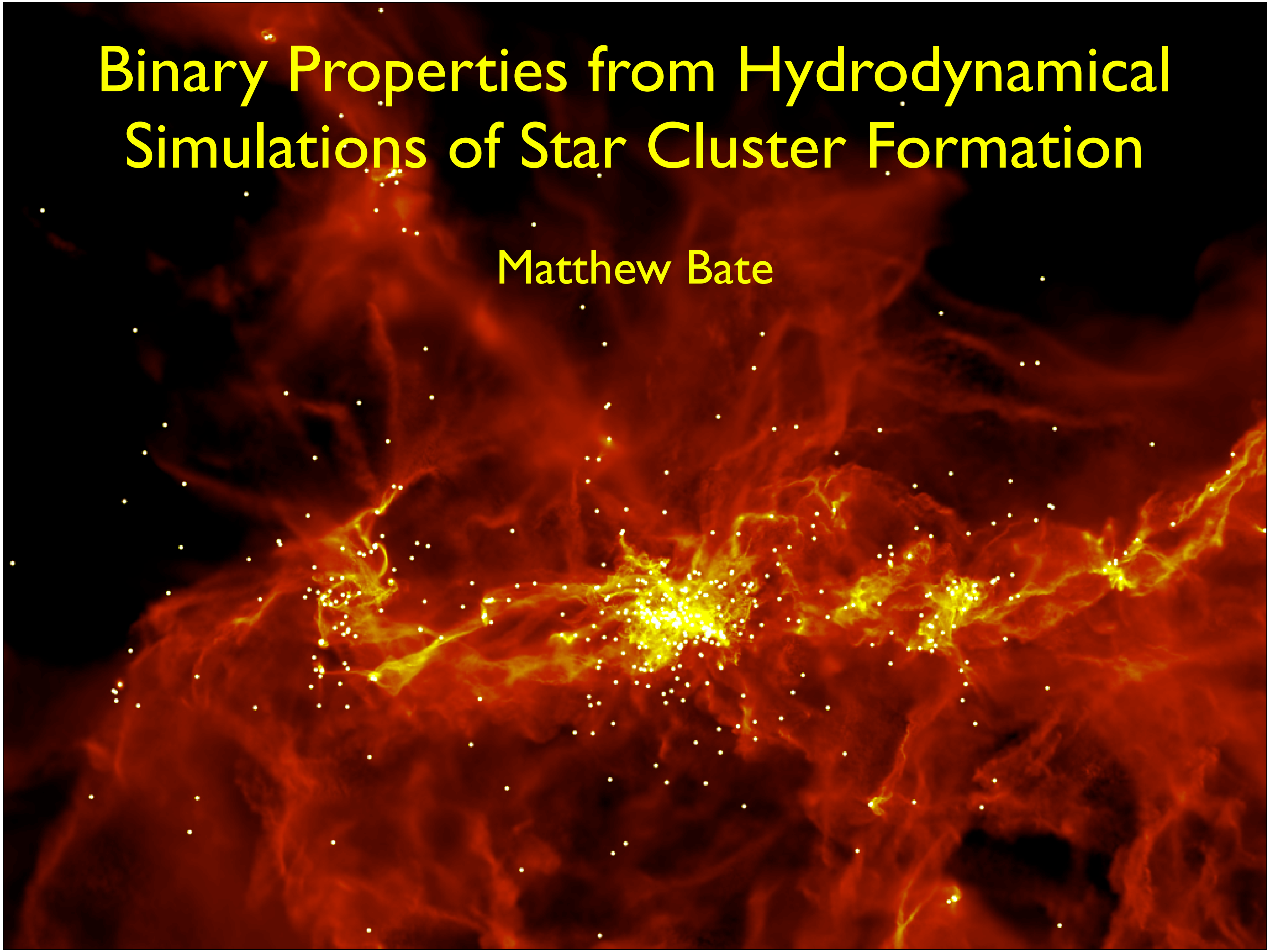
Binary Properties from Hydrodynamical Simulations of Star Cluster Formation

