Atypical chemokine receptor 3 regulates synaptic removal in disease astrocytes

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Abstract

Astrocytes participate in the clearance of obsolete or unwanted neuronal synapses. However, the molecular machinery recruited for the recognition of synapses is not fully clarified, especially in pathological conditions. Here, we investigated the phagocytic process through individual gene silencing using a druggable gene library. Our study demonstrates that astrocyte-mediated synapse engulfment is regulated by the Atypical chemokine receptor 3 (Ackr3). Mechanistically, we have shown that Ackr3 recognizes phosphatidylethanolamine (PE)-bound Cxcl12 at synaptic terminals both in vitro and in cell culture thus serving as a novel marker of synaptic dysfunction. Notably, both the receptor and its ligand are overexpressed in post-mortem AD human brains, and downregulation of the receptor in AD mouse models (5xFAD) significantly diminishes astrocyte-mediated synaptic elimination. Overall, this work unveils a novel, possibly targetable mechanism of astrocyte-mediated synaptic engulfment implicated in the most common neurodegenerative disease.

Introduction

Synapses require constant and multimodal surveillance by glial cells [1]. Appropriate clearance of extraordinary and non-functional synapses is necessary for the homeostasis of the central nervous system (CNS) [2,3].

Like microglia, astrocytes engulf parts of living and dying cells, including synapses and axons both in physiological and pathological context context [4-12].

Multiple EGF-like domains 10 (Megf10) receptor and MER proto-oncogene tyrosine kinase (Mertk) are involved in synaptic removal by astrocytes, possibly forming a molecular complex together with other proteins [1,13]. Interestingly, the process is driven by neuronal activity in the developing and adult brain [4]. Functionally, the lack of Megf10 in astrocytes causes an accumulation of dysfunctional excitatory synapses in the hippocampus thus impacting long term synaptic plasticity and memories [11]. Megf10-mediated synaptic engulfment is an extremely conserved mechanism, with several examples being documented in Drosophila (Draper) and *C. elegans* (CED-1) [14,15]. Recently, the ATP-binding cassette transporter A1 (Abca1) and the engulfment adapter phosphotyrosine-binding domain containing 1 (Gulp1) together with Megf10, have been identified as the responsible molecules for the enhanced astrocytic phagocytosis of synapses in a mouse model for brain ischemia [7]. Phosphatidylserines (PS), exposed by dying cells, are proposed to be recognized by Megf10 on the cell surface possibly through the involvement of bridging molecules whose identity is still unclear (e.g., C1q) [4,16]. Although *via* still unknown pathways, hippocampal astrocytes contact and extensively eliminate synapses by recognizing C1q molecules in Alzheimer's disease (AD) mouse models [12]. In humans, AD astrocytes show enhanced phagocytosis of synapses through the recognition of Milk fat globule-EGF factor 8 protein (Mgf-E8), a PS-binding molecule [17]. Astrocytes also release ATP in an inositol 1,4,5-trisphosphate receptor type 2 (Ip3r2)-dependent manner to regulate synapse elimination [5]. Astrocytes cooperate with microglia to clear up unwanted material within the brain parenchyma [8,10]. Specifically, a cross talk between astrocytes and microglia mediated by released inflammatory molecules have been reported in clearing up synapses [6,18,19].

Despite the recent advances in understanding the role of astrocytes in synapse elimination, scientists are researching the finer details of this process, including the astrocyte-specific receptors and modulators involved, as well as the identification of synaptic tags that astrocytes use to recognize synapses for clearance.

In the present study, we identified Atypical chemokine receptor 3 (Ackr3) as a novel receptor through which astrocytes engulf synapses in pathological conditions. Ackr3 is a CXC chemokine receptor for Cxcl11 and Cxcl12 [20-22]. Ackr3 has been detected in the brain, specifically in neurons and

astrocytes but not microglia [21,22]. Ackr3 is overexpressed in patients affected by various pathologies, including AD [20,23-25]. However, the molecular mechanism behind Ackr3-mediated synaptic pruning is totally unknown. Here, we revealed that Ackr3 specifically recognises Cxcl12 at synaptic terminals. Importantly, the receptor and its ligand are overexpressed in AD and the modulation of Ackr3 expression reduces synaptic removal in AD astrocytes.

Results

Identification of novel regulators of astrocyte-mediated synapse engulfment

To identify novel modulators involved in synapse engulfment mediated by astrocytes, we applied a siRNA-based screening approach (Fig.1A) and measured the internalisation of purified mouse brain neuronal terminals, namely synaptosomes, as final readout. To this aim we first optimised a protocol for the derivation and labelling of synaptosomes and subsequently set the parameters for our phagocytic assay. Synaptosomes have been isolated from whole mouse brains (Fig.S1A) [26] and the purity of the preparation has been assessed by western blot. As shown in Fig.S1B-C, the synaptosome fraction (S) was enriched in synaptic markers such as Vesicle associated membrane protein2 (Vamp2), Synaptophysin (Syp) and Postsynaptic Density Protein 95 (PSD95). The presence of markers associated with myelin and astrocytic contamination, namely Myelin Binding Protein (MBP) and Glial Fibrillary Acidic Protein (GFAP) was instead minimised (Fig.S1 B-C). By means of transmission electron microscopy (TEM) we could identify both pre (PSc) and post (PO) synaptic terminals, thus confirming the ultrastructural integrity of synaptosomes in our preparation (Fig.S1D). Furthermore, we characterised synaptosome protein composition by mass spectrometry analysis and assessed the synaptic gene enrichment using the SynGO geneset tool (https://www.syngoportal.org). As expected, both PSs and PO synaptic structures were represented, once more confirming the reliability of our preparation (Fig.S1E). Finally, to visualise the internalisation of synaptosomes and follow their progression along the phagocytic pathway, synaptosomes have been conjugated with pHrodo-Red TM succinimidyl ester, a pH sensitive dye (pH-RODO) which becomes fluorescent (red) when exposed to an acidic environment (e.g., endo-lysosomes), as described in [27,28]. For the phagocytic assay, primary mouse astrocytes were co-transfected with a siRNA scramble (siControl) and an eGFP-encoding plasmid used to visualize the cell area, as previously described in [29]. We assessed the identity of the eGFP-transfected cells by immunofluorescence staining using GFAP for astrocytes and Ionized calcium-binding adaptor molecule 1 (Iba1) for microglia (Fig.S2A-B). We did not detect any $eGFP^+/GFAP^-$ or $eGFP^+/Iba1^+$ cells, thus confirming that all the eGFP expressing cells were primary astrocytes (Fig.S2A-B). The day after co-transfection, astrocytes were treated with pH-RODO labelled synaptosomes. After washing the excess of synaptosomes, we acquired the images using an automatized live-imaging system and investigated the ability of astrocytes to internalise synaptosomes by calculating the Phagocytic Index (PI) as the ratio between the red area (pH-RODO) and the green area (eGFP) after 12h and 48h (Fig.1A). As shown in Fig.1B (black line), PI increases over time as already reported in [27]. To further confirm that the sparse microglia contamination was not interfering with our readout, we treated our cells with liposomal clodronate,

a well-known compound that eliminates microglial cells without affecting astrocytes and analysed the PI of eGFP^{+} cells over time [30]. As shown in Fig.S2C, we did not detect any statistical differences in the PI in treated and untreated cells. To validate our experimental set up, we genetically manipulated the phagocytic pathway by downregulating Megf10, a receptor that recognises and promotes the engulfment of neuronal terminals [4,31] and Cathepsin B (CtsB), an enzyme that promotes lysosomal degradative capacity (Fig.S2D-F) [32]. The efficacy of the downregulation in primary astrocytes was tested by western blot and compared to a siRNA scramble (siControl) (Fig.S2D). Overall, we confirmed a significant halving of Megf10 and CtsB expression compared to control (Fig.S2D-G). We also analysed the kinetics of internalisation and we observed that the downregulation of Megf10 and CtsB caused significant changes in synaptosome uptake in primary astrocytes (Fig.1B-C). As expected, Megf10 downregulation reduces the phagocytic abilities of astrocytes compared to the siControl at both 12h and 48h (Fig.1B-C). Instead, the downregulation of CtsB causes an accumulation of engulfed synaptosomes, specifically at 48h compared to siControl, likely due to deficits in synaptosome degradation (Fig.1B-C).

We therefore performed a siRNA-based screening relying on the siGENOME Mouse Druggable siRNA Library composed of a total of 2905 genes. Upon the downregulation of each gene in primary astrocytes and the subsequent treatment with synaptosomes, PI values have been plotted at 12h (X axis) and 48h (Y axis) and compared with the control conditions (Fig.1D). Specifically, we have annotated the PI values at 12h and 48h of the siControl, siMegf10 and siCtsB (Fig.1D). As expected, most of the hits clustered around the PI values of astrocytes transfected with the siControl thus suggesting that these downregulated genes were not impacting on astrocyte-mediated synaptic clearance. However, the downregulation of several genes modulated synaptosome internalisation and accumulation. One group of hits (~100), marked in red, represented those genes that when down-regulated reduced synapse internalisation (Fig.1D). Their PI values were in fact below the PI values of siMegf10 transfected cells (Fig.1D). A second group of hits (~200), marked in green, instead represents those genes that potentially interfere with degradation (or enhance internalisation) (Fig.1D). Specifically, the PI values of those hits at 48h are above the PI of siCtsB transfected cells (Fig.1D). To investigate the molecular function (MF) of the hits involved in the synaptosome clearance, we performed a gene ontology (GO) analysis. We observed that those genes identified as red hits showed enrichment in G protein-coupled receptor activity, peptide receptor activity and chemokine receptor activity (Fig.1E, Fig.S3A). Specifically, G protein-coupled receptors and chemokine receptors are the top represented categories. Genes that are mainly represented in these categories are 8 chemokine receptors: Cxcr5, Ackr3, Cxcr2, Cxcr3, Ccr1, Ccr2, Ccr4 and Ackr2 (Fig.S3A, yellow dots). Instead, MF analysis for the green hits identified as top categories proteins

with kinase activity, serine/threonine kinase activity and identical protein binding activity (Fig.1F, Fig.S3B).

Overall, our siRNA-based screening revealed both a cluster of genes encoding proteins with receptor activity that, when down-regulated, affected synaptosomes internalisation and a second group of genes encoding proteins involved in intracellular signalling pathways that, when downregulated promote intracellular synaptosome accumulation.

Ackr3 is required for synaptosome internalisation

Our screening, coupled with the GO analysis, revealed a family of chemokine receptors whose downregulation impairs synaptosomes internalisation mediated by astrocytes. Using the transcriptomic dataset published in [33], we looked at the differential expression of these chemokine receptors in astrocytes, microglia and neurons (Fig.2A). Among these, we selected for validation Ackr3, based on its high expression in astrocytes as compared to the other two cell types. First, we confirmed that Ackr3 is endogenously expressed in primary mouse astrocytes, and it is efficiently downregulated using a siRNA pool against Ackr3 (Fig.S4A). As visualised by western blot, the global downregulation in mouse astrocytes reached 60% as compared to astrocytes transfected with siRNA Control (Fig.S4A-B). We then performed longitudinal live imaging of synaptosome engulfment following the same set up used for the siRNA-based screening. Internalisation was followed over time at different time points: 6h, 12h, 24h, 48h, 78h, 96h, 120h (Fig.2B-C). As expected, the internalisation of synaptosomes was abundantly suppressed in murine astrocytes downregulated for Ackr3 as compared to siControl transfected astrocytes resulting in a statistically significant decrease of the PI at 24h, 48h and 78h (Fig.2C). To further corroborate the involvement of Ackr3 in the modulation of synaptosome internalisation, we overexpressed the receptor in primary astrocytes using a Flag-tagged Ackr3 encoding plasmid (Fig.S4C-D). Here, the PI calculation over time confirmed that the ectopic expression of Flag-Ackr3 enhances astrocytes mediated internalisation of synaptosomes (Fig.S4C-D, blue closed dots) and this phenotype is partially reverted by Ackr3 downregulation (Fig.S4C-D, light blue closed dots). Likewise murine cells, human iPS-derived astrocytes (iHA) abundantly express ACKR3 and its expression can be downregulated by means of siRNA against the receptor (Fig.S4E-F). Interestingly, we observed that both human and mouse Ackr3 is distributed in patchy areas in control astrocytes (treated with PBS), possibly clustered at the plasma membrane and/or in vesicular structures, and that it only partially co-localizes with lysosomal associated membrane protein 1 (Lamp1) (Fig.2D-G; Fig.S5A-D). Instead, in astrocytes treated with TAMRA-labelled synaptosomes, Ackr3 decorates the internalized structures and massively re-localizes into Lamp1-positive vesicular structures (Fig.2E-G; Fig.S5B-D).

