Open cluster environments lead to small planetary systems

Kirsten Vincke, Susanne Pfalzner
Max Planck Institute for Radio Astronomy, Bonn

Stellar aggregates over mass and spatial scales

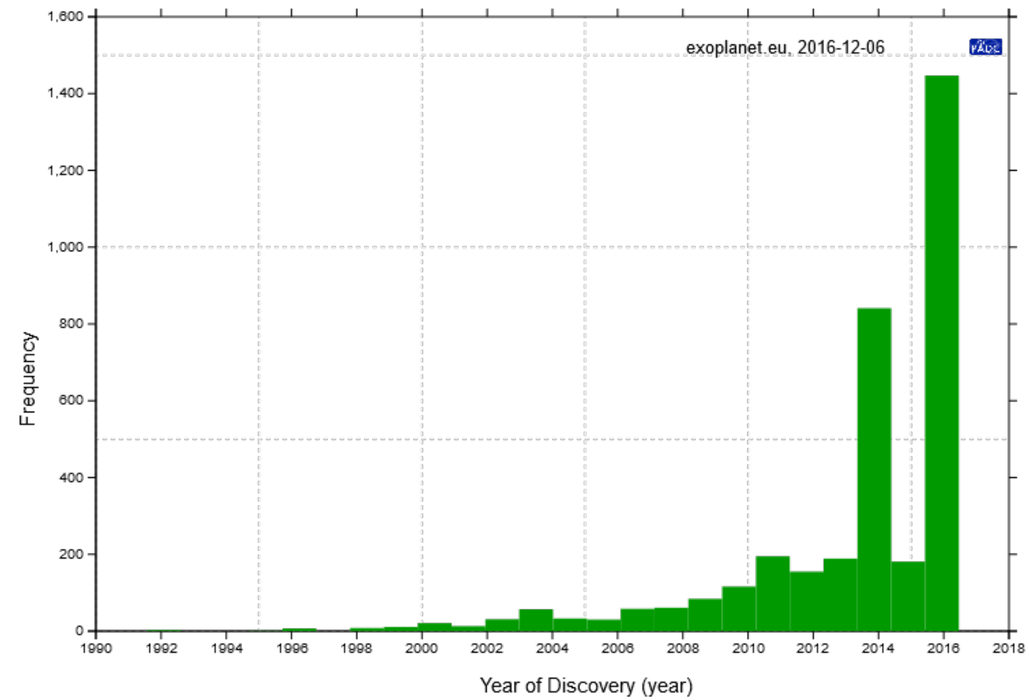
December 5 - 9, 2016
Bad Honnef

Why look at planetary systems in open clusters?

- Planet formation is very complicated
- Much discussion about timescales
- Past decade: 100-1,500 exoplanets/year
- But: mostly around field stars!

  Hard to constrain age!

- Solution: planetary systems in young stellar clusters!
  - Many stars close together
  - Easy to determine age



Observe clusters of different ages → get timeline for planet formation, migration...

Observations of planets in open clusters

Not that easy!

Search for transits (NGC 6791, NGC 2158, NGC 6791) Mochejska et al. (2002, 2004, 2005a)
Radial Velocity measurements (Hyades) Paulson et al. (2004)

few candidates (NGC 2158, Praesepe) Mochejska et al. (2005b), Pepper et al. (2008)

upper limit of planetary frequency in open clusters
NGC 2099: >1.1%-21% Hartman et al. (2009)
- larger than in Galactic field

compilation: 0.31%-5.5% van Saders & Gaudi (2011), Meibom et al. (2013)
- same frequency in open clusters as in field

Planets and planetary systems found in open clusters

Cluster	Cluster age [Myr]	Cluster mass [M_Sun]	Planet mass [M_Jup]	Semi-major axis [AU]	Eccentricity
NCG 4349	200		19.8	2.38	0.19
Praesepe	578	550	0.54	0.057	0
			1.8	0.03	0.011
			7.79	5.5	0.71
Hyades	625	300-400	7.6	1.93	0.151
			0.917	0.06	0.086
NGC 2423	750		10.6	2.1	0.21
NGC 6811	1,000	~3,000	≤ 0.06	0.1352	-
			≤ 0.06	0.1171	-
NGC 2682	3,500-4,000	1,080	0.34	0.07	0.24
			0.40	0.06	0.39
			1.54	0.53	0.35
			0.46	0.05	0.15

