Profound seizure suppression and disease modification by targeting JAK1, a key driver of a pro-epileptogenic gene network.

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ABSTRACT

Epilepsy is the 4th most prevalent neurological disorder with over 50 million cases worldwide[1,2]. While a number of drugs exist to suppress seizures, approximately 1/3 of patients remain drug resistant, and no current treatments are disease modifying[3]. Using network and systems-based approaches, we find that the histone methylase EZH2 suppresses epileptogenesis and slows disease progression, via repression of JAK1 and STAT3 signaling in hippocampal neurons. Pharmacological inhibition of JAK1 with the orally available, FDA-approved drug CP690550 (Tofacitinib)[4,5] profoundly suppresses behavioral and electrographic seizures after the onset of epilepsy across preclinical rodent models of acquired epilepsy. This seizure suppression persists for weeks after drug withdrawal. Identification of an endogenous protective response to status epilepticus in the form of EZH2 induction has highlighted a critical role for the JAK1 kinase and STAT3 in both the initiation and propagation of epilepsy across preclinical rodent models and human disease. Overall, we find that STAT3 is transiently activated after insult, reactivates with spontaneous seizures, and remains targetable for disease modification in chronic epilepsy.

INTRODUCTION

Epilepsy is a highly prevalent neurological disorder with over 50 million cases worldwide[1,2]. Arising from a myriad of etiologies including gene mutations and environmental insults, the unifying characteristic of the epilepsies is the emergence of recurring, spontaneous seizures. Epileptogenesis is the process that links initial insults to the eventual propagation of spontaneous seizures. One of the insults that may initiate epileptogenesis is status epilepticus: an unremitting bout of seizures lasting for more than five minutes, during which the patient does not regain consciousness[6-8]. The first-line treatments for epilepsy are anticonvulsants aimed at controlling seizures. While these medications effectively suppress seizures for some patients, they do not target the processes that orchestrate progression of the disease, and fail to suppress seizures altogether in approximately 1/3 of patients[3]. There is a critical need for treatments that target the progressive decline in seizure threshold that arguably leads to spontaneous seizures.

A poor understanding of the mechanisms underlying epileptogenesis has so far prevented the development of disease biomarkers and translation of antiepileptogenic treatments from pre-clinical rodent models to the clinic. Although others have reported the disease-modifying potential of manipulations to metabolism[9-11], inflammation[12,13], chromatin modification[14], and signal transduction pathways[15], progress has been hindered by a lack of consensus among laboratories employing different models of status epilepticus (SE)[16]. With few exceptions[9,17-20], little effort has been made to identify the principal transcription factors and chromatin modifiers whose function precipitates the gene changes that arise after status epilepticus.

Recently, we applied a systems approach and novel bioinformatic tool[21] to a transcriptomic consortium dataset that incorporated gene expression data across multiple laboratories and models of epilepsy[22]. This allowed for identification of potential mechanisms that span across rodent models of status epilepticus (SE) and human temporal lobe epilepsy (TLE)[23]. With this approach, we identified the histone methylase Enhancer of Zeste

Homolog 2 (EZH2) as a potential driver of gene changes in dentate granule cells post-SE that is induced by an order of magnitude across epilepsy models. Transient pharmacological inhibition of EZH2 post-SE worsened epileptic phenotypes one month later, suggesting that EZH2 induction plays a protective role in epileptogenesis. In addition to EZH2, our analysis predicted Signal Transducer and Activator of Transcription 3 (STAT3) to be a driver of gene activation across models of SE[22,23].

Of the studies that have profiled gene changes in the epileptic brain, nearly all find a robust activation of inflammatory pathways[17-20,23-25]. In the brain, inflammation can be triggered by glial cells[26], but neurons also exhibit an innate immune response that has been associated with hyper-excitability[27]. Anti-inflammatory drugs have been used with varying degrees of success to suppress seizures in human patients[28-31], and some drugs targeting neuroinflammation in rodents have shown antiepileptogenic potential[32-35]. However, the endogenous mechanisms that regulate neurogenic inflammation post-SE are poorly understood.

Herein, we show that EZH2 induction with SE suppresses pathological activation of pro-inflammatory JAK/STAT signaling in neurons, both in animal models and human disease. EZH2 deletion in neurons leads to hyper-activation of the JAK/STAT pathway, robust reductions in seizure threshold after SE, and an exaggerated epileptic phenotype. Pharmacological inhibition of JAK1/3 activity acutely after SE rescues these phenotypes. Finally, targeting STAT3 reactivation after the onset of epilepsy with the JAK inhibitor CP690550 results in an enduring, disease-modifying suppression of spontaneous seizures.

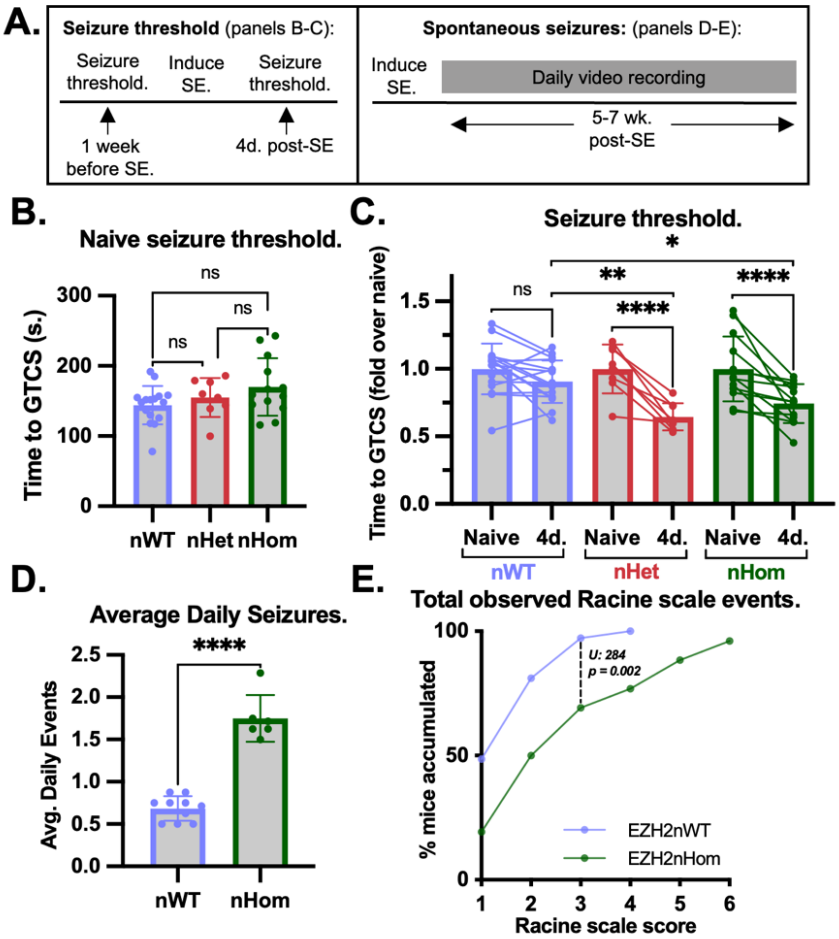

Fig. 1. EZH2 maintains seizure threshold after status epilepticus and mitigates spontaneous seizure frequency and severity. **(A)** Experimental paradigms for panels B-C and D-E. **(B)** Baseline fluorothyl seizure threshold data for C57BL6J EZH2nWT, nHet, and nHom mice. In naïve mice, deletion of EZH2 in neurons does not alter seizure threshold (one-way ANOVA; nWT:nHet p=0.471, nWT:nHom p=0.134, nHet:nHom p=0.471; n=8-16). **(C)** After induction of SE by KA injection, seizure threshold does not change robustly in EZH2nWT mice (p=0.061). EZH2nHet mice exhibit a 35% reduction in seizure threshold post-SE ($p<10^{-4}$), with thresholds 25% lower than kainate-injected EZH2nWT mice (p=0.003). EZH2nHom mice show a 25% reduction in seizure threshold post-SE ($p<10^{-4}$), with thresholds 17% lower than KA EZH2nWT mice (p=0.026) (2-way ANOVA; n=7-14). **(D)** FVB EZH2nWT and nHom mice were injected with KA to induce SE and video recorded from 5-7 weeks post-SE to count and score spontaneous seizure activity. Deletion of an EZH2 allele in neurons leads to a 2.5-fold increase in daily seizure events (unpaired t-test; $p<10^{-4}$; n=6-10). **(E)** Total observed Racine scale events for EZH2nHom and EZH2nWT mice were quantified as a frequency distribution. 50% of EZH2nWT mice had only Class I seizures, while 50% of EZH2nHom mice had Class I and II seizures (Mann-Whitney test; U:284, p=0.002; n=6-10).

RESULTS

Neuronal EZH2 maintains seizure threshold and protects against exacerbated epileptic phenotypes.

We previously identified the histone methyltransferase EZH2 as a potential driver of gene repression post-SE, and EZH2 protein was shown to be potently induced over a 10-day window post-SE in rats and mice across models of epilepsy. EZH2 induction was protective because pharmacological inhibition resulted in accelerated disease progression[23]. To determine the role of EZH2 in epilepsy, we crossed EZH2 floxed mice[36] with

Syapsin1 Cre drivers[37] to delete EZH2 in mature neurons. Neuronal specificity of Cre expression was confirmed via crossing Syn1Cre with *flox*-STOP-*flox*-tdTomato mice and immunofluorescence (Fig. S1A).

Immunofluorescence and western blot analysis confirmed successful ablation of neuronal EZH2 post-SE. Fig. S1B-C show diminished induction of EZH2 on day 4 post-SE in mice lacking one EZH2 allele in neurons (EZH2nHet) or lacking both alleles (EZH2nHom). Staining for EZH2 confirmed reduced induction of neuronal EZH2 in EZH2nHet versus wildtype (EZH2nWT) mice (Fig. S1D, quantified in S1E).

We tested the impact of EZH2 deletion on fluorothyl seizure threshold acutely post-SE, as a correlation between fluorothyl seizure threshold[38] and the development of spontaneous seizures has been suggested[39-42]. We measured time to generalized tonic clonic seizure (GTCS) after exposure to the volatile chemoconvulsant fluorothyl in EZH2nWT, EZH2nHet, and EZH2nHom mice aged 4-6 weeks, before and after kainate-induced SE[43,44] (Fig. 1A). Loss of EZH2 alleles in neurons had no impact on seizure threshold in naïve mice (Fig. 1B), and induction of SE did not alter the seizure threshold of EZH2nWT mice on day 4 post-SE (Fig. 1C). In contrast, robust reductions in threshold were detected after SE in EZH2nHet mice (2-way ANOVA; Mean difference:55±8sec, $p<10^{-4}$) and EZH2nHom mice (Mean difference:46±8sec, $p<10^{-4}$). These were significant reductions compared to EZH2nWT mice (EZH2nWT:EZH2nHet: 28%, $p<0.01$; EZH2nWT:EZH2nHom: 20%, $p<0.05$). These data suggest that EZH2 is required to maintain fluorothyl seizure threshold post-SE.

We considered the possibility that EZH2 loss primed the mice to experience more severe responses to kainate injection, and it was this vulnerability to SE driving the observed reduction in mutant seizure threshold. However, we found no differences in time to first class V seizure and no correlation between time to first class V seizure and time to GTCS post-SE for either EZH2nWT (Pearson correlation; R^2:0.016, $p=0.633$), EZH2nHet (R^2:0.261, $p=0.195$), or EZH2nHom mice (R^2:0.152, $p=0.209$) (Fig. S2A-D).

To test the impact of neuronal EZH2 deletion on spontaneous seizures, we monitored behavioral spontaneous seizures in FVB EZH2nWT and EZH2nHom mice by video weeks five to seven post-SE (Fig. 1A). EZH2nHom mice exhibited a 2.5-fold increase in average daily seizure events compared to EZH2nWT mice (unpaired t-test; $p<10^{-4}$) (Fig. 1D). EZH2nHom mice also exhibited more severe Racine scale seizures than EZH2nWT mice (Mann Whitney test; U: 284, $p<0.01$) (Fig. 1E). These data support the hypothesis that neuronal EZH2 induction is a protective response post-SE.

EZH2 tempers induction of the JAK/STAT pathway post-SE in neurons.

