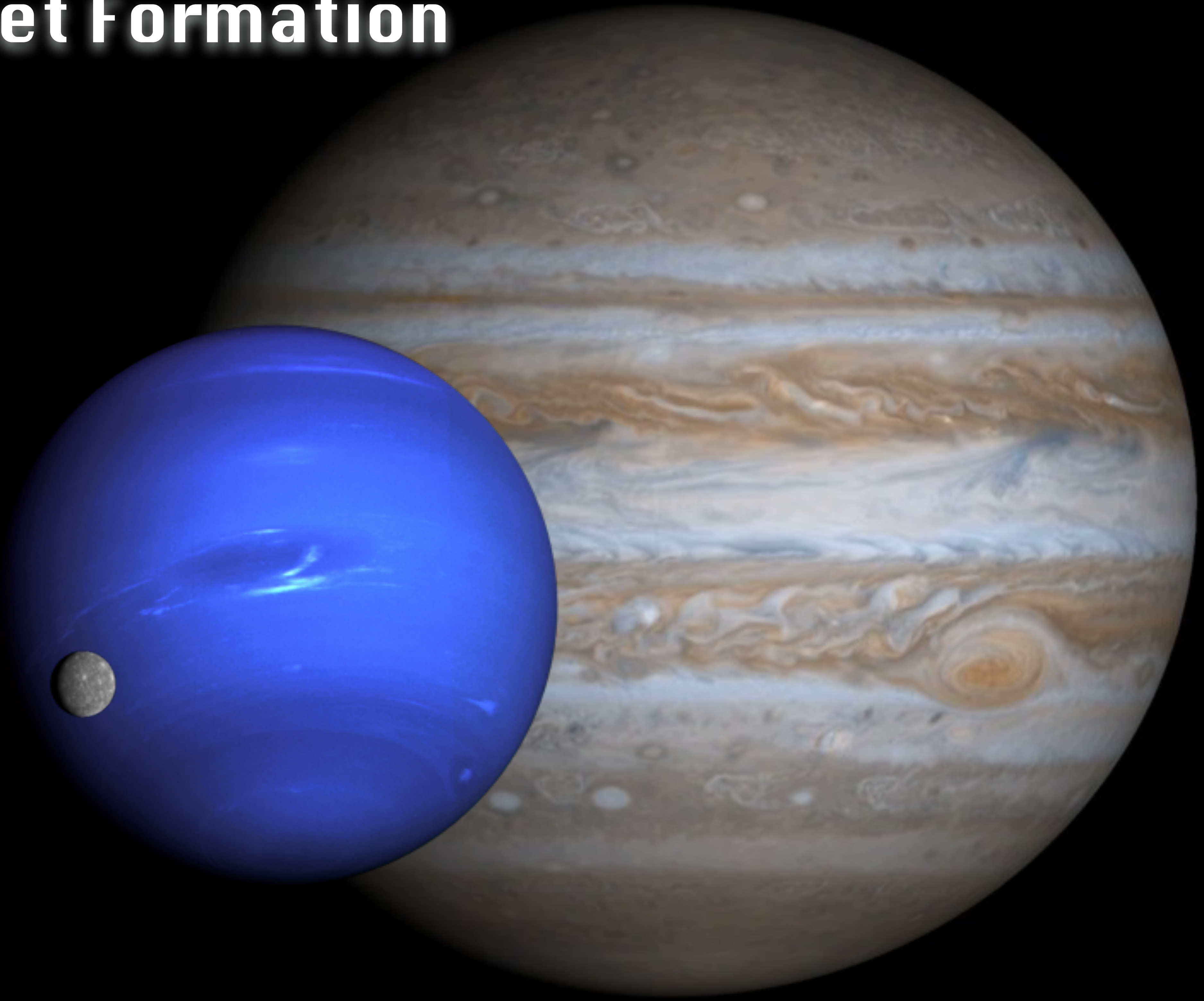
Models of Planet Formation



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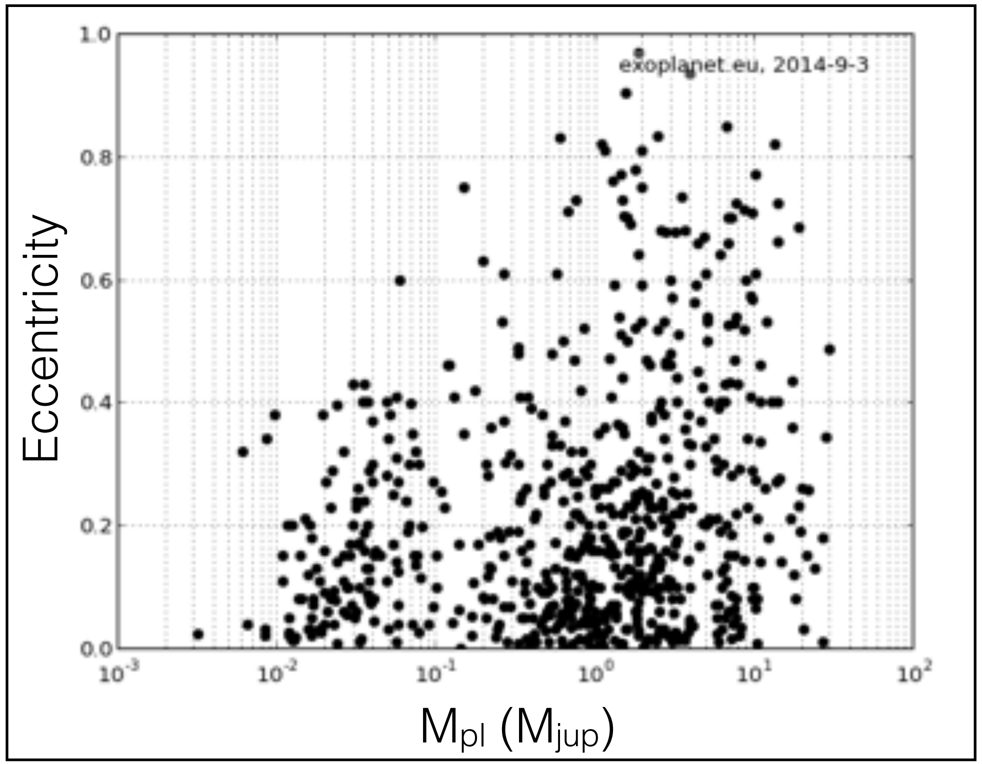
Towards other Earths II – The Star-Planet Connection
Porto, 18 September 2014

