Radiation Magnetohydrodynamics Simulations of Star Formation

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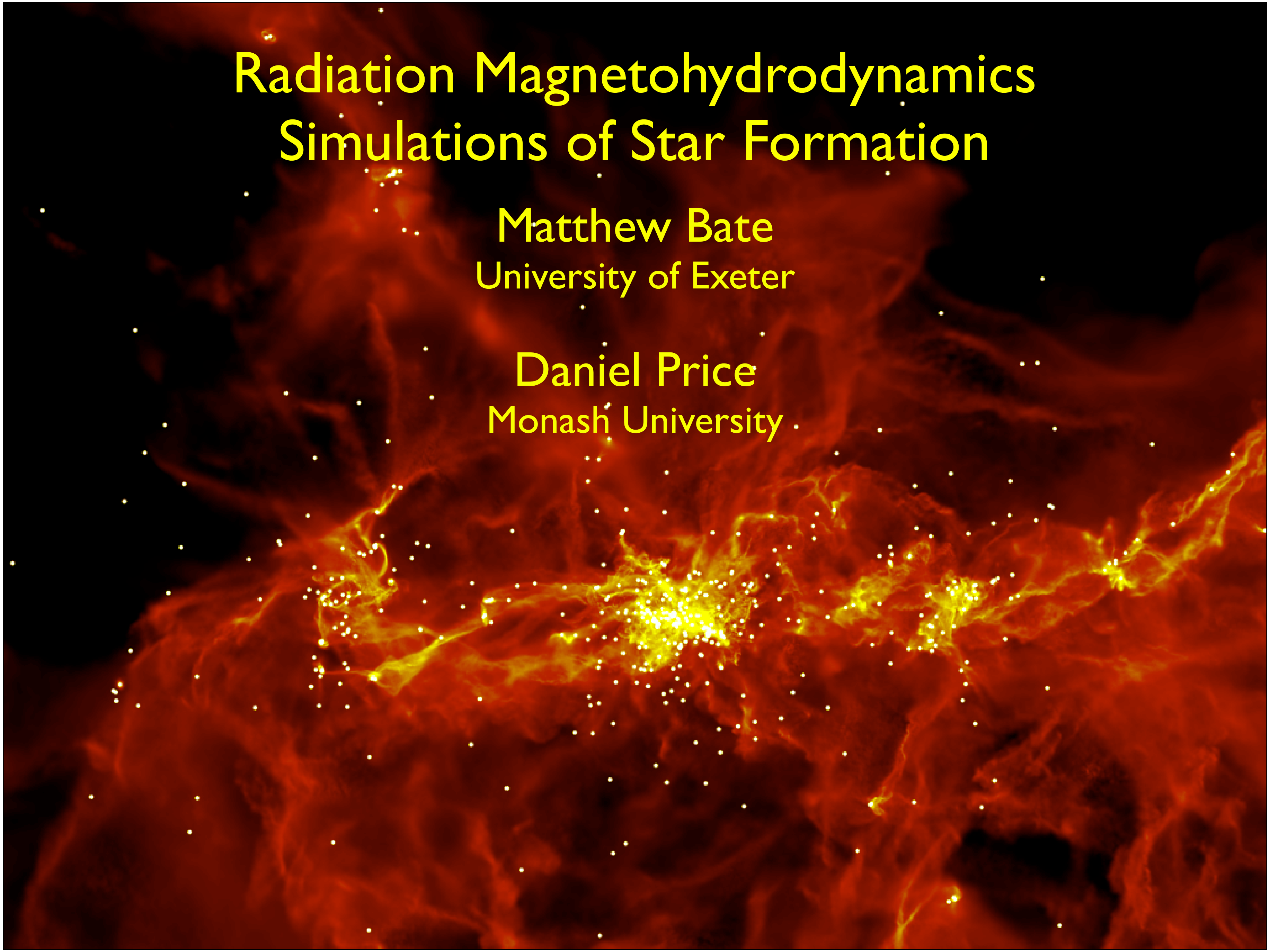

Stellar Properties

- 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

UK Astrophysical Fluids Facility

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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

