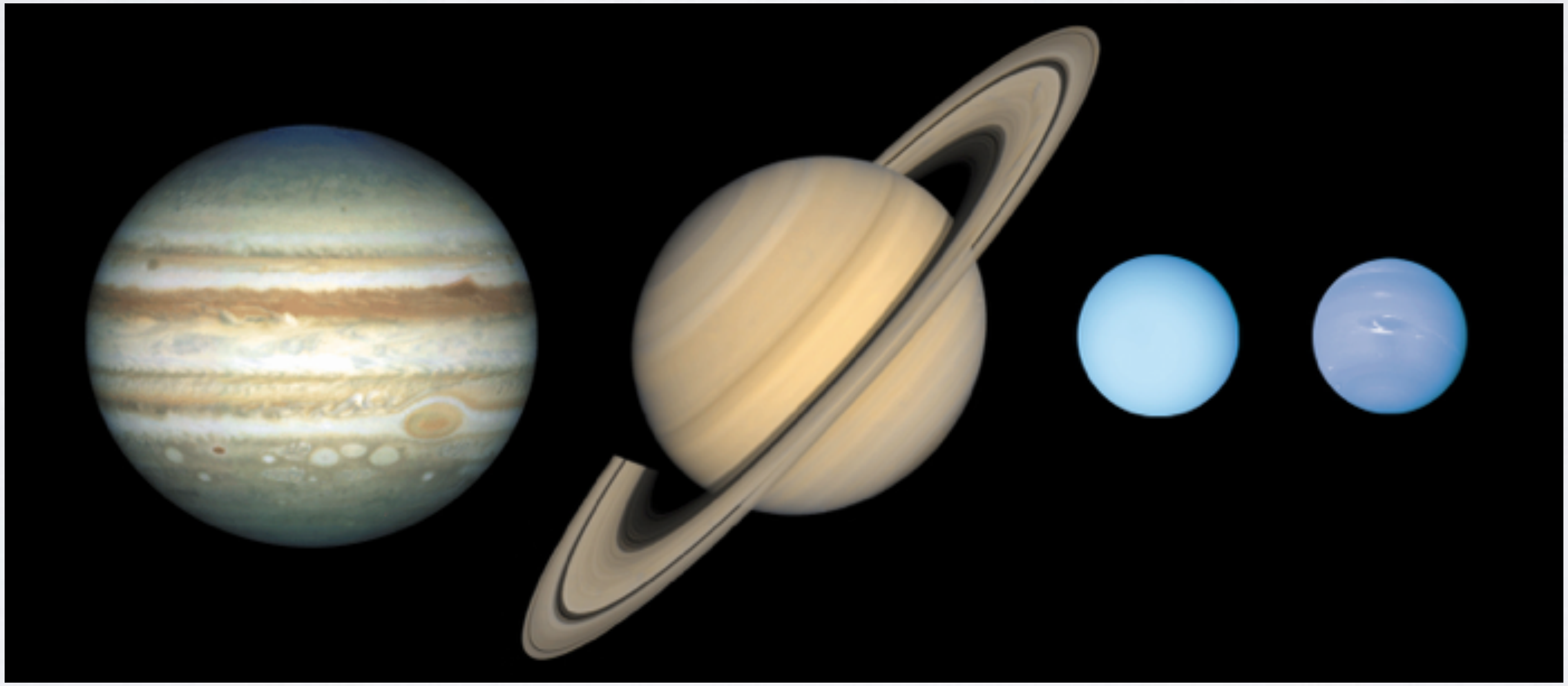
PLANET FORMATION IN THE OUTER DISK

Kaitlin Kratter



THE UNIVERSITY OF ARIZONA
COLLEGE OF SCIENCE
Astronomy
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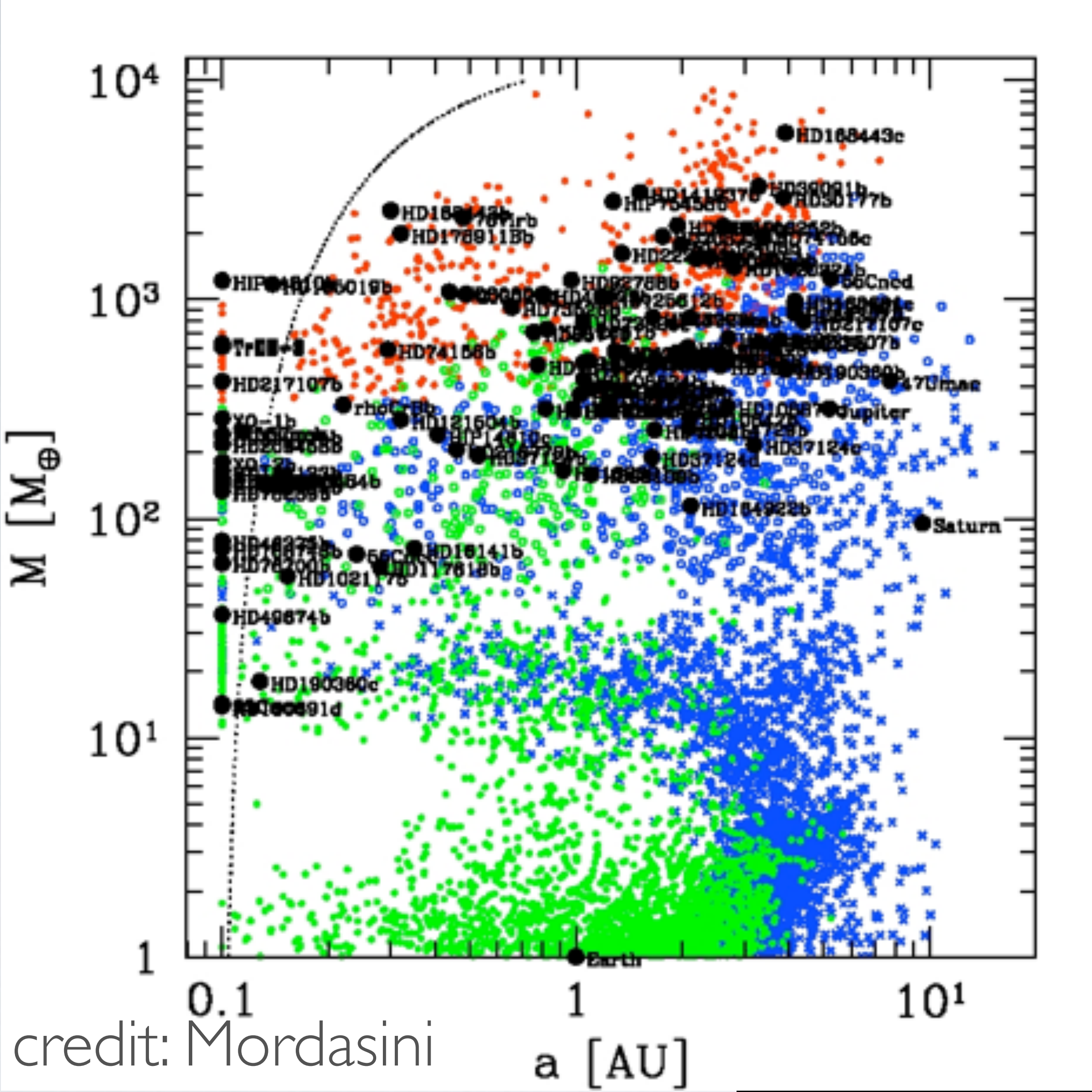
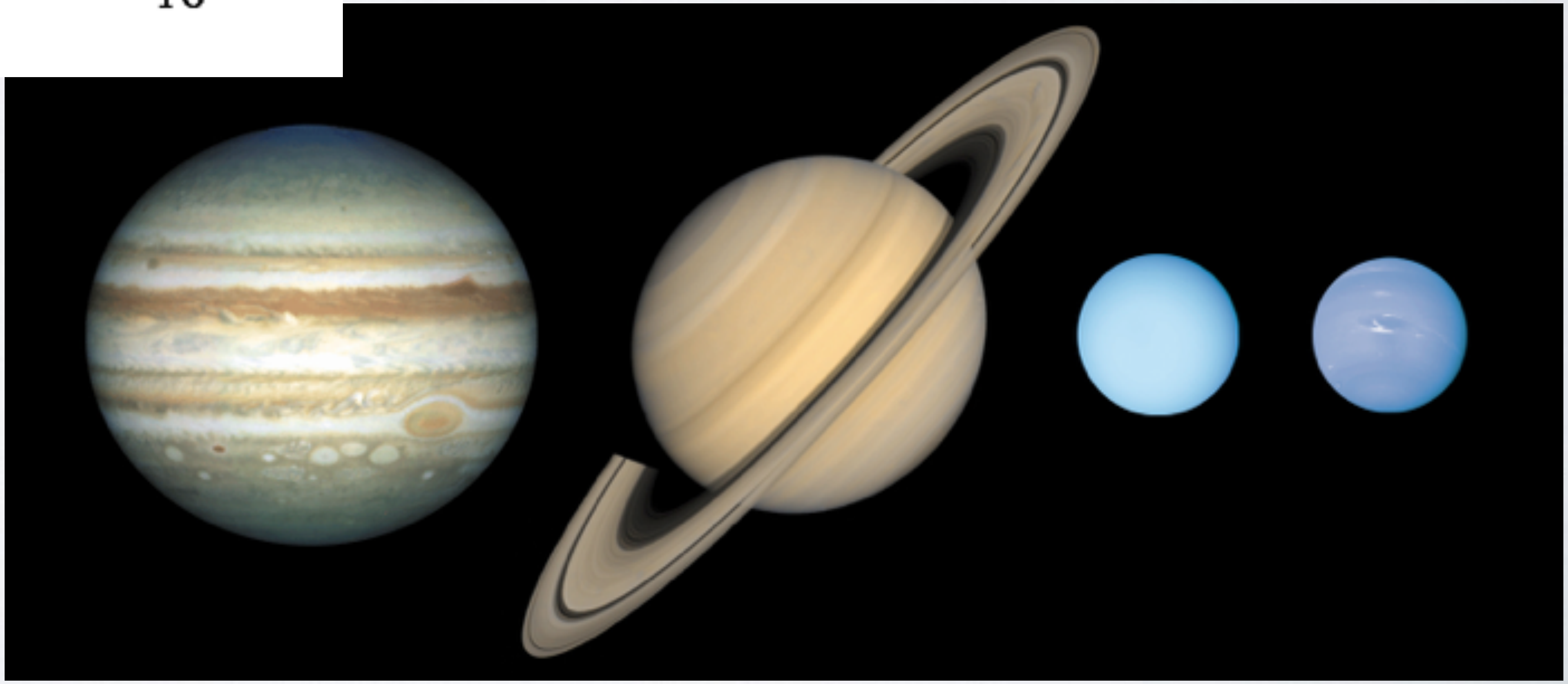


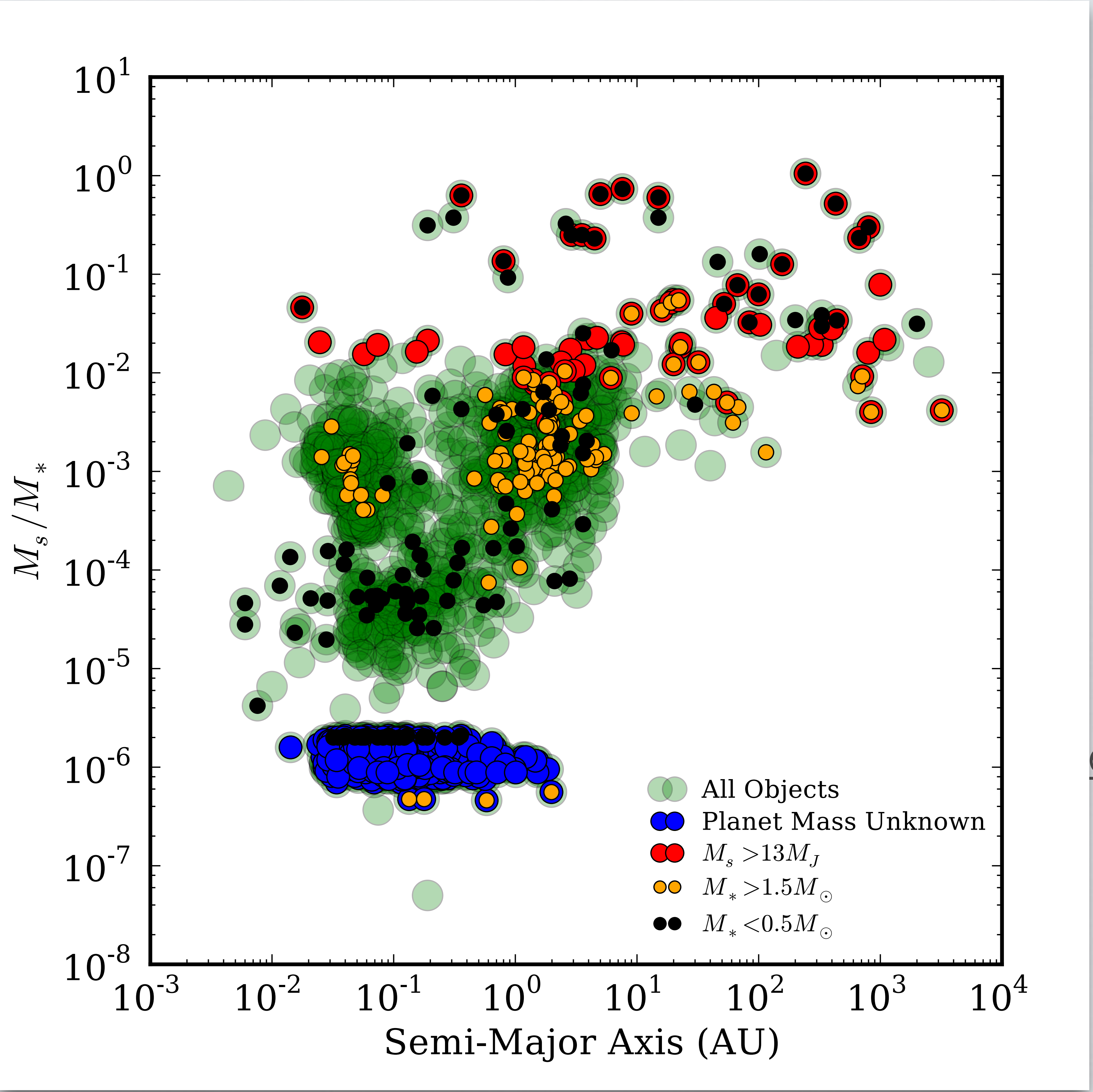
credit: Mordasini

What is the outer disk?

population synthesis tends to neglect even our own outer solar system!



We don't really know about "outer disk" exoplanets…



from exoplanets.eu, up to 30 Mjup

Kratter & Lodato, in prep

What is a planet?

Challenge: come up with a better definition than the IAU…(hint: what changed in 1995?)

