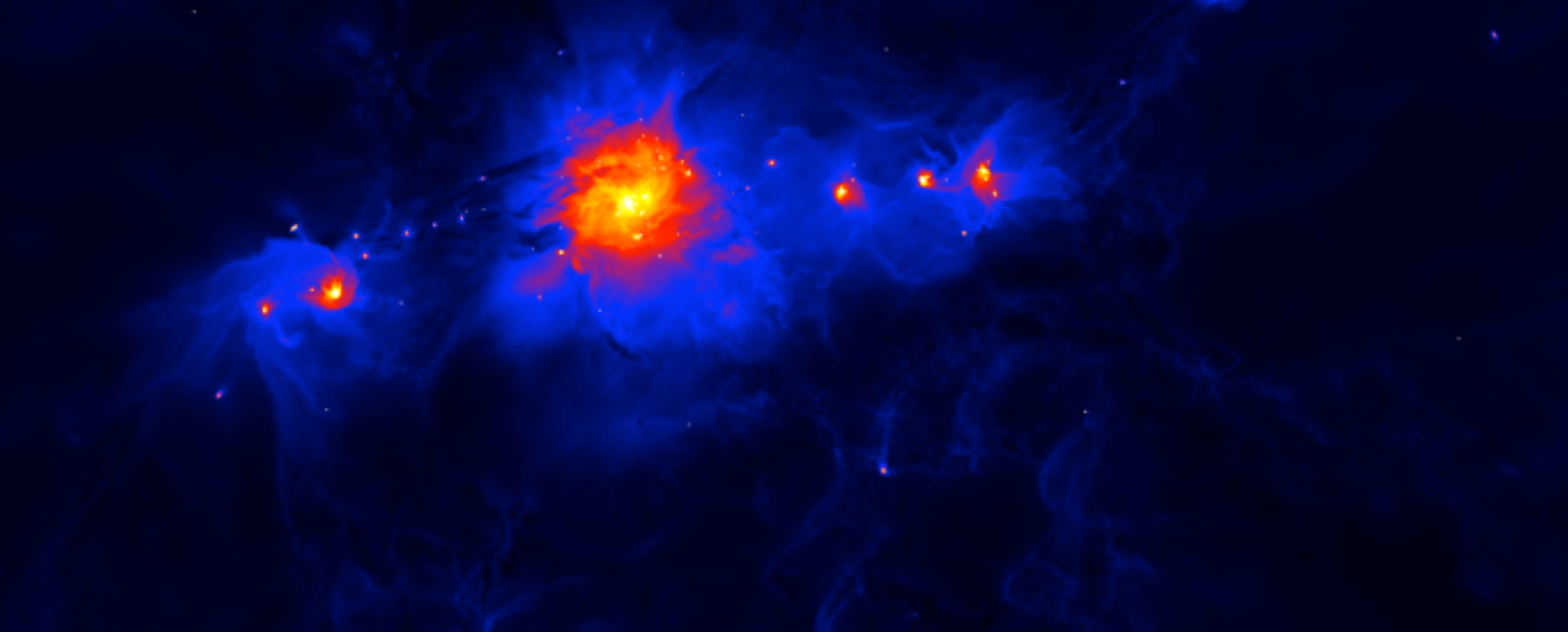
From prestellar cores to stellar systems: fragmentation, properties, and multiplicity of protostars

Matthew Bate
University of Exeter



Stellar Properties

- Initial mass function
  - Observed to be relatively independent of initial conditions, at least in our Galaxy
- Star formation rate and efficiency
  - Observed to be 3-6% of gas mass per free-fall time (Evans et al. 2009)
- Multiplicity
  - Observed to be an increasing function of primary mass
  - Separations, mass ratios, eccentricities
  - High order systems (triples, quadruples)
- Protoplanetary discs
  - Masses, sizes, density distributions

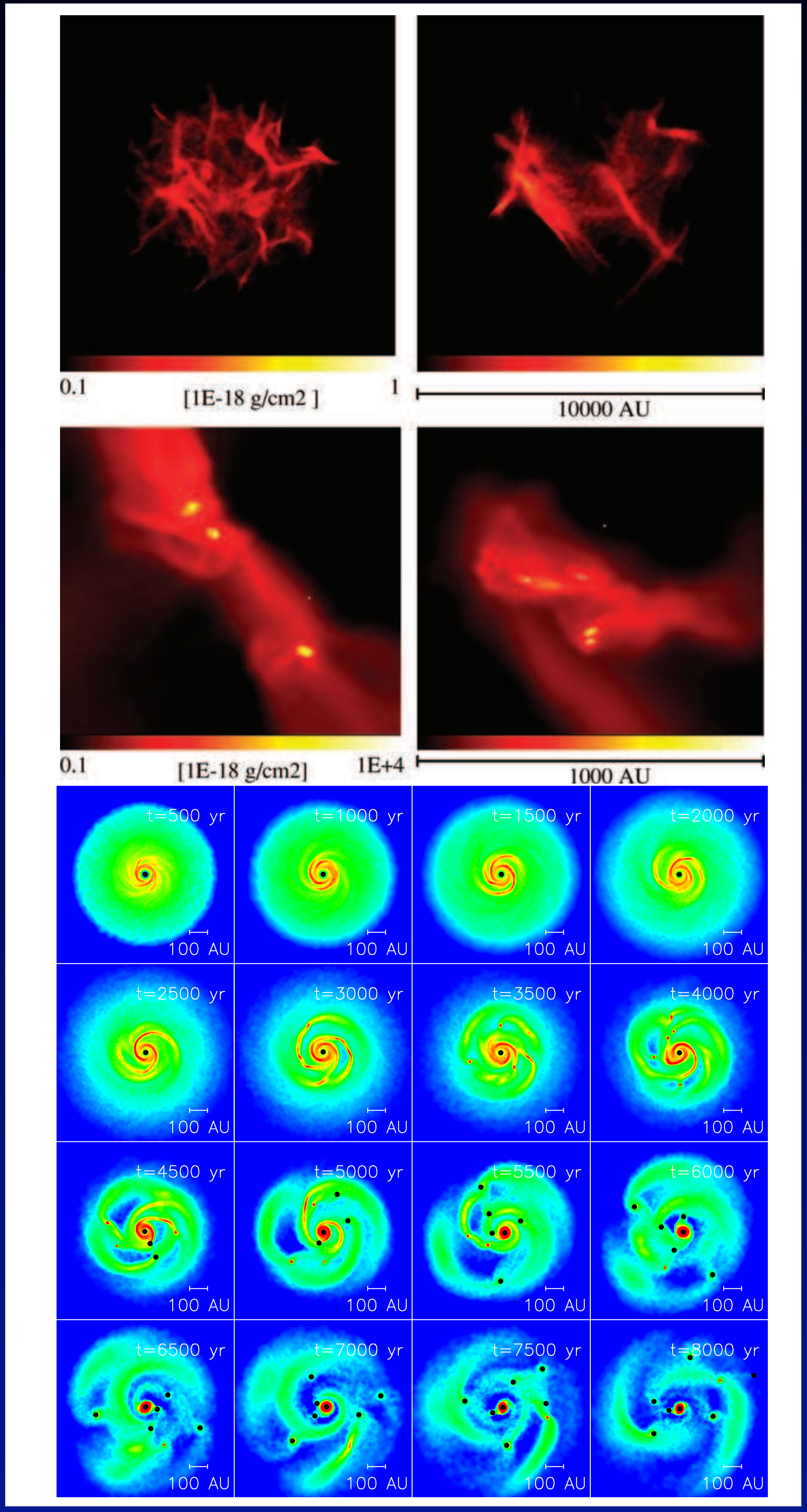
The origins of the statistical properties of stars?

- Most of the calculations performed in the 1980's and 1990's follow the formation of single stars or simple multiple systems
  - e.g. Boss & Bodenheimer 1979, Boss 198*
- Cannot determine the origin of statistical properties
- To investigate statistical properties, either
  - Perform a large ensemble of small calculations
  - Perform a large calculation that forms many stellar systems
    - e.g. a calculation of star cluster formation

Ensembles of small calculations

- Hydrodynamical simulations
  - Formation and dissolution of small-N groups
  - Delgado-Donate et al. (2004a,b); Goodwin, Whitworth & Ward-Thompson (2004a,b,c, 2006)

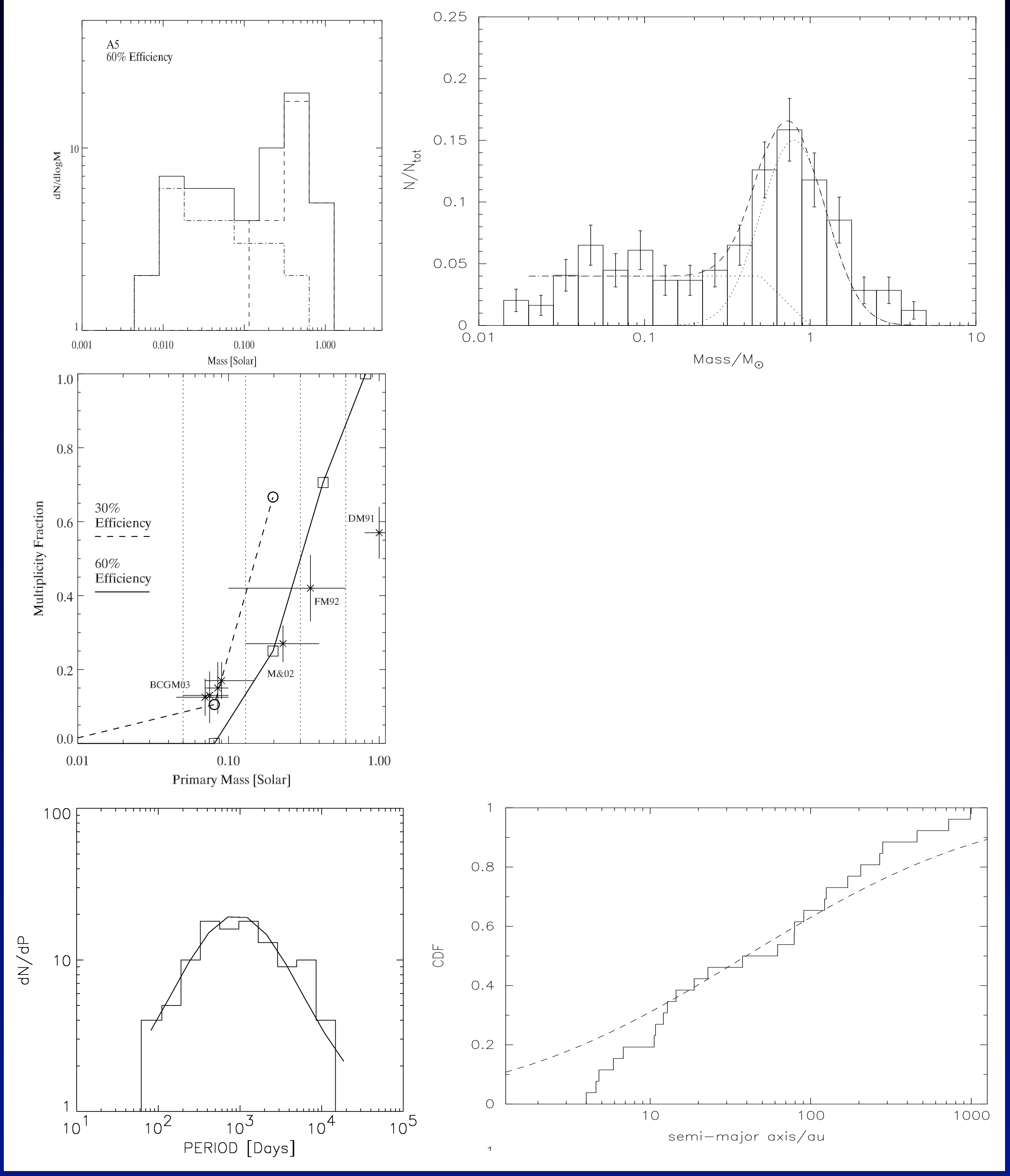
- Simulations including radiative transfer
  - Fragmentation of large, massive discs to produce low-mass companions
  - Stamatellos & Whitworth (2009)



Ensembles of small-N systems

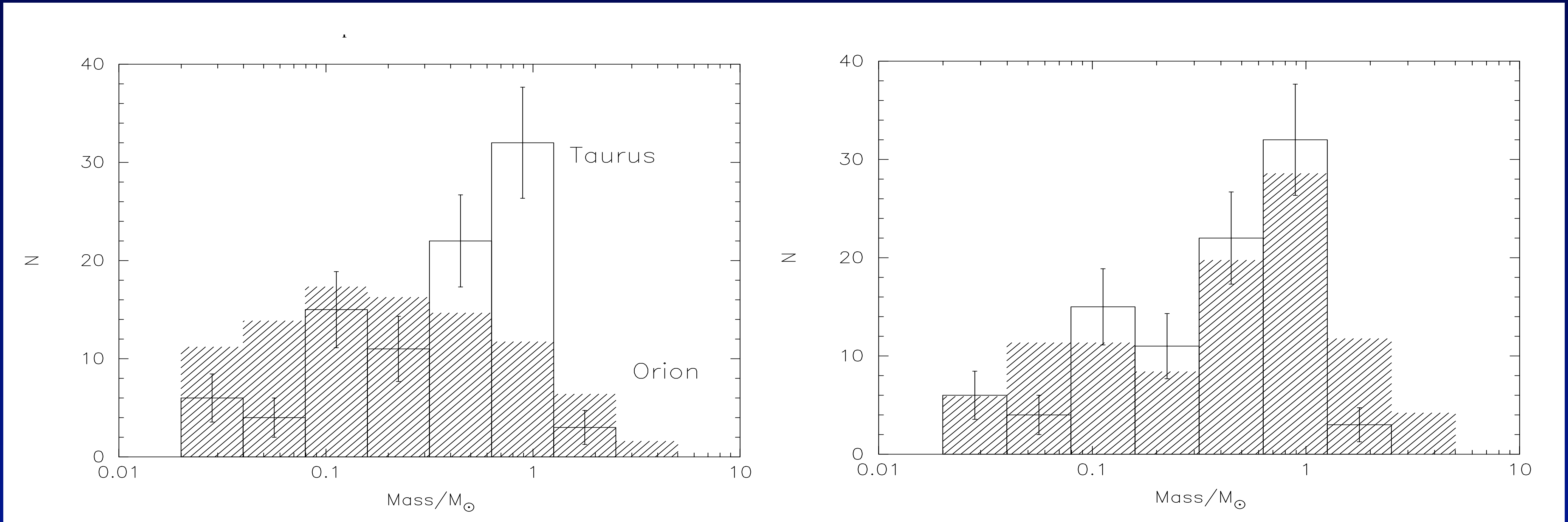
- Mass functions tend to be bimodal
- Multiplicity an increasing function of primary mass
- Reasonable distributions of
  - Semi-major axes
  - Eccentricities

Delgado-Donate et al. 2004a,b, 2006 Goodwin et al. 2004c



An explanation for the IMF in Taurus ?

- Goodwin, Whitworth & Ward-Thompson (2004)
  - Taurus seems to have an excess of solar-type stars
  - Could result from star formation in small-N (~10) groups

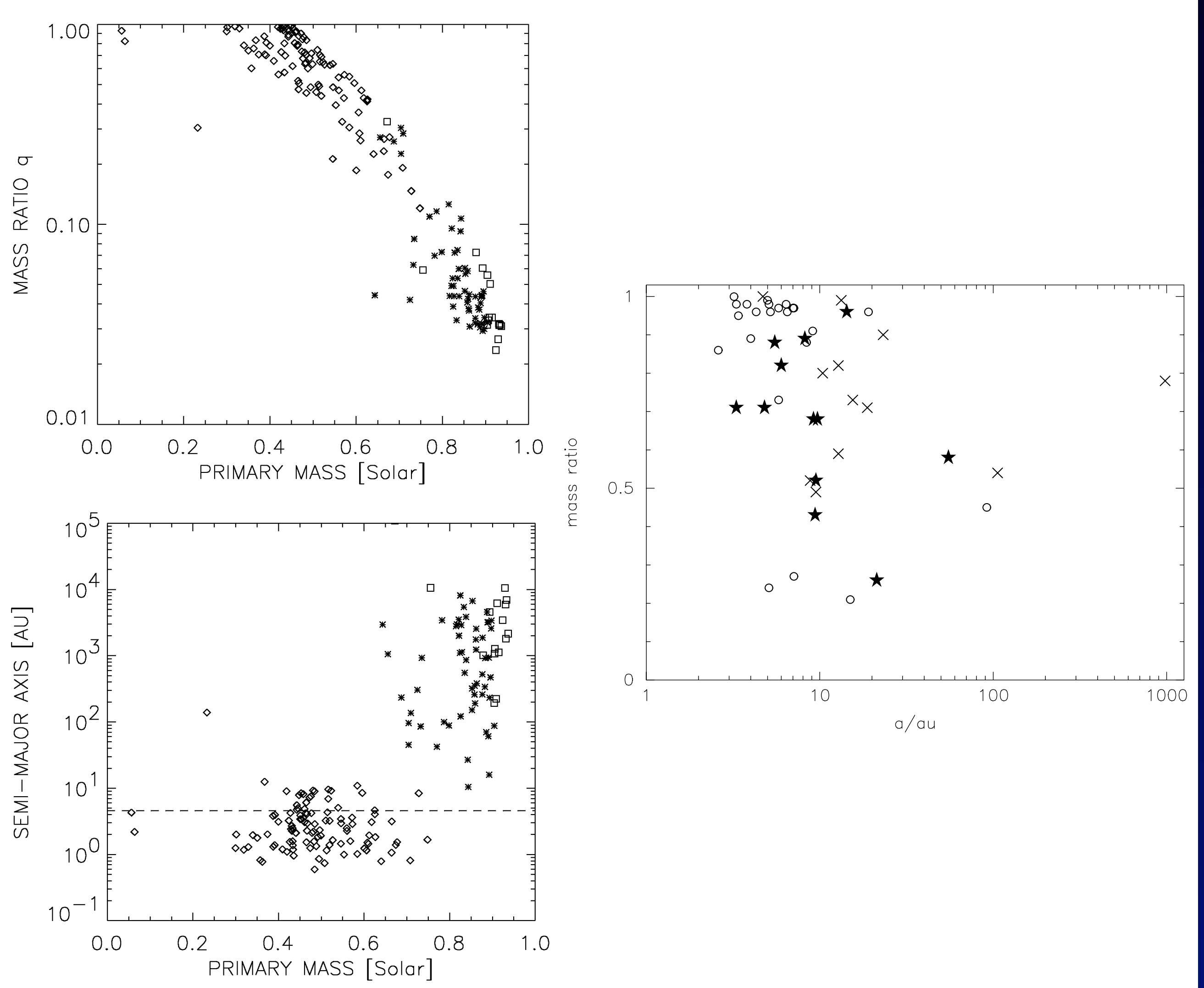


Ensembles of small-N systems

- Mass ratios
  - Closer systems & lower-mass systems
    - Prefer equal masses
  - But binaries tend to be
    - Low-mass
    - Close
    - Have equal masses
  - Low-mass ratios only with higher-order multiples
  - Most wide systems are multiples

