LOSCHMIDT LABORATORIES

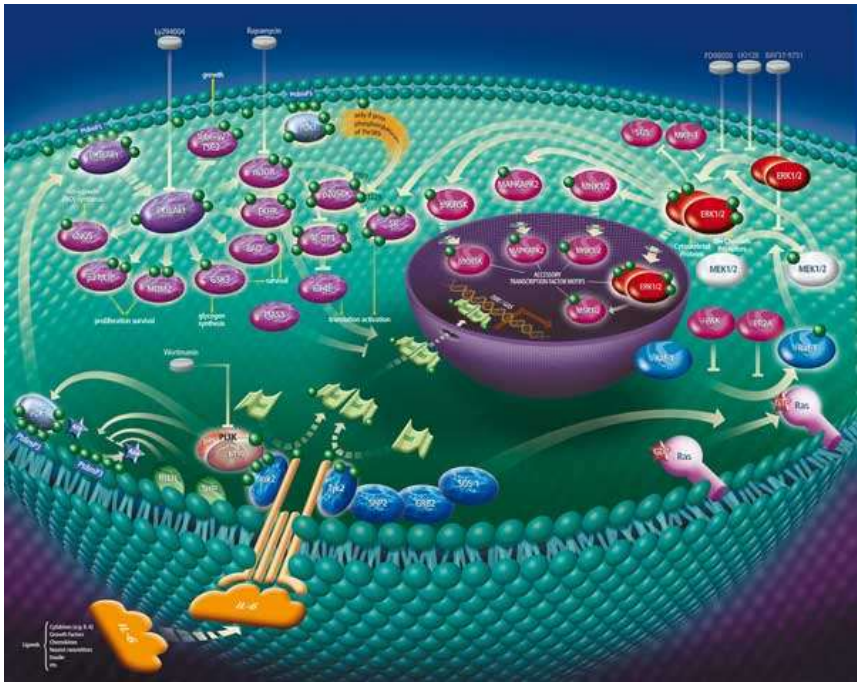
Protein-ligand complexes

Outline

- Biological relevance
- Molecular recognition
- Structure of complexes
- Protein druggability
- Small molecules
- Molecular docking
- Evaluation of complexes
- Transport of small molecules

Biological relevance

- **Cell signaling & regulation**
  - binding of small molecules to receptors
    - molecular function of ligands/receptors
    - selectivity of receptors
  - transport mechanisms
  - homeostasis of the cell
  - …

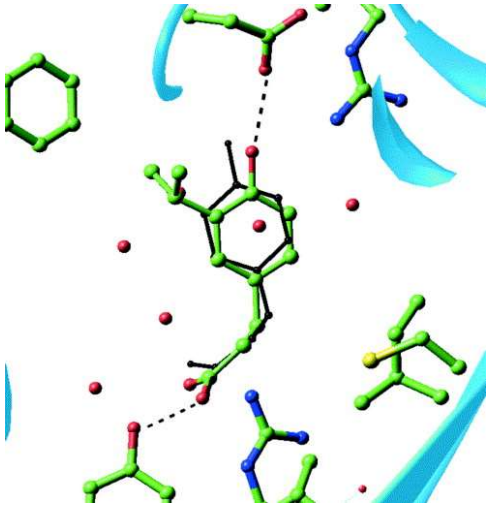


Biological relevance

- **Metabolism**
  - binding of small molecules to enzymes
    - molecular function of enzymes
    - activation of enzymes and molecular pathways
    - bioactivation and clearance of drugs and xenobiotics (P450s,…)
    - enzymatic cascades
    - metabolic interferences (competing pathways)
    - …

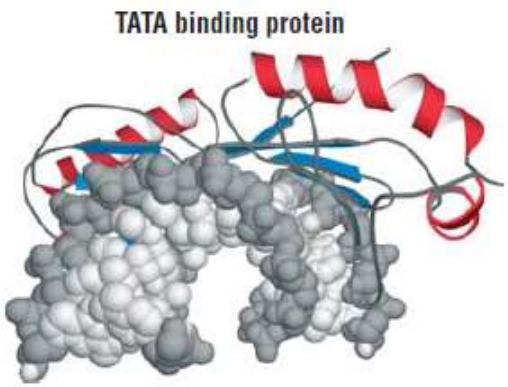
Biological relevance

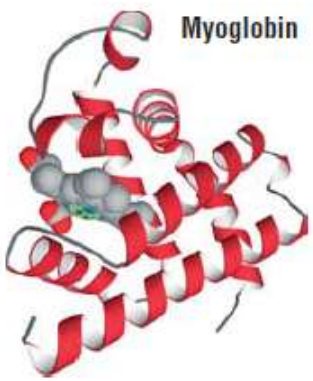
- **Drug discovery**
  - binding of small molecules drug targets (enzymes, receptors, ...)
    - identification of possible inhibitors
    - optimization of inhibition
    - repurposing of drugs – finding new receptors
    - adverse side-effects due to binding to other target
    - …

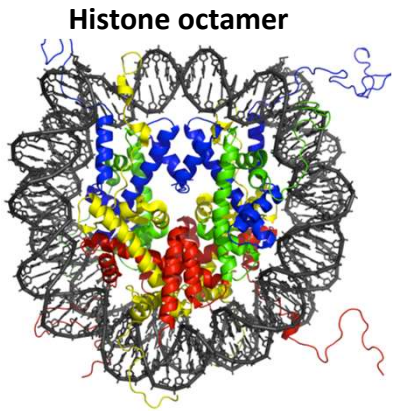


Biological roles

- **Binding**
  - specific binding governed by complementarity
    - shape – non-polar interactions
    - physicochemical – electrostatics and polar interactions



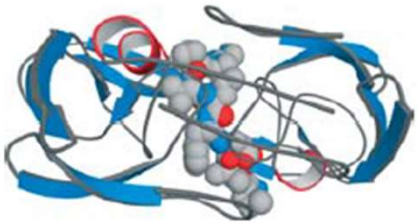




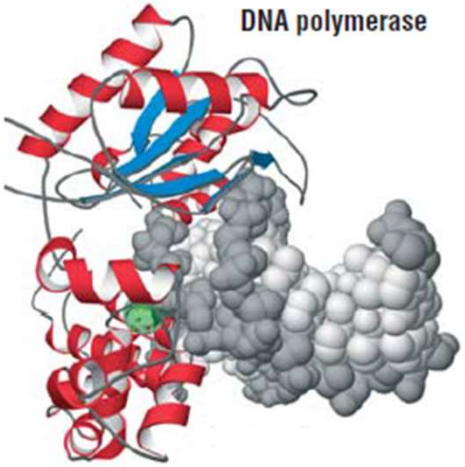
Biological roles

- **Catalysis**
  - chemical reactions can be accelerated by 17 orders of magnitude
  - transition state stabilization
  - tight binding decreases the energy barrier of the reaction

HIV protease



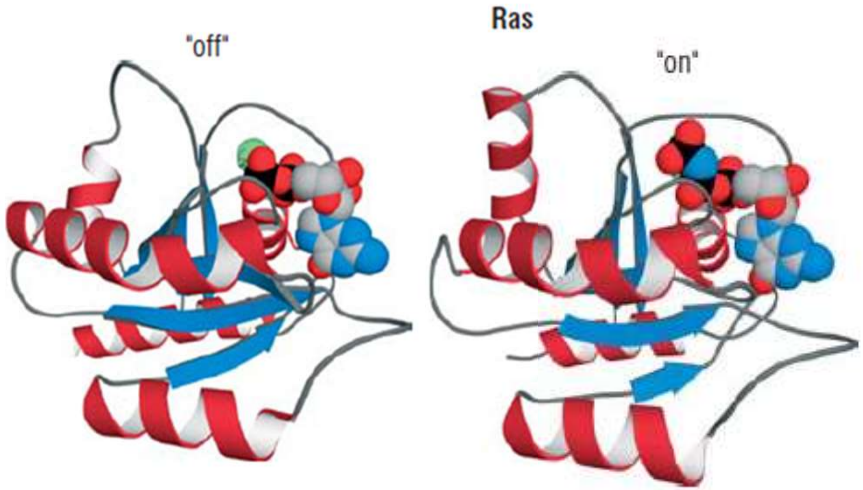
DNA polymerase

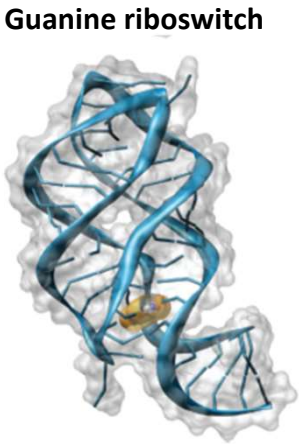


Hammerhead ribozyme

Biological roles

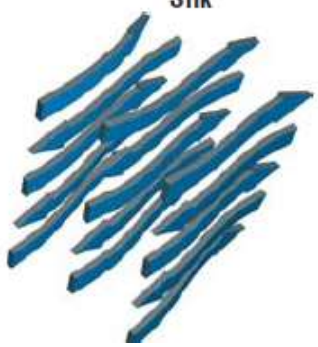
- **Signaling**
  - conformational changes in response to
    - ligand binding
    - properties of surrounding environment (pH, forces…)
  - different conformations recognized by different proteins in signaling pathways -> control of cellular processes

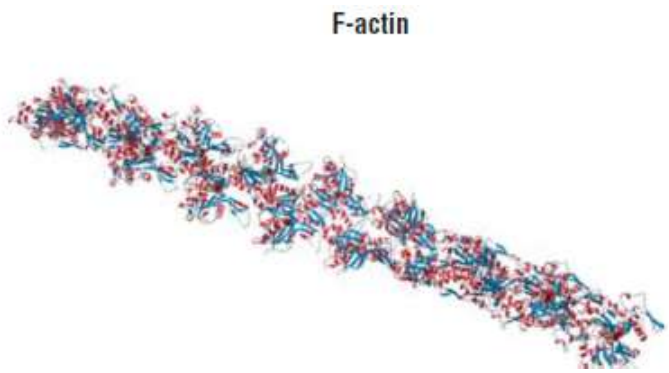




Biological roles

- **Formation of complex structures**
  - structural element of complex systems
  - governed by specific association of protein subunits
    - with themselves
    - other proteins, carbohydrates, lipids, …



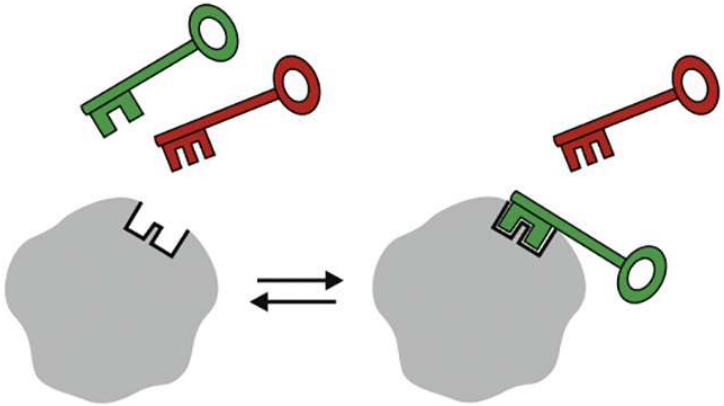


Molecular recognition

- molecular recognition refers to the specific interactions between two or more molecules through noncovalent bonding
- different biological roles
  - specific binding
  - catalysis
  - signaling
- several models to explain recognition

Lock-and-key model

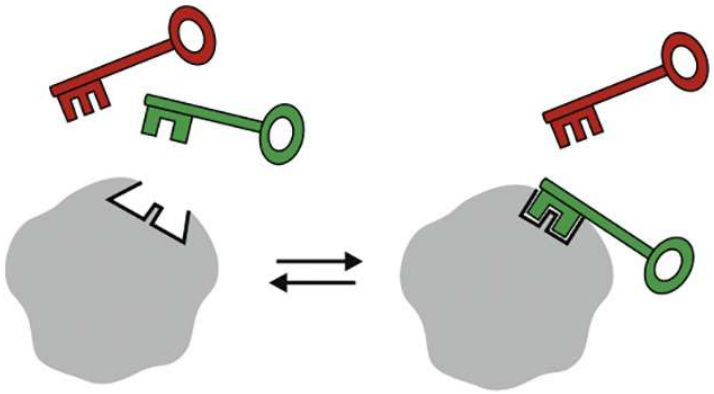
- **E. Fisher – 1894**
- Complementarity between receptor's binding site and ligand moiety
  - size & shape
  - physicochemical properties



- Both ligand and receptor are considered rigid
  - not sufficient to explain allostery, non-competitive inhibition, or catalysis
  - -> model dismissed, only used for educational purposes

Induced-fit model

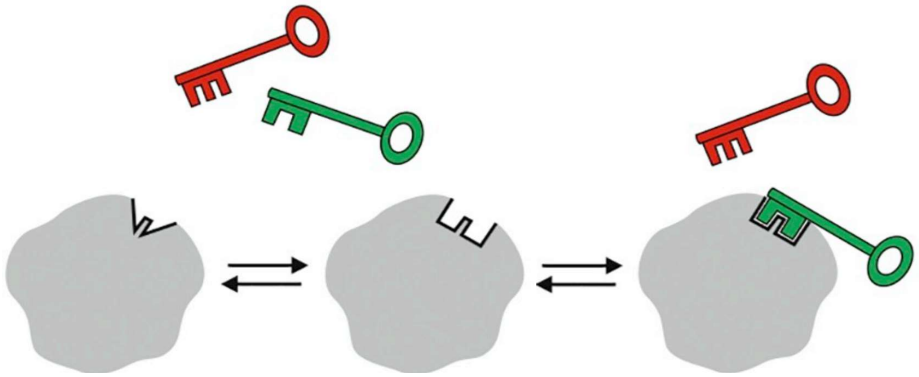
- **D. E. Koshland – 1956**
- Only partial complementarity necessary



- Both ligand and receptor can undergo conformational adjustments upon complexation
  - conformation of the bound receptor does not exists in its free state

Selected-fit model

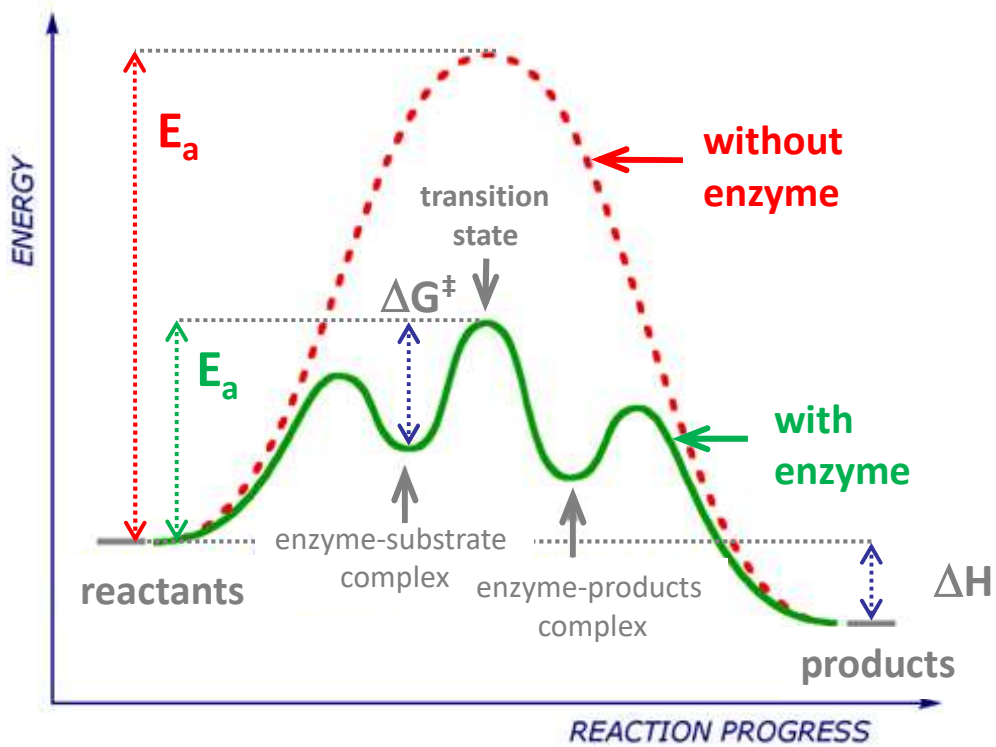
- **B. F. Straub – 1964**
  - this model is also called: conformational selection, fluctuation-fit or population selection
- Receptor and ligand flexible -> considered as ensembles



