The dependence of star cluster formation on initial conditions

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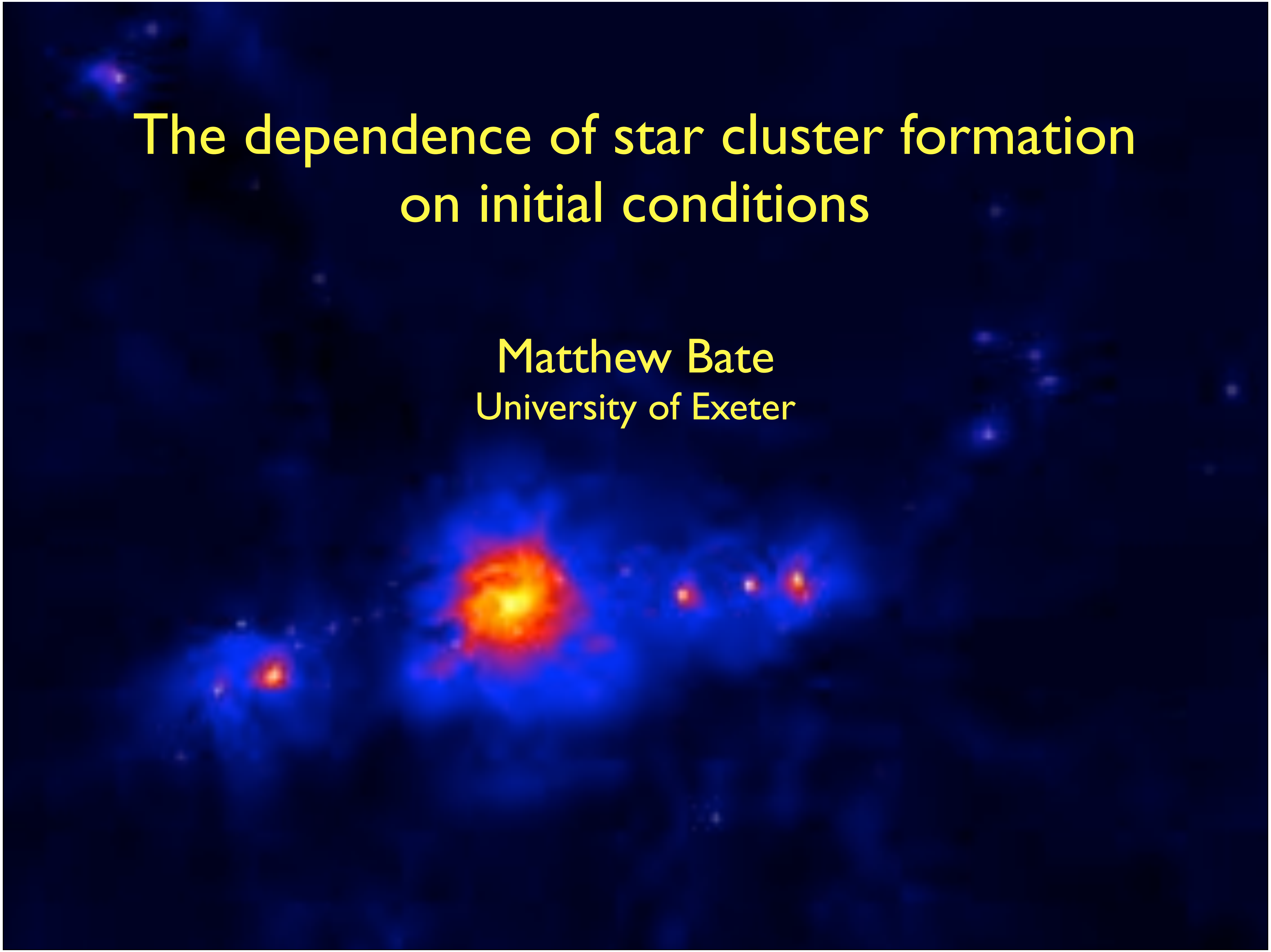


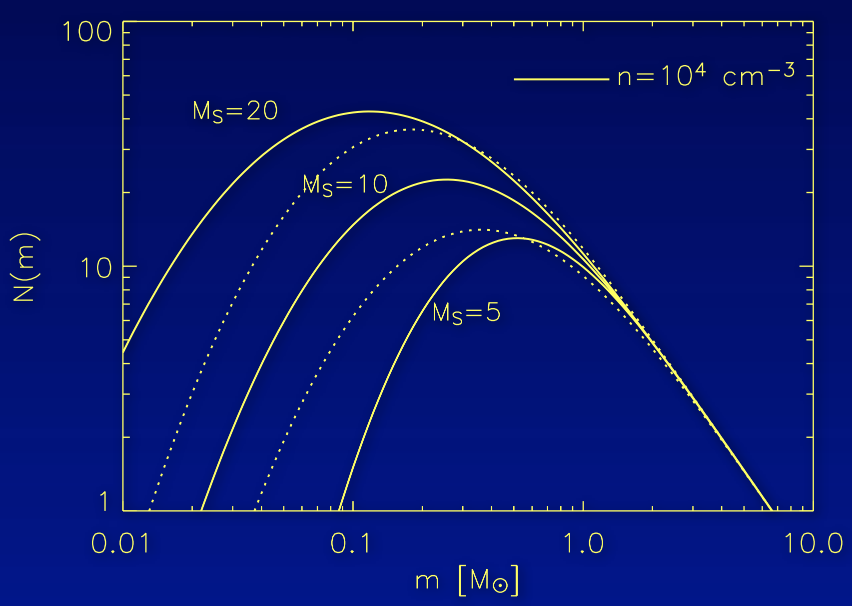
Stellar properties do not greatly depend on initial conditions

- Little evidence for variation of the Galactic IMF
  - Bastian, Covey & Meyer (2010)

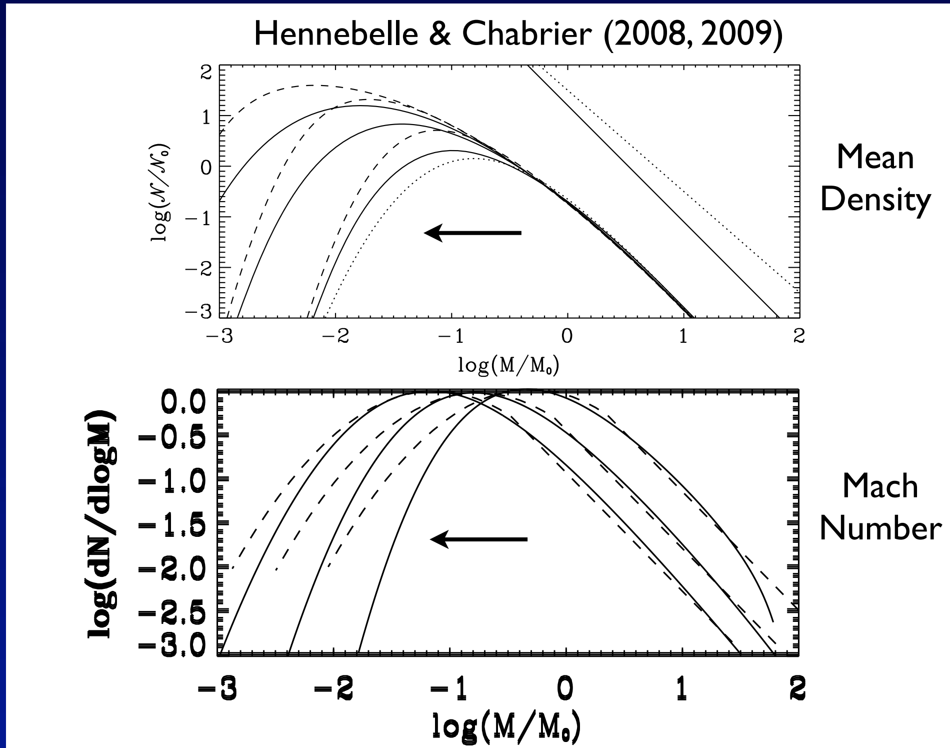
- Little evidence for systematic variations of multiplicity properties
  - Multiplicity of wide systems tends to be
    - Lower at old ages and/or in dense clusters (Duchene & Kraus (2013) and references therein)
    - Not obviously dependent on stellar density - Taurus exception (King et al. 2012a)
  - Separation distributions
    - Evidence for truncation in dense clusters (e.g. Scally, Clarke & McCaughrean 1999; Reipurth et al. 2007)
    - But indistinguishable over at most separations in different regions (King et al. 2012b)

(Turbulent) semi-analytical theories of IMF

- Tend to predict that the IMF depends on
  - Mean Jeans mass (i.e. density and temperature)
  - Turbulent Mach number (more turbulent produces broader range of stellar masses)
  - Padoan & Nordlund (2002,2004); Hennebelle & Chabrier (2008, 2009,2013); Hopkins (2012)



Padoan & Nordlund (2004)

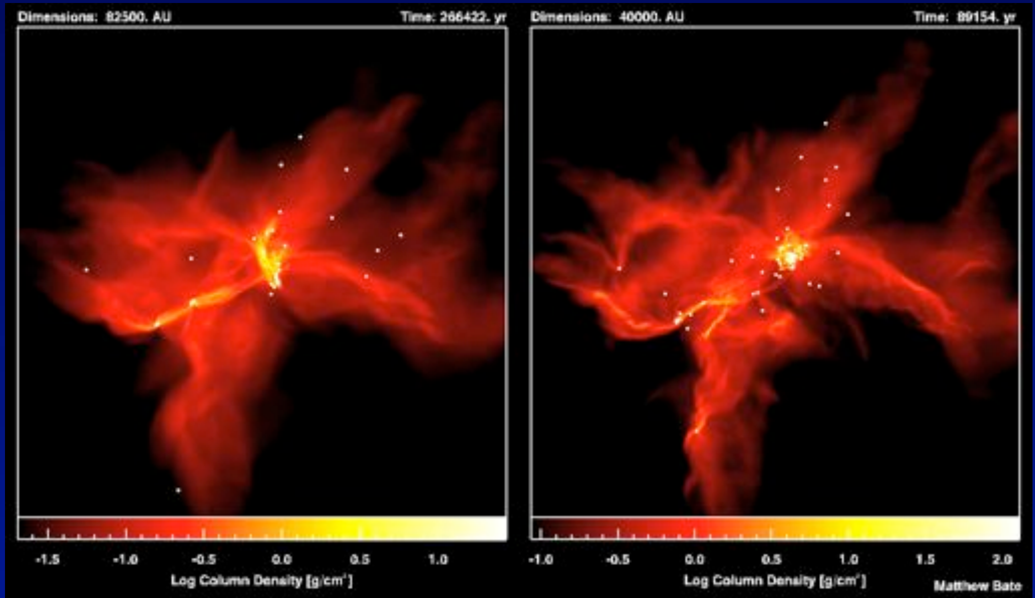


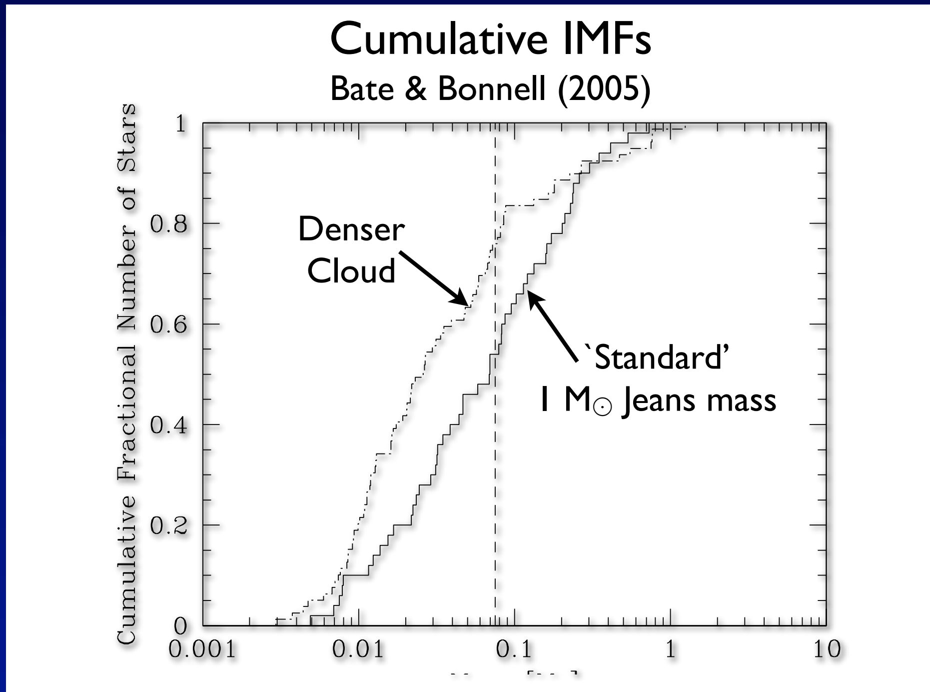
Numerical simulations

- Simplest hydrodynamical simulations also predict an IMF with a characteristic stellar mass than scales with the typical Jeans mass
  - Include gravity, hydrodynamics and a simple equation of state
  - Klessen, Burkert & Bate (1998); Bate & Bonnell (2005); Bate (2005, 2009c)
  - Jappsen et al. (2005); Bonnell, Clarke & Bate (2006)

