# Why are some massive stars found in clusters and others in OB associations?

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Siena, Thursday 31 October 2024

# Queen, Oasis or Bruce Springsteen?

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# The Queen scenario

- Lada & Lada (2003).
- Most stars are formed in clusters.
- Most clusters dissolve when their natal gas is dispersed.
- OB associations are coeval disolved clusters.

Annu. Rev. Astron. Astrophys. 2003. 41:57–115
doi: 10.1146/annurev.astro.41.011802.094844


## EMBEDDED CLUSTERS IN MOLECULAR CLOUDS

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**Key Words** clusters, star formation, initial mass function, circumstellar disks, brown dwarfs

■ **Abstract** Stellar clusters are born embedded within giant molecular clouds (GMCs) and during their formation and early evolution are often only visible at infrared wavelengths, being heavily obscured by dust. Over the past 15 years advances in infrared detection capabilities have enabled the first systematic studies of embedded clusters in galactic molecular clouds. In this article we review the current state of empirical knowledge concerning these extremely young protocluster systems. From a survey of the literature we compile the first extensive catalog of galactic embedded clusters. We use the catalog to construct the mass function and estimate the birthrate for embedded clusters within ∼2 kpc of the sun. We find that the embedded cluster birthrate exceeds that of visible open clusters by an order of magnitude or more indicating a high infant mortality rate for protocluster systems. Less than 4–7% of embedded clusters survive emergence from molecular clouds to become bound clusters of Pleiades age. The vast majority (90%) of stars that form in embedded clusters form in rich clusters of 100 or more members with masses in excess of 50 $M_\odot$. Moreover, observations of nearby cloud complexes indicate that embedded clusters account for a significant (70–90%) fraction of all stars formed in GMCs. We review the role of embedded clusters in investigating the nature of the initial mass function (IMF) that, in one nearby example, has been measured over the entire range of stellar and substellar mass, from OB stars to substellar objects near the deuterium burning limit. We also review the role embedded clusters play in the investigation of circumstellar disk evolution and the important constraints they provide for understanding the origin of planetary systems. Finally, we discuss current ideas concerning the origin and dynamical evolution of embedded clusters and the implications for the formation of bound open clusters.

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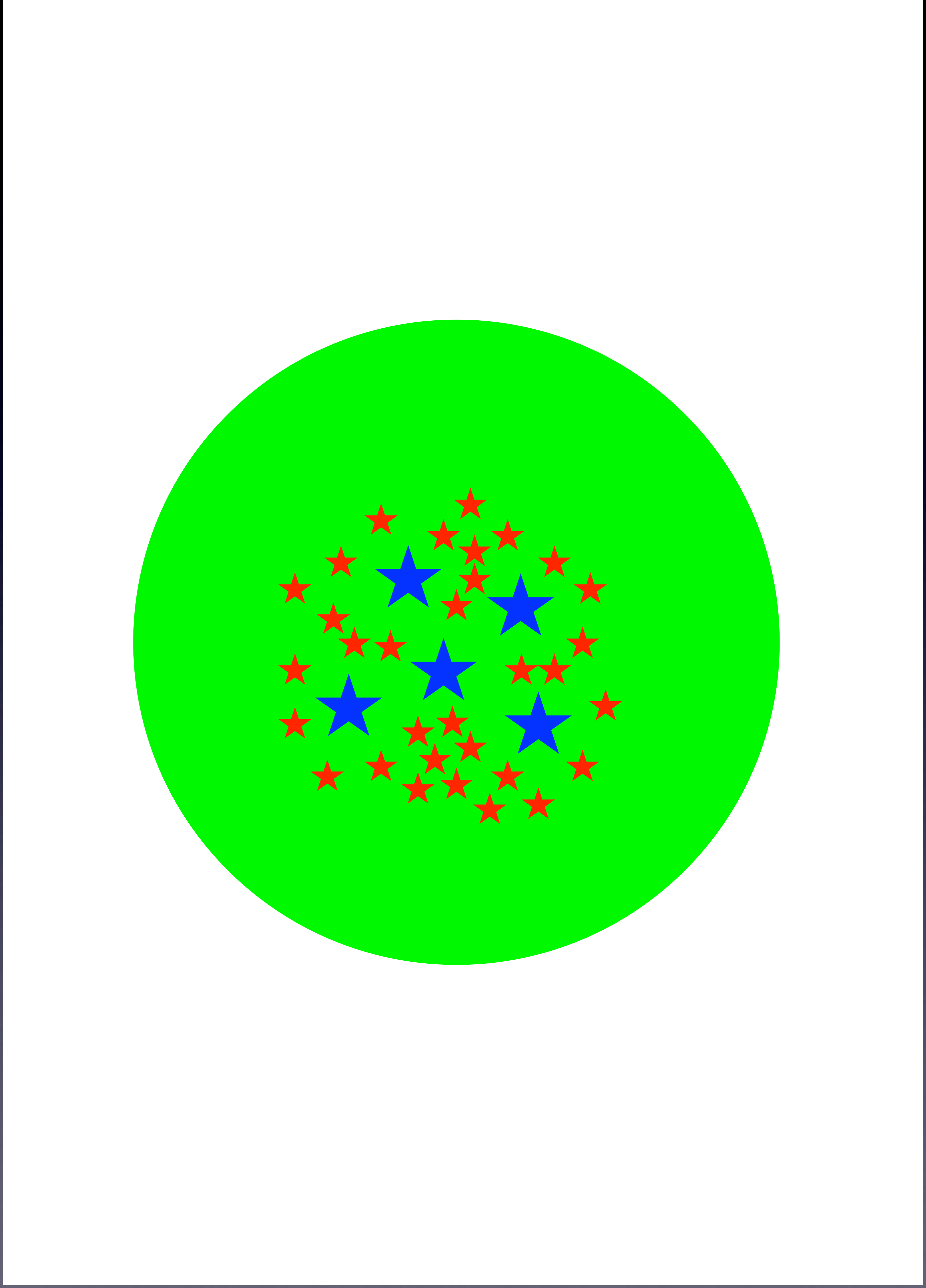

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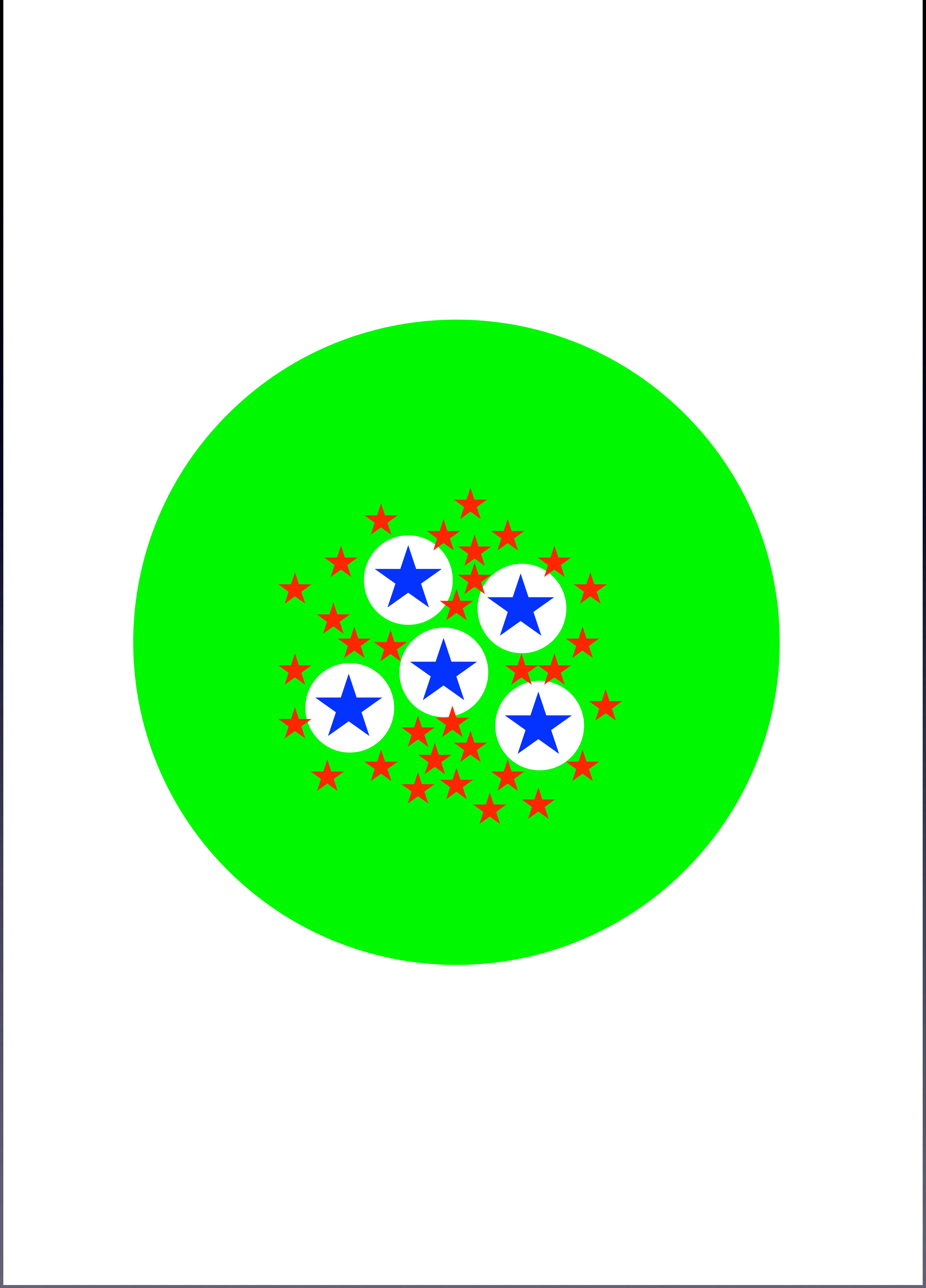

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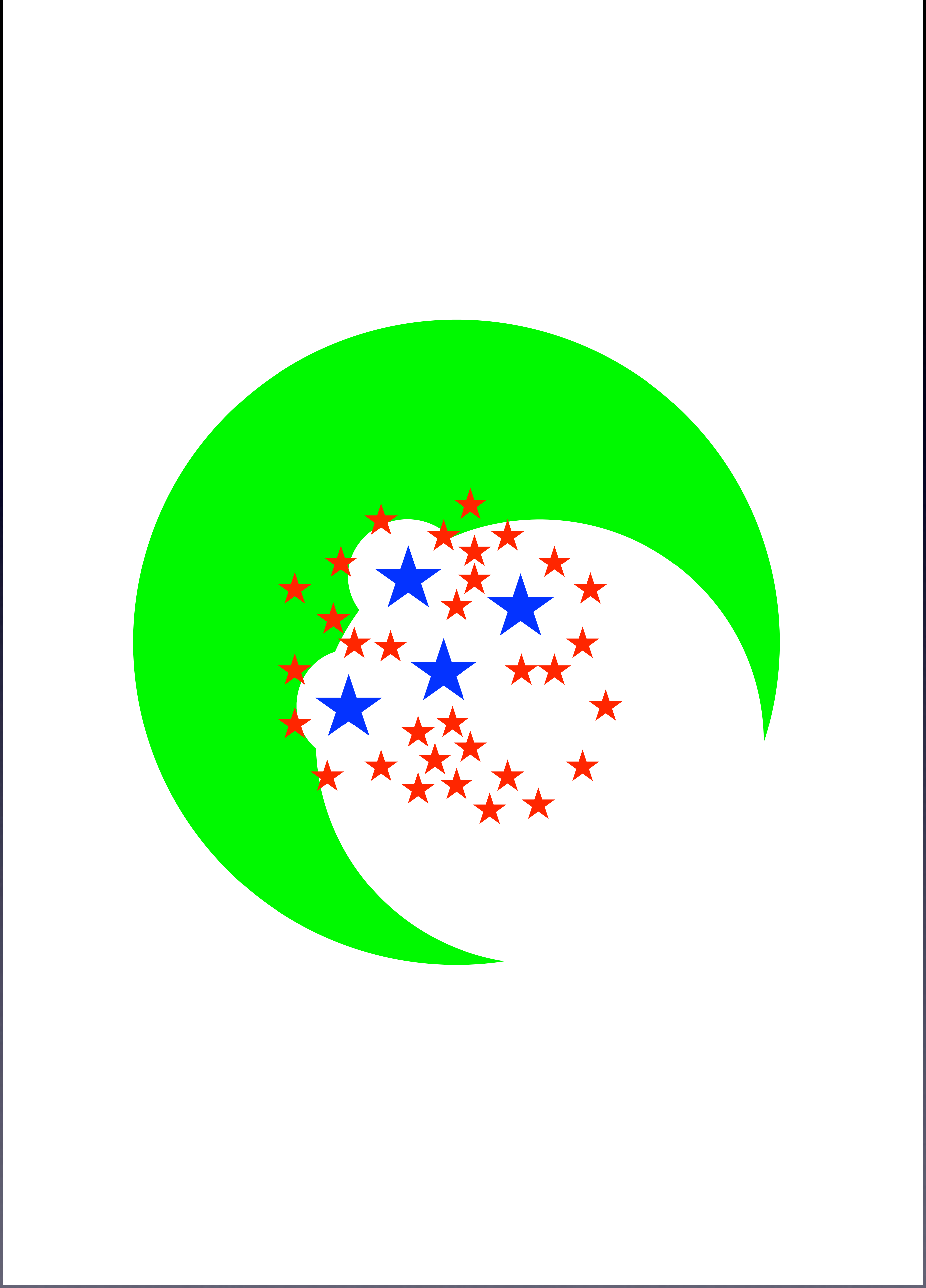

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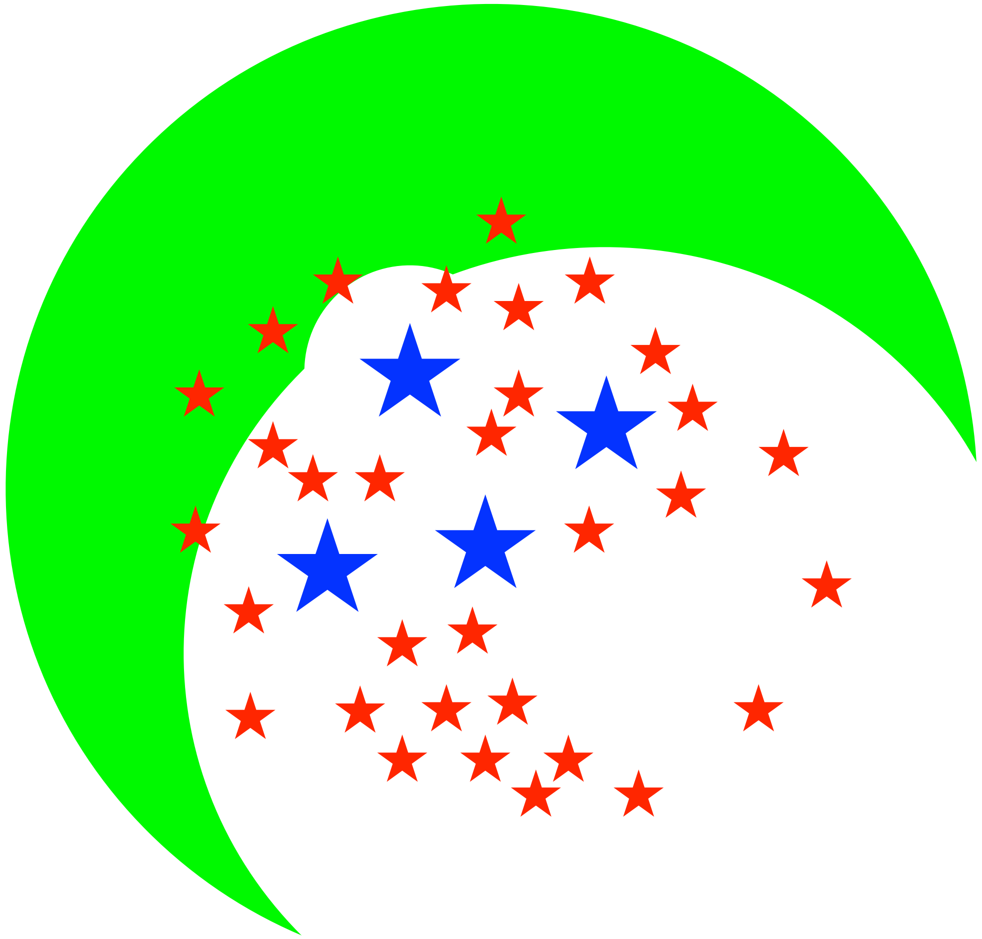

