Fitting CASP Models to NMR Data

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Can We Fit Computational Models into NMR Data?

Inverse Structure Determination

(Make a Model -> Validate/Refine Against Data)

GT Montelione
CASP14 Dec 3, 2020

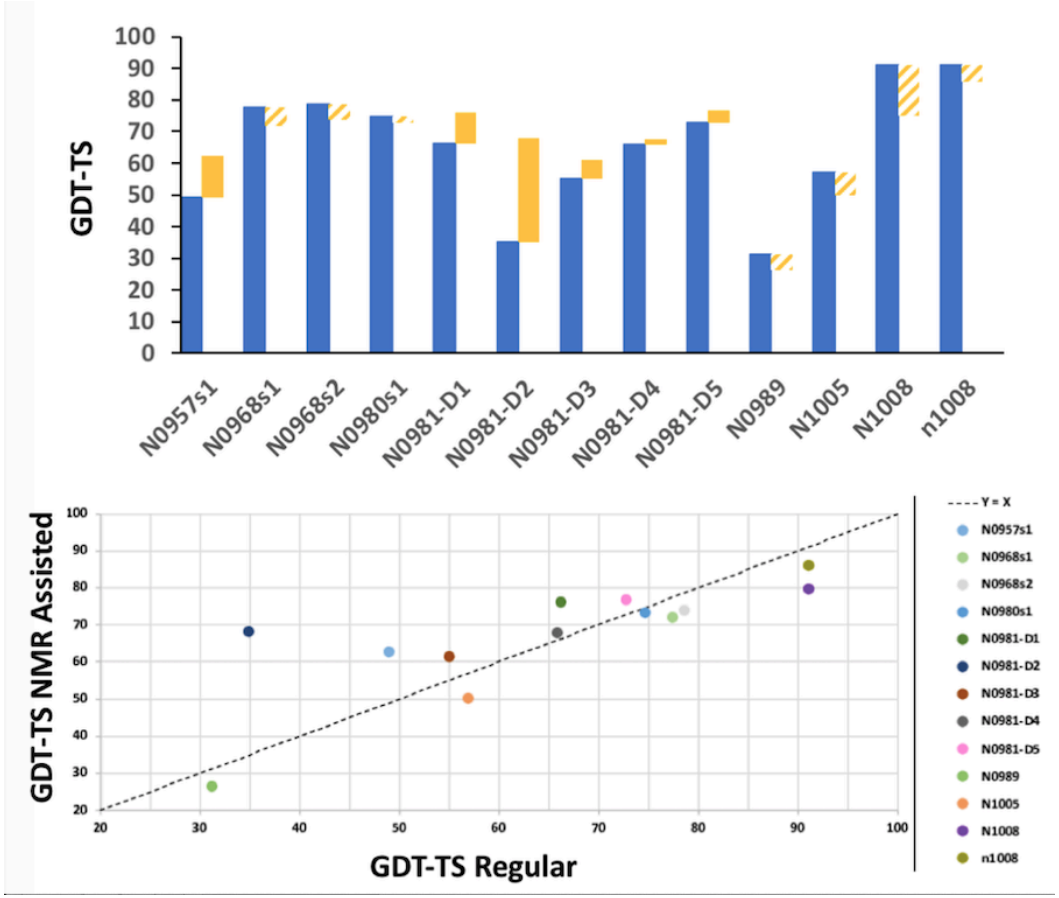
CASP13 – NMR-Guided Modeling
Sparse NMR Data -
Perdeuterated Proteins

11 simulated NMR data sets
2 real NMR data sets

For 6 targets – NMR-guided better than regular prediction

For 7 targets – Best Regular Prediction better than NMR-assisted !!

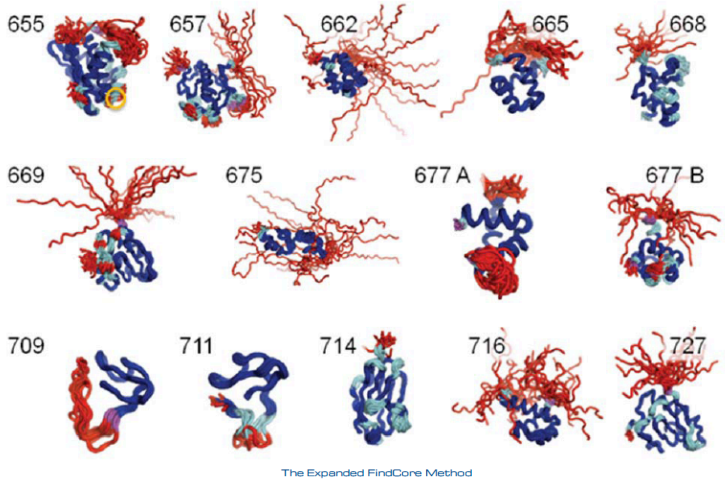
Suggests potential of using Best Regular Prediction to guide NMR structure determination – for difficult targets.



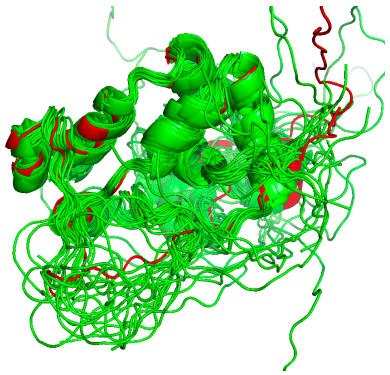
Sala, Huang, et al. PROTEINS 2019

Well- Defined vs Not-well-Defined Regions of NMR Models

Proteins are often more flexible in solution (or in cryoEM ‘glass’) than in the crystal lattice



The Expanded FindCore Method



T1027

FINDCORE2 PDB-Stat (distance variance matrix)

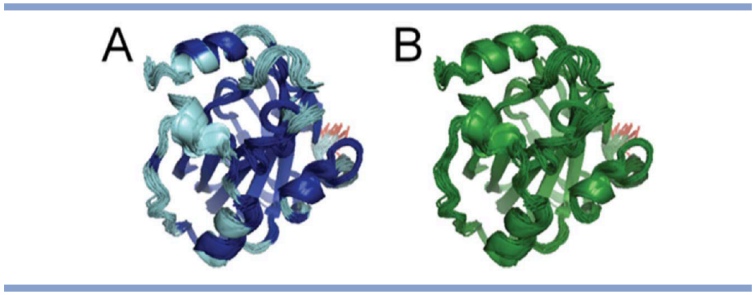


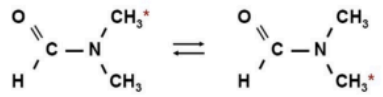
Figure 3

Comparison of FindCore, Expanded FindCore, and CYRANGE methods for identifying core atom sets. (A) FindCore (blue) and Expanded FindCore (cyan) regions of the human Raf-1 kinase inhibitor protein (PDB ID 2L7W). In this case, Expanded FindCore greatly expands upon the original core atom set identified by FindCore, only excluding the poorly converged N-terminal residue (red) from the core. (B) CYRANGE [2] produces a result similar to Expanded FindCore, except that CYRANGE defines its core (green) on a per-residue, rather than per-atom basis.

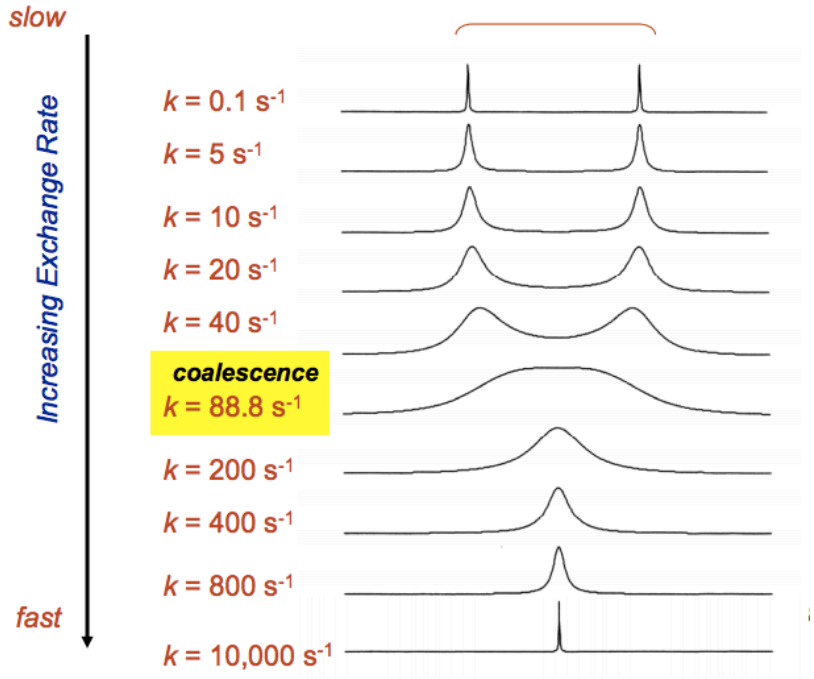
CYRANGE (backbone dihedral angle convergence)

Two-Site Exchange:
Rotation about a partial double bond in dimethylformamide

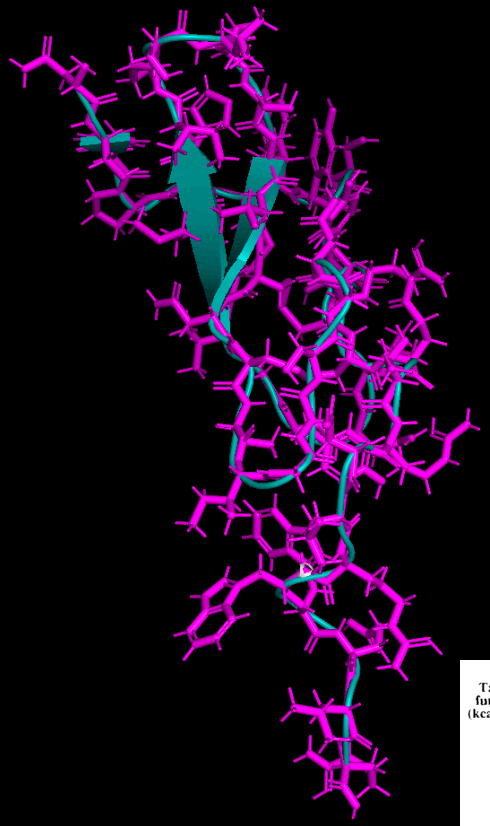
Equal Population of Exchange Sites

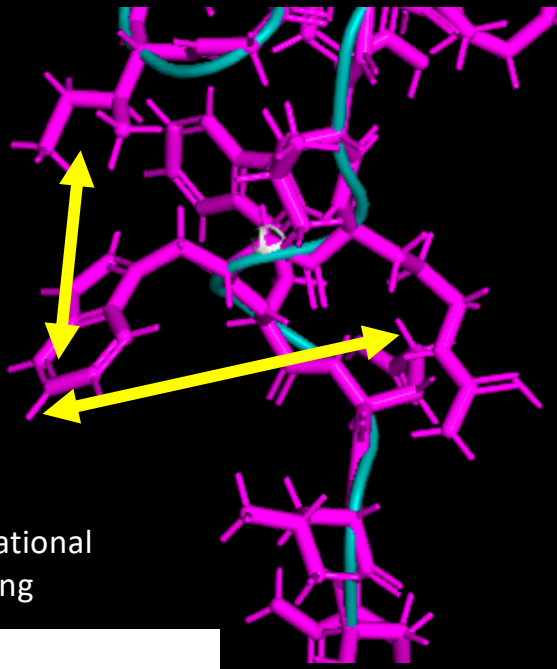


NMR is a powerful tool for studying relationships between protein dynamics and protein function.