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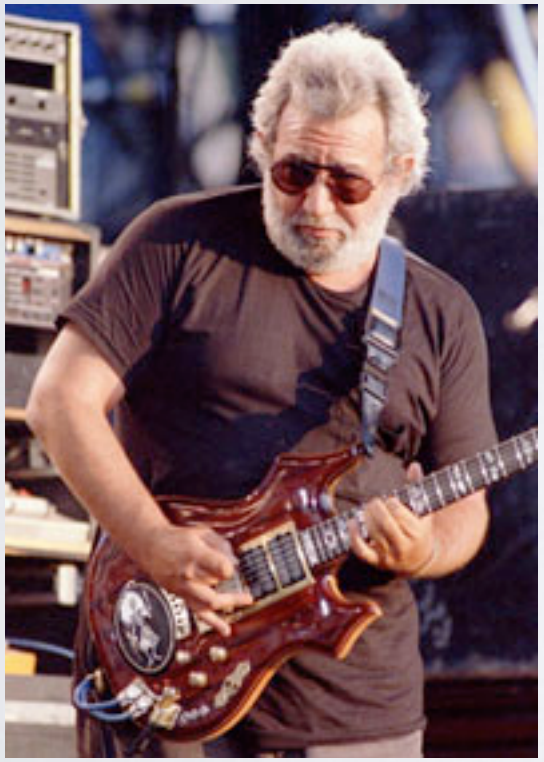
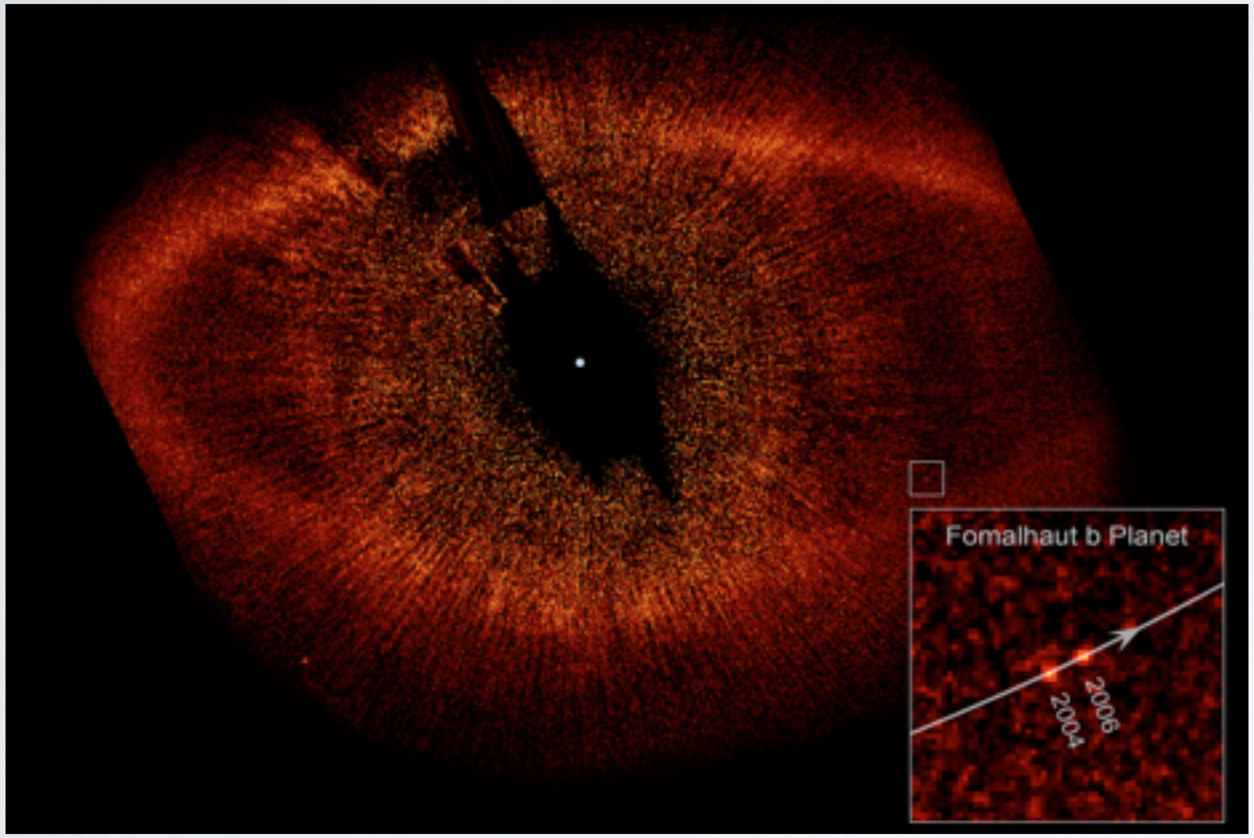
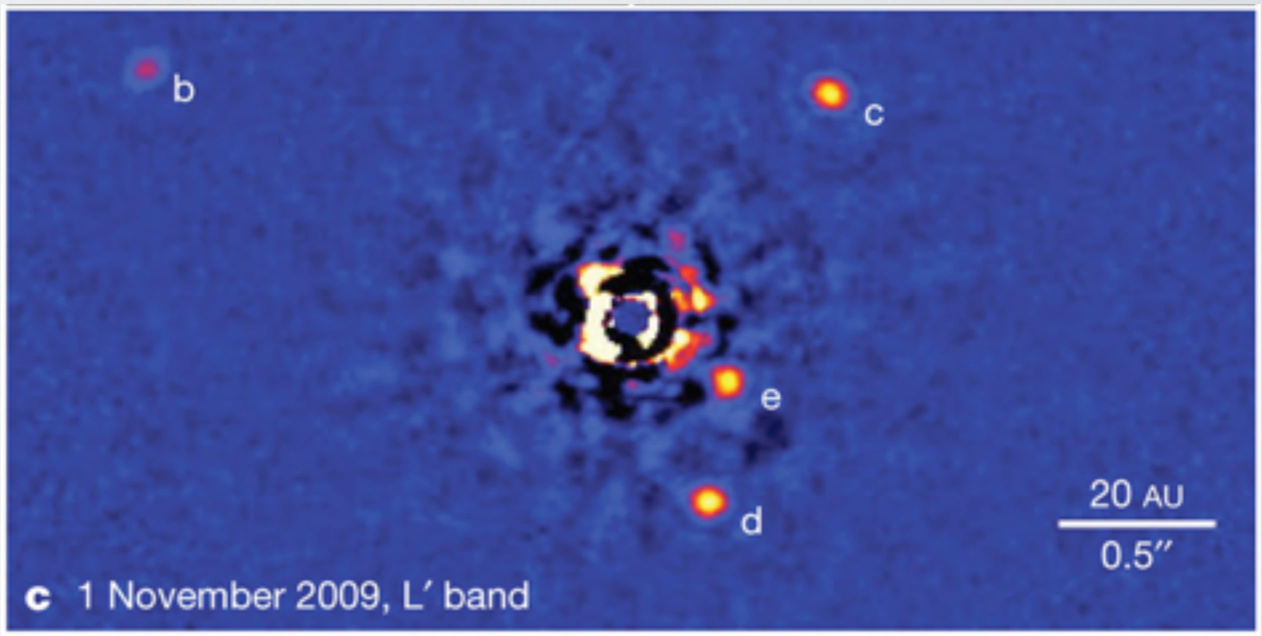


A HANDFUL OF PLANETS CAUSE A *LOT* OF TROUBLE





Marois+ 2009,2011, Kalas 2013

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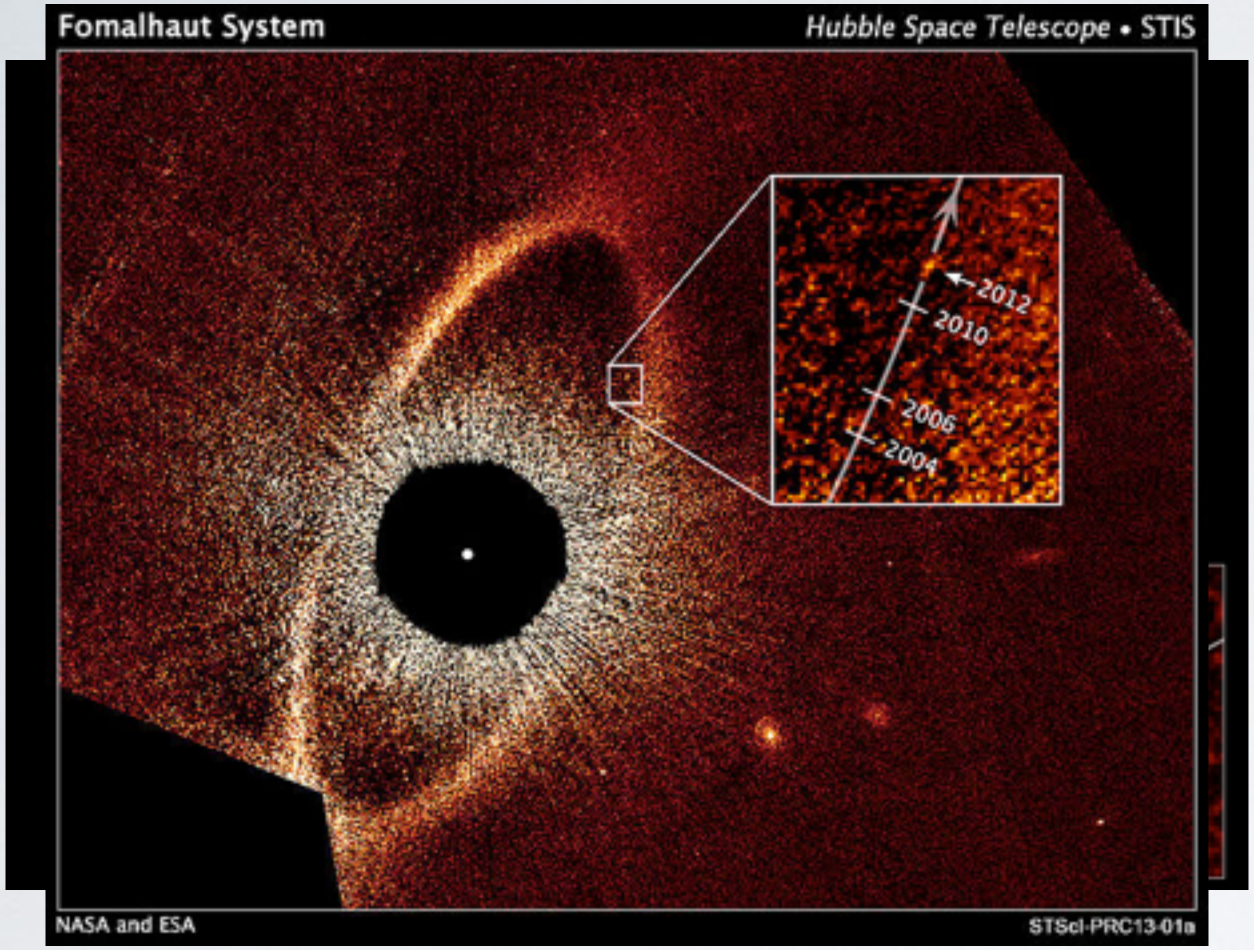

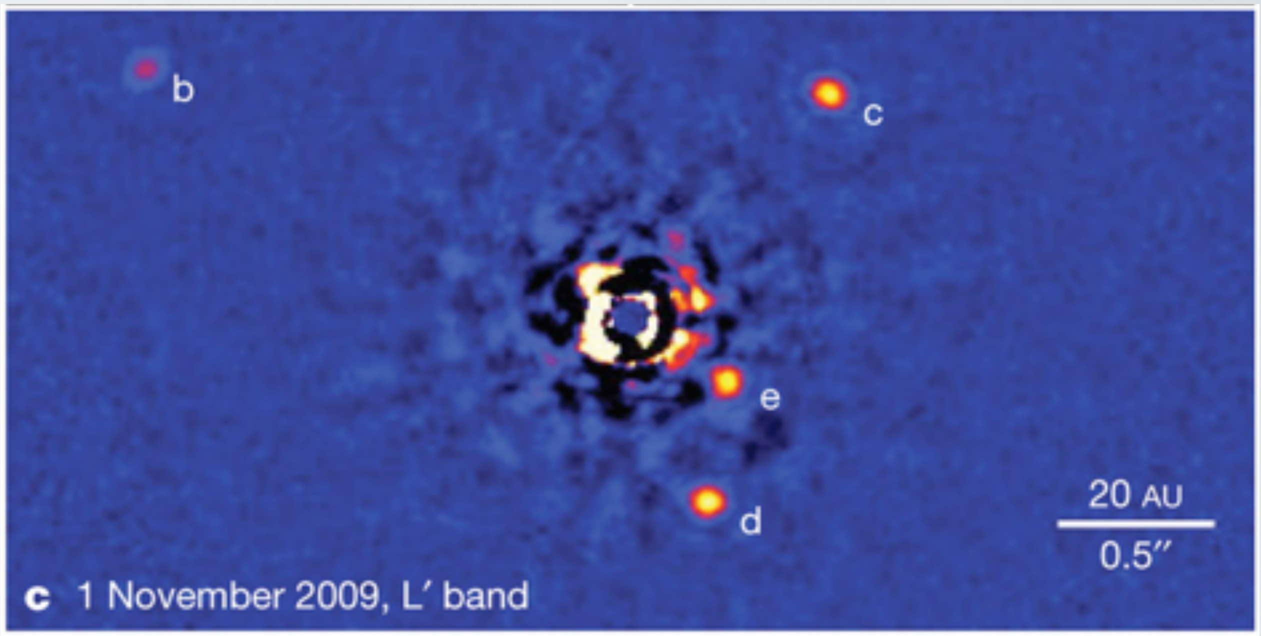

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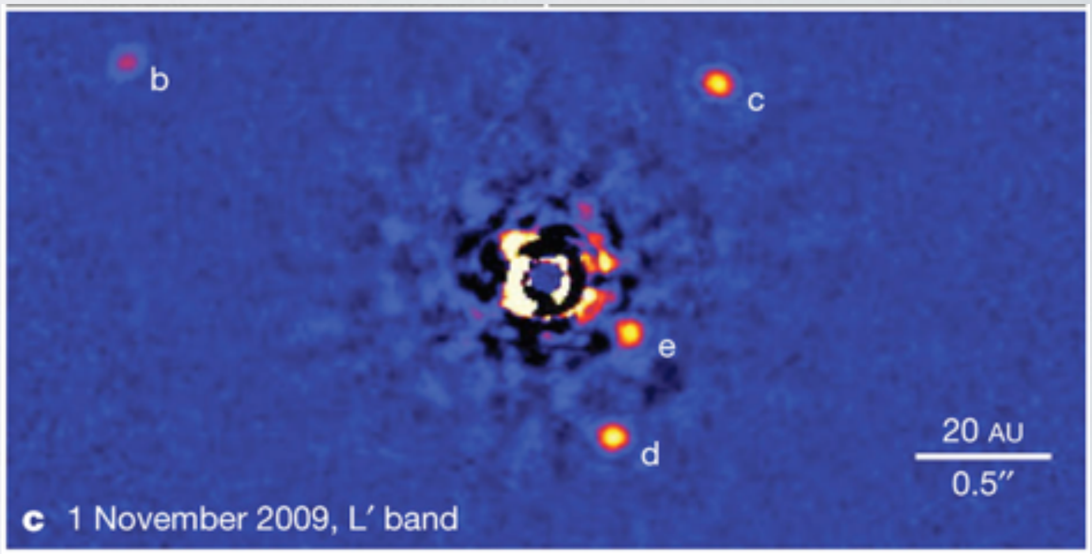
THE RUNTS OF THE LITTER?

(KRATTER ET AL, 2010B)



Hinkley + 10, Marois+ 10,Lafrieniere +11, Janson+11, Ireland+11, Crepp+12

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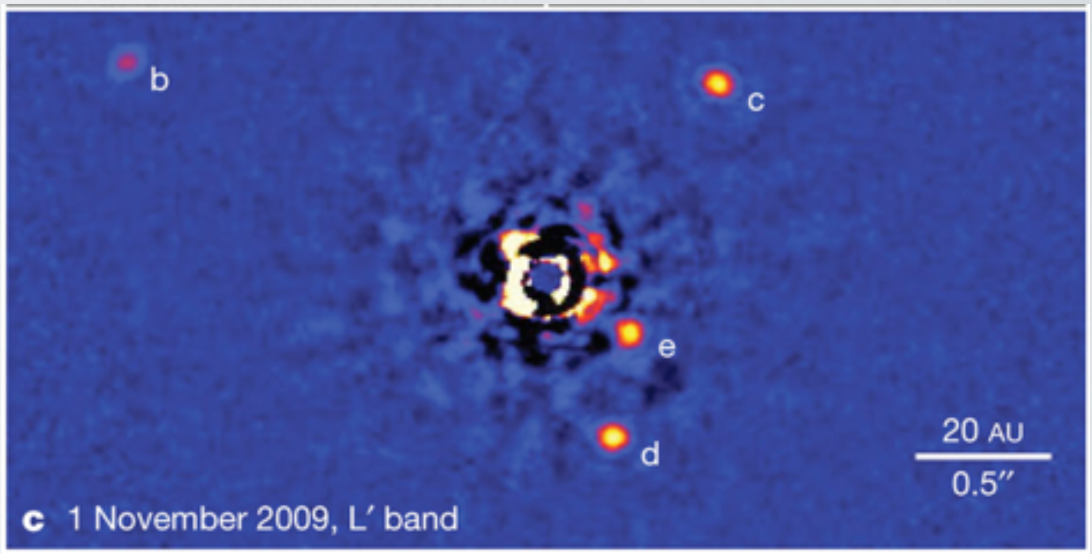

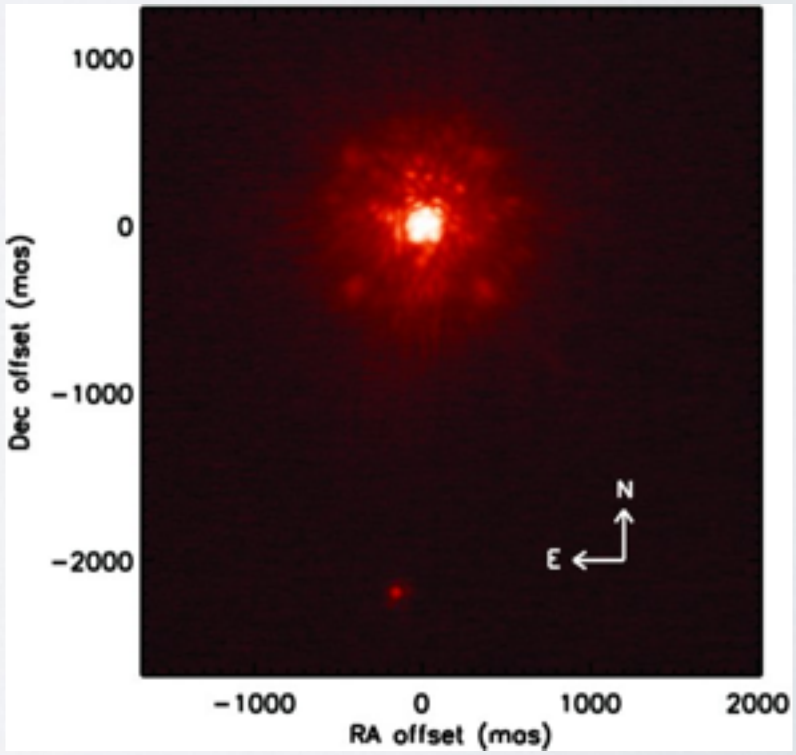

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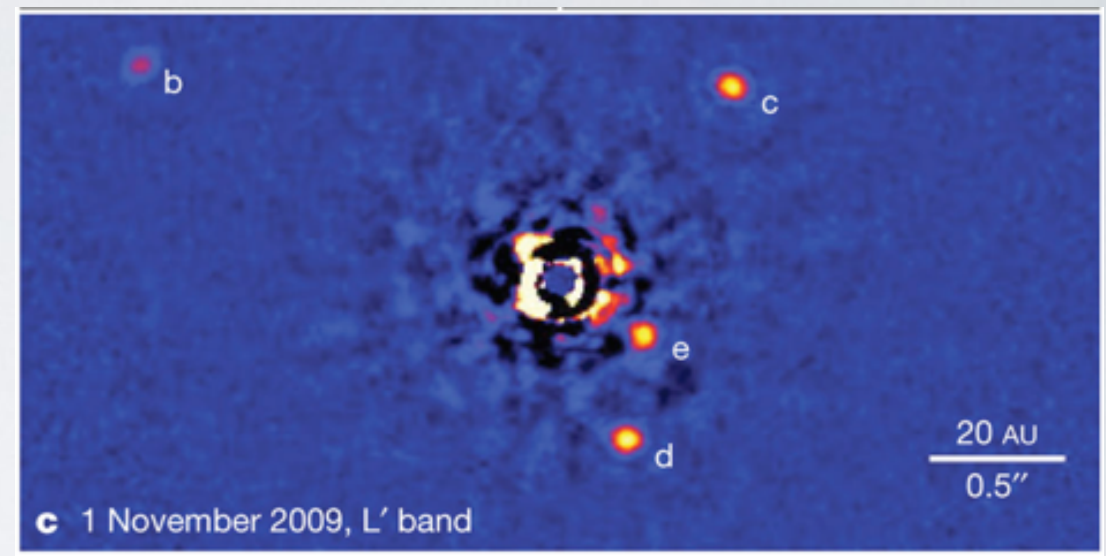