Matthew Bate



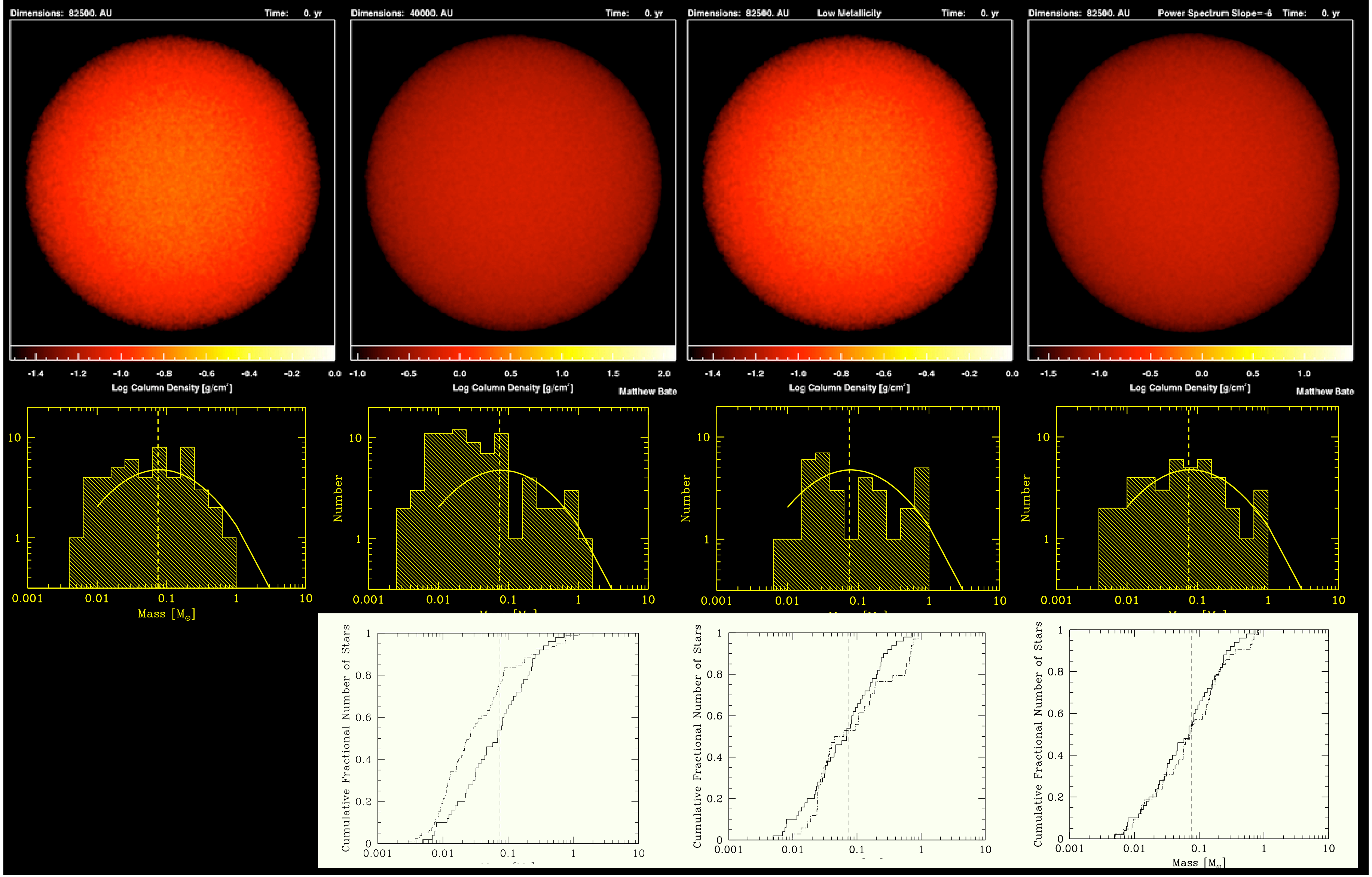
http://www.astro.ex.ac.uk/people/mbate

Typical molecular cloud
Jeans mass 1 M☉, Opacity limit 3 M_J, $P(k) \propto k^{-4}$

Denser cloud
Jeans mass 1/3 M☉

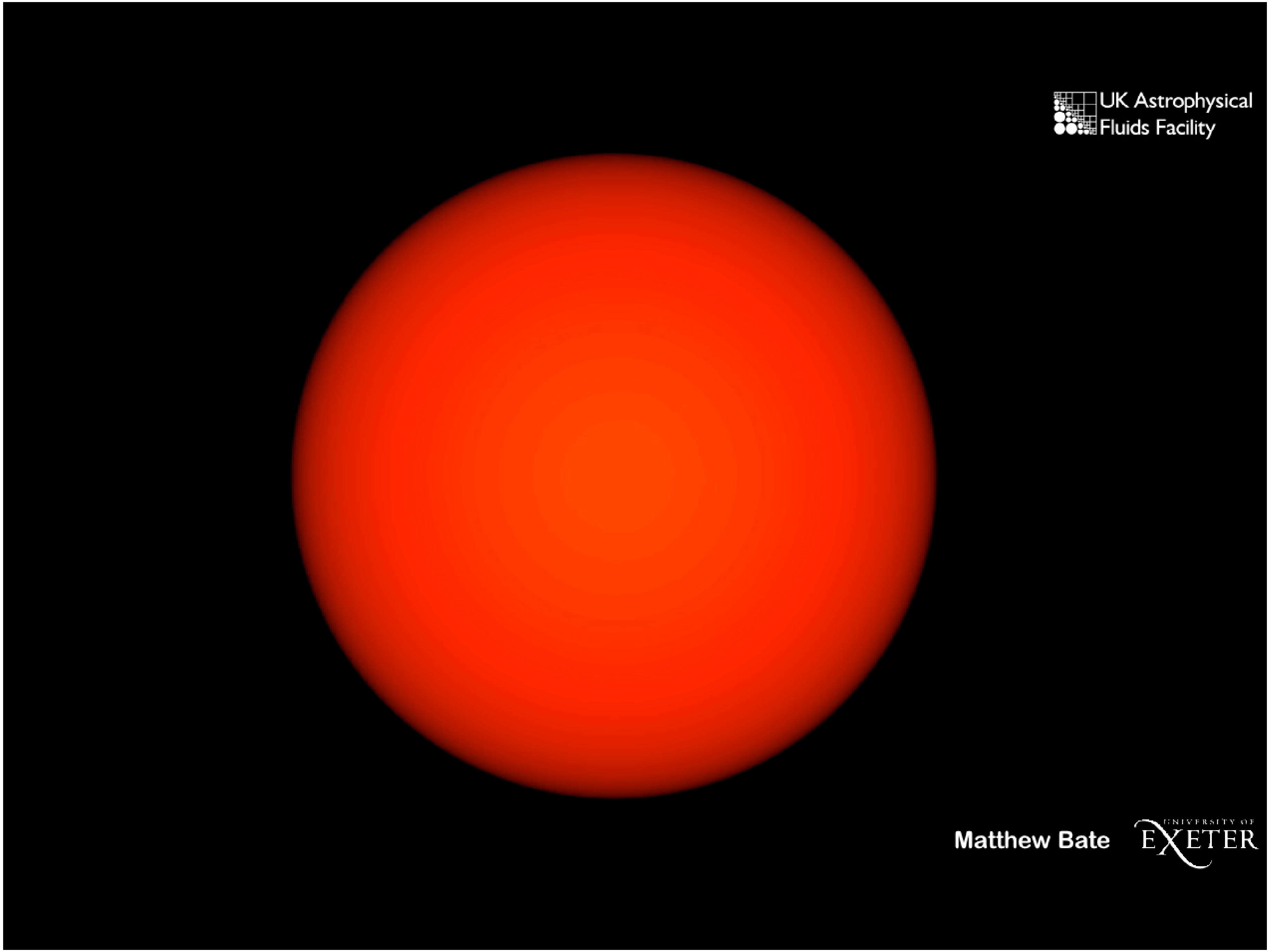
Lower metallicity cloud
Opacity limit 9 M_J

