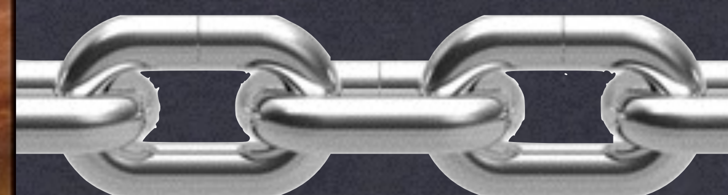
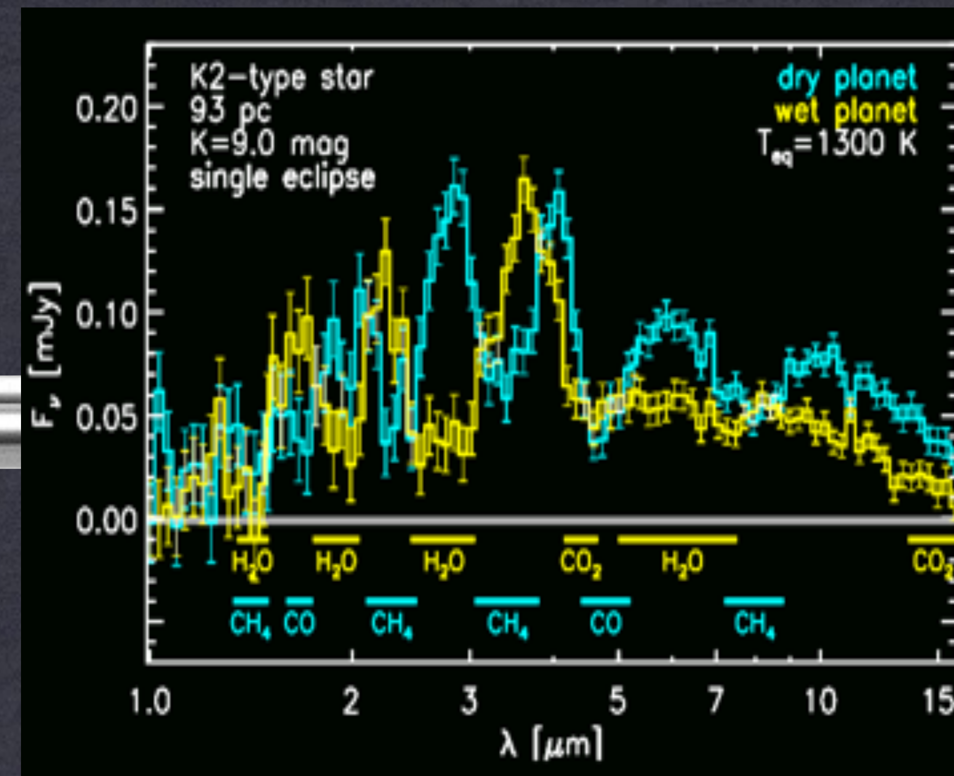
Linking the formation history of planets with their spectrum





C. Mordasini

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Paris IAP 9.1.2015

R. van Boekel, P. Mollière, T. Henning, MPIA
B. Benneke, MIT
W. Benz & Y. Alibert, Uni. Bern

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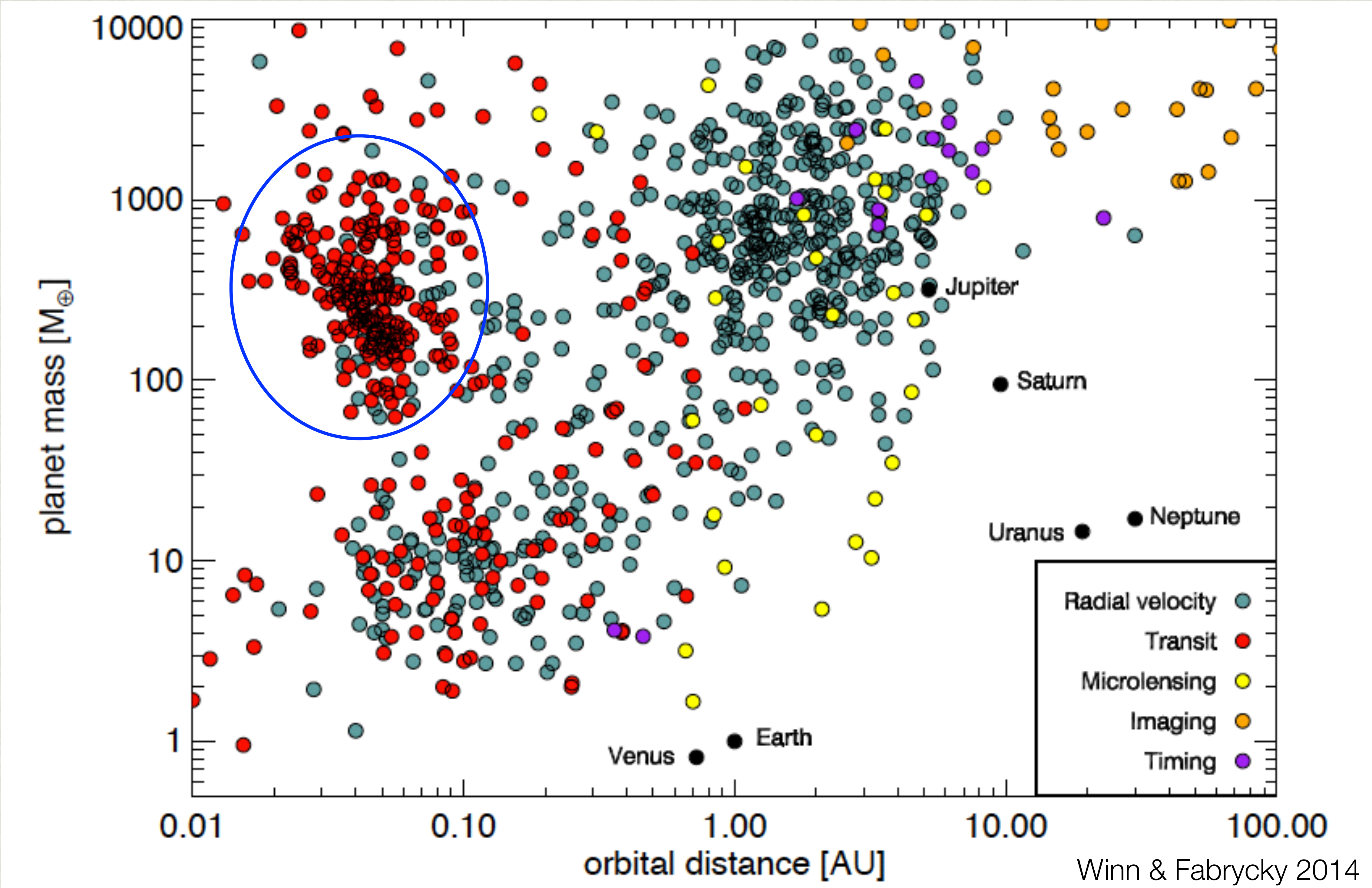
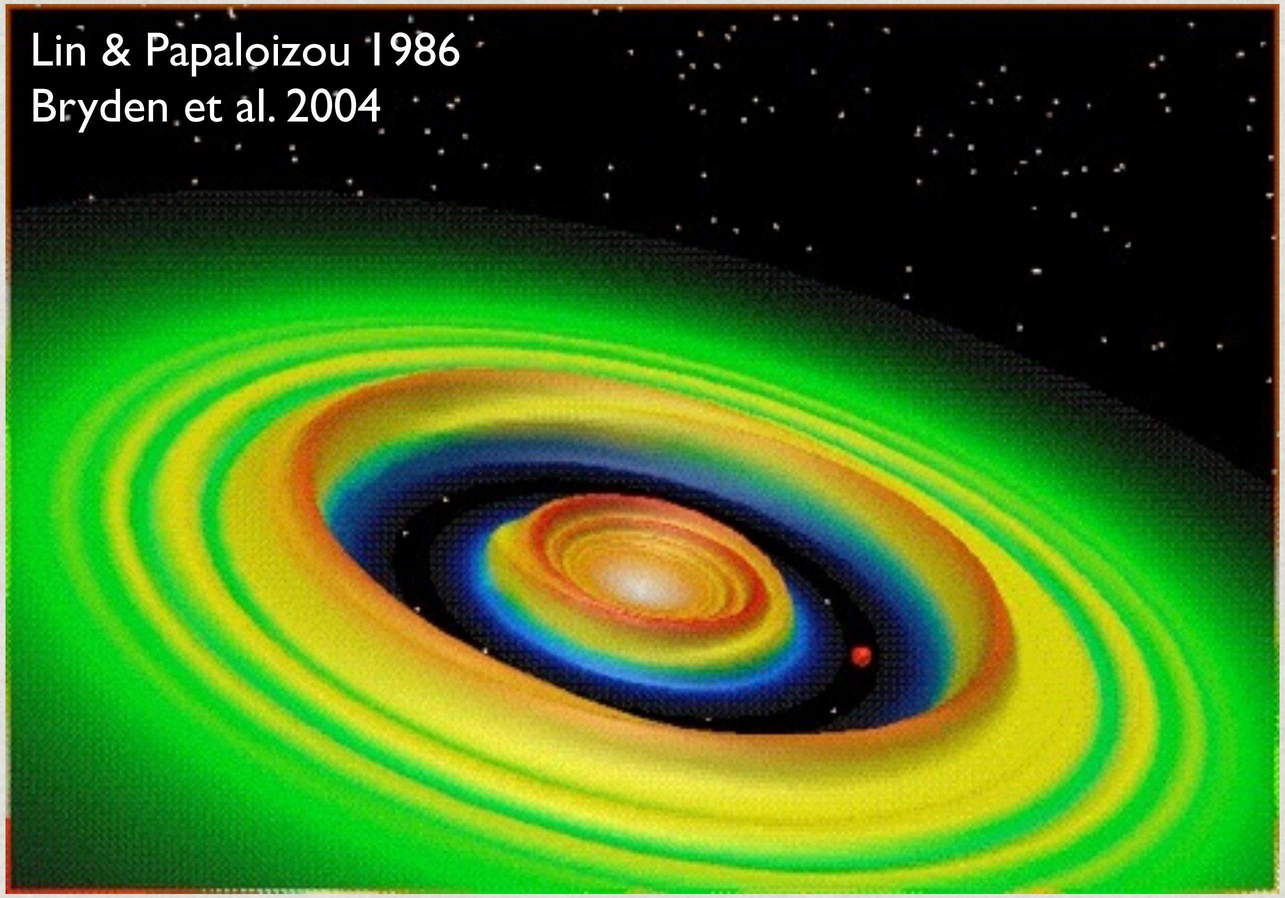
Important open questions

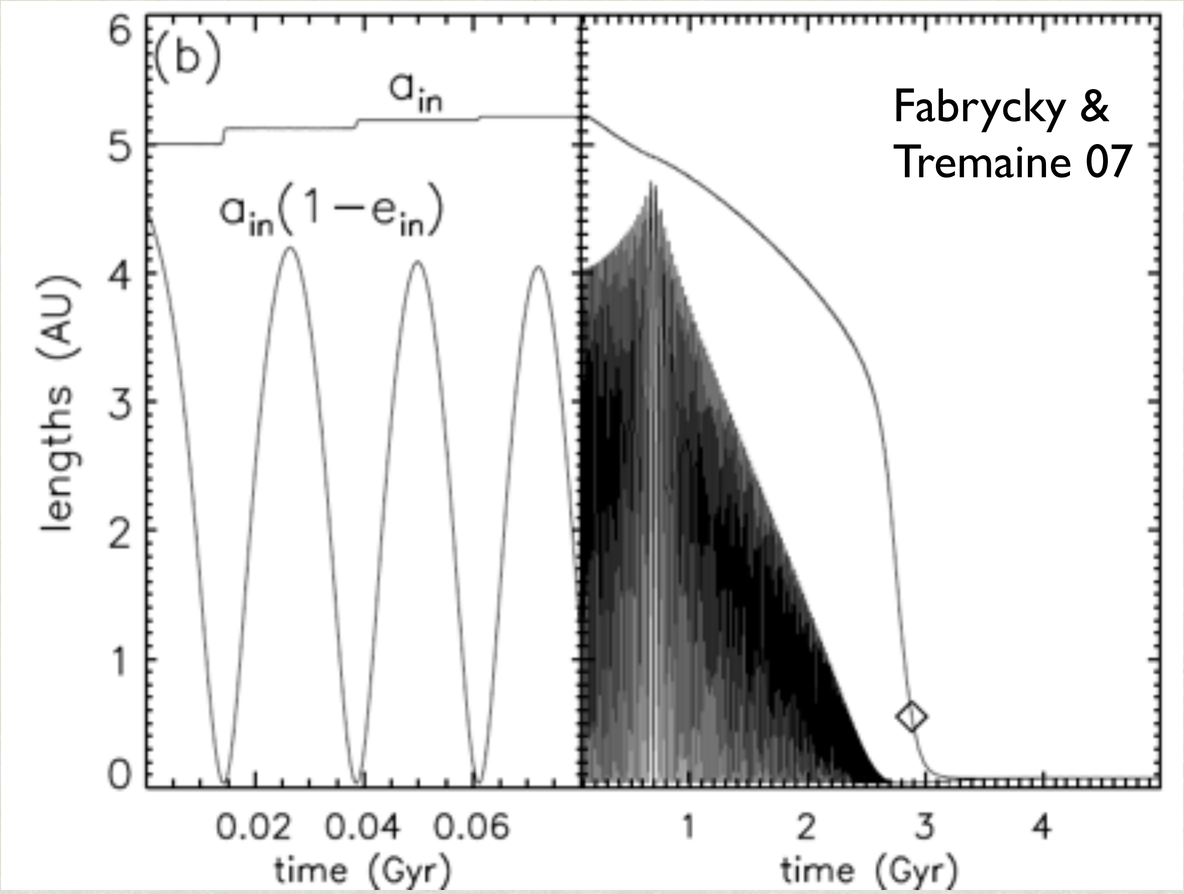


1855 known exoplanets on exoplanet.eu database (J. Schneider et al.)

Formation of Hot Jupiters

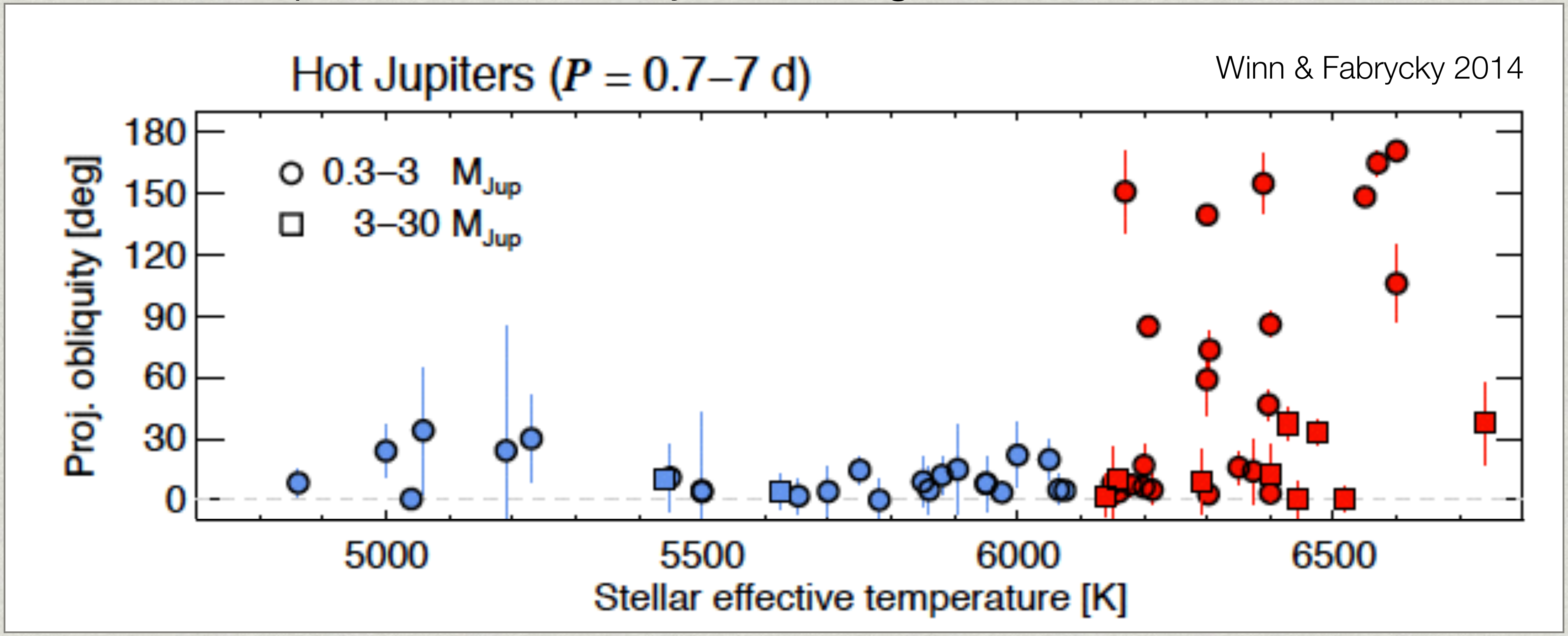
- Protoplanetary disk too hot at ~0.03 AU to form in situ
- Not enough solids to form in situ
- Formed further out, then migrated close to star
    - Disk migration
    - Planet-planet scattering w. tidal circularisation
    - Kozai-Lidov mechanism w. tidal circularisation





Formation of Hot Jupiters II

- Observed obliquities indicate a dynamic origin



- But: Non-aligned protoplanetary disks
    - outcome of star formation
    - magnetic star-disk interactions
    - torques from distant stellar companions
    - differential rotation of photosphere and interior

Spectroscopy to the rescue

- Exoplanet spectra: window into the composition of the planet => clues to formation history.

