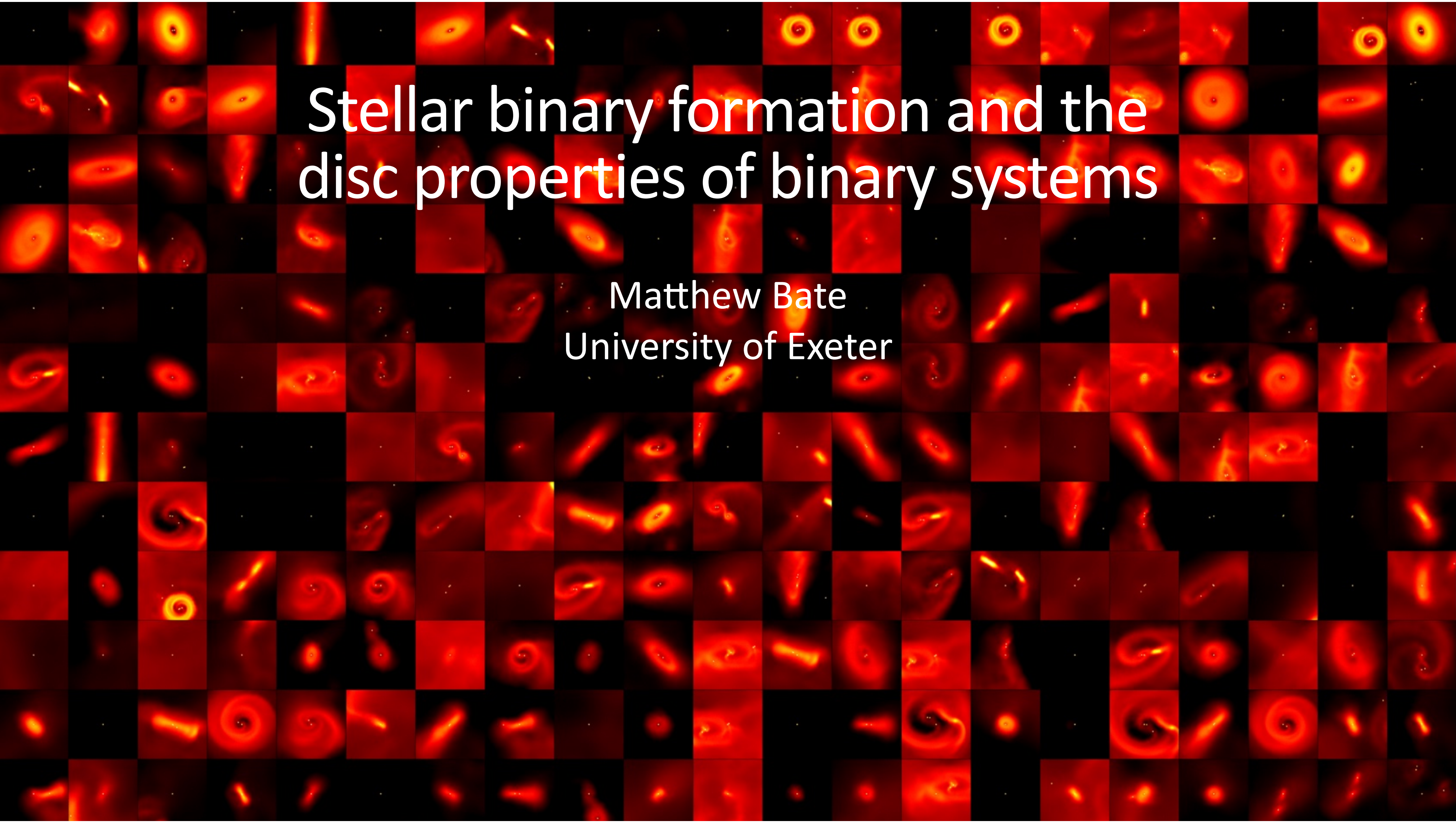


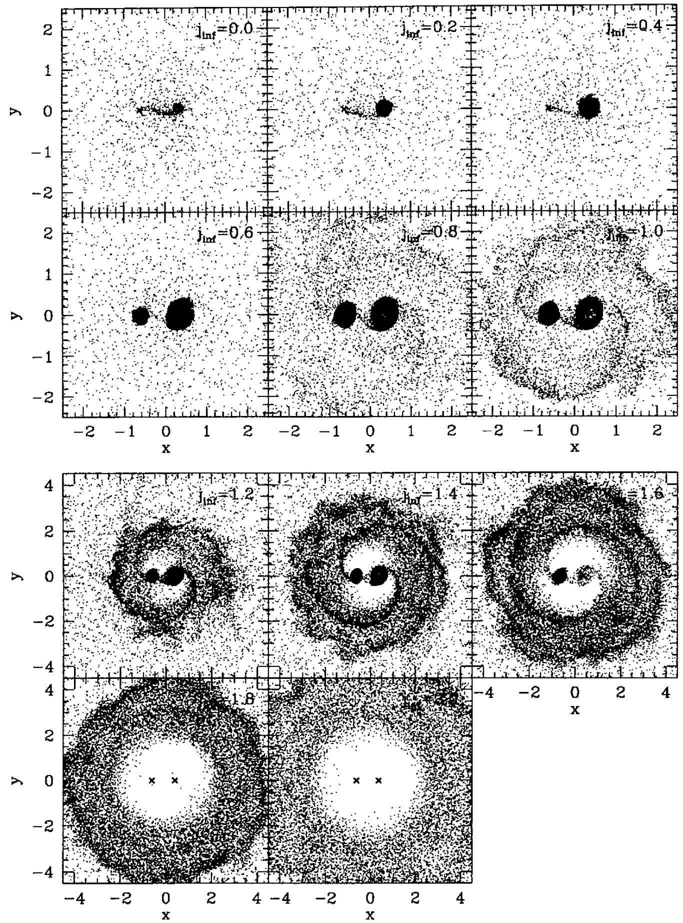
Stellar binary formation and the disc properties of binary systems

Matthew Bate
University of Exeter

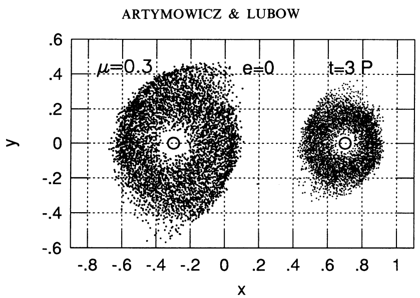
Disc formation in binary systems

- **My PhD thesis (1995) topic: formation of binary systems**
  - SPH simulations, examining the effects of infalling gas on binary mass ratios, separations, formation of discs (Bate 1995; Bate & Bonnell 1997)
  - Similar disc geometries to Lubow & Artymowicz's SPH simulations of circumstellar / circumbinary discs (Artymowicz & Lubow 1994; 1996)
- **Differences: Artymowicz & Lubow (1994, 1996)**
  - Disc only, no envelope, but streams of gas from the inner circumbinary discs onto the binary
  - My work included infalling envelope gas
    - Travels on parabolic orbits — enters vicinity of binary more easily than just accretion streams from discs
    - Can easily lead to separation increasing (if high angular momentum material infalling)

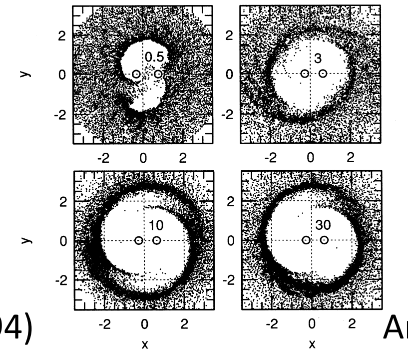
Accretion onto q=0.6 binary, varying gas specific angular momentum

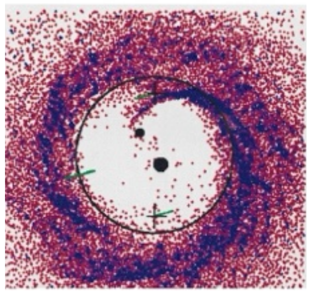


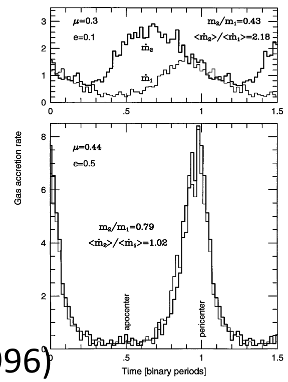
Bate & Bonnell (1997)



Artymowicz & Lubow (1994)





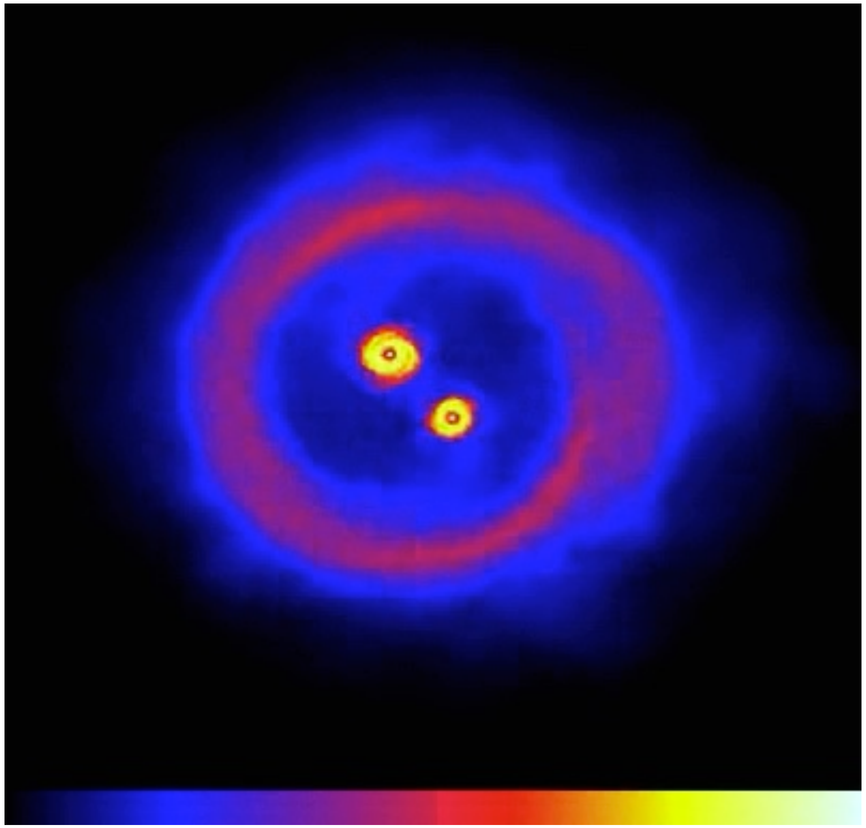


Artymowicz & Lubow (1996)

Formation of isolated binaries in cloud cores

- **Bate (2000) evolution of mass ratio, separation and discs in accreting protobinary systems**
  - Circumbinary disc formation requires the accretion of gas with high specific angular momentum
  - Specific angular momentum > the specific angular momentum of the secondary around the centre of mass (Bate & Bonnell 1997)

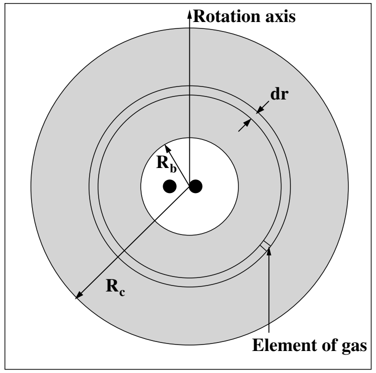
Accretion on to binary in an initially 1/r-density profile, solid-body rotating molecular cloud core

