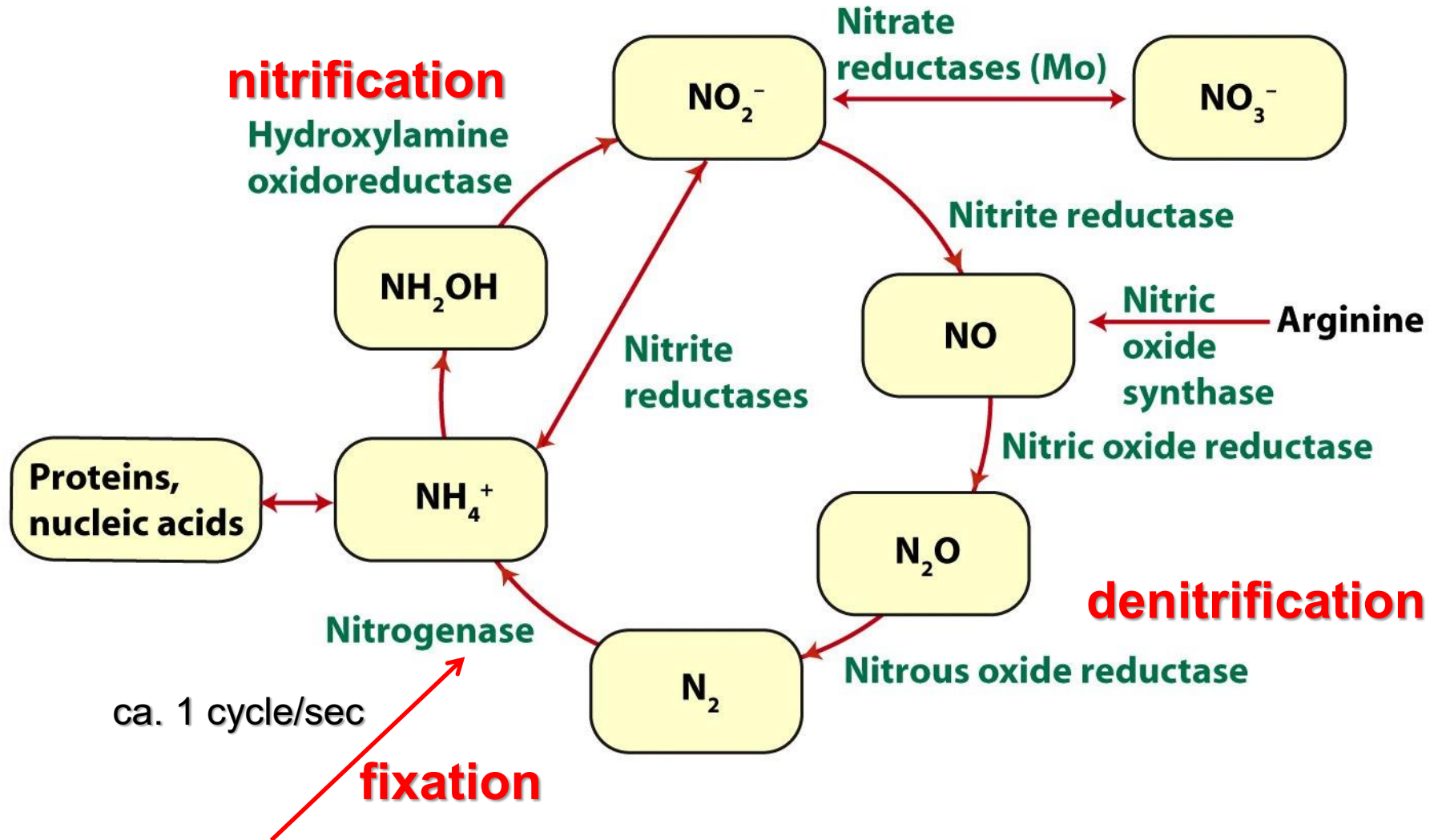


Early transition metals

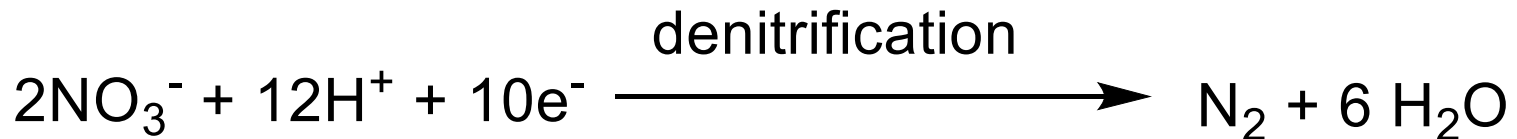
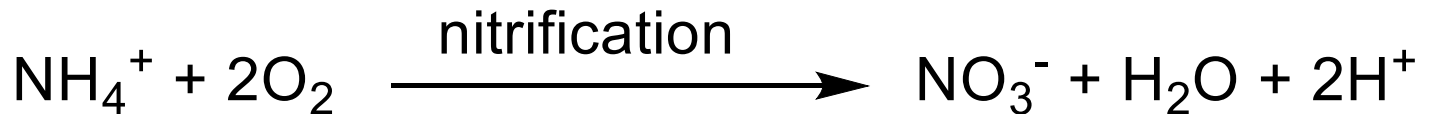
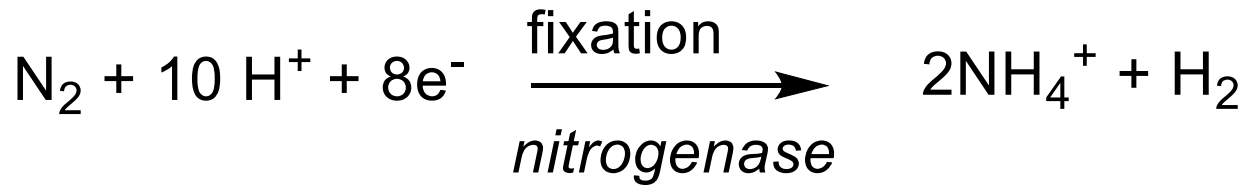
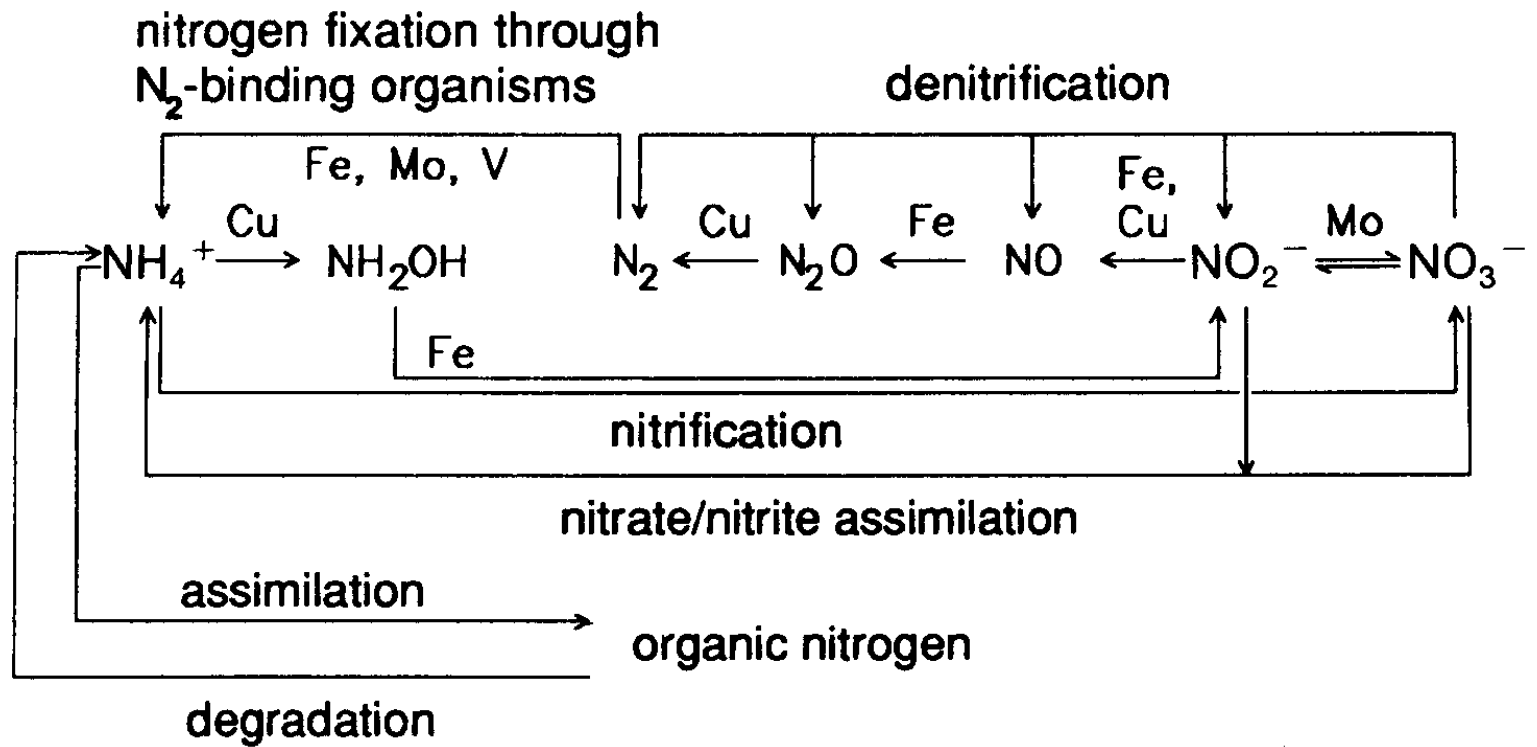


Molybdenum is the only element of the second transition period (4d) that has a biological function. It is bioavailable in the form of molybdate MoO_4^{2-}

