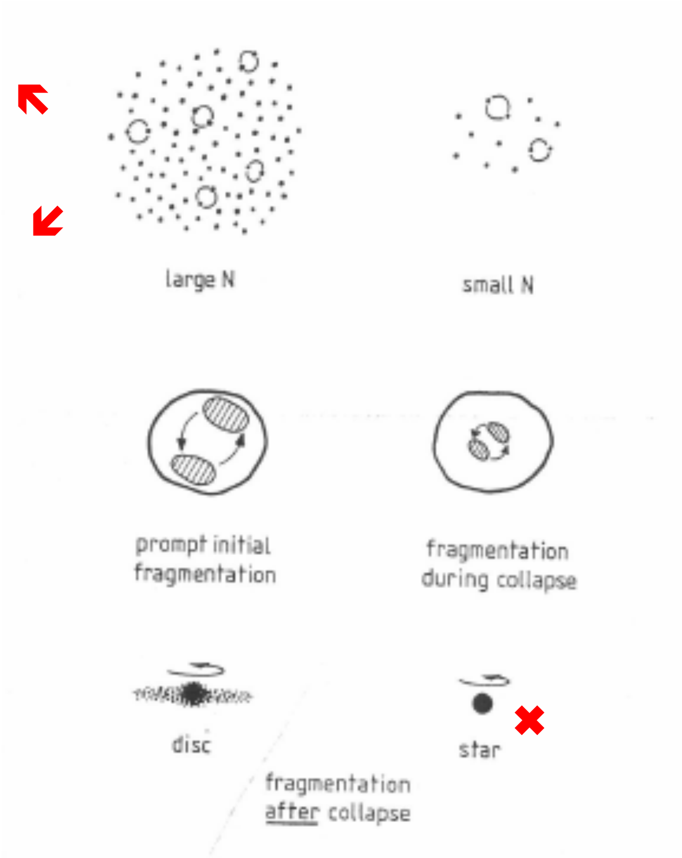
Binary star formation theory in the GAIA era

- Binary formation theories and bottlenecks
- The evidence for dynamical decay of small N groups
- Ultra-wide binaries − clues for origin
- Ultra-wide binaries − insights from GAIA

Binary star formation schematic

Closest pairs
(tidal capture)

Widest pairs
(cluster dissolution)



From Clarke (1992)

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

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

Increasing scale

- ## 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?

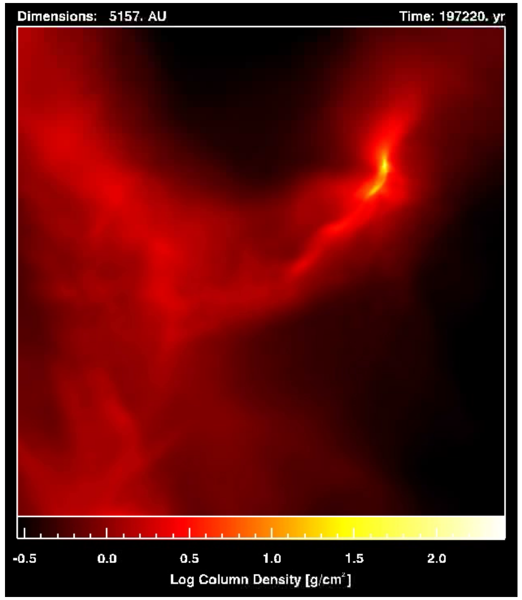
Wurster et al 2017,Kuruwita et al 2017, Wurster & Bate 2019

The first cluster scale simulations:

Input physics *extremely* simple

- Gravity
- Supersonic velocity field
- Simply parametrised thermal physics

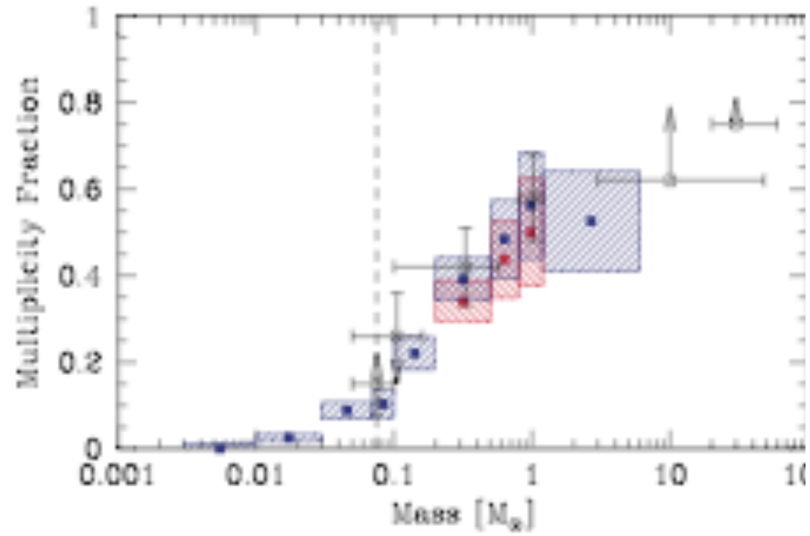
- No feedback
- No magnetic fields
- Resolution poor on scale of individual discs and binaries



Bate et al 2003

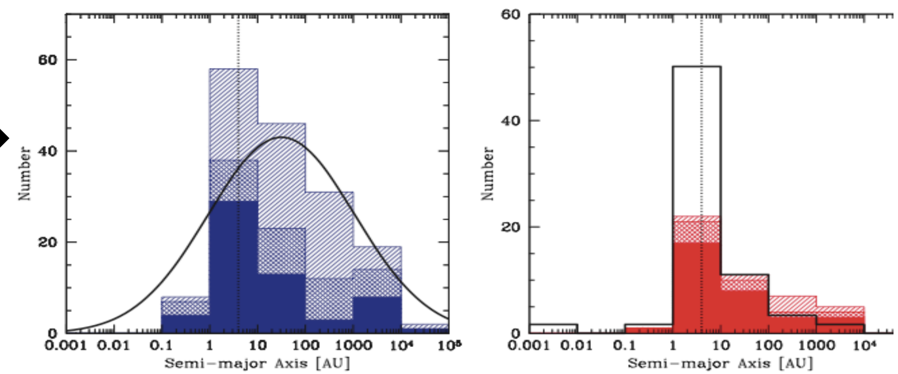
And yet Agreement with observed binary statistics surprisingly good

