Protein Model **Refinement** via **Iterative** Molecular Dynamics simulations

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MD simulation and refinement

Numerically solving
Newtonian equation!

$$F = ma = -\nabla V(r)$$

Physical atomistic force field (CHARMM 36m)

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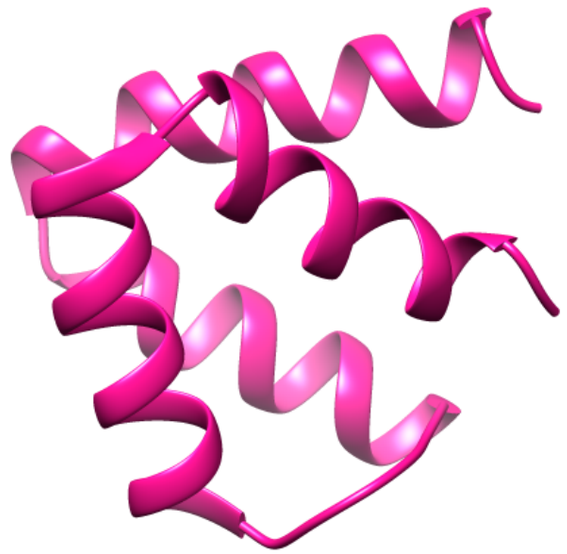

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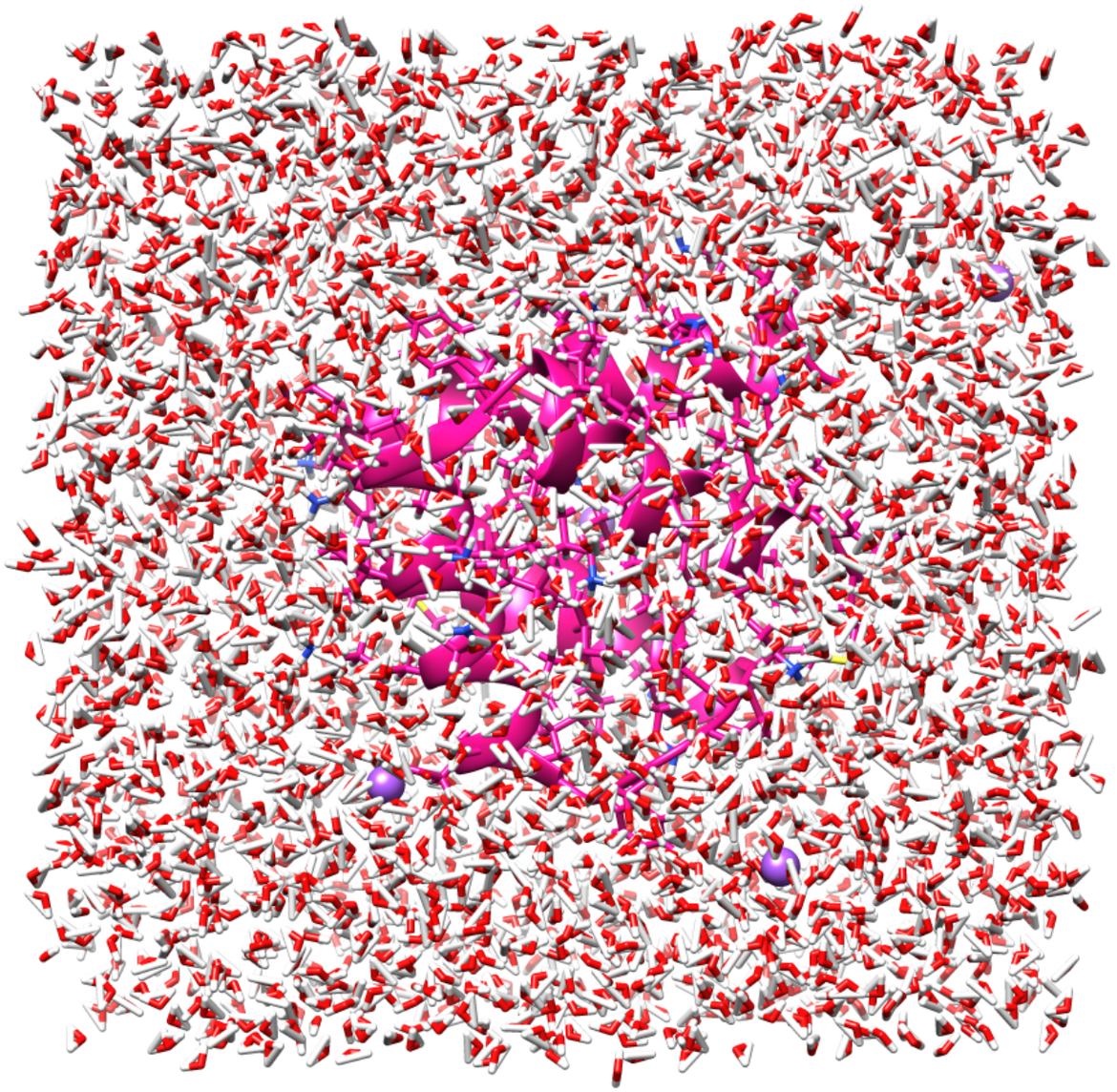

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MD simulation and refinement

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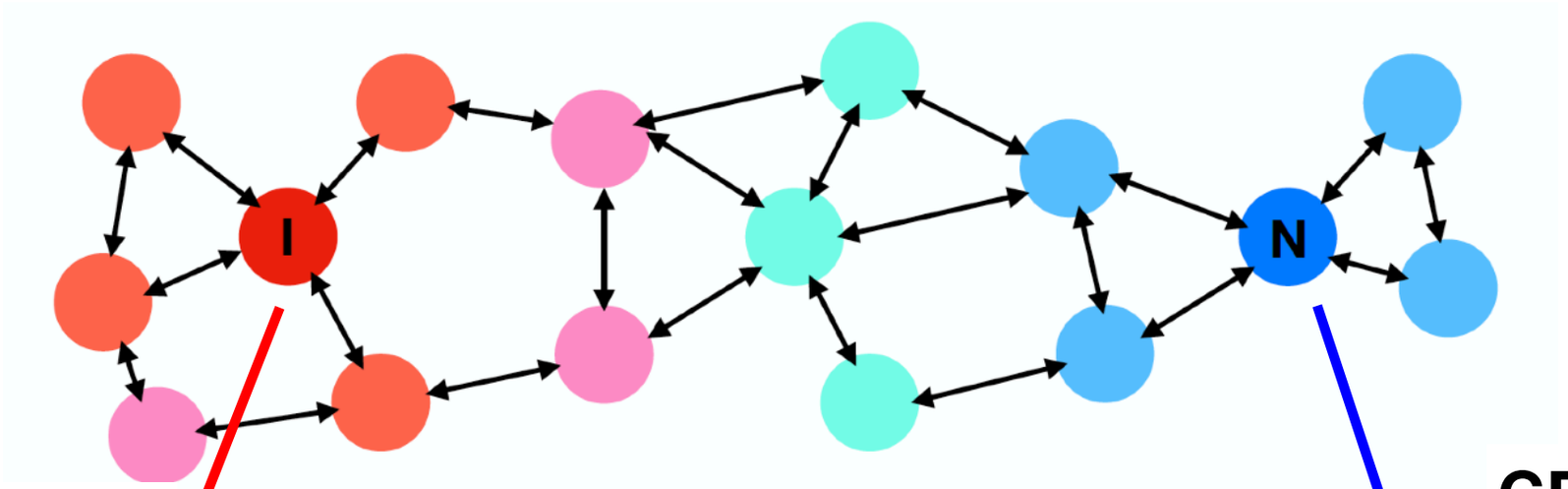
Physical atomistic force field (CHARMM 36m)

Pre-study

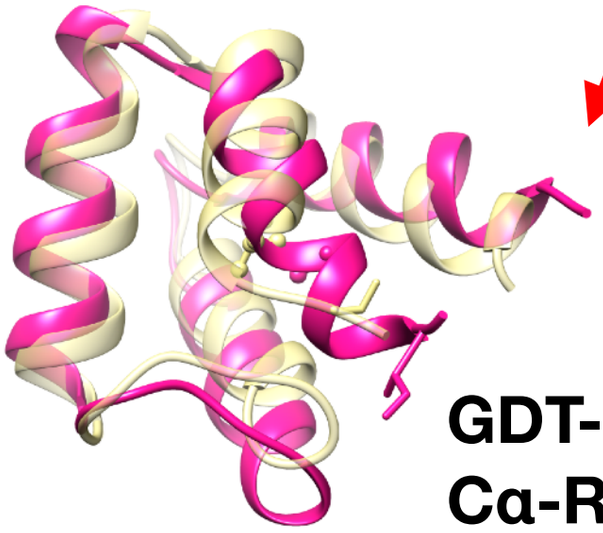
Markov state modeling for refinement

10s μs MD simulations/target with c36m
to identify "**refinement pathway**"

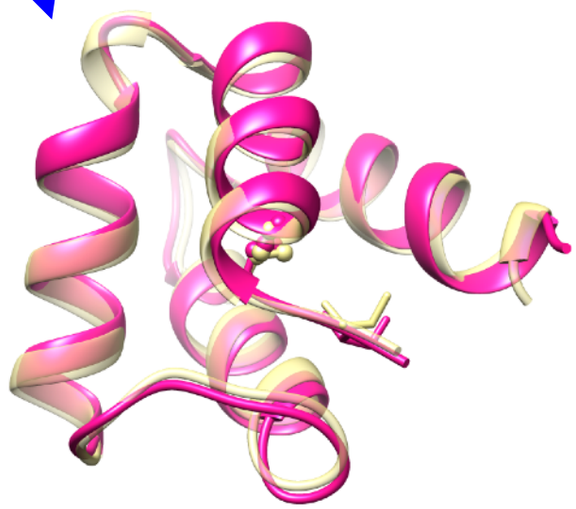


TR816

GDT-HA = 87
Cα-RMSD = 0.8 Å



GDT-HA = 51
Cα-RMSD = 2.5 Å



Lim Heo and Michael Feig, *PNAS* (**2018**)
https://www.pnas.org/content/early/2018/12/07/1811364115.

Pre-study

Native states have the lowest free energies

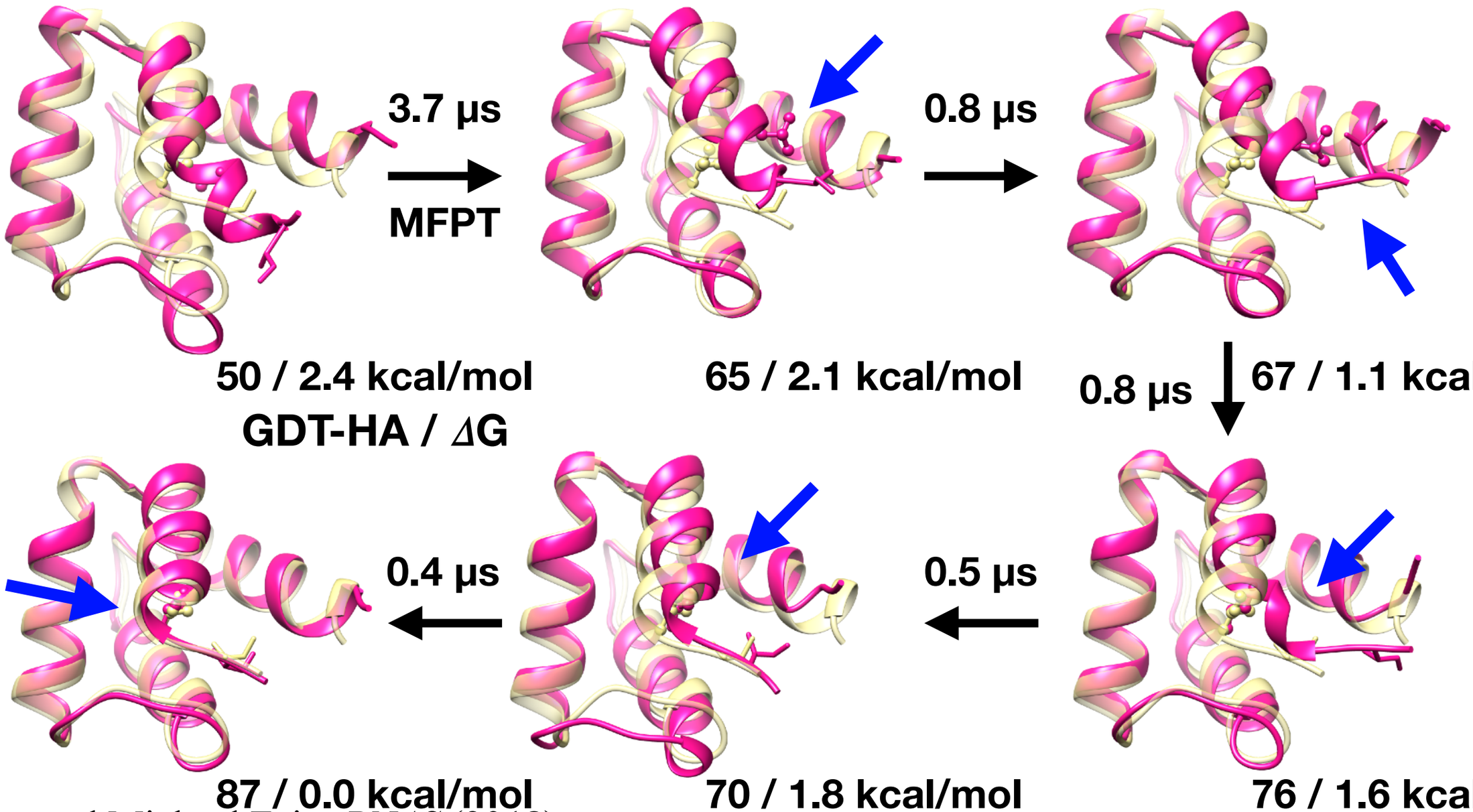
Target	Initial model RMSD [Å]	Native state RMSD [Å]	$\Delta\Delta G$ [kcal/mol]	MFPT [μs]	# of transitions
TR816	2.53	**0.80**	**-2.46**	1.7	5
TR837	2.95	**0.88**	**-2.60**	43.4	7
TR854	2.27	1.04	**-1.59**	1.5	3
TR782	1.93	**0.94**	**-0.65**	39.6	5
TR872	5.59	1.97	**-0.83**	2.9	2
TR921	3.51	**0.90**	**-0.85**	637.9	15
TR769	1.74	1.14	**-1.10**	0.8	2
TR894	2.23	**0.85**	**-1.71**	6.0	5

Lim Heo and Michael Feig, *PNAS* (**2018**)
https://www.pnas.org/content/early/2018/12/07/1811364115.

Pre-study

Partial unfolding and refolding is required

It has to be **partially unfolded and refolded** to get to the native.



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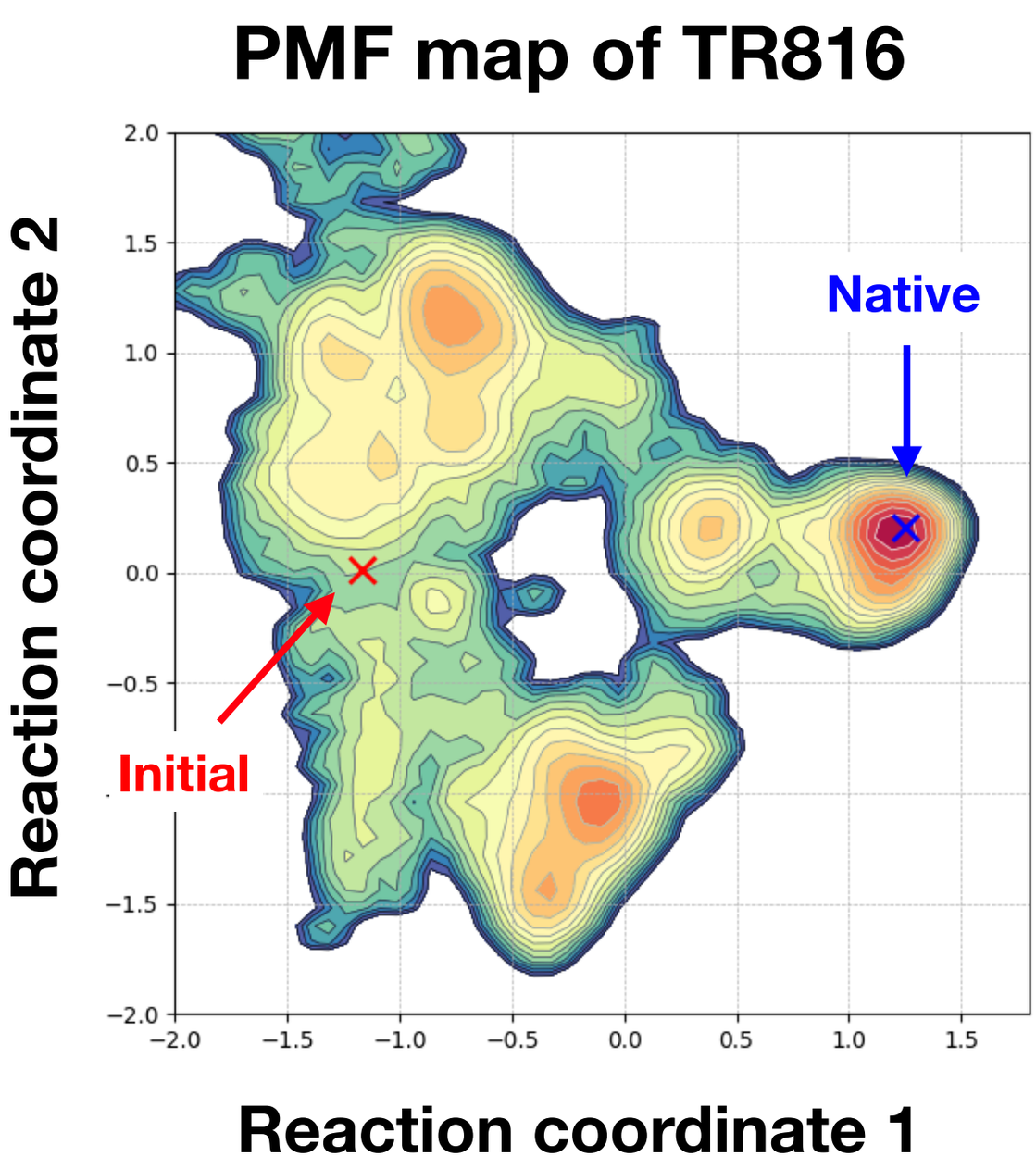
https://www.pnas.org/content/early/2018/12/07/1811364115.

