Protein Model Refinement via Molecular Dynamics Simulations with Improved Sampling Protocols

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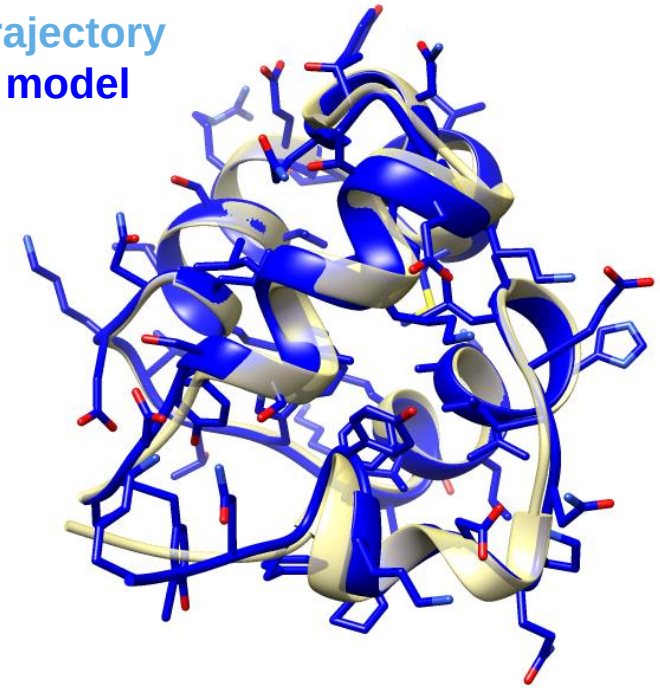
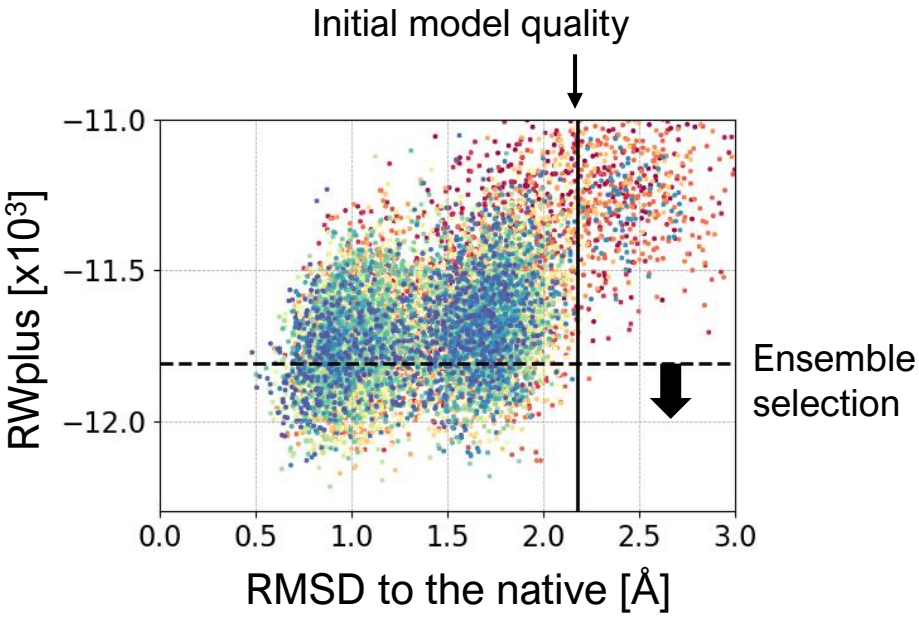
MD simulation and refinement

Native
Initial model
MD trajectory
Final model



Conformational sampling via MD simulations

Progress of sampling



Selecting ensemble of sample structures and averaging selected structures

CASP14 protocol (1)

- **FEIG-S: fully automated** refinement server

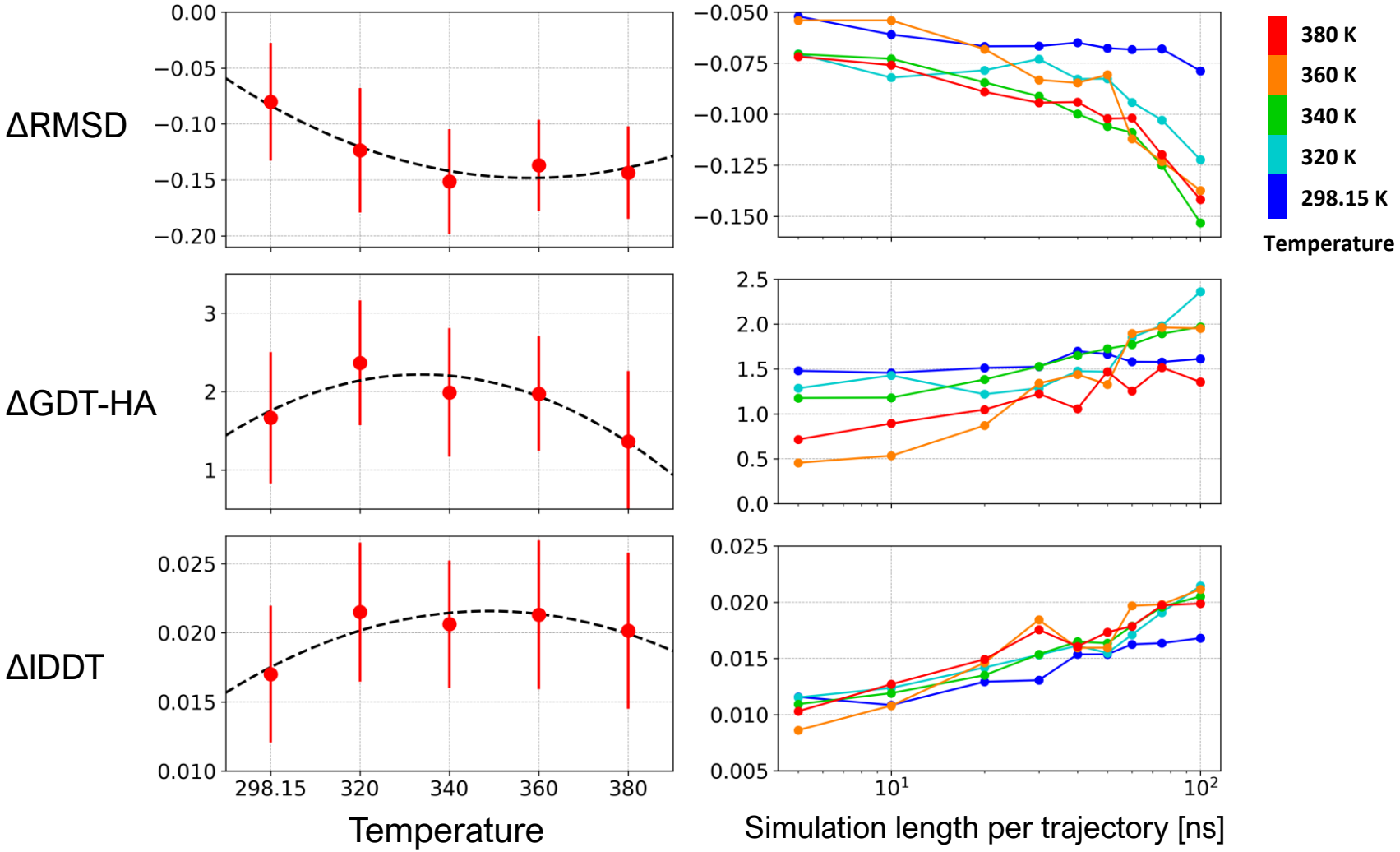
- Structure sampling via MD simulations
  - **Flat-bottom** harmonic restraints:
    Cartesian coordinates of Cα and **distance** between Cαs

$$E_{\text{Combined}}(\lambda) = \lambda \sum_{i} E_{\text{Cartesian}}\left(\mathbf{r}_i ; \mathbf{r}_i^{\text{o}}\right) + (1-\lambda) \sum_{j-i>3} E_{\text{Distance}}\left(d_{ij} ; d_{ij}^{\text{o}}\right)$$

  - Simulations at a **higher temperature**, 360 K
  - **CHARMM36m** with modifications
    - Lower backbone dihedral angle energy barriers
    - Hydrogen-mass repartitioning (heavier hydrogens) → 4 fs/MD step
  - 500 ns/model (= 5 trajectories x 100 ns)
    (16 GPU hours on RTX2080Ti for R1056 (169 residues))
    (c.f. 2.25 μs/model for CASP13 protocol)

* Heo, L. *et al.*, Improved sampling strategies for protein model refinement based on molecular dynamics simulation, *ChemRxiv* (**2020**).

