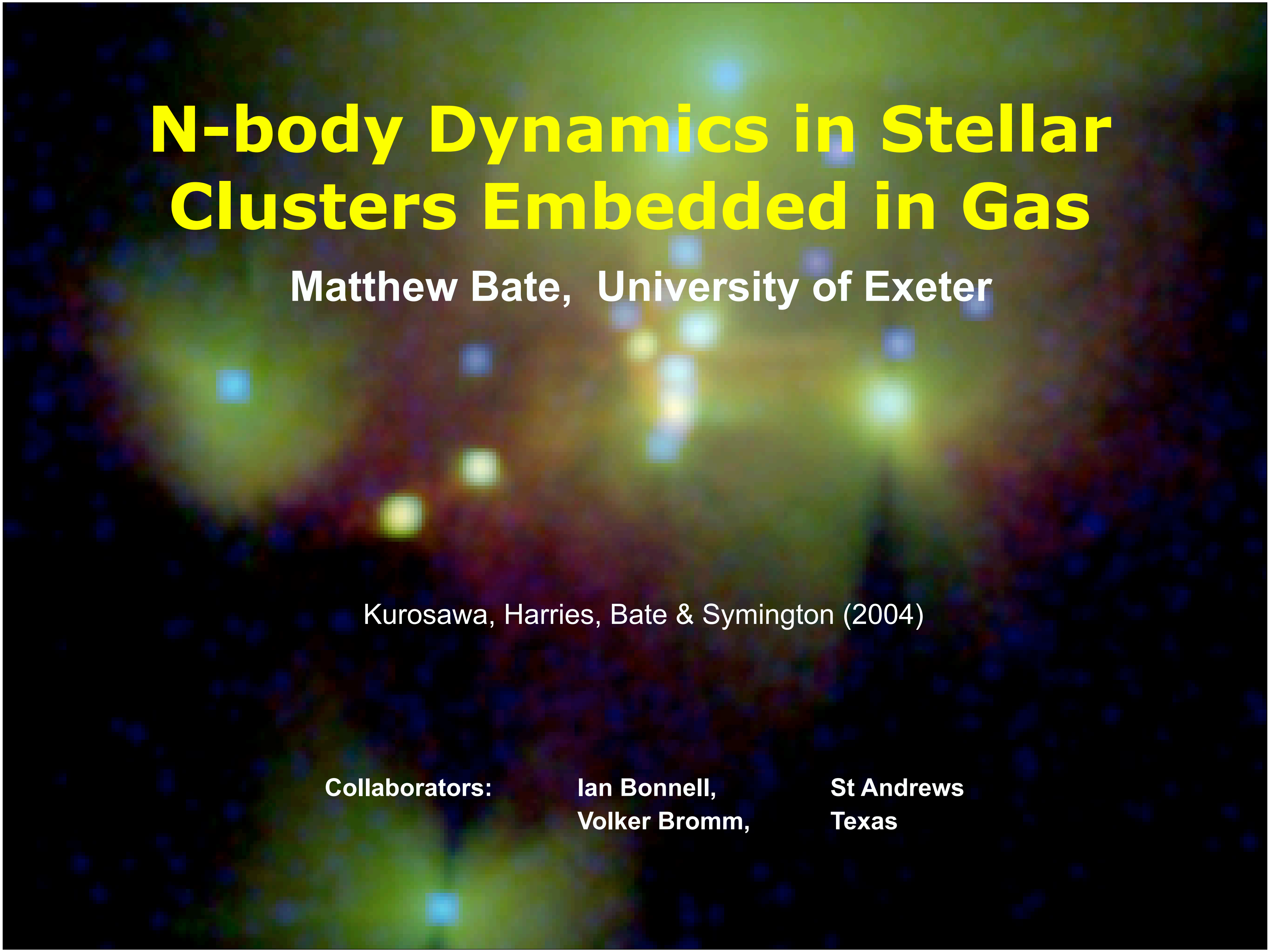
N-body Dynamics in Stellar Clusters Embedded in Gas

Matthew Bate, University of Exeter



Kurosawa, Harries, Bate & Symington (2004)

Collaborators:	**Ian Bonnell,**	**St Andrews**
	Volker Bromm,	**Texas**

Star Formation

- Physics
  - Self-gravity
  - Hydrodynamics
  - Radiative transfer
  - Magnetic fields
    - Non-ideal: ambipolar diffusion, Hall effect, resistivity
  - Multi-fluid
    - Chemistry, dust, ionisation

- Scales
  - Spatial scales: 10 orders of magnitude
    - 10’s of parsecs to less than $R_{\odot}$
  - Timescales: 12 orders of magnitude
    - 10^7 yrs to <5 minutes
  - Densities: >20 orders of magnitude
    - $<10^{-20}$ g cm^{-3} to >1 g cm^{-3}

- Sub-problems
  - Turbulence, chaos, accretion discs, jets/outflows, chemical reactions

Star Formation

- Physics
  - Self-gravity
  - Hydrodynamics
  - Radiative transfer (FLD in SPH: Whitehouse & Bate 2004)
  - Magnetic fields (Price & Monaghan 2003)
    - Non-ideal: ambipolar diffusion, Hall conduction, resistivity
  - Multi-fluid
    - Chemistry, dust, ionisation

- Scales
  - Spatial scales: 10 orders of magnitude (5 orders of magnitude)
    - 10's of parsecs to less than $R_\odot$ (~5 AU to 0.5 pc)
  - Timescales: 12 orders of magnitude (8 orders of magnitude)
    - 10^7 yrs to <5 minutes (~3 hours to 300,000 yrs)
  - Densities: >20 orders of magnitude (8 orders of magnitude)
    - $<10^{-20}$ g cm^{-3} to >1 g cm^{-3} (~10^{-19} to 10^{-11} g cm^{-3})

- Sub-problems
  - Turbulence, chaos, accretion discs, jets/outflows, chemical reactions

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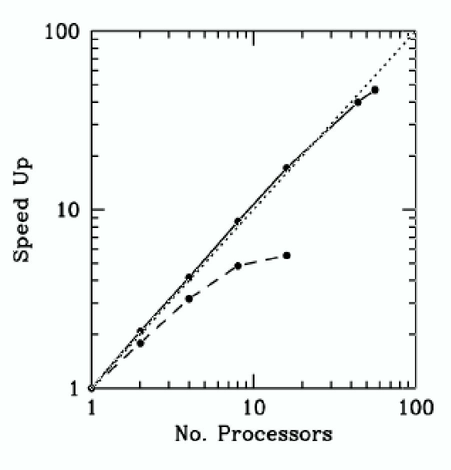
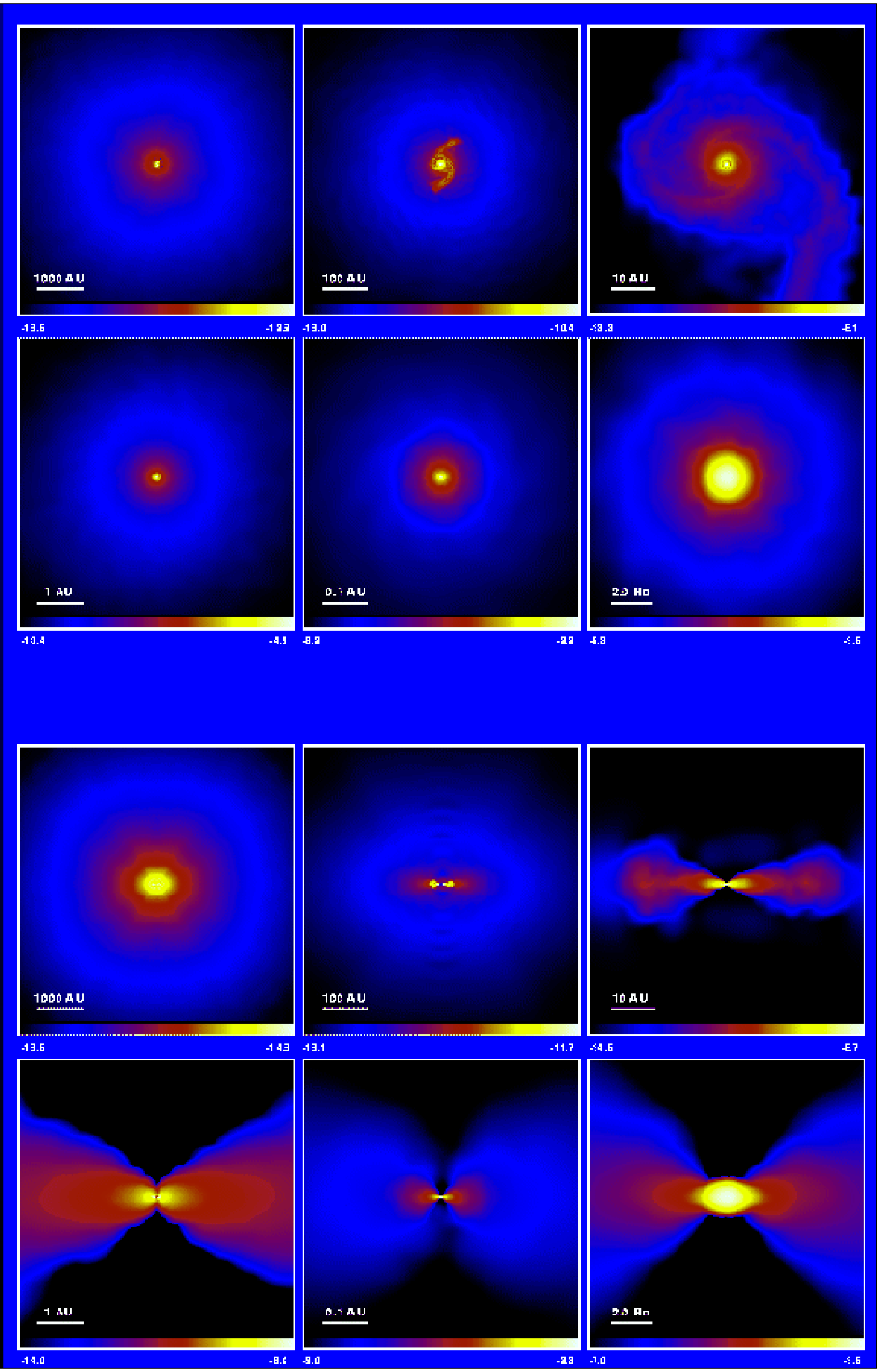
SPH

- Variable smoothing/softening lengths
  - Lagrangian so resolution follows mass
- Individual timesteps
  - Essential for following large range of timescales
  - Can follow collapse to stellar densities
    - Bate (1998): 1 solar mass cloud to form stellar core
      - Need > 3×10^5 particles
- Sink particles
  - Bate, Bonnell & Price (1995)
  - Condensed objects (stars) replaced by point mass
    - Accretes gas that falls within a certain radius
  - Accretion radius 5 AU
    - Spline gravitational softening inside 4 AU
- Parallel
  - OpenMP



Collapse to Stellar Densities

- Bate 1998
  - Collapse of molecular cloud core R~5000 AU to stellar densities
  - Tested to see whether close binaries (separations < 10 AU) could form directly via fragmentation



Goal: Statistical Properties

- Understand the origin of and make predictions for:
  - Star formation timescale
  - Star formation efficiency
  - Initial mass function
  - Kinematics: velocity dispersion
  - Frequency and properties of binaries and multiples
  - Circumstellar disc properties
- Best guess at initial conditions in local SF regions
- How does star formation depend on environment ?
  - Mean Jeans mass of the cloud (density, temperature)
  - Opacity limit for fragmentation
  - Power spectrum of the turbulence, etc

Hydrodynamical Simulations

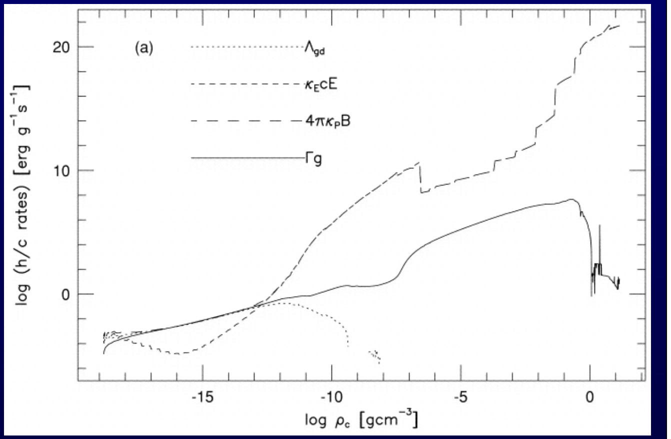
- Initial supersonic (`turbulent') velocity field
  - E.g. Ostriker, Stone & Gammie 2001
  - Divergence-free random Gaussian velocity field
  - $P(k) \sim k^{-4}$ so that $\sigma(\lambda) \sim \lambda^{1/2}$ (Larson 1981)
  - Normalised so cloud contains one turbulent Jeans mass

