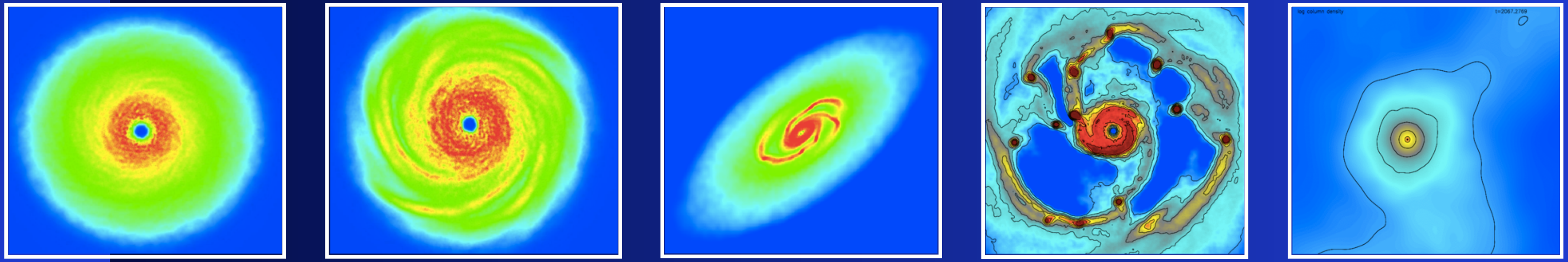
Dimitris Stamatellos
School of Physics & Astronomy
Cardiff University, Wales, UK

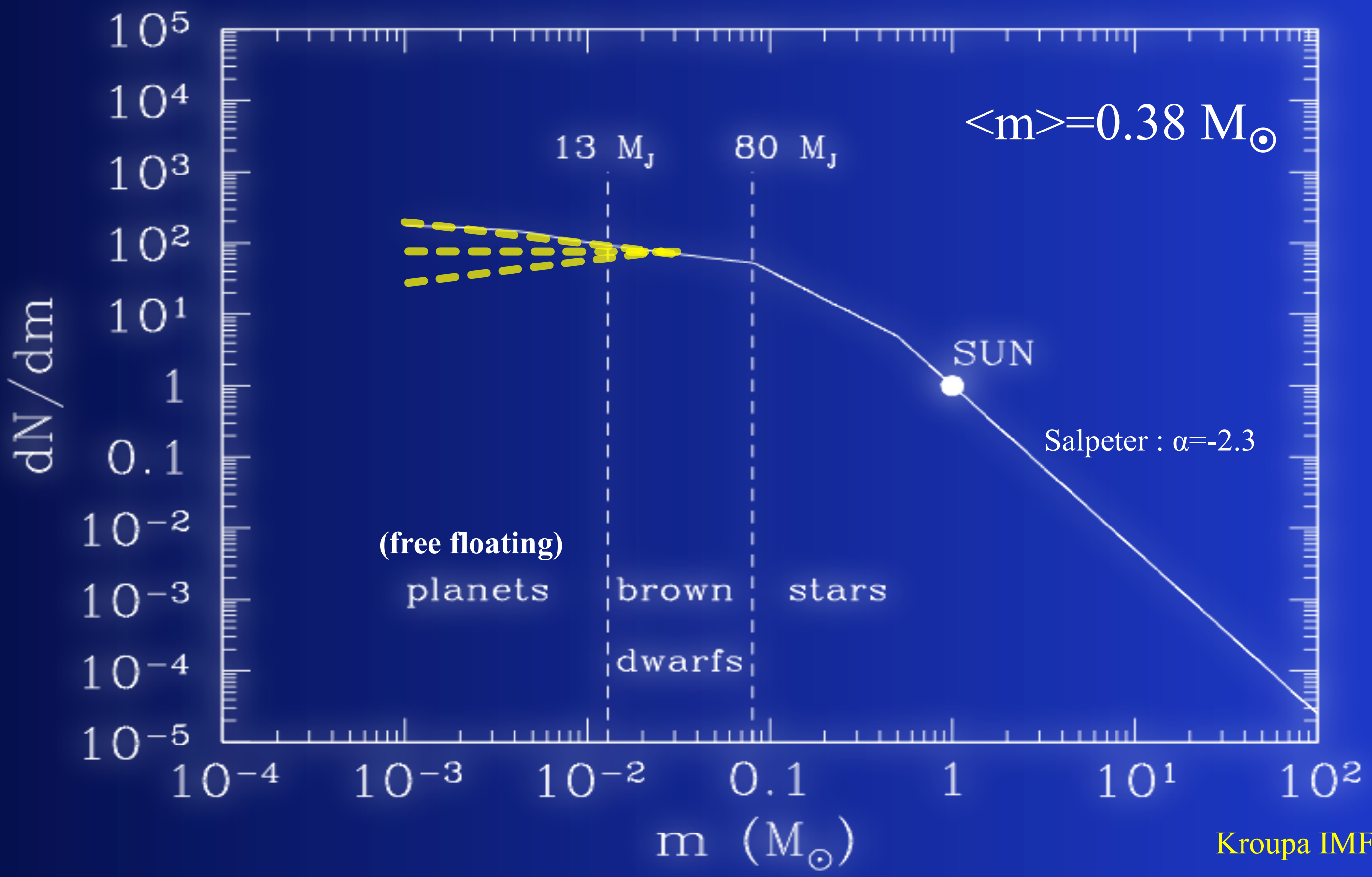
The formation of planets by disc fragmentation

HOT PLANETS AND COOL STARS – MPE, 14 Nov 2012



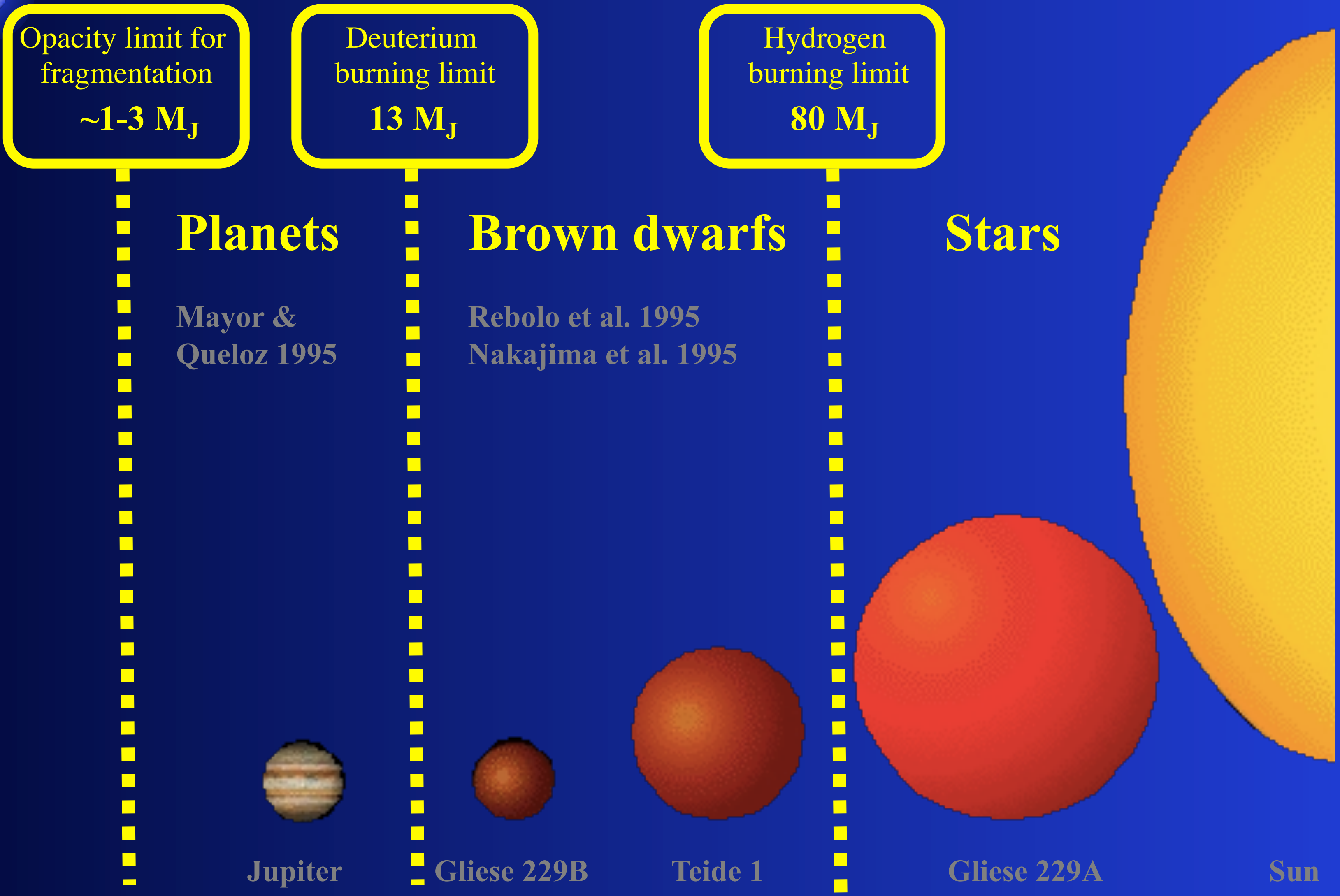
I will use the term “planet” to refer to objects with mass smaller than ~13 M_J that has formed either by **gravitational fragmentation** of protostellar gas or **core accretion**

The ("stellar") initial mass function



Kroupa IMF (2001)

Planets, brown dwarfs and low-mass stars



Opacity limit for fragmentation
~1-3 M_J

Deuterium burning limit
13 M_J

Hydrogen burning limit
80 M_J

Planets

Mayor & Queloz 1995

Brown dwarfs

Rebolo et al. 1995
Nakajima et al. 1995

Stars

Jupiter

Gliese 229B

Teide 1

Gliese 229A

Sun

The formation of low-mass star, brown dwarfs (and planets)

