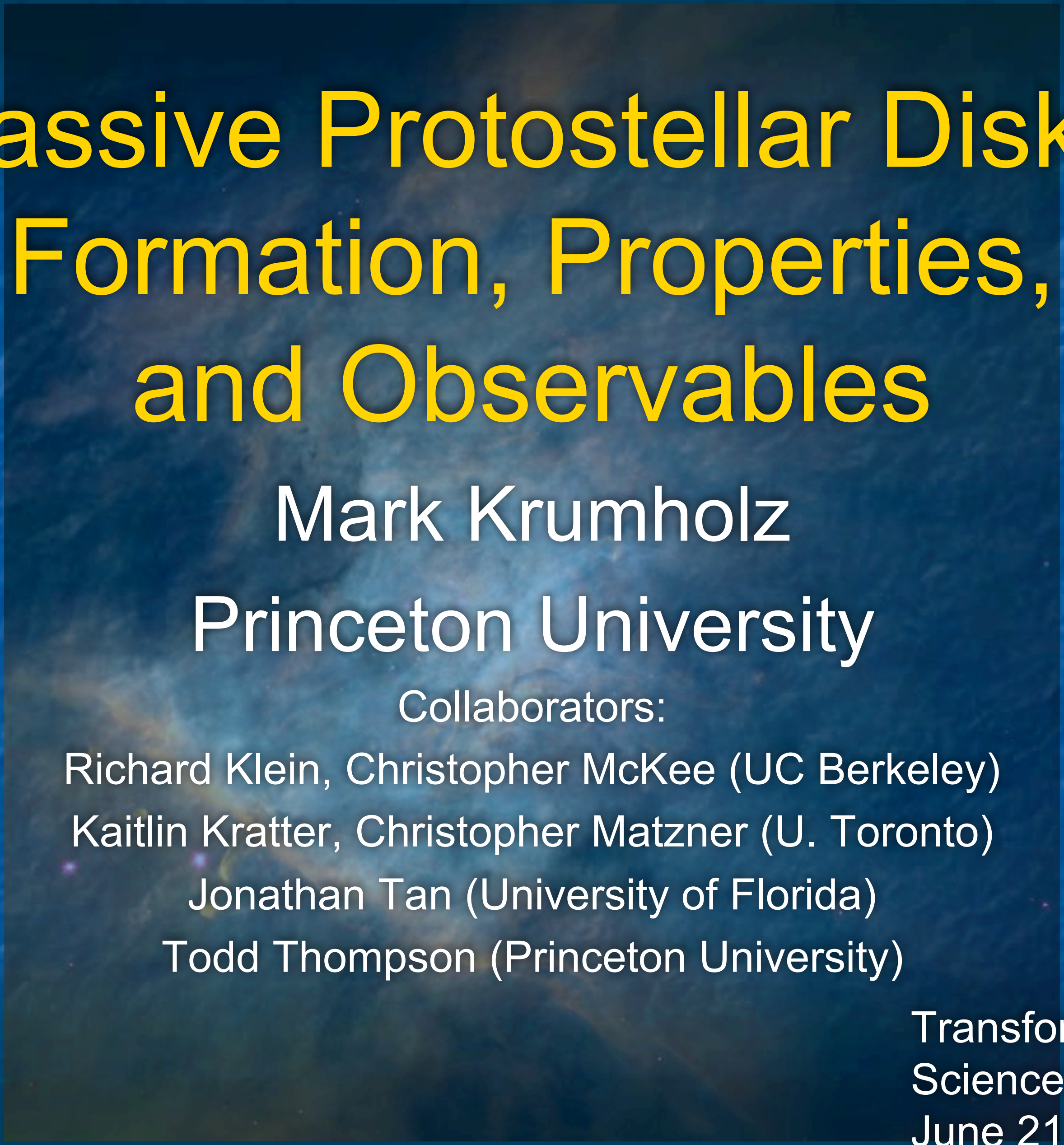


Massive Protostellar Disks: Formation, Properties, and Observables

Mark Krumholz

Princeton University

Collaborators:
Richard Klein, Christopher McKee (UC Berkeley)
Kaitlin Kratter, Christopher Matzner (U. Toronto)
Jonathan Tan (University of Florida)
Todd Thompson (Princeton University)

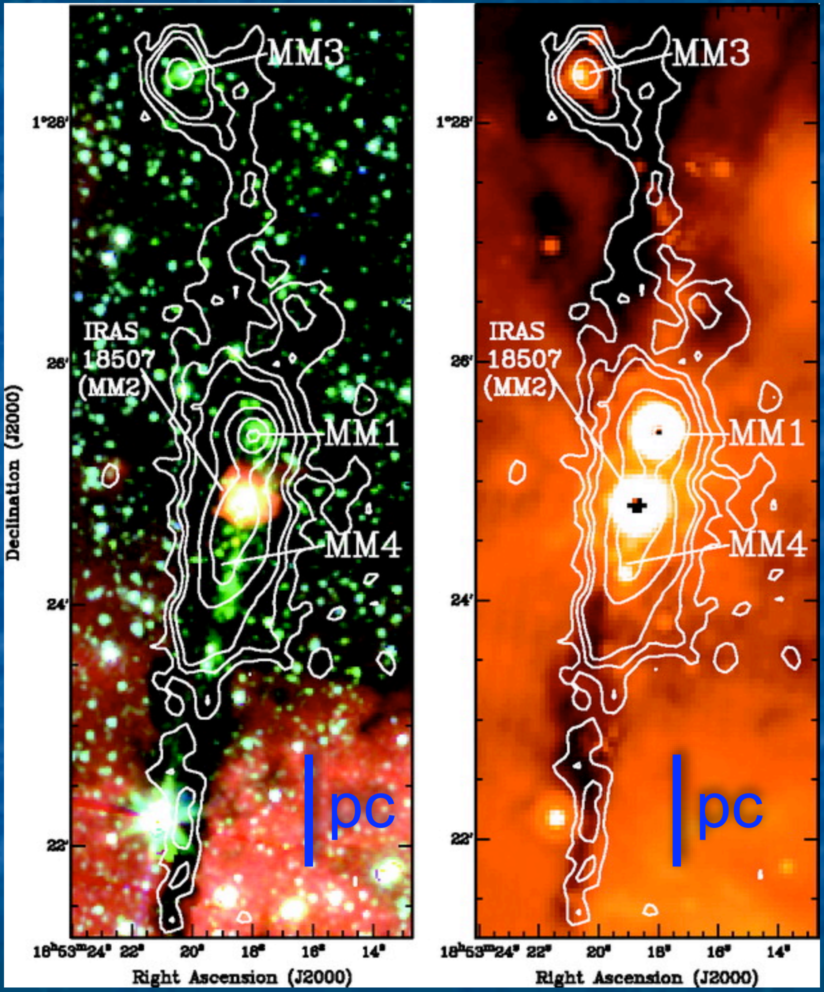
Transformational
Science with ALMA
June 21, 2007

Talk Outline

- Introduction and background for the core accretion model
- Properties of massive disks
- Observational predictions for ALMA and the EVLA
- Distinguishing massive star formation models
- Summary

Sites of Massive Star Formation

(Plume et al. 1997; Shirley et al. 2003; Rathbone et al. 2005; Yonekura et al. 2005)