Refinement at higher temperature



*** CASP10 refinement targets**

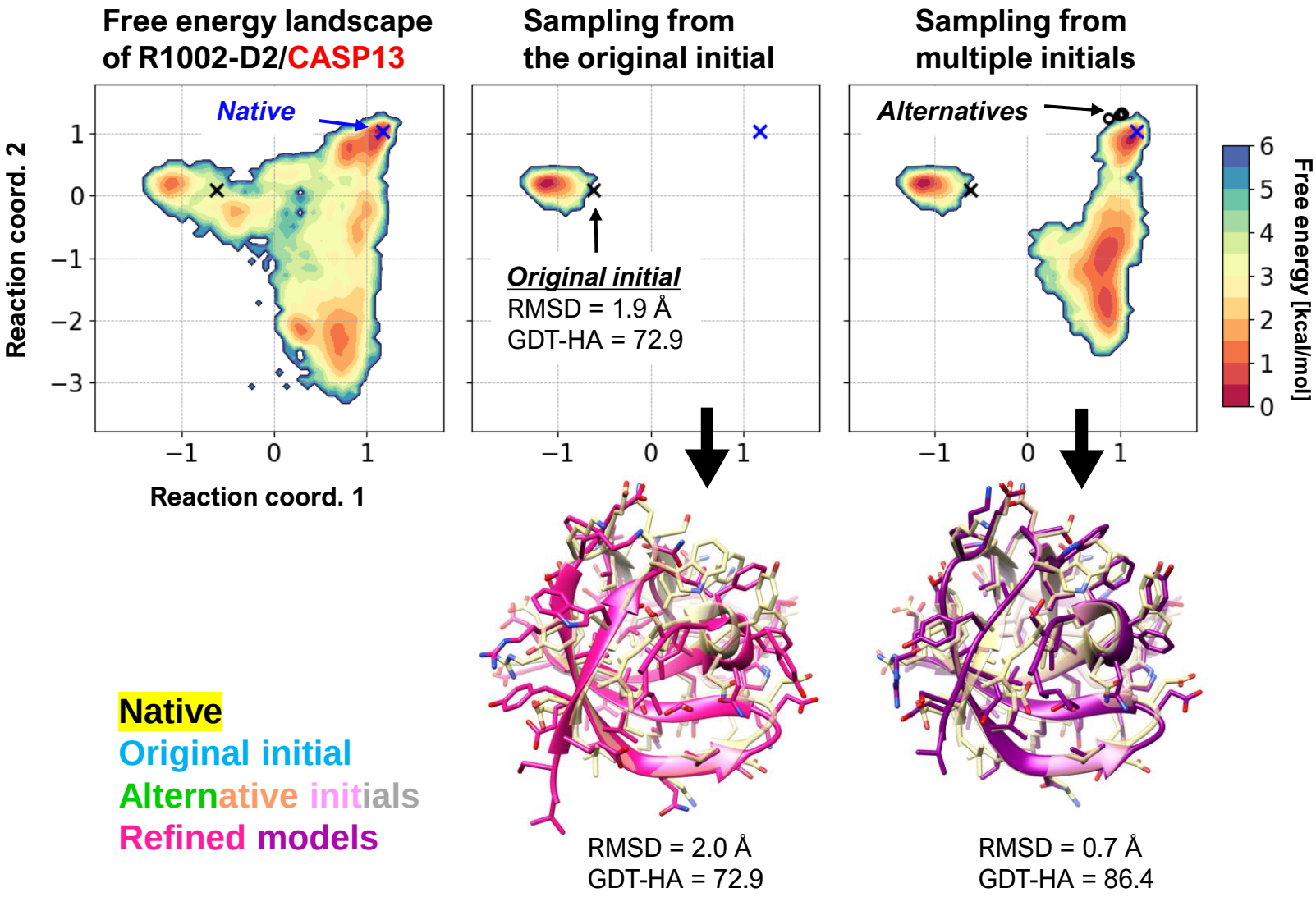
CASP14 protocol (2)

- Use of **multiple initial** models (6 targets)
  - Structure diversification prior to MD sampling to generate **kinetically favored** initial models
  - Simple **TBM** using sequence & structural similarity, further optimization by simplified Rosetta Iterative Hybridize

  - 5 initial models: **original initial** model + **4 alternatives**
  - 500 ns/model → 2.5 μs/target

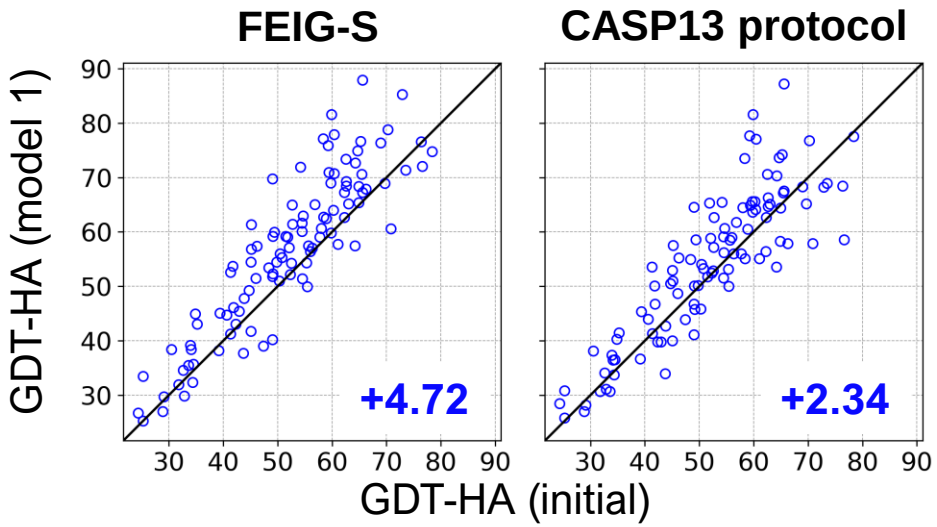
- **FEIG**
  - Hybridizing alternative submitted models from the same server group of the initial model
    - i.e., tFold-IDT model 1,4,5 were hybridized with the initial model of R1091-D2, tFold-IDT model 3

