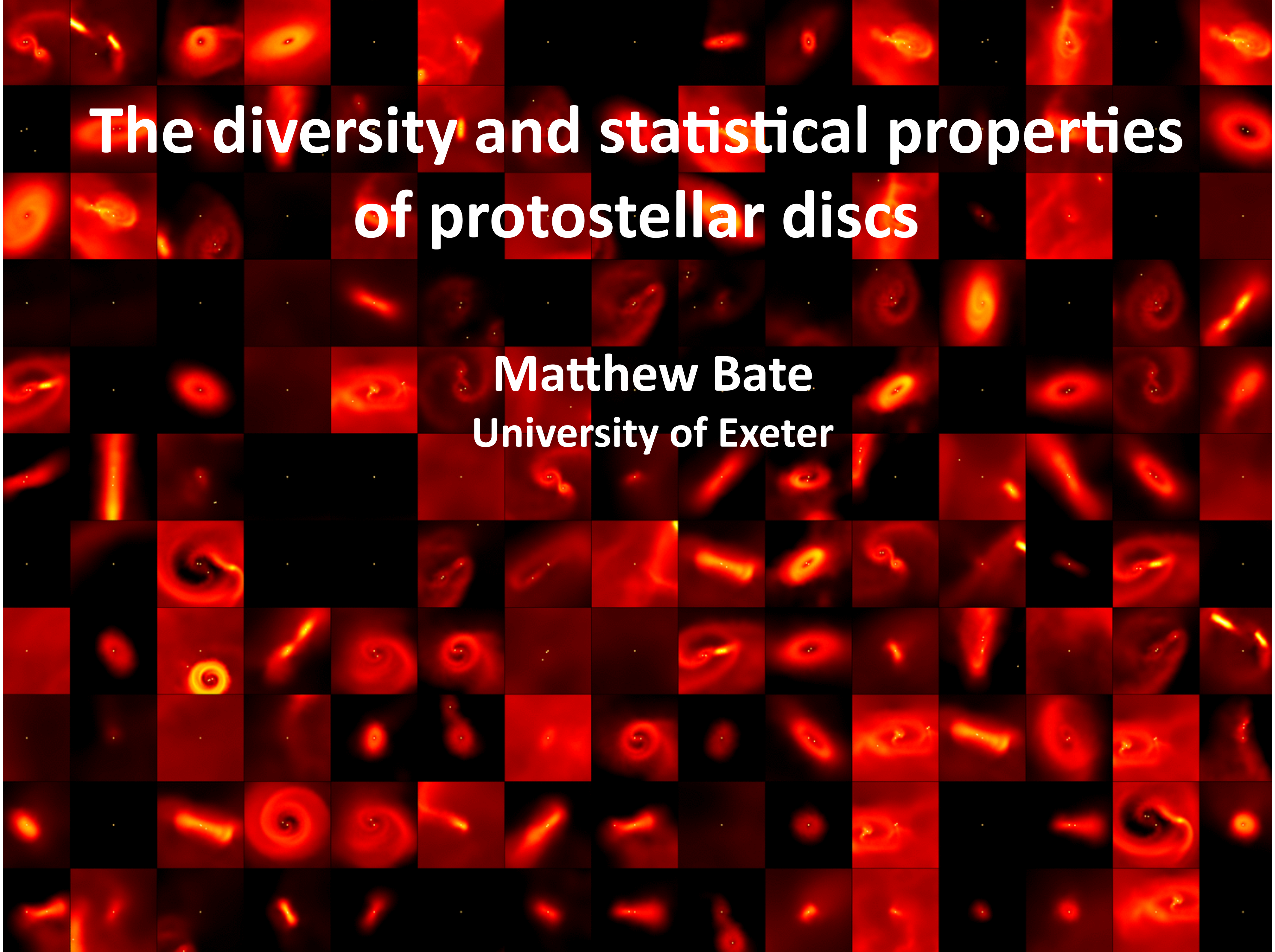
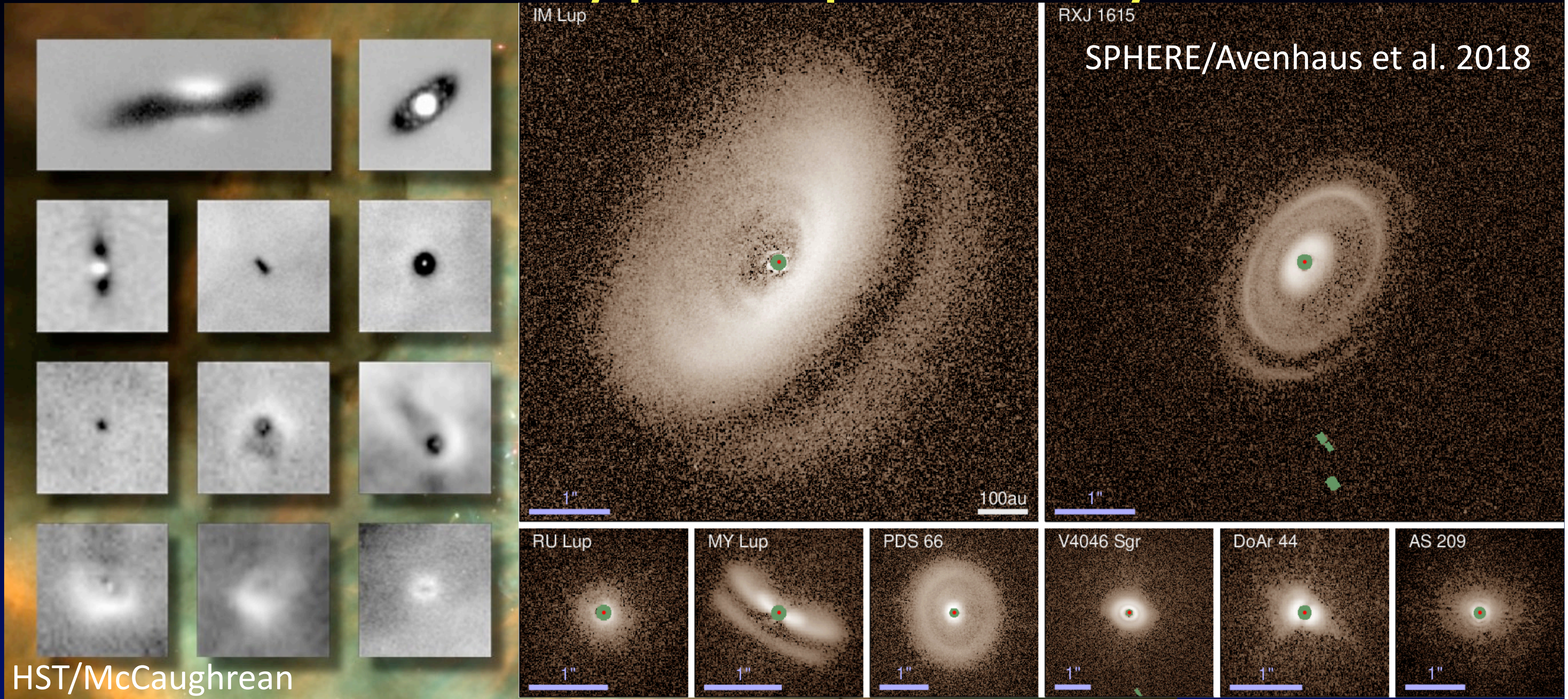