Nitrogen cycle



diazotrophic prokaryote bacteria (leguminous plants): 10^8 ton N_2/y

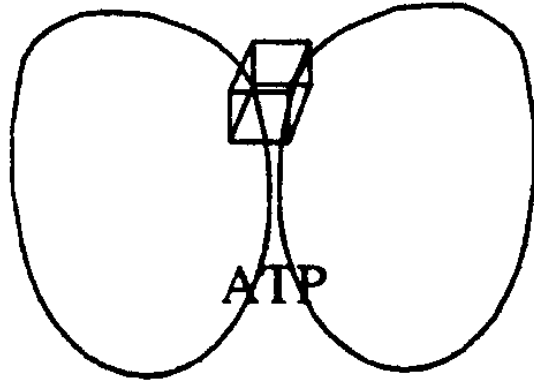


Nitrogenase



1992

ca. 1 cycle/sec

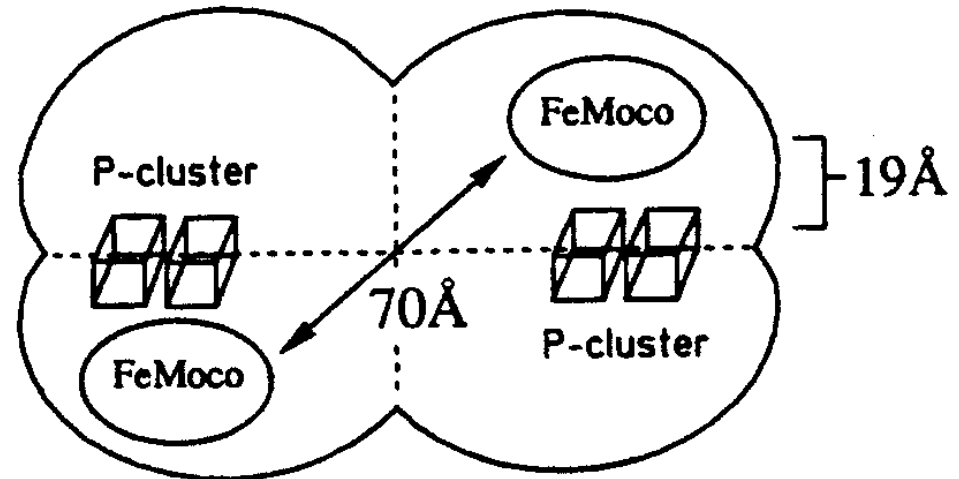


Fe protein

γ_2

60 kDa

+

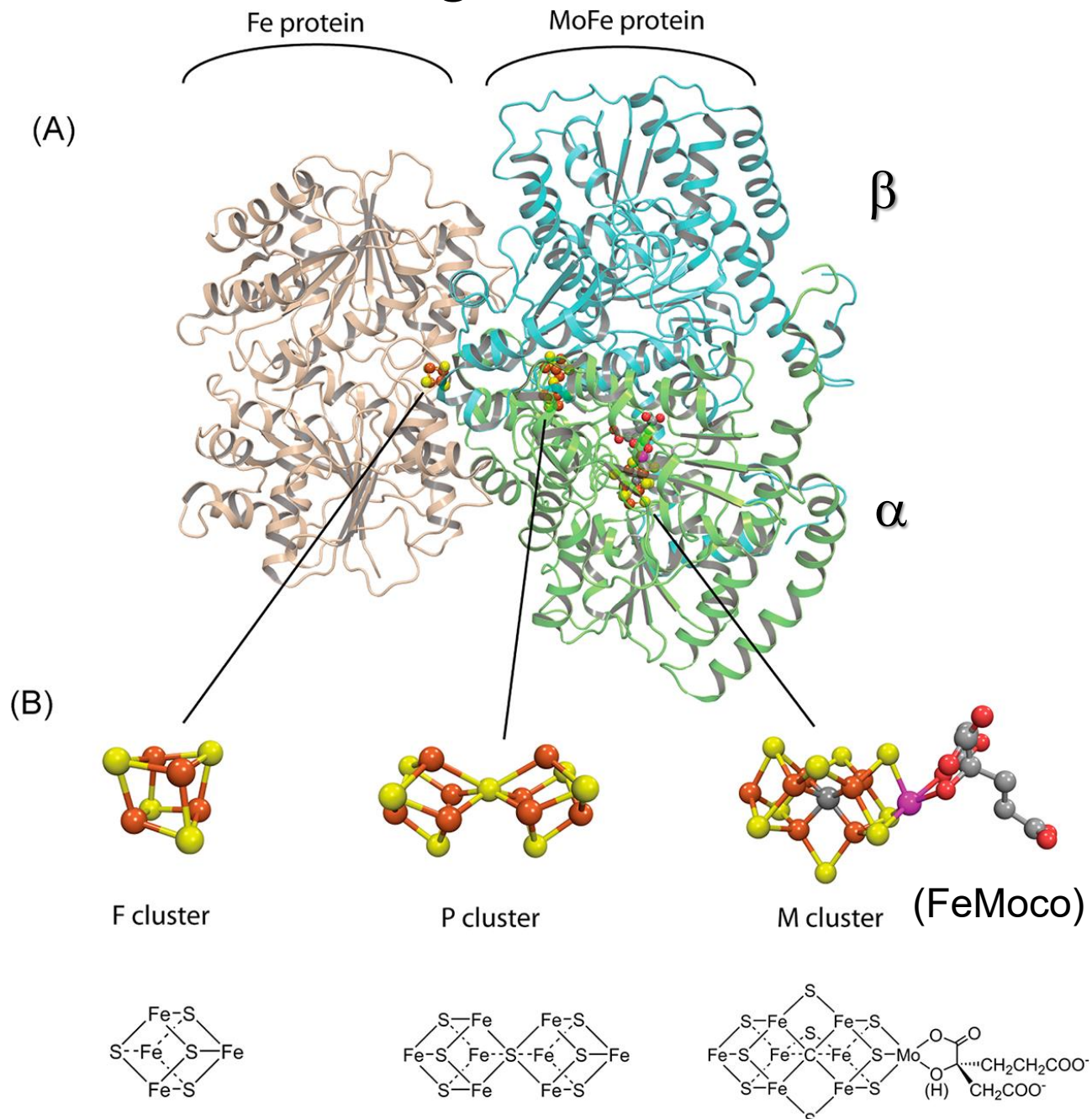


FeMo protein

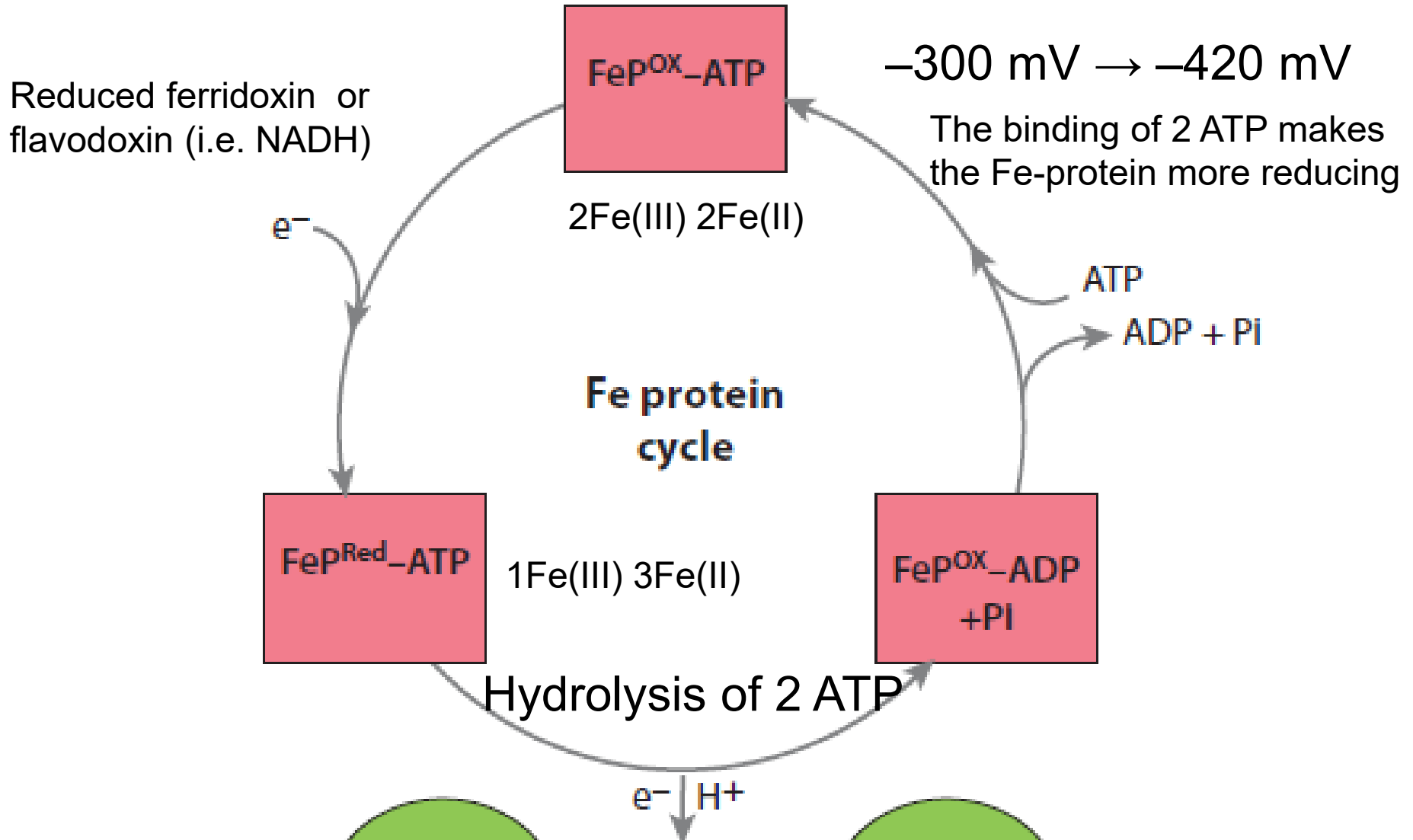
$\alpha_2\beta_2$

220 kDa

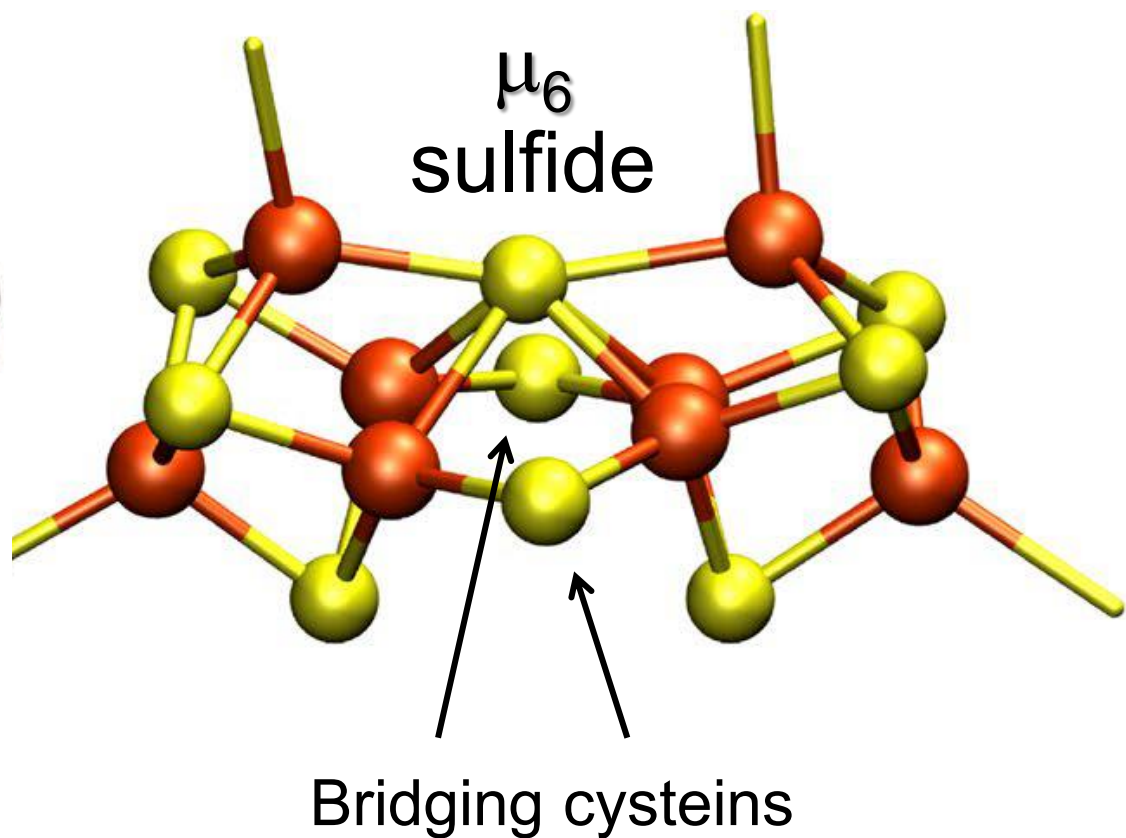
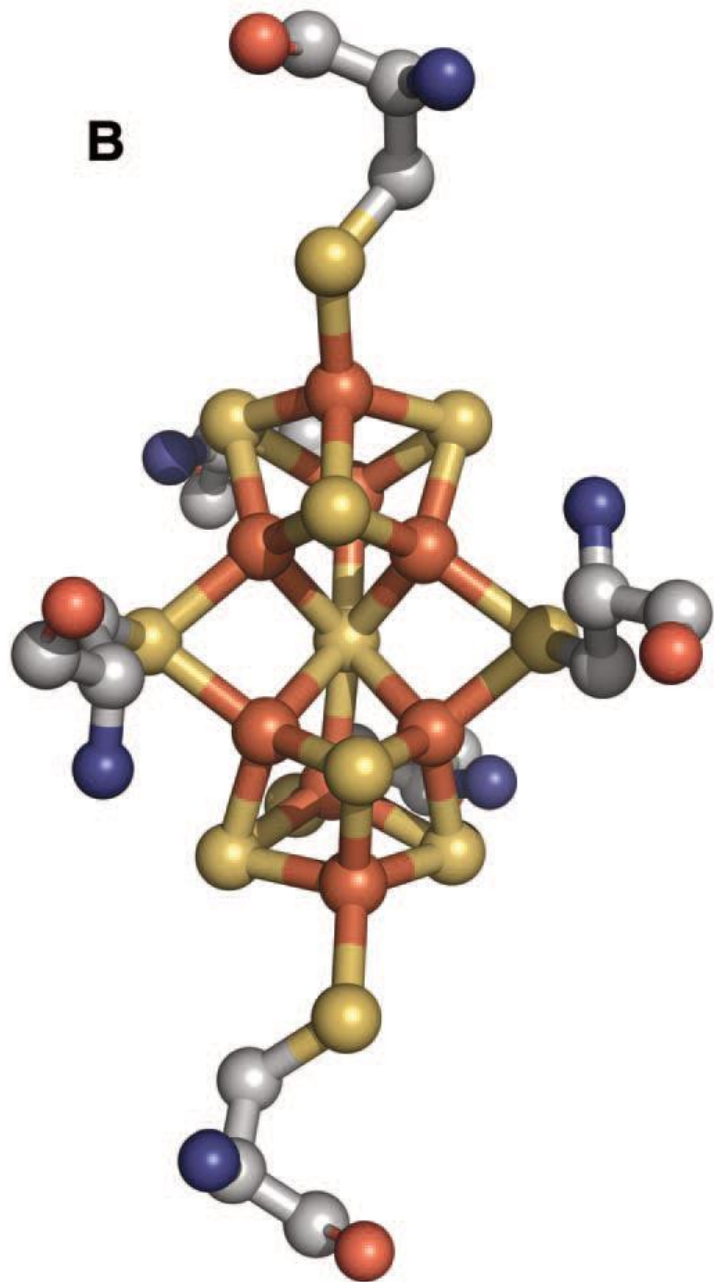
Nitrogenase

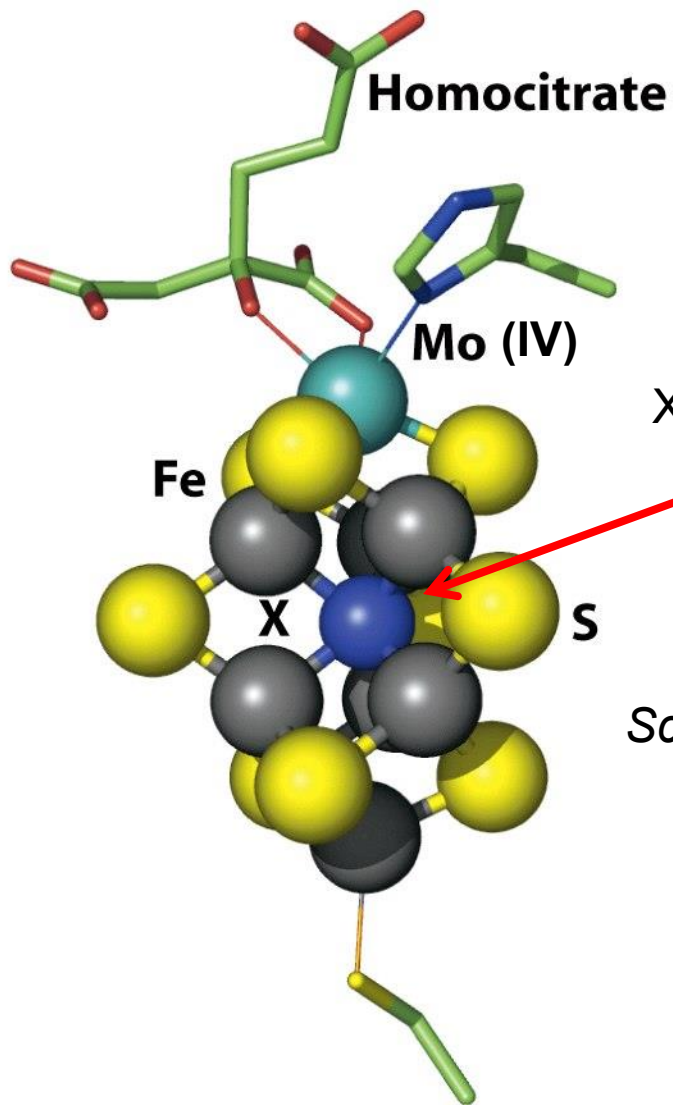


Fe-protein



P-cluster: 8Fe-7S + 6cys
bridges α and β proteins





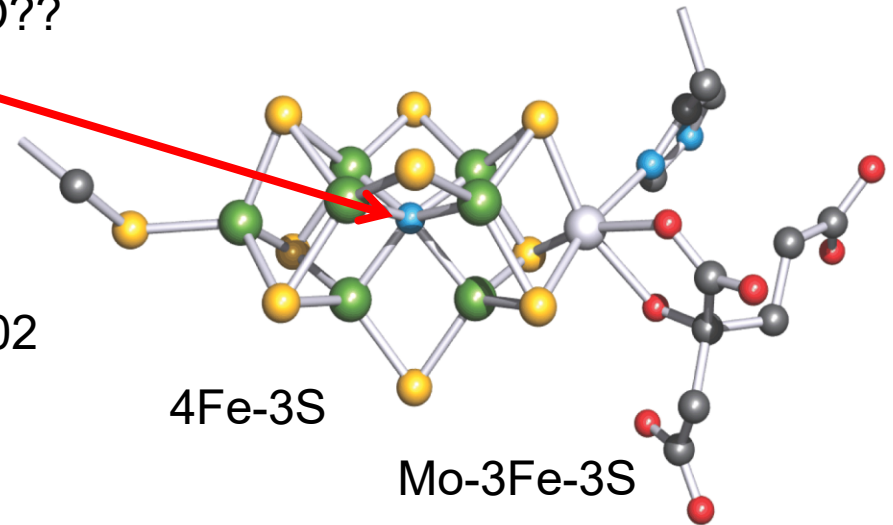
Nitrogenase FeMoCo

FeMo cofactor

7Fe-9S-Mo-homocitrate

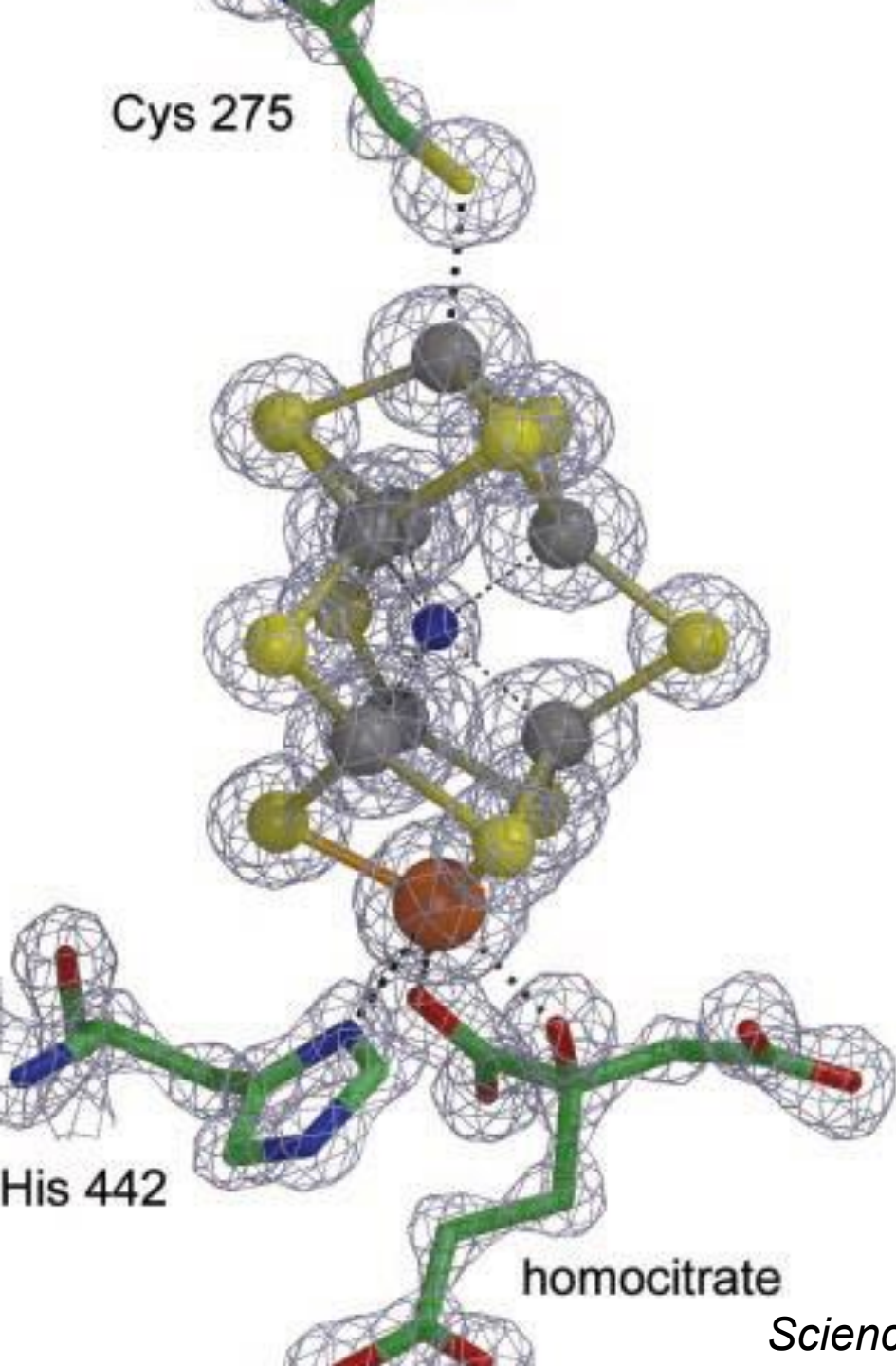
X = C, N, O??