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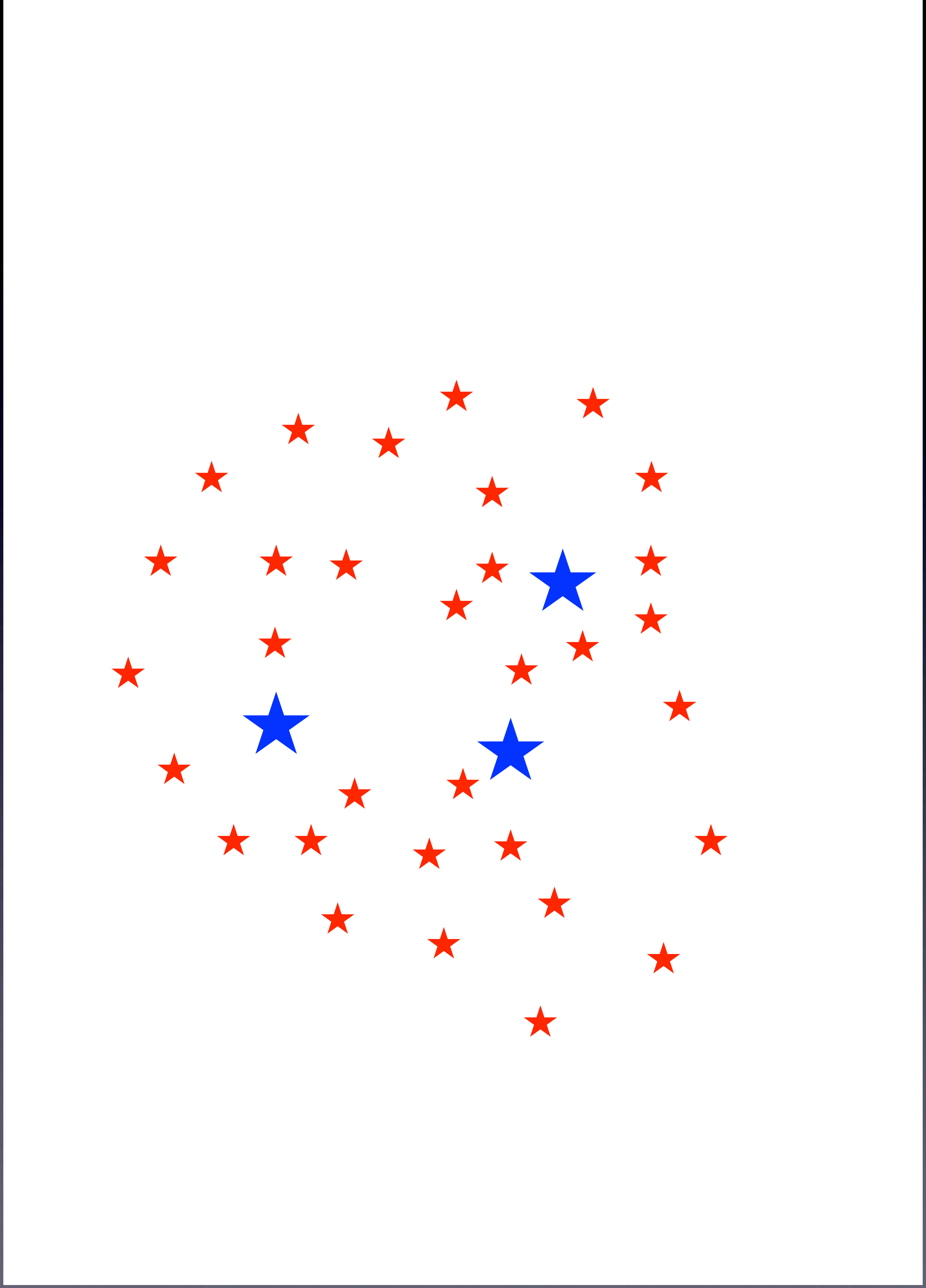

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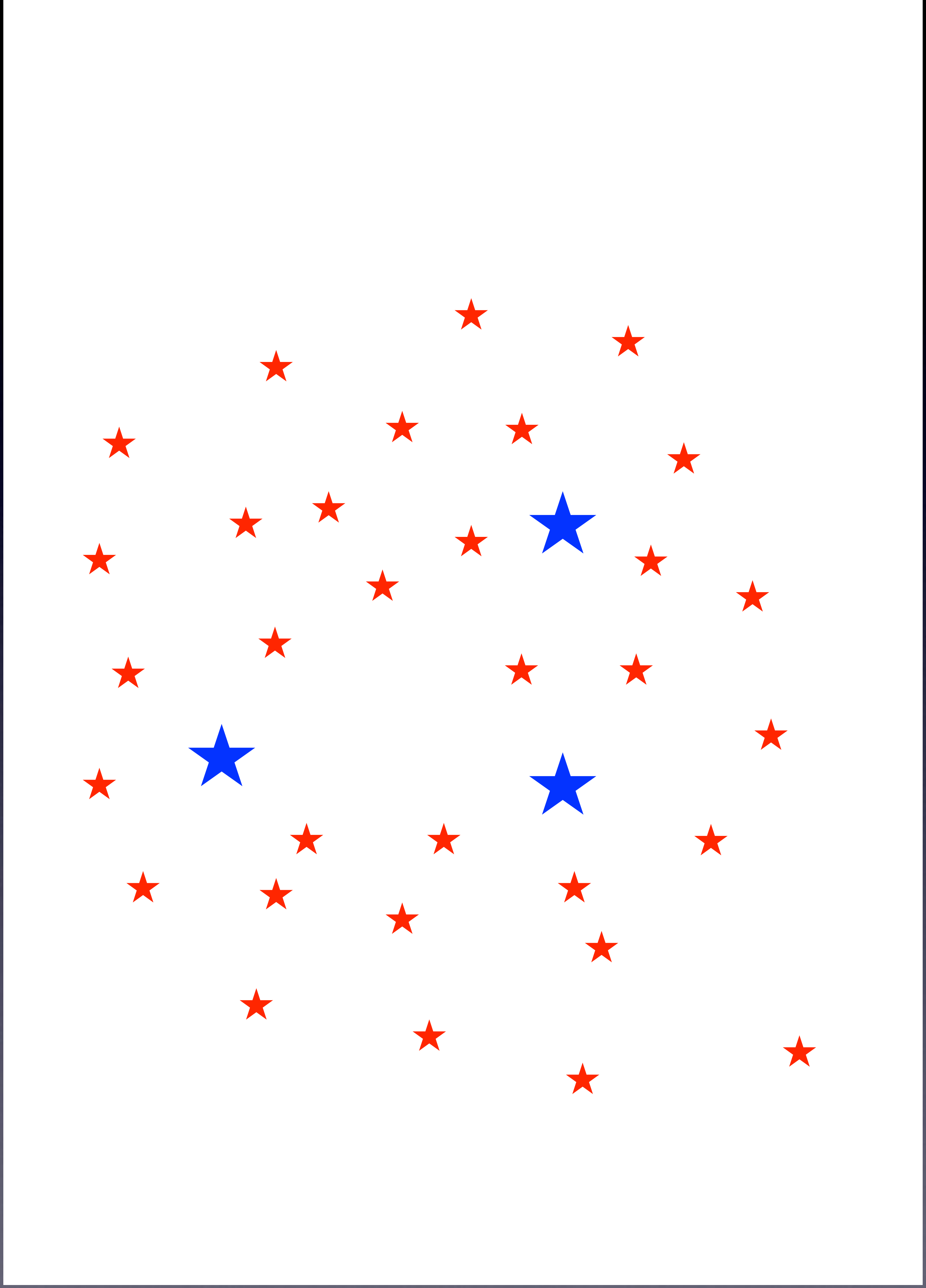

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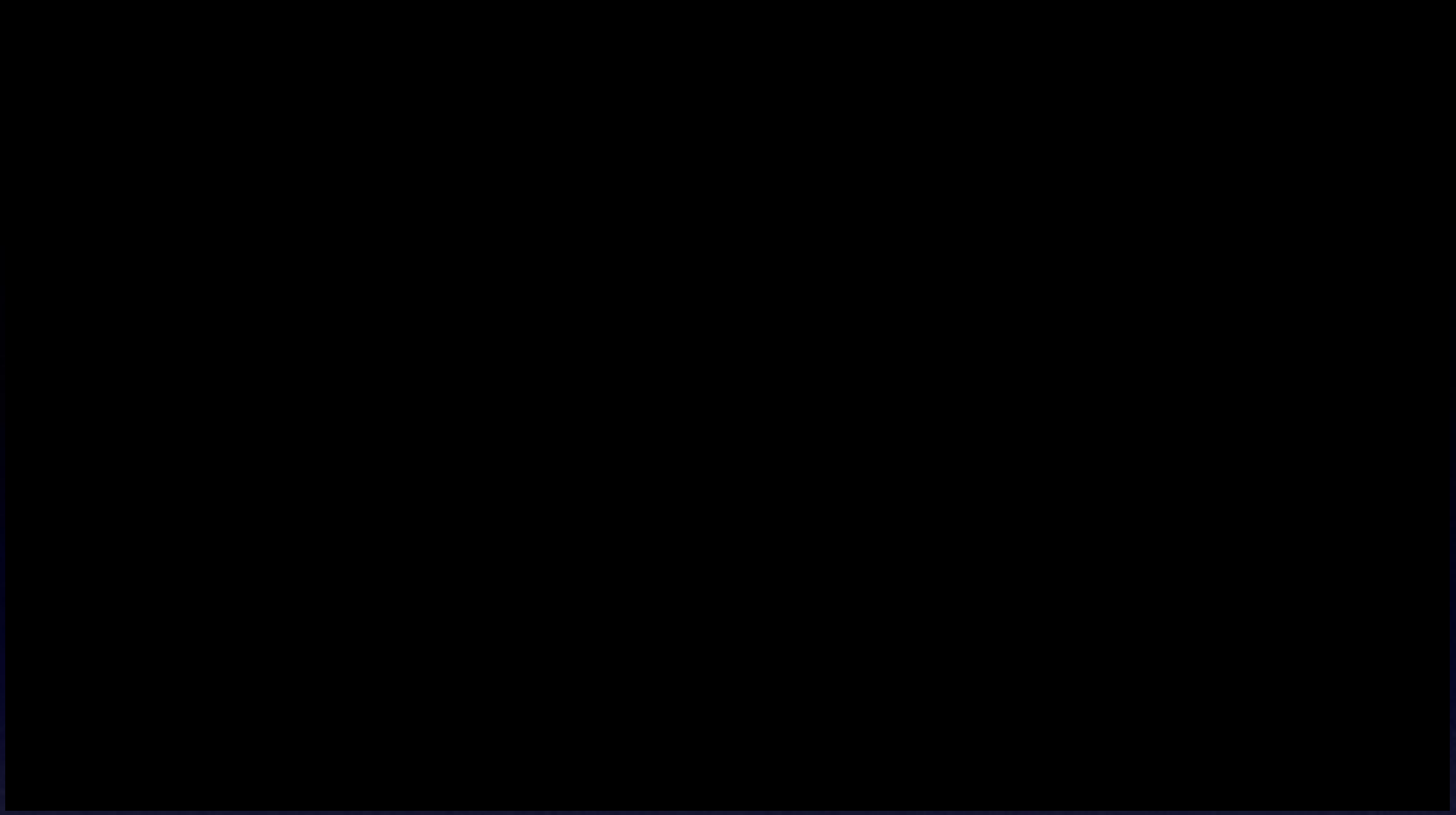

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# The Oasis scenario

- Elmegreen (2010).
- Star formation is hierarchical
- Some stars are formed in clusters and some are born isolated.
- Molecular complexes are collections of bound clouds of different masses and sizes.
- OB associations are (mostly) born that way and not coeval.

*Star clusters: basic galactic building blocks*
*Proceedings IAU Symposium No. 266, 2009*
*R. de Grijs & J. R. D. Lépine, eds.*

doi:10.1017/S1743921309990809

## The nature and nurture of star clusters

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email: bge@us.ibm.com

**Abstract.** Star clusters have hierarchical patterns in space and time, suggesting formation processes in the densest regions of a turbulent interstellar medium. Clusters also have hierarchical substructure when they are young, which makes them all look like the inner mixed parts of a pervasive stellar hierarchy. Young field stars share this distribution, presumably because some of them came from dissolved clusters and others formed in a dispersed fashion in the same gas. The fraction of star formation that ends up in clusters is apparently not constant, but may increase with interstellar pressure. Hierarchical structure explains why stars form in clusters and why many of these clusters are self-bound. It also explains the cluster mass function. Halo globular clusters share many properties of disk clusters, including what appears to be an upper cluster cutoff mass. However, halo globulars are self-enriched and often connected with dwarf galaxy streams. The mass function of halo globulars could have initially been like the power-law mass function of disk clusters, but the halo globulars have lost their low-mass members. The reasons for this loss are not understood. It could have happened slowly over time as a result of cluster evaporation, or it could have happened early after cluster formation as a result of gas loss. The latter model explains best the observation that the globular cluster mass function has no radial gradient in galaxies.

**Keywords.** open clusters and associations: general, solar neighborhood, galaxies: star clusters, stars: formation

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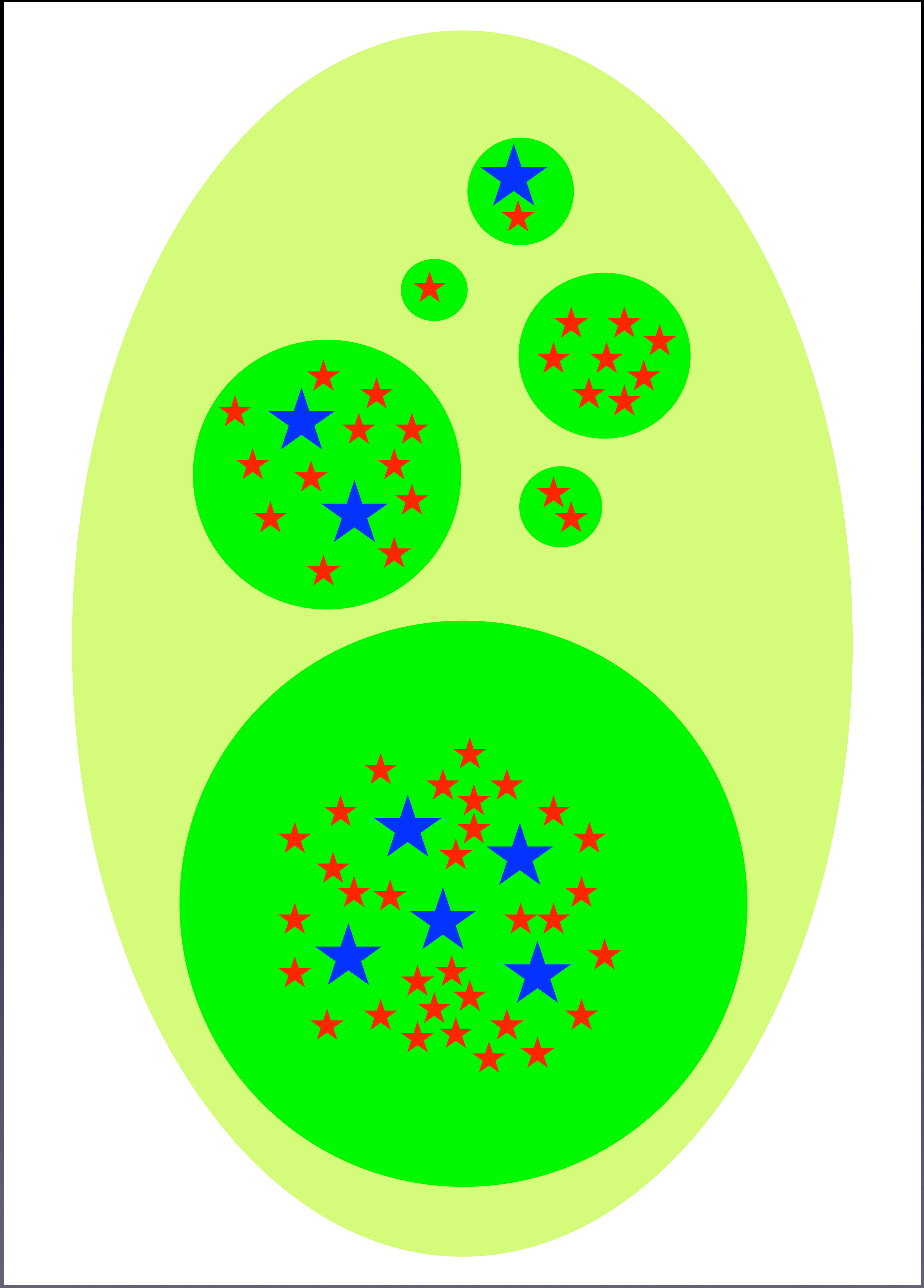

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# The Bruce Springsteen scenario

- Oh & Kroupa (2016).
- Complementary to other scenarios.
- Dynamical interactions eject preferentially massive stars.
- It only happens on very dense clusters and at a very early age.