Overall, our results suggested that Acrk3 is required for astrocytes mediated synaptosome internalisation, establishing a molecular complex directed to the lysosome upon engulfment.

Ackr3 recognizes chemokines on the synaptosome surface

We next examined a possible physical interaction between Ackr3 and the synaptosomes. Being Ackr3 a chemokine receptor [20-22], we investigated the role of its ligands, Cxcl11 (K_d:2.5 nM) and Cxcl12 (K_d:0.3 nM) in the internalisation of synaptosomes [22,34-39]. First, we examined the chemokines' content in the whole mouse brain (WB), in our synaptosome preparation (S) as well as in murine brain cells (primary astrocytes and primary neurons, A and N, respectively) (Fig.S6A). We observed that Cxcl11 is detected in the whole brain lysate and in astrocytes, but it is not present neither in the synaptosome preparation nor in neurons (Fig.S6A). Cxcl12 is instead present in the whole brain lysate as well as in neurons, astrocytes and in the synaptosome preparation (Fig.S6A). We could therefore speculate that the binding between Ackr3 and the synaptosomes is mediated by Cxcl12. To test this hypothesis, we performed a batch of experiments in which we modulated the availability of Cxcl12. First, we set our basal condition by incubating purified Flag-tagged Ackr3 with synaptosomes. As expected, Vamp2, the synaptosome marker, was detected in the input (synaptosome preparation plus Flag-only or Flag-Ackr3-bound resin) both in the presence or absence of Ackr3. However, upon immunoprecipitation (IP), Vamp2 was retained only by the Flag-Ackr3-bound resin but not by the control one (Flag-only) confirming the specificity of Ackr3-synaptosomes interaction (Fig.3A-B). To test the role of Cxcl12 in mediating the binding of Ackr3 with synaptosomes, we saturated purified Flag-Ackr3-bound resin with an excess of recombinant murine SDF-1α-Cxcl12 or with Plerixafor, a well-known allosteric agonist for Ackr3 [40]. We observed that the preincubation of the receptor with either Cxcl12 or Plerixafor interfered with Ackr3-synaptosome binding, as shown by a reduced co-immunoprecipitation of Vamp2 (Fig.3A-B). In a complementary experiment, we saturated purified synaptosomes with an anti-Cxcl12 antibody to reduce the amount of available Cxcl12. As expected, also in this case we observed a decrease in the binding between Ackr3 and the synaptosomes (Fig. S6C). Once attested the presence of Cxcl12 in our synaptosome preparation (Fig.S6A-C) and its functional involvement in the Ackr3-synaptosome interaction, we investigated whether the enrichment of Cxcl12 at the synaptosome surface could have an impact on the synaptosomes internalisation by astrocytes. Of note, intact synaptosomes are competent to bind recombinant Cxcl12 and the amount of retained recombinant chemokine increases with the amount of synaptosomes (Fig.S6D-F). We therefore incubated our synaptosomes with recombinant Cxcl12 to obtain Cxcl12-covered synaptosomes (cS). As shown in Fig.S6C, cS were effectively enriched with Cxcl12. We then investigated whether this overload of Cxcl12 could influence the rate of synaptosome internalization by looking at the PI of primary astrocytes treated with S or with cS. As expected, we

observed that cS were internalised more efficiently as compared to S (Fig.3C-D), thus confirming the functional role of Cxcl12 in synapse internalization. In agreement with our previous results, the internalisation of S and cS synaptosomes was reduced in Ackr3-downregulated astrocytes, further confirming that both Ackr3 and CxCl12 are necessary to promote astrocyte-mediated internalization of synaptosomes.

Taken together, these data reveal that Ackr3 recognizes Cxcl12 at the synaptosome surface and that this chemokine regulates Ackr3-mediated synaptosome uptake by astrocytes.

Cxcl12 binds externalised PE at neuronal surface, a stimulus required for Ackr3-mediated synapse recognition

A subset of chemokines displays high affinity binding for PS and for other anionic phospholipids [41]. We therefore tested the affinity of Cxcl12 for phospholipids. First, we probed PIP Strips™ membranes with recombinant Cxcl12 (Fig.4A). Among the 15 different phospholipids spotted on the array, Cxcl12 showed high affinity for PE and for phosphatidic acid but not for PS (Fig.4B). Although less investigated, PE are also lipids that are externalised in the early phase of neuronal death [37]. We therefore set up a protocol to increase the exposure of PE in primary neurons and investigate whether this was sufficient to promote their interaction with Ackr3. Internalization and externalization of PS and PE are dynamic processes and are regulated by specific phospholipid scramblases and flippases [42,43]. At the synapse, the stimulation of the externalisation of aminophospholipids can be induced by downregulating cell division control protein 50 a (Cdc50a), an accessory subunit of the lipid flippase P4-ATPase [44,45]. First, we confirmed PS exposure in unpermeablized cortical mature neurons using pSIVA, an annexin-based fluorescent biosensor that specifically binds to PS (Fig. S7A-B) [46,47]. Live neurons transfected with siControl or siCdc50a have been incubated with pSIVA and then fixed for subsequent staining of the neuronal marker Vamp2 [48]. We reported a significant increase of Vamp2/pSIVA and PSD95/pSIVA upon Cdc50a downregulation, thus confirming PS externalisation in synaptic structures (Fig.S7A-C). Likewise, we used green fluorescent tagged Duramycin (Duramycin-Fc) to examine the exposure of PE upon Cdc50a downregulation in primary neurons. Indeed, Duramycin is a lantibiotic peptide derived from *Streptoverticillium cinnamoneus*, which binds PE at a 1:1 molar ratio with high affinity and specificity (Kd 4-6 nM) [49,50]. Interestingly, we found that the downregulation of Cdc50a causes a significant exposure of PE at the synapse as visualised by the quantification of Vamp2/Duramycin-Fc and PSD95/Duramycin-Fc co-localization (Fig.S7F). Overall, our data confirmed that the downregulation of Cdc50a increased the exposure of both PS and PE at the level of the synapses.

We therefore used this model to investigate whether a higher exposure of PE increases Cxcl12 amount at the neuronal surface, thus stimulating glial Ackr3-mediated synapse elimination.

We first quantified endogenous Cxcl12 present at the neuronal surface upon the downregulation of Cdc50a and compared to control cells. Unpermeabilized cells were stained for Cxcl12 and F-actin and quantified as the number of Cxcl12^{+} puncta per µm of dendrite section. As shown in Fig.4C-D, there was a slight but not significant difference in the amount of Cxcl12 along dendrites (F-actin) between neurons transfected with siControl and those transfected with siCdc50a. However, the incubation of neurons with exogenous, recombinant Cxcl12 promoted an increase of the chemokine signal along dendrites both in siControl and, more significantly, in siCdc50a transfected neurons (Fig.4C-D). The amount of bound Cxcl12 to the dendrites reflects the level of externalised PE in siControl versus siRNA Cdc50a (Fig.S7D-E-F). This result agrees with the observation that a downregulation of Cdc50a induces the exposure of PE, which likely binds a higher amount of Cxcl12. Notably, treatment with Duramycin before incubation with Cxcl12 prevented the binding between Cxcl12 and the neurons, likely due to competitive binding, thus pointing to PE as the Cxcl12 binding partner at the synapse (Fig.4C-D).

We next sought to determine whether PE-positive synapses were more readily internalised by astrocytes and whether this internalization was regulated by Ackr3. Thus, we set up astrocyte-neuron co-cultures and assessed the number of Vamp2^{+}/PSD95^{+} puncta (synapses) located within astrocytes (marked with cell trace). In agreement with our data, we found that an increase in the exposure of PE in neurons induced by Cdc50a downregulation, promotes the internalization of Vamp2^{+}/PSD95^{+} puncta by astrocytes (Fig.5A-B; Fig.S8A-D). As expected, Ackr3 downregulation impairs the ability of astrocytes to engulf synapses, despite the increased exposure of PE, thus confirming that Ackr3 is fundamental for engulfment of the live synapses (Fig.5A-B); (Fig.S8A-D).

Collectively, these findings reveal that Cxcl12 recognizes PE *in vitro* and this binding is stimulated by PE externalisation at the neuronal membrane. Moreover, Ackr3 is required for synapse recognition upon PE externalisation.

Astrocyte-mediated synapse elimination is dependent on Ackr3 expression during pathology

To assess the role of ACKR3 as a modulator of glial-dependent synaptic removal in AD pathology, we first examined the expression of the receptor in the hippocampus of AD patients and age-matched controls by immunofluorescence. Consistent with previous reports [23], we observed that ACKR3 is significantly overexpressed in the hippocampus of AD patients compared to Healthy controls (Fig.6A-B). As observed in iHA and murine astrocytes (Fig.1D; Fig.S5A), the ACKR3 receptor exhibits a patchy distribution decorating the GFAP-positive filaments (Fig.6A). Moreover, our

analysis revealed an increased co-localization of ACKR3 with GFAP-positive astrocytes in the brains of AD patients compared to controls (Fig. 6C). Consistently, we also found that the CXCL12 chemokine signal is increased and enhances its co-localization with ACKR3 in AD patients compared to age-matched controls (Fig.6D-F). The increased co-localization of CXCL12 with ACKR3 indicates that this receptor-ligand interaction is heightened during pathology, further supporting the role of this pathway in synapse elimination in the context of AD.

To demonstrate the involvement of Ackr3 in the removal of synaptic terminal *in vivo*, we designed experiments using 5xFAD mice, a well-characterized model of AD pathology available in our laboratory [51,52]. First, we validated the expression of Ackr3 and Cxcl12 in 5xFAD mouse brains (Fig.7A-B). Consistent with our observations in the brains of AD patients, we found a significant increase in Ackr3 expression in the hippocampus of 5xFAD mice. Additionally, Ackr3 co-localized with the astrocytic marker S100b in the CA1 hippocampus of 5xFAD mice compared to wild-type (WT) mice (Fig. 7C). However, unlike in human samples, we did not observe an increase in Cxcl12 expression in the whole hippocampus or at the synapses in 5xFAD mice (Fig. S9A-C).

To functionally validate the role of Ackr3 *in vivo,* we used the mCherry-eGFP fluorescent phagocytosis reporter system that we previously developed [11,53-55] (Fig. 7D-E). Briefly, we generated adeno-associated virus 9 (AAV9) vectors encoding a human synapsin promoter (hSYN) to drive the expression of Synaptophysin-mCherry-eGFP (Fig.7D). This vector was injected into the CA3 hippocampus of mice, and the corresponding neuronal terminals were visualized in the CA1 hippocampal region (Fig. 7D). Functional neuronal terminals are detected as yellow puncta, whereas phagocytosed synapses are recognized as red puncta due to the quenching of eGFP (Fig. 7E). To genetically modulate Ackr3 expression at the CA1 region *in vivo*, we generated AAV9 vector encoding shRNA against Ackr3 together with a Blue Fluorescent Protein (BFP) tag under the GfaABC1D promoter to assure expression in astrocytes (Fig.7D). As control, we produced AVV9 vector encoding scramble shRNA with BFP tag under the GfaABC1D promoter (Fig.7D). The efficacy of the Ackr3 downregulation has been validated *in vivo* by quantifying Ackr3 expression in tagBFP positive astrocytes (Fig.S9D-E). Of note, we observed that the absence of Ackr3 does not affect GFAP expression in astrocytes (Fig.S9F). We then monitored the ability of CA1 hippocampal astrocytes to engulf Synaptophysin-mCherry-eGFP synapses *in vivo* in 5xFAD mice following the injection of AAV9-shAckr3 versus AAV9-shScramble (Fig. 7E). We found that downregulation of Ackr3 in astrocytes significantly decreased the amount of the engulfed synapses compared to the control (Fig. 7F). Notably, we did not observe a similar reduction when injecting AAV9-shAckr3 versus AAV9-shScramble in a wild-type background, suggesting the requirement of specific, pathological tags at the synapse for Ackr3-mediated synaptic removal (Fig. S9G-H).