Science, 2002

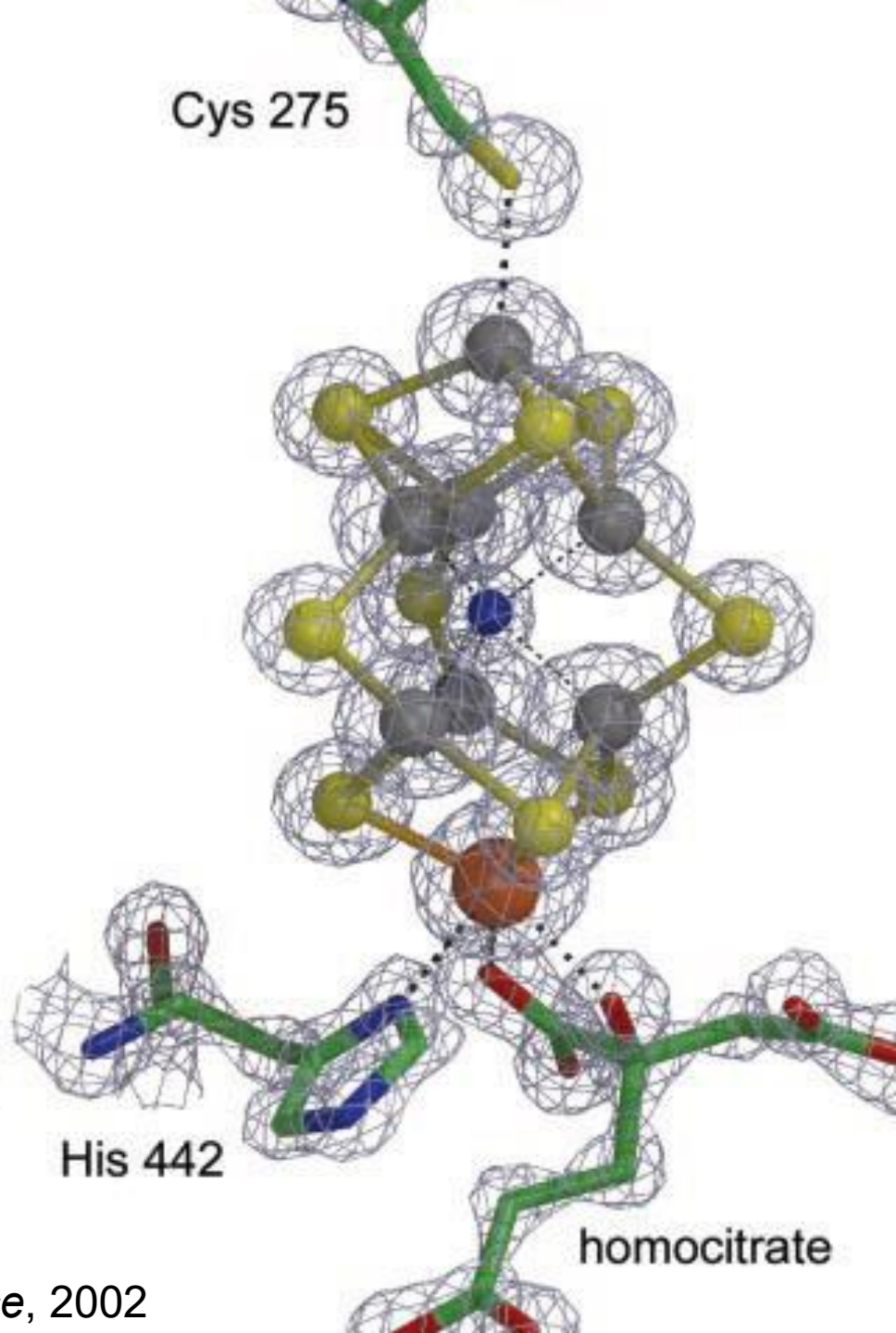


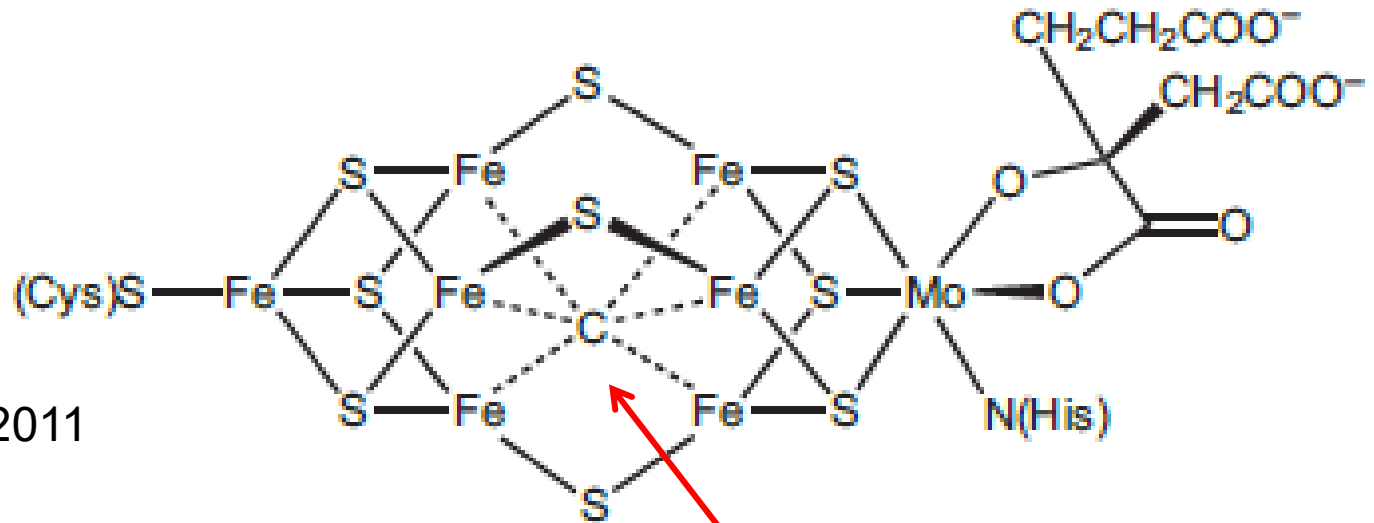
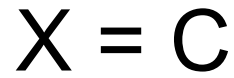
All in a hydrophilic
pocket of protein α

Cys 275



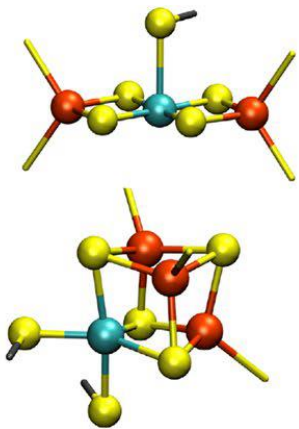
Cys 275





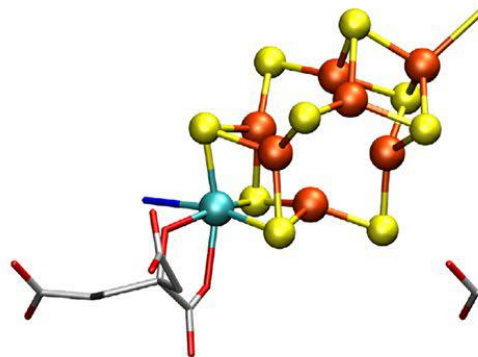
Science, 2011

Carbide, C⁴⁻



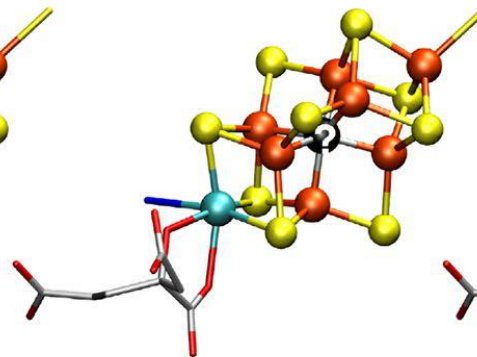
1978

First structural models from EXAFS



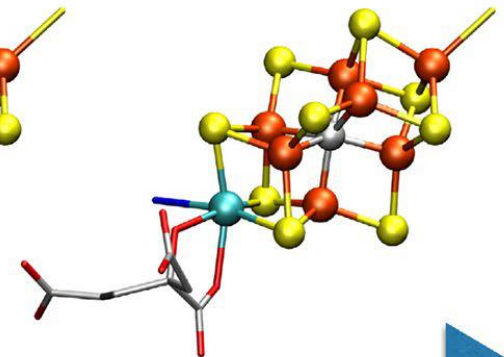
1992

First crystal structure (2.7Å)



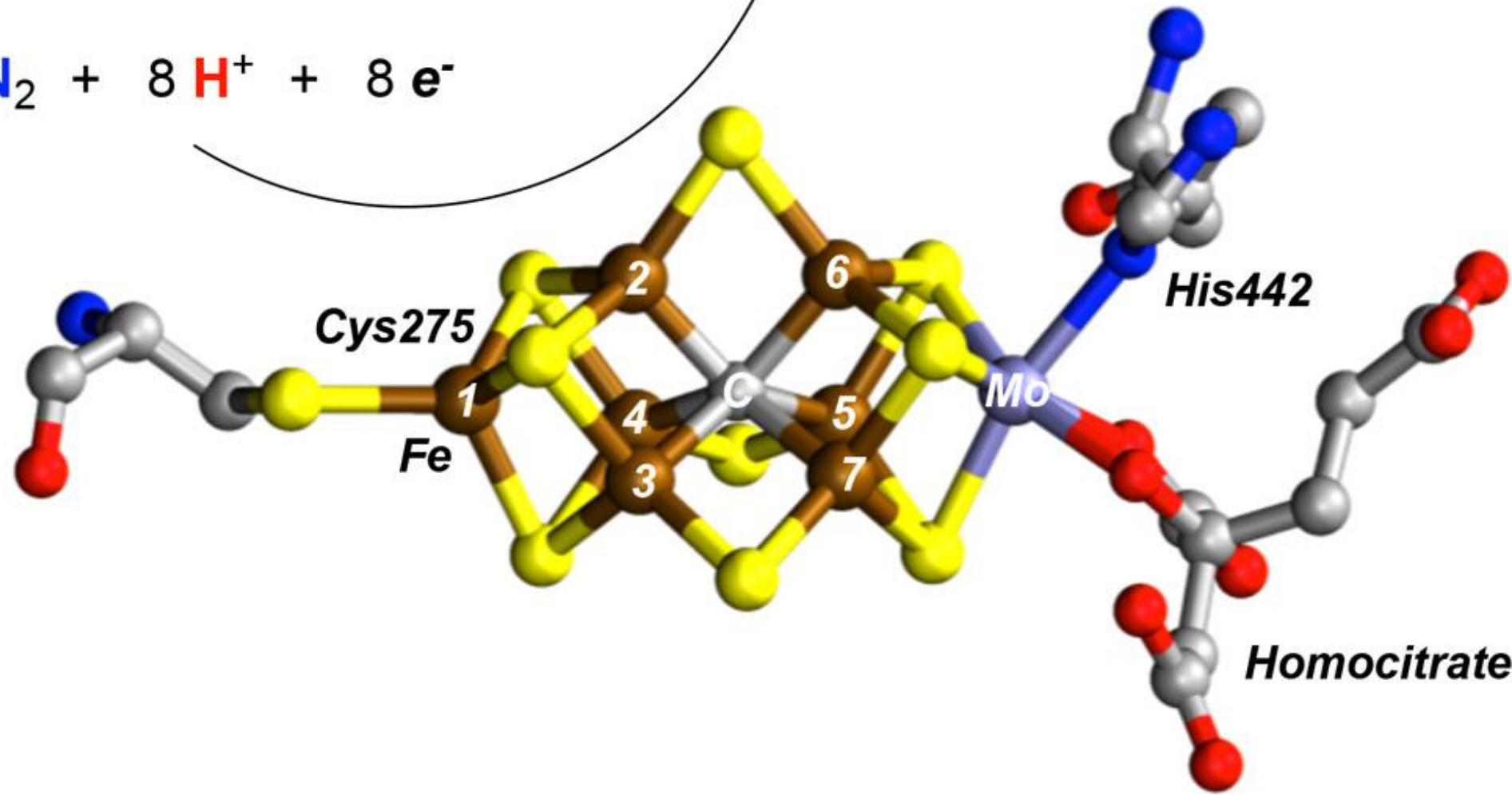
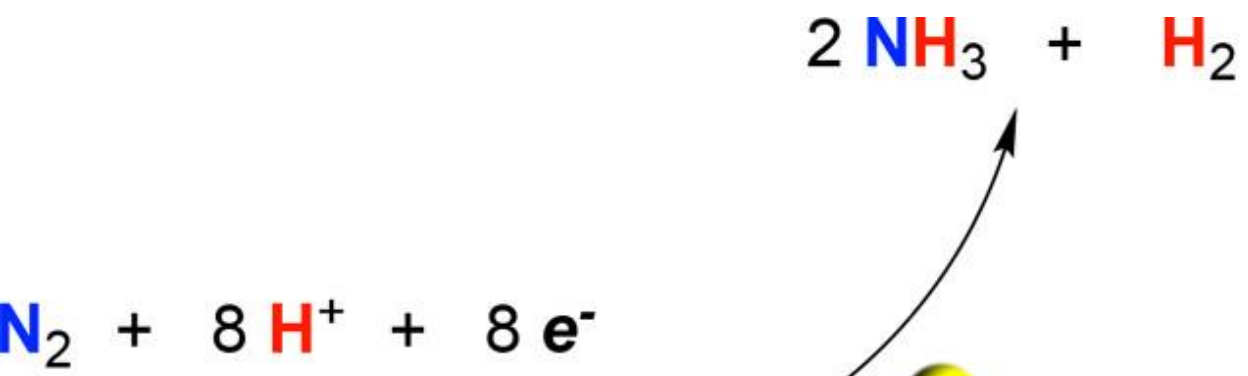
2002

