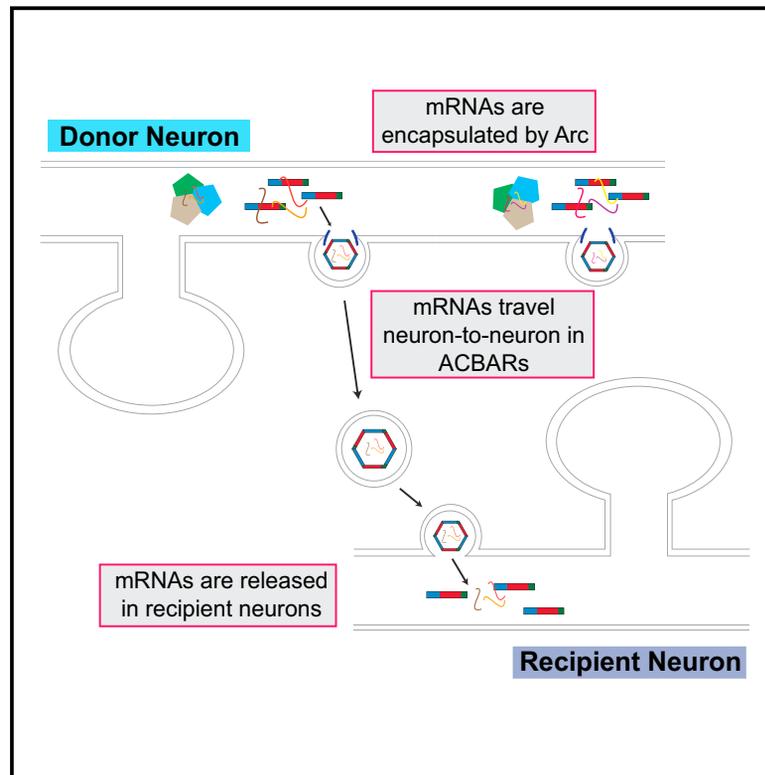


# The Neuronal Gene *Arc* Encodes a Repurposed Retrotransposon Gag Protein that Mediates Intercellular RNA Transfer

## Graphical Abstract



## Authors

Elissa D. Pastuzyn, Cameron E. Day, Rachel B. Kearns, ..., John A.G. Briggs, Cédric Feschotte, Jason D. Shepherd

## Correspondence

jason.shepherd@neuro.utah.edu

## In Brief

The neuronal protein Arc is evolutionarily related to retrotransposon Gag proteins and forms virus-like capsid structures that can transfer mRNA between cells in the nervous system.

## Highlights

- The neuronal gene *Arc* encodes a protein that forms virus-like capsids
- Arc protein exhibits similar biochemical properties as retroviral Gag proteins
- Endogenous Arc protein is released from neurons in extracellular vesicles (EVs)
- Arc EVs and capsids can mediate intercellular transfer of *Arc* mRNA in neurons



# The Neuronal Gene *Arc* Encodes a Repurposed Retrotransposon Gag Protein that Mediates Intercellular RNA Transfer

Elissa D. Pastuzyn,<sup>1</sup> Cameron E. Day,<sup>1</sup> Rachel B. Kearns,<sup>1</sup> Madeleine Kyrke-Smith,<sup>1</sup> Andrew V. Taibi,<sup>1</sup> John McCormick,<sup>2</sup> Nathan Yoder,<sup>1</sup> David M. Belnap,<sup>3,4</sup> Simon Erlendsson,<sup>5,6</sup> Dustin R. Morado,<sup>5</sup> John A.G. Briggs,<sup>5</sup> Cédric Feschotte,<sup>2</sup> and Jason D. Shepherd<sup>1,3,7,\*</sup>

<sup>1</sup>Department of Neurobiology and Anatomy

<sup>2</sup>Department of Human Genetics

<sup>3</sup>Department of Biochemistry

<sup>4</sup>Department of Biology

The University of Utah, Salt Lake City, UT, USA

<sup>5</sup>Department of Biology, University of Copenhagen, Copenhagen, Denmark

<sup>6</sup>MRC Laboratory of Molecular Biology, Cambridge, UK

<sup>7</sup>Lead Contact

\*Correspondence: [jason.shepherd@neuro.utah.edu](mailto:jason.shepherd@neuro.utah.edu)

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## SUMMARY

The neuronal gene *Arc* is essential for long-lasting information storage in the mammalian brain, mediates various forms of synaptic plasticity, and has been implicated in neurodevelopmental disorders. However, little is known about *Arc*'s molecular function and evolutionary origins. Here, we show that *Arc* self-assembles into virus-like capsids that encapsulate RNA. Endogenous *Arc* protein is released from neurons in extracellular vesicles that mediate the transfer of *Arc* mRNA into new target cells, where it can undergo activity-dependent translation. Purified *Arc* capsids are endocytosed and are able to transfer *Arc* mRNA into the cytoplasm of neurons. These results show that *Arc* exhibits similar molecular properties to retroviral Gag proteins. Evolutionary analysis indicates that *Arc* is derived from a vertebrate lineage of Ty3/*gypsy* retrotransposons, which are also ancestors to retroviruses. These findings suggest that Gag retroelements have been repurposed during evolution to mediate intercellular communication in the nervous system.

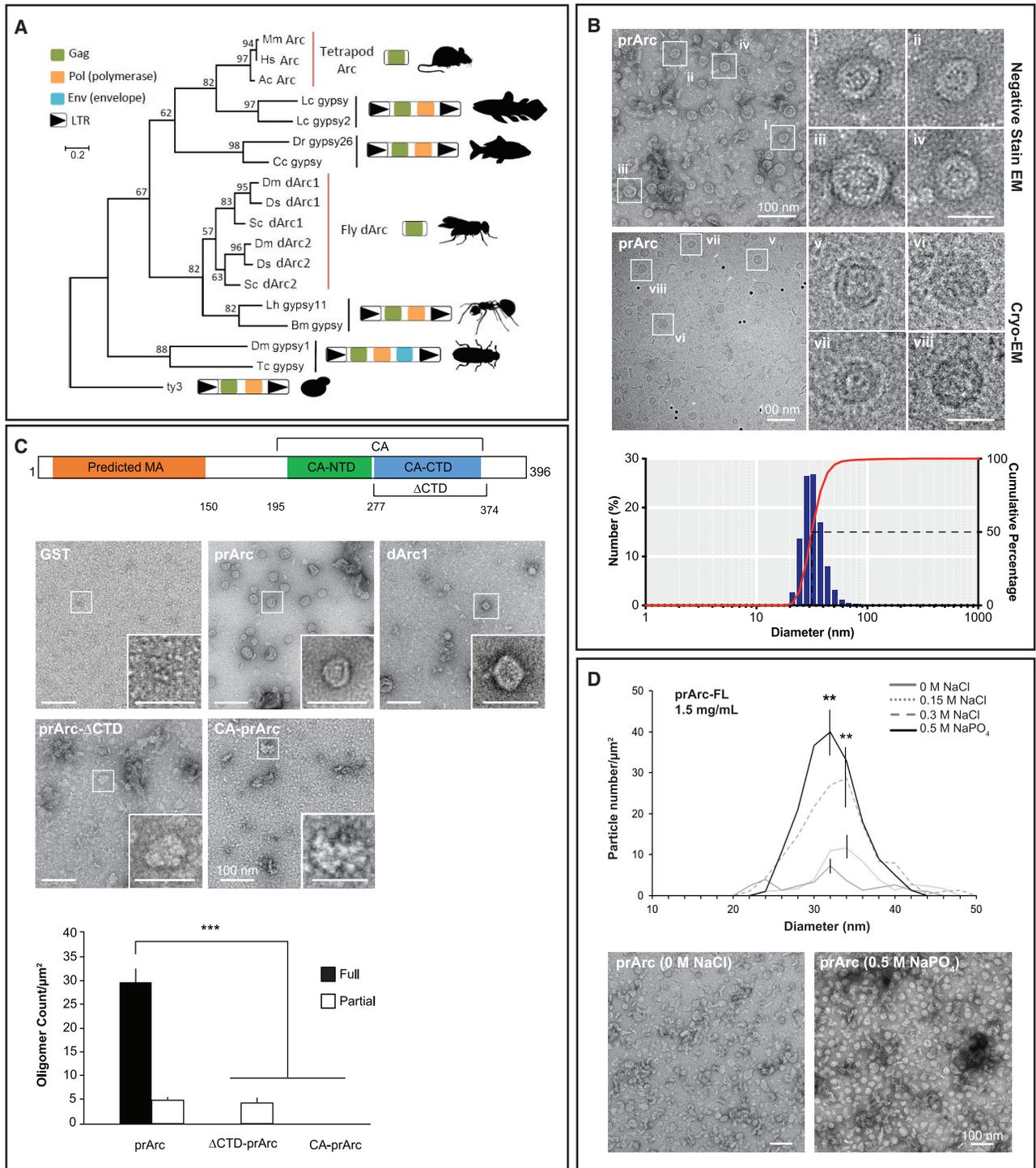
## INTRODUCTION

Brains have evolved to process and store information from the outside world through synaptic connections between interconnected networks of neurons. Despite the fundamental importance of information storage in the brain, we still lack a detailed molecular and cellular understanding of the processes involved and their evolutionary origins. Eukaryotic genomes are littered with DNA of viral or transposon origin, which compose about half of most mammalian genomes (Smit, 1999). A growing body of evidence indicates the sequences encoded by these

elements can provide raw material for the emergence of new functions and regulatory elements (Chuong et al., 2017). In vertebrates, these include dozens of protein-coding genes derived from sequences previously encoded by transposons (Feschotte and Pritham, 2007) or retroviruses (Kaneko-Ishino and Ishino, 2012). Interestingly, many of these transposon-derived genes are expressed in the brain, but their molecular functions remain to be elucidated.

The neuronal gene *Arc* contains structural elements found within viral Group-specific antigen (Gag) polyproteins that may have originated from the Ty3/*gypsy* retrotransposon family (Campillos et al., 2006; Shepherd, 2017; Zhang et al., 2015), although the role these Gag elements play in *Arc* function has not been explored. *Arc* is a master regulator of synaptic plasticity in mammals and is required for protein synthesis-dependent forms of long-term potentiation (LTP) and depression (LTD) (Bramham et al., 2010; Shepherd and Bear, 2011). *Arc* can regulate synaptic plasticity through the trafficking of AMPA-type glutamate receptors (AMPA) via the endocytic machinery (Chowdhury et al., 2006). This endocytic pathway maintains levels of surface AMPARs in response to chronic changes in neuronal activity through synaptic scaling, thus contributing to neuronal homeostasis (Shepherd et al., 2006). *Arc*'s expression in the brain is highly dynamic; its transcription is tightly coupled to encoding of information in neuronal circuits *in vivo* (Guzowski et al., 1999). *Arc* mRNA is transported to dendrites and becomes enriched at sites of local synaptic activity where it is locally translated into protein (Steward et al., 1998; Waung et al., 2008). Intriguingly, aspects of *Arc* mRNA regulation resemble some viral RNAs, as *Arc* contains an internal ribosomal entry site (IRES) that allows cap-independent translation (Pinkstaff et al., 2001). *Arc* is required *in vivo* to transduce experience into long-lasting changes in visual cortex plasticity (McCurry et al., 2010) and for long-term memory (Guzowski et al., 2000; Plath et al., 2006). In addition, *Arc* has been implicated in various neurological disorders that include Alzheimer's disease (AD) (Wu et al., 2011), neurodevelopmental disorders, such as





**Figure 1. Arc Forms Virus-like Capsids via a Conserved Retroviral Gag CA Domain**

(A) Maximum likelihood phylogeny based on an amino acid alignment of tetrapod Arc, fly dArc1, and Gag sequences from related Ty3/gypsy retrotransposons. Schematics of Gag-only Arc genes and Ty3/gypsy elements are included to the right of the tree. In lineages without Arc genes, the most closely related sequences to Arc are Gag-pol polyproteins flanked by long terminal repeats (LTRs) as expected in bona fide Ty3/gypsy retrotransposons.

(B) (Top) Representative negative-stain EM images of full-length purified rat Arc (prArc) protein (1 mg/mL, 42,000 $\times$ ). (i–iv) Magnified view of boxed particles. Scale bars, 30 nm. Representative cryo-EM images of prArc (2 mg/mL, 62,000 $\times$ ). (v–viii) Magnified images of Arc capsids showing the double-layered capsid shell. Scale bars, 30 nm. (Bottom) Dynamic light-scattering analysis of prArc capsids. The weighted size distribution profile is represented as a histogram of the number of particles.

(legend continued on next page)

Angelman (Greer et al., 2010; Pastuzyn and Shepherd, 2017) and Fragile X syndrome (Park et al., 2008), and schizophrenia (Fromer et al., 2014; Managò et al., 2016; Purcell et al., 2014). Thus, precise regulation of Arc expression and activity in the nervous system seems essential for normal cognition.

Despite its importance, little is known about Arc protein biochemistry and molecular function. Here, we uncover a potential role for Arc in mediating intercellular communication via extracellular vesicles (EVs). Synaptic communication is modulated by many other communication pathways that include glia-neuron interactions, and emerging evidence suggests that EVs mediate intercellular signaling in the nervous system (Budnik et al., 2016; Zappulli et al., 2016). EVs can be broadly divided into two groups, microvesicles and exosomes, which are defined both by size and subcellular origin. Microvesicles pinch off from the plasma membrane directly and are usually 100–300 nm in diameter, whereas exosomes are derived from intraluminal vesicles that originate from multivesicular bodies (MVBs) and are usually <100 nm in size. EVs can transport cargo that do not readily cross the plasma membrane, such as membrane proteins and various forms of RNA. The observation that EVs can function in the intercellular transport of these molecules within the nervous system opens an entirely new perspective on intercellular communication in the brain.

Here, we find that Arc protein self-assembles into oligomers that resemble virus capsids and exhibit several other biochemical properties seen in retroviral Gag proteins such as RNA binding. Moreover, Arc is released from neurons in EVs and is able to transfer its own mRNA into neurons. The *Drosophila* Arc homolog, dArc1, also forms capsids and mediates intercellular transfer of its own mRNA at the fly neuromuscular junction, despite originating from a distinct retrotransposon lineage. These data suggest that co-option of retroviral-like Gag elements may have provided an evolutionary pathway for novel mechanisms that mediate intercellular signaling and have been intricately involved in the evolution of synaptic plasticity and animal cognition.

## RESULTS

### Fly and Tetrapod Arc Genes Independently Originated from Distinct Lineages of Ty3/gypsy Retrotransposons

To shed light onto Arc's evolutionary origins, we performed phylogenomic analyses (Figures 1A and S1A). Highly conserved, unique orthologs of the murine Arc genes were identified throughout the tetrapods (mammals, birds, reptiles, amphibians), but were conspicuously absent from all fish lineages and other deuterostomes examined (94 species). The closest rela-

tives of Arc in the coelacanth, zebrafish, and carp genomes were encoded by prototypical Ty3/gypsy retrotransposons, with indications of recent transposition activity. Similarly, orthologs and paralogs of *Drosophila* Arc (*darc1*, *darc2*) were identified in all schizophoran (true) flies represented in the database but were not detected in any other dipteran (e.g., mosquitoes) or protostome species (286 species; Figure S1B). The closest retrotransposon relatives of the fly Arc genes were found in the genomes of the silkworm and Argentine ant. Interestingly, while Arc appears to be a single-copy gene in all tetrapods examined, the gene has experienced multiple rounds of duplication during schizophoran evolution (Figure S1B). Phylogenetically, tetrapod Arc genes cluster with Ty3/gypsy retrotransposons from fish, whereas the fly Arc homologs group with a separate lineage of Ty3/gypsy retrotransposons from insects (Figure 1A). These results indicate that the tetrapod and fly Arc genes originated independently from distinct lineages of Ty3/gypsy retrotransposons but still share significant homology in the retroviral Gag domain.

### Arc Proteins Self-Assemble into Virus-like Capsids

Ty3 retrotransposons can form oligomeric particles that resemble retroviral capsids (Hansen et al., 1992), and Arc also has a propensity to oligomerize (Myrum et al., 2015). Retroviral capsid formation is essential for infectivity and is primarily mediated by the Gag polyprotein, which in HIV contains four main functional domains: matrix/MA, capsid/CA, nucleocapsid/NC, and p6 (Freed, 2015). Arc has both primary sequence (Campillos et al., 2006) and structural similarity to CA of HIV and Foamy Virus Gag polyproteins (Taylor et al., 2017; Zhang et al., 2015), suggesting that Arc may share functional similarities to Gag proteins. To characterize the biochemical properties of Arc protein, we expressed rat Arc in bacteria as a glutathione S-transferase (GST) fusion protein. The expressed protein was purified by affinity and size exclusion chromatography, and the GST tag was removed by proteolysis (Figures S2A and S2B). Purified preparations of rat Arc (prArc) were analyzed using negative-stain electron microscopy (EM) and cryoelectron microscopy (cryo-EM). These experiments revealed that prArc spontaneously forms oligomeric structures that resemble virus-like capsids (Figure 1B). prArc capsids exhibited a double-shell structure with a mean diameter of  $32 \pm 0.2$  nm. Similarly, bacterially expressed and purified dArc1 (Figure S2C), the *Drosophila* Arc homolog, also self-assembled into capsid-like structures (Figure 1C). Purified Arc protein that was expressed in an insect cell expression system also assembled into similar virus-like capsids (data not shown), indicating that oligomerization was not an artifact of bacterial expression. Immature retroviral capsids are formed by the uncleaved Gag polyprotein, and the major stabilizing

(C) Schematic of Arc protein with the predicted matrix (MA) (orange), CA-NTD (green), and CA-CTD (blue) domains. Also depicted are the  $\Delta$ CTD deletion mutant and the CA domain constructs. Representative negative-stain EM images of purified GST, prArc, the *Drosophila* Arc homolog dArc1, prArc- $\Delta$ CTD, and CA-prArc (all 1 mg/mL, 20,000 $\times$ ). Inset scale bars, 50 nm. (Bottom) Quantification of capsid formation. Fully formed capsids include spherical particles that are between 20–60 nm and have clear double shells, while partially formed capsids do not have clear double shells (scale bars, 100 nm). Data are the average of 3 independent experiments  $\pm$  SEM using 3 different prArc preparations. \*\*\* $p < 0.001$ , two-way ANOVA with *post hoc t*-tests.

(D) (Top) To determine properties of Arc capsid stability, we exchanged prArc into buffers with increasing molar concentrations of salt and examined by negative-stain EM. Arc capsids were counted manually and quantified in each buffer condition at a protein concentration of 1.5 mg/mL. Data are the average of 3 independent experiments  $\pm$  SEM using different prArc preparations. \*\* $p < 0.01$ , Student's *t*-test. (Bottom) Representative EM images of prArc under 0 M NaCl and 0.5 M NaPO<sub>4</sub> conditions.

See also Figure S1.

interactions are made by the C-terminal domain (CTD) of the CA region (Mattei et al., 2016). To test whether the putative Arc CA CTD is also required for self-assembly, we expressed and purified a rat Arc mutant protein that lacked this domain (prArc- $\Delta$ CTD, missing amino acids [aa] 277–374, Figures 1C, S2A, and S2B) (Zhang et al., 2015). EM analyses revealed that prArc- $\Delta$ CTD was unable to form double-shelled capsids, although intermediate irregular structures were occasionally observed (Figure 1C). To test whether the Arc CA domain was sufficient for capsid assembly we created a mutant Arc protein that contained aa195–364 (CA-prArc; Figures 1C and S2A). CA-prArc was not sufficient to form capsid-like structures. Arc capsids exhibit other properties similar to HIV capsids, including sensitivity to salt and phosphate levels (Purdy et al., 2008); increasing concentrations of NaCl from 0 to 300 mM resulted in stable prArc capsids and high NaPO<sub>4</sub> further stabilized capsid formation (Figure 1D).