Typical molecular cloud (Bate et al. 2003)
Jeans mass 1 $M_\odot$, Opacity limit 3 M_J, $P(k) \propto k^{-4}$

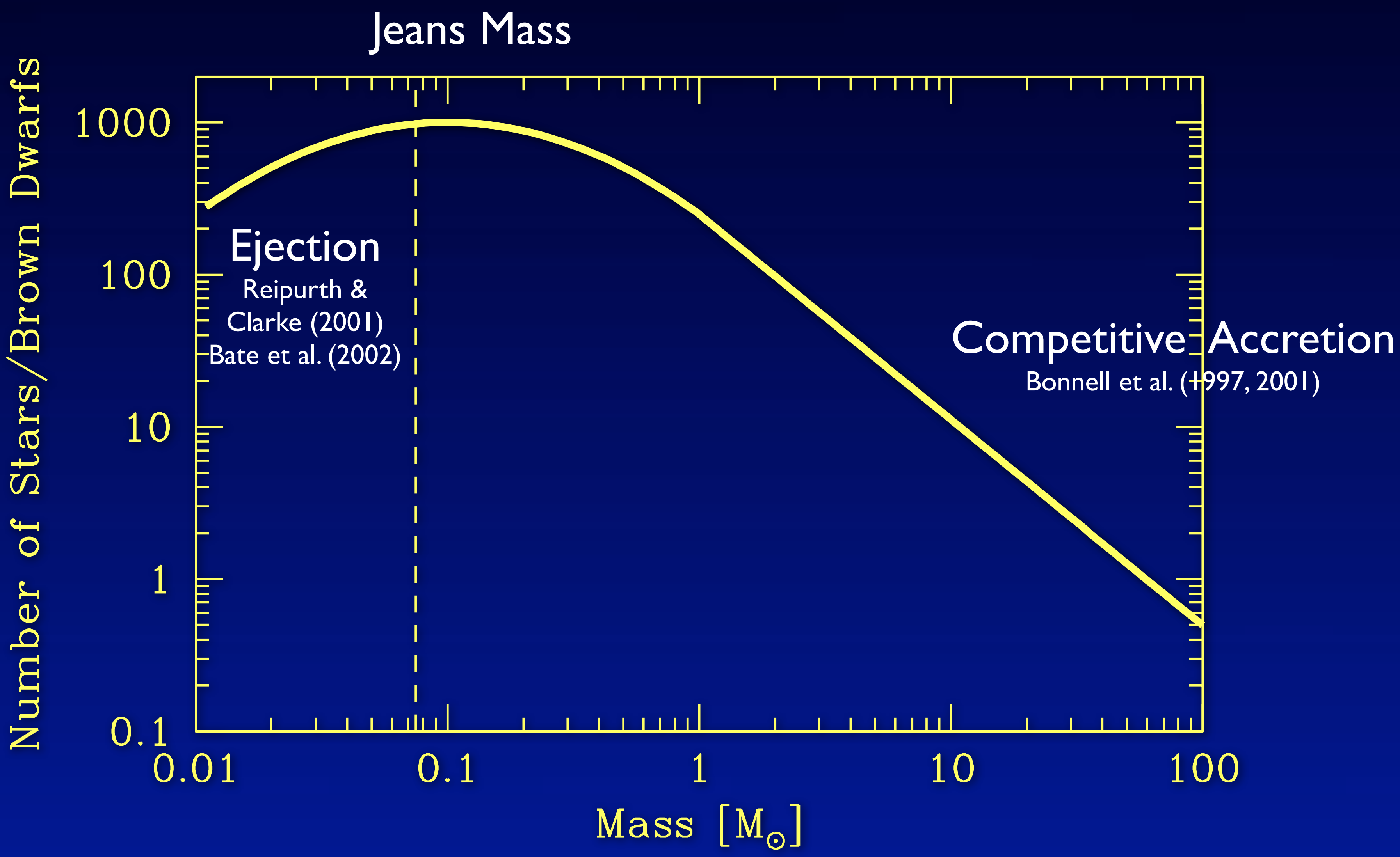
Denser cloud (Bate & Bonnell 2005)
Jeans mass 1/3 $M_\odot$





Competitive accretion the IMF

Competition between accretion and ejection (Bate & Bonnell 2005)



Why do observed stellar properties not seem to depend on initial conditions?

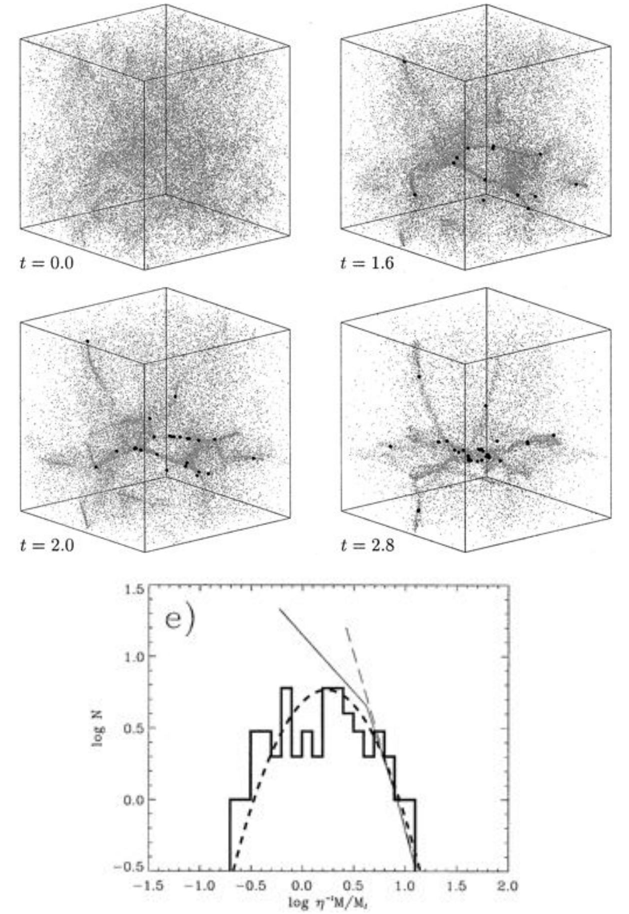
- Either initial conditions do not vary much, or compensate each other
  - Elmegreen, Klessen & Wilson (2008) - actual typical Jeans masses depend weakly on environment
  - Hennebelle & Chabrier (2008, 2009) - appealing to Larson's laws, when Jeans mass increases, Mach number increases so may offset each other
  - Hennebelle (2012) - more detailed compensation between density, velocity dispersion and temperature
- Or star formation process may be self-regulating
  - Physics is must be more complicated than just gravity + hydrodynamics + simple equation of state
    - e.g. Protostellar/stellar feedback, Magnetic fields

Self-regulation via protostellar interactions

- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises may not be so important (Bonnell et al. 1997-2001; Klessen et al. 1998-2001; Bate 2009c)
- Dissipative dynamical interactions between accreting protostars
  - Gives an IMF-like mass distribution (competitive accretion), but depends on global Jeans mass (Bate & Bonnell 2005; Jappsen et al. 2005, Bonnell et al. 2006)
  - Leads to observed multiplicity fractions & properties of multiple systems (Bate 2009a, 2012)
- Radiative interactions (feedback) between accreting protostars
  - Enables the production of an (almost) invariant IMF (Bate 2009b)
- All three together can reproduce observed stellar properties
  - Bate (2012)

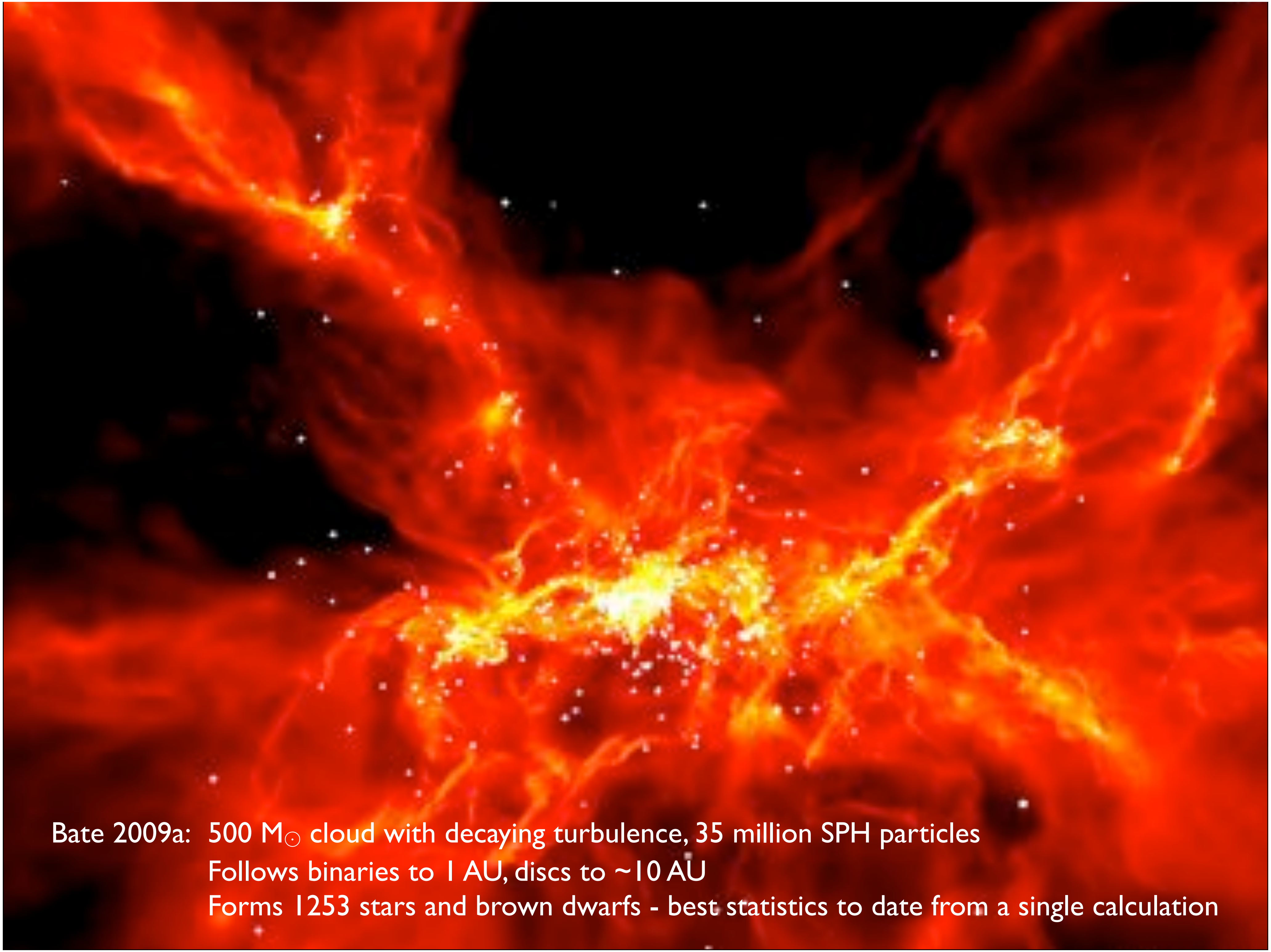
When does competitive accretion operate?