Challenges to Theory

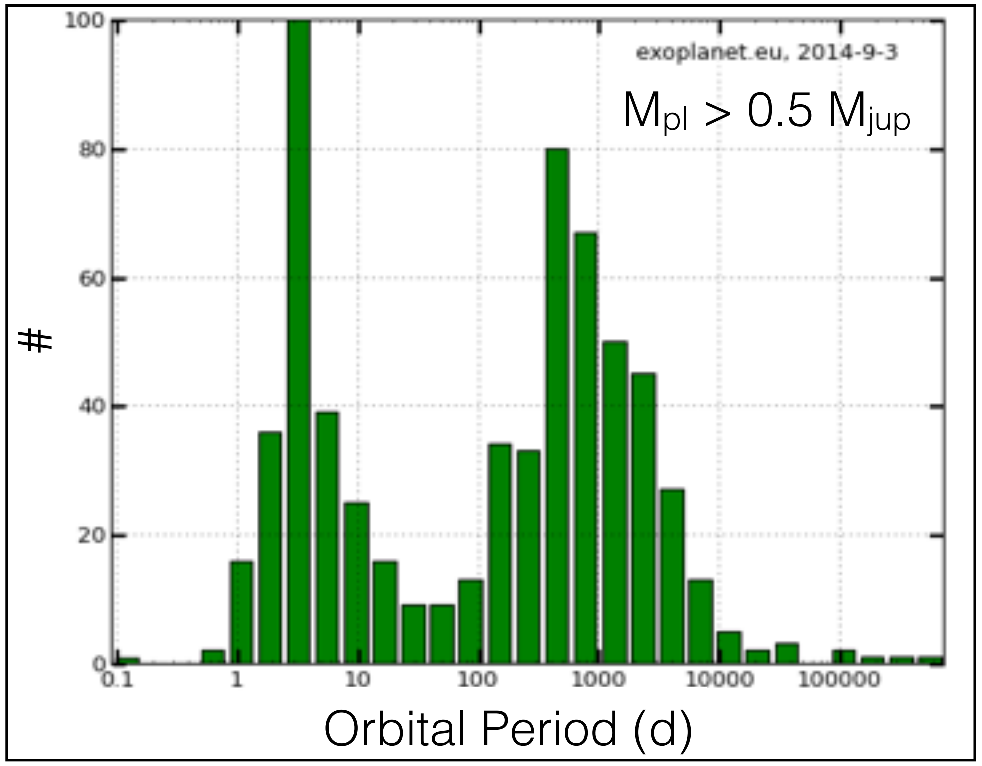
From the Solar System with circular orbits...

Terrestrial Gas Giants Ice Giants

...to the diverse population of exoplanets.



High eccentricities



Close-in giants

Circumbinary planets

Planetesimal Formation

- Dust and ices in disk condense, coagulate, settle

$\Longrightarrow r_{\text{dust}} \lesssim 1$ cm

Collisional growth

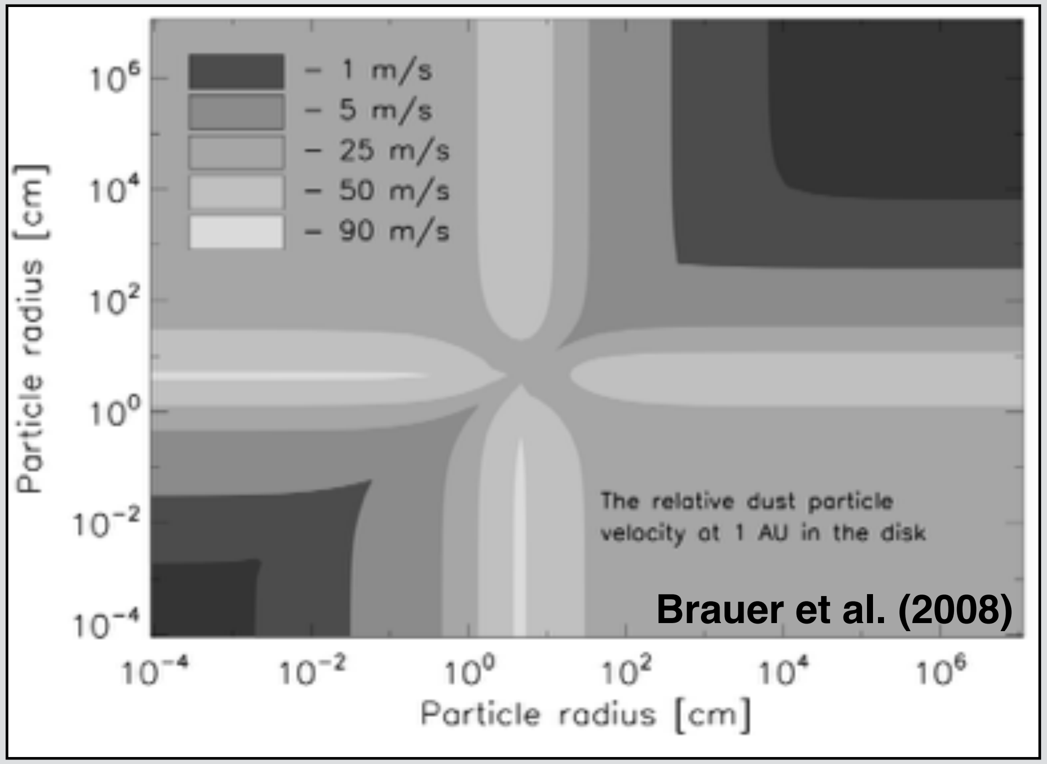
Gravoturbulent formation

Planetesimals

?