- The measured atmospheric composition depends on the
  1. composition of the host star and disk
  2. position(s) where the planet accreted (formation track)
  3. composition of the accreted gas and planetesimals
  4. size of the planetesimals and their strength: envelope enrichment
  5. evolution of the distribution of chemical species within the planet
  6. atmospheric structure and dynamics

- Each migration & accretion history => different atmospheric (like C/O) and bulk composition. But link formation to spectra currently poorly understood.

- To investigate that, couple a *chain of simple models* together that goes *from planet formation to spectra*.

First steps - Preliminary results!

A chain of models

Six chain links:

1. **Planet formation model**: yields fundamental planetary properties (mass, orbital distance). Planetesimal & gas accretion & disk evolution & orbital migration (core accretion paradigm).

2. **Planetary bulk composition**: enrichment of the gaseous envelope

3. **Planet evolution model**: yields planetary M, R, L and atmospheric p-T structure after 5 Gyrs

4. **Chemistry model**: yields the elemental composition

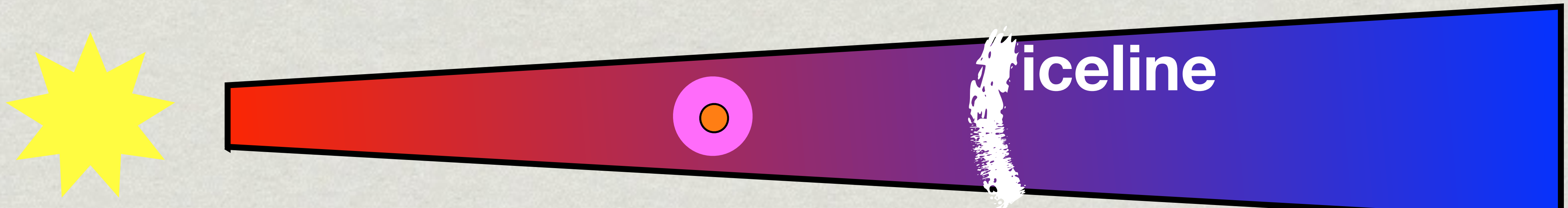
5. **Atmospheric composition**: abundance of H_2O, CO_2, CH_4, CO, ...

6. **Atmospheric model/spectrum**: final observable quantity

Hot Jupiter formation: 2 cases

Case 1: "dry planet"

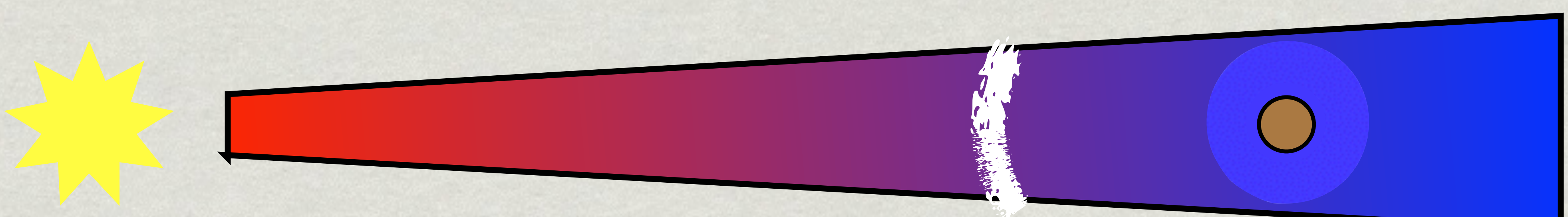
Disk migration



Result: aligned Hot Jupiter with chemical imprint of accretion of hot gas and rocky planetesimals

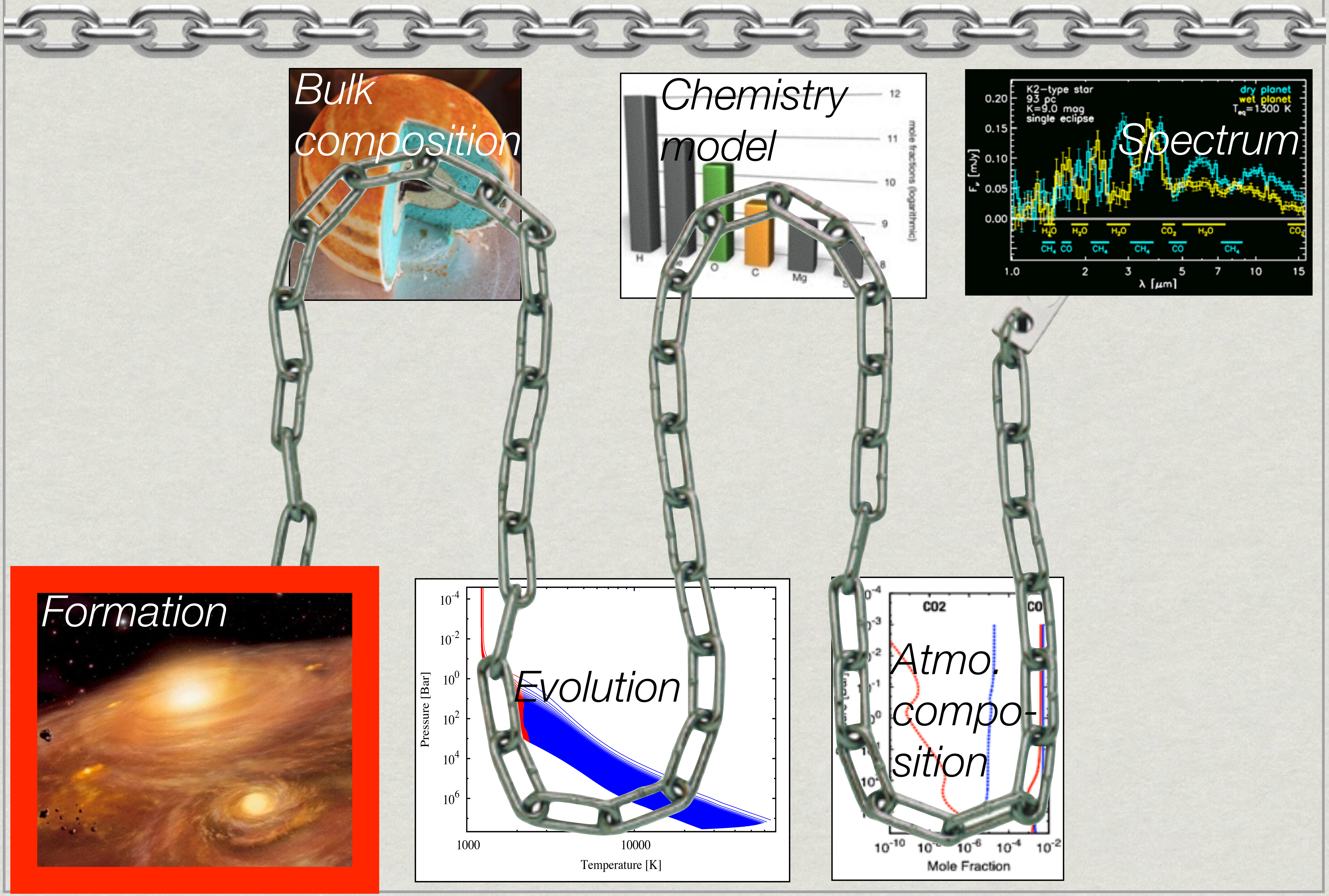
Case 2: "wet planet"

Kozai and tidal circularization



Result: potentially misaligned Hot Jupiter with chemical imprint of accretion of cold gas and icy planetesimals from beyond iceline only

1. Formation


Bulk composition
Chemistry model
mole fractions (logarithmic)
H
O
C
Mg
Spectrum
K2-type star
93 pc
K=9.0 mag
single eclipse
dry planet
wet planet
T_{eq}=1300 K
F_ν [mJy]
λ [μm]
Formation
Evolution
Pressure [Bar]
Temperature [K]
Atmo. compo-sition
CO2
CO
Mole Fraction

Extended core accretion model

- **Accretion of planetesimals.** Safronov rate equation.

$$\frac{dM_Z}{dt} = \Sigma_{\mathrm{P}} \Omega F_{\mathrm{G}} \pi R_{\mathrm{capt}}^2$$

- **Accretion of gas.** 1D structure equations.

$$\frac{\partial m}{\partial r} = 4\pi r^2 \rho \qquad \frac{\partial P}{\partial r} = -\frac{Gm}{r^2}\rho \qquad \frac{\partial T}{\partial r} = \frac{T}{P}\frac{\partial P}{\partial r}\nabla(T,P)$$

- **Disk migration.** Type I (non-isothermal) and II.

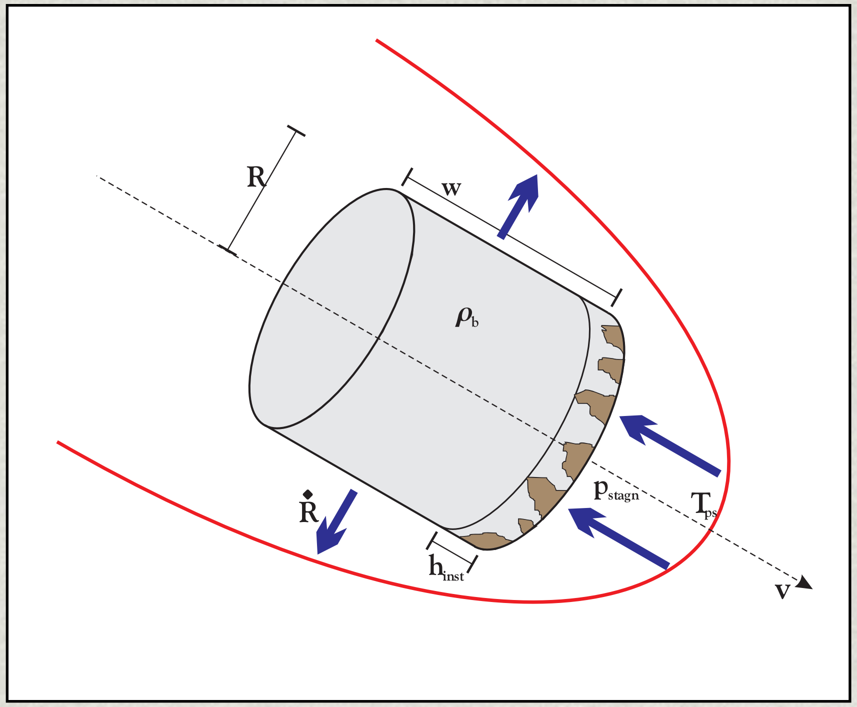
$$\frac{da}{dt} = 2a\frac{\Gamma_{\mathrm{tot}}}{J} \qquad \Gamma_{\mathrm{tot}} = \frac{1}{\gamma}(C_0 + C_1 p_\Sigma + C_2 p_{\mathrm{T}}) \left(\frac{q}{h}\right)^2 \Sigma a^4 \Omega^2$$

- **Disk evolution.** 1+1D viscous evolution, photoevaporation, irradiation

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[3r^{1/2}\frac{\partial}{\partial r}\left(r^{1/2}\nu\Sigma\right)\right] - \dot{\Sigma}_w(r) - \dot{\Sigma}_{\mathrm{pla}}(r)$$

Alibert, Mordasini, Benz 2004, Alibert et al. 2005, Fouchet et al. 2011, Mordasini et al. 2012, Dittkrist et al. 2014

Planetesimal-envelope interaction



Integrate planetesimal trajectory in gaseous envelope.
-penetrate to the core or
-deposit mass in the gaseous envelope
=> envelope enrichment / bulk composition.

Physical effects:

1) Gravity, gas drag

$$M_{\rm pl}\ddot{\mathbf{r}} = -\frac{GmM_{\rm pl}}{r^2}\cdot\frac{\mathbf{r}}{r} - \frac{1}{2}C_D\rho\,\dot{r}^2\frac{\dot{\mathbf{r}}}{\dot{r}}\pi R_{\rm pl}^2$$

2) thermal ablation

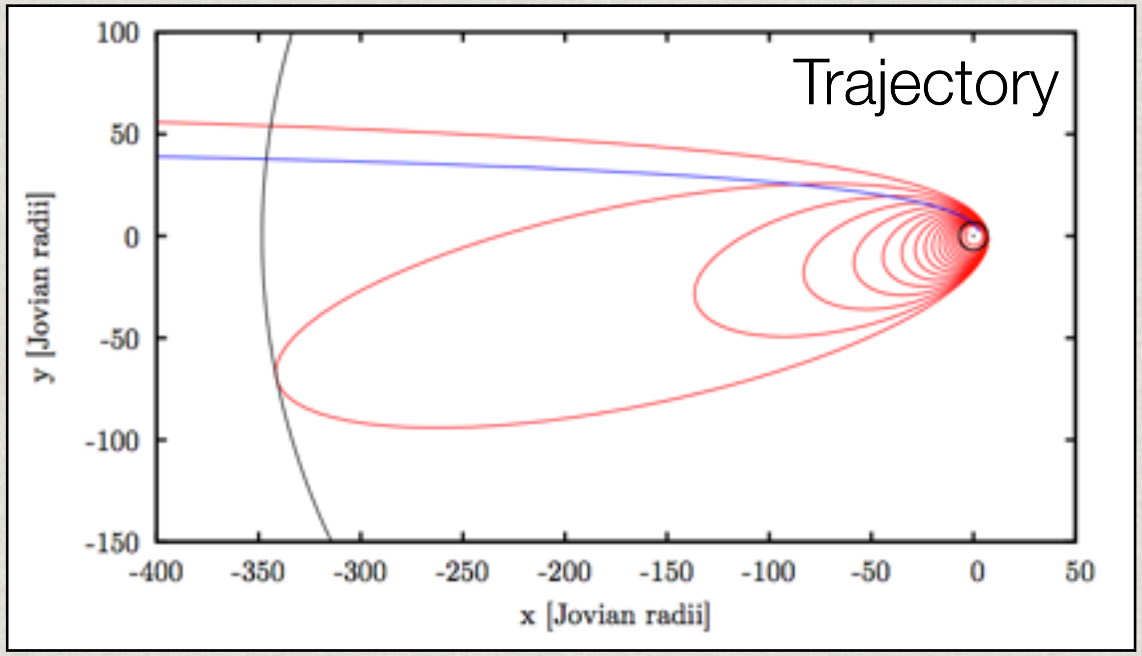
$$\frac{dM_{\rm pl}}{dt} = -C_H\sigma T_{\rm shock}^4\pi R_{\rm pl}^2/Q_{\rm abl}$$

