Not all stars form in clusters
measuring the kinematics of OB associations with *Gaia*

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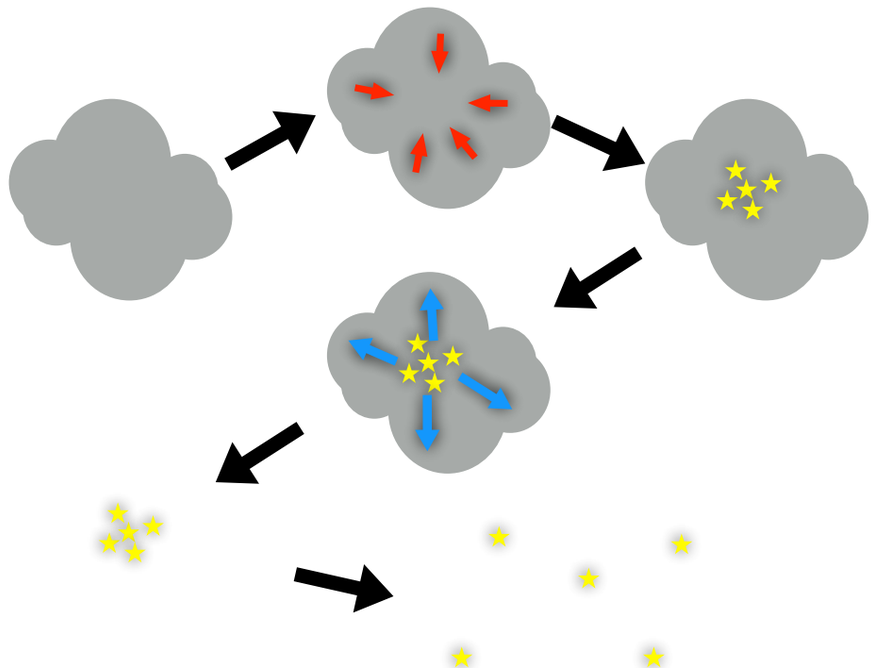
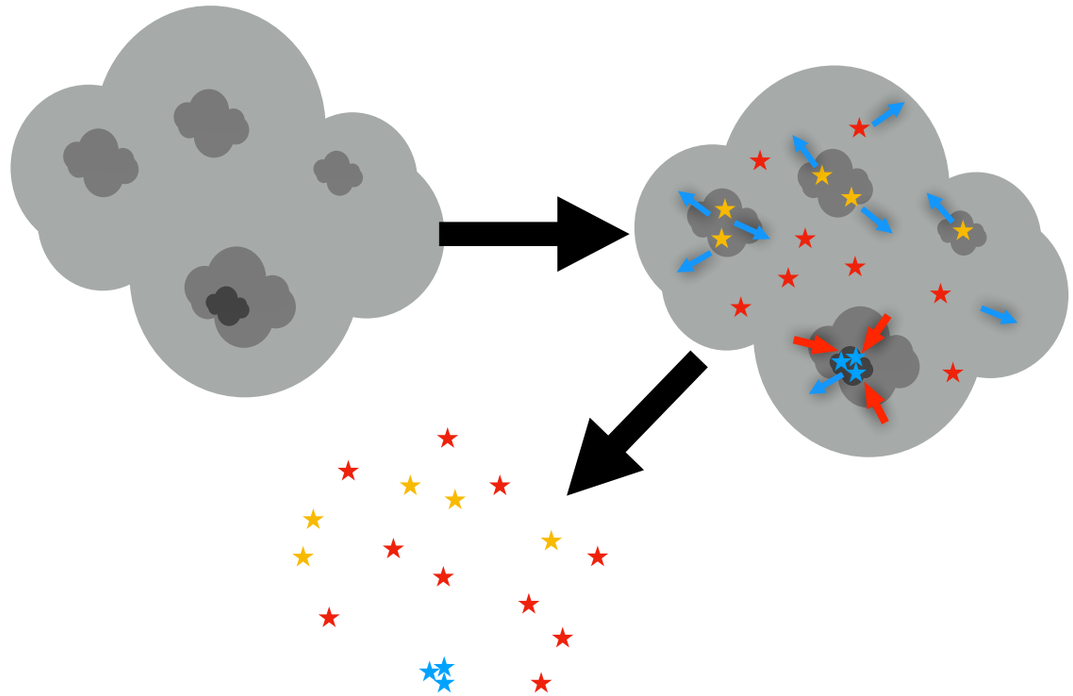
A “classical” view of star formation