Refinement with multiple initials

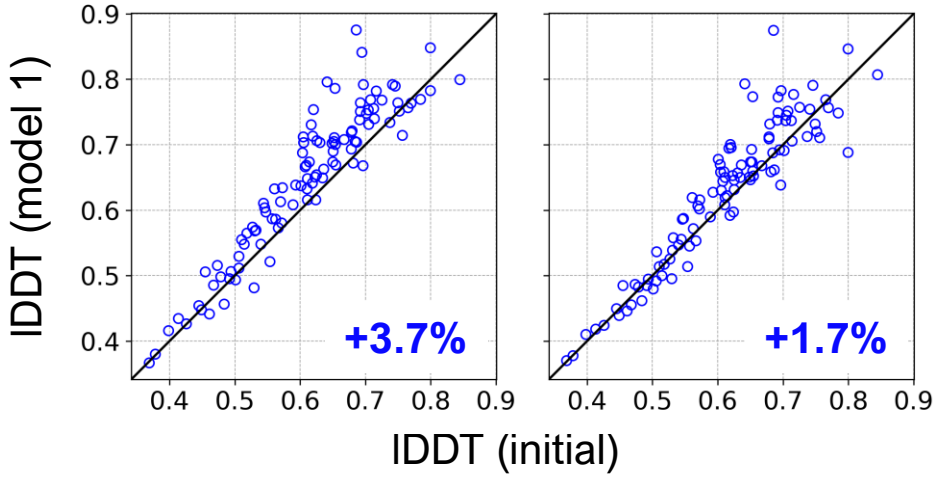


Progress? benchmark results

*** CASP11-13 refinement targets**



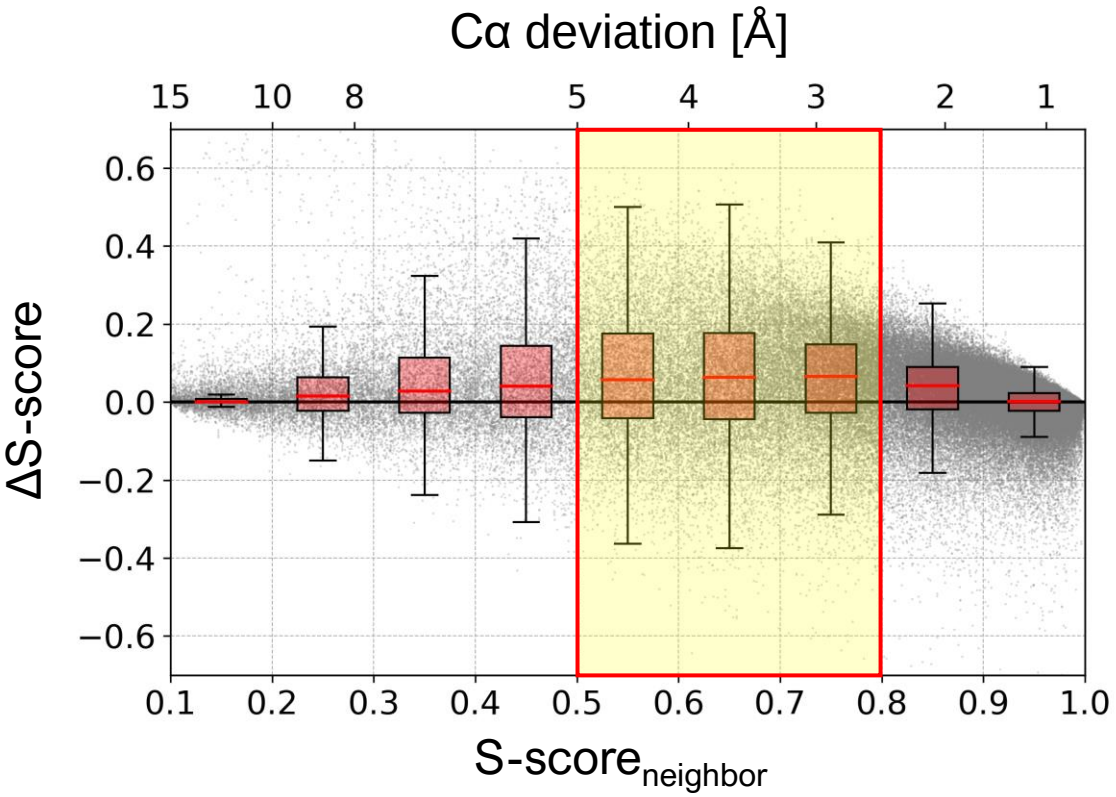
CASP12 protocol: +2.34



CASP12 protocol: +1.5%

Where is refinement possible?

*** CASP11-13 refinement targets**

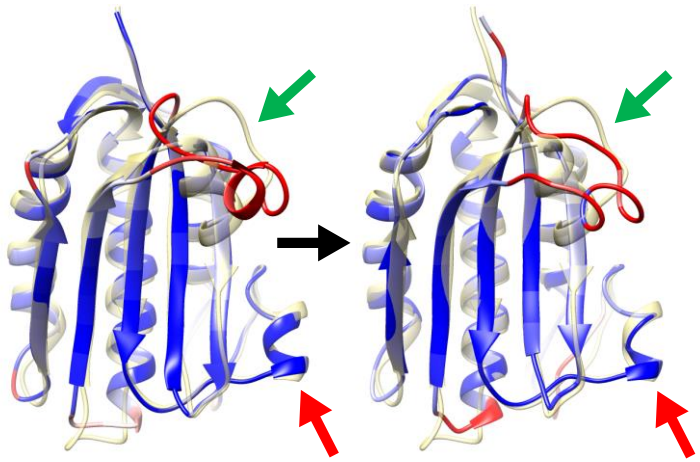


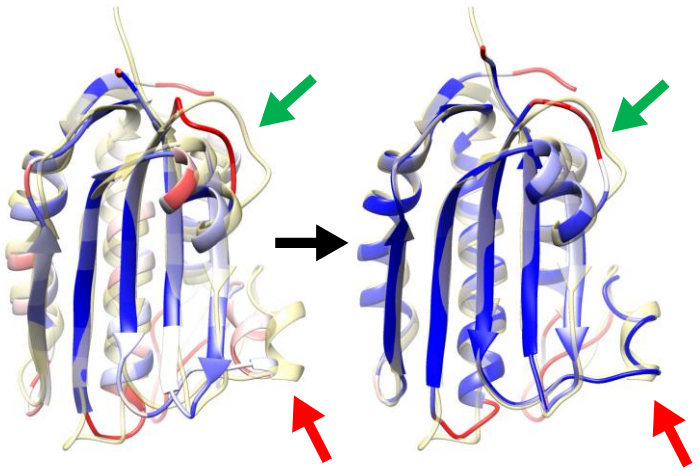
$$\text{S-score} = \frac{1}{\left(1+(d/5\,\text{Å})^2\right)}$$