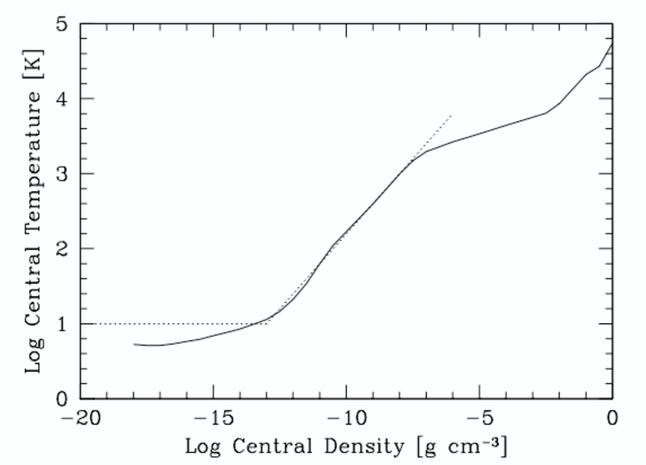
- Resolve down to the opacity limit for fragmentation
  - Local Jeans mass always contains >75 particles (Bate & Burkert 1997; Bate et al. 2003)
  - Limited to 50 $M_\odot$ of gas
  - Molecular cloud sizes 0.4-0.8 pc across
  - <100 stars and brown dwarfs

- Four calculations
  - Standard: mean Jeans mass 1 $M_\odot$, Opacity limit at ~3 M_J
    - Bate, Bonnell & Bromm 2002a,b;2003
  - Denser cloud: mean Jeans mass 1/3 $M_\odot$, Opacity limit at ~3 M_J
    - Bate & Bonnell 2005
  - Lower metallicity: mean Jeans mass 1 $M_\odot$, Opacity limit at ~10 M_J
  - Different power spectrum: $P(k) \sim k^{-6}$

Opacity Limit for Fragmentation

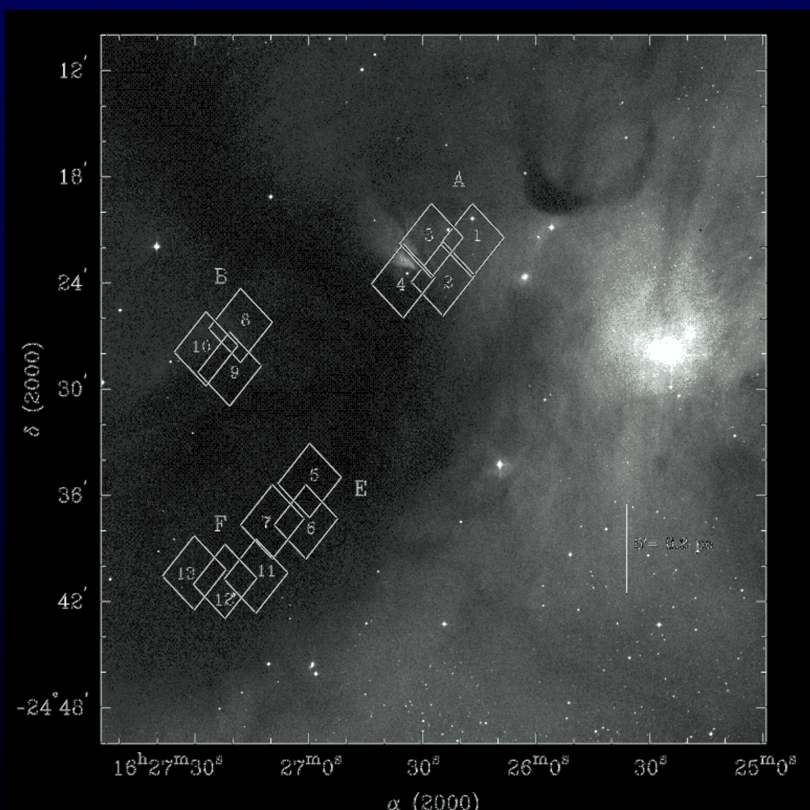
- Hoyle 1953; Low & Lynden-Bell 1976; Rees 1976
  - Low-density gas collapses isothermally (T~10 K)
  - Compressional heating rate << cooling rate
  - Collapse accelerates
  - Heating rate > cooling rate
  - Occurs at ~ 10^{-13} g cm^{-3}
    - Masunaga & Inutsuka 2000
- Pressure-supported core forms (Larson 1969)
  - Size ~ 5 AU
  - Mass ~ 0.005 $M_\odot$ (5 M_J)
- Minimum mass
  - 0.007 $M_\odot$ (7 M_J) Low & Lynden-Bell (1976)
  - 0.01 $M_\odot$ (10 M_J) Boss (1988)
- Grows with time due to accretion from envelope



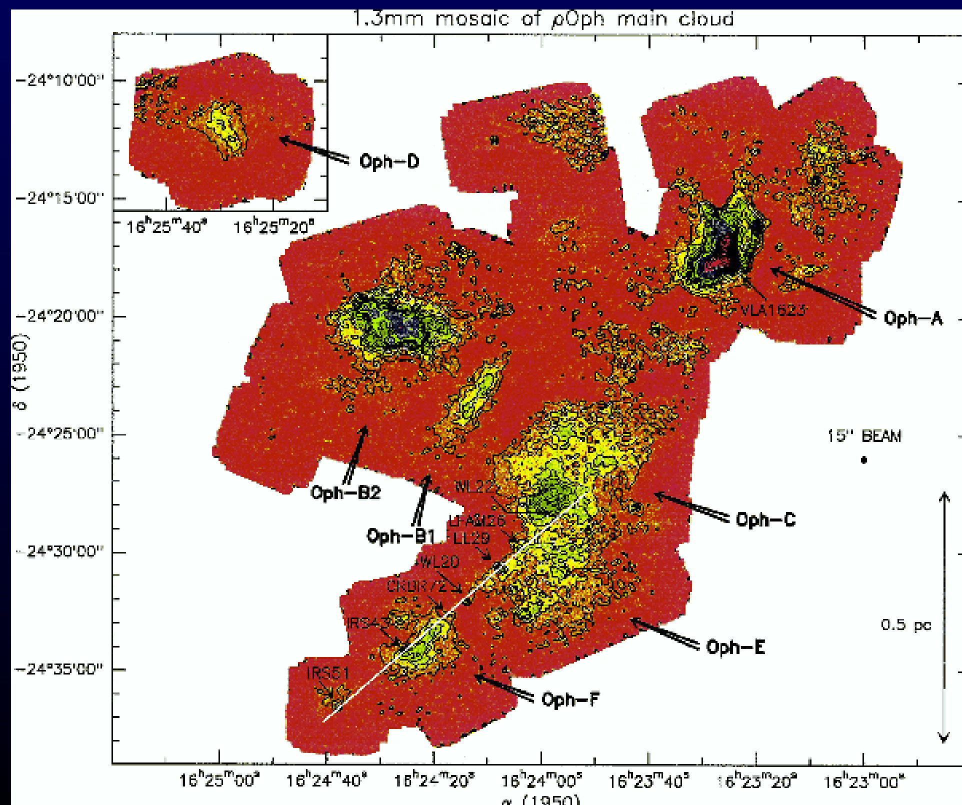


Comparison with Star-forming Regions

- Ophiuchus low-mass star-forming region
  - 550 $M_{\odot}$ within area of 2x1 pc (Wilking & Lada 1983)
  - Contains 6 main dense cores
  - Simulation similar to modelling Oph-F core (mass ~8 $M_{\odot}$)



Allen et al. 2001

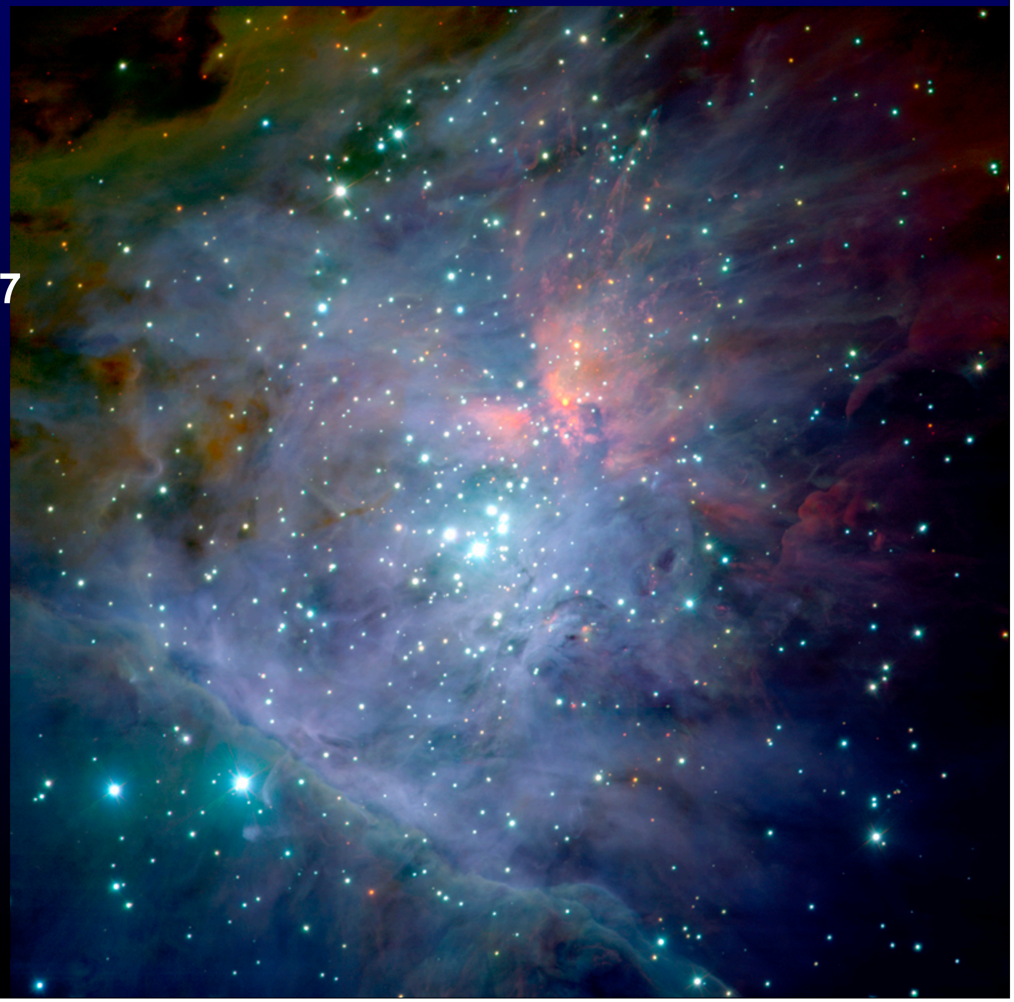


Motte, Andre & Neri 1998

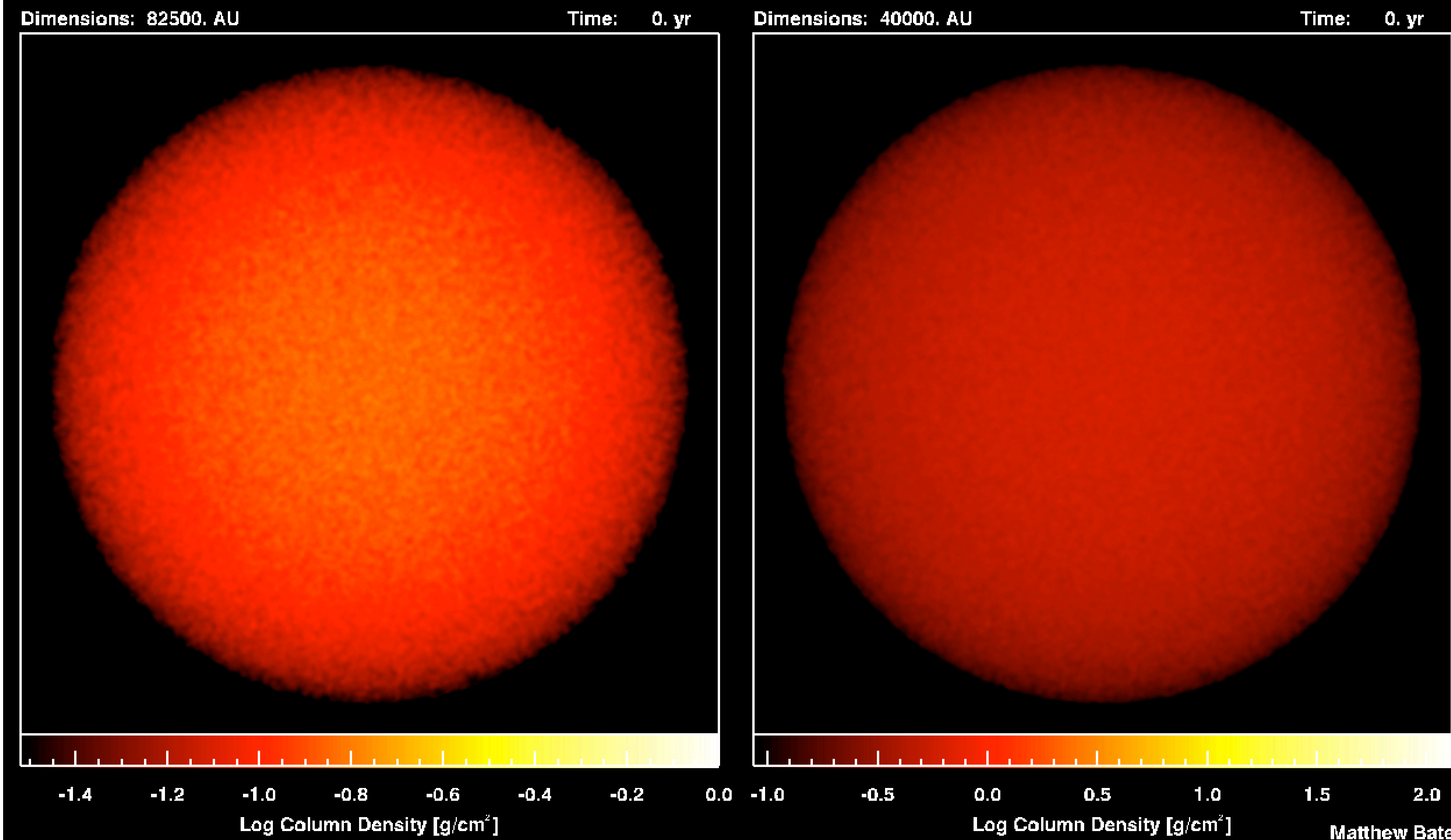
Orion Trapezium Cluster

- Stellar densities in this calculation ~10^3 pc^{-3}
- Stellar densities in Trapezium Cluster
  - Centre ~2×10^4 pc^{-3}
  - Fall off as $(R / 0.07\ pc)^{-2}$
    - Hillenbrand & Hartmann 1997
    - Bate et al. 1998
- Simulation similar to
  - Small region within cluster
  - R ~ 0.3 pc from centre
  - Especially if Orion was originally sub-clustered