Discovery of interstitial atom

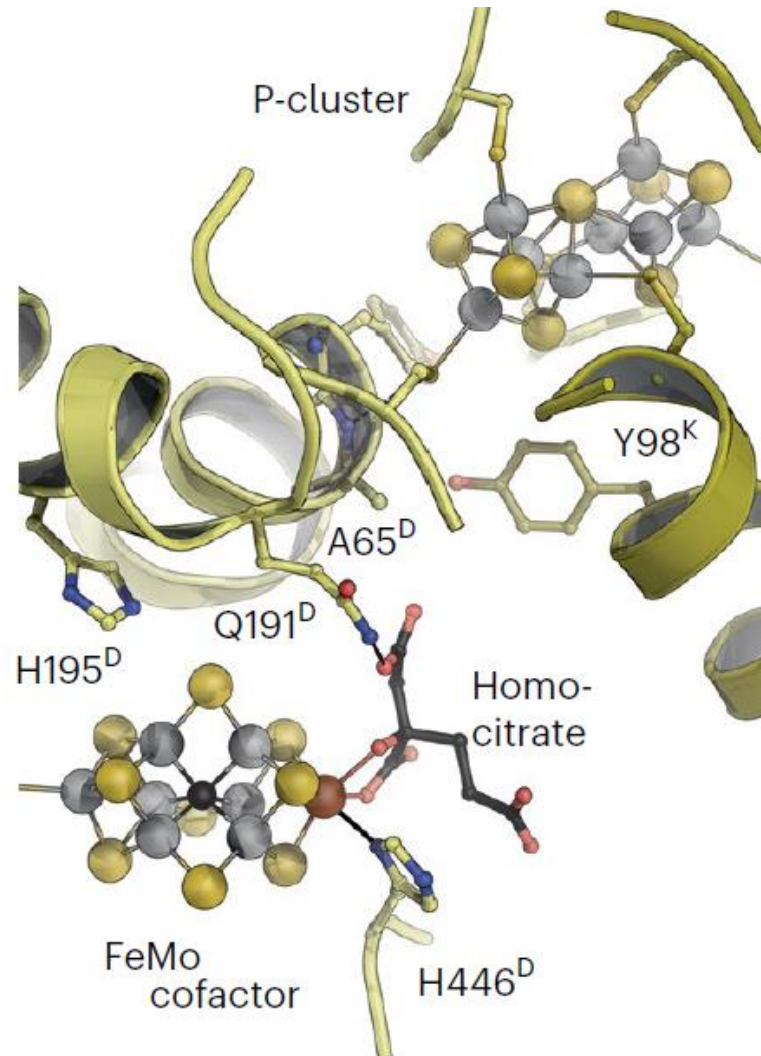


2011

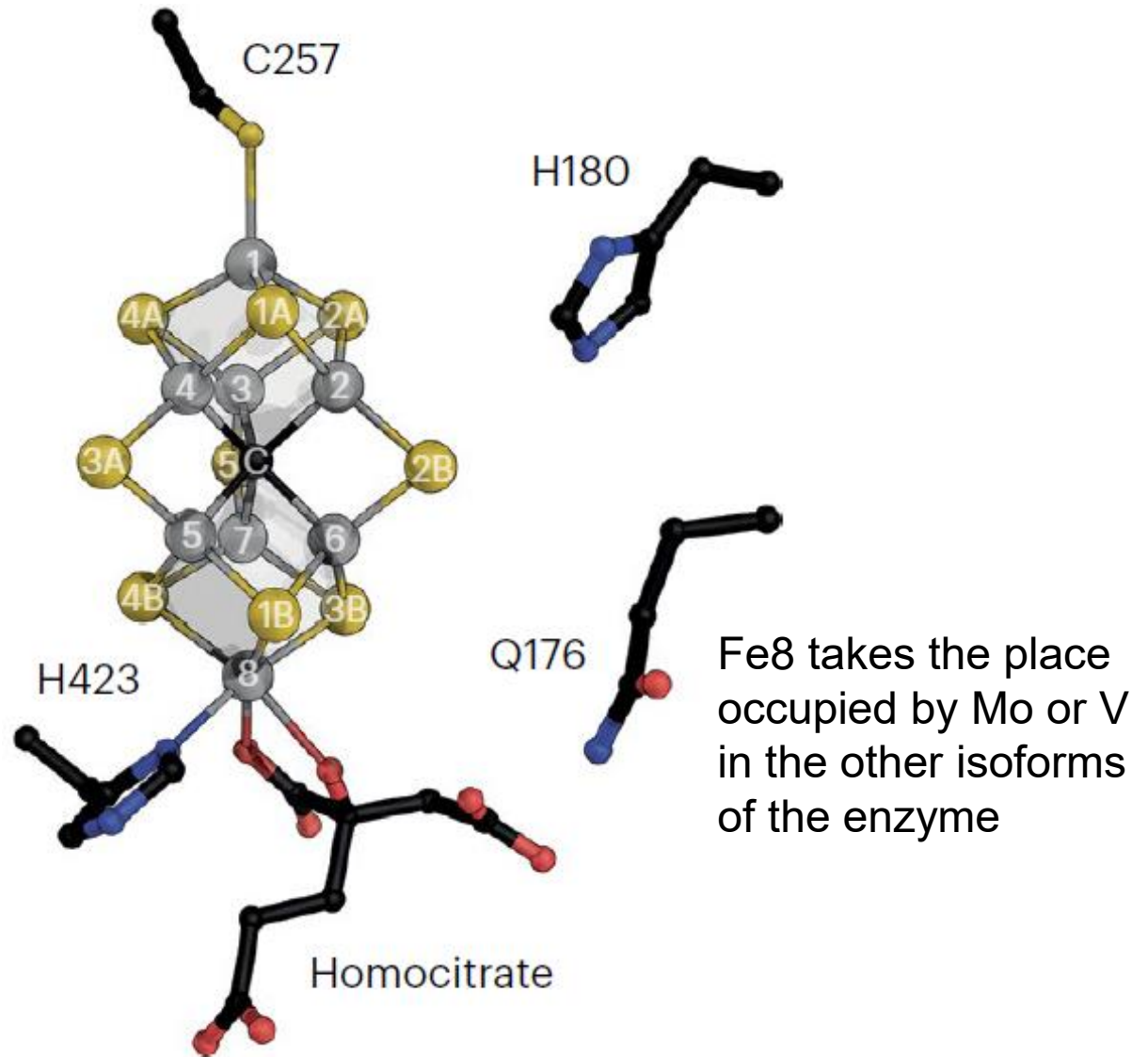
Interstitial atom identified as carbon



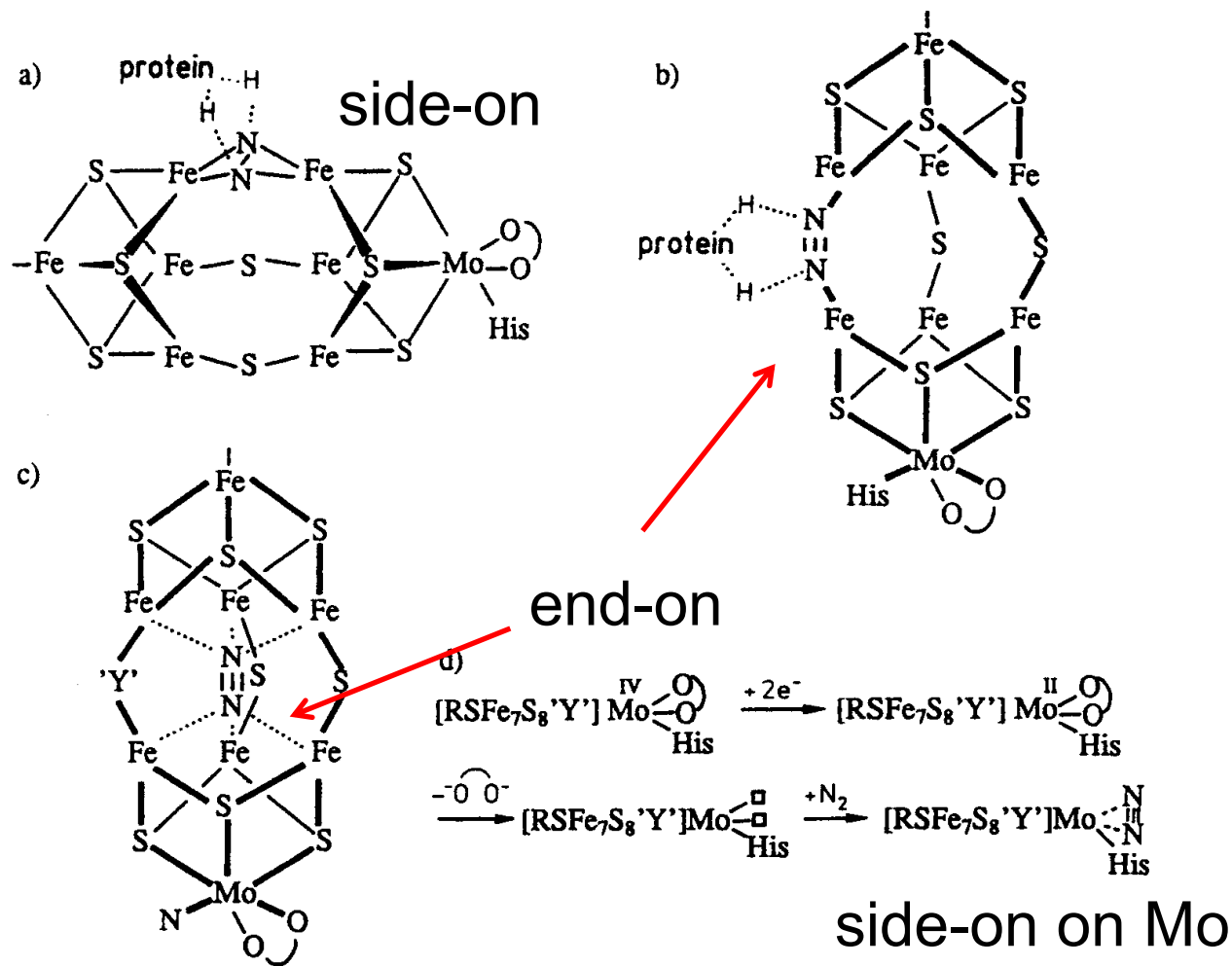
Presumed electron transfer pathway between P-cluster and FeMo cofactor



Structure of the FeFe cofactor

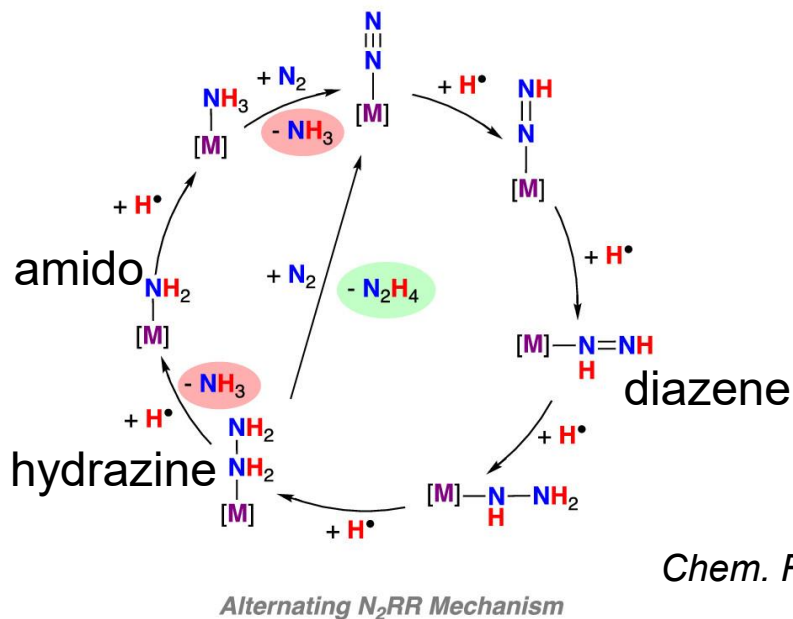
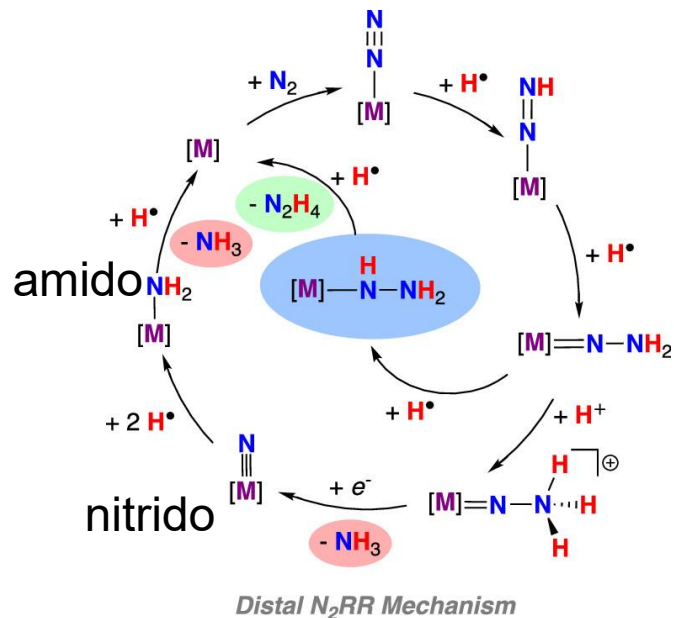


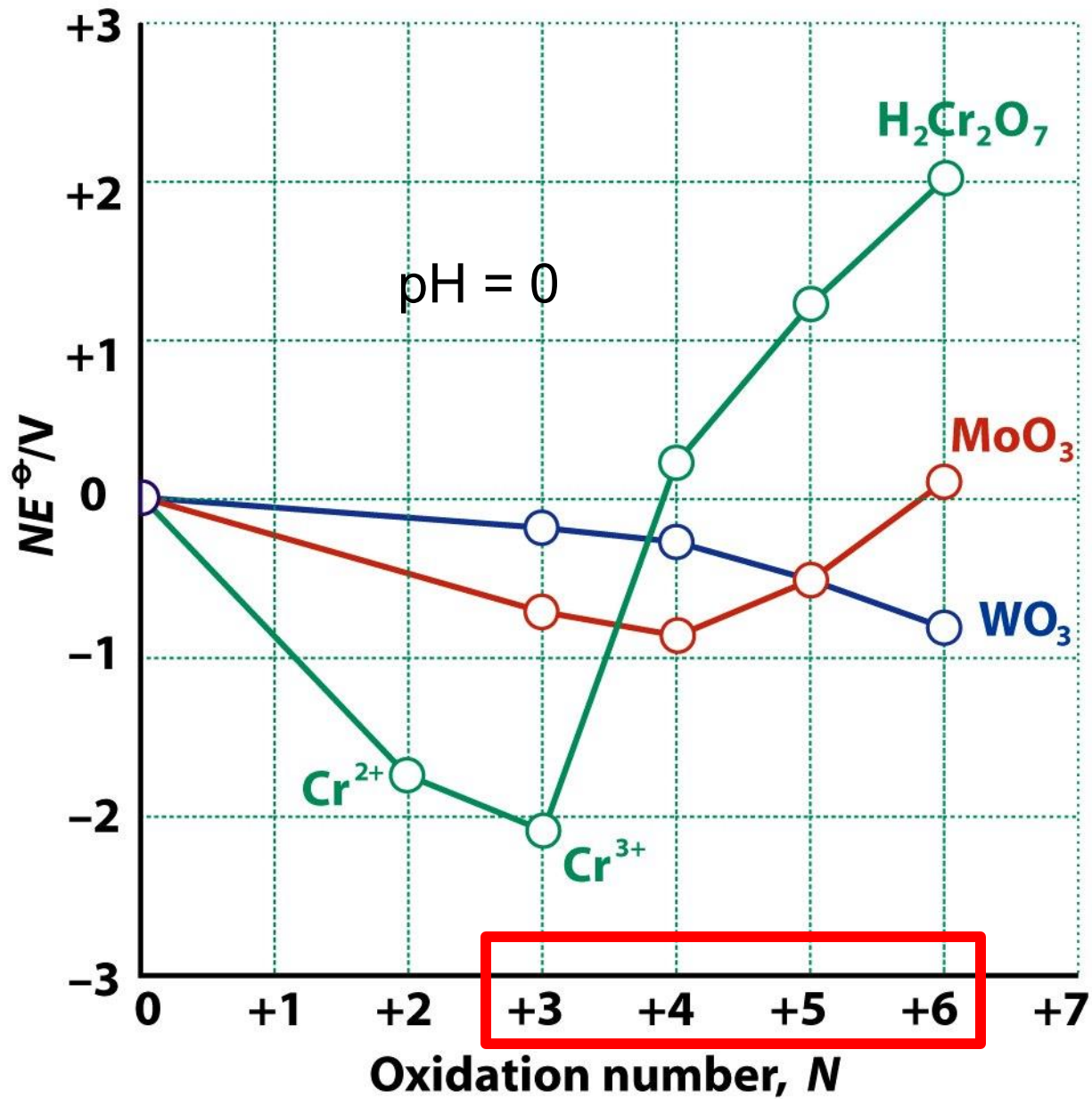
Possible coordination modes of N₂ to FeMoco



