Combining a diffuse ISM model & radiative transfer to model star cluster formation

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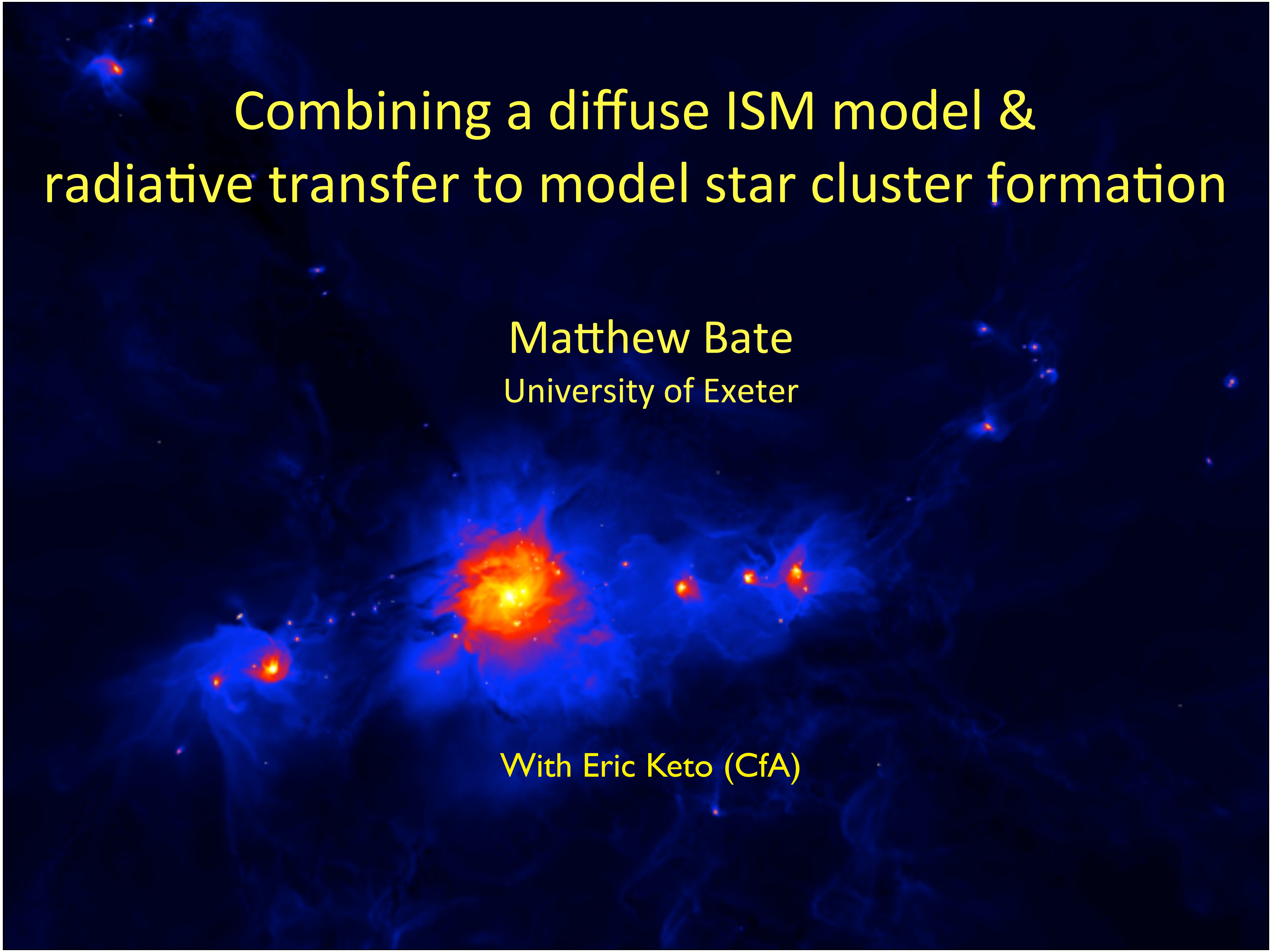


With Eric Keto (CfA)

Star Cluster Formation: Pre-EPoS and since EPoS

- 1997-2005: Mainly self-gravitating hydrodynamical calculations with simple equations of state
  - Competitive accretion can produce an IMF-like distribution of stellar masses
  - IMF depends on mean thermal Jeans mass of initial conditions
  - Bonnell et al. 1997-2006; Klessen et al. 1998-2001; Bate et al. 2002-2005; Jappsen et al. 2005
- 2006-2011: Radiative hydrodynamics (flux-limited diffusion FLD)
  - Importance of thermal heating by low-mass protostars for the IMF
  - Bate 2009; Offner et al. 2009; Krumholz et al. 2010, 2011; Myers et al. 2011
  - Maybe the key to obtaining an IMF that is insensitive to initial conditions (Bate 2009)
- 2012-present: FLD and stellar populations (>100 stars)
  - First calculations to produce realistic stellar populations (e.g. IMF and binarity)
  - Bate 2012; Krumholz et al. 2012

Outstanding problems

- What is the role of additional physics?
  - Magnetic fields: Price & Bate 2008, 2009; Myers et al. 2013, 2014; Krumholz et al. 2016
  - Outflows: Krumholz et al. 2012; Myers et al. 2014

- Does star formation depend on initial conditions and/or environment?
  - Metallicity: Myers et al. 2011; Bate 2014
  - Environment ?
    - Most recent calculations have begun with small, dense molecular clouds (typical of Infrared Dark Clouds, IRDCs)
    - Bertram et al. 2015: Galactic centre environment

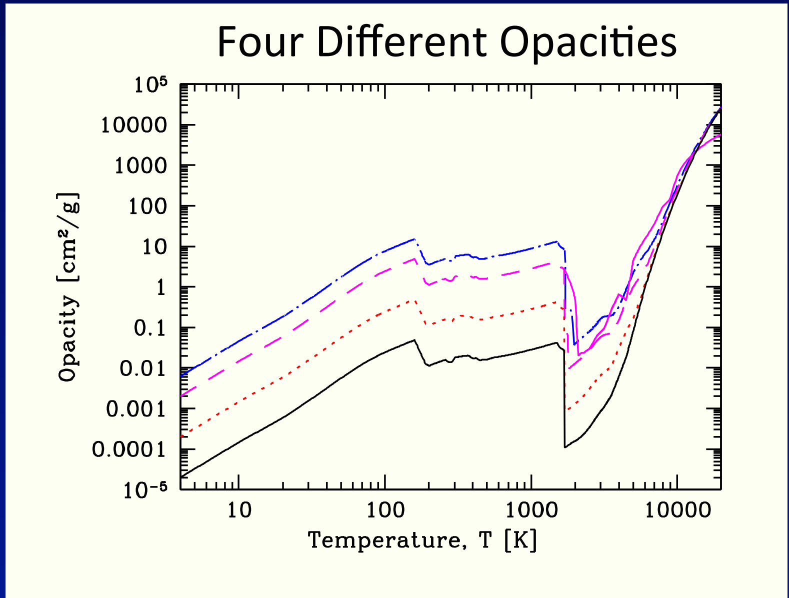
How does the IMF depend on metallicity?

