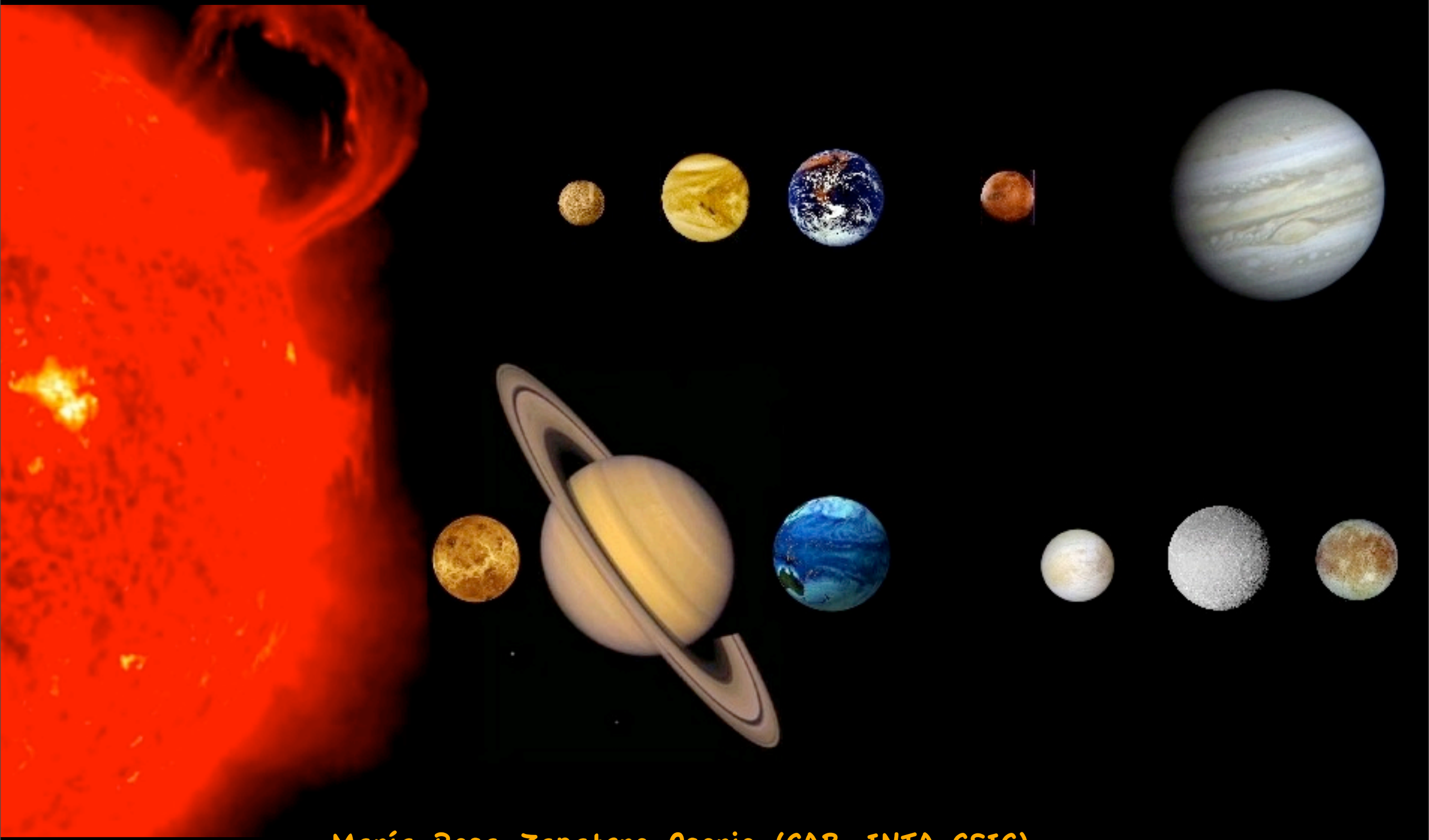
Planets and planetary systems formation: advances and challenges



María Rosa Zapatero Osorio (CAB, INTA-CSIC)

Cartagena, 23 July 2012

Numbers and units

Earth mass = 1 M_{earth} = 5.97 x 10^{24} kg = 0.00315 M_{jup}

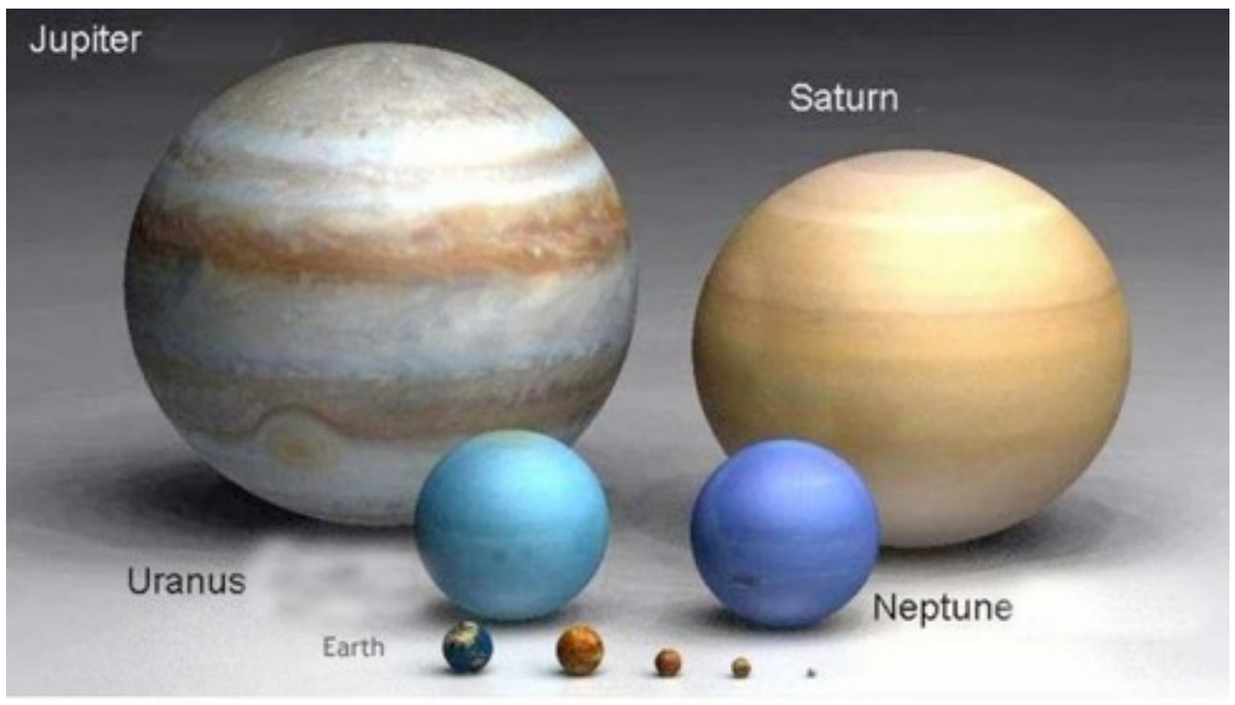
Jupiter mass = 1 M_{jup} = 1.8986 x 10^{27} kg = 317.83 M_{earth}

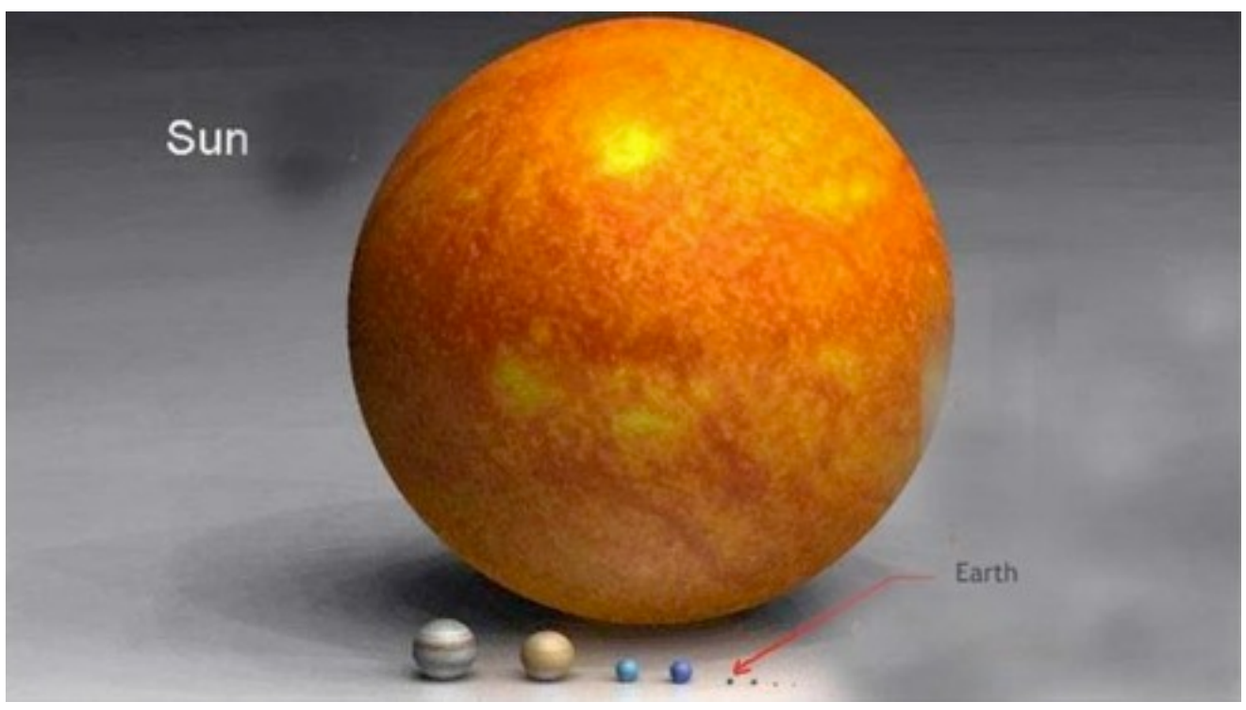
Solar mass = 1 M_{sol} = 1.9889 x 10^{30} kg = 1047.5 M_{jup} = 332950 M_{earth}

1 Myr = 10^{6} yr

1 AU = 149,598,000 km (mean Earth-Sun separation).

a = orbital semi-major axis, orbit "size". Measured in AU.





Outline

- Planet definition.
- Images of planets.
- Planets indirectly detected.
- Theories of planet formation.

Copyright Display will

Planets

Working definition (this presentation): objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity).

Planets

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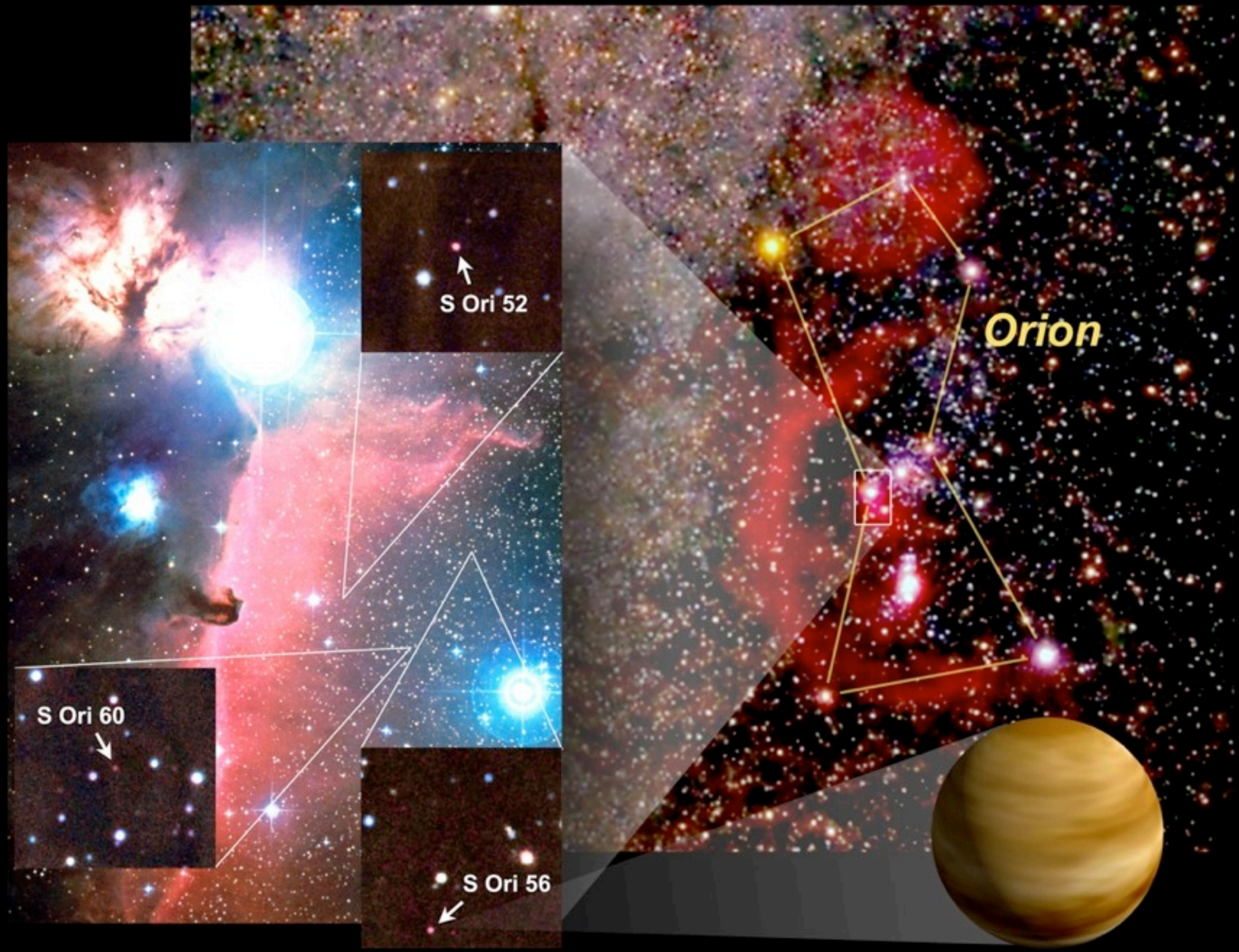
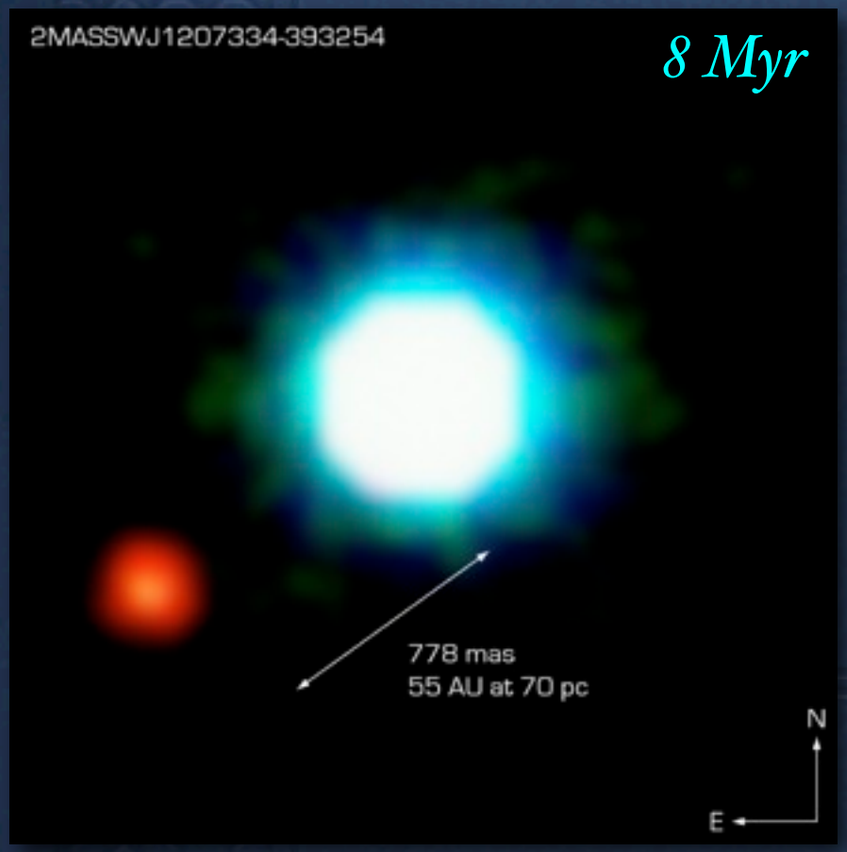
Type	Masses known to date	Ages	Metallicity	N known to date
Free-floating	5-13 M_{jup}	<10 Myr, a few with ~Gyr	approx. solar	a few tens
Orbiting stars a < 5 AU	2 M_{earth}-13 M_{jup}	~1-5 Gyr	0.3-3 x solar	~700
Orbiting stars a > 5 AU	~0.1-13 M_{jup}	0.1-5 Gyr	approx. solar	a few tens
Orbiting stellar corpses	~0.02 M_{earth}-1 M_{jup}	?	?	several