To begin to understand the mechanism behind EZH2-mediated protection, we performed bulk RNAseq on whole hippocampal tissue from naïve and epileptic (4d. post-SE) EZH2nWT and EZH2nHom mice. Of the 10556 expressed genes, 6241 were found to be differentially expressed at an adjusted $p<10^{-2}$ (Likelihood Ratio Test) across the four conditions (saline, kainate, EZH2nWT, EZH2nHom). A community-based network approach was used to group genes into clusters. Leiden clustering generated 12 distinct groups (Fig. 2A). The grey, orange, gold, brown, skyblue, and purple clusters were generally repressed after SE, whereas the red, blue, indigo, yellow, and black clusters were generally increased. We focused on the Black cluster because these 439 genes manifested induction with SE in EZH2nWT mice but showed an exaggerated induction with SE in EZH2nHom mice. We reasoned that these would be genes whose expression is induced with SE but tempered in the presence of EZH2 post-SE, and undergo unfettered induction in the absence of EZH2.

To understand the nature of genes comprising the Black cluster, we performed an ontological analysis. The 439 Black cluster genes were compared to gene lists associated with terms in the KEGG, Reactome, Biocarta and Hallmark databases. (Fig. 2B). The ontology network (see Fig. S3A) highlights the innate immune response (NFkB, Interferon Gamma), microglial processes (Complement) and inflammation (IL6 Jak Stat3) amongst others. The term 'IL6 Jak Stat3' was of particular interest given that our previous work highlighted STAT3 as a driver of gene activation across models of epilepsy[23], and others have identified a role for the JAK/STAT pathway in epileptogenesis[27,32,45-48].

To determine which transcription factors and cofactors (hereafter together referred to as 'Factors') control expression of Black cluster genes, we used MAGIC[21]. STAT3 was the highest scoring Factor (Fig. 2D). When projected as a Gene Regulatory Network (GRN) (Fig. 2C) such that an arrow projects from Factor X to Factor

Y if the gene encoding Factor Y is a transcriptional target of Factor X, STAT3 stood out as a central node. Thus, STAT3 had the highest in-degree, out-degree and total edge count (Fig. 2E) of any Factor in the network. Finally, we assessed the Betweenness Centrality of the network[49] to determine which Factors might be critical for information flow in the GRN. STAT3 had by far the largest Betweenness Centrality of any Factor (Fig. 2F).

To ascertain whether the mouse Black cluster has a counterpart in human epilepsy, we used whole transcriptome data from 129 temporal lobectomy resections collected ante-mortem from human temporal lobe epilepsy (TLE) patients[23,50]. We used k-means clustering to generate 10 gene clusters from the 7658 genes co-expressed across all samples (brown, blue, purple, skyblue, grey, orange, indigo, green, yellow, red). To identify the human TLE cluster most similar to the mouse Black cluster, we performed Fisher exact tests to measure the degree of overlap between the 439 Black cluster genes, and the genes comprising each cluster of the human TLE dataset (Fig. 2G). The human Brown cluster showed the greatest overlap, sharing 65 genes in common with the mouse Black cluster (Fisher exact; Odds: 4.79, p=1.19E-20). We then performed ontological analysis on the genes in the human Brown cluster. The 850 genes were compared to gene lists associated with terms in the KEGG, Reactome, Biocarta and Hallmark databases. (Fig. 2H). The ontology network (see Fig. S3B) highlights inflammation (Cytokine Receptor Interaction/Complement/Innate Immune

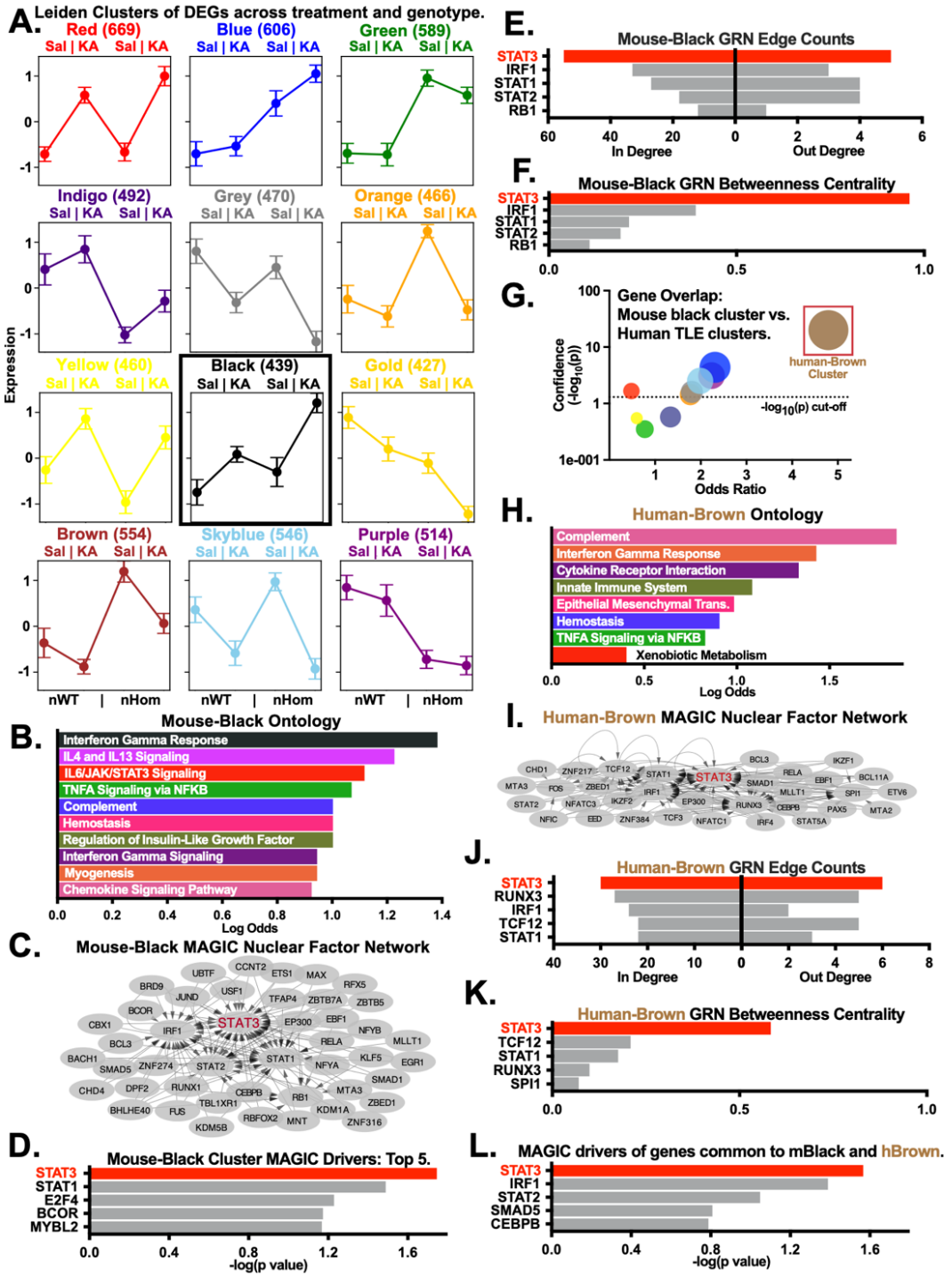

Fig. 2. STAT3 drives hyper-activation of pro-inflammatory gene networks post-SE in EZH2 knockout mice and human temporal lobe epilepsy. **(A)** Leiden clusters from 6241 differentially expressed genes (fold change >1.2x, adjusted p<0.01) across saline, kainate, EZH2nWT, and EZH2nHom conditions. **(B)** Ontological analysis of genes in the Black cluster highlights inflammatory processes. **(C)** MAGIC was used to determine which Factors control the expression of Black cluster genes, and positive hits were projected as a Gene Regulatory Network (GRN). **(D)** Top 5 Factors driving expression in the Black cluster sorted by –log(adjusted p value). **(E, F)** Factors were ranked by their in degree, out degree counts, and betweenness centrality. **(G)** Comparison of 10 human TLE k-means gene clusters to the mouse Black cluster by Fisher Exact test. Plotting -log(adjusted p) versus odds ratio of Fisher tests against the Black cluster shows that the Human Brown cluster is the most similar to the mouse Black cluster (Fisher exact; Odds:4.79, p(adj)=1.2×10^{-20}). Dotted line shows p=0.05. **(H)** Ontological analysis of genes in the human-Brown cluster. The 850 human-Brown cluster genes were compared to gene lists associated with terms in KEGG, Reactome, Biocarta, and Hallmark databases **(I)** MAGIC GRN for Factors driving the human-Brown cluster. **(J, K)** Factors were ranked by their in degree, out degree, and betweenness centrality. **(L)** STAT3 is the top driver predicted by MAGIC to drive expression of genes common to the mouse-Black and human-Brown clusters.

System) and interferon signaling (Interferon Gamma Response). Mirroring results of the black cluster, STAT3 in the human Brown GRN had the highest in-degree, out-degree, and betweenness centrality of any Factor in the network (Fig. 2J-K).

MAGIC called STAT3 as the highest scoring Factor driving expression of the 65 genes co-expressed in early rodent epileptogenesis (mouse Black) and frankly epileptic human tissue (human Brown) (Fig. 2L). This data is consistent with the hypothesis that STAT3-mediated disease mechanisms that are activated acutely in a rodent model of epileptogenesis persist in chronic human epilepsy.

Transient activation of the JAK/STAT pathway after SE in WT mice has been reported by others[23,46] (and Fig. S4A-B, S5A-D). To test for a neuronal EZH2-dependent change in JAK/STAT signaling, we performed western blot analysis on hippocampal lysates from 4d. post-SE WT and EZH2 mutant mice (Fig. 3A-B). On day 4 post-SE, pY705-STAT3 was induced 2-fold in EZH2nWT mice ($p<0.01$) compared to naïve controls, 2.9-fold in EZH2nHet mice ($p<10^{-4}$), and 4.5-fold in EZH2nHom mice (2-way ANOVA; $p<10^{-4}$) (Fig. 3C-D). These results demonstrated an EZH2 gene dose-dependent hyperactivation of STAT3.

Given the involvement of STAT3 in regulating gene expression across acute rodent SE and chronic human epilepsy, we asked whether STAT3 reactivation occurred in chronic rodent epilepsy. We found that at 14 weeks post-SE, epileptic mice showed a 4.7-fold induction of pY705-STAT3 over naïve controls (unpaired t-

