Fork Reversal Safeguards Epigenetic Inheritance during DNA Replication Under Stress

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Abstract

During DNA replication, epigenetic information carried by histone modifications is faithfully propagated and re-established on sister chromatids, ensuring cell identity. DNA replication is tightly coupled to chromatin reassembly, therefore perturbations to DNA replication compromise epigenetic inheritance fidelity; however, the underlying mechanisms remain poorly understood. In this study, we reveal a critical role for replication fork reversal in maintaining the transmission of epigenetic information under replication stress. We show that cells defective in fork reversal exhibit reduced nucleosome density at replication forks, accompanied by the loss of parental histones during their transfer onto nascent DNA. Mechanistically, we showed that PrimPol activation leads to single-stranded DNA gaps in fork reversal deficient cells; PARylation and DNA–protein crosslinking on single-stranded DNA subsequently evicts nucleosomes. Our

findings demonstrate that replication fork reversal, a widespread physiological process, is essential not only for preserving genome integrity but also for safeguarding epigenome stability.

Introduction

In eukaryotic cells, DNA replication is not merely the duplication of genetic material; it is also a critical process for the faithful transmission of epigenetic information[1]. During each S phase of the cell cycle, DNA must be precisely duplicated, and chromatin structure must be accurately reassembled to ensure cell identity, gene expression programs, and overall genome stability[2,3]. This chromatin-based inheritance, referred to as epigenetic information, encompasses histone modifications, DNA methylation, and the regulation by non-coding RNAs[4]. Programmed regulation of epigenetic states is essential for cell differentiation and organismal development[5], whereas aberrant epigenetic changes can drive diseases and tumorigenesis[6-9]. In cancer therapy, instability of the epigenetic landscape exacerbates tumor cell heterogeneity and promotes drug resistance[10]. Therefore, elucidating the mechanisms that safeguard epigenetic stability during DNA replication is of fundamental importance.

During DNA replication, nucleosomes ahead of the fork are disassembled by the FACT (FAcilitates Chromatin Transcription) complex into one H3–H4 tetramer and two H2A–H2B dimers, which are subsequently recycled to their original positions on sister chromatids by multiple histone chaperones after DNA replication[1,11-19]. With the assistance of histone chaperones, like ASF1 and CAF1, recycled parental histones are incorporated together with newly synthesized histones to assemble nucleosomes on nascent DNA[1,20-31]. Post-translational modifications (PTMs) on parental histones serve as templates that are copied onto adjacent new histones through a “read–write” mechanism, thereby completing the replication of epigenetic

information[1,32-36]. Replication-associated factors such as MCM2, PCNA, DNA polymerases ε/α, and fork protection proteins including Tof1, Mrc1, Csm3, and Ctf4 contribute to parental histone transfer[24-26,34,37-47]. As a result, DNA replication exerts profound influence on epigenetic stability. For example, deletion of Pol E3/E4, subunits of leading-strand polymerase ε, causes enrichment of parental histones (i.e. H3K9me3) on the lagging strand, thereby activating expression of the normally repressed LINE-1 (Long Interspersed Element-1) retrotransposon[48]. Conversely, mutations in lagging-strand histone chaperones, such as MCM2-2A, lead to parental histone accumulation on the leading strand[37,38]. Simultaneous disruption of both leading- and lagging-strand histone chaperones results in the loss of parental histones and their modifications, impairing stem cell differentiation[49].

DNA replication frequently encounters obstacles such as complex structured DNA, transcription–replication conflicts, repetitive sequences, and common fragile sites (CFSs)[3,50]. Replication stress induces multiple response pathways, including fork uncoupling, ATR activation, and replication fork reversal[3,50]. Among these, the generation of single-stranded DNA (ssDNA) and fork reversal are the two most common structural intermediates, occurring in diverse cell types in response to various forms of replication stress[51]. Our previous work and those of others have shown that ssDNA can be processed by RAD51-mediated strand invasion together with multiple fork remodelers, including SMARCAL1, ZRANB3, and HLTF, to form reversed forks[51-62]. This process stabilizes replication intermediates and prevents excessive ssDNA accumulation and subsequently fulfills the proper DNA replication. When fork reversal is impaired, cells activate PrimPol to reinitiate DNA synthesis downstream of the leading strand—a process known as repriming[63,64]. Although replication can resume, this generates

abundant ssDNA gaps on nascent DNA, posing a threat to chromatin structure and genome stability[65-67].

While the roles of ssDNA and fork reversal in genome stability have been well studied, their impact on epigenetic stability during replication remains blank. Most existing studies on DNA replication and epigenetics focus on unperturbed conditions[30,31,34,37-39,41,42,47-49,68], while rarely about stressed condition [1]. It is unclear whether and how, under replication stress, fork reversal or ssDNA gaps influence parental histone recycling and nucleosome assembly. This question is particularly relevant in the context of "difficult-to-replicate" genomic regions—such as repetitive sequence regions—which account for over half of the genome and are prone to persistent replication stress, where fork reversal should occurs frequently[69]. In this case, the replication fork is in a dynamic of stalled, repair and restart. Although slow, the fork still moving forward. The epigenetic features of these regions must be faithfully inherited during replication to modulate transcription; however, how replication stress responses—particularly fork reversal—affect the epigenetic inheritance in these regions is not yet clear.

In this study, we demonstrate that replication fork reversal promotes parental histone recycling and nucleosome assembly on sister chromatids by suppressing ssDNA formation, thereby preserving epigenetic stability. In cells lacking fork reversal, activation of the PrimPol primase leads to repriming, generating ssDNA gaps that result in the loss of parental histones and their modifications. Mechanistically, ssDNA triggers PARP1-mediated PARylation and HMCES-dependent DNA–protein crosslink formation, both of which inhibit nucleosome assembly. Our findings reveal a critical role for replication fork reversal in safeguarding epigenetic stability under replication stress.

Results

Replication fork reversal deficiency reduces nucleosome density on nascent DNA under replication stress

To investigate the impact of replication fork reversal on nucleosome assembly at replication forks, we performed SILAC-iPOND-MS (Stable Isotope Labeling by Amino acids in Cell Culture - Isolation of Proteins on Nascent DNA - Mass Spectrometry) analysis in wild type (WT) U2OS cells and fork reversal enzymes, including SMARCAL1, HLTF, ZRANB3, knocking out cells (termed as FRKO) to examine protein composition on nascent DNA, upon hydroxyurea (HU)-induced replication stress (Figure 1A). Compared with wild-type cells, fork reversal–deficient cells exhibited decreased abundance of nearly all histones on nascent DNA. In contrast, the levels of the MCM2–7 helicase complex remained unchanged, indicating that histone reduction was not due to a decrease in replication fork number (Figure 1A), neither reduction of replication progression, which marked by EdU (5-Ethynyl-2'-deoxyuridine) incorporation (Figure S1A). Immunofluorescence analysis of total chromatin bound histone H3 showed no difference between fork reversal–deficient and wild-type cells (Figure S1B–E), suggesting that histone loss was restricted to nascent DNA.

To validate the mass spectrometry results, we pulse labeled nascent DNA with EdU, induced replication stress with HU, and quantified histone H3 on nascent DNA using a proximity ligation assay (PLA). Since fork reversal–deficient cells incorporate EdU more rapidly than wild-type cells (Figure S1A), direct comparison of PLA signals would not accurately reflect histone abundance (Figure 1B, 1C). Therefore, we normalized PLA signals to EdU intensity, yielding a value representing histone abundance per unit length of replicated DNA (Figure 1D). Using this

approach, we observed reduced H3 levels on nascent DNA in fork reversal–deficient cells, consistent with the results in Figure 1A by fork proteomics experiments. This reduction was observed across different HU concentrations (Figure S1F). The PLA analyses of H2A, H2B, and H4 yielded results consistent with those for H3 (Figure 1B-D, Figure S1A), indicating reduced nucleosome density on nascent DNA rather than loss of individual histone types (Figure S1G–I).

We further validated these results using ChOR (Chromatin Occupancy after Replication)-seq, a high-throughput sequencing technique to profiling the occupancy of histone (modifications) and chromatin-associated proteins on newly replicated DNA[70], which confirmed a significant reduction in histone H3 abundance on nascent DNA in fork reversal–deficient cells (Figure 1E–G, Figure S1J), consistent with the proteomic and PLA results.

These experiments were performed in U2OS cells with triple knockout of SMARCAL1, ZRANB3, and HLTF. Since each fork reversal enzyme also has unique functions independent of fork reversal, we tested whether the low nucleosome density phenotype was due to the fork reversal mechanism itself or to specific functions of individual enzymes. PLA analysis of single-knockout U2OS cells for each enzyme, also include FBH1 knockout U2OS cell line, revealed decreased histone abundance at replication forks in all cases (Figure S2A–B). Knockdown of RAD51, which is also essential for fork reversal, phenocopy FRKO cells (Figure 1H and Figure S2C). In the absence of HU treatment, PLA and ChOR-seq showed no reduction in H3 levels in fork-reversal–deficient cells (Figure S2D-F), supporting that histone loss arises specifically under replication stress.

Altogether, the data indicate that fork reversal machinery maintains nucleosome density during replication under persist stressed condition (Figure S2G).

Replication fork reversal deficiency leads to parental histone loss and chromatin decompaction

During DNA replication, parental histones positioned ahead of the fork are disassembled and subsequently recycled onto daughter DNA through highly coordinated mechanisms, where they combine with newly synthesized histones to form nucleosomes. Under conditions of persistent replication stress, the reduced nucleosome density observed on nascent DNA in fork reversal–deficient cells may arise from either impaired parental histone recycling or defective incorporation of new histones, both of which threaten faithful epigenetic inheritance. Importantly, the deposition of certain histone variants, such as CENP-A, macroH2A, and H3.3, occurs independently of DNA replication [71-73]. Thus, detection of these variants on nascent DNA reflects inheritance of parental histones, and their loss can be attributed to defective parental histone recycling (Figure 1A).

Previous studies have shown that certain histone modifications, such as di- and trimethylation of H3K9, H3K27, H3K79, and H4K20, are established on new histones many hours post-replication or even during the subsequent cell cycle, making them markers of parental histones during replication[30,38,48,49,68,74,75]. To assess whether parental histone recycling was impaired, we combined iPOND-MS with propionylation treatment to examine histone modifications at replication forks (Figure 2A). Upon HU-induced replication stress, parental histone–specific marks such as H4K20me2, H3K79me2, H3K27me3, and H3K9me3 were markedly reduced on nascent DNA in fork reversal–deficient cells (Figure 2B, Figure S3A-D). Consistent with this, marks characteristic of newly synthesized histone modifications—such as H4K5ac, H3K56ac, H4K12ac, H3K9ac, and H3K9me1[48,68]—were increased or unchanged (Figure 2B, Figure S3E-I). PLA assays corroborated the mass spectrometry findings (Figure 2C, Figure S3L). These

results suggested loss of parental histones during transmission, with a modest increase in new histone incorporation that only partially compensates for the loss, leading to an overall reduction in nucleosome density on nascent DNA.

To distinguish whether the reduction of H3K9me3 arises from replication stress or from pre-existing global changes, we performed immunofluorescence analysis. A slightly decrease in global H3K9me3 was observed only in 3KO cells following HU treatment (Figure 2D–E; Figure S3M–N), indicating that the loss of this repressive mark in fork reversal–deficient cells is specifically attributable to replication stress.

H3K9me3 and H3K27me3 are parental histone–specific marks that also indicate compact chromatin. We also detected a decrease in the abundance of another compaction marker, H3K9me2 on nascent DNA in fork reversal–deficient cells (Figure 2B, 2F), whereas global cellular H3K9me2 levels doesn't change after HU treatment (Figure S3O-R). These findings consistent with our model in which nucleosome density is reduced.

Proteomics shows loss of H3K9me3, macroH2A.1, macroH2A.2 and reduced CENP-A (Figure 1A, Figure 2B). CENP-A marks alpha-satellite DNA at centromeres, macroH2A.1, macroH2A.2 are deposited in broad chromatin, with a strong bias toward facultative heterochromatin; H3K9me3 is a major component of constitutive heterochromatin and is typically enriched at repetitive genomic elements to suppress their transcription. Our findings indicate that heterochromatin assembly at these repeats may be compromised by parental histone loss during replication. To test this, we analyzed ChOR-seq data to identify genomic regions with decreased H3 occupancy. Compared with non-repetitive regions, repetitive elements exhibited a more pronounced loss of H3, which was also dependent on HU treatment (Figure 2G). Notably, in fork

reversal–deficient cells, nearly all classes of repetitive sequences displayed significant reductions in H3 occupancy (Figure 2H). Previous studies have shown that parental histone loss can lead to transcriptional activation of heterochromatic regions. We therefore examined whether histone loss at repeats during replication results in transcriptional derepression. CUT&RUN-seq profiling of the active transcription mark H3K4me3 revealed both global and repetitive elements increase in FRKO cells (Figure 2I-J). Collectively, these results demonstrate that fork reversal deficiency causes parental histone loss, leading to compromised heterochromatin integrity at repetitive regions.

PrimPol-mediated repriming causes nucleosome density reduction

Next, we want to understand how fork reversal deficiency lead to low nucleosome density and parental histone loss. Histone chaperones are responsible for histone deposition. We asked if fork reversal deficiency impairs the recruitment of parental histone chaperones to the DNA replication fork. In our proteomic dataset from fork reversal–deficient cells, nearly all known histone chaperones localization at replication fork were not altered, compared to wild type (Figure 3A), suggesting that the loss of parental histones and reduced nucleosome density were not due to defects in histone recycling.

