Binary star formation: an integral part of star formation

- Some recent observational highlights

(ALMA and elsewhere)

- Theory and simulations

Successes and problems

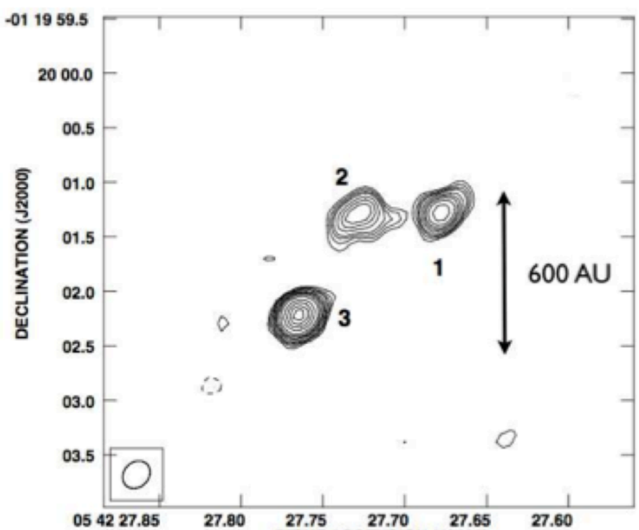
- The evolution of higher order multiplicity

- The future: probing the environment of *close* young pairs

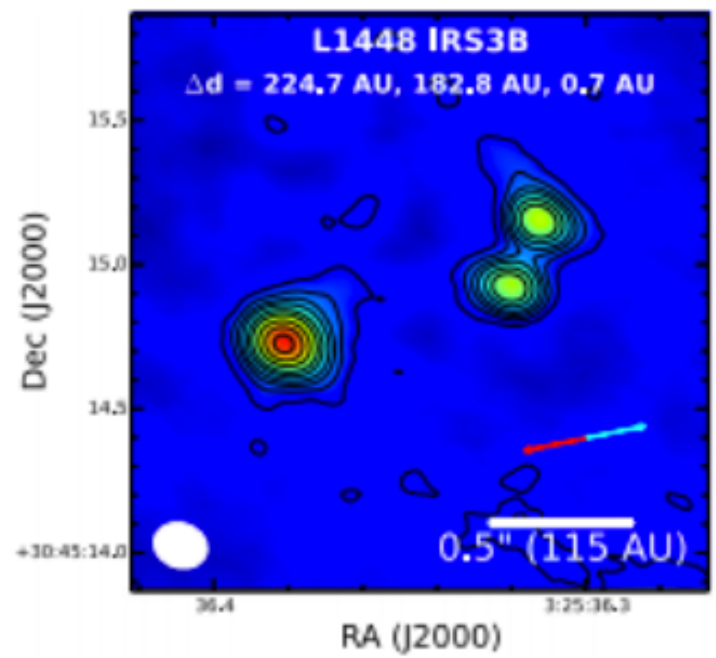
Relevance to circumbinary planets

An observational frontier for binary star formation: insights from ALMA and VLA

Small clusters/non-hierarchical multiples common in deeply embedded, v. young protostars

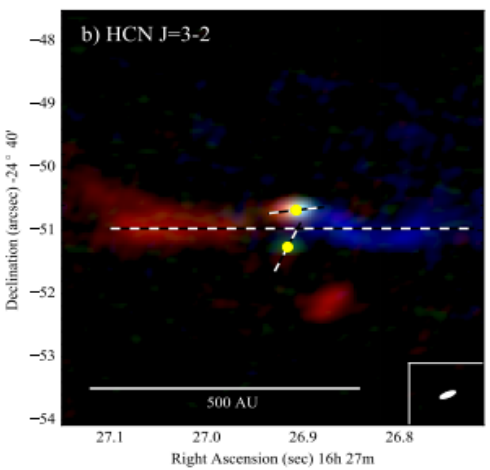


Rodriguez & Reipurth 2014



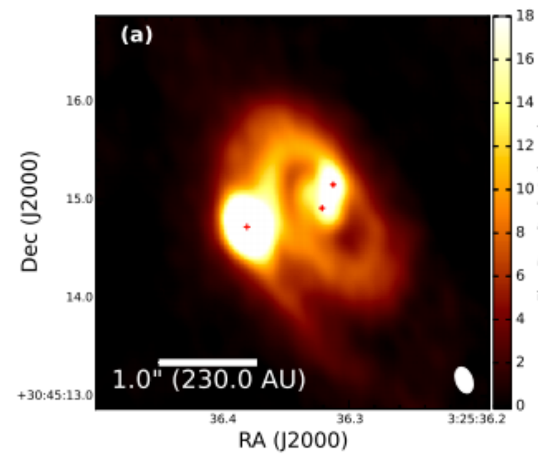
Tobin et al 2016a

Zooming in with ALMA

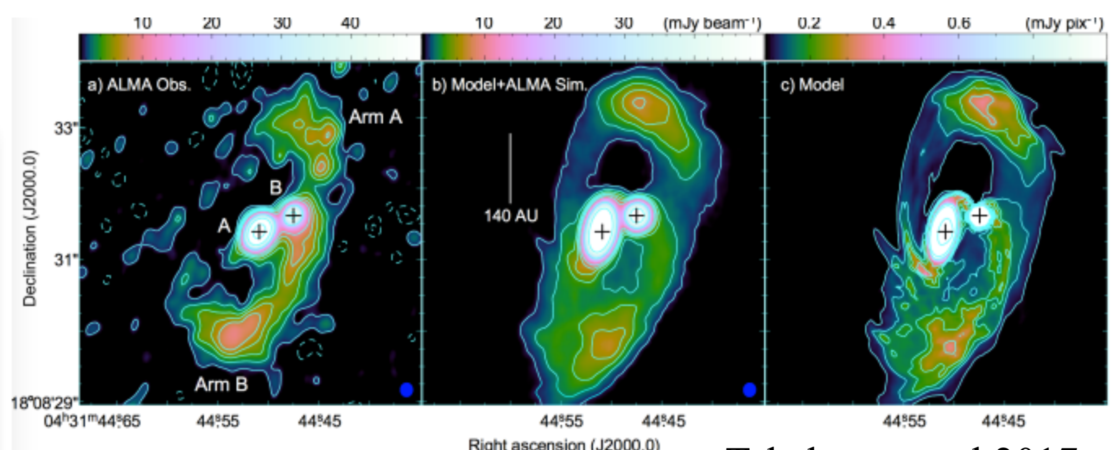


Brinch et al 2016: IRS 43

Note strong misalignment between orbital planes!