- **turbulent fragmentation of molecular clouds (like Sun-like stars)**

e.g. Padoan & Nordland 2002, Bate et al. 2004, Hennebelle & Chabrier 2008; Bate 2012

? ⇒ **isolated/**
free floating planets

- **disc fragmentation**

e.g. Kuiper 1951; Cameron 1978; Boss 1997; Rice et al. 2003; Whitworth & Stamatellos 2006; Stamatellos & Whitworth 2009; Boley 2009

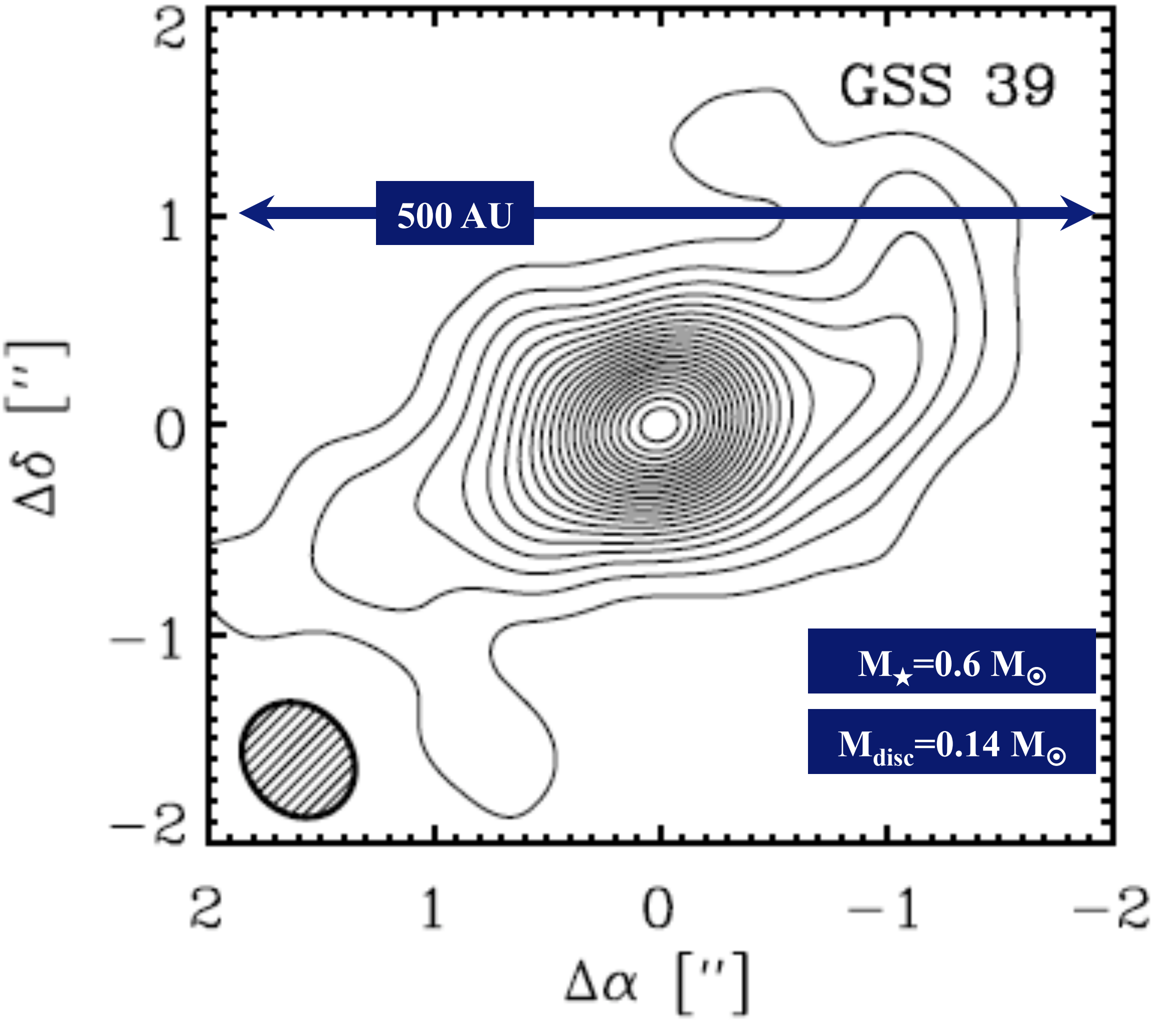
? ⇒ **bound planets**
free floating planets

Is there any evidence for disc fragmentation?

1. The existence of massive discs

2. Wide orbit planets

Observations of discs that on the verge of gravitational instability



Andrews et al. 2009

$M_{\star}$=0.6 $M_{\odot}$

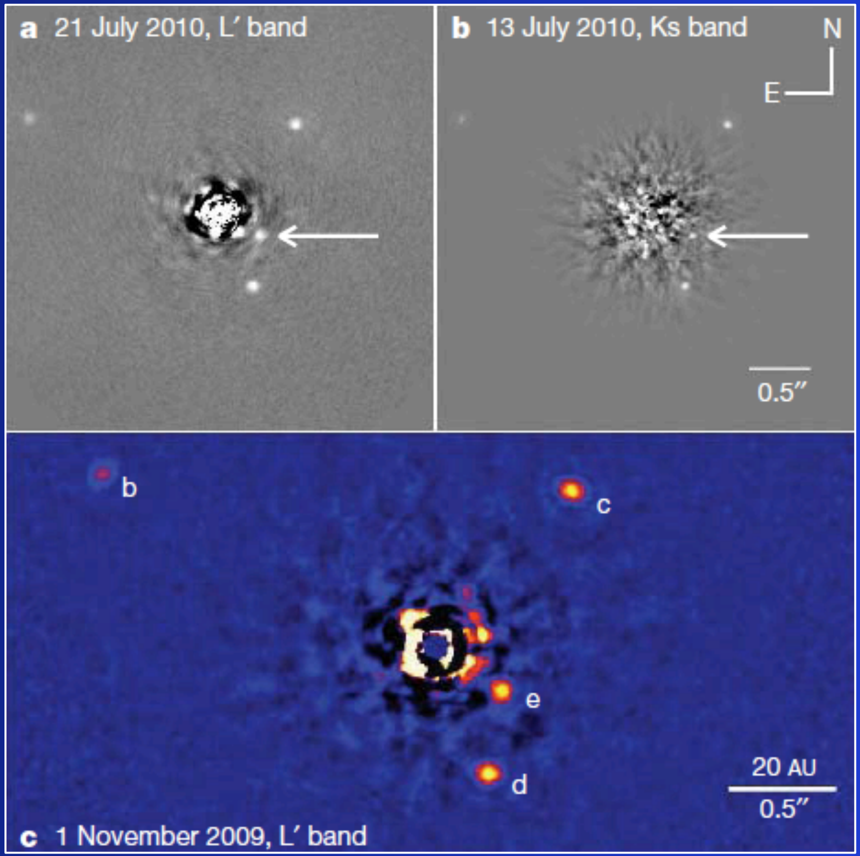
M_{disc}=0.14 $M_{\odot}$

The planets around HR8799

HR8799 (Marois et a. 2008, 2011)

$M_\star$=1.5 $M_\odot$

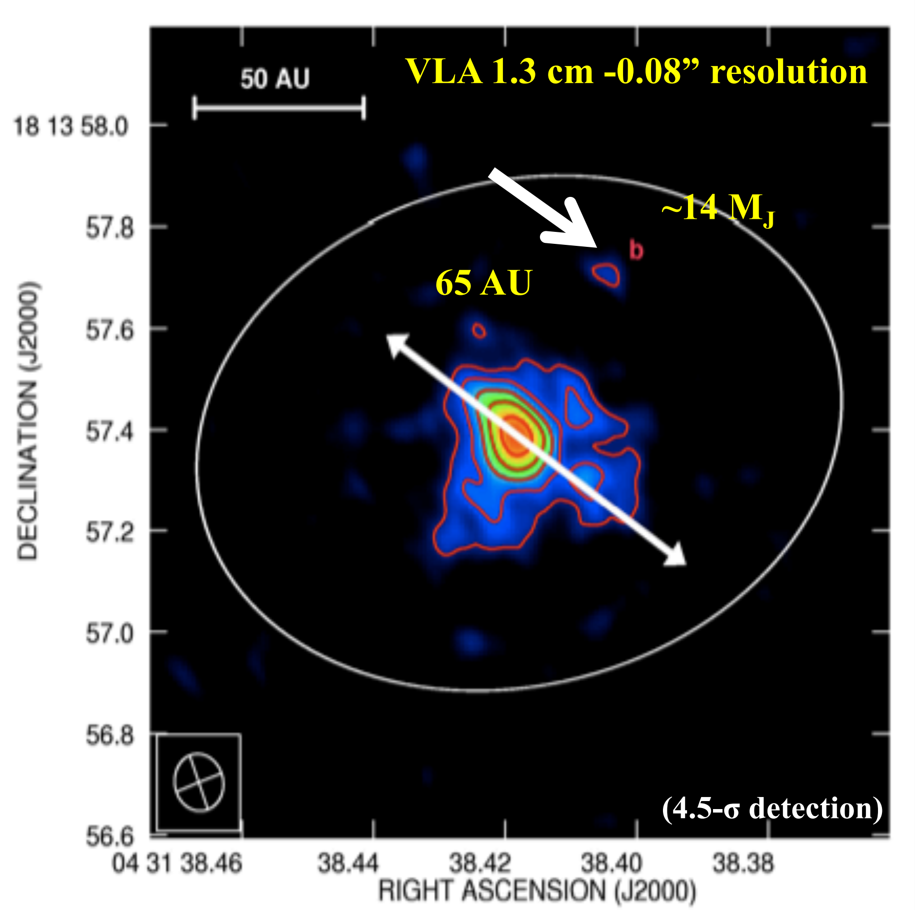
$M_{p,1}$= 10 M_J	$R_{p,1}$=24 AU
$M_{p,2}$= 10 M_J	$R_{p,1}$=38 AU
$M_{p,3}$= 7 M_J	$R_{p,1}$= 68 AU
$M_{p,4}$= 7-10 M_J	$R_{p,1}$= 15 AU

