SNARE mimicry by the CD225 domain of IFITM3 enables regulation of homotypic late endosome fusion

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Abstract

The CD225/Dispanins superfamily consists of integral membrane proteins that regulate vesicular transport and membrane fusion events driving critical cellular functions, including glucose transport, neurotransmission, and antiviral immunity. However, how the conserved CD225 domain contributes to the diverse roles played by CD225 proteins during membrane trafficking was unknown. Here, we reveal that the CD225 domain contains a SNARE-like motif that enables interaction with cellular SNARE fusogens and modulation of SNARE complex formation. We show that CD225 member proline rich transmembrane protein 2 (PRRT2) encodes an R-SNARE-like motif that enables interaction with neuronal Q-SNARE proteins. Importantly, mutations in PRRT2 linked to neurological disease in humans reside within key structural features of the R-SNARE-like motif and cause loss of Q-SNARE binding, revealing that SNARE binding via this motif in PRRT2 is critical for its role in regulating neurotransmission in vivo. Another CD225 member, interferon-induced transmembrane protein 3 (IFITM3), provides cell-intrinsic protection against Influenza A virus infection and has been shown to accelerate the trafficking of incoming virions to lysosomes for degradation. Here we demonstrate that an R-SNARE-like motif in IFITM3 is predicted to adopt a VAMP-like fold and to enable interaction with endosomal Q-SNARE proteins involved in homotypic late endosome fusion. Specifically, IFITM3 binds to Q-SNARE syntaxin 7 in cells and in vitro, and mutations in IFITM3 that abrogate syntaxin 7 binding exhibit a loss of antiviral activity against Influenza A virus, indicating that this previously uncharacterized activity is central to the antiviral mechanism of IFITM3. IFITM3 deficiency in human cells resulted in enhanced co-immunoprecipitation between Q-SNARE syntaxin 7/8 and R-SNARE VAMP8, while IFITM3 overexpression inhibited this interaction. Furthermore, overexpression of IFITM3 WT, but not a mutant of IFITM3 defective for syntaxin 7/8 binding, disrupted assembly of the SNARE complex controlling homotypic late endosome fusion. Our findings invoke a mechanistic model whereby IFITM3 diverts incoming virus towards lysosomes by preventing homotypic late endosome fusion. Our identification of an R-SNARE-like motif in many members of the CD225 family suggests that SNARE modulation plays a previously unrecognized role in the diverse membrane trafficking functions performed by these proteins and provides fresh insight into how their loss of function results in disease or susceptibility to infection.

Introduction

Membrane fusion is a critical process enabling cargo transfer between membrane-bound compartments. The soluble NSF attachment protein receptor (SNARE) proteins are key mediators of membrane fusion and are involved in nearly every vesicular trafficking event in eukaryotic cells[1,2]. SNARE proteins contain a so-called SNARE motif consisting of heptad repeats of generally hydrophobic amino acids surrounding a central hydrophilic residue (R for arginine or Q for glutamine)[3]. The central residue is referred to as the "0" layer while the hydrophobic residues surrounding it are numbered relative to the "0" layer, from "-7" to "+8" (**Figure 1A**). These features enable the assembly of four parallel alpha-helices (one R-SNARE motif and three Q-SNARE motifs) into a coiled-coil trans-SNARE complex across two membranes. Progressive folding of the bundle towards a cis-SNARE complex, in which the SNARE proteins reside within the same membrane, drives membrane fusion[4]. Humans encode a minimum of 38 SNARE proteins which interact selectively to impart specificity and directionality to membrane fusion events between different organelles[5].

Among the best studied are the synaptic SNARE proteins that mediate the exocytosis of neurotransmitters from neurons[6]. Neurotransmitter release at neuronal synapses requires the fusion of synaptic vesicles with the presynaptic plasma membrane, and this requires the assembly of syntaxin 1A and SNAP-25 (in the presynaptic plasma membrane) with VAMP2 (in the synaptic vesicle membrane)[7,8]. The study of neurological diseases associated with impaired neurotransmission has led to the identification of cellular proteins that regulate synaptic SNARE assembly, such as proline-rich transmembrane protein 2 (PRRT2)[9]. Mutations in PRRT2 associated with a range of neurological disorders in humans (including paraoxysmal kinesigenic dyskinia (PKD), infantile epilepsy and convulsions, hemiplagic migraines, ataxia, and intellectual disability) indicated that PRRT2 plays important roles in neurotransmission[9]. Subsequently, it was shown that PRRT2 interacts with Q-SNAREs syntaxin 1A and SNAP-25 and disfavors their interaction with the R-SNARE VAMP2, thereby reducing synaptic SNARE assembly and neurotransmitter release[10-13]. However, a comprehensive understanding of the protein-protein interface enabling this regulatory function of PRRT2 was unknown. PRRT2 belongs to the CD225 superfamily, a group that includes trafficking regulator of GLUT4 (TRARG1/TUSC5) and interferon-induced transmembrane protein 3 (IFITM3)[14]. TUSC5 and IFITM3 regulate vesicular trafficking during glucose transport and virus infection, respectively, through incompletely understood mechanisms.

Here, we report the identification of an R-SNARE-like motif shared among many CD225 family members that enables SNARE binding and modulation of SNARE assemblies. Mutation of residues within the R-SNARE-like motif of PRRT2, TUSC5, and IFITM3 resulted in reduced Q-SNARE binding and loss of their respective functions, as demonstrated experimentally or by associations with human disease. In-depth analysis revealed that IFITM3 interacts with endosomal SNARE proteins and, as a result, inhibits the assembly of the SNARE complex mediating homotypic late endosome fusion. Our findings suggest that cells expressing IFITM3 prioritize the heterotypic fusion pathway whereby late endosomes fuse with lysosomes, resulting in endosomal cargo degradation. Our findings demonstrate that CD225 proteins regulate diverse membrane trafficking processes in different tissues by regulating cellular fusion machinery via a conserved R-SNARE-like motif.

Results

To investigate whether the known SNARE-binding activity exhibited by human PRRT2 may be attributed to the presence of a previously unrecognized SNARE-like motif, we performed multiple protein sequence alignment between PRRT2 and a panel of Q- and R-SNARE proteins. We found that PRRT2 encodes an arginine that aligns with the central arginines present within canonical R-SNARE motifs, which are approximately 53 amino acids in length (**Figure 1A**). Furthermore, like canonical R-SNARE proteins, PRRT2 contains regularly spaced, generally hydrophobic residues extending on both sides of the central arginine. Therefore, PRRT2 contains a putative R-SNARE motif, resembling that which is present in VAMP proteins. Importantly, we also found this R-SNARE-like motif in additional members of the human CD225 protein family, including IFITM1, IFITM2, IFITM3, IFITM5, IFITM10, TUSC5, although the identify and number of hydrophobic layers surrounding the central arginine varied between members (**Figure 1**). The central arginine was lacking in a subset of CD225 family members (**Supplemental Figure 1A**), suggesting either that the R-SNARE-like motif does not trace its origins to the CD225 ancestor or that the motif was lost to decay in certain family members.

Next, since PRRT2 has been described to regulate the SNARE complex controlling neurotransmission[10], we measured whether the R-SNARE-like motif present within PRRT2 confers it with the ability to bind neuronal SNARE proteins. In agreement with previous reports, ectopic PRRT2 co-immunoprecipitated with ectopic Q-SNARE SNAP-25 (**Figure 1B**). Attesting to a critical role played by the R-SNARE-like motif of PRRT2 in mediating this interaction, mutation of the central arginine (R295Q) resulted in decreased co-immunoprecipitation between PRRT2 and SNAP-25 (**Figure 1B**). Furthermore, mutation of one of the hydrophobic layers of the R-SNARE-like motif of PRRT2 (A320V) also abrogated the interaction with SNAP-25, and a G305W mutation that is adjacent to a hydrophobic layer and which inhibits PRRT2 homodimerization[15] also abrogated this interaction (**Figure 1B**). Meanwhile, these mutations in PRRT2 did not affect the interaction between PRRT2 and another Q-SNARE in the neuronal SNARE complex, syntaxin 1A (**Supplemental Figure 1B**). Importantly, all three mutations (R295Q, G305W, and A320V) in PRRT2 occur naturally as polymorphisms in humans and are linked to neurological dysfunction (references)[12,13,16]. Therefore, our results describing an R-SNARE-like motif in human PRRT2 provide a mechanistic basis for the previously described molecular interaction between PRRT2 and neuronal SNARE proteins, as well as an explanation for how R295Q, G305W, and A320V cause loss of PRRT2 function in vivo and neurological dysfunction.

TUSC5 is a CD225 family member expressed in adipose tissue and implicated in the translocation of glucose transporter type 4 (GLUT4) to the cell surface, a process essential for insulin-stimulated glucose transport[17,18]. It was previously reported that TUSC5 co-immunoprecipitated with GLUT4 and SNARE proteins implicated in the vesicular trafficking of GLUT4[19,20]. However, the basis for this interaction was unknown. Like the CD225 family member PRRT2, TUSC5 also encodes a putative R-SNARE-like motif (**Figure 1A**). Accordingly, we found that ectopic TUSC5 co-immunoprecipitated with ectopic syntaxin 4, a Q-SNARE involved in GLUT4 translocation, while a G141W mutation in TUSC5 (analogous to G305W in PRRT2) disrupted this interaction (**Supplemental Figure 1C**). Collectively, these results highlight the presence of a R-SNARE-like motif in CD225 family members that enables coordination of SNARE proteins involved in diverse membrane fusion processes.

The IFITM proteins IFITM1, IFITM2, and IFITM3 are among the best characterized members of the CD225 protein family due to their established roles in cell-intrinsic defense against diverse pathogenic viruses[21,22]. IFITM3 provides constitutive and interferon-induced

protection of cells from endocytic viruses such as Influenza A virus (IAV) by homing to virus-containing endosomes and inhibiting virus-cell membrane fusion, effectively preventing the delivery of the viral core into host cell cytosol (where virus replication begins)[23-26]. Moreover, *Ifitm3* knockout mice and disease-associated single-nucleotide polymorphisms in human *IFITM3* revealed that IFITM3 prevents severe viral disease sequelae in vivo[27,28]. IFITM2 arose through gene duplication of IFITM3 in the ancestor of great apes, and both IFITM2 and IFITM3 proteins accumulate in membranes of the endolysosomal compartment[29]. In addition to preventing virus escape from the endocytic compartment, it has been demonstrated that IFITM3 redirects incoming virions to lysosomes for degradation[26,30,31]. However, the mechanism for this latter effect by IFITM3 was unknown, as was its relevance to the antiviral activity exhibited by IFITM3. Since IFITM3 is an endolysosomal protein, we assessed whether the R-SNARE-like motif in IFITM3 (**Figure 1A**) conferred IFITM3 with the ability to bind and regulate endolysosomal SNARE proteins.