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



Real Star Cluster Formation

- Just finished a calculation 10 times more massive than
  Bate, Bonnell & Bromm 2003, Bate & Bonnell 2005, Bate 2005
    - 500 $M_\odot$ cloud, using 35,000,000 SPH particles
    - Resolves opacity limit for fragmentation
    - Follows:
        - Binaries to 1 AU and discs to ~10 AU radius
        - All binaries (0.02 AU) and discs to ~1 AU radius
- Aims:
    - Model IMF from minimum mass brown dwarf to ~10 $M_\odot$, but still follow binaries, discs, etc
    - Improve statistics: >1000 objects
        - Binaries and multiple systems (e.g. binary brown dwarf statistics, separations, mass ratios)
        - Examine properties as a function of stellar mass (binarity, discs)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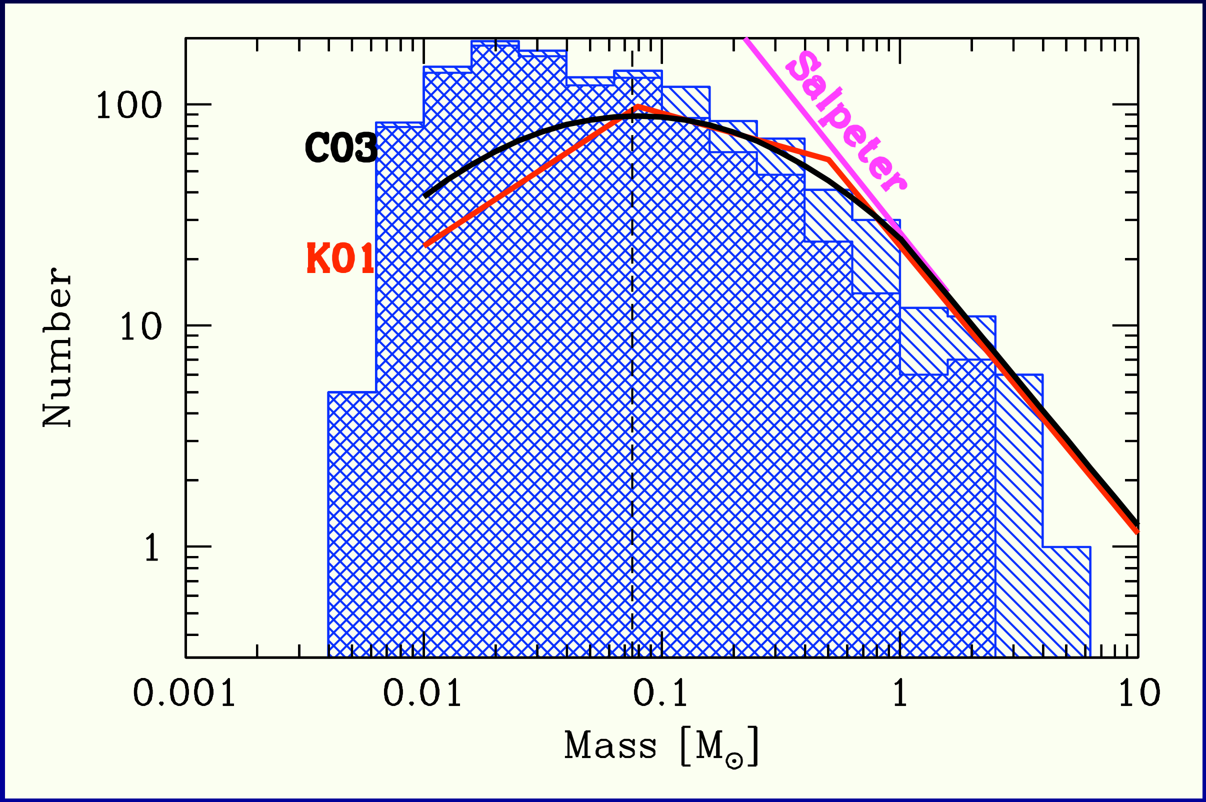
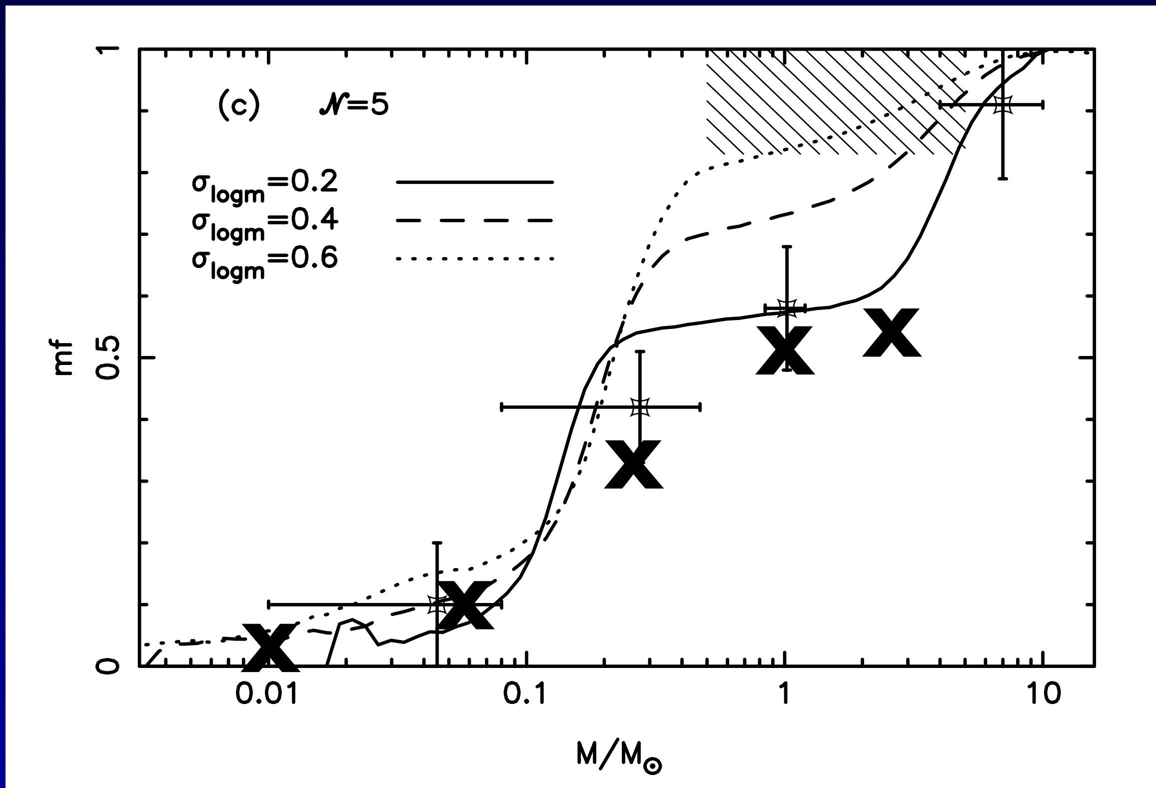
Stellar Mass Distribution