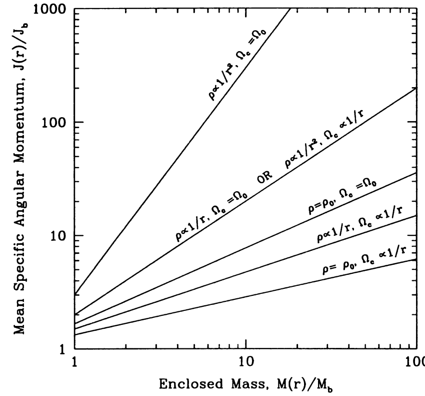


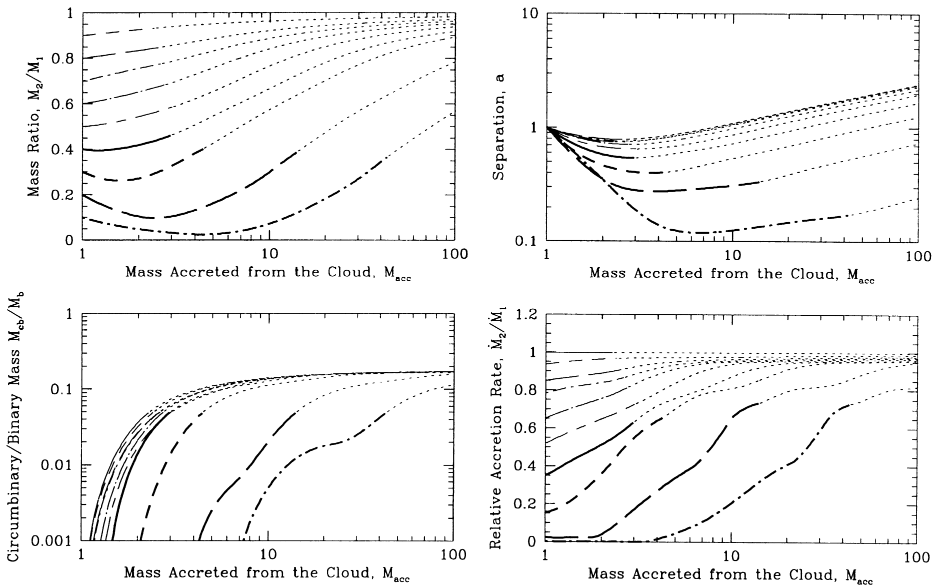
Bate (2000)

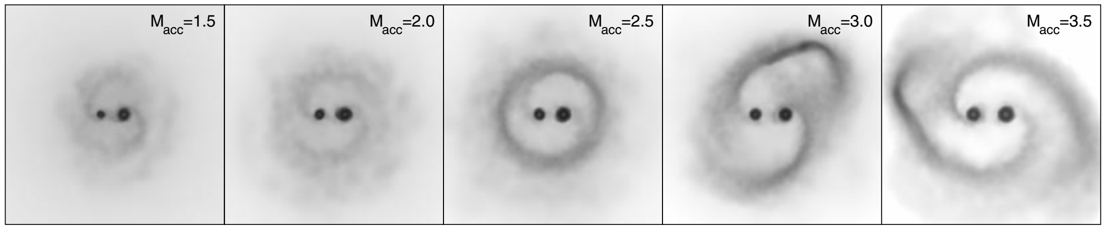
Formation of isolated binaries in cloud cores

- **Bate (2000) evolution of mass ratio, separation and discs in accreting protobinary systems**
  - Used the results of the Bate & Bonnell (1997) series of calculations of the ‘instantaneous’ effect of accretion onto binaries with different mass ratios & gas specific angular momentum
  - Model long-term protobinary evolution
  - Depends on density & angular momentum profiles of cloud cores
  - Results favour initially not strongly centrally-condensed cloud cores (e.g. uniform/Bonnor-Ebert) and/or differential (not solid-body) rotation