Meter barrier?

Fragmentation, drift, …



The relative dust particle velocity at 1 AU in the disk

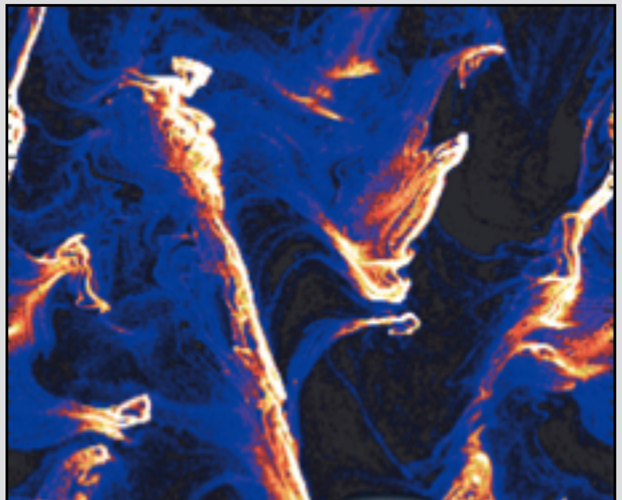
Brauer et al. (2008)

(→)

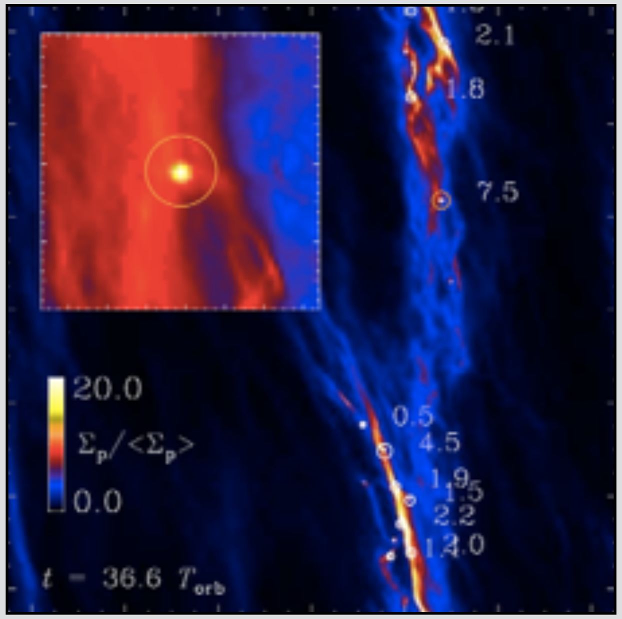
Pebbles

Planetesimals born big?

Johansen & Youdin (2007)



Johansen et al. (2011)



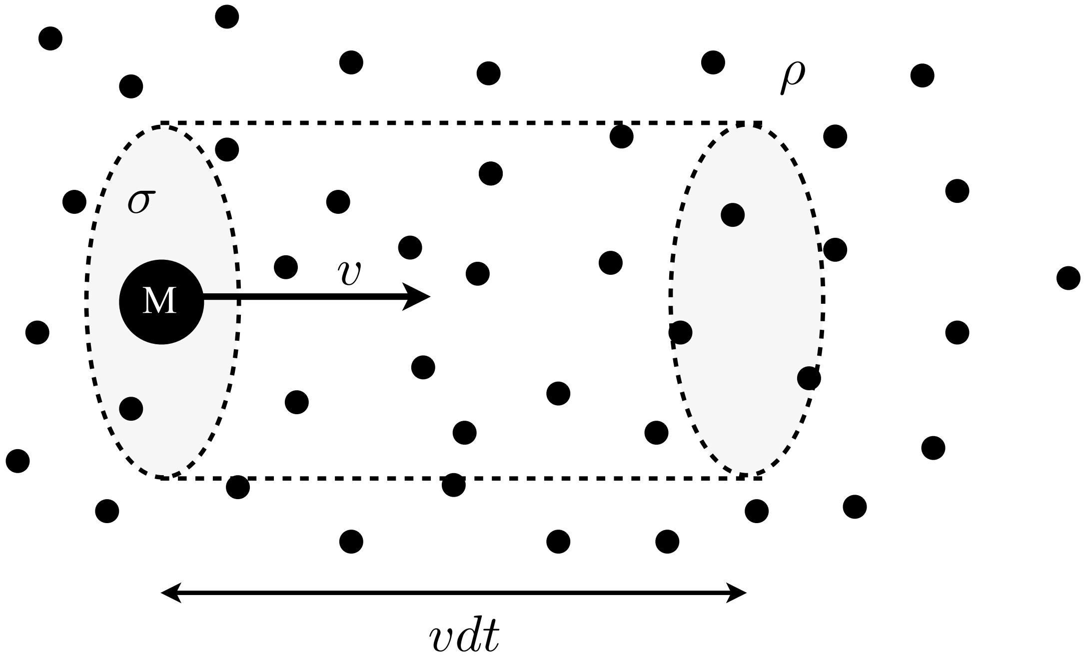
Ceres, r ~ 470 km

> "(…) the current SFD of the asteroids requires that the minimal size of the initial planetesimals was (…) 100 km."

Morbidelli et al. (2009)

Formation of Protoplanetary Embryos

$$\boxed{\frac{dm_p}{dt} = \frac{\sqrt{3}}{2}\Sigma_s \Omega \pi r^2 \left(1 + \frac{v_{esc}^2}{v_\infty^2}\right)}$$



- Feeding zone ~ ± 3.5 $R_{Hill} \propto M^{1/3}$

Assuming circular orbits!