Fusion between compartments of the endolysosomal system are controlled by SNARE complexes consisting of the Q-SNAREs syntaxin 7 (STX7), syntaxin 8 (STX8), Vti1b, and one of two R-SNAREs—VAMP8 or VAMP7 (**Figure 2A**). The STX7-STX8-Vti1b-VAMP8 complex enables late endosome-late endosome (homotypic) fusion while the STX7-STX8-Vti1b-VAMP7 complex is responsible for late endosome-lysosome (heterotypic) fusion[32-35]. Endocytic viruses like IAV exploit the endolysosomal network and the SNARE machinery found therein in order to avoid lysosomal degradation and gain access to host cell cytosol, where virus replication is initiated. VAMP8 and its role in late endosome homotypic fusion was previously reported to promote IAV entry into cells. In contrast, VAMP7 inhibited IAV entry, presumably by favoring the degradation of virus-laden late endosomes with lysosomes[36,37]. Therefore, we tested whether IFITM3 and the R-SNARE-like motif found in its CD225 domain could influence the assembly of SNARE complexes regulating the endolysosomal network.

The R-SNARE-like motif is conserved among the interferon-inducible members of the human IFITM family that exhibit antiviral activity—IFITM1, IFITM2, and IFITM3 (**Figure 2A**). In contrast to a canonical R-SNARE protein like VAMP8, the R-SNARE-like motif of IFITM1-3 lack two layers of hydrophobicity at the amino-terminal end of the motif. Instead, IFITM1-3 encode an amphipathic helix that was shown to mediate cholesterol binding activity, membrane binding, and which is essential for antiviral activity against IAV[15,38-40] (**Figure 2A**). Interestingly, the intact hydrophobic layers forming part of the R-SNARE-like motif downstream of the amphipathic helix include residues that were previously shown to be important for antiviral activity: a cysteine residue previously shown to be palmitoylated[41-43] and two phenylalanine residues shown to be critical for antiviral function[26,44] (**Figure 2A**). Therefore, to provide further evidence that the R-SNARE-like motif of IFITM3 contributes functionally to its antiviral activity, we assessed how mutation of the central arginine (R85Q) or the two phenylalanines (F75A/F78A) impacted antiviral activity against IAV. We also tested the effect of mutating glycine 95 (G95L), since it is adjacent to a hydrophobic layer in the R-SNARE-like motif of IFITM3, is homologous to glycine 305 in PRRT2 and glycine 141 in TUSC5 (**Figure 1B and Supplemental Figure 1C**), and was previously shown by us to be critical for antiviral activity[15]. While IFITM3 WT reduced IAV infection by approximately 80% relative to Empty Vector, all mutants tested exhibited a near-total loss of antiviral activity (**Figure 2B**) despite exhibiting similar steady-state protein levels in transfected cells (**Supplemental Figure 2B**). These results indicate that the antiviral activity of IFITM3 against IAV depends upon a previously uncharacterized R-SNARE-like motif. Furthermore, our findings suggest that interactions with

SNARE machinery may comprise an essential but unrecognized component of IFITM3 function in cells.

Next, we addressed whether the R-SNARE-like motif of IFITM3 adopts a protein fold resembling that of a genuine R-SNARE. Since the atomic structure of IFITM3 is incompletely understood[45] and the influence of interaction partners on its structure has not been explored, we used the TM-align platform[46] to perform protein structure alignment between the R-SNARE-like motif of IFITM3 and the R-SNARE motif of VAMP8. The results supported that IFITM3 and VAMP8 adopt a highly similar alpha helical fold in the region spanning their respective R-SNARE motifs (TM-score = 0.76) (**Supplemental Figure 2A**). To further investigate the SNARE-like structural qualities of IFITM3, we used Alphafold[47,48] and the flexible protein structure alignment algorithm FATCAT[49] to model the R-SNARE-like motif of IFITM3 against a template consisting of the R-SNARE motif of VAMP8, which was previously crystallized in the context of the STX8-STX7-Vti1b-VAMP8 complex[50]. We found that the Alphafold model for the R-SNARE-like motif of IFITM3 exhibited a high degree of structural homology with the R-SNARE motif of VAMP8 (**Figure 2C**). Therefore, IFITM3 encodes an R-SNARE-like motif that is predicted to behave like an endosomal R-SNARE protein.

To determine whether the R-SNARE-like motif of IFITM3 confers it with the ability to bind endolysosomal SNARE proteins in cells, we overexpressed IFITM3 in combination with individual endolysosomal SNARE proteins in HEK293T cells and performed co-immunoprecipitation. We found that IFITM3 immunoprecipitated from transfected cells pulled down relatively high quantities of ectopic STX7, while other endolysosomal SNARE proteins were pulled down to a lesser, or negligible, extent (**Figure 2D**). The association between IFITM3 and STX7 was confirmed by reverse co-immunoprecipitation, whereby immunoprecipitated ectopic STX7 pulled down ectopic IFITM3 (**Supplemental Figure 2C**). Ectopic STX8 also co-immunoprecipitated with IFITM3 but to a lesser extent than STX7 (**Supplemental Figure 2C**). This selective co-immunoprecipitation between IFITM3 and STX7 was not due to elevated STX7 levels in transfected cells (**Figure 2D**). Importantly, mutants of IFITM3 that caused loss of antiviral function (F75A/F78A, R85Q, and G95L) (**Figure 2B**) diminished binding with STX7 and STX8 relative to WT (**Figure 2E and Supplemental Figure 2C**). IFITM3 F75/78A and R85Q exhibited somewhat decreased steady-state levels relative to WT, possibly attesting to the importance of the R-SNARE-like motif in maintaining proper folding and stability of the IFITM3 polypeptide (**Figure 2E**). These results demonstrate that an intact R-SNARE-like motif in IFITM3 enables it to bind to endosomal SNARE proteins, particular Q-SNAREs STX7 and STX8. Furthermore, there exists a functional requirement for the R-SNARE-like motif of IFITM3 during restriction of IAV infection.

We then assessed whether endogenous IFITM3 exhibits SNARE binding activity. Following transfection of ectopic STX7 into HeLa cells competent or deficient for IFITM3, we found that ectopic STX7 pulled down endogenous IFITM3 (**Figure 3A**). As a control, pull down of endogenous IFITM3 by ectopic STX7 was lost in *IFITM3* knockout cells (**Figure 3A**). *IFITM3* knockout was specific, as IFITM2 protein levels were unaffected, and did not influence the overall levels of endolysosomal SNARE proteins (**Supplemental Figure 3A**). Moreover, the presence or absence of IFITM3 did not affect the co-immunoprecipitation between STX7 and other Q-SNAREs STX8 and Vti1b (**Supplemental Figure 3B**). We were unable to detect or immunoprecipitate endogenous STX7 in HeLa cells (data not shown). However, we succeeded in immunoprecipitating endogenous STX8 and found that it pulled down endogenous IFITM3 (**Figure 3B**). To determine whether IFITM3 can bind STX7 directly, we produced and purified

recombinant IFITM3 (**Supplemental Figure 3C-D**) and incubated it with recombinant STX7 (**Supplemental Figure 3E**) *in vitro*. Immunoprecipitation of recombinant STX7 from the reaction resulted in pull down of recombinant IFITM3, and this interaction was lost when F75/78A or G95L mutations were introduced into IFITM3 (**Figure 3C**). Overall, we demonstrate for the first time that IFITM3 interacts directly with endosomal Q-SNAREs via an R-SNARE-like motif that is critical for antiviral activity.

Since STX7 is an essential part of the SNARE complexes controlling homotypic late endosome fusion and heterotypic late endosome fusion, we determined whether IFITM3 regulates the assembly of the STX7-STX8-Vti1b-VAMP8 complex, the STX7-STX8-Vti1b-VAMP7 complex, or both. STX7, VAMP8, and IFITM3 were ectopically co-expressed in HEK293T and STX7 was immunoprecipitated to identify its interaction partners. As shown above, STX7 pulled down IFITM3 WT, while the G95L mutation in IFITM3 abrogated this interaction (**Figure 4A**). Importantly, STX7 pulled down a reduced amount of VAMP8 in the presence of IFITM3 relative to Empty Vector. In contrast, IFITM3 G95L did not affect the STX7-VAMP8 interaction (**Figure 4A**). We performed additional experiments whereby STX7, VAMP7, and IFITM3 were ectopically co-expressed. Here, IFITM3 binding to STX7 did not inhibit the interaction between STX7 and VAMP7. Instead, the STX7-VAMP7 interaction was slightly elevated in the presence of IFITM3 WT, but not IFITM3 G95L (**Supplemental Figure 4A**). These results indicate that IFITM3 binding to STX7 selectively impairs the interaction between STX7 and VAMP8. To address whether endogenous IFITM3 performs a similar function, we immunoprecipitated endogenous STX8 from HeLa. As shown above, endogenous IFITM3 pulls down with endogenous STX8. However, endogenous STX8 pulled down increased quantities of VAMP8 in *IFITM3* knockout cells relative to WT cells (**Figure 4B**). These results support a model whereby IFITM3 acts as a negative regulator of the interaction between STX7/8 and VAMP8. Since it was previously shown that endocytic viruses including IAV may co-opt the STX7-STX8-Vti1b-VAMP8 SNARE complex to promote the virus entry process[36], we performed co-immunoprecipitation experiments in cells that had been inoculated with IAV. Interestingly, we noticed that virus addition resulted in enhanced co-immunoprecipitation between endogenous STX8 and VAMP8 in HEK293T cells. However, in the presence of ectopic IFITM3 WT, this co-immunoprecipitation was diminished, while co-immunoprecipitation between endogenous STX8 and VAMP7 was enhanced (**Figure 4C**). The IFITM3 G95L mutant, in contrast, co-immunoprecipitated with STX8 to a lesser extent than IFITM3 WT and only marginally impacted the STX8-VAMP8 and STX8-VAMP7 interactions (**Figure 4C**). These findings suggest that IFITM3 disfavors the STX7/8-VAMP8 interaction while favoring the STX7/8-VAMP7 interaction. To test whether IFITM3 reduces the assembly of the entire STX7-STX8-Vti1b-VAMP8 SNARE complex involved in homotypic late endosome fusion, we ectopically co-expressed STX7, STX8, Vti1b, and VAMP8 in HEK293T cells. SNARE protein assemblies have been previously characterized as SDS-resistant complexes in whole cell lysates under mildly denaturing conditions[51]. We identified an SDS-resistant complex approximately 200 kD in size or greater by immunoblotting for VAMP8 (**Figure 4D**) or STX8 (**Supplemental Figure 4B**). The complex was sensitive to heat, as high molecular weight bands disappeared after boiling lysates (**Figure 4D and Supplemental Figure 4B**). Consistent with IFITM3 acting as a negative regulator of complex formation, complex abundance was markedly reduced in cells expressing IFITM3 WT (**Figure 4D and Supplemental Figure 4B**). In contrast, IFITM3 G95L only marginally reduced complex formation (**Figure 4D**). Therefore, by binding STX7/8 via an

R-SNARE-like motif and reducing their interaction with VAMP8, IFITM3 impedes formation of the STX7-STX8-Vti1b-VAMP8 complex involved in homotypic late endosome fusion.