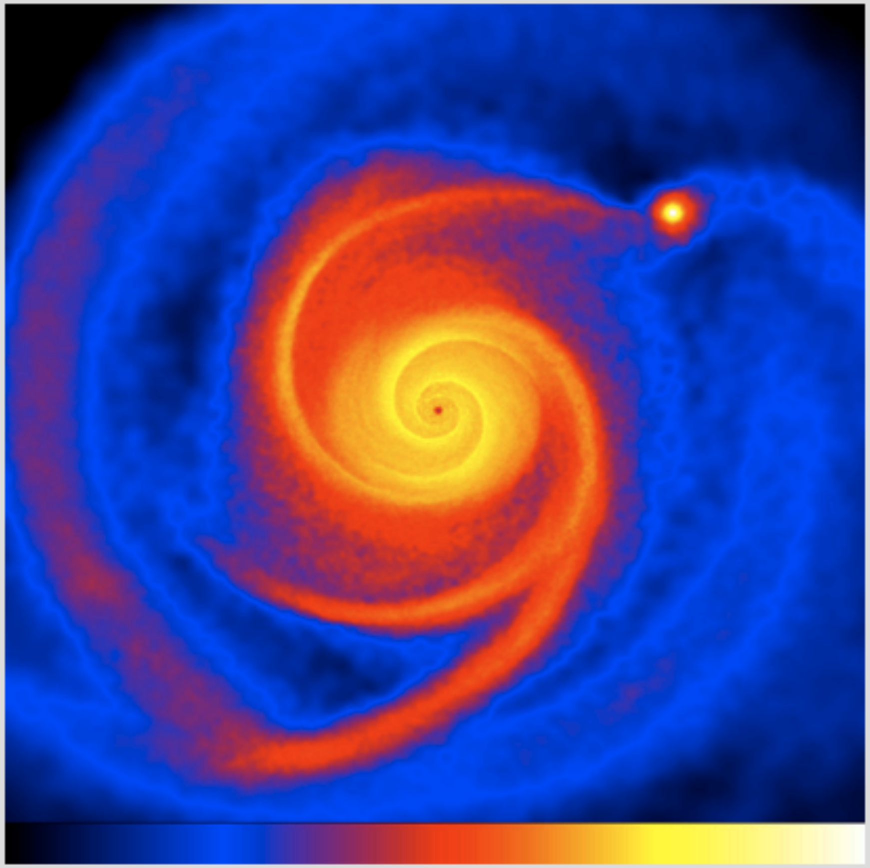


HL Tau: A planet/brown dwarf caught forming?

Primary mass: ~$0.3M_\odot$
Disc mass: ~$0.1M_\odot$
Disc radius: >100 AU

Greaves et al. 2008, MNRAS





When do discs fragment?
Criteria for disc fragmentation

<u>(i) Toomre criterion</u> (Toomre 1964)

Disc must be massive enough

$$\boxed{Q = \frac{c_s(R)\ \Omega(R)}{\pi\ G\ \Sigma(R)} < 1}$$

<u>(ii) Gammie criterion</u> (Gammie 2001; Rice et al. 2003)

Disc must cool on a dynamical timescale

$$\boxed{t_{\rm cool} < (0.5 - 2)\ t_{\rm ORB}}$$

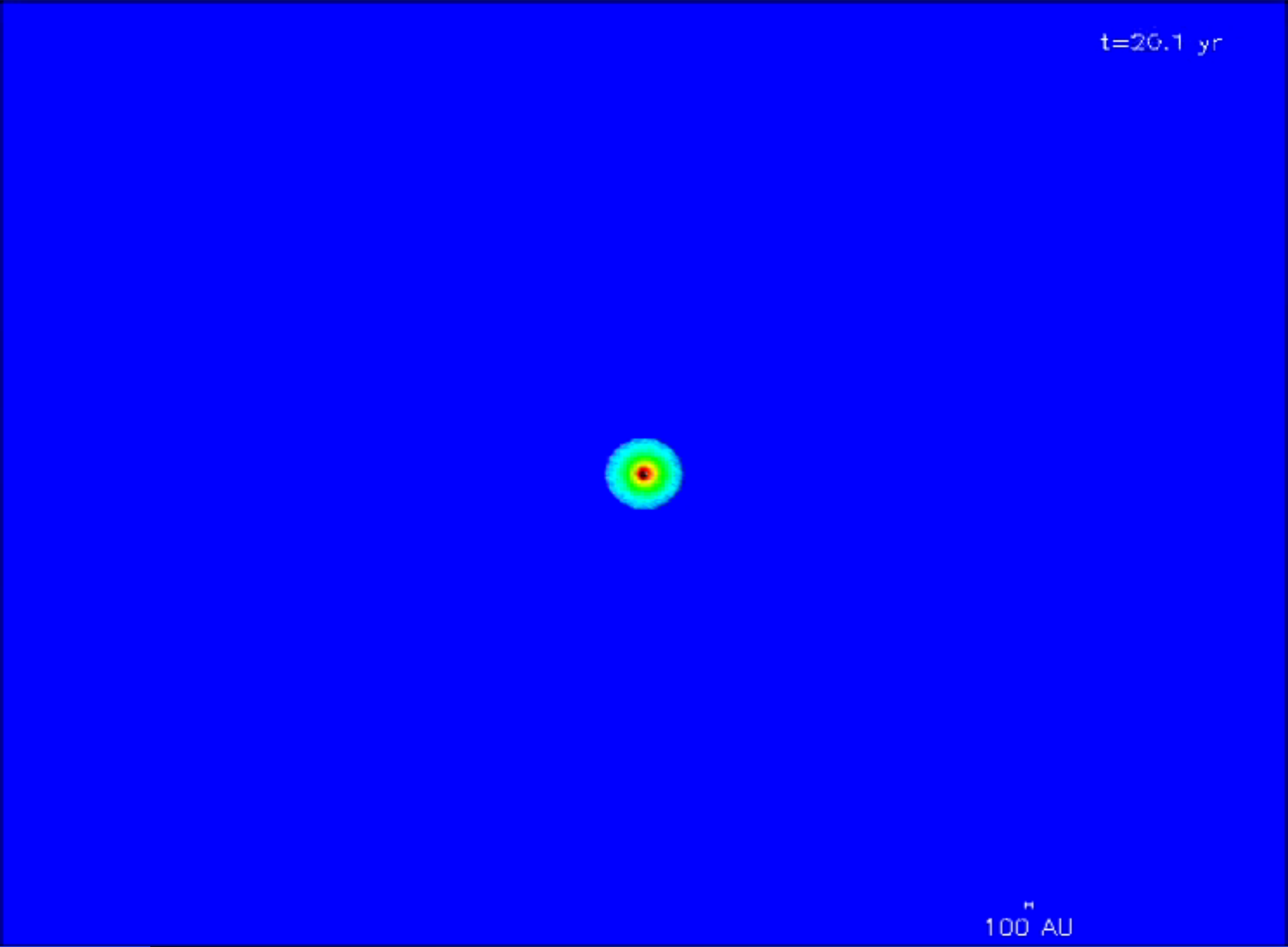
Studing disc fragmentation with hydrodynamic simulations

I. Parameterising radiative cooling (e.g. Gammie, Rice, Lodato, Meru & Bate)

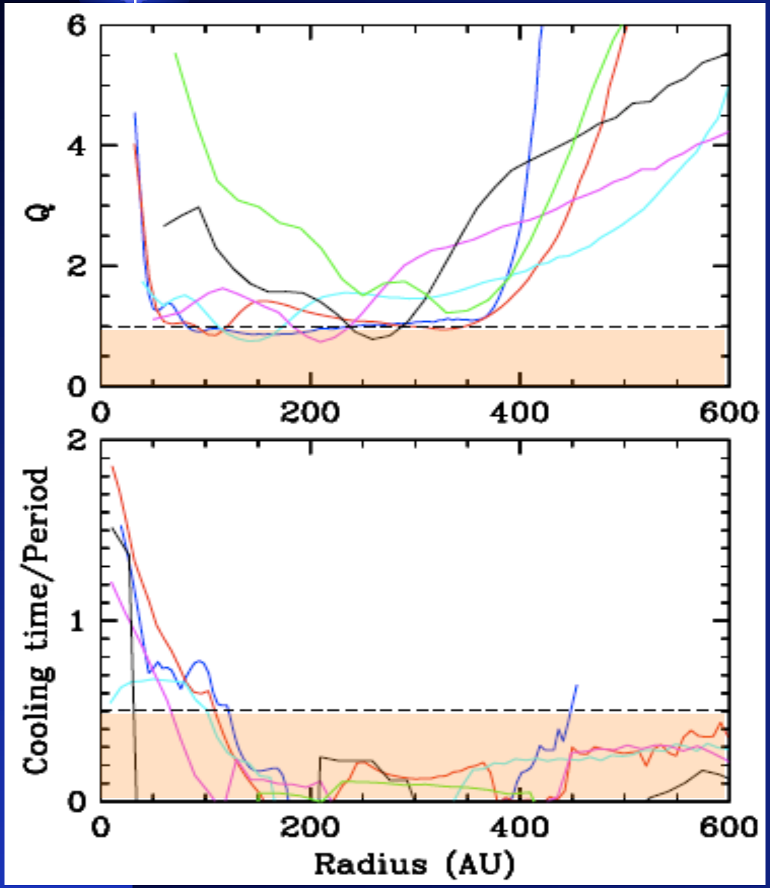
II. Using the diffusion approximation to treat radiative transfer in discs (Stamatellos, Boley, Boss)