- 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 ➔



Solar type VLM

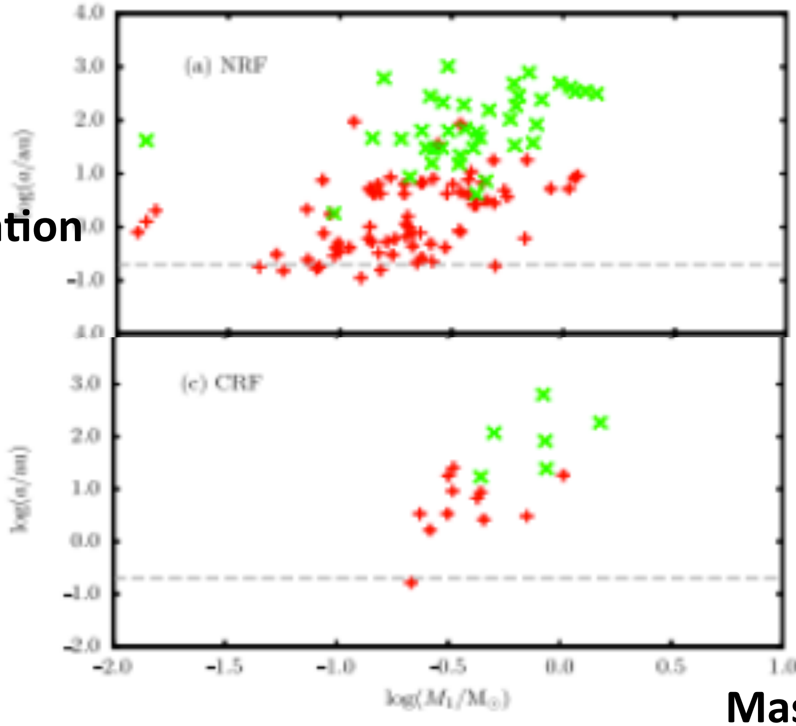
Driven by dynamical hardening and angular momentum loss to circumbinary discs

Also form many higher order multiples: inner planes aligned, outer planes misaligned

Putting in the necessary physics

Effect of thermal feedback on binary properties and incidence

See Ofner et al 2009, 2010; Bate 2012

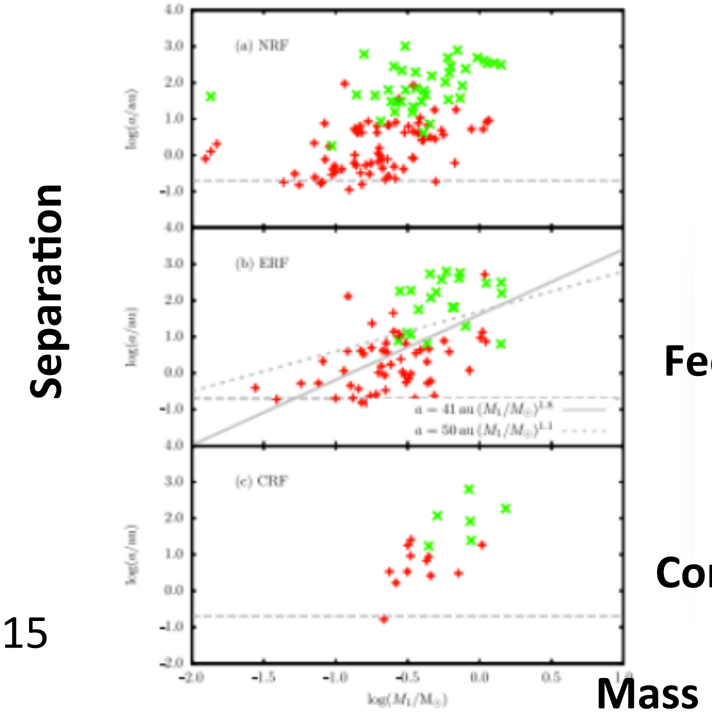


Lomax et al 2015

- 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



No feedback

Feedback in bursts

Continuous Feedback

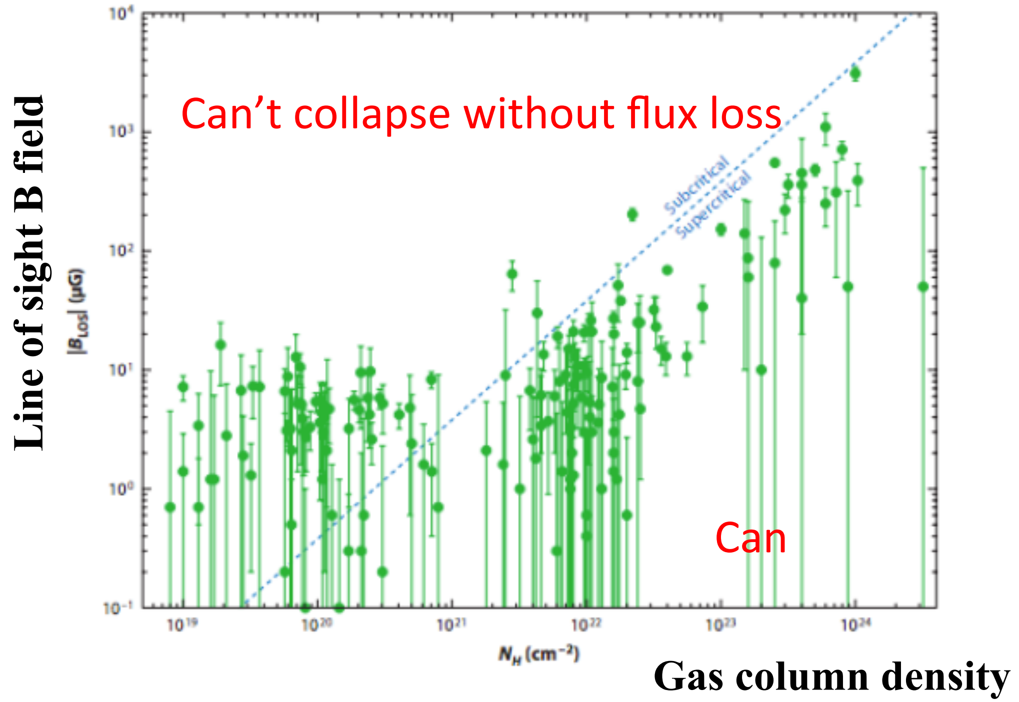
Lomax et al 2015

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)