- Complex is formed in a lock-and-key fashion when two complementary configurations occur
  - conformation of the bound receptor exists also in its free state

Biocatalysis

- Enzymes increase the speed of chemical reactions by decreasing the activation barrier



- Kinetic rate:

$$k = Ae^{\frac{-E_a}{RT}}$$

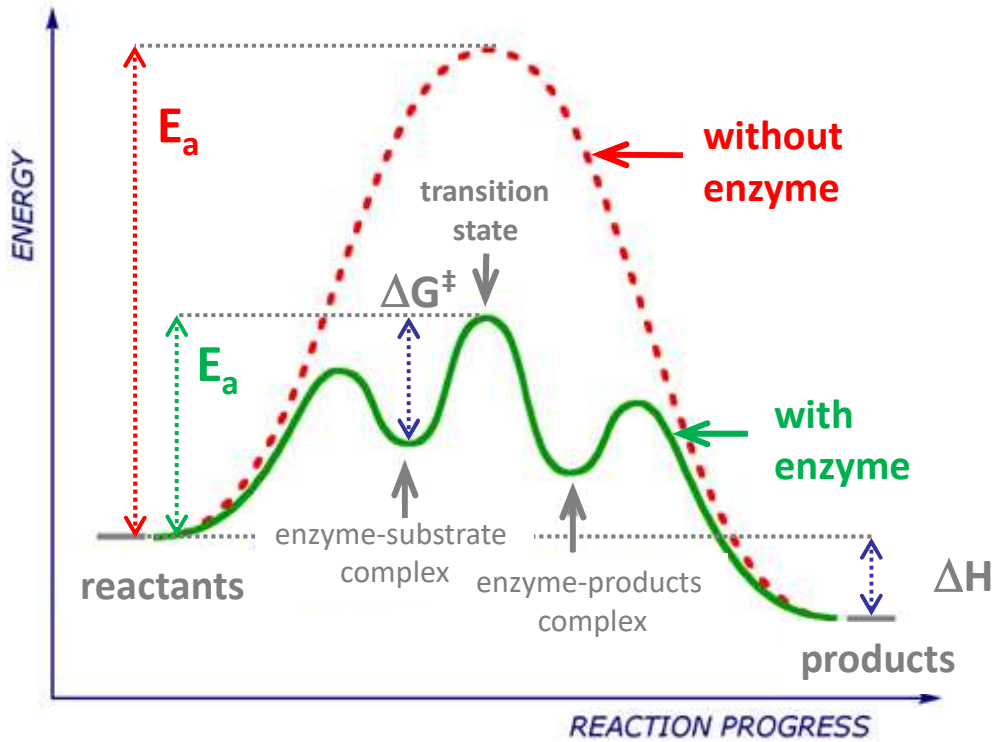
(Arrhenius equation)

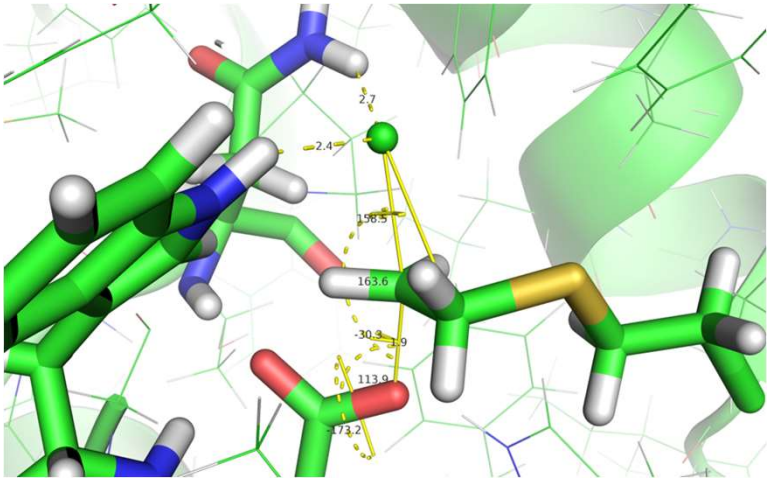
- lower E_a → higher k

  ⇔ faster reaction

Biocatalysis

- Enzymes increase the speed of chemical reactions by decreasing the activation barrier
- Provide environments that stabilize the transition state(s)



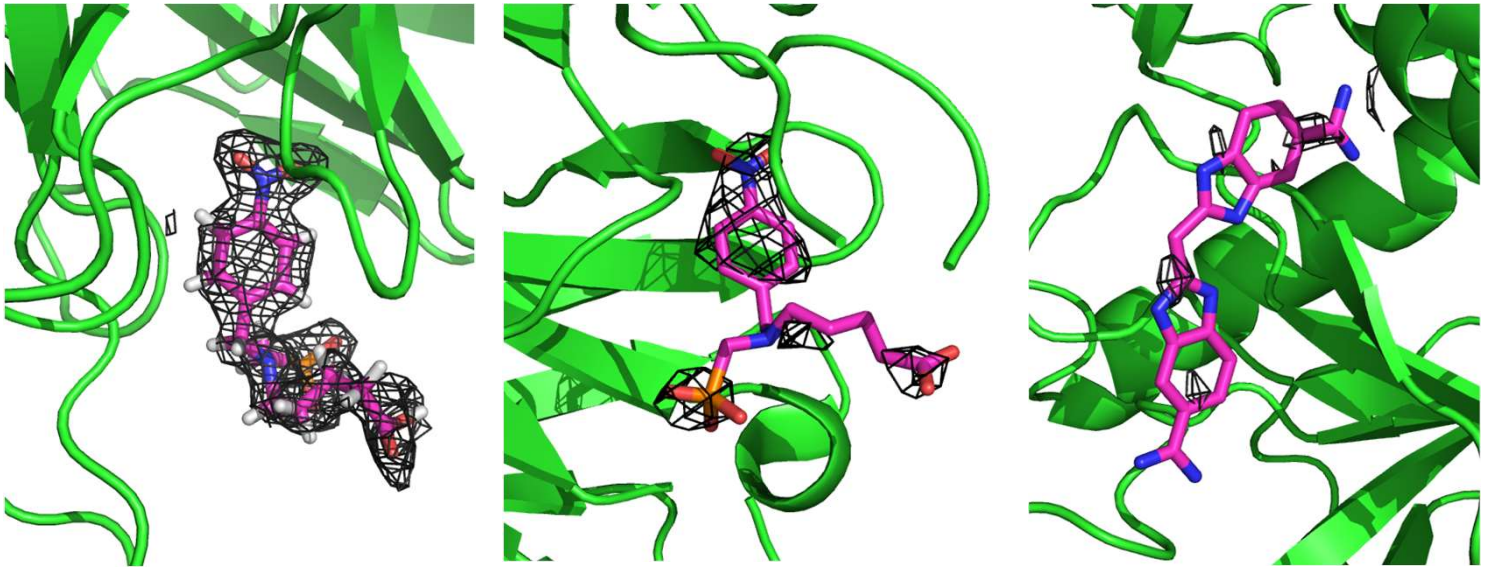


Structure of complexes

- Complexes in RSCB PDB
- Databases of complexes
  - PDBbind
  - BindingDB
  - ChEMBL
  - …

Complexes in RSCB PDB

- **Limited number of available complexes**
  - 135,000 protein structures
  - 101,000 structures with ligands
- **Limited information on conformation of bound ligand**
  - ligands often quite mobile -> uncertainties -> need to be verified



Databases of complexes

- **PDBbind**
  - http://www.pdbbind.org.cn
  - binding affinity data and structural information on about 16,500 complexes
    - ~ 13,500 protein-ligand
    - ~ 120 nucleic acid-ligand
    - ~ 800 protein-nucleic acid
    - ~ 2,000 protein-protein complexes
  - data collected from >29,000 original references
  - provides also "refined set" and a "core set“ compiled as high-quality data sets of protein-ligand complexes for docking/scoring studies

Databases of complexes

- **PDBbind**

Welcome to the PDBbind Database!

PDBbind

Current version: 2012
Total entries: 9,308

Search Result List (18 Hits)

ID		PDB	Subset	Resolution	Kd	pKd	Release	Protein Name
1	☑	1a30	Protein-Ligand	2	Ki=50uM	4.3	1998	HIV-1 protease
2	☑	1adl	Protein-Ligand	1.6	Kd=4.4uM	5.36	1994	trp rna-binding attenuation protein
3	☑	1b39	Protein-Ligand	2.1	Kd=0.120uM	6.92	1998	cyclin dependent kinase 2
4	☑	1b7h	Protein-Ligand	2	Kd=0.0095uM	8.02	1998	oligo-peptide binding protein
5	☑	1b8o	Protein-Ligand	1.5	Ki=23pM	10.64	1999	purine nucleoside phosphorylase
6	☑	1b9j	Protein-Ligand	1.8	Kd=1100nM	5.96	1999	oligo-peptide binding protein
7	☑	1bcu	Protein-Ligand	2	Kd=0.53mM	3.28	1998	thrombin alpha
8	☑	1nwl	Protein-Ligand	2.4	Ki=4.1mM	2.39	2003	tyrosine phosphatase 1b
9	☑	1bxo	Protein-Ligand	.95	Ki=0.10nM	10	1998	penicillopepsin
10	☑	1bxq	Protein-Ligand	1.41	Ki=42nM	7.38	1998	penicillopepsin
11	☑	1c1v	Protein-Ligand	1.98	Ki=0.023uM	7.64	2000	thrombin alpha
12	☑	1c88	Protein-Ligand	1.8	Ki=5.1uM	5.29	2000	tyrosine phosphatase 1b
13	☑	1d09	Protein-Ligand	2.1	Ki=27nM	7.57	2000	aspartate carbamoyltransferase
14	☑	1d7j	Protein-Ligand	1.85	Kd=500uM	3.3	1999	FK506 binding protein
15	☑	1e66	Protein-Ligand	2.1	Ki=0.13nM	9.89	2001	acetylcholinesterase

HOME | BROWSE | DATA | STRUCTURE | SEQUENCE | DOWNLOAD

Search For Complexes

AND	Search in	Protein-Ligand core set	
AND	PDB ID		(e.g. 1a or 1a7x)
AND	Protein Name		(e.g. kinase)
AND	Ligand Name		(e.g. 3-mer)
AND	EC Number	. . . .	(e.g. 2.5.1.2 or 3. .4.2)
AND	Release Year	From To	(e.g. 1998 To 2006)
AND	Resolution	From To	(e.g. 1.7 To 2,or NMR)
AND	Affinity (pKd/pKi/pIC50)	From To	(e.g. 4.3 To 8.5)

