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1 **Reactive astrocytes promote proteostasis in Huntington's** 2 **disease through the JAK2-STAT3 pathway**

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23 **Running title:** STAT3-mediated proteostasis in HD astrocytes

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1 Abstract

2 Huntington's disease is a fatal neurodegenerative disease characterized by striatal
3 neurodegeneration, aggregation of mutant Huntingtin and the presence of reactive astrocytes.

4 Astrocytes are important partners for neurons and engage in a specific reactive response in
5 Huntington's disease that involves morphological, molecular and functional changes. How
6 reactive astrocytes contribute to Huntington's disease is still an open question, especially
7 because their reactive state is poorly reproduced in experimental mouse models.

8 Here, we show that the JAK2-STAT3 pathway, a central cascade controlling astrocyte
9 reactive response, is activated in the putamen of Huntington's disease patients. Selective
10 activation of this cascade in astrocytes through viral gene transfer reduces the number and size of
11 mutant Huntingtin aggregates in neurons and improves neuronal defects in two complementary
12 mouse models of Huntington's disease. It also reduces striatal atrophy and increases glutamate
13 levels, two central clinical outcomes measured by non-invasive magnetic resonance imaging.
14 Moreover, astrocyte-specific transcriptomic analysis shows that activation of the JAK2-STAT3
15 pathway in astrocytes coordinates a transcriptional program that increases their intrinsic
16 proteolytic capacity, through the lysosomal and ubiquitin-proteasome degradation systems. This
17 pathway also enhances their production and exosomal release of the co-chaperone DNAJB1,
18 which contributes to mutant Huntingtin clearance in neurons.

19 Together, our results show that the JAK2-STAT3 pathway controls a beneficial proteostasis
20 response in reactive astrocytes in Huntington's disease, which involves bi-directional signalling
21 with neurons to reduce mutant Huntingtin aggregation, eventually improving disease outcomes.

22 **Keywords:** neuron-astrocyte interactions; JAK2-STAT3 signalling; aggregated protein
23 clearance; viral vectors; neurodegenerative diseases

24 **Abbreviations:** AAV = Adeno-Associated Virus; DARPP32 = Dopamine- and cAMP-Regulated
25 neuronal Phosphoprotein; BSA = Bovine Serum Albumin; DNAJB1 = DnaJ heat shock protein
26 family (Hsp40) member B1; FACS = Fluorescence-Activated Cell Sorting; GFAP = Glial
27 Fibrillary Acidic Protein; Glutamate Chemical Exchange Saturation transfer = gluCEST; HBSS
28 = Hank's Balanced Salt Solution; HSP = Heat Shock Proteins; JAK = Janus Kinase; LV =
29 Lentiviral Vector; mHTT = mutant Huntingtin; RT = Room Temperature; SDS = Sodium
30 Dodecyl Sulfate; SOCS3 = Suppressor Of Cytokine Signalling 3; STAT3 = Signal Transducer
31 and Activator of Transcription 3; Tx = Triton X-100; Ub = Ubiquitin; UPS = Ubiquitin-
32 Proteasome System; WT = Wild type.

33

1 Introduction

2 Huntington's disease is a genetic neurodegenerative disease that causes involuntary
3 movements, psychiatric symptoms and cognitive deficits, with no curative treatment yet
4 available¹. Huntington's disease is caused by an expansion of CAG triplet repeats in the
5 *Huntingtin (HTT)* gene, leading to an abnormal polyglutamine tract in the N-terminal part of the
6 protein HTT². Both loss and gain of function of HTT contribute to the dysfunction and death of
7 projection neurons in the caudate/putamen (striatum in mice) and cerebral cortex. A key
8 neuropathological hallmark of Huntington's disease is the presence of mutant HTT (mHTT)
9 aggregates, primarily in neurons³, but also in glial cells^{4, 5}. In the brain of Huntington's disease
10 patients, astrocytes progressively become reactive, which was initially characterized by their
11 hypertrophic morphology and overexpression of Glial Fibrillary Acidic Protein (GFAP)⁶⁻⁸.
12 Reactive astrocytes also display significant changes in gene expression in the putamen⁹ and
13 cortex⁵ of Huntington's disease patients. Astrocytes are essential partners of neurons, as they
14 perform many key functions including metabolic and trophic support, antioxidant defence and
15 regulation of synaptic transmission and plasticity¹⁰. How are these functions changed in
16 Huntington's disease? Most studies report defective astrocyte functions in Huntington's disease
17 models¹¹, including reduced glutamate uptake¹², altered K⁺ buffering¹³, impaired regulation of
18 blood flow¹⁴, as well as reduced synthesis and release of antioxidants¹⁵, trophic factors¹⁶,
19 gliotransmitters¹⁷ and exosomes¹⁸. However, in most cases, Huntington's disease mouse models
20 poorly replicate the reactive state of astrocytes observed in Huntington's disease human brains,
21 based on GFAP overexpression, hypertrophy^{11, 13} and transcriptional profile, as recently captured
22 with genome-wide transcriptomic analysis^{9, 19, 20}. Therefore, the impact of reactive astrocytes on
23 disease progression is still unclear.

24 The Janus Kinase (JAK)-Signal Transducer and Activator of Transcription 3 (STAT3)
25 pathway is a central cascade controlling astrocyte reactive response²¹. STAT3 activation is found
26 in reactive astrocytes of genetic models of Huntington's disease in mice and non-human
27 primates²². However, it is still unknown whether this pathway is also activated in reactive
28 astrocytes observed in Huntington's disease patients and which astrocyte functions are regulated
29 by this pathway.

30 We previously reported that inhibition of the JAK2-STAT3 pathway in reactive astrocytes in

1 an acute model of Huntington's disease reduces their reactive features and increases the number
2 of mHTT aggregates²². mHTT aggregates are mainly composed of N-terminal fragments of
3 mHTT, which trap several important proteins such as transcription factors or chaperones^{23, 24} and
4 generate deleterious steric hindrance. However, aggregates may also contribute to remove toxic
5 soluble mHTT from the cytosol²⁵. Soluble mHTT can be degraded by the Ubiquitin-Proteasome
6 System (UPS), while aggregates can only be cleared by autophagy coupled to lysosomal
7 degradation^{26, 27}. Astrocytes are reported to have high proteolytic capacity, including for mHTT,
8 which could explain why fewer aggregates are observed in astrocytes than in neurons^{28, 29}. Yet, it
9 is unknown whether the UPS and autophagy/lysosome systems are specifically altered in
10 Huntington's disease astrocytes^{30, 31}, and how these systems can be stimulated in astrocytes to
11 promote mHTT clearance. Another important proteostasis mechanism preventing mHTT
12 aggregation is operated by chaperones, which promote HTT proper folding, prevent abnormal
13 interactions with cellular proteins and guide mHTT to degradation systems^{32, 33}. In particular,
14 Heat Shock Proteins (HSP) prevent mHTT aggregation in different cell types^{32, 34}.

15 Here, we studied how the JAK2-STAT3 pathway controls astrocyte reactive response in
16 Huntington's disease, focusing on their ability to promote cellular proteostasis. We observed
17 STAT3 activation in reactive astrocytes in the brain of Huntington's disease patients. In two
18 complementary mouse models of Huntington's disease, we found that activation of the JAK2-
19 STAT3 pathway in reactive astrocytes reduces both the number and size of mHTT aggregates in
20 neurons, without increasing soluble mHTT levels, and improves several disease hallmarks.
21 Genome-wide transcriptomics and functional analysis showed that JAK2-STAT3 pathway
22 activation induces a specific proteostasis signature in astrocytes associated with higher
23 proteolytic activity. It also induces astrocyte expression of the co-chaperone DNAJB1, which is
24 loaded in exosomes and reduces mHTT aggregation in neurons. Our results show that the JAK2-
25 STAT3 pathway controls a bi-directional communication between reactive astrocytes and
26 neurons in Huntington's disease, which eventually reduces mHTT aggregation and improves
27 neuronal alterations.

28 **Materials and methods**

29 **Mice**

30 Heterozygous knock-in mice (Hdh140 mice) expressing a chimeric mouse/human exon 1

1 containing 140 CAG repeats inserted into the murine *Htt* gene on a C57BL/6J background were
2 originally obtained from the Jackson laboratory (stock # 027409)³⁵. Male and female Hdh140
3 mice and their littermate controls were injected with different viral vectors (see below) at 7-10
4 months and euthanized 4 months later. Wild type (WT), adult male C57BL/6J mice were injected
5 at 2.5 months of age, with different viral vectors and euthanized 1.5 months later.

6 All experimental protocols were reviewed and approved by the local ethics committee
7 (CETEA N°44) and the French Ministry of Education and Research (Approval APAFIS#4554-
8 2016031709173407). They were performed in an authorized animal facility (authorization #D92-
9 032-02), in strict accordance with recommendations of the European Union (2010-63/EEC), and
10 in compliance with the 3R guidelines. Animal care was supervised by a dedicated veterinarian
11 and animal technicians. Mice were housed in groups of 5, under standard environmental
12 conditions (12-hour light-dark cycle, temperature: $22 \pm 1^\circ\text{C}$ and humidity: 50%) in filtered
13 cages, with *ad libitum* access to food and water.

14 **Viral vectors**

15 We either used lentiviral vectors (LV) or adeno-associated vectors (AAV) to drive transgene
16 expression in neurons or in astrocytes, as described in each figure.

17 Self-inactivated LV were produced by transient co-transfection of 293T cells with four
18 plasmids encoding viral structural proteins, the envelope protein and the transgenic cDNA under
19 the control of a phosphoglycerate kinase 1 promoter and followed by the woodchuck hepatitis
20 virus post-transcriptional regulatory element, to enhance transgene expression³⁶. To target
21 neurons, LV were pseudotyped with the G-protein of the vesicular stomatitis virus³⁷. To target
22 astrocytes, LV were pseudotyped with the rabies-related Mokola envelope and lentiviral
23 recombinant genome contained four repeats of the miR124 target to repress transgene expression
24 in neurons³⁶. LV are referred to as “LV_A- or LV_N-name of the transgene” depending the cell type
25 targeted: A for astrocytes and N for neurons. Lentiviral particle titers were determined by ELISA
26 quantification of the nucleocapsid p24 protein.

27 AAV (AAV2, serotype 9) contain the gfaABC1D promoter, a synthetic promoter derived
28 from the GFAP promoter³⁸, and transduce astrocytes. AAV were produced according to
29 validated procedures³⁹. Viral genome concentration was determined by qPCR on DNase resistant
30 particles.

1 Viral vectors encoding murine *Socs3* or *Jak2*^{T875N}, a constitutively active form of JAK2
2 (JAK2ca), were used to respectively, inhibit or activate the JAK2-STAT3 pathway in mouse
3 astrocytes^{22, 39, 40}. They were co-injected with a viral vector encoding the fluorescent proteins *Gfp*
4 or *Td-Tomato* to visualize transduced cells (same total viral load). For some experiments, the
5 same viral vectors were injected in both striata. For other experiments, each striatum of the same
6 mouse received different viruses and data were analysed with paired statistical tests.

7 LVs encoding the first 171 N-terminal amino acids of human *Huntingtin* (*HTT*) cDNA with
8 82 polyglutamine repeats that target either striatal neurons [LV_N-mHTT⁴¹] or astrocytes [LV_A-
9 mHTT⁸] were used as LV-based models of Huntington's disease.

10 Last, we generated LV_A expressing full-length human *DNAJB1* (LV_A-DNAJB1) or the
11 dominant negative mutant corresponding to the J-domain of human *DNAJB1*⁴² [LV_A-DNAJB1-
12 DN]. The initial cDNA was generated by GeneArt Gene Synthesis services (Invitrogen,
13 Carlsbad, CA) based on published sequences, and inserted into a pENTR[®] transfer plasmid.
14 Gateway[®] recombination (ThermoFisher Scientific) was used to clone these cDNA into
15 appropriate self-inactivated LV expression plasmid containing the phosphoglycerate kinase 1
16 promoter, the woodchuck hepatitis virus post-transcriptional regulatory element and four
17 miR124 target sequences.

