Towards a General Theory of Planet Formation

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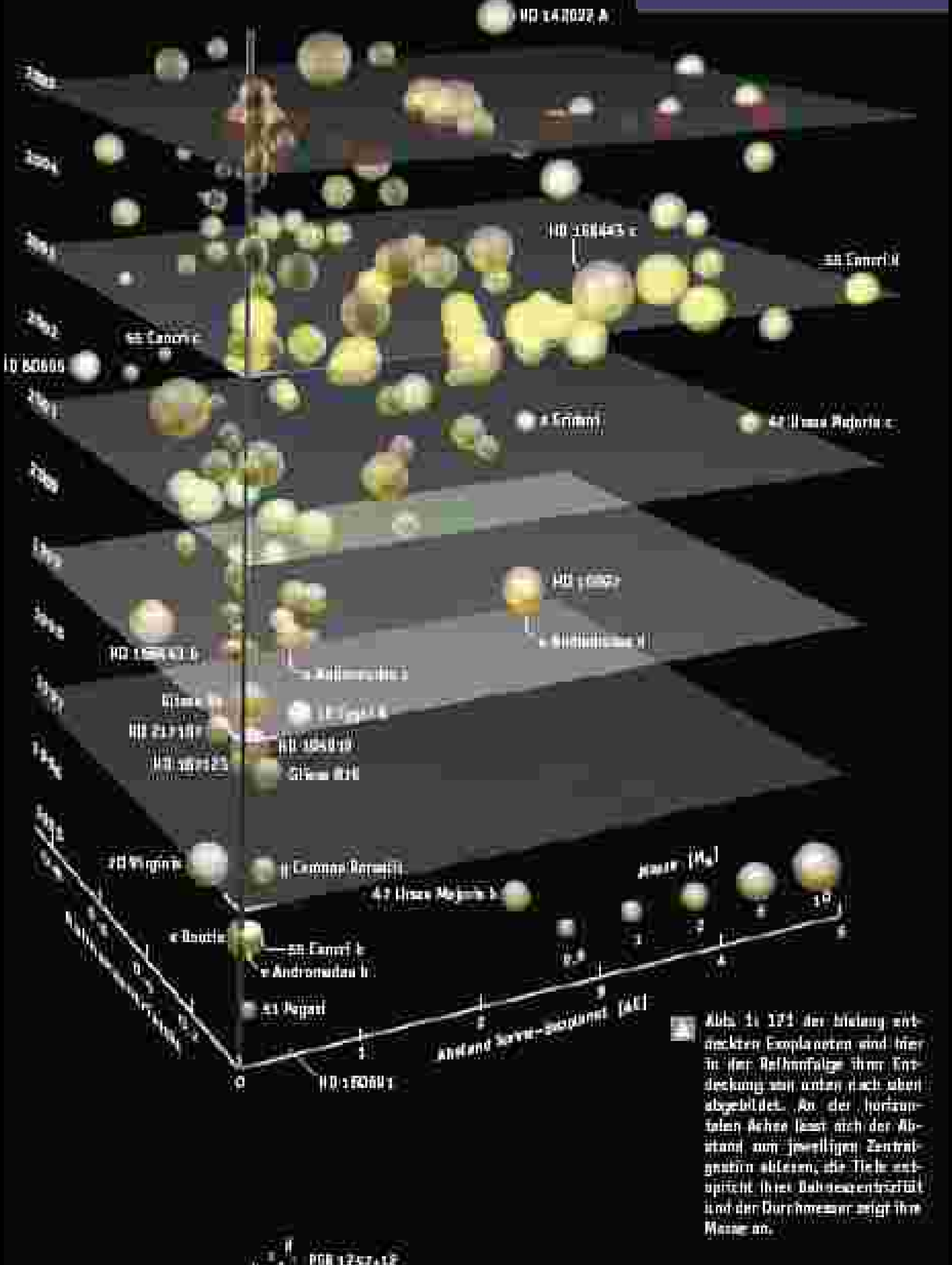


Abb. 1: 171 der bislang entdeckten Exoplaneten sind hier in der Reihenfolge ihrer Entdeckung von unten nach oben abgebildet. An der horizontalen Achse lässt sich der Abstand zum jeweiligen Zentralgestirn ablesen, die Tiefe entspricht ihrer Bahnexzentrizität und der Durchmesser zeigt ihre Masse an.