Tobin et al 2016

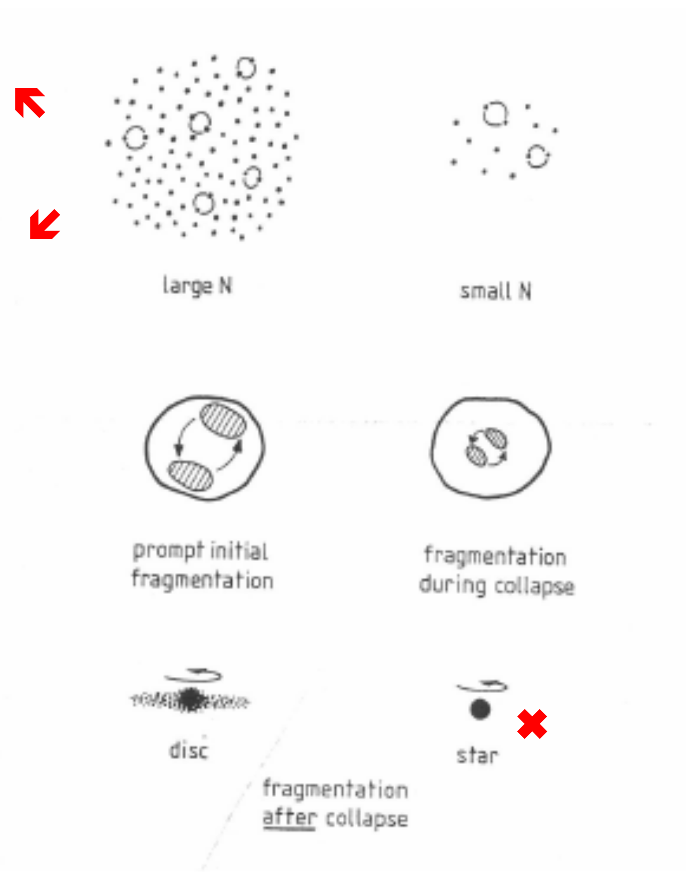


Takahuwa et al 2017

Binary star formation schematic

Closest pairs
(tidal capture)

Widest pairs
(cluster dissolution)



Now understood that binary properties and formation modes are *continuous*

Evolution of simulations

- Hydro. only

Larson 1978, Boss & Bodenheimer 1979, Bodenheimer et al 1980, Boss 1986,Boss 1991,Pongracic et al 1996, Bonnell et al 1991, Bonnell et al 1992, Hubber & Whitworth 2005, Machida 2008,Arreaga & Garcia et al 2010, Walch et al 2010

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Increasing scale

Delgado et al 2003,2004,Goodwin et al 2003,2004

Bate et al 2002,2003a,b,Bate 2009

- Feedback and magnetic fields

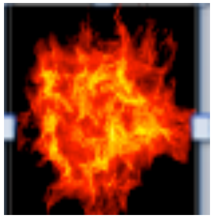
Offner et al 2009,2010,Bate 2012, Machida et al 2008,Hennebelle & Fromang 2008,

Hennebelle & Teyssier 2008, Price & Bate 2007, Kudoh & Basu 2008,2011, Boss 2009, Commercon et al 201

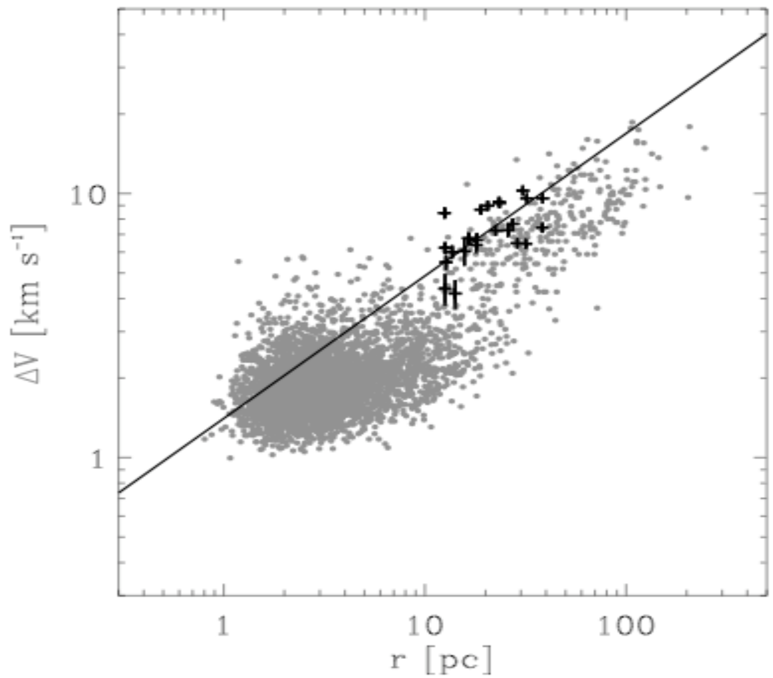
Buerzle et al 2011,Joos et al 2012, Boss & Keiser 2013, Myers et al 2013, Lomax et al 2016,Lewis & Bate 201