- Protostellar seeds in a (uniform) gas reservoir
  - Bonnell et al. (1997, 2001)
- Nonlinearly structured gas (no initial velocities)
  - Klessen et al. (1998); Klessen & Burkert (2000, 2001)
- Strong turbulence (both decaying and large-scale driven turbulence)
  - Klessen 2001; Bate et al. (2003-2005); Bonnell et al. (2003-2010); Bate (2009-2012)



Klessen, Burkert & Bate (1998)

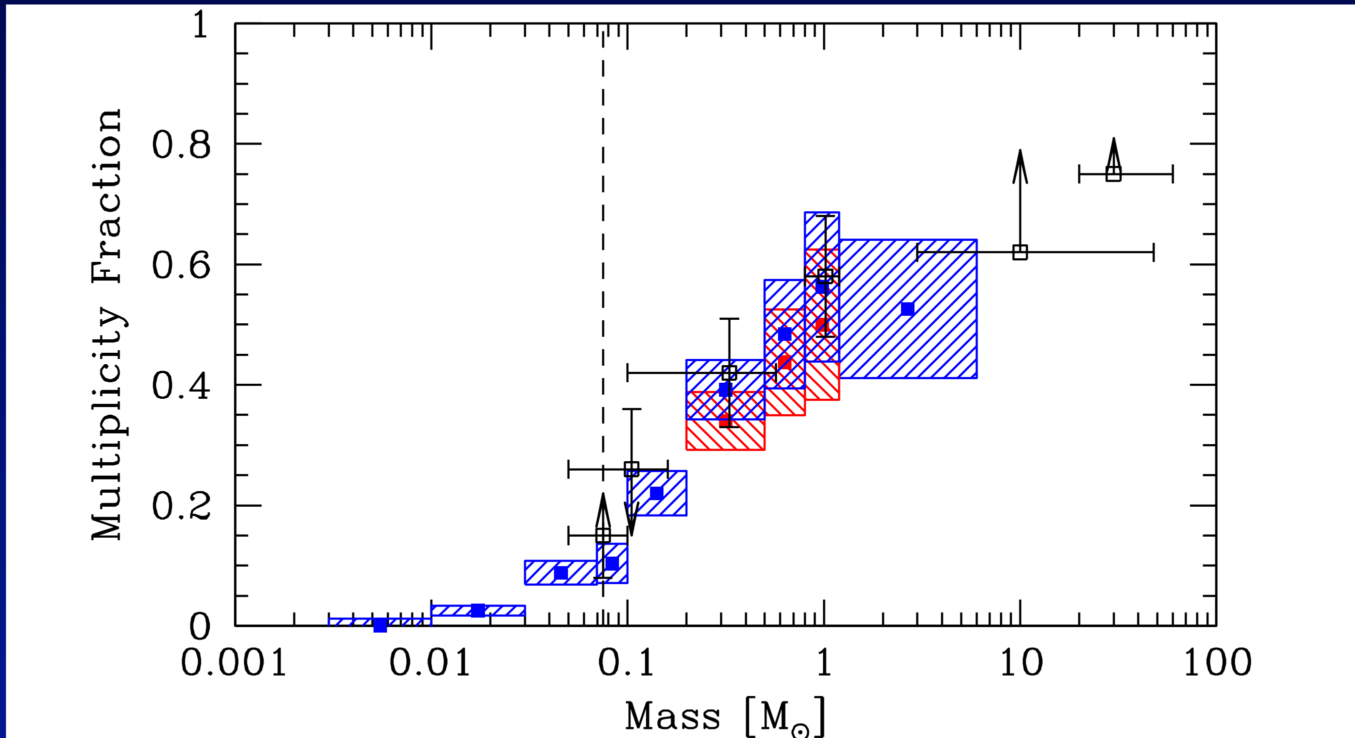
- What doesn't work ?
  - No structure or turbulence (e.g. uniform sphere)
  - Small-scale turbulent driving (Klessen 2001)
  - Centrally-condensed initial conditions resist fragmentation (Girichidis et al. 2011), especially with radiative feedback (Krumholz et al. 2011)



Bate 2009a: $500\ M_\odot$ cloud with decaying turbulence, 35 million SPH particles
Follows binaries to 1 AU, discs to ~10 AU
Forms 1253 stars and brown dwarfs - best statistics to date from a single calculation

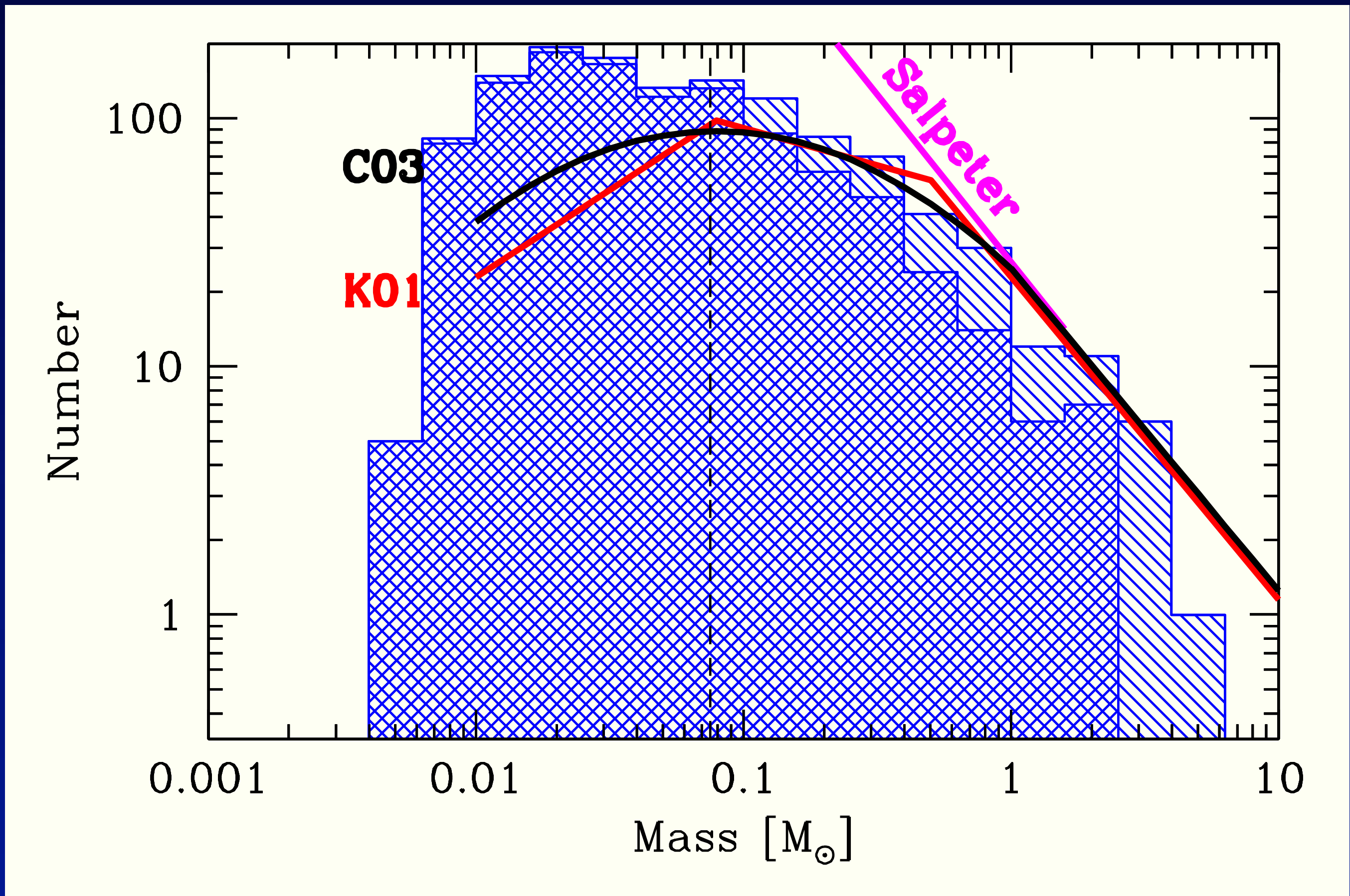
Multiplicity as a Function of Primary Mass

- Dissipative N-body interactions naturally produce a multiplicity that increases with primary mass
  - In binary-single or multiple-multiple encounters, low-mass objects tend to loose companions and high-mass objects tend to retain or gain
- Multiplicity fraction = (B+T+Q) / (S+B+T+Q)
  - Observations: Close et al. 2003; Basri & Reiners 2006; Fisher & Marcy 1992; Duquennoy & Mayor 1991; Preibisch et al. 1999; Mason et al. 1998



Stellar Mass Distribution

- Competitive accretion/ejection gives
  - Salpeter-type slope at high-mass end
  - Low-mass turn over
- >6 times as many brown dwarfs as a typical star-forming region
  - Not due to sink particle approximation - results almost identical for different sink parameters



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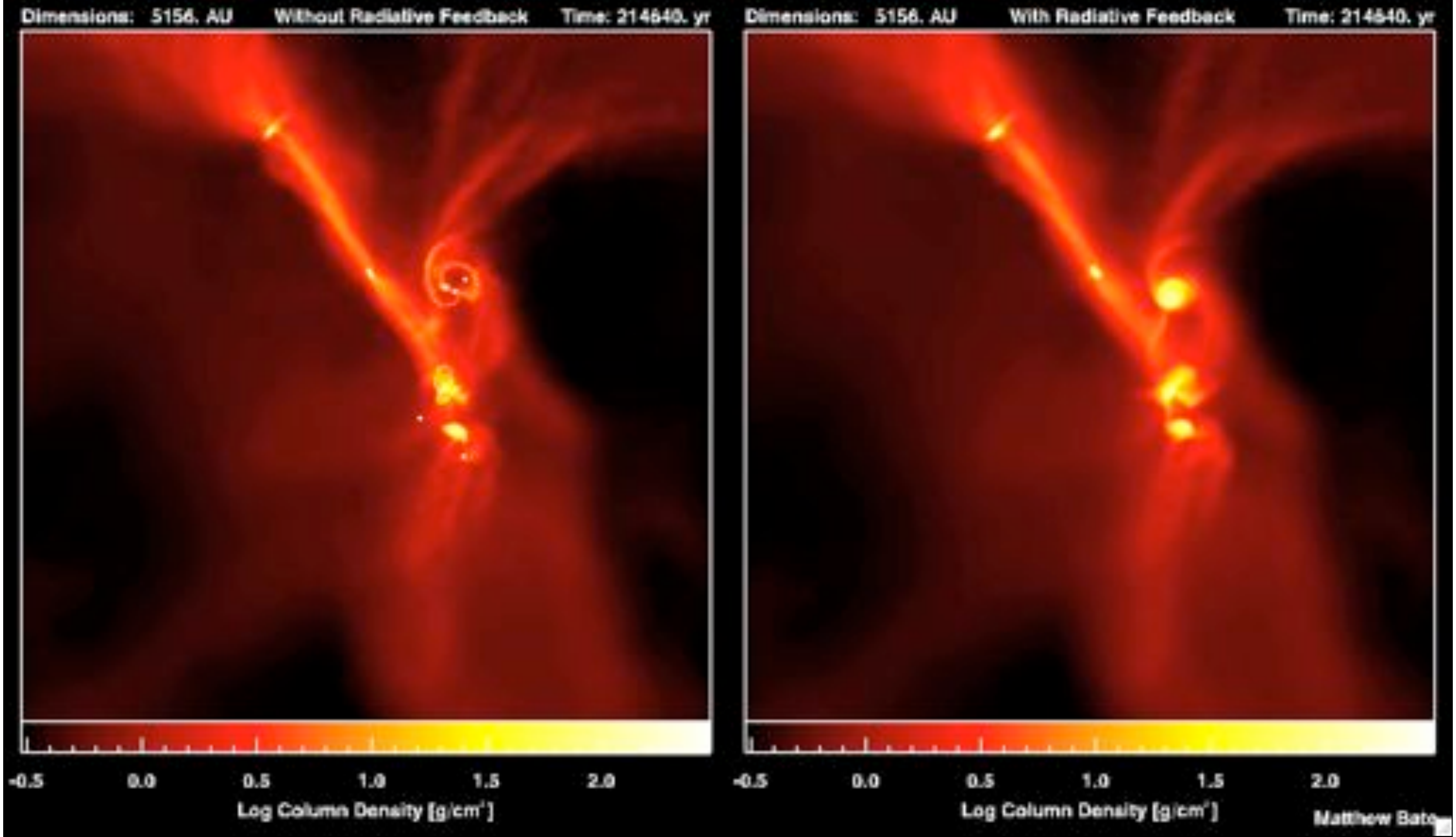
BBB2003: Typical molecular cloud

