The origin and variation of the stellar initial mass function

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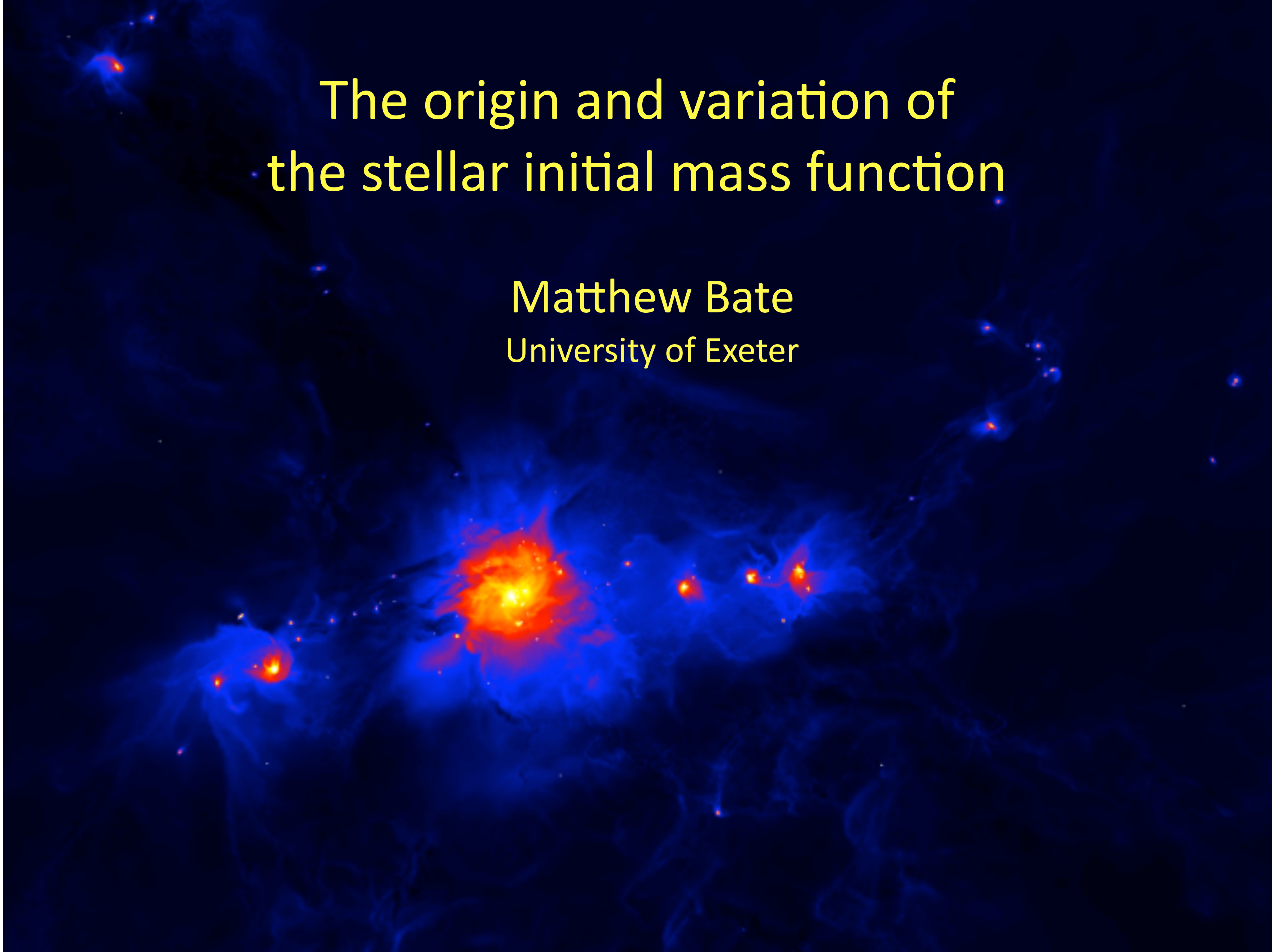
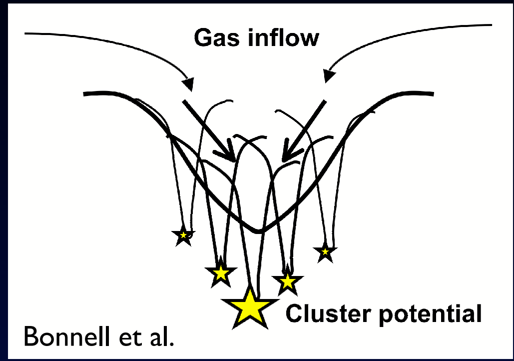
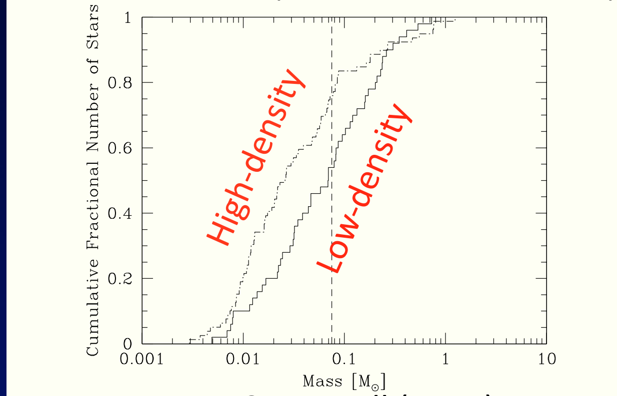


What determines stellar properties?