Wurster et al 2017

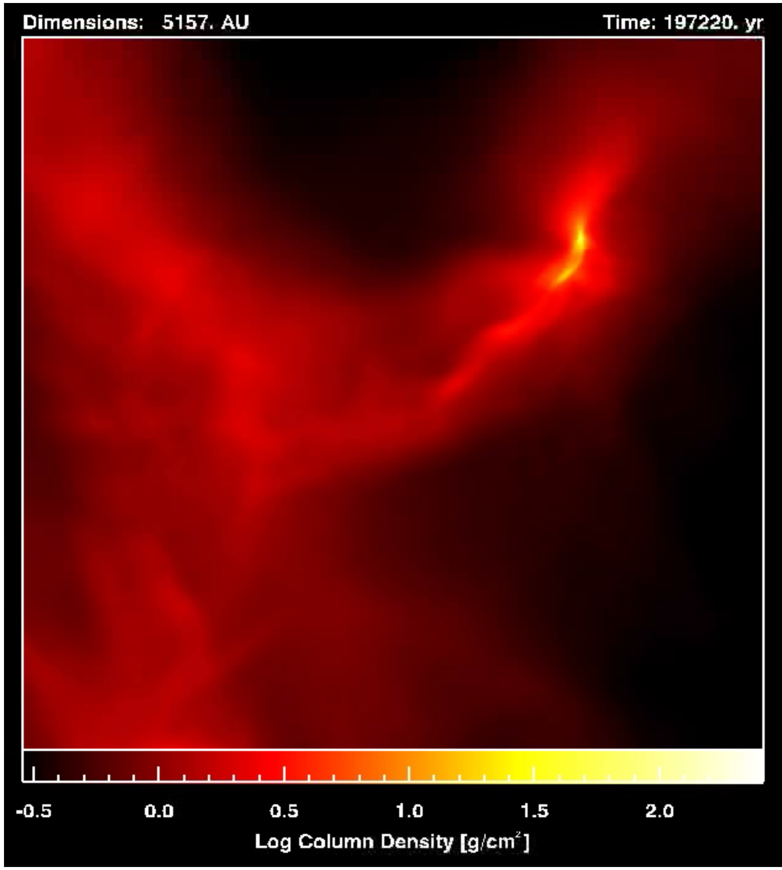
The first cloud scale star formation simulations



` Turbulent' initial conditions motivated by Larson's scaling law for GMCs



Grey = MW (Solomon+ 87, Heyer+01; Black = M33 Rosolowsky+03)



Bate et al 2003

NOTE IMPORTANCE OF FEW BODY INTERACTIONS IN CLOUD SCALE SIMULATIONS

Input physics *extremely* simple

- Gravity
- Supersonic velocity field
- Simply parametrised thermal physics

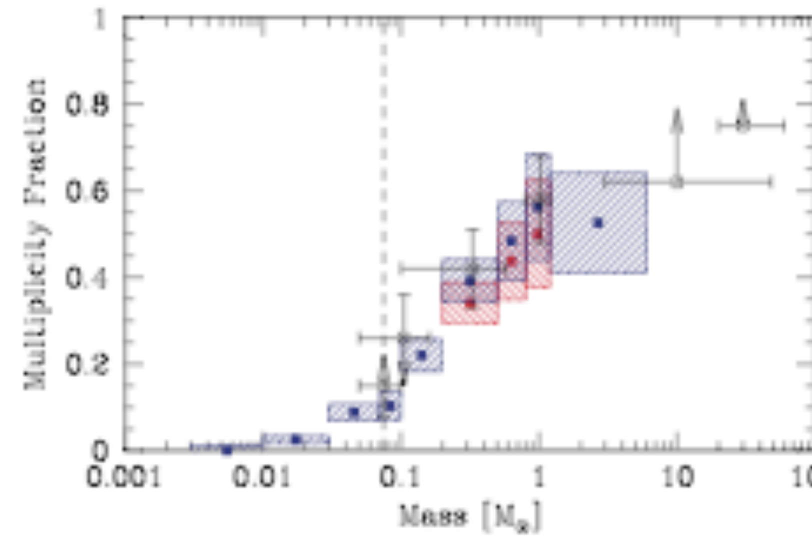
+

- No feedback
- No magnetic fields
- Resolution poor on scale of individual discs and binaries

And yet

Agreement with observed binary statistics surprisingly good

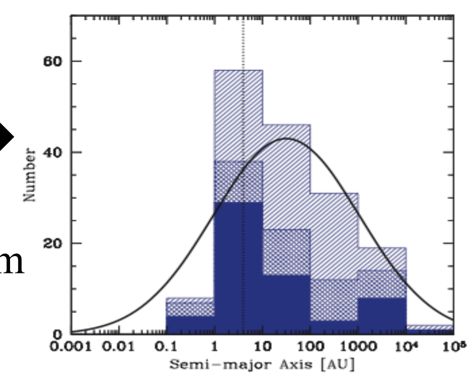
- Best stats on such simple calculations from Bate 2009 (>1250 stars and brown dwarfs)
- Binary fraction as function of primary mass ➔

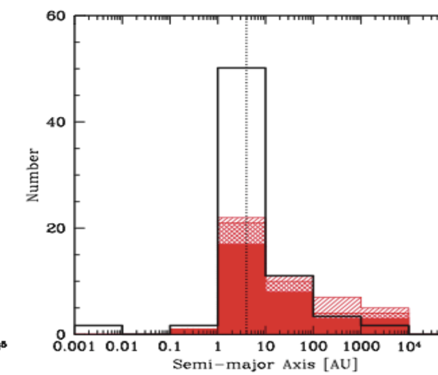


Note: differences for different primary masses are purely dynamical: no feedback in simulations