Our results showing that IFITM3 uses an R-SNARE-like motif to inhibit homotypic late endosome fusion while maintaining, and possibly amplifying, the heterotypic late endosome-lysosome fusion pathway may explain how IFITM3 redirects incoming virions towards lysosomes for degradation[26,30,31]. To test the functional association between SNARE modulation and lysosomal targeting of virions, we examined early steps of IAV entry into cells using confocal immunofluorescence microscopy. In HEK293T cells stably expressing IFITM3 WT or IFITM3 G95L, which differ with respect to STX7 binding potential (**Figure 4A**), IAV was added to cells at a multiplicity of infection of 1 and incubated on ice for 40 mins. Cells were fed warm medium containing Lysotracker, to visualize acidic lysosomes, and placed at 37°C to enable synchronized internalization of virus particles. Four hours later, cells were washed, fixed and immunostained with an antibody against IAV nucleoprotein (NP), which detects incoming, virion-associated NP as well as de novo synthesized NP. In cells expressing Empty Vector, nuclear NP accumulation was apparent at 4 hours post-inoculation in roughly 20% of cells, which signals the initiation of virus replication following successful entry of the virus (i.e. escape from the endocytic compartment) (**Figure 5A-B**). In cells expressing IFITM3 WT, nuclear NP accumulation was virtually absent, consistent with strong inhibition of cellular entry of IAV as reported previously[30]. In contrast, IFITM3 G95L did not reduce nuclear NP accumulation, in agreement with a loss of antiviral activity exhibited by this mutant[15] (**Figure 5A-B**). Interestingly, we observed a negative correlation between the extent of nuclear NP staining and the intensity of Lysotracker staining in cells. IFITM3 WT expression resulted in intensification of Lysotracker fluorescence, consistent with expansion of the lysosomal compartment as described previously[30]. However, expression of IFITM3 G95L did not (**Figure 5C-D**). In cells expressing IFITM3 G95L, most NP protein was localized to the nucleus at four hours post-inoculation. However, some instances of extra-nuclear, bright NP puncta associated with the Lysotracker-positive compartment could be observed, suggesting that a small proportion of incoming IAV virions were trafficked to lysosomes in IFITM3 G95L-expressing cells (**Figure 5D**). However, the occurrence of bright NP puncta colocalizing with Lysotracker-positive vesicles was enhanced in cells expressing IFITM3 WT (**Figure 5D and Supplemental Figure 5**). In IFITM3 WT cells, NP was found to colocalize with Lysotracker to a greater extent than in cells expressing IFITM3 G95L as measured by Pearson's Correlation Coefficient (0.389 in WT versus 0.023 in G95L) (**Figure 5D**). These results support the notion that inhibition of homotypic late endosome fusion and promotion of heterotypic late endosome fusion by IFITM3 underlies its ability to promote trafficking of IAV towards lysosomes. Altogether, this body of work demonstrates that endolysosomal SNARE modulation is a key aspect of the mechanism by which IFITM3 protects cells from invading viruses.

Discussion

Our identification of an R-SNARE-like motif in human CD225 proteins suggests that these proteins act as SNARE mimics to regulate SNARE-mediated membrane fusion events. Even though there are CD225 members that lack the polar arginine or glutamine in the central layer characteristic of a canonical SNARE motif, they encode layered hydrophobicity which may still afford some degree of SNARE modulation (**Supplemental Figure 1A**). For sample, Vti1a is SNARE protein involved in neurotransmission despite encoding an aspartic acid in the central

layer[52] (**Figure 1A**). Moreover, other well-characterized SNARE proteins, like STX8, VAMP8, VAMP7, and Vti1b lack a full complement of hydrophobic layers in their respective SNARE motifs (**Figure 1A**). Since the CD225 family is poorly characterized and contains many proteins with currently unknown functions[14], our discovery of built-in SNARE binding potential within the CD225 domain may serve as a catalyst for uncovering the physiological roles they perform. As such, we provide important insight into the birth and functional expansion of the CD225 domain over the course of evolutionary time.

A limited number of SNARE-like proteins functioning as SNARE mimics have been described before. Two of the best characterized R-SNARE-like proteins in humans are Tomosyn and Amisyn, which adopt VAMP-like protein folds and regulate the same neuronal SNARE complex that PRRT2 does[53-55]. Furthermore, microbial proteins containing SNARE-like sequence and functionality have been discovered in prokaryotes and viruses[56-60]. Interestingly, phylogenetic evidence suggests that the CD225 domain was introduced into eukaryotes following multiple horizontal transmission events from prokaryotes[61]. Therefore, it is possible that the SNARE-like motif of CD225 traces its beginnings to a similar, ancient motif in microbes.

IFITM3 was arguably the most completely understood member of the CD225 family, but our finding that it acts as a SNARE assembly modulator significantly boosts our understanding of its key cellular functions. The closely related proteins, IFITM1, IFITM2, IFITM5, and IFITM10, are also likely to interact with SNARE proteins since they all share an R-SNARE-like motif (**Figure 1A**). Interestingly, one of the most significant series of findings with regards to IFITM function was the characterization of a conserved amphipathic alpha helix in its amino terminus. This helix was shown to be essential for the antiviral activity of IFITM3[38] and necessary for the ability of IFITM3 to reduce cellular membrane fluidity[15]. Following our discovery here, we now know that this amphipathic helix is immediately adjacent to, or part of, an R-SNARE-like motif (**Figure 2A**). Interestingly, a SNARE protein in yeast known as Spo20 also contains an amphipathic alpha helix amino terminal to its SNARE motif, resembling the structural organization of IFITM3[62]. Moreover, another group of SNARE binding proteins known as complexins are also bestowed with an amphipathic helix, and they use it to induce membrane curvature and stabilize fusion pores produced by SNARE complexes[63]. Therefore, it is possible that IFITM3 employs its amphipathic helix in conjunction with its R-SNARE-like motif to sculpt membranes at precisely the sites where endolysosomal SNARE assemblies are triggering membrane fusion. Other structural features lend further support to our case that IFITM3 is a SNARE-like protein. Some SNARE proteins encode a single transmembrane domain to directly anchor into vesicular or target membranes[1], and IFITM3 is similar in that regard[45]. Additionally, palmitoylation is a post-translational modification of cysteine residues that promotes membrane localization, and IFITM3 and various SNARE proteins are known to be palmitoylated[43,64-67].

Notably, the relatively limited structural information previously available for IFITM3 did not indicate the presence of a continuous alpha helix reminiscent of a SNARE motif. In isolation, the region comprising the R-SNARE-like sequence motif of IFITM3 was previously thought to form an amphipathic helix followed by a disordered, intracellular loop[38,45]. The structure of another CD225 protein, PRRT2, was posited to contain a similarly disordered, intracellular loop as well[68]. The typical SNARE fold characteristic of a SNARE motif may only form in the context of a coiled-coil assembly of multiple SNARE alpha helices (trans-SNARE complex). Our description of IFITM3 as a SNARE-like protein capable of interacting with endosomal

SNARE proteins suggests that multiple protein folds and membrane topologies of IFITM3 may be possible, depending on the presence of interacting partners (such as STX7). Thus, attempts to structurally characterize IFITM3 in complex with STX7 other endosomal SNAREs may provide substantial structural insight that has been lacking.

Regarding the structural interface between IFITM3 and endosomal SNARE proteins, the stoichiometry of the interactions remains unclear. We previously characterized a GxxxG motif present in CD225 proteins that enables homomultimerization and which is essential to the functions of PRRT2 and IFITM3[15]. Here we show that mutation of the GxxxG motif in PRRT2 (G305W), TUSC5 (G141W), or IFITM3 (G95L) caused loss of binding with Q-SNAREs SNAP-25, syntaxin 4, or syntaxin 7, respectively (**Figure 1B, Supplemental Figure 1C, and Supplemental Figure 2C**). These glycines reside adjacent to the +3 hydrophobic layer (**Figure 1A**) and may disrupt the structural integrity of the R-SNARE-like motif. Alternatively, these findings may signal a requirement for CD225 proteins to multimerize prior to gaining SNARE binding potential. Another possibility is that the GxxxG motif in CD225 proteins not only controls homomultimerization but also impacts binding with other proteins including SNAREs.

What is more certain is that this newfound ability of IFITM3 to bind endosomal SNARE proteins and inhibit homotypic late endosome fusion may provide a leap in our understanding of how IFITM3 inhibits the cellular entry of a diverse spectrum of enveloped and non-enveloped viruses[21]. By showing that IFITM3 inhibits homotypic late endosome fusion while reinforcing heterotypic late endosome fusion, whereby late endosomes fuse with lysosomes, we provide an explanation for how IFITM3 overexpression causes expansion of the endolysosomal compartment and degradation of virions within it[30]. Taken together with previous findings, we propose a revised model for the molecular mechanism of IFITM3-mediated antiviral activity that is two-pronged: 1) IFITM3 traps incoming virions in late endosomes by inhibiting membrane fusion between the viral and cellular lipid bilayers; and 2) IFITM3 promotes the fusion of late endosomes with lysosomes to facilitate the degradation of trapped viral cargo. Promotion of late endosome-lysosome fusion by IFITM3 is further supported by evidence showing that IFITM3 accelerates the turnover of cellular cargo in lysosomes, namely the Epidermal Growth Factor Receptor (EGFR)[31]. Importantly, the fate of EGFR in cells is also controlled by the STX7-STX8-Vti1b-VAMP7/8 SNARE machinery[69].

In addition to blocking infection through inhibition of virus entry into cells, IFITM3 also performs an antiviral function in cells that are already infected—it has been shown to interact with and inhibit the function of viral fusogens (known as viral envelope glycoproteins) found in virions, which in turn reduces in infectivity of said virions[70-73]. Remarkably, viral fusogens share structural and functional similarities to SNARE proteins, including heptad repeats and the formation of coiled-coil assemblies to drive membrane merger[74,75]. Therefore, our description of an R-SNARE-like motif in IFITM3 may reveal the molecular basis by which IFITM3 interacts with both cellular and viral fusion machinery to control virus infections at multiple levels.

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Declaration of interests

The authors declare no competing interests.