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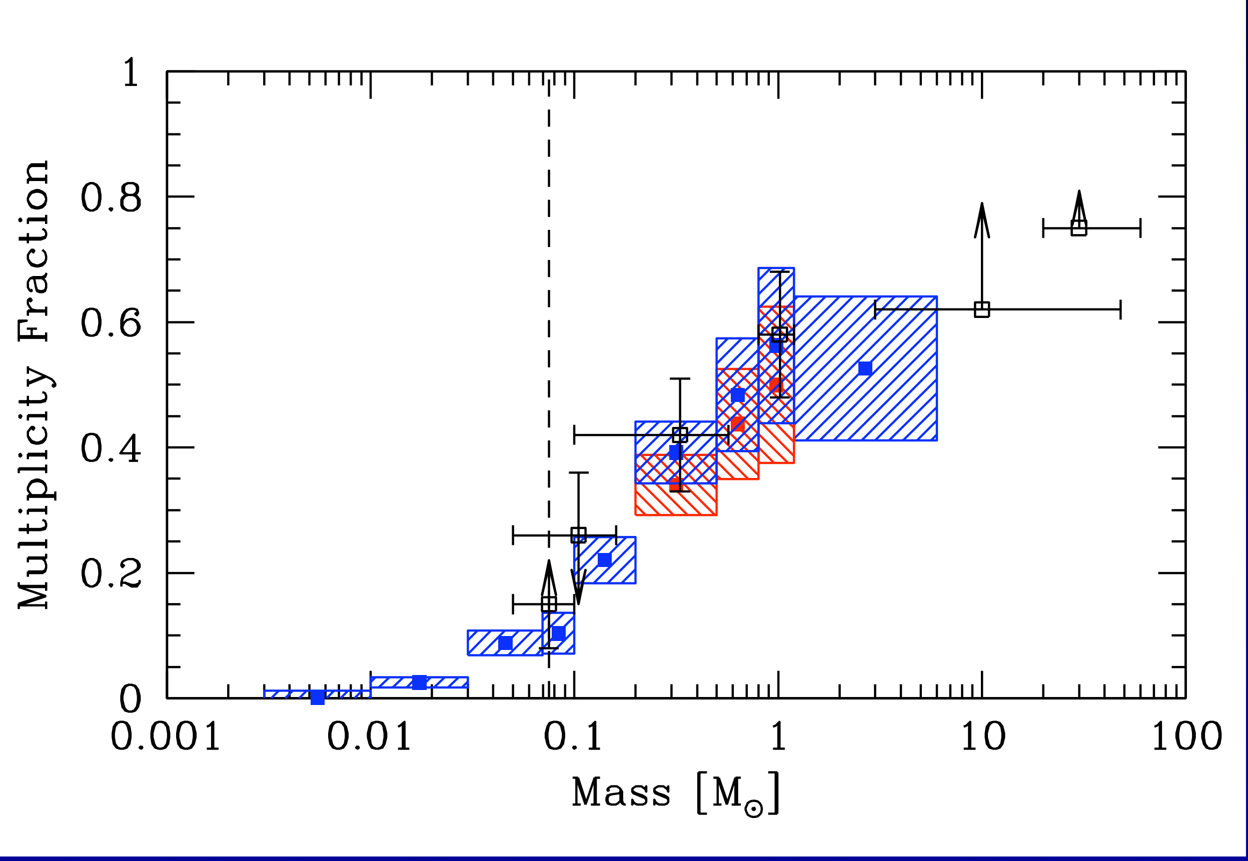
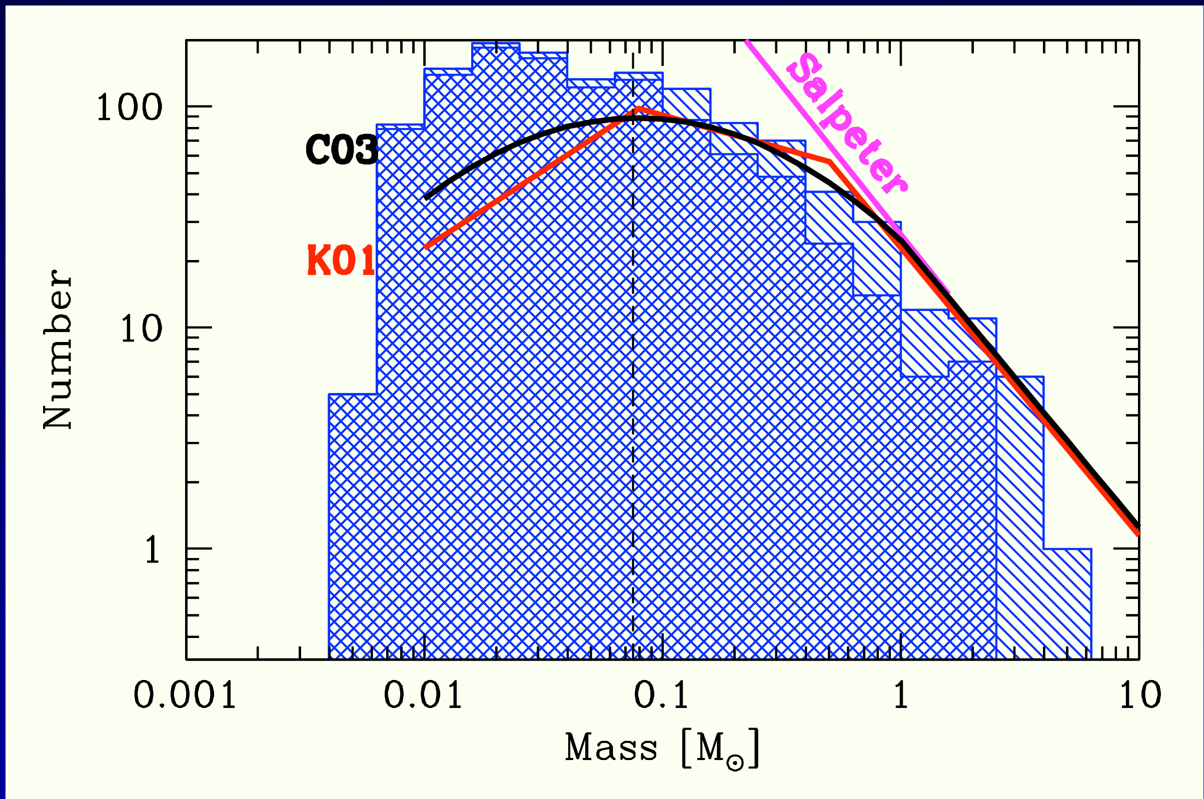
Multiplicity as a Function of Primary Mass

- 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



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



Additional Physics

- Radiative transfer
  - Developed a method for implicit two-temperature grey flux-limited diffusion within SPH (Whitehouse, Bate & Monaghan 2005; Whitehouse & Bate 2006)
  - Star cluster simulations: Bate 2009b
- Magnetic fields
  - Developed by: Price & Monaghan 2005; Price & Rosswog 2006; Rosswog & Price 2007
  - Use Euler potentials: $\mathbf{B} = \nabla\alpha \times \nabla\beta$
  - Star formation simulations: Price & Bate 2007; Price & Bate 2008
- Radiation magnetohydrodynamics
  - Star cluster simulations: Price & Bate 2009

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
  - 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

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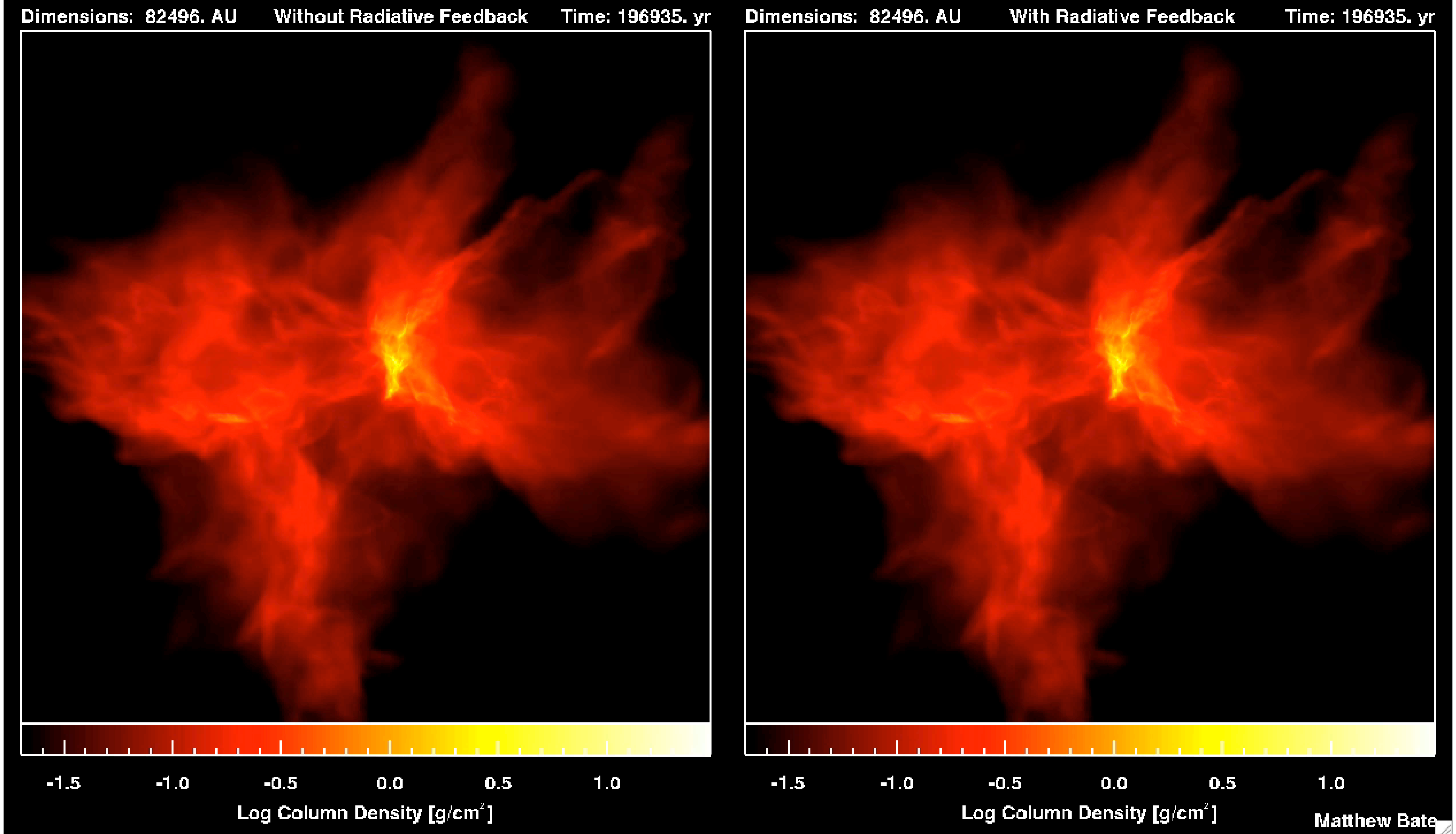
BBB2003: Typical molecular cloud