Search Clear

Save Result As: PDF Format Excel Format

Download structure files: Ligand Protein Protein-Ligand Pocket-Ligand

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PDB ID 1Ogs Quick Search

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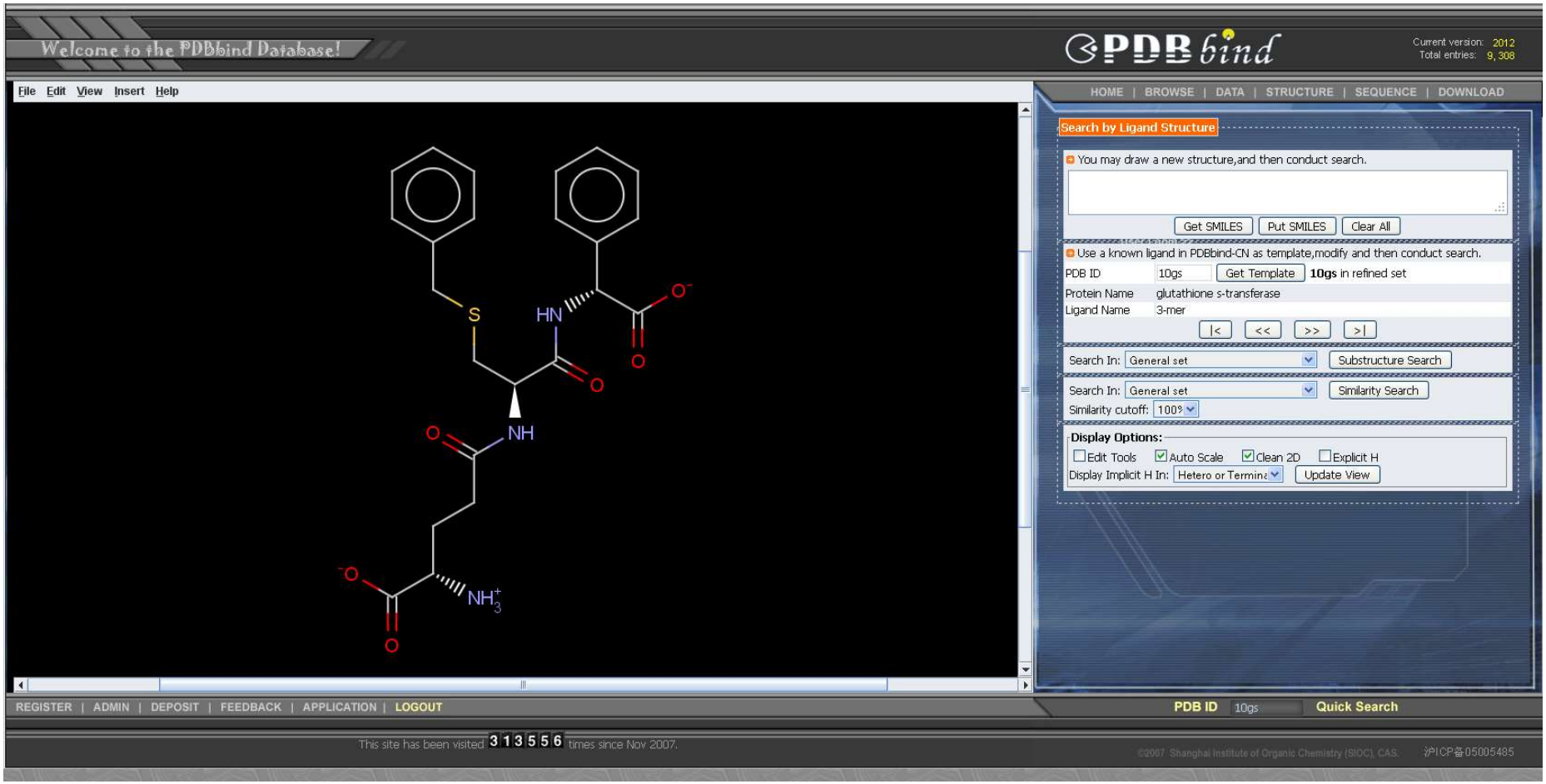
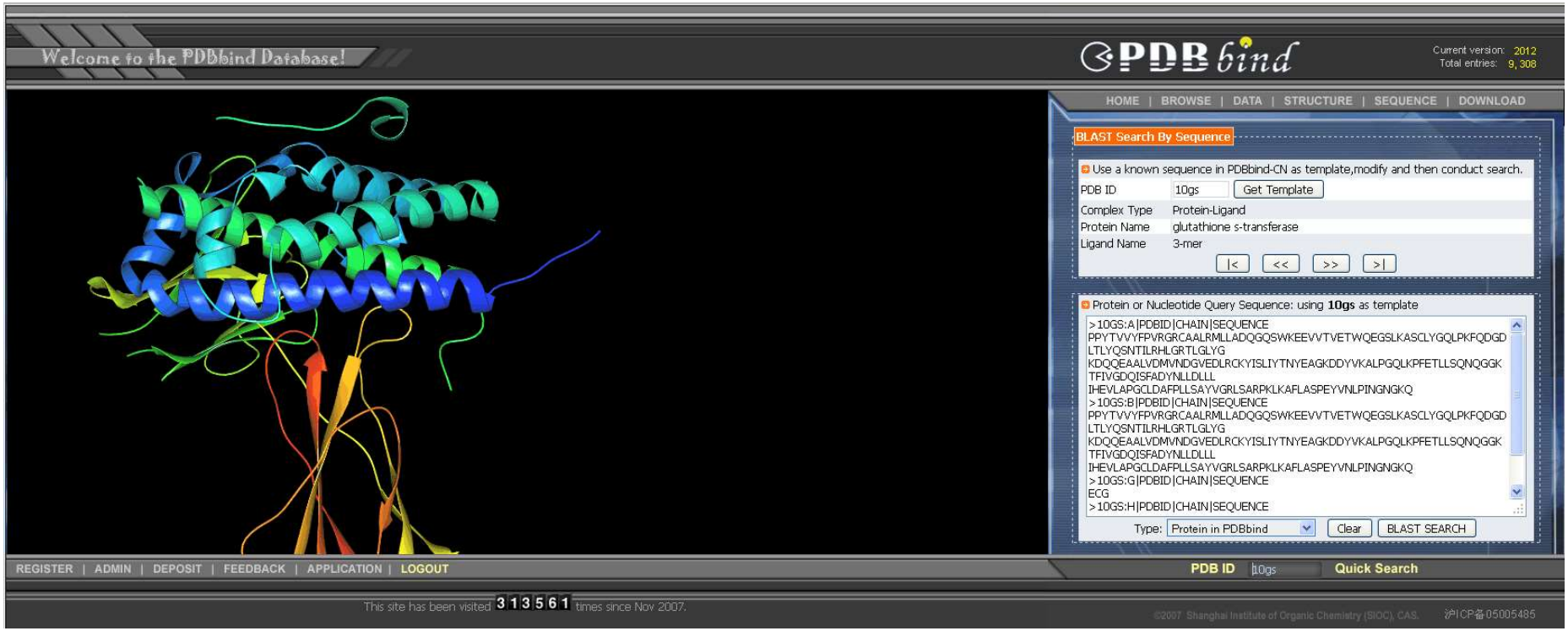
Databases of complexes

- **PDBbind**



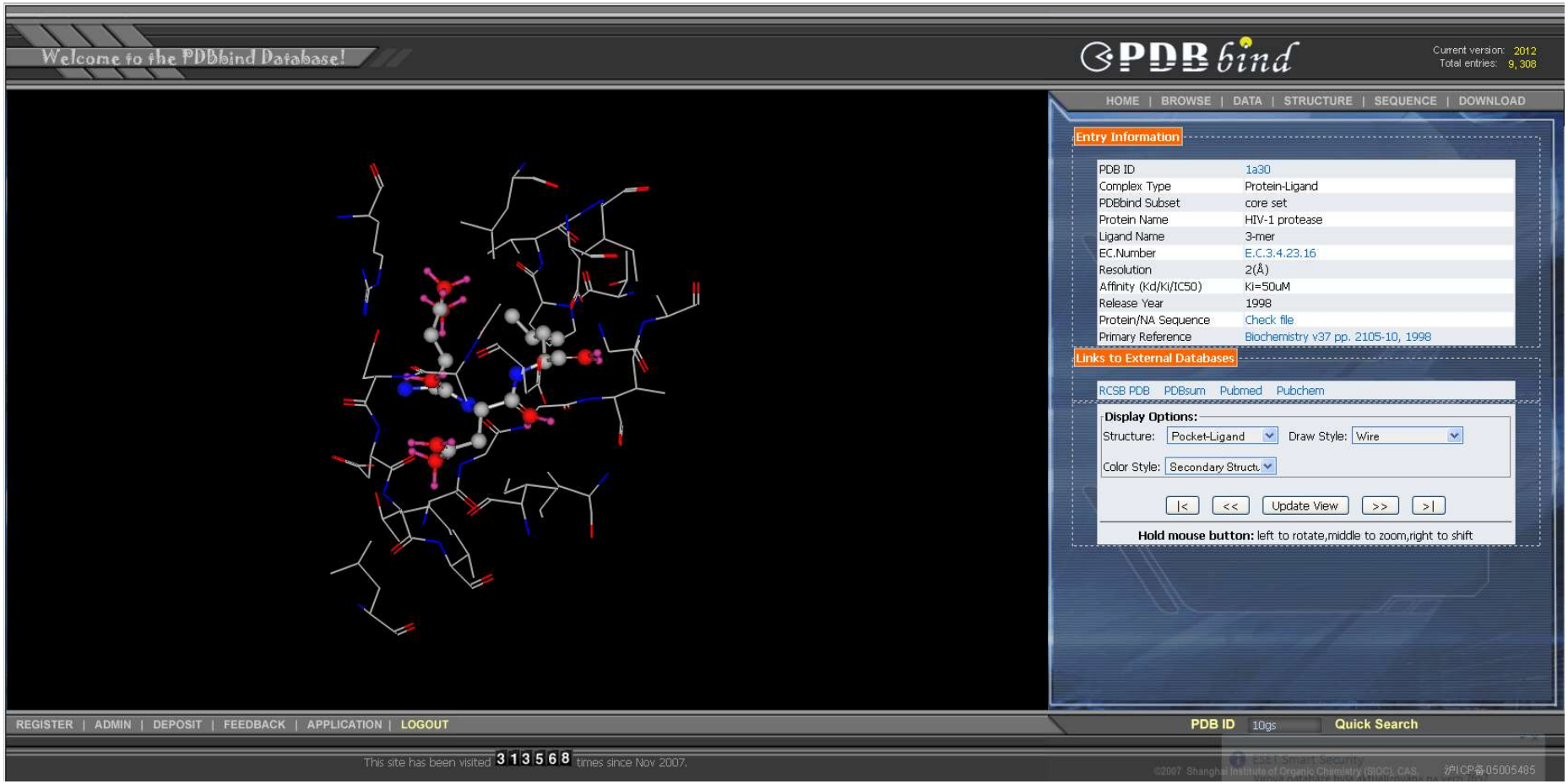
Databases of complexes

- **PDBbind**



Databases of complexes

- **PDBbind**

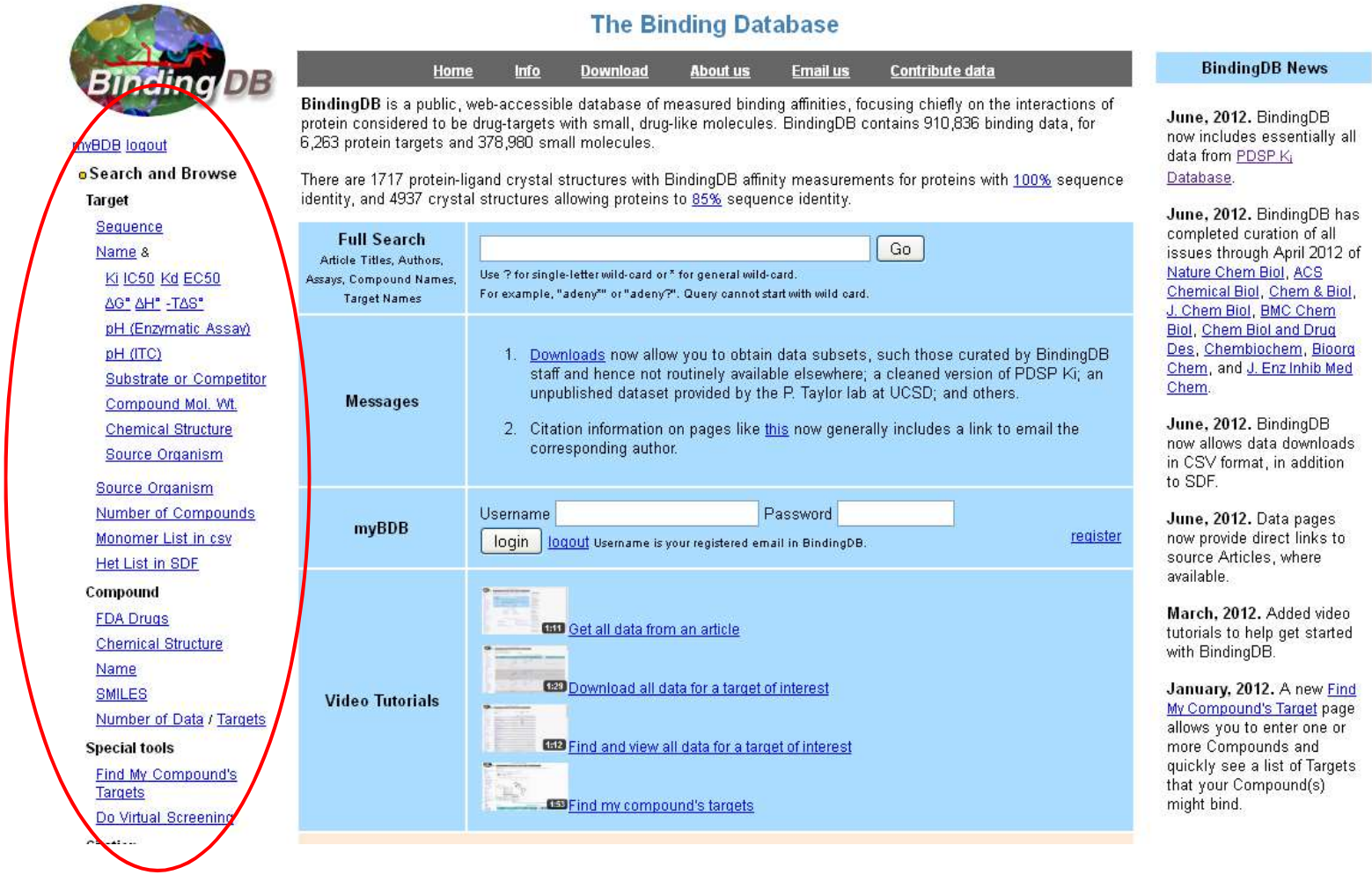


Databases of complexes

- **BindingDB**
  - www.bindingdb.org
  - focus on the interactions of protein considered to be drug-targets with drug-like molecules
  - contains about 1,500,000 entries of binding data
    - 7,000 protein targets
    - 650,000 small molecules
  - crystal structures of complexes with measured affinity
    - ~2,500 - for proteins with 100% sequence identity
    - ~ 6,000 - for proteins up to 85% sequence identity

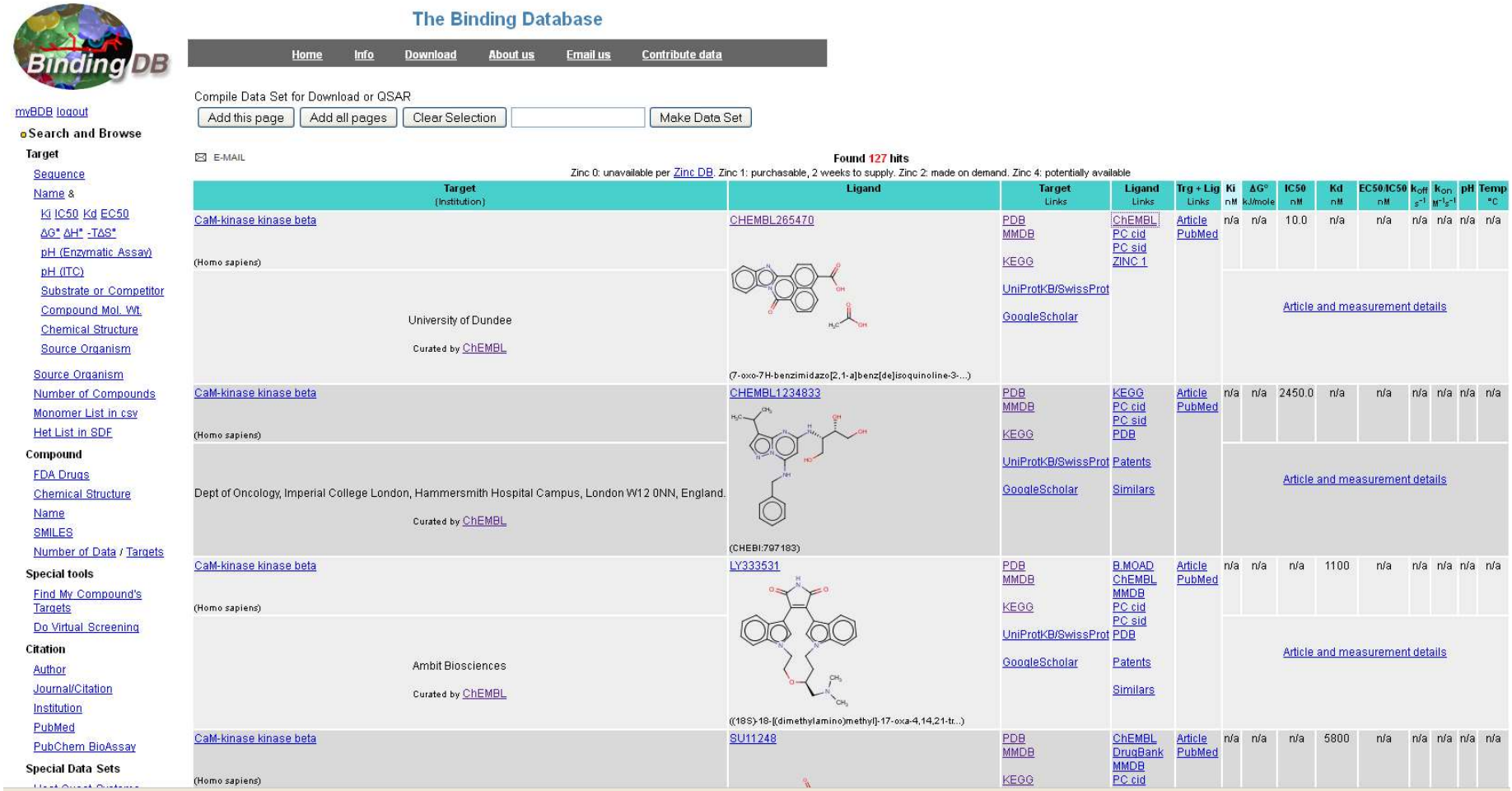
Databases of complexes

❑ BindingDB



Databases of complexes

❑ BindingDB



The Binding Database

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- Search and Browse
  - Target
    - Sequence
    - Name &
      - Ki IC50 Kd EC50
      - ΔG° ΔH° -TΔS°
      - pH (Enzymatic Assay)
      - pH (ITC)
      - Substrate or Competitor
      - Compound Mol. Wt.
      - Chemical Structure
      - Source Organism
    - Source Organism
    - Number of Compounds
    - Monomer List in csv
    - Het List in SDF
  - Compound
    - FDA Drugs
    - Chemical Structure
    - Name
    - SMILES
    - Number of Data / Targets
  - Special tools
    - Find My Compound's Targets
    - Do Virtual Screening
  - Citation
    - Author
    - Journal/Citation
    - Institution
    - PubMed
    - PubChem BioAssay
  - Special Data Sets