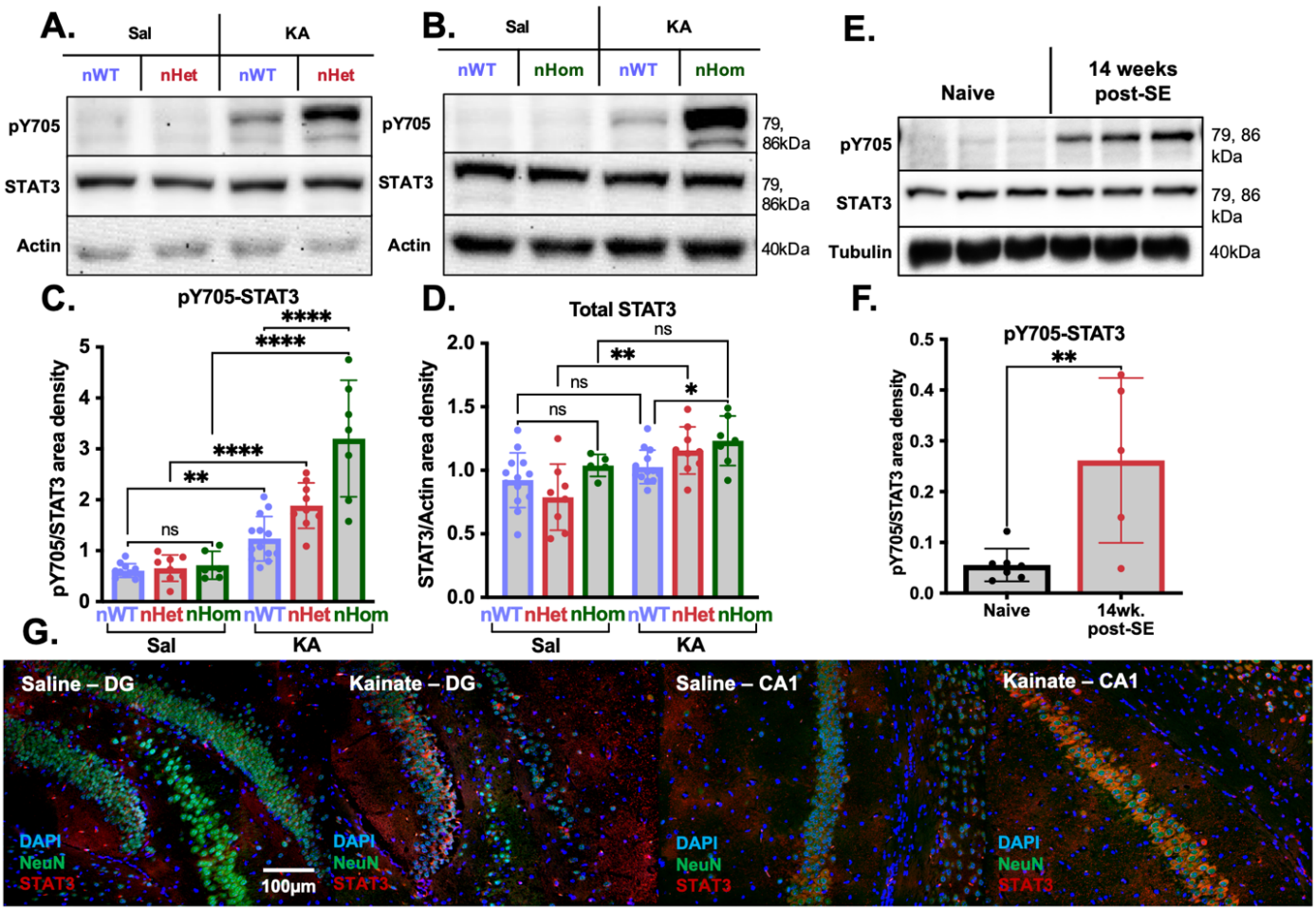

Fig. 3. JAK/STAT pathway components are hyper-activated in neurons of EZH2 knockout mice. EZH2nWT, nHet, and nHom mice were injected with saline or KA to induce SE; hippocampi were harvested on day 4 post-SE. **(A, B)** Representative western blots for pY705-STAT3, total STAT3, and beta-actin on day 4 post-SE. **(C)** pY705-STAT3 levels are unchanged across genotypes in naïve animals ($p=0.220$). pY705-STAT3 is induced by 2-fold in EZH2nWT mice ($p=0.022$), 2.9-fold in EZH2nHet mice ($p<10^{-4}$), and 4.5-fold in EZH2nHom mice post-SE ($p<10^{-4}$). pY705 levels in EZH2nHom mice post-SE are 2.6-fold greater than in EZH2nWT mice post-SE ($p<10^{-4}$) (2-way ANOVA; n=7-12). **(D)** Total STAT3 levels on day 4 post-SE. Total STAT3 is induced by 1.2-fold in nHom mice post-SE, compared to nWT mice post-SE ($p=0.041$). Total STAT3 is induced after seizures in nHet mice by 1.5-fold ($p=0.041$) (2-way ANOVA; n=7-12). **(E)** Representative western blots for pY705-STAT3, total STAT3, and beta actin in naïve and chronically epileptic mice at 14 weeks post-SE. **(F)** pY705-STAT3 is induced 4.7-fold in epileptic mice (unpaired t-test; $p=0.007$, n=5-7). **(G)** 20x images of the dentate gyrus (DG) and CA1 pyramidal cell layer (CA1). Hippocampal slices were collected on day 1 post-SE from saline- and KA-injected mice; immunofluorescence was performed to detect nuclear DNA, NeuN, and total STAT3.

test; $p<0.01$) (Fig. 3E-F).

To define the cell types in which STAT3 is expressed after seizures, we performed immunofluorescence with DAPI, NeuN, and total STAT3 antibodies on day 1 post-SE hippocampi taken from mice injected with saline or kainic acid (Fig 3G). We made use of the fact that the STAT3 gene is induced with STAT3 activation, and so elevated total STAT3 protein was a proxy for activated STAT3. In both the dentate granule and CA1 pyramidal cell layer, we observed a robust induction of total STAT3 in NeuN-positive cells.

EZH2 targets STAT3 via JAK1 to suppress JAK/STAT signaling.

STAT3 was a central factor in the Black cluster GRN whereas, surprisingly, EZH2 was not. In order to understand how STAT3 hyperactivation could have occurred in the absence of EZH2, shRNA was used to knock down EZH2 in the Neuro2A (N2A) neuronal cell line. We observed robust diminution of EZH2 in knockdown cells (shEZH2) (Fig. 4A, quantified by S6A) (unpaired t-test; 3.7-fold, $p<10^{-4}$). This was associated with a marked increase in pY705-STAT3 levels (unpaired t-test; 2.4-fold $p<10^{-4}$) (quantified by S6B). This result suggests that EZH2 suppresses STAT3 activation in a cell-autonomous manner without circuit level alterations.

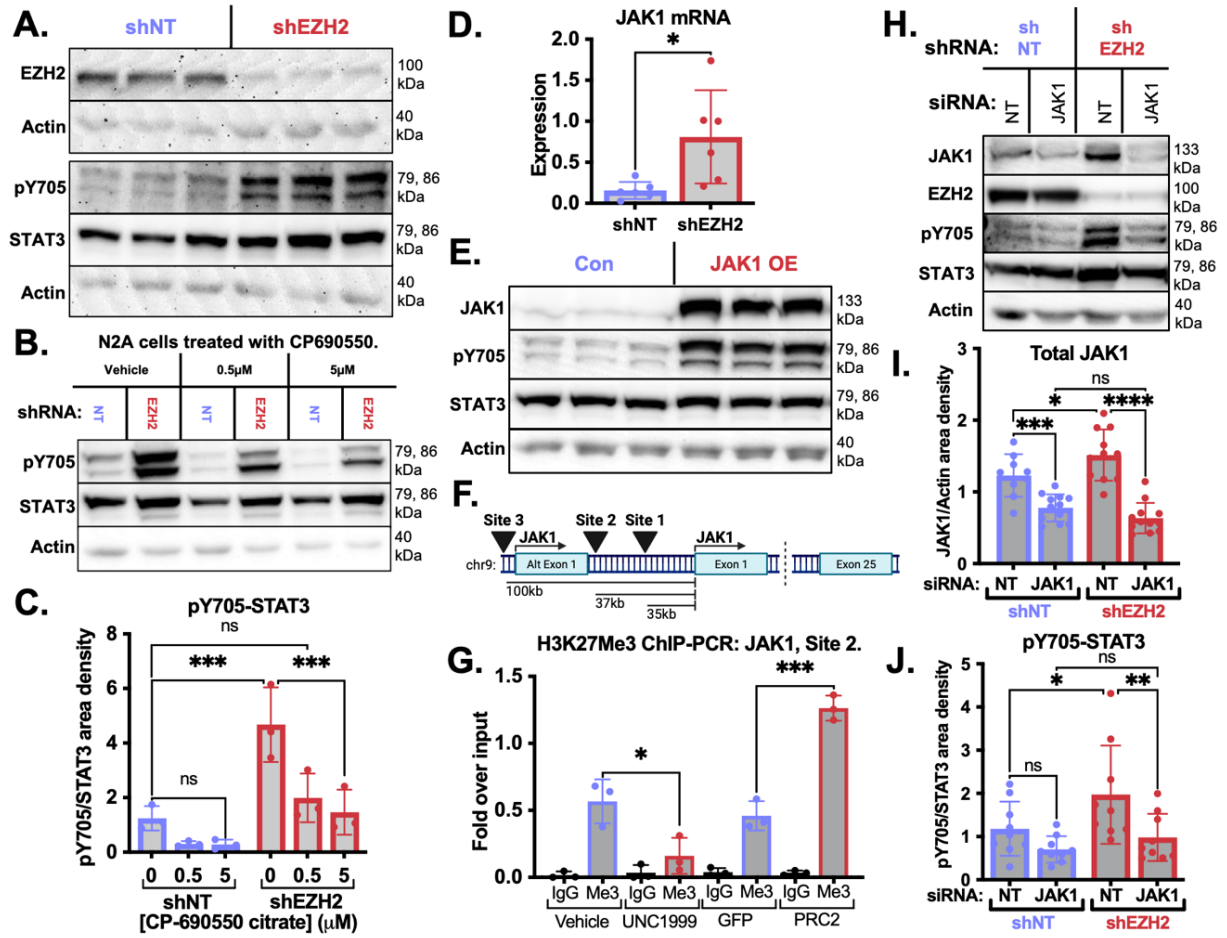

Fig. 4. EZH2 suppresses STAT3 activation via transcriptional repression of JAK1. N2A cells were stably transfected with EZH2 shRNA (shEZH2) or non-targeting shRNA (shNT). **(A)** Knockdown of EZH2 causes induction of pY705-STAT3 and total STAT3 protein (quantified in Fig. S6). **(B,C)** pY705-STAT3 activation in shEZH2 cells is inhibited with the JAK inhibitor CP690550 citrate. pY705-STAT3 is induced in vehicle-treated shEZH2 cells by 3.7-fold (p=0.0004). CP690550 treatment reduces pY705-STAT3 levels of KD cells by 2.3-fold (at 0.5μM) and 3.2-fold (p=0.0006) (at 5μM). At 0.5μM CP, pY705 levels in KD cells are reduced to that of untreated control cells (p=0.18) (2-way ANOVA; n=3). **(D)** JAK1 mRNA expression is induced by 5.1-fold in shEZH2 cells (unpaired t-test; p=0.019; n=6). **(E)** JAK1 protein is induced 5.5 fold (p=0.0008), and pY705-STAT3 by 6.7-fold (p=0.0004) in the absence of changes to total STAT3 upon transfection with FLAG-JAK1 compared to control transfection (unpaired t-tests; n=3). **(F)** Schematics depicting EZH2 binding sites on JAK1. **(G)** H3K27Me3 is enriched at Site 2 at the JAK1 locus. Chromatin IP (ChIP) on N2A cells treated with either vehicle or 10μM UNC1999 for 24 hours, or transfected with expression vectors GFP (control) of cotransfected with GFP-EZH2, SUZ12, and EED (PRC2). Results are graphed as fold H3K27Me3 over input. For JAK1 (Site 2), treatment with UNC1999 reduces H3K27Me3 enrichment by 3.5-fold (p=0.029), and PRC2 overexpression leads to a 2.7-fold increase in H3K27Me3 enrichment (p=0.0006) (unpaired t-tests; n=3). **(H)** Knockdown of JAK1 suppresses pY705-STAT3 activation in shEZH2 cells. shNT and shEZH2 N2A cells transfected with either non-targeting (NT) or JAK1 siRNA were subjected to western blotting to confirm JAK1 and EZH2 knockdown, and assess pY705-STAT3 levels. **(I)** Total JAK1 protein is induced in shEZH2 cells transfected with non-targeting siRNA by 1.2-fold (p=0.023), and reduced in both shNT (p=0.0005) and shEZH2 ($p<10^{-4}$) after JAK1 RNAi (2-way ANOVA; n=9-12). **(J)** pY705-STAT3 is induced in shEZH2:NTsiRNA cells by 1.7-fold (p=0.027) over shNT:NTsiRNA cells. JAK1 RNAi in shEZH2 cells reduces pY705-STAT3 by 2.5-fold (p=0.006), to the levels of shNT:NTsiRNA cells (2-way ANOVA; n=9-12).

To determine whether STAT3-upstream kinases are required for pY705-STAT3 induction in shEZH2 cell lines, we incubated cells with either WP1066 (an analogue of the JAK2 inhibitor AG490[51-53]) or CP690550 citrate (a small molecule inhibitor of JAK1/3 kinase activity[4,5,54]). WP1066 did not impact STAT3 phosphorylation in shEZH2 cells

at any concentration tested (Fig. S7A-C). In contrast, 500nM CP690550 citrate resulted in a 2.3-fold (2-way ANOVA; $p<0.01$) reduction of pY705-STAT3 in shEZH2 cells (Fig. 4B,C), rescuing pY705-STAT3 levels to that of vehicle-treated control cells. Even greater reduction occurred in the shEZH2 cells treated with 5μM CP690550 (3.2-fold, $p<10^{-3}$). CP690550 is a JAK inhibitor selective for JAK1 and JAK3, but JAK3 is not expressed in neurons or N2As (data not shown). We therefore tested whether JAK1 was elevated in the shEZH2 cells. Fig. 4D shows a 5.1-fold induction of JAK1 mRNA over control cells (unpaired t-test; $p<0.05$).