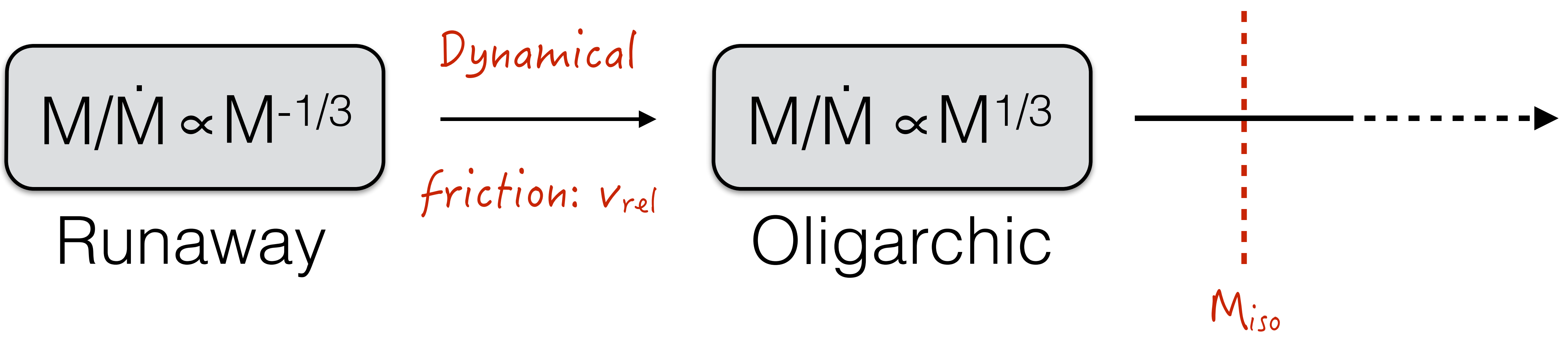
- Isolation mass, ~~MMSN~~ **5 x MMSN**:

This is not the only solution!

a	1 AU	5.2 AU
M	**0.9 M**	**12 M**

Further growth by migration, more massive disk, ...?

- Growth regimes



$M/\dot{M} \propto M^{-1/3}$

Runaway

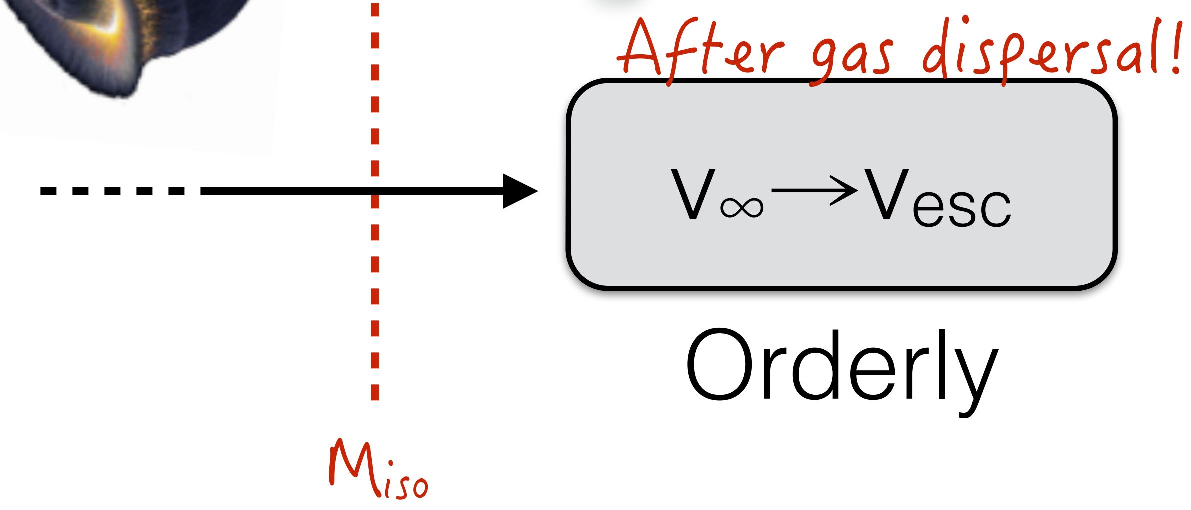
Dynamical friction: v_{rel}

$M/\dot{M} \propto M^{1/3}$

Oligarchic

M_{iso}

Forming Terrestrial & Low-Mass Planets



After gas dispersal!

$V_\infty \rightarrow V_{esc}$

Orderly

M_{iso}

I.e. after giant planet formation!

Strong radial mixing!

- $T_{form} \sim 10^8$ yr

- $M < 30\ M_\oplus$ or $R < 4\ R_\oplus$ with $P < 50$ d planets occurrence

$f_{HARPS} = 40$ % $f_{Kepler} = 30$ % Often multiple systems! Up to 70 % in HARPS!

Formation of close-in dynamically packed systems?

Ida et al. (2013)

- Mutual capture in MMR & migration

→ Disk dispersal: Orderly growth

Chiang & Laughlin (2013), Hansen & Murray (2013)

- In-situ formation? MMEN ~ 7-8 x MMSN

Hands et al. (2014)

- Inward migration of final system?

?

Distinguish using spectra, M-R relation?

Giant Formation: Gravitational Instability

- Planet formation by partial collapse of self-gravitating disk:

$$\boxed{Q = \frac{2c_s\Omega_K}{\pi G\Sigma} \lesssim 1.5} \quad \& \quad \boxed{\frac{\tau_{cool}}{\tau_{orb}} \lesssim 1} \quad \text{, but:} \quad \boxed{\begin{array}{l} c_s \searrow \implies Q \searrow \\ c_s \searrow \implies \tau_{cool} \nearrow \end{array}}$$

Toomre (1964)

Gammie (2001): Collapse on timescale Ω^{-1}.