The diversity and statistical properties of protostellar discs

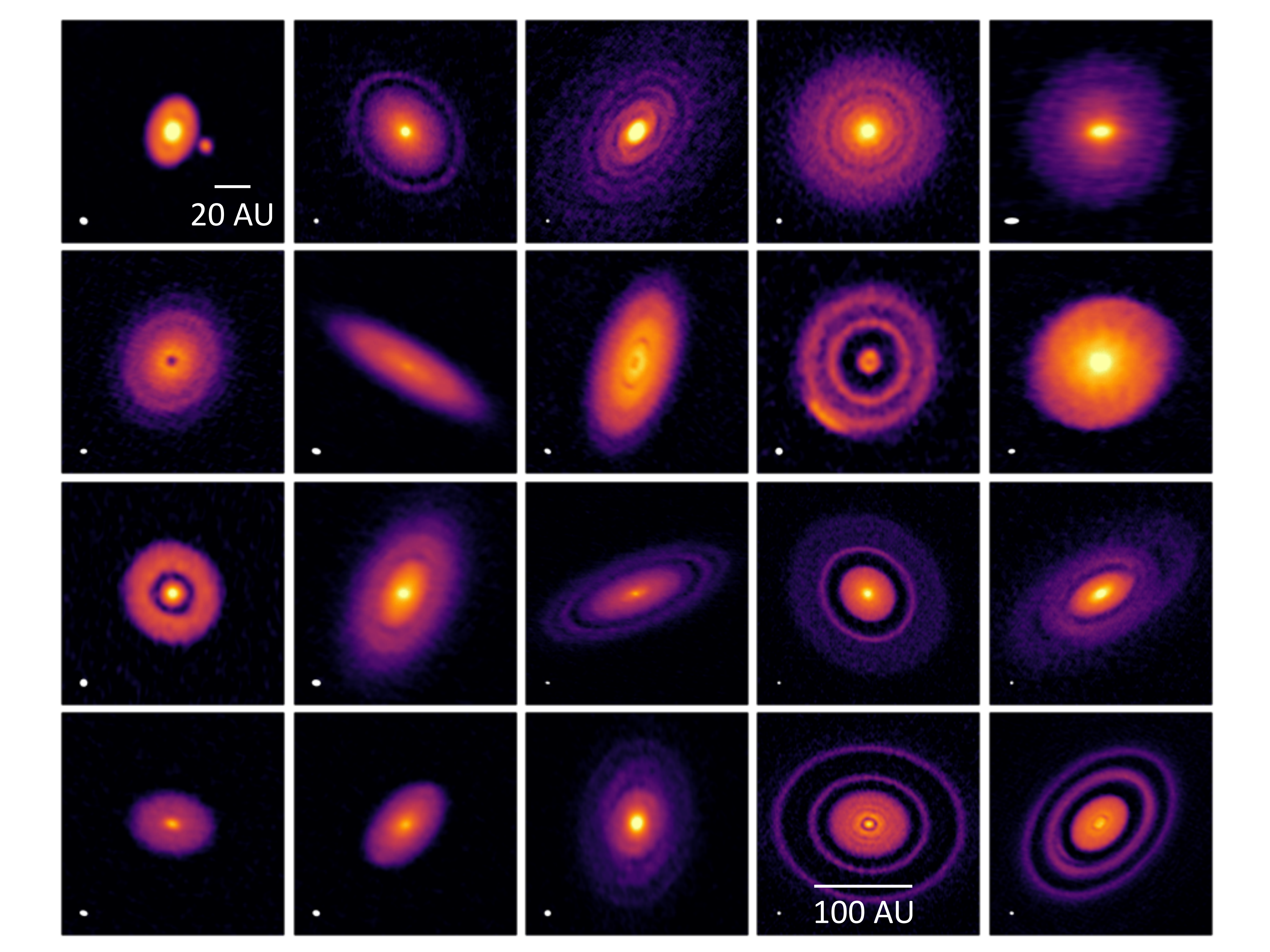
Matthew Bate
University of Exeter

Protostellar/protoplanetary discs



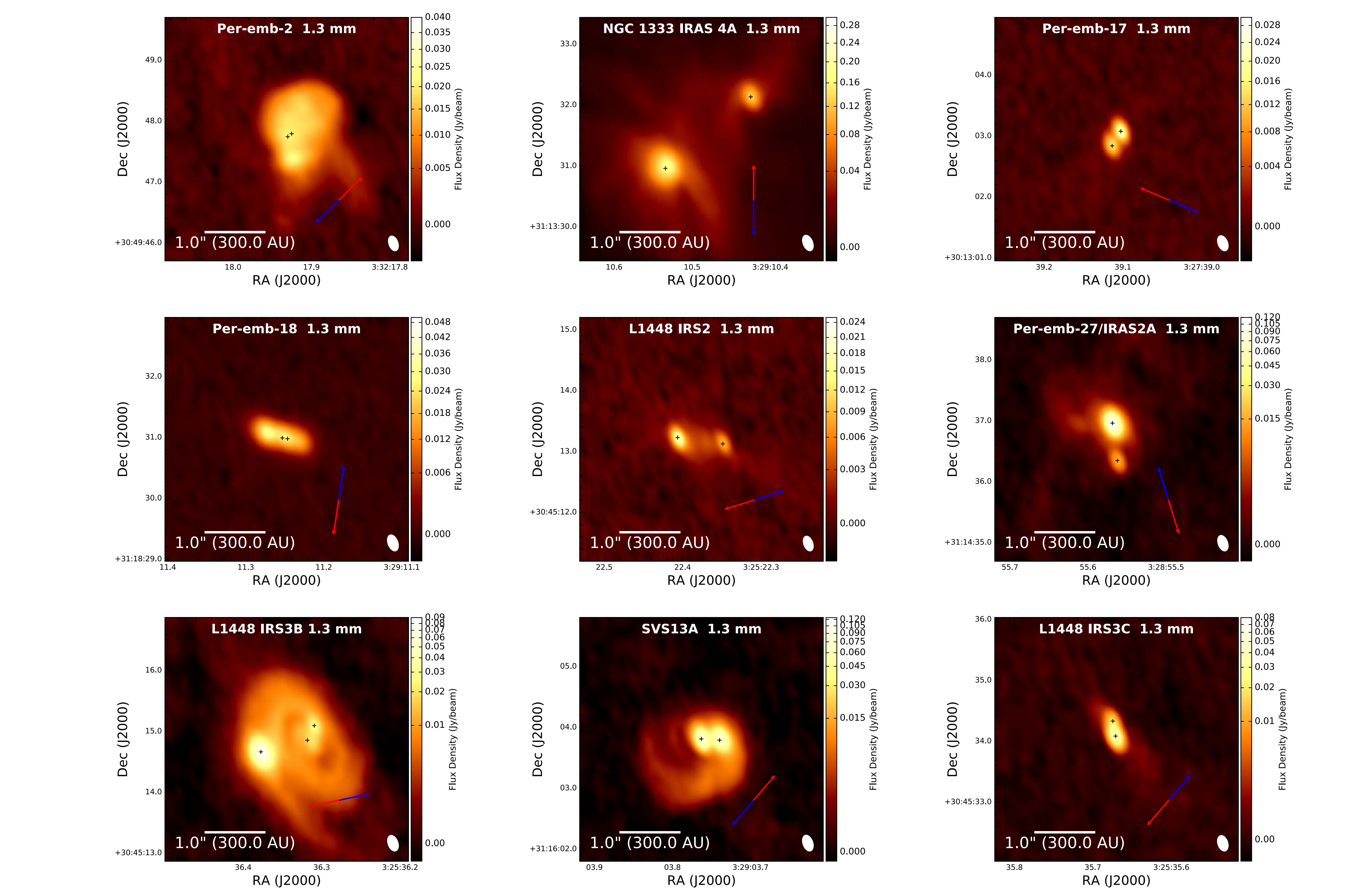
- VLT/SPHERE and GPI are now providing well resolved scattered light images of discs
- Millimetre observations can measure masses, kinematics, sizes
  - e.g. Beckwith et al. 1990; Dutrey et al. 1994, 1996, 1998; Saito et al. 1995
  - ALMA is now providing large samples of well resolved discs

ALMA images of discs in nearby star forming regions



DSHARP ALMA Large Program; Andrews et al. 2018

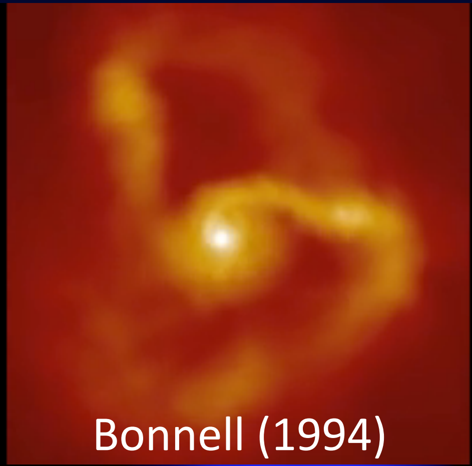
ALMA images of Class 0 multiple systems

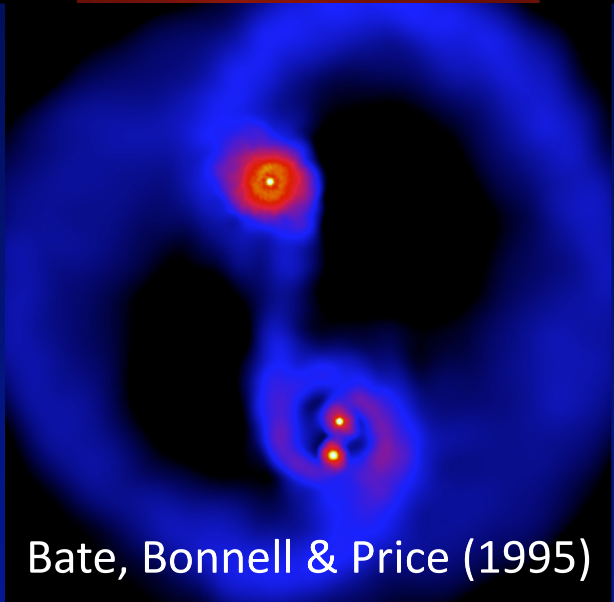


VANDAM Survey; Tobin et al. 2018

Models of disc formation

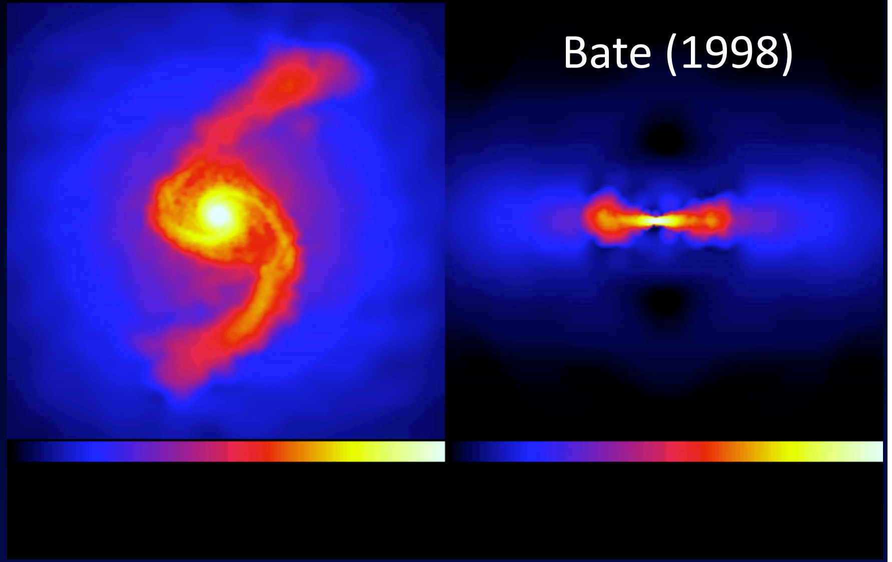
- Hydrodynamical simulations
  - Tscharnuter 1975; Boss 1987; Chapman et al. 1992; Bonnell 1994; Bate, Bonnell & Price 1995
- Focussed more on binary and multiple formation than disc properties
  - Disc fragmentation: Bonnell 1994; Bonnell & Bate 1994a,b; Hennebelle et al. 1995; Kratter et al. 2006, 2010
  - Gravitationally unstable discs: Laughlin & Bodenheimer (19
- Single, binary, multiple star formation
  - Disc properties depend entirely on initial conditions:
    - Initial density structure, rotation, etc

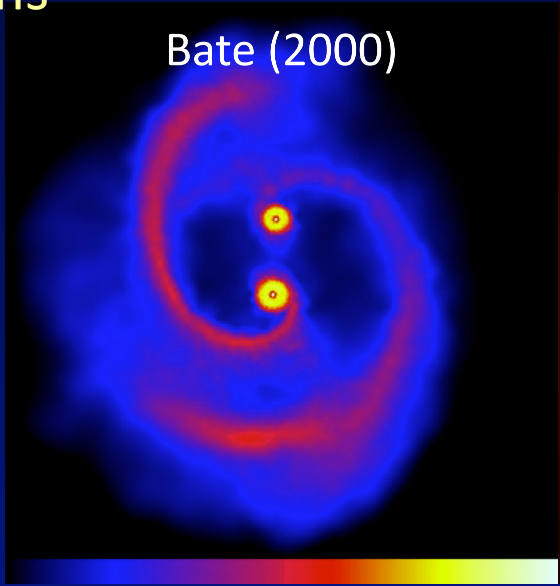

Bonnell (1994)