A&A 590, A107 (2016)
DOI: 10.1051/0004-6361/201628233


Astronomy & Astrophysics

## Dynamical ejections of massive stars from young star clusters under diverse initial conditions

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**ABSTRACT**

We study the effects that initial conditions of star clusters and their massive star population have on dynamical ejections of massive stars from star clusters up to an age of 3 Myr. We use a large set of direct *N*-body calculations for moderately massive star clusters ($M_{ecl} \approx 10^{3.5}\,M_\odot$). We vary the initial conditions of the calculations, such as the initial half-mass radius of the clusters, initial binary populations for massive stars and initial mass segregation. We find that the initial density is the most influential parameter for the ejection fraction of the massive systems. The clusters with an initial half-mass radius $r_h(0)$ of 0.1 (0.3) pc can eject up to 50% (30)% of their O-star systems on average, while initially larger ($r_h(0) = 0.8$ pc) clusters, that is, lower density clusters, eject hardly any OB stars (at most ≈4.5%). When the binaries are composed of two stars of similar mass, the ejections are most effective. Most of the models show that the average ejection fraction decreases with decreasing stellar mass. For clusters that are efficient at ejecting O stars, the mass function of the ejected stars is top-heavy compared to the given initial mass function (IMF), while the mass function of stars that remain in the cluster becomes slightly steeper (top-light) than the IMF. The top-light mass functions of stars in 3 Myr old clusters in our *N*-body models agree well with the mean mass function of young intermediate-mass clusters in M 31, as reported previously. This implies that the IMF of the observed young clusters is the canonical IMF. We show that the multiplicity fraction of the ejected massive stars can be as high as ≈60%, that massive high-order multiple systems can be dynamically ejected, and that high-order multiples become common especially in the cluster. We also discuss binary populations of the ejected massive systems. Clusters that are initially not mass-segregated begin ejecting massive stars after a time delay that is caused by mass segregation. When a large kinematic survey of massive field stars becomes available, for instance through *Gaia*, our results may be used to constrain the birth configuration of massive stars in star clusters. The results presented here, however, already show that the birth mass-ratio distribution for O-star primaries must be near uniform for mass ratios $q \gtrsim 0.1$.

**Key words.** methods: numerical – stars: kinematics and dynamics – stars: massive – open clusters and associations: general – galaxies: star clusters: general

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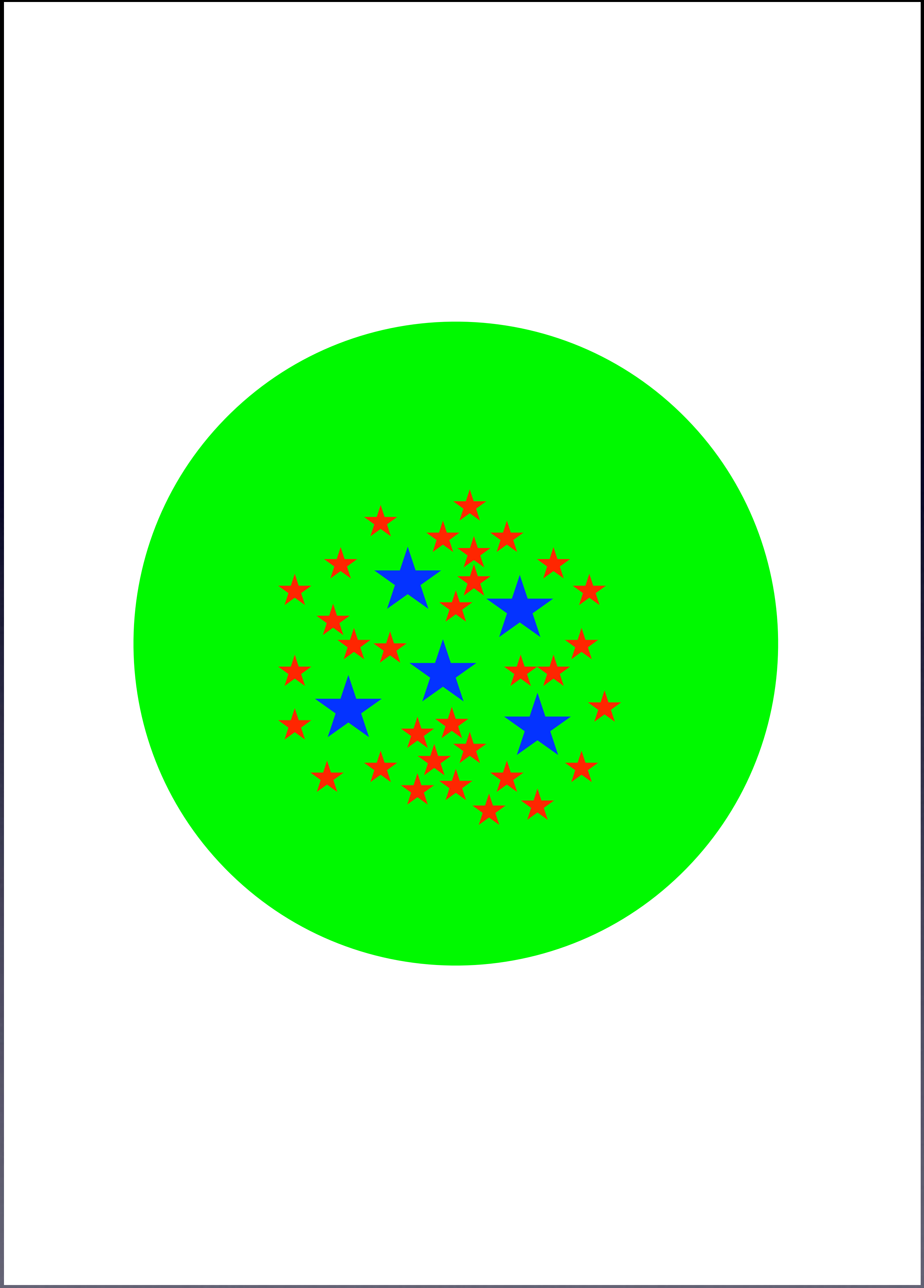

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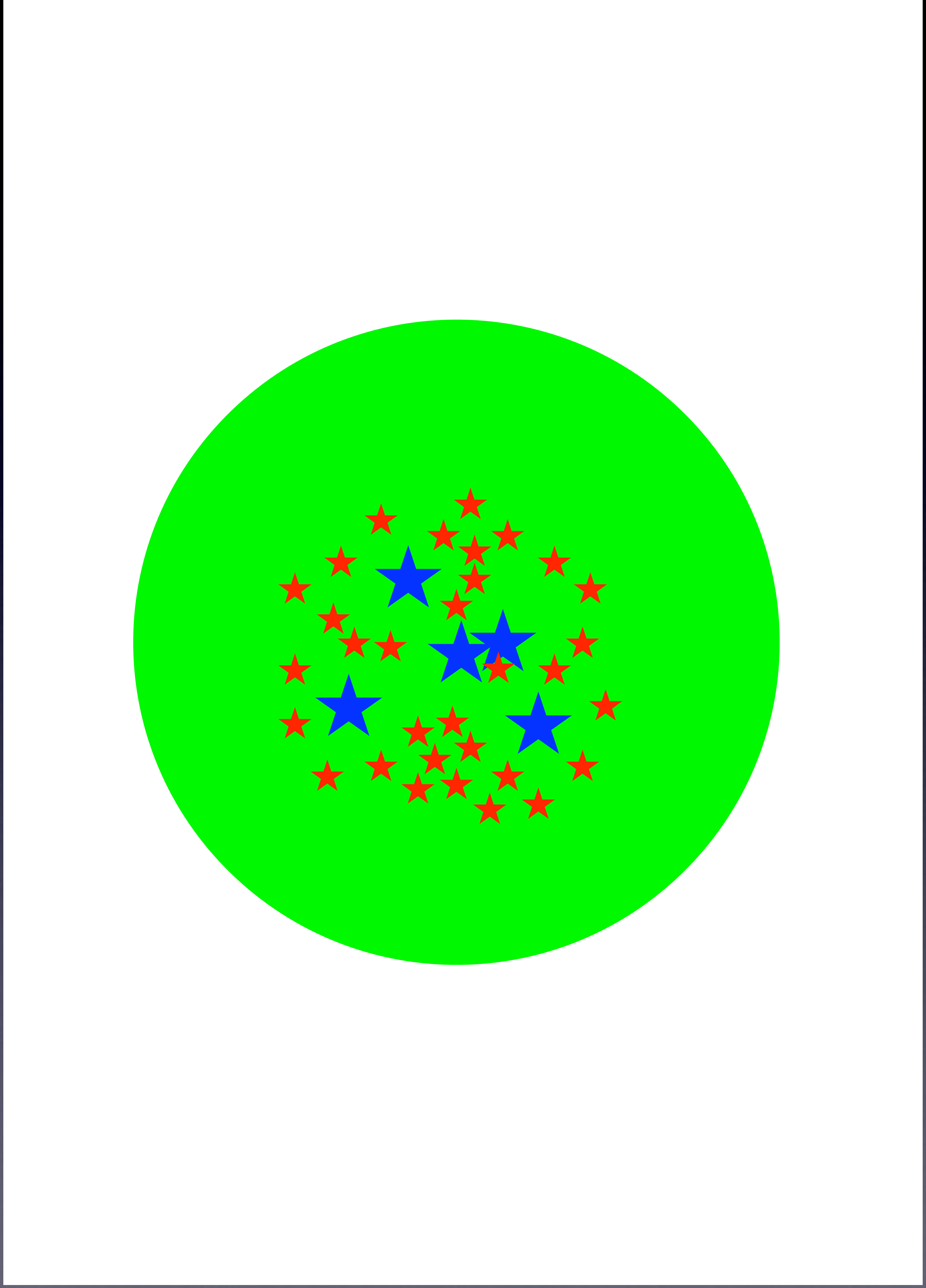

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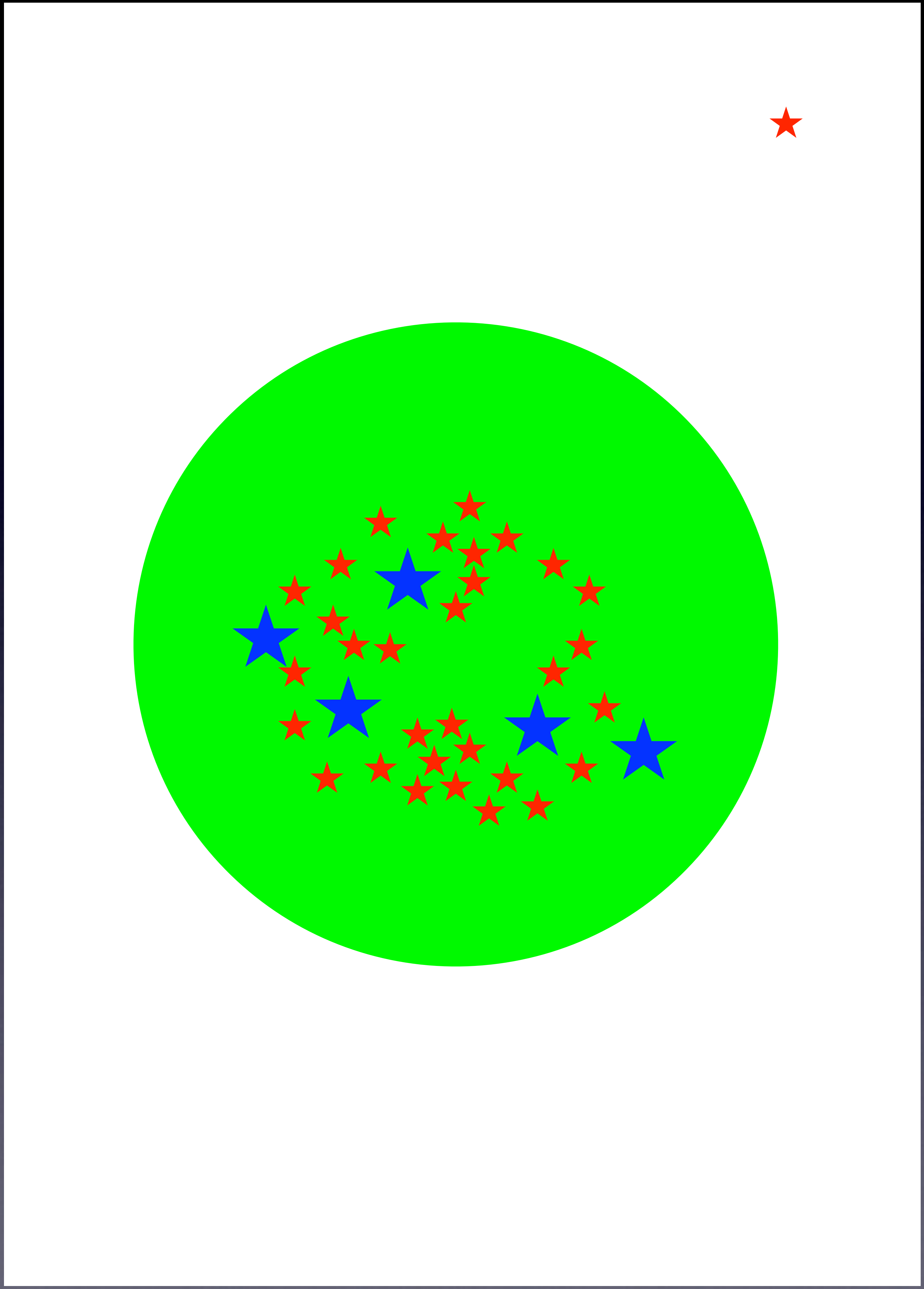

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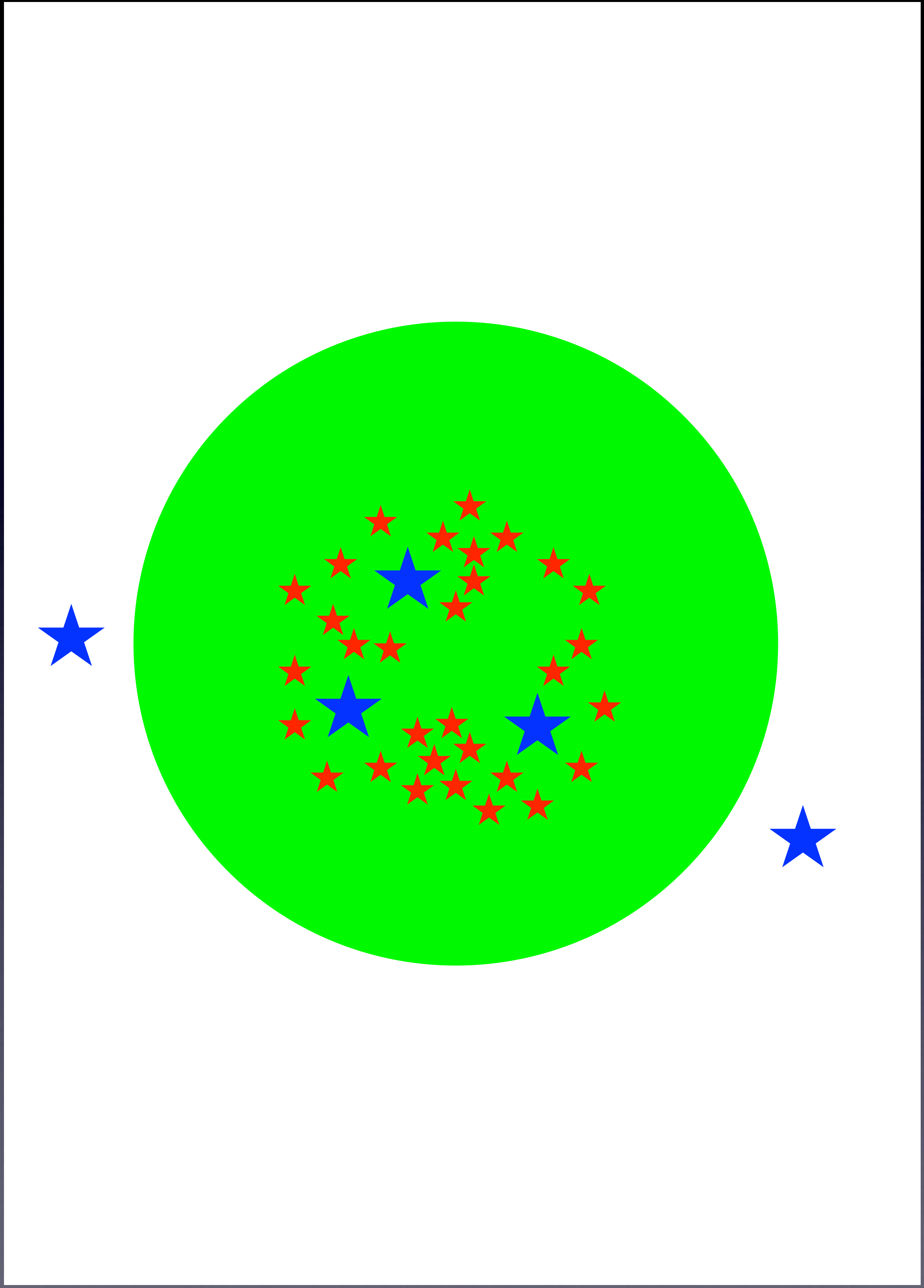

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# Testing the scenarios

- Possible for the first time thanks to *Gaia* and ground-based spectroscopic surveys.
  - ★ PMS and dynamical (expansion) ages.
  - ★ How do OB associations really behave? Expanding or not? Coeval or not?
  - ★ Do expanding clusters have runaways or walkaways?

