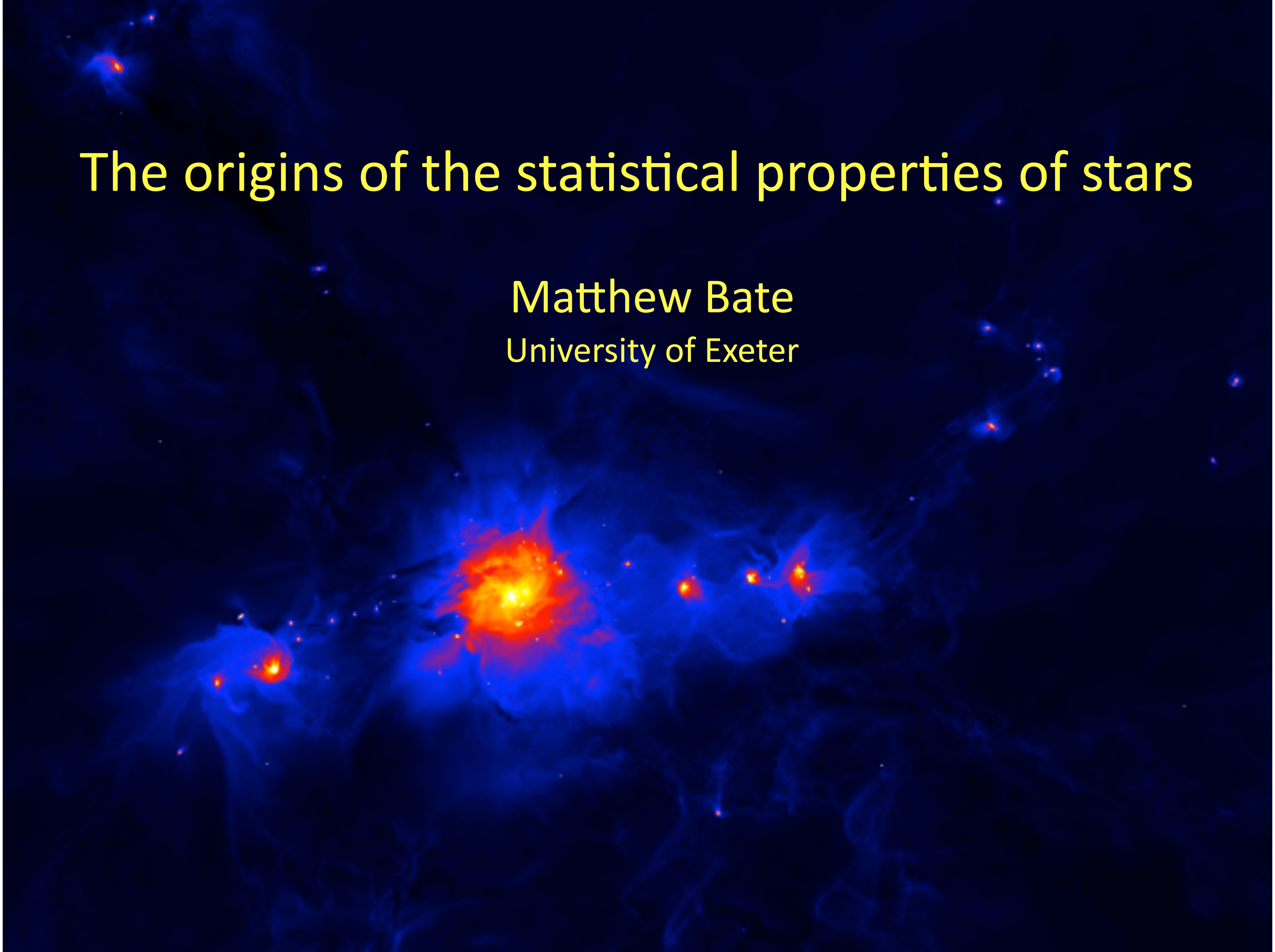
The origins of the statistical properties of stars

Matthew Bate
University of Exeter



UNIVERSITY OF EXETER

A Brief History of Star Formation

1930 - 1950
Realisation that stars are still forming in the Universe today

1950 - 2012
Trying to understand which physical processes are most important in star formation

2012 ⟶
Developing a predictive theory of star formation

1968 -
1-D numerical simulations

1978 -
3-D numerical simulations

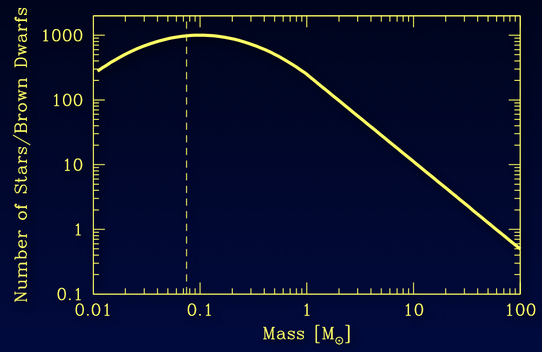
1980's -
Multi-physics simulations

1992 -
Formation of stellar groups

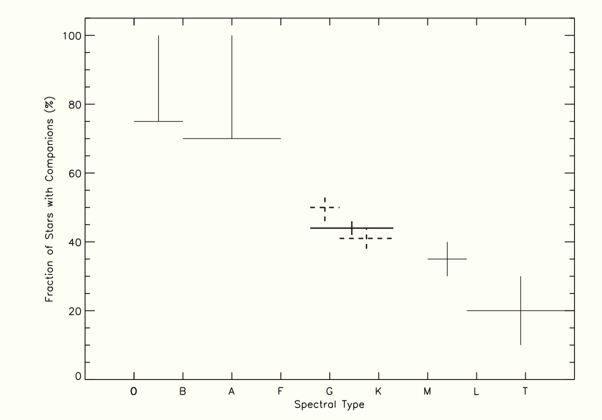
Bate (2012), Krumholz et al (2012) -
Simulations able to reproduce observed the observed properties of stellar systems

Stellar Properties

- Initial mass function
  - Observed to be relatively independent of initial conditions, at least in our Galaxy (Bastian, Covey & Meyer 2010)



- 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)

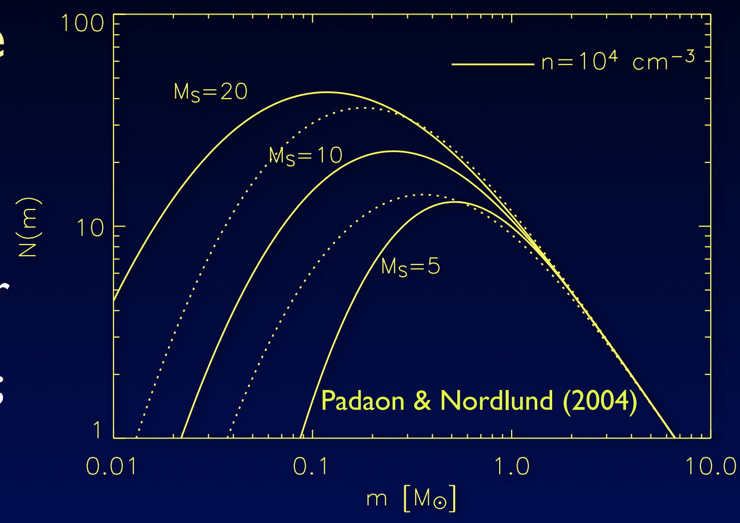


Raghavan et al. (2010)

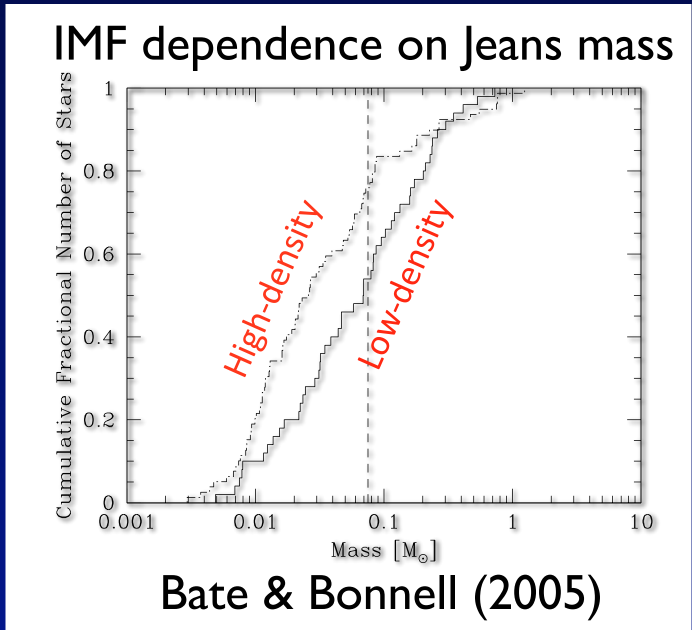
- Protoplanetary discs
  - Masses, sizes, density distributions

The origin of the initial mass function

- Molecular cloud structure - IMF results from core mass function
  - (e.g. Elmegreen 1993; Padoan et al. 1997)
  - IMF may depend on Jeans mass and turbulent Mach number
  - (e.g. Padaon & Norlund 2004; Hennebelle & Chabrier 2008; Hopkins 2012)

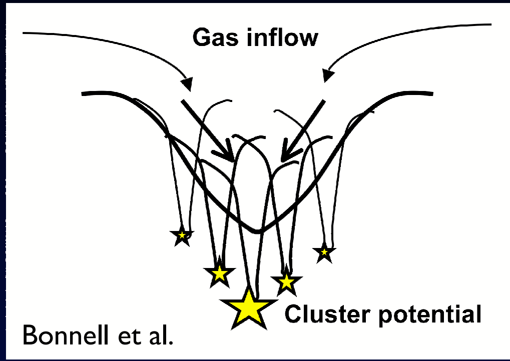


- Competitive accretion - IMF results from "winners" and "losers" competing for mass from a gas reservoir
  - (e.g. Larson 1978, 1992; Zinnecker 1982)
  - IMF may depend on Jeans mass (e.g. Bonnell et al. 1997, 2001; Klessen et al. 1998; Bate, Bonnell & Bromm 2003; Bate & Bonnell 2005; Jappsen et al. 2005; Bonnell et al. 2006)