FEIGLAB group CASP13 refinement protocol

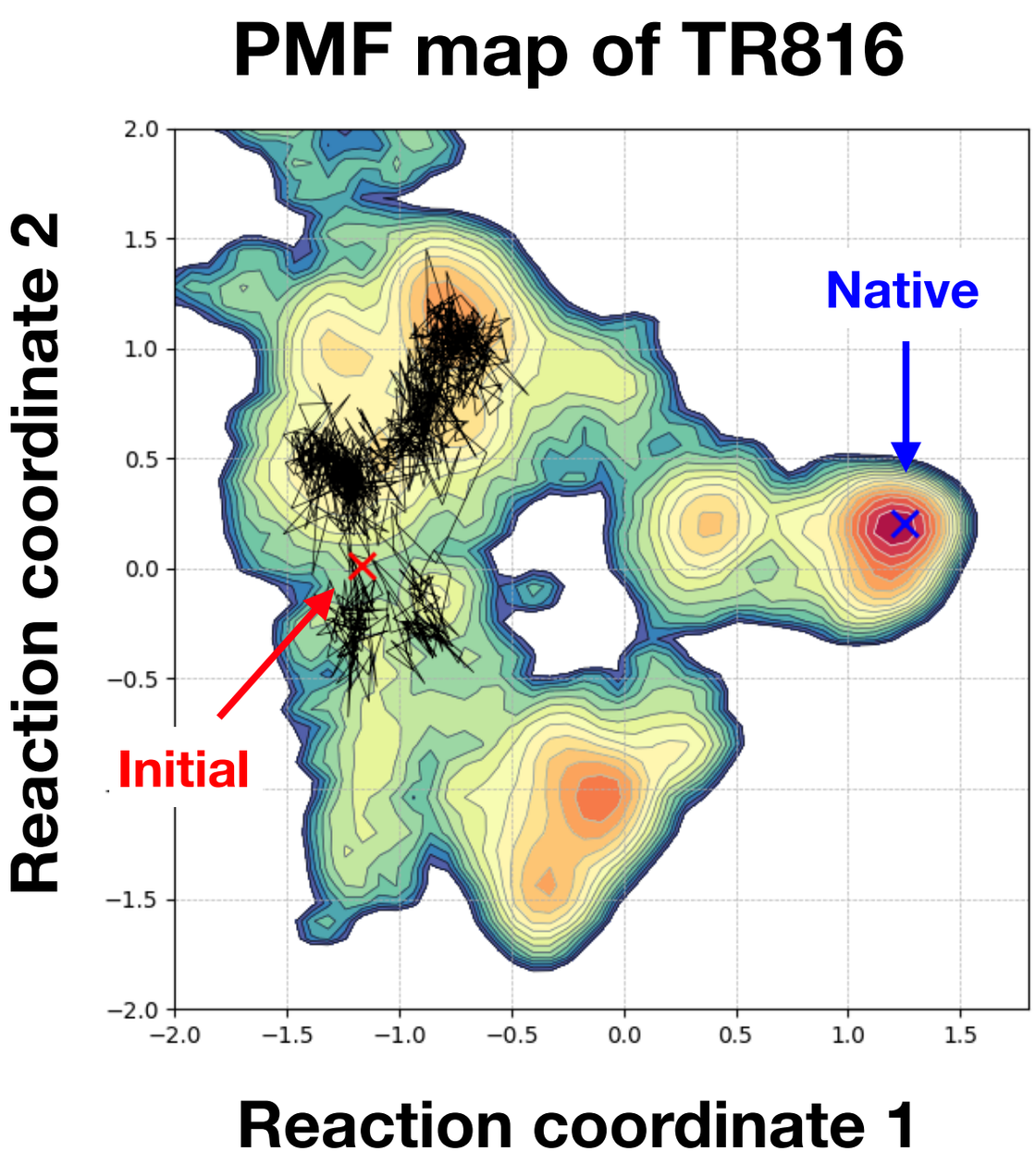
- Main protocol (20 / 31 targets)
  - **Iterative** runs of **MD** simulations
    (2 μs/target; 94 GPU hrs on GTX1080Ti for R0949 (129 aa))
  - **Flat-bottom** harmonic restraints
  - **c36m** with modifications to accelerate sampling
  - Scoring with **Rosetta,** structure **averaging**, and **locPREFMD**

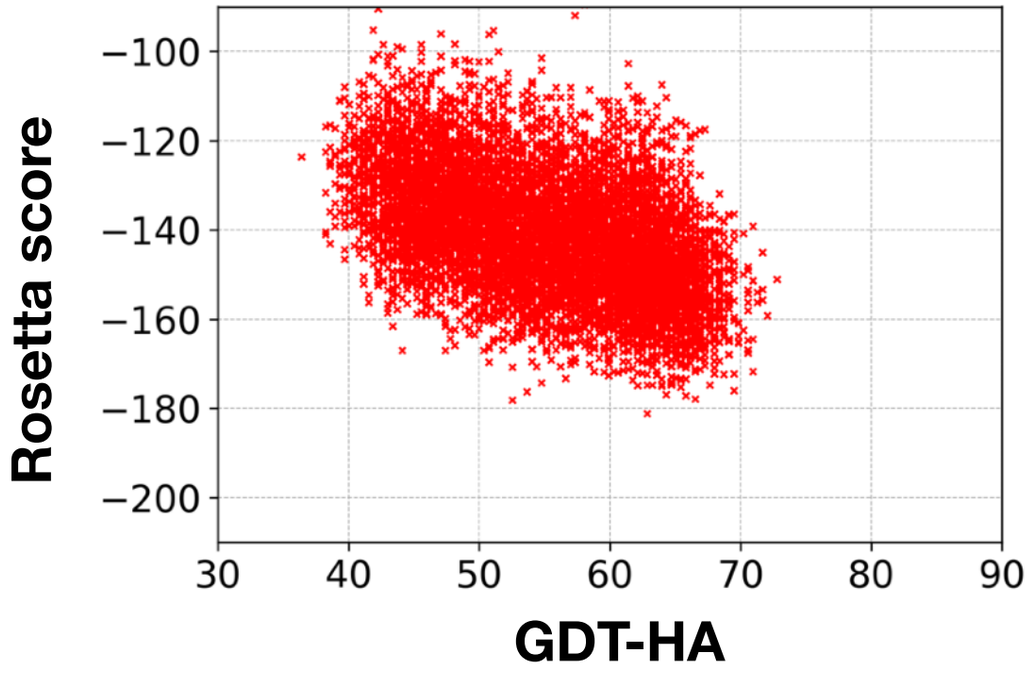
- Conservative protocol (11 / 31 targets)
  - Analogous to **our previous protocol** with reduced simulation time
    (250 ns; 23 GPU hrs on GTX1080Ti for R0949 (129 aa))

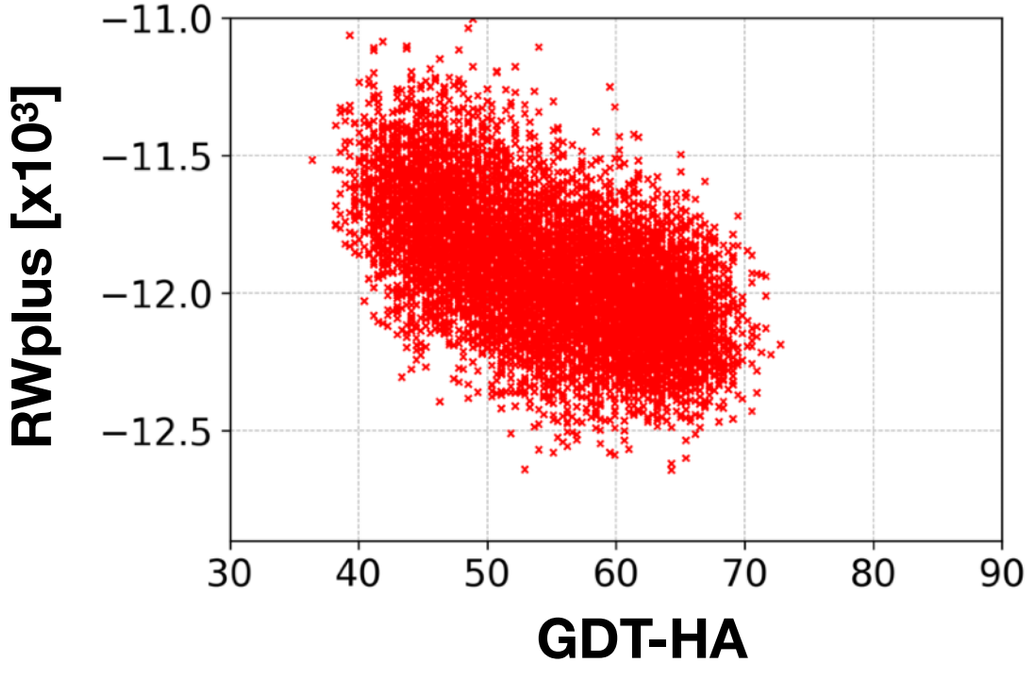
Iterative MD sampling and scoring



Iterative MD sampling and scoring

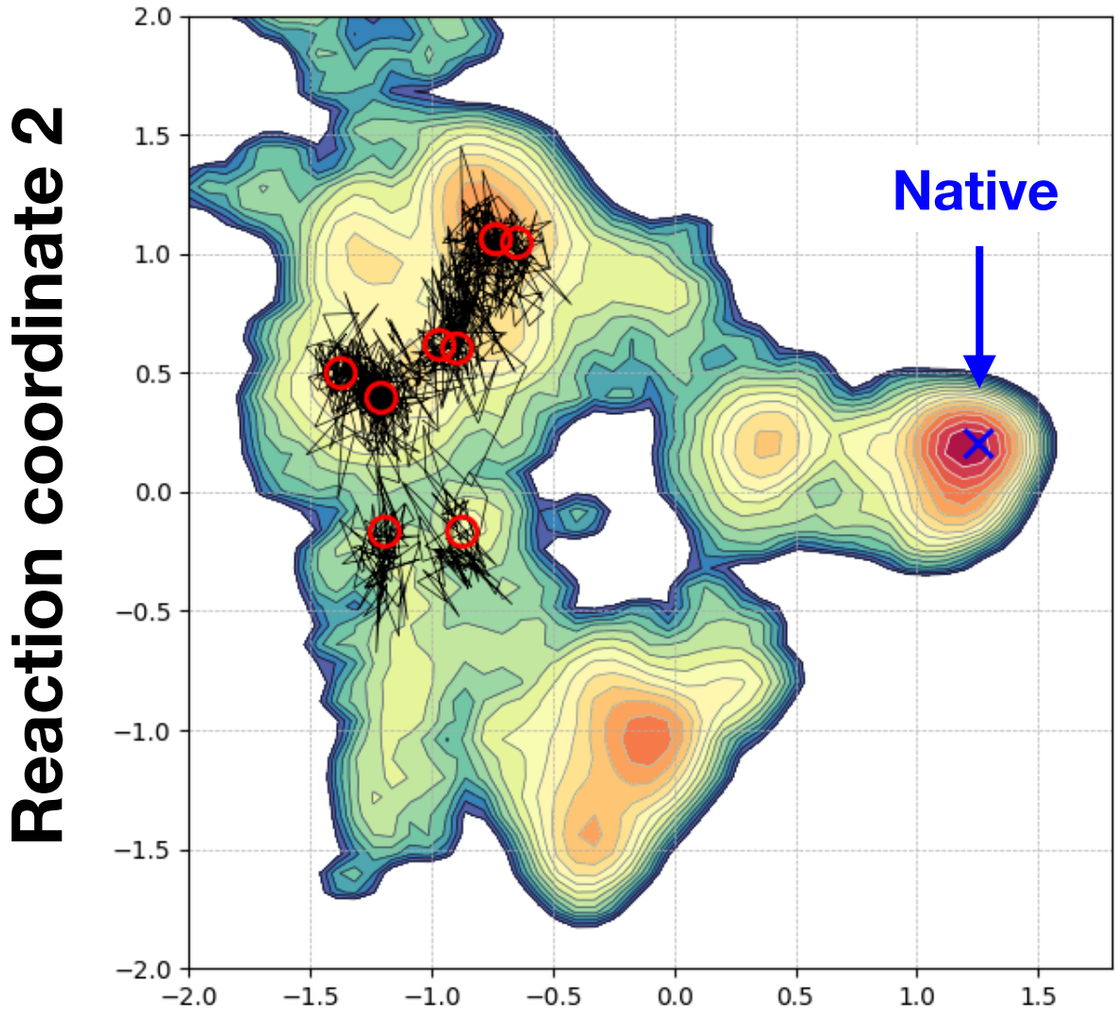


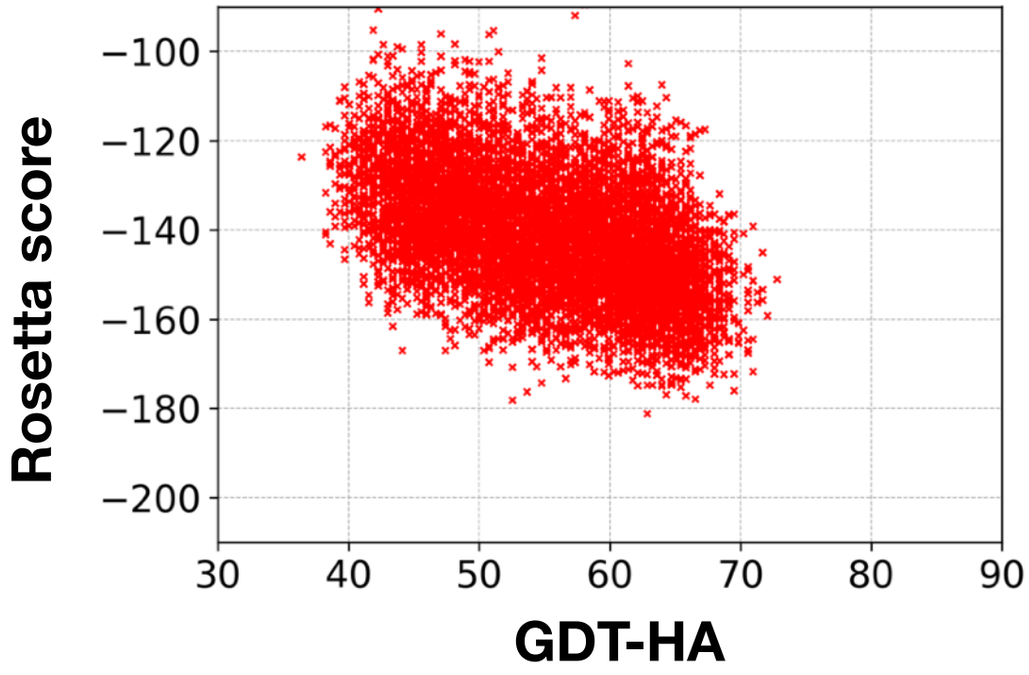


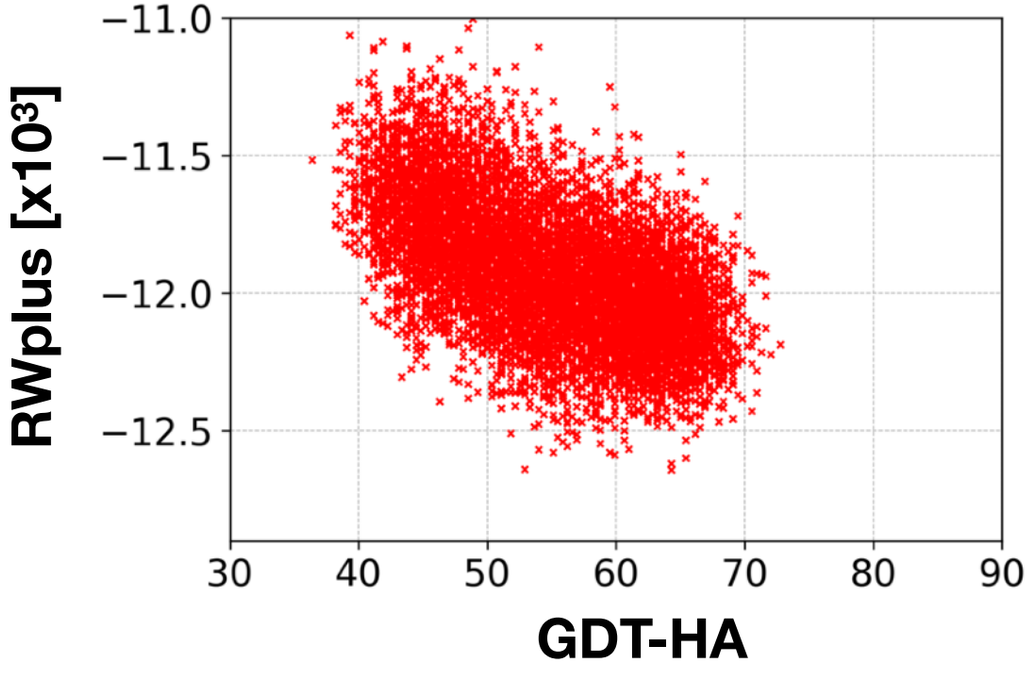


Iterative MD sampling and scoring

PMF map of TR816







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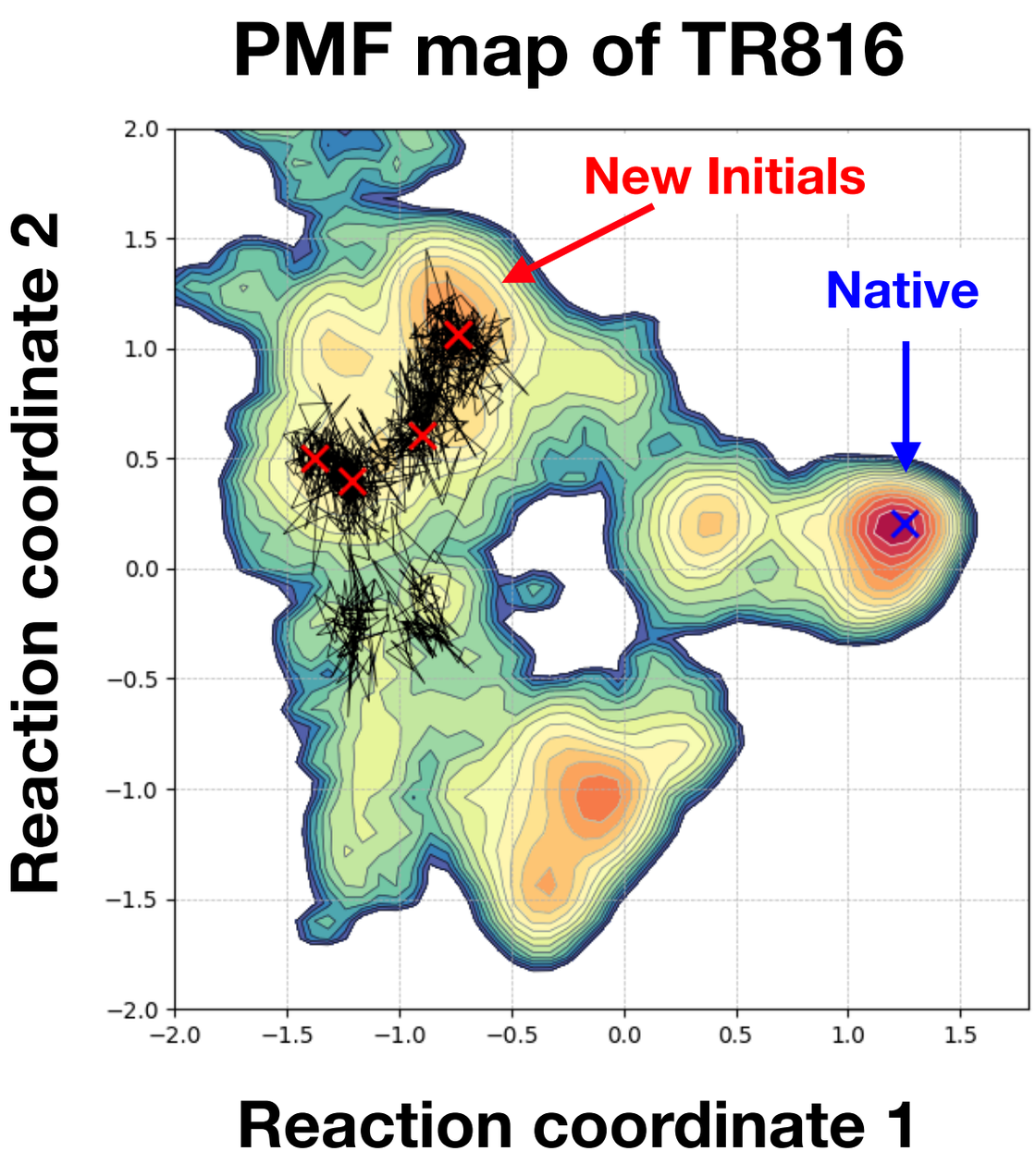