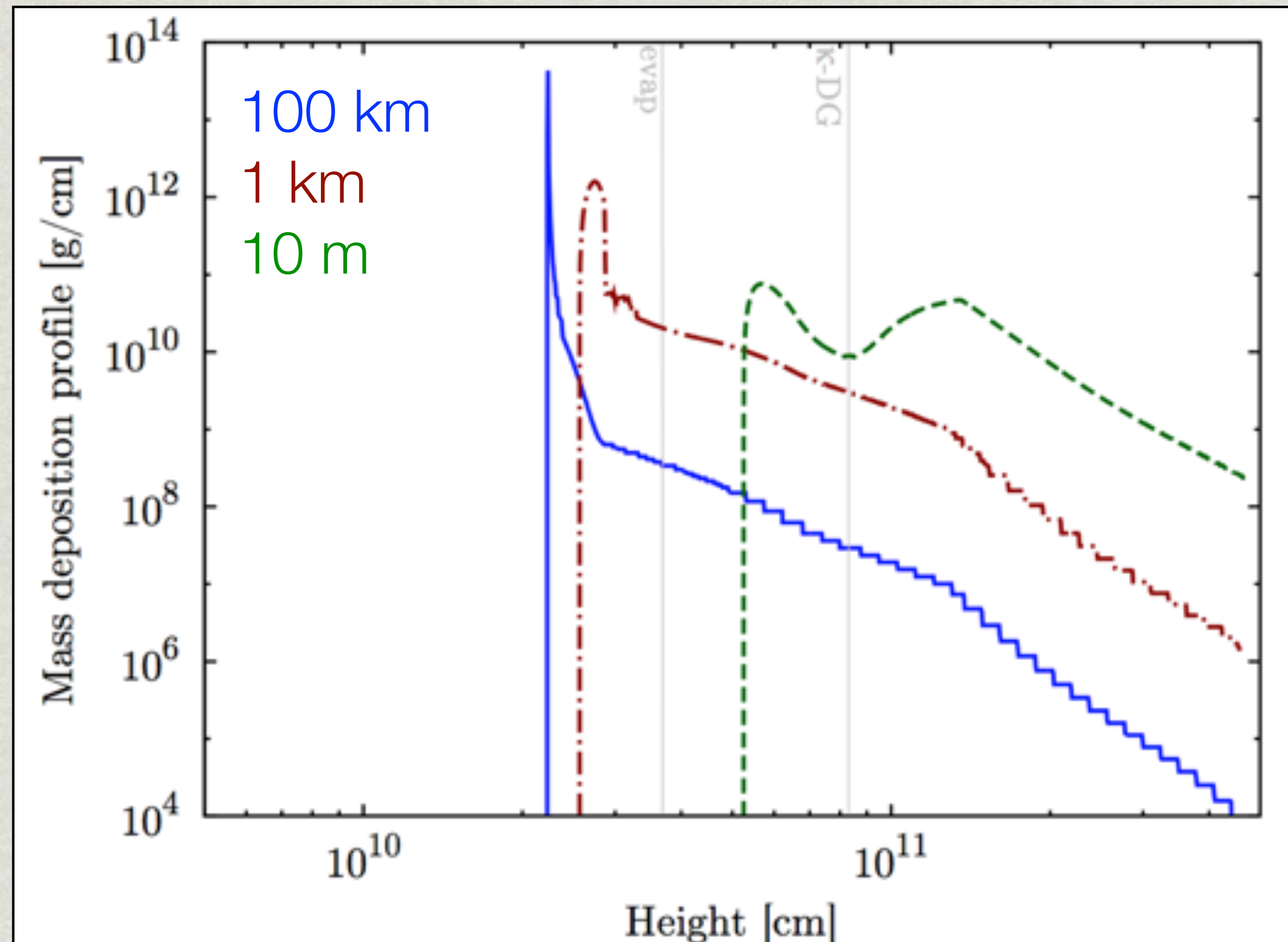
4) aerodynamic disruption

$$\frac{d^2R_{\rm pl}}{dt^2} = \frac{3}{4}\frac{\rho}{\rho_{\rm b}}\frac{\dot{r}^2}{R_{\rm pl}}$$

Mordasini, Alibert, Benz 2005, Mordasini et al. 2014, cf. Podolak et al. 1986, Zahnle 1992

Envelope enrichment





Radial mass deposition profile

Fortney, Mordasini et al. 2013, Mordasini 2014

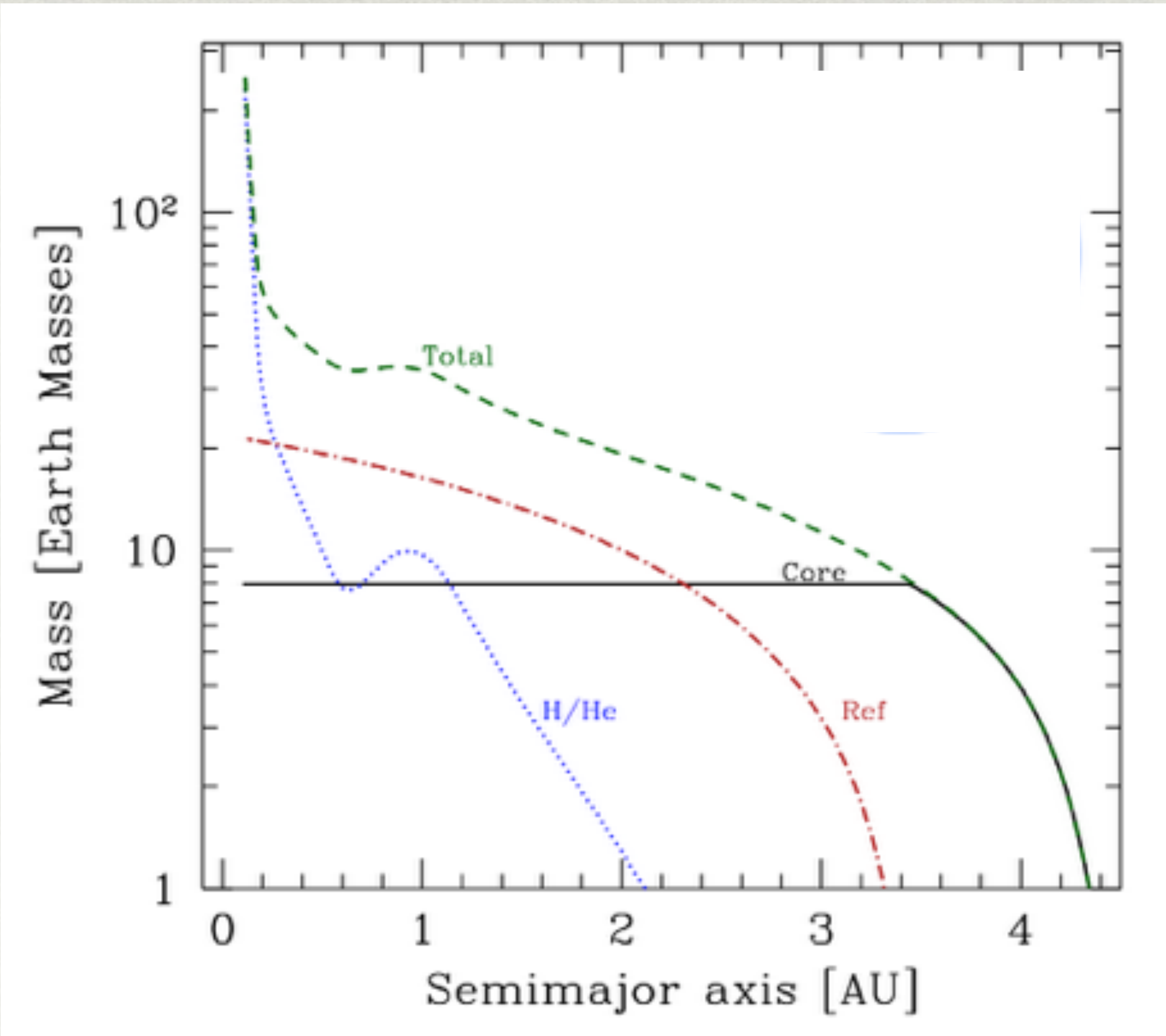
Two specific cases

Simulate the formation & evolution of two close-in extrasolar giant planets with different initial conditions and formation tracks

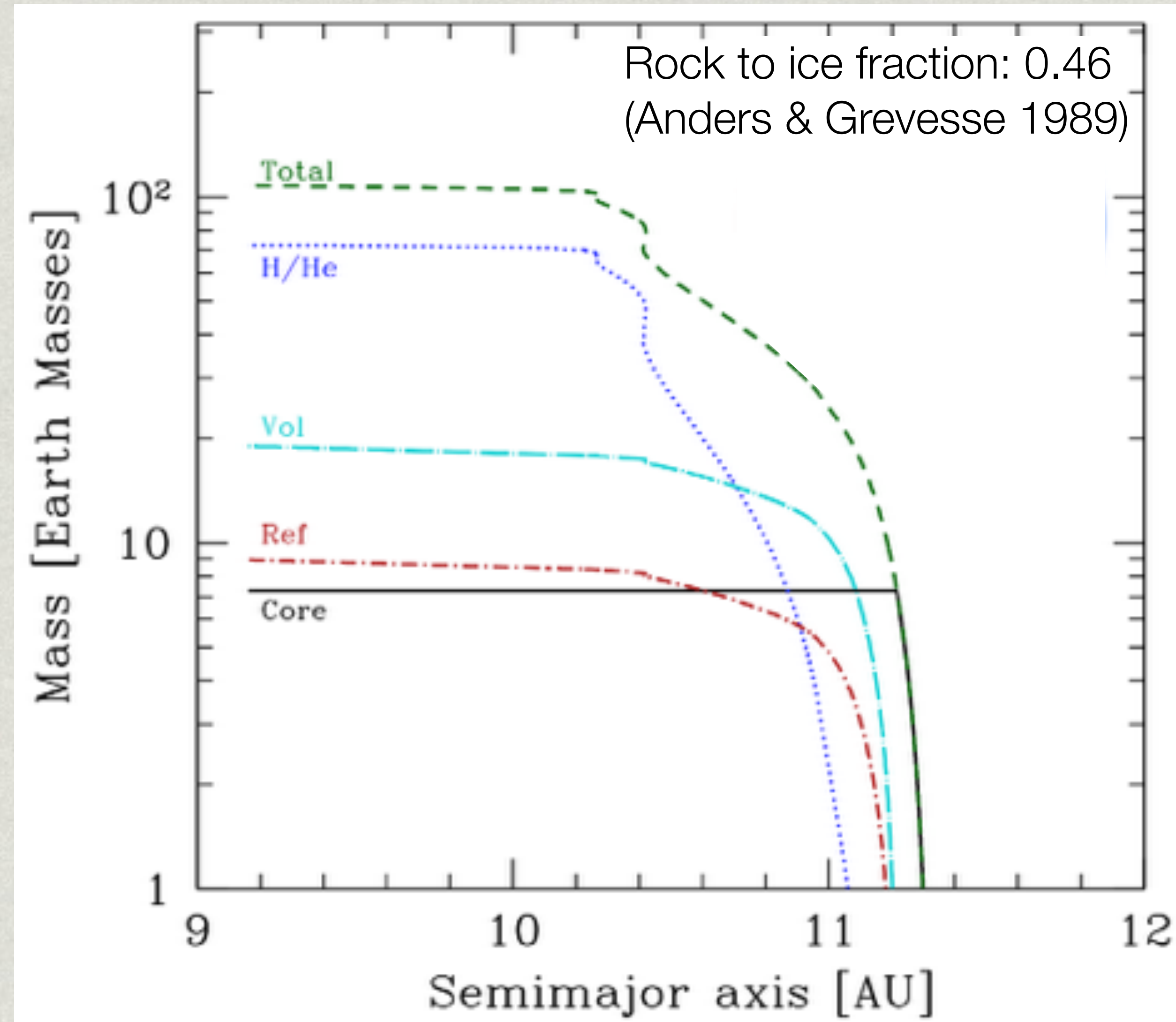
Simulation	"Wet Saturn"	"Dry Jupiter"
Initial disk mass [MMSN]	~6x	~7x
Water iceline [AU]	6.2	6.9
Disk [M/H]	-0.4	0
Starting position embryo [AU]	11.3	4.4
Position at end of disk lifetime[AU]	9.1	inner edge of disk
Accretes only	outside of water iceline	inside of water iceline
Mass at end of disk life [M	108	261
Position for evolution [AU]	0.04	0.04

1 planet per disk model

Formation phase



Dry Jupiter



Wet Saturn

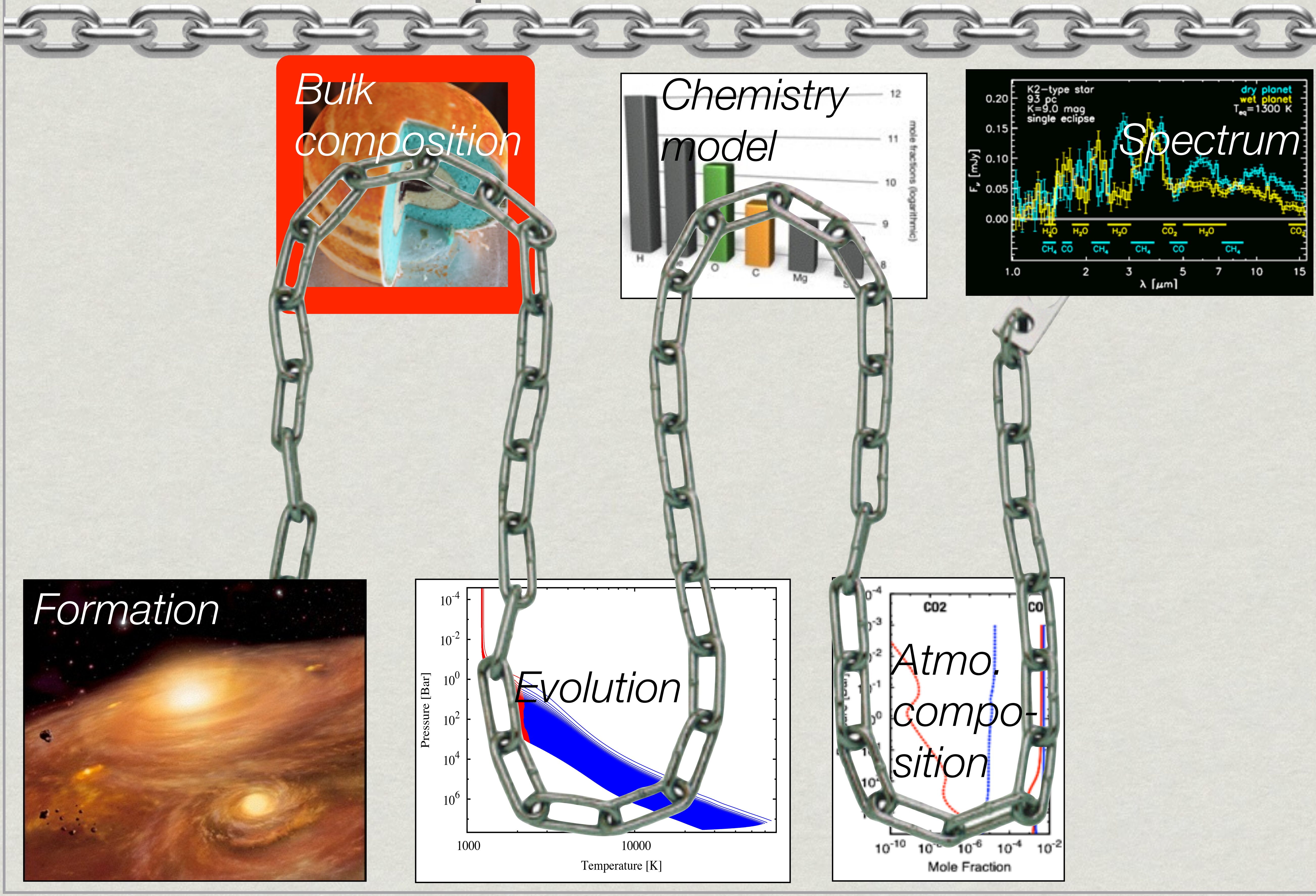
Disk migration to inner disk edge during disk lifetime.