We noted that PrimPol (Primase And DNA Directed Polymerase) levels at replication forks were elevated after HU treatment in fork reversal–deficient cells (Figure 1A), consistent with previous reports of PrimPol activation under fork reversal defects[63,64,76]. We hypothesized that PrimPol activation contributes to nucleosome density loss. Following HU treatment, fork reversal deficient cells exhibited abundant ssDNA gaps on nascent DNA (Figure 3B, Figure S4B–D), mild DNA damage (Figure S4E–F), and a slight cell cycle arrest in G1 phase (Figure S4G).

To test whether PrimPol activation was responsible for reduced nucleosome density, we depleted PrimPol in FRKO cells by siRNA or CRISPR–Cas9 and measured nucleosome density on nascent DNA by PLA. PrimPol loss rescued the reduction in nucleosome density (Figure 3C–D, Figure S4G) and restored H3K9me2/3 levels on nascent DNA (Figure 3E–F). To further determine whether nucleosome loss was due to increased PrimPol protein or its catalytic activity, we reintroduced either wild-type PrimPol or a catalytically inactive point mutant (AxA (catalytic inactivate), CH (primase dead, polymerase competent) mutants) into PrimPol-knockout cells. Only wild-type PrimPol restored nucleosome density loss, demonstrating that repriming activity per se drives the phenotype (Figure 3G-H). Collectively, these results show that in the absence of fork reversal, activation of the PrimPol-mediated repriming pathway leads to parental histone loss and reduced nucleosome density on nascent DNA.

Single-stranded DNA gaps cause low nucleosome density in cells

Given that PrimPol-mediated repriming produces abundant ssDNA gaps on nascent DNA, we hypothesized that ssDNA gaps per se inhibits nucleosome assembly (Figure 3I). To test this hypothesis, we examined nucleosome assembly in cells that ssDNA gaps can be generated through distinct genetic deficiencies. Firstly, loss of BRCA1 or BRCA2—key fork protection factors—combined with HU treatment leads to nucleolytic degradation of nascent DNA, PrimPol activation, and ssDNA gap formation[65,77-81]. In BRCA1- or BRCA2-deficient cells, nucleosome density at replication forks was reduced, while re-expression of wild-type BRCA1 or BRCA2 rescued the defect (Figure 4A–D, Figure S5A–D). Secondly, defects in Okazaki fragment maturation, such as knockdown of DNA ligase 1 (LIG1) or FEN1 (Flap Endonuclease 1), cause ssDNA gaps on the lagging strand[81], which also reduced nucleosome density (Figure 4F–G, Figure S5E–F). Finally, inhibition of RAD51 triggers nucleolytic degradation of nascent DNA

by nucleases such as MRE11, producing ssDNA gaps[80,82]. RAD51 inhibition reduced nucleosome density, and this effect was rescued by co-treatment with MRE11 nuclease inhibitor (Figure 4E, Figure S5G). Taken together, multiple distinct pathways that generate ssDNA gaps—of various origins—lead to reduced nucleosome density, supporting the hypothesis that ssDNA gaps directly contribute to nucleosome density loss.

Single strand DNA gaps do not block nucleosome assembly in the in vitro assay

Whether nucleosomes can form on ssDNA remains controversial. During DSB resection, the generation of long ssDNA tails/overhangs has been shown to evict nucleosomes in some studies[83-89], whereas others have demonstrated nucleosome formation on ssDNA in vitro[90,91], and ChIP-qPCR analyses in yeast have detected histone association with ssDNA[92]. However, whether short ssDNA gaps, as occur at replication forks, can support nucleosome assembly remains unclear.

We synthesized DNA substrates containing ssDNA gaps at the dyed (middle), or entry/exit (side) of a nucleosome, with various lengths (1–31 nt) and performed in vitro nucleosome assembly assays (Figure 5A-B). We observed nucleosomes on both DNA substrates containing up to a 31-nt gap, although their stability was reduced in dyed-gap substrate (Figure 5B). An AlphaFold model of a nucleosome containing an ssDNA gap is shown in Figure 5C and Figure 5D. Thus, in vitro, short ssDNA gaps do not preclude nucleosome formation.

PARylation suppresses nucleosome assembly on ssDNA gaps in fork reversal deficient cells

We reasoned that the ssDNA gap metabolism in cells plays critical roles in nucleosome assembly (Figure 4 and Figure 5). In general, the ssDNA intermediates can be either recognized by RPA complex to activate ATR signaling pathway, or bound by PARP1 to stimulate PARylation

mediated DNA damage repair. (phosphorylated) RPA complex is accumulated upon HU treatment in comparison with WT cells (Figure 6A and Figure S4B-E). Nonetheless, depletion of RPA1 and/or RPA2 did not rescue the low nucleosome density in fork reversal deficient cells (Figure S6B). PARylation is known to loosen chromatin structure, expose DNA to repair factors, and orchestrate DNA repair[93-99]. We therefore tested whether PARP1-mediated PARylation affects nucleosome density by deleting PARP1 in FRKO cells by siRNA. PARP1 deletion reduced PARylation and partially rescued nucleosome density despite persistent ssDNA gaps (Figure 6B-D). Inhibition of PARG, the enzyme that hydrolyzes PAR chains, increased PARylation and decreased nucleosome density in WT cells, further supporting the conclusion that PARylation reduces nucleosome density (Figure 6E and Figure S6C). Together, these findings indicate that ssDNA activates PARP1-mediated PARylation, which in turn inhibits nucleosome assembly on nascent DNA. Interestingly, treatment with the PARP1/2 inhibitor doesn't rescue the low nucleosome density in FRKO cells (Figure 6F), although the PARylation level is comparable with PARP1 depletion, and the ssDNA gaps level remain high (Figure 6D and figure 6G). We also noticed that in the WT cells, olaparib treatment reduces nucleosome density (Figure 6F), We hypothesized that the PARP1 trapping per se can evict nucleosome. This phenotype is consistent with the recent finding that PARP1 inhibition evict histones at forks, therefore, histone turnover can be determinant of PARP inhibitor sensitivity [100]. We observed FRKO cells are more sensitive to PARP inhibitor, although nucleosome didn't further decrease. The hypersensitivity to PARPi in FRKO cells may be caused by excessive ssDNA gaps.

HMCES–DPC inhibits nucleosome assembly on ssDNA

Since PARP1 deletion only partially rescued the reduction in nucleosome density, we sought additional factors that might bind ssDNA and inhibit nucleosome assembly. We noted that in

fork reversal–deficient cells, APOBEC3B levels at replication forks increased by ~1.5-fold (Figure 7A), chromatin-bound APOBEC3B increased by 3–5-fold (Figure S6I), and HMCES showed a modest increase (Figure 7A). APOBEC3B can deaminate cytosine residues, which are subsequently processed by glycosylases to generate AP sites[101]. HMCES, a PCNA-binding protein, has been shown to form covalent DNA–protein crosslinks (DPCs) at AP sites on ssDNA[102-108].

We hypothesized that in fork reversal–deficient cells, the high abundance of ssDNA on nascent DNA allows excess APOBEC3B to generate AP sites, which then form HMCES–DPCs. These DPCs could create steric hindrance that blocks nucleosome assembly. To test this, we performed RADAR assay to examine the HMCES-DPC in fork reversal deficient cells, we found that HMCES-DPC is significantly increased in FRKO cells (Figure 7B). We depleted HMCES or APOBEC3B by siRNA and measured nucleosome density on nascent DNA by PLA (Figure 7C, Figure S7B-C). HMCES depletion significantly rescued nucleosome density in fork reversal–deficient cells, whereas APOBEC3B depletion did not (Figure 7C), likely because AP sites can also form spontaneously on ssDNA independent of APOBEC3B activity. Co-deletion of PARP1 and HMCES completely restored nucleosome density in fork reversal–deficient cells (Figure 7D). HMCES loss can also activate TLS (translesion synthesis) for post replication repair[103], which in turn repair ssDNA gaps[65,76]. We next asked whether the rescue of nucleosome density by HMCES deletion was due to TLS-mediated gap repair. Inhibition of TLS using the REV1 inhibitor JH-RE-06 in HMCES-deficient cells did not reduce nucleosome density (Figure 7E), demonstrating that HMCES–DPC per se, other than the TLS activation, block nucleosome assembly.

To further validate if HMCES-DPC block the nucleosome assembly, we performed the in vitro nucleosome assembly assay. We synthesized the ssDNA gapped substrate with uracil in the middle (AP_{Dyad}) or side (AP_{end}), then treated with UNG, followed by HMCES crosslinking[103,104](Figure S7D-E). Next, we purify the substrate and assemble nucleosomes. Remarkably, the nucleosomes cannot be formed on the substrate that HMCES-DPC is located in the dyad position (Figure 7F); whereas nucleosome can still form on the substrate that HMCES-DPC at the end gaps (Figure 7G). These data indicate that HMCES-DPC forming in the interstitial ssDNA gaps, rather than the ends, impairs the nucleosome assembly directly.

Together, these findings demonstrate that in FRKO cells, PrimPol-mediated repriming generates abundant ssDNA gaps, which activate PARP1-dependent PARylation and promote the formation of HMCES–DPCs. At least these two mechanisms act together to inhibit nucleosome assembly on ssDNA gaps, thereby reducing parental histone recycling and lowering nucleosome density on nascent DNA (Figure 7H).

Discussion

A mechanistic model for fork reversal–dependent epigenetic stability

Under persistent replication stress, replication forks do not remain completely stalled but rather exist in a dynamic balance between repair and restart, progressing slowly yet continuously[109]. In general, the stalled replication fork can be repaired by fork reversal, PrimPol-mediated repriming and DNA damage tolerance machineries. Existing studies of parental histone recycling largely focus on unperturbed forks; whether and how the stalled replication fork resolution machineries orchestrate nucleosome assembly under replication stress has been unknown.

Here, we uncover a critical role for fork reversal in maintaining epigenetic stability during replication under stress. We propose a new mechanistic model: under replication stress, fork reversal suppresses ssDNA gap formation, thereby promoting parental histone recycling and nucleosome assembly on nascent DNA, and preserving the epigenetic state of the chromatin. In the absence of fork reversal machinery, PrimPol-mediated repriming generates abundant ssDNA gaps, activating PARP1-dependent PARylation and induce HMCES–DPC formation, that subsequently inhibit nucleosome deposition and lead to the loss of parental histone modifications (Figure S4A, Figure 5G). Thus, fork reversal safeguards both genome stability and epigenome stability under replication stress.

Parental histone and epigenetic information are lost in fork reversal deficient cells

Prior studies identified H3K9me3 and other marks (H4K20me2, H3K79me2, H3K27me3) as parental-histone markers at forks. By iPOND-MS (Fig. 2), these parental-histone-specific modifications decreased in FRKO cells, whereas new-histone marks (H3K9ac, H4K5ac, H3K56ac, H4K12ac) does not change or slightly increased (Fig. 2B). PLA assays corroborated these findings. Additionally, histone variants MacroH2A.1, MacroH2A.2, H3.3 and CENPA are not deposited during DNA replication and therefore derive from parental chromatin[71-73]; their loss (Fig. 1A), in FRKO cells, provides direct evidence of parental-histone loss. Altogether, these data suggest fork reversal is required to maintain parental histones during replication under persist stress.

Parental-histone loss subsequently leads to epigenome alteration and transcription dysregulation, since canonical parental-histone marks (H4K20me2, H3K9me3, H3K27me3) enforce chromatin compaction and repress transcription. More than half of the genome comprises repetitive DNA

elements, including transposons and retrotransposons, that rely on these heterochromatin marks for silencing. Consequently, the parental-histone loss can activate transcription of repetitive elements, thereby threatening genome stability. Indeed, ChoR-seq analysis of H3-depleted regions revealed reduced nucleosome density at repetitive regions during replication (Fig. 2). CUT&RUN-seq mapping of steady-state H3K4me3 showed increased signal at many repetitive-element promoters, potentially indicating their activation (Fig. 2);

Collectively, our work explains how replication-fork reversal preserves both genome and epigenome stability and highlights repetitive, replication-challenged regions as particularly vulnerable substrates for epigenetic information loss in the absence of fork reversal.

Fork-reversal deficiency selectively impairs parental-, but not new-, histone assembly

First, we tested whether fork-reversal enzymes act as required histone chaperones for parental-histone recycling—or at least as key mediators—whereas deposition of new histones does not depend on them. We found that the known histone chaperones can be properly recruited to replication forks in FRKO cells (Fig. 3A), suggesting that fork-reversal enzymes do not modulate the recruitment of known histone chaperones. However, co-depletion of PrimPol in FRKO cells rescues parental histone loss on nascent DNA (Figure 3), indicating that PrimPol mediated ssDNA gaps formation—rather than loss of fork reversal enzymes per se—drive parental-histone loss. Consistently, ssDNA gaps accumulation, by BRCA1/2-deficiency, Okazaki Fragment processing failure, knockdown of RAD51 and inhibiting MRE11, leads to parental histones loss. On the other hand, re-introducing BRCA1/2 in the BRCA1/2 deficient cells, reducing ssDNA gap formation (REF), can restore parental histone deposition onto replication fork (Figure 4, and Figure S5).