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

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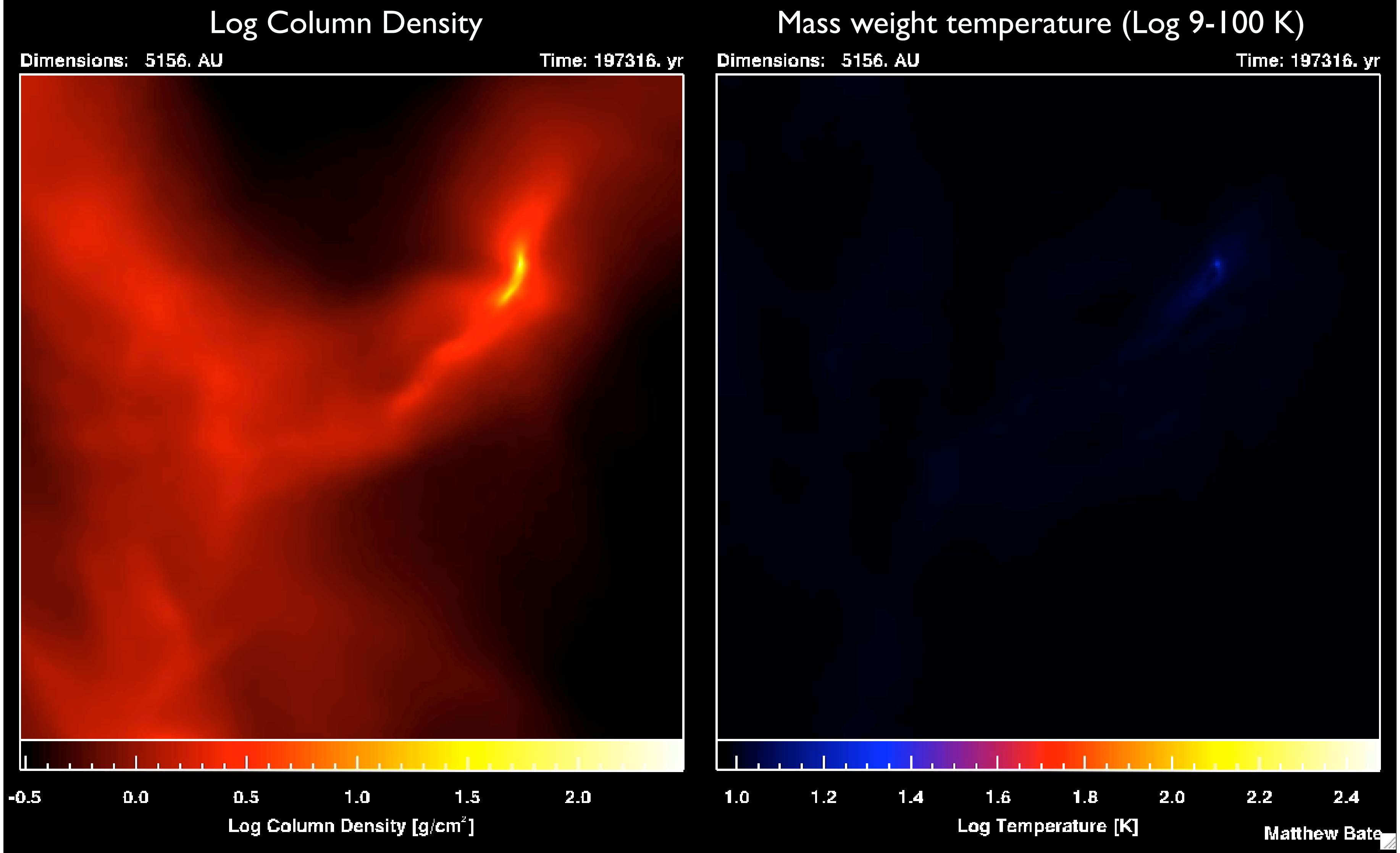
BBB2003: Typical cloud: Jeans mass 1 M$_\odot$, P(k)$\propto$k^{-4} with Radiative Transfer



Impact of Radiative Feedback

- Bate, Bonnell & Bromm (2003)
  - "Typical" density 50 M⊙ molecular cloud (~10^4 cm^{-3})

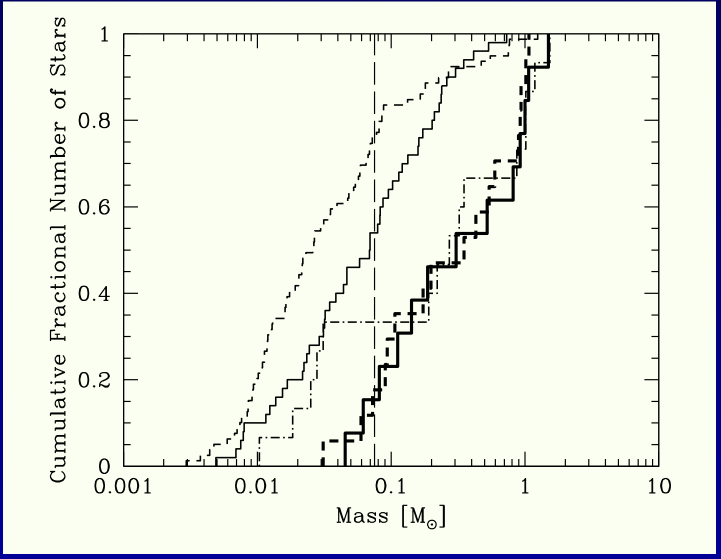
	Stars	Brown Dwarfs	Total
Barotropic Equation of State	23	27	50 (1.40t_{ff})
Radiative Transfer	11	2	13 (1.40t_{ff})

- Bate & Bonnell (2005)
  - Denser 50 M⊙ cloud (~10^5 cm^{-3})

