The birth stellar cluster of the Solar System

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Parker, RC, Davies & Meyer (2014) *MNRAS* **437** 946
Gustafsson, RC et al. (submitted)

Summary

Can the Solar System exist?

Did the Sun come from M67?

Chemical constraints

Meteorites contain decay products of radioactive isotopes ^{26}Al and ^{60}Fe.

Lee et al. (1976)

Most likely source of ^{26}Al and ^{60}Fe is a supernova close to the Sun whilst it still has a planet-forming disc.

E.g. Chevalier (2000)

The Sun should be between 0.1 and 0.3 pc away from the supernova.

Adams et al. (2010)

Recent results cast doubt on ^{60}Fe abundance but still require a clustered formation environment.

Tang & Dauphas (2012)

Dynamical constraints

Dynamical encounters in planetary systems can be very dangerous to planetary systems:

Close encounters can remove planets.

Remaining planets end up on eccentric, inclined orbits that may destabilise the planetary system.

Close encounters of protoplanetary discs with cluster stars can truncate or evaporate the discs.

The Sun is probably one of the ~15% of "singleton" stars that has always been single and never had an encounter

Armitage (2000); Kobayashi & Ida (2001); Adams et al. (2004, 2006); Theis, Kroupa & Theis (2005); Malmberg et al. (2007a, 2007b, 2011); Forgan & Rice (2009); Pfalzner (2013)

Star and cluster masses

Relationship between cluster mass and maximum stellar mass:

May have a physical origin i.e. low-mass clusters with high-mass stars are impossible

(Weidner & Kroupa 2006)

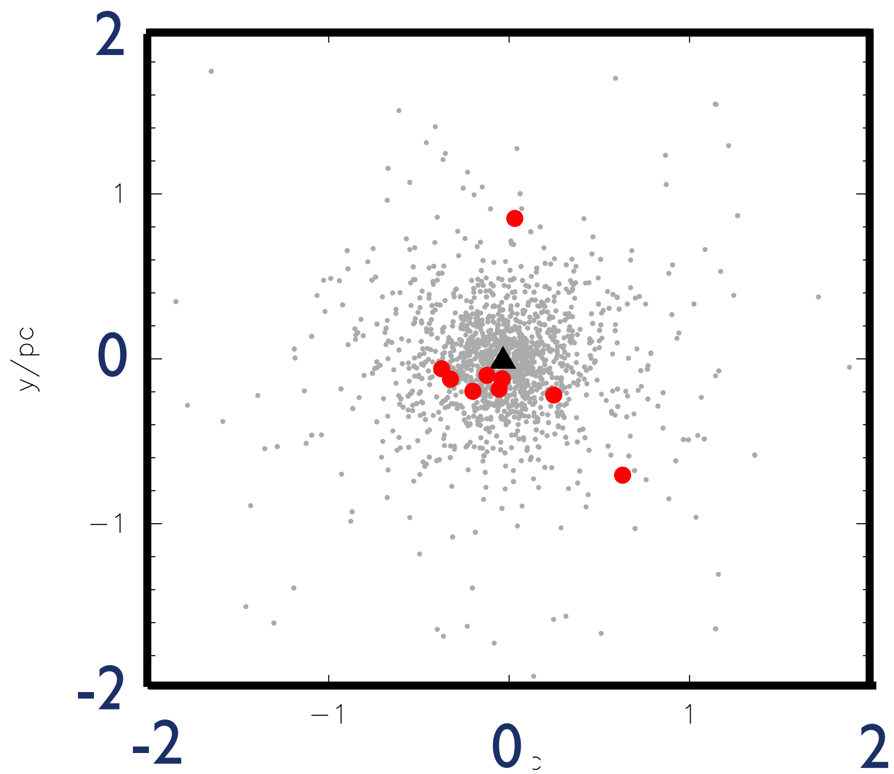
May have a statistical origin; i.e. low-mass clusters with high-mass stars are rare

(Parker & Goodwin 2007; Maschberger & Clarke 2008)

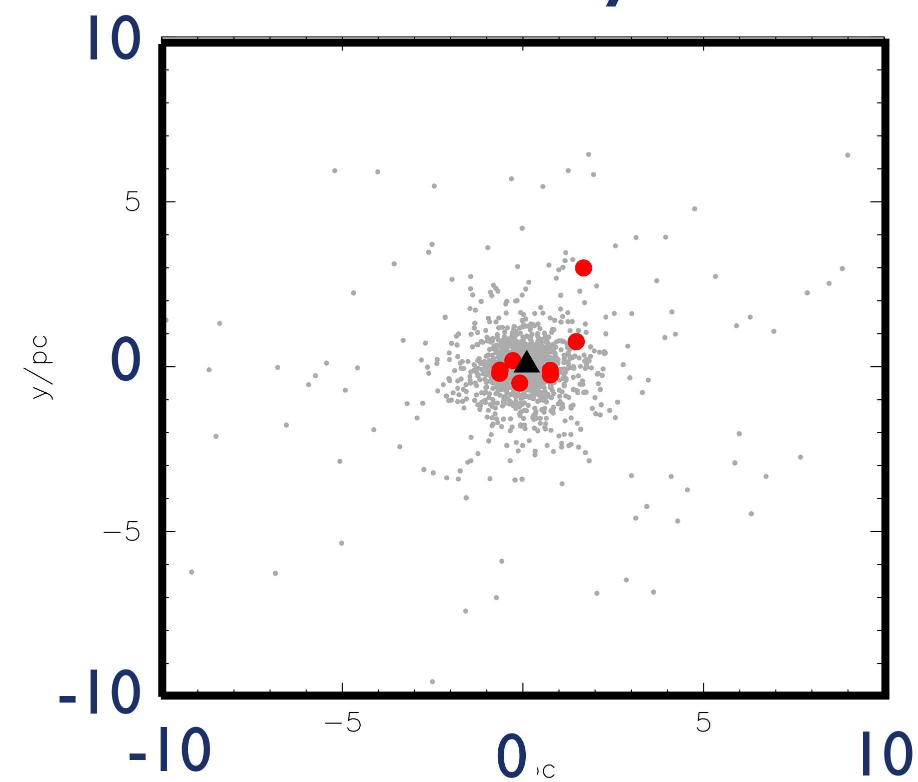
We adopt a cluster model that is consistent with both approaches (2100 stars, one $25\,M_{\odot}$ star, 96 G-dwarfs).