- Unlikely inside 40 AU!

From analytical arguments.

- Needs massive disk!

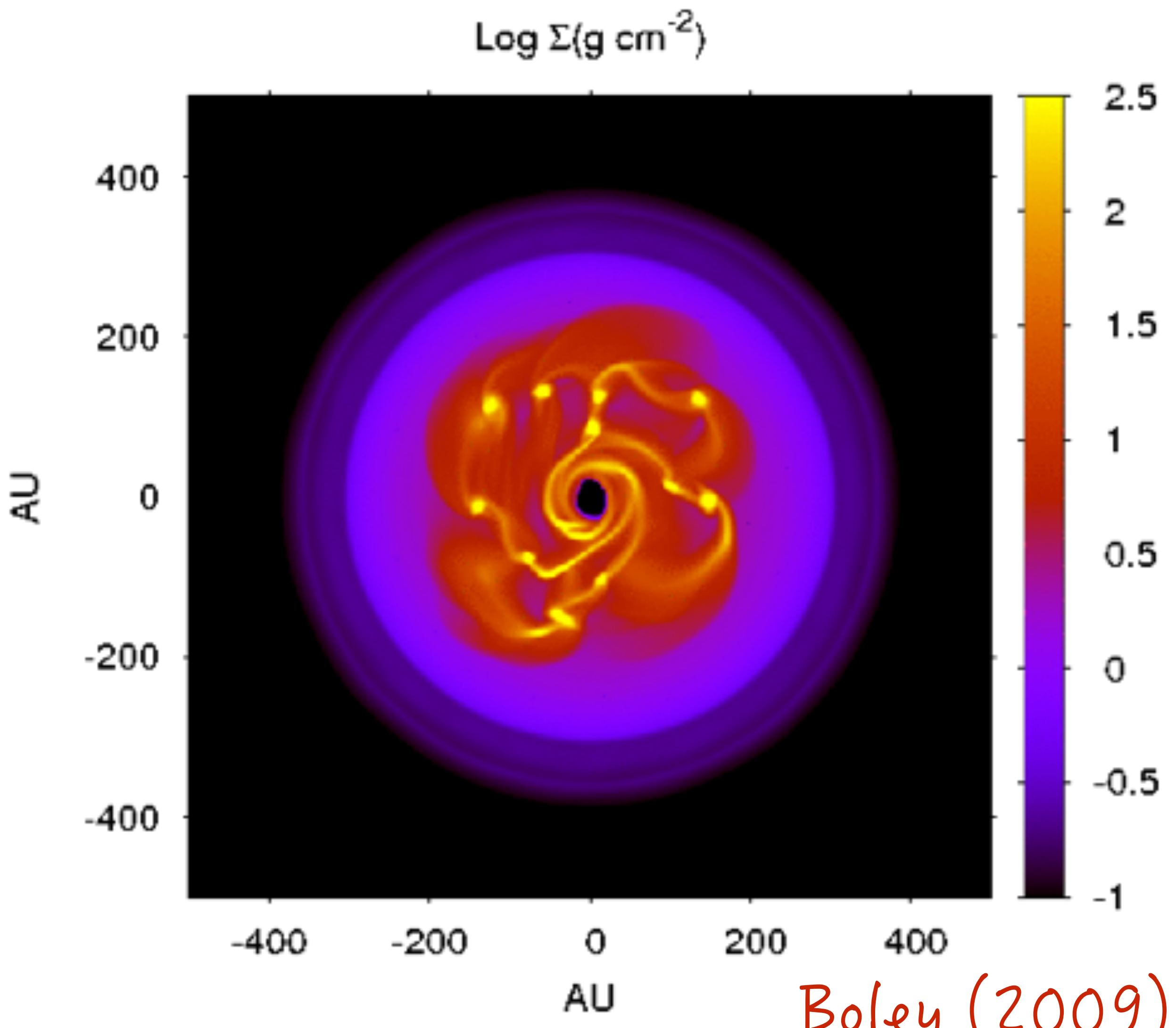
Early, during disk formation?

- No consensus so far!

Boss et al., Mayer et al., Nelson et al., Boley et al.
Cai et al., Stamatellos & Whitworth, ...

- Possibly at r > 100 AU!

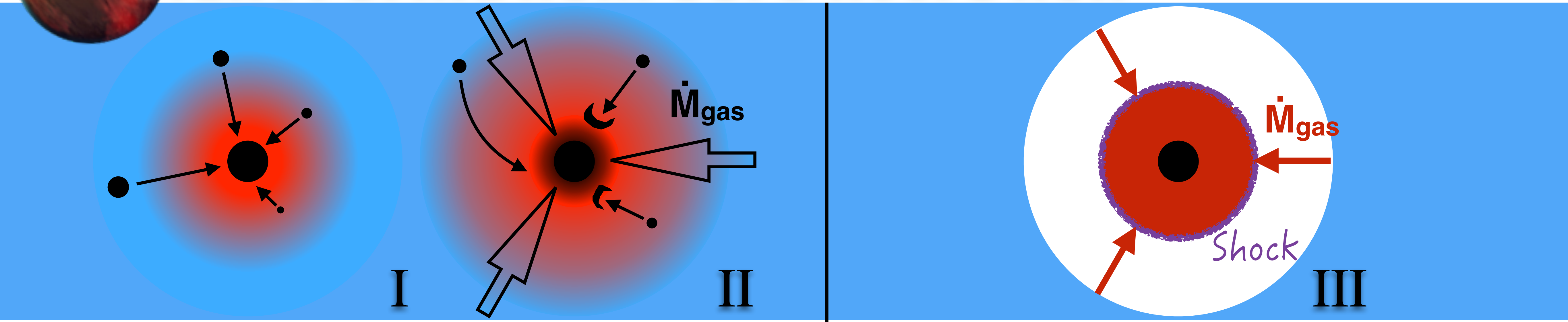
Boley (2009)



Boley (2009)

Giant Formation: Core Accretion

E.g. Pollack et al. (1996)



Attached Phase

I

Tenuous envelope

Embryo → $M_{iso} \sim 10\ M_\oplus$

outside, close to iceline

II

$R_{pl} \sim R_{Hill}$

$\dot{M}_{gas}$ from contraction

Increases solid feeding zone!

