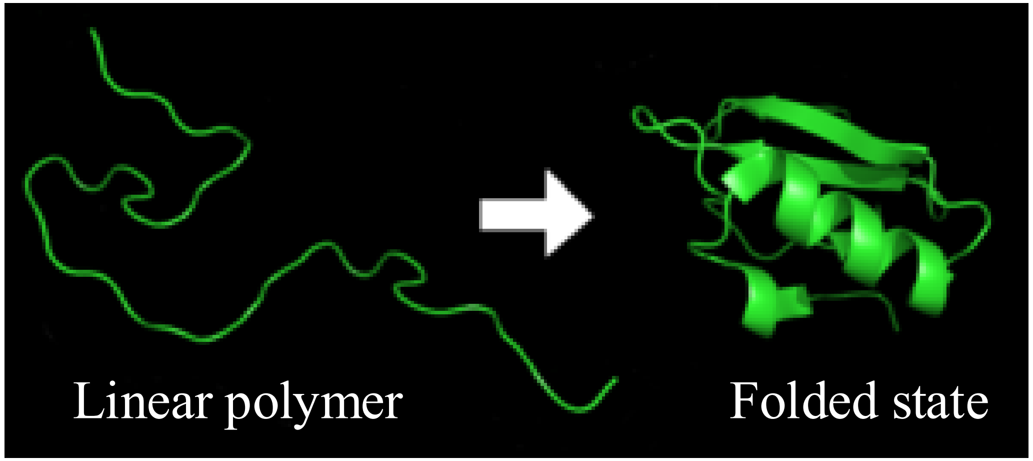
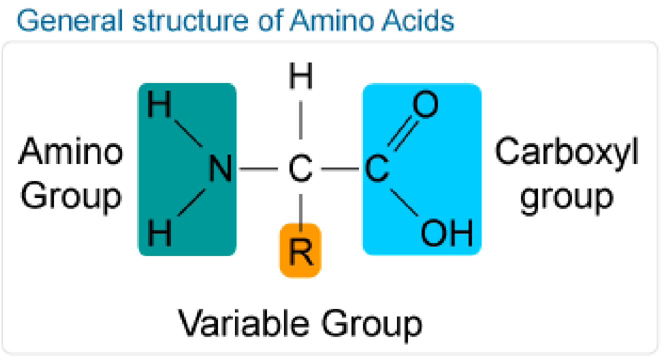
What are proteins?



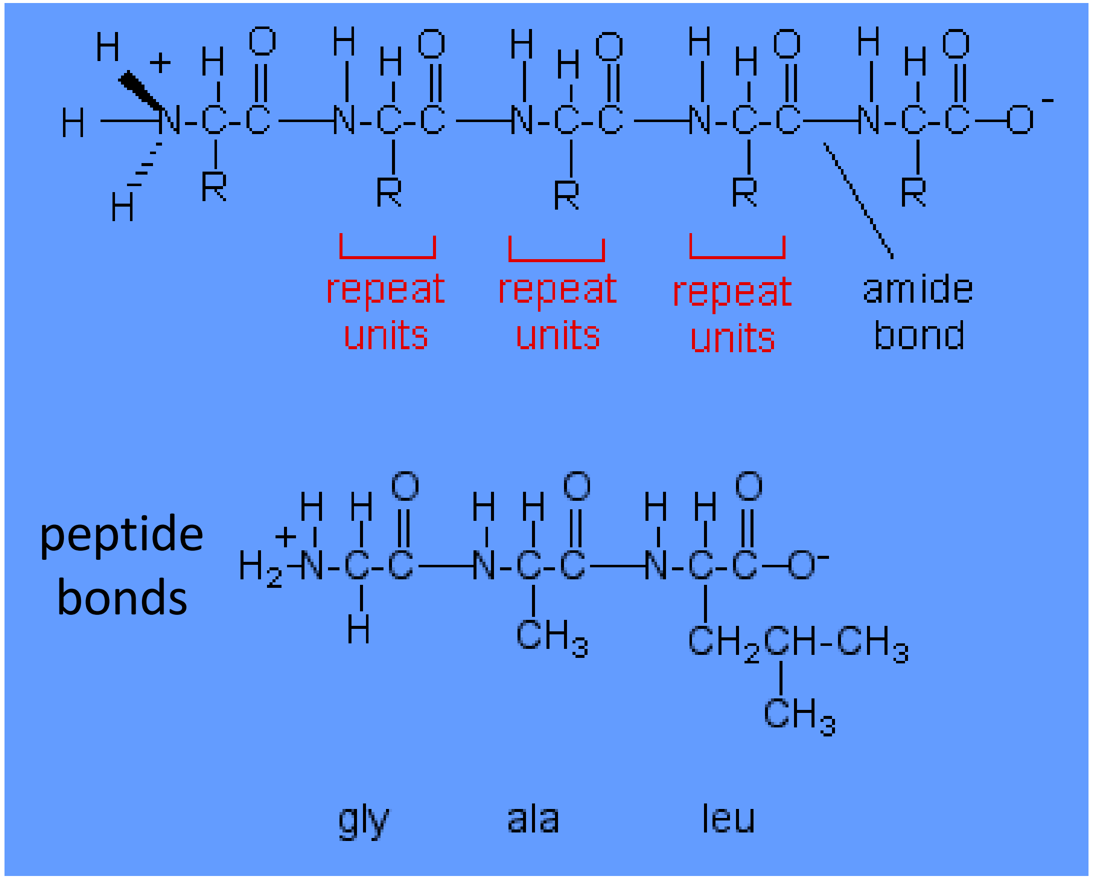
- Proteins are important; e.g. for catalyzing and regulating biochemical reactions, transporting molecules, …
- Linear polymer chain composed of tens (peptides) to thousands (proteins) of monomers
- Monomers are 20 naturally occurring amino acids
- Different proteins have different amino acid sequences
- *Structureless*, extended unfolded state
- Compact, ‘unique’ native folded state (with secondary and tertiary structure) required for biological function
- Sequence determines protein structure (or lack thereof)
- Proteins unfold or denature with increasing temperature or chemical denaturants

Amino Acids I



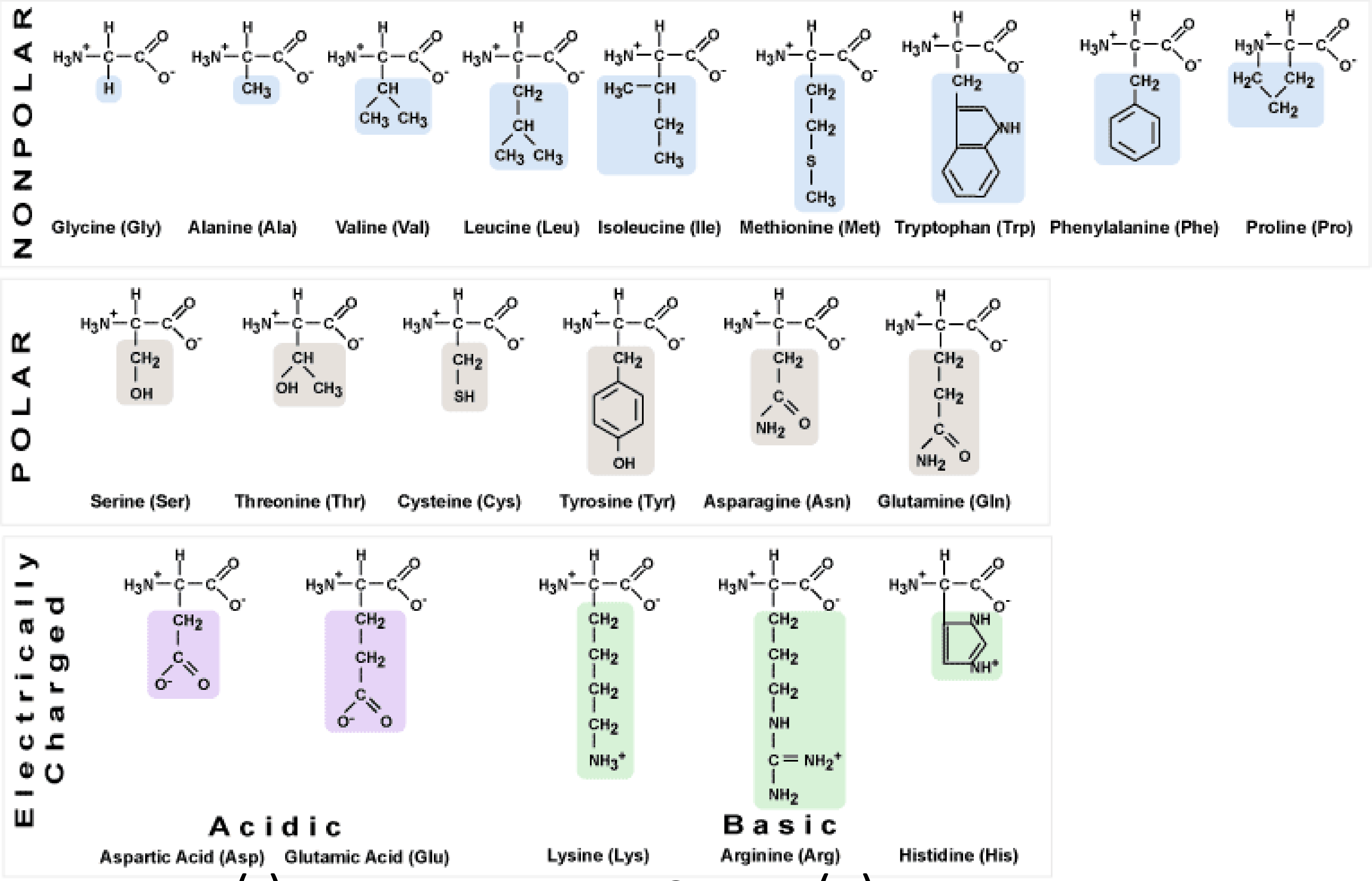
N-terminal C_{α} C-terminal

R
variable
side chain



- Side chains differentiate amino acid repeat units
- Peptide bonds link residues into polypeptides

Amino Acids II

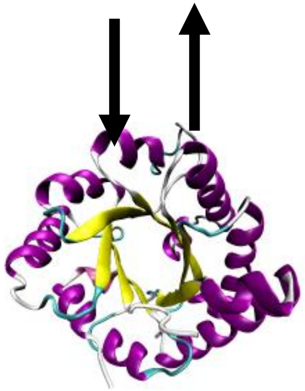


(-) (+)

The Protein Folding Problem:

What is ‘unique’ folded 3D structure of a protein based on its amino acid sequence? Sequence → Structure

Lys-Asn-Val-Arg-Ser-Lys-Val-Gly-Ser-Thr-Glu-Asn-Ile-Lys- His-Gln-Pro- Gly-Gly-Gly-...



Why do proteins fold (correctly & rapidly)??