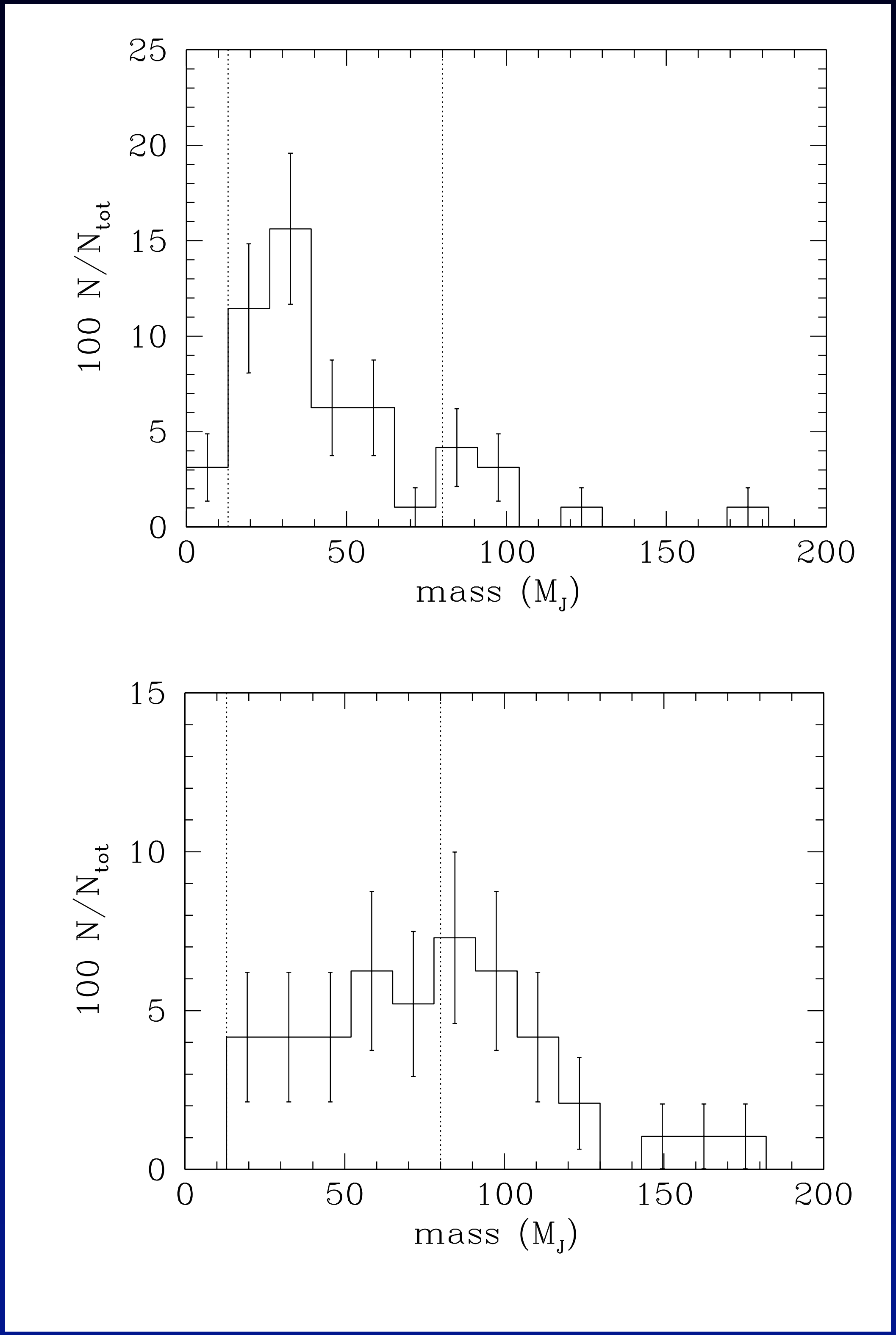
Delgado-Donate et al. 2004a,b

Goodwin et al. 2004c



Ensembles of fragmenting discs

- Mass distribution of ejected objects
  - Mostly brown dwarfs
- Mass distribution of companions
  - Tend to have higher-masses
- Brown dwarf desert out to ~100 AU
  - Tend to form far out and/or be scattered
- Can produce binary brown dwarfs



Ensembles of small systems

- Generally, small-N dynamics naturally produces many observed trends of multiples
  - Increasing multiplicity with primary mass
  - Increasing separation on primary mass
  - More-equal mass ratios for closer separation and/or lower-mass systems
- However, a major problem is how to convolve the results with the real distribution of initial conditions
  - For small-N systems
    - The core mass and size distributions
  - For disc fragmentation
    - The real fractions of large, massive discs
    - And how these vary with primary mass

Star cluster formation (in turbulent clouds)

- Removes the convolution problem
  - Dense cores of all masses form and evolve self-consistently from larger scale flows
  - Interactions between cores and protostellar systems naturally included
- Can be divided into two groups
- Those that resolve the opacity limit for fragmentation
  - Aim to resolve all stars and brown dwarfs, most binary and multiple systems, discs
  - Bate, Bonnell & Bromm (2002a,b, 2003); Bate & Bonnell (2005); Bate (2005, 2009, 2011); Offner et al. (2008)
- Those that do not
  - Can only try to address the origin of the IMF
  - Bonnell et al. (1997, 2001); Klessen, Burkert & Bate (1998); Klessen & Burkert (2001); Bonnell & Bate (2002); Bonnell et al. (2003); Offner et al. (2009); Urban et al. (2010); Krumholz et al. (2011)

Star cluster simulations that resolve the opacity limit

Star cluster simulations that resolve the opacity limit

- `Small' hydrodynamical simulations
  - Bate, Bonnell & Bromm 2002a,b, 2003; Bate & Bonnell 2005; Bate 2005; Bate 2009c
  - Collapse of 50 $M_\odot$ `turbulent' molecular clouds, decaying turbulence
  - 34-79 stars & BDs, resolves discs ($\gtrsim$10 AU radius), binaries ($\gtrsim$1 AU separation)

UNIVERSITY OF EXETER

European Science Foundation

UK Astrophysical Fluids Facility

constellation

Star cluster simulations that resolve the opacity limit

- `Small' hydrodynamical simulations
  - Bate, Bonnell & Bromm 2002a,b, 2003; Bate & Bonnell 2005; Bate 2005; Bate 2009c
  - Collapse of 50 $M_\odot$ `turbulent' molecular clouds, decaying turbulence
  - 34-79 stars & BDs, resolves discs ($\gtrsim$10 AU radius), binaries ($\gtrsim$1 AU separation)
- `Large' hydrodynamical simulations
  - Bate (2009a): 500 $M_\odot$ decaying `turbulence' molecular clouds
  - >1250 stars and BDs, one calculation resolves discs ($\gtrsim$1 AU radius), all binaries

UNIVERSITY OF EXETER

EUROPEAN SCIENCE FOUNDATION

UK Astrophysical Fluids Facility

constellation

Star cluster simulations that resolve the opacity limit

- `Small' hydrodynamical simulations
  - Bate, Bonnell & Bromm 2002a,b, 2003; Bate & Bonnell 2005; Bate 2005; Bate 2009c
  - Collapse of 50 $M_\odot$ `turbulent' molecular clouds, decaying turbulence
  - 34-79 stars & BDs, resolves discs ($\gtrsim$10 AU radius), binaries ($\gtrsim$1 AU separation)
- `Large' hydrodynamical simulations
  - Bate (2009a): 500 $M_\odot$ decaying `turbulence' molecular clouds
  - >1250 stars and BDs, one calculation resolves discs ($\gtrsim$1 AU radius), all binaries
- `Small' radiation hydrodynamical simulations
  - Bate (2009b): 50 $M_\odot$ decaying `turbulence' molecular clouds, turbulence
  - Total of 25 stars and brown dwarfs, resolve discs ($\gtrsim$1 AU radius), all binaries

Star cluster simulations that resolve the opacity limit

- `Small' hydrodynamical simulations
  - Bate, Bonnell & Bromm 2002a,b, 2003; Bate & Bonnell 2005; Bate 2005; Bate 2009c
  - Collapse of 50 $M_\odot$ `turbulent' molecular clouds, decaying turbulence
  - 34-79 stars & BDs, resolves discs (≳10 AU radius), binaries (≳1 AU separation)
- `Large' hydrodynamical simulations
  - Bate (2009a): 500 $M_\odot$ decaying `turbulence' molecular clouds
  - >1250 stars and BDs, one calculation resolves discs (≳1 AU radius), all binaries
- `Small' radiation hydrodynamical simulations
  - Bate (2009b): 50 $M_\odot$ decaying `turbulence' molecular clouds, turbulence
  - Total of 25 stars and brown dwarfs, resolve discs (≳1 AU radius), all binaries
- `Large' radiation hydrodynamical simulation
  - Bate (2012, in press): 500 $M_\odot$ decaying `turbulence' molecular clouds
  - 183 stars and BDs, resolves discs (≳1 AU radius), all binaries

UNIVERSITY OF EXETER

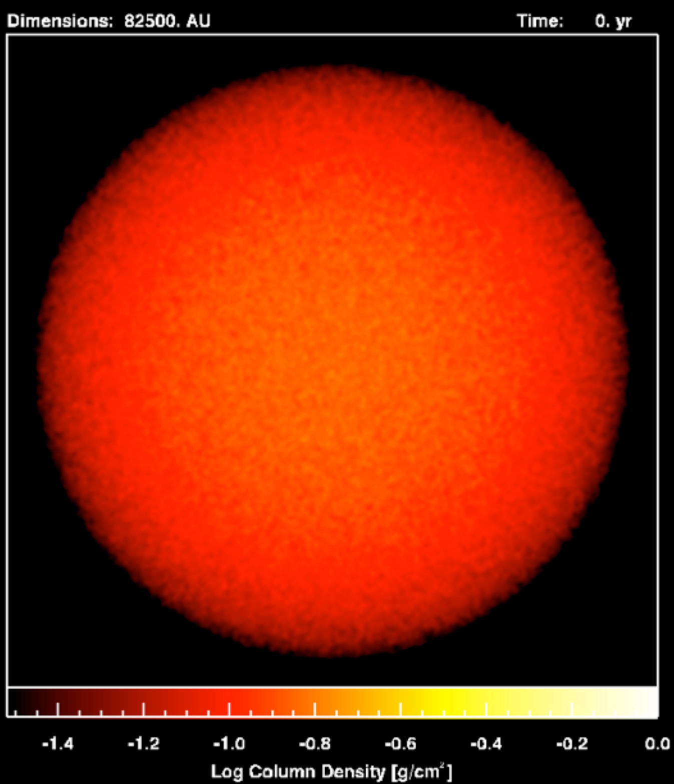
http://www.astro.ex.ac.uk/people/mbate

EUROPEAN SCIENCE FOUNDATION

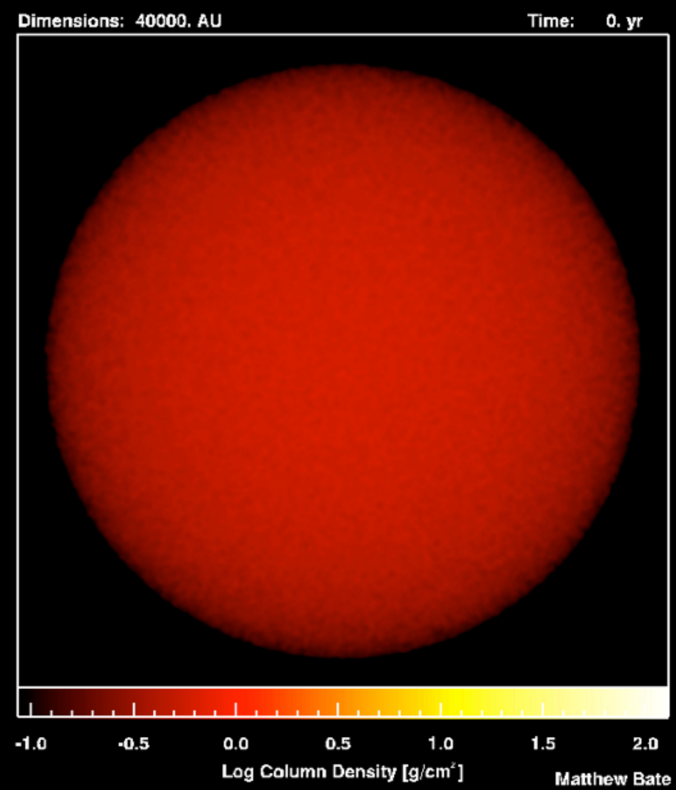
UK Astrophysical Fluids Facility

constellation

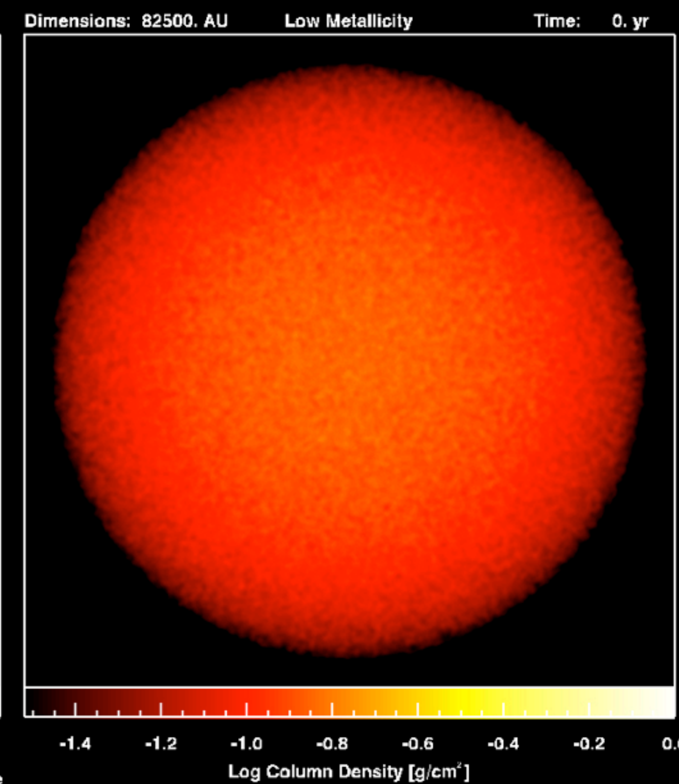
Typical molecular cloud (Bate et al. 2003)
Jeans mass 1 $M_\odot$, Opacity limit 3 M_J, $P(k) \propto k^{-4}$



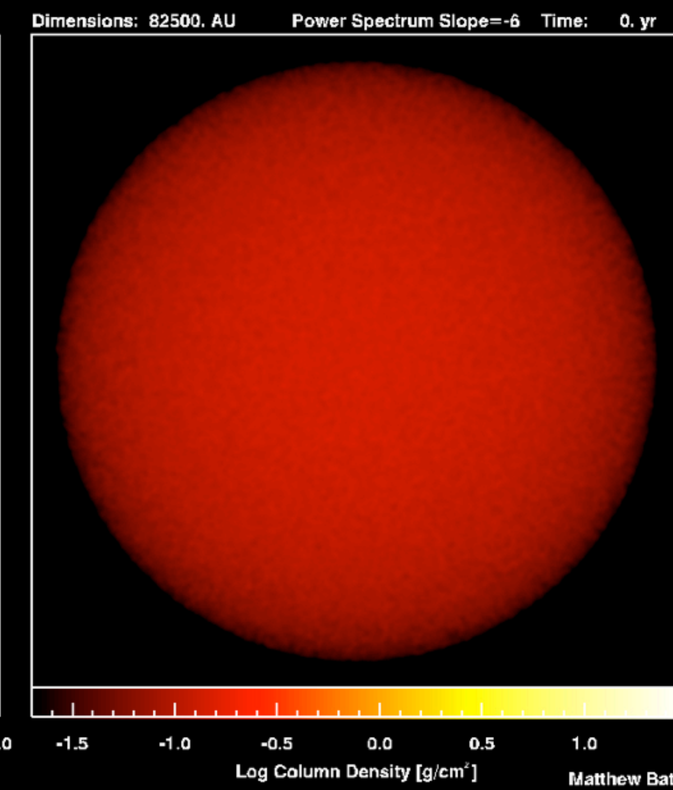
Denser cloud (Bate & Bonnell 2005)
Jeans mass 1/3 $M_\odot$