Questions

1. Are these very small planetary systems (number, properties etc) the exception or the rule in open clusters?

2. Are systems in open clusters different to the ones in associations (e.g. up to 500 AU in Orion Nebula Cluster)?

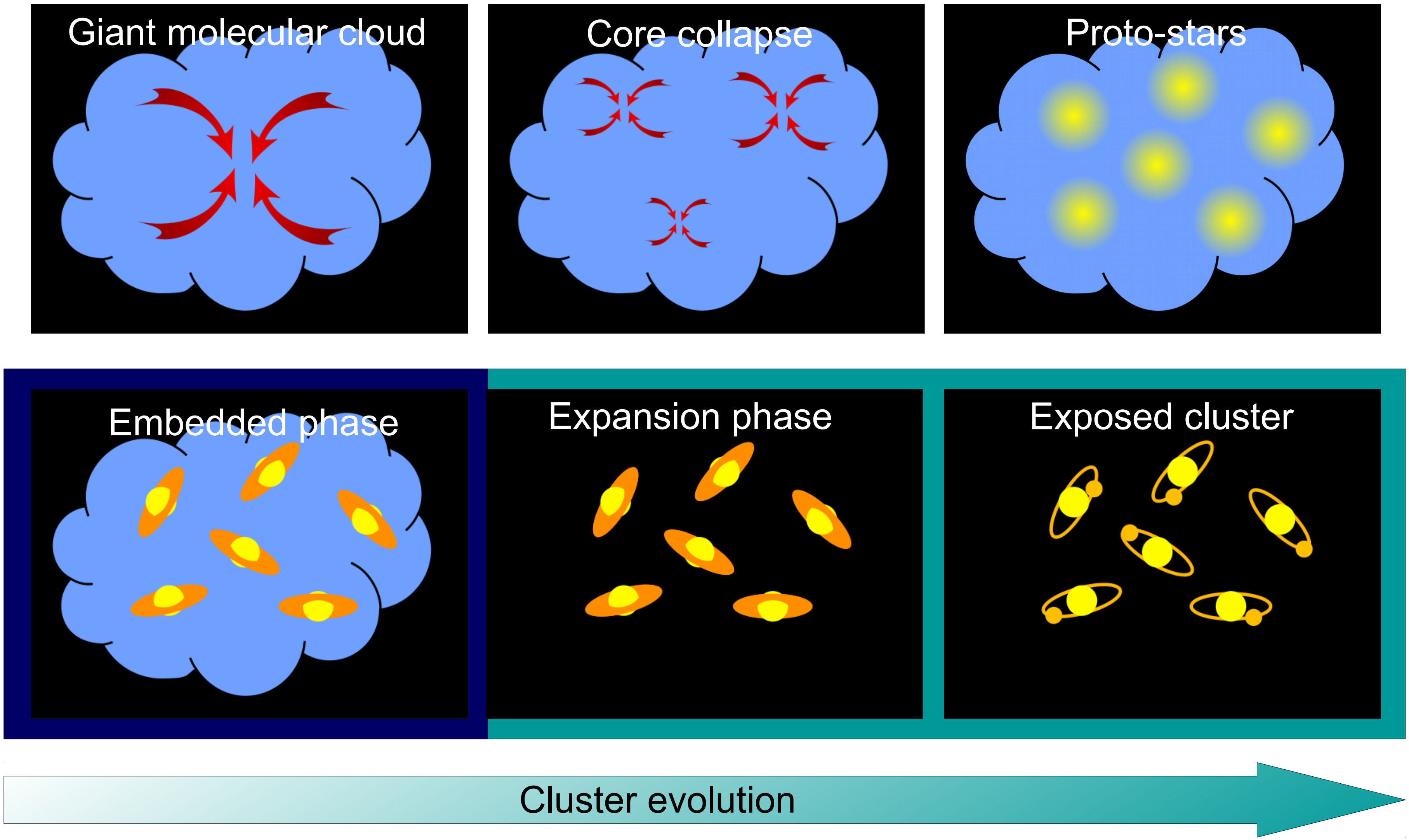
What we do:

Simulate young, massive, compact clusters (starburst cluster)