Jeans mass 1 $M_\odot$, Opacity limit 3 M_J, $P(k) \propto k^{-4}$

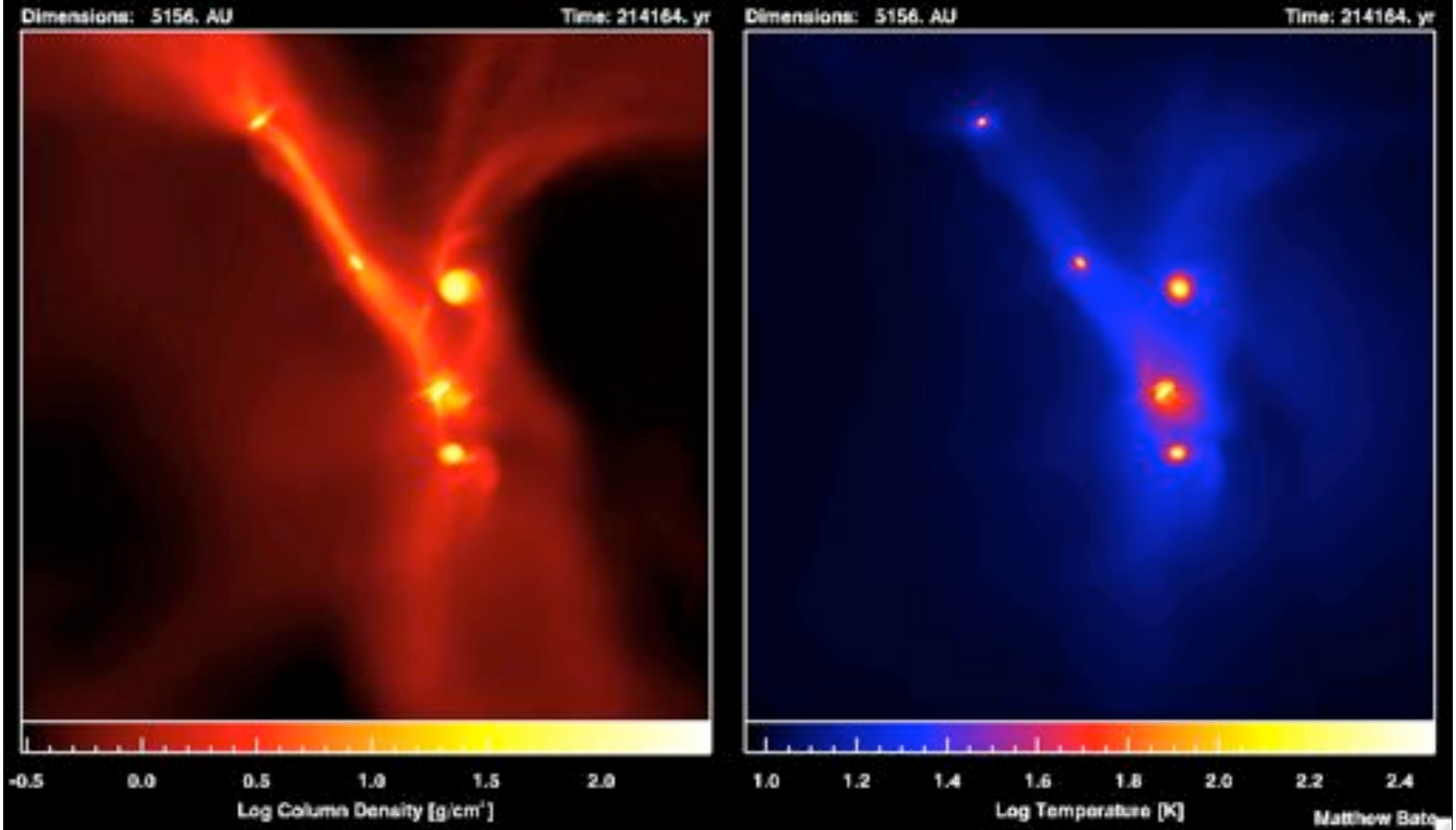
B2009b (BBB2003, but with Radiative Transfer)



http://www.astro.ex.ac.uk/people/mbate

Bate 2009b: Typical cloud: Jeans mass 1 $M_\odot$, $P(k) \propto k^{-4}$ with Radiative Transfer

Log Column Density | Mass weight temperature (Log 9-100 K)



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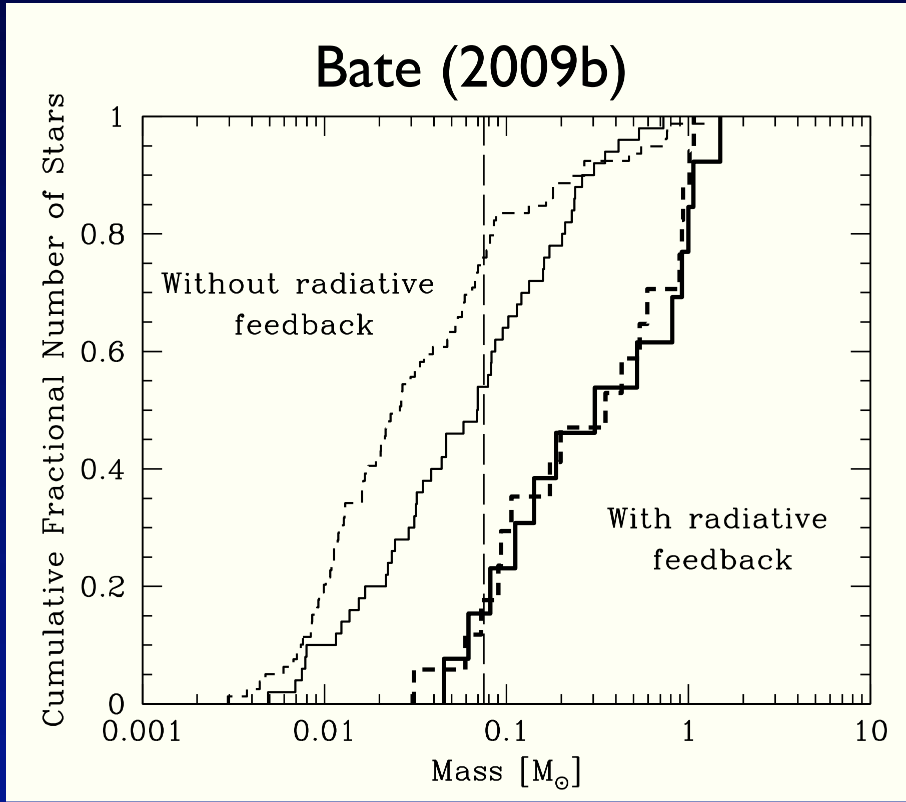
Radiative Feedback and the IMF

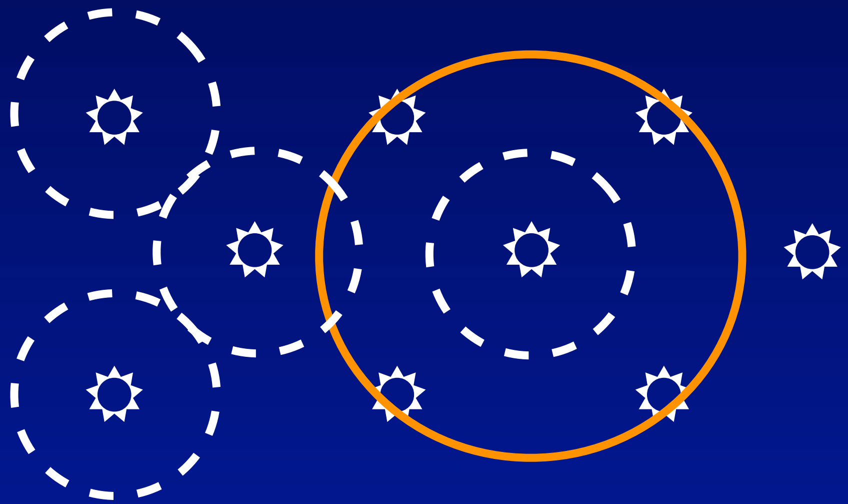
- Radiative feedback reduces the number of objects by factors of 3-5
- Radiative feedback brings the star to brown dwarf ratio in line with observations
  - Observations suggest a ratio of 5 ± 2
    - Chabrier 2003; Greissl et al. 2007; Luhman 2007; Thies & Kroupa 2007,2008; Andersen et al. 2008
  - Small simulations: 25:5 ~ 5
- Furthermore, dependence of the IMF cloud density is removed
  - K-S test on the two IMFs with radiative shows them to be indistinguishable