To test whether Arc forms oligomers in cells, we expressed Arc in HEK293 cells, which lack endogenous Arc, and performed chemical crosslinking to test for the presence of oligomeric species. Arc proteins crosslinked *in situ* formed higher molecular weight species with the SDS-PAGE mobility expected for dimer and trimer subunits (Figure S2D), which is reminiscent of HIV Gag subunits using a similar crosslinking assay (Campbell and Rein, 1999). In contrast, transfected GFP did not form higher molecular weight crosslinks under the same conditions.

### Arc Binds and Encapsulates RNA

Retroviral encapsulation of viral genomic RNA is a complex process mediated by a network of interactions between Gag, RNA and lipid membranes (Mailler et al., 2016). HIV Gag contains zinc-finger knuckle motifs in the NC domain that mediate viral RNA binding and selection (Carlson et al., 2016), but in the absence of viral RNA, Gag can also bind cellular mRNAs, which may reflect nonspecific RNA interactions with the basic MA and NC domains (Comas-Garcia et al., 2016). Interestingly, Foamy Virus Gags do not contain zinc-finger domains and bind RNA through C-terminal glycine-arginine-rich patches (Hamann and Lindemann, 2016), indicating that distinct Gag domains from different viral families have evolved to perform similar biochemical processes. Like Foamy Virus Gag, Arc does not appear to contain zinc-finger domains but may bind RNA through ionic interactions in its N terminus. We observed that prArc appeared to co-purify with RNA or other nucleic acids, as the preparations had a higher A<sub>260/280</sub> spectrophotometric ratio than would be expected for a pure recombinant protein (prArc 1.04 ± 0.024; Endophilin3A 0.55 ± 0.006; n = 3, p < 0.01; Figure S2B). We therefore hypothesized that Arc might bind and encapsulate RNA. To ascertain whether prArc capsids contain mRNA, we determined levels of Arc mRNA and a highly abundant bacterial mRNA, *asnA* (Zhou et al., 2011), using qRT-PCR. We detected both Arc and *asnA* mRNA (Figure 2A). However, Arc mRNA levels were ~10-fold higher than *asnA*. Bacterial cell lysate contained ~15-fold higher Arc mRNA levels than *asnA* (Figure 2A), suggesting that prArc capsids show little specificity for a particular mRNA, but encapsulate abundant RNA according to stoichiometry. If mRNA is encapsulated in capsids, it should be resistant to ribonuclease (RNase) treatment. RNase did not degrade Arc or

*asnA* mRNA, but significantly degraded exogenous free GFP mRNA (Figure 2B), indicating that Arc and *asnA* mRNA were protected from RNase degradation.

We tested whether Arc protein associates with Arc mRNA *in vivo* by immunoprecipitating Arc protein from mouse cortical lysate, followed by qRT-PCR (Figure 2C). Arc mRNA was found to selectively immunoprecipitate (IP) with Arc protein, while *GAPDH* was not enriched in Arc IPs. These results suggest that Arc protein and its mRNA form a complex in neurons *in vivo*.

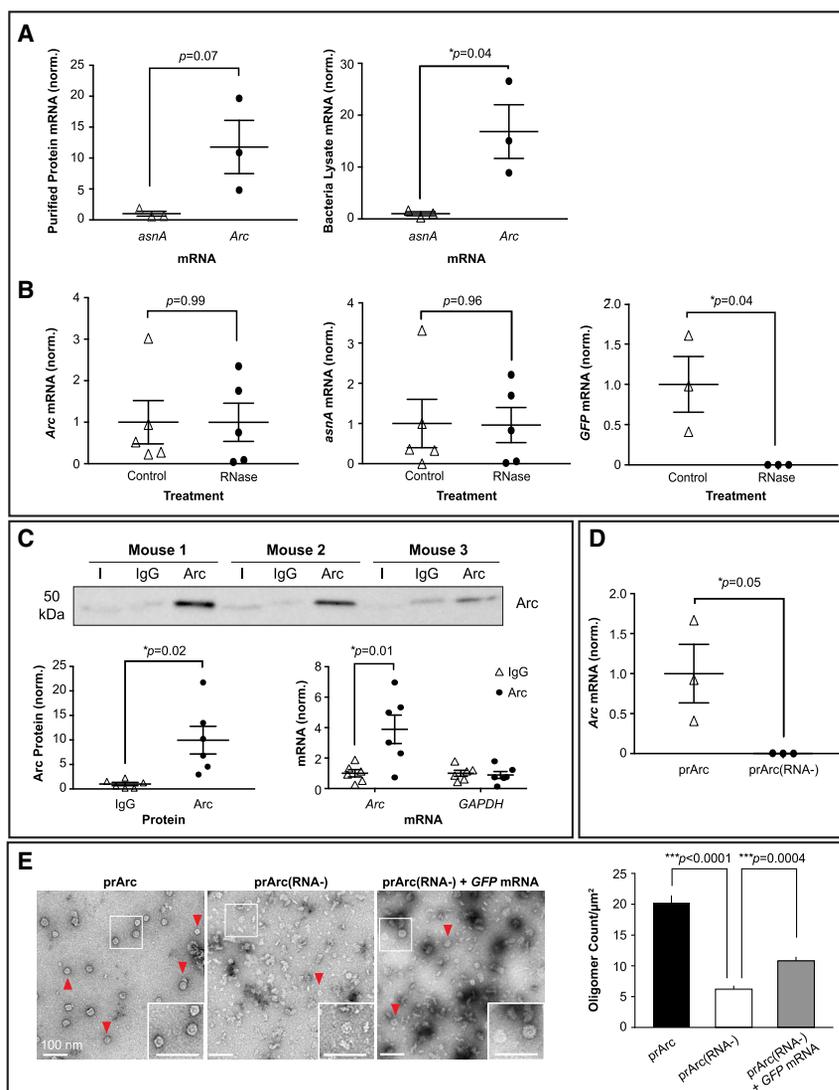
### Arc Capsid Assembly Requires RNA

To form the immature viral capsid, HIV Gag must bind RNA (Mailler et al., 2016). To test whether Arc capsid formation requires RNA, we purified full-length Arc protein as above and then stripped bound nucleic acids (“prArc(RNA–),” Figure S3A) as previously performed on HIV Gag (Ganser et al., 1999). This procedure reduced the A<sub>260/280</sub> ratio significantly (prArc(RNA–) 0.68 ± 0.03, prArc 1.04 ± 0.024; n = 3, p < 0.05) and we were unable to detect Arc mRNA association by qRT-PCR (Figure 2D). Stripping RNA resulted in significantly fewer fully formed capsids (Figure 2E), suggesting that Arc capsids require RNA for normal assembly. To show directly that RNA facilitated Arc capsid assembly, we exogenously added GFP mRNA to prArc(RNA–) (7.3% w/w), which resulted in significantly more fully formed Arc capsids.

### Arc Protein and Arc mRNA Are Released by Neurons in Extracellular Vesicles

Retroviral capsids and EVs are released from cells using similar cellular machinery, such as the MVB pathway (Nolte-t Hoen et al., 2016). Since Arc exhibits many of the biochemical properties of a viral Gag protein, we tested whether Arc protein might also be released from cells. We harvested media from Arc-transfected HEK293 cells and purified the EV fraction. This fraction contained vesicular structures that were < 100nm and resembled exosomes (Figure S3B). Arc protein was detected in the EV fraction, which was also positive for the EV marker ALIX, but lacked actin (Figure 3A). Conversely, Arc- $\Delta$ CTD-transfected HEK cells exhibited little expression in the EV fraction (Figure 3B), suggesting that proper Arc capsid assembly may be required for Arc release via EVs. We performed qRT-PCR on the EV fraction from HEK cell media and detected Arc mRNA that was resistant to RNase treatment (Figure 3C).

Native Arc protein was also found in the EV fraction prepared from media harvested from DIV15 cultured cortical mouse neurons (Figure 3D). Since Arc mRNA associates with Arc protein in brain lysate, we used RT-PCR to show that Arc mRNA is also present in EVs purified from neurons (Figure 3E). Arc protein in EVs was resistant to trypsin digestion (Figure S3C), indicating that Arc protein and RNA were protected or bound in a complex within EVs. To directly determine whether Arc protein is present in EVs, we conducted immunogold-labeling of endogenous Arc in the EV fraction from cultured neurons and found that Arc is present in a subpopulation of EVs (Figure 3F). To test whether Arc release in EVs is activity dependent, we purified the EV fraction from media collected from untreated or KCl-treated wild-type (WT) cultured cortical neurons (Figure S3D). KCl treatment, which increases neuronal activity, resulted in significantly more Arc released into the media.



**Figure 2. Arc Protein Interacts with mRNA**

(A) (Left) qRT-PCR of *Arc* mRNA and the bacterial mRNA *asnA* from prArc. (Right) qRT-PCR of *Arc* and *asnA* mRNA from total bacteria lysate. Data presented as the mean  $\pm$  SEM normalized to the average of the *asnA* group (Student's *t*-test,  $n = 3$  independent protein preparations,  $*p < 0.05$ ).

(B) Protein preparations were treated with or without RNase A for 15 min, and qRT-PCR was performed. RNase treatment did not affect *Arc* and *asnA* mRNA levels (paired *t*-test,  $n = 5$  independent protein samples), but significantly degraded exogenous/free *GFP* mRNA (paired *t*-test,  $n = 3$  independent samples,  $*p < 0.05$ ). Data are presented as  $\pm$  SEM normalized to the average of the untreated group.

(C) (Top) Representative western blots of Arc protein that was immunoprecipitated (IP) from WT mouse cortical tissue using an Arc or immunoglobulin G (IgG) antibody. Input (I) = 10% total lysate. (Bottom, left) Quantification of Arc protein IP showing significant enrichment of Arc protein using an Arc antibody. (Bottom, right) qRT-PCR was performed on the eluted fractions from the IP. *Arc* mRNA was specifically pulled down in the IP (two-way ANOVA with repeated-measures and Sidak's multiple comparisons: Arc+Arc versus Arc+IgG,  $p = 0.01$ ; Arc+Arc versus GAPDH+Arc,  $p = 0.013$ ; Arc+Arc versus GAPDH+IgG,  $p = 0.011$ ). Data are presented as the mean  $\pm$  SEM normalized to the average of the IgG group.

(D) qRT-PCR of *Arc* mRNA from prArc and prArc(RNA-). There was significantly less *Arc* mRNA in the prArc(RNA-) preparations. Presented as the mean  $\pm$  SEM normalized to the average of the prArc group (Student's *t*-test,  $n = 3$  independent samples,  $*p = 0.05$ ).

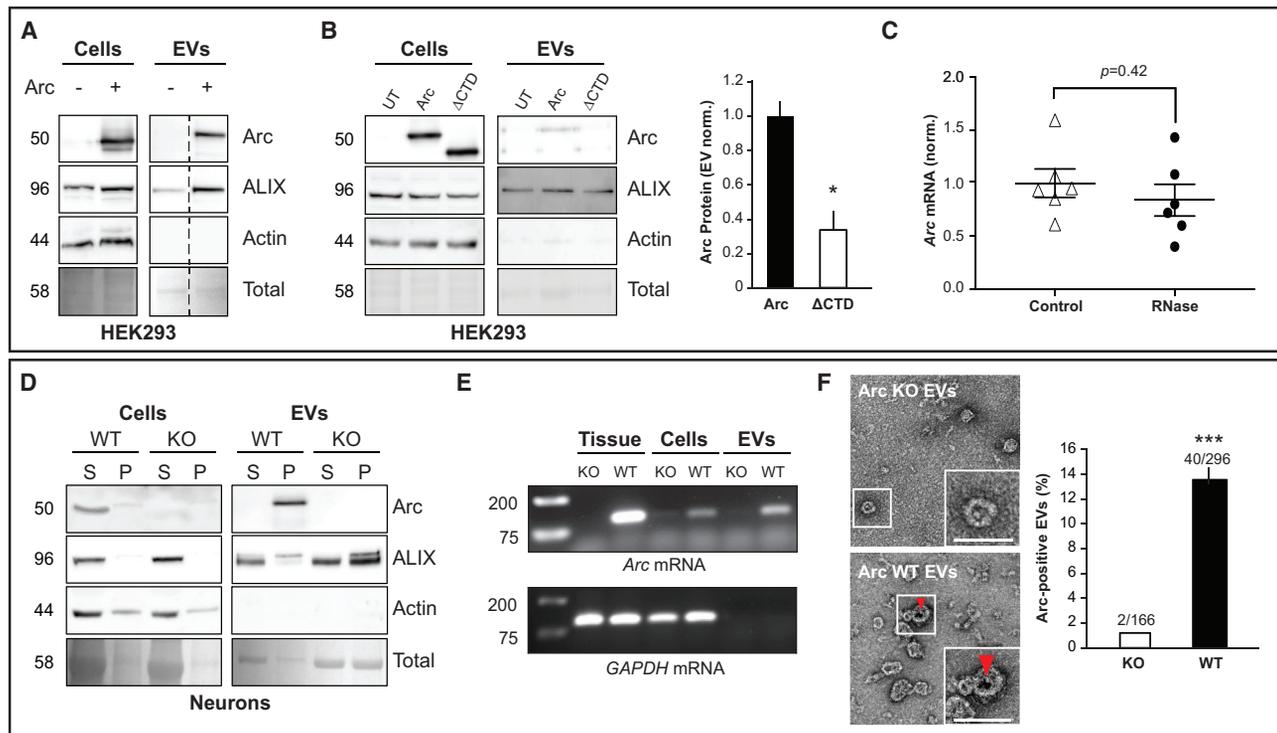
(E) (Left) Representative negative-stain EM images of prArc, prArc(RNA-), and prArc(RNA-) incubated with 7.3% (w/w) *GFP* mRNA at RT for 2 hr (0.25 mg/mL, 15,000 $\times$ ). Fully formed capsids are indicated by red arrows (scale bars, 100 nm). (Right) Capsids were quantified as in Figure 1C. Data are presented as the average of 6 images from each condition  $\pm$  SEM.  $***p < 0.0001$ , unpaired *t*-test. See also Figure S2.

### Arc Mediates Intercellular Transfer of mRNA in Extracellular Vesicles

Virus particles are able to infect cells through complex interactions of the viral envelope and host cell membrane, while EVs can also transfer cargo such as RNAs cell-to-cell (Valadi et al., 2007). We predicted that Arc might be able to transfer mRNA, either directly via mRNA encapsulated in prArc or in Arc-containing EVs. We transfected GFP/myc-Arc or nuclear-GFP into HEK (donor) cells and collected media from these cells after 18 hr, which was then incubated with untransfected, naive HEK (recipient/"transferred") cells for 24 hr. We observed high Arc expression in a sparse population of naive HEK cells (Figure 4A), while cells incubated with media from cells transfected with nuclear-GFP alone did not express nuclear-GFP. Fluorescent *in situ* hybridization (FISH) for *Arc* mRNA revealed high levels of *Arc* mRNA in recipient cells. Uptake of Arc protein and mRNA was endocytosis-dependent, as application of Dy-

nasore (a potent inhibitor of clathrin-dependent endocytosis [Macia et al., 2006]) significantly blocked transfer of Arc protein (Figure S4A). Since encapsulation of RNA by Arc capsids is nonspecific *in vitro*, we tested whether Arc could co-transfer highly abundant mRNAs. Donor HEK cells were transfected with myc-Arc and/or a membrane-bound GFP (mGFP), and media were collected after 24 hr. Recipient HEK cells showed clear transfer of both GFP protein and mRNA when donor cells contained Arc (Figure 4B). No transfer was observed from cells transfected only with mGFP. These data suggest that Arc EVs released from HEK cells are capable of transferring highly abundant mRNAs cell-to-cell.

To test whether Arc capsids can transfer Arc mRNA into neurons, we incubated cultured hippocampal neurons from Arc knockout (KO) mice with prArc. Since the Arc KO line contains GFP knocked into the Arc locus (Wang et al., 2006), we imaged Arc in the red channel and were unable to detect GFP



**Figure 3. Arc Is Released from Cells in Extracellular Vesicles**

(A) HEK cells in 10-cm dishes were transfected with full-length rat WT myc-Arc and media collected 24 hr later. Representative western blots ( $n = 3$  independent experiments) show Arc protein in total cell lysates (cells) and the EV fraction purified from cell media in Arc transfected (+) and untransfected (–) cells. ALIX was used as an EV fraction marker. Ponceau stain was used to visualize the total amount of protein in each lane. The dashed line indicates splicing marks in the blot to compare the (–) and (+) EV lanes. All data are from the same blot, and experiments were performed at the same time.

(B) HEK293 cells were transfected with myc-Arc-WT or myc-Arc- $\Delta$ CTD, and media was collected 24 hr later. Representative western blots ( $n = 3$  independent experiments) show Arc protein in total cell lysates (cells) and the EV fraction from cell media. Arc levels in the EV fraction were normalized to Arc protein levels in the cell lysate for each experiment, and data are presented normalized to WT levels ( $n = 3$ ). \* $p < 0.05$ , Student's  $t$ -test.

(C) HEK EV fractions were untreated (control) or treated with RNase ( $n = 6$  independent cultures) prior to RNA extraction. qRT-PCR was used to measure Arc mRNA levels, and data are presented as the mean  $\pm$  SEM normalized to the average of the untreated group. Paired  $t$ -test.

(D) Media were harvested from DIV15 cultured cortical neurons obtained from WT and Arc KO mice after 24 hr incubation, and the EV fraction was purified from collected media. Blots indicate levels of Arc, ALIX, and actin from supernatant (S)/soluble fraction and pellet (P)/insoluble fraction for total cellular lysate (cells). (S)/last wash of the ultracentrifugation purification protocol and final pellet (P)/EV fraction for purified EV fraction (EVs). 2.5% of S and P were loaded for cellular lysates. 5% of S and P were loaded for the EV fraction.

(E) RT-PCR using Arc and GAPDH primers was performed on WT or KO mouse cortical tissue, mouse cortical DIV15 WT or KO neurons (cells), and EVs purified from media collected from WT or KO cultured neurons. Arc mRNA was present in all three preparations, whereas GAPDH mRNA was absent from EVs.