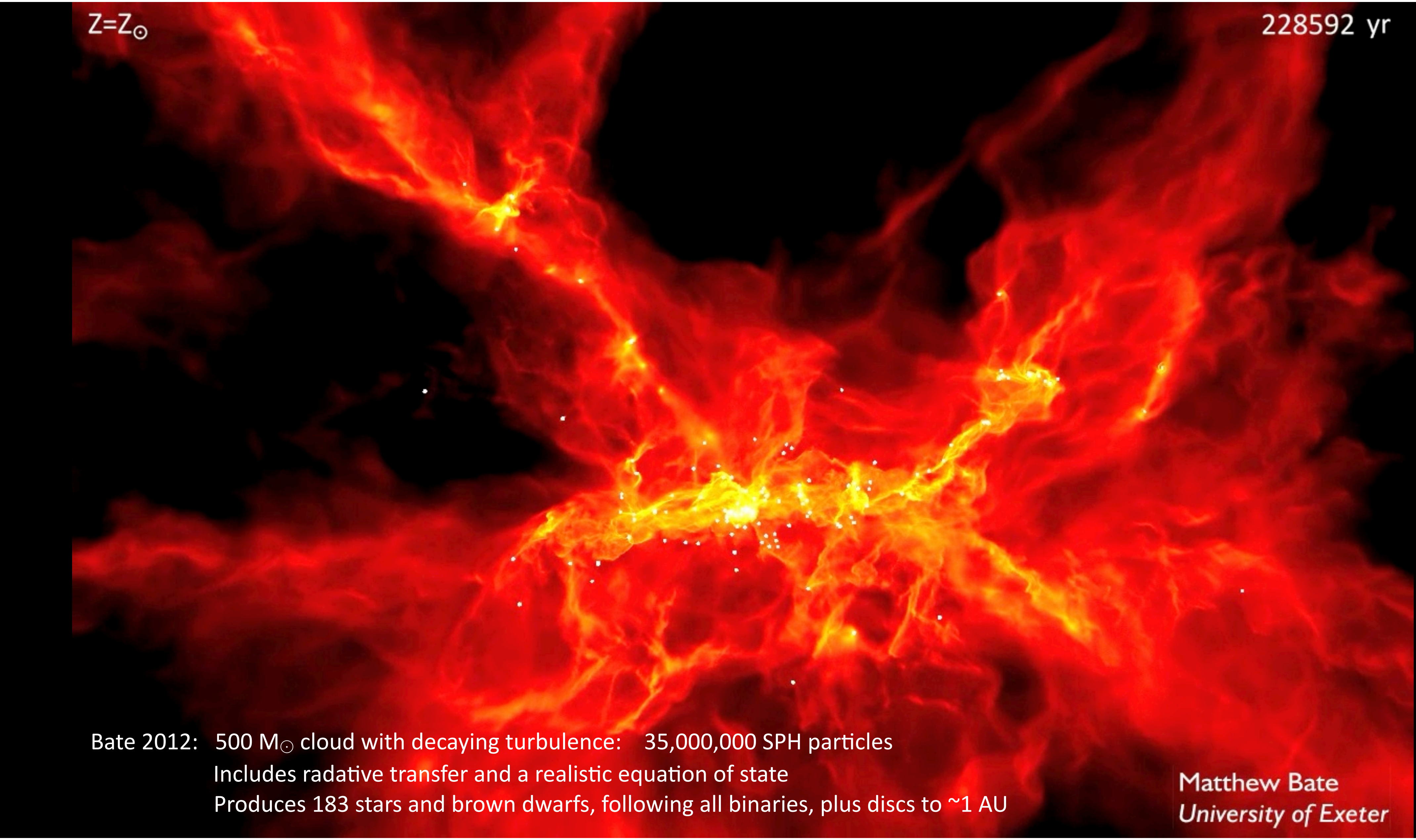




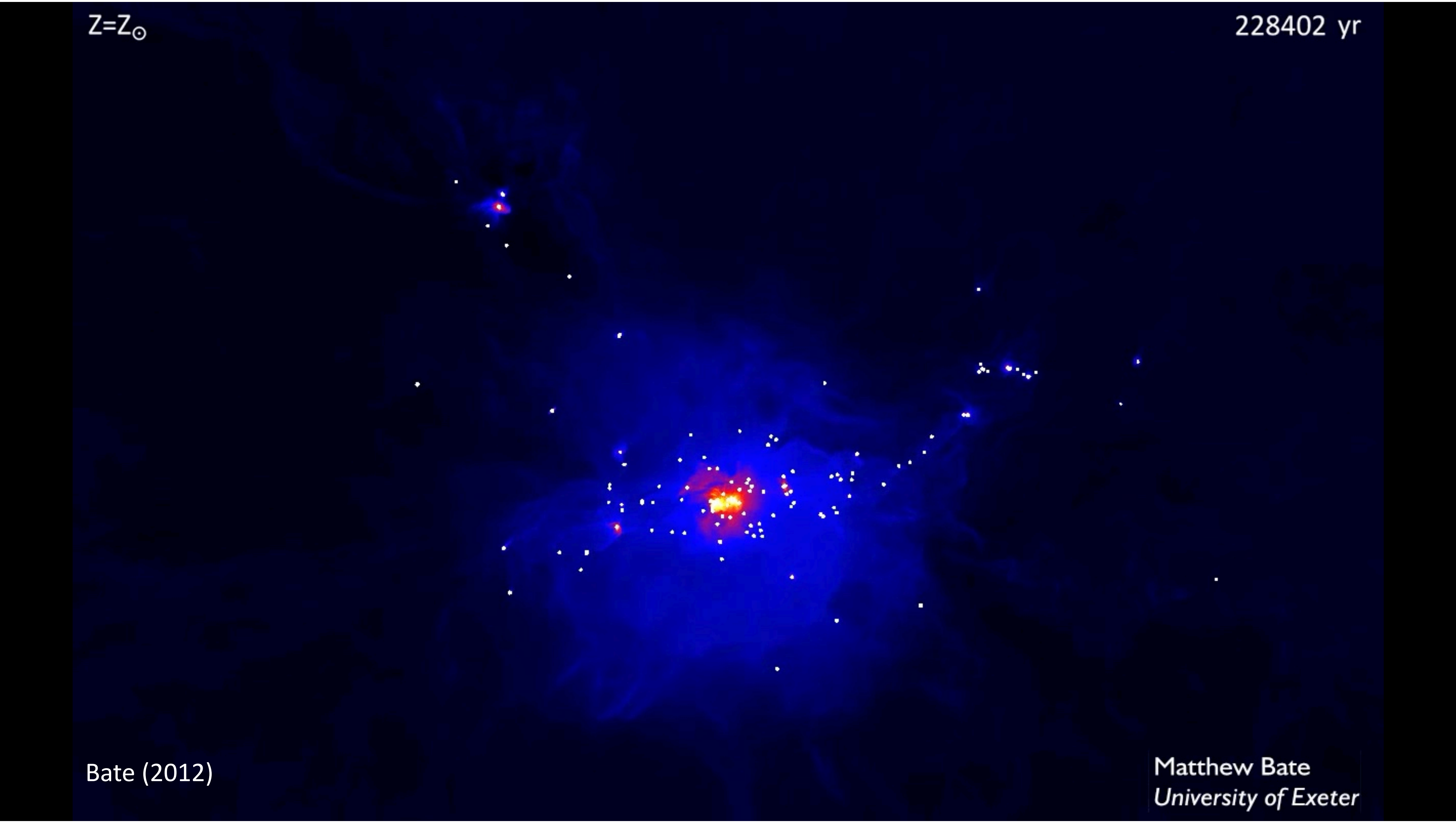


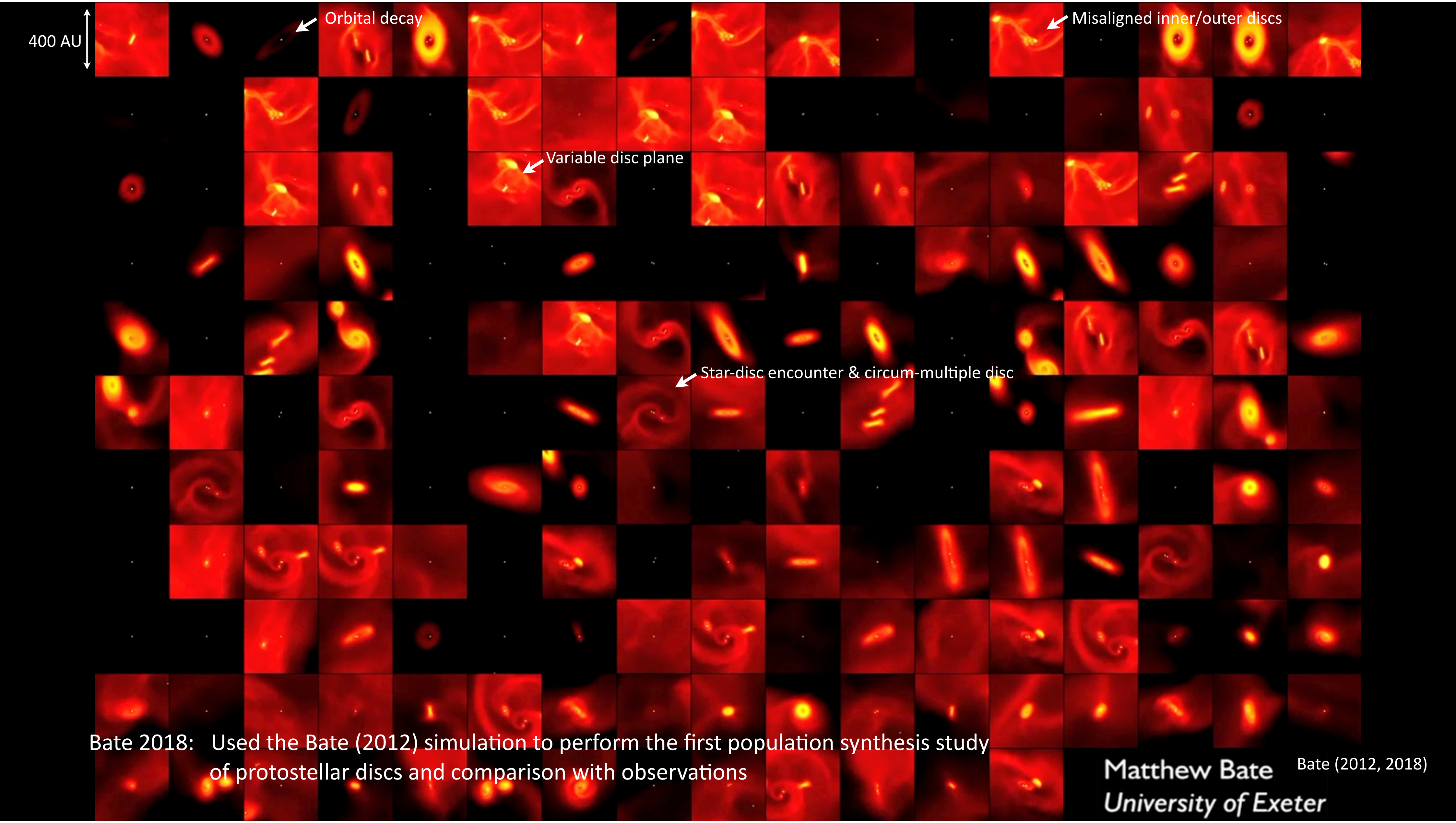
Accretion on to binary in an initially 1/r-density profile, solid-body rotating molecular cloud core: Later infall builds up the circumbinary disc

Bate (2000)



Bate 2012: 500 $M_\odot$ cloud with decaying turbulence: 35,000,000 SPH particles
Includes radative transfer and a realistic equation of state
Produces 183 stars and brown dwarfs, following all binaries, plus discs to ~1 AU


$Z=Z_\odot$
228402 yr
Bate (2012)
Matthew Bate
University of Exeter



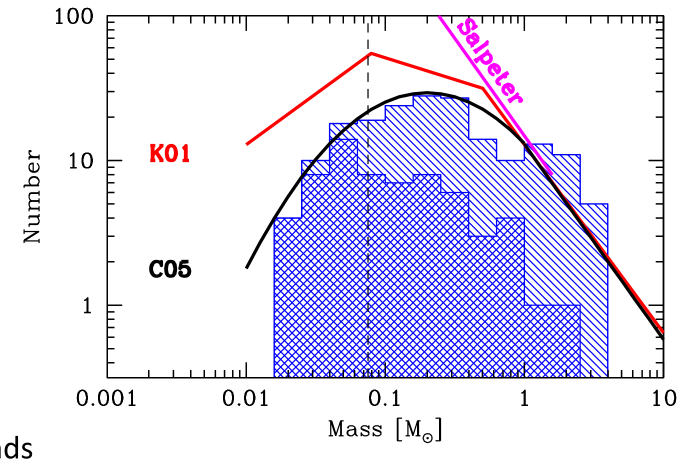
Bate 2018: Used the Bate (2012) simulation to perform the first population synthesis study of protostellar discs and comparison with observations

Bate (2012, 2018)

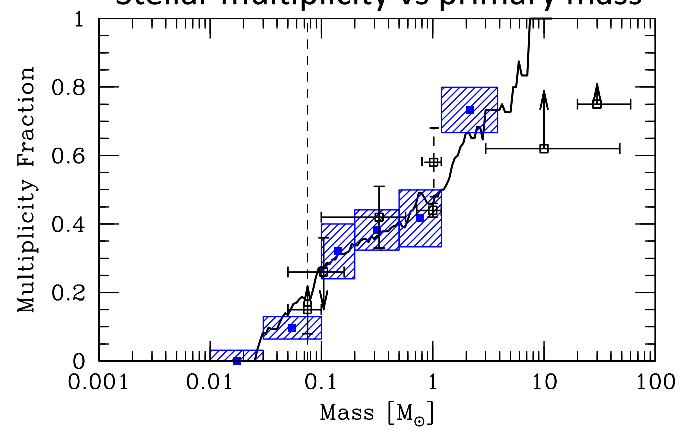
Able to reproduce observed properties of low-mass stars

- **Since Bate (2012), RHD simulations can produce realistic Galactic populations**
- **Self-regulation via protostellar interactions**
  - **Gravitational fragmentation of structured molecular gas to form stellar groups**
    - Exactly how the structure arises is not so important (Bonnell et al. 1997-2001; Klessen et al. 1998-2001; 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: Bonnell et al. 1997,2001), 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 interactions (feedback) between accreting protostars, change local Jeans mass**
    - Enables the production of an (almost) invariant IMF (Bate 2009b; Krumholz 2011)
  - **All three together can reproduce observed Galactic stellar properties**
  - **Other physics like magnetic fields, outflows, etc, 2nd-order effects**
    - e.g. Wurster, Bate & Price (2019) for non-ideal MHD

Protostellar mass function



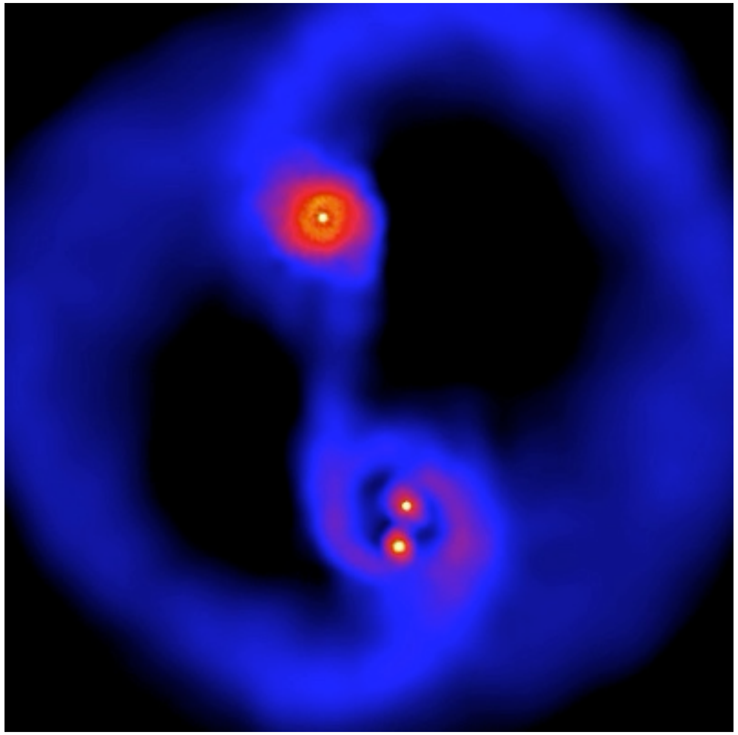
Stellar multiplicity vs primary mass



Bate (2012)

Binary formation mechanisms

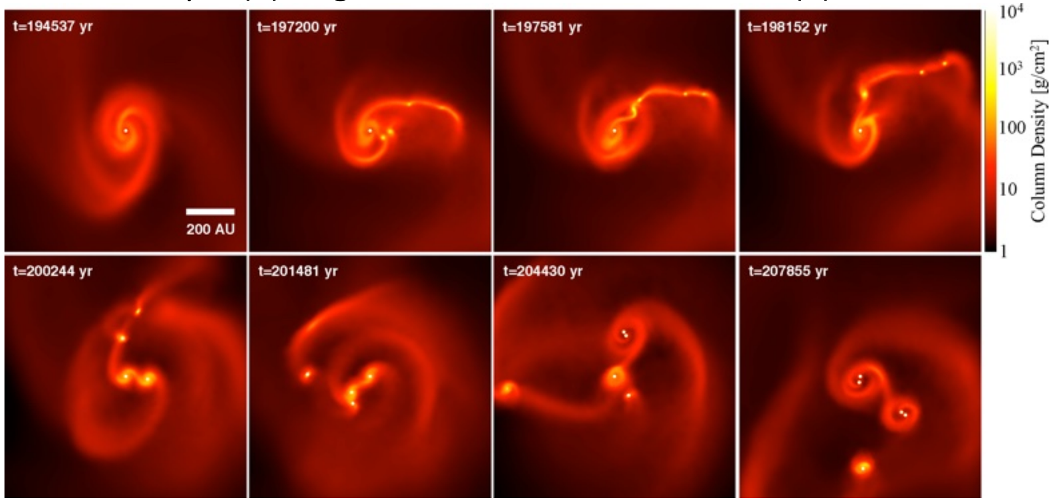
- **Prompt / turbulent fragmentation**
  - `Prompt' fragmentation (Pringle 1989), due to collapse of highly-structured molecular clouds
    - Simplest cases: cos($m\theta$) density perturbations (m=2) to otherwise spherical cloud cores
    - Boss & Bodenhemier (1979); Boss (1986), etc
  - Commonly described as `turbulent' fragmentation these days
    - Offner et al. (2009)
- **Disc fragmentation**
  - Requires massive discs (typically >10% central object mass)
  - Rapid cooling (of order the dynamical timescale) for an isolated disc
  - See review by Kratter & Lodato (2016)
  - Much easier if the disc is rapidly accreting
    - Bonnell (1994); Bonnell & Bate (1994); Whitworth et al. (1995); Hennebelle et al. (2004)
    - Particularly relevant for binary star formation (hard to avoid BD+ masses)
- **Encounters of unbound triples**
  - Insignificant (infrequent) in most stellar environments
- **Star-disc (dissipative) encounters**
  - Two initially unbound stars become bound through dissipative close encounter
  - Clarke & Pringle (1991a,b) — not significant for binary formation, in a virialised cluster like the Orion Nebular Cluster with typically Class II disc masses
  - Discs tend to be truncated without enough kinetic energy being dissipated (Hall, Clarke & Pringle 1996)