Free-floating planets

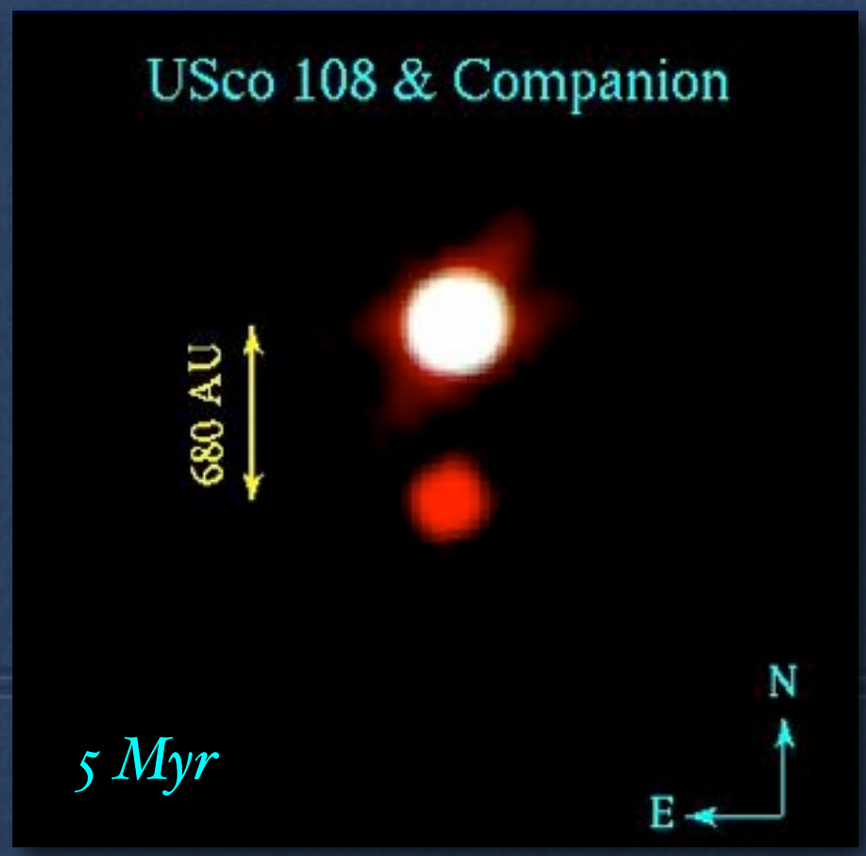


Diseño: Gabriel Pérez / IAC

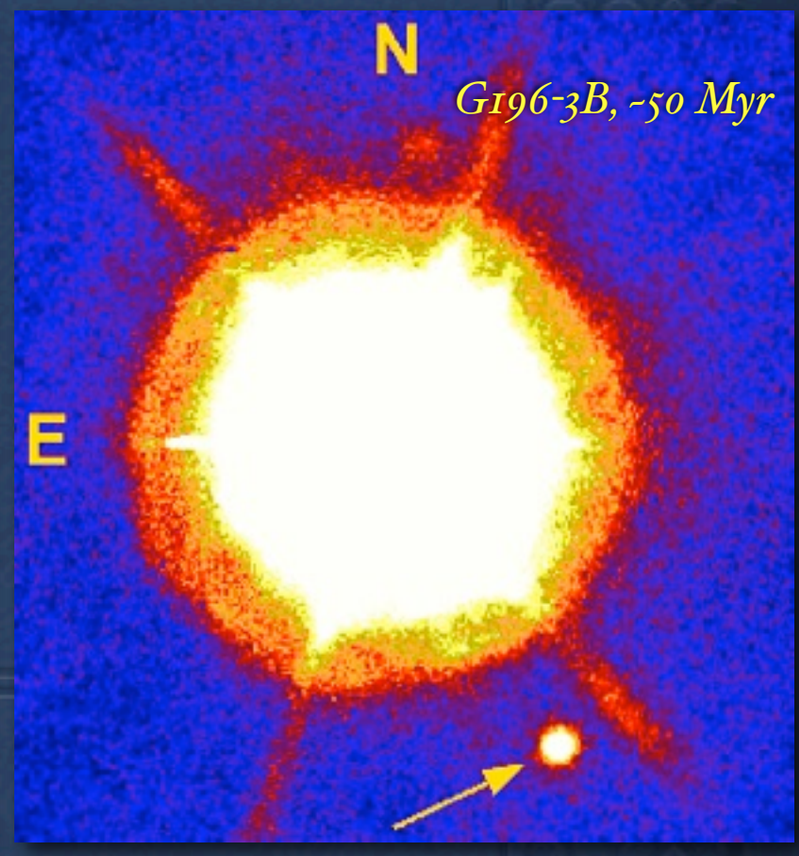
Planets in wide orbits



Planet (5 M_{jup}) around a brown dwarf (25 M_{jup}) in the TW Hya association (Chauvin et al. 2004).

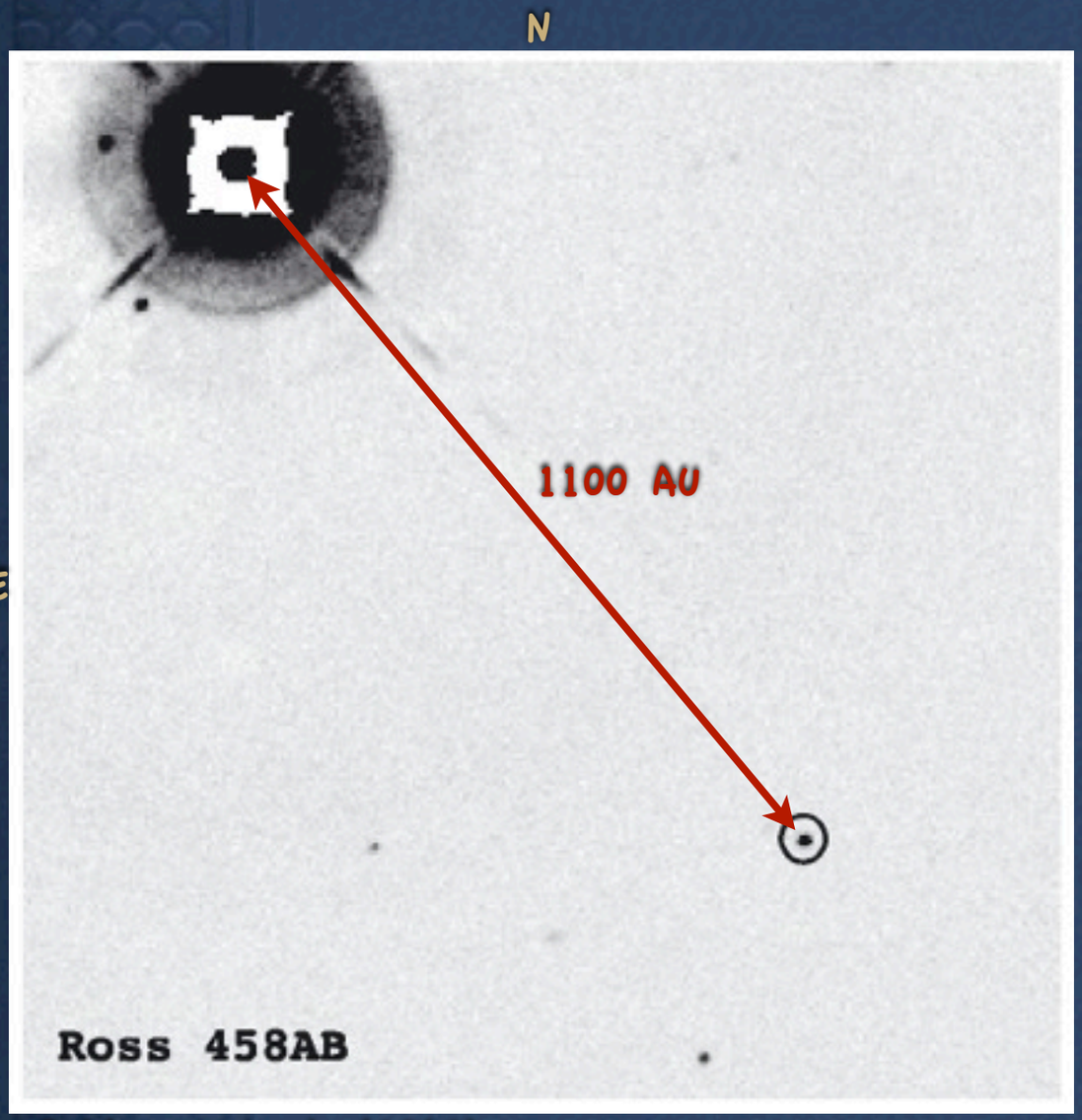


Planet (13 M_{jup}) around a brown dwarf (50 M_{jup}) in the Upper Sco association (Béjar et al. 2008).



Brown dwarf (10-25 M_{jup}) around a low-mass star (0.4 M_{sol}) in the field, orbital separation of ~350 AU (Rebolo et al. 1998, Science).

Ross 458C: a distant planet



Goldman et al. (2010)

Ross 458C is orbiting a binary star.
Likely age: 150-800 Myr.
Metal-rich system: [Fe/H] = +0.2-0.3.

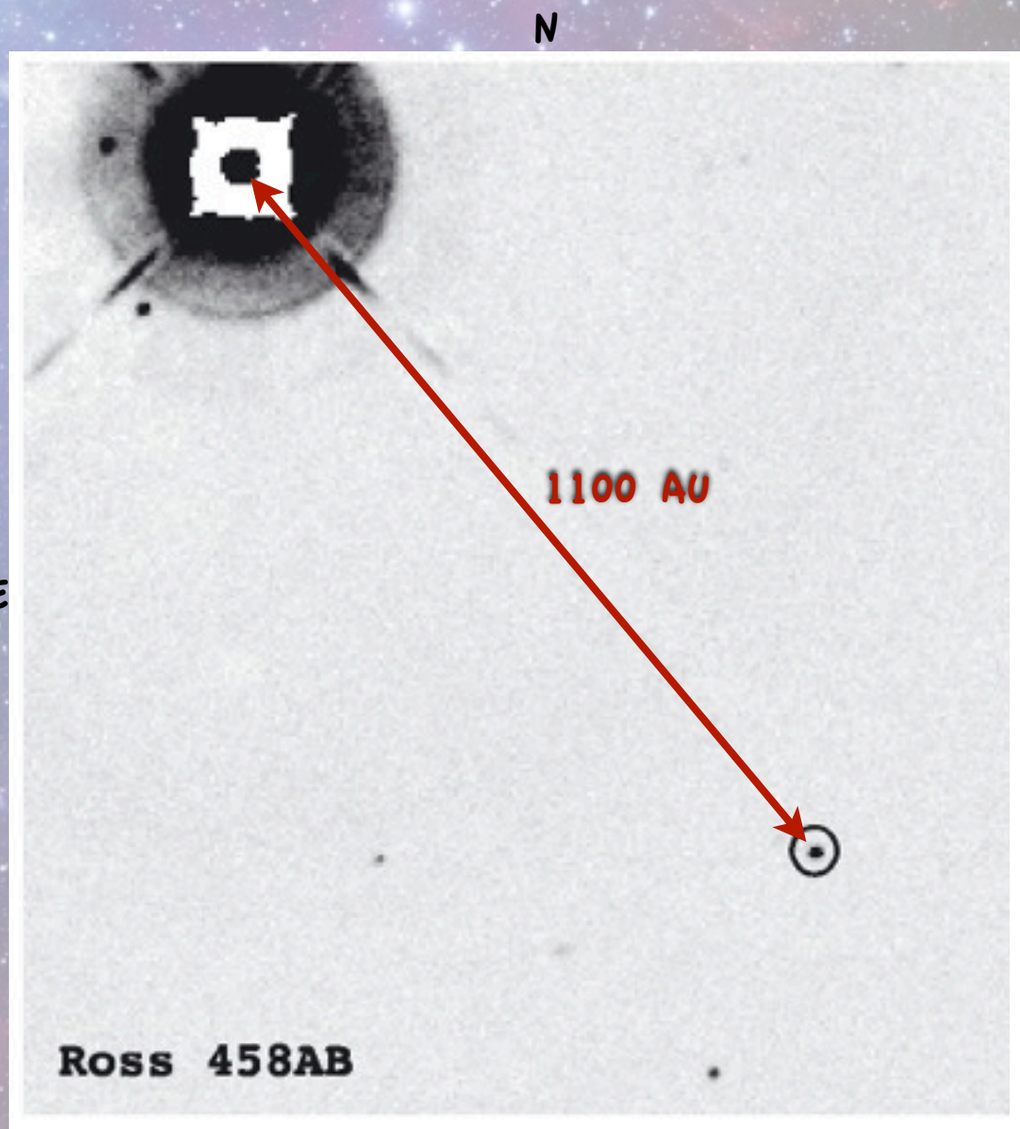
Stellar orbital separation: 5.4 AU.
Planet - binary star separation: 1100 AU.

Stellar mass: 0.6 + 0.09 M_{sol}.
Planet mass: ~10 M_{jup}.

Stellar temperatures: ~3800 K,~2500 K.
Planet temperature: ~650 K

Ross 458C: a distant planet

Planet atmosphere rich in methane, water vapor, and ...