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Found 127 hits

Zinc 0: unavailable per Zinc DB. Zinc 1: purchasable, 2 weeks to supply. Zinc 2: made on demand. Zinc 4: potentially available

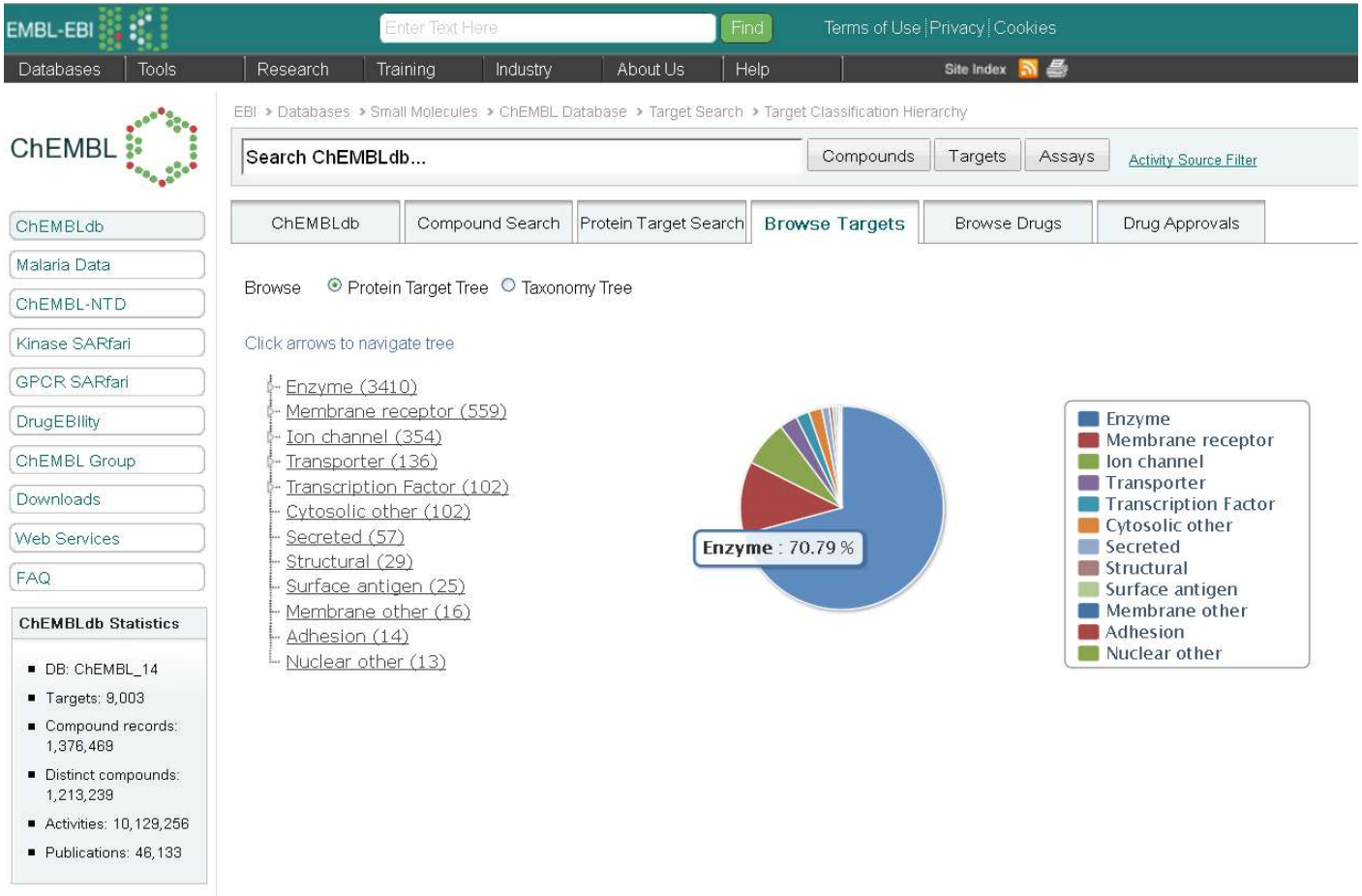
Target (Institution)	Ligand	Target Links	Ligand Links	Trg + Lig Links	Ki nM	ΔG° kJ/mole	IC50 nM	Kd nM	EC50/IC50 nM	k_{off} s^{-1}	k_{on} $M^{-1}s^{-1}$	pH	Temp °C
CaM-kinase kinase beta (Homo sapiens)	CHEMBL265470	PDB, MMDB, KEGG, UniProtKB/SwissProt, GoogleScholar	ChEMBL, PC cid, PC sid, ZINC 1	Article, PubMed	n/a	n/a	10.0	n/a	n/a	n/a	n/a	n/a	n/a
University of Dundee (Curated by ChEMBL)	(7-oxo-7H-benzimidazo[2,1-a]benz[de]isoquinoline-3-...)				Article and measurement details								
CaM-kinase kinase beta (Homo sapiens)	CHEMBL1234833	PDB, MMDB, KEGG, UniProtKB/SwissProt, GoogleScholar	KEGG, PC cid, PC sid, PDB, Patents, Similars	Article, PubMed	n/a	n/a	2450.0	n/a	n/a	n/a	n/a	n/a	n/a
Dept of Oncology, Imperial College London, Hammersmith Hospital Campus, London W12 0NN, England. (Curated by ChEMBL)	(CHEBI:797183)				Article and measurement details								
CaM-kinase kinase beta (Homo sapiens)	LY333531	PDB, MMDB, KEGG, UniProtKB/SwissProt, GoogleScholar	B.MOAD, ChEMBL, MMDB, PC cid, PC sid, PDB, Patents, Similars	Article, PubMed	n/a	n/a	n/a	1100	n/a	n/a	n/a	n/a	n/a
Ambit Biosciences (Curated by ChEMBL)	((18S)-18-[(dimethylamino)methyl]-17-oxa-4,14,21-tr...)				Article and measurement details								
CaM-kinase kinase beta (Homo sapiens)	SU11248	PDB, MMDB, KEGG	ChEMBL, DrugBank, MMDB, PC cid	Article, PubMed	n/a	n/a	n/a	5800	n/a	n/a	n/a	n/a	n/a

Databases of complexes

- **ChEMBL**
  - https://www.ebi.ac.uk/chembldb/
  - is a manually curated database of bioactive molecules with drug-like properties
  - database of binding, functional and ADME (Absorption, Distribution, Metabolism, and Excretion) and Toxic. information
  - contains nearly 15,000,000 activity data
    - ~12,000 protein targets
    - ~1,700,000 distinct small molecules
  - data collected from >67,000 original publications
  - intelligent clustering of relevant information

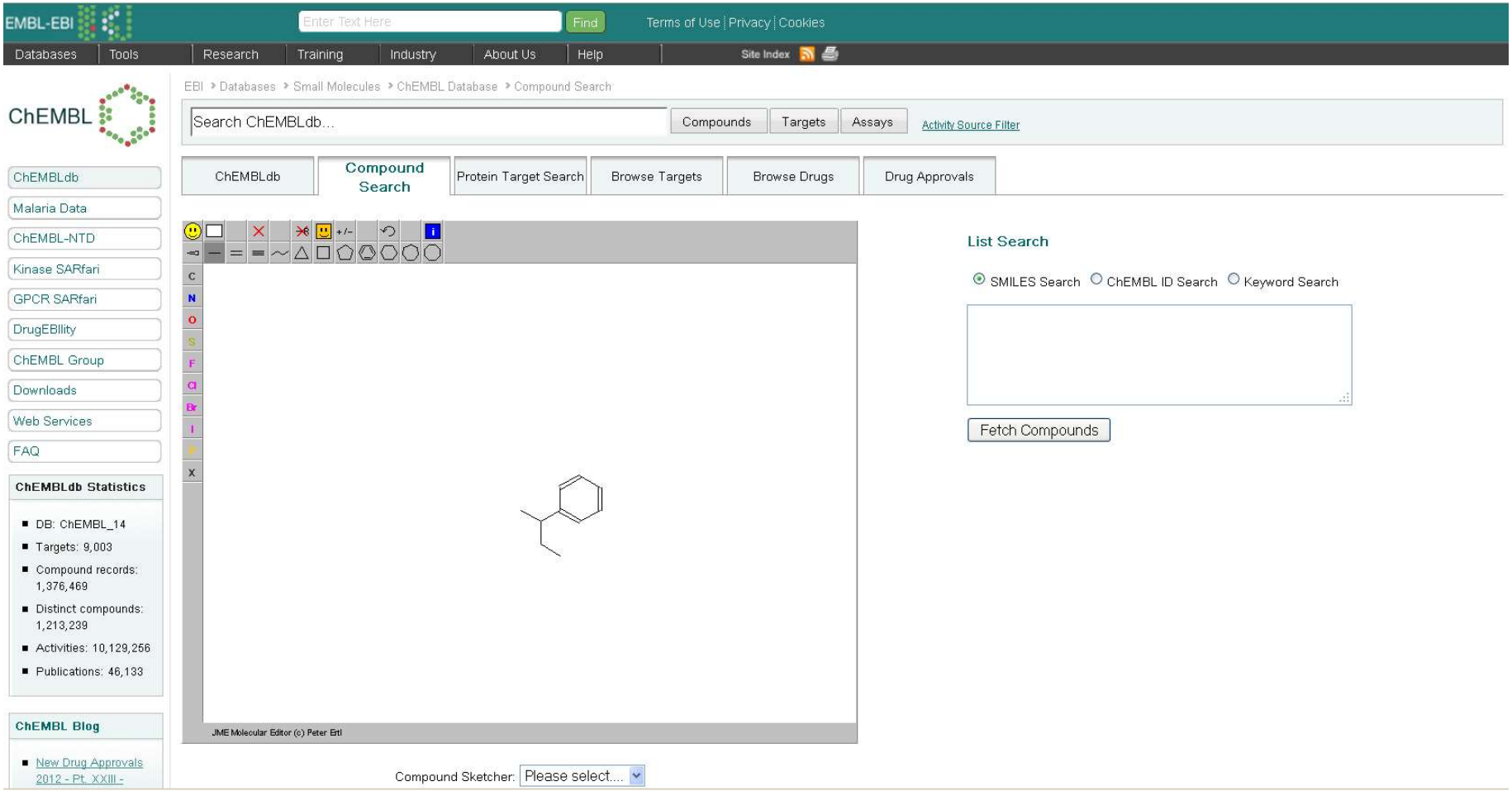
Databases of complexes

- **ChEMBL**



Databases of complexes

- **ChEMBL**



Databases of complexes

- **ChEMBL**

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ChEMBL

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Malaria Data
ChEMBL-NTD
Kinase SARfari
GPCR SARfari
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ChEMBLdb Statistics

- DB: ChEMBL_14
- Targets: 9,003
- Compound records: 1,376,469
- Distinct compounds: 1,213,239
- Activities: 10,129,256
- Publications: 46,133

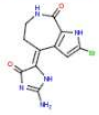
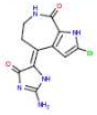
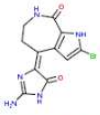
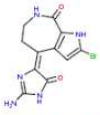
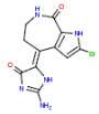
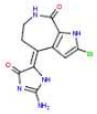
ChEMBL Blog

- New Drug Approvals 2012 - Pt. XXIII - Omacetaxine mepesuccinate (SYNRIBOTM)
- Paper: Mapping small molecule binding data to structural domains

EBI > Databases > Small Molecules > ChEMBL Database > Bioactivity Results

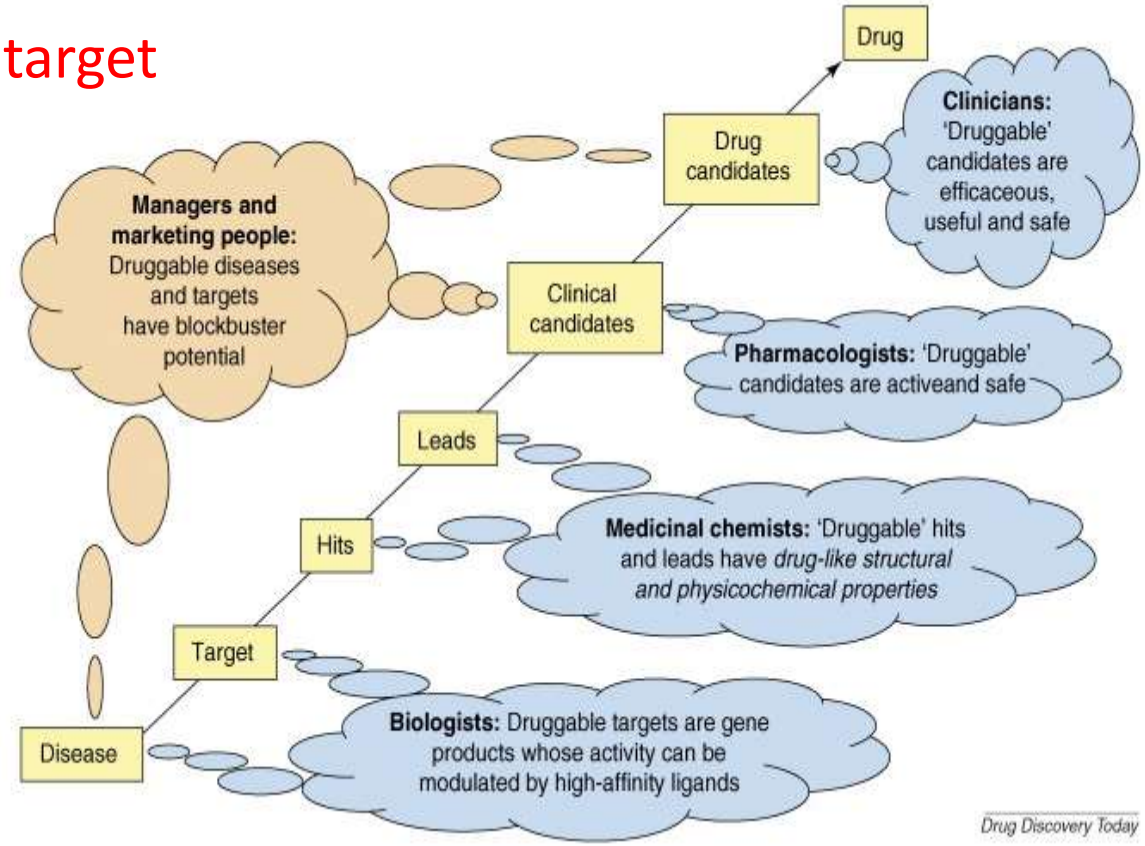
ChEMBL Bioactivity Search Results: 1197

1 2 3 4 5 6 [Next] [End] Please select...