To determine whether induction of JAK1 is sufficient to induce STAT3 activation, we overexpressed JAK1 in N2A cells (Fig. 4E). JAK1 shows a 5.6-fold induction upon overexpression (unpaired t-test; $p<10^{-3}$), and pY705-STAT3 is induced by 6.7-fold (unpaired t-test; $p<10^{-3}$) in the absence of changes to total STAT3 (quantified in S8A-B). This suggests that CP690550 works to suppress STAT3 activation primarily through JAK1 downstream of EZH2.

To understand how EZH2 regulates JAK1 activity, we noted three putative EZH2 binding sites in the gene body and promoter region of JAK1 using ENCODE tracks in the UCSC Genome Browser[55] (Fig. 4F, Fig. S9A). We performed chromatin immunoprecipitation with anti-H3K27Me3 antibodies to determine whether EZH2 methylase activity was enriched at any of these sites. In Fig. 4G H3K27Me3 was enriched at site 2. Incubation of cells with UNC1999 (an EZH2 inhibitor[23,56]) for 24 hours resulted in a 3.5-fold loss of signal (unpaired t-test; $p<0.05$). Overexpression of EZH2, SUZ12, and EED (the core components of Polycomb) increased H3K27Me3 signal by 2.7-fold compared to overexpression of GFP as a control (unpaired t-test; $p<10^{-3}$). PAX2 and actin were immunoprecipitated as positive and negative controls for H3K27Me3 enrichment, respectively (Fig. S9B-C); ChIP-PCR results for JAK1 (Site 1), JAK1 (Site 3), JAK2, and STAT3 were also collected (Fig. S9D-G). None of these sites showed both a loss of H3K27Me3 enrichment after UNC1999 treatment and an increase in signal upon overexpression of Polycomb. These data are consistent with the hypothesis that EZH2 targets JAK1 transcription to temper activation of STAT3.

Finally, to corroborate our pharmacological findings, we transfected control and shEZH2 cells with siRNA against JAK1 or a non-targeting transcript, and validated knockdown of EZH2 and JAK1 by western blot (Fig. 4H). Total JAK1 protein is induced 1.2-fold upon EZH2 knockdown (2-way ANOVA; $p<0.05$). JAK1 RNA interference reduced JAK1 protein levels in both control (2-way ANOVA; 1.6-fold, $p<10^{-3}$) and shEZH2 cells (2.4-fold, $p<10^{-4}$) (Fig. 4I). Knockdown of JAK1 expression in shEZH2 cells was sufficient to rescue pY705-STAT3 levels to that of control cells transfected with non-targeting siRNA (2-way ANOVA; 2.0-fold, $p<0.01$) (Fig. 4J). These data support the hypothesis that CP690550 rescues STAT3 hyperactivation primarily through targeting JAK1.

Transient JAK inhibition acutely post-SE rescues epileptic phenotypes in EZH2 knockout mice.

To test whether loss of EZH2-mediated regulation of JAK1 contributed to the exacerbated disease progression observed in EZH2 mutant mice, we treated EZH2nWT and EZH2nHet mice with CP690550 after induction of SE. Because the hyper-induction of pY705-STAT3 in mutant mice occurred already at day 1 post SE (Fig. S10A-C), we injected mice with CP690550 or vehicle at 6, 12, and 24 hours post-SE. A cohort of mice was sacrificed three hours after final injection to assess hippocampal STAT3 activation by western blot to confirm target engagement (Fig. S10D-E). Consistent with the previous result (see Fig. 1B), neuronal deletion of EZH2 did not alter fluorothyl seizure threshold in naïve mice (Fig. 5B). CP690550 treatment raised the 4d. post-SE seizure threshold of EZH2nHet mice by 30 seconds (1-way ANOVA; $p<0.05$), rendering them indistinguishable from epileptic EZH2nWT mice (1-way ANOVA; $p>0.05$) (Fig. 5C). Thus, CP690550 rescued the increased seizure susceptibility phenotype associated with the loss of neuronal EZH2. These data support the hypothesis that EZH2 maintains seizure threshold post-SE by tempering activation of the JAK/STAT pathway.

To test whether transient CP690550 treatment immediately after SE mitigated long-term disease progression, mice were video recorded from weeks five to seven post-SE (Fig. 5A). CP690550 treatment immediately after SE reduced daily seizure frequency by 41% in EZH2nHom mice 5 weeks later (1-way ANOVA; $p<10^{-4}$). EZH2nHom seizure frequency was reduced from 2.6-fold above EZH2nWT to 1.5-fold (1-way ANOVA; $p<0.01$) (Fig. 5D). EZH2nHom mice treated acutely with CP690550 also exhibited a dramatic reduction in seizure

severity from untreated EZH2nHom mice (Mann-Whitney test; U:138.5, $p<0.01$), such that they were indistinguishable from WT mice (Fig. 5E).

To test whether CP690550 could rescue the increased seizure burden of EZH2nHom mice if administered during the chronic period, we recorded spontaneous seizures for two weeks post-SE in EZH2nWT and nHom mice starting 5 weeks post SE, followed by another 2-week recording period during which the EZH2nHom mice received daily injections of CP690550 (Fig. 5A). Daily CP690550 treatment in the chronic period reduced seizure severity and frequency by 80% in EZH2nHom mice (1-way ANOVA; $p<10^{-4}$) (Fig. 5F-G). Indeed, seizure frequency of EZH2nHom+CP mice was reduced to below EZH2nWT levels (1-way ANOVA; 1.9-fold, $p<10^{-3}$). Given the robust seizure suppression when administered during the chronic period, we considered the possibility that CP690550 may simply be an anticonvulsant. To test this, we measured seizure threshold using both flurothyl and PTZ (pentylenetetrazole)[57,58] in mice pre-treated with vehicle or CP690550 (15mg/kg, i.p.) thirty minutes prior to testing. This time was chosen because peak plasma levels are observed thirty minutes after oral administration[59] CP690550 pre-treatment had no effect on flurothyl or PTZ seizure threshold (Fig. S10F-G).

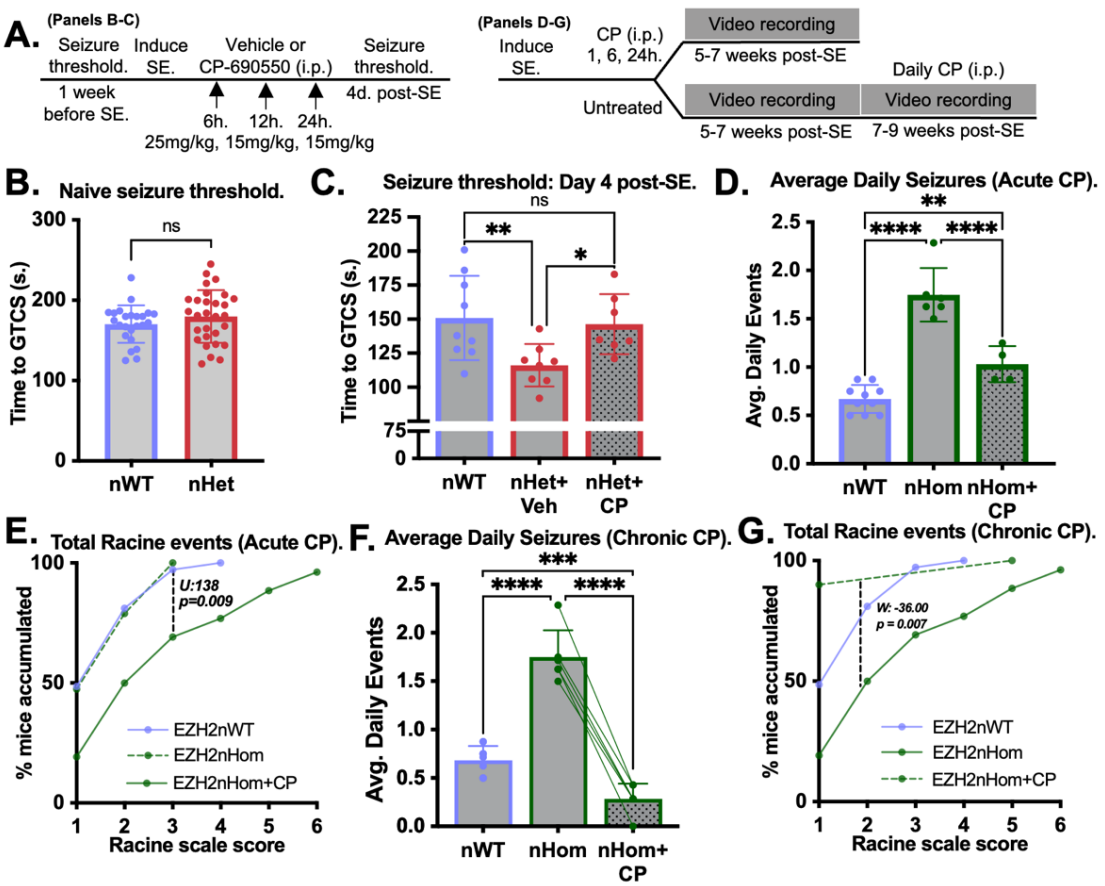

Fig. 5. JAK inhibition rescues seizure threshold reductions and spontaneous seizure burden in EZH2nKO mice. **(A)** (For panels B-C) Naïve seizure threshold was measured in C57 EZH2nWT and nHet mice one week prior to KA injections. **(B)** Deletion of an EZH2 allele does not alter seizure threshold in naïve mice (unpaired t-test; p=0.246; n=24-29). (**C**) nHet mice were injected with vehicle or CP690550 at 6, 12, and 24h. post-SE. Seizure threshold was measured 4 days post-SE. Untreated nHet mice show a 35 second reduction in seizure threshold (p=0.007) compared to nWT mice. CP690550 raises seizure thresholds of nHet mice by 30 seconds (p=0.025), extinguishing the difference between treated nHet and nWT mice (p=0.709) (1-way ANOVA; n=7-9). (**D**) FVB EZH2nWT and nHom mice received CP690550 or no treatment at 1, 6, and 24h. post-SE, and SRS activity was monitored by video from 5-7 weeks post-SE (see panel A). nHom mice treated acutely 6,12 and 24 hours post-SE with CP690550 exhibit a 41% reduction in daily seizures compared to untreated nHom mice ($p<10^{-4}$); a 34% difference remains between treated nHom mice and nWT mice (p=0.0073) (1-way ANOVA; n=4-10). **(E)** Racine scale events represented as a frequency distribution. Acute CP690550 treatment reduces seizure severity in nHom mice (Mann Whitney; U:138.5, p=0.009; n=4-10) to nWT levels (U:357, p=0.955). 50% of nWT and treated nHom mice had Class I seizures, while 50% of untreated nHom mice had Class I and II seizures. **(F)** SRS activity was monitored from 5-7 weeks post-SE, after which nHom mice received daily 10mg/kg CP690550 injections during monitoring from 7-9 weeks post-SE (see panel A). CP treatment reduced daily seizures by 80% in nHom mice ($p<10^{-4}$); treated nHom mice exhibit daily seizure frequencies 58% lower than nWT mice (p=0.0008) (1-way ANOVA; n=6-10). **(G)** Total observed Racine scale events represented as a frequency distribution. Daily CP690550 reduces seizure severity in nHom mice. 90th percentile seizure severities of nHom mice before and after treatment: 5.3 and 1, respectively (Wilcoxon matched pairs signed rank; W:-36.00, p=0.007, n=6). 90th percentile severity of WT mice: 2.6 (Mann Whitney test comparing nWT and treated nHom mice; U:119, p=0.042; n=6-10).

CP690550 profoundly suppresses electrographic and behavioral spontaneous seizures in epileptic WT mice.