# PMS vs. dynamical ages

nature astronomy

Article https://doi.org/10.1038/s41550-023-02132-4

**Insights into star formation and dispersal from the synchronization of stellar clocks**

Received: 5 June 2023

Accepted: 16 October 2023

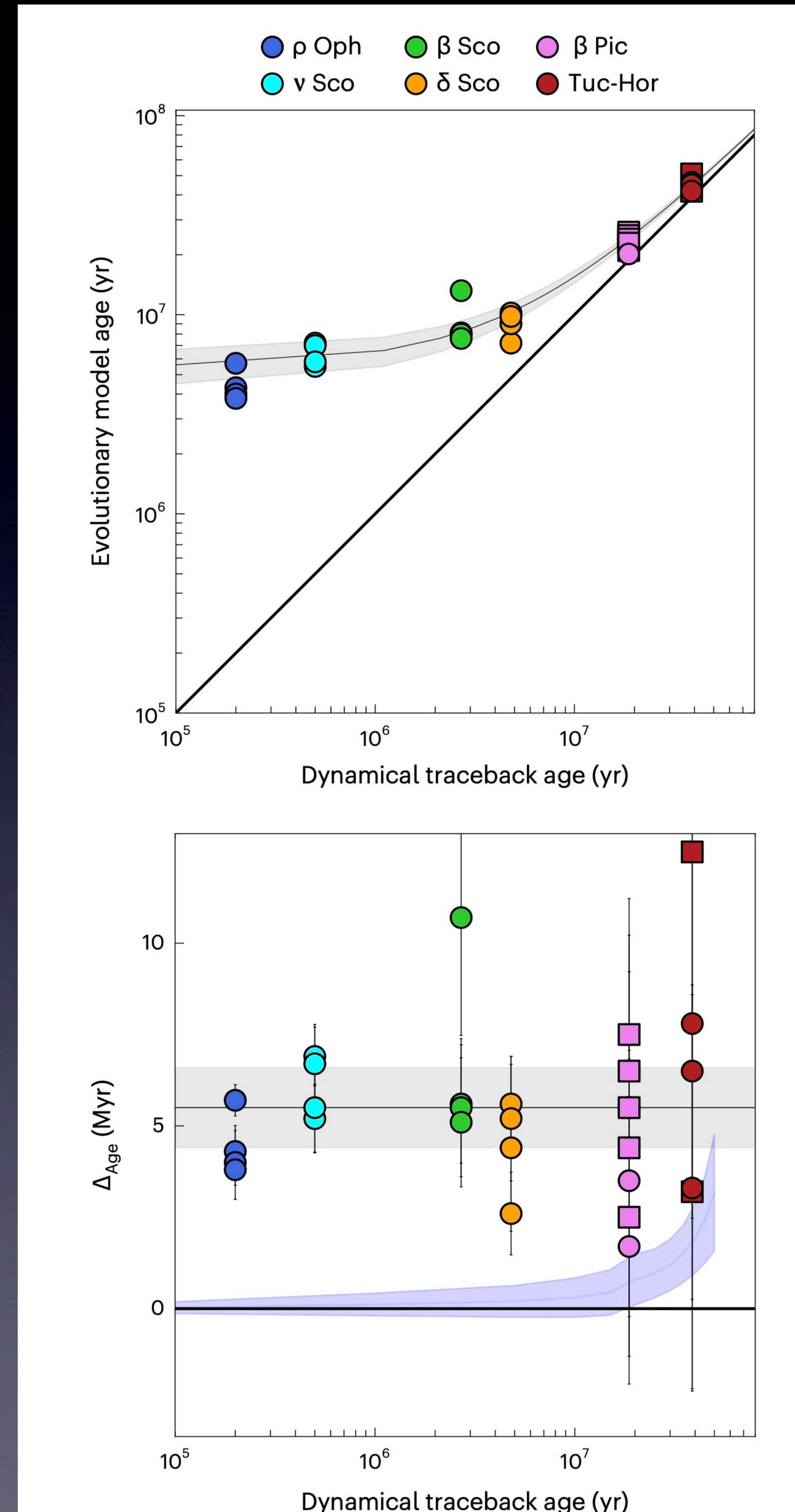
Published online: 23 November 2023

Check for updates

Núria Miret-Roig[1], João Alves[1], David Barrado[2], Andreas Burkert[3,4,5], Sebastian Ratzenböck[1,6] & Ralf Konietzka[4,7,8]

Age is one of the most fundamental parameters of a star, yet it is one of the hardest to determine as it requires modelling various aspects of stellar formation and evolution. When we compare the ages derived from isochronal and dynamical traceback methods for six young stellar associations, we find a systematic discrepancy. Specifically, dynamical traceback ages are consistently younger by an average of $\langle\Delta_{\mathrm{Age}}\rangle = 5.5 \pm 1.1$ Myr. We rule out measurement errors as the cause of the

- PMS ages are ~5.5 Ma older than dynamical (expansion) ages ⟹ Queen rules!…
- … but all are low-mass clusters and still relatively compact.



# Real OB associations

- OB associations have complex kinematic substructures and are not coeval.
- They cannot be traced back to one or several dissolving clusters.
- But large-scale expansions with $t_{exp}$ ~ age of stars can be detected.
- Due to initial molecular complex turbulence, never bound.
- Oasis rules!

## OB Associations and their origins

Nicholas J. Wright
*Astrophysics Group, Keele University, Keele, ST5 5BG, UK*

Check for updates

ARTICLE INFO

*Keywords:*
OB Associations
Star clusters
Young stars
Star formation
Stellar kinematics and dynamics

ABSTRACT

OB associations are unbound groups of young stars made prominent by their bright OB members, and have long been thought to be the expanded remnants of dense star clusters. They have been important in astrophysics for over a century thanks to their luminous massive stars, though their low-mass members have not been well studied until the last couple of decades. This has changed thanks to data from X-ray observations, spectroscopic surveys and astrometry from *Gaia* that allows their full stellar content to be identified and their dynamics to be studied, which in turn is leading to changes in our understanding of these systems and their origins, with the old picture of Blaauw (1964a) now being superseded. It is clear now that OB associations have considerably more substructure than once envisioned, both spatially, kinematically and temporally. These changes have implications for the star formation process, the formation and evolution of planetary systems, and the build-up of stellar populations across galaxies.

## Large-scale expansion of OB stars in Cygnus

Alexis L. Quintana ★ and Nicholas J. Wright
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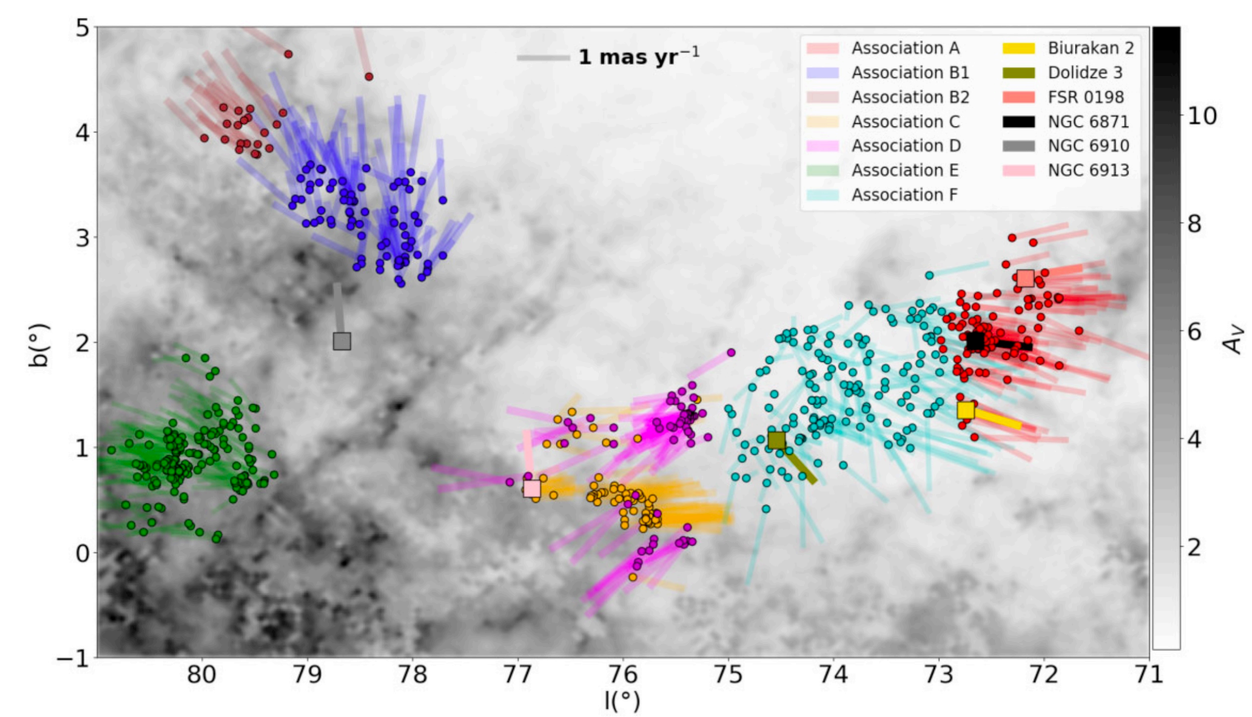
Accepted 2022 May 30. Received 2022 May 24; in original form 2022 March 23

**ABSTRACT**

The proper motions (PMs) of OB stars in Cygnus have recently been found to exhibit two large-scale kinematic patterns suggestive of expansion. We perform a 3D traceback on these OB stars, the newly identified OB associations and related open clusters in the region. We find that there are two groups of stars, associations and clusters and that they were each more compact in the past, reaching their closest approach $7.9^{+3.0}_{-1.8}$ and $8.5^{+0.8}_{-2.8}$ Myr ago. We consider two main scenarios for the driver of these large-scale expansion patterns: feedback-driven expansion from a previous generation of massive stars, and expansion as a result of the turbulent velocity field in the primordial molecular cloud. While it is tempting to attribute such large-scale expansion patterns to feedback processes, we find that the observed kinematics are fully consistent with the turbulent origin, and therefore that the injection of further energy or momentum from feedback is not required. Similar conclusions may be drawn for other star forming regions with large-scale expansion patterns.



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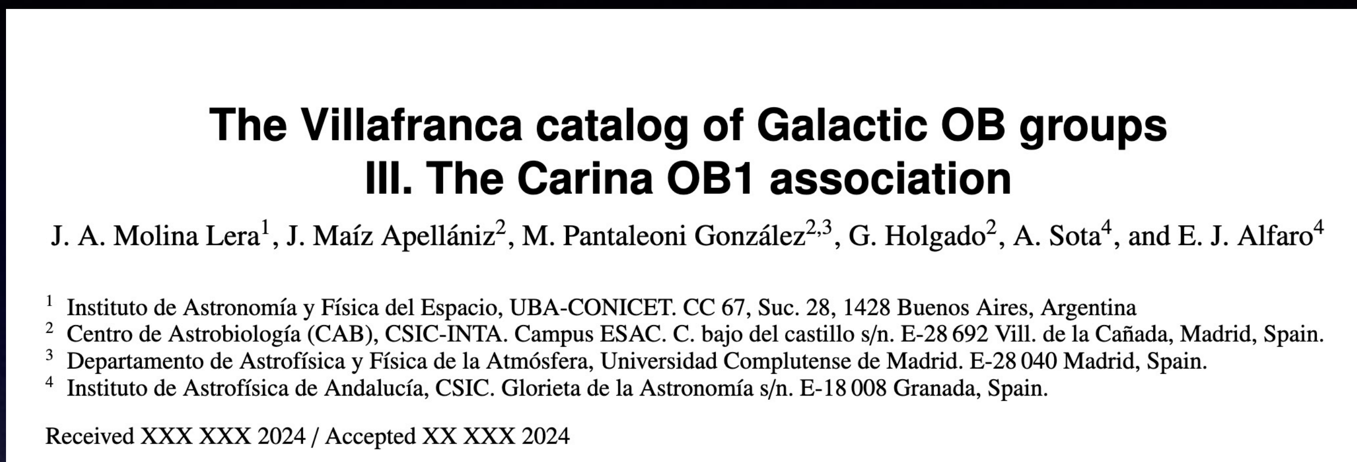

## The Villafranca catalog of Galactic OB groups
## III. The Carina OB1 association

J. A. Molina Lera[1], J. Maíz Apellániz[2], M. Pantaleoni González[2,3], G. Holgado[2], A. Sota[4], and E. J. Alfaro[4]

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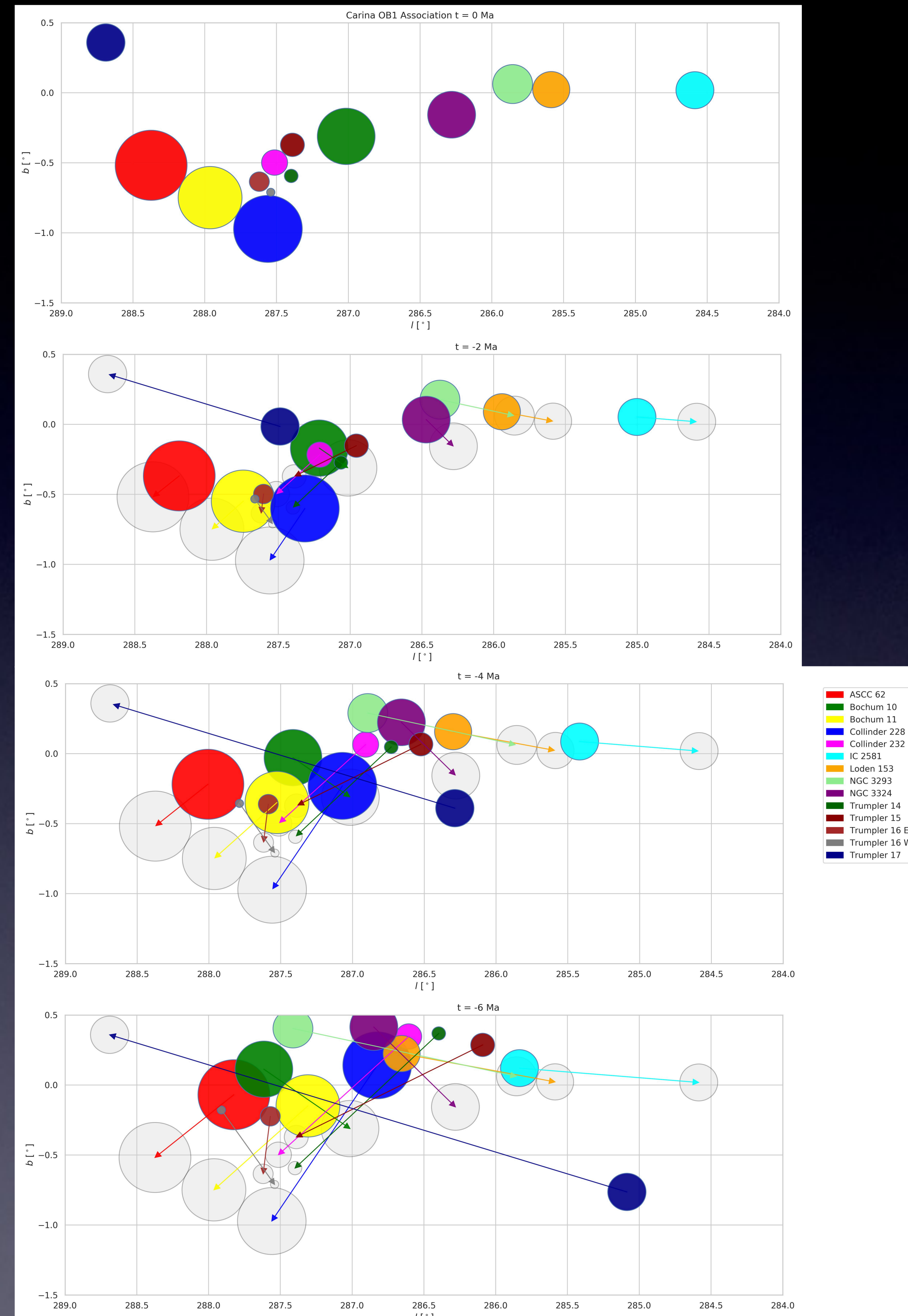
[2] Centro de Astrobiología (CAB), CSIC-INTA. Campus ESAC. C. bajo del castillo s/n. E-28 692 Vill. de la Cañada, Madrid, Spain.
[3] Departamento de Astrofísica y Física de la Atmósfera, Universidad Complutense de Madrid. E-28 040 Madrid, Spain.
[4] Instituto de Astrofísica de Andalucía, CSIC. Glorieta de la Astronomía s/n. E-18 008 Granada, Spain.