EXOPLANETS

Mass
→ radius of sphere

Orbital Radius
→ towards right

Eccentricity
→ backwards

Year of Discovery
→ upwards

PLANET FORMATION

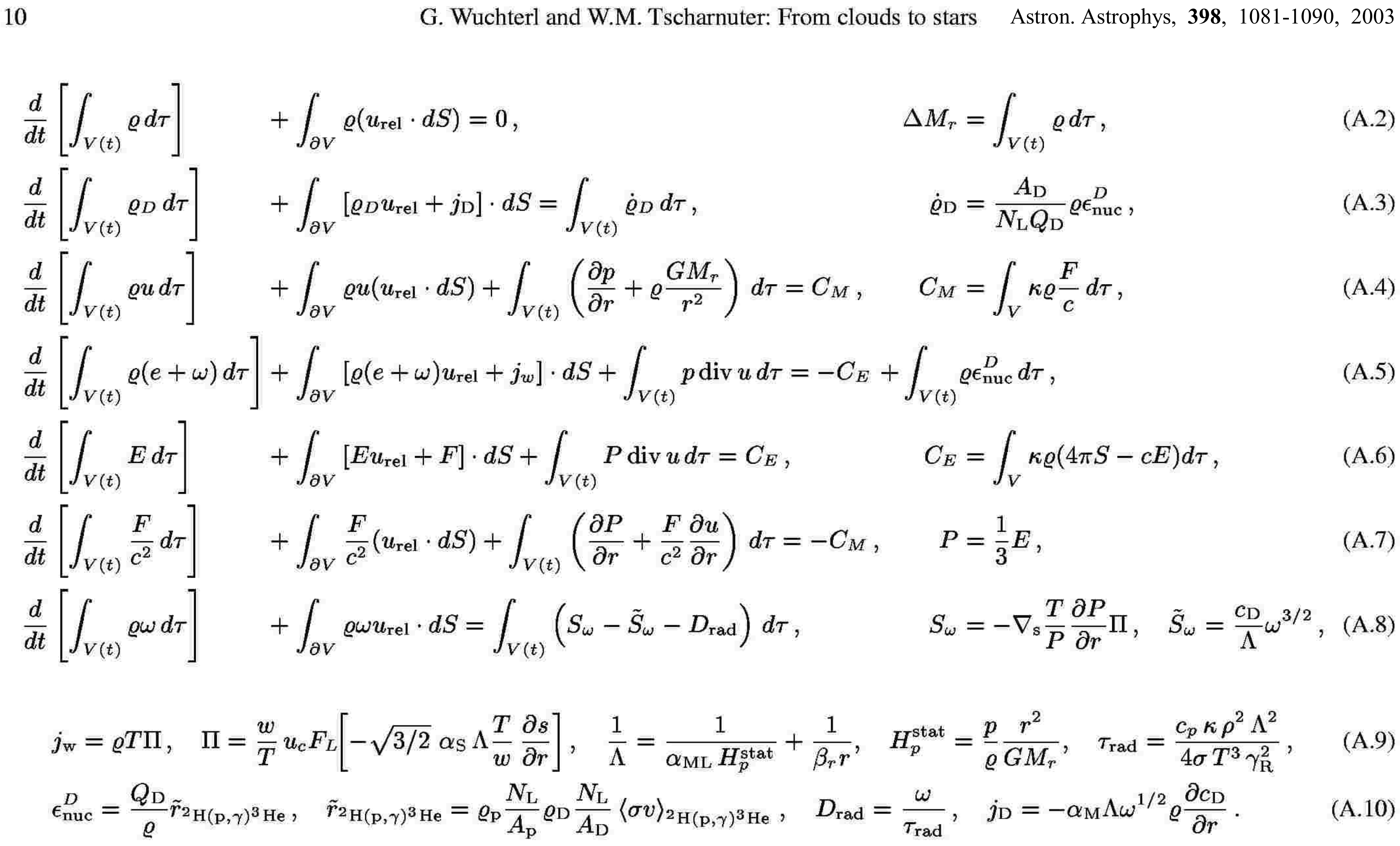
Forming self-gravitating objects in a nebula-disk

Forget the Nebula

There is no time left to sort it out before planet 1000

- If it can't be determined, try anything that is plausible!
- ***A plausible protoplanetary nebula is anything that does not gravitationally fragment into stellar objects.***
- Use e.g. Toomre-instability as a proxy for gravitational instability.

One set of Equations, Sun-calibrated



10 G. Wuchterl and W.M. Tscharnuter: From clouds to stars Astron. Astrophys, **398**, 1081-1090, 2003

$$\frac{d}{dt}\left[\int_{V(t)} \varrho\, d\tau\right] + \int_{\partial V} \varrho(u_{\rm rel}\cdot dS) = 0\,, \qquad \Delta M_r = \int_{V(t)} \varrho\, d\tau\,, \tag{A.2}$$

$$\frac{d}{dt}\left[\int_{V(t)} \varrho_D\, d\tau\right] + \int_{\partial V} [\varrho_D u_{\rm rel} + j_{\rm D}]\cdot dS = \int_{V(t)} \dot\varrho_D\, d\tau\,, \qquad \dot\varrho_{\rm D} = \frac{A_{\rm D}}{N_{\rm L} Q_{\rm D}}\varrho\epsilon^D_{\rm nuc}\,, \tag{A.3}$$

$$\frac{d}{dt}\left[\int_{V(t)} \varrho u\, d\tau\right] + \int_{\partial V} \varrho u(u_{\rm rel}\cdot dS) + \int_{V(t)}\left(\frac{\partial p}{\partial r} + \varrho\frac{GM_r}{r^2}\right) d\tau = C_M\,, \qquad C_M = \int_V \kappa\varrho\frac{F}{c}\, d\tau\,, \tag{A.4}$$

$$\frac{d}{dt}\left[\int_{V(t)} \varrho(e+\omega)\, d\tau\right] + \int_{\partial V} [\varrho(e+\omega)u_{\rm rel} + j_w]\cdot dS + \int_{V(t)} p\,{\rm div}\, u\, d\tau = -C_E + \int_{V(t)} \varrho\epsilon^D_{\rm nuc}\, d\tau\,, \tag{A.5}$$

$$\frac{d}{dt}\left[\int_{V(t)} E\, d\tau\right] + \int_{\partial V} [E u_{\rm rel} + F]\cdot dS + \int_{V(t)} P\,{\rm div}\, u\, d\tau = C_E\,, \qquad C_E = \int_V \kappa\varrho(4\pi S - cE) d\tau\,, \tag{A.6}$$

$$\frac{d}{dt}\left[\int_{V(t)} \frac{F}{c^2}\, d\tau\right] + \int_{\partial V} \frac{F}{c^2}(u_{\rm rel}\cdot dS) + \int_{V(t)}\left(\frac{\partial P}{\partial r} + \frac{F}{c^2}\frac{\partial u}{\partial r}\right) d\tau = -C_M\,, \qquad P = \frac{1}{3}E\,, \tag{A.7}$$

$$\frac{d}{dt}\left[\int_{V(t)} \varrho\omega\, d\tau\right] + \int_{\partial V} \varrho\omega u_{\rm rel}\cdot dS = \int_{V(t)}\left(S_\omega - \tilde S_\omega - D_{\rm rad}\right) d\tau\,, \qquad S_\omega = -\nabla_{\rm s}\frac{T}{P}\frac{\partial P}{\partial r}\Pi, \quad \tilde S_\omega = \frac{c_{\rm D}}{\Lambda}\omega^{3/2}\,, \tag{A.8}$$