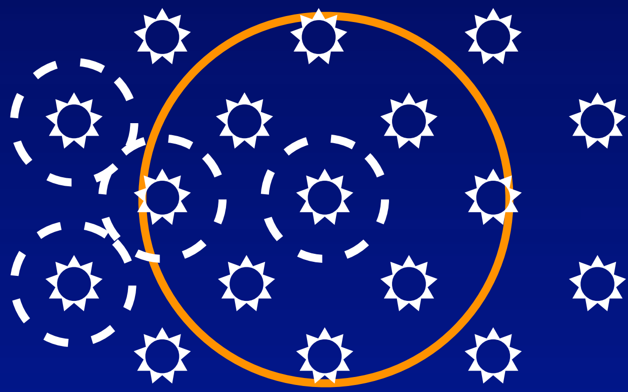
The Apparent Invariance of the IMF

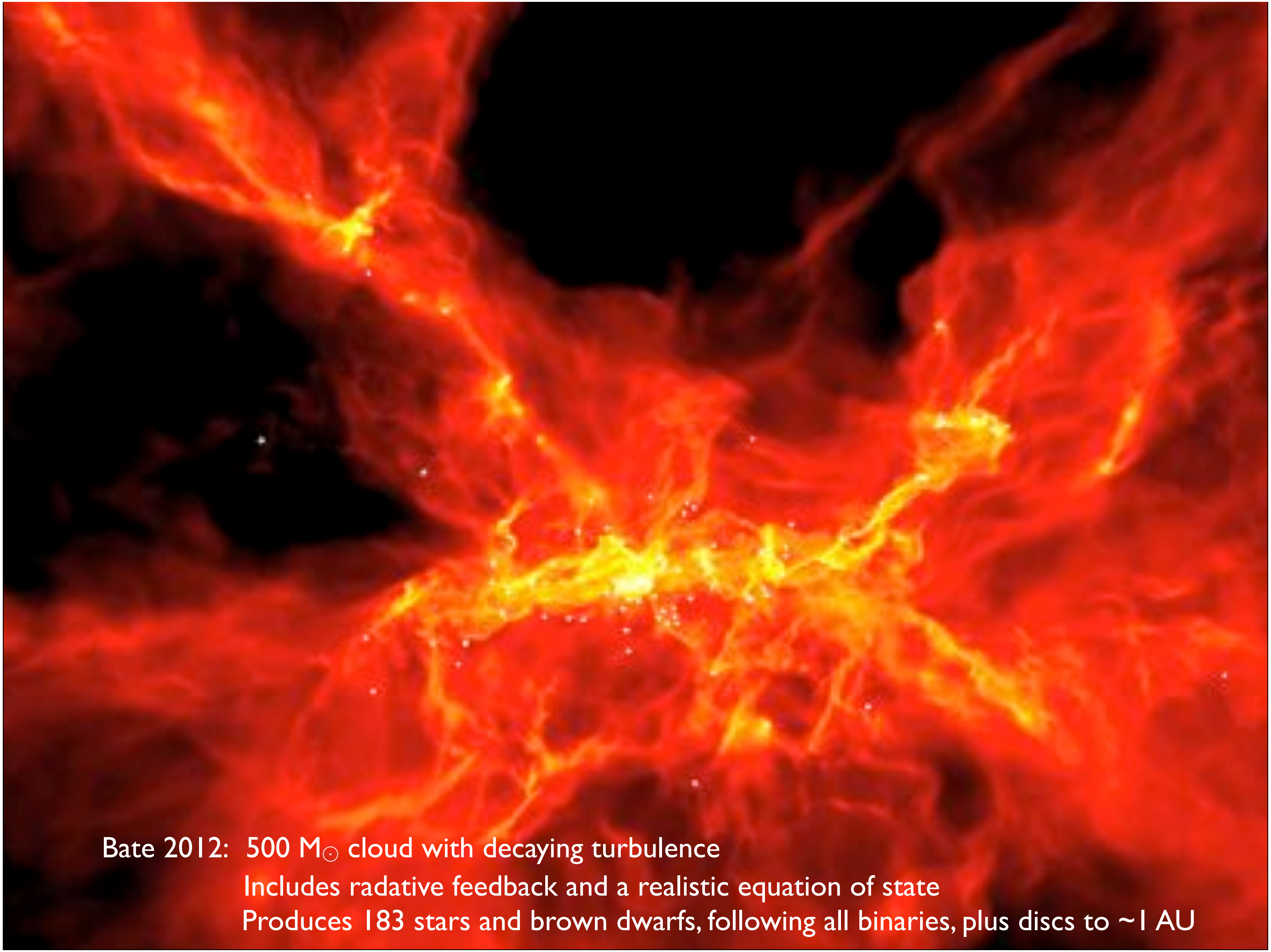
- Bate 2009b
  - In the absence of stellar feedback, cloud fragments into objects separated by Jeans length
  - Jeans length and Jeans mass *smaller* for denser clouds
  - But, heating of the gas surrounding a newly-formed protostar inhibits nearby fragmentation
  - Effectively increases the effective Jeans length and Jeans mass
  - Effective Jeans length and Jeans mass increases *by a larger fraction* in denser clouds
  - This greater fractional increase largely offsets the natural decrease in Jeans mass in denser clouds
  - Bate (2009b) show that this effective Jeans mass depends very weakly on cloud density

Low-density Cloud



Higher-density Cloud





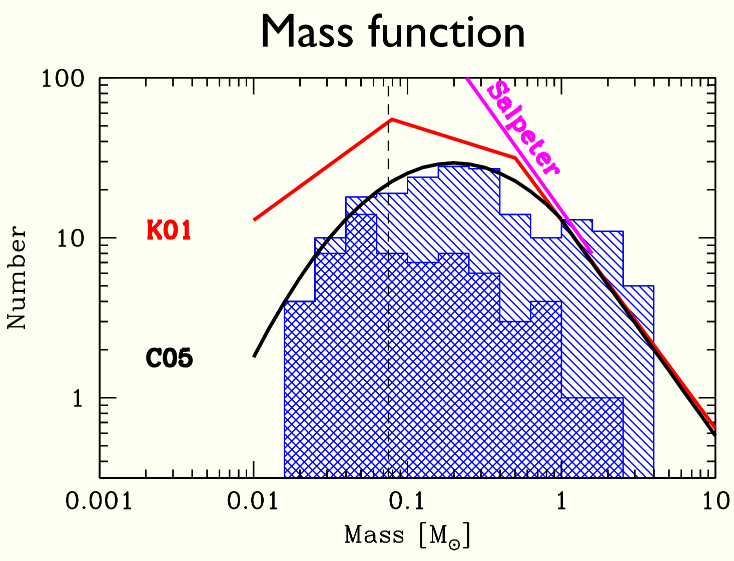
Bate 2012: 500 $M_\odot$ cloud with decaying turbulence

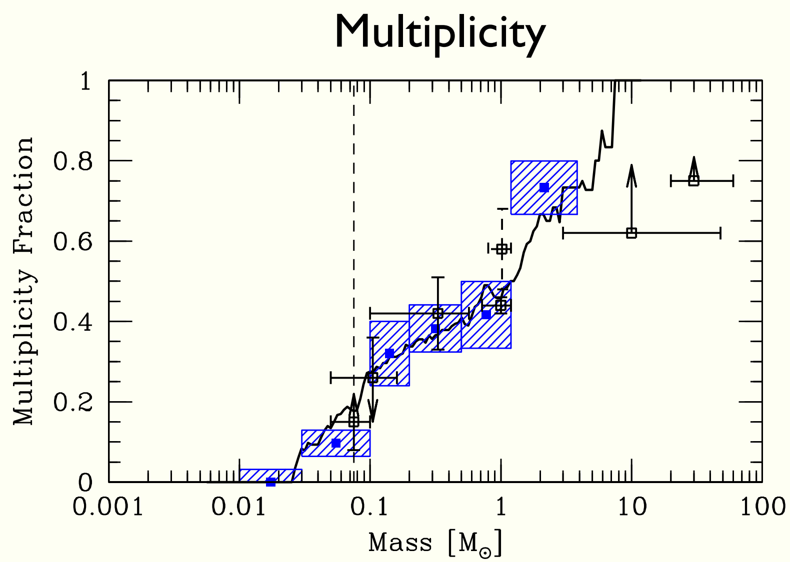
Includes radative feedback and a realistic equation of state

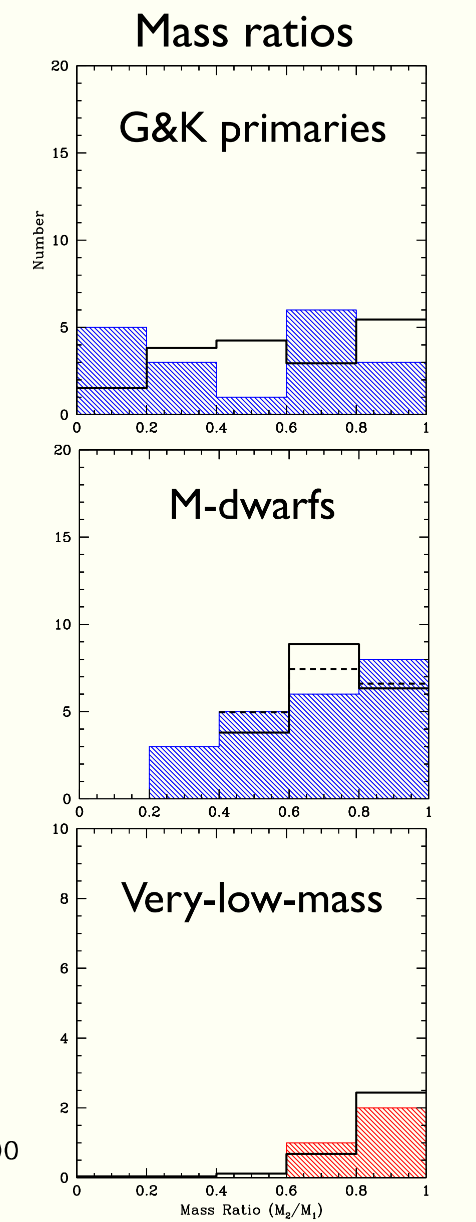
Produces 183 stars and brown dwarfs, following all binaries, plus discs to ~1 AU

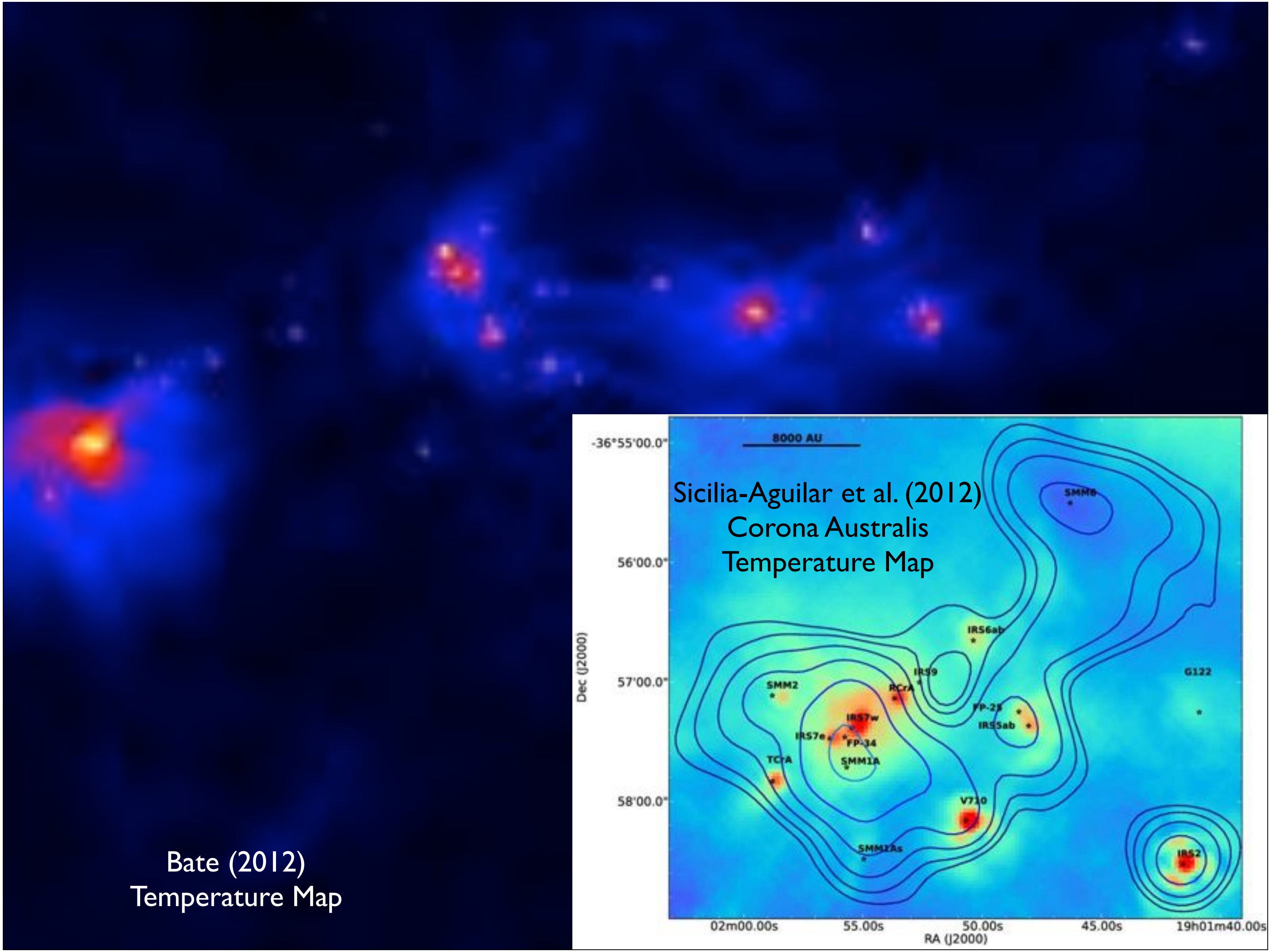
First Large-Scale Calculation Consistent with Wide Range of Observed Stellar Properties

- Mass function consistent with Chabrier (2005)
  - Stars to brown dwarf ratio: N(1.0-0.08)/N(0.03-0.08) = 117/31 = 3.8
- Multiplicity consistent with field
- Binary mass ratios consistent with field