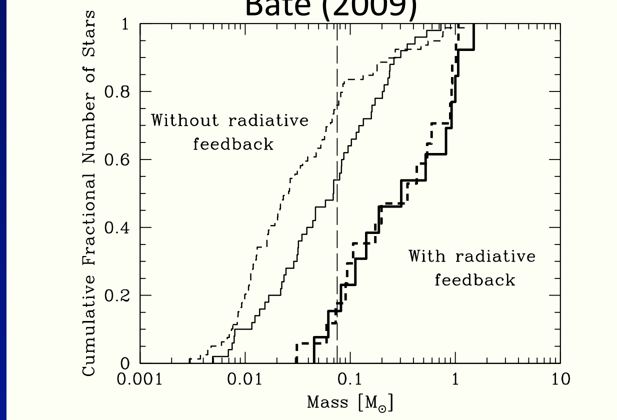
- Gravitational fragmentation of structured molecular gas to form stellar groups
  - Exactly how the structure arises is probably not so important (see Bate 2009c; Bertelli Motta et al. 2016; Liptai et al. 2016)
- Dissipative dynamical interactions between accreting protostars
  - Gives an IMF-like mass 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





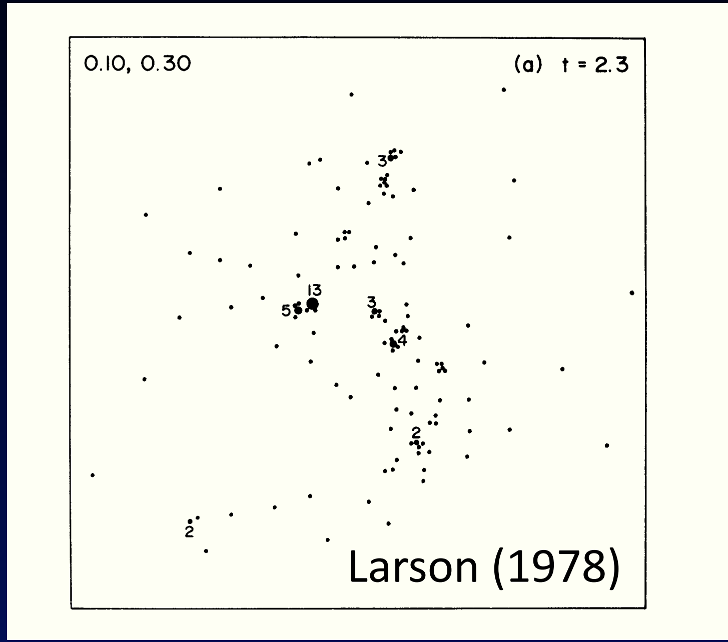
Bate & Bonnell (2005)

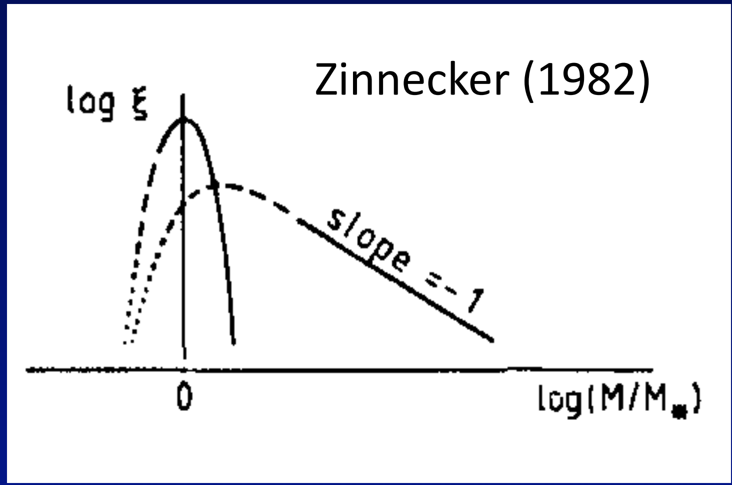
Bate (2009)



Competitive accretion & dynamical interactions

- Larson (1978)
  - "…the final mass spectrum is determined at least in part by accretion processes and the competition between different accreting objects."
- Zinnecker (1982)
  - "…a simple analytic accretion model for the protostellar mass spectrum … in which protostellar cores compete for the accretion of the gas…"
  - Competition for mass as $\dot{M} \propto M^2$ produces a Salpeter-like mass function

