Brown Dwarf Formation from Early Ejection: Results from Recent SPH Simulations

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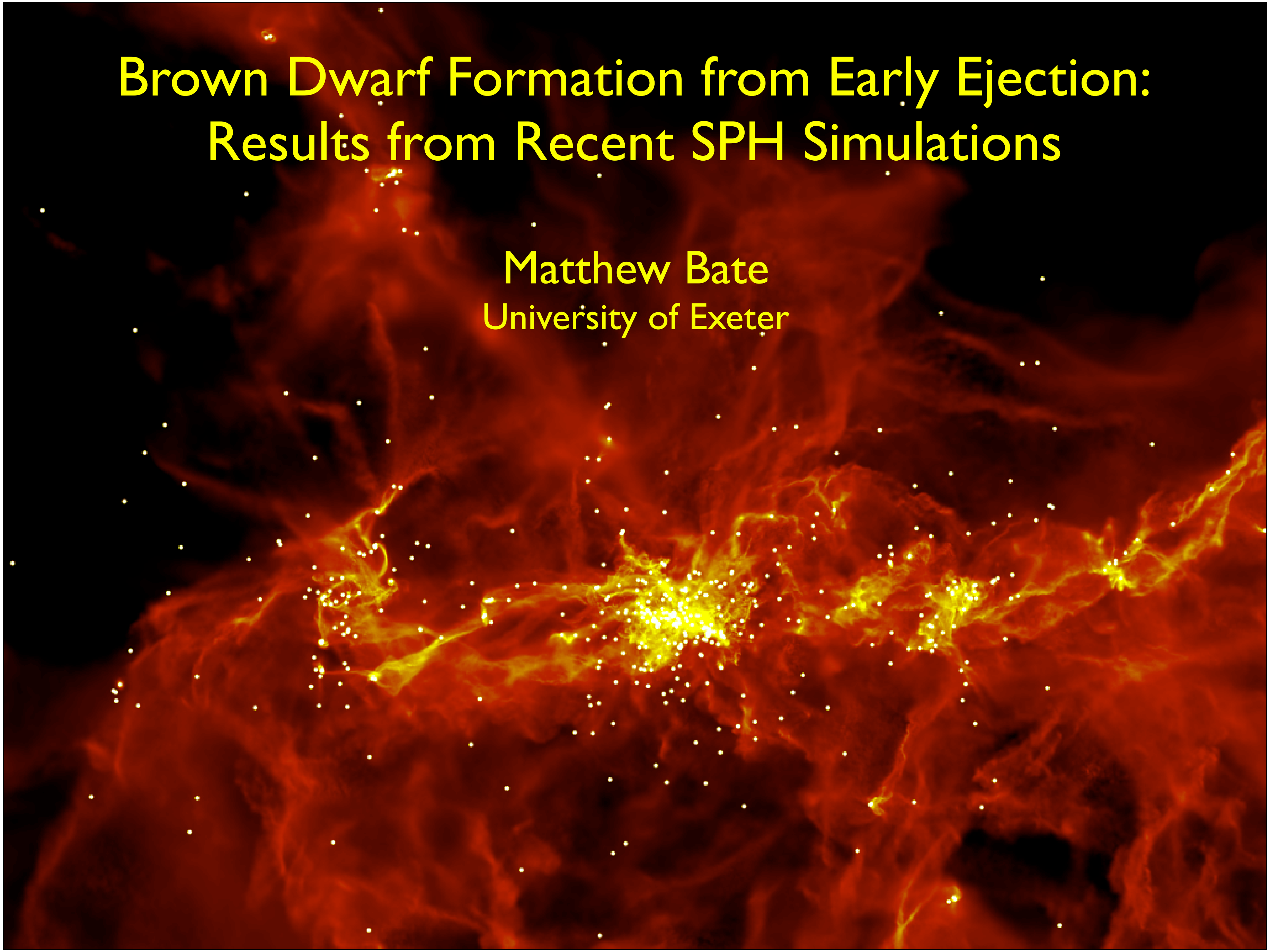
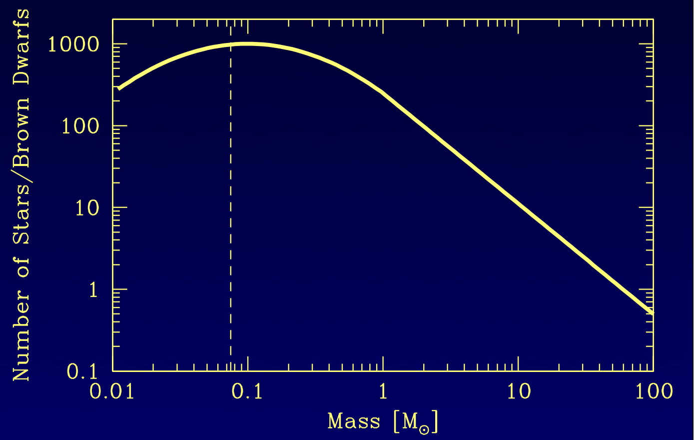


Stellar Properties

- Distribution of stellar masses
  - Observed to be relatively invariant, at least in our Galaxy (Kroupa 2001; Chabrier 2003)
- Star formation rate and efficiency
  - Observed to be 3-6% of gas mass per free-fall time (Evans et al. 2009)
- Fraction of binary and multiple stars
  - Observed to be an increasing function of primary mass
  - Separations, mass ratios, eccentricities
  - High order systems (triples, quadruples)
- Protoplanetary discs
  - Masses, sizes, density distributions



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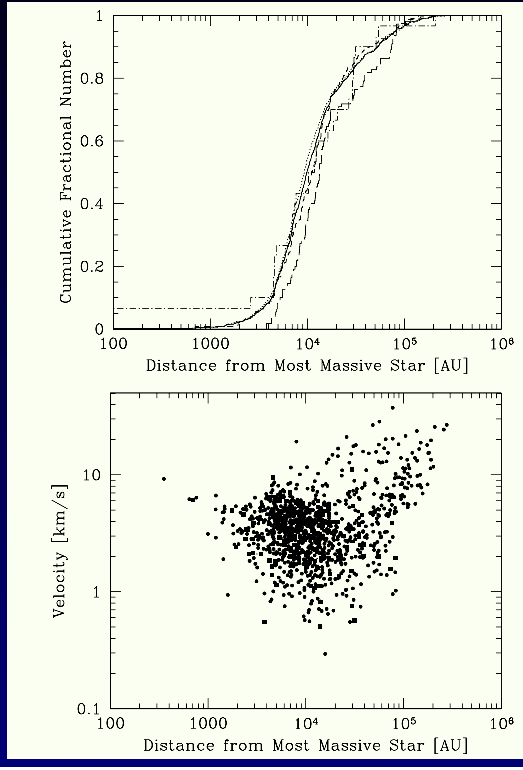
Bate 2009a: 500 M$_\odot$ cloud with decaying turbulence, 35 million SPH particles
Follows binaries to 1 AU, discs to ~10 AU
Forms 1254 stars and brown dwarfs - best statistics to date from a single calculation