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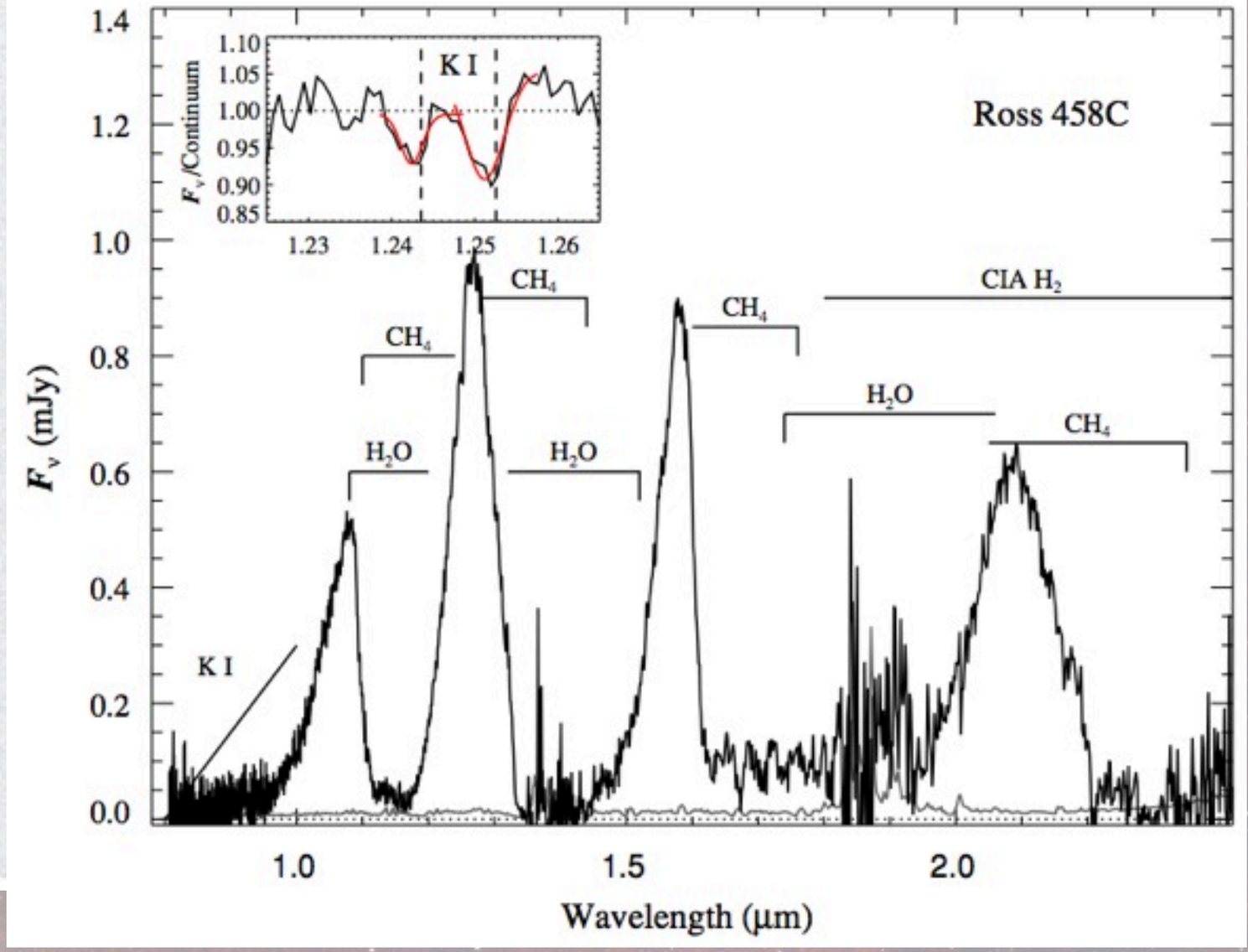
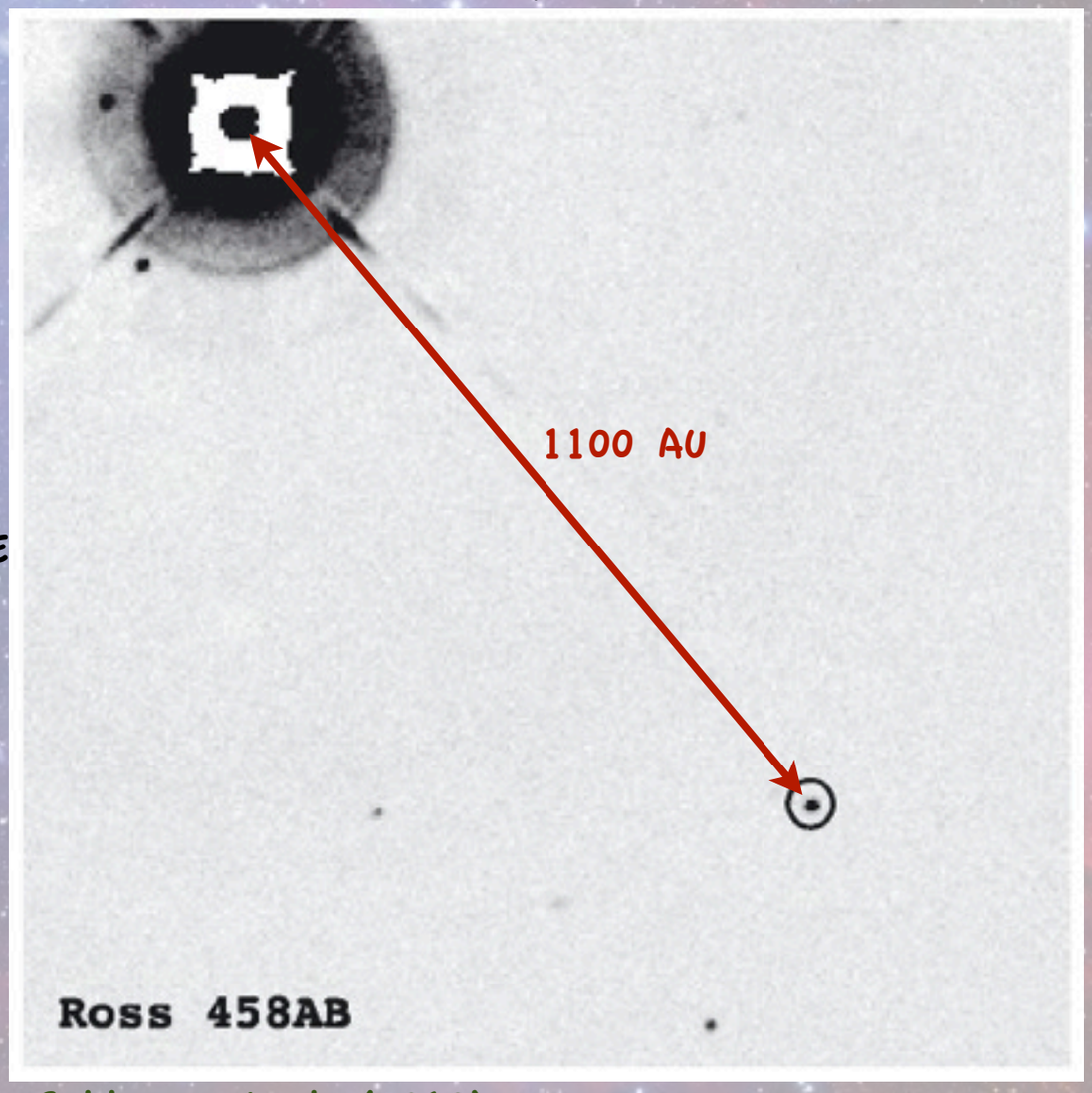


Burgasser et al. (2010)

Ross 458C: a distant planet

... condensate clouds!!!



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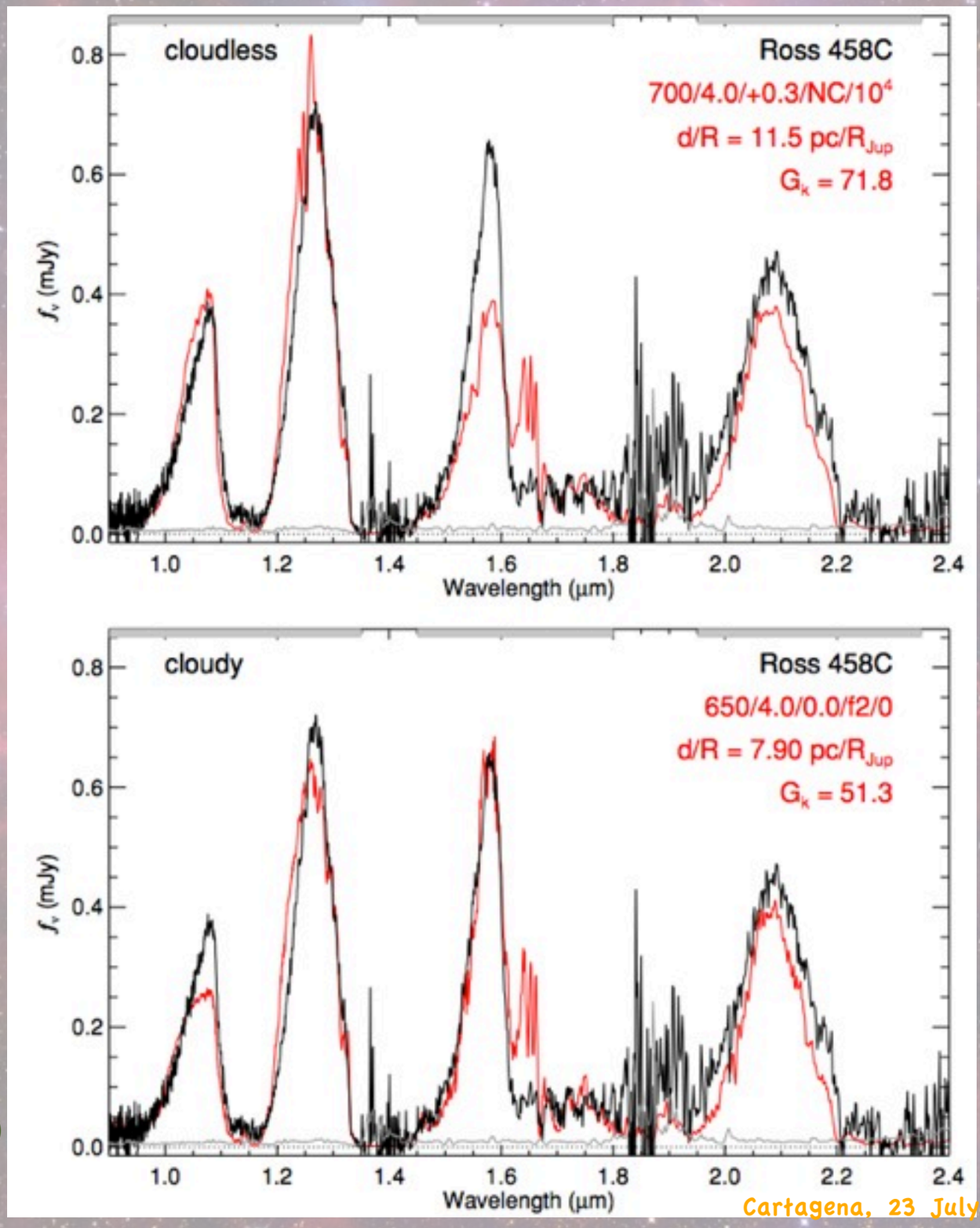

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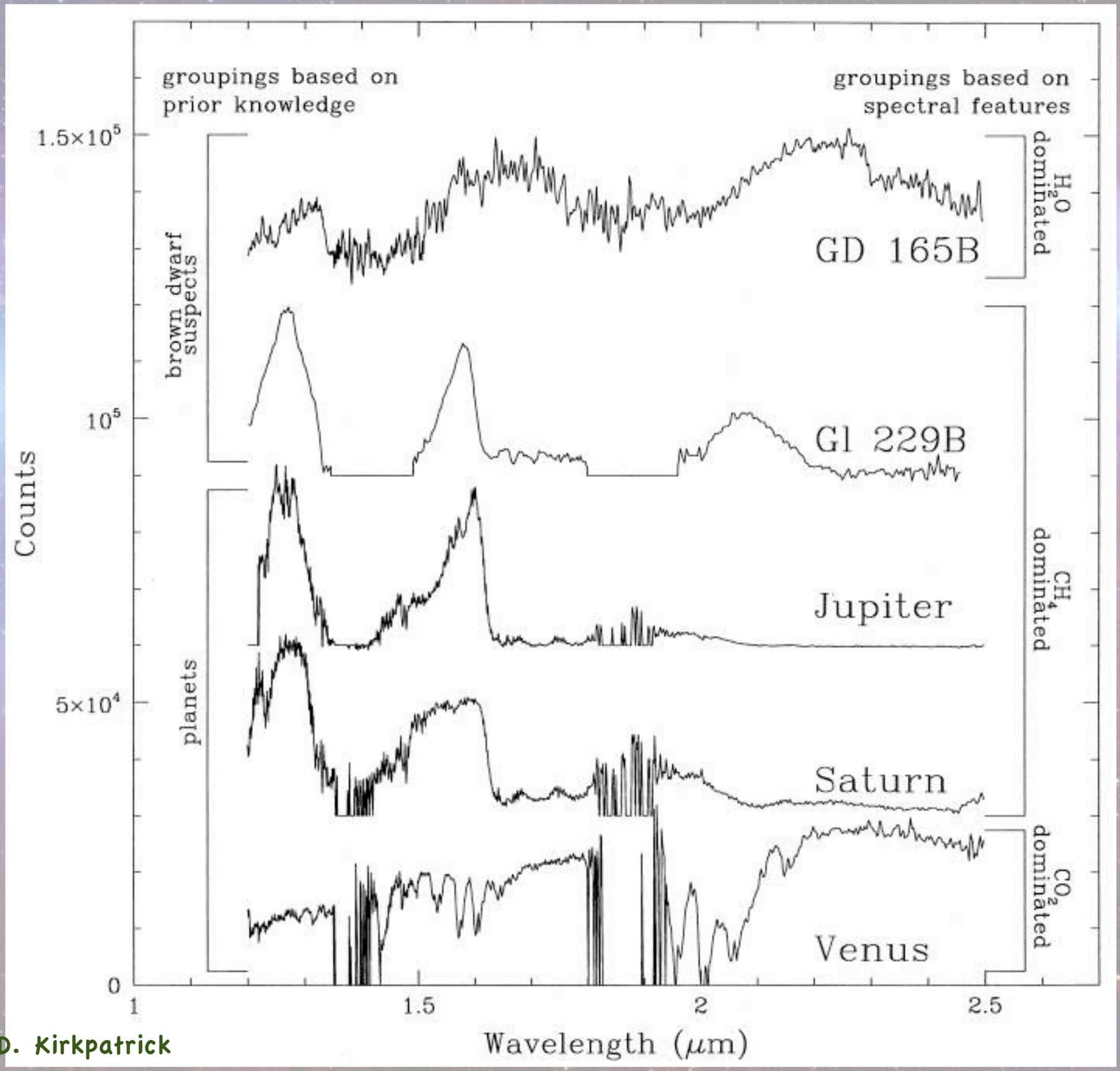
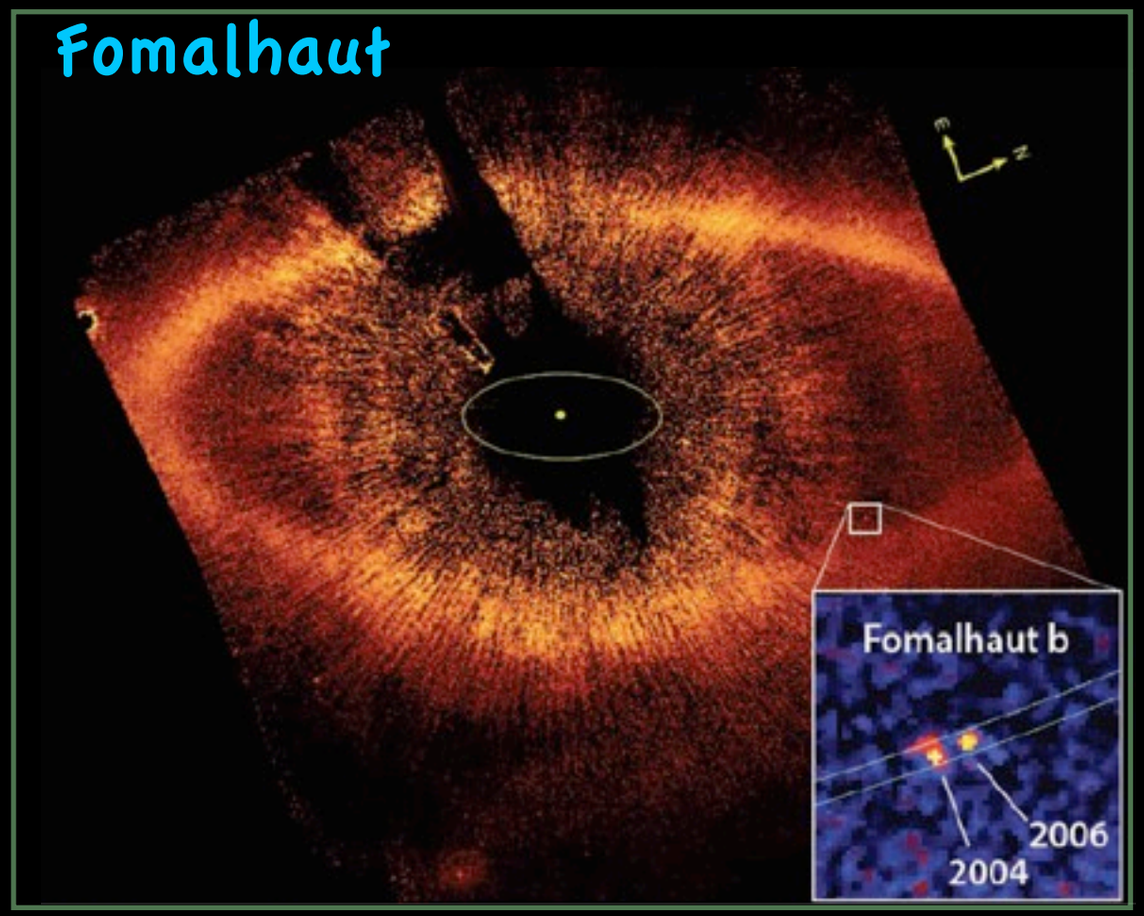