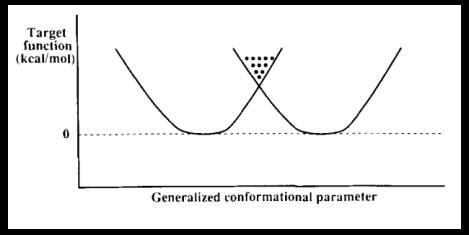


http://www.bioc.aecom.yu.edu/labs/girvlab/nmr/course





Conformational Pinning



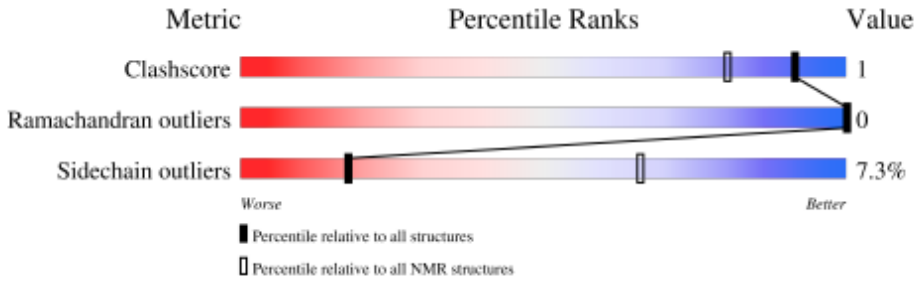
3EGF Montelione, G.T.; … Wüthrich, K.; Scheraga, H.A. Proc Natl Acad Sci 1987

Tejero, R.; Bassolino-Klimas, D.; Bruccoleri, R.E.; Montelione, G.T. **Protein Science** 1996

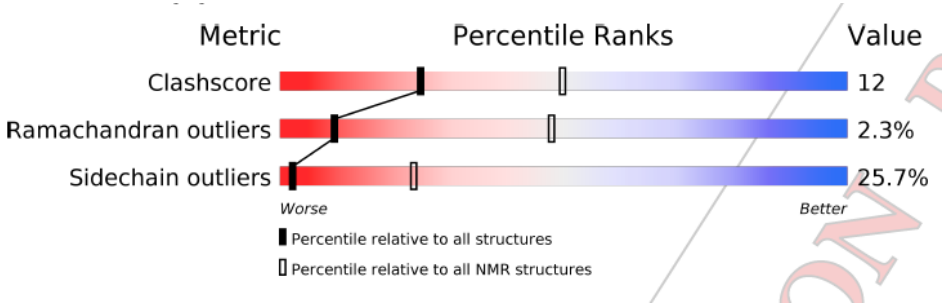
Knowledge-Based Validation for 3 CASP NMR Targets

PDB Structure Validation Server – Slider Bars

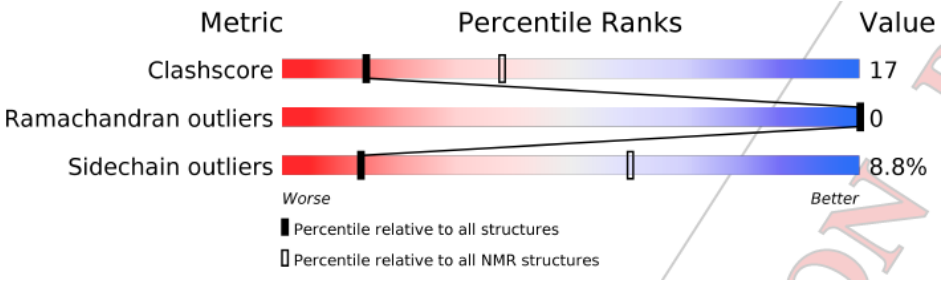
Great thanks to the labs who determined these structures and shared their NMR data !



T1029
N. Zhang
A. LiWang

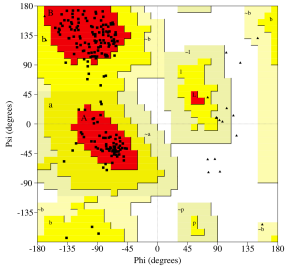


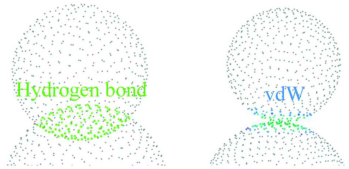
T1027
N. Kobayashi
Y. Kuroda

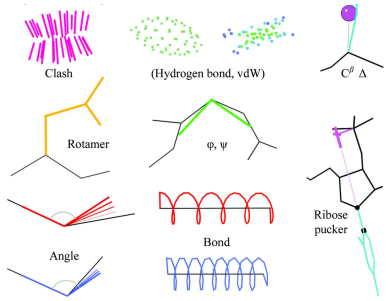


T1055
B. Bersch

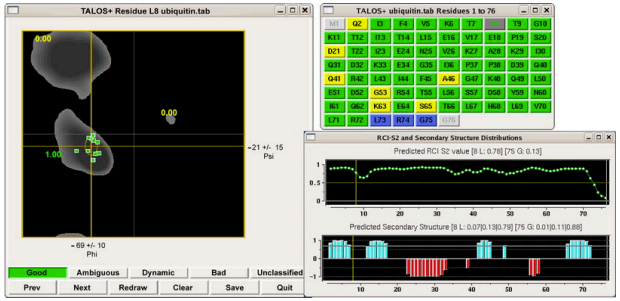
Knowledge-Based - Have I made something that looks like “a protein structure”?

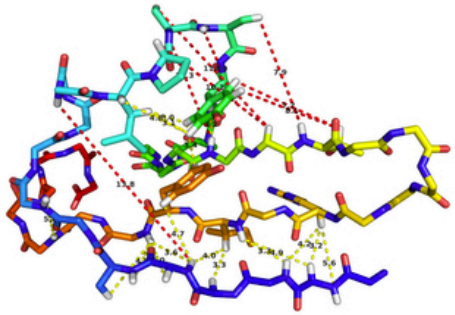






Model vs Data - Does the structure explain the experimental data?





Model vs Data Validation

NMR Restraint Analysis

Back Calculation of NOESY Peaks
(Relaxation Matrix, RPF-DP scores)

Back Calculation of Residual Dipolar Couplings

Back Calculation of Chemical Shifts

GT Montelione
CASP14 Dec 3, 2020

Model vs Data Validation

NMR Restraint Analysis

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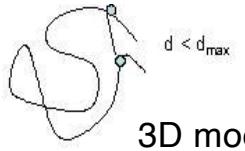
CASP14 Dec 3, 2020

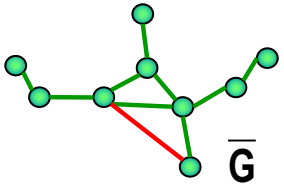
RPF-DP Scores



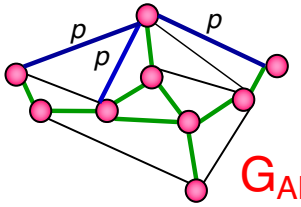
3D model

$$\text{Recall} = \frac{TP}{TP + FN} \qquad \text{Precision} = \frac{TP}{TP + FP}$$

$$F\text{-measure} = \frac{2 \times \text{Recall} \times \text{Precision}}{\text{Recall} + \text{Precision}}$$