Our data support a model: in fork-reversal–deficient cells, parental histones bound to ssDNA are unstable and are evicted (Figure 3, Figure 4, and Figure 5). As ssDNA gaps are gradually repaired to generate dsDNA post-replication, re-chromatinization occurs after parental histones loss, in which new histones are deposited onto the repaired forks(Figure 2). Several observations support this model: (1) nucleosomes can form on ssDNA gaps unstably and are evicted in contexts such as BRCA1/2 deficiency, HMCES-DPC formation (in vitro and in vivo), PARylation, and in vitro nucleosome-assembly assays on ssDNA gaps; and (2) ssDNA gaps is gradually repaired—by homologous recombination (HR) in S-phase and/or by TLS in G2-phase. In our studies, both RAD51 depletion and inhibition (inhibits HR repair, in Figure 1C and Figure 4F) further reduces nucleosome density in fork-reversal–deficient cells (Figure 3C and ref.), whereas TLS inhibition does not (Figure 3D), indicating ongoing ssDNA repair in the HR setting since HU treatment traps cells in S phase.

Fork reversal is essential for both genome stability and epigenome stability

DNA replication must preserve both genome and epigenome stability. Fork reversal allows cells to maintain this integrity under replication stress. In the absence of fork reversal, PrimPol-mediated repriming enables replication restart downstream of DNA lesions to complete replication. This process preserves genome integrity at the price of generating abundant ssDNA gaps on nascent DNA, which can be repaired by post-replication repair machineries (Figure 3). However, the loss of parental histones affects the regulation of gene expression in daughter cells, since rebuilding heterochromatin relies on parental histone modifications, such as H3K9me3. Consequently, the derepression of repetitive genes activated, for example, LINE-1 is expressed upon loss of parental histones. Co-inhibition of repriming in fork reversal–deficient cells reduce

ssDNA gap formation and slows down replication, allowing parental histone recycling but increasing sensitivity to replication stress (Figure 3, Figure S4). We propose that the physiological function of fork reversal is not only to safeguard genome but also epigenome stability under replication stress.

Limitations and future directions

Although our study identifies a key role for fork reversal in regulating epigenetic stability, several important questions remain: First, fate of parental histones during fork reversal – It remains unclear whether parental nucleosomes ahead of the fork are recycled directly onto the reversed arm, released into a free pool, or repositioned via a "sliding" mechanism. Current technology does not allow real-time spatial tracking of nucleosomes during fork reversal, limiting mechanistic insight. Second, relationship between PARylation and HMCES–DPC– Whether these are independent, cooperative, sequential, or feedback-regulated pathways remains unknown. Additional ssDNA-binding proteins may work with HMCES to sterically hinder nucleosome assembly. Third, extent of compensation by new histone deposition – Although new histone marks (e.g., H3K56ac) increased in response to parental histone loss, whether this quantitatively restores nucleosome density is uncertain. Our data suggest incomplete compensation, possibly due to absence of compaction-associated marks such as H3K9me3. Fourth, epigenetic restoration post-replication – Despite loss of parental marks on nascent DNA, global H3K9me2/3 levels were unchanged, suggesting a possible post-replicative "epigenetic repair" mechanism. Whether this restoration is locus-specific remains unknown, and has implications for whether epigenetic stability is truly preserved. Fifth, feedback effects on replication fork stability – Some histone modifications lost in fork reversal–deficient cells, such

as H3K9me2/3 and H4K20me3, also contribute directly to fork protection. Whether their loss further destabilizes forks and exacerbates replication stress remains to be determined.

Addressing these questions will require integrating high-resolution chromatin mapping, single-molecule localization, quantitative proteomics, and in situ functional assays to fully elucidate chromatin fate under replication stress.

Methods

Cell lines

U2OS and MDA-MB-436 cells were cultured in DMEM with 9% fetal bovine serum (FBS)corning. PEO4, PEO1, and DLD-1 cells were cultured in RPMI-1640 with 9% fetal bovine serum (FBS). UWB1.289 cells were cultured in a 1:1 mixture of RPMI-1640 medium and Mammary Epithelial Growth Medium (MEGM), supplemented with fetal bovine serum (FBS) and antibiotics. U2OS cells for iPOND mass spectrometry experiments were cultured in SILAC-compatible DMEM (Thermo) + 10% dialyzed FBS (Thermo Fisher Scientific, catalog no. A33822; R&D Systems, catalog no. S12850H), supplemented with either isotopically light or heavy 13C, 15N lysine, and 13C,15N arginine (Cambridge Isotope Laboratories)[109]. Cells were cultured at 37°C and 5% CO2 with humidity. All cell lines were regularly tested for mycoplasma and verified using short tandem repeat profiling.

Genome editing

PrimPol knockout by CRISPR-Cas9 using the SpCas9(BB)-2A-Puro (PX459) V2.0 plasmid (Addgene #62988) as described[110] with single guide RNA (sgRNA) #1 (5'-CTGCCAAGCAAGTCAAGAGC-3'),

Label free iPOND-mass spectrometry

Proteomics changes in U2OS cells were determined using iPOND-SILAC MS as described previously[109]. Briefly, EdU labeled and indicated drug treated cells were harvested following cross-linking with 1% formaldehyde for 10 min and quenched with glycine. Cells were permeabilized in 0.25% Triton X-100/PBS for 30 min. Heavy labeled and light labeled cells were combined 1:1 prior to performing the click reaction for 2 hrs. Dynabeads MyOne Streptavidin C1 (Thermo Fisher, Cat# 65002) were utilized to capture DNA-protein complexes, washed, and elute with elution buffer (25mM biotin, 0.4% SDS, 50mM Tris-HCl Ph8.5) at 65°C for 3 hrs. Supernatant, containing eluted fractions, were incubated at 95°C for 10 mins for reverse crosslinking. For histone modification detection, lysine residues were chemically modified by propionylation for 30 min at room temperature with 2.5% propionic anhydride (Sigma-Aldrich, 8.00608) in ammonium bicarbonate (pH 7.5). Subsequently, proteins were digested with 200 ng of trypsin (Thermo Fisher, 90057) in 50 mM ammonium bicarbonate overnight, and the supernatant was desalted by C18 Stagetips (reversed-phase resin) and carbon Top-Tips (Glygen, TT1CAR) according to the manufacturer's instructions. After desalting, the eluent was speed-vacuumed dried and stored at −20°C until MS analysis.

PrimPol complementation

PrimPol WT, AxA, and CH mutants are subcloned from pcDNA3.1/nV5-DEST to pLNCX2 with forward primer: 5'-CAGATCTCGAGATGAATAGAAAATGGGAAGCAA-3', reverse primer: 5'-CTGCGGCCGCCTCTTGTAATACTTCTATAATTAG-3'. pLNCX2-Primpol WT and mutants vectors were co-transfected with p-VSVG into GP2-293 cells with Polyethylenimine (PEI). Twenty-four hours post-transfection, the culture medium was replaced with fresh medium, and viral supernatants were harvested at 48 and 72 hours. The pooled viral supernatants were subsequently used to infect U2OS Primpol knockout #206 cells. Stable cell lines were established by selection with 100 µg/ml G418.

DNA combing assays

Cells were labeled with the nucleoside analogs as indicated in the figures and figure legends. DNA combing was then performed using a DNA combing instrument as previously described[52]. The S1 nuclease digestion assay was also completed as previously described[64].

Immunofluorescence

For analysis of proteins in the insoluble/chromatin fraction, cells were detergent extracted with 0.5% Triton X-100 and subsequently fixed in 4% paraformaldehyde. Slides were blocked with 1% goat serum in PBST (0.1% triton-X100) and incubated with primary antibodies. EdU incorporation was visualized by click chemistry with an Alexa Fluor 488-conjugated azide. Immunofluorescent images were obtained and analyzed by ImageXpress microscopy and software.

PLA assay

Proximity ligation assays (PLAs) were performed using the Sigma kit (Duolink DUO92002, DUO92004, DUO92008) according to the manufacturer's instructions, with the following modifications as described previously [111]. Cells were pre-extracted and fixed as described in the immunofluorescence method, then blocked with 3% BSA and processed via click chemistry with biotin-azide and Alexa Fluor 488-conjugated azide (ratio 4:1). The following primary antibody pairs were used: rabbit H2A (CST 12349) (1:100 dilution), H3 (Abcam ab1791) (1:100 dilution), H3K9ac (Millipore 07-352) (1:100 dilution), H3K9me3 (CST 13969) (1:100 dilution), H4 (CST 13919) (1:100 dilution); mouse biotin (Millipore B7653) (1:100 dilution) and mouse H2B (Abcam ab52484) (1:100 dilution), H3K9me2 (Abcam ab1220) (1:100dilution) and rabbit biotin (CST 5597) (1:100 dilution).

CHOR-Seq

ChoR-seq assay performed as previous described[70]. ChOR-seq assay was performed on wild-type (WT) and triple-knockout (3KO) U2OS cells (three biological replicates each) to characterize histone H3 on nascent DNA following previous described (reference). In briefly, cells were labeled with 10 uM EdU for 15 min, followed by treatment with or without 1 mM hydroxyurea (Sigma, Cat. no. H8627) for 4 h. Cells were then fixed in fixation buffer A (truChIP Chromatin Shearing Kit, Covaris, Cat. No. 520127), and 11.1% formaldehyde was added to a final concentration of 1% for 10 min with gentle agitation at room temperature. The reaction was quenched by adding buffer E for 5 min. Fixed cells were washed twice in ice-cold PBS and then collected for 5 min at 500 g at 4 °C, snap-frozen, and stored at −80 °C or processed immediately. Nuclei were isolated using truChIP Chromatin Shearing Kit according to the instruction and sonicated chromatin fragments between 100 and 500 bp. Sheared chromatin was centrifuged at

14,000 rpm at 4 °C for 10 min, and the supernatant was collected for subsequent steps. In parallel, Drosophila S2 cells were labeled with 10 μM EdU for 48 h, fixed, lysed, and sonicated identically. EdU-labeled S2 chromatin was added to each sample after sonication at 0.05% (w/w) as a spike-in for cross-sample normalization. For each ChIP, 100 μg mixed chromatin were diluted up to 500 μl with dialysis buffer [4% glycerol, 10 mM tris-HCl, 1 mM EDTA, and 0.5 mM EGTA (pH 8)] and 400 μl of incubation buffer [2.5% Triton X-100, 0.25% sodium deoxycholate, 0.25% SDS, 0.35 M NaCl, and 10 mM tris-HCl (pH 8)] supplemented with leupeptin, aprotinin, and phenylmethylsulfonyl fluoride (PMSF). Chromatin was precleared with Protein A/G Magnetic Beads (Thermo Fisher Scientific, Cat. no. 88803) for 1 h at 4°C and then incubated with 10 ug H3 antibody (Abcam, Cat. no. ab1791) overnight at 4 °C. The following day, the mix was captured 3 h at 4°C with pre-blocked Protein A/G Magnetic Beads [incubated in BSA (1 mg/ml) in RIPA buffer overnight]. Subsequently, beads were washed three times in ice-cold RIPA buffer [140 mM NaCl, 10 mM tris-HCl, 1 mM EDTA, 1% Triton X-100, 0.1% SDS, and 0.1% sodium deoxycholate (pH 8)], three times in high-salt RIPA buffer (0.5 M NaCl), once in LiCl buffer [250 mM LiCl, 10 mM tris-HCl, 1 mM EDTA, 0.5% IGEPAL CA-630, and 0.5% sodium deoxycholate (pH 8)], and twice in TE buffer [10 mM tris-HCl and 1 mM EDTA (pH 8)]. The washed beads were resuspended with 100 μl TE buffer, transferred to a PCR tube, added 5 μl RNase A (New England Biolabs, Cat. No. T3018L), and incubated for 1 h at 37 °C. Thereafter, SDS and NaCl were added to a final concentration of 0.5% and 100 mM, respectively, and samples were incubated with 10 ug proteinase K (Research Products International, Cat. no. P50220) for 10 h at 37 °C followed by 6 h incubation at 65 °C for decross-linking. DNA was purified using the MinElute PCR purification kit (QIAGEN, Cat. No. 28004). All immunoprecipitated DNA subjected to end repair, A-tailing, and adaptor ligation using the

NEBNext® Ultra™ II DNA Library Prep Kit (New England Biolabs, Cat.no. E7645S) following the manufacturer's instructions and cleaned up with AMPure XP beads (Beckman Coulter, Cat. no. B23318). Then, Click-iT was performed on indexed DNA for 1 h at room temperature under the following conditions: 10 × PBS, 0.5 mM picolyl-azide-PEG4-biotin (Sigma, Cat. no. CHM02H272), 0.5 mM Tris(3-hydroxypropyltriazolylmethyl)amine (THPTA) (Sigma-Aldrich, Cat. no. 762342), 0.1 mM CuSO4, and 10 mM sodium ascorbate (Sigma, Cat. no. A4034). DNA fragments between 200 and 700 bp were size-selected using AMPure XP beads and resuspended in TE buffer. Next, to capture biotinylated products, 10 ul MyOne Streptavidin T1 beads (Invitrogen, Cat. no. 65602) were washed three times with 1 × BWT buffer [5 mM tris-HCl (pH 7.5), 0.5 mM EDTA, 1 M NaCl, and 0.05% (v/v) Tween 20] and resuspended in 2 × BWT buffer at a volume equal to the volume of biotinylated DNA. Streptavidin beads were then mixed with biotinylated DNA and rotated at 20 rpm for 2 h at room temperature. Beads containing biotinylated DNA were washed four times with 1 × BWT buffer, twice with 1 × EBT buffer [10 mM tris-HCl (pH 8.5) and 0.05% (v/v) Tween 20]. Last, beads were resuspended in double distilled water. PCR amplification was performed following the NEBNext® Ultra™ II DNA Library Prep Kit protocol using the streptavidin bead suspension as a template (11 cycles of PCR). Following PCR, streptavidin beads were purified using a magnet, and the supernatant was cleaned up with AMPure XP beads at a ratio of 0.8 ×. Fragment distribution of libraries was checked using the Fragment Analyzer system (Agilent - Tape Station - DNA5000 HS kit), libraries were pooled and sequenced paired-end on NovaSeq X Plus Series.