Lower metallicity cloud (Bate2005)
Opacity limit 9 M_J



Large-scale `turbulence' (Bate 2009c)
$P(k) \propto k^{-6}$



UNIVERSITY OF EXETER

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

European Science Foundation

UK Astrophysical Fluids Facility

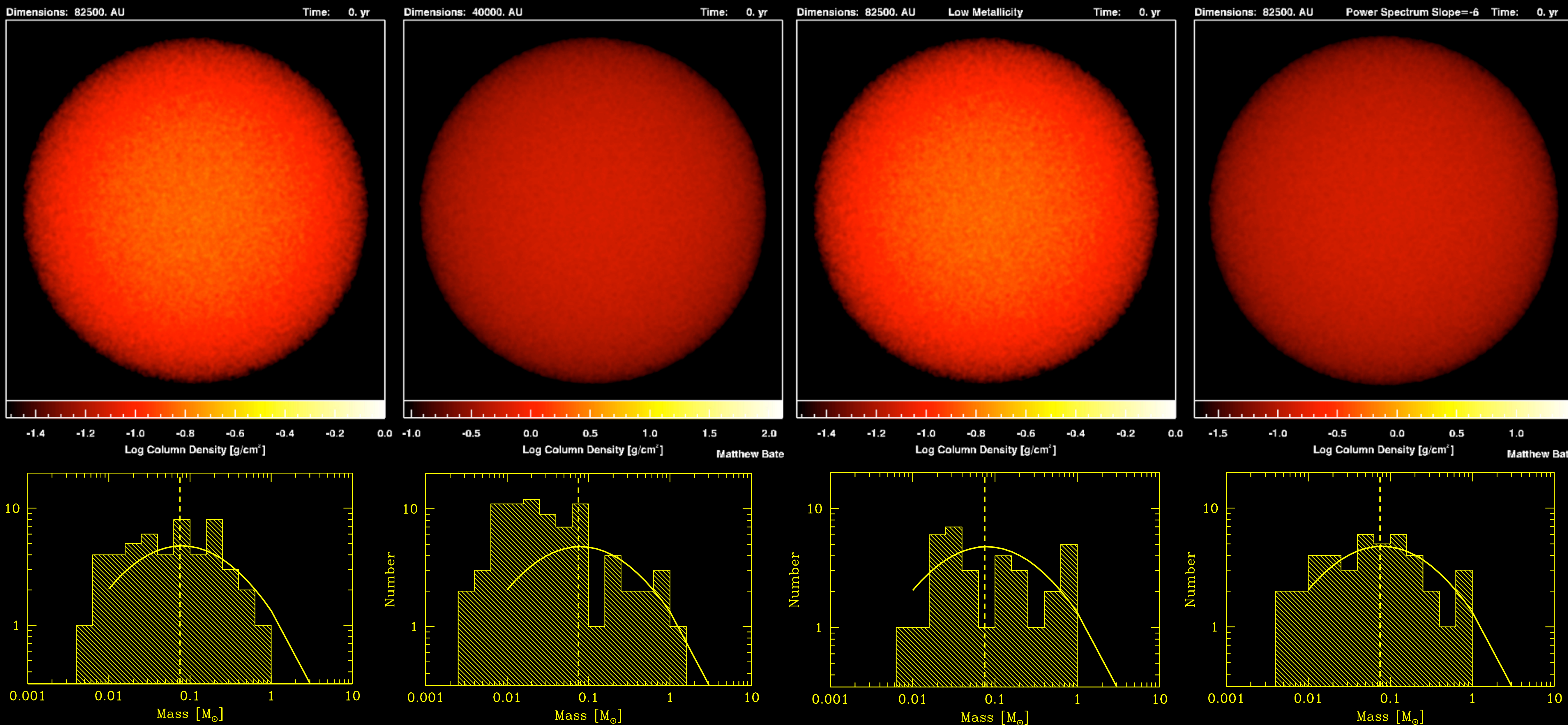
constellation

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 $M_\odot$

Lower metallicity cloud (Bate2005)
Opacity limit 9 M_J

Large-scale `turbulence' (Bate 2009c)
$P(k) \propto k^{-6}$



UNIVERSITY OF EXETER

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

EUROPEAN SCIENCE FOUNDATION

UK Astrophysical Fluids Facility

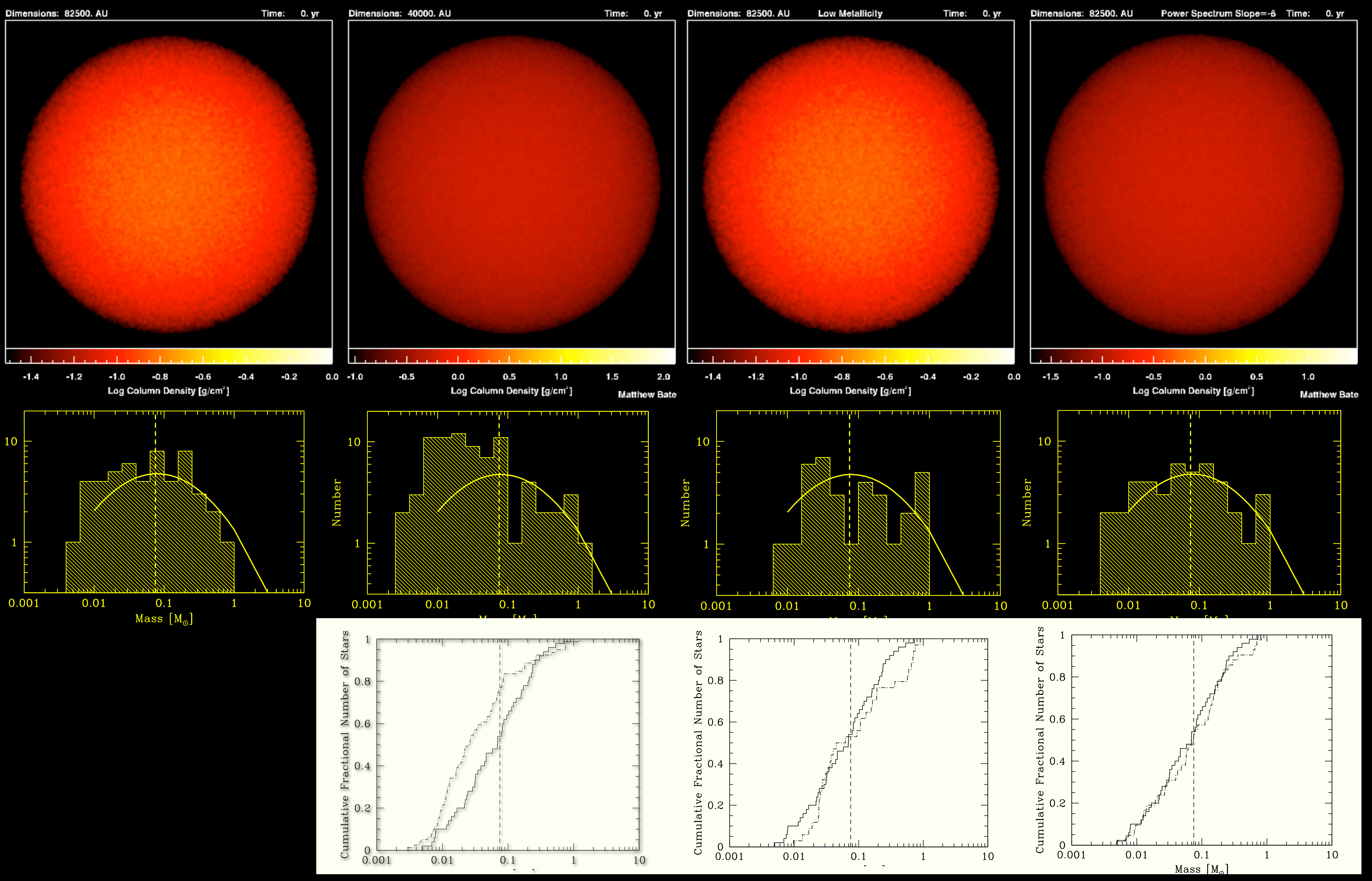
constellation

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 $M_\odot$

Lower metallicity cloud (Bate2005)
Opacity limit 9 M_J

Large-scale `turbulence' (Bate 2009c)
$P(k) \propto k^{-6}$



UNIVERSITY OF EXETER

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

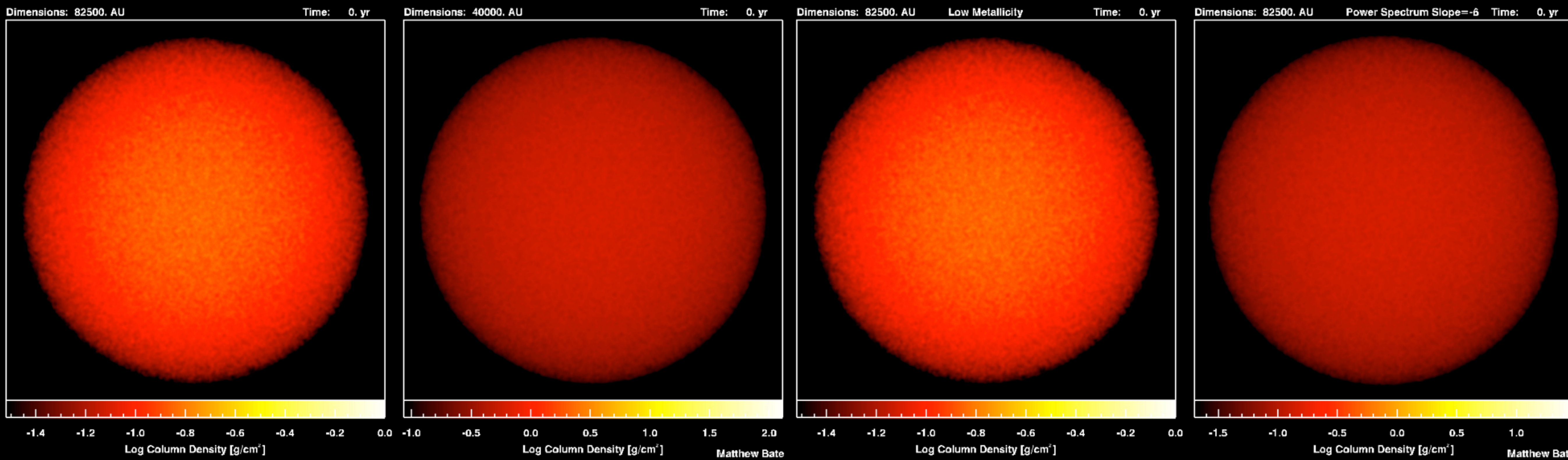
EUROPEAN SCIENCE FOUNDATION — UK Astrophysical Fluids Facility — constellation

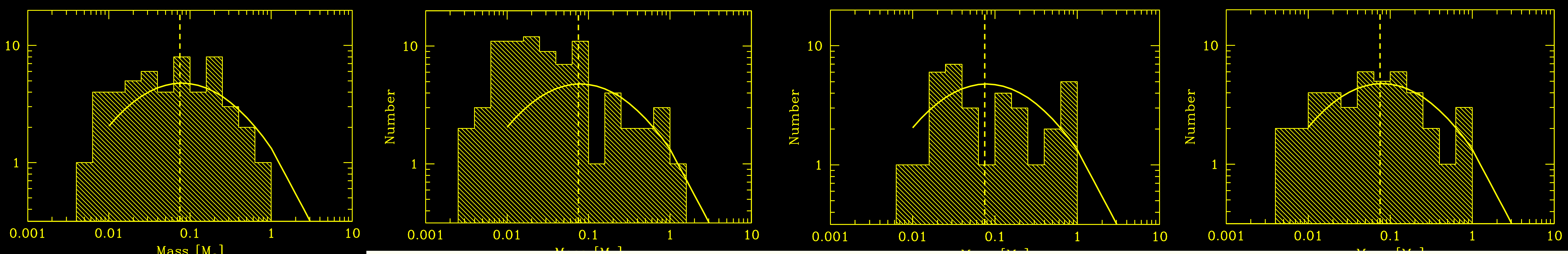
Typical molecular cloud (Bate et al. 2003)
Jeans mass 1 $M_\odot$, Opacity limit 3 M_J, $P(k)\propto k^{-4}$

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

Lower metallicity cloud (Bate2005)
Opacity limit 9 M_J

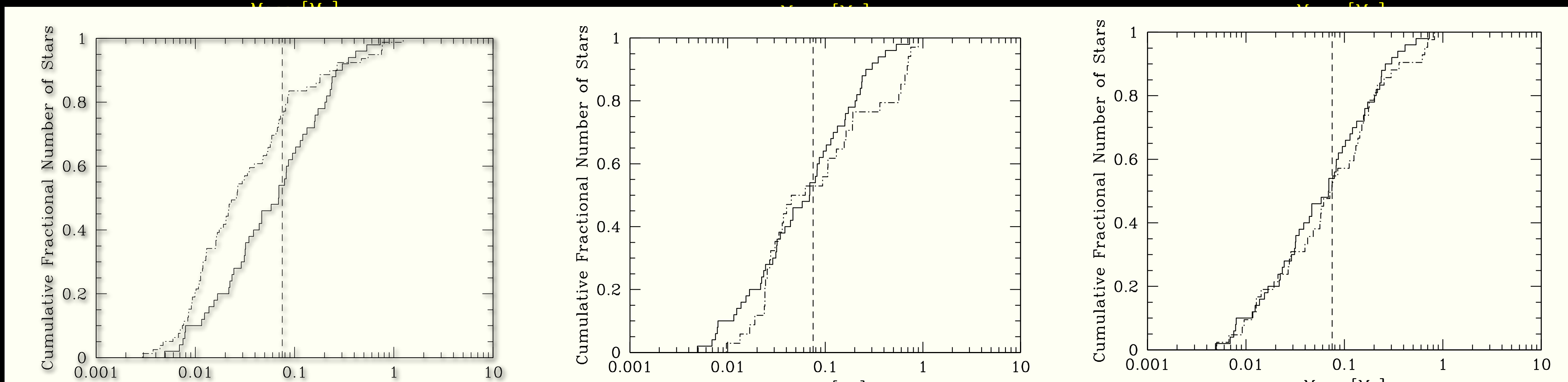
Large-scale `turbulence' (Bate 2009c)
$P(k)\propto k^{-6}$





Characteristic stellar mass depends on the cloud's mean Jeans mass (Bate & Bonnell 2005; Jappsen et al 2005; Bonnell et al. 2006)

Denser/cooler clouds produce more brown dwarfs

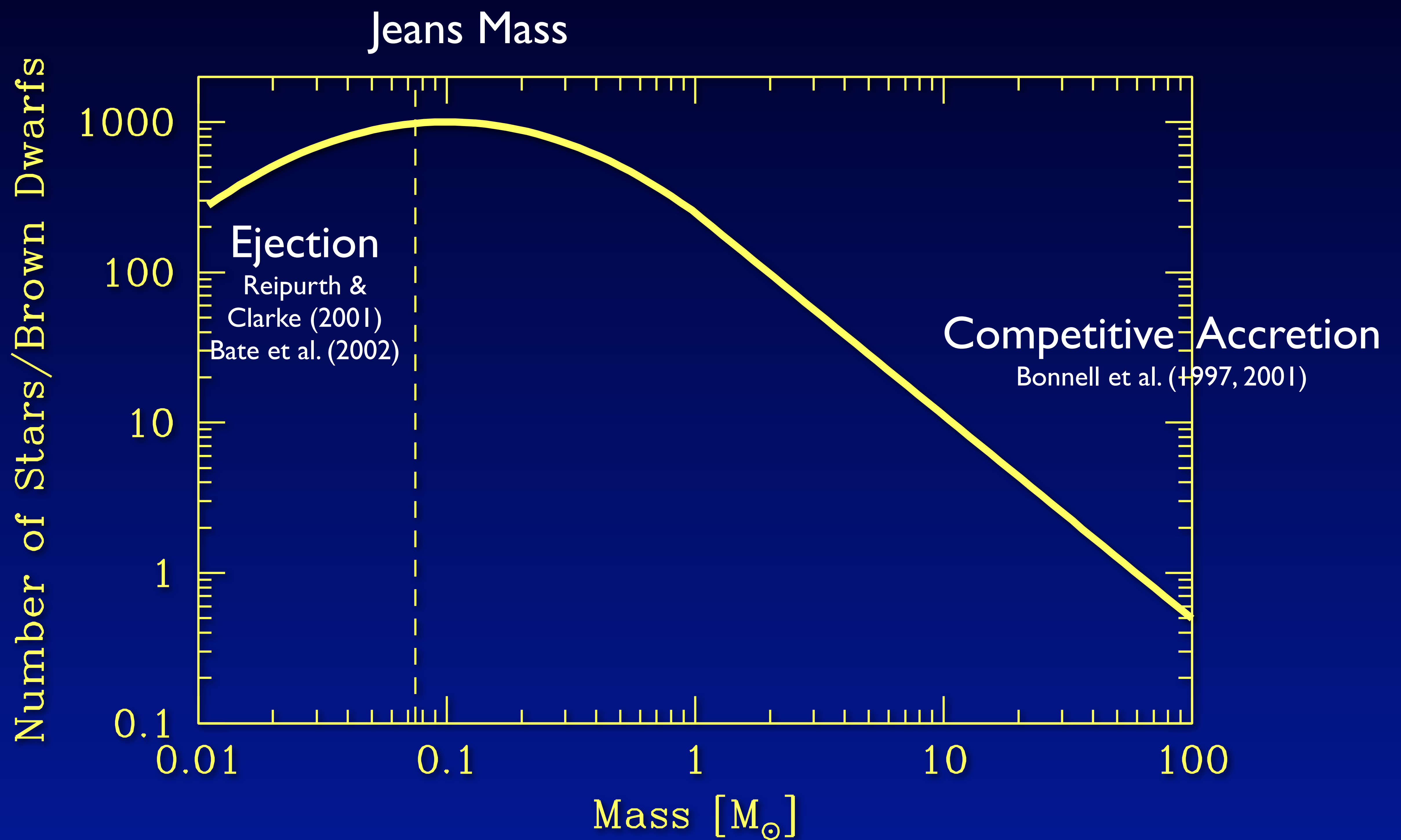


Fragmentation and Initial Conditions

- Strongly centrally-condensed initial conditions are difficult to fragment
  - Burket, Bate & Bodenheimer (1997) - individual cores
  - Krumholz et al. (2007), Girichidis et al. (2011) - turbulent clouds
- Continuously driven high-amplitude turbulence
  - Small-scale driving inhibits cluster-mode fragmentation (Klessen 2001)
- Results from turbulent fragmentation are relatively robust
  - As long as the calculation generates lots of substructure which collapses to form stellar groups, a competitive accretion environment dominates
  - e.g. Klessen, Burkert, Bate (1998); Klessen & Burkert (2001a,b) began with no turbulence, just Gaussian density fluctuations

What is the Origin of the IMF?