Levinthal's paradox:

For a protein with N amino acids, number of backbone conformations/minima

$$N_c \sim \mu^{2N}$$

μ = # allowed dihedral angles

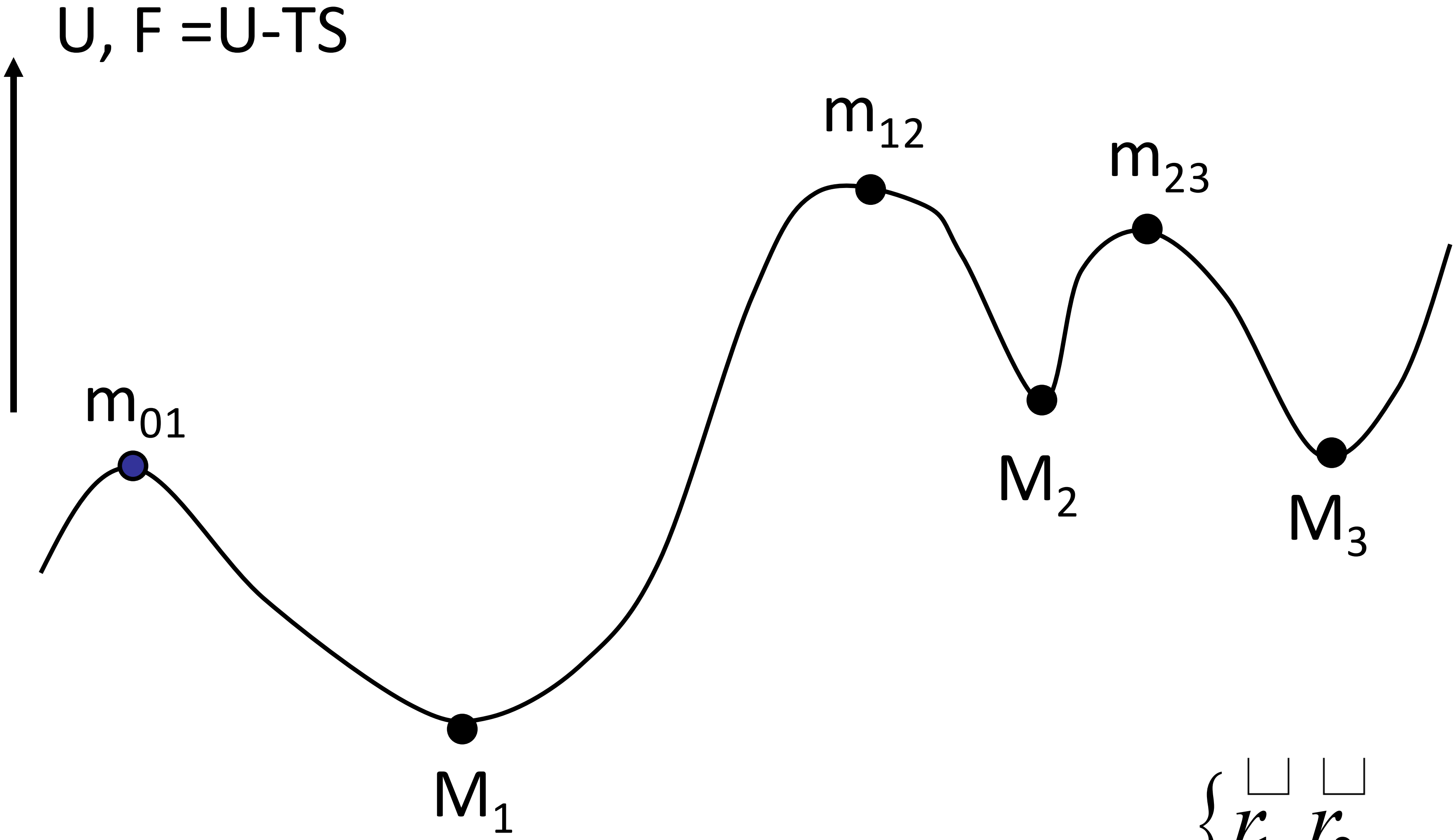
How does a protein find the global optimum w/o global search? Proteins fold much faster.

$N_c \sim 3^{200} \sim 10^{95}$

$\tau_{fold} \sim N_c\, \tau_{sample} \sim 10^{83}$ s vs $\tau_{fold} \sim 10^{-6}$-10^{-3} s

$\tau_{universe} \sim 10^{17}$ s

Energy Landscape

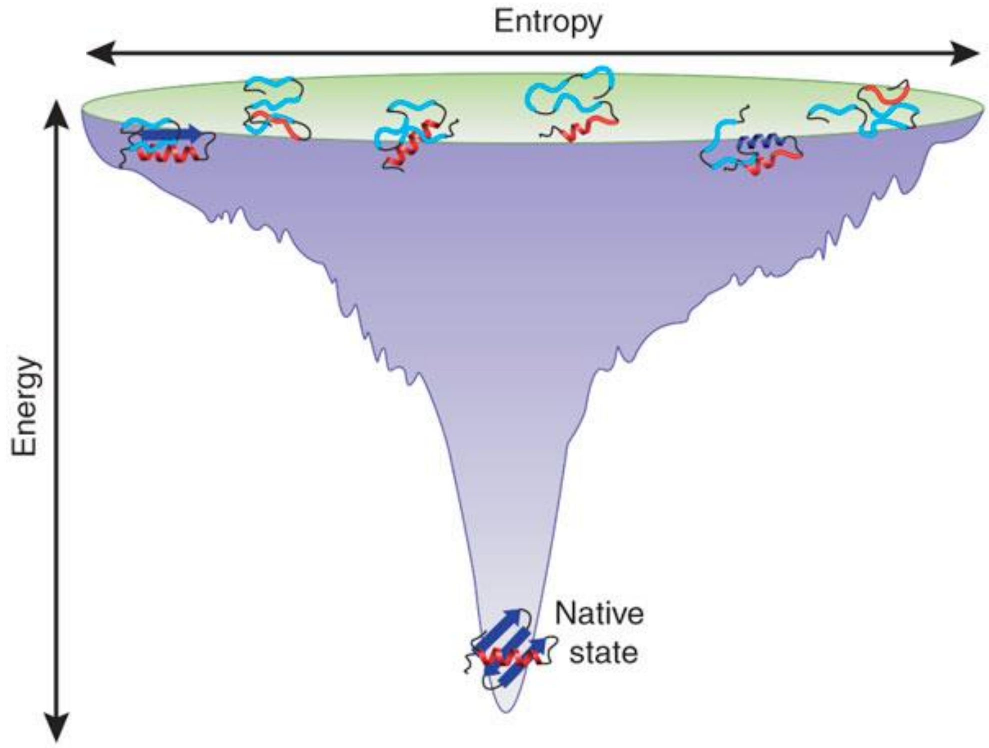


$$\{\overset{\sqcup}{r}_1, \overset{\sqcup}{r}_2, \ldots, \overset{\sqcup}{r}_N\}$$

all atomic coordinates; dihedral angles

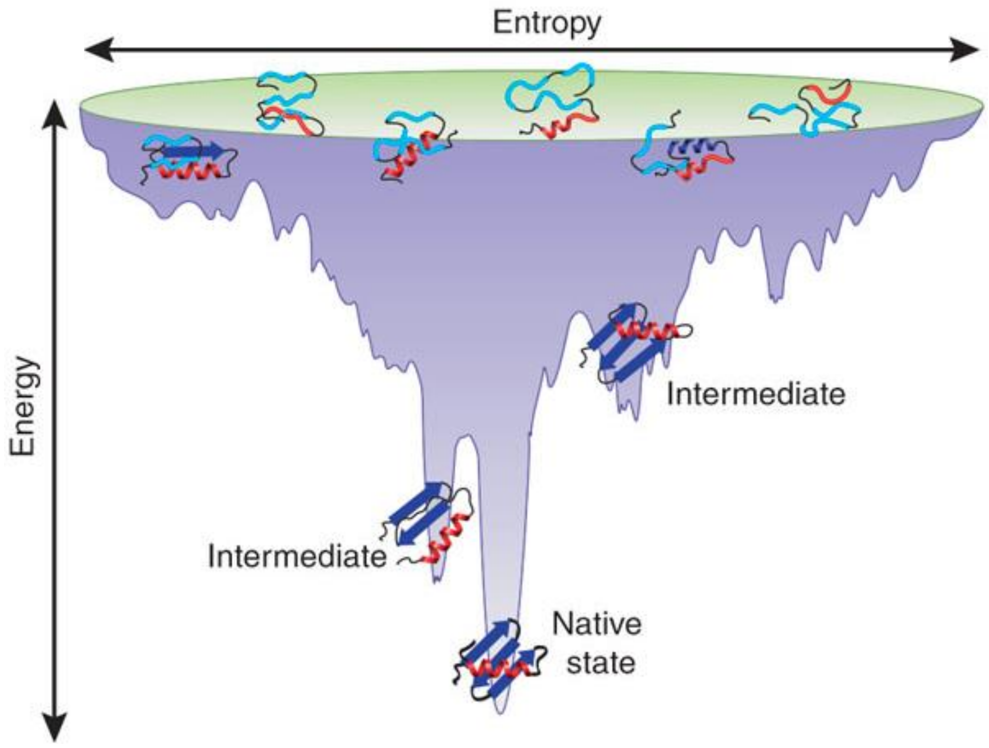
$$\overset{\sqcup}{\square} U = 0 \quad \begin{cases} \nabla^2 U > 0 & \text{Minimum (M)} \\ \nabla^2 U = 0 & \text{saddle point} \\ \nabla^2 U < 0 & \text{Maximum (m)} \end{cases}$$