Radar Assay

Cells were lysed in Radar buffer (4M Guanidine thiocyanate, 1% Sarkosyl, 2% Triton X-100, 1% 1,4-dithioerythritol, 100 mM Sodium Acetate pH5.0, 20 mM Tris pH 8.0, 20 mM EDTA pH8.0; adjusted to pH 6.5). Genomic DNA was sonicated and precipitated with ethanol, resuspended in 8 mM NaOH, and quantified using Qbit fluorometry. Samples were then subjected to slot-blot onto nitrocellulose membrane??, which were subsequently immunoblotted with HMCES primary antibody and corresponding secondary antibody. ibody and corresponding secondary antibody.)

RNA interference

All siRNA transfections were performed using DharmaFECT reagents according to the manufacturer's instructions. Experiments were performed 2 days after transfection. See table for siRNA sequences. Qiagen AllStars Negative Control Nontargeting (NT) siRNA was used in samples where a gene-selective siRNA is not indicated or to bring the total amount of siRNA to equal molar concentrations when comparing samples with one versus two siRNAs.

HMCES purification

HMCES protein purification using a protocol as described previously[112]. Briefly, pNIC-HMCES vector was transformed in *E. coli* cells. Cells were grown in terrific broth (TB) medium at 37°C till OD600 reached 0.7. Protein expression was induced by addition of 0.5 mM isopropyl- β-D-thiogalactoside (IPTG) for 4 hrs. Cell pellets were collected and resuspended in buffer A (20 mM HEPES/KOH pH 7.5, 500 mM KCl, 5 mM $MgCl_2$, 30 mM imidazole, 10% glycerol, 0.1% IGEPAL, 0.04 mg/ml Pefabloc SC, cOmplete EDTA-free protease inhibitor cocktail, and 1 mM TCEP). Wash steps used buffer B (20 mM HEPES/KOH pH 7.5, 500 mM KCl, 5 mM $MgCl_2$, 1

mM TCEP). Protein was eluted from Strep-Tactin® XT Superflow® high-capacity cartridges with buffer B supplemented with 50 mM biotin, and from HiTrap Heparin HP columns with buffer C (20 mM HEPES/KOH pH 7.5, 1 M KCl, 5 mM $MgCl_2$, 1 mM TCEP). Size-exclusion chromatography and protein storage were carried out in buffer D (20 mM HEPES/KOH pH 7.8, 150 mM KCl, 5 mM $MgCl_2$, 10% glycerol, 1 mM TCEP).

Quantification and statistical analysis

The statistical test was performed using GraphPad Prism and R software. The statistics for the high-content microscopy experiments was performed on the mean of individual replicates. Statistical analyses were completed using Prism. A Kruskal-Wallis test was used for experiments with more than two samples, and P values were calculated by Prism for the multiple comparisons. A two-tailed t test was used to compare two samples with normally distributed data. No statistical methods or criteria were used to estimate sample size or to include/exclude samples. Statistical details of individual experiments can be found in the figure legends and in Results. Experiments shown are representative of at least two biological replicates unless otherwise indicated in the figure legend.

Acknowledgement:

We would like to thank David Cortez Lab for the SMARCAL1, HLTF, ZRANB3 single and triple knockout U2OS cell lines. Alessandro Vindigni lab for the pcDNA3.1/nV5-DEST PrimPol WT and Mutants vectors; Sharon Cantor lab for the FANCJ KO cell lines, and FANCJ WT vectors; Weixing Zhao lab for the MDA-MB-436 and BRCA1 complemental cell lines, DLD-1 WT and BRCA2 knockout cell lines.

Author contribution:

W.L. conceptualized the project. Q.W. and C.Z. performed PLA, IF, iPOND, western blot assays. Y.D. and T.Z. performed Mass spectrometry experiments. N.I.M and T.M.W performed in vitro nucleosome assembly assays. M.G. and S.T. purified HMCES proteins and performed RADAR assay. W.L. and Q.W. wrote the manuscript with contributions from all the authors.

Figure Legend

Figure 1. Fork reversal deficiency reduces nucleosome density on nascent DNA

A) iPOND-SILAC-MS analysis of proteins bound to nascent DNA in HU-treated wild-type (WT) and fork reversal enzyme knockout (FRKO) U2OS cells. WT and FRKO cells were labeled with light and heavy isotopes for ⩾4 weeks, pulse-labeled with EdU and treated with 1mM HU for 4 h prior to iPOND. N = 4 biological replicates; error bars represent SD.

B–D) PLA for EdU and H3 in WT or FRKO cells labeled with 10 μM EdU and treated with 1 mM HU. B) Representative images (Texas Red = PLA signal; green = EdU). C) PLA foci per cell; each dot represents a single cell. D) PLA signal normalized to EdU intensity. ⩾1,000 cells/sample were analyzed with MetaXpress (Molecular Devices). N ⩾ 10. p-values from two-tailed unpaired t-test.

E) Heatmaps of H3 ChOR-seq signal in WT and FRKO cells treated with HU, normalized to spike-in chromatin from D. melanogaster S2 cells. N = 2.

F–G) Genome browser views of H3 ChOR-seq from the same experiment in (E), normalized to reads per million using exogenous spike-in. N = 2.

H) PLA for EdU and H3 in WT or FRKO cells with siRAD51 knockdown. N = 3. p-values from Kruskal–Wallis test.

Figure 2 Fork reversal deficiency leads to parental histone loss on nascent DNA

A) Schematic of iPOND–propionylation-MS workflow to detect histone modifications on nascent DNA in WT and FRKO U2OS cells treated with EdU together with 1mM HU for 4 h.

B) Log_2 fold-change of histone modifications in FRKO vs. WT cells. Modification-specific peptide counts were normalized to unique peptide numbers, and FRKO/WT ratios plotted on log_2 scale. N = 3.

C) PLA for EdU and H3K9me3 in WT and FRKO cells treated as in (A). PLA signals normalized to EdU intensity. ⩾1,000 cells/sample. N = 3. p-values from two-tailed unpaired t-test.

D–E) Immunofluorescence for H3K9me3 in S-phase WT and FRKO cells. D) Cells pulse-labeled with EdU (10 min). E) Cells labeled with EdU and treated with HU (4 h). Quantification by QIBC. N = 3.

F) PLA for EdU and H3K9me2 in WT and FRKO cells treated as in (A). PLA signals normalized to EdU intensity. ⩾1,000 cells/sample. N = 3.

G) ChOR-seq analysis of H3 occupancy categorized into total genome, non-repeats, and repeats, in WT and FRKO cells under HU or no-HU conditions. Signal normalized using D. melanogaster spike-in chromatin. N = 2. p-values from unpaired t-test.

H) H3 ChOR-seq signal at specific repeat classes in WT and FRKO cells under HU. Error bars = SD of two replicates; $p < 10^{-4}$ by paired t-test.

I) Average CUT&RUN profiles of H3K4me3 in WT and FRKO cells across all promoters. Signal normalized to spike-in chromatin. N = 2.

J) CUT&RUN analysis of H3K4me3 enrichment at repetitive elements in WT and FRKO cells. Error bars = SD of two replicates; $p < 10^{-4}$ by paired t-test.

Figure 3 PrimPol deletion rescues low nucleosome density

A) iPOND-SILAC-MS analysis of histone chaperones on nascent DNA (data from Figure 1A). N = 4, error bars = SD.

B) S1 nuclease-treated DNA fiber assay to detect ssDNA gaps. N = 3. p-values from Kruskal–Wallis test.

C–G) PLA for EdU and histone marks in indicated conditions. C–E) H3; F) H3K9me2; G) H3K9me3. PLA signals normalized to EdU intensity; ⩾1,000 cells/sample. N ⩾ 3. p-values from Kruskal–Wallis test.

H) Western blot for PrimPol in KO and complemented cells.

I) Model schematic.

Figure 4. Single-stranded DNA gaps reduce nucleosome density on nascent DNA in cells

A–E) PLA for EdU and H3 in the indicated cell lines and treatments. PLA signals normalized to EdU intensity; ⩾1,000 cells/sample. N ⩾ 3. p-values from Kruskal–Wallis test.

Figure 5. Nucleosomes can assemble on ssDNA-gapped substrates with reduced stability in vitro

A–B) Nucleosome reconstitution assays using DNA substrates containing ssDNA gaps at the dyad (A) or entry/exit site (B). Gaps of varying sizes were tested. Gels show nucleosome core particle (NCP) formation; quantification shown below.

C–D) Structural models of ssDNA-gapped nucleosomes predicted by AlphaFold. C) ssDNA gap at dyad. D) ssDNA gap at entry/exit.

Figure 6. PARylation reduces nucleosome density in fork reversal–deficient cells

A) Immunofluorescence of PARylation in WT and FRKO cells. Cells were labeled with EdU (10 min, no HU) or EdU + HU (4 h). Integrated PARylation intensity quantified. N = 3. p-values from Kruskal–Wallis test.

B) PLA for EdU and H3 under indicated conditions. PLA normalized to EdU intensity; ⩾1,000 cells/sample. N = 9. p-values from Kruskal–Wallis test.

C) Immunofluorescence of PARylation in indicated conditions. N = 3.

D) S1 nuclease DNA fiber assay to detect ssDNA gaps. N = 3. p-values from Kruskal–Wallis test.

E–F) PLA for EdU and H3 in indicated conditions, quantified as in (B). N ⩾ 7.

G) Immunofluorescence for PARylation in the indicated conditions. N = 3.

Figure 7. HMCES-DPC at ssDNA gaps reduces nucleosome density in fork reversal–deficient cells

A) APOBEC3B and HMCES levels on nascent DNA measured by iPOND-SILAC-MS. N = 4.

B) RADAR assay detecting HMCES-DPC in WT and FRKO cells. N = 3.

C–E) PLA for EdU and H3 in indicated conditions (as in Figure 1B). N ⩾ 7. p-values from Kruskal–Wallis test.

F–G) Nucleosome reconstitution assays showing nucleosomes fail to form on dyad ssDNA gaps but can form at side gaps. Gels show NCP bands. AP-DNA = abasic-site DNA; AP-NCP = nucleosomes assembled on abasic DNA. L = ladder, D = DNA, N = nucleosome.

H) Model schematic of how ssDNA adducts interfere with nucleosome formation at gaps.

Supplementary Figure Legends

Figure S1. Fork reversal deficiency reduces nucleosome density on nascent DNA (related to Figure 1).

A) EdU incorporation in WT and FRKO cells treated with EdU + HU (as in Fig. 1B). EdU detected by azide–488 click reaction.

B–E) Immunofluorescence for H3 in WT and FRKO cells under indicated conditions. N = 3; p-values from two-tailed unpaired t-test.

F) PLA for EdU and H3 at different HU concentrations. N = 3; p-values from Kruskal–Wallis test.

G–I) PLA for EdU and H2A (G), H2B (H), and H4 (I). Left: PLA foci/cell; middle: EdU intensity; right: normalized PLA/EdU. $\geqslant$1,000 cells/sample. N $\geqslant$ 3.

J) Quantitative ChOR-seq for H3. Average profiles across H3 peaks in WT and FRKO cells, normalized by reference-adjusted RPM using D. melanogaster spike-in. N = 2; Wilcoxon signed-rank test.

Figure S2. Low nucleosome density is due to fork reversal deficiency, not depletion of individual fork reversal enzymes (related to Figure 1).

A–B) PLA for EdU and H3 in individual fork reversal enzyme KO cells. N = 3.

C) Western blot showing siRAD51 knockdown efficiency.

D) PLA for EdU and H3 in WT and FRKO cells without HU. Cells labeled with EdU (10 min) and harvested for PLA. N = 3; p-values from unpaired t-test.

E) ChOR-seq analysis of H3 occupancy in WT and FRKO cells without HU, normalized to spike-in chromatin.

F) Heatmaps of H3 ChOR-seq signal (from E). N = 2.

G) Model schematic: fork reversal prevents nucleosome loss under replication stress.

Figure S3. Fork reversal deficiency leads to parental histone loss (related to Figure 2).

A–K) Histone modifications quantified in WT and FRKO cells by iPOND–propionylation-MS. Modification level = modified peptide count/unique peptide count. N = 3; error bars = SD.

L) PLA for EdU and H3K9ac in WT and FRKO cells, treated as in Fig. 1B. Signals normalized to EdU. N = 3.

M–R) Immunofluorescence for H3K9me2 and H3K9me3 in indicated conditions. N = 3; unpaired t-test.

Figure S4. Fork reversal deficiency leads to PrimPol-mediated ssDNA gaps and DNA damage (related to Figure 3).

A) S1 nuclease DNA fiber assay detecting ssDNA gaps. N = 3; Kruskal–Wallis test.

B) Native IdU immunofluorescence for parental ssDNA detection. U2OS cells labeled with IdU (50 μM, 48 h), then chased 2 h in fresh medium and treated with HU (1 mM, 4 h). IdU stained without denaturation. N = 3.