Overall, our data show that Ackr3 is overexpressed under pathological conditions and serves as a specific receptor for astrocyte-mediated synapse elimination in AD mice.

Discussion

Synaptic removal mediated by astrocytes involves a complex and not yet fully understood interaction of molecular signals, receptors, and tagging mechanisms. To better characterize this phenomenon, we employed a genetic approach to identify novel, cell-specific regulators involved in astrocyte-mediated synapse engulfment and uncovered key molecular interactions driving this process. GO analysis identified G protein-coupled receptors and C-C chemokine receptors as top GO terms involved in synaptosome internalization. Additionally, we identified categories related to intracellular signalling pathways (e.g., kinases) that influences the accumulation of internalized synaptosomes possibly through enhancing the internalization rate or blocking the degradation kinetics. Among the hits that diminish synaptosome internalization, chemokine receptors emerged as potential regulators. Specifically, the screening highlighted eight chemokine receptors: Cxcr5, Ackr3, Cxcr2, Cxcr3, Ccr1, Ccr2, Ccr4, and Ackr2. Thus, we checked the expression of these eight chemokine receptors in acutely isolated astrocytes from mouse brains using datasets published in [33]. Notably, we identified Ackr3 (also known as Cxcr7) as the one with the highest expression in murine astrocytes but not in microglia. In accordance with the transcriptomic data, Ackr3-mediated signalling has been reported in cultured astrocytes and its expression is associated with astrocyte reactivity and disease in mouse and human brains [23,36,56-58]. Ackr3 has been suggested to act as either a scavenger of extracellular Cxcl12 (also known as SDF-1) or a modulator of the primary Cxcl12 receptor, Cxcr4 [59-61]. However, studies on different models have proposed a plethora of Ackr3 functions in glial, endothelial, and tumor cells [62-67]. One study by Ma and colleagues demonstrated that macrophages treated with Ackr3 ligands (e.g., Cxcl12) exhibited increased uptake of FITC-labeled *E. coli*, indicating a significant enhancement in cellular phagocytosis [68]. This effect was eliminated by siRNA silencing of Ackr3, confirming that the observed increase in phagocytosis was due to Ackr3 activity [68]. Here, we demonstrated that the knockdown of Ackr3 in primary astrocytes led to a reduced ability to internalize synaptosomes, highlighting for the first time the role of Ackr3 in this process. Further characterization revealed that Ackr3 interacts with Cxcl12 distributed on the synaptosome surface. Specifically, we showed that Cxcl12 recognizes externalized PE at the synaptosome as well as at live synapses, identifying PE-bound Cxcl12 as a novel marker of synaptic dysfunction. Supporting our data, a recent paper showed that a subset of chemokines binds exposed PS and acts as a signal for macrophage-mediated phagocytosis [41]. Although both PS and PE exposure have been associated with neuronal degeneration [69], only PS has been previously reported to act as an "eat me" signal for astrocytes at the synapse [4,16]. Additional investigation should be directed to understanding how this PE or PS synaptic tagging is regulated and tuned over time and space. Our

study demonstrated that the amount of PE-bound Cxcl12 influences Ackr3-mediated synaptic recognition and internalization by astrocytes. Of note, the significant increase of Cxcl12 attached to neuronal terminals and the astrocyte-mediated tagged synapse removal upon the induction of PE externalization were achieved only when exogenous chemokine was supplied. Therefore, further experiments are needed to define the source of the Cxcl12 and the stimulus inducing chemokine release from the cells (e.g., neurons or astrocytes). The expression and distribution of Cxcl12 and its receptors is associated with neurodegenerative disorders such as AD [23,70]. This is of particular importance because synaptic removal by astrocytes is increasingly recognized as playing a significant role in AD. Both human astrocytes and microglia contribute to synaptic loss via the MFG-E8 opsonophagocytic mechanism in AD [17]. Moreover, complement system dysregulation [12,71,72] and chronic inflammation can enhance glia-mediated synaptic destruction in AD [19]. However, astrocyte-specific mechanisms have been only partially elucidated. Here, we reported that astrocytic Ackr3 and its ligand are overexpressed in the hippocampus of AD patients, correlating with the reported increased synaptic loss in AD. Moreover, we demonstrated that astrocyte-specific deletion of Ackr3 decreases synapse engulfment in the hippocampus of 5xFAD AD mice but not in control animals, highlighting a critical role of Ackr3 in promoting synapse elimination only in the pathological context. What drives Ackr3 overexpression in a pathological context needs to be further elucidated.

In conclusion, our study unveils a novel molecular pathway involving Ackr3 in astrocyte-mediated synapse elimination, which may have implications for understanding synaptic dysfunction in neurodegenerative diseases like AD. Of note, Ackr3 is a druggable molecule, and targeting Ackr3 and related signalling pathways could potentially offer future therapeutic strategies to preserve synaptic integrity and mitigate disease progression. Further studies are needed to reveal new insights into the complex interplay between astrocytes and synapses, elucidating the precise mechanisms through which Ackr3 signalling modulates synapse engulfment.

MATERIALS AND METHODS

Animals

C57Bl/6J wild-type mice were provided by the Jackson Laboratory and used for the *in vitro* studies. Housing and handling of C57Bl/6J mice were done in compliance with national guidelines. All animal procedures were approved by the Ethical Committee of the University of Padova and the Italian Ministry of Health (license 46/2012 and 105/2019). For the *in vivo* studies, experiments were approved by the Institutional Animal Care and Use Committee (IACUC) of Korea Advanced Institute of Science and Technology (KAIST). Wild-type C57BL/6J mice were purchased from DBL, and B6SJL-Tg(APPSwFlLon,PSEN1*M146L*L286V)6799Vas/Mmjax (5xFAD) mice were gifted by Prof. Chan Hyuk Kim (Seoul National University). Mice were maintained on a 12-hour light cycle and had *ad libitum* access to chow and water. Both sexes were included in all experiments.

Plasmids and AAV virus preparation

The pEGFP-N1 plasmid obtained from Clontech (Mountain View, CA, USA) and CXCR7-Tango plasmid (Flag-tagged ACKR3; Plasmid #66265, Addgene) were used for mammalian expression of the eGFP and Flag-ACKR3 protein, respectively. Plasmids were amplified as described in [29].

For *in vivo* experiments, pAAV-GfaABC1D-tagBFP-miR30 plasmid was generated by combining the tagBFP sequence with the miR30 sequence (Horizon, pGIPZ plasmid) using overlapping PCR and subcloned into pAAV-GfaABC1D-eGFP plasmid (Addgene #176861). The pAAV-GfaABC1D-tagBFP-miR30-scramble and pAAV-GfaABC1D-tagBFP-miR30-shAckr3 constructs were subcloned into the pAAV-GfaABC1D-tagBFP-miR30 vector with the following target sequences.

Gene	Target sequence
scramble	5’-CAACAAGATGAAGAGCACCAA-3’
Ackr3	5’-CTTCACTATCATTGCGATCTT-3’

The AAV virus was harvested as previously described [73,74]. Briefly, HEK293 cell lines were transfected with ITR-containing transfer plasmid (pAAV-GfaABC1D-tagBFP-miR30-scramble, pAAV-GfaABC1D-tagBFP-miR30-shAckr3, and pAAV-hSyn-Synaptophysin-mCherry-eGFP), a helper plasmid (Addgene #112867), and a pAAV9 capsid plasmid (Addgene #198016) with polyethylenimine (PEI, Sigma). For AAV virus purification from the cell media, supernatant was collected after 72h and 120h. Cells were harvested and lysed by freezing/thawing after 120h. Both the cell lysate and supernatant were purified with PEG8000 (Sigma) and ammonium sulfate (Sigma).

The AAV virus was concentrated using Amicon Ultra (Merck), and the viral titer was quantified with quantitative PCR (qPCR) as previously described [74].

Mouse primary astrocyte cultures

Mouse primary striatal astrocytes were obtained from postnatal pups between day 1 and 3 (P1-3) as described in [29,75]. Briefly, brains were dissected from the skull and placed in cold Dulbecco's Phosphate Buffered Saline (DPBS, Biowest). Olfactory bulbs and cortices were removed and striata were selected. After the dissection, supplemented medium composed of Basal Medium Eagle (BME, Biowest), 10% fetal bovine serum (FBS, Corning), 100 U/ml penicillin and 100 µg/ml streptomycin was added to the tissues and the striata were then sifted through a 70-µm cell strainer (Sarstedt) using a syringe plunger. The cell suspension was centrifuged (300×g, 15 min) and the pellet was washed twice with supplemented medium. Cells were seeded in cell culture flasks at the density of 5×10^6 cells/10 ml medium and maintained in supplemented medium at 37°C and 5% CO_2 atmosphere. The culture medium was changed after 7 days and subsequently after every 3–4 days. When cell confluency reached about 80%, contaminant microglia were detached by shaking the flask (800) for 2h at room temperature (RT). After shaking, the medium containing microglia was removed and replaced with fresh supplemented medium.

Generation of human induced astrocytes (iHA)

Human iPS-derived astrocytes were obtained as described in [76]. Briefly, human iPSCs were differentiated to neural precursor cells (NPCs) in laminin 521 (LN521) and laminin 211 (LN211) (both from Biolamina). Differentiation of NPCs to progenitor astrocytes was triggered in 50% laminin 111 (LN111) and 50% LN211 (Biolamina) using the astrocyte differentiation medium (STEMdiff astrocyte differentiation #100-0013, StemCell). To maintain the appropriate cell density (70% of confluence) cells were splitted once a week for 21 days. Finally, astrocytes progenitor cells were maturated in Astrocyte Maturation Medium (STEMdiff astrocyte maturation #100-0016, StemCell) for 60 to 75 days.

Primary cortical neurons

Primary cortical neurons were obtained from postnatal pups between day 0 and 1 (P0-P1) as in [77]. Briefly, cortices were removed, snipped into smaller pieces, transferred in papain solution (Worthington Biochemical Corporation) and further triturated. The suspension was incubated for 40 min at 37°C and spun down in a swinging-bucket rotor for 5 min at 200xg. The supernatant was discarded and 3 ml of solution containing DNase and Trypsin inhibitors were added to the pellet:

after pipetting 3 times, the tubes were incubated for 10 min at RT to allow the bigger pieces of tissue to precipitate. Then, the supernatant was gently pipetted drop-by-drop upon 5 mL of bovine serum albumin (BSA) and Trypsin inhibitor solution and spun down for 10 min at 100xg. After discarding the supernatant, the pellet was resuspended in 5 ml of Neurobasal (Life Technologies) supplemented with 5% FBS, 2% B27 supplement (Invitrogen), 0.5 mM Glutamine (Life Technologies), penicillin (100Units/ml) and streptomycin (100µg/ml) (Life Technologies). $2x10^5$ cells were plated onto 12mm glass coverslips in 24-well plates and grown in Neurobasal medium supplemented as above and cultured in a 5% CO_2 atmosphere at 37°C. After 7 days, 50% of the Neurobasal medium was removed and replaced with fresh one. Experiments were performed at DIV10.

Neuron-glia co-cultures

To obtain neuron-glia co-cultures, primary neurons and astrocytes were prepared as described above and plated in a 5:1 ratio. Astrocytes were labelled using a pre-treatment with CellTrace Violet Cell Proliferation Kit (Thermo Fisher Scientific) at a final concentration of 1µg/ml for 20 min at 37°C and then added to the neuronal cultures. Co-cultures were incubated at 37°C and 5% CO_2 and the synapse-engulfment experiments were carried out after 48h.

Cell transfection

For the screening, primary astrocytes were seeded in µClear 384-well (PerkinElmer) plates at a seeding density of $4x10^3$ cells/well using Janus Liquid Handler (PerkinElmer). The day after, astrocytes were transfected using the G-014675-E2 Mouse Druggable Subset Dharmacon siGENOME® SMARTpool® siRNA Library Lot.1400 (Dharmacon). siRNA SMARTpool was mixed with pEGFP-N1 plasmid obtained from Clontech (Mountain View, CA, USA) at a final concentration of 50nM; this mixture was then combined with Lipofectamine 2000 (Thermo Scientific) following a 1:3 RNA-DNA/Lipofectamine ratio. The mixture was diluted in OPTIMEM (Gibco) and incubated for 20 min at RT to allow the formation of liposomal complexes. After 90 min, the transfection medium was replaced with complete BME.