Gas drag: $R_{capture}$ ↗

Planetesimal break-up

Detached Phase

III

$M_{env} \rightarrow M_{core}$: "Collapse"

Mizuno (1980), Stevenson (1982)

quasi-static

↓

Disk-limited $\dot{M}_{gas}$

Accretion shock!

Hot Start?

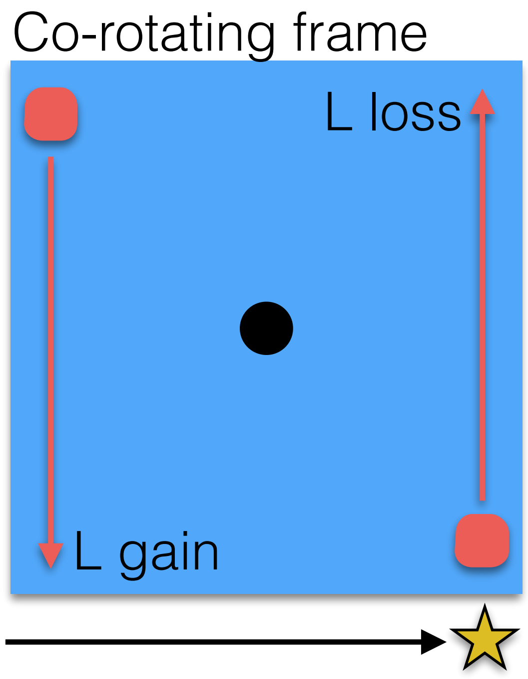
Cold Start?

!

"Core-assisted gas capture instability" another possible method? → Sergei Nayakshin's talk!

Migration

Important right from the start: 51 Peg b !



- From simple model (impulse approximation)

$$\boxed{\begin{matrix} \Sigma_{\rm gas} \nearrow \\ M_{\rm pl} \nearrow \end{matrix} \Longrightarrow \tau_{\rm mig} \searrow}$$

Lin & Papaloizou (1986)

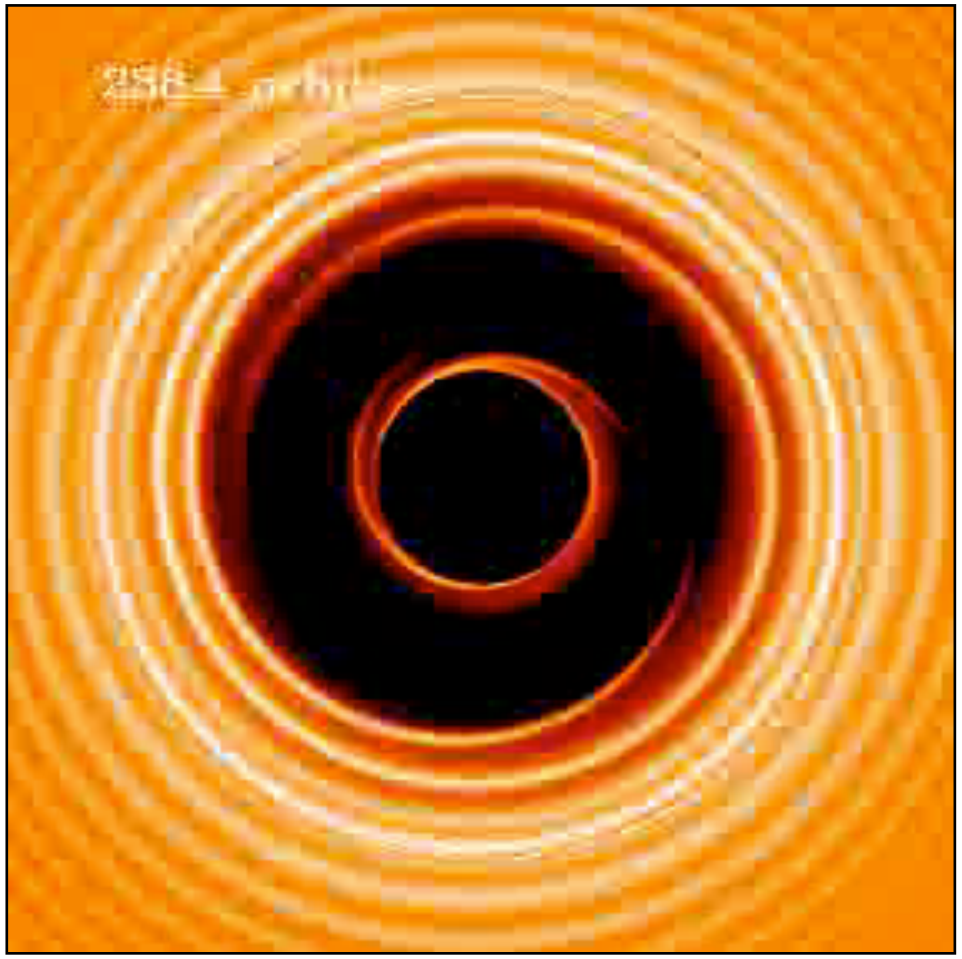
- Low $M_{\rm pl}$: Type-I migration

Isothermal disk: $\tau_{\rm mig} \sim 10^4$ yrs

Too short!

Isothermal & adiabatic torques?

Inward! Outward! Covergence zones?