- Statistics much improved over earlier calculations: 1254 objects at 1.50 t_{ff}
  - Binaries: 146   Triples: 40   Quadruples: 25   Quintuples: 20
- More brown dwarfs than typical star-forming region
  - Lack of radiative feedback may result in too much small-scale fragmentation
  - Sink particle approximation may over produce ejected objects (interactions not dissipative)



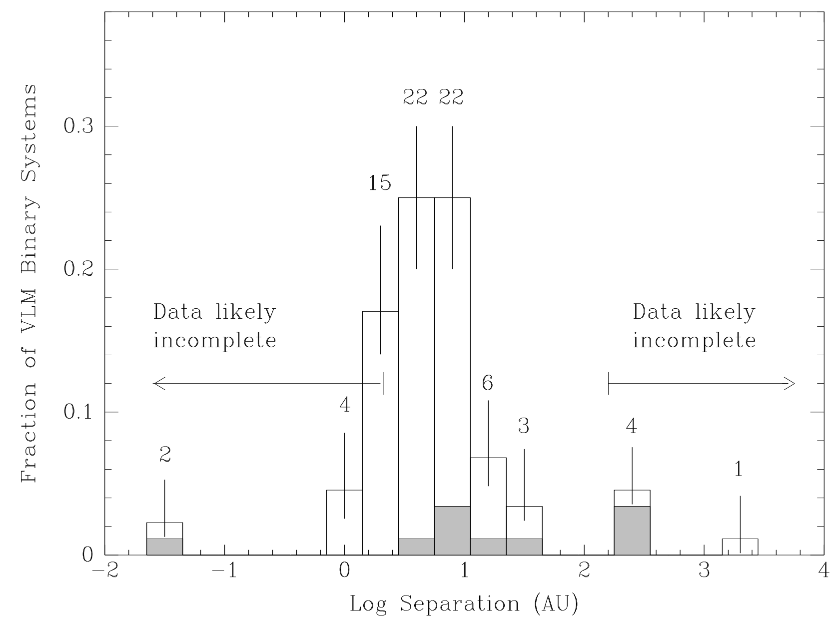
Binarity as a Function of Primary Mass

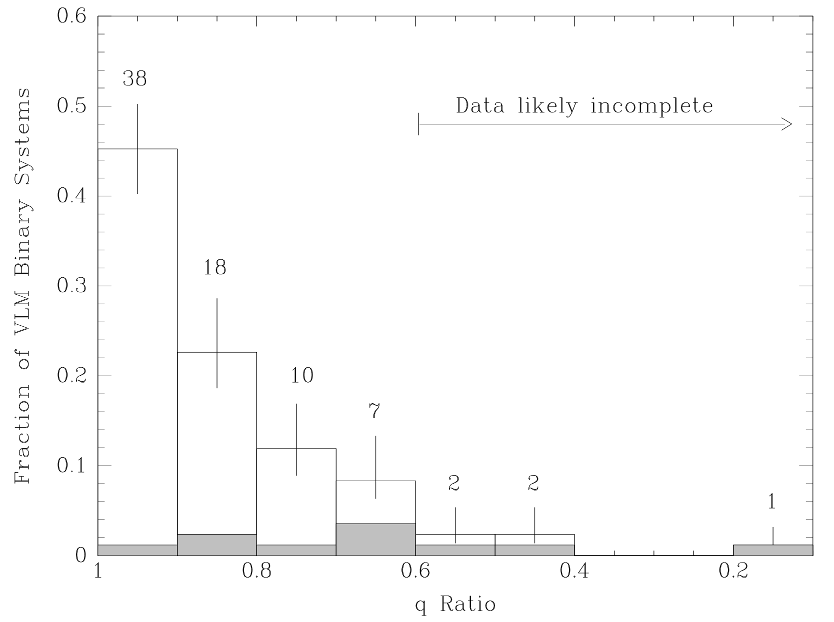
- Figure from Hubber & Whitworth (2005)
  - Observations: Martin et al. 2000; Fisher & Marcy 1992; Duquennoy & Mayor 1991; Shatsky & Tokovinin 2002
  - New large cluster calculation: **X**



Testing Models through Binarity

- Binarity as a function of primary mass
  - Distributions of separation and mass ratios
- Binary brown dwarfs
  - Frequency:
    - ~15% from AO surveys (e.g. Siegler et al. 2003);
    - <20-25% (Basri & Reiners 2006)
  - Close separations (http://paperclip.as.arizona.edu/~nsiegler/VLM_binaries/)





Binary Frequency

- Many *stars* currently members of multiple systems: 405 stars
  - Binary stars: 70
  - Single stars: 228
  - Star + Brown dwarf binaries: 37
- Frequency of binary *stars* : 70/335=21%

- Brown dwarfs and VLM stars (mass < 0.09 $M_\odot$): 849 BDs
  - Binary brown dwarfs/VLM stars: 39 (5 actually triple BDs)
  - Brown dwarf + Star binaries: 37
  - Single brown dwarfs: 734