18 Immunostaining quantification

19 Levels of GFAP immunoreactivity and GFAP⁺ volumes were quantified on 10x-tiled images
20 of serial sections along the antero-posterior axis of the striatum, acquired with an epifluorescence
21 microscope (Leica DM6000, Nussloch, Germany). Virally transduced GFP⁺ area was manually
22 segmented on each section and the corresponding mean intensity signal for GFAP in this area
23 was extracted with Image J. Background intensity signal was measured on unstained regions of
24 the same section and subtracted to the GFAP total signal. The volume was calculated from the
25 area measured on each section by the Cavalieri method⁴⁰.

26 To quantify lesion size, images of DARPP32 immunostained serial striatal sections were
27 acquired at the 5x objective with an epifluorescence microscope (Leica DM6000). DARPP32-
28 depleted area in the striatum was manually segmented with Image J on each serial section, and
29 the total volume calculated with the Cavalieri method.

1 To quantify astrocyte soma area and STAT3 immunoreactivity, stacked confocal images of
2 GFP and STAT3 immunostained sections were acquired with a 40× objective (three brain
3 sections per mouse, three fields per section, 10 to 16 z-steps of 1 μm, maximum intensity stack).
4 GFP⁺ cell bodies were manually segmented and their individual area and mean grey value for
5 STAT3 were measured with Image J.

6 The total number and surface of EM48⁺ and Ubiquitin⁺ aggregates were quantified on serial
7 striatal sections along the antero-posterior axis, scanned with an Axio scanZ.1 (Zeiss,
8 Oberkochen, Germany) at the 40× objective in bright field microscopy mode, with multi-plan
9 focusing. Aggregates were automatically detected by the Morphostrider software (ExploraNova),
10 with intensity, size and shape thresholds, after manual segmentation of the striatum on each
11 section. The total number of aggregates within each striatum was then calculated. To quantify the
12 distribution of EM48⁺ aggregates in DARPP32⁺ neurons and GFP⁺ astrocytes, stacked confocal
13 images (16 z-steps of 1 μm, maximum intensity stack) were acquired on a Leica TCS SP8
14 confocal fluorescent microscope with a 40x objective (three brain sections per mouse, three
15 fields per section). Aggregates were automatically detected with ImageJ software, with intensity,
16 size and shape thresholds. Laser intensity, detection settings and analysis parameters were
17 identical between each mouse of the same cohort. The number of aggregates in each cell type
18 and the total number were manually quantified using ImageJ cell counter plugin.

19 **Quantification of cathepsin and proteasome activities in astrocytes**

20 Hdh140 mice previously injected with astrocyte-specific AAV-GFP or AAV-Td-Tomato in
21 the striatum to label astrocytes, were perfused with cold PBS for 4 min. Their striata were rapidly
22 collected in Hank's Balanced Salt Solution (HBSS; Sigma). Cells were mechanically and
23 enzymatically dissociated with fire-polished Pasteur pipettes and the neural tissue dissociation
24 kit with papain (Miltenyi Biotec, Bergisch Gladbach, Germany), following manufacturer's
25 instructions. After filtration through a 50 μm-filter, myelin removal beads II and MS columns
26 (Miltenyi Biotec) were used to deplete myelin from cell suspensions. Cells were then
27 resuspended in 0.5% PNB buffer (Perkin Elmer, FP1020) and incubated for 30 min with 1 μM
28 fluorescent cathepsin probe (iABP, Vergent Bioscience, Minneapolis, MN, #40200) or with 200
29 nM proteasome probe (UbiQ, Bio BV, Amsterdam, the Netherlands, #UbiQ-018) at RT. Cells
30 were centrifuged at 300 g for 5 min at 4°C and resuspended in 400 μl HBSS. They were sorted

1 on a BD Influx cell sorter. GFP expressed by infected astrocytes was detected at 530/40 nm (488
2 nm excitation) and the cathepsin probe was detected at 670/30 nm (646 nm excitation). Td-
3 Tomato expressed by infected astrocytes was detected at 579/34 nm (561 nm excitation) and the
4 proteasome probe at 530/40 nm (488 nm excitation). Control samples of unlabelled or mono-
5 fluorescent brain cells were used to define detector gains and sorting gates, which were kept
6 constant for all samples. No compensation was required to accurately quantify the two
7 fluorescent signals within the same cell. Cells were gated on a side scatter/ forward scatter plot,
8 then singlets were selected and finally the percentage of GFP⁺/Cathepsin⁺ or Td-
9 Tomato⁺/Proteasome⁺ astrocytes was quantified in each mouse, after setting the gates on GFP⁺ or
10 Td-Tomato⁺ astrocytes incubated without a probe (i.e. “Fluorescence Minus One” controls,
11 **Supplementary Fig. 1B**).

12 **Statistics**

13 Values for individual samples are shown on graphs. Arithmetic means are represented by a
14 horizontal line and paired samples from two groups are connected by a line. Sample size was
15 chosen based on prior experience to yield adequate power to detect specific effects. Mice of the
16 appropriate genotype were randomly allocated to experimental groups and processed
17 alternatively. Statistical analysis was performed with Statistica software (StatSoft, Tulsa, OK)
18 and graphs were prepared with GraphPad Prism 7 (La Jolla, CA). Paired or unpaired two-tailed
19 Student *t*-test were used to compare two groups, or two-way ANOVA to compare four groups.
20 Normality of residues and homoscedasticity were assessed. If any condition of application was
21 not fulfilled, we used non-parametric tests: two groups were compared by the Mann-Whitney or
22 Wilcoxon matched-pair tests. Percentages were first changed to proportions and transformed by
23 the *arcsine* function, before being analysed by paired or unpaired *t*-test.

24 Investigators were partially blinded to the group when performing experiments and analysis,
25 as the group can be deduced by the presence of aggregates or GFP levels for example. The
26 significance level was set at $p < 0.05$. In each figure legend, N refers to the number of mice.

27 **Data availability**

28 Microarray datasets are deposited on GEO under reference GSE107486. RNAseq datasets are
29 deposited on GEO under reference GSE171141.

1 Detailed protocols for stereotactic injections, immunohistology, protein extraction, exosome
2 isolation, immunoblot, RNA extraction and RT-qPCR, microarray, RNAseq analysis and
3 identification of transcription factors as well as magnetic resonance imaging are provided as
4 **Supplementary material.**

5 **Results**

6 **STAT3 activation in reactive astrocytes in Huntington's disease patients**

7 STAT3 is involved in the control of reactive astrocytes in multiple CNS diseases and
8 corresponding animal models²¹, but it has never been studied in the brain of Huntington's disease
9 patients. As the active tyrosine-phosphorylated epitope on STAT3 is poorly preserved in such
10 post-mortem samples, increased nuclear accumulation of total STAT3 is used as a surrogate of
11 its activation²¹. We performed STAT3 immunostainings in the putamen of Huntington's disease
12 patients (Vonsattel grade III⁶) and their age- and sex-matched controls. There was a stronger
13 STAT3 immunoreactivity in Huntington's disease patients (**Fig. 1A, B**), especially in regions
14 showing neurodegeneration, as seen by their lower density in NeuN⁺ neurons and higher density
15 in hypertrophic GFAP⁺ astrocytes (**Fig. 1C**). Many STAT3⁺ cells had a typical astrocyte
16 morphology and displayed nuclear accumulation of this transcription factor (**Fig. 1B, C**), an
17 indication of pathway activation.

18 We also analysed available transcriptomic data of nuclei isolated from the cingulate cortex of
19 grade III/IV Huntington's disease patients⁵ to identify potential active transcription factors in
20 Huntington's disease astrocytes. Several bioinformatics tools (based on literature mining or DNA
21 motif recognition in the promoter of differentially expressed genes, see Methods) identified
22 STAT3 as a potential regulatory transcription factor in Huntington's disease astrocytes, with
23 significant associated *p* values (**Supplementary table 1**).

24 Together, these results support a role for STAT3 in driving astrocyte reactive changes in
25 Huntington's disease.

26 **Astrocytic JAK2-STAT3 pathway reduces neuronal mHTT aggregation in two**
27 **mouse models of Huntington's disease**

1 To determine the molecular and functional regulation operated by STAT3 in Huntington's
2 disease reactive astrocytes, we took advantage of our viral vectors that transduce striatal
3 astrocytes with high efficiency and selectivity (**Supplementary Fig. 1A**), to either activate or
4 inhibit the JAK2-STAT3 pathway^{39, 40}.

5 We first studied knock-in Hdh140 mice that express a humanized *HTT* gene with 140 CAG
6 repeats under its own endogenous promoter³⁵. These mice develop progressive Huntington's
7 disease symptoms with small intra-neuronal mHTT aggregates, early transcriptional defects in
8 neurons, but very mild morphological and molecular reactive changes in astrocytes^{20, 43}. In this
9 model, we thus stimulated the JAK2-STAT3 pathway in striatal astrocytes by virus-mediated
10 expression of a constitutively active form of JAK2 (JAK2ca).

11 A lentiviral vector targeting astrocytes and encoding JAK2ca (LV_A-JAK2ca) was injected in
12 7-9 month-old heterozygous Hdh140 mice, with a LV_A encoding GFP (LV_A-GFP) to visualize
13 infected astrocytes (Hdh140-JAK2ca mice, **Fig. 2A**). Controls were Hdh140 mice injected with
14 LV_A-GFP at the same total viral titer (Hdh140-GFP mice), and brains from both groups were
15 analysed 4 months later (**Fig. 2A**). Immunostaining on mouse brain sections showed that JAK2ca
16 activated STAT3 (**Fig. 2B**) and induced the two cardinal features of reactive astrocytes:
17 overexpression of the intermediate filaments GFAP (**Fig. 2B, C**) and soma hypertrophy (**Fig. 2B,**
18 **D**). JAK2ca also increased mRNA levels of *Vimentin* and *Serpina3n*, two markers of reactive
19 astrocytes (**Fig. 2E, F**). We controlled that JAK2ca did not impact total mRNA levels of murine
20 *Htt* and *mHTT*, which were expressed at similar levels in Hdh140-JAK2ca and Hdh140-GFP
21 groups (Student *t*-test, $n = 3-4/\text{group}$, $df = 5$, $t = 1.367$, $p = 0.230$ and $t = 1.276$, $p = 0.258$
22 respectively, data not shown).

23 JAK2ca expression in Hdh140 astrocytes significantly reduced the total number of mHTT
24 aggregates in the striatum (**Fig. 2G, H**). The size of EM48⁺ aggregates was also significantly
25 decreased in Hdh140-JAK2ca mice (**Fig. 2I**). Most EM48⁺ aggregates were in small neuronal
26 processes, while more than 30% of them were found in the nucleus or cell body of striatal
27 neurons expressing dopamine- and cAMP-regulated neuronal phosphoprotein (DARPP32), and
28 less than 1% of all mHTT aggregates were found in GFP⁺ astrocytes (**Fig. 2J, K**). Despite the
29 marked reduction in the number of mHTT aggregates, this relative distribution was not
30 significantly impacted by JAK2ca (Student *t*-test on *arcsine*-transformed data, $n = 3-4/\text{group}$, df

1 = 5, $t = 1.983$, $p = 0.104$ for DARPP32⁺ neurons, $t = 0.517$, $p = 0.627$ for GFP⁺ astrocytes, **Fig.**
2 **2K**).

3 To determine whether soluble mHTT was also reduced by JAK2ca, we analysed Triton X-100
4 (Tx)-soluble protein extracts prepared from the striatum of WT and Hdh140 mice injected with
5 LV_A-GFP or LV_A-JAK2ca. Immunoblotting with the 1C2 antibody that recognizes preferentially
6 the elongated polyglutamine stretch of mHTT⁴⁴ showed similar Tx-soluble mHTT levels in both
7 groups (**Fig. 2L, M**). We then immunoblotted proteins from the Tx-insoluble, SDS-soluble
8 fraction with the 2B4 antibody, which preferentially binds to the N-terminal part of mHTT⁴⁵.
9 High molecular weight forms of mHTT corresponding to aggregated fragments of mHTT were
10 detected only in samples from Hdh140 mice. The levels of high molecular weight aggregated
11 mHTT were lower in the Hdh140-JAK2ca group, in accordance with histological data of reduced
12 mHTT aggregation with JAK2ca (**Fig. 2N, O**).