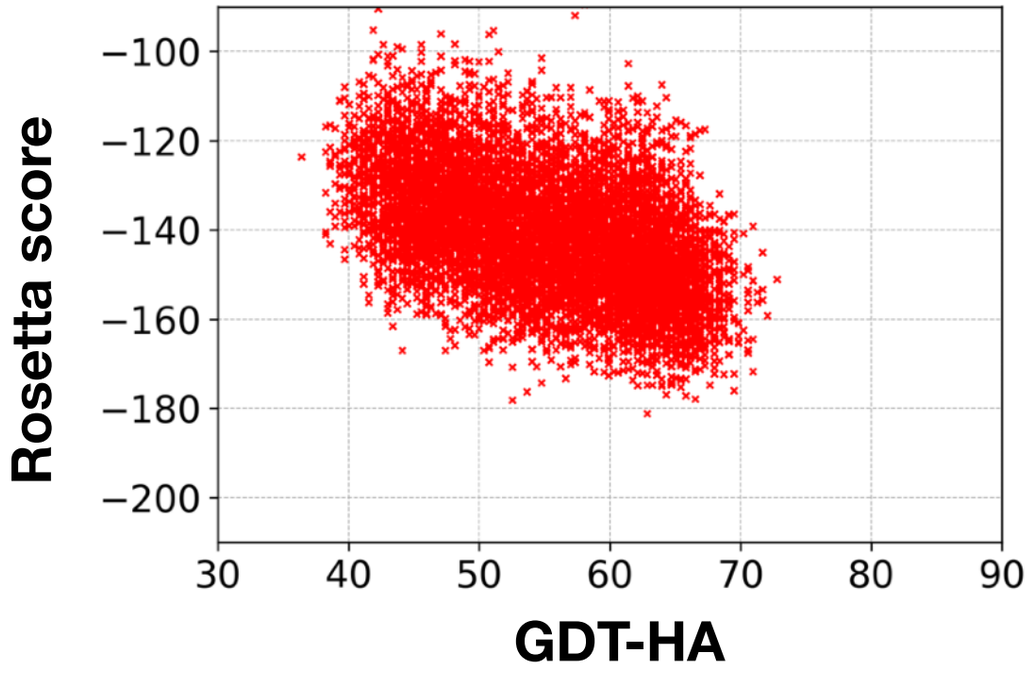

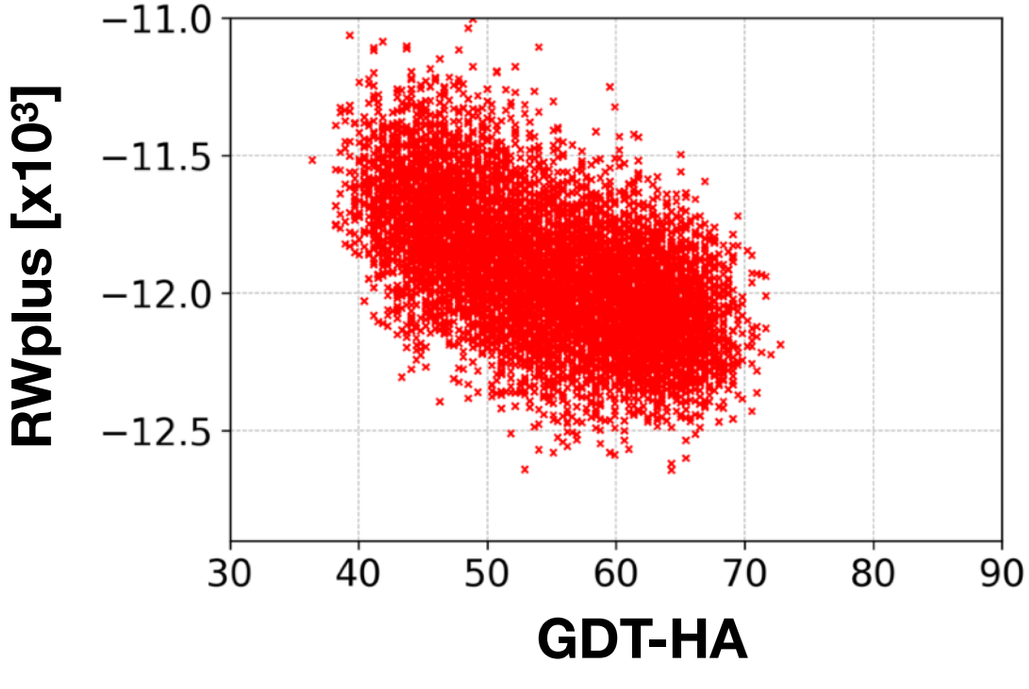

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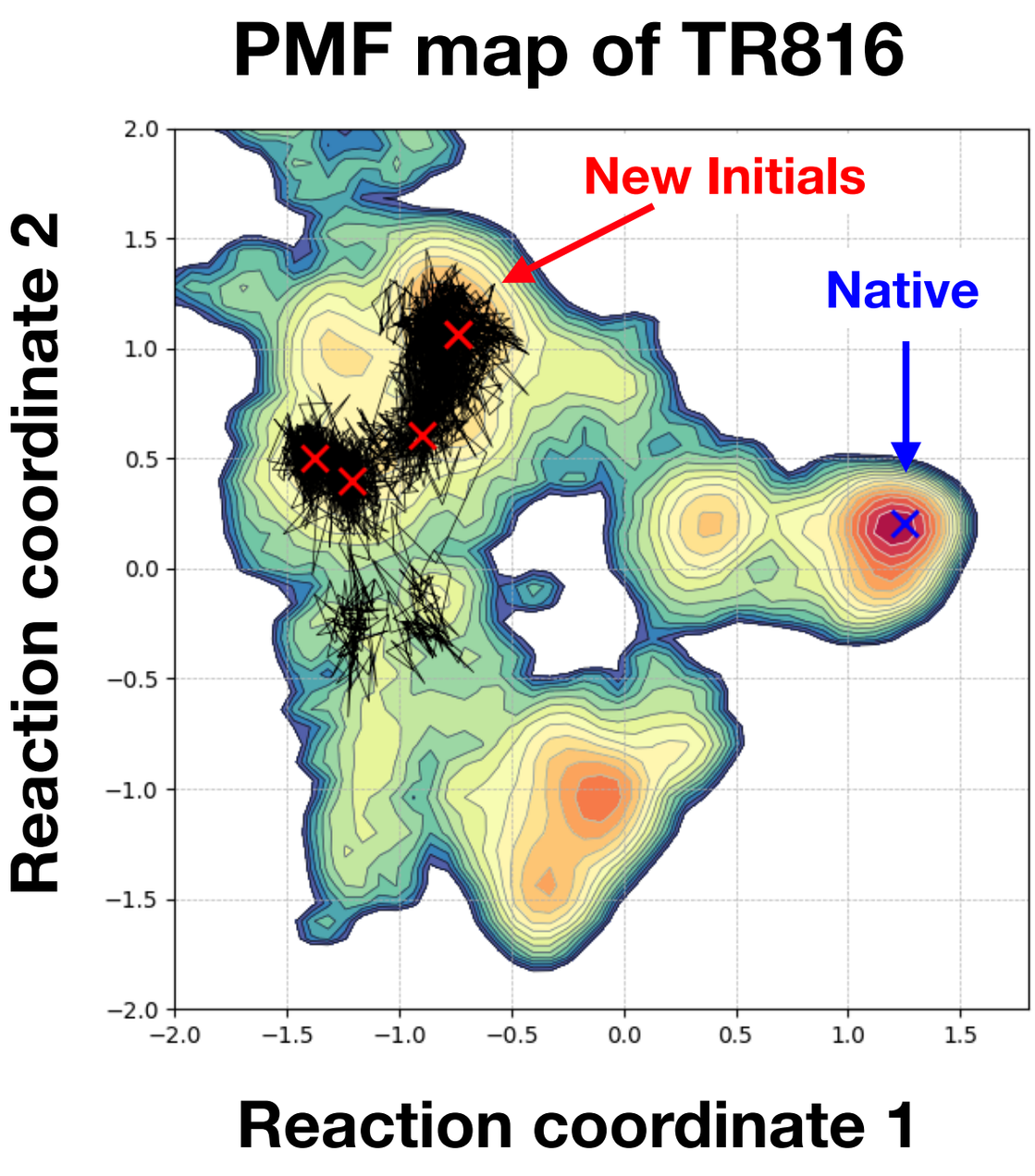

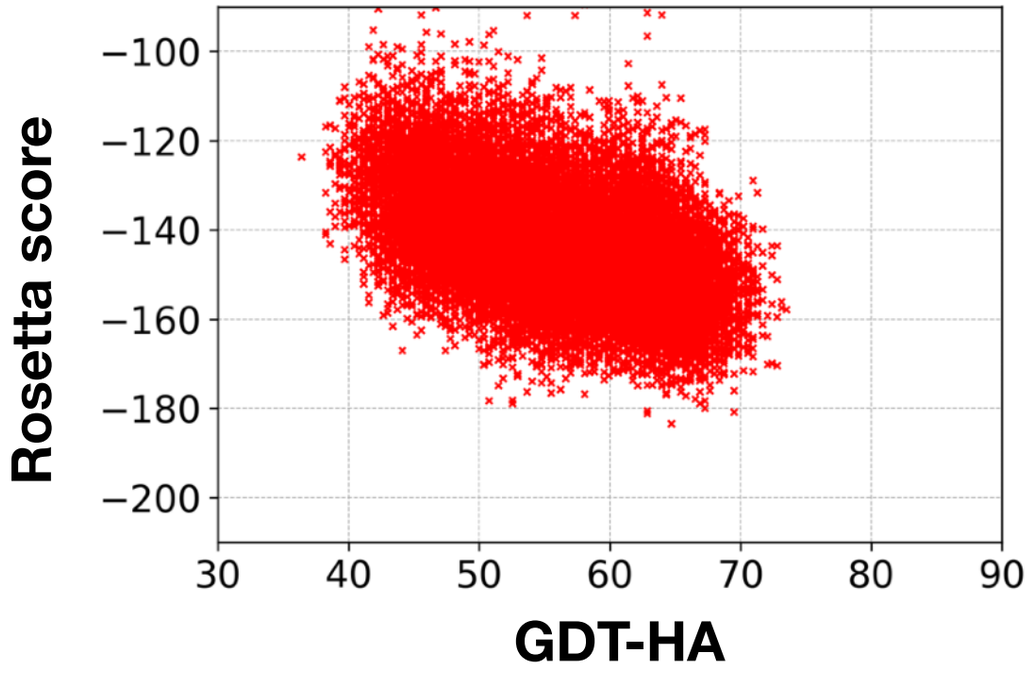

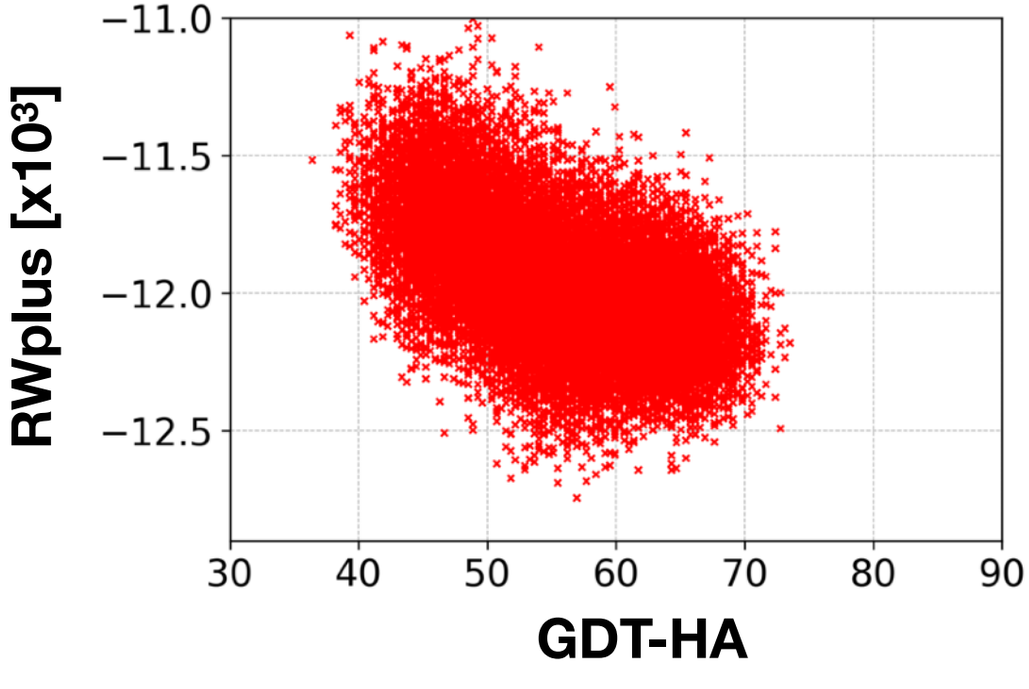

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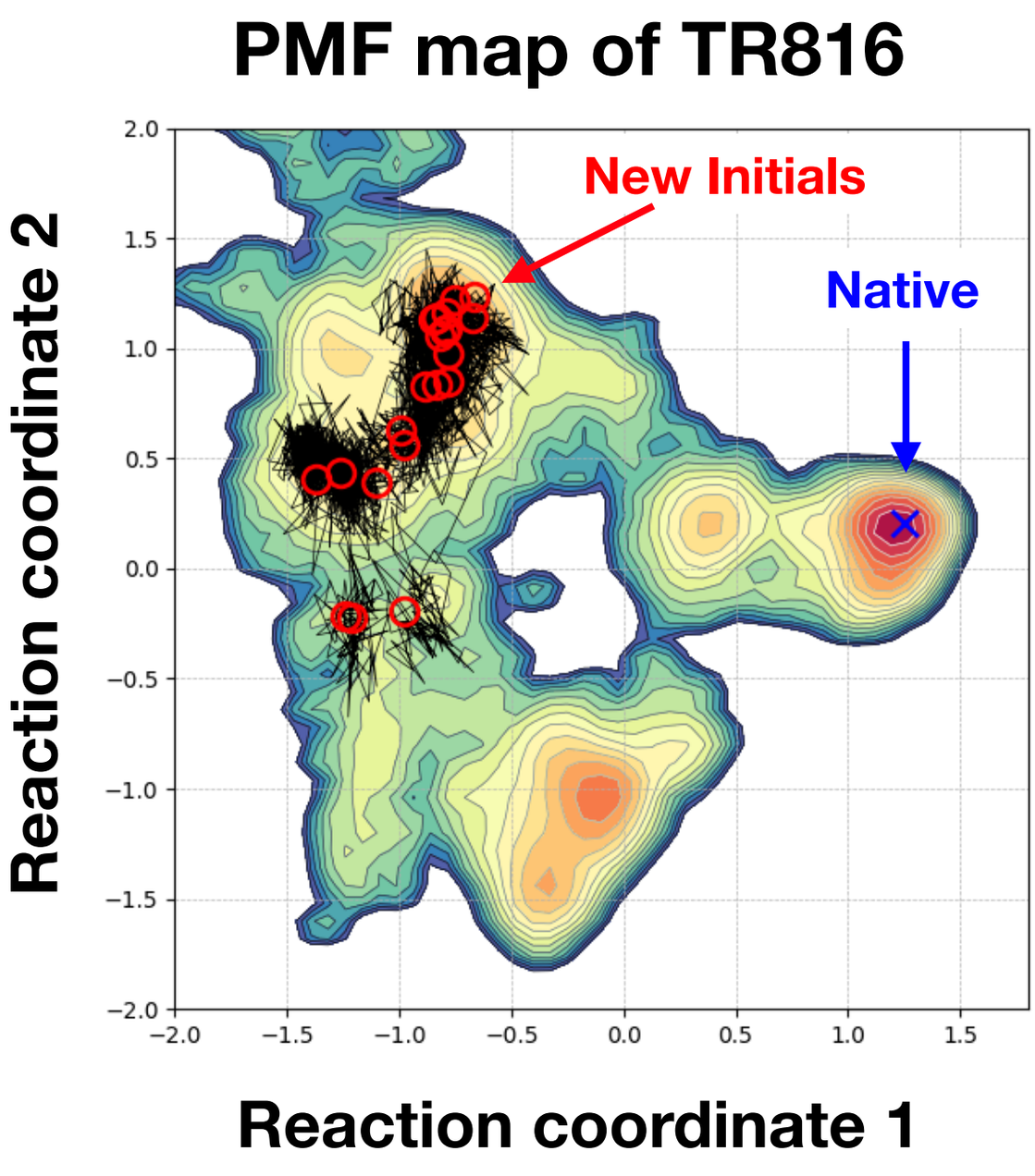

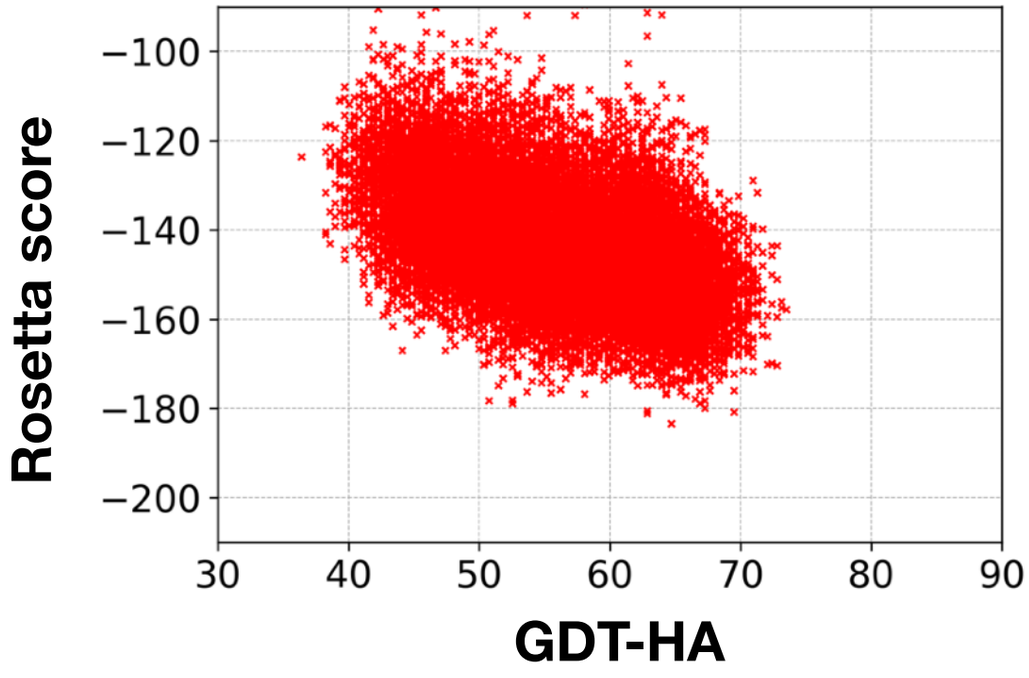

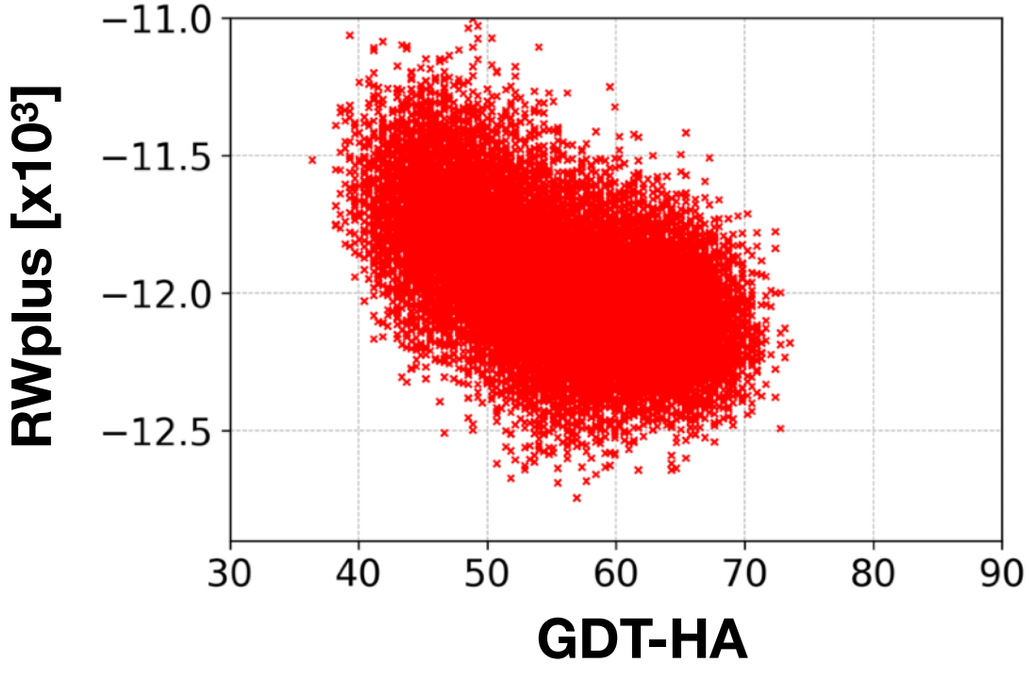

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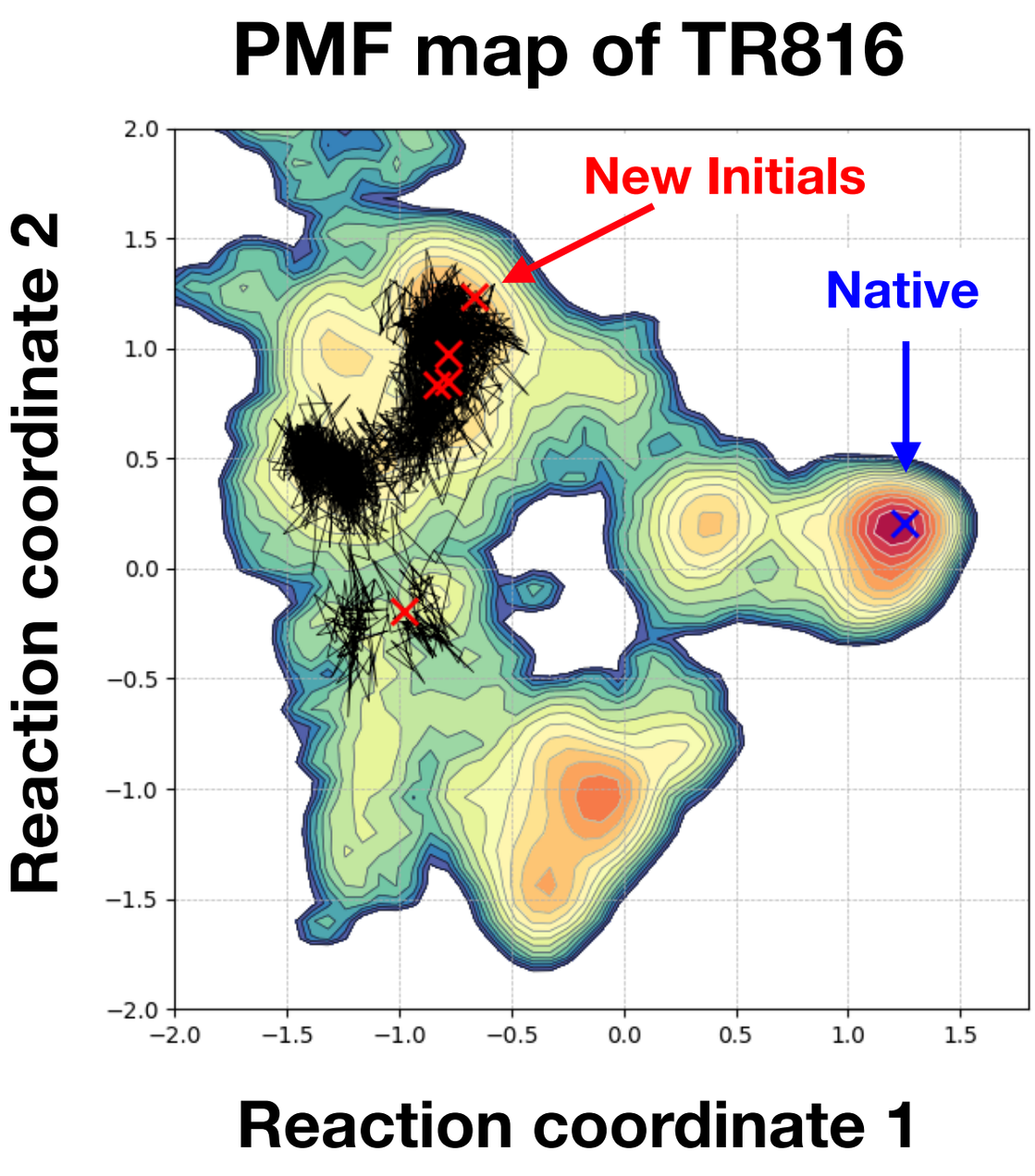