Parent	Ingredient	Bioactivity	Operator	Value	Units	Activity Comment	Assay ChEMBL ID	Assay Source	Assay Type	Description	ChEMBL Target ID	Target Name	Organism	Target Mapping	Curated By	Reference	Name in Reference
Chiral CHEMBL162	Chiral CHEMBL162	IC50	<	1	nM		CHEMBL680866	Scientific Literature	B	Inhibition of Extracellular signal-regulated kinase 2 (Erk2)	CHEMBL4040	MAP kinase ERK2	Homo sapiens	Homologous protein	Expert	J. Med. Chem., (2002) 45:17:3772	Staurosporin
Chiral CHEMBL162	Chiral CHEMBL162	IC50	=	2.5	nM		CHEMBL729502	Scientific Literature	B	Inhibition of Mitogen-activated protein kinase (MAPK)phosphorylation by activated MEK-1	CHEMBL4040	MAP kinase ERK2	Homo sapiens	Protein	Expert	J. Med. Chem., (2002) 45:2:529	staurosporine
 CHEMBL361708	 CHEMBL361708	IC50	=	6	nM		CHEMBL828116	Scientific Literature	B	In vitro inhibitory concentration against human mitogen-activated protein kinase-1 (MEK-1) by using [gamma-33P]-ATP] as radioligand	CHEMBL4040	MAP kinase ERK2	Homo sapiens	Protein	Expert	Bioorg. Med. Chem. Lett., (2004) 14:16:4319	Hymenialdisine
 CHEMBL359106	 CHEMBL359106	IC50	=	6	nM		CHEMBL729502	Scientific Literature	B	Inhibition of Mitogen-activated protein kinase (MAPK)phosphorylation by activated MEK-1	CHEMBL4040	MAP kinase ERK2	Homo sapiens	Protein	Expert	J. Med. Chem., (2002) 45:2:529	4
 CHEMBL361708	 CHEMBL361708	IC50	=	9	nM		CHEMBL729502	Scientific Literature	B	Inhibition of Mitogen-activated protein kinase (MAPK)phosphorylation by activated MEK-1	CHEMBL4040	MAP kinase ERK2	Homo sapiens	Protein	Expert	J. Med. Chem., (2002) 45:2:529	5

Protein druggability

- **Druggability** = likelihood of finding bioavailable, selective, low-molecular weight molecules that bind with high affinity to the pharmacological target



Protein druggability

- **Prediction of protein druggability**
  - by similarity to known target
    - sequence of binding domain
    - structure of binding site
  - from databases of known targets
  - using predictive web servers

- **Unfortunately, many resources are only private or commercial**

Protein-ligand interactions server

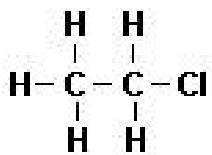
- **Proteins *Plus***
  - https://proteins.plus/
  - provides global support for the initial steps of dealing with protein structures
  - structure search, quality assessment, protein pocket detection, protein-ligand and protein-protein interactions
  - predicts binding sites and estimate their druggability

Small molecules

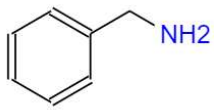
- Representation of small molecules
- Databases of small molecule
  - Cambridge Structural Database
  - PUBCHEM database
  - ZINC database
- Preparation of small molecule structure

Representation of small molecules

- 1D – atom based (empirical formula)
  - C_2H_5Cl
- 2D – chemical structure diagram -> connection
  - topology or SMILES (Simplified Molecular Line Entry System)

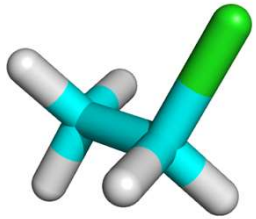


→ CCCl

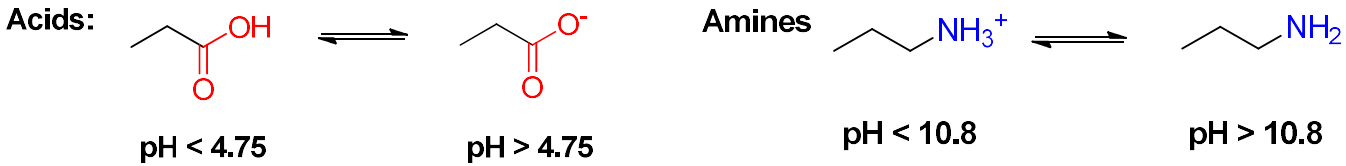


→ C1=CC=C(C=C1)CN

- 3D – atomic coordinates
  - usually: PDB or MOL2 files



- Beware: may have different protonated states

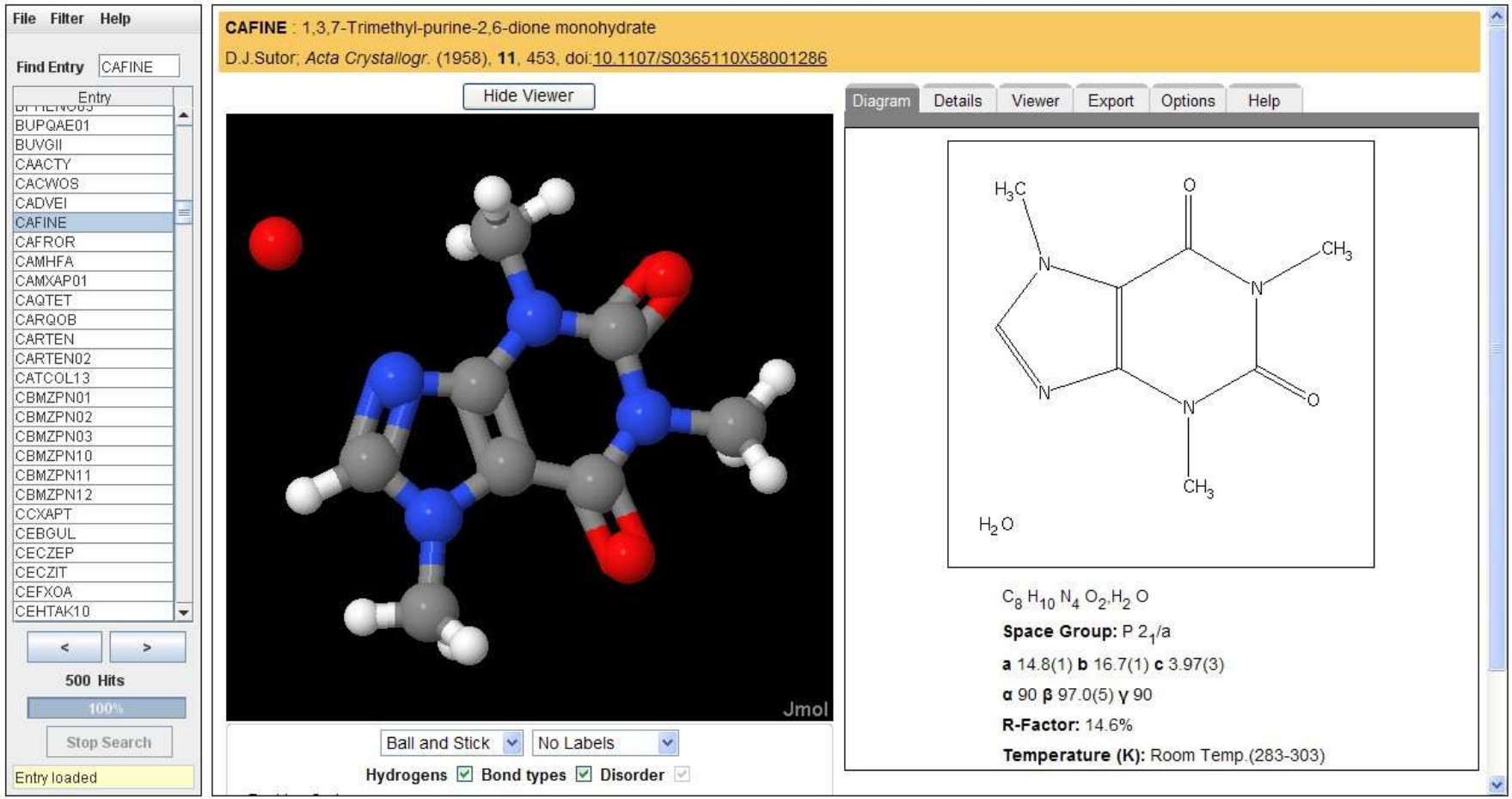


Databases of small molecule

- **Cambridge Structural Database**
  - http://www.ccdc.cam.ac.uk/products/csd/
  - the world largest repository of small molecule crystal structures
  - >900,000 structures with 3D coordinates available
  - CSD is distributed commercially
  - free interactive demo for educational purposes (only ~750 structures)
    - https://www.ccdc.cam.ac.uk/Community/educationalresources/teaching-database/

Databases of small molecule

❑ Cambridge Structural Database



Databases of small molecule

- **PubChem**
  - http://pubchem.ncbi.nlm.nih.gov/
  - world largest open repository of experimental data identifying the biological activities of small molecules
  - **Substances** – 270 M chemical entities
  - **Compound** – 111 M unique chemical structures. Compounds may be searched by chemical properties and are pre-clustered by structure comparison into identity and similarity groups
  - **BioAssays** – ~1,4 M biological experiments
  - **Bioactivities** – ~300 M biological activity data points

Databases of small molecule

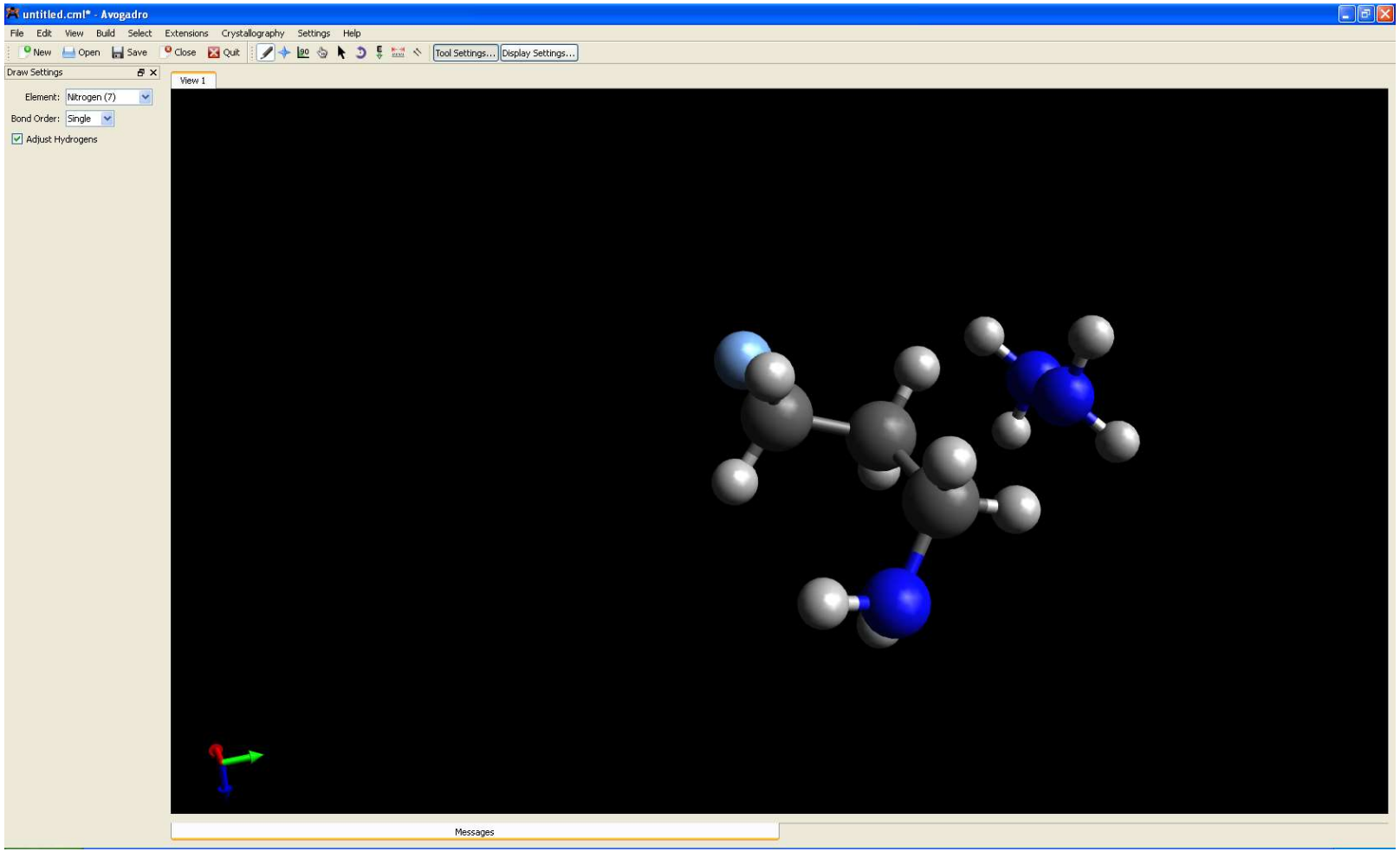
- **ZINC database**
  - http://zinc.docking.org/
  - free public resource for ligand discovery
  - 3D coordinates in ready-to-dock formats (i.e. – added hydrogens, partial atomic charges, …)
  - molecules in biologically relevant protonated and tautomeric forms
  - about 35,000,000 unique molecules grouped by classes
    - 20,000,000 – commercially available molecules
    - 10,000,000 – drug-like molecules
    - 1,000,000 – bioactive molecules
    - …

Preparation of small molecule structure

- **AVOGARO**
  - https://avogadro.cc/
  - free, open source molecule editor and visualizer
  - intuitive & easy to use
  - useful to convert file formats
  - embedded molecular minimization and molecular mechanics
  - interface to quantum chemistry packages