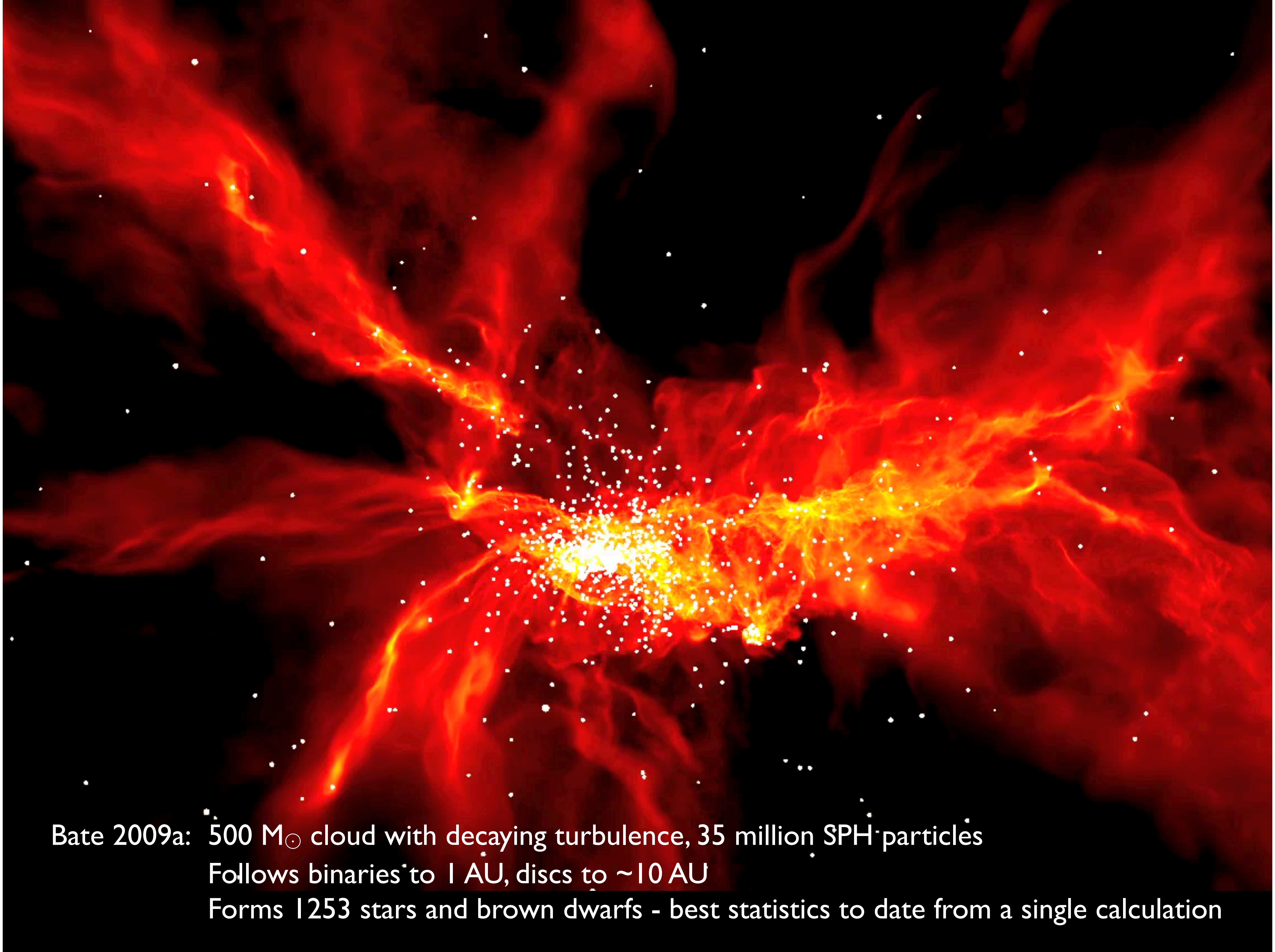


What determines stellar properties?

- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises is probably not so important



- Dissipative dynamical interactions between accreting protostars
  - Gives an IMF-like mass distribution (competitive accretion), but depends on global Jeans mass
  - Leads to observed multiplicity fractions and properties of multiple systems
- Radiative feedback (interactions) from accreting protostars
  - Enables the production of an (almost) invariant IMF
- All three together can reproduce observed stellar properties

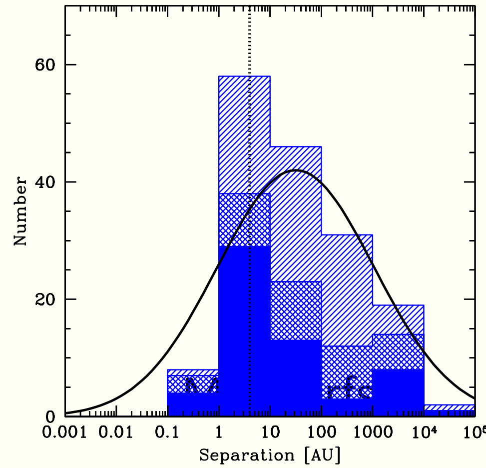


Bate 2009a: 500 $M_\odot$ cloud with decaying turbulence, 35 million SPH particles
Follows binaries to 1 AU, discs to ~10 AU
Forms 1253 stars and brown dwarfs - best statistics to date from a single calculation

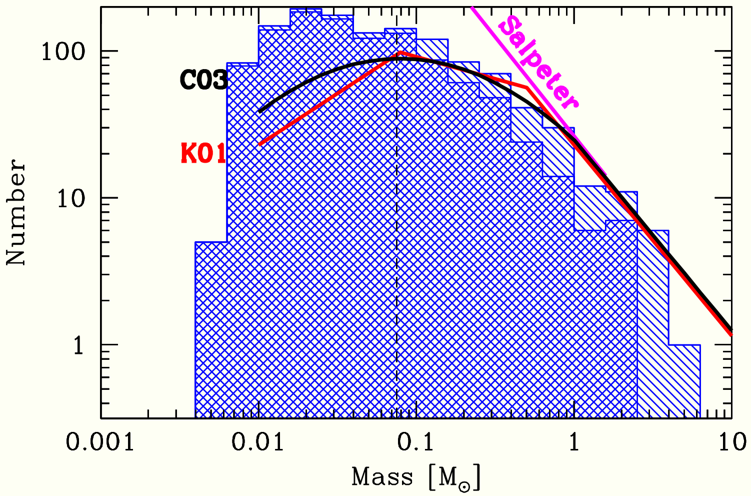
Bate (2009): First hydrodynamical calculation to produce more than 1000 stars and brown dwarfs

- Multiplicity consistent with field
- Separations closer for lower-mass binaries
- Mean inclination of orbital planes of triple systems
  - 65 ± 6º compared to observed 67 ± 6º (Sterzik & Tokovinin 2002)
- But twice as many brown dwarfs as stars
  - >6 times the observed BD/star ratio