Materials and Methods

Tissue culture, cell lines, and expression constructs

HEK293T (CRL-3216) and HeLa (CCL-2) were purchased from ATCC and cultivated at 37°C and 5% CO_2 in DMEM (Gibco) complemented with 10% fetal bovine serum (Hyclone) and 1% penicillin-streptomycin (Gibco). HeLa *IFITM3* KO cells were generated as previously described[76]. pQCXIP retroviral vectors encoding human IFITM3 (tagged with FLAG on amino terminus), PRRT2 (tagged with FLAG on carboxy terminus), or TUSC5 (tagged with FLAG on the amino terminus) were previously described[15] or synthesized by Integrated DNA Technologies (IDT) as gBlock fragments and cloned into pQCXIP using BamH1 and EcoR1 restriction enzymes. Mutations were introduced via QuikChange Lightning Site-Directed Mutagenesis (Agilent). HEK293T stably expressing pQCXIP-Empty Vector, pQCXIP-IFITM3 WT, or pQCXIP-IFITM3 G95L were described previously[15]. pcDNA3.1 encoding SNARE proteins (SNAP25, Syntaxin 1A, Syntaxin 4, Syntaxin 7, Syntaxin 8, Vti1b, VAMP8, and VAMP7) tagged with HA or myc at the amino terminus were synthesized by IDT as gBlock fragments and cloned into pcDNA3.1 using BamH1 and EcoR1 restriction enyzmes.

Antibodies, immunoblotting, and immunoprecipitations

Whole cell lysis was performed in a buffer containing 50 mM Tris-HCl pH 7.4, 1.0% TritonX-100 (Sigma), 150 mM NaCl, and 1 mM EDTA. Immunoprecipitation was performed as follows: antibodies were loaded with Dynabeads (Invitrogen) for 1 hr at 4°C while rotating; Dynabead-conjugated antibodies were added to whole cell lysates for 3 hr at 4°C while rotating to capture antibody-antigen complexes; immunoprecipitated fractions were isolated using the DynaMag-2 magnet (Invitrogen) and washed three times with lysis buffer prior to addition of NuPage LDS Sample Buffer (Invitrogen) and NuPage Sample Reducing Agent (Invitrogen); the immunoprecipitated and non-immunoprecipitated fractions were heat denatured at 100°C for 5 min; samples were loaded into Criterion XT 12% Bis-Tris polyacrylamide gels (Bio-Rad) for SDS-PAGE using NuPAGE MES SDS Running Buffer (Invitrogen). Proteins were transferred to Amersham Protran Nitrocellulose Membrane (GE Healthcare), and membranes were blocked with Intercept Blocking Buffer-PBS (Li-COR) prior to incubation with primary and secondary antibodies. The following antibodies were used in this study: anti-STX8 (110-083; Synaptic Systems); anti-STX7 (110-072; Synaptic Systems), anti-Vti1b (164-002; Synaptic Systems), anti-VAMP8 (104-302; Synaptic Systems), anti-VAMP7 (ab36195; Abcam), anti-HA (901514, clone 16B12; Biolegend), anti-HA (ab9110; Abcam (this was used for immunoprecipitation)), anti-myc (C3956, Sigma), anti-FLAG M2 (F1804; Sigma), anti-IFITM3 (ab109429; Abcam), anti-IFITM2/3 (66081-1-Ig, Proteintech), and anti-actin (SC-47778; Santa Cruz Biotechnology). Goat anti-mouse and goat anti-rabbit secondary antibodies conjugated to DyLight 680 or 800 (Li-COR) and the Li-COR Odyssey CLx imaging system were used for generating immunoblots, Membrane images were analyzed using ImageStudioLite (Li-COR).

Sequence retrieval and protein alignments

Protein sequences for CD225 proteins, Q-SNAREs, and R-SNAREs were retrieved from UniProt. Multi-sequence alignments were performed with MEGA11 and manually trimmed to the 53-residue SNARE motif. UniProt numbers for SNAREs are as follows: syntaxin1, Q16623; syntaxin4, Q12846; syntaxin 6, O43752; syntaxin7, O15400; syntaxin8, Q9UNK0; SNAP23,

O00161; Vti1a, Q96AJ9; Vti1b, Q9UEU0; VAMP1, P23763; VAMP2, P63027; VAMP3, Q15836; VAMP5, O95183; VAMP7, P51809; VAMP8, Q9BV40; Ykt6, O15498; Syn8p, P31377; Tomosyn/STXBP5, Q5T5C0; Amisyn/STXBP6, Q8NFX7.

Recombinant IFITM3 protein production

Recombinant human IFITM3 protein (WT, F65/68A, and G95L) was produced by cloning the nucleotide sequence appended with a Strep-II tag at the amino terminus into pET3XC and transforming it into Rosetta 2 DE3 pLysS Competent Cells (Sigma). A single colony of transformed cells was grown in LB overnight at 37°C. One mL of the culture was expanded in 200 mL 2YT medium (Sigma) at 37°C until the optical density reached 0.4, and the temperature was lowered to 18°C for 1 hr before induction with 0.4 mM IPTG (Tecknova) for 20 hr. Pelleted cells were frozen at -80°C before proceeding to protein purification. Thawed cells were resuspended in ice cold lysis buffer (at 10% w/v) consisting of 20 mM Tris-HCl pH 7.6, 100 mM NaCl, 1 mM DTT, 0.5 mg/ml lysozyme (Sigma), 1 mM PMSF (Sigma), 0.025% (v/v) Triton X-100 (Sigma), and 1X Complete Protease Inhibitors (Roche). Sample was stirred at 4°C for 20 min before applying 2 freeze-thaw cycles by transferring the sample container between dry ice and a room temperature water bath. The thawed lysate was stirred at room temperature for 15 min after adding 5 U/mL benzonase (Sigma) prior to pulse sonication for 30 s at 4°C. Sample was clarified by centrifugation at 5000 g for 10 min and the supernatant was further centrifuged at 40000 g for 60 min. The pellet was thoroughly resuspended in the lysis buffer (modified to include 1 mM EDTA and excluding lysozyme) and centrifuged at 40000 g for 60 min. This process was then performed a second time. The pellet was extracted twice with 20 mM Tris-HCl pH 7.6, 100 mM NaCl, 20% glycerol, 2% (v/v) Anapoe-X-100 (Anatrace), 1 mM DTT (Gold Bio), and 0.1 mM AEBSF (Santa Cruz Biotechnology) at 4°C while stirring for 4 hr each. The protein in the pellet was extracted with 20 mM Tris-HCl pH 7.6, 0.6% Sarkosyl (w/v) (Sigma), and 2 mM DTT. Strep-II-fused IFITM3 was purified by affinity chromatography using Strep-Tactin Sepharose Resin (IBA Lifesciences). Protein was >90% pure as determined by SDS-PAGE and Coomassie blue staining (**Supplemental Figure 3D**). Protein concentration was determined by Bio-Rad Protein Assay and stored at a concentration of 15-30 mg/mL at -80°C. In the final reaction mixture of purified, recombinant IFITM3, the Sarkosyl concentration was 0.00002%.

In vitro protein-protein co-immunoprecipitation

Two µg of recombinant Strep-II tagged IFITM3 WT or F75/78A or G95L were incubated with 2 µg of recombinant His-tagged STX7 (IHUSTX7RN6HISLY50UG; Innovative Research) in 0.3 mL of binding buffer (20 mM HEPES pH 7.4, 150 mM NaCl, 0.2% TritonX-100, and 0.1% BSA) overnight at 4°C. The samples were incubated with 1 ug of IFITM3 antibody for 1 hr. The antibody-antigen complex was captured with 15 uL of Dynabeads (Invitrogen). After washing the samples 3 times with binding buffer (lacking BSA), proteins captured by beads using the DynaMag-2 were solubilized in 20 uL of 1X NuPAGE LDS Sample Buffer and 1X NuPAGE Sample Reducing Reagent (Invitrogen), and heat denatured at 100°C for 5 min. SDS-PAGE and immunoblotting were performed and proteins were detected as described above.

Structural modeling of the R-SNARE-like motif of IFITM3

The R-SNARE-like motif of IFITM3 (residues 55-113) and the R-SNARE motif of VAMP8 (residues 13-65) were compared by predictive protein structure alignment and

comparison algorithm TM-align[46]. A TM score of 0.75847 was recorded, indicating that the two regions are likely to adopt the same alpha helical protein fold. Structural comparison between the R-SNARE-like motif of IFITM3 and the R-SNARE motif of VAMP8, which was previously crystallized as part of the STX7-STX8-Vti1b-VAMP8 trans-SNARE complex (PDB: 1GL2)[50], was performed using Alphafold version 3[77] with assistance from the Colabfold server[48]. A structure for the R-SNARE-like motif of IFITM3 was predicted using the R-SNARE motif of VAMP8 as a template. The Alphafold structure was then aligned with that of VAMP8 using the FATCAT server[49]. The aligned structures were then visualized and reoriented for figure presentation using ChimeraX[78].

Influenza A Virus infection

Influenza A Virus [A/PR/8/34 (PR8), H1N1] supplied as clarified allantoic fluid was purchased from Charles River Laboratories. Infectious virus titers were calculated using a flow cytometry-based method in HEK293T cells[79], and infections were performed as follows: HEK293T cells (transiently transfected with 1.5 µg pQCXIP-Empty Vector, pQCXIP-FLAG-IFITM3 WT, or pQCXIP-FLAG-IFITM3 G95L were seeded in 24-well plates (50,000 per well) overnight and overlaid with virus diluted in 225 µL of complete DMEM (multiplicity of infection = 0.01) for approximately 18 hr. Cells were washed with 1X D-PBS (Gibco), detached with Trypsin-EDTA (Gibco), fixed/permeabilized with Cytofix/Cytoperm (BD), immunostained with anti-IAV NP (ab20343; Abcam), and analyzed on a LSRFortessa flow cytometer (BD).