Assumption: accreted gas volatile free (might not true if disk midplane MRI dead)

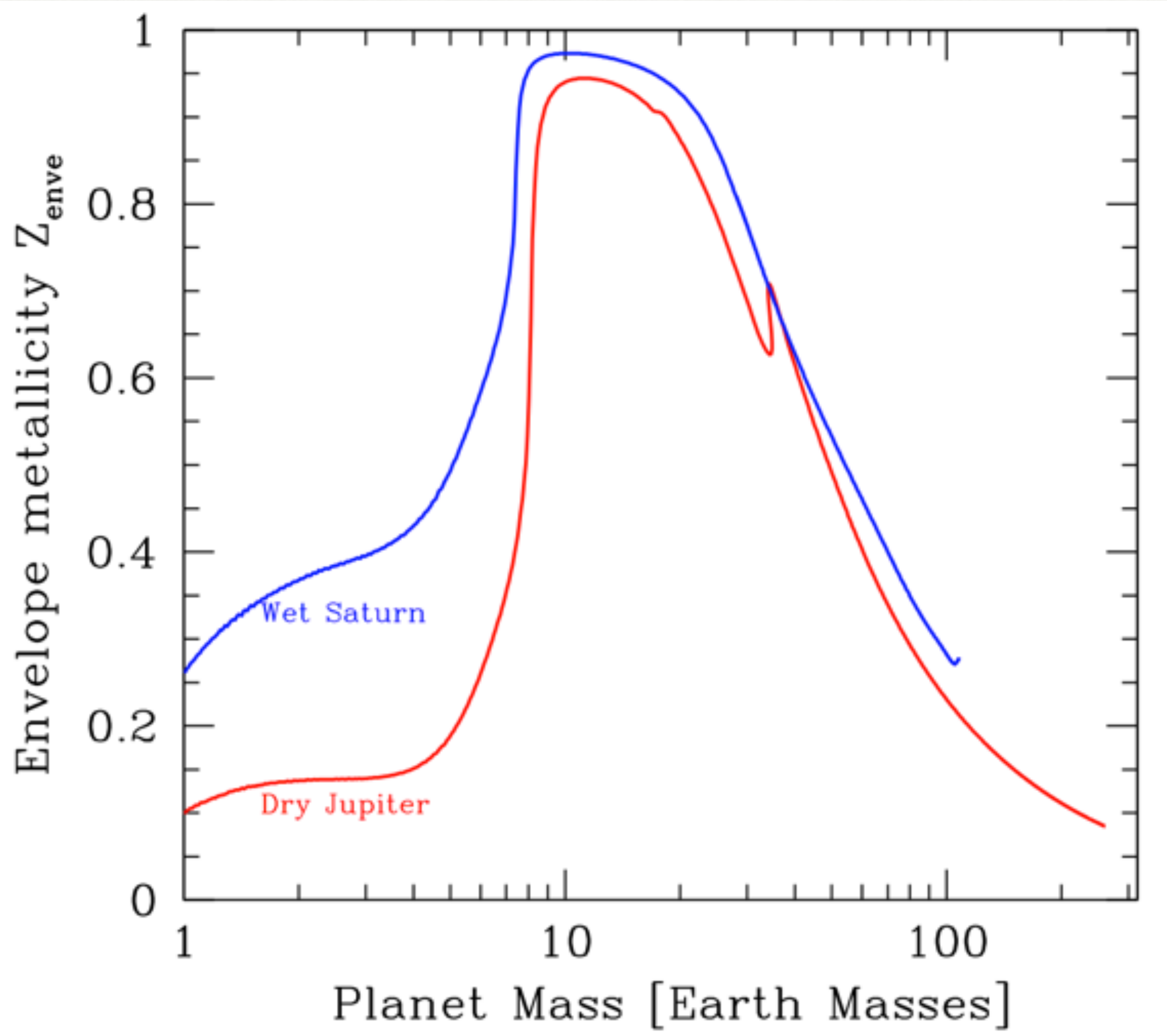
Scattering/Kozai migration to 0.04 AU after disk dissipation.

Assumption: no accretion during this process

2. Bulk composition



Envelope enrichment by impacts



100 km planetesimals.
Accreted gas: pure H/He

Final Z_{enve}:

"Dry Jupiter": 0.09
"Wet Saturn": 0.28

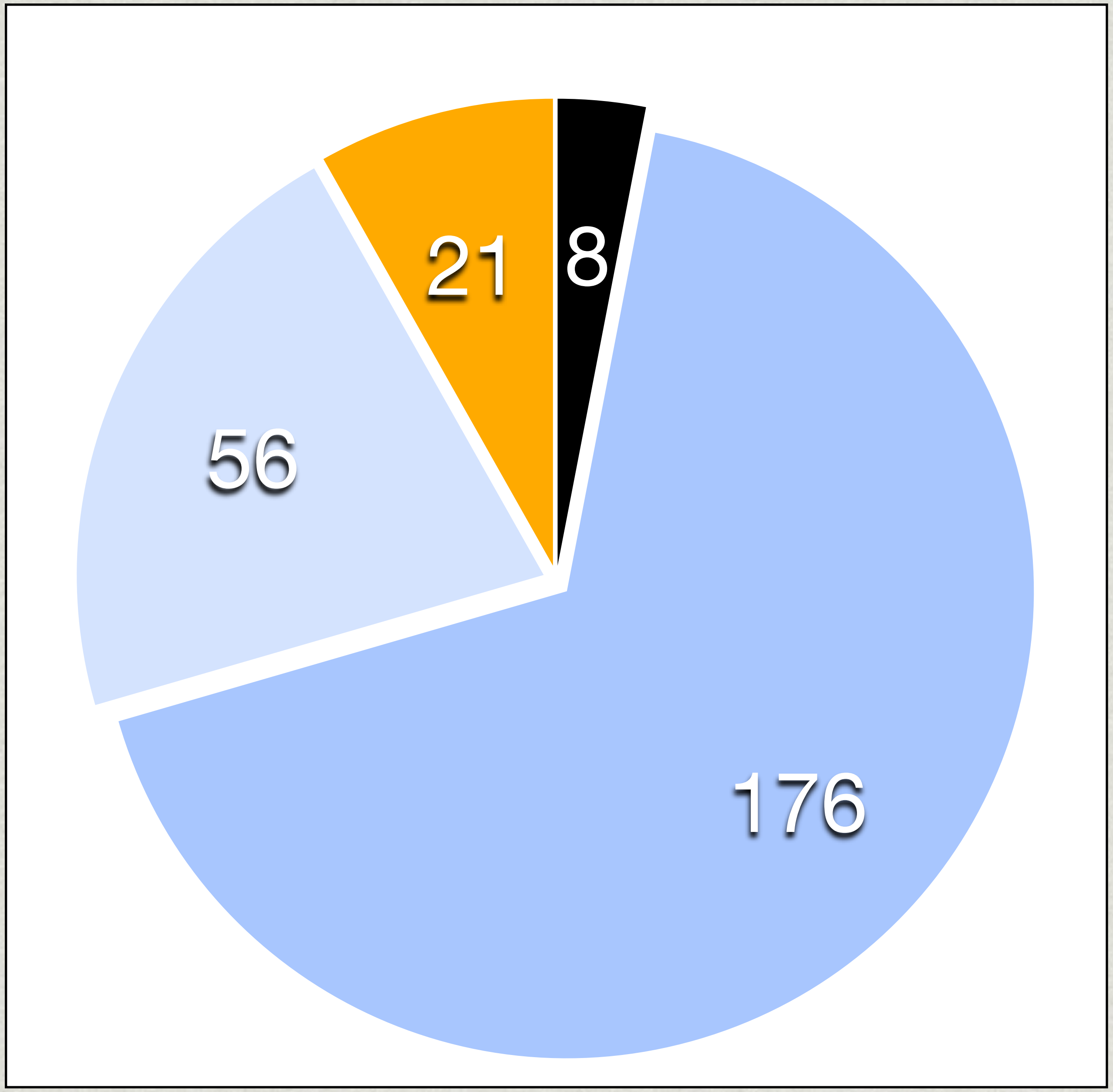
Dominant over contribution from gas!

Low-high-low. Icy planetesimals more fragile.

Compositional gradients?
Semiconvection?

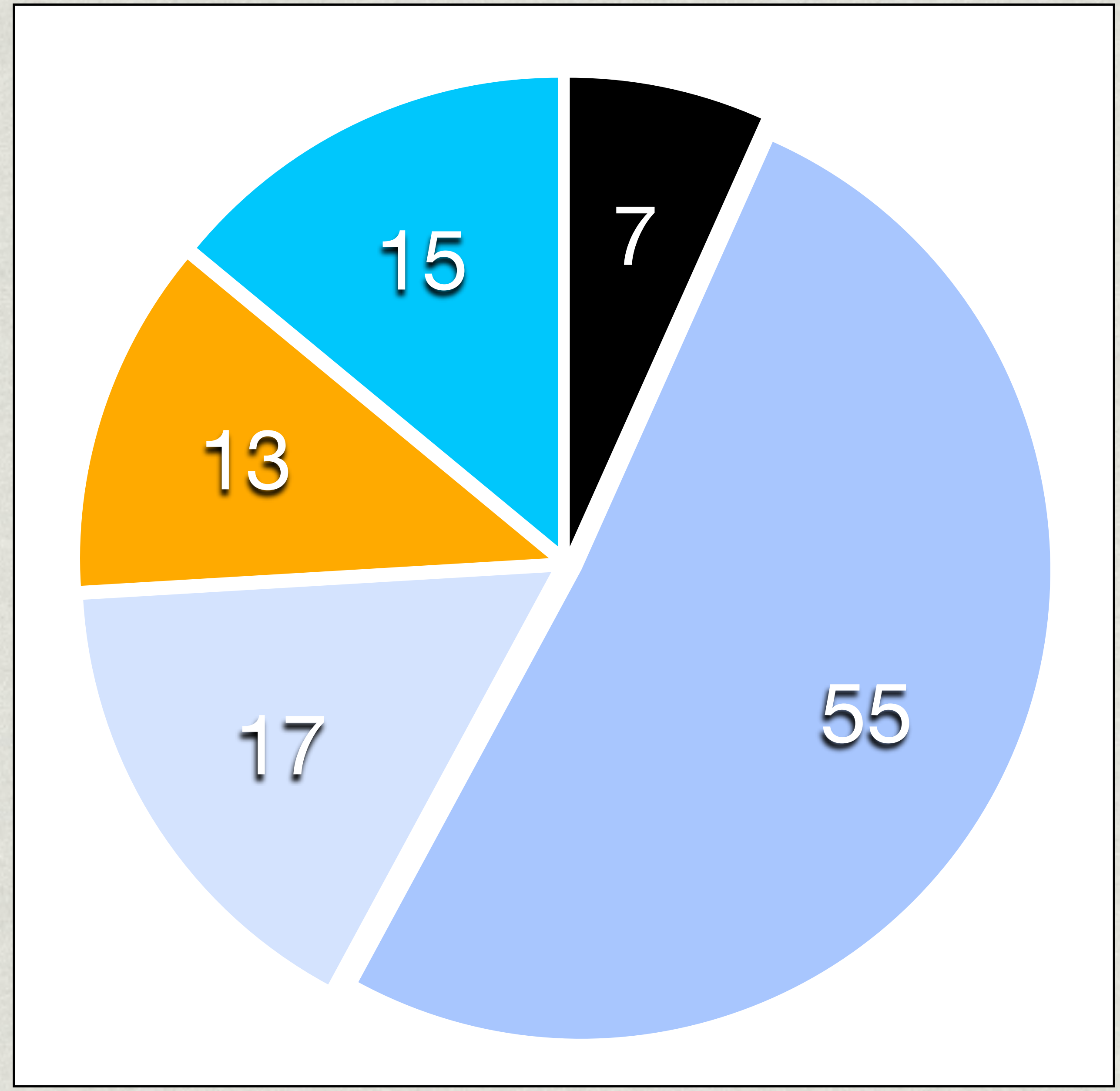
Final bulk composition

Dry Jupiter



Wet Saturn

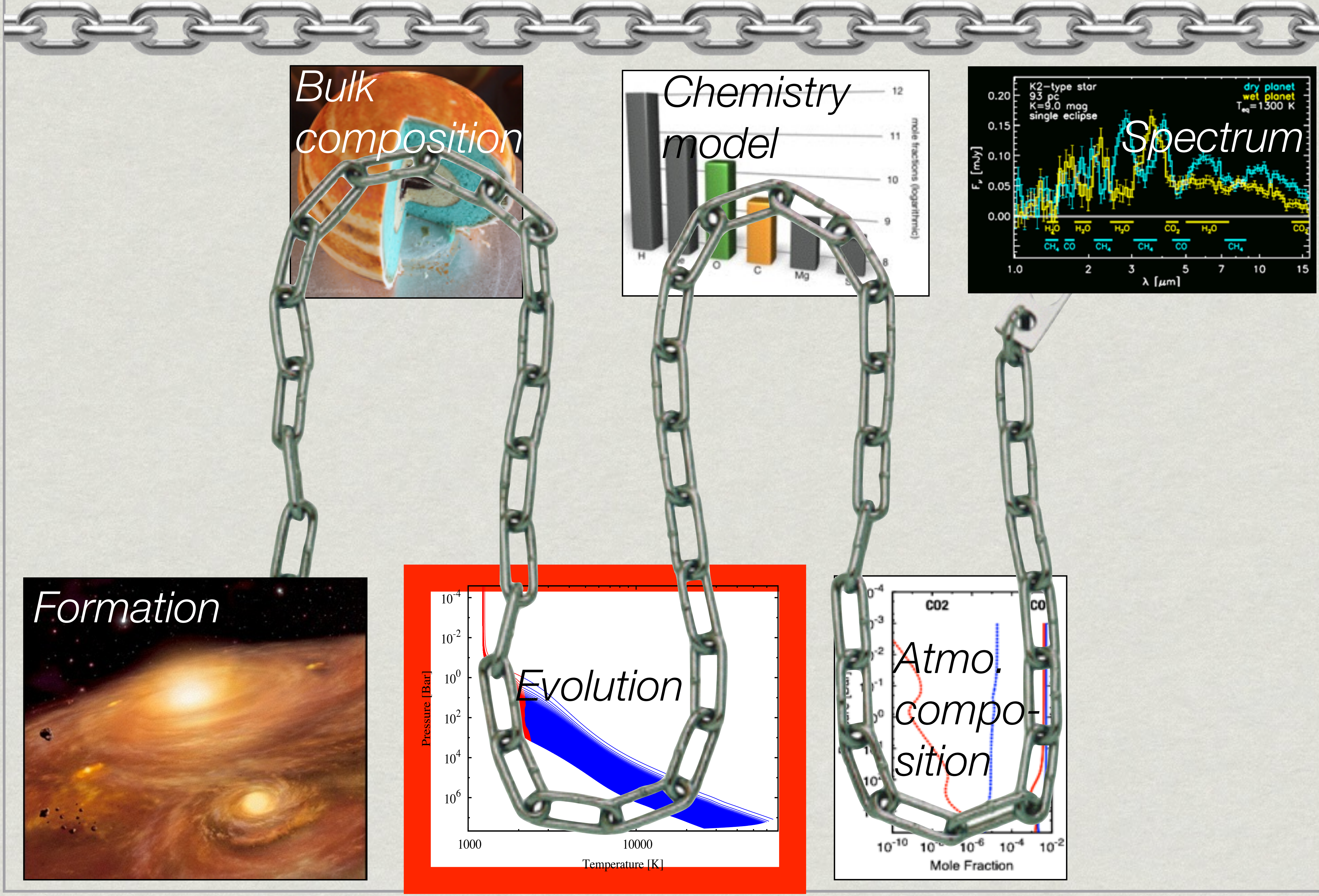
Rock to ice fraction:
solar=0.46 (Lodders 2003)



Mass/M_{Earth}: Solid core, Hydrogen, Helium, Refractories, Volatiles

The envelope of the "wet Saturn" is more enriched since a) more solids further away from the star (larger feeding zone) b) lower H/He mass c) icy planetesimal more fragile

3. Evolution



Bulk composition
Chemistry model
Spectrum
K2-type star
93 pc
K=9.0 mag
single eclipse
dry planet
wet planet
λ [μm]
Formation
Evolution
Pressure [Bar]
Temperature [K]
Atmo. compo-sition
Mole Fraction

Evolution model

- **Interior structure.** 1D structure equations. Fully convective interiors.

$$\frac{\partial m}{\partial r} = 4\pi r^2 \rho \qquad \frac{\partial P}{\partial r} = -\frac{Gm}{r^2}\rho \qquad \frac{\partial T}{\partial r} = \frac{T}{P}\frac{\partial P}{\partial r}\nabla(T,P)$$

- **Atmosphere.** Simple 1D semi-gray model for strongly irrad. planets (Guillot 2010)

$$T^4 = \frac{3T_{\rm int}^4}{4}\left(\frac{2}{3}+\tau\right) + \frac{3T_{\rm equi}^4}{4}\left(\frac{2}{3}+\frac{2}{3\gamma}\left[1+\left(\frac{\gamma\tau}{2}-1\right)e^{-\gamma\tau}\right]+\frac{2\gamma}{3}\left(1-\frac{\tau^2}{2}\right)E_2(\gamma\tau)\right)$$

- **Atmospheric escape.** X-ray and EUV driven.