Crutcher 2012

Even weak fields potentially problematical for binary formation

Magnetic processes in a collapsing dense core

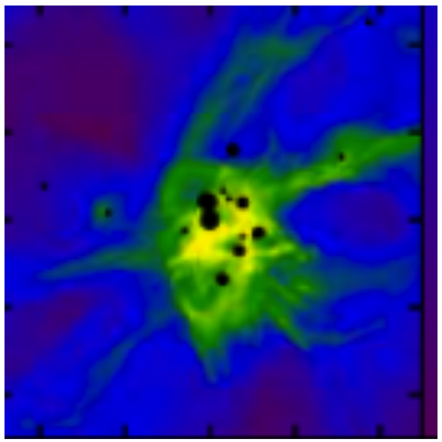
II. Fragmentation. Is there a fragmentation crisis?

P. Hennebelle[1] and R. Teyssier[2] 2008

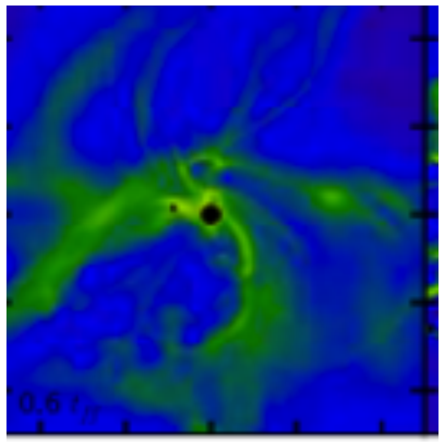
Magnetic braking inhibits disc formation and hence fragmentation: material funneled on to single central star via filaments

Massive turbulent core

Myers et al 2013



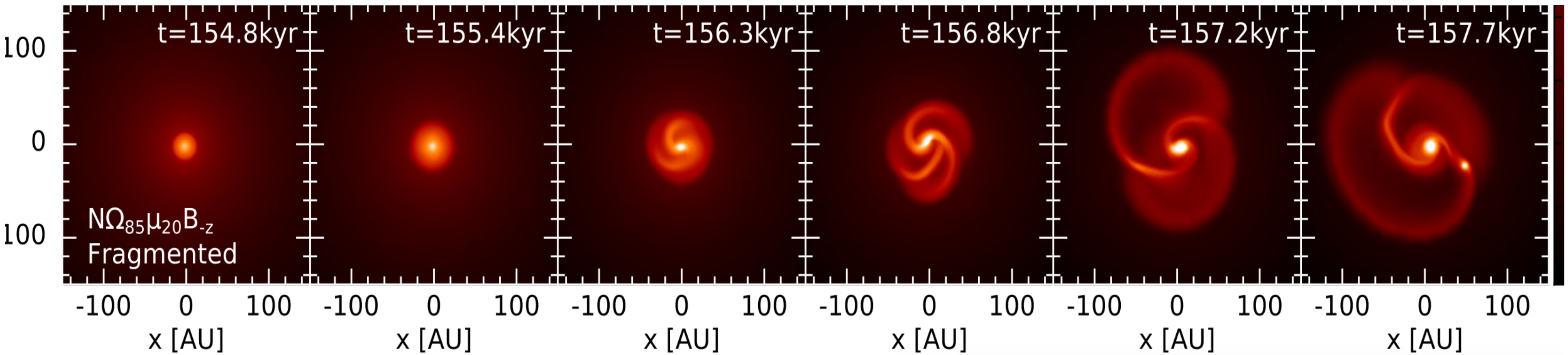
No B



B

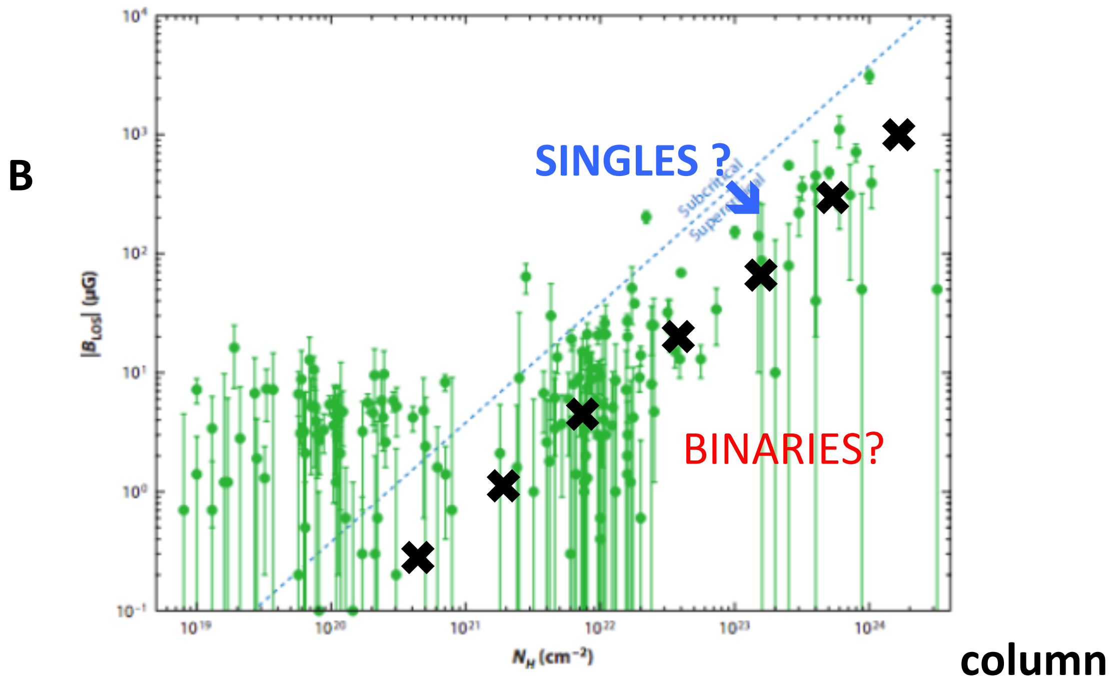
Where fragmentation occurs, it is favoured by:

- Inclusion of non-ideal MHD effects — Wurster et al 2017
- Rapid rotation — Wurster & Bate 2019
- Weak B fields (high μ) — Lewis & Bate 2017



Wurster & Bate 2019; see also Kuruwita et al 2017

If binary formation requires μ > 10:



◆is there enough weakly magnetised gas to explain a high binary frequency? ◆Do the resulting binaries differ from those formed in pure hydro. calcs.?