- Most, if not all, stars form in clusters
- Gas and stars in virial equilibrium
- Stellar feedback expels gas
- Because the star formation efficiency is low, the cluster then expands, possibly becoming unbound (Hills 1980; Goodwin & Bastian 2006; Baumgardt & Kroupa 2007)
- Only ~10% of star formation ends up in bound clusters (e.g. Lada & Lada 2003)
- We refer to this as the **monolithic model of star formation**



An alternative model of star formation

- Star formation follows the fractal nature of the molecular clouds from which they form (e.g. Elmegreen 2002,2008, Bastian+2007, Bonnell+2011, Kruijssen 2012)



- Stars form from a continuous distribution of gas densities and star formation efficiency is dependent on gas density

- This means that star formation is clustered but not all stars form in gravitationally bound clusters

- This eliminates the need for gas-expulsion-driven expansion

- We refer to this as the **hierarchical model of star formation**

Gaia - the billion star mapper

Parallaxes —> distances

RA and Dec —> X and Y (pc)

Proper motions (mas/yr) —> velocities (km/s)

ESA/ATG medialab; background: ESO/S. Brunier

Gaia-DR1/TGAS

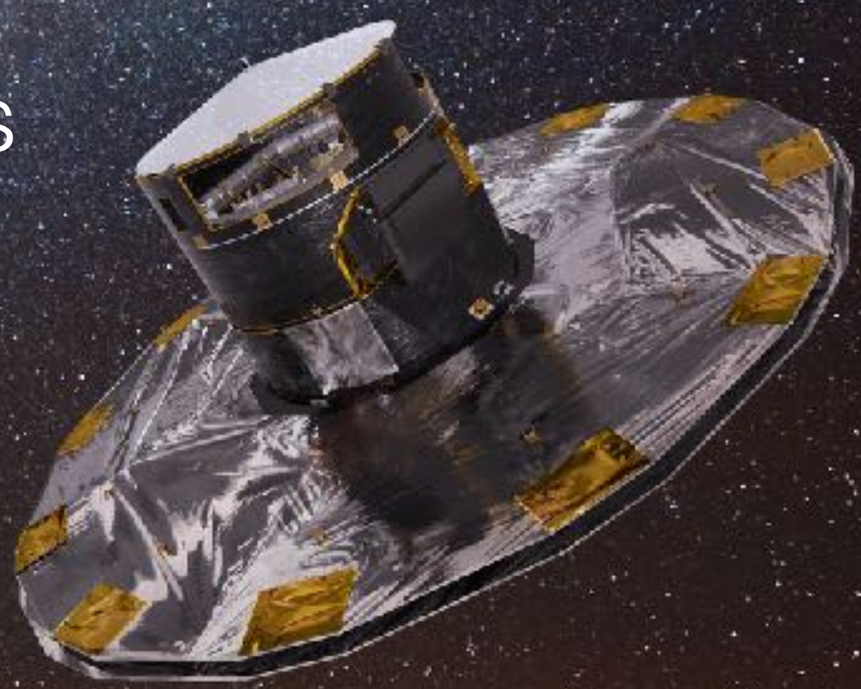
The Tycho-Gaia Astrometric Solution (TGAS)

- a combination of the 1st Gaia data release and the existing Tycho2 astrometric catalogue