13 We then took advantage of another lentiviral mouse model of Huntington's disease that better
14 replicates the strong neurodegeneration and subsequent astrocyte reactivity observed in patients⁸.
15 ²². This model involves lentivirus-mediated expression of the 171 first amino acids of human
16 HTT with 82 CAG repeats specifically in striatal neurons^{8, 41} (**Fig. 3A**). In this model, we
17 performed the inverse manipulation of the JAK2-STAT3 pathway in astrocytes, by blocking it
18 with its inhibitor Suppressor Of Cytokine Signalling 3 (SOCS3). SOCS3 efficiently blocked
19 STAT3 activation and reactive changes in astrocytes (**Fig. 3B-F**)²². Moreover, SOCS3
20 expression in striatal astrocytes increased the aggregation of mHTT in neurons, as seen with
21 EM48 immunostaining (**Fig. 3G, H**). Less than 2% of mHTT aggregates were found in GFP⁺
22 astrocytes (**Fig. 3H**), and this distribution was not changed by SOCS3 (Student *t*-test on *arcsine*-
23 transformed data, $n = 6/\text{group}$, $df = 5$, $t = 0.917$, $p = 0.401$). mHTT aggregates are ubiquitinated
24 and the total number of Ubiquitin (Ub)⁺ aggregates was also increased by SOCS3 (**Fig. 3I, J**). In
25 addition, aggregates were larger in the SOCS3 group than in the GFP group (**Fig. 3K**), revealing
26 both quantitative and qualitative changes in neuronal mHTT aggregates following JAK2-STAT3
27 inhibition in astrocytes.

28 **Activation of JAK2-STAT3 pathway in astrocytes is beneficial for striatal neurons**

29 We next evaluated how JAK2-STAT3 pathway activation in astrocytes impacted several

1 disease outcomes. Hdh140 mice do not show the massive striatal neurodegeneration typical of
2 Huntington's disease patients, but they replicate the early transcriptional defects in striatal
3 neurons, in particular for *Ppp1r1b* transcripts (which encode the striatal protein DARPP32). In
4 Hdh140 mice, JAK2ca expression in striatal astrocytes significantly increased levels of the
5 neuronal transcript *Ppp1r1b* (**Fig. 4A**), suggesting a beneficial effect on neurons. To further
6 demonstrate JAK2ca beneficial effects on clinically-relevant pathological outcomes, we next
7 performed magnetic resonance imaging. Eighteen month-old heterozygous Hdh140 mice display
8 significant striatal atrophy⁴⁶, likely due to the atrophy of striatal neurons themselves⁴⁷, and not to
9 their death, as neuronal loss was described only in older homozygous Hdh140 mice⁴³. Striatal
10 volume can be measured accurately with T₂-weighted magnetic resonance imaging⁴⁸, and striatal
11 atrophy is observed at prodromal stages in Huntington's disease patients⁴⁹. Hdh140 mice also
12 display lower striatal levels of the major neurotransmitter and metabolic intermediate
13 glutamate⁴⁸, again replicating an early pathological hallmark of Huntington's disease patients⁵⁰.
14 Brain glutamate distribution can be mapped with a high resolution using glutamate Chemical
15 Exchange Saturation Transfer (gluCEST)⁵¹, revealing local reduction in glutamate abundance in
16 Hdh140 mice⁵². Hdh140 mice were injected in one striatum with LV_A-JAK2ca + LV_A-GFP and
17 the other striatum with LV_A-GFP as an internal control, and imaged 2 months later. The volume
18 of the striatum injected with LV_A-JAK2ca was significantly larger than the contralateral striatum
19 injected with LV_A-GFP (**Fig. 4B**), showing reduced atrophy with JAK2ca. Likewise, gluCEST
20 imaging revealed significantly higher striatal levels of glutamate with JAK2ca (**Fig. 4C**), further
21 supporting beneficial effects of JAK2-mediated astrocyte reactivity on two pathological
22 hallmarks of Huntington's disease.

23 In the lentiviral model, mHTT causes local neuronal degeneration, visible as DARPP32-
24 depleted lesion (**Fig. 4D**). SOCS3 significantly increased the lesion volume (**Fig. 4E**), and
25 reduced *Ppp1r1b* mRNA levels (**Fig. 4F**).

26 Overall, our data show that activation of the JAK2-STAT3 pathway in reactive astrocytes
27 reduces the number and size of mHTT aggregates in neurons and mitigates Huntington's disease
28 neuronal alterations; while blocking the pathway has opposite effects.

29 **JAK2ca regulates the expression of proteostasis genes in astrocytes**

30 How can JAK2-STAT3 pathway activation in reactive astrocytes impact mHTT aggregation

1 in neurons? As the JAK2-STAT3 cascade regulates gene expression, we investigated
2 transcriptional changes induced by JAK2ca by comparing the transcriptome of acutely sorted
3 astrocytes isolated from WT-JAK2ca and WT-GFP control mice by microarray (**Fig. 5A**).
4 Transduced astrocytes were collected by fluorescence-activated cell sorting (FACS) based on
5 their GFP expression. GFP⁻ cells, comprising microglia, neurons, oligodendrocyte precursor cells
6 (OPC), oligodendrocytes and few non-infected astrocytes, were collected together. There were
7 1,415 differentially expressed transcripts (fold change > 1.5, $p < 0.05$), between GFP⁺ and GFP⁻
8 cell samples in control WT-GFP mice (**Fig. 5B**). Besides *eGfp*, many known astrocyte gene
9 markers were enriched in GFP⁺ cells (e.g. *AldoC*, *Aqp4*, *Gjal*, *Gjb6*, *Slc1a2*, *Slc1a3*).
10 Conversely, known markers for microglial cells, neurons, OPC, oligodendrocytes were enriched
11 in GFP⁻ cells (e.g. *Aif*, *Trem2*, *P2ry12*, *Pde10a*, *Snap25*, *Pdgfra*, *Myt1*). The sorting procedure
12 being validated, we next compared the gene expression profile of GFP⁺ astrocytes isolated from
13 WT-GFP and WT-JAK2ca mice.

14 Astrocyte samples from these two groups clustered separately by principal component
15 analysis (**Fig. 5C**). We found 888 probes (802 unique transcripts) differentially expressed
16 between JAK2ca-astrocytes and control GFP-astrocytes, including *Jak2* mRNA itself
17 (**Supplementary Fig. 2F**). A Gene Ontology (GO) analysis revealed a significant enrichment in
18 many GO-biological processes linked to immunity and inflammation, confirming that JAK2ca
19 triggers reactive changes in astrocytes, which were also evidenced by morphological changes
20 (**Supplementary Fig. 2A-H**)³⁹.

21 Among the differentially expressed genes between GFP- and JAK2ca-astrocytes, there was a
22 specific enrichment in biological processes linked to lysosomes and UPS, as well as other
23 processes related to proteostasis (**Fig. 5D**). KEGG pathway analysis also revealed a significant
24 enrichment in the term “lysosome” in JAK2ca-reactive astrocytes ($p = 0.0005$). Several
25 cathepsins (*Ctsc*, *Ctss* and *Ctsz*) were upregulated by JAK2ca in astrocytes (**Fig. 5D**). Genes
26 linked to proteostasis formed a complex network of co-regulated genes in JAK2ca-astrocytes
27 (**Fig. 5D**).

28 To confirm that the JAK2-STAT3 pathway was also able to induce a proteostasis gene signature
29 in astrocytes in a Huntington’s disease context, we sorted striatal astrocytes from Hdh140-GFP
30 and Hdh140-JAK2ca mice based on their GFP expression, and performed RNAseq analysis (**Fig.**

1 **5E**). Again, sorted astrocytes expressed high levels of astrocyte-specific genes and low or
2 undetectable levels of known markers for microglia, neurons, cells of the oligodendrocyte
3 lineage and endothelial cells (**Supplementary Fig. 2I**). Principal component analysis showed
4 that astrocytes from Hdh140-GFP and Hdh140-JAK2ca mice formed two distinct clusters (**Fig.**
5 **5F**). We found 269 genes differentially expressed between Hdh140-GFP and Hdh140-JAK2ca
6 astrocytes. *Jak2* levels were significantly higher in JAK2ca-astrocytes than GFP-astrocytes
7 (**Supplementary Fig. 2J**). Murine *Htt*, on the contrary, was expressed at low levels in sorted
8 astrocytes from both groups (rpkm value = 1.859 and 2.120 for GFP- and JAK2ca-astrocytes;
9 adjusted *p*-value = 0.999), showing that JAK2ca does not change *Htt* transcription in striatal
10 astrocytes. Among the 269 differentially expressed genes in Hdh140-JAK2ca astrocytes, 212
11 genes were present in the full list of 30,845 unique probes detected by microarray analysis of
12 WT striatal astrocytes (i.e. striatal astrocyte transcriptome). And among these 212 genes, only 20
13 (10%) were also differentially expressed in WT-JAK2ca astrocytes compared to WT-GFP
14 astrocytes. However there was a significant convergence on the functions of the differentially
15 expressed genes between the two studies. In particular, many of the differentially expressed
16 genes in Hdh-140-JAK2ca astrocytes were linked to immunity/inflammation, as found in WT-
17 JAK2ca astrocytes (**Supplementary Fig. 2E**). Likewise, as in WT-JAK2ca astrocytes, there was
18 a significant enrichment in GO pathways related to proteostasis, including the molecular function
19 “Heat shock protein binding” and the cellular components “lytic vacuole” and “lysosome” (**Fig.**
20 **5G**). Gene Set Enrichment Annotation (GSEA) also identified the term “phagosome”, as
21 significantly enriched in Hdh140-JAK2ca astrocytes, with a majority of up-regulated genes
22 (normalized enrichment score = 1.759, adjusted *p* value = 0.039). Globally, we found that 53%
23 of GO molecular functions, 71% of GO cellular components and 67% of GO biological
24 processes were shared between Hdh140-JAK2ca astrocytes and WT-JAK2ca astrocytes (**Fig.**
25 **5H**).

26 Overall, this transcriptomic analysis shows that JAK2ca induces a specific proteostasis gene
27 signature in striatal astrocytes both in WT and Hdh140 mice.

28 **JAK2ca increases proteolytic capacity in Huntington’s disease astrocytes**

29 It is important to establish that the identified transcriptional changes translate into detectable
30 changes in astrocyte function⁵³. To assess proteolytic activity of the two major clearance

1 pathways specifically in astrocytes of Huntington's disease mice, we used cell-permeable,
2 activity probes for the lysosomal enzymes cathepsins and for the proteasome (**Supplementary**
3 **Fig. 1B**).

4 We incubated acutely dissociated striatal cells from Hdh140-GFP and Hdh140-JAK2ca mice
5 in a pan-cathepsin activity probe that becomes fluorescent when metabolized by cathepsins⁵⁴.
6 We then measured probe fluorescence in GFP⁺ astrocytes from the two groups by FACS (**Fig.**
7 **6A**). There was a significantly larger fraction of GFP⁺ astrocytes with high cathepsin activity in
8 Hdh140-JAK2ca mice (**Fig. 6B**), revealing that JAK2ca increases lysosomal activity in
9 astrocytes.

10 Another fluorescent probe was used to measure proteasome activity in acutely dissociated
11 astrocytes (**Fig. 6C**)⁵⁵. As the excitation/emission spectrum of this probe overlaps with GFP, we
12 used a viral vector encoding the red fluorescent protein Td-Tomato instead of GFP to detect
13 astrocytes in both groups. Again, the fraction of Td-Tomato⁺ astrocytes with high proteasome
14 activity was larger in Hdh140-JAK2ca mice than in Hdh140-Td-Tomato mice (**Fig. 6C**),
15 showing that reactive astrocytes also have a higher proteasome activity.

16 As several ubiquitin ligases were differentially expressed in JAK2ca-astrocytes (**Fig. 5D**), we
17 assessed ubiquitination by immunoblotting striatal homogenates with a Ub antibody. We did not
18 observe major changes in the pattern of Ub immunoreactivity or in total Ub levels between
19 Hdh140-GFP and Hdh140-JAK2ca mice, both in Tx- and SDS-soluble fractions (**Fig. 6D, E**),
20 suggesting that only the proteolytic step of the UPS is stimulated by JAK2ca, without global
21 changes in the ubiquitination profile of mouse striatum.