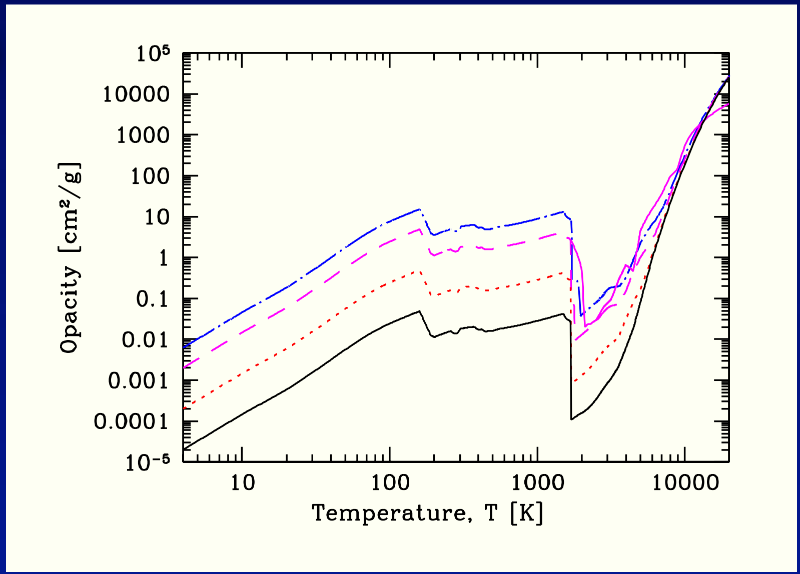


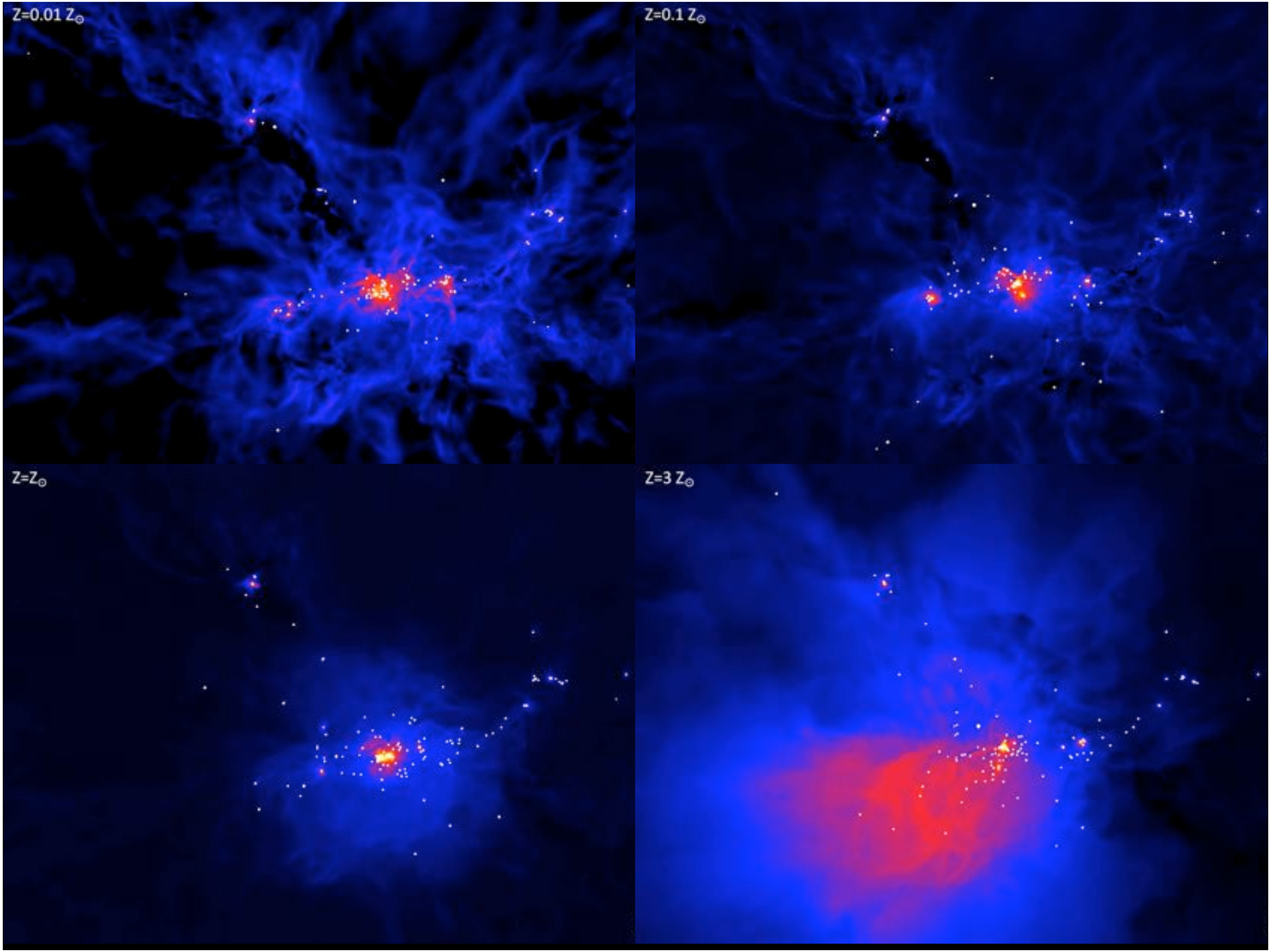



Bate (2012)
Temperature Map
Sicilia-Aguilar et al. (2012)
Corona Australis
Temperature Map
8000 AU
-36°55'00.0"
56'00.0"
57'00.0"
58'00.0"
Dec (J2000)
02m00.00s
55.00s
50.00s
45.00s
19h01m40.00s
RA (J2000)
SMM6
IRS6ab
IRS9
G122
SMM2
RCrA
IRS7w
FP-25
IRS5ab
IRS7e
FP-34
TCrA
SMM1A
V710
SMM1As
IRS2

Dependence of Stellar Properties on Metallicity: Opacity

- Bate (2014) repeated Bate (2012), but with opacities for 3 different \`metallicities'
  - Use opacities corresponding to metallicities Z=0.01 $Z_\odot$,0.1 $Z_\odot$, $Z_\odot$, and 3 $Z_\odot$
  - Does NOT take into account all of the effects of reduced metallicities
    - Assumes dust cooling still dominates
    - Breaks down as gas and dust temperatures decouple
  - Gas opacities from Ferguson et al. (2005)
  - Each calculation produces 170 - 200 stars (733 total)
    - Look for variation of stellar properties

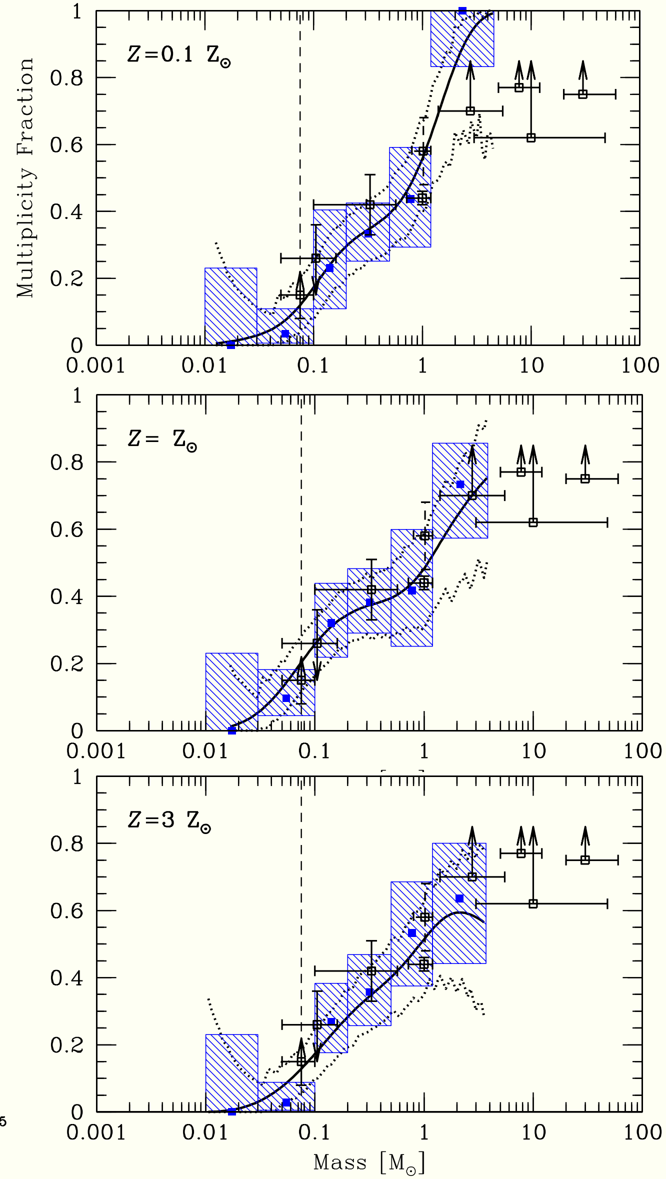



Z=0.01 Z⊙
Z=0.1 Z⊙
Z=Z⊙
Z=3 Z⊙

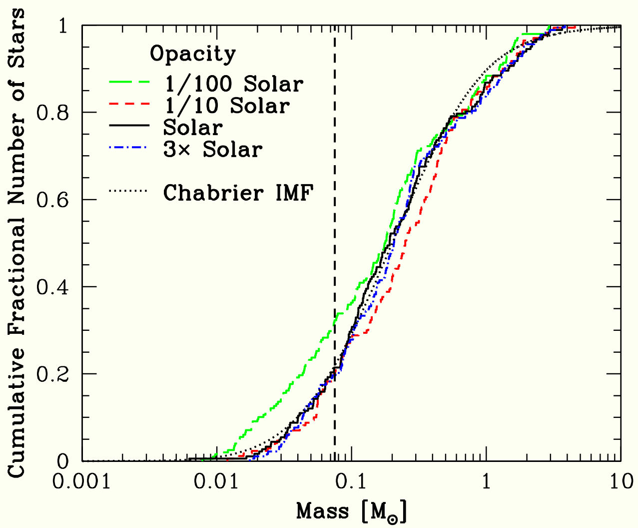
Dependence of Stellar Properties on Opacity

- No significant dependence of any stellar property
  - Despite varying opacity by a factor of 300
- IMFs consistent with Chabrier (2005)
- Multiplicity is a strong function of primary mass
  - In good agreement with observational surveys

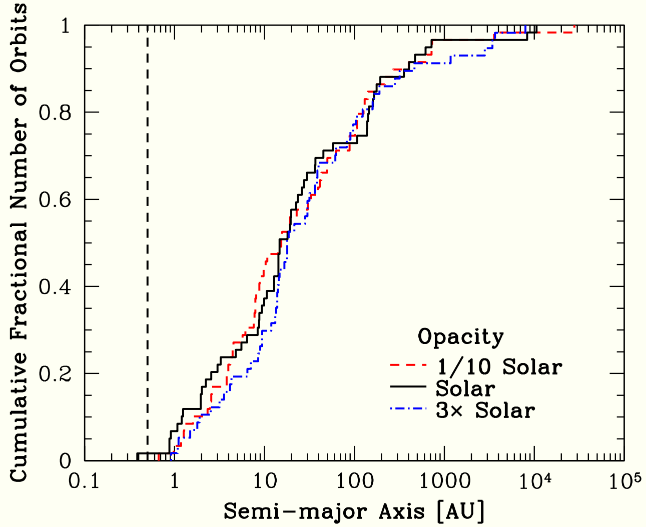
Multiplicity vs Primary Mass



Cumulative IMFs



Cumulative Separation Dist.