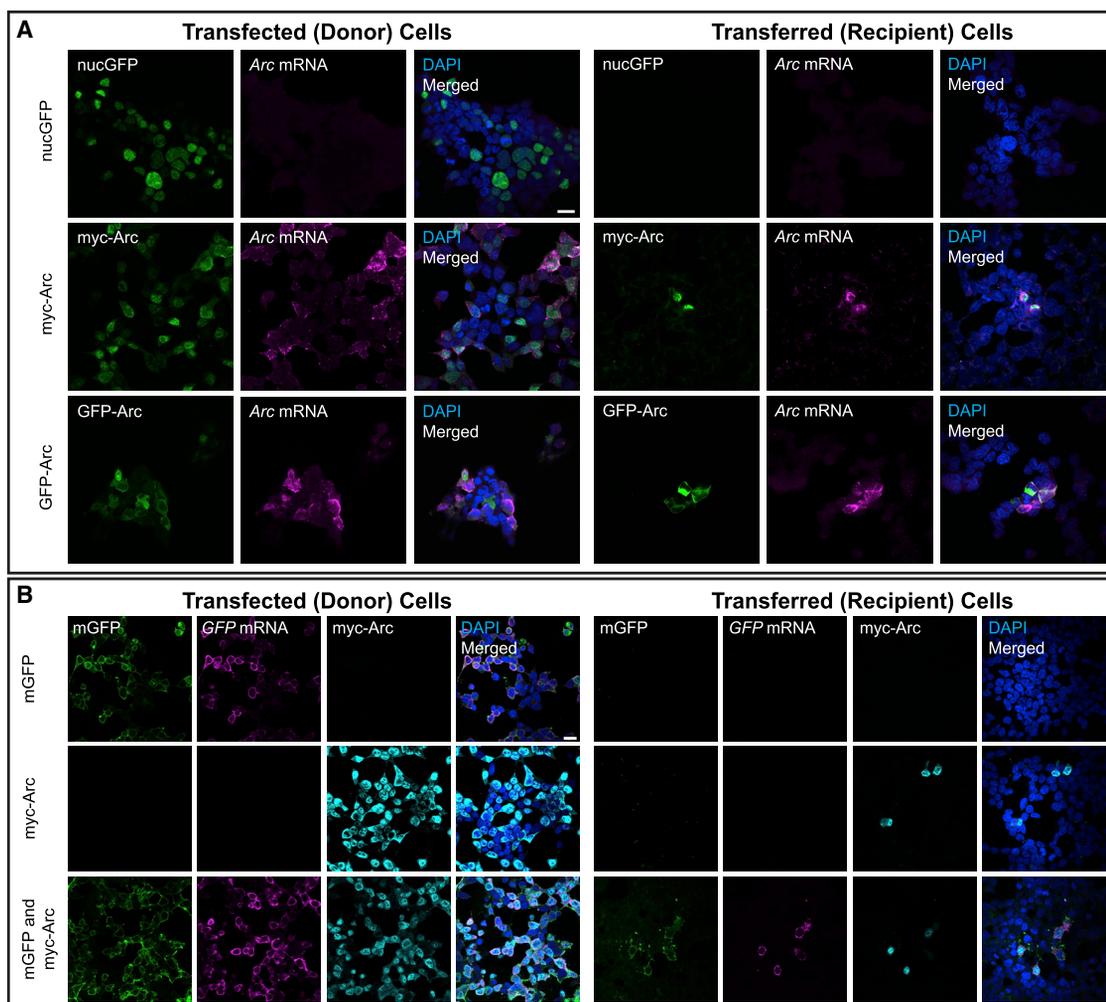
(F) (Top) Immunogold labeling for Arc in EVs obtained from the same Arc KO or WT cultured neuronal media in (D). Red arrow indicates a 10 nm immunogold particle (20,000 $\times$ ). (Bottom) Quantification of EVs (vesicular structures  $< 100$  nm) that were Arc-positive  $\pm$  SEM using immunogold labeling ( $n = 3$  independent experiments/EV preparations). \*\*\* $p < 0.001$ , Student's  $t$ -test.

See also Figure S3.

fluorescence in the green channel (Figure S4B). We observed uptake of Arc protein into KO neurons above antibody background levels (see Figure S4C for antibody specificity) within 1h of protein incubation, which peaked around 4h of incubation (Figure 5A). To directly determine whether Arc capsids can transfer Arc mRNA into neurons, we measured Arc mRNA levels in Arc KO neurons incubated with prArc. Arc FISH showed robust and high levels of transferred Arc mRNA after 4h of incubation with prArc (Figure 5B). RNase treatment of prArc prior to incubation had no effect on mRNA transfer (Figure S5A), further suggesting that Arc capsids are able to protect and encapsulate Arc mRNA. Blocking endocytosis using Dynasore prevented uptake of both prArc protein and Arc mRNA (Figure S5B). Transferred mRNA

and protein were evident both in early endosomes (marked by Rab5) and non-endosome compartments in dendrites (Figure S5C). Both uptake and transfer of purified prArc- $\Delta$ CTD and CA-prArc protein and mRNA was significantly less than the full-length protein, indicating that capsid formation is required for uptake into neurons (Figures 5C and 5D). Lack of protein uptake was not due to poor detection by the custom-made Arc polyclonal antibody (Figure S5D). Strikingly, prArc(RNA–) was unable to be taken up but instead coated the outside of neurons (Figure S6), further suggesting that intact Arc capsids are required for uptake and transfer.

To test whether endogenous Arc can transfer mRNA, we incubated Arc KO cultured hippocampal neurons with purified EVs



**Figure 4. Arc Extracellular Vesicles Mediate Intercellular Transfer of Protein and mRNA in HEK293 Cells**

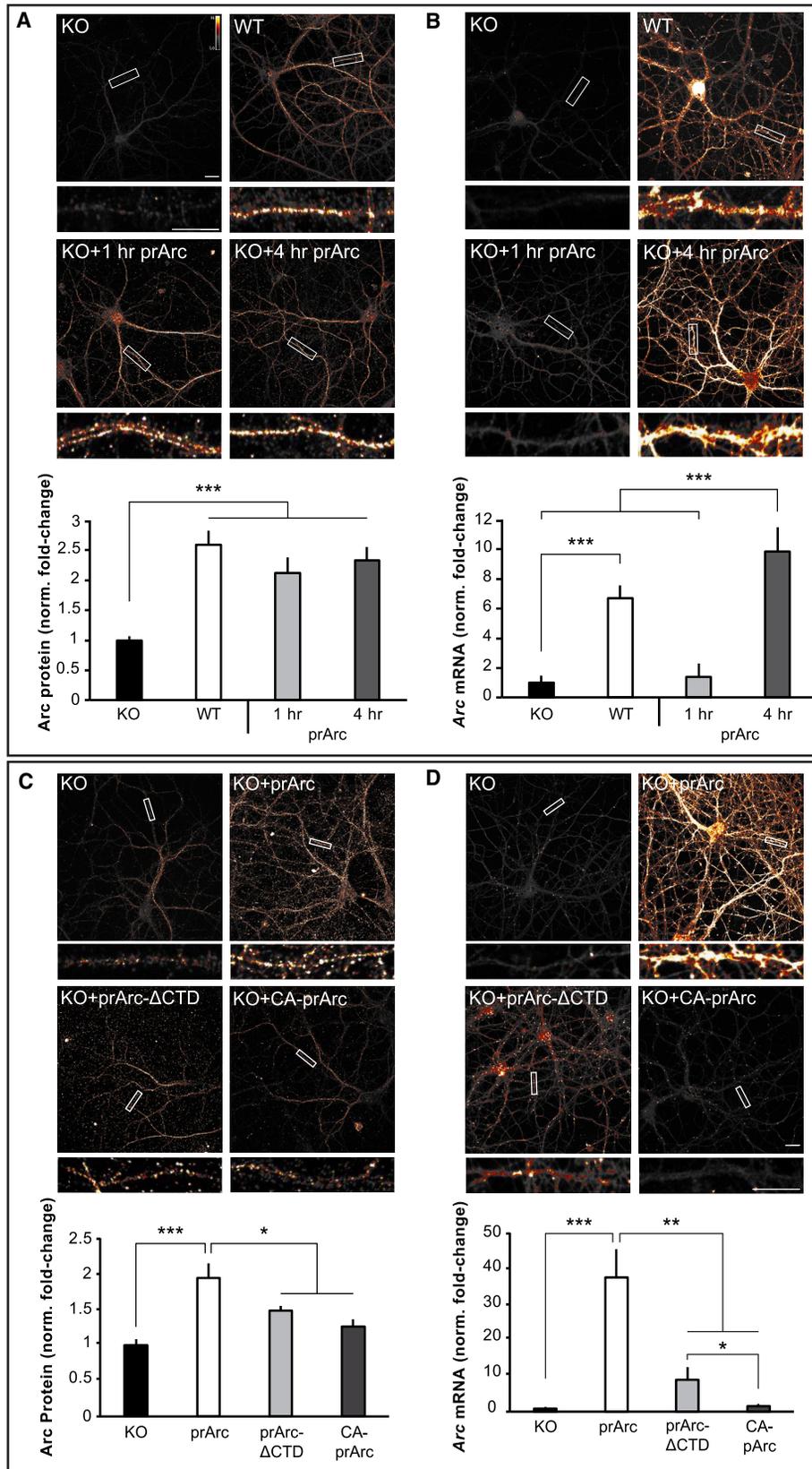
(A) Donor HEK cells in 10-cm dishes were transfected with GFP-Arc, myc-Arc, or nuclear GFP (nucGFP) for 6 hr. Culture media containing plasmid DNA and transfection reagents was then removed and replaced with fresh culture media. 18 hr later, this media was removed and used to replace media on naive recipient HEK cells on coverslips in 12-well plates. 24 hr later, these cells were fixed, and combined FISH for Arc mRNA and immunocytochemistry (ICC) for Arc protein was performed. (Left) Representative images of HEK cells grown on coverslips and transfected with the same protocol used for the 10-cm dishes, showing Arc protein (ICC) and Arc mRNA (FISH). (Right) Representative images of recipient HEK cells showing Arc mRNA, and protein were present in cells that received media from GFP-Arc- and myc-Arc-transfected cells, but not nucGFP-transfected cells. Scale bar, 20  $\mu$ m. Representative of 7 independent experiments and cultures.

(B) Donor HEK cells in 10-cm dishes were transfected like in (A) with membrane GFP (mGFP), myc-Arc, or both constructs together. The media was replaced after 6 hr, and 18 hr later, transferred to naive recipient HEK cells in 12-well plates. 24 hr later, cells were fixed, and combined FISH/ICC for GFP mRNA and Arc protein was performed. (Left) Representative images of transfected HEK cells grown on coverslips, showing mGFP fluorescence, Arc protein, and GFP mRNA. (Right) Representative images of recipient HEK cells that show co-transfer of GFP protein and mRNA with Arc protein. No GFP transfer was observed in the mGFP only group. Scale bar, 20  $\mu$ m. Representative of 3 independent experiments and cultures.

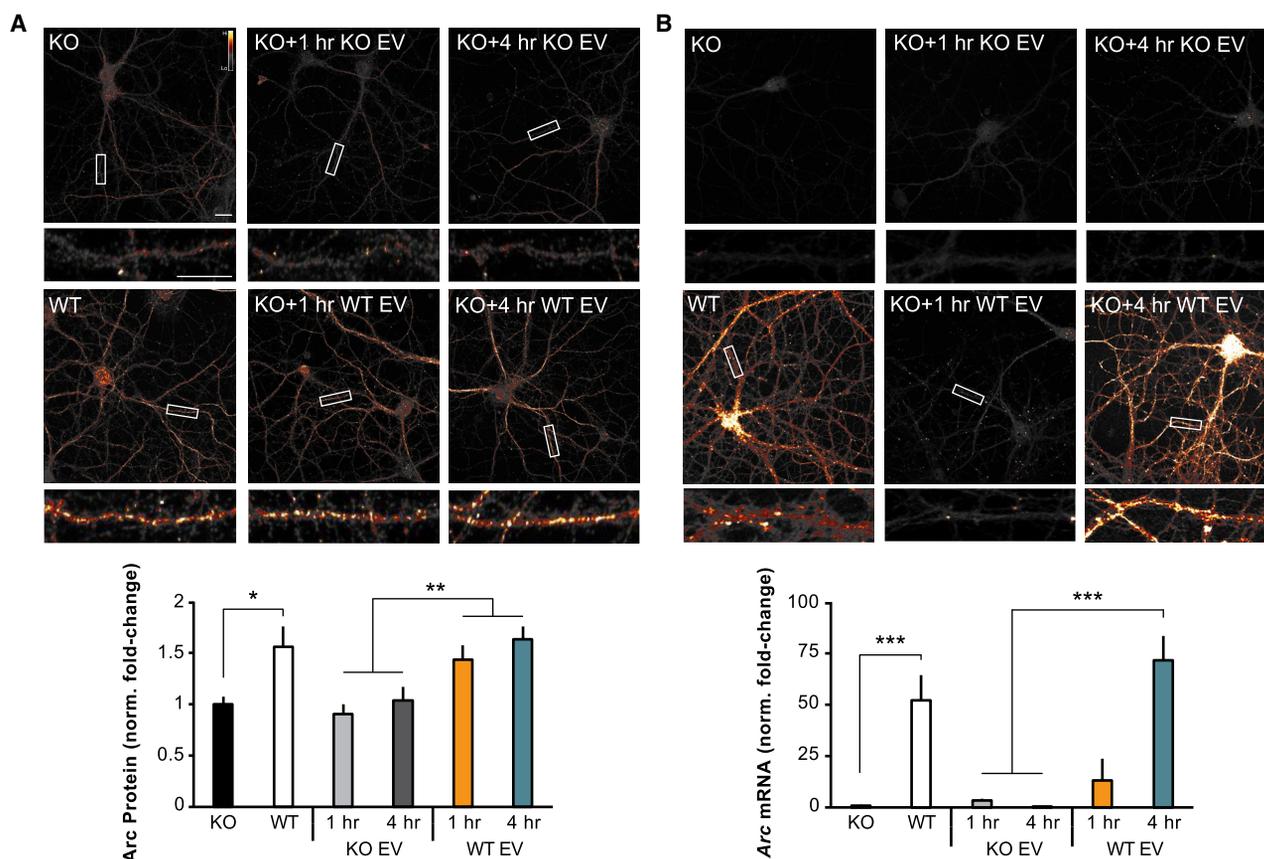
See also [Figure S4](#).

prepared from media from WT or KO cortical neurons. Arc KO neurons incubated with WT EVs showed a clear increase in dendritic Arc levels, while KO neurons incubated with EVs derived from KO cells exhibited no increase in dendritic Arc levels ([Figure 6A](#)). In addition, FISH showed that Arc mRNA in WT EVs was transferred into KO neurons ([Figure 6B](#)). Uptake of Arc mRNA was not significantly affected by prior treatment of EVs with RNase ([Figure S7A](#)), indicating that uptake was not due to

free or unbound Arc mRNA in the EV fraction. Blocking endocytosis with Dynasore prevented the uptake of Arc protein and mRNA from EVs ([Figure S7B](#)). Notably, transferred Arc mRNA expression exhibited cell-wide localization in both early endosomes and non-endosome compartments ([Figure S7C](#)) and was virtually indistinguishable from Arc mRNA distribution in WT neurons. These data indicate that endogenous Arc released via EVs is able to transfer Arc mRNA neuron-to-neuron.



(legend on next page)



### Figure 6. Endogenous Arc Transfers Arc mRNA into Neurons via Extracellular Vesicles

(A) Representative images of Arc ICC from DIV15 cultured hippocampal Arc KO neurons treated for 1 or 4 hr with 10 µg of the EV fraction prepared from 10-cm dishes of DIV15 high-density cortical WT or Arc KO neurons. 1 and 4 hr treatment with KO EVs did not increase dendritic Arc levels, whereas 1 and 4 hr of treatment with WT EVs significantly increased dendritic Arc protein levels.

(B) Neurons were treated like in (A); representative images of Arc mRNA (FISH) are shown. 1 and 4 hr treatment with KO EV did not increase dendritic Arc mRNA levels. 1 hr treatment with WT EV did not significantly increase dendritic Arc levels, whereas 4 hr treatment increased dendritic Arc mRNA levels. 30-µm segments of two dendrites/neuron were analyzed for integrated density measurements in all groups ( $n = 10$  neurons). Arc mRNA and Arc protein levels were normalized to untreated KO neurons and displayed as fold change  $\pm$  SEM. Student's *t*-test: \* $p < 0.05$ . \*\* $p < 0.01$ . \*\*\* $p < 0.001$ . Scale bars, 10 µm. Representative of 6 independent experiments using different EV preparations and cultures.

See also Figure S7.

### Transferred Arc mRNA Can Undergo Activity-Dependent Translation

If Arc mRNA associated with Arc capsids is transferred into the cytoplasm of neurons, we predicted that we would observe an

increase in dendritic Arc protein by inducing translation of Arc mRNA through activation of the group 1 metabotropic glutamate receptor (mGluR1/5) by the agonist DHPG, as previously shown for endogenous Arc (Wang et al., 2008). As predicted, Arc

### Figure 5. Arc Capsids Transfer Arc mRNA into Neurons

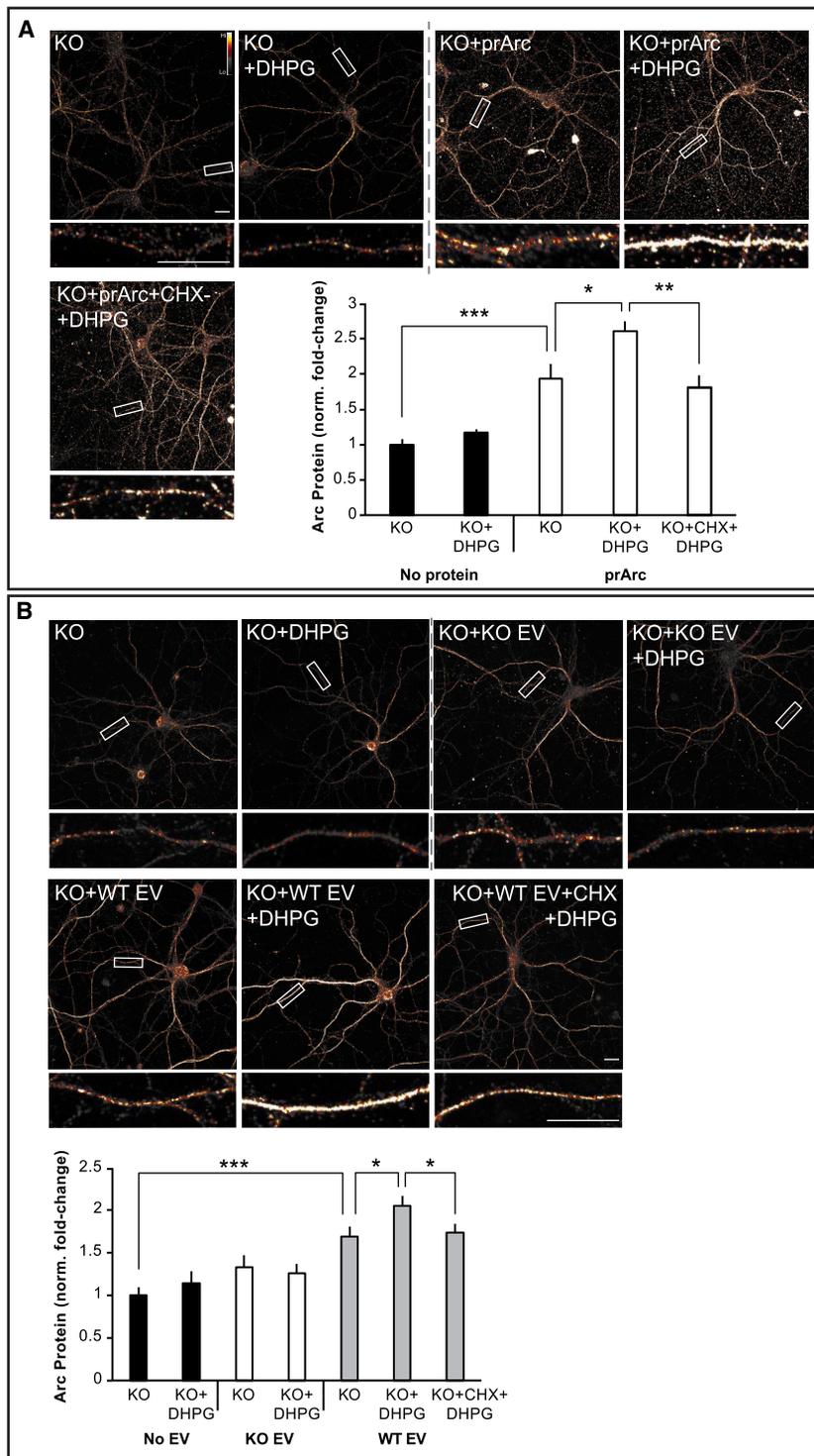
(A) Representative images of Arc ICC from DIV15 cultured hippocampal Arc KO neurons treated for 1 or 4 hr with 4 µg prArc or WT control neurons. prArc-treated neurons show increased dendritic Arc levels relative to untreated KO neurons.

