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## Inhibitors of UHRF1 base flipping activity showing cytotoxicity against cancer cells

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1 **Inhibitors of UHRF1 base flipping activity showing cytotoxicity against cancer**  
2 **cells**

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25 **Abstract**

26 Ubiquitin-like containing PHD and RING finger domain 1 (UHRF1) is a nuclear multi-domain  
27 protein overexpressed in numerous human cancer types. We previously disclosed the anthraquinone  
28 derivative UM63 that inhibits UHRF1-SRA domain base-flipping activity, although having DNA  
29 intercalating properties. Herein, based on the UM63 structure, new UHRF1-SRA inhibitors were  
30 identified through a multidisciplinary approach combining molecular modelling, biophysical assays,  
31 molecular and cell biology experiments. We identified AMSA2 and MPB7, that inhibit UHRF1-SRA  
32 mediated base flipping at low micromolar concentrations, but do not intercalate into DNA, which is  
33 a key advantage over UM63. These molecules prevent UHRF1/DNMT1 interaction at replication  
34 forks and decrease the overall DNA methylation in cells. Moreover, both compounds specifically  
35 induce cell death in numerous cancer cell lines, displaying marginal effect on non-cancer cells, as  
36 they preferentially affect cells with high level of UHRF1. Overall, these two compounds are  
37 promising leads for the development of anti-cancer drugs targeting UHRF1.

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39 **Keywords:** Epigenetics, DNA methylation; UHRF1 base flipping inhibitors; fluorescence; virtual  
40 screening.

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## 50 **Introduction**

51 Cancer is one of the leading causes of death worldwide, accounting for nearly 10 million deaths in  
52 2020<sup>1</sup>. Despite significant advances, the current anticancer therapies lack of specificity and lead to  
53 severe side effects. Furthermore, cancers in advanced stages are characterized by aggressiveness and  
54 metastasis, which makes it difficult to control their progression using current anticancer drugs<sup>2</sup>.  
55 Importantly, epigenetics is tightly associated to tumorigenesis, being involved in several critical steps  
56 ranging from cancer priming, development, progression and metastasis. Dysregulation of epigenetic  
57 methylation patterns is a hallmark for cancer<sup>3-7</sup>, while disruption of methylation patterns at specific  
58 loci, such as tumor suppressor genes (TSGs) promoters, correlates to tumorigenesis<sup>8-14</sup>. As a result,  
59 cell cycle (p15<sup>INK4b</sup>, p14<sup>ARF</sup>) and DNA repair pathways (hMLH1, MGMT) are altered, inhibiting  
60 apoptosis (DAPK) and promoting angiogenesis. In addition, epigenetic alterations can reverse  
61 chemotherapy effects<sup>15</sup>. Therefore, epigenetic modulators appear as valuable anti-cancer targets<sup>16-22</sup>.  
62 DNA methylation is maintained by a Epigenetic Code Replication Machinery (ECCRM) that  
63 faithfully propagates methylation patterns during DNA replication<sup>18,22</sup>. In this complex, DNA  
64 methyltransferase 1 (DNMT1) is guided by Ubiquitin-like, containing PHD and RING fingers  
65 domains, 1 (UHRF1) protein. Through its SET and RING-associated (SRA) domain, UHRF1  
66 recognizes the CpG motifs of hemi-methylated DNA, which is constituted of the parental methylated  
67 DNA strand and the newly synthesized one. Following recognition, the SRA domain flips out the 5-  
68 methylcytosine (5mC) of the parent strand from the DNA helix<sup>23,24</sup>. This base flipping activity  
69 triggers DNMT1 recruitment at the replication forks, leading to methylation of the opposite cytosine  
70 on the unmethylated strand<sup>21,22,25</sup>. In addition, through its Tandem Tudor domain (TTD) and plant  
71 homeodomain (PHD), UHRF1 interacts with histone 3 (H3) and through its C-terminal RING  
72 domain, ubiquitinylates H3K23 and H3K18 residues<sup>4,23,24,26,27,27-32</sup>. Overall, UHRF1 plays a pivotal  
73 role in G<sub>1</sub>/S transition<sup>33,34</sup> and the epigenetic silencing of tumor suppressor genes (TSGs) such as  
74 p16<sup>INK4A</sup>, p14<sup>ARF</sup>, BRCA1, RB1, KISS1, RASSF1, CDKN2A and RAR $\alpha$ <sup>10,12,16-19,35-39</sup>. As UHRF1 is

75 a well-known oncogene overexpressed in numerous human cancer types<sup>10,18</sup>, pharmacological  
76 inhibition of UHRF1 activity or expression represents a promising perspective in anticancer therapy  
77 to reactivate silenced TSGs, and induce apoptosis<sup>10,40</sup>.

78 Currently, several therapeutic strategies aim to inhibit DNA methylation in cancer cells<sup>41</sup>.  
79 Demethylating compounds include nucleoside (5-azacytidine and decitabine)<sup>42,43</sup> and non-nucleoside  
80 analogs (Hydralazine and Procainamide)<sup>44</sup> but show strong drawbacks, such as chemical instability,  
81 cytotoxicity on non-cancer cells and poor selectivity for DNMT1<sup>45-47</sup>. Due to the high expression of  
82 UHRF1 in cancer cells and its key activity on TSGs, UHRF1 represents a promising anticancer target  
83 for the development of DNA methylation modulators that might bear better features than current  
84 demethylating drugs<sup>48,49</sup>. So far, several natural and synthetic inhibitors of UHRF1 have been  
85 reported, including uracil derivatives<sup>50</sup>, 4-benzylpiperidine-1-carboximidamide<sup>51</sup>, mitoxantrone,  
86 anthracycline inhibitors of topoisomerase II<sup>52-54</sup> and UM63<sup>55</sup>. This last compound shares some  
87 chemical features with mitoxantrone, and inhibits UHRF1 in the low micromolar range by binding to  
88 5mC binding pocket of SRA<sup>55</sup>. Moreover, UM63 prevents DNMT1/UHRF1 interaction and decreases  
89 DNA methylation in HeLa cells proving the druggability of the SRA binding pocket. However, the  
90 DNA intercalating properties of UM63 represent a weakness that should be absent in next generations  
91 of UHRF1 inhibitors. Recently, UF146, another UHRF1 inhibitor targeting SRA domain was  
92 identified. This compound was shown to efficiently eradicate leukemia initiating cells in a myeloid  
93 leukemia patient-derived xenograft model, confirming the high potential of UHRF1 inhibitors in  
94 anticancer therapy<sup>56</sup>. UF146 is structurally related to UM63 and mitoxantrone, but unfortunately it  
95 qualifies as a pan-assay interference compounds (PAINS)<sup>57,58</sup> due to its quinone moiety. Noteworthy,  
96 PAINS are molecules bearing undesired functional groups that might react unpredictably with  
97 numerous biological targets rather than with the desired target, giving rise to false positive results<sup>58</sup>.

98 In this context, the aim of this work was to identify and characterize improved potent UHRF1  
99 inhibitors based on UM63 pharmacophoric features through a combination of molecular modeling,  
100 biophysical assays and biological studies. Two effective UHRF1 inhibitors, i.e., the

101 hydroxyanthracene derivative AMSA2 (namely, anthrarobin) and the imidazoquinoline derivative  
102 MPB7, were identified. Both compounds prevent SRA-induced base flipping, decrease the overall  
103 DNA methylation in cancer cells, do not qualify as PAINS, and are not DNA intercalators, thus  
104 becoming promising compounds for anticancer applications.

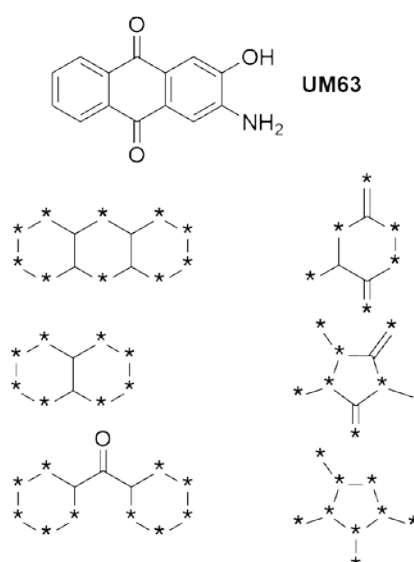
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## 106 **Results**

### 107 **Hits selection by virtual screening**

108 To identify different chemotypes that might bind into the 5mC binding pocket of the SRA domain,  
109 the Aldrich Market Select and MolPort databases were screened *in silico*. Based on the chemical  
110 structure of UM63 and its substructures, i.e., an effective UHRF1 inhibitor that binds the 5mC pocket  
111 of SRA previously disclosed by our group<sup>55</sup>, a SMARTS-based pre-filtration of the databases was  
112 carried out (**Fig. 1**). Specifically, SMARTS patterns were designed to preserve the major  
113 pharmacophores or functional groups that were thought to be relevant for UM63 binding to SRA  
114 domain. These include large structures such as the tricyclic anthracene-like core that mimics UM63,  
115 as well as simplified structures to enhance chemical diversity in the final screening library.

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118 **Figure 1:** Chemical structure of UM63 and its substructures that were used in the generation of SMARTS patterns for  
119 chemical databases pre-filtration. \* represents any connected atom including H.