VLT, ESO PR 03a0/1



Standard Model   Denser Cloud



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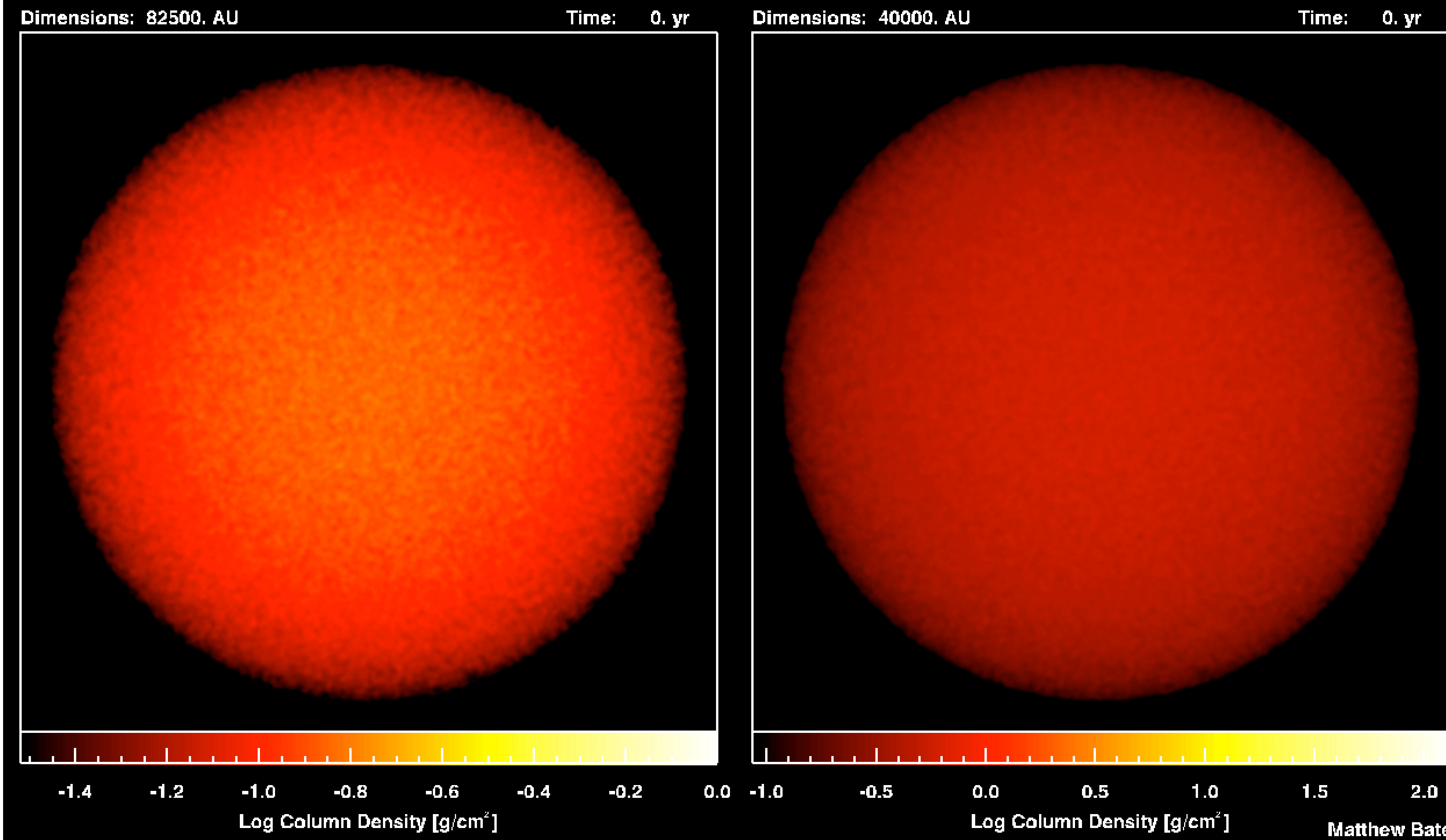
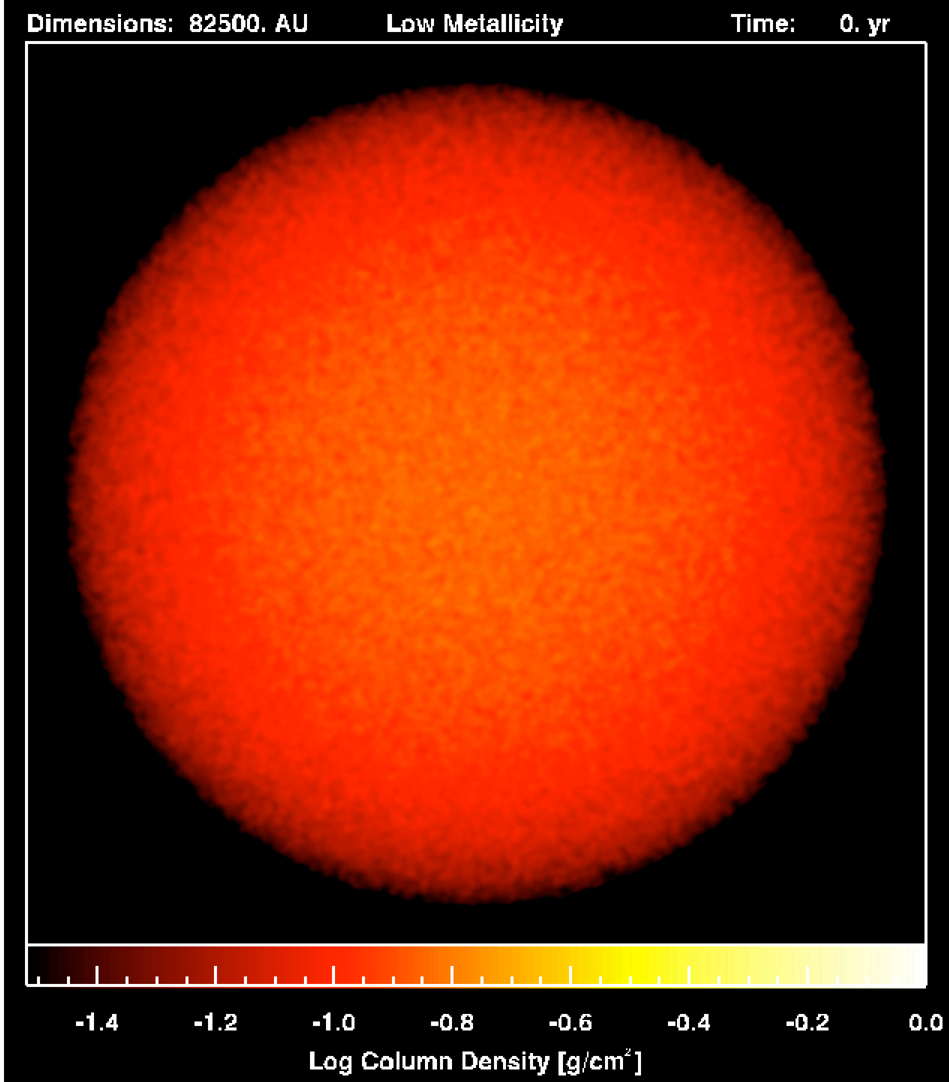
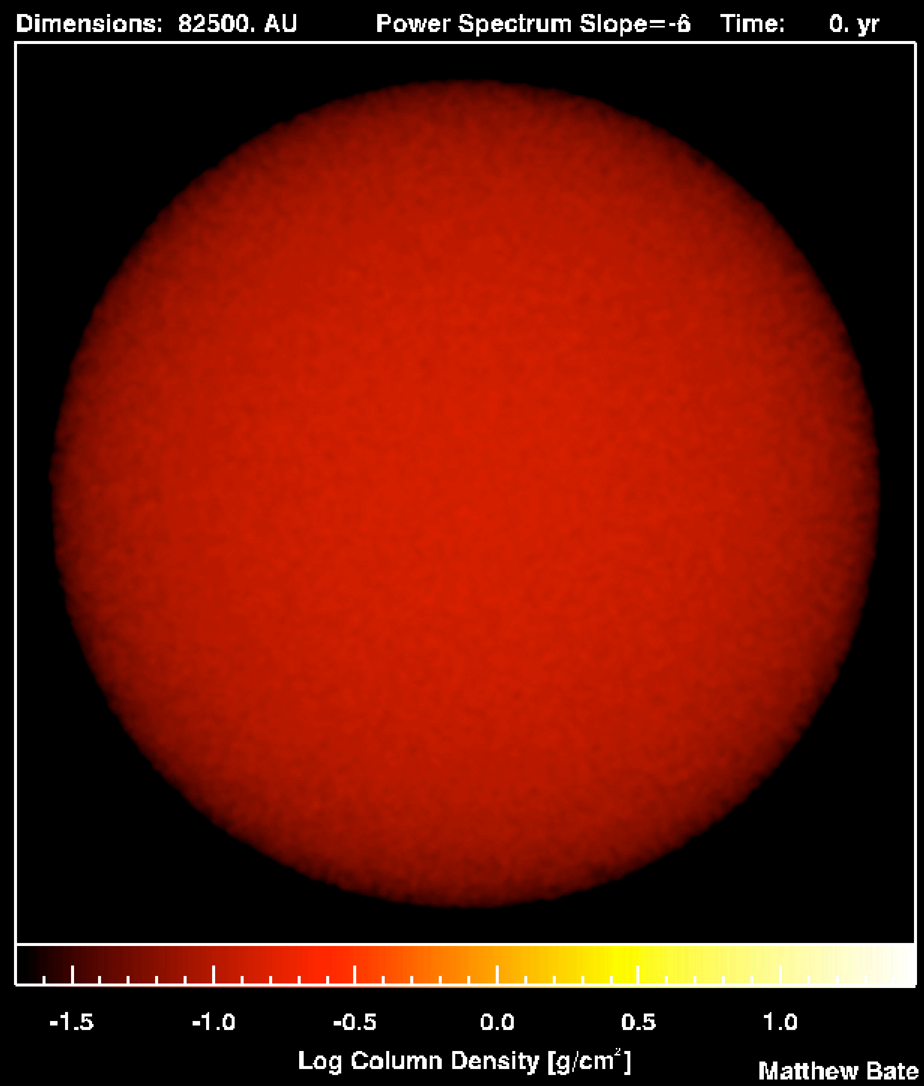
Standard Model / Denser Cloud