For the live-imaging experiments, immunocytochemistry and western blot procedures, astrocytes and neurons were transfected following the protocol described above. Instead, iHA were seeded in µClear 96-well (Greiner) plates coated with LN111/LN211 (Biolamina). The day after, cells were transfected with siRNA Ackr3 (Mouse) SMARTPool (Dharmacon) at a final concentration of 100nM in combination with 0.5 µg of pmaxGFP™ (LONZA) and Lipofectamine Stem Transfection Reagent (Thermo Fisher Scientific) following 1:1 siRNA-DNA/Lipofectamine ratio.

Synaptosome purification and dye-conjugation

Synaptosomes were prepared as described in [78]. Briefly, four Sucrose Tris-Percoll solutions (23-15-10-3% of Percoll, respectively) were stratified into a centrifuge tube. Whole brain tissues were homogenised in a solution containing 10mM Tris, 0.32M sucrose (pH 7.4) and protease inhibitors using a glass-Teflon tissue grinder (0.25mm clearance). After centrifugation (1,000xg for 5 min at 4°C), the supernatant was added to the discontinuous density gradient solution. Upon centrifugation (33,500xg for 6 min at 4°C), the synaptosome fraction was located between the 23% and the 15% density gradient solutions. Synaptosomes were then collected and re-suspended in physiological solution (140mM NaCl; 3mM KCl; 1.2mM $MgSO_4$; 1.2mM NaH_2PO_4; 10mM HEPES; 10mM glucose; dissolved in distilled water, pH 7.4). A final centrifugation step at 20,000xg for 10 min at 4°C was performed and the pellet containing the synaptosome fraction was quantified and either conjugated or stored at -80°C in PBS containing 5% DMSO.

Conjugation was performed as described in [4,27]. Synaptosomes were incubated with pH-RODO™ Red, succinimidyl ester (pH-RODO) (Thermo Scientific) or 5-TAMRA (5-Carboxytetramethylrhodamine) (Thermo Scientific) in 0.1M Na_2CO_3 (pH 9.0) at RT with gentle agitation. After 2h, unbound pH-RODO was washed-out with DPBS by performing six rounds of centrifugations at 21,092xg for 2 min. pH-RODO-conjugated synaptosomes were re-suspended with DPBS containing 5% DMSO for subsequent freezing.

For chemokine binding assay, 10 µg of synaptosomes were incubated with recombinant Cxcl12 (DBA italia) at a final concentration of 250nM for 1h at 37°C with gentle agitation. After 2h of incubation, unbound Cxcl12 was washed-out with DPBS by performing four rounds of centrifugations at 21,092xg for 2 min.

Mass spectrometry (LC–MS/MS)

Synaptosomes (20 µg) were sent for proteomic analysis at EMBL Proteomics Core Facility in Heidelberg, Germany, for identification and quantification of proteins in complex mixtures. Samples were subjected to in-solution tryptic digestion using a modified version of the Single-Pot Solid-Phase-enhanced Sample Preparation (SP3) [79]. Data were analysed with MaxQuant and the iBAQ algorithm which represents the abundances of a protein within a sample. Methods are fully established and detailed in [80-82].

Transmission electron microscopy analysis

Synaptosomes were centrifuged at 21,092xg for 2 min at RT and resuspended in Fixative buffer (glutaraldehyde 2.5% in 0.1M sodium cacodylate buffer) for 1h at 4°C. The samples were postfixed

using 1% osmium tetroxide and 1% potassium ferrocyanide in 0.1M sodium cacodylate buffer for 1h at 4°C. After three washes in 0.1M sodium cacodylate buffer samples were dehydrated in a graded ethanol series and embedded in epoxy resin (Sigma-Aldrich). Ultrathin sections (60-70 nm) were obtained using Ultrotome V (LKB) ultramicrotome and counterstained using a saturated solution of uranyl acetate in ethanol 50% and lead citrate 2,5% in water). Sections were imaged as described in [29,75].

AAV stereotaxic injection

Mice were anesthetized with isoflurane (Piramal) and maintained using a veterinary vaporizer (Surgivet). AAV9-GfaABC1D-tagBFP-miR30-scramble or AAV9-GfaABC1D-tagBFP-miR30-shAckr3 (1×10^{13} vector genomes (vg)/ml, 300nl) and AAV9-hSyn-Synaptophysin-mCherry-eGFP (1×1013 vg/ml, 300nl) were injected unilaterally into the hippocampus CA1 (CA1; ML: +1.2 mm, AP: -2.0 mm, DV: −1.25 mm from bregma) and the hippocampus CA3 (CA1; ML: +2.5 mm, AP: -2.0 mm, DV: −2.35 mm from bregma), respectively. All surgery was performed with a stereotaxic frame (Kopf) and a motorized Hamilton syringe pump (Harvard apparatus) with glass pipettes (WPI). After the incision was sutured, the mice were recovered and returned to their home cage. All injection were performed 3 weeks before sacrifice. Both males and females were included in injections.

Antibodies

ANTIBODY	Code	Dilution
Alexa Fluor 488 goat anti-rabbit	Invitrogen #A11034	IF: 1:200
Alexa Fluor 488 goat anti-mouse	Invitrogen #A11004	IF: 1:200
Alexa Fluor 568 goat anti-rabbit	Invitrogen #A11004	IF: 1:200
Alexa Fluor 568 goat anti-mouse	Invitrogen #A31553	IF: 1:200
Alexa Fluor 647 goat anti-mouse	Invitrogen #A10008	IF: 1:200
Alexa Fluor 647 goat anti-rabbit	Invitrogen #A21449	IF: 1:200
anti-Factin	Abcam #ab78520	IF: 1:1000
Flag M2-peroxidase	Sigma-Aldrich #A8592	WB: 1:5000
mouse anti-Cxcr7	Cell Signaling #PA359	IF: 1:400

mouse anti-GAPDH	Cusabio #CSB-MA000195	WB: 1:5000
mouse anti-GFAP	Cell Signaling #34502	IF: 1:400
mouse anti-PSD95	Abcam #ab2723	WB: 1:10000, IF: 1:200
mouse anti-Vamp2	*Homemade* provided by Prof.Ornella Rossetto	IF: 1:200
mouse anti-β-actin	Sigma Aldrich #A3853	WB: 1:10000, IF: 1:200
rabbit anti-CtsB	Abcam [CA10] #ab58802	WB: 1:1000
rabbit anti-Cxcr7	Thermo Fisher, # PA3-069	WB: 1:2000, IF: 1:500 IHC: 1:500
rabbit anti-GFAP	Abcam #ab4674	WB: 1:10000, IF: 1:400
rabbit anti-Iba1	Wako #019-19741	IF: 1:200
rabbit anti-iTAC/Cxcl11	Cell Signaling #51007	WB: 1:2000, IF: 1:500
rabbit anti-MBP	Abcam #ab40390	WB: 1:1000
rabbit anti-Megf10	Sigma-Aldrich #ABC10	WB: 1:1000
rabbit anti-SDF-1/Cxcl12	Cell Signaling #3740	WB: 1:2000, IF: 1:500
rabbit anti-Synaptophysin	EMD Millipore MAB258	WB: 1:1000
rat anti-Lamp-1 (clone 1D4B)	Abcam #ab25245	IF: 1:1000
DyLight 405 donkey anti-rabbit	Jackson ImmunoResearch #711-475-752	IF: 1:500
DyLight 405 donkey anti-chicken	Jackson ImmunoResearch #703-475-155	IF: 1:500
Alexa Fluor 488 donkey anti-rabbit	Invitrogen #A-21206	IF: 1:1000
Alexa Fluor 594 donkey anti-guinea pig	Jackson ImmunoResearch #706-585-148	IF: 1:1000
Alexa Fluor 594 donkey anti-chicken	Jackson ImmunoResearch #703-585-155	IF: 1:1000
rabbit anti-SDF1/CXCL12	Abcam #ab9797	IF: 1:500

guinea pig anti-S100B	SYSY #287 004	IF: 1:300
chicken anti-GFAP	Aves labs #GFAP	IF: 1:1000
guinea pig anti-VGLUT1	Millipore #AB5905	IF: 1:1000

Table 1. The table illustrates the Antibodies code and dilution for each techniques (IF: immunofluorescence; WB: Western-Blot).

Immunofluorescence

For the staining of cultured astrocytes, $1x10^5$ cells/well of primary striatal astrocytes and iHA were plated onto 12mm glass coverslips (Thermo-Scientific) in 24-well plates coated with Poly-lysine (Sigma) or in 50% laminin 111 (LN111) and 50% LN211 (Biolamina). After treatments, fixation was performed with 4% w/v Paraformaldehyde (PFA) (Merck/Sigma), pH 7.4, for 20 min at RT. Cells were permeabilized with 0.1% v/v Triton® X-100 in DPBS for 20 min and successively incubated for 60 min with blocking solution (5% v/v FBS in DPBS) to saturate non-specific sites. Primary antibodies diluted in blocking solution were then added to the permeabilized cells overnight (O/N) at 4°C in a humidity chamber. The day after, after washing of the primary antibody solution, secondary antibodies diluted in blocking solution were incubated for 1h at RT. Cover glasses were then washed three times in PBS and were mounted on a microscope slide (Thermo Scientific) using Mowiol (Calbiochem) supplied with DAPI.

For the staining of the human hippocampi, paraffin-embedded sections (8 µm) were cut using a microtome (Thermo Scientific). To remove paraffin wax, 8 µm slices were washed in xylene and rehydrated in 100% ethanol. Slices were treated for 15 min with a quenching solution containing 50mM NH_4Cl in phosphate buffer saline (PBS) for immunofluorescence analysis. Slices were then washed in TBS-T and incubated at 90 °C for 15 min with a citrate buffer (10mM sodium citrate and 0.1M citric acid dissolved in distilled water; pH 7.0) to perform epitope retrieval. Subsequently, slices were saturated for 1h at RT in a blocking solution containing 1% BSA, 15% goat serum, 0.25% gelatine, 0.20% glycine, and 0.5% Triton X-100. Slices were then incubated O/N at 4 °C with primary antibodies diluted in blocking solution The following day, slices were washed in TBS-T and incubated for 1h at RT with a mixture of the secondary antibodies Upon washes in TBS- T, slices were incubated for 5 min with Hoechst (1:10,000; Invitrogen) to visualize the nuclei and mounted with Mowiol (Calbiochem).

For *in vivo* experiments, mice were anesthetized using avertin (0.2g/ml, Sigma) and transcardially perfused with phosphate-buffered saline (PBS) followed by 4% paraformaldehyde (PFA, Bio-Solution). The brains were post-fixed for 12h in 4% PFA at 4°C, then cryoprotected in 30% sucrose (Sigma)/PBS for 24h at 4°C. After the brain samples were embedded and frozen in OCT compound (Leica), consecutive brain sections (30 μm) were collected in PBS. Each section was subsequently treated with a blocking solution (4% bovine serum albumin, 0.3% Triton X-100 in PBS) for 1 hour at room temperature (RT) and incubated with the primary antibodies in blocking solution for at least 24h at 4°C: The sections were rinsed five times with PBST (0.1% Tween 20 in PBS, Sigma) and incubated with secondary antibodies for 12h at 4°C. After multiple washes in PBST, the sections were coverslipped with an antifade mounting medium (Vectorshield).

Gene Ontology (GO) enrichment analysis

Molecular function enrichment analysis was performed using GO [83] categories. The list of genes that abolish the ability of astrocytes to internalize synaptosome (red hits) and those that elicited the opposite (green hits) were analyzed testing the enrichment analysis of MF GO terms by using the ClusterProfiler R package [84,85]. MF GO terms with an adjusted p-values lower than 0.05 were considered for data interpretation and the top 10 ranked terms with the lowest p-value were represented in figures. Figures were generated with dotplot and cnetplot functions. All the analyses have been performed with R version 4.1.2 and Bioconductor version 3.14 [86].