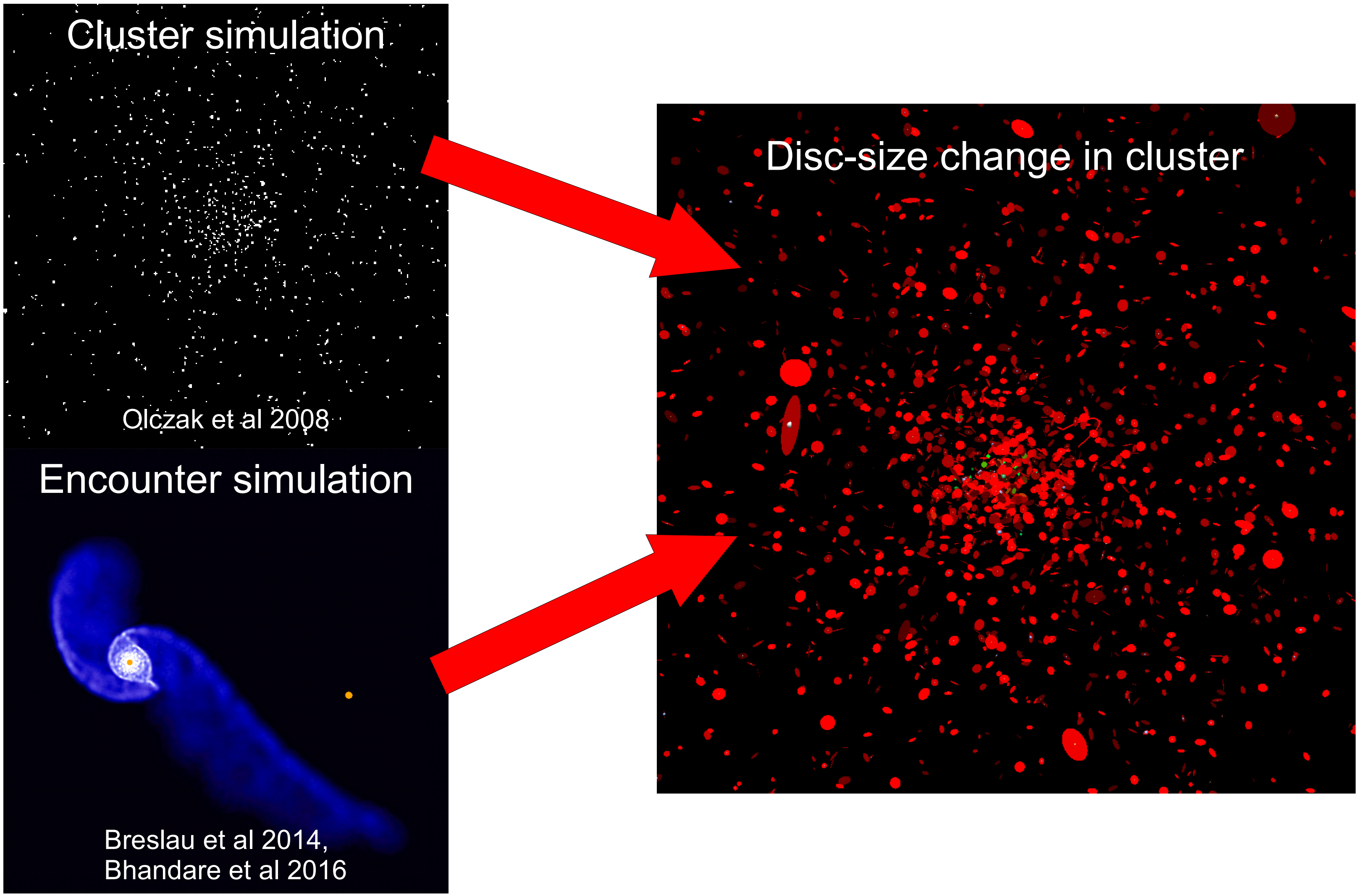
- Embedded phase
- Gas-expulsion
- Expansion phase

Investigate influence of environment on disc size (encounters)

Formation of stars & discs in stellar clusters



Simulations overview

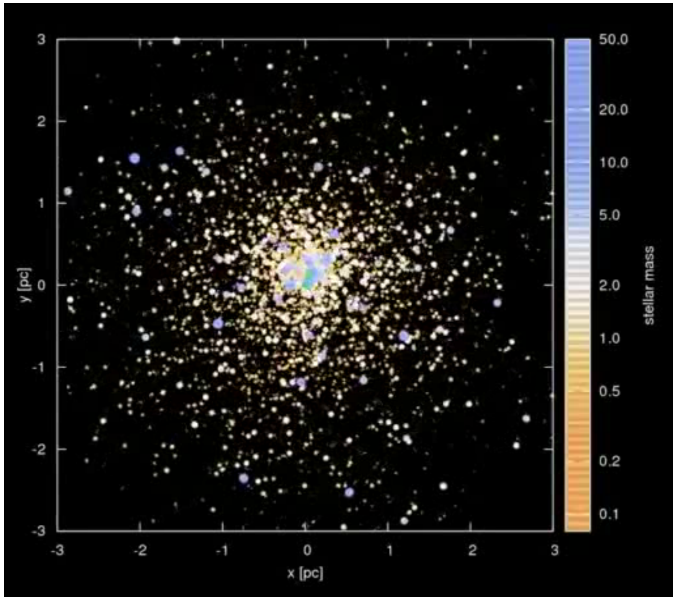


Simulations - clusters

Nbody6++ simulations (Aarseth 2003)

