

1 **HIV-1 capsids possess dynamic pores that import nucleotides with kinetic**  
2 **perfection**

3

4 **During the early stages of infection, the HIV-1 capsid protects viral components from cytosolic**  
5 **sensors, such as cGAS, and nucleases, such as TREX, while allowing access to nucleotides for**  
6 **efficient reverse transcription<sup>1</sup>. Here we show that each capsid hexamer has a size-selective pore**  
7 **bounded by a ring of six arginine residues and a ‘molecular iris’ formed by the N-terminal  $\beta$ -**  
8 **hairpin. The arginine ring creates a strongly positively charged channel that recruits the four**  
9 **nucleotides with on-rates that near diffusion limits. Progressive removal of pore arginines results**  
10 **in a dose-dependent and concomitant decrease in nucleotide affinity, reverse transcription and**  
11 **infectivity. This positively charged channel is universally conserved in lentiviral capsids despite**  
12 **the fact that it is strongly destabilising without nucleotides to counteract charge repulsion. We**  
13 **also describe a channel inhibitor, hexacarboxybenzene, which competes for nucleotide binding**  
14 **and efficiently blocks encapsidated reverse transcription demonstrating the tractability of the**  
15 **pore as a novel drug target.**

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17 There is increasing evidence that the HIV-1 capsid remains intact as it traverses the cytoplasm of a  
18 newly-infected cell. Prematurely-uncoated viruses trigger innate immune sensing<sup>2</sup>, assembled capsid  
19 proteins are required to properly engage the nuclear pore complex<sup>3</sup>, and intact capsids have been  
20 observed at the nuclear envelope<sup>4</sup>. Reverse transcription has been postulated to occur within the HIV-1  
21 virion during cytoplasmic transit, yet structural analyses of the HIV-1 capsid have not defined a pore  
22 through which small molecules such as dNTP’s might pass. One possible location for a pore would be  
23 the 6-fold axis at the centre of each capsid protein (CA) hexamer but this is not evident from existing  
24 hexamer structures as it is obscured by the N-terminal  $\beta$ -hairpin. By comparing all the available CA  
25 crystal structures with resolved  $\beta$ -hairpins<sup>5-11</sup>, including monomeric crystal forms, we observed that the  
26  $\beta$ -hairpin can adopt alternate conformations that differ by up to 15 Å (as measured by the displacement  
27 of Q7) (Fig. 1a). When reconstructed in the context of a hexamer, several of these  $\beta$ -hairpin  
28 conformations result in a pore about the six-fold axis (Fig. 1b). The different  $\beta$ -hairpin conformations  
29 are the result of a pivoting movement of up to 37.5° about the N-terminal proline, an essential capsid  
30 residue that forms a salt-bridge with D51<sup>12</sup> (Fig. 1a, Supplementary Video 1). In structures where the  
31 pore would be open, D51 also participates in a second salt-bridge interaction with H12. Conversely, in  
32 structures where the pore would be closed, including all previously solved disulfide-stabilised  
33 hexamers (CA<sub>Hexamer</sub>), a water molecule has displaced the H12 side-chain and coordinates a tetrahedral  
34 hydrogen-bond network between H12, T48, Q50 and D51. We hypothesized that the protonation state  
35 of H12 may be crucial in determining which arrangement is favored and therefore that the  
36 conformation of the  $\beta$ -hairpin in published structures will have been influenced by the pH at which  
37 they were solved. Remarkably, when the relative displacement of the  $\beta$ -hairpin (Q7 C $\alpha$ ) is plotted  
38 against crystallization pH the structures resolve into two groups; at pH < 7 an open pore  $\beta$ -hairpin  
39 conformation is observed whereas at pH > 7 a closed pore conformation is favored (Fig. 1c, Extended  
40 Data Table 1). The same correlation is observed when the distance between D51 and H12 is plotted

41 against pH, confirming the importance of H12 in determining  $\beta$ -hairpin conformation. Structures  
42 solved at pH 7 display the greatest  $\beta$ -hairpin variability, consistent with maximum pore flexibility  
43 occurring under physiological conditions. The likely reason why a pore has not been detected in  
44 published CA<sub>Hexamer</sub> structures is because they were solved at a basic pH where H12 is deprotonated  
45 and a closed pore is favored. To test this hypothesis and demonstrate that the pore can open in the  
46 context of an assembled hexamer, we sought to crystallise CA<sub>Hexamer</sub> under acidic conditions. We  
47 obtained a previously unreported crystal form at pH 5.5, the structure of which contains a  $\beta$ -hairpin in  
48 the open conformation and an exposed pore (Fig. 1b).

49

50 Using all available CA structures to define a range of movement for the  $\beta$ -hairpin, we observed that the  
51 pivoting about P1 results in an iris-like motion, which creates an aperture on the outer surface of the  
52 capsid (Fig. 2a). In the open state, a chamber 25 Å deep and 3240 Å<sup>3</sup> in volume is revealed, which  
53 culminates in a ring of six arginine side-chains from residue 18 (Fig. 2b, Supplementary Video 2). This  
54 cluster of basic residues in close proximity results in highly electropositive foci at the centre of each  
55 hexamer. The R18 residues adopt multiple conformations (Extended Data Fig. 1a) to give a maximum  
56 pore diameter of 8 Å, sufficient to allow transit of a dNTP molecule. We therefore reasoned that this  
57 feature might provide an efficient means to recruit dNTP's into the capsid interior (Fig. 2a) whilst  
58 excluding larger molecules. We therefore tested whether CA<sub>Hexamer</sub> can interact with dNTP's by  
59 fluorescence anisotropy and found that all four nucleotides bind with remarkably high affinity of  
60 between 6-40 nM (Fig. 2c). All biophysical measurements were undertaken in an 'intracellular buffer'  
61 (see Methods) that is designed to match salt concentrations in the cell. We also observed that  
62 physiological concentrations of inorganic phosphate had little effect on dNTP binding and that the pore  
63 could not distinguish between dNTP's and rNTP's (Extended Data Fig. 2) consistent with the  
64 observation that rNMP's are often incorporated into newly-synthesised viral DNA<sup>13</sup>. Analyzing the  
65 kinetics of interaction by stopped-flow revealed that binding is driven by an extremely rapid on-rate of  
66  $> 2 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ , although this is likely an underestimate as the reaction becomes immeasurably fast at  
67 increasing reactant concentrations (Fig. 2d&e). Separate dissociation experiments in which fluorescent  
68 dCTP was displaced with excess unlabeled dCTP determined that the off-rate is also fast at  $> 12 \text{ s}^{-1}$   
69 (Fig. 2f), equivalent to a half life of 58 ms. Calculation of on-rates for all four nucleotides based on  
70 their steady-state affinities and off-rates confirms that HIV-1 hexamers achieve association rates  
71 between  $10^8$ - $10^9 \text{ M}^{-1} \text{ s}^{-1}$ . These are unusually rapid association kinetics, typically found in enzymes that  
72 have achieved so-called kinetic perfection. Such ultra-rapid enzymes are rare because of the strong  
73 fitness advantage needed for their selection over merely very fast equivalents<sup>14</sup>. The rapid on-rate of  
74 dNTP recruitment that HIV achieves may be the result of an electrostatically assisted association  
75 binding mechanism, as has been described for barnase/barstar<sup>15</sup>. Importantly, the combination of fast  
76 on and off rates suggests that while the HIV-1 capsid may recruit dNTP's extremely efficiently, these  
77 nucleotides quickly dissociate to become available as substrates for reverse transcription.

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79 To test our hypothesis that it is the ring of arginine residues that is responsible for nucleotide  
80 recruitment, we solved the structure of HIV-1 CA<sub>Hexamer</sub> in complex with dATP and found that it binds

81 as predicted in the center of the arginine ring via its phosphate groups (Fig. 2g). While there is electron  
82 density for the phosphates, the position of the base can only be modeled, likely because hexamer  
83 rotational symmetry allows the dATP base to occupy six equivalent positions, averaging its density  
84 over a large volume (Extended Data Fig. 1). Comparison with a structure solved under identical  
85 conditions, but in the absence of dATP, confirms that the observed density corresponds to the  
86 nucleotide. To further investigate the importance of R18 in the recruitment of dNTP's, we produced  
87 R18G and R18A CA<sub>Hexamer</sub> mutants. Neither R18G nor R18A affected the overall structure of the  
88 protein and neither displayed measurable nucleotide binding (Fig. 3a&b). To determine whether  
89 formation of the arginines into a ring is required, we performed binding experiments on wild-type  
90 protein in the presence of DTT, which reduces the disulphide bonds that stabilise the hexameric  
91 construct, resulting in monomeric CA. No binding was observed to monomeric CA demonstrating that  
92 once the pore is disassembled, the capsid can no longer recruit dNTP's (Fig. 3b).

93  
94 The concentration of positive charge provided by the R18 ring is an unusual feature and might be  
95 expected to exert a destabilizing influence on the capsid lattice. Conversely, it has been calculated that  
96 arginine pairs can stabilize protein interfaces<sup>16</sup>, while arginine clusters have been postulated to have a  
97 stabilizing effect<sup>17</sup>. We performed differential scanning fluorimetry (DSF) to compare the relative  
98 stability of CA<sub>Hexamer</sub> with and without the electropositive pore. We observed a remarkable stability of  
99 the R18G hexamer relative to wild-type complex, corresponding to a surprisingly large increase in T<sub>m</sub>  
100 of 4 °C (Fig. 3c, Extended Data Fig. 3). A similar increase in stability was observed in wild-type  
101 hexamer in the presence of dNTP's, while no stabilization was observed when dNTP's were added to  
102 R18G hexamer (Fig. 3d). Taken together, these results suggest that the pore is indeed a destabilising  
103 feature that is tolerated by the capsid lattice in order to facilitate nucleotide binding. An alignment of  
104 capsid sequences predicts an electropositive pore to be conserved across retrovirus genera, with the  
105 exception of the gammaretroviruses (Extended Data Fig. 4). While there appears to be no R18-  
106 equivalent in gammaretroviruses, analysis of the published MLV capsid structure reveals a large  
107 channel running down the six-fold axis with an inward facing Arg residue at position 3 (Mortuza *et al.*  
108 2008). This residue may have a role in attracting dNTP's, but it is unlikely that the MLV capsid has  
109 the same size-selectivity as the HIV capsid as the pore is much wider.