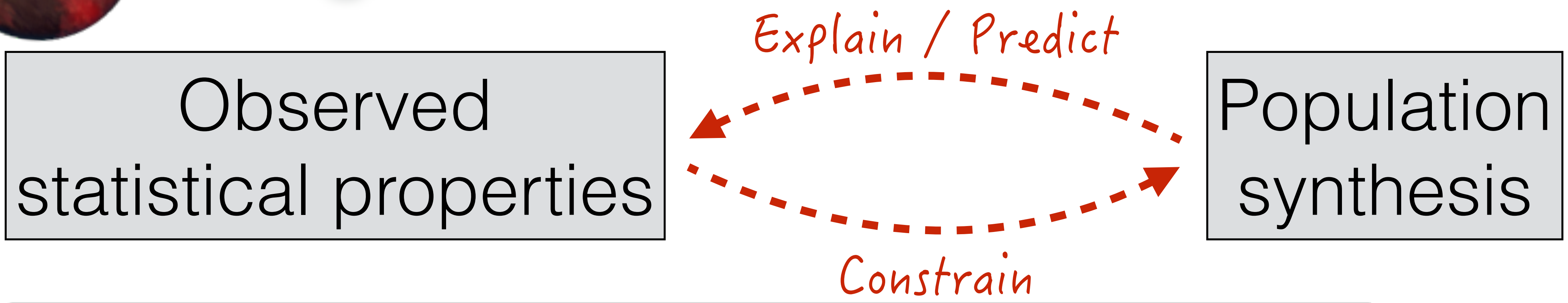
- High $M_{\rm pl}$: Type-II: Gap opens!

$$\boxed{\begin{matrix} R_{\rm Hill} > H \\ \tau_{\rm gap} < \tau_{\rm visc} \end{matrix}} \qquad \boxed{\tau_{\rm mig} = \tau_{\rm visc}}$$

Slow! For high $M_{\rm pl}$ even slower!

Other processes for close in planets are possible: Planet-planet interaction, Kozai migration!

Theory – Observation: Connection



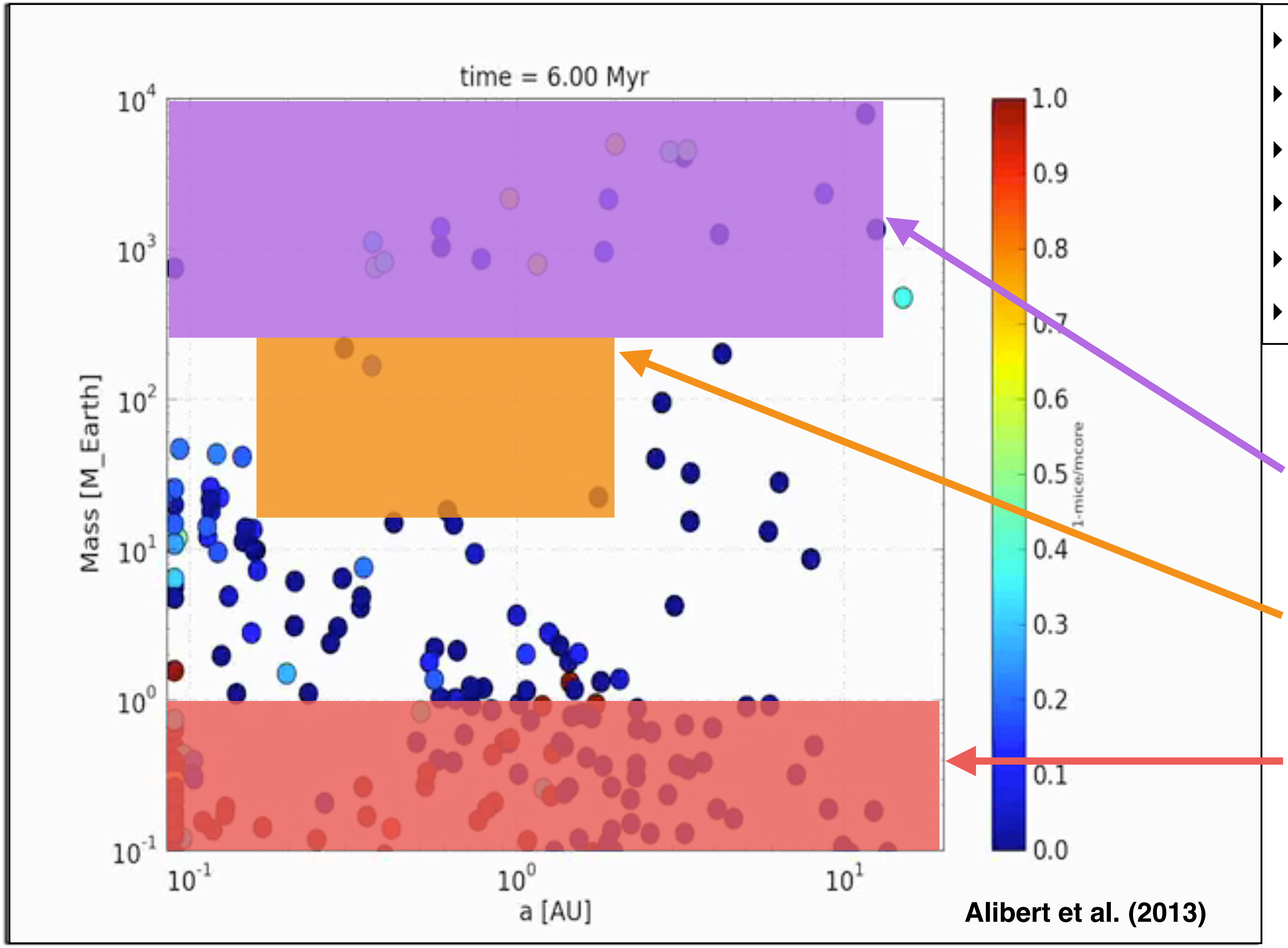
Observed statistical properties

Explain / Predict

Constrain

Population synthesis

Ida & Lin (2004)
Alibert et al.
Mordasini et al.