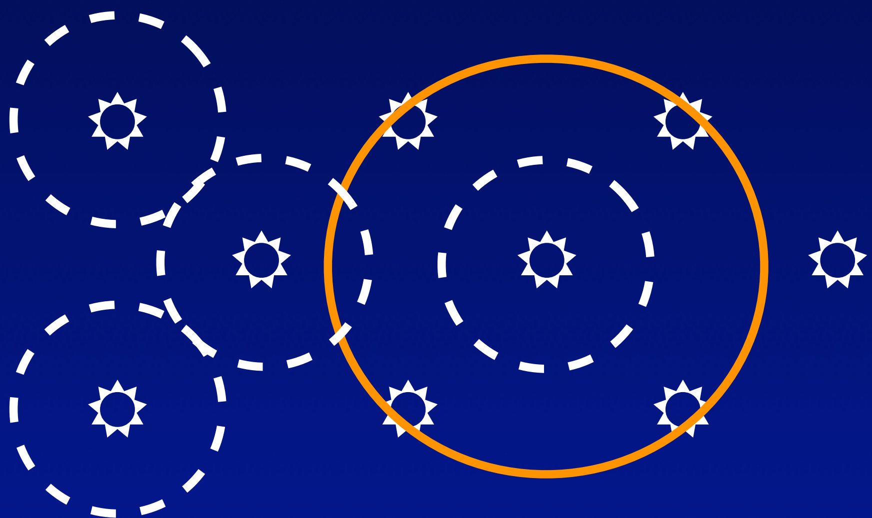




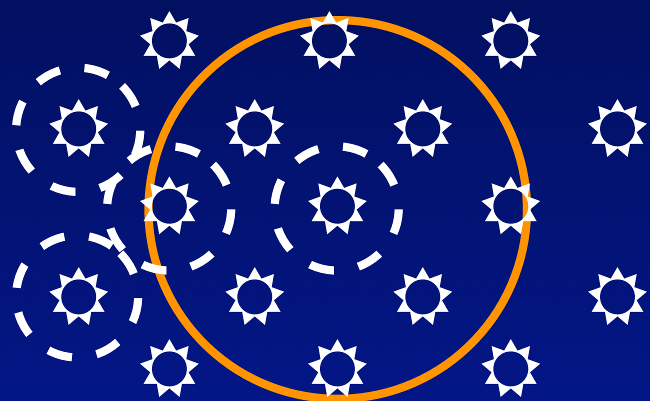
The Apparent Invariance of the IMF

- 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

Low-density Cloud



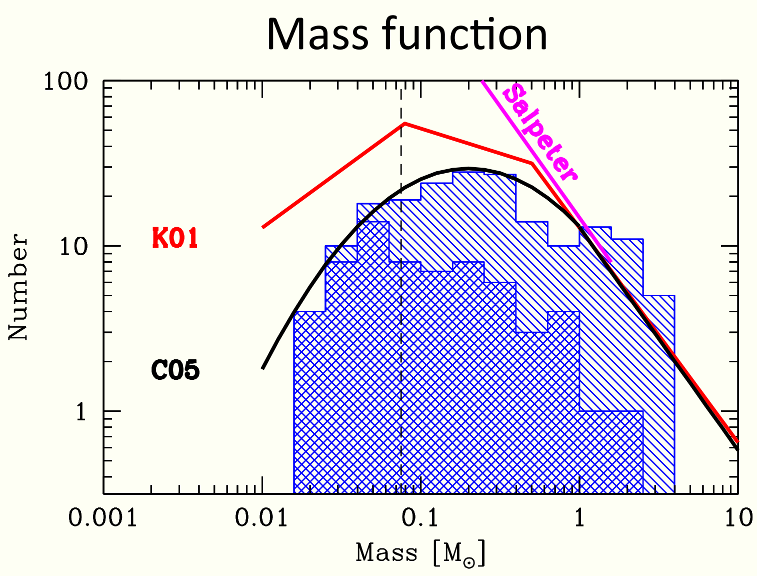
Higher-density Cloud

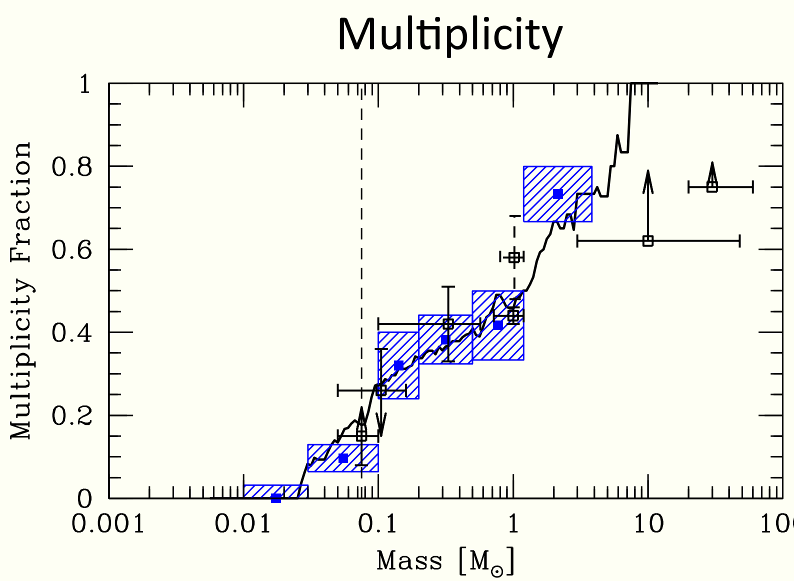


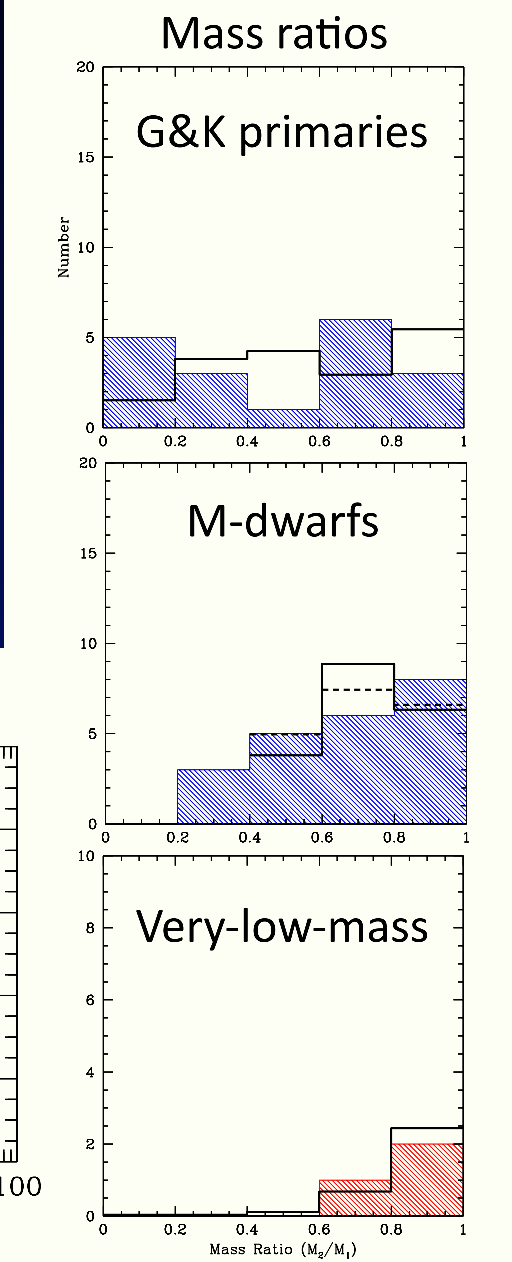
Bate 2012: 500 $M_{\odot}$ cloud with decaying turbulence
Includes radative feedback and a realistic equation of state
Produces 183 stars and brown dwarfs, following all binaries, plus discs to ~1 AU

