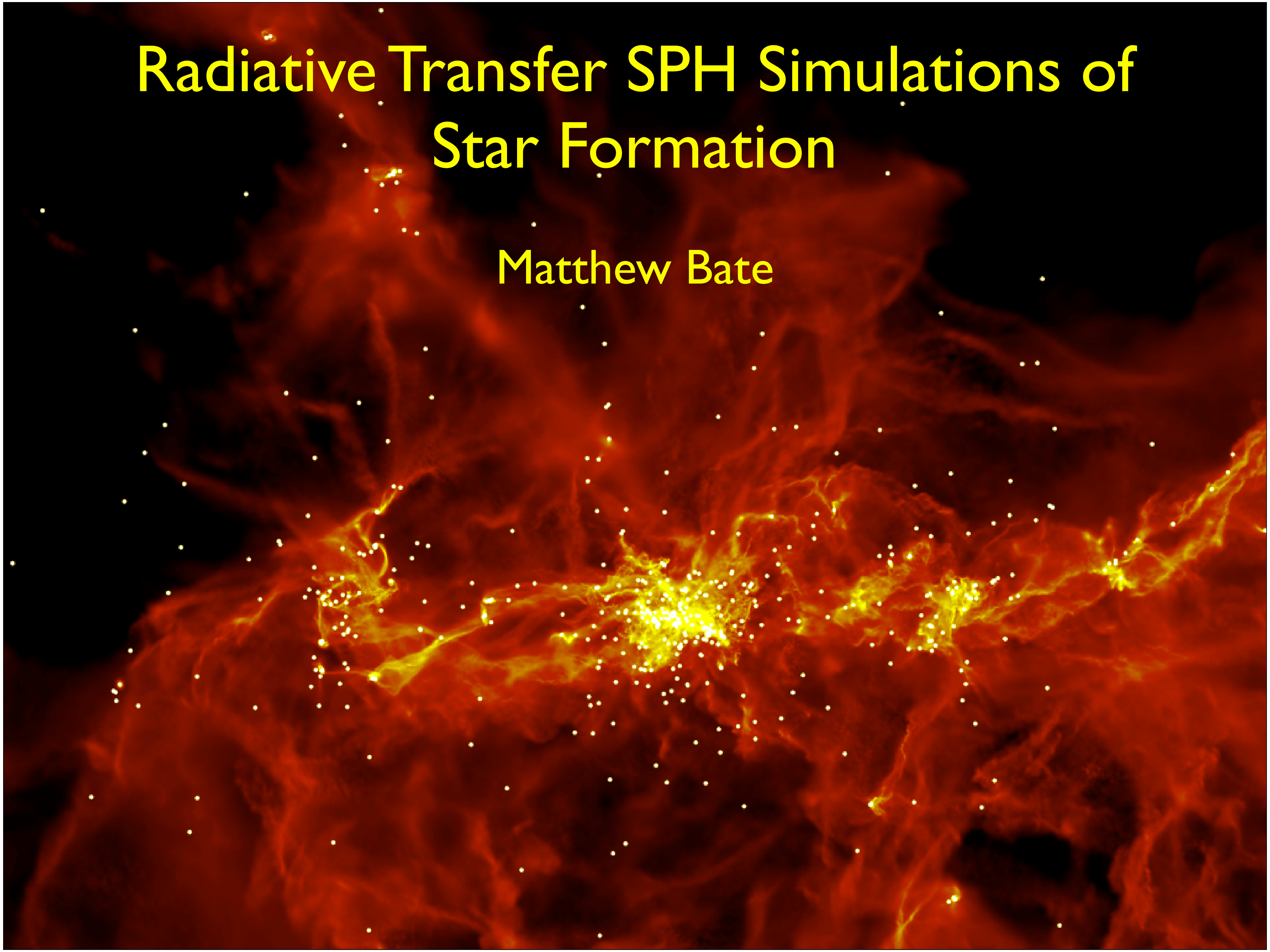
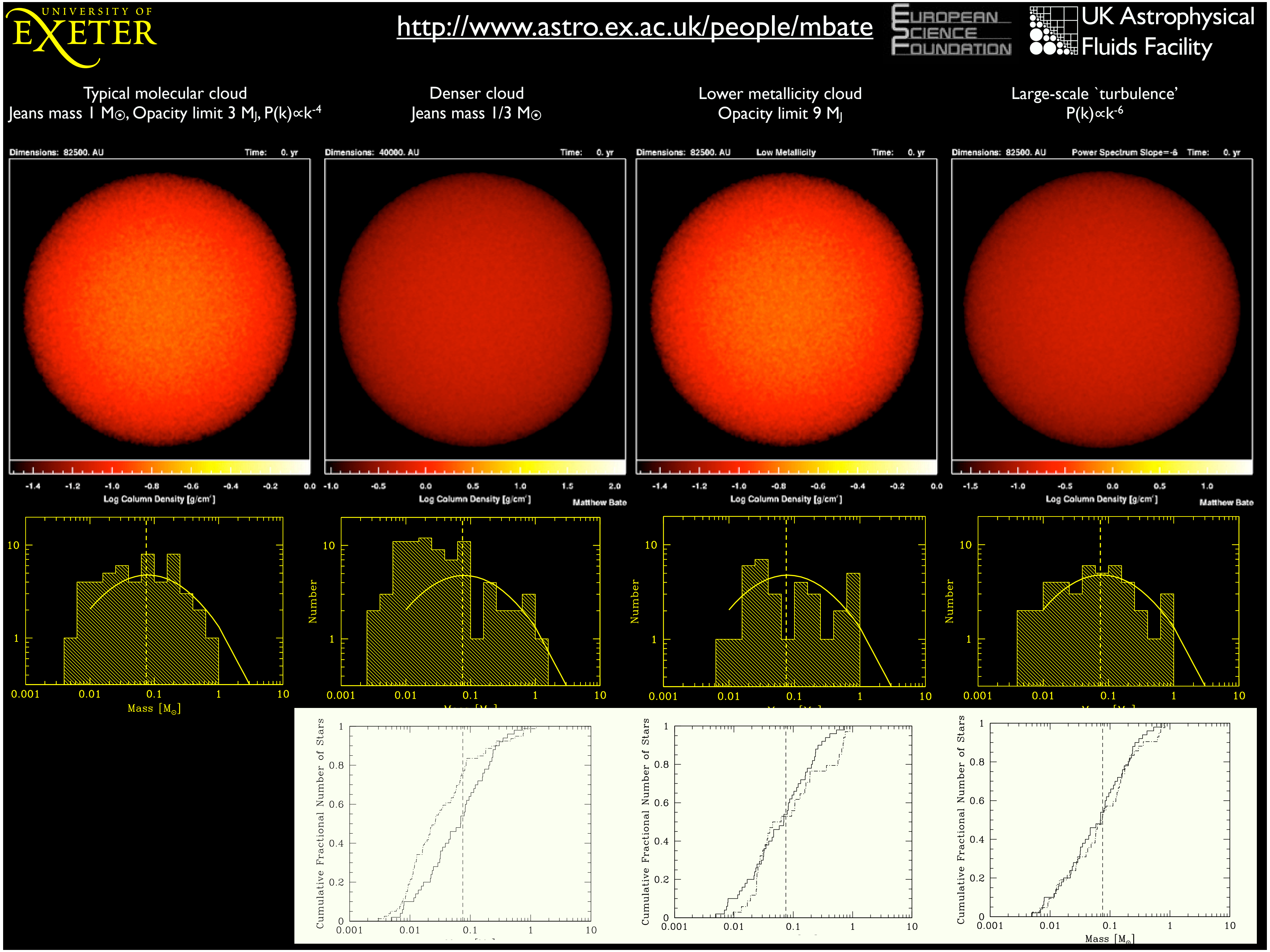
Radiative Transfer SPH Simulations of Star Formation