Influenza A Virus cellular entry assay

An 8-well µ-Slide dish (80826; Ibidi) was coated with 3 mg/mL PureCol (Advanced Biomatrix) for 1 hr at room temperature and then allowed to dry overnight. HEK293T stably expressing pQCXIP-Empty Vector, pQCXIP-FLAG-IFITM3 WT, or pQCXIP-FLAG-IFITM3 G95L were seeded at 20,000 cells per well in DMEM completed with 10% fetal bovine serum and 1% penicillin-streptomycin and incubated at 37°C overnight. Cells were placed on ice for 5 min and then remained on ice while medium was removed and replaced with 120 uL complete DMEM containing Influenza A virus PR8 (multiplicity of infection = 1). Cells mock ionoculated with PBS served as a negative control. Inoculated cells were incubated on ice for 40 min to allow for virus adhesion. Medium was removed, cells were washed twice with D-PBS, and medium was replaced with 150 uL complete DMEM containing 50 nM Lysotracker Deep Red (L12492; Invitrogen) and incubated at 37°C for 4 hr. Medium was removed, cells were washed twice with D-PBS, and cells were fixed/permeabilized with Cytofix/Cytoperm (BD) for 10 min at room temperature. Cells were washed twice with PermWash buffer (BD) and blocked with Intercept Blocking Buffer (PBS) (Li-COR) for 1 hr at room temperature. Cells were immunostained with anti-NP (BE0159; InvivoMab) at a 1:200 dilution in Intercept Antibody Diluent (PBS) (Li-COR) for 1 hr at room temperature. Cells were washed twice in PermWash buffer and goat anti-mouse IgG (H+L) Alexa Fluor 888 secondary antibody (Invitrogen) at 1:300 dilution in Intercept Antibody Diluent (PBS) was added for 1 hr at room temperature. Cells were washed twice in PermWash Buffer and Hoechst 33342 (H3570; Invitrogen) was added for 5 min at room temperature. Cells were washed once in PermWash Buffer and overlaid with 200 uL D-PBS for image acquisition on a Leica Stellaris 5 confocal microscope using the 63X oil objective. Confocal Z stacks of 20-30 optical sections were acquired for each field of view, and multiple fields were imaged per condition. Images were extracted and subjected to analysis in Fiji. To quantify Lysotracker staining, the Corrected Total Cell Fluorescence (CTCF) was measured for

the middle Z slice of the entire field. To quantify nuclear NP accumulation, colocalization between NP and Hoechst was measured for the middle Z slick of each cell in the field and a ratio of NP+ nuclei: total nuclei was calculated.

Statistics

Statistical differences were determined with one-way ANOVA test corrected for multiple comparisons, using an alpha cut-off of 0.05. *P* values are indicated in the figure captions.

Figure Legends

Figure 1: CD225 proteins contain a motif resembling an R-SNARE motif.
(A) A selection of SNARE proteins from yeast and mammals were aligned with proteins with SNARE-like motifs, and a 53-residue stretch of sequence is shown. Proteins are grouped by Q-SNARE, R-SNARE, or R-SNARE-like, and CD225 proteins are labeled as a subset of the R-SNARE-like proteins. Residues in red text are the central polar arginine or glutamine residues characteristic of canonical SNARE proteins and are labeled as the central "0" layer. Surrounding heptad repeats of hydrophobic residues are labeled from "-7" to "+8" in relation to the "0" layer, and sites highlighted in yellow correspond to hydrophobic residues. Underlined residues are those found in PRRT2 that are associated with neurological dysfunction. (B) Left: HEK293T cells were co-transfected with SNAP25-HA and either PRRT2-FLAG (WT, R295Q, G305W, or A320V) or Empty Vector. SDS-PAGE and immunoblotting were performed with anti-HA and anti-FLAG in whole cell lysates. Anti-actin was used as loading control. Right: From co-transfected cells, SNAP25-HA was immunoprecipitated with anti-HA followed by SDS-PAGE and immunoblotting with anti-HA and anti-FLAG. Immunoglobulin chain was used as loading control. Numbers and tick marks left of blots indicate position and size (in kilodaltons) of protein standard in ladder. The FLAG/HA ratio was calculated for each lane and made relative to WT (set to 100%). Immunoblots were performed independently three times, and a representative example is shown. Sc; Saccharomyces cerevisiae. Ig; immunoglobulin. IP; immunoprecipitation. EV; empty vector. WT; wild-type.

Supplemental Figure 1:
(A) Human CD225 proteins were aligned and trimmed to a 53-residue stretch of sequence covering the SNARE motif. Proteins are grouped by whether they contain an arginine at the central "0" layer (R-SNARE-like) or not. Surrounding heptad repeats of hydrophobic residues are labeled from "-7" to "+8" in relation to the "0" layer, and sites highlighted in yellow correspond to hydrophobic residues. (B) Left: HEK293T cells were co-transfected with STX1A-HA and either PRRT2-FLAG (WT, R295Q, G305W, or A320V) or Empty Vector. SDS-PAGE and immunoblotting were performed with anti-HA and anti-FLAG in whole cell lysates. Anti-actin was used as loading control. Right: From co-transfected cells, STX1A-HA was immunoprecipitated with anti-HA followed by SDS-PAGE and immunoblotting with anti-HA and anti-FLAG. Immunoglobulin chain was used as loading control. (C) Left: HEK293T cells were co-transfected with STX4-HA and either TUSC5-FLAG (WT or G141W) or Empty Vector. SDS-PAGE and immunoblotting were performed with anti-HA and anti-FLAG in whole cell lysates. Anti-actin was used as loading control. Right: From co-transfected cells, STX4-HA was immunoprecipitated with anti-HA followed by SDS-PAGE and immunoblotting with anti-HA and anti-FLAG. Immunoglobulin chain was used as loading control. Numbers and tick marks left

of blots indicate position and size (in kilodaltons) of protein standard in ladder. Immunoblots were performed independently three times, and a representative example is shown. Ig; immunoglobulin. IP; immunoprecipitation. EV; Empty Vector. WT; wild-type.

Figure 2: IFITM3 contains an R-SNARE-like motif and interacts with ectopic endosomal Q-SNARE STX7.

(A) Human endosomal SNARE proteins were aligned with aligned with human IFITM proteins, and a 53-residue stretch of sequence is shown. Residues in red text are the central polar arginine or glutamine residues characteristic of canonical SNARE proteins and are labeled as the central "0" layer. Surrounding heptad repeats of hydrophobic residues are labeled from "-7" to "+8" in relation to the "0" layer, and sites highlighted in yellow correspond to hydrophobic residues. Black underlined residues in IFITM3 which were mutated for functional experiments. Green underlined residues in IFITM3 correspond to the previously described amphipathic alpha helix. (B) HEK293T cells were transfected with IFITM3-FLAG (WT, F75/78A, R85Q, or G95L) and, 48 hours later, challenged with IAV (A/PR/8/34 (PR8), H1N1) at a multiplicity of infection of 0.10. 18 hours post-infection, cells were fixed, permeabilized, immunostained with anti-FLAG and anti-NP, and analyzed by flow cytometry. The percentage of NP+ cells was measured as a fraction of FLAG+ cells and made relative to Empty Vector (set to 100%). Statistical differences between WT and F75/78A, R85Q, or G95L were measured by one-way ANOVA test (*, $p < 0.0001$). (C) Structural prediction of the R-SNARE-like motif of IFITM3 was performed with Alphafold and FATCAT. Residues 55-113 of IFITM3 were modeled against a template of the R-SNARE motif of VAMP8 which was previously crystallized as part of the STX7-STX8-Vti1b-VAMP8 trans-SNARE complex (PDB: 1GL2). (D) HEK293T cells were co-transfected with IFITM3-FLAG or Empty Vector and a construct encoding a single SNARE protein: STX7-HA, STX8-HA, Vti1b-HA, VAMP8-HA, or VAMP7-myc. SDS-PAGE and immunoblotting were performed with anti-HA, anti-myc, and anti-FLAG in whole cell lysates. Anti-actin was used as loading control. Right: From co-transfected cells, IFITM3-FLAG was immunoprecipitated with anti-FLAG followed by SDS-PAGE and immunoblotting with anti-HA, anti-myc, and anti-FLAG. Immunoglobulin chain was used as loading control. Co-transfection of Empty Vector and STX7-HA was used as a negative control for immunoprecipitation. (E) HEK293T cells were co-transfected with STX7-HA and either IFITM3-FLAG (WT, F75/78A, or R85Q) or Empty Vector. SDS-PAGE and immunoblotting were performed with anti-HA and anti-FLAG in whole cell lysates. Anti-actin was used as loading control. Right: From co-transfected cells, IFITM3-FLAG was immunoprecipitated with anti-FLAG followed by SDS-PAGE and immunoblotting with anti-FLAG and anti-HA. Immunoglobulin chain was used as loading control. Co-transfection of Empty Vector and STX7-HA was used as a negative control for immunoprecipitation. The HA/FLAG ratio was calculated for each lane and made relative to WT (set to 100%). Numbers and tick marks left of blots indicate position and size (in kilodaltons) of protein standard in ladder. Immunoblots were performed independently three times, and a representative example is shown. IAV; Influenza A virus. Ig; immunoglobulin. IP; immunoprecipitation. EV; Empty Vector. WT; wild-type.

Supplemental Figure 2:

(A) The R-SNARE-like motif of IFITM3 and the R-SNARE motif of VAMP8 (53 residues each) were compared by predictive protein structure alignment and comparison algorithm TM-align. A TM score of 0.75847 was recorded, indicating that the two regions are likely to adopt the same

alpha helical protein fold. (B) HEK293T cells were co-transfected with STX8-HA and either Empty Vector or IFITM3-FLAG (WT, F75/78A, or G95L). SDS-PAGE and immunoblotting were performed with anti-HA and anti-FLAG in whole cell lysates. Anti-actin was used as loading control. (C) From co-transfected cells, STX8-HA, STX7-HA, or Vti1b-HA were immunoprecipitated with anti-HA followed by SDS-PAGE and immunoblotting with anti-HA and anti-FLAG. Immunoglobulin chain was used as loading control. Co-transfection of Empty Vector and STX8-HA was used as a negative control for immunoprecipitation. The FLAG/HA ratio was calculated for each lane and made relative to WT (set to 100%). Numbers and tick marks left of blots indicate position and size (in kilodaltons) of protein standard in ladder. Immunoblots were performed independently three times, and a representative example is shown. Ig; immunoglobulin. IP; immunoprecipitation. EV; Empty Vector. WT; wild-type.

Figure 3: Endogenous IFITM3 interacts with endosomal Q-SNAREs in cells and in vitro via an R-SNARE-like motif.

(A) HeLa cells (WT or *IFITM3* KO) were transfected with STX7-HA. SDS-PAGE and immunoblotting were performed with anti-HA and anti-IFITM3 in whole cell lysates. Anti-actin was used as loading control. Right: STX7-HA was immunoprecipitated with anti-HA antibody followed by SDS-PAGE and immunoblotting with anti-HA and anti-IFITM3. Immunoglobulin chain was used as loading control. An isotype matched antibody was used as a control for immunoprecipitation. (B) Endogenous STX8 was immunoprecipitated from HeLa (WT or *IFITM3* KO) with anti-STX8 followed by SDS-PAGE and immunoblotting with anti-STX8 and anti-IFITM3. Immunoglobulin chain was used as loading control. An isotype matched antibody was used as a control for immunoprecipitation. (C) Recombinant STX7 and recombinant IFITM3 (WT, F75/78A, or G95L) were mixed together in vitro and reaction inputs were visualized by SDS-PAGE and immunoblotting with anti-STX7 and anti-IFITM3. Right: recombinant STX7 was immunoprecipitated with anti-STX7 followed by SDS-PAGE and immunoblotting with anti-STX7 and anti-IFITM3. Immunoglobulin chain was used as loading control. Numbers and tick marks left of blots indicate position and size (in kilodaltons) of protein standard in ladder. Immunoblots were performed independently three times, and a representative example is shown. Ig; immunoglobulin. IP; immunoprecipitation. EV; Empty Vector. WT; wild-type. r; recombinant.