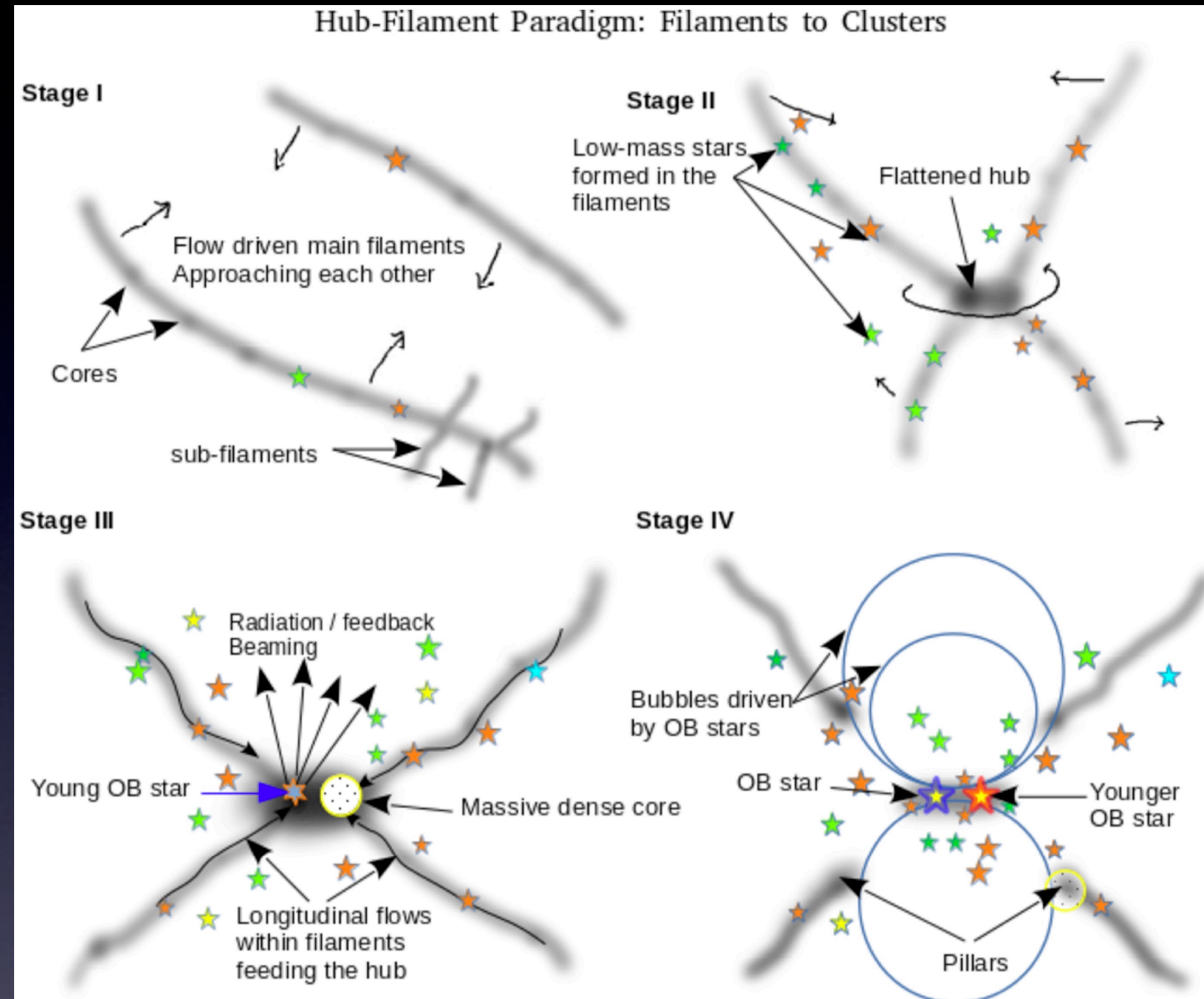
Received XXX XXX 2024 / Accepted XX XXX 2024




- Overall expansion of the different regions of the association (clusters or subassociations).
- (Most) clusters/subassociations are not expanding.
- Oasis rules!

# The conveyor belt model

- Usually applied to pc scales to explain massive-star and cluster formation.
- Can also be applied to tens of pc scales to explain OB associations.




**How do bound star clusters form?**

Mark R. Krumholz[1,2,3,4★] and Christopher F. McKee[5]

[1]Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia
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ABSTRACT

Gravitationally bound clusters that survive gas removal represent an unusual mode of star formation in the Milky Way and similar spiral galaxies. While forming, they can be distinguished observationally from unbound star formation by their high densities, virialized velocity structures, and star formation histories that accelerate towards the present, but extend multiple free-fall times into the past. In this paper, we examine several proposed scenarios for how such structures might form and evolve, and carry out a Bayesian analysis to test these models against observed distributions of protostellar age, counts of young stellar objects relative to gas, and the overall star formation rate of the Milky Way. We show that models in which the acceleration of star formation is due either to a large-scale collapse or a time-dependent increase in star formation efficiency are unable to satisfy the combined set of observational constraints. In contrast, models in which clusters form in a 'conveyor belt' mode where gas accretion and star formation occur simultaneously, but the star formation rate per free-fall time is low, can match the observations.

**Unifying low- and high-mass star formation through density-amplified hubs of filaments**

**The highest mass stars (>100 $M_\odot$) form only in hubs★**

M. S. N. Kumar[1], P. Palmeirim[1], D. Arzoumanian[1], and S. I. Inutsuka[2]

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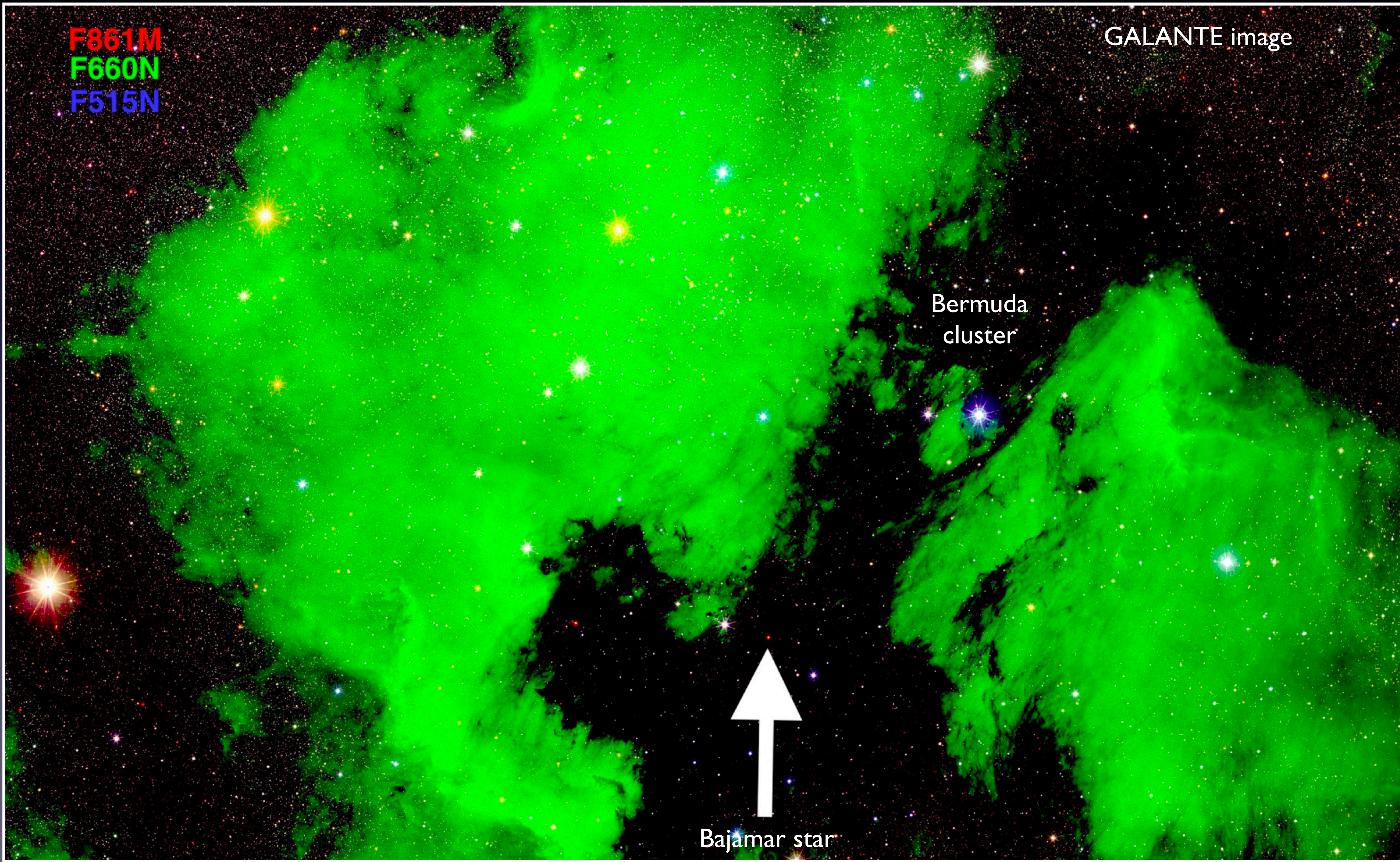
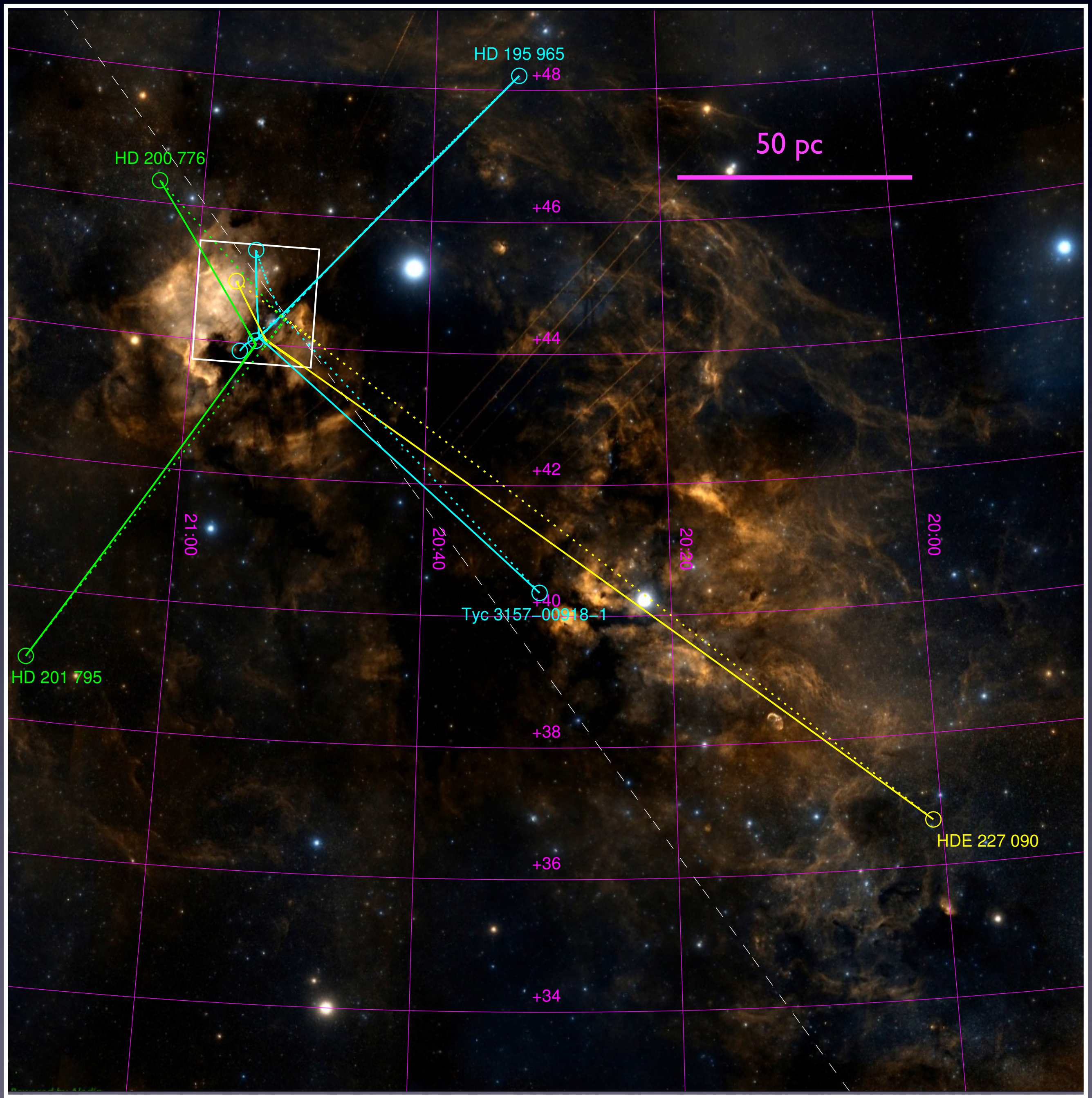
# Escape from the Bermuda cluster: Orphanization by multiple stellar ejections

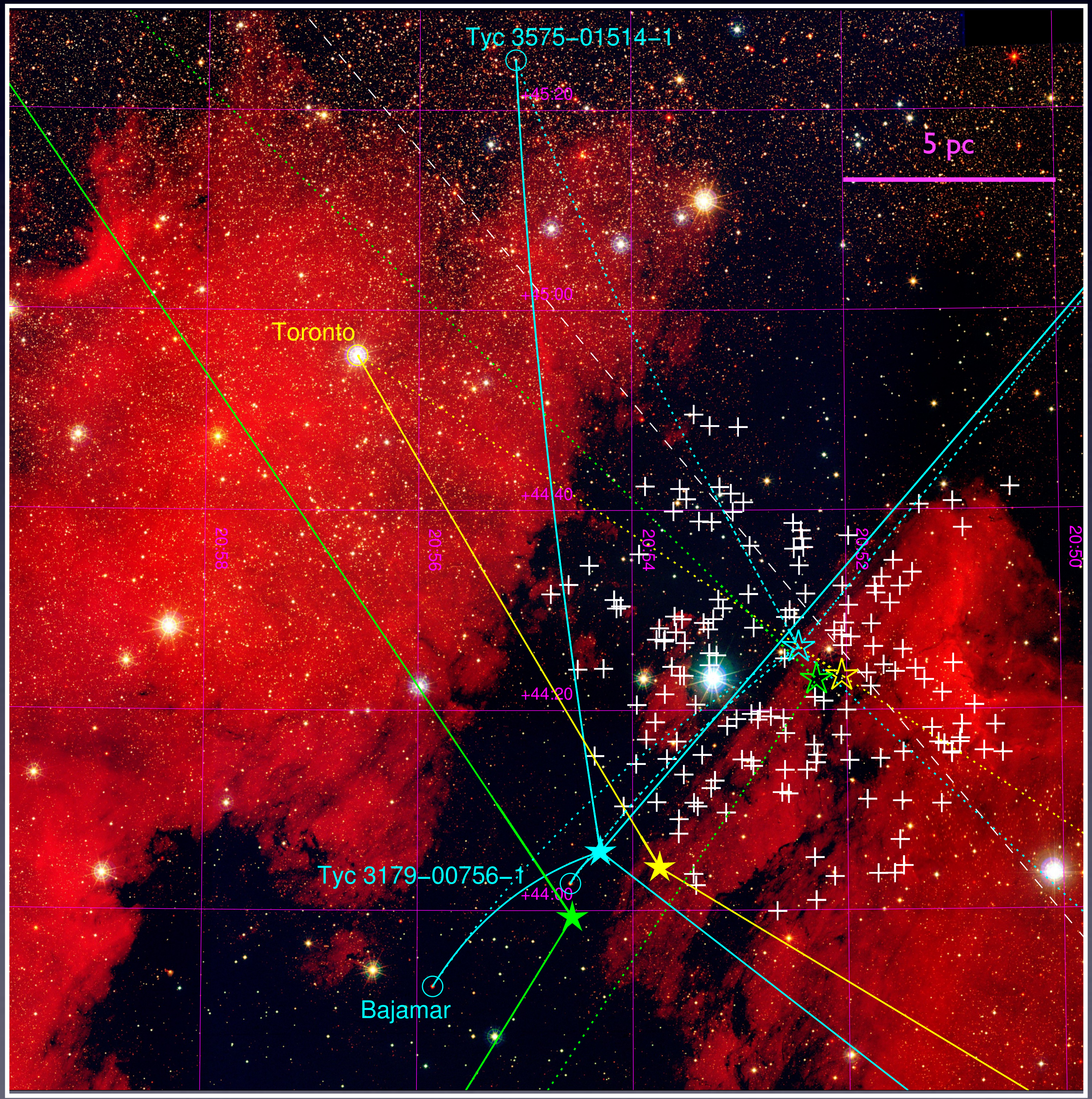
J. Maíz Apellániz[1], M. Pantaleoni González[1,2], R. H. Barbá[3,†], and M. Weiler[4]



# Three ejection events

- 1.5, 1.6 and 1.9 million years ago… and the cluster age is likely ~2 Ma.
- Orphan clusters: 12+ ejected stars, including the most massive three.
- The population of runaway and walkaway stars: vagabond neutron stars and black holes.
- 400-500 $M_{\odot}$, IMF from top heavy to Kroupa.
- Too much mass lost: the Bermuda cluster has become unbound.