Dynamical evolution

Start



6.6 Myr



▲ $25\,M_\odot$ star

● Other massive stars

Cluster expands, stars interact, mass segregation occurs

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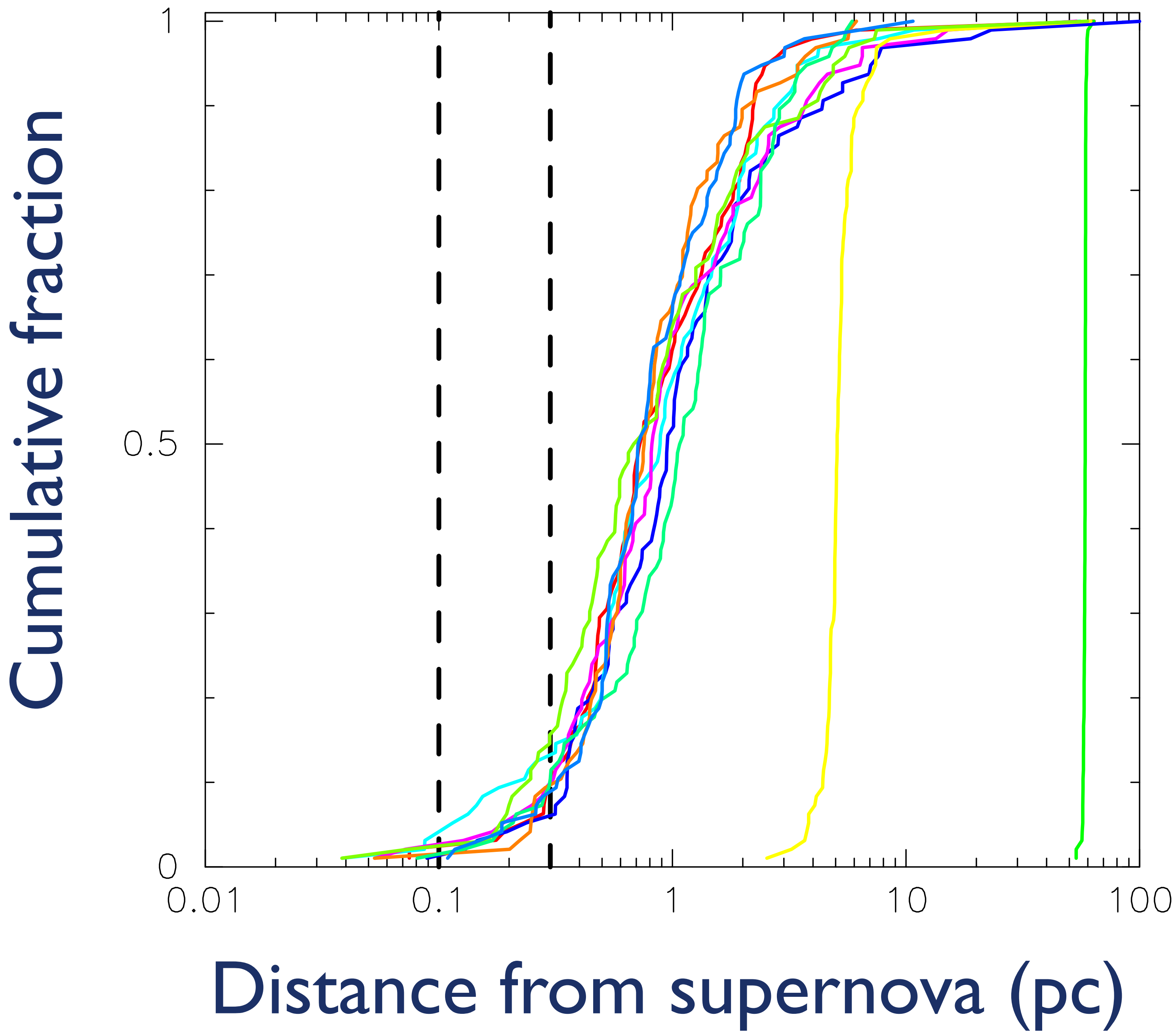
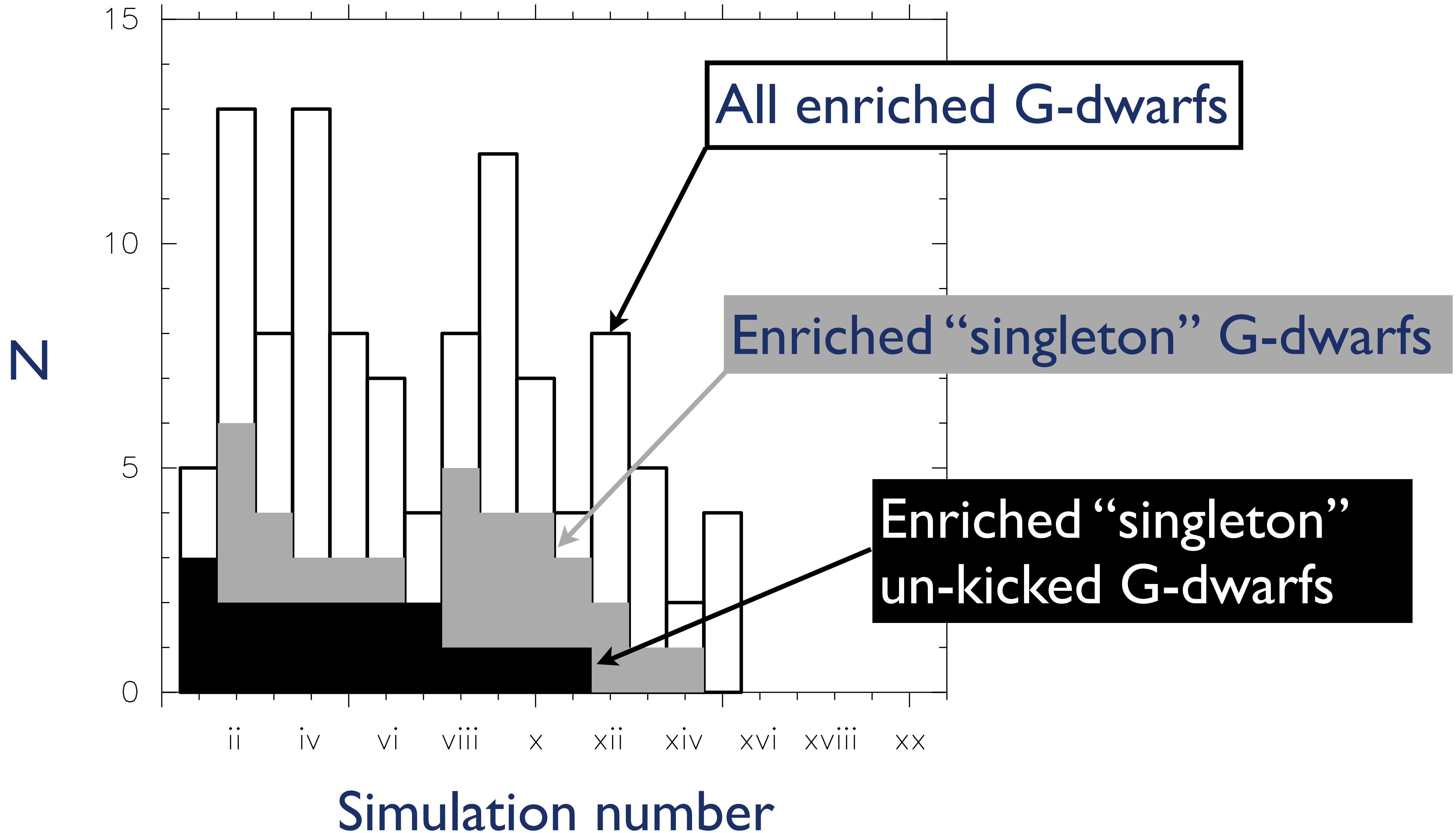
Distances from supernova