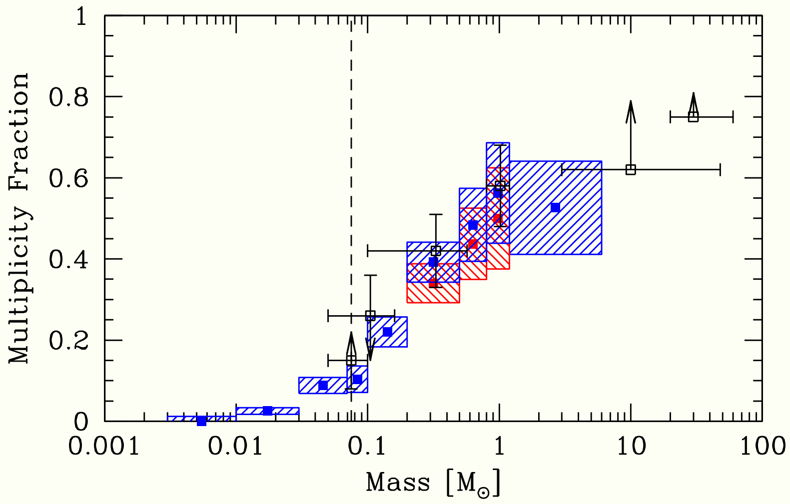
Median stellar separation: 26 AU



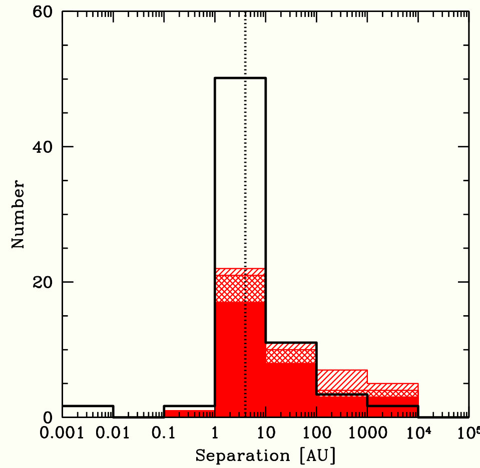
Mass function



Multiplicity



Median very-low-mass separation: 10 AU



UNIVERSITY OF EXETER

EUROPEAN SCIENCE FOUNDATION

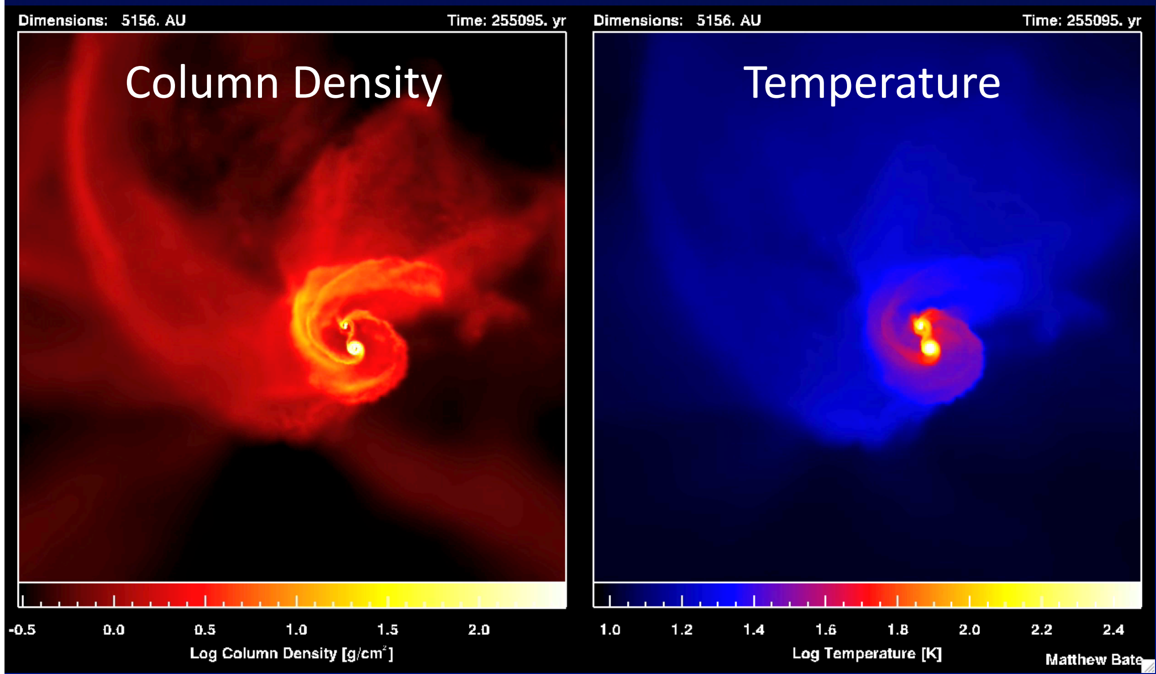
constellation

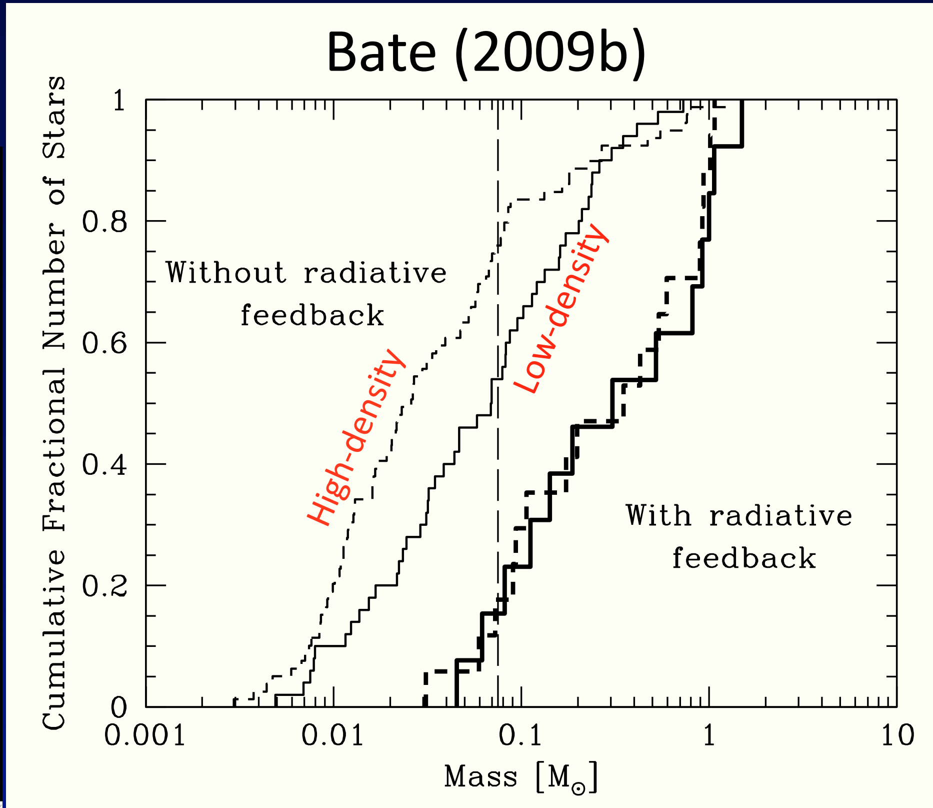
What determines stellar properties?

- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises may not be so important (Bonnell et al. 1997-2001; Klessen et al. 1998-2001; Bate 2009c)
- Dissipative dynamical interactions between accreting protostars
  - Gives an IMF-like mass distribution (competitive accretion)
  - Leads to observed multiplicity fractions & properties of multiple systems (Bate 2009a, 2012)
- But
  - IMF depends on global Jeans mass (Bate & Bonnell 2005; Jappsen et al. 2005, Bonnell et al. 2006)

Protostellar radiative feedback and the IMF

- Thermal heating by protostars reduces fragmentation
  - Krumholz (2006), Bate (2009b), Offner et al. (2009)
- Brings star to brown dwarf ratio in line with observations
  - Bate (2009b, 2012)
- Weakens dependence of IMF on global Jeans mass (density & temperature)
  - Bate (2009b)





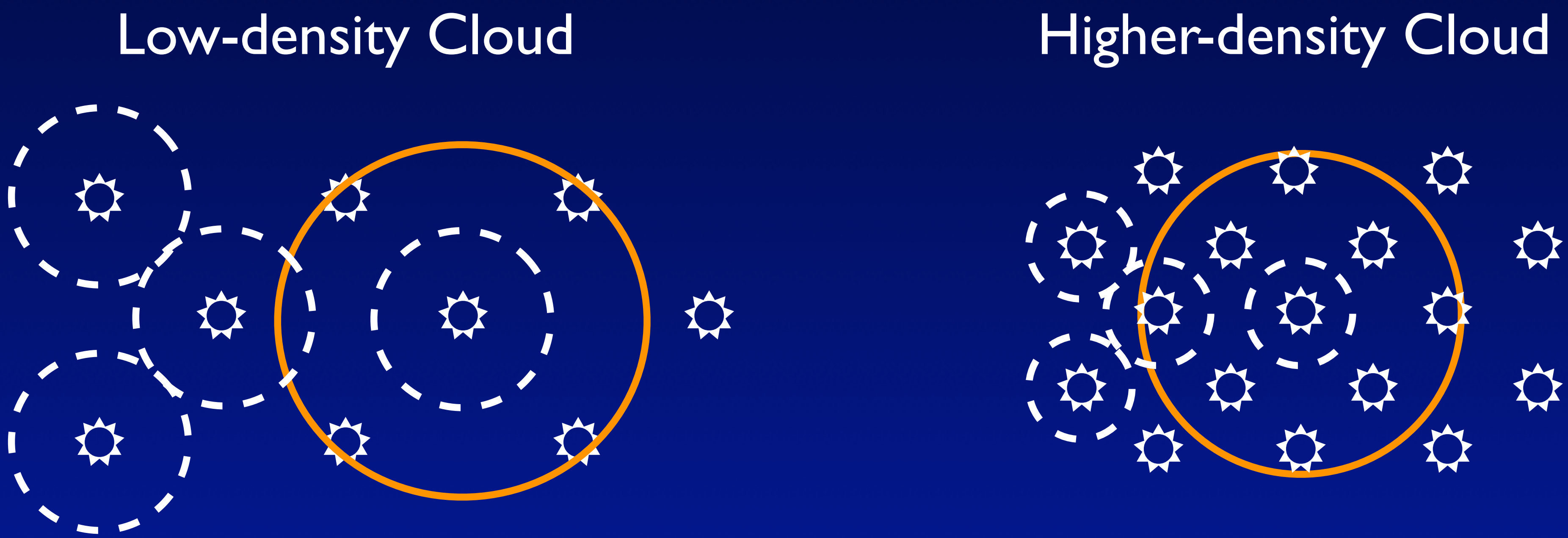
UNIVERSITY OF EXETER

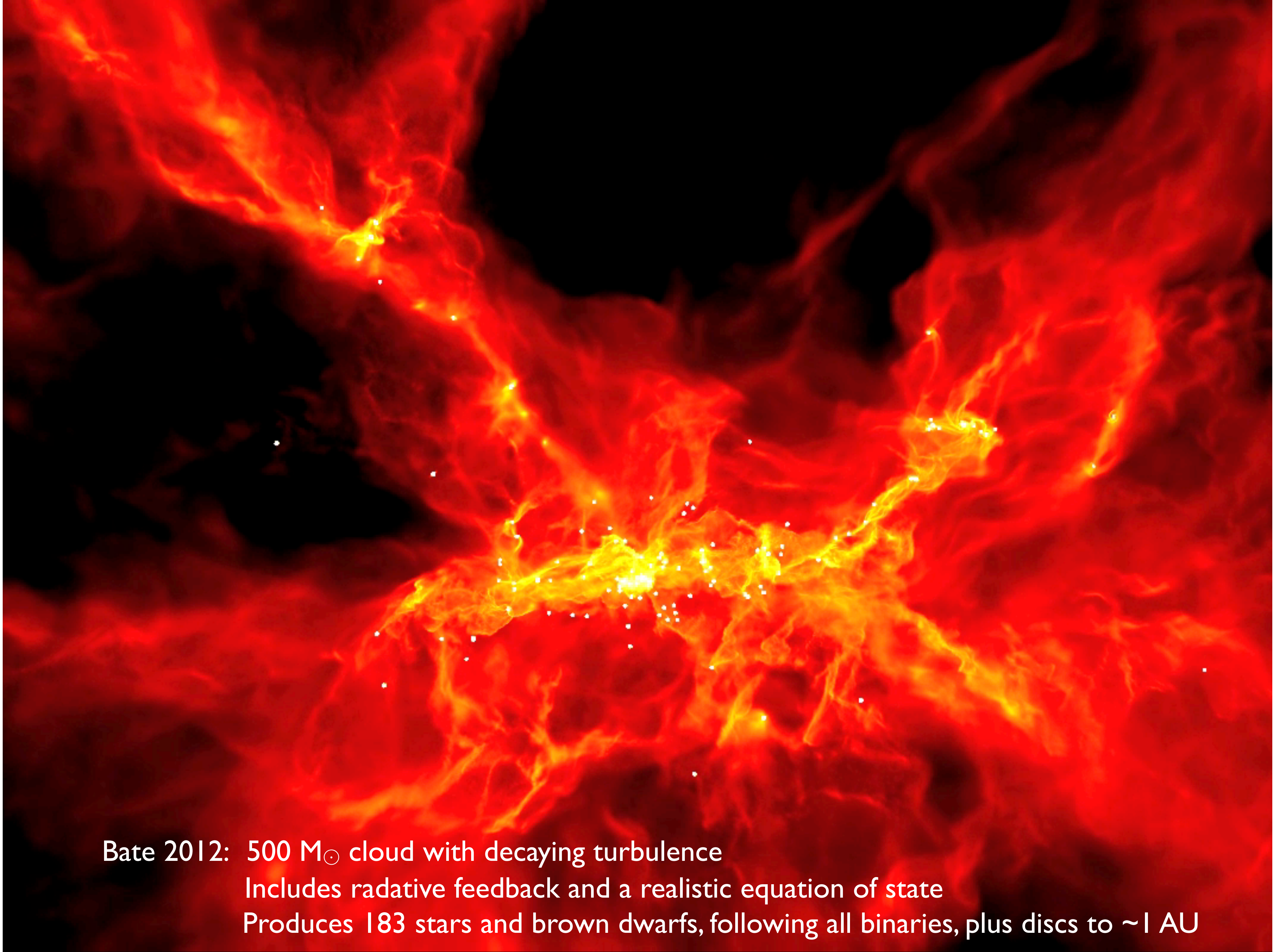
European Science Foundation

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





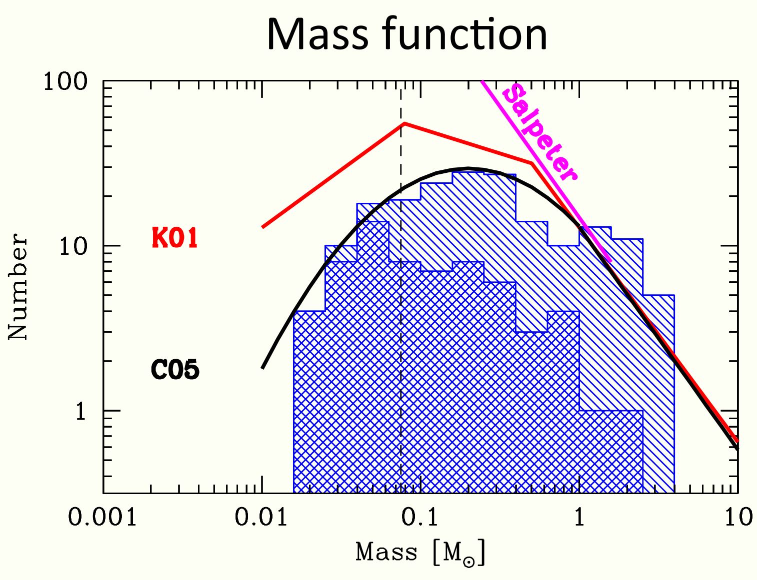
Bate 2012: 500 $M_\odot$ cloud with decaying turbulence