(B) Neurons were treated like in (A); representative images of Arc mRNA (FISH) are shown. 4 hr of prArc treatment significantly increased dendritic Arc mRNA levels in KO neurons.

(C) Representative images of Arc ICC from DIV15 cultured hippocampal KO neurons treated with 4 µg prArc, prArc-ΔCTD, or CA-prArc for 4 hr. KO neurons treated with prArc-ΔCTD and CA-prArc showed lower levels of Arc protein than prArc-treated neurons.

(D) Neurons were treated like in (C); representative images of Arc mRNA are shown. Neurons treated with prArc-ΔCTD and CA-prArc showed lower levels of Arc mRNA than prArc-treated neurons. Dendritic segments boxed in white are magnified beneath each corresponding image. 30-µm segments of two dendrites/neuron were analyzed for integrated density measurements in all groups ( $n = 10$  neurons). Arc mRNA and Arc protein levels were normalized to untreated KO neurons and displayed as fold change  $\pm$  SEM. Student's *t*-test: \* $p < 0.05$ , \*\* $p < 0.01$ , and \*\*\* $p < 0.001$ . Scale bars, 10 µm. Images are false-colored with the Smart LUT from ImageJ. All data are representative of 3–7 independent experiments using different protein preparations and cultures.

See also Figure S5.



**Figure 7. Arc Capsid- and EV-Transferred Arc mRNA Is Accessible for Activity-Dependent Translation**

(A) Representative images of Arc ICC from DIV15 cultured hippocampal Arc KO neurons treated for 4 hr with 4  $\mu$ g prArc. To induce translation of Arc mRNA, 30 min prior to fixation, neurons were treated with the mGluR1/5 agonist DHPG (100  $\mu$ M) for 5 min, and then drugs were washed out. 1 hr prior to fixation, a subset of neurons were pretreated with cycloheximide (CHX; 180  $\mu$ M) to block protein translation. prArc significantly increased dendritic Arc expression in KO neurons, and DHPG treatment further increased dendritic Arc levels, which was blocked by pretreatment with CHX. DHPG had no effect on untreated KO neurons.

(B) Representative images of Arc ICC from DIV15 hippocampal Arc KO neurons treated for 4 hr with 10  $\mu$ g of the EV fraction prepared from 10-cm dishes of DIV15 high-density cortical WT or Arc KO neurons. A subset of neurons was treated with DHPG and CHX like in (A). WT EVs significantly increased dendritic Arc expression in KO neurons, whereas KO EVs had no effect. DHPG treatment had no effect on dendritic Arc expression in untreated KO neurons or KO EV-treated KO neurons. However, DHPG treatment significantly increased dendritic Arc levels in WT EV-treated KO neurons, which was blocked by pretreatment with CHX. 30- $\mu$ m segments of two dendrites/neuron were analyzed for integrated density measurements in all groups ( $n = 10$  neurons). Arc mRNA and Arc protein levels were normalized to untreated KO neurons and displayed as fold change  $\pm$  SEM. Student's *t* test: \* $p < 0.05$ , \*\* $p < 0.01$ , and \*\*\* $p < 0.001$ . Scale bars, 10  $\mu$ m. Representative of 3 independent experiments using different EV/protein preparations and cultures.

for 4 hr and then treated with DHPG exhibited an increase in dendritic Arc levels that was also dependent on protein synthesis (Figure 7B). Although these experiments cannot definitively distinguish *de novo* translated Arc from protein that was taken up, these data suggest that Arc capsids or EVs are capable of transferring Arc mRNA between neurons and that this mRNA is available in the cytoplasm of dendrites for activity-dependent translation.

## DISCUSSION

Here, we show that mammalian Arc protein exhibits many hallmarks of Gag proteins encoded by retroviruses and retrotransposons: self-assembly into capsids, RNA encapsulation, release in EVs, and intercel-

lular transmission of RNA. These data suggest that Arc can mediate intercellular trafficking of mRNA via Arc EVs (which we term "ACBARs" for "Arc Capsids Bearing Any RNA"), revealing a novel molecular mechanism by which genetic information may be transferred between neurons.

ular transmission of RNA. These data suggest that Arc can mediate intercellular trafficking of mRNA via Arc EVs (which we term "ACBARs" for "Arc Capsids Bearing Any RNA"), revealing a novel molecular mechanism by which genetic information may be transferred between neurons.

### Arc Functions as a Repurposed Gag Protein

Our data show a remarkable conservation of viral Gag properties in Arc. Since Arc shows structural homology to the Gag CA domain (Zhang et al., 2015), the capability of self-assembly into oligomeric capsids is perhaps not too surprising. However, Arc seems to retain other important biochemical properties of Gag that are not intuitive from its sequence. Despite lacking clear zinc-finger RNA binding domains such as in HIV Gag, Arc encapsulates RNA, and RNA binding seems critical for capsid formation. This is reminiscent of Foamy Virus Gags, which have evolved different RNA-binding motifs to HIV Gag (Hamann and Lindemann, 2016) and also structurally resemble Arc (Taylor et al., 2017). HIV Gag-RNA interactions are complex and involve multiple components of Gag, including the MA domain, and are regulated by host cellular factors (Maillet et al., 2016). Gag MA-RNA interactions are also critical for virus particle formation at membranes (Kutluay et al., 2014). Moreover, if viral RNA is not present, Gag encapsulates host RNA, and any single-stranded nucleic acid longer than ~20–30 nt can support capsid assembly (Campbell and Rein, 1999), indicating a general propensity to bind abundant RNA. Indeed, precisely how viral RNA is preferentially packaged into Gag capsids in cells remains an intensive area of investigation (Comas-Garcia et al., 2016).

The uptake and transfer of RNA by purified Arc protein is surprising as this occurs in the absence of an “envelope” or lipid bilayer. Uptake of both purified Arc capsids and endogenous EVs occurs through endocytosis. While EVs and exosomes are easily taken up through the endosomal pathway, it remains unclear how RNA can cross the endosomal membrane without membrane fusion proteins (Tkach and Théry, 2016). Our data suggest that, like non-enveloped viruses, Arc protein itself contains the ability to transfer RNA across the endosomal membrane. While it remains unclear how non-enveloped capsids transfer RNA into the cytoplasm, some studies suggest this could occur through specific receptor-capsid interactions, or via a pH-dependent conformational change of the capsid that allows either pore formation or lytic degradation of membranes (Tsai, 2007). We speculate that Arc protein may interact with the endosomal membrane to allow transfer of mRNA into the cytoplasm as the capsid is disassembled. This is reflected in the lag between protein uptake and mRNA expression seen in our experiments, which may be a result of the time it takes for mRNA to become accessible to our FISH probes. The lipid membrane around ACBARs *in vivo* may dictate targeting and uptake, whereas the Arc capsid within protects and allows transfer of RNA. Intriguingly, prArc that lacks RNA is unable to form capsids and cannot be taken up, suggesting uptake may be a regulated process that requires properly formed capsids. Since Arc seems to regulate a naturally occurring mechanism of RNA transfer, we believe that harnessing this pathway may allow new means of genetic engineering or RNA delivery into cells, using ACBARs, that may avoid the hurdle of immune activation.

### Arc's Gag Homology Reveals a New Signaling Pathway in Neurons

Exosome and EV signaling has emerged as a critical mechanism of intercellular communication, especially in the immune system and in cancer biology (Becker et al., 2016). However, the role of

intercellular signaling through EVs in the nervous system has only recently been investigated, with studies suggesting that these pathways may play important roles in synaptic plasticity (Budnik et al., 2016; Zappulli et al., 2016). Canonical exosomes are formed in MVBs, which are derived from the endosomal pathway and usually require the ESCRT complex to be released (Raposo and Stoorvogel, 2013), although the biogenesis of EVs in general is more varied. HIV Gag is able to form virions independent of the MVB pathway, although the ESCRT machinery is still required for particle release; thus, Arc may form ACBARs independent of the canonical exosome pathway. These pathways are not mutually exclusive, and elucidating the biogenesis of ACBARs within neurons will require further investigation.

Since Arc is rapidly synthesized locally in dendrites (Park et al., 2008; Waung et al., 2008), it is conceivable that high local concentrations of Arc protein promote capsid assembly in dendrites where encapsulation of dendritically localized mRNAs could occur. Since Arc capsids do not seem to show specificity in RNA binding *in vitro* and Arc EVs can transfer highly abundant mRNAs, we speculate that the specificity of ACBAR cargo is conferred by the precise spatial and temporal expression of Arc protein in neurons (Figure S7D). Consistent with the identification of Arc mRNA associated with Arc protein from brain, Arc mRNA levels are highly and uniquely abundant in dendrites *in vivo* after bouts of neuronal activity or experience (de Solis et al., 2017). Gag-RNA interactions are regulated by host cellular proteins such as Staufen (Mouland et al., 2000), a protein that is also a critical regulator of dendritic mRNA trafficking in neurons, including Arc mRNA (Heraud-Farlow and Kiebler, 2014). The parallels between dendritic mRNA regulation and virus-RNA interactions are striking, suggesting that cellular factors may play an important role in ACBAR biogenesis and RNA packing. Many questions remain: What other cargo do ACBARs contain? What are the docking mechanisms for ACBARs? Is there spatial/temporal specificity of intercellular signaling in the brain?

Our data also indicate that Arc may mediate intercellular signaling to control synaptic function and plasticity in a non-cell-autonomous manner. Although there is a paucity of data on neuronal EVs, previous studies have shown that EVs can be secreted in an activity-dependent manner and include AMPARs as cargo (Fauré et al., 2006). Since Arc has previously been implicated in AMPAR trafficking at synapses and spine elimination (Chowdhury et al., 2006; Mikuni et al., 2013) at weak synapses (Okuno et al., 2012), a potential role for ACBARs may be to eliminate synaptic material. Arc also regulates homeostatic forms of plasticity, such as AMPAR scaling (Shepherd et al., 2006) and cross-modal plasticity across different brain regions (Kraft et al., 2017), which could be regulated at the circuit level in a non-cell autonomous manner. We favor the idea that released Arc functions to carry intercellular cargo that alters the state of neighboring cells required for cellular consolidation of information.

Previous studies have shown that *Drosophila* neuromuscular junction plasticity requires trans-synaptic signaling mediated through the Wnt pathway in exosomes (Korkut et al., 2009). Interestingly, the *Drosophila* Arc homolog dArc1 exhibits similar properties of intercellular transfer of mRNA in the fly nervous system and is one of the most abundant proteins in *Drosophila* EVs

(Lefebvre et al., 2016), suggesting a remarkable convergence of biology despite a large evolutionary divergence of these species. A recent study has also implicated Arc in the mammalian immune system (Ufer et al., 2016), where it controls dendritic cell-dependent T cell activation, expanding the potential repertoire and importance of Arc-dependent intercellular signaling beyond the nervous system. Moreover, EVs have been implicated in the pathology of various neurodegenerative disorders, as several pathogenic proteins, such as prions,  $\beta$ -amyloid peptide, and  $\alpha$ -synuclein, are released from cells in association with EVs (Zappulli et al., 2016). In AD, immunohistochemical analysis in brain sections from patients with AD showed enrichment of the exosomal marker ALIX around neuritic plaques (Rajendran et al., 2006). This suggests that EVs may provide a significant source of extracellular A $\beta$  peptide. Arc regulates the activity-dependent cleavage of APP and  $\beta$ -amyloid production through interactions with presenilin (Wu et al., 2011), suggesting that ACBARs may also be involved in AD pathogenesis.

### Evolution of Synaptic Plasticity and Cognition

Ty3/*gypsy* retrotransposons are ancient mobile elements that are widely distributed and often abundant in eukaryotic genomes and are considered ancestral to modern retroviruses (Malik et al., 2000). There is evidence that coding sequences derived from Ty3/*gypsy* and other retroviral-like elements have been repurposed for cellular functions repeatedly during evolution (Feschotte and Gilbert, 2012). For instance, multiple envelope genes of retroviral origins have been co-opted during mammalian evolution to promote cell-cell fusion and syncytiotrophoblast formation in the developing placenta (Cornelis et al., 2015). There are more than one hundred Gag-derived genes in the human genome alone (Campillos et al., 2006), and genetic KO of their murine orthologs have revealed that some, like *Arc*, are essential for cognition (Irie et al., 2015). However, the molecular function of these Gag-derived proteins has been poorly characterized, and whether they were co-opted to serve similar cellular processes remains an open question. This study and the accompanying article now reveal that two distantly related Gag-derived genes have been independently co-opted in fly and tetrapod ancestors to participate in a similar process of EV-dependent intercellular trafficking of RNA in the nervous system. Given the plethora of retroelements populating eukaryotic genomes, we speculate that many other Gag proteins have been repurposed for cellular processes that await discovery in a variety of organisms.

### STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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### SUPPLEMENTAL INFORMATION

Supplemental Information includes seven figures and one table and can be found with this article online at <https://doi.org/10.1016/j.cell.2017.12.024>.

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### AUTHOR CONTRIBUTIONS

E.D.P. performed immunoprecipitation, cultured neuron, immunocytochemistry, and the fluorescent *in situ* hybridization experiments. C.E.D. and R.B.K. performed the biochemistry and the electron microscopy experiments. A.V.T. and M.K.-S. performed the qPCR experiments. D.B. assisted with the electron microscopy experiments. J.M. and C.F. performed the phylogenomic analysis. S.E., D.R.M., and J.A.G.B. conducted the cryo-EM and the DLS experiments. N.Y. performed the initial biochemical and the electron microscopy experiments. E.D.P., C.E.D., and J.D.S. conceived and designed experiments. J.D.S. wrote the manuscript; all authors discussed results and edited the manuscript.

### DECLARATION OF INTERESTS

The authors declare no competing interests.

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## STAR★METHODS

## KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
<b>Antibodies</b>		
rabbit polyclonal anti-Arc	Custom made (ProteinTech)	N/A
rabbit polyclonal anti-Arc	Synaptic Systems	Cat. #156-003
NucBlue fixed cell stain	Thermo Fisher Scientific	Cat. #R37606
chicken polyclonal anti-MAP2	Abcam	Cat. #ab5392
Alexa Fluor 405, 488, and 647 secondary antibodies (made in donkey against chicken, rabbit, or mouse)	Jackson ImmunoResearch	Cat. #703-605-155, 711-605-152, 703-545-155, 711-545-152, 715-605-151
Alexa Fluor 555 secondary antibody (made in donkey against rabbit)	Thermo Fisher Scientific	Cat. #A31572
sheep polyclonal anti-digoxigenin-POD	Sigma-Aldrich	Cat. #11207733910
mouse monoclonal anti-Arc (clone C-7)	Santa Cruz	Cat. #sc-17839
rabbit polyclonal anti-ALIX	Dr. Wesley Sundquist, U. of Utah	N/A
mouse monoclonal anti-actin (HRP-conjugated)	Abcam	Cat. #ab20272
chicken polyclonal anti-GFP	Aves	Cat. #GFP-1010
goat anti-rabbit, mouse, or chicken HRP-conjugated secondary antibodies	Jackson ImmunoResearch	Cat. #103-035-155, 111-035-003, 115-035-003
mouse monoclonal anti-Rab5	BD Biosciences	Cat. #610724
<b>Bacterial and Virus Strains</b>		
DH5 $\alpha$ Competent <i>E. coli</i> .	Thermo Fisher Scientific	Cat. #18265017
BL21 Competent <i>E. coli</i> .	Thermo Fisher Scientific	Cat. #C600003
<b>Chemicals, Peptides, and Recombinant Proteins</b>		
polyethyleneimine "MAX"	Polysciences, Inc.	Cat. #24765
Dynasore	Abcam	Cat. #ab120192
(S)-3,5-DHPG	Tocris Bioscience	Cat. #0805
cycloheximide	Sigma-Aldrich	Cat. #C7698-1G
RNase A	Omega Bio-tek	Cat. #D6942-02
RNase A	Thermo Fisher Scientific	Cat. #EN0531
SUPERase-In RNase inhibitor	Thermo Fisher Scientific	Cat. #AM2694
16% formaldehyde solution	Thermo Fisher Scientific	Cat. #28906 and 28908
normal donkey serum	Jackson ImmunoResearch	Cat. #017-000-121
Fluoromount aqueous mounting medium	Sigma-Aldrich	Cat. #F4680-25ML
prehybridization solution (2X)	Sigma-Aldrich	Cat. #P1415-50ML
Denhardt's solution (50X)	Thermo Fisher Scientific	Cat. #750018
formamide	Fisher Scientific	Cat. #BP227-100
blocking reagent	Sigma-Aldrich	Cat. #11096176001
normal sheep serum	Jackson ImmunoResearch	Cat. #013-000-121
Protein A agarose	Thermo Fisher Scientific	Cat. #15918014
normal rabbit IgG	Santa Cruz	Cat. #sc-2027
deoxyribonuclease I from bovine pancreas	Sigma-Aldrich	Cat. #DN25-100MG
papain	Worthington Biochemicals	Cat. #LS003126
poly-L-lysine	Sigma-Aldrich	Cat. #P2636-100MG
cytosine $\beta$ -D-arabinofuranoside	Sigma-Aldrich	Cat. #C1768-100MG
TRIZOL Reagent	Thermo Fisher Scientific	Cat. #15596026