Matthew Bate




UNIVERSITY OF EXETER
http://www.astro.ex.ac.uk/people/mbate
EUROPEAN SCIENCE FOUNDATION
UK Astrophysical Fluids Facility
Typical molecular cloud
Jeans mass 1 M⊙, Opacity limit 3 MJ, P(k)∝k-4
Denser cloud
Jeans mass 1/3 M⊙
Lower metallicity cloud
Opacity limit 9 MJ
Large-scale `turbulence'
P(k)∝k-6
Dimensions: 82500. AU
Time: 0. yr
Dimensions: 40000. AU
Low Metallicity
Power Spectrum Slope=-6
Log Column Density [g/cm²]
Matthew Bate
Number
Mass [M⊙]
Cumulative Fractional Number of Stars

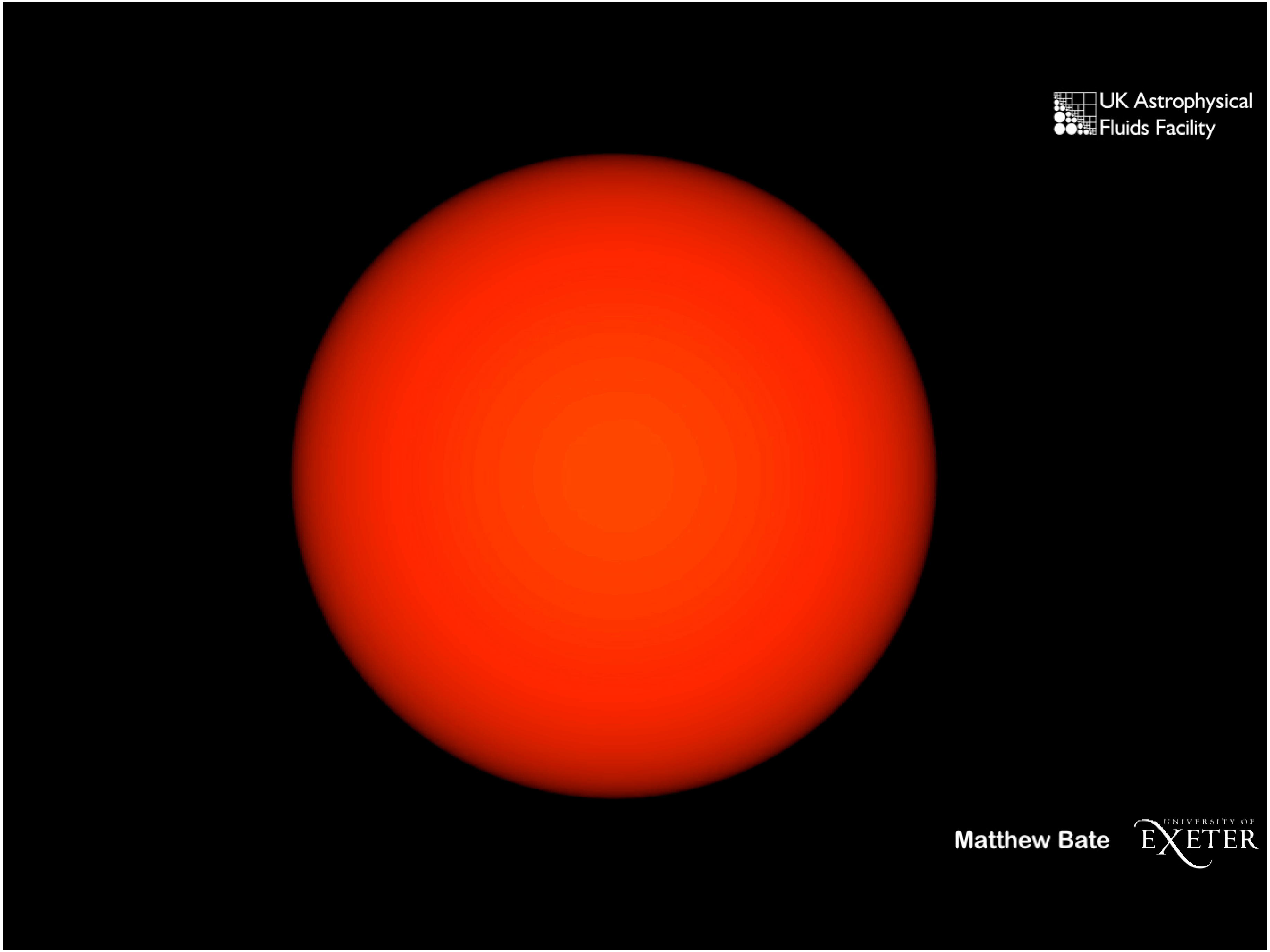
UNIVERSITY OF EXETER

European Science Foundation

UK Astrophysical Fluids Facility

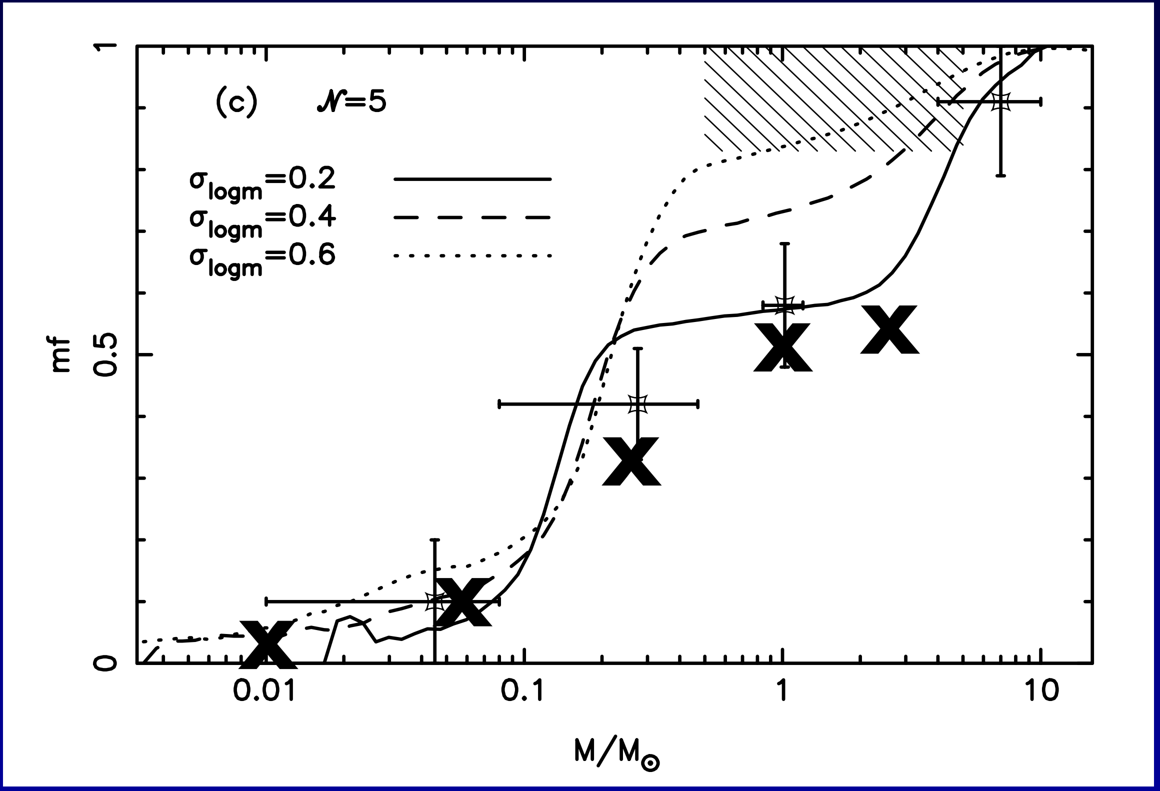
Real Star Cluster Formation

- Recently 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
- Statistics much improved over earlier calculations
  - 1254 objects at 1.50 t_{ff}
  - Binaries: 146 Triples: 40 Quadruples: 25 Quintuples: 20