110  
111 The observation that HIV-1 has evolved the fastest possible rate constant for nucleotide recruitment  
112 suggests that dNTP import may be a limiting factor in reverse transcription and infectivity. To  
113 determine how the efficiency of nucleotide recruitment impacts on these measures of viral fitness, we  
114 constructed a matched set of chimeric WT:R18G CA<sub>Hexamer</sub> and viruses (see Extended Data Fig. 5 for  
115 chimera controls). R18G was chosen as its capsid morphology has previously been demonstrated to be  
116 indistinguishable from WT<sup>19</sup>. Furthermore, R18G was able to saturate the activity of capsid-binding  
117 restriction factor TRIM5 $\alpha$ , confirming that assembled capsids enter the cytoplasm<sup>20</sup> (Extended Data  
118 Fig. 6). We tested our chimeric hexamers for dNTP binding and found that an incorporation ratio of 5:1  
119 (5 arginines to 1 glycine) had a minimal impact on affinity (Fig. 3e). However, as the proportion of  
120 glycine residues was increased, there was a dose-dependent decrease in dNTP binding. Testing HIV-1

121 GFP VSV-G pseudotyped chimeric viruses for infectivity revealed a similar pattern of R18  
122 dependence, in which there was little change in infectivity at a ratio of 5:1 but a dominant negative  
123 effect at higher G18 ratios (Fig. 3f). Assuming a binomial distribution of arginines and glycines in viral  
124 hexamers, the data fit a model in which removal of two or more arginines from the pore is detrimental  
125 to the virus (Extended Data Fig. 7), which is consistent with the observation that removal of one  
126 arginine has little impact on dNTP affinity. Importantly, there is close correlation between chimera  
127 infectivity and nucleotide affinity, consistent with the recruitment of dNTP's impacting directly on  
128 viral infection (Fig. 3g). Such a mechanism would be expected to influence infection at the level of  
129 reverse transcription and indeed a similarly close correlation is observed between chimera affinity and  
130 the production of early reverse transcripts (Fig 3h).

131

132 We propose that reverse transcription takes place within the protected environment of the capsid by  
133 recruiting nucleotides through a strongly electropositive pore at the center of each capsid hexamer. In  
134 order to explore this further we performed endogenous reverse transcription (ERT) assays in which  
135 HIV-1 capsid cores were purified from virions<sup>21</sup> and their reverse transcriptase activity quantified *in*  
136 *vitro* (Extended Data Fig. 8). Efficient strong-stop reverse transcription (the first DNA synthesis step)  
137 was observed upon incubation of cores with dNTP's. Moreover, addition of DNase I, RNase A or the  
138 promiscuous nuclease Benzonase failed to prevent encapsidated reverse transcription (Fig. 4a,  
139 Extended Data Fig. 8e). This demonstrates that dNTP's can access the interior of the capsid but larger  
140 nucleases cannot, supporting the notion of a size selective pore. Processivity beyond strong-stop was  
141 observed but at lower efficiency, in agreement with published data<sup>22</sup>.

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143 If the R18 pore is responsible for dNTP import, it is conceivable that capsid mutations that affect the  
144 movement of the  $\beta$ -hairpin may also affect the efficiency of reverse transcription. Of the residues  
145 primarily responsible for the hairpin movement (Fig 1a), P1 and D51 are invariant, with mutations at  
146 these positions resulting in non-infectious particles due to defective capsid assembly<sup>12</sup>. His12 is also  
147 highly conserved, however, in ~2% of sequences it has been replaced by a tyrosine. As tyrosine is not  
148 titratable over physiological pH's, we hypothesised that the H12Y mutation would result in the  $\beta$ -  
149 hairpin favouring one conformation. Solving the crystal structure of this mutant revealed that under the  
150 high-pH condition, Y12 displaces the bound water molecule and makes a hydrogen-bond contact with  
151 Asp51 (Fig. 4b). Despite contacting D51 directly, the larger sidechain of Y12 relative to H12 causes  
152 the  $\beta$ -hairpin to favour the closed conformation (Fig. 4c). Importantly H12Y does not completely shut  
153 the pore because residues 4-9 do not occupy a single defined state (Extended Data Fig. 9). The  $\beta$ -  
154 hairpin therefore retains a degree of flexibility despite rigidification about the P1-D51 'hinge'.  
155 Nevertheless we predicted that favouring the closed conformation should result in H12Y having  
156 reduced RT kinetics while retaining some infectivity and this is what we observe (Fig. 4d).

157

158 To provide further evidence that nucleotides are being recruited through the R18 pore to allow ERT,  
159 we sought a small molecule inhibitor that would block the pore. Small polyanionic compounds have  
160 been used previously to block analogous arginine-rich pores<sup>23</sup>. We found that the hexacarboxybenzene

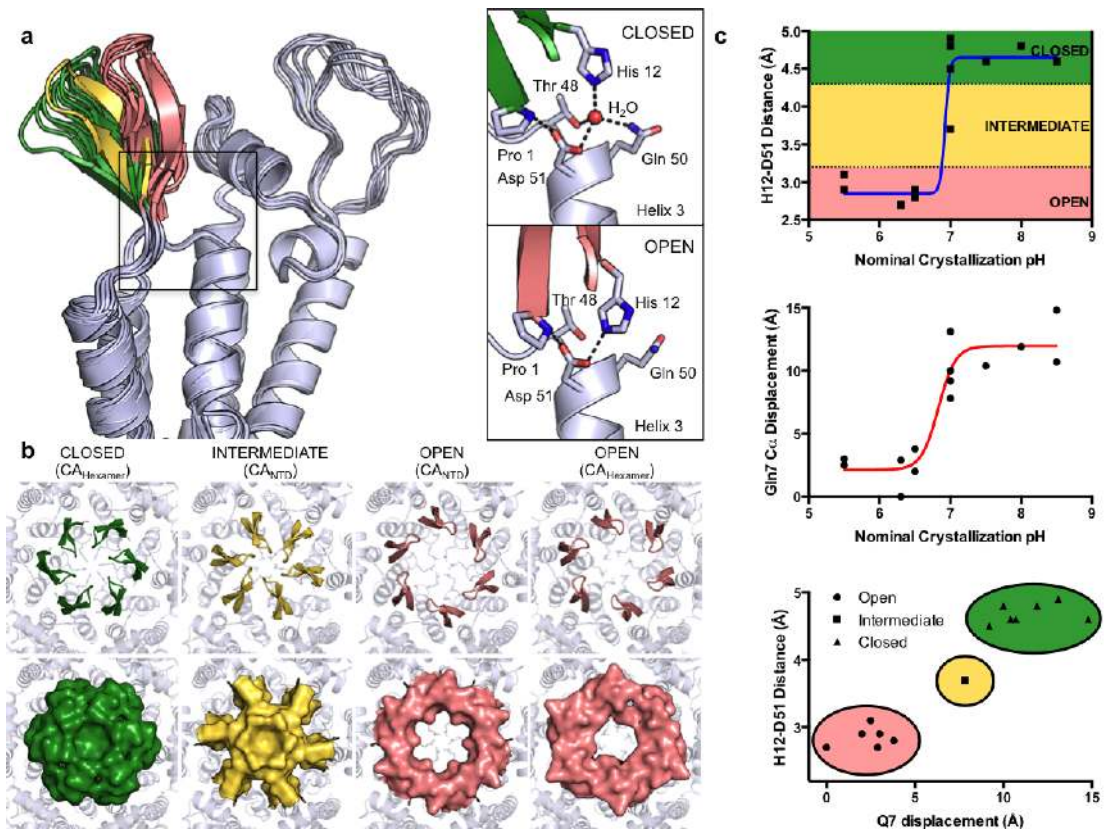
161 series (which are polyanionic at physiological pH) bound to CA<sub>Hexamer</sub> and competed for nucleotide  
162 binding as measured by fluorescence anisotropy and DSF, respectively (Fig. 4e&f, Extended Data Fig.  
163 3). Activity broadly increased with the number of negative charges present within the compound, with  
164 hexa- or pentacarboxybenzene being the most effective. DSF indicated that the compounds did not  
165 bind in the absence of R18 or when hexamers were reduced by DTT, and the crystal structure of the  
166 hexacarboxybenzene-bound CA<sub>Hexamer</sub> confirmed that the compound was co-ordinated by R18 within  
167 the central pore (Fig. 4f&g). At sufficiently high concentration, tetra-, penta- and hexacarboxybenzene  
168 fully inhibit reverse transcriptase, presumably by competing with dNTP's (Extended Data Fig. 8f).  
169 However, in ERT assays, when reverse transcriptase is enclosed within an intact viral capsid,  
170 tetracarboxybenzene has no effect on reverse transcription, with only a small effect observed for  
171 pentacarboxybenzene (Fig. 4h). In contrast, hexacarboxybenzene inhibited ERT almost completely.  
172 The failure of tetracarboxybenzene to inhibit ERT demonstrates that a compound sufficiently small to  
173 pass through the channel is still efficiently excluded from the capsid interior if it cannot bind the pore.  
174 This result emphasises the chemical selectivity of the pore and its role in dNTP import during reverse  
175 transcription.

