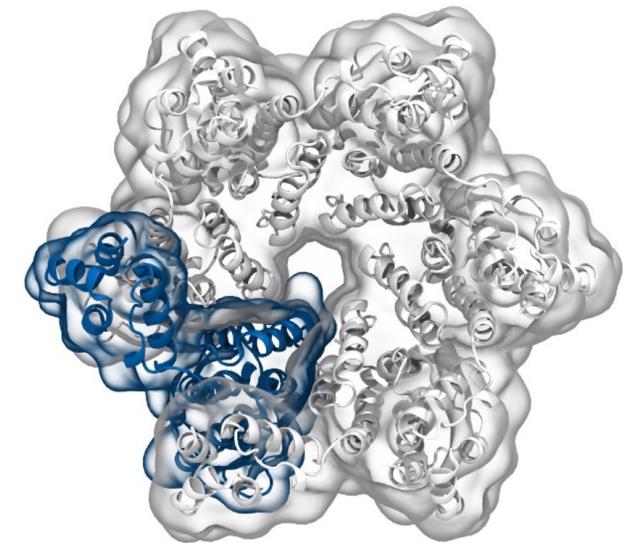
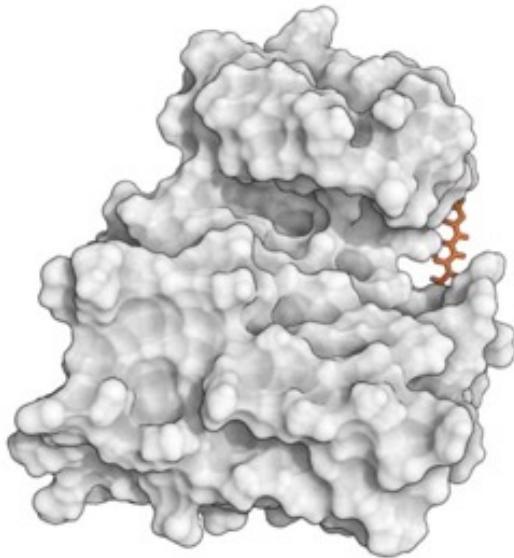


Simulation of Biomolecules

Introduction



Dr Matteo Degiacomi

Durham University

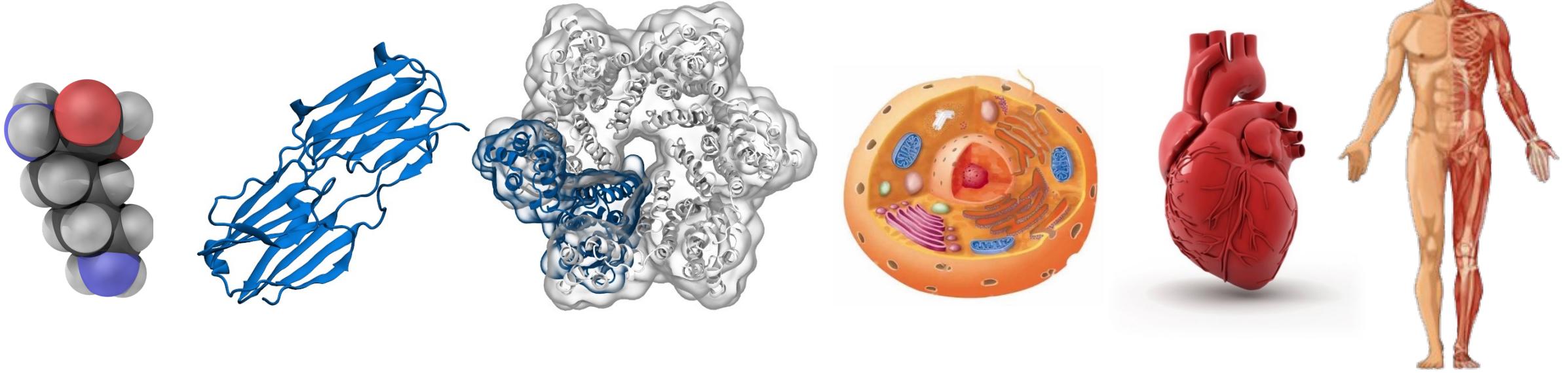
matteo.t.degiacomi@durham.ac.uk

Dr Antonia Mey

University of Edinburgh

antonia.mey@ed.ac.uk

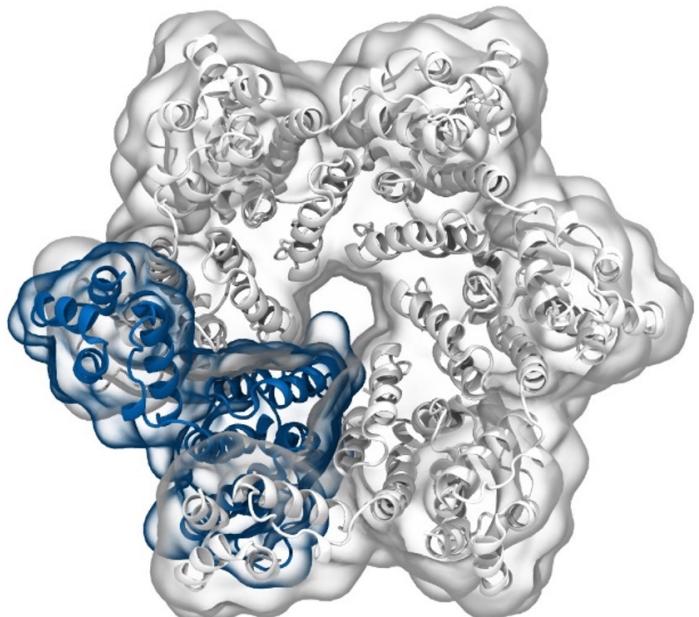
Life emerges from molecular assembly



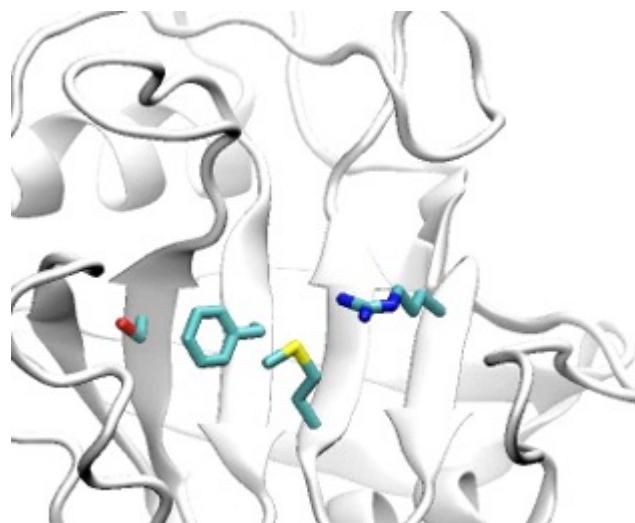
COMPLEXITY

Structure and dynamics determine protein (mal)function

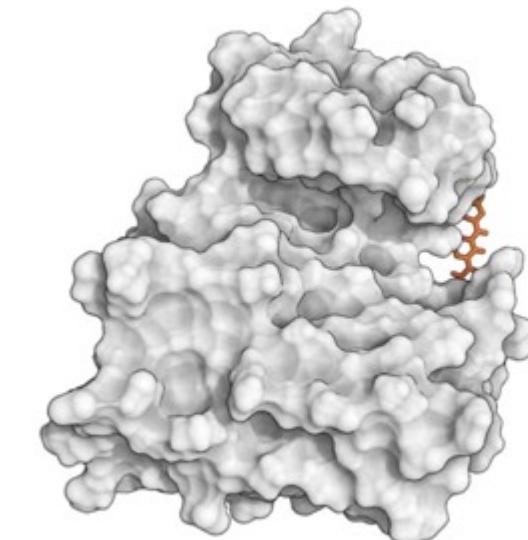
HIV Capsomer



Cyclophilin



Tyrosine kinase – dasatanib

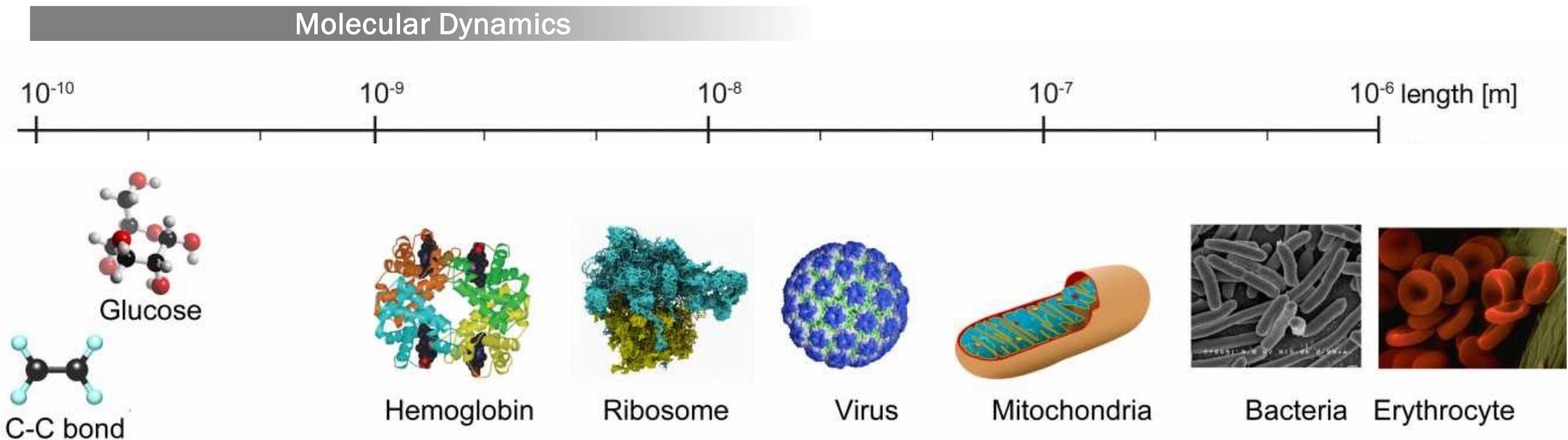


M.T. Degiacomi, *Structure*, 2019

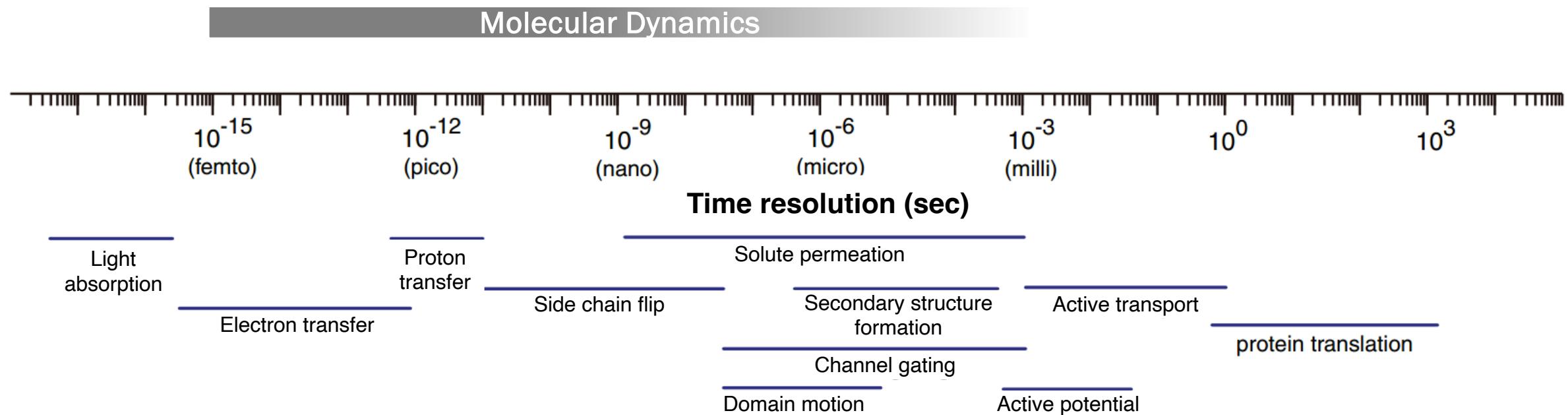
Wapeesittipan, Mey, et al., *Comms. Chem.*, 2019

Y Shan et al. *JACS*, 2011

Sizes in biochemistry



Timescales in biochemistry

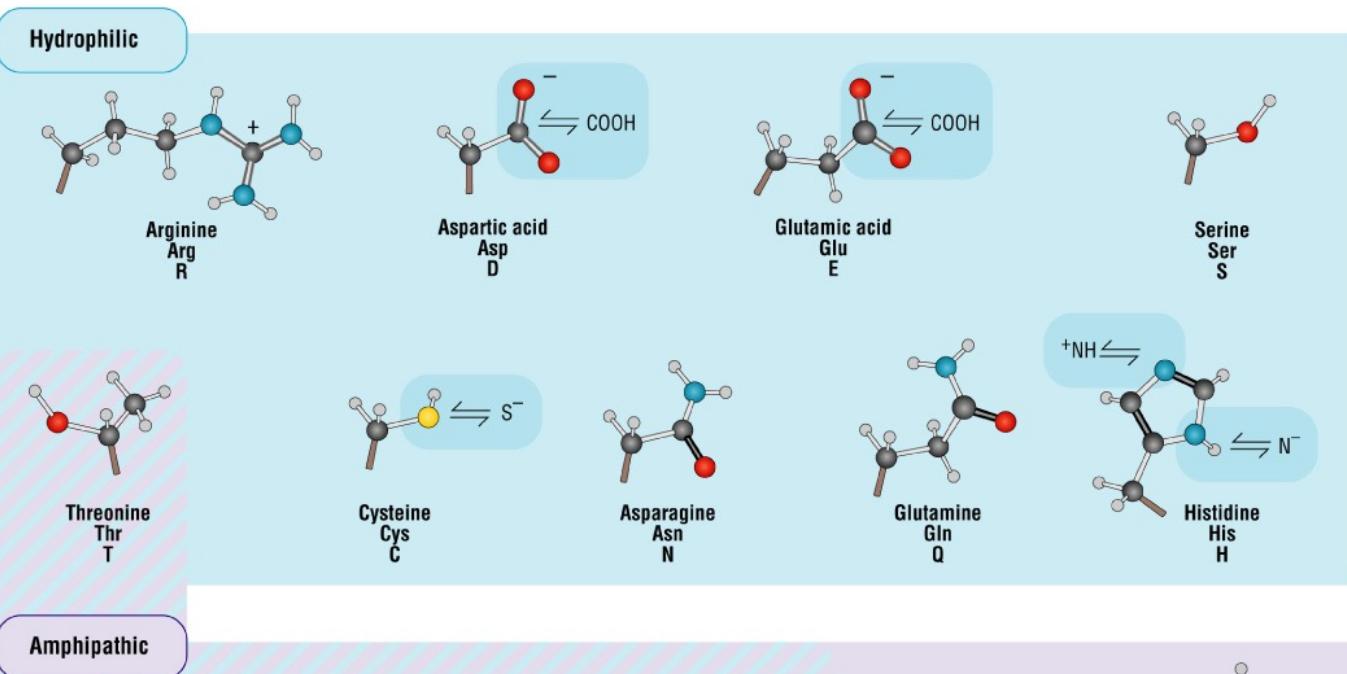
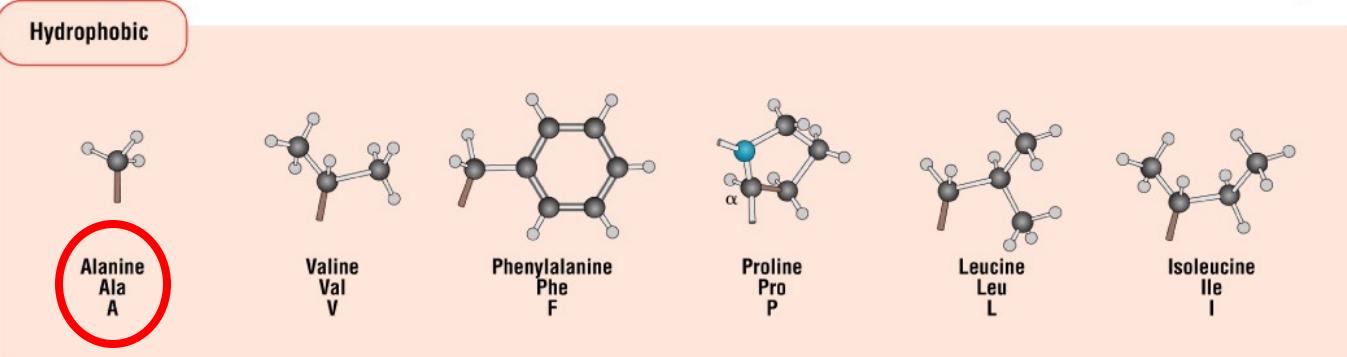
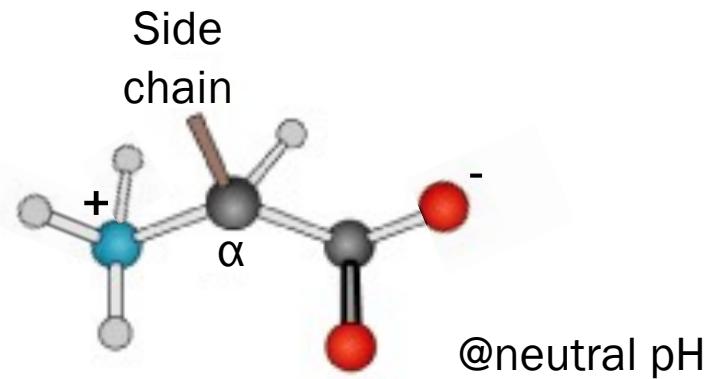


Part 1: What is a protein?

Proteins are amino acids polymers

Amino acids are composed of:

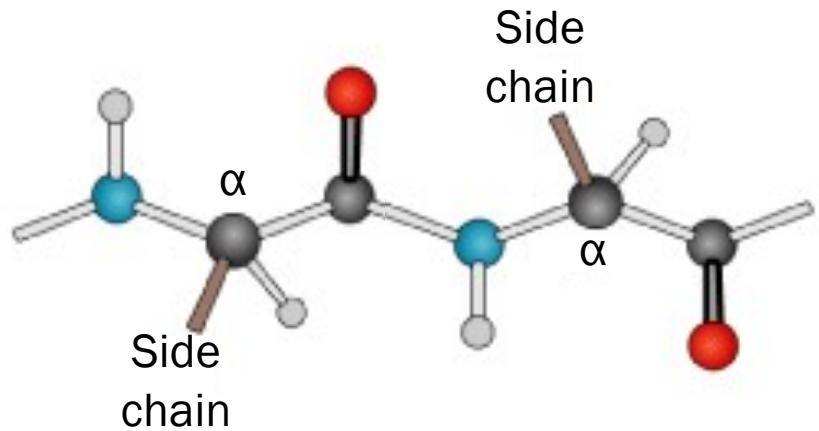
- **Backbone** (conserved)
- **Side chain** (variable)



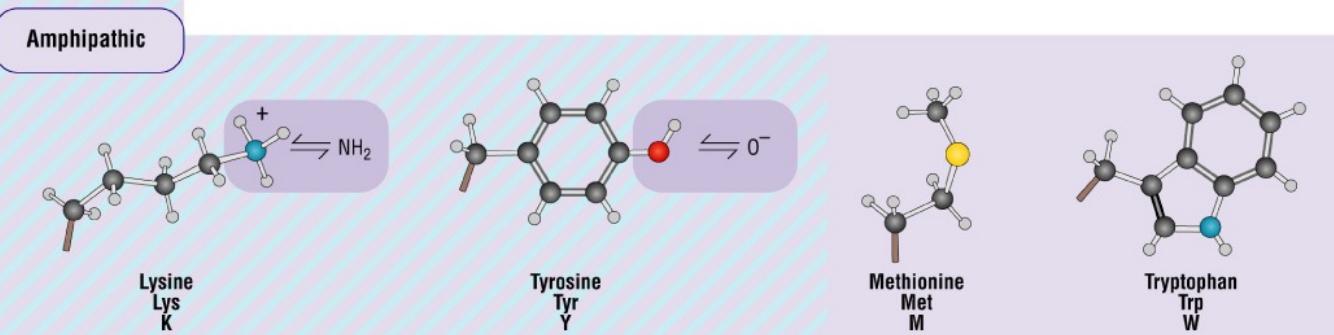
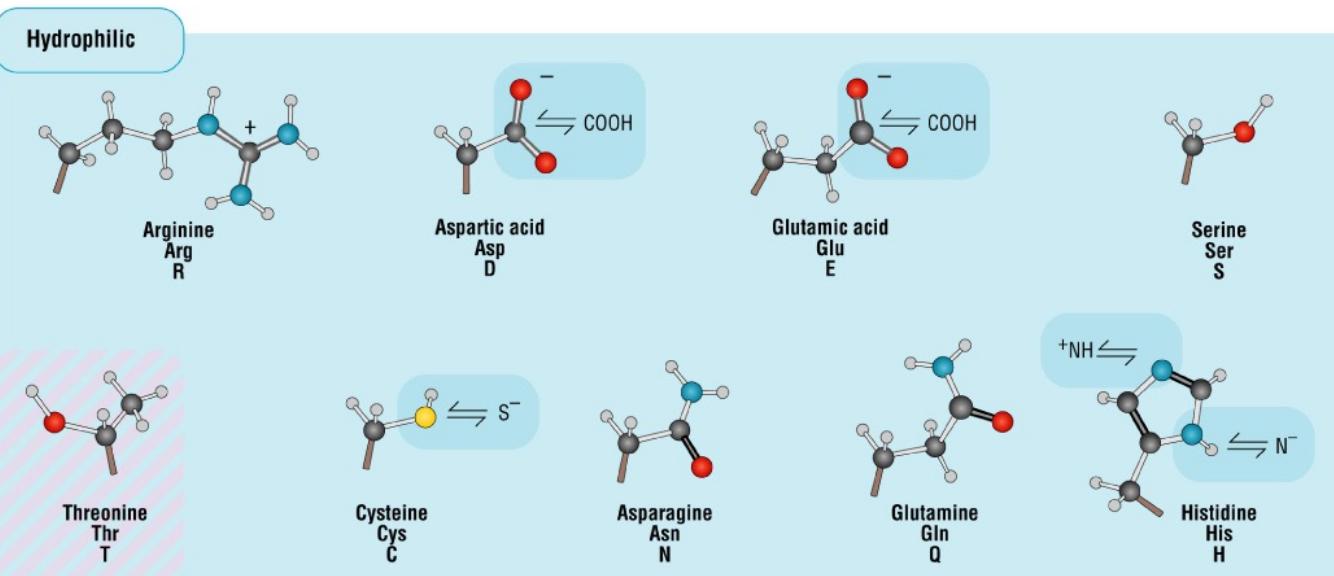
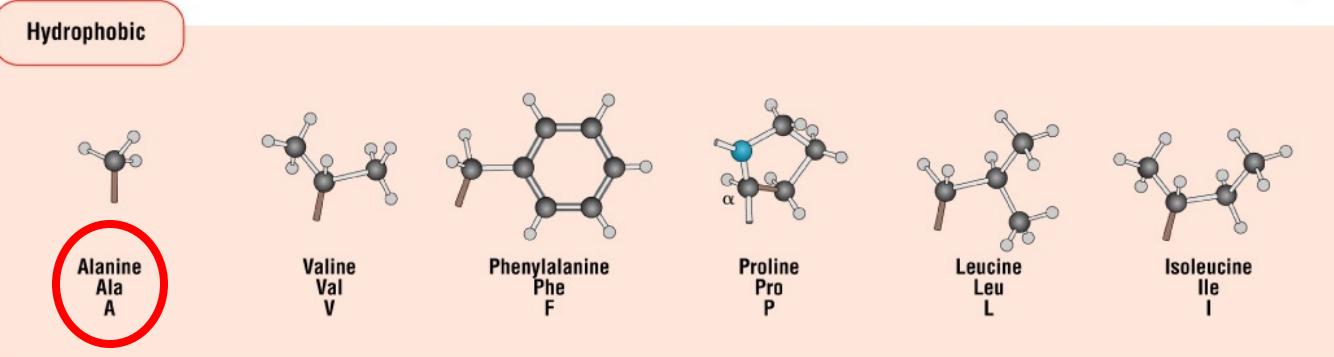
Proteins are amino acids polymers