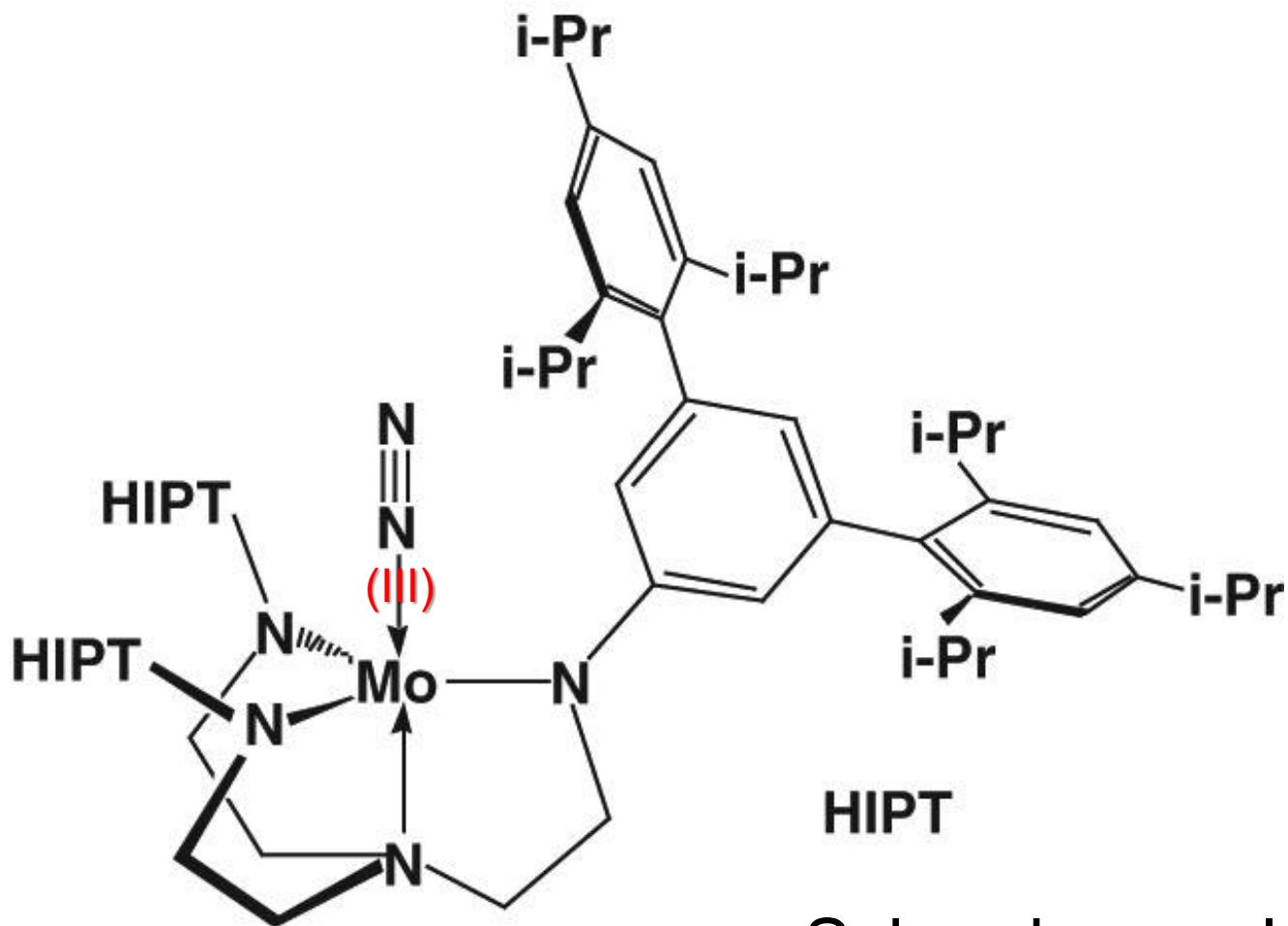
FeMoco binds N₂ only after having been reduced by 4 electrons

Distal and Alternating hypothetical catalytic cycles





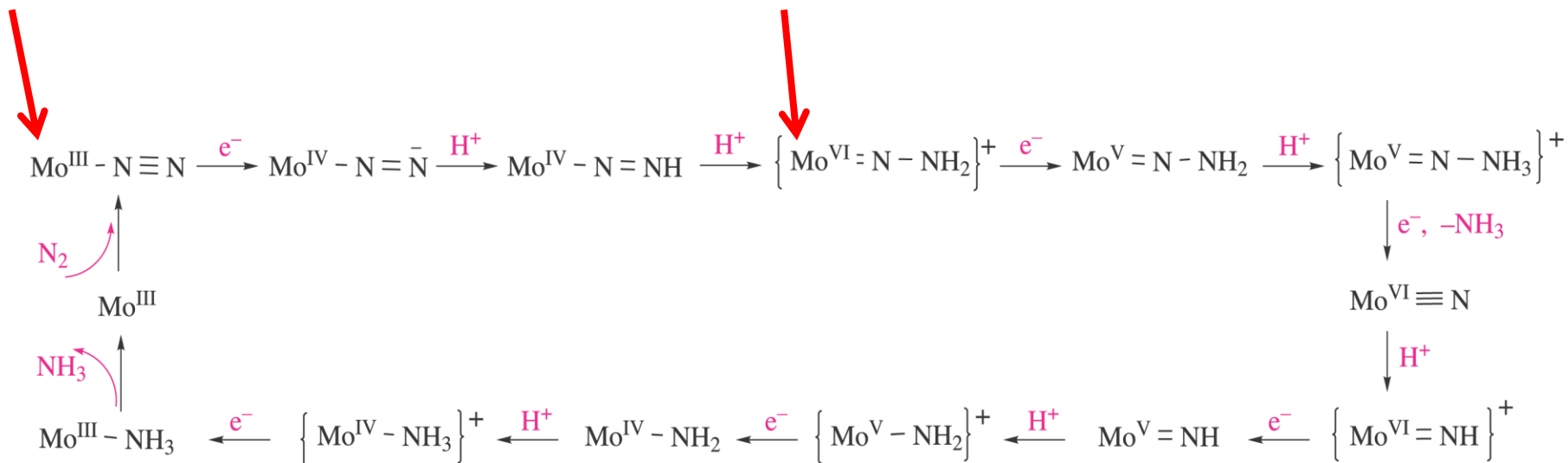
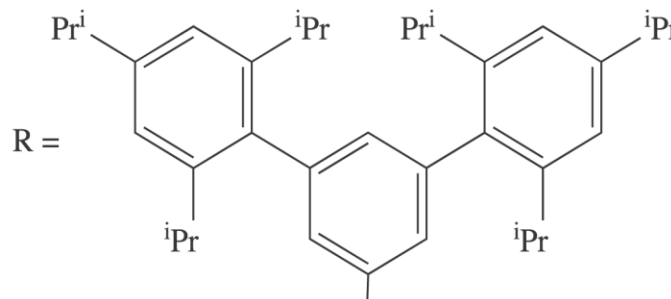
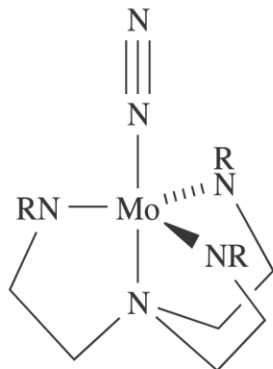
Models



HIPT

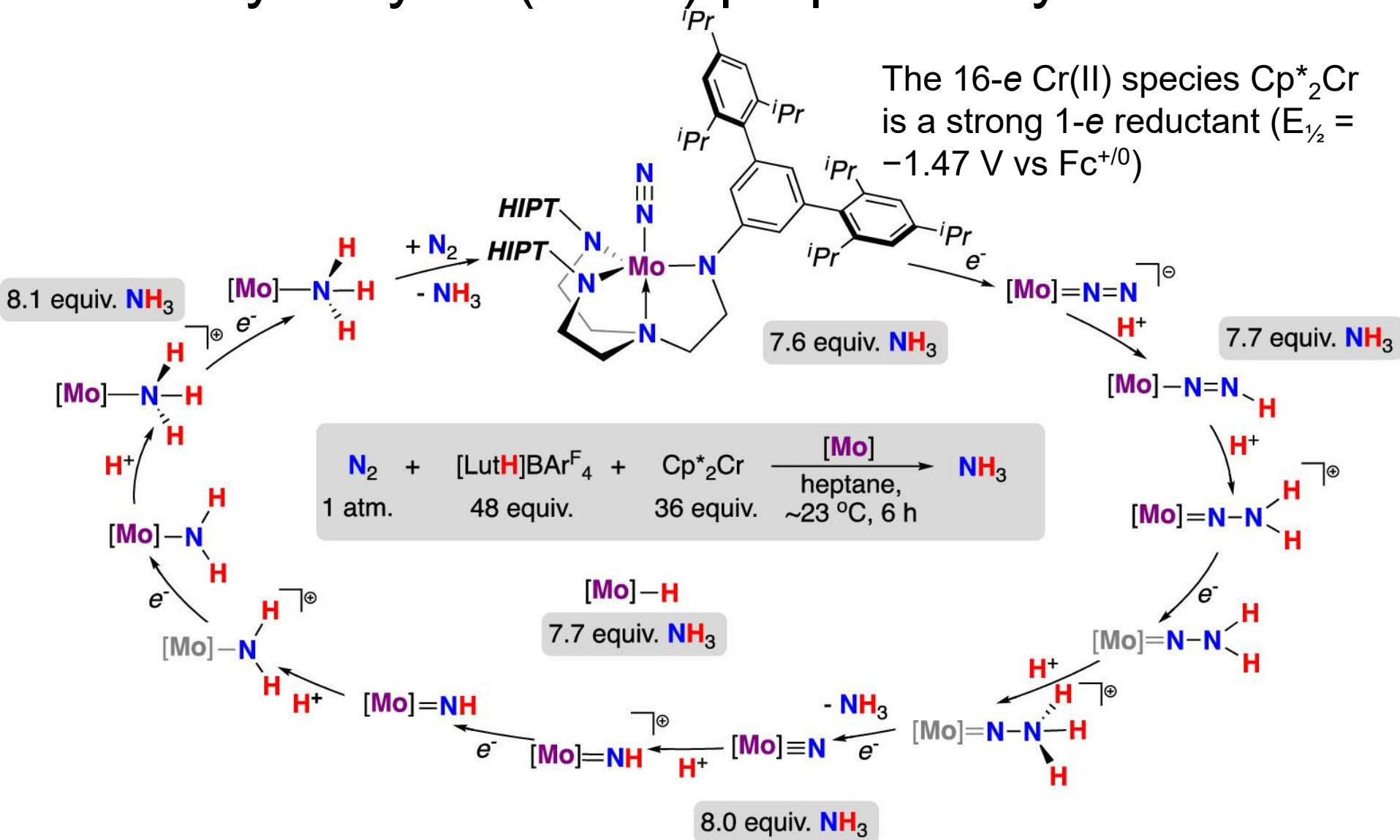
Schrock complex
(*Science* 2003)

Scheme of the N₂ to NH₃ "catalytic" reduction on Mo



8 catalytic cycles, *distal* mechanism

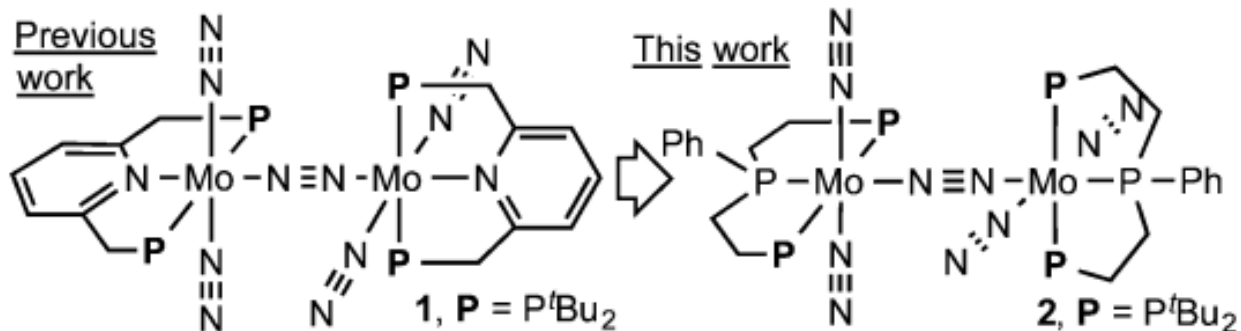
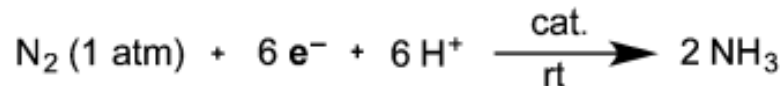
Catalytic cycle (*distal*) proposed by Schrock



Characterized species are in purple, those hypothesized are in grey

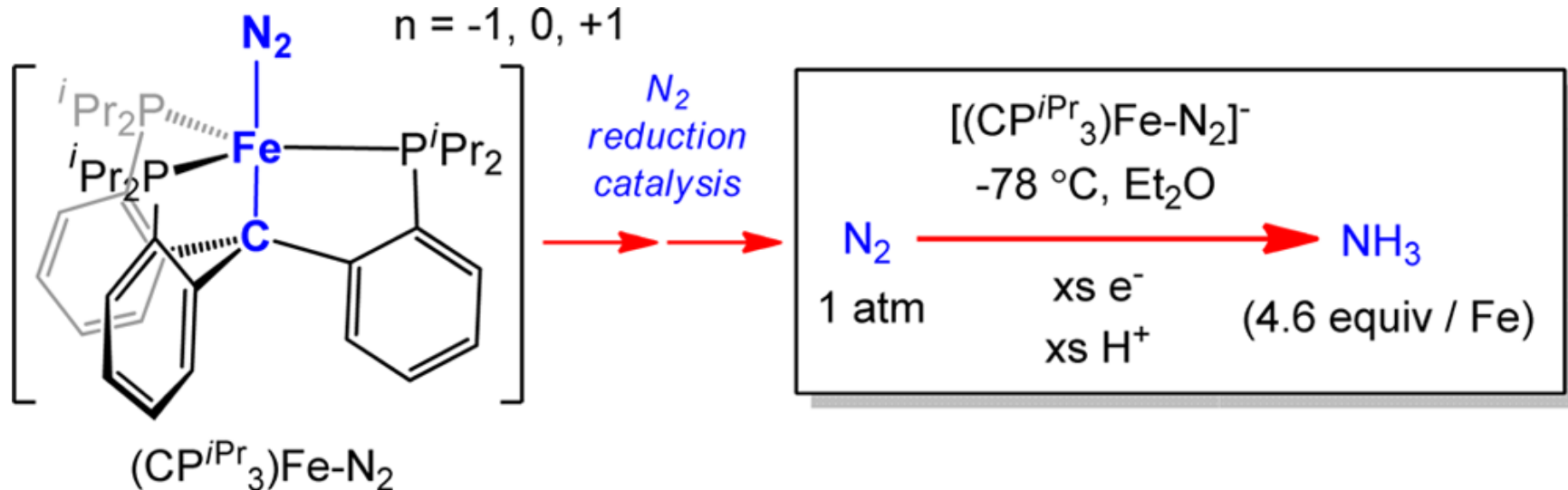
Nishibayashi Mo complexes (2011 e 2015)