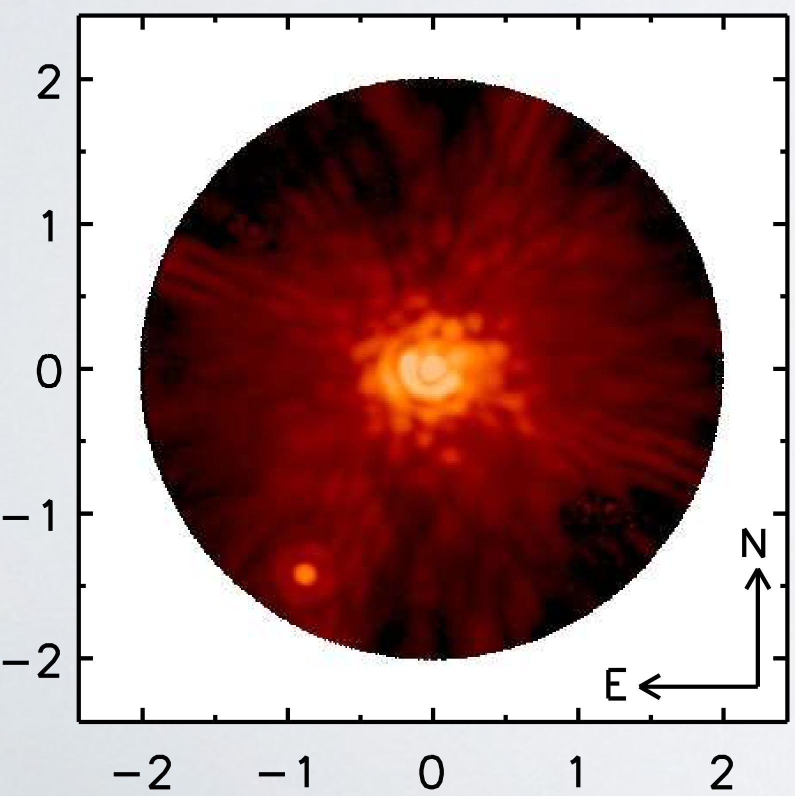

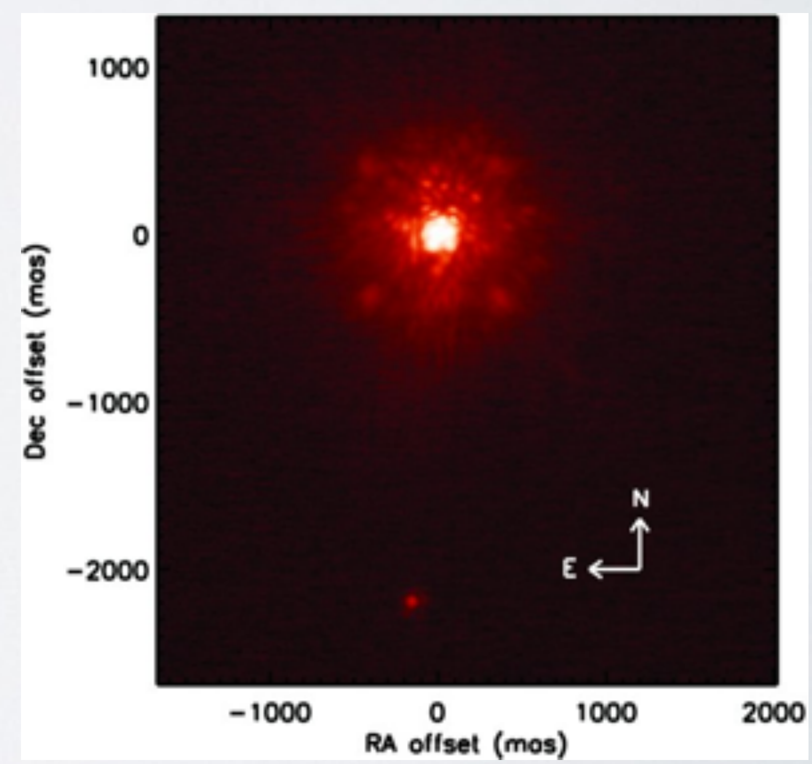

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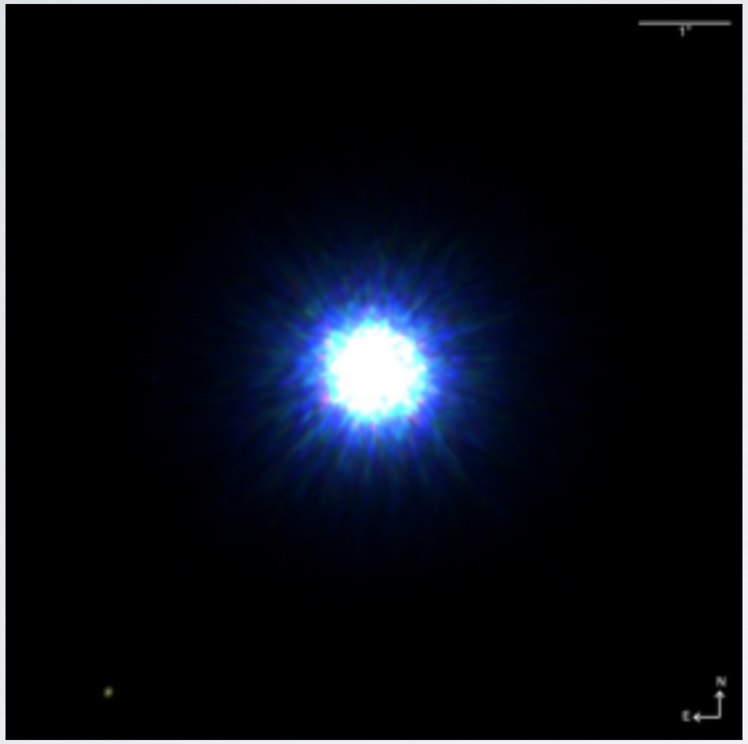

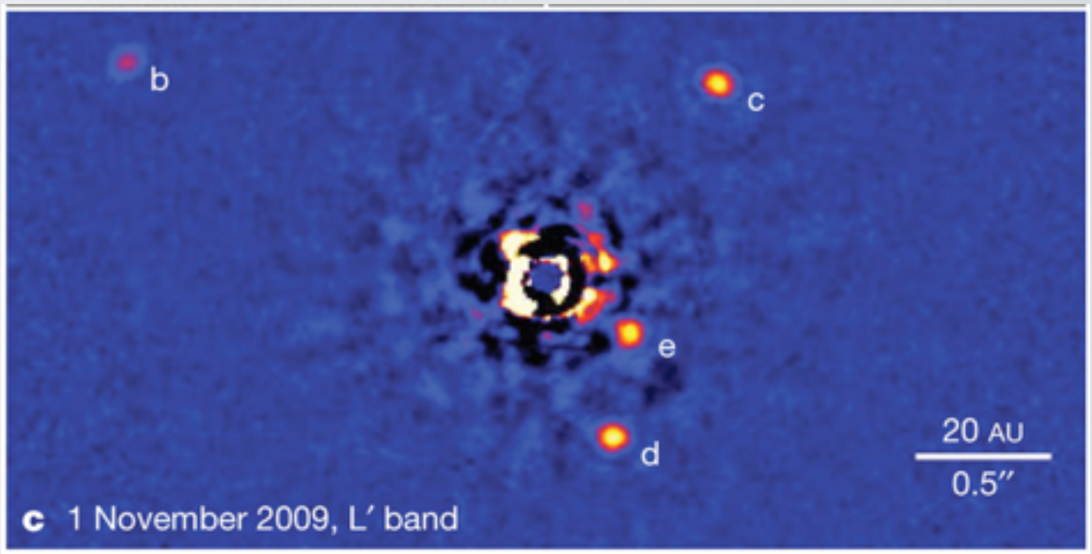

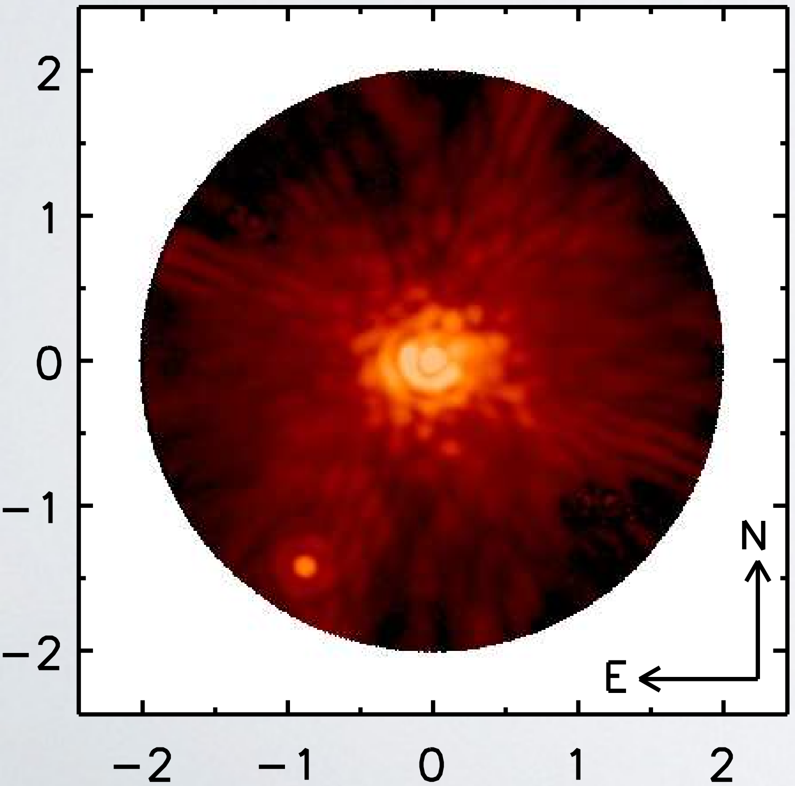

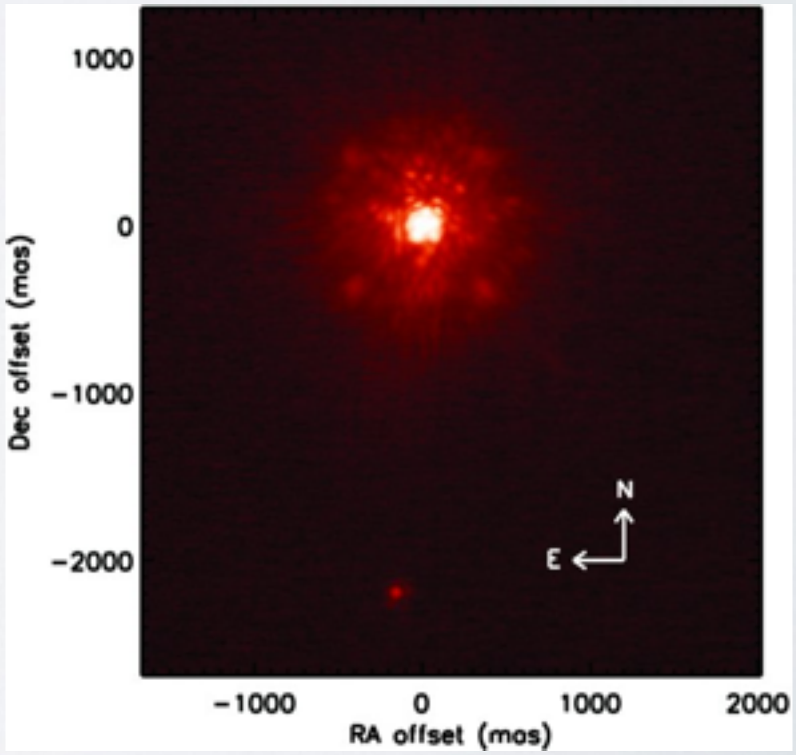

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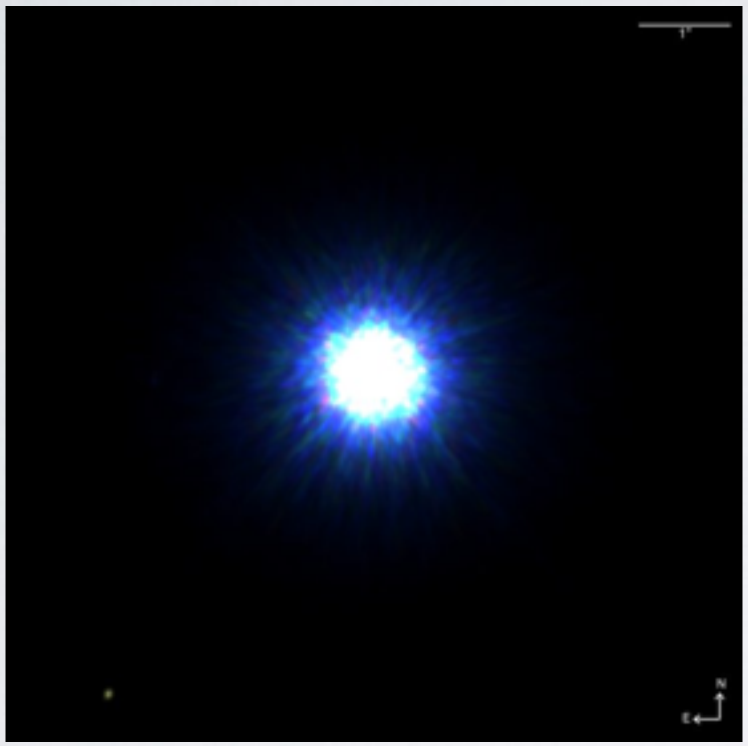