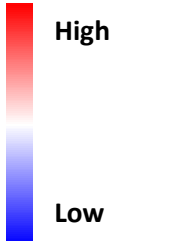
$$\text{S-score}_{\text{neighbor}}(r) = \frac{\sum_s w(s)\ \text{S-score}(r+s)}{\sum_s w(s)}$$

$$w(s) = e^{-(s/s_0)^2/2}$$

Example of more refinable model

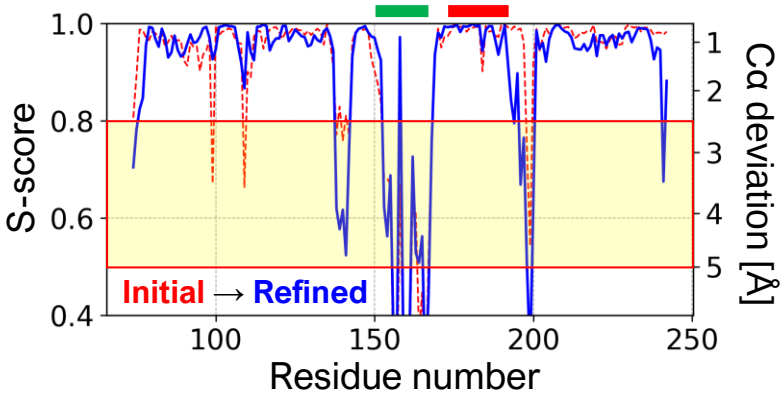


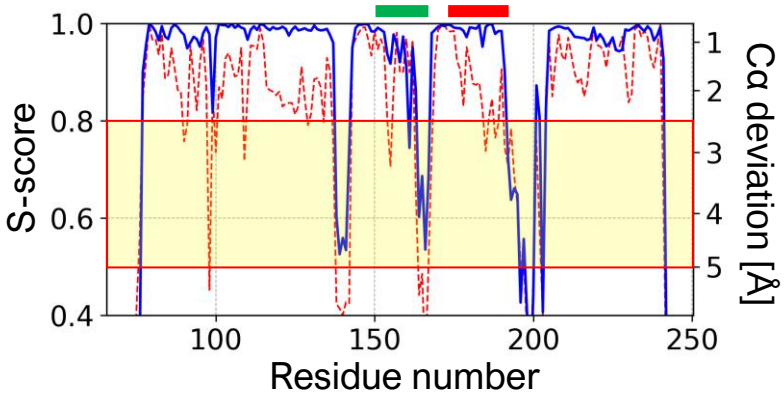




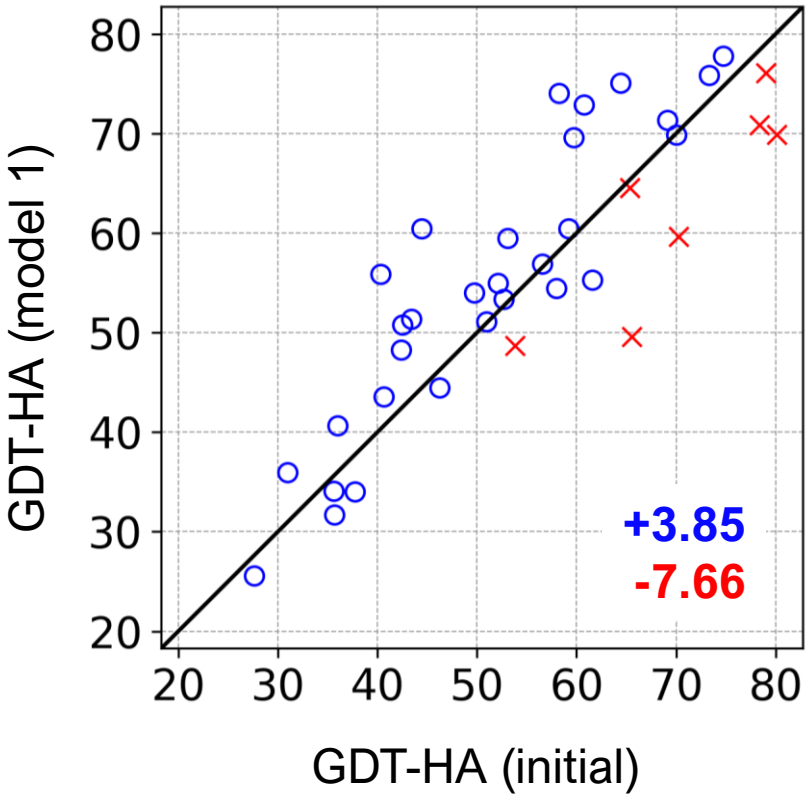
TR893 (original)
GDT-HA = 69.7 → 66.3 (-3.4)
lDDT = 0.737 → 0.719 (-0.018)

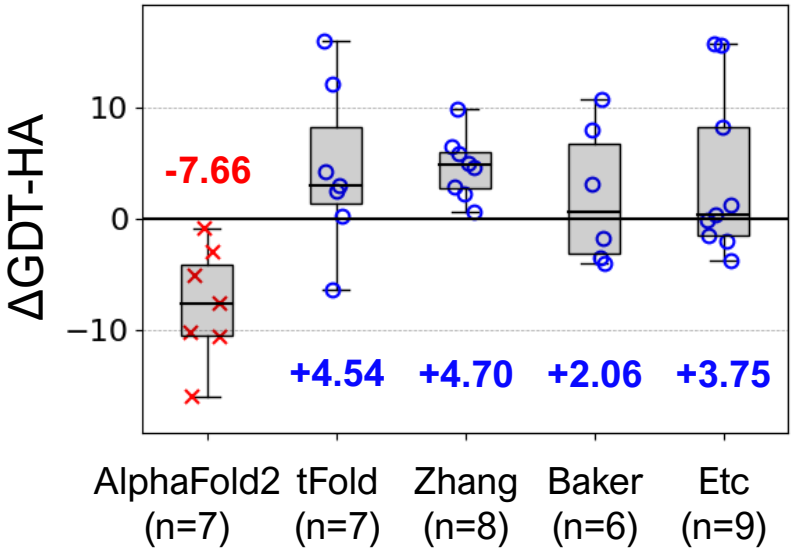
TR893 (alternative)
GDT-HA = 49.3 → **73.7** (+24.4 / **+4.0**)
lDDT = 0.681 → **0.777** (+0.096 / **+0.040**)