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177 As a semi-permeable reaction chamber, the HIV-1 capsid is reminiscent of bacterial  
178 microcompartments – primitive ‘organelles’ that utilize a protein coat to isolate toxic reaction  
179 intermediates from the cytoplasm<sup>24</sup>. Microcompartments import substrates through a size-selective  
180 pore to be consumed by enzymes located inside a chamber<sup>25</sup>. Similarly, dNTP's translocated inside the  
181 HIV capsid will be hydrolysed by encapsidated reverse transcriptase. Coupling import with hydrolysis  
182 may create a local chemical gradient, promoting interior movement despite the release of captured  
183 dNTP's on either side of the pore. Appositely, a subset of microcompartments, carboxysomes, contain  
184 positively charged amino acids that are thought to selectively transport bicarbonate and ribulose-1,5-  
185 bisphosphate over uncharged CO<sub>2</sub> and O<sub>2</sub><sup>26</sup>. Some microcompartment structures have gated channels  
186 located at the six-fold axes in their protein lattice, to control substrate entry and product release. The  
187 fact that a similar ‘gate’ potentially exists in the HIV-1 capsid, provided by the ‘molecular iris’ of the  
188 β-hairpin, suggests that the virus could use this as a mechanism to regulate reverse transcription. In  
189 addition, the regulation of capsid stability through dNTP recruitment, and possibly DNA synthesis,  
190 provides a model whereby HIV-1 may co-regulate DNA synthesis and uncoating to facilitate  
191 cytoplasmic DNA synthesis that remains invisible to cytoplasmic DNA sensing. Finally, the high  
192 degree of conservation of R18 coupled with the fact that the pore can be obstructed chemically  
193 identifies the pore as a novel target for drug development.

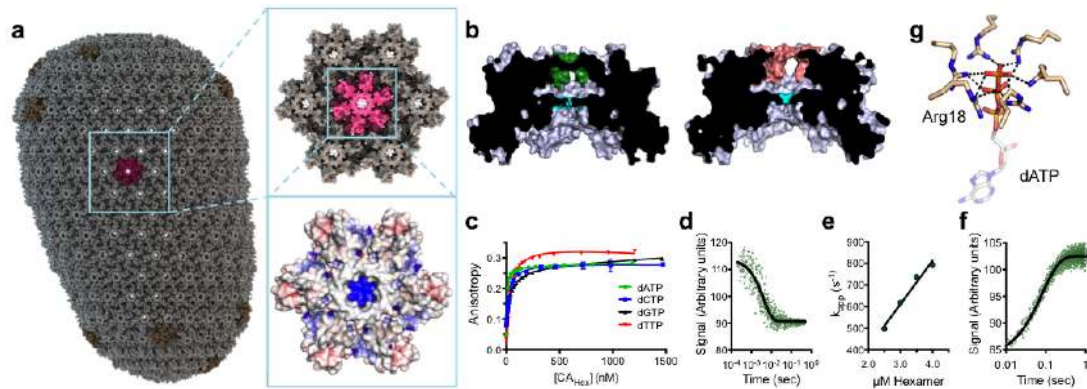
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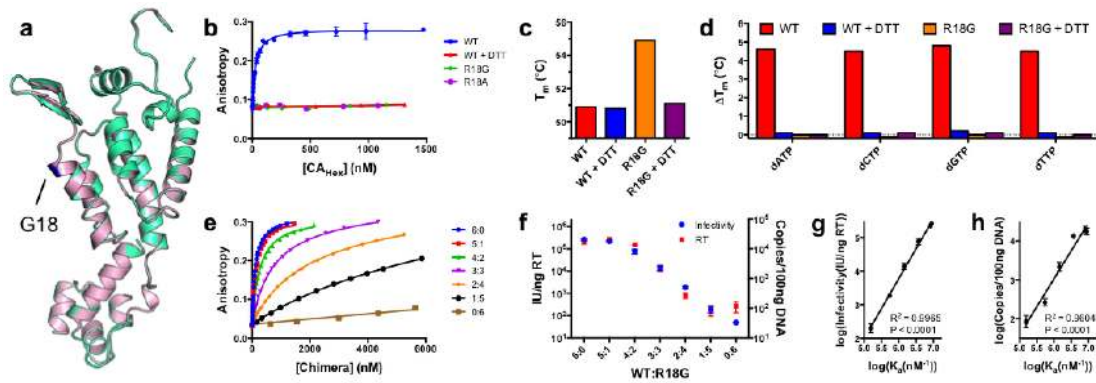
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 198 **Figure 1: HIV-1 capsid hexamers have a pore at the center of their 6-fold symmetry axis. a,**  
 199 Superposition of N-terminal domains from solved capsid structures (PDB IDs: 1AK4, 2GON, 2X83,  
 200 3H4E, 3NTE, 3P05, 4B4N and previously unpublished entries). A detailed view of the boxed region  
 201 shows that the  $\beta$ -hairpin toggles between closed (green) and open (pink) states as a result of the  
 202 hydrogen-bond network about P1, H12, and D51. **b,**  $\beta$ -hairpin (coloured) conformations dictate the  
 203 presence of a pore at the 6-fold axis. Hexamers of CA N-terminal domain ( $CA_{NTD}$ ) structures have  
 204 been assembled using symmetry operators from  $CA_{Hexamer}$  structures. **c,** Analysis of the salt-bridge  
 205 between H12 and D51 and the movement of the  $\beta$ -hairpin as a function of crystallization pH. Acidic  
 206 crystallization conditions promote an open  $\beta$ -hairpin conformation whilst basic conditions favor the  
 207 closed state.

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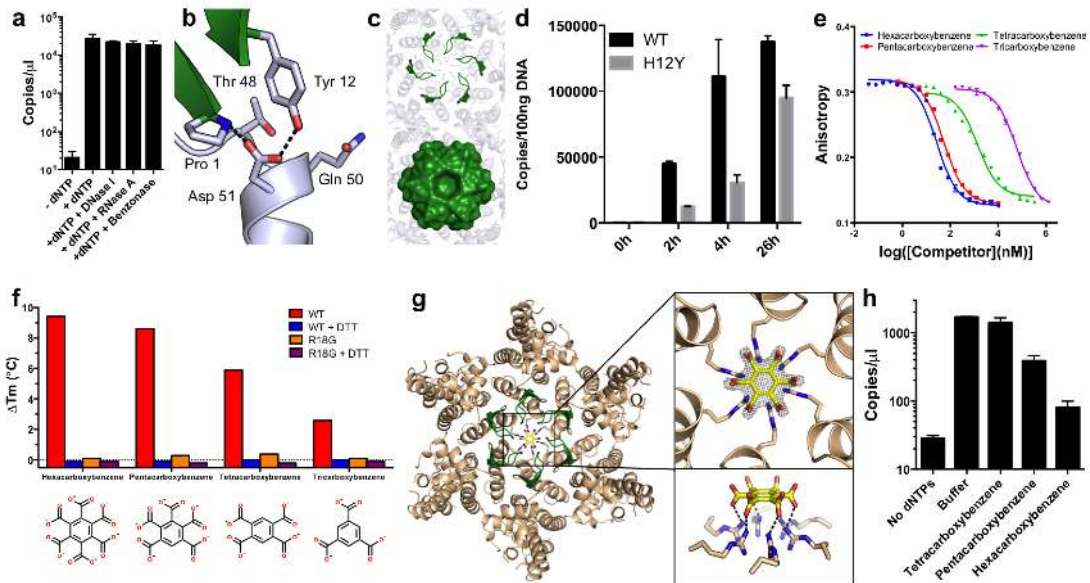
**Figure 2: The HIV-1 capsid pore is strongly electropositive and recruits dNTP's with rapid association and dissociation kinetics.** **a**, Model of an HIV-1 virion with hexamers in an open conformation reveals that the capsid is porous. Mapping the surface electrostatic potential shows that the pores are highly electropositive. **b**, Cross sections through the closed ( $\beta$ -hairpin green) and open ( $\beta$ -hairpin pink)  $CA_{Hexamer}$  showing a central chamber that is accessible in the open state. R18 (cyan) creates a bottleneck at the base of the chamber underneath the  $\beta$ -hairpin. **c**, Fluorescence anisotropy measurements of dNTP's binding to  $CA_{Hexamer}$ . **d**, Example of pre-steady state association kinetics of dCTP with  $CA_{Hexamer}$ . **e**, Apparent rate constant ( $k_{app}$ ) at increasing  $CA_{Hexamer}$  concentrations. **f**, Dissociation of unlabeled dCTP: $CA_{Hexamer}$  by excess fluorescent-dCTP. **g**, R18 co-ordinates the phosphates in a dATP-bound  $CA_{Hexamer}$  structure.



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**Figure 3: Conserved capsid residue R18 is crucial for nucleotide recruitment, reverse transcription and infectivity.** **a**, Superposed single monomers of R18G (light-pink) and wild-type (light-green) CA<sub>Hexamer</sub>. **b**, Binding of capsid variants to dCTP as measured by fluorescence anisotropy. **c**, DSF stability measurements expressed as T<sub>m</sub> for WT and R18G ± DTT. **d**, DSF measurements of the effect of dNTP's on the stability of WT and R18G expressed as ΔT<sub>m</sub> relative to unbound. **e**, Fluorescence anisotropy titrations of dTTP-binding by chimeric CA<sub>Hexamers</sub> with different R:G ratios at position 18. **f**, Comparison of infectivity and reverse transcription of chimeric viruses. **g,h**, Correlation between HIV-1 capsid dTTP affinity, viral infectivity **g** and reverse transcription **h**.