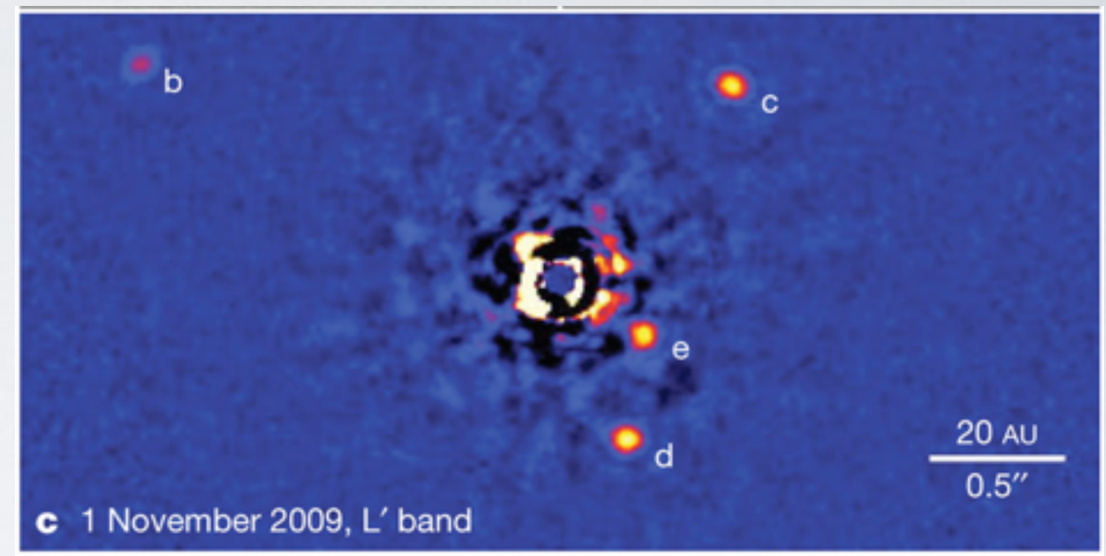

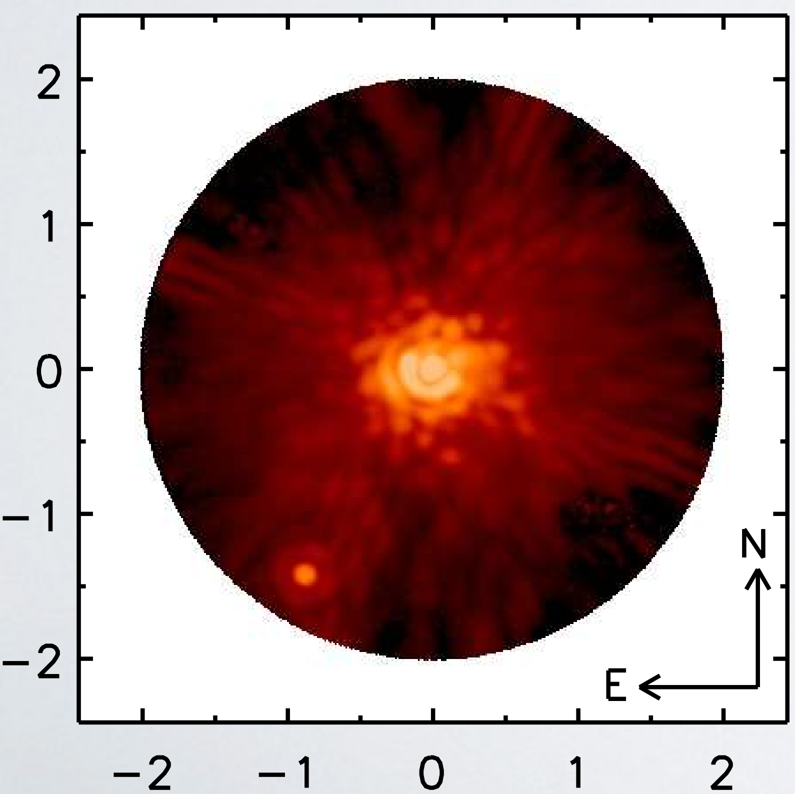

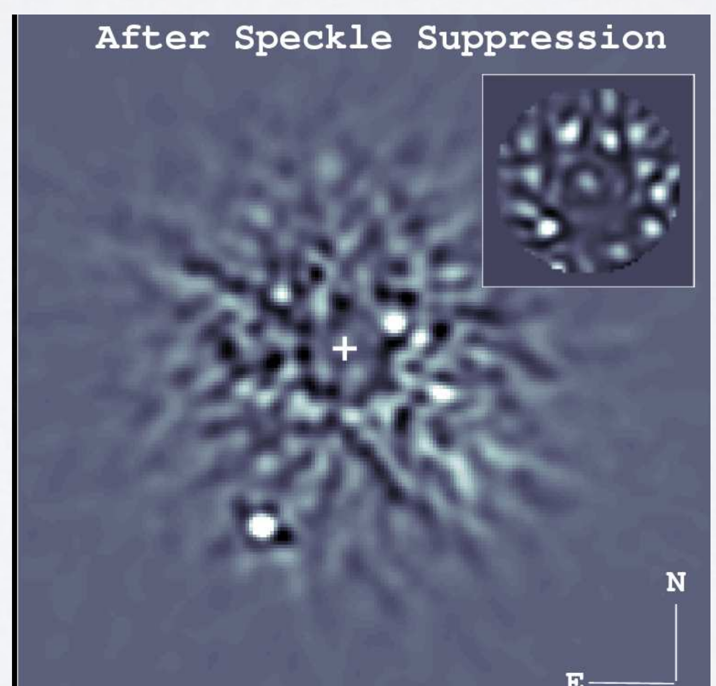

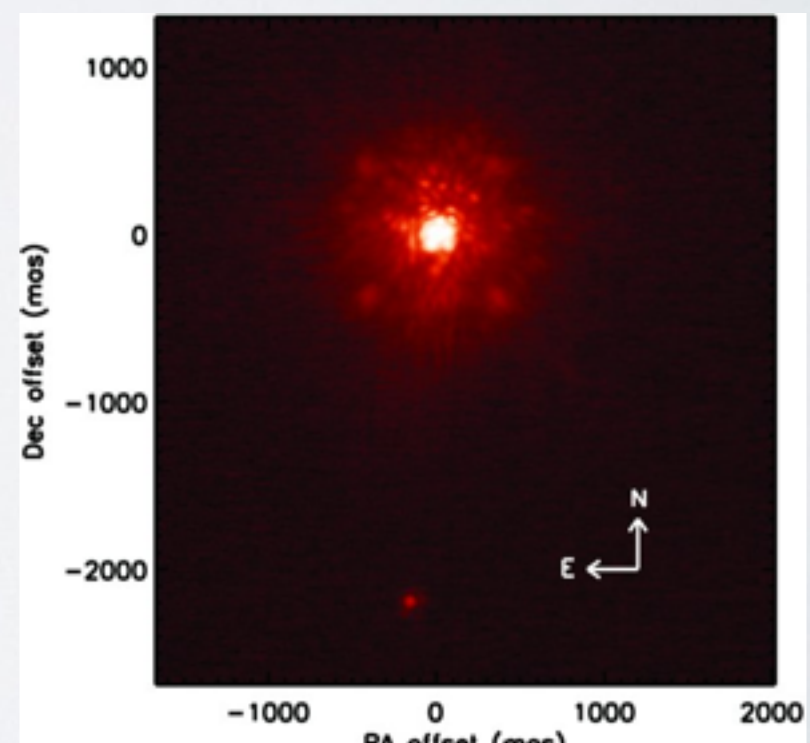

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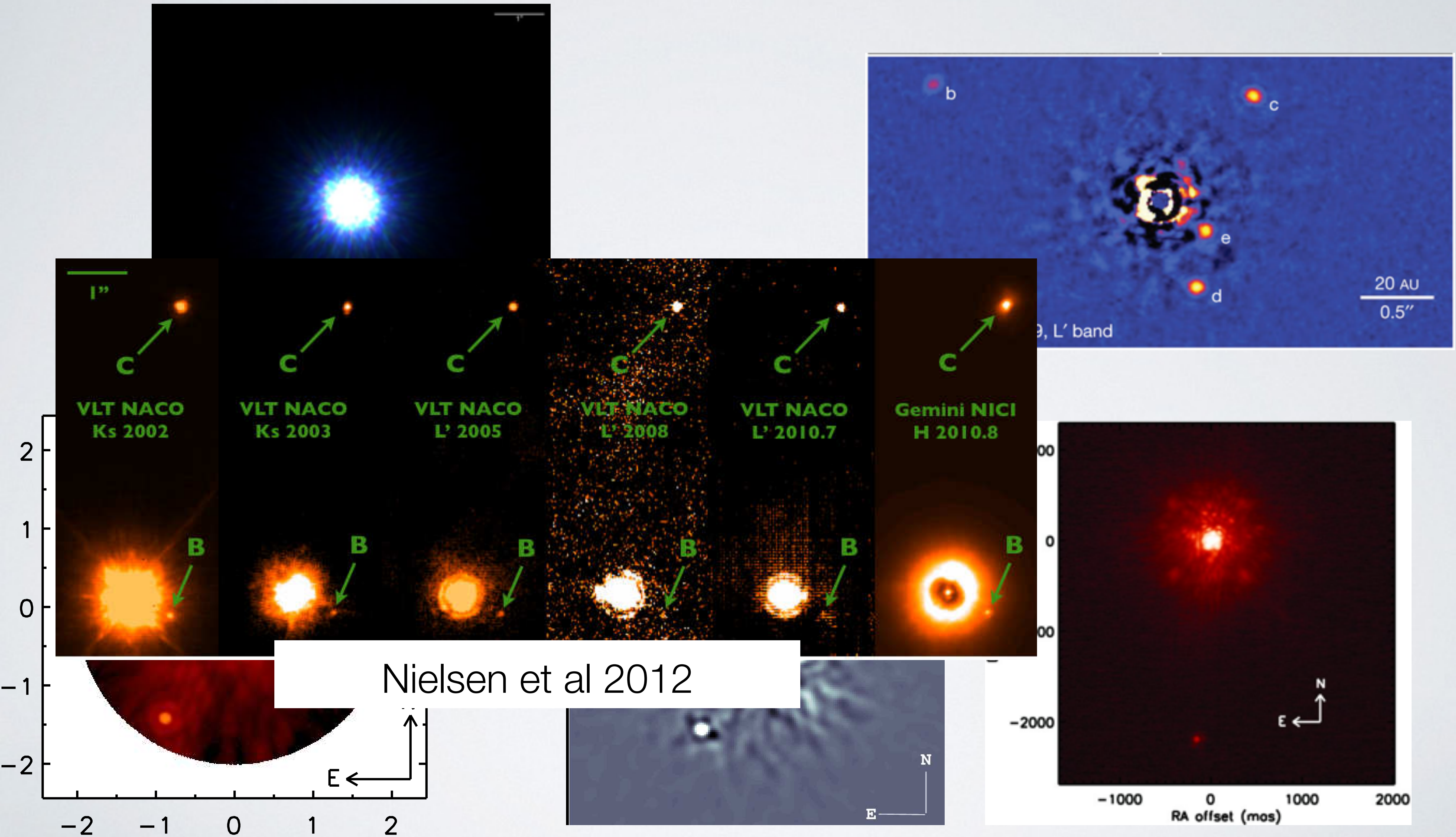

Nielsen et al 2012

Hinkley+ 10, Marois+ 10,Lafrieniere +11, Janson+11, Ireland+11, Crepp+12

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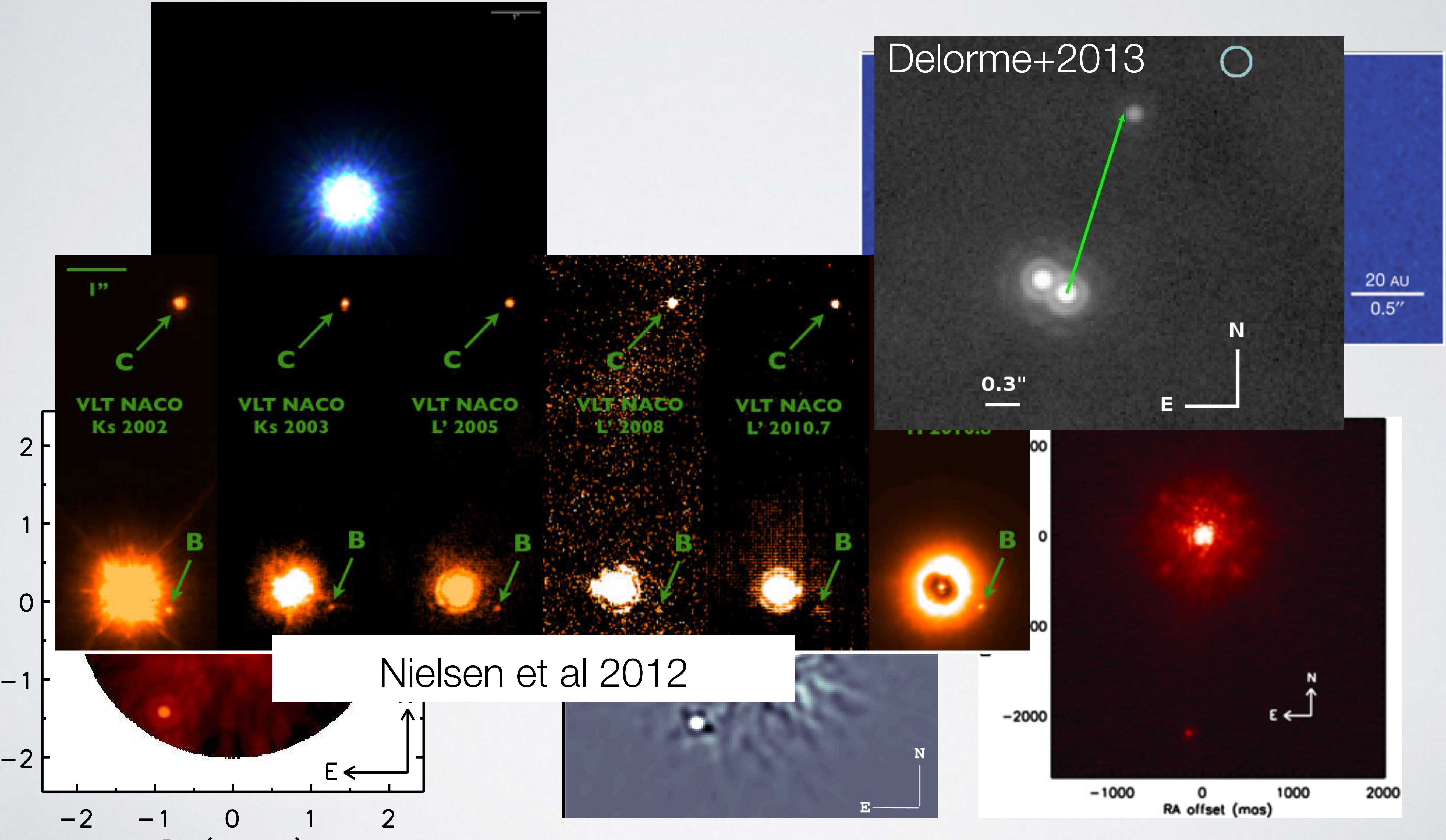

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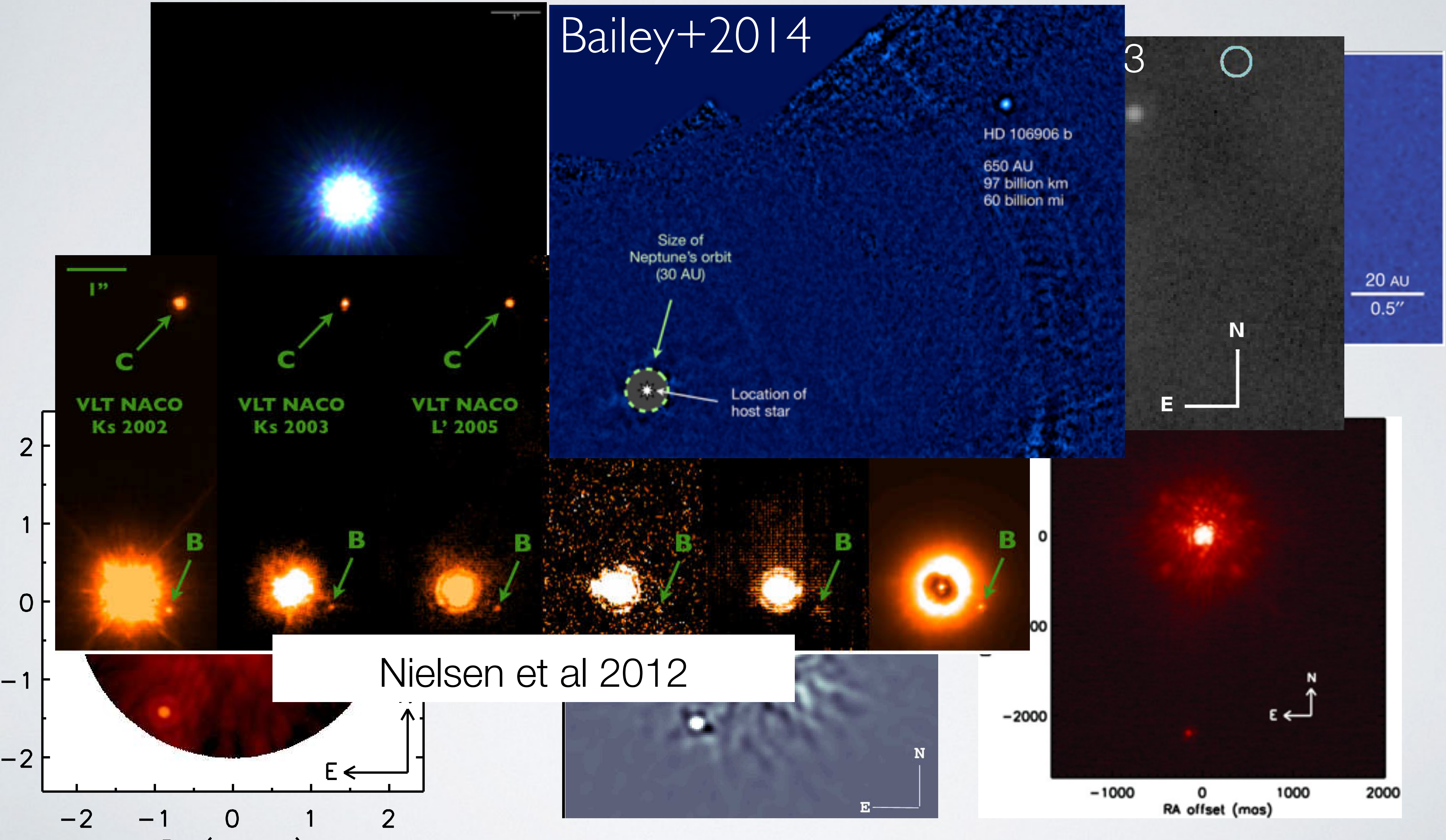