CP690550 treatment during the chronic period reduced seizure frequency in EZH2nHom mice to below WT levels, so we tested its effect on WT epileptic mice. Chronic administration of CP690550 following intrahippocampal injection of kainate (IHKA) in WT epileptic mice significantly diminished spontaneous

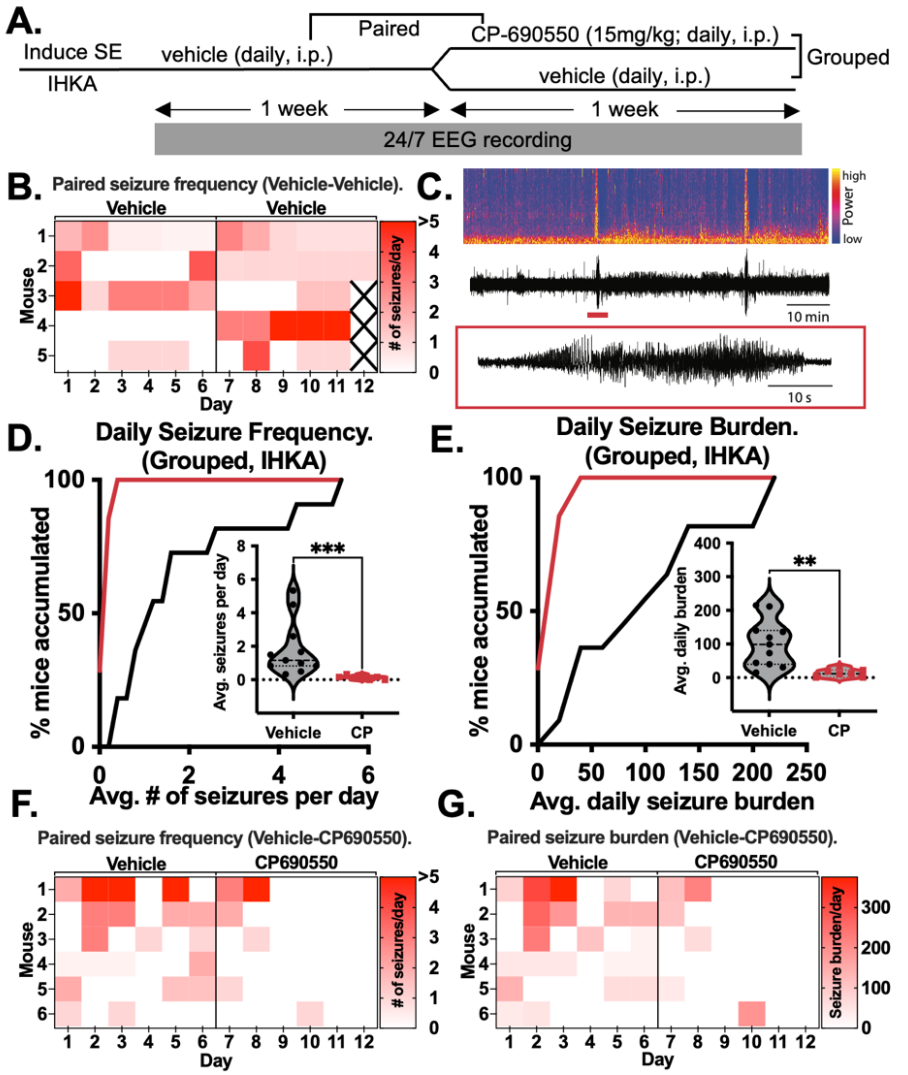

Fig 6. CP690550 profoundly suppresses spontaneous seizures in epileptic wildtype mice. **(A)** SE was induced via IHKA, and mice equipped with EEG headmounts. All under continuous EEG recording, vehicle (i.p.) was administered daily for one week followed by one week of daily vehicle or CP690550 treatment (i.p., 15mg/kg). **(B)** Vehicle-treated mice have spontaneous seizures across both weeks of the experiment. **(C)** Example power spectrum, trace, and seizure. **(D-E)** Grouped comparisons for seizure frequency and burden were displayed as a cumulative frequency distributions and violin plots. For cumulative graphs, bin centers are marked. 50% of vehicle-treated mice had up to 1.1 seizures per day on average, while 50% of CP-treated mice had up to 0.1 seizures per day. 50% of untreated mice showed seizure burdens of 99 per day, while 50% of treated mice showed burdens of up to 11 (Kolmogorov-Smirnov test; **Frequency:** D:0.9091, p=0.0003; **Burden:** D:0.7083, p=0.0162; n=5-12). **(F-G)** Heat maps display paired data for seizure frequency and burden. With the exception of one seizure observed on day 10, CP treatment eliminated seizures for the last four days of treatment.

recurrent seizures. In a paradigm involving one week of daily vehicle (i.p.) administration followed by an additional week of either vehicle or CP690550 injections (15mg/kg, i.p.) under continuous EEG recording (Fig. 6A), CP690550 treatment during the chronic period profoundly suppressed spontaneous seizures. Notably, 50% of vehicle-treated mice exhibited up to 1 seizure per day, with corresponding daily seizure burdens up to 99 (Fig. 6D-E). In contrast, 50% of CP690550-treated mice displayed up to 0.1 seizures per day, with daily seizure burdens up to 11. CP690550 treatment robustly reduced both spontaneous seizure frequency (Kolmogorov-Smirnov test; D:0.9091, $p<10^{-3}$) and burden (D:0.7083, $p<0.01$) in epileptic wildtype mice.

Additionally, while all animals experienced seizures during vehicle treatment, 17% of mice experienced no seizures at all during CP690550 treatment (Fig. 6F-G). Animals treated with vehicle throughout the experiment exhibited seizures consistently, contrasting with the profound reduction observed during CP690550 treatment (Fig. 6B, F-G).

Next, we continued exploration of CP690550's antiepileptogenic potential by inclusion of the systemic kainate model of epilepsy, as well as adopting video-based behavioral seizure monitoring. These experimental modifications aimed to generalize the efficacy of CP690550 across epilepsy models, minimize potential confounding effects introduced by headmount implantation, and prioritize clinically relevant seizure endpoints. Additionally, expansion of the observation period by two weeks after drug washout provided insights into any potential disease-modifying effects of CP690550 (Fig. 7A). Using a different model of epilepsy and method of seizure detection, we showed that CP690550 substantially curtailed seizures.

During weeks 11-12 post-SE, 75% of vehicle-treated mice exhibited up to 1.6 seizures per day and seizure burdens up to 10.7, while 75% of CP690550-treated animals had up to 0.05 seizures per day with seizure burdens up to 0.5 (Fig. 7B-C) (Kolmogorov-Smirnov test; **Frequency:** D:0.8333, $p<0.05$, **Burden:** D:0.8333, $p<0.05$). In paired analyses, vehicle-treated mice exhibited ongoing spontaneous seizure activity[60] (Fig. 7D,G), while CP690550 markedly suppressed seizures (Fig. 7E,H). CP690550 eliminated seizures in 60% of mice during treatment, and 40% of mice across both treatment and washout.

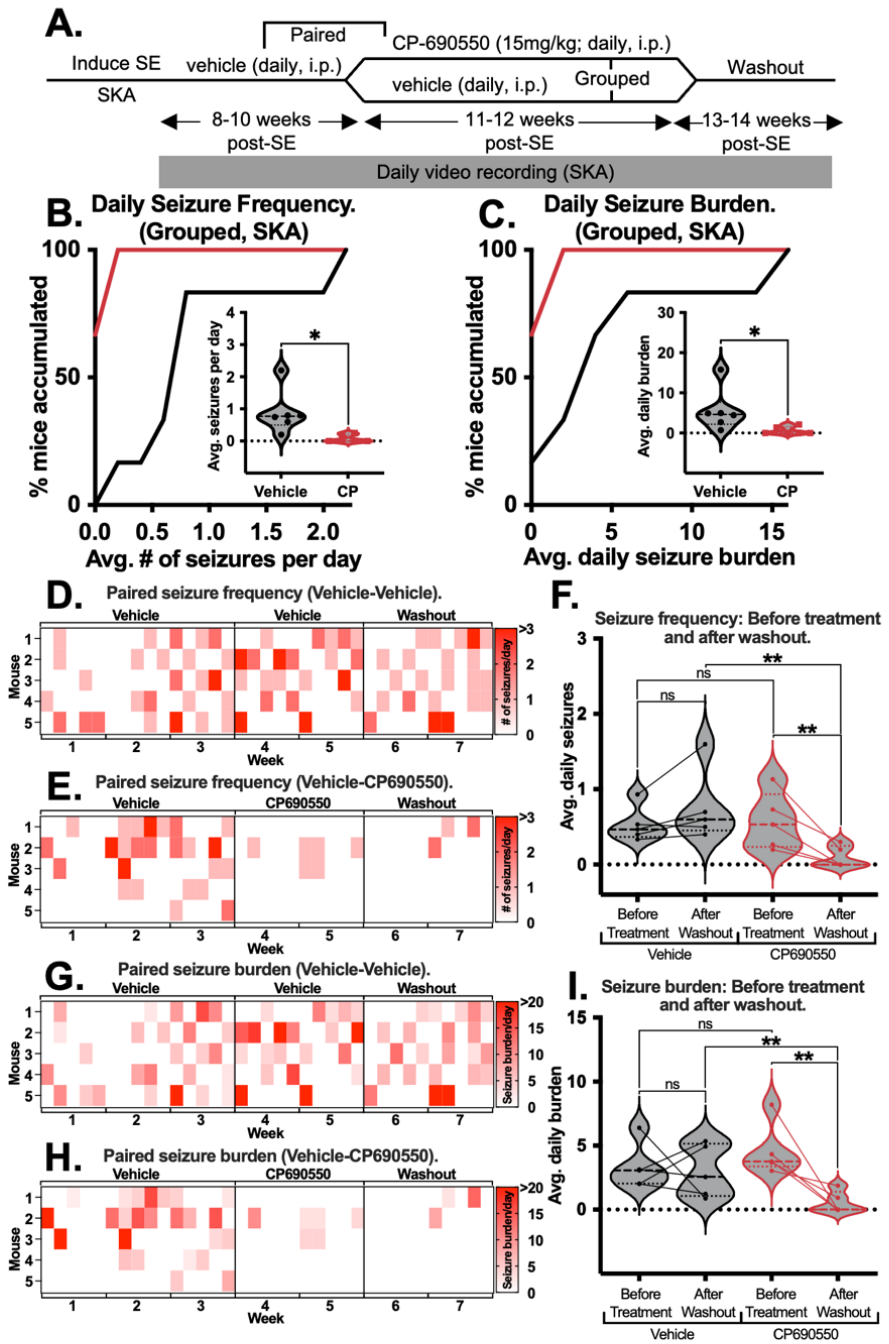

Fig 7. CP690550 profoundly suppresses spontaneous seizures in epileptic wildtype mice. **(A)** SE was induced via systemic kainate (SKA), and behavioral spontaneous seizure activity was monitored by video from weeks 8-14 post-SE. Vehicle (i.p.) was administered daily for three weeks followed by two weeks of daily vehicle or CP690550 treatment (i.p., 15mg/kg). Video recording continued for two weeks after drug washout. **(B-C)** Grouped comparisons for seizure frequency and burden were displayed as a cumulative frequency distributions and violin plots. For cumulative graphs, bin centers are marked. 75% of vehicle-treated mice had up to 1.6 seizures per day with daily burdens up to 10.7, while 75% of CP-treated mice had up to 0.05 seizures per day with daily burdens up to 0.5 (Kolmogorov-Smirnov test; **Frequency:** D:0.8333, p=0.015; **Burden:** D:0.8333, p=0.026; n=6-7). Heat maps display paired data for seizure frequency **(D-E)** and seizure burden **(G-H)**. CP690550 treatment eliminated seizures in 40% of mice during weeks 11-12 post-SE. Seizure frequency **(F)** and seizure burden **(I)** before treatment and after washout for vehicle- and CP690550-treated animals. Vehicle-treated mice show no robust change in seizure frequency (p=0.106) or burden (p=0.115) from before treatment to washout, while CP690550-treated mice exhibit an ongoing 83% reduction in frequency (p=0.005) and 88% reduction in burden (p=0.009) after drug is withdrawn. Compared to vehicle-treated mice during washout, this represents an 87% reduction in frequency (p=0.006) and 81% reduction in burden (p=0.002) (2-way ANOVA; n=5).