What can be learned while waiting for clarity from simulations?

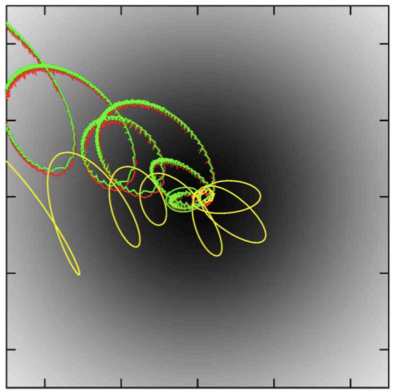
Insights from observations

- Binary stats as function of primary mass (Moe & di Stefano 2017)
- Higher order multiplicity statistics (Tokovinin 2014 , Riddle et al 2015, Halbwachs et al 2017)
- Observations of circumstellar material in protobinaries (ALMA, VLA⋯)

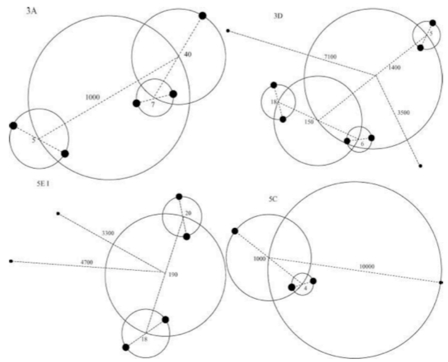
⋯⋯GAIA

The importance of small N clusters in binary formation

Large scale simulations imply fundamental unit of star formation should be the small N cluster*

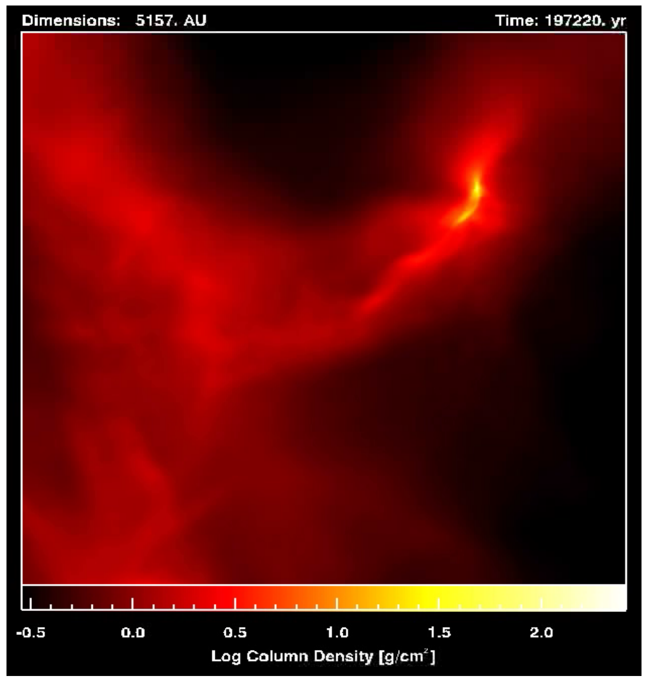


Reipurth & Mikkola 2015



Delgado et al 2004

Interplay between small N cluster dynamics and accretion shapes final multiple populations

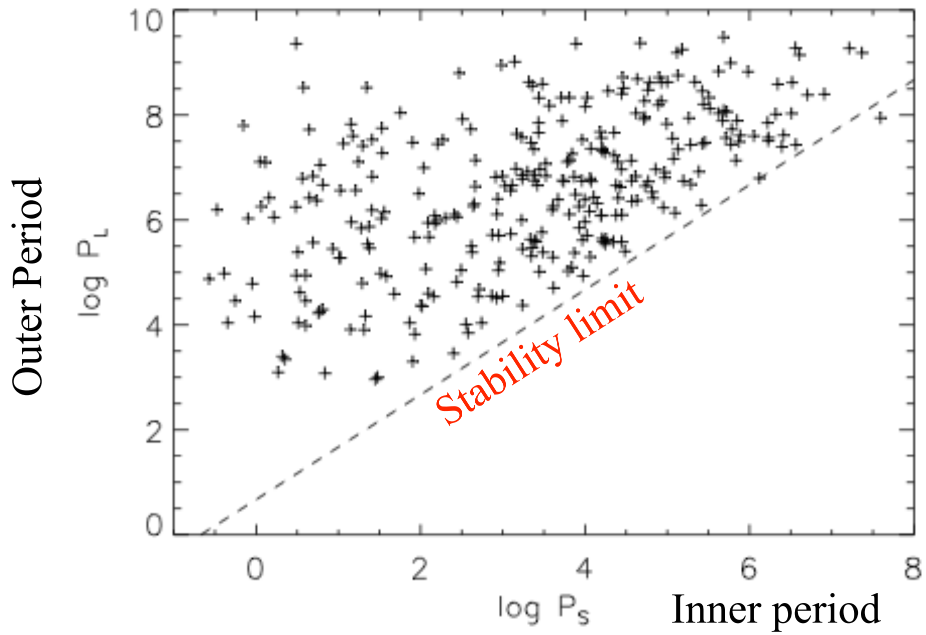


* Irrespective of whether such clusters are located in larger clusters...

Evidence for clustered origin

- Incidence of **stable** hierarchical multiples in main sequence populations (see Tokovinin (2014) for multiplicity statistics of 4846 F and G dwarfs within 67 pc): incidence of N>2 ~ 13%.