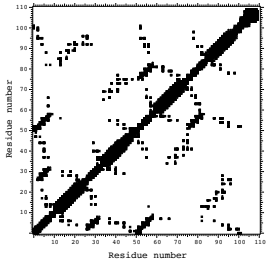


— TP
— FP
— FN
TN

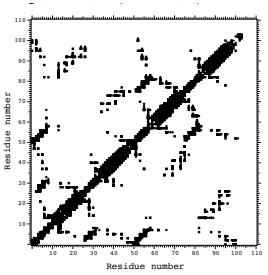


G_{ANOE}

← R and NOE

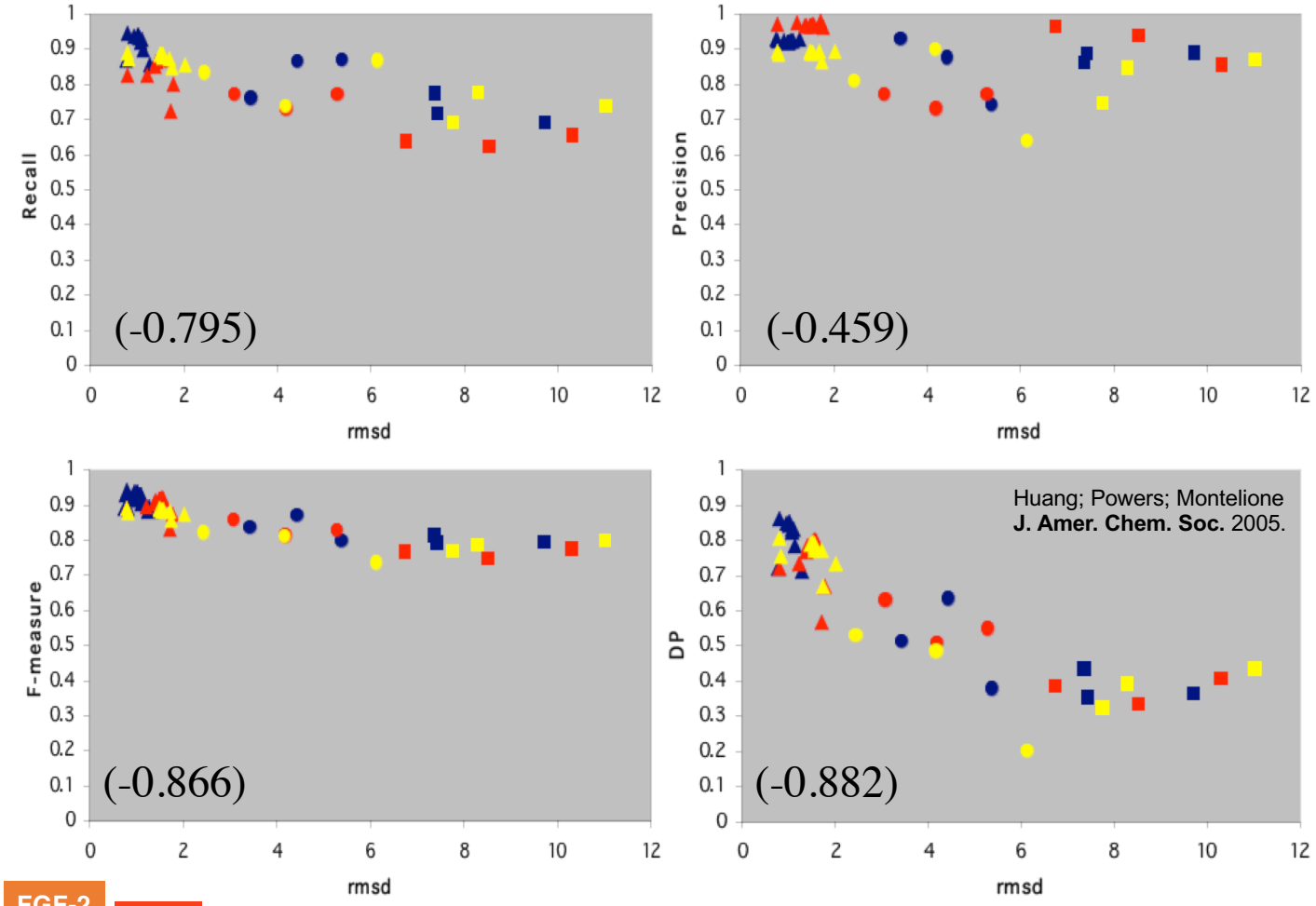


By comparing the differences between the two graphs $\overline{G}$ (derived from the structure) and G_{ANOE} (derived from the peaklists), a global measure of the goodness-of-fit of the query structures with the original peaklists can be formulated.



Similar to lDDT developed later by Schwede and coworkers

Huang, Y J ; Powers, R ; Montelione, G T **J. Amer. Chem. Soc.** 2005, 127: 1665.
Huang, Y J ; Rosato, A ; Singh, G ; Montelione, G T **Nucleic Acids Research** 2012, 40:542



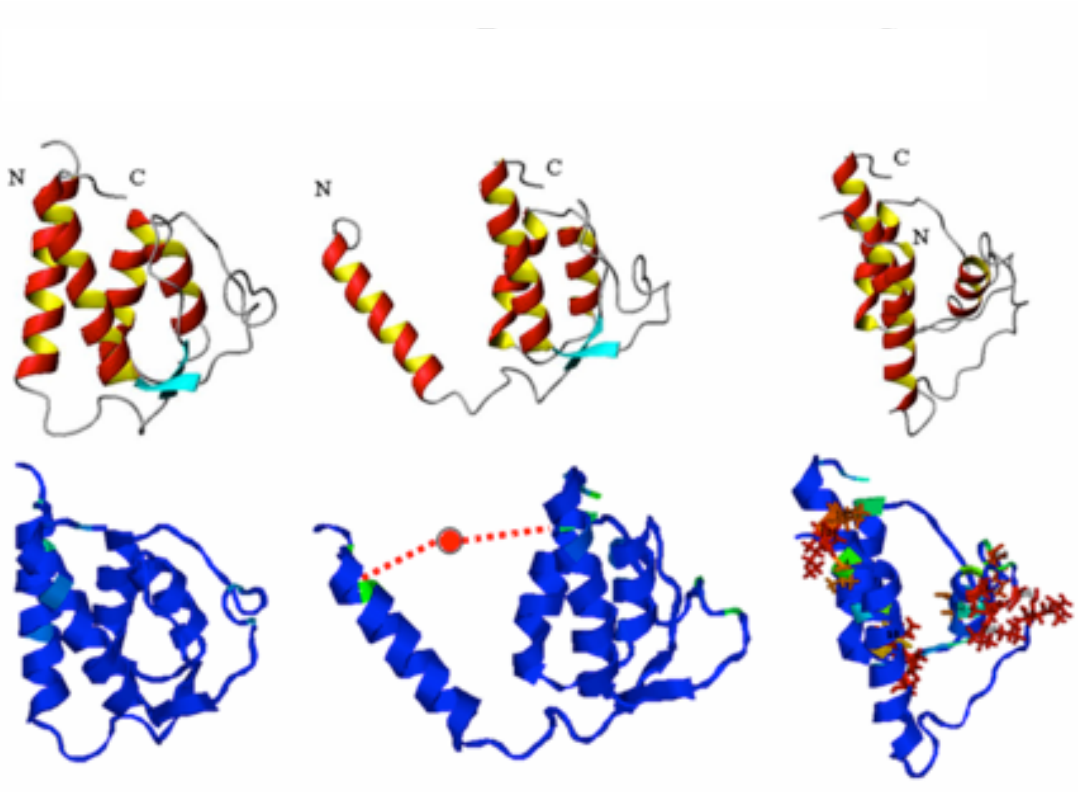
FGF-2

IL-13

MMP-1

△ < 2 Å ○ Partially correct □ Different fold

Recall and Precision Violations



Huang et al.

JACS 2005

Recall = 0.825, Precision = 0.971
F = 0.892 and DP = 0.723

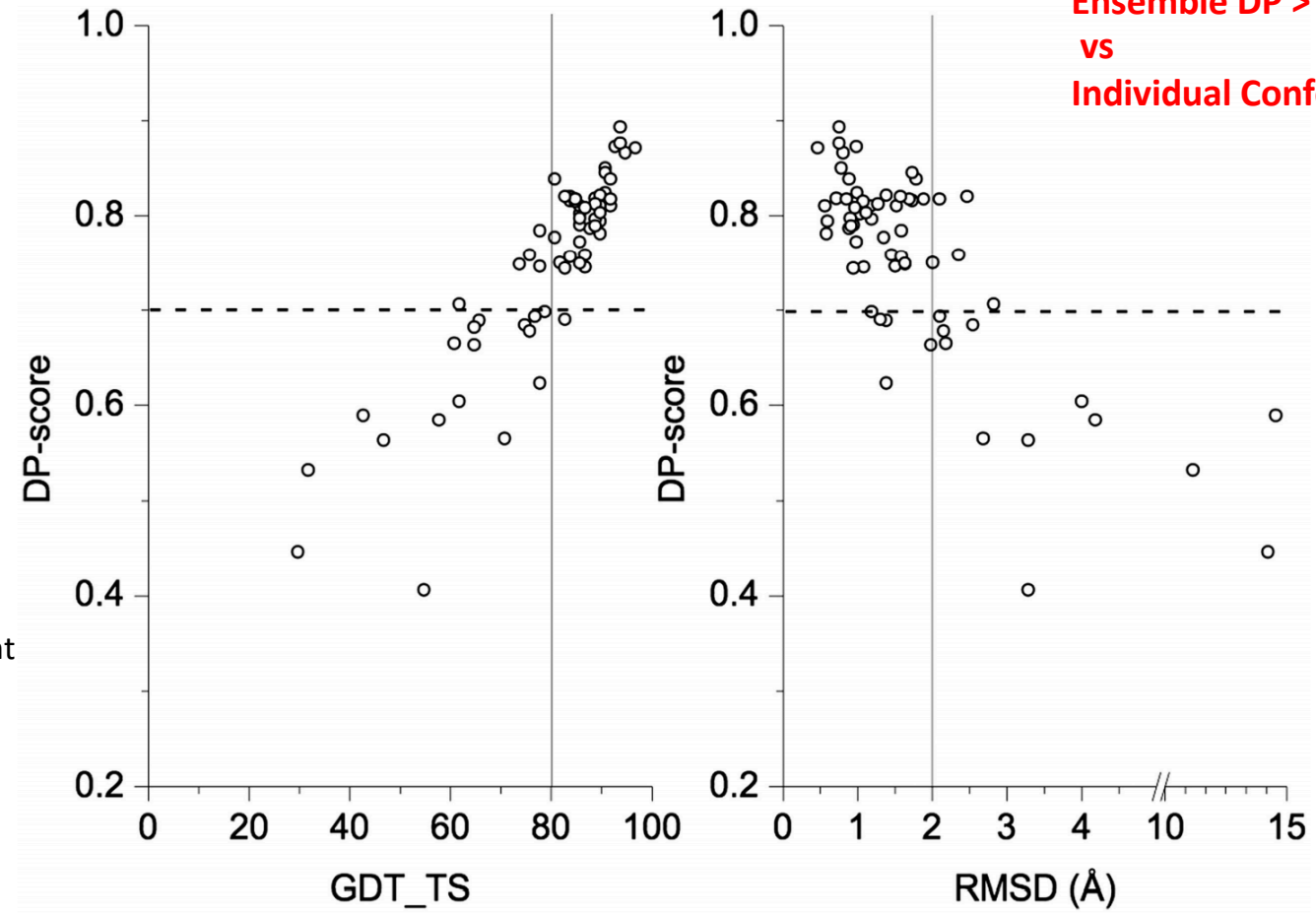
Recall Violations

Recall = 0.769, Precision = 0.969
F = 0.857 and DP = 0.629

Precision Violations

Recall = 0.729, Precision = 0.917
F = 0.812 and DP = 0.508

Critical Assessment of Automated Protein Structure Determination by NMR (CASD-NMR)