Supplemental Figure 3:

(A) HeLa cells (WT or *IFITM3* KO) were subjected to whole cell lysis, SDS-PAGE, and immunoblotting with anti-IFITM2/3, anti-STX8, anti-Vti1b, anti-VAMP8, anti-VAMP7, and anti-actin. Red and green arrows indicate IFITM3 and IFITM2, respectively, recognized by the anti-IFITM2/3 antibody. (B) STX7-HA was transfected into HeLa (WT or *IFITM3* KO) and immunoprecipitated with anti-HA followed by SDS-PAGE and immunoblotting with anti-HA, anti-IFITM3, anti-STX8, and anti-Vti1b. Immunoglobulin chain was used as loading control. An isotype matched antibody was used as a control for immunoprecipitation. (C) Purified recombinant IFITM3 protein (WT, F75/78A, or G95L) of varying inputs (6, 12 or 18 µg) were subjected to SDS-PAGE and visualized by Coomassie stain. (D) 20 µg of purified recombinant IFITM3 protein (WT, F75/78A, or G95L) were subjected to SDS-PAGE and immunoblotting with anti-IFITM3. (E) Recombinant STX7 was subjected to SDS-PAGE and immunoblotting with anti-STX7. Numbers and tick marks left of blots indicate position and size (in kilodaltons) of protein standard in ladder. Immunoblots were performed independently three times, and a

representative example is shown. Ig; immunoglobulin. IP; immunoprecipitation. EV; Empty Vector. WT; wild-type. r; recombinant.

Figure 4: IFITM3 regulates endosomal trans-SNARE assembly by inhibiting the interaction between STX7/8 and VAMP8.

(A) HEK293T cells stably expressing Empty Vector, IFITM3 WT-FLAG, or IFITM3 G95L-FLAG were co-transfected with STX7-HA and VAMP8-myc. Whole cell lysates were subjected to SDS-PAGE and immunoblotting with anti-HA, anti-FLAG, and anti-myc. Actin was used as a loading control. Right: STX7-HA was immunoprecipitated with anti-HA followed by SDS-PAGE and immunoblotting with anti-HA, anti-FLAG, and anti-myc. The myc/HA ratio was calculated for each lane and made relative to Empty Vector (set to 100%). (B) Endogenous STX8 was immunoprecipitated from HeLa cells (WT or *IFITM3* KO) with anti-STX8 followed by SDS-PAGE and immunoblotting with anti-STX8, anti-IFITM3, and anti-VAMP8. Immunoglobulin chain was used as loading control. The VAMP8/STX8 ratio was calculated for each lane and made relative to HeLa WT (set to 100%). An isotype matched antibody was used as a control for immunoprecipitation. (C) HEK293T cells stably expressing Empty Vector, IFITM3 WT-FLAG, or IFITM3 G95L-FLAG were inoculated with IAV (+) or medium (-) for 18 hours and subjected to whole cell lysis. Endogenous STX8 was immunoprecipitated with anti-STX8 followed by SDS-PAGE and immunoblotting with anti-STX8, anti-FLAG, anti-VAMP8, and anti-VAMP7. The VAMP8/STX8 and VAMP7/STX8 ratios was calculated for each lane and made relative to Empty Vector, no virus (set to 100%). (D) HEK293T stably expressing Empty Vector, IFITM3 WT-FLAG, or IFITM3 G95L-FLAG were co-transfected with STX7-HA, STX8-HA, Vti1b-HA, and VAMP8-Myc. Following whole cell lysis, samples were either boiled at 100°C (+) or not (-). SDS-PAGE and immunoblotting was performed with anti-myc and anti-FLAG. Actin was used as loading control. Numbers and tick marks left of blots indicate position and size (in kilodaltons) of protein standard in ladder. Immunoblots were performed independently three times, and a representative example is shown. Ig; immunoglobulin. IP; immunoprecipitation. EV; Empty Vector. WT; wild-type.

Supplemental Figure 4:

(A) HEK293T cells stably expressing Empty Vector, IFITM3 WT-FLAG, or IFITM3 G95L-FLAG were co-transfected with STX7-HA and VAMP7-myc. Whole cell lysates were subjected to SDS-PAGE and immunoblotting with anti-HA, anti-FLAG, and anti-myc. Actin was used as a loading control. Right: STX7-HA was immunoprecipitated with anti-HA followed by SDS-PAGE and immunoblotting with anti-HA, anti-FLAG, and anti-myc. The myc/HA ratio was calculated for each lane and made relative to Empty Vector (set to 100%). (B) HEK293T stably expressing Empty Vector or IFITM3 WT-FLAG were co-transfected with STX7-HA, STX8-HA, Vti1b-HA, and VAMP8-Myc. Following whole cell lysis, samples were either boiled at 100°C (+) or not (-). SDS-PAGE and immunoblotting was performed with anti-STX8 and anti-FLAG. Actin was used as loading control. Numbers and tick marks left of blots indicate position and size (in kilodaltons) of protein standard in ladder. Immunoblots were performed independently three times, and a representative example is shown. IIP; immunoprecipitation. EV; Empty Vector. WT; wild-type.

Figure 5: IFITM3 traffics incoming IAV to lysosomes in a G95-dependent manner.

(A) HEK293T cells stably expressing Empty Vector, IFITM3 WT-FLAG, or IFITM3 G95L-FLAG inoculated with IAV at a multiplicity of infection of 1 and incubated on ice for 40 minutes. Cells were washed, fresh medium containing Lysotracker Deep Red (50 nM) was added, and cells were placed at 37°C for 4 hours. Four hours later, cells were fixed and immunostained with anti-NP antibody and Hoechst and analyzed by confocal immunofluorescence microscopy. Mock-inoculated (PBS) Empty Vector cells were used as a negative control. Scale bar = 15 microns. Medial Z-slices representative of each condition are shown. (B) The percentage of NP+ nuclei was quantified in Empty Vector, IFITM3 WT-FLAG, or IFITM3 G95L-FLAG cells. Symbols represent fields of view containing approximately 15-30 total cells and mean percentage plus standard error is shown. (C) The Corrected Total Cell Fluorescence (CTCF) intensity of Lysotracker staining was quantified in Empty Vector, IFITM3 WT-FLAG, or IFITM3 G95L-FLAG cells. Symbols represent fields of view containing approximately 15-30 total cells and mean CTCF intensity plus standard error is shown. Statistical differences between the indicated conditions were determined by one-way ANOVA (*, $p < 0.005$). (D) Examination of NP signal in relation to Lysotracker staining in HEK293T stabling expressing IFITM3 WT-FLAG or IFITM3 G95L-FLAG. White boxes indicate fields of view selected for detailed analysis. Right: detailed view of three different Z slices from confocal stack. White boxes indicate fields of view selected for further detailed analysis. White arrows indicate bright NP puncta that colocalize with Lysotracker or which tightly appose a Lysotracker+ compartment. Colocalization between NP and Lysotracker was measured by calculating the Pearson's Correlation Coefficient using Imaris software. Coefficients were calculated from medial Z-slices from three fields of view containing 5-15 cells per condition and presented as means plus standard deviation. Scale bar = 15 microns. EV; Empty Vector. WT; wild-type. hpi; hours post-inoculation. CTCF; Corrected Total Cell Fluorescence. PCC; Pearson's Correlation Coefficient.

Supplemental Figure 5:

An additional example of IAV trafficking to lysosomes in cells expressing IFITM3 WT. A succession of Z slices from the confocal stack are shown. White arrows indicate bright NP puncta that colocalize with Lysotracker or which tightly appose a Lysotracker+ compartment. Scale bar = 5 microns.