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

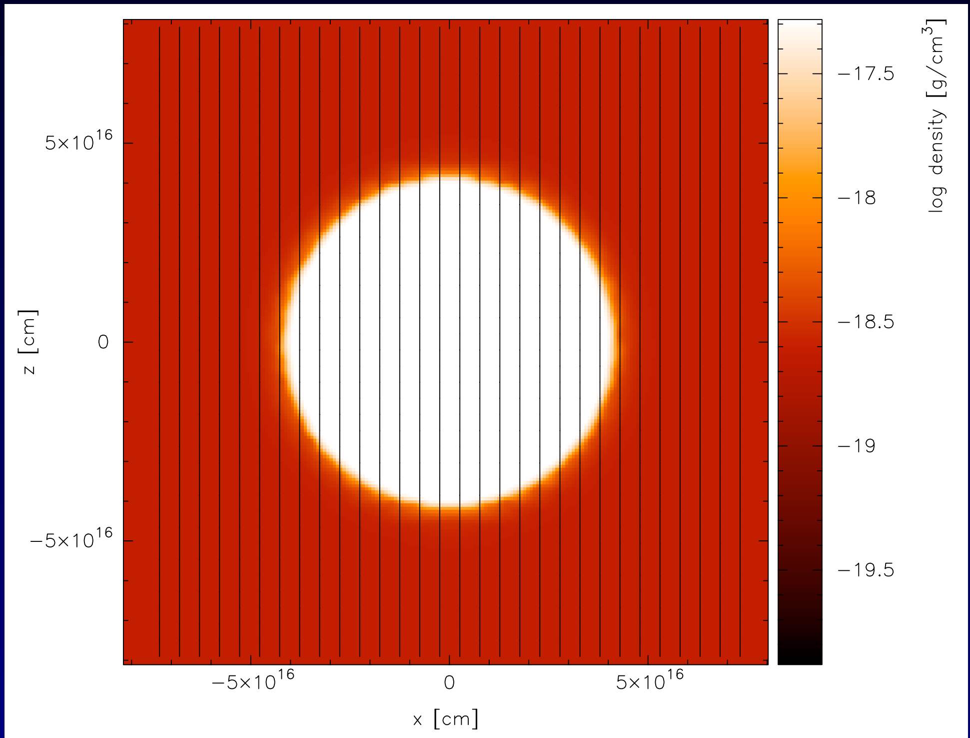
Radiative Feedback and the IMF

- 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
- Furthermore, dependence of the IMF on cloud density is removed
  - K-S test on the two IMFs with radiative feedback shows them to be indistinguishable
- Bate 2009b
  - Heating of the gas surrounding a protostar increases the effective Jeans length and mass
  - Can show that this effective Jeans mass depends very weakly on cloud density



Magnetic Fields and Star Formation

Single & Binary Star Formation: Price & Bate 2007



Resolution ~ 300,000 particles in core
(30,000 required to resolve Jeans mass,
ie. fragmentation)

- Dense core R=4x10^{16}cm=0.013pc =2674 AU
- Embedded in low density medium
- M=1 $M_\odot$ in core
- Initial uniform B_z field
- T = 10K
- Solid body rotation
- Equation of state:

$$P = K\rho^\gamma$$

$$\gamma = 1, \qquad \rho \leq 10^{-14} \mathrm{g\ cm}^{-3},$$

$$\gamma = 7/5, \qquad \rho > 10^{-14} \mathrm{g\ cm}^{-3},$$

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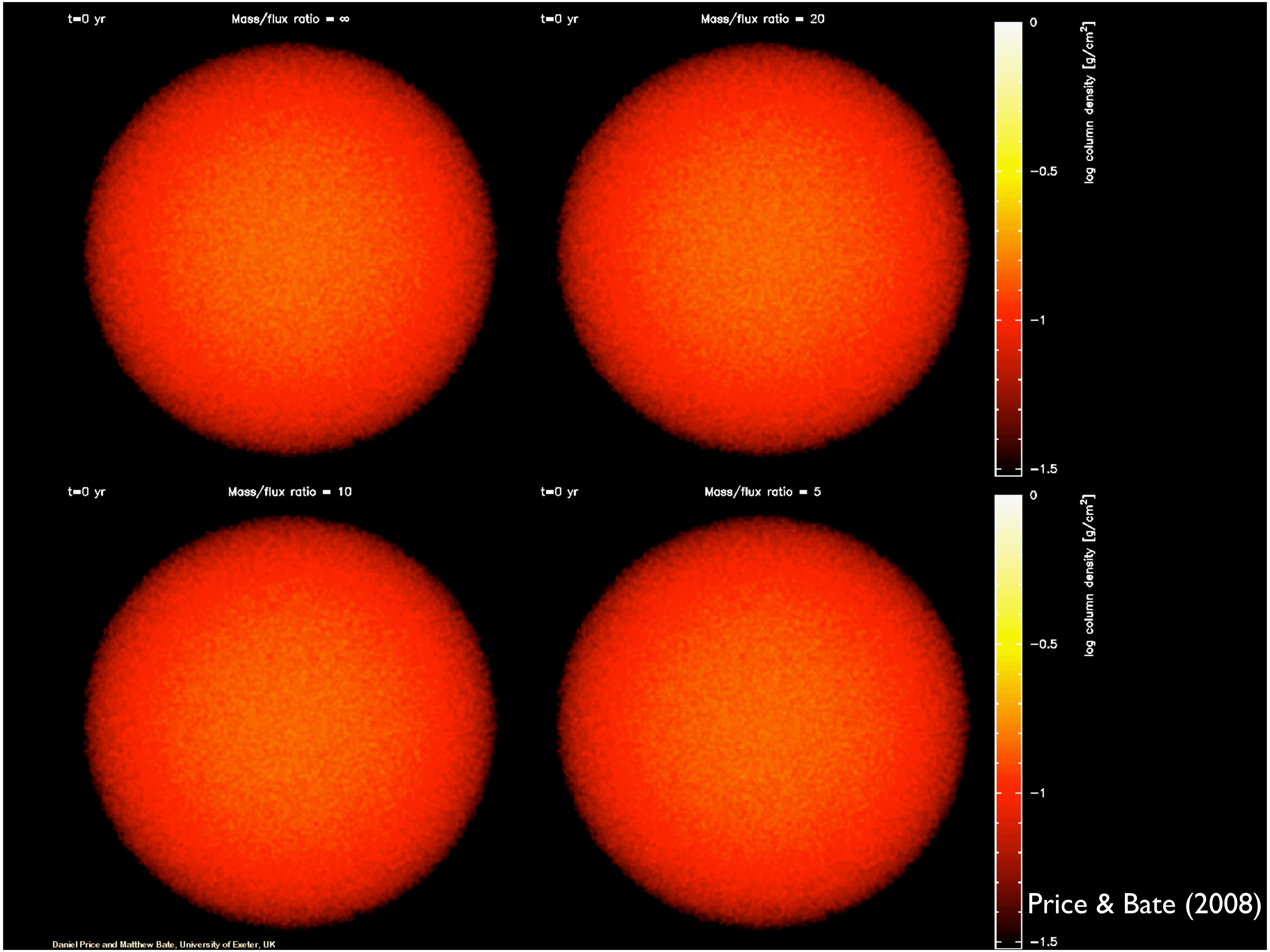
Magnetic Fields and Binary Formation: B_z