UK Astrophysical
Fluids Facility
Matthew Bate
UNIVERSITY OF
EXETER

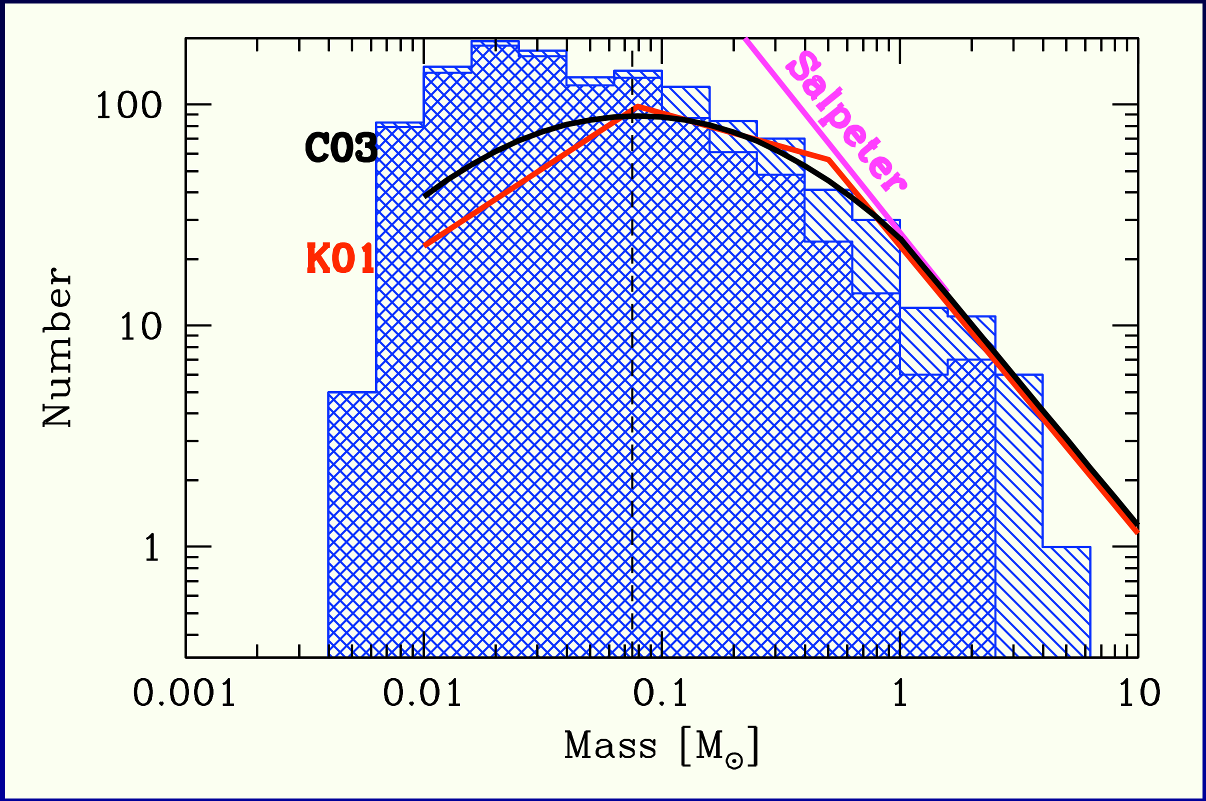
Binarity as a Function of Primary Mass

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



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

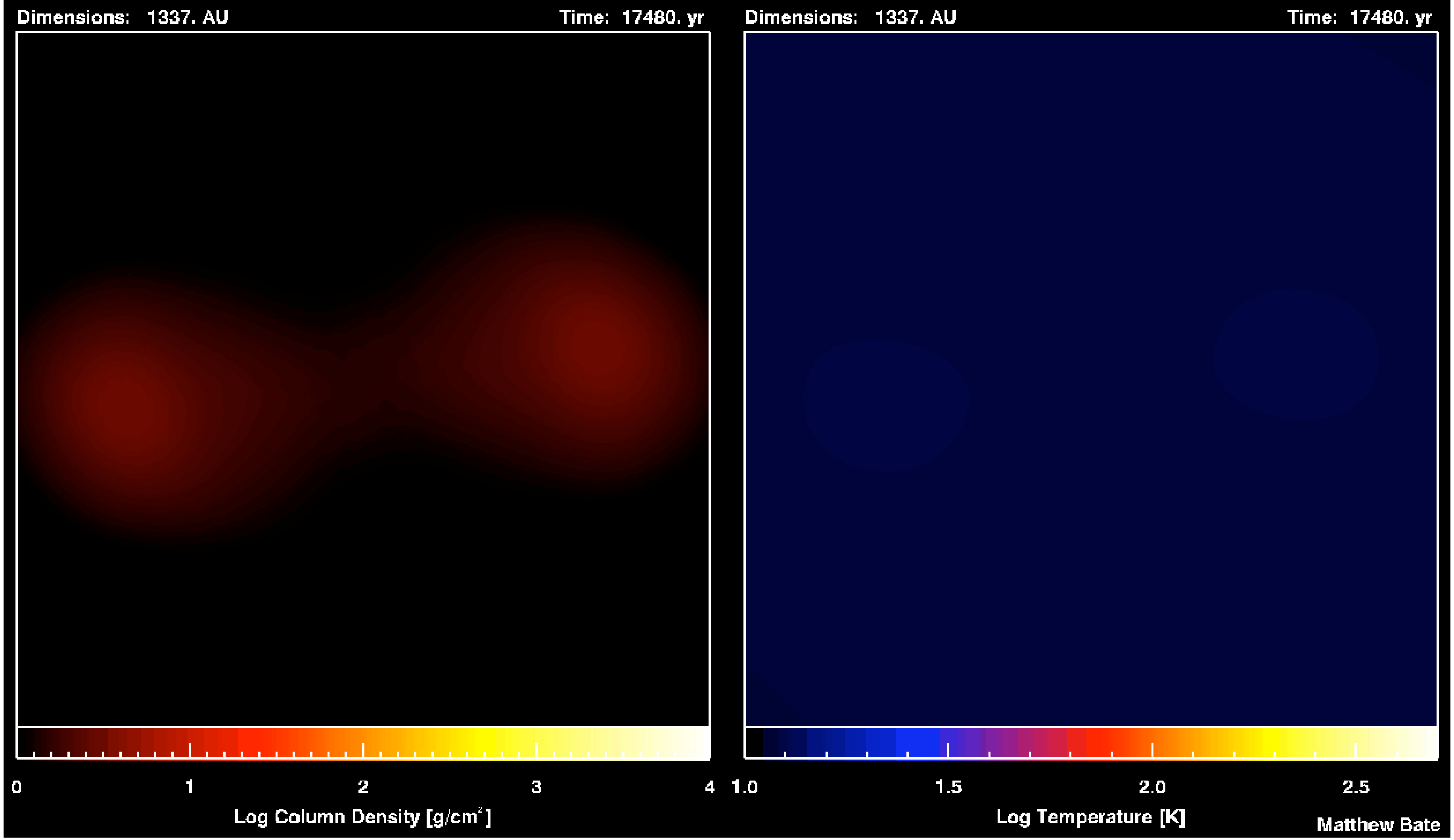
UK Astrophysical Fluids Facility

Where to now?

- Statistics now good enough to know that pure hydrodynamics + sink particles cannot reproduce observations in detail
- Need to include additional physics
- Magnetic fields