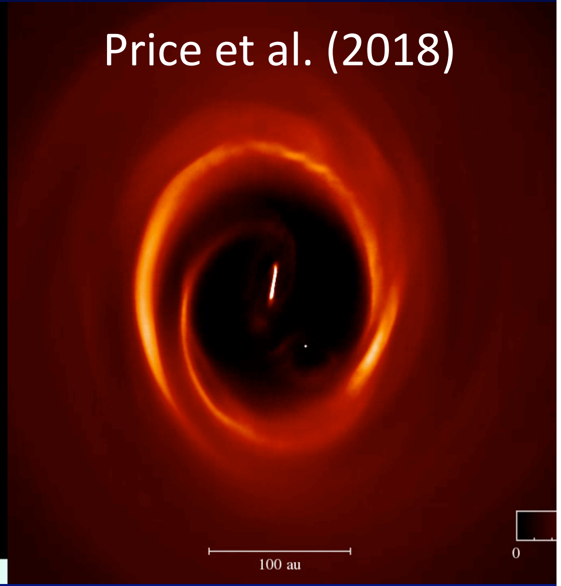

Bate, Bonnell & Price (1995)

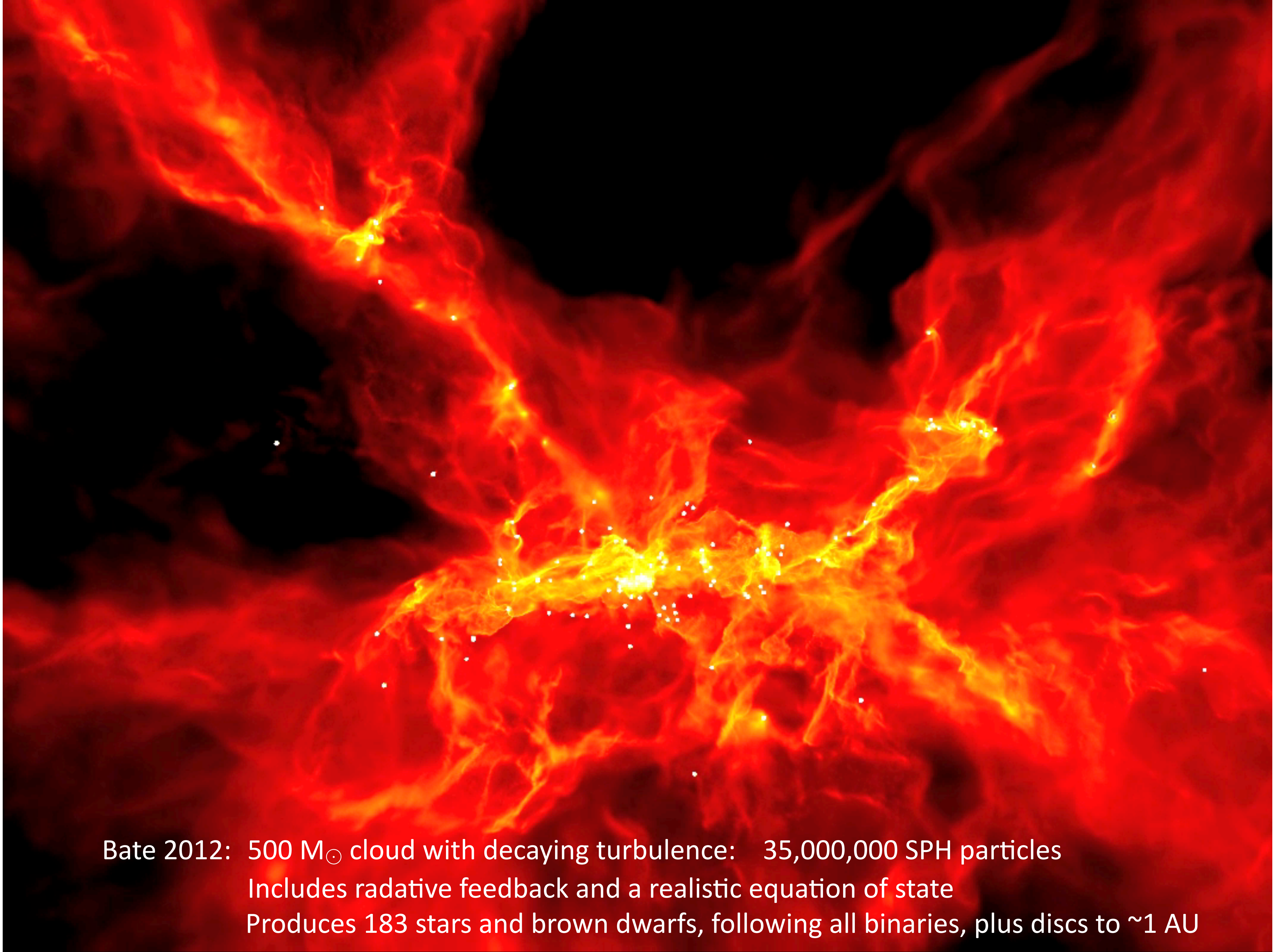
Models of disc formation

- Discs can form early, even before the star
  - Rotating first hydrostatic core disc-like
  - Bate 1998, 2011; Saigo & Tomisaka 2006; Machida et al. 2010
- We can follow the long-term dynamical evolution of discs in multiple systems
  - e.g. Bate 2000; Price et al. 2018
- Star cluster-scale calculations
  - Most employ sink particles with sizes ~100 AU, so don't resolve discs
  - Exceptions (sinks <10 AU): Bate et al. 2003-2005; Offner et al. 2008, 2009; Bate 2009-2019





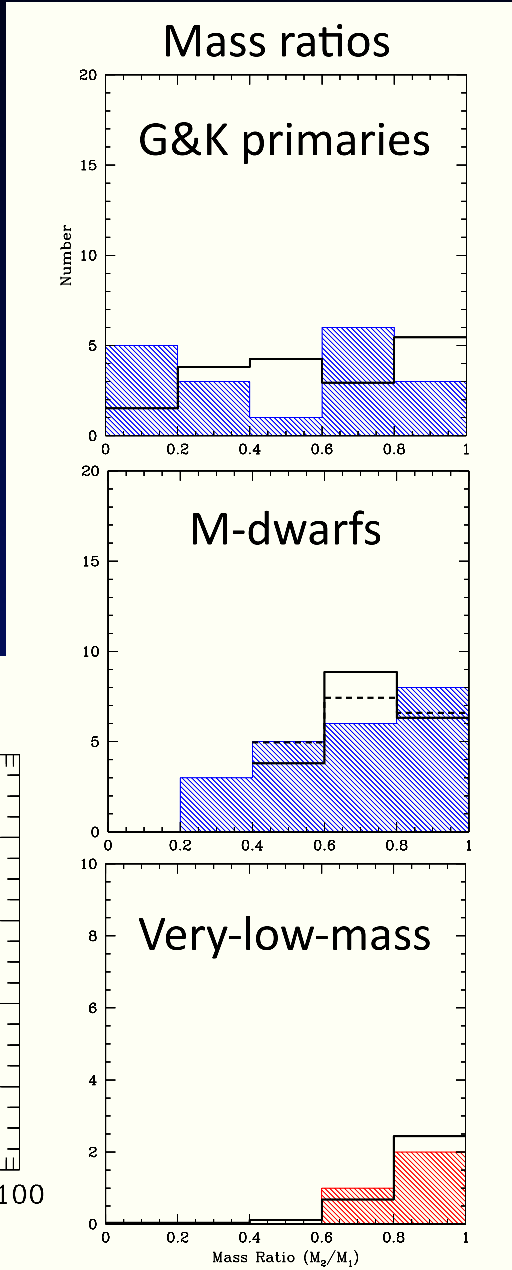


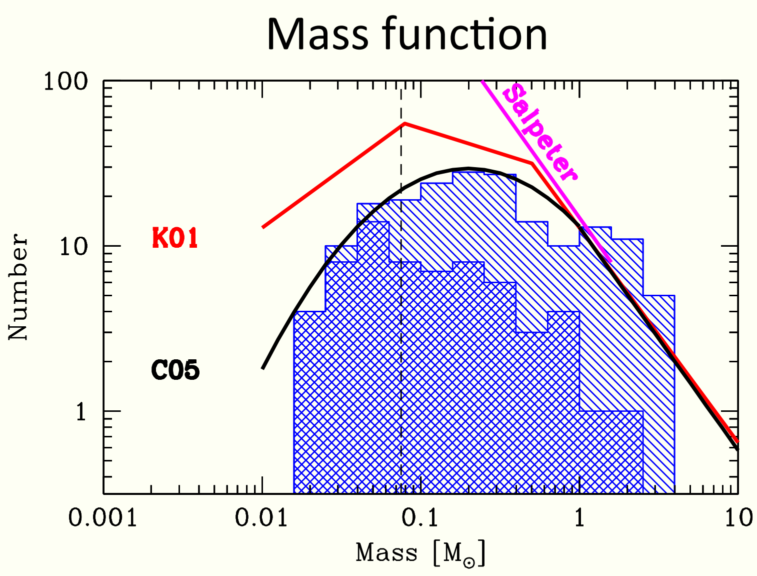


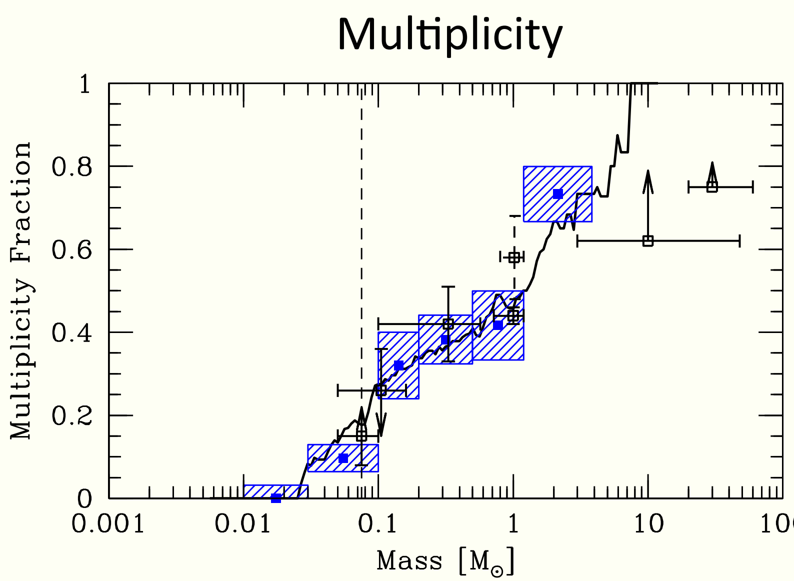
Bate 2012: 500 $M_{\odot}$ cloud with decaying turbulence: 35,000,000 SPH particles
Includes radative feedback and a realistic equation of state
Produces 183 stars and brown dwarfs, following all binaries, plus discs to ~1 AU