Daniel Price and Matthew Bate, University of Exeter, UK

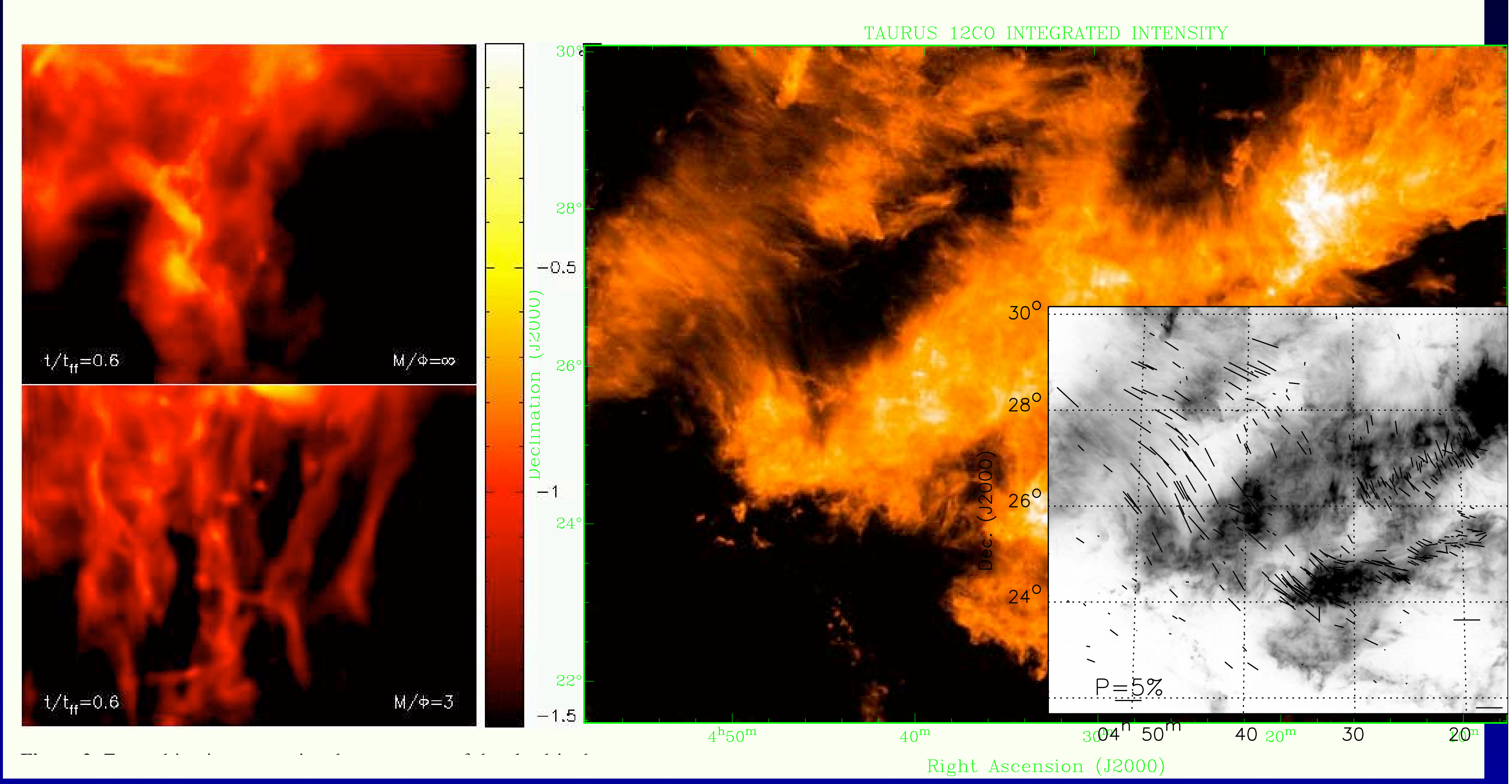
Magnetic Fields and Binary Formation: B_x

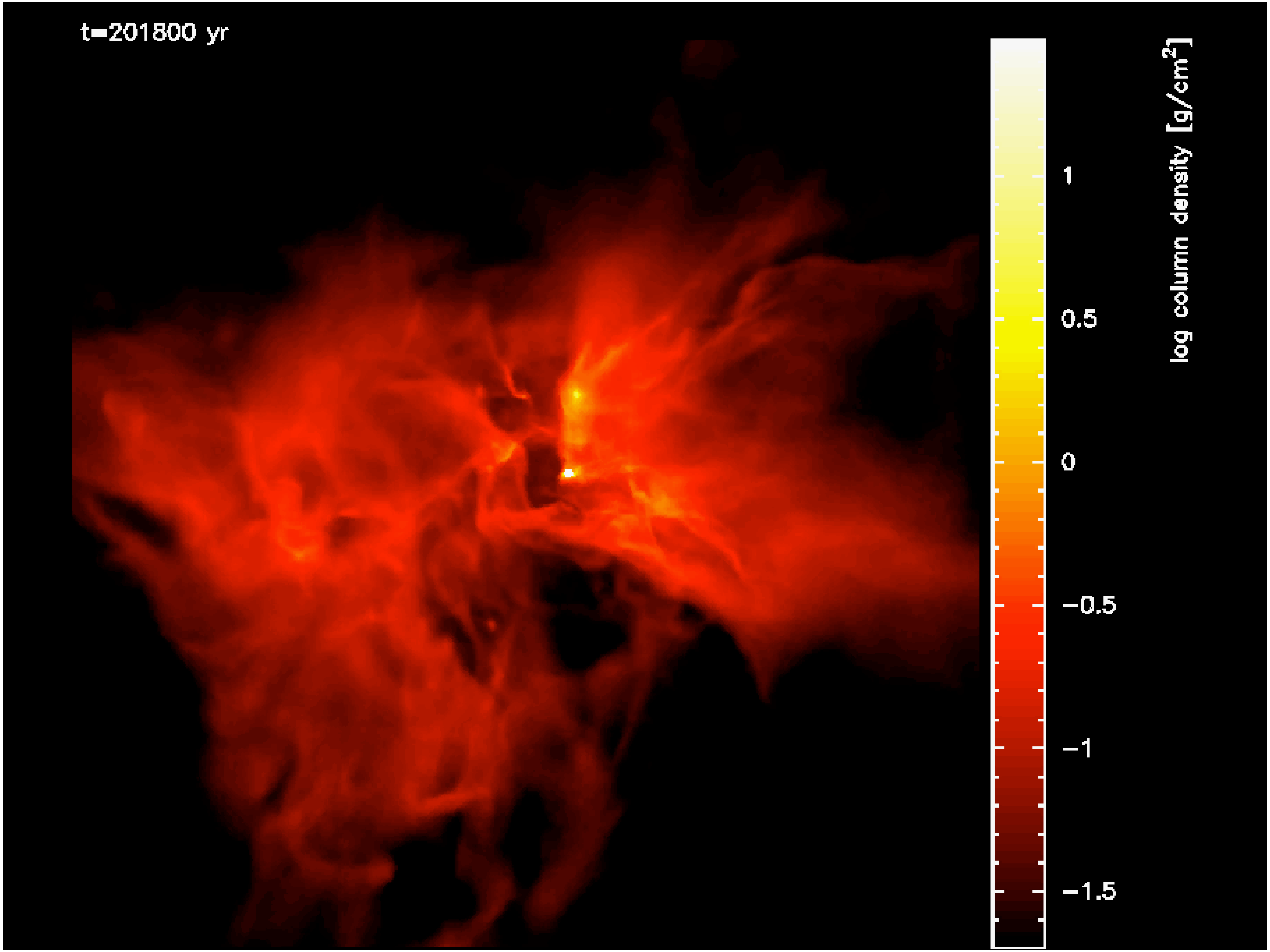
Daniel Price and Matthew Bate, University of Exeter, UK


t=0 yr
Mass/flux ratio = ∞
t=0 yr
Mass/flux ratio = 20
0
−0.5
−1
−1.5
log column density [g/cm²]
t=0 yr
Mass/flux ratio = 10
t=0 yr
Mass/flux ratio = 5
0
−0.5
−1
−1.5
log column density [g/cm²]
Price & Bate (2008)
Daniel Price and Matthew Bate, University of Exeter, UK