  - Price & Monaghan 2005; Price & Rosswog 2006; Rosswog & Price 2007
  - Star formation simulations: Price & Bate 2007; Price & Bate, submitted
- Radiative transfer
  - Have developed a method for flux-limited diffusion within SPH (Whitehouse, Bate & Monaghan 2005; Whitehouse & Bate 2006)
  - Currently performing star cluster simulations with radiative transfer

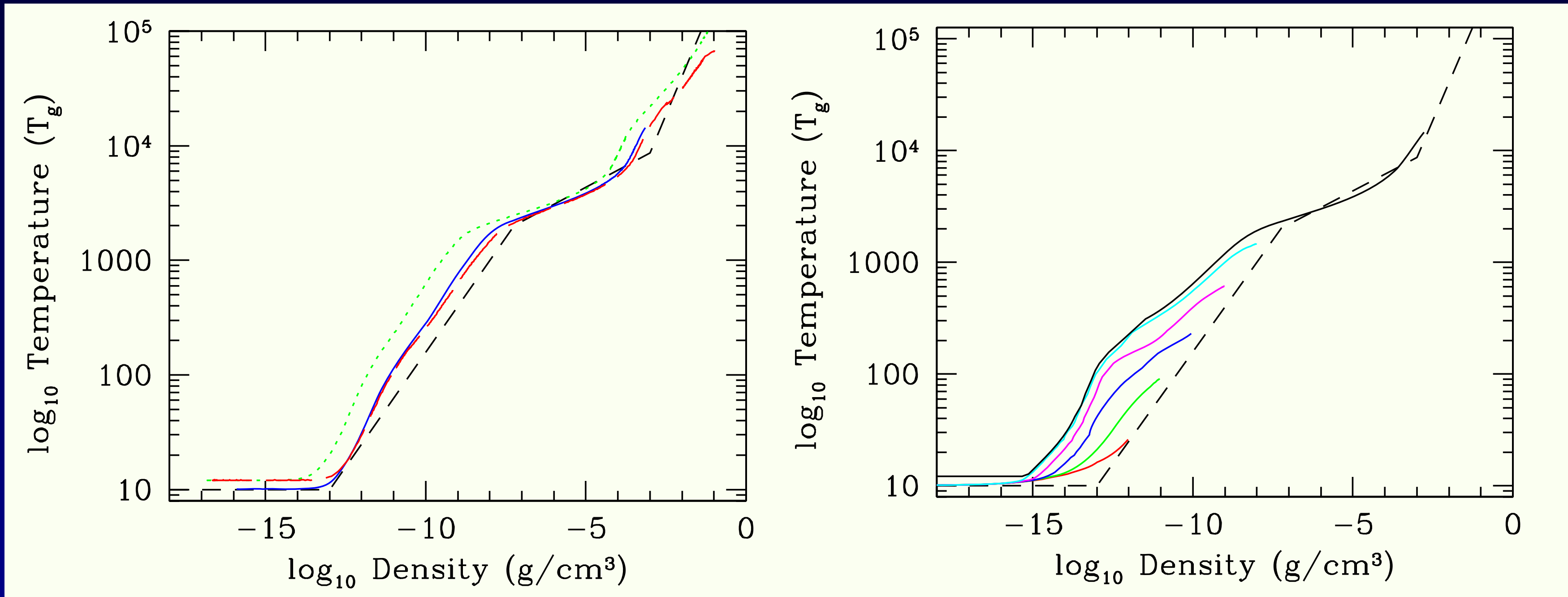
Binary Star Formation

- Whitehouse & Bate 2006
  - 1 M$_\odot$ molecular cloud core with m=2 density perturbation (Boss & Bodenheimer 1979)