- Separation distribution ➔

Driven by dynamical hardening and angular momentum loss to circumbinary discs



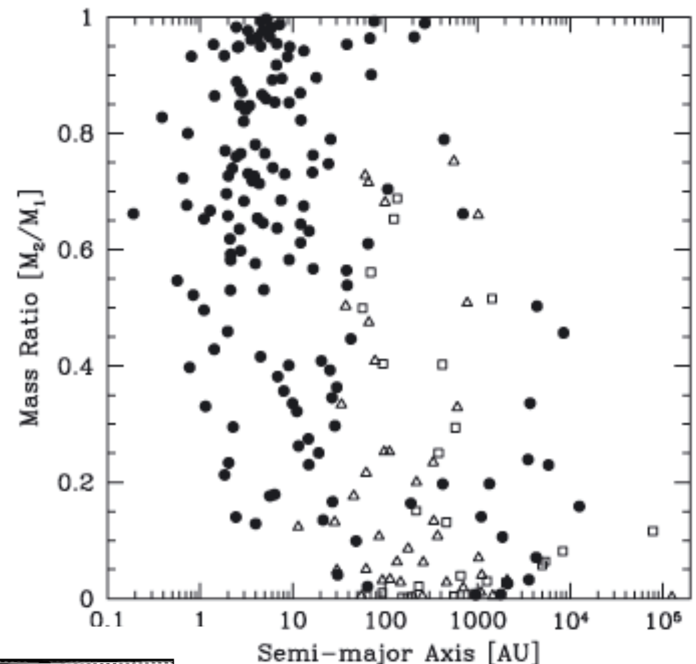


Solar type   VLM

Agreement with observed binary statistics surprisingly good

Tendency towards more equal mass ratios for smaller separations

…. This is due to importance of accretion from circumbinary disc



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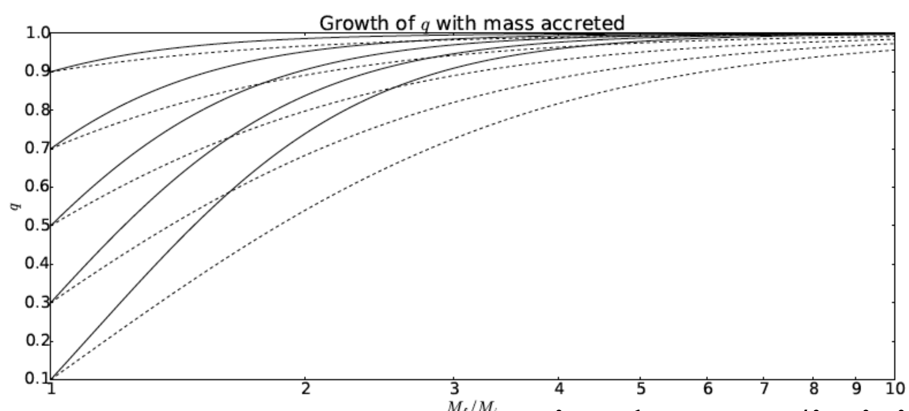