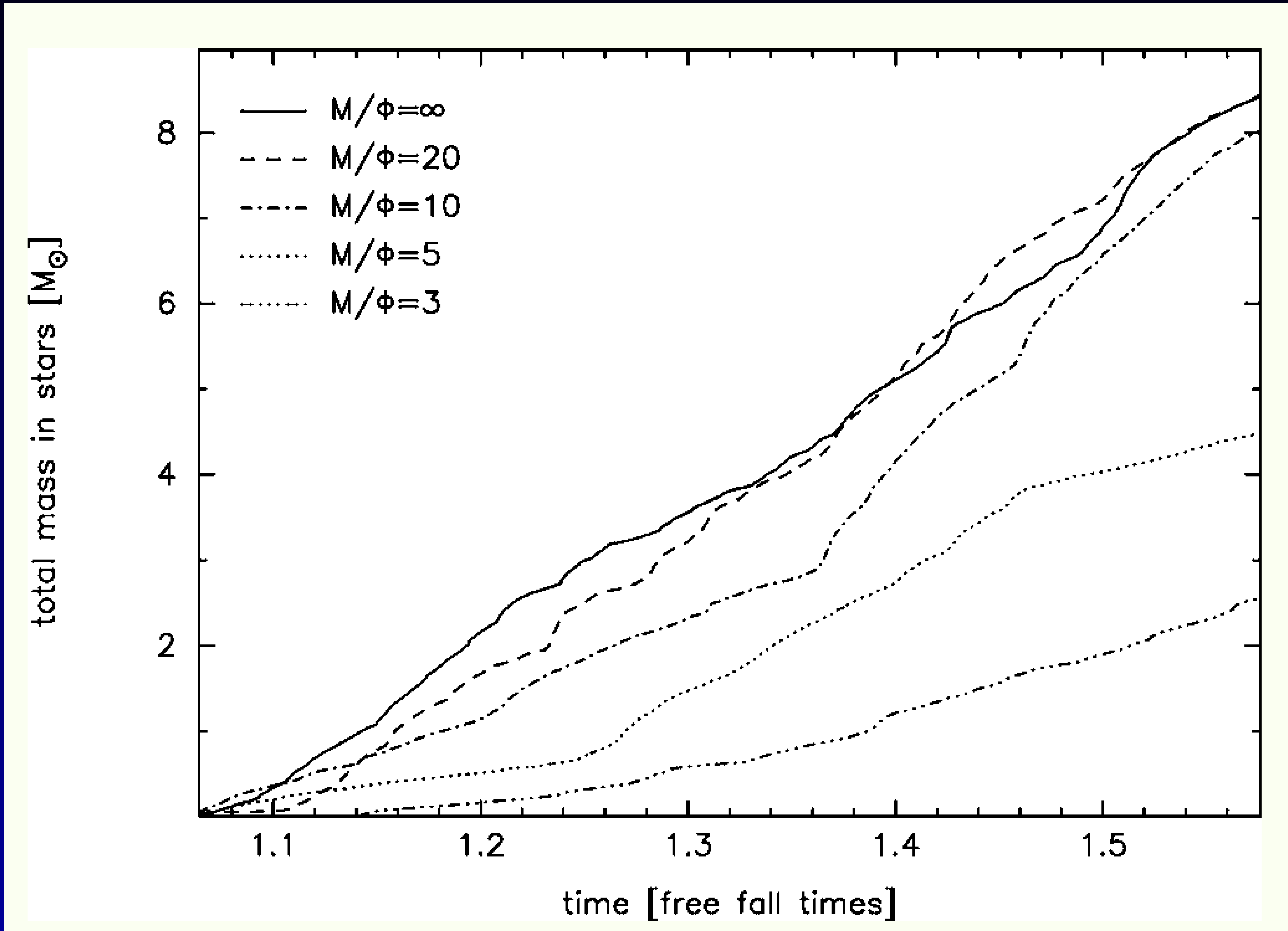
Density Striations Aligned with Field

- Column density striations seen in simulations and observations
  - ^{12}CO striations aligned with magnetic field in Taurus (Goldsmith et al. 2005, 2008)




t=201800 yr
1
0.5
0
−0.5
−1
−1.5
log column density [g/cm^2]