22 To directly measure the intrinsic capacity of astrocytes to clear mHTT, we used viral vectors
23 to force mHTT expression in astrocytes (LV_A-mHTT). WT mice were injected in the right
24 striatum with LV_A-mHTT, LV_A-SOCS3, and LV_A-GFP, and in the control left striatum with
25 LV_A-mHTT and LV_A-GFP, at the same total viral titer (**Fig. 6F**). Expression of mHTT in
26 astrocytes also triggered STAT3 activation, as evidenced by its nuclear accumulation, and
27 induced reactive changes in astrocytes (**Fig. 6G**)⁸. In this model as well, SOCS3 efficiently
28 reduced GFAP levels (**Fig. 6G, H**), STAT3 nuclear accumulation (**Fig. 6G, I**) and astrocyte
29 soma hypertrophy (**Fig. 6G, J**). If the JAK2-STAT3 pathway enhances proteolytic activity in

1 astrocytes, we reasoned that blocking this pathway with SOCS3 would increase mHTT
2 aggregation in astrocytes. Indeed, we observed that the total number of mHTT aggregates in the
3 striatum was increased with SOCS3 (**Fig. 6K, L**). Moreover, SOCS3 increased mHTT aggregate
4 size (**Fig. 6K, M**). In this model, mHTT forms both nuclear and cytoplasmic inclusions in
5 astrocytes (**Fig. 6K**). The fraction of nuclear aggregates in GFP⁺ astrocytes was not changed by
6 SOCS3 (19.1% and 22.0% respectively in GFP and SOCS3 groups, Student *t*-test on *arcsine*-
7 transformed data, $n = 6/\text{group}$, $df = 5$, $t = 0.787$, $p = 0.458$). These results show that the JAK2-
8 STAT3 pathway stimulates astrocyte intrinsic capacity for mHTT clearance.

9 **JAK2ca induces chaperone expression in astrocytes**

10 Interestingly, several GO-molecular functions linked to chaperones and protein folding were
11 significantly regulated by JAK2ca both in WT and Hdh140 astrocytes (**Fig. 5D, G**). Chaperones
12 prevent mHTT aggregation^{32, 56} and can be released extracellularly in exosomes⁵⁷.

13 We focused on the co-chaperone DNAJB1 [DnaJ heat shock protein family (Hsp40) member
14 B1], a member of the HSP40 family, which is induced nearly 3-fold by JAK2ca in WT astrocytes
15 (**Fig. 5D**). DNAJB1 immunoreactivity was higher in the putamen of Huntington's disease
16 patients, specifically at the core of the degenerative area devoid of NeuN⁺ neurons and with
17 abundant hypertrophic GFAP⁺ astrocytes (**Fig. 7A**).

18 JAK2ca significantly increased DNAJB1 protein levels in the striatum of Hdh140 mice as
19 seen by immunostaining (**Fig. 7B, D**) and immunoblotting (**Fig. 7C**), while *Dnajb1* mRNA
20 levels were significantly reduced by SOCS3 in the lentiviral model of Huntington's disease (**Fig.**
21 **7E**). In Hdh140 mice, DNAJB1 displayed a diffuse cytosolic staining but also formed small
22 nuclear inclusion-like structures, suggesting that DNJAB1 can be in close association with
23 mHTT aggregates (**Fig. 7D**).

24 We next studied whether DNAJB1 was found in exosomes and whether DNAJB1 exosomal
25 content was impacted by JAK2-STAT3 activation in Hdh140 mice. Exosomal vesicles were
26 isolated by biochemical fractionation from the striatum of Hdh140-GFP and Hdh140-JAK2ca
27 mice, and they did contain DNAJB1 (**Supplementary Fig. 1C**). DNAJB1 normalized levels
28 displayed a strong tendency to be higher in exosomes of Hdh140-JAK2ca mice than in Hdh140-
29 GFP control mice ($p = 0.056$, **Fig. 7F**).

1 To assess whether DNAJB1 released by JAK2ca-astrocytes contributes to reduce mHTT
2 aggregation in neurons, we generated viral vectors targeting astrocytes and encoding a dominant-
3 negative form of human *DNAJB1* (DNAJB1-DN), which prevents DNAJB1 interaction with the
4 HSP70 chaperone⁴², without impacting its loading into exosomes⁵⁷. DNAJB1-DN was expressed
5 in astrocytes in Hdh140-JAK2ca and Hdh140-GFP mice (**Fig. 8A**). DNAJB1-DN, detected by its
6 V5 tag, was confirmed to be expressed in striatal GFP⁺ astrocytes, throughout their cell body and
7 fine processes (**Fig. 8B**). Interestingly, small V5⁺ cytoplasmic vesicles were also observed
8 (although rarely) in nearby DARPP32⁺ neurons (**Fig. 8C**). Some vesicles were co-labelled with
9 the endo-lysosomal marker LAMP1 (**Supplementary Fig. 1D**), suggesting that DNAJB1 can
10 indeed be shuttled from astrocytes to neurons through exosomes. JAK2ca was still able to
11 increase GFAP levels in Hdh140 astrocytes in presence of DNAJB1-DN (**Fig. 8D**). However, co-
12 expression of DNAJB1-DN blocked JAK2ca-mediated reduction of EM48⁺ aggregate numbers
13 (**Fig. 8E**) and even decreased *Ppp1r1b* mRNA levels (**Fig. 8F**).

14 Conversely, we tested whether DNAJB1 restoration was able to oppose SOCS3 detrimental
15 effects in the lentiviral model of mHTT overexpression. In the striatum of WT mice, we injected
16 a viral vector targeting astrocytes and encoding a full length human *DNAJB1* (LV_A-DNAJB1)
17 with LV_A-SOCS3 or LV_A-GFP together with LV_N-mHTT (**Fig. 8G**). DNAJB1 did not interfere
18 with SOCS3-mediated reduction of GFAP levels in Huntington's disease astrocytes (**Fig. 8H**).
19 However, when DNAJB1 was expressed in astrocytes, SOCS3 no longer exacerbated mHTT
20 aggregation (**Fig. 8I**), neuronal lesion (**Fig. 8J**), or reduced *Ppp1r1b* mRNA levels (**Fig. 8K**),
21 suggesting that DNAJB1 expression in astrocytes counteracts SOCS3 deleterious effects.

22 Our results suggest that the co-chaperone DNAJB1 produced by JAK2-STAT3 reactive
23 astrocytes helps reduce mHTT aggregation and neuronal alterations in Huntington's disease.

24 **Discussion**

25 *We studied how the JAK2-STAT3 pathway shapes the proteostasis response of reactive*
26 *astrocytes in Huntington's disease. We found that STAT3 is activated in reactive astrocytes of*
27 *Huntington's disease patients. Thanks to two complementary mouse models of Huntington's*
28 *disease allowing the selective and reciprocal manipulation of the JAK2-STAT3 pathway in*
29 *striatal astrocytes, we show that this cascade controls astrocyte reactive state and reduces both*

1 the number and size of mHTT aggregates forming in neurons.

2 The reduction of mHTT aggregation by JAK2-STAT3 pathway activation in astrocytes is not
3 due to lower mHTT expression, as *Htt* mRNA levels and Tx-soluble mHTT concentrations were
4 not reduced by JAK2ca. Importantly, JAK2ca-mediated reduction in mHTT aggregation did not
5 trigger an increase in soluble mHTT levels either. This observation rules out that JAK2ca
6 prevents mHTT from coalescing into aggregates or favours the accumulation of soluble mHTT
7 after its dissociation from aggregates. Instead, activation of the JAK2-STAT3 pathway in
8 reactive astrocytes appears to promote the full degradation of mHTT insoluble oligomers or
9 aggregates, which could be mediated by autophagy-lysosomal removal of aggregates or
10 chaperone-mediated extraction of mHTT and targeting to the UPS for complete clearance.

11 *In keeping with this, transcriptomic analysis of acutely sorted astrocytes following JAK2-*
12 *STAT3 pathway activation in WT and Huntington's disease mice reveals extensive changes in*
13 *genes linked to lysosomal degradation and the UPS. This result is in accordance with the single*
14 *nuclei RNAseq analysis of astrocytes from the cingulate cortex of grade III/IV Huntington's*
15 *disease patients, reporting a significant enrichment in proteostasis functions⁵. Lysosomes and*
16 *UPS are active in all brain cells and changes in expression or activity in astrocytes could be*
17 *masked by larger changes in other cell-types if assessed in typical bulk analyses. We thus*
18 *implemented two FACS-based assays to measure cathepsin and proteasome activity specifically*
19 *in astrocytes. We found that JAK2ca increases both proteolytic activities in Huntington's disease*
20 *astrocytes. In addition, our ability to induce mHTT expression selectively in astrocytes by viral*
21 *gene transfer provides a direct demonstration that the JAK2-STAT3 pathway increases reactive*
22 *astrocyte capacity to clear mHTT.*

23 As aggregates mainly form in neurons, trans-cellular signalling mechanisms must take place
24 between neurons and reactive astrocytes (**Fig. 8L**). Can mHTT be transferred from neurons to
25 reactive astrocytes where they would be degraded more efficiently? In a landmark study in
26 *Drosophila*, it was shown that mHTT exon 1 tagged with mCherry shuttles from neurons to
27 neighbouring phagocytic glia and forms aggregates with endogenous HTT in glia⁵⁸. Other
28 studies showed that mHTT can be exchanged between brain cells in *Drosophila*, in mice⁵⁹⁻⁶¹, and
29 even in humans as mHTT aggregates were detected in healthy embryonic neurons grafted in the
30 brain of Huntington's disease patients⁶². mHTT can be packaged in exosomes of different cell

1 types^{63, 64} and be taken up by neighbouring cells, including neurons. Exchange of mHTT may
2 also involve direct cell-to-cell contacts via tunnelling nanotubes⁶⁵ or unconventional secretory
3 pathways⁶⁶. Most studies were performed *in vitro* or in non-neuronal cells, therefore, the precise
4 mechanisms of mHTT exchange from neurons to astrocytes in the mammalian brain remain to be
5 elucidated. Of note, a recent study showed that astrocyte-specific silencing of mHTT in a genetic
6 mouse model of Huntington's disease reduces both astrocyte and neuronal mHTT aggregates²⁰,
7 further supporting the concept of a tight partnership between these two cell types to degrade
8 mHTT.

9 An alternative and non-exclusive mechanism for reduced neuronal mHTT aggregation upon
10 JAK2-STAT3 pathway activation in astrocytes, is that reactive astrocytes release proteins that
11 promote mHTT clearance within neurons (**Fig. 8L**). Our transcriptomic study shows that several
12 chaperones are induced by JAK2ca in reactive astrocytes. In particular, *DNAJB1* protein levels
13 were higher in Hdh140-JAK2ca mice and this co-chaperone was abundant in extracellular
14 exosomes, and in the lesioned striatum of Huntington's disease patients. Chaperones are known
15 to be released in exosomes and mediate trans-cellular proteostasis^{34, 57}. Moreover, exosomes
16 isolated from cultured astrocytes were shown to reduce mHTT aggregation in mice¹⁸.
17 *Interestingly, single nuclei RNaseq shows that DNAJB1, as well as other chaperones are*
18 *significantly overexpressed in astrocytes from the cingulate cortex of grade III/IV Huntington's*
19 *disease patients⁵ and the putamen of grade II/III patients⁹, showing that this beneficial*
20 *proteostasis response may also occur in astrocytes from Huntington's disease patients.*

21 Through *its J domain, DNAJB1 interacts with HSP70 to stimulate its ATP-dependent*
22 *chaperone activity⁶⁷. This domain is also implicated in DNAJB1 loading into exosomes^{42, 57}. The*
23 *J domain alone cannot activate HSP70 and has a dominant-negative action on the endogenous*
24 *DNAJB1⁴². Expression of this mutant in astrocytes abrogated JAK2ca-mediated beneficial*
25 *effects in Hdh140 mice, showing DNAJB1 involvement in JAK2ca effects. Conversely,*
26 *expression of DNAJB1 in astrocytes cancelled SOCS3 deleterious effects on neuronal death and*
27 *transcriptional defects in the lentiviral model. Small vesicles of tagged DNAJB1 were sometimes*
28 *observed in neurons nearby infected astrocytes, further supporting the shuttling of DNAJB1 from*
29 *astrocytes to neurons. Overall, our data strongly suggest that DNAJB1, produced by reactive*
30 *astrocytes following JAK2-STAT3 pathway activation, promotes mHTT clearance.*

1 DNAJB1 was shown to be the rate-limiting chaperone to suppress aggregation of a short
2 fragment of mHtt⁶⁸. Interestingly, HSPs not only prevent mHTT aggregation but can also
3 solubilize proteins trapped in aggregates like transcription factors and favour mHTT degradation
4 by addressing to the UPS or autophagy-lysosomes^{33, 69}. Of note, DNAJB1 was recently shown to
5 promote α -synuclein disaggregation⁷⁰. HSP-mediated extraction of housekeeping proteins or
6 mHTT itself from aggregates is expected to reduce their size, which is consistent with our
7 observations. Therefore, HSPs have multiple actions that can *in fine* protect neurons against
8 mHTT toxicity, as shown in different experimental systems based on HSP overexpression⁷¹⁻⁷³.
9 Here, we show that neurons rely on the endogenous production of chaperones by astrocytes to
10 reduce mHTT aggregation.