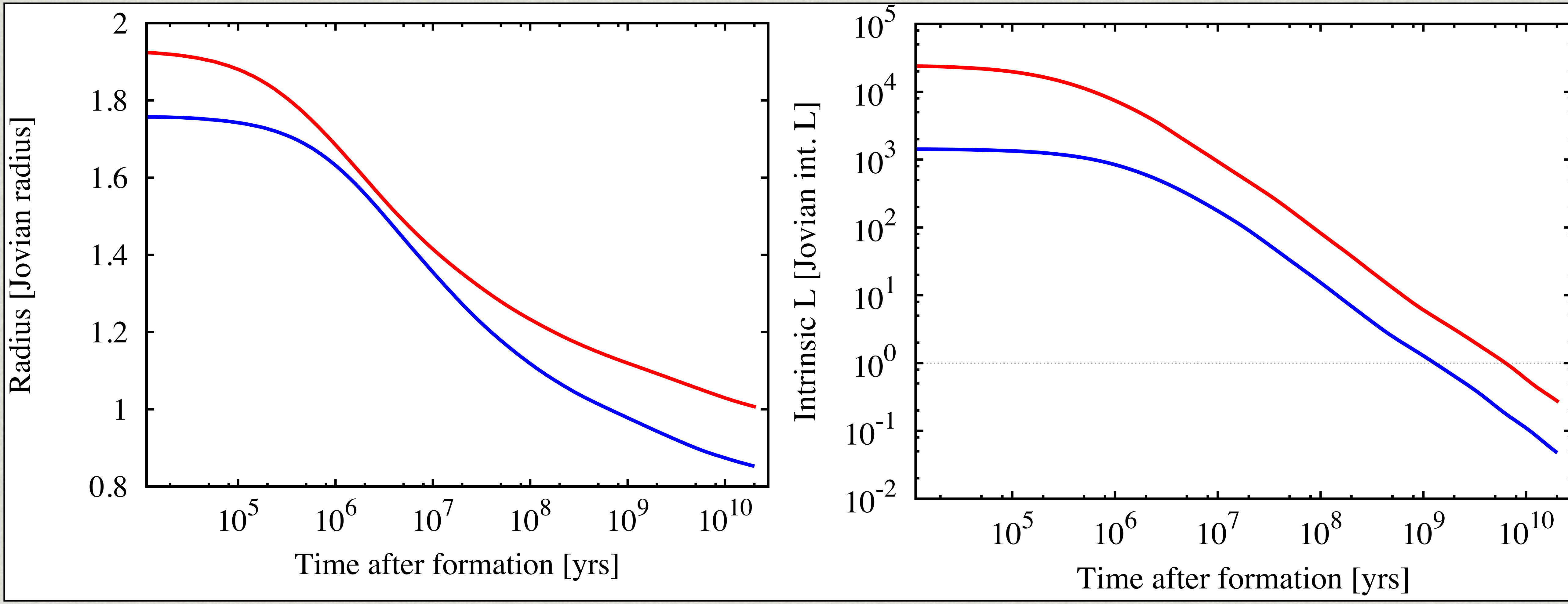
$$\frac{dM_{\rm rr-lim}}{dt} = 4\pi\rho_{\rm s}c_{\rm s}r_{\rm s}^2 \qquad \frac{dM_{\rm e-lim}}{dt} = \frac{\epsilon_{\rm UV}\pi F_{\rm UV}R_{\rm UV}^3}{GMK_{\rm tide}}$$

Note: opacity takes global enrichment level into account, but not elemental composition. EoS neither self-consistent.

Mordasini et al. 2012, Jin, Mordasini et al. 2014, Guillot 2010, Freedman et al. 2008, Murray-Clay et al. 2009, Owen & Jackson 2012

Evolution: cooling & contraction

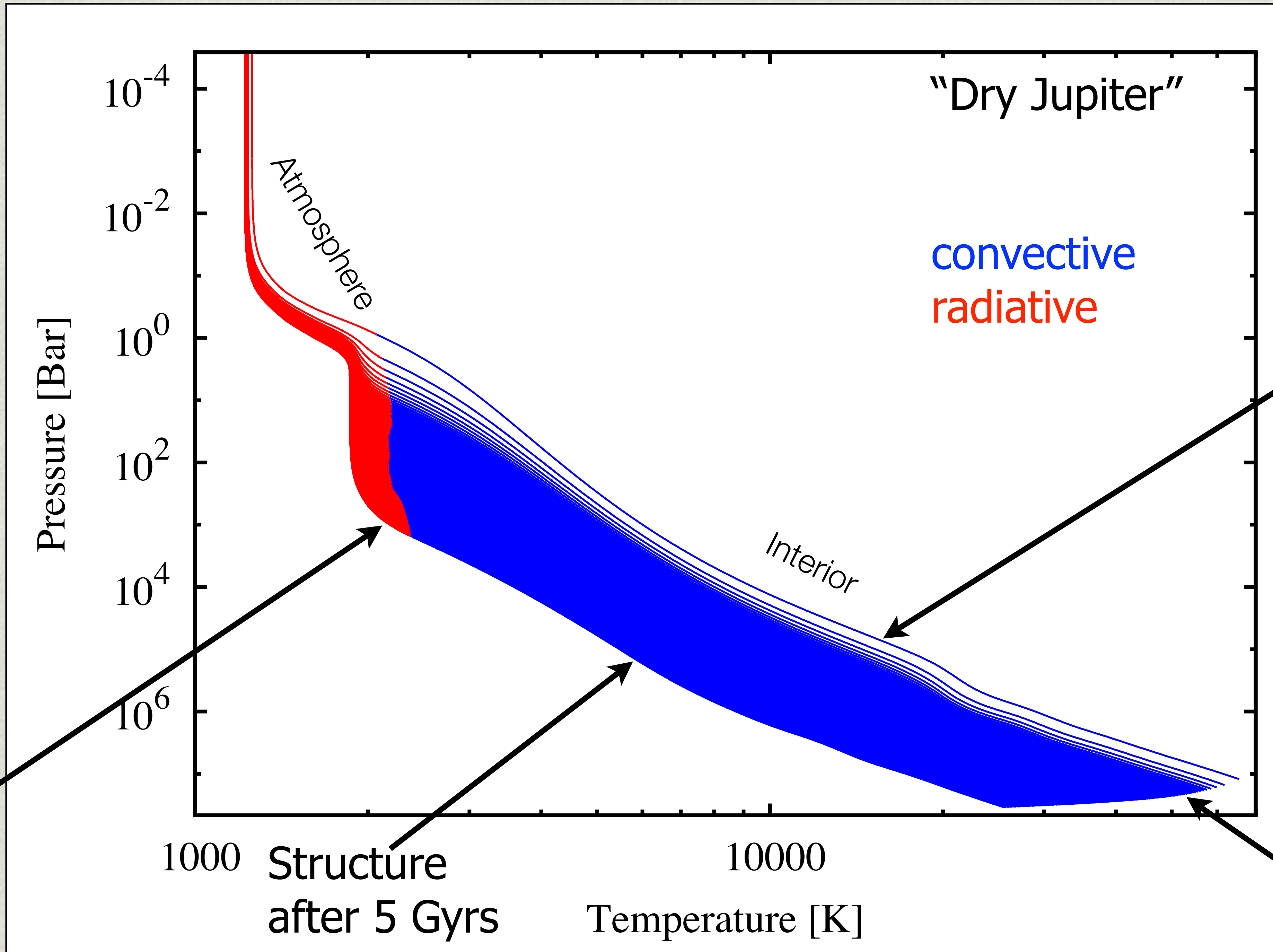
Evolve planets at 0.04 AU over Gyr timescales.



dry Jupiter
wet Saturn

Self-consistent coupling with formation phase: not only mass, but also opacity (approximately) and thermodynamic state (entropy).

Evolution: p-T structure



First structure immediately after end of formation

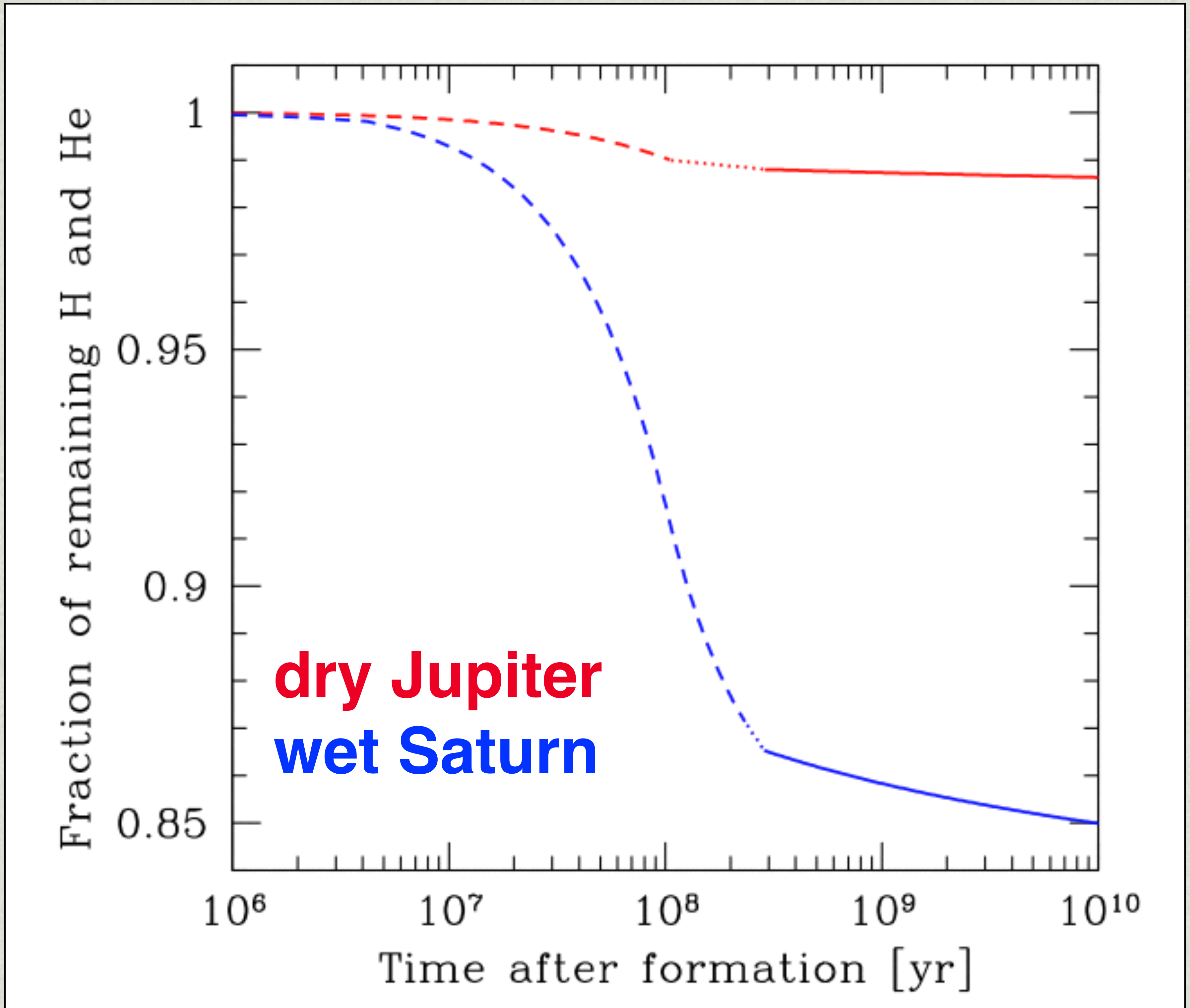
Deep radiative zone.

Core-envelope boundary

Interior cools, atmosphere "fixed" by stellar irradiation (no stellar evolution).

cf. Guillot & Showman 2002

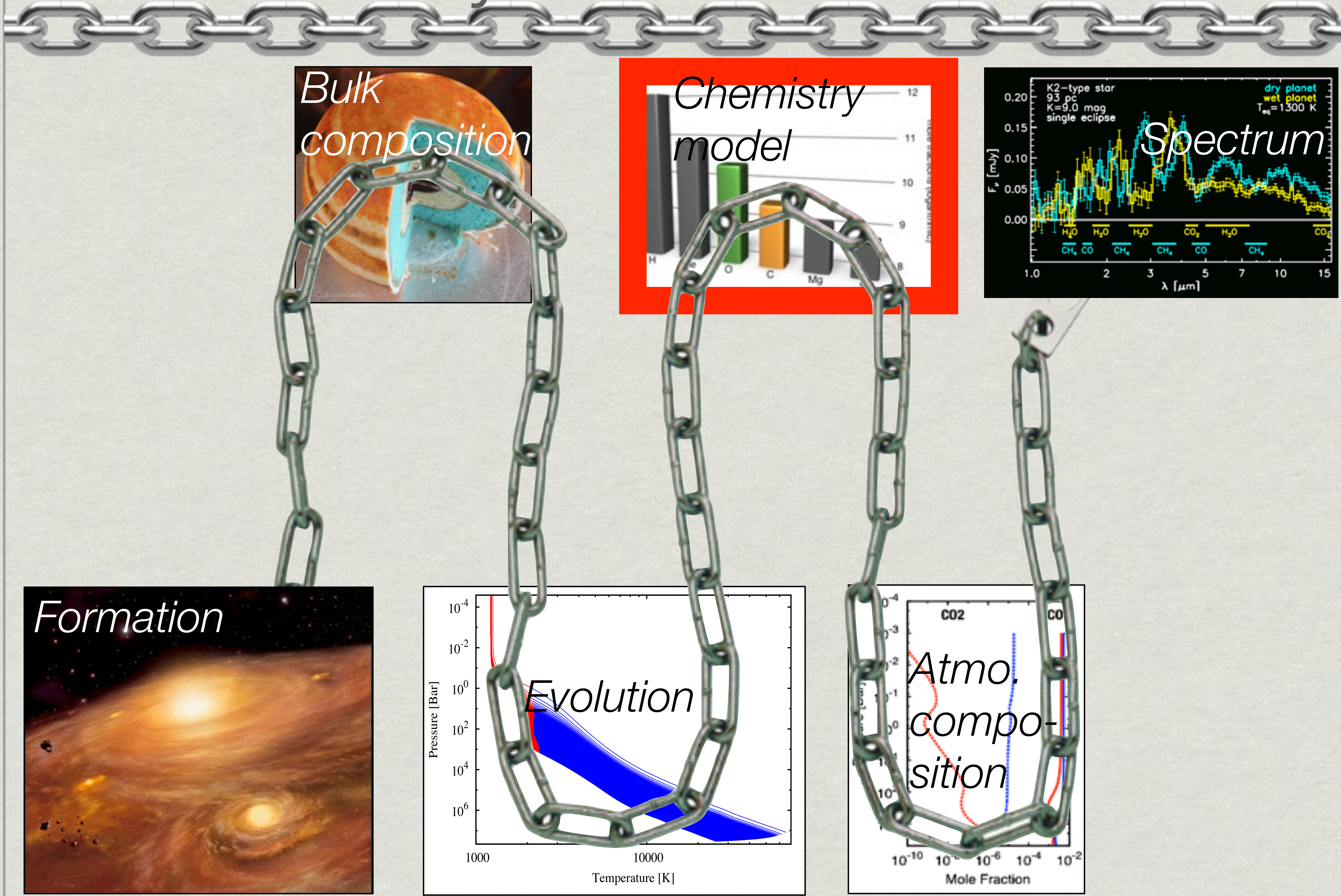
Evolution: envelope evaporation



-X-ray driven (dashed)
-UV driven, radiation-recombination limited (dotted)
-UV driven,energy limited (solid)

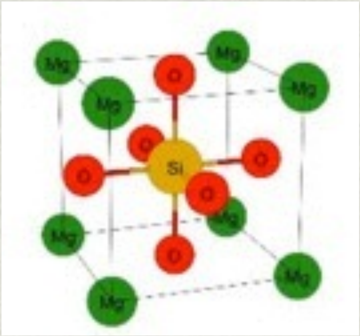
For these relatively massive planets at 0.04 AU, escape is not very important (loose only ~1 and ~15% of H/He)

4. Chemistry model



Chemistry model

Specify what “refractory” or “ice” is chemically.