Radial Distributions of Properties

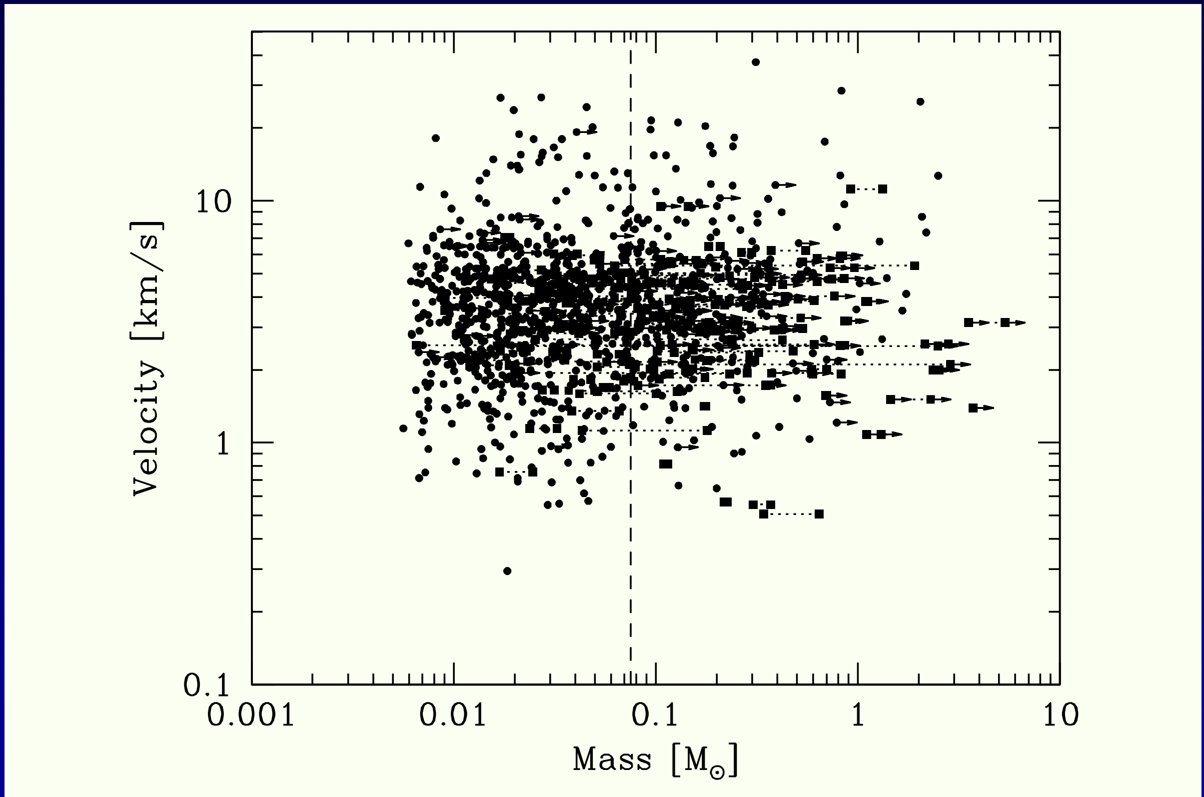
- The calculation produces a very dense cluster
  - Half-mass radius is just 10,000 AU (0.05 pc)
- No significant mass segregation in the cluster or halo
  - Contrary to the usual picture of competitive accretion, perhaps due to the recent mergers of sub-clusters
  - Binary fractions decrease & velocity dispersion increases
    - But only outside 3 half-mass radii
    - Kohler et al. 2006 investigated ONC binaries at 1-2 half-mass radii



Quantity / Distance range	< 1000 AU	$1000 - 3000$ AU	$3000 - 10^4$ AU	$1 - 3 \times 10^4$ AU	$3 - 10 \times 10^4$ AU	$> 1 \times 10^5$ AU
Median mass [$M_\odot$]	0.18	0.024	0.035	0.056	0.054	0.045
Upper quartile mass [$M_\odot$]	0.30	0.091	0.098	0.15	0.18	0.095
Maximum mass [$M_\odot$]	5.3	2.9	3.7	2.5	2.1	2.0
Velocity dispersion [km/s]	6.1	4.0	4.2	4.3	8.2	13.8
Number objects	8	56	569	408	172	41
Number binaries	2	8	68	55	13	0
Binary fraction	0.33	0.167	0.136	0.156	0.082	0.0

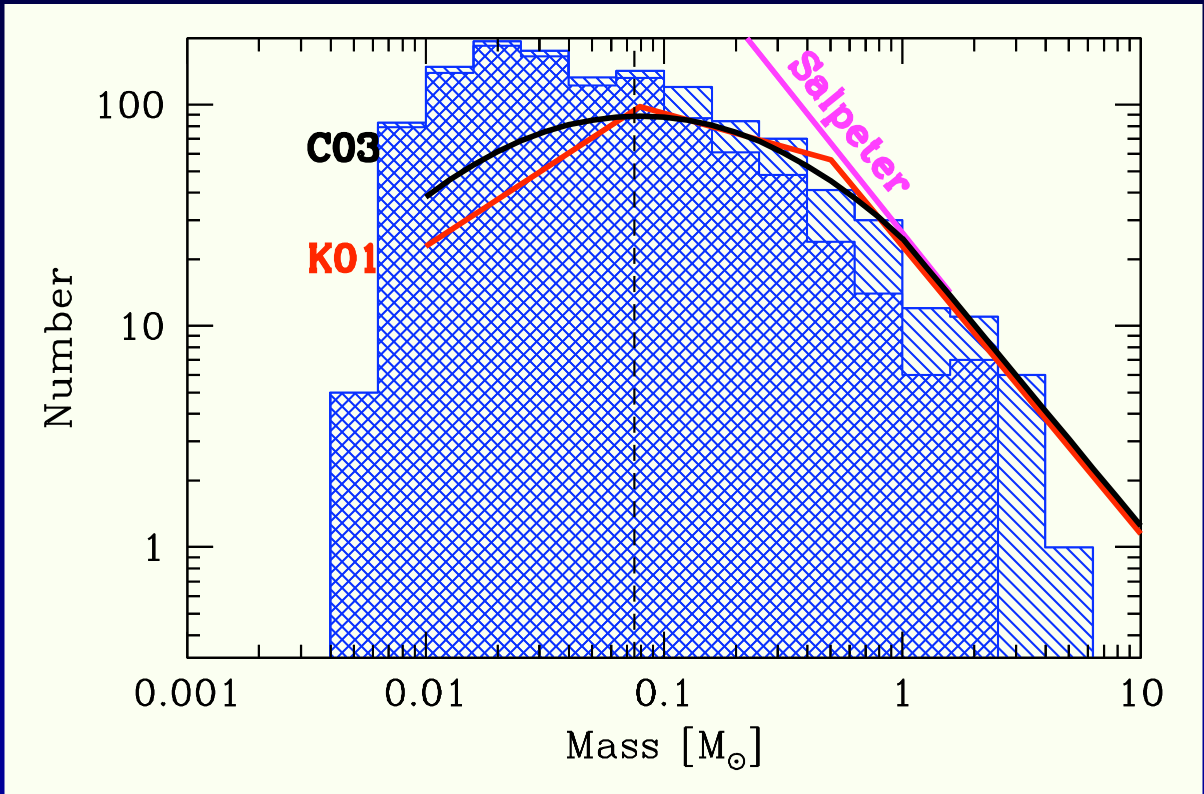
Velocity Dispersion

- No strong dependence of stellar velocities on stellar mass
  - VLM objects have a smaller velocity dispersion than stars (80%) (c.f. Joergens)
  - Binaries have ~60% of the velocity dispersion of single stars



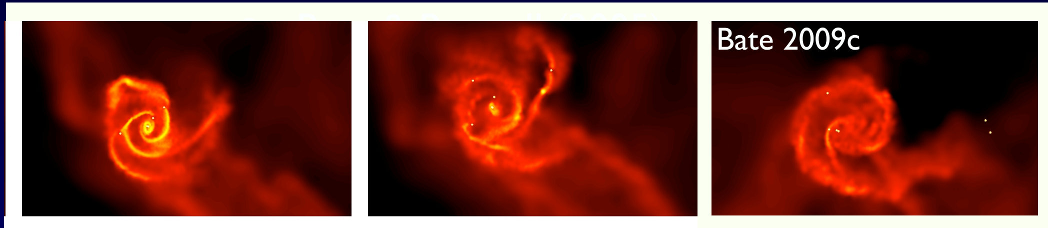
Stellar Mass Distribution

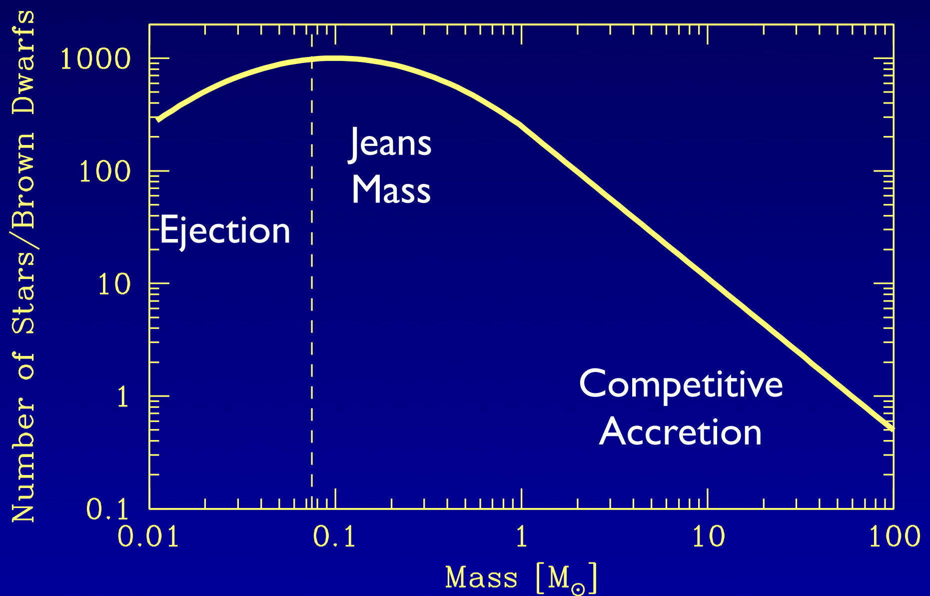
- Competitive accretion/ejection gives
  - Salpeter-type slope at high-mass end
  - Low-mass turn over
- ~4 times as many brown dwarfs as a typical star-forming region
  - Not due to sink particle approximation - results almost identical for different sink parameters