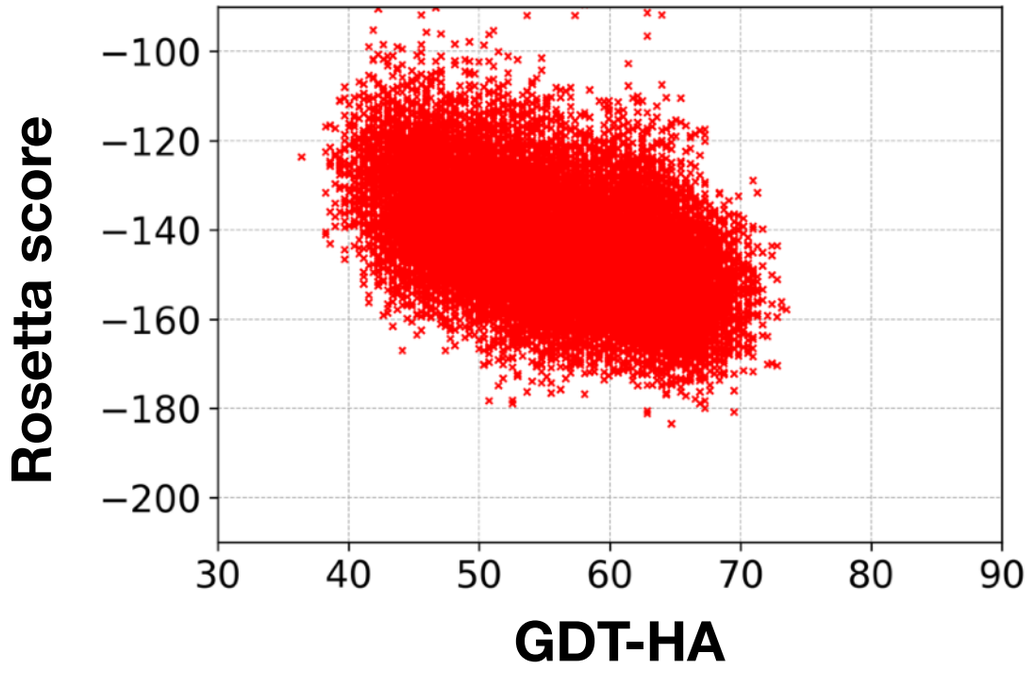

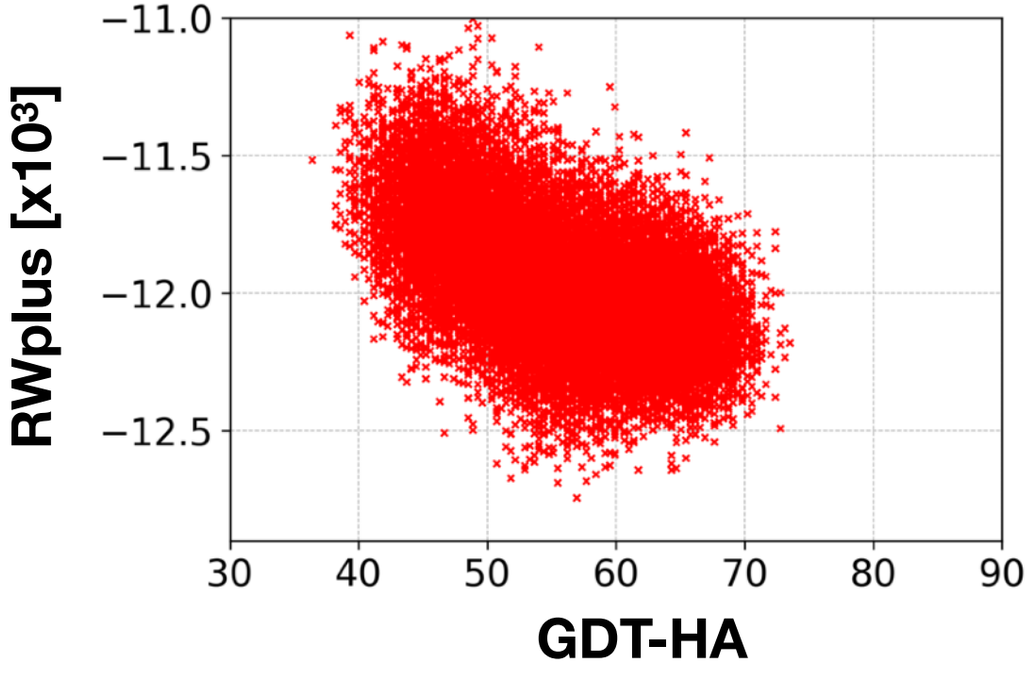

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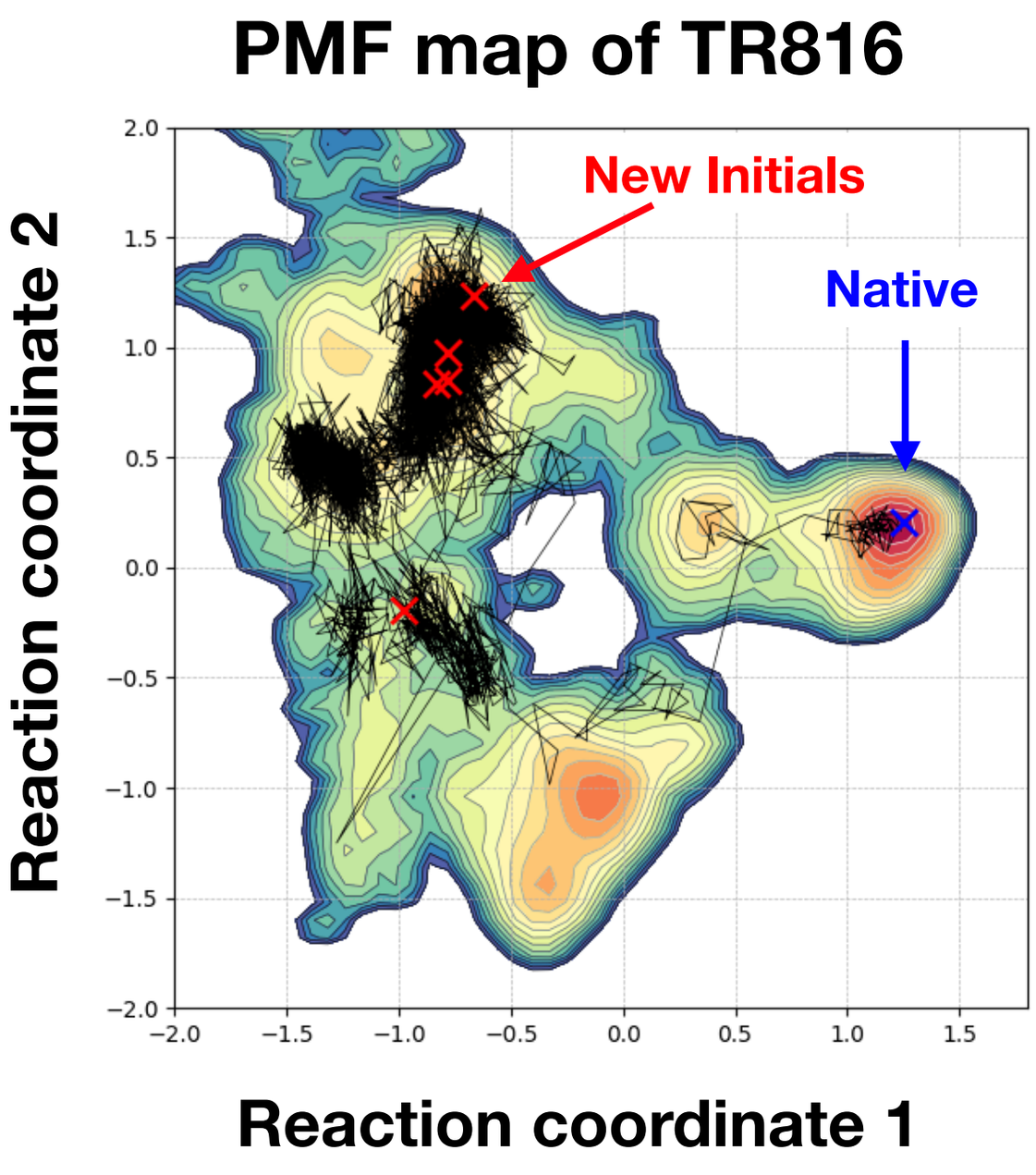