Low Metallicity   Turbulence P(k)~k^{-6}





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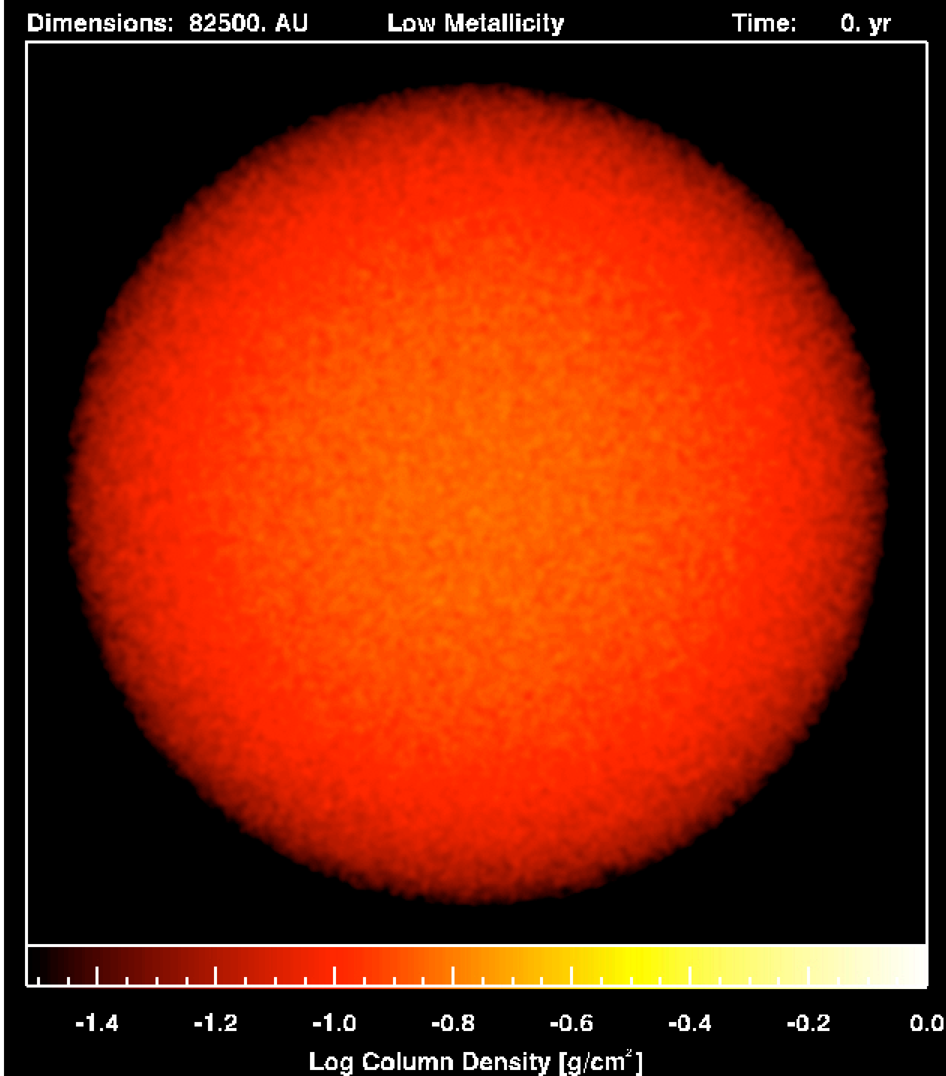
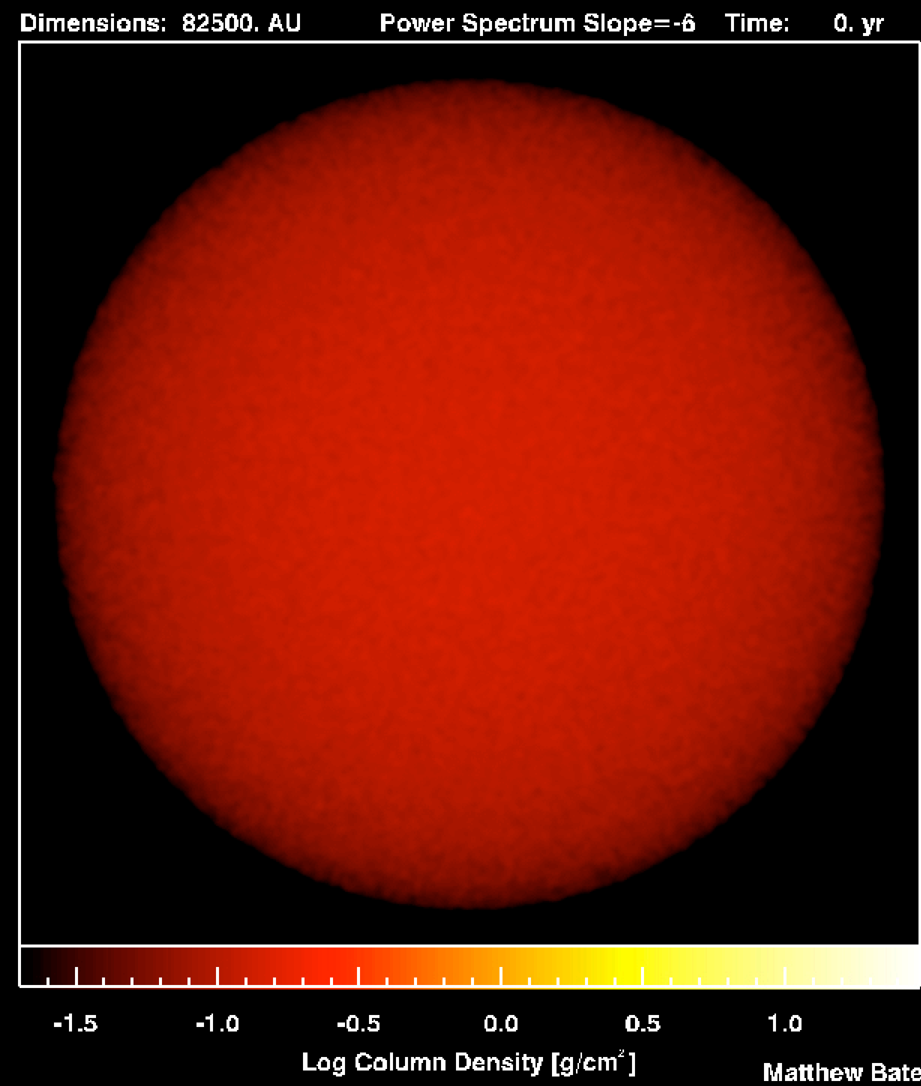


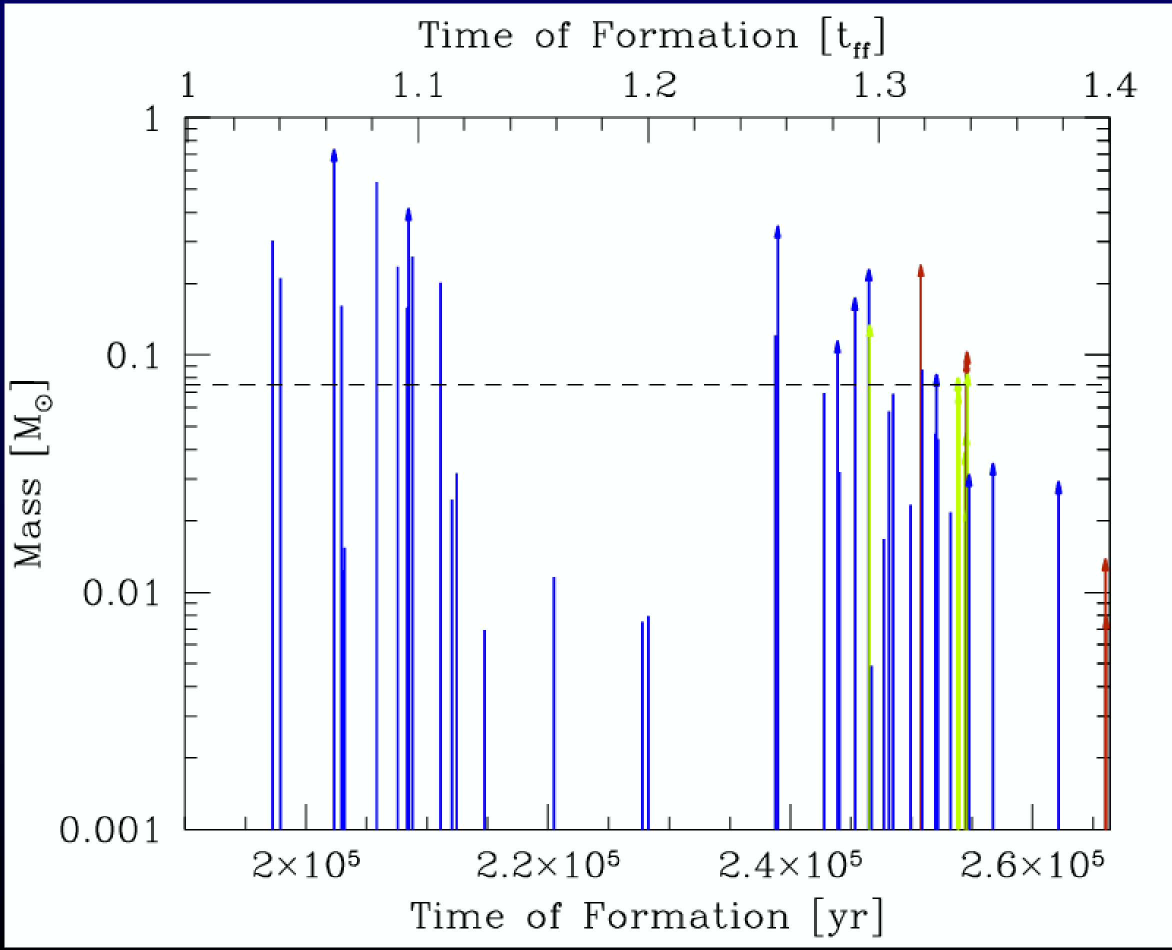


Star Formation Timescale

Star formation occurs on dynamical timescale in localised bursts

- **Dense core forms**
- **Stars form on core's dynamical timescale**
- **Gas depleted**
- **Potential well gathers more gas**
- **Star formation again**

- **Main core undergoes two bursts ~20000 yr separated ~20000 yr**



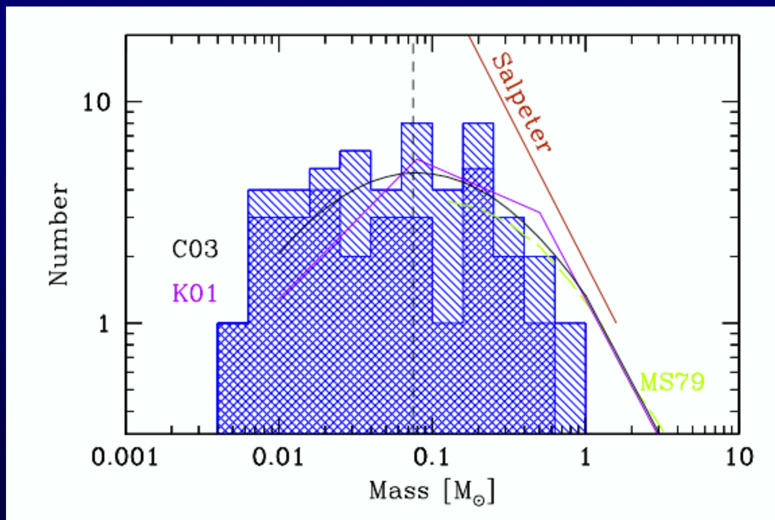
Star Formation Efficiency

- For each core, local SF efficiency high
  - Bursts
- Overall efficiency for cloud low

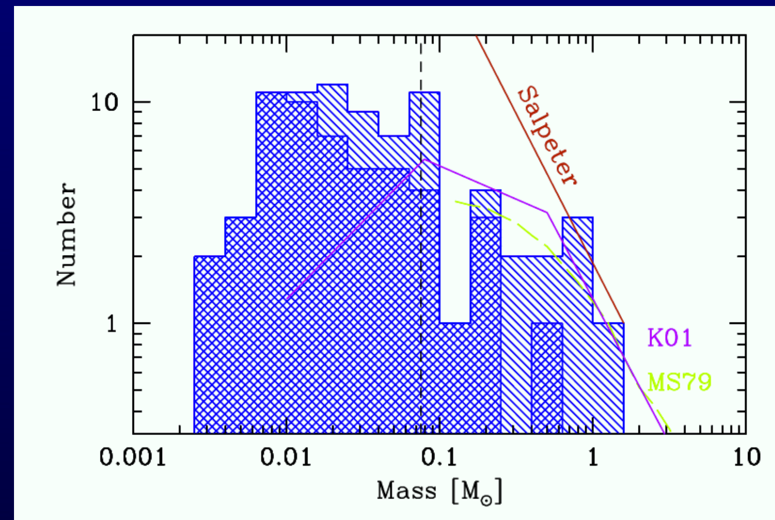
Core	Initial Gas M_o	Final M_o	No. Stars	No. Brown Dwarfs	Mass Stars/BD	SF Efficiency
1	3.0	3.7	17	21	5.0	58%
2	0.9	1.0	3	4	0.5	32%
3	1.1	1.1	3	2	0.4	30%
Cloud	50.0	44.1	23+	27-	5.9	12%