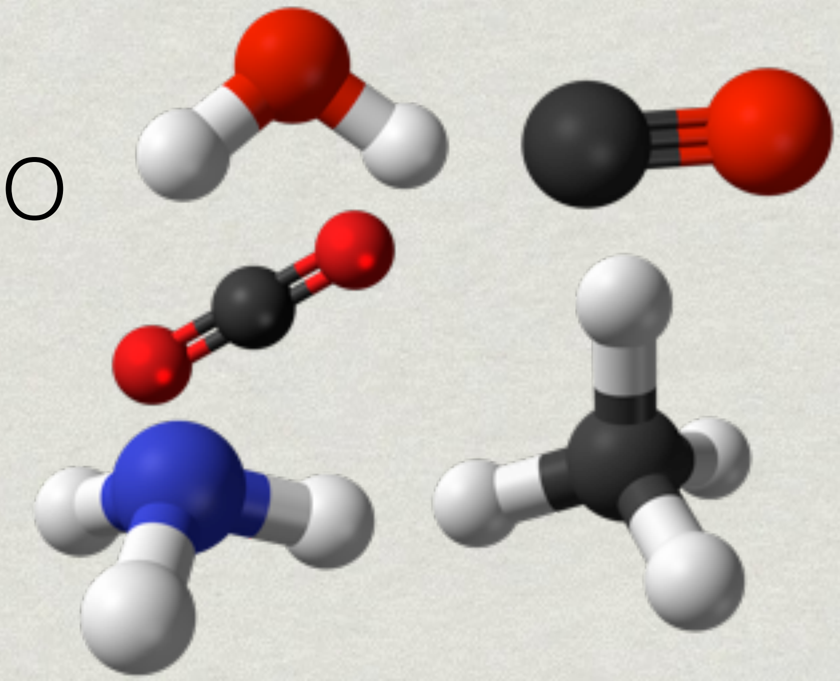
Refractories:

33 wt% Iron Fe

44 wt% Silicate Perovskite $MgSiO_3$

22 wt% Carbon C

From local ISM dust composition (Nuth et al. 1998).



Volatiles:

61 nb% Water H_2O

12 nb% Carbon monoxide CO

19 nb% Carbon dioxide CO_2

2.4 nb% Methane CH_4

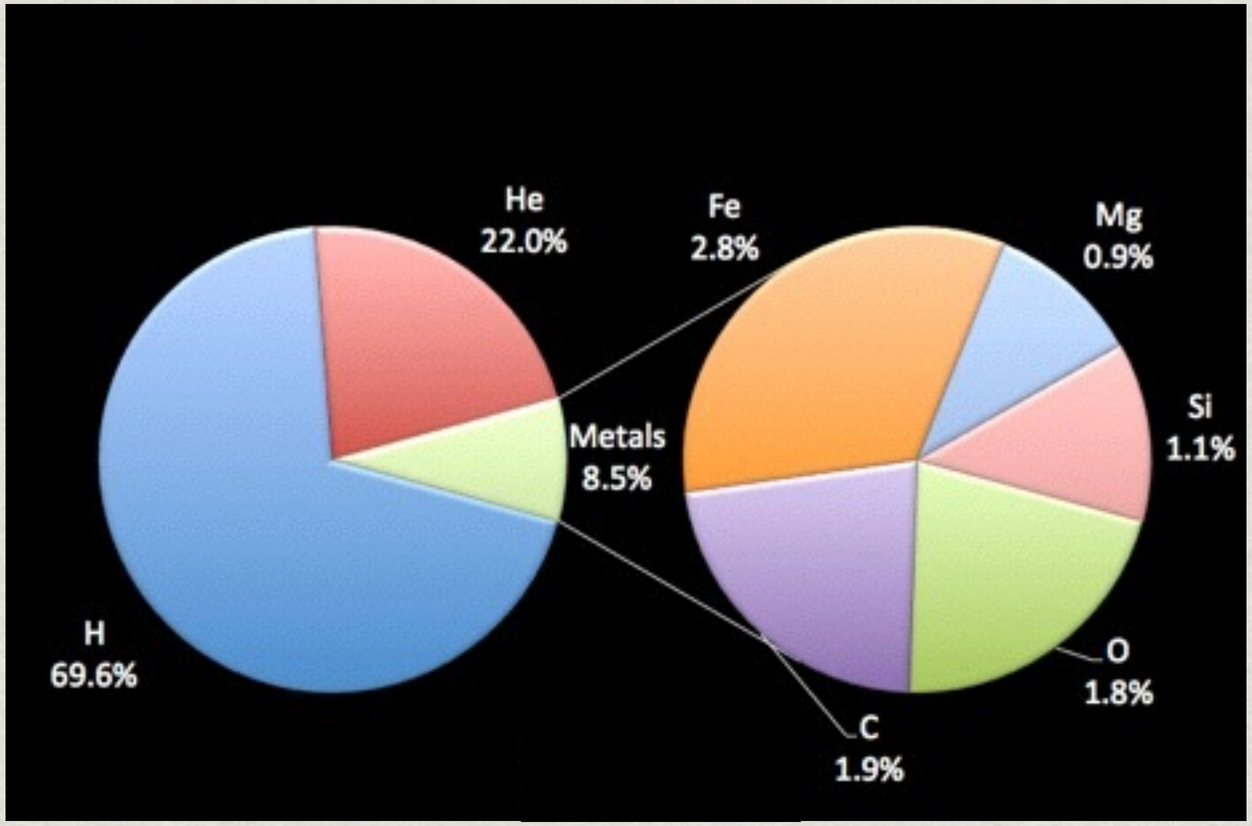
6.1 nb% Ammonia NH_3

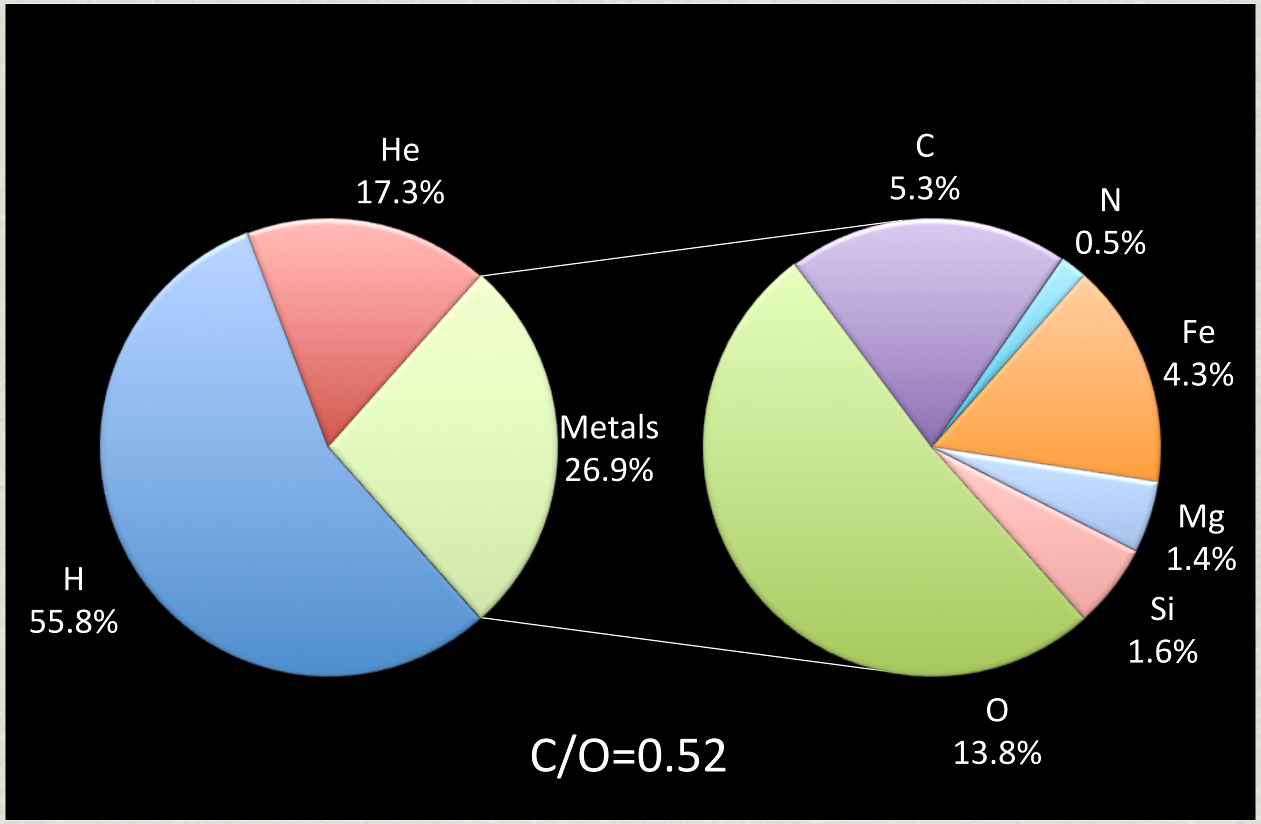
Derived from observed abundances in protoplanetary disks (Pontoppidan et al. 2005). Roughly similar values are also observed in comets (Bockelee-Morvan et al. 2004)

Assume uniform mixing of atmosphere and envelope (!). No temporal evolution (!). Heavy atoms might settle to the deep interior (Fortney et al. 2008, Spiegel et al. 2009)

Elemental composition

Mass % of H, He, O, C, Fe, Mg, Si, N in the gaseous envelope.





Dry Jupiter

Wet Saturn

C/O= 1.39

(by number. Solar=0.54)

C/O= 0.52

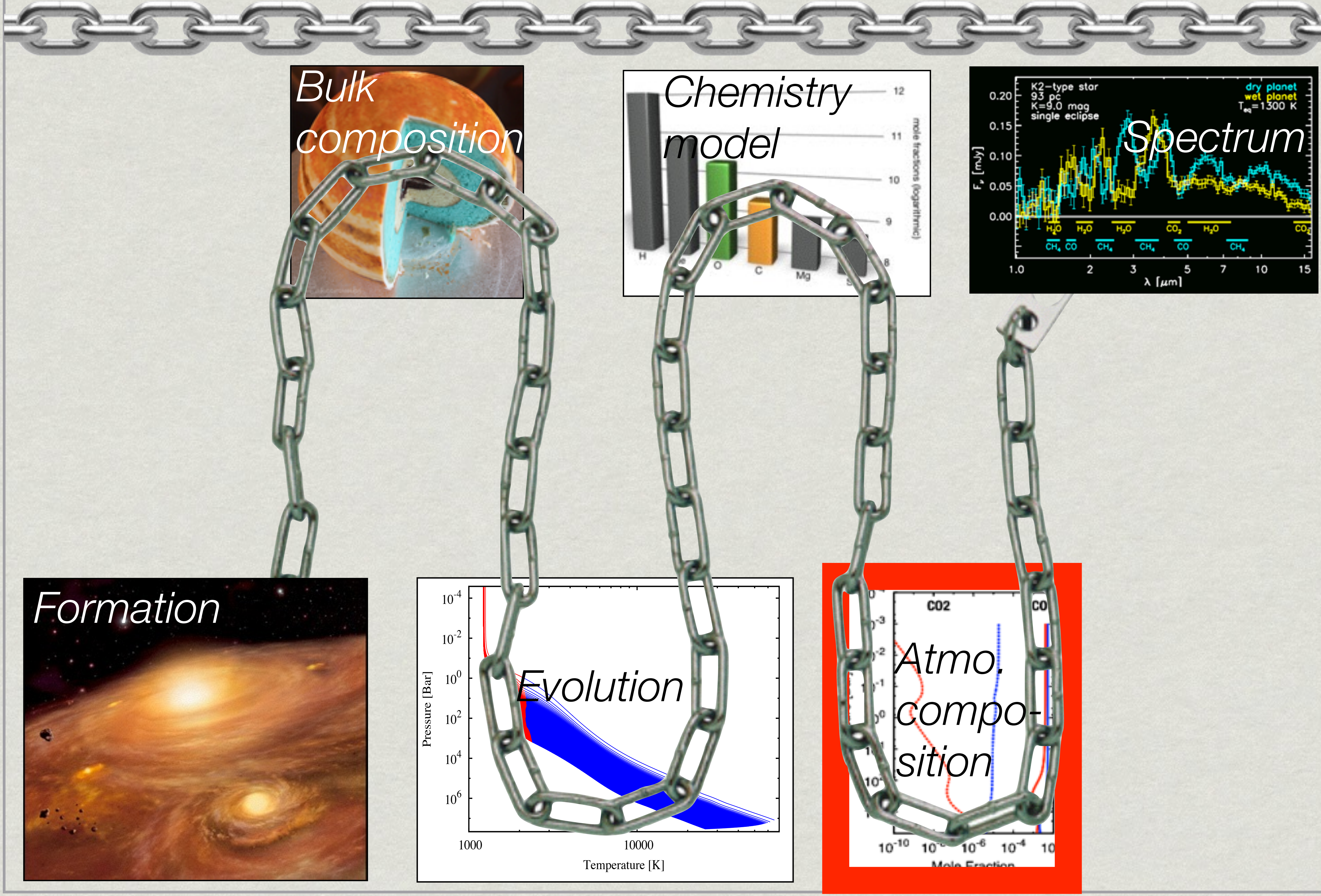
-EGPs formed inside water iceline: C-rich