$$j_{\rm w} = \varrho T\Pi\,, \quad \Pi = \frac{w}{T}u_c F_L\left[-\sqrt{3/2}\,\alpha_{\rm S}\,\Lambda\frac{T}{w}\frac{\partial s}{\partial r}\right], \quad \frac{1}{\Lambda} = \frac{1}{\alpha_{\rm ML}\, H_p^{\rm stat}} + \frac{1}{\beta_r r}, \quad H_p^{\rm stat} = \frac{p}{\varrho}\frac{r^2}{GM_r}, \quad \tau_{\rm rad} = \frac{c_p\,\kappa\,\rho^2\,\Lambda^2}{4\sigma\, T^3\,\gamma_{\rm R}^2}\,, \tag{A.9}$$

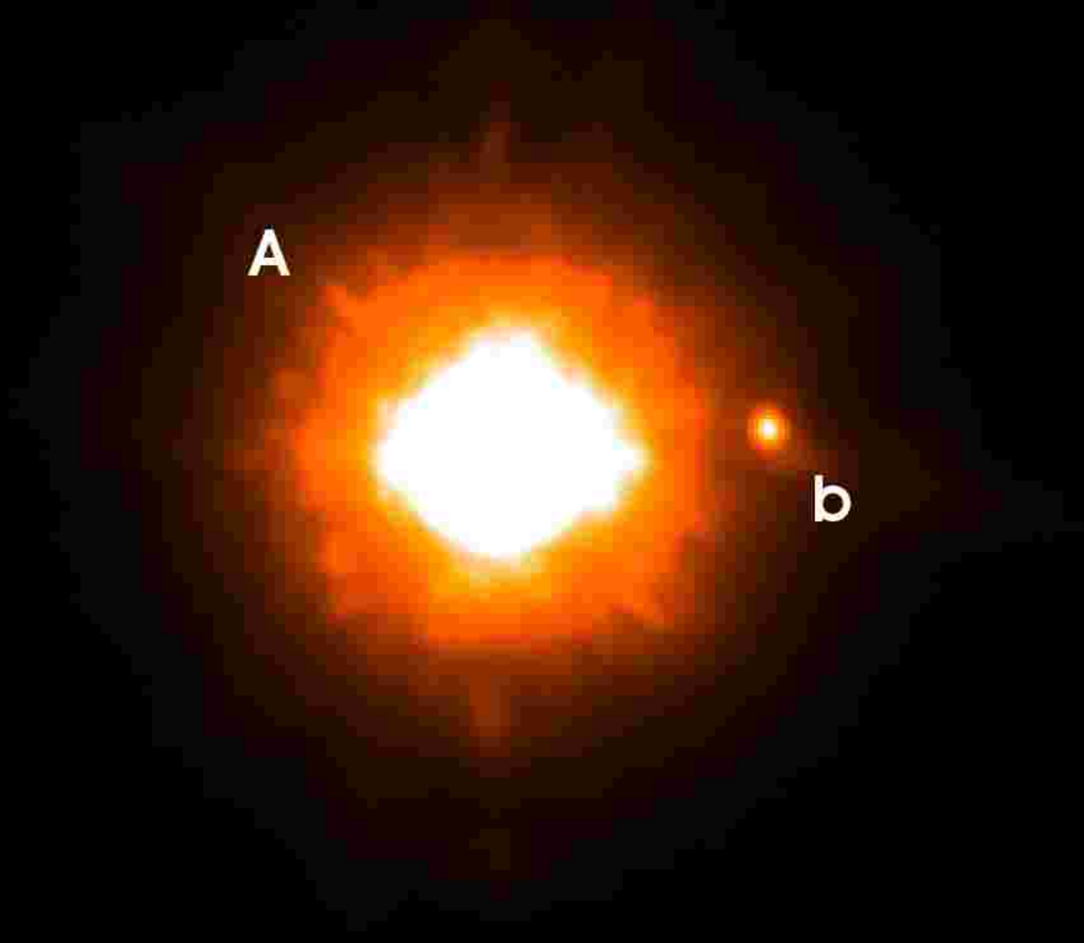
$$\epsilon^D_{\rm nuc} = \frac{Q_{\rm D}}{\varrho}\tilde r_{{}^2{\rm H(p,\gamma)^3He}}\,, \quad \tilde r_{{}^2{\rm H(p,\gamma)^3He}} = \varrho_{\rm p}\frac{N_{\rm L}}{A_{\rm p}}\varrho_{\rm D}\frac{N_{\rm L}}{A_{\rm D}}\langle\sigma v\rangle_{{}^2{\rm H(p,\gamma)^3He}}\,, \quad D_{\rm rad} = \frac{\omega}{\tau_{\rm rad}}\,, \quad j_{\rm D} = -\alpha_{\rm M}\Lambda\omega^{1/2}\varrho\frac{\partial c_{\rm D}}{\partial r}\,. \tag{A.10}$$

Extreme Planet Formation

- Close-in: planet formation is simple and fast, if nebulae are diverse.
- How about far out?