Courtesy of J. D. Kirkpatrick

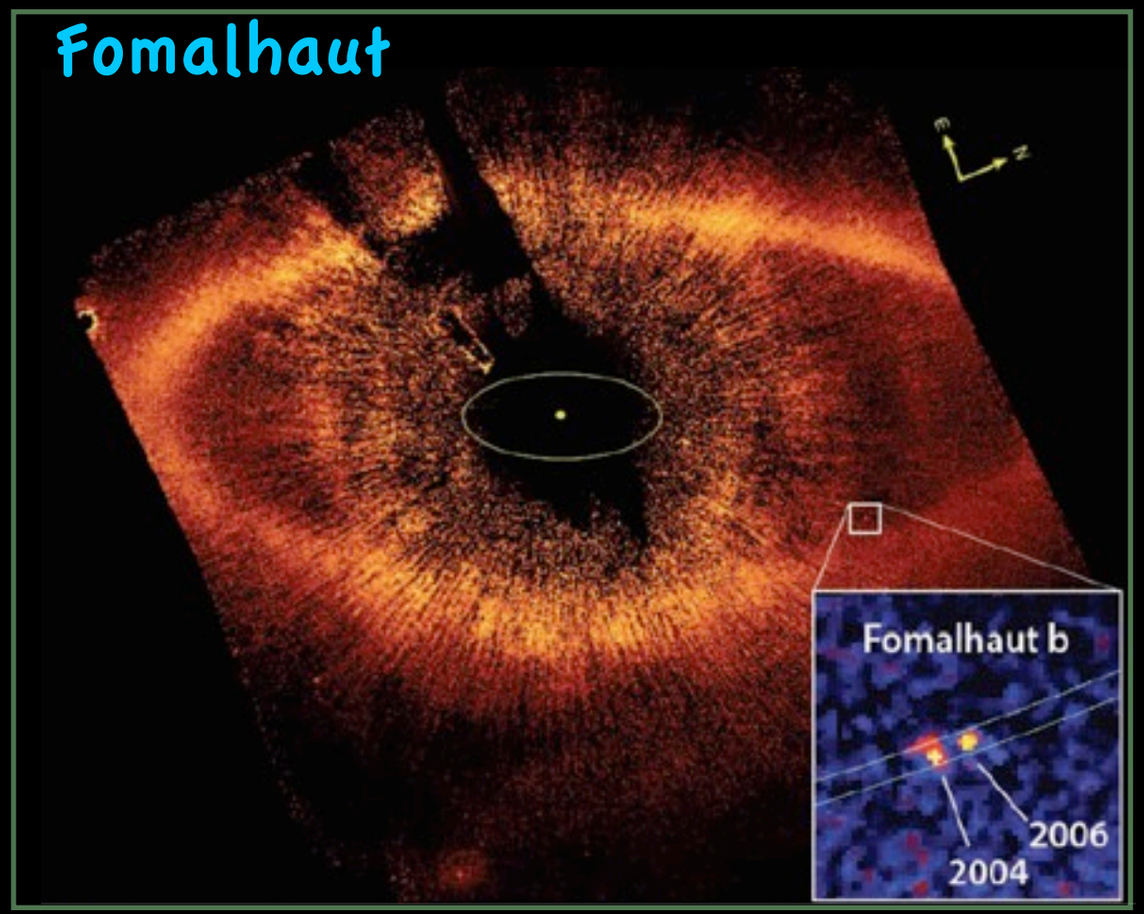
Planets orbiting massive stars with debris disks



A planet orbiting at 115 AU from the A3V, 100-300-Myr star Fomalhaut (Kalas et al. 2008, Nature)

Cartagena, 23 July 2012

Planets orbiting massive stars with debris disks



A planet orbiting at 115 AU from the A3V, 100-300-Myr star Fomalhaut (Kalas et al. 2008, Nature)

Three planets around the 1.5-M_{sol}, 30-160-Myr star HR 8799 in counter clockwise orbits (Marois et al. 2008, 2010, Nature):

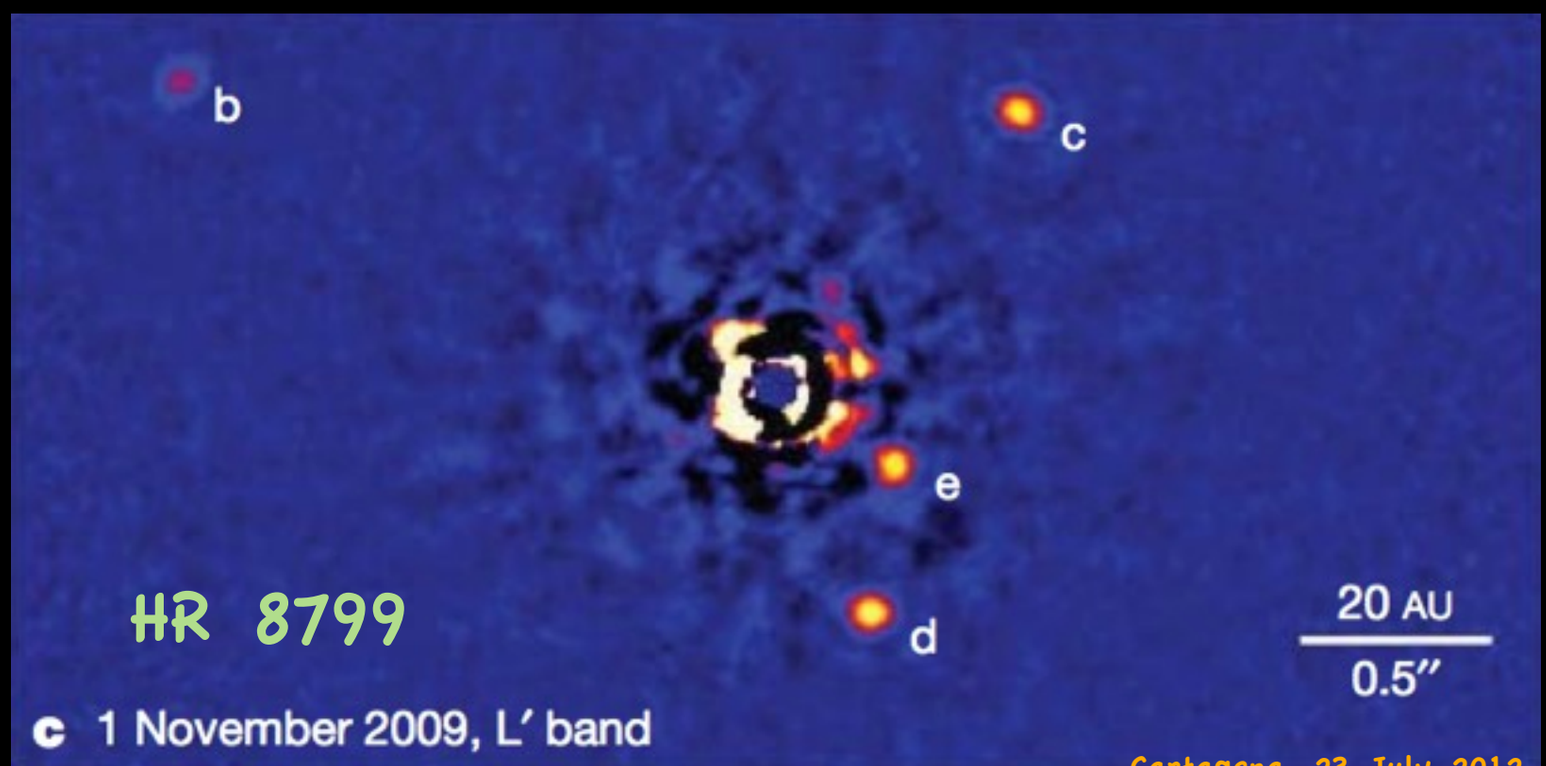
b = 7 M_{jup}, 68 AU

c = 10 M_{jup}, 38 AU

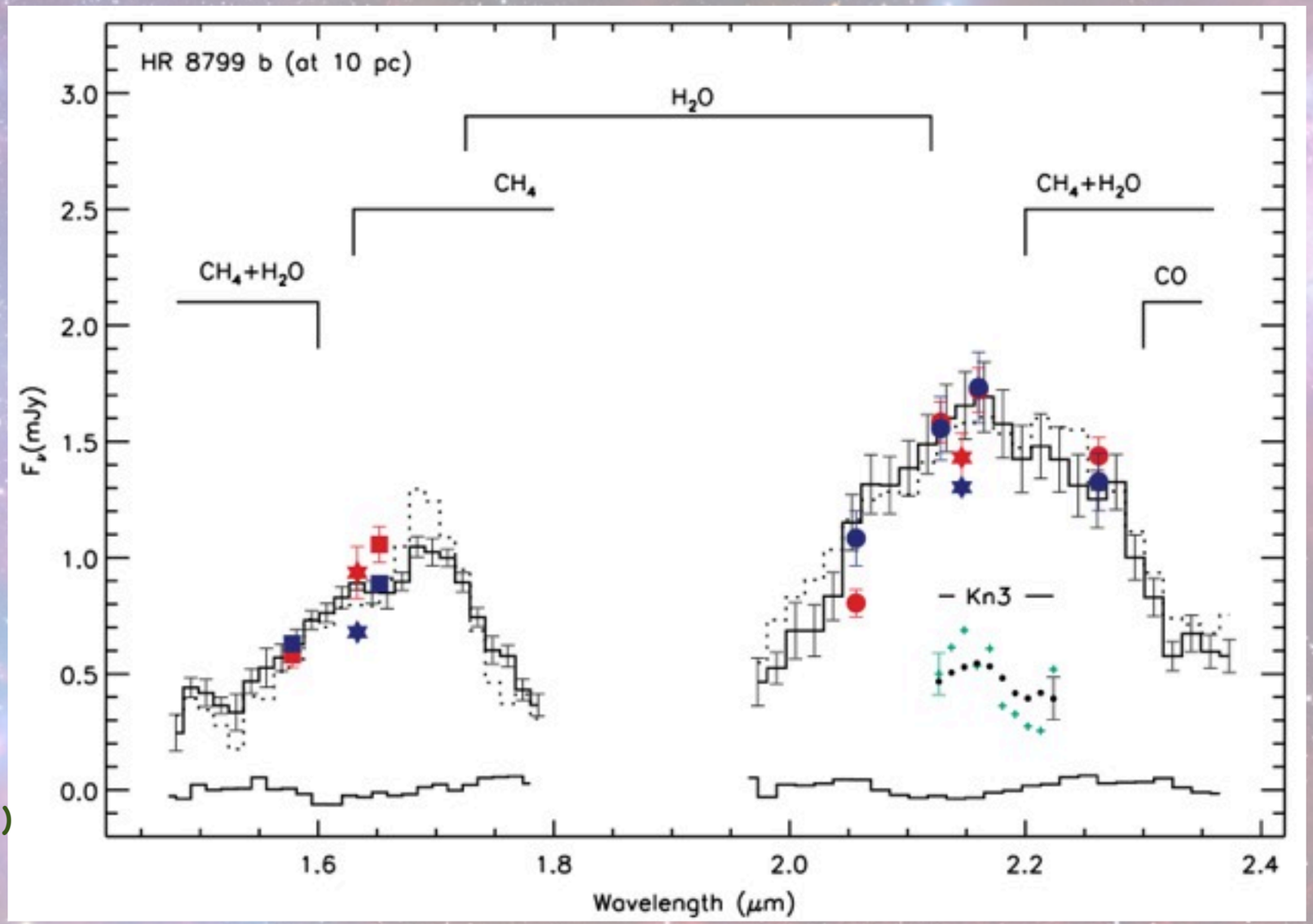
d = 10 M_{jup}, 24 AU

e = 5-13 M_{jup}, 14.5 AU

The debris disk appears to be encircling the HR 8799 planetary system (350 μm) and is situated between 100 and 300 AU (Patience et al. 2011).