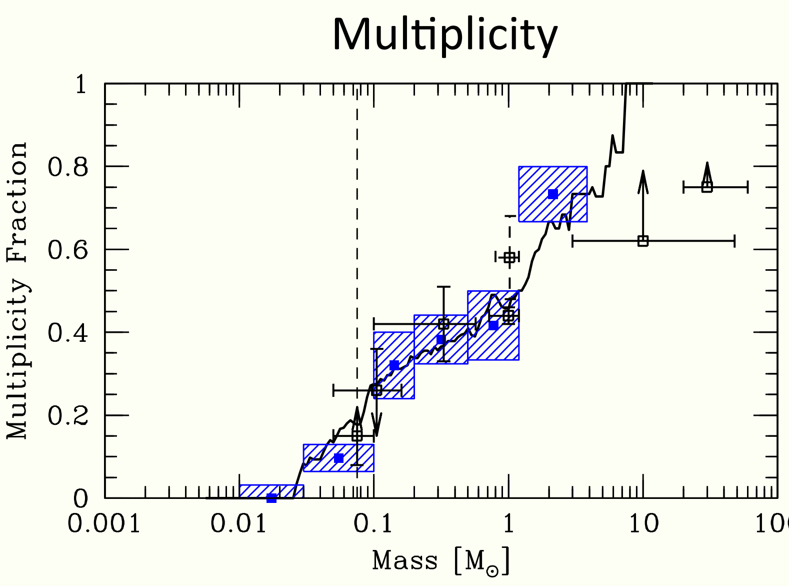
Includes radative feedback and a realistic equation of state

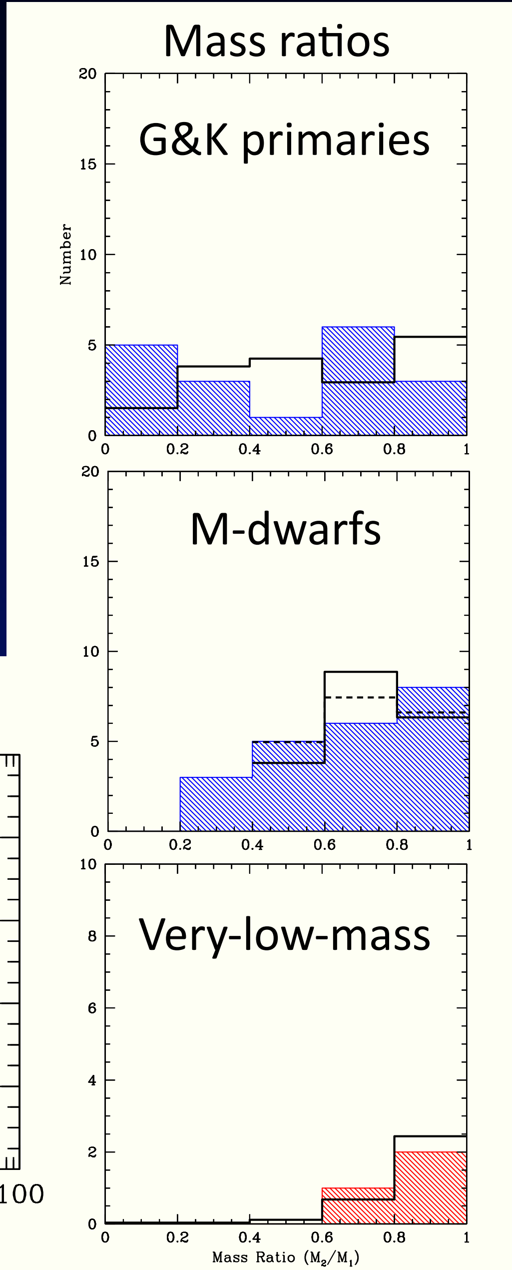
Produces 183 stars and brown dwarfs, following all binaries, plus discs to ~1 AU

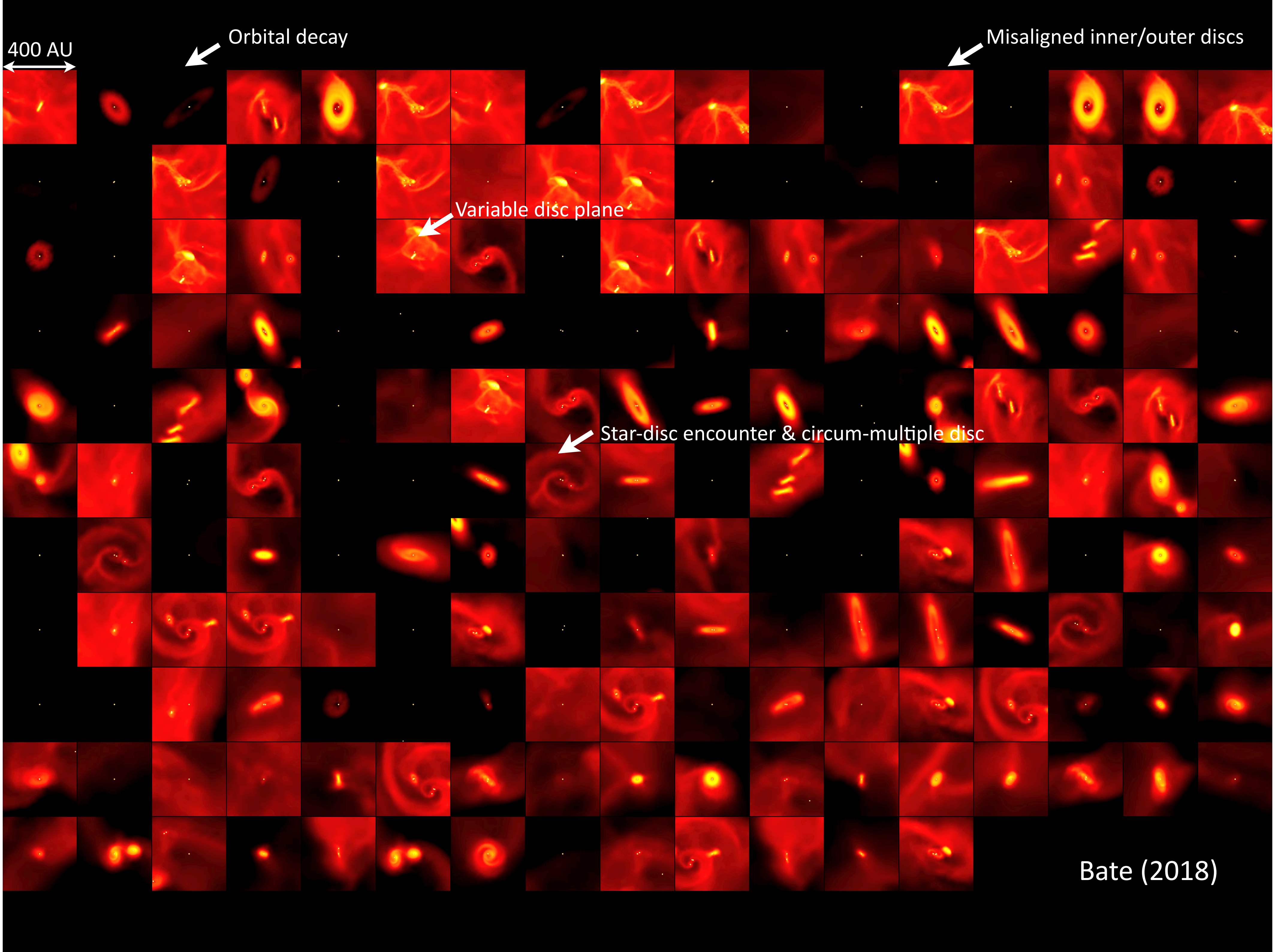
Bate (2012): First large-scale calculation consistent with wide range of observed stellar properties

- Mass function consistent with Chabrier (2005)
    - Stars to brown dwarf ratio:
      N(1.0-0.08)/N(0.03-0.08) = 117/31 = 3.8
- Multiplicity consistent with field
- Binary mass ratios consistent with field



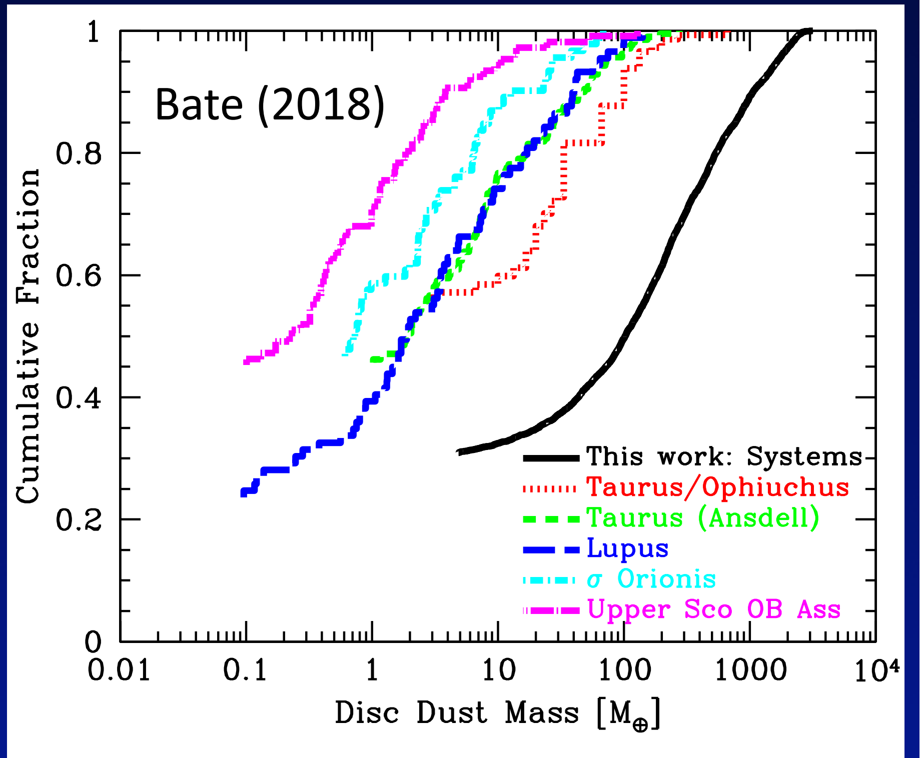





400 AU
Orbital decay
Misaligned inner/outer discs
Variable disc plane
Star-disc encounter & circum-multiple disc
Bate (2018)