C–E) Immunofluorescence for RPA2 (C), RPA2-S8 phosphorylation (D), and γH2AX-S139 (E). N = 3.

F) QIBC for cell cycle analysis.

G) Western blot for PrimPol knockdown efficiency.

Figure S5. Single-stranded DNA gaps inhibit nucleosome assembly in cells (related to Figure 4).

A–G) PLA for EdU and H3 in indicated treatments. PLA foci/cell and EdU intensity shown (same data as Fig. 4). N = 3; p-values from unpaired t-test.

Figure S6. PARylation and HMCES-DPC at ssDNA gaps inhibit nucleosome assembly in FRKO cells (related to Figures 6).

A) Model schematic.

B) PLA for EdU and H3 in siRPA1 and/or siRPA2 cells (treated as in Fig. 1B). N ⩾ 5; Kruskal–Wallis test.

C) Immunofluorescence for PARylation. N = 3.

D) Survival assay in olaparib. 100 WT or FRKO cells plated per 10-cm dish, treated with indicated olaparib concentrations 24 h post-plating, and maintained for 10 d.

Figure S7. HMCES-DPC at ssDNA gaps reduces nucleosome density in FRKO cells (related to Figure 7).

A) Western blot for chromatin-bound APOBEC3B in WT and FRKO cells ± HU.

B–C) Western blot for HMCES (B) and APOBEC3B (C) to confirm knockdown efficiency in WT and FRKO cells.

D-E) HMCES-ssDNA crosslink preparation. Gels show HMCES–DNA crosslink products. AP-DNA = abasic DNA; L = ladder.

Figure 1 Fork reversal deficiency reduces the nucleosome density on nascent DNA

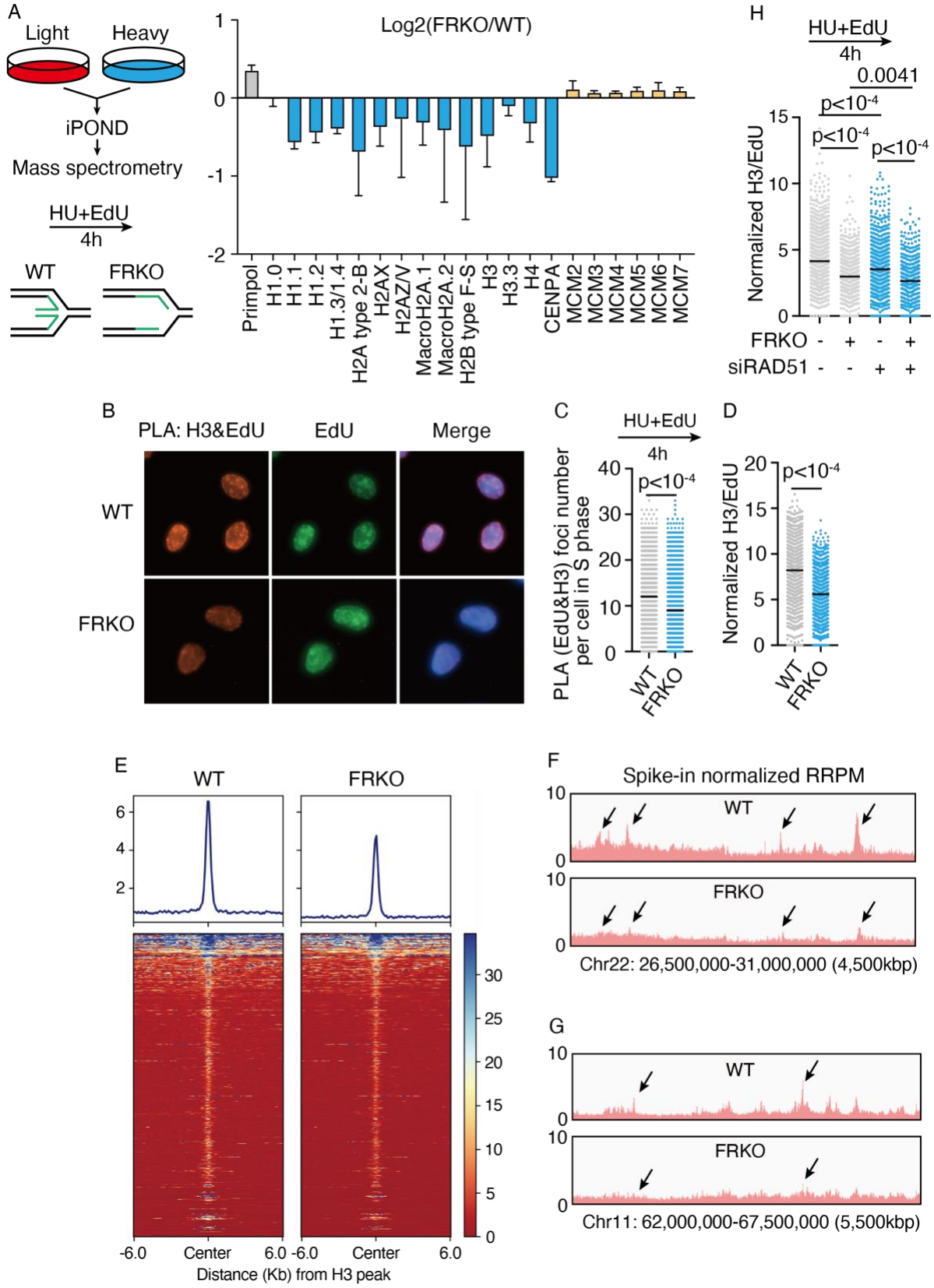


Figure 2 Fork reversal deficiency leads to parental histone loss on nascent DNA

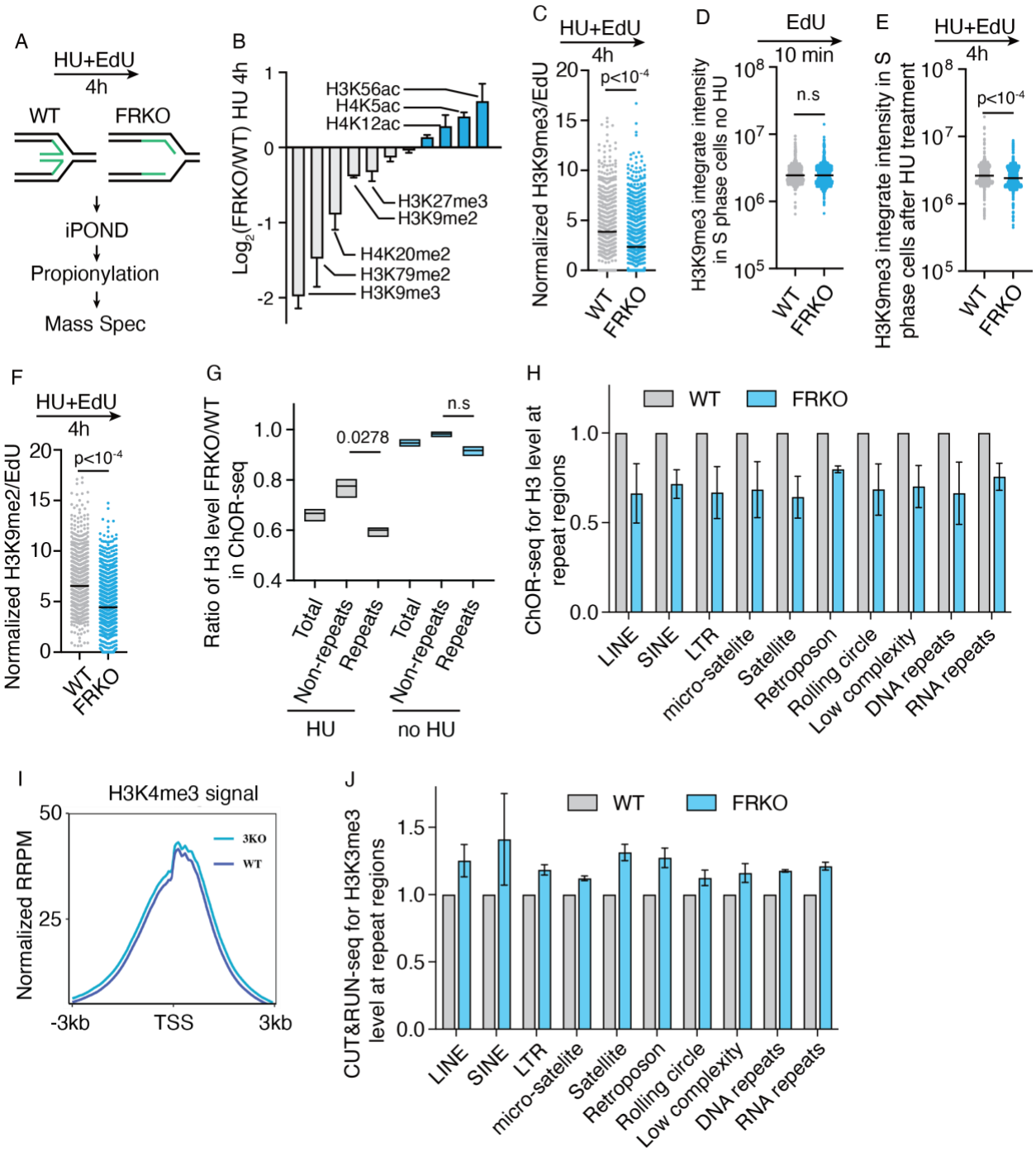


Figure 3 PrimPol deletion rescues low nucleosome density but compromise HU sensitivity

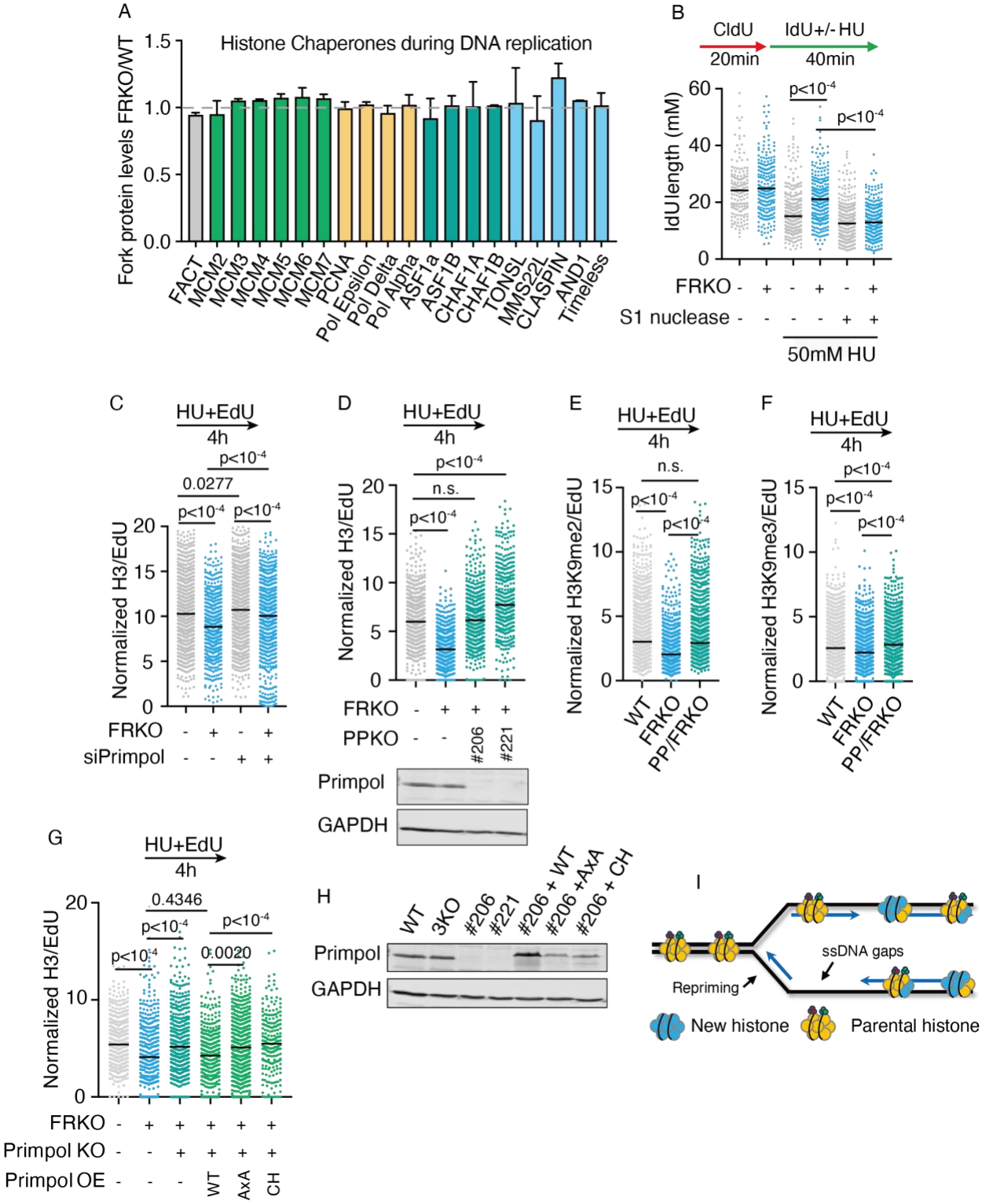


Figure 4 Single-Stranded DNA Gaps Decrease Nucleosome Density on Nascent DNA in Cells