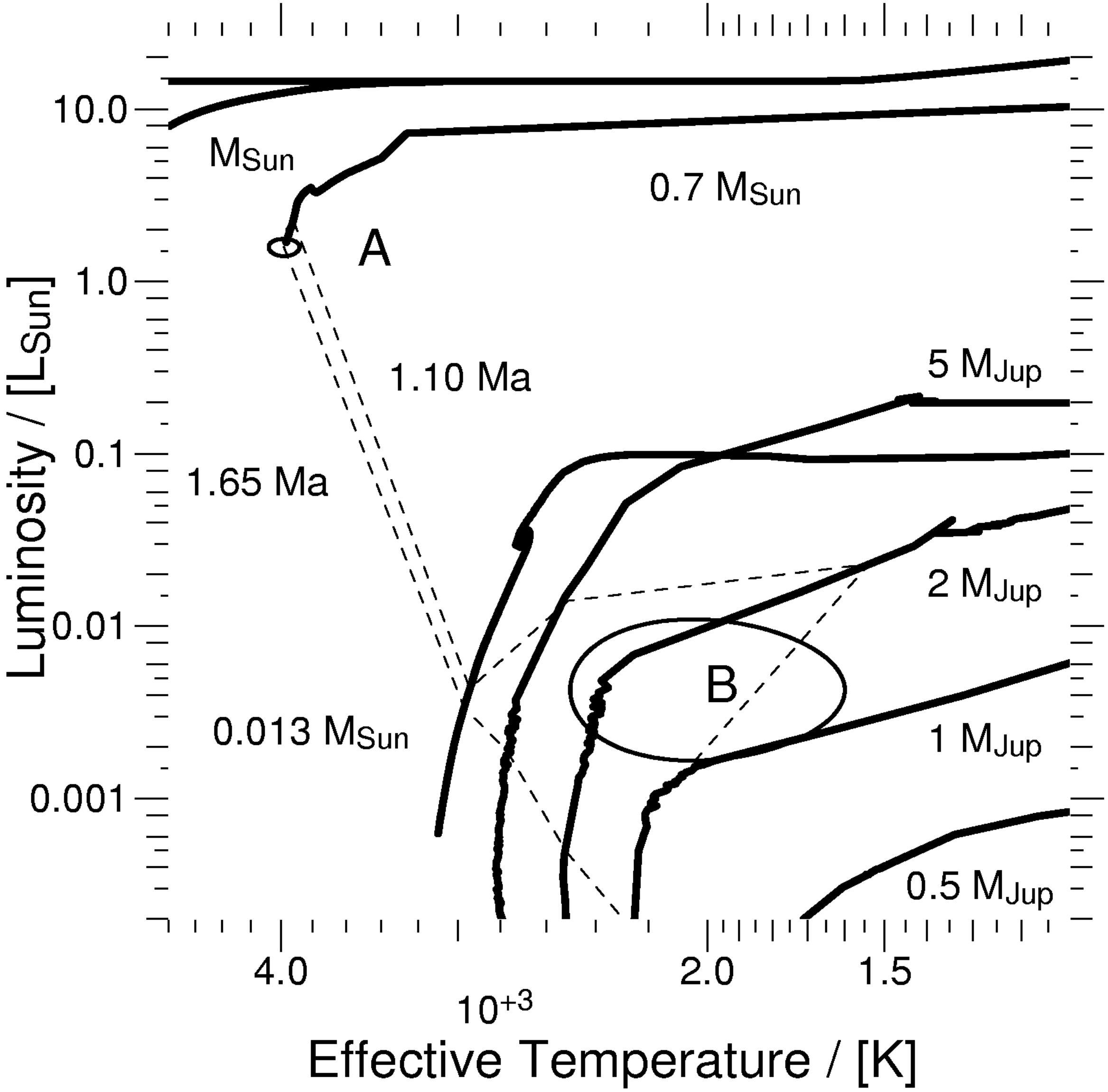
GQ Lupi

ESO VLT NACO June 2004



Neuhäuser, Guenther, Wuchterl, Mugrauer, Bedalov, Hauschildt

GQ Lupi b + Stars,BD+planets



Stars: Collapse of Bonnor-Ebert spheres

Brown Dwarfs: same as stars

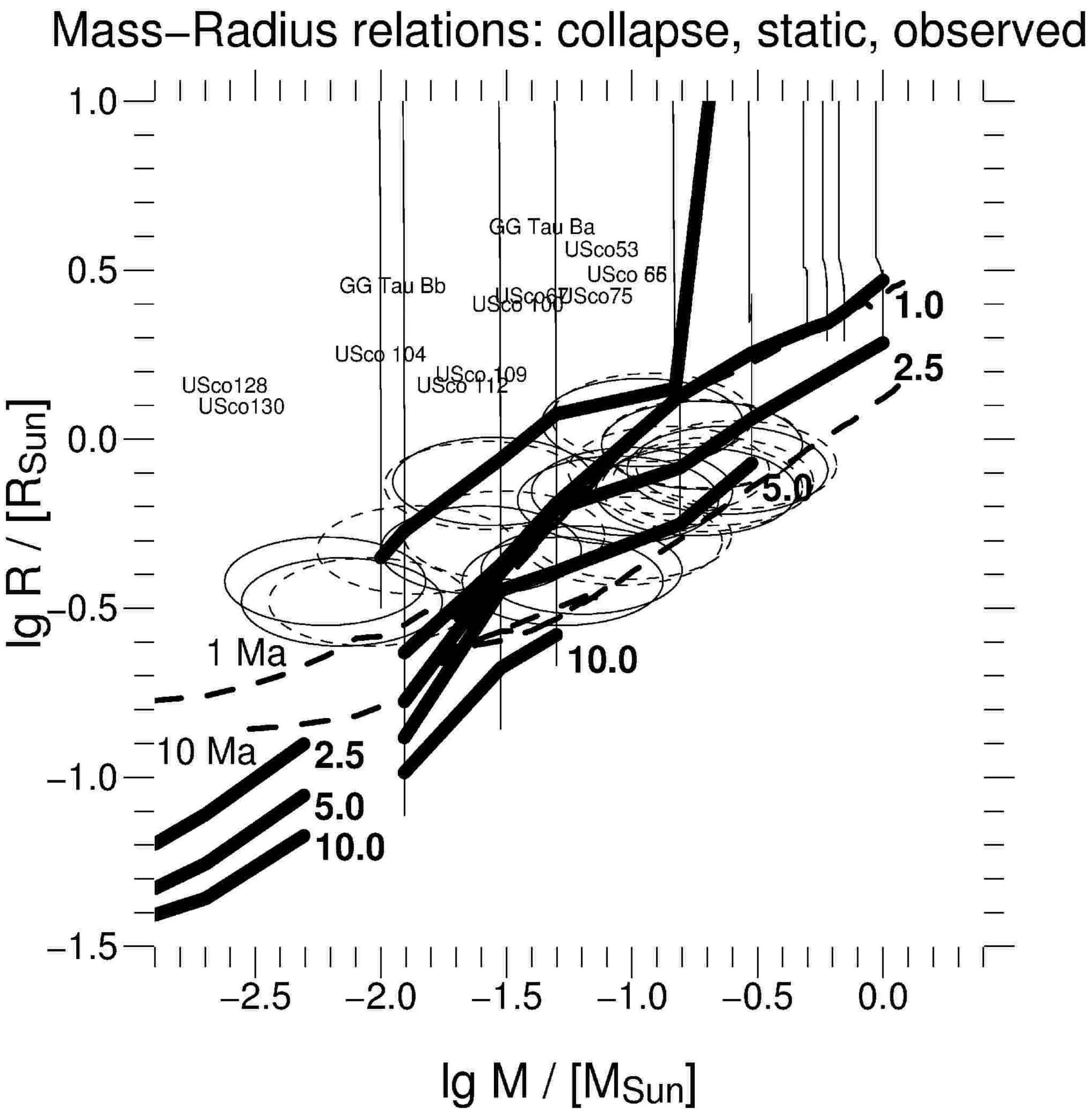
Planets: Nucleated instability, plausible, Toomre-stable nebulae, particle in box accretion