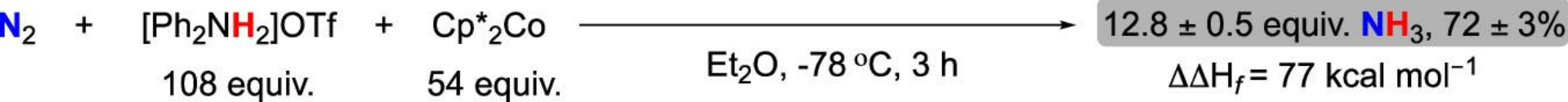
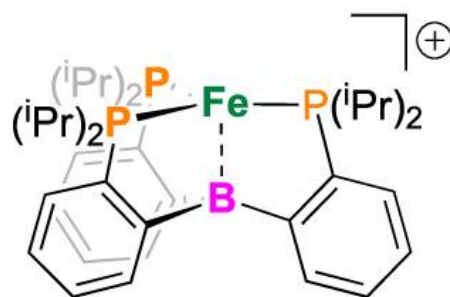
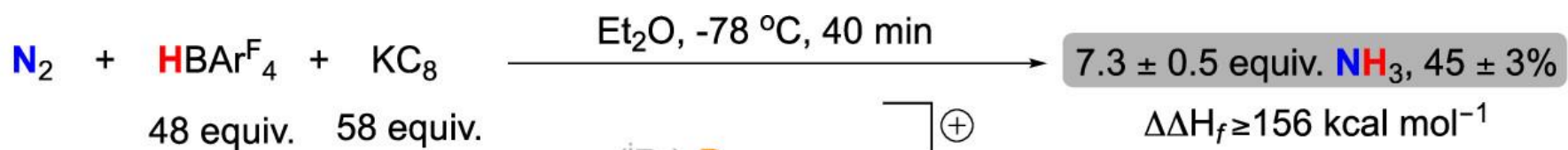
26 catalytic cycles, reductant CoCp^*_2



Peters complex (2014)

4.6 catalytic cycles, reductant K(crown)





electronic and spin structure of FeMoco

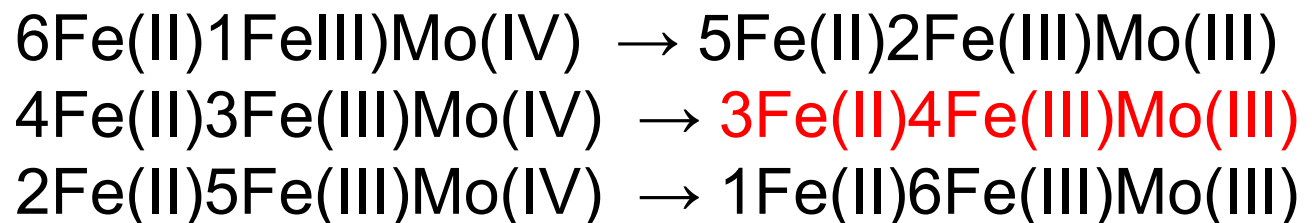
The electronic and spin state of each metal atom of FeMoco during the catalytic cycle should be determined.

The tetrahedral iron ions are always high spin.

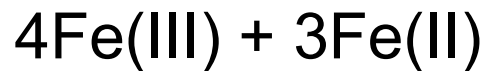
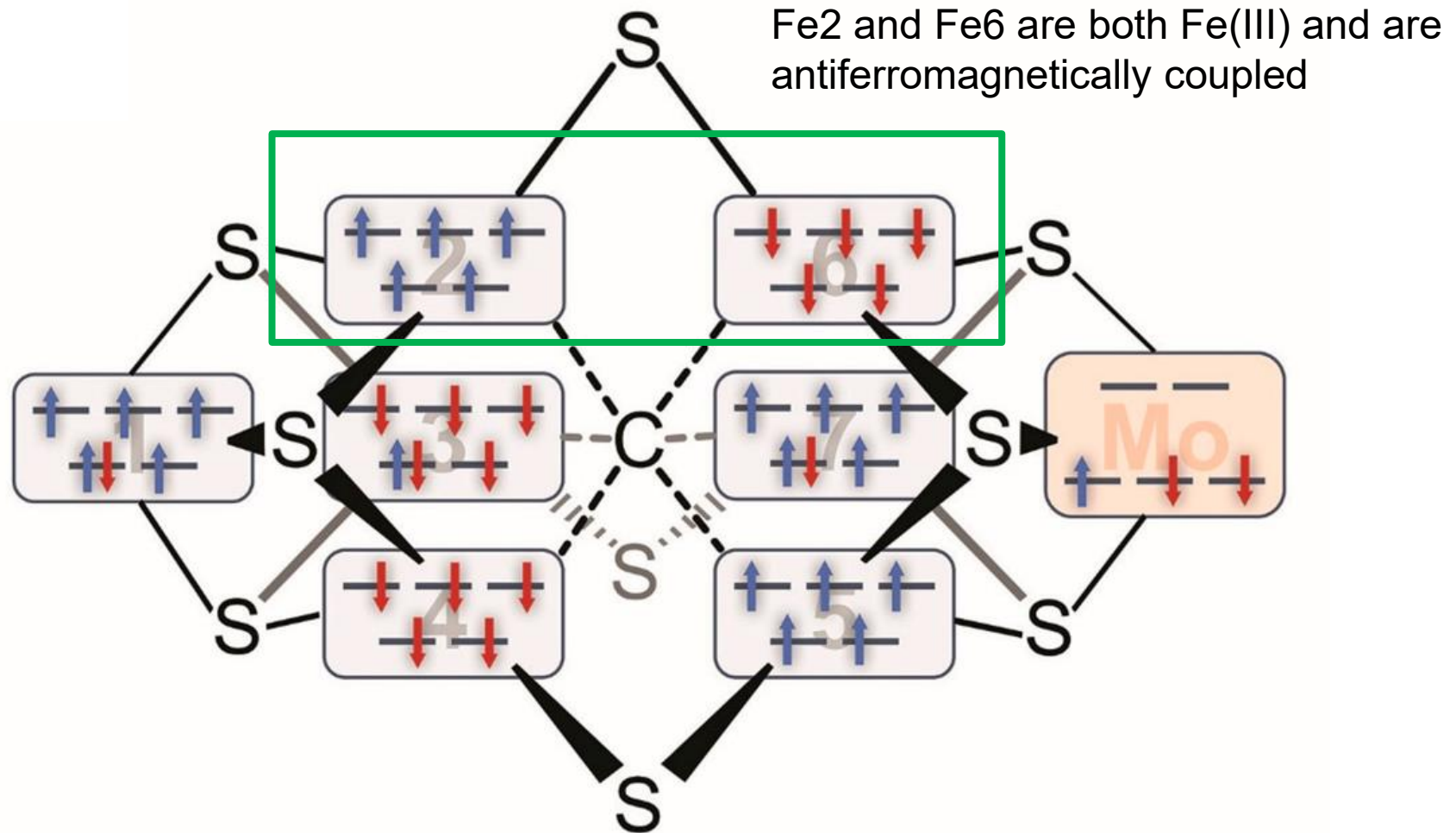
Resting state: $S = 3/2$

- | | | |
|---------------------------------------------|-----------------------|-----------------------|
| 1) $[\text{MoFe}_7\text{S}_9\text{C}]^{3-}$ | 6Fe(II)1Fe(III)Mo(IV) | |
| 2) $[\text{MoFe}_7\text{S}_9\text{C}]^{1-}$ | 4Fe(II)3Fe(III)Mo(IV) | Mo(IV), d^2 $S = 0$ |
| 3) $[\text{MoFe}_7\text{S}_9\text{C}]^{1+}$ | 2Fe(II)5Fe(III)Mo(IV) | |

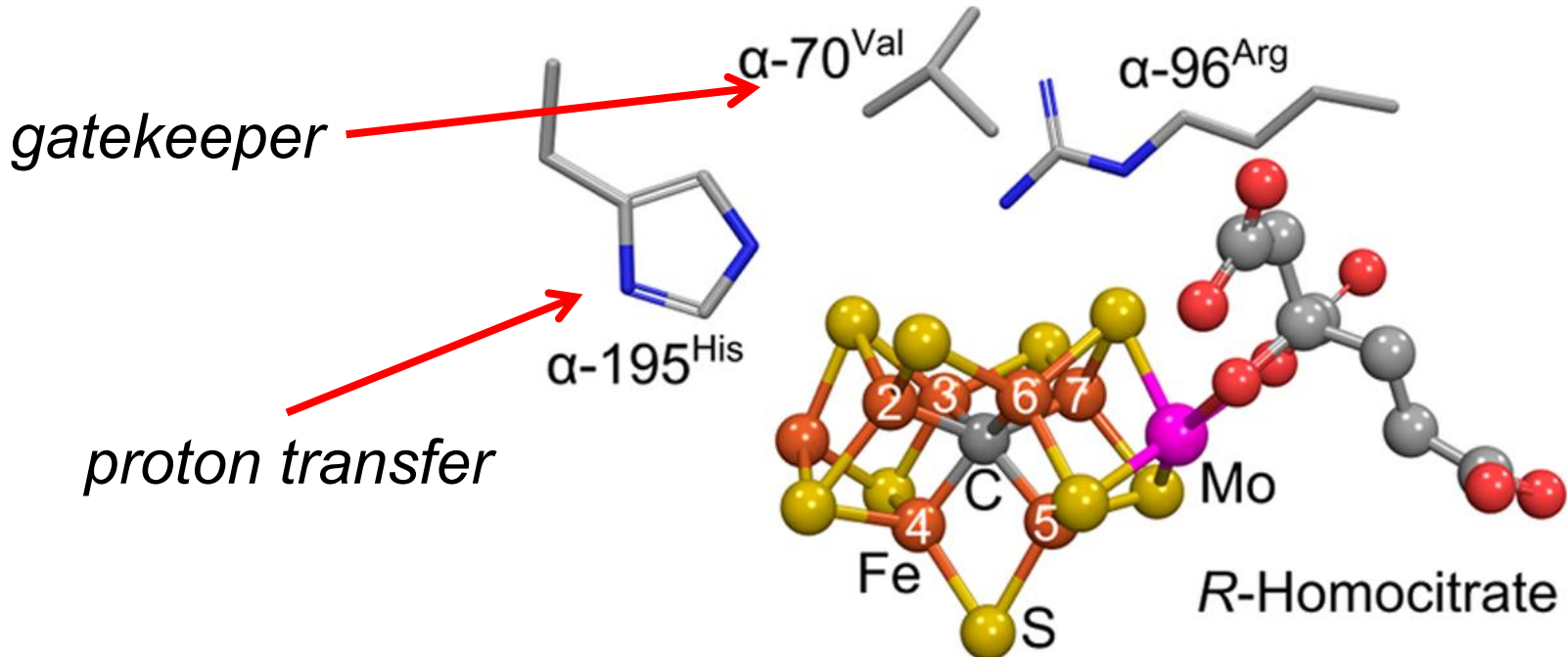
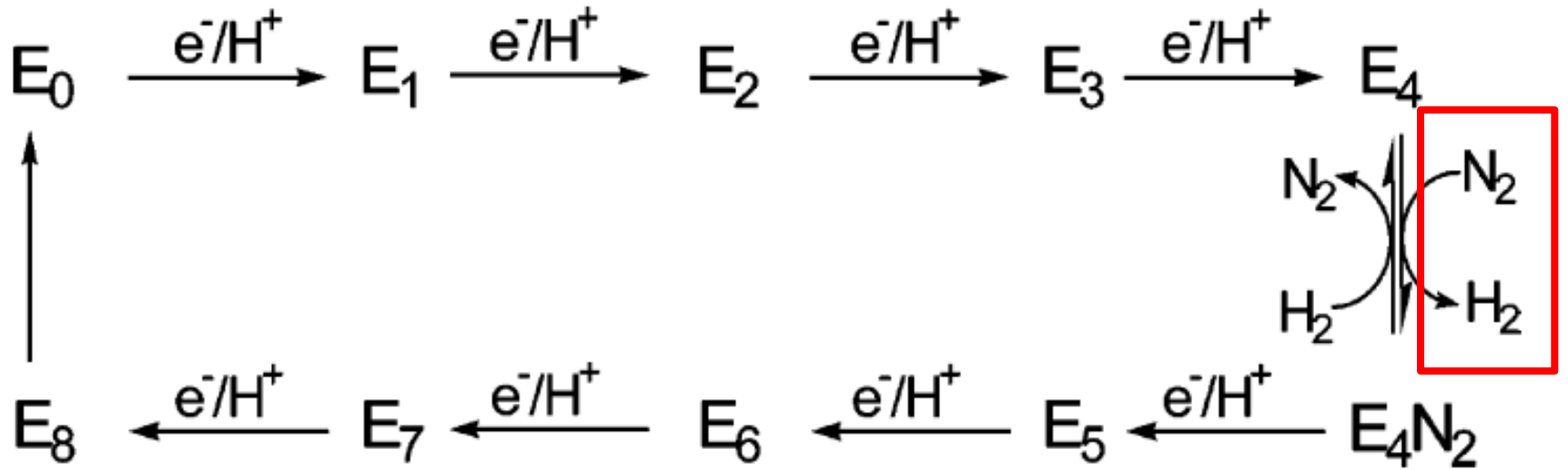
2014: Mo(III), d^3 low spin ($\uparrow\uparrow\downarrow$)? (violation of Hund's rule)



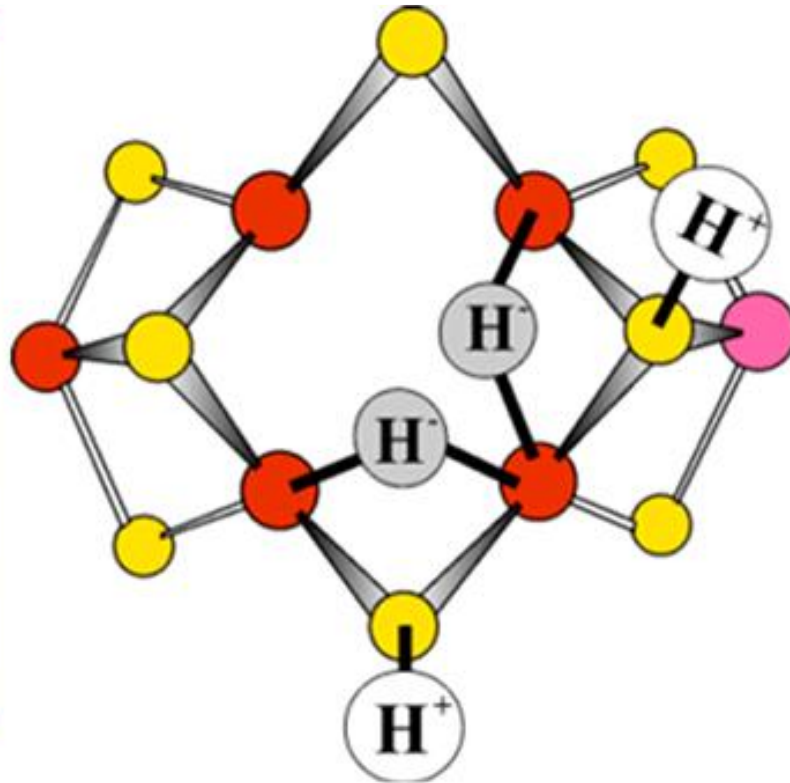
Currently most accepted electronic and spin structure of FeMoco