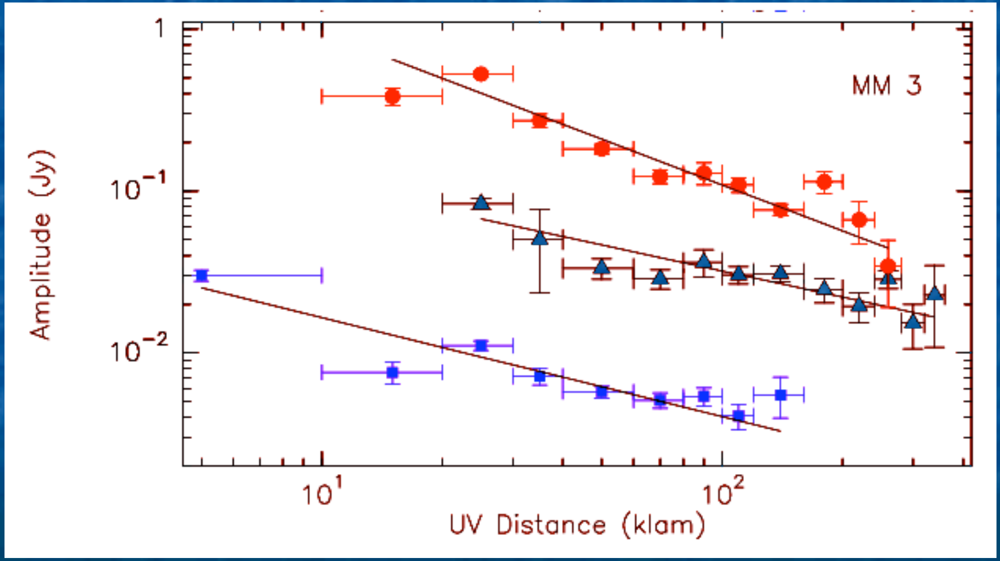


Spitzer/IRAC (left) and Spitzer/MIPS (right), Rathbone et al. (2005)

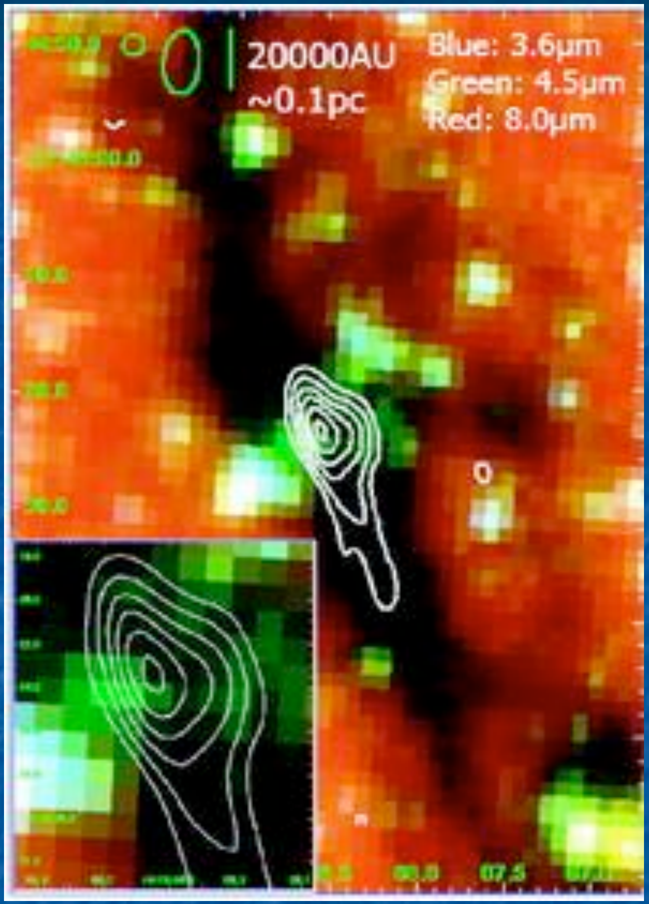
- Massive stars form in gas clumps seen in mm continuum or lines, or in IR absorption (IRDCs)
- Typical properties:
  - $M \sim 10^3 - 10^4 \, M_\odot$
  - $R \sim 1$ pc
  - $\Sigma \sim 1$ g cm^{-2}
  - $\sigma \sim$ few km s^{-1}
- Properties very similar to young rich clusters

Massive Cores

- Largest cores in clumps: M ~ 100 $M_\odot$, R ~ 0.1 pc
- Cores have powerlaw density profiles, index $k_\rho \approx 1.5$
- Some are starless



Core density profile in 3 wavelengths, Beuther et al. (2007)

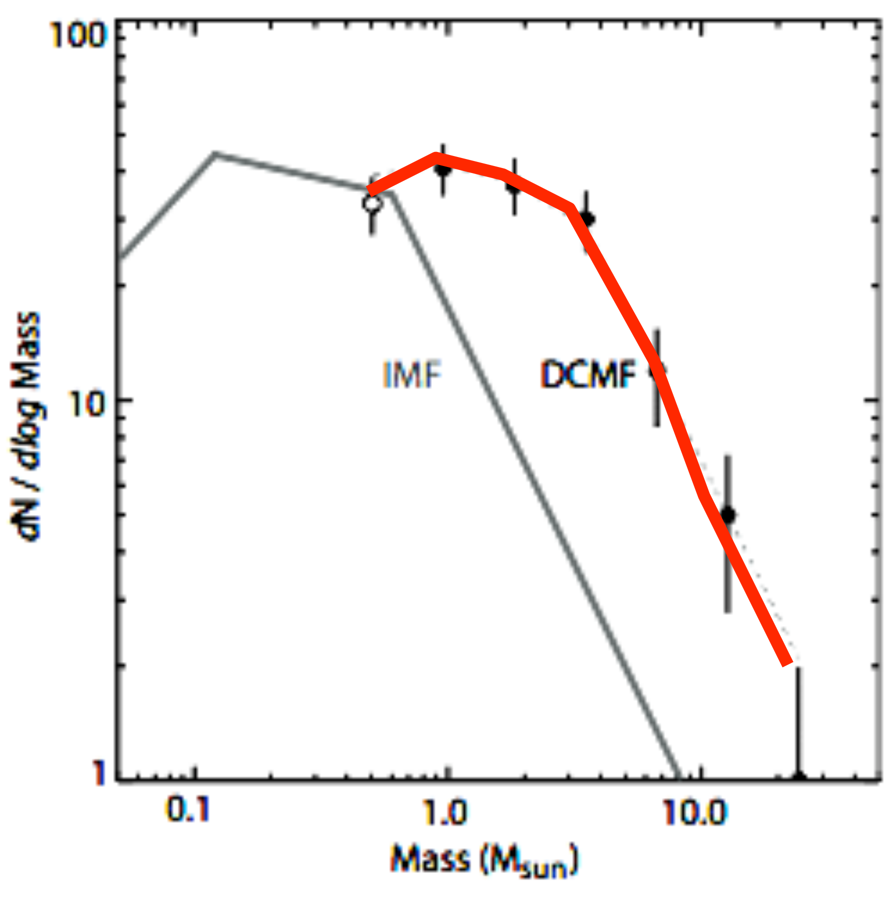


Core in IRDC 18223-3, Spitzer/IRAC (color) and PdBI 93 GHz continuum (contours), Beuther et al. (2005, 2007)