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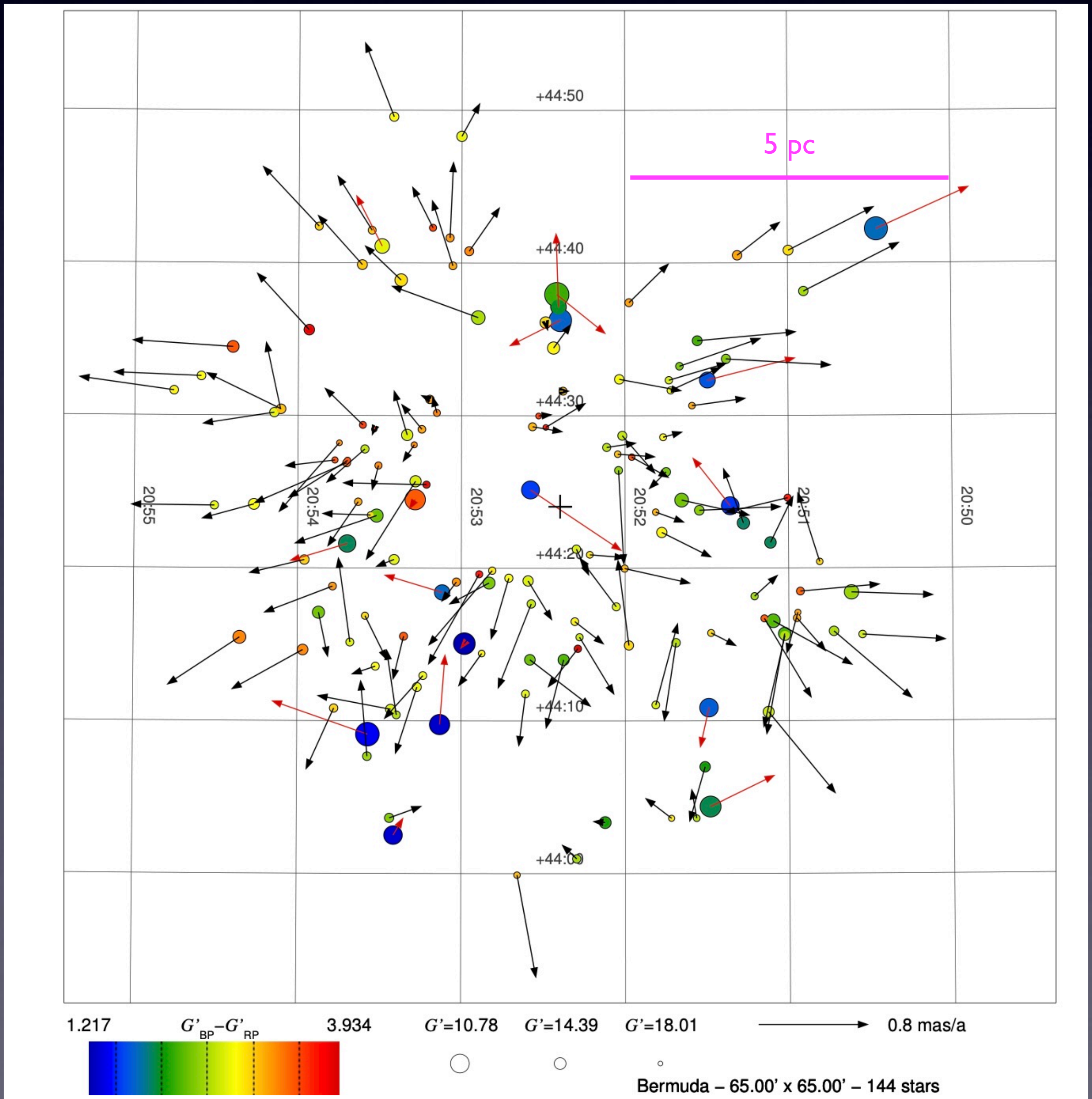
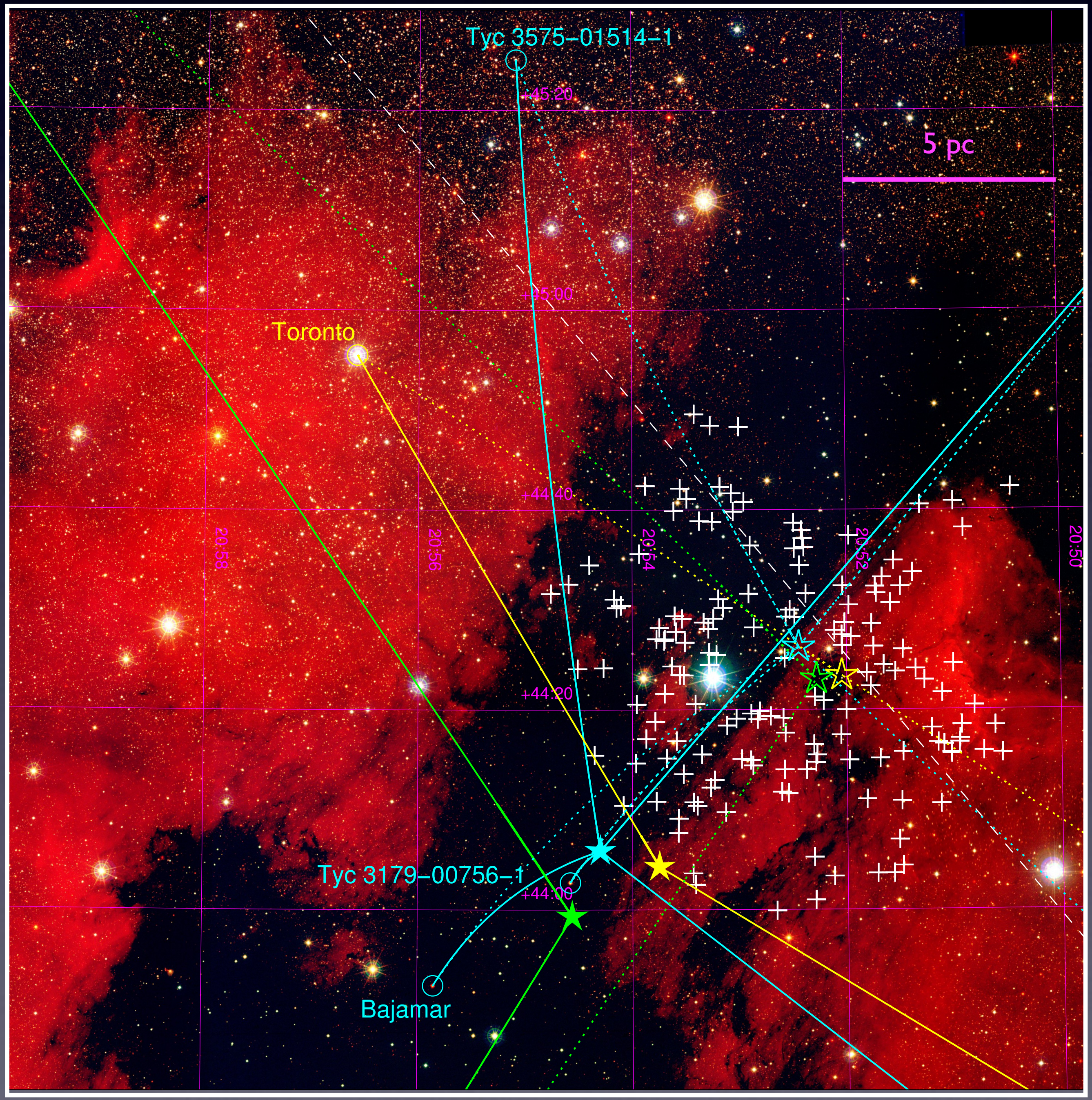
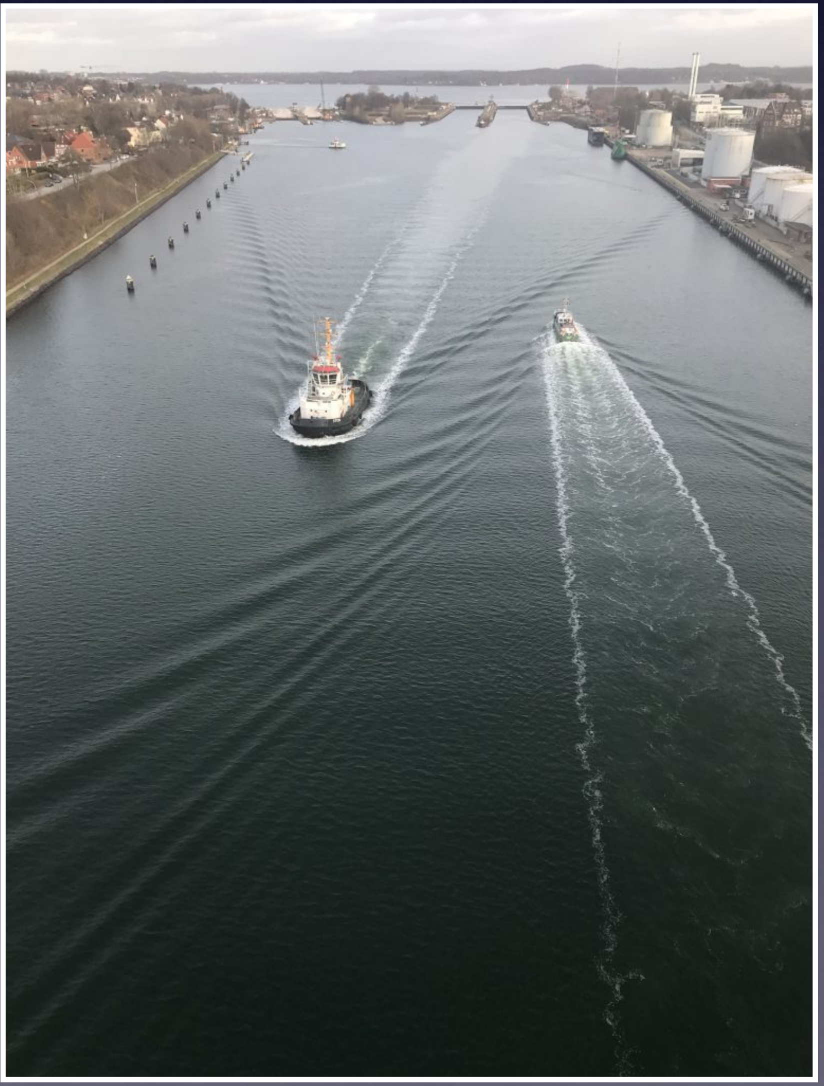


# Bow shocks from the ejected stars

- The Boss also rules!



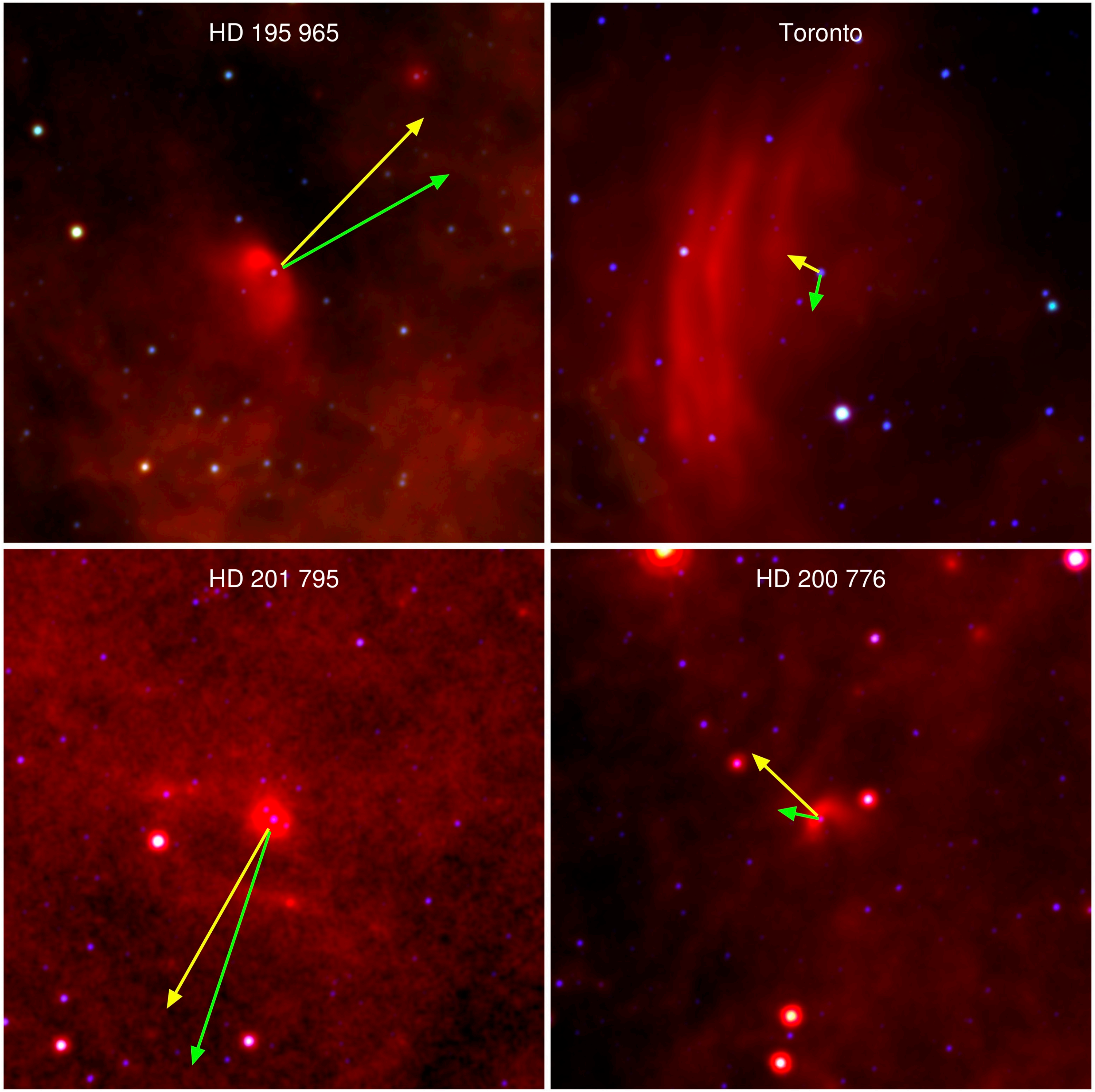



**Fig. B.1.** *WISE* W4+W3+W2 RGB mosaics for four walkaway/runaways systems. Each field is 20′ × 20′ (4.7 pc × 4.7 pc at a distance of 798 pc) and is oriented with north toward the top and east toward the left. In each mosaic the runaway candidate is at the center and the arrows show the absolute (green) and the relative-to-the cluster proper motions (yellow).