FEIG-S: CASP14 results

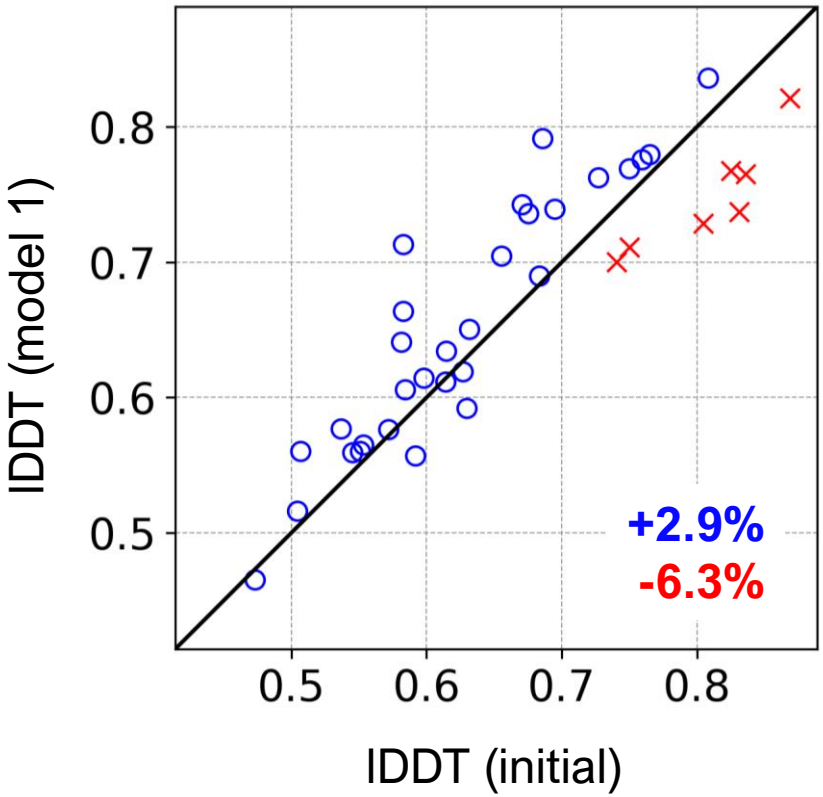


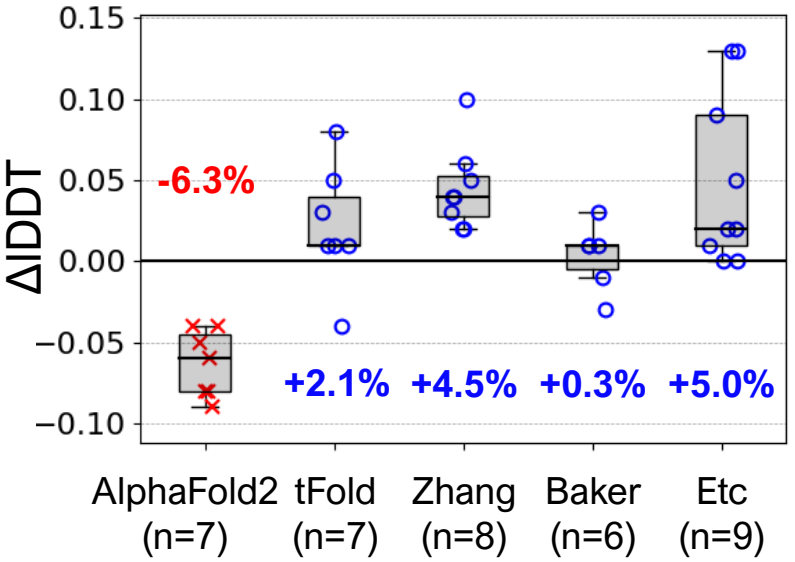


CASP13 protocol: +1.70 / -5.89
CASP12 protocol: +1.39 / -0.53

Targets
originated from AlphaFold2 (7 domains)
originated from other groups (30 domains)

FEIG-S: CASP14 results

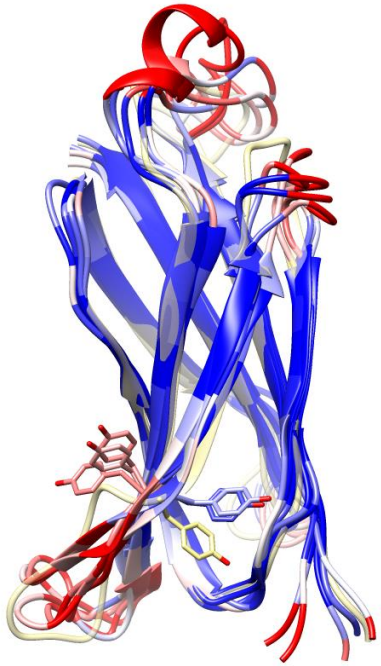


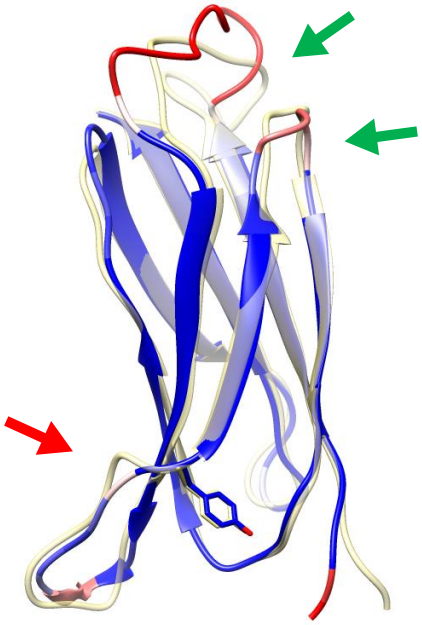


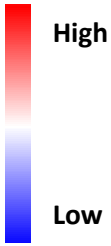
CASP13 protocol: +1.1% / -5.5%
CASP12 protocol: +0.6% / -3.3%

Targets
originated from AlphaFold2 (7 domains)
originated from other groups (30 domains)

What was improved?



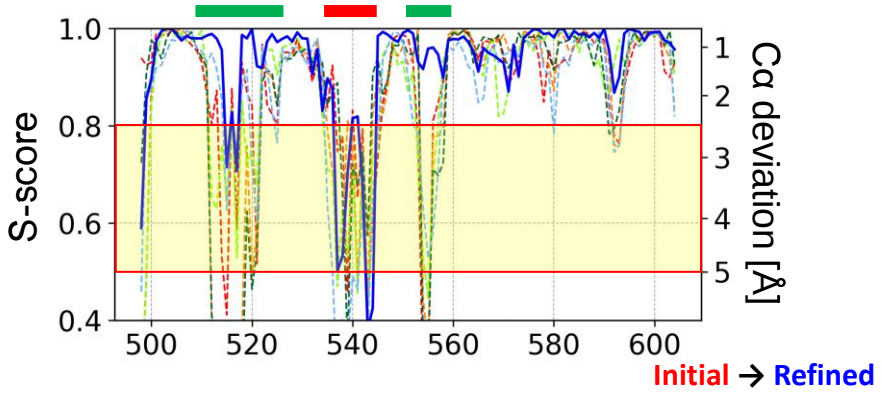




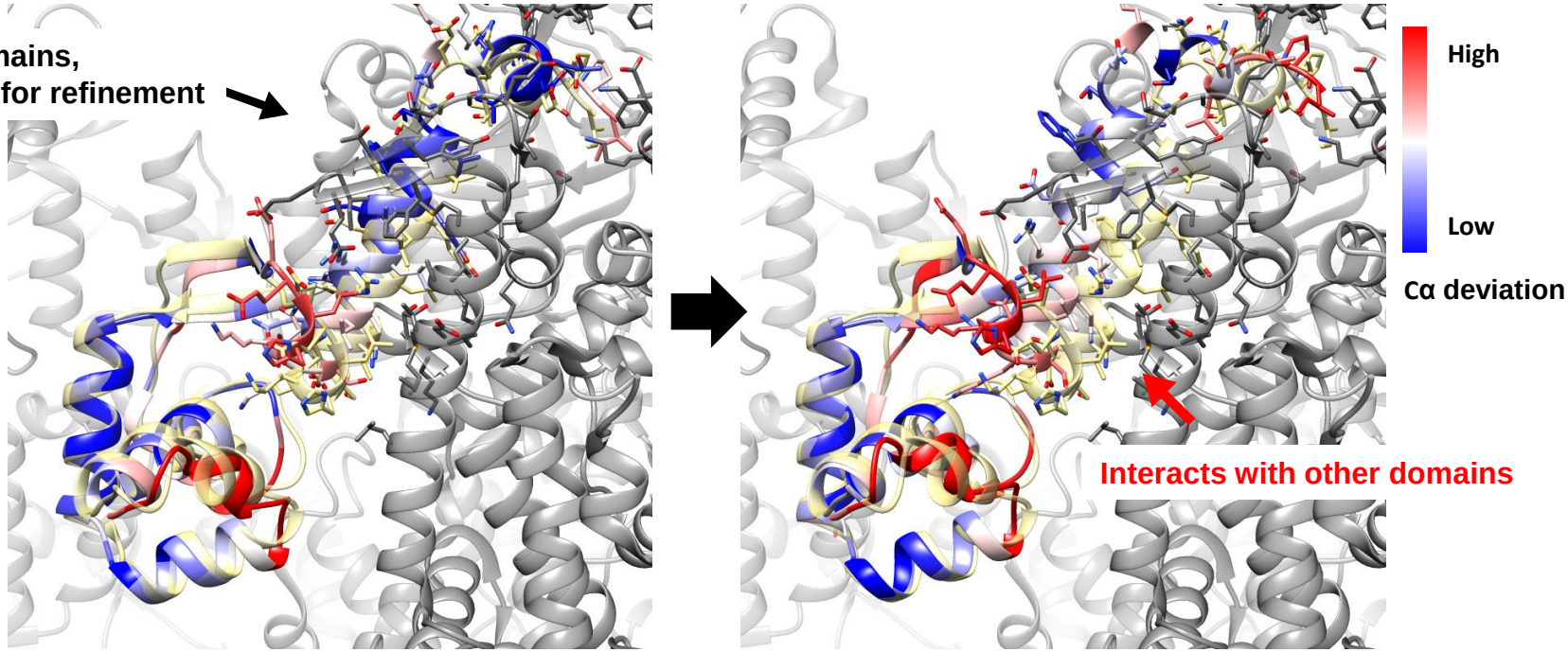
R1091-D2 (tFold-IDT)

GDT-HA = 60.8 → 76.9 (+16.1)

lDDT = 0.695 → 0.760 (+0.065)



What went wrong?