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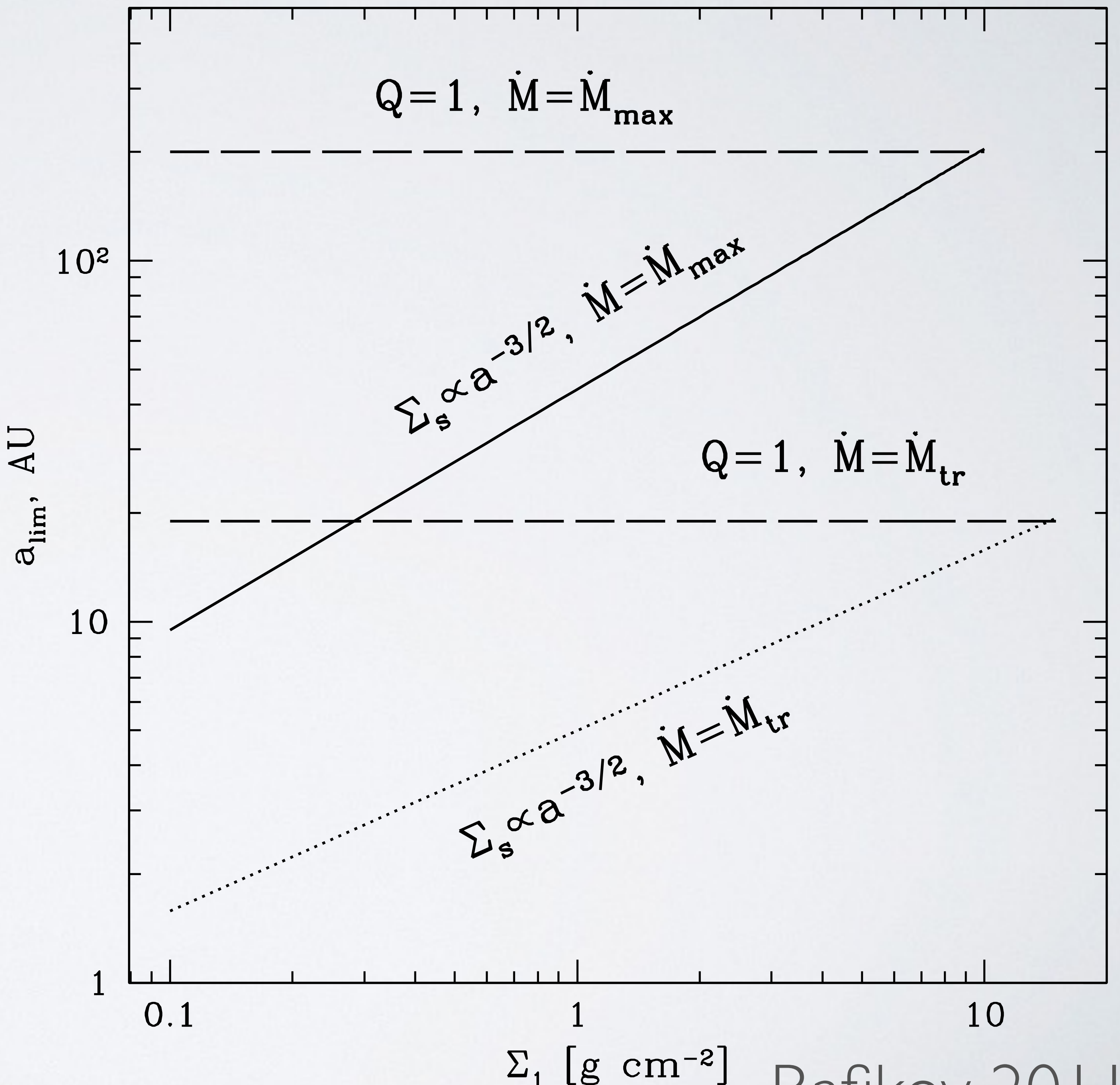
WHAT'S SO HARD ABOUT PLANET FORMATION IN THE OUTER DISK?

- Classic Answer:
  - It takes longer than the disk lifetime to build a big enough solid core to trigger runaway atmospheric growth
  - Even extreme assumptions about accretion (zero velocity dispersion) struggle

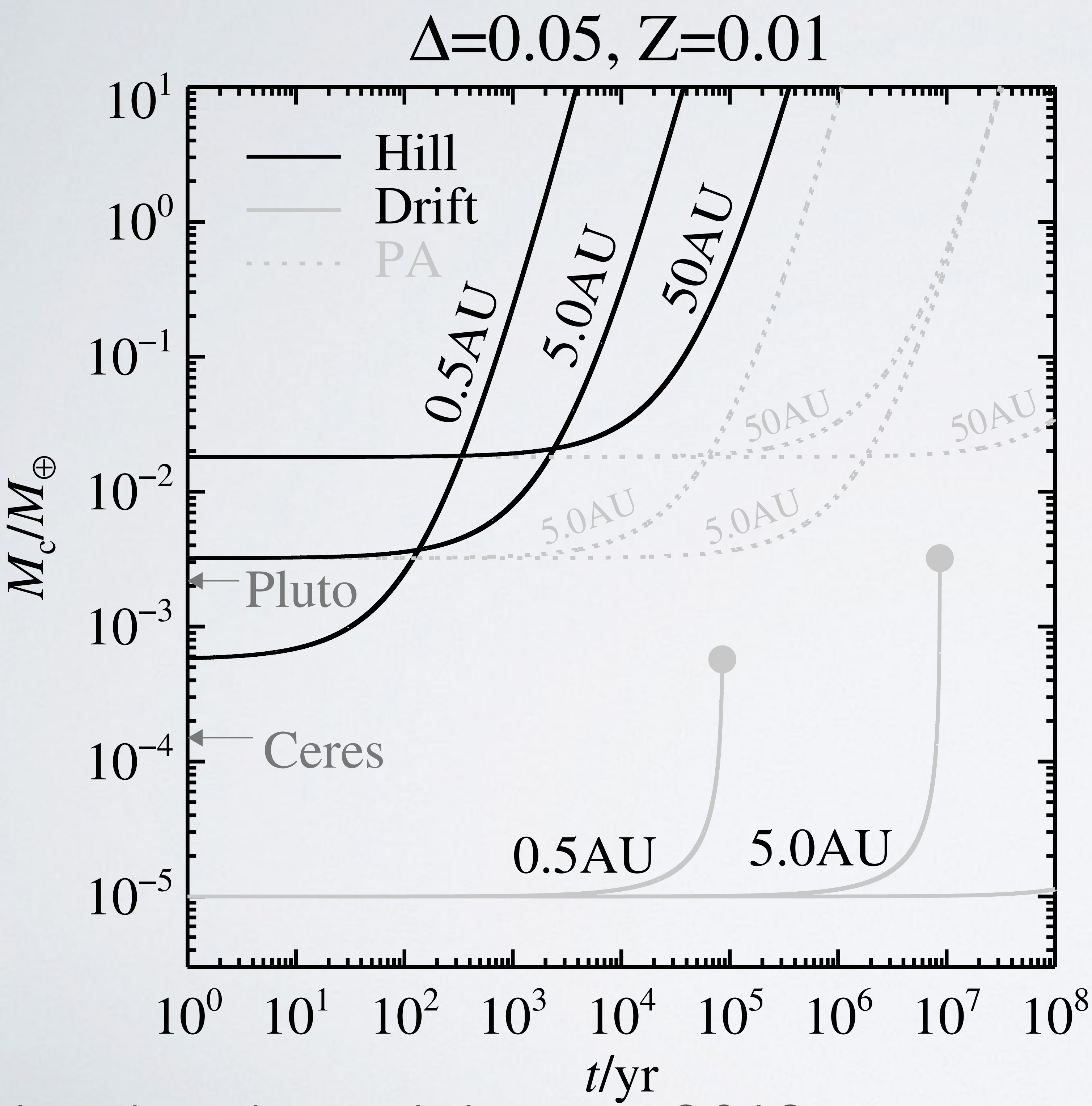
"Classic" Runaway growth problem

- Without considering gas-drag, growth by CA in 3 Myr requires extreme assumptions about the planetesimal velocity dispersion and disk mass, which are hard to satisfy simultaneously



Rafikov 2011

Growth timescales change when including aerodynamic pebble capture

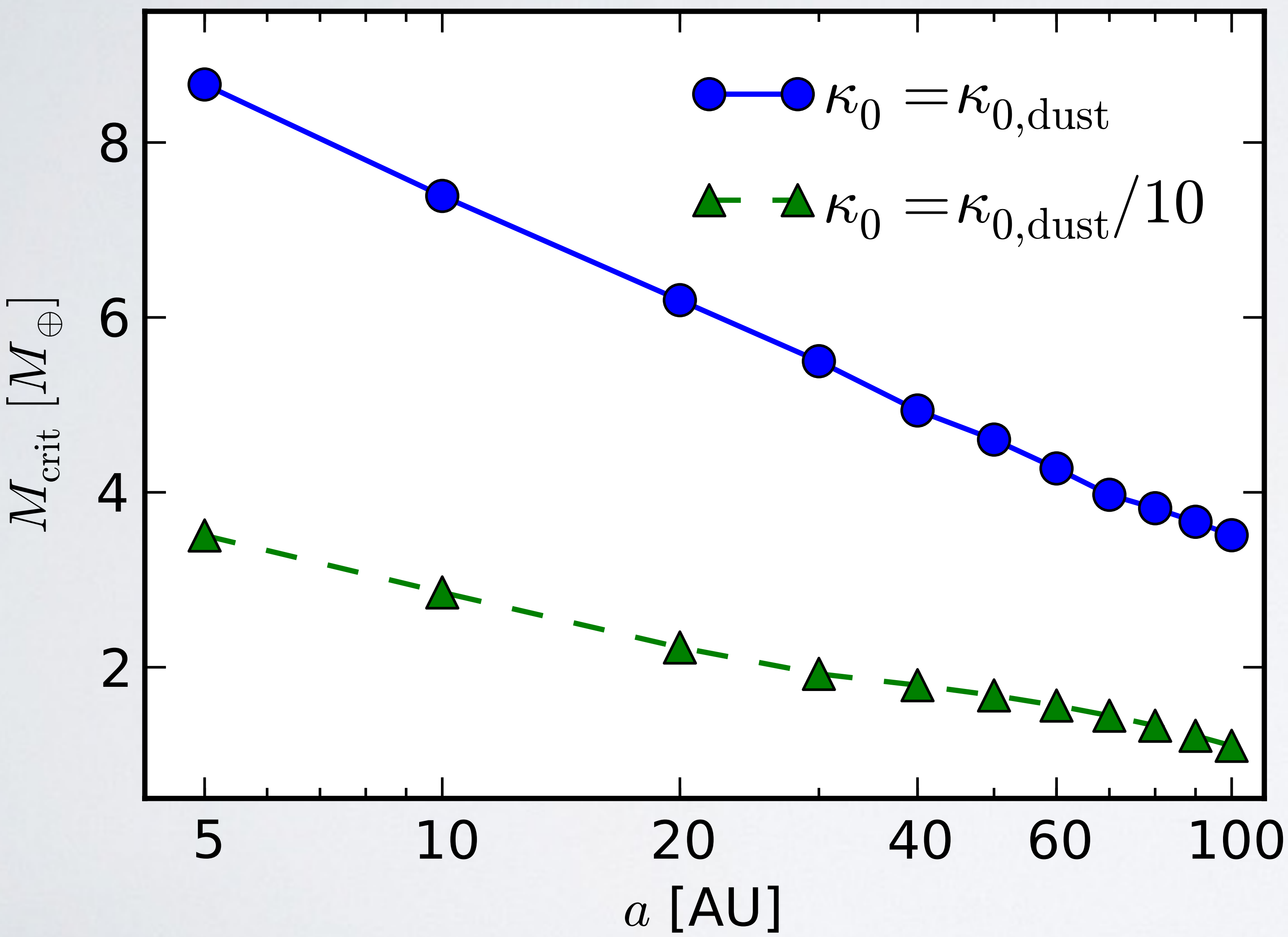


Lambrechts & Johansen 2012

- Gas giants can in principal form even at 50 AU in disk lifetime
- Problem is first mass doubling time, not the last

BUT: need initial ~pluto mass cores…

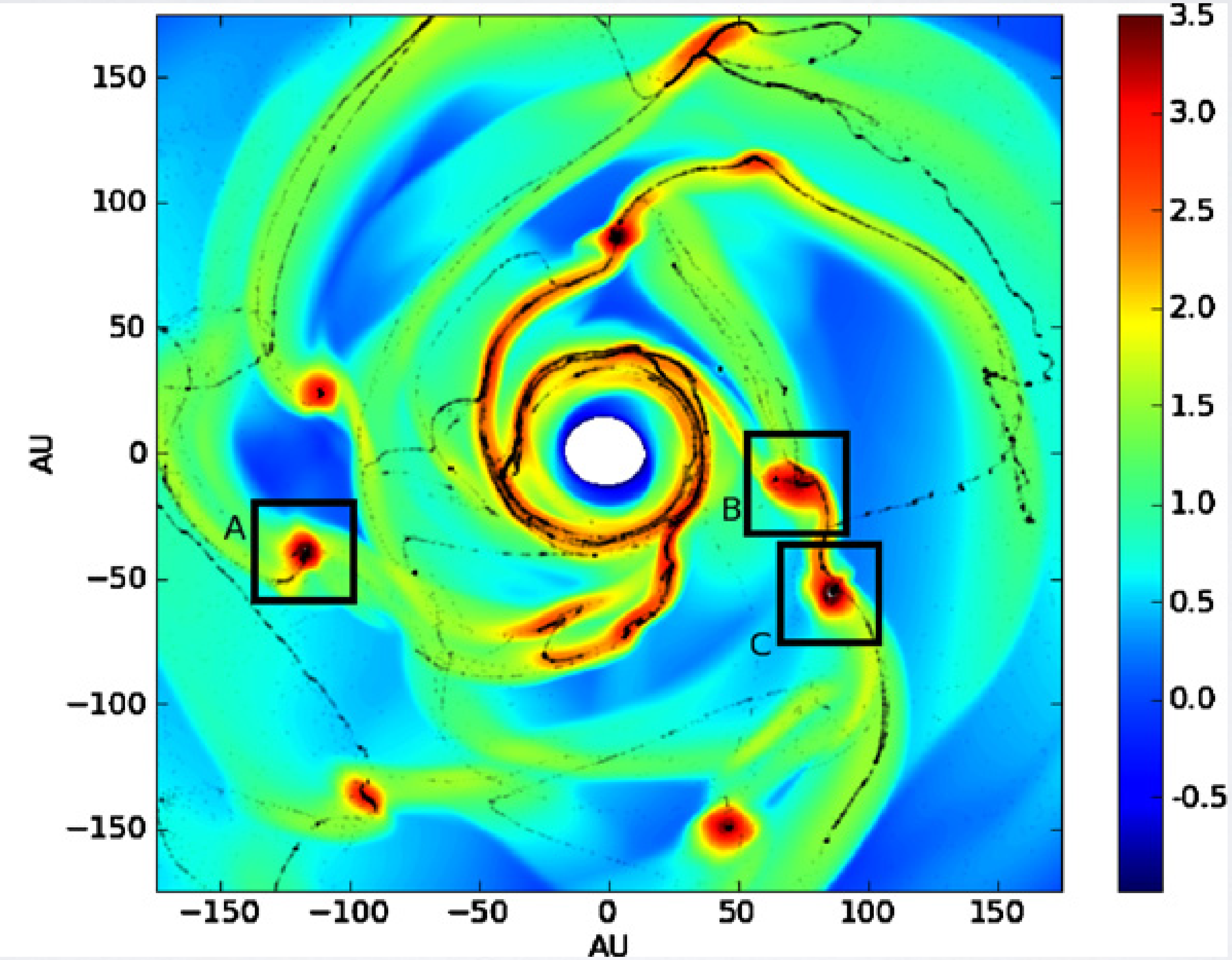
The critical core mass to trigger runaway growth declines with semi-major axis



- Even though growth times are slower, less core growth is required
- Temperature goes down, Bondi radius goes up, and opacity declines

Piso & Youdin 2014

WHAT ABOUT THE EVOLUTION OF GI FRAGMENTS?



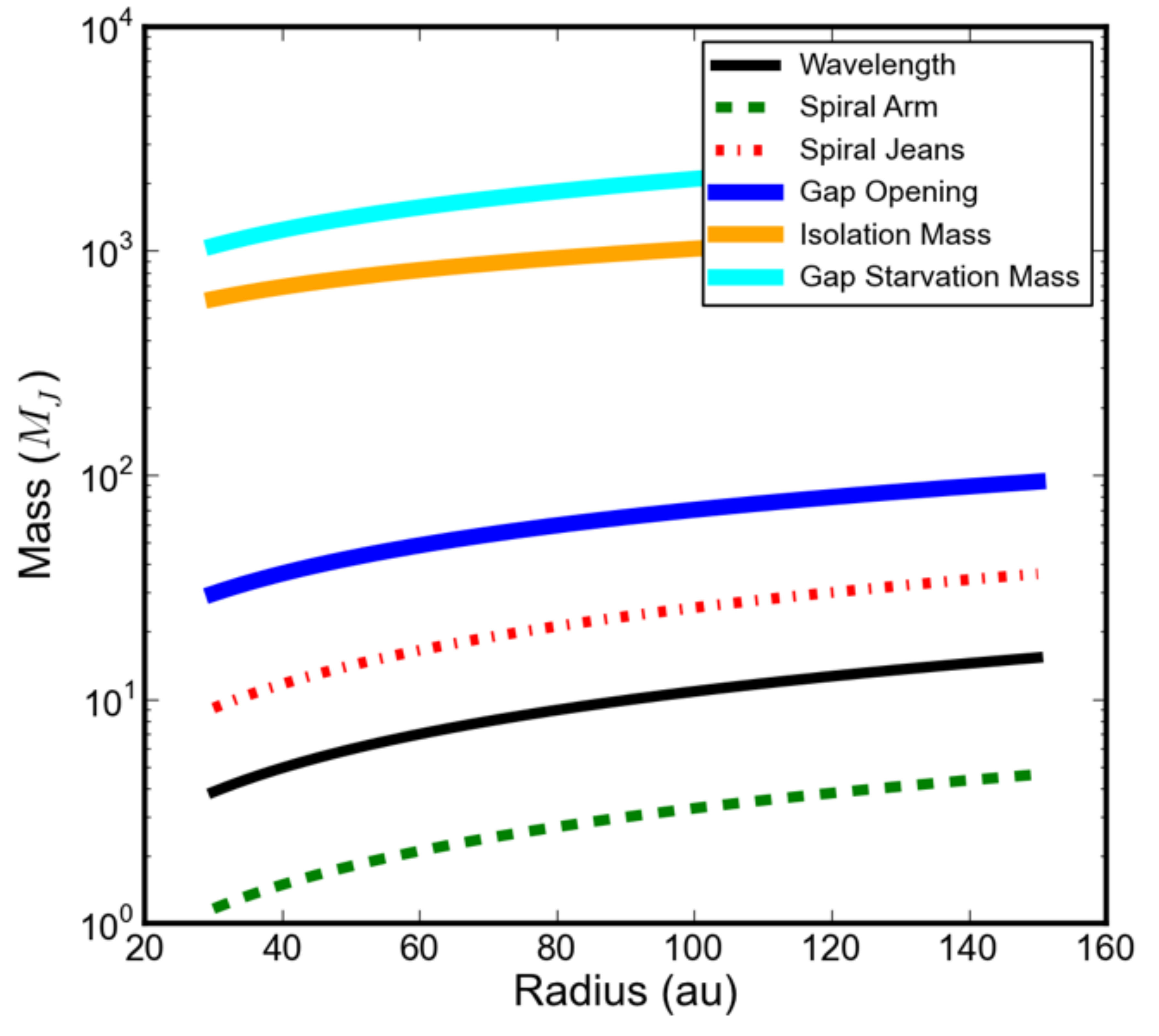
Boley+2011

First order: how massive are fragments?