Preparation of small molecule structure

- **AVOGARO**

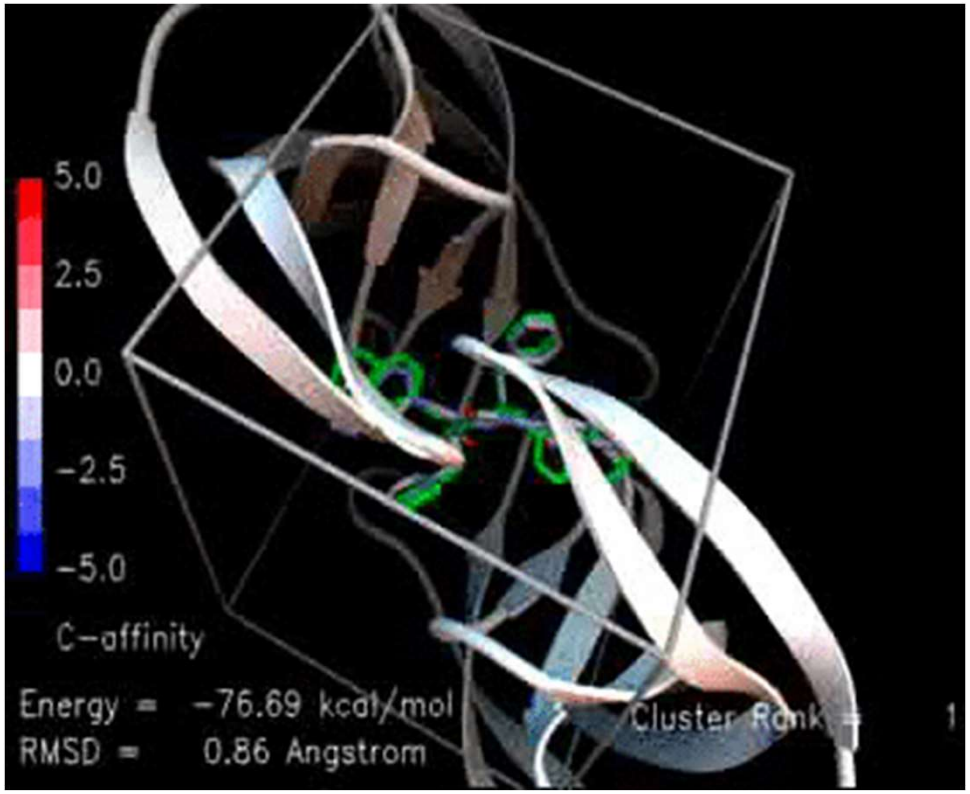


Preparation of small molecule structure

- **Open Babel**
  - https://openbabel.org/
  - free, open source
  - widely used molecule format converter
  - command line and graphical interface

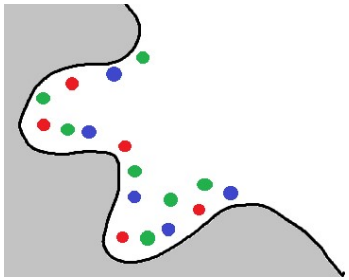
Molecular docking

- Useful when experimental data is not available or for screening purposes
- Several components/steps
  - Receptor representation
  - Ligand representation
  - Searching
  - Scoring

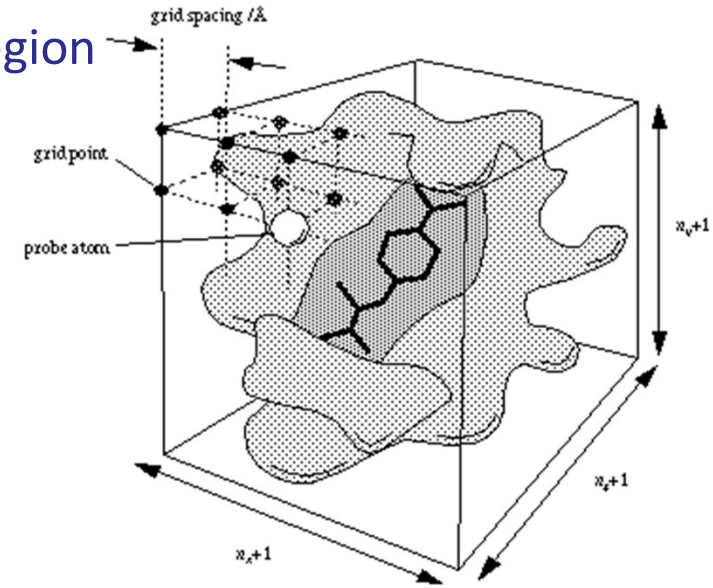


Receptor representation

- **Receptor represented only by relevant binding site**
  - descriptor representation – derived from geometry or/and interaction sites of binding site (H-bond donor/acceptor, hydrophobic contacts, …)

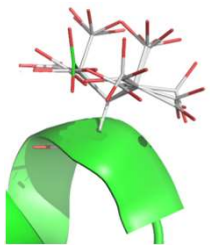


  - grid representation – entire searched region is covered by orthogonal equidistant points carrying information about interaction of probe atom at this point with receptor atoms



Receptor representation

- **Receptor flexibility**
  - **fully rigid approximation**
  - soft docking – employs tolerant “soft” scoring functions to simulate plasticity of otherwise rigid receptor
  - explicit side-chain flexibility – optimization of residues by rotating part of their structure or rotation of whole side-chains using predefined rotamer libraries



  - docking to molecular ensemble of protein structure – obtained from multiple crystal structures, from NMR structure determination or from a trajectory produced by MD simulation

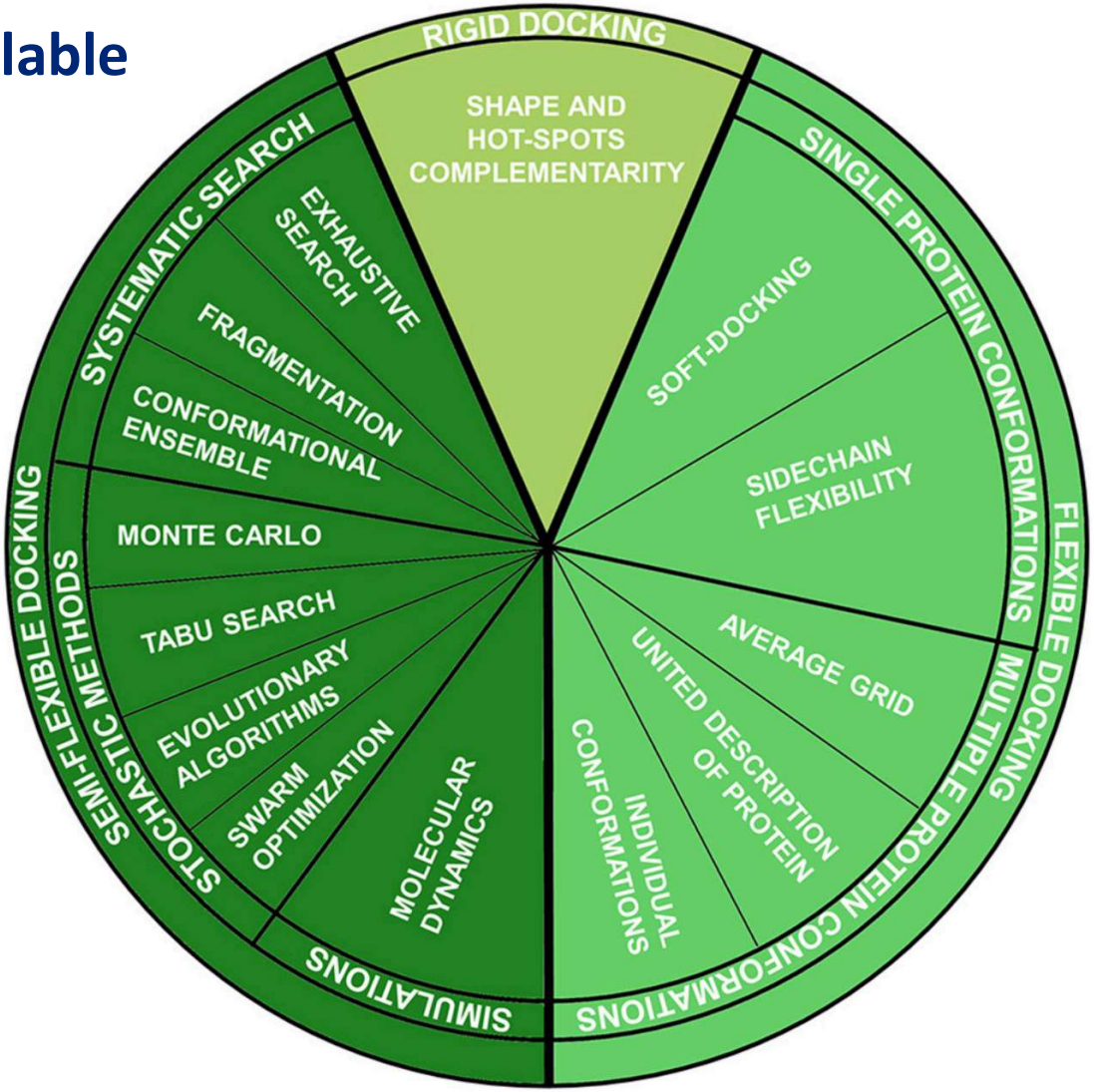
Ligand representation

- **Ligands represented by all atoms or just some**
  - non-polar hydrogens can be united with their respective parent carbon atoms to reduce number of atoms in calculation
- **Ligand flexibility**
  - mostly only rotation about single bonds
  - docking of a library of pre-generated ligand conformations – applicable only to quite rigid ligands due to exponential increase in number of possible conformers with number of rotatable bonds
  - direct sampling of ligand conformation space during searching
  - fragment-based techniques – ligand is cut into several fragments and rigidly docked into binding site

Molecular docking – searching

- **Many algorithms available**
  - Rigid docking 👎
  - Semi-flexible 👍
  - Flexible docking 👍👍

    (but costly)



Molecular docking – searching

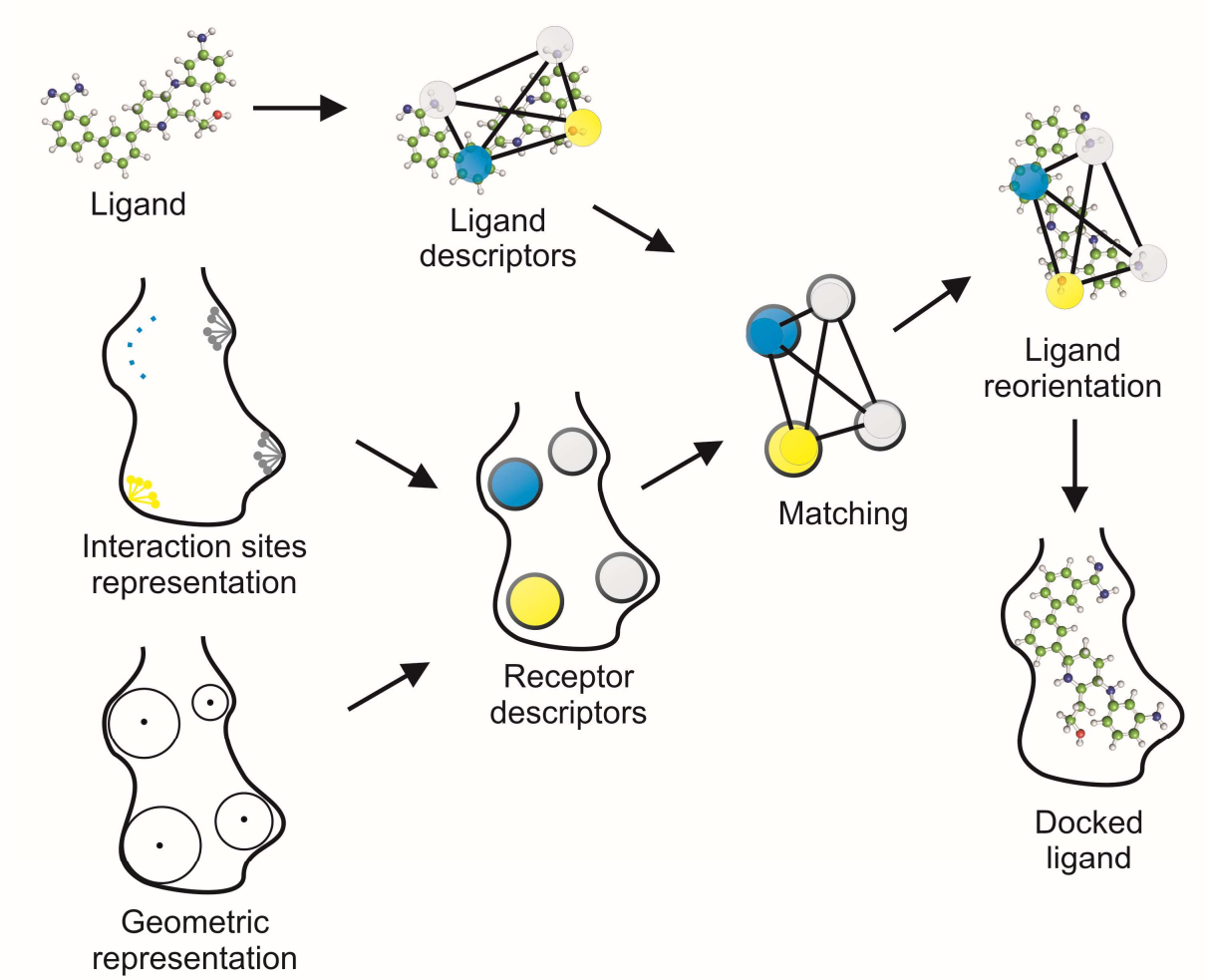
- **Geometry-based and combinatorial algorithms**
  - assumes that binding is governed by shape and/or physicochemical complementarity between the ligand and the receptor
  - assumes that the degree of complementarity is proportional to the binding energy which is not always true especially for more polar ligands
- **Energy-driven and stochastic algorithms**
  - tries to locate directly the global minimum of the binding free energy corresponding to the experimental structure
  - random basis of these methods requires multiple independent runs of docking calculations to achieve consistent results

Geometry-based algorithms

- **Matching algorithms**
  - represent a ligand and a receptor binding site by descriptors derived from their geometry and/or presence of particular interaction sites
  - try to align/match complementary parts of ligand and binding site and in this way predict the ligand binding mode
- **SW packages**
  - DOCK – http://dock.compbio.ucsf.edu/
  - SLIDE – http://www.kuhnlab.bmb.msu.edu/software/slide/
  - …