Neuhäuser et al. 2005

GQ Lupi b

- Cloud collapse models show GQ Lupi b to be substellar and mass less than 13 Jupiters;
- Gravitationally stable nebulae + particle in box runaway core accretion at 5 AU forms b component and gives coeval 2-3 MJ solution for primary and secondary masses;
- Convective radiation hydro of formation shows planetary mass and origin for the observed properties.
- Present models predict eccentric orbit; Note that 2003 UB_{313} extends SoSy to 100 AU.

Any Checks?

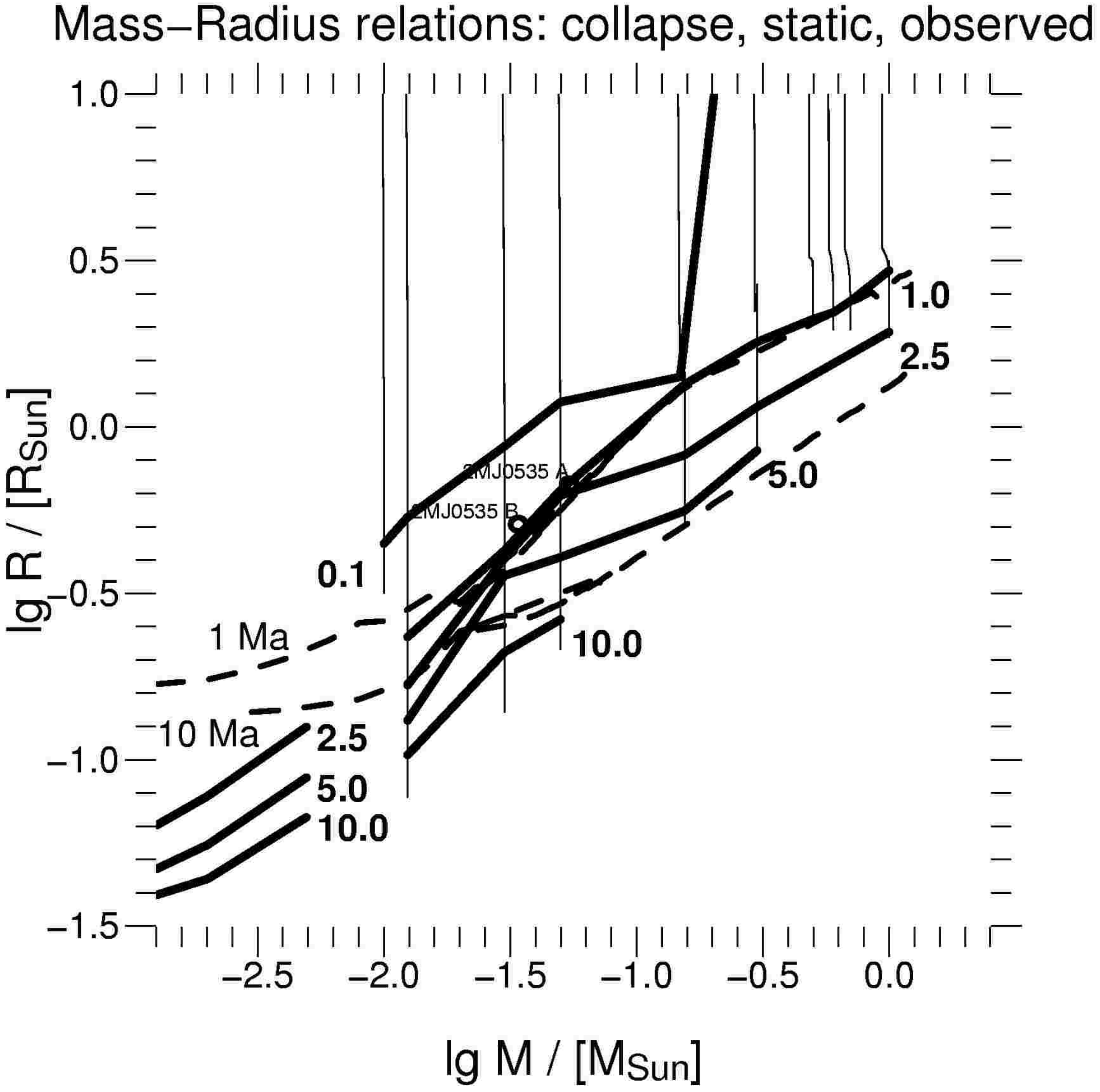


Upper Sco

GG Tau

Wuchterl 2005

Obs:
Mohanty
et al.
2004



2MJ0535

Eclipsing
Double
Line
Spectroscopic
Binary

in

ORI

Stassun et al.
PPV

HD 149026 b
Transiting Saturn
with 70 earth masses core

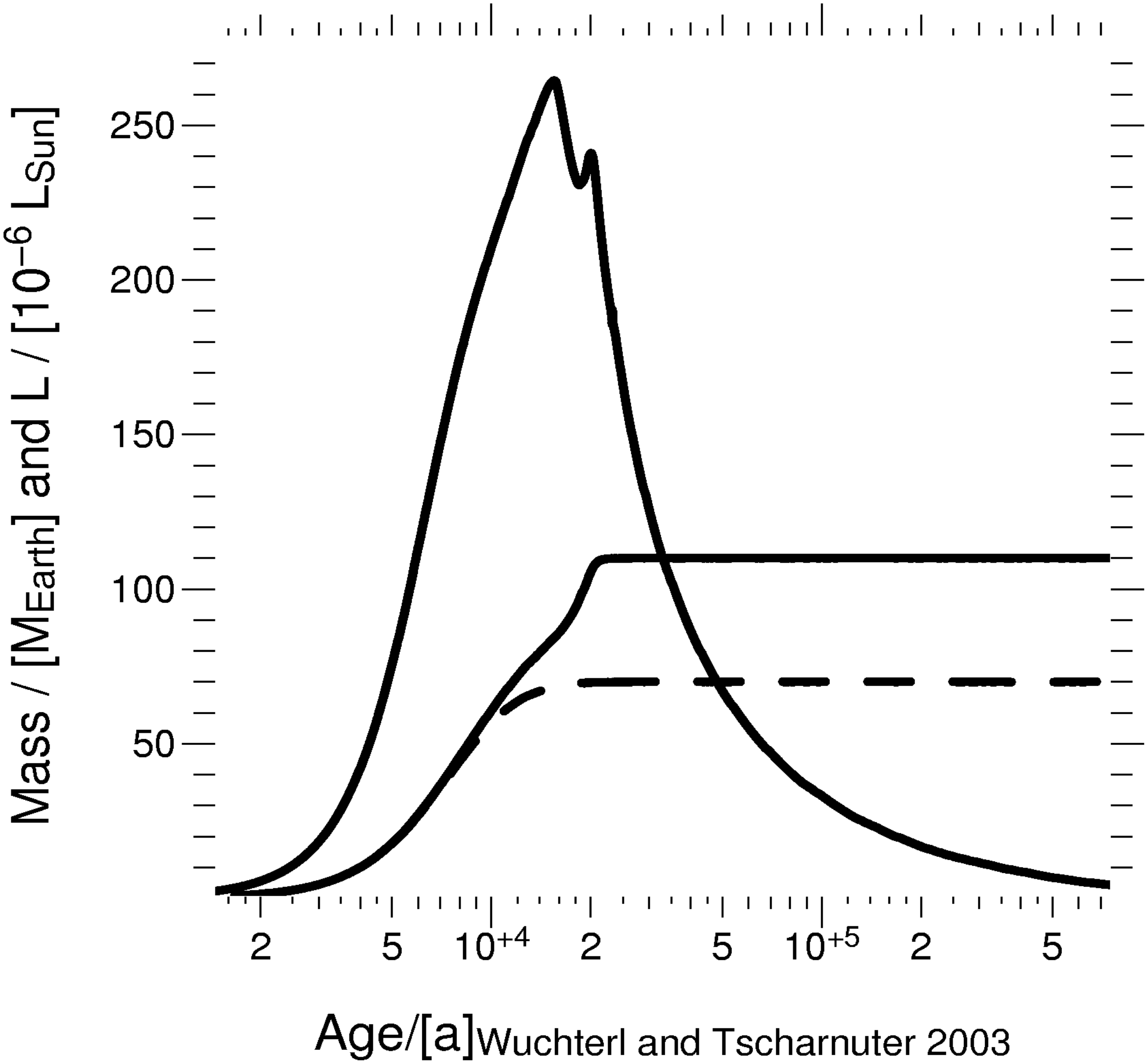
Sato, Fischer et al. 2005

Determine plausible nebula conditions
that produce core and envelope
as observed

But what about formation? Hydrodynamics for HD 149026b

- Take nebula conditions from equilibrium manifold of planets
- Core with simple, particle in box planetesimal accretion
- Calculate accretion history
- Mass reservoirs required by equilibrium

HD149026b: Mass and Luminosity CRFD+PiB(10)



Wuchterl and Tscharnuter 2003

HD 129046b

- Dynamics allows core and envelope accretion to masses required by equilibrium
- Full radiation hydrodynamic calculation with convection shows the envelope to remain *quasi-static* throughout the entire evolution
- Pegasi planets may have simple, static evolution, that is straight forward to calc.
- Linear prediction of diverse planetary pathways confirmed.
- How to make it far out with 70 ME core?

A note on mass availability

If we would be in the 51 Peg System, our minimum mass nebula would then contain sufficient amounts of solids and gas, by construction!