Clue I: The Core Mass Function

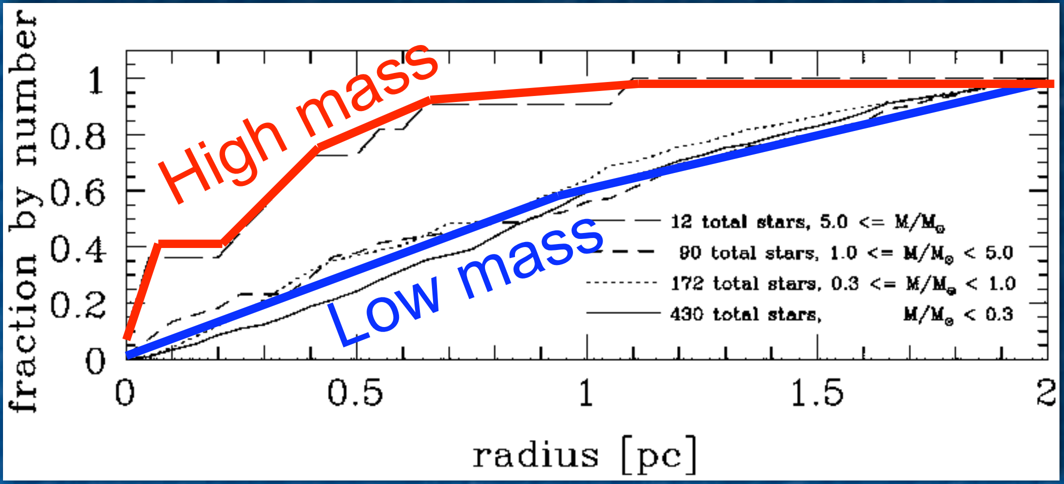
(Motte, Andre, & Neri 1998, Johnstone et al. 2001,
Reid & Wilson 2005, 2006, Lombardi et al. 2006, Alves et al. 2007)

- The core MF is similar to the stellar IMF, but shifted to higher mass a factor of a few
- Correspondence suggests a 1 to 1 mapping from core mass to star mass

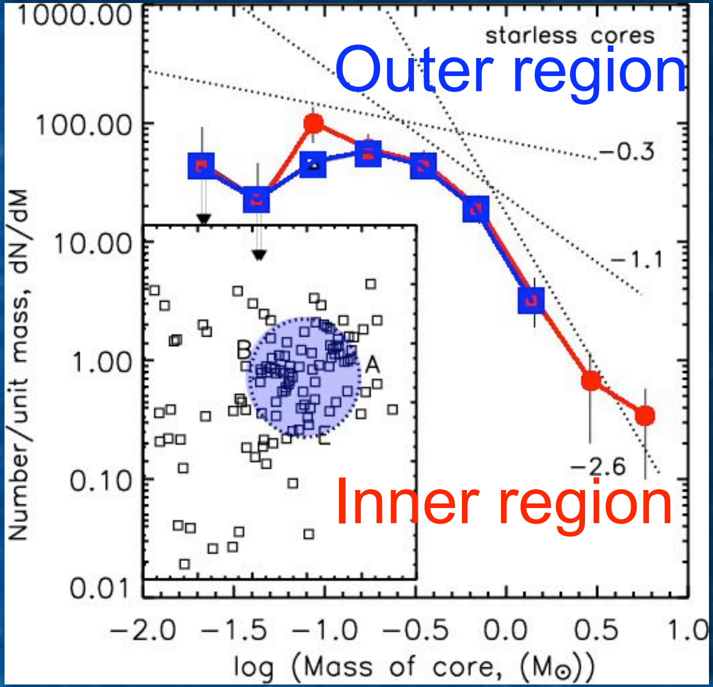


Core mass function in Pipe Nebula (red) vs. stellar IMF (gray) (Alves, Lombardi, & Lada 2007)

Clue II:
Core Spatial Distributions



Fraction of stars vs. radius for stars of low mass (blue) and high mass (red) stars in the ONC (Hillenbrand & Hartmann 1998)



Core mass function for inner (red) and outer (blue) parts of ρ Oph, Stanke et al. (2006)

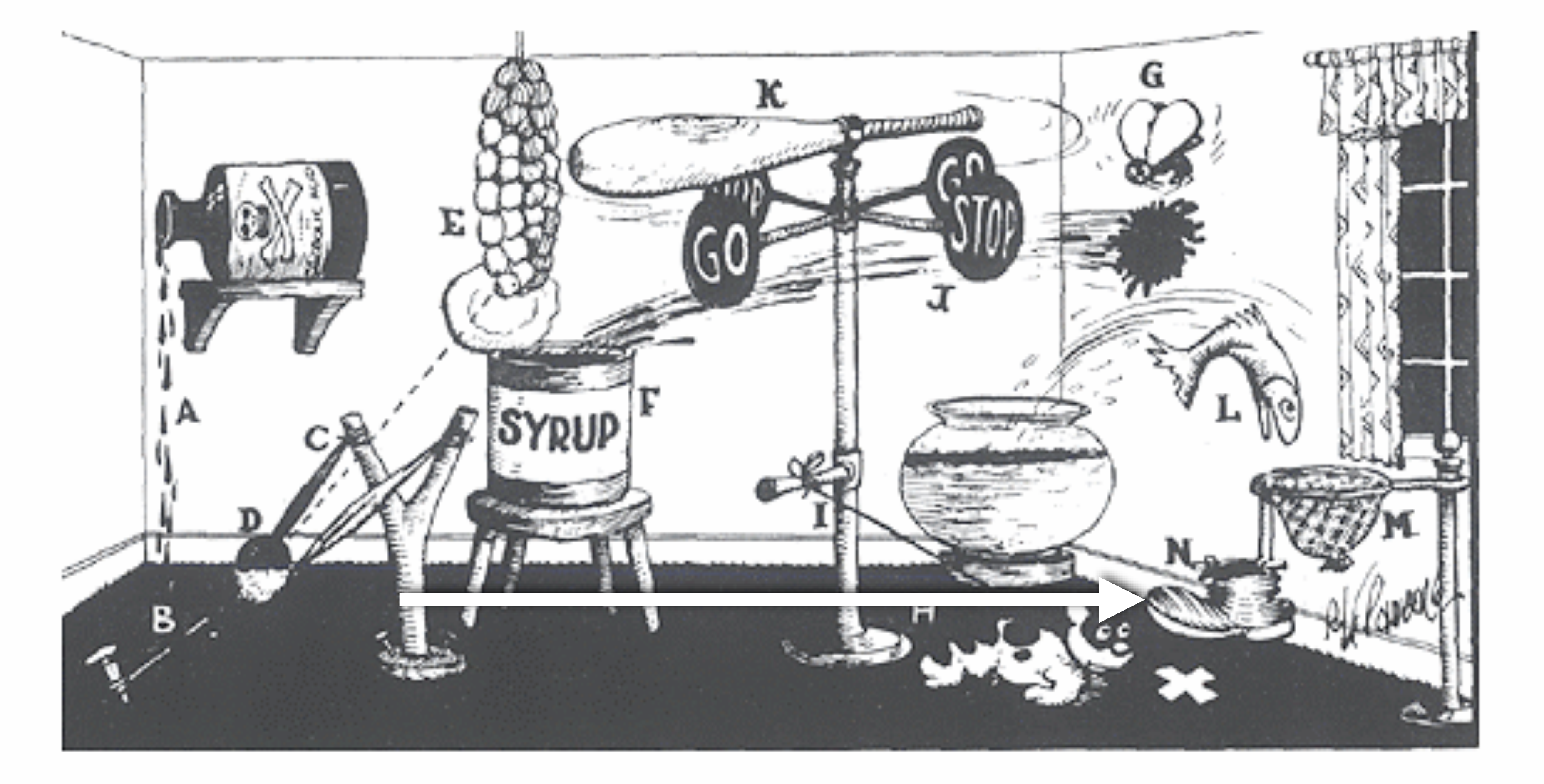
For both stars and cores, the mass function is position-independent at low mass, but high mass objects are only in cluster / clump centers

The Core Accretion Model

is that cores are the progenitors of individual stars or star systems. A collapsing core is also, therefore, the structure responsible for creating protostellar disks.