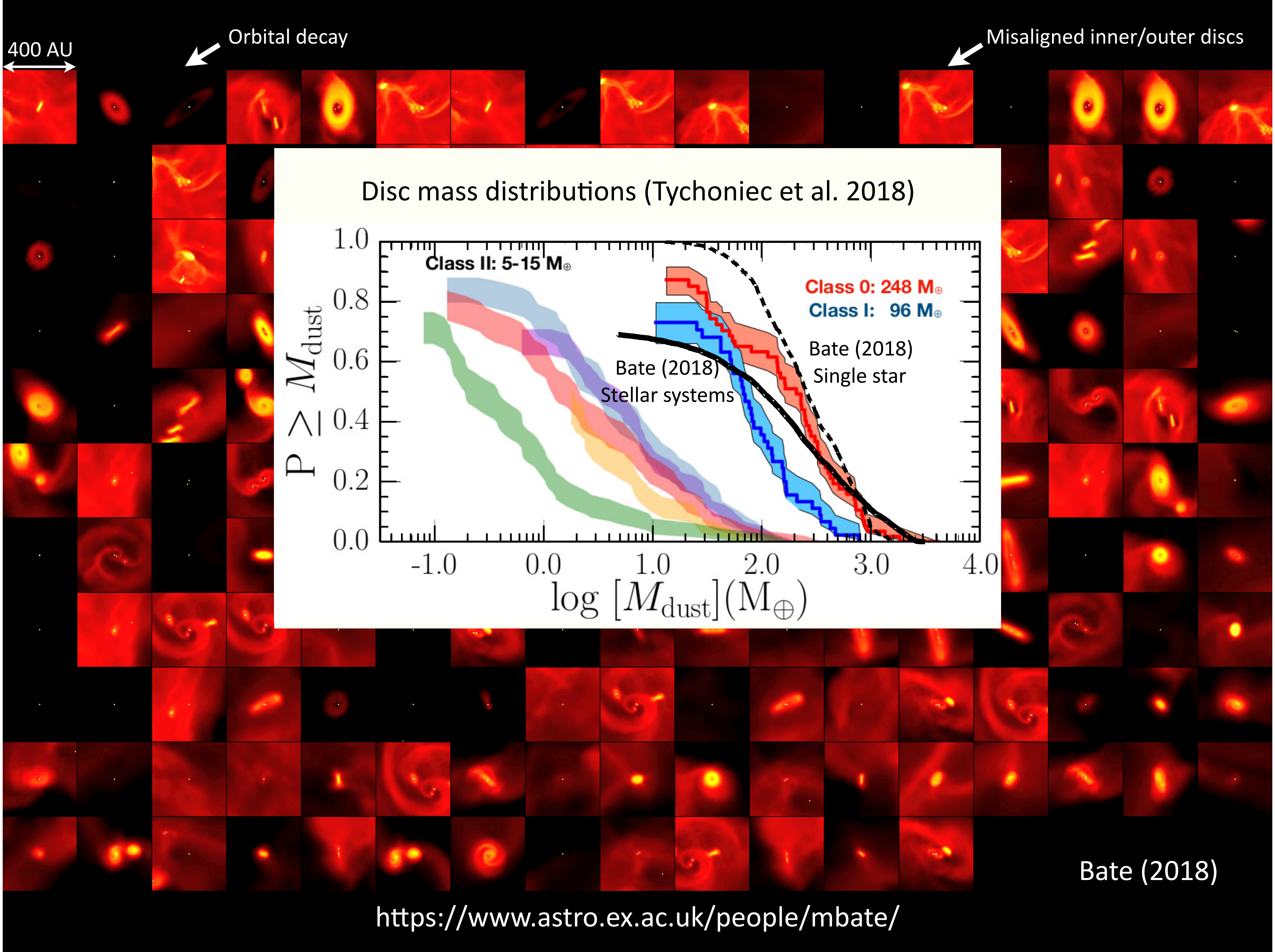
Bate (2012): First large-scale calculation consistent with wide range of observed stellar properties

- 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
Disc mass distributions (Tychoniec et al. 2018)
Class II: 5-15 M⊕
Class 0: 248 M⊕
Class I: 96 M⊕
Bate (2018)
Single star
Bate (2018)
Stellar systems
P ≥ $M_{\rm dust}$
log $[M_{\rm dust}]$(M⊕)
1.0
0.8
0.6
0.4
0.2
0.0
-1.0
0.0
1.0
2.0
3.0
4.0
Bate (2018)
https://www.astro.ex.ac.uk/people/mbate/