<u>Embedded, young, compact clusters:</u>

- 32,000 (single) stars
- Half-mass radius: 0.2 pc
- eSFE = 0.7 (Pfalzner & Kaczmarek 2013a,b)
- Stellar masses: IMF (0.08 – 150 M_{Sun})
- Gas mass modeled directly!
- Density profiles:
  - Stellar: King (W9)
  - Gas: Plummer
- Embedded phase: 0-1 Myr
- Gas expulsion: instantaneous
- Simulation time: 3 Myr

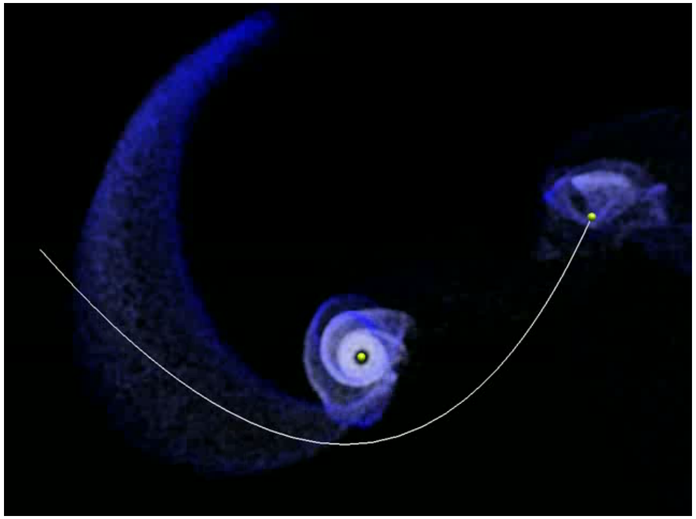


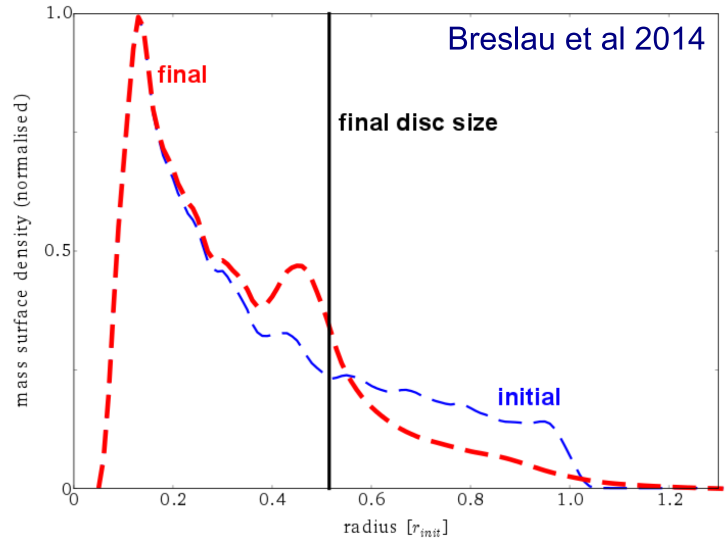
Steinhausen

<u>Output: encounter parameters</u>

Masses, periastron distance, distance to cluster center, eccentricity, time & duration