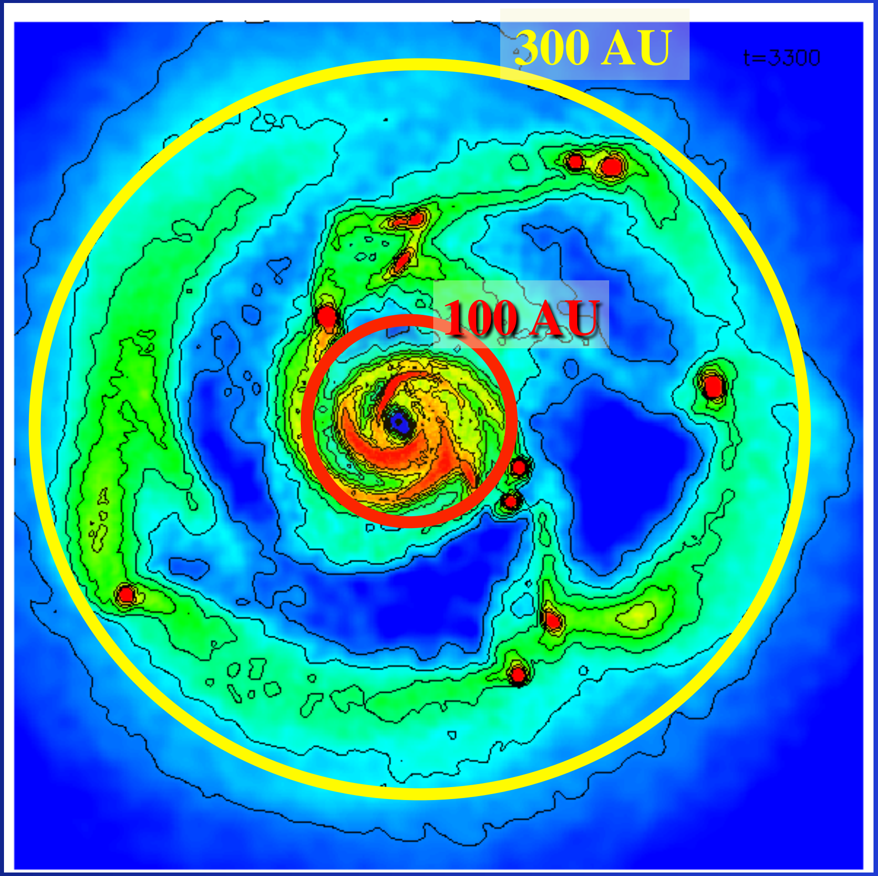
- Dust & gas opacities
  - Ice mantle melting
  - Dust sublimation
  - Molecular opacity
  - H^- absorption
  - B-F/F-F transitions
- Equation of state
  - Vibrational & rotational degrees of freedom of H_2
  - H_2 dissociation
  - H ionisation
  - Helium first and second ionisation

Stamatellos et al. 2007, A&A; Forgan et al. 2009, MNRAS


t=26.1 yr
100 AU

Disc fragmentation





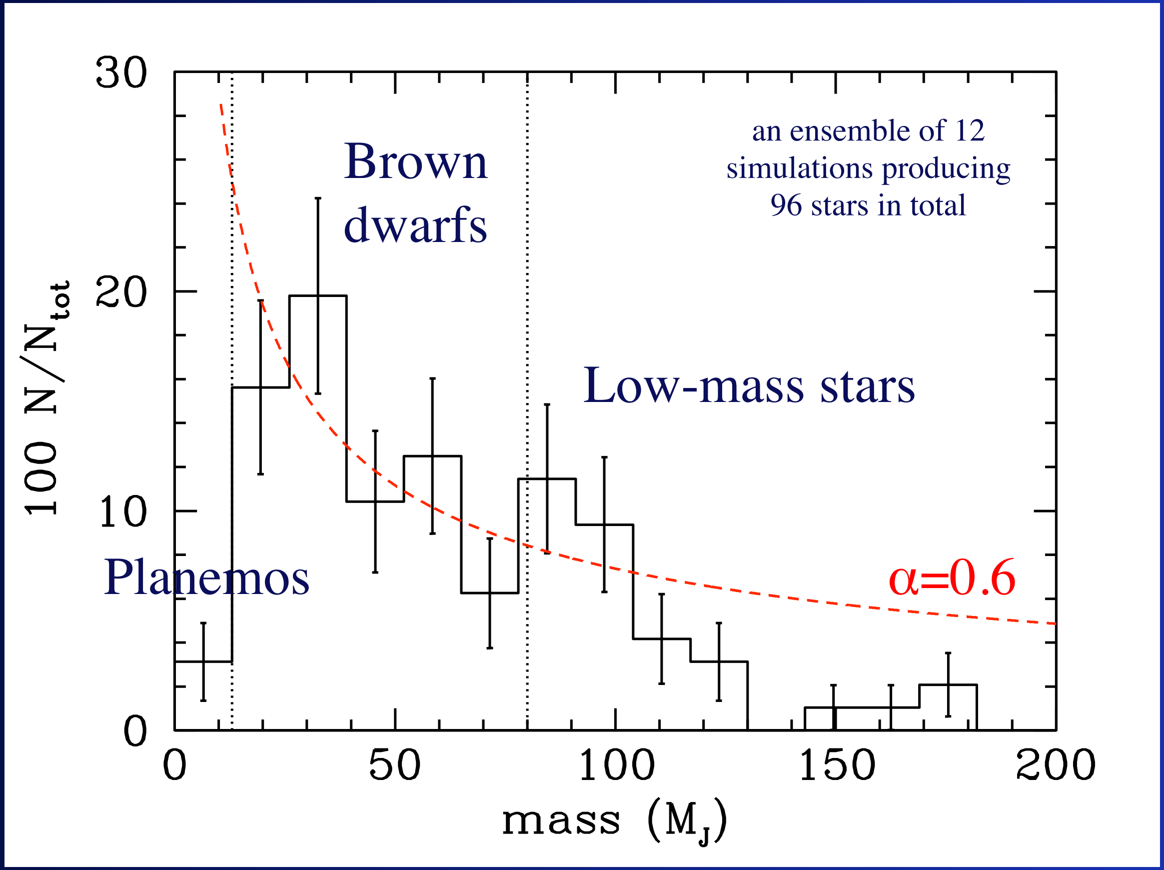
✓ **Forming hot Jupiters <u>in situ</u> by disc fragmentation is unlikely (e.g. Stamatellos & Whitworth 2008, 2009)**

What type of objects do you form by disc fragmentation?

Stamatellos & Whitworth 2009, MNRAS

✓ *Most of the objrcts form in the disc are brown dwarfs (67%).*

✓ *The rest are H-burnings stars (30%) and planets (3%).*



$$\Delta N/\Delta M \sim M^{-\alpha}$$

Pleiades: $\alpha=0.6\pm0.11$

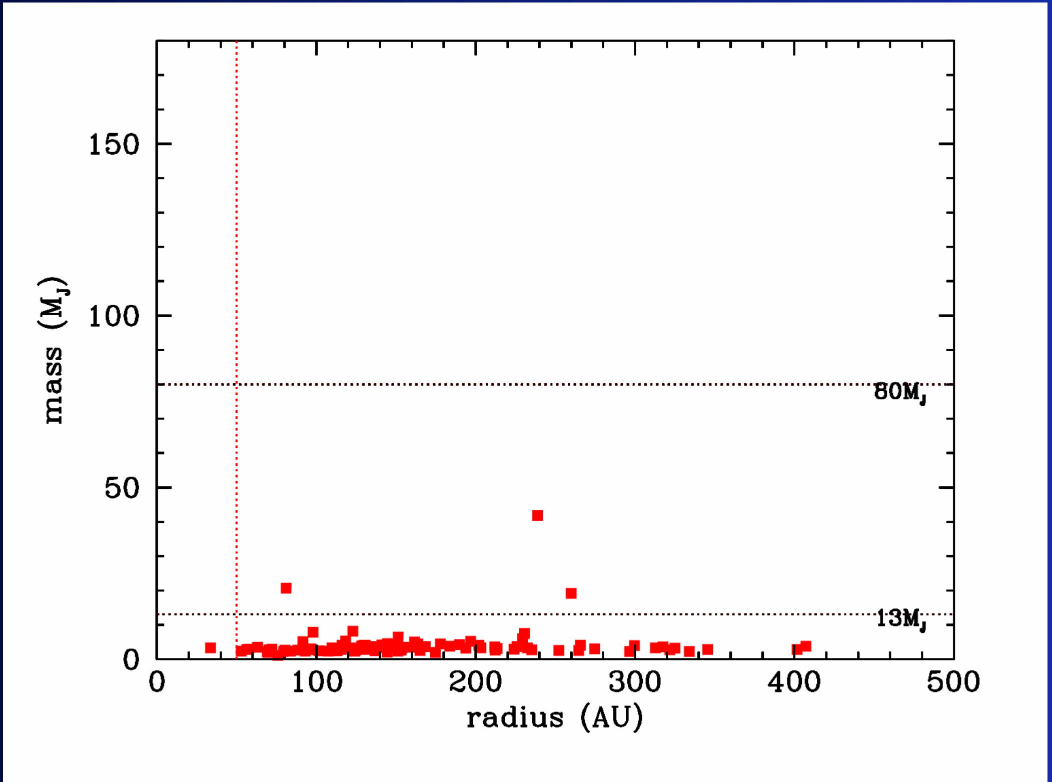
(Moraux et al. 2003)

σ Orionis: $\alpha=0.6\pm0.20$

(Caballero et al. 2007)

This is not an IMF.
It represents the mass spectrum of only one formation mechanism (for one set of initial conditions).