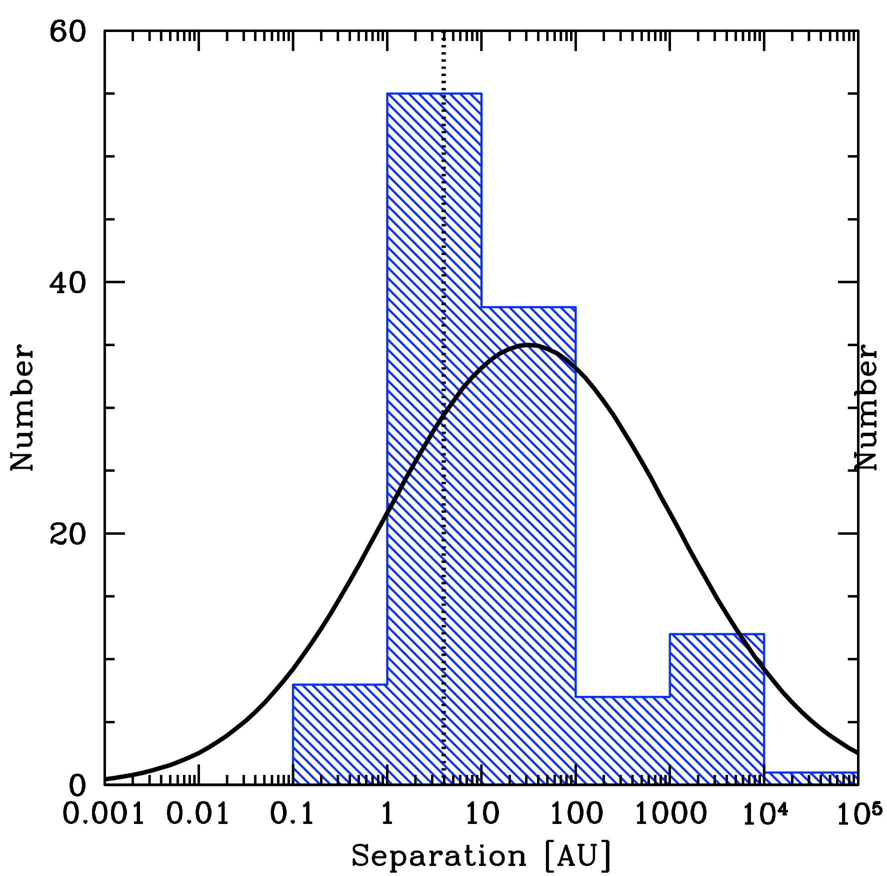
- Frequency of binary brown dwarfs/VLM stars: 39/723=5.4%

Binary Brown Dwarf Frequency

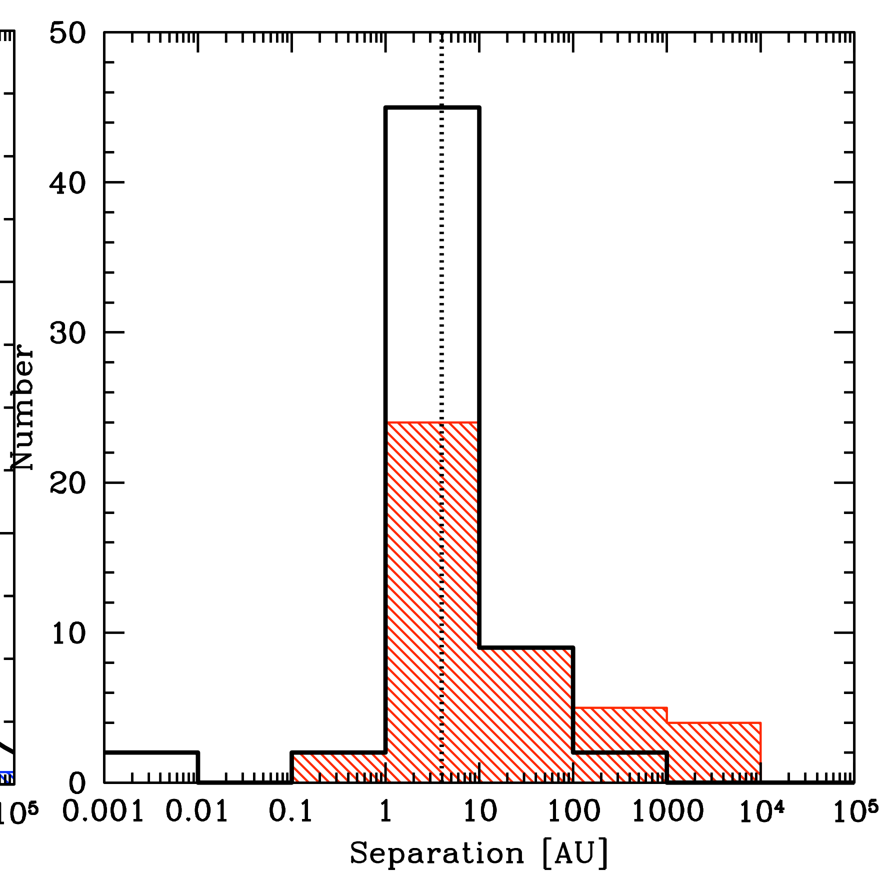
- Frequency of binary brown dwarfs/VLM stars: 39/723=5.4%
- But many brown dwarfs have masses < 0.03 $M_\odot$
  - Would not have been observed in surveys for binarity
- Take only primaries with masses 0.03 to 0.09 $M_\odot$
  - Binary brown dwarfs/VLM stars: 30
  - Single brown dwarfs: 261
- Frequency of binary brown dwarfs/VLM stars: 30/291=10.3%
- Take mass ratio q>0.4
  - Binary brown dwarfs/VLM stars: 23
  - Single brown dwarfs: 268
- Frequency of binary brown dwarfs/VLM stars: 23/291=7.9%