NASA/JPL/Spitzer/MIPS/IRAC/Caltech/W. Reach (SSC/Caltech)

The Core Accretion Model



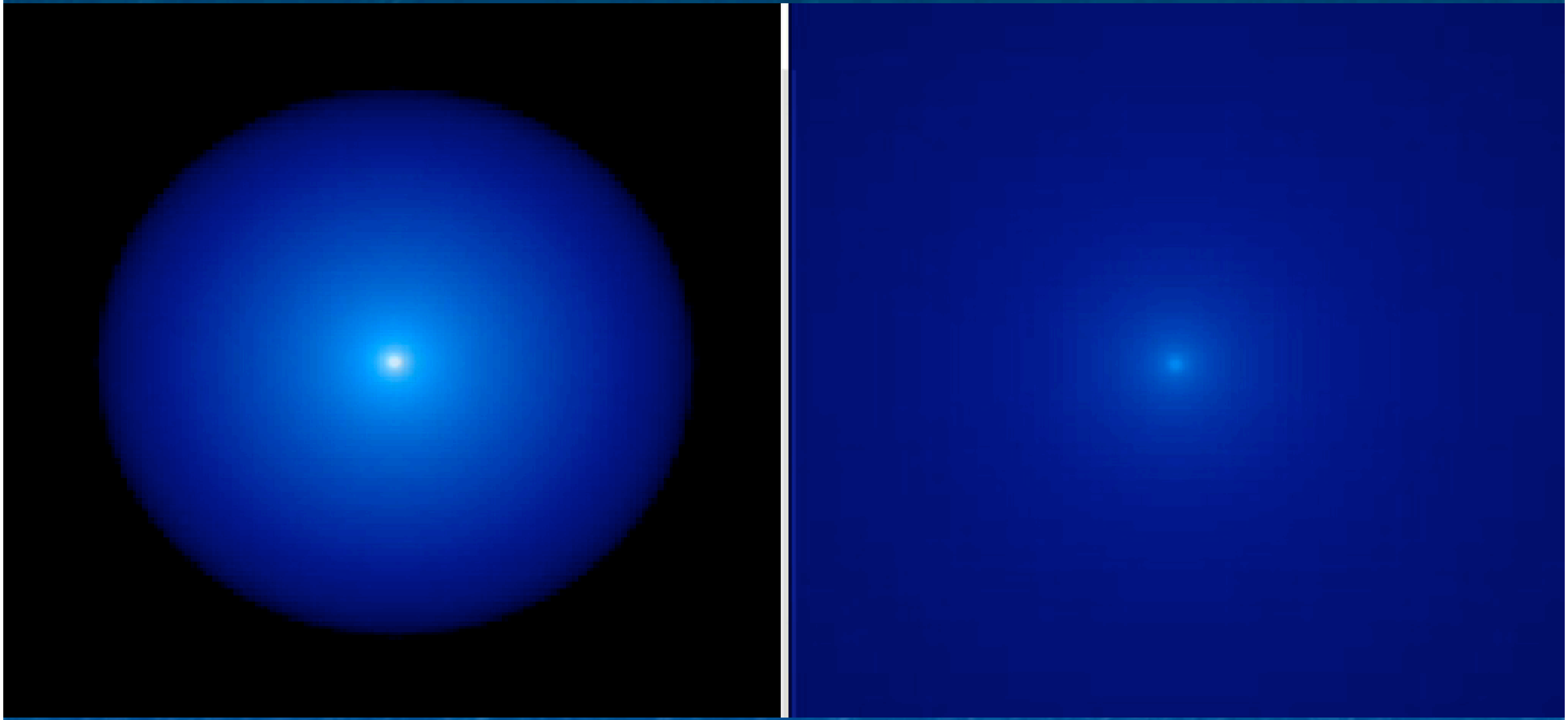
Simulations of Massive Cores

- Start with observed massive core properties: M ≈ 100 $M_\odot$, r ≈ 0.1 pc, virialized turbulence (σ ≈ few km/s), centrally condensed with $k_\rho \approx 1.5$
- Use the Orion AMR gravity-radiation-hydro code (Krumholz, Klein, & McKee 2007a, ApJ, 656, 959, and KKM, 2007b, ApJS, in press, astro-ph/0611003)

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) &= -\nabla P - \rho \nabla \phi - \lambda \nabla E \\
\frac{\partial}{\partial t}(\rho e) + \nabla \cdot [(\rho e + P)\,\mathbf{v}] &= -\rho \mathbf{v} \cdot \nabla \phi - \kappa_{\mathrm{P}} \rho (4\pi B - cE) + \lambda \mathbf{v} \cdot \nabla E \\
\frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{v} E + \mathbf{v} \cdot \mathcal{P}) &= \kappa_{\mathrm{P}} \rho (4\pi B - cE) - \lambda \mathbf{v} \cdot \nabla E + \nabla \cdot \left(\frac{c\lambda}{\kappa_{\mathrm{R}}} \nabla E \right) \\
\nabla^2 \phi &= 4\pi G \rho
\end{aligned}
$$

Mass conservation
Momentum conservation
Gas energy conservation
Rad. energy conservation
Self-gravity

Simulation of a Massive Core



- Simulation of 100 $M_{\odot}$, 0.1 pc turbulent core
- LHS shows Σ in whole core, RHS shows 2000 AU region around most massive star