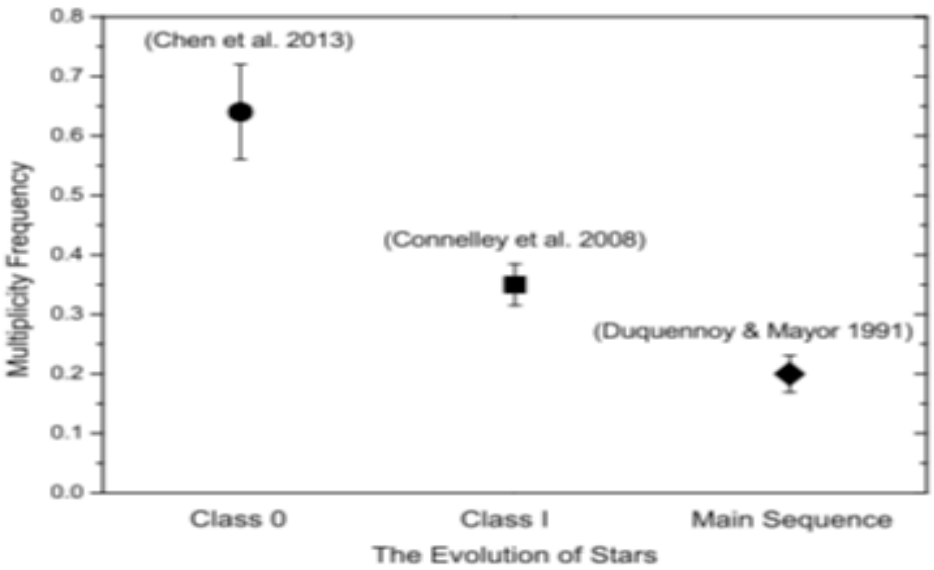
N	3	4	>4
Incidence	**8%**	**4%**	**1%**



Note systems fill all stable parameter space,
=> likely many systems decayed 3 ➔ 2 + 1

Early decay of multiples confirmed by evolution of multiplicity statistics

For 50 Au < a <5000Au Chen et al 2013



$$MF = \frac{B+T+Q}{S+B+T+Q}$$

1-MF= fraction systems that are singles

$$CSF = \frac{B+2T+3Q}{S+B+T+Q}$$

CSF=mean no. of companions per star

Class 0 (youngest protostars): MF is 3 x main seq., CSF is 4 x main seq.

Subsequent larger scale VLA survey with homogeneous resolution confirmed this conclusion:

Multiplicity and Companion Star Fractions

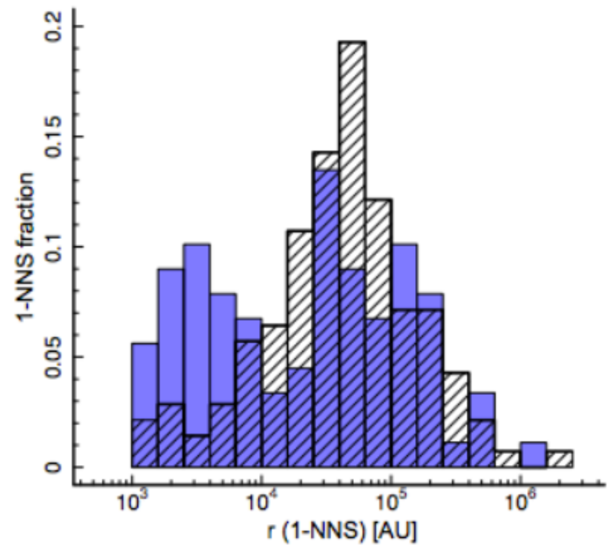
Sample/Sub-sample	Separation Range	S:B:T:Q:5:6	MF	CSF
Full Sample	15–10,000 au	37:15:5:2:2:1	0.40 ± 0.06	0.71 ± 0.06
Class 0	15–10,000 au	13:7:5:2:2:1	0.57 ± 0.09	1.2 ± 0.20
Class I	15–10,000 au	20:6:0:0:0:0	0.23 ± 0.08	0.23 ± 0.08

Tobin et al 2016

Evidence that young binaries are associated with ejected distant companions

- *All* close Class I binaries have another YSO within ~ 25000 AU Connelley et al 2009
- In older (Class II) systems, binaries more likely to have ~ 10000 AU scale companions than singles

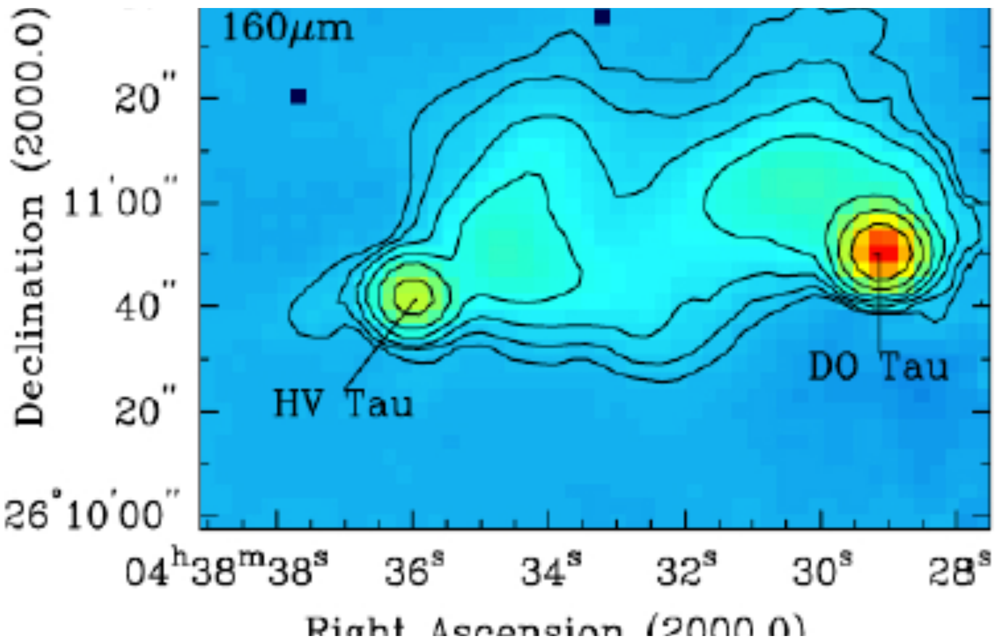
Joncour et al 2017: Solid=binary; hatched =single