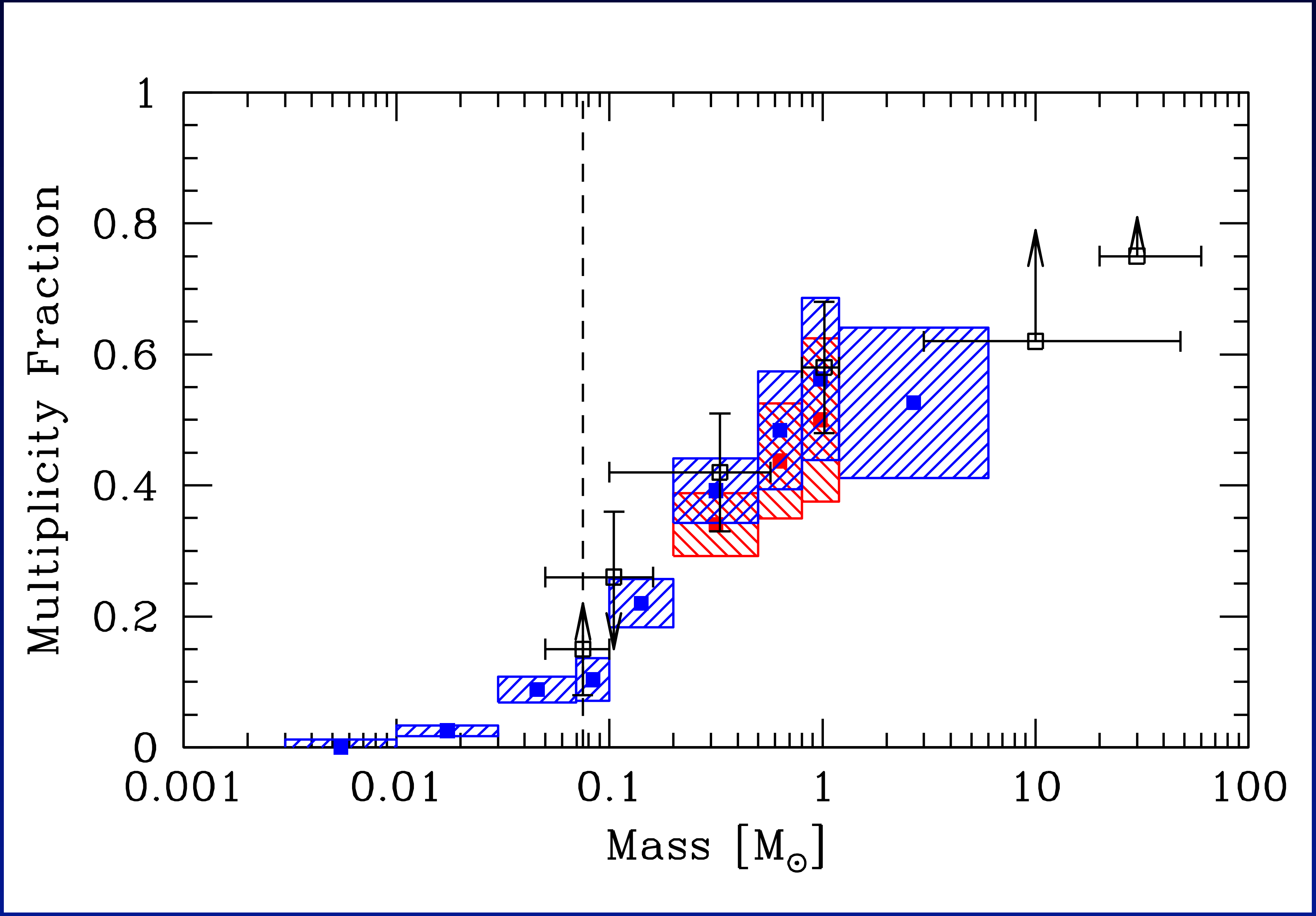
Competition between accretion and ejection (Bate & Bonnell 2005)



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

- 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



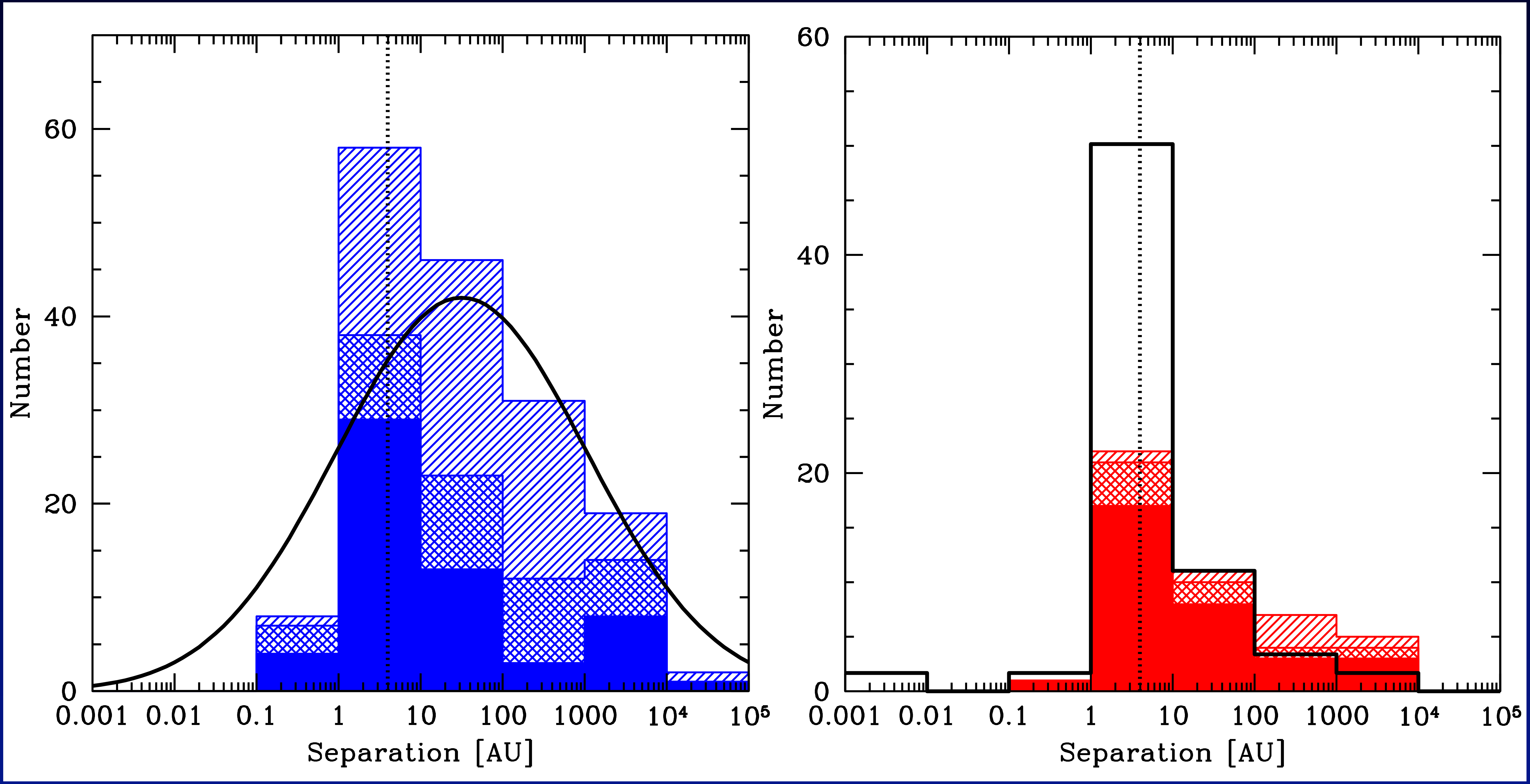
Star/VLM Object Separation Distributions

Stars: binary, triple, quad separations

Median separation: 26 AU

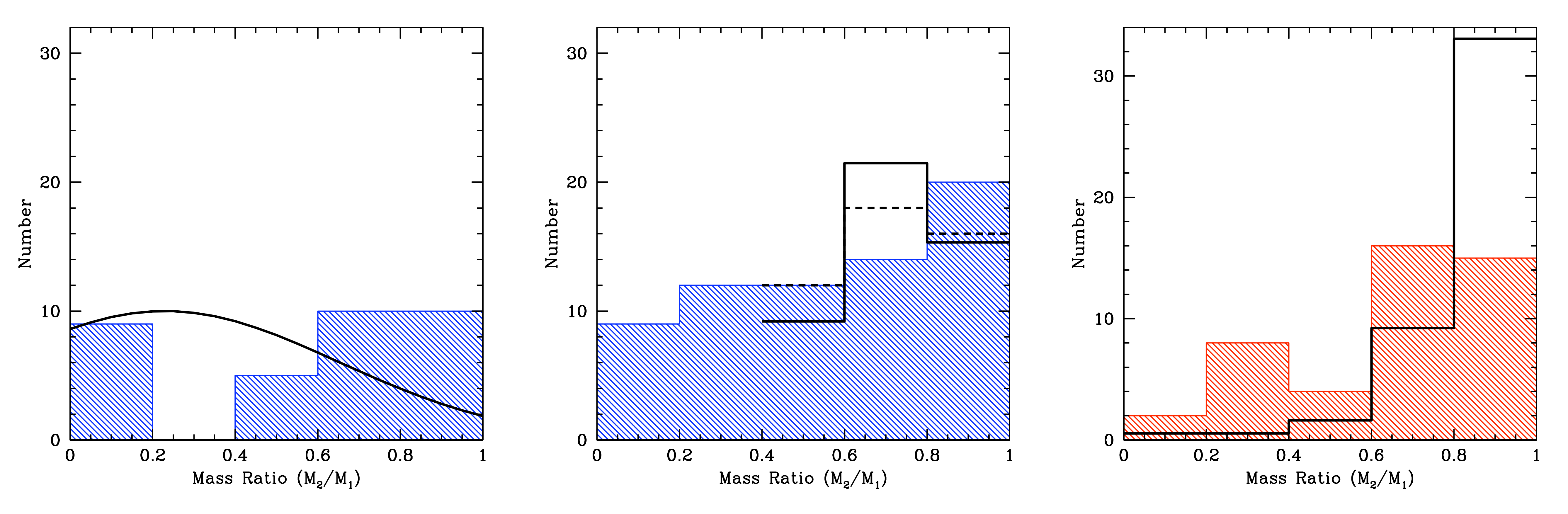
VLM objects: binaries, triples, quads

Median separation: 10 AU



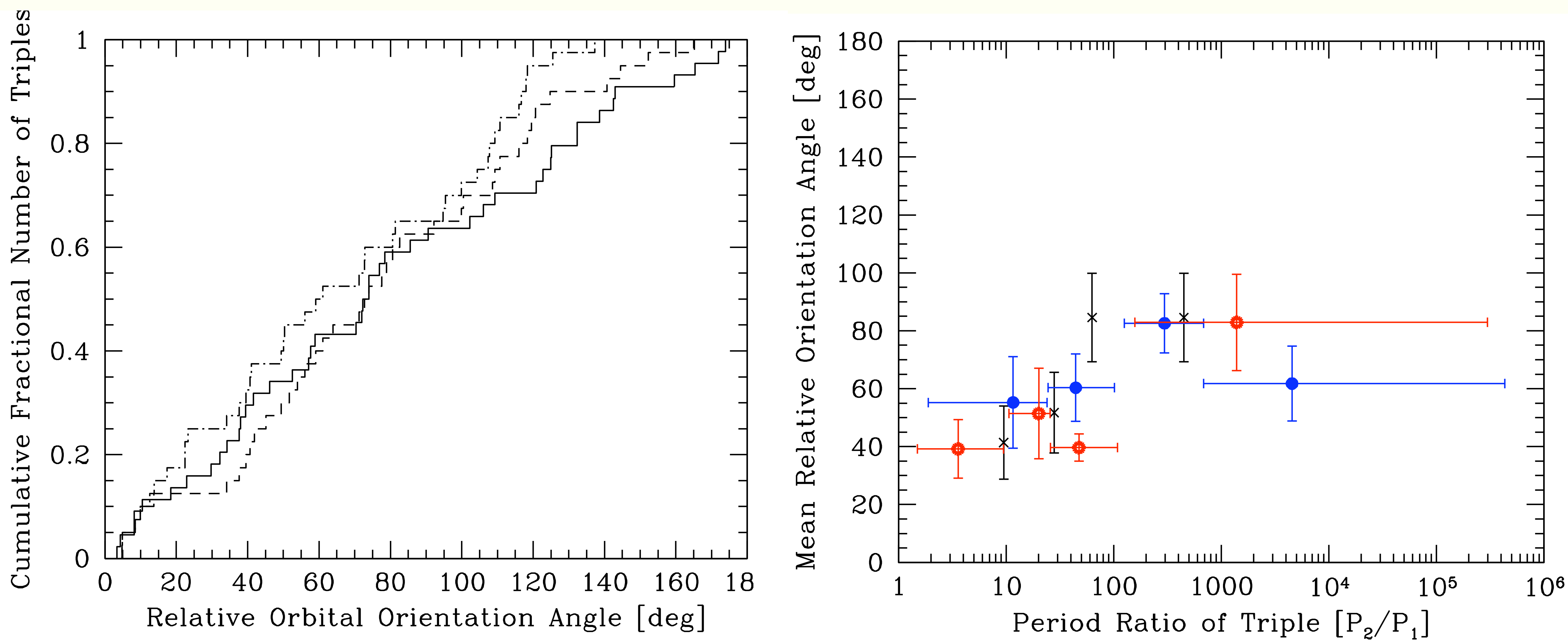
Star/VLM Object Binary Mass Ratio Distributions

Stars: M>0.5 $M_\odot$	Stars: 0.1<M<0.5 $M_\odot$	VLM objects: M<0.1 $M_\odot$
59% have q>0.6	51% have q>0.6	71% have q>0.6



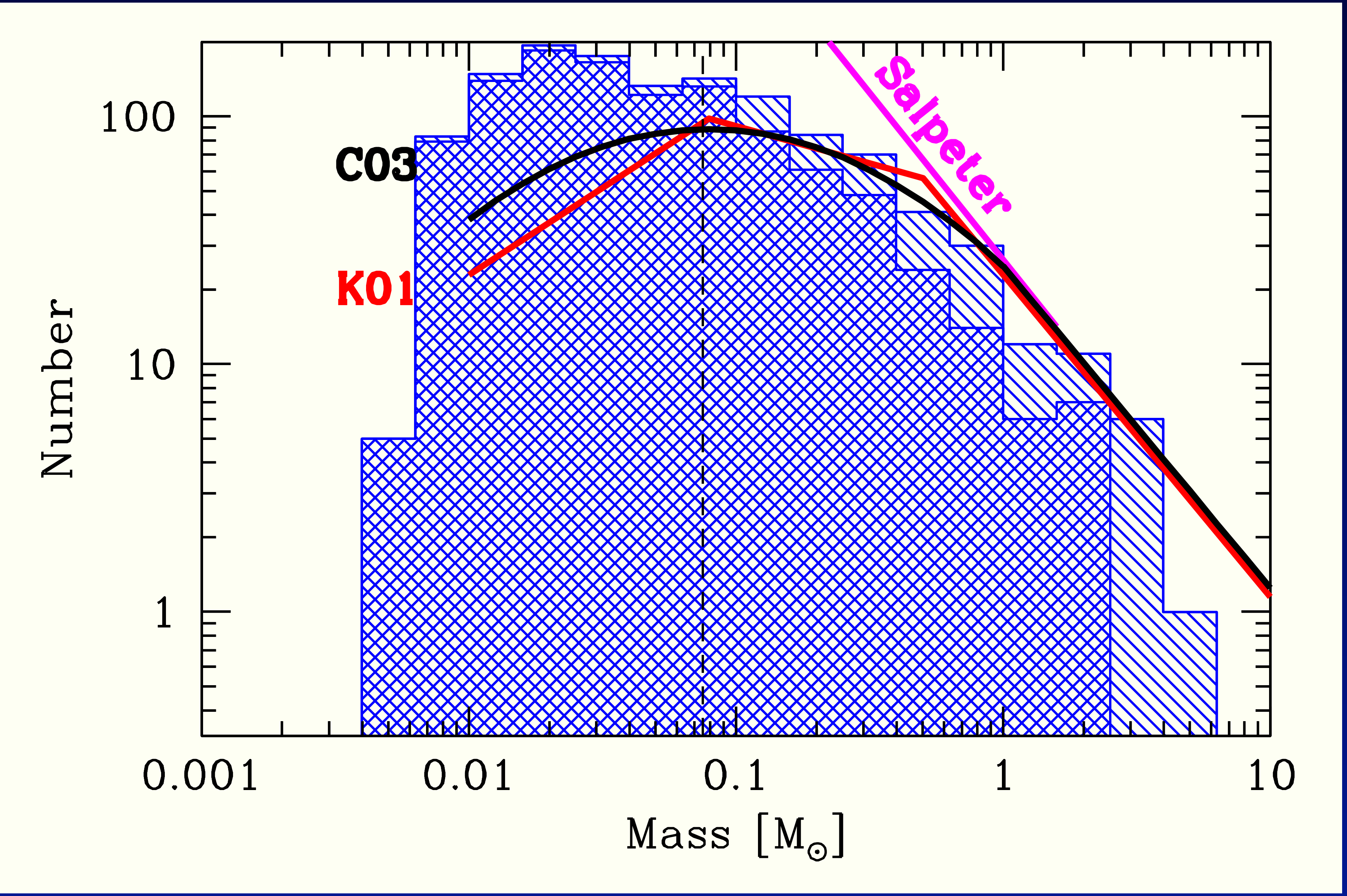
Relative Orbital Orientations of Triples

- Mean angle between orbital planes: 67 ± 9° (Sterzik & Tokovinin 2002)
  - Hydrodynamical simulation (40 systems, including 17 sub-components of quads): 65 ± 6°
  - Cumulative distributions match observations (K-S test: 54%)



Stellar Mass Distribution

- Competitive accretion/ejection gives
  - Salpeter-type slope at high-mass end
  - Low-mass turn over
- >4 times as many brown dwarfs as a typical star-forming region
  - Not due to sink particle approximation - results almost identical for different sink parameters