Typically about 10% of G-dwarfs are enriched

Dynamical effects



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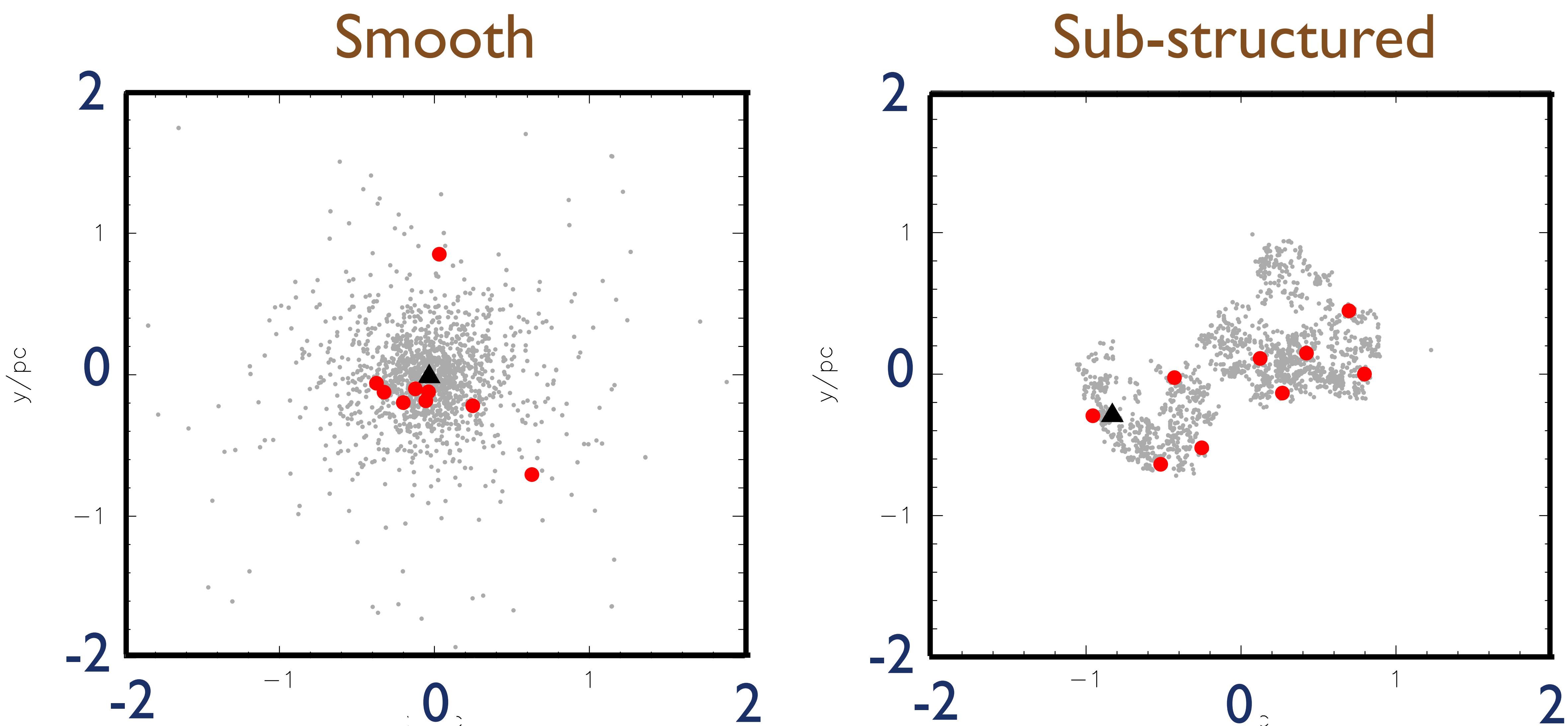
Spatial distribution

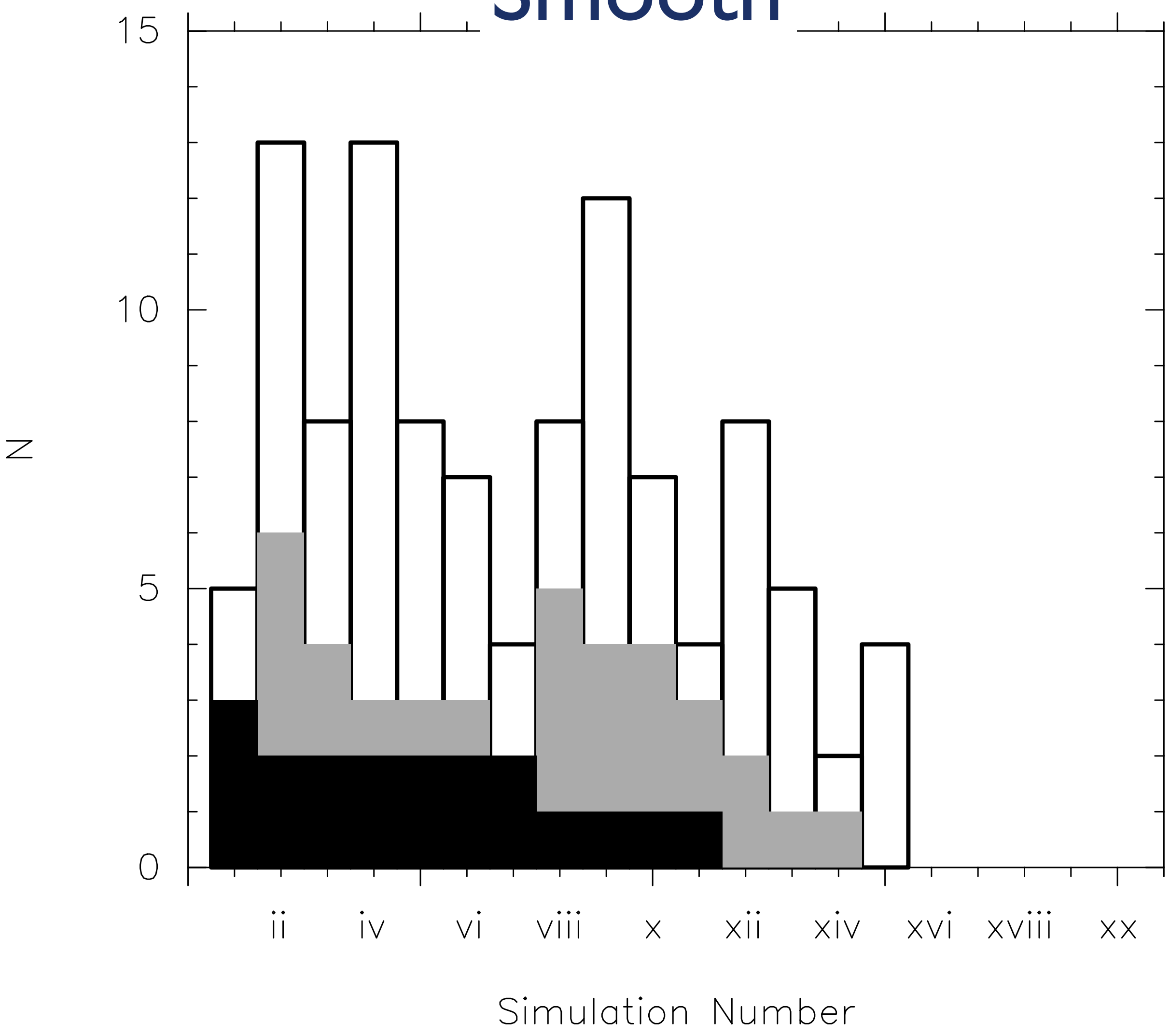
Young clusters are significantly sub-structured.