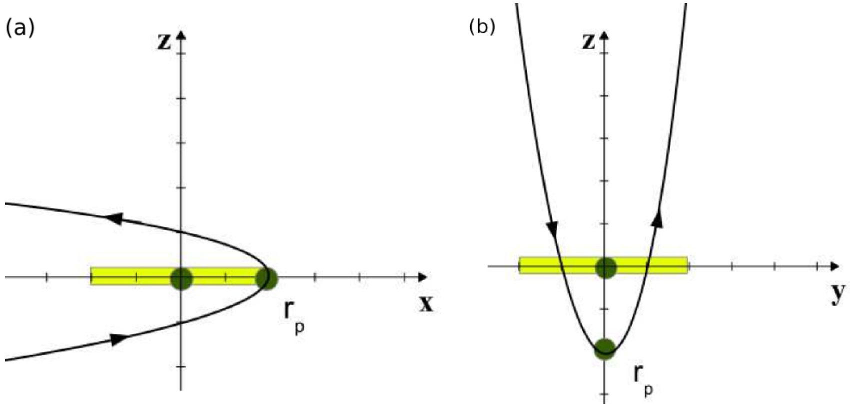
Simulations - discs



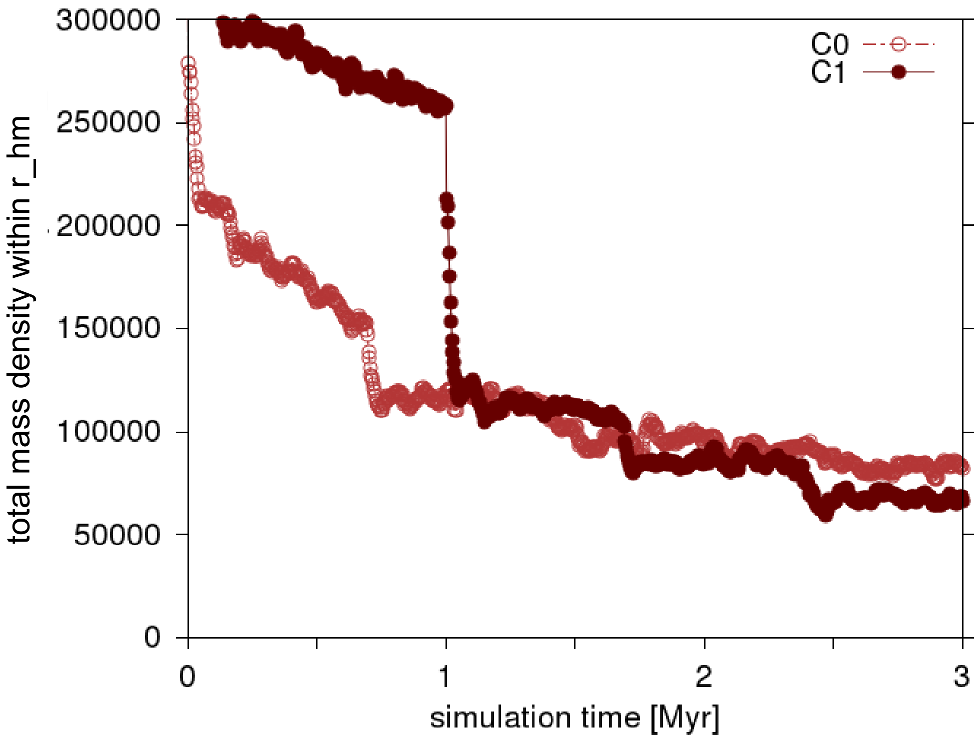


Disc size = highest contrast → Steepest point in density distribution

- Mass-less tracer particles (no viscosity, no self-gravity) Breslau et al. (2014)
- Orbit of perturber (possibly) inclined to disc plane (include all orientations!) Bhandare et al. (2016)
- Initial disc size: 200 AU

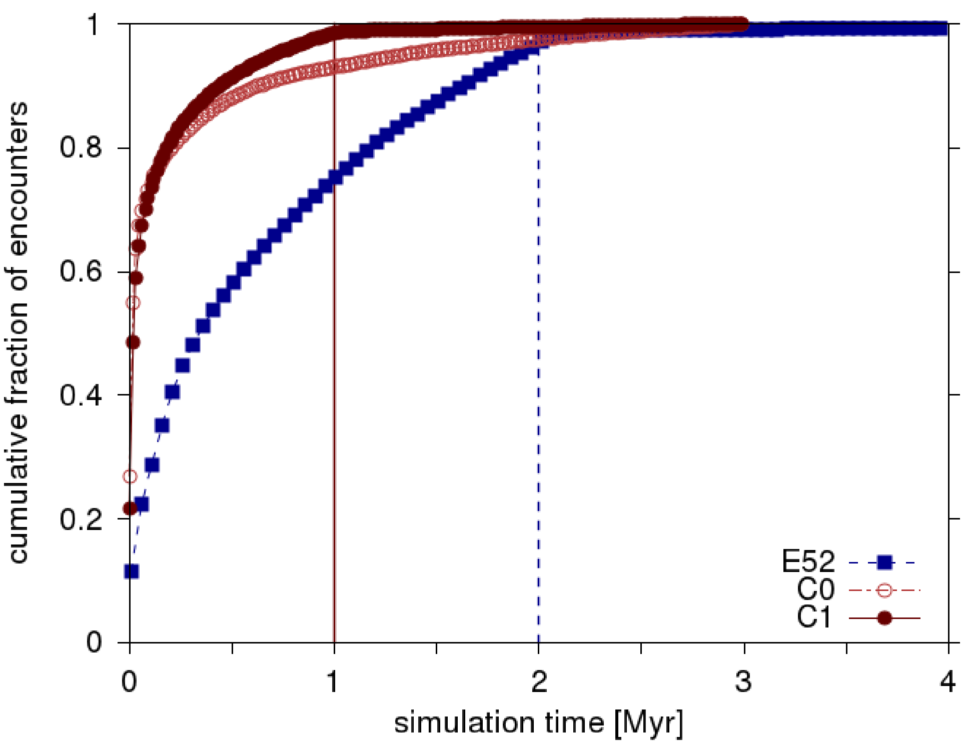


Mass-density evolution in clusters



- Total mass density (stars+gas) within half-mass radius (0.2pc)
- Model C0: “0” Myr embedded
  Model C1: 1 Myr embedded
- Steep drop in density after gas expulsion
- What does that mean for encounters?