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**Figure 4: HIV-1 reverse transcription is inhibited by blockade of the capsid pore**

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**a**, In vitro endogenous reverse transcription measuring strong-stop transcripts.

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**b**, Residues surrounding Y12 in the H12Y hexamer structure.

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**c**, Cartoon and surface representations of the  $\beta$ -hairpin in the H12Y hexamer.

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**d**, WT and H12Y reverse transcription kinetics.

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**e**, Competition binding of carboxybenzene compounds to  $CA_{Hexamer}$ .

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**f**, Change in wild type and R18G  $CA_{Hexamer}$   $T_m$  as measured by DSF in the presence of carboxybenzene compounds.

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**g**,  $CA_{Hexamer}$  crystal structure in complex with hexacarboxybenzene, which is co-ordinated by R18.

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**h**, Effect of carboxybenzene compounds on endogenous reverse transcription.

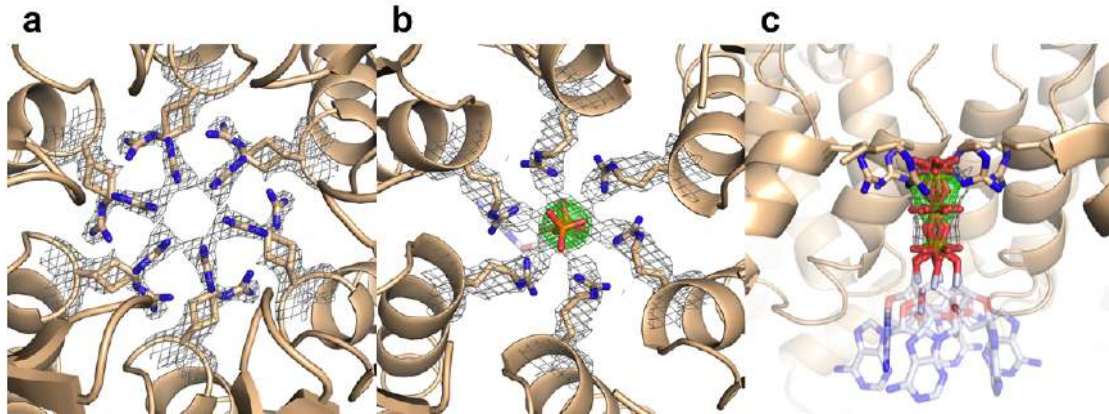
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308 **Extended Data Figure 1: dATP binds to the R18 pore at the centre of the capsid hexamer.** 2Fo-

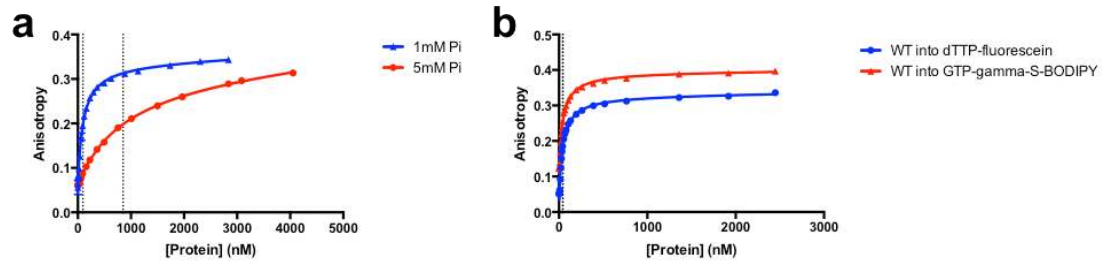
309 Fc density (grey mesh) contoured at  $1.0\sigma$  about R18 for the unbound (a) and dATP-bound (b)

310 CA<sub>Hexamer</sub> structures. Fo-Fc omit density (green mesh) contoured at  $3.0\sigma$  is shown for the dATP-bound

311 structure. c, dATP lies on the crystallographic 6-fold axis and significant rotationally-averaged density

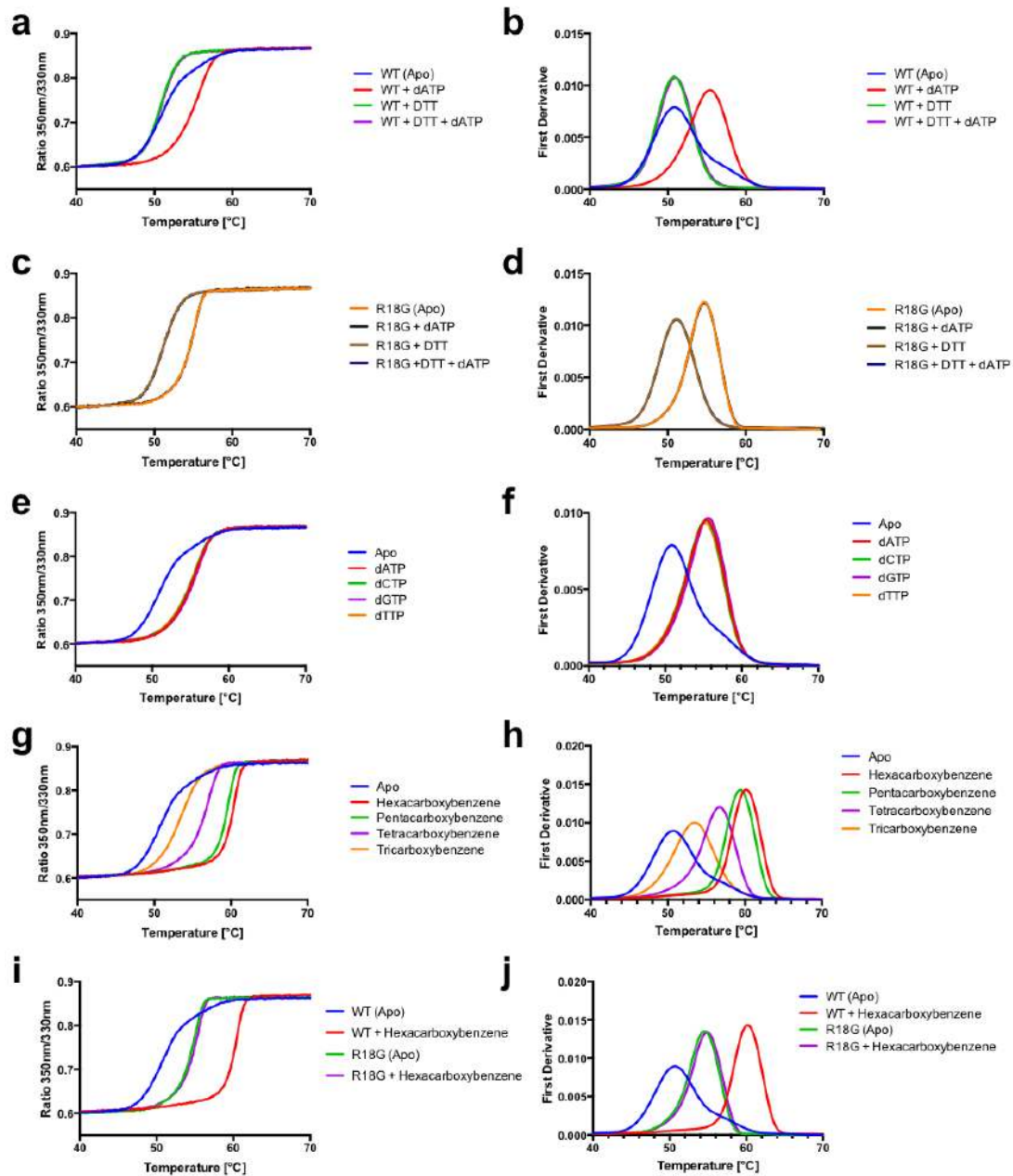
312 is observed only for the triphosphate group.

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**Extended Data Figure 2: Controls for dNTP-binding experiment.** **a**, Titration of CA<sub>Hexamer</sub> into 2 nM fluorescein-labelled dTTP in the presence of 1 mM (physiological) or 5 mM inorganic phosphate. Under the 1 mM conditions, there is no significant effect on hexamer binding to dTTP. At 5 mM apparent affinity is decreased to 851 nM, demonstrating that inorganic phosphate can compete for the pore. However, given that the intracellular [dNTP] is approximately 100 μM, under intracellular conditions dNTP binding would dominate. **b**, Titration of CA<sub>Hexamer</sub> into BODIPY-labelled rGTP-γ-S and fluorescein-labelled dTTP. Each binds with the same affinity suggesting that the R18 pore is unable to discriminate between ribose and deoxyribose nucleoside triphosphates. The difference in the magnitude of the fluorescence anisotropy signals is due to differences in fluorophore excited state lifetimes. K<sub>D</sub> values are indicated by a dotted line.



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**Extended Data Figure 3: DSF melt curves.** The left-hand panels report the ratio of tryptophan fluorescence emission at 350nm and 330nm as a function of temperature. The right-hand panels report the first derivative of the same data, the peak of which is used to determine the  $T_m$  value. **a, b**, Effect of dATP and DTT on WT  $CA_{Hexamer}$ . **c, d**, Effect of dATP and DTT on R18G  $CA_{Hexamer}$ . **e, f**, Effect of each dNTP on WT  $CA_{Hexamer}$ . **g, h**, Comparison of the effects of carboxybenzene compounds on WT  $CA_{Hexamer}$ . **i, j**, Comparison of the effects of hexacarboxybenzene on WT and R18G  $CA_{Hexamer}$ .