- Sub-solar metallicities
  - Molecular gas generally hotter (less 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?

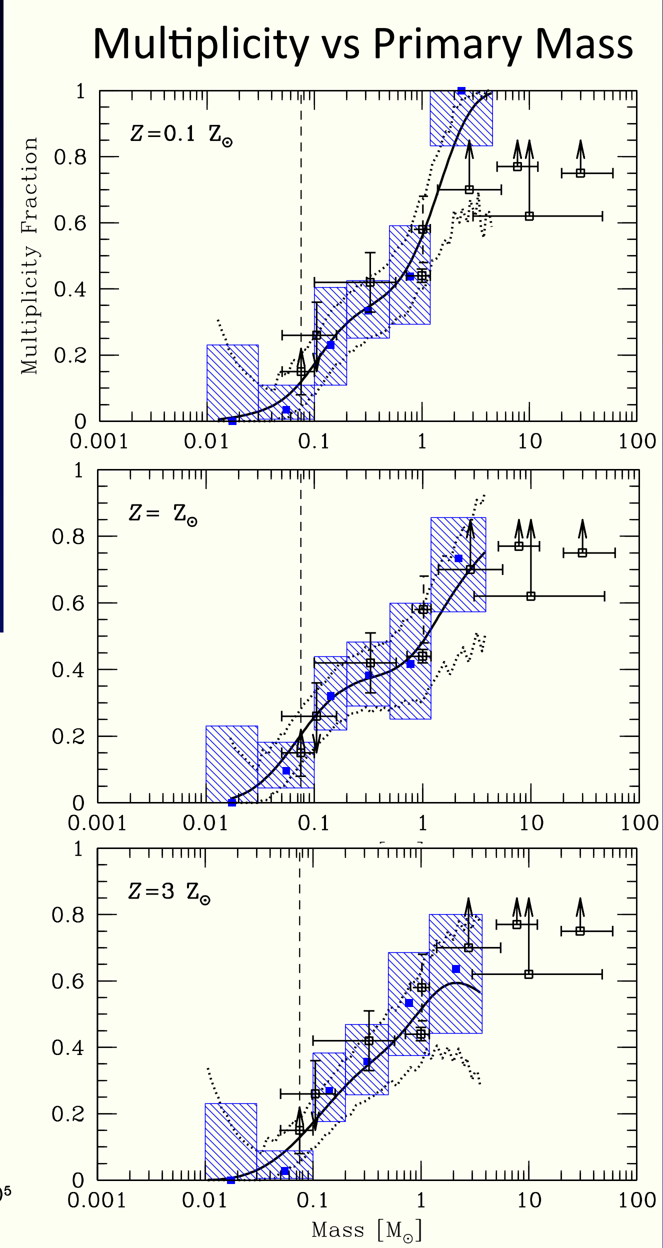
Dependence of stellar properties on metallicity: Opacity

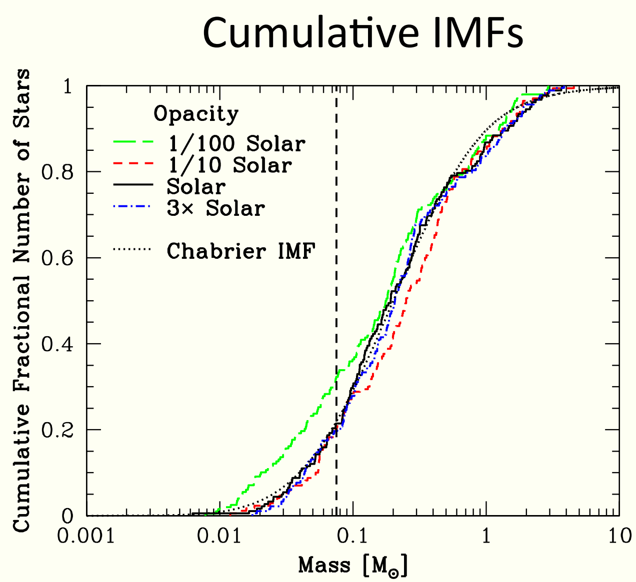
- Myers et al. (2011)
  - Calculations with opacities ranging over a factor of 20, each producing ~40 stars
  - No strong dependence of stellar mass function on opacity
- Bate (2014) repeated Bate (2012), but with opacities for 3 different `metallicities'
  - Use opacities corresponding to metallicities $Z=0.01\,Z_\odot$, $0.1\,Z_\odot$, $Z_\odot$, and $3\,Z_\odot$
  - Does NOT take into account all of the effects of reduced metallicities
    - Assumes dust cooling still dominates
    - Breaks down as gas and dust temperatures decouple
  - Gas opacities from Ferguson et al. (2005)
  - Each calculation produces 170 - 200 stars (733 total)
    - Look for variation of mass function and multiplicity

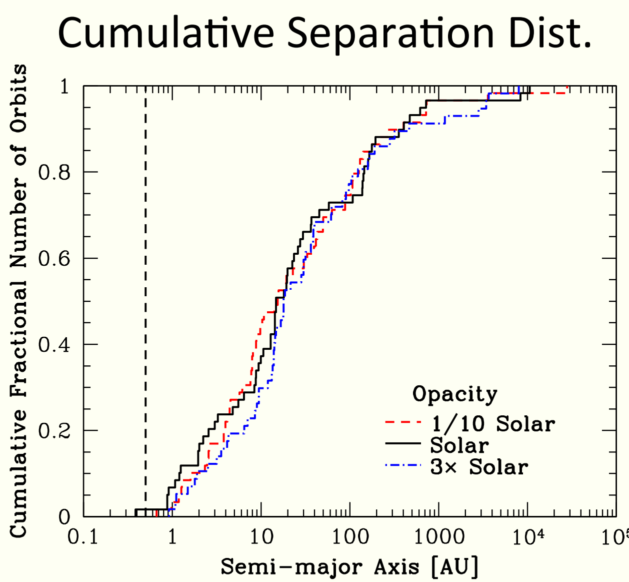


Dependence of stellar properties on opacity

- No significant dependence of any stellar property
  - Despite varying opacity by a factor of 300
- IMFs consistent with Chabrier (2005)
- Multiplicity is a strong function of primary mass
  - In good agreement with observational surveys