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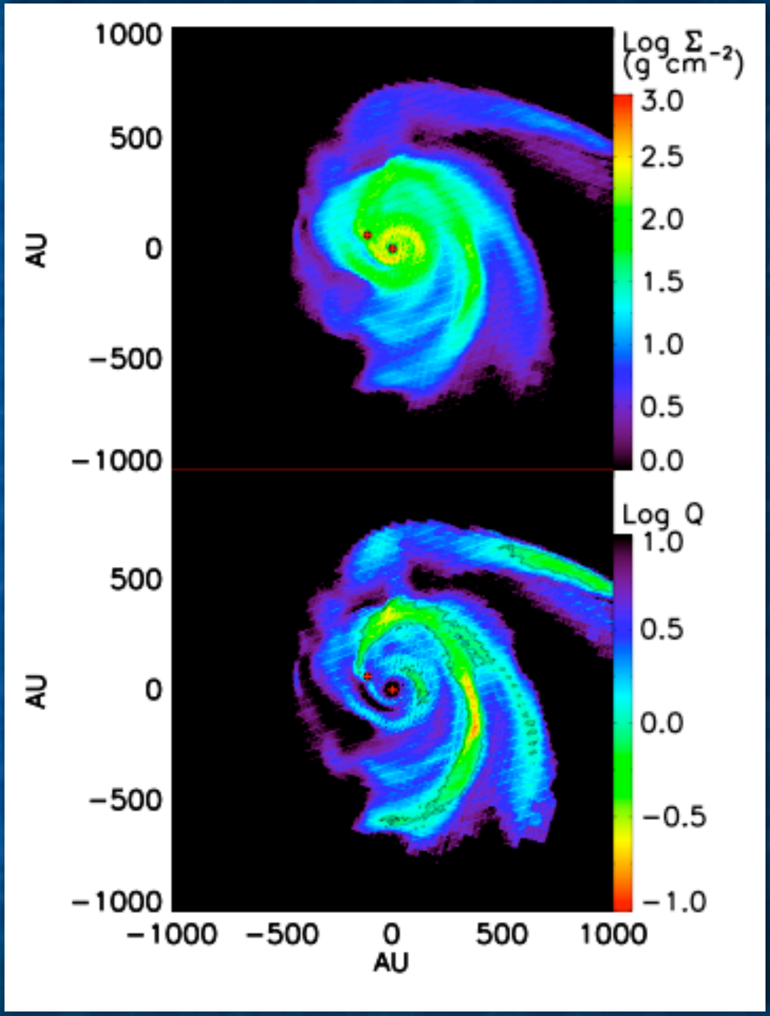
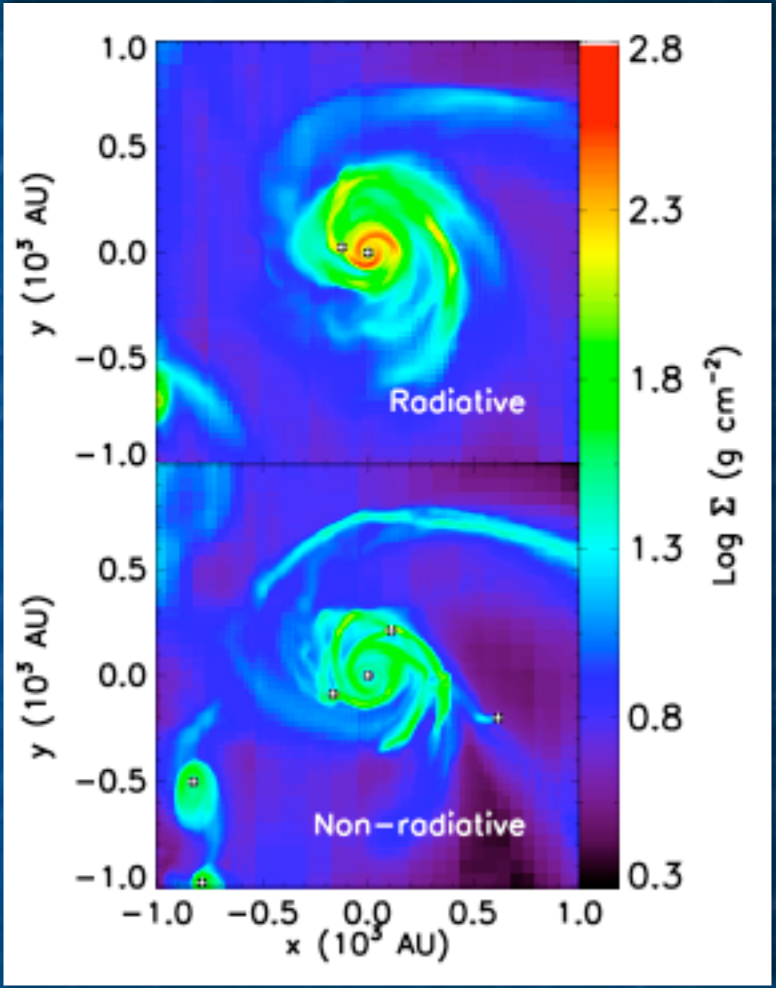
Massive Disk Properties

- $M_{disk} / M_* \approx 0.2 - 0.5$, $r_{disk} \sim 1000$ AU
- Global GI creates strong m = 1 spiral pattern
- Spiral waves drive rapid accretion; $\alpha_{eff} \sim 1$
- Disks reach Q ~ 1, form stellar fragments
- Small fragments migrate in; some become twins via mass transfer (Krumholz & Thompson 2007)



Surface density (upper) and Toomre Q (lower)

Aside: Radiative Transfer Matters!



Column density with and without RT, for identical times and initial conditions

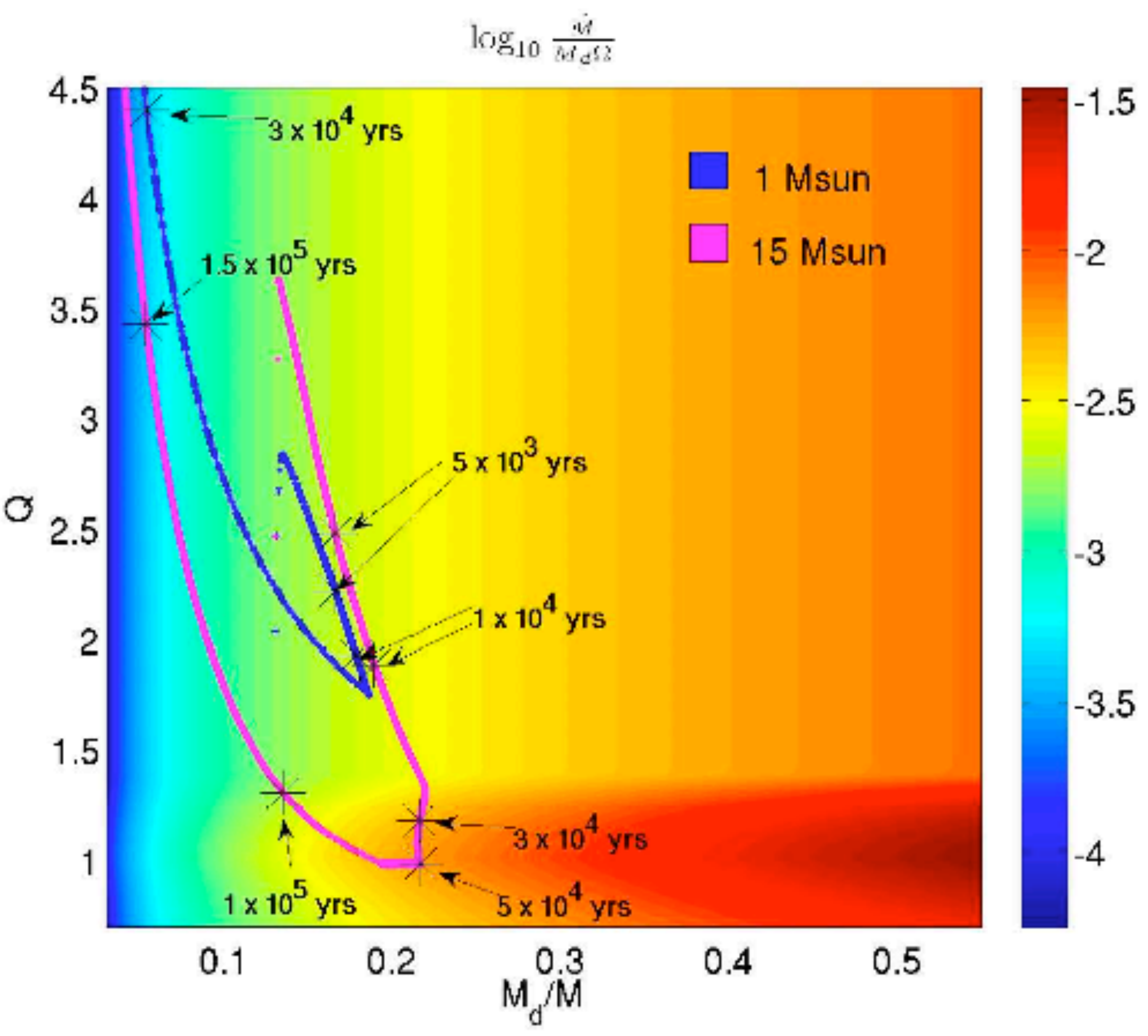
- With RT: 3 fragments, M_{disk} / M_* ~ 0.5, inner disk column density ~ 1000 g cm^{-2}
- Without RT: more than 7 fragments, M_{disk} / M* ~ 0.15, inner disk column density ~ 100 g cm^{-2}
- Conclusion: simulations without RT get incorrect bulk properties of massive disks

Understanding Massive Disks

(Kratter & Matzner 2006, Kratter, Matzner & Krumholz, 2007, in preparation)