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121 By database pre-filtration through SMARTS patterns, ~1.3 and ~3.7 million molecules were selected  
122 from Aldrich Market Select and MolPort (around 15% and 48% of the initial databases, respectively)  
123 which were submitted to molecular docking with FRED program from OpenEye (FRED 3.0.1:  
124 OpenEye Scientific Software, Santa Fe, NM. <http://www.eyesopen.com>)<sup>59</sup>. The X-ray  
125 crystallographic structure of the human SRA domain of UHRF1 bound to hemi methylated (HM)  
126 DNA was used as a rigid receptor (PDB\_ID: 3CLZ)<sup>59</sup>. Based on FRED Chemgauss4 score, top  
127 ranking 1000 compounds were selected for further investigations. Among them, a few derivatives  
128 share the main scaffold with UM63, while others have different chemotypes, including naphthalene,  
129 benzoic acid, carbamide, guanidine, and various heterocyclic derivatives. To maximize chemical  
130 diversity in the final selection of virtual hits, these 1'000 top ranking virtual hits were further clustered  
131 based on a combination of fingerprints and substructure search through a well-established  
132 cheminformatics approach<sup>60-62</sup>. Finally, combining visual inspection of docking poses with chemical  
133 diversity analysis led to the selection of 27 virtual hits from Aldrich Market Select (**Fig. S1**) and 37  
134 virtual hits from MolPort (**Fig. S2**), which were submitted to experimental validation.

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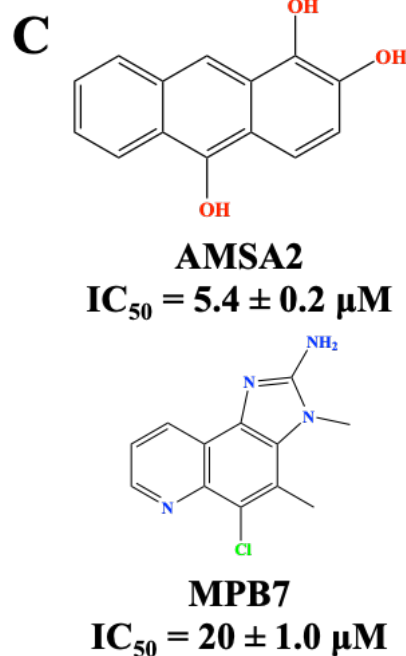
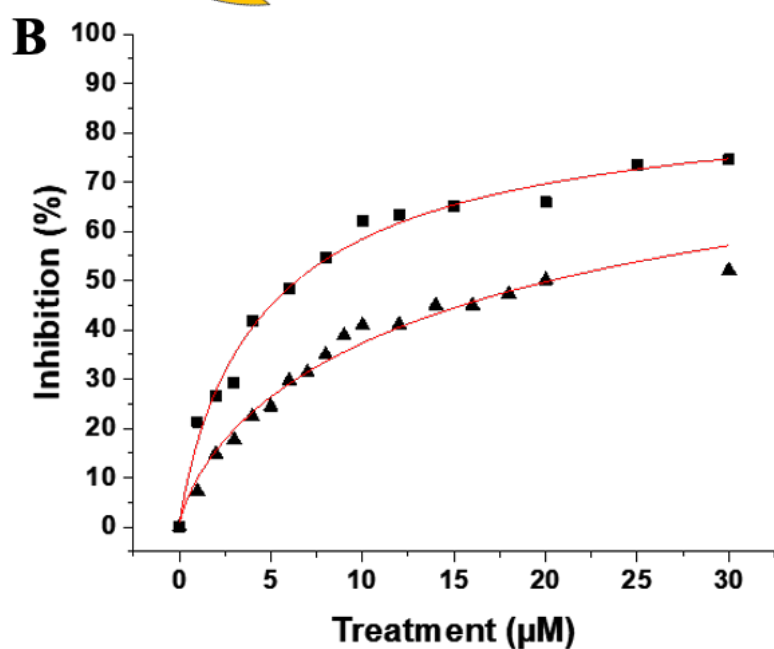
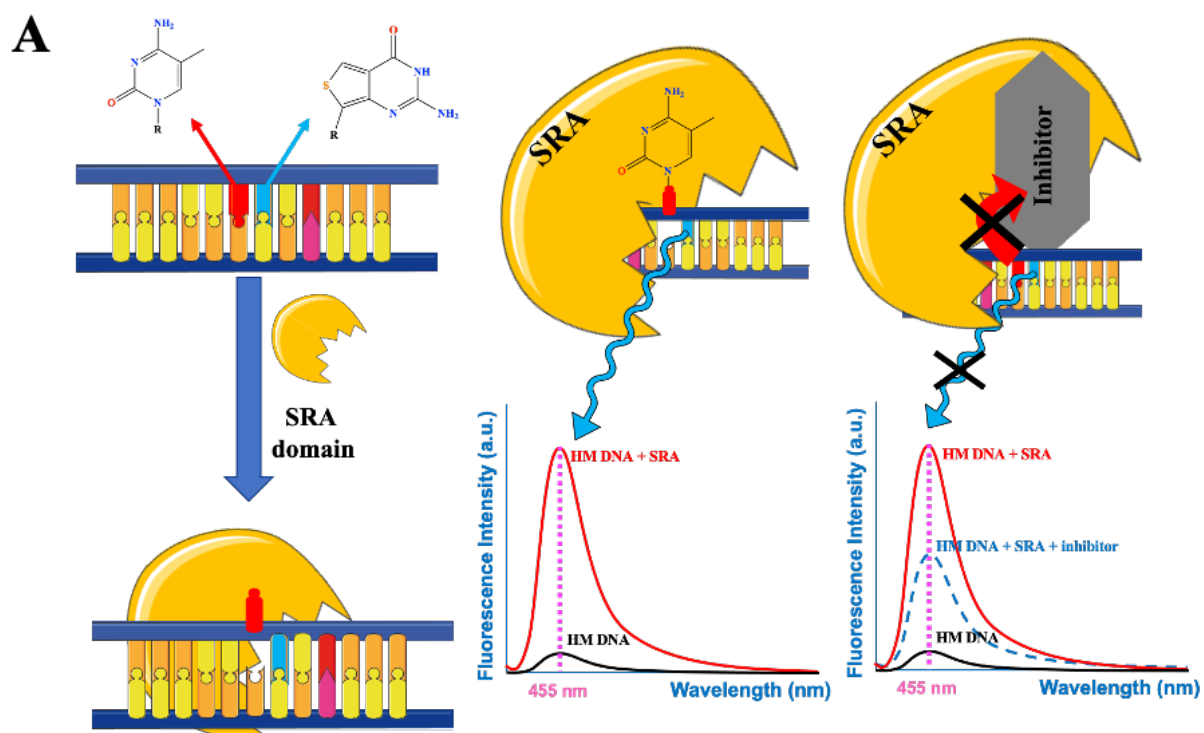
### 136 ***In vitro* screening and characterization of virtual hits**

137 The 64 compounds selected by virtual screening were then tested *in vitro* using a highly sensitive  
138 fluorescence-based assay that monitors the 5mC base flipping activity. This assay takes advantage of  
139 the photophysical features of thienoguanosine (<sup>th</sup>G), an isomorphous guanosine surrogate<sup>63-65</sup>,  
140 incorporated into the 12-bp duplex whose structure in complex with SRA has been solved by X-ray  
141 crystallography<sup>24</sup>. In this HM duplex, <sup>th</sup>G was used to replace the G residue at position 7 in the single  
142 CpG site (**Fig. 2A**). <sup>th</sup>G perfectly replaces G in this duplex and sensitively responds to the SRA-  
143 induced base flipping of the flanking 5mC with a strong fluorescence increase<sup>66,67</sup>. Therefore, a small  
144 molecule able to bind into the 5mC binding pocket of SRA can be identified through a decrease of  
145 the <sup>th</sup>G fluorescence intensity (**Fig. 2B**).

146 By monitoring the base flipping interference of the 64 virtual hits at 10  $\mu\text{M}$ , ten compounds showed  
147 an inhibitory effect  $> 30\%$  and were selected for further analyses (**Table S1**). Next, the dose-response  
148 curves of the 10 selected compounds were recorded on the SRA-induced base flipping assay (**Table**  
149 **S2**). In parallel, as DNA intercalating properties of UM63 were a major drawback, we also tested  
150 their DNA intercalating properties by competition with ethidium bromide (EtBr) for the HM DNA  
151 duplex (UM63 intercalation data from Zaayter et al, 2019 are reported in **Fig. S3**, blue triangles).  
152 From these two assays, we selected the most efficient compounds with an  $\text{IC}_{50}$  value  $\leq 20 \mu\text{M}$  on the  
153 base flipping assay and  $< 20\%$  ejection of EtBr at 30  $\mu\text{M}$  concentration (**Table S2**). This combination  
154 of assays allowed to prioritize three compounds, i.e. AMSA2, AMSE2 and MPB7. Among them,  
155 AMSA2 and AMSE2 are structurally related to UM63, with which they also share comparable  $\text{IC}_{50}$   
156 values ( $5.4 \pm 0.2 \mu\text{M}$ ,  $4.5 \pm 0.2 \mu\text{M}$  and  $4.4 \pm 0.5 \mu\text{M}$  for AMSA2, AMSE2 and UM63, respectively).  
157 UM63  $\text{IC}_{50}$  data Zaayter et al, 2019 are reported in **Fig. S3**, green squares. Since AMSE2 is  
158 structurally related to benzo[*a*]pyrene, a carcinogenic agent that can cause skin, lung, and bladder  
159 cancer in humans and in animals<sup>68</sup>, this compound was discarded. MPB7 exhibits a slightly higher  
160  $\text{IC}_{50}$  ( $20 \pm 1.0 \mu\text{M}$ ) compared to AMSA2, and it is a member of imidazoquinoline family, which is a  
161 class of immunomodulatory drugs with anticancer features<sup>69-72</sup>. Accordingly, we focused following  
162 studies on AMSA2 and MPB7 (**Fig. 2C**), which both show remarkable inhibition of UHRF1 base  
163 flipping activity and marginal DNA intercalating ability, thus overcoming the major limitation of  
164 UM63.