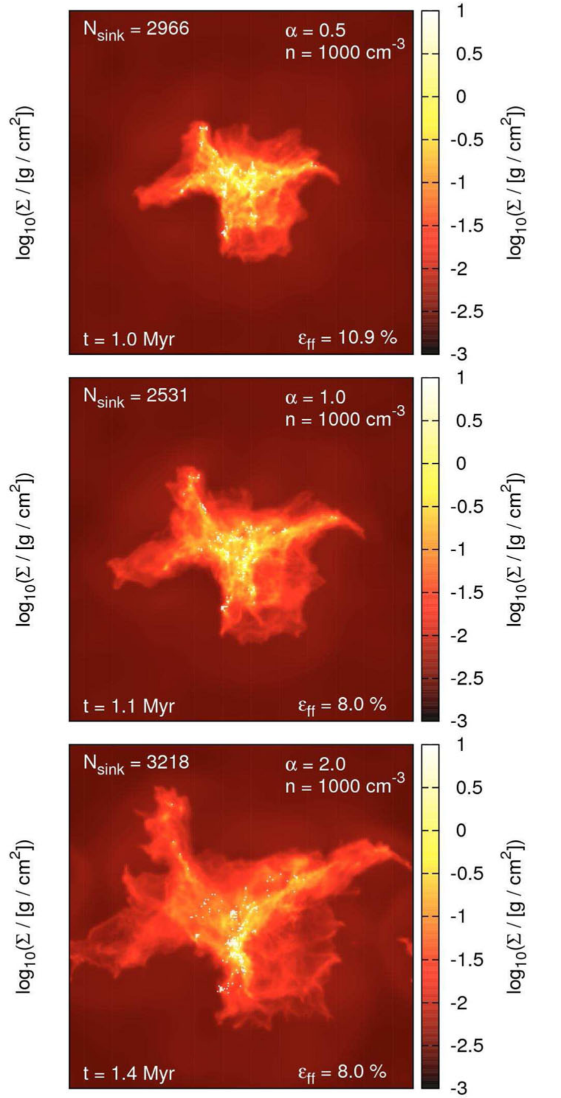






Two types of thermodynamical calculation

- Calculations of star cluster formation
  - Ignore complicated physics of the diffuse ISM
  - but include the radiative effects of protostars
  - (e.g. Bate 2009-2014; Offner et al. 2009; Krumholz et al. 2010-2012; Myers et al. 2011-2014)
    - Temperature accurate near protostars
    - Large-scales isothermal (set by boundary conditions)
    - No distinction between gas and dust temperatures (only valid $>10^5$ cm^{-3})
- Thermodynamical calculations of molecular clouds
  - Treat low-density thermochemical evolution of molecular clouds in detail
  - but exclude radiative feedback from protostars
  - (e.g. Glover et al. 2010-2012; Hocuk et al. 2015; Bertram, Glover et al. 2015)

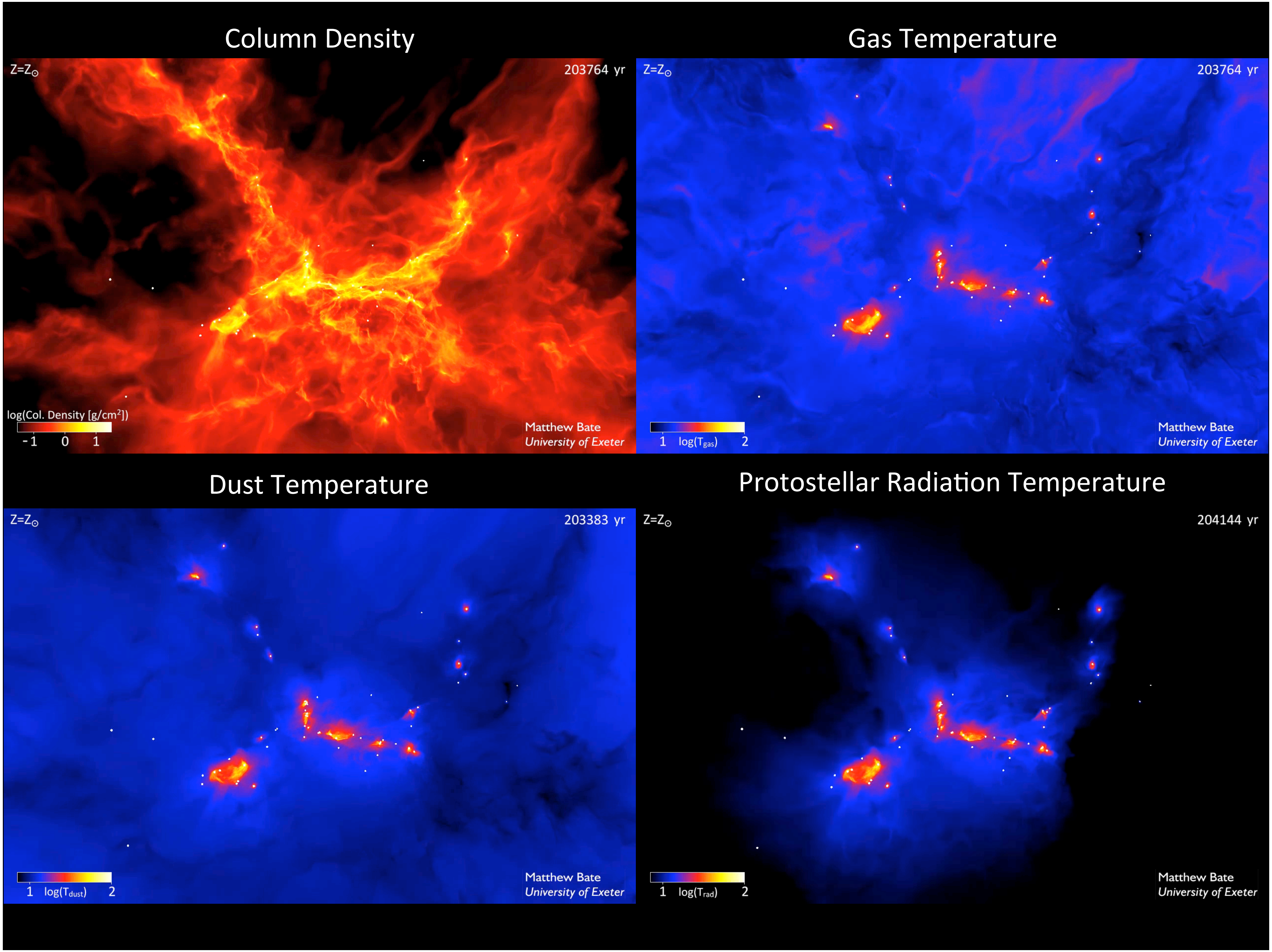


Bertram et al. (2015)

Combining radiative transfer & a diffuse ISM model

- Combining (Bate & Keto 2015) should allow more accurate models of star-forming regions and the resulting stellar populations
  - Gould-Belt star-forming regions (lower mean densities)
  - Low metallicities (external radiation environment more important, weaker gas/dust coupling)
  - Extreme environments (e.g. galactic centres, starburst, high-z)

- Diffuse ISM model similar to Glover et al. (2007, 2010)
  - Separate gas, dust and radiation temperatures
  - Gas heating: cosmic rays, photoelectric
  - Gas cooling: recombination cooling, C+, OI atomic lines, molecular lines (Goldsmith 2001)
  - Dust heating: assume equilibrium with radiation field (combined interstellar + protostellar)
  - Gas-dust collisional thermal coupling
  - BUT simple chemistry: carbon (CO, C^0, C^+) and hydrogen (HI and H_2)