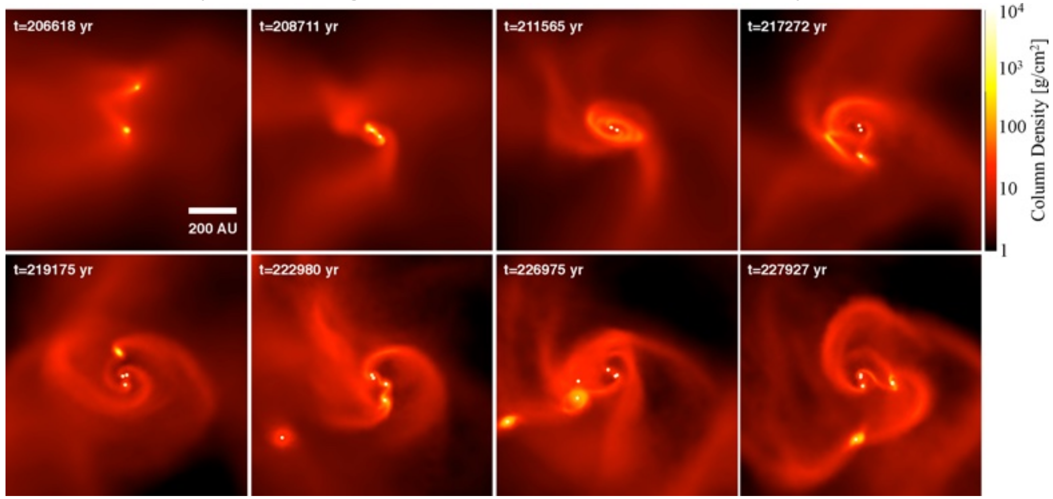
Bate, Bonnell & Price (1995)

Binary formation in a clustered environment

Multiple (5) fragmentations of a circumstellar(+) disc



Multiple (3) fragmentations of a circumbinary(+) disc



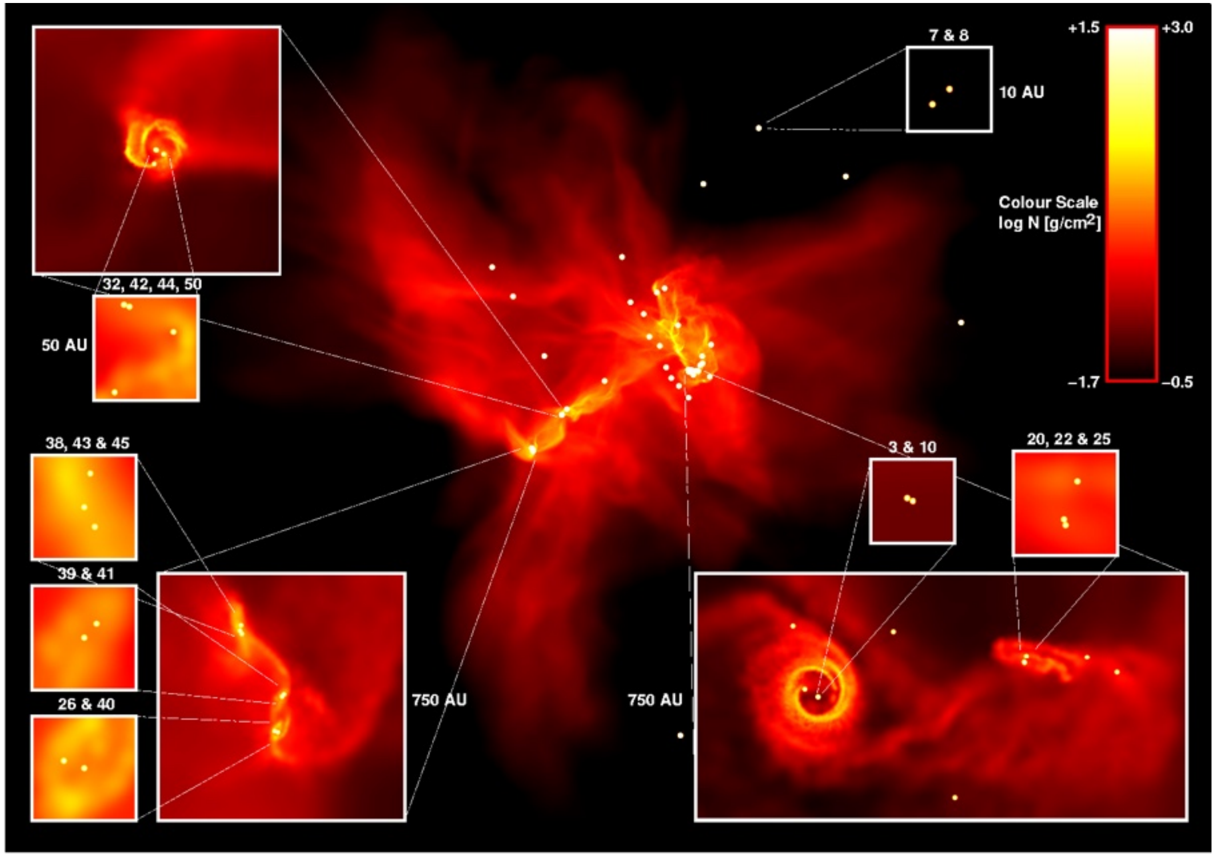
- **Prompt / turbulent fragmentation**
  - Primary formation mechanism for multiples
  - But frequently also involves star-disc encounters
    - >48 cases, involved in the formation of 32 binaries & 14 triples (28 binaries and 12 higher-order systems at the end)
    - Protostars that are weakly (un)bound, become bound or more-tightly bound
    - Cluster initially sub-virial

- **Disc fragmentation**
  - 10 discs undergo fragmentation
  - Producing 25/183 stars or brown dwarfs (i.e. ~1/7 of the objects)

Formation of spectroscopic (close) binaries

- **Bate, Bonnell & Bromm (2002b)**
  - Showed that three processes were involved in producing close (<10 au) binaries
    - Hardening of existing wider binaries by dynamical encounters in unstable multiple systems
    - Orbital decay by:
      - Accretion of gas from the cloud/envelope that has low specific angular momentum
      - Loss of orbital angular momentum to a circumbinary disc
  - Together, these 3 processes produced a realistic fraction of close binaries

Close binaries (<10 au) at the end of the Bate et al. (2002) simulation

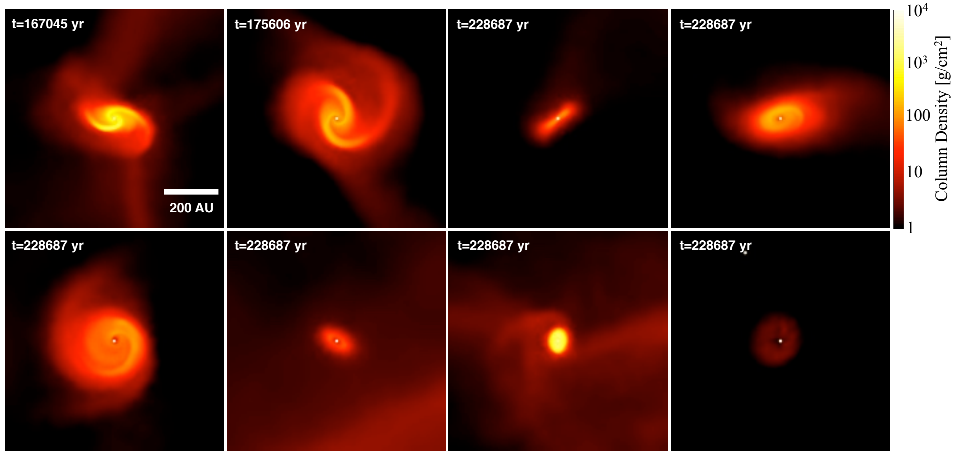


Types of discs

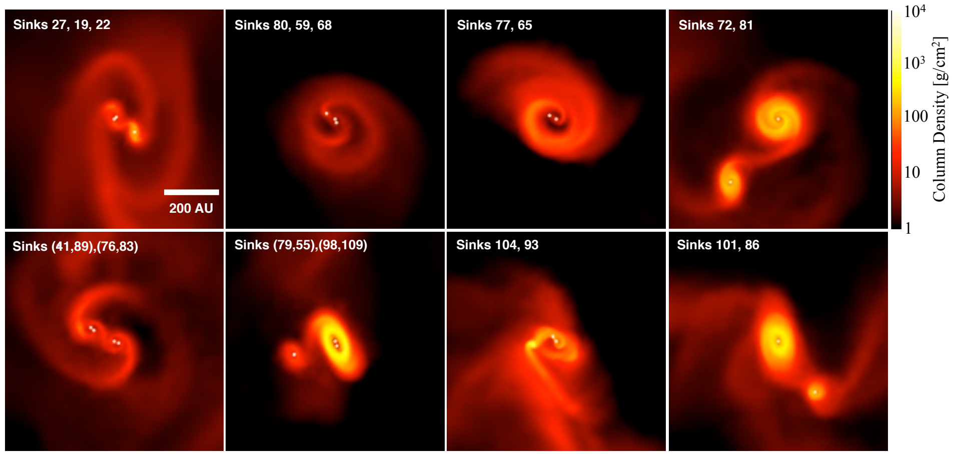
- **Discs of single protostars**
  - May be gravitationall unstable (spiral structures)
  - Analysed the discs produced in Bate (2012) simulation

- **Discs of multiple systems**
  - Binaries: 2 circumstellar discs, & a circumbinary disc
  - Triples: up to 5 discs:
    - 3 circumstellar, a circumbinary, & a circum-triple disc
  - Quadruples: up to 7 discs !
  - May have spiral structure due to torques
  - May be misaligned with each other and/or with orbit(s)

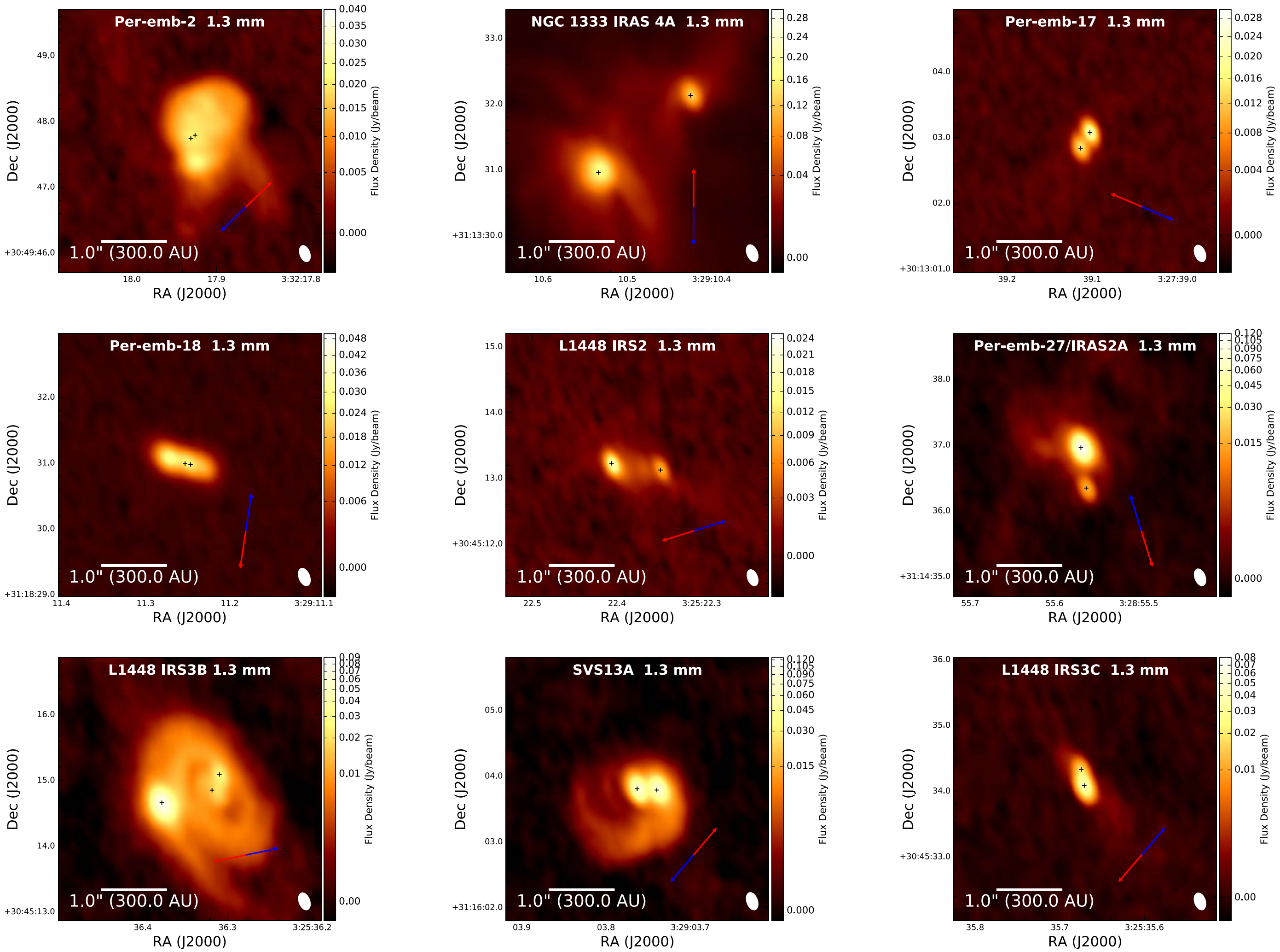
Examples of discs of single protostars (Bate 2018)