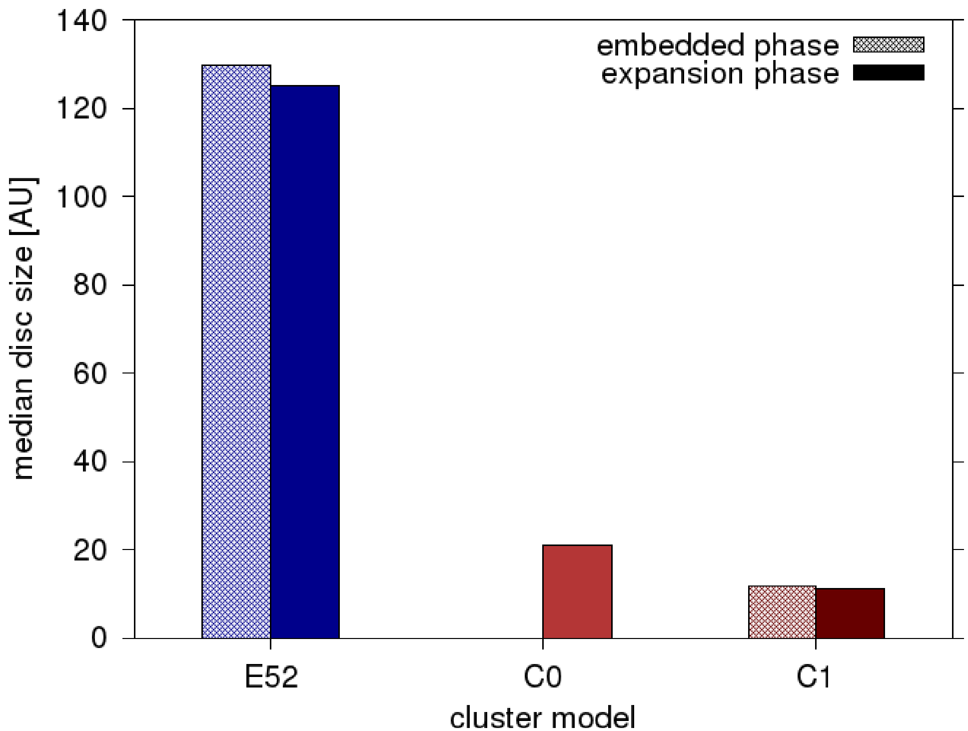
Encounter statistics

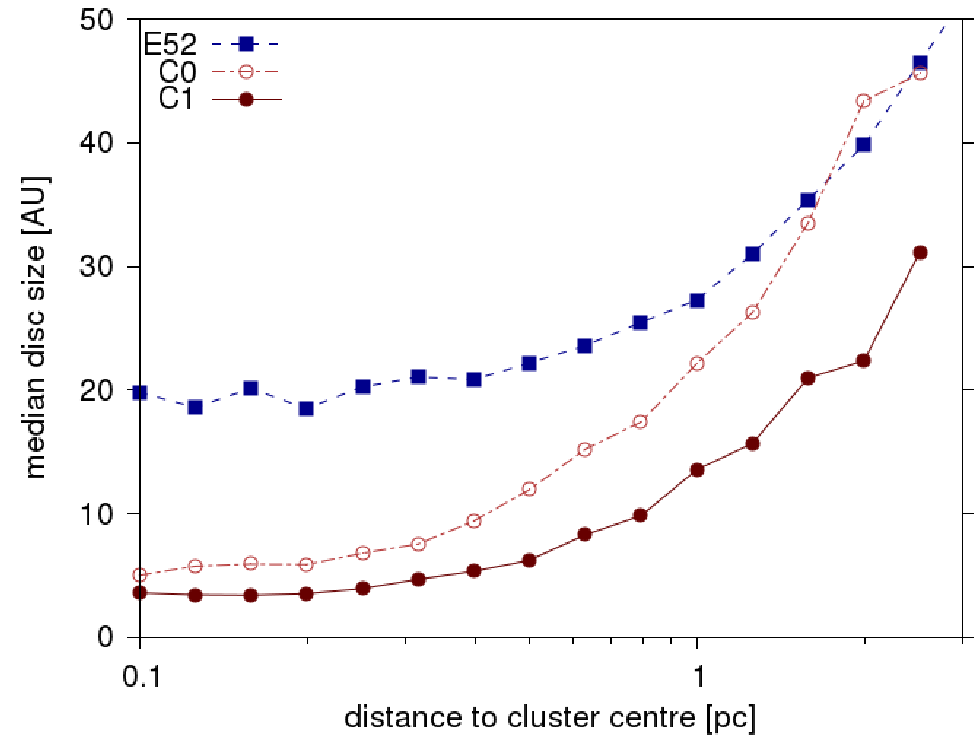


- For comparison:
  model E52 = massive association
  (32,000 stars, r_{hm} = 1.3 pc, 2 Myr emb.)
- C0: encounters happen frequently throughout 3 Myr
- C1: almost all encounters happen in embedded phase