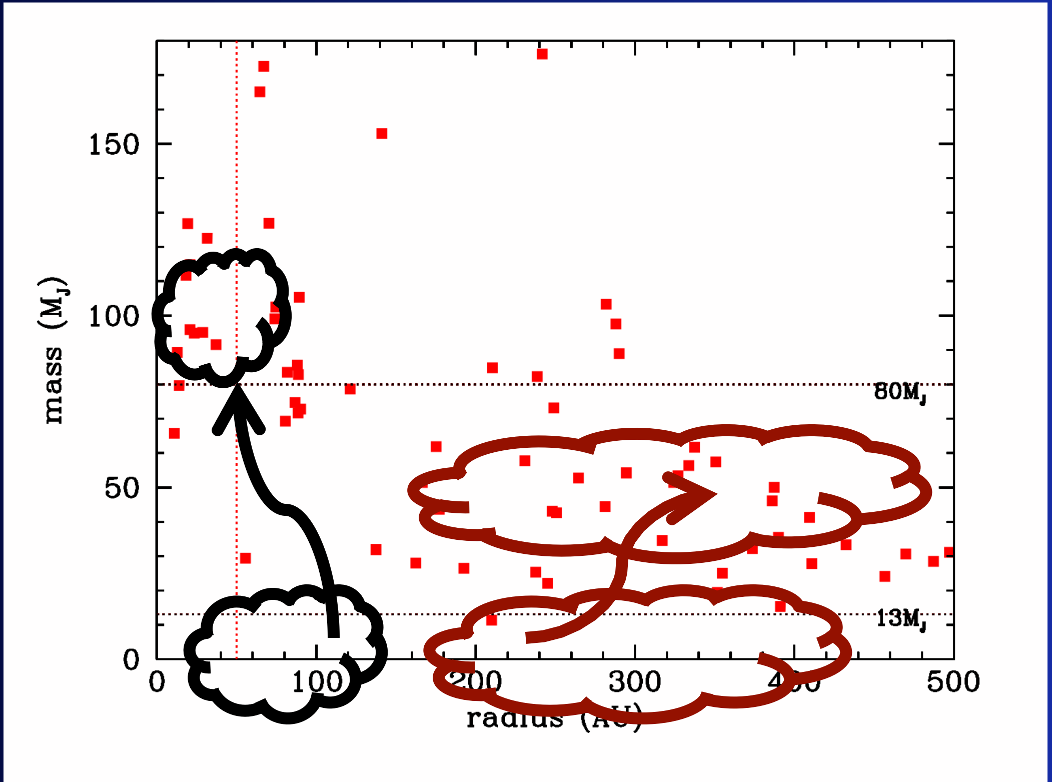
From proto-planets to brown dwarfs



time ~ 5,000 yr

an ensemble of 12 simulations producing 96 stars in total

From proto-planets to brown dwarfs

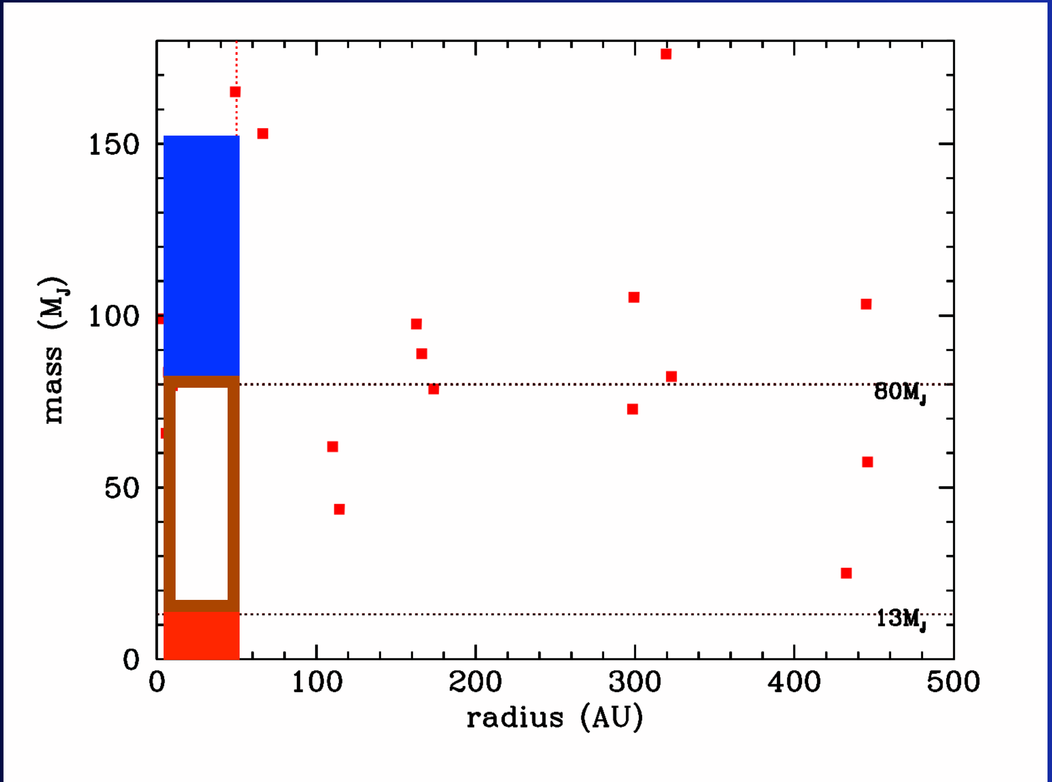


time ~ 20,000 yr

an ensemble of 12 simulations producing 96 stars in total

From proto-planets to brown dwarfs

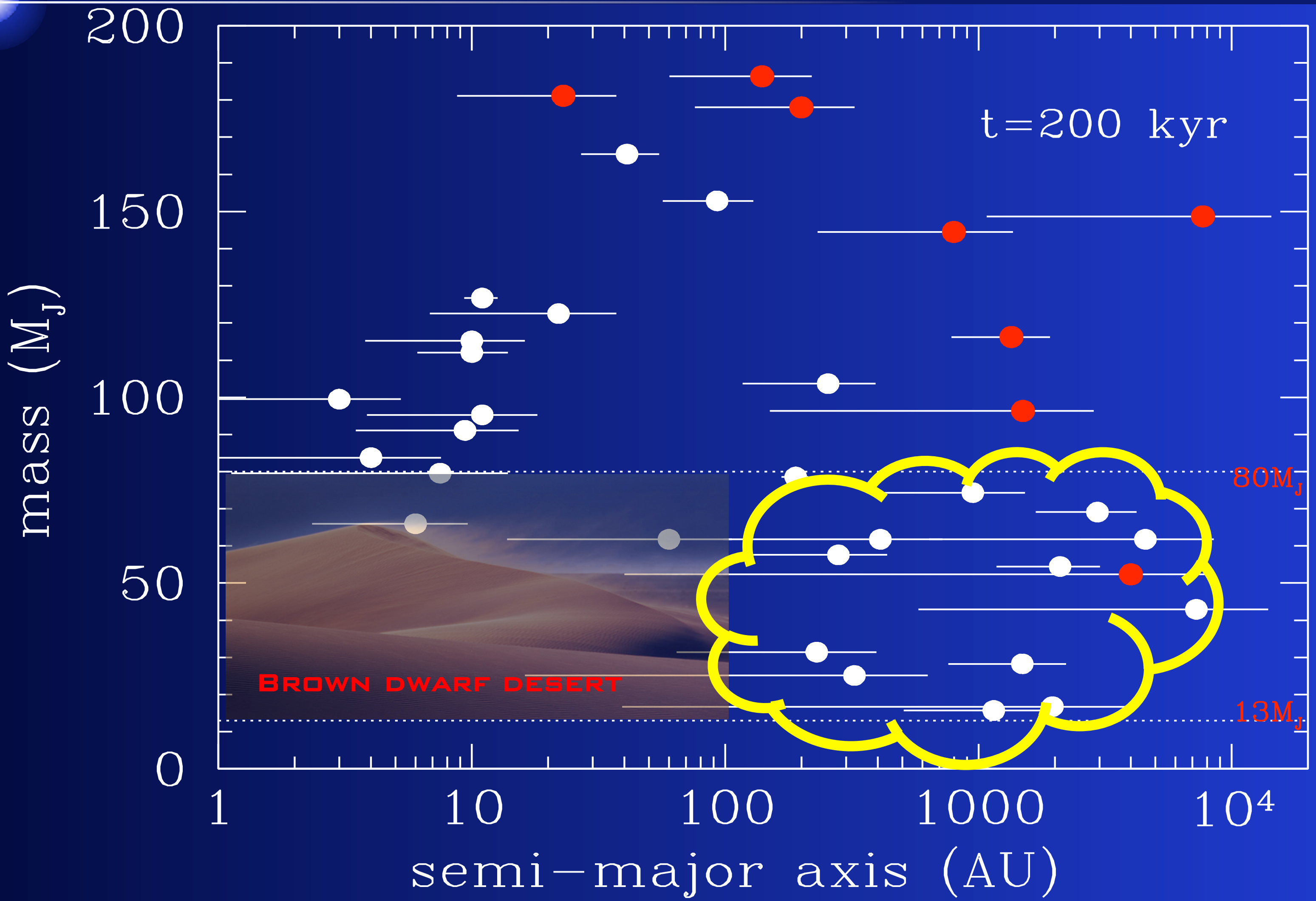
- There are many planets and low-mass stars close (<5 AU) companions to Sun-like stars, but almost no brown dwarfs (Marcy & Butler, 2000) .
- The brown dwarf desert may extend out to ~1000 AU (Gizis et al. 2001) but is less "dry" of brown dwarfs outside ~50 AU (Neuhauser et al. 2003).