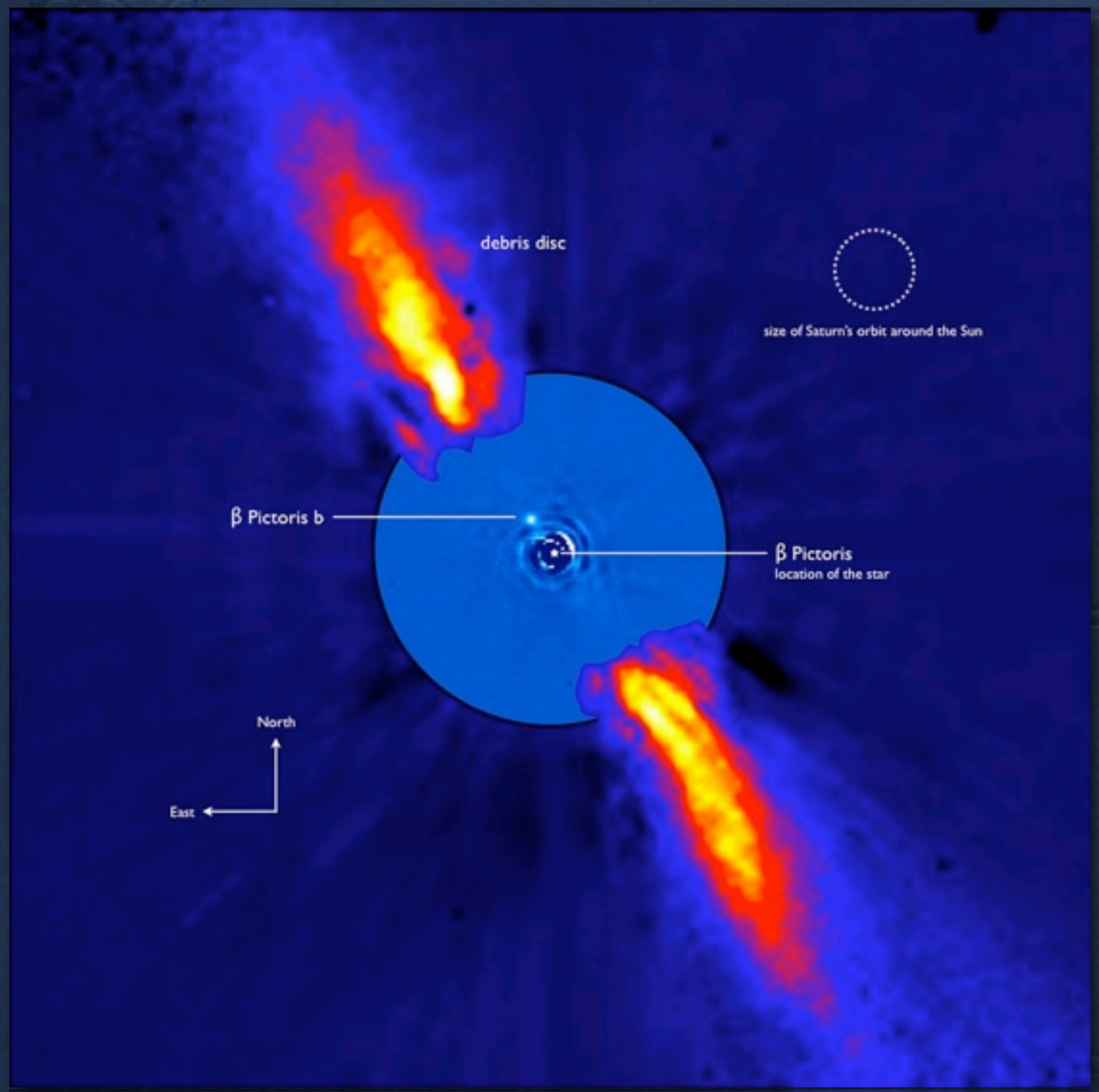
Spectral energy distribution of planet HR 8799b



Barman et al. (2011)

- Thick photospheric dust cloud opacity is invoked to explain the planet's red colors and relatively smooth near-infrared spectrum.
- Strong water vapor absorption is detected, indicating a hydrogen-rich atmosphere.
- Weak CH_4 absorption hints at efficient vertical mixing and a disequilibrium CO/CH_4 ratio at photospheric depths.

Images of planets orbiting massive stars with debris disks



Lagrange et al. (2008)

Planet ß Pictoris b orbiting the 1.75-Msol star ß Pictoris, which has an age of 12 Myr and one of the largest debris disks ever seen (1100 AU).

The planet has an estimated mass of 8-10 M_{jup} and it is located at about 10 AU from its parent star.

The young age of this planetary system (12 Myr) proves that giant gas planets can form in a few Myr.

Images of planets orbiting massive stars with debris disks

Since discovery, ß Pictoris b was reobserved three times in the following few years. The planet moved from one side of the star in 2003 to the other side in 2009 (Lagrange et al. 2010), suggesting that ß Pictoris b may complete one full orbit in about 17 yr.

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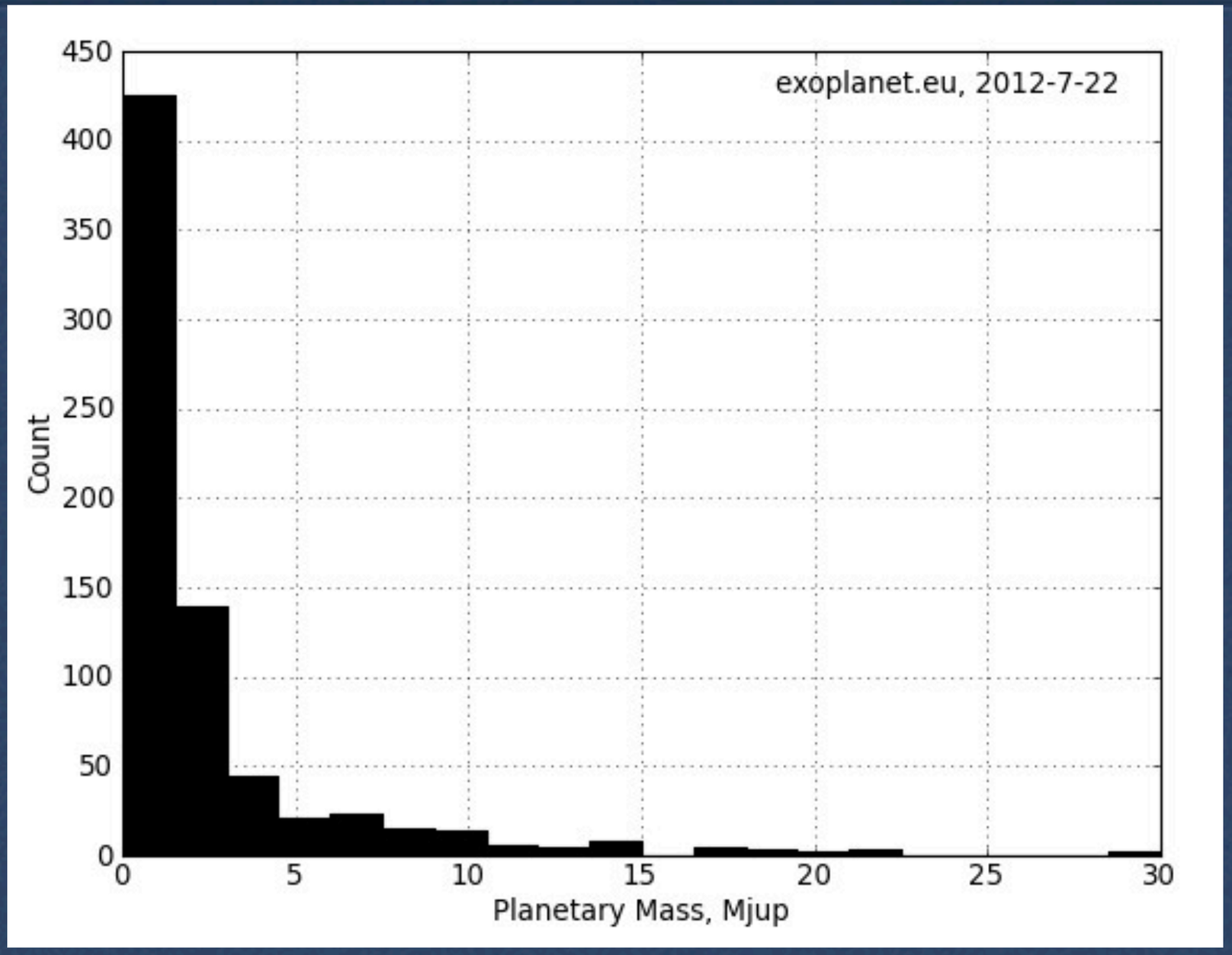
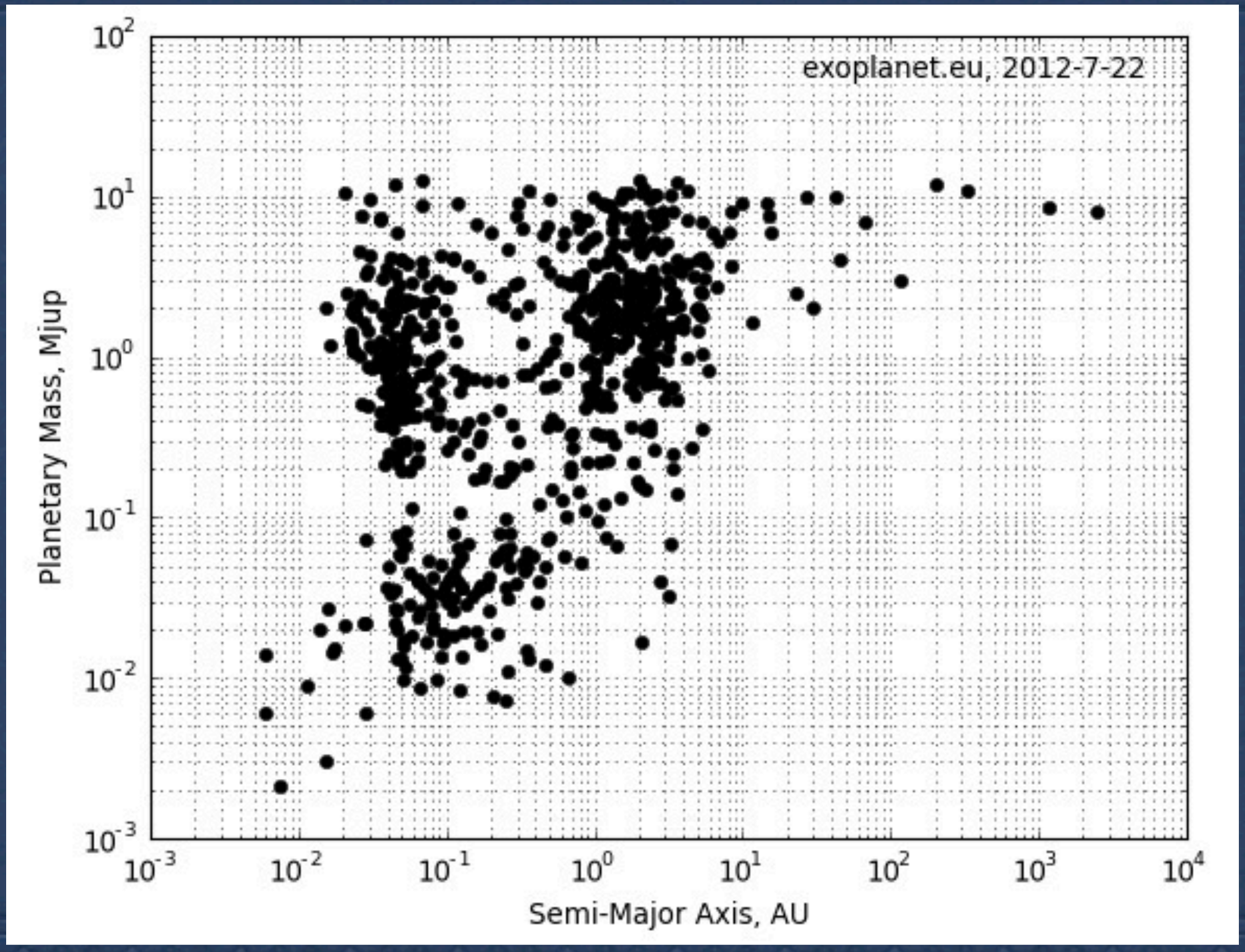
Planets found by indirect techniques



Planets bound to stars with semi-major axis a ≤ 5 AU.
About 3-30% of solar-type stars harbor Jupiter-like planets.

Planets found by indirect techniques



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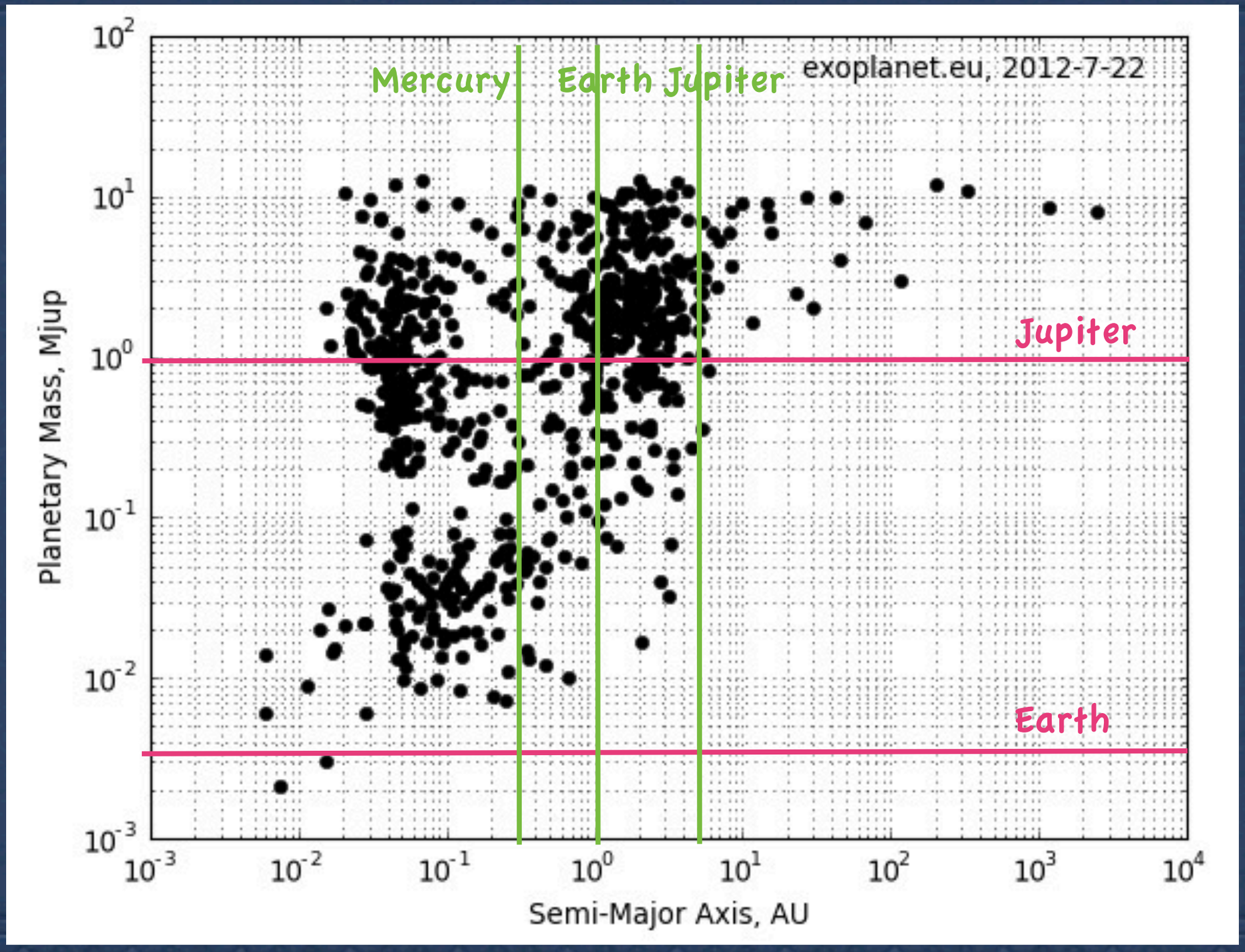