Ensemble DP > 0.7
vs
Individual Conformer DP > 0.6

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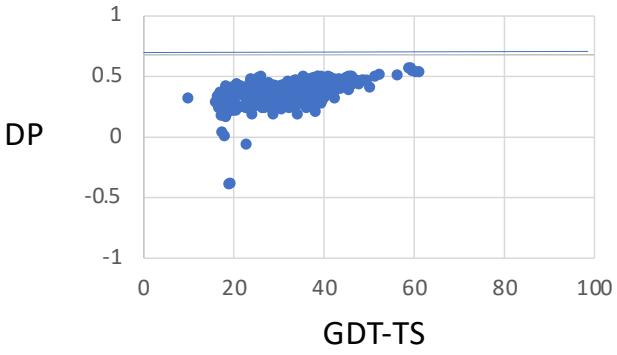
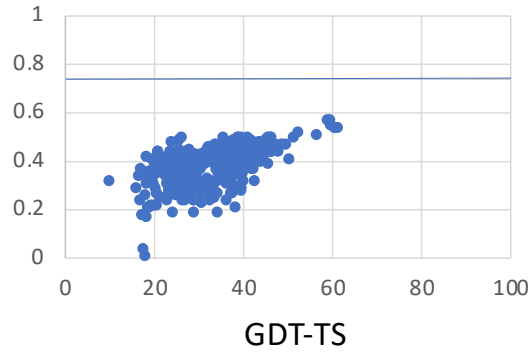
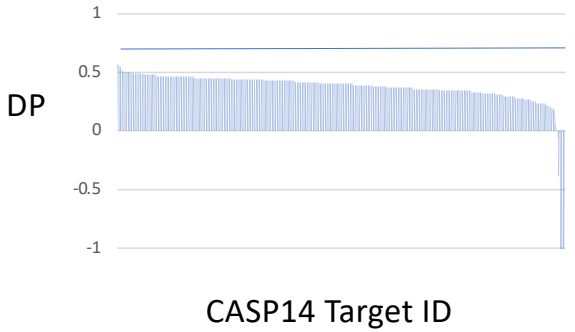
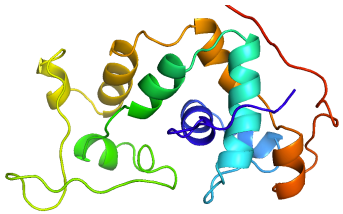
CASP14 Target T1027



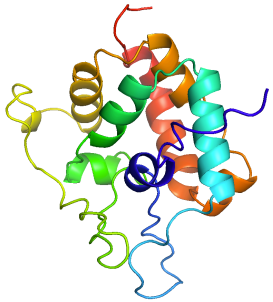




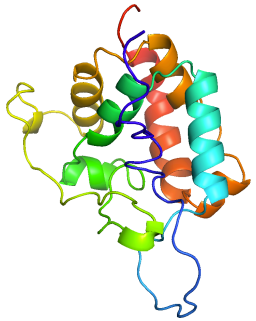


NMR_19 (DP best)

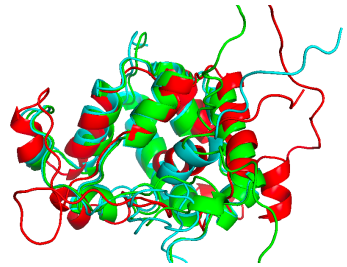
DP: 0.68 (R 0.89, P 0.80)



CASP14 427_4 (DP best)
GDT_TS: 59.3
DP: 0.57 (R 0.85, P 0.78)



CASP14 427_1 (GDT_TS best)
GDT_TS: 61.1
DP: 0.54 (R 0.84, P 0.76)



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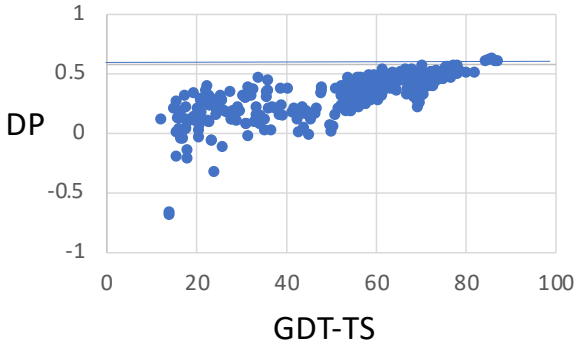
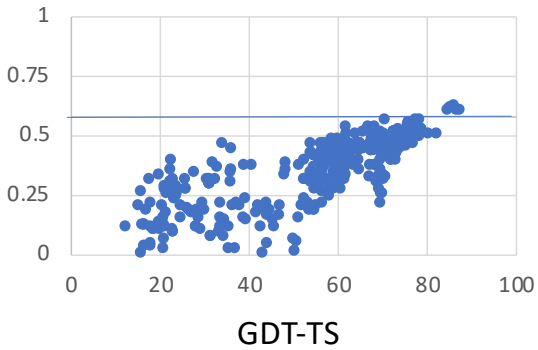
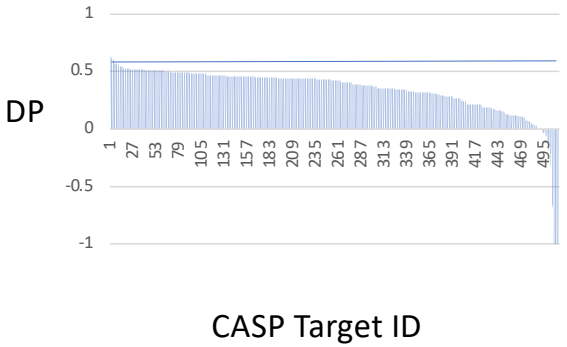
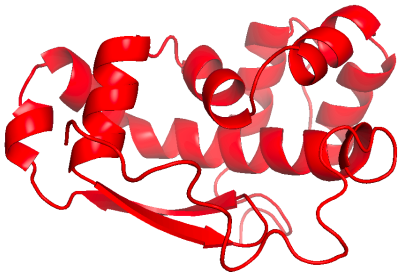
CASP14 Target T1055



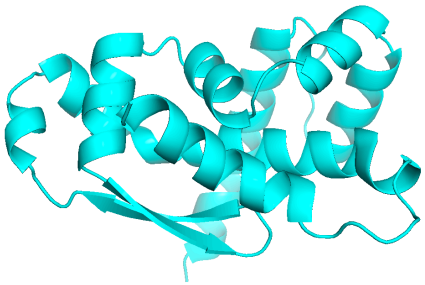




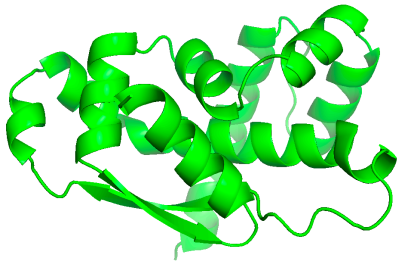


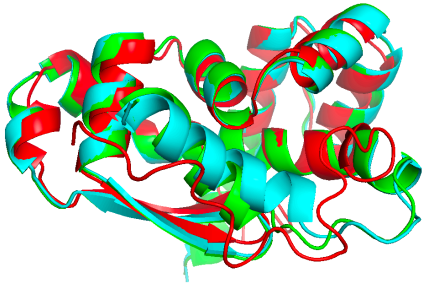
NMR (DP best)

DP: 0.58 (R 0.97, P 0.76)



CASP14 427_2 (DP best)
GDT_TS: 85.8
DP: 0.63 (R 0.96, P 0.78)





CASP14 427_3 (GDT_TS best)
GDT_TS: 87.1
DP: 0.61 (R 0.95, P 0.78)

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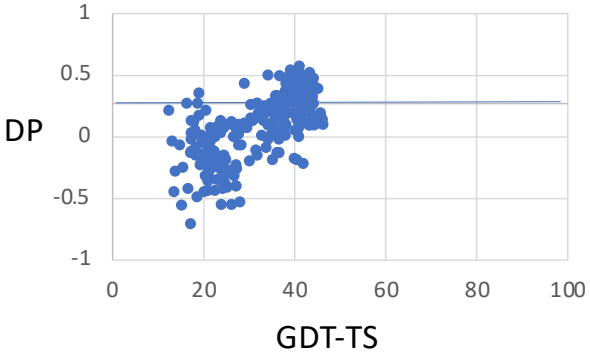
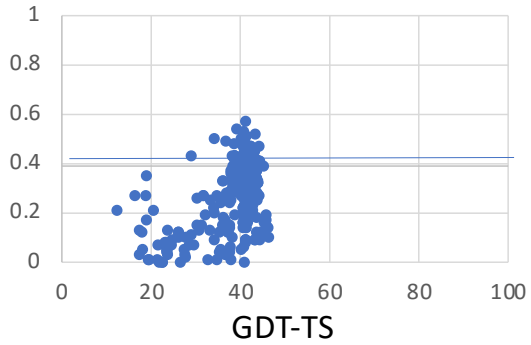
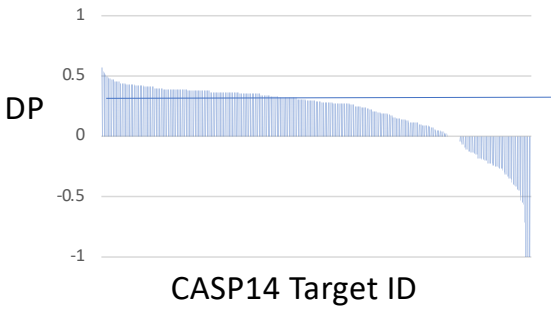
CASP14 Target T1029

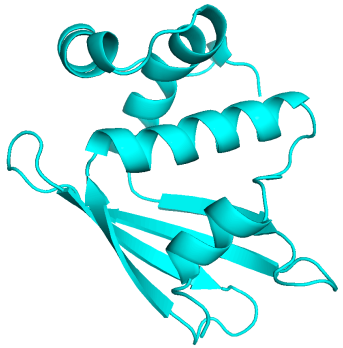




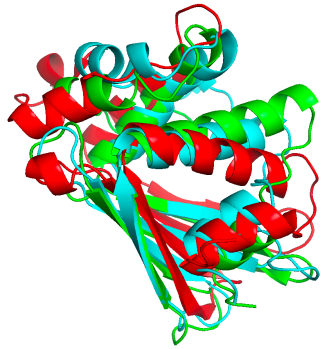


NMR (DP best)

DP: 0.27 (R 0.89, P 0.57)



CASP14 323_4 (DP best)
GDT_TS: 41.4
DP: 0.57 (R 0.90, P 0.62)



CASP14 071_2 (GDT_TS best)
GDT_TS: 46.4
DP: 0.10 (R 0.91, P 0.54)