- Accretion rate onto star + disk is $\sim \sigma^3 / G \sim 10^{-3}\ M_\odot / \mathrm{yr}$ in a massive core, but max transfer rate through a stable disk ($\alpha \ll 1$) is $\sim c_s^3 / G \sim 5 \times 10^{-5}\ M_\odot / \mathrm{yr}$ at T = 100 K
- Core accretes faster than stable disk can process ⇒ massive, unstable disks
- Study disk evolution using semi-analytic core model, including accretion, radiative heating, parameterized treatment of angular momentum transport

Model Disk Evolution

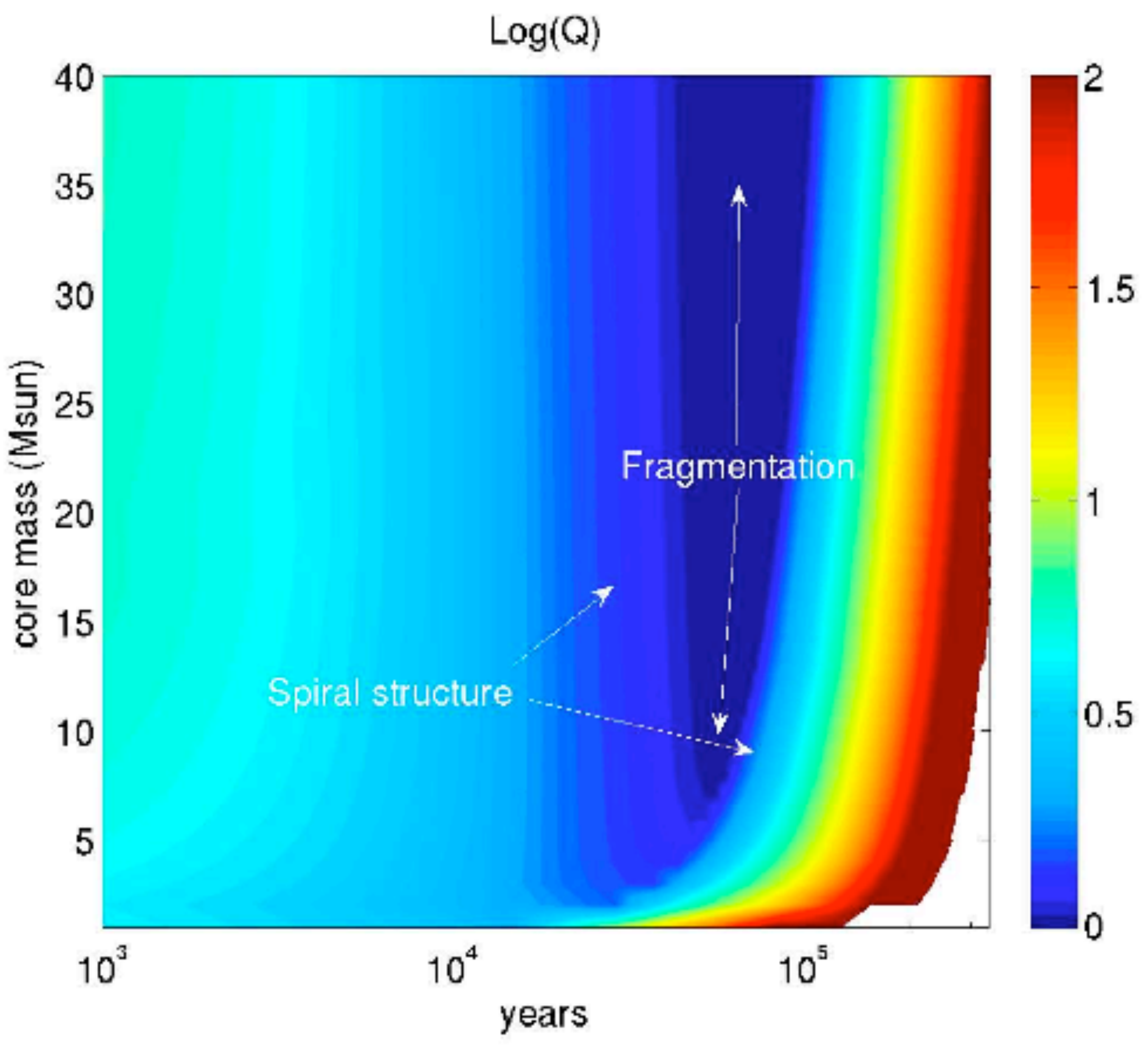


The plot shows the evolution of disks in 1 $M_\odot$ and 15 $M_\odot$ cores.

Prediction:

M_{disk} / M_* increases with M_* or M_{core}; Toomre Q decreases with M_* or M_{core}

Variation in Disk Properties



The plot shows Q as a function of core mass and the evolutionary time of the system.

Prediction:
incidence of spiral structure and disk fragmentation both increase with M_{core} or M_*

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  A proper theorist attitude toward observations
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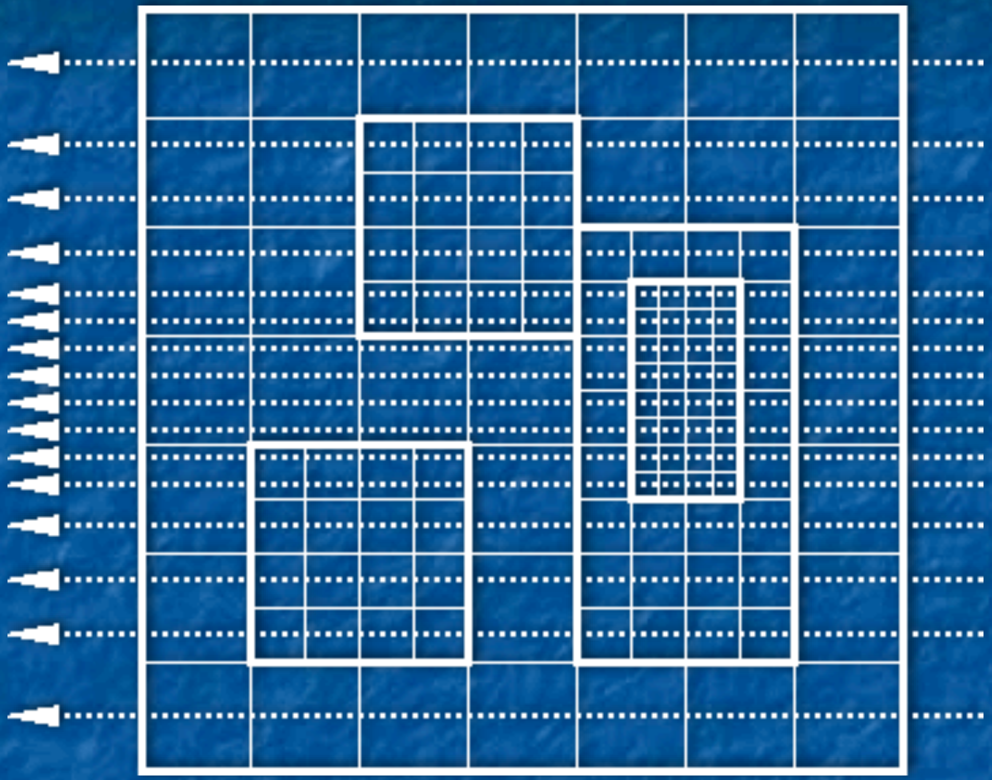
A proper theorist attitude toward observations

General Considerations on Massive Disk Observations

(Krumholz, Klein, & McKee, 2007c, ApJ, in press, arXiv:0705.0536)

