

# Clumps In The Outer Disk: The First-Core Stage And Consequences For Planet Formation

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## Collaborators

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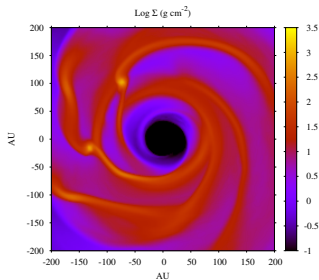
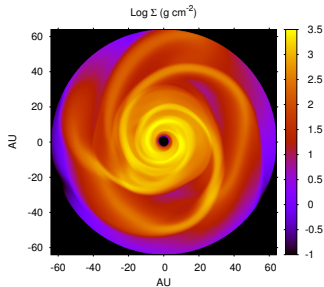
University College London: *J. M. C. Rawlings*

University of Chicago: *Fred Ciesla*

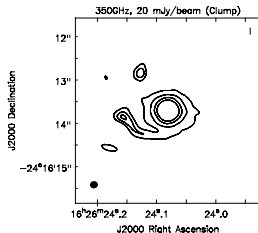
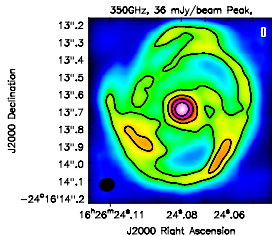
UCLA: *Ravit Helled*

# The Pre-MMSN Era

Surface  
Density



Synthetic  
ALMA images  
at 350 GHz



# This Talk:

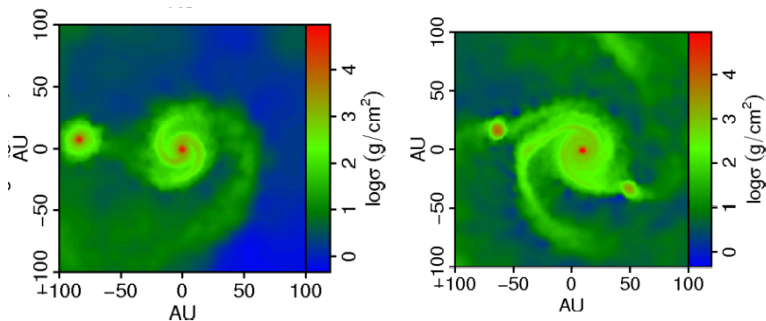
- It is *NOT* disk instability *instead* of core accretion
- Principal questions facing disk instability:
  - ▶ If fragments form and remain bound, what do they become?
  - ▶ If fragments form, what are the consequences of their destruction?

# This Talk:

- It is *NOT* disk instability *instead* of core accretion
- Principal questions facing disk instability:
  - ▶ If fragments form and remain bound, what do they become?
  - ▶ If fragments form, what are the consequences of their destruction?

# Fragmentation and Formation of Bound Objects

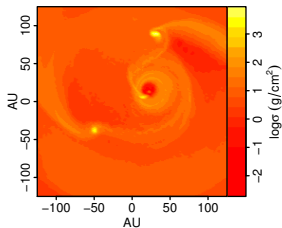
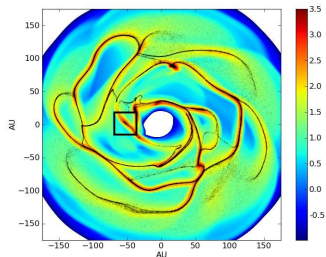
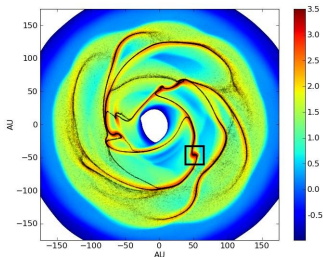
- *IF* clumps remain bound, what do they become: Stars, brown dwarfs, planets?