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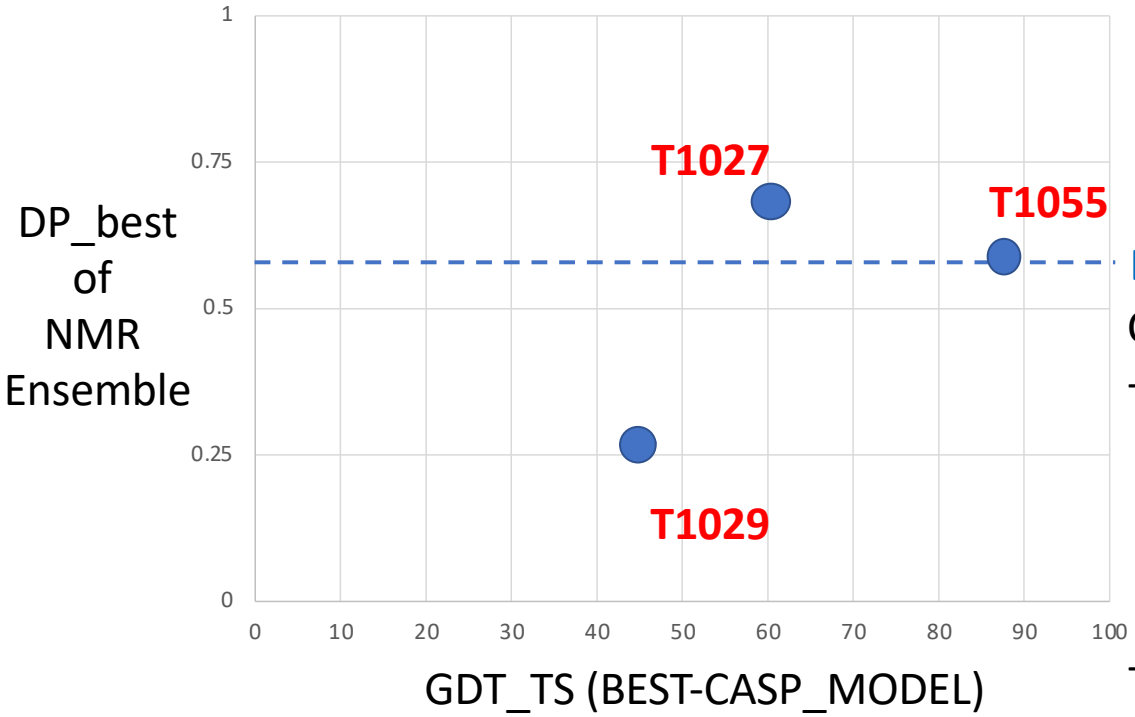
DP (NMR) vs GDT_TS (BEST_CASP_MODEL)



DP threshold

Conclusions

- Best regular prediction models can sometimes fit NMR data better than the "NMR structure" reported (as observed in CASP13)

- Highly dynamic proteins are difficult to model correctly

- CASP is advised to institute more rigorous quality control on NMR targets

T1027 168 residues
T1029 125 residues
T1055 148 residues

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Can Sparse NMR Data Guide Structure Prediction?

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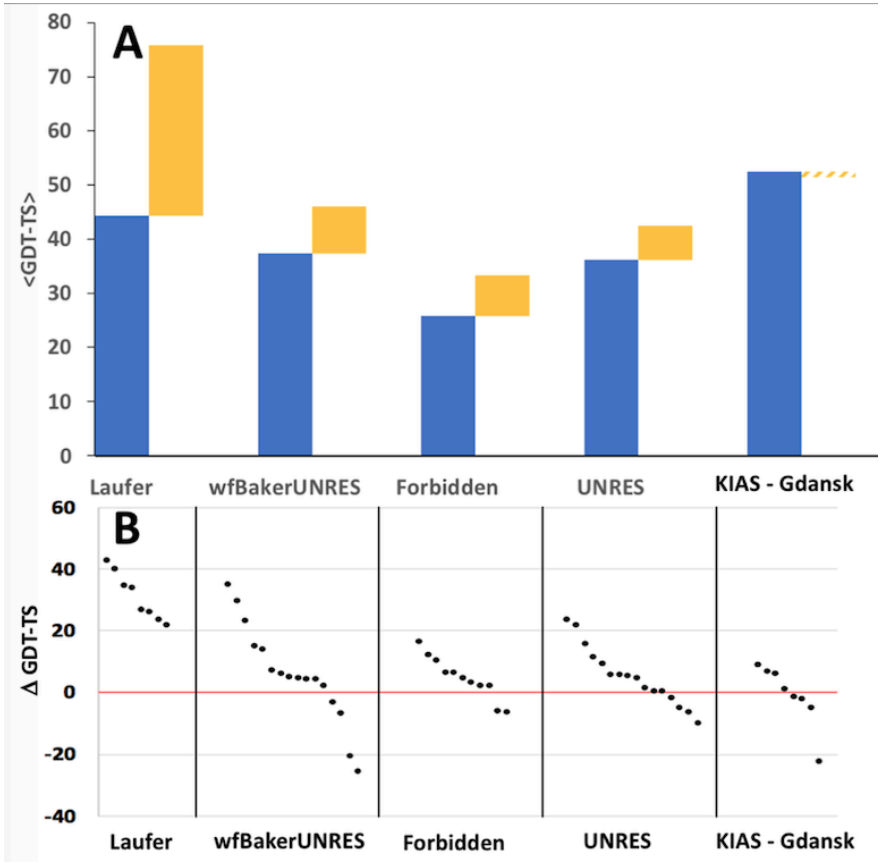
CASP14 Dec 3, 2020

CASP13 – NMR-Guided Modeling – Perdeuterated Proteins

11 simulated data sets
2 real data sets

In most cases where predictor submitted both regular and NMR-guided predictions, the NMR-guided models are more accurate



Sala, Huang, et al. PROTEINS 2019

CASP14 NMR Guided Prediction

No Simulated NMR Data Sets

Two Targets – Perdeuterated Integral Membrane Proteins in Micelles

- T1077 YfaZ 170 Residues Unknown Function
- T1088 MipA 238 Residues Drug Transporter

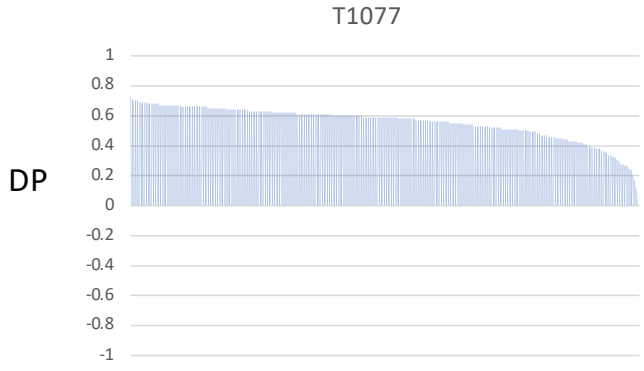
No structures available for any member of these two large pfam families

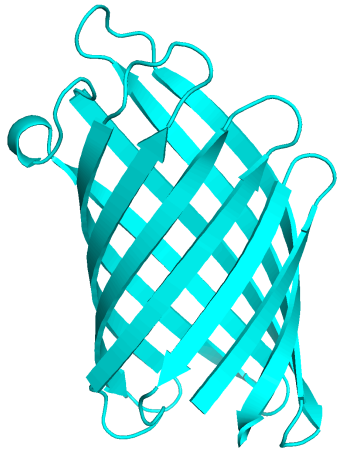
Samples prepared with ^{2}H,^{15}N,^{13}C-enrichment and ILV ^{13}C Methyl labeling in perdeuterated micelles.

Backbone and sidechain methyl resonance assignments
HN/HN and HN/Me NOEs -> Ambiguous Contacts -> 9 CASP Predictor Groups
Chemical Shifts -> Backbone dihedral angle ranges -> 9 CASP Predictor Groups
EC contacts (C. Sander & K. Brock) -> EC-NMR structures

GT Montelione
CASP14 Dec 3, 2020

Target T1077
YfaZ in detergent micelles
EC-NMR
Perdeuterated Sparse Restraints

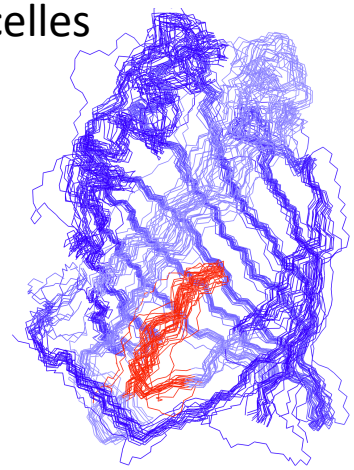




DP = 0.71

GT Montelione
CASP14 Dec 3, 2020

Target 1088 MipA in detergent micelles
EC-NMR
Perdeuterated Sparse Restraints
~ 1000 Conformational Restraints
~ 4.2 restraints / residue

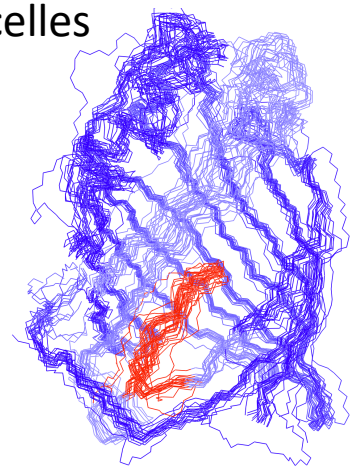


Extensive exchange broadening in red hairpin; do not see many HN-HN NOEs

Chemical shift data indicate hairpin is not beta strand -> rather suggests dynamic structure