# Stock 18

## An in-depth analysis of the differentially expanding star cluster Stock 18 (Villafranca O-036) using *Gaia* DR3 and ground-based data

J. Maíz Apellániz[1], A. R. Youssef[2], M.S. El-Nawawy[2⋆], W. H. Elsanhoury[3,4], A. Sota[5], M. Pantaleoni González[1,6], and A. Ahmed[2]

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[6] Departamento de Astrofísica y Física de la Atmósfera. Universidad Complutense de Madrid. E-28 040 Madrid, Spain.

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**ABSTRACT**

*Context.* The Villafranca project is combining *Gaia* data with ground-based surveys to analyze Galactic stellar groups (clusters, associations, or parts thereof) with OB stars.
*Aims.* We want to analyze the poorly studied cluster Stock 18 within the Villafranca project, as it is a very young stellar cluster with a symmetrical and compact H II region around it, Sh 2-170, so it is likely to provide insights into the structure and dynamics of such objects at an early stage of their evolution.
*Methods.* We use on the one hand *Gaia* astrometry, photometry, spectrophotometry, and variability data and ground-based spectroscopy and imaging to determine the characteristics of Stock 18. We use them to analyze its core, massive-star population, extinction, distance, membership, internal dynamics, density profile, IMF, stellar variability, and Galactic location.
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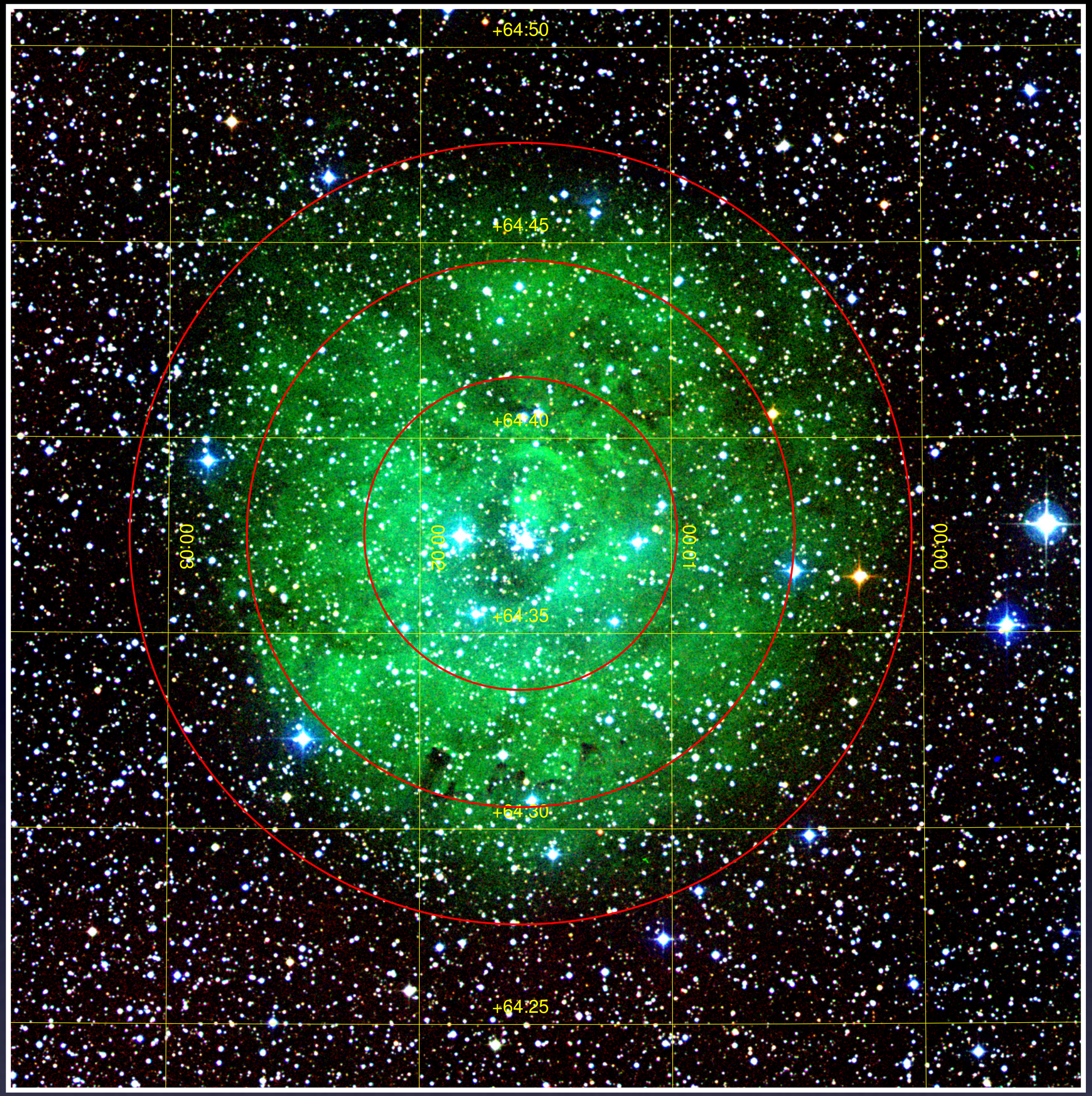
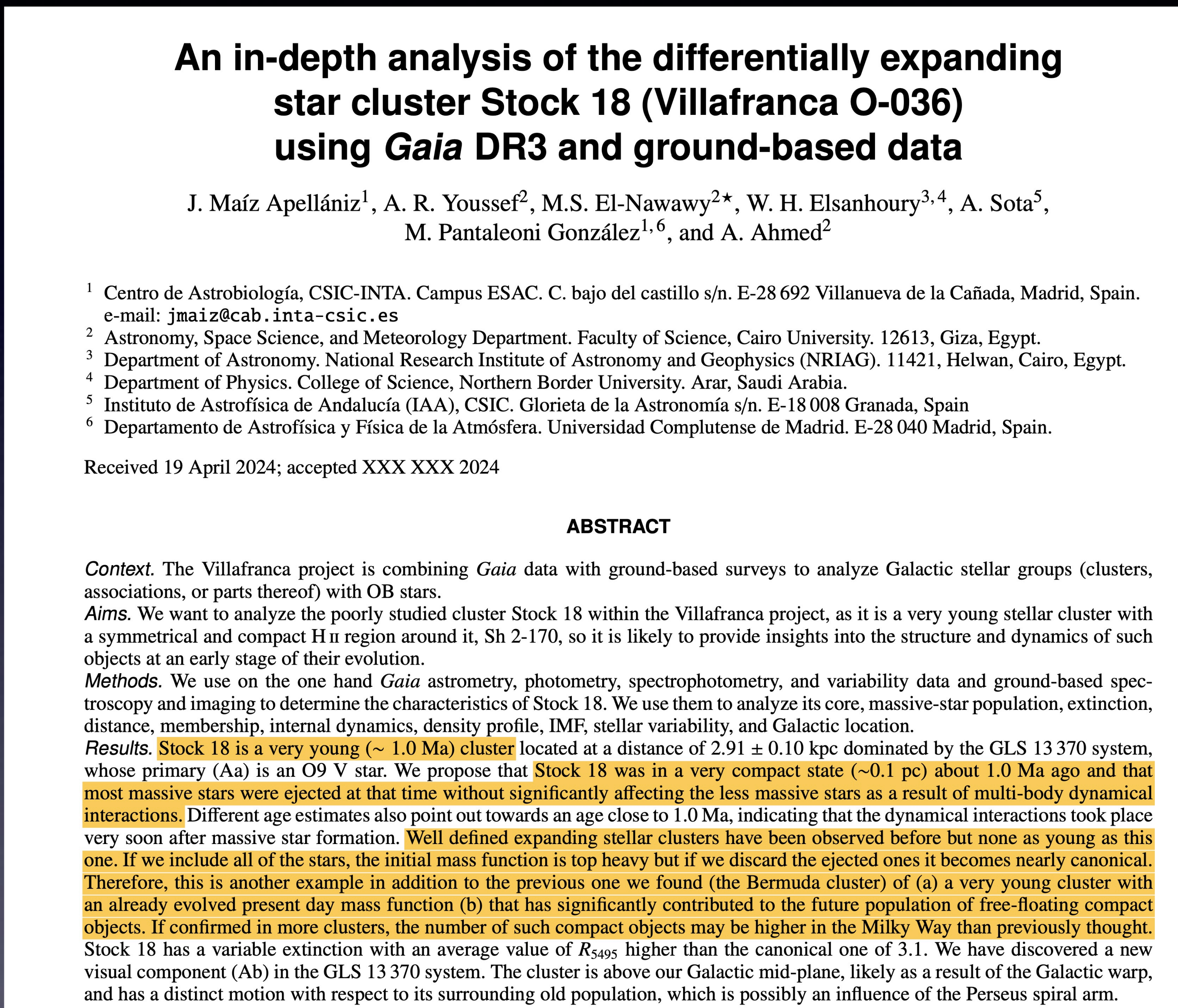



- Very young: ~1.0 Ma.

# Stock 18



## An in-depth analysis of the differentially expanding star cluster Stock 18 (Villafranca O-036) using *Gaia* DR3 and ground-based data

J. Maíz Apellániz[1], A. R. Youssef[2], M.S. El-Nawawy[2⋆], W. H. Elsanhoury[3,4], A. Sota[5], M. Pantaleoni González[1,6], and A. Ahmed[2]

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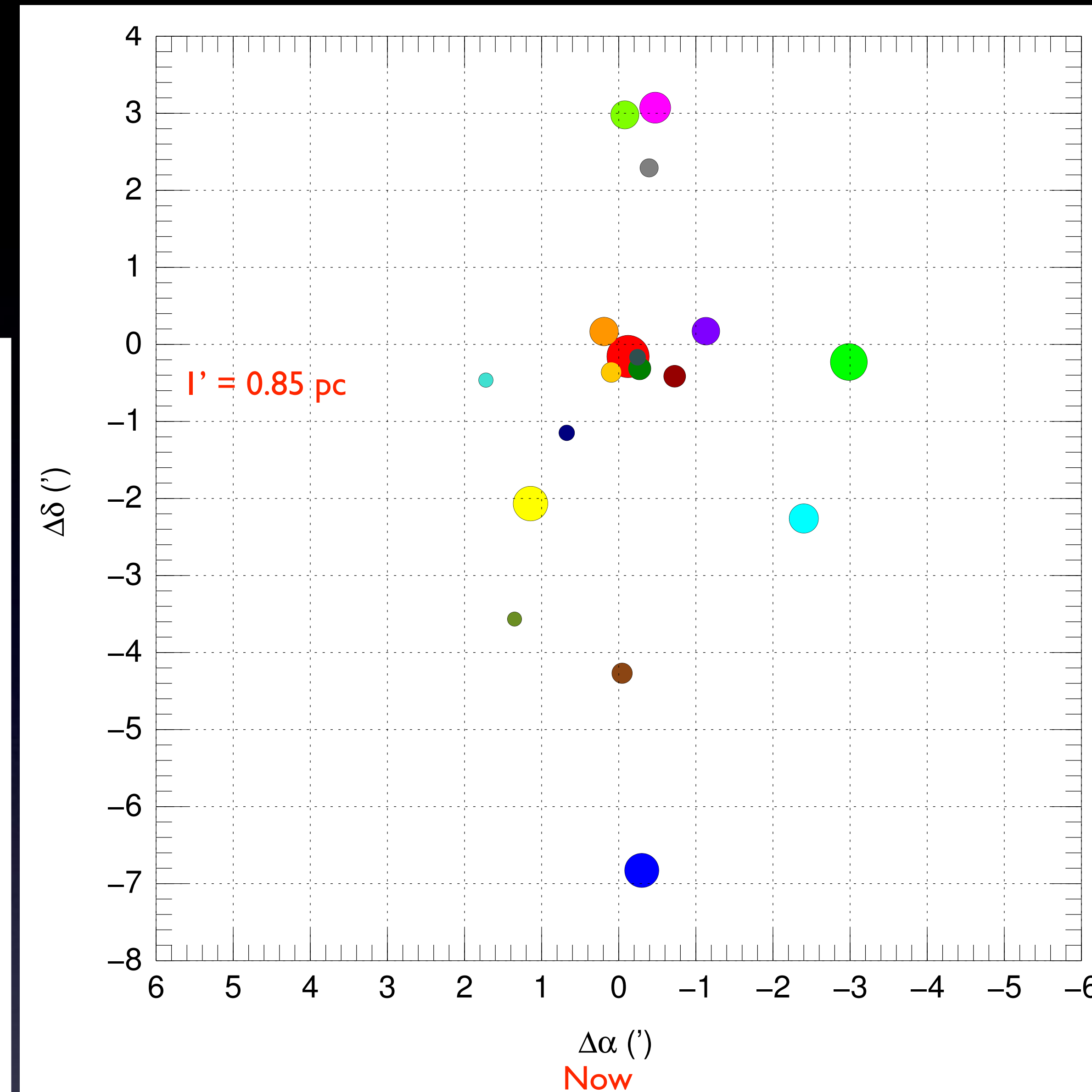


- Very young: ~1.0 Ma.
- Stars with $M \geq 5$ M$_\odot$.

# Stock 18

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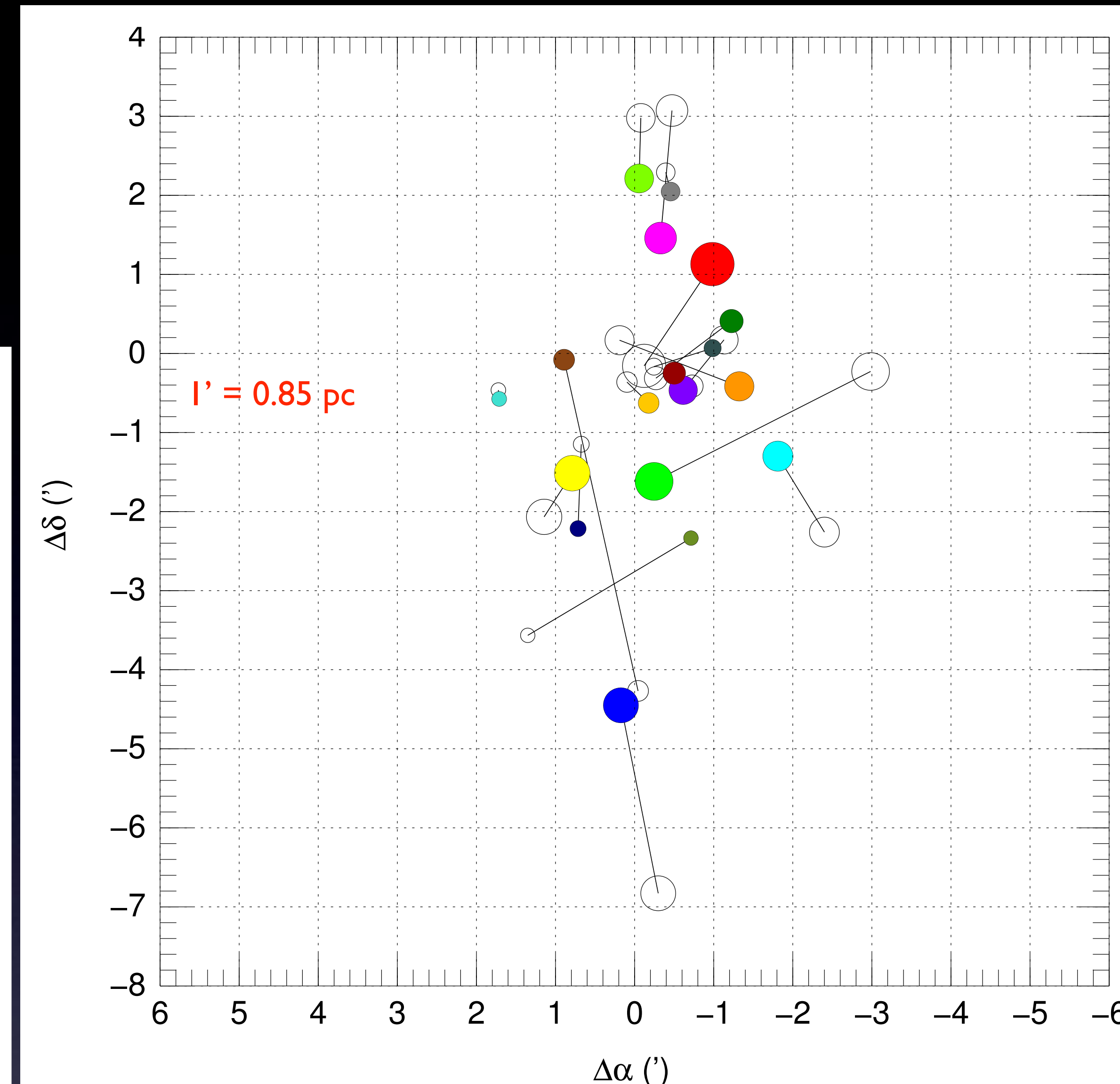


0.61 Ma ago, direct proper motions

- Very young: ~1.0 Ma.
- Stars with $M \geq 5\ M_\odot$.
- Stars with $M < 5\ M_\odot$ currently have a similar radial distribution.