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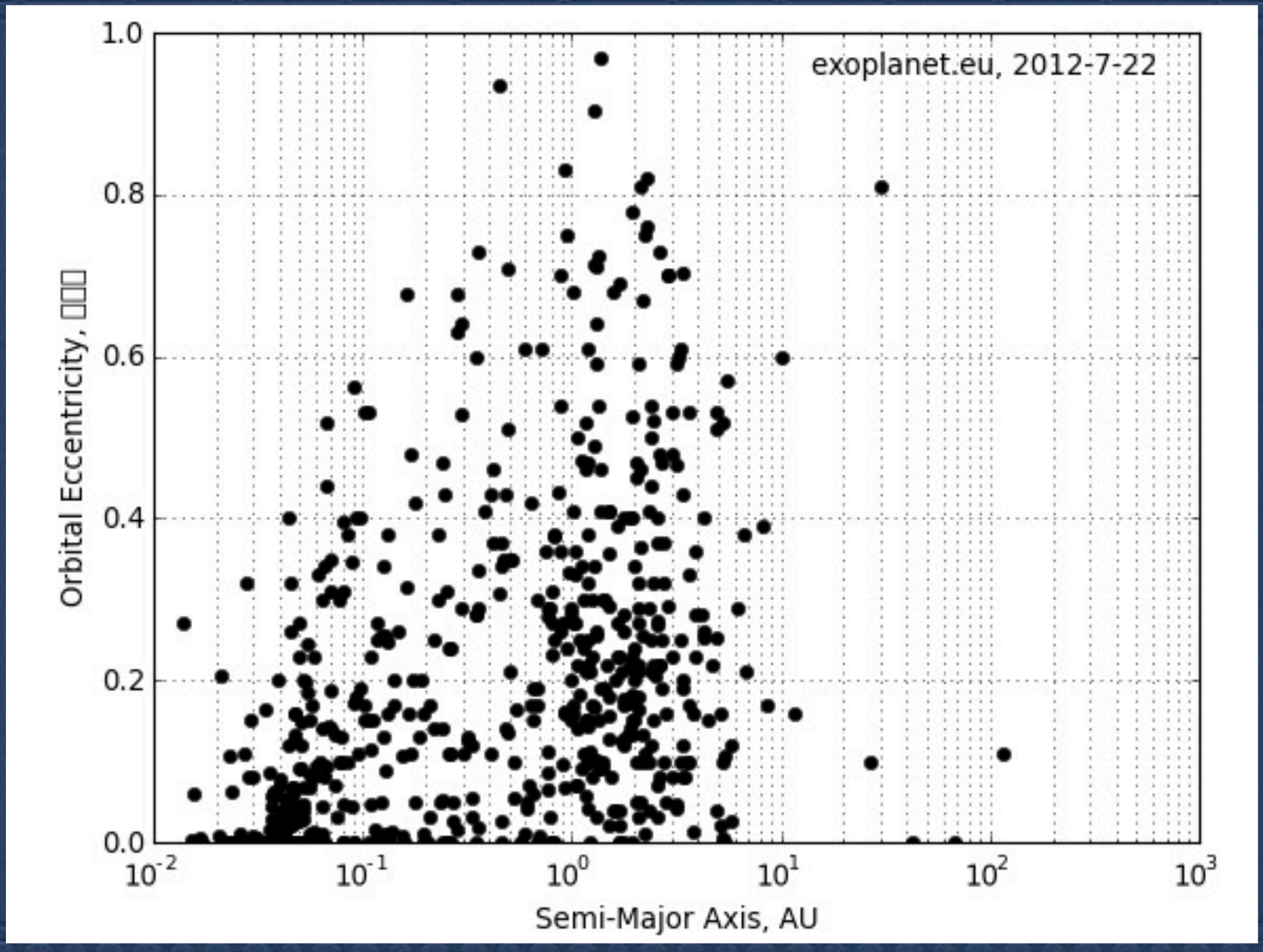

Planets bound to stars.

Some observational facts ...

- Giant planets appear unbound and bound to stars and brown dwarfs.
- Planet formation must be a “rapid” process: planets are also observed with ages ≤ 20 Myr.
- Free-floating planets can host “protoplanetary” disks.
- Giant planets populate all type of orbits around stars: very close-in (a<1 AU) and very distant orbits (a~1000 AU), circular and very elliptical orbits.
- For bound planets and orbits of less than 5 AU, less massive planets are more abundant than giant planets.
- For bound planets and solar-type host stars, giant planets are more abundant around metal-rich stars.

Some observational facts ...

... that must be explained by the theory of planet formation

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Theoretical scenarios for planet formation

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- Disk fragmentation through gravitational instability.
- Cloud fragmentation and collapse (stellar model).

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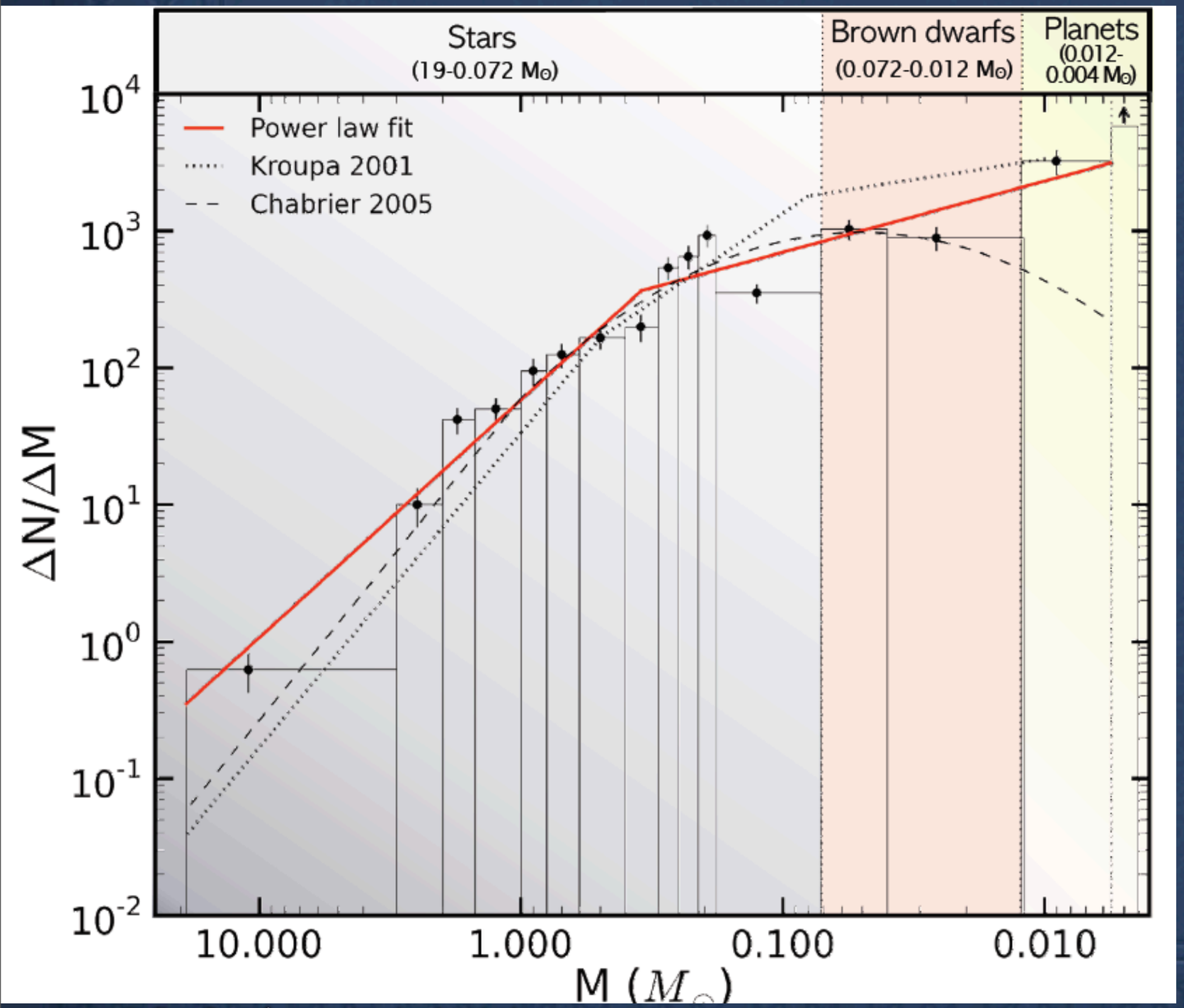
Other viable scenarios:

- Premature ejection of protostellar embryos (competitive accretion in clusters, ejection or cores from unstable multiple systems).
- Photoevaporation of pre-existing cores.

Molecular cloud fragmentation and collapse

- Mechanism believed to give rise to stars and stellar clusters.
- Star, brown dwarf and planet formation occurs down to the opacity limit for fragmentation.
- The opacity limit happens when molecular gas ceases to collapse isothermally and begins to heat up. The dynamical collapse is stopped and a pressure-supported fragment forms with an initial mass of 3-10 M_{jup} (model dependent).
- All available models make predictions that can be tested against observations.

Molecular cloud fragmentation and collapse



Peña Ramírez et al. (2012)

- Mass census of stars, brown dwarfs and free-floating planets of the σ Orionis cluster (3 Myr, 352 pc, solar metallicity).
- Rising function: number of objects increases for lower mas. Steeper slope for stars more massive than the Sun. Shallower slope for brown dwarfs and planets.

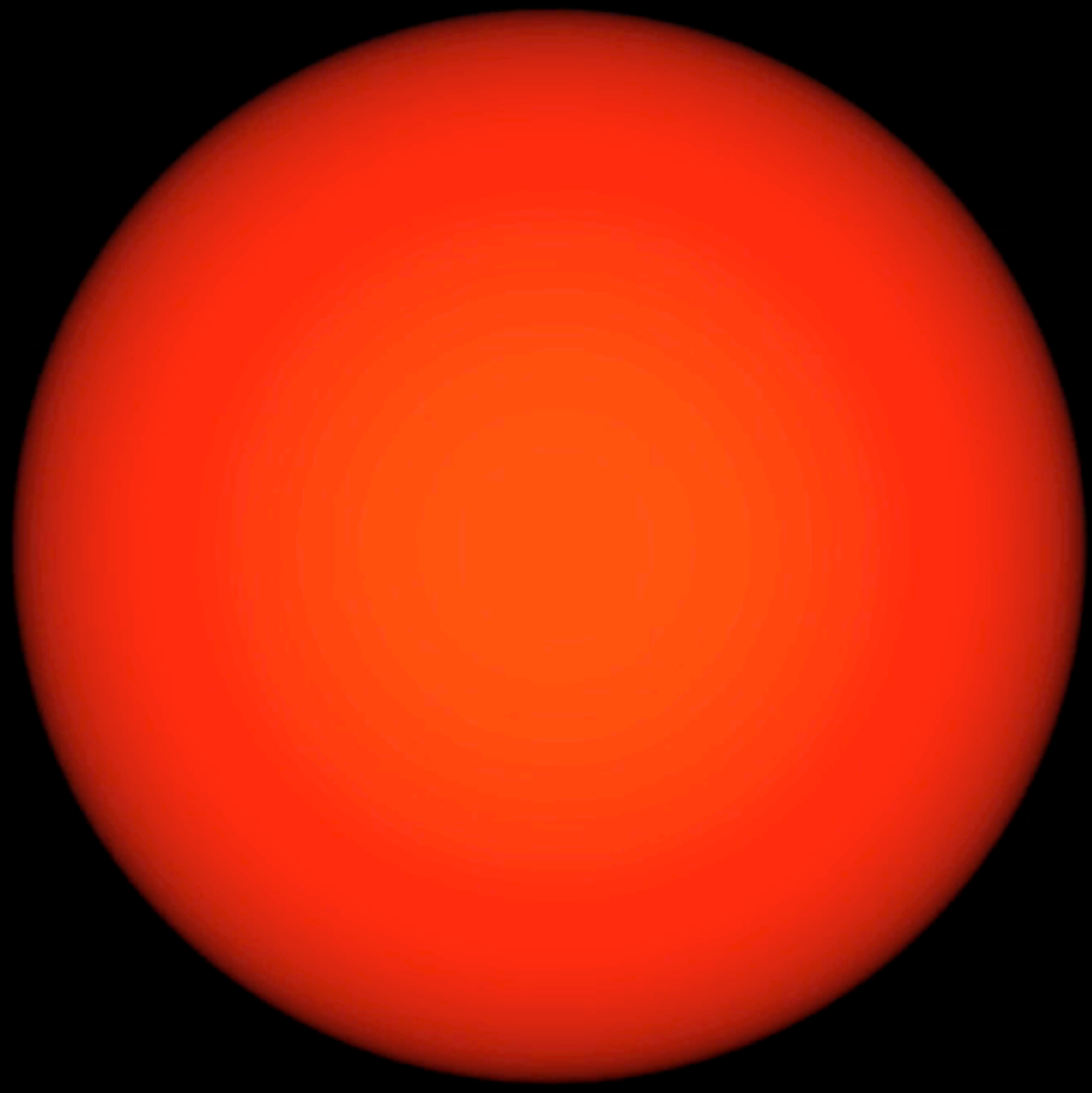
Molecular cloud fragmentation and collapse

Initial conditions: 50 M_{sol}, T=10 K.

Dynamical interactions play an important role!!!

Molecular cloud fragmentation and collapse

UK Astrophysical Fluids Facility



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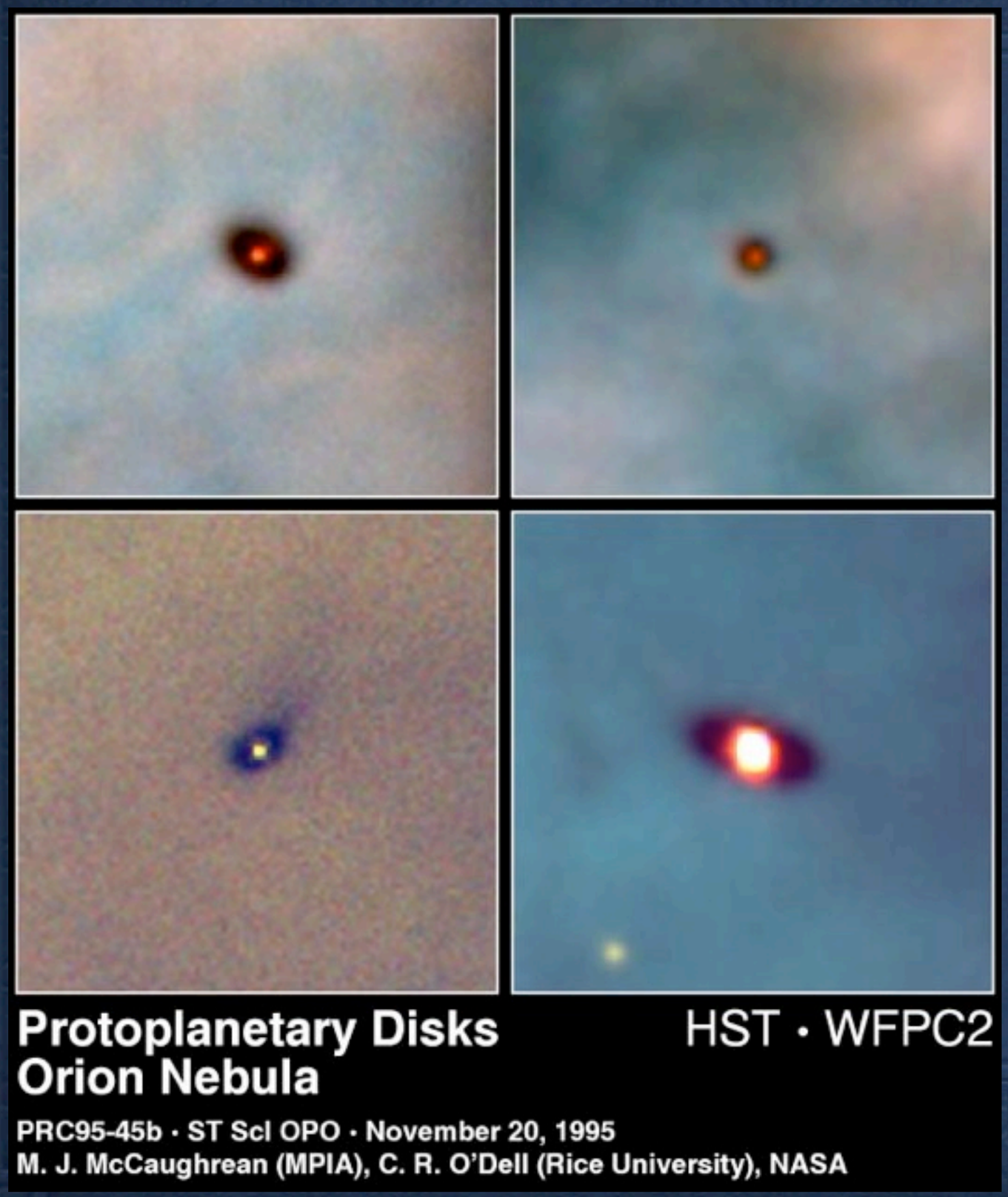
Matthew Bate

University of Exeter

Disks around young stars



Observations reveal the presence of disks of gas and dust around young stars (<10 Myr).