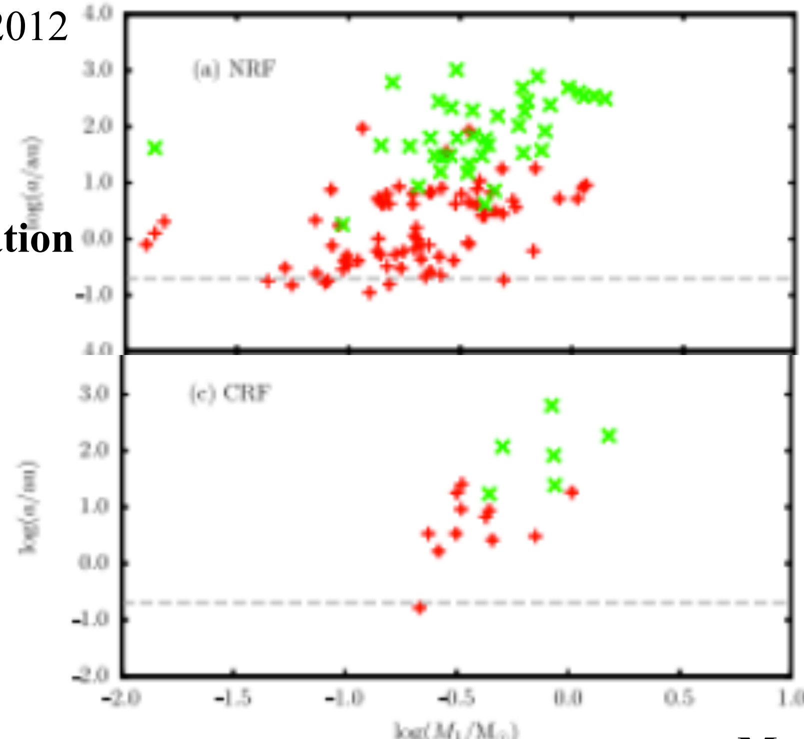
Young & Clarke 2015

Final mass/initial mass

Effect of thermal feedback on binary properties and incidence

See Ofner et al 2009, 2010; Bate 2012

Separation



No feedback

Continuous Feedback

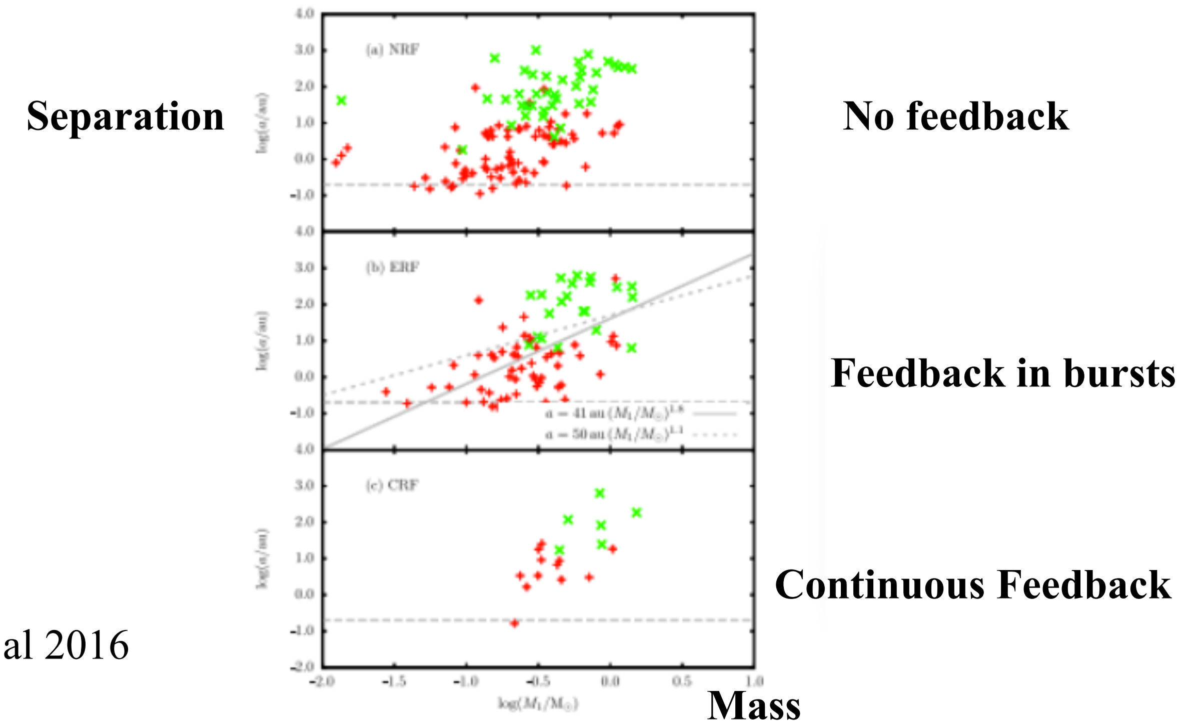
Lomax et al 2016

Mass

- Affects *quantity* of binaries formed
- No systematic differences in *properties* of binaries formed

Simulations exaggerate feedback by assuming accretion luminosity is released *continuously*

Incompatible with observed protostellar luminosity function



Lomax et al 2016

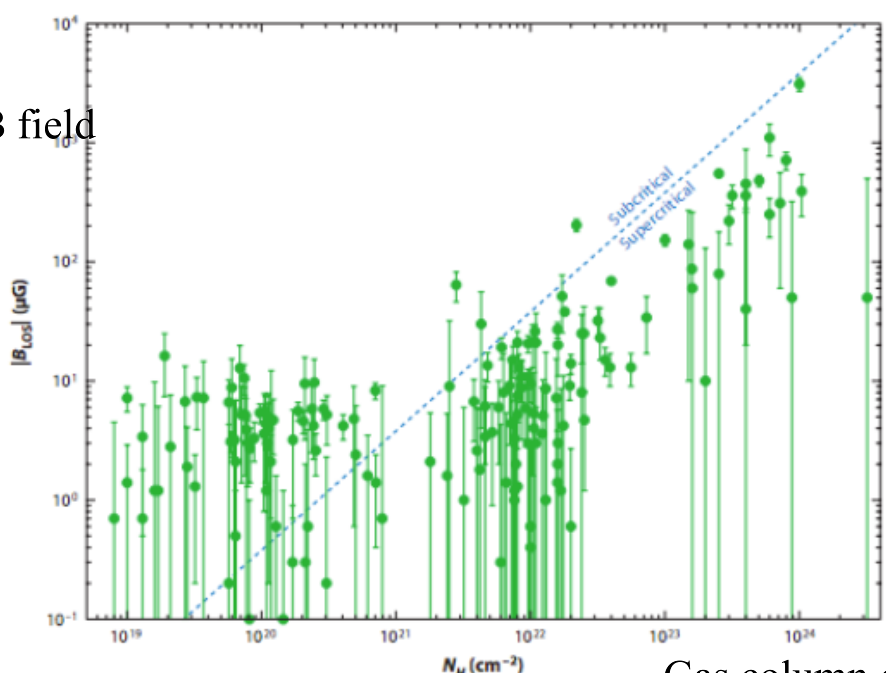
- Liberating accretion energy in bursts (gravo-magnetic cycles, limit cycle ~ 10^4 yrs) relieves binary production problem

Effect of introducing magnetic fields at realistic level

Expense of simulations => hard to assemble stats.

- Parametrise magnetic fields in terms of μ (mass to flux ratio normalised to critical value for collapse) $M/\Phi_B = c_\Phi/\sqrt{G},$

Line of sight B field



Gas column density

Crutcher 2012

Even weak fields apparently problematical for binary formation

Magnetic processes in a collapsing dense core

II. Fragmentation. Is there a fragmentation crisis?

P. Hennebelle[1] and R. Teyssier[2]

2008

Cf Lewis & Bate 2017 : fragmentation only for $\mu > 20$ (Very supercritical mass;flux ratios)

Possible solutions: non-ideal MHD effects? ✖

Sub-critical cores can now collapse but only form single stars

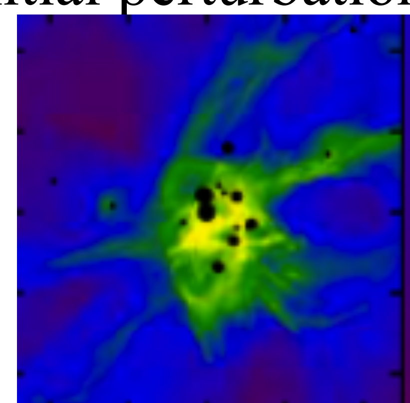
Supercritical cores' fragmentation properties little affected by non-ideal effects: Wurster et al 2017

Large amplitude initial perturbations/turbulent initial conditions?