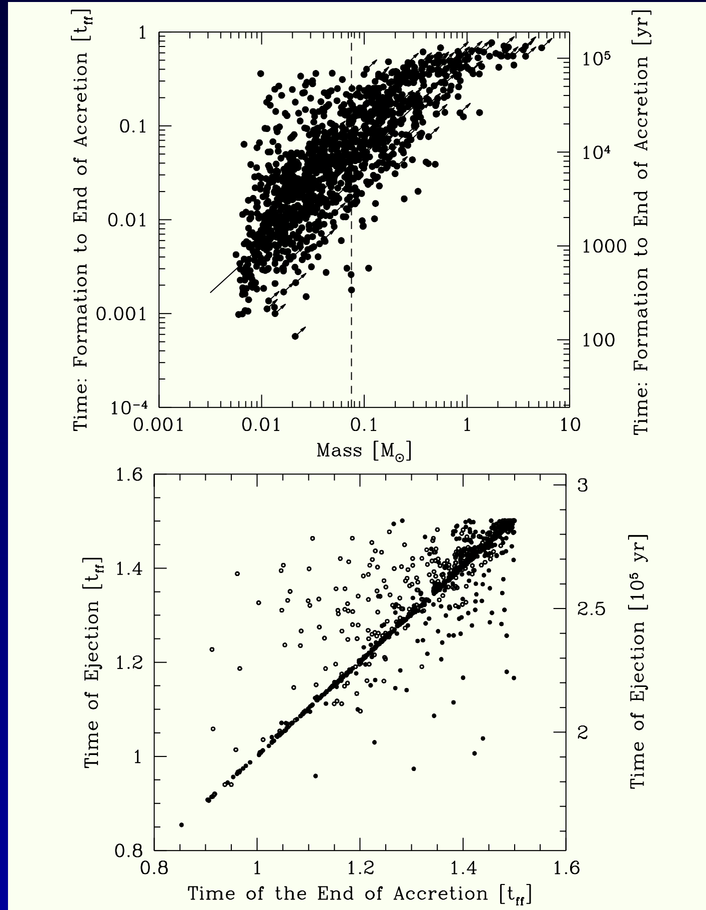


IMF: Competitive Accretion and Ejection

- Stars and brown dwarfs
  - Form with opacity limited masses, accrete to larger masses
  - Final masses depend on how long they accrete
  - Accretion typically terminated by ejection

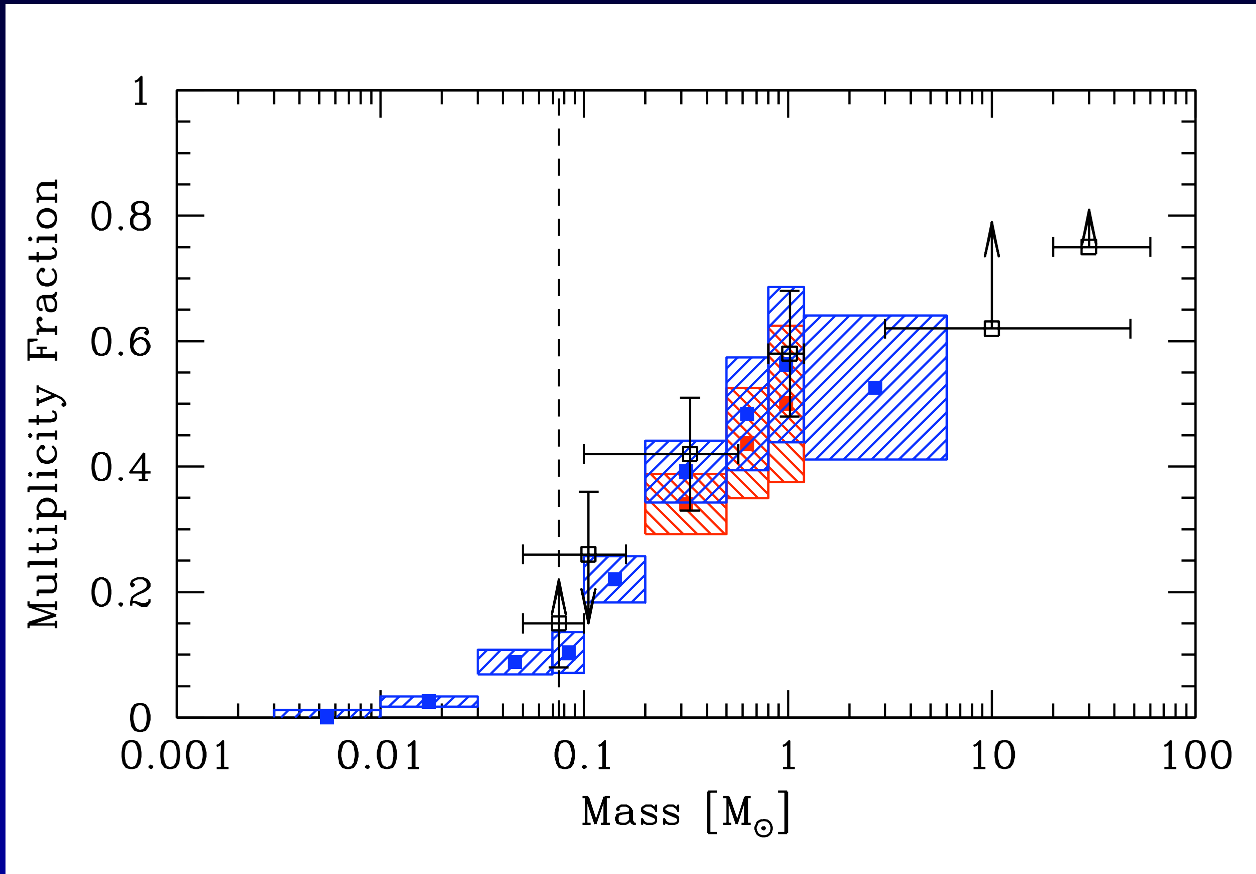






Multiplicity as a Function of Primary Mass

- 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



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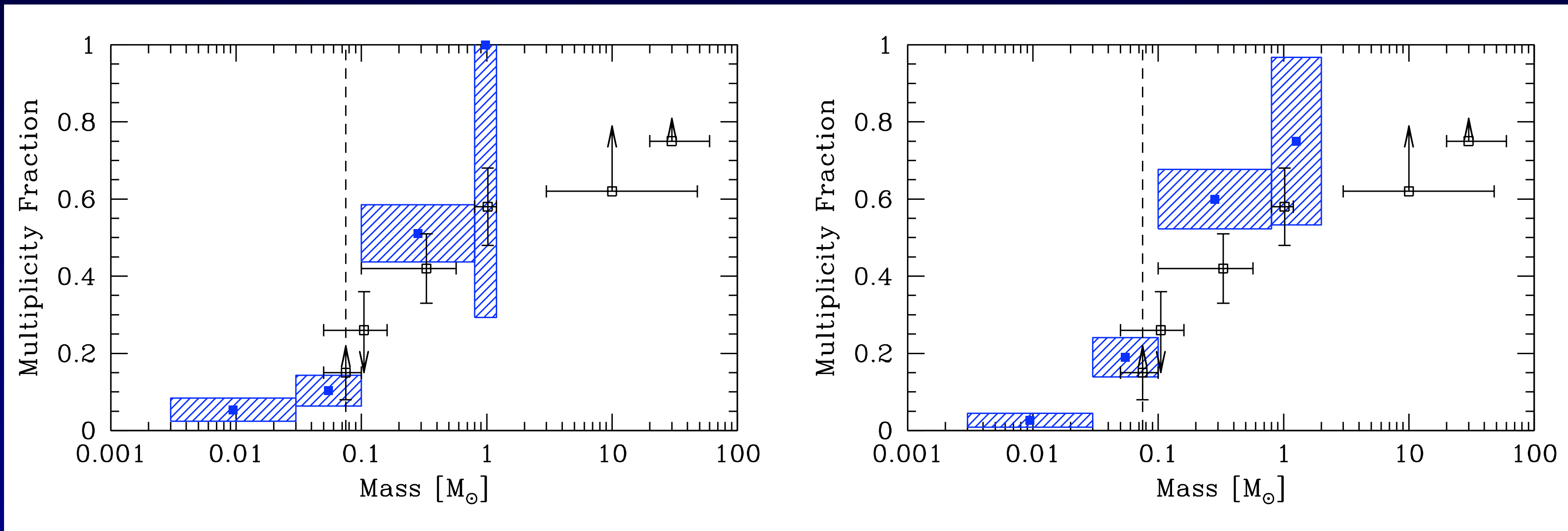
Dependence of Multiplicity on Sink Particle Radius