Column Density
Z=Z⊙
203764 yr
log(Col. Density [g/cm²])
-1 0 1
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Gas Temperature
Z=Z⊙
203764 yr
1 log(T_gas) 2
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Dust Temperature
Z=Z⊙
203383 yr
1 log(T_dust) 2
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Protostellar Radiation Temperature
Z=Z⊙
204144 yr
1 log(T_rad) 2
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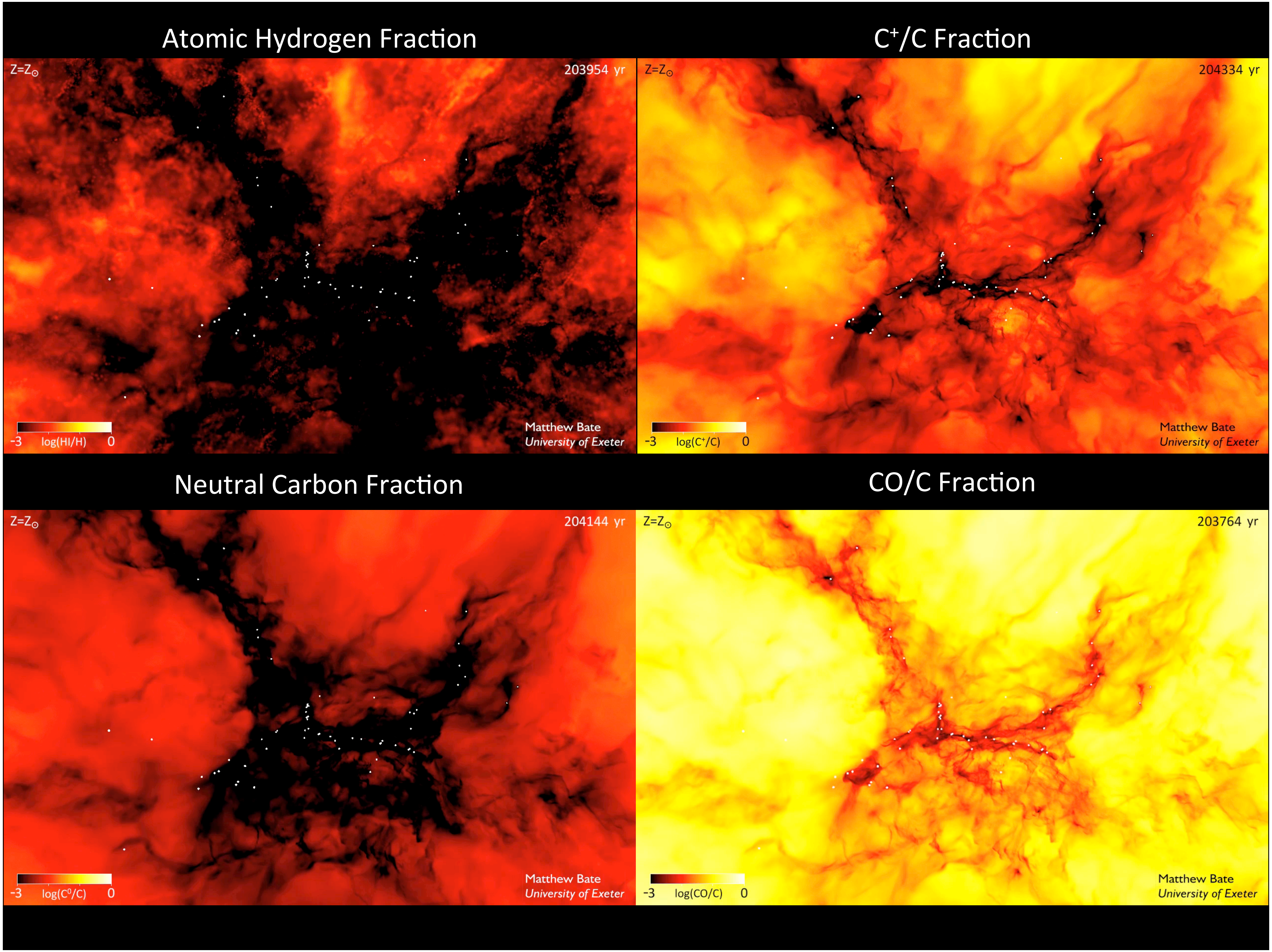
Atomic Hydrogen Fraction
Z=Z⊙
203954 yr
-3 log(HI/H) 0
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C+/C Fraction
Z=Z⊙
204334 yr
-3 log(C+/C) 0
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Neutral Carbon Fraction
Z=Z⊙
204144 yr
-3 log(C0/C) 0
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CO/C Fraction
Z=Z⊙
203764 yr
-3 log(CO/C) 0
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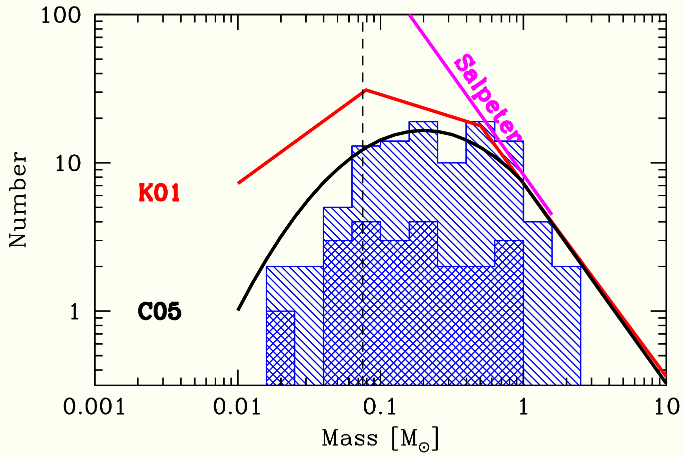
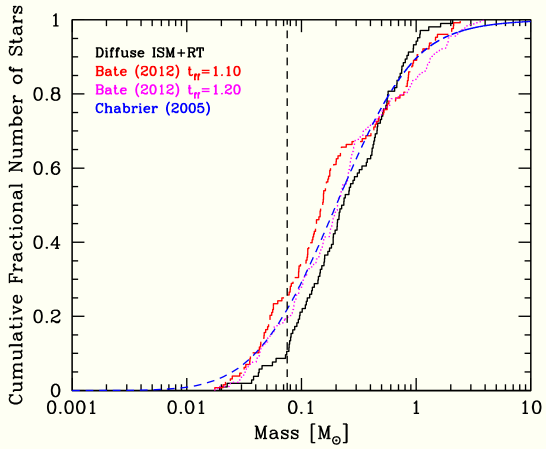
Mass function & multiplicity

- Preliminary results: calculation only run to 1.1 t_{ff} so far
  - 104 stars and brown dwarfs
  - Bate 2012 followed to 1.2 t_{ff} (183 stars and brown dwarfs)
- Median mass in good agreement with Chabrier (2005) IMF
  - Spread not quite as broad yet
- Multiplicities of solar-type stars currently higher than field
  - Most are in high-order multiples that may be expected to evolve dynamically