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ALV [alpharetrovirus] - - - P A V I K T E G - - P A W T P L E P K L I T R L A D T Y R A K G L R S P - I T M A E V E A L M S S P L L P H D V T
RSV [alpharetrovirus] - - - P V V I K T E G - - P A W T P L E P K L I T R L A D T Y R T K G L R S P - I T M A E V E A L M S S P L L P H D V T
JSRV [betaretrovirus] - - - P V F E N N N Q - - R Y Y E S L P F K Q L K E L K I A C S Q Y G P T A P - F T I A M I E S L G T Q A L P P N D W K
MMTV [betaretrovirus] P V Y F M G E S D D D D T P V W E P L P L K T L K E L Q S A Y R T M G P S A P - Y T L Q V V D M V A S Q W L T P S D W H
FeLV [gammaretrovirus] - - - P L R E G P N N R P Q Y W P F S A S D L Y N W K S H N P P F S Q D P V A - L T N L I E S I L Y T H Q P T W D D C Q
MLV [gammaretrovirus] - - - P L R L G G N G Q W Q Y W P F S S S D L Y N W K N N N P S F S E D P G K - L T A L I E S V L T T H Q P T W D D C Q
BLV [deltaretrovirus] - - - - P I I S E G N R N R H R A W A L R E E Q D I K K E T E N K A P G S Q V W I Q T L R L A I L Q A D P T P A D L E
HTLV_1 [deltaretrovirus] - - - P V M H P H G A P P N H R P W Q M K D L Q A I K Q E V S Q A A P G S P Q F M Q T I R L A V Q Q F D P T A K D L Q
HIV-1 [lentivirus] - - - P I V Q N L Q G Q M V H Q A T S P R R T L N A W V K V V E E K A F S P E - - V I P M F S A L S D G A T P Q D L N
EIAV [lentivirus] - - - P I M I D G A G N R N F R P L T P R G Y T T W V N T I Q T N G L L N E - - A S Q N L F G I L S V D C T S E M N

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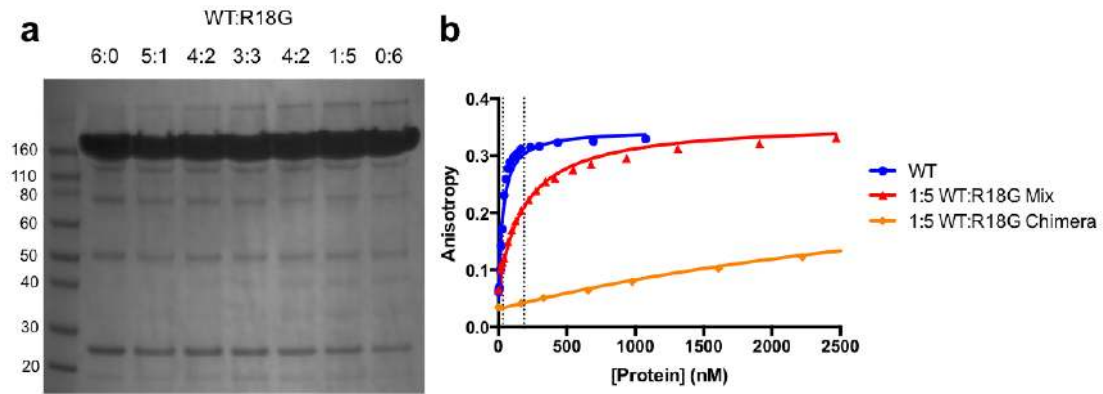
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**Extended Data Figure 4: Alignment of selected retrovirus capsid sequences bordering the electropositive pore.** The position equivalent to R18 in HIV is marked with an arrow.

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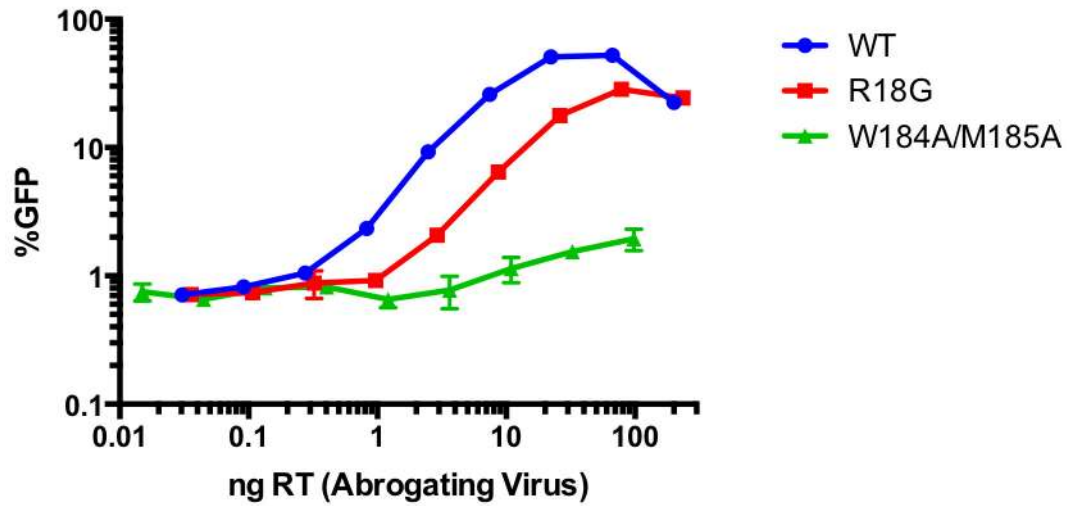
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**Extended Data Figure 5: Confirmation of CA<sub>Hexamer</sub> Chimera Assemblies.** **a**, Non-reducing SDS-PAGE of CA<sub>Hexamer</sub> WT:R18G chimera samples demonstrates that the recombinant proteins had reassembled into hexamers. Molecular weight standards (kDa) are presented in the first lane. **b**, Comparison of 1:5 homohexamer mix and the equivalent chimera. The 1:5 WT:R18G mix experiences a six-fold loss of apparent  $K_d$ , as expected for a 6-fold dilution of WT with a non-binding mutant. In contrast, the 1:5 chimera chimera has a 58-fold decrease in  $K_d$ , demonstrating that chimeric hexamers had indeed formed.





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348 **Extended Data Figure 6: R18G is capable of abrogating TRIM5 $\alpha$ -mediated restriction.** Rhesus

349 TRIM5 $\alpha$  provides a potent block to infection of HIV in FRhK-4 cells. Titration of a non-GFP-

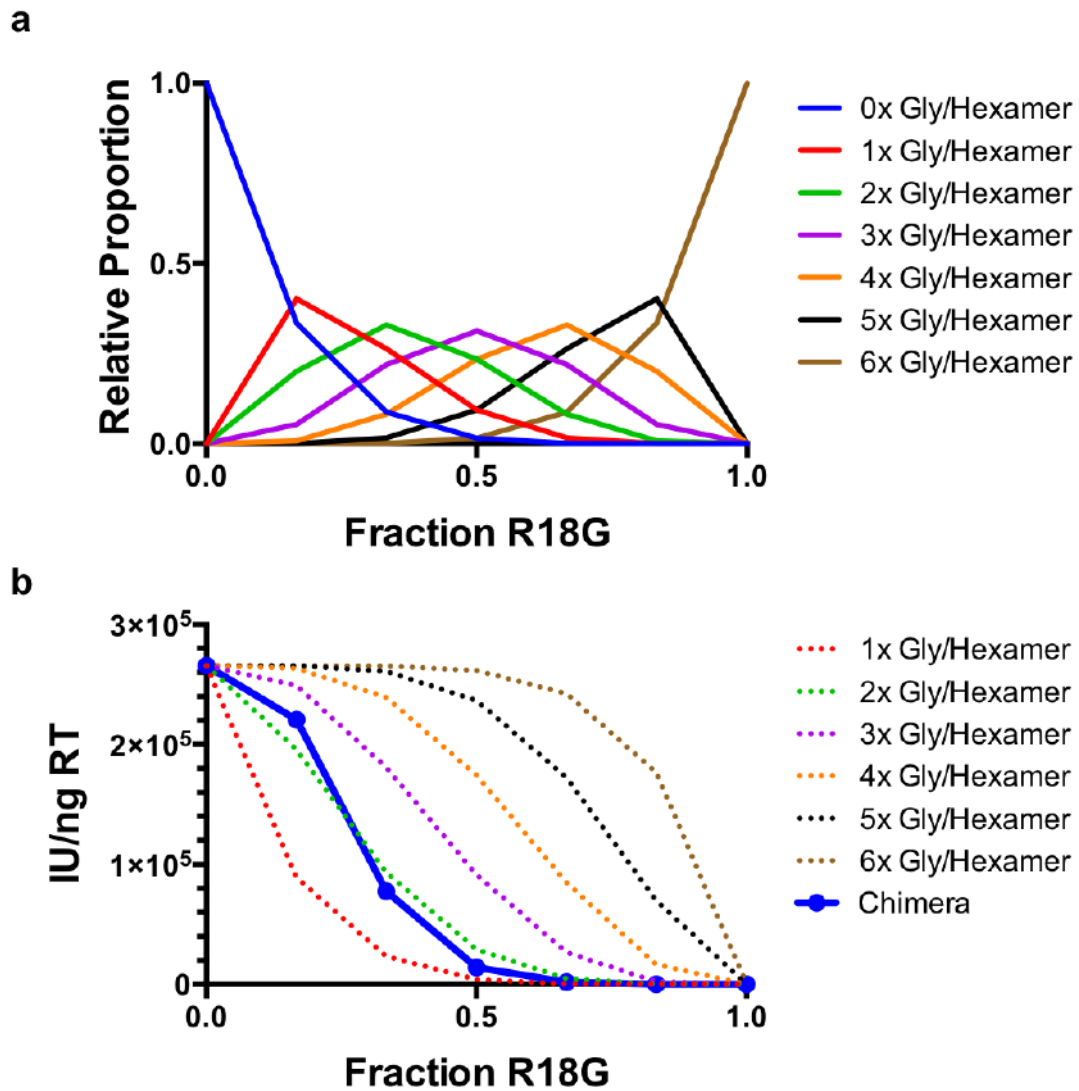
350 expressing virus can compete for TRIM5 $\alpha$ -binding and relieve the restriction of a GFP-expressing

351 virus only if it delivers an assembled capsid into the cytoplasm. R18G abrogates restriction but

352 W184A/M185A, which is incapable of forming assembled capsids due to loss of the CTD-CTD

353 dimerization interface, does not.