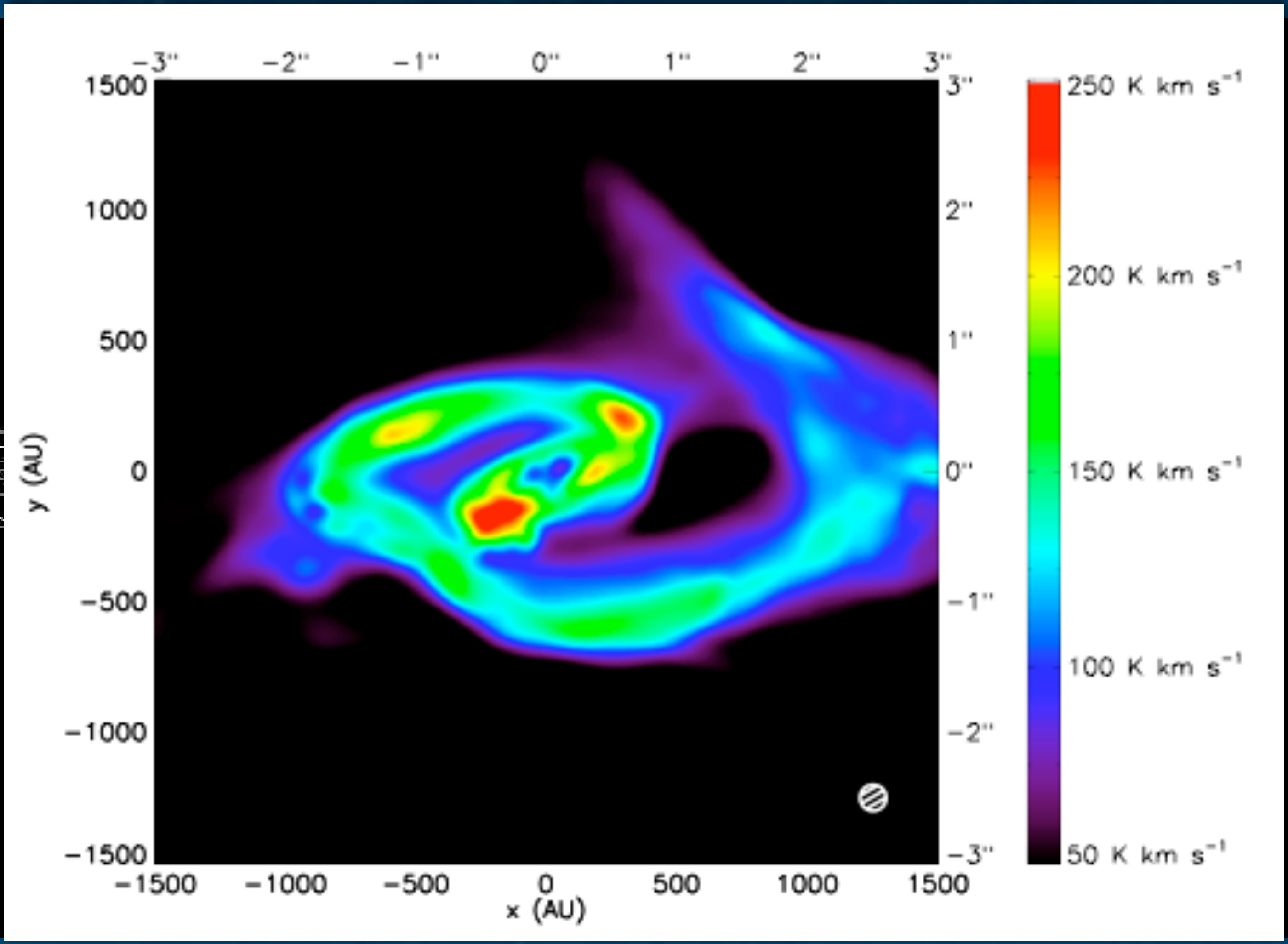
- Density > 10^{10} cm^{-3} $\Rightarrow$ all species in LTE
- T > 50 – 100 K $\Rightarrow$ can use high temp. lines to avoid envelope contamination
- Inner disk column density ~ 10^3 g cm^{-2} $\Rightarrow$ dust optical depth ~ 1 at 100 GHz
  - Bad: kinematics in central few hundred AU impossible with ALMA (need EVLA)
  - Good: spiral arms have optical depth ~ 1 in dust / strong lines, very easy to do with ALMA

Predictions from Simulations



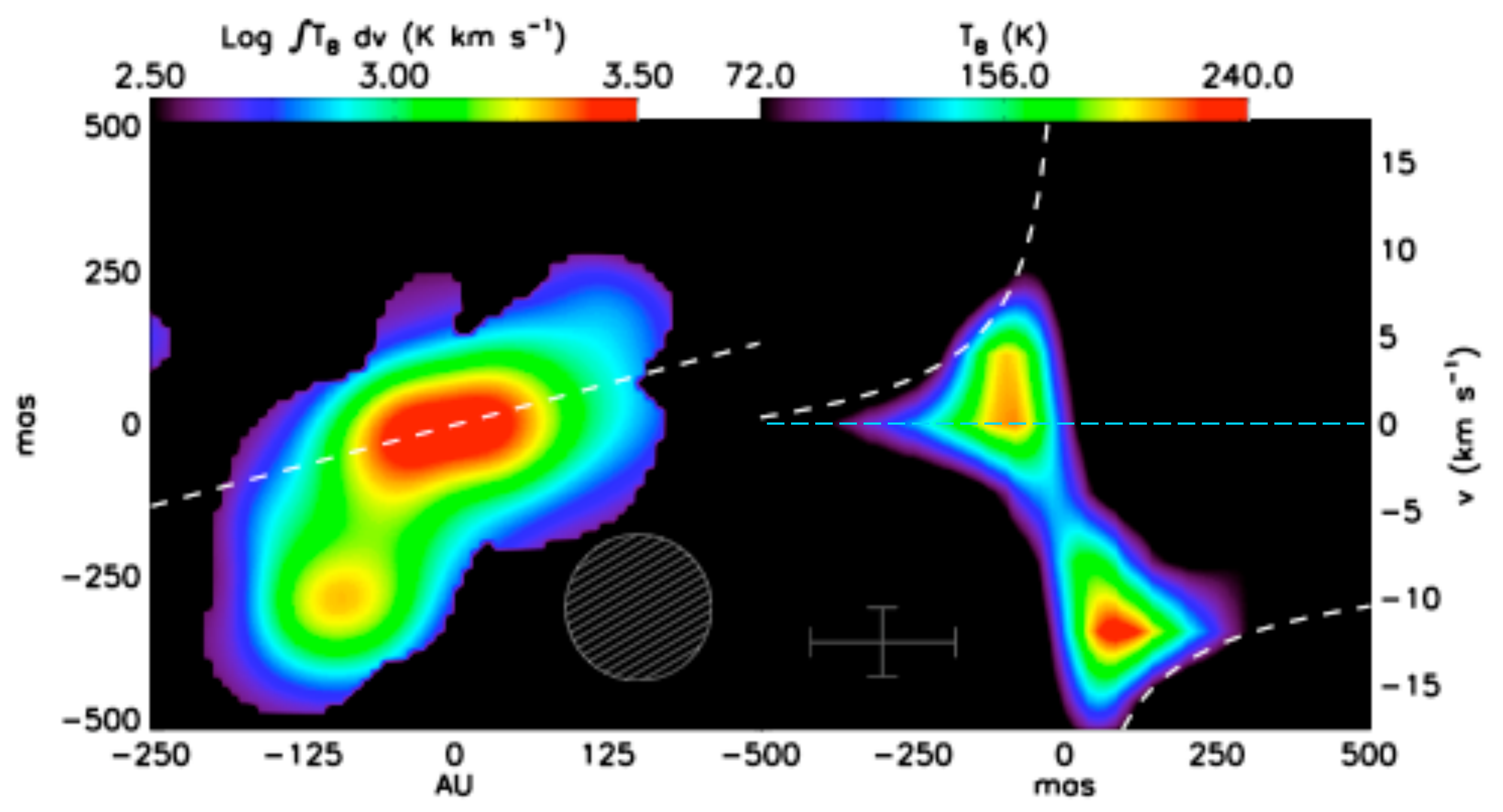
- Solve transfer equation on rays through adaptive grid
- Include molecular line and dust continuum processes at radio and sub-mm
- Model ALMA, EVLA performance
- Simulations must include radiative transfer to make realistic predictions
- Caveats: chemistry, outflows