11 The toxicity of mHTT aggregates is still discussed^{24, 69, 74} and mHTT aggregates could have a
12 biphasic action⁷⁵. At early stages, they could trap soluble toxic mHTT and prevent its deleterious
13 interaction with key cellular partners. Later, mHTT aggregates could be detrimental by
14 sequestering transcription factors, housekeeping proteins or microRNAs, leading to neuronal
15 dysfunction and necrotic death^{24, 76}. It is important to note that most studies were based on *in*
16 *vitro* systems allowing time-lapse monitoring of aggregates, but which cannot fully replicate the
17 complex brain environment where neurons interact with multiple glial cells and cope with mHTT
18 for months, and even decades in patients. Here, in two complementary mouse models of
19 Huntington's disease, we report that reduced mHTT aggregation is associated with improved
20 neuronal features, showing that the JAK2-STAT3 pathway shapes a beneficial reactive response
21 in striatal astrocytes. Thanks to sensitive magnetic resonance imaging approaches, we also
22 demonstrate that this pathway reduces striatal atrophy and increases glutamate levels, which are
23 two clinically-relevant disease hallmarks, observed at early stage in patients^{49, 50}. Interestingly,
24 we found that the JAK2-STAT3 pathway is still able to activate a protective proteostatic program
25 in Huntington's disease astrocytes. However, the endogenous activation of the JAK2-STAT3
26 pathway observed in striatal astrocytes from patients seems to be an insufficient protective
27 response to fully prevent neurodegeneration. Early and widespread stimulation of this astrocytic
28 pathway could enhance neuronal resilience in patients.

29 In conclusion, we show that the JAK2-STAT3 pathway activates a beneficial proteostasis
30 program in reactive astrocytes, which helps striatal neurons handle toxic mHTT. Our study

1 uncovers two non-mutually exclusive, bi-cellular mechanisms to reduce mHTT aggregation in
2 neurons in Huntington's disease (**Fig. 8L**). The first mechanism relies on mHTT exit from
3 neurons and clearance within reactive astrocytes and the second involves the release of
4 chaperones from reactive astrocytes to promote neuronal proteostasis. Astrocytes are not only
5 defective in Huntington's disease as usually reported, they may also acquire enhanced capacities
6 to promote mHTT clearance and neuronal functions, following activation of specific signalling
7 cascades. Our results open new therapeutic avenues to further enhance the natural partnership
8 between reactive astrocytes and vulnerable neurons in Huntington's disease.

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4 **Competing interests**

5 The authors declare no competing interests.

6 ***Author contribution***

7 LA, CE: conception; LA, LBH, MACS, CE: design of the work; LA, LBH, PG, MACS, CD,
8 MAP, FP, ASH, MG, MGG, GA, MK, JF: acquisition of data; LA, LBH, MRP, PG, NS, CH,
9 NR, PdlG, JF, RO: analysis of data; LA, LBH, MRP, JF, EBo, SB, RO, EBr, MACS, CE:
10 interpretation of data; MCG, ND, RM, APB, GB: Provided reagents or materials; JFD, PH, EBr,
11 CE: Provided funding; LA, CE: manuscript writing. All authors revised and approved the
12 manuscript.

13 **Supplementary material**

14 Supplementary material is available at *Brain* online.

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- 23

1 **Figure legends**

2 **Figure 1. STAT3 nuclear accumulation in the putamen of Huntington's disease patients**

3 STAT3 immunoreactivity is higher in the putamen of Huntington's disease patients (**B, C**) than
 4 in control subjects (**A**), especially in regions displaying many hypertrophic GFAP⁺ astrocytes,
 5 and major neurodegeneration, as seen with the loss NeuN staining (**C**). STAT3 is often found
 6 accumulated in the nucleus of cells with a typical astrocyte morphology (arrows and high
 7 magnification in **B** and **C**). Representative images from 4 subjects/group.

8 **Figure 2. JAK2ca induces astrocyte reactivity and reduces neuronal mHTT aggregation in** 9 **Hdh140 mice**

10 **A.** Hdh140 mice (7-9 month-old) were injected in the striatum with LV_A-GFP or LV_A-JAK2ca +
 11 LV_A-GFP, at the same total virus load, and their brains analysed 4 months later. **B.** Low
 12 magnification images (left) show the GFP⁺ transduced area (outlined, green) and GFAP staining
 13 (magenta) in the striatum of Hdh140-GFP and Hdh140-JAK2ca mice. High magnification
 14 images (right) of astrocytes stained for GFP (green), GFAP (magenta), and STAT3 (cyan).
 15 JAK2ca triggers STAT3 activation, as seen by its nuclear accumulation, increases GFAP and
 16 vimentin levels and induces morphological changes in astrocytes. Note that the basal expression
 17 of GFAP is nearly undetectable in Hdh140 mice, suggesting very mild reactive changes in this
 18 model. **C, D.** GFAP⁺ volume (**C**) and soma area of GFP⁺ astrocytes (**D**) are significantly
 19 increased by JAK2ca. Student *t*-test. *n* = 3-5/group, *df* = 5, **C**: *t* = 8.081, *p* = 0.0005; **D**: *t* = 4.703,
 20 *p* = 0.0053. **E, F.** JAK2ca increases *Vimentin* (**E**) and *Serpina3n* (**F**) mRNA levels. Student *t*-
 21 test. *n* = 3-5/group, *df* = 5, **E**: *t* = 2.917, *p* = 0.0331; **F**: *t* = 3.748, *p* = 0.0133. **G.** Bright field
 22 images of EM48⁺ aggregates in the striatum of Hdh140-GFP and Hdh140-JAK2ca mice. The
 23 striatal region displaying EM48⁺ aggregates is outlined on low magnification images. **H, I.** Total
 24 number (**H**) and size (**I**) of EM48⁺ aggregates are significantly decreased by JAK2ca in the
 25 striatum of Hdh140 mice. Student *t*-test. *n* = 3-5/group, *df* = 5, **H**: *t* = 6.606, *p* = 0.0012; **I**: *t* =
 26 3.142, *p* = 0.0256. **J.** Confocal images of striatal sections stained for GFP (green), EM48 (white)
 27 and DARPP32 (magenta). EM48⁺ aggregates are mostly found in neurons labelled with
 28 DARPP32 (arrowhead) and very rarely in GFP⁺ astrocytes (green, arrow). **K.** JAK2ca decreases
 29 the total number of EM48⁺ aggregates, but the distribution of EM48⁺ aggregates between GFP⁺
 30 astrocytes and DARPP32⁺ neurons is not changed. **L, M.** Immunoblotting on the Tx-soluble

1 fraction of mHTT with the 1C2 antibody. Similar levels of mHTT are detected in Hdh140-GFP
2 and Hdh140-JAK2ca mice, while mHTT is undetectable in WT mice. There is no mHTT
3 cleavage fragments detected by this antibody in both Hdh140-GFP and Hdh140-JAK2ca mice.
4 Paired *t*-test, $n = 5$, $df = 4$, $t = 1.845$ $p = 0.139$. **N, O.** Immunoblotting on the SDS-soluble
5 fraction of high molecular weight species (HMW) of mHTT with the 2B4 antibody. JAK2ca
6 decreases the levels of insoluble HMW mHTT species in Hdh140 mice. Band intensity was
7 normalized to actin. Paired *t*-test. $n = 5/\text{group}$, $df = 4$, $t = 3.367$, $p = 0.0281$.

8 **Figure 3. SOCS3-inhibition of the JAK2-STAT3 pathway in astrocytes increases the** 9 **number and size of neuronal mHTT aggregates**

10 **A.** Two month-old WT mice were injected with $\text{LV}_N\text{-mHTT} + \text{LV}_A\text{-GFP}$ in one striatum and
11 with $\text{LV}_N\text{-mHTT} + \text{LV}_A\text{-SOCS3} + \text{LV}_A\text{-GFP}$ in the contralateral striatum, at the same total virus
12 load. Their brains were analysed 6 weeks later. **B.** Low magnification images show the
13 transduced GFP^+ area (green, outlined) in the striatum and immunostaining for GFAP (magenta).
14 **C.** High magnification confocal images of astrocytes stained for GFP (green), GFAP (magenta)
15 and STAT3 (cyan). **D-F.** Immunoreactivity for GFAP (**D**) and STAT3 (**E**), as well as astrocyte
16 soma area (**F**) are significantly decreased by SOCS3. Paired *t*-test. $n = 5\text{-}6/\text{group}$, **D:** $df = 5$, $t =$
17 4.349 , $p = 0.0074$; **E:** $df = 4$, $t = 8.651$, $p = 0.0010$; **F:** $df = 4$, $t = 2.961$, $p = 0.0415$. **G.** The
18 striatal volume with EM48^+ aggregates is significantly increased by SOCS3. Paired *t*-test. $n =$
19 $6/\text{group}$, $df = 5$, $t = 3.096$, $p = 0.0270$. **H.** Confocal images of striatal sections stained for GFP
20 (green), EM48 (white), neurotrace (magenta) and DAPI (blue). Large EM48^+ aggregates of
21 mHTT are mostly found in neurons stained for neurotrace, occupying their entire nucleus
22 (arrowhead). Only few GFP^+ astrocytes display an EM48^+ aggregate (arrow). **I.** Immunolabeling
23 for ubiquitin (Ub) shows Ub^+ aggregates in the striatum (delimited with black dots). **J.** The
24 number of Ub^+ inclusions is significantly increased by SOCS3. Wilcoxon matched-pair test, $n =$
25 $5/\text{group}$, $p = 0.0431$. **K.** Ub^+ inclusions are larger in the striatum injected with $\text{LV}_A\text{-SOCS3}$ than
26 $\text{LV}_A\text{-GFP}$. Paired *t*-test. $n = 5/\text{group}$, $df = 4$, $t = 3.406$, $p = 0.0271$.

27

1 **Figure 4. Activation of the JAK2-STAT3 pathway in astrocytes has beneficial effects**
 2 **on striatal neurons**

3 **A.** Mice were injected as in **Fig. 2A**. Striatal *Ppp1r1b* mRNA levels are higher in Hdh140-
 4 JAK2ca mice than in Hdh140-GFP mice. Student *t*-test. $n = 3-5/\text{group}$, $df = 5$, $t = 3.028$, $p =$
 5 0.0291 . **B.** T_2 -weighed magnetic resonance images show that LV_A-JAK2ca reduces striatal
 6 atrophy in Hdh140 mice. Note the larger ventricle in the side injected with the control vector
 7 LV_A-GFP, caused by striatal atrophy (arrow). Wilcoxon matched-pair test, $p = 0.0313$. **C.**
 8 Quantification of gluCEST contrast in Hdh140 mice reveals higher glutamate levels in the
 9 striatum injected with LV_A-JAK2ca. Paired *t*-test, $n = 6$, $df = 5$, $t = 5.641$, $p = 0.0024$. Two
 10 representative mice are shown, each on a different anatomical position. Region of interest are
 11 shown with black dash on each striatum. **D-F** Mice were injected as in **Fig. 3A**. **D.** Low and high
 12 magnification images of striatal sections stained for DARPP32 (red) showing the striatal lesion
 13 caused by mHTT, appearing as a an area devoid of DARPP32+ neurons (white dotted lines). **E.**
 14 Striatal DARPP32⁻ lesions are significantly larger in the SOCS3 group. Wilcoxon matched-pair
 15 test, $n = 6/\text{group}$, $p = 0.0277$. **F.** SOCS3 decreases mRNA levels of the neuronal transcripts
 16 *Ppp1r1b* (*Darpp32*). Student *t*-test. $n = 4-5/\text{group}$, $df = 7$, $t = 3.931$, $p = 0.0057$.