Roughness of Energy Landscape



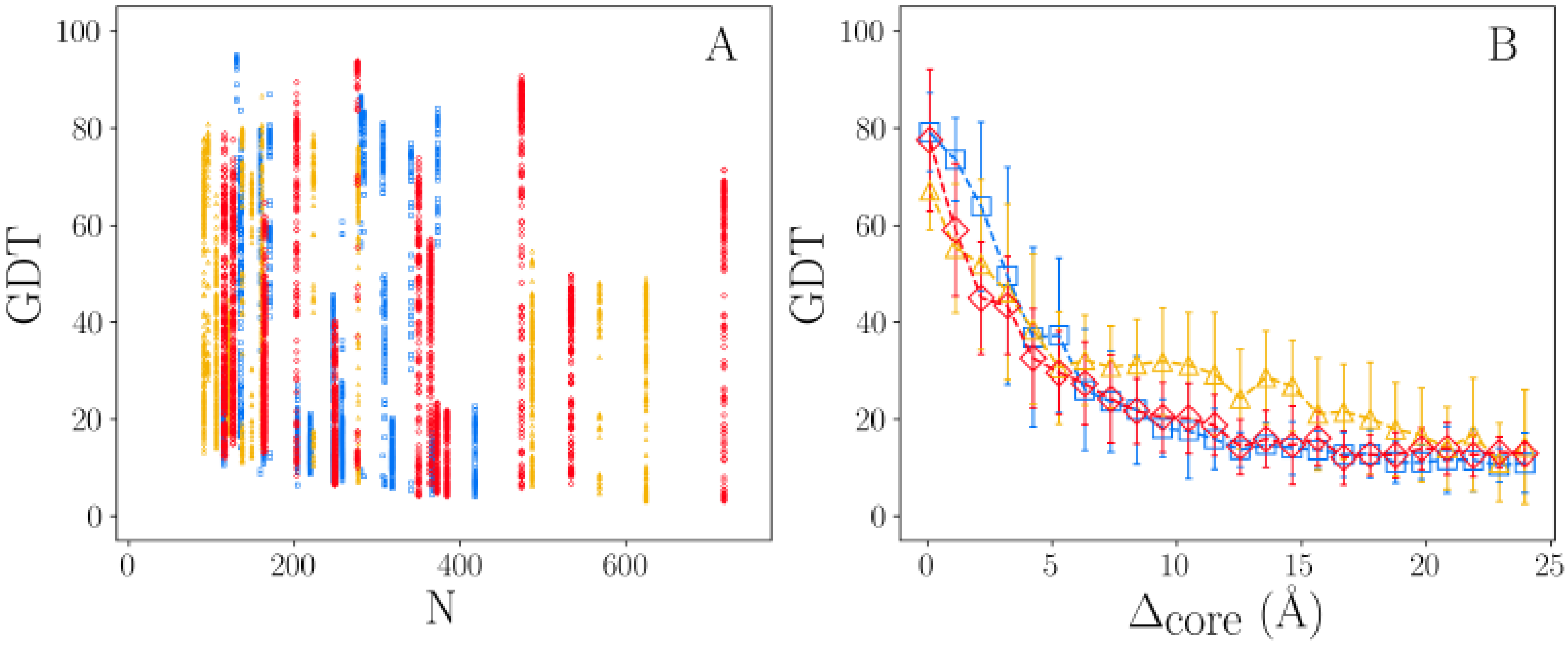
smooth, funneled

(Wolynes et. al. 1997)



rough

Critical Assessment of Structure Prediction (CASP)



Hoval et. al., *Protein Science* (2018)
Moult et. al., *Protein Science* (2018)

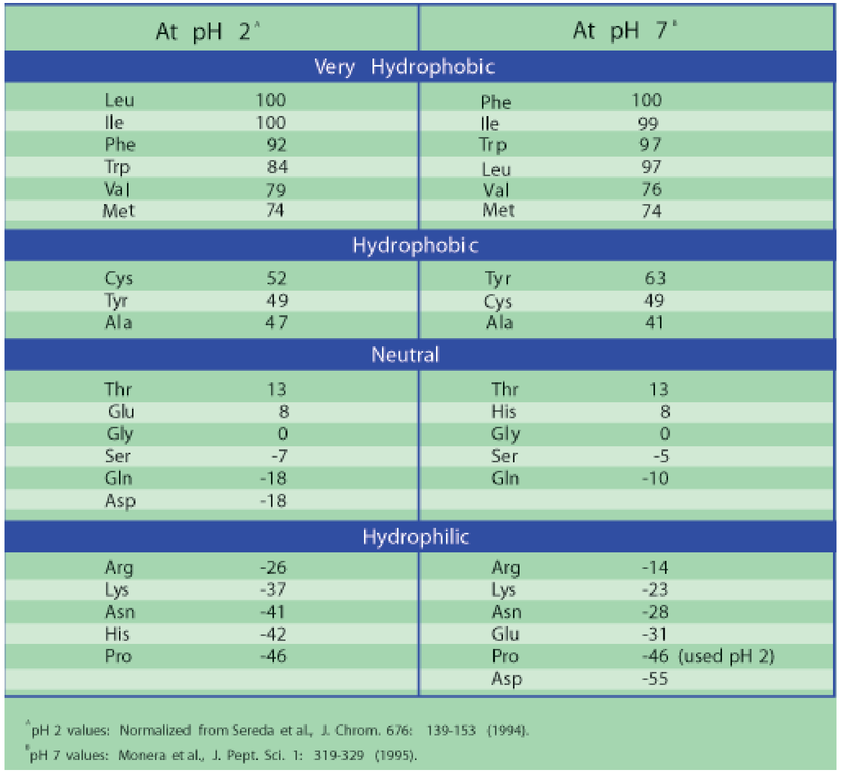
Driving Forces

- Folding: hydrophobicity, hydrogen bonding, van der Waals interactions, …
- Unfolding: increase in conformational entropy, electric charge…

inside H (hydrophobic)

outside P (polar)

Hydrophobicity index

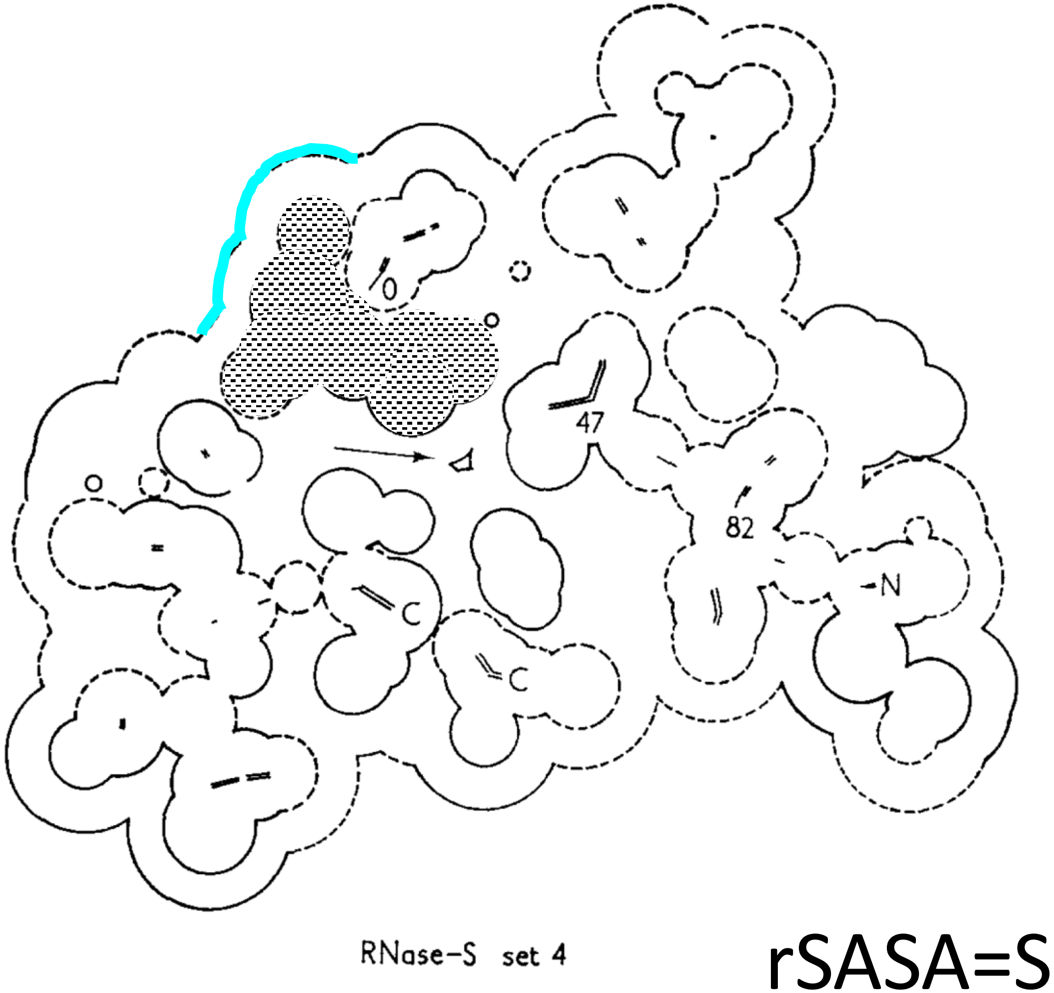


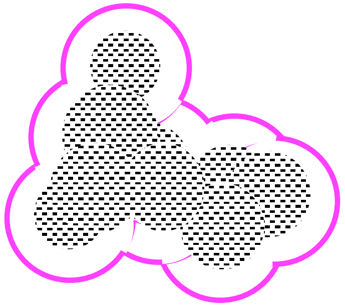
At pH 2[A]		At pH 7[B]	
Very Hydrophobic			
Leu	100	Phe	100
Ile	100	Ile	99
Phe	92	Trp	97
Trp	84	Leu	97
Val	79	Val	76
Met	74	Met	74
Hydrophobic			
Cys	52	Tyr	63
Tyr	49	Cys	49
Ala	47	Ala	41
Neutral			
Thr	13	Thr	13
Glu	8	His	8
Gly	0	Gly	0
Ser	-7	Ser	-5
Gln	-18	Gln	-10
Asp	-18		
Hydrophilic			
Arg	-26	Arg	-14
Lys	-37	Lys	-23
Asn	-41	Asn	-28
His	-42	Glu	-31
Pro	-46	Pro	-46 (used pH 2)
		Asp	-55

[A] pH 2 values: Normalized from Sereda et al., J. Chrom. 676: 139-153 (1994).

[B] pH 7 values: Monera et al., J. Pept. Sci. 1: 319-329 (1995).