# Stock 18

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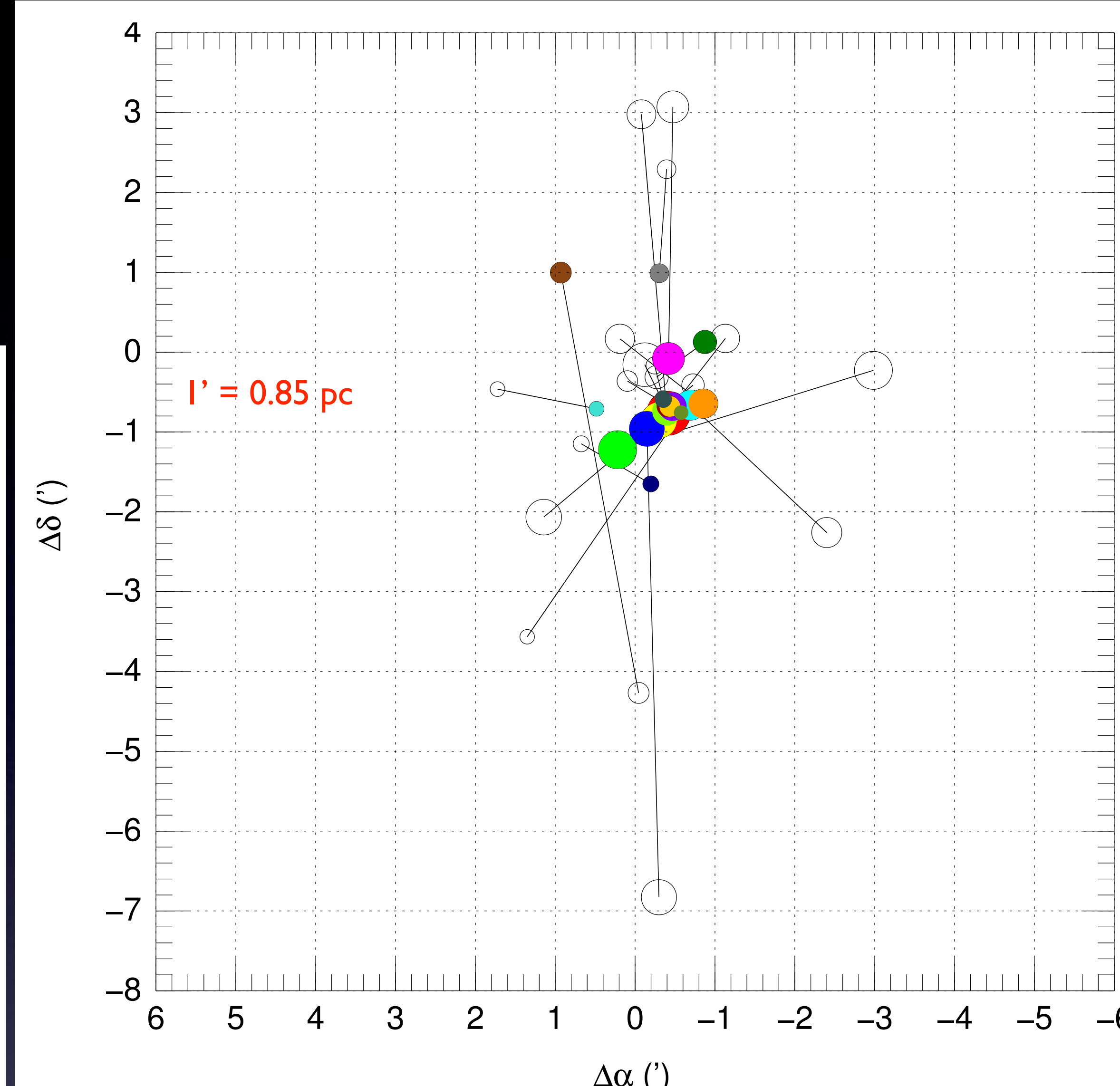


0.88 Ma ago, Monte Carlo proper motions

- Very young: ~1.0 Ma.
- Stars with $M \geq 5$ M$_\odot$.
- All massive stars within 0.1 pc of another one 0.8-1.1 Ma ago.
- Differentially expanding.
- IMF from top heavy to Kroupa.
- The Boss also rules!

# Any more examples?

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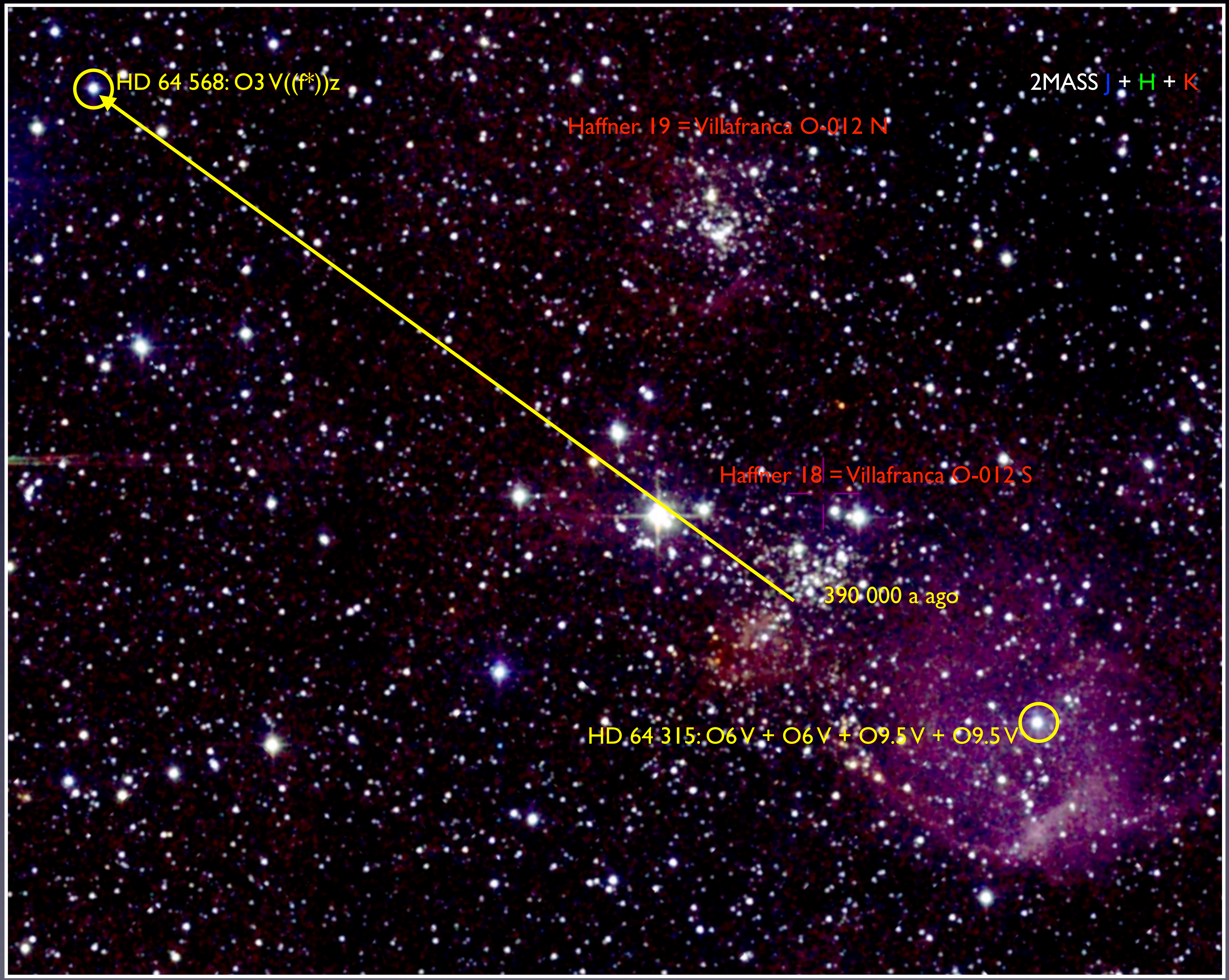

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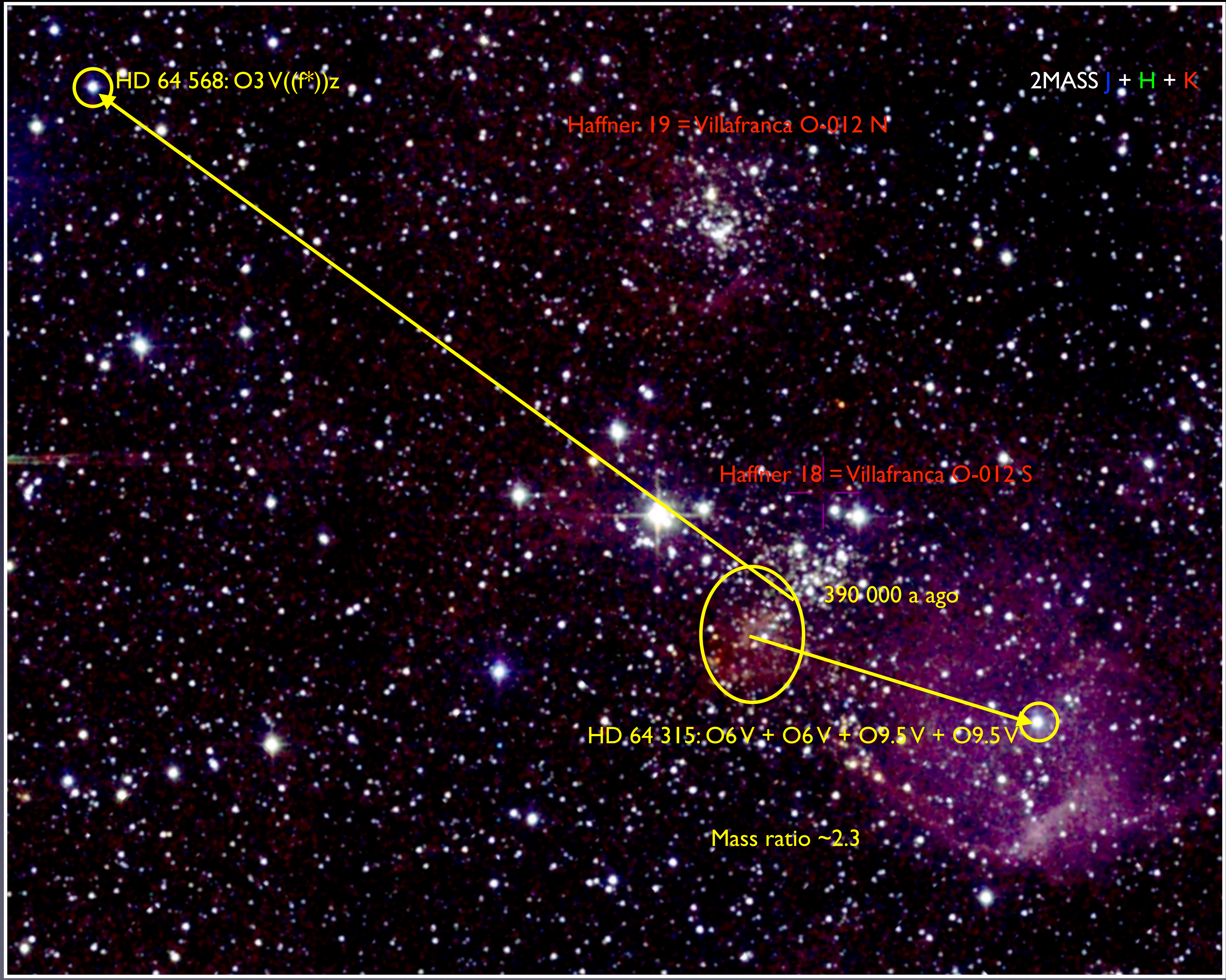

# Any more examples?

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## THE ORIGIN OF RUNAWAY STARS

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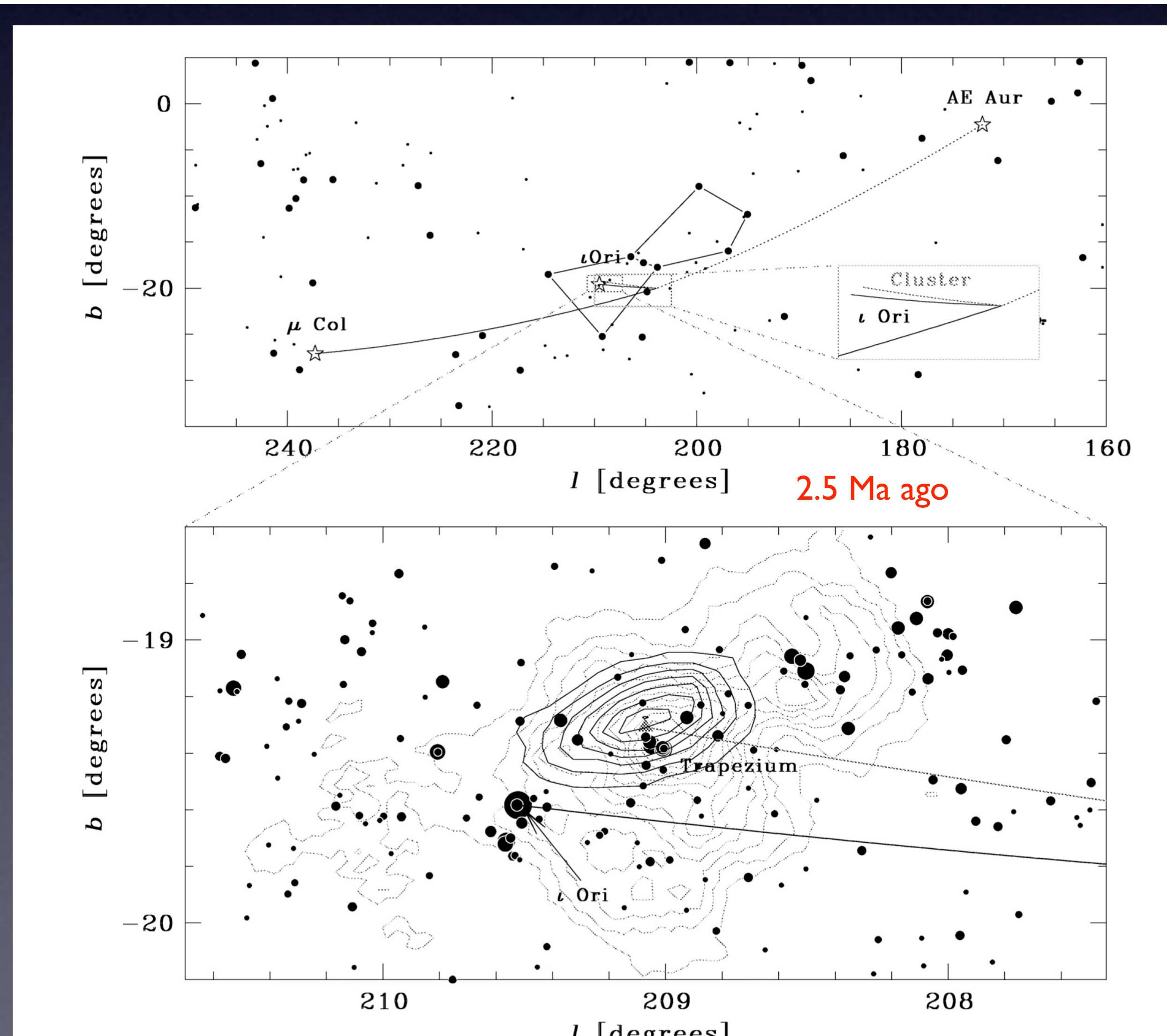

# Summary

- Oasis (*Born in a different cloud*) is the dominant effect.
  - ★ Star formation is hierarchical and forms from large bound clusters to isolated stars depending on the initial conditions.
  - ★ OB associations are mostly born that way.
- Bruce Springsteen (*Born to run*) plays a significant role in some cases.
  - ★ Compact clusters can eject a significant number of stars just after formation.
  - ★ The real IMF there is top heavy but becomes Kroupa-like after the ejections.
  - ★ More compact objects are flying through the Galaxy than expected.
- Queen (*I want to break free*) is a second order effect.
  - ★ Cluster expansion due to gas loss affects clusters but is not the dominant reason for the dispersion of young stars.