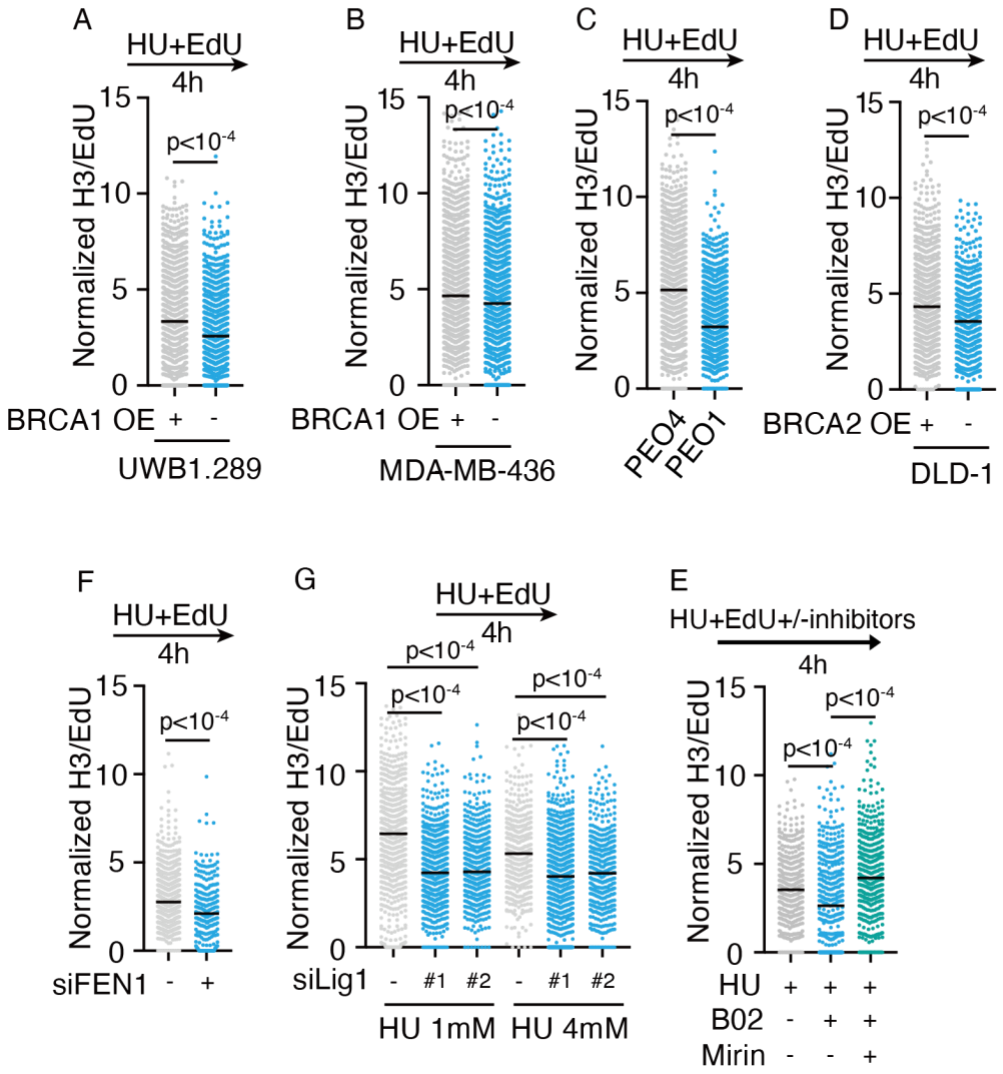


Figure 5 Nucleosomes can form on ssDNA gapped substrate in vitro

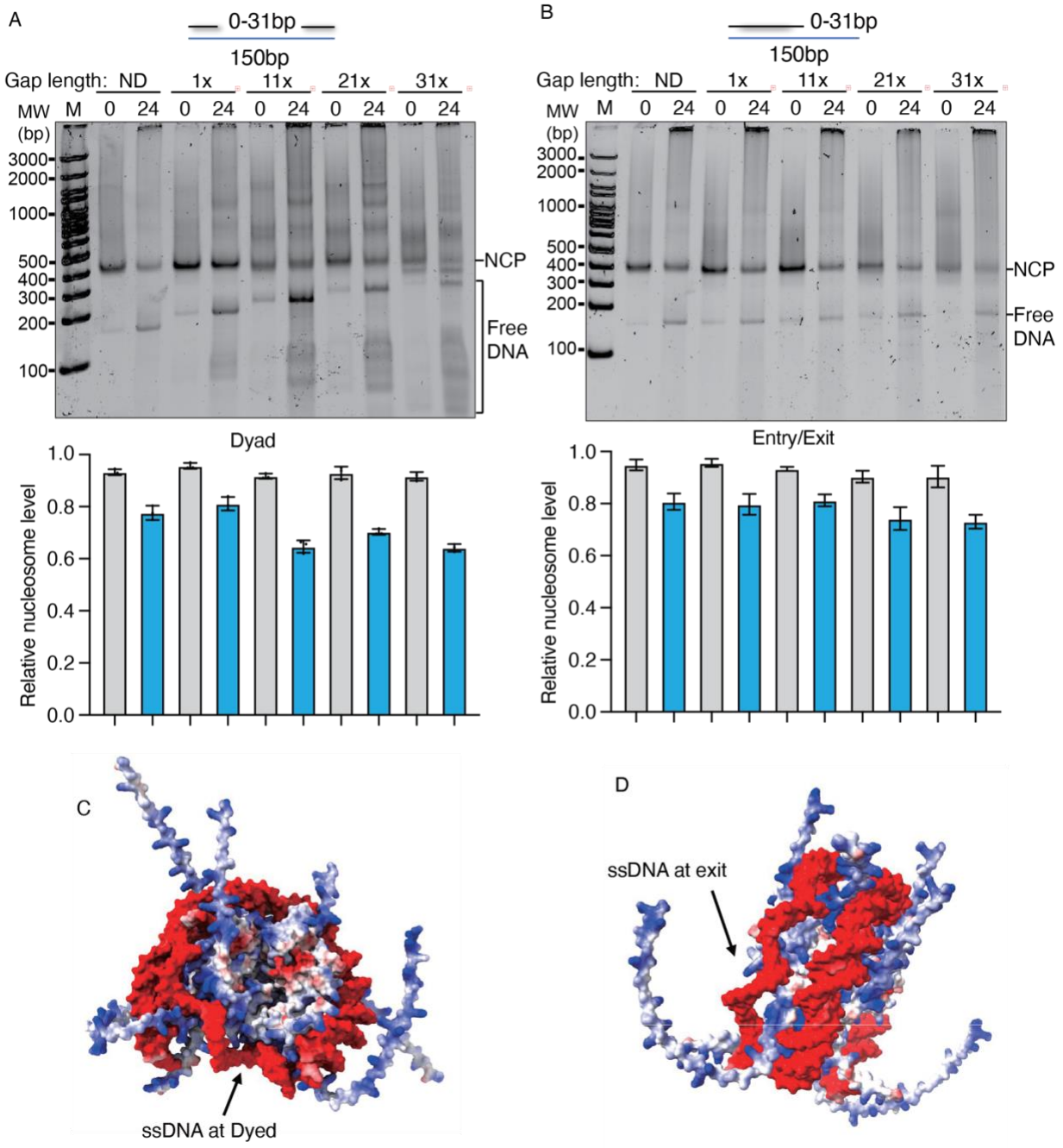


Figure 6 PARylation reduces nucleosome density in fork reversal deficient cells

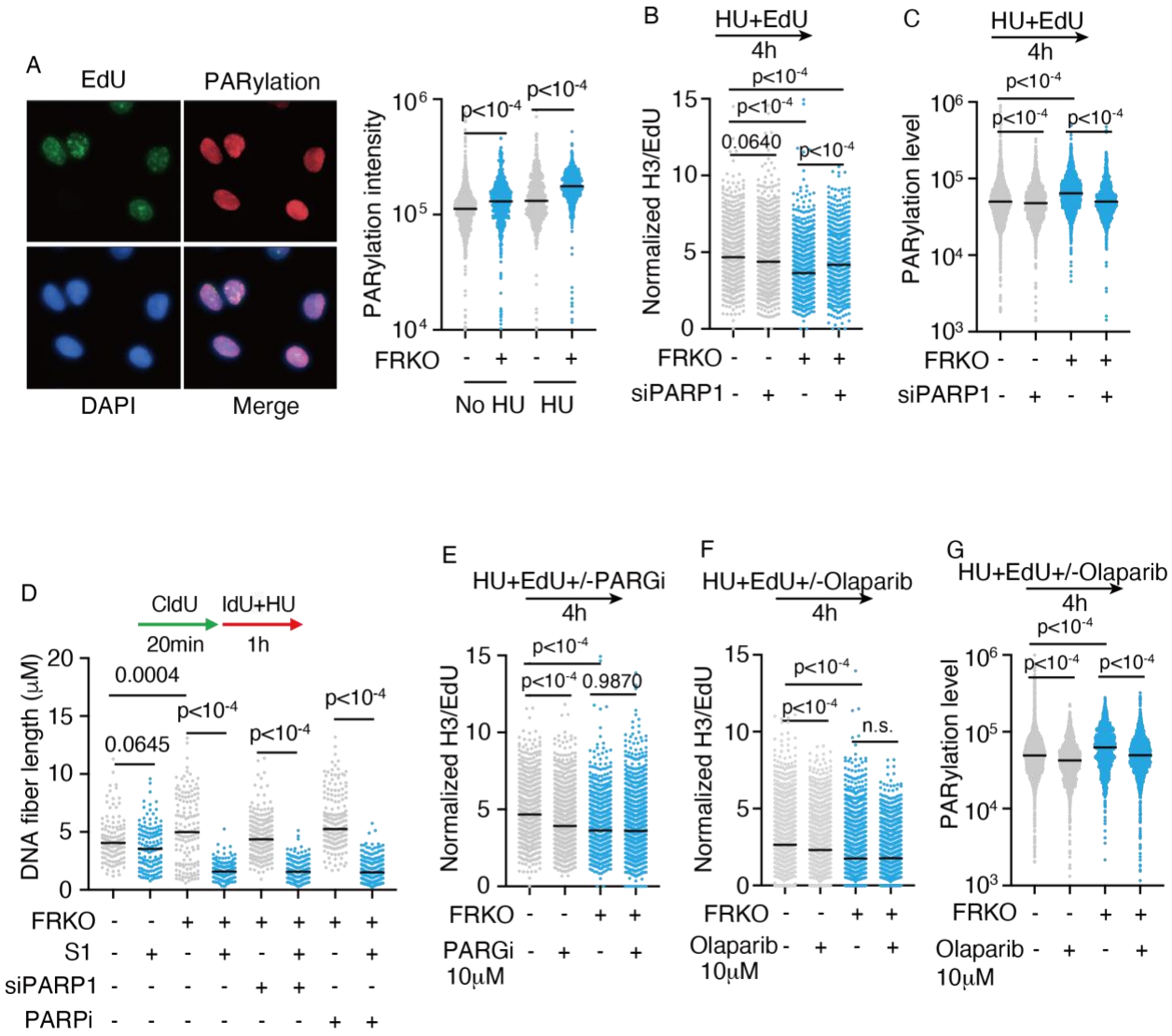


Figure 7 HMCES-DPC at ssDNA gaps reduces nucleosome density in fork reversal deficient cells