Stellar Properties and Opacity

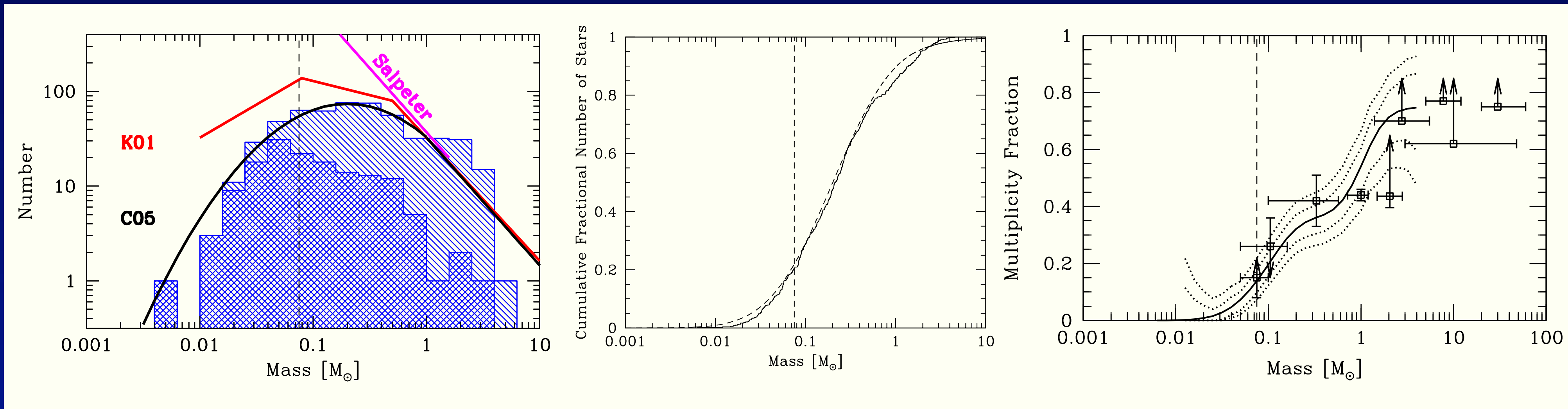
- If IMF is so dependent on radiative feedback, why are stellar properties so independent of opacity?
- Temperature of dust around a protostar (optically thin)

$$T \propto L_*^{1/4} r^{-2/(4+\beta)}$$

  - where β depends on absorption properties of dust (e.g. Ivezic & Elitzur 1997)
- If gas is
  - Thermally coupled to the dust (as assumed in Bate 2014), and
  - Infrared radiation is optically thin (valid or marginally valid for Bate 2014)
- Then, gas temperature around protostars does not depend on magnitude of opacity
  - i.e. Effects of radiative feedback should be similar

Overall Stellar Properties

- Since the individual IMFs and multiplicities are indistinguishable we can combine the results from the three calculations with the highest opacities (535 stars and brown dwarfs)
  - Bate (2014): Best numerically-determined stellar properties to date
  - The IMF and multiplicity as a function of primary mass are indistinguishable from observations
  - Ratio of stars to brown dwarfs ~3.8:1 (c.f. Andersen et al. 2008: 5 ± 2)

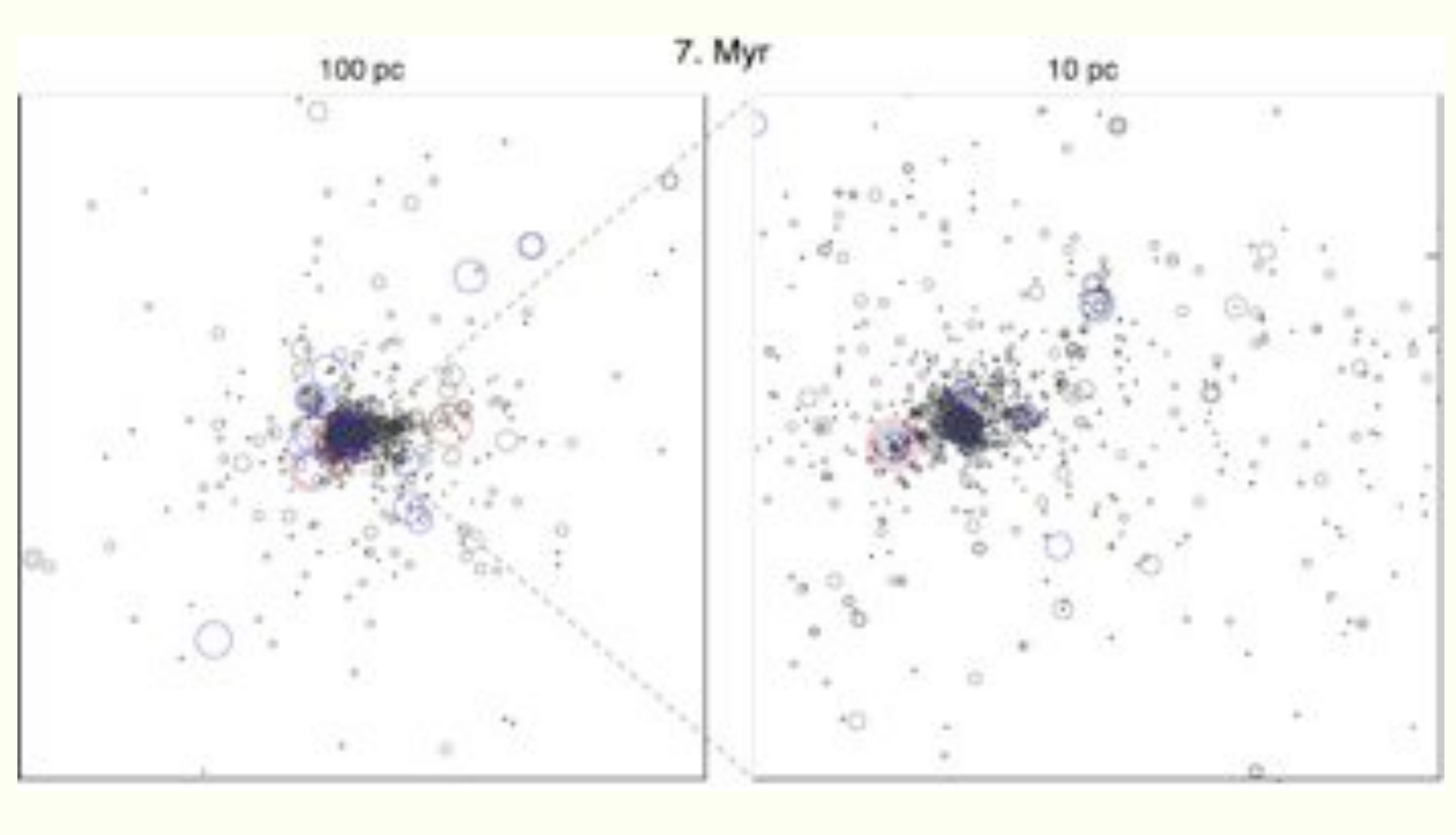


Long-term Evolution?

- Hydrodynamical evolution only followed for ~3×10^5 yr
- How does the cluster evolve on 10 Myr timescales?
  - Does gas dispersal unbind the cluster (only 15-38% of mass in stars)?
  - Destruction or formation of binary and multiple systems?
    - Kroupa (1995a,1995b): N-body simulations beginning with 100% binaries found many binaries were quickly destroyed
    - Is it possible to form very wide binaries in the halo of ejected stars?
- Moeckel & Bate (2010) used N-body6 code to evolve end state of Bate (2009a)'s hydrodynamical simulation to an age of 10 Myr
  - Four cases:
    - Instantaneous gas removal
    - Gas decreases to 10% after 0.3 Myr
    - Gas decreases to 10% after 1 Myr
    - No gas removal

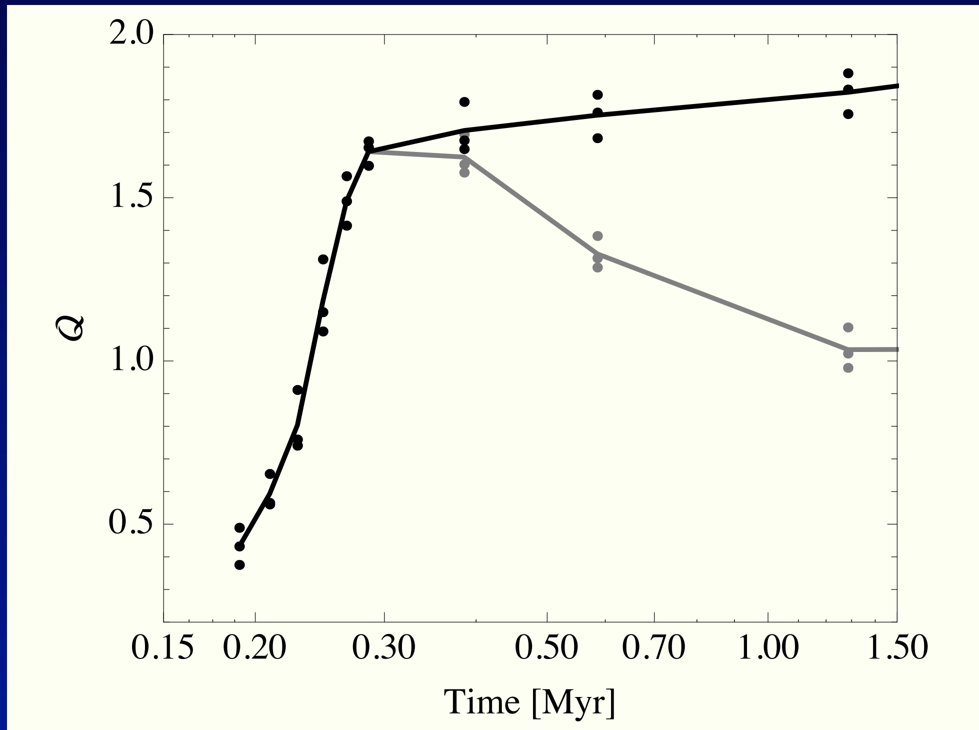
Evolution over 10 Myr

Instantaneous Gas Removal (Moeckel & Bate 2010)



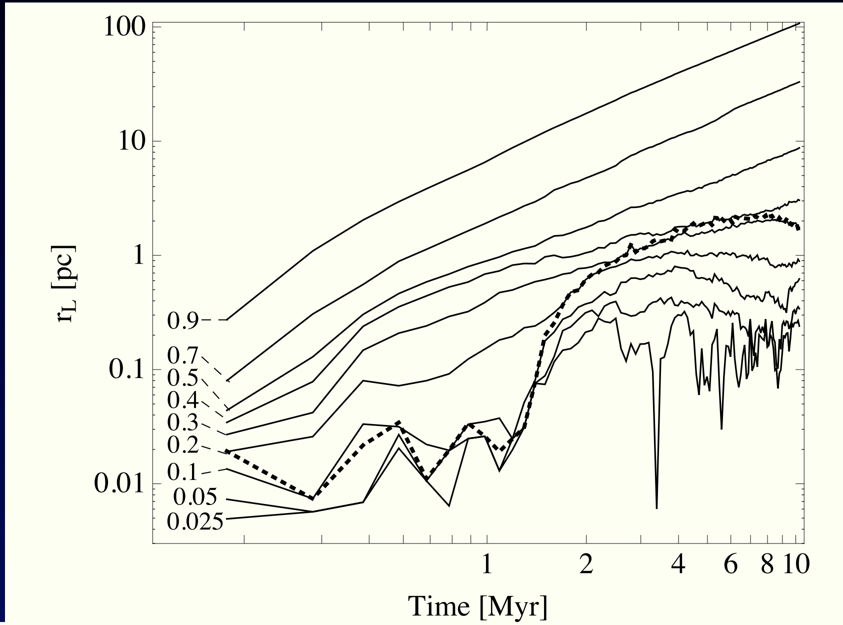
The Evolution of Cluster Structure

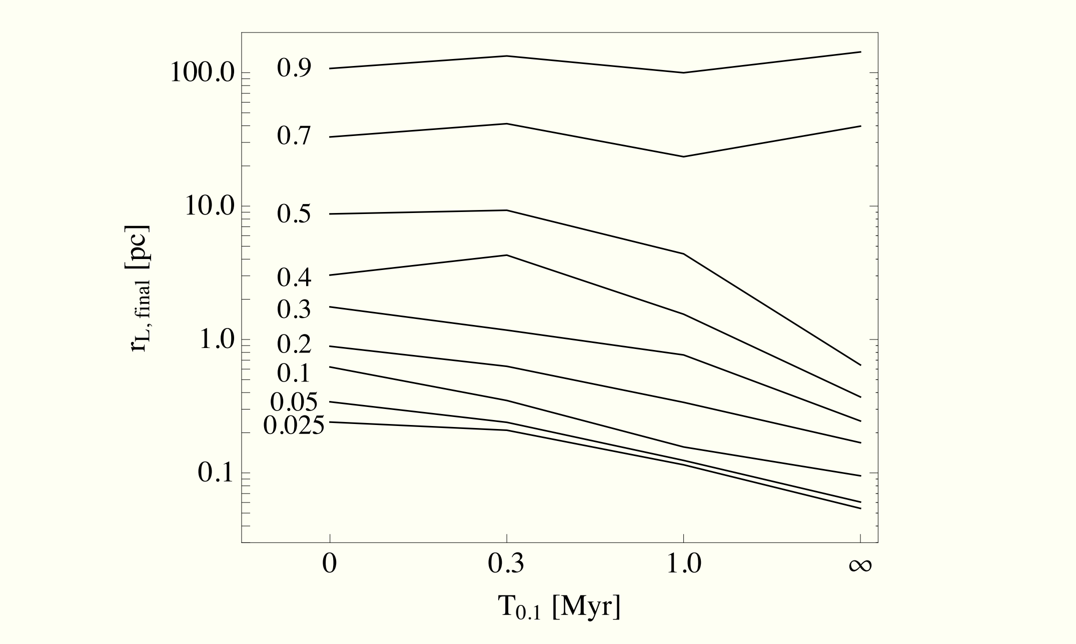
- Hydrodynamical evolution
  - Stars form along filaments in sub-clusters
  - Sub-clusters merge to form one massive cluster surrounded by a halo of ejected stars
- N-body evolution
  - Cluster expands by a factor of ~20 (from 0.05 pc to 2 pc - comparable to ONC)
  - More stars ejected
  - Ejected stars continue to expand
- Quantify using Q parameter
  - Cartwright & Whitworth (2004)
  - Q<0.8: Sub-structure / fractal
  - Q=0.8: No structure
  - Q>0.8: Density gradient or cluster/halo