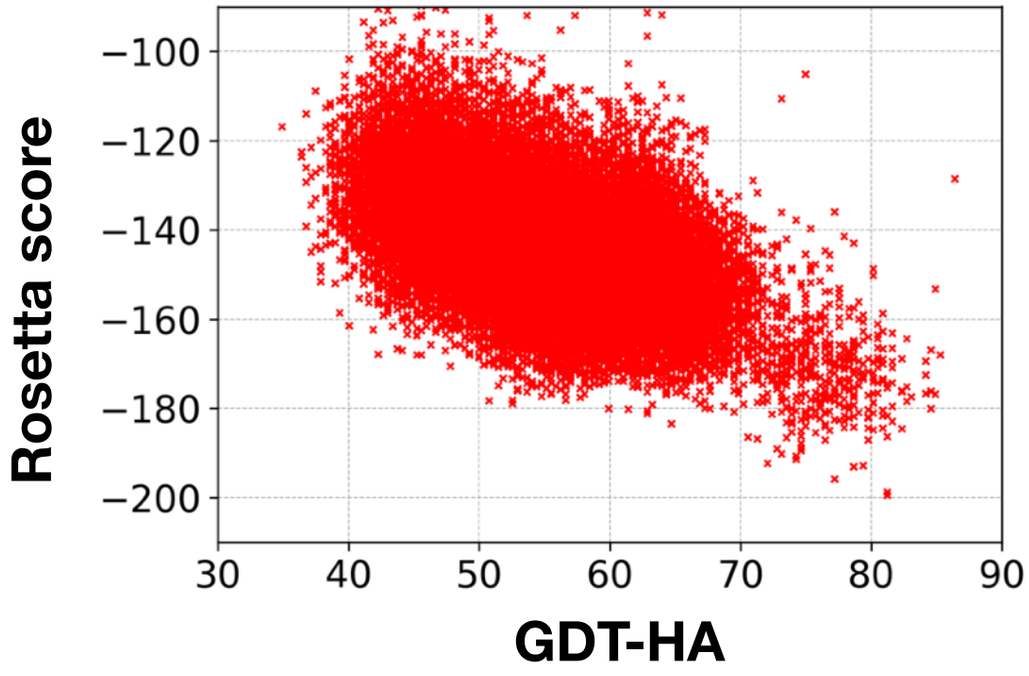

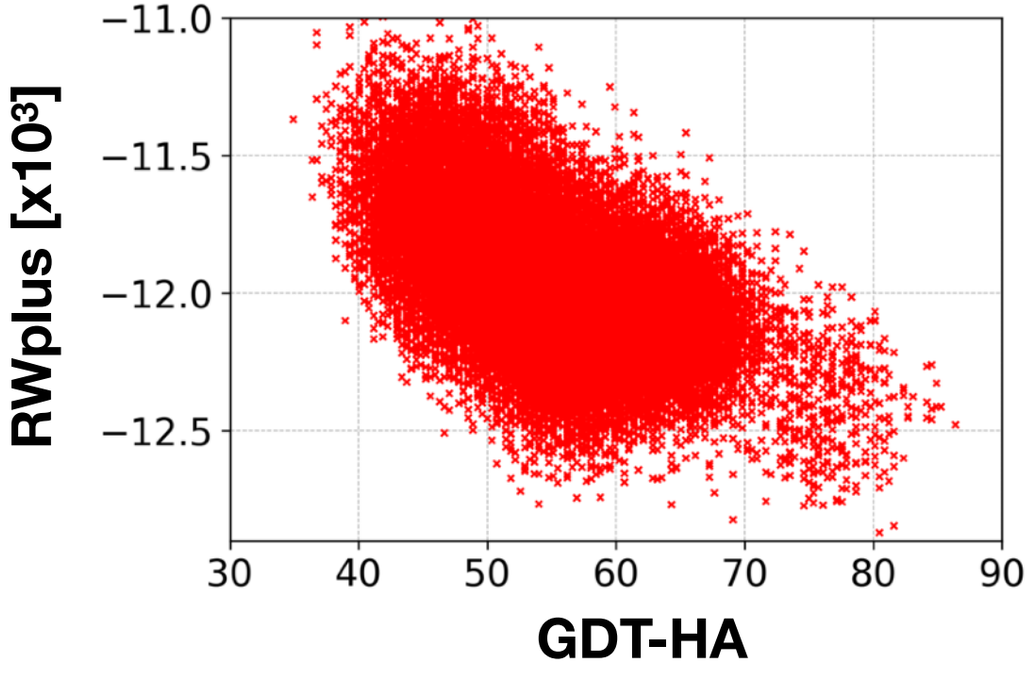

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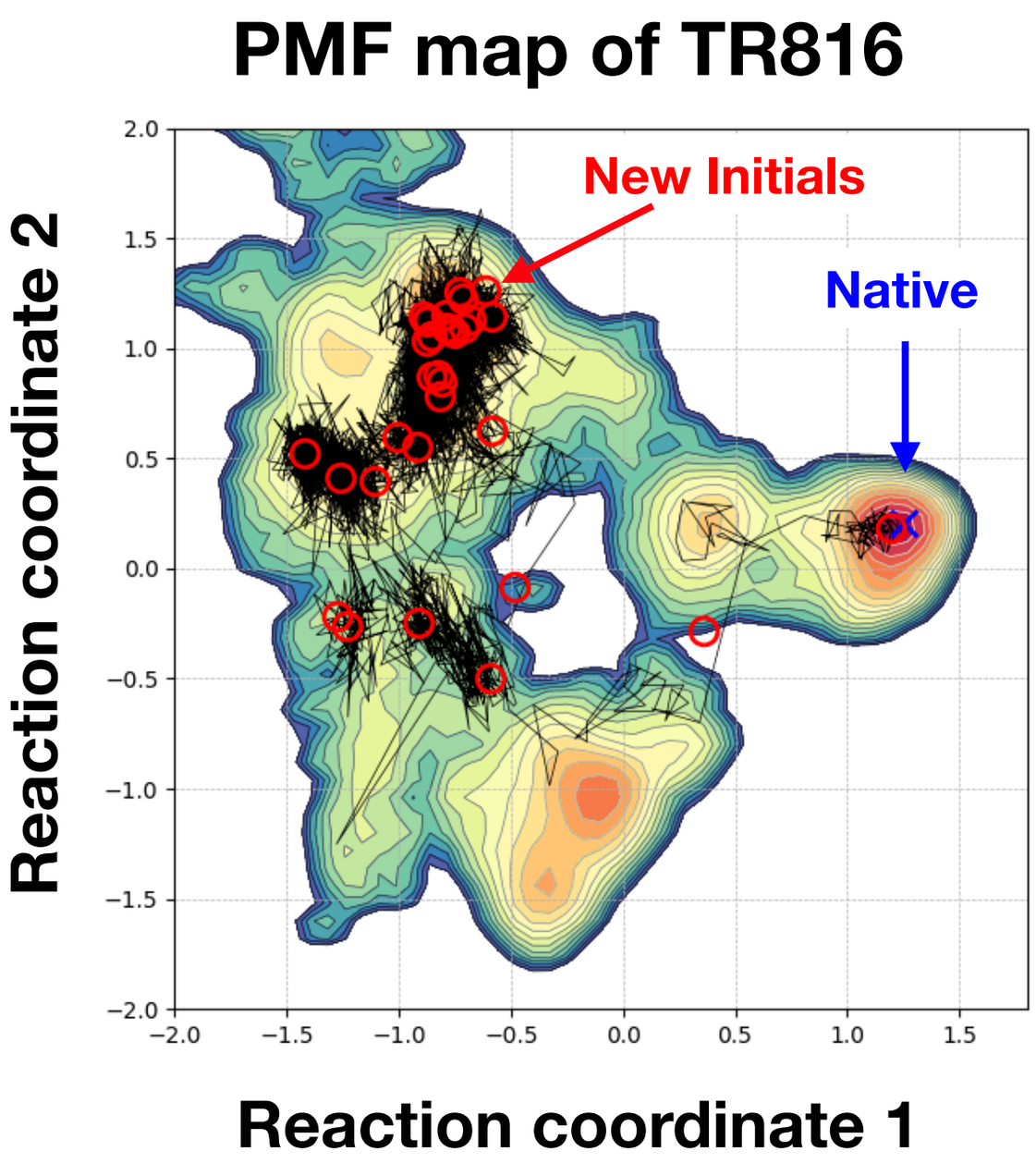
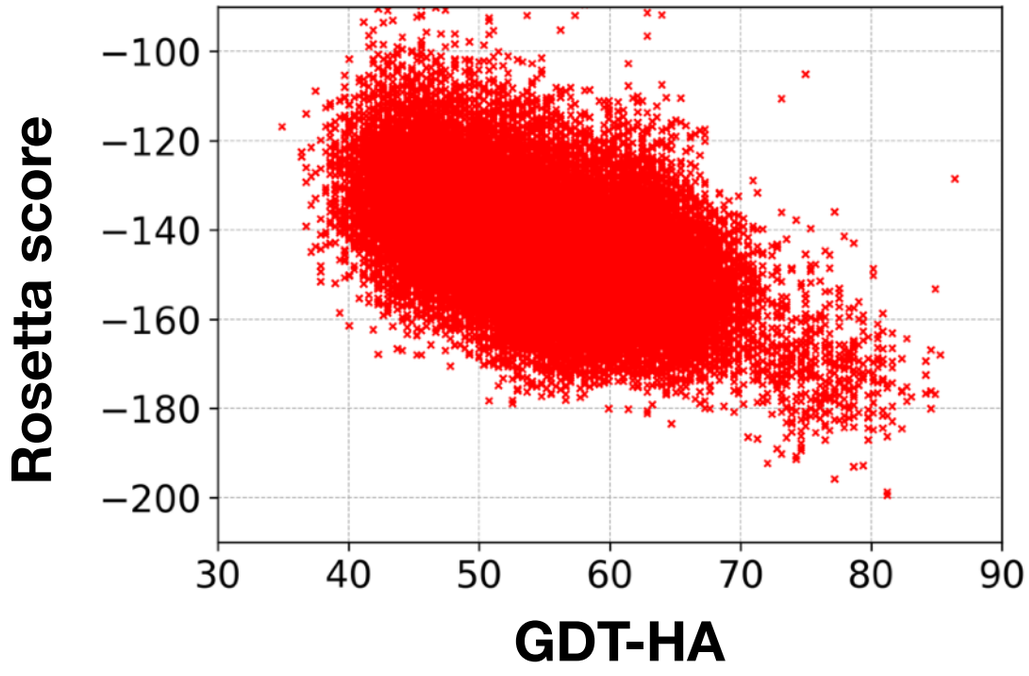
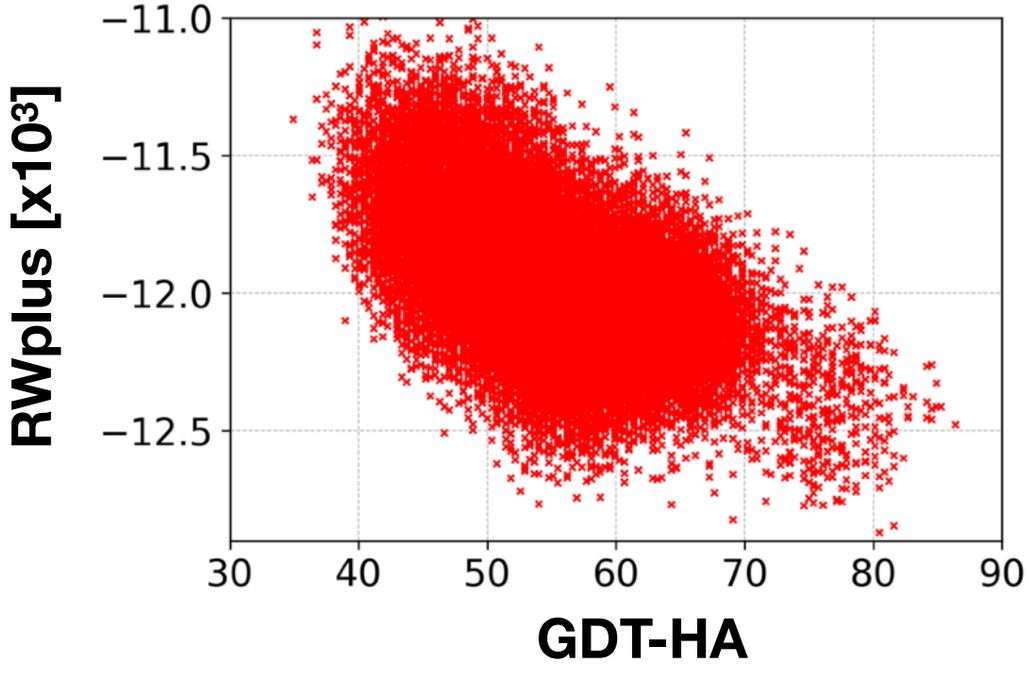
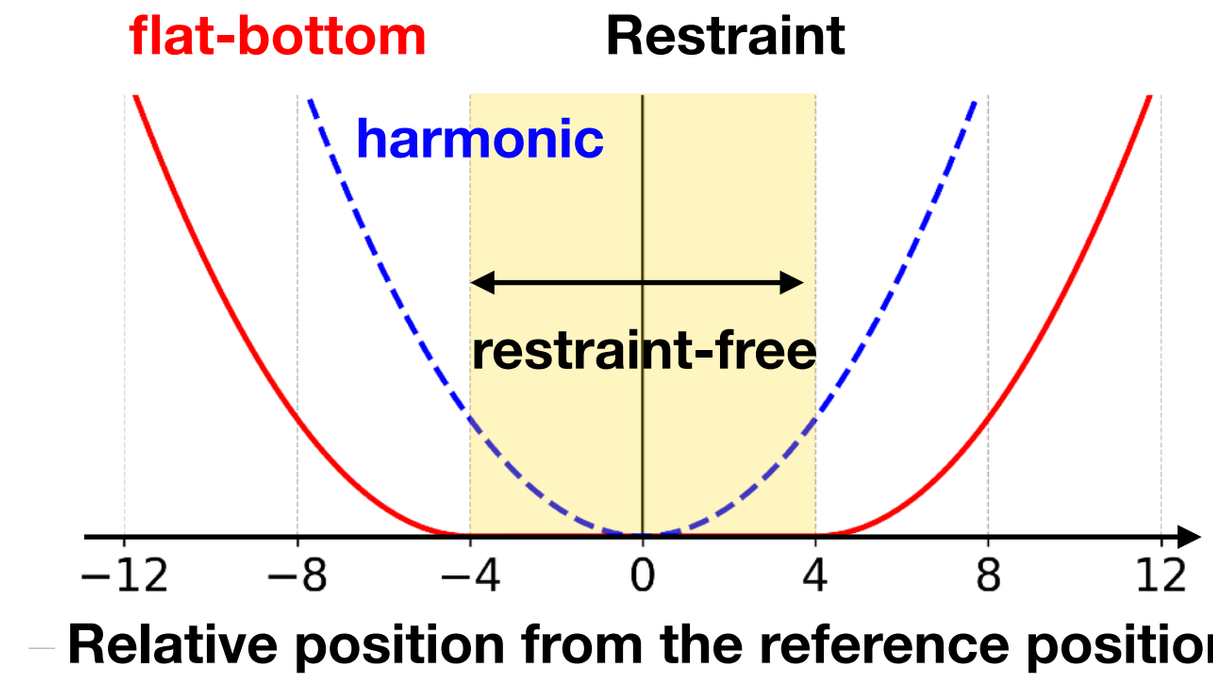
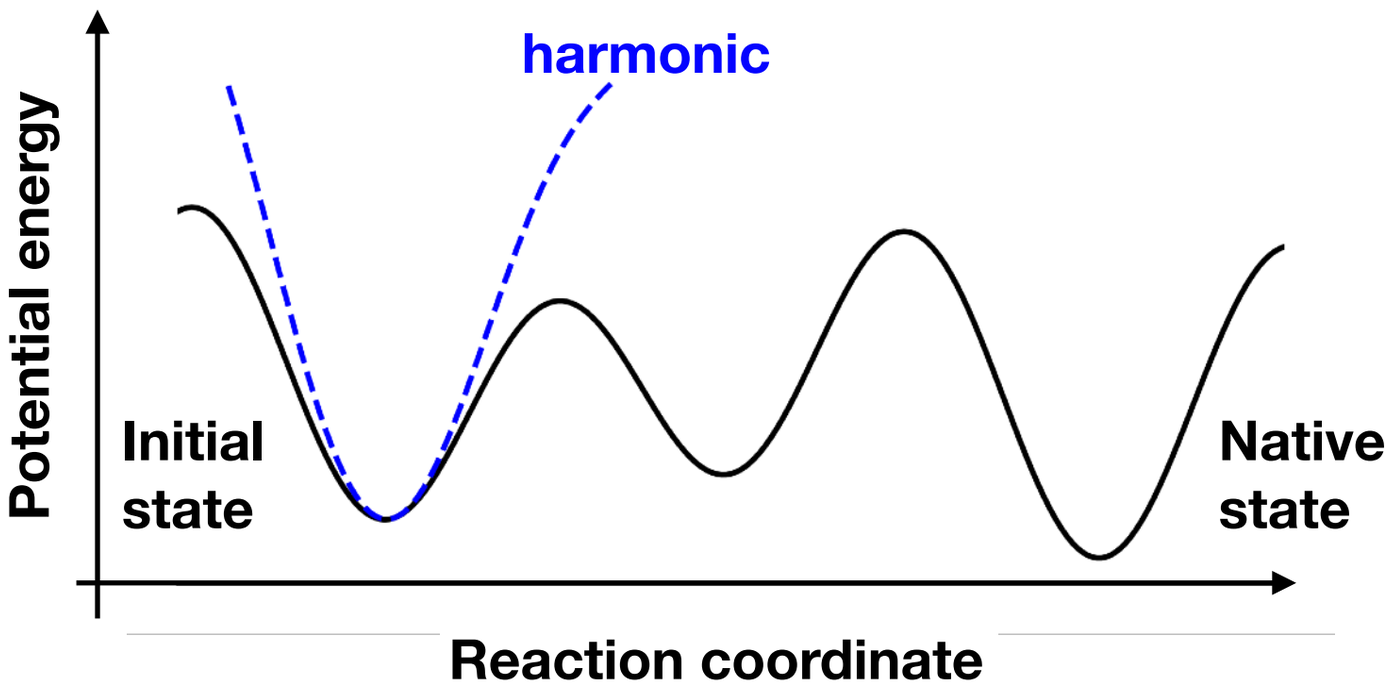






Flat-bottom harmonic restraints





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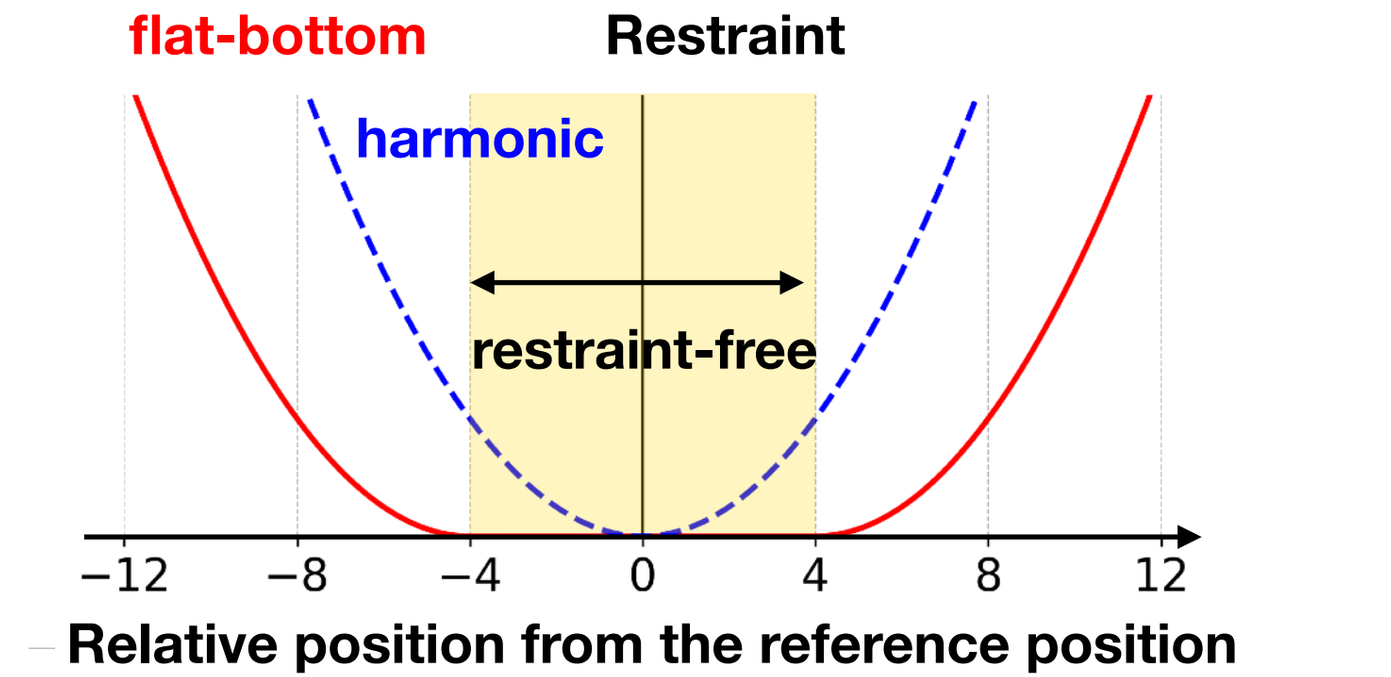

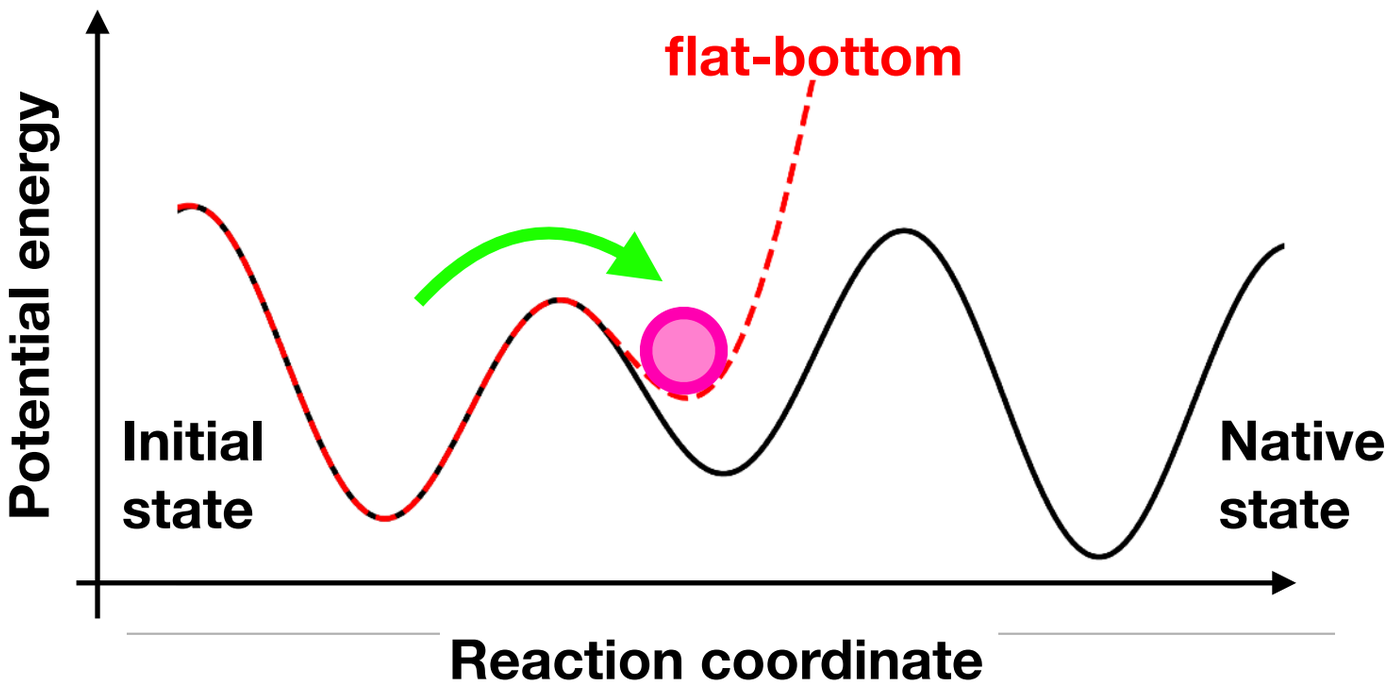

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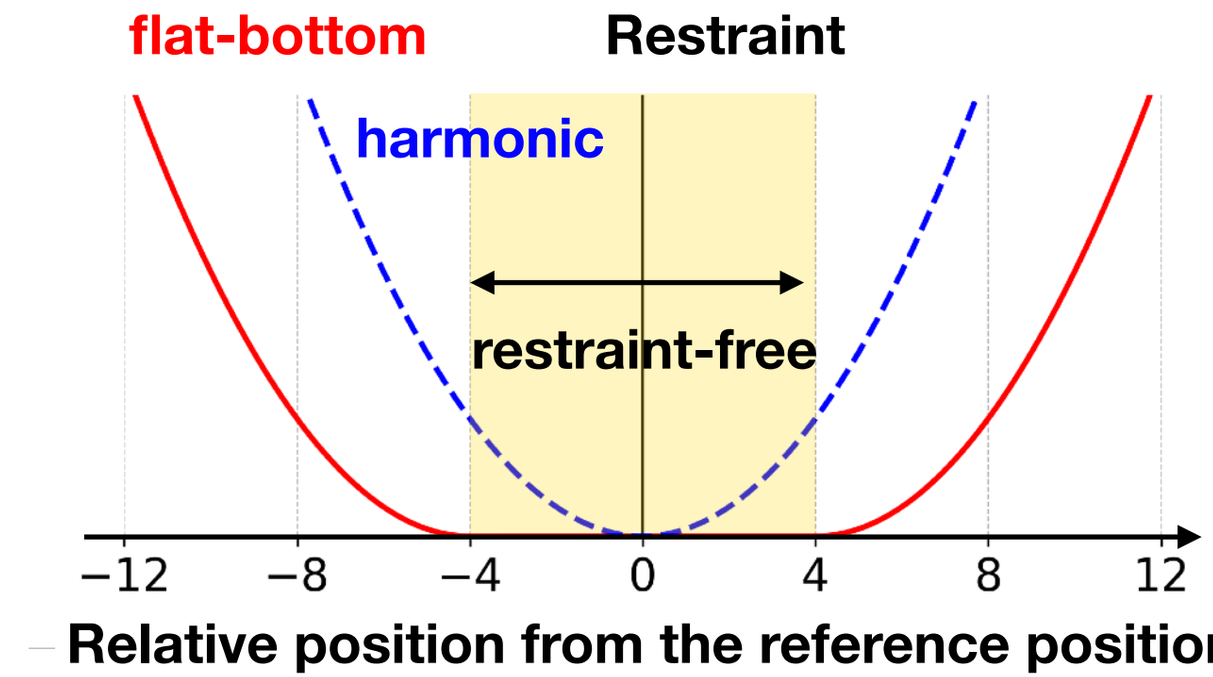

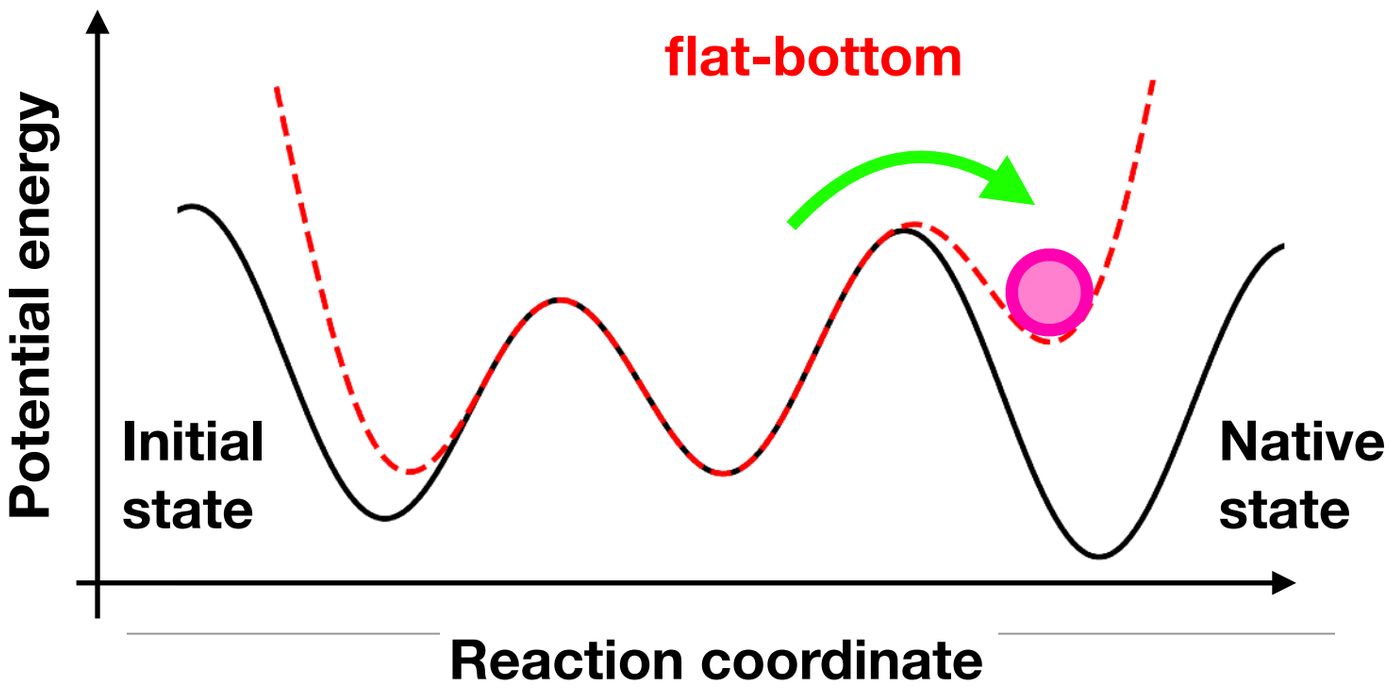

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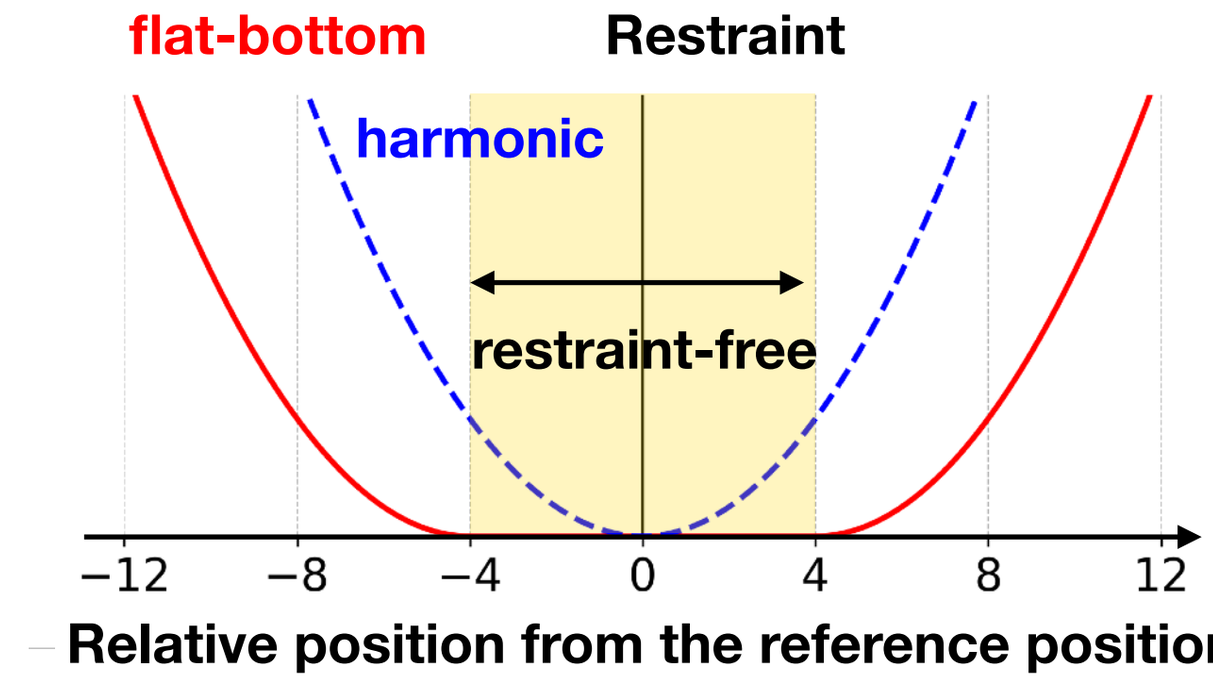