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357 **Extended Data Figure 7: Modelling the effect of progressive removal of arginines from the pore.**358 **a**, Binomial distribution model for the relative proportion of capsid hexamers carrying a discrete359 number of glycines at position 18 at defined bulk ratios of WT:R18G. **b**, Six models (dotted lines)

360 predicting the effect of replacing arginine 18 with glycines. Each model assumes a different number of

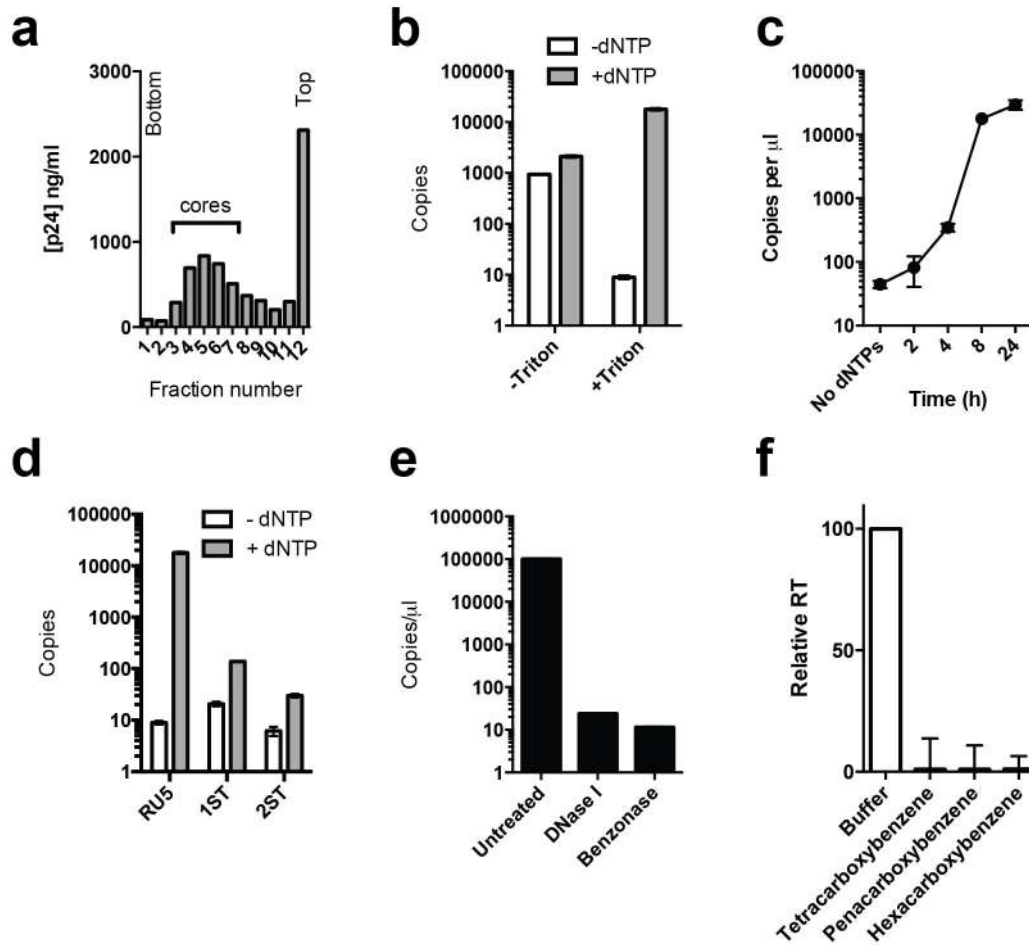
361 glycines is required to render the pore defective. The data from WT:R18G chimeric virus

362 measurements (solid line) is consistent with a model in which four or more arginines (i.e. 2 or fewer

363 glycines, green) are required to maintain a functional pore.

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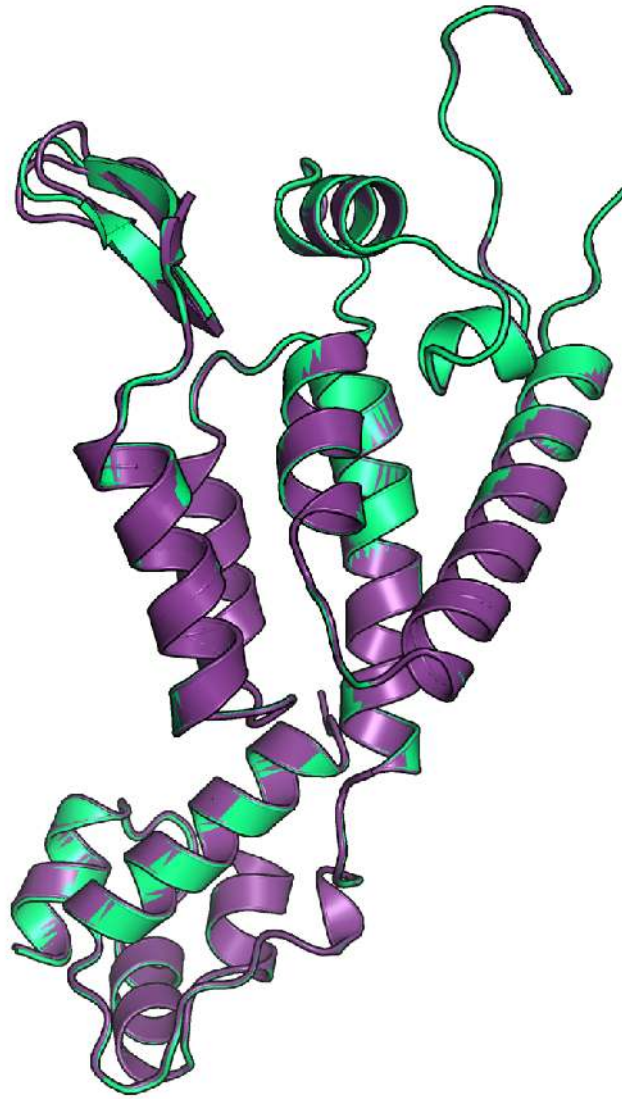
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367 **Extended Data Figure 8: ERT assay.** a, HIV-1 cores were prepared by ultracentrifugation through a  
 368 Triton X-100 layer over a sucrose gradient. Resulting fractions were subjected to ELISA for p24 and  
 369 fractions 3 – 7 were pooled for further experiments. b, Endogenous RT activity for strong stop in the  
 370 presence of DNase I using HIV-1 fractions that were prepared with or without the Triton X-100 spin-  
 371 through layer. Input levels of p24 were normalized between reactions. c, dNTP's were added to HIV-1  
 372 cores prepared by Triton X-100 spin-through in the presence of DNase I. Reactions were stopped at the  
 373 indicated time point by shifting to  $-80^{\circ}$  C and levels of strong stop were quantified. d, Levels of strong-  
 374 stop (RU5), first-strand transfer (1ST) and second-strand transfer (2ST) DNA after overnight  
 375 incubation of HIV-1 cores with or without dNTP's in the presence of DNase I. e, Levels of naked HIV-  
 376 1 DNA genomes untreated or incubated overnight with DNase I or Benzonase. f, Effect of  
 377 carboxybenzene compounds on recombinant reverse transcriptase activity.

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380 **Extended Data Figure 9: Comparison of WT and H12Y crystal structures.** The H12Y monomer  
381 (in the context of the hexamer, purple) superposes on the WT (green) with RMSD = 0.2471 Å.  
382 Residues 4-9 of the H12Y structure have been modeled in two alternate conformations owing to  
383 flexibility towards the tip of the hairpin.

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**Extended Data Table 1: Details of structures used for  $\beta$ -hairpin analysis**

Molecule	Chain	Resolution	Crystallization pH	Q7 Displacement	H12-D51 distance
5HGL	A	3.1	5.5	3	2.9
5HGL	B	3.1	5.5	2.5	3.1
5HGK	A	1.76	6.3	0	2.7
5HGK	B	1.76	6.3	2.9	2.7
3NTE	A	1.95	6.5	2	2.9
3NTE	B	1.95	6.5	3.8	2.8
2X83	A	1.7	7	7.8	3.7
1AK4	C	2.36	7	10	4.8
2X83	B	1.7	7	9.2	4.5
4B4N	A	1.81	7	13.1	4.9
3H4E	A	2.7	7.5	10.4	4.6
2GON	C	1.9	8	11.9	4.8
3P05	B	2.5	8.5	14.8	4.6
3P05	C	2.5	8.5	10.7	4.6