- Decreasing the sink particle accretion radius slightly increases the VLM binary frequency

Accretion radius: 5 AU

Accretion Radius: 0.5 AU



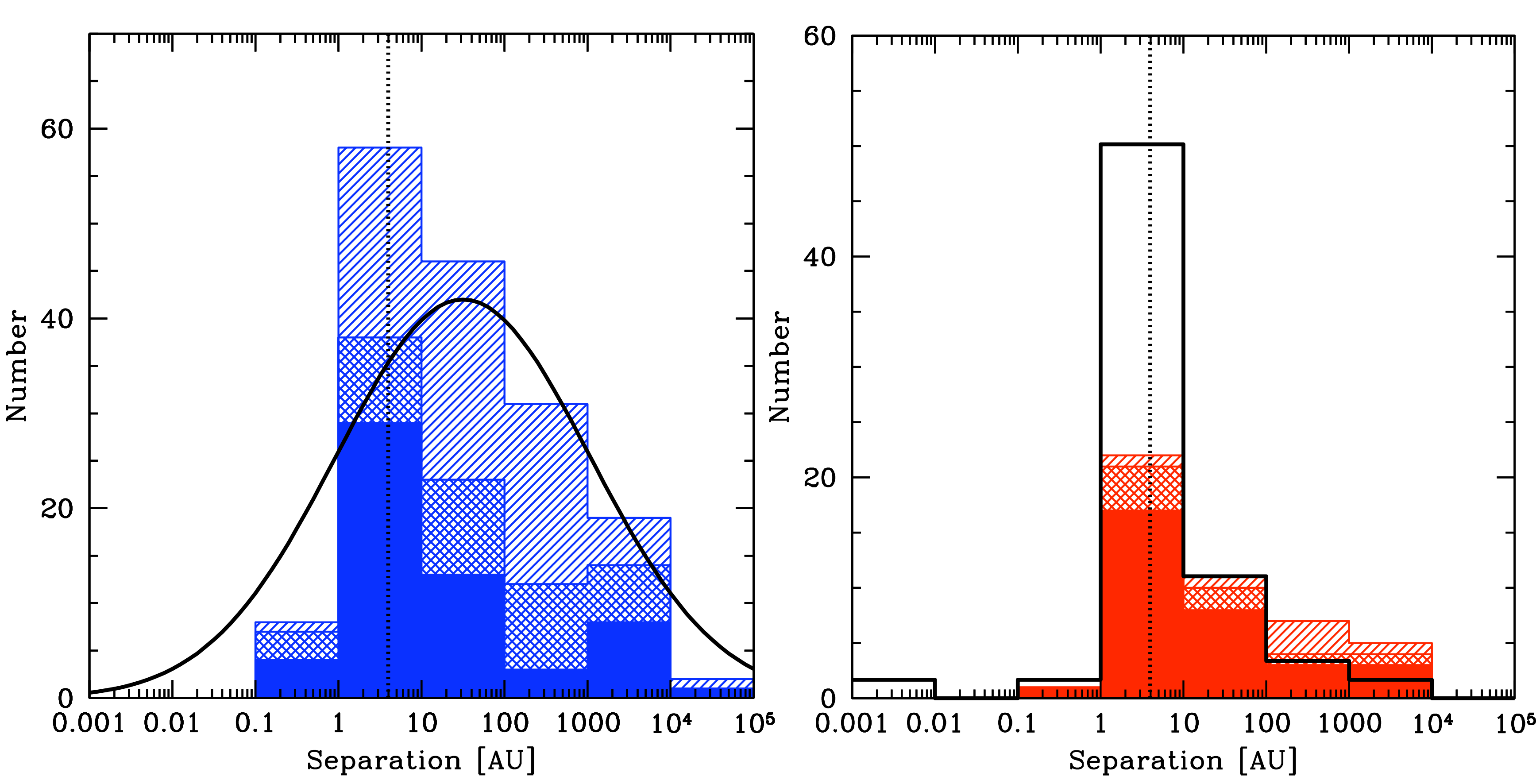
Star/VLM Object Separation Distributions