UNIVERSITY OF EXETER

European Science Foundation

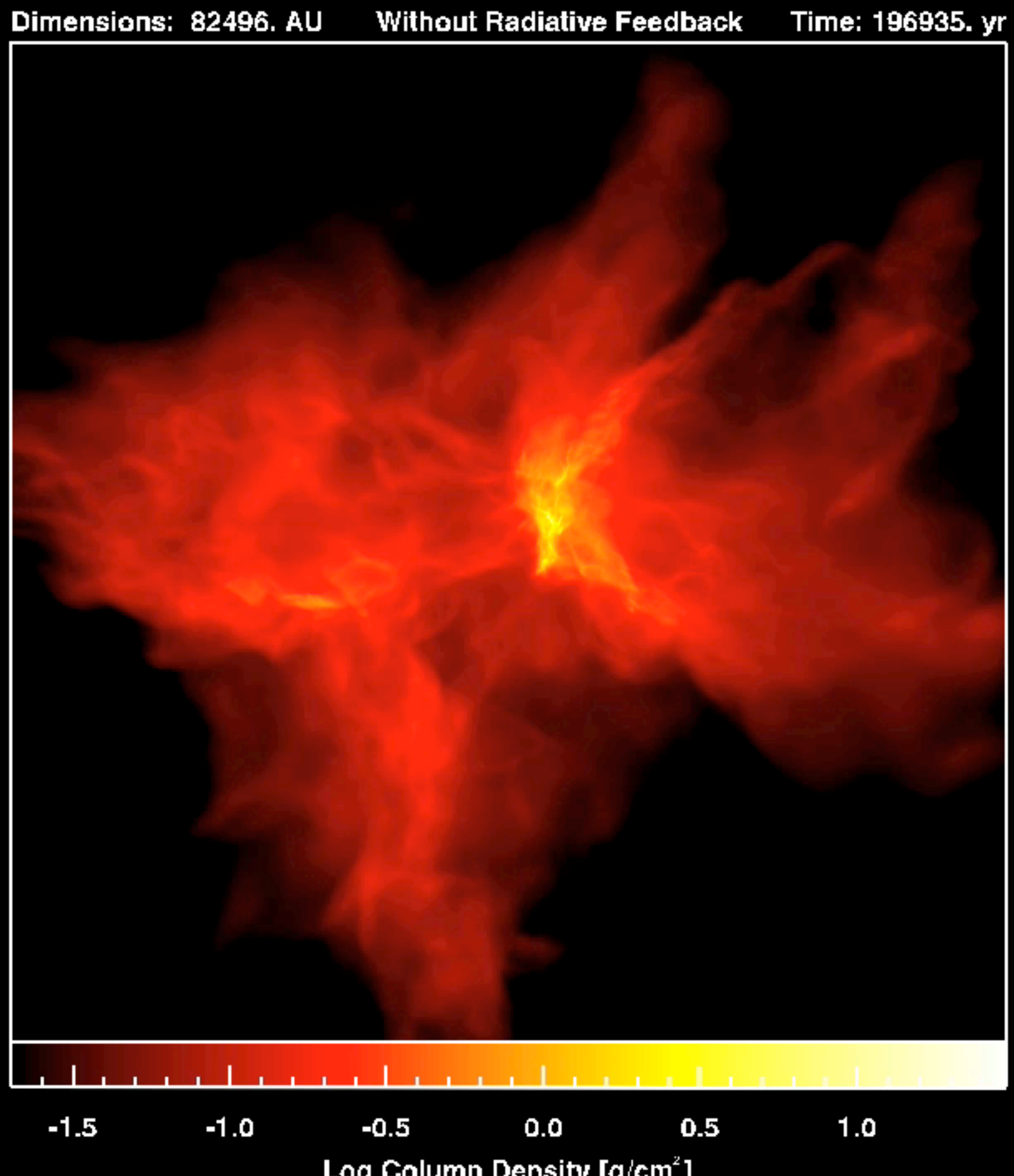
UK Astrophysical Fluids Facility

constellation

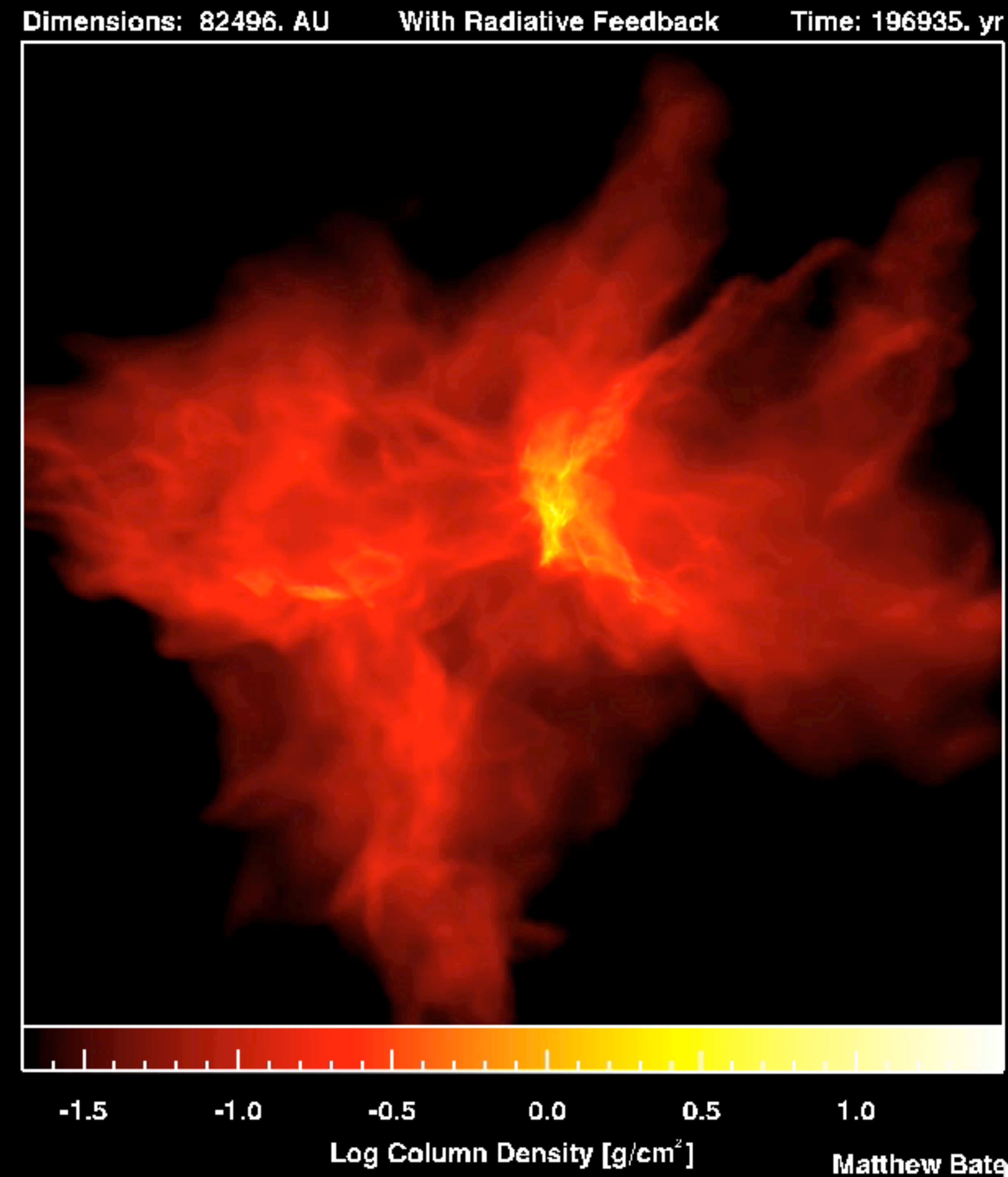
Hydrodynamical Star Formation

- Can perform simulations that form large numbers of objects
- Statistical uncertainties similar to those from observations
- Comparison with observations shows what we get right and wrong
  - Many properties and trends are in good agreement with observations
    - General form of the IMF
    - Multiplicity with primary mass
    - Trends for separation and mass ratio distributions
    - Orbital planes of triple systems
  - One main glaring inconsistency:
    - Too many brown dwarfs
- Long-term evolution improves the agreement with field observations
  - Very wide binaries can be produced in cluster halo (Moeckel & Bate 2010)
  - Fraction of unequal-mass solar-type binaries can be increased with rapid gas dispersal
- Need to move on with additional physics

BBB2003: Typical molecular cloud
Jeans mass 1 $M_{\odot}$, Opacity limit 3 M_J, $P(k) \propto k^{-4}$



BBB2003, but with Radiative Transfer

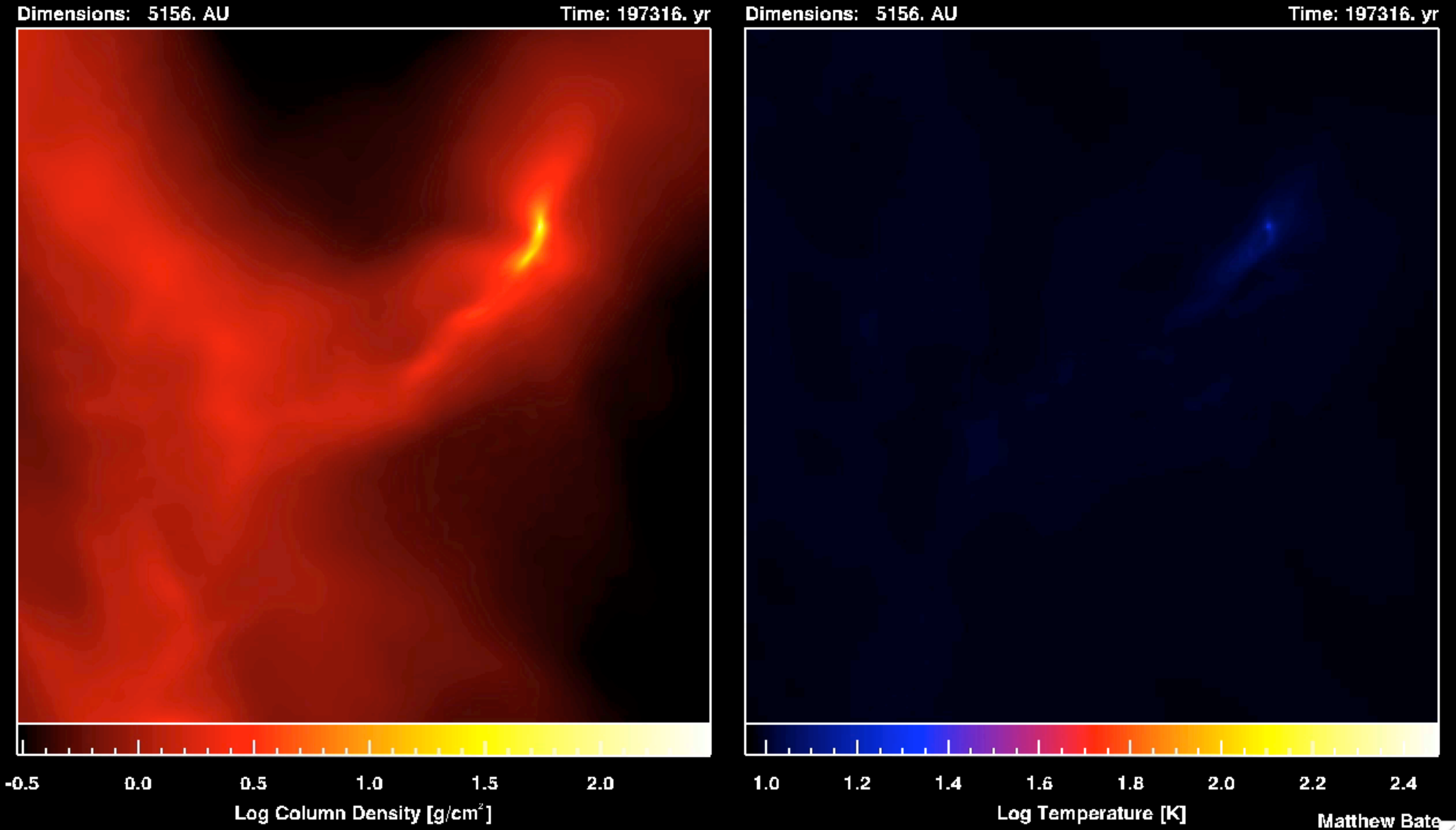


http://www.astro.ex.ac.uk/people/mbate

BBB2003: Typical cloud: Jeans mass 1 $M_{\odot}$, $P(k) \propto k^{-4}$ with Radiative Transfer

Log Column Density

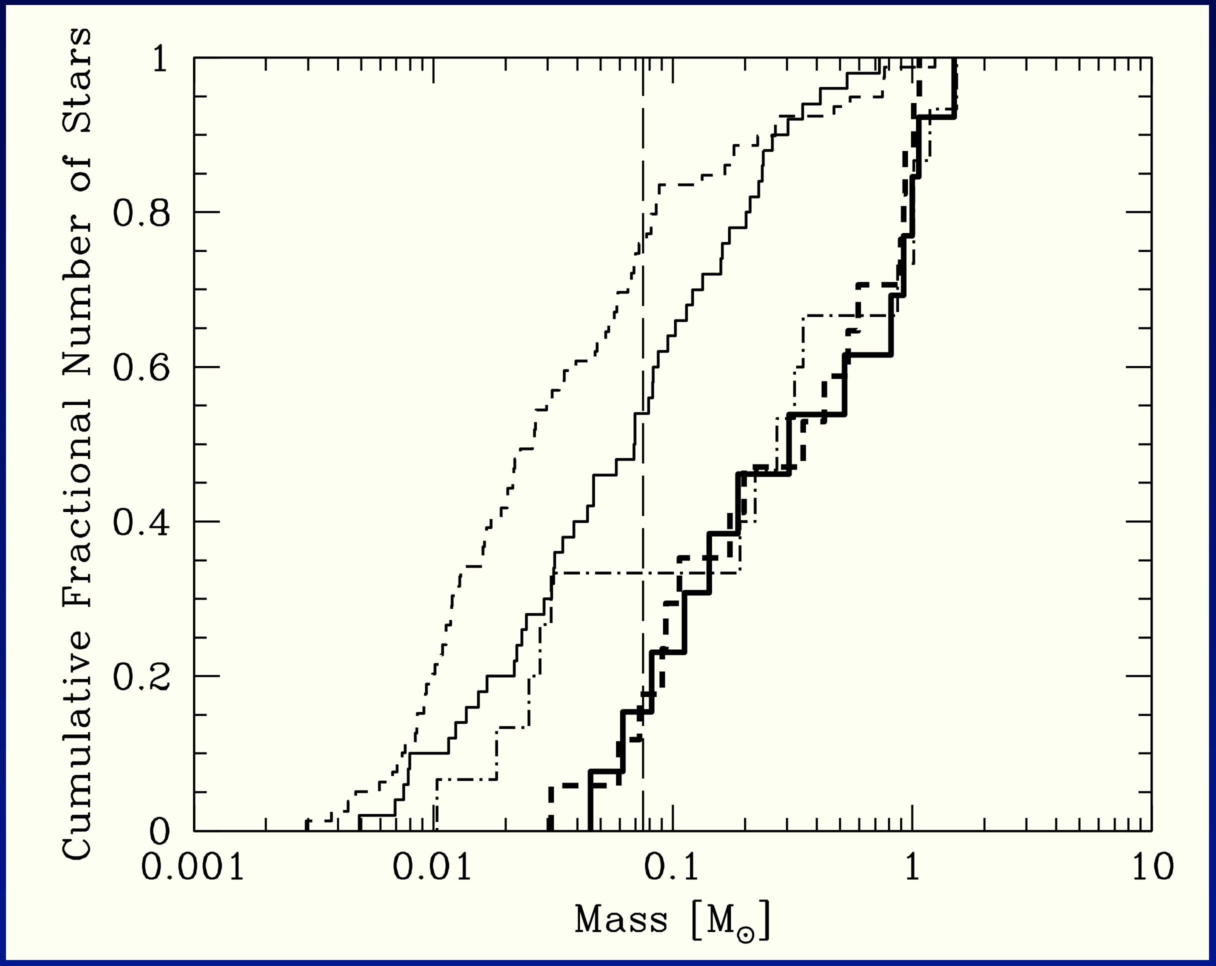
Mass weight temperature (Log 9-100 K)



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

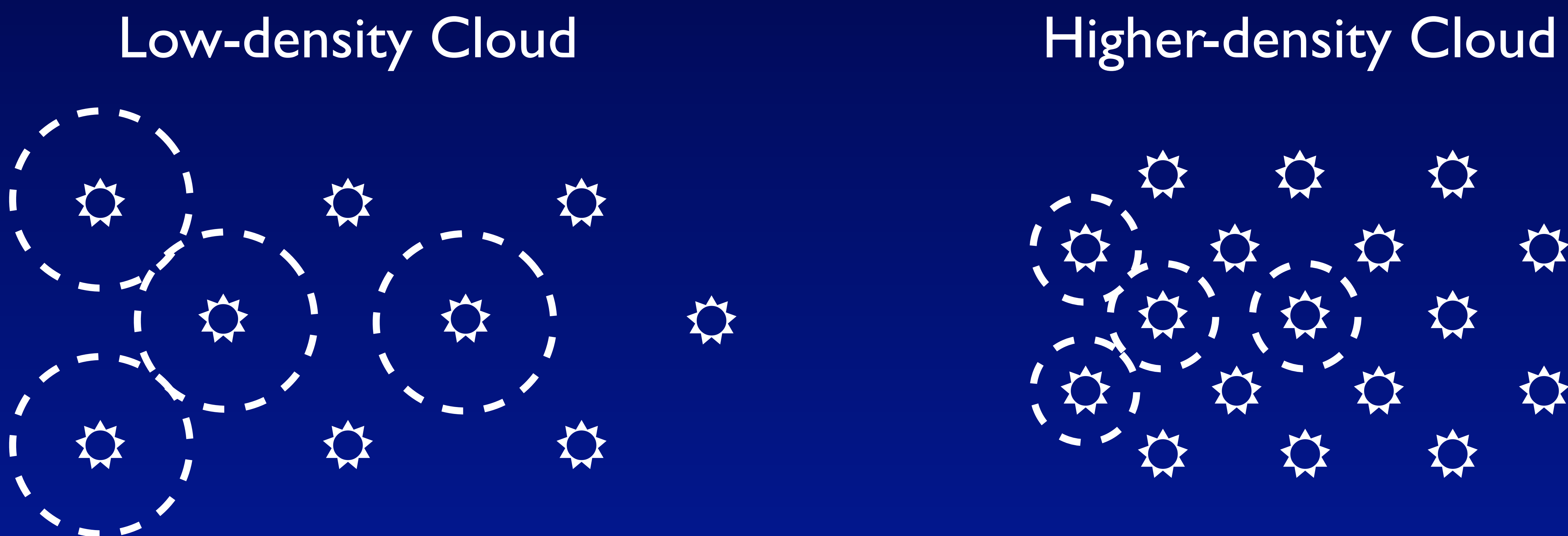
Radiative Feedback and the IMF

- 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
  - 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