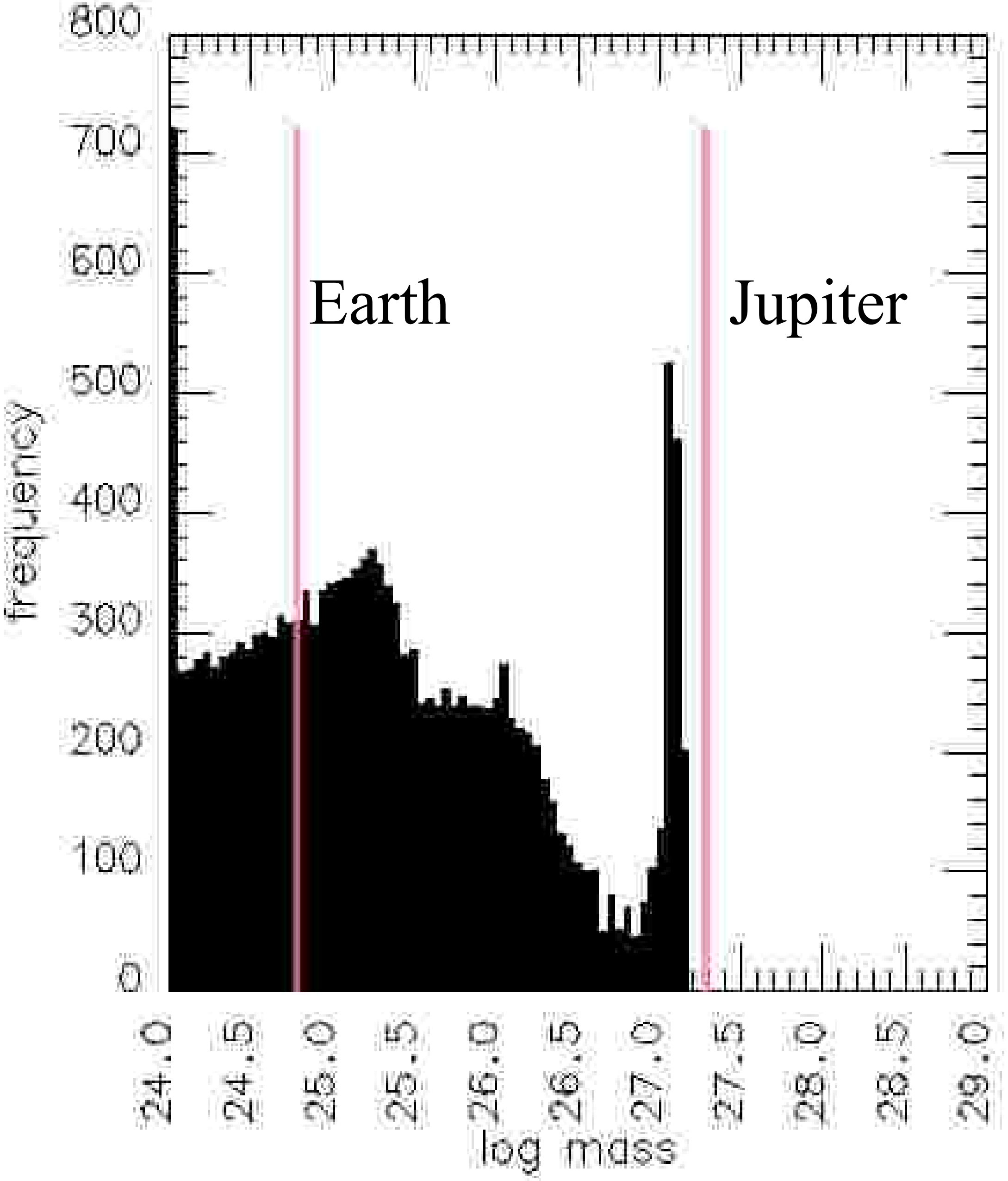
Ready for CoRoT?

COROT Mark I Mass Spectra

Stars: spectral types A,G,K,M;
Periods: 1 to 64 days.