Examples of discs in multiple systems (Bate 2018)



ALMA images of Class 0 multiple systems

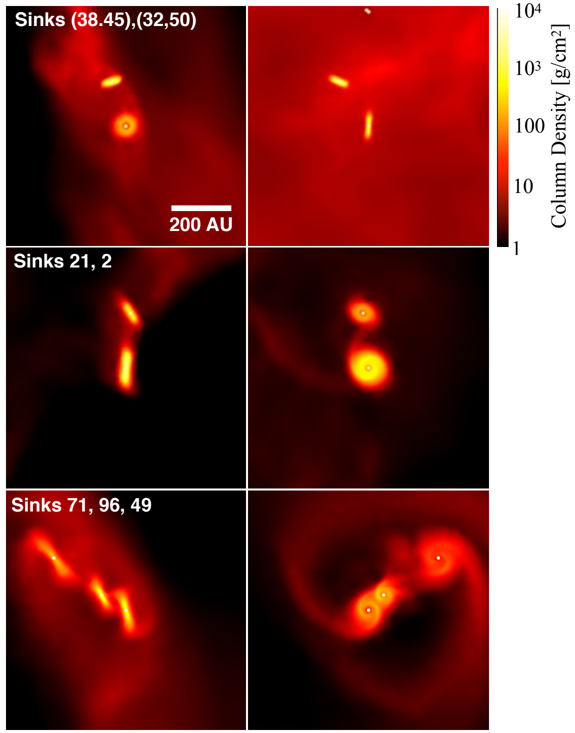


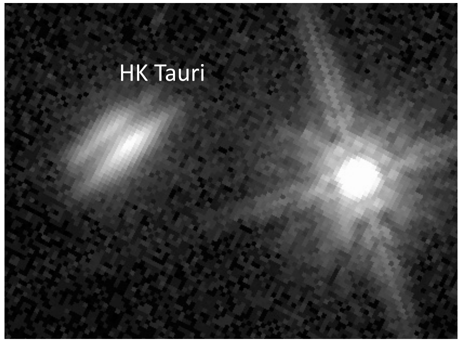
VANDAM Survey
(Tobin et al. 2018)

Disc (mis)alignment

- **Discs of multiple protostellar systems**
  - Have a strong tendency for alignment for pairs with separations < 100 AU
  - Discs of pairs in triple or quadruples tend to be more aligned than for binaries, especially wide pairs
  - Discs tend to become more aligned with age

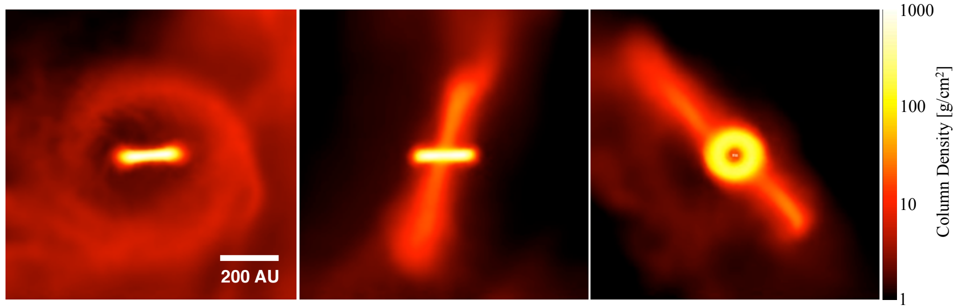
Examples of misaligned circumstellar discs (Bate 2018)





- **One instance of a ‘broken’ disc**
  - Inner disc and outer disc are misaligned by 75°
  - Outer disc formed later by accretion of new gas

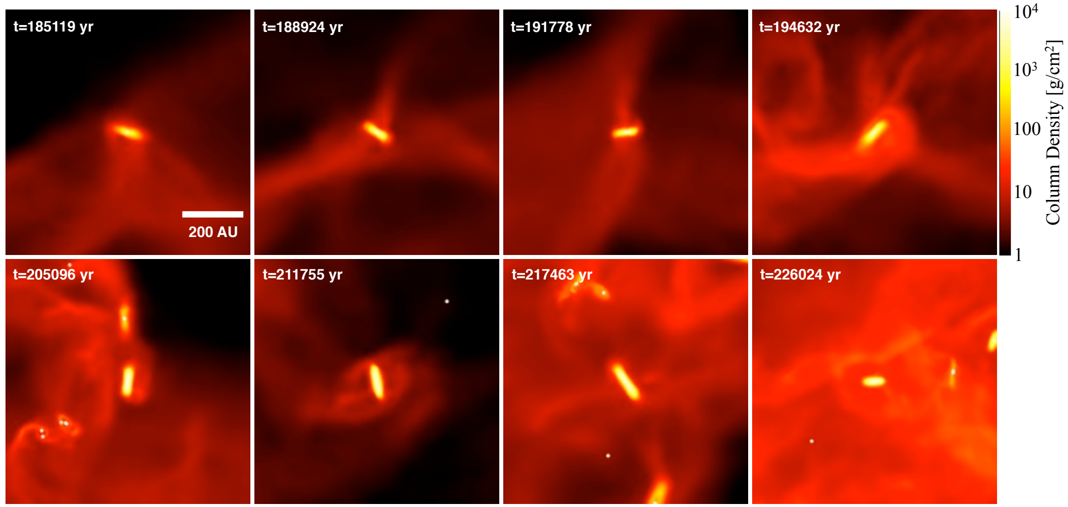
One case of a `broken’ disc, misaligned by 75° (Bate 2018)



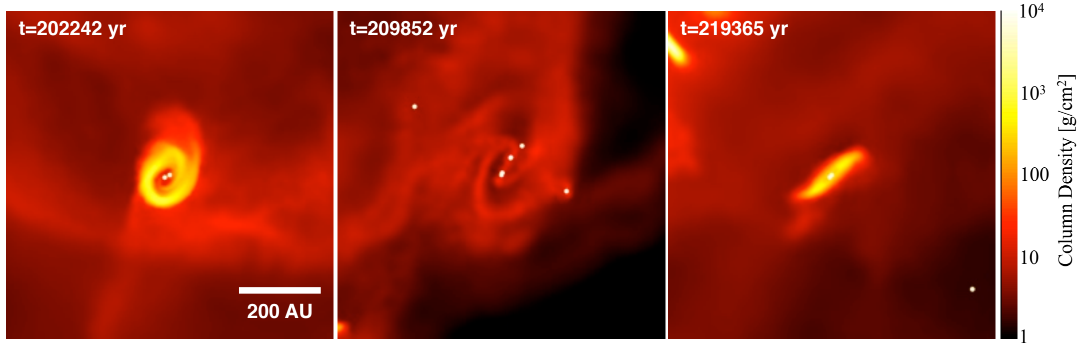
Disc evolutionary processes

- **Accretion**
  - 10 cases of substantial reorientation of discs via accretion from turbulent cloud
  - One case of reorientation by 220° !
- **Erosion/stripping**
  - Ram-pressure stripping: 7 discs
  - Dynamical encounters: 26 discs
  - Combination: 18 discs
  - Several cases of stripped discs being reformed by later accretion
    - Detailed studies:Moeckel & Throop 2009; Wijnen et al. 2016, 2017a,b)

Reorientation of a disc through 220° due to ongoing accretion



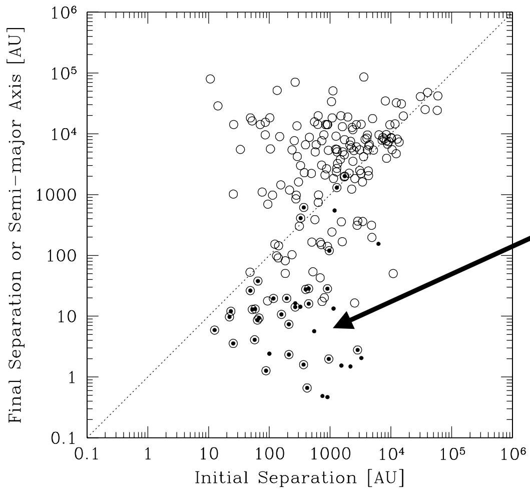
An example of a binary whose disc is stripped and later reformed



Disc evolutionary processes II

- **Disc fragmentation**
  - 10 discs fragment, 6 producing multiple fragments (6,5,3,3,2,2)
  - 25 protostars produced by disc fragmentation (~1/7)
- **Star/disc encounters & disc-assisted capture**
  - Very common: >48 cases
  - Naturally produce multiple systems with misaligned discs
    - (e.g. Bate 2012; Offner et al. 2016)
  - Greatly assist in orbital decay

Final separation semi-major axis vs initial separation (Bate 2012)

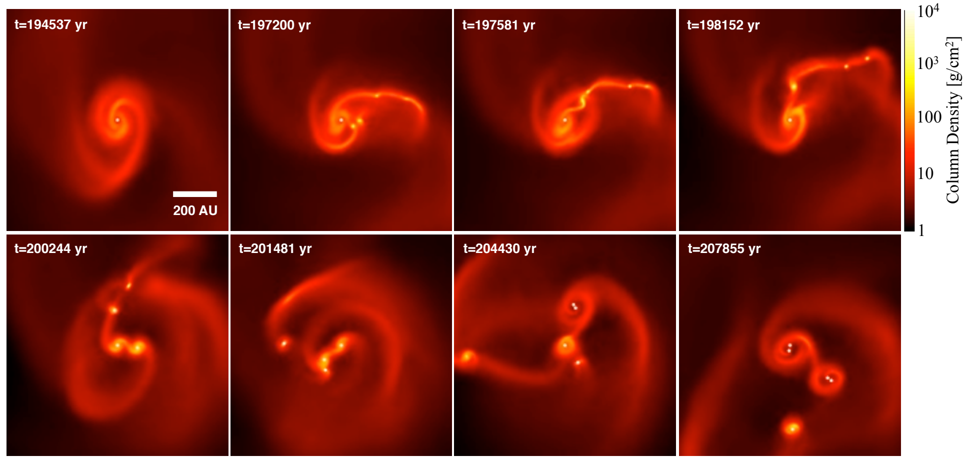


Systems with initial separations <1000 AU usually become much tighter

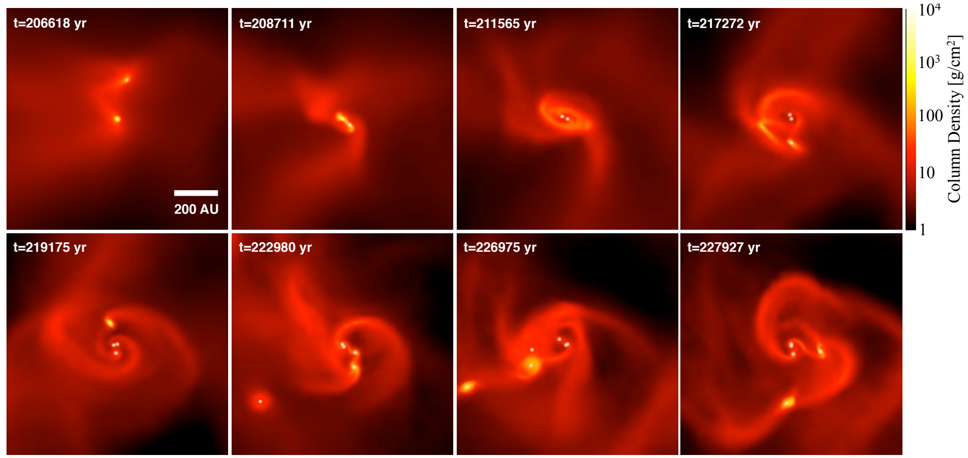
Circles: closest other object at formation, final vs initial distance