Catalytic cycle

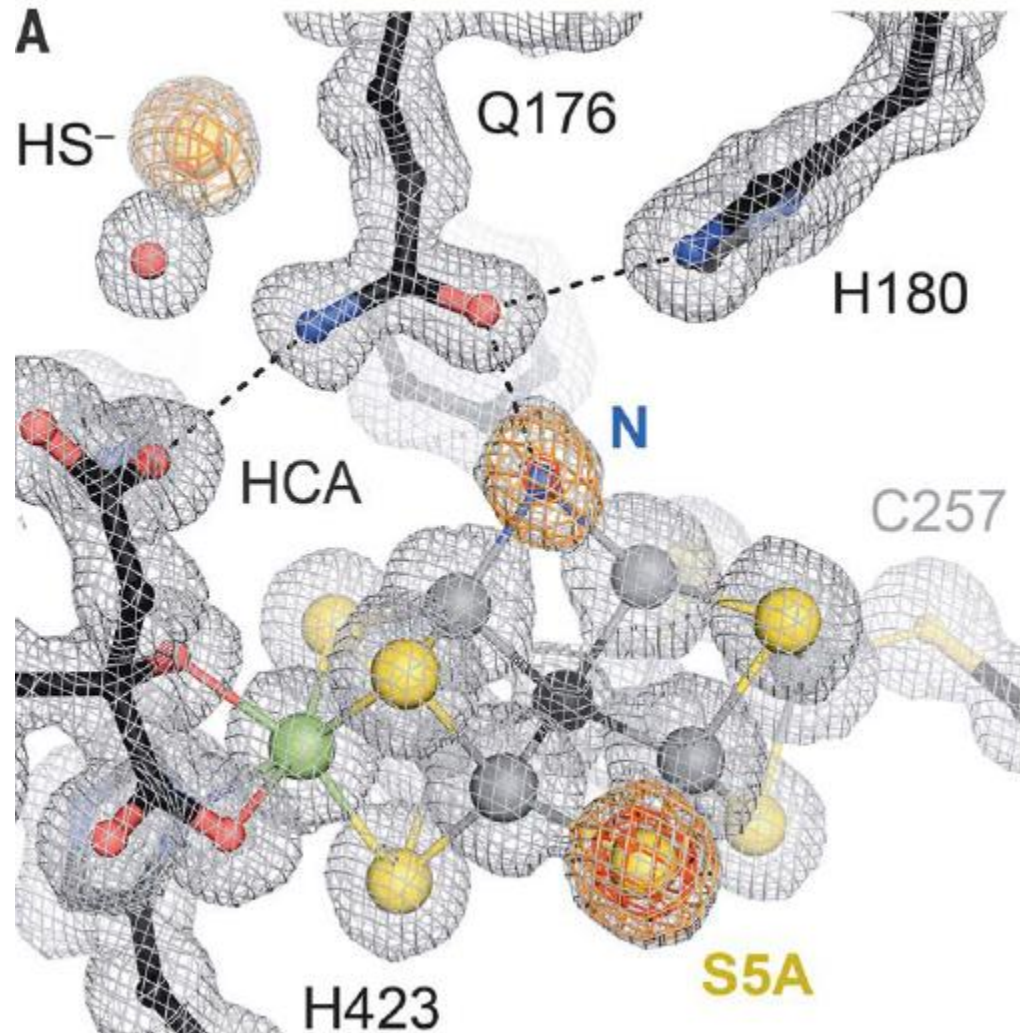


«Old» model for E_4 based on spectroscopic evidence

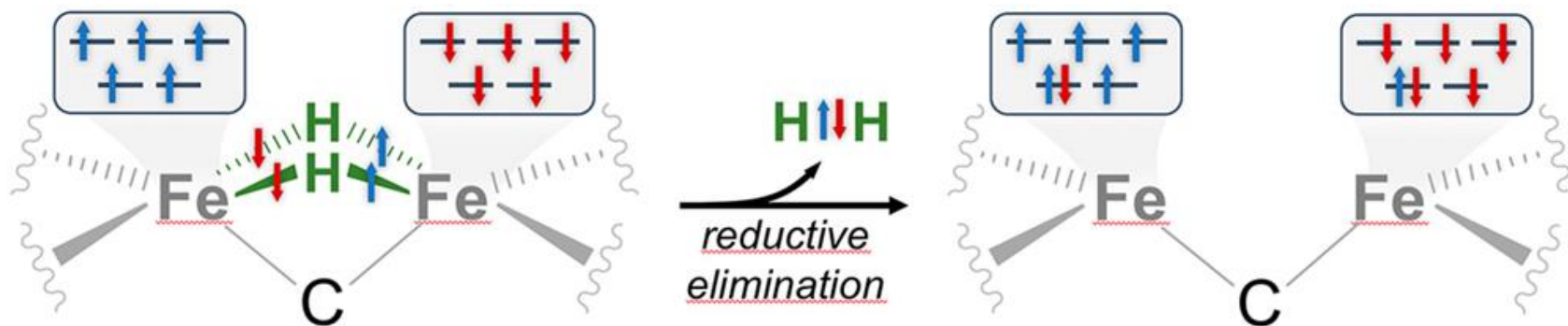


The first 4 electrons accumulate on hydrides and not on iron atoms

Intermediate in the FeV cofactor catalytic cycle with (presumably) a protonated NH in the active site bridging Fe2 and Fe6

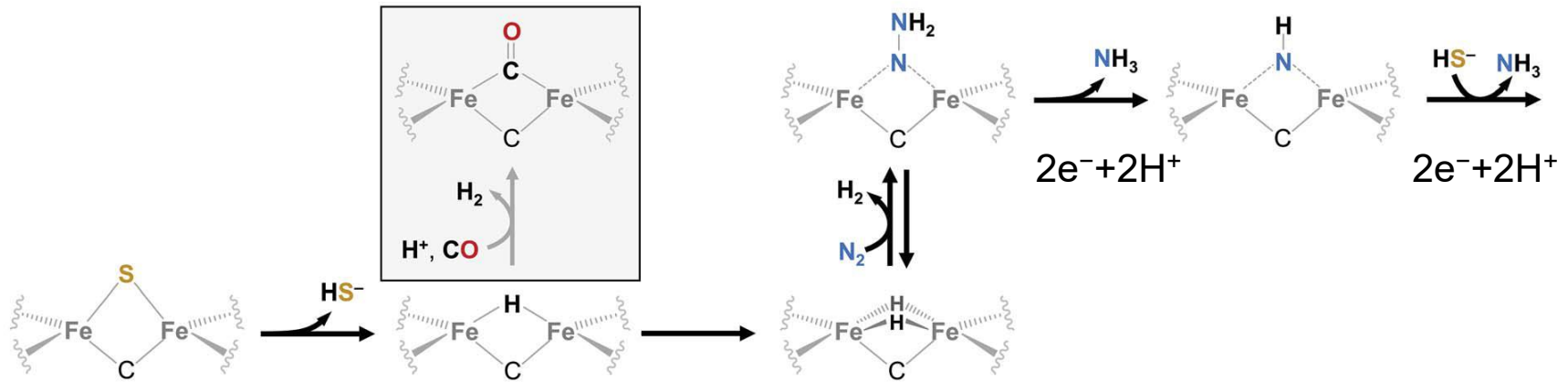


More recent model for E_4 based on spectroscopic evidence considering the SH displacement

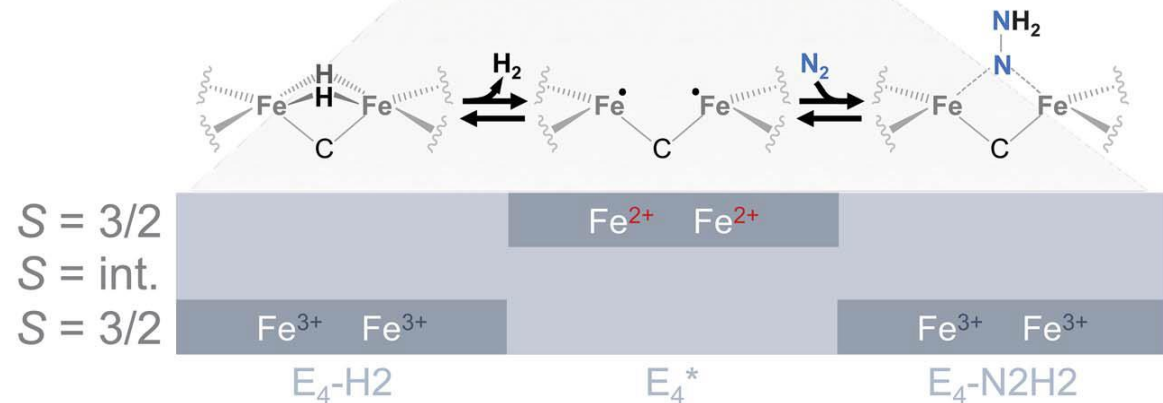


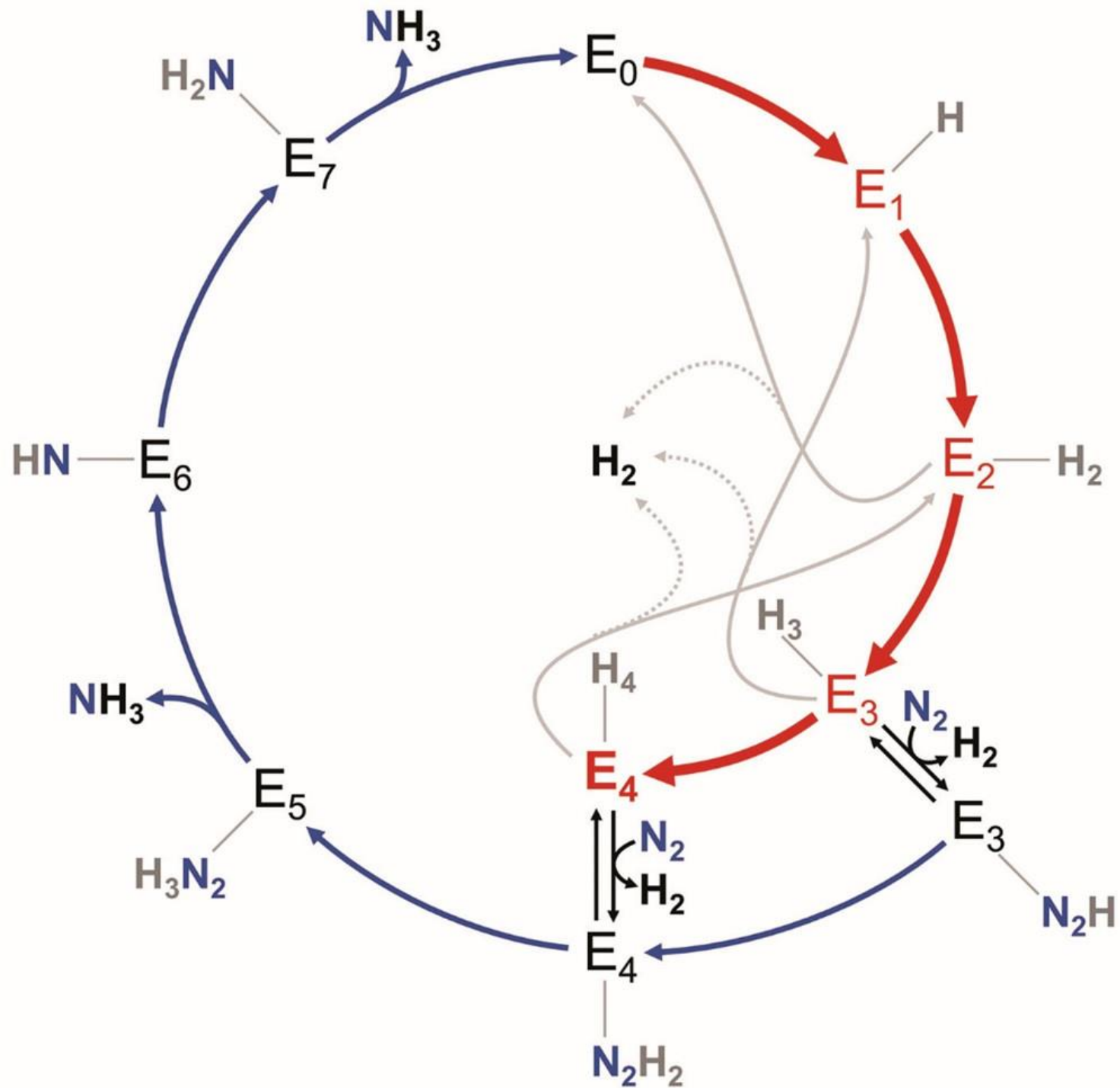
Spin-allowed process

Most recent hypothesis on the catalytic cycle



In the catalytic cycle, FeMoco changes its overall oxidation state by one unit only (in the E_n odd states)





Other molybdenum enzymes: oxotransferases

Mo enzymes typically catalyze the oxidation (oxygenation) or reduction of **small molecules**. The transfer of electrons (2) is typically coupled to the transfer of an O atom (from water). The active sites are **mononuclear**.

Molybdenum is an essential trace metal also in humans (ca. 10 mg) in at least 3 enzymes: sulfite oxidase, xantine oxidase and aldehyde oxidase.