Images from Hayfield et al. 2011; see also, e.g., Stamatellos et al. 2007, Boley 2009, Kratter et al. 2010

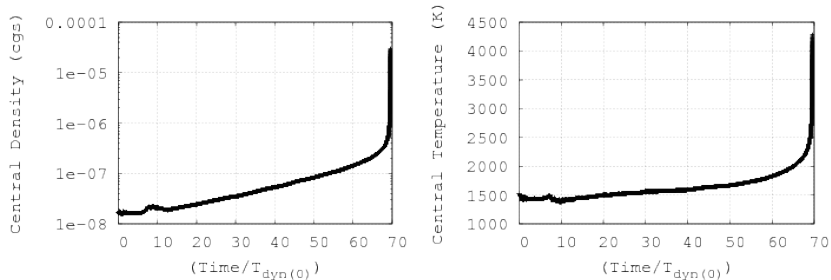
# Tidal Destruction

*IF* the clumps do not contract fast enough, then...



Top: Boley et al. 2011, Left: Boley et al. 2010; See also Rice et al. 2004; Nayakshin (2010)

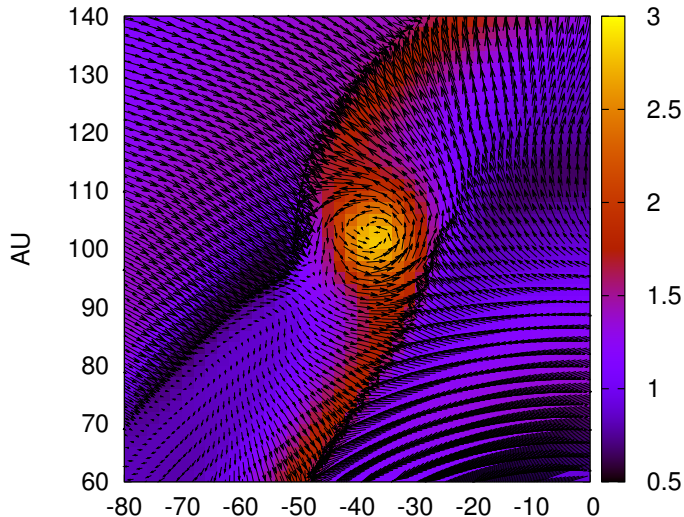
# Collapse Due To $H_2$ Dissociation $\rightarrow$ Substellar Companion



Images: From new 3D RT sims. See also, e.g. Bodenheimer et al. 1980, Helled & Bodenheimer 2011