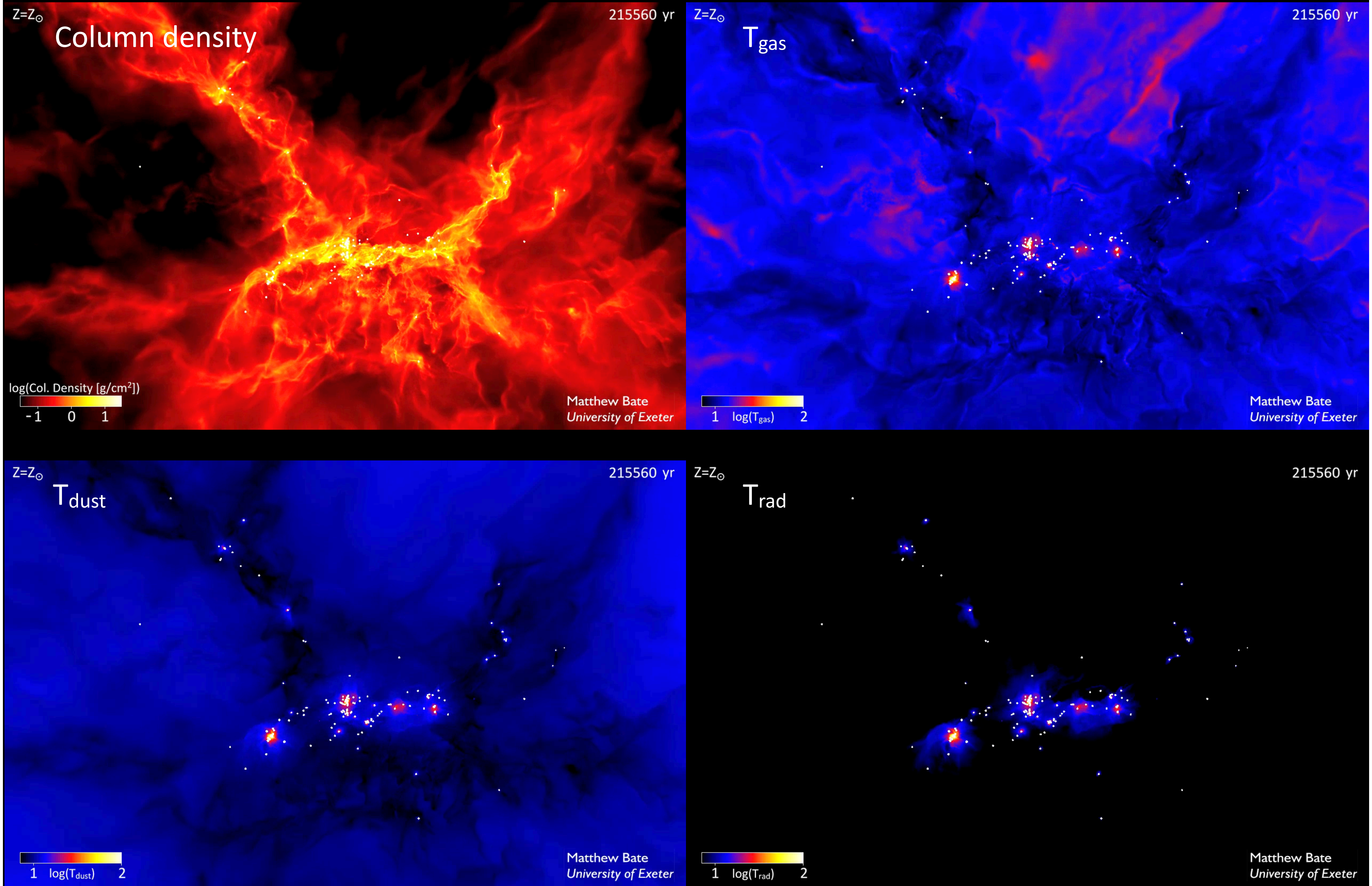
A Predictive Theory of Star Formation

- Now that we can produce realistic stellar populations
  - Bate (2012)