Disk masses: 0.01-0.1 M_{sol} = 10-104 M_{jup} = 3300-33000 M_{earth}.

Disks around young stars

Fly through the Orion nebula
(simulation using HST images).

Disks around young stars

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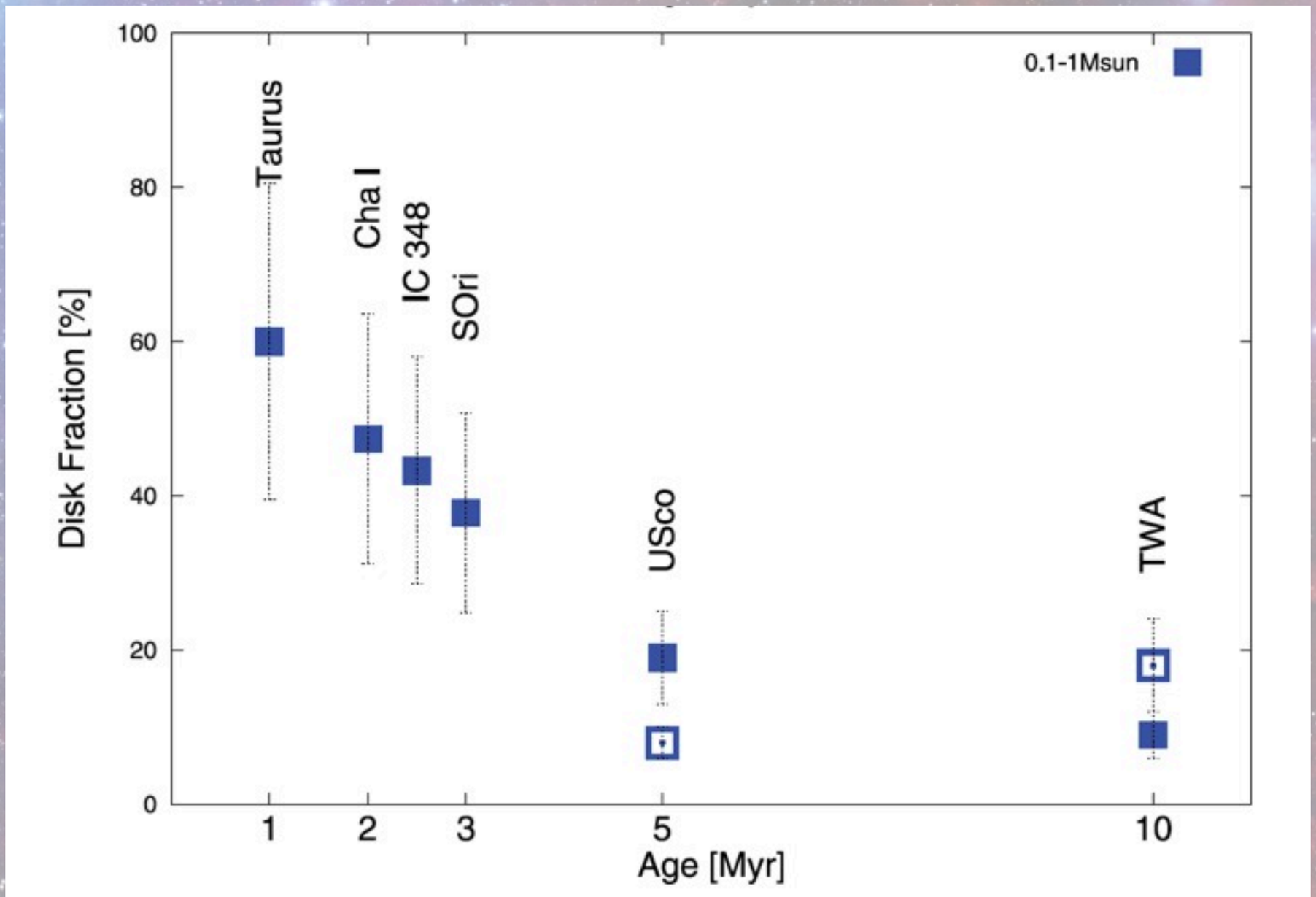
Disks around young stars



Riaz et al. (2012)

- Disks of gas and dust surrounding young stars have rather short lives (<10 Myr).
- Planet formation, including super-Jupiters, must be "fast".

Disk fragmentation, gravitational instability

- Requires high mass disks (>10% of host star mass), rapid cooling, rapid loss of angular momentum.
- Formation of giant planets (Jupiter-like) at large separations (typically > 10 AU) from the parent star.

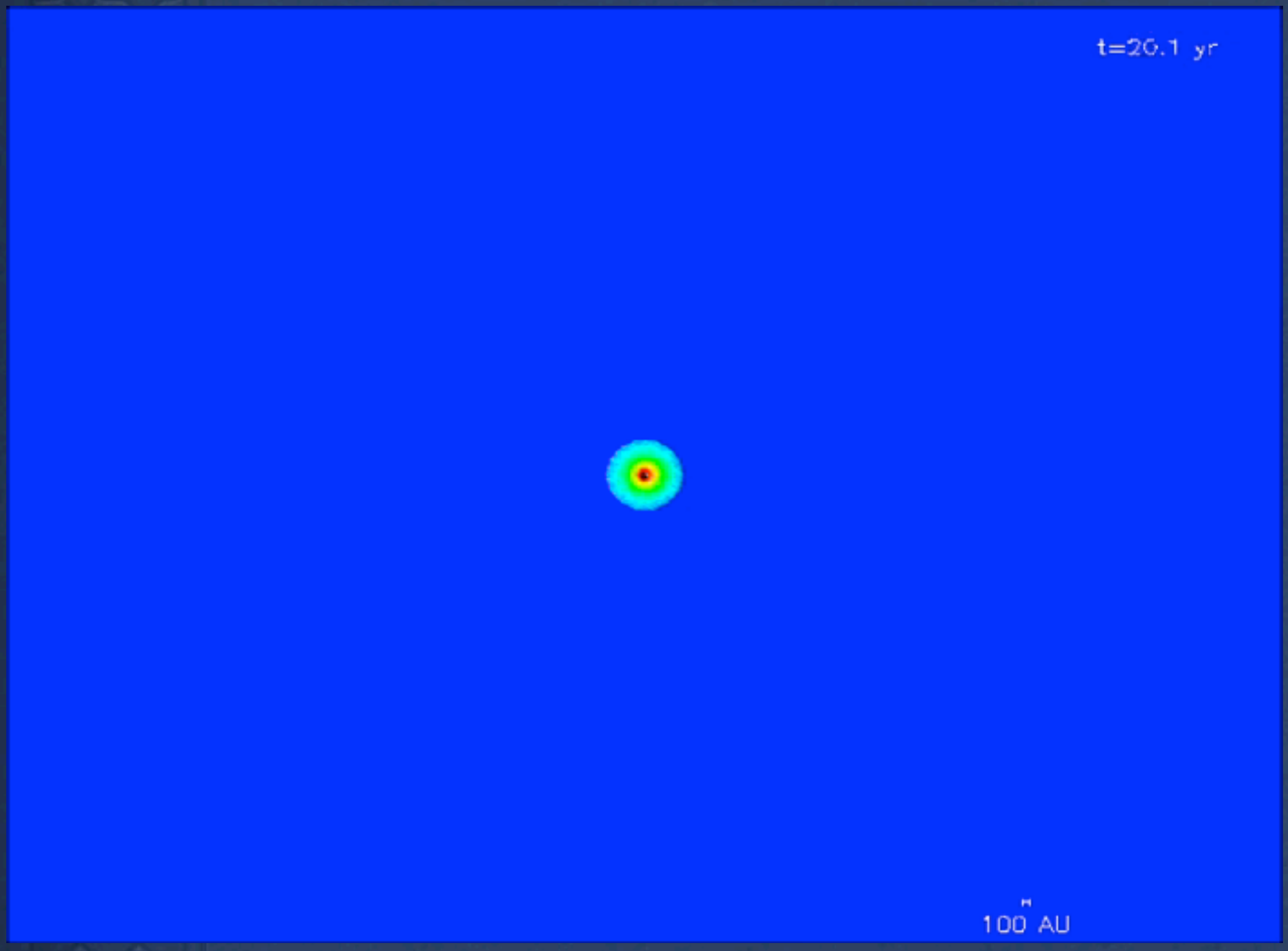
Stamatellos & Whitworth (2009)

Simulation:

$M_{disk} = M_{star}$;

R_{disk} = a few hundred AU

Disk fragmentation, gravitational instability



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Core accretion (traditional model)

- Formation of dust particles and grain growth has been observed in planetary disks of young stars. The gas of the disk is gone in less than 10 Myr.

- Small agregates (dust on icy grains) are formed by condensation in the disk. Many of them collide to form larger and larger objects - until planet-size objects are eventually built-up. Aggregates of M>10 M_{earth} can accrete gas.

Artist's impression

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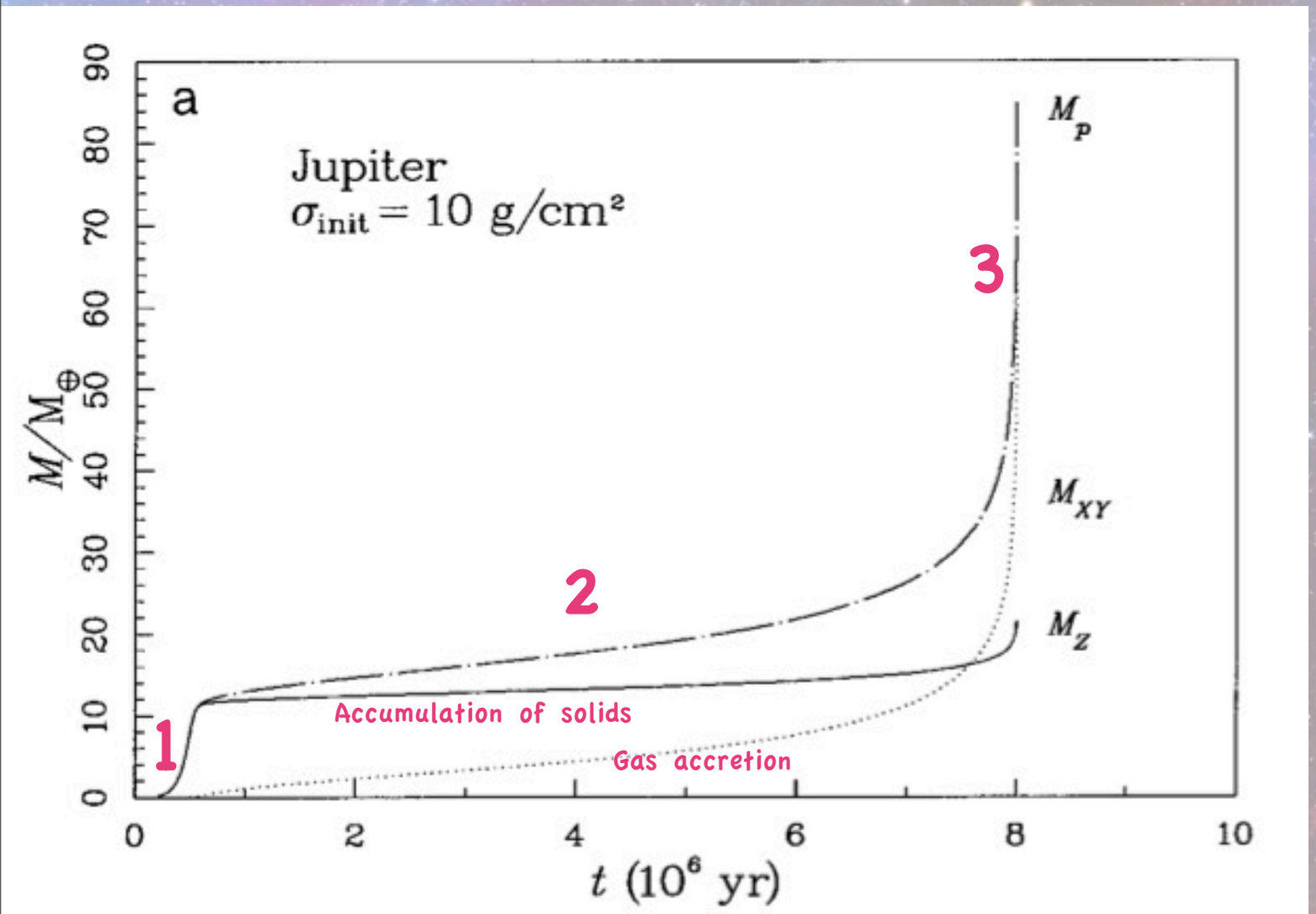
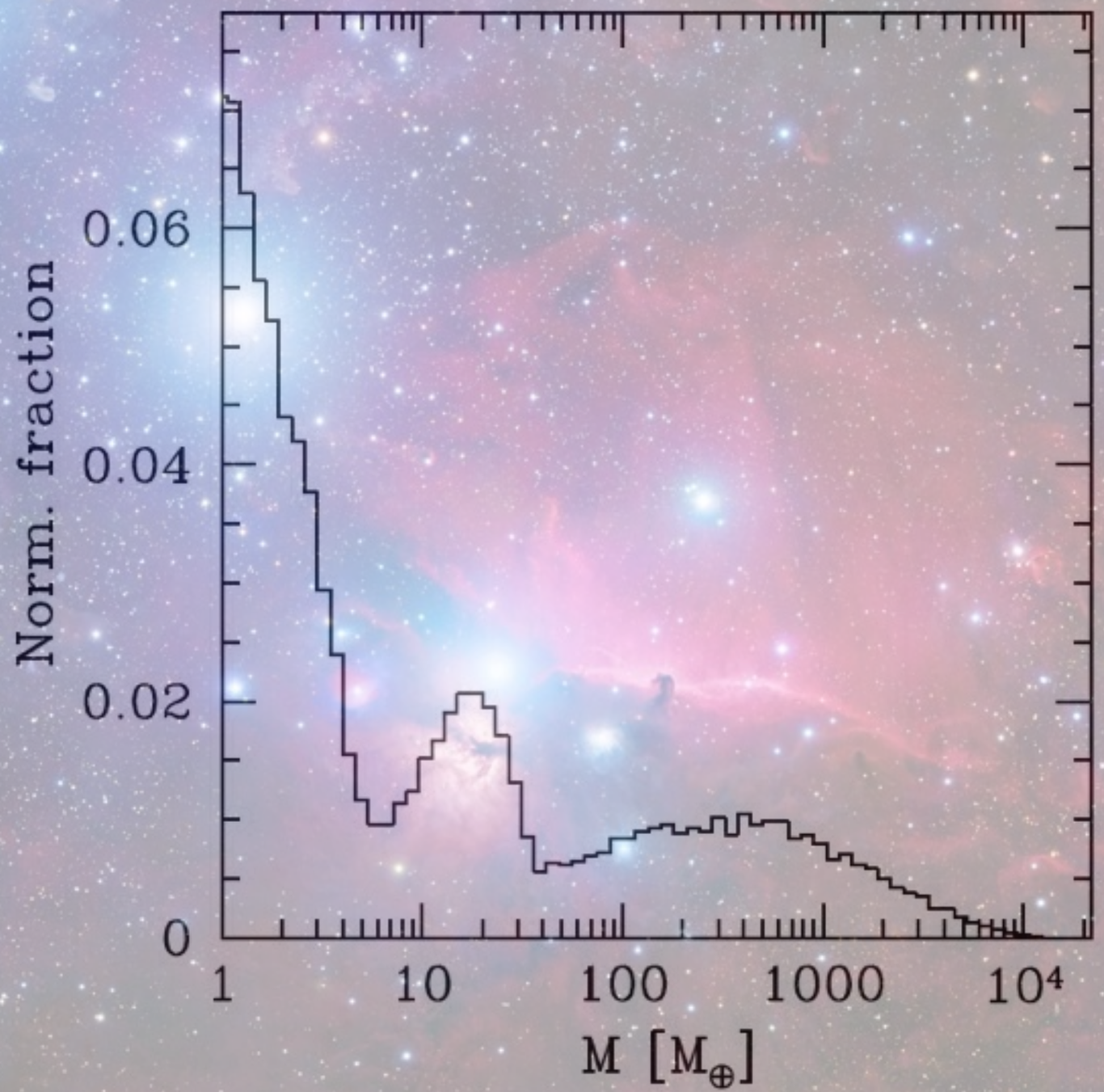


- **First stage:** first ~5x10^5 yr, planet accumulates solids by rapid runaway accretion. Phase ends when planet has severely depleted its feeding zone of planetesimals.
- **Second stage:** constant accretion rate of gas and solids (~7-8 Myr).
- **Third stage:** planet's growth accelerates by accreting gas.