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





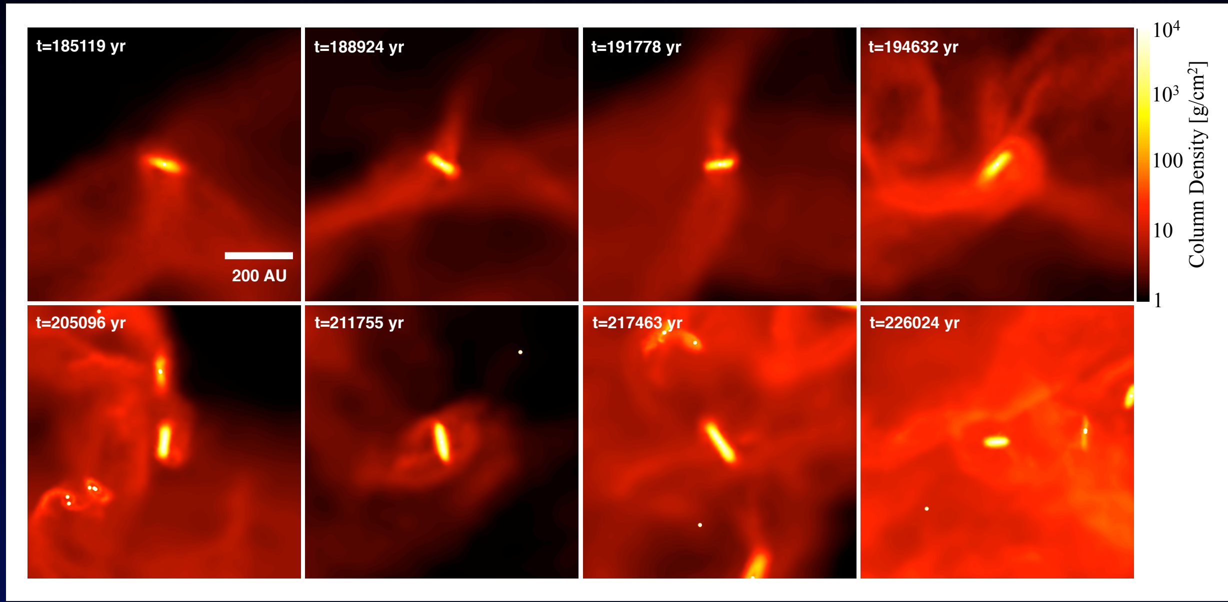


Population synthesis of discs (Bate 2018)

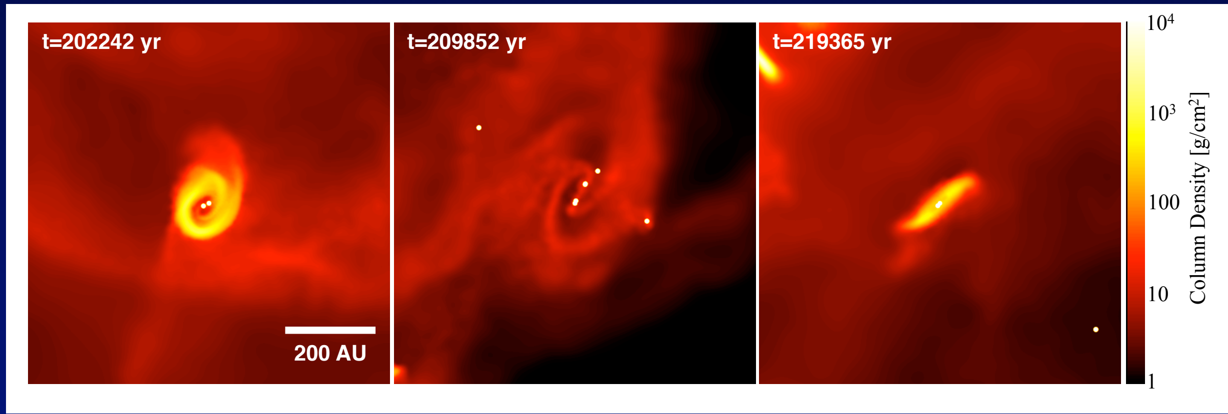
- Bate (2012) radiation hydrodynamical cluster formation calculation
  - Produced 183 stars and brown dwarfs, realistic mass function and multiple systems
  - Sink particle radii 0.5 AU: small enough to resolve most discs
- Limitations
  - SPH calculations resolution depends on mass - low-mass discs poorly resolved
  - Discs only modelled up to 10^5 yrs, most ~10^4 yrs (i.e. Class 0/I rather than Class II)

Disc evolutionary processes I

- Accretion
  - Disc reorientation: 220º
  - 10 cases of substantial reorientation

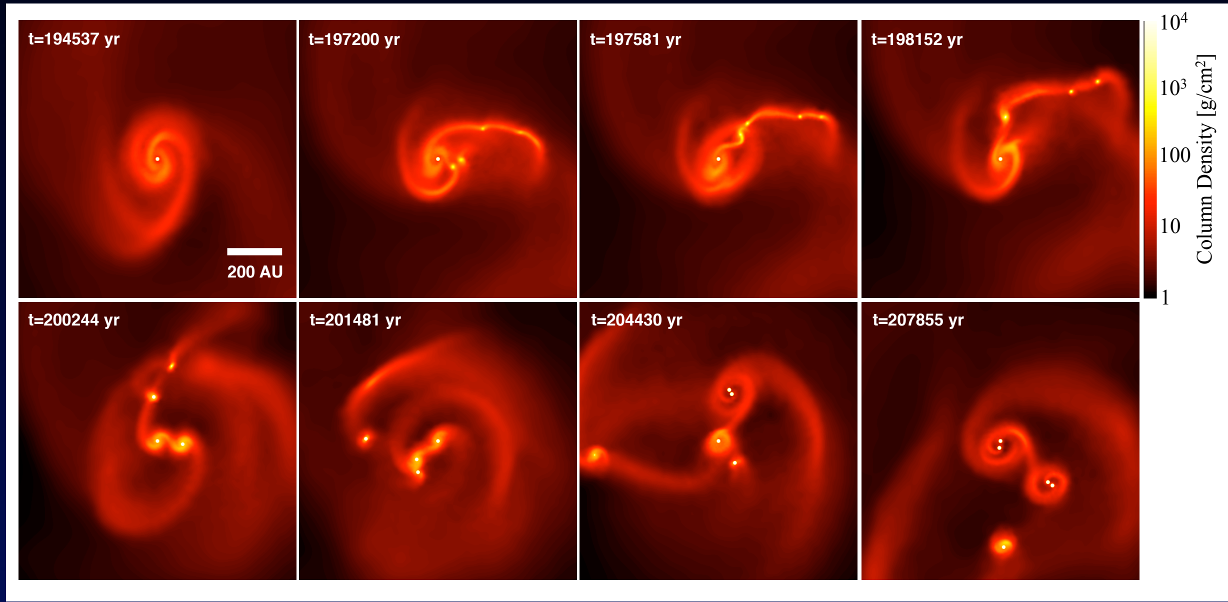


- Erosion/stripping
  - Ram-pressure stripping: 7 discs
  - Dynamical encounters: 26 discs
  - Combination: 18 discs
  - Several cases of stripped discs reforming by later accretion
  - Detailed studies: Moeckel & Throop 2009; Wijnen et al. 2016, 2017a,b



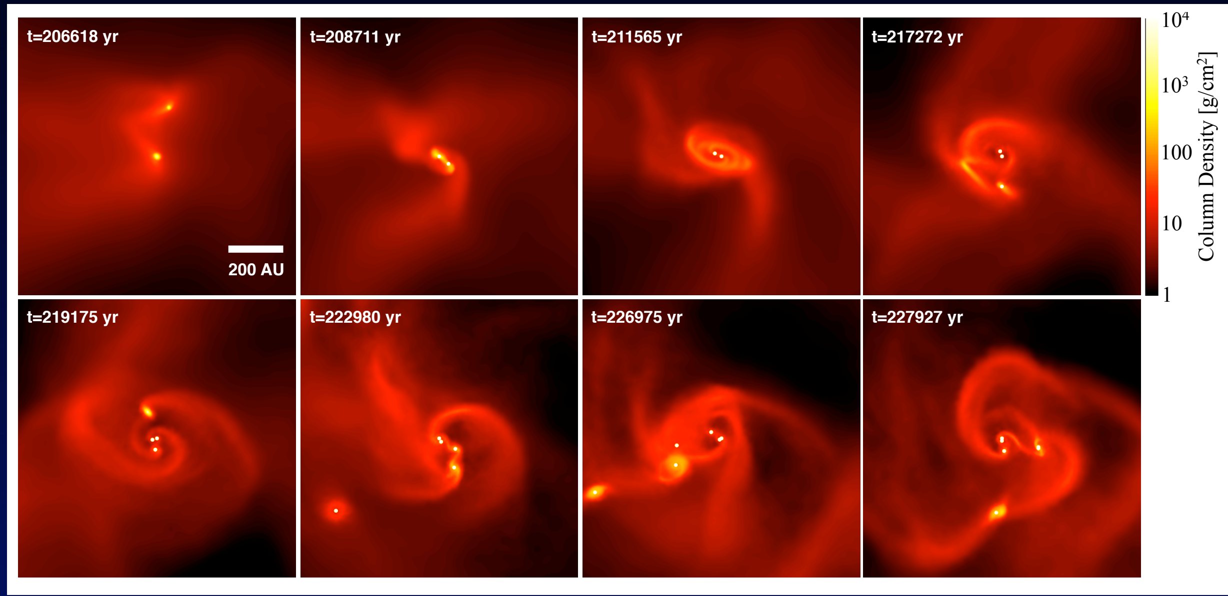
Disc evolutionary processes II

- Disc fragmentation
  - 10 discs fragment
  - 6 produce multiple fragments (6,5,3,3,2,2)
  - 25 protostars produced by disc fragmentation (~1/7)