# Clump Formation in Global Simulation

Surface density (color bar in log cgs) and velocity vectors in frame of planet

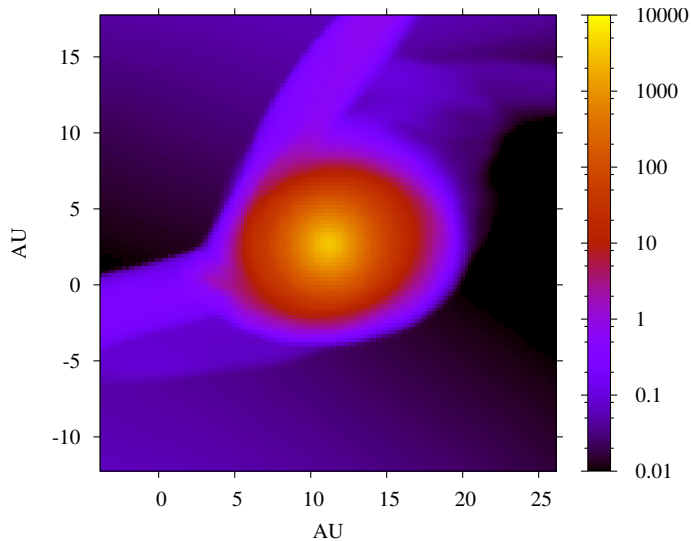




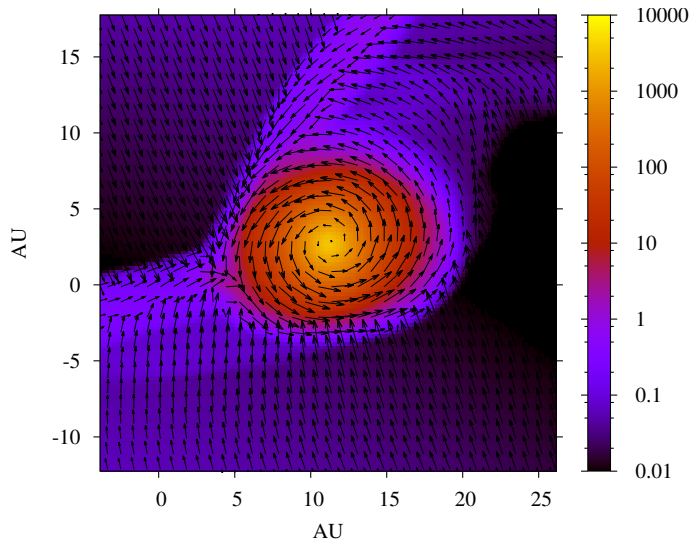
# Clump Evolution in Local Simulation

Clump Evolution

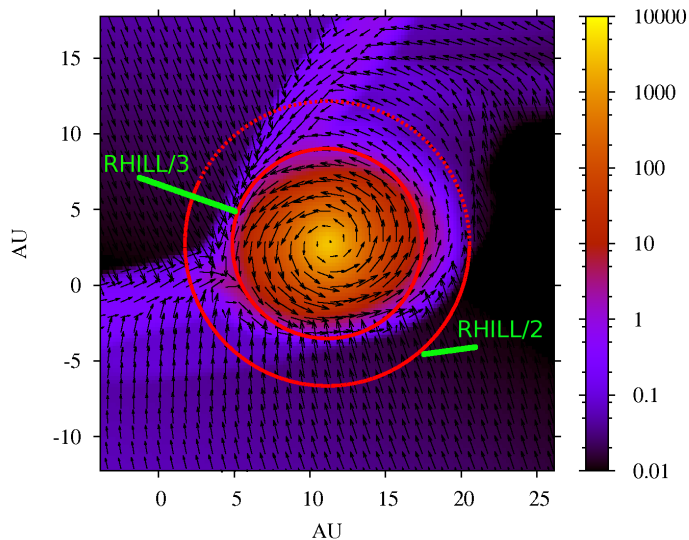
# Clump Evolution in Local Simulation



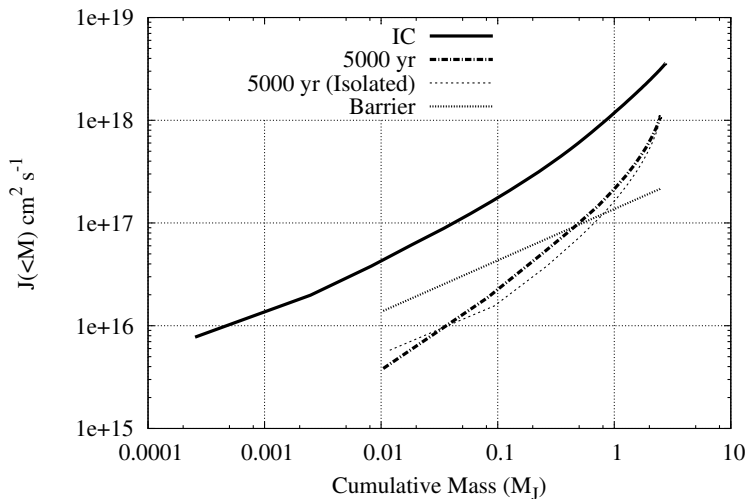
# Clump Evolution in Local Simulation



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# Clump Evolution in Local Simulation



## Summary: Growth of Low-mass Fragments (few $M_J$ )

- Rotational support  $\sim 30\%$ , Pressure support  $\sim 70\%$
- Tidally limited to  $R_{\text{Hill}}/3$
- Angular momentum-limited collapse mass  $0.4 M_J$  for the  $2.5 M_J$
- Substantial angular momentum evolution is required.
- Evolution seems to be limited by the cooling time and variations in orbital distance

# Consequences For Delayed Collapse

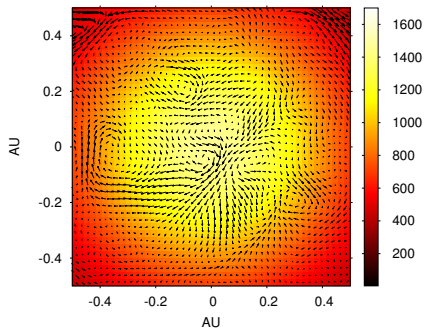
## Delayed First-Core Phase:

- Prolongs clump phase for observations
- Makes tidal destruction/stripping possible.
  - ▶ Massive-core gas giants
  - ▶ Solid processing in the outer nebula
  - ▶ Injection of large building blocks

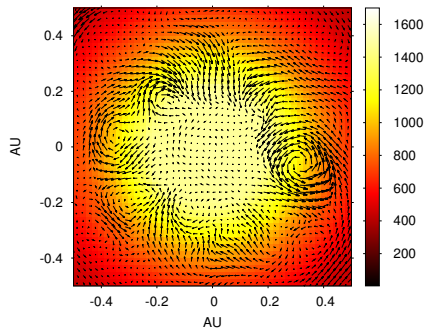
See recent papers by Boley, Nayakshin. See also Baruteau et al. 2011 and Michael et al. 2011 for migration

# Contracting Clumps: High-temperature processing, differentiation

10  $M_J$  clump, full extent  $R = 1$  AU



Left:  $T_c <$  dust sublimation

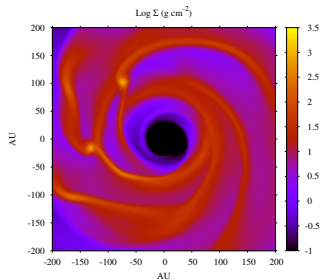
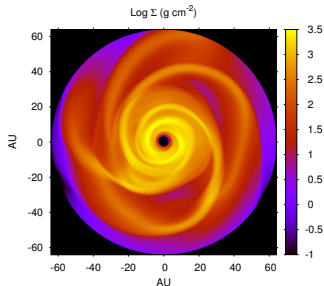


Right  $T_c >$  dust sublimation

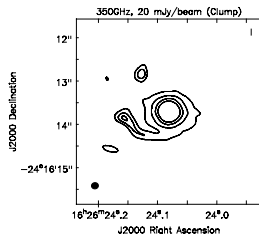
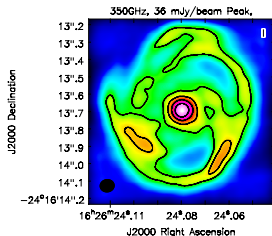


# What did we miss by starting with the MMSN?

Surface Density



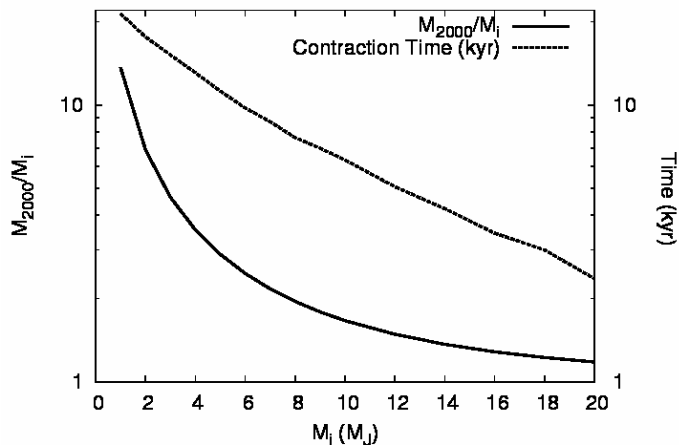
Synthetic  
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## See these posters

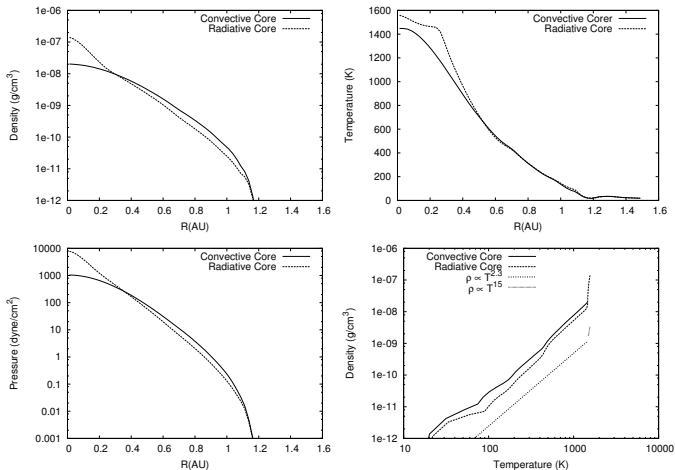
- Megan Shabram – *Circumplanetary Disks Around Wide-Orbit Planets: Formation Theory, Observations, and Moon Systems*
- Marina Galvagni – *3D Simulations of the Collapse of Protoplanetary Clumps in Disk Instability Using a New Equation of State*