Sub-structure increases early dynamical activity.

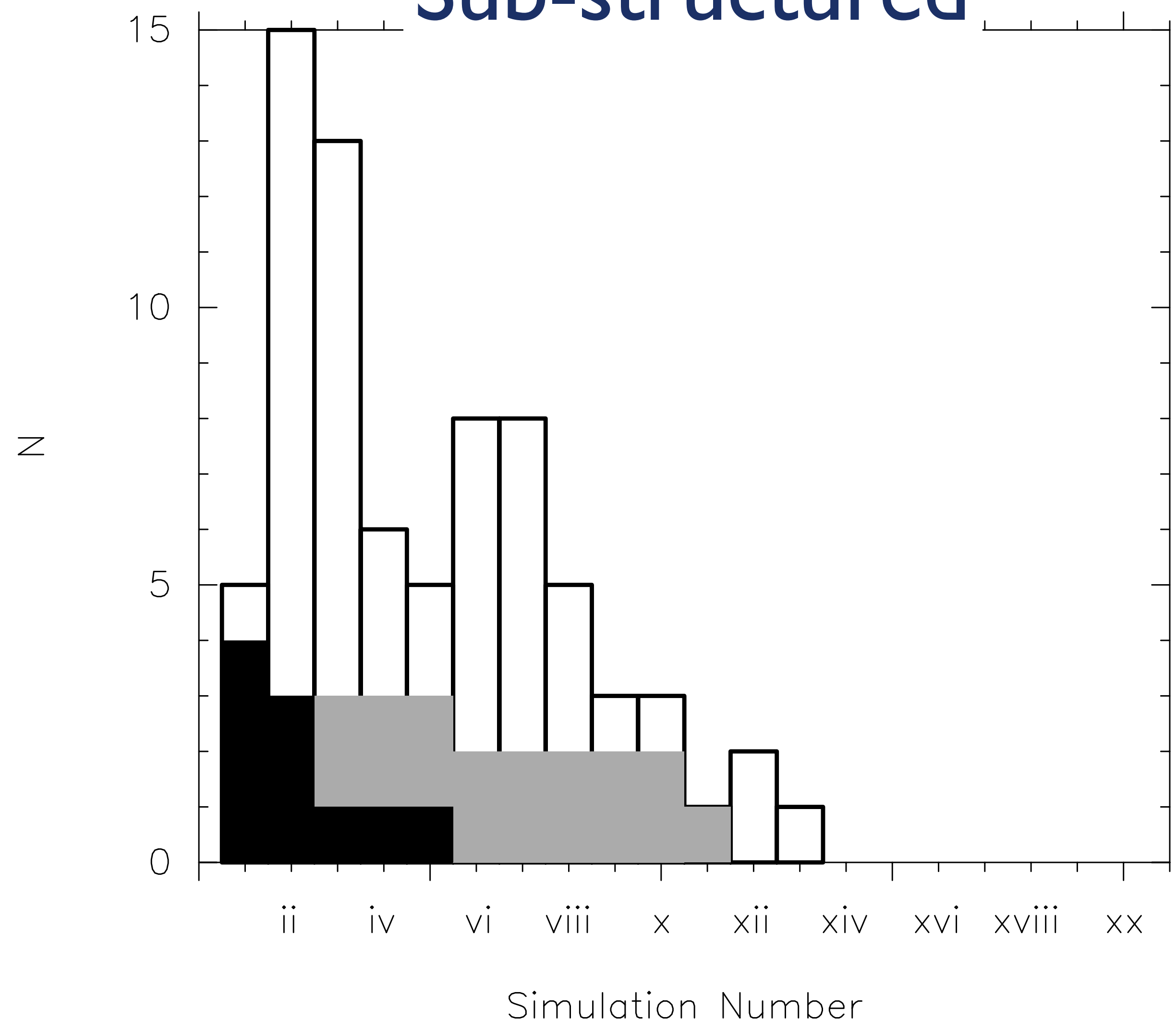


Effects of sub-structure

Smooth



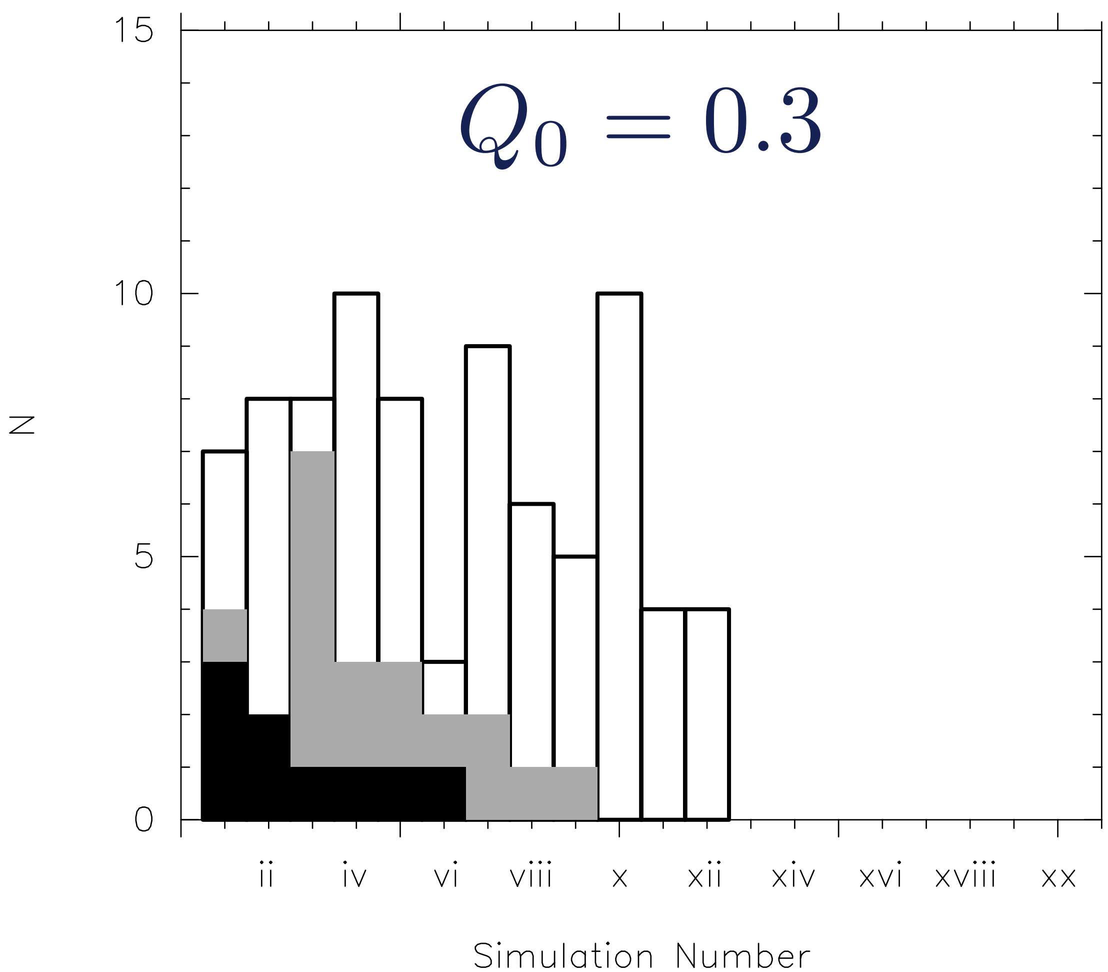
Sub-structured

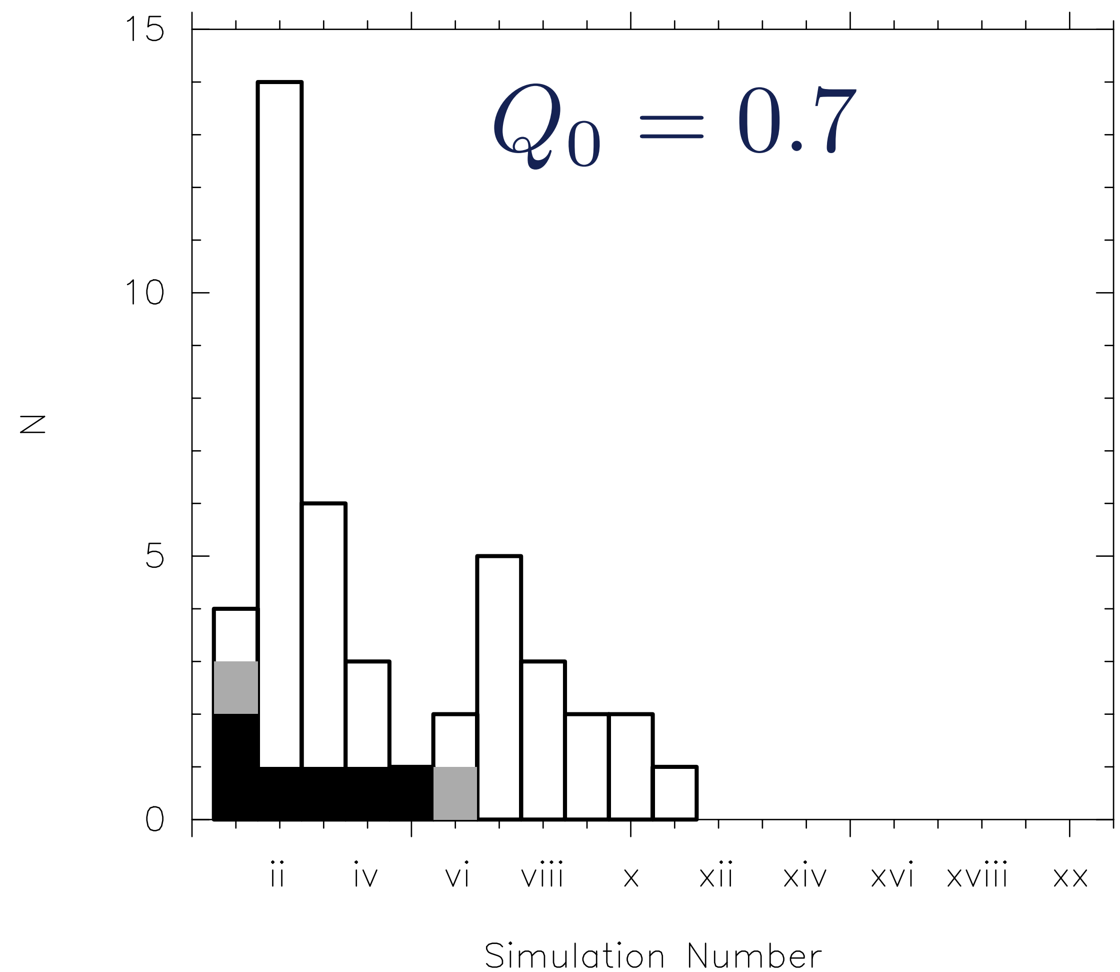


Sub-structure reduces number of enriched, unperturbed stars (but not by much)

Effect of virial ratio

$$Q = \frac{\text{kinetic energy}}{\text{potential energy}}$$





Virial ratio has a small effect on results

Summary

A typical 2000-star cluster contains a massive star suitable to enrich the Solar System.

On average a few G-dwarfs are close enough to be enriched.