Star/Brown Dwarf Separation Distributions

- Stars: binary & triple separations



Brown dwarfs: binaries & triples

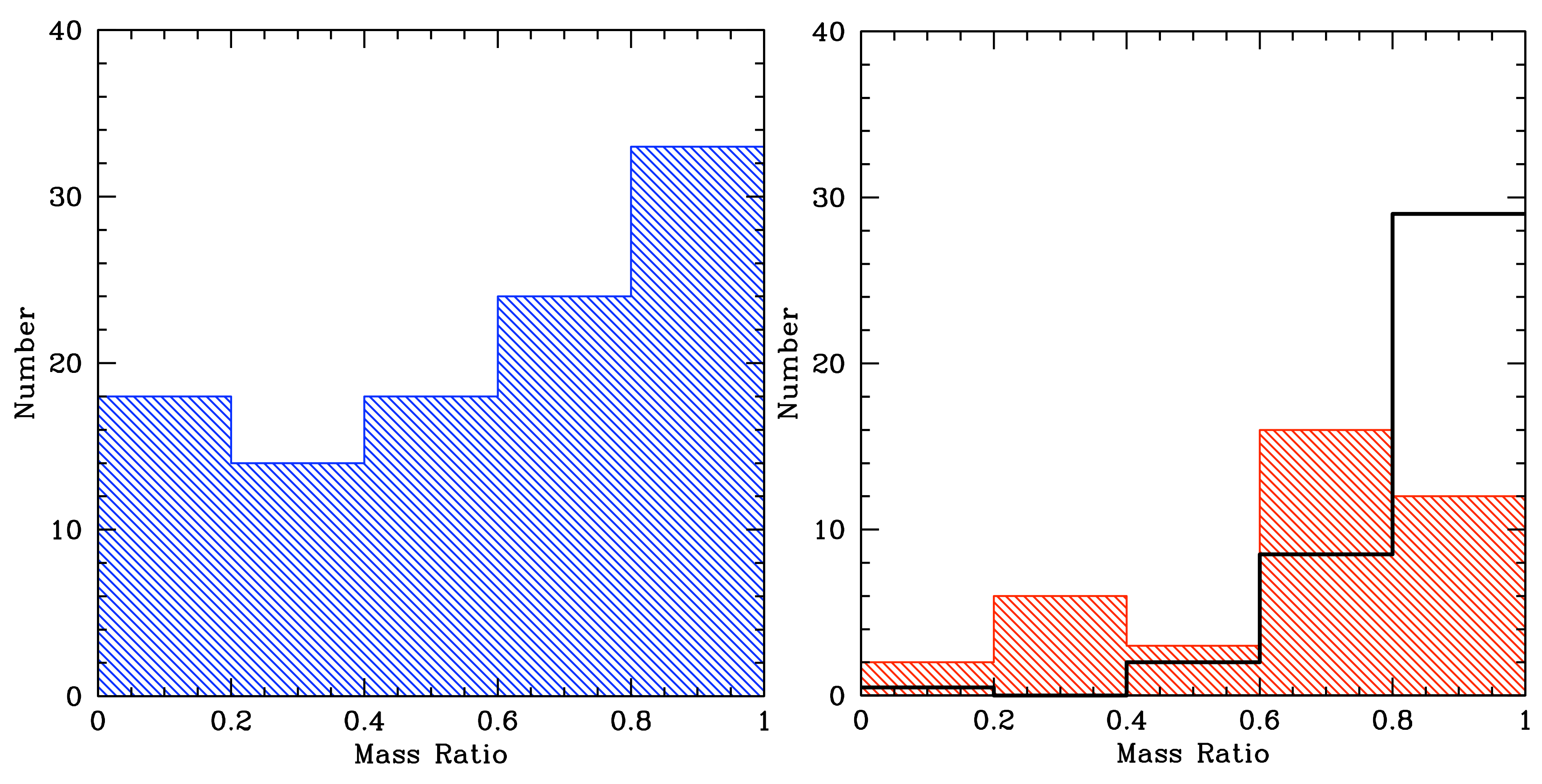


Star/Brown Dwarf Binary Mass Ratio Distributions

- Stars: binary mass ratios
  - 53% have q>0.6

Brown dwarfs: binary mass ratios

82% have q>0.6

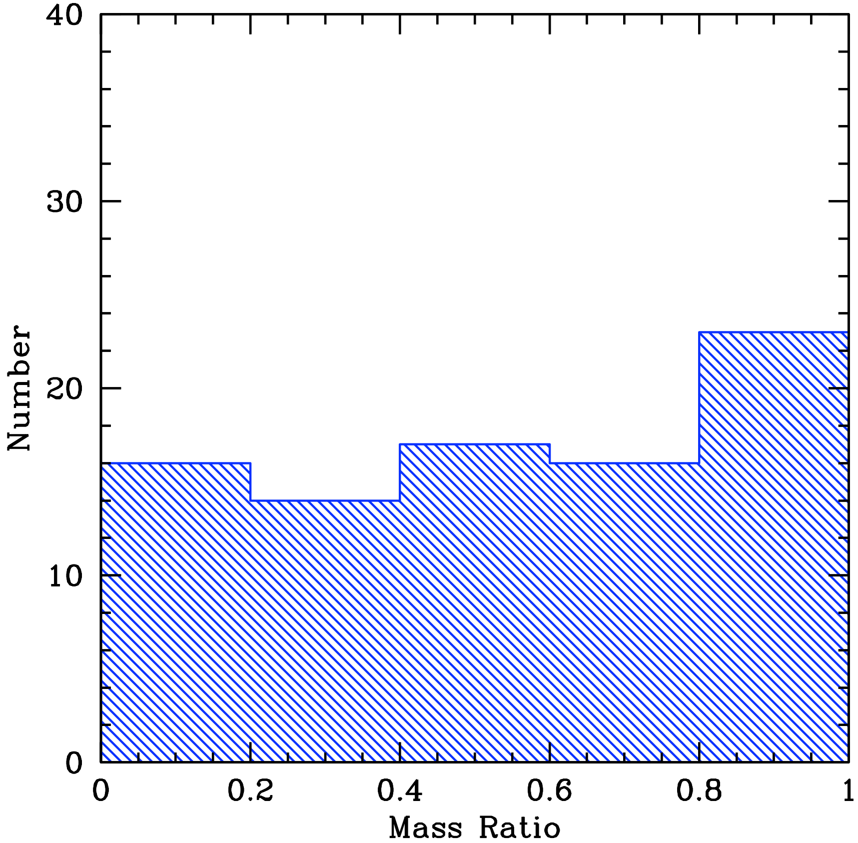


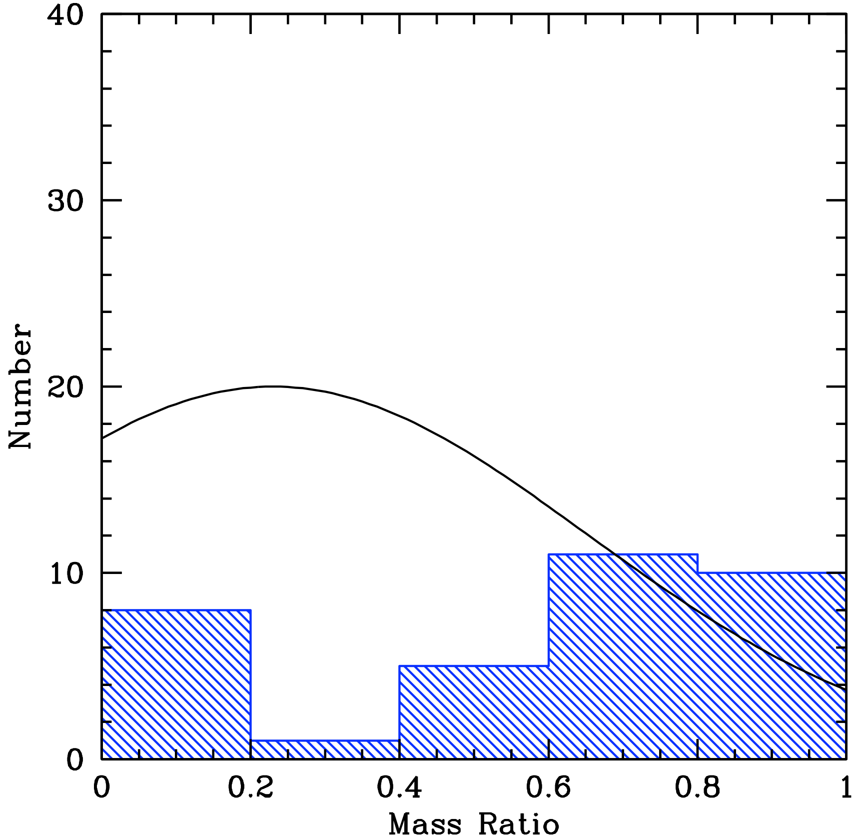
Stellar Binary/Triple Mass Ratio Distributions