	CA <sub>NTD</sub> (OPEN)	CA <sub>Hexamer</sub> (OPEN)	CA <sub>Hexamer</sub> + dATP	CA <sub>Hexamer</sub> (APO, CLOSED)	CA <sub>Hexamer</sub> (R18G)	CA <sub>Hexamer</sub> + Hexacarboxy -benzene	CA <sub>Hexamer</sub> (H12Y)
<b>Data collection</b>							
Space group	P2 <sub>1</sub>	C222 <sub>1</sub>	P6	P6	P6	P6	P6
Cell dimensions							
<i>a</i> , <i>b</i> , <i>c</i> (Å)	43.72, 23.85, 129.55	89.69, 159.27, 249.40	90.81, 90.81, 56.68	90.73, 90.73, 56.75	90.81, 90.81, 56.88	90.76, 90.76, 56.76	90.60, 90.60, 56.93
$\alpha$ , $\beta$ , $\gamma$ (°)	90, 96.31, 90	90, 90, 90	90, 90, 120	90, 90, 120	90, 90, 120	90, 90, 120	90, 90, 120
Resolution (Å)	39.87-1.76 (1.86-1.76)	19.99-3.10 (3.27-3.10)	45.98-2.03 (2.08-2.03)	26.69-1.90 (1.94-1.90)	46.09-2.00 (2.05-2.00)	45.38-1.95 (2.00-1.95)	56.93-1.70 (1.73-1.70)
<i>R</i> <sub>merge</sub>	0.065 (0.227)	0.094 (0.552)	0.112 (0.551)	0.121 (0.748)	0.166 (0.831)	0.105 (0.862)	0.095 (0.813)
<i>I</i> / $\sigma$ <i>I</i>	13.3 (5.0)	7.1 (1.9)	8.2 (1.9)	8.3 (2.1)	6.5 (1.9)	11.7 (2.1)	9.0 (2.4)
Completeness (%)	91.9 (80.6)	97.4 (92.0)	94.9 (69.1)	99.8 (100.0)	100.0 (100.0)	97.9 (99.5)	95.1 (94.7)
Redundancy	4.6 (4.6)	2.4 (2.4)	2.9 (2.4)	5.1 (4.8)	6.0 (5.9)	6.8 (6.5)	4.8 (4.9)
<b>Refinement</b>							
Resolution (Å)	39.87-1.76 (1.81-1.76)	19.99-3.10 (3.18-3.10)	45.98-2.04 (2.10-2.04)	26.69-1.90 (1.95-1.90)	39.32-2.00 (2.05-2.00)	45.38-1.95 (2.00-1.95)	56.93-1.70 (1.74-1.70)
No. reflections	23837 (1552)	30312 (2044)	15488 (1084)	19999 (1468)	17285 (1246)	18188 (1347)	26370 (1949)
<i>R</i> <sub>work</sub> / <i>R</i> <sub>free</sub>	0.190/0.224 (0.233/ 0.286)	0.250/0.281 (0.368/ 0.399)	0.236/0.263 (0.316/ 0.384)	0.200/0.225 (0.266/ 0.342)	0.205/0.221 (0.216/ 0.255)	0.194/0.221 (0.266/ 0.299)	0.197/0.232 (0.265/ 0.285)
No. atoms							
Protein	2284	9358	1558	1623	1605	1612	1688
Ligand/ion	1	193	30	-	-	24	-
Water	338	-	82	124	105	119	123
<i>B</i> -factors							
Protein	27.928	54.173	26.577	30.265	27.732	30.878	27.523
Ligand/ion	38.516	83.117	109.040	-	-	95.409	-
Water	24.730	-	30.031	35.719	28.567	34.088	33.604
R.m.s. deviations							
Bond lengths (Å)	0.007	0.008	0.007	0.007	0.007	0.008	0.006
Bond angles (°)	1.222	1.156	0.991	0.998	1.046	1.281	1.009

## 390 **Methods**

391

### 392 **Protein production and purification**

393 The CA N-terminal domain and the disulfide-stabilised CA<sub>Hexamer</sub> were expressed and purified as  
394 previously described<sup>8,27</sup>. The R18G mutation was introduced by QuikChange site-directed  
395 mutagenesis. Chimeric CA<sub>Hexamers</sub> were produced by mixing the desired ratio of pre-assembled WT and  
396 R18G CA<sub>Hexamer</sub> (16 mg/ml) followed by a four-step dialysis: i) Disassembly in TRIS (pH 8.0, 50mM),  
397 NaCl (40mM), β-mercaptoethanol (20mM); ii) Reassembly in TRIS (pH 8.0, 50mM), NaCl (1 M), β-  
398 mercaptoethanol (20mM); iii) Oxidation in TRIS (pH 8.0, 50mM), NaCl (1 M); Redispersion in TRIS  
399 (pH 8.0, 20mM), NaCl (40mM). In the context of the chimera experiments, WT and R18G were also  
400 subjected to this process so that samples were matched with the other ratios. Reassembled hexamers  
401 were observed by non-reducing SDS-PAGE. Chimeric hexamers were compared with mixes of  
402 homohexamers by fluorescence anisotropy (see below and Extended Data Fig. 5) in order to  
403 demonstrate that chimeras had indeed formed.

404

### 405 **Crystallisation, structure solution and analysis**

406 All crystals were grown at 17 °C by sitting-drop vapour diffusion in which 100 nL protein was mixed  
407 with 100 nL precipitant and suspended above 80 uL precipitant. The CA N-terminal domain  
408 (15mg/ml) ‘open’ conformation was crystallised from PEG3350 (20%), Ammonium chloride (0.2M,  
409 pH 6.3). Crystals were cryoprotected in precipitant supplemented with 25% glycerol. The CA<sub>Hexamer</sub>  
410 (15 mg/ml) ‘open conformation’ was crystallised from PEG4000 (12%), NaCl (0.1M), MgCl<sub>2</sub> (0.1M),  
411 sodium citrate (0.1M, pH 5.5). Crystals were cryoprotected in precipitant supplemented with 20%  
412 MPD. The remaining CA<sub>Hexamer</sub> structures (apo, dATP-bound, R18G and hexacarboxybenzene-bound)  
413 were all obtained from 10-12mg/ml protein mixed with PEG550MME (13-14%), KSCN (0.15M),  
414 TRIS (0.1M, pH 8.5) and cryoprotected with precipitant supplemented with 20% MPD. For the dATP-  
415 bound structure, the protein was supplemented with 10 mM dATP immediately prior to crystallisation;  
416 while for the hexacarboxybenzene structure, the protein was likewise supplemented with 1 mM  
417 hexacarboxybenzene (TRIS-buffered to pH 8.0). All crystals were flash-cooled in liquid nitrogen and  
418 data collected either in-house using Cu K $\alpha$  X-rays produced by a Rigaku FR-E rotating anode generator  
419 with diffraction recorded on a mar345 image plate detector (marXperts), or at beamline I02 at Diamond  
420 Light Source. The datasets were processed using the CCP4 program suite<sup>28</sup>. Data were indexed and  
421 integrated with IMOSFLM<sup>29</sup> and scaled and merged with either POINTLESS and SCALA<sup>30</sup> or  
422 AIMLESS<sup>31</sup>. Structures were solved by molecular replacement using PHASER<sup>32</sup> and refined using  
423 REFMAC5<sup>33</sup>. Between rounds of refinement, the model was manually checked and corrected against  
424 the corresponding electron-density maps in COOT<sup>34</sup>. Solvent molecules and bound ligands were added  
425 as the refinement progressed either manually or automatically within COOT and were routinely  
426 checked for correct stereo-chemistry, for sufficient supporting density above a 2Fo-Fc threshold of  
427 1.0 $\sigma$  and for a reasonable thermal factor. The quality of the model was regularly checked for steric  
428 clashes, incorrect stereochemistry and rotamer outliers using MOLPROBITY<sup>35</sup>. Final figures were  
429 rendered in The PyMOL Molecular Graphics System, Version 1.5.0.4 Schrödinger, LLC. Surface

430 electrostatics were calculated using the APBS PyMOL plugin<sup>36</sup> and cavity volume measurements with  
431 3V<sup>37</sup>. Data collection and refinement statistics are presented in Extended Data Table 2. The ‘fullerene  
432 cone’ model of an HIV-1 virion is based on 3J3Q<sup>38</sup> but using the inter-hexamer packing from 4XFY<sup>39</sup>  
433 and an open  $\beta$ -hairpin conformation.

434

#### 435 **Fluorescence Anisotropy**

436 Fluorescence anisotropy measurements were performed at 22 °C on a Cary Eclipse Fluorescence  
437 Spectrophotometer (Agilent). Fluorescein-labelled dNTP’s were obtained from Perkin Elmer and used  
438 for saturation binding experiments at a concentration of 2nM prepared in ‘Intracellular Buffer’:  
439 potassium gluconate (110mM), KCl (25mM), NaCl (5mM), MgCl<sub>2</sub> (2mM), HEPES (10mM), final pH  
440 7.2. CA<sub>Hexamer</sub> disassembly was achieved by the addition of DTT (4mM), and was performed routinely  
441 at the conclusion of each saturation binding experiment to confirm the absence of non-specific binding.  
442 It was found that the triphosphate was not stable over the timescale of the competition binding  
443 experiments; so fluorescein-labelled dNTP’s were substituted for a non-hydrolysable BODIPY-labelled  
444 GTP- $\gamma$ -S (ThermoFisher Scientific). Saturation binding experiments determined that this non-  
445 hydrolysable analogue bound with unchanged affinity to the CA<sub>Hexamer</sub> ( $K_d = 14$ nM). 200 mM stock  
446 solutions of hexacarboxybenzene (Sigma), pentacarboxybenzene (MP Biomedicals), 1,2,4,5-  
447 tetracarboxybenzene (Sigma), and 1,3,5-tricarboxybenzene (Fluka) were prepared in 50mM TRIS and  
448 adjusted to pH 8.0. For competition binding experiments, the competitor was titrated into a mix of  
449 CA<sub>Hexamer</sub> (28nM) and BODIPY-GTP- $\gamma$ -S (2nM). All fluorescence anisotropy measurements are  
450 representative of at least two experiments. Each point is measured in quadruplicate and plotted as  
451 mean  $\pm$  standard deviation. In many cases error bars lie within the datapoint. Saturation binding and  
452 competition binding curves were fit using GraphPad Prism (GraphPad Software, Inc.).