Geometry-based algorithms

- **Matching algorithms**

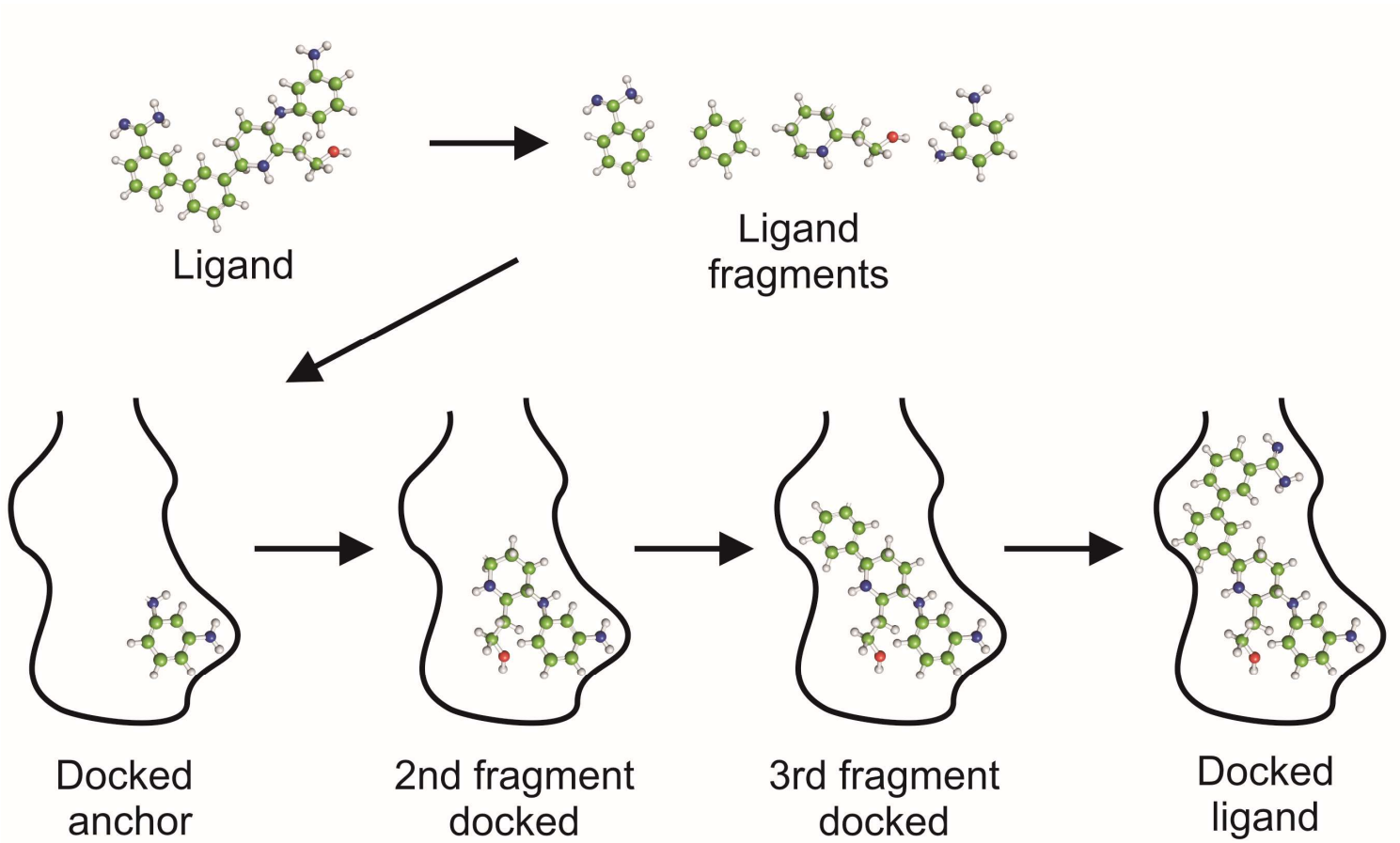


Geometry-based algorithms

- **Fragment-based algorithms**
  - ligand is initially fragmented into rigid parts
  - two approaches to obtain whole docked molecule
    - incremental construction – fragments are incrementally docked into the receptor until whole ligand is constructed
    - fragment-placing and linking – all fragments are docked simultaneously and then joined together
- **SW packages**
  - FlexX – http://www.biosolveit.de/FlexX/
  - eHITS – http://www.simbiosys.ca/ehits/
  - …

Geometry-based algorithms

- **Fragment-based algorithms**

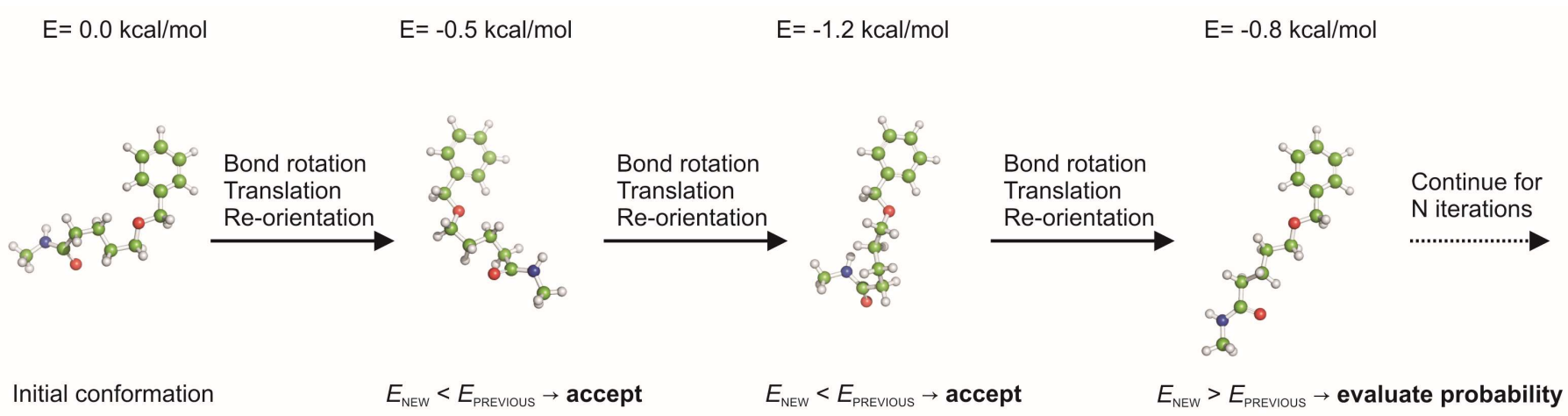


Stochastic energy-driven algorithms

- **Monte Carlo algorithms**
  - explore protein-ligand interactions space by iteratively introducing random changes into a position, orientation or conformation of the ligand and evaluating new configuration using acceptance criterion
  - new configuration is always accepted if its energy is more favorable then the energy of previous configuration or accepted with some probability reflecting energy difference to previous configuration
- **SW packages**
  - Autodock Vina – http://vina.scripps.edu
  - Glide – http://www.schrodinger.com/Glide
  - …

Stochastic energy-driven algorithms

- **Monte Carlo algorithms**

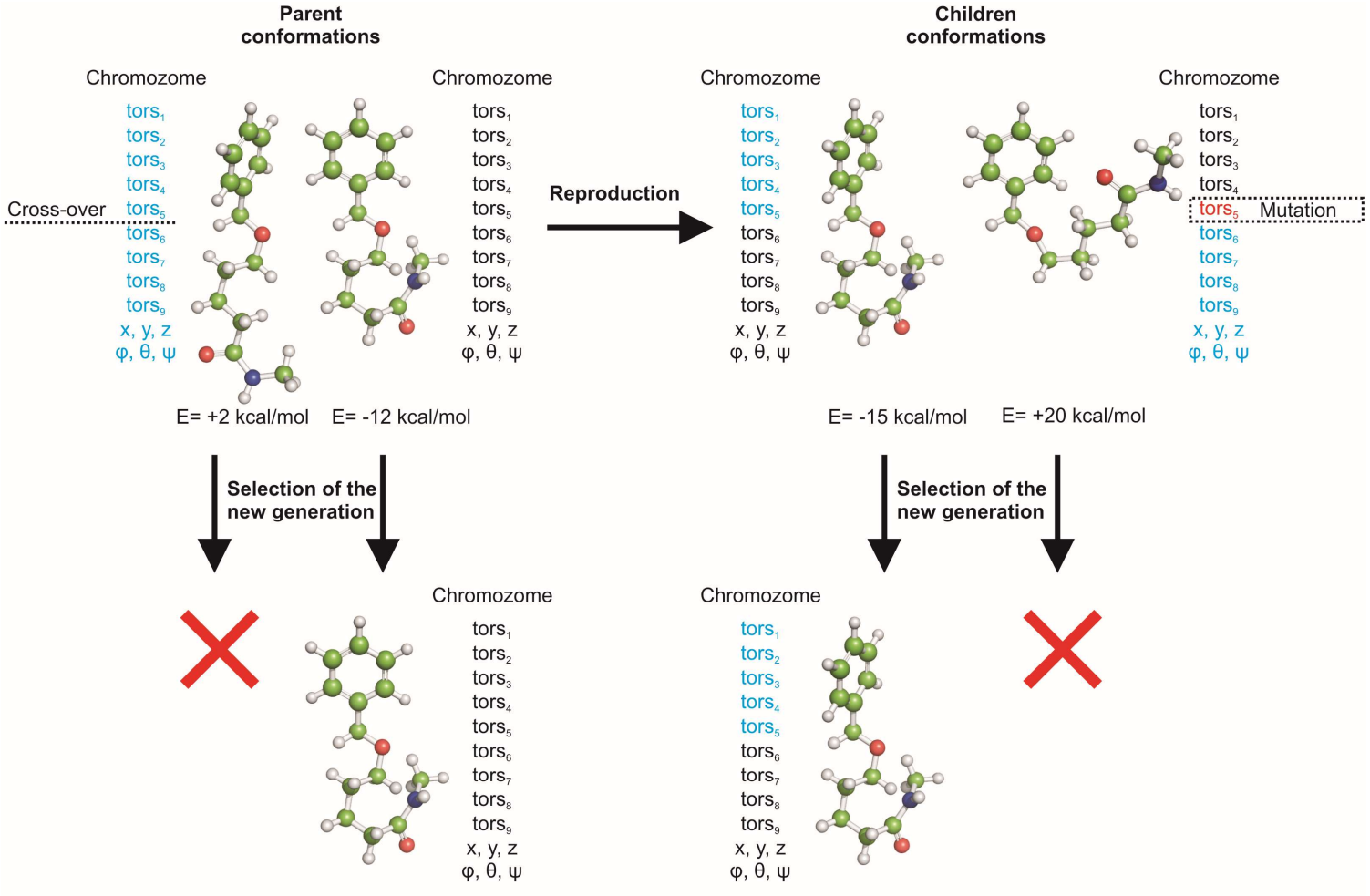


Stochastic energy-driven algorithms

- **Genetic algorithms**
  - configurations of all ligands from randomly generated initial population are encoded in their genes which are subject of random genetic modification (crossover, single point mutation, …)
  - individual with better fitness (corresponds to its binding energy) has higher chance to survive and reproduce to next generation
  - overall fitness of population is increasing with each new generation
- **SW packages**
  - AutoDock – http://autodock.scripps.edu
  - GOLD – http://www.ccdc.cam.ac.uk/products/life_sciences/gold/
  - …

Stochastic energy-driven algorithms

❑ Genetic algorithms



Molecular docking – scoring

- **Scoring function**
  - evaluate all the binding modes from the searching algorithms
  - must be computationally efficient and provide accurate description of protein-ligand interactions
- **Application of scoring functions to rank**
  - several configurations of one ligand bound to one protein – essential for prediction of the best binding mode
  - different ligands bound to one protein – determination of substrate or inhibitor specificity
  - one ligand bound to several different proteins – functional annotation of proteins and study of drug selectivity

Molecular docking – scoring

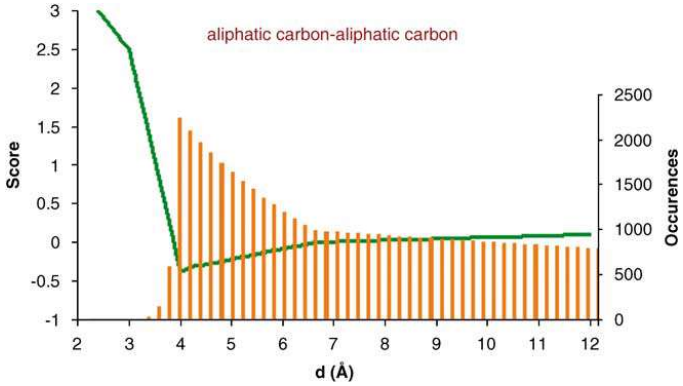
- **Categories of scoring functions**
  - **empirical**
    - derived by fitting of following equation to experimental binding affinities of known protein-ligand complexes

$$\Delta G_{bind} = \alpha.\Delta G_{hb} + \beta.\Delta G_{lipo} + \gamma.\Delta G_{el} + \delta.\Delta G_{rot} + \ldots$$

    - rapid evaluations
    - arbitrary selection of terms included in the equation -> failure when binding is governed by some excluded type of interaction
    - weights are dependent on the chosen training set

Molecular docking – scoring

- **Categories of scoring function**
  - **knowledge-based**
    - capture the knowledge about protein-ligand binding that is implicitly stored in structural data by statistical analysis
    - atom-pair potentials derived from distances found for such pair in training structural data
    - rapid evaluations
    - describe all types of interactions without any preselection
    - problem when structural data do not contain sufficient information on particular atom-pairs (e.g. halogens, metals, …)



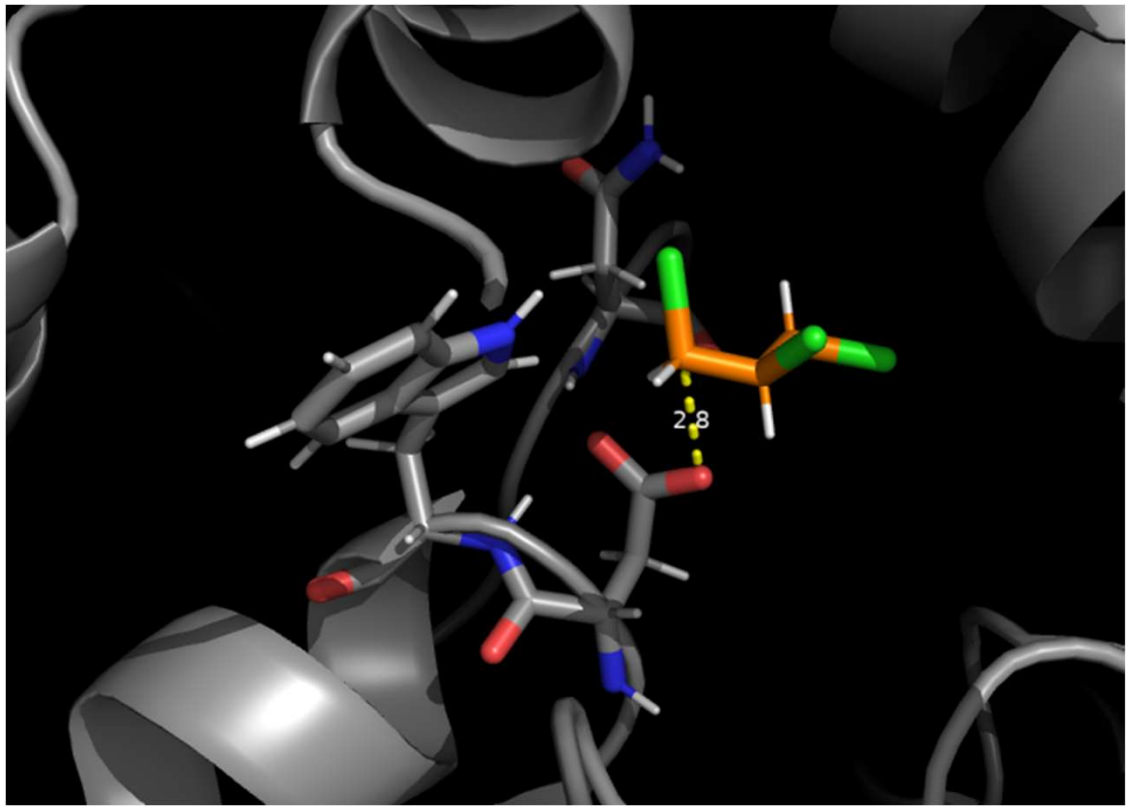
Molecular docking – scoring

- **Categories of scoring function**
  - **force field-based**
    - use the non-bonded terms of well-established force fields
    - provide precise affinities
    - high computational demands -> employed for calculating the affinity of some selected binding modes (not during searching)

$$E_{total} = \sum_{\text{bonds}} K_r(r - r_0)^2 + \sum_{\text{angles}} K_\theta(\theta - \theta_0)^2$$
$$+ \sum_{\text{torsions}} \frac{V_n}{2}[1 \pm \cos(n\phi - \gamma)]$$
$$+ \sum_{\text{non-bonded}} \left[\frac{A_{ij}}{r_{ij}^{12}} - \frac{C_{ij}}{r_{ij}^{6}} + \frac{q_i q_j}{r_{ij}}\right]$$