17 **Figure 5. JAK2ca regulates the expression of proteostasis genes in astrocytes**

18 **A.** Two month-old WT mice were injected in the striatum with AAV-GFP or AAV-JAK2ca +
 19 AAV-GFP ($N = 4/\text{group}$), at the same total virus load. After 2 months, GFP⁺ striatal astrocytes
 20 were acutely sorted and their transcriptome analysed by microarray. **B.** Validation of astrocyte
 21 isolation. The volcano plot shows the 1,415 differentially expressed genes between GFP⁺
 22 astrocytes and GFP⁻ cells in WT-GFP mice (in green overexpressed in GFP⁺ cells; in orange,
 23 overexpressed in GFP⁻ cells). eGFP and established cell-type specific markers are shown. GFP⁺
 24 cells express typical astrocyte markers while GFP⁻ cells express markers for microglial cells,
 25 neurons, cells of the oligodendrocyte lineage and endothelial cells. **C.** Principal component
 26 analysis shows a clear segregation of the four WT-GFP and four WT-JAK2ca astrocyte samples.
 27 **D.** GO analysis on the list of JAK2ca-regulated genes in GFP⁺ astrocytes reveals a significant
 28 enrichment in several biological processes linked to autophagy/lysosome or UPS and in
 29 molecular functions linked to chaperones. Network plot with the genes involved in the selected
 30 GO pathways. $n = 4/\text{group}$. **E.** Hdh140 mice (8-10 month-old) were injected in the striatum with

1 AAV-GFP or AAV-JAK2ca + AAV-GFP, at the same total virus load. After 4 months, GFP⁺
 2 striatal astrocytes were collected and analysed by RNAseq. **F.** The five Hdh140-GFP samples
 3 cluster apart from the six Hdh140-JAK2ca astrocyte samples, on a principal component analysis
 4 graph. **G.** GO analysis reveals a significant enrichment in genes involved in molecular functions
 5 (MF), cellular components (CC) and biological processes (BP) linked to proteostasis. The x axis
 6 represents the ratio of the number of differentially expressed genes over the total number of
 7 genes belonging to a GO entry, DEG = differentially expressed genes. $n = 5-6/\text{group}$. **H.** Venn
 8 diagrams for the enriched GO molecular functions, cellular components and biological functions,
 9 from the list of differentially expressed genes in WT-JAK2ca and Hdh140-JAK2ca astrocytes.
 10 There is a majority of common terms.

11 **Figure 6. JAK2ca increases cathepsin and proteasome intrinsic activities in**
 12 **Huntington's disease striatal astrocytes**

13 **A-C.** The striatum of Hdh-JAK2ca mice and their control Hdh140-GFP or Hdh140-Td-Tomato
 14 was collected, cells dissociated and incubated with a quenched fluorescent pan-cathepsin activity
 15 probe (**B**) or a proteasome activity probe (**C**). The percentage of GFP⁺ astrocytes with cathepsin
 16 activity (**B**) or the percentage of Td-Tomato⁺ astrocytes with proteasome activity (**C**) was
 17 quantified in each mouse. Hdh140-JAK2ca mice display a higher percentage of astrocytes with
 18 cathepsin or proteasome activity. Paired *t*-test on *arcsine*-transformed data. **C:** $n = 9/\text{group}$, $df =$
 19 8 , $t = 3.183$, $p = 0.0129$. **D:** $n = 7/\text{group}$, $df = 6$, $t = 6.001$, $p = 0.0010$. **D, E.** Immunoblotting for
 20 Ub was performed on striatal Tx-soluble and SDS-soluble fractions from WT-GFP, WT-
 21 JAK2ca, Hdh140-GFP and Hdh140-JAK2ca mice. Immunoreactivity pattern and total Ub levels
 22 are not different between groups. Band intensity was normalized to α -tubulin. For Tx-soluble:
 23 Two-way (genotype, treatment) ANOVA, $n = 5-6/\text{group}$, $df = 1$, Genotype: $F = 0.038$, $p =$
 24 0.8481 ; Treatment: $F = 0.224$, $p = 0.6421$, Genotype x Treatment: $F = 0.776$, $p = 0.3900$. For
 25 SDS-soluble: Kruskal-Wallis test $n = 5-6/\text{group}$, $p = 0.3211$. **F-M.** Two month-old WT mice
 26 were injected in one striatum with LV_A-mHTT and LV_A-GFP and the contralateral striatum with
 27 LV_A-mHTT, LV_A-SOCS3 and LV_A-GFP (same total viral load) to force mHTT expression in
 28 astrocytes. Their brains were analysed 6 weeks later. **G.** Low magnification images showing
 29 GFP⁺ transduced area (outlined, green) and GFAP staining (magenta) in the mouse striatum.
 30 Confocal images of striatal sections stained for GFP (green), GFAP (magenta) and STAT3

1 (cyan). SOCS3 reduces GFAP immunoreactivity and nuclear accumulation of STAT3 in
 2 astrocytes. **H-J**. Quantification of GFAP immunoreactivity (**H**), STAT3 immunoreactivity (**I**)
 3 and astrocyte soma area (**J**). SOCS3 significantly decreases all these parameters. **H**: Wilcoxon
 4 matched-pair test, $n = 6/\text{group}$, $p = 0.0277$. **I**: Paired t -test. $n = 6/\text{group}$, $df = 5$, $t = 4.354$, $p =$
 5 0.0073 . **J**: Paired t -test. $n = 6/\text{group}$, $df = 5$, $t = 5.442$, $p = 0.0028$. **K**. Confocal images of striatal
 6 sections stained for GFP (green), EM48 (white) and DAPI (blue). Large EM48⁺ aggregates form
 7 in astrocyte nucleus (arrow), while small aggregates are mainly found in astrocyte processes
 8 (arrowhead). **L, M**. The total number (**L**) and the size (**M**) of EM48⁺ aggregates are significantly
 9 increased by SOCS3. Paired t -test. $n = 6/\text{group}$, $df = 5$, **L**: $t = 3.246$, $p = 0.0228$. **M**: $t = 2.778$, p
 10 $= 0.0390$.

11 **Figure 7. The *JAK2-STAT3* pathway increases *DNAJB1* expression in astrocytes**

12 **A**. DNAJB1 display a strong immunoreactivity in the degenerative putamen region that is filled
 13 with GFAP⁺ astrocytes in Huntington's disease patients. **B, C**. Immunostaining (**B**) and
 14 immunoblotting (**C**) show higher DNAJB1 protein levels in the striatum of Hdh140-JAK2ca
 15 mice than Hdh140-GFP mice. Band intensity was normalized to α -tubulin. **B**: Student t -test. $n =$
 16 $3-5/\text{group}$, $df = 5$, $t = 2.658$, $p = 0.0450$. **C**: Paired t -test. $n = 5/\text{group}$, $df = 4$, $t = 4.079$, $p =$
 17 0.0151 . **D**. Confocal images of striatal sections stained for GFP (green), DNAJB1 (white) and
 18 DARPP32 (magenta). DNAJB1 displays a diffuse cytosolic staining and forms small nuclear
 19 inclusions in neurons (arrow) of Hdh140 mice. **E**. *Dnajb1* mRNA levels are significantly
 20 decreased by SOCS3 in LV_N-mHTT mice. Student t -test. $n = 4-5/\text{group}$, $df = 7$, $t = 2.525$, $p =$
 21 0.0395 . **F**. DNAJB1 is present in exosomes isolated from Hdh140 striata and its levels,
 22 normalized by stain free staining, tend to be higher in Hdh140-JAK2ca than Hdh140-GFP
 23 exosomes. Student t -test. $n = 4-5/\text{group}$, $df = 7$, $t = 2.290$, $p = 0.0558$.

24 **Figure 8. DNAJB1 is involved in the anti-aggregation effects of the JAK2-STAT3** 25 **pathway**

26 **A**. Hdh140 mice (8-9 month-old) were injected in one striatum with LV_A-GFP + LV_A-DNAJB1-
 27 DN and with LV_A-JAK2ca + LV_A-GFP + LV_A-DNAJB1-DN in the contralateral striatum, at the
 28 same total virus load. Their brains were analysed 4 months later. **B**. Representative confocal
 29 images showing striatal sections stained for GFP (green) and V5 (cyan) in astrocytes. **C**. V5⁺
 30 vesicles (cyan, arrows) are observed in the cytoplasm of DARPP32⁺ striatal neurons (magenta).

1 High magnification of a single z plane and orthogonal views are shown on the right, DAPI is
2 shown in blue. Contrary to infected astrocytes expressing high levels of V5 throughout their
3 cytoplasm, including in their fine processes infiltrating the neuropil (arrowheads), neurons
4 display V5 staining only in few cytoplasmic vesicles, ruling out a direct infection of striatal
5 neurons by LV_A-DNAJB1-DN. Additional negative controls are shown in **Supplementary Fig.**
6 **1D. D.** JAK2ca increases GFAP immunoreactivity in astrocytes overexpressing DNAJB1-DN in
7 Hdh140 mice. Wilcoxon matched-pair test, $n = 8/\text{group}$, $p = 0.0077$. **E.** In presence of DNAJB1-
8 DN, the total number of EM48⁺ aggregates is no longer decreased by JAK2ca. Wilcoxon
9 matched-pair test, $n = 8/\text{group}$, $p = 0.7794$. **F.** *Ppp1r1b* mRNA levels are significantly reduced
10 by JAK2ca in Hdh140 mice expressing DNAJB1-DN. Wilcoxon matched-pair test, $n = 8/\text{group}$,
11 $p = 0.0431$. **G.** Two month-old WT mice were injected in one striatum with LV_N-mHTT + LV_A-
12 GFP + LV_A-DNAJB1 and the contralateral striatum with LV_N-mHTT + LV_A-SOCS3 + LV_A-
13 DNAJB1, at the same total virus load and analysed 6 weeks later. **H.** SOCS3 reduces GFAP
14 immunoreactivity in LV_N-mHTT mice, even in presence of DNJAB1. Paired *t*-test. $n = 9/\text{group}$,
15 $df = 8$, $t = 3.534$, $p = 0.0077$. **I.** SOCS3 no longer increases the EM48⁺ volume when astrocytes
16 co-express DNAJB1. Paired *t*-test. $n = 9/\text{group}$, $df = 8$, $t = 2.004$, $p = 0.0851$. **J, K.** Likewise,
17 striatal DARPP32 lesions (**J**) and *Ppp1r1b* mRNA levels (**K**) are no longer different between the
18 two groups. **J:** Paired *t*-test. $n = 9/\text{group}$, $df = 8$, $t = 0.632$, $p = 0.5451$. **K:** Wilcoxon matched-
19 pair test, $n = 8/\text{group}$, $p = 0.8203$. **L. Bi-directional communication between JAK2-STAT3-**
20 **induced reactive astrocytes and neurons to promote proteostasis in Huntington's disease:**
21 The JAK2-STAT3 pathway induces a reactive response in striatal astrocytes and activates a
22 transcriptional program that promotes proteostasis, reduces mHTT aggregation and improves
23 neuronal status. Two complementary and non-exclusive mechanisms involving striatal neurons
24 and JAK2-STAT3-dependent reactive astrocytes may take place. **1.** Reactive astrocytes display a
25 higher intrinsic proteolytic activity that promotes mHTT degradation. Neurons could shuttle their
26 mHTT to astrocytes for clearance. The exact mechanisms and the form of mHTT exchanged
27 (monomers, fibrils, cleaved fragments...) remain to be determined. **2.** Reactive astrocytes over-
28 express chaperones such as DNAJB1 that can be released in exosomes towards neurons to
29 promote their proteostasis.