Drug washout occurred over the weekend following week 12 post-SE[59]. Mice treated with CP690550 continued to show profound seizure reduction for at least 2 weeks post-washout compared to vehicle-treated mice (2-way ANOVA; **Frequency:** 87% reduction, p<0.01, **Burden:** 81% reduction, p<0.01). This data supports the hypothesis that CP690550 exerts robust disease modification in a preclinical rodent model of epilepsy.

DISCUSSION

We show that CP690550 (Tofacitinib), an FDA approved, orally available drug with no known behavioral side effects, exerts a potent and enduring seizure-suppressive effect when administered transiently across rodent preclinical epilepsy models. We demonstrate that CP690550 shuts down a pro-epileptic gene network centered around STAT3 by inhibition of JAK1, an endogenous gene target of the protective chromatin modifier EZH2. We provide evidence that the STAT3 upstream kinase JAK1 is a novel therapeutic target for seizure suppression and disease modification across epilepsy models.

After status epilepticus, we find EZH2 protein is potently induced in hippocampal pyramidal and dentate granule neurons across models of epilepsy[23]. Previously, we reported that treatment of mice with the SAM-competitive EZH2 inhibitor UNC-1999 exacerbated spontaneous seizures, and here we find that deletion of EZH2 in mature neurons has the same effect. Induction of Polycomb group (PcG) proteins has been studied in association with other brain insults. For example, sublethal ischemic insults lead to induction of PcG proteins in mouse cortical neurons, and *in vitro* overexpression of PRC1 component BMI1 was sufficient to protect against oxygen-glucose deprivation-associated injury[61]. Further, sevoflurane (a volatile anesthetic that exerts positive allosteric modulation on $GABA_A$ receptors[62] and antagonizes NMDA receptors[63]) mediates the protective induction of EZH2 and H3K27Me3 to attenuate hypoxic-ischemic brain injury, reducing hippocampal autophagy and improving post-injury behavioral

522 assessments in rats. Intriguingly, these improvements are reversed when rats treated with sevoflurane also
523 receive a dose of the EZH2 inhibitor GSK126[64]. These studies, along with our findings, point to a potentially
524 general protective role for EZH2 in brain insults.
525
526 EZH2 deletion in neurons results in large transcriptomic changes that manifest after SE (Fig. 2). The mouse
527 Black gene cluster houses genes whose expression are relatively unchanged in naïve EZH2nWT and
528 EZH2nHom animals, induced after SE in EZH2nWT, and hyper-induced in EZH2nHom mice after SE. This
529 pattern suggests that EZH2 might be responsible for tempering expression of genes in this cluster because its
530 deletion results in their unfettered activation. The Black cluster ontological analysis produces terms associated
531 with innate immunity, neuroinflammation, and the JAK/STAT pathway. Network analysis places STAT3 in the
532 center of the Black GRN, and immunofluorescence confirms induction of STAT3 in neurons post SE. While
533 activation of the JAK/STAT pathway in non-neuronal cells post-SE is well-characterized[26,47,65,66], the role of
534 STAT3 in neurons, especially in epilepsy, has been less studied; thus the mechanisms of neurogenic
535 inflammation post-SE are not clear[45]. Cytokines released from glial cells following seizures increase neuronal
536 excitability[67], and type I IFNs increase excitability in neocortical pyramidal neurons via PKC[68]. Others report
537 that seizure-induced activation of the JAK/STAT pathway reduces the number of gamma-aminobutyric acid
538 (GABA) type A alpha1 receptors expressed in neurons following seizures, influencing GABA(A)R-dependent
539 inhibition[27]; this group has also utilized pharmacological inhibition of STAT3[32] and genetic ablation of the
540 STAT3 SH2 domain[45] to reduce spontaneous seizure frequency in rodent models of epilepsy. Thus, activation
541 of neuroinflammatory pathways, including the JAK/STAT pathway, has been shown to modulate neuronal
542 excitability. However, our work is the first to identify an endogenous protective mechanism induced by SE that
543 works to temper JAK/STAT activation and associated neurogenic inflammation. Our's is also the first to
544 demonstrate an enduring protective effect of targeting this pathway in chronic epilepsy after the onset of
545 spontaneous seizures.
546
547 In order to understand the mechanism by which EZH2 suppresses STAT3 activation, and to rule out the
548 possibility that STAT3 hyper-induction in EZH2 mutant mice might be a consequence of worsened disease
549 progression more generally, rather than loss of EZH2 *per se*, we turned to an *in vitro* cell line model. Knocking
550 down EZH2 in N2A cells results in induction of STAT3 Y705 phosphorylation. This activation is not via
551 secretion of soluble factors as swapping media from control and knockdown cells fails to activate STAT3 (data
552 not shown). WP1066, a JAK2 inhibitor[51-53] fails to suppress activated STAT3 in shEZH2 cells whereas
553 CP690550 (a JAK1/3 inhibitor) (Fig. 4B-C) and direct knockdown of JAK1 (Fig. 4H-J) succeeds. Given that
554 JAK3 is not expressed in these cells, we conclude that EZH2 tempers JAK1. Finally, we find that EZH2 directly
555 interacts with the JAK1 locus (Fig. 4G). Increased activation of STAT3 at pY705-STAT3 as a result of EZH2
556 inactivation has also been observed in a transformed murine cell model of early T cell precursor acute
557 lymphoblastic leukemia; EZH2 inactivation leads to enrichment of documented STAT3 target genes, increased
558 expression of IL6RA, and an exaggerated pY705-STAT3 induction in response to IL6 stimulation[69]. STAT-
559 upstream receptors and kinases are also regulated by EZH2. In prostate cancer EZH2 directly targets the
560 interferon gamma receptor gene INFGR1 to dampen JAK2/STAT1 signaling, and EZH2 depletion restores
561 expression of IFN target genes as well as STAT1 phosphorylation.[70]
562
563 Others have identified EZH2 as an activator of JAK/STAT signaling as well as a target of the pathway. When
564 phosphorylated by AKT at serine 21, EZH2 disassociates from Polycomb to enhance STAT3 transcriptional
565 activity through di-methylation of STAT3-K49 in glioblastoma cells[71-73]; we have performed western blotting to
566 assess this posttranslational mark in mouse hippocampi post-SE and find no change in STAT3-K49Me2 after
567 seizures or deletion of EZH2 (data not shown). Thus, this mechanism does not appear to play a role in N2As or
568 the mouse brain. In NK/T-cell lymphoma, JAK3 phosphorylates EZH2 to mediate a switch in its function,
569 promoting the transcriptional upregulation of oncogenes through the interaction of EZH2 and Pol-II[74]. To our
570 knowledge, ours is the first report of EZH2 repressing JAK/STAT activation through JAK1.
571
572 Analysis of human TLE samples identifies a cluster of genes strikingly similar to the STAT3-driven mouse
573 Black cluster; the human Brown cluster is a group of genes associated with innate immunity and
574 neuroinflammation. Like the mouse Black cluster, the most influential driver of gene expression is STAT3. This
575 is a possible explanation for why CP690550 suppresses disease whether it is administered shortly after SE
576 (Fig. 5), or after the onset of spontaneous seizures (Fig. 6). The robust overlap between clusters of genes, one
577 from frankly epileptic human samples and another from rodents, suggests a couple of points. Firstly, EZH2-

STAT3 mediated mechanisms identified in mice are clinically relevant. Secondly, the EZH2-STAT3 mechanism evoked acutely after insult plays a role later in chronic epilepsy; this is supported by the identification of STAT3 as a driver of gene expression, its transient activation acutely post-SE, and its reactivation in chronic rodent epilepsy (see Fig. 3).

EZH2nKO mice show both a decreased seizure threshold 4 days post SE as well as exaggerated seizure burden 5 weeks later compared to WT mice. CP690550 administration for 24 hours post-SE is sufficient to rescue both these phenotypes. This suggests that STAT3 hyper-induction drives seizure threshold reductions and spontaneous seizure increases in mutant mice. The observation that CP690550 profoundly suppresses spontaneous seizures when administered to EZH2nHom mice during the chronic period is consistent with reactivation of JAK/STAT signaling during the chronic period (Fig. 3E-G, 5F-G, 6C-K). This supports the possibility that mechanisms involved in disease initiation (e.g., activation of neuroinflammatory pathways) continue to perpetuate disease chronically. Leveraging the brain's own protective mechanism, we use CP690550 to buttress EZH2 suppression of JAK1. CP690550 profoundly suppresses seizures in WT epileptic mice across models of epilepsy. Following cessation of CP690550 treatment we observe robust disease modification for at least two weeks. Whether this disease-modifying effect is permanent will be the focus of future studies in the lab.

Anti-inflammatory drugs that have been used to suppress seizures in human patients[28-31] or have shown antiepileptogenic potential[32-35] in rodents pose several drawbacks: some or all are proposed only as supplemental therapies[28,29], risk worsened disease outcomes[29], show only transient effects[30], or are effective in only a subset of epilepsy patients[29,31]. We argue that an approach involving multiple animal models and multiple laboratories to identify drivers of disease increases the likelihood that druggable targets will be viable across human etiologies. With this approach we identify EZH2 as a protective negative regulator of the JAK/STAT pathway in epilepsy. Our current data is consistent with the hypothesis that CP690550 mitigates spontaneous seizures in chronic epilepsy and is disease-modifying. The cross-model approach by which we identified JAK1 and selected CP690550 suggests this drug may be useful across multiple epilepsies.

Recently, others find that neuron-specific deletion of the STAT3 SH2 domain plateaus, but does not reduce, seizure frequency in chronic epilepsy[45], whereas CP690550 treatment greatly reduces seizures. The explanation for this difference may be that there is incomplete ablation of STAT3 in their model, or it may suggest that the more robust therapeutic effect of CP690550 is attributable to JAK/STAT pathway suppression in non-neuronal cells (e.g., peripheral immune cells, microglia, etc.) as well as neurons.

The JAK/STAT pathway is likely one of many processes orchestrating disease progression. The data presented here represents the first evidence that EZH2 regulates JAK/STAT function through JAK1/STAT3 in epileptogenesis to suppress disease progression. Transient treatment with CP690550 not only mitigates exaggerated disease in EZH2 mutant mice, but is seizure suppressing and chronically disease modifying in WT mice in two different epilepsy models. Together, these data suggest an ongoing interplay between EZH2 and the JAK/STAT pathway, starting in early epileptogenesis and persisting in chronic epilepsy.

We conclude that EZH2 tempers the JAK/STAT pathway in epilepsy as a protective response but is ultimately overwhelmed. Buttressing this protective program with the FDA approved, orally available drug CP690550 thwarts disease progression and offers a novel therapeutic approach to treating epilepsy.

METHODS

Bioinformatics

Reads were mapped to the mm39 build mouse genome and subjected to Likelihood Ratio Tests using Deseq2[75]. Transcripts per million were calculated and genes were classified as expressed if they had at least 3 TPM in all samples of any one of the 4 conditions (saline:WT, kainate:WT, saline:EZH2nHom, kainate:EZH2nHom). Deseq2 output was then filtered for only expressed genes and adjusted p-values were recalculated for the reduced number of genes. Genes with an adjusted $p<.01$ and 1.2-fold change were subjected to Leiden clustering with resolution=0.5 using the scanpy Leiden tool[76]. Ontology was performed on all clusters using Ontomancer (manuscript in preparation). Briefly, Biocarta, Hallmark, KEGG, and Reactome

.gmt files were downloaded from https://www.gsea-msigdb.org/gsea/downloads.jsp. Gene sets associated with every term in the databases were collected. For each Leiden cluster, Scores (S_t) for each term, t, were calculated as:

$$S_t = \sqrt{(\log\ O_t)^2 + (-\log P_t)^2}$$

Where O_t and P_t, are the odds ratio and p values from Fisher exact tests for the overlap of Leiden cluster genes and genes for each term t. Only terms with odds ratios>1 and p values<0.05 were kept for further analysis. For each term, a gene list is generated containing the overlap of genes in the cluster and term, G_t. A term x term similarity matrix was generated where similarity between term i and j is the Fisher exact test log odds ratio $O_{i,j}$ for the intersection of genes in the terms G_i and G_j. This was converted to a network where nodes are terms. Edge weights were calculated as:

$$weight = (\log(O_{i.j}) / \max \log O)^6$$

Where max log odds is the maximum log odds value across all comparisons. The 6 power was used to separate nodes for visualization. Networks were generated using the scanpy Leiden tool with resolution=2. Each community was named after the highest scoring term in that community. Networks were visualized via Python's networkx and Plotly tools.