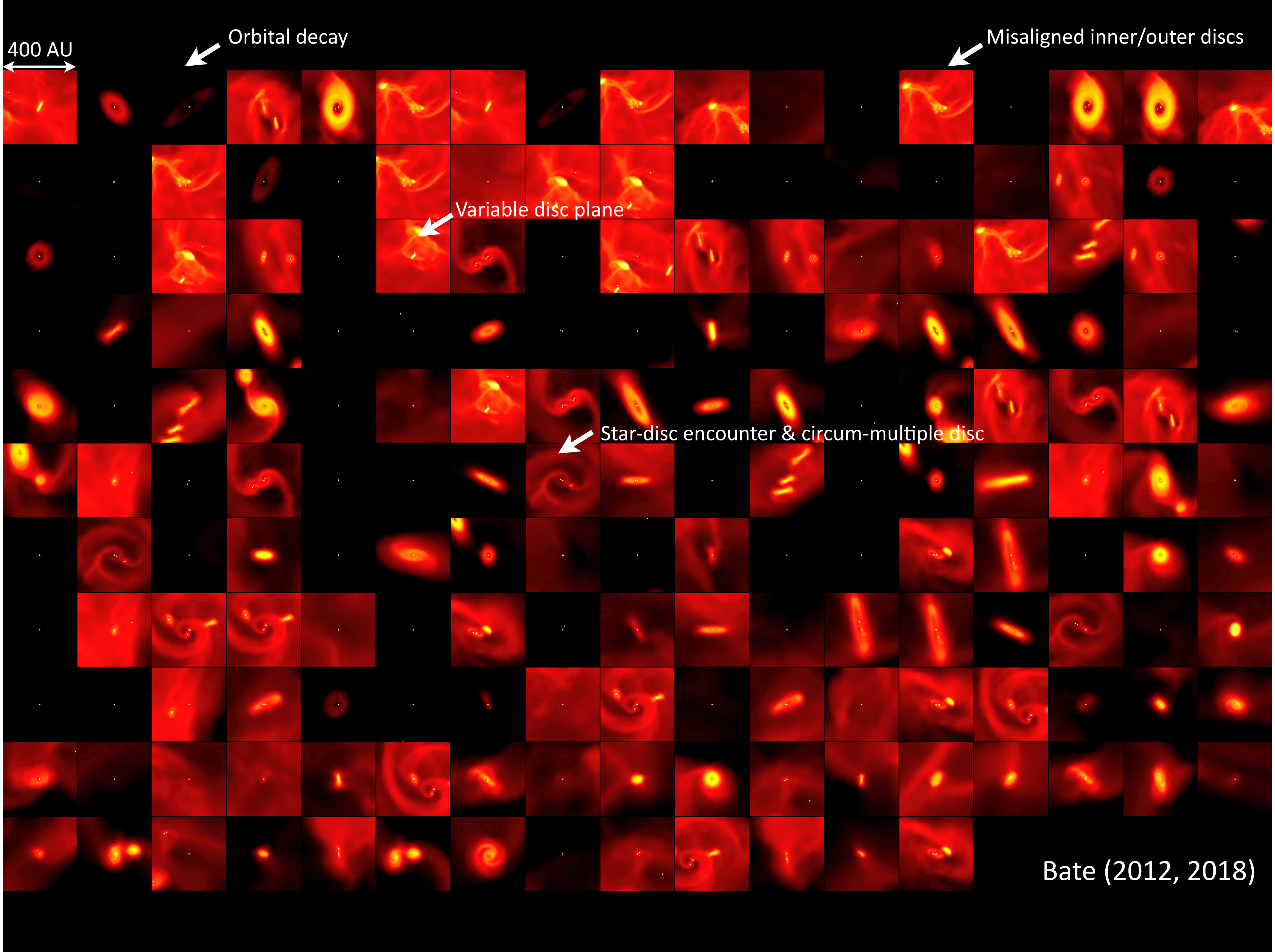


Disc evolutionary processes III

- Star-disc encounters and disc-assisted capture
  - Very common: >48 cases
  - Naturally produce multiple systems with misaligned discs (e.g. Bate 2012, Offner et al. 2016)



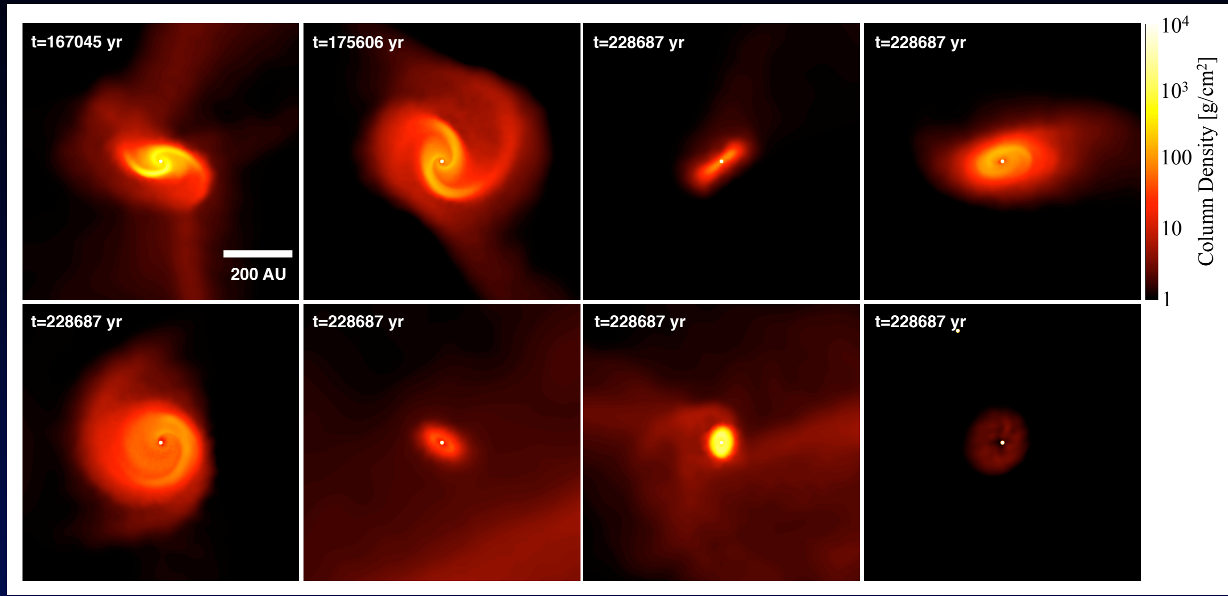
- Other studies of star-disc encounters and capture
  - Clarke & Pringle (1991) concluded rates too low for significant binary formation
  - But assumed virialised groups/clusters
  - Gas velocity dispersions (protostars) ~1/3 of older stellar populations (Bate et al. 2003; Andre et al. 2007; Foster et al. 2015; Rigliaco et al. 2016; Sacco et al. 2017)
  - Detailed star-disc simulations: Hall et al. (1996); Moeckel & Bally (2006)



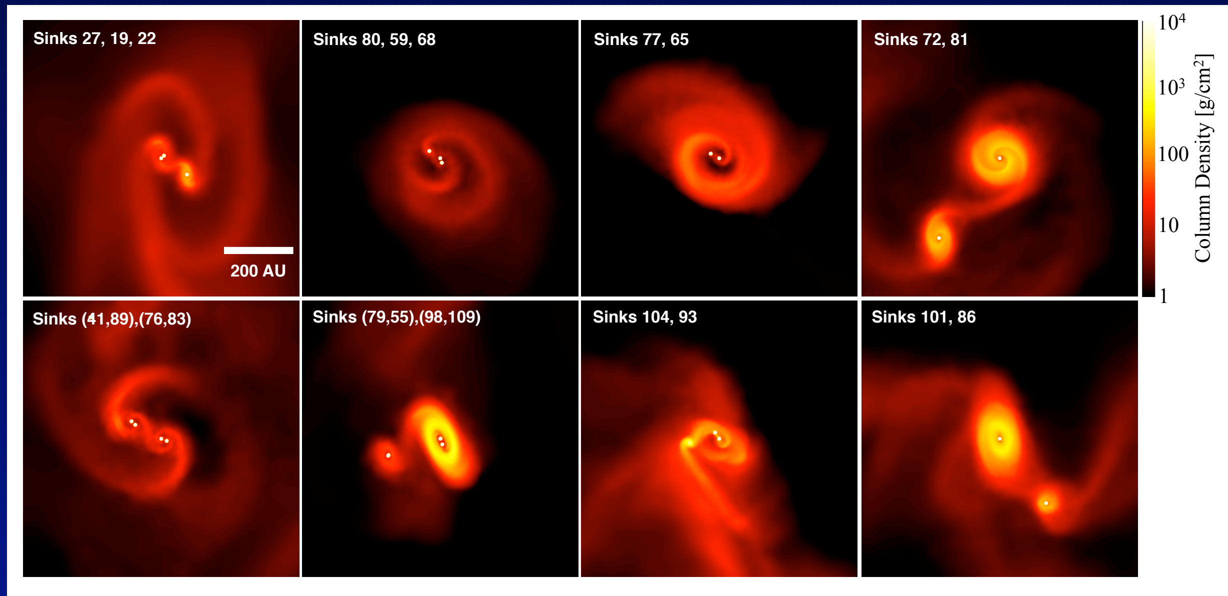
400 AU
Orbital decay
Misaligned inner/outer discs
Variable disc plane
Star-disc encounter & circum-multiple disc
Bate (2012, 2018)

Types of disc

- Discs of single protostars
  - May be gravitationally unstable (spiral structures)