30

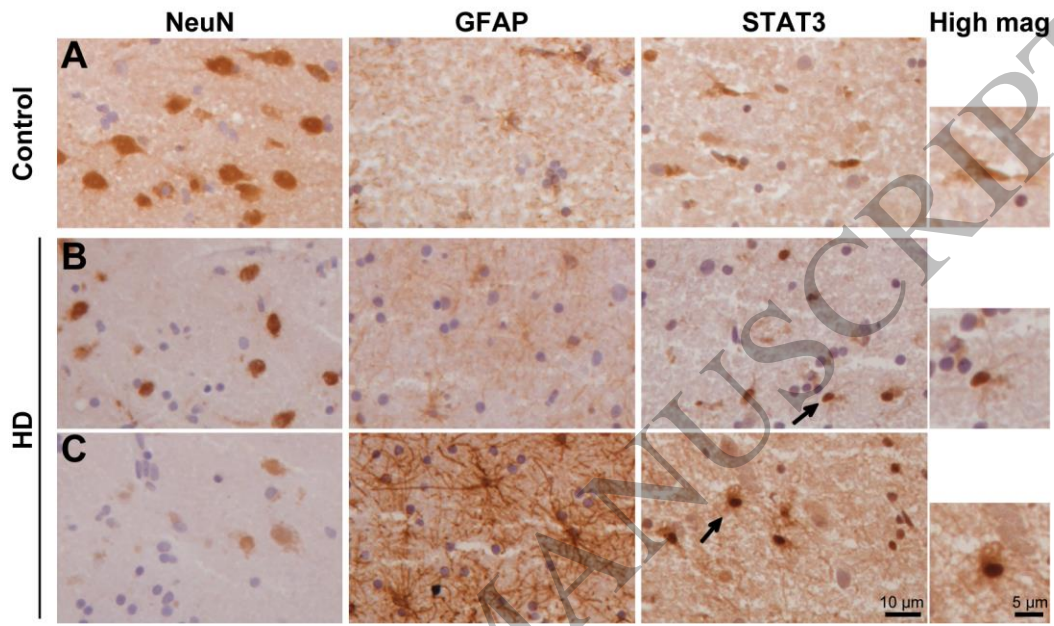
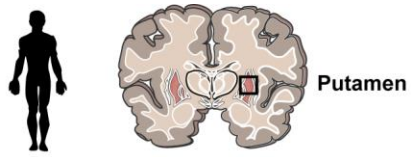


Figure 1
138x107 mm (1.7 x DPI)

1
2
3
4

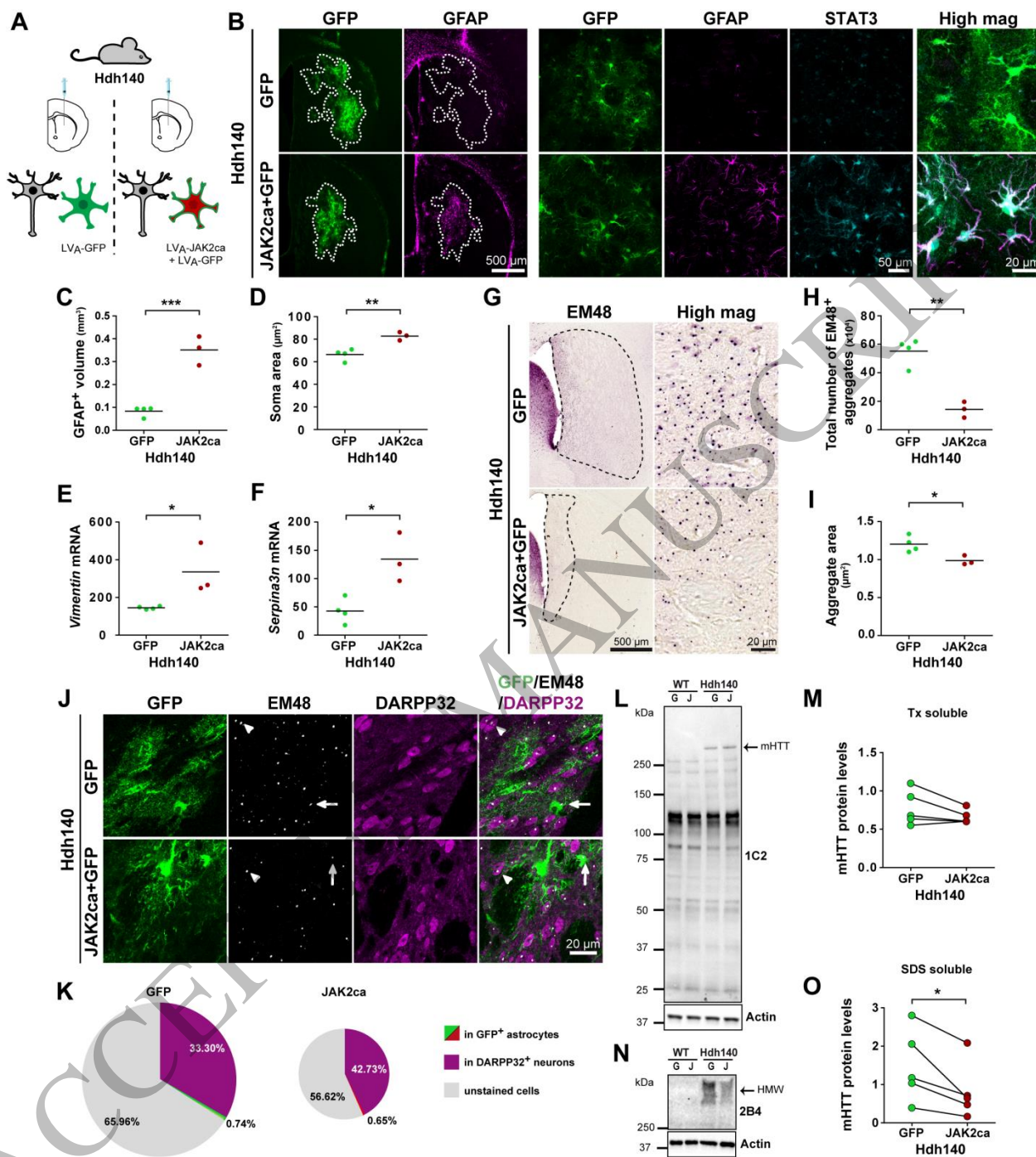


Figure 2
209x233 mm (1.7 x DPI)

1
2
3
4

1

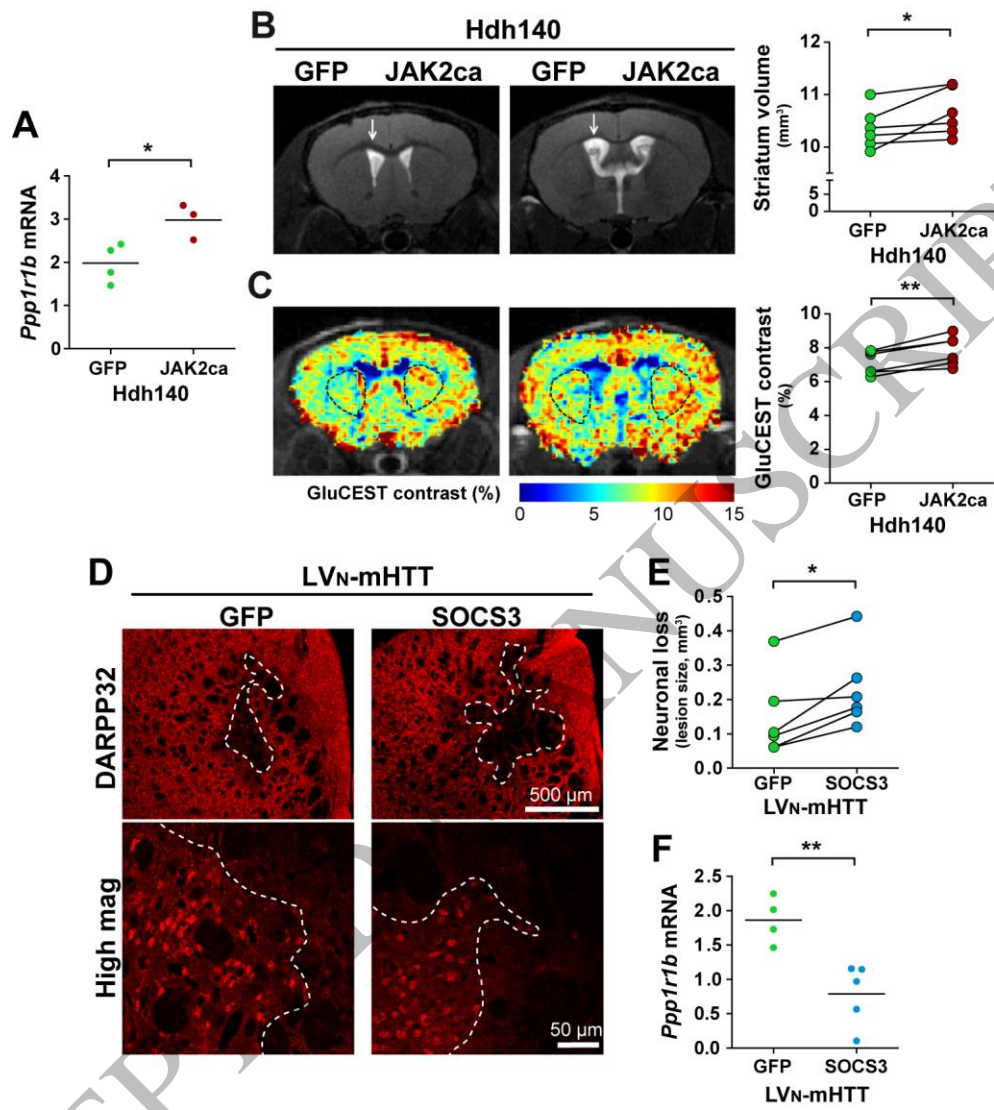


Figure 4
130x146 mm (1.7 x DPI)

2

3

4

5

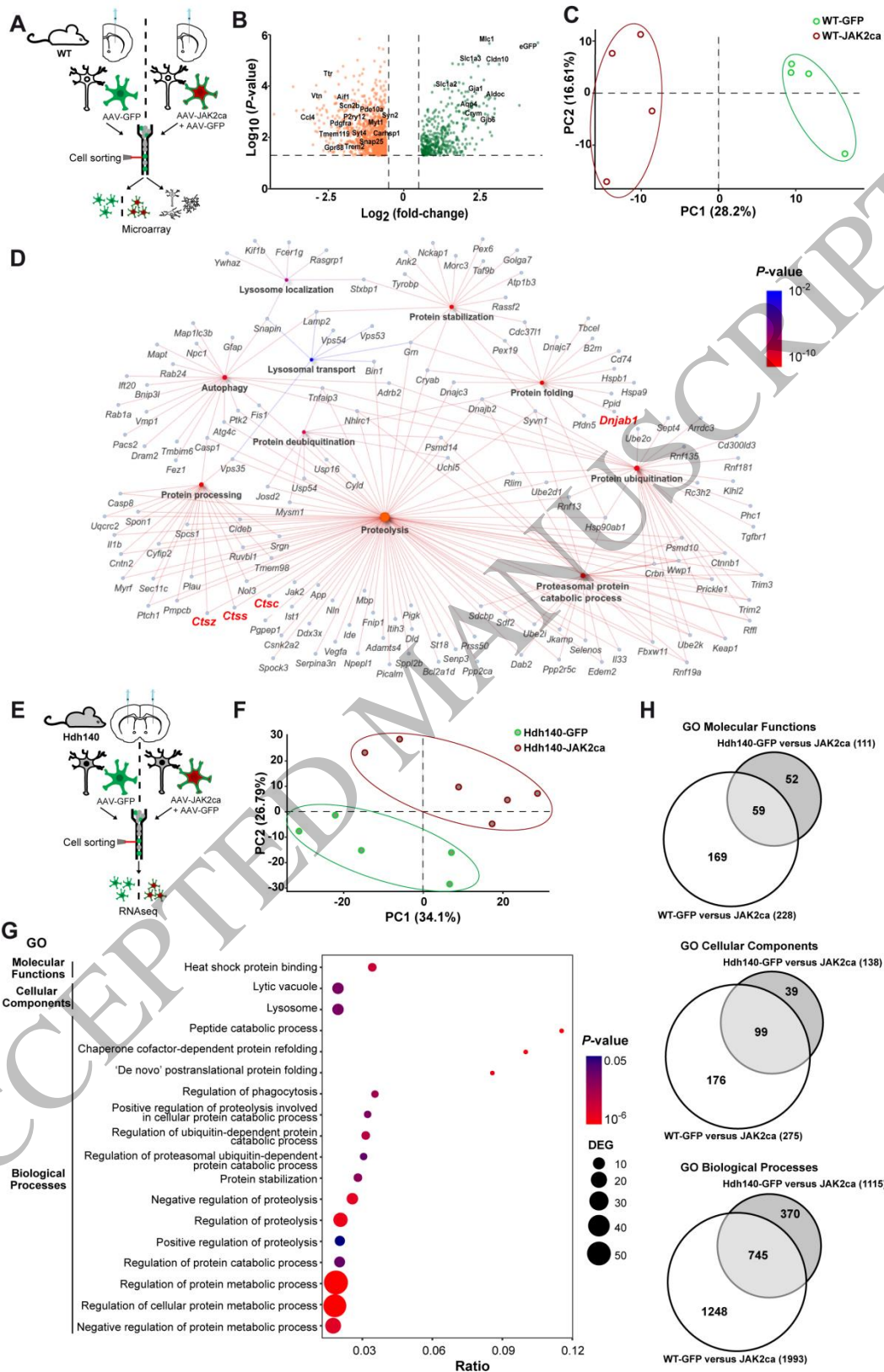


Figure 5
189x294 mm (1.7 x DPI)