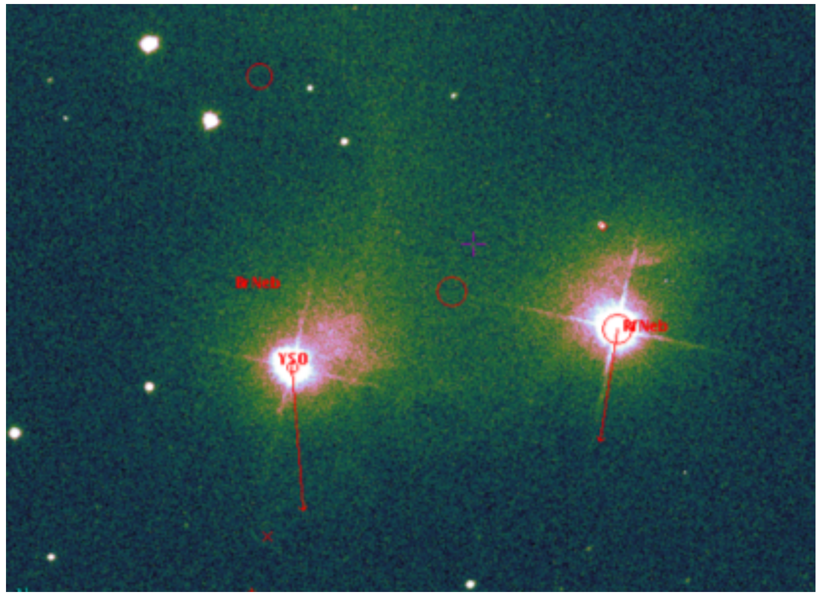


Herschel/HST imaging demonstrates common origin of apparently isolated systems

<===== 10^4 AU =======>

HST scattered light

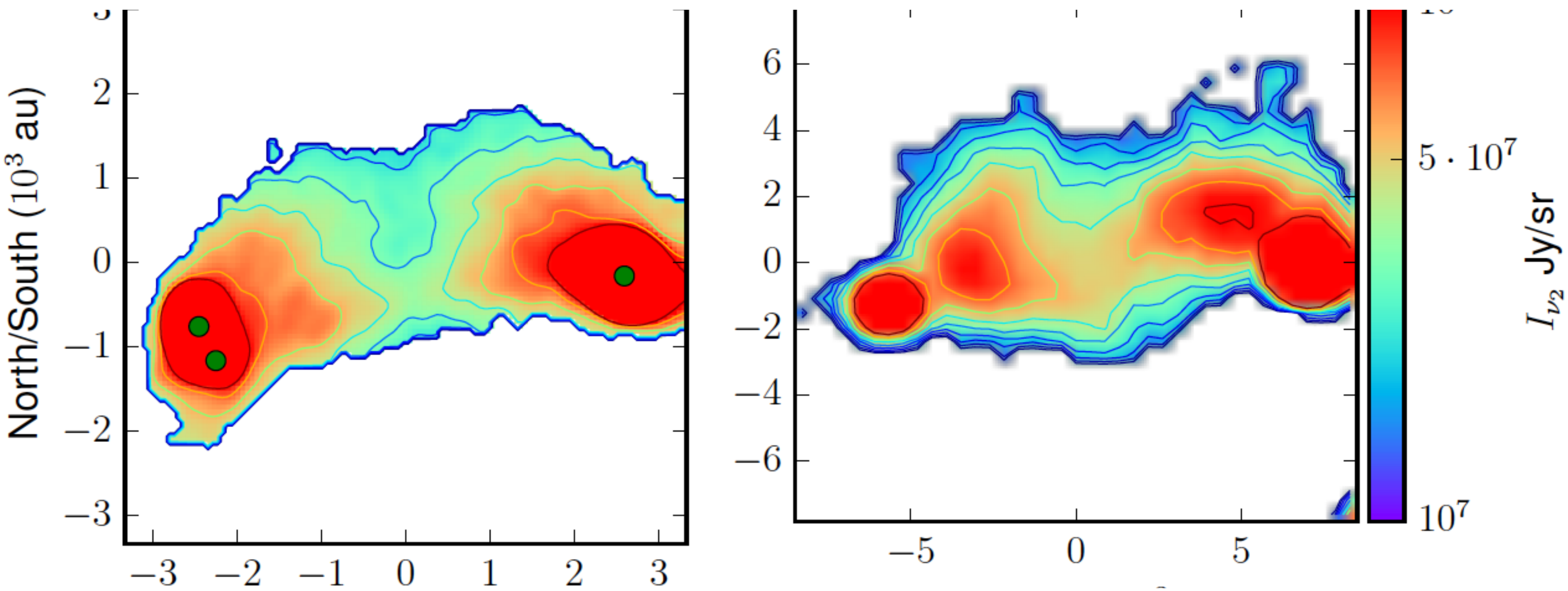




Howard et al 2013

HV Tau is itself a triple system (a ~ 10 & 500 AU)

Detailed hydro. modeling consistent with DO Tau being ejected ~ 0.1 Myr ago in encounter that truncated disc of HV Tau C



Model 160 µm map

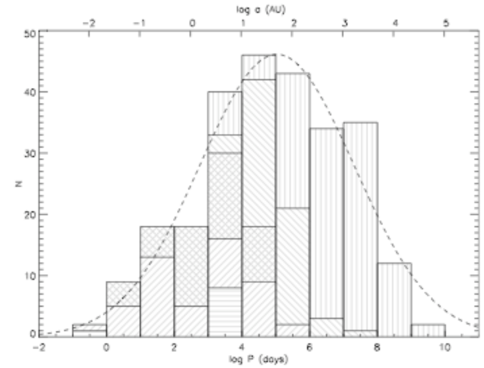
Herschel map @ 160 µm

Winter, Clarke & Booth 2018

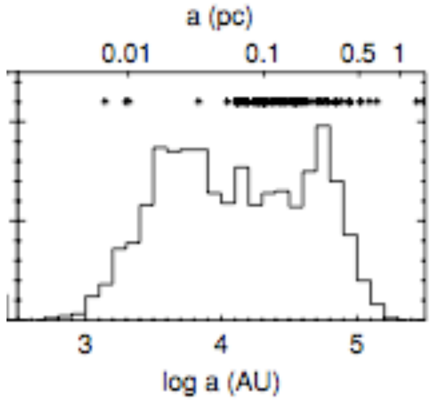
N.B. Constraints from GAIA DR2 limited by fact that HV Tau is a triple