Solvent Accessible Surface Area and rSASA





━ $SASA_{res}$

━ $SASA_{dip}$

$$rSASA = SASA_{res}/SASA_{dip} = [0,1]$$

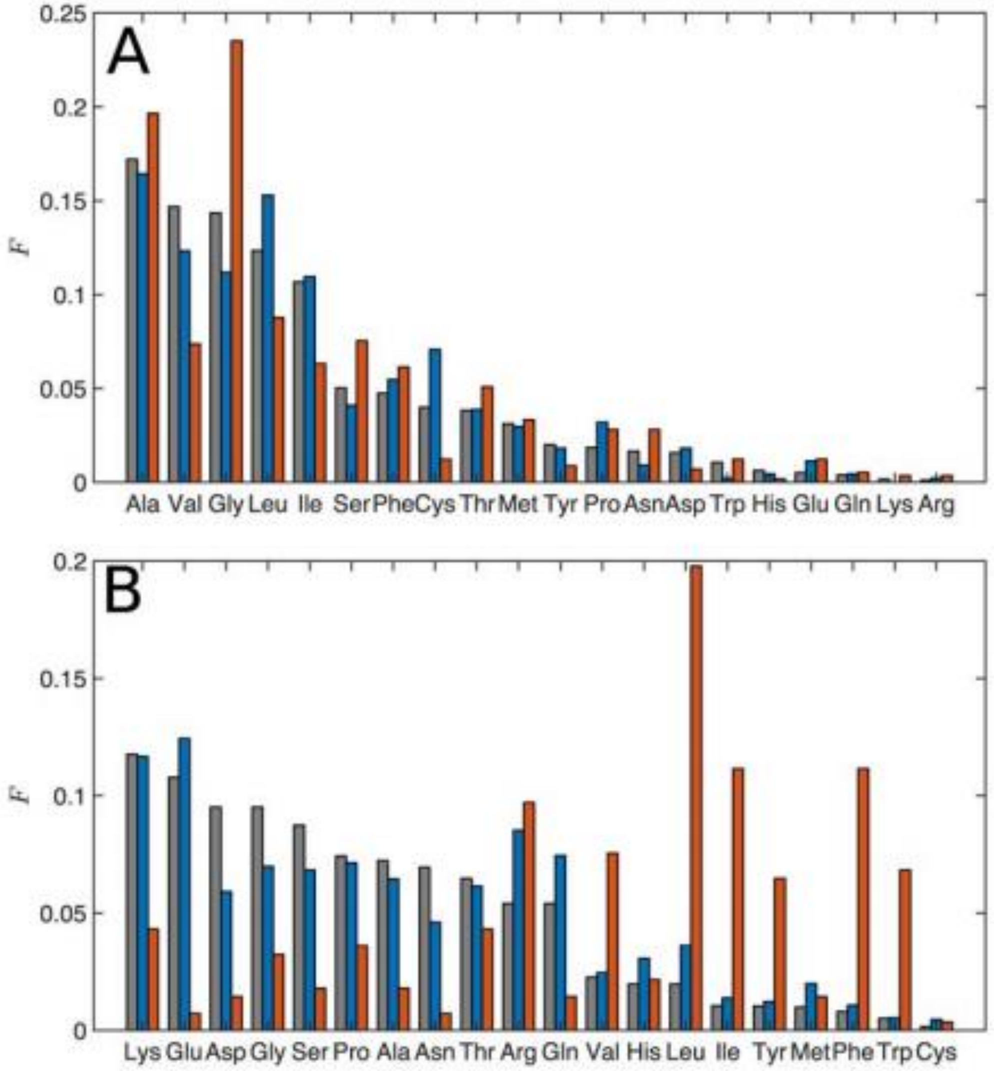
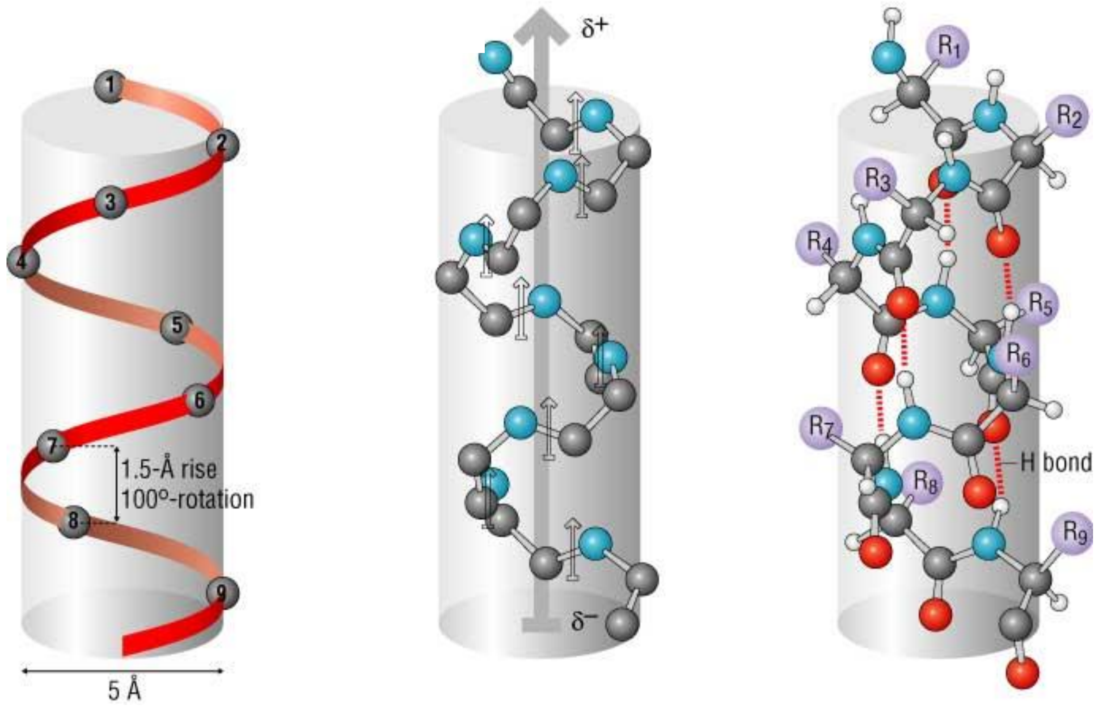
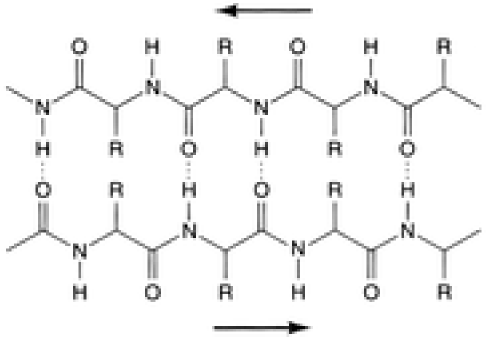


FIGURE 5 Fractions of amino acids with A, rSASA $\leq 10^{-3}$ and B, rSASA>0.5 for residues in the Dun1.0 (grey), PPI (blue), and TM (red) datasets. The fractions are defined relative to the total number of residues in each rSASA category. C, The fractions of core residues (light bars) and non-core residues (rSASA>0.5, dark bars) among the 11 non-charged residues (Ala, Gly, Ile, Leu, Met, Phe, Ser, Thr, Trp, Tyr, and Val) [Color figure can be viewed at wileyonlinelibrary.com]

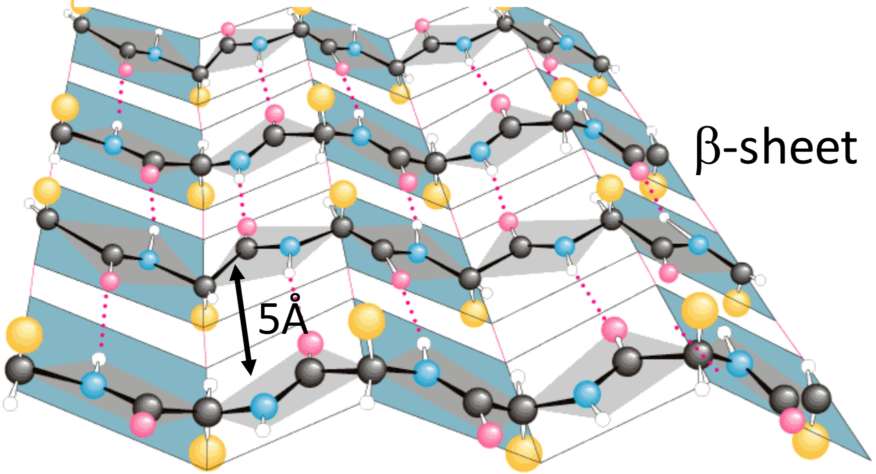
Secondary Structure: Loops, α-helices, β-strands/sheets