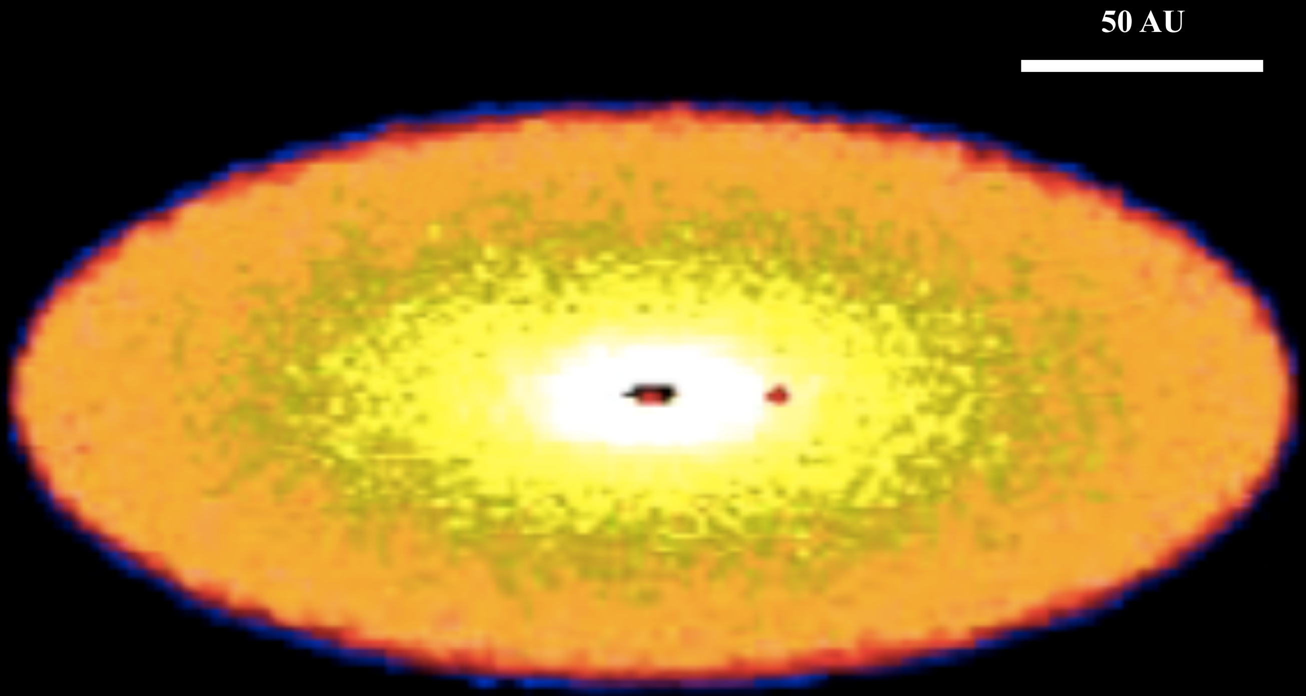
time ~ 200,000 yr

an ensemble of 12 simulations producing 96 stars in total

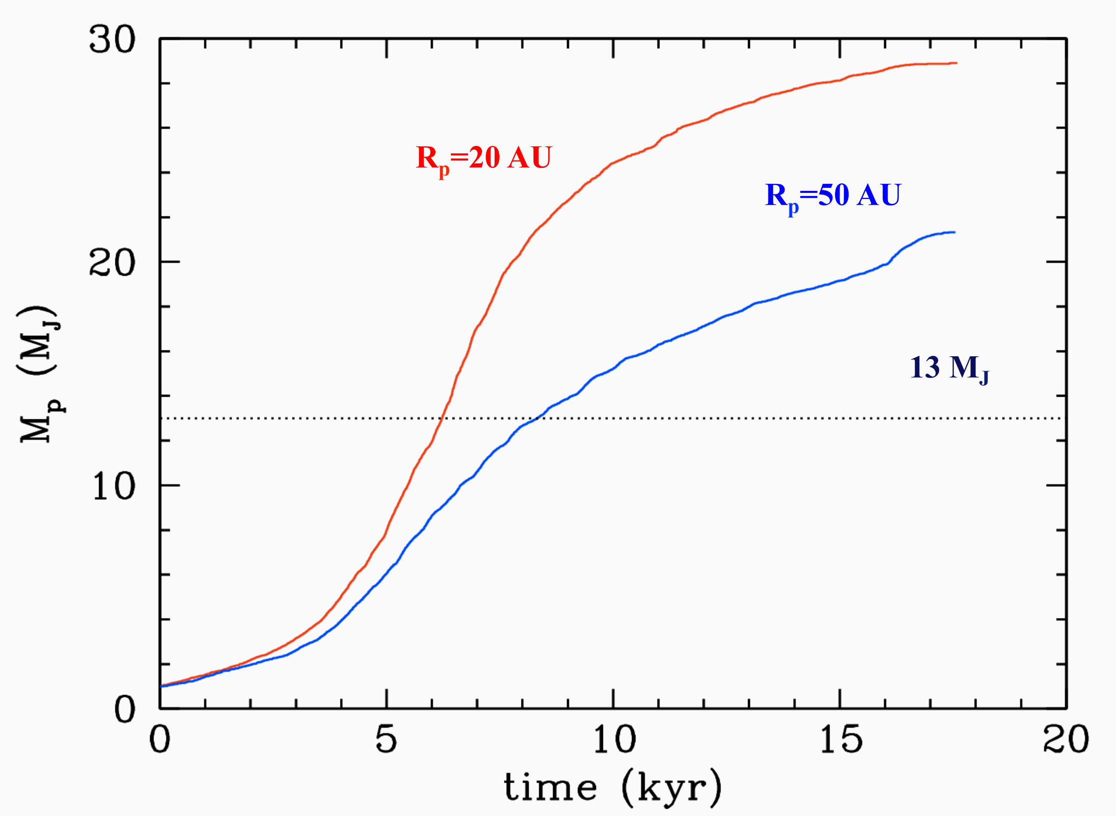
The brown dwarf desert: where did the brown dwarfs go?



From proto-planets to brown dwarfs



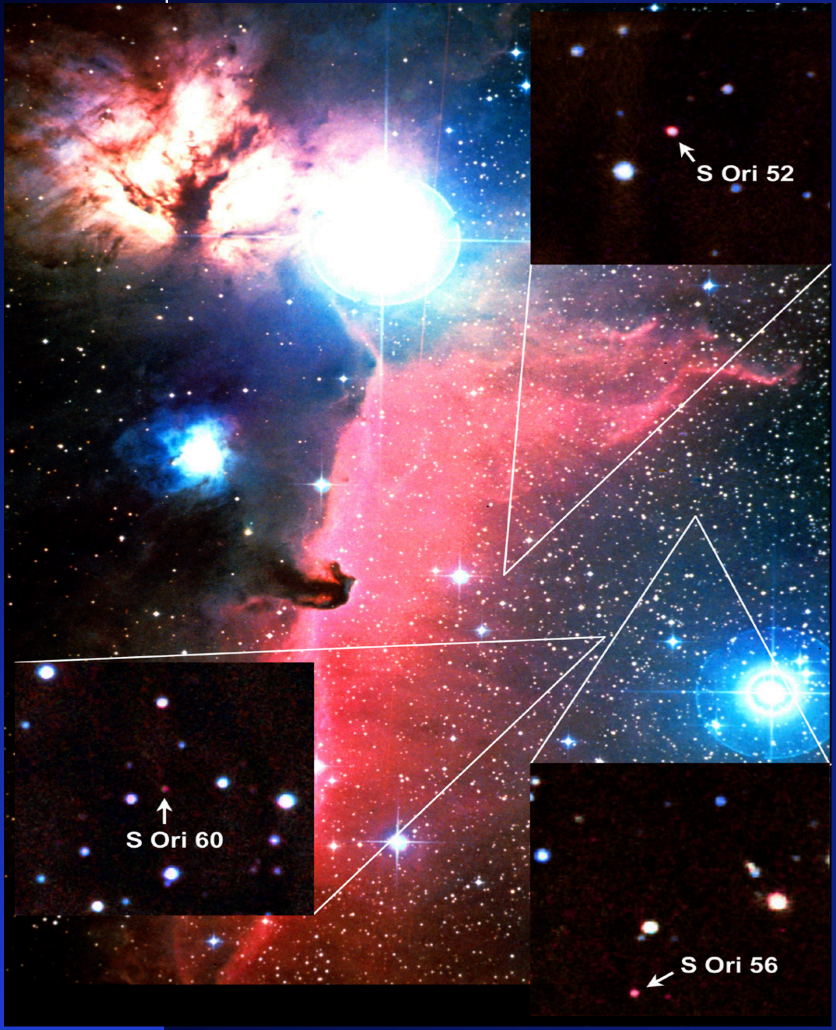
From proto-planets to brown dwarfs



- ✓ We find that even if a proto-planet forms in the disc it is unlikely that it remains a planet as it quickly accretes material from the disc to become brown dwarf (Stamatellos in prep.)

How to keep an object that forms in the disc a planet?