Alibert et al. (2013)

- 10 Embryos/disk
- $M_{ini} = 0.01\ M_\oplus$
- Full N-body
- $M_{star} = 1\ M_\odot$
- Migration (Type I and II)
- $\alpha = 7 \times 10^{-3}$

Giants

Planetary desert

Prototerrestrial cores

Theory – Observation: Comparison

(✓) - Giant planet frequency - $[Fe/H]_{star}$

(✓) - Giant planet frequency - semi major axis

✓ - Giant planet mass distribution

? - Formation of close-in packed systems

? - Origin of planetary atmospheres

From nebula? From collisions? Outgassing? Evaporation?

? - Large eccentricities of planetary systems

Santos et al. (2004), Fischer & Valenti (2005), Udry & Santos (2007), Marcy et al. (2005), Mayor et al. (2011), Ida et al. (2013), Chiang & Laughlin (2013), Hansen & Murray (2013) ,Hands et al. (2014), Fabrycky & Tremaine (2007), Adibekyan et al. (2013), Mordasini et al., Alibert et al., Schlaufmann (2014), Dawson & Murray-Clay (2013)

Planetary Spectra from Formation?

Formation

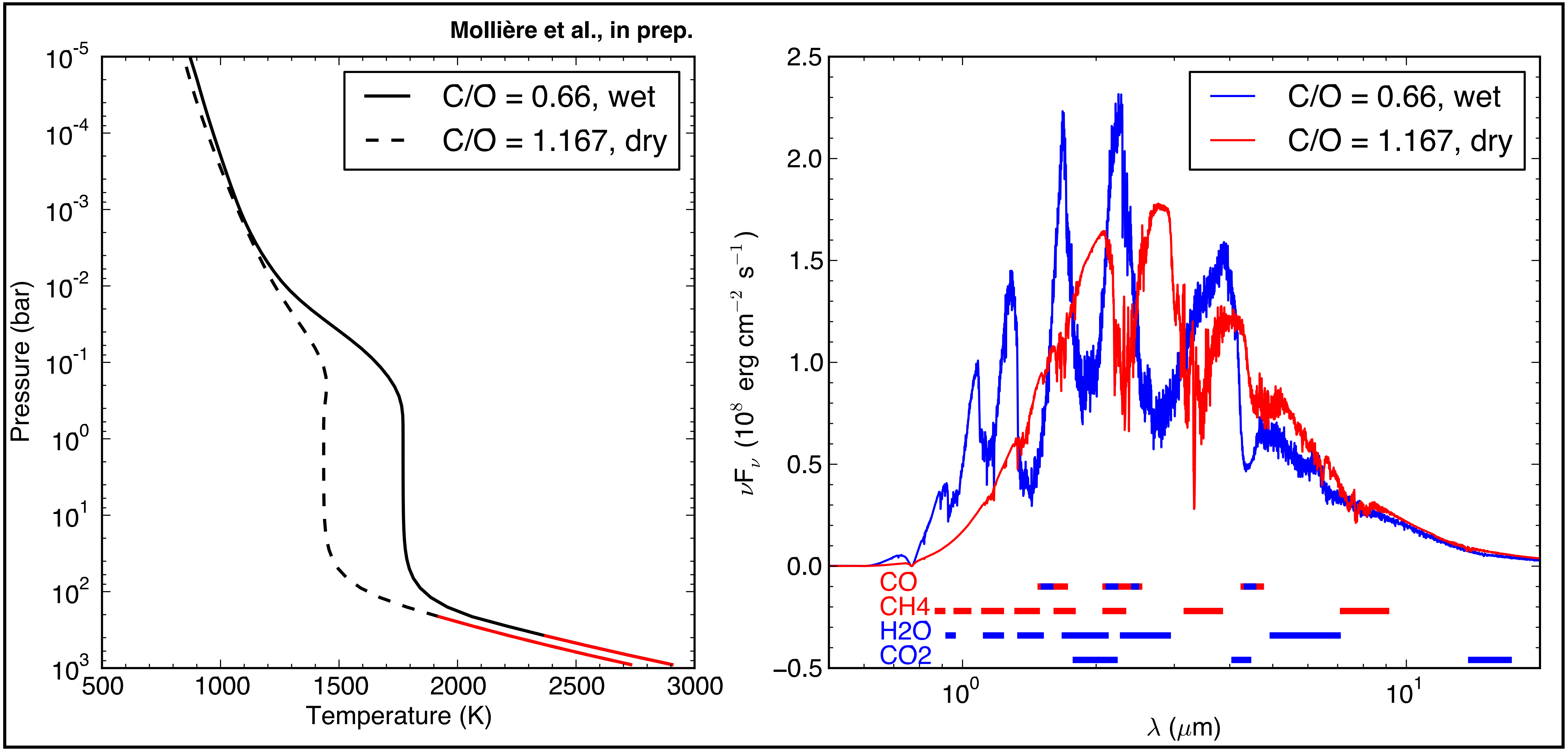
Composition

Evolution

Atmospheric structure

Spectrum

van Boekel et al. (in prep.)



Mollière et al., in prep.

Summary

- Planet formation models encompass many processes

Collapse • Formation of the disk • Disk chemistry • Disk evolution • Planetesimal formation • Grain & planetesimal drift & migration • Planetesimal dynamics • Dynamical coupling of EGP and planetesimals • Planet formation mode • Planetary migration • Evaporation • Planetary structure evolution • Planetary atmospheres, atmospheric dynamics • …

Many individual processes and their coupling have to be understood better and in a qualitative & quantitative way!

Thanks for your attention!