UNIVERSITY OF EXETER

European Science Foundation

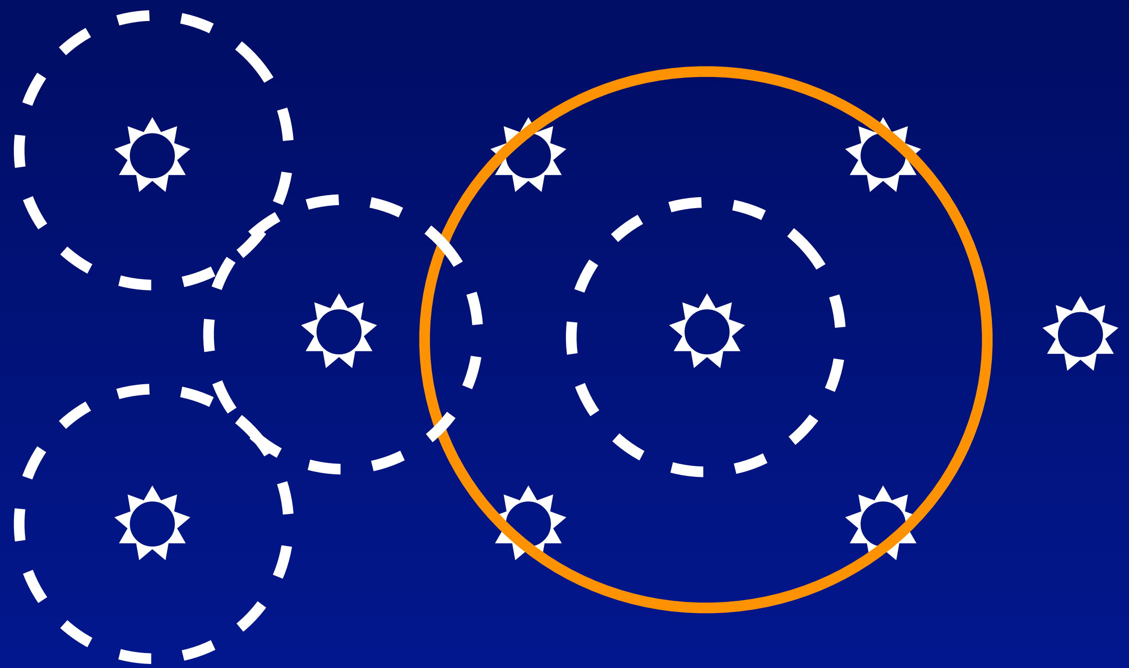
UK Astrophysical Fluids Facility

constellation

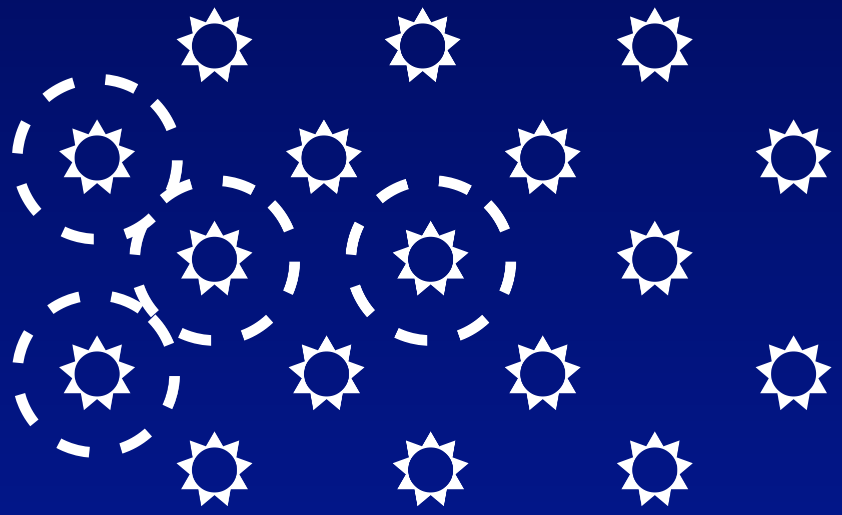
The Apparent Invariance of the IMF

- 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



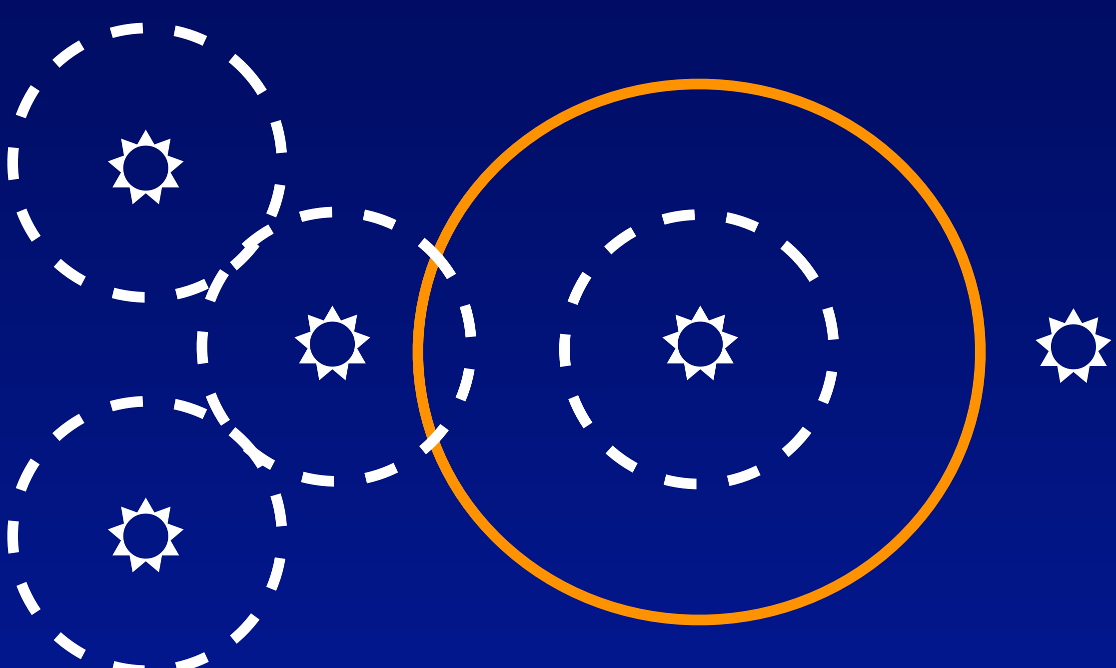
Higher-density Cloud



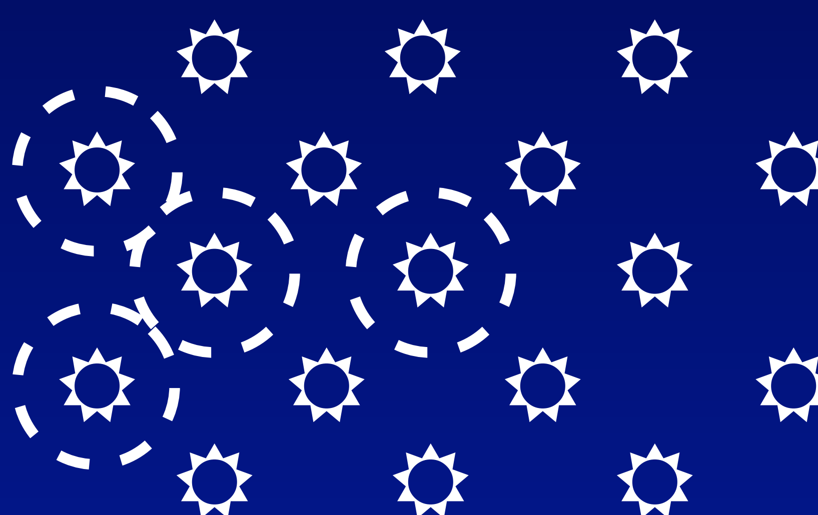
The Apparent Invariance of the IMF

- 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



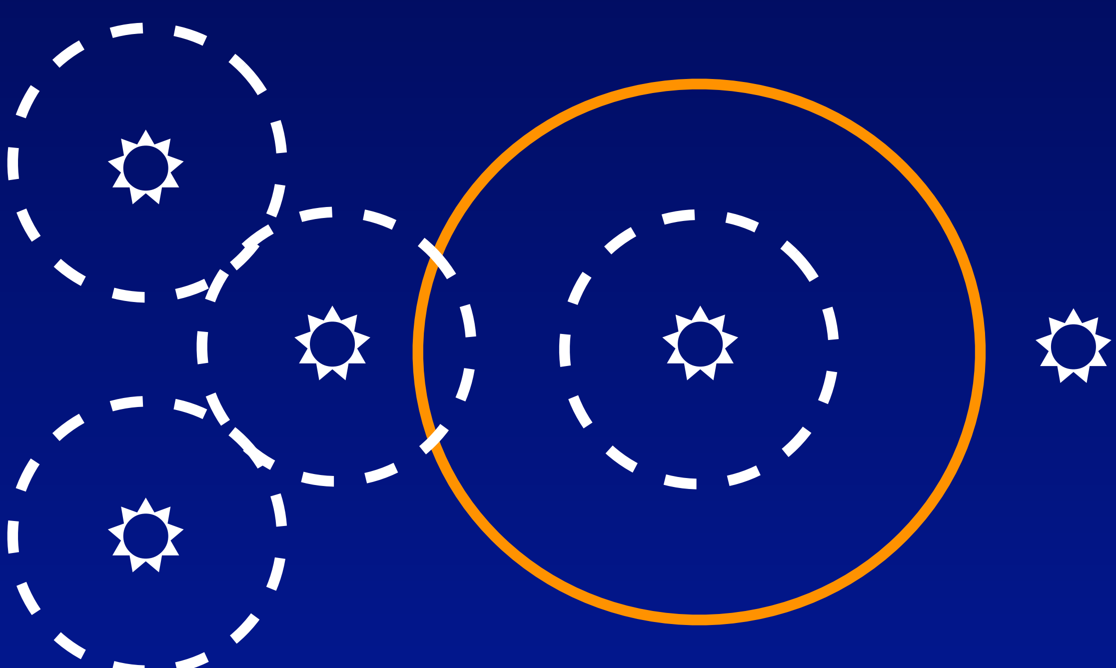
Higher-density Cloud



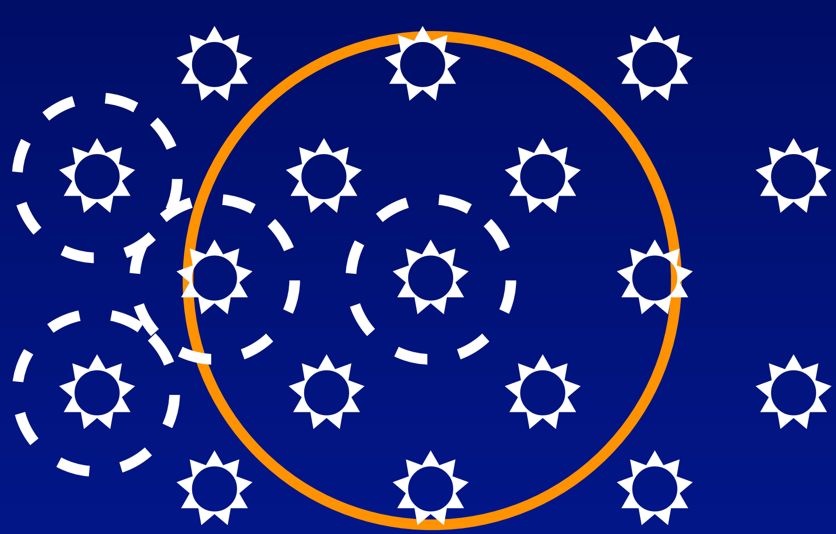
The Apparent Invariance of the IMF

- 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



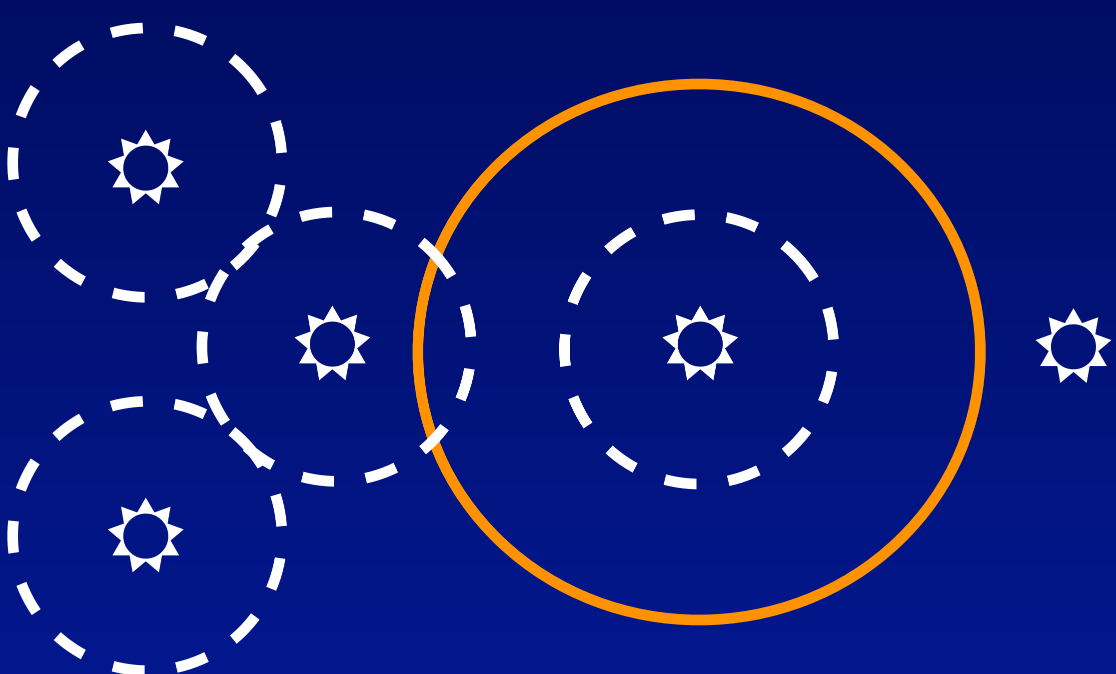
Higher-density Cloud



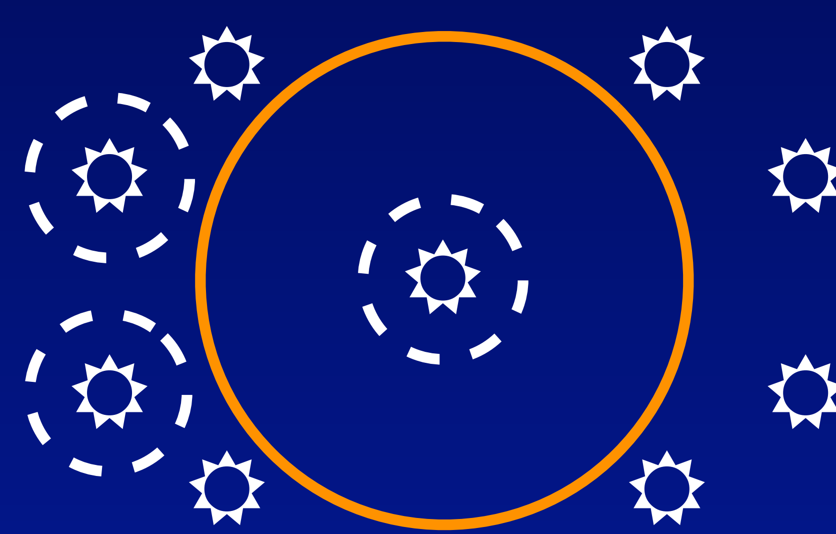
The Apparent Invariance of the IMF

- 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



Large-scale Simulations with Radiative Feedback

- Bate (2012) re-ran Bate (2009a) including radiative feedback and a realistic equation of state
  - 500 $M_\odot$ cloud, using 35,000,000 SPH particles
  - Resolves opacity limit for fragmentation
  - Follows:
    - All binaries (0.02 AU) and discs to ~1 AU radius
- Not able to follow calculation so far
  - Reached 1.2 initial cloud free-fall times (compared to 1.5 for hydrodynamical calculation)
  - Formed 183 stars and brown dwarfs
    - Including 28 binary systems, 5 triples, 7 quadruples
  - Original calculation at the same time: 590 stars and brown dwarfs

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 and discs to ~1 AU

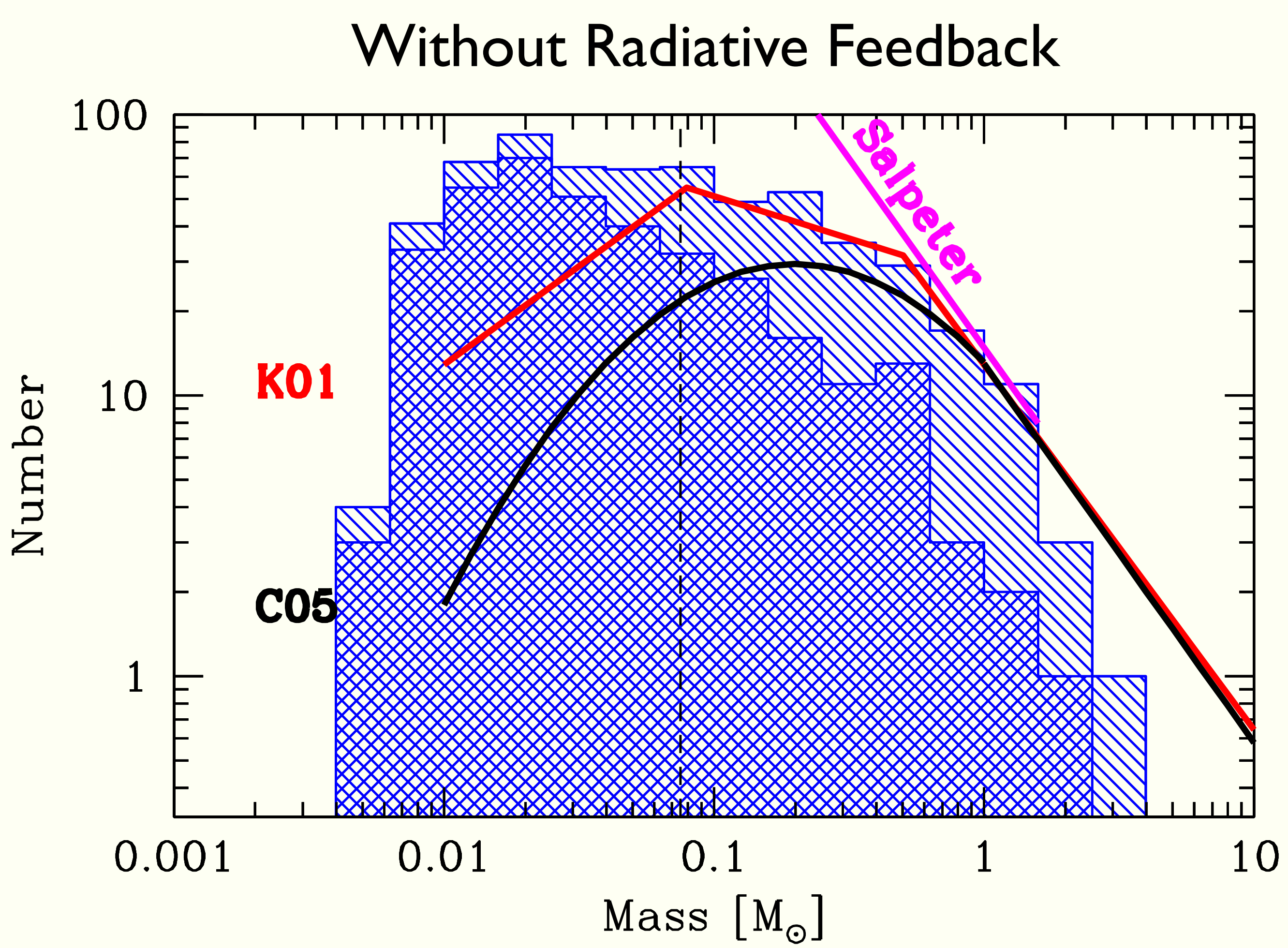
Large-scale Simulations with Radiative Feedback