-EGPs formed outside water iceline: O-rich

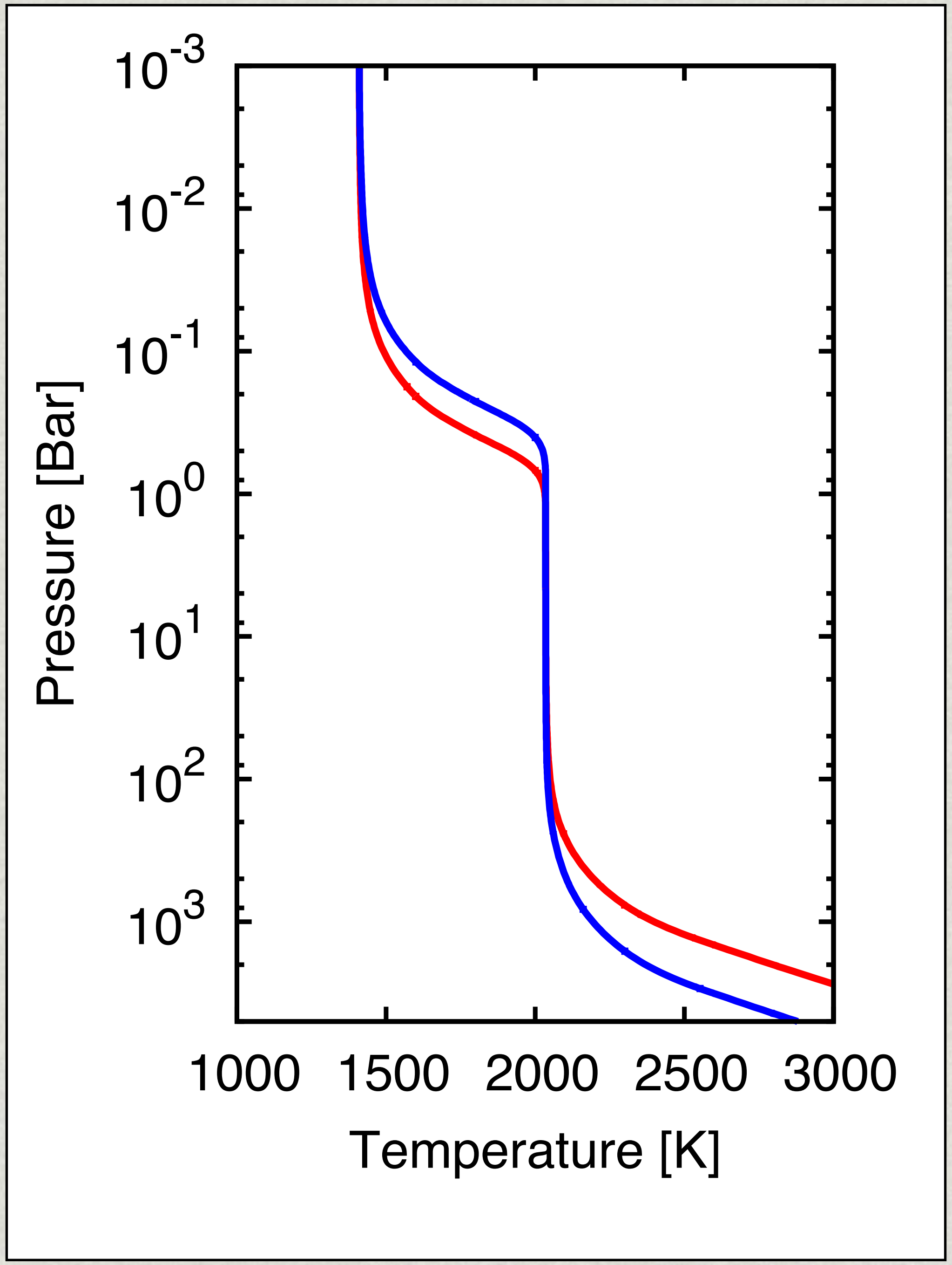
Different for very massive planets and other chemistry models

cf. Öberg et al. 2011, Ali Dip et al. 2014

5. Atmospheric composition



Atmospheric composition



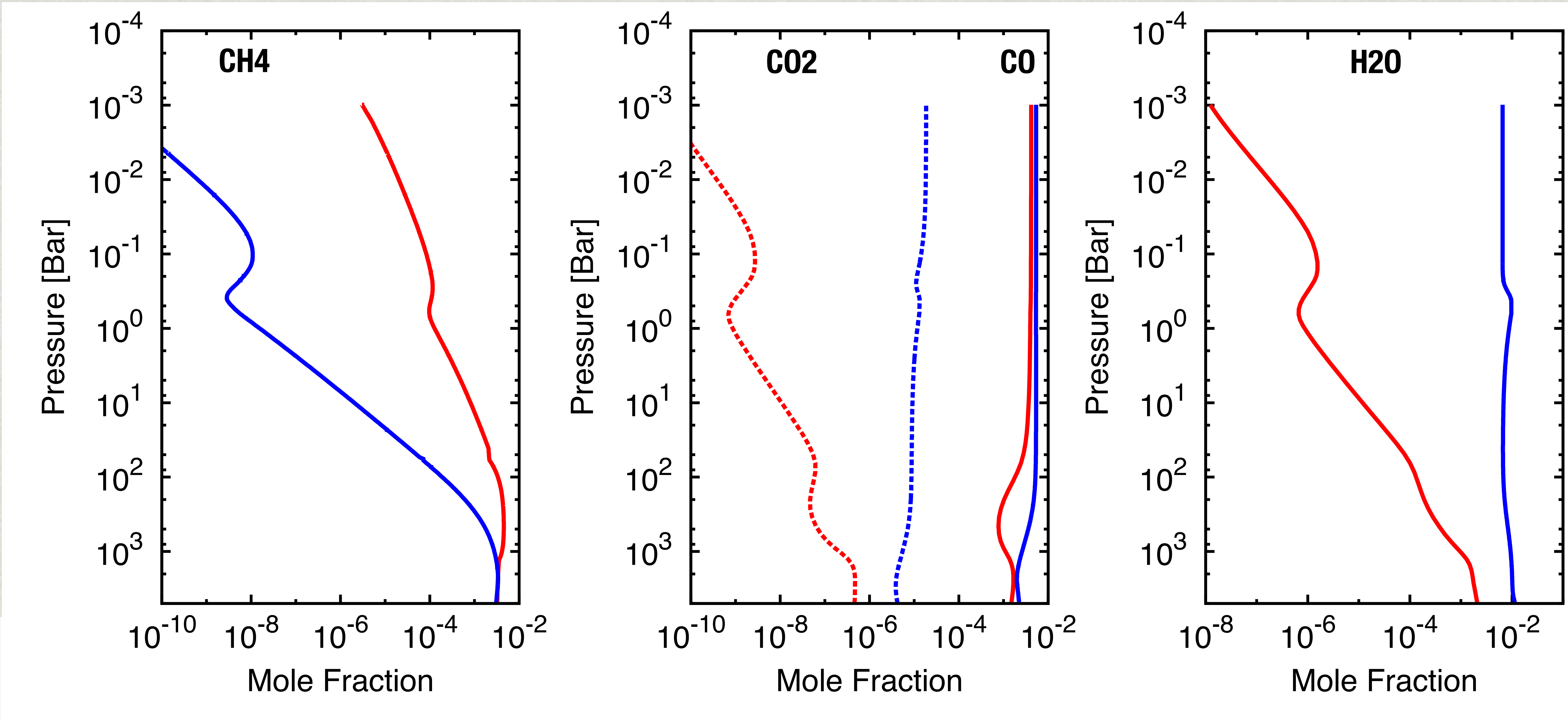
Use p-T structure at 5 Gyrs, and elemental abundances from formation to calculate molecular composition of atmosphere.

NASA code CEA (Gordon & McBride 1996): classical Gibbs minimization

Simplifications:
-LTE
-no photochemistry

Species:
H_2,He,H,CH_4,CO,H_2O,CO_2,C_2H_2,OH,O,HCHO,CH_3, ...

Molecular abundances



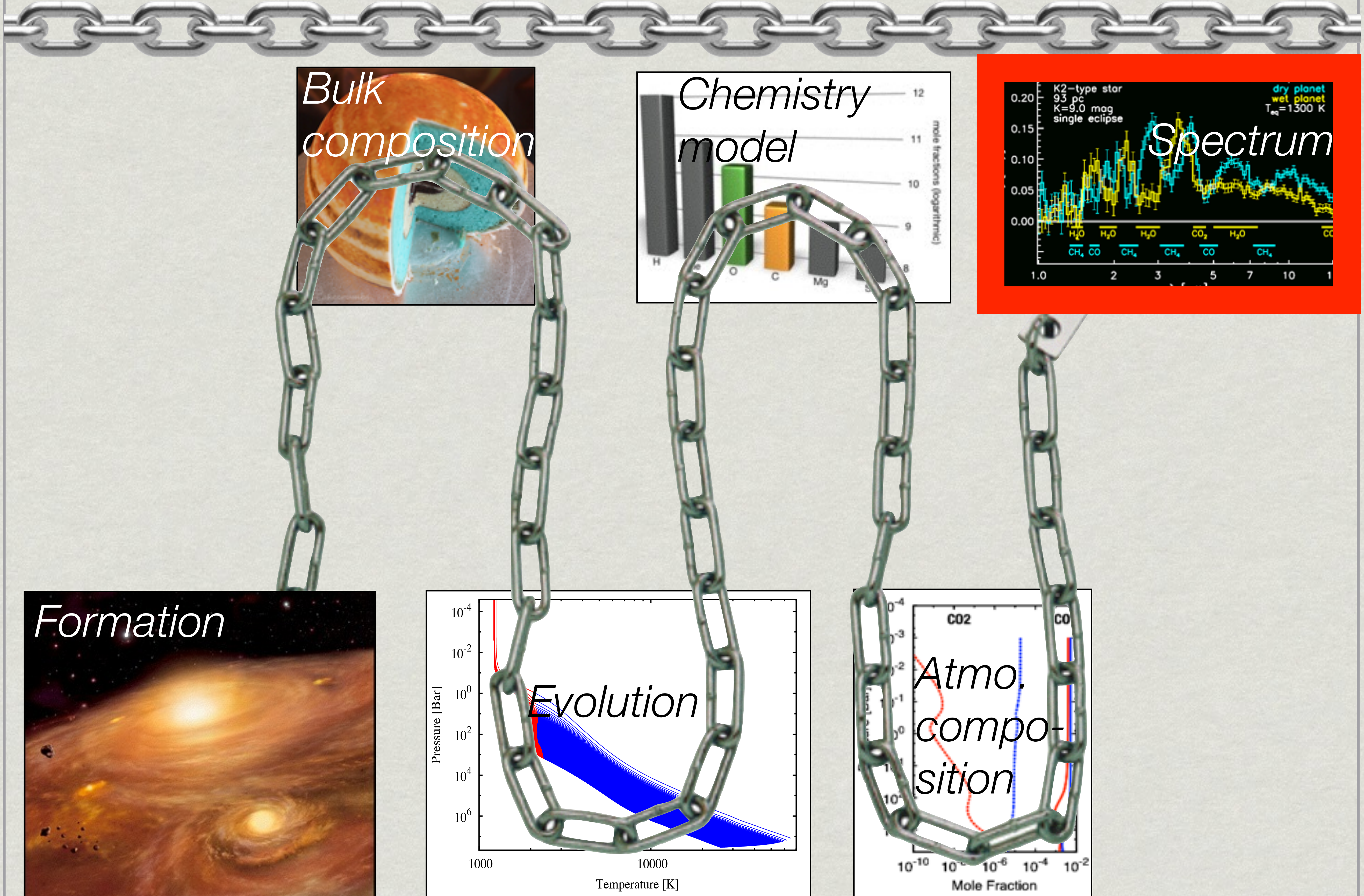
First form CO. Then either form H_2O (C/O<1) or CH_4 (C/O>1)