α-helix





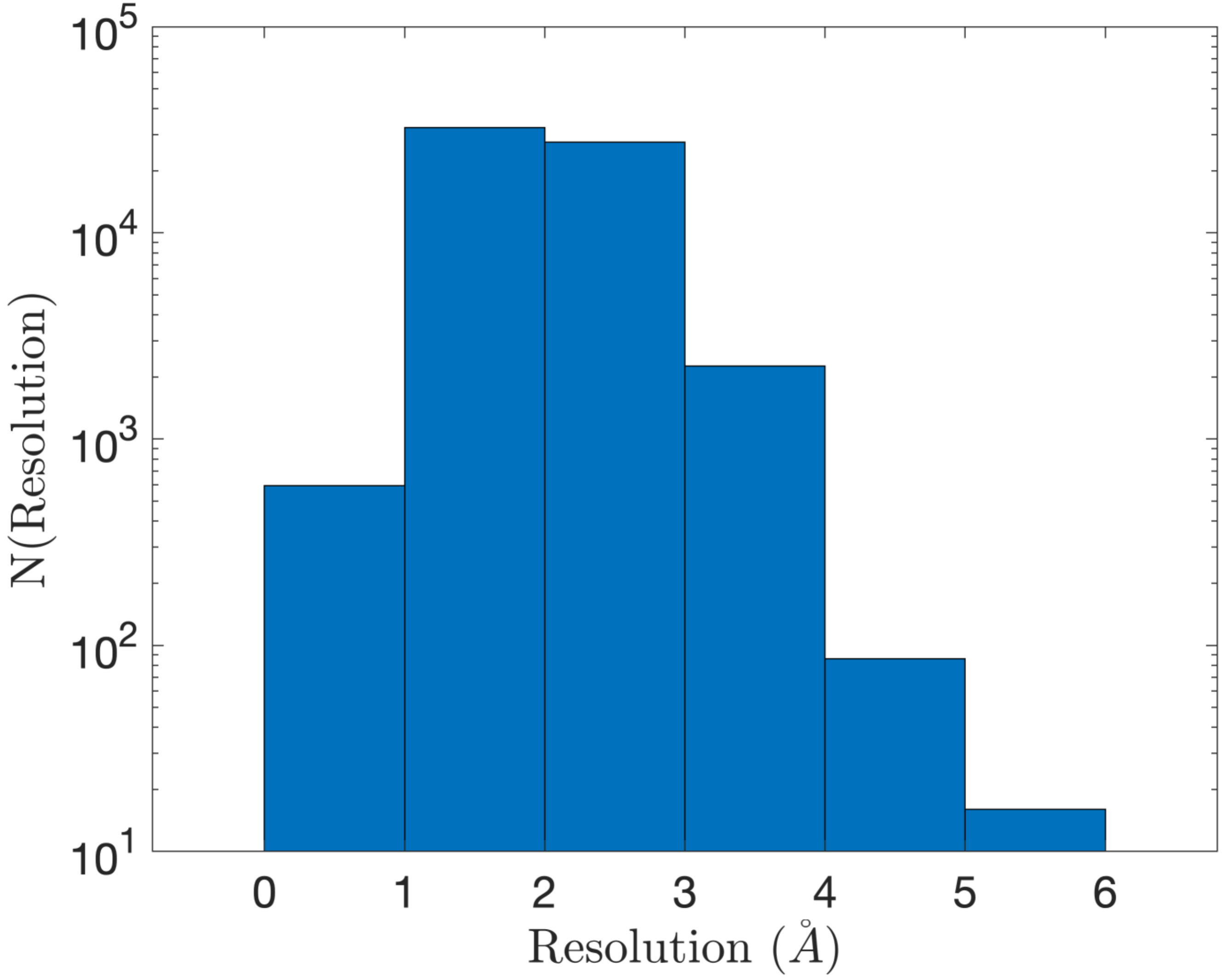
β-strand



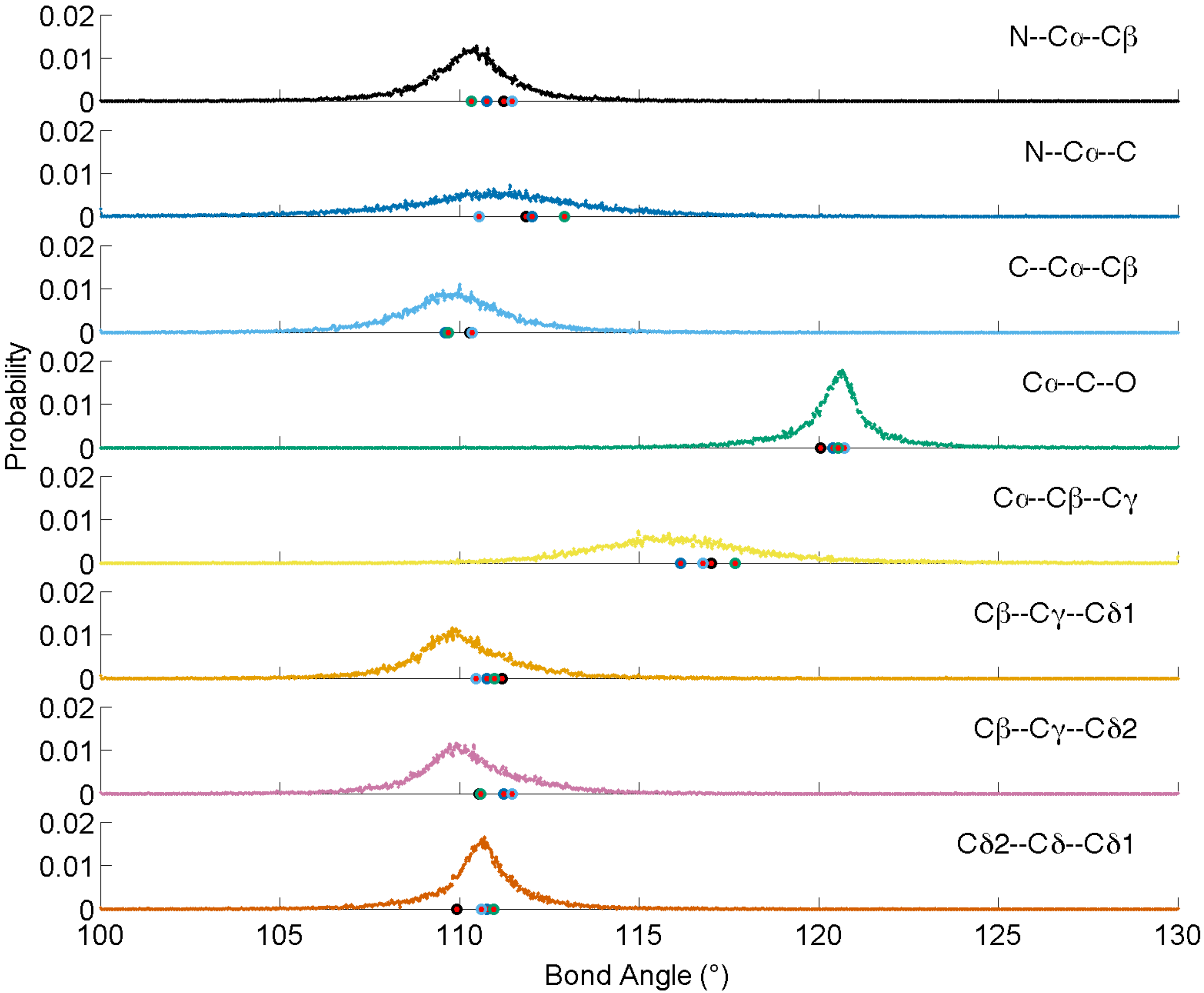
- Right-handed; three turns
- Vertical hydrogen bonds between NH_2 (teal/white) backbone group and C=O (grey/red) backbone group four residues earlier in sequence
- Side chains (R) on outside; point upwards toward NH_2
- Each amino acid corresponds to 100°, 1.5Å, 3.6 amino acids per turn
- $(\phi,\psi)=(-60°,-45°)$
- α-helix propensities: Met, Ala, Leu, Glu

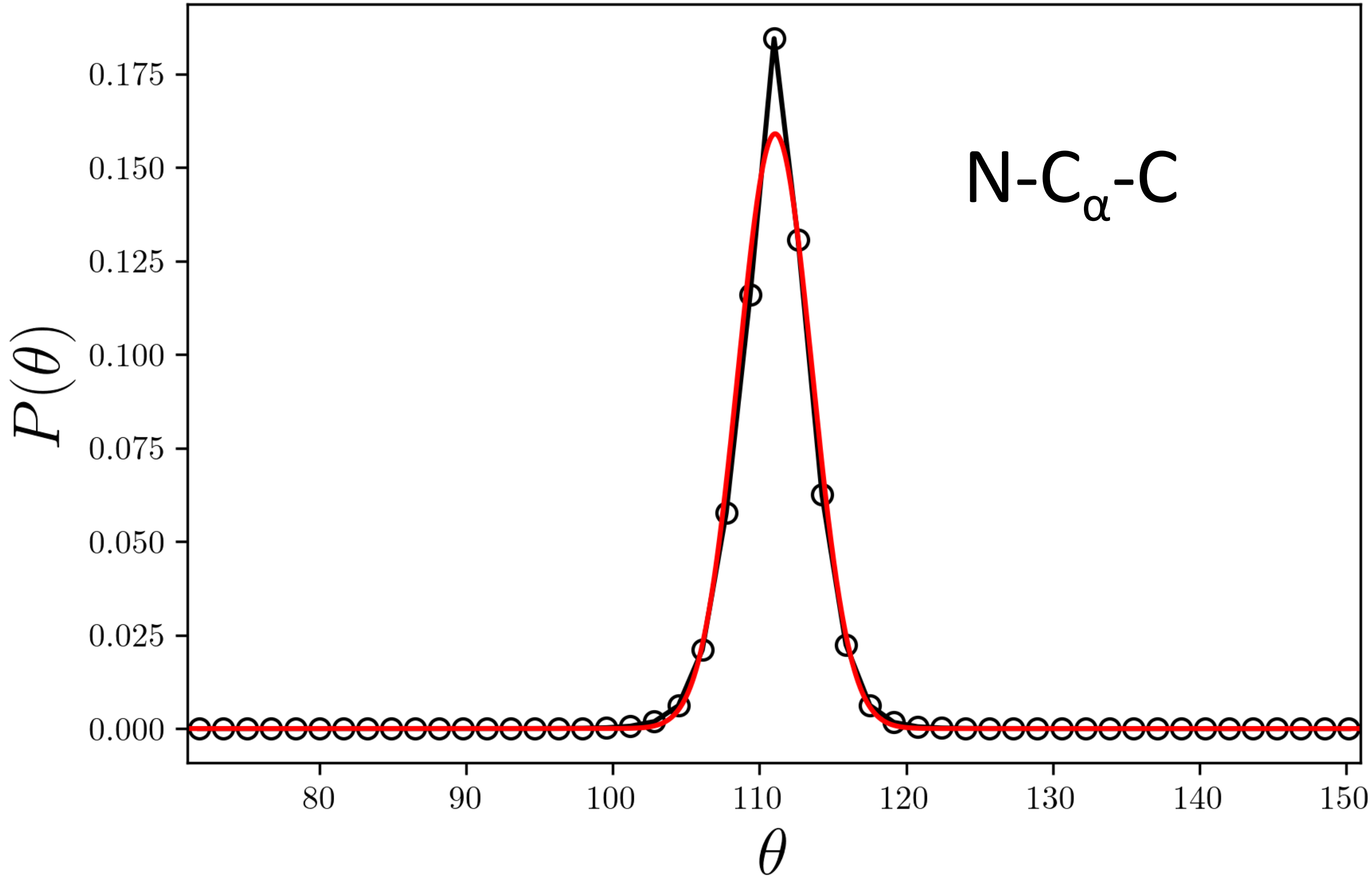
- 5-10 residues; peptide backbones fully extended
- NH (blue/white) of one strand hydrogen-bonded to C=O (black/red) of another strand
- C_α ,side chains (yellow) on adjacent strands aligned; side chains along single strand alternate up and down
- $(\phi,\psi)=(-135°,135°)$
- β-strand propensities: Val, Thr, Tyr, Trp, Phe, Ile