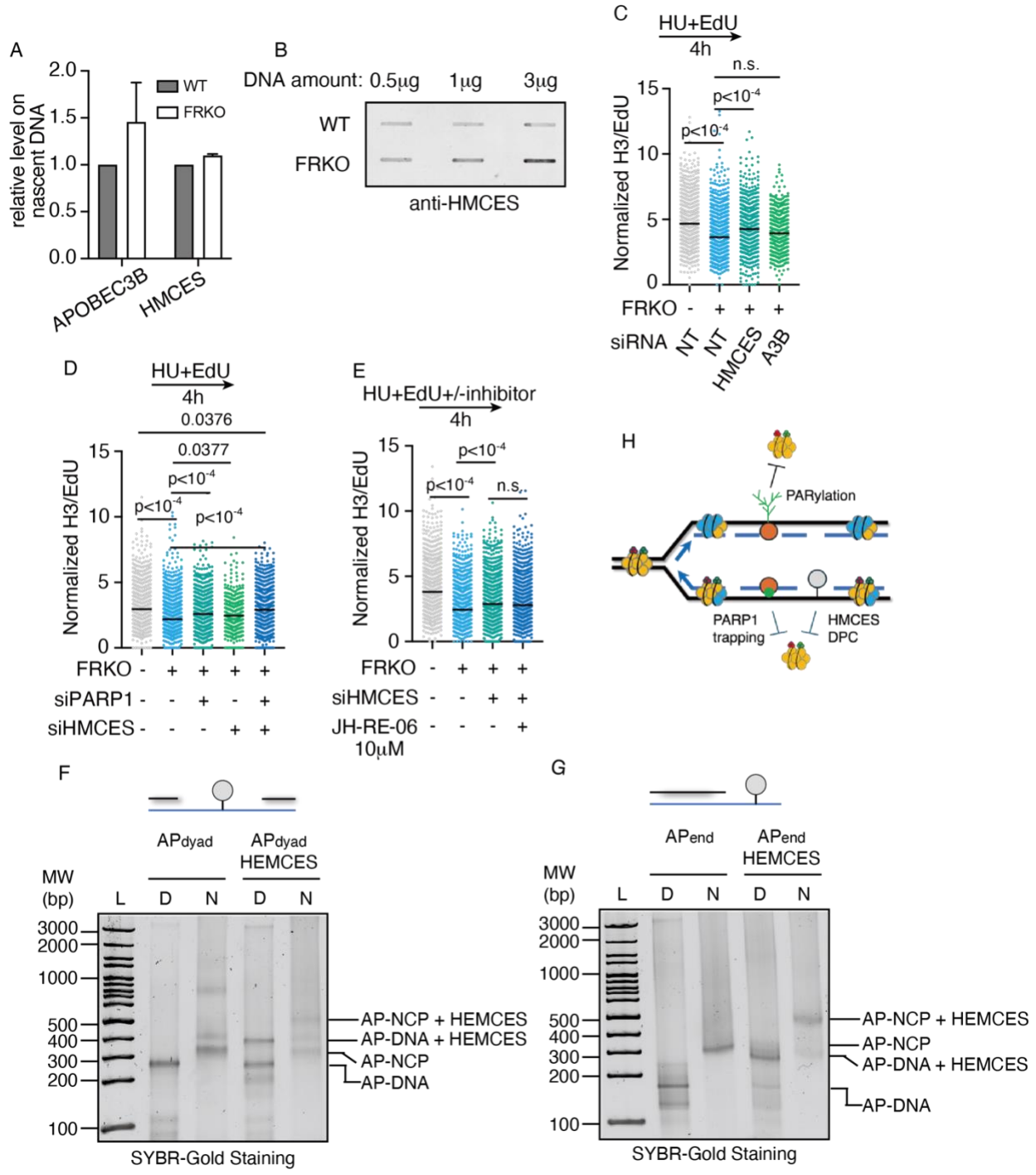


Figure S1 Fork reversal deficiency reduces the nucleosome density on nascent DNA

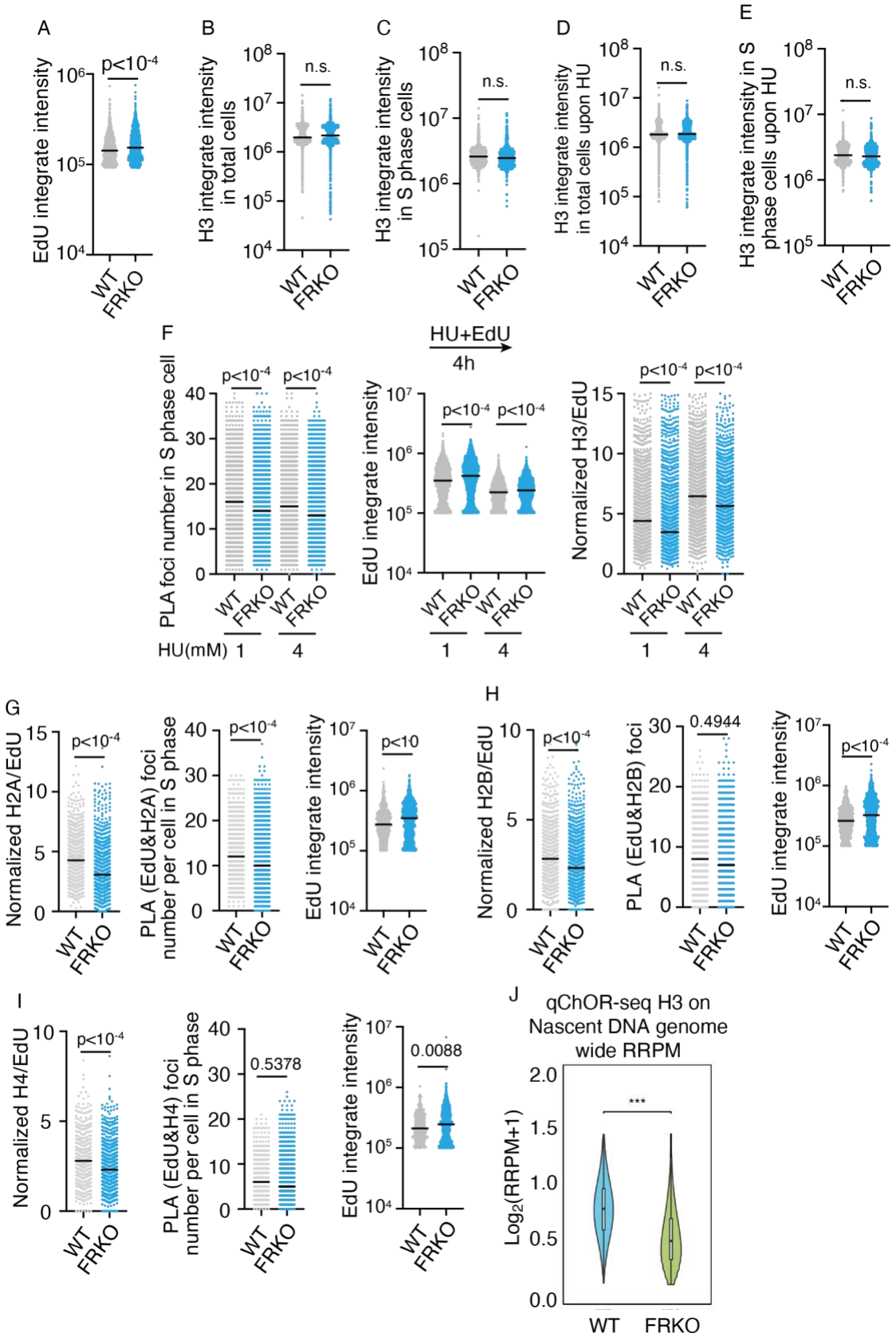


Figure S2 Low density of nucleosome is due to fork reversal deficiency rather than individual fork reversal enzyme depletion

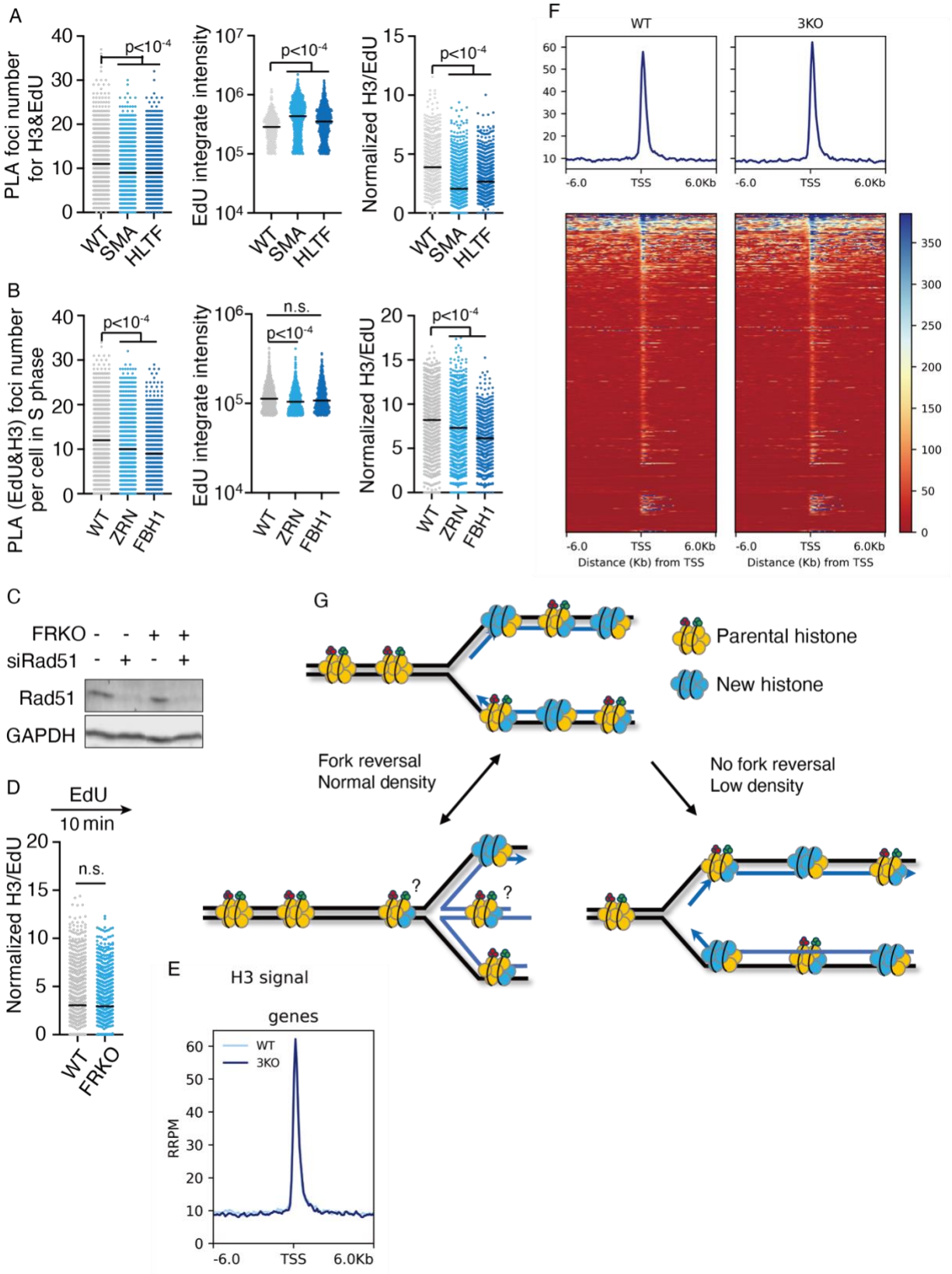


Figure S3 related to Figure 2 Fork reversal deficiency leads to parental histone loss

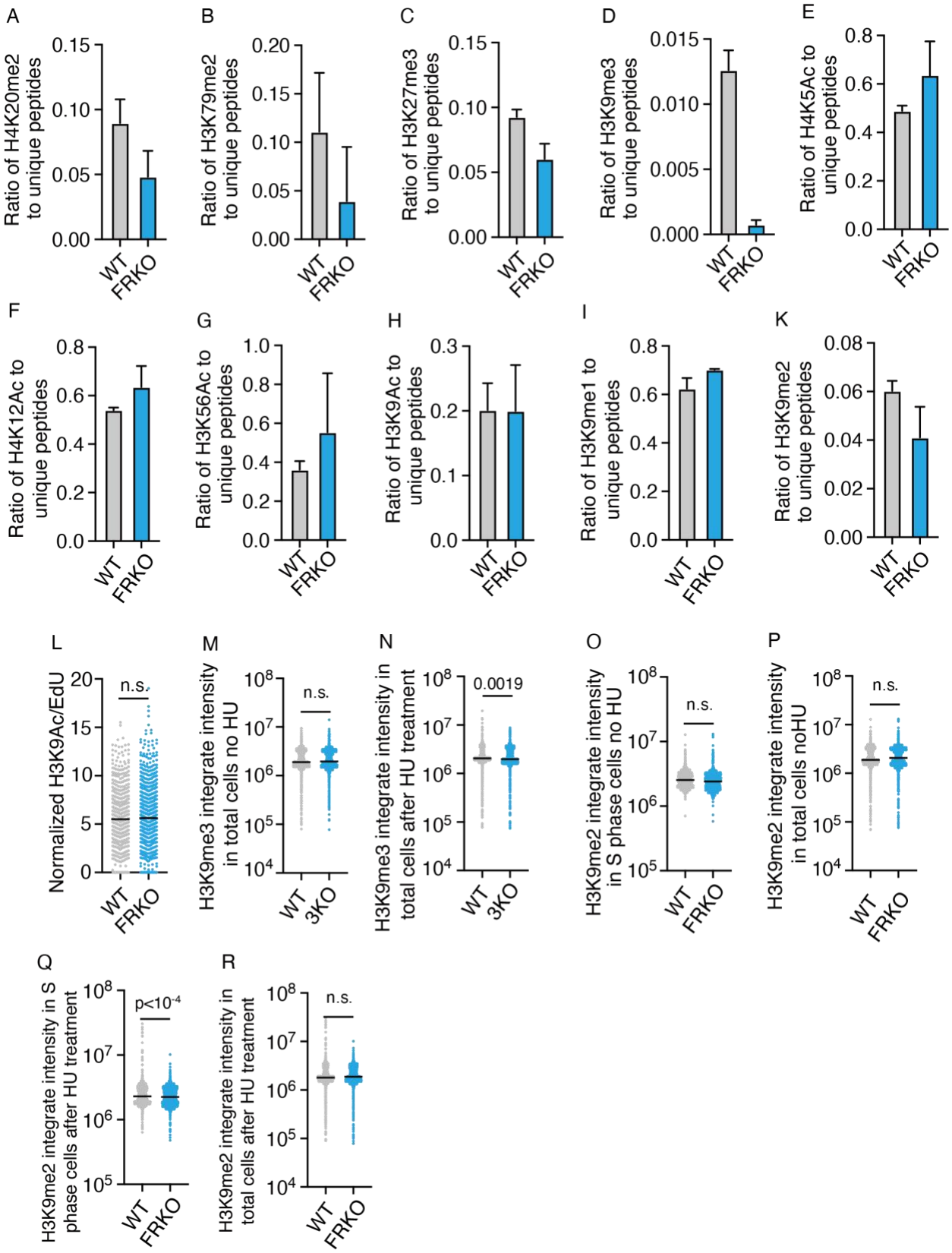


Figure S4 Fork reversal deficiency leads to primpol mediated ssDNA gaps and DNA damage