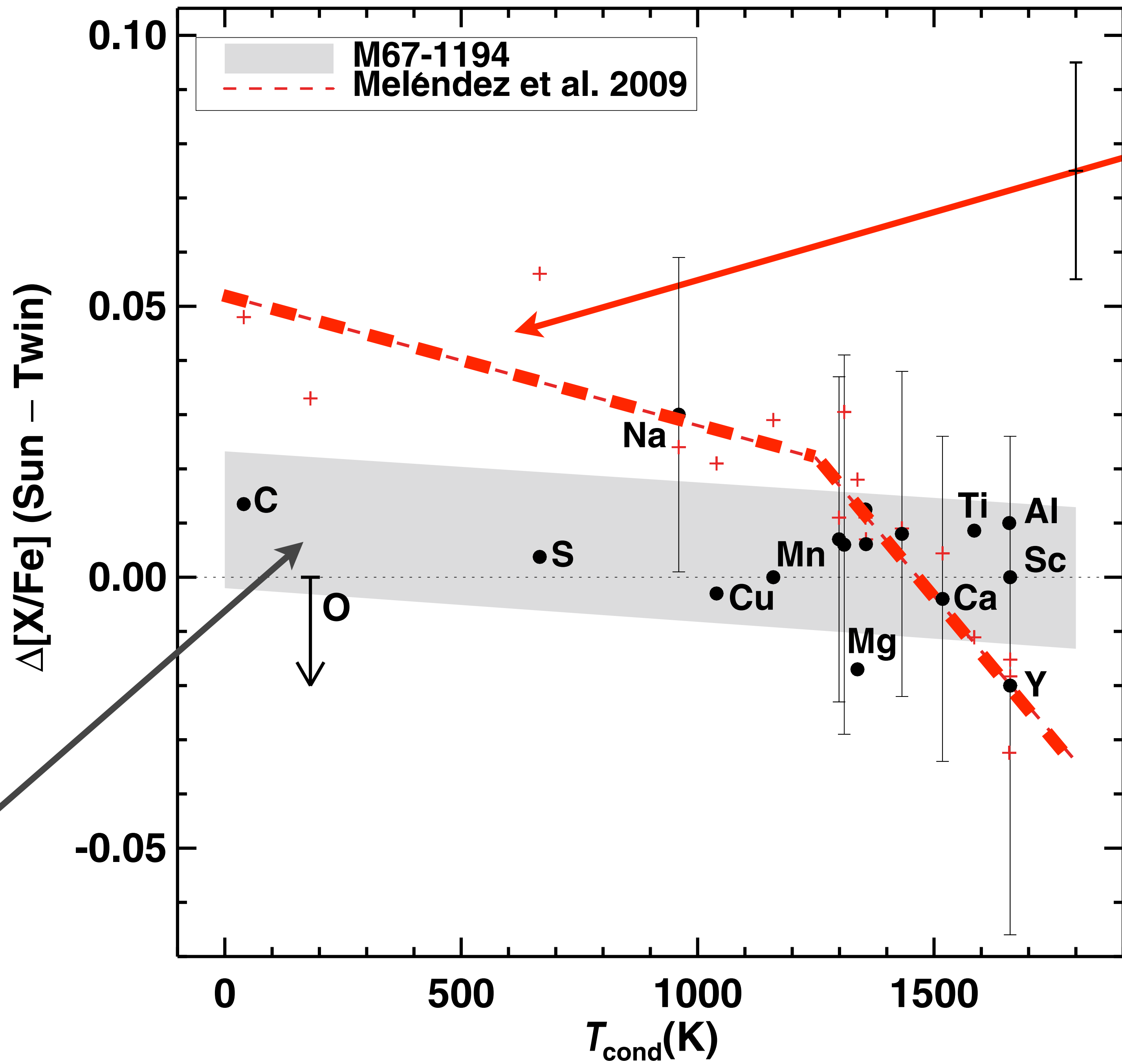
In about a third of these clusters there is a G-dwarf that is both close enough and dynamically unperturbed.

Planetary systems enriched like the Solar System should be unusual, but common

Parker, RC, Davies & Meyer (2014) *MNRAS* **437** 946

Did the Sun come from M67?