- Initial mass estimates all scale with

$$\Sigma H^2$$

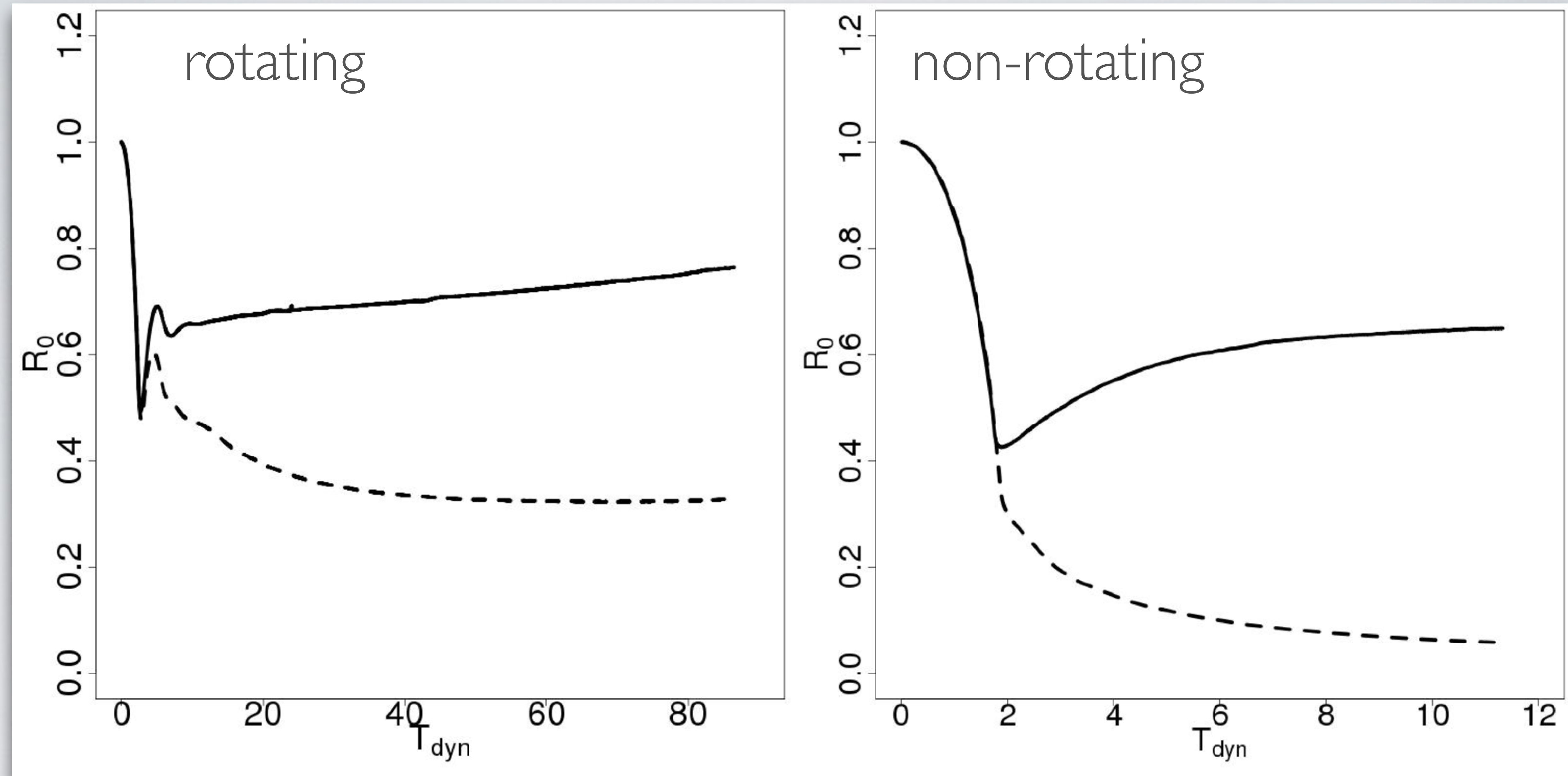
- Fragments that are not disrupted can also easily grow from the parent disk



Kratter+2010, Boley+2010, Forgan & Rice 2013, Young & Clarke 2015

FRAGMENT EVOLUTION: COOLING

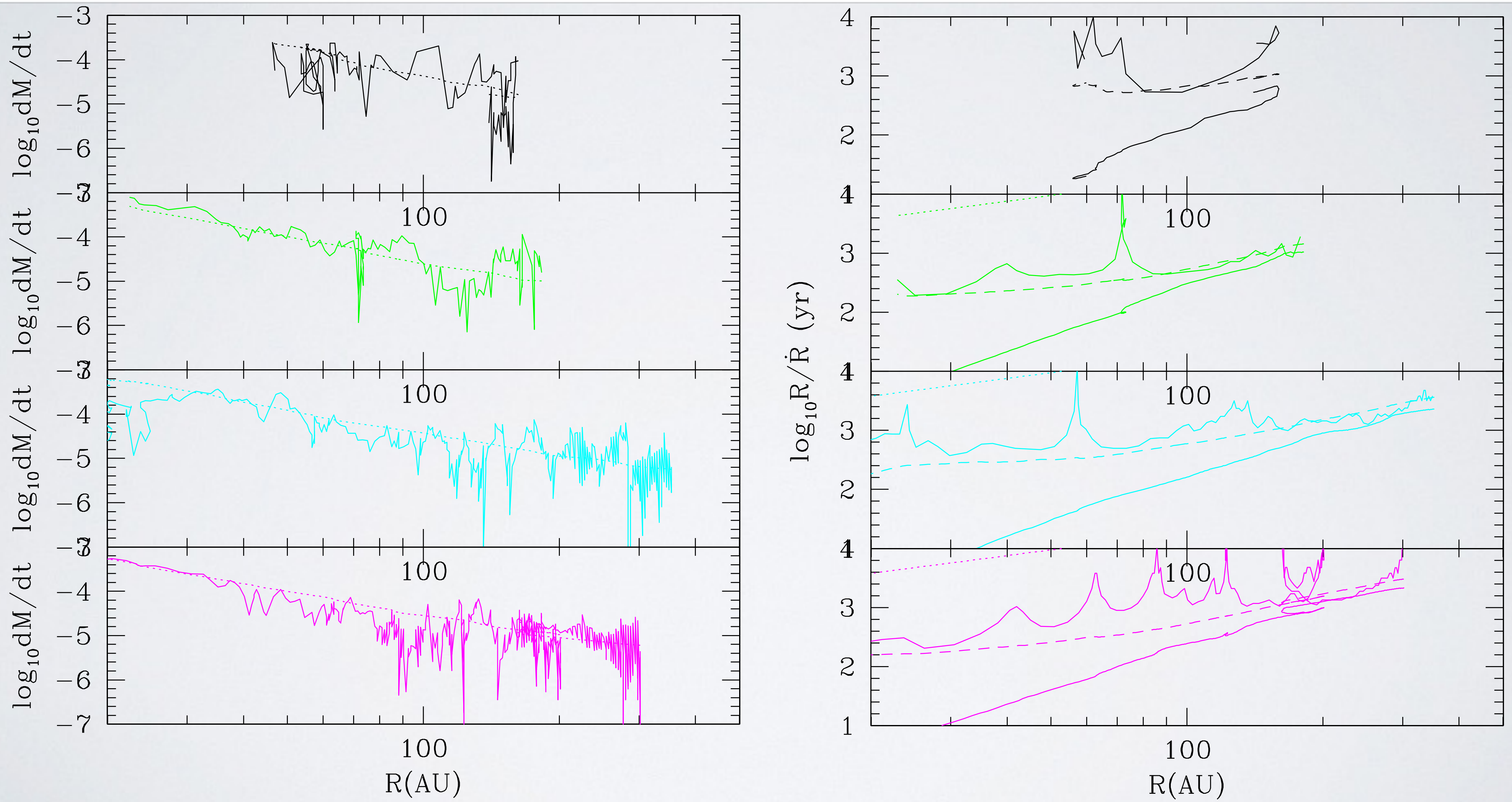
Galvagni+2012



- Collapse calculations including realistic cooling collapse to <1 Rh in 1-10 dynamical times.
- At fixed radius, they should survive (see Kratter & Murray-Clay for analytic collapse requirement)

Growth, Migration, Disruption

Fragments migrate inwards on ~10 outer dynamical timescales.

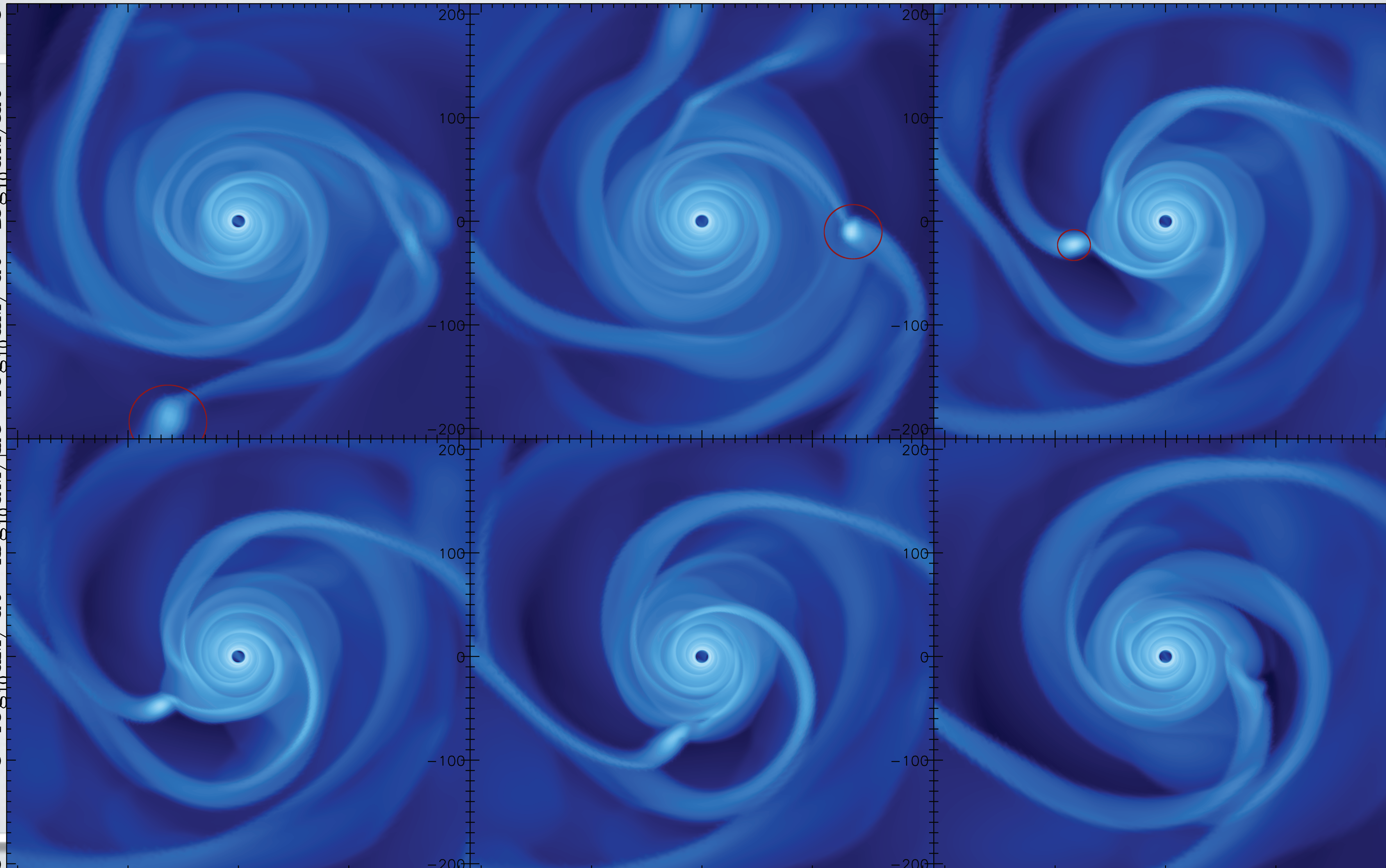


Zhu et al 2012

Growth, Migration, Disruption

Fragments migrate inwards on ~10 outer dynamical timescales.

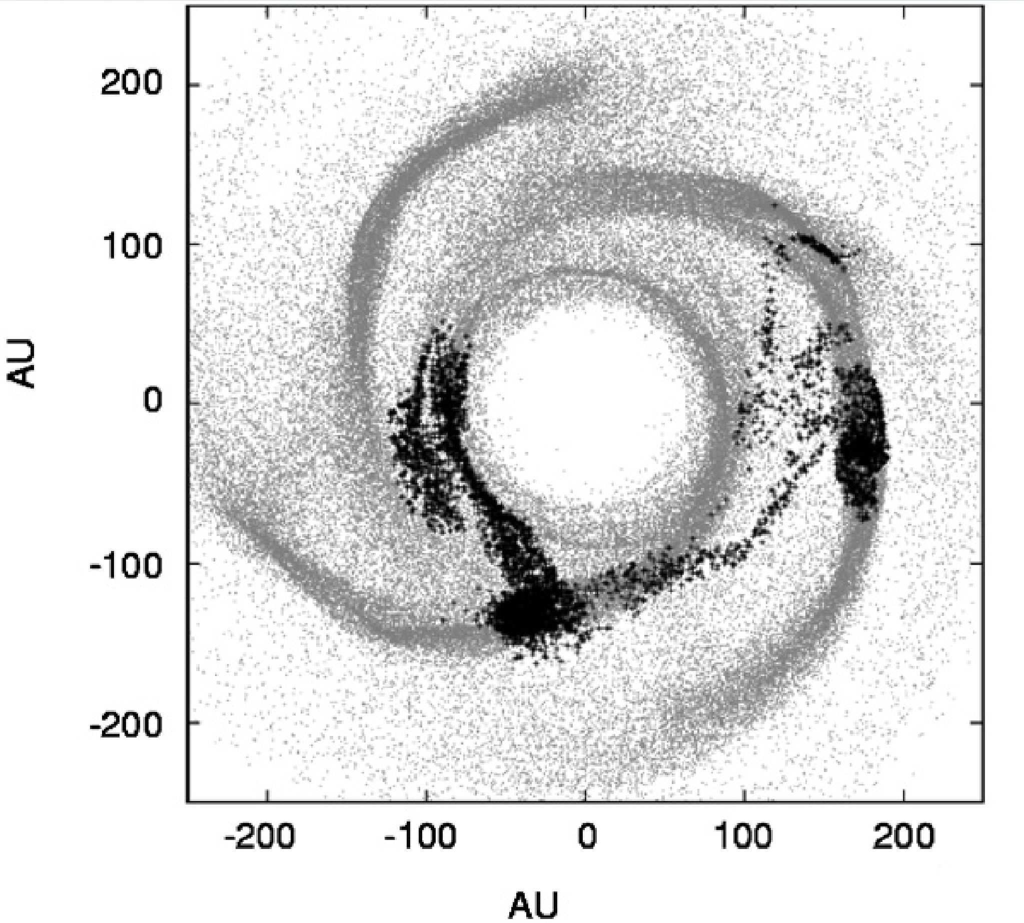
$$\tau_{mig} = 784 \left(\frac{M_c}{0.01 M_\odot}\right)^{-1} \left(\frac{R}{100 AU}\right)^{1.75} yr$$



Zhu et al 2012

WHAT ABOUT SOLIDS IN GI?

- solids (if they grow…) can collect in spiral arms (pressure bumps), and sediment into a core (though won't work for cores > 6Mj)
- Tidal disruption could leave behind the differentiated core, leading to rocky planets in the inner disk
- Fragments can also become enriched after formation, but timescale is short if they are migrating.
- If they don't migrate, then GI "planets" at large radii might have substantial metal enrichment.