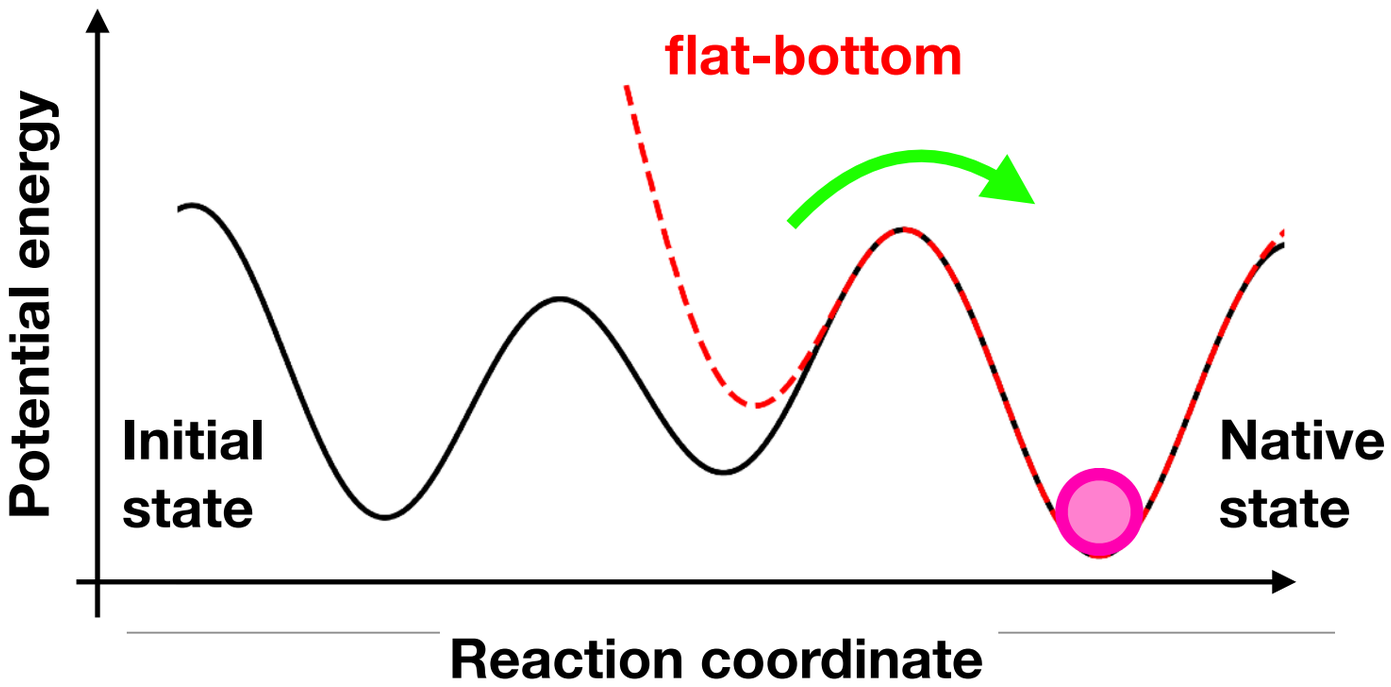

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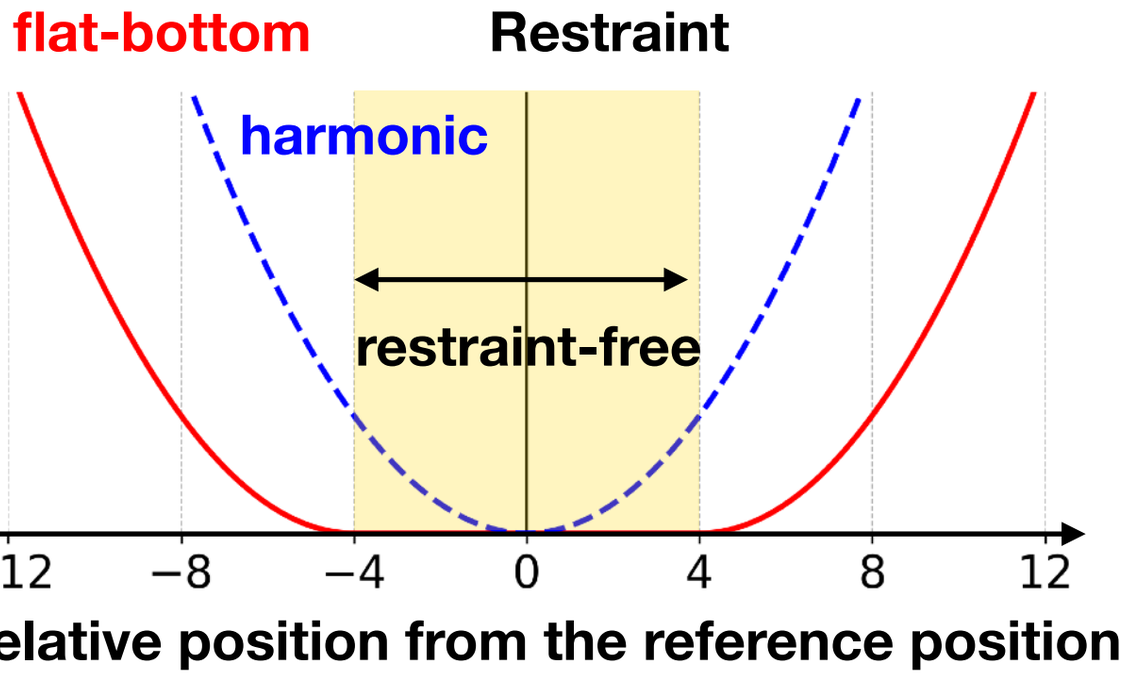

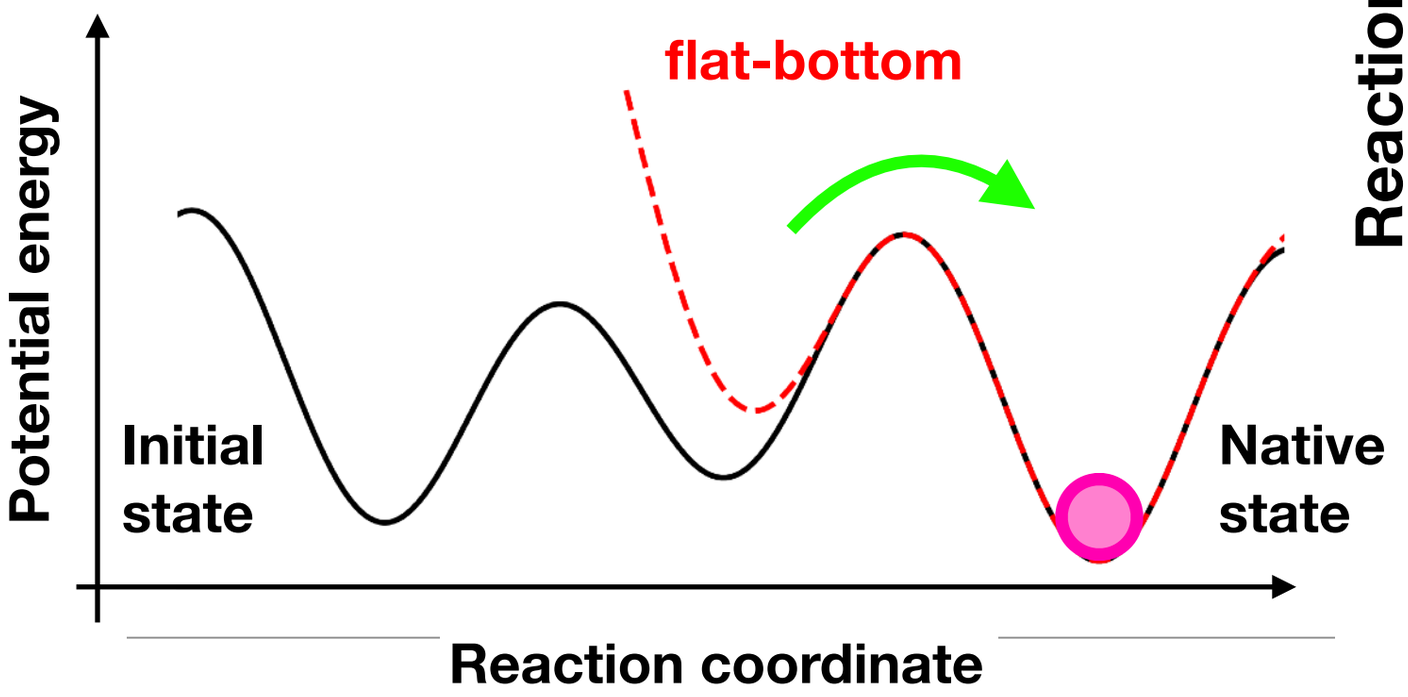

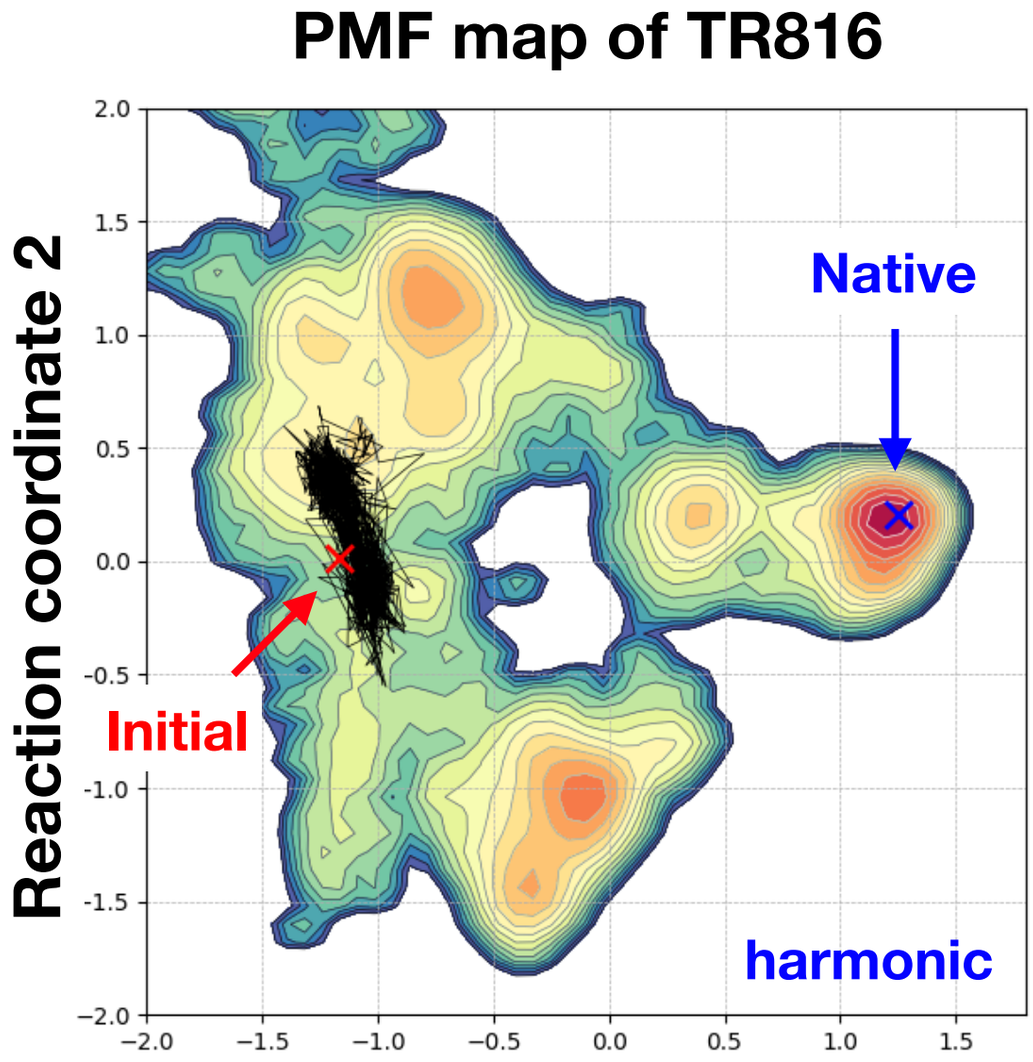

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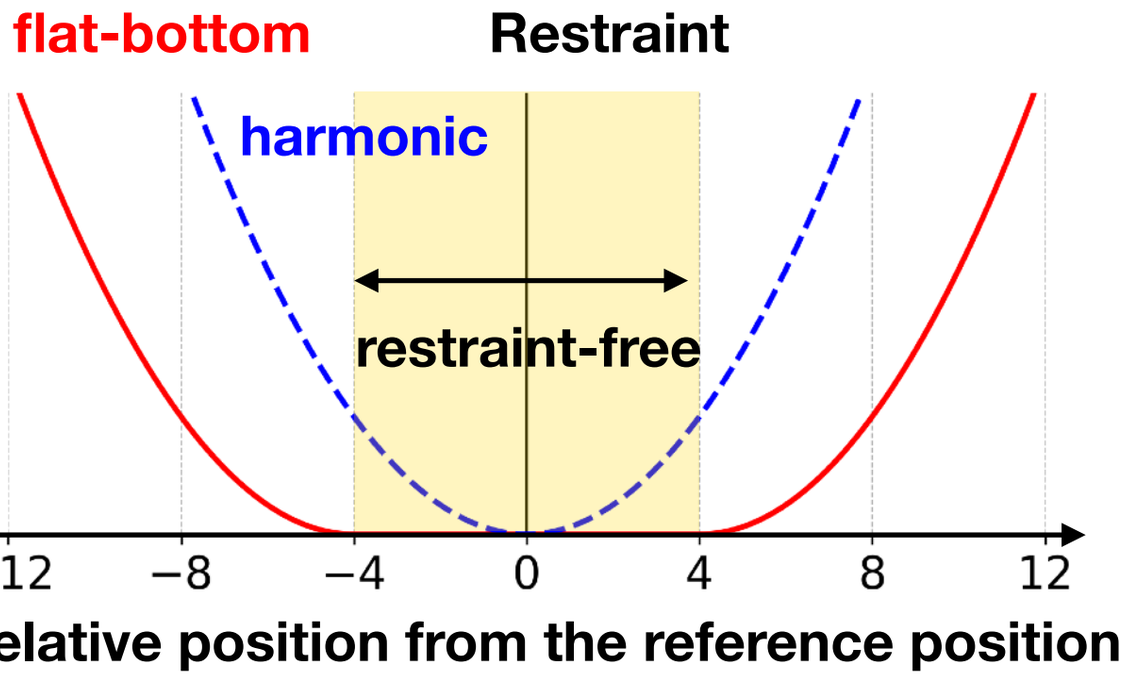
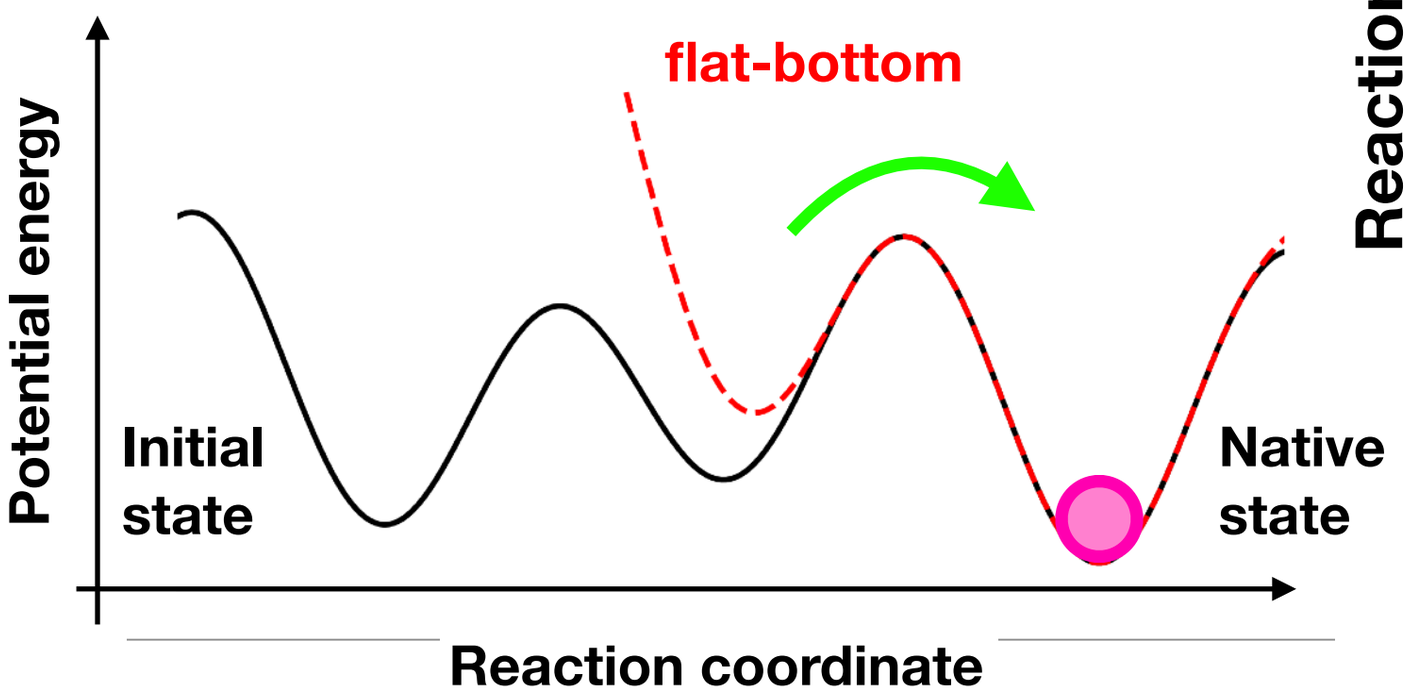
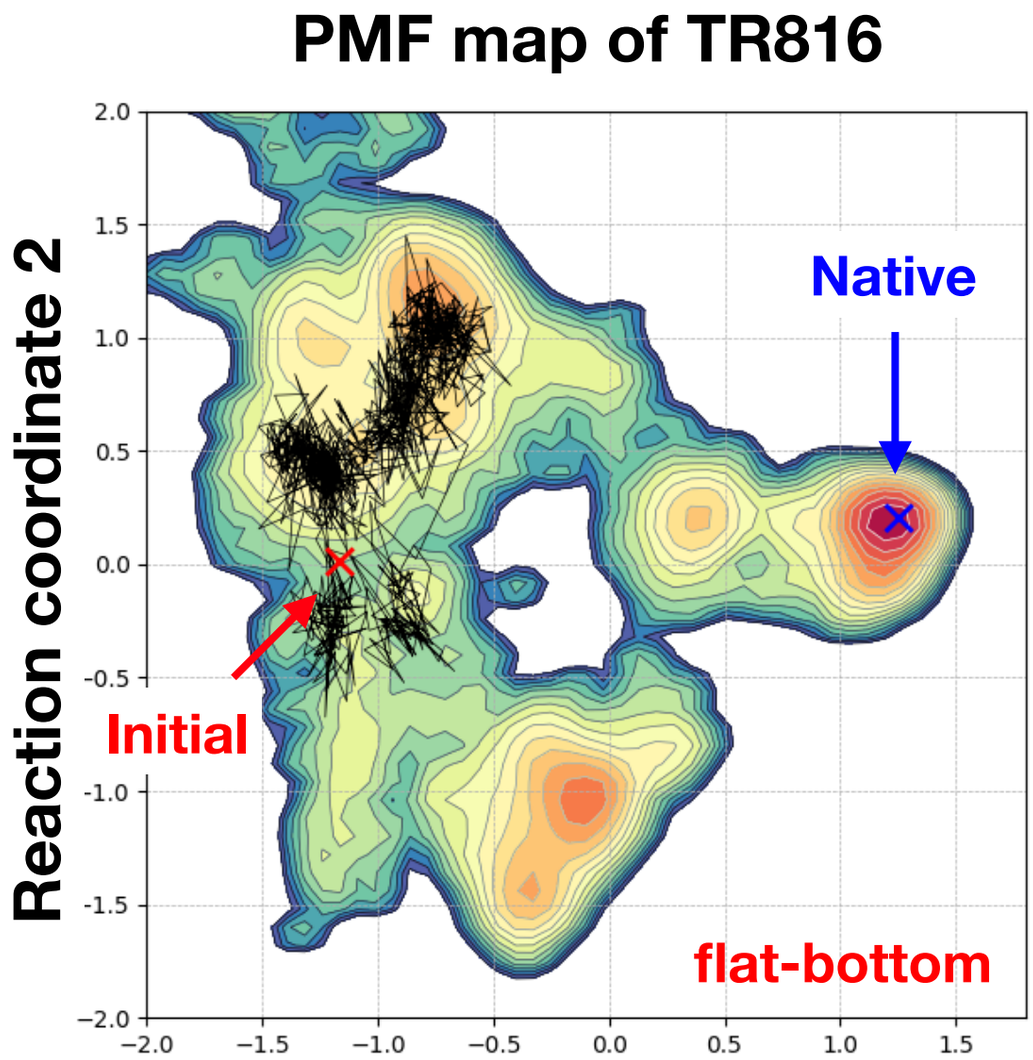
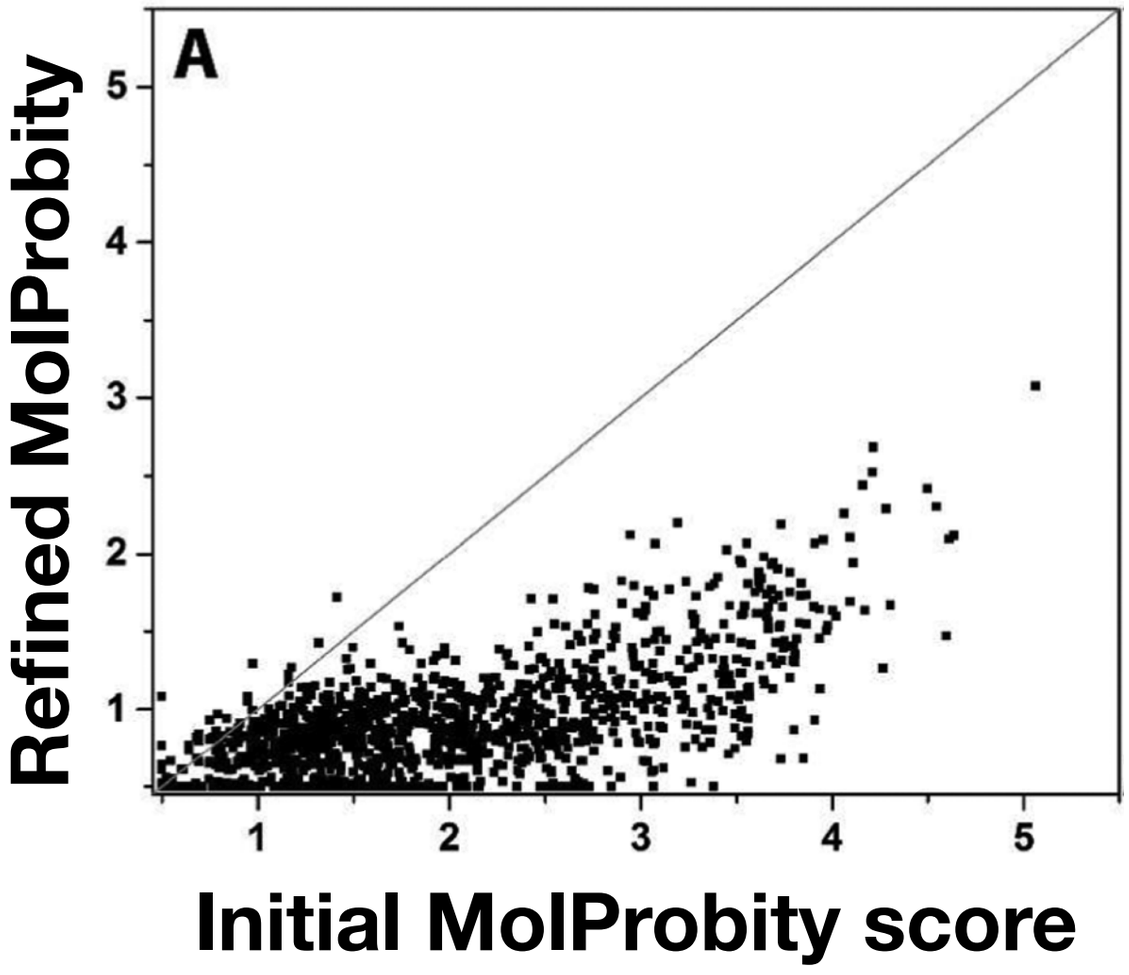