The formation of free-floating planets



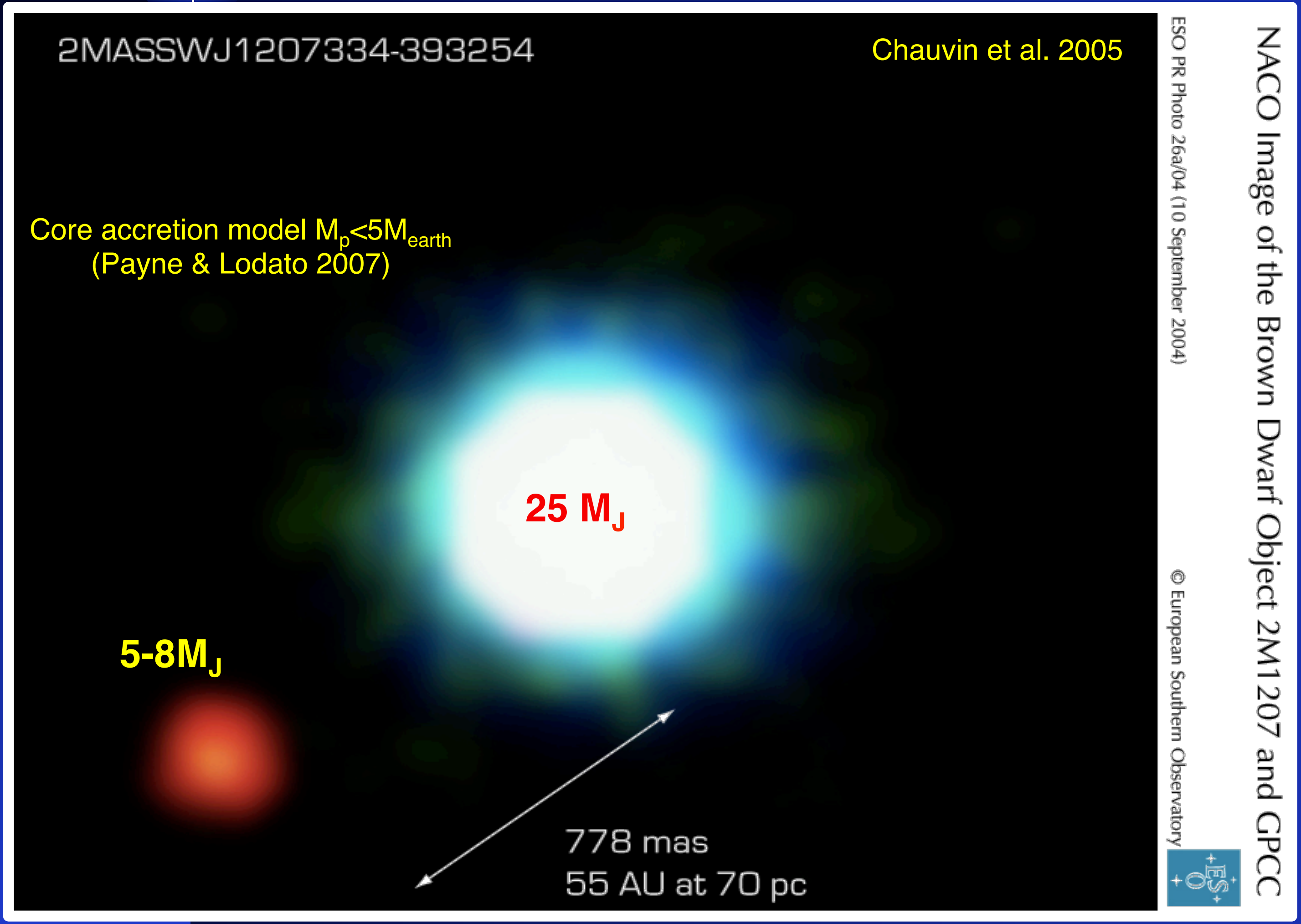
✓ Planetary-mass objects (e.g. Lucas & Roche 2000; Zapatero Osorio et al. 2000, Lodieu et al. 2007) are formed with this mechanism and subsequently liberated in the field to become "free-floating planets".

✓ Many of them have small discs (disc mass 7-14 M_J)

✓ We predict that brown dwarfs outnumber planemos by a factor of at least ~10

✓Recent microlensing observations suggest that is a large number of free-floating planets (Sumi et al. 2011)

Low-mass binaries



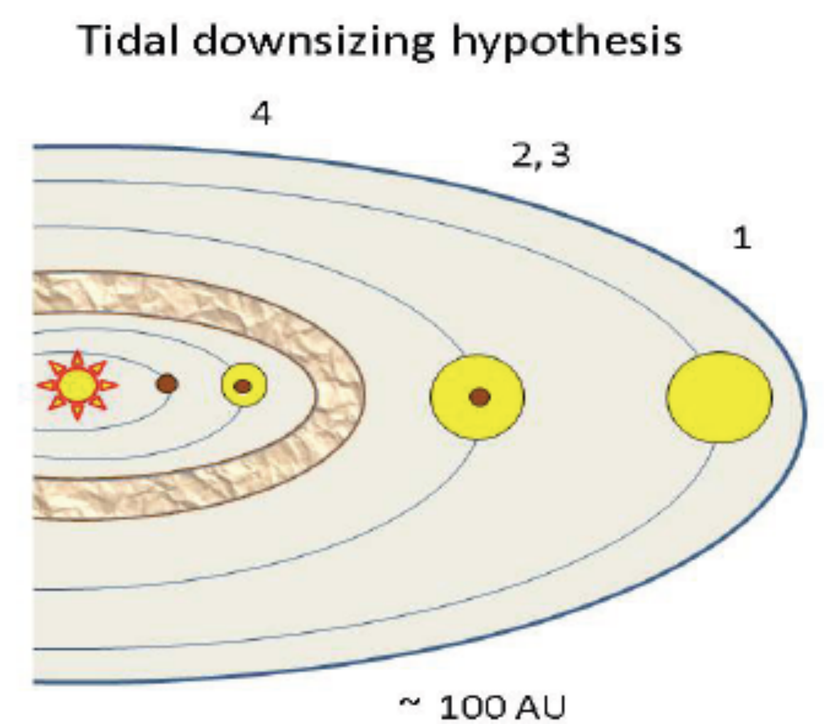
Burningham et al. 2010

Primary: 75 M_J
Secondary: 30 M_J
Separation: 45-135 AU

Burningham et al. 2009

Primary: 270 M_J
Secondary: (20-32) M_J
Separation: 400 AU

Tidal downsizing



Courtesy of S . Nayakshin

- Clumps form at distances >100 AU from the central star (e.g. Stamatellos & Whitworth 2008, 2009)
- They contract slowly (Kelvin-Helmholtz timescale) and migrate inwards
- Grains can sediment to the centre forming solid cores
- Gas envelope can be totally or partially tidally stripped
- A gas giant or rocky planet forms

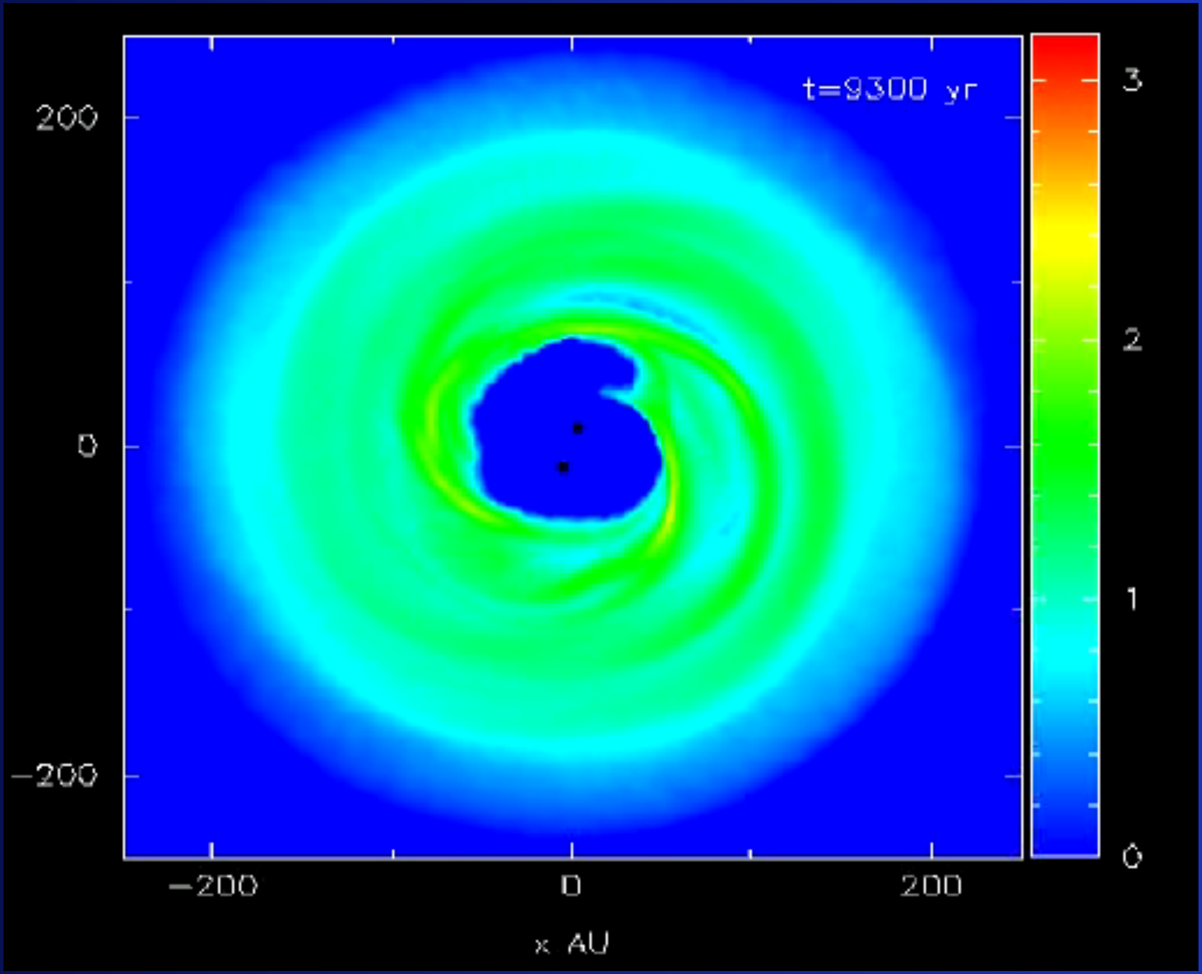
Boley 2010; Nayakshin 2010; Liu et al. 2012

How to keep an object that forms in the disc a planet?