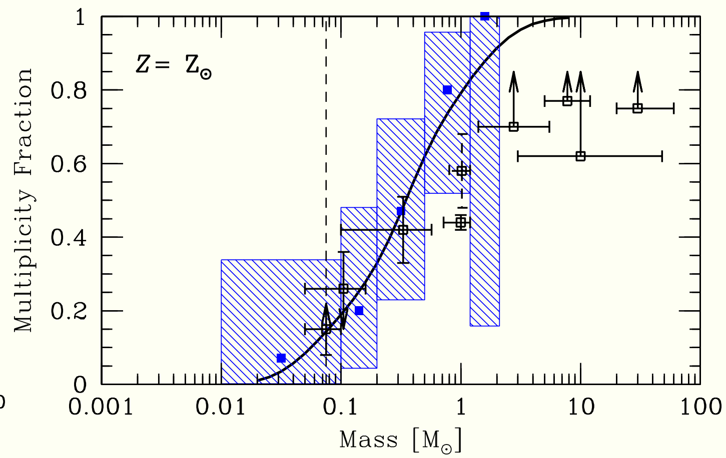
Differential IMF

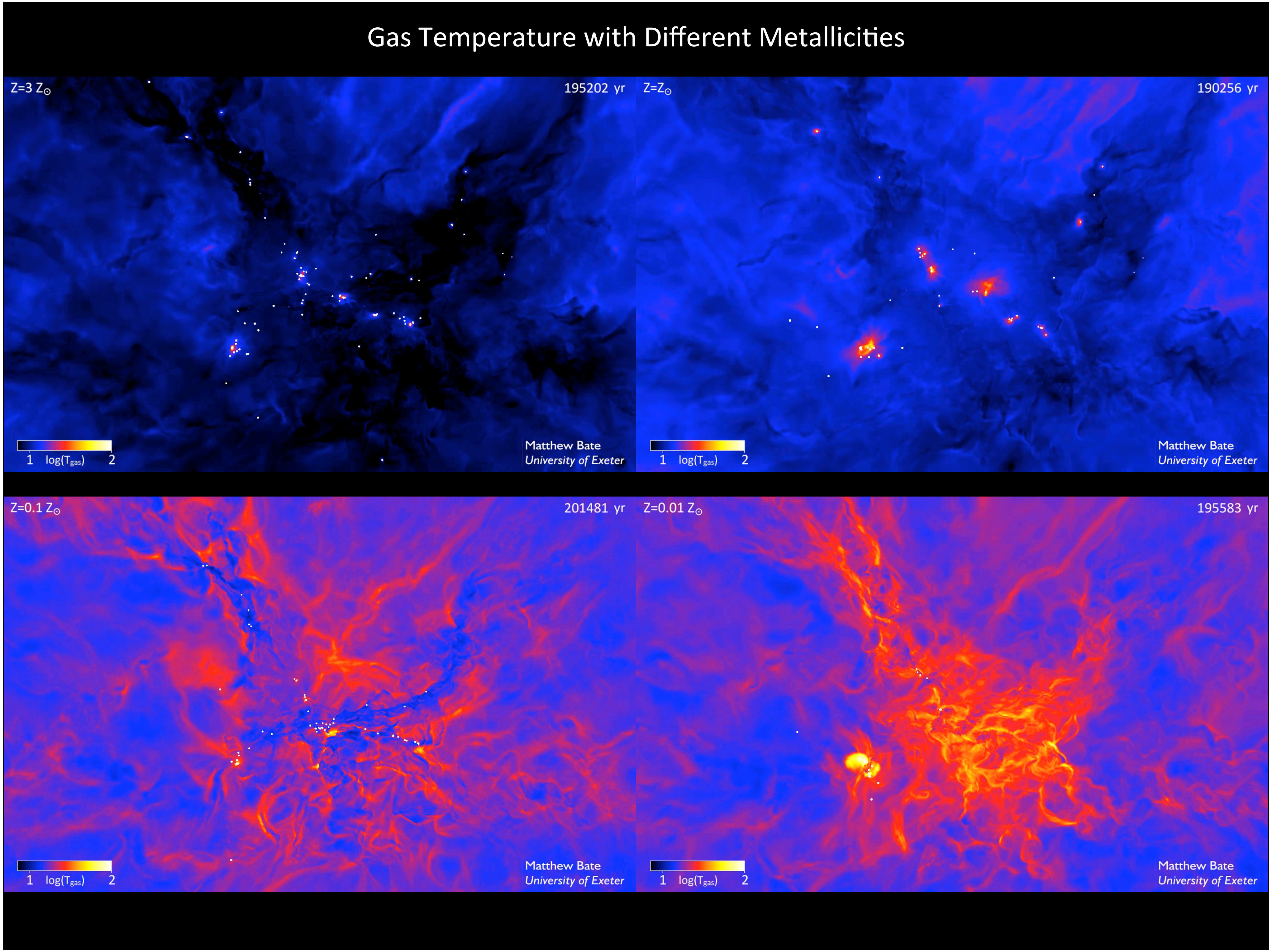


Cumulative IMF



Multiplicity vs Primary Mass




Gas Temperature with Different Metallicities
Z=3 Z⊙
195202 yr
Z=Z⊙
190256 yr
Z=0.1 Z⊙
201481 yr