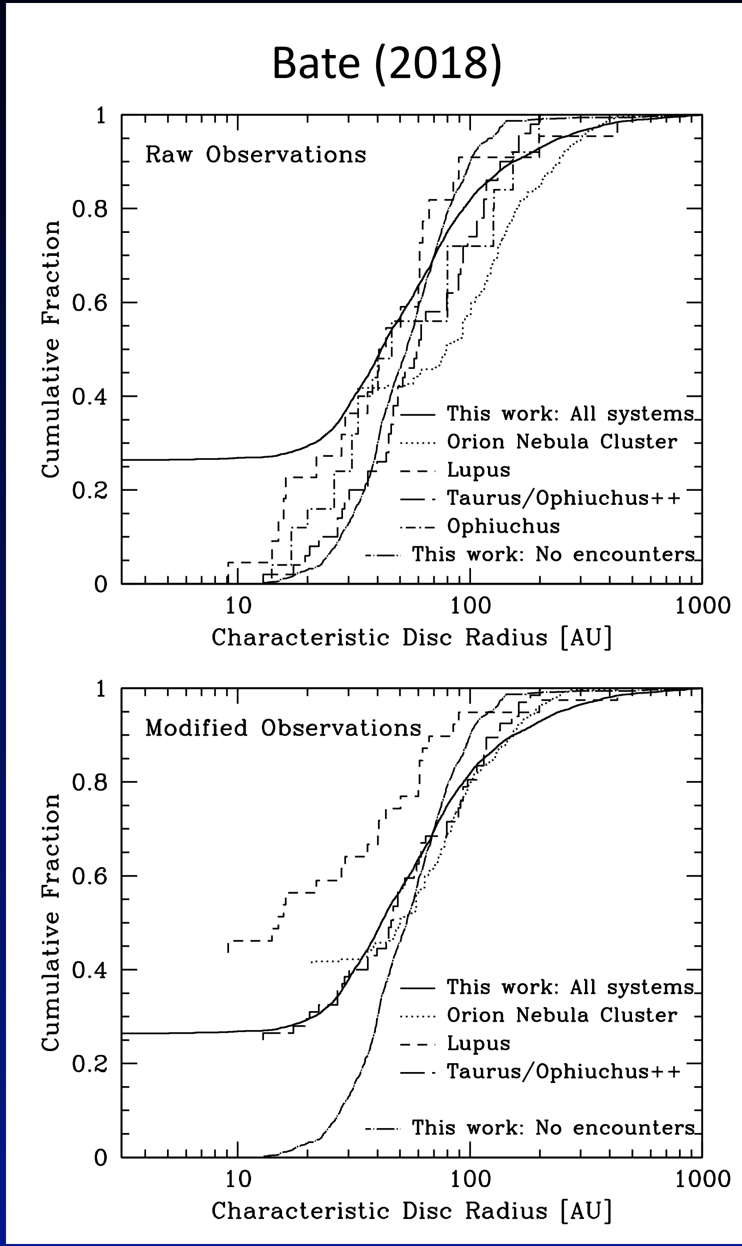
Disc masses vs Class II observations

- Typical ages of protostars from simulation ~10^4 yrs (oldest 9×10^4 yrs)
  - Younger than typical Class II young stars
  - Expect higher disc masses at young ages
  - Discs only resolved down to 0.01-0.03 $M_\odot$ (dust mass 30-100 $M_\oplus$)
- Disc mass distribution compared to
  - Taurus/Ophiuchus (Andrews & Williams 2007)
  - Taurus (Andrews et al 2013; Ansdell et al 2016)
  - Lupus (Ansdell et al 2016)
  - σ Orionis (Ansdell et al 2017)
  - Upper Sco OB Association (Barenfeld et al. 2016)
- Protostellar disc masses
  - 30-300 times more massive than Class II



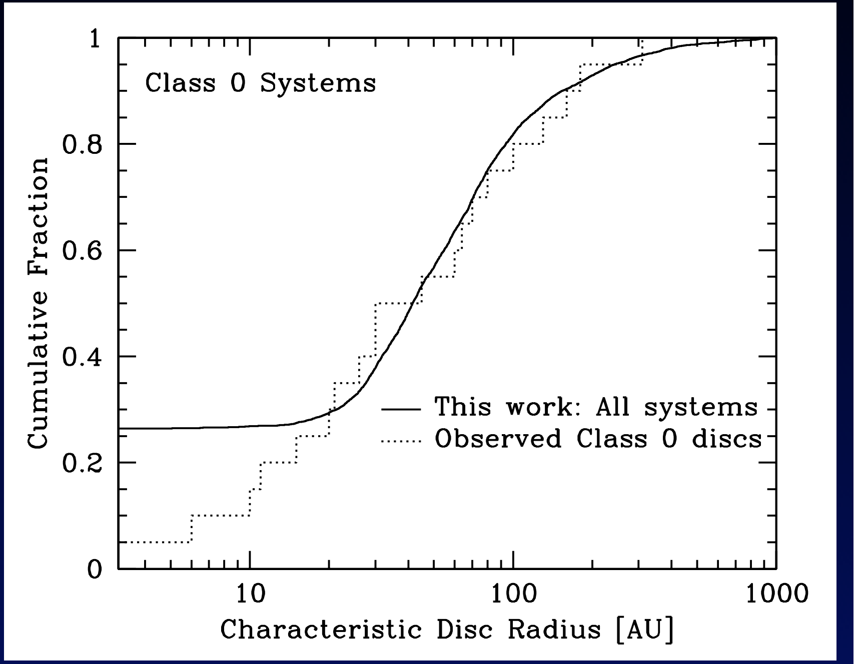
Disc radii vs Class II observations

- Distribution of radii
  - Radius containing 63.2% of total mass
  - Observations need to resolve discs
  - Issues with how to treat completeness
  - Disc radii typically ~10-200 AU
  - Simulated disc radii in good agreement with Class II
  - Dynamical interactions important for small discs
  - Largest discs tend to be around multiple systems
- Other correlations
  - Discs sizes smaller for lower-mass protostars
  - Weak disc mass to radius relation $M_d \propto M_*^{0.2-0.4}$
  - Disc mass to stellar mass ratio $M_d \propto M_*^{0.85}$ for $M_* < 0.5\ M_\odot$



Disc radii vs Class 0 observations

- Fewer observations than for Class II
- Observed disc masses
  - Range from 0.01-1.7 $M_\odot$ (dust masses 20-6000 $M_\oplus$)
  - Nicely cover simulated mass range
- Observed disc radii
  - In good agreement with simulated discs
  - Implication: discs decrease in *mass* from Class 0 to Class II
  - But *do not change size* from Class 0 to Class II
  - Not expected for viscous evolution (angular momentum loss from outflows?)
- Much to be learnt from larger surveys of Class 0 discs



What determines stellar properties?

- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises may not be so important (Bonnell et al. 1997-2001; Klessen et al. 1998-2001; Bate 2009c)
- Dissipative dynamical interactions between accreting protostars
  - Gives an IMF-like mass distribution (competitive accretion), but depends on global Jeans mass (Bate & Bonnell 2005; Jappsen et al. 2005, Bonnell et al. 2006)
  - Leads to observed multiplicity fractions & properties of multiple systems (Bate 2009a, 2012)
- Radiative feedback (interactions) from accreting protostars
  - Enables the production of an (almost) invariant IMF (Bate 2009b)
- All three together can reproduce observed stellar properties
  - Bate (2012)

Protostellar INTERACTIONS !

- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises may not be so important (Bonnell et al. 1997-2001; Klessen et al. 1998-2001; Bate 2009c)
- Dissipative dynamical interactions between accreting protostars
  - Gives an IMF-like mass distribution (competitive accretion), but depends on global Jeans mass (Bate & Bonnell 2005; Jappsen et al. 2005, Bonnell et al. 2006)
  - Leads to observed multiplicity fractions & properties of multiple systems (Bate 2009a, 2012)
- Radiative feedback (interactions) from accreting protostars
  - Enables the production of an (almost) invariant IMF (Bate 2009b)
- All three together can reproduce observed stellar properties
  - Bate (2012)

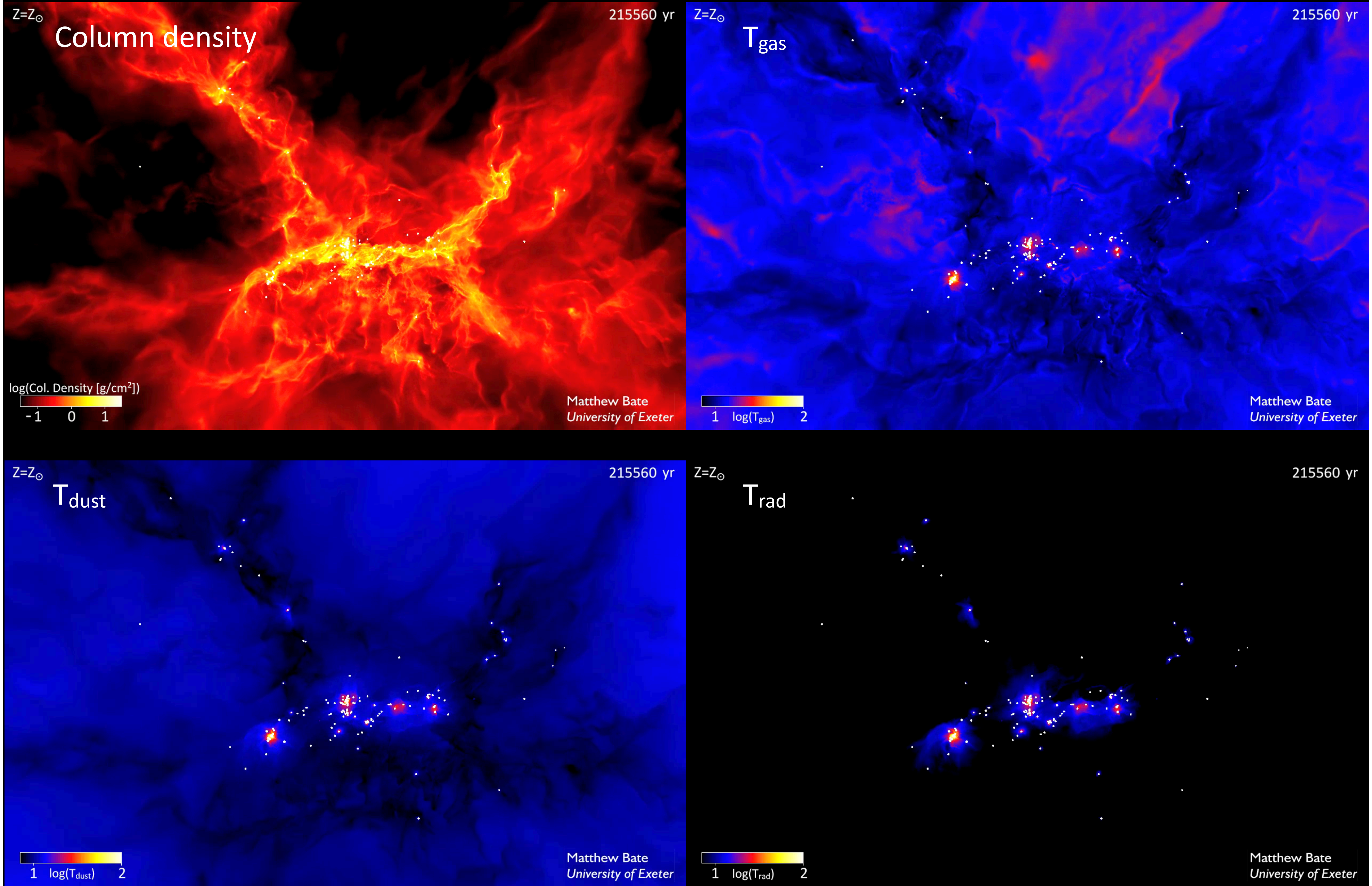
A Predictive Theory of Star Formation

- Bate (2012) marks a turning point
  - We can finally produce realistic stellar populations
- The challenge now is to develop a predictive theory of star formation
  - Initial conditions
    - Cloud structure and kinematics
    - Metallicity
    - Magnetic fields
  - Environment
    - Level of external radiation (e.g. high-z, starbursts)
    - Location (e.g. outer galaxy, galactic centre)