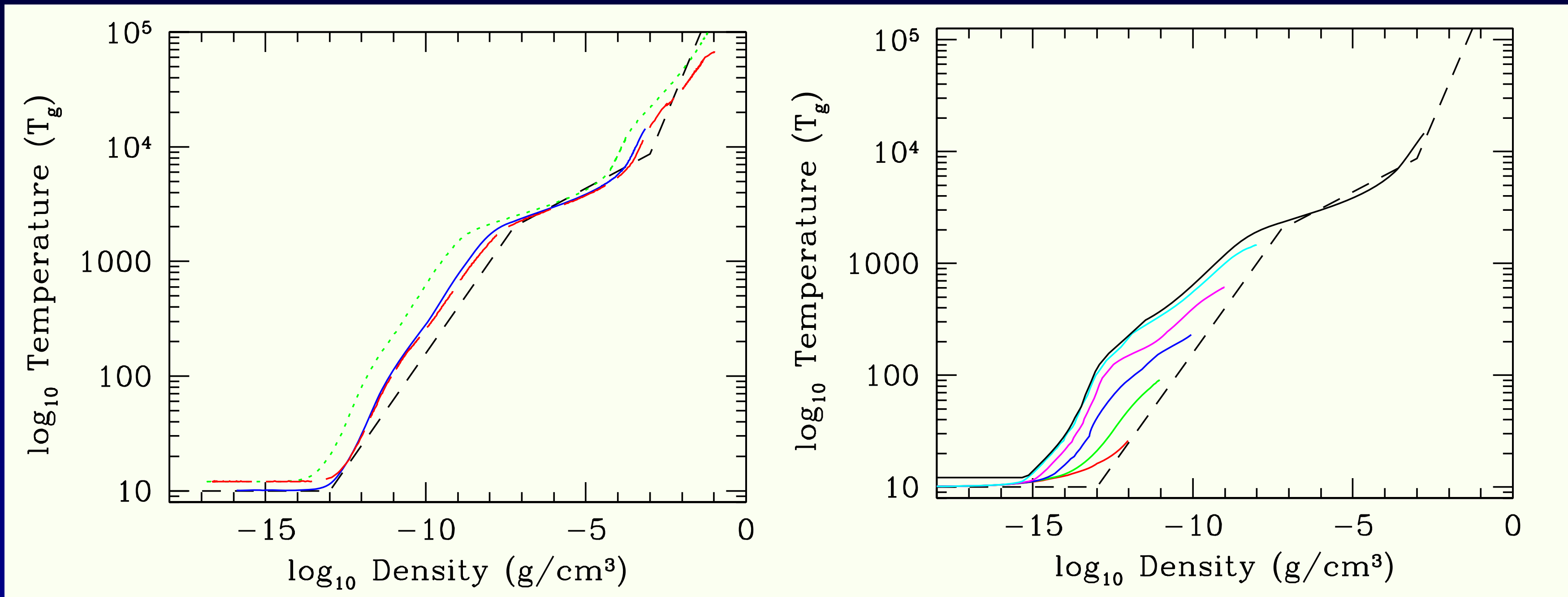
Radiative Feedback

- Radiative heating is expected to significantly alter fragmentation
- Whitehouse & Bate (2006)
  - Temperature given by barotropic equation of state too low by up to factor 10 shortly before and after protostar formation



Radiative Feedback

- Radiative heating is expected to significantly alter fragmentation
- Whitehouse & Bate (2006)
  - Temperature given by barotropic equation of state too low by up to factor 10 shortly before and after protostar formation



- Krumholz (2006); Krumholz, Klein & McKee (2007)
  - Radiative feedback from forming massive star can inhibit fragmentation of surrounding cloud

Star Cluster Formation

- 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 $M_\odot$
  - Barotropic equation of state, 3,500,000 SPH particles
- Sink particles
  - Original calculations: Sink Radii 5 AU, gravity softened within 4 AU
  - Radiative transfer calculations: Sink Radii 0.5 AU, no gravitational softening
- Radiative transfer
  - 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