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**Figure 2:** *In vitro* screening of virtual hits preventing SRA-induced base flipping. (A) Principle of the base flipping assay. (B) Dose-response curves of AMSA2 (black squares) and MPB7 (black triangles). The red lines correspond to the fit of the data points with equation 2 from Materials and Methods. (C) AMSA2 and MPB7 structures and their  $IC_{50}$  values determined from the fits in panel B.

172 We then evaluated the ability of AMSA2 and MPB7 to dissociate the SRA/HM DNA complex, by  
 173 monitoring the fluorescence anisotropy of the fluorescein-labelled HM duplex. In its free form, the  
 174 labelled duplex exhibited a very low anisotropy value (~0.016) while, in complex with SRA, the  
 175 anisotropy value increased to 0.17. Addition of increasing concentrations of AMSA2 and MPB7 up

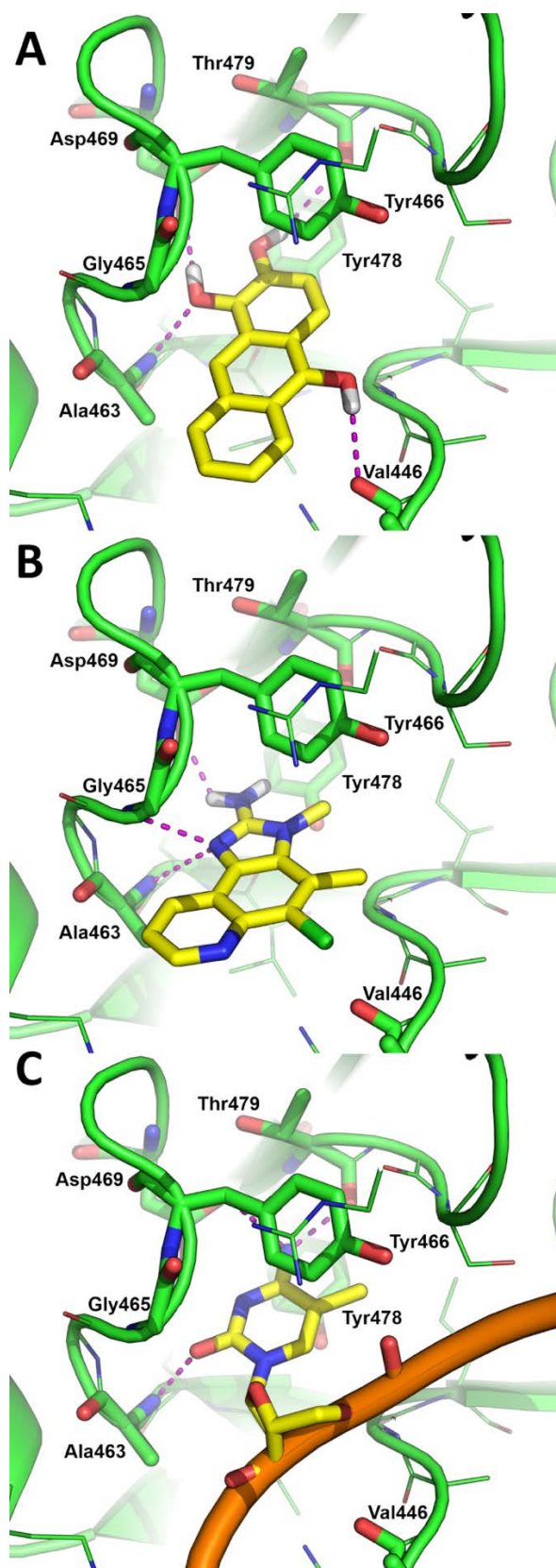
176 to 200  $\mu$ M only slightly decreases the anisotropy value (**Fig. S4**), indicating that AMSA2 and MPB7  
177 inhibit SRA-induced base flipping, without dissociating the SRA/HM DNA complex.

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### 179 **Binding mode of AMSA2 and MPB7 in the SRA binding pocket**

180 To further assess the interaction of AMSA2 and MPB7 with the 5mC binding pocket of SRA,  
181 molecular docking simulations were carried out using more extensive sampling parameters compared  
182 to virtual screening.

183 Both molecules establish H-bonds with key residues of UHRF1 that are known to interact with the  
184 flipped 5mC as well as with the backbone of HM DNA<sup>24</sup>, such as Val446, Ala463, Gly465, Asp469,  
185 and Thr479 (**Fig. 3**). The aromatic ring of both compounds is  $\pi$ -stacked to the side chain of Tyr478  
186 in a parallel-displaced orientation. Similar to the binding mode of 5mC in the X-ray crystallography  
187 structure, the side chain of Tyr466 establishes hydrophobic/aromatic interactions with the compounds  
188 on the opposite side compared to Tyr478. The catechol moiety of AMSA2 establishes an extensive  
189 network of H-bond interactions with the backbone of Ala463 and Thr479, as well as with the side  
190 chain of Asp469 (**Fig. 3A**), while the isolated hydroxyl group is H-bonded to the backbone of Val446.  
191 The aminoimidazole moiety of MPB7 is largely engaged in H-bonds with the backbone of Ala463  
192 and Gly465, while it interacts with the side chain of Asp469 (**Fig. 3B**). Overall, these binding modes  
193 strongly overlap with the binding mode of the natural substrate 5mC (**Fig. 3C and Fig. S5**), which  
194 might provide a structural explanation to the inhibitory effects of AMSA2 and MPB7 as observed in  
195 experimental studies.



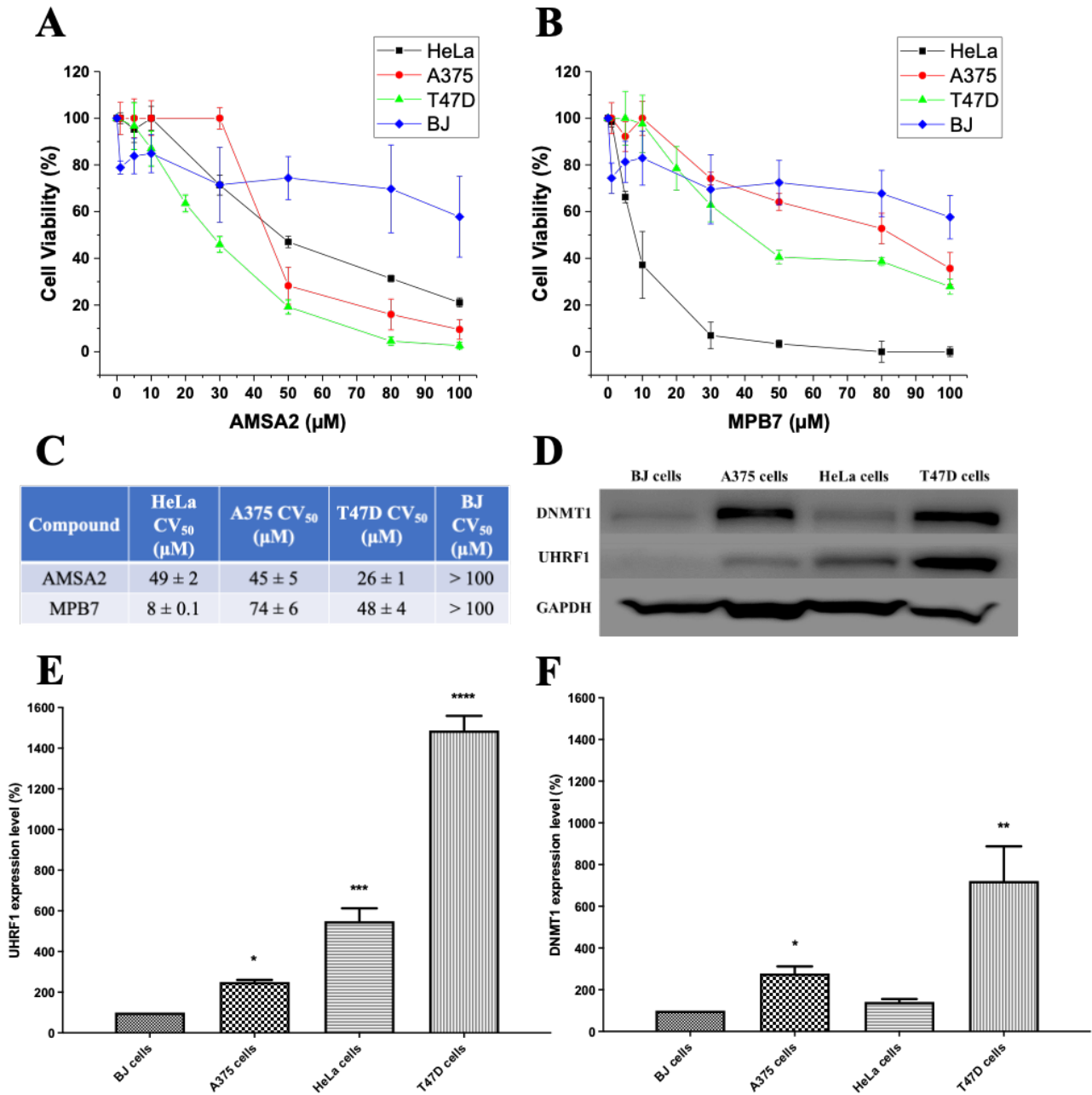
**Figure 3:** Docking-based binding mode of AMSA2 (A) and MPB7 (B) and X-ray crystallography pose of 5mC (C) within the 5mC binding site of SRA. AMSA2, MPB7, and 5mC are shown as yellow sticks while the crystallographic structure of SRA (PDB\_ID: 3CLZ) is shown as green cartoon. Residues within 5 Å from the ligands are shown as lines, while those contacted by the inhibitors and discussed in the main text are labelled and shown in sticks. H-bond interactions are highlighted by magenta dashed lines.