Transcriptomic data from public datasets

Expression matrices of publicly available dataset have been downloaded from GEO database (details of sequencing and experimental procedures on GSE52564 series). An RNA-sequencing transcriptome and splicing database of glia, neurons, and vascular cells of the cerebral cortex [33]. The data have been filtered by the 8 genes responsible for the expression of chemokine receptors, and a log expression matrix of these eight gene has been plotted thorough R package ComplexHeatmap (version 2.18.0), and column are clustered through the "euclidean" method. All the analyses have been performed with R version 4.3.2 and Bioconductor version 3.18.

Immunoprecipitation and pull-down Assay

Flag-Human CXCR7(ACKR3)-Tango (Plasmid #66265, Addgene) immune-purification was performed as described in [87]. Briefly, transfected Hek293FT cells were lysed in an appropriate volume of RIPA buffer. Lysates were centrifuged for 30 min at 14,000×g and subsequently incubated with anti-Flag M2 agarose resin beads O/N at 4 °C with gentle agitation. Immuno-purified Flag-

ACKR3 was then incubated O/N at 4°C with 60 µg of intact synaptosomes. The following day, anti-Flag beads were centrifuged for 1 min at 9000xg and washed several times with lysis buffer. Samples were then resolved by SDS-PAGE and Western Blot.

Pip Strips

PIP Strips (Thermo Scientific) were incubated with blocking buffer 1X Tris-buffered saline (TBS), 0.1% Tween-20, 3% BSA for 1h at RT. Then, recombinant murine SDF-1α-CXCL12, (Peprotech) was added at 0.1µg/ml in blocking buffer and incubated for 1h at RT. Strips were washed with TBS, 0.1% Tween-20 (TBS-T) and bound SDF-1α-CXCL12 chemokine was detected with anti-murine SDF-1α-CXCL12 antibody (diluted 1:2000, Peprotech) followed by an HRP-conjugated anti-rabbit antibody (diluted 1:16000, Abcam, Cambridge, Massachusetts, USA). Strips were developed with Immobilon Forte Western HRP substrate (Millipore) and the VWR Imager Chemi Premium.

Western Blot Analysis

Samples were lysed in an appropriate volume of RIPA buffer (20mM Tris-HCl pH 7.5, 150mM NaCl, 1mM EDTA, 0.5mM sodium pyrophosphate ($Na_4P_2O_7$), 1mM β-glycerophosphate ($C_3H_7Na_2O_6P$), 1mM sodium orthovanadate (Na_3VO_4) containing 1% protease inhibitor cocktail (Sigma-Aldrich). Protein concentration was determined through the Pierce BCA Protein Assay Kit following the manufacturer's instructions (Thermo Scientific) and 25 µg of each sample was prepared for SDS-PAGE. Electrophoresis was performed using ExpressPlus PAGE precast gels 4-20% (GeneScript). After electrophoresis, protein samples were transferred to PVDF membranes (Bio-Rad) through a Trans-Blot TurboTM Transfer System (Bio-Rad) in semi-dry conditions, with 1x transfer buffer (Bio-Rad) at 25V for 20 min. Membranes were incubated with 5% milk (blocking buffer) diluted in TBST at RT for 1h and then incubated for 1h at RT with appropriate horseradish peroxidase (HRP)-conjugated secondary antibodies (Invitrogen). The visualization of the signal was conducted using Immobilon Forte Western HRP substrate (Millipore) and the VWR Imager Chemi Premium. Images were acquired in .tiff format and processed with the ImageJ software to quantify the total intensity of each single band.

For dot-blot assay, 10-20-30 µg of synaptosomes were spotted onto nitrocellulose membranes (Bio-Rad) and allowed to dry. Membranes were incubated with blocking buffer at RT for 1h. Then, recombinant Cxcl12was added at 0.1 µg/ml diluted in blocking buffer and incubated for 1h at RT. Proteins were identified by the appropriate primary antibodies against Vamp2, PSD95 and Cxcl12 antibodies. Then the membrane was incubated for 1h at RT with appropriate horseradish peroxidase (HRP)-conjugated secondary antibodies (Invitrogen). The visualization of the signal was conducted

using Immobilon Forte Western HRP substrate (Millipore) and the VWR Imager Chemi Premium. Images were acquired in .tiff format and processed with the ImageJ software to quantify the total intensity of each single band.

Human Samples and clinical data

All procedures were carried out in accordance to the Declaration of Helsinki. Samples were anonymous to the investigators and used in accordance with the directives of the Committee of the Ministers of EU member states on the use of samples of human origin for research. Donor subjects gave their written informed consent prior to death according to regulations of the Body Donation Program of the Institute of Human Anatomy, Department of Neuroscience, University of Padova.

ID	Age	Sex	Hypertension	PMI	Neurological Signs	Neuropathological Evaluation	Cause of Death
#1AD	83	M	Y	5	Cognitive decline, Alzheimer type	AD neuropathological changes, chronic ischaemic vascular disease	Ischaemic heart disease, respiratory failure
#2AD	80	F	Y	4	Cognitive decline, Alzheimer type	AD neuropathological changes, chronic ischaemic vascular disease	Respiratory failure
#3AD	87	M	Y	6	Cognitive decline, Alzheimer type	AD neuropathological changes, diffuse hypoxic/ischaemic damage	Pneumonia, multiorgan failure
#1HC	80	M	N	2	No signs	No relevant alterations	Multiorgan Failure
#2HC	84	F	Y	3	No signs	No relevant alterations	Ischaemic heart disease
#3HC	85	F	Y	4	No signs	No relevant alterations	Metastatic Lung Carcinoma (no CNS involvement)

Table 2. Sample demographic and clinical data of the human cases of AD and Healthy control (HC) used in this study. The table illustrates sex, age, hypertension, Post-Mortem Interval (PMI), Neurological signs, Neuropathological evaluation and Cause of Death.

Image acquisition and analysis

For live-imaging studies in primary striatal astrocytes or iHA, images were acquired at 32-bit intensity resolution over 1024×1024 pixels through the Operetta High Content Imaging System (Perkin Elmer) or ApoTome2 (Carl Zeiss) using a 10x long working distance dry objective. eGFP-positive and pH-RODO positive areas were assessed using Harmony Software (Perkin Elmer). Phagocytic Index was calculated as total pH-RODO positive area normalized by total eGFP positive area multiplied by 100.

For post-fixation imaging of primary striatal astrocytes or iHA, images were acquired at 8-bit intensity resolution over 1024×1024 pixels, through Leica SP5 or Leica TCS STED CW SP8 confocal microscope and a HC PL FLUOTAR×40/0.70 oil objective or HC APO L 40x/0.80 W U-V-I immersion objective. After setting the threshold, the JACoP plugin (ImageJ, https://imagej.nih.gov/ij/plugins/track/jacop2.html) was applied for the quantification of co-localization between Ackr3 signal and the Lamp1 and TAMRA-positive structures, graphically displayed as the Pearson's Correlation Coefficient.

For post-fixation imaging of primary neurons and neurons-astrocytes co-cultures, images were acquired at 8-bit intensity resolution over 1024×1024 pixels, through Leica SP5 and a HC PL FLUOTAR×40/0.70 oil objective. For PE-exposure and synapses internalization experiment, after setting the threshold, ComDet plugin (https://imagej.net/Spots_colocalization_ (ComDet)), using the following parameters: max co-localization distance (0.4 pixels for pSIVA and Duramycin and 0.2 pixels for Vamp/Psd95 experiment) and particles dimension (Vamp2/PSD95: 3 pixels and pSIVA/Duramycin: 2 pixels). 3D reconstructions were done using IMARIS software (Bitplane 9.9.1). For Cxcl12 quantification: after setting the threshold, we identified a 50 nm rectangle based on F-actin positive dendrites. The number of Cxcl12 dots were assessed by "puncta count" output using the ComDet plugin, with the following parameter: particle dimension (Cxcl12: 2 pixels) and normalized by the ROI's dimension.

For human tissues, images were acquired at 8-bit intensity resolution over 1024 × 1024 pixel on a Leica SP5 confocal microscope using an HC PL FLUOTAR 40x/0.70 oil objective. Using ImageJ, the IntDen of ACKR3, GFAP and CXCL12 signals upon setting scale and threshold were measured. The co-localization of GFAP/ACKR3^{+} cells was defined using the JACoP plugin.

For *in vivo* analysis, all images were acquired using an Airyscan LSM880 confocal microscope (Zeiss) and processed with ImageJ (Fiji). For colocalization and expression analysis, each plane of the z-stack images was processed using the ImageJ Distance Analysis (DiAna) plugin [88]. For excitatory pre-synapse phagocytosis (ExPre) analysis, mCherry-alone signals were obtained by subtracting mCherry signals from eGFP signals. The DiAna plugin was then used to assess colocalization between mCherry alone signals and tagBFP, normalized by eGFP area. All representative images were merged in the z-stack planes.

Statistical Analysis

Results are expressed as mean ± standard deviation (SD). Data were analysed with unpaired t tests or Two-way ANOVA (Gaussian distribution) respectively followed by Tukey's multiple

comparisons test. Levels of significance were defined as $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$. Statistical analysis was performed with Prism 9 (GraphPad).

FIGURES

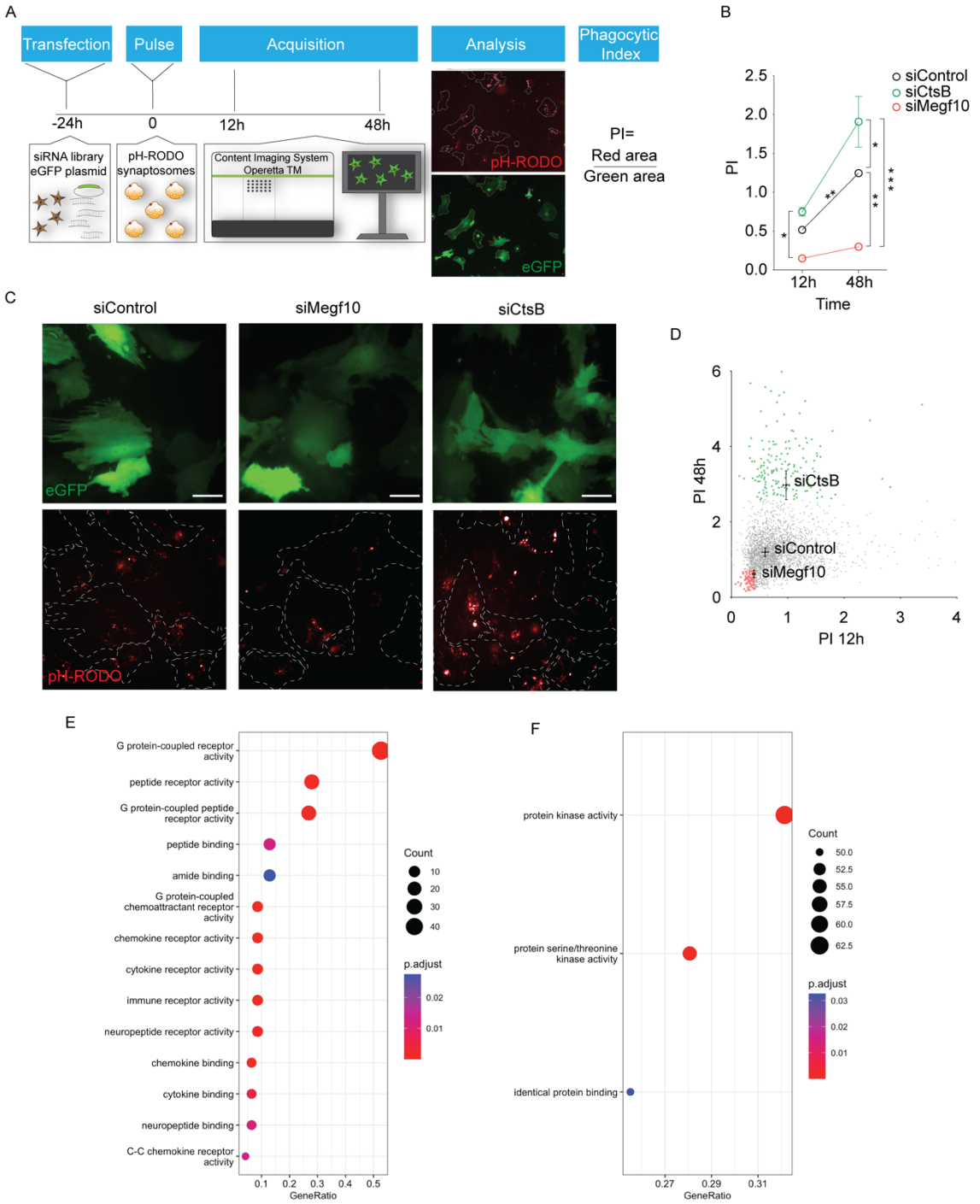

FIGURE 1. Genetic screening reveals novel modulators of synaptosome engulfment.