dry Jupiter : O only from silicates

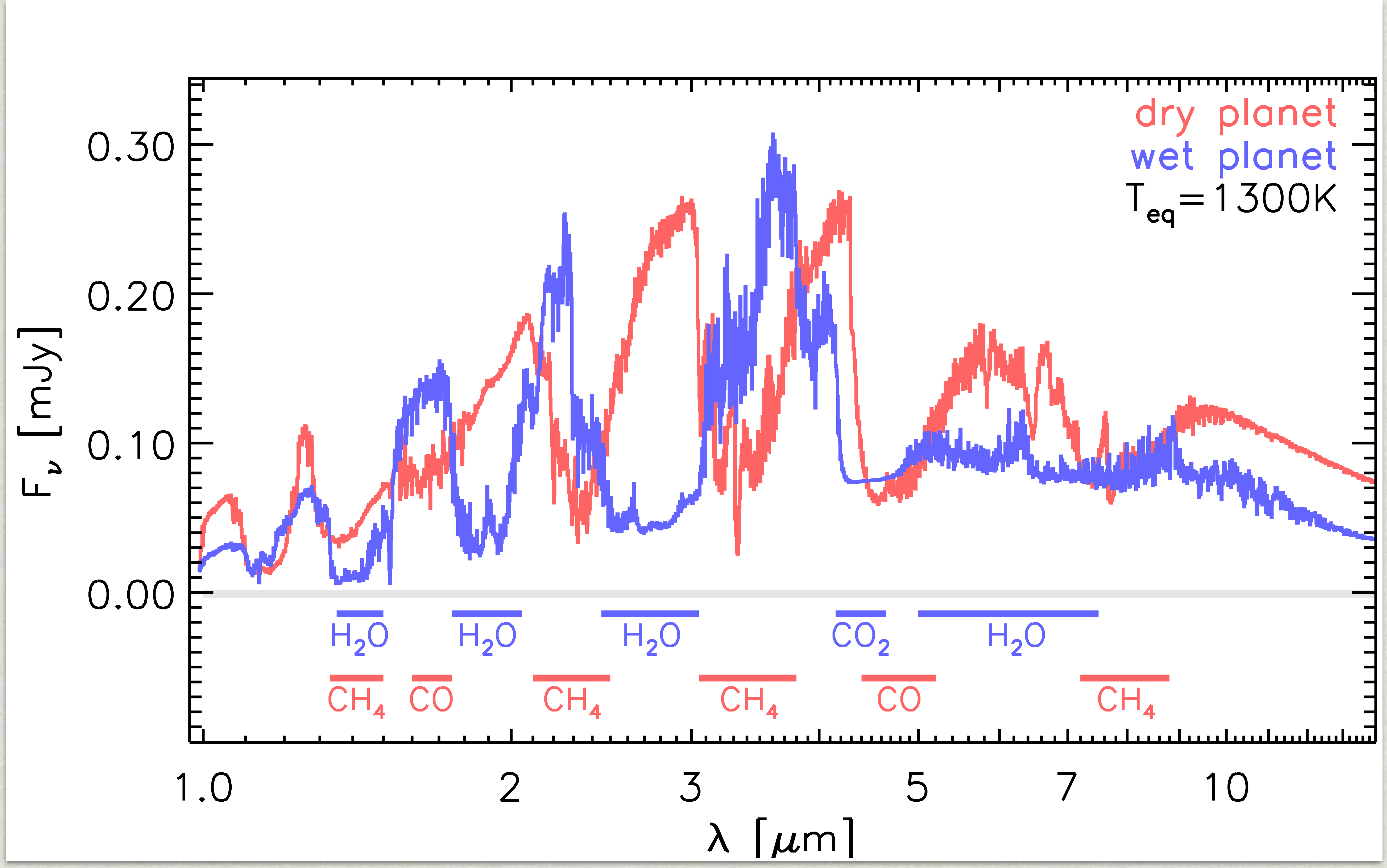
wet Saturn : O from water and silicates

difference of several orders of magnitude

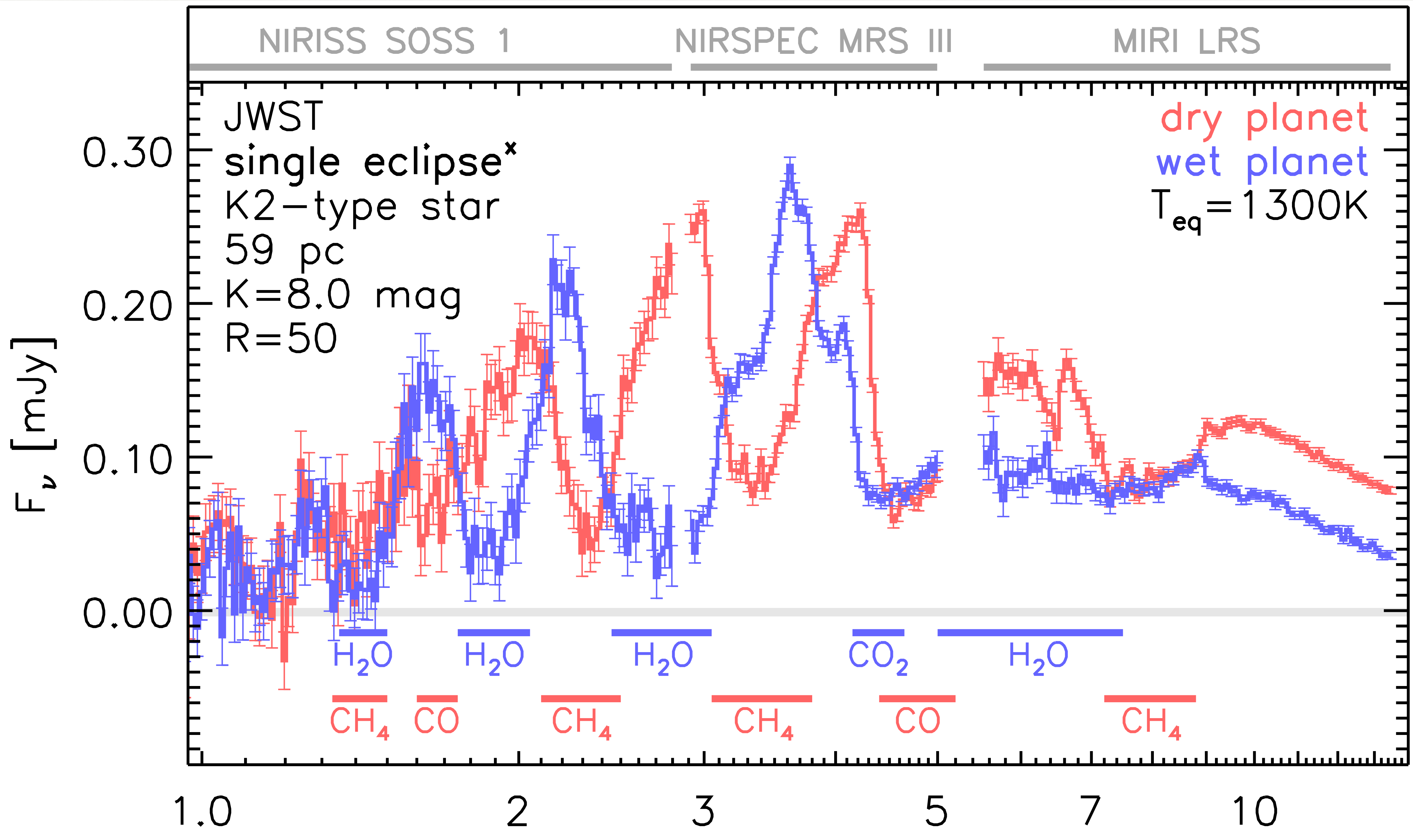
6. Spectrum


Bulk composition
Chemistry model
Spectrum
K2-type star
93 pc
K=9.0 mag
single eclipse
dry planet
wet planet
Formation
Evolution
Pressure [Bar]
Temperature [K]
Atmo. compo-sition
Mole Fraction

Model Spectra



Simulated JWST Spectra



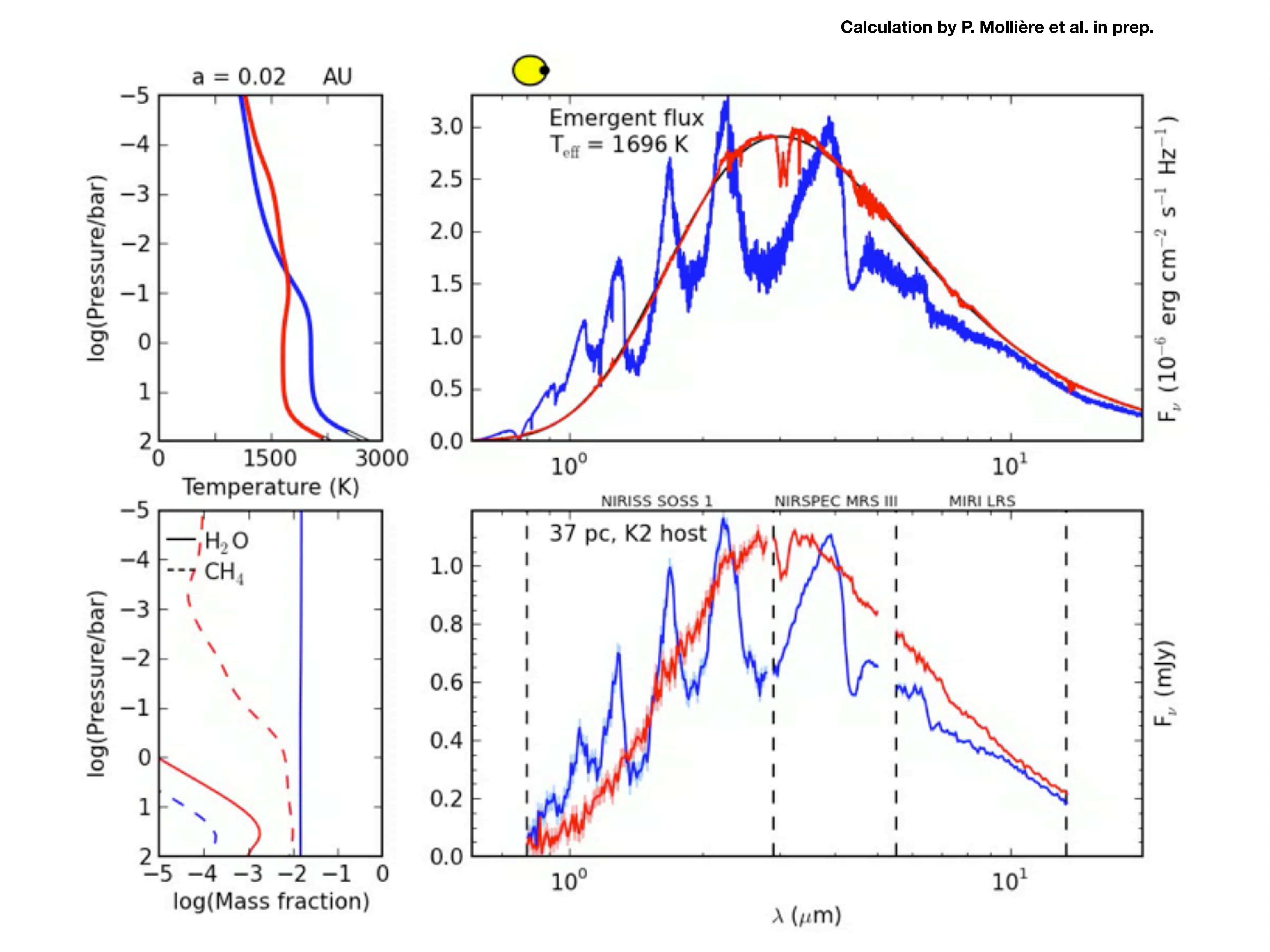
van Boekel et al. 2012, SPIE, 8442, 1

Difference very clearly detected

Parameter study: orbital distance

dry Jupiter

wet Saturn



Parameter study: chemistry

Explore range of plausible compositions based on observations and theory for non-nominal chemistry models

Gas

- H, He, optionally volatiles

Refractory material

- 4/9 Silicates, 2/9 Carbon, 3/9 Iron
- 33% silicates, 10% Fe, 10% FeS, 46% “CHON”

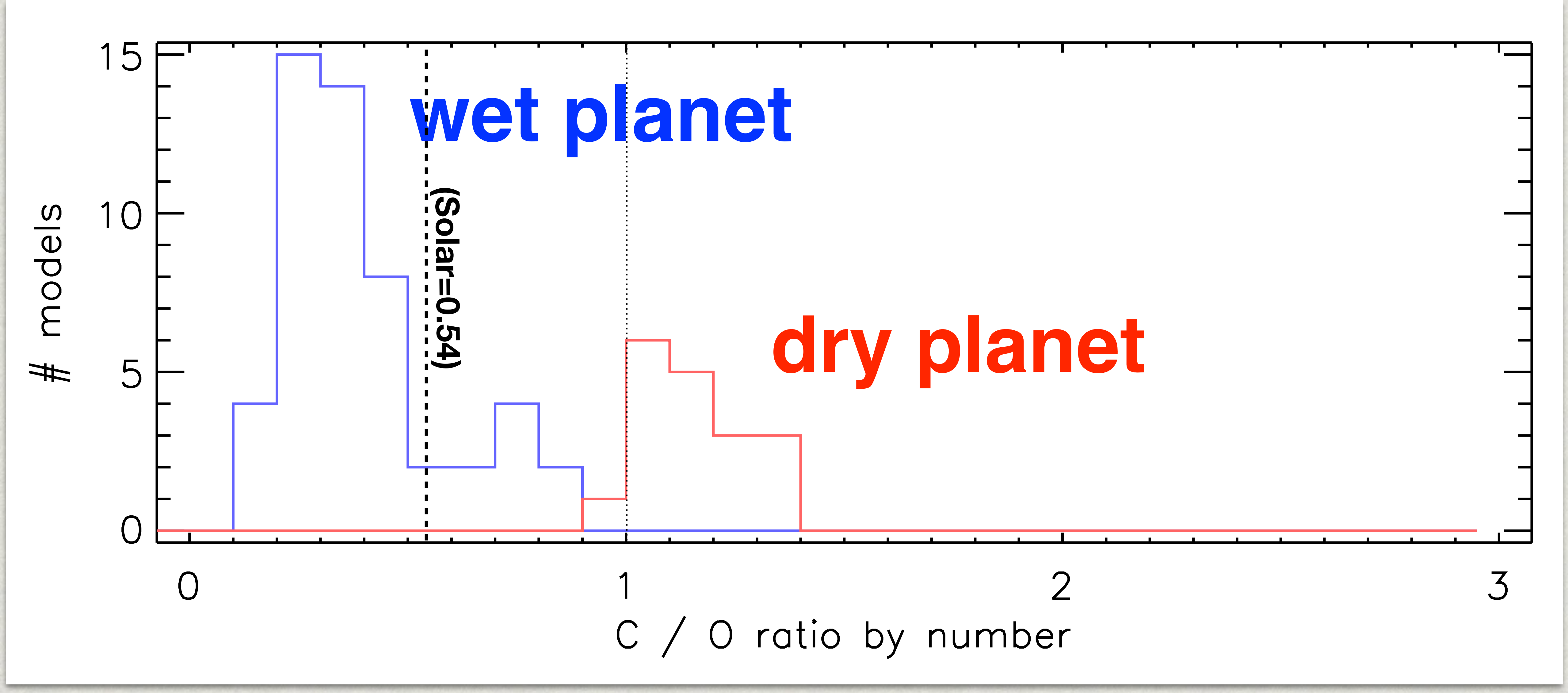
Volatile material

- H2O, CH4, CO, CO2, NH3
- solar nebula model, comets, disks
- different volatile to refractory ratios

H_2O	CO	CO_2	CH_4	NH_3	reference
100	0	0	0	0	
100	0	0	65	18	Lodders (2003)
100	10	5	1	1	Bockelée-Morvan et al. (2004)
100	6	19	0	0	K. Altwegg (pers. com.)
100	99	32	4	10	Pontoppidan et al. (2005)

Parameter study: chemistry II

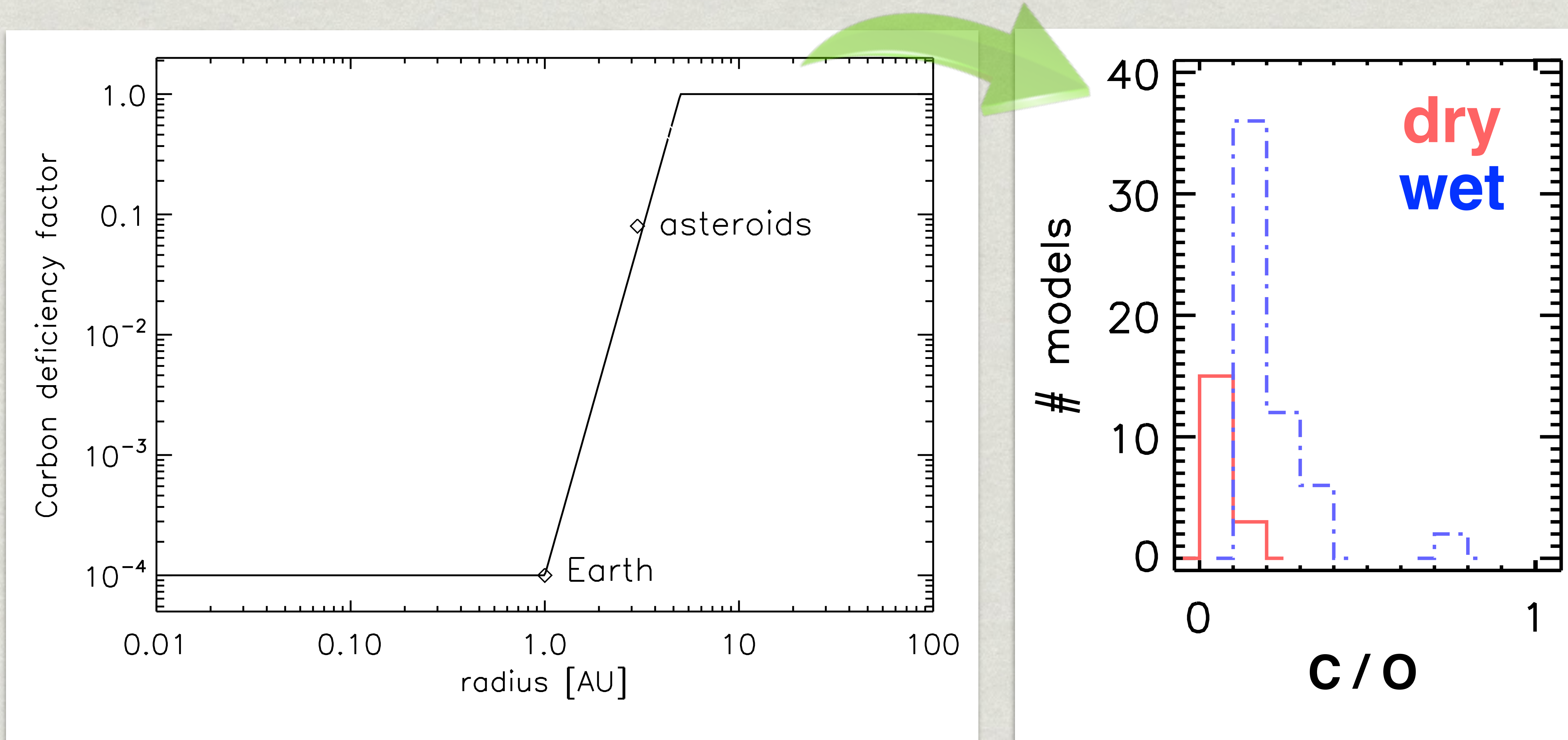
Resulting C/O for different chemistry models



Range of C/O, but global trend remains

Parameter study: chemistry III

Carbon-depleted solids in the inner disk regions?



Completely changes the conclusion!

Next steps

- Formation: include N-body effects
- Interior/Evolution: compositional gradients, semiconvection, fully non-gray atmospheric model
- Self-consistent EoS and opacity
- Chemistry: comparison with condensation models
- Atmosphere: non-equilibrium chemistry, clouds, settling of heavy species

Many uncertainties in all models parts...
Observational guidance important

Conclusions

Spectra of mature planets contain clues about their formation(?)

Here: formation location → C/O ratio

- EGPs formed inside iceline: C-rich (?)
- EGPs formed outside iceline: O-rich

caution: carbon deficiency?

very different spectral signatures

- O-rich: water-dominated spectra
- C-rich: methane-dominated spectra
- observable in large numbers with JWST!

caution: T-dependent chemistry