Solar twins and M67

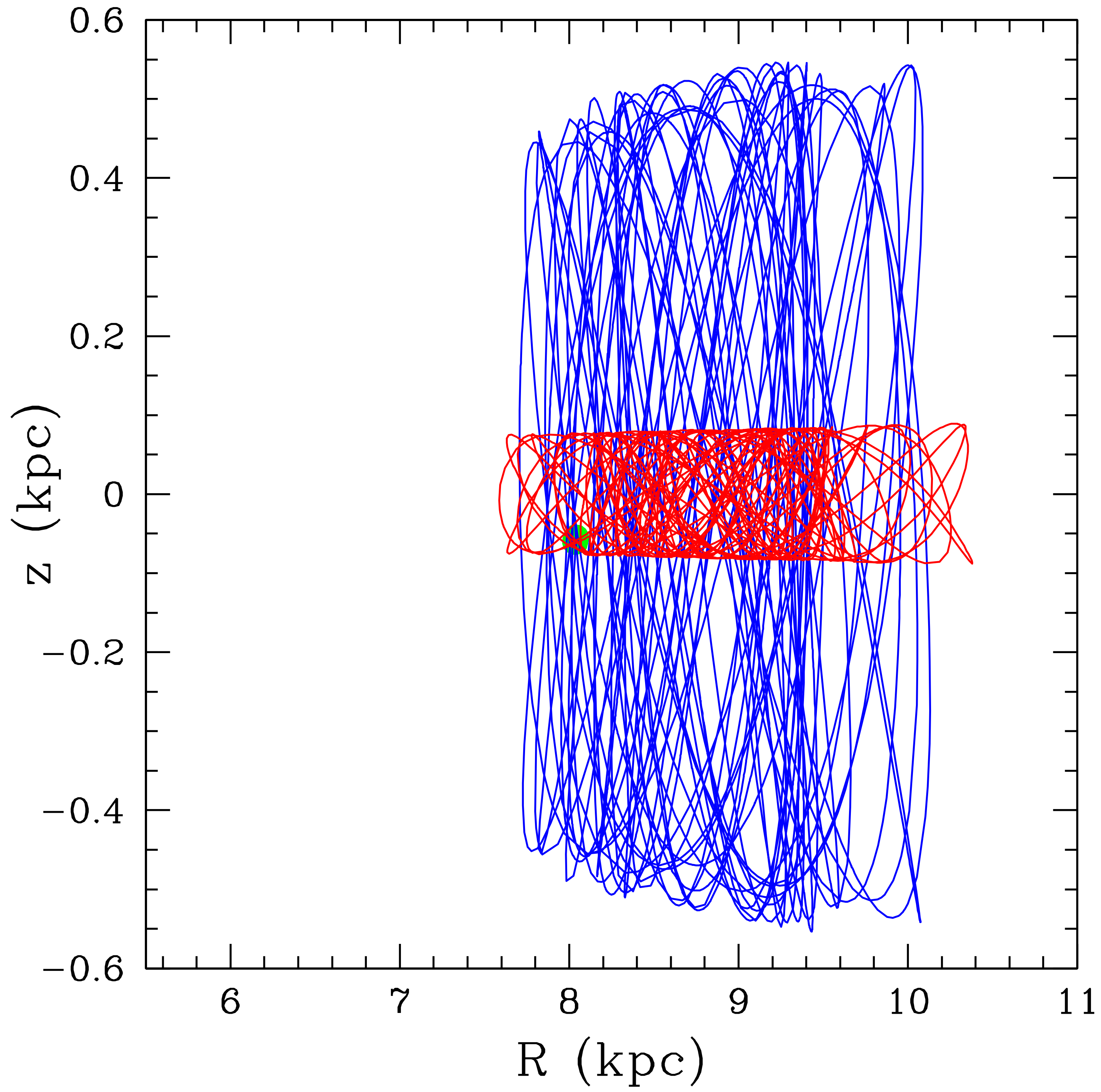


Trend for solar twins outside M67

Range of trends for M67-1194

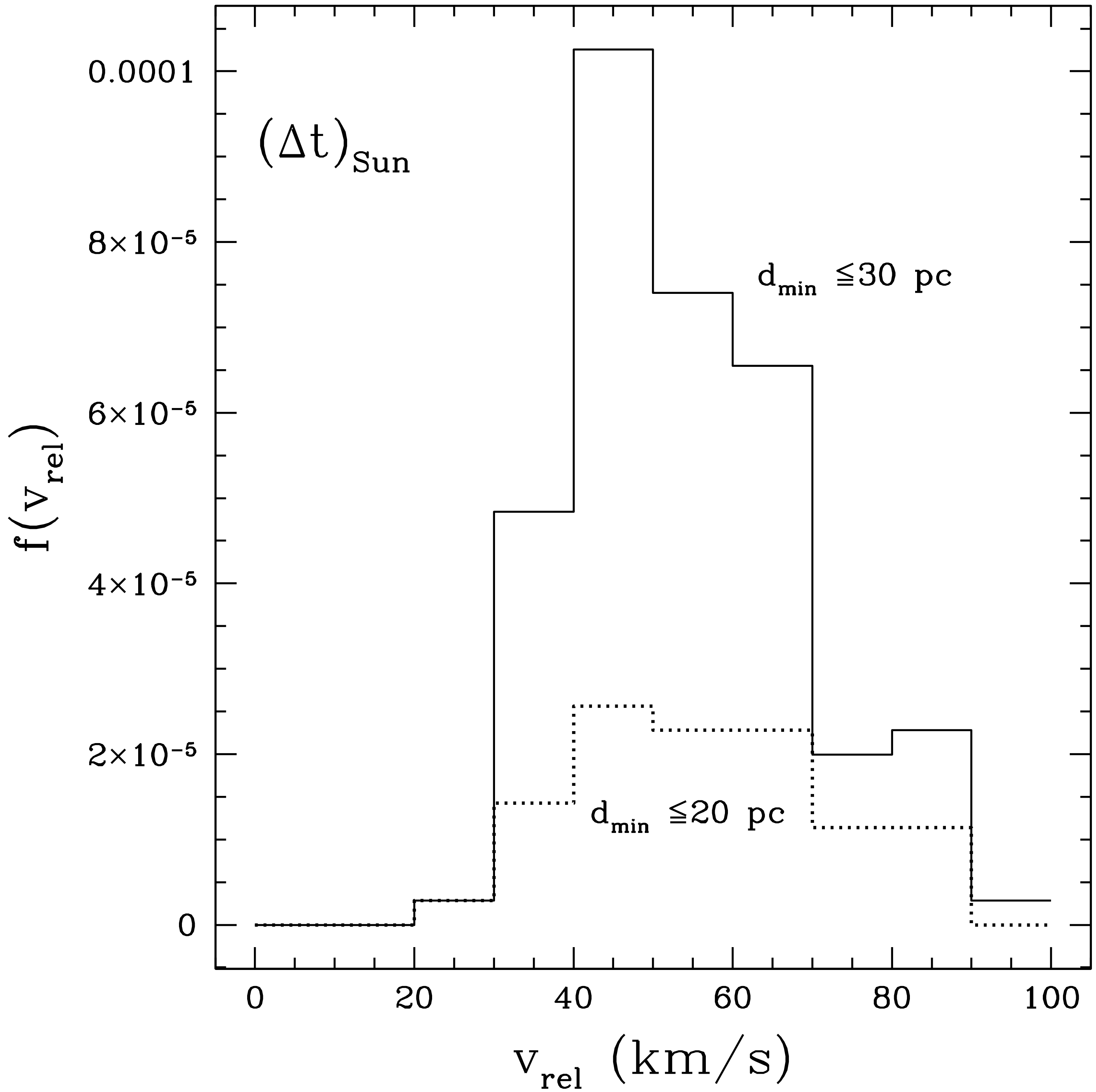
Önehag et al. (2011) *A&A* **528** 85

The Sun's orbit differs from M67's



Pichardo et al. (2012) *AJ* **143** 73

The Sun was not born in M67?