- Average number of disc-size changing or disc-destroying encounters/star:

C0	C1	E52
~3.2	~4.0	~1.4

Median disc size

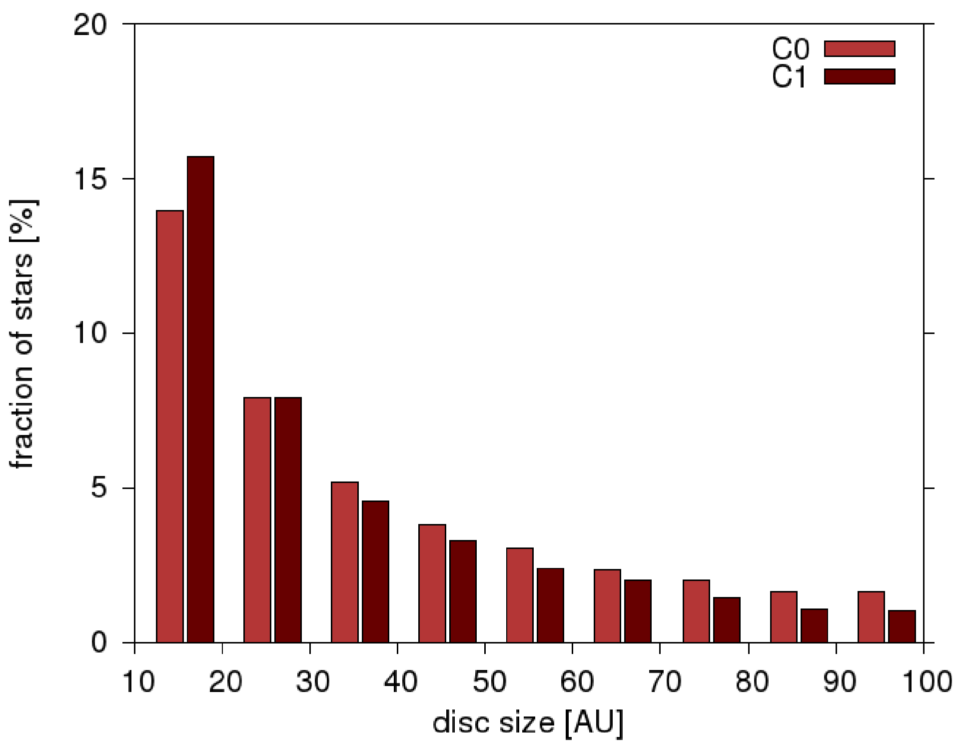




- Median disc size in compact clusters: 10 – 20 AU
- ~ factor of 10 smaller than in association