Amino acids are composed of:

- **Backbone** (conserved)
- **Side chain** (variable)



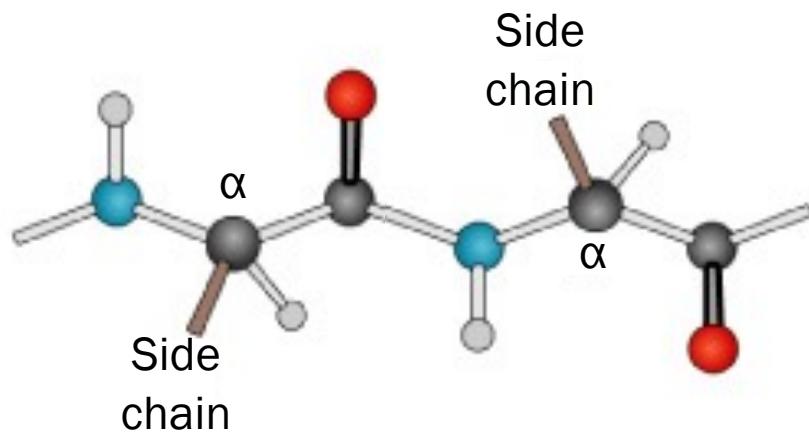
Amino acids polymerize forming a *peptidic bond* (condensation)



Proteins are amino acids polymers

Amino acids are composed of:

- Backbone (conserved)
- Side chain (variable)



Amino acids polymerize forming a *peptidic bond* (condensation)

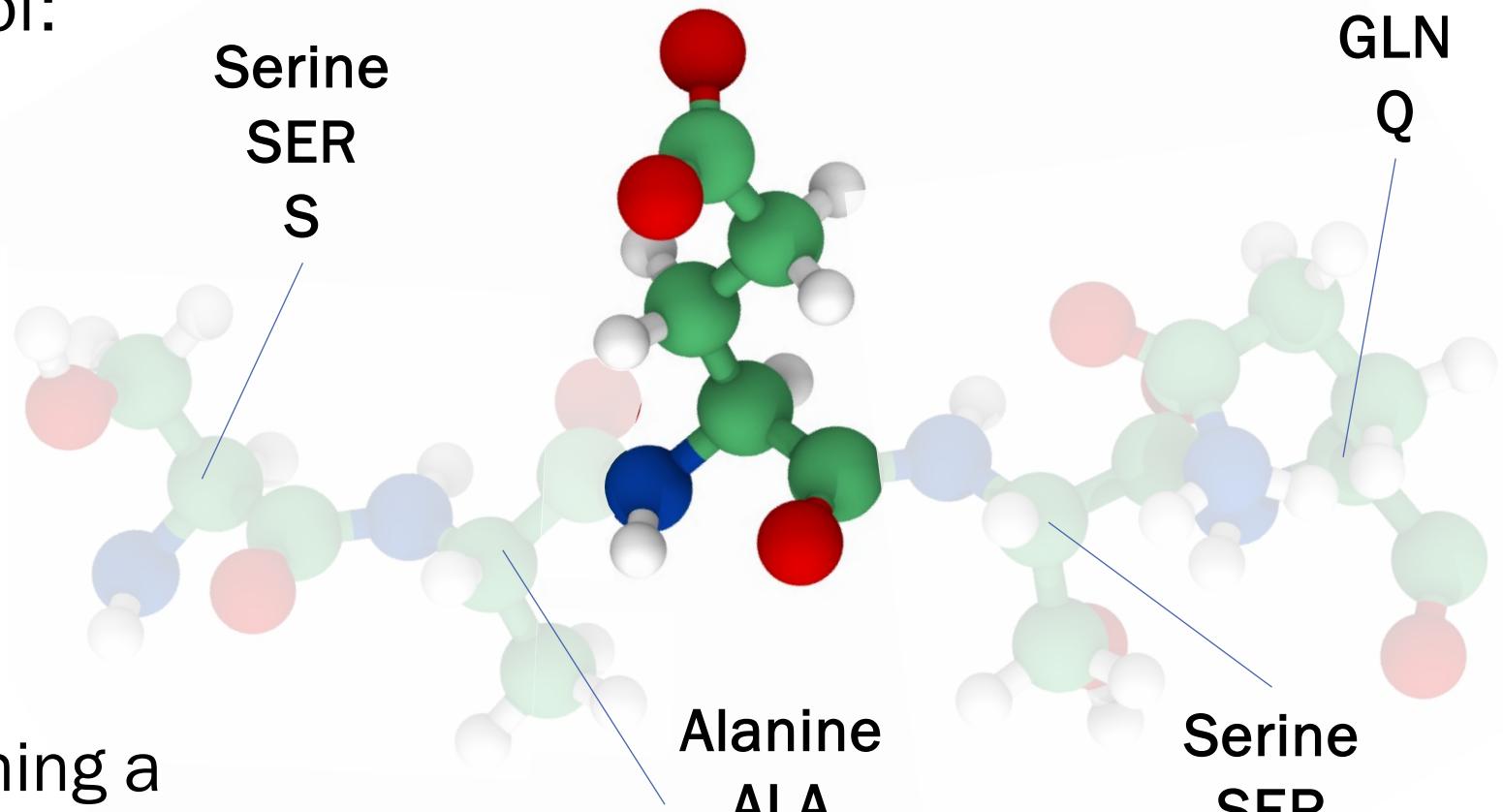
Glutamic acid
GLU
E

Glutamine
GLN
Q

Serine
SER
S

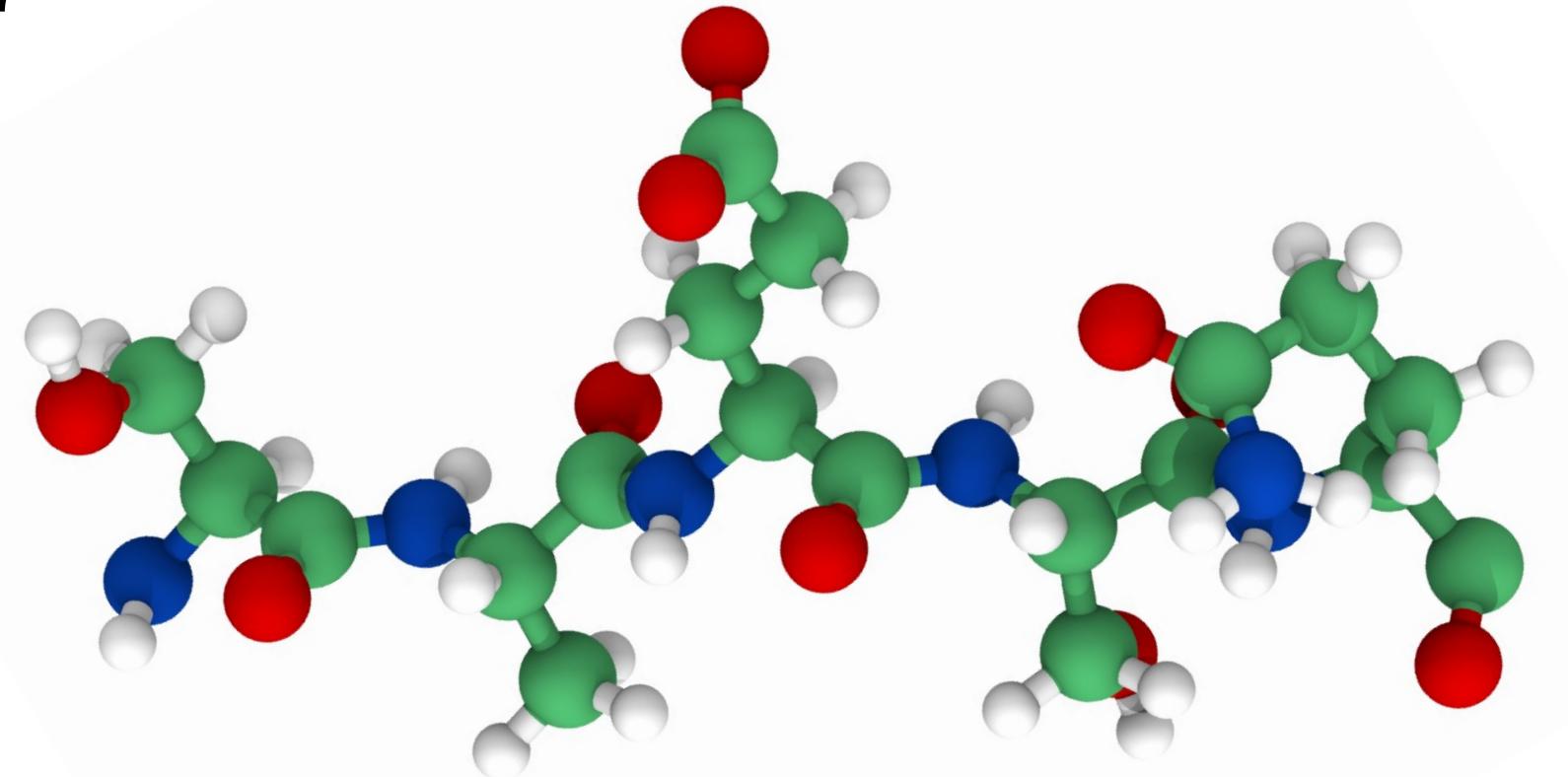
Alanine
ALA
A

Serine
SER
S



Protein Primary Structure: Sequence

SAESQ

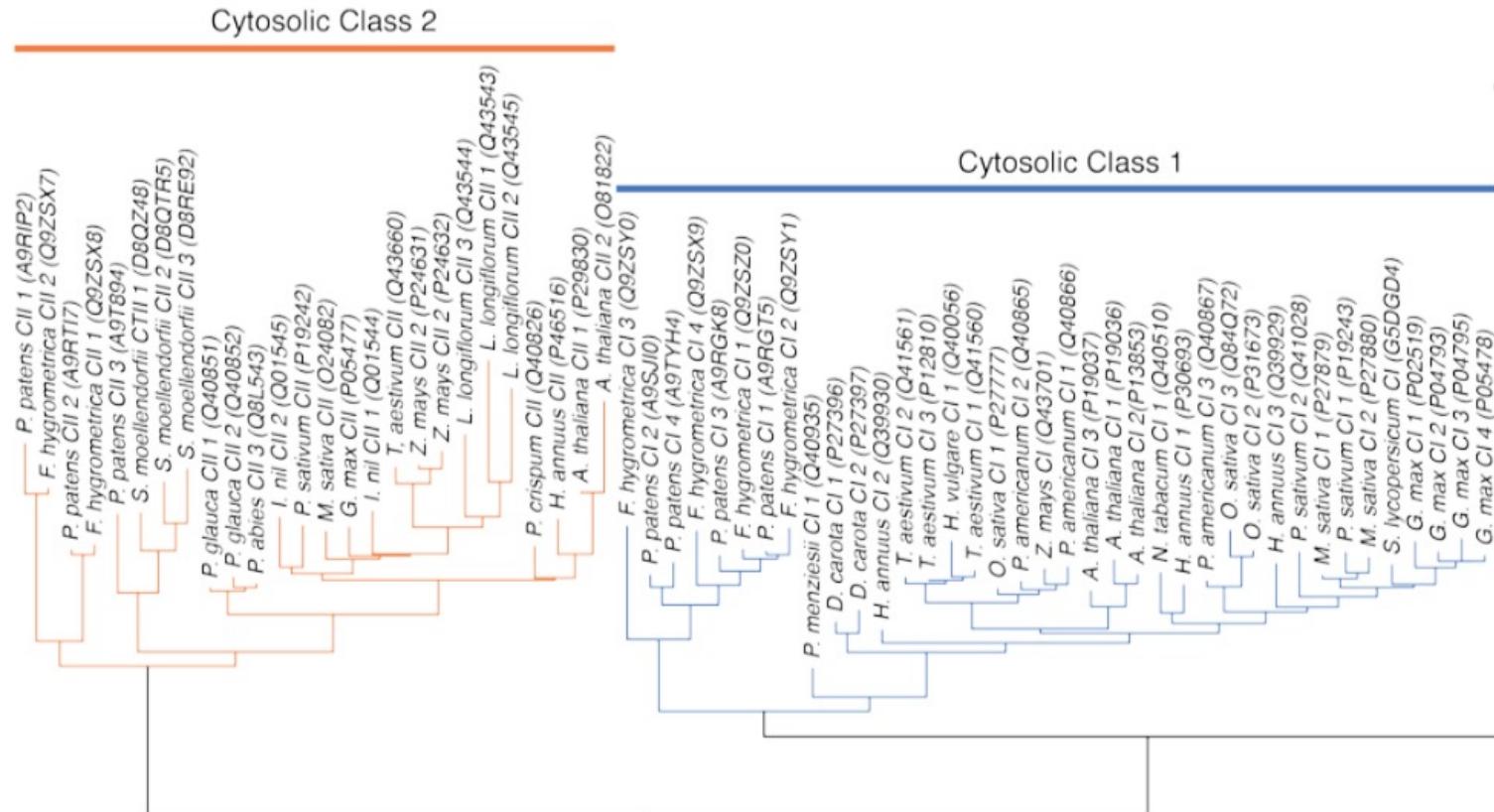


Proteins with similar sequence, likely:

- have similar functions in an organism
- are evolutionarily related

Protein Primary Structure: Sequence

Angiosperm 1 MSLIPSFFSGRRSNVFD-PF--SL-DVWDPLKD-FPFSNSSPSASPRENPAFV-STRVDWKETPEAHVFKA
DLPGLKKEEVKVEVE
Gymnosperm 1 MSIIPSFFGRRSSSAFD-PF--SL-DVWDPLFRAFTDLGGGPGSGQFVNEASAVA-NTQIDWKETPEAHIFKA
DLPGLKKEEVKIELE
Bryophyte 1 MAL--SLFGSRGNGVFD-PF--EFGSVWDPFSA---PESGLSRKLAGDAHAGA-NTRIDWRETPEAHIFKA
DLPGLRKEEVKIQVV
Angiosperm 2 -----MDLDSPLFNTLHHIMDLTDDTTEKNLNAPRTTYVRDAKAMA-ATPADVKEHPNSYVFMVDMPGVKSGDIKVQVE
Gymnosperm 2 -----MAMD-PSLITVQHLLGVPDD-LEKLLNAPTHSYMRDTKAMA-STPVDVKEYPNSYVFIIDMPGLKSNDIKVQVE
Bryophyte 2 -----MEFVVFDTD-PFLTS LHQLVHEPESDLERKIKRKRRSQHDEPRHVTIATPVDVKEKKDAYLFIA
DVPGLQKTDIEVQIE

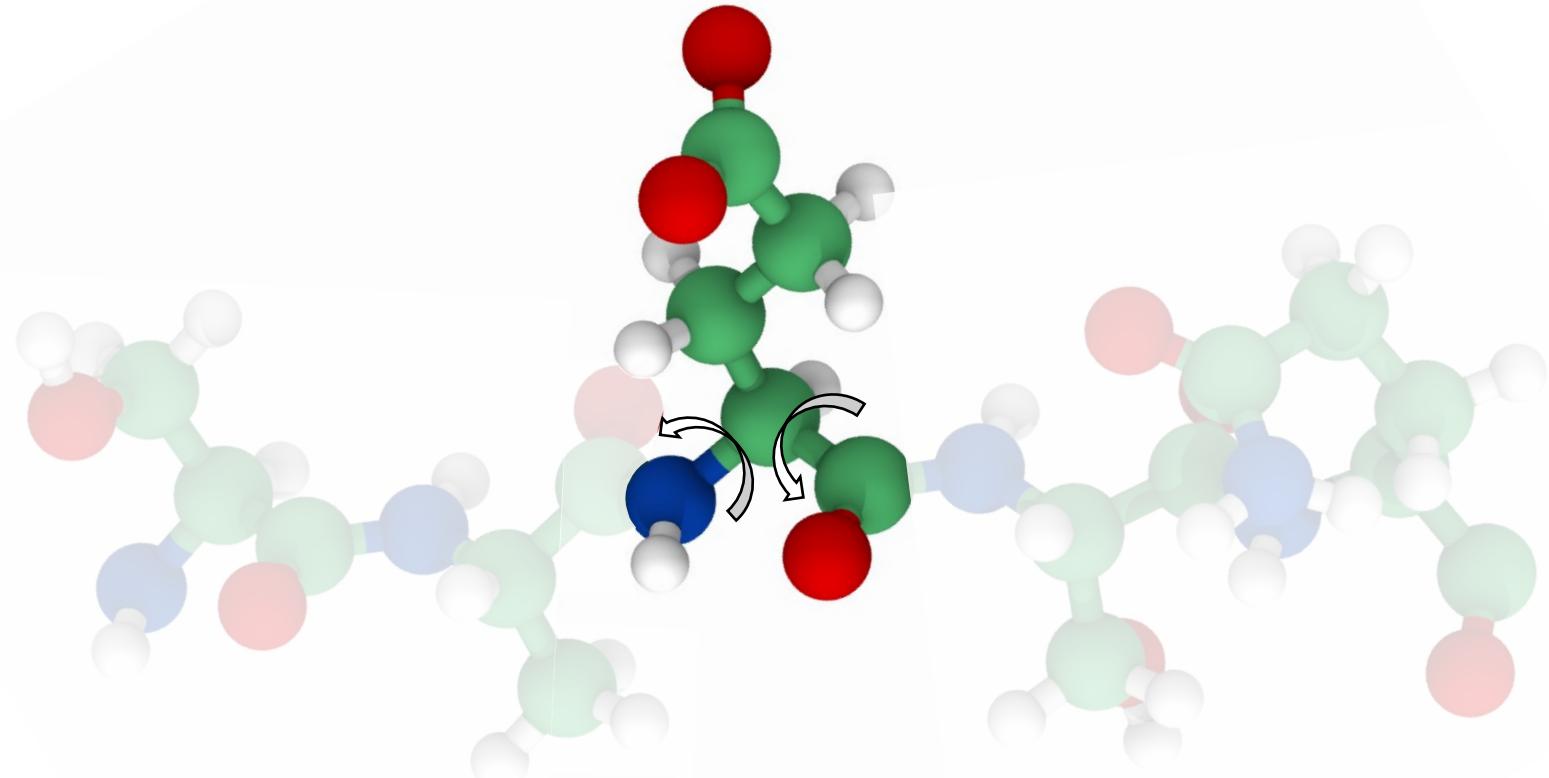


Proteins with similar sequence, likely:

- have similar functions in an organism
- are evolutionarily related

Protein Secondary Structure

The amino acid chain path is determined by backbone torsional angles

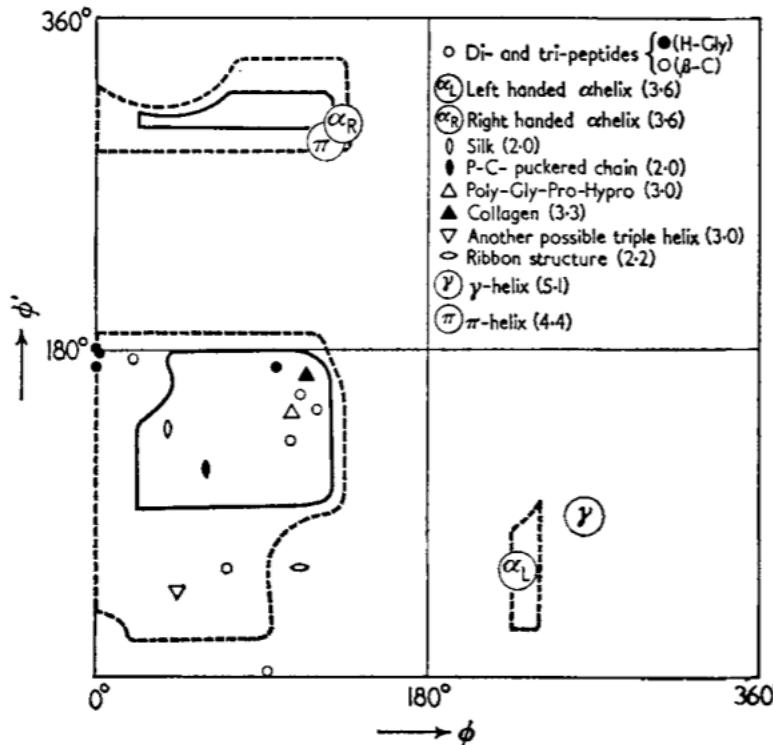
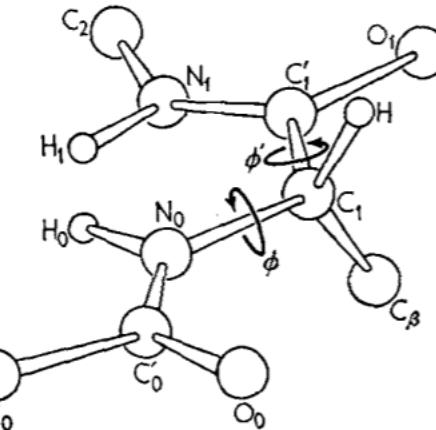


Protein Secondary Structure

The amino acid chain path is determined by backbone torsional angles

Ramachandran plot: scatter plot of amino acids backbone torsional angles

G.N. Ramachandran, C. Ramakrishnan, V. Sasisekharan. *Stereochemistry of polypeptide chain configurations*. Journal of Molecular Biology, 1963