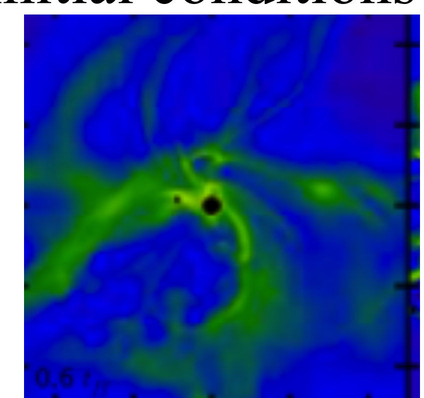
Myers et al 2013

Massive turbulent core

No B



B



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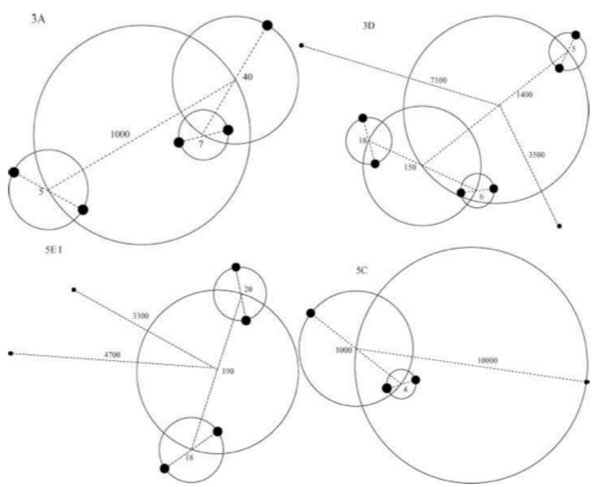
Higher order multiplicity and its evolution

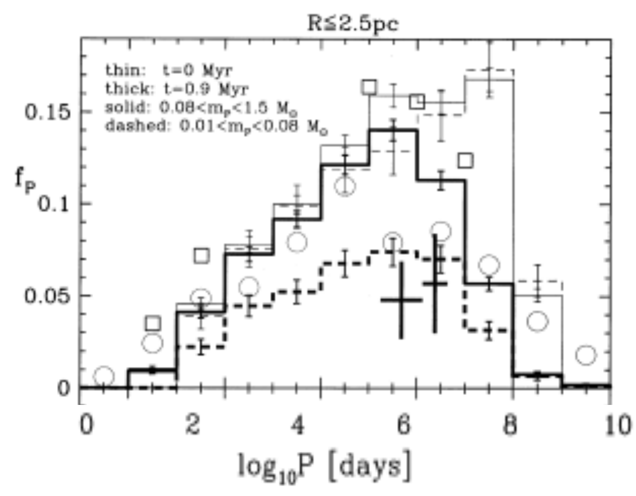
Delgado-Donate et al 2004



- Fragile multiples decay and reconfigure Moeckel & Bate 2010, Reipurth & Mikkola 2014

Also in dense clusters weakly bound components are removed by environmental processing

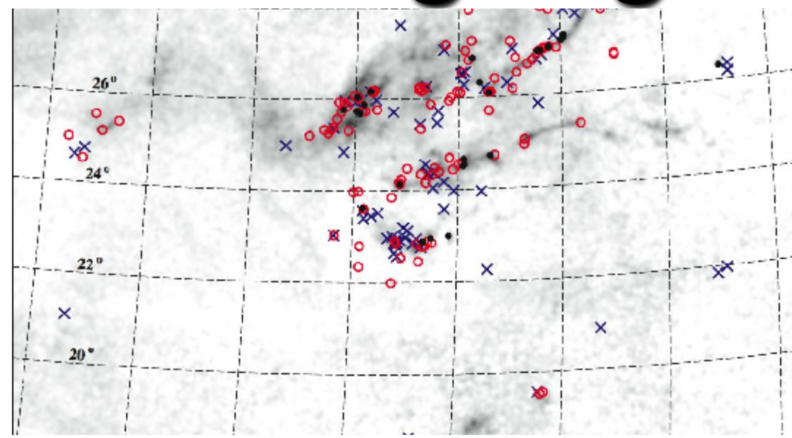
➔



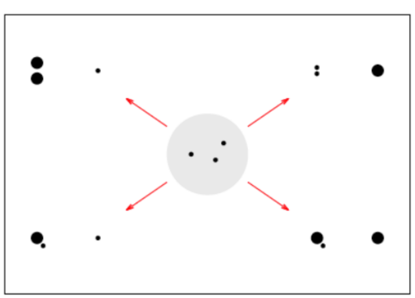
Kroupa et al 2001, Parker et al 2011, Marks & Kroupa 2014

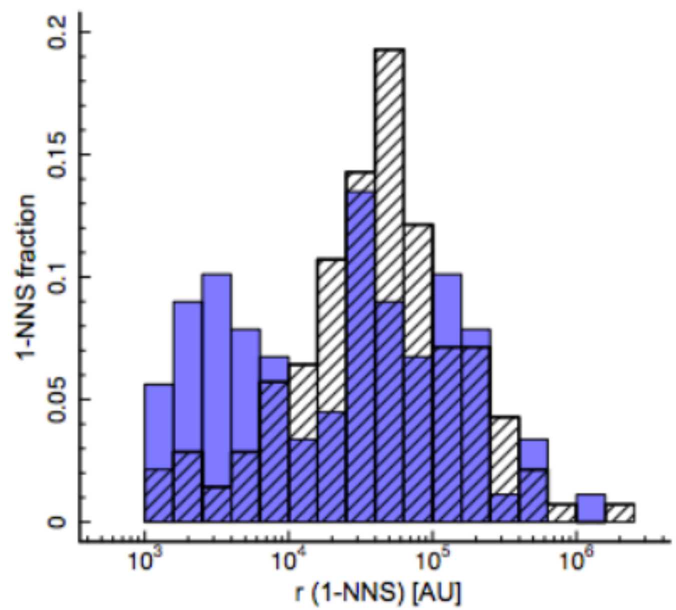
Is there evidence for decay of multiples in star forming regions?