locPREFMD

- Quickly resolves stereochemical problems
- http://feiglab.org/locprefmd

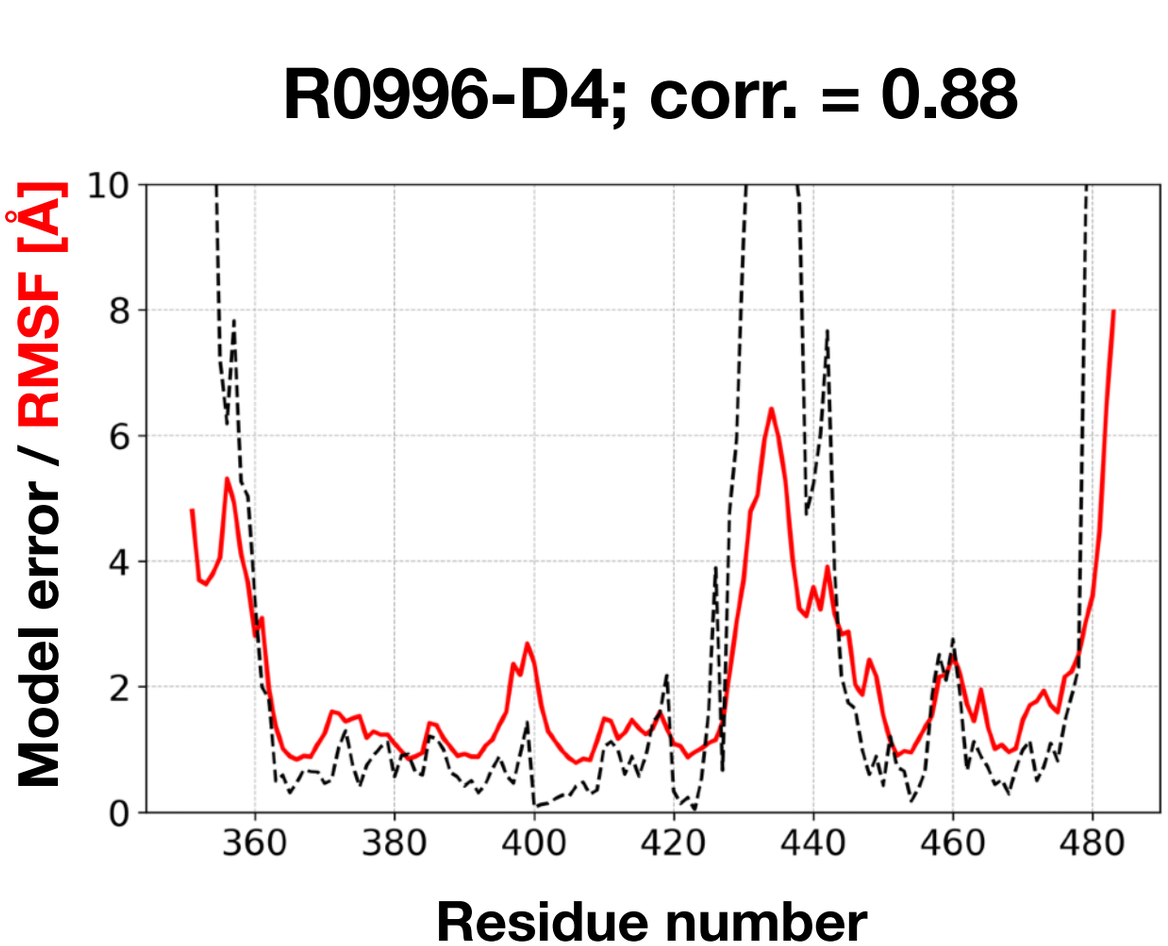


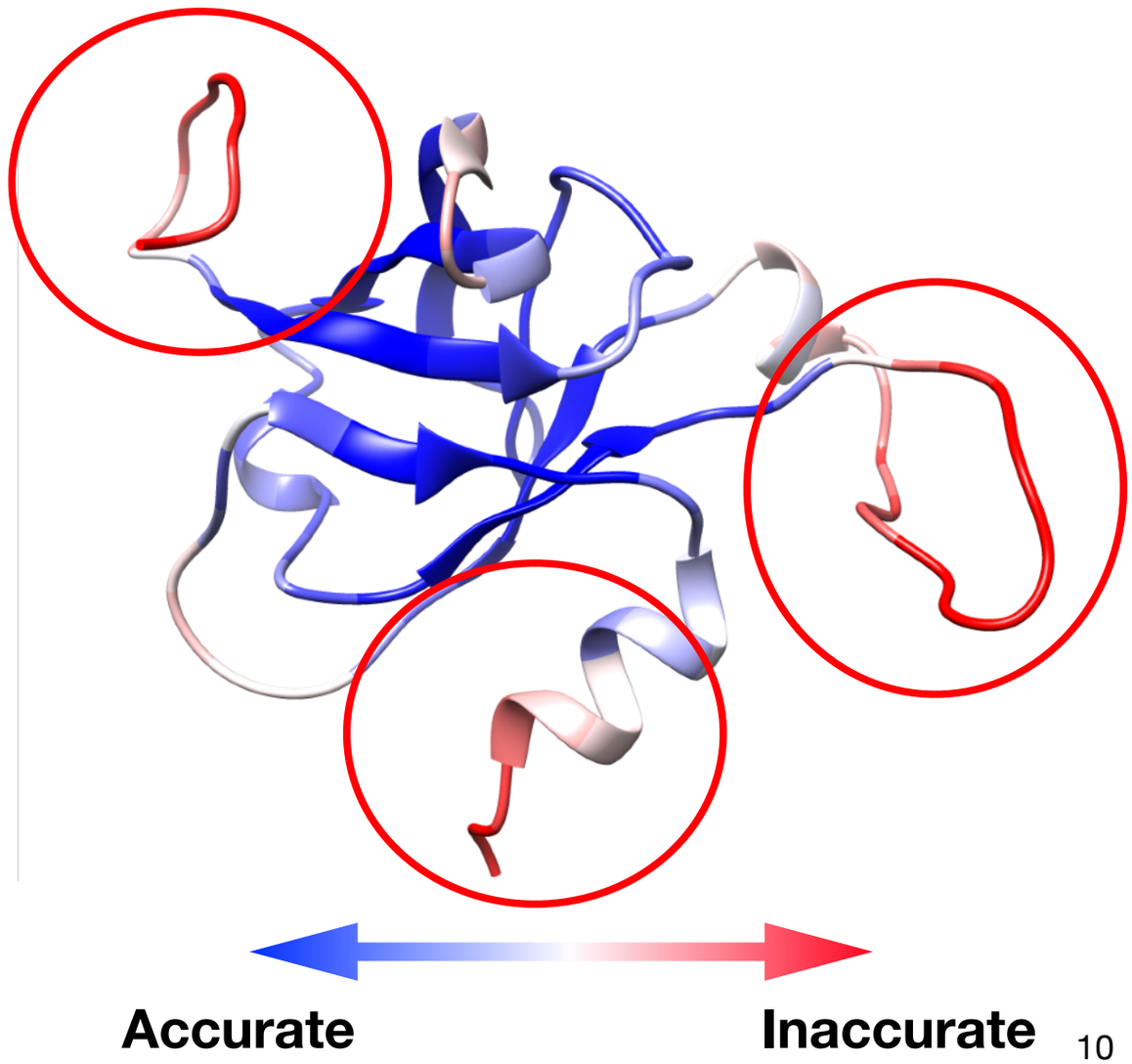
	Initial	Refined
MolP	2.00	0.91
Clash	23.27	0.11
Rotamer outlier	3.6%	1.1%
Rama outlier	2.0%	1.1%

Michael Feig, *J. Chem. Inf. Model.* (**2016**) 56(7): 1304-1312.

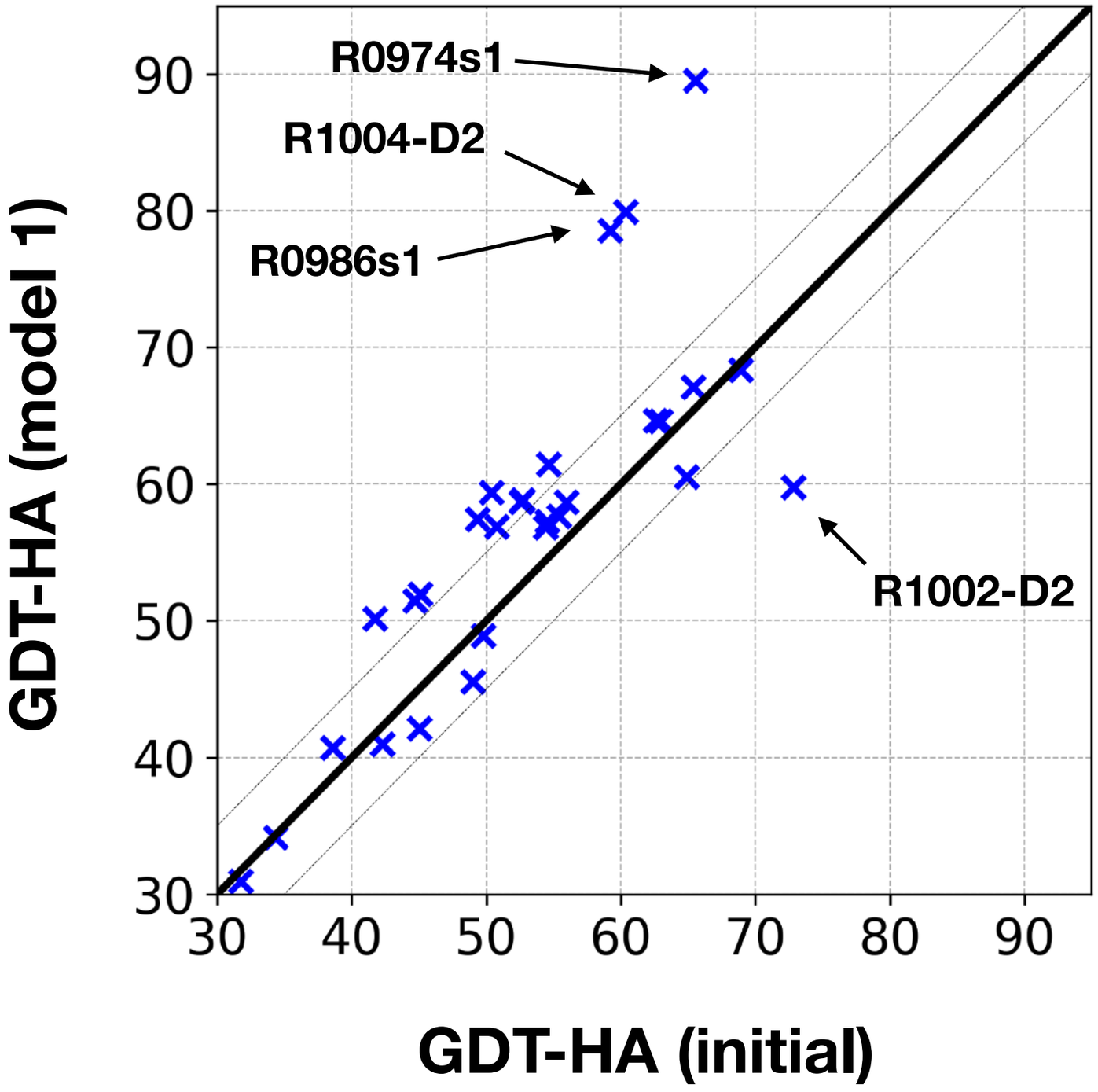
Error estimations

- Running 2 x 5 ns MD simulations without restraint for a model
- Residue-wise **RMSF** is highly correlated with residue-wise error!





CASP13 results with the current protocol

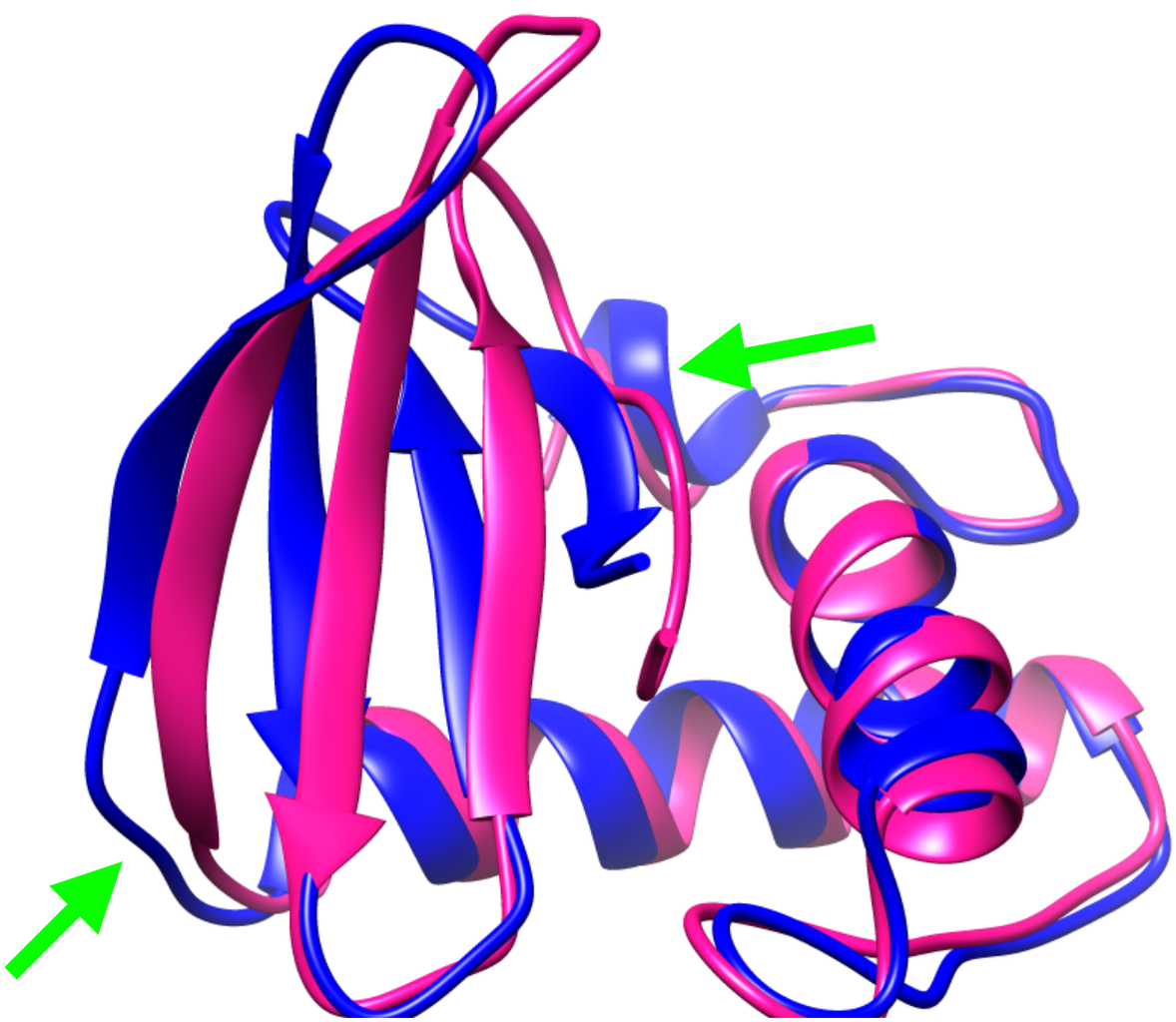


20/29 (69%) improved

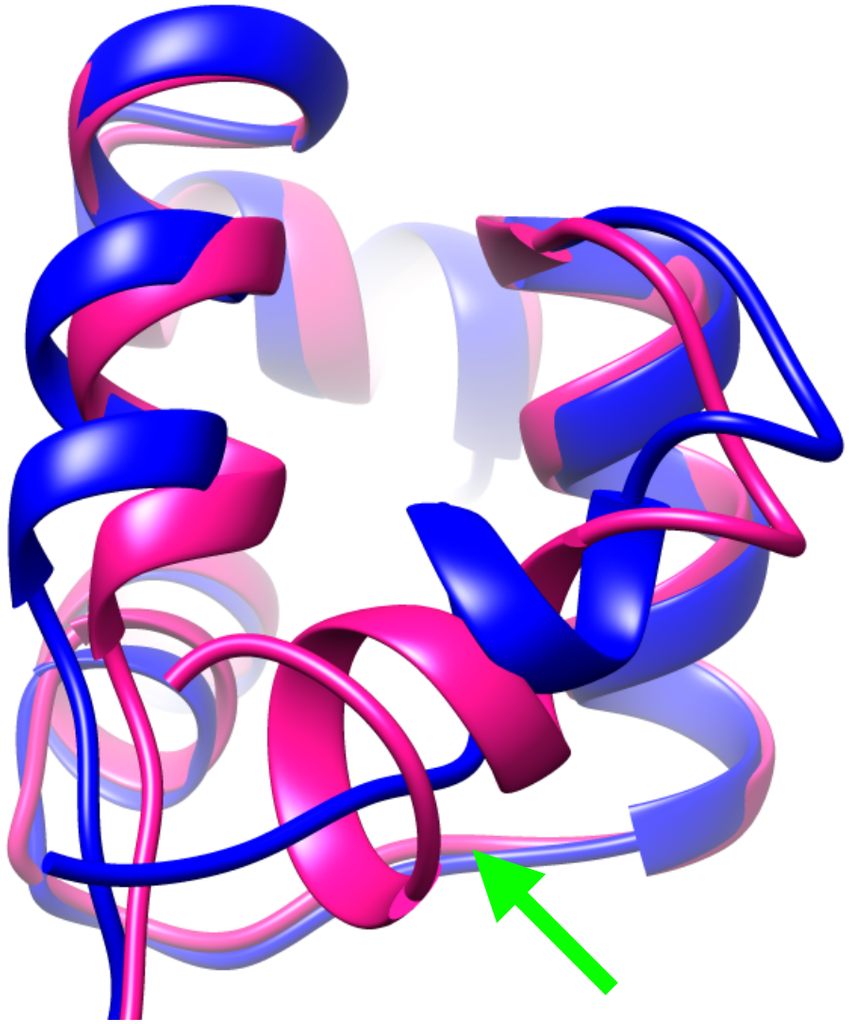
ΔGDT-HA = +3.99

What are improved?