Large-scale Simulations with Radiative Feedback

- Comparison of the IMFs obtained without and with radiative feedback

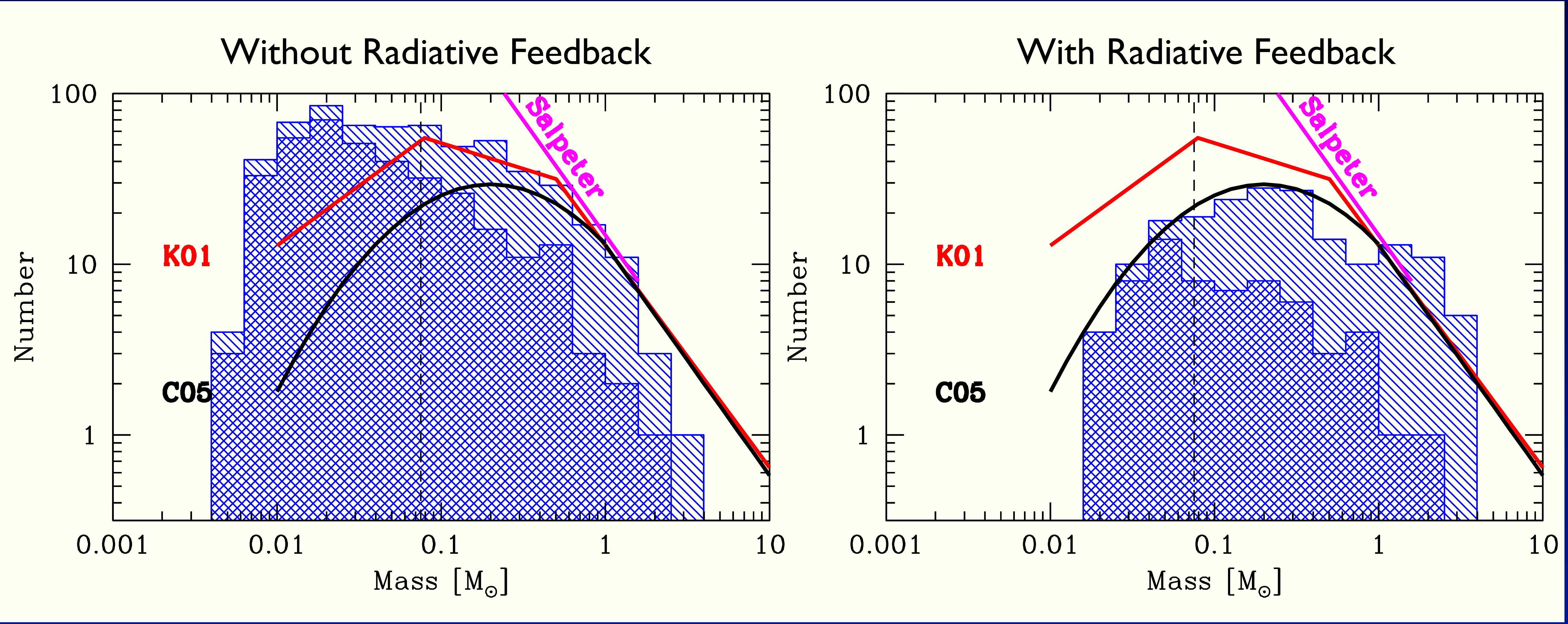
Large-scale Simulations with Radiative Feedback

- Comparison of the IMFs obtained without and with radiative feedback



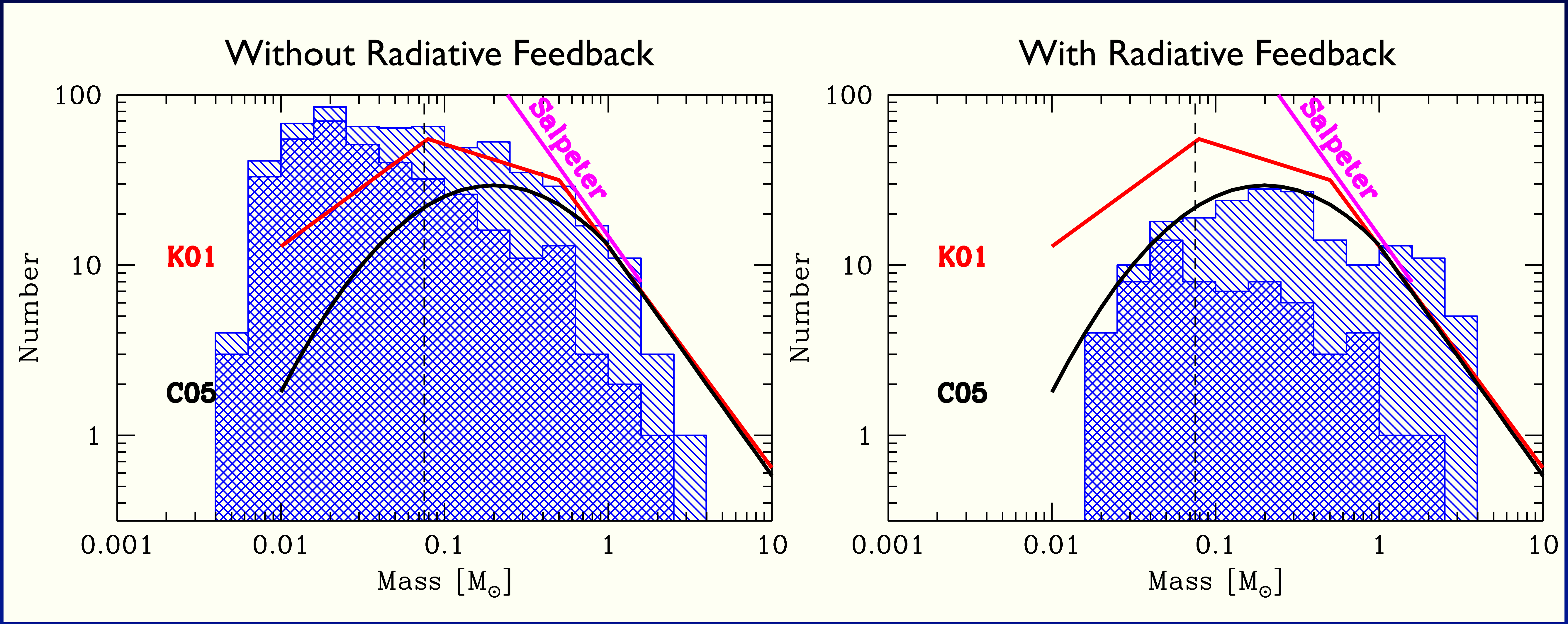
Large-scale Simulations with Radiative Feedback

- Comparison of the IMFs obtained without and with radiative feedback



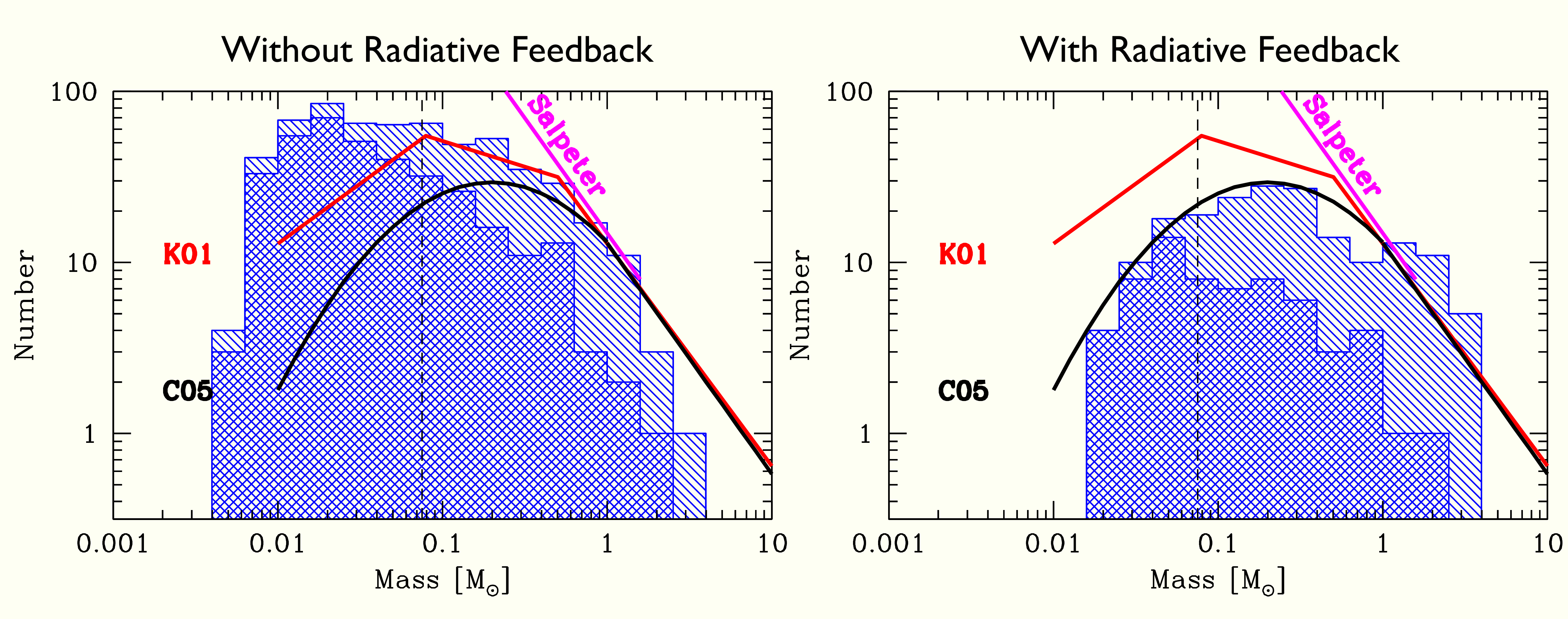
Large-scale Simulations with Radiative Feedback

- Comparison of the IMFs obtained without and with radiative feedback
  - Many fewer brown dwarfs, confirming Bate (2009b), Offner et al. (2009) but better stats



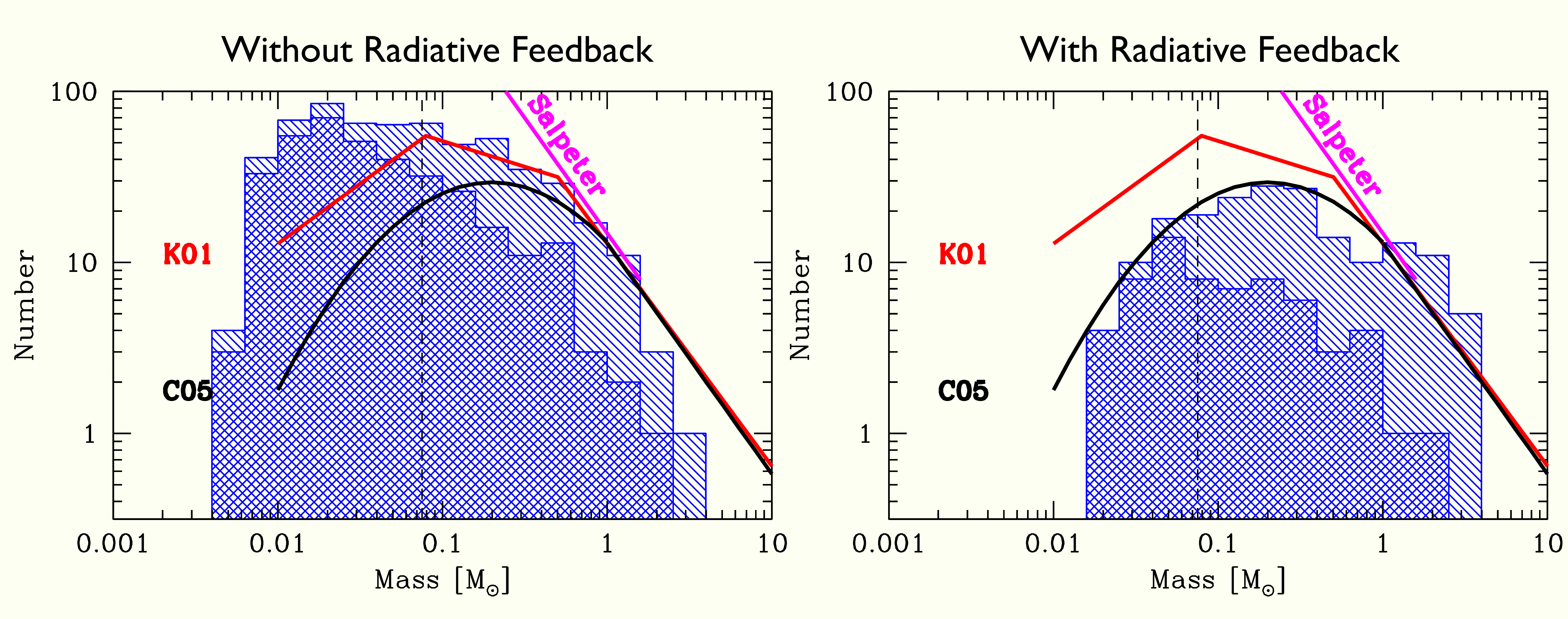
Large-scale Simulations with Radiative Feedback

- Comparison of the IMFs obtained without and with radiative feedback
  - Many fewer brown dwarfs, confirming Bate (2009b), Offner et al. (2009) but better stats
  - More stars than brown dwarfs: Ratio: N(1.0-0.08)/N(0.03-0.08) = 117/31 = 3.8



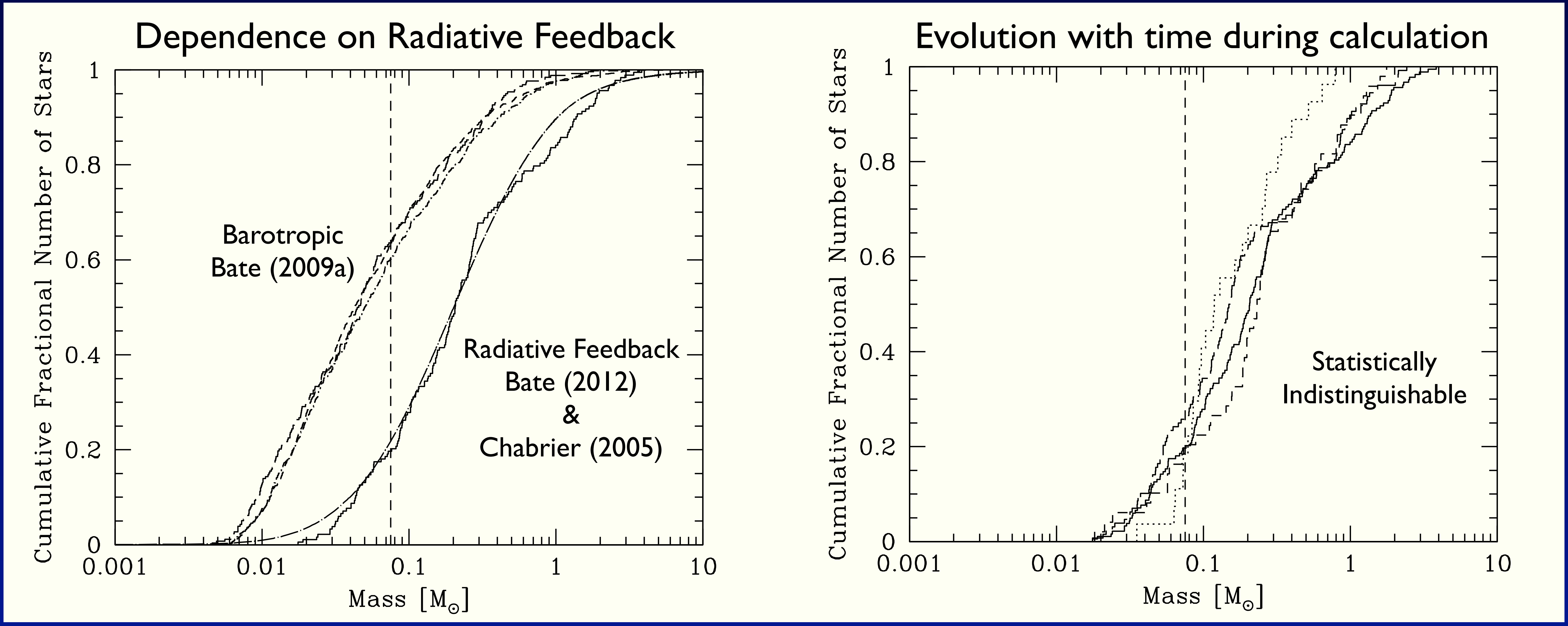
Large-scale Simulations with Radiative Feedback

- Comparison of the IMFs obtained without and with radiative feedback
  - Many fewer brown dwarfs, confirming Bate (2009b), Offner et al. (2009) but better stats
  - More stars than brown dwarfs: Ratio: N(1.0-0.08)/N(0.03-0.08) = 117/31 = 3.8
  - Mass function consistent with Chabrier (2005) parameterisation of the Galactic IMF