Best test-bed is a sparse system like Taurus Auriga



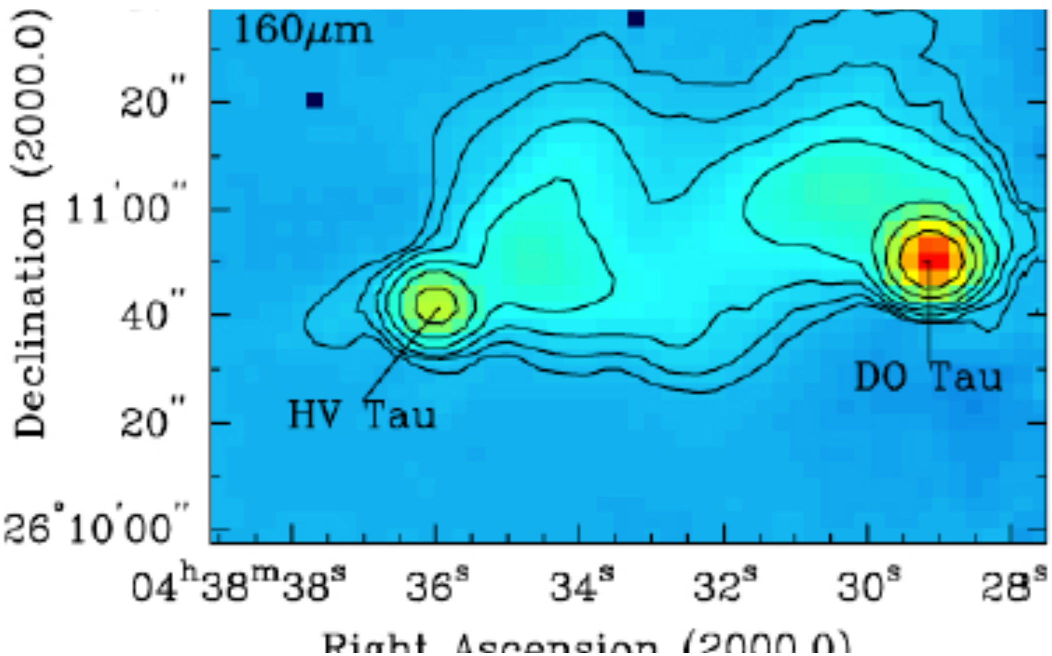
Joncour et al 2017 find that binaries are more likely to have additional neighbour within ~ 10^ AU than single stars

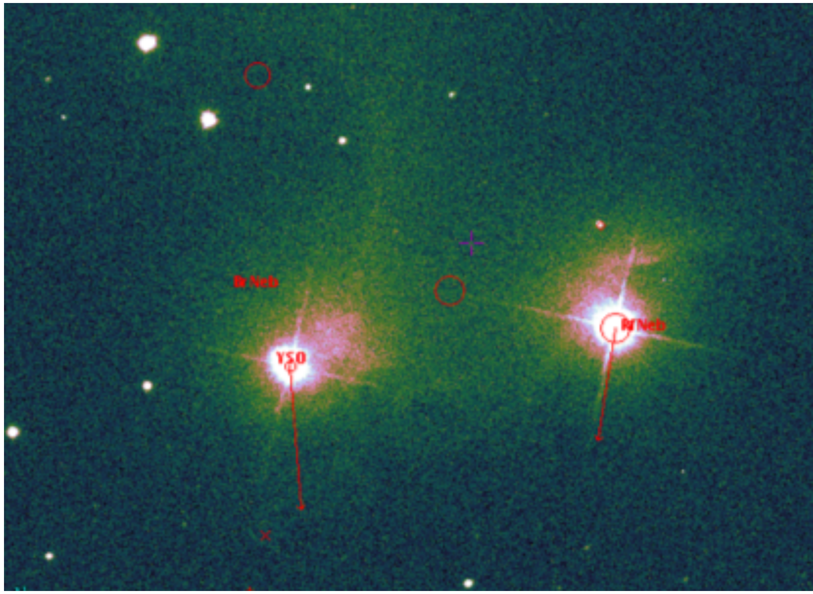




Solid=binary; hatched =single

In at least one case decaying multiple origin is clearly correct



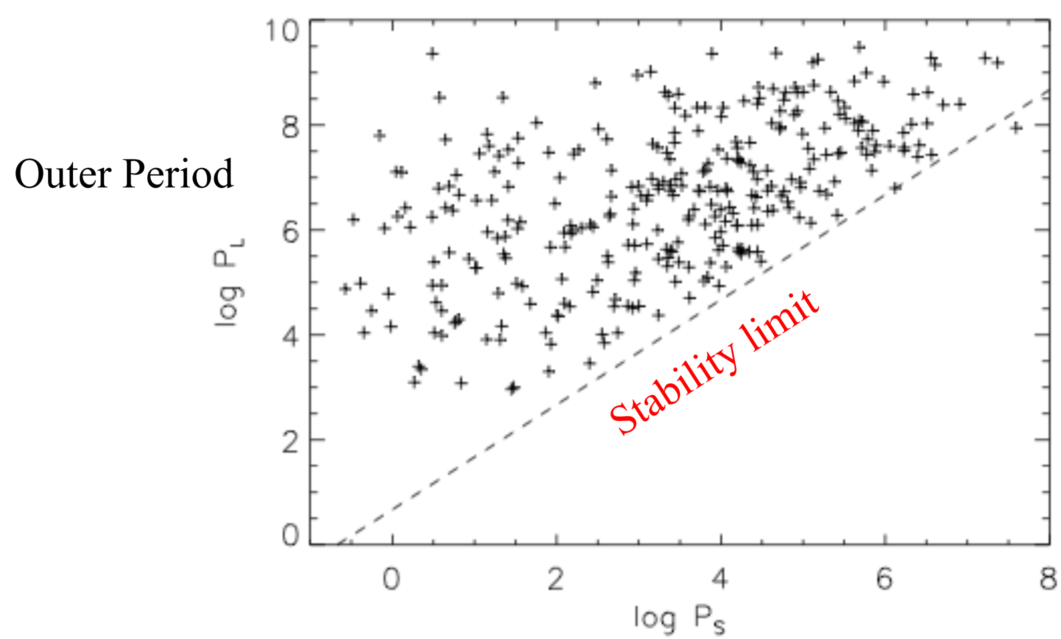


Spiral structure in Herschel and HST image is smoking gun of previous star-disc interaction – and HV Tau is itself a triple system….