- Primaries with M<0.5 M☉
  - Flat: Reasonable agreement with FM92

Primaries with M>0.5 M☉

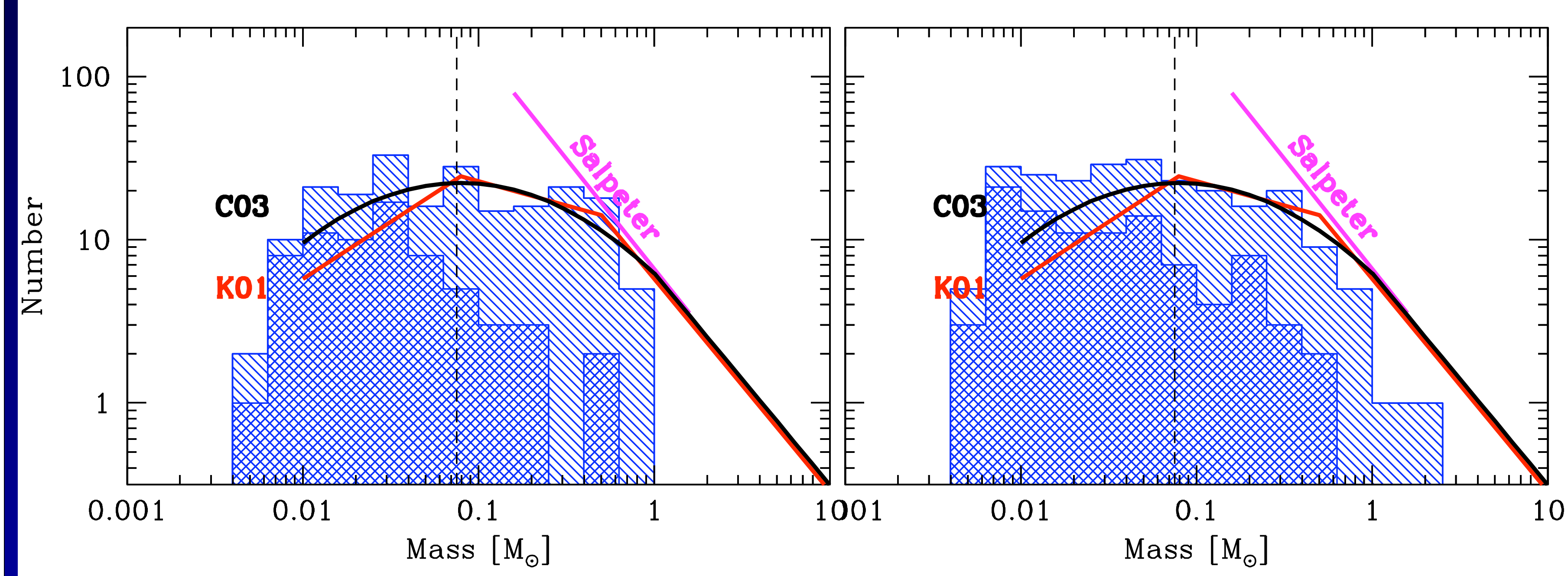
Not enough low-q systems, c.f. DM91





Gravity Softening/Accretion Radii

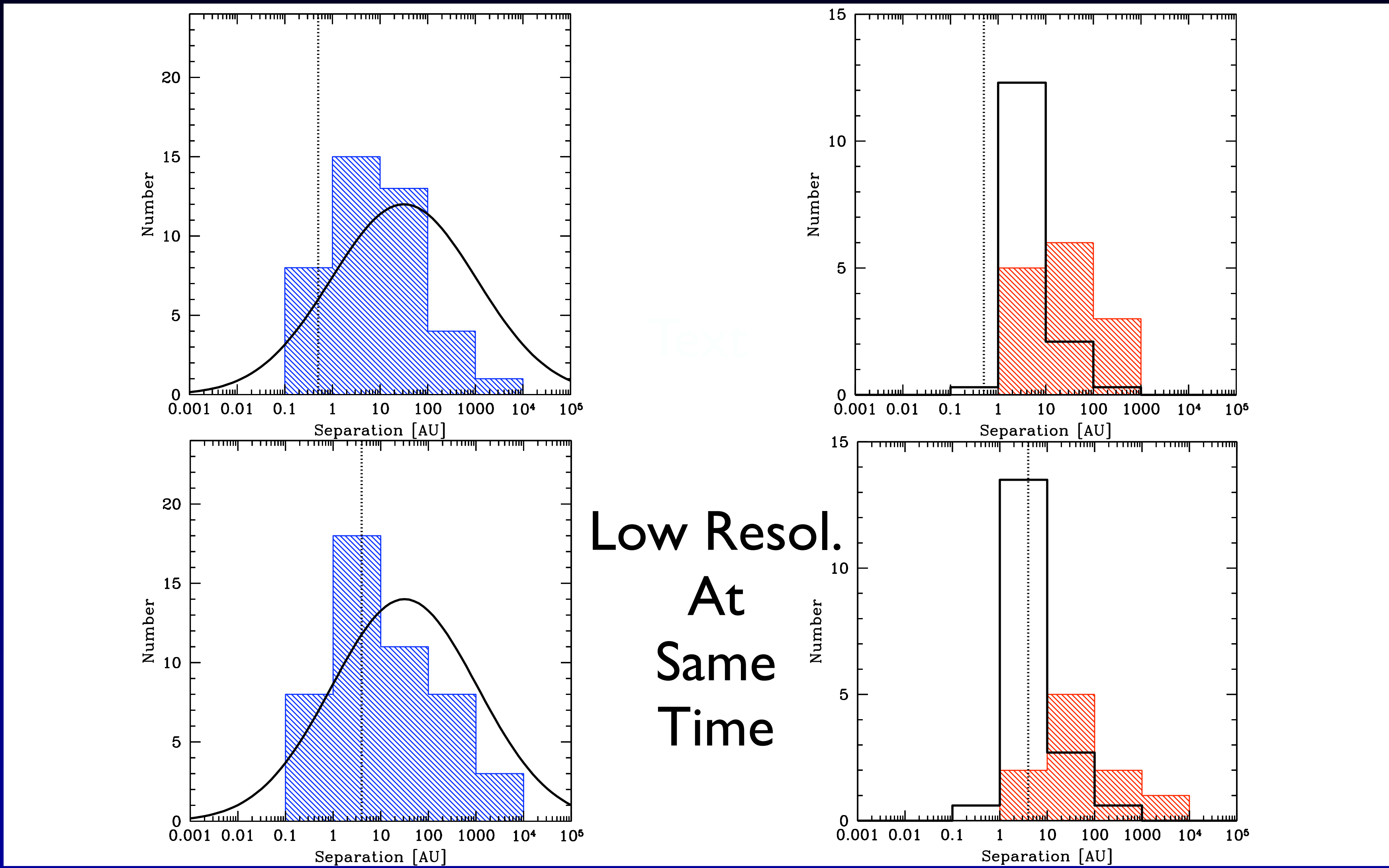
- Re-ran part of the calculation
  - No gravitational softening between stars (merge when pass within 0.02 AU)
  - Accretion radii reduced by order of magnitude to 0.5 AU
  - Formed 236 objects at 1.03 t_{ff} compared to 208 at same time with larger accretion radii/softening



Star/Brown Dwarf Separation Distributions (High Resol.)

- Stars: binary & triple separations

Brown dwarfs: binaries & triples



Low Resol. At Same Time

Binary Brown Dwarf Frequency

- Frequency of binary brown dwarfs/VLM stars: 13/124 = 11% (vs 8%)
- Take only primaries with masses 0.03 to 0.09 $M_\odot$
  - Binary brown dwarfs/VLM stars: 11
  - Single brown dwarfs: 41
- Frequency of binary brown dwarfs/VLM stars: 11/54 = 20% (vs 11%)
- Take mass ratio q>0.4
  - Binary brown dwarfs/VLM stars: 7
  - Single brown dwarfs: 45
- Frequency of binary brown dwarfs/VLM stars: 7/54 = 13% (vs 6%)

Wide VLM Binaries

- Observers have been finding a few wide binary brown dwarfs
  - e.g. Luhman 2004; Billeres et al. 2005; Close et al. 2006; Jayawardhana & Ivanov 2006; Caballero 2007
  - Up to 5100 AU (Artigau et al. 2007)
  - Allen et al. (2007) find frequency between 40-1000 AU < 2.3% from survey of 132 M7-L8
  - May be higher fraction in star-forming regions than field (Konopacky et al. 2007)
- Some claim this is evidence against ejection
- But hydrodynamical simulations form wide systems
  - Bate & Bonnell (2005) produced two wide VLM systems: 66 AU, 126 AU