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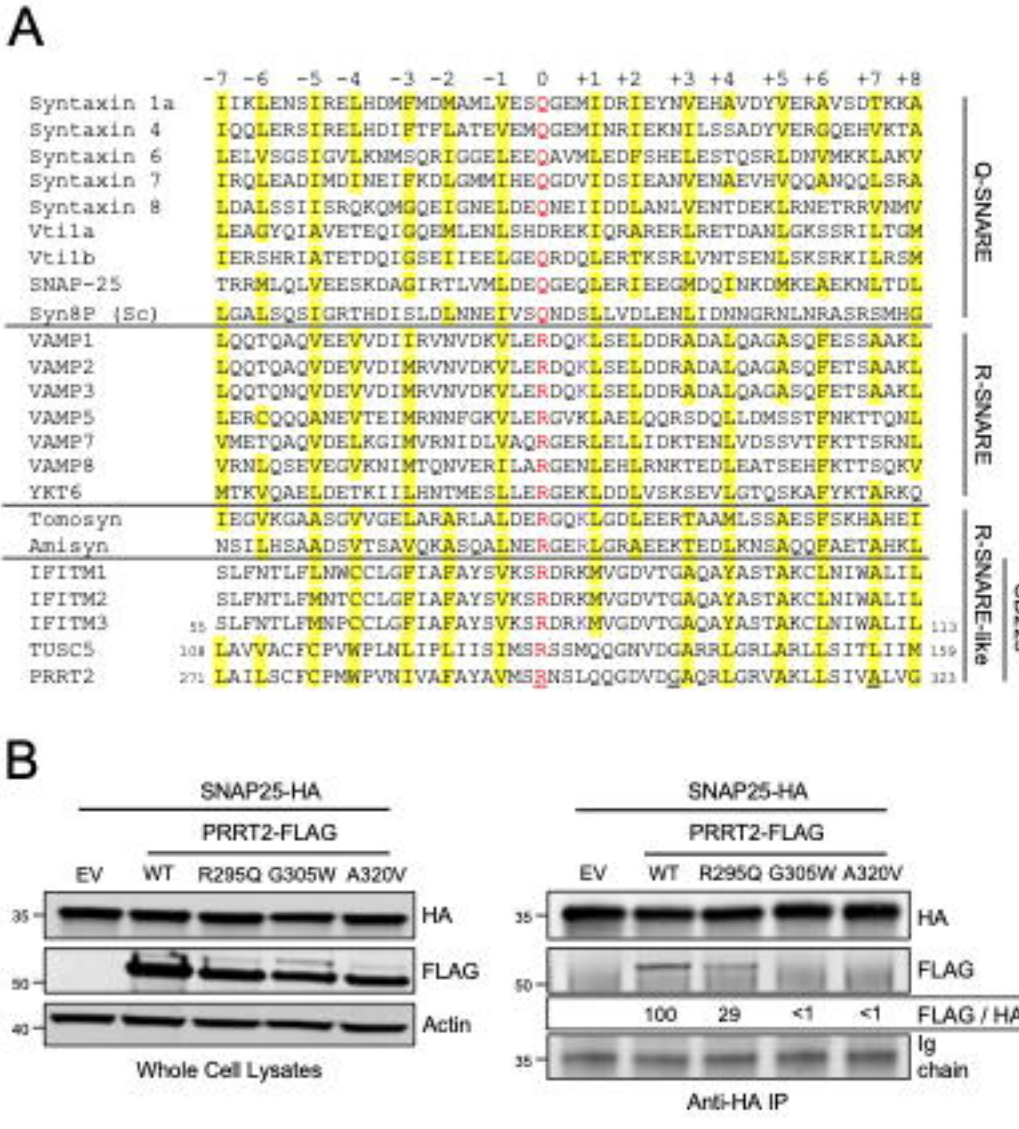
Figure 1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Syntaxin 4 IQQLERSIRELHDIFTFLATEVEMQGEMINRIEKNILSSADYVERGQEHVKTA
Syntaxin 6 LELVSGSIGVLKNMSQRIGGELEEQAVMLEDFSHELESTQSRLDNVMKKLAKV
Syntaxin 7 IRQLEADIMDINEIFKDLGMMIHEQGDVIDSIEANVENAEVHVQQANQQLSRA
Syntaxin 8 LDALSSIISRQKQMGQEIGNELDEQNEIIDDLANLVENTDEKLRNETRRVNMV
Vti1a LEAGYQIAVETEQIGQEMLENLSHDREKIQRARERLRETDANLGKSSRILTGM
Vti1b IERSHRIATETDQIGSEIIEELGEQRDQLERTKSRLVNTSENLSKSRKILRSM
SNAP-25 TRRMLQLVEESKDAGIRTLVMLDEQGEQLERIEEGMDQINKDMKEAEKNLTDL
Syn8P (Sc) LGALSQSIGRTHDISLDLNNEIVSQNDSLLVDLENLIDNNGRNLNRASRSMHG
Q-SNARE
VAMP1 LQQTQAQVEEVVDIIRVNVDKVLERDQKLSELDDRADALQAGASQFESSAAKL
VAMP2 LQQTQAQVDEVVDIMRVNVDKVLERDQKLSELDDRADALQAGASQFETSAAKL
VAMP3 LQQTQNQVDEVVDIMRVNVDKVLERDQKLSELDDRADALQAGASQFETSAAKL
VAMP5 LERCQQQANEVTEIMRNNFGKVLERGVKLAELQQRSDQLLDMSSTFNKTTQNL
VAMP7 VMETQAQVDELKGIMVRNIDLVAQRGERLELLIDKTENLVDSSVTFKTTSRNL
VAMP8 VRNLQSEVEGVKNIMTQNVERILARGENLEHLRNKTEDLEATSEHFKTTSQKV
YKT6 MTKVQAELDETKIILHNTMESLLERGEKLDDLVSKSEVLGTQSKAFYKTARKQ
R-SNARE
Tomosyn IEGVKGAASGVVGELARARLALDERGQKLGDLEERTAAMLSSAESFSKHAHEI
Amisyn NSILHSAADSVTSAVQKASQALNERGERLGRAEEKTEDLKNSAQQFAETAHKL
R-SNARE-like
IFITM1 SLFNTLFLNWCCLGFIAFAYSVKSRDRKMVGDVTGAQAYASTAKCLNIWALIL
IFITM2 SLFNTLFMNTCCLGFIAFAYSVKSRDRKMVGDVTGAQAYASTAKCLNIWALIL
IFITM3 55 SLFNTLFMNPCCLGFIAFAYSVKSRDRKMVGDVTGAQAYASTAKCLNIWALIL 113
TUSC5 108 LAVVACFCPVWPLNLIPLIISIMSRSSMQQGNVDGARRLGRLARLLSITLIIM 159
PRRT2 271 LAILSCFCPMWPVNIVAFAYAVMSRNSLQQGDVDGAQRLGRVAKLLSIVALVG 321
CD225
B
SNAP25-HA
PRRT2-FLAG
EV WT R295Q G305W A320V
35 HA
50 FLAG
40 Actin
Whole Cell Lysates
SNAP25-HA
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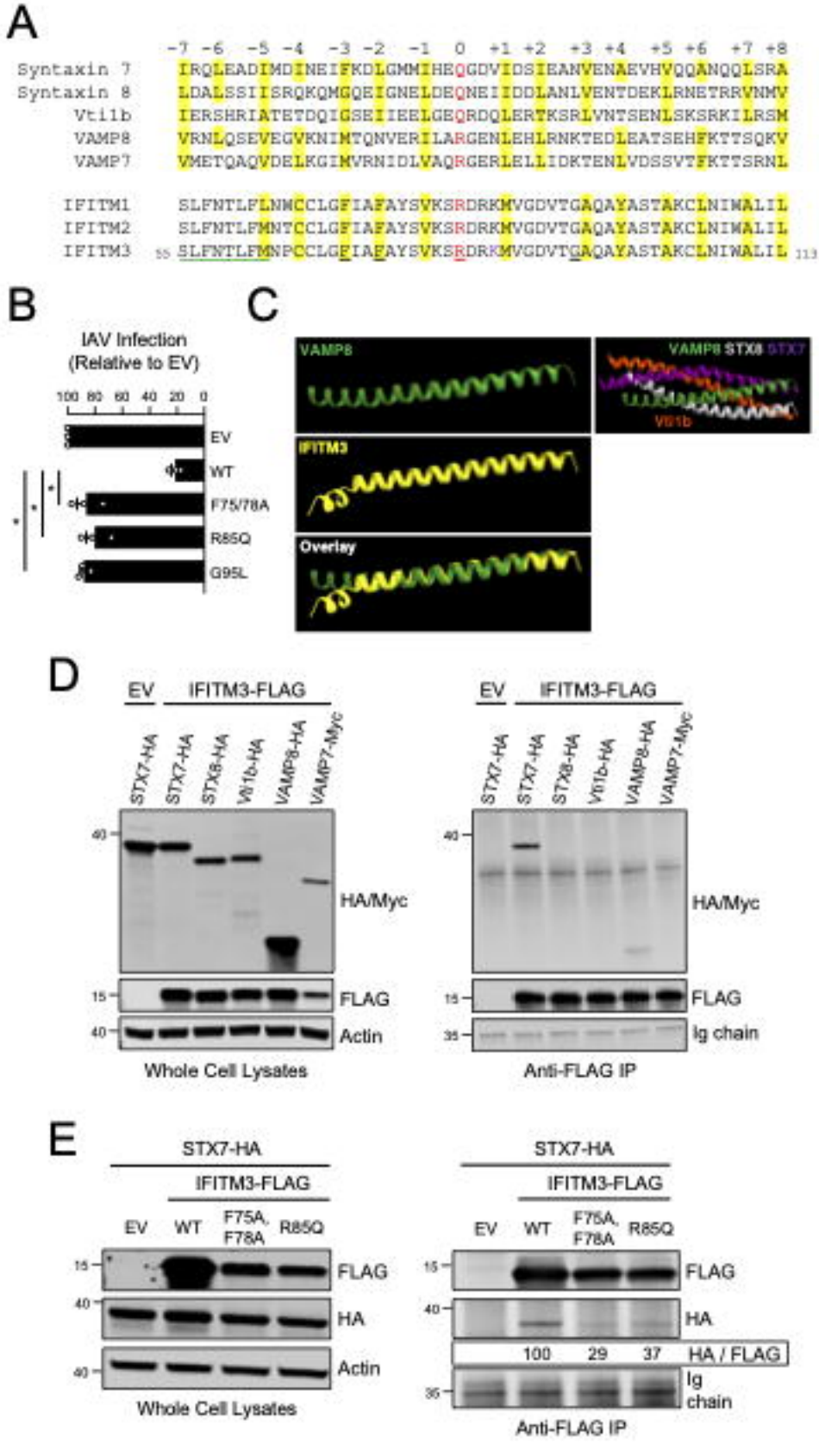
Figure 2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VAMP8 VRNLQSEVEGVKNIMTQNVERILARGENLEHLRNKTEDLEATSEHFKTTSQKV
VAMP7 VMETQAQVDELKGIMVRNIDLVAQRGERLELLIDKTENLVDSSVTFKTTSRNL
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IFITM2 SLFNTLFMNTCCLGFIAFAYSVKSRDRKMVGDVTGAQAYASTAKCLNIWALIL
IFITM3 55 SLFNTLFMNPCCLGFIAFAYSVKSRDRKMVGDVTGAQAYASTAKCLNIWALIL 113
B
IAV Infection
(Relative to EV)
100 80 60 40 20 0
EV
WT
F75/78A
R85Q
G95L
C
VAMP8
VAMP8 STX8 STX7
Vti1b
IFITM3
Overlay
D
EV IFITM3-FLAG
STX7-HA
STX7-HA
STX8-HA
Vti1b-HA
VAMP8-HA
VAMP7-Myc
40
HA/Myc
15
FLAG
40
Actin
Whole Cell Lysates
EV IFITM3-FLAG
STX7-HA
STX7-HA
STX8-HA
Vti1b-HA
VAMP8-HA
VAMP7-Myc
40
HA/Myc
15
FLAG
35
Ig chain
Anti-FLAG IP
E
STX7-HA
IFITM3-FLAG
EV WT F75A, F78A R85Q
15
FLAG
40
HA
40
Actin
Whole Cell Lysates
STX7-HA
IFITM3-FLAG
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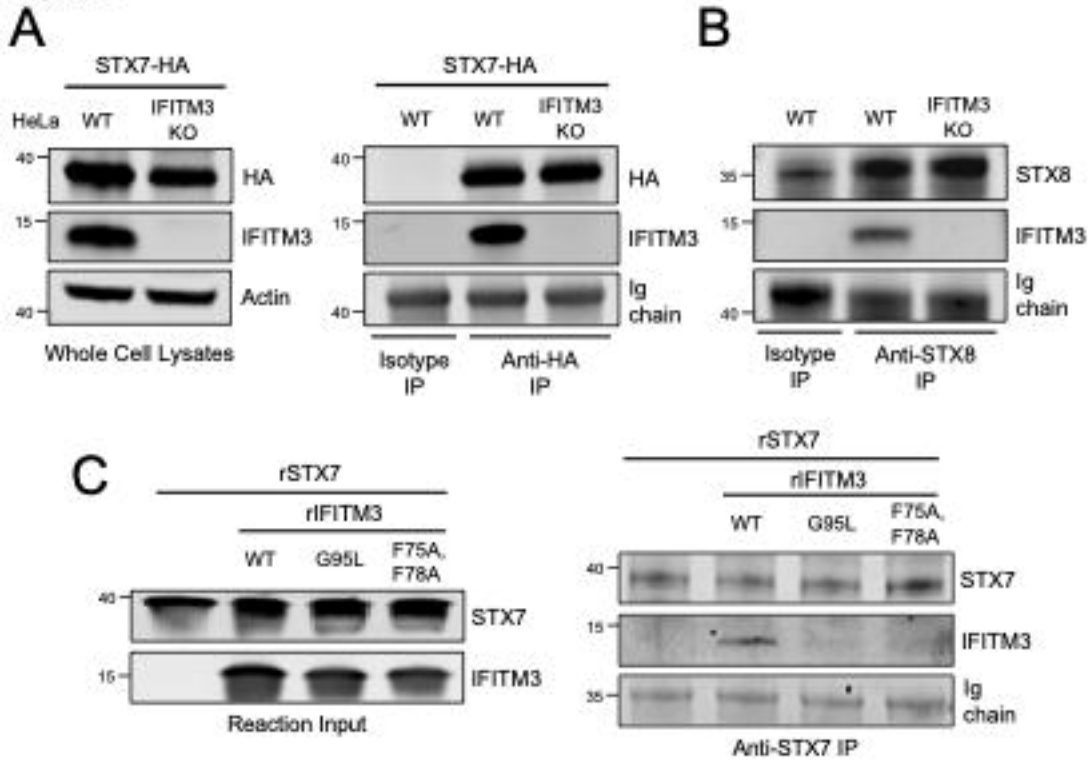
FLAG
40
HA
100 29 37 HA / FLAG
35
Ig chain
Anti-FLAG IP