	C0/C1	E52
Core (0.3 pc):	~ 4 – 7 AU	~ 20 AU
1 pc:	~ 12 – 20 AU	~ 30 AU

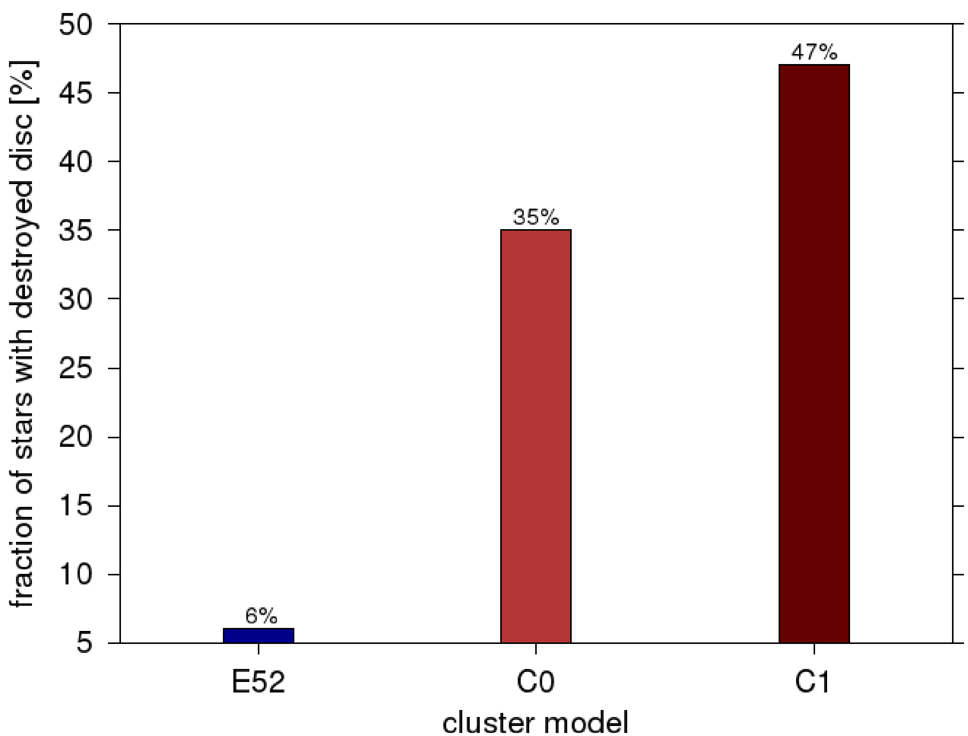
Disc-size distribution and disc destruction



- Very small disc sizes, e.g.
  14% - 16% between 10 – 20 AU

- C0: 9% > 100 AU 31% < 50 AU
  C1: 5% > 100 AU 32% < 50 AU
  E52: 18% > 100 AU 20% < 50 AU

Disc-size distribution and disc destruction



- Very small disc sizes, e.g.
  14% - 16% between 10 – 20 AU

C0:	9% > 100 AU	31% < 50 AU
C1:	5% > 100 AU	32% < 50 AU
E52:	18% > 100 AU	20% < 50 AU

- What about disc destruction?
- Assume discs < 10 AU to be destroyed
- More than 1/3 of all discs in C0 destroyed
- Nearly half of all discs in C1 destroyed!

Summary

- Simulations show: we would expect much smaller discs (> factor 6-10) in compact clusters than in associations

	Median size [AU]	Destroyed (<10 AU)	< 50 AU	sum
C0	11	35%	31%	66%
C1	21	47%	32%	79%
E52	121	6%		

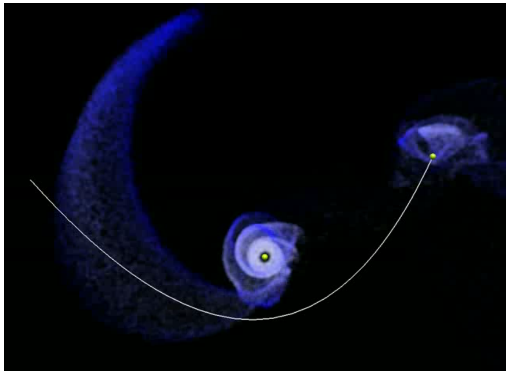
- Encounters shape discs in compact clusters quickly (first 0.1 Myr)
- Eventually forming planetary systems could be even smaller than disc size (external photoevaporation, formation inside disc, inward migration etc.) but disc can also expand (viscosity, e.g. Rosotti et al. 2014)

Application

- Example in Praesepe: planetary system

	Cluster Age [Myr]	Cluster mass [M_Sun]	Planet mass [M_Jup]	Semi-major axis [AU]	Eccentricity
Praesepe	578	550	1.8	0.03	0.011
			7.79	5.5	0.71

- After encounter:
  - inner disc: material on almost circular orbits
  - outer disc: much material on very eccentric orbits!



- Method applicable not only to discs but also to planetary systems ($m_{planet} << m_{star}$)
- Stellar encounter after planet formation could have caused eccentric orbit of outer planet while inner planet remained almost unperturbed

References for planets in open clusters and cluster properties

- NGC 4349: Lovis & Mayor (2007)
- NGC 2632: Delrome et al (2011), Kraus & Hillenbrand (2007), Quinn et al. (2012), Malavolta et al. (2016)
- Hyades: Perryman et al (1998), Sato et al. (1997), Quinn et al. (2014)
- NGC 2423: Lovis & Mayor (2007)
- NGC 6811: Janes et al. (2013), Meibom et al. (2013)
- NGC 2682: Sarajedini et al (2009), Richer et al. (1998), Brucalassi et al. (2014), Pietrinferni et al. (2004), Brucalassi et al. (2016)