Resulting IMFs

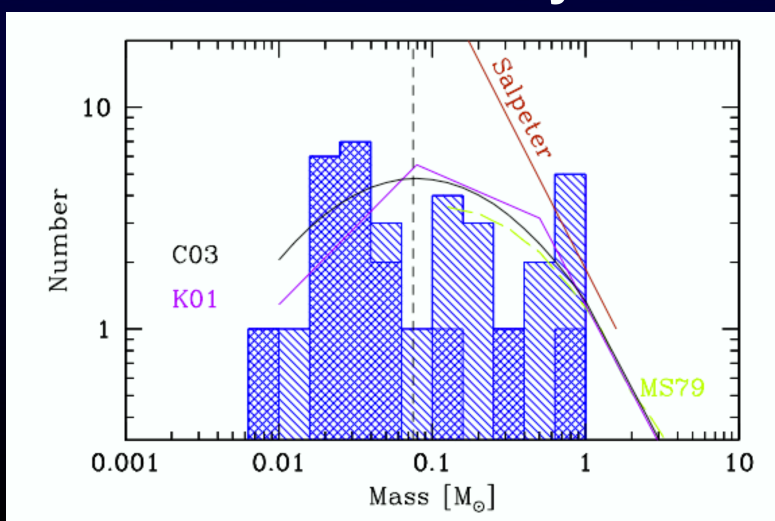
Standard calculation



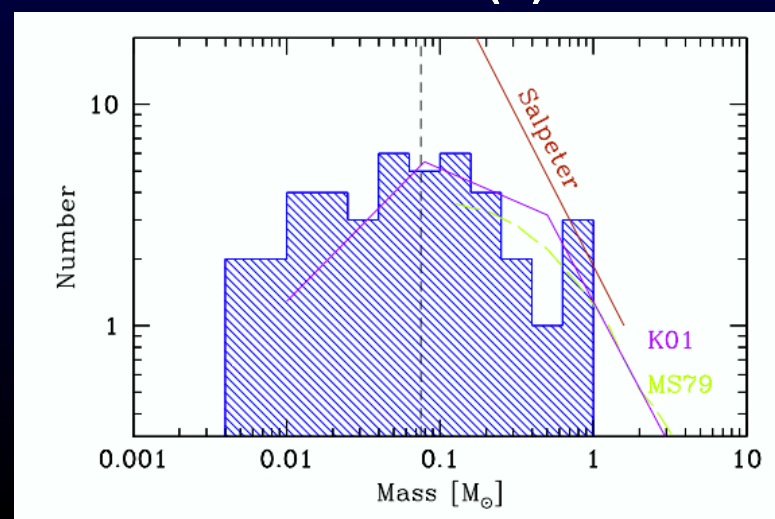
Denser cloud



Low metallicity

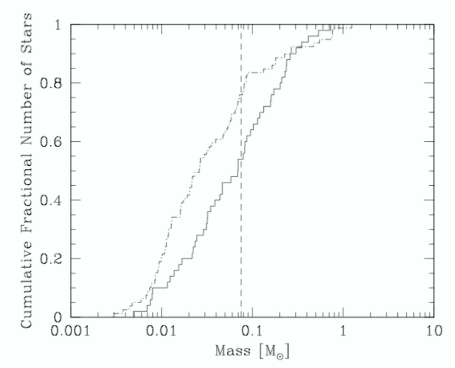


Turbulence P(k)~k^{-6}

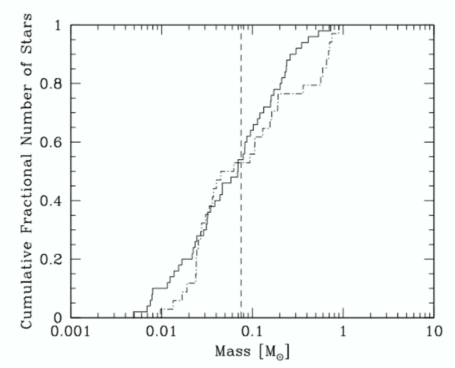


Variations with Initial Conditions?

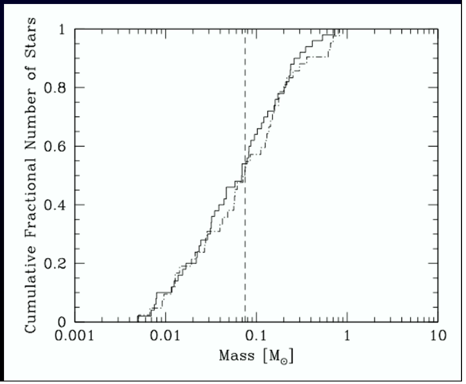
- **Denser cloud (1/3 of original thermal Jeans mass)**
  - Median mass decreased by factor of 3.04
  - Higher proportion of brown dwarfs
  - K-S test gives only 1.8% probability of same IMF



- **Increasing minimum fragment mass by factor of 3**
  - Increases the minimum mass of a brown dwarf
  - Median mass almost unchanged (20% smaller)
  - 45% probability of being drawn from the same populations



- **Dramatic change to initial velocity power spectrum**
  - No statistically-significant change in the IMF !
  - 95% probability of being drawn from the same population!



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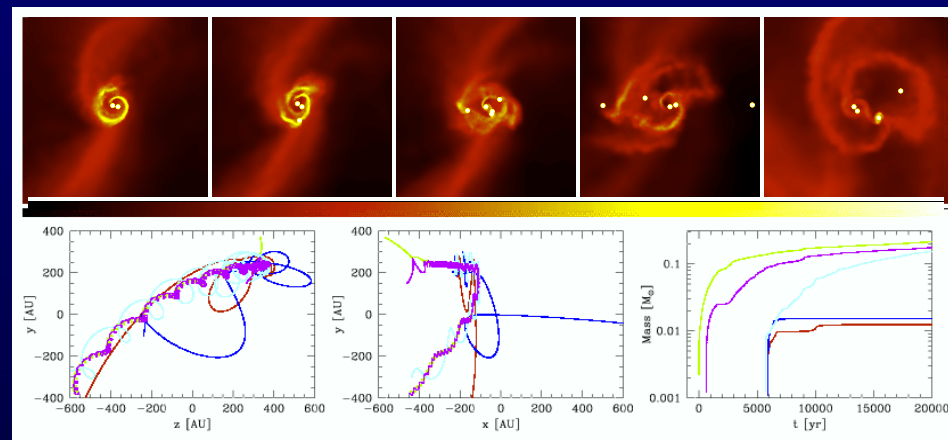
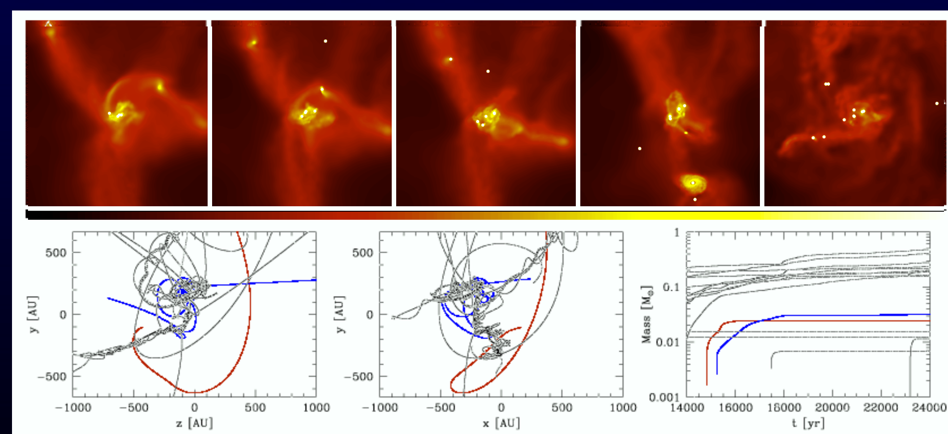
Brown Dwarf Formation

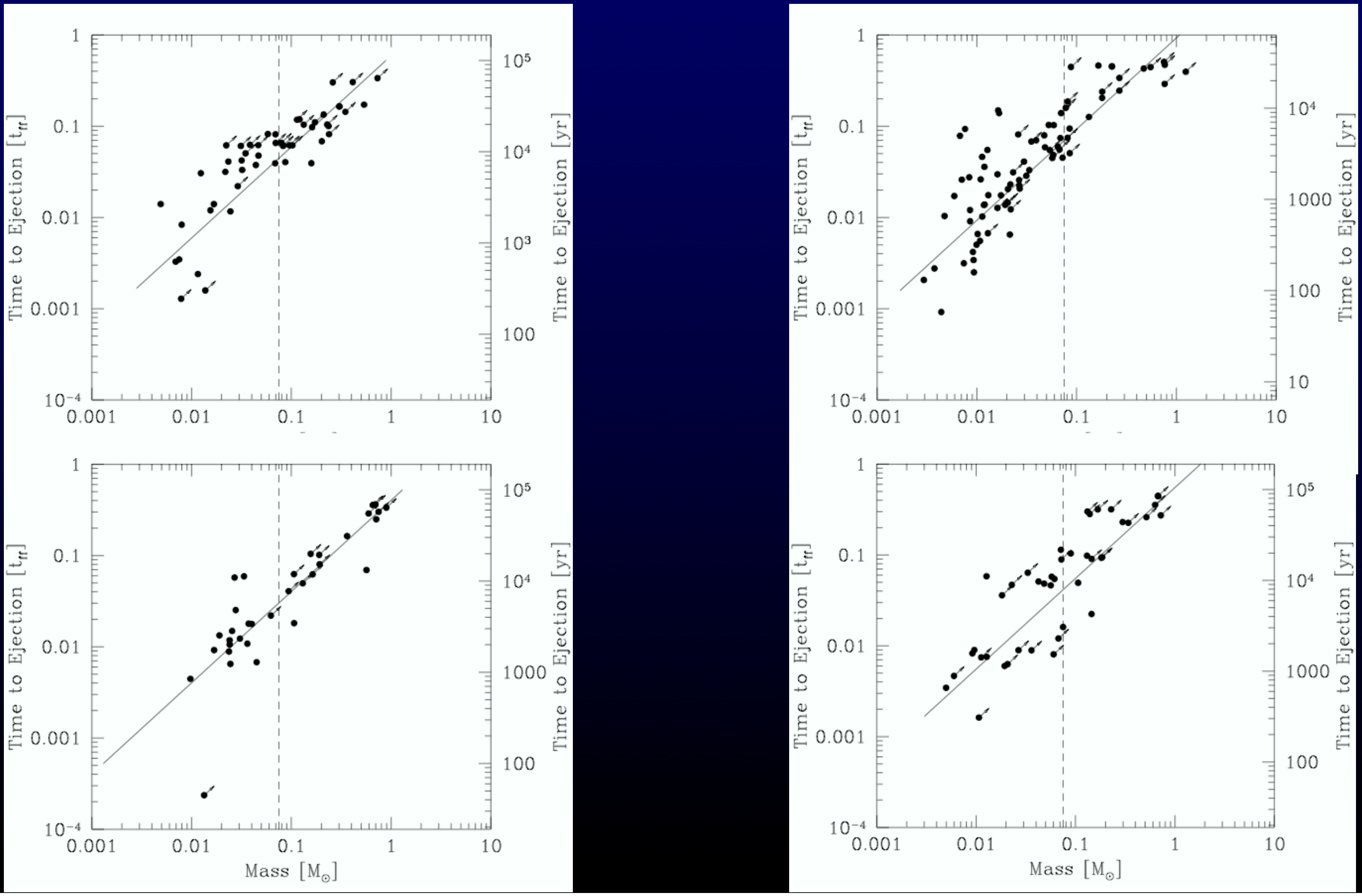
- How do brown dwarfs form?
  - Bate, Bonnell & Bromm 2002
  - 3/4 in massive circumstellar discs via disc fragmentation
    - Bonnell 1994; Whitworth et al. 1995; Burkert et al. 1997
  - 1/4 in dense collapsing filaments
  - Opacity limit for fragmentation sets initial mass
  - Must avoid accreting to higher masses
  - Ejected from unstable multiple systems (c.f. Reipurth & Clarke 2001)
    - Stops accretion before they attain stellar masses





Final Masses: Accretion vs Ejection

- Plot time between formation and ejection versus final mass
  - Brown dwarfs have sub-stellar masses because they are ejected soon after they form