http://www.astro.uni-jena.de/corot

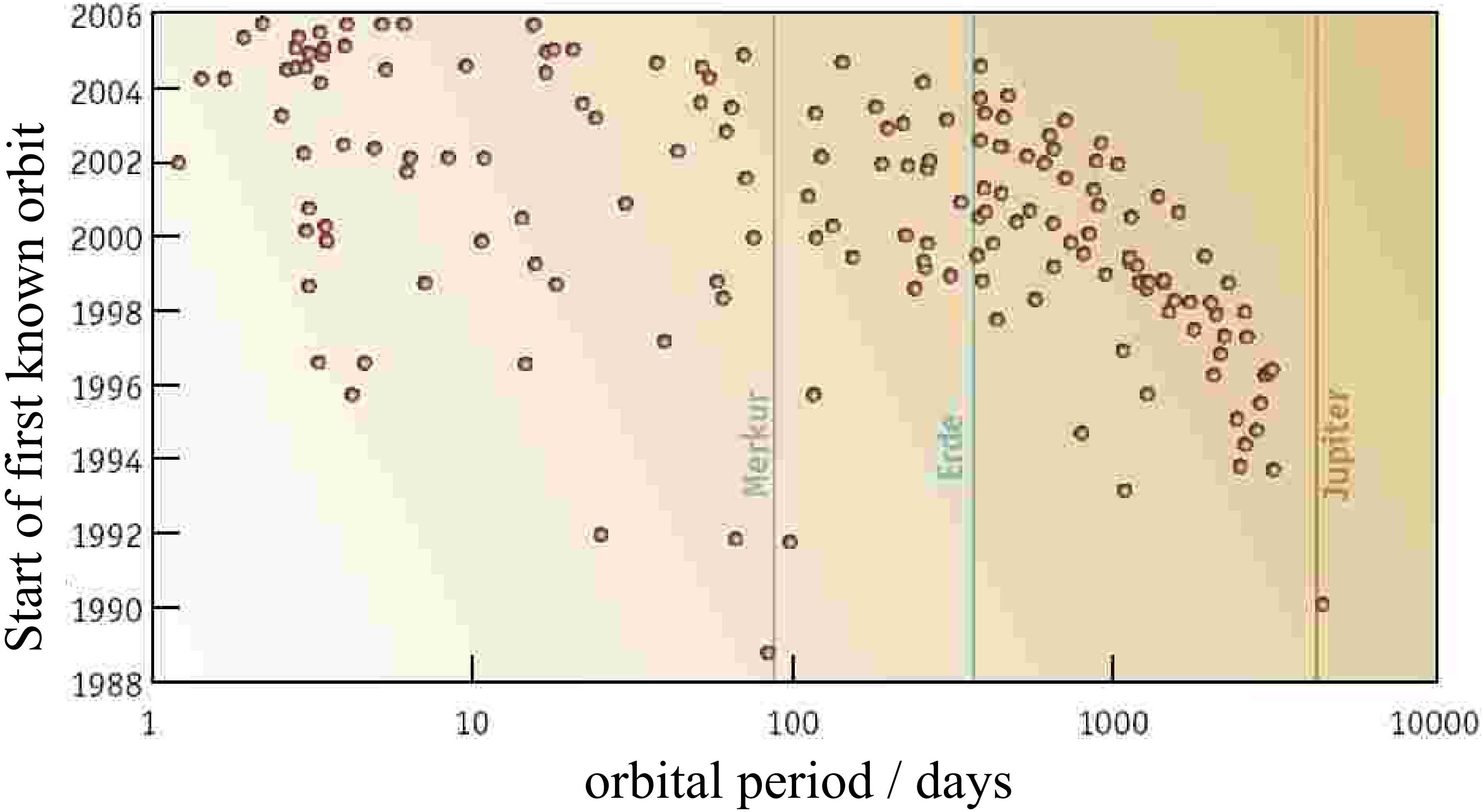
Christopher Broeg 2005



Planet masses in 4 day orbit around a solar mass

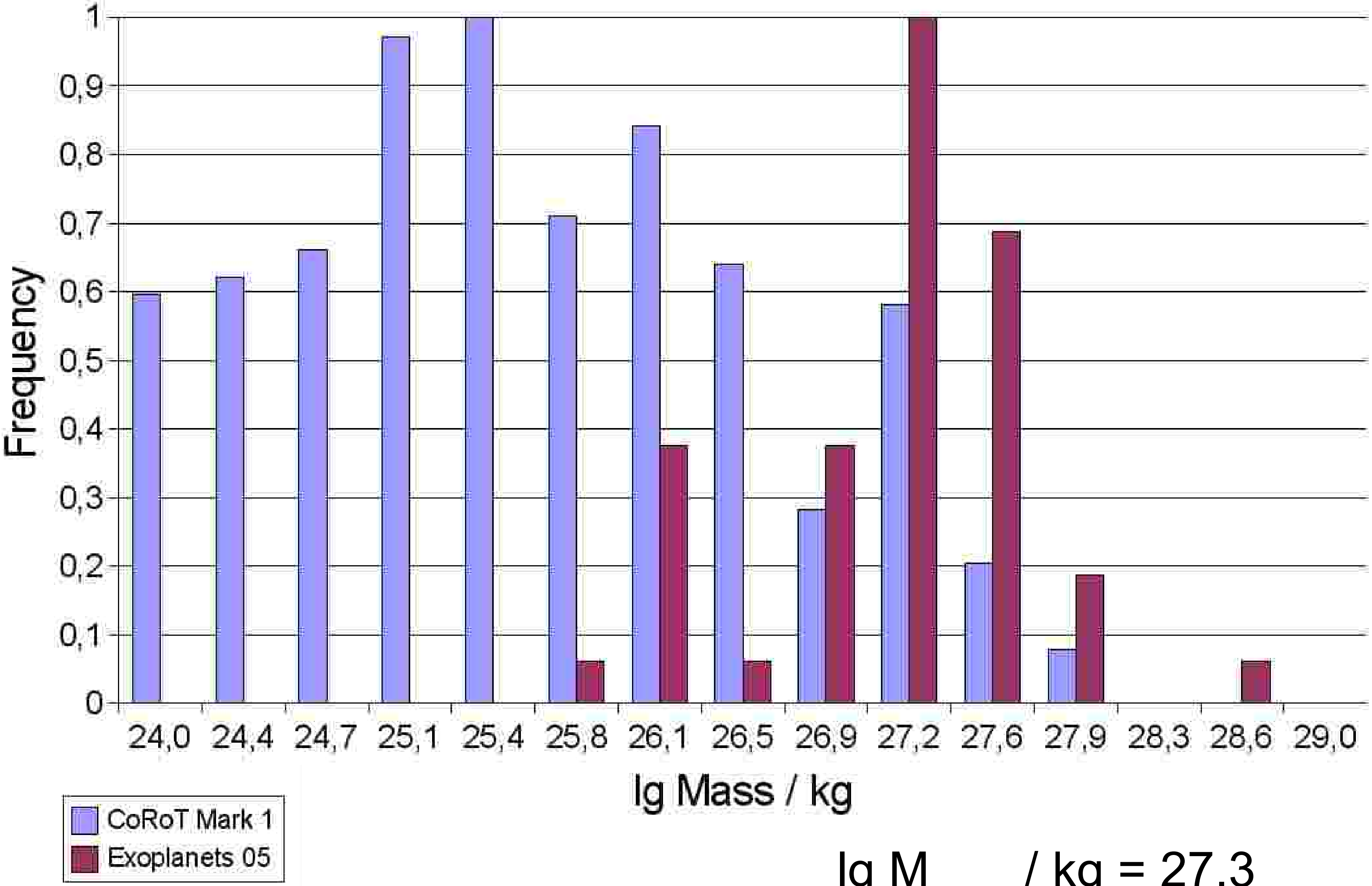
Exoplanets: First known orbits

Planets plotted at publication date minus orbital period



Exoplanet Masses

CoRoT Mark 1 (Theory $M_*=M_{Sun}$) vs. 2005 Obs.



$\lg M_{Jupiter} / \mathrm{kg} = 27.3$

CONCLUSION

- One theoretical approach for 0.04 to 100 AU
- Determines masses for very young planets
- Solves the large core puzzle for HD 149026b
- First principles predictions of planetary mass spectra for CoRoT