R1040v1 (AlphaFold2)

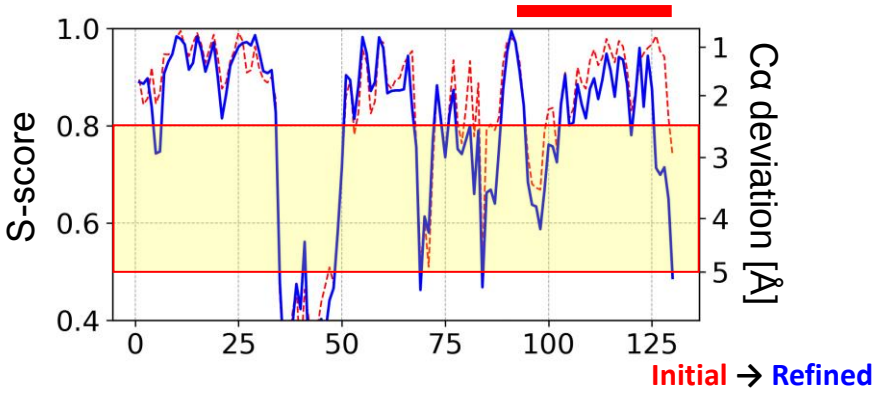
GDT-HA = 53.9 → 48.7 (-5.2)

lDDT = 0.741 → 0.700 (-0.041)

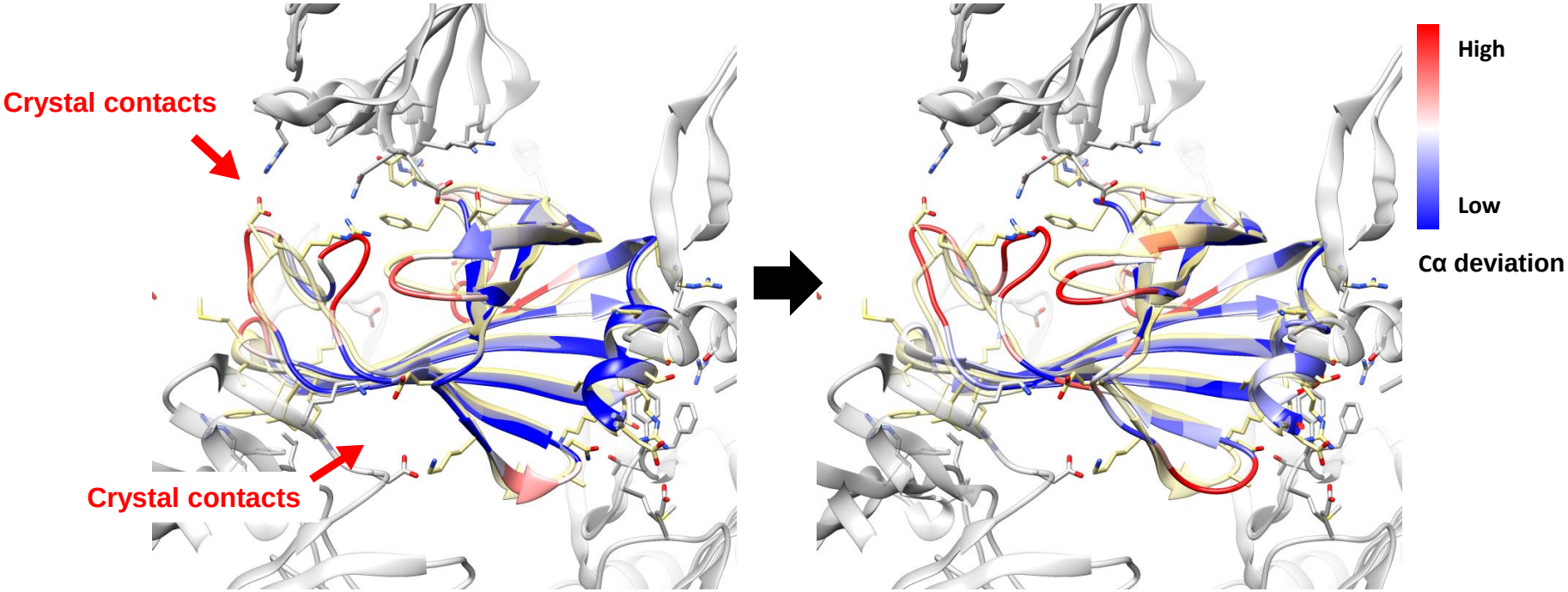
For non-interfacial residues

GDT-HA = 67.0 → 68.3 (+1.3)

lDDT = 0.713 → 0.711 (-0.002)



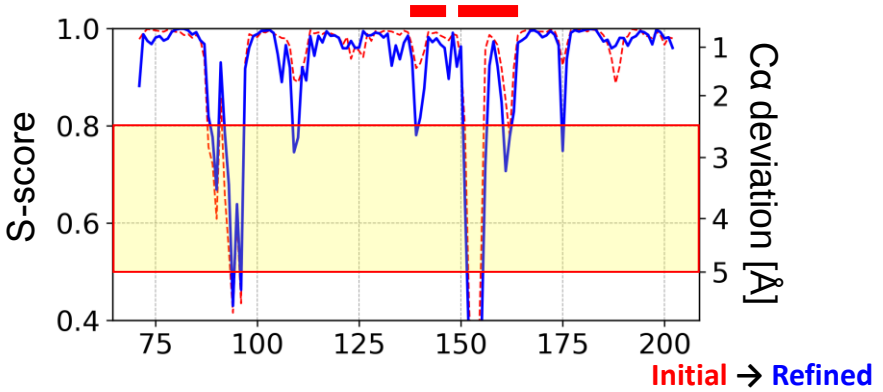
What went wrong?