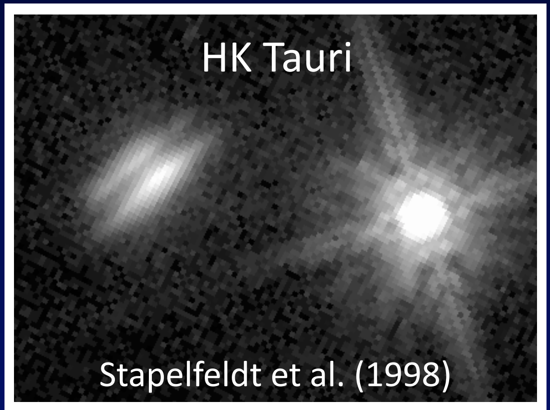


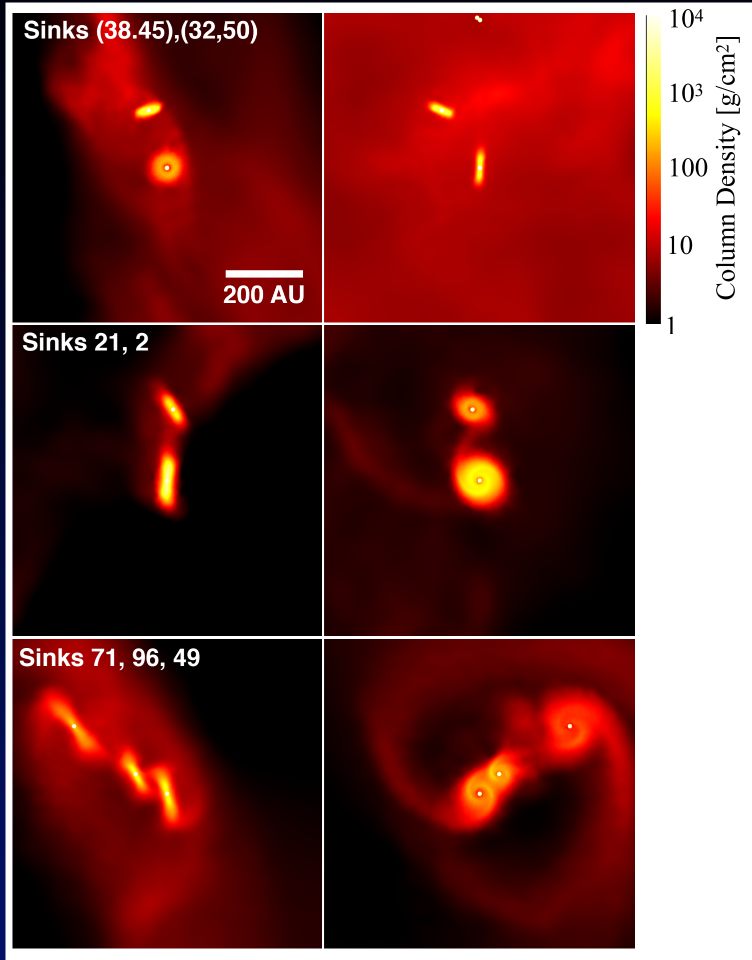
- Discs of multiple systems
  - Binaries: 2 circumstellar discs, & a circumbinary disc
  - Triples: up to 5 discs: 3 circumstellar, a circumbinary, & a circum-triple disc
  - Quadruples: up to 7 discs !
  - May have spiral structure due to torques
  - May be misaligned with each other and/or with orbit(s)



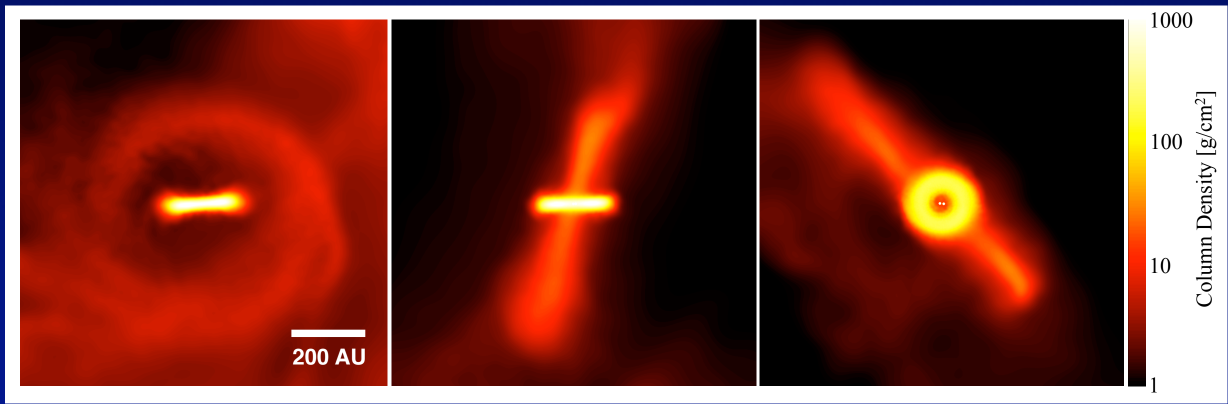
Disc (mis)aligment

- Discs of multiple protostars
  - 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



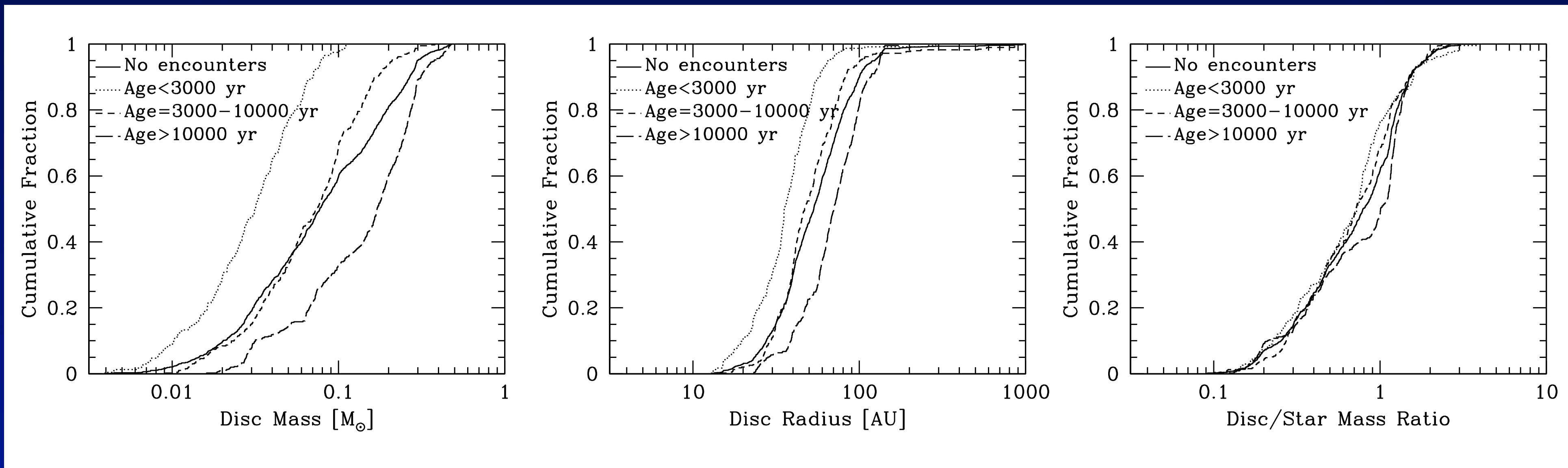


- One `broken' disc
  - Inner disc and outer disc are misaligned by 75º
  - Outer disc formed later by accretion of new gas



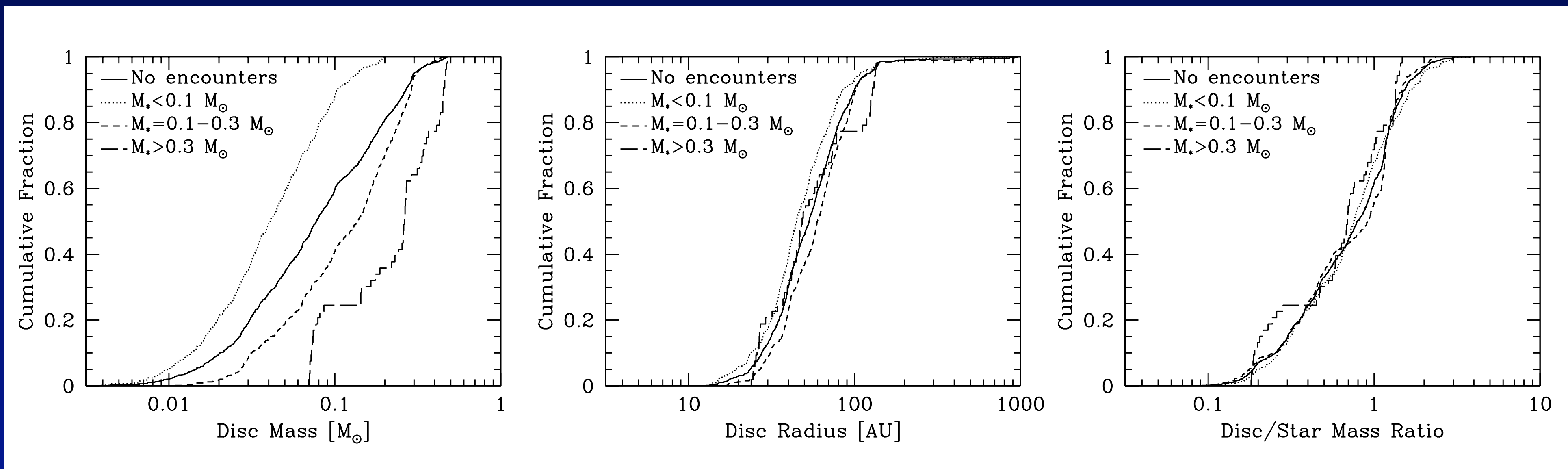
Properties of circumstellar discs: age

- Single protostars that have never had an encounter
  - Disc masses and radii increase with age (< 3x10^4 yrs)
  - Disc/star mass ratio distribution independent of age: star and disc grow together
- For all protostellar discs
  - Fraction of disc-less protostars increases with time (mainly due to interactions)