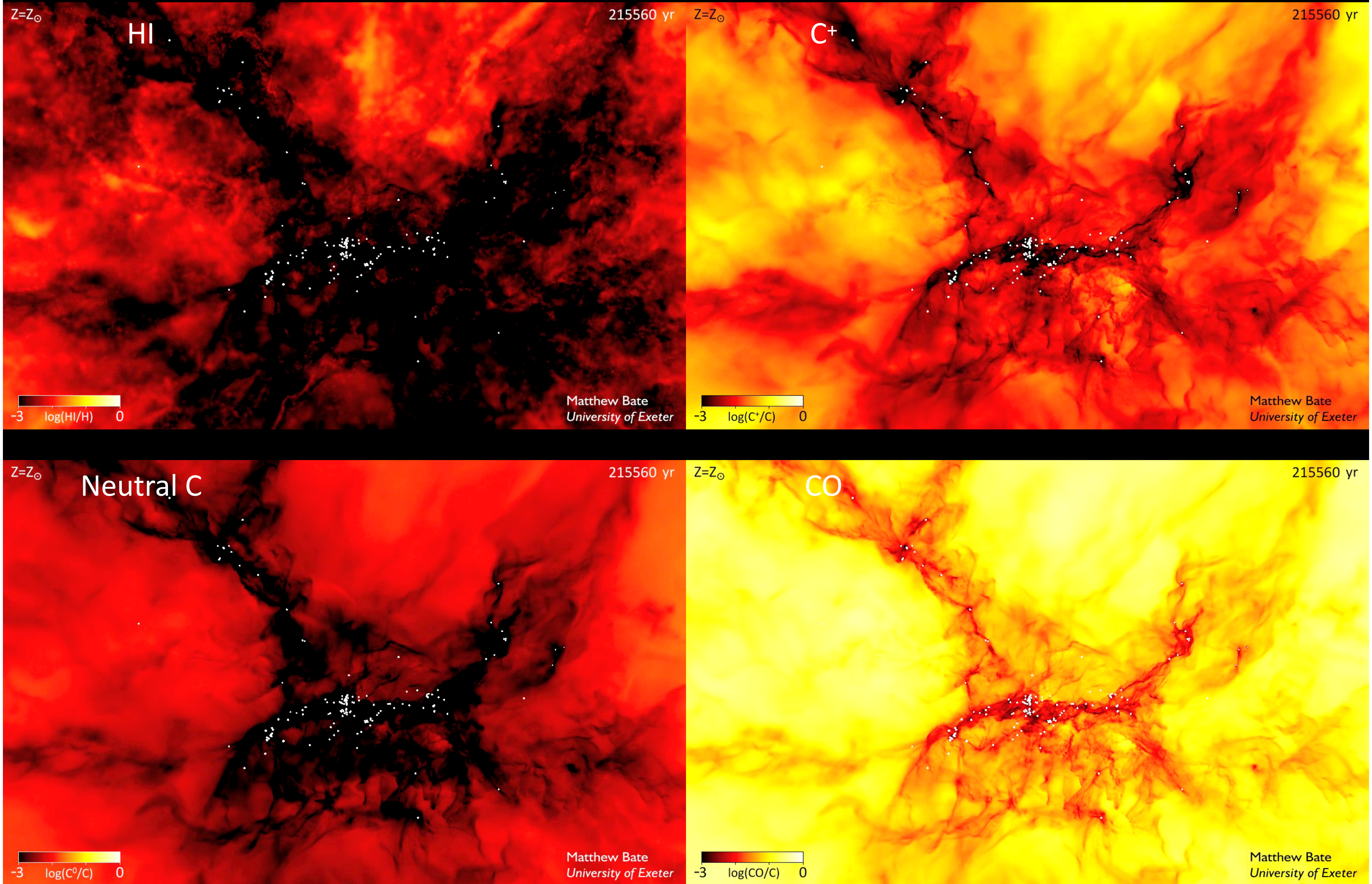
Does the IMF vary? - Metallicity

- Sub-solar metallicities
  - Molecular gas generally hotter (reduced line-cooling and dust cooling)
  - Jeans mass larger ($\propto T^{3/2}$)
  - Characteristic stellar mass larger?
- Sub-solar metallicities
  - Reduced opacity
  - Collapsing gas optically thin and able to cool quickly at higher densities
  - Jeans mass smaller ($\propto 1/\sqrt{\rho}$)
  - Characteristic stellar mass smaller?
- Past calculations varied only opacities
  - Myers et al. (2011); Bate (2014) - no strong dependence of IMF on opacity

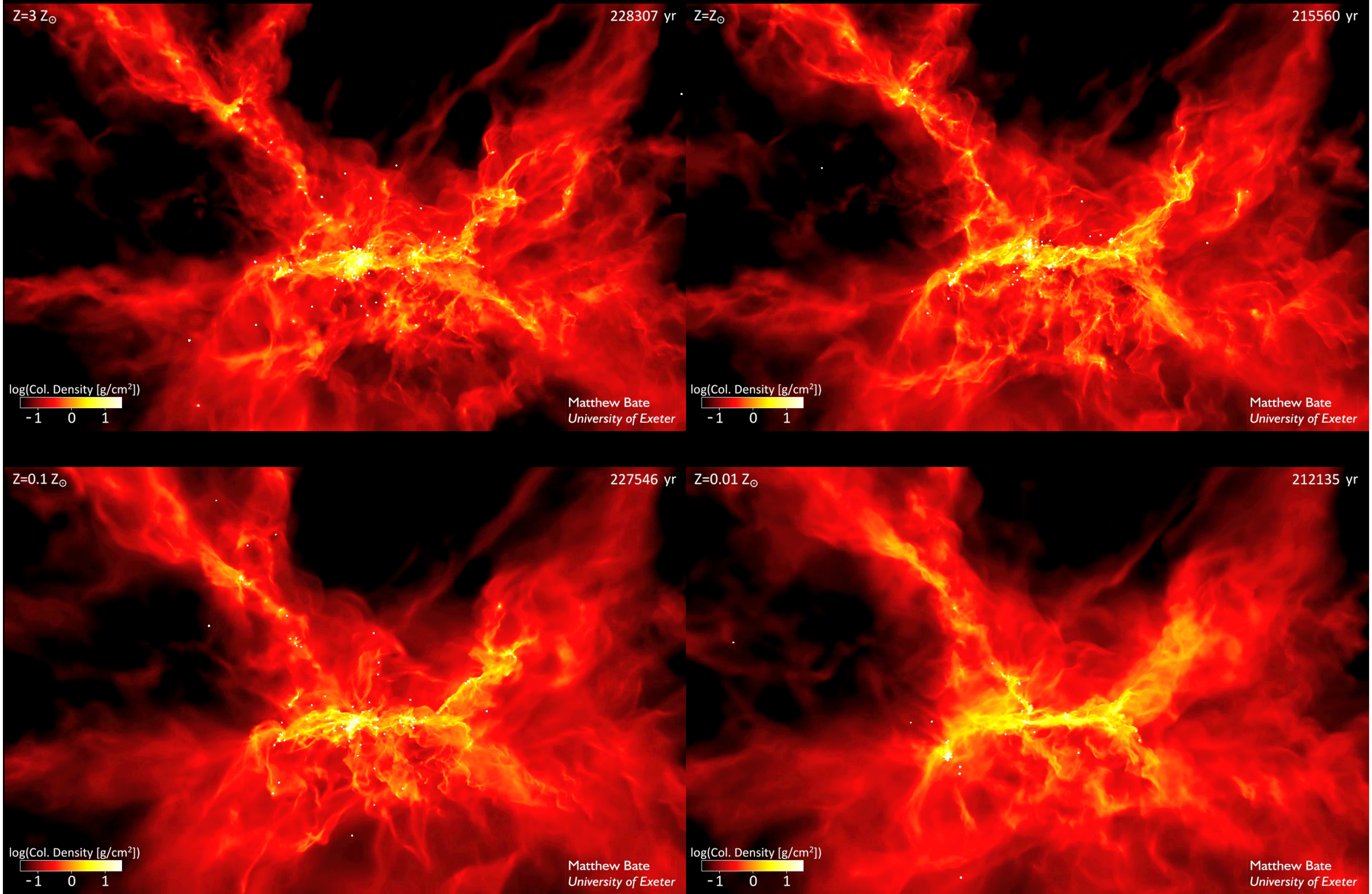
Radiative transfer with separate gas, dust, radiation temperatures (Bate & Keto 2015)



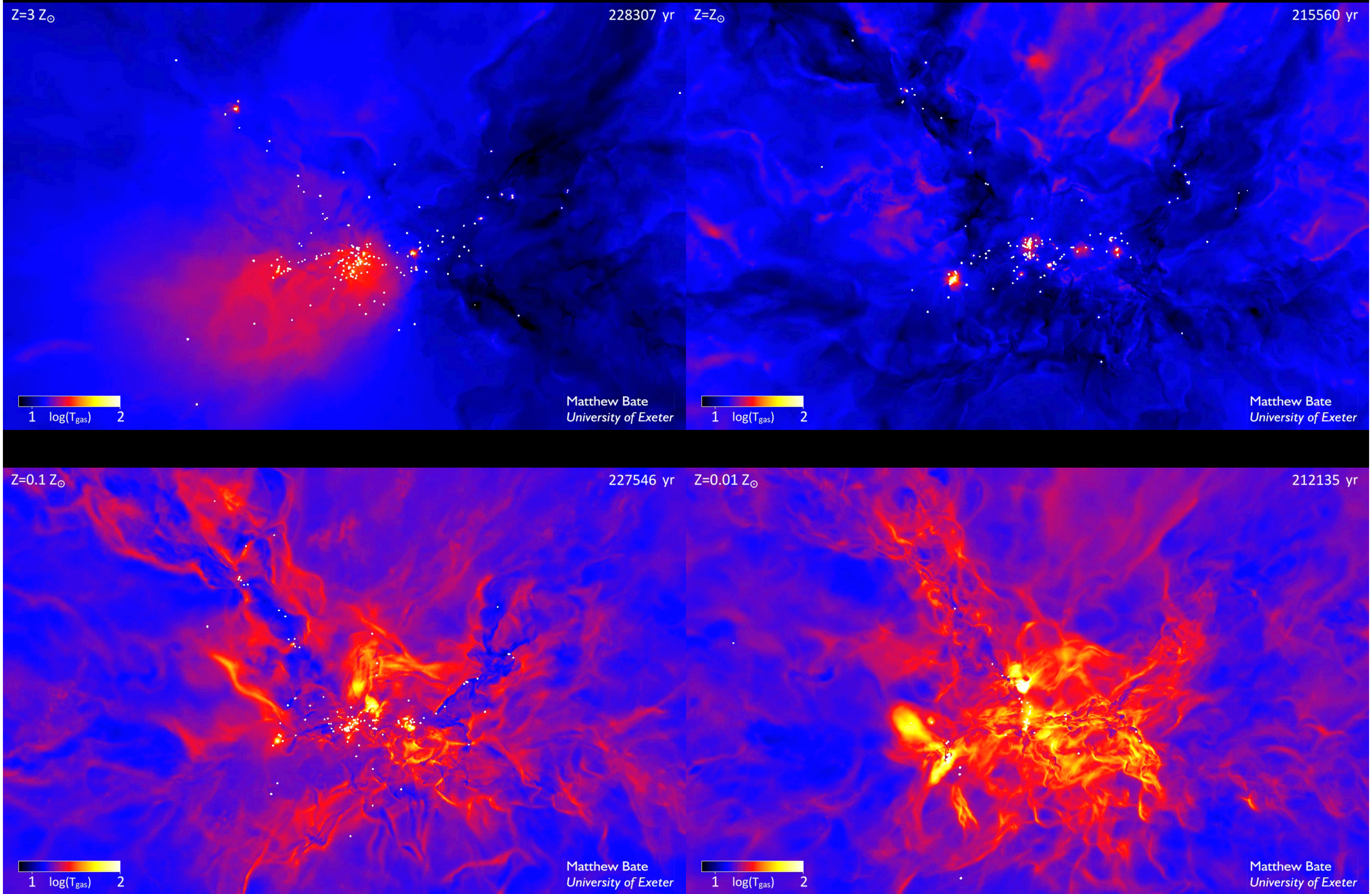
Radiative transfer and a model for the diffuse ISM (Bate & Keto 2015)