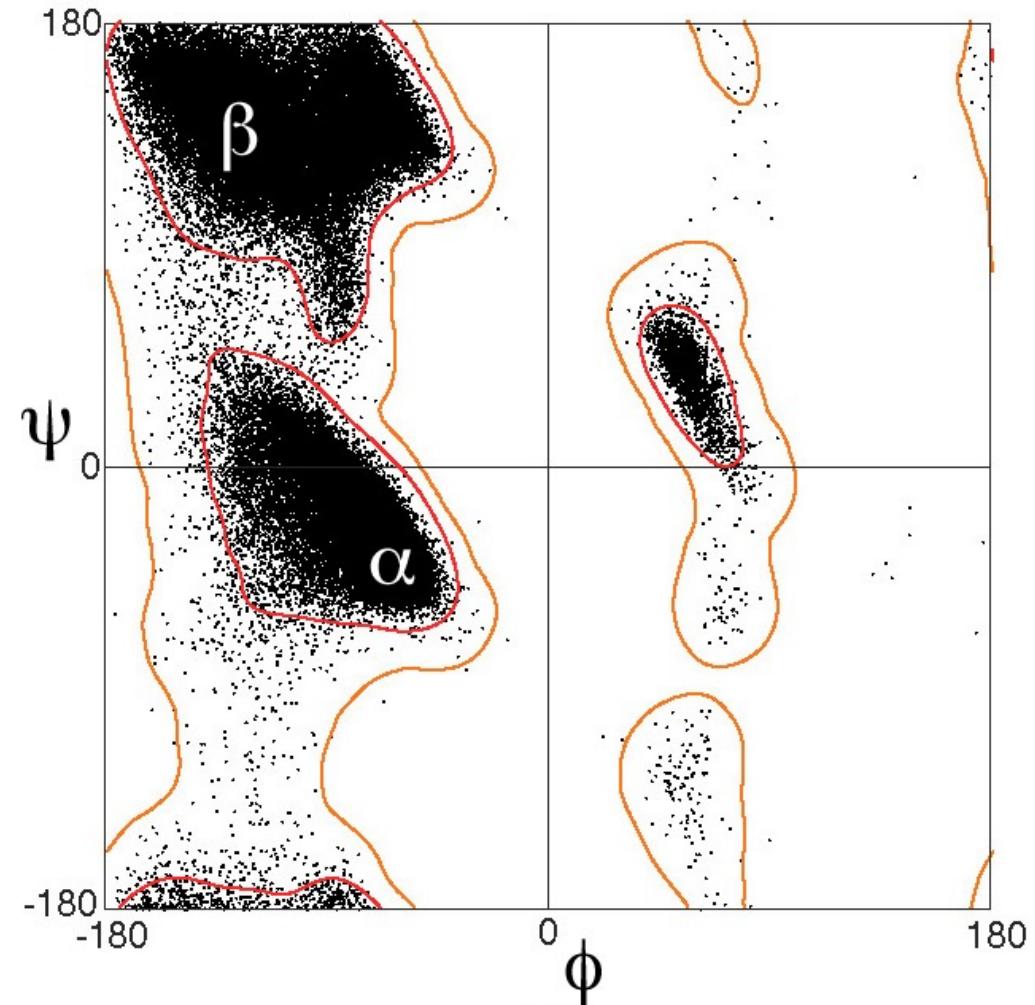
Protein Secondary Structure

The amino acid chain path is determined by backbone torsional angles

Ramachandran plot: scatter plot of amino acids backbone torsional angles

DSSP classification defines 7 secondary structure elements (regions in the plot):

- H = α -helix
- G = 3_{10} helix
- I = π -helix
- B = residue in isolated β -bridge
- E = extended strand
- T = hydrogen bonded turn
- S = bend



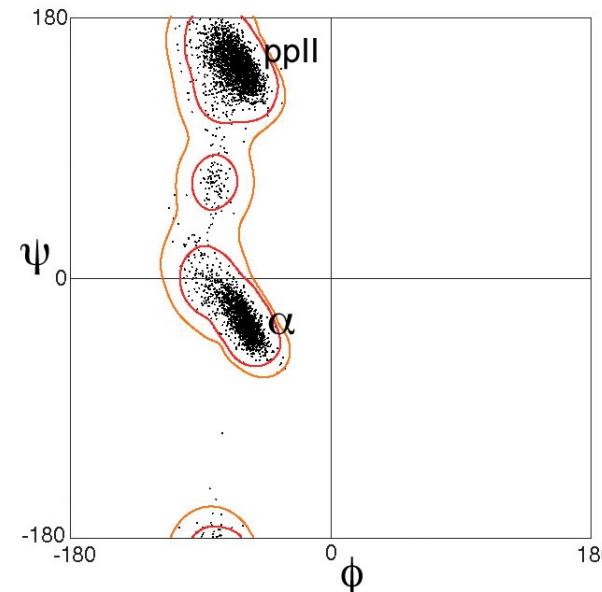
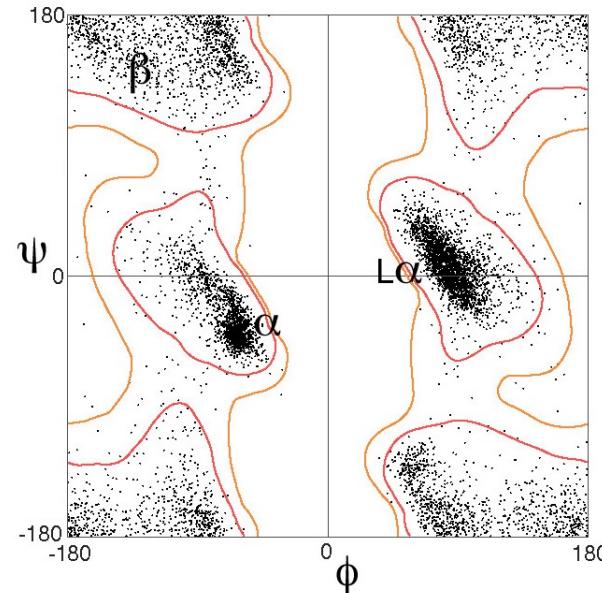
[Extra] Protein Secondary Structure

The amino acid chain path is determined by backbone torsional angles

Ramachandran plot: scatter plot of amino acids backbone torsional angles

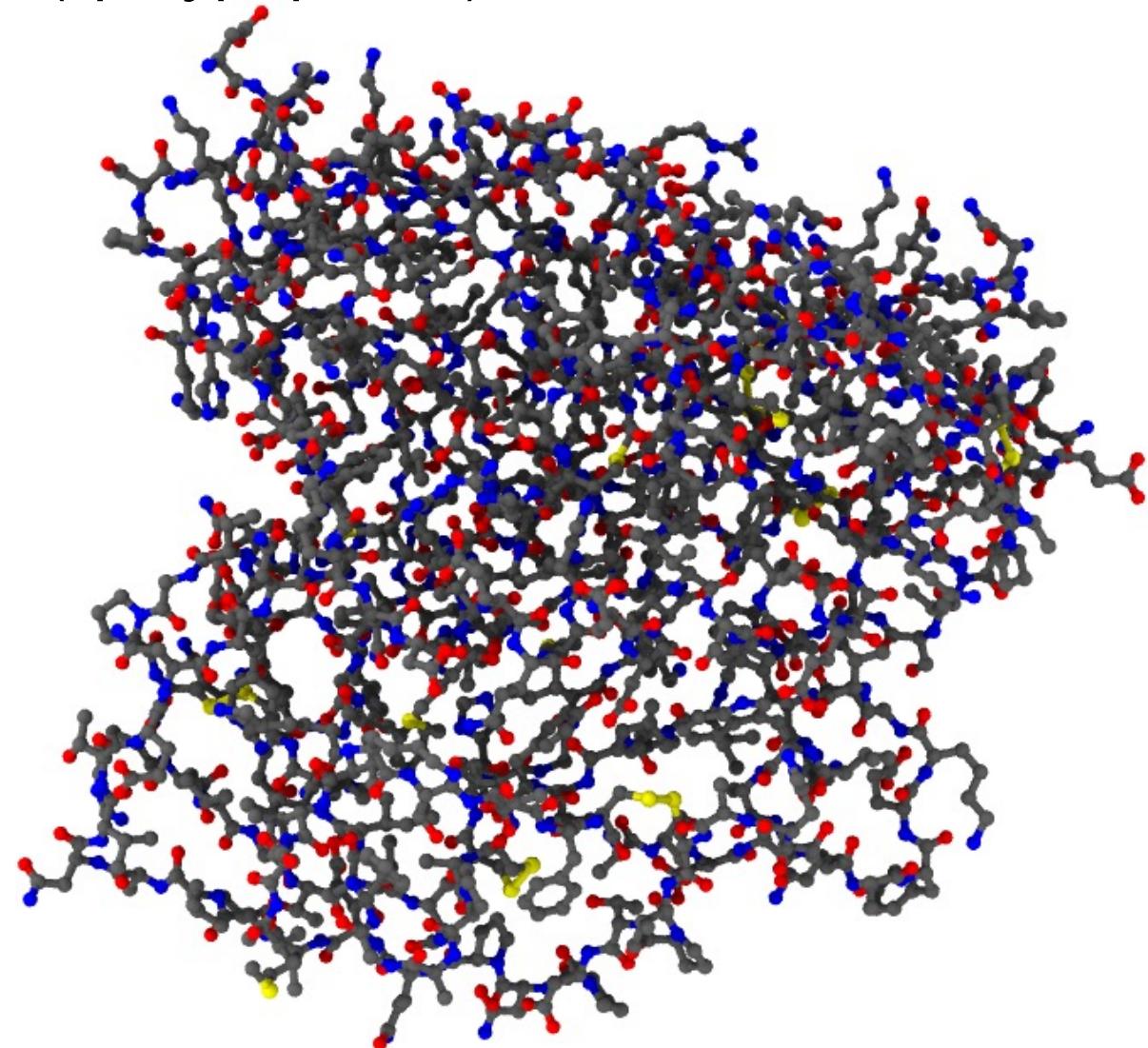
DSSP classification defines 7 secondary structure elements (regions in the plot):

- H = α -helix
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- E = extended strand
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- S = bend



Protein tertiary structure: folding

Protein («polypeptide»): 10 to >1000 amino acids



Protein tertiary structure: folding

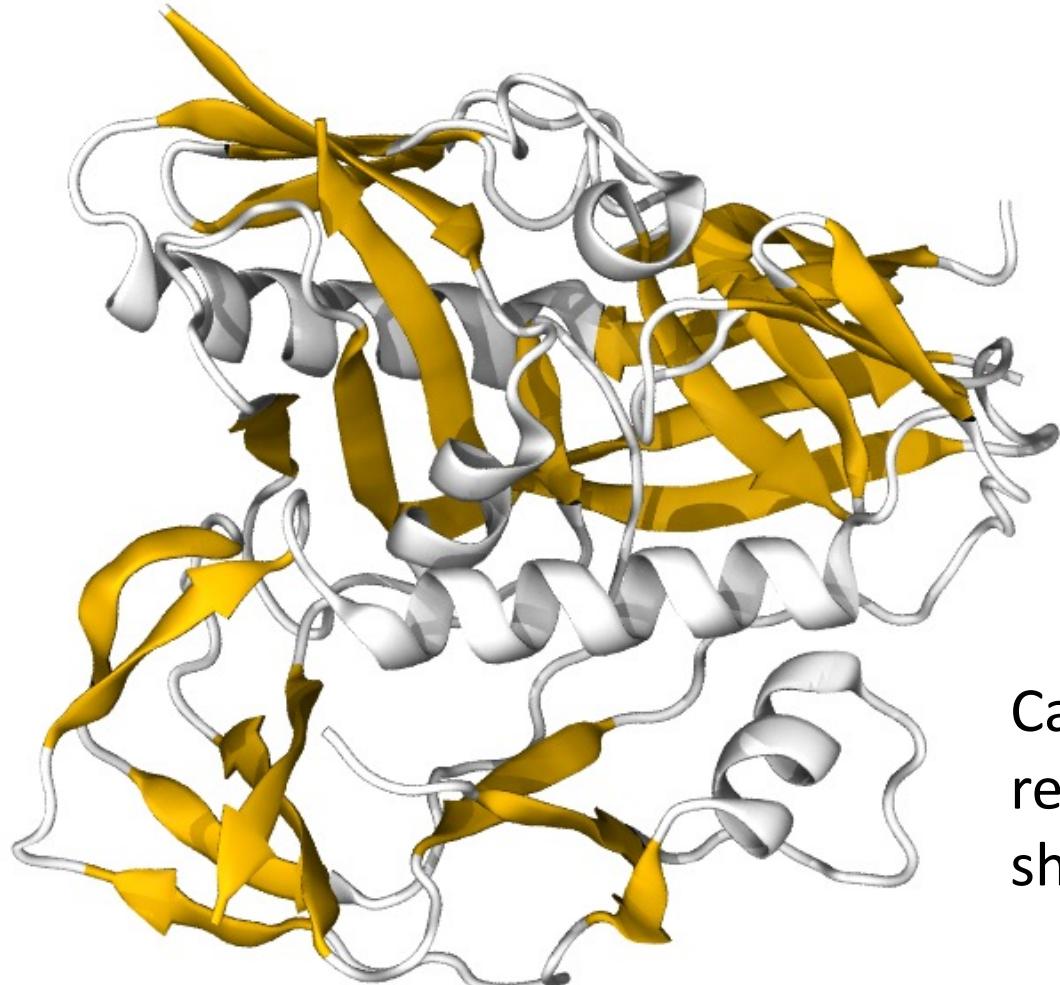
Protein («polypeptide»): 10 to >1000 amino acids



Cartoon
representation:
helices

Protein tertiary structure: folding

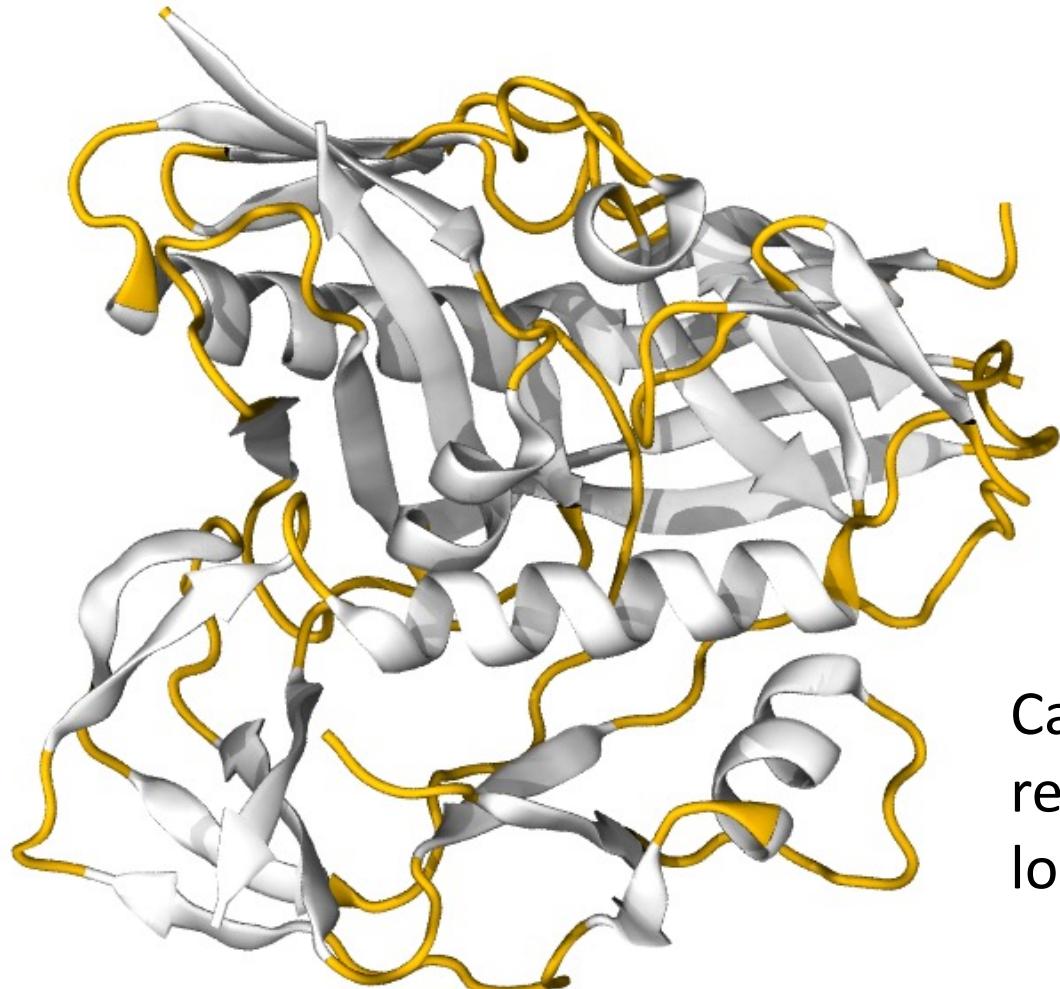
Protein («polypeptide»): 10 to >1000 amino acids



Cartoon
representation:
sheets

Protein tertiary structure: folding

Protein («polypeptide»): 10 to >1000 amino acids



Cartoon
representation:
loops

Protein tertiary structure: folding

Protein («polypeptide»): 10 to >1000 amino acids



Anfinsen's dogma

The three-dimensional structure of a protein in its native environment is solely determined by its amino acid sequence.



Christian Anfinsen. *Principles that govern the folding of protein chains*. Science, 1973

Hydrogen bonds

Electrostatic interaction. Structure:

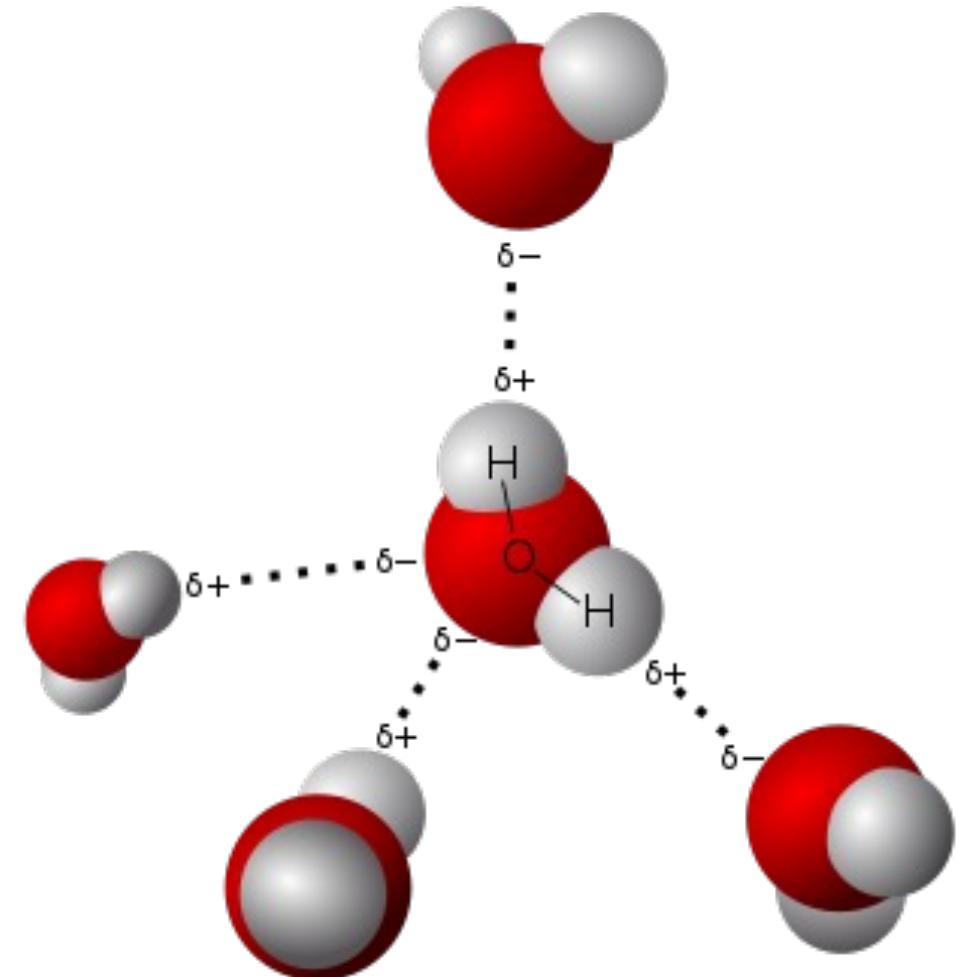
- donor-acceptor distance typically 1.6-2 Å
- donor-acceptor-hydrogen angle must be small

Hydrogen bond energy in biomolecular

systems typically 5-25 kJ/mol, e.g.:

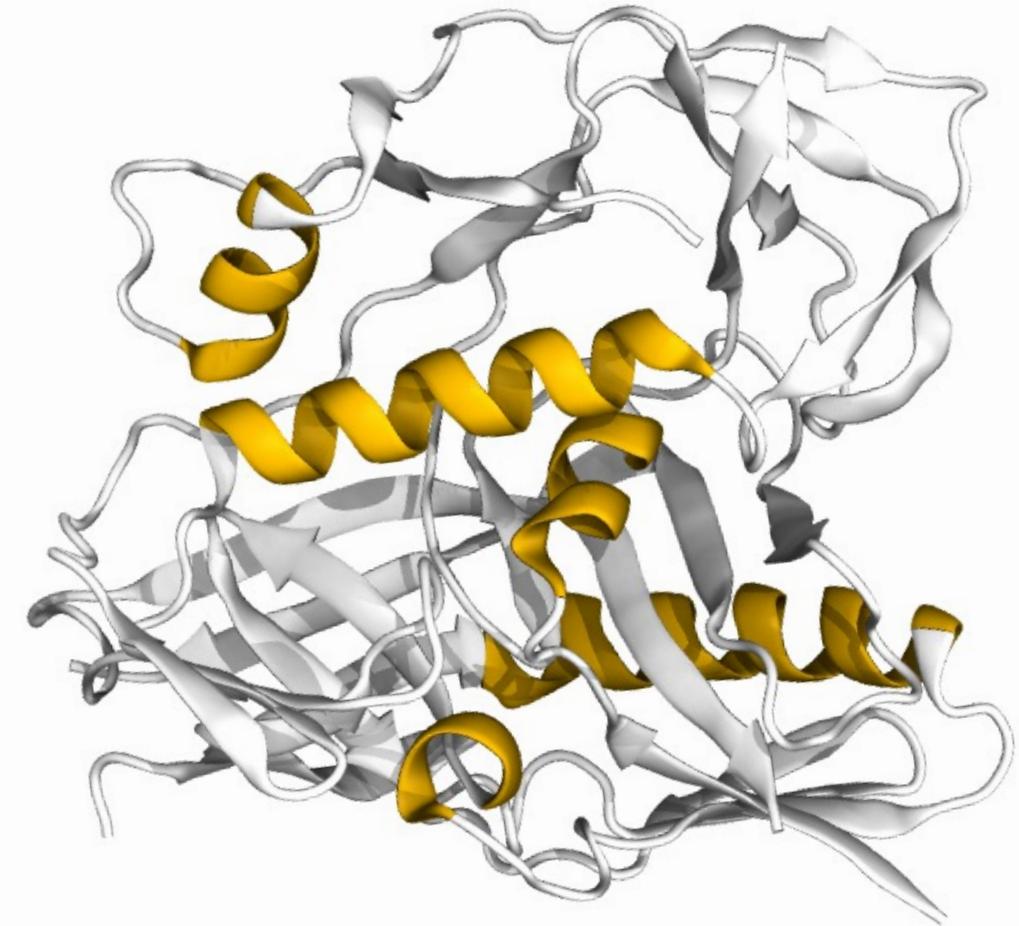
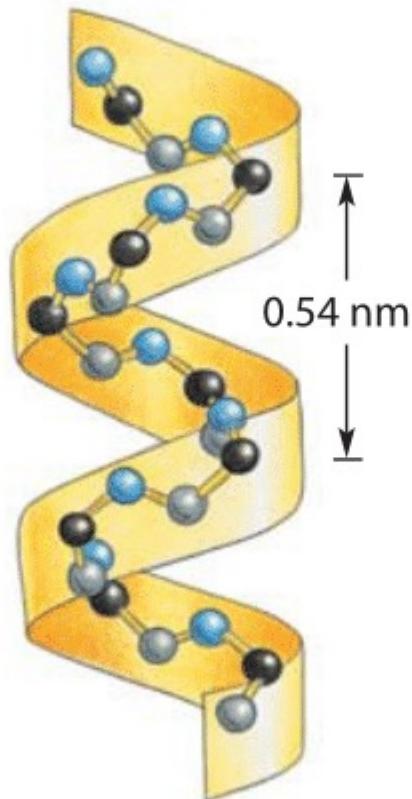
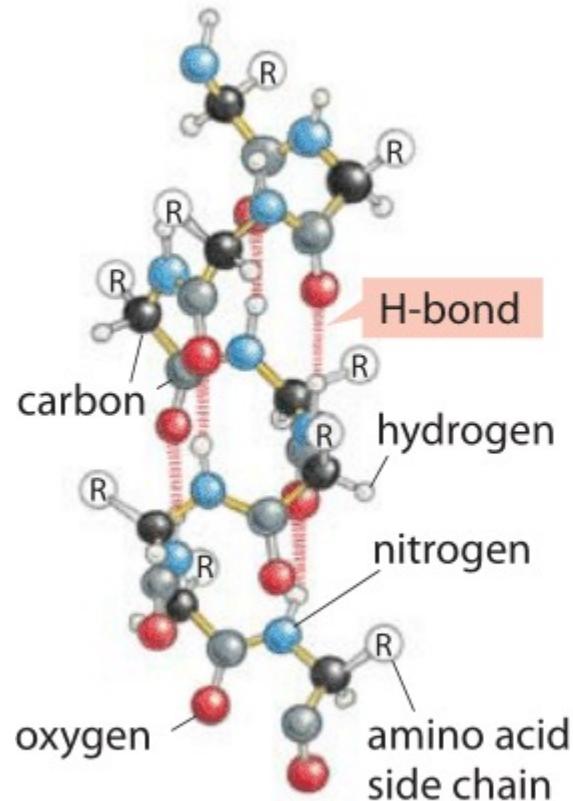
- O-H \cdots O , 21 kJ/mol (5.0 kcal/mol)
- N-H \cdots O , 8 kJ/mol (1.9 kcal/mol)