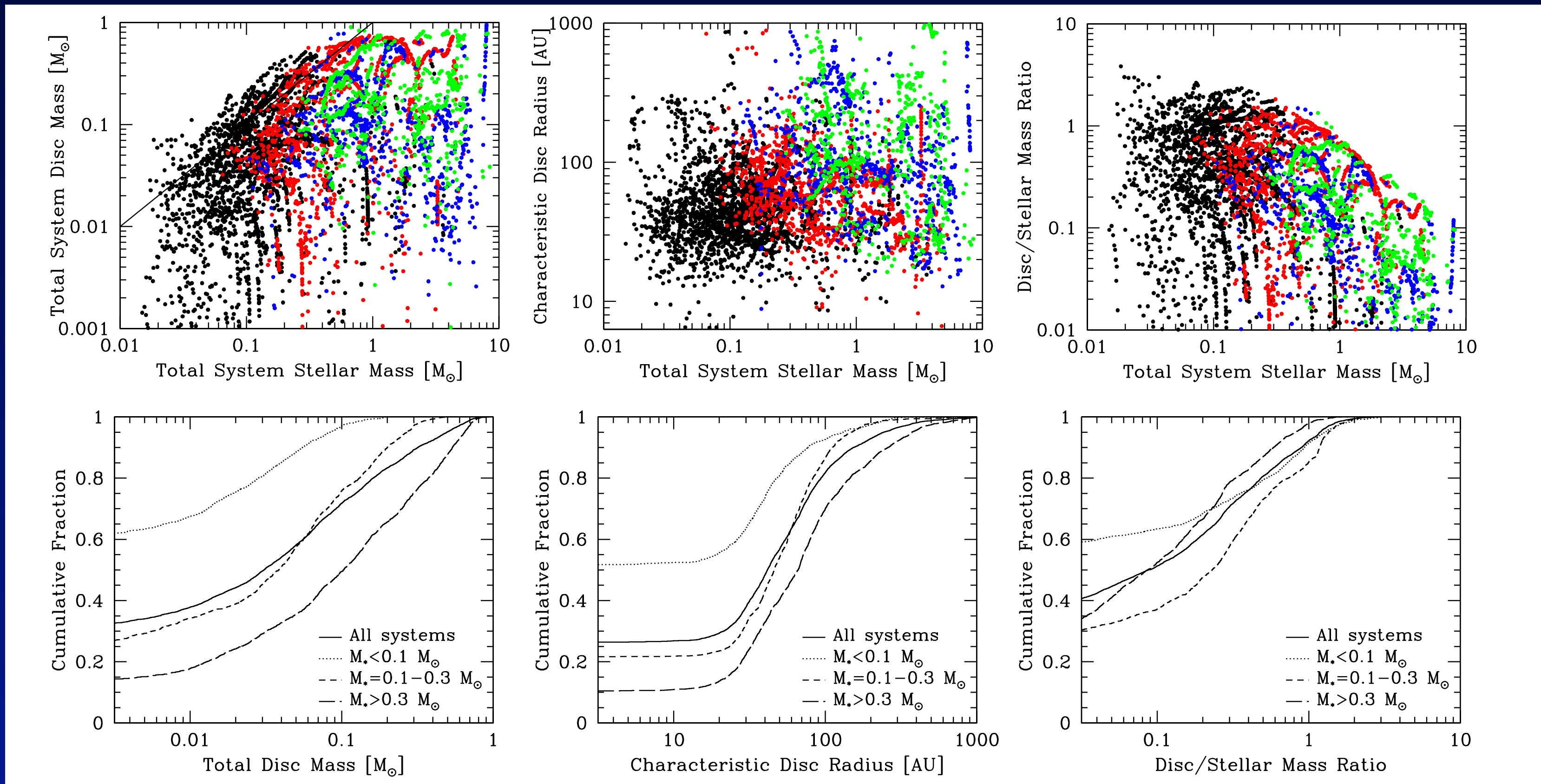
Properties of circumstellar discs: star mass

- Single protostars that have never had an encounter
  - Disc masses are larger for greater stellar mass
  - Disc radius does not depend greatly on stellar mass
  - Disc/star mass ratio distribution independent of stellar mass
- Surface density profiles of discs of single protostars
  - Flatter ($\Sigma(r) \propto r^{-1}$) than the Minimum Mass Solar Nebula (MMSN) model ($\Sigma(r) \propto r^{-3/2}$)



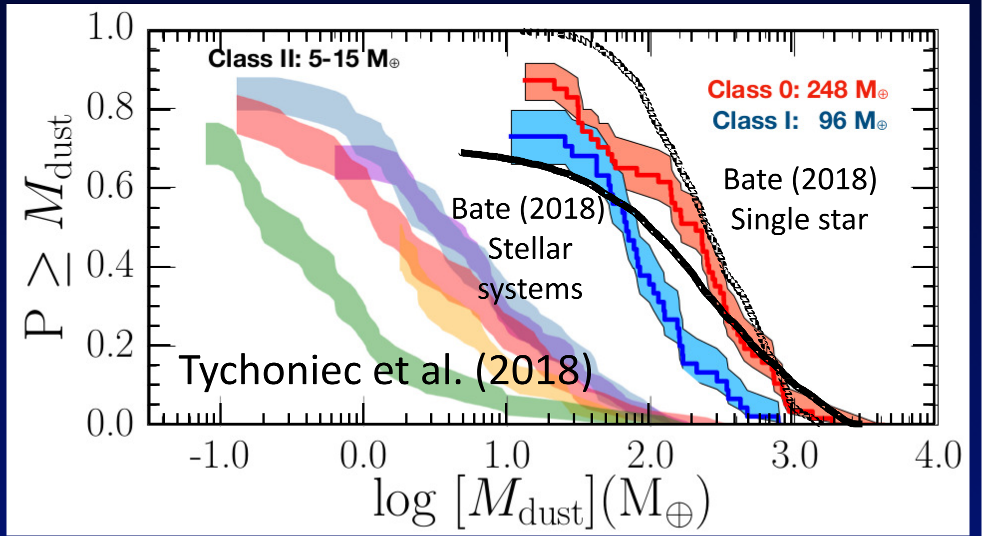
Properties of discs of systems: star mass

- Disc masses increase linearly with stellar mass to ~0.5 M$_\odot$
- Disc radii increase weakly with stellar mass
- Disc/star mass ratios similar for <0.5 M$_\odot$
  - Decrease roughly linearly for stellar masses >0.5 M$_\odot$



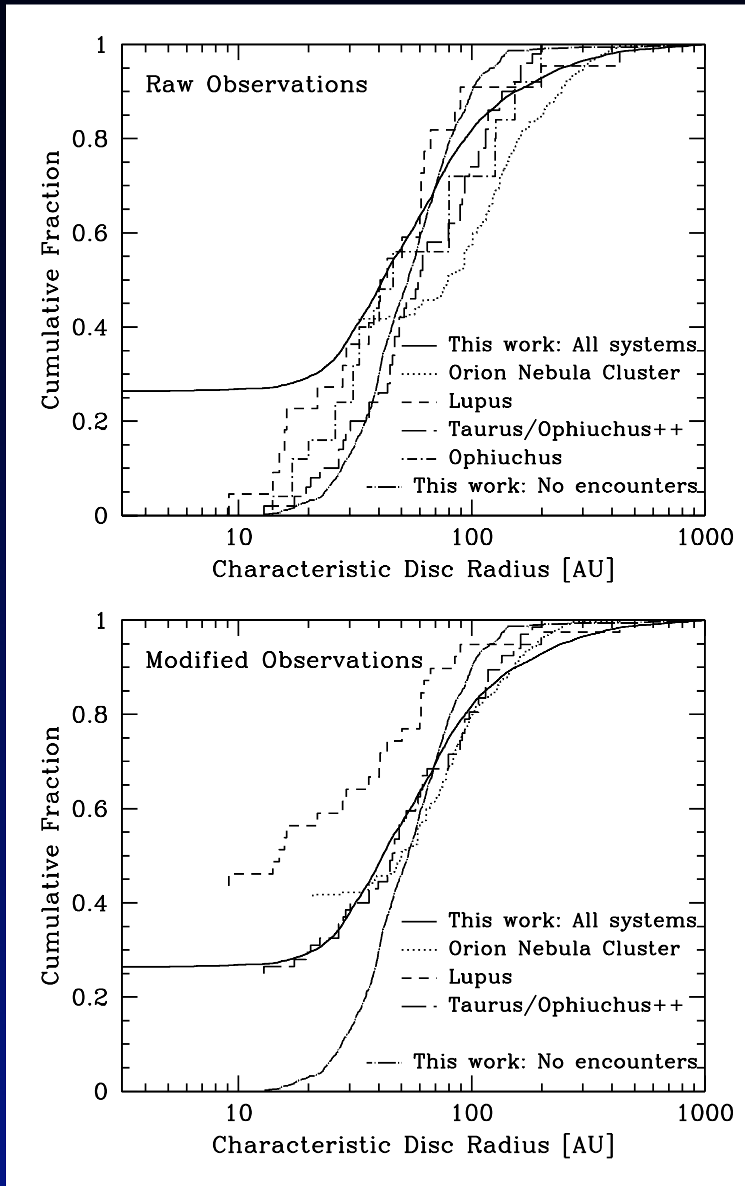
Comparison with observations: Disc masses

- 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
- Protostellar disc masses
  - 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)
  - Good agreement with Class 0/I disc masses
    - Perseus using VLA (Tychoniec et al. 2018)