Evaluation of complexes

- Intermolecular interactions
- Binding energies

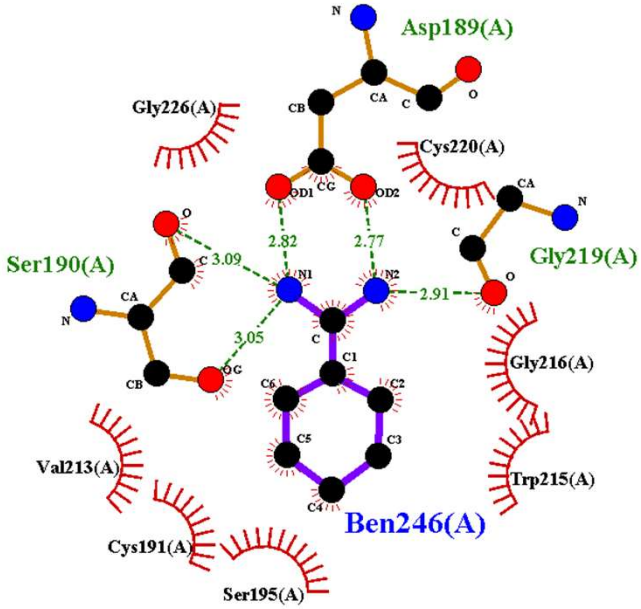


Intermolecular interactions

- **Most common types**
  - Hydrogen bonds
  - Hydrophobic
  - Aromatic
  - Ionic bonds

Intermolecular interactions

- **Visualization**
  - schematic diagrams showing hydrogen bonds and hydrophobic contacts



- **Tools**
  - LigPlot+
    - stand alone application
    - http://www.ebi.ac.uk/thornton-srv/software/LigPlus/
    - pre-calculated for protein-ligand complexes in PDBsum

Binding energies

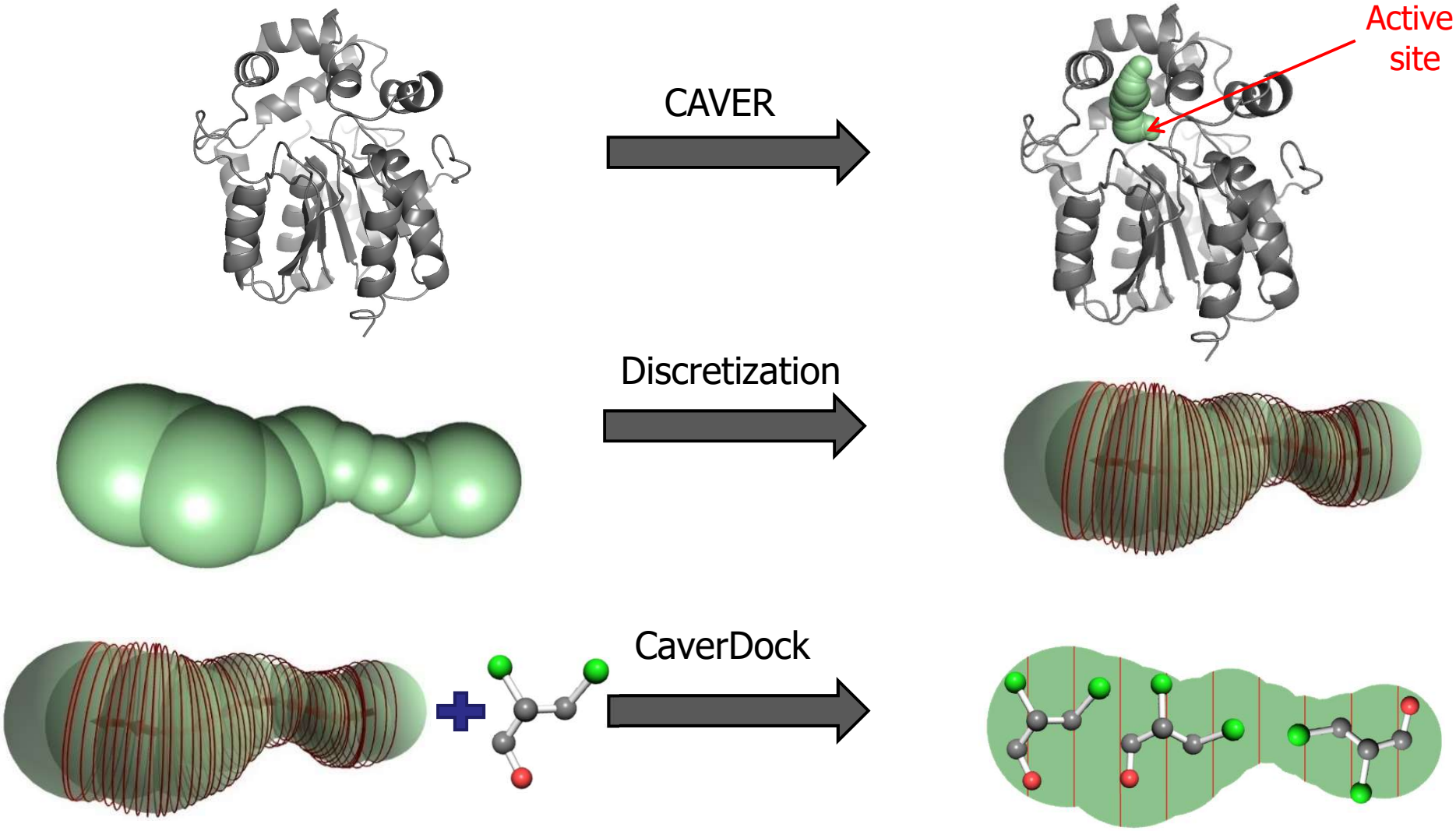
- **Binding Affinity Prediction of Protein-Ligand server**
  - http://www.scfbio-iitd.res.in/software/drugdesign/bappl.jsp
  - calculates binding free energy of a protein-ligand complex using all-atom-energy-based empirical scoring function

Transport of small molecules

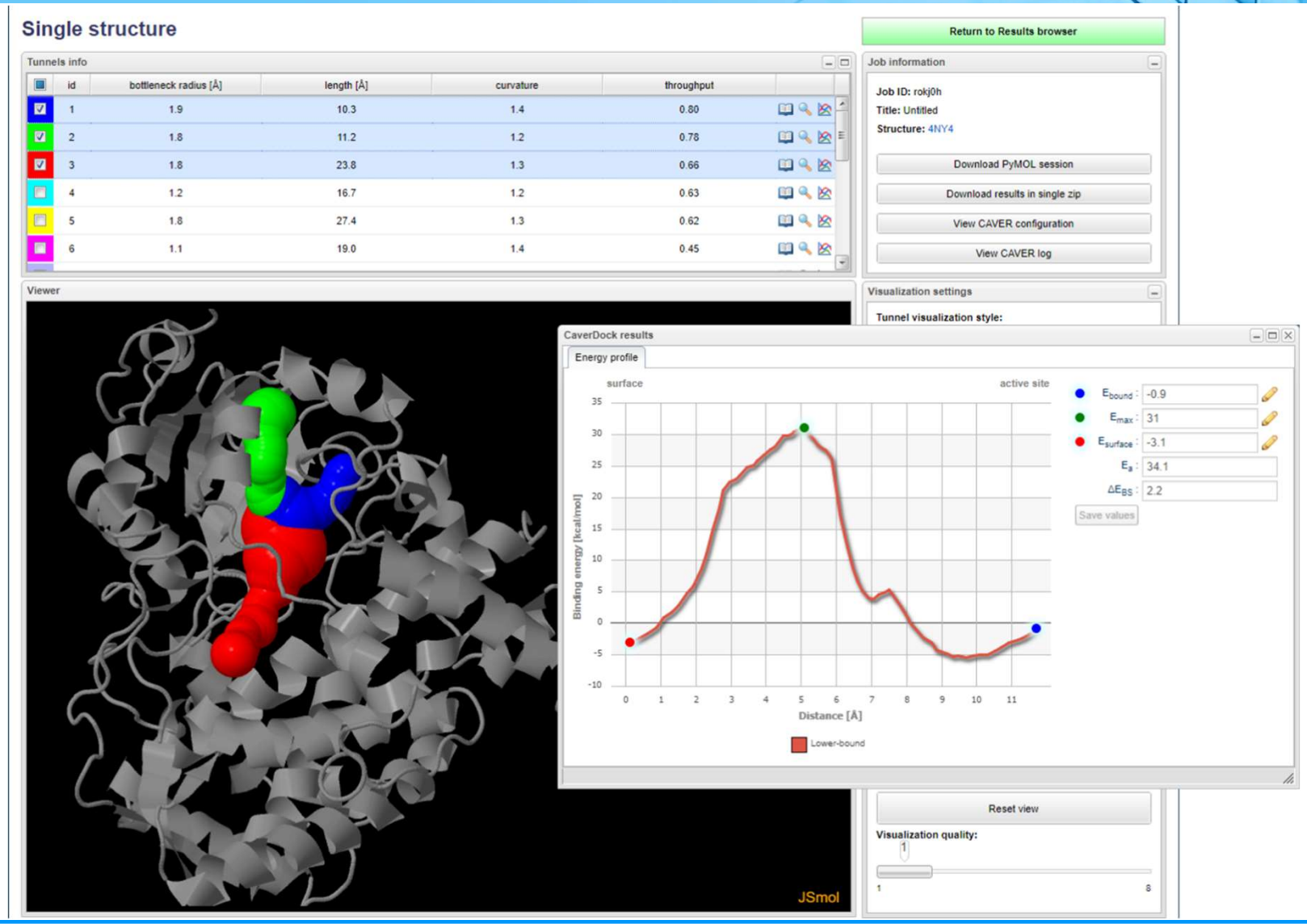
- **CaverDock**
  - https://loschmidt.chemi.muni.cz/caverdock/
  - Analysis of tunnels by Caver
  - Discretization of identified tunnel into discs
  - Molecular docking by AutoDock Vina to every disc

- **Caver Web**
  - https://loschmidt.chemi.muni.cz/caverweb/
  - Web interface for Caver and CaverDock

Transport of small molecules

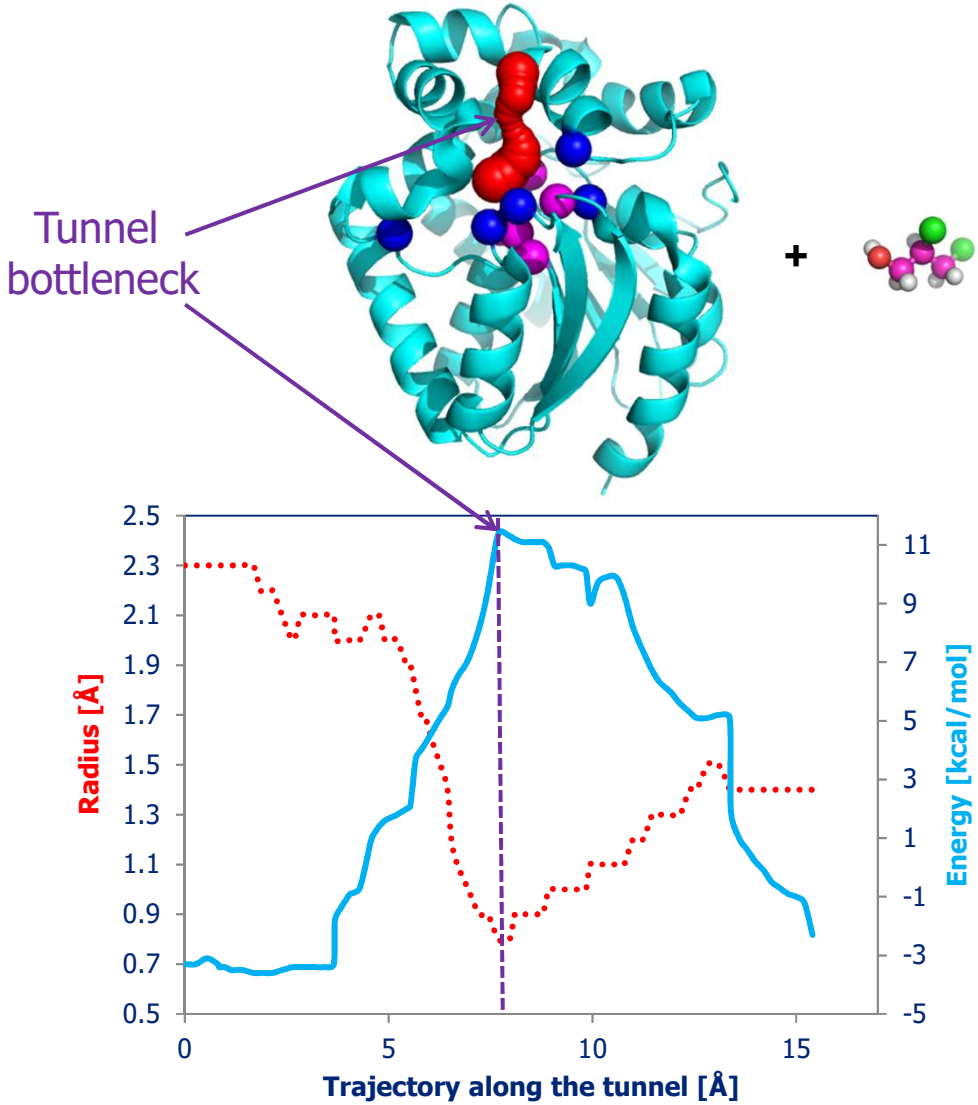


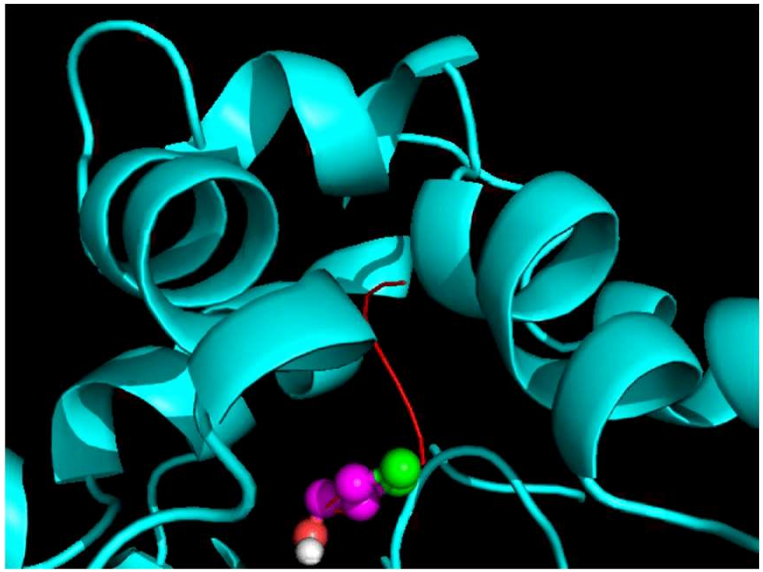
Transport of small molecules



Transport of small molecules

- **CaverDock**





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