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203 **AMSA2 and MBP7 decrease cancer cell viability in correlation with UHRF1 expression level**

204 The effect of AMSA2 and MPB7 on the viability of cervical cancer cells (HeLa), melanoma cancer  
205 cells (A375) and breast ductal carcinoma cells (T47D) expressing different UHRF1 levels<sup>10</sup> was  
206 tested for 48 h by using the MTT assay. Selected compounds were also tested on healthy foreskin  
207 fibroblasts (BJ). Notably, both compounds show a dose-dependent effect on cancer cells with only  
208 marginal effects on BJ cells (**Fig. 4A** and **B**). Previous cell viability data from UM63<sup>55</sup> were added  
209 in **Fig. S3**, red circles. Evaluation of the concentrations leading to a 50% decrease in cell viability  
210 ( $CV_{50}$ ) (**Fig. 4A** and **B**) revealed that MPB7 ( $CV_{50}$  ~8  $\mu$ M) was more active than AMSA2 ( $CV_{50}$  ~49  
211  $\mu$ M) or UM63 ( $CV_{50}$  ~30  $\mu$ M)<sup>55</sup> on HeLa cells. In contrast, MPB7 was two-fold less active than  
212 AMSA2 on A375 and T47D cells. Finally, both compounds show low impact on the viability of BJ  
213 cells ( $CV_{50}$  > 100  $\mu$ M).

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215  
 216 **Figure 4:** Effect of AMSA2 and MPB7 on cell viability (A-C), and correlation with UHRF1 and DNMT1 expression  
 217 levels (D-F). Cell viability on treatment with AMSA2 (A) and MPB7 (B) was investigated using a MTT assay. HeLa,  
 218 A375, T47D and BJ data points are shown as black squares, red circles, green triangles and blue diamonds, respectively.  
 219 Each concentration has been tested in hexaplicate with at least 3 different biological replicates. In the Table of panel C,  
 220 the concentrations leading to a 50% decrease in cell viability (CV<sub>50</sub>) were deduced from the curves in panels A and B.  
 221 (D) Western blots and (E) UHRF1 expression level and (F) DNMT1 expression level. Western blot images were  
 222 processed with ImageJ software and the intensity of each band was normalized to the corresponding GAPDH band. The  
 223 results between groups were statistically compared by one-way ANOVA with post-hoc Bonferroni test using GraphPad-  
 224 Prism (version 5.04) software. Statistical significance is represented as *ns* > 0.05, \**p* < 0.05, \*\**p* < 0.01, and \*\*\**p* < 0.001,  
 225 \*\*\*\**p* < 0.0001 versus control.  
 226

227 As both compounds were selected based on their ability to inhibit UHRF1, we next investigated  
228 whether their differential effect on healthy and cancer cells depends on UHRF1 expression levels  
229 (**Fig. 4D**). In line with the preferential effect of the compounds on the viability of cancer cells, UHRF1  
230 expression was significantly higher in cancer cell lines as compared to BJ cells (**Fig. 4E**). Concerning  
231 DNMT1, its expression level was low in both BJ and HeLa cells, which poorly correlates with the  
232 observed effects on cell viability (**Fig. 4F**). Taken together, our data are in line with the hypothesis  
233 that both compounds may impair cell viability by targeting UHRF1. Since HeLa cells were found to  
234 be particularly sensitive to MPB7, they were selected for further investigations.

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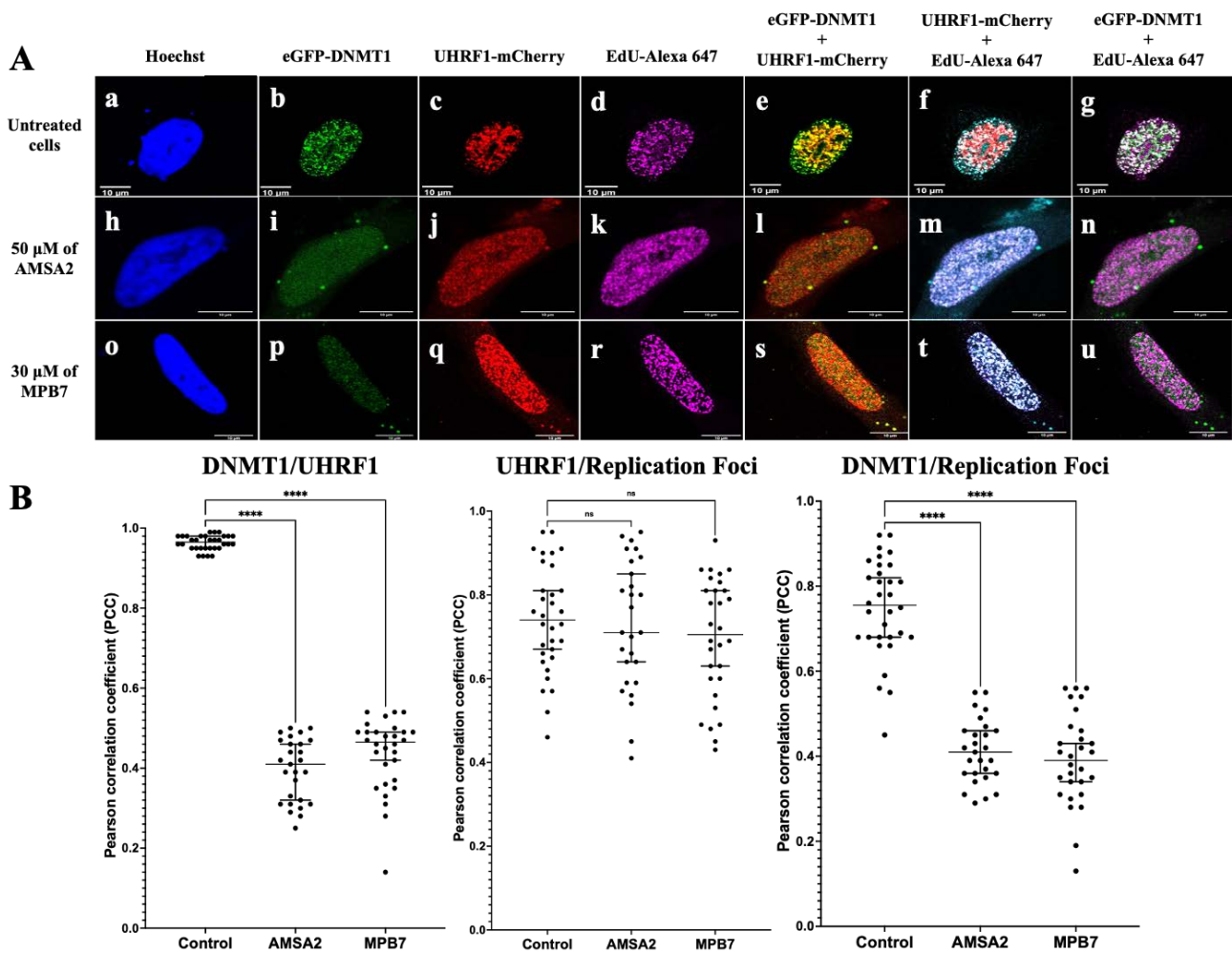
#### 236 **AMSA2 and MBP7 prevent DNMT1 recruitment at the replication foci**

237 To confirm that AMSA2 and MBP7 target UHRF1 in cancer cells, we investigated by confocal  
238 microscopy their ability to impact UHRF1 functions in cells. UHRF1 has been previously shown to  
239 recruit DNMT1 onto the replication foci<sup>21,22,55,73,74</sup>, a function that is inhibited by UM63<sup>55</sup>. To  
240 evaluate if AMSA2 and MPB7 exhibit similar properties, we transiently transfected HeLa cells with  
241 eGFP-DNMT1 and UHRF1-mCherry and then analyzed the co-localization of the two proteins at the  
242 replication foci in the presence of 30  $\mu$ M of MPB7 and 50  $\mu$ M of AMSA2 after 24 h of treatment.  
243 These two concentrations were chosen based on the dose-response curves of the two compounds on  
244 HeLa cells (**Fig. 4A** and **B**). HeLa cells were additionally labeled with both EdU-Alexa647 and  
245 Hoechst dye, to highlight the replication foci and nuclei, respectively (**Fig. 5**).

246 In non-treated HeLa cells, both UHRF1 and DNMT1 were well co-localized at the replication foci  
247 (yellow dots, **Fig. 5** panel **e**), in full line with previous observations<sup>21,22,25,55,74</sup>. AMSA2 and MPB7  
248 had no effect on the localization of UHRF1 at replication foci (**Fig. 5** panels **m** and **t**), as confirmed  
249 by the unchanged Pearson Correlation Coefficient (PCC) between UHRF1-mCherry and Edu (**Fig.**  
250 **5B**). The marginal impact of the compounds on the localization of UHRF1 at the replication foci is  
251 consistent with our anisotropy data (**Fig. S5**), suggesting that AMSA2 and MPB7 do not dissociate  
252 SRA/HM DNA complexes. In contrast, AMSA2 and MPB7 induced a significantly decreased co-

253 localization between DNMT1 and UHRF1 signals (**Fig. 5** panels **l** and **s**) associated with a decrease  
254 of DNMT1 localization at the replication foci (**Fig. 5** panels **n** and **u**). This was confirmed by the  
255 significant PCC decrease for the overlap of the two labelled proteins ( $0.99 \pm 0.01$  in non-treated cells  
256 vs  $0.4 \pm 0.01$  in treated cells, **Fig. 5B**) and the overlap of eGFP-DNMT1 and EdU signals ( $0.79 \pm$   
257  $0.05$  in non-treated cells vs  $0.4 \pm 0.01$  in cells treated with the hits, **Fig. 5B**).

258 In conclusion, our data show that both AMSA2 and MPB7 inhibit DNMT1 recruitment onto  
259 replication foci, likely as a result of UHRF1 base flipping inhibition.