A. Experimental design. Primary astrocytes were transfected with eGFP encoding plasmids in combination with siRNA oligonucleotides. The next day, cells were exposed to pHRODO-labelled synaptosomes and the phagocytic kinetics were measured through long-term fluorescence live imaging at 12 and 48 h. To quantify phagocytosis, the area (μm^2) of red fluorescence (pHRODO) signal was normalized to the eGFP positive area (μm^2) (Phagocytic Index, PI). **B.** PI of primary astrocytes transfected with siRNA Control (black line), siRNA against Megf10 (red line) and siRNA

against CtsB (green line). (siControl at 12h vs 48h, p=0.0014; 12h: siCtsB vs. siMegf10 p= 0.0453; 48h: siControl vs. siMegf10 p=0.0037; siControl vs. siCtsB p= 0.0266; siCtsB vs. siMegf10 p <0.0001). N=40 images per condition were analysed; N=3 biological replicates. Statistical analysis was performed using Two-Way ANOVA with Tukey's multiple comparison test. **C.** Representative images of primary astrocytes transfected with Control, Megf10 and CtsB siRNA and the eGFP-encoding plasmid at 48h. pH-RODO fluorescence has been analyzed within the eGFP positive area (dotted line) Scale bar 20 µm. **D.** Graph representing the PI at 12h vs 48h of primary astrocytes transfected with the siGENOME Mouse Druggable siRNA Library (one dot=1 hit). Downregulation of genes that abolishes the ability of astrocytes to internalize synaptosomes were highlighted as red hits; while downregulation of genes that enhances PI values compared to control were highlighted as green hits. Five images per condition were analysed. **E.** Dotplot of red hits. Genes are plotted with a qvalue <0.5. Bubble plots highlight p.adjusted values of the GO categories (color scale) and the number of hits falling in the GO categories (size scale). Gene ratio defines the percentage of the enriched hits in the given GO term. **F.** Dotplot of green hits. Genes are plotted with a qvalue <0.5. Bubble plots highlight p.adjusted values of the GO categories (color scale) and the number of hits falling in the GO categories (size scale). Gene ratio defines the percentage of the enriched hits in the given GO term.

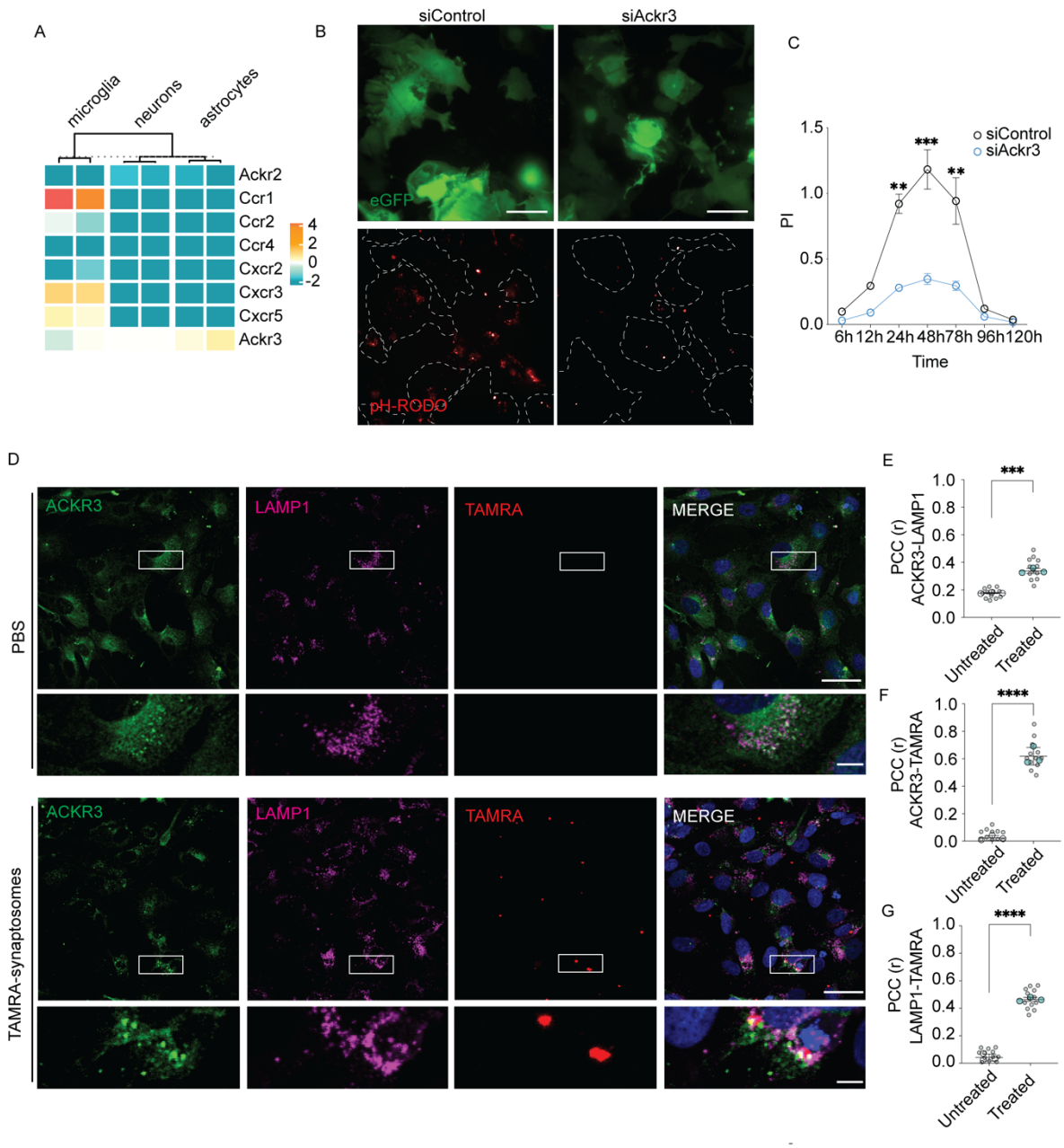

FIGURE 2. Ackr3 regulates synaptosome internalization in astrocytes.

A. Transcriptomic data showing the differential expression of the chemokine receptors in astrocytes, microglia and neurons isolated from mice. The heatmap shows the RNA-seq analysis obtained from [33]. Columns show the duplicates for each type of cell, while rows represent the genes **B.** Representative images of primary astrocytes transfected with siControl and siAckr3 together with an eGFP-encoding plasmid followed by pH-RODO synaptosome treatment (48h). Scale bar 20 µm. **C.** PI of primary astrocytes transfected with siControl and siAckr3 at 6h, 12h, 24h, 48h, 78h, 96h and 120h upon synaptosomes treatment. Ackr3 (blue line) downregulation displayed a significant higher PI at 24h, 48h and 78h compared to control (24h: Ackr3 vs. Control p=0.0002; 48h: Ackr3 vs. Control p <0.0001; 78h: Ackr3 vs. Control p=0.0002). N=30 images per conditions were analysed; N=3

biological replicates. Statistical analysis was performed using Two-Way ANOVA with Tukey's multiple comparison test. **D.** Representative z-stack confocal images of iHA treated with PBS or TAMRA-labelled synaptosomes (red). Cells were stained with anti-Ackr3 (green) and anti-Lamp1 (purple) antibodies. Scale bar 20 µm; insets 5 µm. **E.** Pearson's correlation coefficient (PCC) of human ACKR3/TAMRA co-localization (untreated vs. treated p=0.0004). **F.** PCC of TAMRA/LAMP1-positive compartment co-localization (untreated vs. treated p<0.0001). **G.** PCC of ACKR3/LAMP1-positive compartment co-localization (untreated vs. treated p<0.0001). **E-G.** N=6 images for conditions were analysed; N=3 subjects. Statistical analysis in E-G was performed using unpaired t-tests.

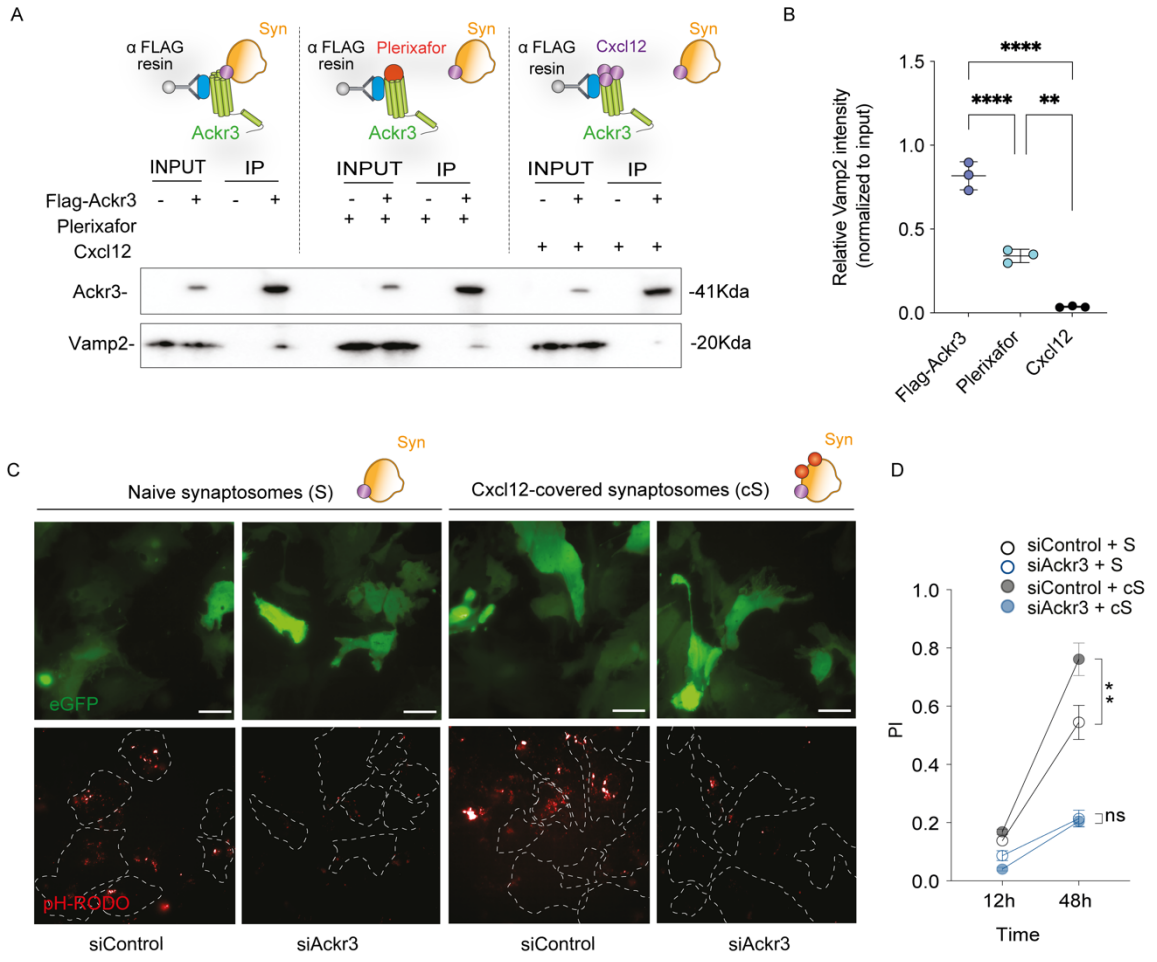

FIGURE 3. Cxcl12 modulates synaptosome recognition.