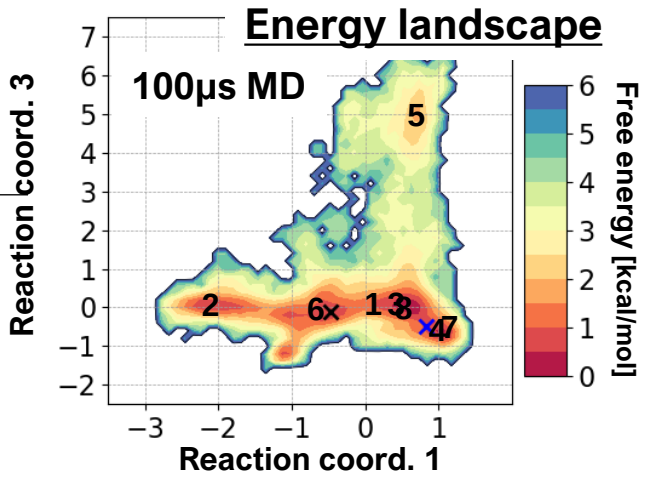
R1074v1 (AlphaFold2)

GDT-HA = 78.4 → 70.8 (-7.6)

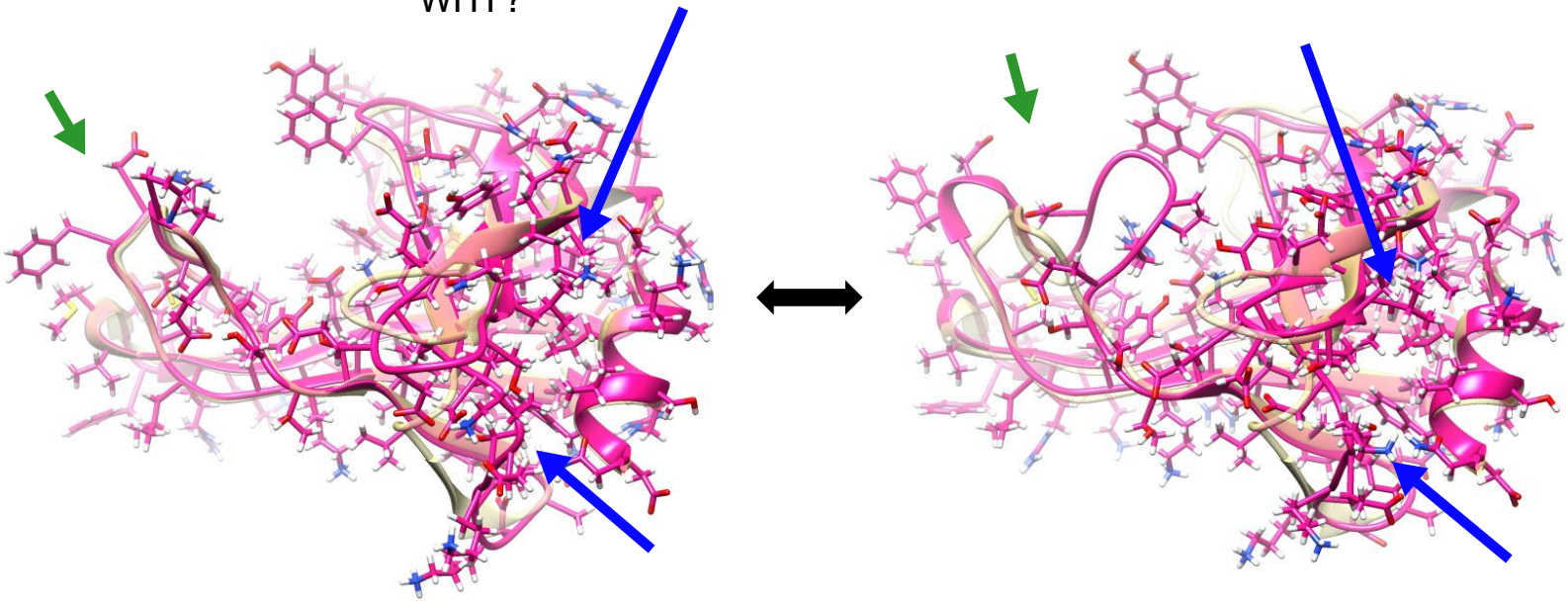
lDDT = 0.836 → 0.765 (-0.071)



What went wrong?



Many exposed **hydrophobic** residues.
WHY?



Crystal structure-like state

FE = 0.5 kcal/mol
GDT-HA = 82
RMSD = 1.4 Å

AlphaFold model-like state

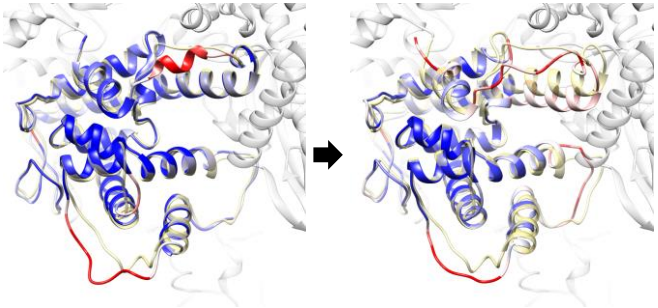
FE = 0.0 kcal/mol
GDT-HA = 74
RMSD = 2.5 Å

What went wrong?

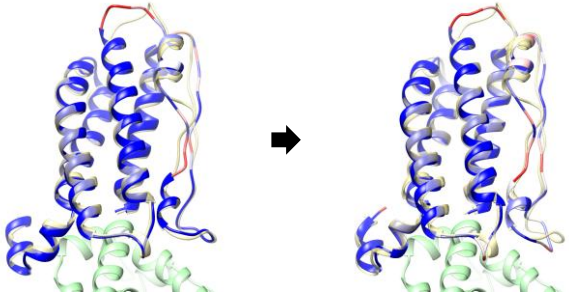
Domain-domain interactions

R1042v2 (AlphaFold2): 65.6 → 49.6 (**-16.0**)

R1041v1 (AlphaFold2): 70.3 → 59.6 (**-10.7**)



R1053v2 (AlphaFold2): 80.1 → 69.9 (**-10.2**)



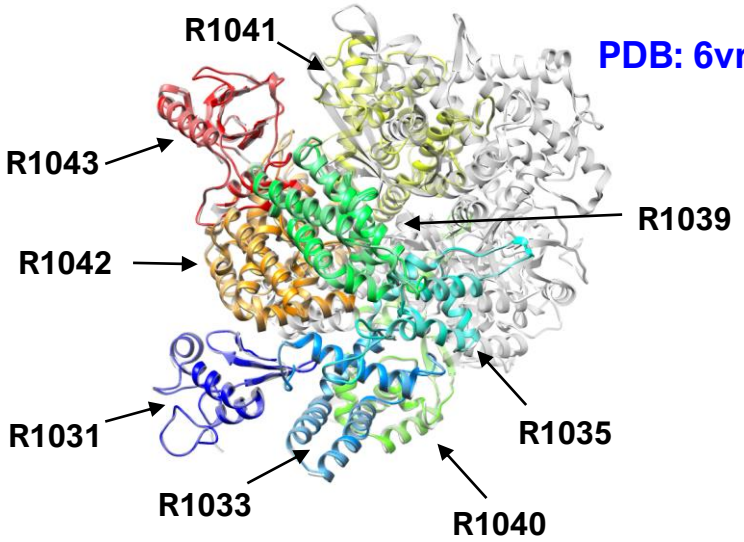
R1045s2 (tFold): 61.6 → 55.3 (**-6.3**)

R1040v1 (AlphaFold2): 53.9 → 48.7 (**-5.2**)

R1042v1 (BAKER-exp): 35.7 → 31.7 (**-4.0**)

R1033 (E2E): 37.8 → 34.0 (**-3.8**)

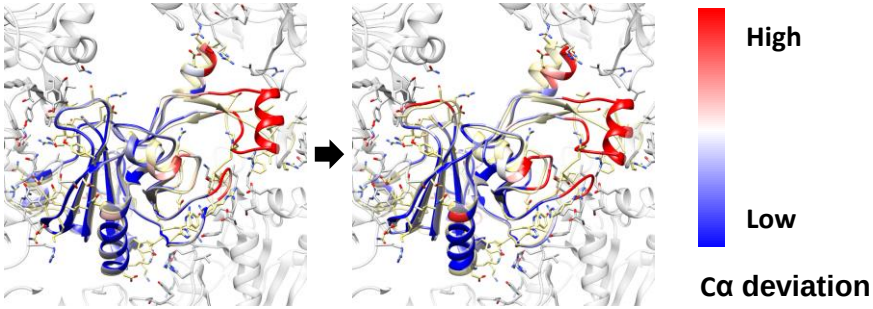
*** GDT-HA changes via refinement (FEIG-S) are shown.**