N_s=62,938 monomeric xtal structures

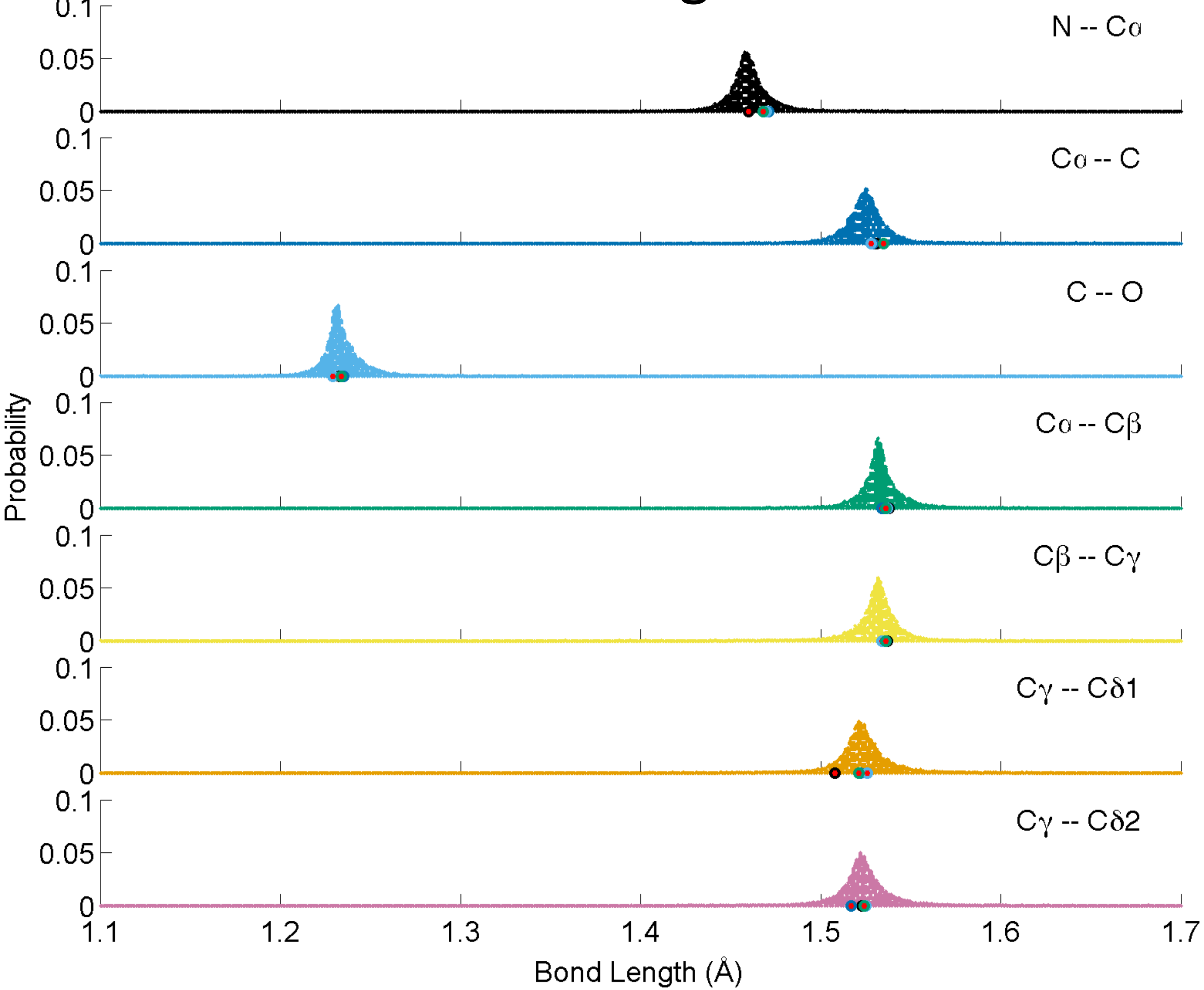


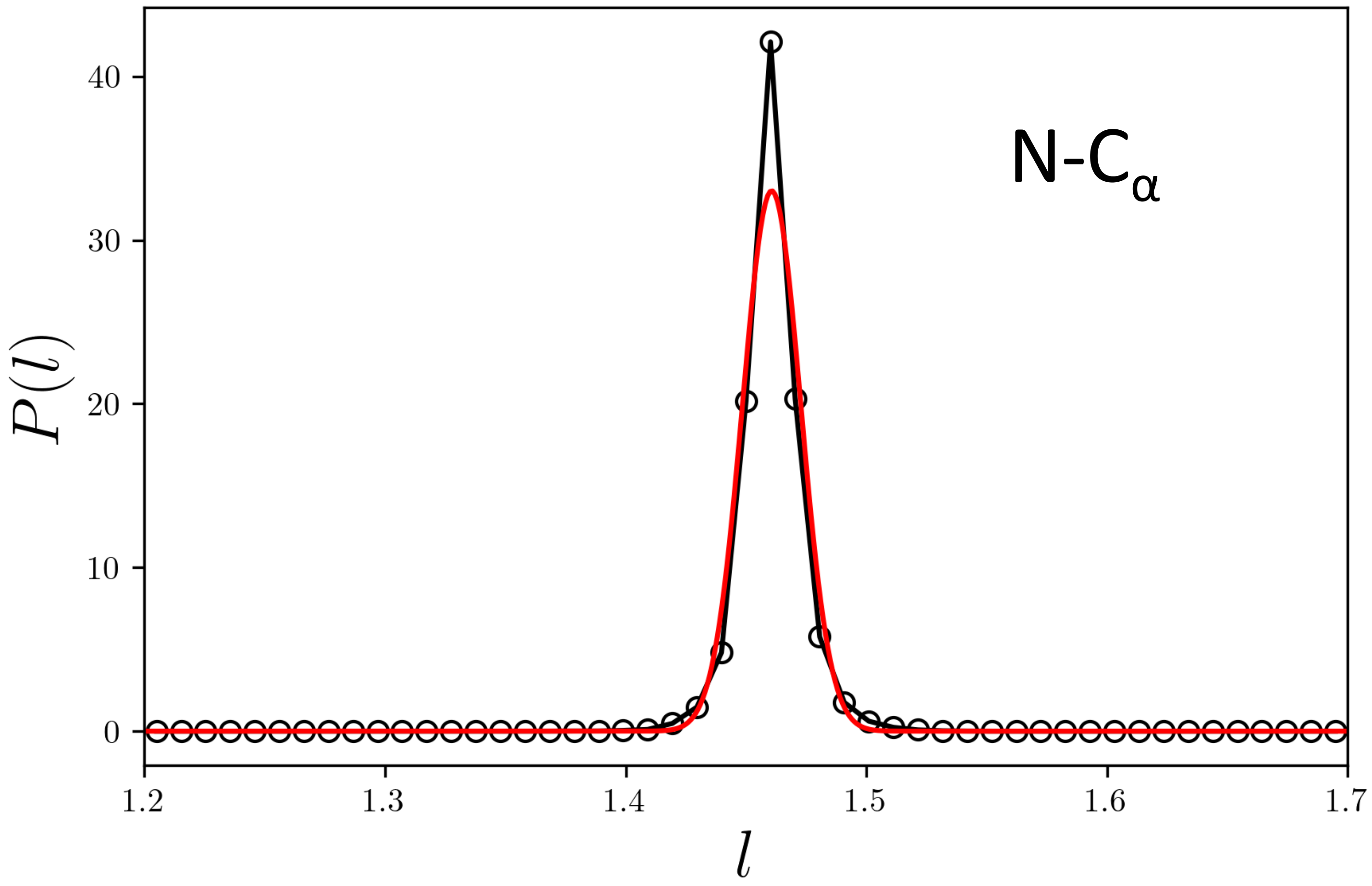
Bond Angles


N--Cα--Cβ
N--Cα--C
C--Cα--Cβ
Cα--C--O
Cα--Cβ--Cγ
Cβ--Cγ--Cδ1
Cβ--Cγ--Cδ2
Cδ2--Cδ--Cδ1
Probability
0.02
0.01
0
100
105
110
115
120
125
130
Bond Angle (°)

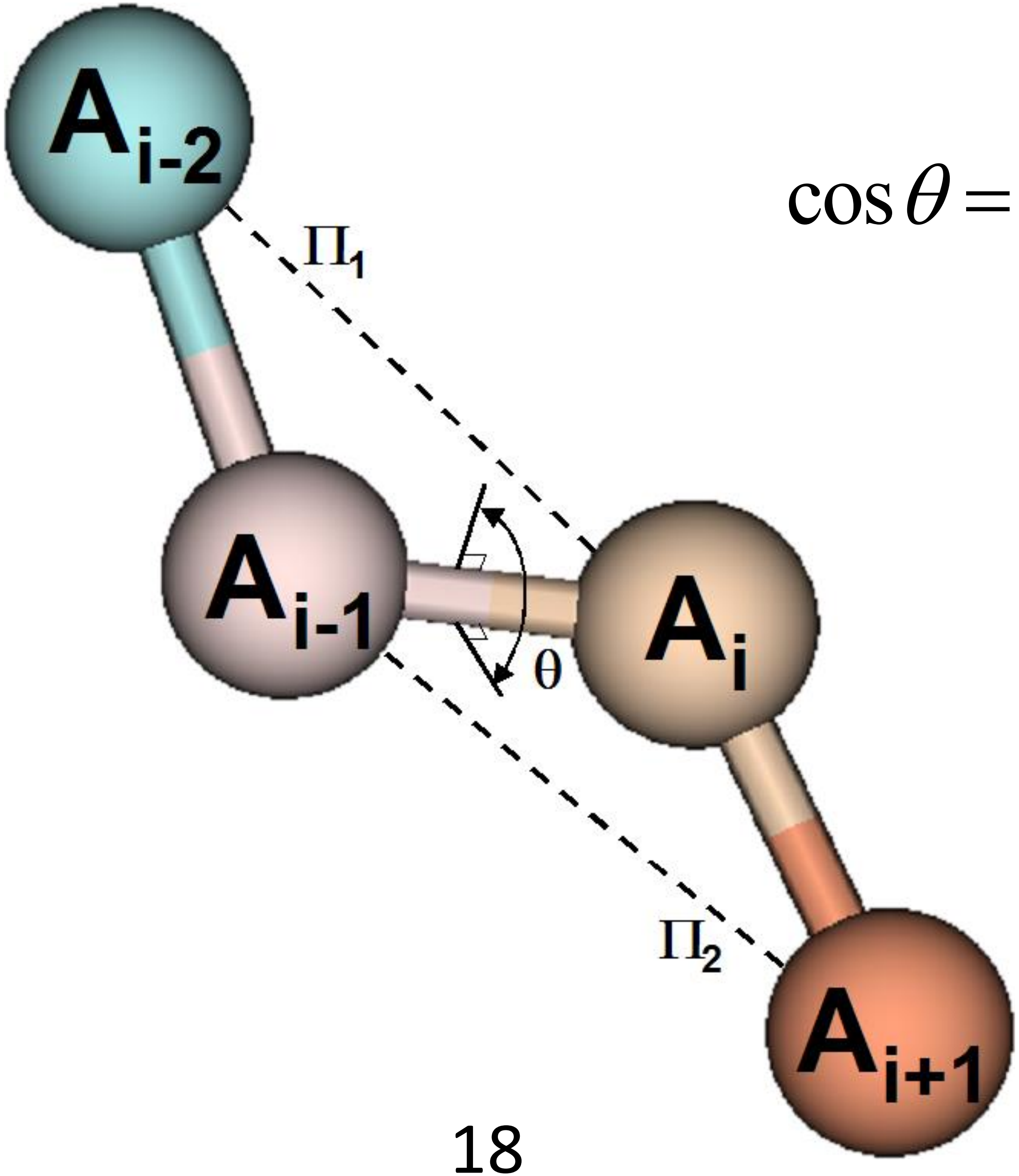

N-C_α-C
$P(\theta)$
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
80
90
100
110
120
130
140
150
θ

Bond Lengths




N-C_α
$P(l)$
l
0
10
20
30
40
1.2
1.3
1.4
1.5
1.6
1.7

Backbonde Dihedral Angles



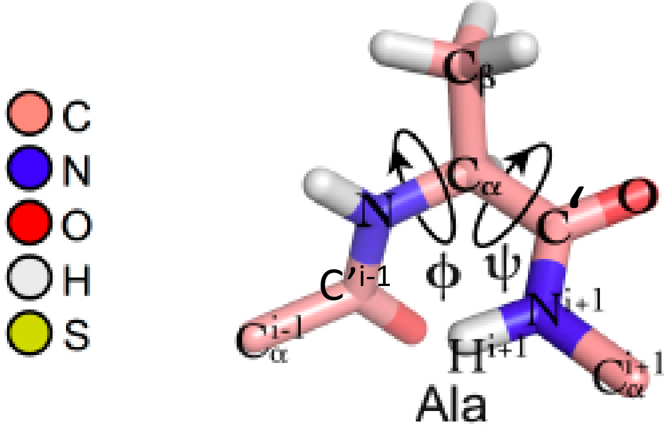
$$\cos\theta = \hat{\pi}_1 \,\mathrm{i}\, \hat{\pi}_2$$