Star Formation Rate

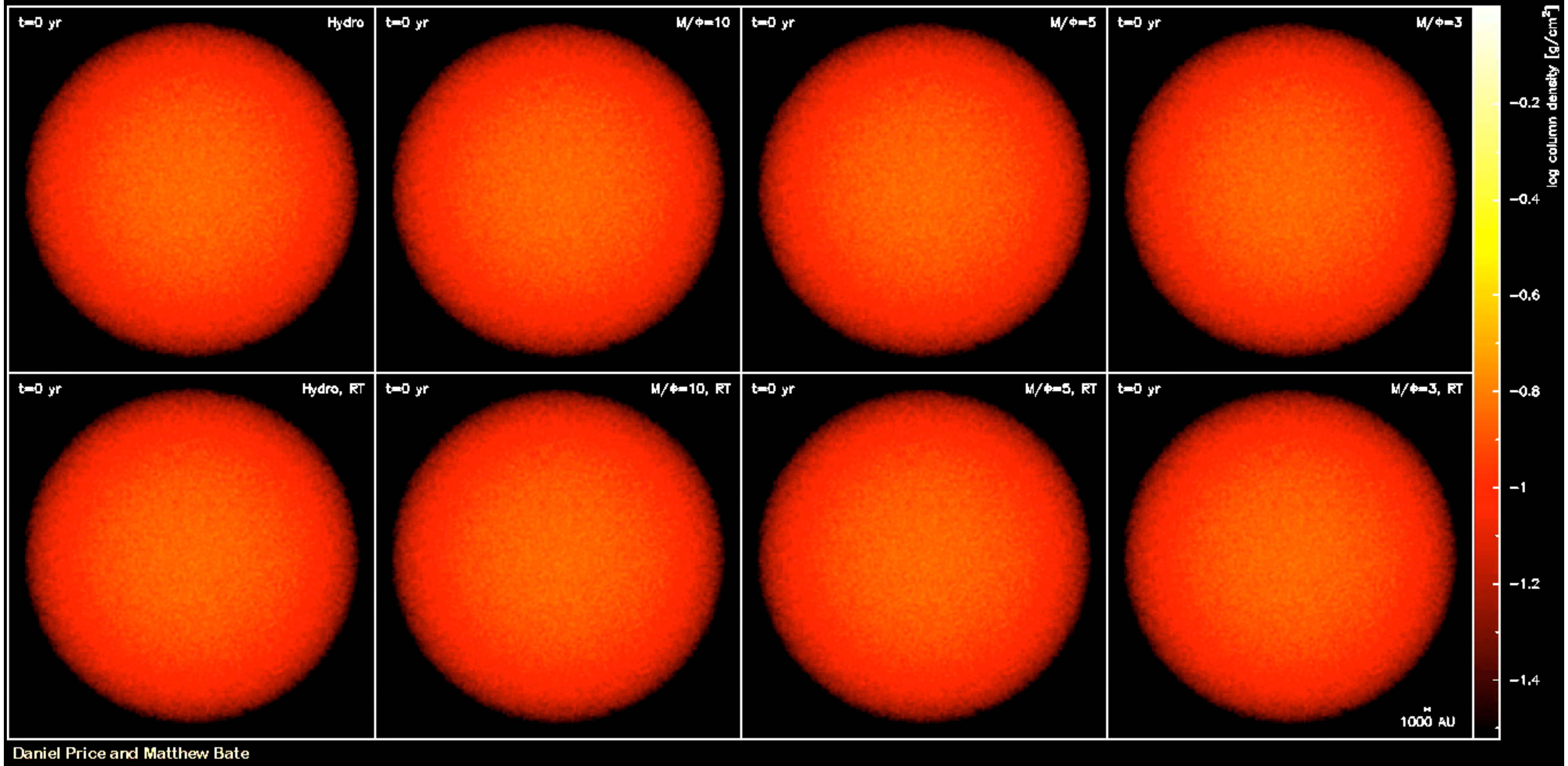


20% SFE_{ff}

Radiation Magnetohydrodynamical Simulations

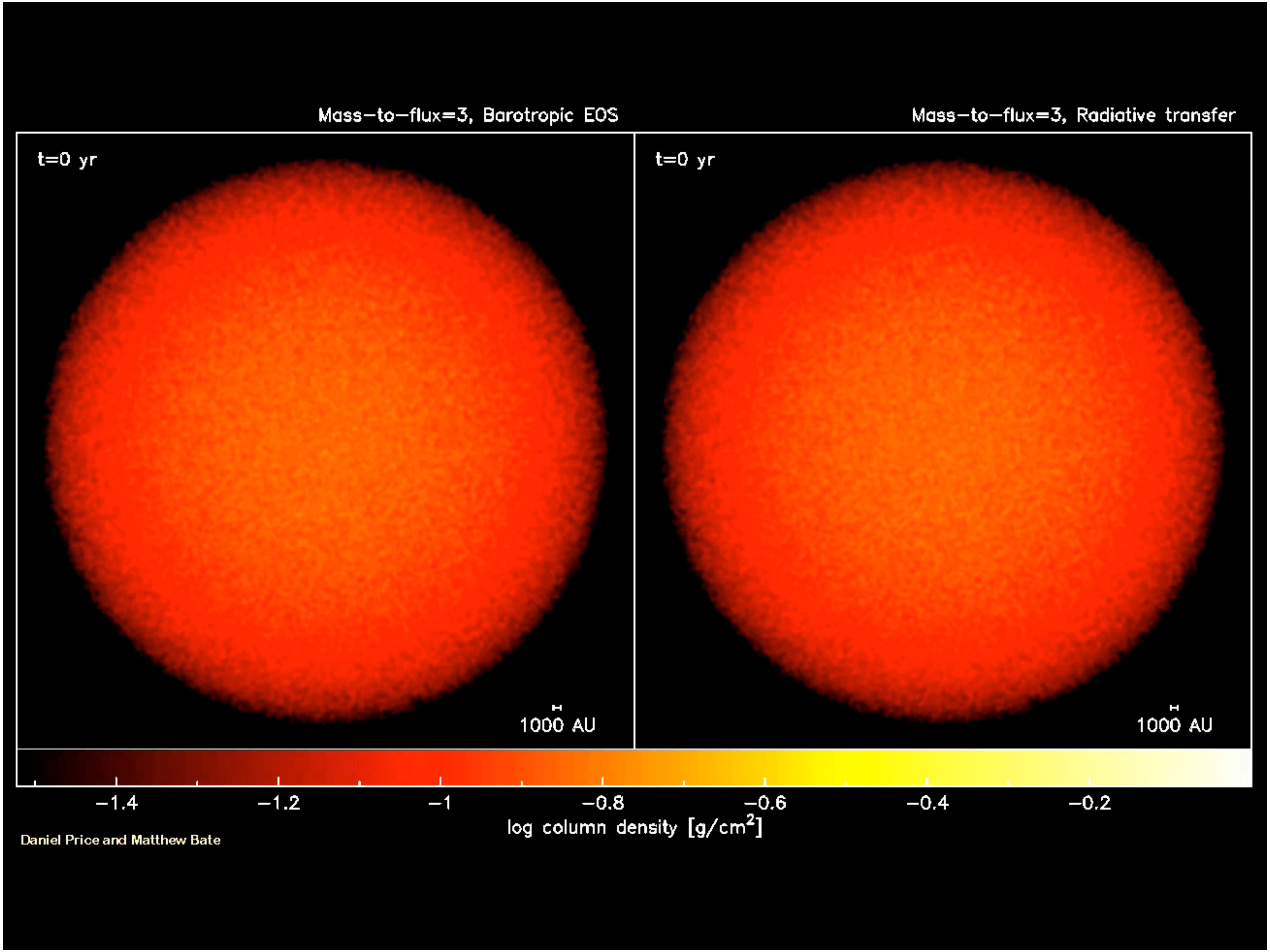
Price & Bate (2009)

Hydrodynamical | Mass-to-flux ratio: 10 | Mass-to-flux ratio: 5 | Mass-to-flux ratio: 3



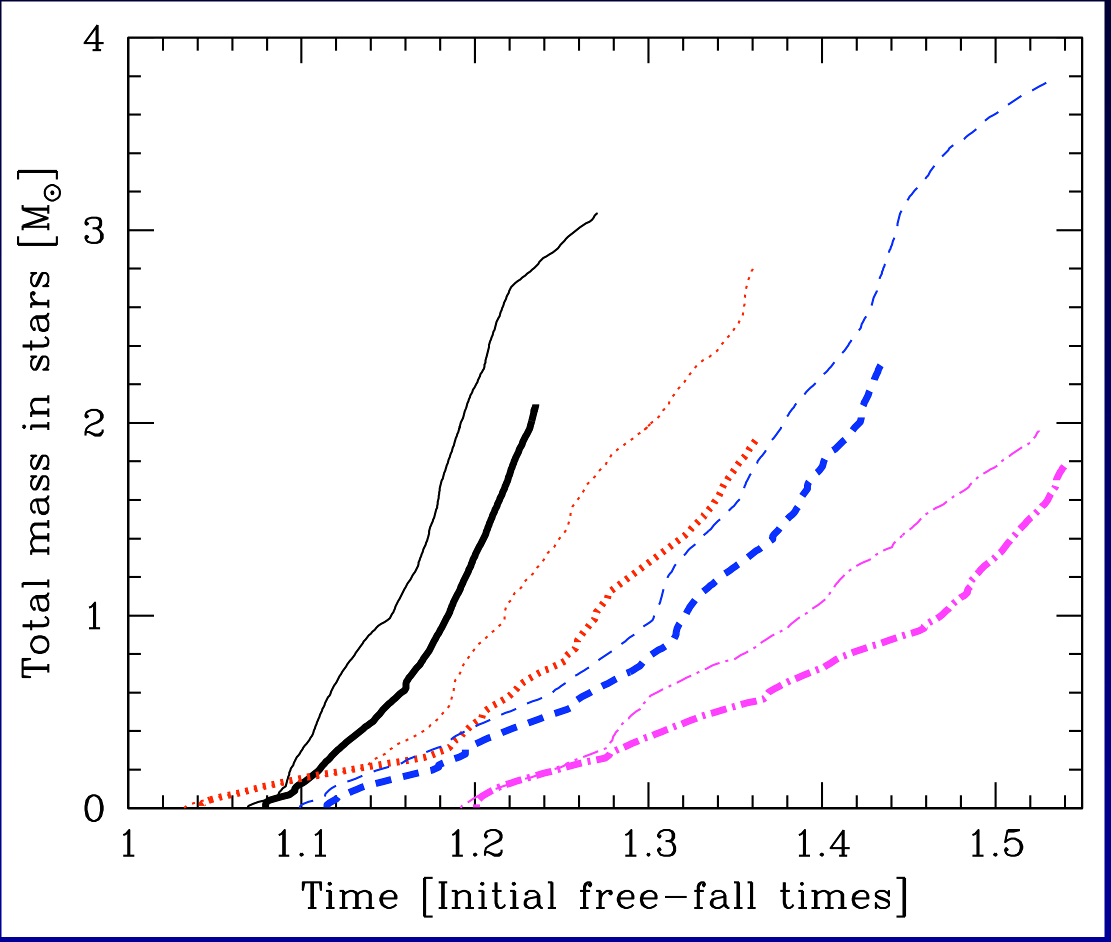
Upper panels: Without radiative feedback