Stars: binary, triple, quad separations

Median separation: 26 AU

VLM objects: binaries, triples, quads

Median separation: 10 AU

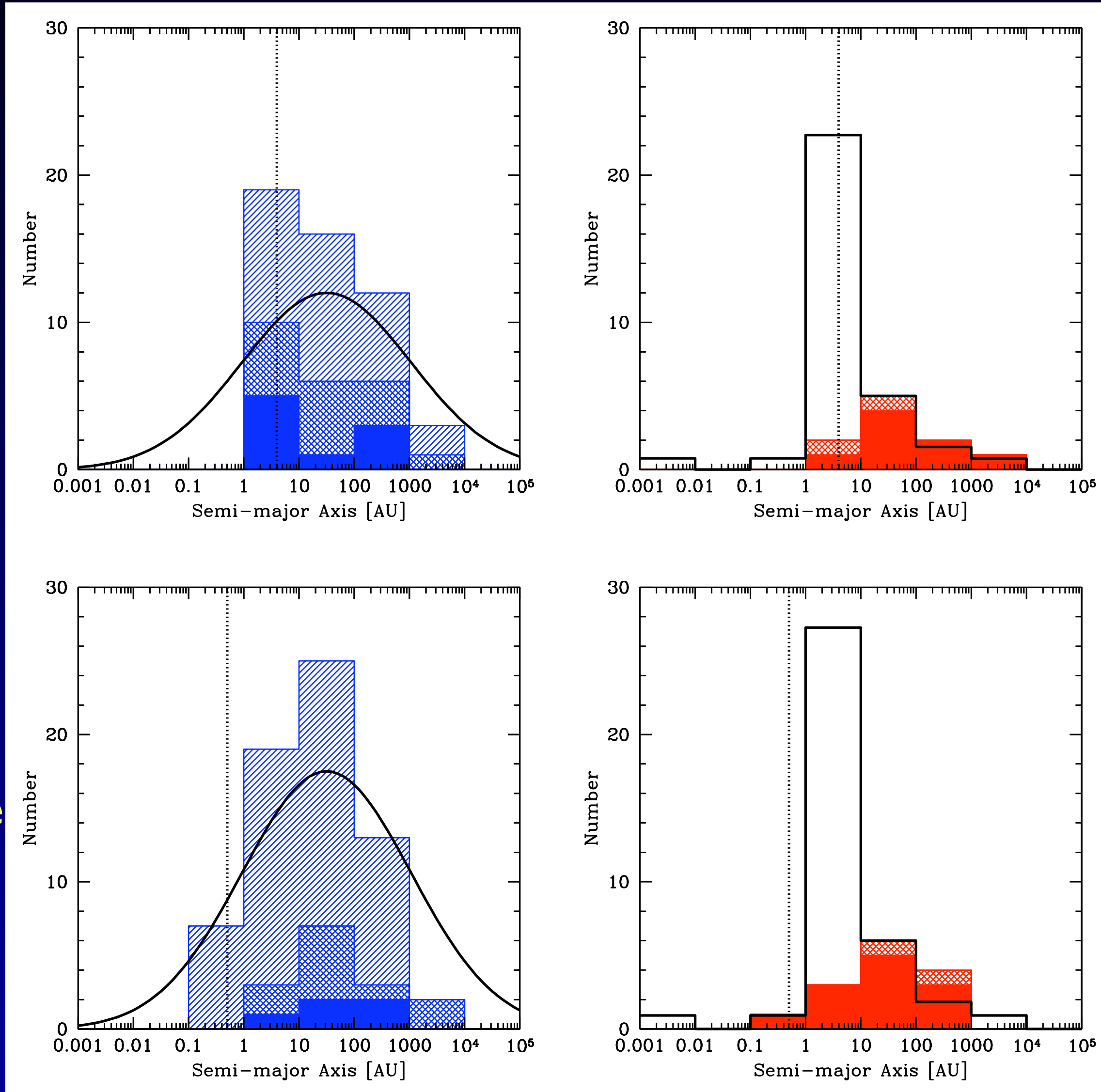


Solid line: Duquennoy & Mayor 1991

Solid line: VLM archive: www.vlmbinaries.org

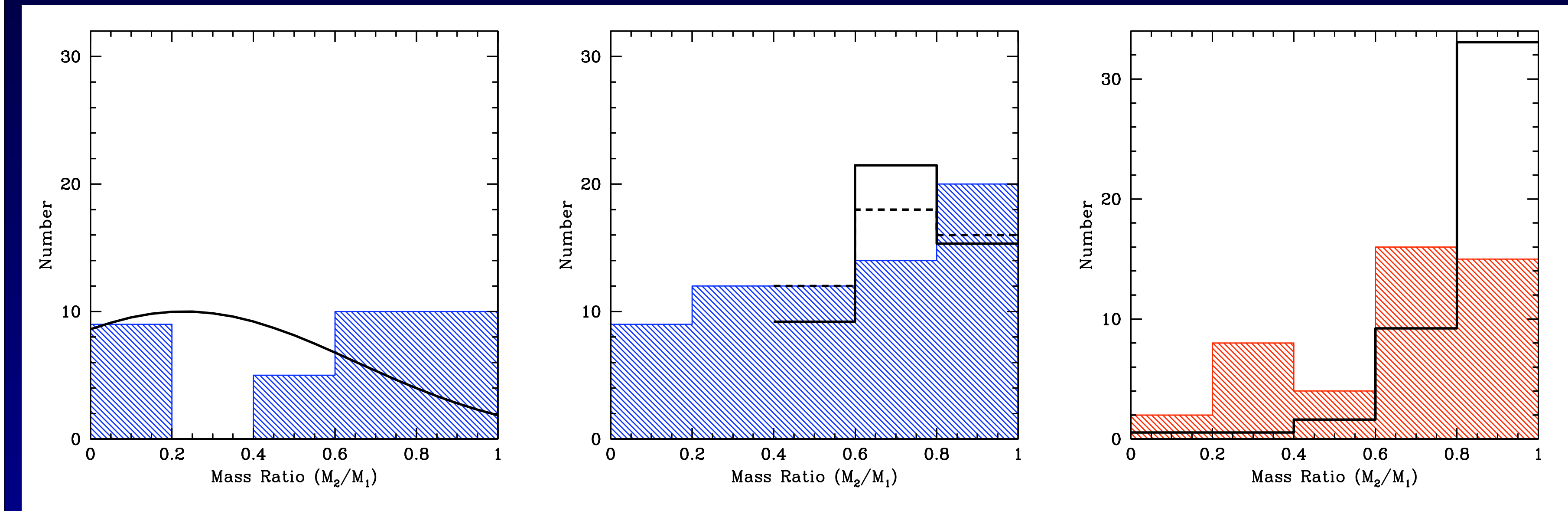
Star/VLM Object Separation Distributions

- Distributions depend on sink particle size
- Reducing sink particle size from 5 to 0.5 AU
  - Produces log-normal stellar separation distribution
  - Increases binary fraction for VLM objects
- Also separations of VLM objects decrease with time



Star/VLM Object Binary Mass Ratio Distributions

Stars: M>0.5 M⊙	Stars: 0.1<M<0.5 M⊙	VLM objects: M<0.1 M⊙
59% have q>0.6	51% have q>0.6	71% have q>0.6

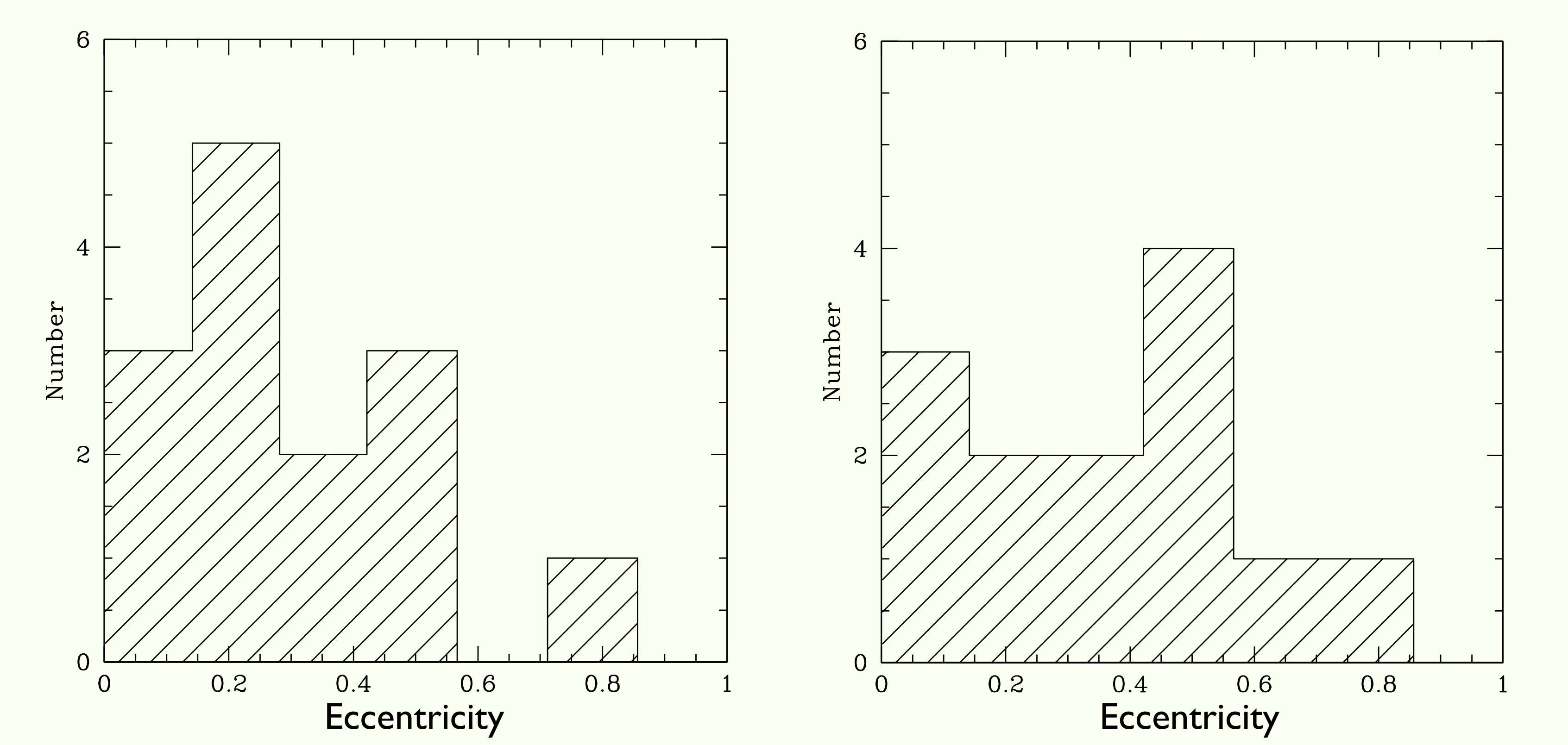


VLM Binary Eccentricity Distribution

- Trent Dupuy: presented first eccentricity distribution for VLM binaries
  - Tend to have low eccentricities

Observations

Calculation (accretion radii 0.5 AU)