ALMA: Rotating m = 1 Spiral



Simulated 1000 s / pointing ALMA observation of disk at 0.5 kpc in CH_3CN 220.7472 GHz, T_{up} = 69 K (KKM 2007c, ApJ, in press)

EVLA: Offset Keplerian Rotation



Simulated 24 hr / pointing EVLA observation of disk at 0.5 kpc in NH_3(8,8) hyperfine line, 26.5910 GHz, T_{up} = 687 K (KKM, 2007c, ApJ, in press)

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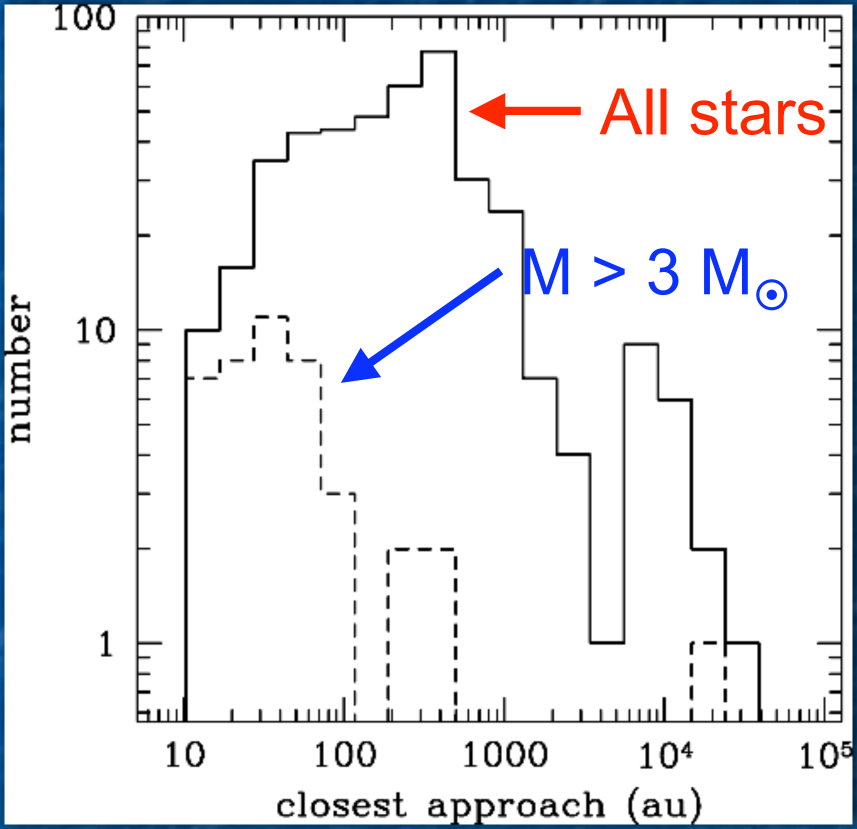
Competitive Accretion / Collision Model

- There is no direct core to star mapping
- Gas always fragments to Jeans mass at T ~ 10 K; all stars born small, ~ 0.1 – 0.5 $M_{\odot}$
- Close encounters between protostars common, especially for massive stars
- Requires that gas clumps undergo global collapse, turn into stars in a time of order t_{ff} (Krumholz, McKee, & Klein, 2005, Nature, 438, 332)

Disks in the Competitive Accretion / Collision Model

- In CA model, almost all massive stars have close encounters that truncate their disks
- Disks can grow back, but this takes a while
- CA prediction: a non-trivial fraction of massive stars should be close to diskless

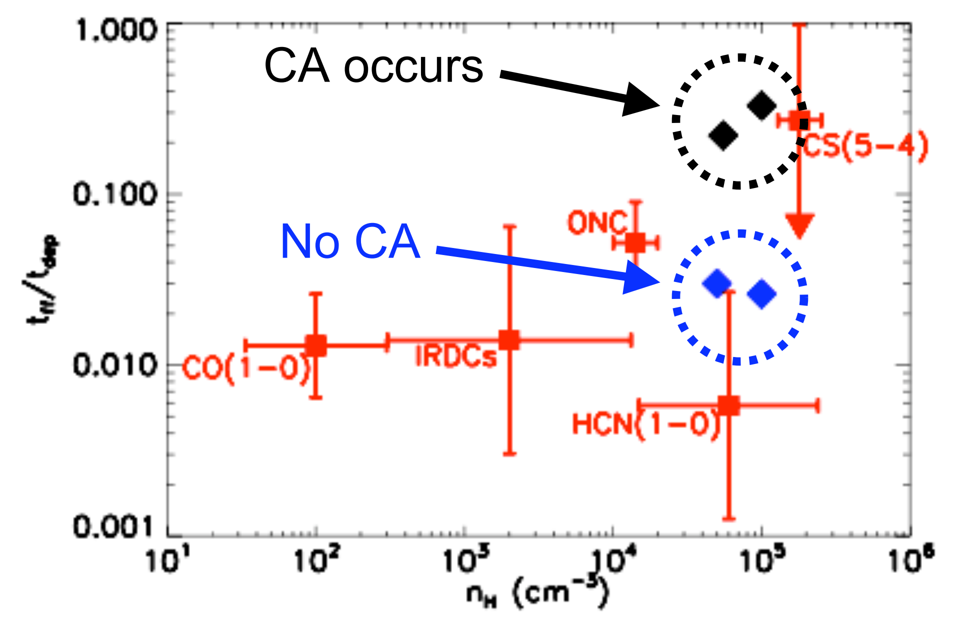


Distribution of encounter distances in a competitive accretion simulation (Bonnell et al. 2003)

Looking for Global Collapse Using the Star Formation Rate

(Krumholz & Tan, 2007, ApJ, 654, 304)

- Compute ratio of SFR to free-fall time in observed objects of varying densities (e.g. Gao & Solomon 2004, Wu et al. 2005, Rathborne et al. 2006)
- Compute ratio from simulations with and without competitive accretion



Ratio of free-fall time to depletion time in gas clouds of varying density

Can do this test much better with ALMA!

Summary

- The core accretion model predicts
  - Massive protostellar disks have $r \sim 1000$ AU, $m \sim M_* / 2$, $m = 1$ spirals, v offset ~ few km s^{-1}
  - M_{disk} / M_*, r_{disk}, spiral mode strength, fragmentation all increase with M_*
- CA models predict a diskless population, and $t_{ff} \sim t_{dep}$ in protocluster gas
- ALMA and EVLA can test these predictions in reasonable integration times
  - ALMA is good for fast mapping of outer disks
  - EVLA is slower, but can see inner disks

Finally and most importantly, thanks to the organizers for putting together this meeting…

…and thanks to the audience for showing up at 9 AM on a Saturday morning!