- the challenge 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)

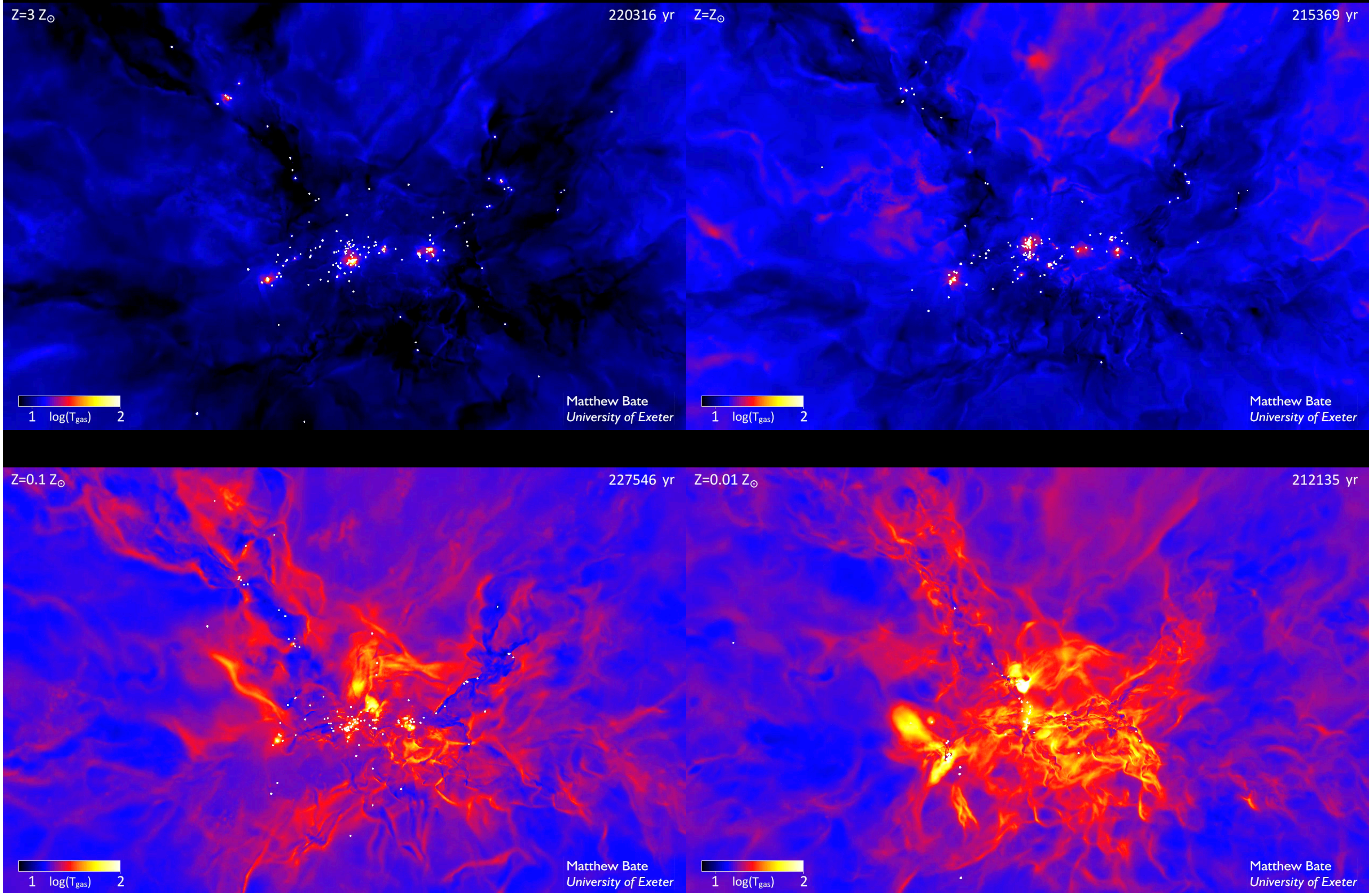
Does the IMF vary with metallicity?