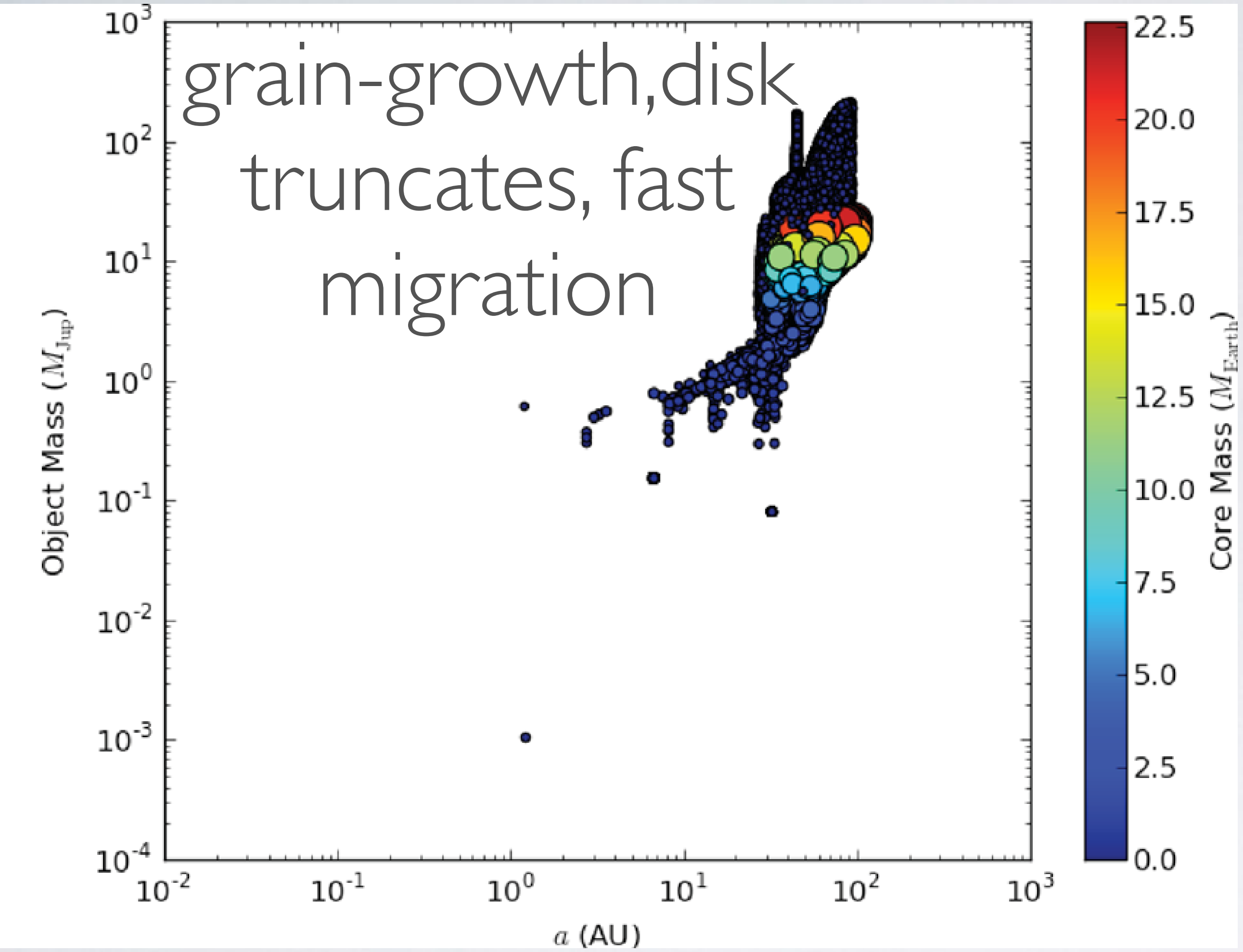


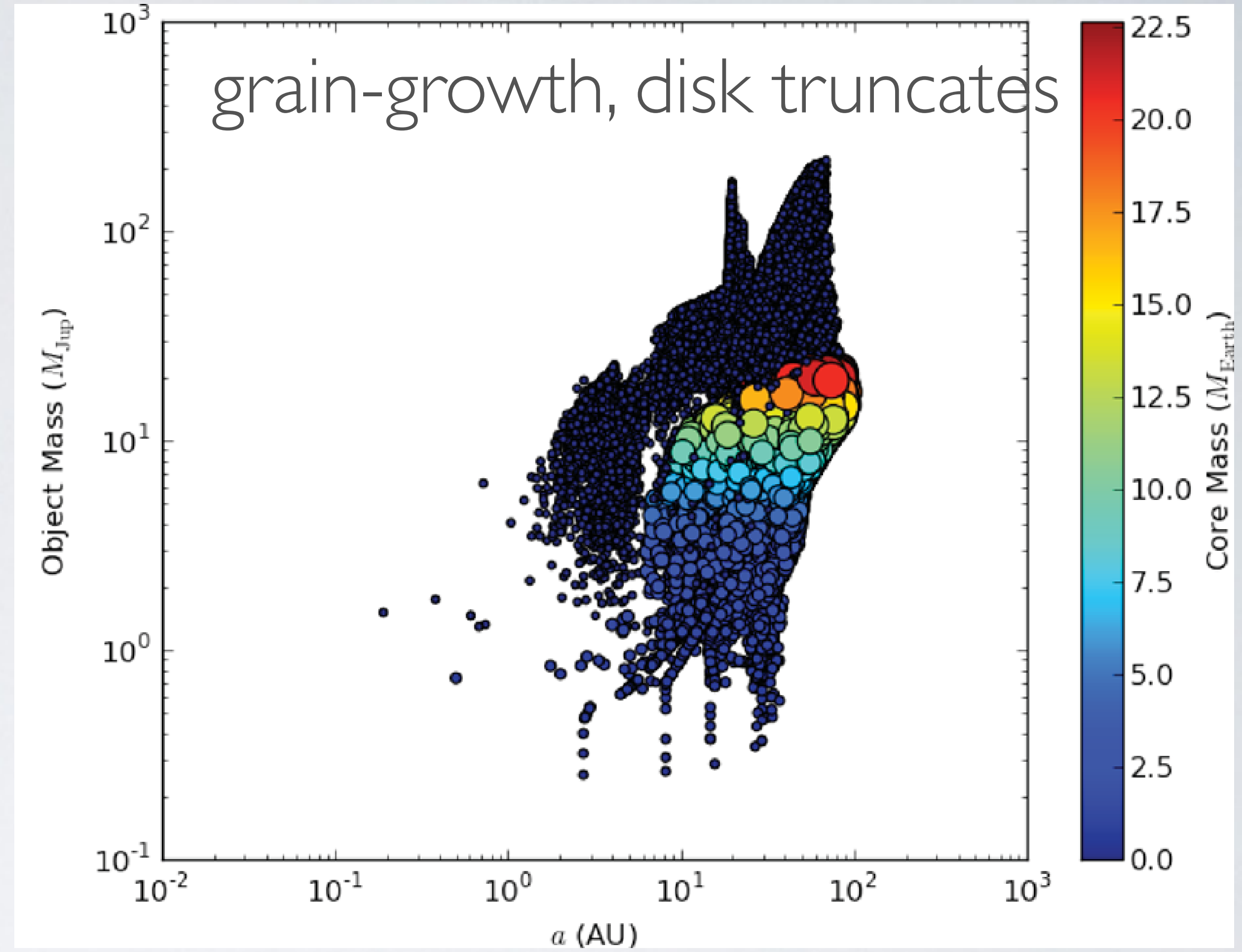
Boley +2011

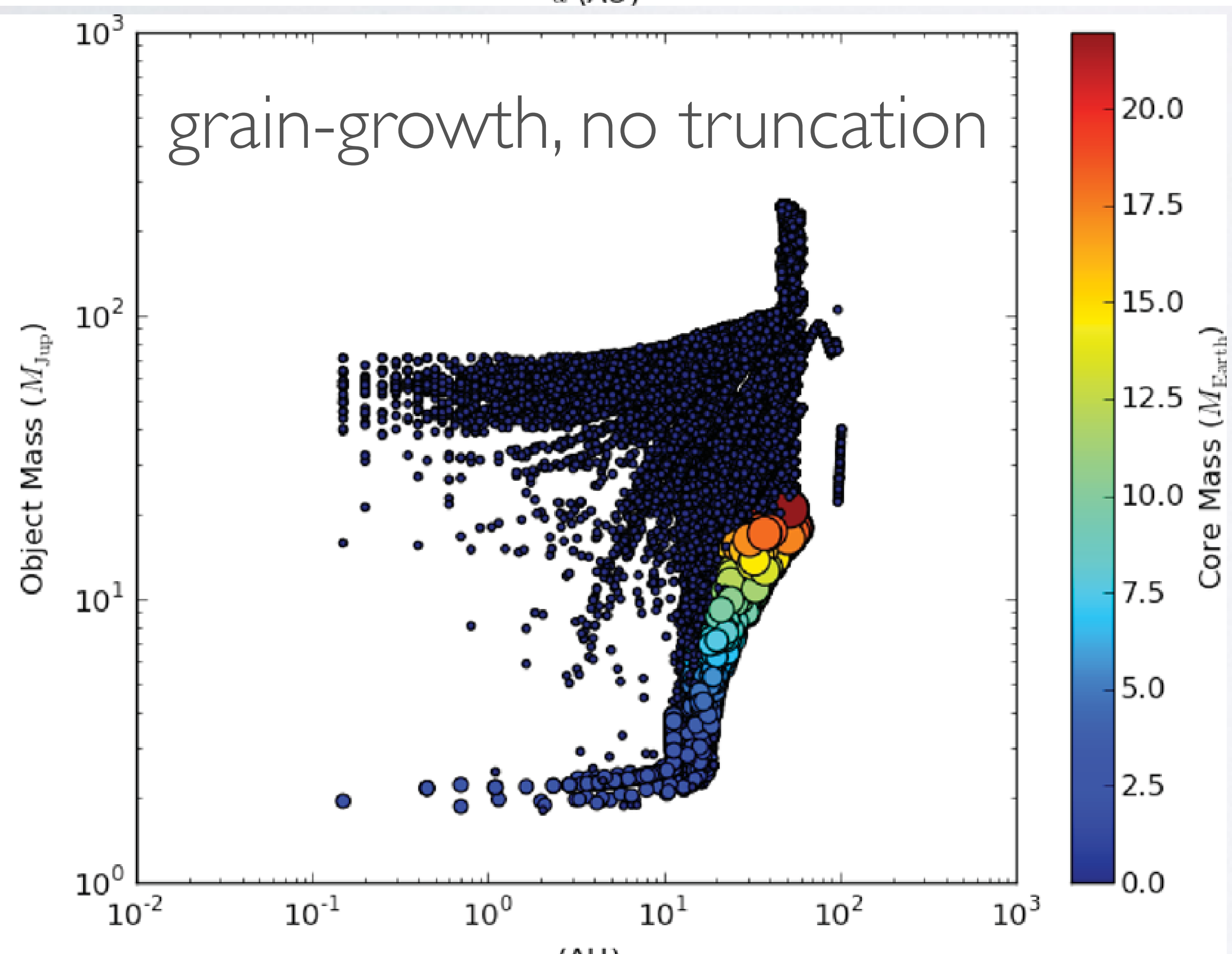
Most promising role is not for wide orbit planets!

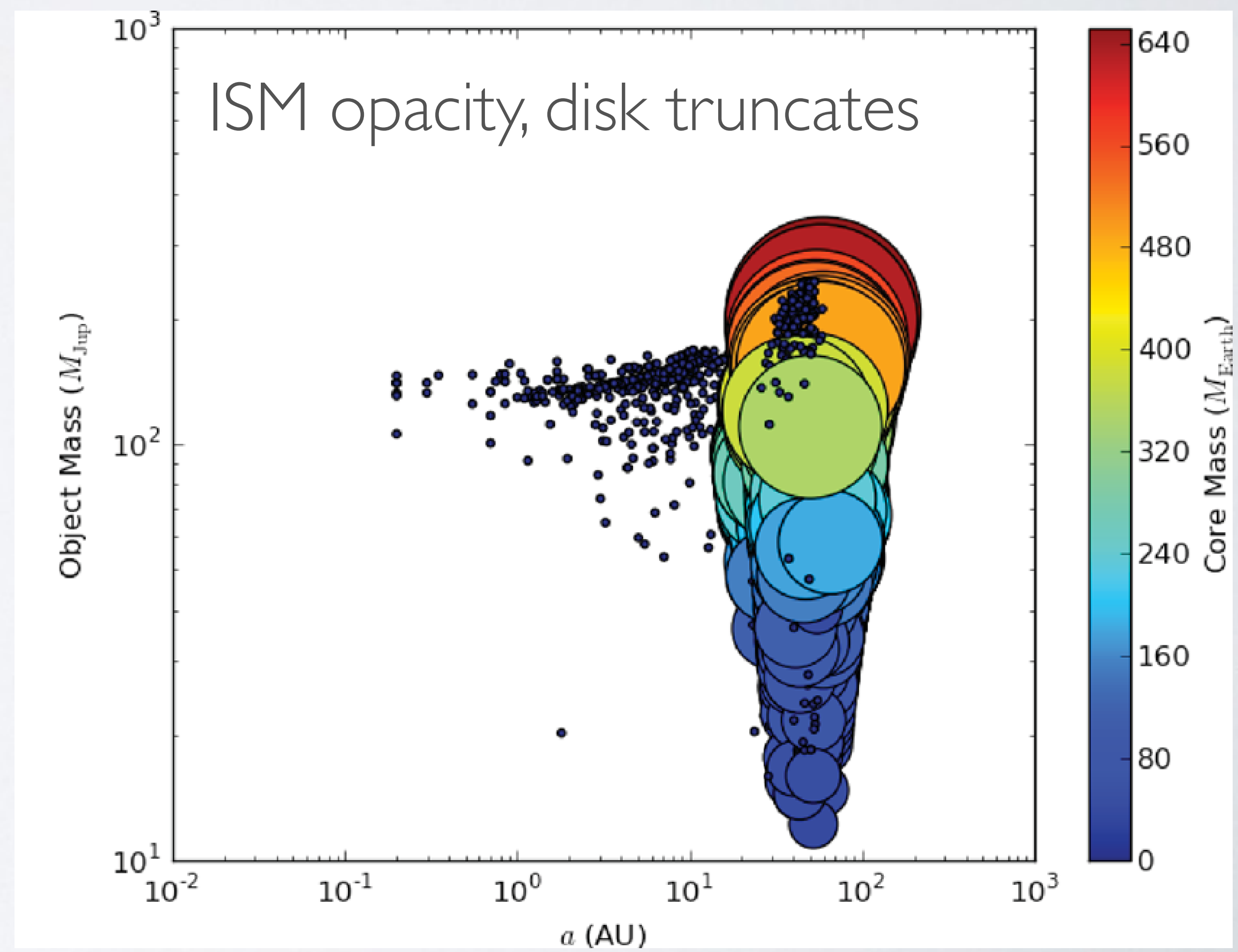
PUTTING IT ALL TOGETHER

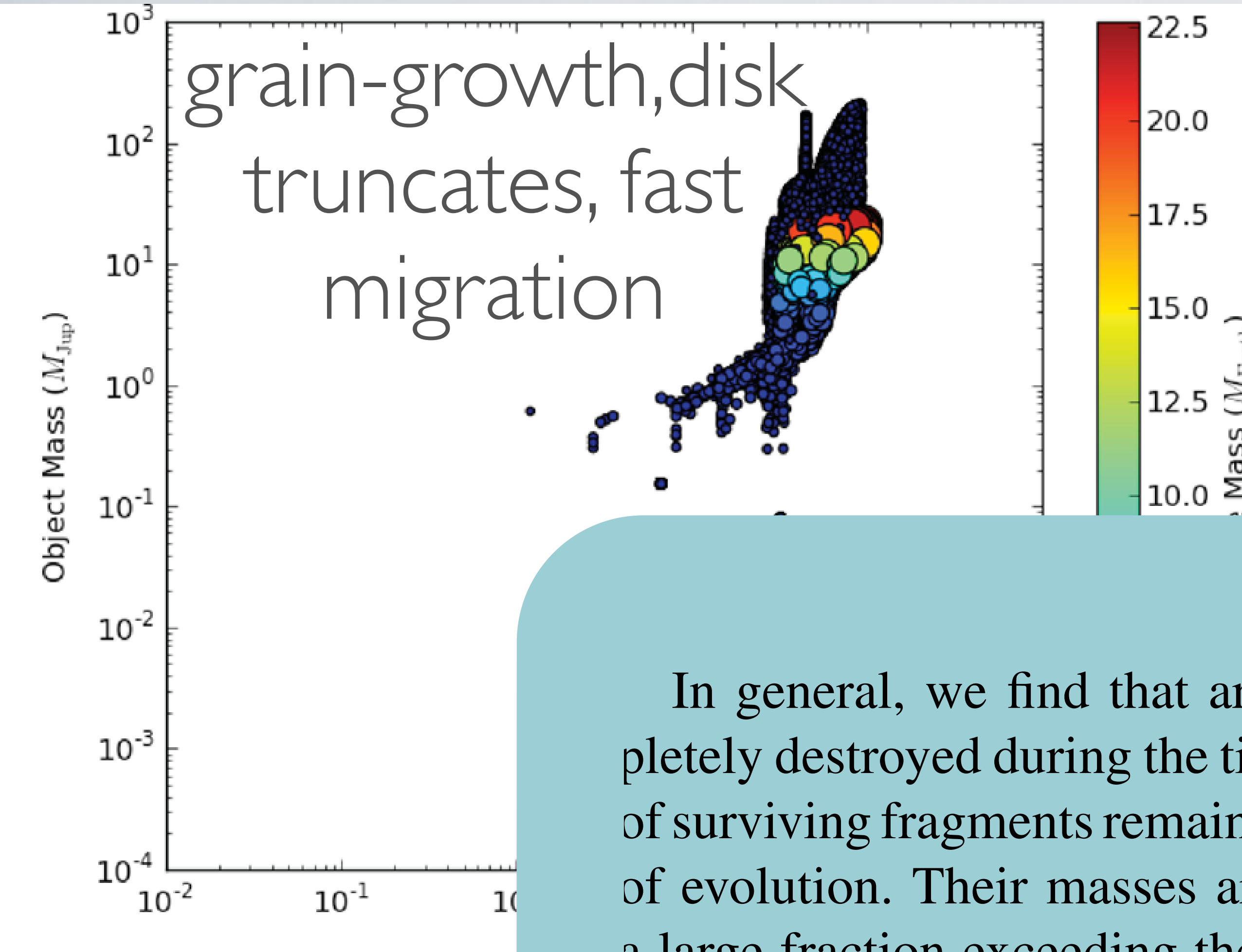
- GI population synthesis: Forgan & Rice 2013
  - **Pros**: various opacities, migration models, core growth, sedimentation
  - **Cons**: no subsequent gas accretion onto cores, no subsequent gas accretion onto the disk