Dots: final vs initial separation of binaries

Example of multiple disc fragmentation (Bate 2018)



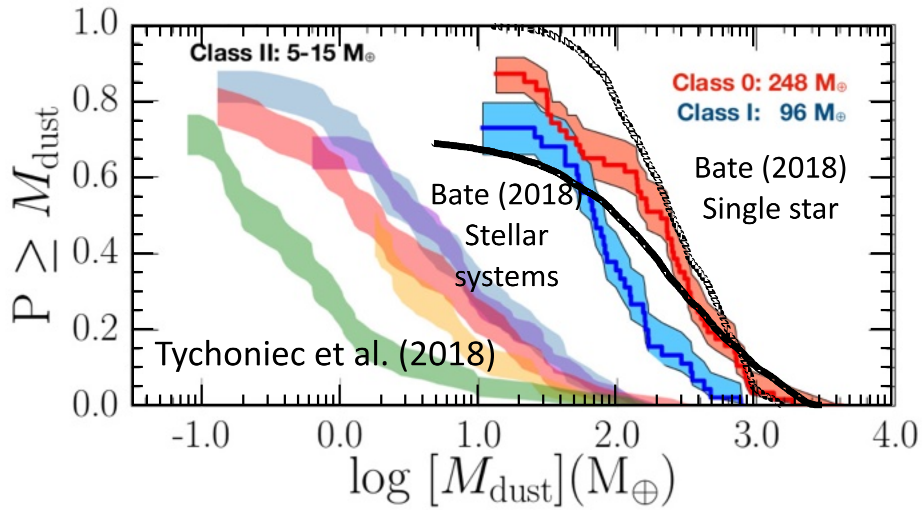
Example of star-disc capture (Bate 2018)



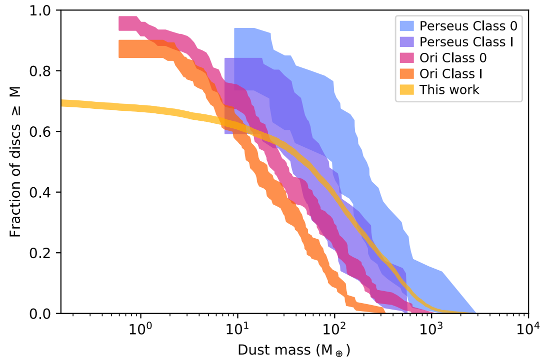
Comparison of disc masses & radii with observations

- **Typical ages of protostars from simulations: ~10^4 yrs (oldest 9×10^4 yrs)**
  - Younger than typical Class II young stars
  - Expect higher discs masses at young ages
- **Protostellar disc masses from observations**
  - Class 0/I disc masses
    - Perseus & Orion using VLA & ALMA (Tychoniec et al. 2018, 2020; Tobin et al. 2020)
  - 30-300 times more massive than Class II discs
    - 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)
- **Disc masses & radii from simulations in good agreement with Class 0/I observed discs**
  - Bate (2018); Elsender & Bate (2021)

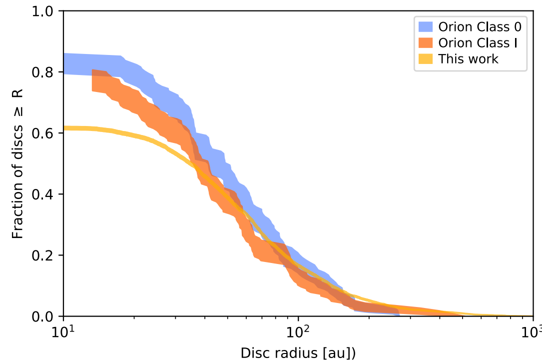
Cumulative disc masses



Cumulative disc masses



Cumulative disc radii



Discs from Bate (2019) analysed by Elsender & Bate (2021)

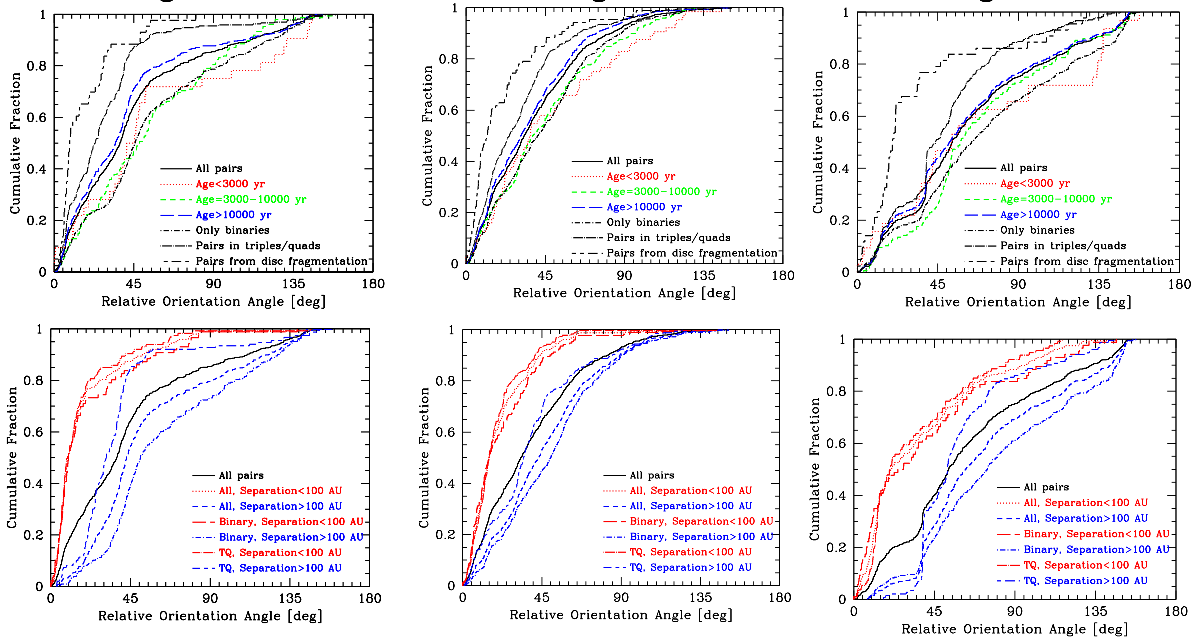
CS Disc-CS disc, CS Disc-orbit mutual alignment (Bate 2012)

- **Disc fragmentation**
  - Similar (well aligned) circumstellar disc-disc, disc-orbit, and spin-spin distributions
- **Overall binaries**
  - Disc-disc and disc-orbit more aligned than spin-spin

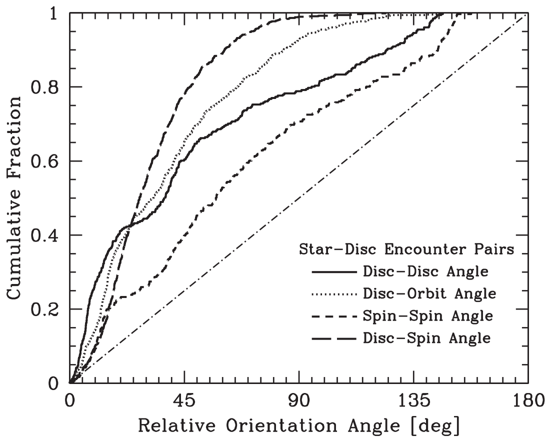
CS Disc - CS Disc alignment

CS Disc - Binary Orbit alignment

Spin - Spin alignment



Binaries formed with star-disc capture (Bate 2012)

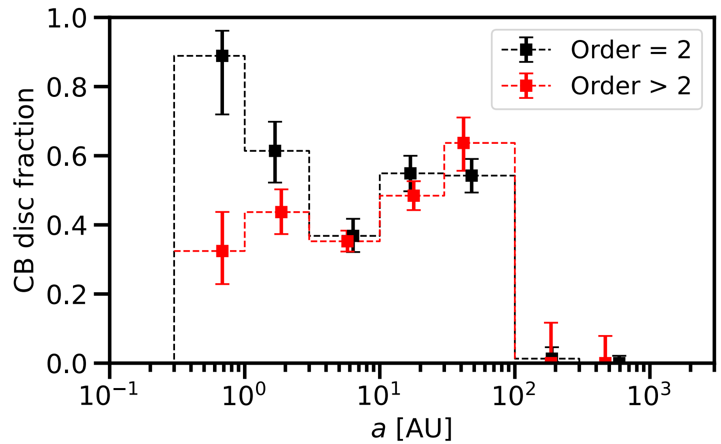


Circumbinary discs?

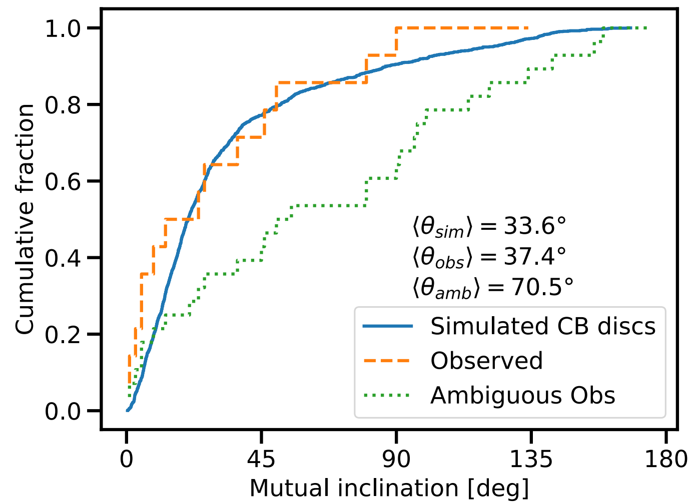
- **Circumbinary discs KITP meeting in spring 2022**
  - What are the properties of circumbinary discs from simulations?