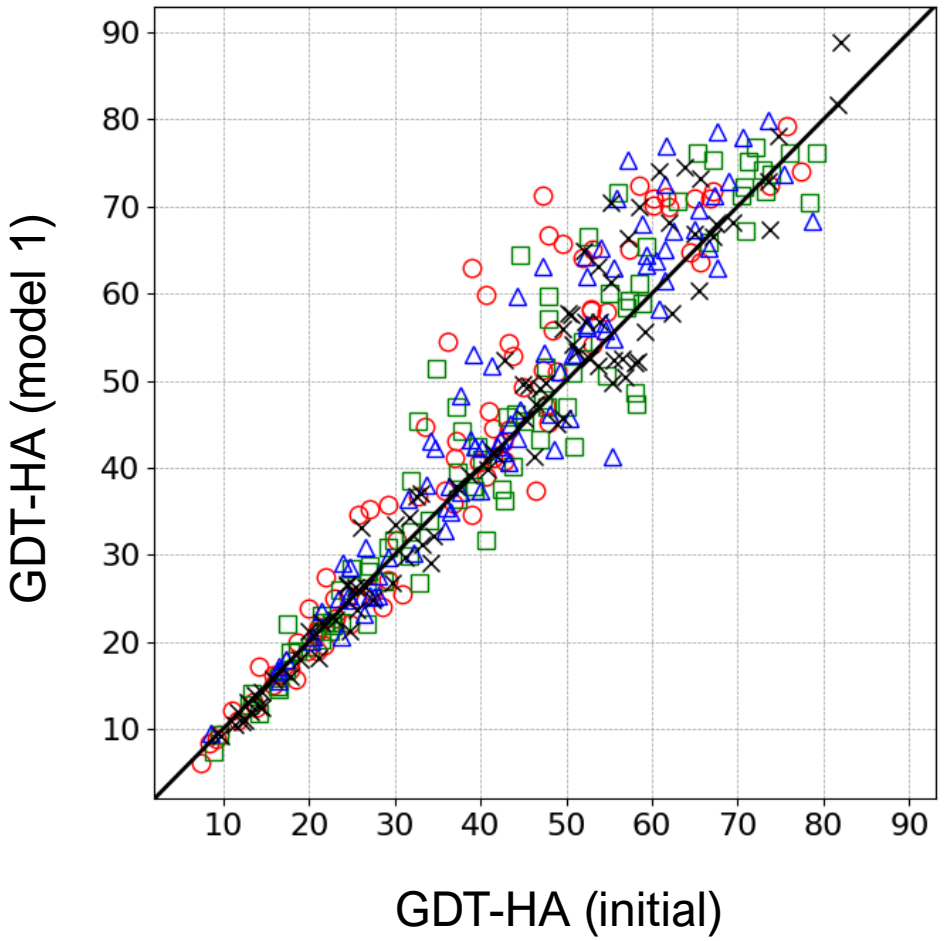
Crystal contacts

R1074v1 (AlphaFold2): 78.4 → 70.8 (**-7.6**)

R1067v2 (AlphaFold2): 79.1 → 76.0 (**-3.1**)



Refinement in the era of ML



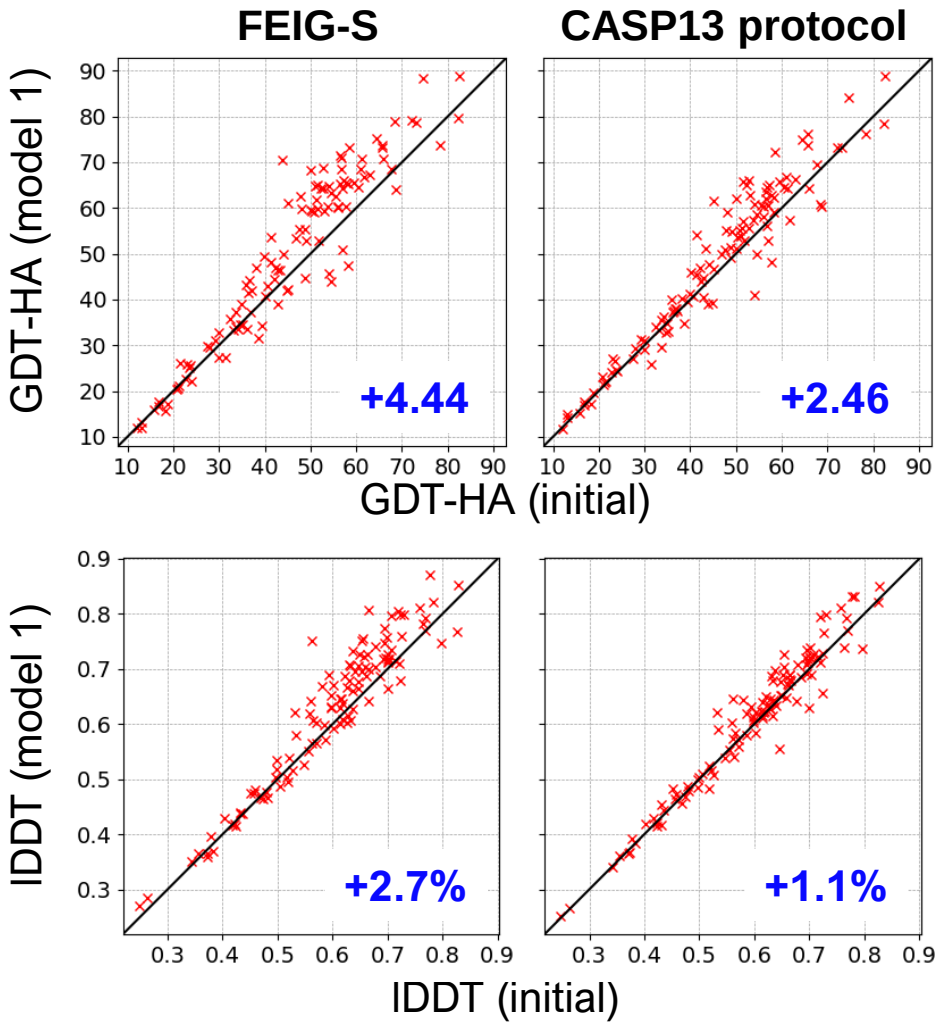
FEIG-S (trRosetta+TBM):
37.2 → **40.6 (+3.4)**

FEIG-R1 (RaptorX model 1):
41.9 → **43.1 (+1.2)**

FEIG-R2 (Zhang-s model 1):
44.5 → **47.2 (+2.8)**

FEIG-R3 (Baker-s model 1):
42.2 → **43.3 (+1.1)**

Refinement of CASP13 AlphaFold models



CASP12 protocol: +1.38

CASP12 protocol: +0.5%

* Heo, L. and Feig, M., High-accuracy protein structures by combining machine-learning with physics-based refinement, *Proteins* (**2020**).

Summary

- We improved sampling procedure for refinement
  - Optimized MD simulation procedure
  - Used multiple initial models

- Successes
  - Roughly correct residues could be improved
- Limitations
  - Errors with significant energy barrier could not be fixed
- Failures
  - Occasionally missing inter-domain/protein contacts made models worse

Acknowledgements

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MICHIGAN STATE UNIVERSITY

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- NIH funding (R35 GM126948)
- XSEDE computing resources (TG-MCB09003)