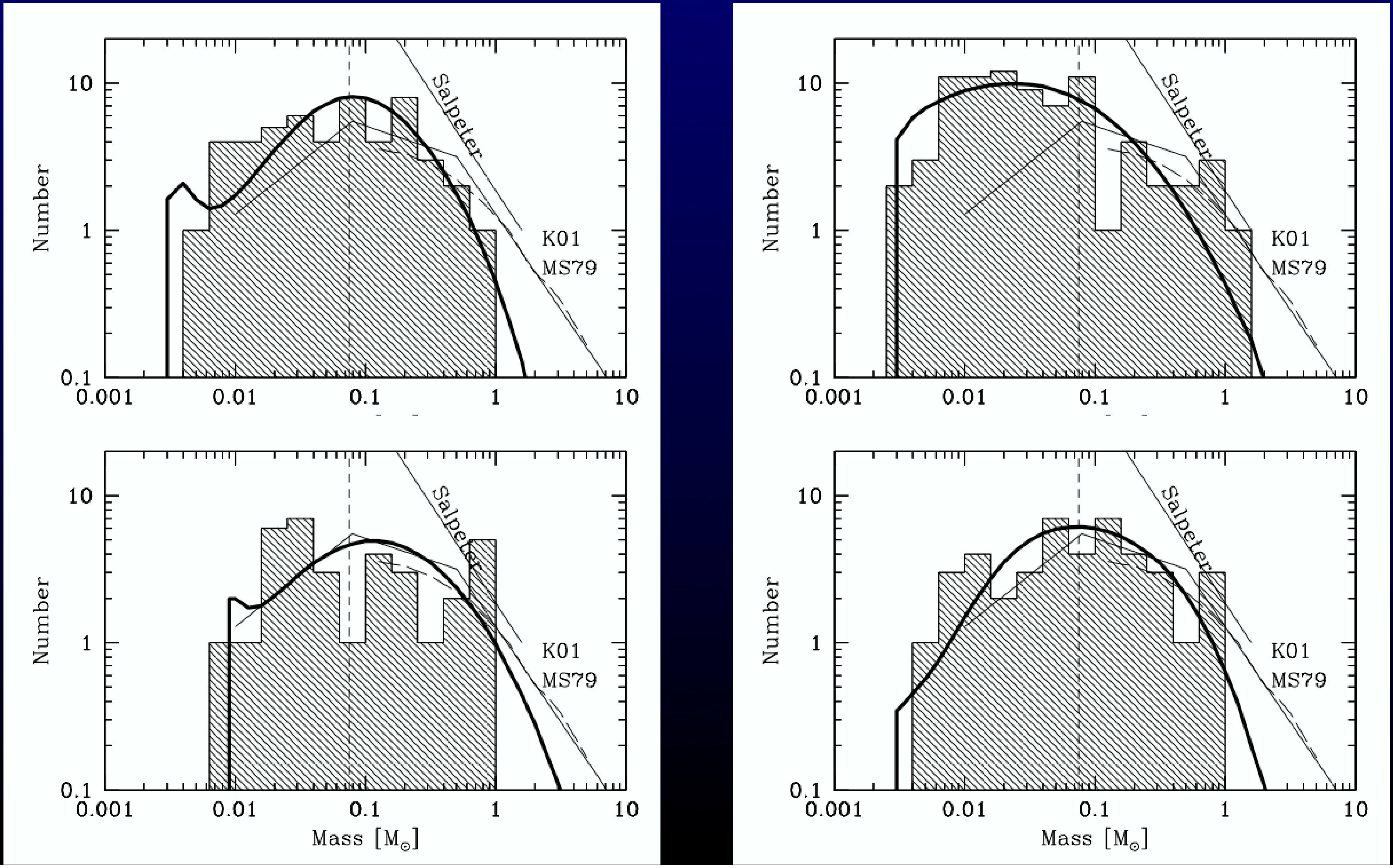


Simple Accretion/Ejection Model

- Assumptions (Bate & Bonnell 2005)
  - Initial masses set by the opacity-limit (e.g. 3 M_J), then objects accrete at a constant rate until ejected
  - Individual accretion rates drawn from log-normal distribution with mean $\bar{\dot{M}}$ and variance σ
  - Ejections occur stochastically with characteristic timescale t_{eject} (the same for all objects)
    - Probability of not being ejected proportional to $\exp(-t/t_{eject})$
    - See also Basu & Jones 2004
- Three parameters
  - $\bar{M} = \bar{\dot{M}}\, t_{eject}$
  - σ
  - Minimum mass due to opacity limit (metallicity)

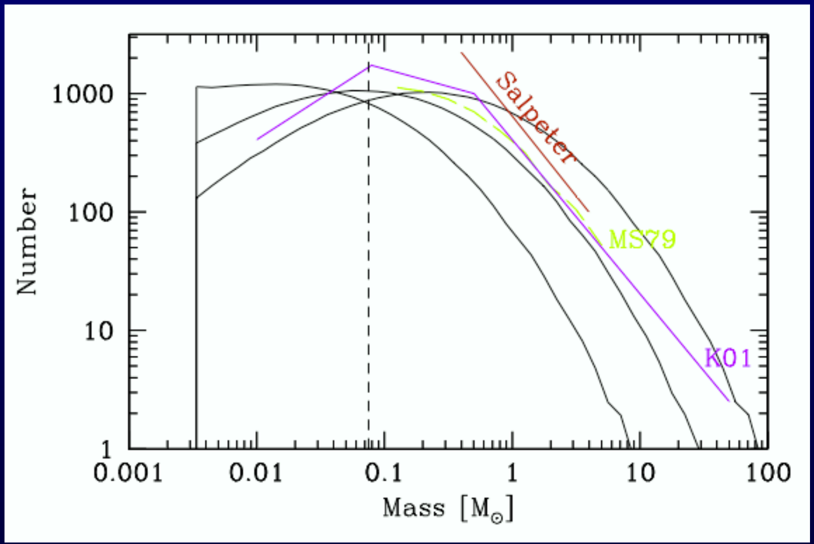
Reproduces Hydrodynamical Results

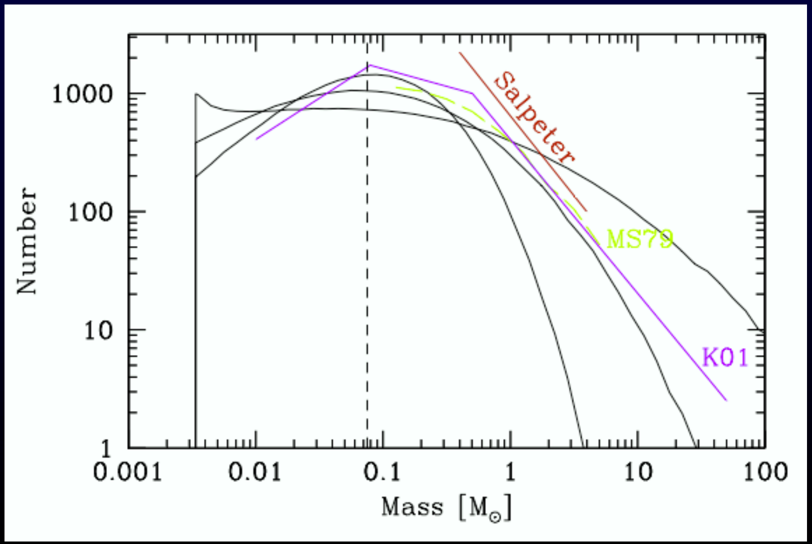
- Parameter values taken directly from simulations



Dependence of IMF on Initial Conditions

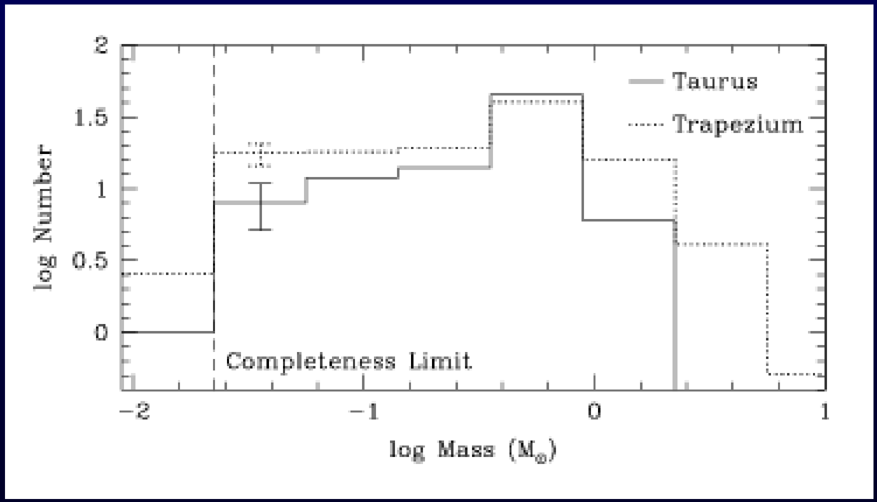
- Variation of peak mass
  - Accretion rate prop. to c_s^3/G
  - Ejection timescale prop. to $(G\rho)^{-1/2}$
    - ~ crossing time for small groups
  - Varies with mean thermal Jeans mass
    - Definition of Jeans mass: $c_s^3/(G^3\rho)^{1/2}$
    - Stellar groups more compact
    - Ejection time decreases
  - In practice, mean Jeans mass determined by thermodynamic behaviour
    - Jappsen et al. 2004, Larson 2005
- Increase dispersion in accretion rates
  - Shallower slope of high-mass IMF
  - Near Salpeter for σ ~ 0.7 dex
  - Dispersion higher for denser cloud





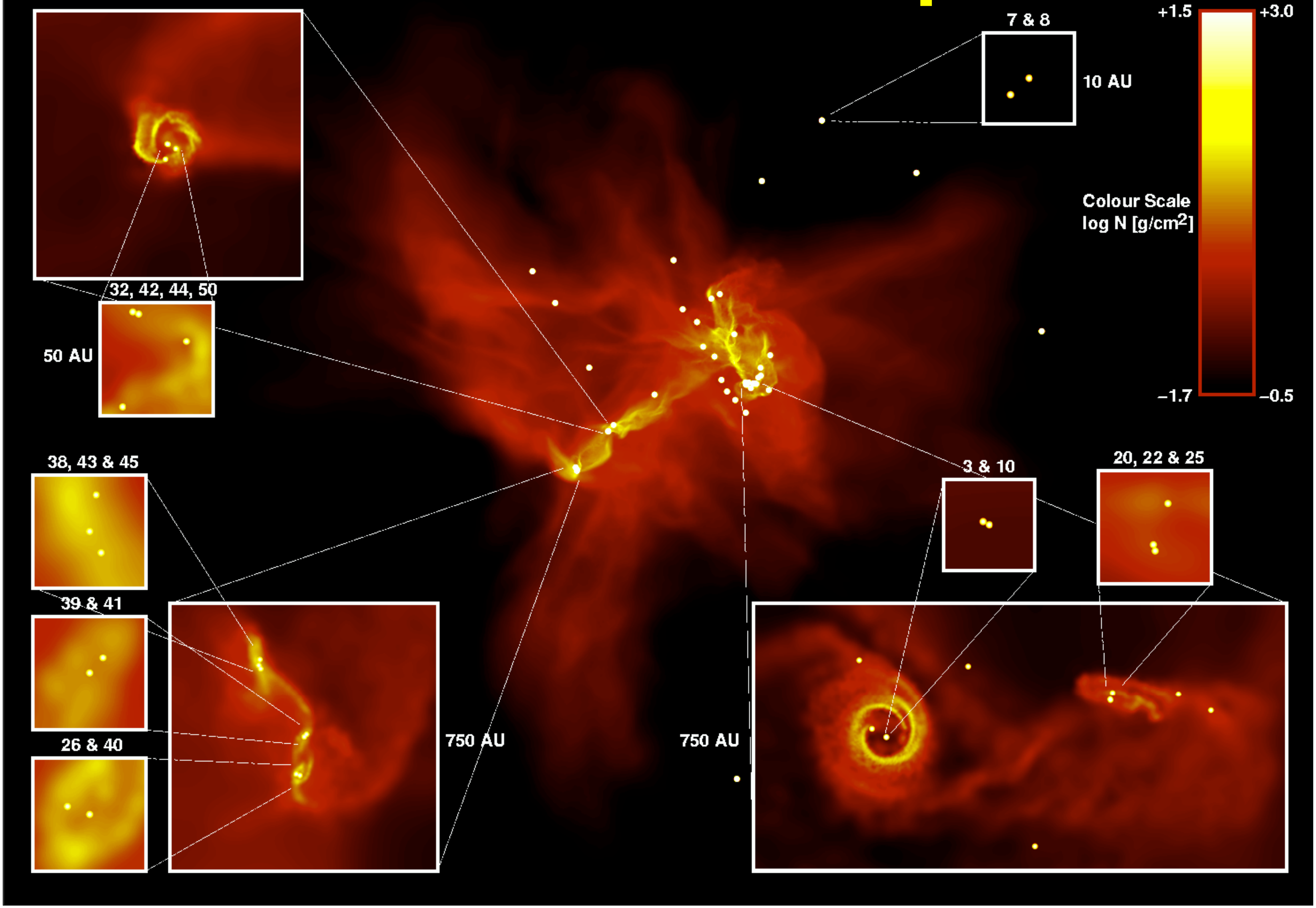
Comparison with Observations

- Taurus star-forming region
  - Low density, typical thermal Jeans mass: few $M_\odot$
- Trapezium cluster
  - High density, smaller inferred Jeans mass: ~ 1 $M_\odot$
- Taurus has a factor of 1.5-2 fewer brown dwarfs
  - Briceno, Luhman, et al. (2002)



- Higher thermal Jeans mass -> fewer brown dwarfs

Binaries and Multiples



Close Binary Formation

- Opacity limit for fragmentation sets
  - Minimum initial binary separation of ~10 AU
  - 2 x Jeans length when gas becomes non-isothermal
- 7 close binaries (< 10 AU) out of 50 objects
- Close binaries form through combination of
  - Dynamical encounters and exchanges
    - see Tokovinin (2000)
  - Gas accretion
    - e.g. Bate (2000)
  - Interaction with circumbinary and circumtriple discs
    - Pringle (1991); Artymowicz et al. (1991)
- Results published in Bate, Bonnell & Bromm (2002)