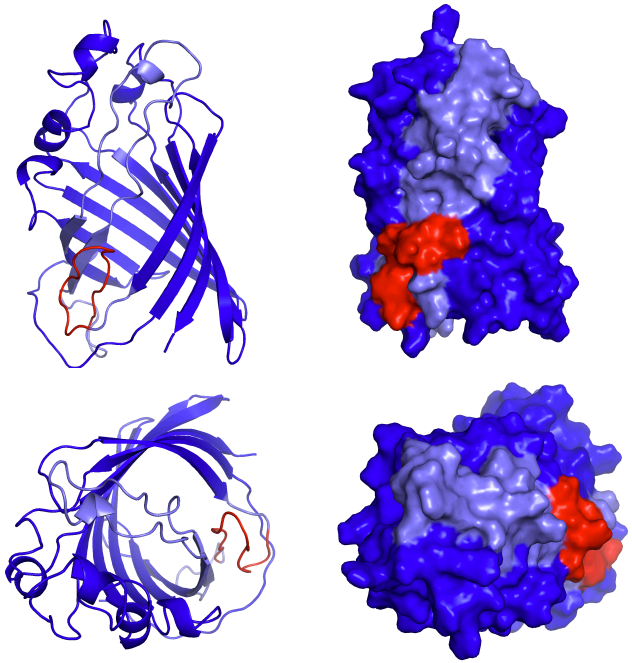
GT Montelione
CASP14 Dec 3, 2020

Target 1088 MipA in detergent micelles
EC-NMR
Perdeuterated Sparse Restraints
~ 1000 Conformational Restraints
~ 4.2 restraints / residue

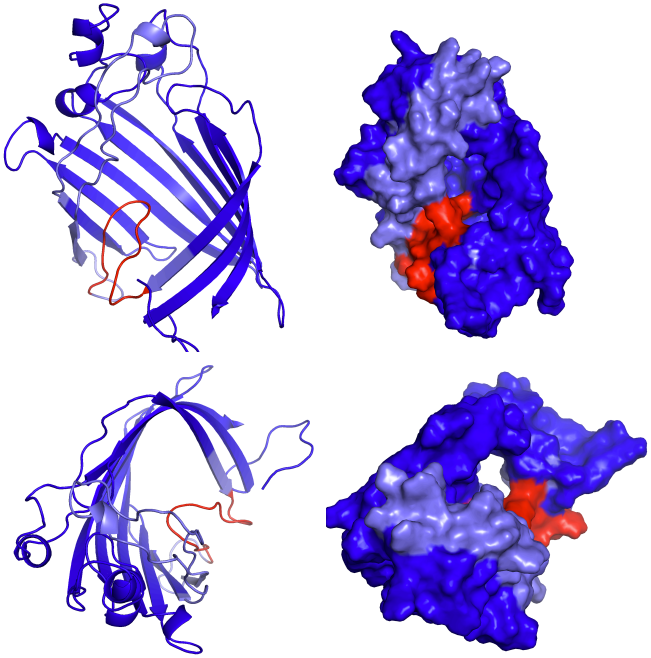


Extensive exchange broadening in red hairpin; do not see many HN-HN NOEs

Chemical shift data indicate hairpin is not beta strand -> rather indicate a dynamic local structure



NMR_10 Closed Conformer
DP = 0.53



NMR_13 Open Conformer
DP = 0.49

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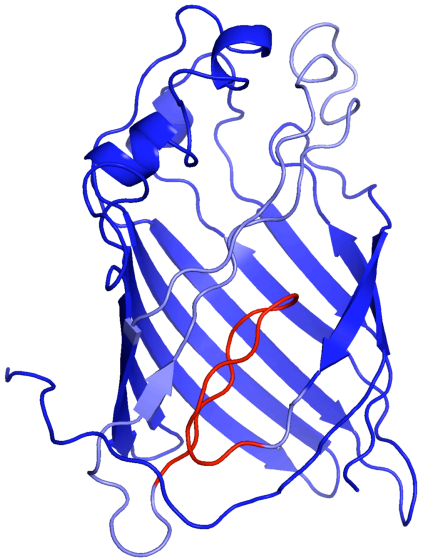
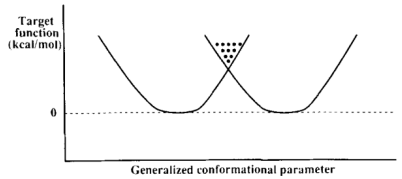


T1088

MipA – Integral Membrane Protein – Multi Drug Transporter

NMR data indicate exchange broadening in red hairpin; 13C chemical shifts inconsistent with static beta-strands

Experimental NMR structures – each conformer is best fit to all of the data.



Need to instead model the distribution that is best fit to the ensemble- averaged NMR data

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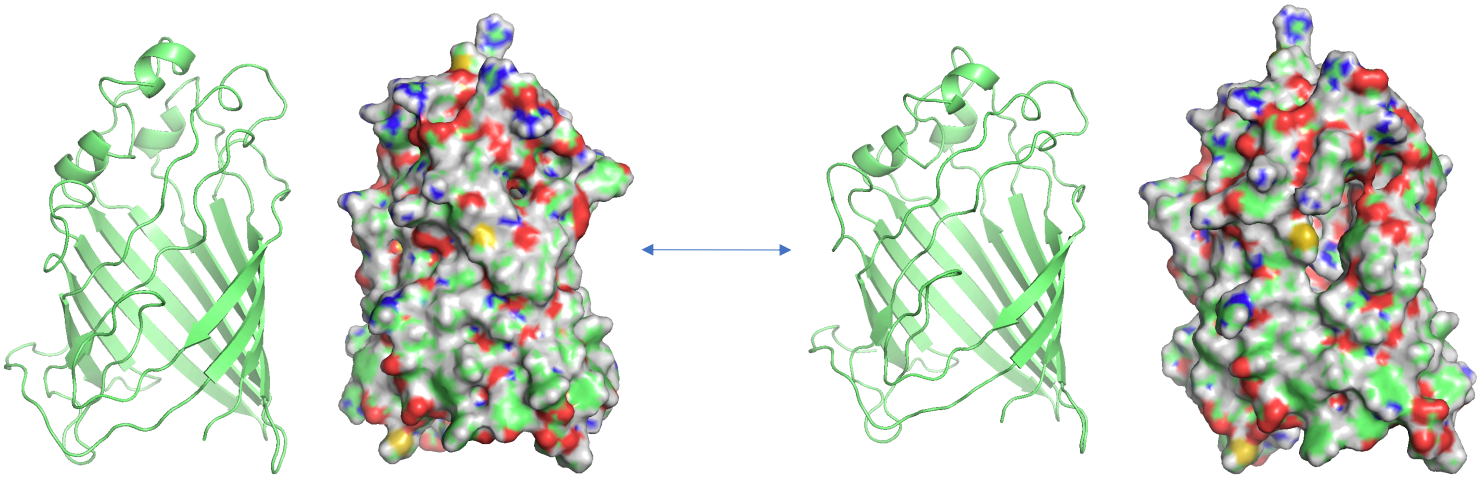
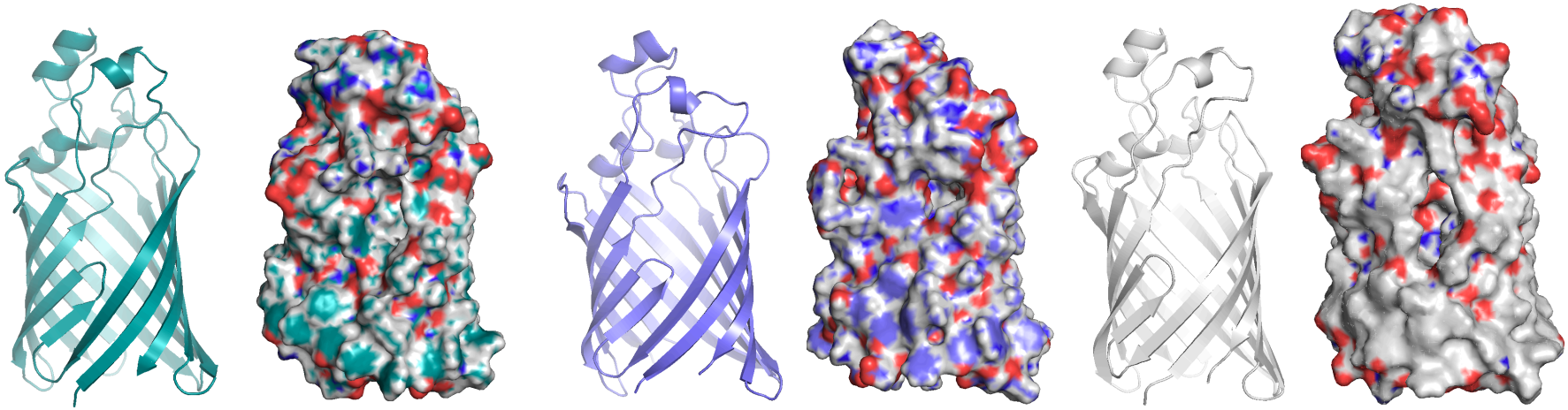


EC-NMR closed form

EC-NMR open form

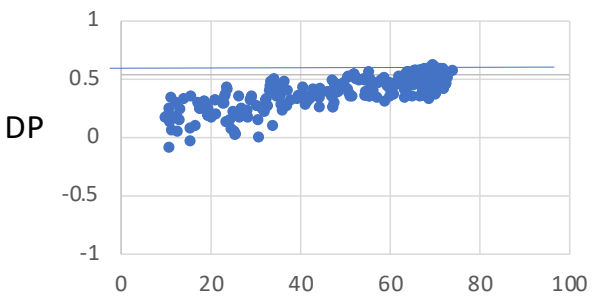


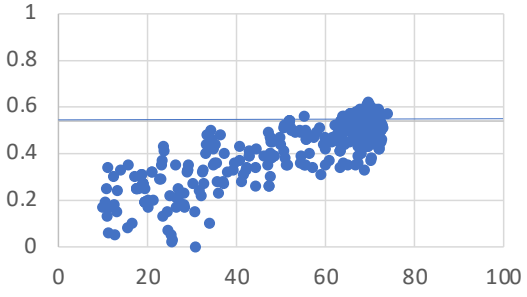
T1088 362_2 closed form

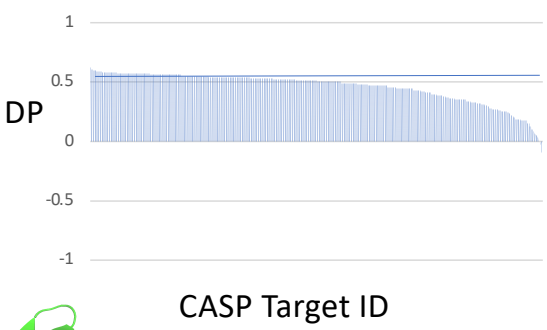
T1088 314_5 smaller cavity

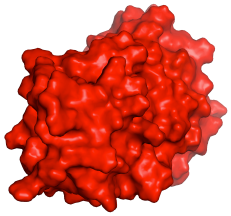
T1088 226_5 open form

GT Montelione
CASP14 Dec 3, 2020



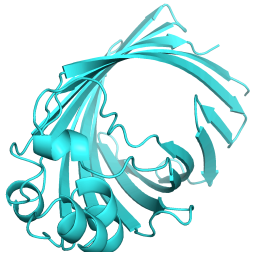


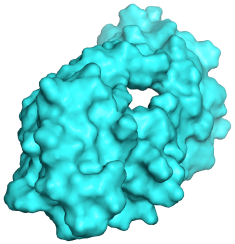




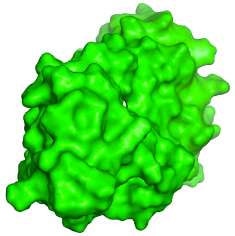
NMR_8 Closed

DP: 0.53 (R 0.73, P 0.63)