Magenta: Initial
Blue: Refined



R0986s1
GDT-HA: 59.2 → 78.5 (+19.3)
RMSD: 1.8 Å → 1.0 Å (-0.8 Å)

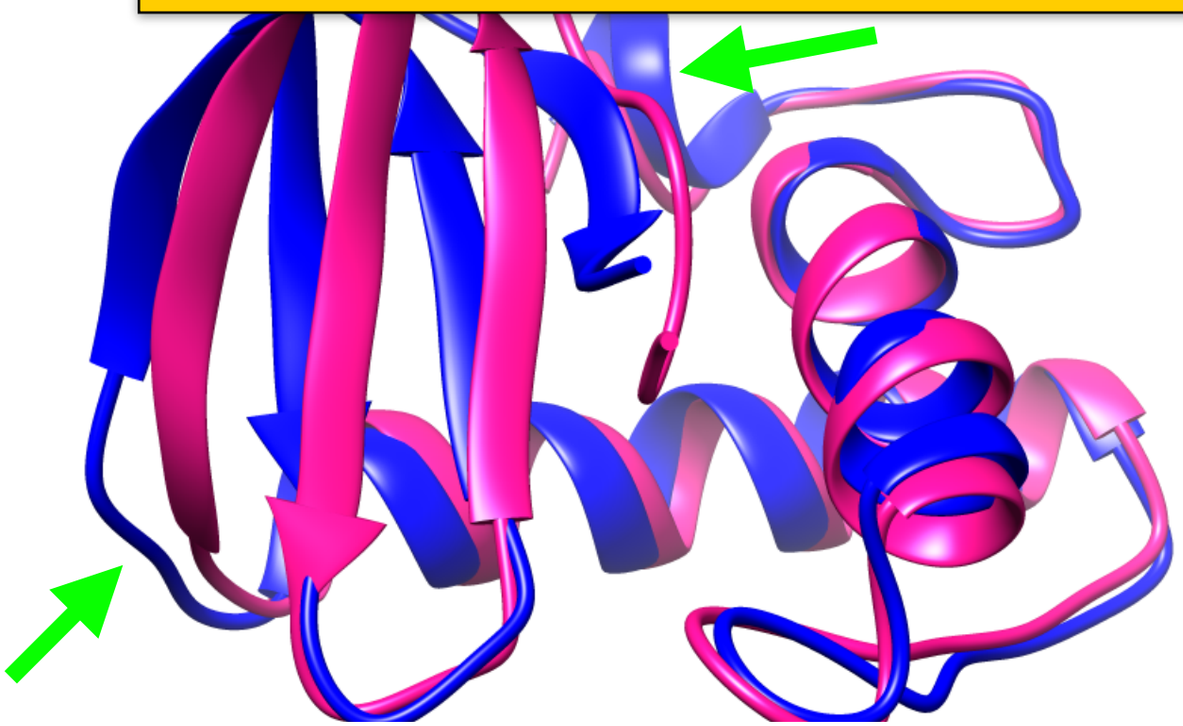


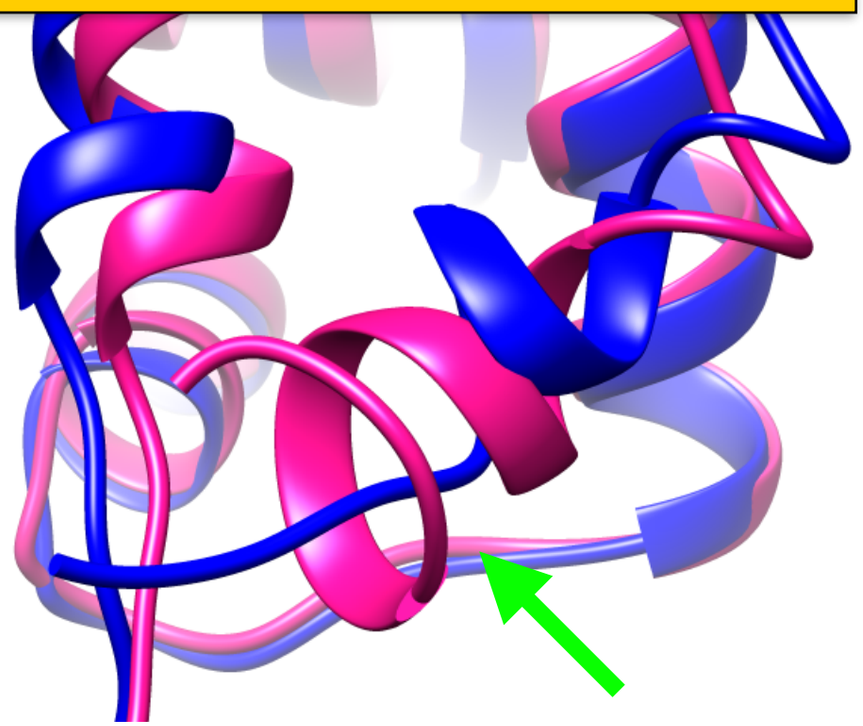
R0974s1
GDT-HA: 65.6 → 89.5 (+23.9)
RMSD: 2.2 Å → 0.8 Å (-1.4 Å)

What are improved?

Magenta: Initial
Blue: Refined

Secondary structure rearrangement
Partial folding/unfolding of structure elements



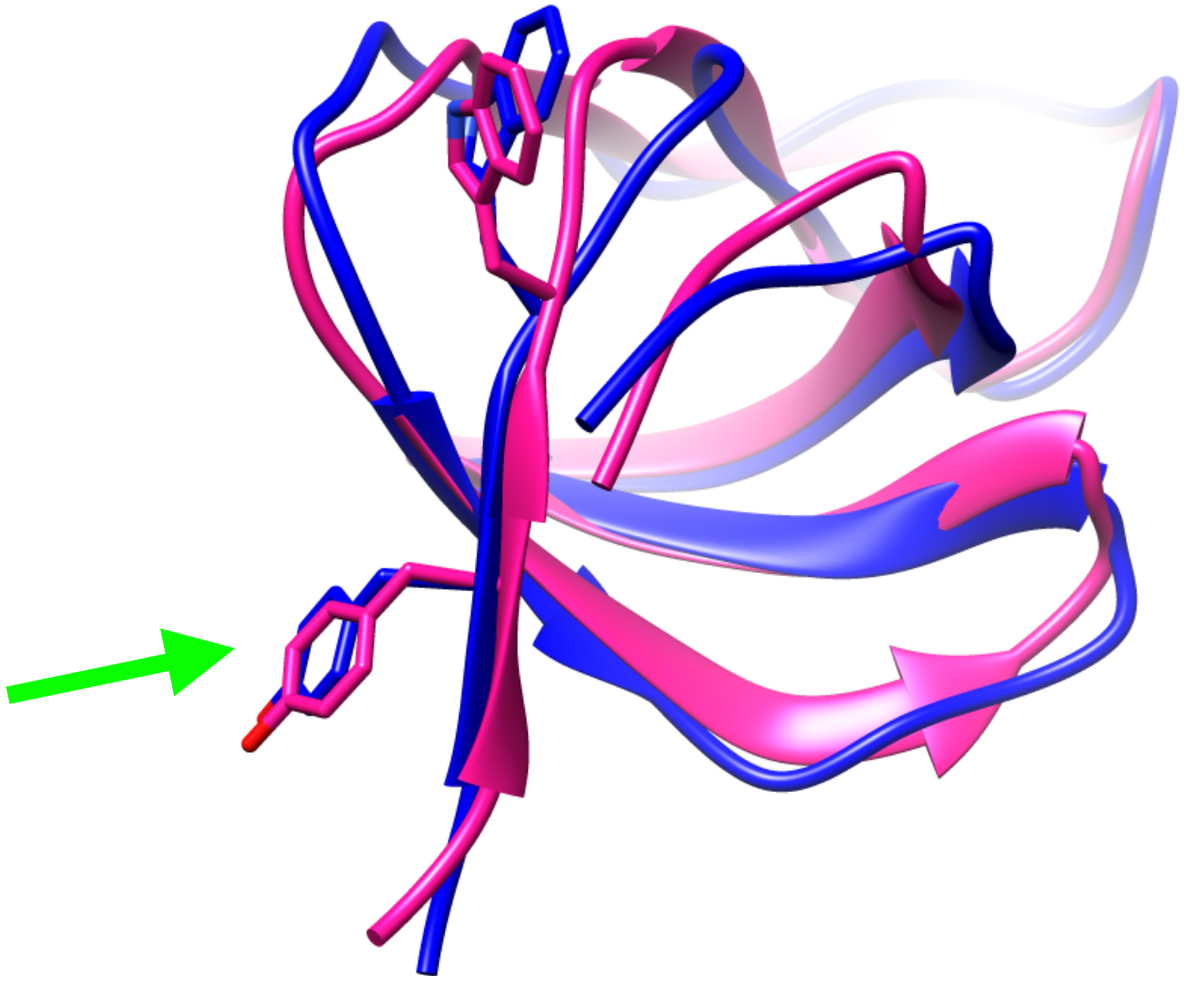


R0986s1
GDT-HA: 59.2 → 78.5 (+19.3)
RMSD: 1.8 Å → 1.0 Å (-0.8 Å)

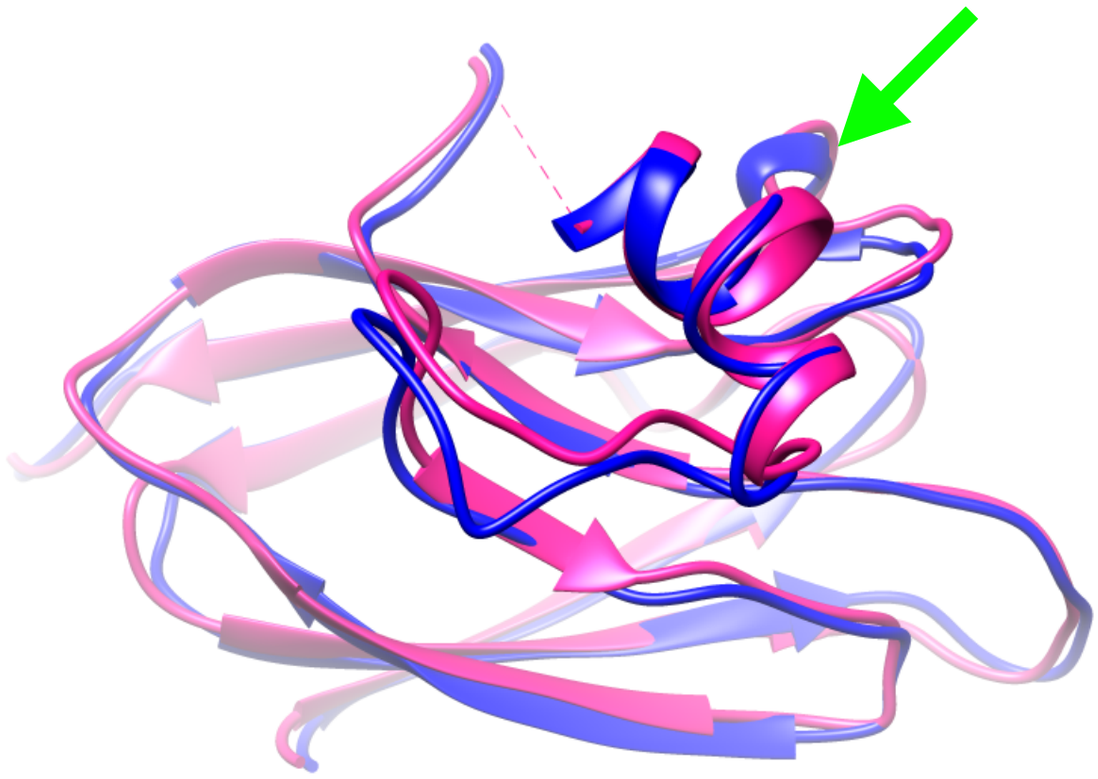
R0974s1
GDT-HA: 65.6 → 89.5 (+23.9)
RMSD: 2.2 Å → 0.8 Å (-1.4 Å)

What went wrong?

Magenta: Initial
Blue: Refined



R1002-D2
GDT-HA: 72.9 → 59.8 (-13.1)
RMSD: 1.9 Å → 2.3 Å (+0.4 Å)

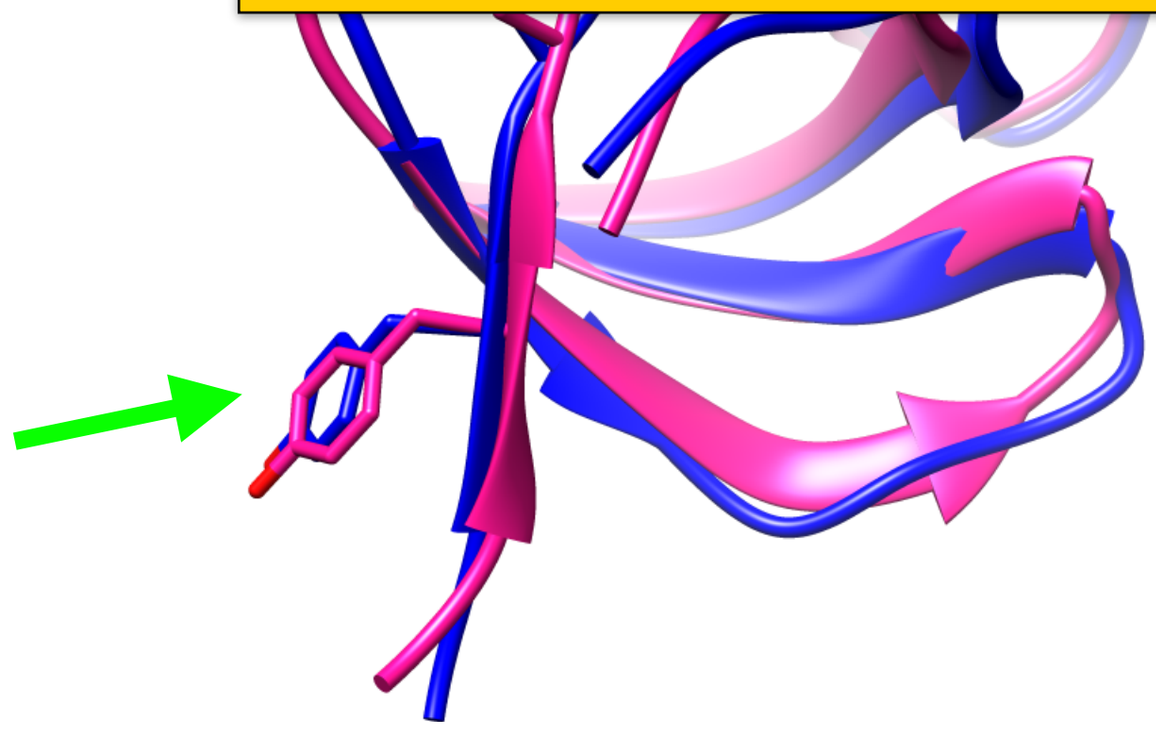


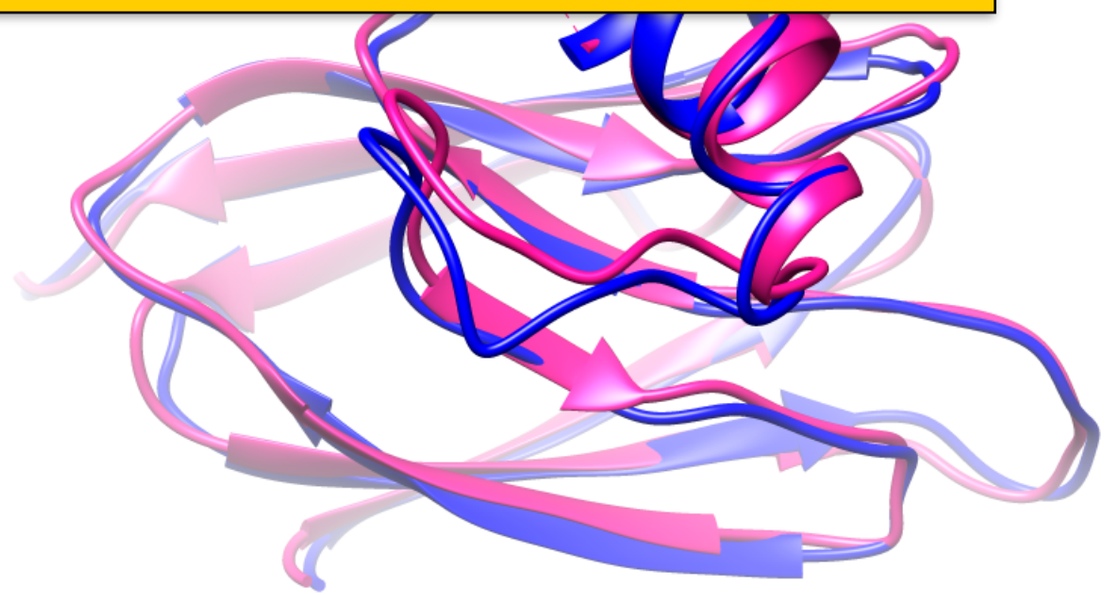
R0949
GDT-HA: 49.0 → 45.5 (-3.5)
RMSD: 7.0 Å → 7.1 Å (+0.1 Å)

What went wrong?

Magenta: Initial
Blue: Refined

Incorrect sequence alignment
Too far from the native structure





R1002-D2
GDT-HA: 72.9 → 59.8 (-13.1)
RMSD: 1.9 Å → 2.3 Å (+0.4 Å)

R0949
GDT-HA: 49.0 → 45.5 (-3.5)
RMSD: 7.0 Å → 7.1 Å (+0.1 Å)

Summary

- Purely **physics**-based method

- Successes
  - **Smaller** targets via **iterative** MD sampling
  - **Partial folding, unfolding, and rearrangement** allowed by **flat-bottom** harmonic restraints
- Failures
  - **Incorrect topology** (fixing sequence alignment errors) because of **insufficient** sampling

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