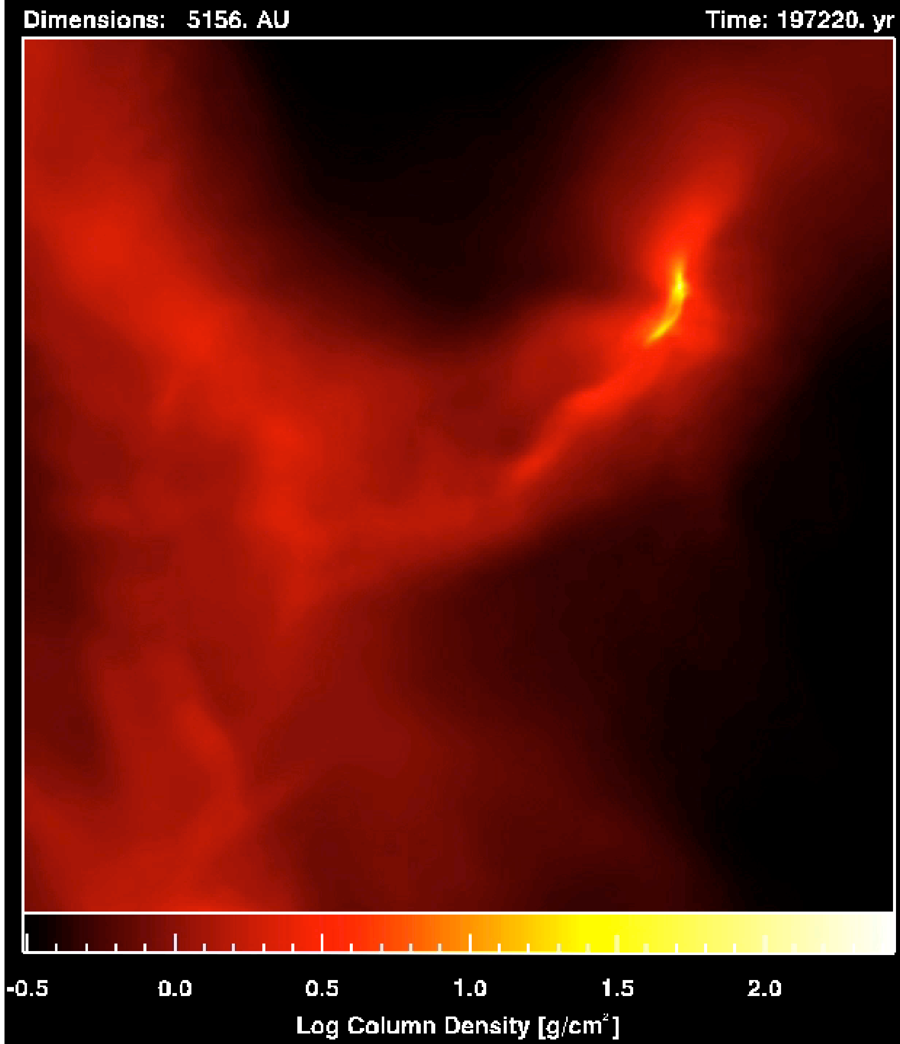
UNIVERSITY OF EXETER

European Science Foundation

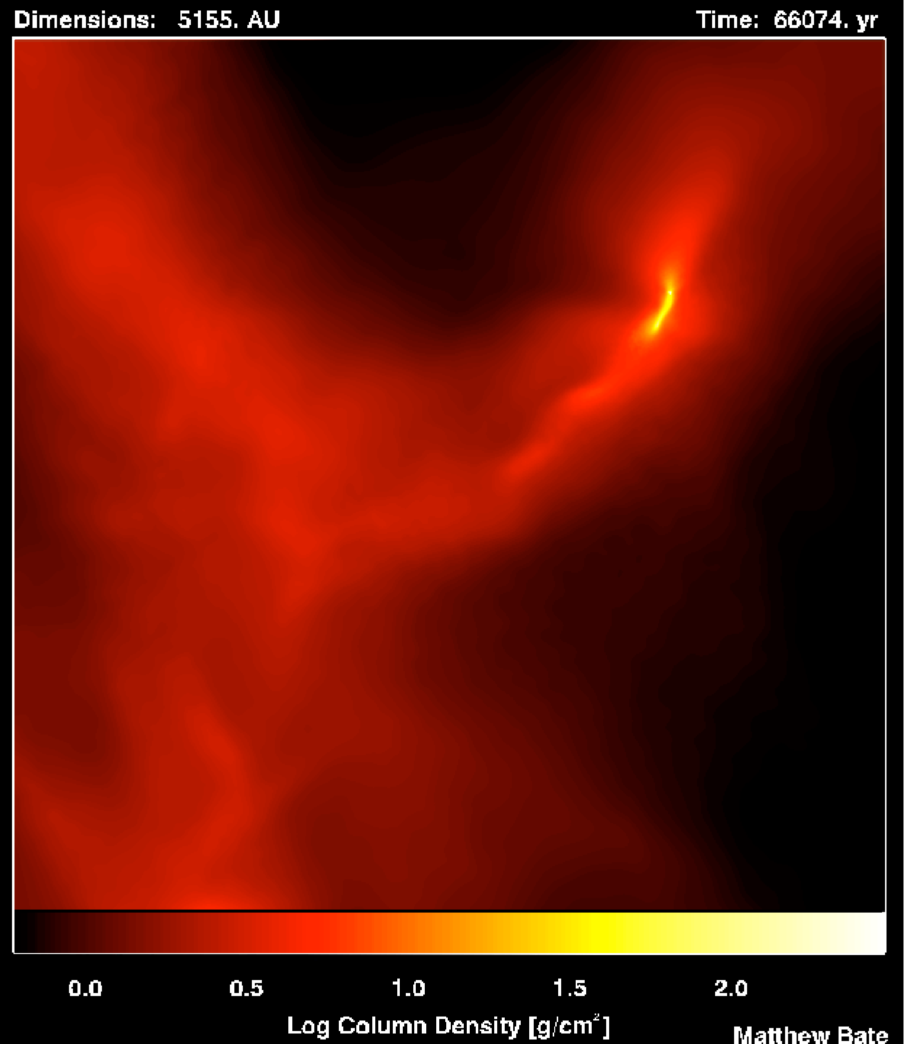
UK Astrophysical Fluids Facility

BBB2003: Typical molecular cloud

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



BBB2003, but with Radiative Transfer



Matthew Bate

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