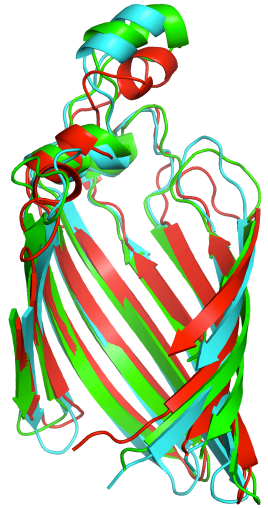




CASP14 226_5 (DP best)
GDT_TS: 69.5
DP: 0.62 (R 0.75, P 0.73)



CASP14 314_5 (GDT_TS best)
GDT_TS: 73.9
DP: 0.57 (R 0.73, P 0.68)



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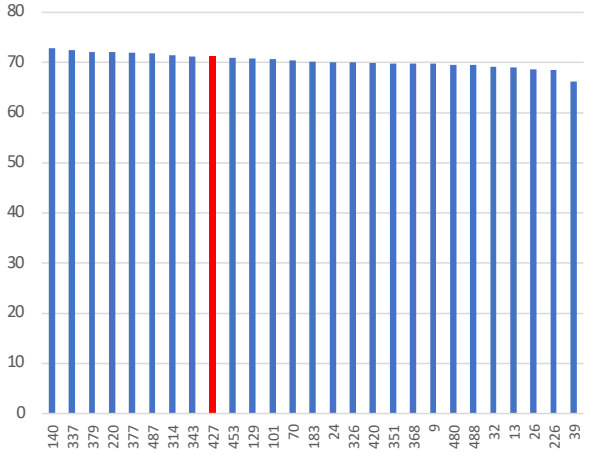
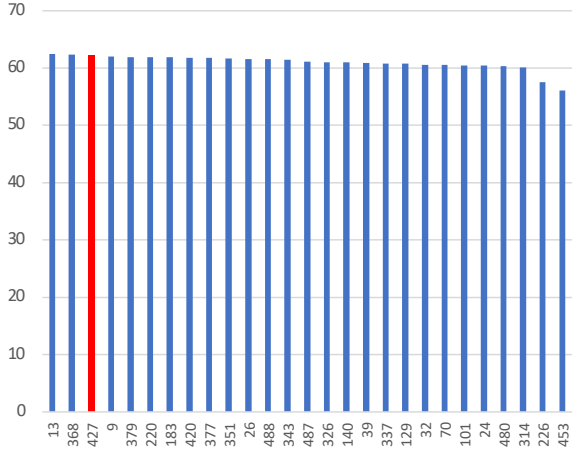
CASP14 Dec 3, 2020

T1088 Ranking – Regular Prediction (top 27 groups)

GDT_TS_First

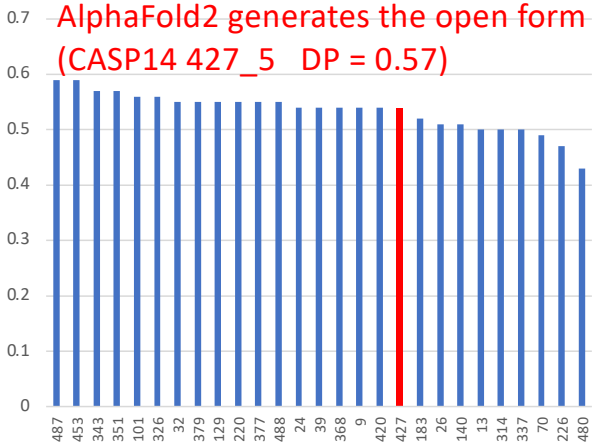


Combined_First



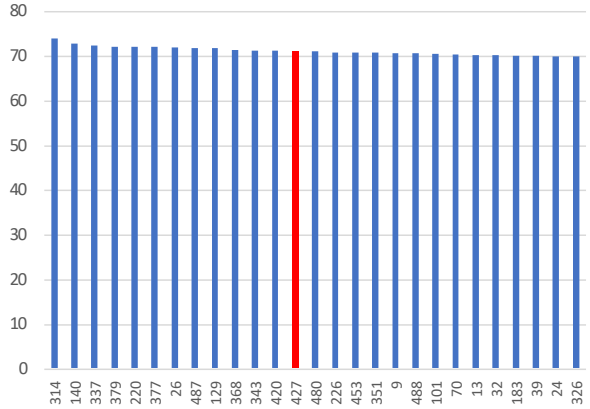
DP_First

AlphaFold2 generates the open form (CASP14 427_5 DP = 0.57)

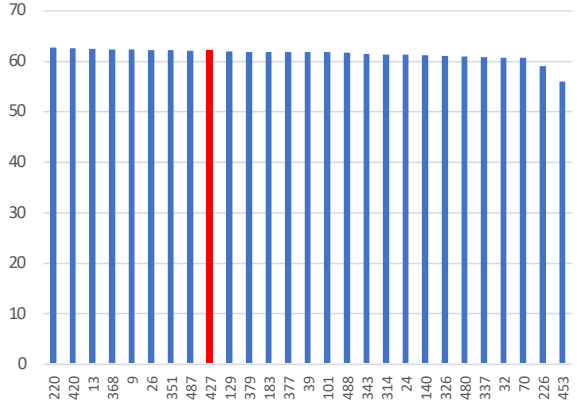


GDT-HA*0.4 + GDT-SC*0.4 + RPF * 0.4 + SphereGrinder * 0.4 + CAD-AA * 0.4 + MolProbity * 0.2)/2.2

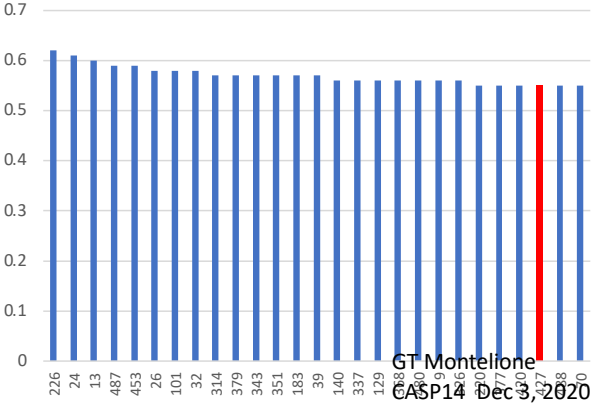
GDT_TS_BEST



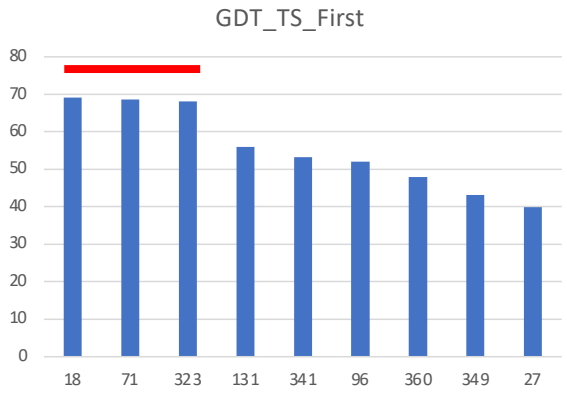
Combined_Best

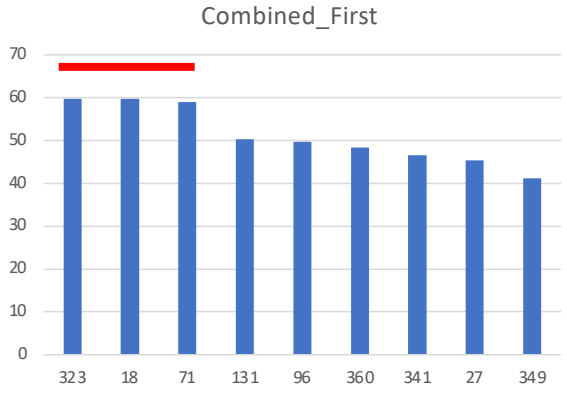


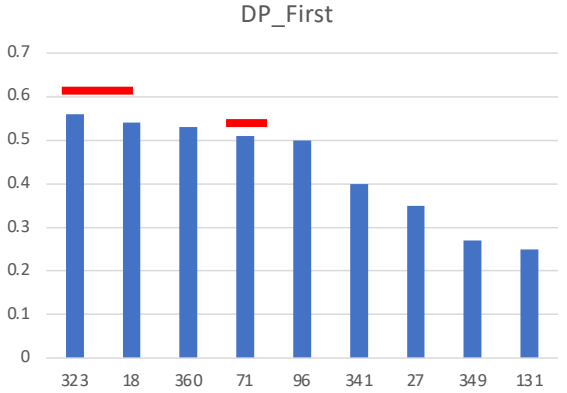
DP_Best



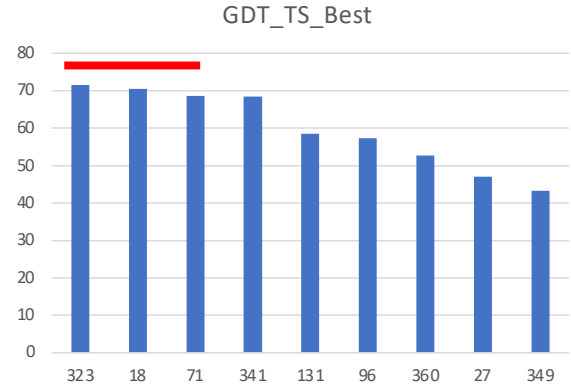
NMR Guided Predictions
N1088 Ranking - Nine Prediction Groups