453

#### 454 **Rapid reaction kinetics**

455 Experiments were carried out using a dual-channel fluorescence TgK single-mix SF-61SX2 stopped-  
456 flow spectrometer. All samples were prepared in Intracellular Buffer. Mixing was performed 1:1, using  
457 an excitation wavelength of 488 nm and a 520 nm cutoff filter. Association experiments were carried  
458 out at 0.25  $\mu$ M dCTP and a range of  $\mu$ M CA<sub>Hexamer</sub> concentrations. Dissociation experiments were  
459 carried out using 20  $\mu$ M unlabeled dCTP and a pre-formed fluorescein-labeled 1 $\mu$ M dCTP: CA<sub>Hexamer</sub>  
460 complex. Relaxation rates were determined using a single exponential model:  $F = \Delta F \exp(-k_{obs}t) + F_e$ ,  
461 where F is the observed fluorescence,  $\Delta F$  is the fluorescence amplitude,  $k_{obs}$  is the observed pseudo  
462 first-order rate constant, and  $F_e$  is the end-point fluorescence. The bimolecular association rate constant  
463 ( $k_{on}$ ) was determined by fitting the linear relationship between  $k_{obs}$  and the increasing pseudo-first order  
464 concentrations of CA<sub>Hexamer</sub> to:  $k_{obs} = k_{on}[CA_{Hexamer}] + k_{reverse}$ . For stopped flow experiments, every 0.5 s  
465 measurement included >2000 datapoints, each of which was oversampled 99 times. At least three  
466 independent mixing experiments were averaged for each ligand concentration.

467

#### 468 **Differential Scanning Fluorimetry**



469 DSF measurements were performed using a Prometheus NT.48 (NanoTemper Technologies) over a  
470 temperature range of 20-95 °C using a ramp rate of 2.5 °C/min. CA<sub>Hexamer</sub> samples were prepared at a  
471 final concentration of 1mg/ml in Intracellular Buffer (+/- DTT (4mM)). dNTP's or competitors were  
472 added at 200 µM. DSF scans are single reads. Consistency between like points yields an uncertainty in  
473  $T_m$  of no greater than 0.2 °C.

474

#### 475 **Cells and Viruses**

476 Replication deficient VSV-G pseudotyped HIV GFP vectors were produced in HEK293T cells as  
477 described previously<sup>3</sup>. Site-directed mutagenesis of CA was performed using the QuikChange method  
478 (Stratagene) against the Gag-Pol expression plasmid, pCRV-1. Chimeric viruses were produced by  
479 mixing the appropriate ratio of WT or mutant pCRV-1 prior to transfection. Reverse transcriptase  
480 activity was quantified using a colorimetric ELISA assay (Roche) and was found not to vary  
481 significantly between viruses. Production of mature particles was confirmed by western blot for p24  
482 from pelleted virus, with no observable difference between chimeras.

483

#### 484 **Infection Experiments**

485 Infections of HeLa cells were performed in the presence of 5 µg/ml polybrene. GFP expressing cells  
486 were enumerated on a BD LSRII Flow Cytometer (BD Biosciences) 2 days post-transfection after  
487 fixation of cells in 4% paraformaldehyde. Chimera infectivity was determined by a 6-point titration of  
488 each chimera onto HeLa cells. Values are the mean ± standard deviation calculated from all points for  
489 which the proportion of infected cells after 48 h was between 1% and 50%.

490

#### 491 **TRIM5 $\alpha$ Abrogation Assay**

492 'Abrogating virus' (VSV-G pseudotyped HIV Puromycin vectors) was produced as described above,  
493 with the exception that the *gfp* gene was replaced with the *pac* gene to ensure the virus did not confer  
494 fluorescence upon infection. Virus was concentrated by ultracentrifugation with an SW28 rotor at  
495 25,000 rpm for 2 h. The abrogating virus capsids were WT, R18G or W184A/M185A (a mutant with a  
496 known assembly defect that cannot compete for TRIM5 $\alpha$ ). VSV-G pseudotyped HIV GFP vectors  
497 were titrated on FRhK-4 cells in the presence of 5 µg/ml polybrene to determine the volume of virus  
498 required to achieve 1% infection. In a separate experiment, cells were then coinfecting with that  
499 amount HIV-GFP vector and a titration of VSV-G pseudotyped HIV Puromycin vectors (the  
500 abrogating virus). GFP expressing cells were measured in duplicate and enumerated as above. Results  
501 are representative of three experiments and are presented as mean ± standard deviation. For many  
502 points the error bars lie within the datapoint.

503

#### 504 **Quantitative PCR**

505 For analysis of reverse transcription products, viral supernatant was treated with 250 U/ml DNase  
506 (Millipore) for 1 h prior to infection. Cells were harvested 6h post infection. DNA was extracted using  
507 DNeasy Blood and Tissue Kit (Qiagen). GFP copies were quantified using primers GFPF  
508 (CAACAGCCACAACGTCTATATCAT), GFPR (ATGTTGTGGCGGATCTTGAAG) and probe

509 GFPP (FAM-CCGACAAGCAGAAGAACGGCATCAA-TAMRA) against a standard curve of CSGW  
510 on an ABI StepOnePlus Real Time PCR System (Life Technologies). Chimera reverse transcription  
511 measurements are representative of 3 experiments with each point measured in triplicate. Results are  
512 presented as mean  $\pm$  standard deviation. For H12Y, a timecourse was also performed, in which each  
513 time point was measured in triplicate and presented as above.

514

#### 515 **Preparation of HIV-1 cores**

516 HIV-1 capsid cores were prepared using a protocol based on<sup>21</sup> with modifications. 90ml HEK293T  
517 supernatant containing VSV-G pseudotyped HIV-1 GFP was pelleted over 20% sucrose dissolved in  
518 core prep buffer (CPB; 20 mM Tris pH 7.4, 20 mM NaCl, 1 mM MgCl<sub>2</sub>) in an SW28 rotor (Beckman)  
519 at 25,000 rpm at 4° C. Pellets were gently resuspended at 4° C in CPB for 1 h with occasional agitation.  
520 Resuspended pellets were treated with DNase I from bovine pancreas (Sigma Aldrich) for 1 h at 200  
521  $\mu$ g/ml at room temperature to remove contaminating extra-viral DNA. Virus was subjected to spin-  
522 through detergent stripping of the viral membrane as follows. A gradient at 80-30% sucrose was  
523 prepared in SW40Ti ultracentrifuge tubes and overlaid with 250  $\mu$ l 1% Triton X-100 in 15% sucrose,  
524 followed by 250  $\mu$ l 7.5% sucrose. All solutions were prepared in CPB. 750  $\mu$ l DNase-treated,  
525 concentrated virus was layered on top of the gradient and subjected to 32,500 rpm at 4° C for 16 h. The  
526 preparation was fractionated and the location of cores was determined by ELISA for p24 (Perkin  
527 Elmer). Core-containing fractions were pooled and snap frozen before storage at -80° C.

528

#### 529 **Endogenous reverse transcription assays**

530 Viral cores were diluted to 400  $\mu$ g/ml p24 with 60% sucrose in CPB and pre-treated with nucleases for  
531 1h before addition of dNTPs. Final concentrations of dNTP's were 100  $\mu$ M each, DNase I and RNase  
532 A were at 100  $\mu$ g/ml and Benzonase was at 250 U/ml. 20  $\mu$ l reactions were incubated at room  
533 temperature for 16 h unless indicated otherwise and were stopped by shifting to -80° C. DNA was  
534 prepared using DNeasy Blood and Tissue kit (Qiagen) after addition of 200  $\mu$ l PBS with of 50  $\mu$ g/ml  
535 salmon sperm carrier DNA to each sample. Reverse transcript products were detected using TaqMan  
536 Fast Universal PCR Mix (ABI) and RU5 primers to detect strong stop DNA<sup>40</sup> (RU5 fwd  
537 TCTGGCTAACTAGGGAACCCA, RU5 rev CTGACTAAAAGGGTCTGAGG and RU5 probe FAM-  
538 TTAAGCCTCAATAAAGCTTGCCCTTGAGTGC-TAMRA), GFP primers to detect first strand  
539 transfer products (described above) and primers for second strand transfer products<sup>40</sup> (2ST fwd  
540 TTTTAGTCAGTGTGGAAAATCTGTAGC, 2ST rev TACTCACCAGTCGCCGCC and 2ST probe  
541 FAM-TCGACGCAGGACTCGGCTTGCT-TAMRA). Where used, carboxybenzene compounds were  
542 dissolved in CPB, pH adjusted with NaOH and added to reactions at a final concentration of 20mM. In  
543 order for dNTP concentration to be limiting, these reactions were performed in the presence of 1  $\mu$ M  
544 each dNTP and reactions were stopped 5 h after their addition. ERT experiments were performed in  
545 experimental triplicate and are representative of several experimental replicates. Data are represented  
546 as mean  $\pm$  sem

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548 **Supplementary Video 1: Structural morph between the closed and open states of CA<sub>Hexamer</sub>.** On  
549 the left the protein is represented in cartoon format, coloured according to secondary structure. The  
550 sidechain of L6 is shown as sticks to emphasise that it is this residue that results in pore closure. On  
551 the right P1, H12, T48, Q50, and D51 are represented as sticks to show that the movement of the  $\beta$ -  
552 hairpin is driven by the formation of a salt-bridge between H12 and D51. Distances shown are in  
553 Ångstroms.

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555 **Supplementary Video 2: Pore opening exposes R18.** Surface representation of the morph depicted  
556 in Supplementary Video 1. The  $\beta$ -hairpin and R18 are coloured yellow and blue, respectively.

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### 558 **Extended Data References**

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