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 261 **Figure 5:** AMSA2 and MPB7 effect on DNMT1/UHRF1 co-localization onto replication foci. (A) Confocal images  
 262 showing eGFP-DNMT1 and UHRF1-mCherry distribution in HeLa cells labeled with EdU-Alexa 647 and Hoechst  
 263 dye. Panels **a** to **g** correspond to untreated cells (control), **h** to **n** correspond to cells treated with AMSA2 at 50  $\mu$ M and  
 264 to **o** to **p** correspond to cells treated with MPB7 at 30  $\mu$ M. **a**, **h** and **o** panels show Hoechst dye (nucleus). **b**, **i** and **p** panels  
 265 show eGFP-DNMT1. **c**, **j** and **q** panels show UHRF1-mCherry. **d**, **k** and **r** panels show EdU-Alexa 647 (replication foci  
 266 in S Phase). **e**, **l** and **s** panels show co-localization of eGFP-DNMT1 with UHRF1-mCherry. **f**, **m** and **t** panels show the  
 267 localization of eGFP-DNMT1 onto replication foci (Edu-Alexa 647). **g**, **n** and **u** panels show the localization of UHRF1-  
 268 mCherry onto replication foci (Edu-Alexa 647). White bar indicates size of 10  $\mu$ m. (B) Dot plot representation of the  
 269 Pearson correlation coefficient (PCC) values for the co-localization of DNMT1/UHRF1, UHRF1/Foci and DNMT1/Foci  
 270 in the confocal images. Each dot corresponds to one cell. The total number of analyzed cells was 30 for control, AMSA2  
 271 at 50  $\mu$ M and MPB7 at 30  $\mu$ M from at least three different biological replicates. Results between groups were statistically  
 272 compared by one-way ANOVA with post-hoc Bonferroni test using GraphPad-Prism (version 5.04) software. Statistical  
 273 significance is represented as *ns* > 0.05, \**p* < 0.05, \*\**p* < 0.01, and \*\*\**p* < 0.001, \*\*\*\**p* < 0.0001 versus control.  
 274



275 **Inhibition of SRA base flipping is associated with a drop in global DNA methylation level**

276 We next investigated whether AMSA2 and MPB7 affects the global DNA methylation of HeLa cells  
277 after 48 h of treatment by using an immunofluorescence assay with a specific monoclonal antibody  
278 against 5mC (**Fig. 6A**). As a positive control, we treated HeLa cells with 100  $\mu$ M of 5-azacytidine,  
279 an FDA-approved DNMT1 inhibitor, which leads to 83% decrease of 5mC fluorescence compared to  
280 untreated cells.

281 AMSA2 was observed to reduce global DNA methylation by only 10% at 10  $\mu$ M concentration but  
282 by 75% at 50  $\mu$ M (**Fig. 6B**). A stronger effect was observed with MPB7, which decreased the global  
283 methylation level by 87% and 93% at 10 and 30  $\mu$ M, respectively. Therefore, MPB7 at 10  $\mu$ M and  
284 AMSA2 at 50  $\mu$ M efficiently decreased 5mC fluorescence, similarly to 100  $\mu$ M of azacytidine,  
285 suggesting that both inhibitors of UHRF1 base flipping effectively decrease the methylation level in  
286 cancer cells.

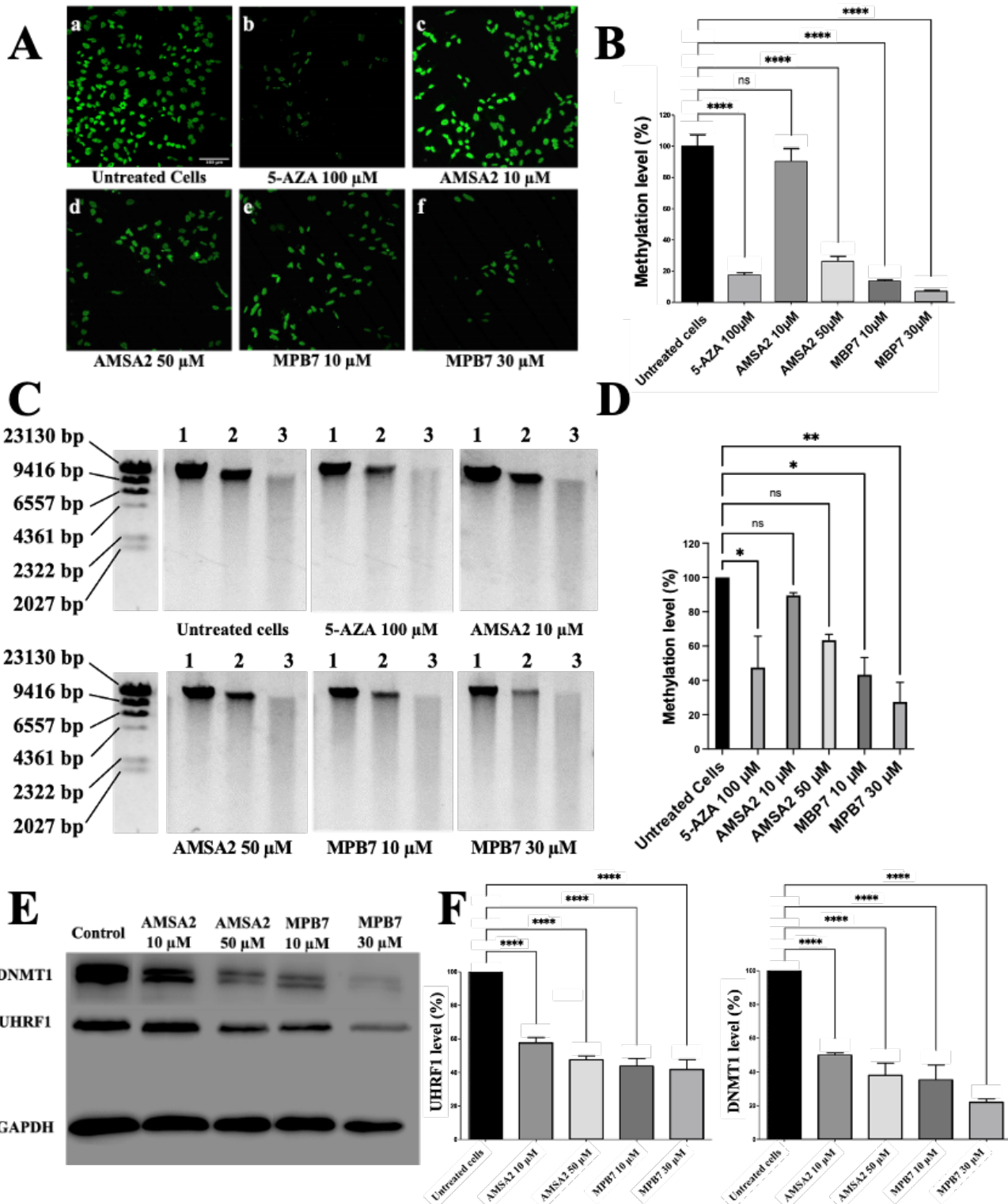
287 We also confirmed the effect after 48 h of treatment with AMSA2 and MPB7 on global DNA  
288 methylation with digestion by methyl sensitive and insensitive restriction endonucleases, *HpaII* and  
289 *MspI*, respectively (**Fig. 6C**). HeLa cells treated with 100  $\mu$ M of 5-azacytidine was used as positive  
290 control. As a result, AMSA2 reduced the global DNA methylation by 11% at 10  $\mu$ M and 37% at 50  
291  $\mu$ M, while a stronger effect was observed with MPB7, which decreased the global methylation level  
292 by 58% and 74% at 10 and 30  $\mu$ M, respectively (**Fig. 6D**). 100  $\mu$ M of 5-azacytidine led to 47%  
293 decrease.

294 At this stage, the molecular mechanisms that link the initial inhibition of UHRF1 base flipping  
295 activity by AMSA2 and MPB7 and the decrease of DNA methylation observed at 48 h are unknown.

296 Among the possible scenarios, a decrease in DNMT1 protein level could be an obviously possible  
297 step in these mechanisms. To check this hypothesis, we monitored UHRF1 and DNMT1 protein  
298 levels after AMSA2 and MPB7 treatments for 48 h (**Fig. 6E**). A very significant decrease in both  
299 UHRF1 and DNMT1 protein levels was observed with both compounds (**Fig. 6F**), suggesting that

300 part of the observed decrease in the global DNA methylation level might be due to a decrease in  
 301 DNMT1 protein level in the treated cells.