amino acids' backbone and polar side chains
can be donor/acceptor



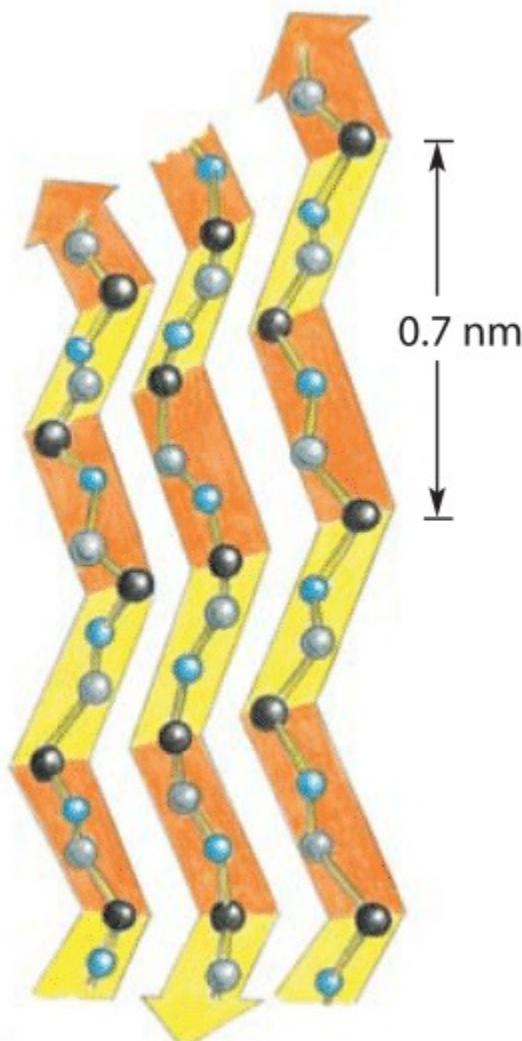
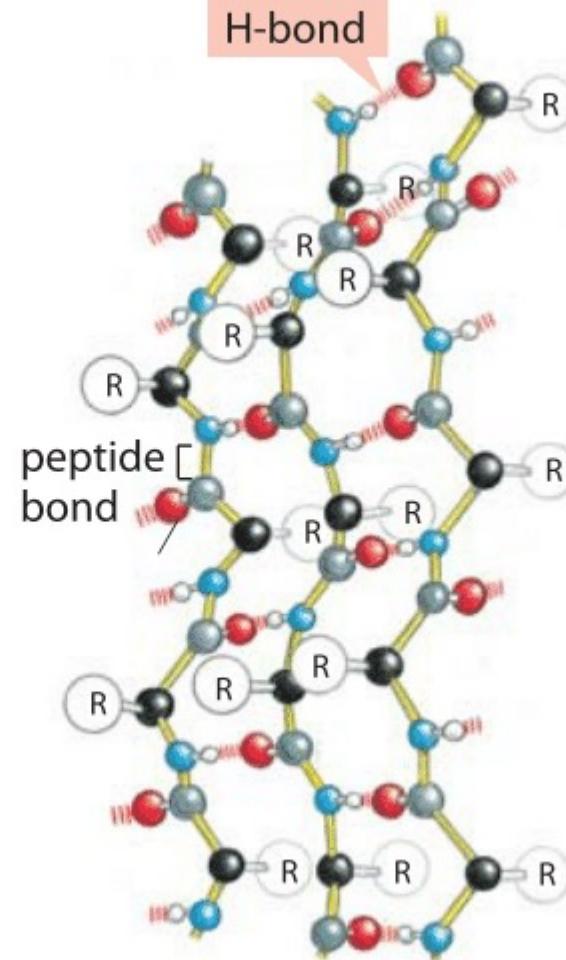
Hydrogen bonding on protein backbone

alpha helix

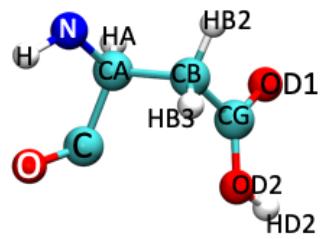


Hydrogen bonding on protein backbone

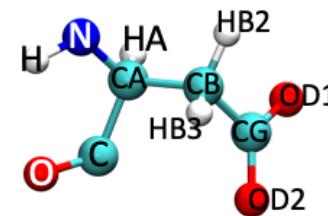
beta sheet



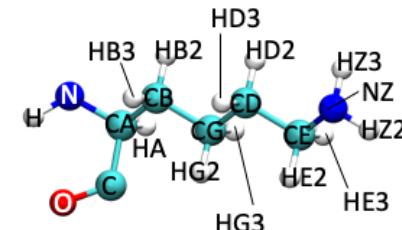
Hydrogen bonding: effect of *local* pH



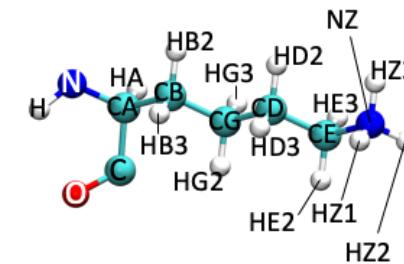
ASH, Aspartic acid*, D



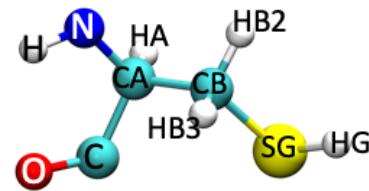
ASP, Aspartate, D



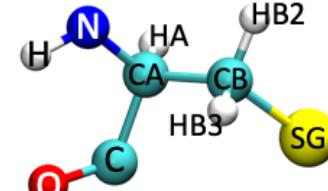
LYN, Lysine*, K



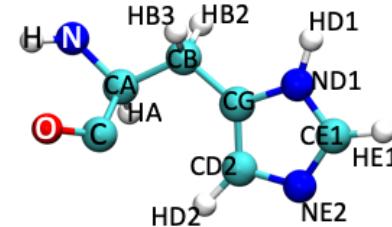
LYS, Lysine, K



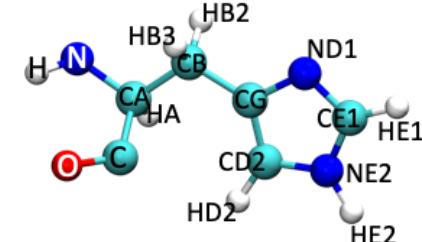
CYS, Cysteine, C



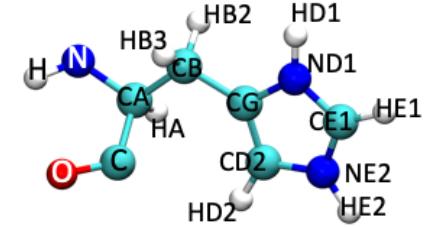
CYX, Cysteine**, C



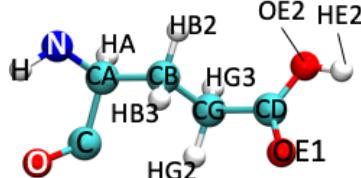
Histidine*, H



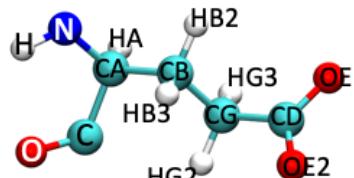
HIE, Histidine, H



HIP, Histidine*, H



GLH, Glutamic Acid*, E

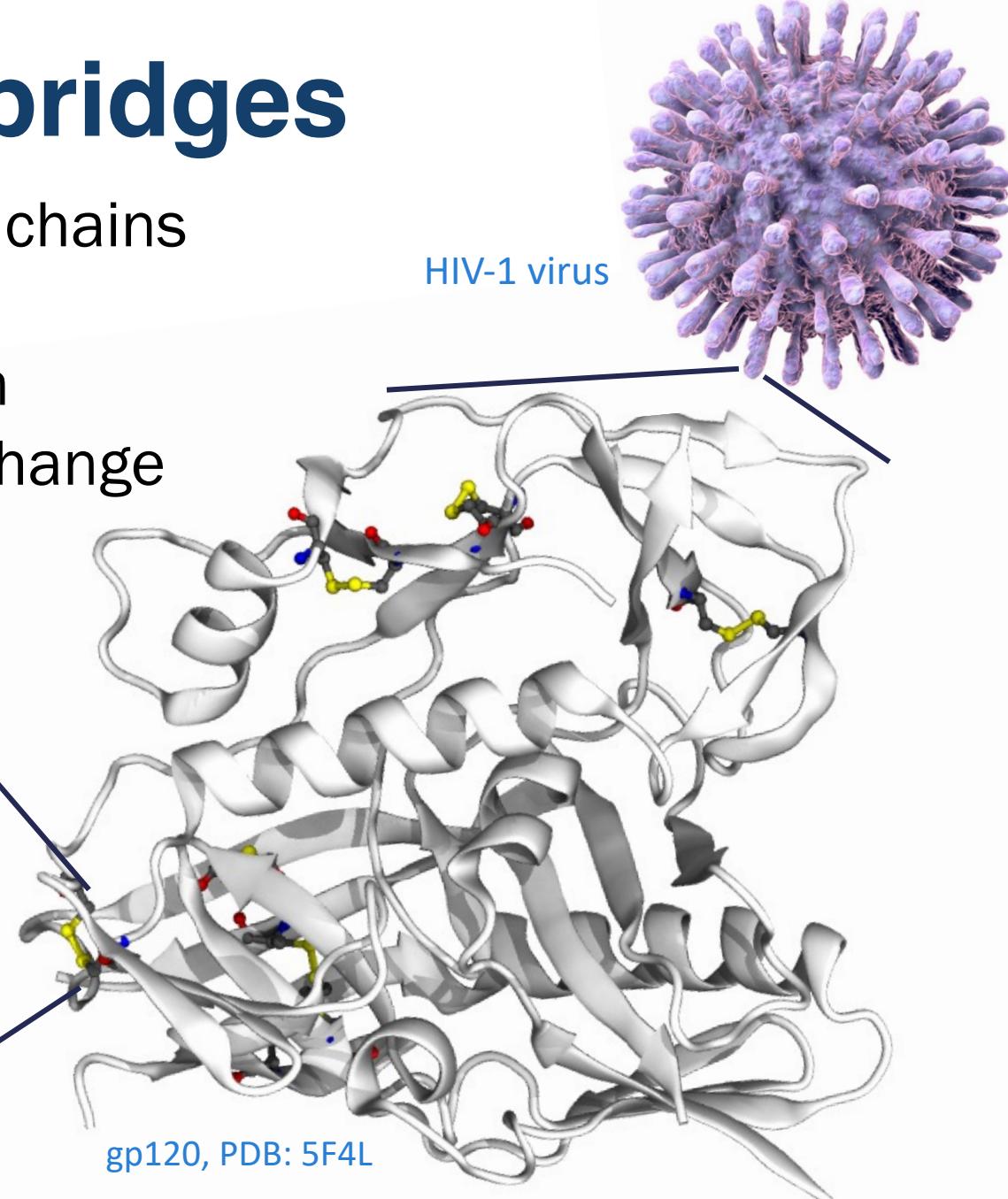
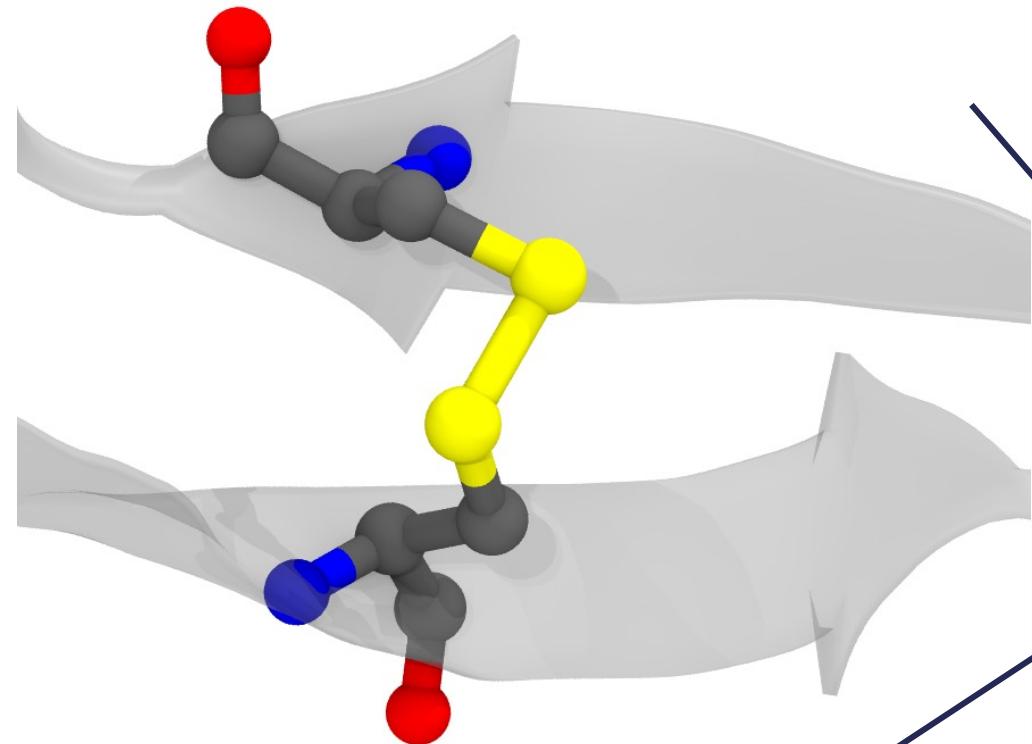


GLU, Glutamate, E

Disulfide bridges

Under *oxidising* conditions, cysteine side chains can form a covalent bond.

- Protein more resistant to denaturation
- Changes in conditions → structural change



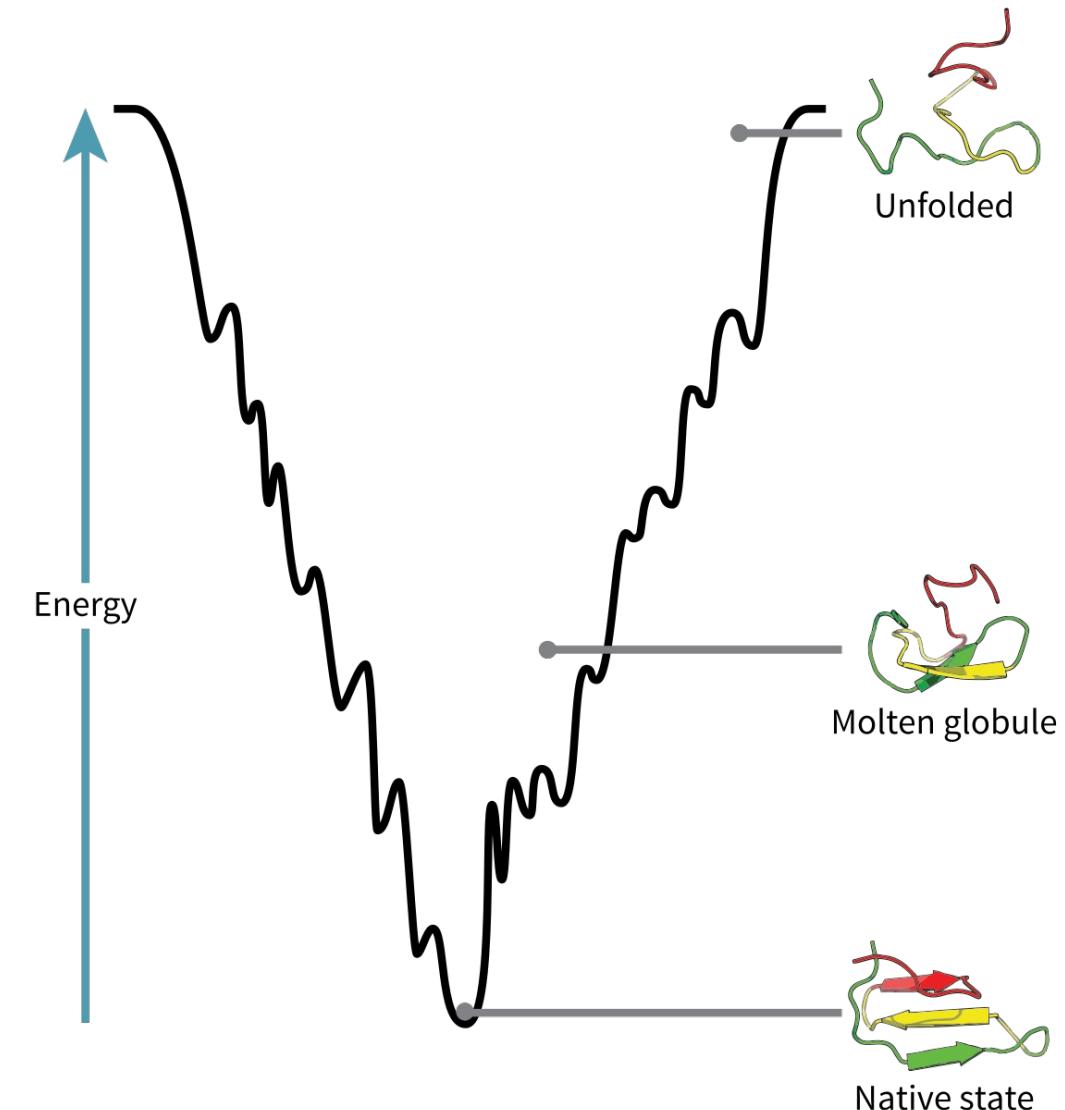
[Extra] Proteins fold in low energy structures

$$\Delta G = \Delta H - T\Delta S$$

Proteins fold spontaneously, i.e. $\Delta G < 0$

$\Delta S_{\text{protein}}$ is < 0

$\Delta S = \Delta S_{\text{protein}} + \Delta S_{\text{water}} > 0$



[Extra] Proteins fold in low energy structures

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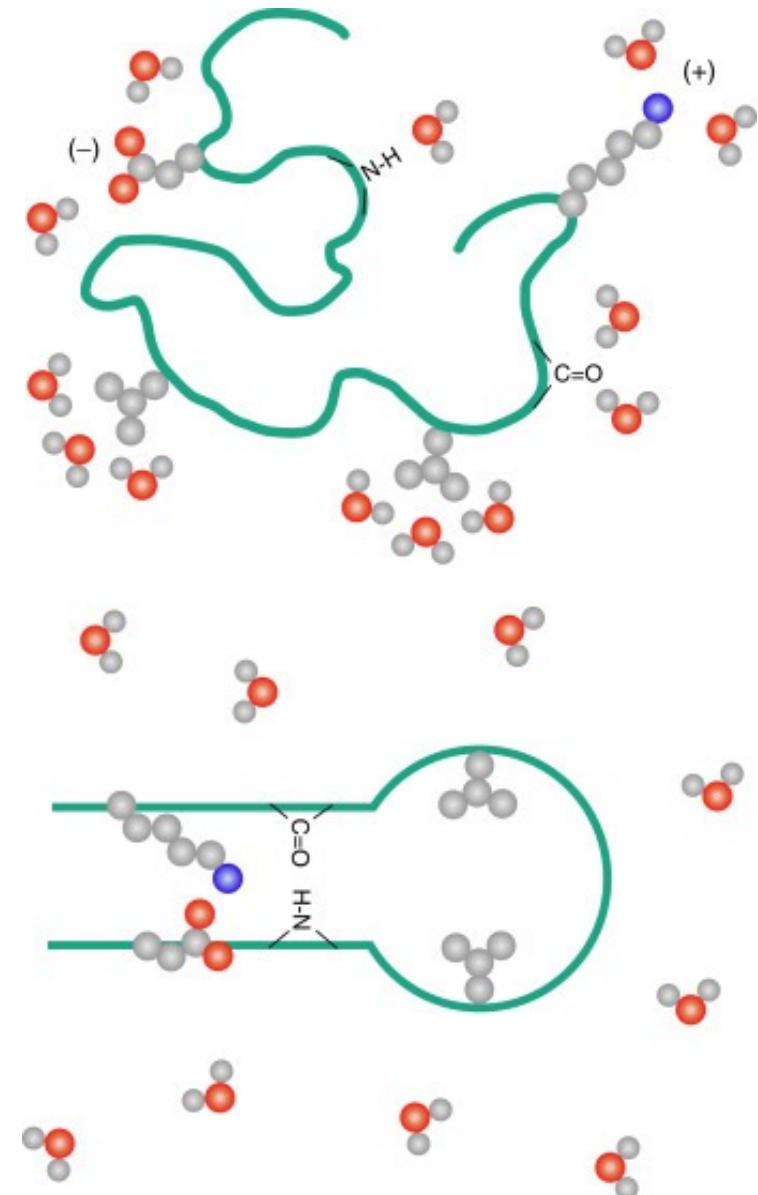
$\Delta S_{\text{protein}}$ is < 0

$$\Delta S = \Delta S_{\text{protein}} + \Delta S_{\text{water}} > 0$$

$H = U + PV$; at physiological conditions $\Delta H \approx \Delta U$

ΔH is small: a folded protein forms bonds with itself, an unfolded one forms bonds with water.

Hydrophobic collapse drives folding!