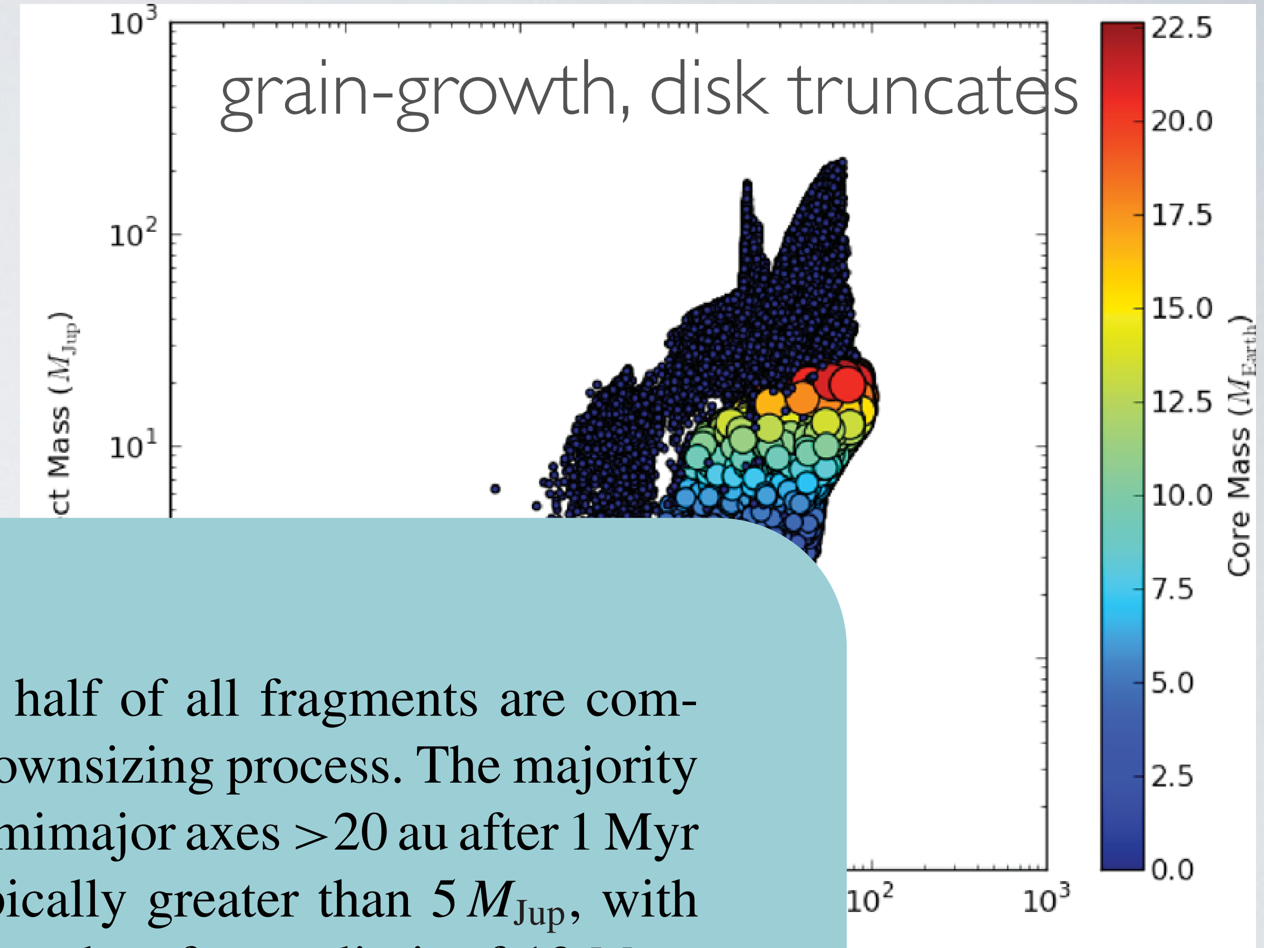

grain-growth,disk truncates, fast migration
Object Mass ($M_{\rm Jup}$)
a (AU)
Core Mass ($M_{\rm Earth}$)
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0 22.5

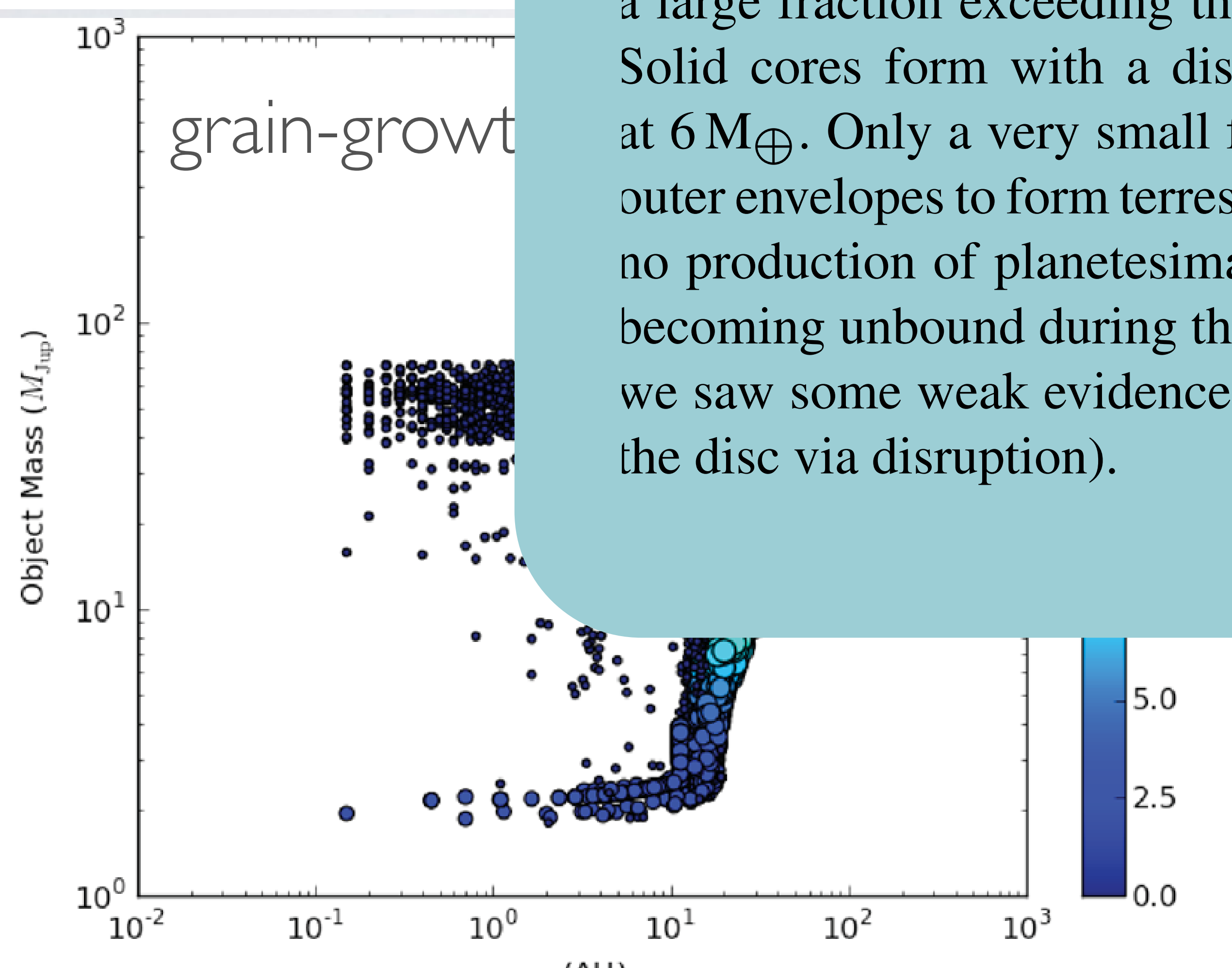

grain-growth, disk truncates
Object Mass ($M_{\rm Jup}$)
a (AU)
Core Mass ($M_{\rm Earth}$)
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0 22.5

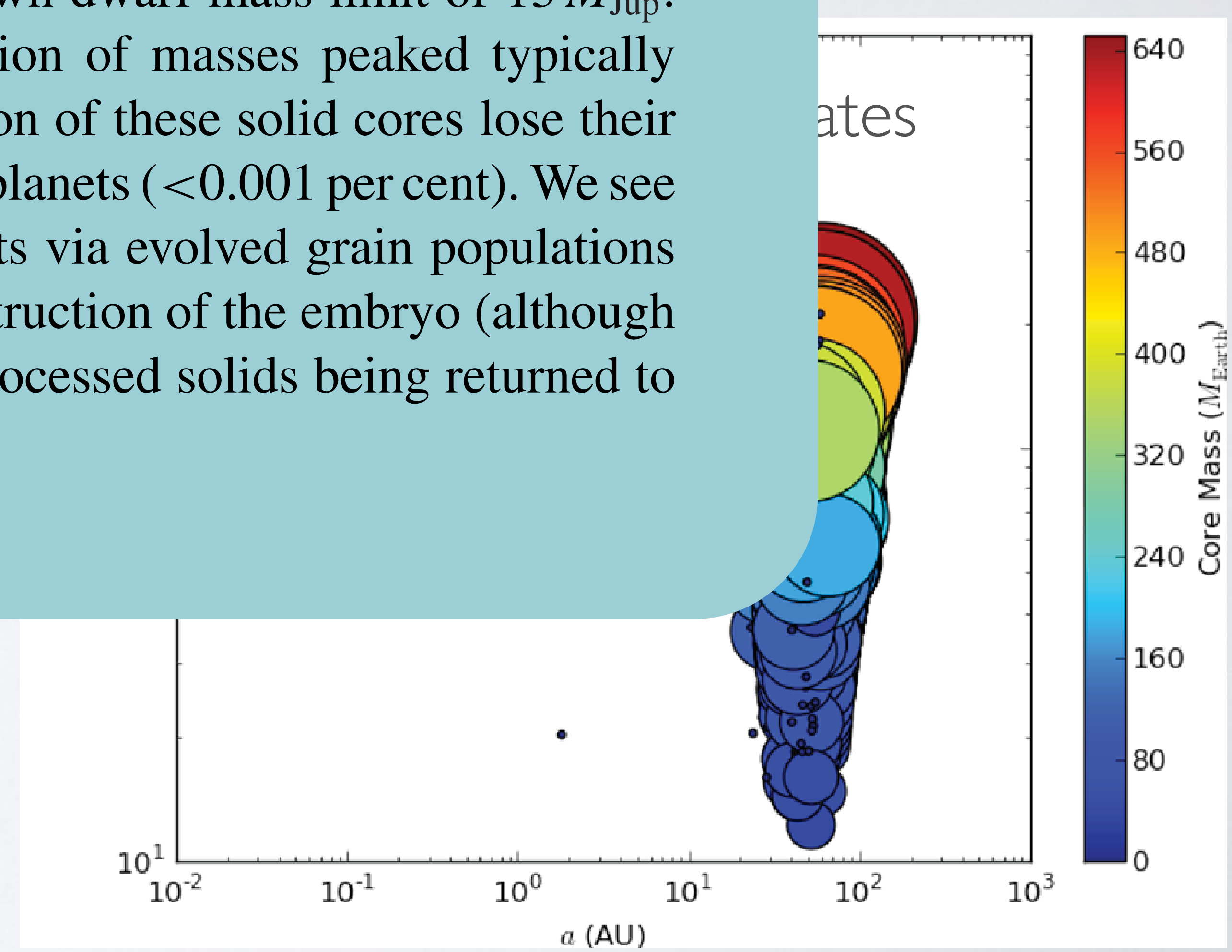

grain-growth, no truncation
Object Mass ($M_{\rm Jup}$)
a (AU)
Core Mass ($M_{\rm Earth}$)
10^{0} 10^{1} 10^{2} 10^{3}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0


ISM opacity, disk truncates
Object Mass ($M_{\rm Jup}$)
a (AU)
Core Mass ($M_{\rm Earth}$)
10^{1} 10^{2} 10^{3}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
0 80 160 240 320 400 480 560 640



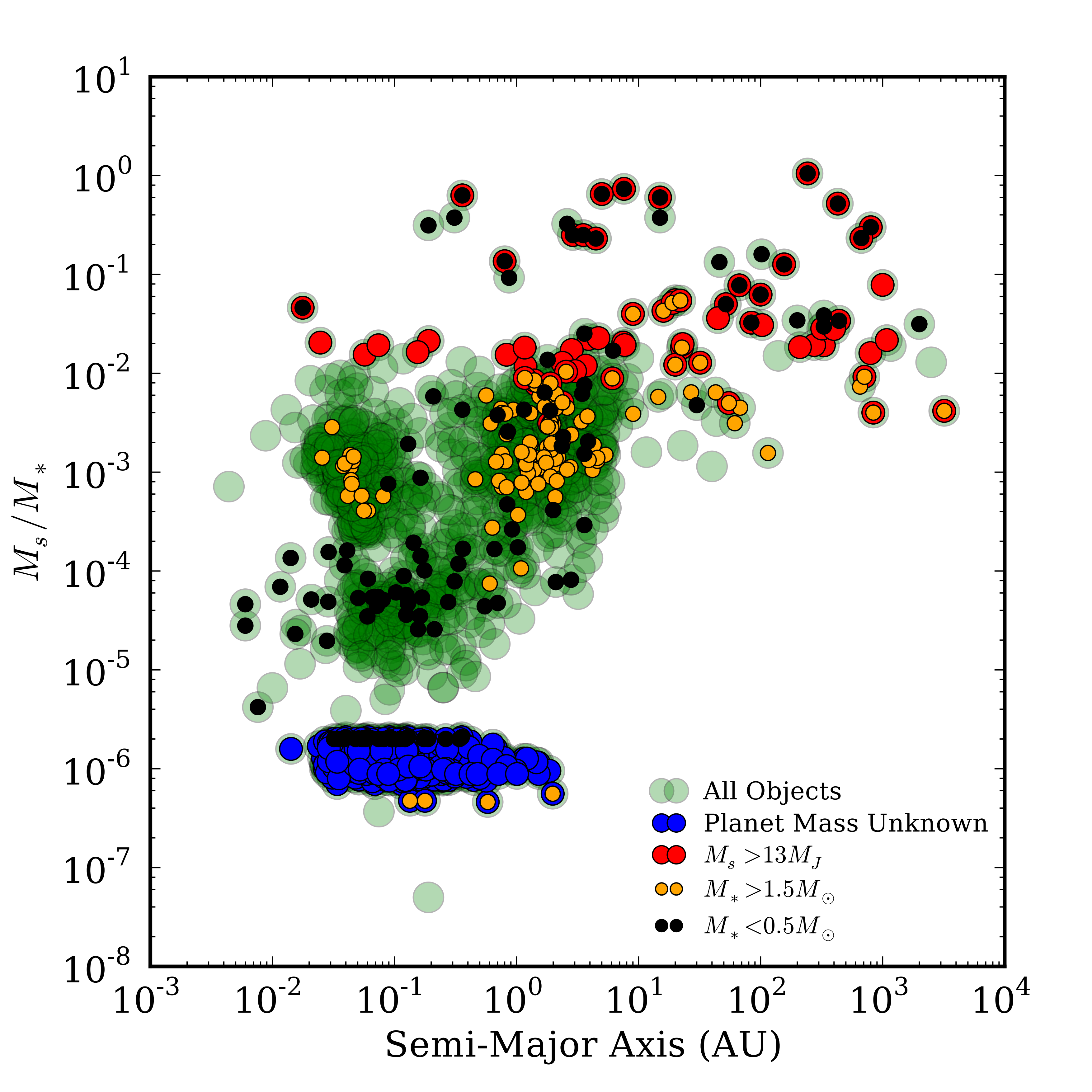






In general, we find that around half of all fragments are completely destroyed during the tidal downsizing process. The majority of surviving fragments remain at semimajor axes >20 au after 1 Myr of evolution. Their masses are typically greater than 5 $M_{\rm Jup}$, with a large fraction exceeding the brown dwarf mass limit of 13 $M_{\rm Jup}$. Solid cores form with a distribution of masses peaked typically at 6 $M_\oplus$. Only a very small fraction of these solid cores lose their outer envelopes to form terrestrial planets (<0.001 per cent). We see no production of planetesimal belts via evolved grain populations becoming unbound during the destruction of the embryo (although we saw some weak evidence of processed solids being returned to the disc via disruption).

We don’t really know about “outer disk” exoplanets, but…



- more recent CA models find it easier to make giant planets at large radii
- more recent GI models make objects which we have not observed…