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REAGENT or RESOURCE	SOURCE	IDENTIFIER
Chloroform	Sigma-Aldrich	Cat. #C2432-500ML
PowerUp SYBR Green Master Mix	Thermo Fisher Scientific	Cat. #A25742
SYBR Safe DNA Gel Stain	Thermo Fisher Scientific	Cat. #S33102
protease inhibitor cOmplete ULTRA tablets, EDTA-free	Sigma-Aldrich	Cat. #95892791001
pepstatin	Roche	Cat. #11524488001
PMSF	Roche	Cat. #10837091001
leupeptin	Roche	Cat. #11034626001
sprotinin	Roche	Cat. #10981532001
lysozyme from chicken egg white	Sigma-Aldrich	Cat. #L6876
Glutathione Sepharose 4B affinity resin	GE Healthcare	Cat. #17075601
PreScission Protease	GE Healthcare	Cat. #27-0843-01
uranyl acetate	Agar Scientific	Cat. #AGR1260A
<b>Critical Commercial Assays</b>		
DIG RNA labeling kit (SP6/T7)	Sigma-Aldrich	Cat. #11175025910
illustra MicroSpin G-50 columns	GE Healthcare	Cat. #27-5330-01
TSA Plus Cyanine 3 kit	PerkinElmer	Cat. #NEL744001KT
RNeasy Micro Kit	QIAGEN	Cat. #74004
Direct-zol RNA Micro Kit	Zymo	Cat. #R2062
Purelink Midi Plasmid Prep Kit	Promega	Cat. #A2492
QiaQuick Gel Purification Kit	QIAGEN	Cat. #28706
EZNA Plasmid Mini Kit	Zymo	Cat. #D6942-02
HiScribe T7 High Yield RNA Synthesis Kit	New England Biolabs	Cat. #E2040S
High Capacity cDNA Synthesis Kit	Applied Biosystems	Cat. #4368814
PCR Purification Kit	QIAGEN	Cat. #28104
<b>Deposited Data</b>		
N/A		
<b>Experimental Models: Cell Lines</b>		
Human: HEK293T cells	ATCC	Cat. #CRL-11268
<b>Experimental Models: Organisms/Strains</b>		
Mouse: C57BL/6-Arc <sup>tm1Srl</sup> /J	Dr. Kuan Hong Wang, NIH	Jackson Labs: stock #007662
<b>Oligonucleotides</b>		
See <a href="#">Table S1</a>	N/A	N/A
<b>Recombinant DNA</b>		
pGEX-6p1-GST-ArcFL	This manuscript	N/A
pGEX-6p1-GST-ArcΔCTD	This manuscript	N/A
pET11a-ArcCA	This manuscript	N/A
pGEX-4T1-GST-dArc1	Dr. Mark Metzstein, U of Utah	N/A
pBluescript-SKII-GFP	This manuscript	N/A
pBluescript-SKII-ArcUTRs	Dr. Kristen Keefe, U of Utah	N/A
pGL4.11-arc7000-mEGFP-ArcUTRs	Dr. Haruhiko Bito, U of Tokyo	N/A
eGFP-C3-Arc	Dr. Kimberly Huber, UT Southwestern	N/A
pBOS-nuclear-GFP	Addgene	#11154
<b>Software and Algorithms</b>		
MUSCLE	EMBL-EBI, Hinxton, Cambridge, UK	<a href="https://www.ebi.ac.uk/Tools/msa/muscle/">https://www.ebi.ac.uk/Tools/msa/muscle/</a>
Boxshade plot server	Swiss Institute of Bioinformatics, Switzerland	<a href="https://www.ch.embnet.org/software/BOX_form.html">https://www.ch.embnet.org/software/BOX_form.html</a>

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REAGENT or RESOURCE	SOURCE	IDENTIFIER
A Plasmid Editor (APE)	University of Utah	<a href="http://biologylabs.utah.edu/jorgensen/wayned/ape/">http://biologylabs.utah.edu/jorgensen/wayned/ape/</a>
tBLASTn	NIH	<a href="https://blast.ncbi.nlm.nih.gov/Blast.cgi?PROGRAM=tblastn&amp;PAGE_TYPE=BlastSearch">https://blast.ncbi.nlm.nih.gov/Blast.cgi?PROGRAM=tblastn&amp;PAGE_TYPE=BlastSearch</a>
Rebase	Genetic Information Research Institute, Mountain View, CA	<a href="http://www.girinst.org/rebase/">http://www.girinst.org/rebase/</a>
MEGA7	Pennsylvania State University	<a href="http://www.megasoftware.net/">http://www.megasoftware.net/</a>
BLASTp	NIH	<a href="https://blast.ncbi.nlm.nih.gov/Blast.cgi?PAGE=Proteins">https://blast.ncbi.nlm.nih.gov/Blast.cgi?PAGE=Proteins</a>
ImageJ	NIH	<a href="https://imagej.nih.gov/ij/">https://imagej.nih.gov/ij/</a>

**CONTACT FOR REAGENT AND RESOURCE SHARING**

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Jason D. Shepherd ([jason.shepherd@neuro.utah.edu](mailto:jason.shepherd@neuro.utah.edu)).

**EXPERIMENTAL MODEL AND SUBJECT DETAILS****Cell lines**

HEK293T cells were purchased from ATCC (#CRL-11268). Cells were maintained at 37°C with 5% CO<sub>2</sub> in DMEM media supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin (Thermo Fisher Scientific, Waltham, MA) and passaged every 3–4 days at 70% confluency. For transfections and transfer experiments, HEK cells were seeded to 10-cm dishes or collagen-coated glass coverslips in 12-well plates.

**Mouse models****Wild-type and Arc knock-out mice**

C57BL/6 Arc knock-out (KO) mice (C57BL/6-Arc<sup>tm1Stu</sup>/J, a kind gift from Dr. Kuan Wang, NIH) have GFP knocked in to the Arc ORF (Wang et al., 2006). Arc KO and wild-type (WT) mice used in these studies were littermates from heterozygous (Arc<sup>+/-</sup>) crosses. Both male and female mice were used. No differences between sexes in the experiments conducted in this study were noted, and data from both sexes were therefore grouped together. Mice were housed in breeding pairs, or group-housed with littermates of the same sex after weaning (2–5 mice/cage), on a 12:12 h day:night cycle, with food and water provided *ad libitum*. Hippocampal and cortical primary neuron cultures were prepared from E18 embryos, while brain lysates were taken from P30–50 mice. Mice were test- and procedure-naïve before terminal experiments. All animal experiments were approved by the Institutional Animal Care and Use Committee of the University of Utah.

**Primary neuron culture**

Primary neuron cultures were prepared from male and female E18 Arc KO or WT mouse cortex and hippocampus as previously described (Shepherd et al., 2006). Tissue was dissociated in DNase (0.01%; Sigma-Aldrich, St. Louis, MO) and papain (0.067%; Worthington Biochemicals, Lakewood, NJ), and then triturated with a fire-polished glass pipette to obtain a single-cell suspension. Cells were pelleted at 500xg for 4 min, the supernatant removed, and cells resuspended and counted with a TC-20 cell counter (Bio-Rad, Hercules, CA). Neurons were plated on glass coverslips (Carolina Biological Supply, Burlington, NC) coated with poly-L-lysine (0.2 mg/mL; Sigma-Aldrich) in 12-well plates (Greiner Bio-One, Monroe, NC) at 90,000 cells/mL, or in 10-cm plastic dishes at 800,000 cells/mL. Neurons were initially plated in Neurobasal media containing 5% horse serum, 2% GlutaMAX, 2% B-27, and 1% penicillin/streptomycin (Thermo Fisher Scientific) in a 37°C incubator with 5% CO<sub>2</sub>. On DIV4, neurons were fed via half media exchange with astrocyte-conditioned Neurobasal media containing 1% horse serum, GlutaMAX, and penicillin/streptomycin, 2% B-27, and 5 μM cytosine β-D-arabino-furanoside (AraC) (Sigma-Aldrich). Neurons were fed with astrocyte-conditioned media every three days thereafter.

**METHOD DETAILS****Plasmids**

The open reading frame (ORF) of full-length rat Arc (NP\_062234.1) cDNA was subcloned from pRK5-myc-Arc. The insert was amplified by PCR, digested with *Bam*H1 and *Xho*1, and ligated into the pGEX-6p1 (GE Healthcare, Little Chalfont, UK) expression vector

between the *Bam*H1 and *Xho*1 restriction sites. The GST-Arc ORF was similarly amplified and cloned into the pFastBac1 vector (Thermo Fisher Scientific) between the *Bam*H1 and *Xho*1 restriction sites. prArc- $\Delta$ CTD was generated by blunt end cloning after PCR amplification of the Arc ORF from pGEX-6p1-Arc, excluding sequence coding aas 277-374. aas 195-364 of the Arc ORF (CA-prArc) was similarly cloned into the pET11a vector, which contained a His tag. pBluescript-SKII-GFP was generated by restriction digest of mEGFP (BBA16881.1) from pGL4.11-arc7000-mEGFP-ArcUTRs (generously provided by Dr. Haruhiko Bito, University of Tokyo) and subsequent ligation into the *Kpn*I and *Sac*I restriction sites flanking the insert in pBluescript-SKII-ArcUTRs plasmid (generously provided by Dr. Kristen Keefe, University of Utah). The pGEX-4T-1 *Drosophila* Arc1 (NP\_610955.1) construct was provided by Dr. Mark Metzstein, University of Utah. EGFP-C3-Arc and pRK5-myc-Arc were generously provided by Dr. Kimberly Huber (UT Southwestern) and Dr. Paul Worley (Johns Hopkins University), respectively. All protein expression constructs were transformed into DH5 $\alpha$  *E. coli* cells and individual colonies were screened by Sanger Sequencing (GeneWiz, South Plainfield, NJ) sequencing services, using primers synthesized by Integrated DNA Technologies (Coralville, IA). Trace files were analyzed using A Plasmid Editor (APE) freeware available from the University of Utah. Sequenced verified constructs were then transformed into BL21-DE3 bacterial cells for protein expression. See Table S1 for specific oligo primer sequences.

### Protein purification

Starter bacteria cultures for protein expression were grown overnight at 37°C in LB supplemented with ampicillin and chloramphenicol. Starter cultures were used to inoculate large-scale 500 mL cultures of ZY auto-induction media. Large-scale cultures were grown to OD<sub>600</sub> of 0.6-0.8 at 37°C at 150 rpm and then shifted to 19°C at 150 rpm for 16-20 h. Cultures were then pelleted at 5000xg for 15 min at 4°C and cell pellets were resuspended in 30 mL lysis buffer (500 mM NaCl, 50 mM Tris, 5% glycerol, 1 mM DTT, pH 8.0 at room temperature (RT) for Arc constructs and GST; 300 mM KCl, 50 mM Tris, 1% Triton X-100, 1 mM DTT, pH 7.4 at RT for Endophilin3A) and flash frozen in liquid nitrogen. Frozen pellets were thawed quickly at 37°C and brought to a final volume of 1 g pellet:10 mL lysis buffer, supplemented with DNase, lysozyme, aprotinin, leupeptin, PMSF, and pepstatin. Lysates were then sonicated for 8-10x45 s pulses at 90% duty cycle and pelleted for 45 min at 21,000xg. For GST-tagged constructs, cleared supernatants were then passed through a 0.45  $\mu$ m filter and incubated with pre-equilibrated GST Sepharose 4B affinity resin in a gravity flow column overnight at 4°C. Bound protein was then washed twice with two column volumes (20 resin bed volumes each) of lysis buffer, re-equilibrated with 150 mM NaCl, 50 mM Tris, 1 mM EDTA, 1 mM DTT, pH 7.2 at RT, and cleaved on-resin overnight at 4°C with PreScission Protease (GE Healthcare) for the GST-tagged constructs, or thrombin (Sigma-Aldrich) for dArc1. Cleaved proteins were then buffer exchanged to 150 mM NaCl, 50 mM Tris, pH 7.4 at RT to kill protease activity, run on an S200 size exclusion column to separate the cleaved protein, and peak fractions were pooled. GST was affinity-purified as described above using Sepharose 4B resin and eluted directly using 15 mM reduced L-glutathione, 10 mM Tris, pH 7.4 at RT. His-tagged CA-prArc was affinity-purified as described above using Ni<sup>+</sup> resin (Roche, Basel, Switzerland) and eluted directly using 250 mM imidazole, 10 mM Tris, pH 7.4 at RT. GST and CA-prArc were then buffer exchanged to 150 mM NaCl, 50 mM Tris, pH 7.4 at RT. To strip Arc protein of nucleic acids for prArc(RNA-) preparations, cell pellets were lysed in 20 mM NaCl, 50 mM Tris, 5% glycerol, 2 mM MgCl<sub>2</sub>, 1 mM DTT, pH 8.0 at RT as described above. Nucleic acids were precipitated from cell supernatants by dropwise addition of 10% PEI, pH 8.0 to a final concentration of 0.1% followed by incubation at 4°C for 20 min and pelleting for 20 min at 27,000xg. The resulting supernatant was then precipitated by addition of saturated ammonium sulfate to a final concentration of 30%. Precipitated protein was pelleted at 10,000xg for 10 min, resuspended in 60 mL lysis buffer, and affinity purified. The cleaved affinity-purified product was then dialyzed to Q-column buffer A (Q-A; 20 mM NaCl, 50 mM Tris, pH 7.4 at RT) overnight. Dialyzed protein was then subjected to anion exchange chromatography (HiTrap Q, GE Healthcare) with a gradient of Q-A buffer to Q-B buffer (1 M NaCl, 50 mM Tris, pH 7.4). Average yields for purified proteins were 10.5 mg (8-13 mg) per liter of cell culture.

### Electron microscopy

#### Negative stain

For all negative stain specimens, copper 200-mesh grids coated with Formvar and carbon (Electron Microscopy Sciences or Ted Pella, Redding, CA) were glow discharged for 20-45 s in a vacuum chamber at 30mA. 3.5  $\mu$ L sample was then applied to the grid for 35-45 s and excess sample was wicked away using filter paper. Grids were then immediately washed 2-4x for 5 s with 30  $\mu$ L water droplets, then once with 1% uranyl acetate (UA) on parafilm. Excess water/UA was wicked away and then a final droplet of UA was applied for 30 s. Excess UA was wicked away and grids were air-dried for 30-60 s. Imaging was performed using either an FEI T12, FEI Tecnai Spirit microscope operated at 120 kV equipped with a Gatan Orius SC200B CCD camera or JEOL 1400 electron microscope.

#### Cryo-EM

Purified Arc protein was dialysed into 300 mM NaCl, 50 mM Tris, pH 7.4 and concentrated twice using Amicon 100 MWCO centrifugal filters (Millipore, Burlington, MA) to yield a final protein concentration of ~2 mg/mL. 10 nm diameter gold beads were added to the sample. Degassed 2/2-3C C-flat grids (Electron Microscopy Sciences, Hatfield, PA) were glow discharged for 45 s at 30 mA. Sample was applied to the grid 2 times for 30 s, and the grid was plunge frozen in liquid ethane using a FEI Vitrobot Mark IV. Micrographs were acquired using a FEI Tecnai G<sup>2</sup> F20 microscope operated at 200 kV, equipped with a FEI Falcon II direct detector. The nominal defocus was 1.3  $\mu$ m.

### EM quantification

Grids were surveyed visually to check for uniformity of sample application. For each experiment, six images were taken from randomly selected grid squares. Full and partially formed particles between 20–40 nm were then counted manually using ImageJ. Counts were then divided by the image field of view ( $2.07 \mu\text{m}^2$ ) and data presented as oligomer count/ $\mu\text{m}^2$ .

### Arc capsid assembly assay

GFP mRNA was added to prArc(RNA-) (5 mg/mL in low salt buffer: 20 mM NaCl, 50 mM Tris, pH 7.4 at RT) at a nucleic acid:protein ratio of 7.3% (w/w) (corresponding to 1 molecule of Arc to 10 nucleotides). Reactions were then diluted to 1 mg/mL of prArc(RNA-) by dropwise addition of low salt buffer or capsid assembly buffer (500 mM NaPO<sub>4</sub>, 50 mM Tris, 0.5 mM EDTA, pH 7.5 at RT) and incubated for 2 h at RT. Following incubation, negative stain EM grids were prepared of each reaction at 0.25 mg/mL and capsid formation was quantified by manual counting of 6 images. Fully formed capsids included spherical particles between 20–50 nm with clear double shells. Similar results were seen in three independent protein preparations.

### Dynamic light scattering

Purified Arc protein was subjected to dynamic light scattering measurements on a Malvern Zetasizer Nano ZSP instrument. The scattering was carried out at 25°C and at a fixed angle of 173° (backward scattering). The scattered intensity is represented as number of particles under the assumption that the scattering intensity from spherical particles is proportional to the size to the sixth power.

### Phylogenetic reconstruction

NCBI genome sequence databases were queried using the human or *Drosophila melanogaster* Arc protein sequence using tBLASTn. Repbase was also queried using the CENSOR program to identify known repeat families with high sequence similarity to mammalian or brachyceran Arc genes, respectively. The following sequence IDs were used for analysis: (GenBank locus) Mm ARC—AHBB01089569; Hs ARC—LIQK02016549; Ac ARC—AAWZ02020354; Lc gypsy2—AFYH01030203; CC gypsy—LHQP01046008; Dm ARC1—JSAE01000572; Ds ARC1—CAKG01020471; Sc ARC1—LDNW01019671; Dm ARC2—JXOZ01003752; Ds ARC2—AWUT01001000; Sc ARC2—LDNW01019670; Bm gypsy—BABH01046987; Tc gypsy—AAJJ02003810. Repbase: Lc gypsy—Gypsy2-1-I\_Lch; Dr gypsy26—Gypsy-26-I\_DR; Lh gypsy11—Gypsy-11\_LH-I; Dm gypsy1—Gypsy1-I\_DM; ty3—TY3. Protein (Arc and Gag) sequences that were found to have high similarity to Arc proteins and Gags of other related Ty3/gypsy elements were aligned using the MUSCLE program. Trimmed Arc/Gag alignments were uploaded to MEGA7 for subsequent maximum likelihood phylogenetic reconstruction using default parameters, and 500 bootstrap iterations were performed to generate a lineage tree. *Drosophila melanogaster* dArc1 and dArc2 protein sequences were used to query schizophoran fly protein databases using BLASTp. More hits were observed than expected if *darc1* were present in one-to-one orthologs in the species examined. Protein FASTA sequences were aligned using MUSCLE and a maximum likelihood phylogram was generated using MEGA.

### HEK cell experiments

#### Transfections

HEK cells were transfected using polyethylenimine (PEI) at a ratio of 3  $\mu\text{g}$  PEI:1  $\mu\text{g}$  DNA diluted in Opti-MEM (Thermo Fisher Scientific). Cells were transfected at approximately 60%–70% confluency. For EV isolation and media transfer experiments, culture media was exchanged 4–6 h post-transfection to remove PEI and DNA, and media was harvested 24 h later.

#### Transfection and transfer

Media from transfected HEK cells was harvested 24 h post-transfection and centrifuged at 500 $\times$ g for 4 min to remove dead cells and debris. Media from untransfected, naive cells was removed and replaced with the cleared transfected media and incubated for an additional 24 h. Following incubation, cells were fixed and combined immunocytochemistry/fluorescence *in situ* hybridization (ICC/FISH) for Arc or GFP protein and RNA was performed as described below.

#### Endocytosis blockade

To block endocytosis, a group of naive HEK cells plated on coverslips in 12-well plates that were receiving media from GFP-Arc-transfected HEK cells were treated at the same time with 80  $\mu\text{M}$  Dynasore (Abcam, Cambridge, MA) for the first 6 h, then the media was removed and replaced with fresh HEK media. 18 h later, Dynasore-treated and untreated HEK cells were fixed. The entire 18-mm coverslip was viewed with a 20 $\times$  objective and the number of clusters of GFP-Arc-transferred cells was manually counted. Representative images were obtained using a 20 $\times$  objective on an Olympus FV1000 confocal microscope (Tokyo, Japan).

### Neuron transfer experiments

DIV15 cultured neurons were used for all neuronal experiments. For purified Arc protein incubation experiments, neurons were treated with 4  $\mu\text{g}$  of purified prArc, prArc- $\Delta$ CTD, CA-prArc, or prArc(RNA-) protein in normal neuronal feeding media and incubated for 1 or 4 h. For extracellular vesicle (EV) incubation experiments, neurons were treated with 10  $\mu\text{g}$  protein from the purified EV fraction obtained from eight 10-cm dishes of DIV15 cultured cortical neurons in which E18 WT cortical neurons had been plated at 800,000 cells/mL (see “Cell Culture” methods), and incubated for 1 or 4 h. A subset of neurons in the purified protein- and EV-treated experiments was treated with 100  $\mu\text{M}$  of the group 1 mGluR agonist dihydroxyphenylglycine ((S)-3,5-DHPG; Tocris Bioscience, Bristol, UK) for 5 min, which was then washed out and replaced with previously conditioned neuronal media, and neurons were allowed to rest for 25 min before fixation. To block protein translation during DHPG treatment, a subset of neurons was pretreated

with 180  $\mu$ M cycloheximide (CHX, Sigma-Aldrich) 30 min before DHPG. CHX was left in the media for 1 h total. To block endocytosis, neurons were pretreated with 80  $\mu$ M Dynasore (Abcam, Cambridge, MA) for 30 min before adding purified protein. For RNase treatments, a sample of either prArc or WT EV was incubated with RNase A (1:1000; Omega Bio-tek, Norcross, GA) for 15 min, then SUPERase-In RNase Inhibitor (1 U/ $\mu$ L; Thermo Fisher Scientific) immediately before being added to neurons. The treated samples were then added to neurons and incubated for 4 h.