Column Density with Different Metallicities

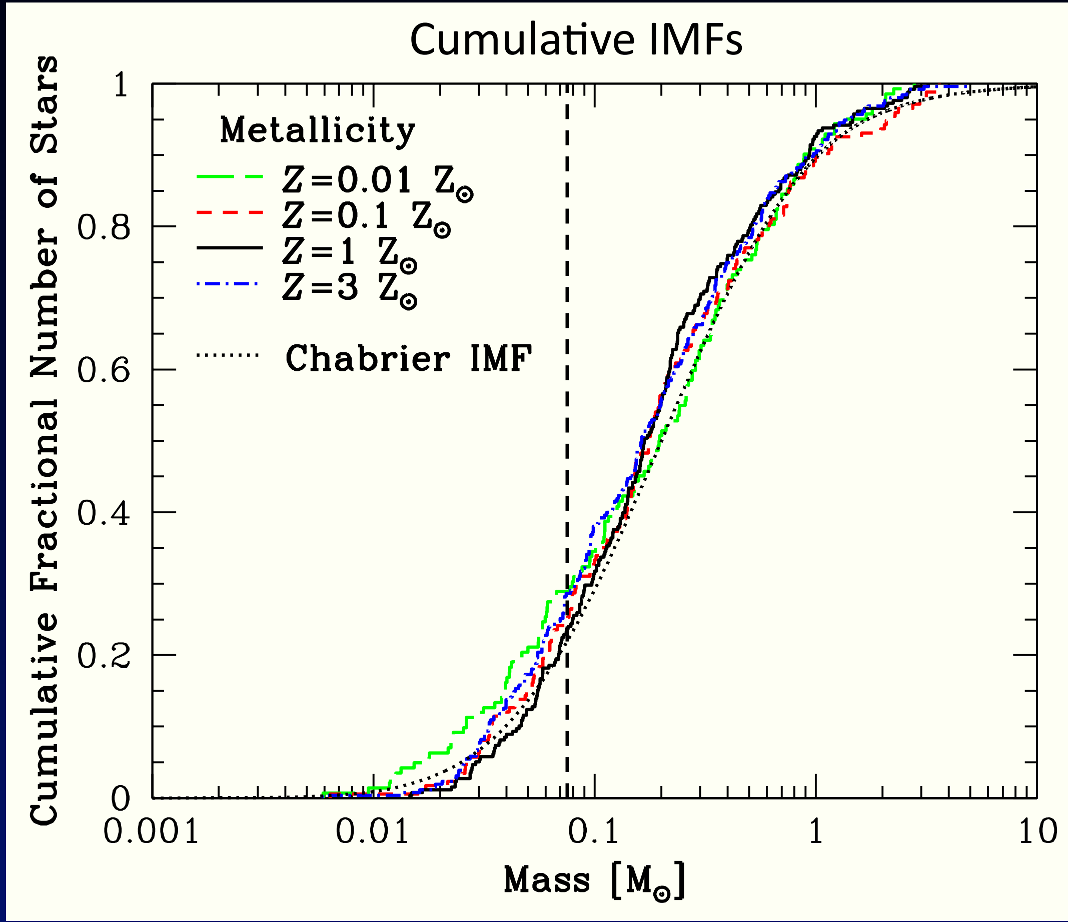


Gas Temperature with Different Metallicities



Dependence of the mass function on metallicity

- Results at end (t_{ff}=1.20):
  - Z=0.01 Z$_\odot$ 142 stars and BDs
  - Z=0.1 Z$_\odot$ 174 stars and BDs
  - Z=Z$_\odot$ 255 stars and BDs
  - Z=3 Z$_\odot$ 258 stars and BDs

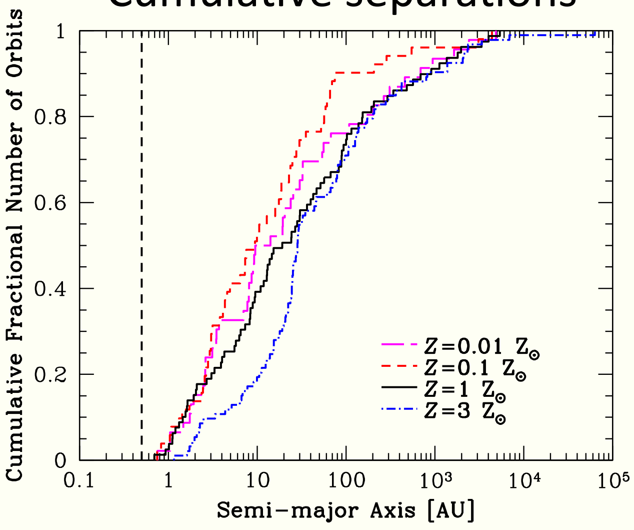


- Median masses range from 0.163-0.195 M$_\odot$ (Chabrier 2005 has 0.20 M$_\odot$)
- Low metallicity seems to produce slightly more brown dwarfs
  - Reduced opacities: greater cooling at higher densities and more small-scale fragmentation

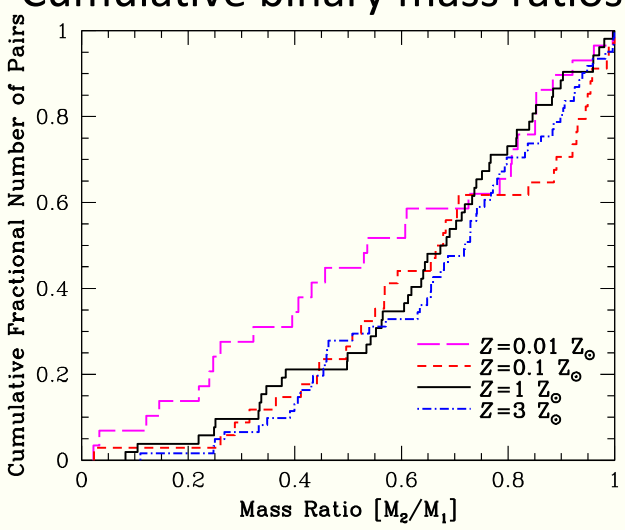
Dependence of multiplicity on metallicity

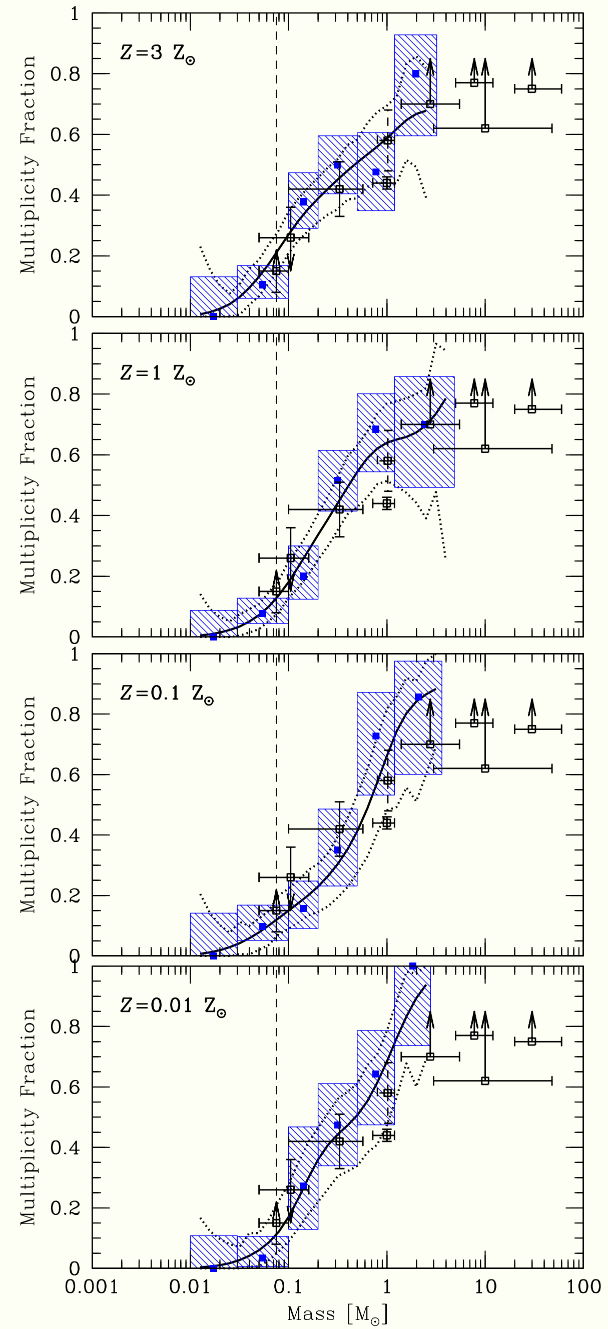
- No strong dependence of overall multiplicity
  - Multiplicity strongly increases with primary mass
- Indications that
  - Separations may decrease with decreasing metallicity
  - No significant difference in binary mass ratio distributions