Z=0.01 Z⊙
195583 yr
1 log(T_gas) 2
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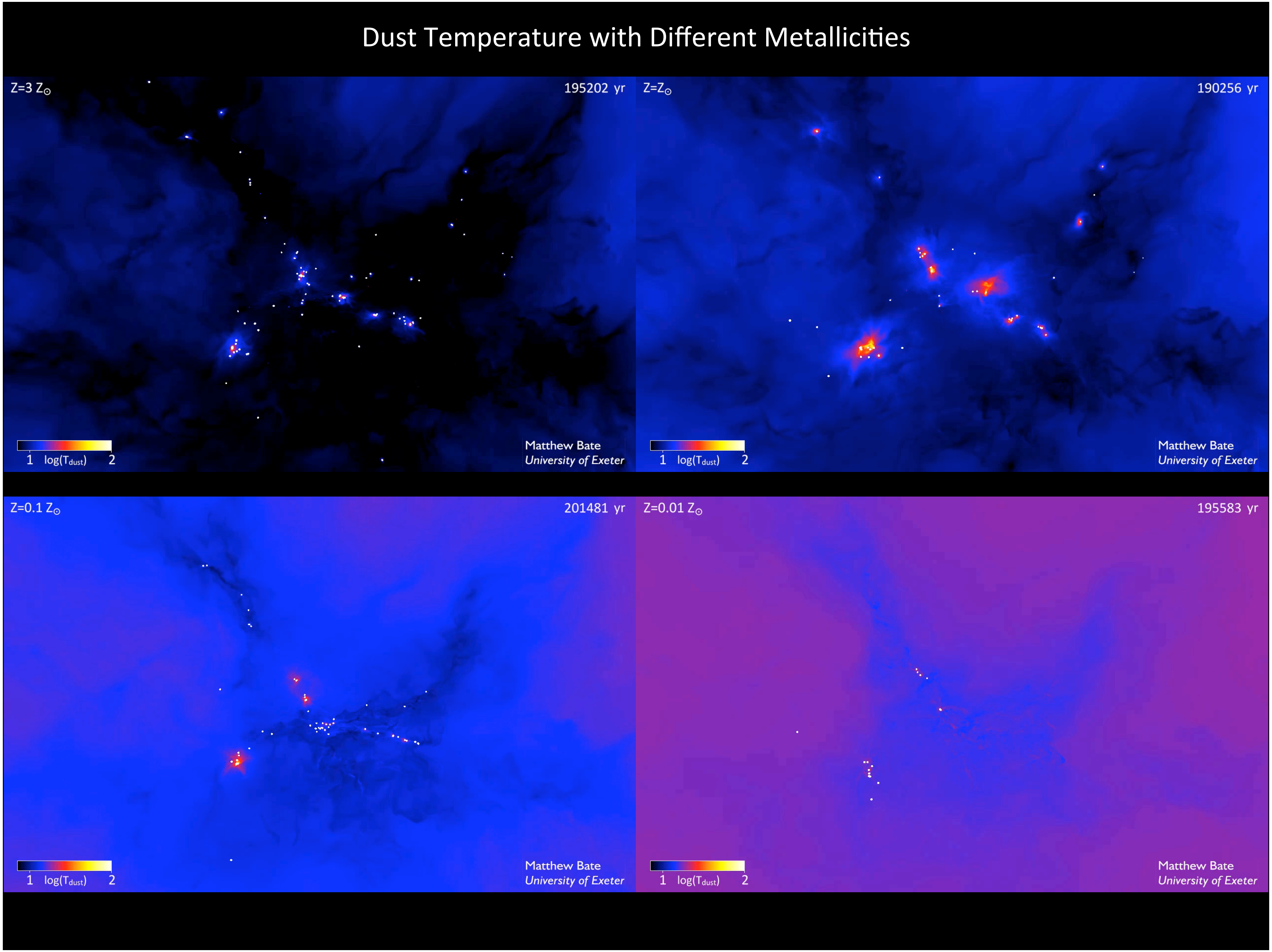
Dust Temperature with Different Metallicities
Z=3 Z⊙
195202 yr
Z=Z⊙
190256 yr
Z=0.1 Z⊙
201481 yr
Z=0.01 Z⊙