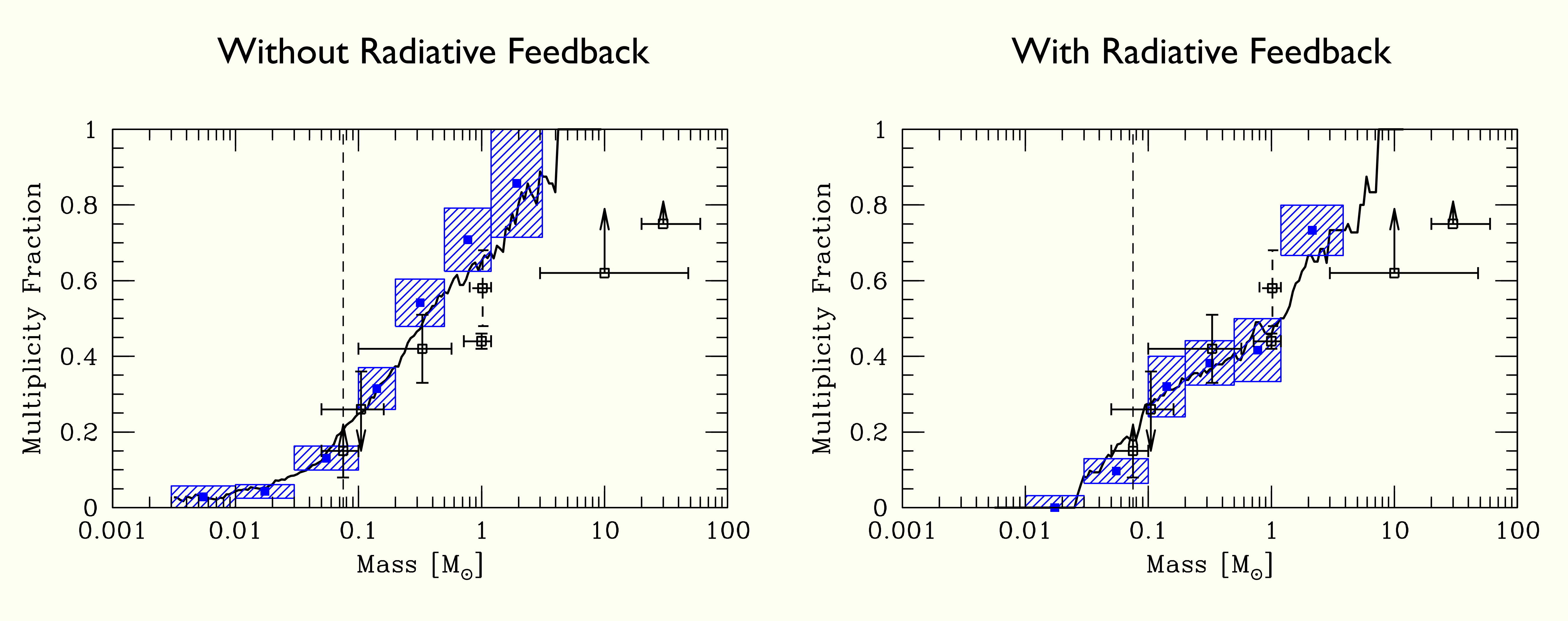
Cumulative Mass Functions

- Comparison of the IMFs
  - Left panel: Without and with radiative feedback
    - Mass function consistent with Chabrier (2005) parameterisation of the Galactic IMF
  - Right panel: with radiative feedback at four different times (indistinguishable)



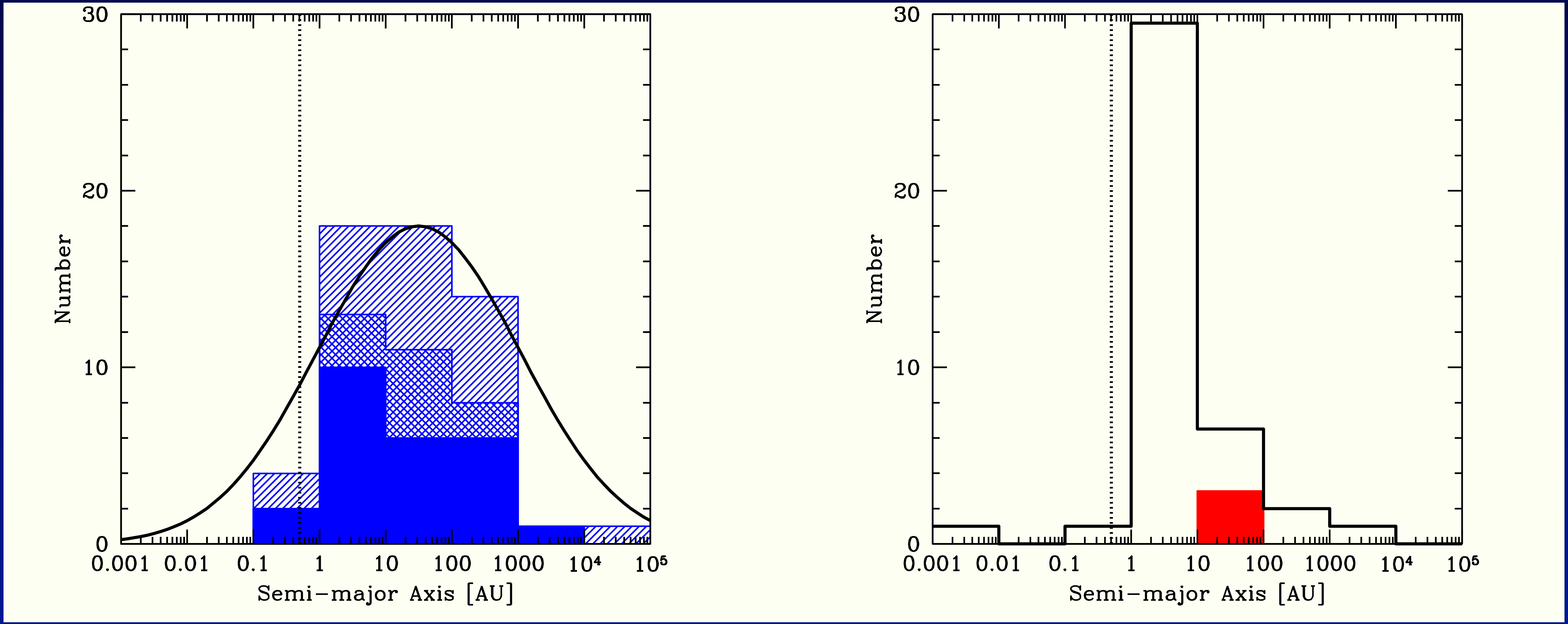
Multiplicity with Radiative Feedback

- Multiplicity as a function of primary mass
  - Comparison with Close et al. (2003); Basri & Reiners (2006); Fisher & Marcy (1992); Raghavan et al. (2010); Duquennoy & Mayor (1991); Preibisch et al. (1999); Mason et al. (1998)
  - Multiplicities similar for low-mass stars, perhaps a little lower for intermediate masses
  - Smaller numbers, but still consistent with observations



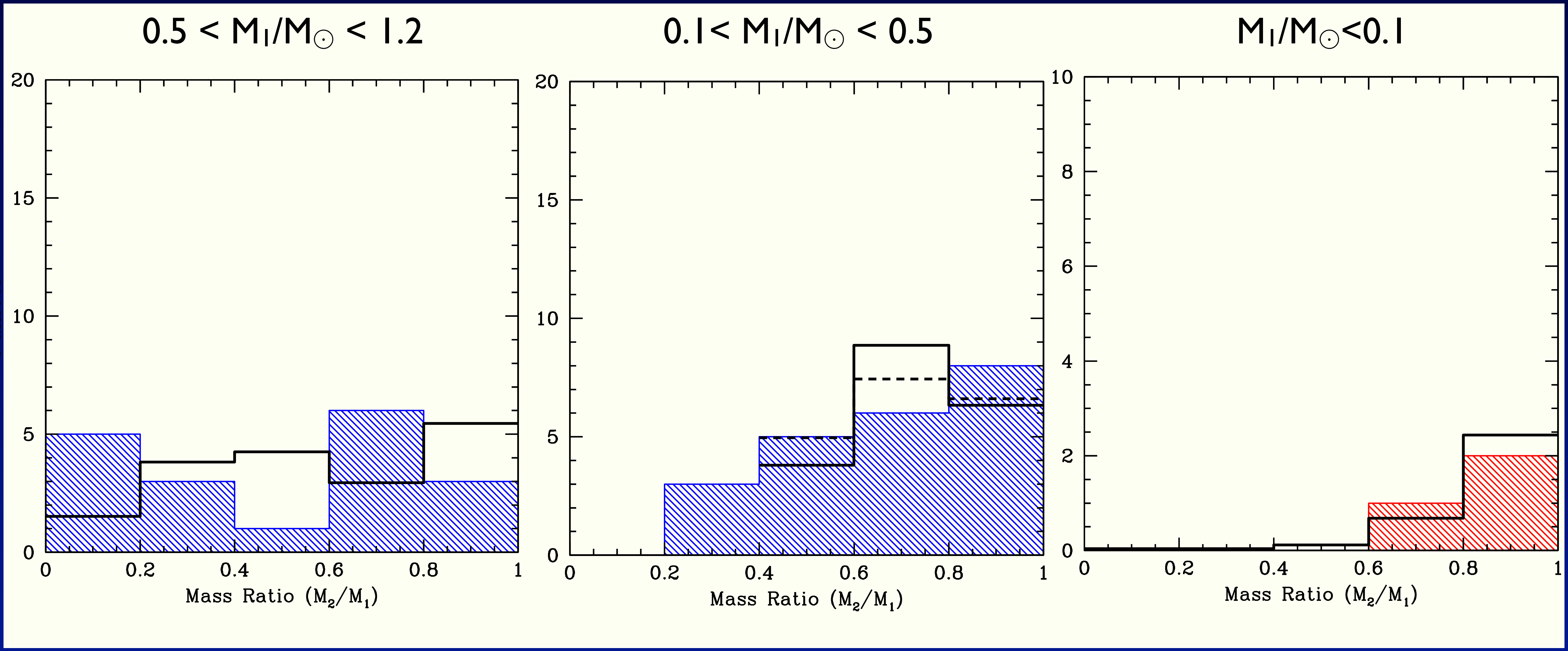
Multiple Star Separations with Radiative Feedback

- Separation distributions as a function of primary mass
  - Comparison with Raghavan et al. (2010) and vlmbinaries.org
  - Stellar binaries have a broad range of separations
  - Very-low-mass binaries (binary brown dwarfs) have separations < 20 AU



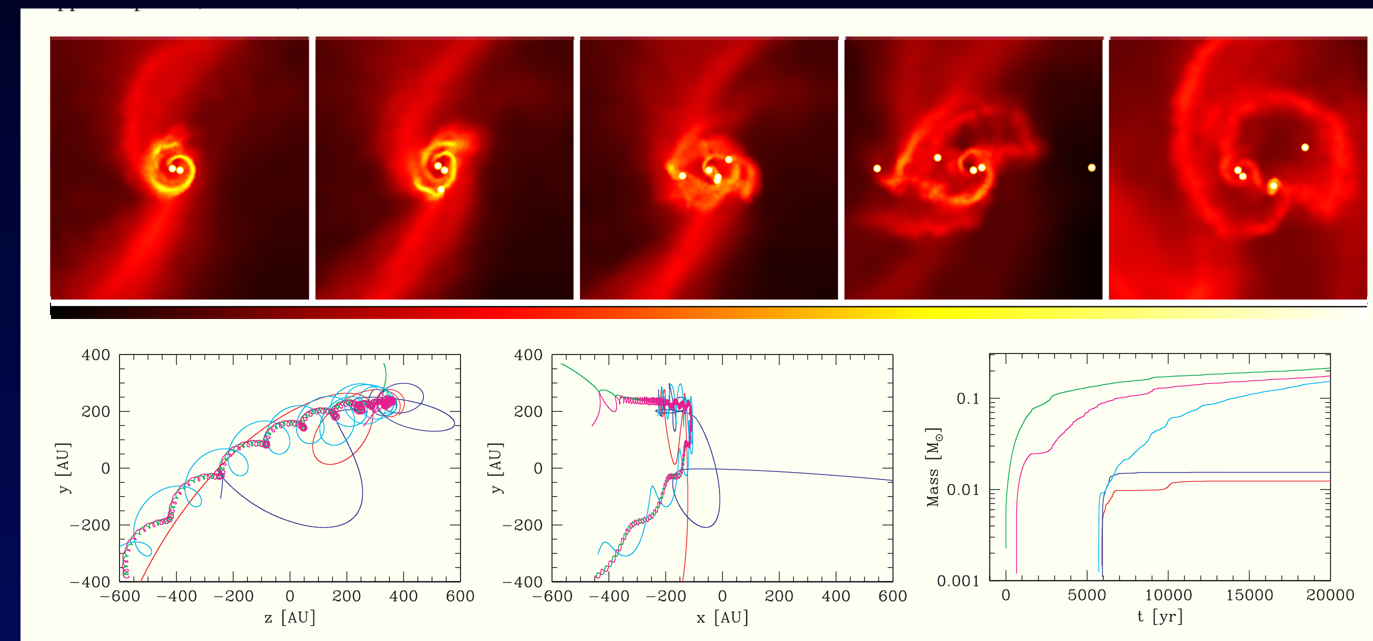
Binary Star Mass Ratios with Radiative Feedback

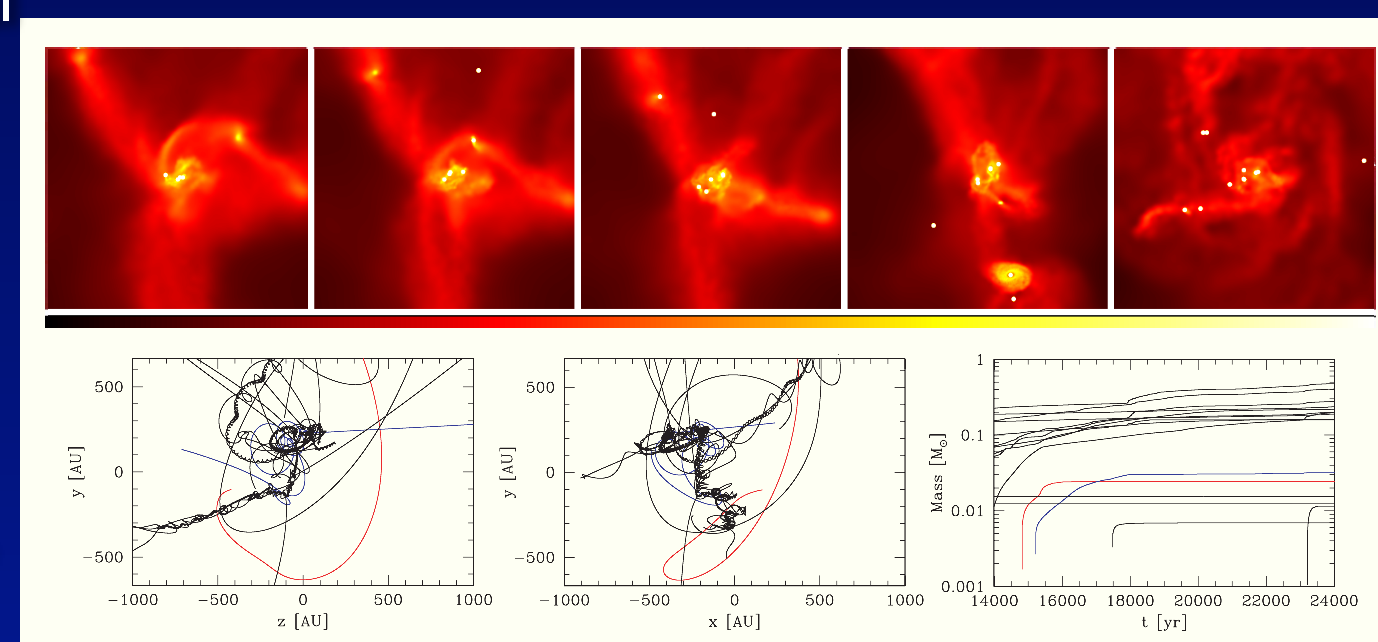
- Binary mass ratios as a function of primary mass
  - Comparison with surveys of Raghavan et al. (2010), Fisher & Marcy (1992), vlmbinaries.org
  - Very-low-mass objects (brown dwarfs) have near-equal masses
  - More massive primaries have consistently flatter distributions



Brown dwarf formation

- How do brown dwarfs form?
  - Bate, Bonnell & Bromm 2002a
  - 3/4 in massive circumstellar discs via disc fragmentation
    - Bonnell 1994; Whitworth et al. 1995; Burkert et al. 1997
  - 1/4 in dense 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





Brown dwarf formation

Brown dwarf formation

- Radiative feedback strongly inhibits disc fragmentation

Brown dwarf formation

- Radiative feedback strongly inhibits disc fragmentation
- Bate (2012)
  - 34 VLM objects that have stopped accreting at the end of the calculation
  - No more than 7 (20%) form via disc fragmentation
  - 80% of the VLM objects form in filaments created by the turbulence
  - However, dynamical interactions with other objects are instrumental in terminating their accretion before they attain stellar masses

Brown dwarf formation

- Radiative feedback strongly inhibits disc fragmentation
- Bate (2012)
  - 34 VLM objects that have stopped accreting at the end of the calculation
  - No more than 7 (20%) form via disc fragmentation
  - 80% of the VLM objects form in filaments created by the turbulence
  - However, dynamical interactions with other objects are instrumental in terminating their accretion before they attain stellar masses
- Comparison with Bate et al. (2002)
  - Formed more brown dwarfs than stars
  - Correct very-low-mass end of the IMF is obtained when radiative feedback stops (almost all) disc fragmentation, but allows (most) filament fragmentation

Conclusions

Conclusions

- Dynamical interactions between protostars and protostars and clouds
  - Are key for the properties of multiple systems
  - Can reproduce many of the observed properties or trends for multiple stars

Conclusions

- Dynamical interactions between protostars and protostars and clouds
  - Are key for the properties of multiple systems
  - Can reproduce many of the observed properties or trends for multiple stars
- Radiative feedback **and** dynamical interactions
  - Are necessary to reproduce the IMF
  - Together: mass function and multiplicity in good agreement with observations
  - Radiative feedback solves the over-production of brown dwarfs
  - Help to produce a `universal' IMF (severely weakens the dependence on initial Jeans mass)