### Immunocytochemistry

After treatments, neurons were washed twice with 37°C 4% sucrose/1X phosphate-buffered-saline (PBS; 10X: 1.4 M NaCl, 26.8 mM KCl, 62 mM Na<sub>2</sub>HPO<sub>4</sub>, 35.3 mM KH<sub>2</sub>PO<sub>4</sub>, pH 7.4), then fixed for 15 min with 4% sucrose/4% formaldehyde (Thermo Fisher Scientific) in 1X PBS. Neurons were washed 3  $\times$  5 min with 1X PBS, permeabilized for 10 min with 0.2% Triton X-100 (Amresco, Solon, OH) in 1X PBS, and blocked for 30 min in 5% normal donkey serum (Jackson ImmunoResearch, West Grove, PA) in 1X PBS. Neurons were then incubated in primary antibody diluted in block for 1 h at RT, washed 3  $\times$  5 min in 1X PBS, and incubated in secondary antibody diluted in block for 1 h at RT. Neurons on coverslips were mounted on glass slides in Fluoromount (Thermo Fisher Scientific) and dried overnight at RT. Primary antibodies used were: rabbit anti-Arc (1:1000; custom-made; ProteinTech, Rosemont, IL); rabbit anti-Arc (1:1000; Synaptic Systems, Goettingen, Germany); chicken anti-MAP2 (1:5000; ab5392; Abcam); mouse anti-Rab5 (1:1000; BD Biosciences, San Jose, CA); DAPI nuclear stain (Molecular Probes, Thermo Fisher Scientific). Secondary antibodies used were: Alexa Fluor 405, 488, 555, or 647 for the appropriate animal host (1:750; Thermo Fisher Scientific or Jackson ImmunoResearch).

### Combined FISH/ICC in neurons and HEK cells

The fluorescent *in situ* hybridization (FISH) procedure for Arc and GFP was based on a previously published protocol (Daberkow et al., 2007). We used a full-length rat Arc ribonucleotide probe (rat and mouse Arc are 99% identical at the aa level) or EGFP (see cloning strategy above in “Plasmids”) as in the published protocol, but modified the protocol for use in cultured neurons and HEK cells instead of brain sections. Arc and GFP plasmids were linearized with Not1 and purified via standard phenol/chloroform extraction. The linearized antisense Arc or GFP were used to make a ribonucleotide probe that had DIG-UTP incorporated using a T7 DIG RNA labeling kit (Sigma-Aldrich), then purified with a G-50 spin column (GE Healthcare). Cells were washed once with 37°C 4% sucrose/1X PBS, then fixed for 15 min with 4% sucrose/4% formaldehyde in 1X PBS. Cells were washed 3  $\times$  5 min with 1X PBS, permeabilized in 0.2% Triton X-100 for 10 min, washed 2  $\times$  5 min in 1X PBS, then 5 min with 2X saline-sodium citrate (SSC; 20X: 3 M NaCl, 300 mM citric acid trisodium salt dihydrate, pH 7). Cells were prehybridized in 1X prehybridization solution (Sigma-Aldrich) for 30 min. The DIG-labeled Arc or GFP ribonucleotide probe was diluted 1:3 with ddH<sub>2</sub>O, denatured at 90°C for 5 min, put on wet ice for 2 min, then mixed with RNA hybridization buffer (23.75 mM Tris-HCl, 1.19 mM EDTA, 357 mM NaCl, 11.9% dextran sulfate, 1.19X Denhardt's solution (Thermo Fisher Scientific), 2.5% nuclease-free water, 60% formamide (Fisher Scientific, Hampton, NH)). The Arc probe (1:500) or GFP probe (1:750) was hybridized to the cultured cells at 56°C for 16 h. The following day, cells underwent a series of washes to decrease background signal: 3  $\times$  5 min 2X SSC, 15 min in RNase A (1:1000; Omega Bio-tek) at 37°C, 10 min 2X SSC at RT, 10 min 0.2X SSC at RT, 15 min 0.2X SSC at 56°C, 10 min 0.2X SSC at RT, 5 min TNT (0.1 M Tris-HCl, 0.15 M NaCl, 0.05% Tween-20, pH 7.5). Cells were then blocked in TNB (0.1 M Tris-HCl, 0.15 M NaCl, 0.5% w/v blocking reagent (Sigma-Aldrich), pH 7.5) with 2.5% sheep serum (Jackson ImmunoResearch) and 2.5% donkey serum for 30 min. In the primary antibody step, a DIG-HRP (1:1000; Sigma-Aldrich) and either MAP2 (1:2500; Abcam), Arc (1:500; custom-made), or Rab5 (1:500; BD Biosciences) antibody were diluted together in TNB with 2.5% sheep serum and 2.5% donkey serum and incubated on the cells for 1 h. After 3  $\times$  5 min washes in TNT, the DIG-HRP signal was developed using a TSA Plus Cyanine 3 kit (1:50; PerkinElmer, Waltham, MA) for 30 min. Cells were washed for 5 min in TNT and 5 min in 1X PBS, then secondary antibody was diluted 1:750 in 5% donkey serum and 1X PBS and incubated on the cells for 1 h to detect MAP2, Arc, or Rab5. Nuclei were stained with DAPI (Thermo Fisher Scientific), then coverslips were mounted on glass slides with Fluoromount and dried overnight at RT.

### Cell imaging and analysis

#### Imaging

Coverslips were imaged using a 60X oil objective on an Olympus FV1000 confocal microscope (Tokyo, Japan) and images were analyzed using ImageJ software (National Institutes of Health, Bethesda, MD). Neurons included for analysis were selected in an unbiased manner by looking at MAP2 dendritic morphology for cell health. Coverslips were viewed blind to find the brightest immunofluorescence in each independent experiment, and this value was then used to set the image acquisition settings for that experiment. Images from all coverslips in that experiment were then acquired using the exact same settings.

#### Analysis of dendritic Arc protein and mRNA expression

During analysis, images were blindly thresholded (to remove background fluorescence and to ensure images were analyzed in the linear range) to the brightest immunofluorescence in an individual experiment, and the same threshold was applied to all other images in that experiment. Integrated density (average pixel intensity  $\times$  area) of two 30- $\mu$ m dendritic segments/neuron was measured from each coverslip. In general, thick proximal dendritic branches were avoided in our analysis to control for potential differences in dendritic volume. The KO control group in each experiment, whether ICC or FISH, was set as “1,” and the integrated density values in the other groups were normalized to this and are displayed in the graphs as fold-change  $\pm$  SEM. For representative images in the figures, the Smart look-up table (LUT) in ImageJ was applied to highlight differences in Arc expression between groups.

### **Analysis of Arc/Rab5 colocalization**

Two 30- $\mu$ m dendritic segments/neuron were selected for analysis of Arc protein or mRNA colocalization with Rab5 protein. The Arc channel and Rab5 channel were thresholded to the same value across all images. Using ImageJ, a mask was made of the thresholded section of dendrite for both Rab5 and Arc. The Arc mask was applied to the Rab5 mask and the number of overlapping puncta was quantified. The number of Arc particles overlapping Rab5 was divided by the total number of Arc particles in the stretch of dendrite to determine the Arc/Rab5 colocalization.

### **Western blots**

#### **Immunoblotting and analysis**

Western blot samples were mixed with 4X Laemmli buffer (40% glycerol, 250 mM Tris, 4% SDS, 50 mM DTT, pH 6.8) and heated at 70°C for 5 min. SDS-PAGE gel electrophoresis was used to separate protein samples. Separated samples were transferred to a nitrocellulose membrane (GE Healthcare). Following transfer, membranes were briefly stained with 0.1% Ponceau stain, then destained with 1% acetic acid to remove background, for imaging of total protein. Membranes were blocked in 5% milk + 1X tris-buffered saline (TBS; 10X: 152.3 mM Tris-HCl, 46.2 mM Tris base, 1.5 M NaCl, pH 7.6) for 30 min at RT, then incubated in primary antibody in 1X TBS for either 1 h at RT or overnight at 4°C. Membranes were washed 3  $\times$  10 min in 1X TBS, then incubated in an HRP-conjugated secondary antibody (Jackson ImmunoResearch) in block for 1 h at RT. After 3  $\times$  10 min in 1X TBS, a chemiluminescent kit (Bio-Rad, Hercules, CA) was used to detect the protein bands, and the membranes were imaged on an Azure c300 gel dock (Azure Biosystems, Dublin, CA). Blots were analyzed and quantified using the Gel Analysis plugin in ImageJ.

#### **Antibodies**

Antibodies were used at the following concentrations: Arc (1:1000; mouse monoclonal, Santa Cruz), Arc (1:1000; rabbit polyclonal, custom, Protein Tech), ALIX (1:500; rabbit polyclonal, custom, provided by Dr. Wesley Sundquist), actin (1:1000; HRP-conjugated, Abcam), GFP (1:1000; chicken polyclonal, Aves). All secondary antibodies were used at a dilution of 1:10,000 (HRP-conjugated goat anti-rabbit, goat anti-mouse, goat anti-chicken, Jackson ImmunoResearch).

### **Coomassie gels**

Samples for analysis via SDS-PAGE were mixed with 4X Laemmli buffer and heated at 70°C for 5 min. Protein samples were separated on 10% SDS gels. Gels were then stained with 0.1% Coomassie blue stain (0.1% w/v Coomassie blue, 50% methanol, 10% acetic acid, 40% water) for 30 min and destained overnight in destain solution (50% methanol, 10% acetic acid, 40% water). Gels were visualized using an Azure c300 gel dock under the auto-exposure setting on the visible channel. Gel exposures were analyzed and quantified using the Gel Analysis plugin in ImageJ.

### **Immunoprecipitation**

WT and Arc KO cortices were dissected out and homogenized in 150 mM NaCl, 50 mM Tris, 1% Triton X-100, 0.5% sodium deoxycholate, 0.05% SDS, pH 7.4 (IP lysis buffer), with protease inhibitor added fresh (Roche). Homogenates were pelleted at 200 $\times$ g for 5 min at 4°C to remove tissue debris. Supernatants were removed, diluted from 2 mL to 4 mL, and rocked at 4°C for 10 min before being pelleted at 17,000 $\times$ g for 10 min at 4°C to remove insoluble material. Cleared supernatants were removed, a small aliquot was taken as the input, and the remainder used for immunoprecipitation. Supernatants were immunoprecipitated with either Arc antibody (rabbit polyclonal, custom-made; Protein Tech) or normal rabbit IgG (Santa Cruz Biotechnology, Santa Cruz, CA) at 1  $\mu$ g/500  $\mu$ L lysate for 2 h at 4°C with gentle rocking. Following antibody incubation, a 10% volume of washed 50/50 Protein A bead slurry (Thermo Fisher Scientific) was added to the antibody/lysate mixture and incubated for an additional hour at 4°C with rocking. Bead-antibody complexes were then pelleted briefly at low speed, supernatants were removed, and beads were washed three times with IP buffer. Washed beads were then resuspended in 200  $\mu$ L IP buffer. With half of the bead slurry, protein was eluted from the beads with 17  $\mu$ L 4X Laemmli buffer for 5 min at RT, then 50  $\mu$ L IP buffer was added and the solution was removed from the beads into a new tube and heated at 70°C for 5 min. The input (10% lysate volume) and 30  $\mu$ L each of the IgG and antibody elutions were separated by SDS-PAGE on a 10% acrylamide gel and immunoblotted as described above. The bands for the input and IgG and Arc elutions were analyzed using the Gel Analysis plugin in ImageJ, and the data were represented graphically as a ratio of the signal from each elution over the input signal from each individual mouse. With the other half of the bead slurry, the IP buffer was adjusted to 1% SDS and 0.8 mg Proteinase K (New England Biolabs, Ipswich, MA) was added. Samples were then incubated at RT for 30 min with rocking and total RNA was extracted as described below.

### **Chemical crosslinking of Arc proteins *in situ***

Transfected HEK cells expressing myc-Arc-WT or a GFP control were briefly trypsinized, quenched with DMEM (Thermo Fisher Scientific), and pelleted. Media was removed and pelleted cells were then crosslinked with 0.4% formaldehyde in PBS for 10 min with rocking at RT. Cell suspensions were immediately quenched with Tris to a final concentration of 50 mM and repelleted. Supernatants were removed and cell pellets were then lysed with 150 mM NaCl, 50 mM Tris, 1% Triton X-100, pH 7.4 (lysis buffer) for 20 min at 4°C with rocking. Lysates were cleared by centrifugation at 21,000 $\times$ g for 10 min at 4°C and cleared supernatants were then run on a 4%–8% gradient gel and analyzed via western blot with antibodies for Arc (mouse monoclonal, Santa Cruz) and GFP (chicken polyclonal, Aves).

### RNA extraction

For all samples, total RNA was extracted using TRIzol (Thermo Fisher Scientific). TRIzol-extracted samples were mixed 5:1 with chloroform, incubated at RT for 3 min, and pelleted at 12,000 $\times$ g at 4°C for 10 min. The resulting aqueous phase was taken and mixed 1:1 with isopropanol, incubated at RT, and pelleted at 12,000 $\times$ g at 4°C for 10 min. The resulting supernatant was removed and pellet washed with cold 75% ethanol. Washed pellets were then repelleted at 7500 $\times$ g for 5 min at 4°C. The supernatant was removed and dried pellets were resuspended in ddH<sub>2</sub>O.

### RT-PCR

Total RNA concentrations were measured by A<sub>260/280</sub> on a Nanodrop (Thermo Scientific). Reverse transcription reactions were carried out using a High Capacity cDNA Reverse Transcription Kit (Applied Biosystems, Foster City, CA) with 100–200 ng of RNA as template. Resulting cDNAs were amplified using rat Arc, GAPDH primer sets for 35 cycles with a 60°C annealing temperature. Resulting PCR products were analyzed on 1.5% agarose gels stained with SYBR Safe (Thermo Fisher Scientific). Rat Arc primers: Fwd, ACCATATGACCACCGGCGGC; Rev, TCCAGCATCTCAGCTCGGCAC. GAPDH primers: Fwd, CATGGCCTCCGTGTTCTTA; Rev, GCCTGCTTACCACCTTCTT. RT-PCR gels were quantified using the ImageJ gel analyzer tool.

### qRT-PCR

To determine the amount of RNA associated with Arc protein, quantitative RT-PCR was performed on mRNA prepared from 1: whole mouse cortices immunoprecipitated with Arc and IgG protein, 2: EV fractions prepared from HEK cells (see below, “Extracellular vesicle purification”), and 3: lysate and purified protein from bacteria (BL21, Thermo Fisher Scientific) transfected with rat Arc plasmid (pGEX-GST-ArcFL). Some samples were treated with RNase (25  $\mu$ g, RNase A, Thermo Fisher Scientific) to determine if the mRNA associated with Arc protein was protected from degradation relative to exogenously added GFP antisense RNA (generating using T7 RNA polymerase from linearized pBluescript-SKII-GFP). Preparation 1: Mice were sacrificed after 24 h of dark-housing and 2 h of enriched environment. Whole cortices were dissected and homogenized in IP lysis buffer as described above. After immunoprecipitation, bead slurry was incubated in guanidine thiocyanate containing RLT lysis buffer and column purification of RNA was performed using QIAGEN RNeasy Micro Kit (QIAGEN, Hilden, Germany). Total eluate was used for reverse transcription using High Capacity cDNA Reverse Transcription Kit with 50 U of Multiscribe Reverse Transcriptase and random oligo primers (Thermo Fisher Scientific). Preparations 2 and 3: total RNA was extracted using TRIzol (Thermo Fisher Scientific) as described above (“RNA extraction”). Reverse transcription reactions (25°C for 10 min, 37°C for 2 h, 85°C for 5 min) were carried out using a High Capacity cDNA Reverse Transcription Kit. Resulting cDNA was prepared for qPCR using PowerUp SYBRgreen Master Mix (Thermo Fisher Scientific) in a 96-well plate with primers against rat Arc, GAPDH and asnA (see above, “RT-PCR”; asnA primers: Fwd, GCGTGGATGCCGACACGTTG; Rev, ATACCGCCGCCGATGGTCTG). qPCR was performed on a QuantStudio 3 Real Time PCR System (Thermo Fisher Scientific) using the following protocol: Pre-incubation: 50°C for 2 min, 95°C for 2 min. Amplification: 40 cycles of 95°C for 15 s, 60°C for 15 s, and 72°C for 1 min. Melt curve: 95°C for 1 s, 60°C for 20 s, continuous ramp at 0.15°C/s up to 95°C. Ct values of greater than 30 were considered undetectable. Differences in expression were determined using the standard curve method, where a standard DNA sample was serially diluted (10-fold), analyzed for the gene of interest, and the linear equation calculated. The resulting linear equation was used to determine where the Ct values of test samples fell within the standard curve and the result was transformed ( $\log_{10}$ ) to reflect the dilution of the standard sample. Differences were calculated measuring the fold-change from the average of the control values for any given group (test/average control).

### Extracellular vesicle purification

Extracellular vesicles (EVs) were purified from HEK cell and primary neuronal cultures as previously described (Lachenal et al., 2011). Media was spun successively at 2,000 and 20,000 $\times$ g to remove dead cells and debris, and then at 100,000 $\times$ g to pellet EVs. The crude EV pellet following the initial high-speed spin was resuspended in cold PBS and repelleted at 100,000 $\times$ g for 1 h at 4°C in an SW41 rotor. The washed EV pellet was further purified by centrifugation over a 10%–20% sucrose-PBS gradient at 100,000 $\times$ g overnight at 4°C. The resulting pellet was washed in cold PBS to remove excess sucrose and then repelleted at 100,000 $\times$ g for 1 h at 4°C. The final, washed pellet was resuspended in PBS and used for downstream analysis with EM, western blotting, and neuron treatments.

### Trypsin digestion and RNase assays

Trypsin was added to prArc and EVs at 0.05 mg/mL for 30 min at RT followed by addition of 1 mM PMSF for 10 min to inactivate trypsin. Untreated and trypsin-treated samples were then analyzed by western blot. RNase A was added to WT neuron lysates and EVs at 50  $\mu$ g/mL for 15 min at 37°C. Untreated and RNase-treated samples for RT-PCR were then directly extracted with TRIzol.