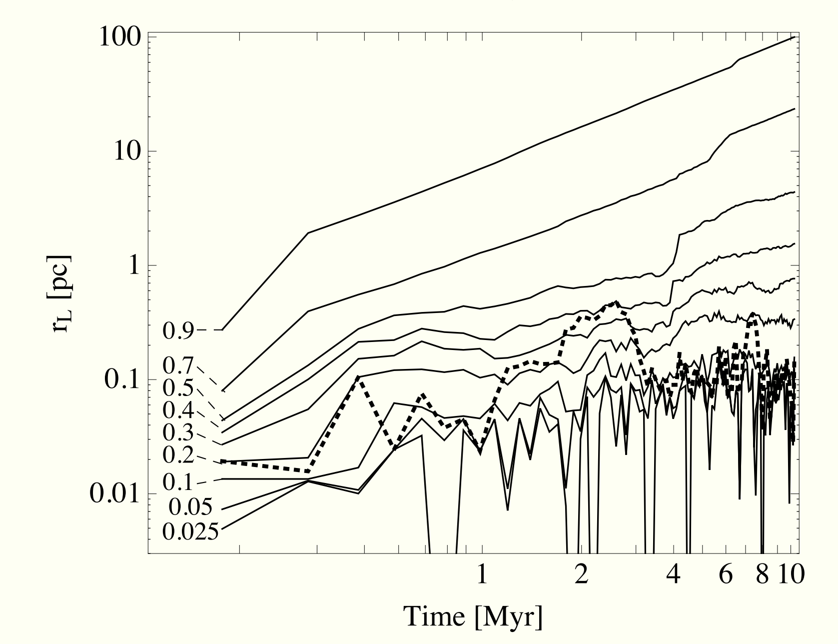


Lagrangian Radii

- Remnant cluster
  - Contains 30-40% of stellar mass
  - Expands from 0.05 pc to 1-2 pc over 4-10 Myr except in the case without gas removal
- Halo
  - Freely expands to >100 pc in <10 Myr







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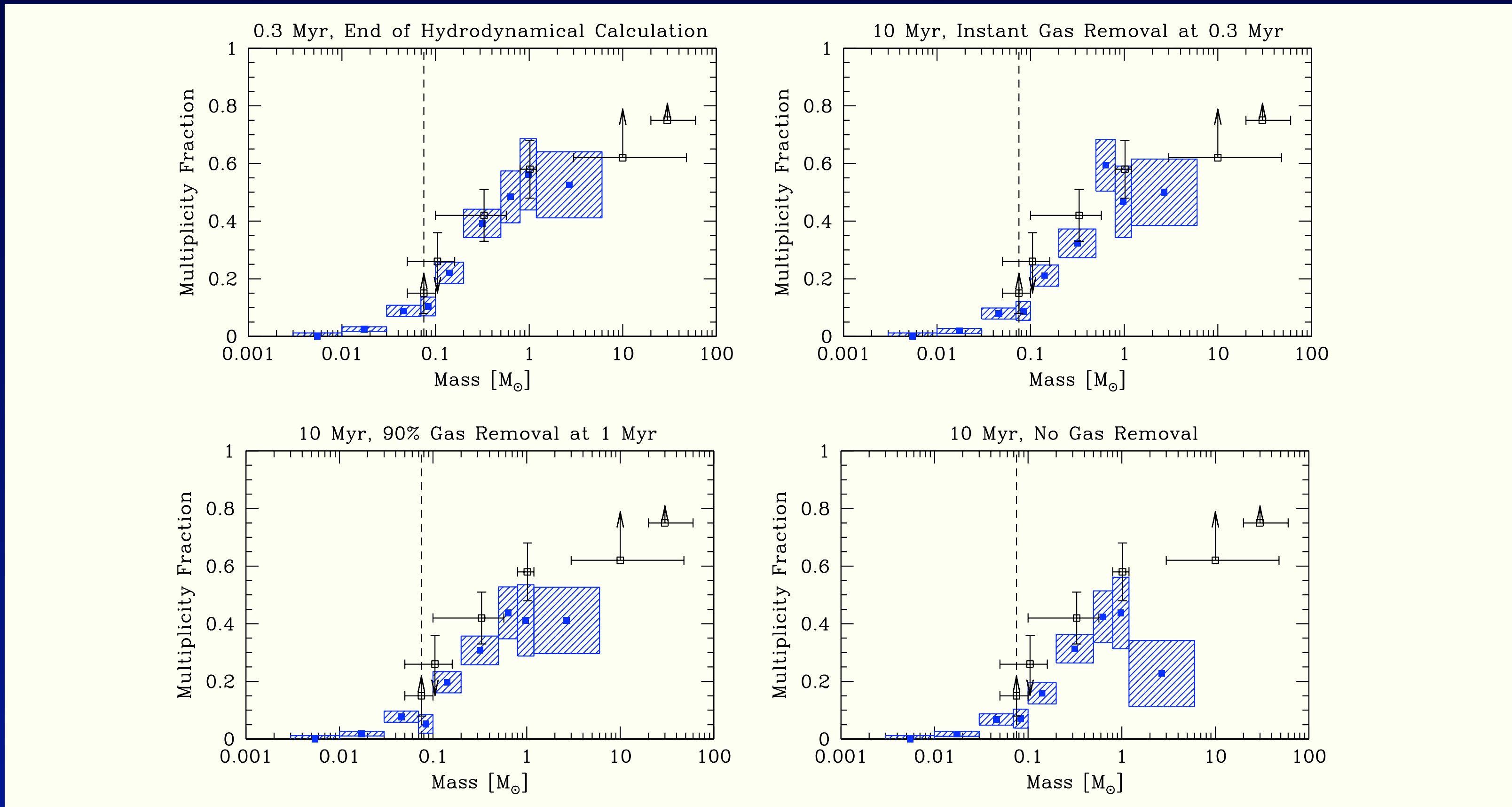
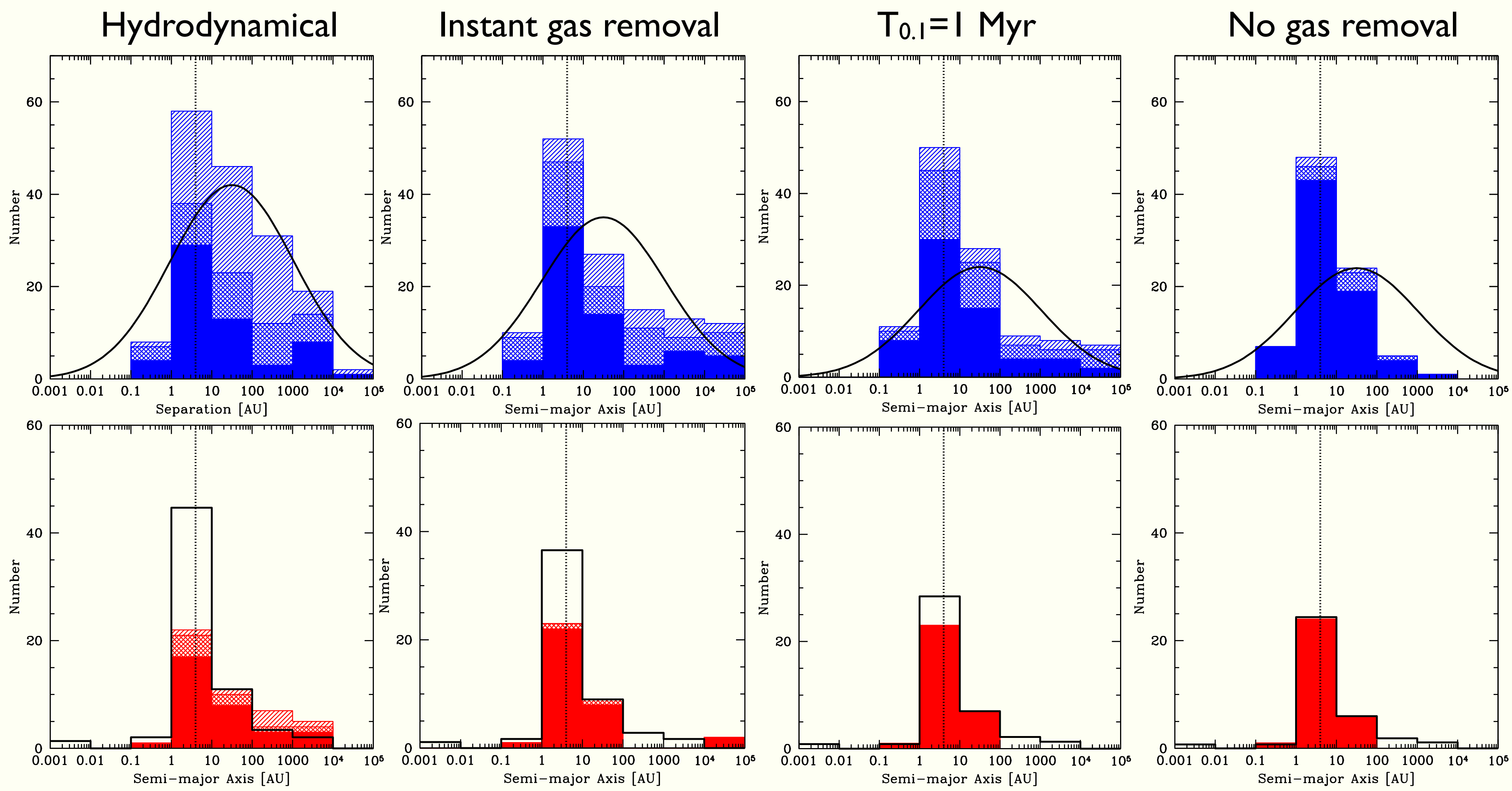
Stellar Multiplicity

- End of hydrodynamical calculation
  - Multiplicity (= B+T+Q / [S+B+T+Q]) is an increasing function of primary mass
- Evolution over 10 Myr has little impact on multiplicities
  - Primordial multiple systems formed in a cluster are naturally resistant to disruption
  - Cannot separate star formation from multiple system formation



Separation Distributions

- Decay of high-order (quadruple) systems
- All cases, except no gas removal, form a significant number of very wide (>10^4 AU) systems (see also Kouwenhoven et al. 2010)
- Little evolution of VLM systems, except that wide (>60 AU) systems broken up



Conclusions

- Invariance of stellar properties:
  - Interstellar conspiracy or self-regulation ?
- Protostellar interactions may provide self-regulation and stellar properties
  - Gravitational fragmentation of structured molecular gas to form stellar groups
  - Dissipative dynamical interactions between accreting protostars
    - Gives an IMF-like mass distribution (competitive accretion), but depends on global Jeans mass
    - Leads to observed multiplicity fractions & properties of multiple systems
  - Radiative feedback (interactions) from accreting protostars
    - Enables the production of an (almost) invariant IMF
  - All three together can reproduce observed stellar properties (Bate 2012, 2014)
- Cluster evolution
  - Star clusters may begin very dense (e.g. half-mass radii < 0.1 pc) and expand at 1-2 Myr
  - Wide binaries may form during cluster dissolution (Moeckel & Bate 2010; Kouwenhoven et al. 2010)