- **Elsender, Bate, Lakeland, Jensen & Lubow (2023)**
  - Examined CB discs from Bate (2019) star cluster calculation
  - No circumbinary discs for binary semi-major axes > 100 au
  - *Young* CB discs common for closer systems
    - Binaries: increasing fraction with decreasing separation
    - Triples/quads: ≈ 1/2 of component binaries have CBD
  - Preference for discs & orbits to be aligned
    - ≈ 2/3 mutual inclinations are < 30°
    - But about 5-10% are retrograde

Frequency of circumbinary discs vs binary separation



Relative inclination of circumbinary disc & binary orbital vectors



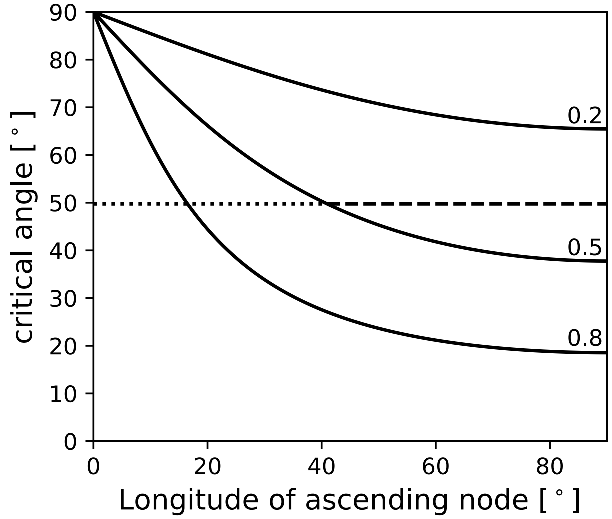
Using polar discs to constrain initial CB disc alignment & binary eccentricity

- **Simone Ceppi, Nicolas Cuello, et al. (2024)**

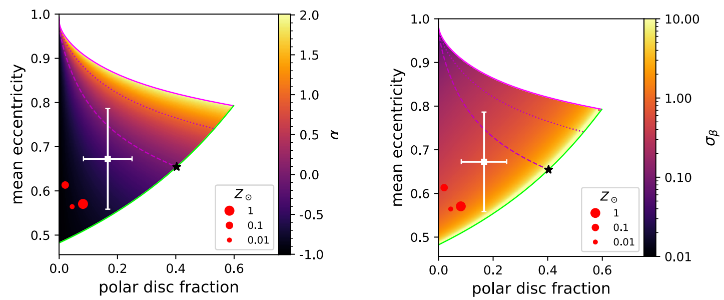
- **Inclined circumbinary discs tend to either**
  - Align with the binary's orbital plane due to viscous dissipation (Bate et al. 2000; Lubow & Ogilvie 2000)
  - Align perpendicular to the binary's orbital plane, if the binary is eccentric and the initial inclination is high enough (Aly et al. 2015; Martin & Lubow 2017, 2019)

- **Can potentiallly use to constrain the initial alignment and eccenticity distributions**
  - Measure the polar disc fraction and the average orbital eccentricity for systems with polar discs
  - Can constrain the distributions of initial eccentricity and mutual inclination in multiple stellar systems at birth

Critical misalignment angle as functions of binary eccentricity and ascending node angle



Constraints on initial inclination distribution $P(\theta) \propto \exp(-\theta/\sigma_B)$ and eccentricity $P(e) \propto e^{\alpha}$



Do stellar properties 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?
- **Early calculations varied only opacities**
  - Myers et al. (2011); Bate (2014) - no strong dependence of IMF on opacity

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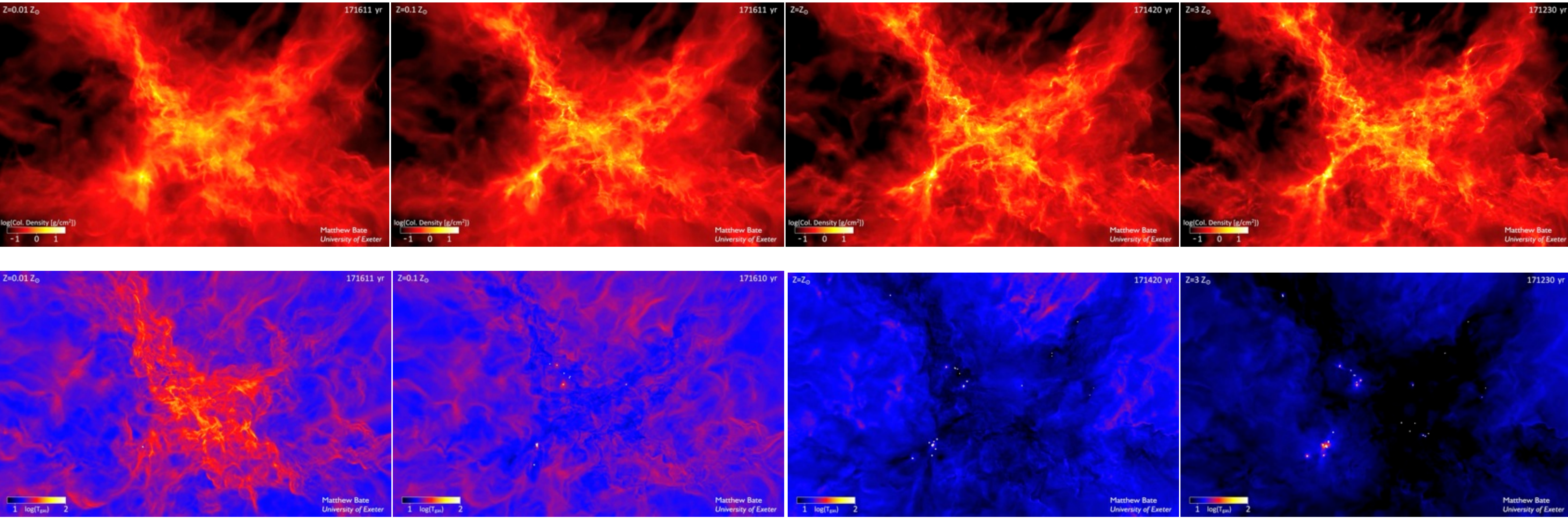
Does star formation vary with metallicity?

Z=0.01 $Z_\odot$ | Z=0.1 $Z_\odot$ | Z=$Z_\odot$ | Z=3 $Z_\odot$

Gas Column Density



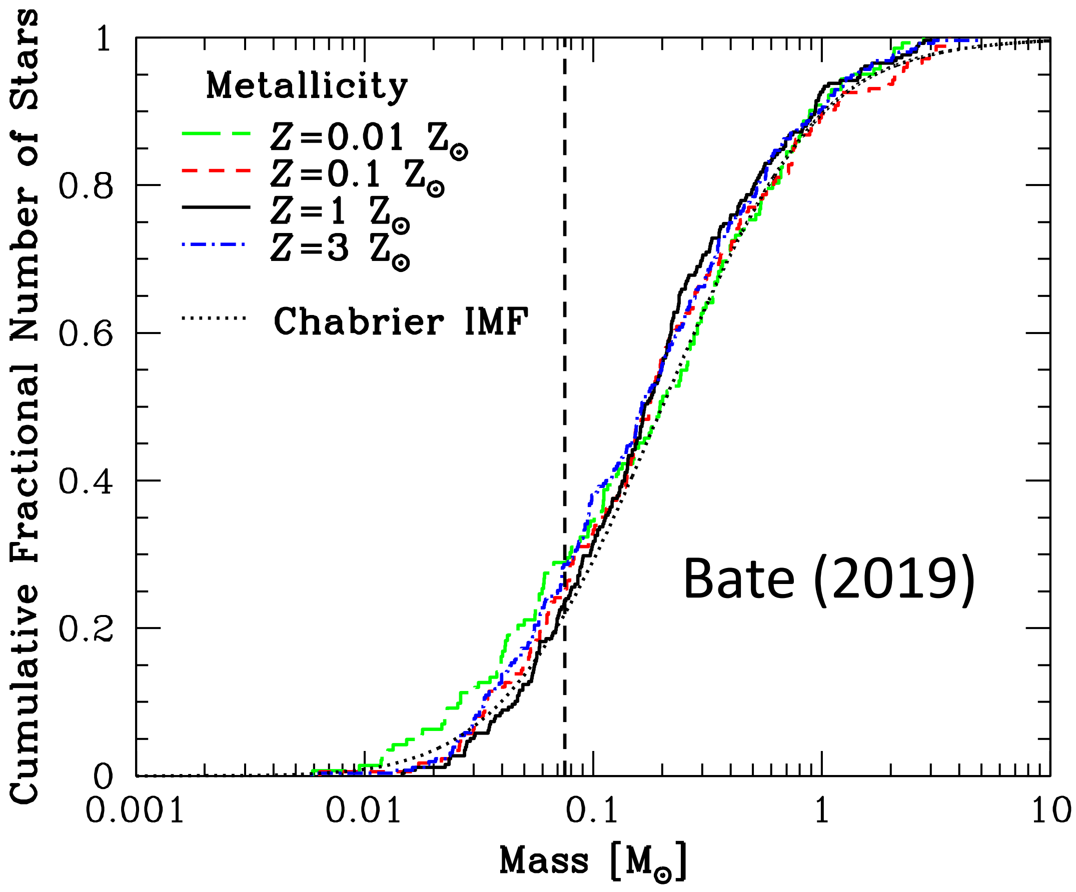
Gas Temperature

Bate (2019)

Does the IMF vary with metallicity?

- **Not for present-day star formation**
- **Why not?**
  - Hotter gas (higher Jeans mass) on large scales
  - Counteracted by lower opacities (stronger cooling) at high densities on small scales
  - Happen to cancel each other out!

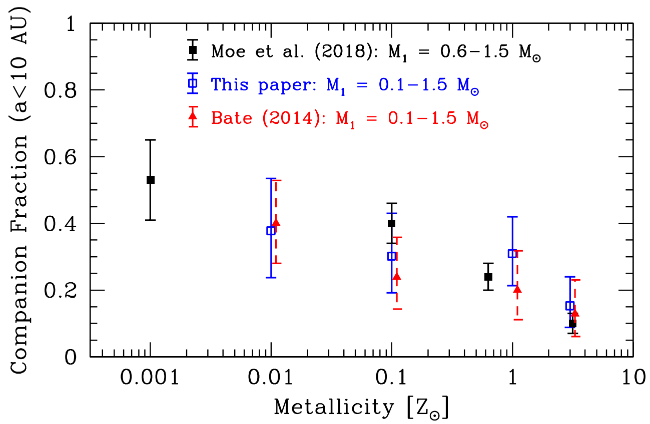
Cumulative protostellar mass function



Metallicity dependence of close binaries

- **Three papers in 2018 found close binary fractions for solar-type stars are anti-correlated with metallicity**
  - Badenes et al. (2018); El-Badry & Rix (2018); Moe, Kratter & Badenes (2019)
- **Anti-correlation is also found in the simulations of Bate (2014, 2019)**
  - Moe et al. (2019) and El-Badry & Rix (2018) both proposed that this was due to increased disc fragmentation at low metallicity
- **In the simulations, two main causes of more close binaries at low metallicity:**
  - More rapid cooling gives shorter first hydrostatic core lifetimes; less likely to merge
  - Lower opacities lead to more small-scale fragmentation in general
    - Core, filament & disc fragmentation

Close binary frequency versus metallicity

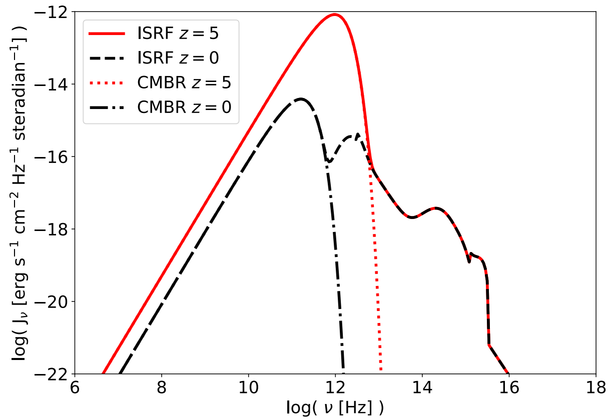


Bate (2019)

Do stellar properties vary with redshift?