Ultra-wide binaries

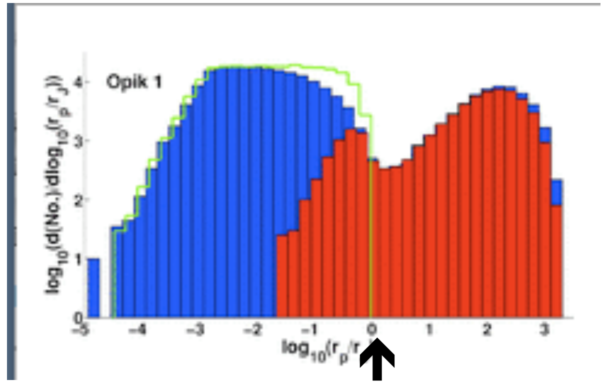
Raghavan et al 2010: a distn of solar type binaries



Dhital et al 2010: cpm pairs (~ few % of population belong to such pairs)



Jiang & Tremaine 2010



- Period distribution is modified by environmental effects

  Stochastic encounters + Galactic tide

Jacobi radius ~ 3 x 10^5 AU

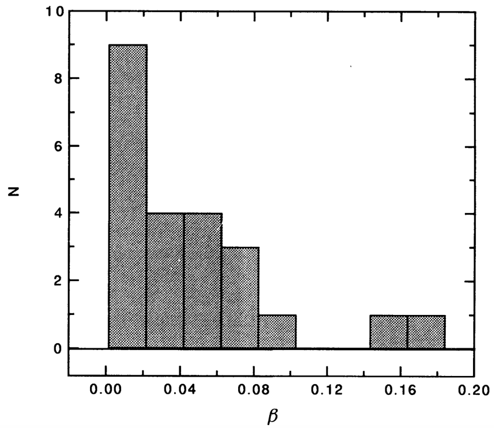
- At 10^3-10^4 AU a possible testbed for MOND…

Pittordis & Sutherland 2018,2019; Hernandez et al 2014,2019

- Formation route a puzzle….

Star forming cores don't contain enough angular momentum to form such binaries unless they have low mass outliers or high eccentricity

β=rot. K.e./total



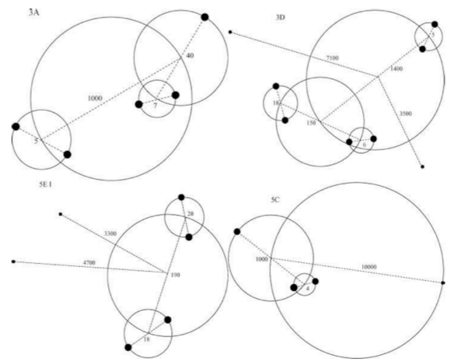
Goodman et al 1993

- Initial core (radius r_c ~ 10^4 AU) has equivalent angular momentum to a circular equal mass binary at radius ~ β r_c

For eccentric outlier containing fraction f of core mass, angular momentum conservation permits maximum separation ~ β r_c/((1-e)f^2)

Can all ultra-wide binaries form by reconfiguration of unstable multiples?

Probably not:



Delgado et al 2004

- Not all wide binaries have inner multiples

Law et al 2011

- Mass ratio distribution is ~ flat so no strong preference for low mass outliers

Tokovinin & Lepine 2012

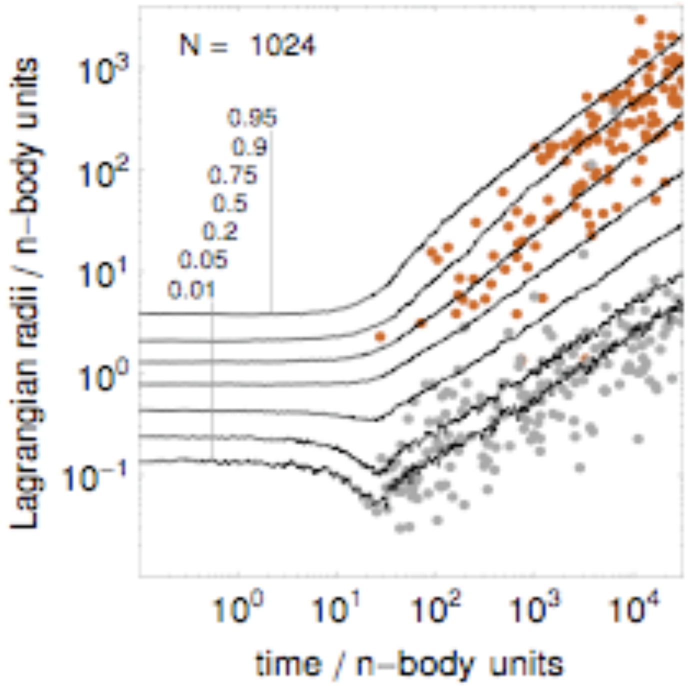
Alternative mechanism for ultra-wide binary formation

- Grey points = three-body capture binaries

  (close and formed in cluster core)

- Orange points = ultra-wide binaries formed in outer region of dissolving cluster

Predicted abundance: ~ 1 pair per decade of separation per cluster: require <N> ~ 100 to explain incidence of ultra-wide pairs



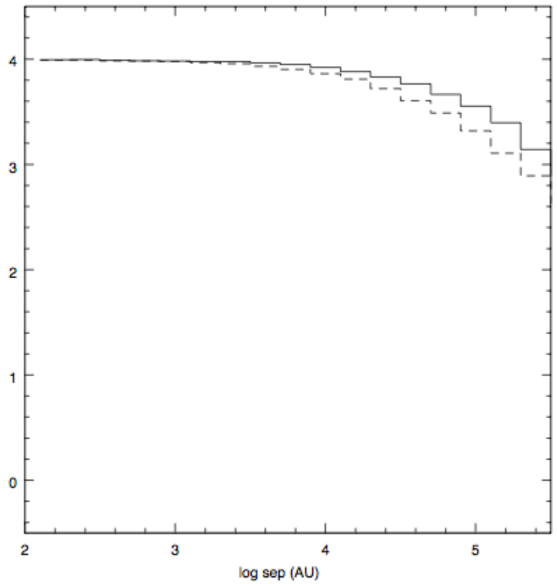
Moeckel & Clarke (2011)
See also Kouwenhoven et al 2010