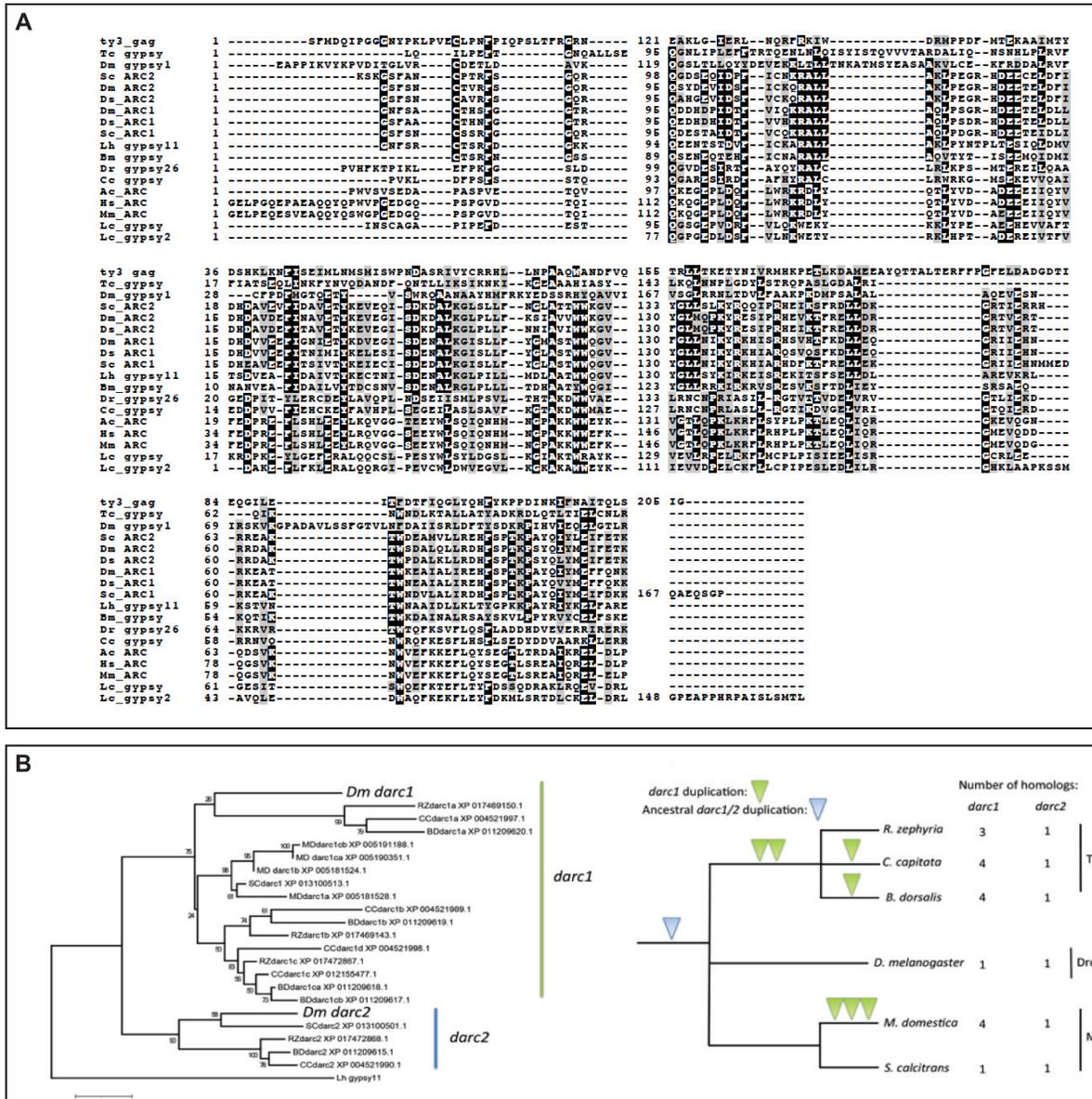
### Immunogold labeling

Immunogold labeling was performed with modifications as previously described (Korkut et al., 2013). Samples were fixed overnight in 2% formaldehyde at 4°C with gentle rocking. Samples were then applied to glow discharged Formvar copper mesh grids (Ted Pella) and allowed to adhere at room temperature for 10 min. Samples were then quenched by 3 washes of 0.1 M Tris, pH 7.4. Samples

were then permeabilized for 10 min at RT, blocked, and stained for Arc (1:500; custom-made). 5 nm gold-conjugated secondary antibodies were used for staining without silver enhancement. Following antibody labeling, grids were negative stained as described above.

### **QUANTIFICATION AND STATISTICAL ANALYSES**

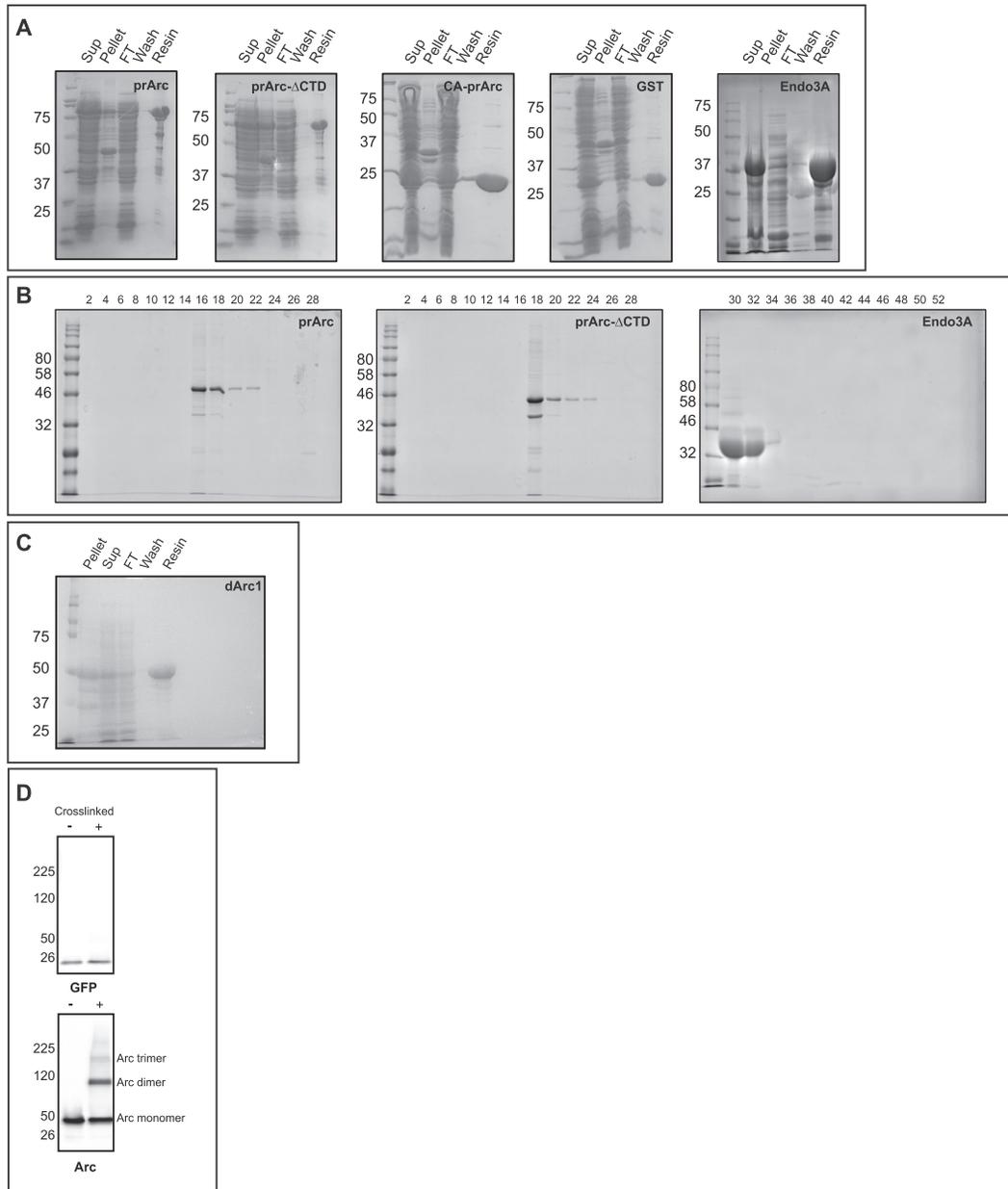
Two-way ANOVA with or without repeated-measures (with *post hoc* Sidak's tests) or two-tailed unpaired *t*-tests were performed using GraphPad Prism (GraphPad Software, San Diego, CA) or JMP Pro statistical software (SAS; Cary, NC). Significance was set at  $p < 0.05$ . All data shown are representative of at least two experimental replicates. Details of the statistics (*N*, number of experimental replicates, description of how the data are displayed) can be found in figure legends and/or the Results section.



**Figure S1. Alignment of Primary aa Sequences of Ty3/Gag Elements and Origin of Dipteran Arc Genes, Related to Figure 1**

(A) Translated genomic DNA sequences corresponding to Arc or gypsy Gag proteins were aligned using MUSCLE (<https://www.ebi.ac.uk/Tools/msa/muscle/>). Aligned sequences were shaded using the boxshade plot server ([https://embnet.vital-it.ch/software/BOX\\_form.html](https://embnet.vital-it.ch/software/BOX_form.html)), using default parameters (50% sequences sharing aa identity for shading). Note: the alignments only contain fragments of Arc genes, not the full-length sequences with start sites. Species included: Mm—*Mus musculus*, house mouse; Hs—*Homo sapiens*, human; Ac—*Anolis carolinensis*, Carolina anole lizard; Lc—*Latimeria chalumnae*, West Indian Ocean coelacanth; Dr—*Danio rerio*, zebrafish; Cc—*Cyprinus carpio*, common carp; Dm—*Drosophila melanogaster*, common vinegar fly; Ds—*Drosophila suzukii*, spotted-wing fly; Sc—*Stomoxys calcitrans*, stable fly, Lh—*Linepithema humile*, Argentine ant; Bm—*Bombyx mori*, silkworm; Tc—*tribolium castaneum*, red flour beetle.

(B) (left) Maximum likelihood phylogenetic analysis of Arc homologs found in *Drosophilidae*, *Muscidae*, and *Tephritidae* flies. Multiple copies of *darc1* were observed throughout *tephritid* flies and in the house fly, *Musca domestica*. For each sequence, the GenBank accession number is given after the abbreviated species names. *Tephritidae*: RZ—*Rhagoletis zephyria*; CC—*Ceratitis capitata*; BD—*Bactrocera dorsalis*. *Muscidae*: MD—*Musca domestica*; SC—*Stomoxys calcitrans*. (right) Putative duplication history of dArc in *schizophoran* flies as inferred from the phylogenetic analysis in (A). Since all *schizophoran* flies examined possess a homolog of *darc1* and *darc2*, the duplication of the ancestral dArc must have occurred prior to the divergence of these species (blue triangle). This ancestral duplication event was followed by multiple rounds of duplication of *darc1* (green triangles) in some of the lineages: two duplication events in the common ancestor of the *Tephritidae*, one additional duplication in the lineage of *Ceratitis capitata*, and one additional duplication in the lineage of *Bactrocera dorsalis*. Independently, *darc1* experienced three rounds of duplication in the lineage of *Musca domestica*. By contrast, *darc2* has apparently remained a single copy gene in the species examined.



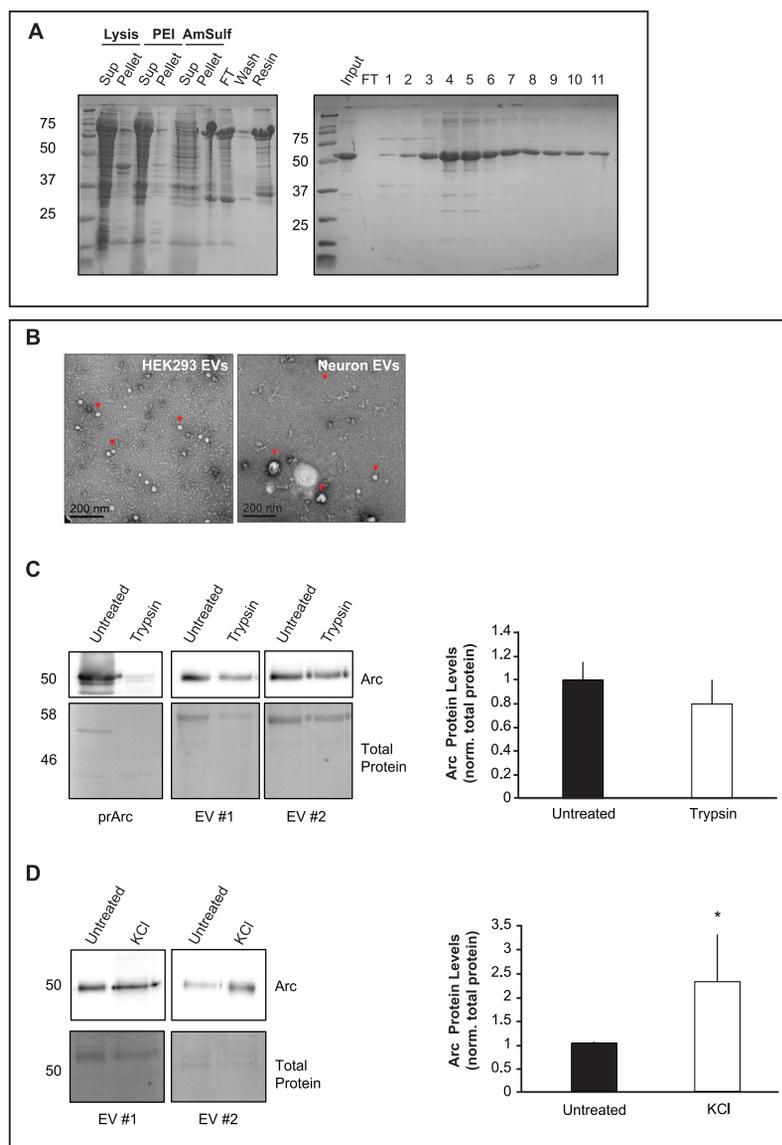
**Figure S2. Recombinant Protein Purification and Experiments, Related to Figure 2**

(A) (left to right) Representative Coomassie gel of affinity purifications of full-length rat Arc (prArc), prArc- $\Delta$ CTD, CA-prArc, GST, and Endo3A showing similar expression levels to that of prArc. prArc- $\Delta$ CTD and Endo3A were prepared in the same manner as prArc. GST was directly eluted from the affinity resin using 15mM L-glutathione. His-tagged CA-prArc was eluted from Ni<sup>2+</sup> affinity resin using 250mM imidazole. All proteins were then buffer exchanged into 150mM NaCl, 50mM Tris, pH 7.4 following GST-tag cleavage by Precision Protease or elution. Buffer conditions were adjusted for all proteins for each experiment: 500mM NaPO<sub>4</sub>, 50mM Tris, pH 7.4 for capsid stability. Analyses showing the partitioning of bacterially-expressed protein into soluble (sup) and insoluble (pellet) fractions (lanes 1, 2), capture of the protein on a GST or Ni<sup>2+</sup> affinity matrices (lanes 3-5 show the flow through (FT), wash and captured protein, respectively). This panel demonstrates the protein expression levels and the efficacy and efficiency of affinity capture.

(B) Representative Coomassie gels of peak fractions of prArc, prArc- $\Delta$ CTD, and Endo3A eluted from S200 size exclusion columns. Peak fractions were pooled and concentrated to a final stock concentration of 1mg/mL. prArc was concentrated to 1mg/mL from each purification for use in all biochemistry/EM experiments, unless noted. For cell biology experiments, prArc was diluted to 0.4mg/mL and 4  $\mu$ g total protein was used per condition.

(C) Representative Coomassie gel of affinity purification of *Drosophila* dArc1 from BL21 bacteria lysates demonstrating similar expression levels to rat prArc.

(D) HEK293 cells in 12-well plates were transfected with full-length rat WT Arc or GFP plasmids using Lipofectamine at equal DNA concentrations and subjected to formaldehyde crosslinking *in situ*. Cell lysates were blotted with anti-GFP or anti-Arc antibodies. Note that higher molecular species corresponding to Arc dimers and trimers can be observed in the crosslinked Arc sample, but not in the GFP sample.



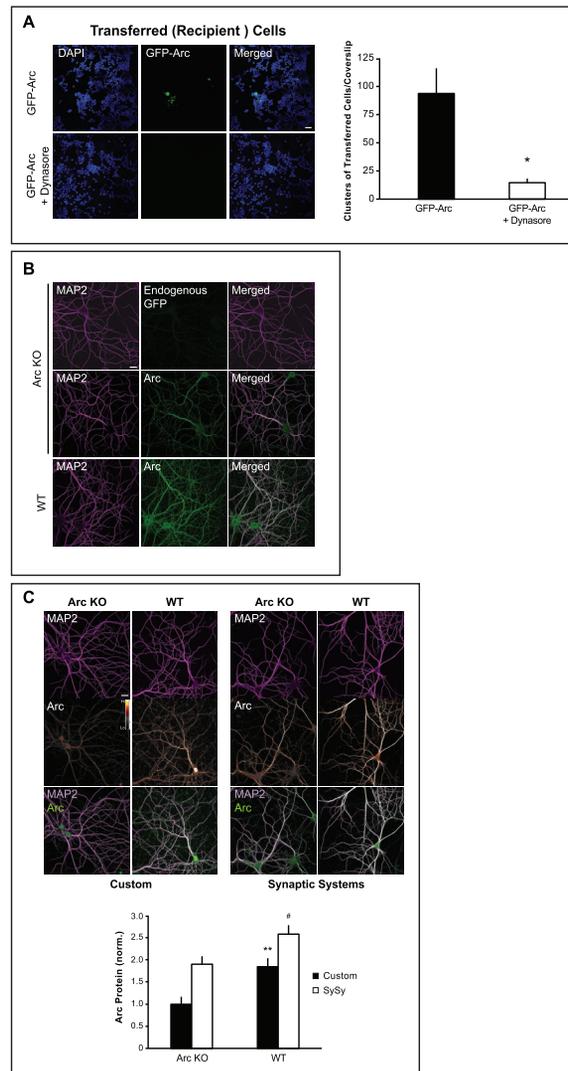
**Figure S3. RNA Binding Experiments and Properties of Arc EVs, Related to Figures 2 and 3**

(A) Representative Coomassie gels of nucleotide stripping of prArc. (left) Cells were lysed in 20mM NaCl, 50mM Tris, 2mM MgCl<sub>2</sub>, 5% glycerol, 1mM DTT, pH 8.0. Fractions shown are supernatant and pellet fractions of cellular lysis after pelleting at 21,000xg for 45 min. The supernatant from this step was treated with 0.1% PEI to precipitate nucleic acids. This treatment resulted in a shift in the A<sub>260/280</sub> ratio from 1.71 ± 0.018 to 1.29 ± 0.023, indicating a drop in nucleic acid content. The sample was pelleted at 27,000xg for 20 min and the resulting supernatant was treated with ammonium sulfate (AmSulf) precipitation to concentrate Arc and pelleted at 10,000xg for 10 min. The AmSulf pellet containing Arc was then subjected to affinity purification as above. (right) Representative Coomassie gel of peak fractions of cleaved, affinity purified PEI treated Arc from an anion exchange column. This chromatography step further stripped bound nucleic acids from Arc. Peak fractions were concentrated to 1mg/mL and the final measured A<sub>260/280</sub> ratio for these fractions was 0.68 ± 0.03 (n = 3), indicating that PEI-treated prArc was largely free of nucleic acids.

(B) (left) Representative negative stain EM images of purified EVs from Arc-transfected HEK293 cell media collected for 24 h used for western blot analysis. (right) Representative negative stain EM images of purified EVs from WT cultured neuron media collected for 24 h used for western blot analysis. Red arrows indicate purified EVs.

(C) (left) Western blot of Arc in untreated EVs or EVs treated with trypsin (0.05mg/mL) for 30 min. prArc was used as a positive control for trypsin activity. (right) Quantification of Arc western blot normalized to total protein. Trypsin degraded prArc but had no effect on Arc protein present in neuronal EVs.