302



303  
 304 **Figure 6:** AMSA2 and MPB7 effect on global methylation level in HeLa cells, as evaluated by using labelled monoclonal  
 305 antibody against 5mC (A, B), methylation sensitive enzymes (C, D) and effect on UHRF1 and DNMT1 protein levels (E,  
 306 F). (A) Confocal immunofluorescence images showing untreated cells (panel a), cells treated with 100  $\mu$ M of 5-  
 307 azacytidine (panel b), cells treated with 10  $\mu$ M (panel c) and 50  $\mu$ M (panel d) of AMSA2 and cells treated with 10  $\mu$ M

308 (panel e) and 30  $\mu$ M (panel f) of MPB7 for 48 h. (B) Quantification of the methylation level from the confocal data. 30  
309 pictures for each treatment were analyzed along with controls from at least 3 different biological replicates. (C) Gel  
310 images showing digested DNA from untreated cells, cells treated with 100  $\mu$ M of 5-azacytidine, 10  $\mu$ M and 50  $\mu$ M of  
311 AMSA2 and 10  $\mu$ M and 30  $\mu$ M of MPB7 for 48 h; **column 1**, undigested DNA; **column 2**, DNA digested with *HpaII*  
312 (methylation sensitive restriction endonuclease); **column 3**, DNA digested with *MspI* (methylation insensitive restriction  
313 endonuclease). (D) Quantification of the DNA methylation levels from the enzymatic assay performed on two biological  
314 replicates. Gel images were processed with ImageJ software and the intensity of each band was compared to the  
315 corresponding band in untreated cells. (E) Western blots showing UHRF1 and DNMT1 protein levels in untreated HeLa  
316 cells (control), and in HeLa cells treated with 10  $\mu$ M and 50  $\mu$ M of AMSA2 or with 10  $\mu$ M and 30  $\mu$ M of MPB7 for 48  
317 h. (F) Quantification of UHRF1 and DNMT1 protein levels from western blot data performed on at least 3 different  
318 biological replicates. Gel images were processed with ImageJ software. The intensity of each protein band was normalized  
319 to the intensity of the corresponding GAPDH band and then compared to the intensity of the corresponding protein band  
320 in untreated cells. Data between groups were statistically compared by one-way ANOVA with post-hoc Bonferroni test  
321 using GraphPad-Prism (version 5.04) software. Statistical significance is represented as *ns* > 0.05, \* *p* < 0.05, \*\* *p* < 0.01,  
322 and \*\*\* *p* < 0.001, \*\*\*\* *p* < 0.0001 versus control.  
323

## 324 Discussion

325 Epigenetic marks govern cell identity by controlling the expression of specific genes. UHRF1 is a  
326 key player in the maintenance of epigenetic patterns by orchestrating DNA methylation and  
327 recognition of histone modifications. Importantly, while UHRF1 expression is globally low in non-  
328 cancer cells, peaking only in G<sub>1</sub> and G<sub>2</sub>/M phase<sup>33</sup>, it is found overexpressed throughout the cell cycle  
329 in several types of human cancers, promoting cell proliferation and dedifferentiation<sup>10</sup>. The  
330 importance of UHRF1, in particular its SRA domain, is highlighted from mutagenesis experiments  
331 in which embryonic stem cells (ESCs) with UHRF1-knockout show DNMT1 dissociation from  
332 chromatin<sup>21,22,75</sup> and UHRF1-deficient embryos show global demethylation and lethality after  
333 granulation<sup>21</sup>. Therefore, UHRF1 appears as a valuable target for the development of anticancer  
334 agents that impact cancer cells with a high specificity over non-cancer cells.

335 Since DNMT1 recruitment onto replication foci is triggered by 5mC base flipping at HM CpG sites  
336 induced by the SRA domain of UHRF1<sup>21,22,24,76</sup>, our strategy was to target the 5mC binding pocket  
337 of SRA using a multidisciplinary approach combining molecular modelling, biophysical assays and  
338 molecular and cellular biology. Two molecules, i.e., AMSA2 (1,2,10-trihydroxyanthracene,  
339 anthrarobin) and MPB7 (2-amino-5-chloro-3,4-dimethyl-3H-imidazo[4,5-*f*]quinoline) were  
340 highlighted as efficient inhibitors of SRA-mediated base flipping. AMSA2 shares the anthracene core  
341 with the parent UM63, confirming the importance of anthracene/anthraquinone scaffold to target the

342 SRA base flipping activity<sup>40,54,55,77</sup>. MPB7 is a member of imidazoquinoline family, a class of  
343 immunostimulant drugs with pro-apoptotic properties<sup>69-72</sup>. These two molecules have activities  
344 comparable to UM63 in inhibiting SRA base flipping, but do not show any significant DNA  
345 intercalating properties, which is a key advantage over UM63. Indeed, though several anticancer  
346 compounds are DNA intercalators, their mechanism of action *in cellulo* is unpredictable, as they can  
347 trigger genome damages and mutagenesis through binding to unspecific DNA sequences, which could  
348 lead to several adverse effects including cancerogenesis<sup>78</sup>.

349 Molecular modelling revealed that AMSA2 and MBP7 bind similarly to 5mC within the SRA binding  
350 pocket, which explains their ability to prevent the SRA-mediated base flipping of 5mC. Moreover,  
351 AMSA2 and MPB7 are projected towards the solvent-accessible area near the entrance of the SRA  
352 binding pocket. As a consequence, the distal phenyl ring of AMSA2 and the pyridine ring of MPB7  
353 were near the entrance of the 5mC binding site and represented thus a potential site for further hit-to-  
354 lead optimization (**Fig. S5**).

355 Interestingly, AMSA2 and MPB7 only marginally dissociated the SRA/HM DNA complex,  
356 suggesting that they might form a ternary complex while inhibiting base flipping activity. By  
357 preventing 5mC flipping in the bound CpG motif, these compounds might perturb UHRF1  
358 conformational switch into its active form<sup>28,55,66,79</sup> thus inhibiting the E3-ligase activity of the RING  
359 domain<sup>29,80,81</sup> and the recruitment of DNMT1, ultimately leading to a DNA methylation decrease.

360 This scenario has been validated in HeLa cell model, evidencing that both compounds inhibit DNMT1  
361 recruitment onto replication foci, which ultimately led through a still unknown pathway to a  
362 significant decrease in DNA global methylation. UHRF1 inhibition was also confirmed by the effect  
363 of both compounds on cell viability, which depended on UHRF1 expression level. Indeed, both  
364 compounds efficiently decreased the cell viability of the three tested cancer cell lines overexpressing  
365 UHRF1 (HeLa, A375 and T47D), but did not significantly impact non-cancer BJ cells, which display  
366 low expression of UHRF1.

367 The cascade of events between the initial inhibition of UHRF1 base flipping by AMSA2 and MPB7  
368 and the decrease in cell viability as well as DNA methylation observed after 48 h is still unknown.  
369 Nevertheless, our data strongly suggest that part of the decrease in global DNA methylation could be  
370 related to the decrease in DNMT1 protein level, probably as a result of its degradation by the  
371 proteasome. Studies are in progress to further identify the molecular pathways underlying the activity  
372 of the two compounds on DNA methylation and cell viability in relation to their inhibitory activity  
373 on UHRF1.

374 To date, FDA approved a few drugs, such as nucleoside analogues 5-azacitidine and decitabine<sup>41-44</sup>,  
375 aiming to control DNA hypermethylation by inhibiting DNMT1 activity. These drugs are  
376 incorporated in both DNA and RNA during the S phase substituting the Cs. Upon incorporation, these  
377 two drugs form a covalent bond in the presence of DNMT1, driving it to proteasome degradation<sup>82,83</sup>.  
378 Due to their mechanism of action and given the very high structural similarity with natural  
379 nucleosides, these drugs exhibit a poor therapeutic index and selectivity, as they can be incorporated  
380 in both cancer and non-cancer cells.

381 Furthermore, natural products such as flavonoids have been reported to downregulate UHRF1 and  
382 consequently to reduce global DNA methylation in HeLa cells<sup>38,84</sup>. These molecules were thus  
383 identified as potential UHRF1 inhibitors, but their mechanism of action is still unclear and none of  
384 them reached yet the clinical phase<sup>50-55</sup>. Recently, Hu and co-workers disclosed a new molecule  
385 UF146 as an inhibitor of the UHRF1-SRA/Sin3A-associated protein 30 (SAP30) interaction,  
386 preventing the transcription of MXD4 affecting the self-renewal of leukemia initiation cells (LICs)<sup>56</sup>.  
387 Although UF146 formally qualifies as a PAINS<sup>57,58</sup> due to the presence of the quinone moiety, it is  
388 structurally related to UM63 and mitoxantrone, which corroborates the screening strategy adopted in  
389 this work for the identification of new chemotypes of UHRF1 inhibitors.

390 Taken together, our data indicate that AMSA2 and MPB7 are promising UHRF1 inhibitors that inhibit  
391 the base flipping activity of the SRA domain and prevent DNMT1 recruitment on the replication foci.  
392 The two compounds also decreased the DNA methylation level, which compromises the viability of

393 the treated cells. Cancer cells were found to be more sensitive than normal cells, likely as a  
394 consequence of their higher UHRF1 expression levels. The investigation of the cellular mechanisms  
395 and anticancer activities of the two compounds is currently in progress.

396

## 397 **Materials and Methods**

### 398 **Chemicals, oligonucleotides and protein**

399 All tested compounds were purchased from Aldrich Market Select (Milwaukee, Wisconsin, USA)  
400 and MolPort (Riga, Latvia). The MPB7 purity provided by the vendor (Toronto Research Chemicals,  
401  $\geq 98\%$ ) and the AMSA2 purity determined in our lab by HPLC were  $> 95\%$  (**Fig. S6**). Both  
402 compounds were initially dissolved in 99% pure DMSO (Sigma Aldrich) as stock solutions, aliquoted  
403 (avoiding freeze-thaw cycles) and stored at  $-20\text{ }^{\circ}\text{C}$  until further use. 5-azacitidine ( $\geq 98\%$ , HPLC)  
404 was purchased from Sigma Aldrich. DNA duplexes were prepared by annealing equal molar amounts  
405 of complementary oligonucleotides in a PCR thermocycler (BIO-RAD T100TM) using 20 mM  
406 phosphate buffer pH 7.5, 150 mM NaCl. Unlabeled 5'-GGGCCmCGCAGGG-3' and complementary  
407 5'-CCCTGCGGGCCC-3' oligonucleotides were purchased from IBA GmbH Nucleic Acids Product  
408 Supply (Germany) in a HPLC-purified form. Labelled 5'-GGGCCmC<sup>th</sup>GCAGGG-3' oligonucleotide  
409 with thienoguanosine (<sup>th</sup>G) at position 7 was purchased from TriLink Biotechnologies (USA). The  
410 5'-GGGCCmCGCAGGG-3' sequence labelled with 6-Carboxyfluorescein (6FAM) at the 5' end was  
411 purchased from Eurogentec (Belgium). The SRA domain (residues 408-643) of UHRF1 was  
412 expressed and purified as described previously<sup>85</sup>.