Are higher order multiples among main-sequence stars just survivors of natal mini-clusters?

- Tokovinin (2014) examined multiplicity statistics of 4846 F and G dwarfs within 67 pc

Multipl.	N_{obs}	N_{est}
Single	3083	*2616*
Binary	1420	*1523*
Triple	286	*294*
Quadruple	51	*324:*



Inner period

Note systems fill all stable parameter space!

Are very wide main sequence companions a relic of multiple system decay?

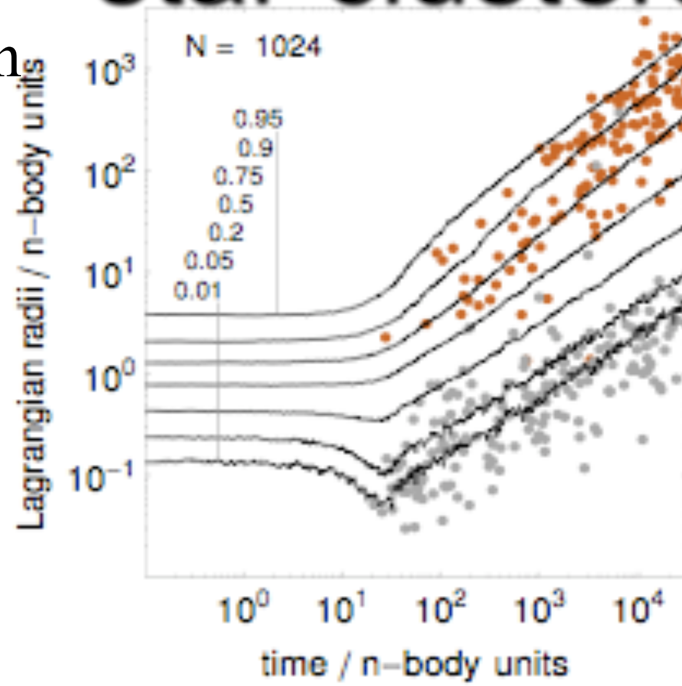
- Probably not – v. wide pairs are *not* preferentially associated with primaries that are themselves binaries   Law et al 2011

Need a mechanism that randomly makes very wide pairings independent of their individual multiplicity…..

New mechanism for creating ultra-wide binaries in dissolving star clusters

Moeckel & Bate 2010
Kouwenhoven et al 2010

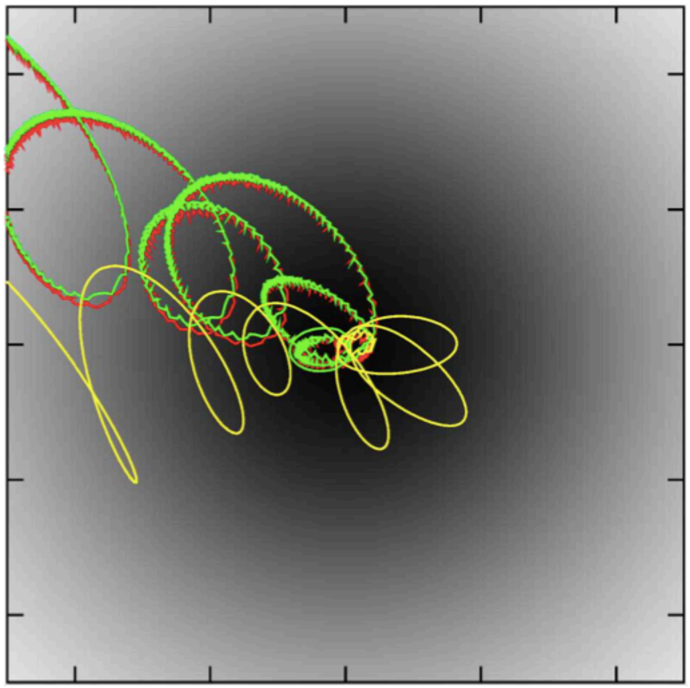
Two body relaxation drives drives cluster expansion post core collapse



Permanent soft binaries formed in outer regions of cluster

In expanding phase expect some temporary soft binaries to stay together: creates a few permanent wide pairs per decade of separation per cluster

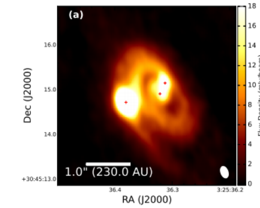
Multiplicity history can be complex…



Multiplicity decays in relaxation of natal grouping

- ..but then an opportunity for re-association during dispersal of larger cluster

Finally…



- Can we expect to image even *close* binary formation with ALMA?

Main impediment is not ALMA's resolution but good sample of *close* pms binaries

- Multi-object spectrographs are throwing up large samples of pre-main sequence *spectroscopic* binaries E.g. Fernandez et al 2017
- Prospect of characterising their circumbinary discs important to understanding important population of circumbinary planets discovered by Kepler.

Armstrong et al 2014

Summary

- Pure Hydro. Simulations reproduce binary stats very well but miss physics
- Notion that binaries emerge from within small N groups becoming observationally testable
- ALMA beginning to define system geometry for accreting protobinaries