Figure 3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40
15
STX7
IFITM3
Reaction Input
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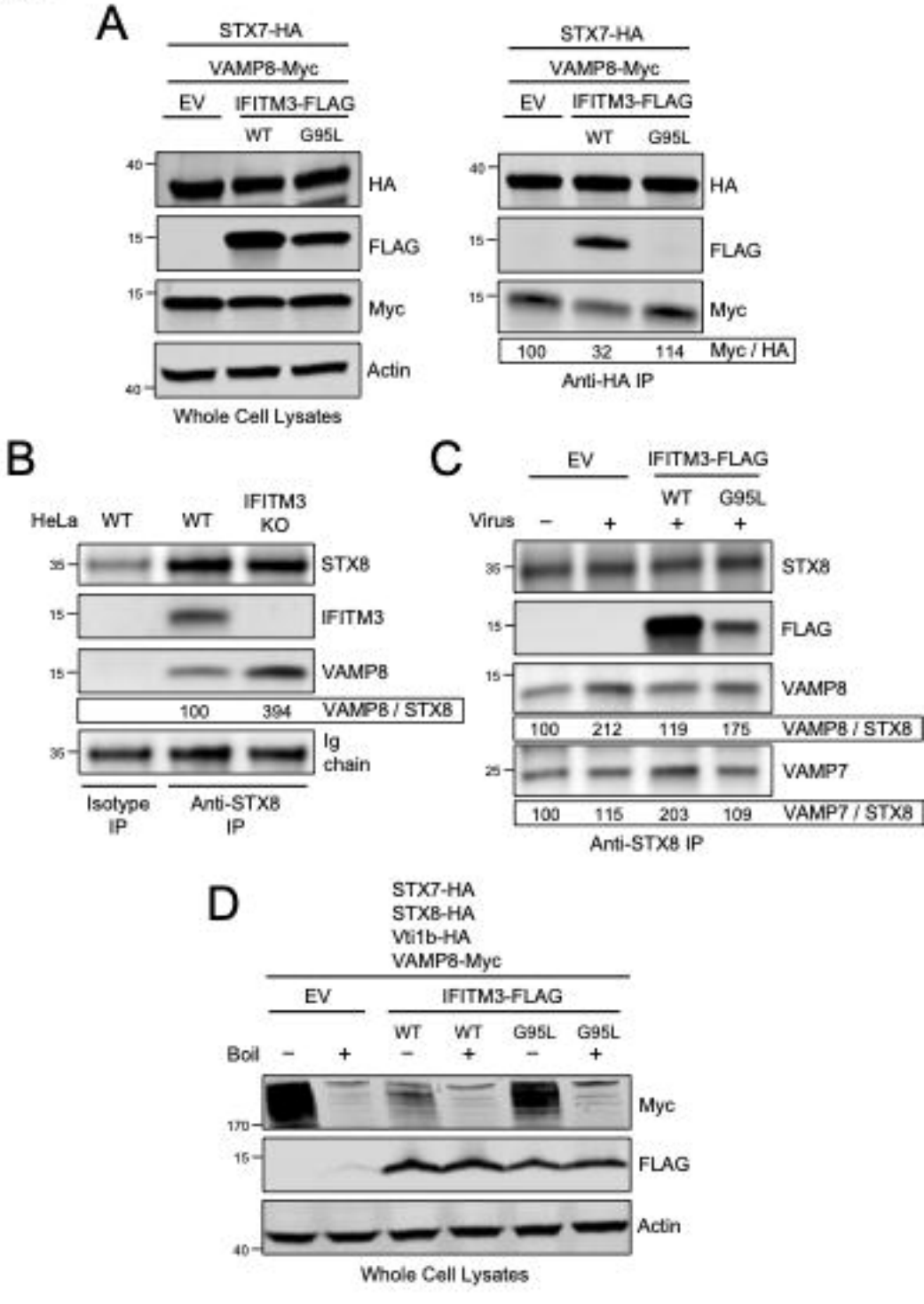
Figure 4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FLAG
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Actin
40
Whole Cell Lysates
STX7-HA
VAMP8-Myc
EV
IFITM3-FLAG
WT
G95L
40
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FLAG
15
Myc
100
32
114
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HeLa
WT
WT
IFITM3 KO
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STX8
15
IFITM3
15
VAMP8
100
394
VAMP8 / STX8
35
Ig chain
Isotype IP
Anti-STX8 IP
C
EV
IFITM3-FLAG
WT
G95L
Virus
−
+
+
+
35
STX8
15
FLAG
15
VAMP8
100
212
119
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VAMP8 / STX8
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VAMP7
100
115
203
109
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EV
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WT
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+
−
+
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Myc
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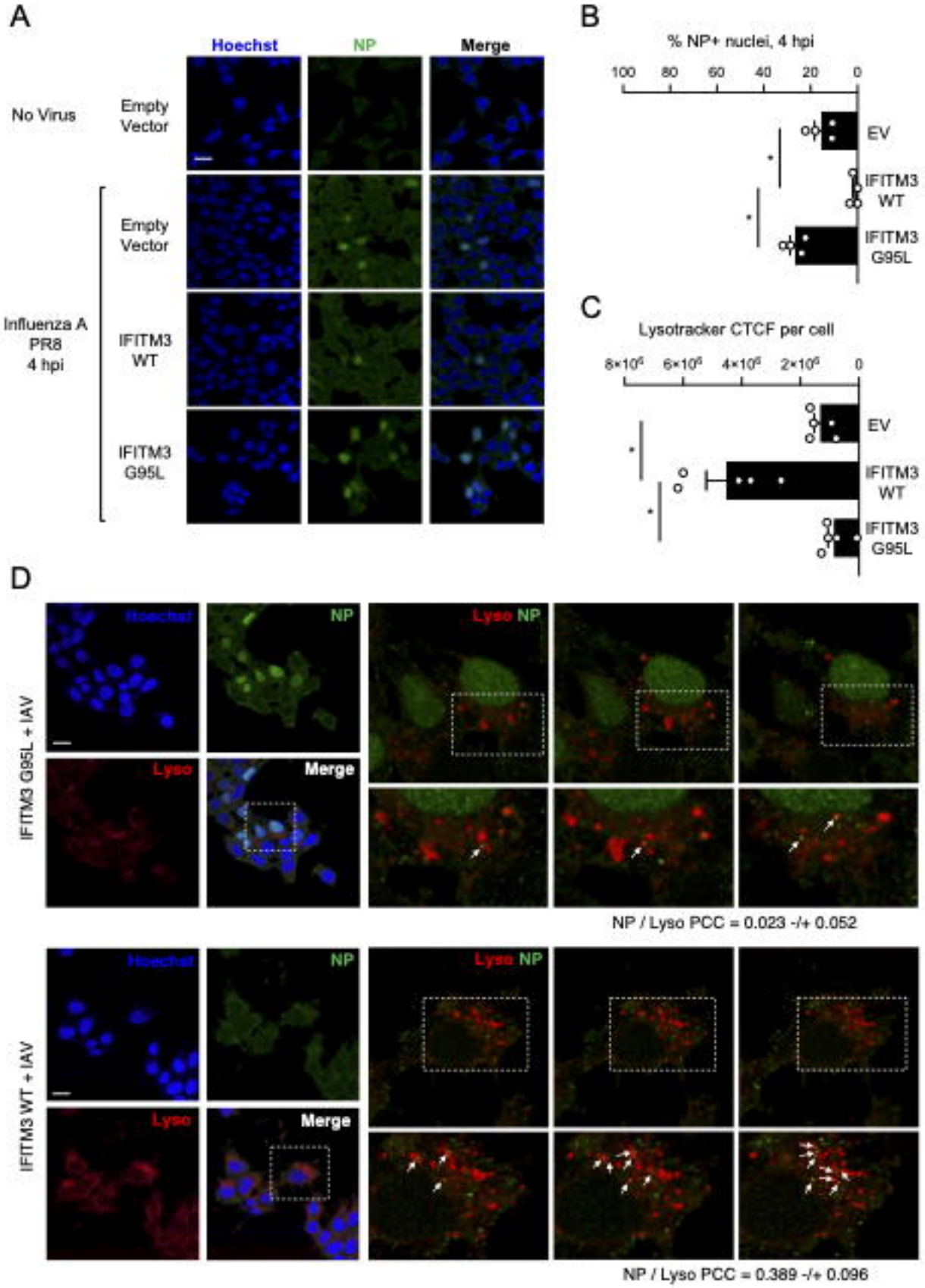
FLAG
Actin
40
Whole Cell Lysates

Figure 5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100
80
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40
20
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EV
IFITM3 WT
IFITM3 G95L
C
Lysotracker CTCF per cell
8×10^6
6×10^6
4×10^6
2×10^6
0
EV
IFITM3 WT
IFITM3 G95L
D
IFITM3 G95L + IAV
Hoechst
NP
Lyso
Merge
Lyso NP
NP / Lyso PCC = 0.023 -/+ 0.052
IFITM3 WT + IAV
Hoechst
NP
Lyso
Merge
Lyso NP
NP / Lyso PCC = 0.389 -/+ 0.096