- New calculation forms 6/39 with separations >100 AU
  - Separations 40-1000 AU with masses > 0.03 $M_\odot$: 4 + 4 triples: Frequency: 2.7%
  - Widest system is 8400 AU

Brown Dwarfs in Triple Systems

- Similarly, there are several VLM triple systems known
  - GL569B is a triple consisting of three ~0.04 M brown dwarfs (Simon et al. 2007)
- Binary brown dwarf companions to stars
  - GJ569B; HD130948B, Epsilon Indi B, GJ1001B, Gl417B,LP213-67, etc
  - See Siegler's VLM object archive and references therein
- New calculation
  - 5 triple brown dwarfs (tertiary separations ranging from 86 to 1021 AU)
  - Only one BBD companion to a star (61 AU star-BBD separation)
  - 15 single BD companions to stellar binaries
  - Of the 37 star-BD binaries, 5 have BD tertiary, 1 has stellar tertiary

Conclusions: Hydrodynamical Simulations

- New large-scale calculation provides statistics better than observations
- IMF similar to observed IMF
  - Very small uncertainties - high-mass end: Salpeter-type slope; turnover at low-masses
  - Somewhat too many brown dwarfs
    - Likely due to incorrect thermodynamics (radiative transfer) [or magnetic fields?]
- Binarity in good agreement with observations
  - Binarity is an increasing function of primary mass
  - Frequency of binary brown dwarfs compatible with observations ~20% for high-resolution version of simulation
  - Naturally produce a small fraction of wide binary brown dwarfs (agrees with observ.)
  - Even able to produce some triple brown dwarfs
  - Separation distributions of binary stars and brown dwarfs plausible

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