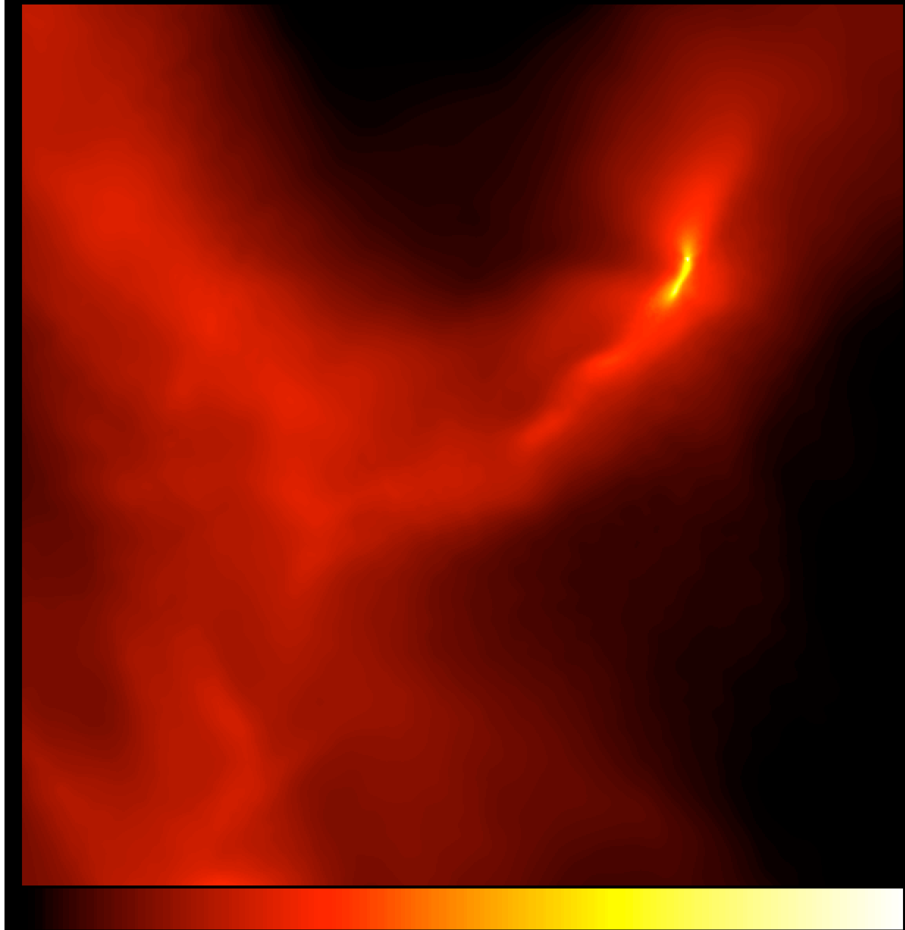
UNIVERSITY OF EXETER

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

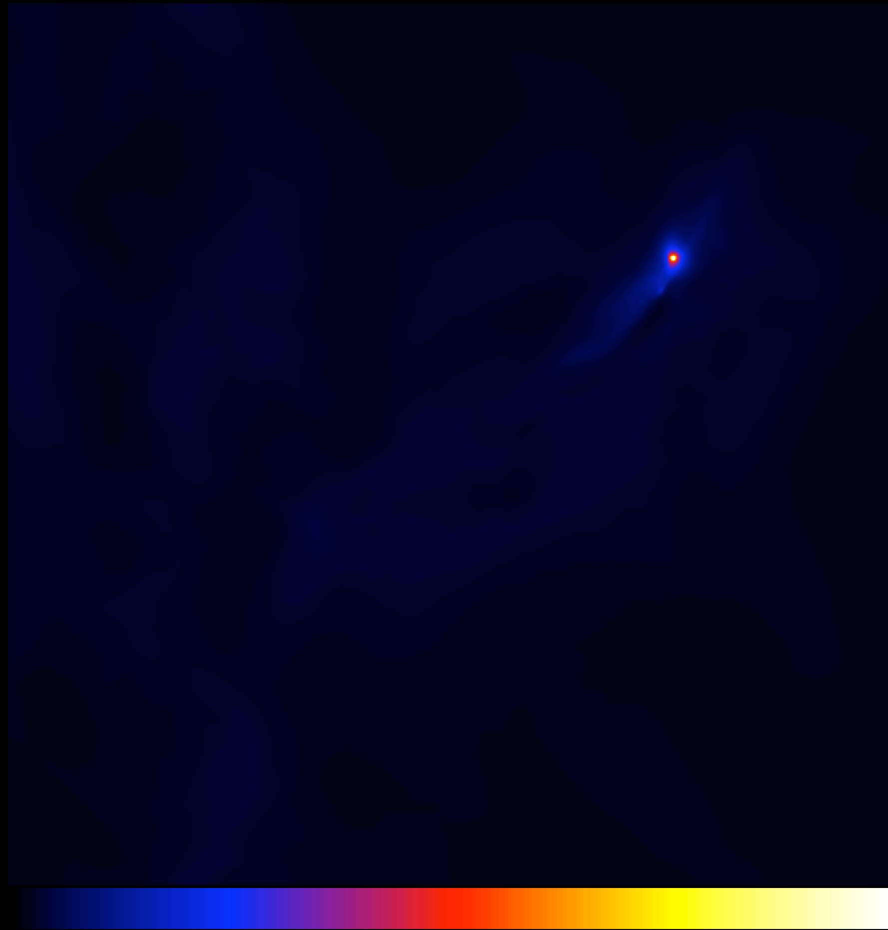
EUROPEAN SCIENCE FOUNDATION

UK Astrophysical Fluids Facility

Log Column Density



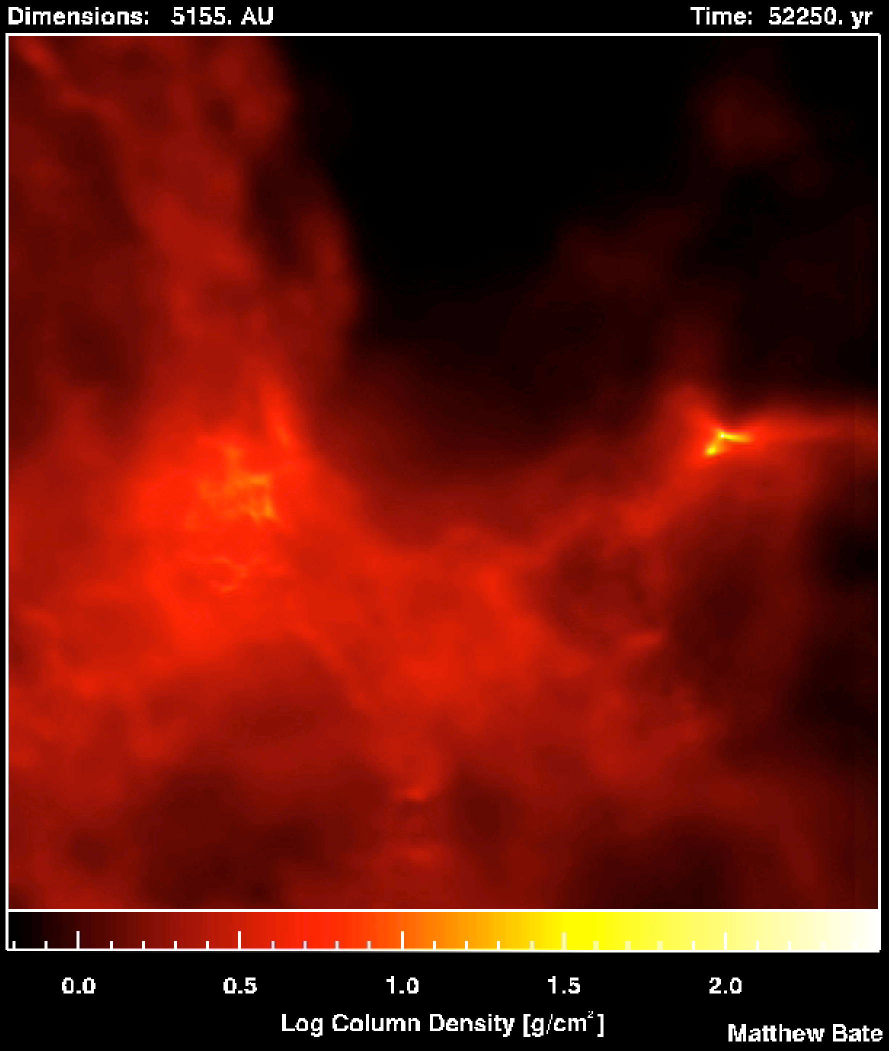
Mass weight temperature (Log 9-100 K)