- 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)

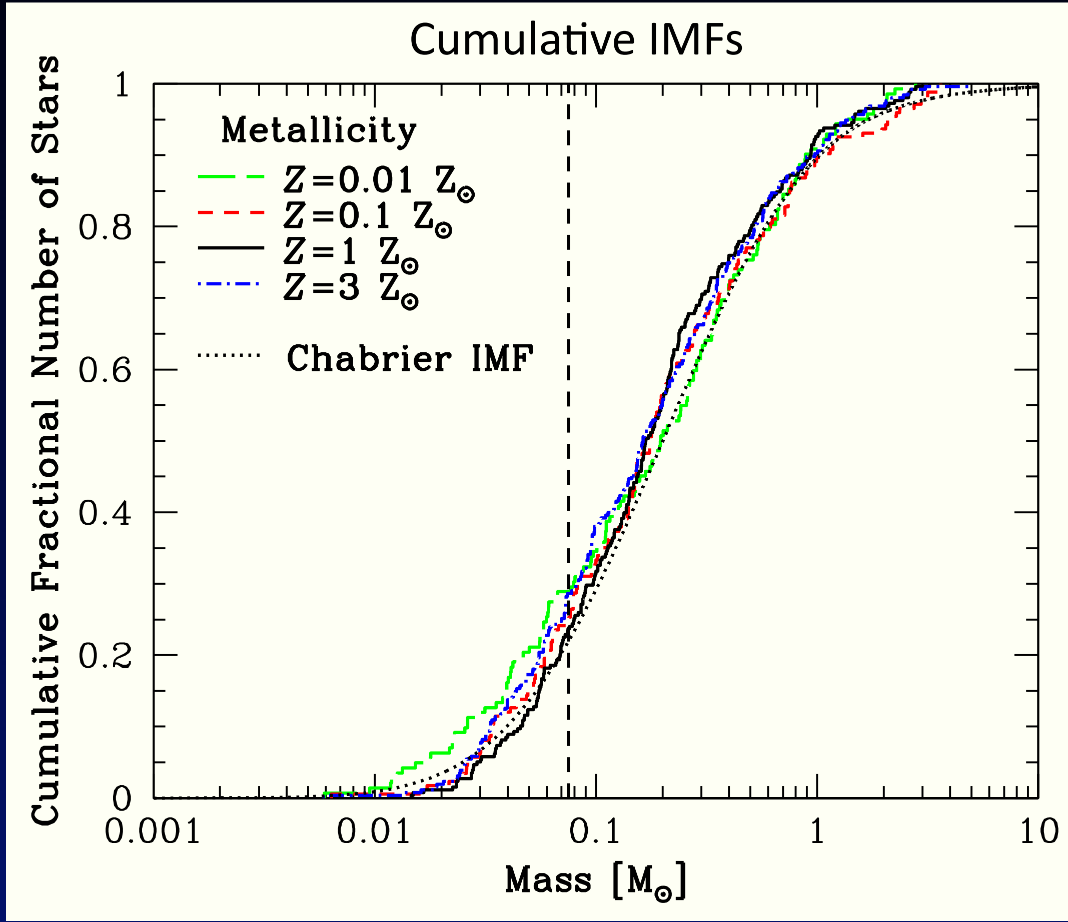


Gas Temperature with Different Metallicities



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

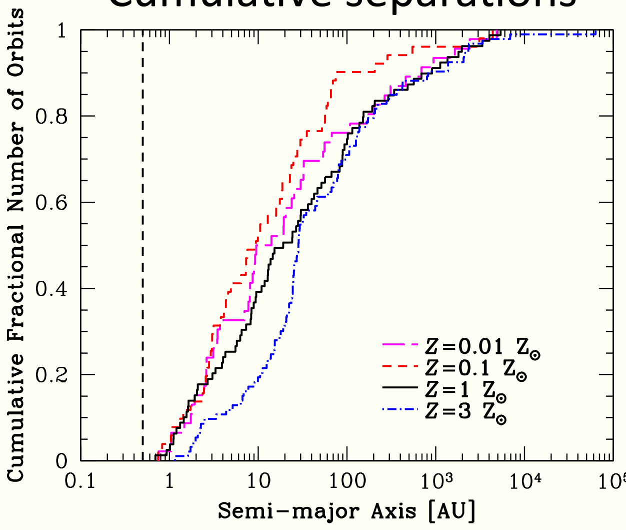


- Median masses range from 0.163-0.195 $M_\odot$ (Chabrier 2005 has 0.20 $M_\odot$)
- Low metallicity seems to produce slightly more brown dwarfs
  - Reduced opacities: greater cooling at higher densities and more small-scale fragmentation

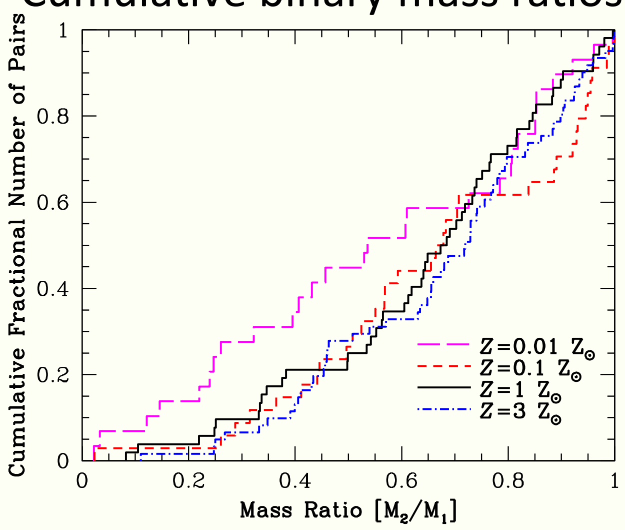
Dependence of multiplicity on metallicity