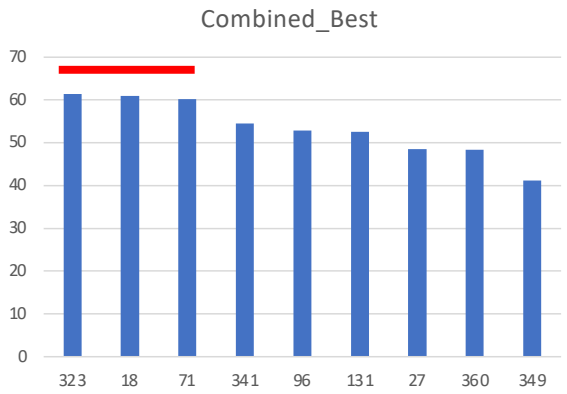


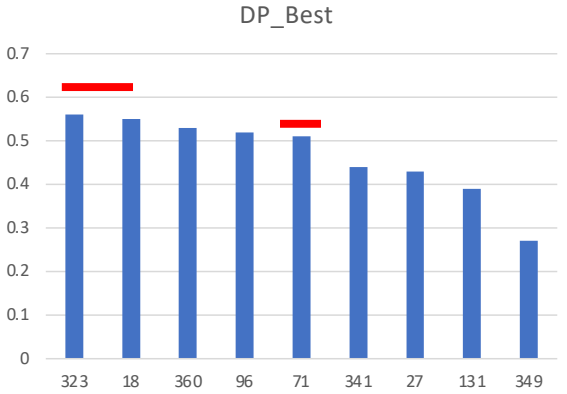




GDT-HA*0.4 + GDT-SC*0.4 + RPF * 0.4 + SphereGrinder * 0.4 + CAD-AA * 0.4 + MolProbity * 0.2)/2.2







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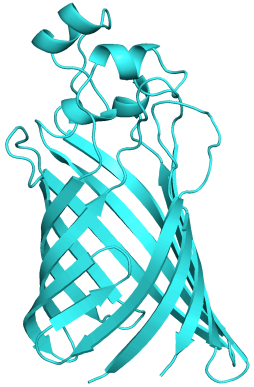
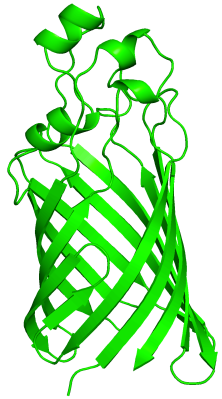
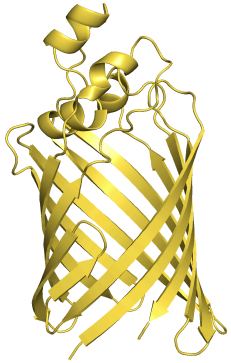
CASP14 NMR-Guided Prediction Results



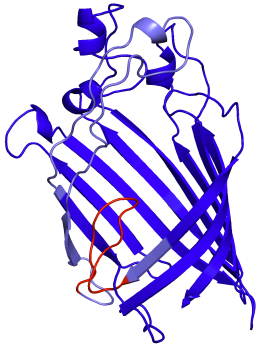
N1088_323_1
DP = 0.56
GDT_TS = 68.0



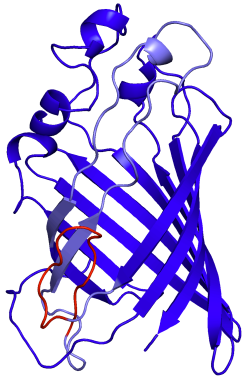
N1088_018_2
DP = 0.55
GDT_TS = 70.4



N1088_071_1
DP = 0.51
GDT_TS = 68.6



EC-NMR – open
DP = 0.49



EC-NMR – closed
DP = 0.53

Note that the best DP score for all CASP models is regular prediction result
DP: 0.62 CASP14 226_5

For NMR-Assisted Target N1088 - the 3 top groups are:
323 DellaCorteLab
18 UNRES-template
71 Kihara Lab

Experimental NMR structures – each conformer is best fit to all of the data. Can we use CASP models to segregate the data to more accurately determine the structures of each state?

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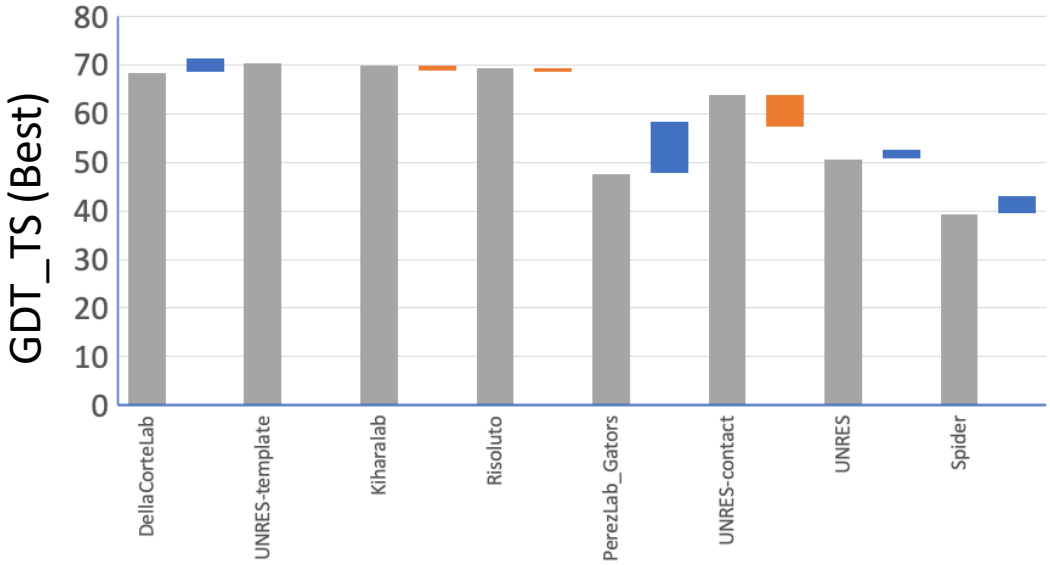
CASP14 – NMR-Guided Modeling – Perdeuterated Integral Membrane Protein

N1088 MipA 238 residues

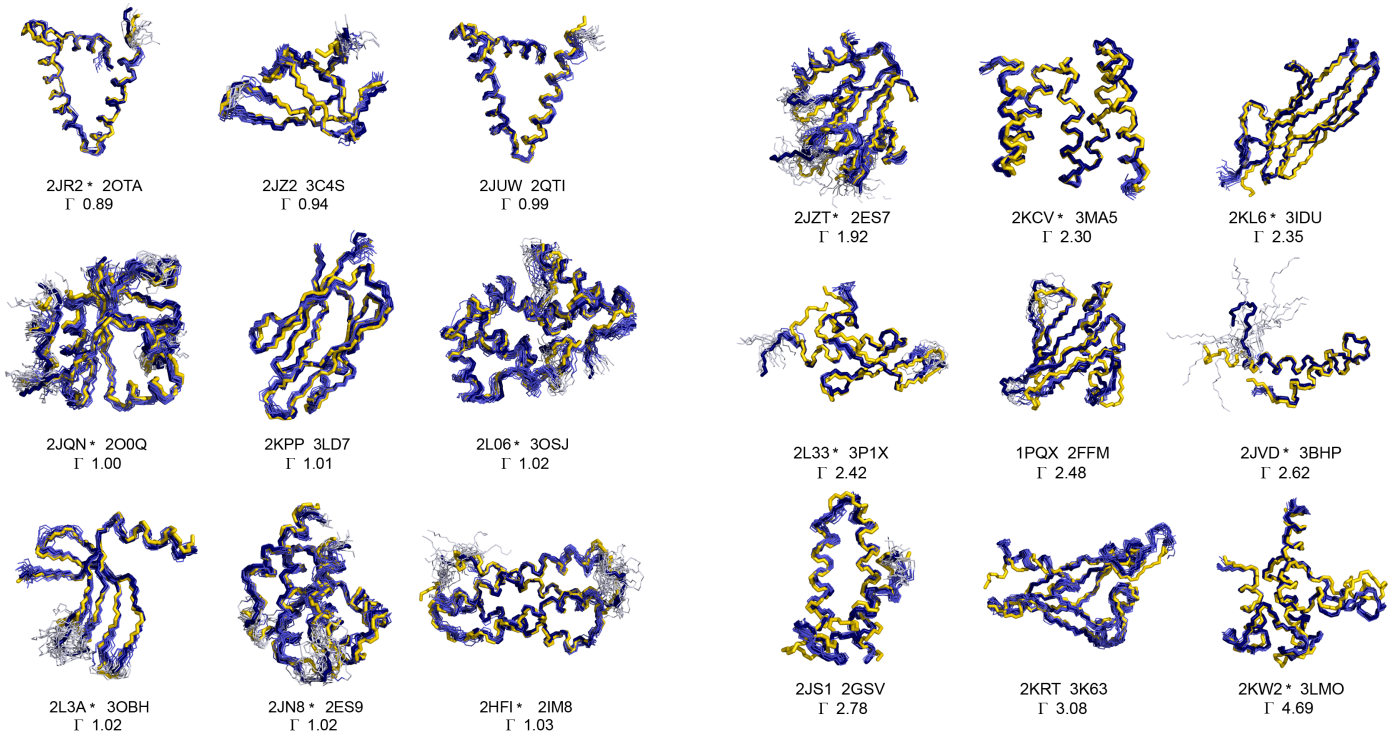
4 groups – NMR data improved prediction accuracy, as much as 10 GDT points

1 group – NMR data degraded prediction accuracy

3 groups – NMR data did not much impact accuracy



41 NMR X-ray Pairs



Structure

Ways & Means

Improved Technologies Now Routinely Provide Protein NMR Structures Useful for Molecular Replacement

Binchen Mao,[1] Rongjin Guan,[1] and Gaetano T. Montelione[1,2,*]

Structure 2011

Conclusions

Integral membrane protein N1088 MipA functions as a drug transporter to confer antibiotic resistance.

NMR data indicate dynamic equilibrium with fast / intermediate exchange between closed and open forms. Regular CASP Prediction models include both closed and open forms.

Some predictors could use NMR data to improve their models (PerezLab)

Some NMR-Guided Prediction models fit to NMR NOESY data better than sparse EC-NMR structure (DellaCorte, UNRES-template, UNRES)

Some Regular Prediction models fit to NMR NOESY data better than any NMR-guided models → could be used to guide data analysis