[Extra] Levinthal's paradox

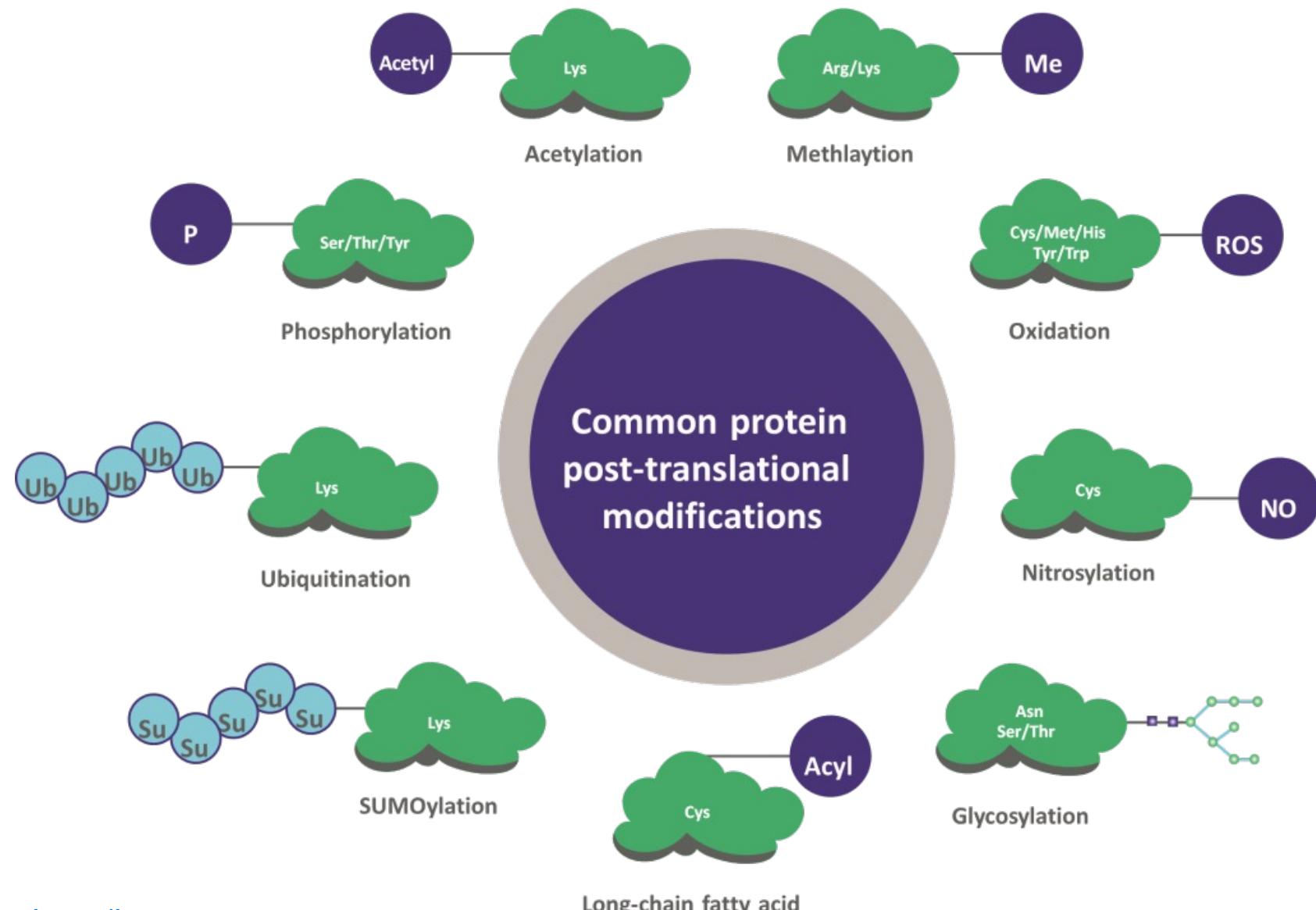
How can proteins find their unique fold in sub-second timescales?

- 100 amino acids-long protein
 - $2 \times 100 - 2 = 198$ backbone torsional angles
 - each torsional angle has on average 3 stable positions
 - 3^{198} different configurations
 - side chain rotation in the fs timescale (10^{-12} s)
 - random search worst case scenario: $10^{-12} \times 3^{198} \approx 10^{-12} \times 10^{99} = 10^{87}$ s
 - age of the universe \approx 13.7 billion years = 4.32×10^{17} s
- Protein folding cannot be a random process**

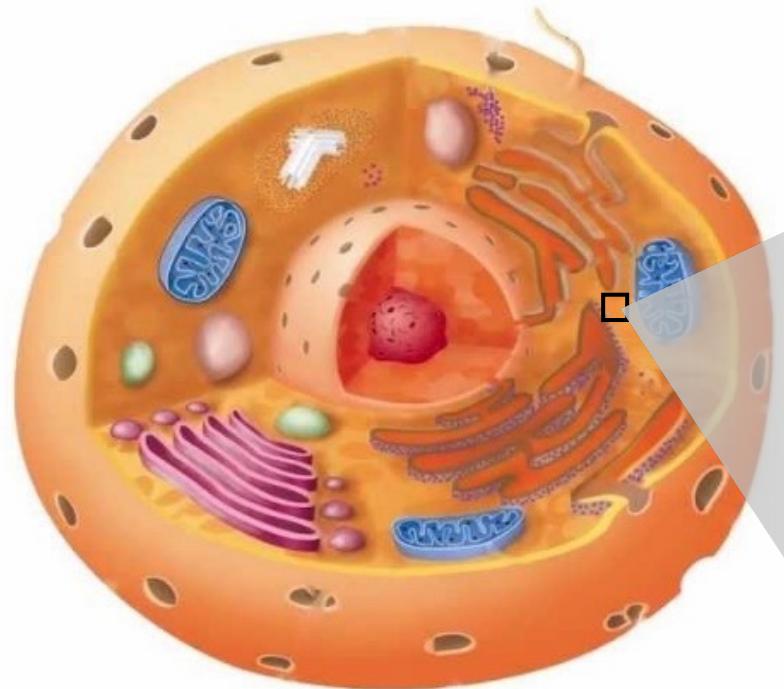
Post-translational modifications (PTMs)

Once expressed, proteins can be modified by the covalent binding of other molecules.

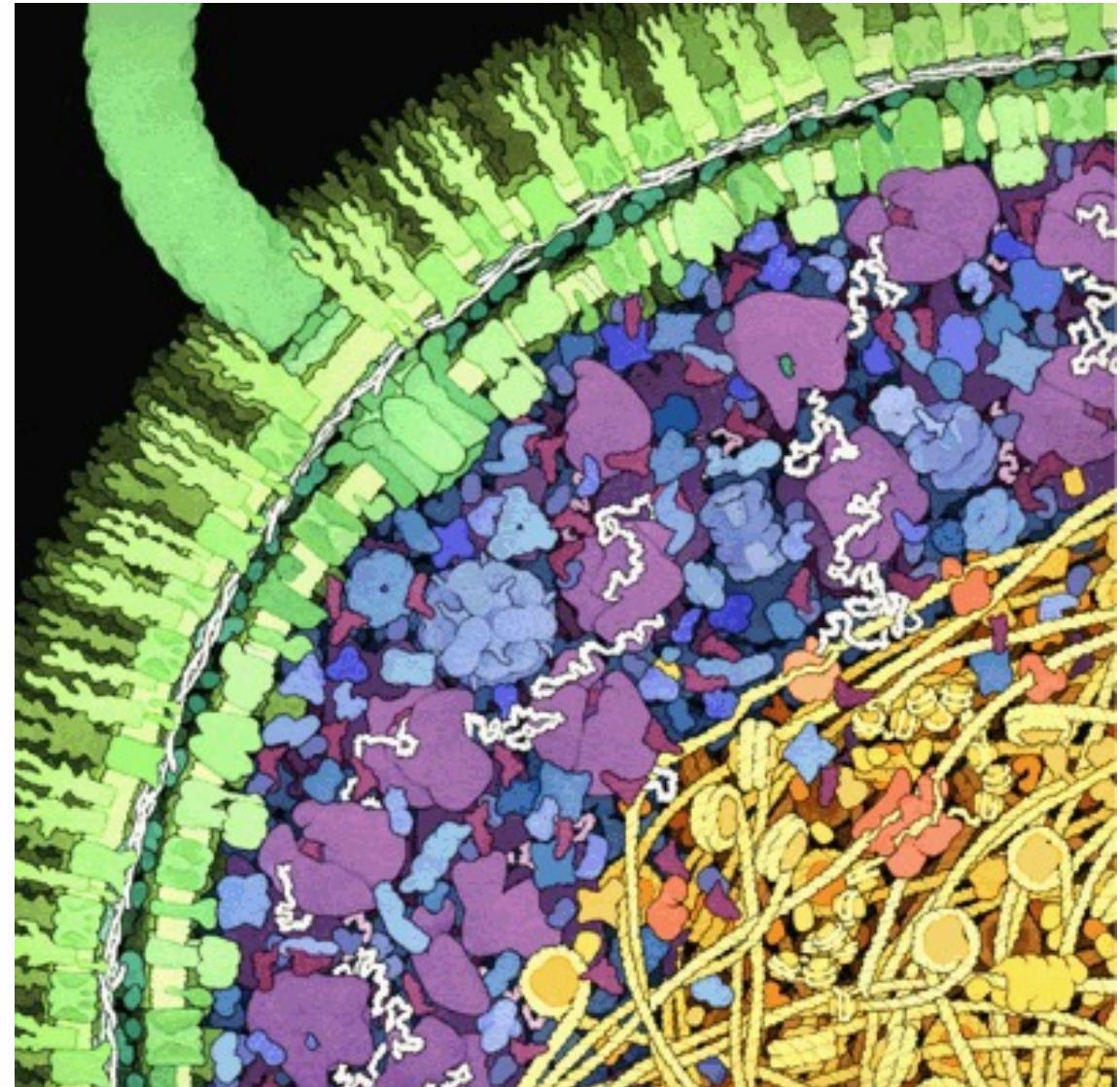
The addition/removal of most PTMs is controlled by the organism, to modulate protein function.



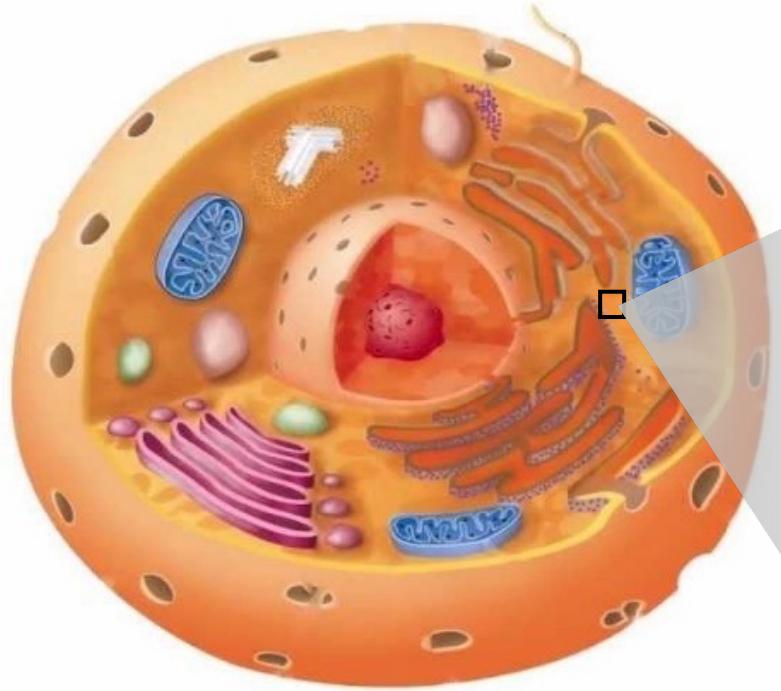
The intracellular space



Crowded environment!



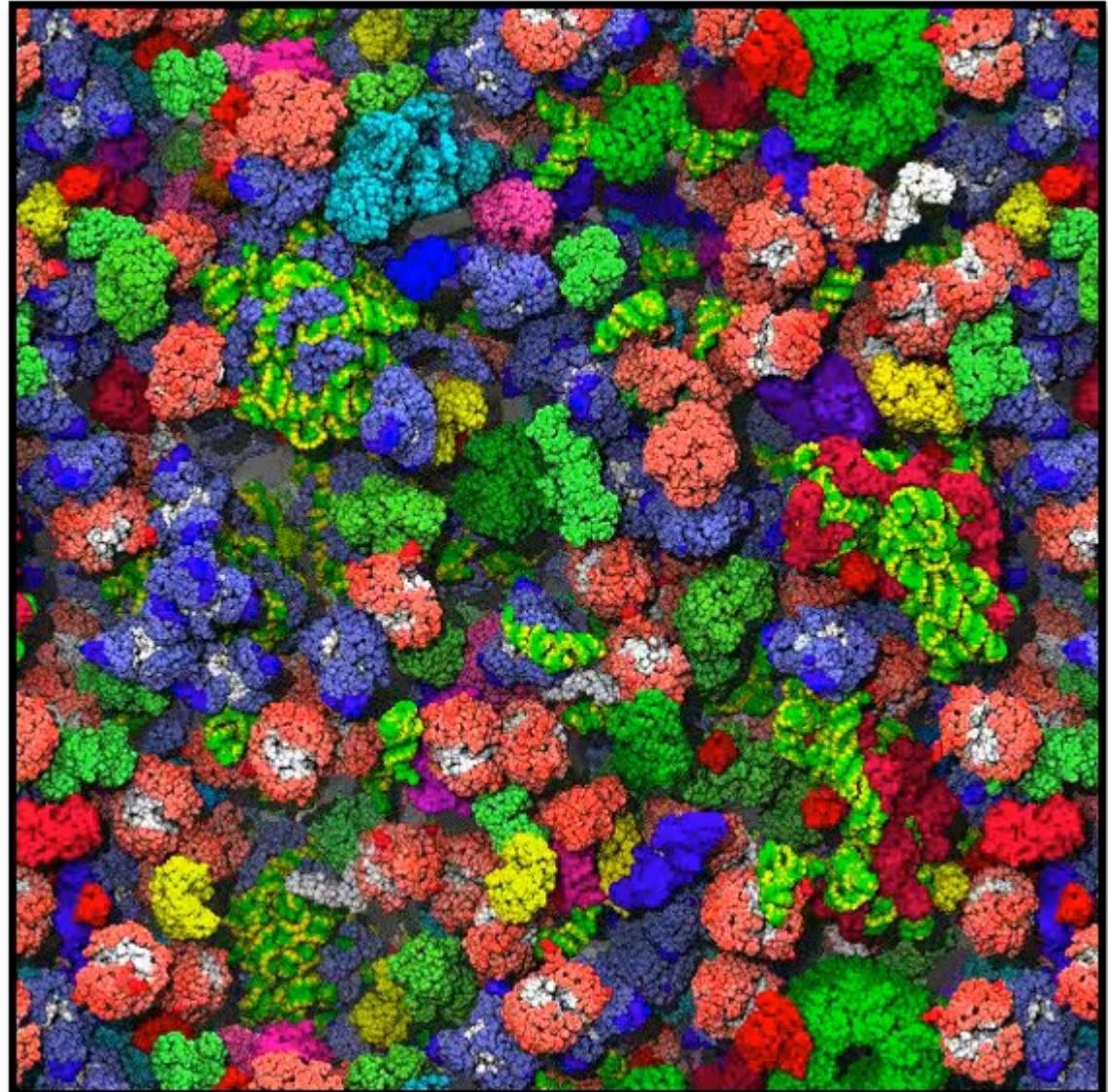
The intracellular space



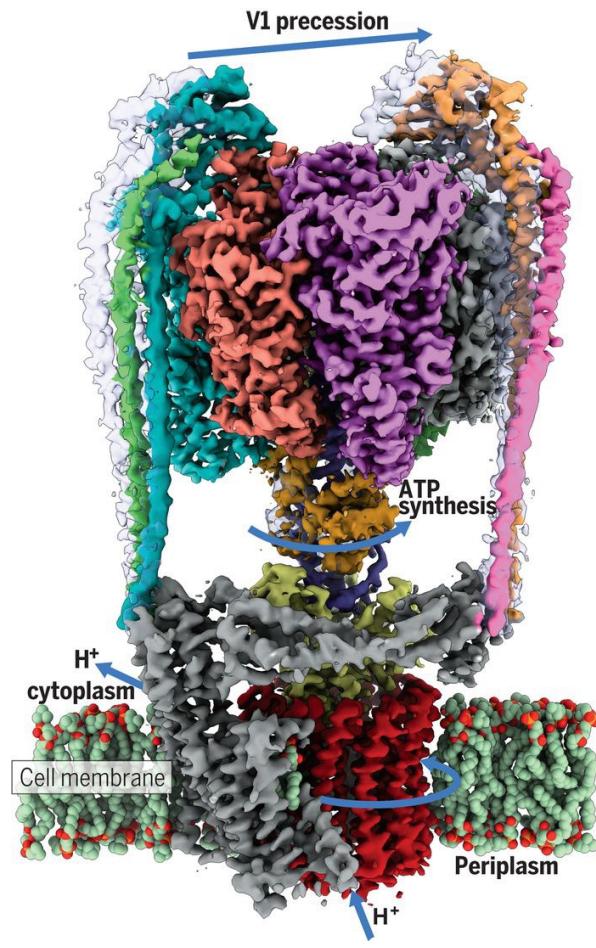
Crowded environment!

Brownian motion: proteins bump into other molecules all the time!

Most contacts are short-lived

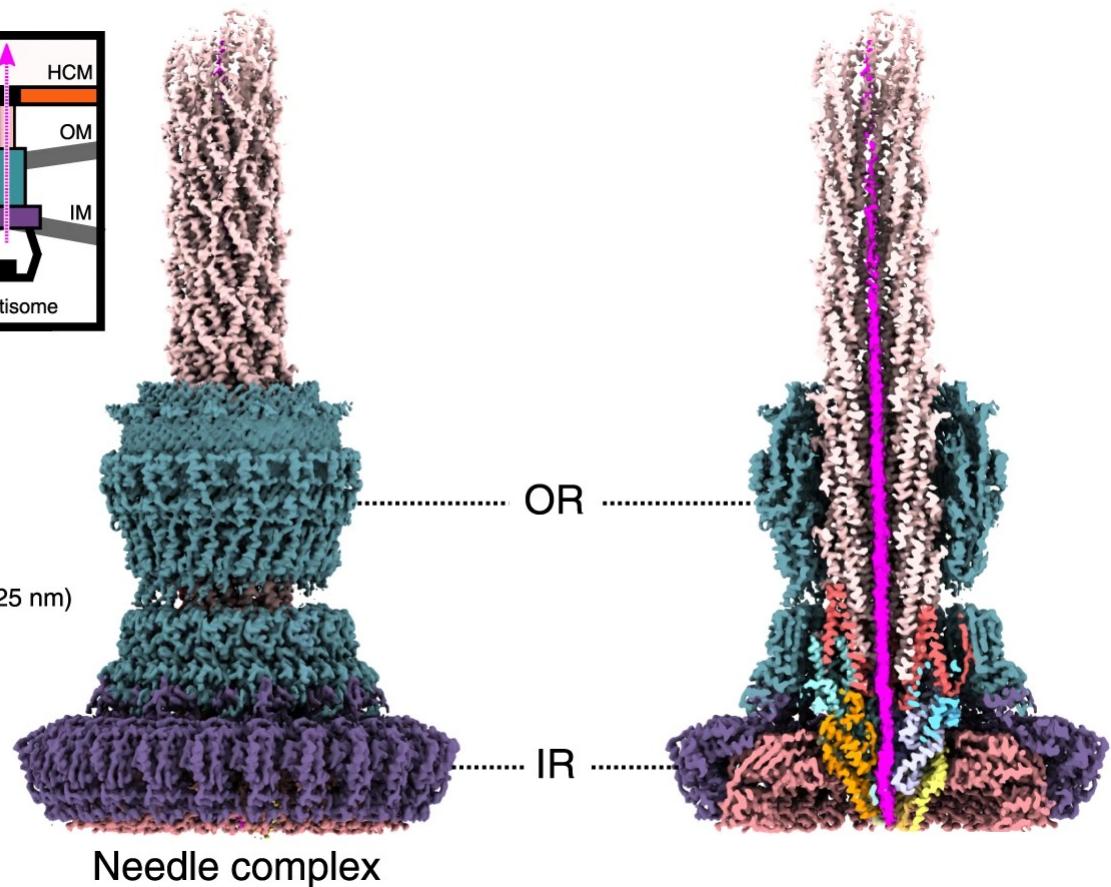
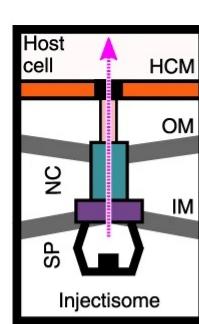


Protein quaternary structure: assembly



ATP syntase

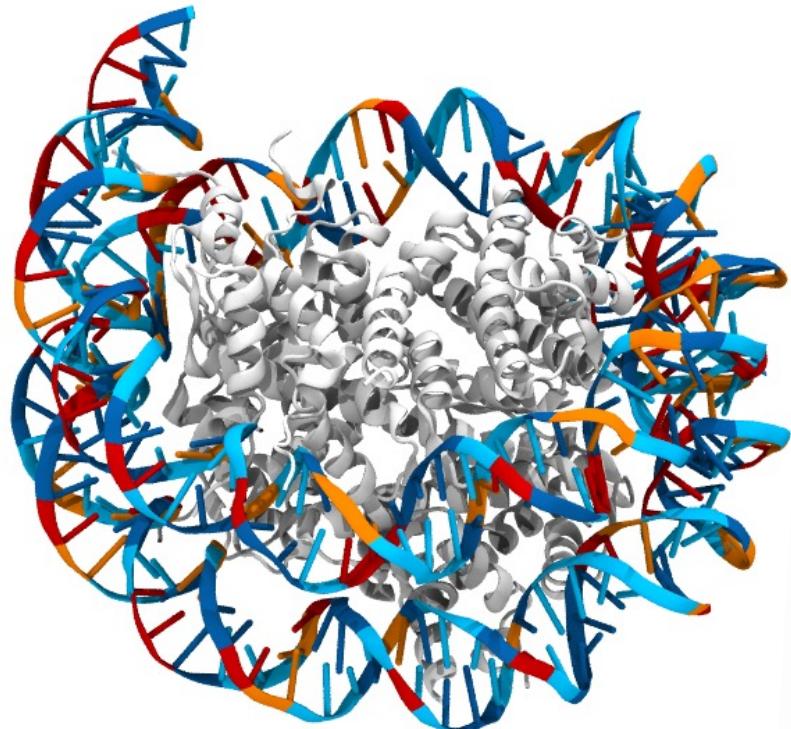
L. Zhou and L. A. Sazanov, *Structure and conformational plasticity of the intact Thermus thermophilus V/A-type ATPase*, *Science*, 2019



Injectisome

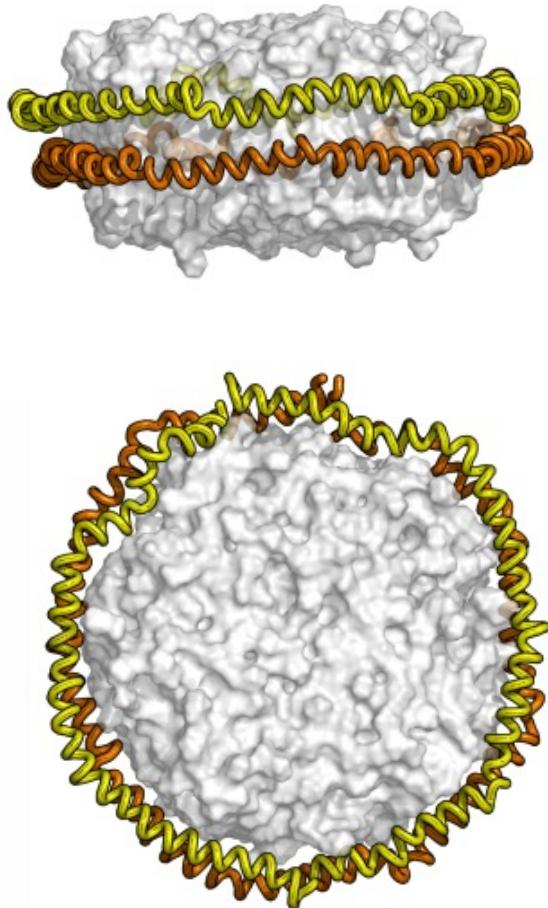
S. Miletic et al., *Substrate-engaged type III secretion system structures reveal gating mechanism for unfolded protein translocation*, *Nature Comms*, 2021