413

### 414 **Absorption Spectroscopy**

415 Absorption spectra were recorded on a Cary 4000 UV-visible spectrophotometer (Varian) using  
416 quartz cuvettes (Hellma Analytics) of 1 cm optical path length. Absorption coefficients of 112,950  
417  $\text{M}^{-1}\text{cm}^{-1}$  and 97,300  $\text{M}^{-1}\text{cm}^{-1}$  at 260 nm were used for the single strand non-labelled 5'-

418 GGGCCmCGCAGGG-3' and complementary 5'-CCCTGCGGGCCC-3' sequences, respectively.  
419 Absorption coefficients at 260 nm of 103,000 M<sup>-1</sup>cm<sup>-1</sup> and 131,800 M<sup>-1</sup>cm<sup>-1</sup> were used for the single  
420 strand <sup>th</sup>G-labelled 5'-GGGCCmC<sup>th</sup>GCAGGG-3' and 6FAM-labelled 5'-GGGCCmCGCAGGG-3'  
421 sequences, respectively. Absorption coefficients at 260 nm of 183,340 M<sup>-1</sup>cm<sup>-1</sup> and 209,900 M<sup>-1</sup>cm<sup>-1</sup>  
422 were used for the <sup>th</sup>G-labelled and 6FAM-labelled duplexes, respectively. For SRA, an absorption  
423 coefficient of 43,890 M<sup>-1</sup>cm<sup>-1</sup> at 280 nm was used. All the experiments were performed at 20°C in  
424 20 mM phosphate buffer pH 7.5, 50 mM NaCl, 2.5 mM TCEP and PEG 0.05% to avoid protein  
425 adsorption to the quartz cuvette<sup>66</sup>.

426

### 427 **Steady-State Fluorescence Spectroscopy**

428 Fluorescence spectra were collected at 20 °C on a FluoroLog spectrofluorometer (Horiba) equipped  
429 with a thermostated cell compartment. For <sup>th</sup>G-labelled duplexes, excitation wavelengths ranging  
430 from 320 to 360 nm were used. For ethidium bromide, excitation was at 526 nm, slits 5 nm. All the  
431 spectra were corrected for lamp fluctuations and instrumental wavelength-dependent bias as well as  
432 for the fluorescence of the buffer and the compounds selected by *in silico* screening.

433 To determine whether positive hits are able to dissociate the complexes of SRA with HM duplex, we  
434 performed fluorescence anisotropy measurements with 6FAM-labelled HM duplexes. Increasing  
435 concentrations of the hits were added to the SRA/HM duplex complex. For each addition, the  
436 fluorescence anisotropy of the complex was monitored with a FluoroLog spectrofluorometer (Horiba)  
437 in T-format. Anisotropy values were the average of 10 measurements per data point. Excitation was  
438 at 495 nm, slits 2 nm, and emission was at 517 nm, slits 4 nm.

439

### 440 **Molecular modelling**

441 The Aldrich Market Select and MolPort commercial libraries of compounds containing 8'512'248  
442 and 7'591'844 entries, respectively, at the time of this study (May 2019), were downloaded in  
443 SMILES format. Filtration was performed with the FILTER application implemented in OMEGA

444 (version 2.5.1.4) from OpenEye<sup>86</sup> (OpenEye Scientific Software, Santa FE, NM.  
445 <http://www.eyesopen.com>) using the SMARTS strings corresponding to the scaffold of UM63 and  
446 its substructures. Two SMARTS strings were drawn based on UM63 full structure, while 6 SMARTS  
447 strings were drawn based on the possible UM63's substructures. Filtration of the initial libraries  
448 against the SMARTS strings led to 1'352'537 and 3'746'065 molecules from Aldrich Market Select  
449 and MolPort, respectively, whose protonation state was assigned by QUACPAC from OpenEye  
450 (version 2.5.1.4) (OpenEye Scientific Software, Santa FE, NM. <http://www.eyesopen.com>).  
451 Conformational analysis was performed with OMEGA (version 2.5.1.4) keeping all default settings  
452 and allowing the storage of up to 600 conformers per molecule. The crystallographic structure of the  
453 SRA domain of UHRF1 bound to hemi-methylated DNA (PDB\_ID: 3CLZ)<sup>24</sup> was used as a rigid  
454 receptor in molecular docking simulations after removing DNA and water molecules<sup>28</sup>. Docking-  
455 based virtual screening was performed with FRED from OpenEye (version 3.0.1) using default  
456 settings and retaining only the best pose of each docked molecule. At the end of this process, 150  
457 potential hits were selected for further visual inspection, based on their score. Finally, coupling visual  
458 inspection with the analysis of the score led to the prioritization of 64 molecules for experimental  
459 testing.

460 Subsequent in-depth docking investigation on AMSA2 and MPB7 was carried out with FRED, using  
461 the highest docking resolution settings and retaining 10 poses in order to explore the AMSA2 and  
462 MPB7 binding mode with a higher precision compared to virtual screening settings.

463

#### 464 ***In vitro* fluorescence-based base flipping assay**

465 The first round of *in vitro* screening was performed by using a fluorescence-based base flipping assay  
466 with 0.5  $\mu\text{M}$  of <sup>3</sup>H-labelled HM DNA and 1.5  $\mu\text{M}$  of SRA domain in 20 mM phosphate buffer at pH  
467 7.5, 50 mM NaCl, 2.5 mM TCEP, PEG 20.000 0.05%. Before the screening, each compound was  
468 checked for its fluorescence using <sup>3</sup>H excitation range (320 to 360 nm). If the compound showed  
469 fluorescence, its emission spectrum in buffer was recorded for subtraction. For the first round of



470 screening, the compounds were tested at 10  $\mu$ M. Absorbance measurements were collected in parallel  
471 to check for aggregation. The inhibition percentage of the SRA-induced base flipping for a given  
472 compound was determined using:

$$473 \quad \%inhibition = \frac{F.I.(dsDNA+SRA) - F.I.(dsDNA+SRA+inhibitor)}{F.I.(dsDNA+SRA) - F.I.(dsDNA)} * 100 \quad (1)$$

474 where  $F.I.(dsDNA)$ ,  $F.I.(dsDNA+SRA)$ , and  $F.I.(dsDNA+SRA+inhibitor)$ , correspond to the fluorescence intensity of  
475 <sup>th</sup>G-labelled HM duplex alone, in the presence of SRA, and in the presence of both SRA and inhibitor,  
476 respectively.

477 Compounds with an inhibitory effect > 30% at 10  $\mu$ M were selected and their half maximal inhibitory  
478 concentration ( $IC_{50}$ ) was determined on the same assay using 2  $\mu$ M of <sup>th</sup>G-labelled HM DNA and 3  
479  $\mu$ M SRA. The compounds were added to this mixture at concentrations ranging from 1 to 40  $\mu$ M.  
480 Absorbance measurements were collected in parallel to check for aggregation. The percentage of  
481 inhibition was determined by equation (1) and the resulting dose-response curve was fitted using:

$$482 \quad \%inhibition = I_0 + \frac{I_f - I_0}{1 + 10^{\{(\log(IC_{50}) - C) * p\}}} \quad (2)$$

483 where  $I_0$  and  $I_f$  correspond to the percentage of inhibition in the absence and at saturating  
484 concentration of the hit, respectively.  $C$  is the concentration of the hit, and  $p$  is the Hill coefficient<sup>87</sup>.

485

## 486 **Cell culture**

487 HeLa cells (ATCC, CCL-2 Amp, HeLa; Cervical Adenocarcinoma; Human), A375 (ATCC, CRL-  
488 1619 A-375; Malignant Melanoma; Human), T47D (ATCC, CRL-2865 T47D-KBluc; Ductal  
489 Carcinoma; Human) and BJ (ATCC, CRL-2522 BJ; Normal fibroblast; Human) were grown in  
490 DMEM (Dulbecco's Modified Eagle's Medium) or RPMI (Roswell Park Memorial Institute) 1640  
491 culture media, supplemented with 10% FBS (fetal bovine serum) and penicillin (100 U/mL) and  
492 streptomycin (100 U/mL) (Invitrogen Corporation Pontoise, France). Cells were grown at 37 °C with  
493 5% CO<sub>2</sub>. HeLa, A375 and T47D were purchased from ATCC. BJ cells were kindly gifted from Dr.  
494 Christian Muller (Faculty of Pharmacy, Illkirch, France).

495

## 496 **Cell proliferation and viability**

497 HeLa, A375, T47D, and BJ cells were seeded in 96-well plate at a density of  $5 \times 10^3$  cells/well, kept  
498 for 24 h in DMEM medium supplemented with 10% FBS to allow cell attachment and then incubated  
499 for additional 48 h in the presence of the selected compounds at different concentrations, along with  
500 the control sample, in the absence of any compound. Each concentration was tested in hexaplicate.  
501 One hundred microliters of tetrazolium dye 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium  
502 bromide (MTT) reagent (1 mg/mL) were added to each well. Then, cells were incubated for 4 h at 37  
503 °C. The medium was discarded and 50  $\mu$ L of dimethylsulfoxide (DMSO) were added to each well to  
504 dissolve formazan salts. Plates were gently mixed until the dissolution of the formazan crystals. Then,  
505 absorbance at 540 nm was measured on a plate reader Xenius (SAFAS, Monaco) in a single point  
506 format, with bandwidth 2 nm, integration time 1 s. Four measurements were performed for each well,  
507 with a shift of 0.2 mm between two measurements and the average value was calculated. All values  
508 were corrected by subtracting the absorbance of the cell culture medium alone. The percentage of  
509 inhibition for each compound was calculated using:

$$510 \quad \%inhibition = \frac{(Treated\ Cells - Untreated\ cells)}{Untreated\ Cells} * 100 \quad (3)$$

511

## 512 **Plasmids and transient transfection**

513 UHRF1-mCherry plasmid (tag: mCherry, resistance: ampicillin, vector backbone: pCMV-mCherry,  
514 promoter: CMV) and eGFP-DNMT1 plasmid (tag: eGFP at N-terminal, resistance: kanamycin, vector  
515 backbone: pEGFP-C2, promoter: CMV) were used. To transfect the selected plasmids in HeLa cells,  
516 jetPEI™ (Life Technologies, Saint Aubin, France) was used following the manufacturer's protocol.