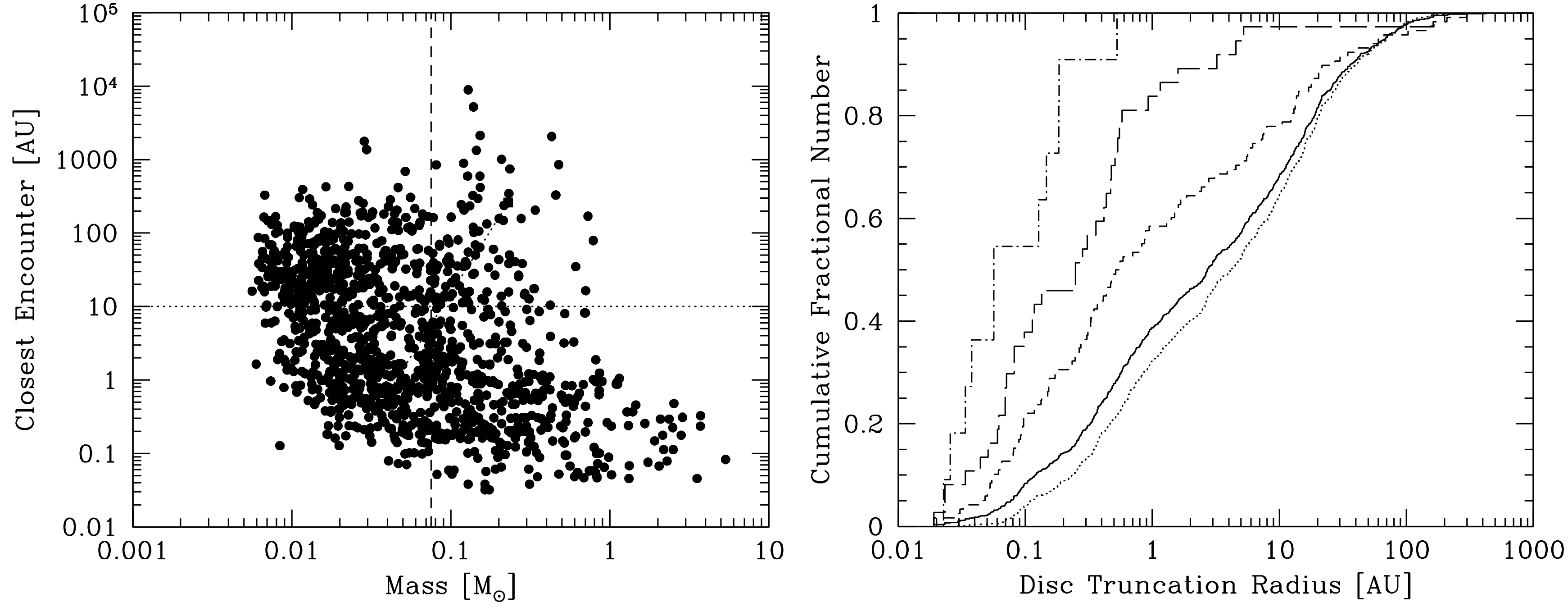


VLM Companions to Stars

- Frequency of ~10%
  - Independent of primary mass (from 0.1 $M_\odot$ up to solar masses)
  - BUT, typical separation increases with primary mass
    - 0.1-0.2 $M_\odot$: 3/14 systems have separations < 30 AU
    - 0.2-0.5 $M_\odot$: 3 at < 10 AU, 1 at 50 AU, 3 at > 1000 AU
    - 0.5-0.8 $M_\odot$: 3 with separations 27-65 AU
    - Solar type primaries: 2 cases, both with separations >1000 AU
- Impossible to examine increased frequency of binary VLM companions to stars with current statistics
  - Stamatellos & Whitworth 2009 type simulations

Discs: Closest Encounter Distance

- Dense star cluster produces many close encounters, truncating discs
- All stars > 1 $M_\odot$ have had encounters closer than 2 AU
  - Doesn't mean don't have discs - if not ejected, discs often re-form through accretion
- Brown dwarfs: encounter distances from < 1 AU to > 100 AU
  - Those without close encounters may have large discs



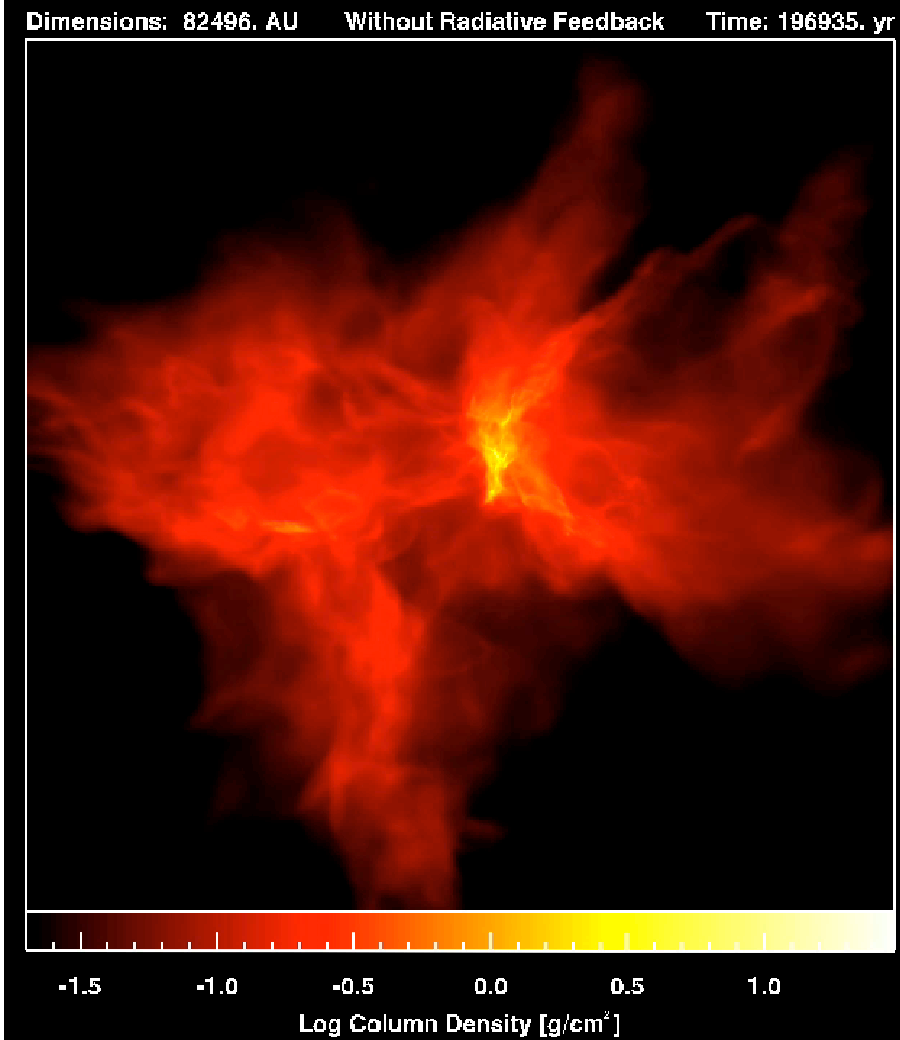
Hydrodynamical Star Formation

- Can now perform simulations that form large numbers of objects
- Statistical uncertainties are the same as 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
  - Two glaring inconsistencies:
    - Too many brown dwarfs
    - To few wide, unequal mass solar-type binaries
- Need to move on with additional physics