(D) Activity dependence of Arc secretion. Purified EV fraction from media collected from DIV15 cortical neurons in 10-cm dishes from untreated WT neurons was compared with treatment with KCl. Media was freshly exchanged with basal media or media supplemented with KCl to a final concentration of 50mM. Following media exchange, cells were incubated for 1 h and media was collected and the EV fraction was purified. (left) Western blots of Arc and total protein from the purified EV fraction from cultured neuronal media. (right) Quantification of Arc protein levels, normalized to total protein. KCl treatment resulted in significantly more Arc released into the media (n = 2; p < 0.05).

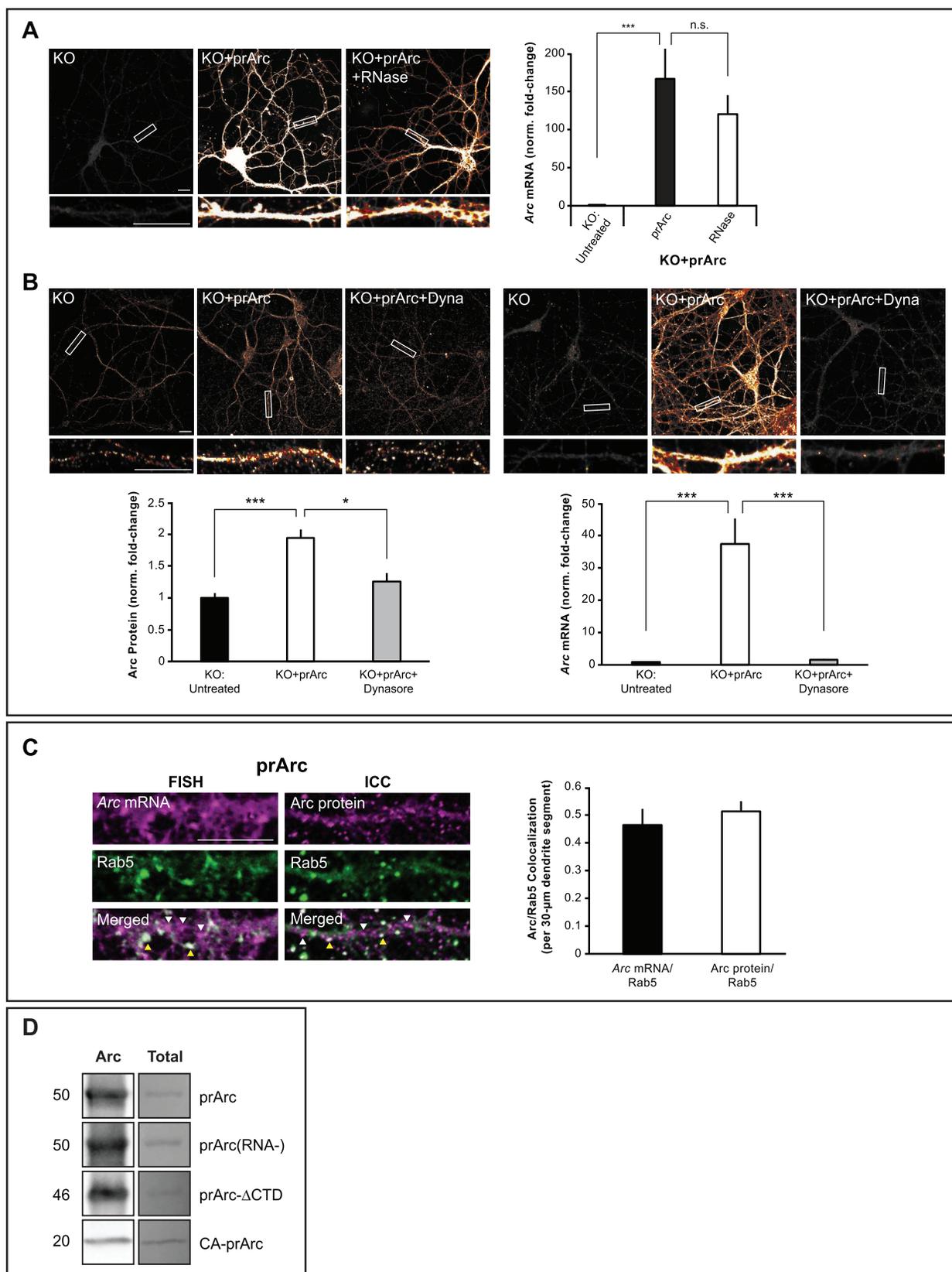


**Figure S4. HEK Cell Experiments and Custom-Made Arc Antibody Control Experiments, Related to Figure 4**

(A) HEK293 cells in 10-cm dishes were transfected with GFP-Arc as in Figure 4. 18 h later, media from GFP-Arc-transfected HEK cells in 10-cm dishes was transferred to naive HEK cells in 12-well plates, and 80  $\mu$ M Dynasore was added in one group at the same time to block endocytosis. After 6 h, the Dynasore-treated media was exchanged for fresh HEK media. 18 h later, cells were fixed and clusters of GFP-Arc-expressing cells over an entire 18mm coverslip were manually counted through a 20X objective ( $n = 3$  coverslips/group). (left) Representative images of one 20X field of view. (right) Dynasore significantly reduced the number of clusters of GFP-Arc-positive cells over the entire coverslip. Student's  $t$ -test: \* $p < 0.05$ . Scale bar = 50  $\mu$ m. Representative of three independent experiments and cultures with similar results.

(B) DIV15 cultured hippocampal Arc KO and WT neurons were immunostained for the dendritic protein MAP2 with Alexa Fluor 555 only (top row), or both MAP2 (Alexa 555) and Arc (Alexa 488; bottom two rows). Imaging settings for Arc were determined based on Arc immunostaining in WT neurons (bottom row). No GFP fluorescence from GFP knocked in to the Arc locus in the KO neurons was visible under these imaging conditions. Example of two independent experiments.

(C) DIV15 cultured hippocampal Arc KO and WT neurons were fixed and immunostained with either a custom-made rabbit polyclonal Arc antibody (ProteinTech) or the commercially available Synaptic Systems rabbit polyclonal Arc antibody, as well as the dendritic protein MAP2. All groups were imaged with the same acquisition settings. 30- $\mu$ m segments of two dendrites/neuron were analyzed in all groups ( $n = 10$  neurons) and were chosen using MAP2 staining. Both antibodies were able to detect a difference between Arc KO and WT neurons, although the signal:noise was better using the custom-made antibody. Arc in the soma/nucleus varies widely from neuron to neuron with both antibodies, under basal conditions. Student's  $t$ -test: \*\*Arc KO versus WT with custom antibody,  $p < 0.01$ . #Arc KO versus WT with Synaptic Systems ("SySy") antibody,  $p < 0.05$ . Arc images are false-colored with the Smart LUT in ImageJ to better display differences in Arc expression. Example of two independent experiments.



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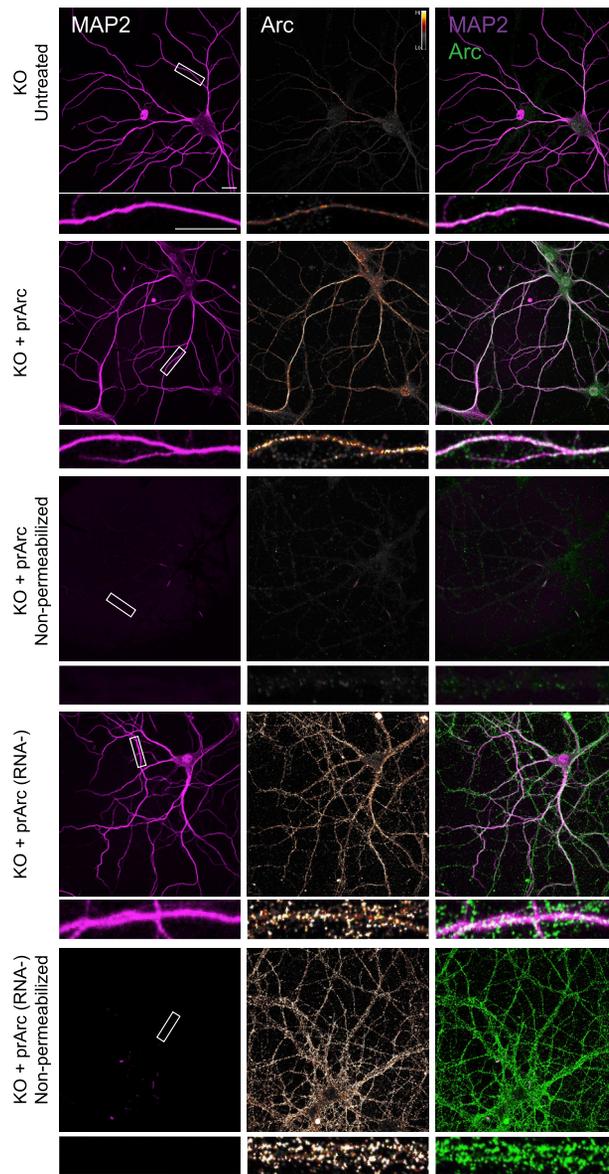
**Figure S5. RNase and Uptake Experiments, Related to Figure 5**

(A) To test whether *Arc* mRNA is protected in prArc capsids, samples were subjected to 15 min treatment with RNase A, then RNase inhibitor (1U/ $\mu$ L) to quench activity, prior to incubation with neurons. (left) Representative images of *Arc* mRNA in DIV15 cultured hippocampal Arc KO neurons incubated with the treated or untreated prArc samples for 4 h. (right) prArc treatment resulted an increase in dendritic *Arc* mRNA levels in Arc KO neurons. prArc treated with RNase did not affect *Arc* mRNA transfer.

(B) DIV15 cultured hippocampal Arc KO neurons were treated for 4 h with 4  $\mu$ g prArc. In one group, 30 min before prArc was added, neurons were pretreated with 80 $\mu$ M Dynasore to block endocytosis. (left) Representative images of *Arc* protein and mRNA levels. (right) Pretreatment with Dynasore significantly blocked uptake/transfer of prArc protein and *Arc* mRNA. Student's *t*-test: \**p* < 0.05. \*\*\**p* < 0.001. Example of three independent experiments (A, B). Scale bars in all panels = 10  $\mu$ m.

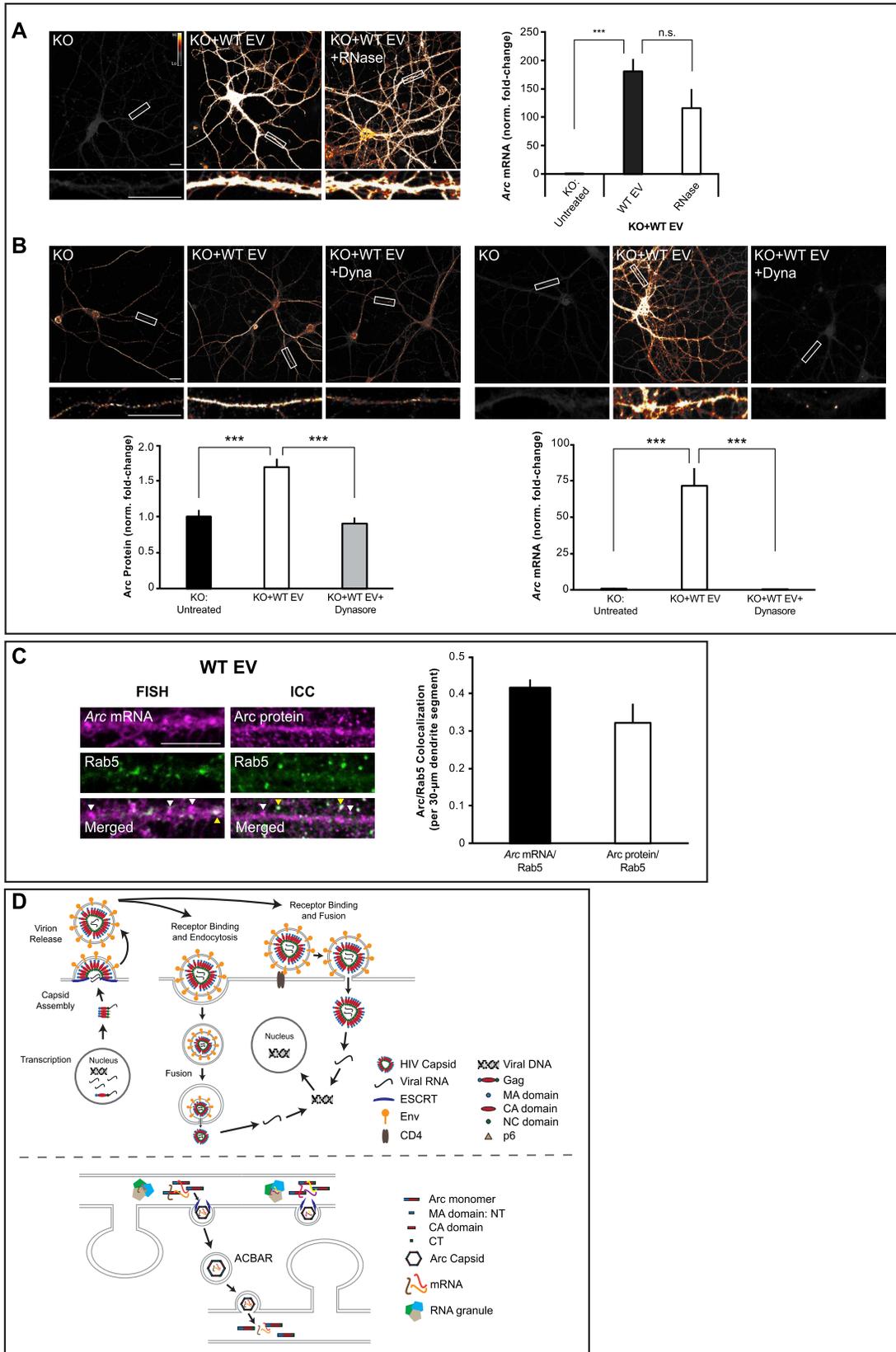
(C) DIV15 cultured hippocampal Arc KO neurons were treated for 4 h with 4  $\mu$ g prArc. Either combined FISH/ICC for *Arc* mRNA and Rab5 protein, or ICC for *Arc* and Rab5 protein, was performed. (left) Representative images of dendrites showing *Arc* mRNA plus Rab5 protein or *Arc* and Rab5 protein. (right) *Arc* protein and mRNA showed around 50% colocalization in dendrites with Rab5. White arrowheads indicate *Arc* alone, and yellow arrowheads indicate *Arc*/Rab5 colocalization. Example of two independent experiments. Scale bar = 10  $\mu$ m.

(D) Purified protein samples of prArc, prArc(RNA-), prArc- $\Delta$ CTD, and CA-prArc were separated by SDS-PAGE, and the resulting western blot was immunostained for *Arc* using our custom-made *Arc* antibody. The antibody successfully detected all of the mutant constructs, suggesting that the lack of *Arc* immunostaining observed in transfer experiments was not a result of an inability of the antibody to detect the mutants. "Total" is Ponceau stain for total protein for each sample.



**Figure S6. Purified Arc Stripped of Nucleic Acids Cannot Be Taken Up by Neurons, Related to Figure 5**

DIV15 cultured hippocampal Arc KO neurons were treated with 4  $\mu\text{g}$  prArc or prArc(RNA-) for 4 h before being fixed. One group from each treatment was not permeabilized during the immunocytochemistry procedure for Arc and MAP2. prArc-treated neurons that were non-permeabilized showed little to no MAP2 and Arc immunostaining. However, prArc(RNA-)-treated neurons showed no difference in Arc immunostaining between permeabilized and non-permeabilized conditions, although MAP2 immunostaining was still absent in the non-permeabilized condition, suggesting that prArc(RNA-) accumulates on the outside of the neurons. Dendritic segments boxed in white are shown magnified beneath each corresponding image. Scale bars = 10  $\mu\text{m}$ . Example of three independent experiments. Arc images are false-colored with the Smart LUT from ImageJ to highlight differences in Arc expression. Merged images have MAP2 immunostaining in magenta and Arc in green.



### Figure S7. RNase and Uptake Experiments, Related to Figure 6

(A) To test whether *Arc* mRNA is protected in neuronal EVs, EVs prepared from 10-cm dishes of DIV15 cultured WT cortical neurons were subjected to 15 min treatment with RNase A, then RNase inhibitor (1U/ $\mu$ L) to quench activity, prior to incubation with neurons. DIV15 cultured hippocampal Arc KO neurons were incubated with 10  $\mu$ g of the treated or untreated WT EV samples for 4 h. (left) Representative images of *Arc* mRNA levels in neurons. (right) WT EV treatment resulted in an increase in dendritic *Arc* mRNA levels in Arc KO neurons. WT EV treated with RNase did not affect *Arc* mRNA transfer.

(B) DIV15 cultured hippocampal Arc KO neurons were treated for 4 h with 10  $\mu$ g of the EV fraction harvested from the media of 10-cm dishes containing DIV15 high-density cultured cortical WT or Arc KO neurons. In one group, 30 min before EVs were added, neurons were pretreated with 80 $\mu$ M Dynasore to block endocytosis. (top) Representative images of *Arc* protein levels (left) or *Arc* mRNA levels (right). (bottom) Pretreatment with Dynasore significantly blocked uptake of *Arc* protein and mRNA from WT EVs. *Arc* protein and mRNA expression was normalized to Arc KO and is displayed as fold-change  $\pm$  SEM. Dendritic segments boxed in white are shown magnified beneath each corresponding image. 30- $\mu$ m segments of two dendrites/neuron were analyzed in all groups ( $n = 10$  neurons) and were chosen using MAP2 staining. Student's *t*-test: \*\*\* $p < 0.001$ . Scale bars = 10  $\mu$ m. Example of three independent experiments. Images are false-colored with the Smart LUT from ImageJ to highlight differences in *Arc* expression.

(C) DIV15 cultured hippocampal Arc KO neurons were treated for 4 h with 10  $\mu$ g of WT EVs, then fixed. Either combined FISH/ICC for *Arc* mRNA and Rab5 protein, or ICC for *Arc* and Rab5 protein, was performed. (left) Representative images of dendrites showing *Arc* mRNA plus Rab5 protein or *Arc* and Rab5 protein. (right) *Arc* mRNA and protein showed 30%–40% colocalization in dendrites with Rab5. White arrowheads indicate *Arc* alone, and yellow arrowheads indicate *Arc*/Rab5 colocalization. Example of two independent experiments. Scale bar = 10  $\mu$ m.

(D) Model: Comparison of HIV Gag and *Arc* capsid life cycle. (top) HIV Gag protein self-assembles (via the CA domain) in the cytosol and at the plasma membrane (by myristoylation of the MA domain), while the capsid encapsulates viral RNA (via the NC domain). The immature HIV capsid is released from the cell in an ESCRT-dependent manner (via the p6 domain) with membrane that contains the viral envelope protein (Env). The mature virus particles bind host cells through surface receptors (such as CD4) and membrane fusion occurs. Alternatively, in some cell types virus particles are first endocytosed prior to fusion and particles released into the cell after full fusion occurs in the endosome. Viral RNA is released and then reverse transcribed into viral DNA that is integrated into the host genome. (bottom) *Arc* mRNA is trafficked out into dendrites in RNA granules that contain a selection of different mRNAs. Local translation of *Arc* mRNA takes place in dendrites in response to neuronal activity. High concentrations of *Arc* protein self-assemble and form *Arc* capsids, which encapsulate select mRNAs that are spatially proximal, including *Arc* mRNA. *Arc* capsids are released from dendrites in Arc Capsids Bearing Any RNA (ACBARs) and transfer of mRNA and other putative cargo takes place in neighboring dendrites.