A. Western blot analysis of pull-down assay using purified Flag-Ackr3 as bait and intact synaptosomes as prey. Untreated Flag-Ackr3 or preincubated Flag-Ackr3 with Plerixafor and Cxcl12 has been tested. Bound synaptosomes were detected using anti-Vamp2. **B.** Quantification of

immunoprecipitated Vamp2 (IP) normalized to total Vamp2 (input). N=3 biological replicates. Statistical analysis was performed using One-Way ANOVA with Tukey's multiple comparison test (Flag-Ackr3 vs. Plerixafor $p<0.0001$ Flag-Ackr3 vs. Cxcl12 $p<0.0001$; Plerixafor vs. Cxcl12 $p=0.0011$). **C.** Representative fluorescence images of primary astrocytes transfected with siRNA Control or siRNA against Ackr3 together with eGFP-encoding plasmid upon 48h of S or cS treatment. Scale bar 20 µm. **D.** PI of primary astrocytes transfected with siRNA Control (grey) or siRNA against Ackr3 (light blue) at 12 and 48 h upon treatment with S (empty dots) or cS (filled dots). N=12 images per condition were analysed; N=3 biological replicates. Statistical analysis was performed using Two-Way ANOVA with Tukey's multiple comparison test (12h: siRNA Control treated with S vs. siRNA Control treated with cS $p=0,0009$; 12h: siRNA against Ackr3 treated with S vs. siRNA against Ackr3 treated with cS $p>0.9999$; 48h: siRNA Control treated with S vs. siRNA Control treated with cS $p=0.0093$; 48h: siRNA against Ackr3 treated with S vs. siRNA against Ackr3 treated with cS $p>0.9999$).

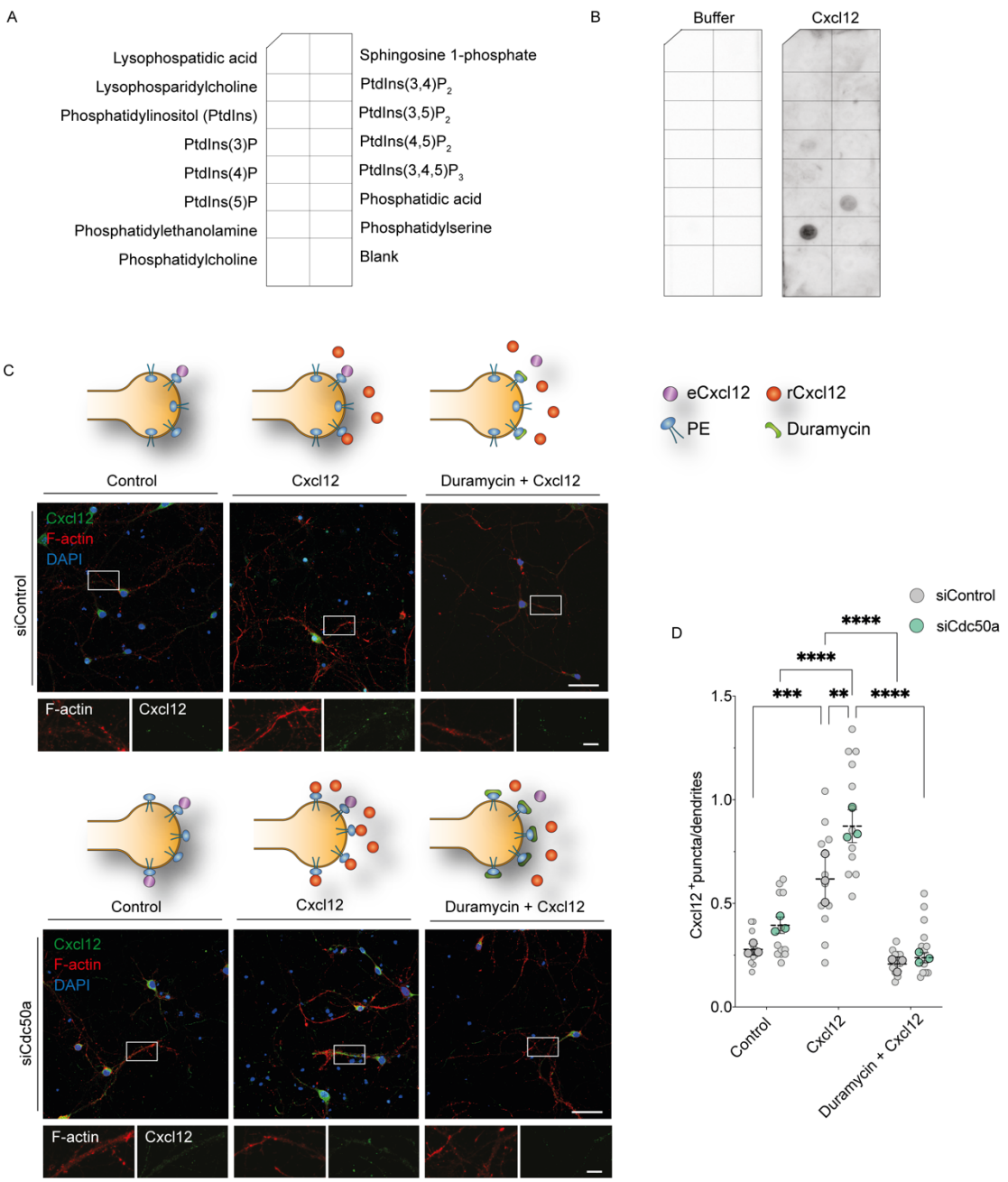

FIGURE 4. Cxcl12 binds externalized PE.

A. Schematic picture of arrays spotted with 15 different phospholipids. **B.** Array incubated with RIPA buffer (left) or 0.1µg/ml of recombinant Cxcl12 (right). Bound chemokine was detected with the anti-Cxcl12 antibody. **C.** Representative fluorescence images of primary cortical neurons transfected with siRNA Control or siRNA against Cdc50a. Fixed, unpermeabilized cells were treated or not (control) with recombinant Cxcl12 in the presence or in the absence of duramycin preincubation. Insets show Cxcl12 (green) puncta along the F-actin positive neuronal dendrites (red).

Scale bar 20 µm; inset scale bar 5 µm. **D.** Quantification of Cxcl12-positive puncta along the neuronal dendrites (Control/siControl vs. Cxcl12/siControl p=0,0003; Control/siControl vs. Cxcl12/siCdc50 p<0.0001; Control/siCdc50a vs. Cxcl12/siControl p=0.0077; Control /siCdc50a vs. Cxcl12/siCdc50a p<0.0001; Cxcl12/siControl vs. Cxcl12/siCdc50a p=0,0038; Cxcl12/siControl vs. Duramycin+Cxcl12/siControl p<0.0001; Cxcl12/siControl vs. Duramycin + Cxcl12/siCdc50a p=0.0001; Cxcl12/siCdc50a vs. Duramycin + Cxcl12/siControl p<0.0001; Cxcl12/siCdc50a vs. Duramycin+Cxcl12/siCdc50a p<0.0001). N=12 images per condition were analysed; N=3 biological replicates. Statistical analysis was performed using Two-Way ANOVA with Tukey's multiple comparison test.

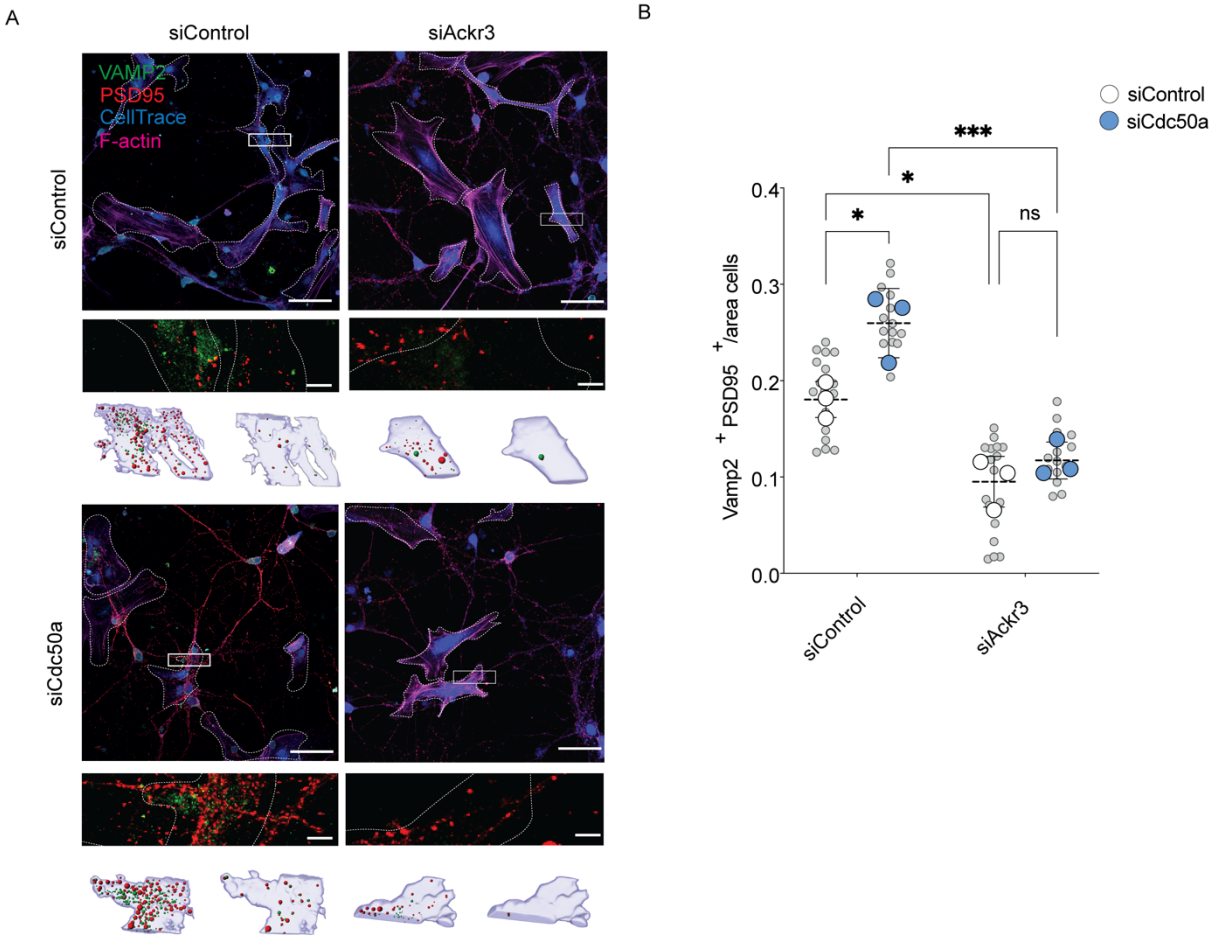

FIGURE 5. PE externalization stimulates Ackr3-mediated synaptic removal.

A. Representative fluorescence images of primary neurons co-cultured with primary astrocytes. Neurons were transfected with siRNA Control or siRNA against Cdc50a. Synaptic terminals were stained with anti-PSD95 (red) and anti-Vamp2 (green). Dendritic trees are marked using F-actin (magenta). Astrocytes were transfected with siRNA Control or siRNA against Ackr3 and pre-stained with Cell Trace (blue). 3D rendering showing synaptic terminal inside the astrocytes: red spots

(PSD95+ puncta) and green spots (VAMP2+ puncta) (left reconstruction) and Vamp2+/PSD95+ co-localizing spots (right reconstruction). 3D reconstructions were done using IMARIS software (Bitplane 9.9.1). Scale bar 20 µm, inset scale bar 5 µm **B.** Number of synaptic terminals (Vamp2+/PSD95+) within the astrocyte area (siControl astrocytes/siControl neurons vs. siControl astrocytes/siCdc50a neurons p=0,0237; siControl astrocytes/siControl neurons vs. siAckr3 astrocytes/siControl neurons p=0,0163; siControl astrocytes/siCdc50a neurons vs. siAckr3 astrocytes/siCdc50a neurons p=0,0007; siAckr3 astrocytes/siControl neurons vs. siAckr3 astrocytes/siCdc50a neurons p=0,7321) N=3 biological replicates. Statistical analysis was performed using Two-Way ANOVA with Tukey's multiple comparison test.