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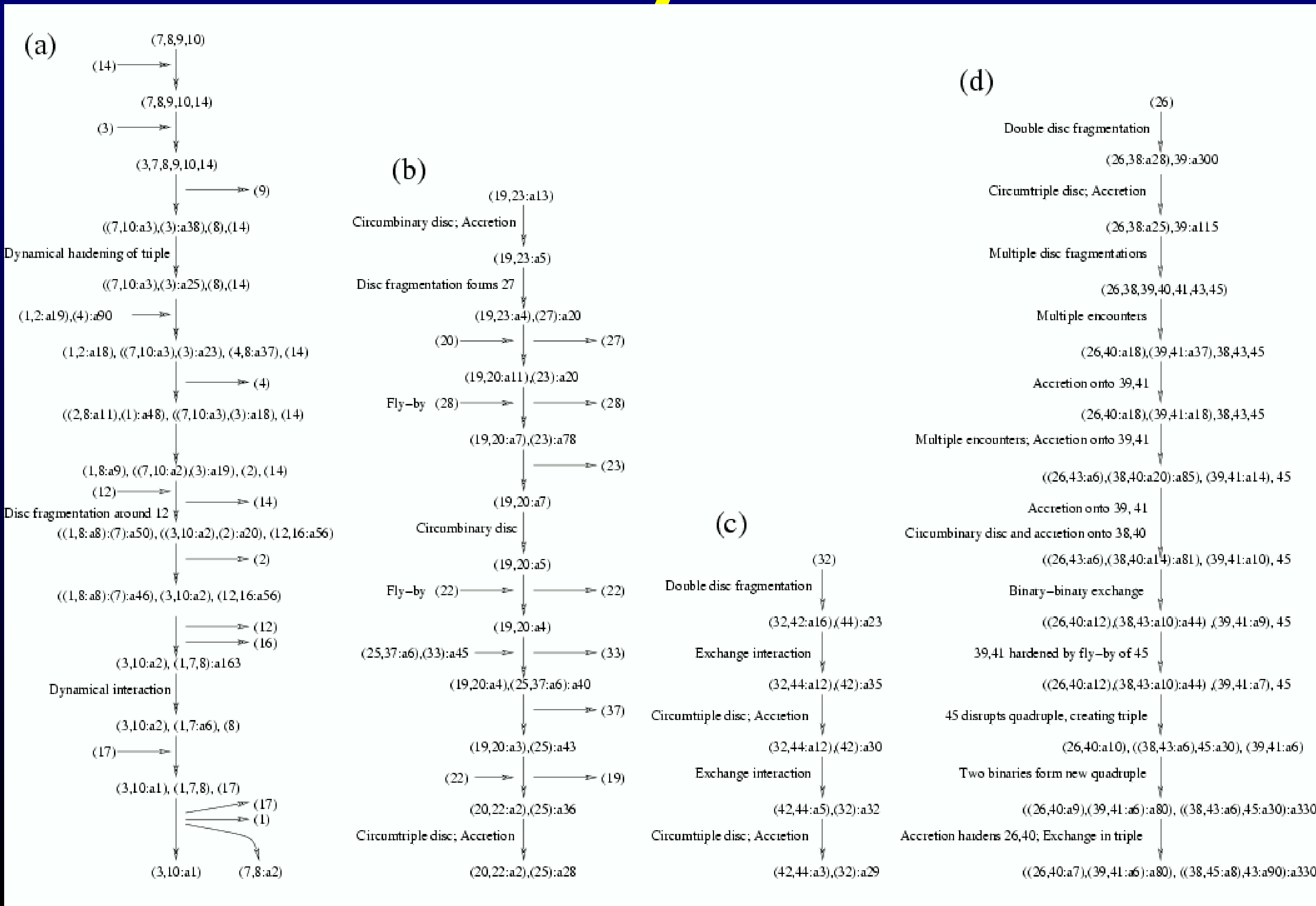
Close Binary Formation



Close Binary Properties

- Close binary frequency: 7/43 = ~16%
  - Duquennoy & Mayor (1991): ~20%
- Frequency dependent on primary mass
  - ~20 brown dwarfs, only one binary brown dwarf
  - 11 stars with $M>0.2\ M_{\odot}$, 5 in close binaries
  - Due to exchange interactions which eject lowest-mass
- Preference for equal mass ratios
  - All have mass ratios $q>0.3$
  - Due to accretion (Bate 2000) + exchange interactions
- 6 of 7 close binaries have wider companions
  - Mayor & Mazeh (1987); Tokovinin (1997, 2000)

Binary Brown Dwarfs

- Calculation 1
  - 1 BBD from ~20 brown dwarfs: 6 AU (acc)
  - Frequency ~5%

- Calculation 2
  - 3 BBD: 2 AU (acc), 21 AU (acc), 66 AU (stable)
  - 2 BD+VLM (<0.09 $M_{\odot}$): 15 AU (acc), 136 AU (stable)
  - Frequency: 5/60 ~8%

- Calculation 3
  - 0 BBD from 18 brown dwarfs

- Observations
  - Observed frequency ~15%
    - Reid et al. 2001; Close et al. 2002,2003; Bouy et al. 2003; Burgasser et al. 2003; Gizis et al. 2003; Martin et al. 2003
  - Almost all binary brown dwarfs close (<15 AU)
    - Luhman (2004): Wide (200 AU) binary brown dwarf?

Velocity Dispersion

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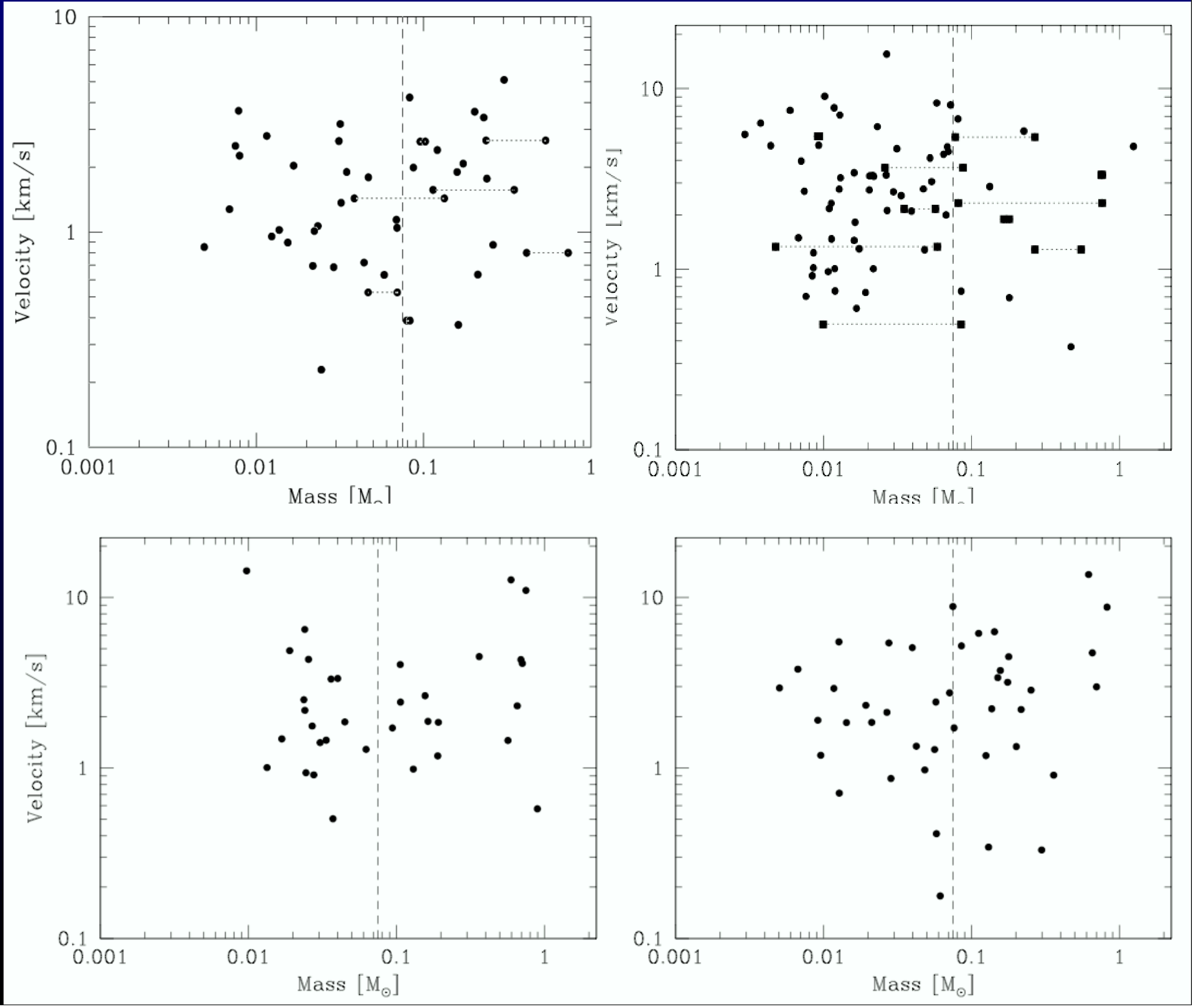
Stars & brown dwarfs ejected

Vel. Disp. Independent of
- **mass**
- **binarity**

3-D RMS vel. disp.
- **2.1 km/s**
- **4.3 km/s**
- **4.6 km/s**
- **4.1 km/s**



Ophiuchus Main Cloud

Greyscale

550 M_o of gas

(Wilking & Lada 1983)

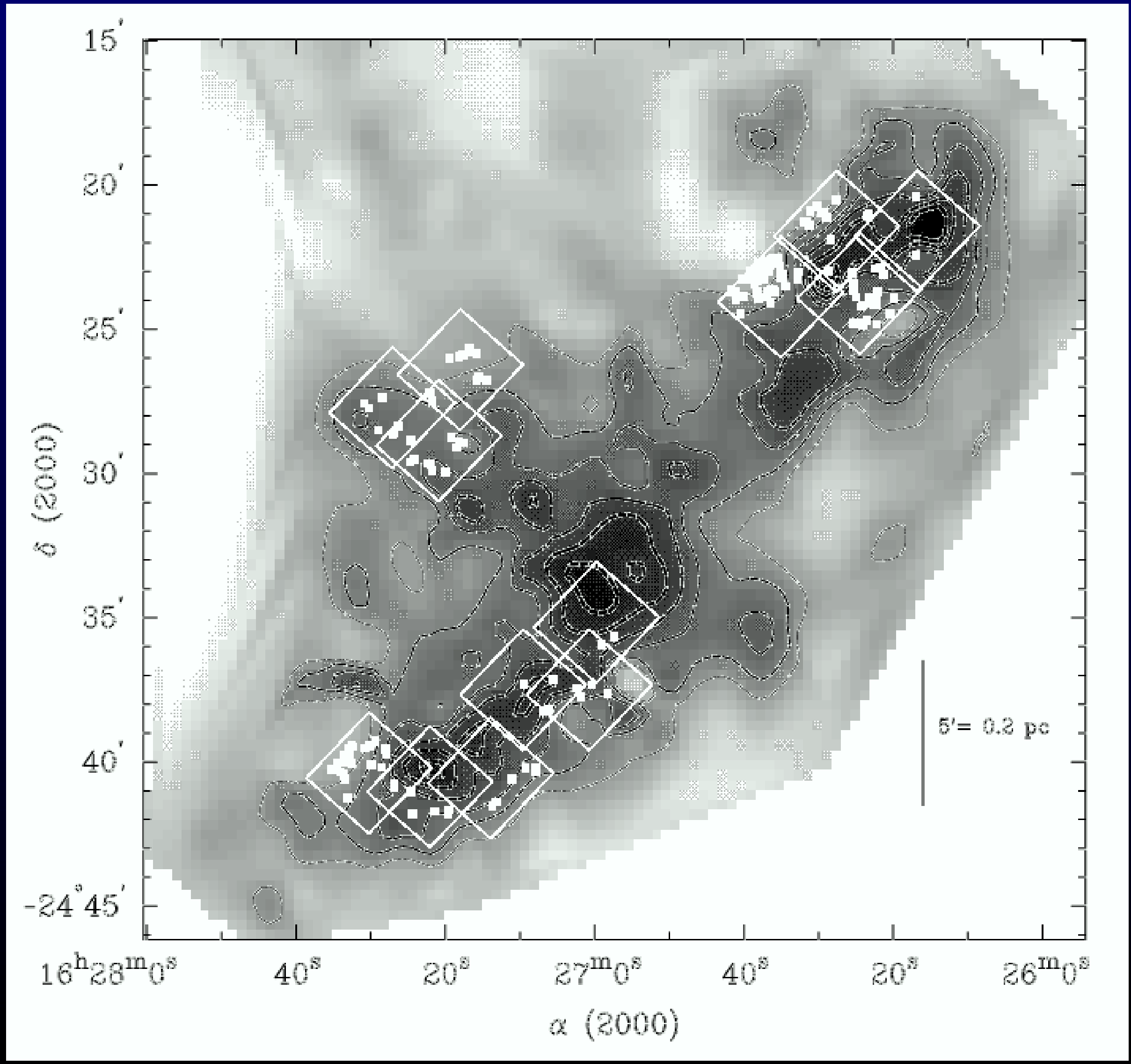
Fields

HST young stars

(Allen et al 2001)

Perhaps the young stars formed in the dense cores and were subsequently ejected?