- **Primordial star formation**
  - e.g. Bromm et al. 1999; Abel et al. 2000
  - Thought to produce massive stars due to absence of metals and inefficient cooling
  - Present-day star formation: cooling dominated by dust
- **What about star formation at intermediate redshifts & metallicities?**
  - Good reason to assume some change: cosmic microwave background radiation (CMBR) scales as $T_{CMBR}(z) = (1+z)\ T_{CMBR}(z=0)$
  - At z=5, T_{CMBR}=16.4 K, much hotter than present-day molecular clouds
- **Bate (2023): Study star formation at z=5**
  - Assume only CMBR changes (remainder of interstellar radiation field (ISRF) unchanged)
  - Could be stronger (e.g. in starburst environment or near AGN)
  - Perform calculations with metallicites: Z=1, 0.1, 0.01 $Z_{\odot}$

ISRF / CMBR

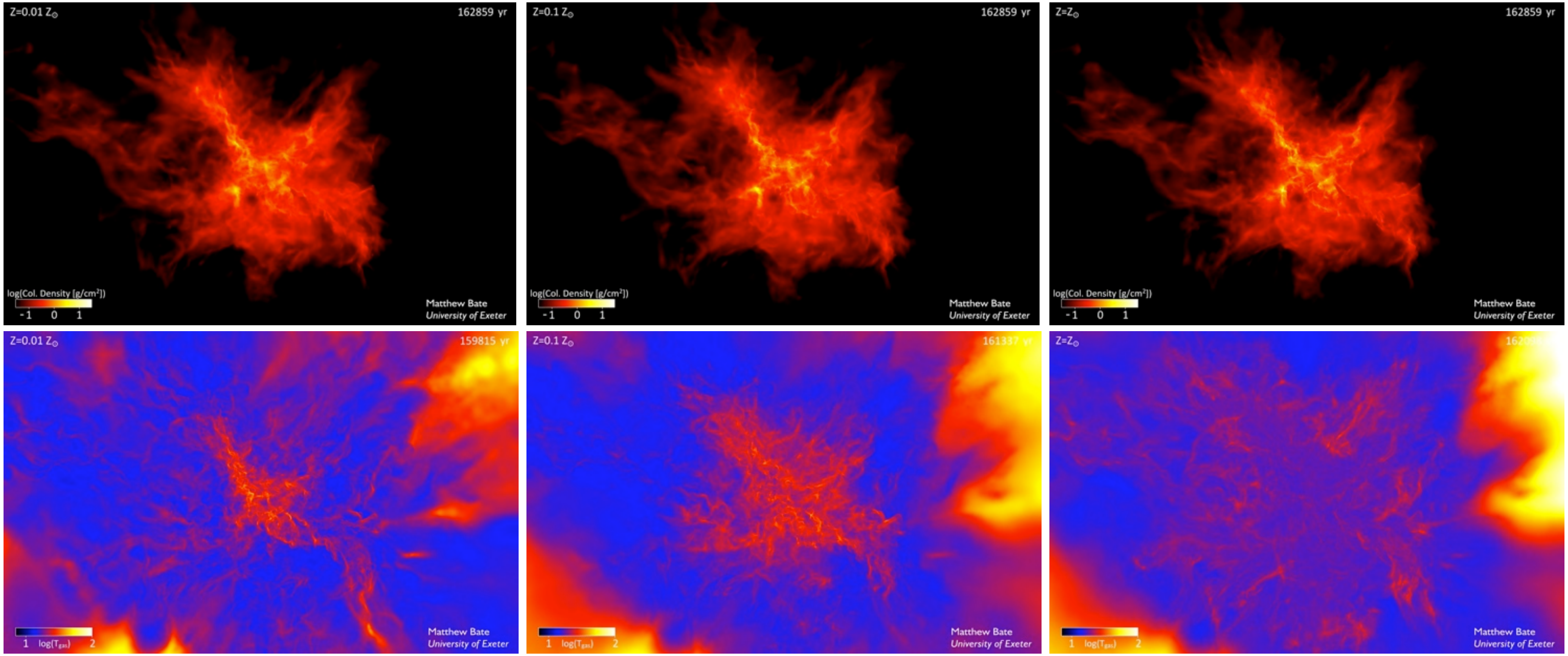


Bate (2023)

Star cluster formation at z=5 and metallicity (Z=0.01-1 $Z_\odot$)

Z=0.01 $Z_\odot$ | Z=0.1 $Z_\odot$ | Z=$Z_\odot$

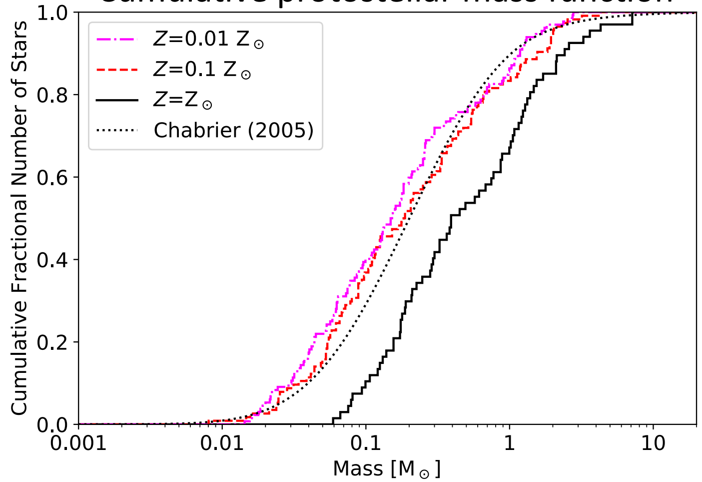
Gas Column Density



Gas Temperature

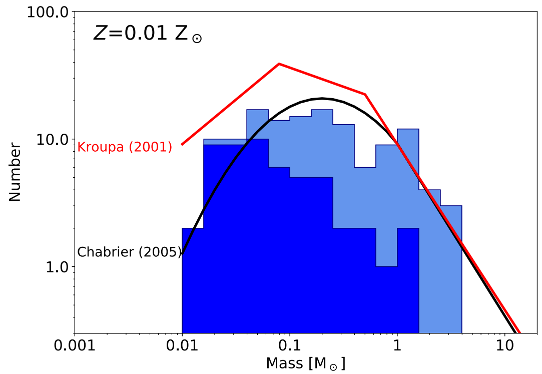
Bate (2023)

RHD simulations of star cluster formation at z=5

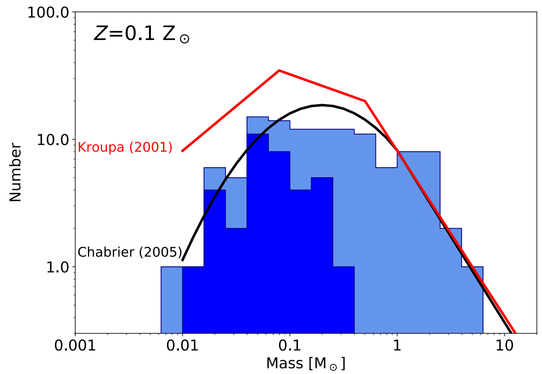


- **IMFs at *z*=5 do depend on metallicity**
  - Low-metallicity ($Z \lesssim 0.1\ Z_\odot$) similar to Chabrier (2005)
  - Solar-metallicity ($Z \approx Z_\odot$) is bottom-light
    - Deficit of low-mass stars and brown dwarfs
    - Characteristic mass ~0.5 $M_\odot$, as opposed to 0.2 $M_\odot$ for present-day
    - Mass-to-light ratio ~10 times smaller $(M/L)_{\mathrm{Chabrier}}$ for $Z \approx Z_\odot$ at z=5 (still assuming Salpeter slope at high-mass)

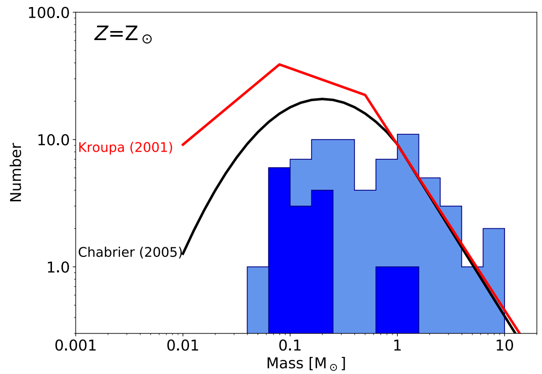
IMF: Z=0.01 $Z_\odot$



IMF: Z=0.1 $Z_\odot$



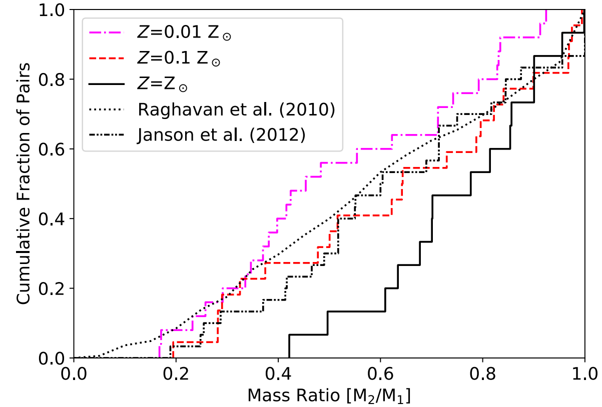
IMF: Z = $Z_\odot$



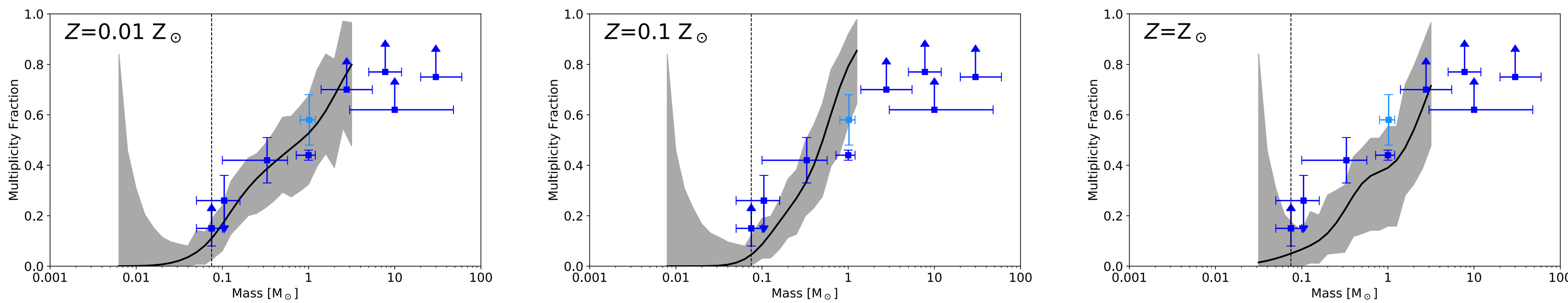
Stellar multiplicity at z=5

- **Weak dependence of multiplicity on metallicity at *z*=5 (Bate 2023)**
  - Multiplicity decreases with increasing metallicity
  - Z=0.01 $Z_\odot$ similar to Galactic IMF
  - Z=1 $Z_\odot$ significantly lower (≈1/2 to 2/3)
- **Mass ratios closer to unity for higher metallicity**
- **Separation distributions similar**

Cumulative binary mass ratio distributions



Stellar multiplicity vs primary mass



Conclusions

- **Formation of circumbinary discs requires accretion of gas with high specific angular momentum**
  - Depends on specific angular momentum profile of molecular cloud cores

- **Close binaries (<10 au separations) cannot form directly**
  - Formed by hardening of wider binaries, through dynamical interations, gas accretion, and interaction with circumbinary discs
  - Anti-correlation of frequency with metallicity, due to enhanced small-scale fragmentation and more rapid cooling of first hydrostatic cores at low metallicity

- **Young discs in radiation hydrodynamical simulations of star cluster formation**
  - Properties in good agreement with observations (masses, radii, orientations)
  - Sculpted by accretion, dynamical interations (magnetic fields do not seem necessary)

- **Circumbinary discs**
  - (Young) discs around binaries with separations <100 au common, >100 very rare
  - Tend to be aligned with binary's orbital plan (~80% within 45^{o})