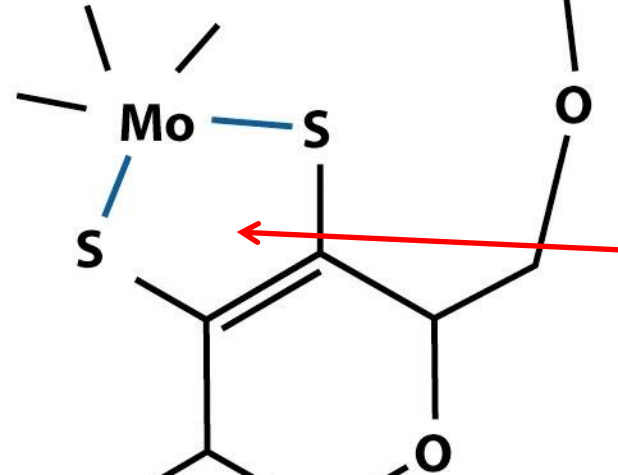
Three families of Mo oxotransferases

- xanthine-oxidase (incl. aldehyde oxidases)
- sulfite-oxidase (incl. nitrate reductase)
- DMSO-reductase

molybdenum cofactor

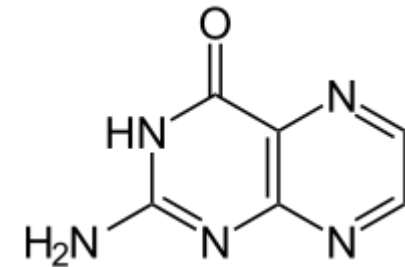
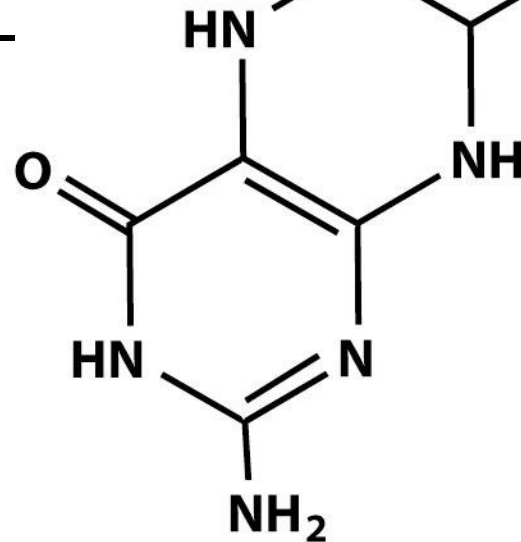
X-O₃P

X can be a nucleobase



dithiolene

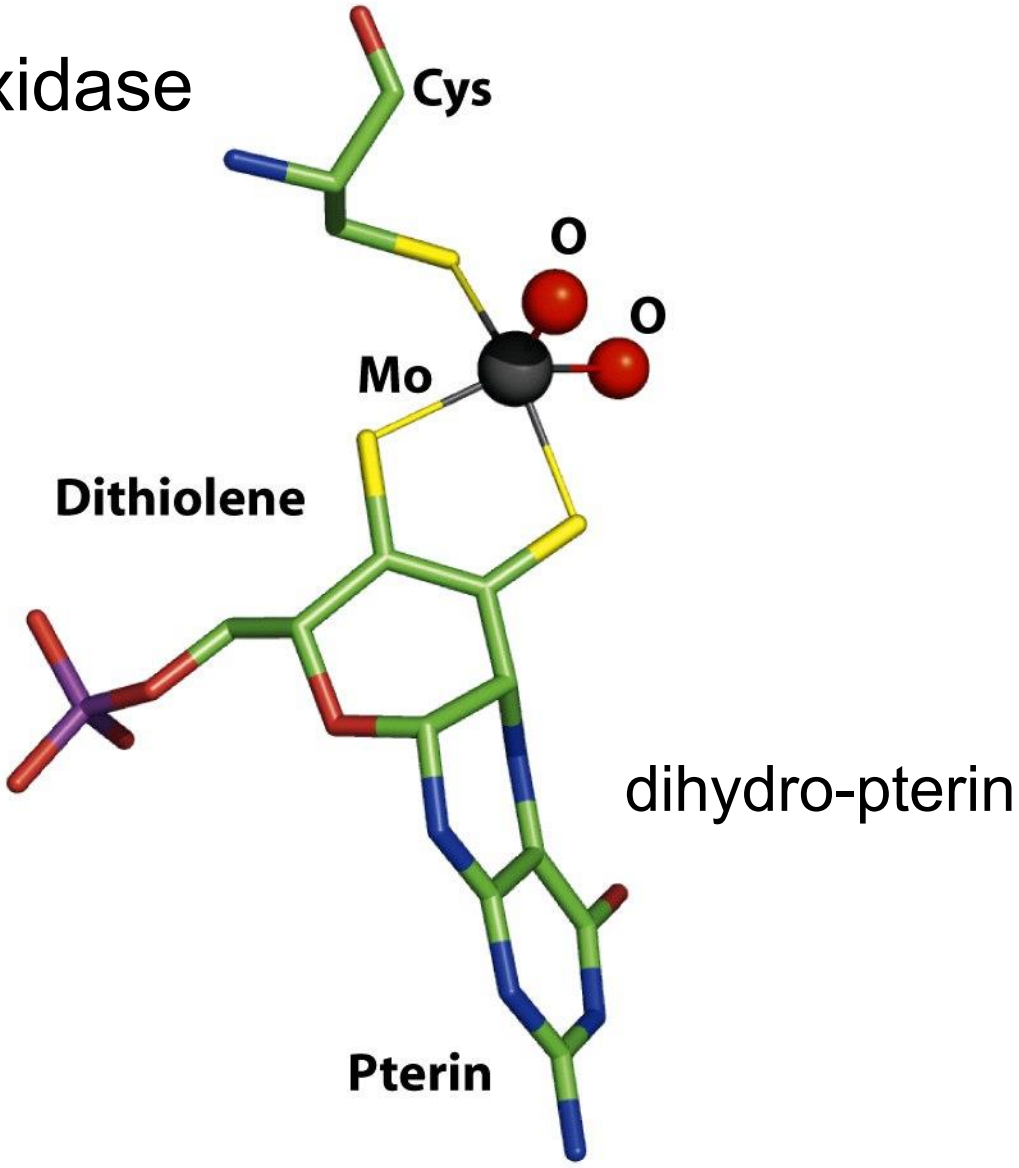
di-hydro or tetra-hydro pterin



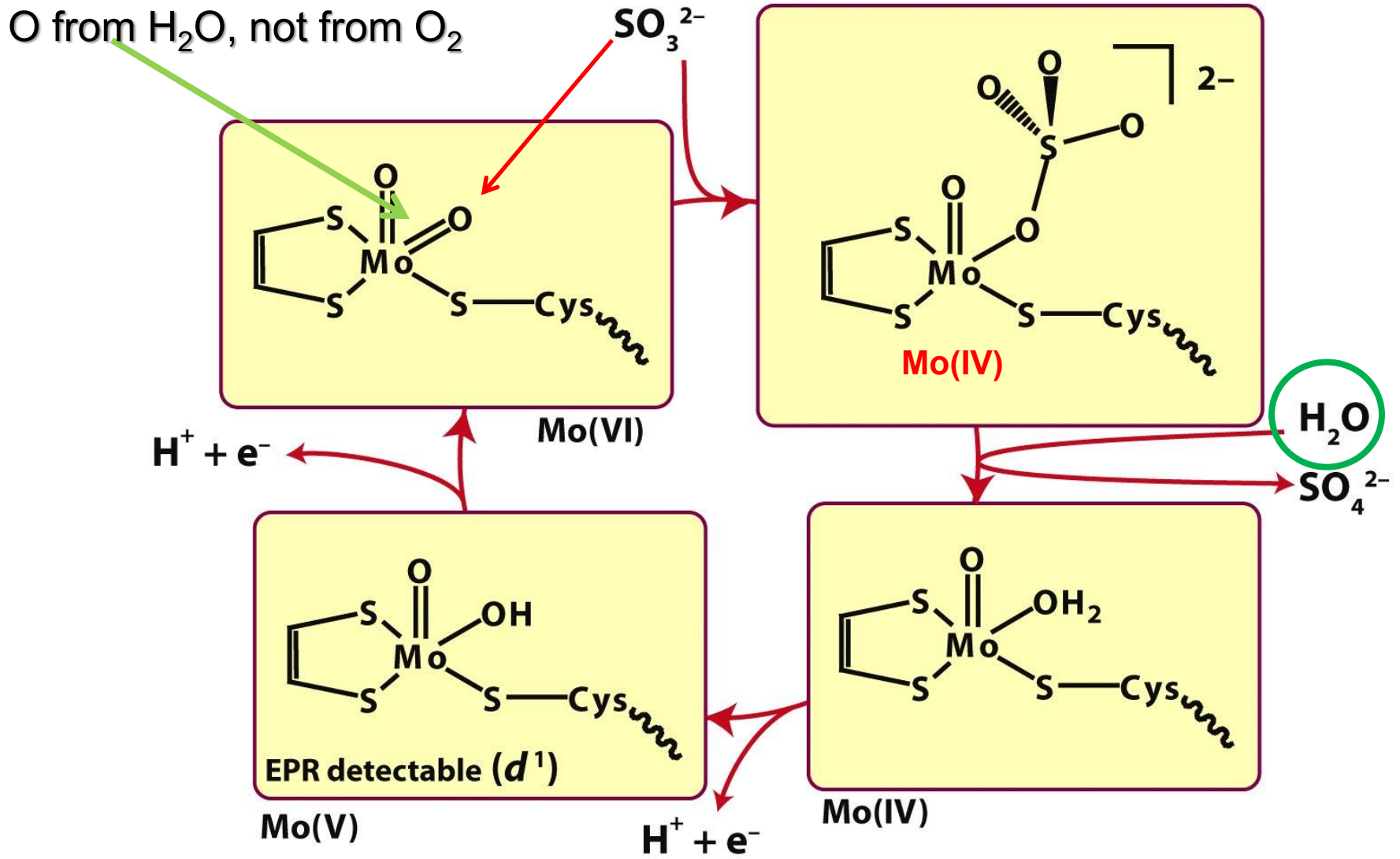
pterina

Molybdopterin as ligand

Site of sulfite-oxidase

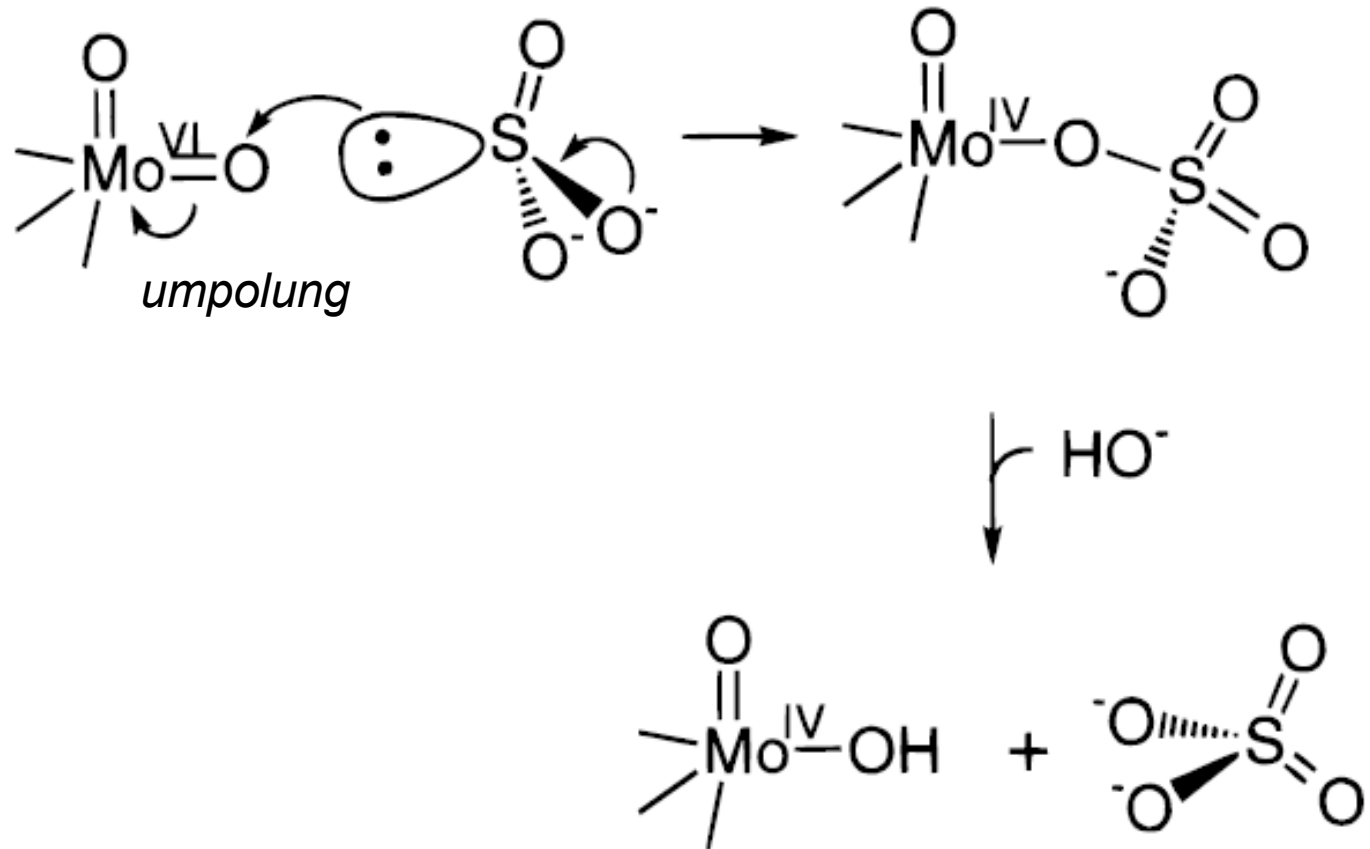


Catalytic cycle of sulfite-oxidase

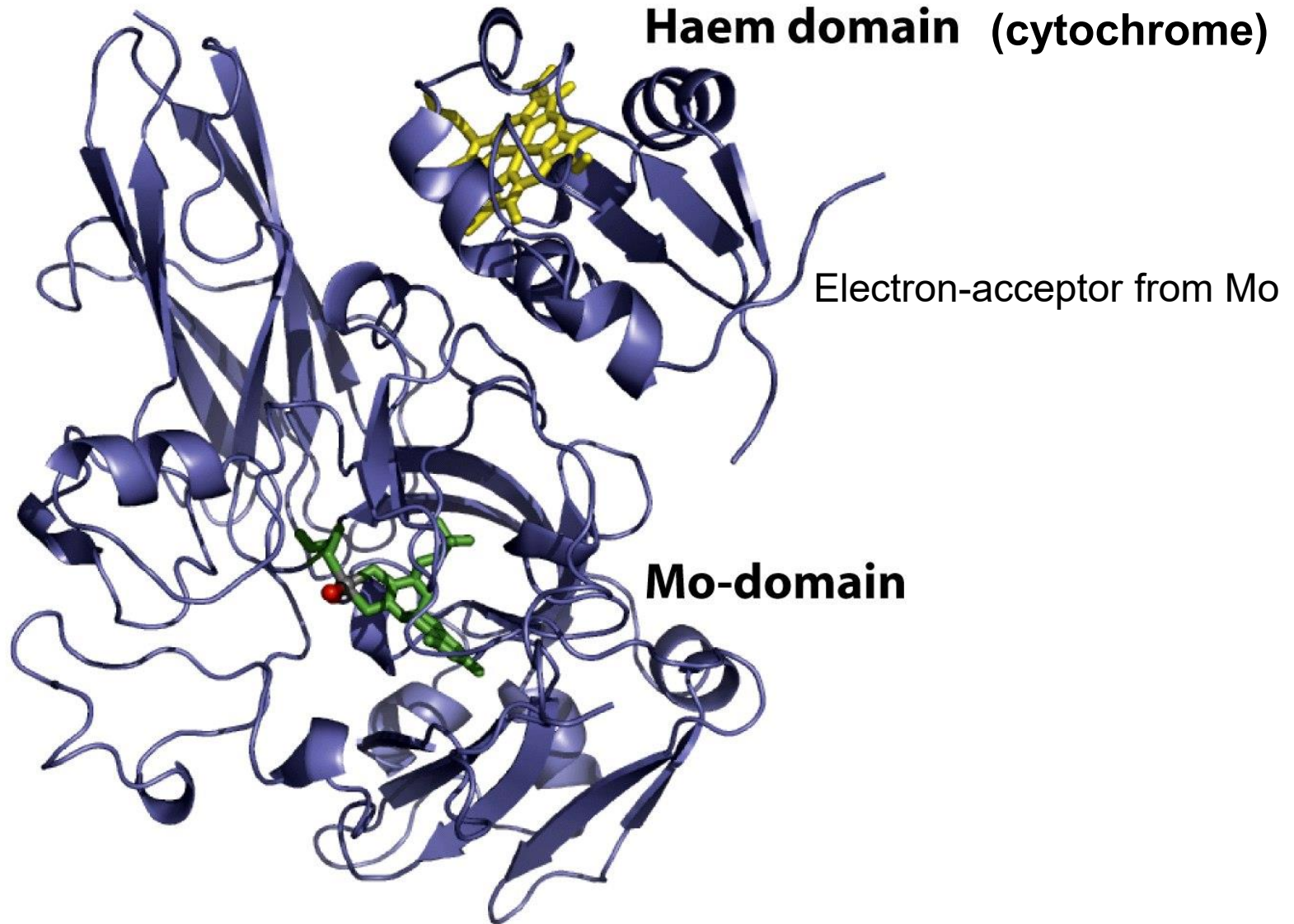


Mo has three stable oxidation states, Mo(IV), Mo(V) and Mo(VI)

Detail in the oxygen transfer mechanism



Structure of the sulfite-oxidase



Enthalpy scale for oxygen atom transfer reactions