1
2
3

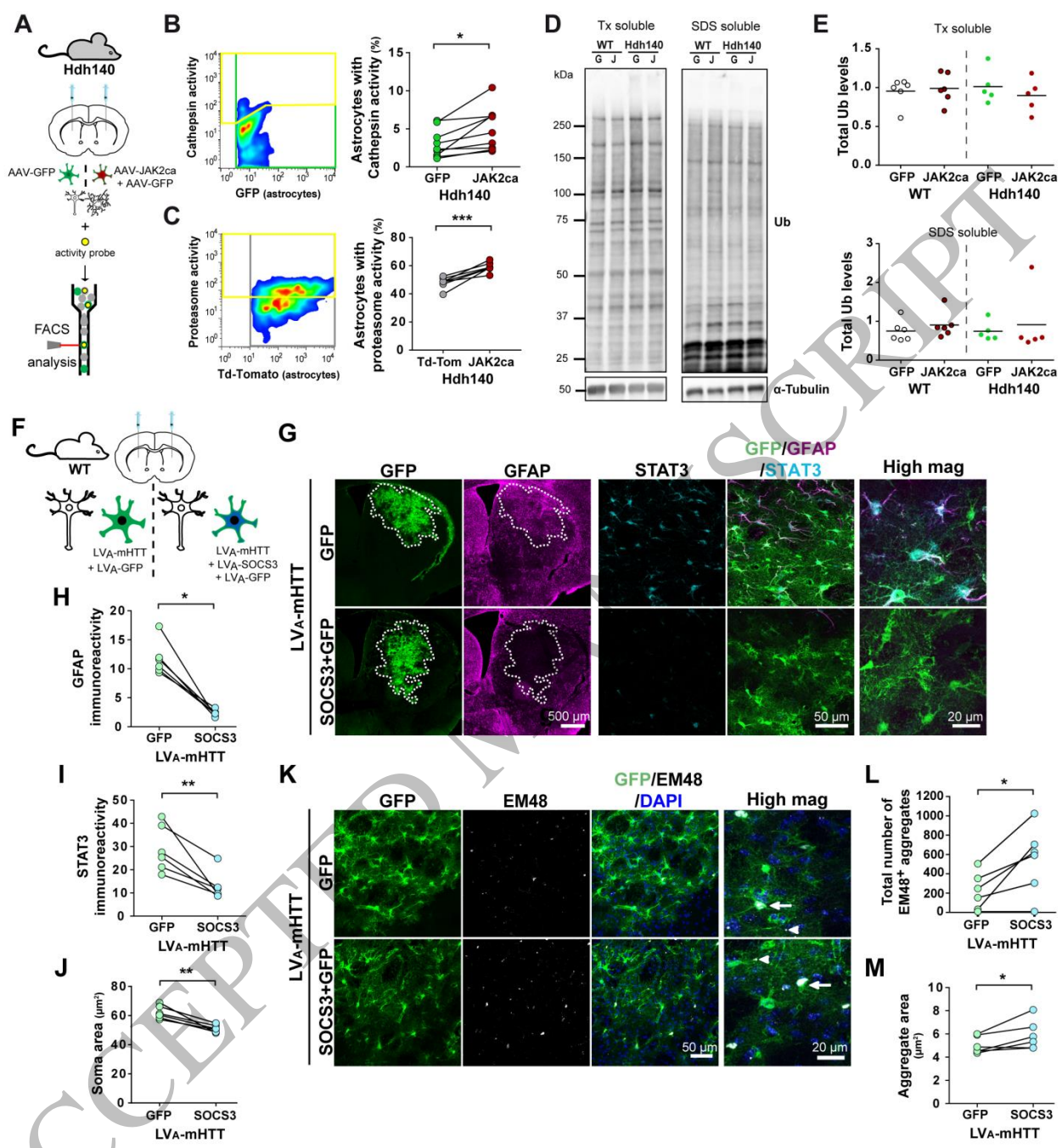


Figure 6
209x223 mm (1.7 x DPI)

1
2
3
4

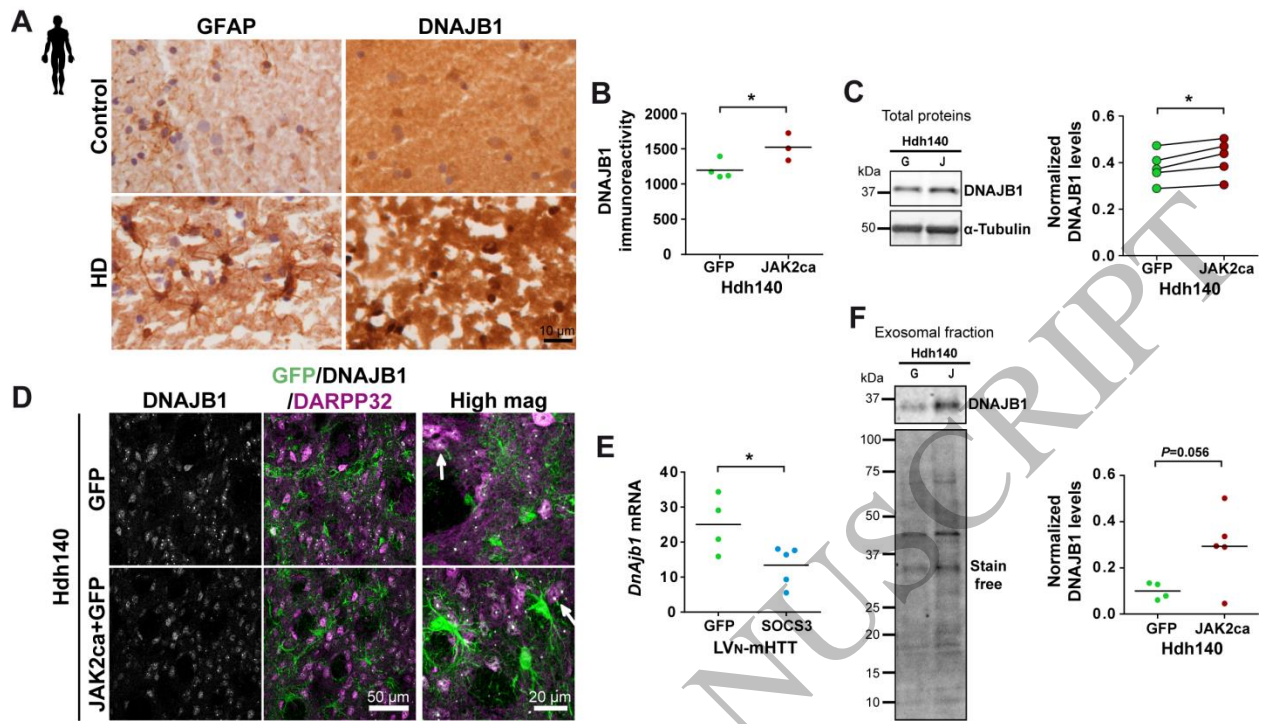


Figure 7
205x117 mm (1.7 x DPI)

1
2
3
4

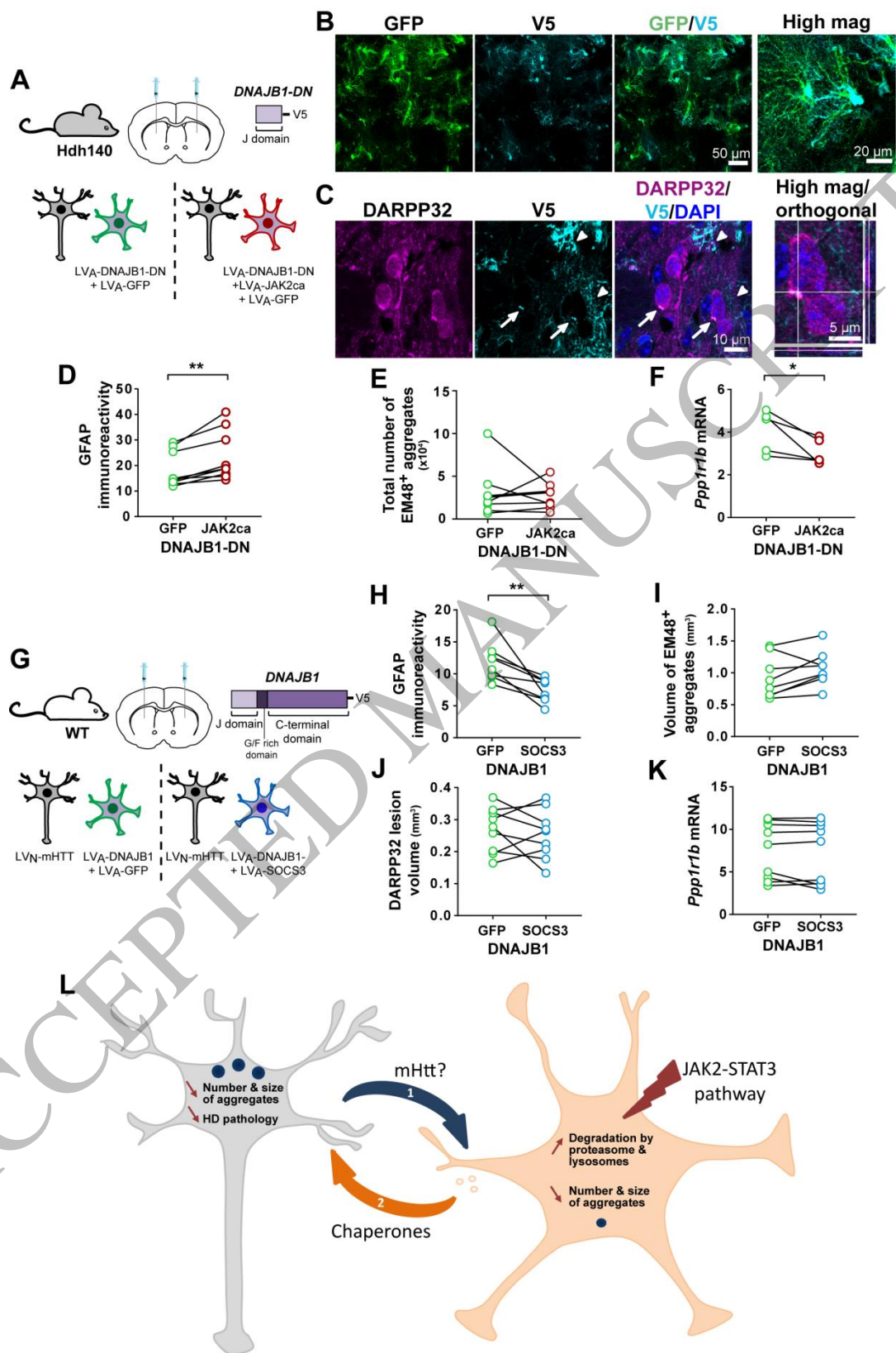


Figure 8
161x245 mm (1.7 x DPI)

1
2
3