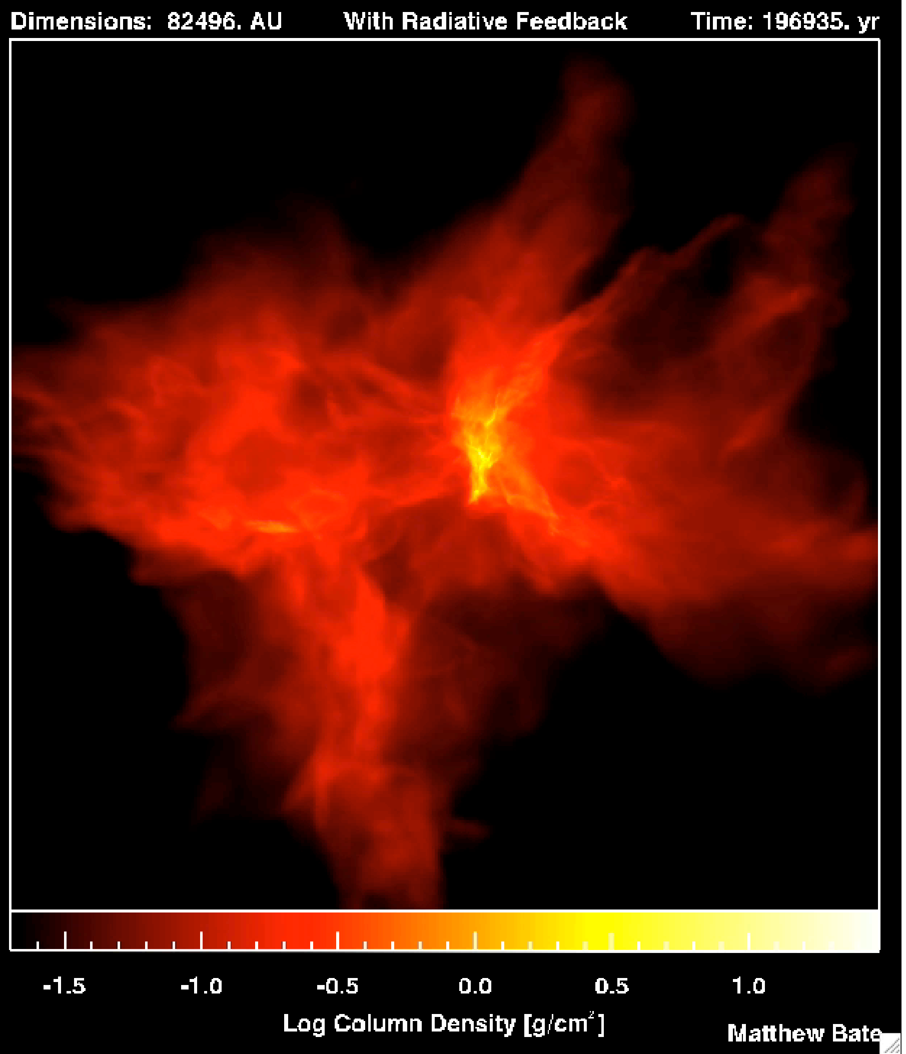
Star Cluster Formation with Radiative Feedback

- Repeat Bate, Bonnell & Bromm 2003, Bate & Bonnell 2005
  - 50 $M_\odot$ molecular clouds, Decaying `turbulence' $P(k) \propto k^{-4}$
  - Diameters 0.4 pc and 0.2 pc, Mean thermal Jeans masses 1 $M_\odot$ and 1/3 $M_\odot$
  - 3,500,000 SPH particles
- Sink particles
  - Radiative transfer calculations: Sink Radii 0.5 AU, no gravitational softening
- Radiative transfer
  - Implicit, grey flux-limited diffusion
    - Separate radiation and matter temperatures, but assumes gas = dust temperature
    - See poster by Andrea Urban (S266)
  - No feedback from protostars
    - Intrinsic protostellar luminosity unimportant
    - Accretion luminosity underestimated (energy liberated from 0.5 AU to stellar surface)
  - Gives a lower limit on the effects of radiative feedback

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

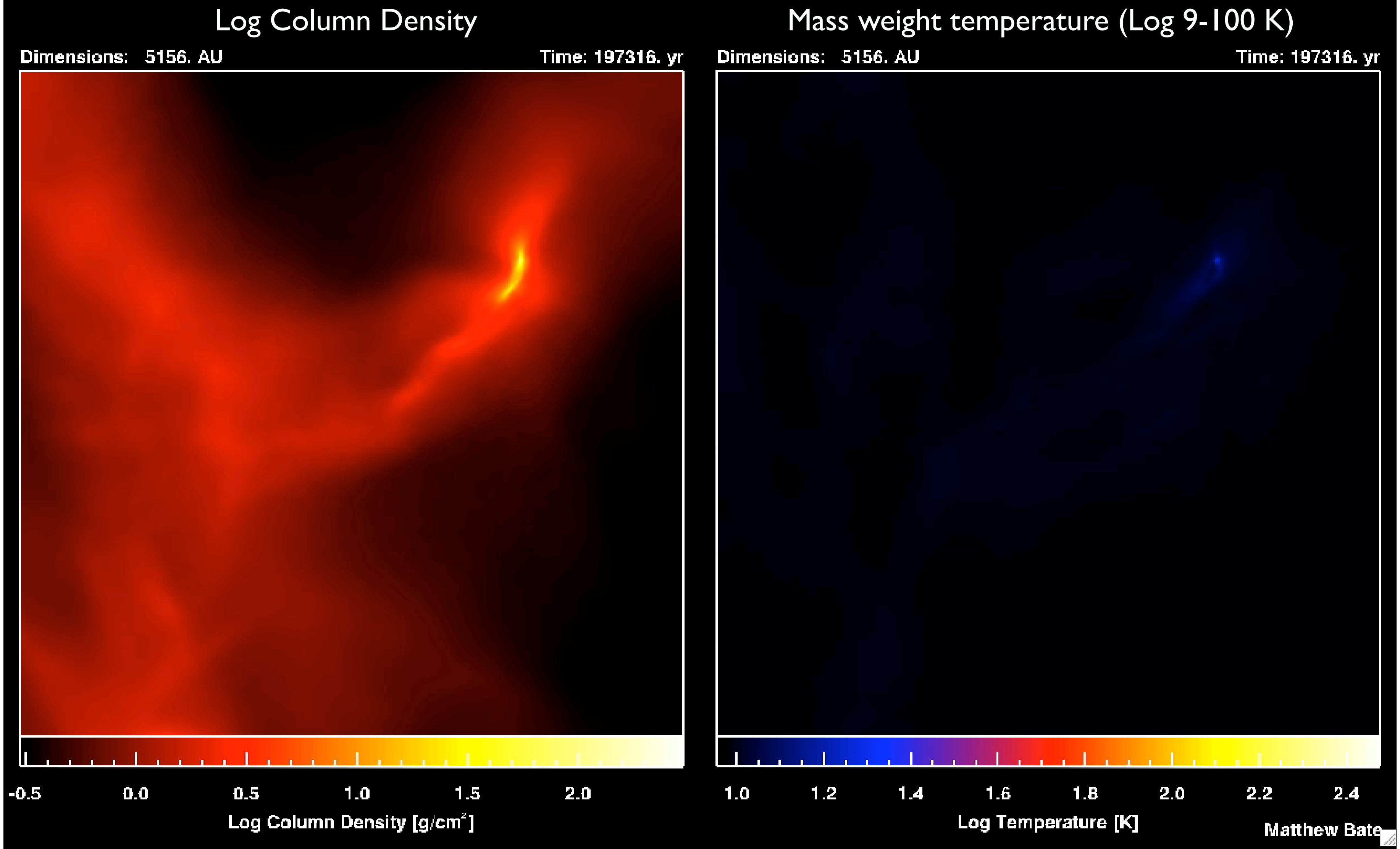


BBB2003, but with Radiative Transfer



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

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



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Impact of Radiative Feedback

- Bate, Bonnell & Bromm (2003)
  - "Typical" density 50 $M_\odot$ molecular cloud ($\sim 10^4$ cm^{-3})

	Stars	Brown Dwarfs	Total
Barotropic Equation of State	23	27	50 (1.40t_{ff})
Radiative Transfer	11	2	13 (1.40t_{ff})

- Bate & Bonnell (2005)
  - Denser 50 $M_\odot$ cloud ($\sim 10^5$ cm^{-3})

	Stars	Brown Dwarfs	Total
Barotropic Equation of State	19	60	79 (1.40t_{ff})
Radiative Transfer	14	3	17 (1.40t_{ff})