3N-6 DoF

-(N-1) Bond lengths

-(N-2) Bond angles

=N-3 Dihedral angles



ϕ: $C'^{i-1}NC_{\alpha}C'$

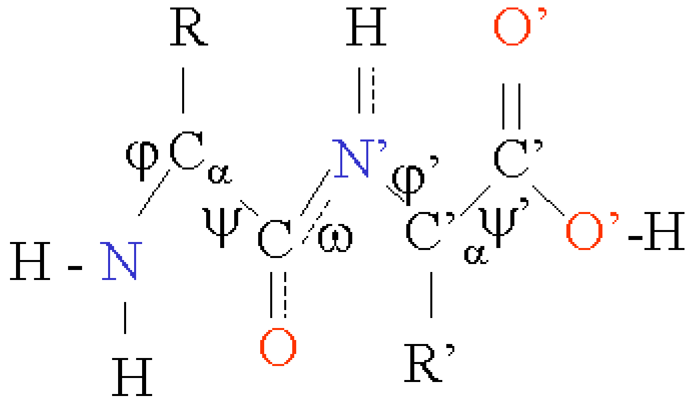
ψ: $NC_{\alpha}C'N^{i+1}$

ω_1:$C^{i-1}{}_{\alpha}C'^{i-1}NC_{\alpha}$

ω_2:$C_{\alpha}C'N^{i+1}C^{i+1}{}_{\alpha}$

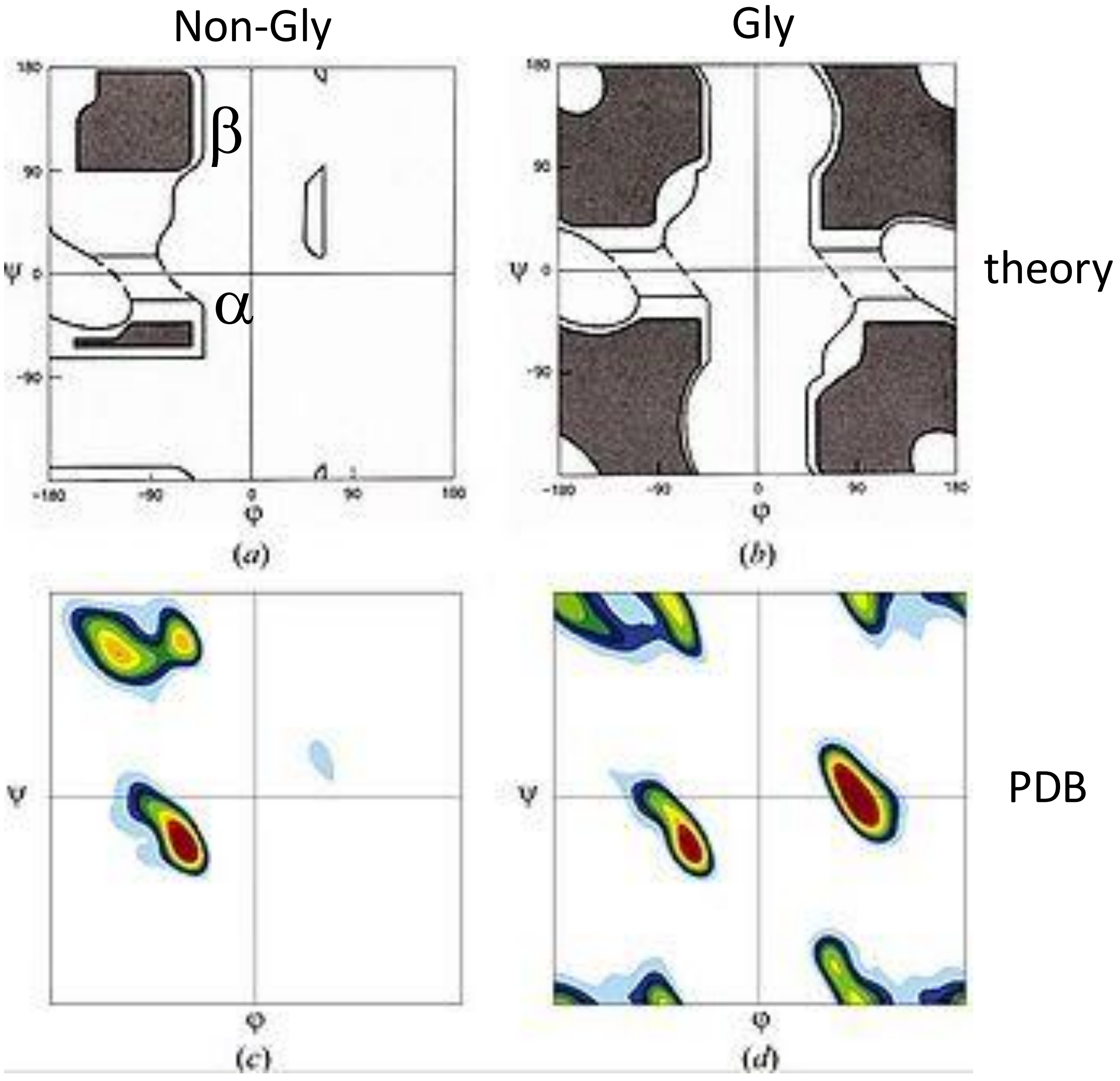
Ramachandran Plot: Determining Steric Clashes

Backbone dihedral angles



4 atoms define dihedral angle:

$C_{-1}NC_{\alpha}C$	ϕ
$C_{\alpha,-1}C_{-1}NC_{\alpha}$	ω=0,180°
$NC_{\alpha}CN_{+1}$	ψ