517

## 518 **Antibodies**

519 Primary antibodies used in this study include rabbit polyclonal anti-DNMT1 (Invitrogen, PA5-  
520 30581), mouse monoclonal anti-UHRF1 (engineered as described previously<sup>33</sup>), rabbit monoclonal  
521 anti-GAPDH (Merck Millipore MAB374) and mouse monoclonal anti-5-methylcytosine (Active  
522 Motif 39649). Polyclonal anti-Mouse (HRP Conjugate Promega France, W4021), polyclonal anti-  
523 Rabbit (HRP Conjugate Promega France, W4011) and polyclonal anti-Mouse (H+L) (Cross-adsorbed  
524 alexa fluor 488, Invitrogen A-11001) were used as secondary antibodies.

525

## 526 **Western Blots**

527 HeLa, A375, T47D and BJ cells were seeded at a final density of  $7.5 \times 10^4$  cells/mL in a 6-well plate  
528 and kept for 24 h in DMEM medium supplemented with 10% FBS to allow cell attachment. Cells  
529 were then incubated for 48 h with AMSA2 (10 and 50  $\mu$ M) and MPB7 (10 and 30  $\mu$ M) along with  
530 untreated cells. Then, cells were harvested, washed with PBS and then sonicated in ice cold lysis  
531 buffer (10 mM Tris-HCl pH 7.5, 150 mM NaCl, 1 mM EDTA and 1% NP40) supplemented with  
532 cOmplete™ Protease Inhibitor Cocktail (PIC) (Roche Germany, 11836170001). Total proteins were  
533 quantified by Bradford protein assay. Protein samples were denatured by heating at 95°C for 5 min  
534 in Laemmli sample buffer (Bio-Rad, 1610747) freshly supplemented with  $\beta$ -mercaptoethanol. 40  $\mu$ g  
535 of proteins from each sample were loaded to SDS-PAGE (10%). Electrophoresis was performed in  
536 Tris-Glycine migration buffer (Tris 25 mM, Glycine 192 mM, SDS 0.1%, pH 8.8) by using a minigel  
537 system (Bio-Rad). After migration, proteins were transferred to PVDF (polyvinylidene difluoride)  
538 membranes, previously activated by methanol in transfer buffer (Tris 25 mM, Glycine 192 mM and  
539 30% methanol, pH 6.8). PVDF membranes were blocked with Superblock T20 blocking buffer  
540 (Thermo-scientific-37516) for 1 h at RT. After blocking, membranes were incubated overnight with  
541 the corresponding primary antibodies at 4°C. Membranes were then washed thrice with TBST buffer  
542 before being incubated with secondary antibodies for 1 h at RT. After further washing in TBST,  
543 signals were visualized with an Image Quant LAS 4000 apparatus (GE Healthcare Life Sciences,  
544 USA) using chemiluminescent ECL system (Clarity™ ECL western blotting substrate, Bio-Rad,

545 France, 170-5060). The images were captured with the Image Studio Lite (Li-Core Biosciences,  
546 USA) software and further processed with ImageJ software. The band signal for each sample was  
547 normalized with the corresponding GAPDH signal using the following formula:

$$548 \quad \text{Normalized signal} = \frac{X/N.C.}{GAPDH,N.C./X,GAPDH} \quad (4)$$

549 where  $X$  is the band signal;  $N.C.$  is the band signal of the negative control (untreated cells);  $GAPDH$ ,  
550  $N.C.$  is the band signal of GAPDH for untreated cells;  $X$ ,  $GAPDH$  is the corresponding GAPDH band  
551 signal of treated cells.

552

### 553 **Confocal microscopy**

554 To assess UHRF1 and DNMT1 co-localization, HeLa cells were seeded in 6-well plate on a coverslip  
555 at a density of  $5 \times 10^4$  cells/mL and kept for 24 h in DMEM medium supplemented with 10% FBS to  
556 allow cell attachment. Then, cells were co-transfected with eGFP-DNMT1 and UHRF1-mCherry  
557 plasmids and incubated for 24 h with AMSA2 50  $\mu$ M or MPB7 30  $\mu$ M, along with the control, in the  
558 absence of any compound. Cells were fixed with 4% paraformaldehyde for 15 min and then,  
559 permeabilized with 0.5% Triton X-100 for 20 min at RT. Cells were then incubated with Hoechst at  
560 2  $\mu$ g/mL, to stain nuclei. Cells in S phase were detected by using the Click-iT™ Plus EdU Cell  
561 Proliferation Kit for Imaging, with Alexa Fluor™ 647 dye (Thermo Fisher Scientific USA C10640)  
562 according to the manufacturer's protocol. All samples were imaged with a Leica TCS SPE confocal  
563 microscope equipped with an HXC PL APO63 $\times$ /1.40 OIL CS oil immersion objective. Hoechst,  
564 eGFP-DNMT1, UHRF1-mCherry and EdU-Alexa 647 were excited at 405 nm (laser 10 mW), 488  
565 nm (laser 25 mW), 561 nm (laser 10 mW) and 635 nm (laser 18 mW), respectively. The detection  
566 range for the four dyes was 430-480 nm, 493-548 nm, 571-683 nm, 645-754 nm, respectively. All  
567 the images were processed with the ImageJ software. Co-localization of tagged proteins was  
568 evaluated through Pearson correlation coefficient (PCC), obtained with the "Squassh" plugin of  
569 ImageJ<sup>88</sup>.

570 In order to quantify the global methylation level, HeLa cells were seeded in 6-well plate on a coverslip  
571 at a density of  $7.5 \times 10^4$  cells/mL, kept for 24 h in DMEM media supplemented with 10% FBS to allow  
572 cell attachment and then incubated for 48 h with AMSA2 (10 and 50  $\mu$ M) or MPB7 (10 and 30  $\mu$ M),  
573 along with the control sample or in the absence of any compound. Cells were fixed with 4%  
574 paraformaldehyde for 15 min and then, permeabilized with 0.5% Triton X-100 for 20 min at RT.  
575 Next, DNA was denatured using 4 M HCl for 20 minutes at RT, which was then removed and  
576 neutralized with 100 mM Tris HCl pH 8.8 for 10 min at RT. Subsequently, samples were blocked  
577 with Superblock T20 blocking buffer for 1 h at RT and then incubated with primary antibody against  
578 5mC o/n at 4 °C. After washing three times with PBS 1% BSA supplemented with 0.05% Tween,  
579 anti-goat secondary antibody coupled to Alexa Fluor 488 was added. All samples were imaged with  
580 a Leica TCS SPE confocal microscope equipped with a 20X air (0.7 NA) immersion lens objective.  
581 Then, images were further processed with ImageJ software and global DNA methylation signal was  
582 calculated as the mean fluorescence in the field per number of particles captured in a single image  
583 without zoom<sup>89</sup>.

584

#### 585 **DNA global methylation inhibition assay**

586 HeLa cells were seeded in 6-well plate at a density of  $7.5 \times 10^4$  cells/mL, kept for 24 h in DMEM  
587 media supplemented with 10% FBS to allow cell attachment and then incubated for 48 h with AMSA2  
588 (10 and 50  $\mu$ M), MPB7 (10 and 30  $\mu$ M) and 5-azacytidine (100  $\mu$ M) (Sigma-Aldrich), along with  
589 untreated cells. QIAamp® DNA Kit (QIAGEN, Catalog no. 51304) was used for DNA purification.  
590 Enzymatic digestion of DNA by methylation sensitive and insensitive enzymes, *HpaII* and *MspI*  
591 respectively, was assessed on 1% agarose gel in TBE buffer. The enzymatic digestion was performed  
592 on 0.45  $\mu$ g of DNA extracted from treated or untreated cells. Sample preparation and enzymatic  
593 reactions were performed following the protocol of the EpiJET DNA Methylation Analysis Kit  
594 (*MspI/HpaII*) (ThermoFisher, Catalog no. K1441).

595

596 **Statistical analysis**

597 All experiments were repeated at least three times and the obtained data were statistically compared  
598 by one-way ANOVA with post-hoc Bonferroni test using GraphPad-Prism (version 5.04) software.

599

600 **Supporting Information**

- 601 • Aldrich Market Select (AMS) structures list.
- 602 • MolPort (MP) structures list.
- 603 • Results first round of *in vitro* screening.
- 604 • Results second round of *in vitro* screening.
- 605 • UM63 data from Zaayter et al, 2019.
- 606 • Anisotropy data for AMSA2 and MPB7.
- 607 • AMSA2 and MPB7 binding mode overlapping with 5mC
- 608 • Purity data and instrument method.

609

610 **Authorship contributions**

611 Conceptualization, supervision and funding acquisition: Mousli M., Mori M., Mély Y.; Data  
612 acquisition and discussion: Ciaco S., Mazzoleni V., Javed A., Mousli M., Mori M., Mély Y.; Protein  
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614 Writing - review and editing: Ciaco S., Mazzoleni V., Javed A., Mousli M., Mori M., Mély Y.  
615 All authors have read and agreed to the published version of the manuscript.

616

617 **Declaration of competing interest**

618 The authors declare that they have no known competing financial interests or personal relationships  
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620

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631

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