Pichardo et al. (2012) *AJ* **143** 73

M67's orbit has changed!

Star formation rate at M67's latitude today, from:

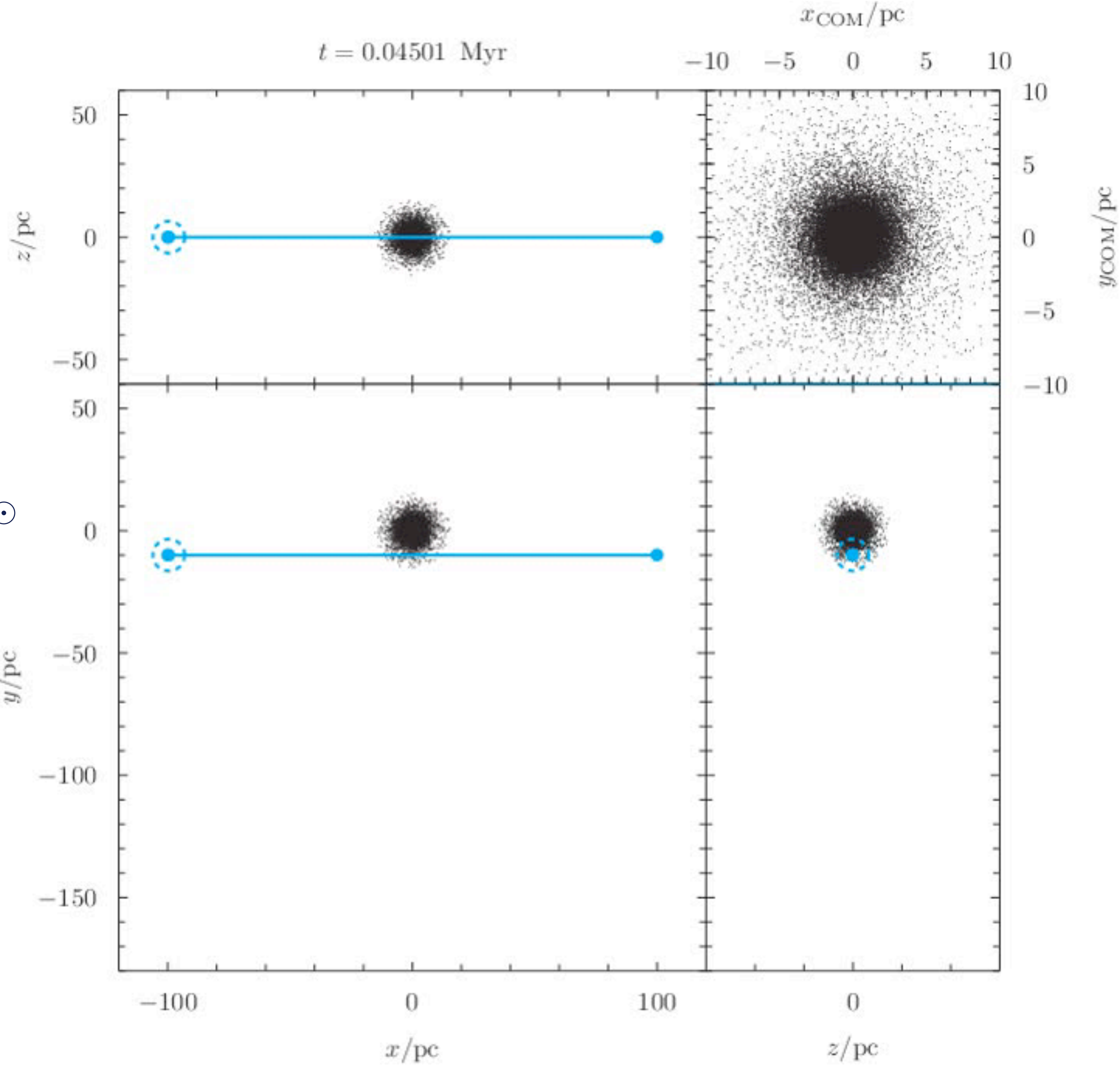
$$\text{A-stars: } \dot{n} \leq 2 \times 10^{-4}\,\text{pc}^{-3}\,\text{Gyr}^{-1}$$
$$\text{B-stars: } \dot{n} \leq 10^{-4}\,\text{pc}^{-3}\,\text{Gyr}^{-1}$$