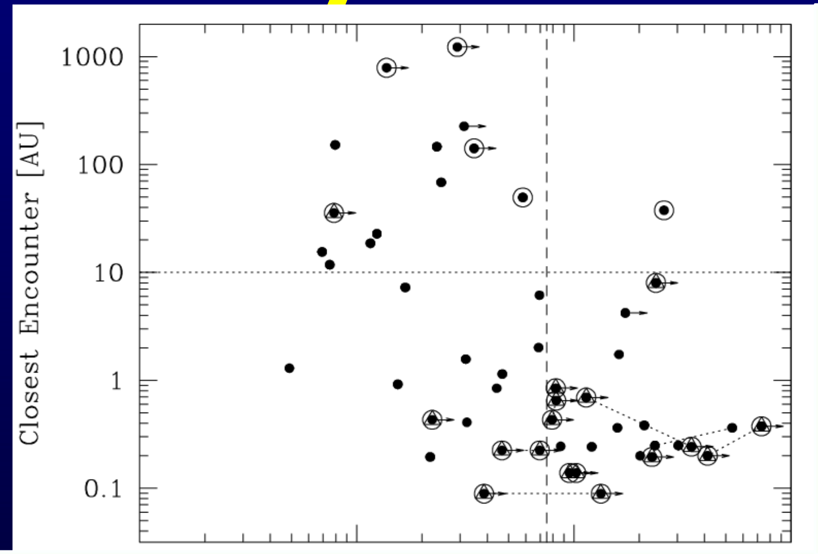
- 2 km/s = 0.2 pc in 10^5 yrs
- Proper motions?

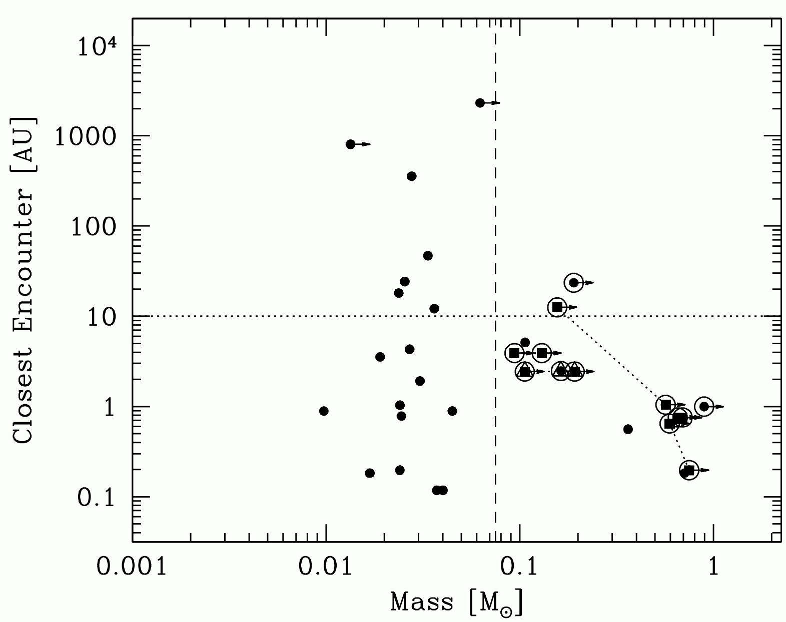


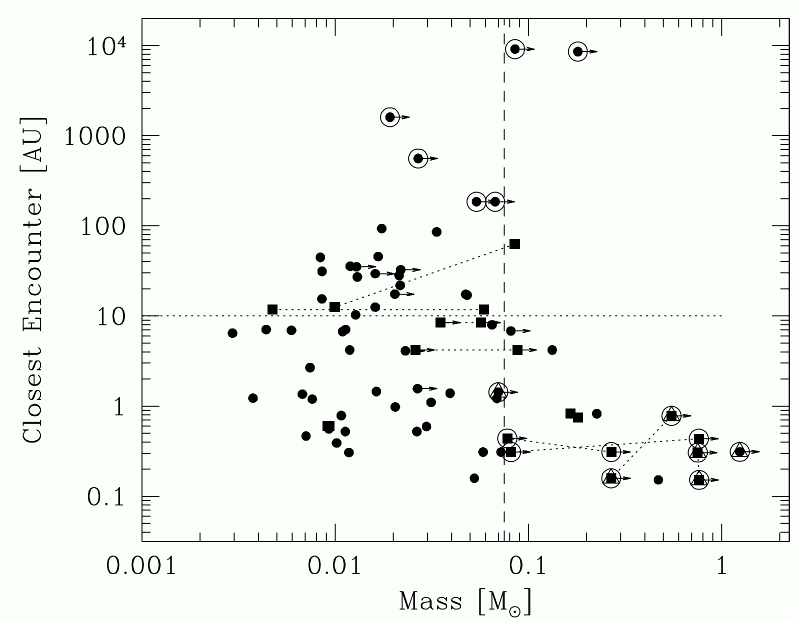
Sizes of Protoplanetary Discs

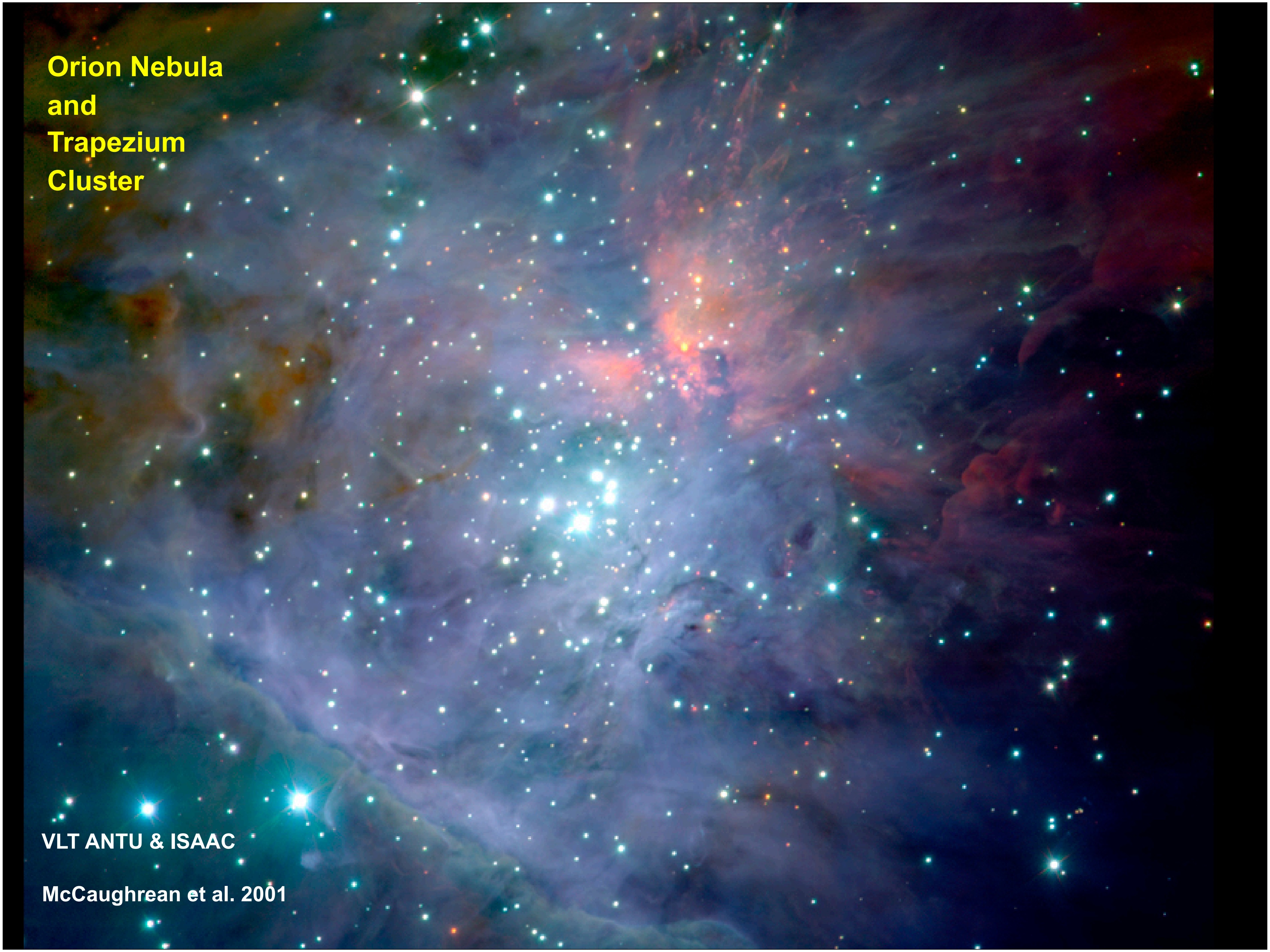
- Star formation highly dynamic
  - Many discs truncated by encounters
  - Few resolved discs (>10 AU radius) are left
    - Especially in the densed simulation

- Is this realistic?

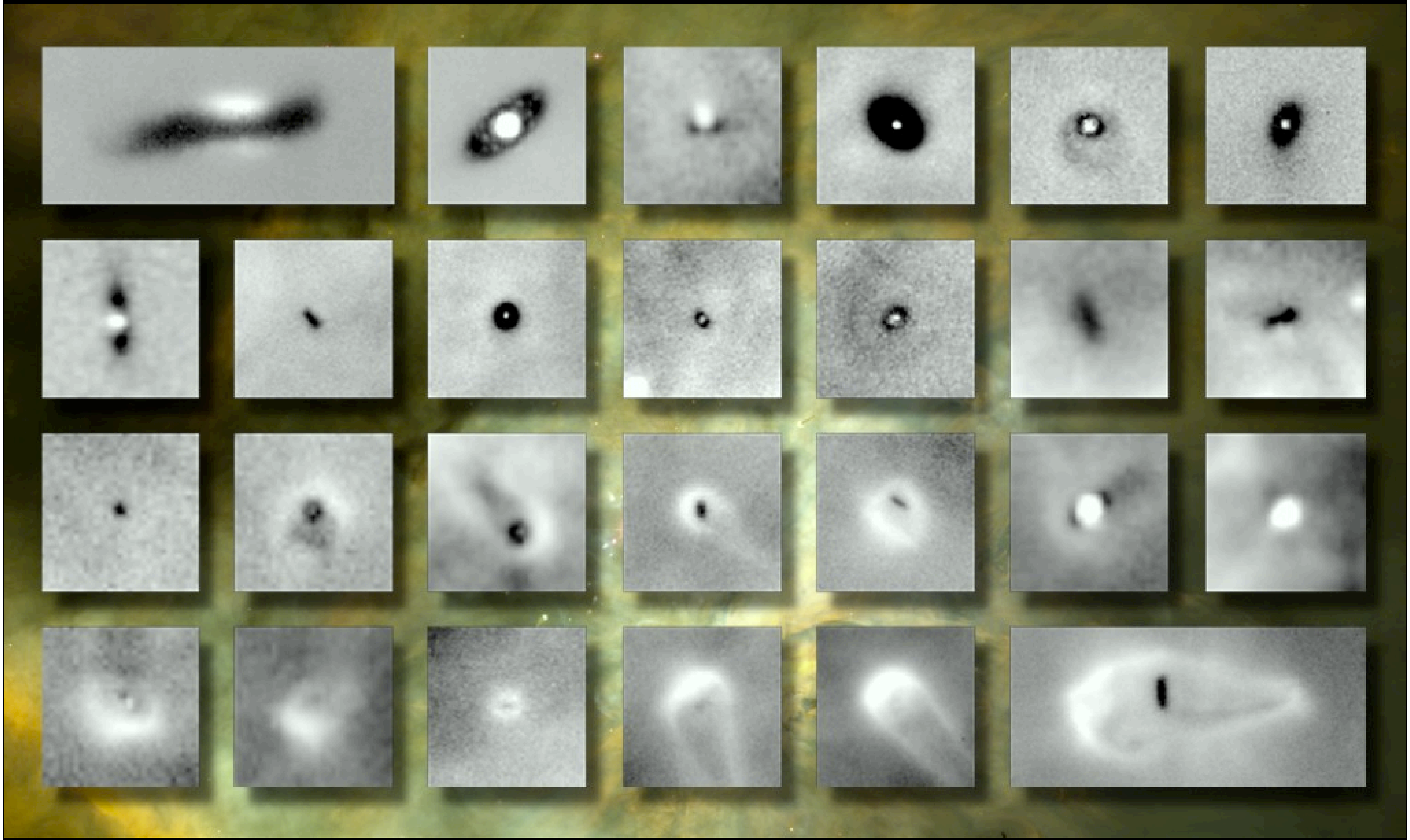







Orion Nebula
and
Trapezium
Cluster
VLT ANTU & ISAAC
McCaughrean et al. 2001


HST (O'Dell and McCaughrean)



Courtesy of Mark McCaughrean, Exeter

Discs in the Trapezium Cluster

- HST resolves silhouette discs to ~40 AU radius
  - Resolves 41 discs from ~350 stars
  - Only ~10% of stars have discs >40 AU radius
    - Rodmann 2002
- ~80% stars have IR excess indicative of discs
  - Lada et al. 2000
- Implies most discs have radii < 40 AU
  - Serious implications for planet formation

Conclusions

- Can perform simulations that form statistically significant numbers of stars
  - Much physics still missing or simplified
- Dynamical (N-body) interactions crucial for determining stellar properties
- Initial mass function (IMF) originates from interplay between accretion/ejection
  - Stars and brown dwarfs form the same way
  - Brown dwarfs are those objects ejected sooner after they form
- Close binaries form (in part) through dynamical interactions
  - Exchange interactions lead to
    - Higher binary frequency for more massive objects
    - Mass ratios near unity for close binaries
- Discs are truncated by dynamical interactions
  - May inhibit the formation of large planetary systems in dense environments