MAGIC was performed on all clusters essentially as described[21] but with r=1, and GTFs were ignored. GTFs were defined as any ENCODE Factors containing the strings "TBP", "POL", "GTF", or "TAF".

Gene Regulatory Network was projected using Cytoscape[77] using MAGIC outputs. Factors were connected to their targets with edges defined as ChIP signal extracted from the Target Folder generated by MAGIC. Target genes of Factors that were not themselves Factors were removed to generate the GRN. Network statistics were calculated in Cytoscape[77].

Analysis of human TLE expression data.

GSE63808[50] from GEO contained 129 transcriptomes from resected hippocampal TLE tissue. Probes with an Illumina p-value<0.05 in at least 20% of samples were retained in the analysis; the probes were consolidated to gene symbols by taking the median probe expression value per symbol. These 9076 genes formed the background list for ontological and MAGIC analyses. Expression values were normalized by the median expression value in that sample. Genes kept for further analysis exhibited variance greater that the median coefficient of variance across all samples. The resulting 7658 unique genes were subjected to k-means clustering using the k-means tools from Sci-kit learn[78] to divide genes into 10 clusters (brown, blue, purple, skyblue, grey, orange, indigo, green, yellow, red).

Overlap between each of the 10 human TLE clusters with mouse Black cluster genes was measured by Fisher exact test with the Benjamini-Hochberg correction for multiple comparisons. Ontological and MAGIC analyses were performed on the highest-scoring human Brown cluster as described in the previous section.

Cell culture conditions, lentiviral knockdown, and PRC2 overexpression.

Cells were grown in 5% CO_2 at 37°C. Neuro2a cells were grown in MEM (#10-009-CV Corning, Manassas, VA) with 1.0g/L glucose, 1.5g/L L-Glutamine, and 10% fetal bovine serum (#26140-079 Gibco, Grand Island, NY). Stable EZH2 knockdown in Neuro2a cells for western blot and RNA analysis was achieved using SMARTvector lentiviral delivery of shRNA per the manufacturer instructions. Puromycin selection began 48 hours after infection and maintained during cell expansion and experimentation. SMARTvector lentiviral mouse EZH2 mEF1a-TurboRFP shRNA (#V3SM7592-232015353, Dharmacon, Lafayette, CO) targeted the sequence *ATCGTAGTAAGTACCAATG*, and non-targeting mEF1a-TurboRFP control particles (#S10-005000-01) were used as an infection control.

For overexpression of Polycomb, all plasmids were ordered and modified (if necessary) from Addgene (Watertown, MA). Control cells were transfected with pAdtrack-CMV (#16405). To overexpress PRC2, cells were transfected with pCMVHA-hEZH2 (#24230), pCMVHA-EED (#24231), and pCMVHA-SUZ12 (#24232). The EZH2 plasmid was modified in-house to produce an HA-EZH2-GFP fusion protein. All transfections were carried out with Lipofectamine 3000 transfection reagent (#L3000015, Invitrogen).

Animal care

All animal procedures and experiments were performed with approval from the University of Wisconsin-Madison School of Medicine and Public Health Instructional Animal Care and Use Committee, or the Institutional Animal Care and Use Committee of Emory University, as appropriate, and according to NIH national guidelines and policies.

Transgenic mice. Cre-driver and EZH2 floxed mice were ordered from Jackson Laboratories (#003966, #022616, Bar Harbor, ME). Mice were bred on a C57BL6 background. Using the previously described Synapsin1-Cre system [37] *EZH2*$^{+/-}$*; Syn1Cre*$^{+/-}$ (EZH2nHet) mice were generated by mating *EZH2*$^{flox/+}$*; Syn1Cre*$^{+/-}$ females with *EZH2*$^{flox/flox}$ and *EZH2*$^{flox/+}$ males [36]. *EZH2*$^{+/+}$*; Syn1Cre*$^{+/-}$ (EZH2nWT) mice were generated from mating pairs containing an *EZH2*$^{flox/+}$ male. To assess Cre expression, we used a reporter mouse with a lox-P flanked STOP cassette preventing transcription of tdTomato (#007909 Jackson Laboratories) [79]. Reporter males were bred with *Syn1Cre*$^{+/-}$ females to generate Cre-positive animals and Cre-negative controls.

Repeated low-dose KA model. Male and female C57BL6 and FVB mice were bred and housed under a 12-hour light/dark cycle with access to food and water *ad libitum*. C57BL6 mice were allowed to reach 4-6 weeks of age, and FVB animals 5-7 weeks of age, before undergoing experimentation. Kainate injections were performed at the same time of day (~10 A.M.), and mice were returned to home cages before the start of the dark cycle (~5 P.M.). Mice were housed with littermates for the duration of the experiment, with males and females separated at weaning.

We used a repeated low-dose kainate mouse model to induce SE. To begin, mice were weighed and singly housed in observation chambers for the duration of the injections. Mice were injected intraperitoneally (i.p.) with 5.0mg/kg synthetic kainic acid (KA) dissolved in 0.9% saline (#7065, Tocris Bioscience, Bristol, United Kingdom). At twenty-minute intervals, mice were given 5.0mg/kg injections of KA up to the third injection. The dosage was then reduced to 3.75mg/kg. Animals continued to receive 3.75mg/kg injections of KA every twenty minutes until each reached SE. The subsequent KA injection was skipped if an animal experienced two or more Class V seizures within a single twenty-minute interval. Injections resumed for the next round, unless the animal reached SE. During induction of SE, seizures were scored using a modified Racine Scale [80] where I = freezing, behavioral arrest, staring spells; II = head nodding and facial twitches; III = forelimb clonus, whole-body jerks or twitches; IV = rearing; V = rearing and falling; VI = violent running or jumping behavior. Animals were considered to have reached SE after experiencing at least five Class V or VI seizures within a 90-minute window. KA mice were observed for 1-2 hours after SE. Animals were injected with 0.9% saline (s.c.), and soft gel food was provided in home cages. In the days following injection, animals were weighed and injected with 0.9% saline (s.c.) if body weight decreased by more than 0.5g.

Pilocarpine model of status epilepticus. Adult C57Bl/6 mice (8-12 weeks old, Charles River) were injected with terbutaline (4 mg/kg ip, Sigma T2528) and methylscopolamine (4 mg/kg ip, Sigma S8502) to alleviate respiratory and cardiovascular effects of pilocarpine, then 30 min later received saline or pilocarpine (280 mg/kg ip as free base, Sigma P6503) as described[34]. After 1 h of SE, seizures were interrupted by diazepam (10 mg/kg ip).

IHKA model of status epilepticus. The intrahippocampal kainic acid (IHKA) model was employed to generate chronically epileptic mice as previously described[81]. Kainic acid (100 nL of 20 mM; vIHKA) or vehicle (100 nL of sterile saline; vIHSA) was stereotaxically injected into the hippocampus using the following coordinate (from Bregma): 3.6 mm posterior, -2.8 mm lateral, and 2.8 mm depth. Only mice which experienced status epilepticus and went on to develop spontaneous recurrent seizures were used in the current study.

743 **Fluorothyl and PTZ seizure threshold testing.** Male and female C57BL6 mice were bred and housed
744 under a 12-hour light/dark cycle with access to food and water *ad libitum*. Animals were allowed to reach 4-6
745 weeks of age before undergoing experimentation. Fluorothyl seizure threshold tests were performed at the
746 same time of day (~10 A.M.), and mice were returned to home cages before 5 P.M. Mice were housed with
747 littermates for the duration of the experiment, with males and females separated at weaning. All seizure
748 threshold tests were video recorded, and seizure behavior was scored by a blinded observer. Two tests per
749 mouse were performed: the first at one week prior to kainate injections and the second at four days post-SE.
750 Seizure threshold tests were performed on male and female EZH2nWT wildtypes and EZH2nHet
751 mutant mice using 100% bis(2,2,2-trifluoroethyl) ether (#287571, Sigma-Aldrich, St. Louis, MO). All tests were
752 performed in a fume hood. Mice were placed in an airtight 10L. Plexiglas chamber (8.5"X10.75"X6.75").
753 Fluorothyl was infused into the chamber via a peristaltic pump at a rate of 40μL/minute onto a piece of
754 Whatman filter paper placed at the top of the chamber. The time to generalized tonic clonic seizure (GTCS)
755 was recorded from the start of fluorothyl infusion. Mice reached GTCS when they exhibited a complete loss of
756 postural and motor control. After experiencing a generalized tonic clonic seizure, mice were rapidly removed
757 from the chamber, and fluorothyl infusion was terminated. Mice were transferred to a recovery cage and kept
758 isolated until motor control and normal behavior returned (~10 minutes). Mice were returned to home cages
759 after recovery. PTZ was dissolved at 5mg/mL in 0.9% normal saline, and a single 45mg/kg dose was
760 administered (i.p.). Time to generalized tonic clonic seizure was recorded.
761
762 **Long-term video monitoring for spontaneous seizures.** Male and female FVB mice were bred and
763 housed under a 12-hour light/dark cycle with access to food and water *ad libitum*. Animals were allowed to
764 reach 5-7 weeks of age before undergoing experimentation. Video recording was performed at the same time
765 of day (~10 A.M.), and mice were returned to home cages before 5 P.M. Mice were singly housed in chambers
766 for the duration of recording with access to food and water. During daily CP690550 treatment, mice were
767 weighed and injected daily before recording began. Videos were reviewed and scored by an experimenter
768 blinded to treatment and genotype using the aforementioned modified Racine scale. In the final experiment
769 described by Figure 7, only Racine class III-VI seizures were recorded. For each mouse, daily seizure burden
770 was calculated as: (Total # of seizures * Average seizure duration (s))/(Total recording hours).
771
772 **CP690550 citrate treatment of KA mice.** Following kainate injections, an independent researcher (not
773 the experimenter) randomly assigned mice to drug and vehicle conditions, and prepared both solutions. Drug
774 and vehicle solutions were coded as "A" or "B." CP690550 citrate (tofacitinib citrate) (#4556, Tocris Bioscience,
775 Bristol, United Kingdom) was dissolved in a mixture of 70% saline (0.9%)/15% ethanol/15% DMSO. The 70%
776 saline/15% ethanol/15% DMSO solution was administered as vehicle. The independent researcher provided
777 the blinded experimenter with the drug solutions and a list of all mice assigned to group A or B; this researcher
778 did not participate in any seizure threshold testing or kainate injections. CP690550 or vehicle was delivered to
779 mice intraperitoneally at 6, 12, and 24 hours post-SE. The drug doses for each of these time points,
780 respectively, were 25mg/kg, 15mg/kg, and 15mg/kg.
781
782 **Continuous EEG recording and seizure detection.**
783 At the time of stereotaxic IHKA or IHSA injections, mice were implanted with chronic EEG recording
784 headmounts (Pinnacle Technology, cat. #8201) which was affixed to the skull with 4 screws: 2 screws serving
785 as EEG leads placed in the anterior and posterior cortex, 1 as a reference ground, and 1 as the animal ground.
786 The headmounts were secured with dental cement. 24/7 EEG recordings were collected at 4 KHz using a
787 100X gain preamplifier high pass filtered at 1KHz (Pinnacle Technology, cat. #8292-SE) and tethered turnkey
788 system (Pinnacle Technology, cat. #8200).
789 Seizures were detected using a custom analysis pipeline developed in-house in python (seizy;
790 https://github.com/neurosimata/seizy) as previously described[81]. Briefly, EEG traces were automatically
791 detected using a thresholding method from traces that were downsampled (decimated) to 100 Hz and divided
792 into 5 second segments. Power (2-40 Hz) and line length were used to identify seizures. Seizures were only
793 included if two consecutive 5 second segments were classified as seizures (minimum 10 seconds length) and
794 were manually verified by an experienced investigator with expertise in electrographic seizure detection.
795 Seizure frequency was calculated as the # of seizures per day by measuring total number of seizures a mouse
796 had over a 24-hour period. The average seizure duration was calculated by taking the mean seizure duration
797 for each mouse in each recording period. For each mouse, seizure burden was calculated as: (Total # of
798 seizures * Average seizure duration)/(Total EEG recording hours).