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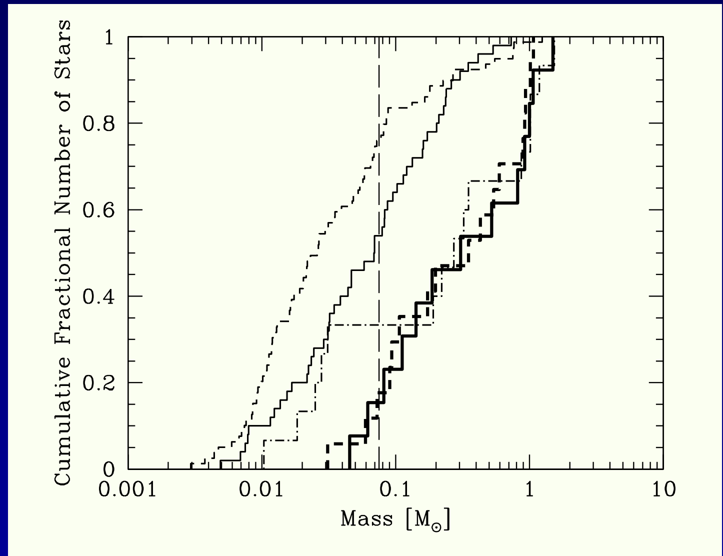
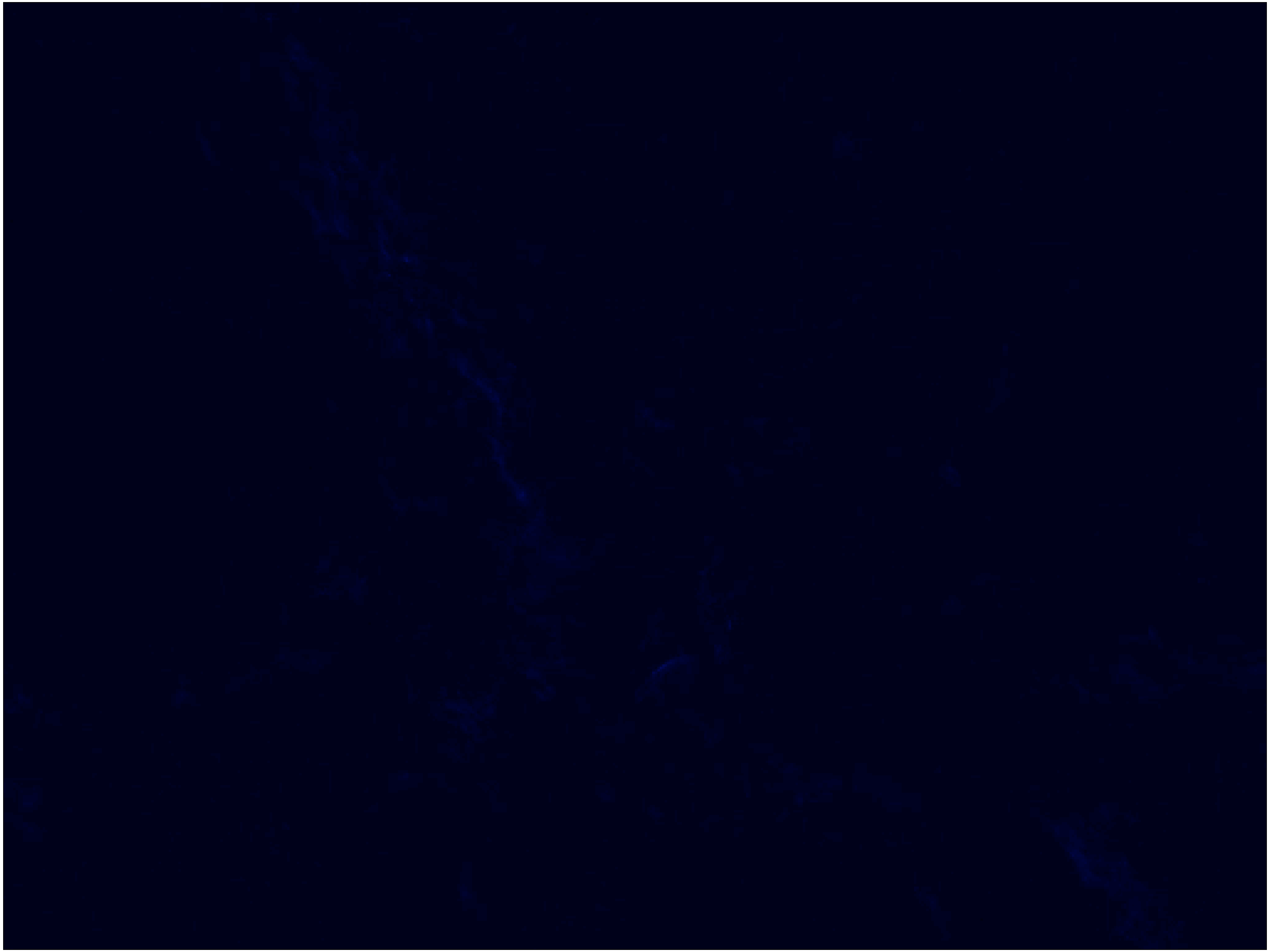
Radiative Feedback and the IMF

- 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; Andersen et al. 2008
  - Simulations: 25:5 ~ 5
    - Bate 2009b
- Furthermore, dependence of the IMF cloud density is removed
  - K-S test on the two IMFs with radiative shows them to be indistinguishable



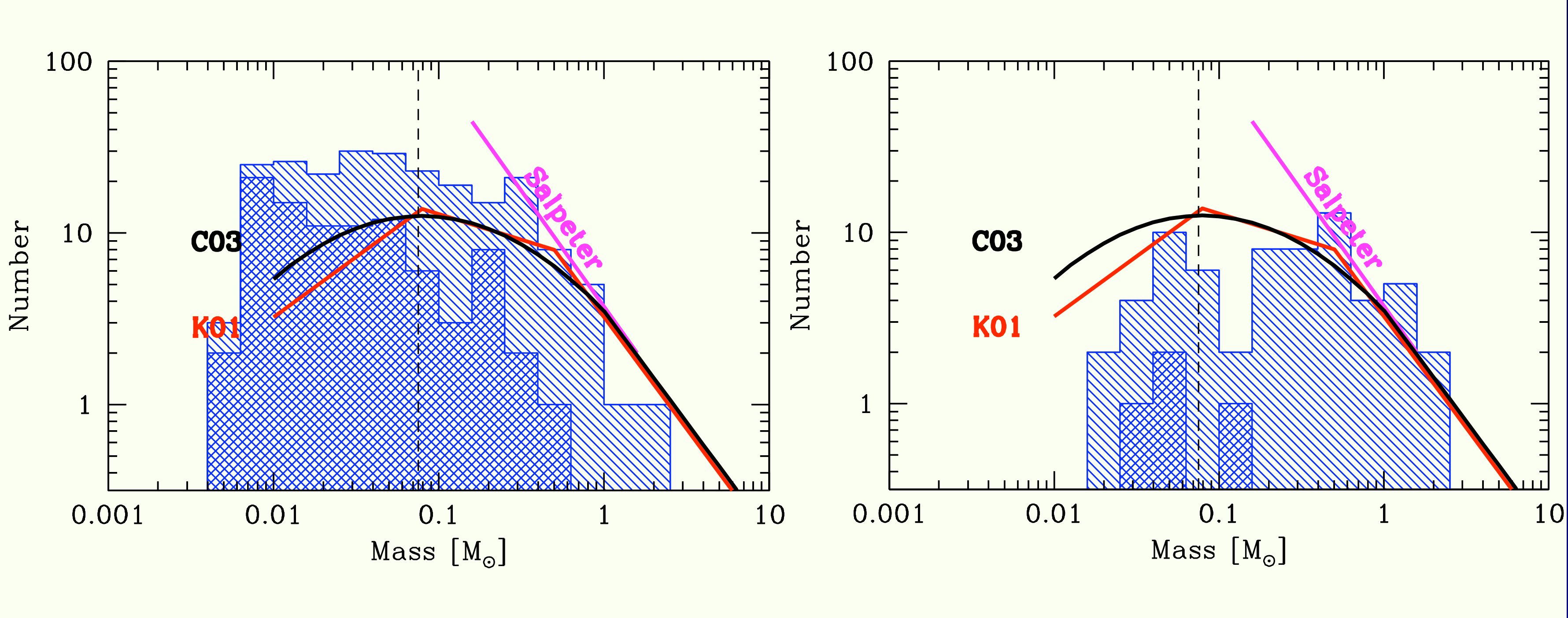
Large-scale Simulations with Radiative Feedback

- Currently re-running Bate (2009a) with radiative feedback
  - 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
- Results so far
  - Just reached 1.06 initial cloud free-fall times
  - Formed 89 stars and brown dwarfs
    - Including 1 binary brown dwarf system: 15 AU separation, 0.04 eccentricity
  - Original calculation at the same time: ~300 stars and brown dwarfs



Large-scale Simulations with Radiative Feedback

- Comparison of the IMFs obtained without and with radiative feedback
  - As expected, many fewer brown dwarfs
    - Stars to brown dwarfs without radiative feedback: 74:154 ~ 1/2 vs with feedback 42:22 ~ 2
  - Remains to be seen how other stellar properties compare



- The Future:
  - Self-gravitating radiation magnetohydrodynamical simulations
  - Statistics as good or better than observational surveys

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