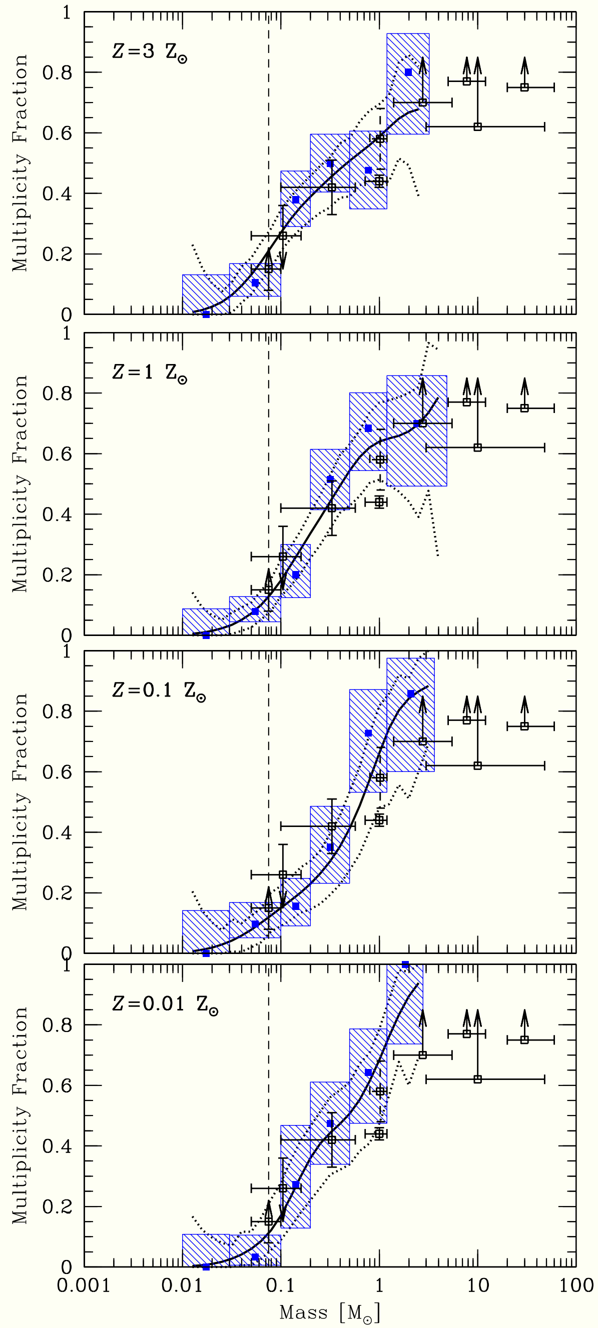
- No strong dependence of overall multiplicity
  - Multiplicity strongly increases with primary mass
- Indications that
  - Separations may decrease with decreasing metallicity
    - see Moe & Kratter (2018) for observational evidence
  - No significant difference in binary mass ratio distributions

Cumulative separations



Cumulative binary mass ratios





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 predict the variation of stellar properties
  - 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