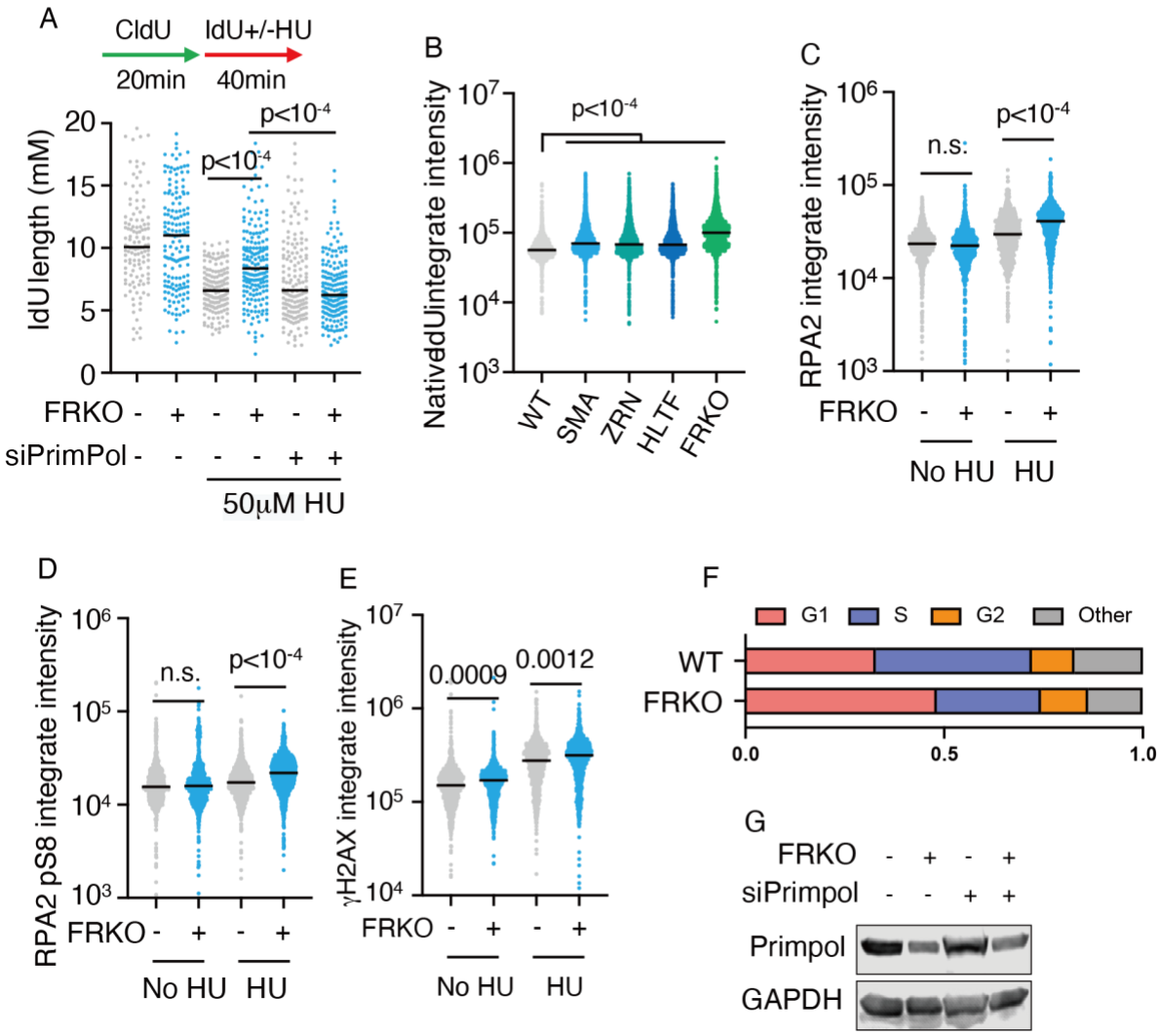


Figure S5 Single-stranded DNA gaps loosen the nucleosome assembly on nascent DNA in cells, related to Figure 4

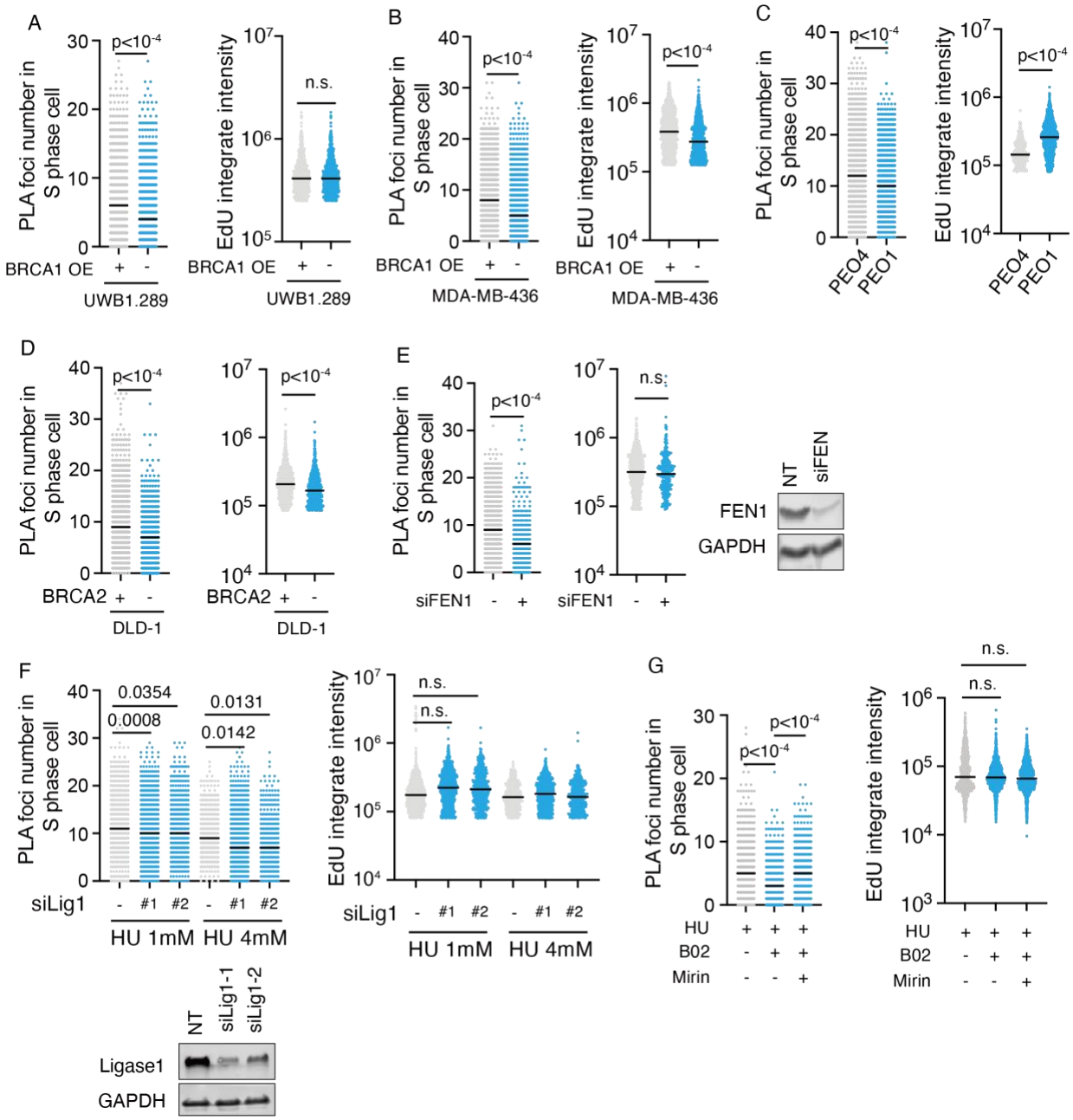


Figure S6 PARylation at ssDNA gaps reduces nucleosome density in fork reversal deficient cells

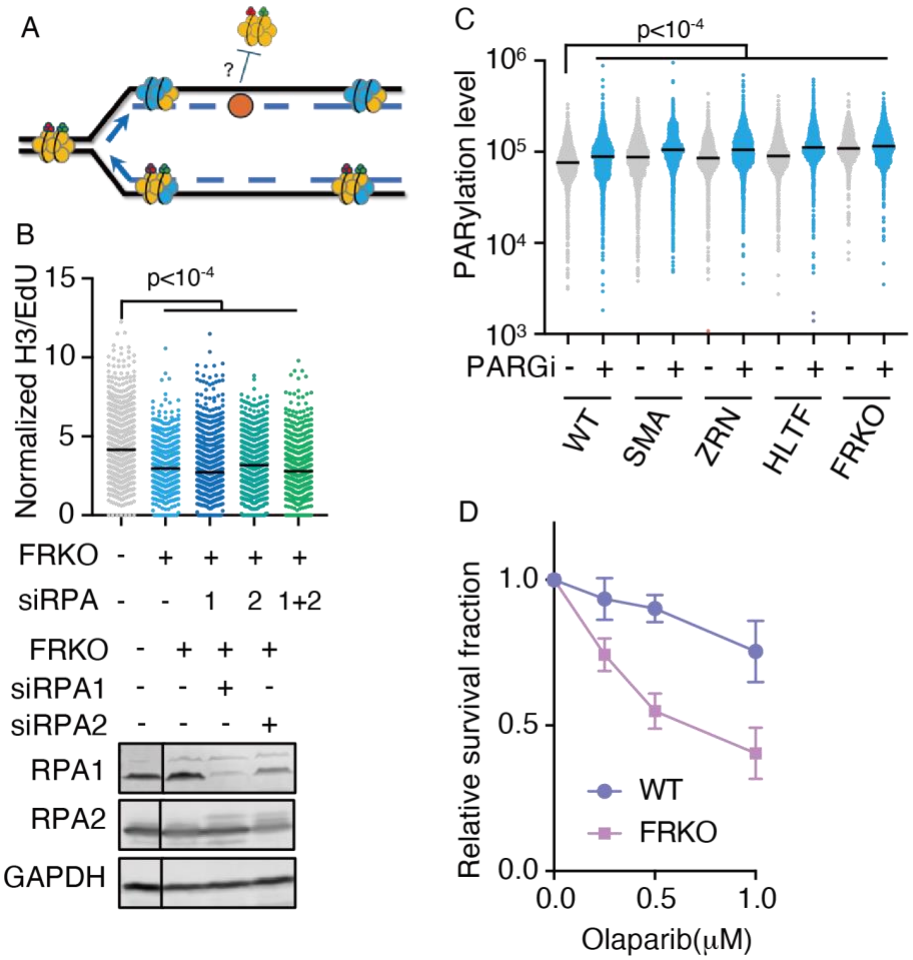
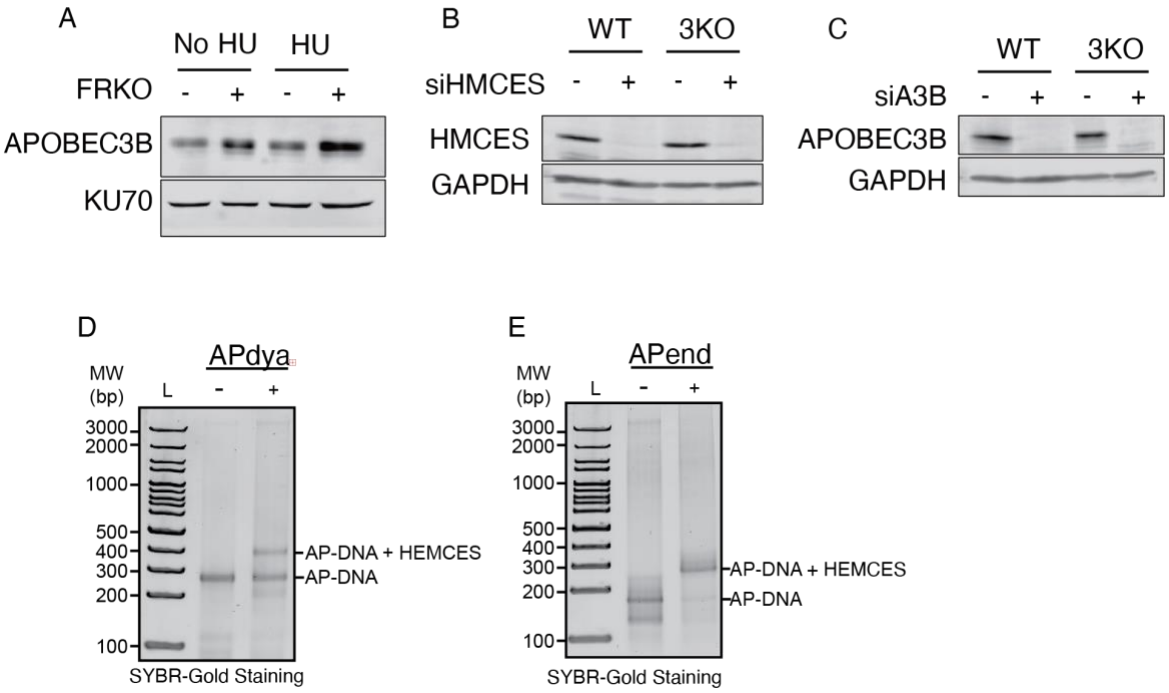


Figure S7 HMCES-DPC at ssDNA gaps reduces nucleosome density in fork reversal deficient cells



Reference

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