Predictions for ultra-wide binary formation in dissolving clusters

- Random pairing from IMF

But consistent with observed uniform q distribution if take account of environmental processing

Number per log a



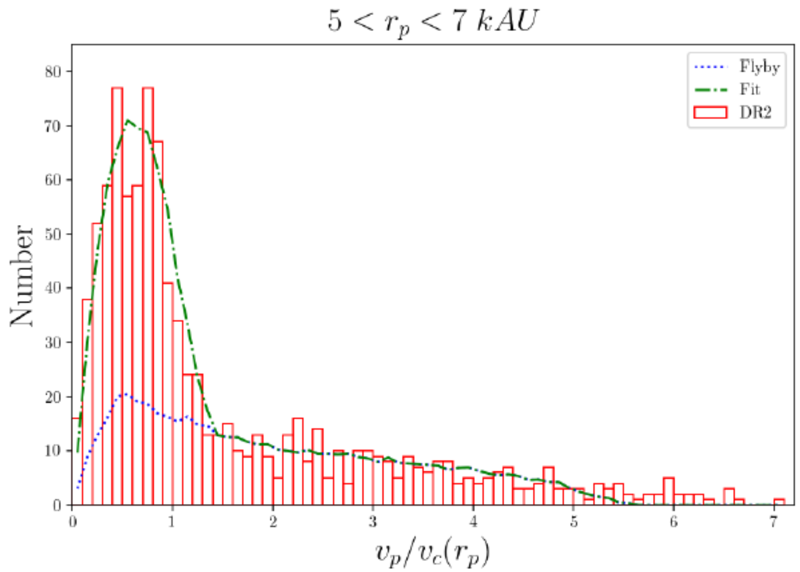
Log sep.

A uniform distn. in log a undergoes q dependent disruption on Gyr timescales: solid q=1 (Jiang & Tremaine 2011), dashed q=0.1 (Goodwin & Clarke in prep.)

- Individual components have same multiplicity fraction as field
- Predicts thermal eccentricity distribution: GAIA should eventually distinguish formation scenarios

Kouwenhoven et al 2010

Wide binary kinematics from GAIA



Relative proper motions of wide binaries normalised to velocity of Newtonian circular binary in sky plane: Pittordis & Sutherland 2019

- Expect all values < √2 for bound pairs

- Unexplained `shelf' of pairs with higher values

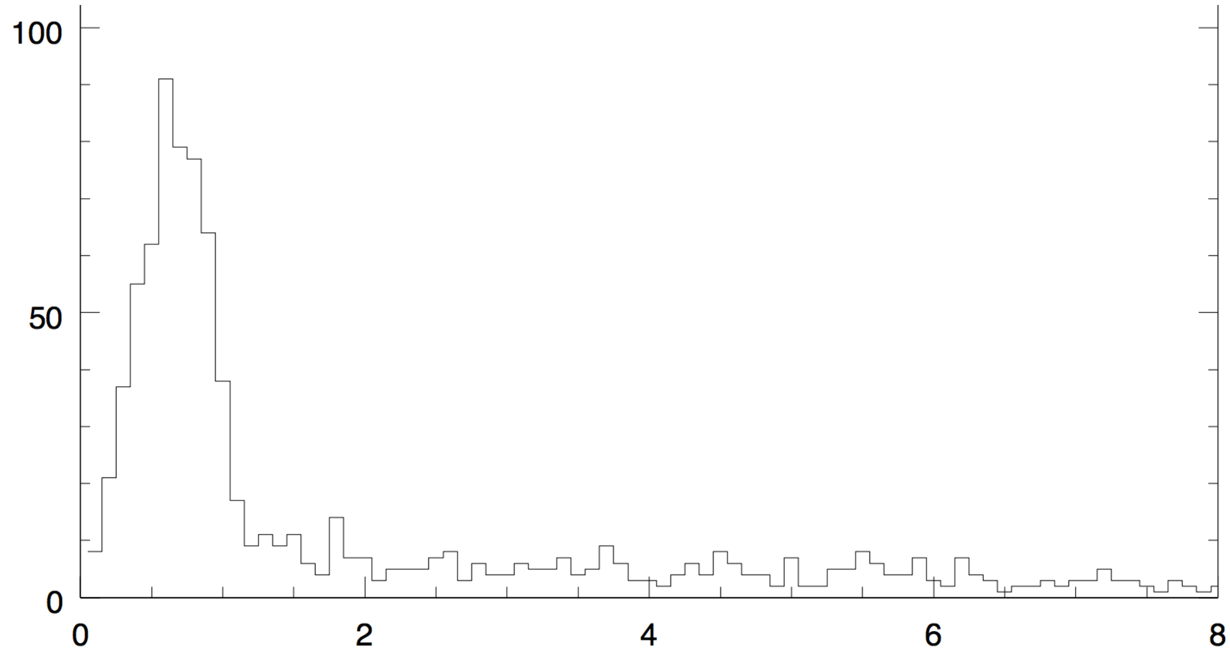
Evidence for MOND?

An alternative explanation

- Inner binary components with a < 100 AU are unresolved by GAIA
- If these components are unequal in mass,

photocentre moves wrt centre of mass of inner binary

Simulate population of randomly oriented binaries of which fraction f contains an inner binary with a in range 5-100 AU



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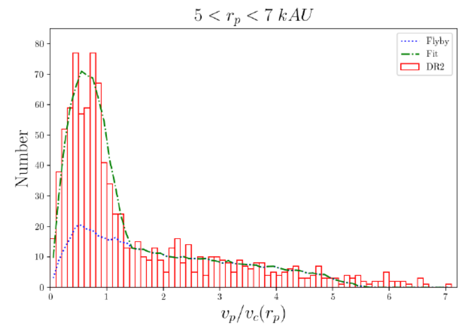

Shelf plausibly associated with contamination by triples − need to eliminate from sample before use to test gravity theories

Take home points:

- End to end simulations with plausible physics can't currently reproduce multiplicity data

B fields are the problem but they clearly exist

- GAIA can address key issues wrt initial clustering and wide binary creation mechanisms

(measuring eccentricity distributions from on-sky data)

- Intrepreting proper motion data of wide binaries

(to constrain formation mechanism or to test MOND) requires proper correction for inner binaries