Lower panels: With radiative feedback


Mass–to–flux=3, Barotropic EOS
Mass–to–flux=3, Radiative transfer
t=0 yr
t=0 yr
1000 AU
1000 AU
−1.4
−1.2
−1
−0.8
−0.6
−0.4
−0.2
log column density [g/cm^2]
Daniel Price and Matthew Bate

Star Formation Rate

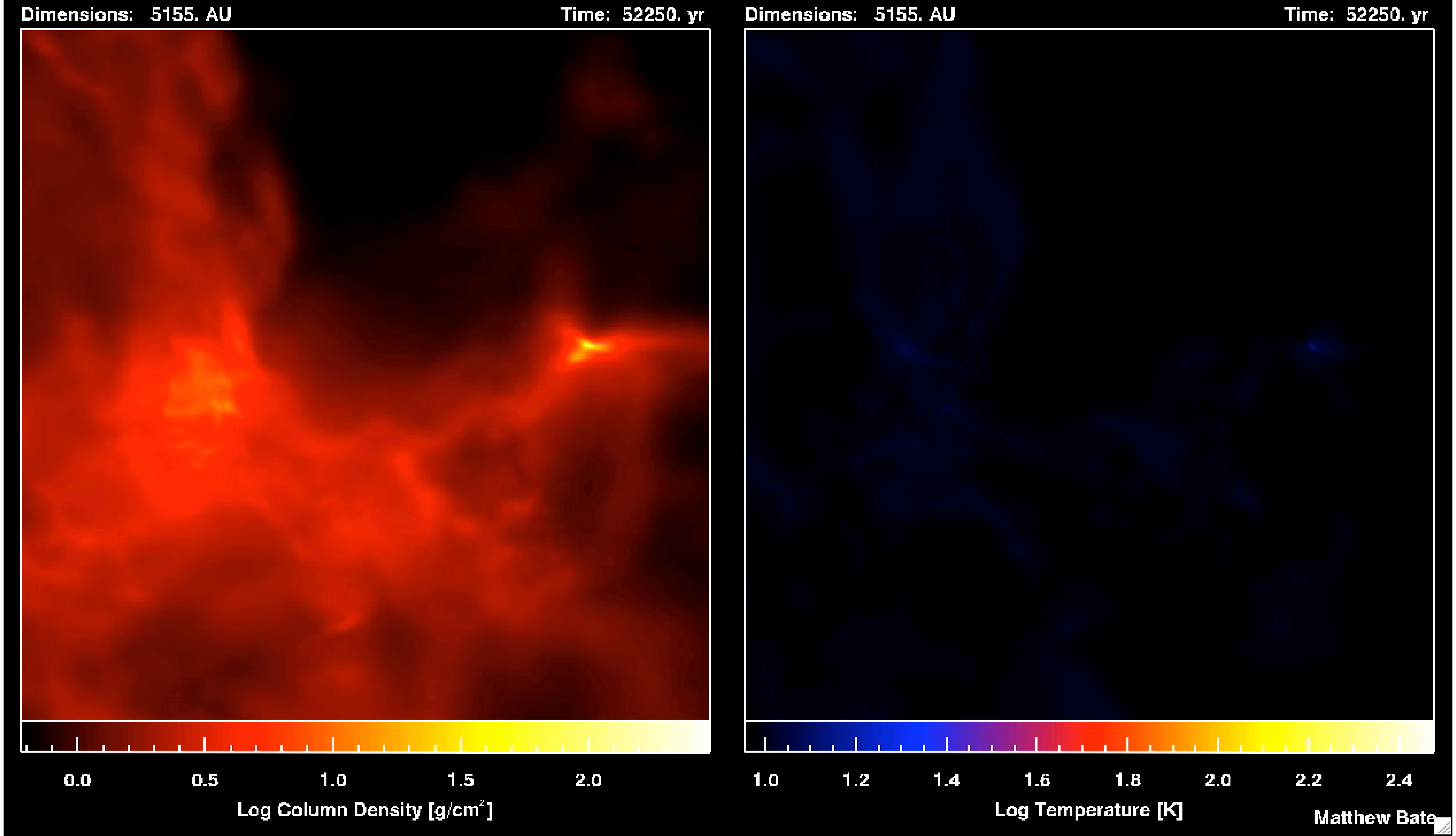
- Star formation rate decreases monotically with
  - Increasing magnetic field strength
  - Radiative feedback
- Observationally
  - Evans et al. 2009
  - Spitzer c2d survey, 5 clouds
  - ~3-6% SFR/t_{ff}
- Numerical results
  - 10-32% SFR/t_{ff}
- Strongest field, with radiative feedback
  - ~10% SFR/t_{ff}



Conclusions

- Hydrodynamical/sink particle simulations
  - Statistics now good enough that meaningful comparison can be made with observations
    - Reasonable multiplicity, separation distributions
    - Too many brown dwarfs, too few unequal mass stellar binaries
- Radiative feedback has a huge effect even for low-mass star formation
  - Number of objects reduced by factor ~4
  - Fewer dynamical ejections, potentially solving the brown dwarf problem
    - Without RT: more brown dwarfs than stars
    - With RT: ~ 4:1 stars:brown dwarfs
  - Radiative feedback also weakens the dependence of the IMF on the cloud's mean Jeans mass
- The effects of magnetic fields are complicated
  - Magnetic pressure can be more important than magnetic tension in inhibiting fragmentation
  - Although magnetic tension is responsible for magnetic braking, it can aid binary formation
  - Strong magnetic fields (plasma beta <1)
    - Decrease the star formation efficiency, bringing it into line with observational estimates
    - Do not seem to alter stellar masses much; rather decrease rate at which objects form
    - Can produce large-scale voids and magnetic structures in the gas

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



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- The calculations were performed on the UK Astrophysical Fluids Facility (UKAFF) and the University of Exeter Supercomputer