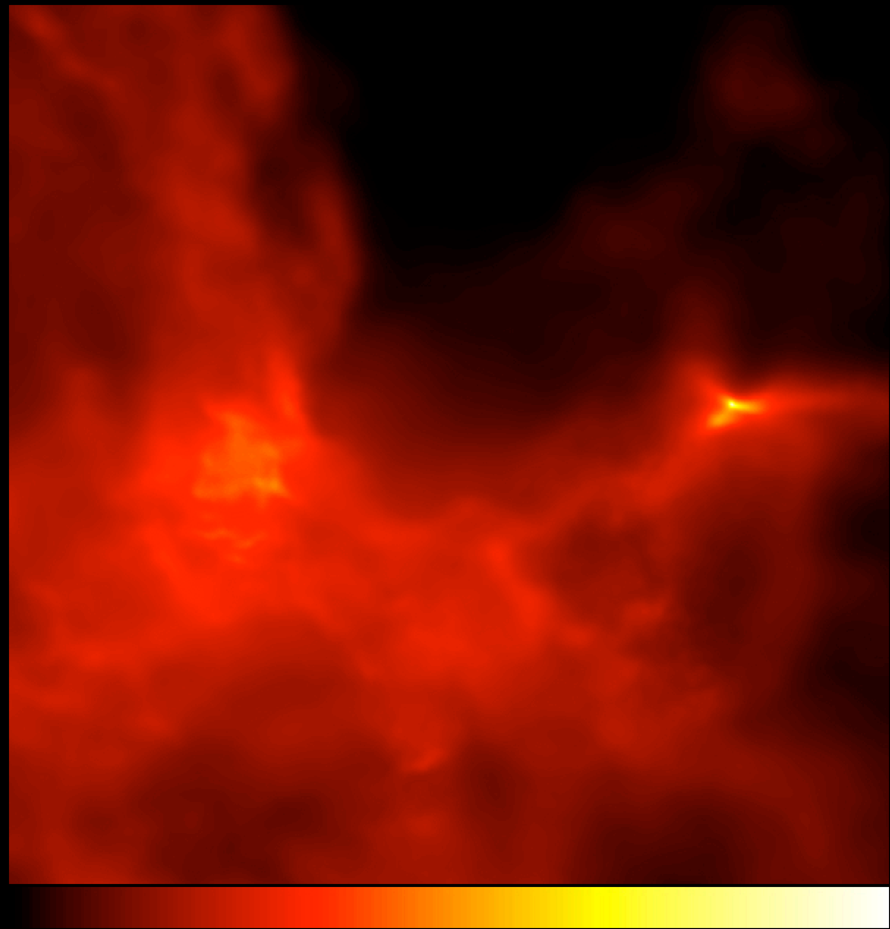


BB2005: Denser molecular cloud

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

BB2005, but with Radiative Transfer





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

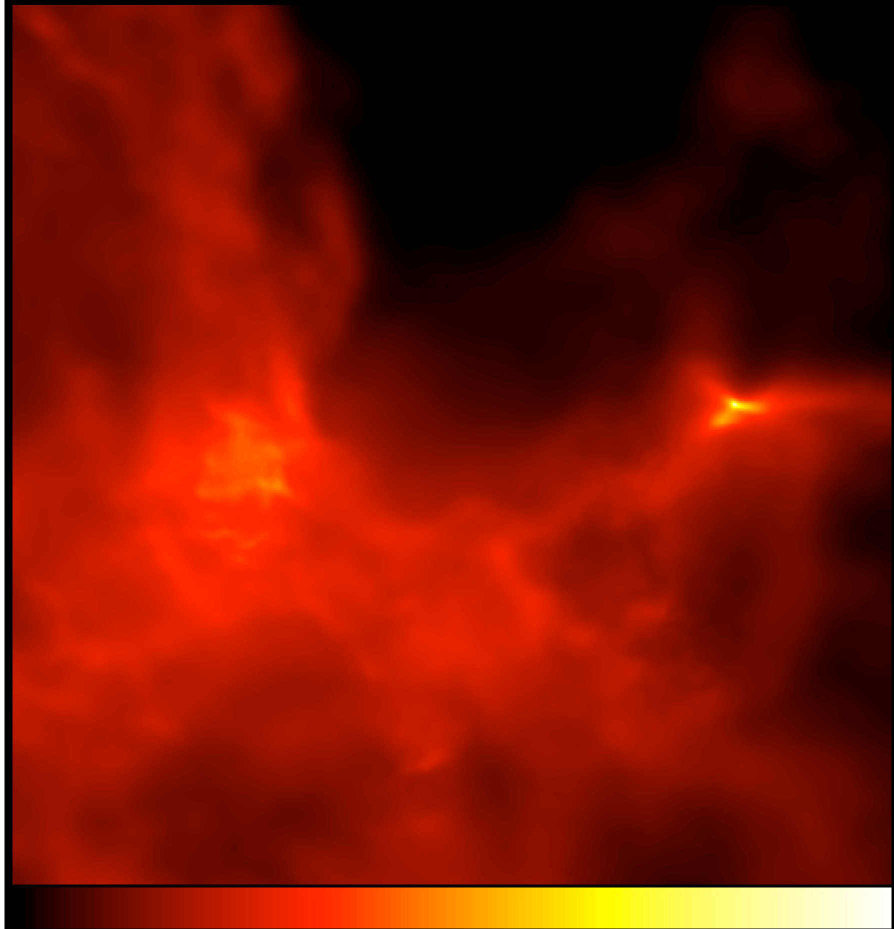
UNIVERSITY OF EXETER

BB2005: Dense cloud: Jeans mass 1/3 $M_{\odot}$, $P(k) \propto k^{-4}$ with Radiative Transfer

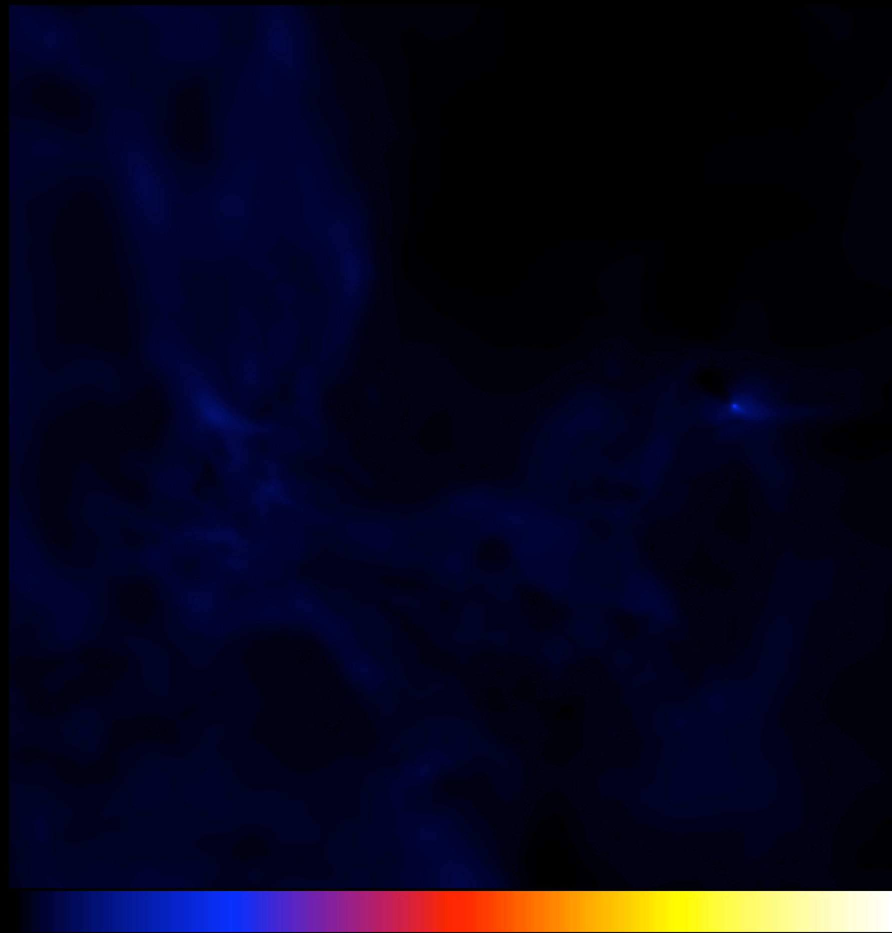
EUROPEAN SCIENCE FOUNDATION

UK Astrophysical Fluids Facility

Log Column Density



Mass weight temperature (Log 9-100 K)



Impact of Radiative Feedback

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

	Stars	Brown Dwarfs	Total
Barotropic Equation of State	23	27	50 ($1.40t_{ff}$)
Radiative Transfer	7	0	7 ($1.30t_{ff}$)

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

	Stars	Brown Dwarfs	Total
Barotropic Equation of State	19	60	79 ($1.40t_{ff}$)
Radiative Transfer	14	3	17 ($1.37t_{ff}$)

UNIVERSITY OF EXETER

European Science Foundation

UK Astrophysical Fluids Facility

Conclusions

- Radiative feedback has a huge effect even for low-mass star formation
  - Radiative feedback heats discs and nearby filaments, stops them from fragmenting
  - Number of objects reduced by factor ~5
- Fewer dynamical ejections
  - Without RT: more brown dwarfs than stars
  - With RT: ~ 7:1 stars:brown dwarfs
- Temperature field is highly time-dependent
  - `Flickering' of temperature depending on protostellar accretion rate
  - Dynamical interactions between discs increase mass accretion rate, accretion luminosity
- Next: add extra luminosity from accretion on <0.5 AU scales