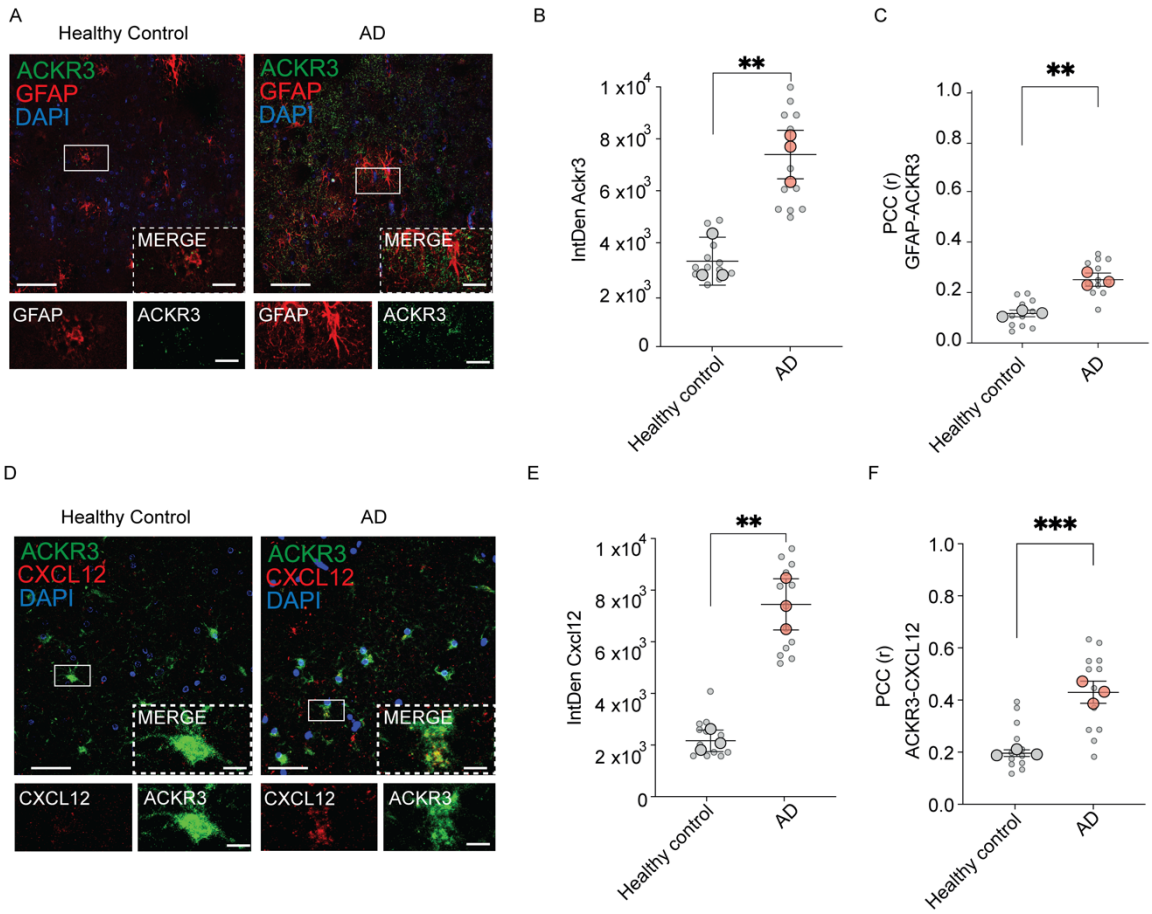

FIGURE 6. Astrocytic Ackr3 expression is AD patients.

A. Representative double-labeling images for ACKR3 (green) and GFAP (red) in AD human hippocampus and age-matched controls; scale bar 50 µm, inset 20 µm. **B.** Quantitative analysis of ACKR3 IntDen; N=3 age-matched control samples and AD hippocampus samples. Statistical analysis was performed using unpaired t test (Healthy control vs. AD p<0.0001) **C.** PCC of ACKR3

co-localizing with GFAP-positive astrocytes; N=3 age-matched control samples and AD hippocampus samples. Statistical analysis was performed using unpaired t test (Healthy control vs. AD p<0.0001). **D.** Representative double-labelling images for ACKR3 (green) and Cxcl12 (red) in AD human hippocampus and age-matched control; scale bar 50µm, inset 20µm. **E.** Quantitative analysis of CXCL12 IntDen; N=3 age-matched control samples and AD hippocampus samples. Statistical analysis was performed using unpaired t test (Healthy control vs. AD p= 0.0008)

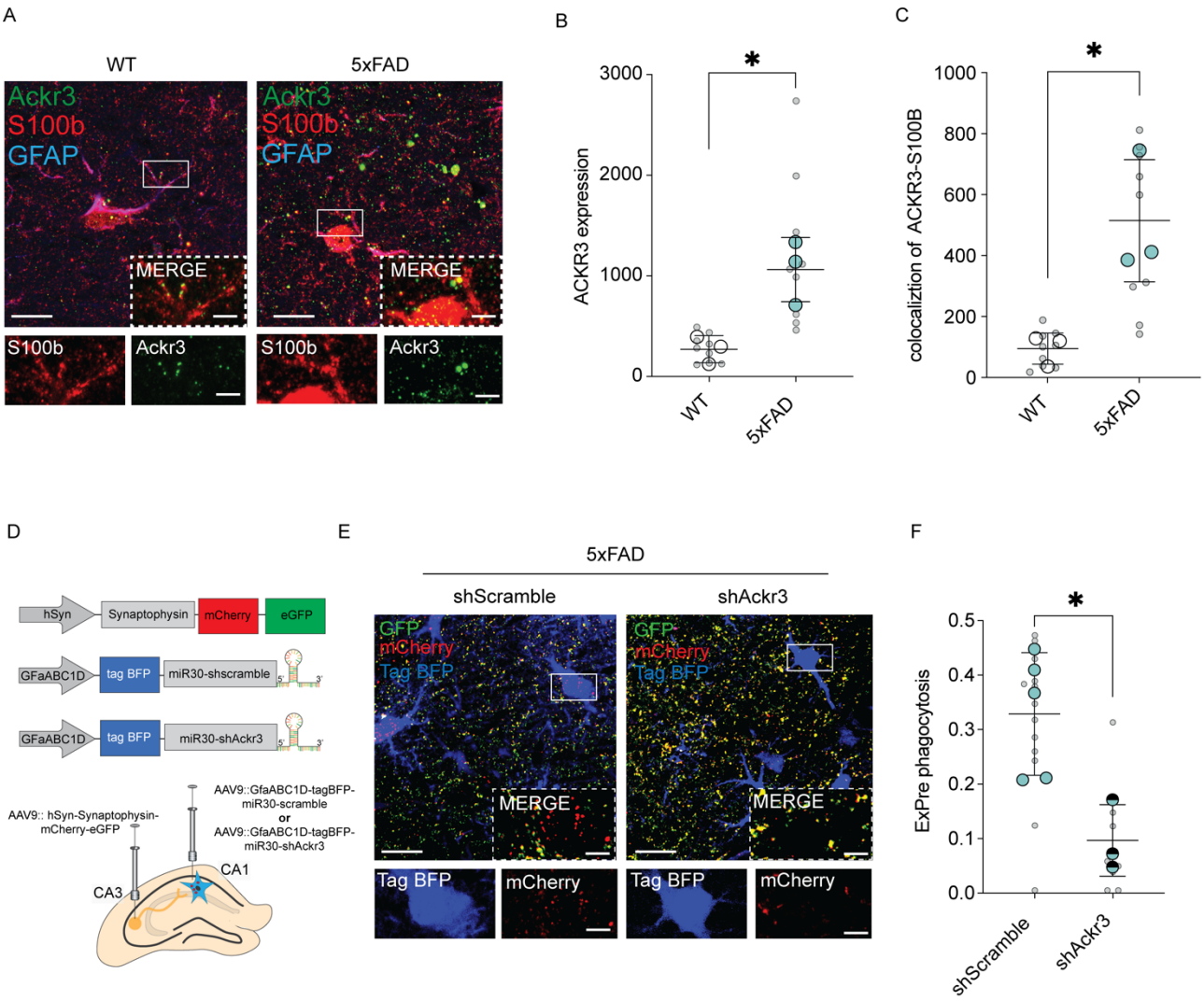

FIGURE7. Astrocytic Ackr3 expression is stimulated in 5xFAD mice.

A. Representative confocal images for ACKR3 (green), GFAP (blue) and S100β (red) in CA1 hippocampus of 4-month-old 5xFAD and wild-type mice. Scale bar 50 µm, inset 20 µm. **B.** Quantitative analysis of Ackr3 expression in the hippocampus of 5XFAD and WT mice; N=3 samples for both WT and 5XFAD 4-month-old mice. Statistical analysis was performed using unpaired t test (WT vs. 5XFAD p=0,0170). **C.** Quantitative analysis of ACKR3 co-localizing with S100β−positive astrocytes in the hippocampus of 5XFAD and WT mice; N=3 samples for both WT and 5XFAD 4-month-old mice. (WT vs. 5XFAD p= 0,0147). Statistical analysis was performed using unpaired t test. **D.** Schematic illustration of: mCherry-eGFP synapse reporter, astrocytic shRNA-scramble and astrocytic shRNA-Ackr3 reporters. Experimental scheme of AAV reporter injection in the CA1 and CA3 hippocampal region of 1-year-old 5xFAD mice. **E**. Representative confocal z-stack images of GFP- (green) and mCherry- (red)-positive excitatory synapses in the hippocampus of 1-year-old 5XFAD mice injected with AVV9-GfaABC1D-tagBFP-shScramble and AVV9-GfaABC1D-tagBFP-ShAckr3. Scale bar 50 µm, inset 20 µm. **F.** Quantitative analysis showing the volume of ExPre engulfed by astrocytes in the hippocampus of 1-year-old 5XFAD mice injected with AVV9-GfaABC1D-tagBFP-shScramble and AVV9-GfaABC1D-tagBFP-ShAckr3. Scale bar 20 µm; N=5 samples for WT and N=3 samples for 5XFAD mice. Statistical analysis was performed using unpaired t test (WT vs. 5XFAD p= 0,0017).

ABBREVIATIONS

Adeno-associated virus 9	AAV9
Alzheimer's disease	AD
ATP-binding cassette transporter A1	Abca1
Atypical chemokine receptor 3	Ackr3
Basal Medium Eagle	BME
Cathepsin B	CtsB
Cell division control protein 50 a	Cdc50a
Central nervous system	CNS
Cxcl12-covered synaptosomes	cS
Dulbecco's Phosphate Buffered Saline	DPBS
Fetal bovine serum	FBS
Glial Fibrillary Acidic Protein	GFAP
Gene ontology	GO
Human iPS-derived astrocytes	iHA
Human synapsin promoter	hSYN
Immunoprecipitation	IP
Inositol 1,4,5-trisphosphate receptor type 2	Ip3r2
Luria-bertani	LB
MER proto-oncogene tyrosine kinase	Mertk
Myelin Binding Protein	MBP
Naive Synaptosomes	S
Pearson's Correlation Coefficient	PCC
Phosphatidylethanolamine	PE
Phosphatidylserines	PS
Phosphotyrosine-binding domain containing 1	Gulp1
pHrodo-Red TM succinimidyl ester	pH-RODO
Post synapses compartment	PO
Postsynaptic density	PSD
Postsynaptic Density Protein 95	PSD95
Pre synapses compartment	PSc

siRNA Ackr3	siAckr3
siRNA Control	siControl
Synaptophysin	Syp
Transmission electron microscopy	TEM
Vesicle associated membrane protein2	Vamp2
Wild-type	WT

AUTHOR CONTRIBUTIONS

VG conceived and designed the experiments, supervised the whole project and wrote the paper. PJ conducted the experiments in vivo, analysed the data and generated the figures. GE analysed the data and generated the figures. ML and ECA conducted the gene ontology analysis. PRG generated human ipsc-derived astrocytes. LI and KG prepared the primary culture. MS carried out the conjugation experiments. AE, AP and DCR provided the human brain samples. ECO has contributed to manuscript editing and optimization. FP generated the 3D reconstruction. FC supervised the analysis of the data obtained from human ipsc-derived astrocytes. WSC supervised the analysis of the data obtained from in vivo experiments and contributed to manuscript editing and optimization. LC conceived and designed the experiments, supervised the whole project and wrote the paper. All authors contributed to data analysis and preparation of the manuscript.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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