Pollack et al. (1996)

Core accretion (traditional model)



Mordasini et al. (2009)

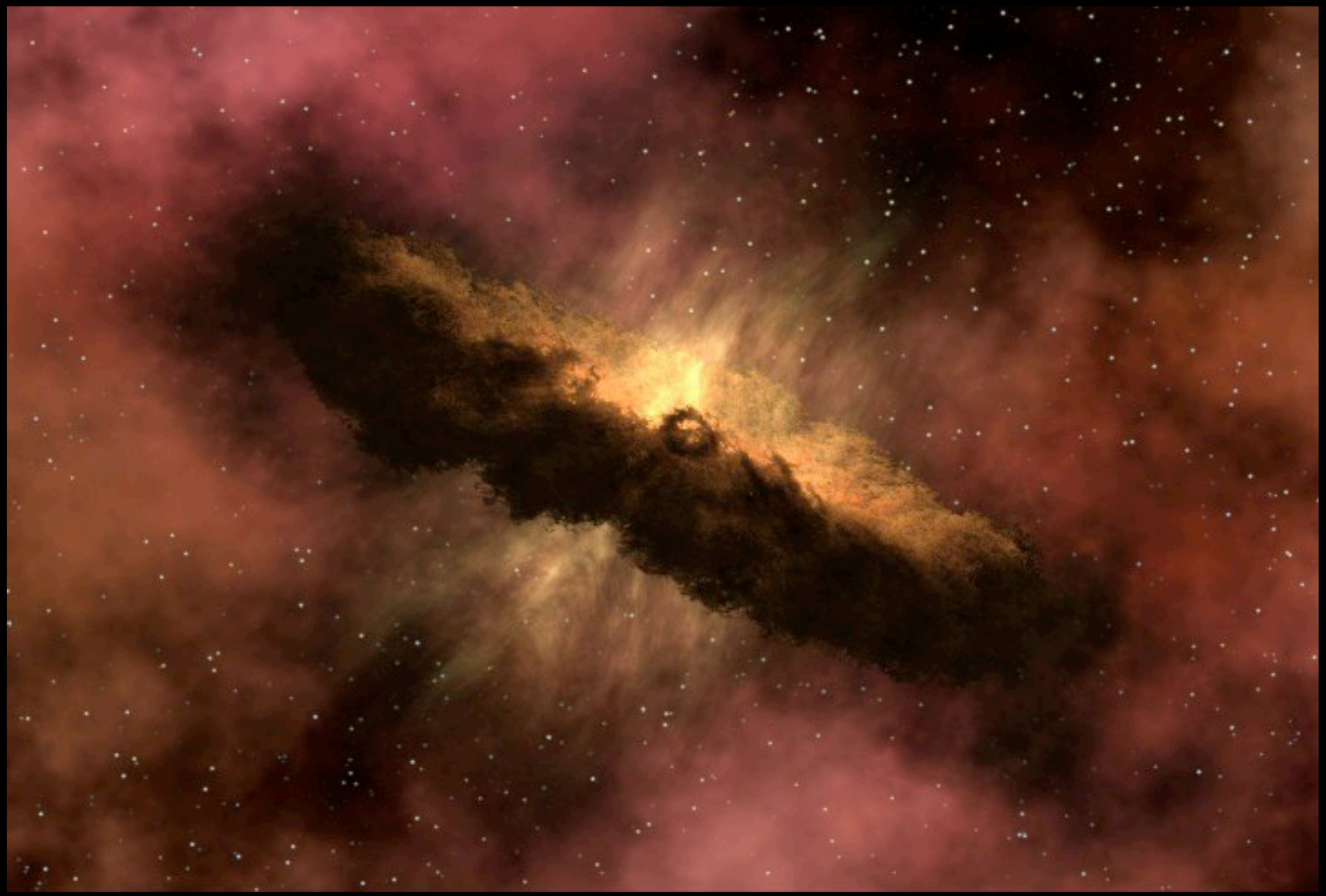
- Planetary census corresponding to the moment in time when the gaseous protoplanetary disk disappears. The largest changes are expected to occur at low masses (below 20 M_{earth}).
- If this prediction is true, current observations might only be the tip of the iceberg.

Disk inner holes

- Inner holes have been observed. They can be excarved by the presence of planets or by disk photoevaporation due to the high-energy photons from the central star.
- Both phenomena have been observed. Substellar objets inhabiting the inner hole do exist (e.g., Huélamo et al. 2011).

Artist's impression

Disk inner holes



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Photoevaporation (radiative feedback)

Heating of (disk) gas to thermal escape velocities.

Artist's impression

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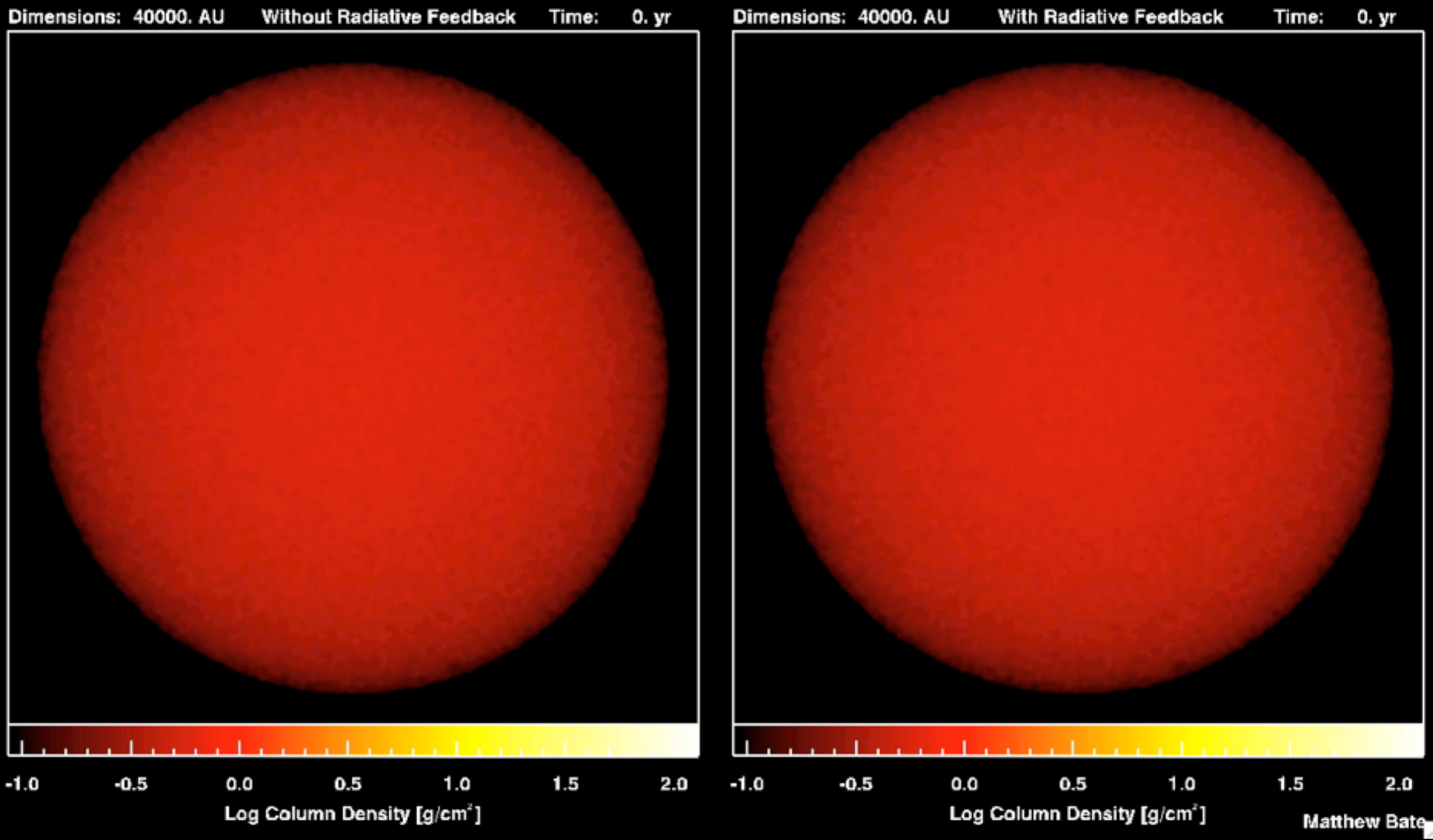
Heating of (disk) gas to thermal escape velocities.

Artist's impression

Molecular cloud fragmentation and collapse + radiative feedback

50 M_{sol}, 10 K, mean molecular weight of 2.38, 0.180 pc (0.6 ly)

Molecular cloud fragmentation and collapse + radiative feedback



50 M_{sol}, 10 K, mean molecular weight of 2.38, 0.180 pc (0.6 ly)

Comparison of three theories

Core accretion

- One model can explain comets, asteroids, moons, solid planets, gaseous planets, ...
- Explains planet composition vs mass. And planet frequency vs stellar metallicity.
- Takes Myr (depending on M_{core} and atmosphere opacity).
- Unable to explain Jupiter-like planets at large orbits.

Disk fragmentation

- Creates Jupiter-like planets at large orbits. Planet migration?
- Rapid formation (planet growth), but cooling rate limits contraction.
- Requires unphysical initial conditions.
- Separate models for solid and "liquid" planets.

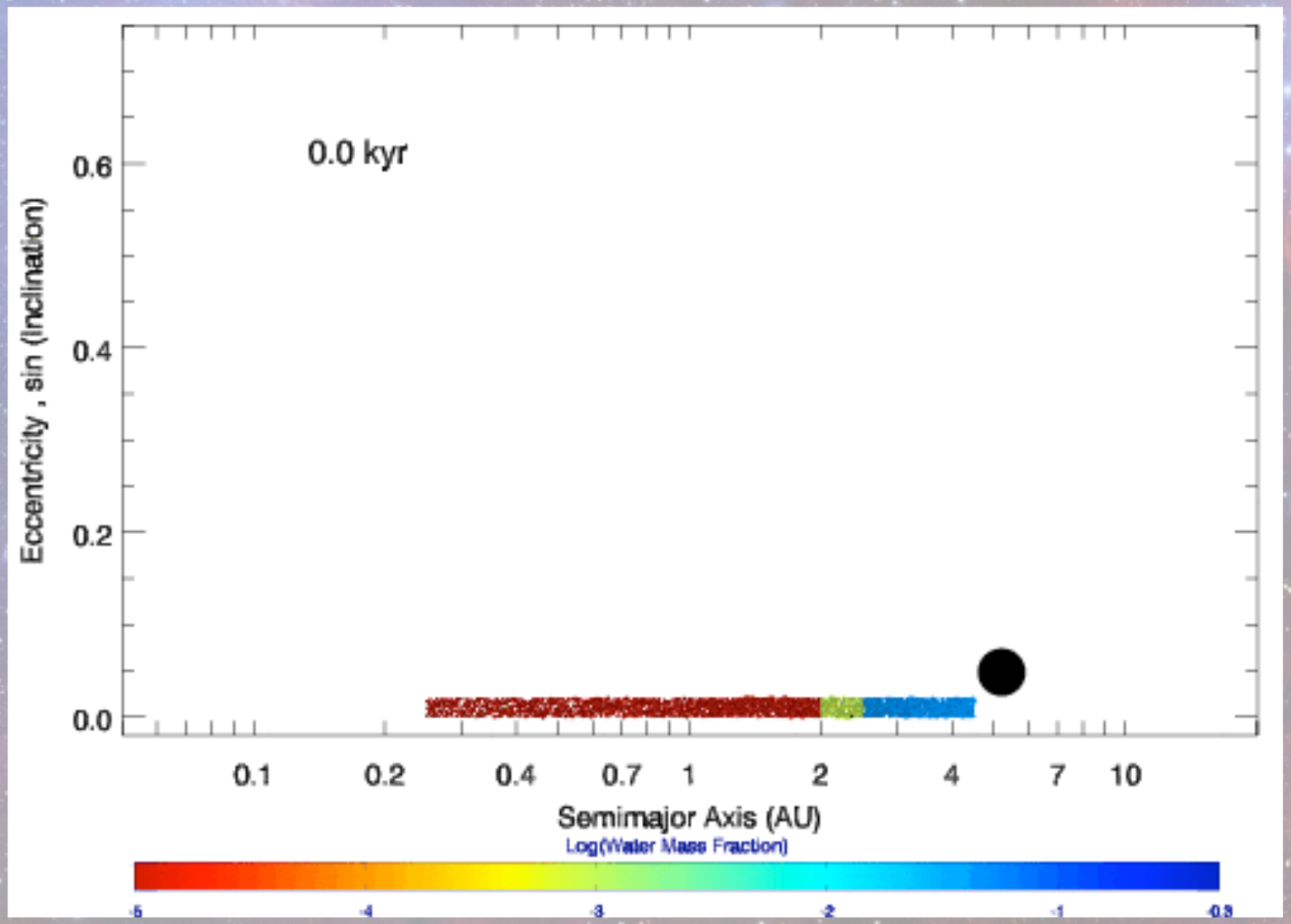
Cloud fragmentation

- Rapid process.
- Multiple stars are common in Nature.
- Forms objects above the opacity limit for fragmentation (3-10 M_{jup}).
- Separate models for solid and "liquid" planets.

- Explain near coplanarity and circularity of planetary orbits.

Planet migration

Growth and dynamical evolution of protoplanetary material from small bodies to terrestrial planets during and after the migration of a giant planet.



- Simulation: disk of 17 M_{earth} divided between 80 Moon- to Mars-sized "planetary embryos" and 1200 planetesimals.
- Inner disk is iron-rich and water-poor; outer disk is water-rich and iron-poor.
- A 1-M_{jup} planet is migrated from 5 to 0.25 AU in 10^5 yr.
- RESULTS: two super-Earths + the Jupiter-like planet. Most of the remaining material was scattered by the giant planet.

Raymond et al. (2006)

Final remarks

The study of exoplanetary systems and isolated planets is very demanding in terms of technological advances.

- High flux contrast (>10^5).
- High spatial resolution (sub-AU resolution at d > 10 pc).
- Stable instruments with imaging and spectroscopic capabilities.
- High spectral resolution power spectrographs.
- Large photon collector telescopes.