To form at these lattitudes M67 requires a box
1 kpc x 1 kpc x 100 pc x 1 Gyr

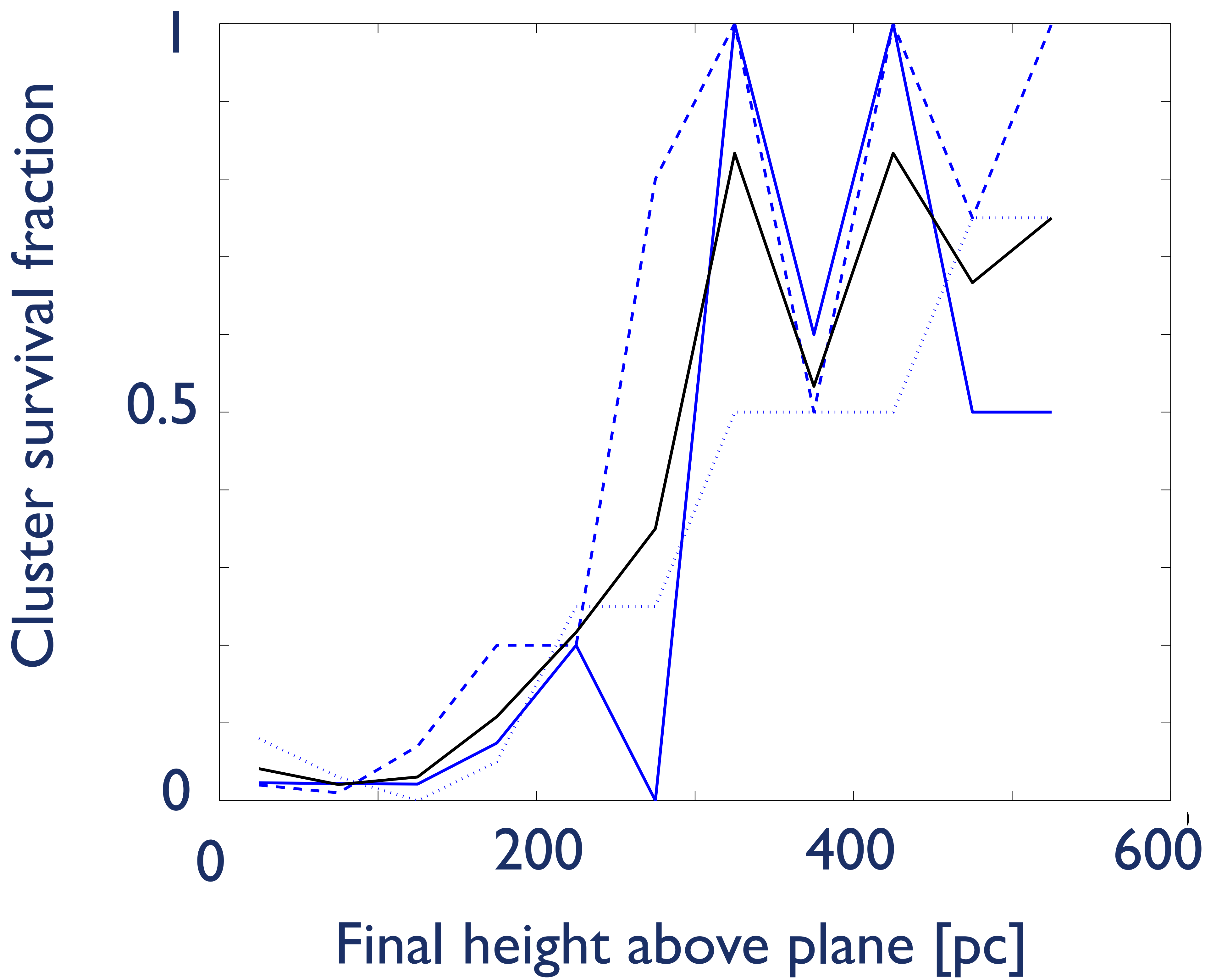
- There should be lower-mass counterparts
- The B-stars are probably mostly runaways
- Our assumptions were very optimistic

Scattering off a giant molecular cloud

$$M = 3 \times 10^5\, M_\odot$$
$$b = 10\,\mathrm{pc}$$
$$r_\mathrm{h} = 2\,\mathrm{pc}$$
$$v_\infty = 10\,\mathrm{km\,s^{-1}}$$
$$\frac{\Delta E}{E} \simeq 0.25$$



Survival of stellar clusters



Summary

M67 did not form on its current orbit.

We show that it could have survived being scattered from the disc into its present orbit by encounters with giant molecular clouds.

Careful abundance analysis suggests M67 is an interesting candidate for the birthplace of the Sun.

Gustafsson, RC, Davies & Rickman
(submitted to *A&A*)

Conclusions

Can the Solar System exist?

Meteoritic abundances suggest that the Sun probably formed in a stellar cluster.

Unperturbed G-dwarfs form in 2000-star clusters, but are relatively unusual.

Did the Sun come from M67?

The stars with the most solar-like abundances are in M67.

A solar origin in M67 is not ruled out by dynamical arguments.