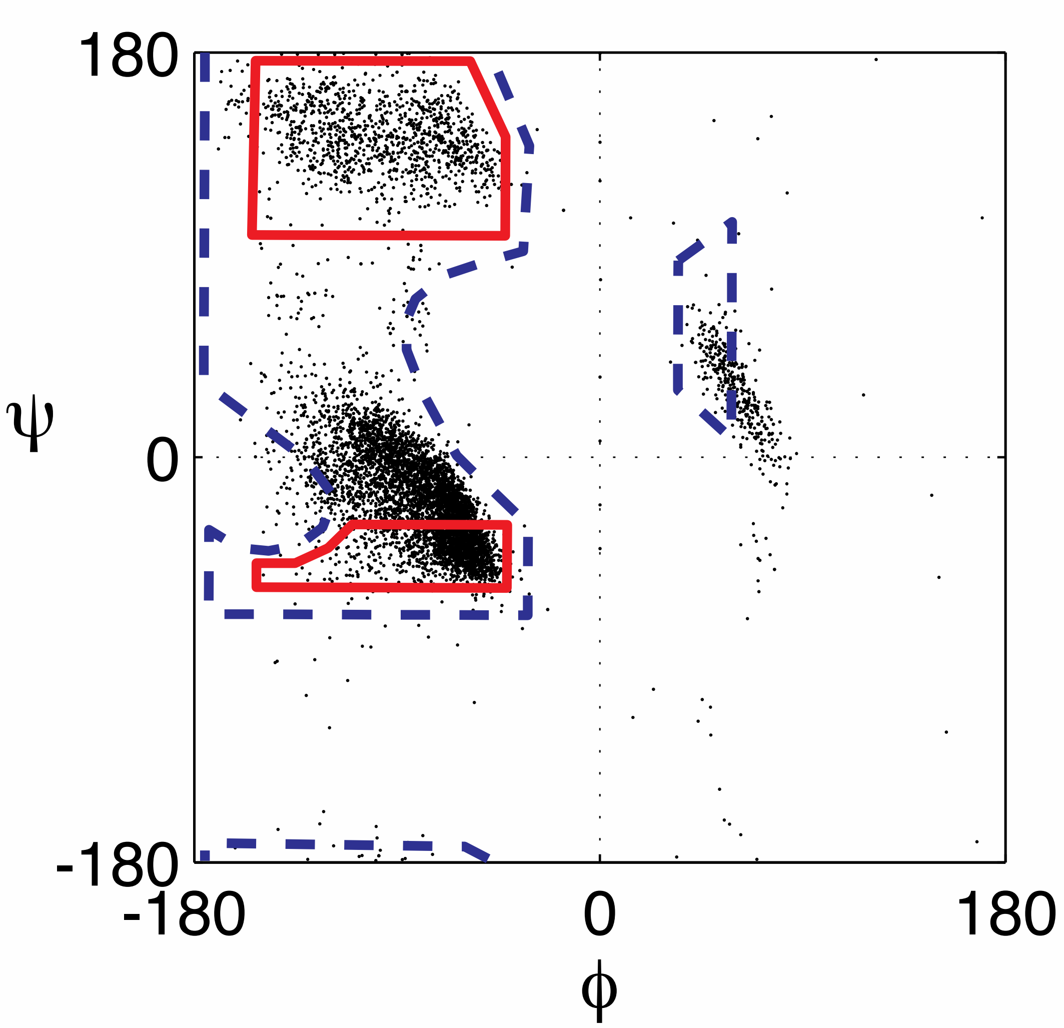


▨ vdW radii

— < vdW radii

- - - backbone flexibility

Backbone dihedral angles from PDB



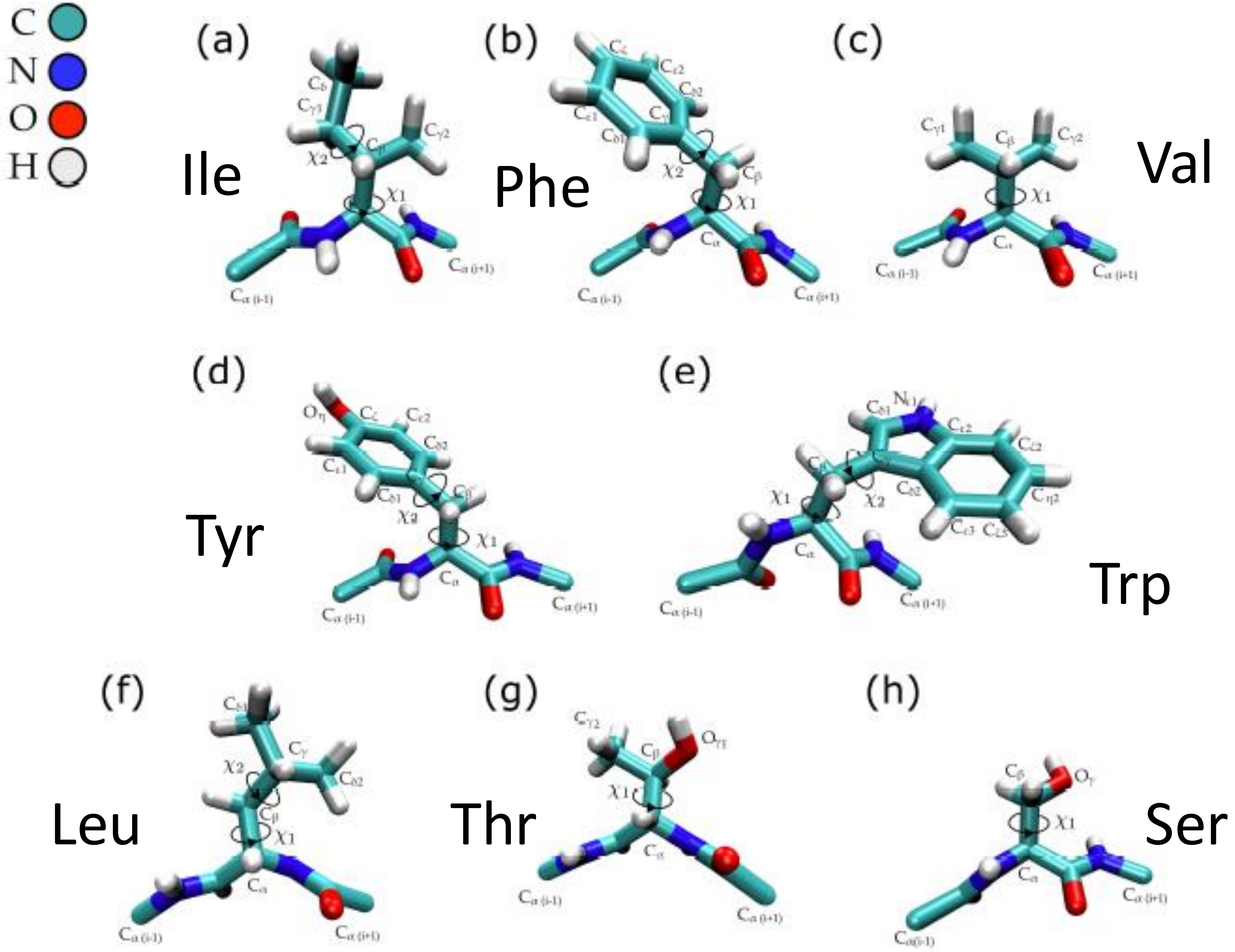
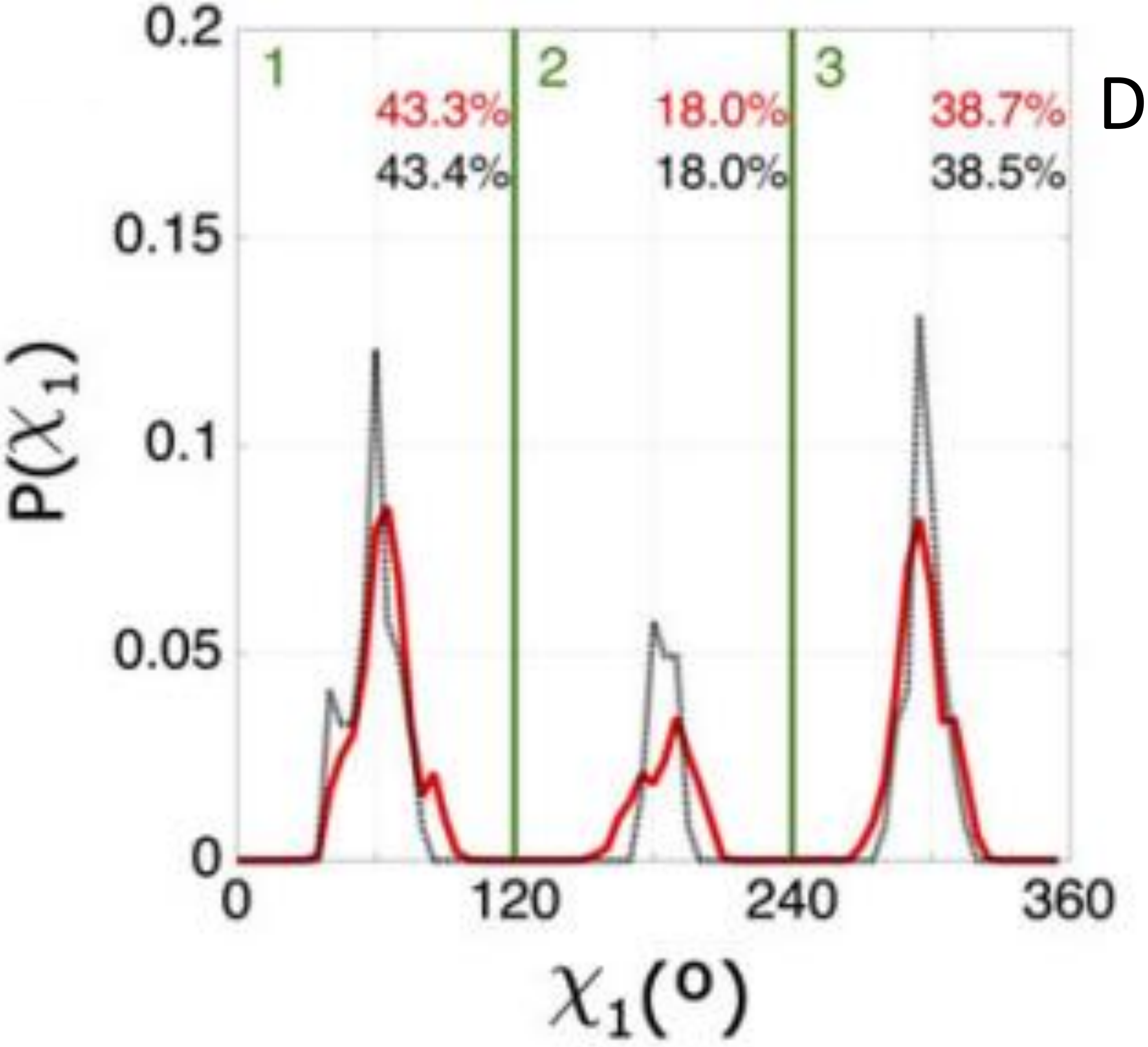


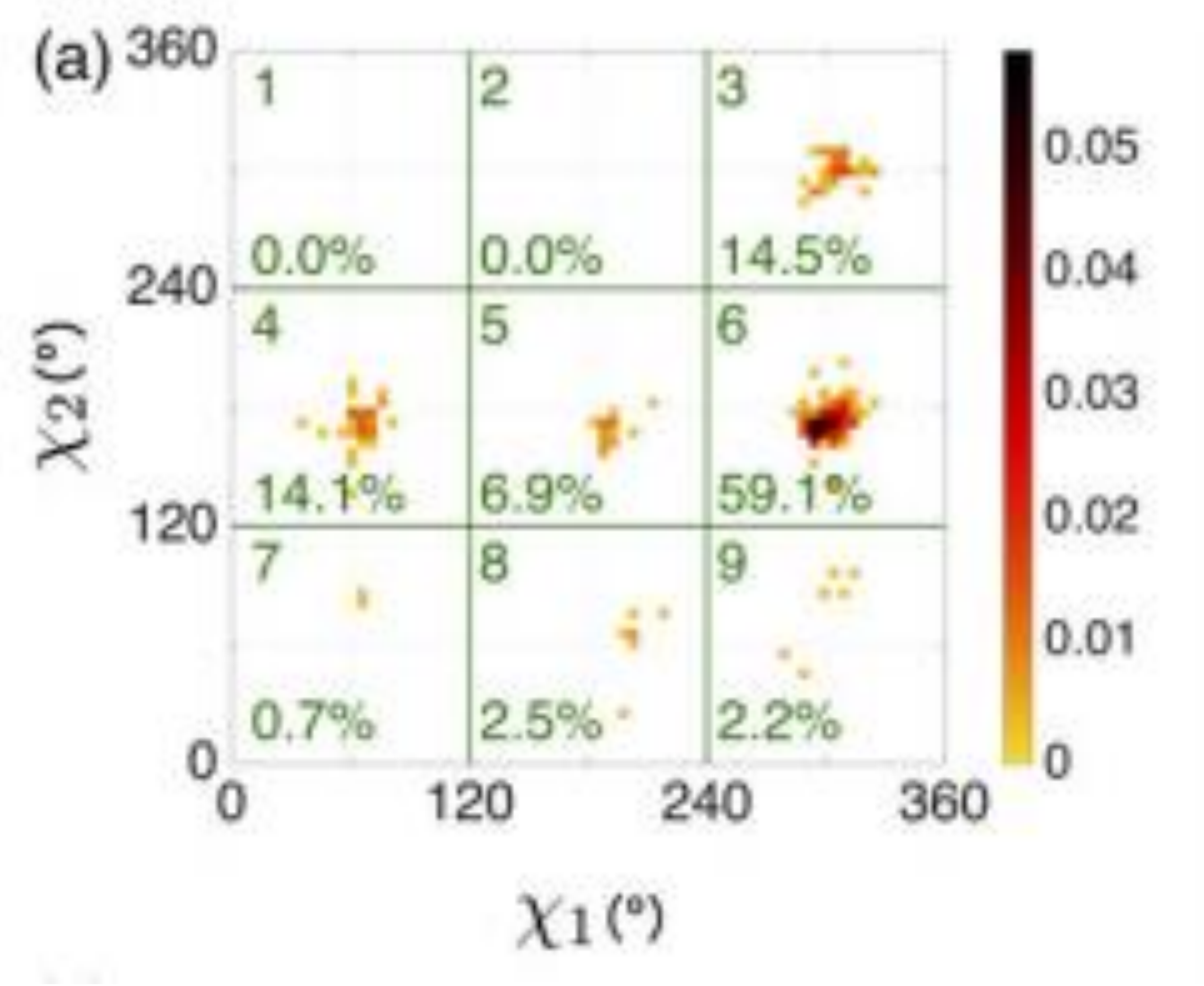
Figure S1: Stick representations of (a) Ile, (b) Phe, (c) Val, (d) Tyr, (e) Trp, (f) Leu, (g) Thr, and (h) Ser dipeptide mimetics. The carbon, nitrogen, oxygen, and hydrogen atoms are shaded green, blue, red, and white, respectively. The side chain dihedral angles χ_1 and χ_2 and several key atoms are labeled. The residues before (i-1) and after (i+1) the ith central residue are labeled at the C_α atom.

Thr



Dunbrack 1.0

Ile


(a)
360
240
120
0
0
120
240
360
χ2 (°)
χ1 (°)
1
0.0%
2
0.0%
3
14.5%
4
14.1%
5
6.9%
6
59.1%
7
0.7%
8
2.5%
9
2.2%
0.05
0.04
0.03
0.02
0.01
0