I. By throwing out of the disc before it can grow in mass

II. By suppresing and reversing its mass growth through tidal effects

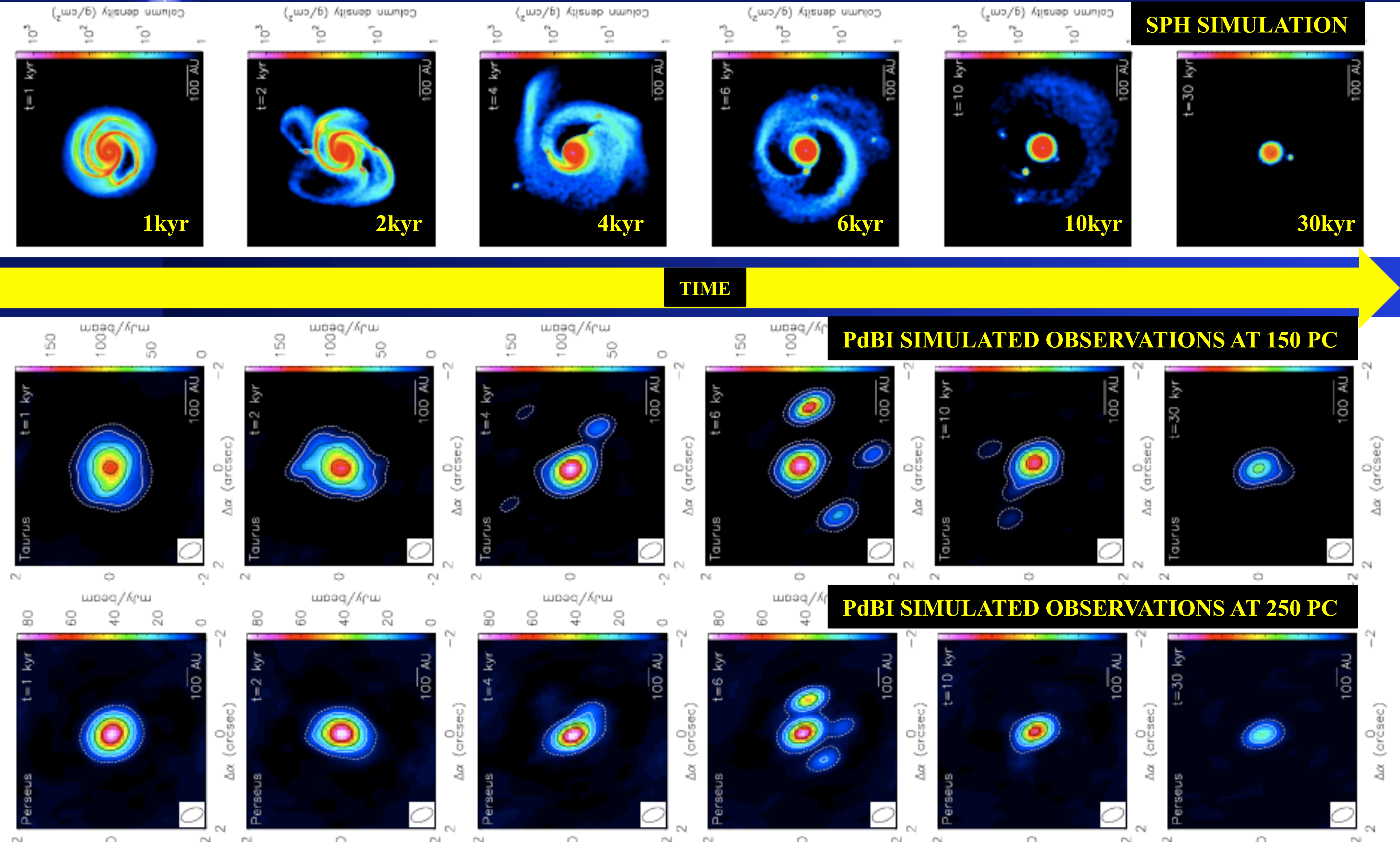
Circumbinary planets: Disc fragmentation in circumbinary discs?



Stamatellos et al. , in preparation

Can fragmenting discs be observed? You have to be extremely lucky

Stamatellos, Maury et al. 2011, MNRAS



SPH SIMULATION

TIME

PdBI SIMULATED OBSERVATIONS AT 150 PC

PdBI SIMULATED OBSERVATIONS AT 250 PC

Is there a way to tell whether an observed planet has formed by gravitational instability or core accretion?

Core accretion vs disc fragmentation
(I) Planet mass

- Disc fragmentation produces giant planets (but a giant planet's mass can be reduced through tidal stripping, so that it can became a terrestrial planet).

- Core accretion produces giant and terrestrial planets

Core accretion vs disc fragmentation (II) Planet orbital radius

- Disc fragmentation cannot form in situ close orbit giant planets (but they may form in the outer disc regions and then migrate inwards)

- Core accretion cannot form in situ wide orbit giant planets (but they may form inwards and scattered outwards through 3 body interactions)

Core accretion vs disc fragmentation (III) Planet metallicity

- Disc fragmentation produces produces low-metallicity planets? Disc instability may have a variety of heavy-element compositions, ranging from sub- to super-nebular values. High levels of enrichment can be achieved through enrichment at birth, planetesimal capture, and differentiation plus tidal stripping (Helled et al. 2006; Boley et al. 2011)

- Core accretion produces high-metallicity planets

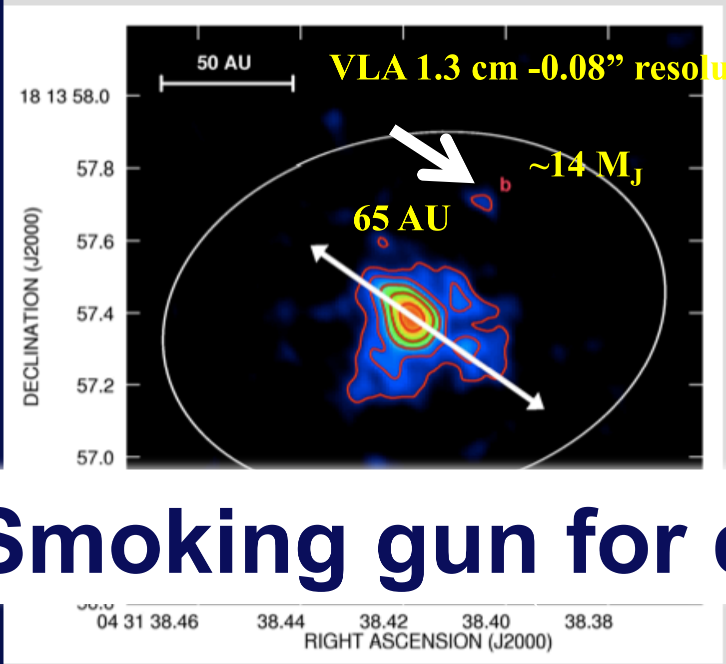
Core accretion vs disc fragmentation (IV) Formation timescale

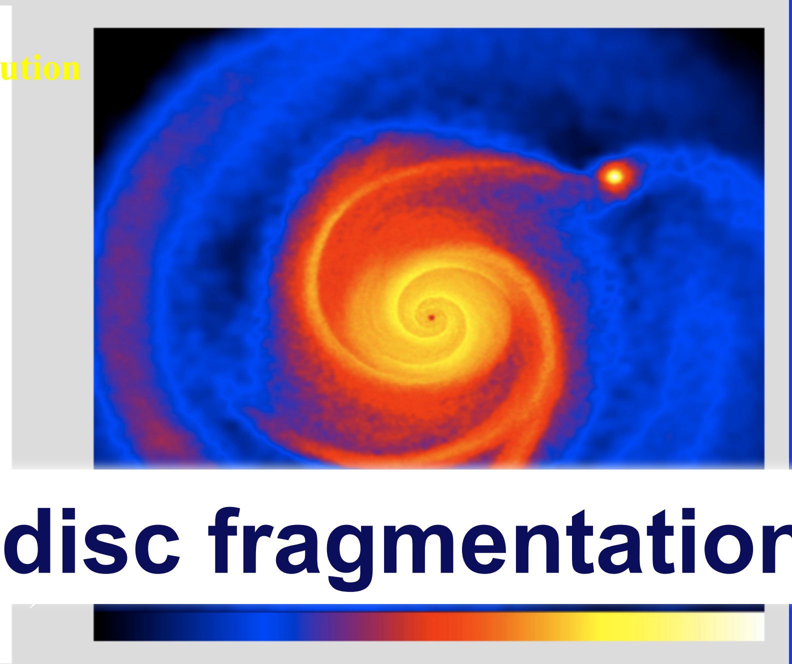
- Disc fragmentation produces planets on a dynamical timescale (a few thousand years)
- Core accretion produces planets within a few Myr

Greaves et al. 2008, MNRAS

HL Tau

Age~0.1 Myr





Smoking gun for disc fragmentation

Summary

- **Disc fragmentation may produce bound and free-floating planets**

- **The main problem is to keep the objects forming in the disc in the planetary mass regime (on the other hand the main problem of core accretion is to grow the planet mass to the giant regime).**

- Hot Jupiters cannot form in situ by disc fragmentation

- Disc fragmentation may produce both giant and terrestrial planets