Tissue isolation and homogenization

After KA seizure induction and/or treatment with CP690550 citrate, animals were sacrificed by rapid decapitation. Whole hippocampal hemispheres were harvested and flash-frozen in liquid nitrogen or on dry ice. Single hemispheres were lysed in Radioimmunoprecipitation Assay Buffer (RIPA: 50mM Tris, 150mM NaCl, 1% nonidet P-40, 0.5% sodium deoxycholate, 0.1% SDS) with mammalian protease inhibitor (1:1000, Sigma or 1860932 ThermoScientific) and phosphatase inhibitor (1:1000, Sigma or 78428 ThermoScientific). Protein from cell lines was harvested in Triton lysis buffer (3% 5M NaCl, 10% glycerol, 0.3% Triton X-100, 5% 1M Tris pH8.0) after PBS washes. Tissue was homogenized in lysis buffer by probe sonication (Fisher Scientific, Sonic Dismembrator, Model 100, Hampton, NH) on power 3 for two rounds, with 10 pulses per round. Supernatants were isolated by centrifugation and quantified using the DC Protein Assay (Bio-Rad, Hercules, CA) or BCA assay (ThermoScientific 23227). Protein extracts were stored at -80˚C. 5x loading buffer (0.5mM Tris, 10% SDS, 50% glycerol, 10mM EDTA, and 1% beta-mercaptoethanol) was added to each sample to reach a 1x final concentration. Extracts in loading buffer were boiled at 95˚C for 5 minutes and stored for up to one month at -20˚C until run on an acrylamide gel.

Western blotting

Protein extracts in loading buffer were loaded at 20µg per lane and resolved by electrophoresis in hand-poured acrylamide gels with a 5% acrylamide stacking layer (125mM Tris pH6.8, 5% acrylamide, 0.01% ammonium persulfate, 0.01% SDS, 0.01% TEMED) and an 8% acrylamide separating layer (375mM Tris pH8.8, 8% acrylamide, 0.015% ammonium persulfate, 0.015% SDS, 0.08% TEMED). Gels were transferred to polyvinyl difluoride membranes (PVDF; Millipore, Bedford, MA) using Tris-glycine transfer buffer (20mM Tris, 1.5M glycine, 20% methanol). Membranes were blocked with 5% bovine serum albumin (Fisher Scientific, Fair Lawn, NJ) diluted in low-salt Tris-buffered saline (w/w TBST; 20mM Tris pH7.5, 150mM NaCl, 0.1% Tween 20) with mammalian protease inhibitor (1:2000) and phosphatase inhibitor (1:2000), or Odyssey blocking solution (LI-COR, 927-60001) for 1 hour at room temperature. Primary antibodies were diluted in the same blocking buffer and incubated with membranes overnight at 4˚C. Antibodies include: EZH2 (1:1000, #5426 Cell Signaling, Danvers, MA), pY705-STAT3 (1:2000, #9145S Cell Signaling), STAT3 (1:1000, #12640 Cell Signaling), JAK2 (1:1000, #3230 Cell Signaling), JAK1 (1:1000, #3344S Cell Signaling), pY1034/35-JAK1 (1:1000, #74129S Cell Signaling), pY1007/08-JAK2 (1:500, ab32101, Abcam, Cambridge, UK), and Actin (1:10,000, #691001 MP Biomedicals) or GAPDH (1:10,000; Millipore, CB1001). The next day, the membranes were washed three times in 1X TBST and incubated with horseradish peroxidase-conjugated goat-anti-mouse or -rabbit secondary antibodies for one hour at room temperature (1:10,000, Invitrogen #31430, #31460, Rockford, IL). Membranes were subsequently washed three times in TBST, and membranes were developed in SuperSignal West Femto ECL reagent (ThermoFisher, Waltham, MA). Bands were imaged using a ChemiDoc-It Imaging System (UVP Vision-Works, Upland, CA) and quantified using UVP Vision Works software or ImageJ. Band intensities were graphed and analyzed using Prism 9 software (GraphPad Software, La Jolla, CA).

RNA extraction and clean-up for whole hippocampal RNAseq

Hippocampi were harvested from saline- and kainate-treated EZH2nWT and EZH2nHom mice on day 4 post-SE (n=5 per treatment/genotype). RNA was extracted from hippocampal tissue with Trizol (#1559602, Life Technologies, Carlsbad, CA), and concentration was determined by spectrometry. This was followed by a treatment with DNase (#AM2238, Invitrogen). RNA clean-up was carried with the RNeasy Mini Kit (#74104, Qiagen, Hilden, Germany). Purified samples were submitted to the Gene Expression core at the University of Wisconsin-Madison Biotechnology Center for library preparation and sequencing (https://biotech.wisc.edu).

Chromatin immunoprecipitation and qPCR.

4% formaldehyde was used to crosslink proteins to chromatin before neutralization of the reaction in 125mM glycine, and washes in 1X PBS (pH 7.4). Chromatin was fragmented in Triton-X lysis buffer and 1:100 protease inhibitors; lysates were sonicated and centrifuged to remove cell debris. Protein concentration of the

854 supernatant was quantified with BioRad Bradford assay reagent (#5000006). Chromatin was incubated
855 overnight at 4 degrees Celsius with antibodies against H3K27Me3 (#9733 Cell Signaling) or rabbit IgG. The
856 next day, protein A/G magnetic beads (#88803, ThermoScientific) were blocked in BSA and salmon sperm
857 DNA while chromatin samples were centrifuged, after which chromatin-antibody complexes were added to the
858 beads to incubate. Washes were performed in a low-salt ChIP buffer (1% SDS, 1% Triton X-100, 0.4% 500mM
859 EDTA, 2% 1M Tris pH8.1, 3% 5M NaCl). Decrosslinking buffer (1% SDS, 100mM $NaHCO_3$, 200mM NaCl) was
860 then added to IgG samples, H3K27Me3 samples, and inputs; decrosslinking reactions were allowed to
861 incubate overnight in a 65 degree Celsius water bath. Phenol-choloform DNA extraction was performed the
862 next day. Quantitative PCR was performed with 2x SYBR green mix (#RR420L, Takara Bio, Otsu, Shiga,
863 Japan) and primers against JAK1, STAT3, JAK2, PAX2, Hoxc10, and beta actin (primers listed at the end of
864 the methods section). Signal was calculated from standard curves generated by serial dilution of an input
865 sample, and enrichment values were expressed as fold over input. RNA for RT-PCR was extracted with Trizol,
866 and concentration was determined by spectrometry. PCR reactions were run with primers against JAK1 and
867 GAPDH. cDNA synthesis was run on the MJ Mini Thermocycler from Bio-Rad, and PCR reactions were run on
868 the MJ Research DNA Engine Opticon 2 Continuous Fluorescence Detector using Opticon Monitor software.
869
870 **Immunofluorescence**
871
872 Whole brains were harvested on day 3 or 4 post-SE, bisected sagitally, fixed in 4% paraformaldehyde,
873 dehydrated in a series of graded TBS-Tween/ethanol solutions, embedded in paraffin, sectioned at 5μm and
874 subjected to immunofluorescence for EZH2, H3K27me3, NeuN, GFAP, total STAT3, and DAPI. Heat induced
875 antigen retrieval was performed in a 10mM citric acid buffer (pH 6.0). After a blocking step, rabbit anti-EZH2
876 (1:50) (#5246 Cell Signaling), rabbit anti-H3K27me3 (1:300) (#39155 Active Motif), mouse anti-NeuN (1:200
877 ab104224 Abcam, or 1:500 MAB377 from Millipore) primary antibodies were applied and incubated overnight
878 at 4°C. Slides were washed with PBS then incubated with goat-anti-mouse or goat-anti-rabbit Alexa Fluor 488
879 (ab150113 Abcam or A11005, A11008 from InVitrogen, respectively) and goat-anti-rabbit Alexa Fluor 594
880 (ab150080 Abcam or Jackson ImmunoResearch) secondary antibodies at a concentration of 1:200 for one or
881 two hours at room temperature, followed in some experiments by two-hour incubation at room temperature
882 with Alexa Fluro 488-conjugated mouse anti-GFAP antibody (1:200) (#53-9892-82 Invitrogen). Nuclear DNA
883 was stained with DAPI (300 nM) or a DAPI-containing mounting media (#H-1200 Vector Laboratories,
884 Burlingame, CA). Slides were imaged at 20-40x magnification using a fluorescent microscope (Nikon E600
885 microscope with fluorescence or Zeiss Axio Observer A1 epifluorescence microscope). Images were captured
886 with Zeiss Axiovision or Cellsens software (Olympus Life Science Solutions, Center Valley, PA). Image
887 analysis and quantification was performed in ImageJ (NIH, https://imagej.nih.gov/ij/). EZH2 antibody specificity
888 was confirmed before usage, as shown in Fig. S1A.
889
890 **Statistical analysis**
891
892 For all statistical analysis – with the exception of RNAseq data – FDR < 0.05 corrected for multiple
893 comparisons was considered statistically significant. Data were graphed as mean ± standard deviation (SD) in
894 Prism 9 software (Graphpad Software, La Jolla, CA). Statistical tests were also performed in Prism. Western
895 blot, seizure threshold, and spontaneous seizure data was analyzed by 2-way or 1-way ANOVA with the
896 Benjamini-Hochberg FDR method for multiple comparisons, or by unpaired t-test where appropriate.
897
898 Primer List
899 mouse-JAK1-Site1 (ChIP):
900 (forward) *CTCTGCTCGCTTTCCCGGAGATGC*
901 (reverse) *CTCGGAGGCTGGAGCGTGACTTCT*
902
903 mouse-JAK1-Site2 (ChIP):
904 (forward) *TGACTCGCACCCAGCCTGAAATGG*
905 (reverse) *GCGGCCCAGTCACCCGAAGAAATA*
906
907 mouse-JAK1-Site3 (ChIP):
908 (forward) *TTCGCGGGGCAAGGGAAAGGATTC*
909 (reverse) *CCACCGCTCAGGGCTCTGGGTTTT*

mouse-JAK2 (ChIP):
(forward) *CGCCGCTGCGGGATGTGAGTGC*
(reverse) *GGAGGCGGGATCGCAGGGAGAACC*

mouse-STAT3 (ChIP):
(forward) *CGGGCGAGCGCTGTACTTCCTA*
(reverse) *AAGCGAGCCGTATCAGGGCATTTA*

mouse-PAX2 (ChIP):
(forward) *GCGGCGCTCAGTCGCGTTCATAG*
(reverse) *CTCCCCGGAGTCTGGGCAGTCCA*

mouse-Hoxc10 (ChIP):
(forward) *GCGGGGGCCCTCTGCCTAAT*
(reverse) *CCCGGCCCTGGGCTCACACT*

mouse-JAK1 (RT-PCR):
(forward) *GCGCCCAGCCTCGCTCGTC*
(reverse) *AACGCCATGGCATTGCAGTCCTCT*

mouse-GAPDH (RT-PCR):
(forward) *ACGGCAAATTCAACGGCACAGTCA*
(reverse) *TGGGGGCATCGGCAGAAGG*

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1141 **SUPPLEMENTAL FIGURES**

1142

1143 S1. Synapsin1-Cre expression and recombination occur in neurons, and conditional
1144 knockout diminishes EZH2 induction post-SE.

1145

1146 S2. Neuronal ablation of EZH2 does not alter latency to 1st Class V seizure during
1147 kainate injections.

1148

1149 S3. Ontology networks for the mouse-Black and human-Brown clusters.

1150

1151 S4. Transient induction of STAT3 in wildtype animals is observed across models of SE.

1152

1153 S5. Other STAT family proteins are hyper-induced in EZH2nKO mice.

1154

1155 S6. Western blot quantifications in shNT and shEZH2 N2A cells.

1156

1157 S7. JAK2 activity is not required for hyper-activation of STAT3 in the absence of EZH2.

1158

1159 S8. Western blot quantifications in N2A cells transfected with control plasmids or
1160 overexpressing JAK1.

1161

1162 S9. H3K27Me3 ChIP-PCR at JAK1 (Sites 1 and 3), JAK2, and STAT3.

1163

1164 S10. CP treatment window selection and target engagement.