195583 yr
1 log(T_dust) 2
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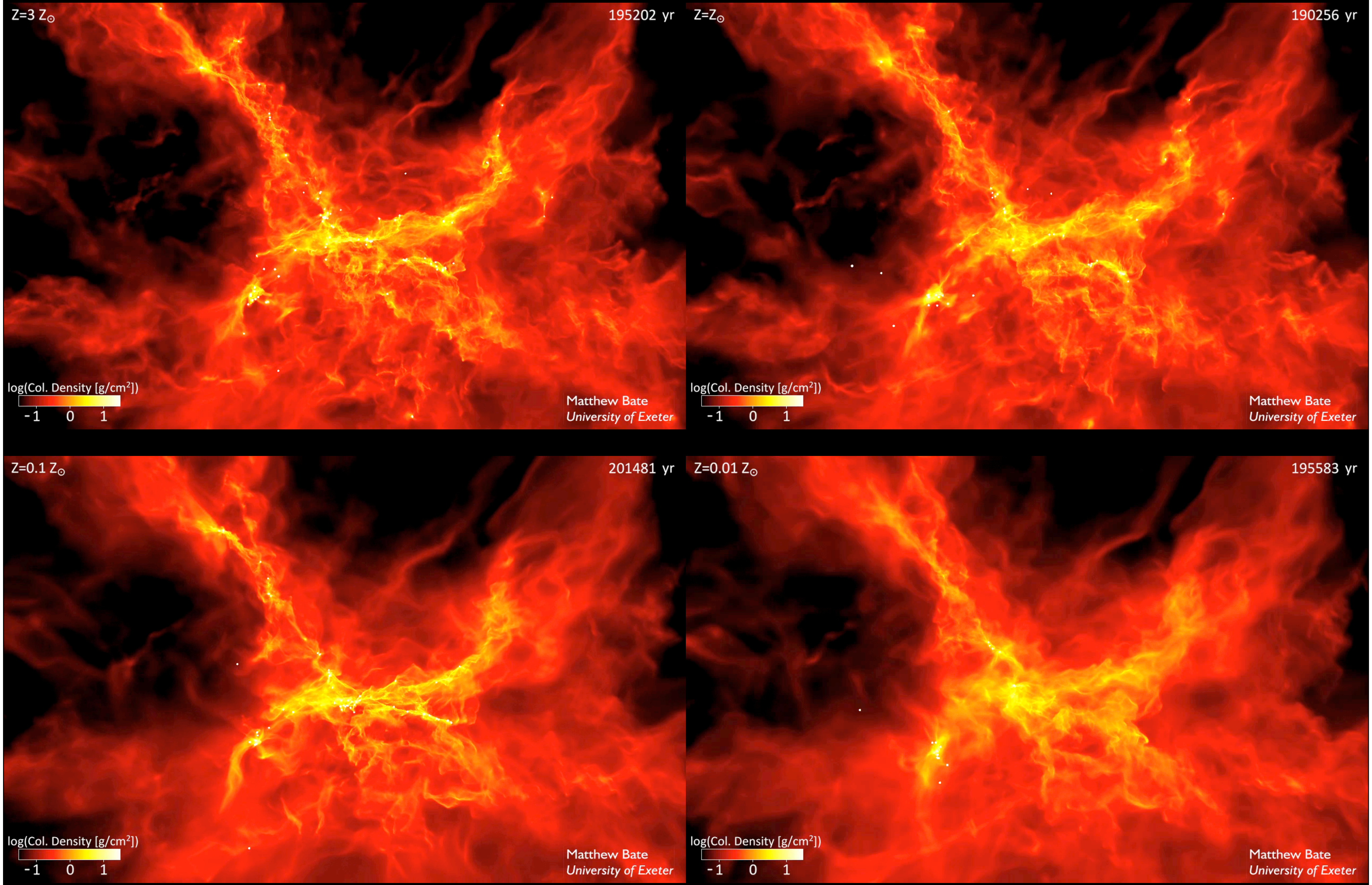
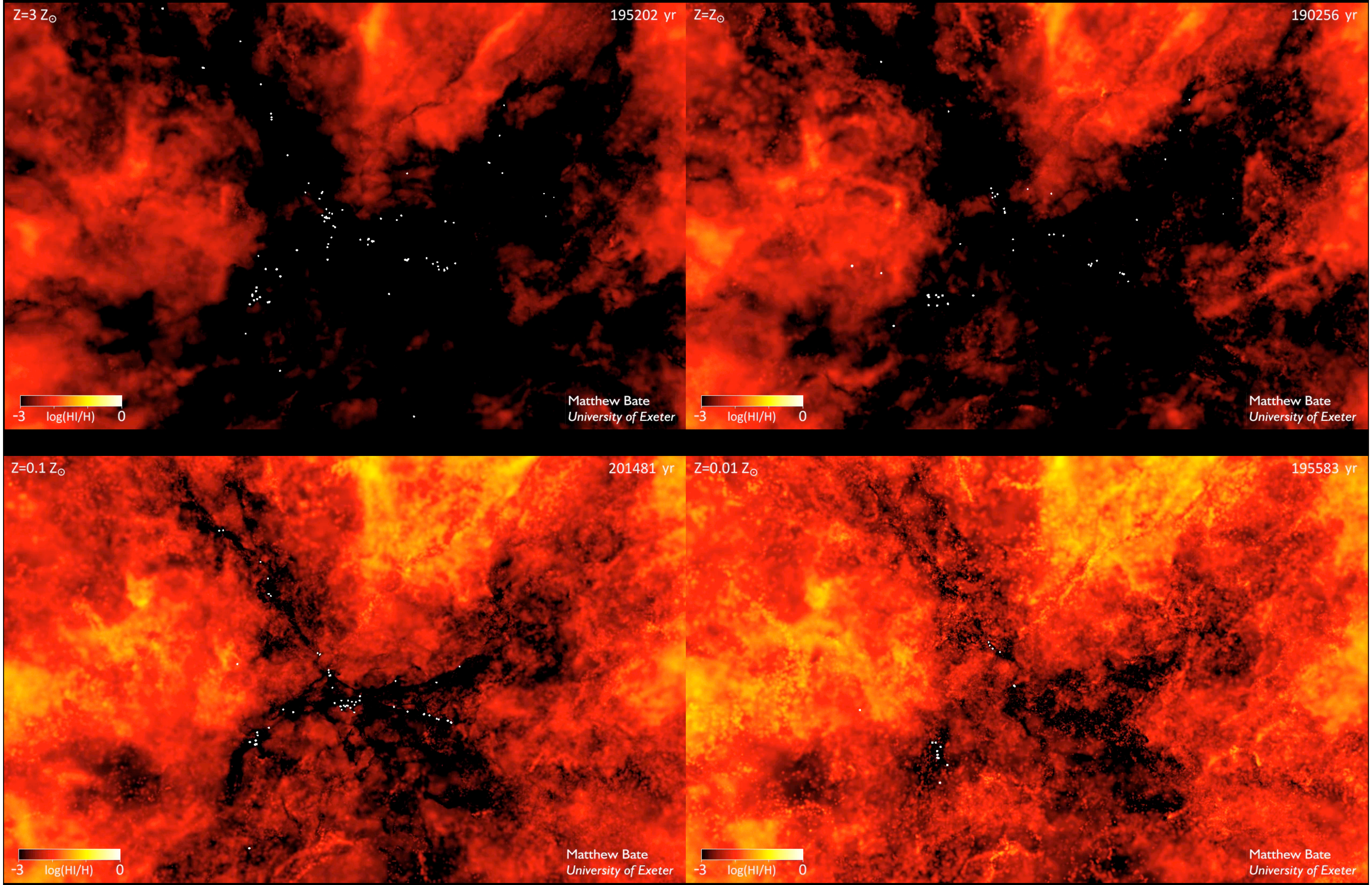
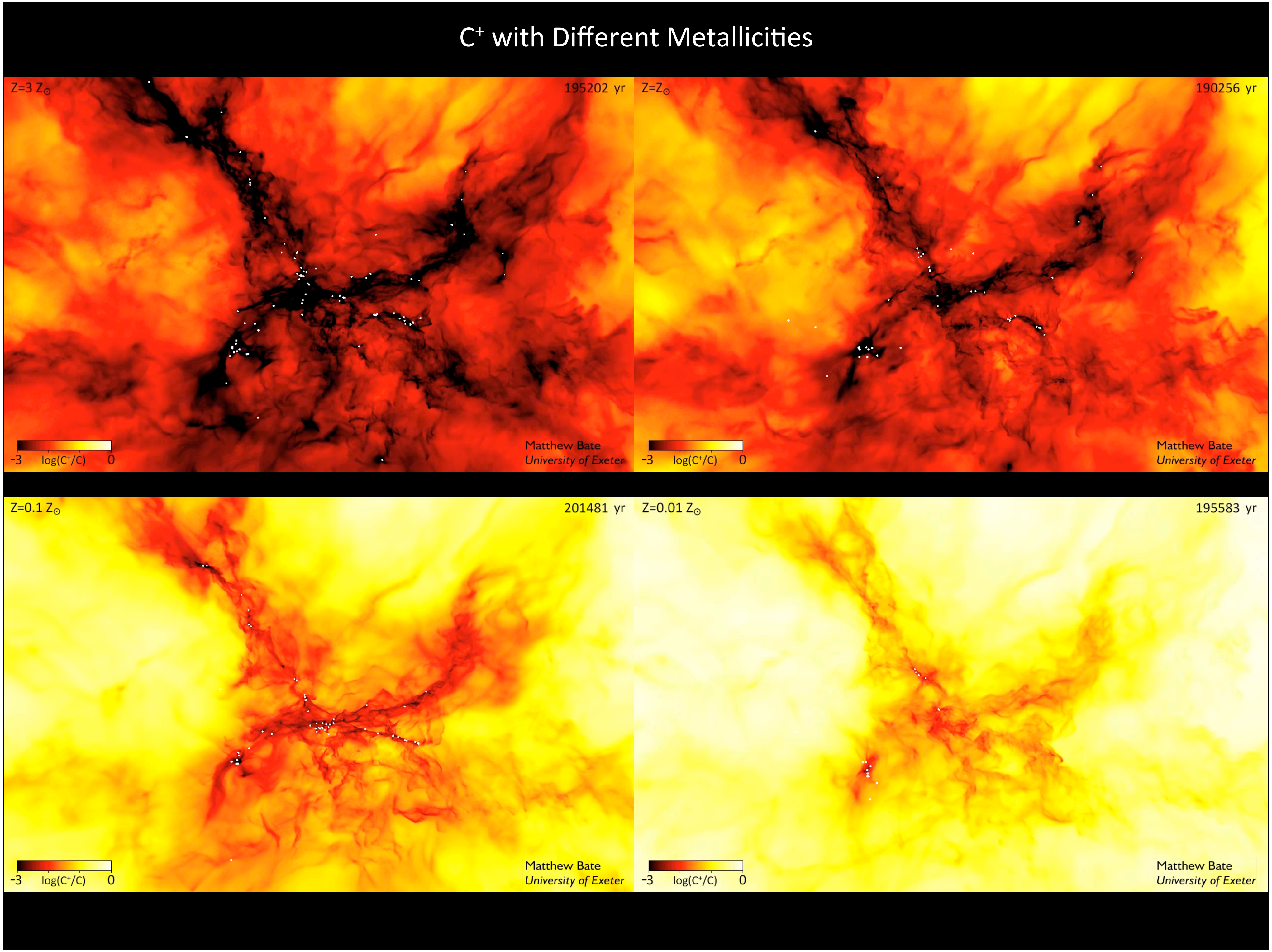
Column Density with Different Metallicities