The structure determines the function



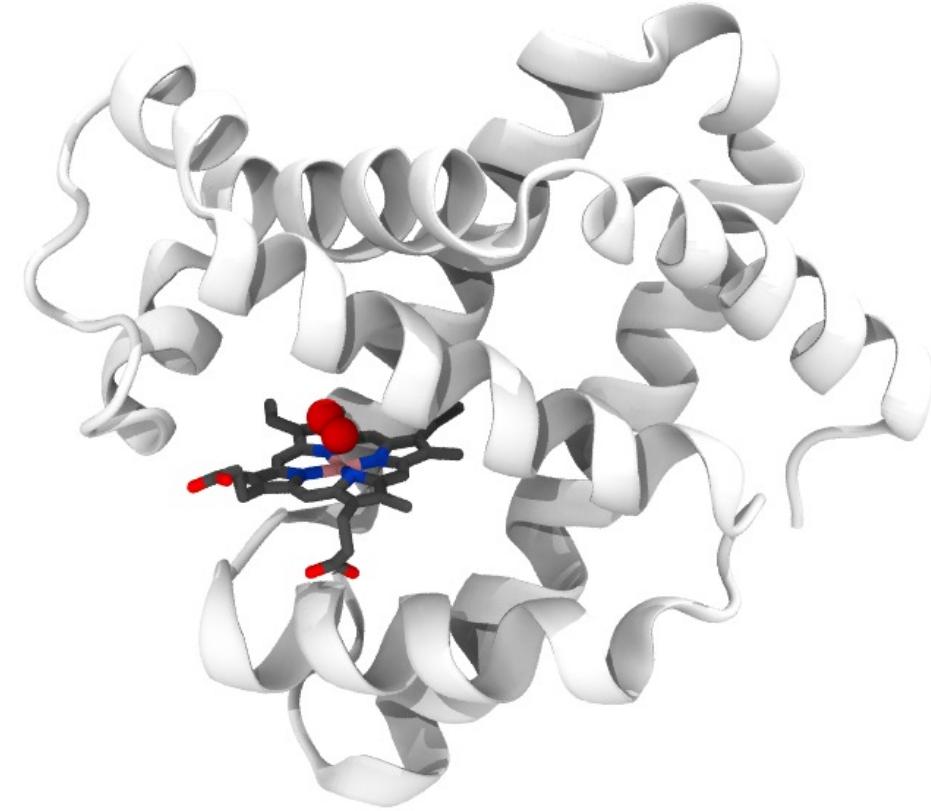
Nucleosome (PDB: 5CPI)

K. Luger et al., *Crystal Structure of the nucleosome core particle at 2.8 Å resolution*, Nature, 1997



Lipoprotein (PDB: 1AV1)

D.W. Bohrani et al., *Crystal structure of truncated human apolipoprotein A-I suggests a lipid-bound conformation*, PNAS, 1997



Myoglobin (PDB: 1MBO)

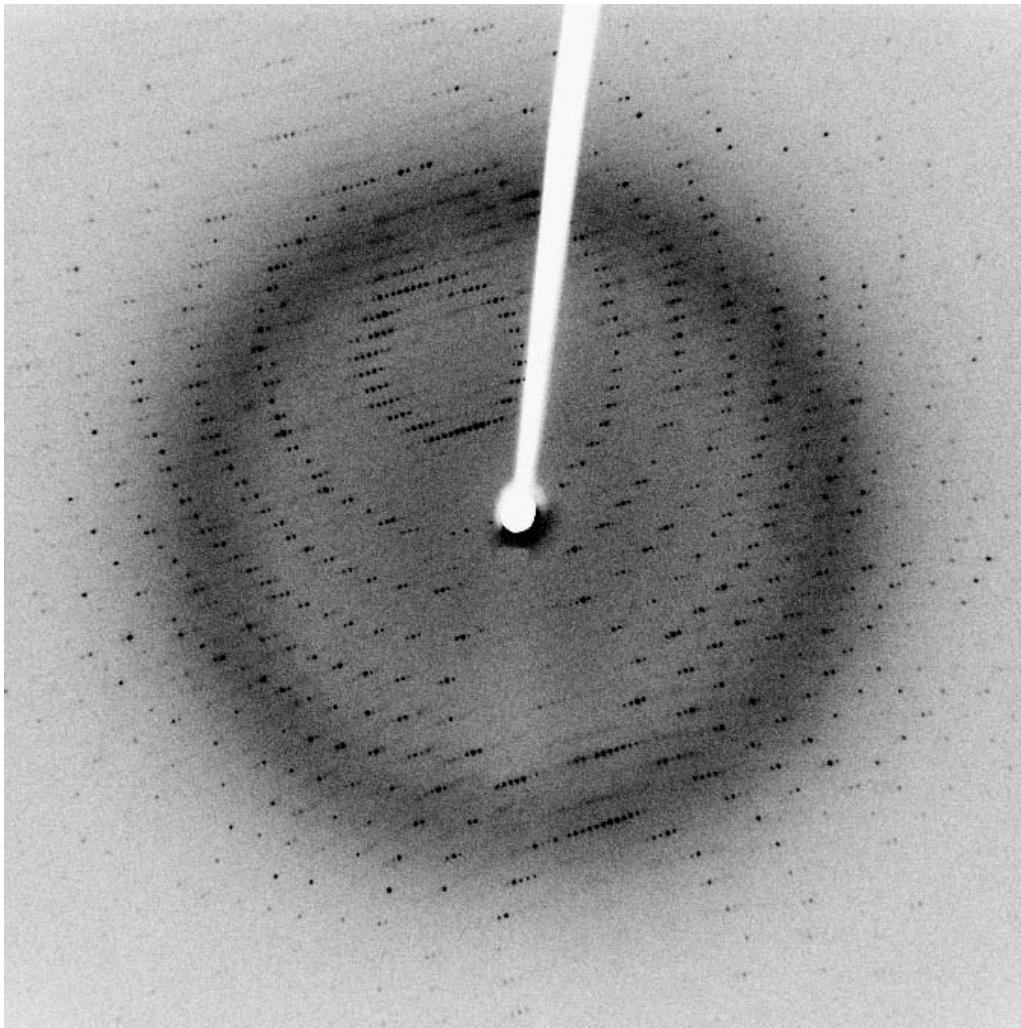
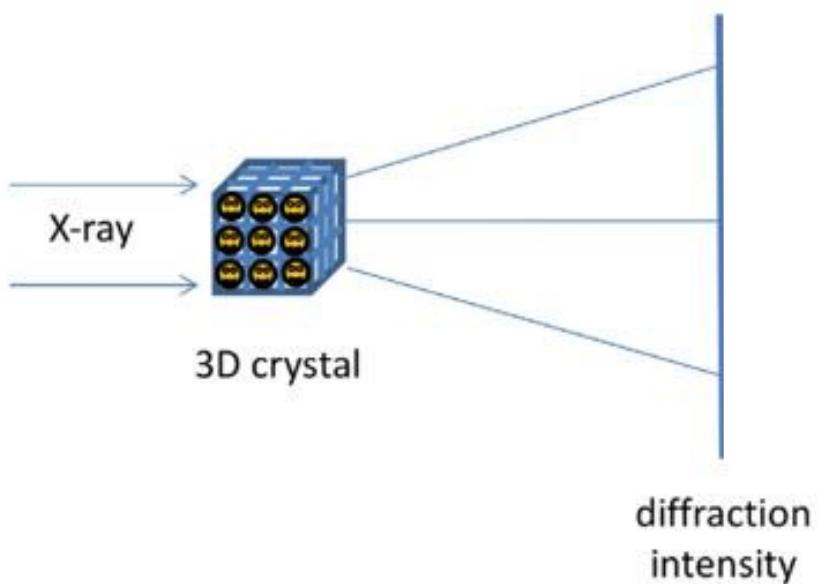
J.C. Kendrew et al., *A three-dimensional Model of the Myoglobin Molecule obtained by X-Ray Analysis*, Nature, 1958

Proteins, illness, and drug design

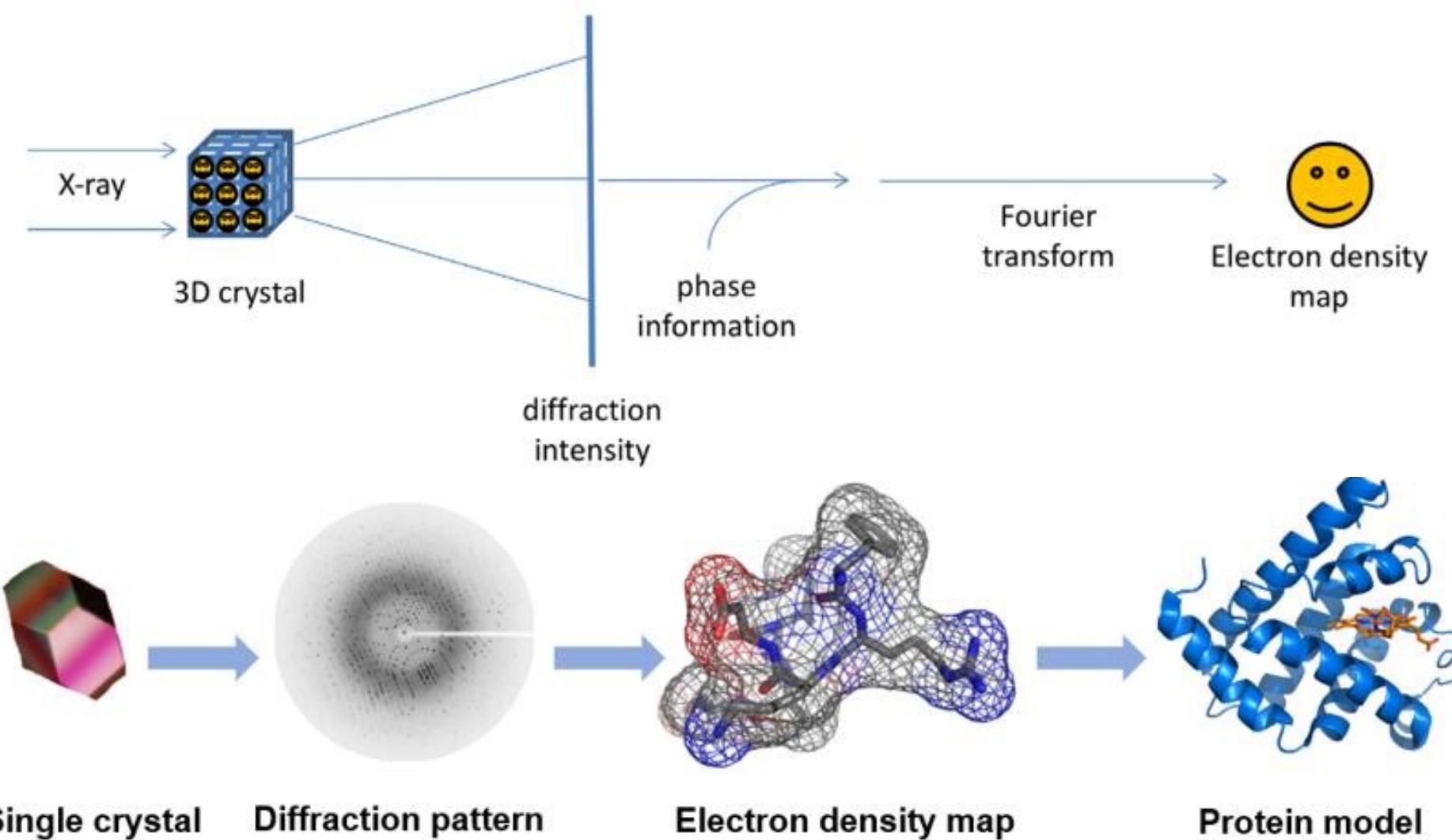
- **Proteins and diseases** (e.g. covid-19, salmonella, flu, ...)
 - pathogen's own metabolism/structure
 - pathogen's weapon
- **Proteins and disorders** (e.g. Cancer, Alzheimer, ...)
 - own protein misfolds
 - own protein folds, but has different dynamics
- **Drug**
 - Small molecule designed to specifically bind to a protein, so as to affect its function

Part 2: structure determination

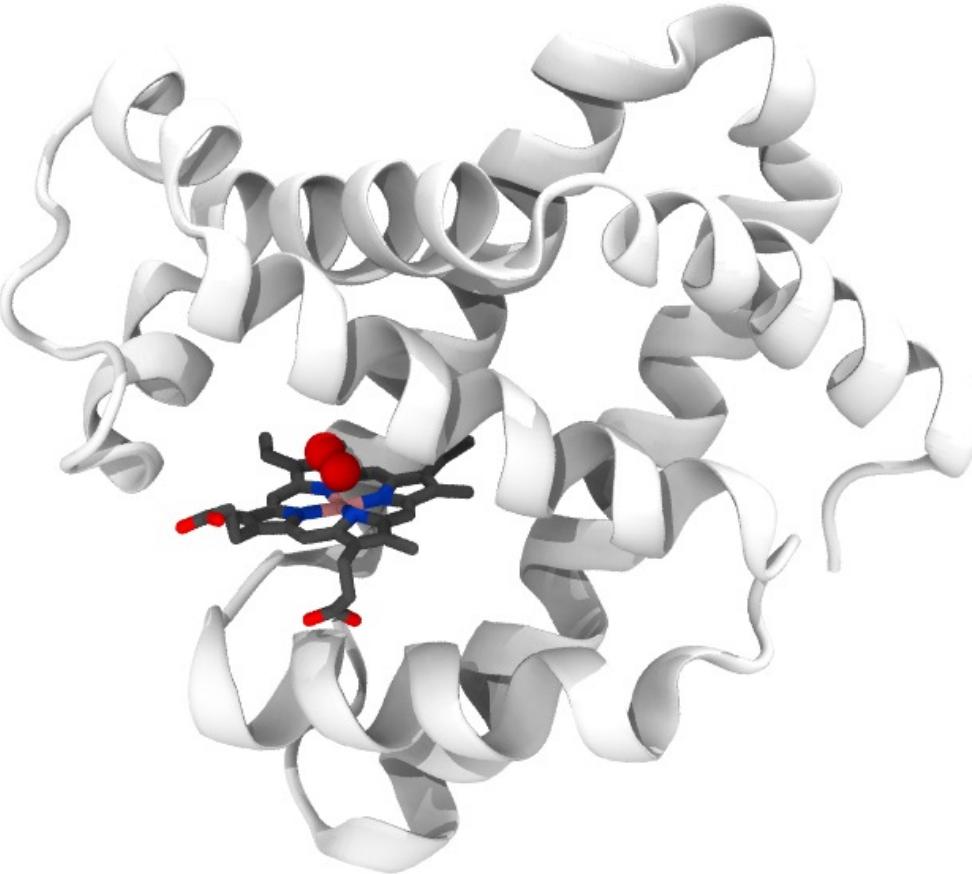
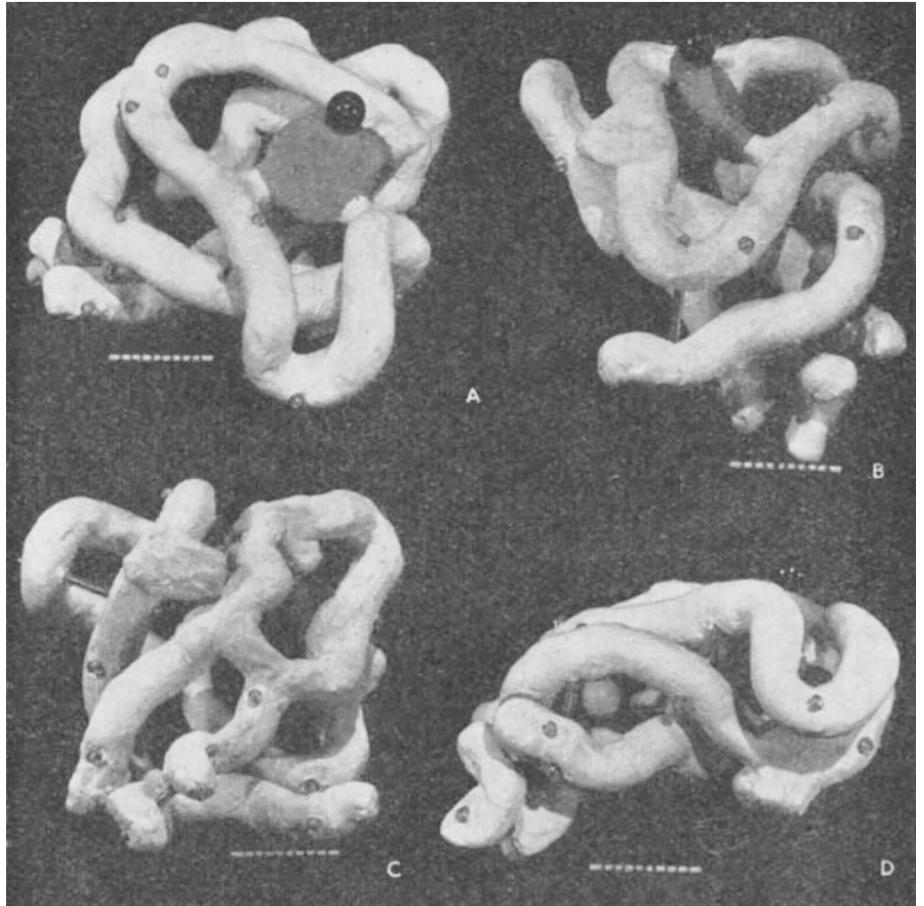
Structure determination: X-ray crystallography



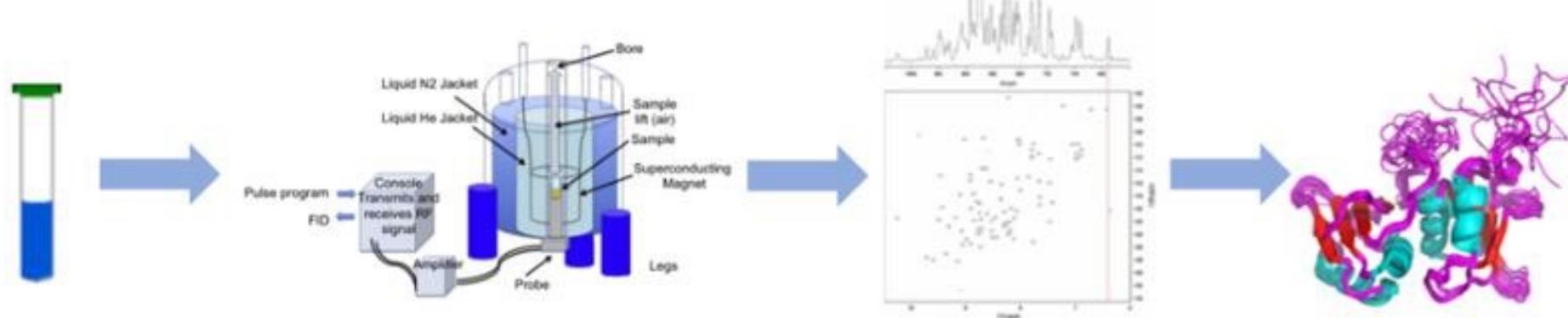
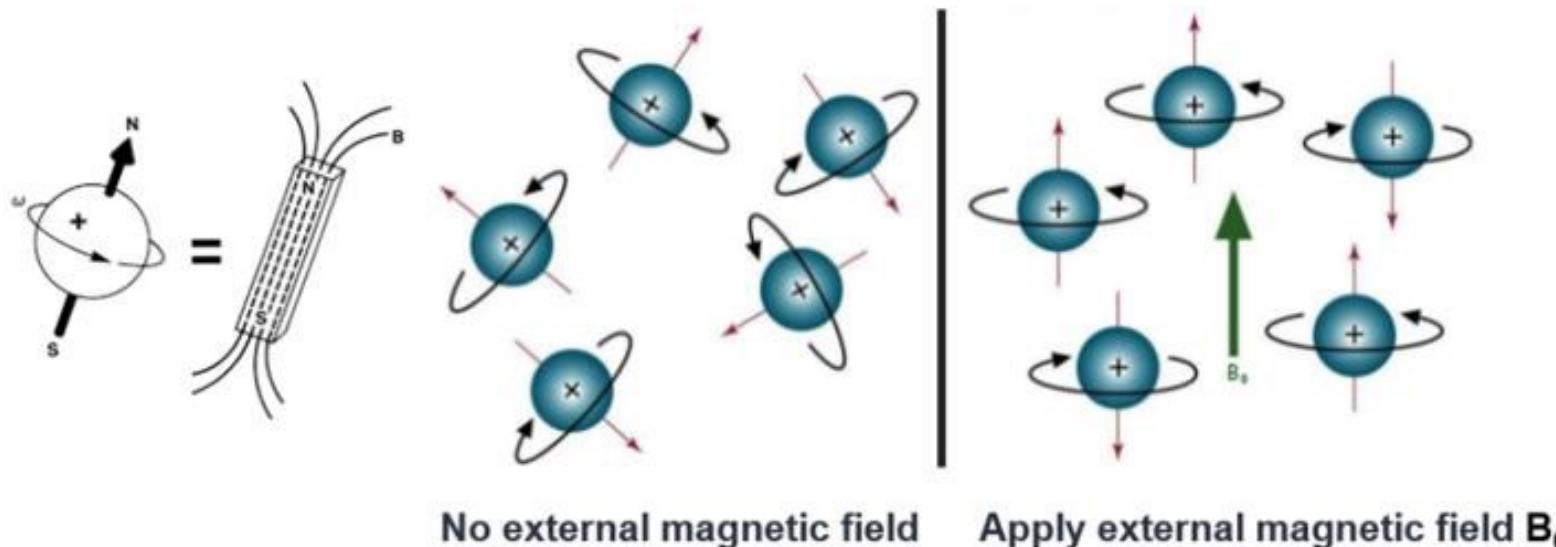
Structure determination: X-ray crystallography



Structure determination: X-ray crystallography



Structure determination: Nuclear Magnetic Resonance (NMR)



Sample preparation

Data acquisition

Spectral processing

Structural analysis

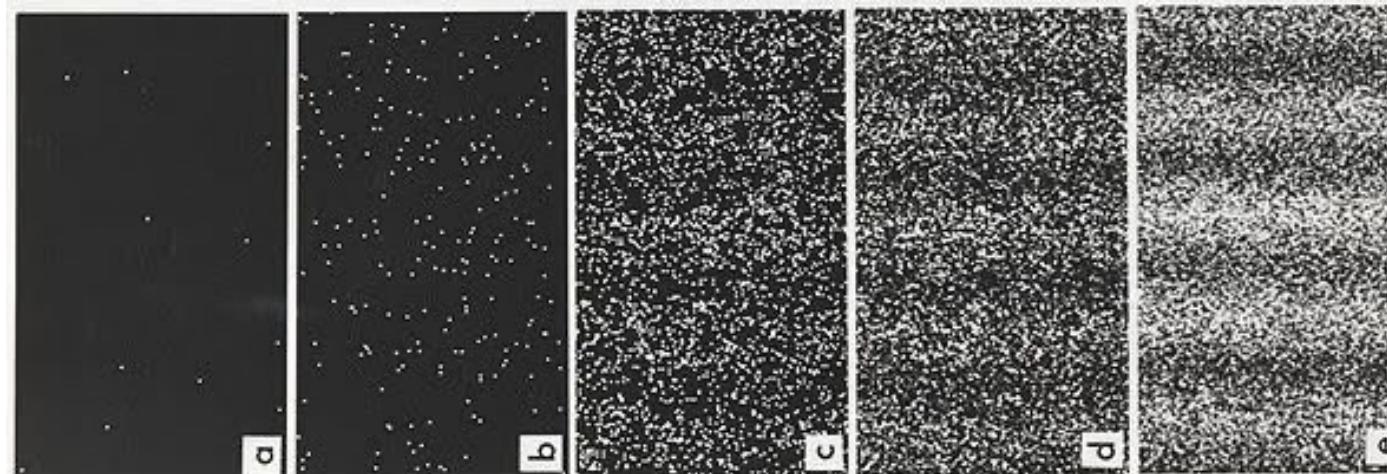
[Extra] Structure determination: Electron Microscopy (EM)

- Particles as «waves that transfers energy and momentum»

$$\lambda = \frac{h}{p}$$

λ : wavelength
 p : momentum
 h : Planck constant

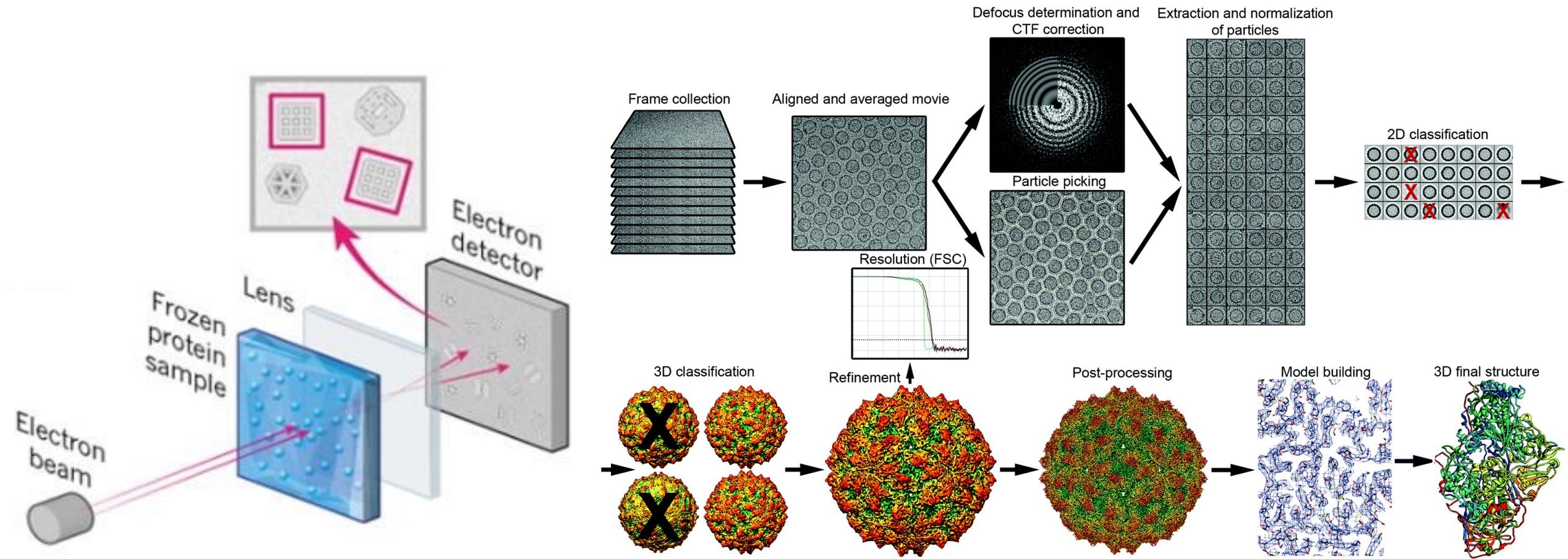
- Davisson–Germer experiment: electrons diffract too!