Comparison with observations: Disc radii

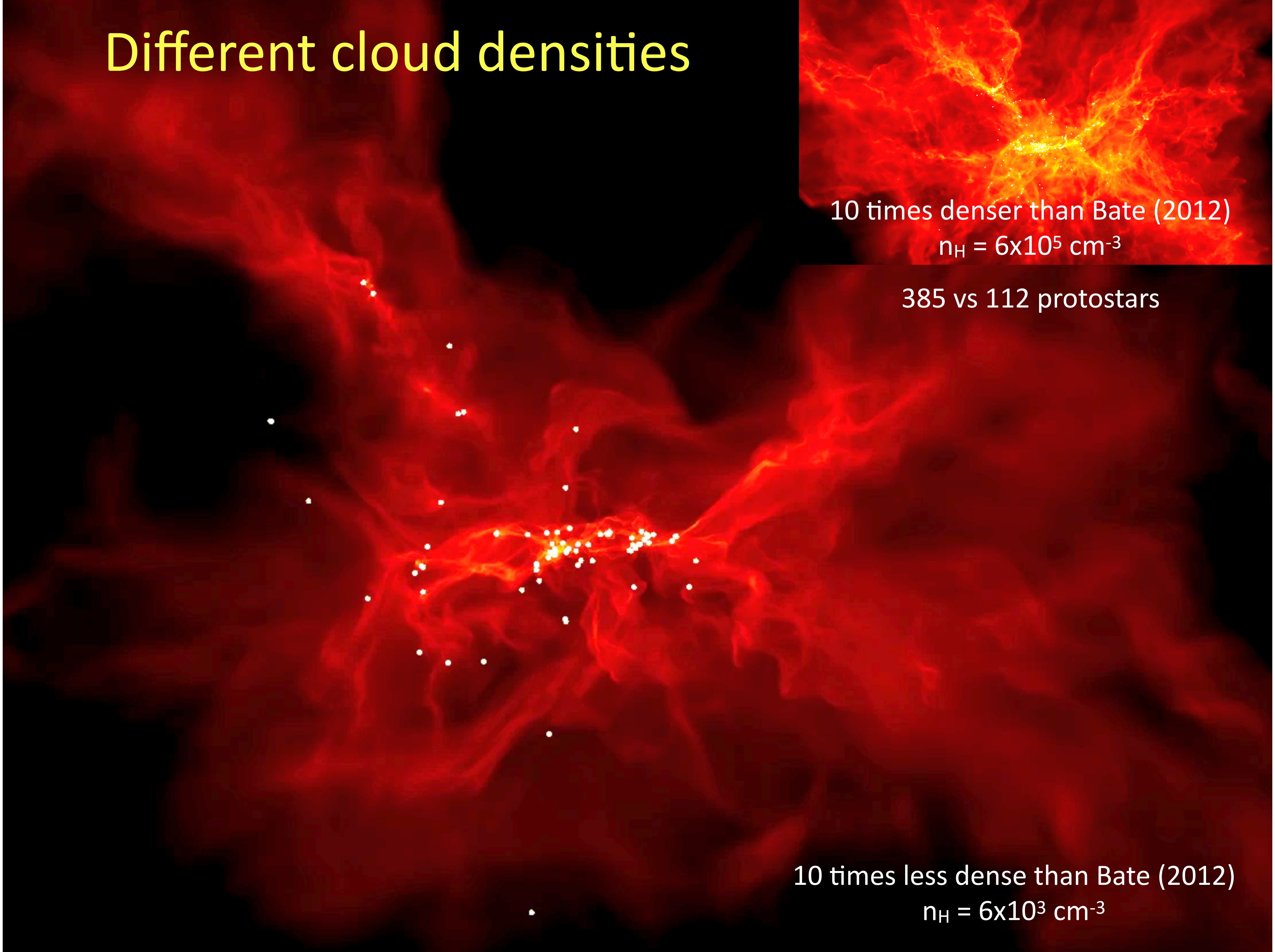
- Distribution of radii
  - Radius containing 63.2% of total mass
  - Observations need to resolve discs
  - Issues with how to treat completeness
  - Disc radii typically ~10-200 AU
  - Simulated disc radii in good agreement with Class II
  - Dynamical interactions important for small discs
  - Largest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



Dependence on initial conditions?

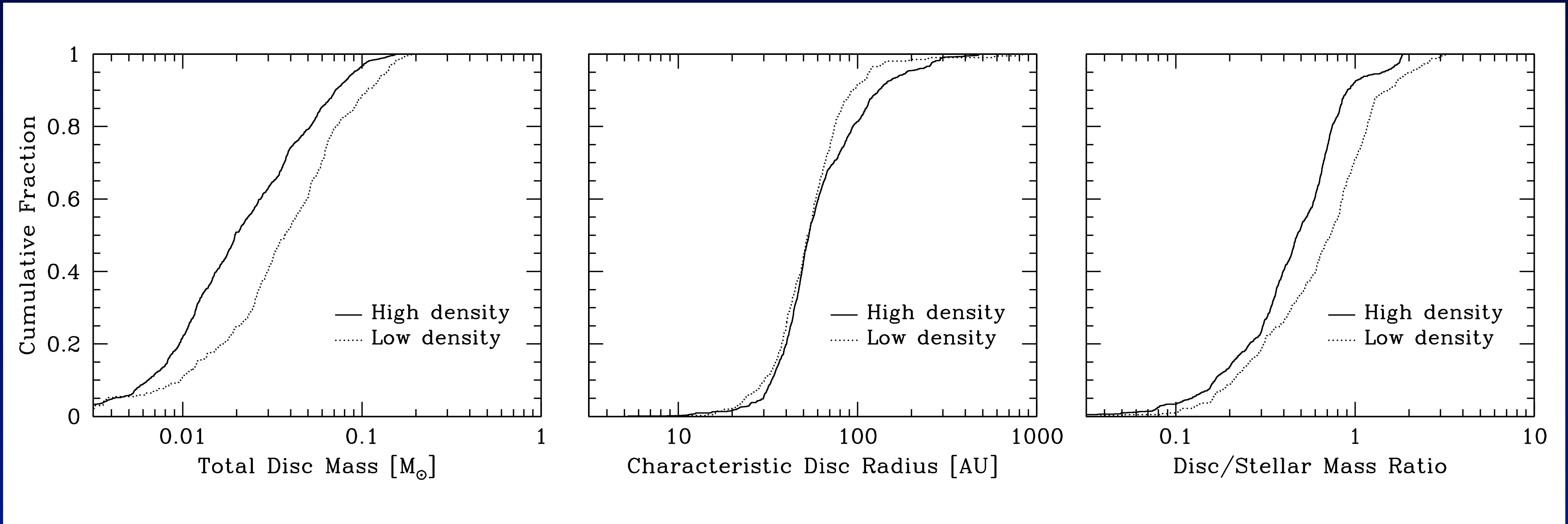
- Performing star formation simulations with different initial conditions
  - Metallicity (Bate 2019)
    - Disc movies available at http://www.astro.ex.ac.uk/people/mbate/
    - Disc properties not yet analysed
  - Cloud mean density
  - Different interstellar radiation field
  - Redshift

Different cloud densities



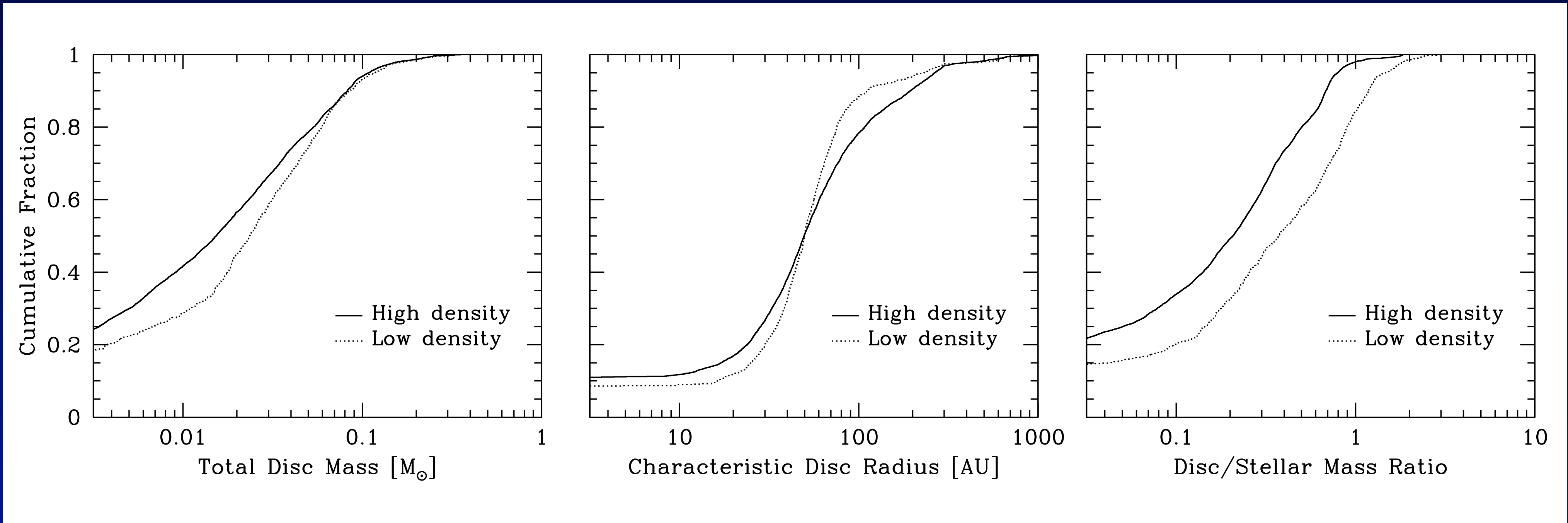
Dependence on cloud & stellar density

- Single protostars that have never had encounters
  - Disc masses approx 2 times greater for low-density initial conditions compared to high density
  - Median disc radii similar, but only half the number of large (>100 AU) discs at low-density
  - Disc-to-star mass ratios 50% greater for low-density initial conditions



Dependence on cloud & stellar density

- Protostellar systems (single & multiple systems)
  - Disc masses at ages <3000 yrs approx 2 times greater for low-density initial conditions compared to high density, but similar when older
  - Median disc radii similar, but only half the number of large (>100 AU) discs at low-density
  - Disc-to-star mass ratios ~2 times higher for low-density initial conditions



Conclusions

- Hydrodynamical calculations predict a wide diversity of protostellar discs
  - Misaligned discs in wide multiple systems should be the norm
- Wide variety of evolutionary processes
  - Dynamical encounters between protostars
  - Star-disc encounters (frequently involved in binary and multiple system formation)
  - Ram-pressure erosion/stripping of discs
  - Disc fragmentation (minority)
- Protostellar discs properties
  - Astounding agreement of masses and radii with observed Class 0/I objects
- Future calculations
  - Need to probe stellar properties over a much broader range of initial conditions
    - Disc properties seem robust to changing the cloud density by 2 orders of magnitude
    - Low-mass stellar mass distribution has *VERY* weak dependence on metallicity ($Z>=0.01\ Z_{\odot}$)