# Mass Growth vs. Collapse Timescales

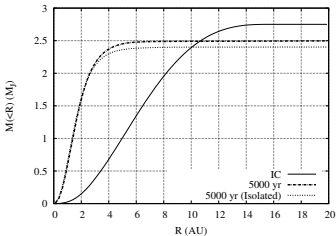
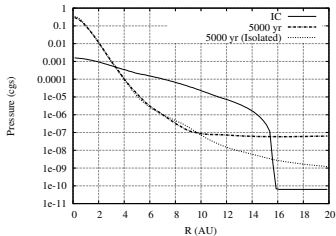
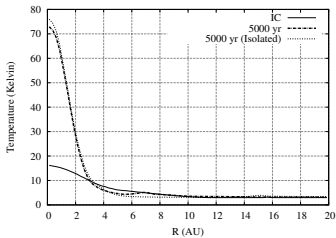
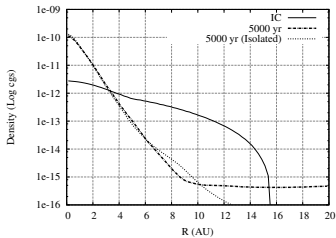


# Clump Structure – 10 $M_J$

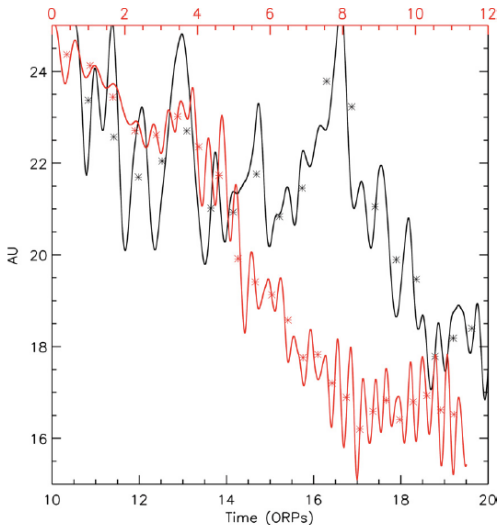
Profiles for a 10  $M_J$  clump



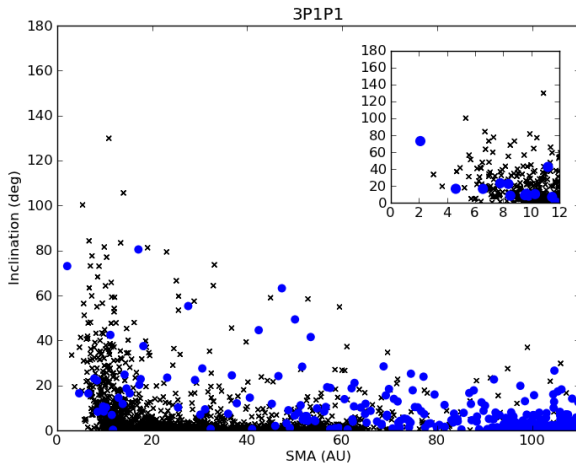
# Rotating Clump – 2.5 $M_J$



# Migration in a GI-Active Disk

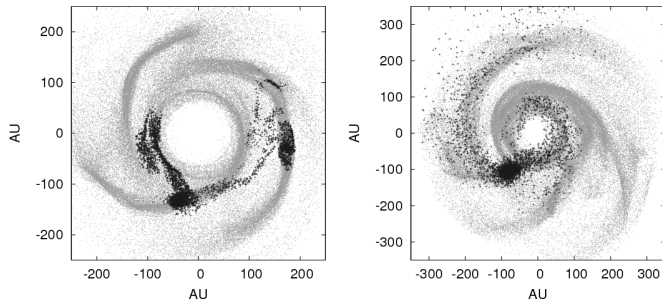


# Things Scatter Inward, too



Boley, Payne, and Ford in prep.

# Clumps Will Scatter Very Large Solids



Boley et al. 2011