Cumulative separations



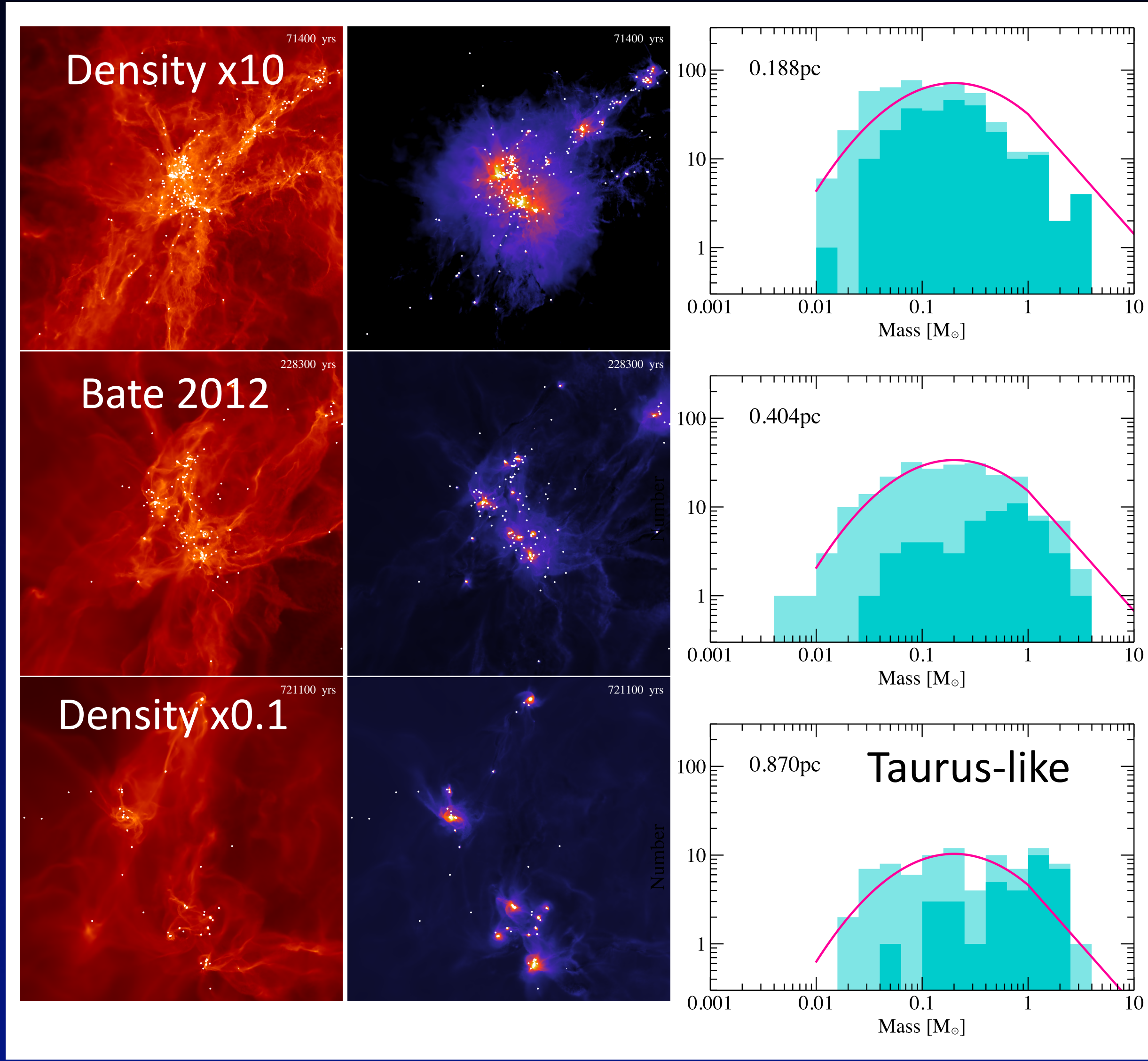
Cumulative binary mass ratios





IMF dependence on density revisited

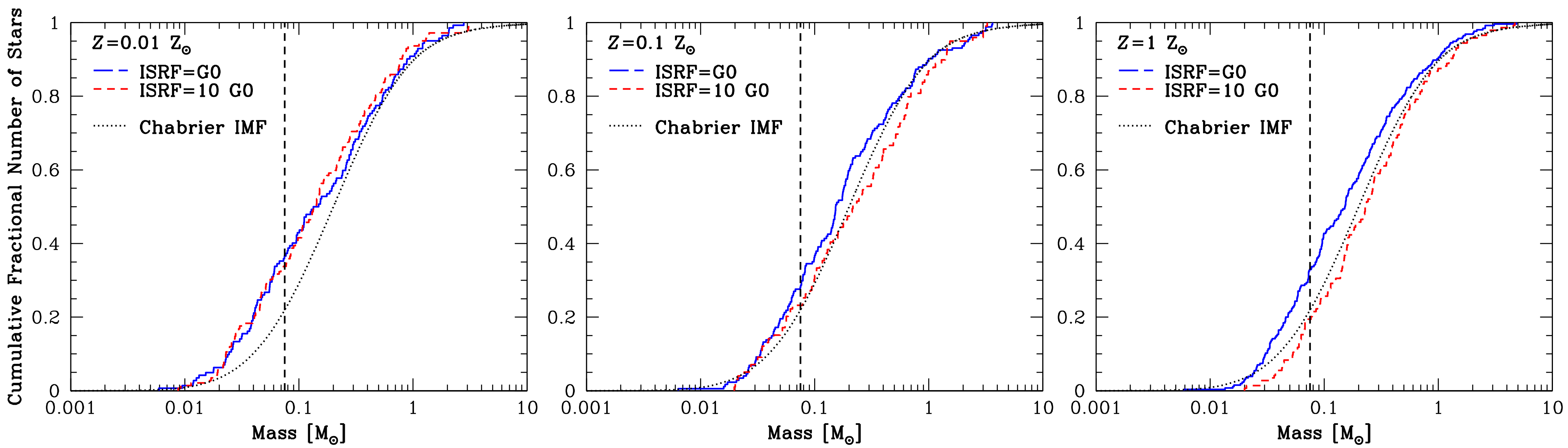
- Bate (2009b)
  - Thermal feedback weakened dependence of IMF on mean cloud density
- Jones & Bate (2018)
  - Revisit with larger calculations (better statistics)
  - Find characteristic stellar mass scales as $M_c \propto \rho^{-1/5}$
  - Mass function slightly broader at lower densities (excess of solar-type stars)



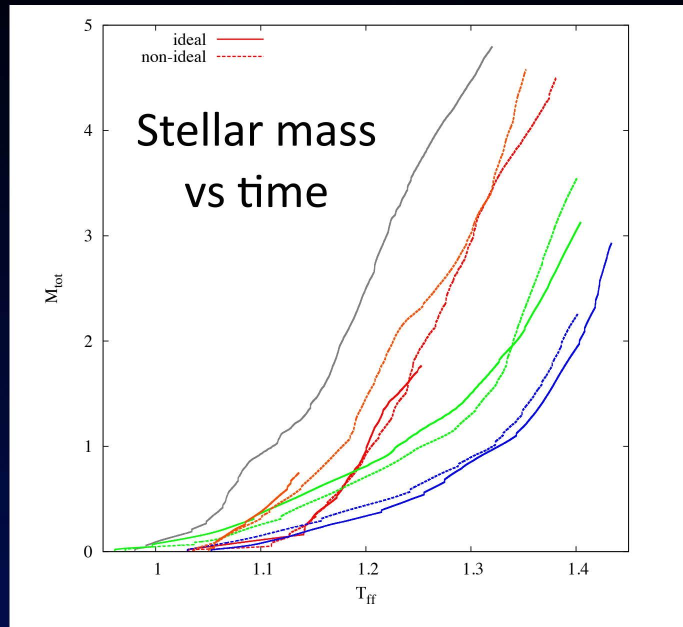
IMF dependence on interstellar radiation

- Interstellar radiation field (ISRF) externally heats molecular clouds
  - X10 increase over the standard ISRF
  - Metallicities of $Z = 0.01, 0.1, Z_\odot$ and 1
  - Such effects may occur in star-burst environments, or near galactic centres
- Characteristic stellar mass increases by a factor of 2 for solar metallicity
  - No effect for $Z = 0.01\ Z_\odot$

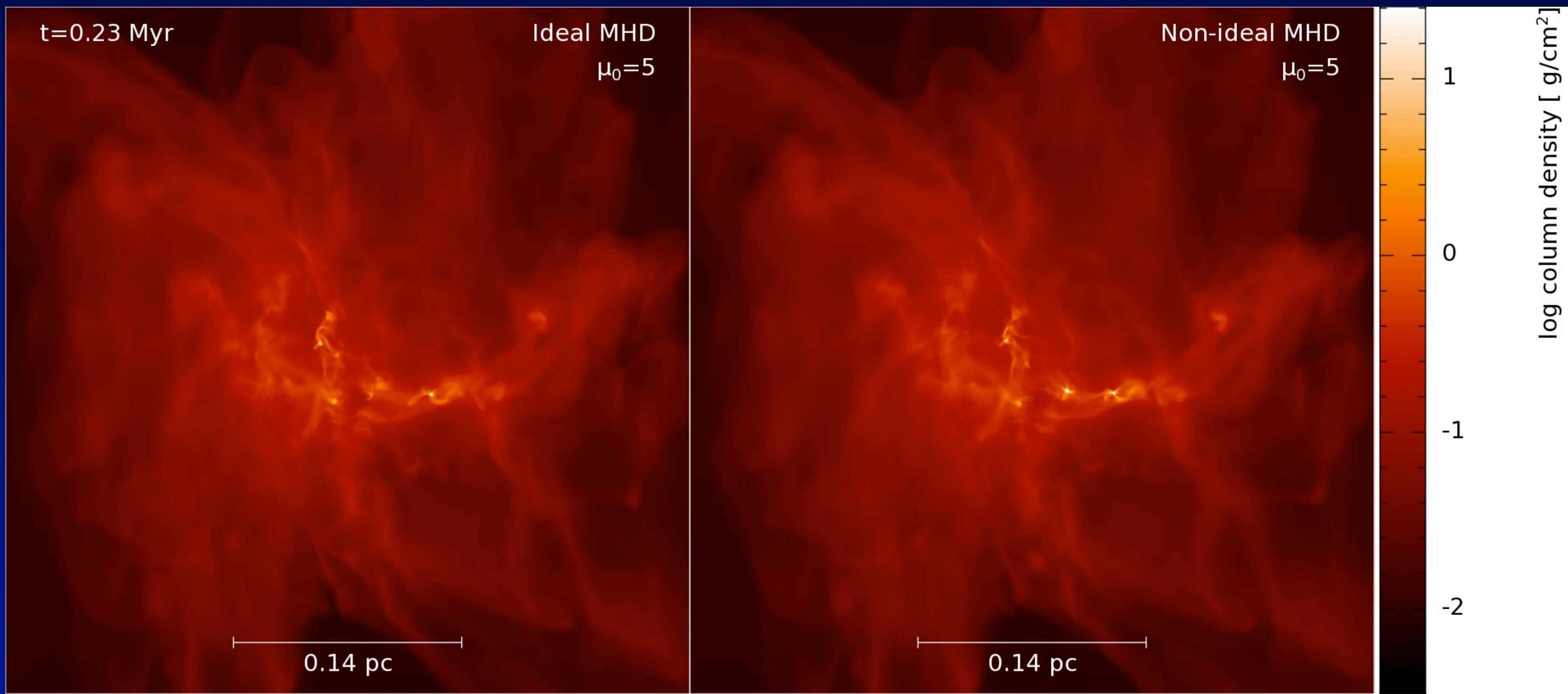
Blue, solid lines: standard ISRF. Red, dashed lines: x10 ISRF



Magnetised clusters



- Wurster, Bate & Price, in prep
  - Non-ideal MHD, including ambipolar diffusion, Hall effect, and Ohmic resistivity
  - Includes radiative transfer and diffuse ISM model



Conclusions

- Characteristic stellar mass depends
  - More on small-scale thermodynamics (thermal feedback) and dynamical interactions
  - Than large-scale initial density, temperature, turbulence, and magnetic fields
  - Calculations including thermal feedback can reproduce observed stellar properties (Bate 2012, 2014; Krumholz et al. 2012)
- Working to develop predictive theory of star formation
  - Stellar properties are resilient to changes in initial conditions and environment
  - However, small changes in IMF and multiple star properties starting to be identified
    - Low-mass stellar mass distribution has *VERY* weak dependence on metallicity ($Z>=0.01\ Z_{\odot}$)
    - Weak dependencies on cloud density and level of interstellar radiation field
  - Still need to
    - Probe stellar properties over a much broader range of initial conditions
    - Extend to massive stars