Louis De Broglie
1892-1987

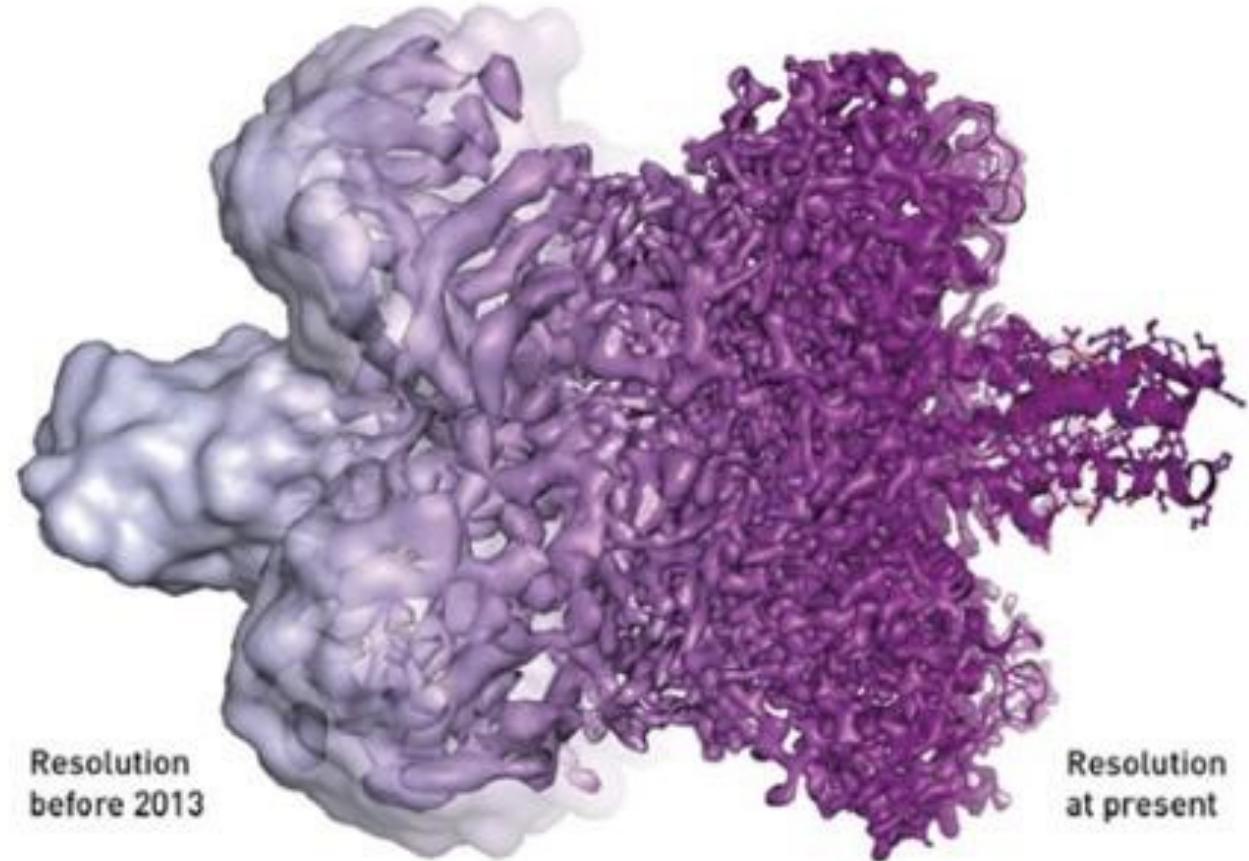
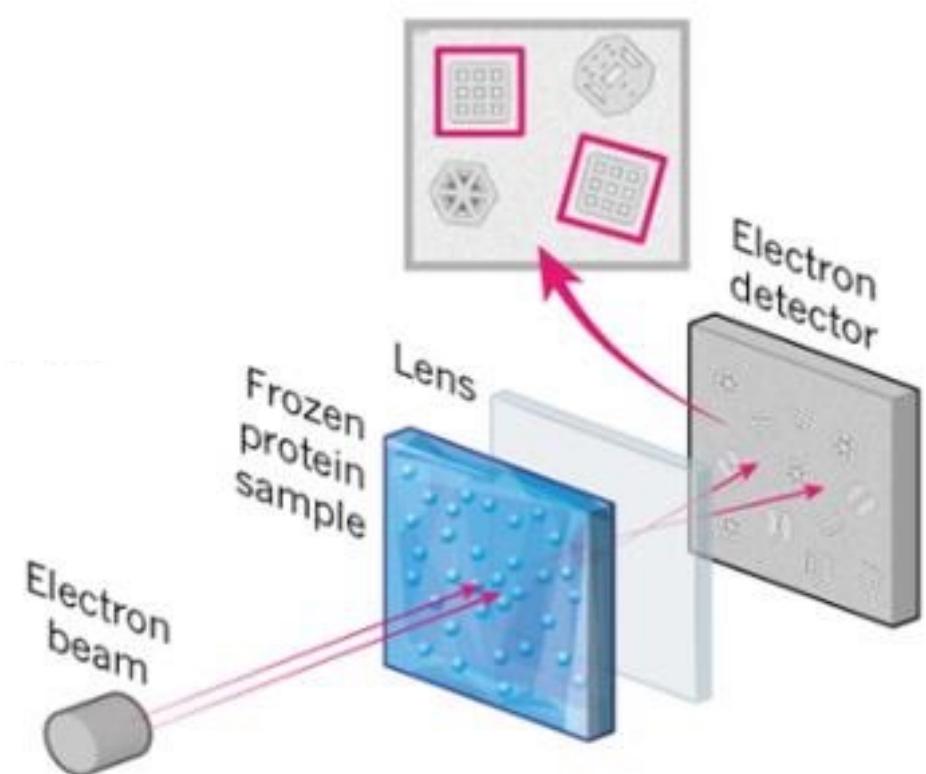
A. Tonomura *et al.*, *Demonstration of single-electron buildup of an interference pattern*, American Journal of Physics, 1989

Structure determination: Electron Microscopy (EM)



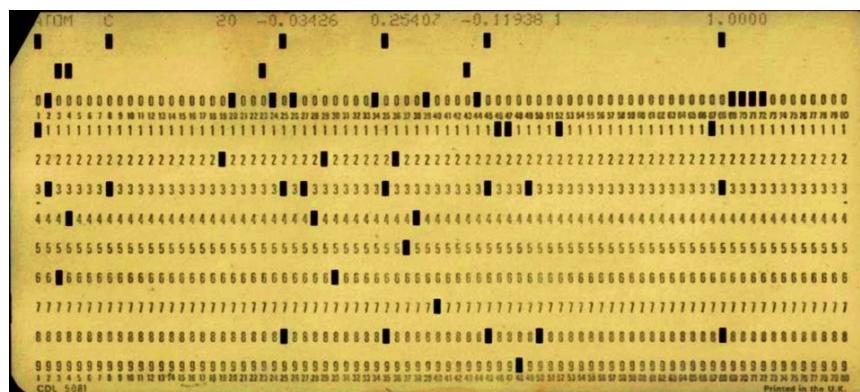
Structure determination: Electron Microscopy (EM)

Resolution Revolution



The Protein Data Bank (PDB)

- Molecular structures are deposited in the Protein Data Bank (PDB)
 - 1971: foundation of PDB at Brookhaven National Laboratory



A yellow rectangular card with a grid of black dots representing a protein structure. The card has some printed text at the top and bottom. The top line reads: ATOM C 20 -0.03426 0.25407 -0.11938 1 1.0000. The bottom line reads: Printed in the U.K. CDL 5081.



The Protein Data Bank (PDB)

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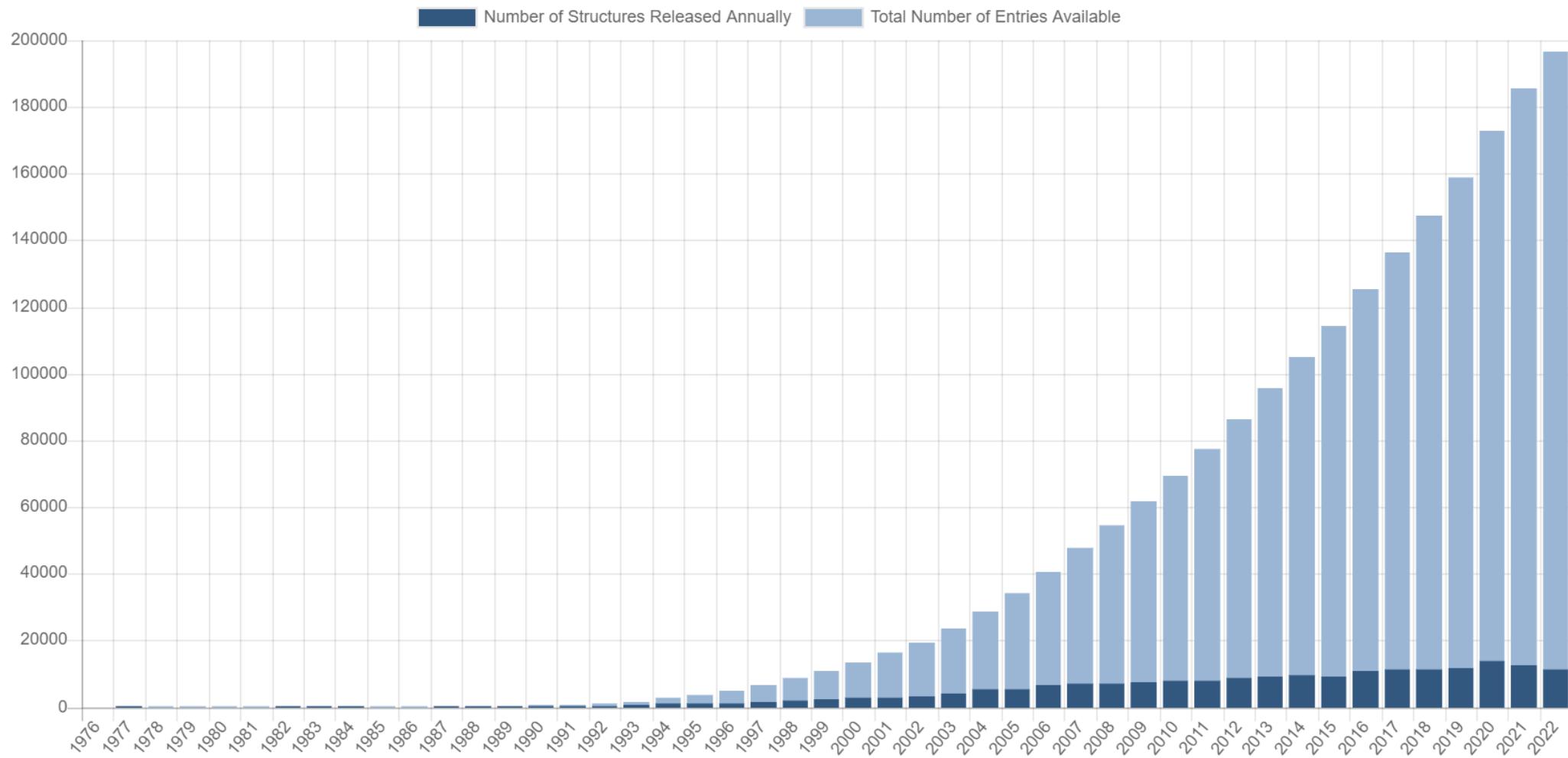


- 2003: wwPDB founded
 - now with four deposition centres
- Each molecule assigned a unique **4-characters code** (e.g. 1MBO, 1AV1, ...)

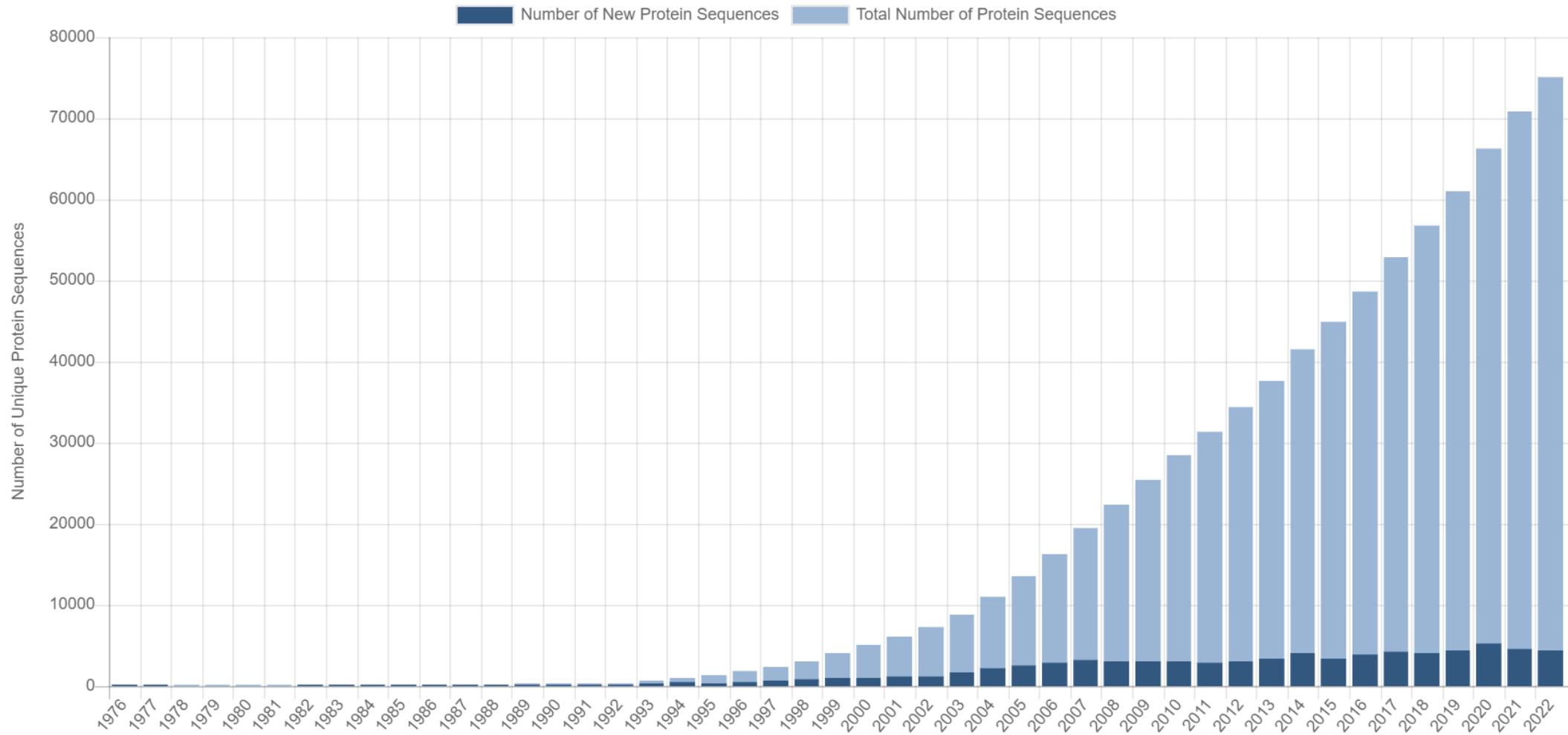
H.Berman, K.Henrick and H. Nakamura, *Announcing the worldwide Protein Data Bank*. Nature Structural & Molecular Biology, 2003

wwPDB consortium , *Protein Data Bank: the single global archive for 3D macromolecular structure data*, Nucleic Acids Research, 2019

The Protein Data Bank (PDB)



The Protein Data Bank (PDB)



known protein **structures**: ~80'000 (*PDB, 90% identity*)

known protein **sequences**: ~190'000'000 (*UNIPROT*)

Protein fold prediction

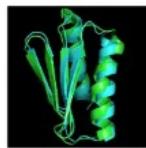
Protein Sequence

SQETRKKCTEMKKFKNCEVRCDESNHCVRCSDTKYTLC



prediction

Structure



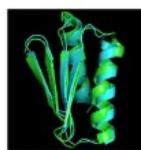
CASP, since 1994 biennial competition on protein fold prediction: predictioncenter.org

Protein fold prediction

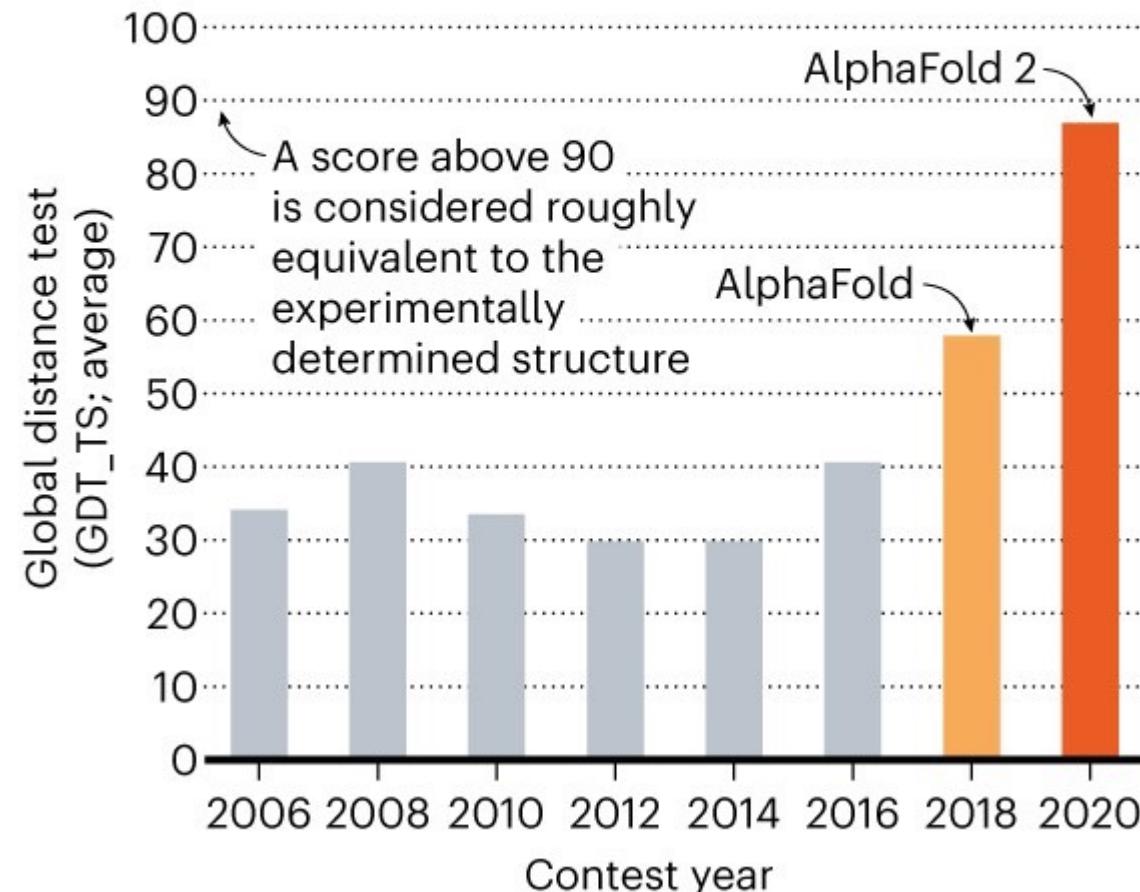
Protein Sequence

SQETRKKCTEMKKFKNCEVRCDESNHCVRCSDTKYTLC

prediction



Structure

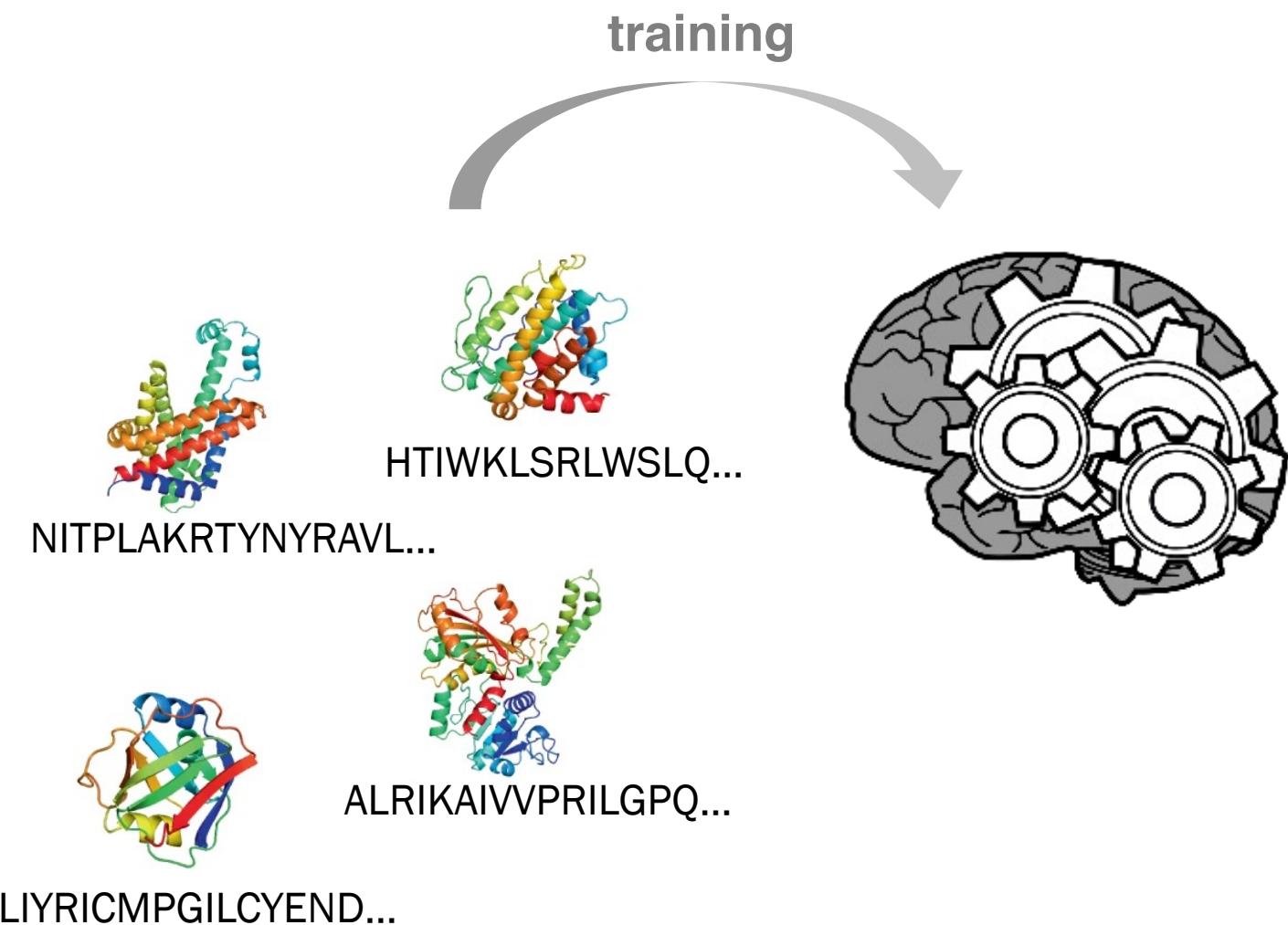


A.W. Senior et al., *Improved protein structure prediction using potentials from deep learning*, Nature, 2020