HI with Different Metallicities




C+ with Different Metallicities
Z=3 Z⊙
195202 yr
Z=Z⊙
190256 yr
Z=0.1 Z⊙
201481 yr
Z=0.01 Z⊙
195583 yr
-3 log(C+/C) 0
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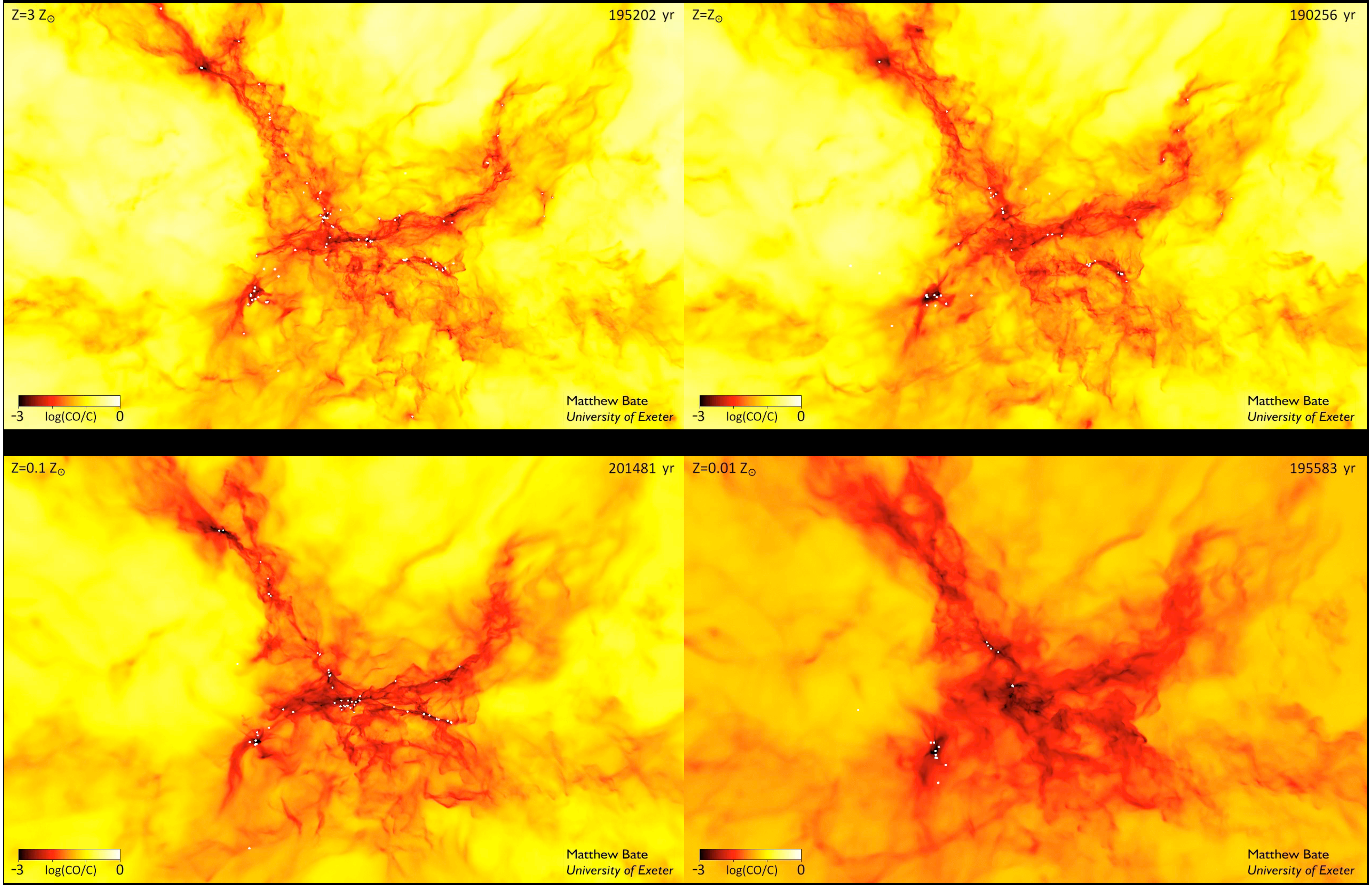
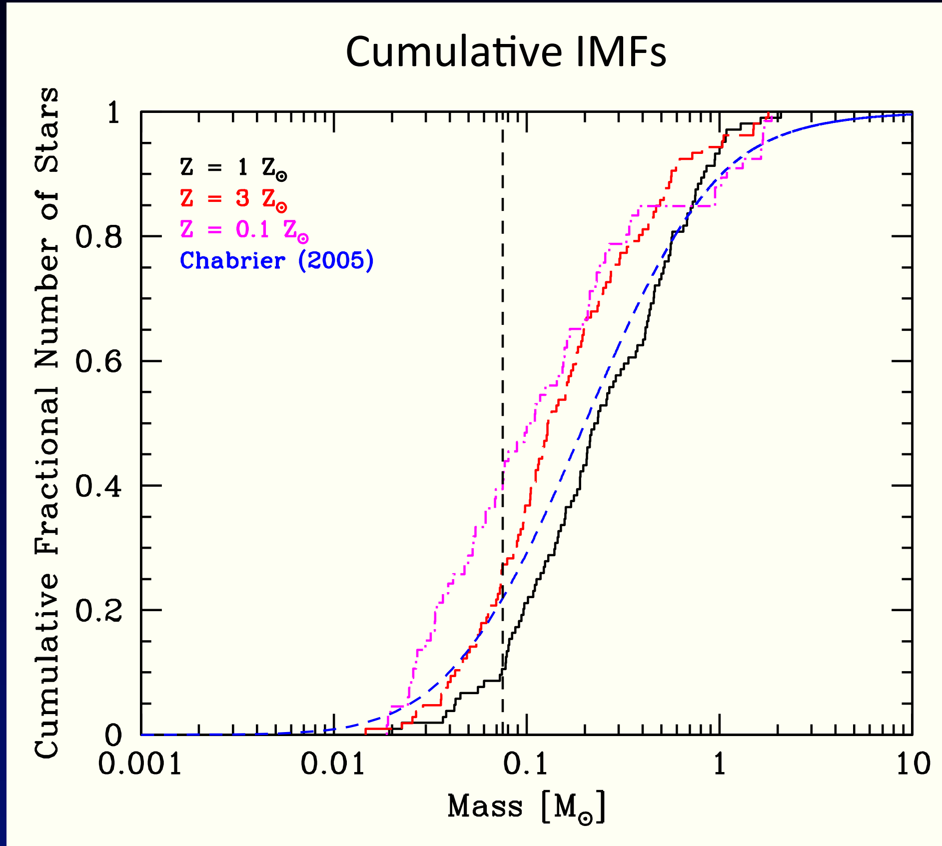
CO with Different Metallicities



Dependence of the mass function on metallicity

- Preliminary results:
  - $Z=0.1\ Z_\odot$ 66 stars and BDs at 1.05 t_{ff}
  - $Z=Z_\odot$ 104 stars and BDs at 1.09 t_{ff}
  - $Z=3\ Z_\odot$ 106 stars and BDs at 1.01 t_{ff}
- Median masses within factor ~2



- Solar metallicity currently has the highest characteristic stellar mass
  - Higher metallicity, greater extinction reduces gas temperatures & increases fragmentation
  - Lower metallicity, low opacities allow greater cooling at high densities

Conclusions

- Diffuse ISM model + radiative transfer will allow realistic calculations of
  - Varying metallicities
  - Lower-density molecular clouds (e.g. Taurus, Ophiuchus)
  - Different environments (e.g. stronger interstellar radiation (ISR) fields)
- Stellar properties (IMF & multiplicity) highly insensitive to dust opacities
- Calculations investigating metallicity dependence underway
  - Gas structure, composition, and temperatures do depend on metallicity
  - So far, no strong dependence of protostellar mass function on metallicity