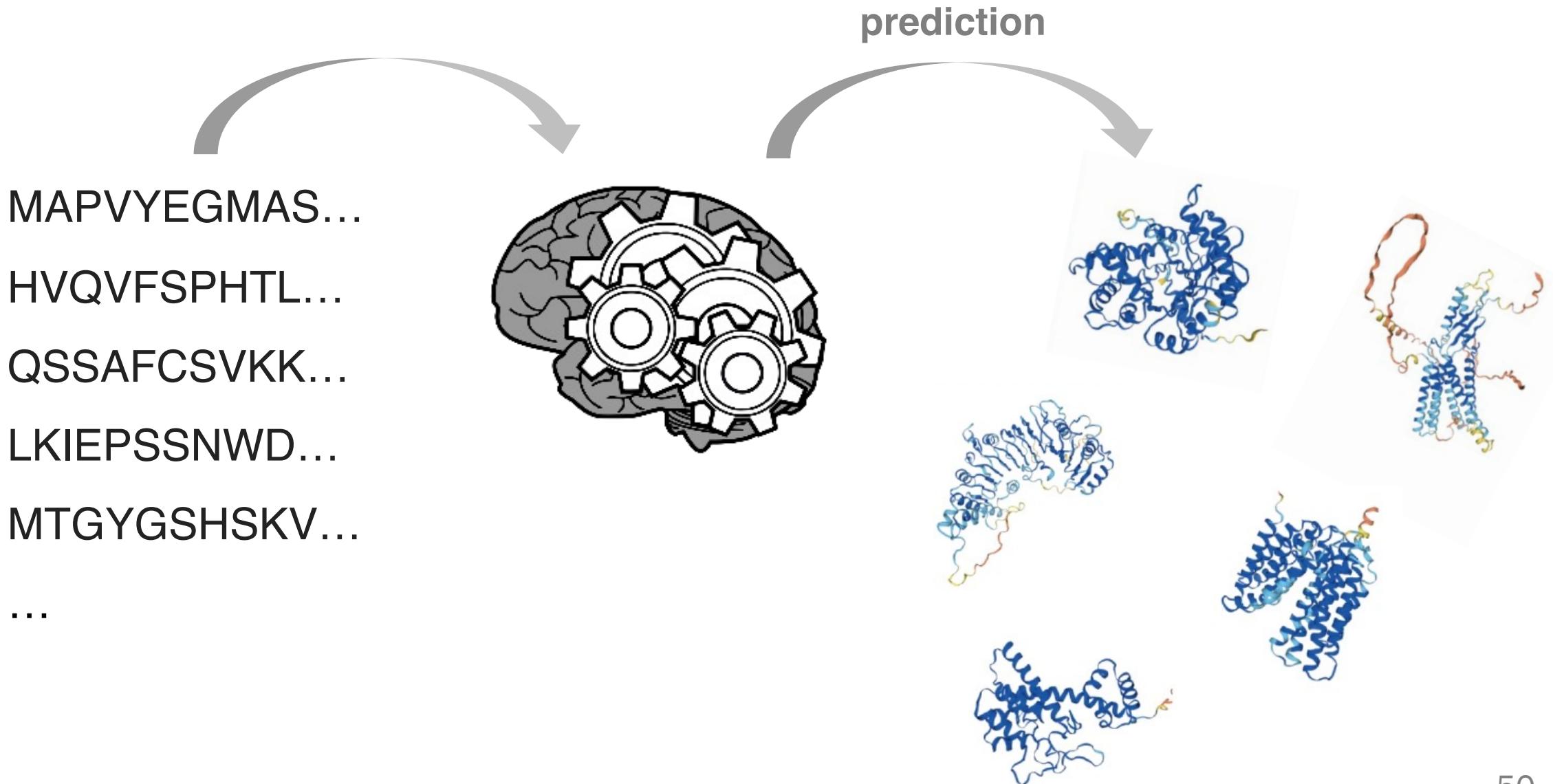
J. Jumper et al., *Highly accurate structure prediction with AlphaFold*, Nature, 2021

E. Callaway, 'It will change everything': DeepMind's AI makes gigantic leap in solving protein structures, Nature, 2021

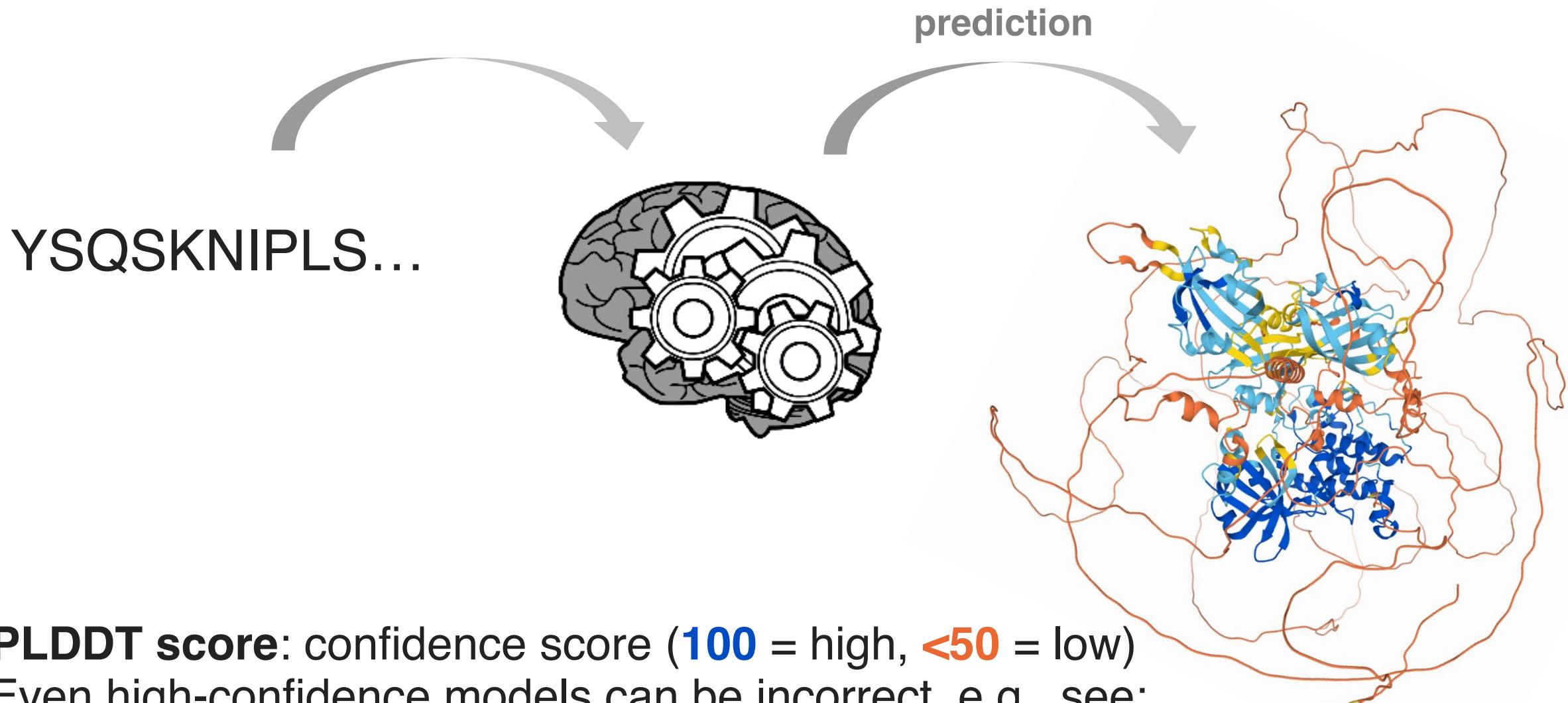
Protein fold prediction: AlphaFold2



Protein fold prediction: AlphaFold2



Protein fold prediction: AlphaFold2

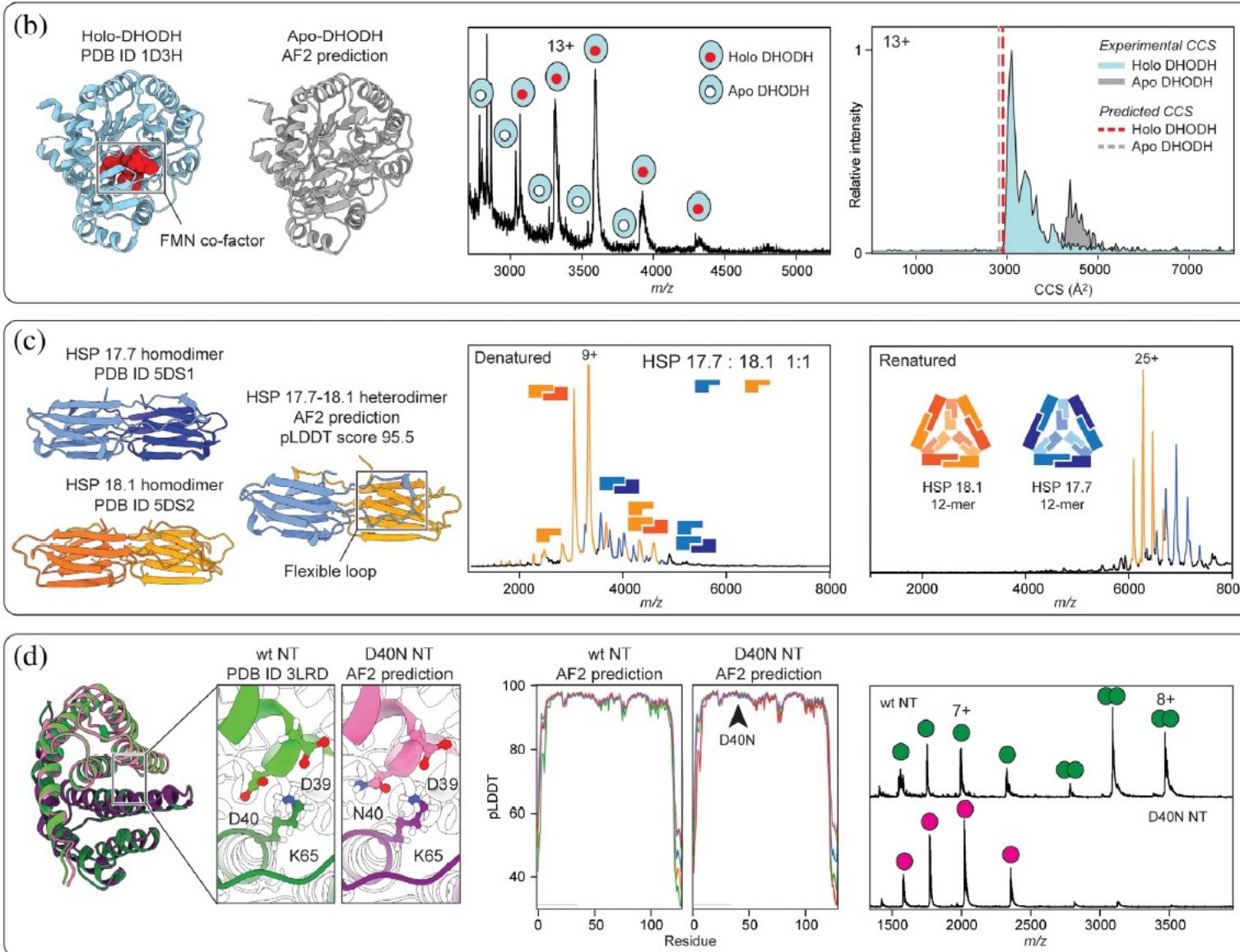


PLDDT score: confidence score (**100** = high, **<50** = low)

Even high-confidence models can be incorrect, e.g., see:

T.M.Allison et al., Protein Science, 2022

Protein fold prediction: warning!



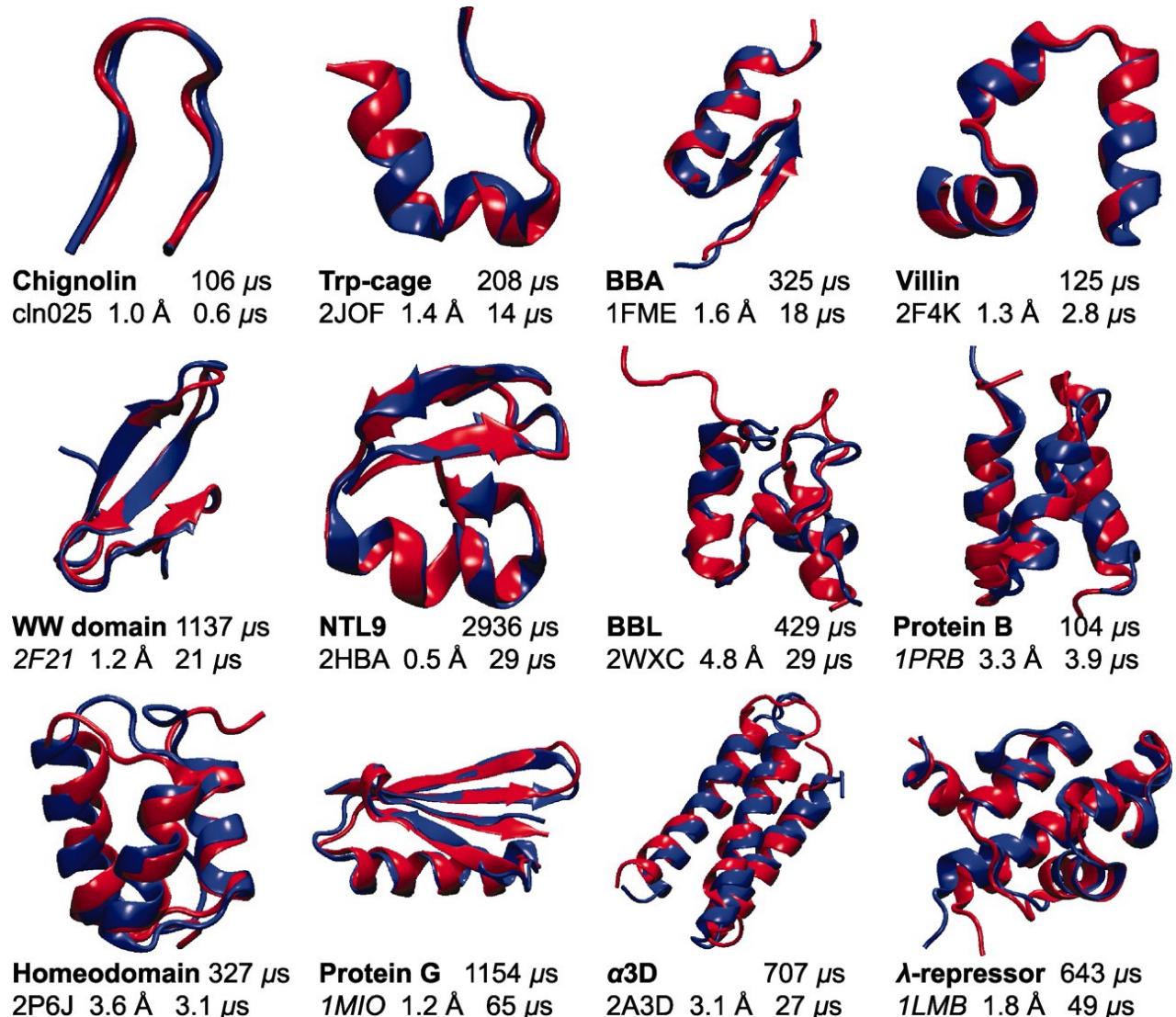
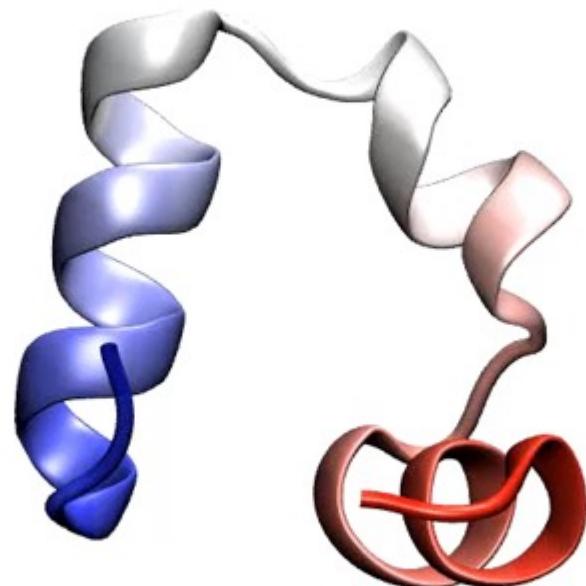
Apo protein predicted folded like holo state, but it should be unfolded

High-confidence hetero multimer predicted, but proteins do not co-assemble

High-confidence homodimer of mutated protein predicted, but mutation abolishes complex formation

Watching proteins fold: simulation

- Following experimentally the *folding pathway* of a protein is difficult
- Folding of small fast-folding ($<100\ \mu s$) proteins can be studied via simulation

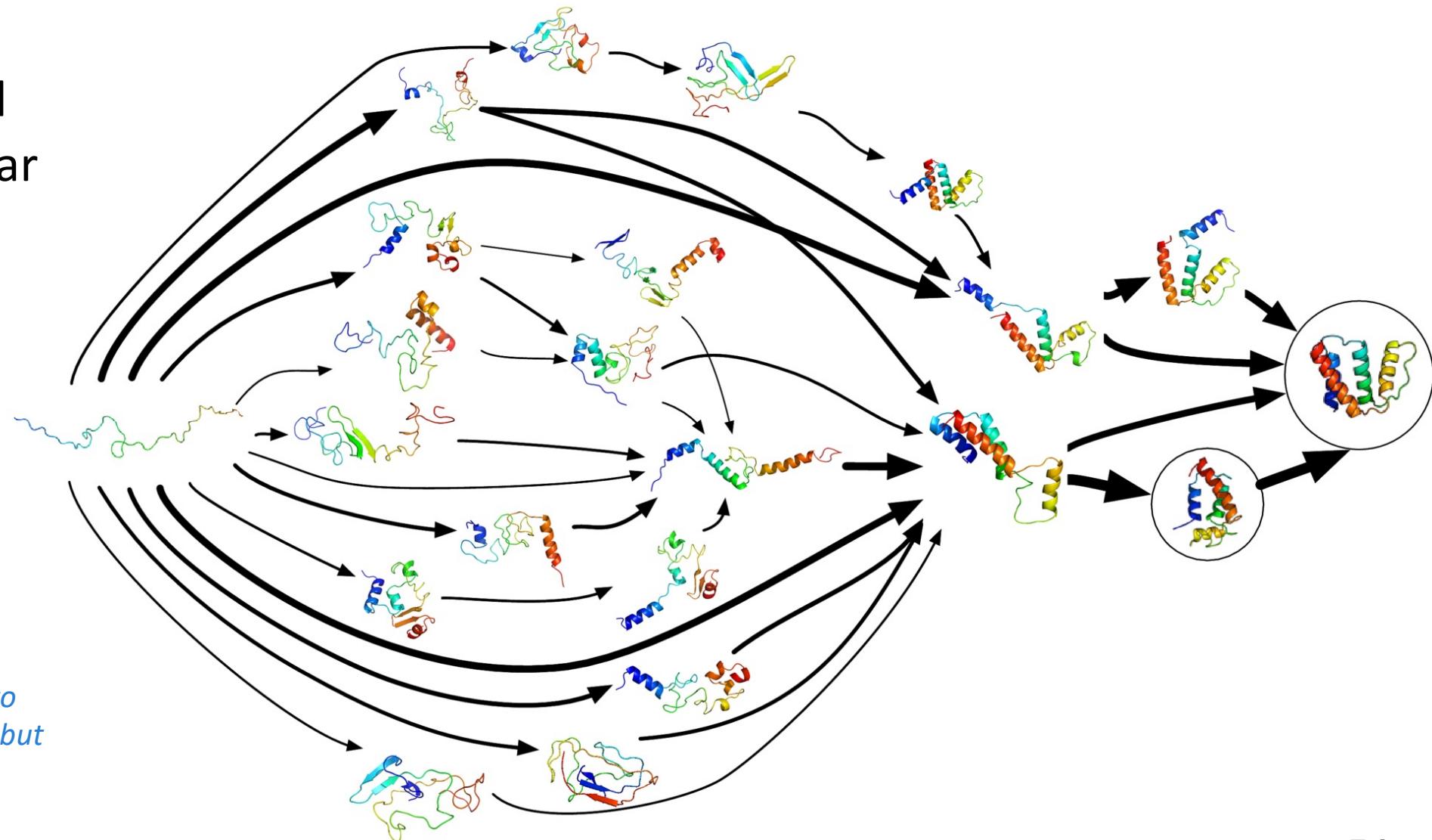


Folding@Home

Combine distributed computing, molecular simulation and Markov State Modelling (MSM) to predict protein folding pathways.

www.foldingathome.org

V. S. Pande, K. Beauchamp, G. R. Bowman, *Everything you wanted to know about Markov State Models but were afraid to ask. Methods*, 2010



**Next: how to prepare a protein structure so that
it is ready for molecular modelling?**