Parallaxes and proper motions for ~2 million stars

Parallax uncertainties ~ 0.32 mas

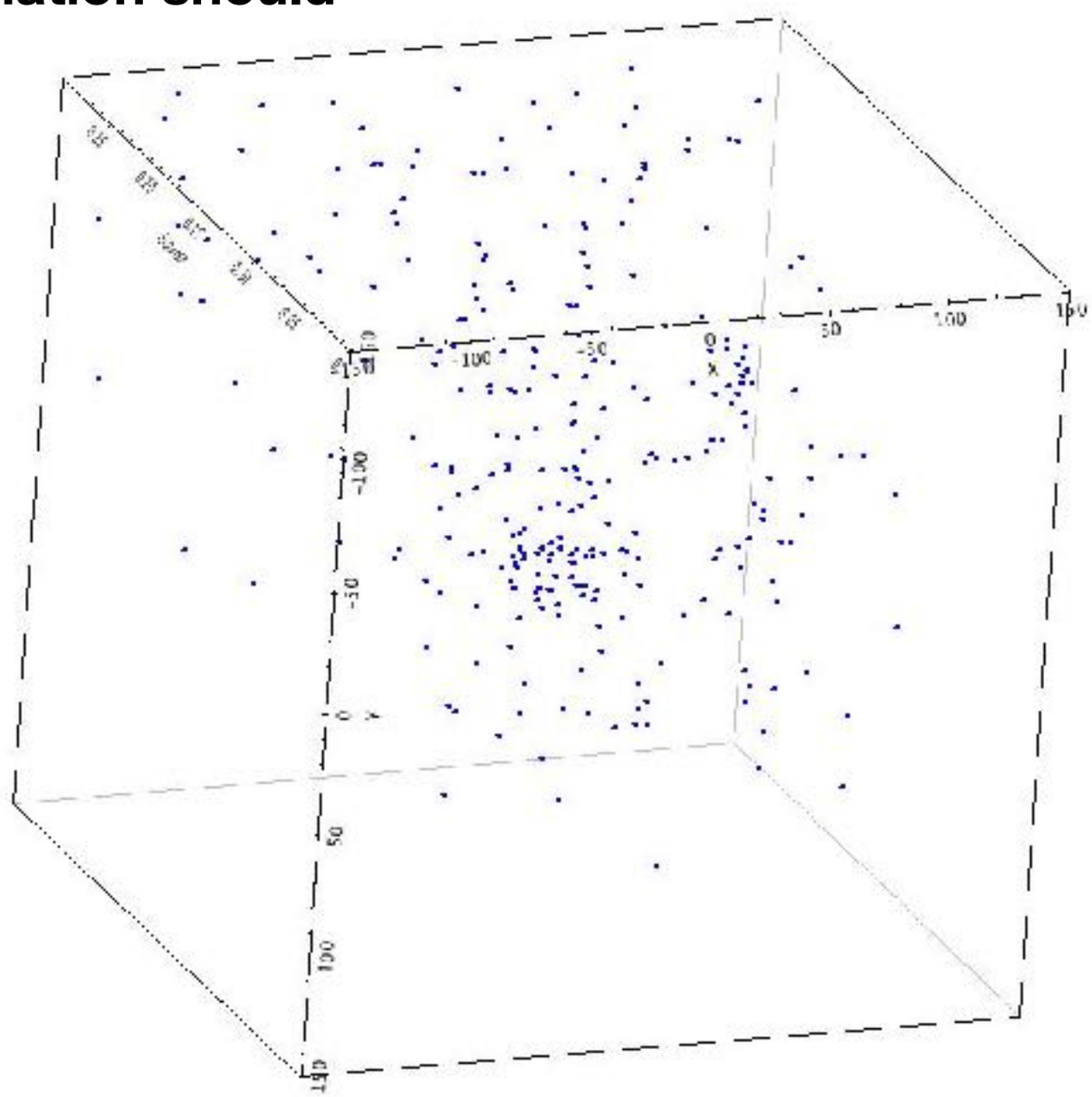
PM uncertainties ~ 1.32 mas/yr



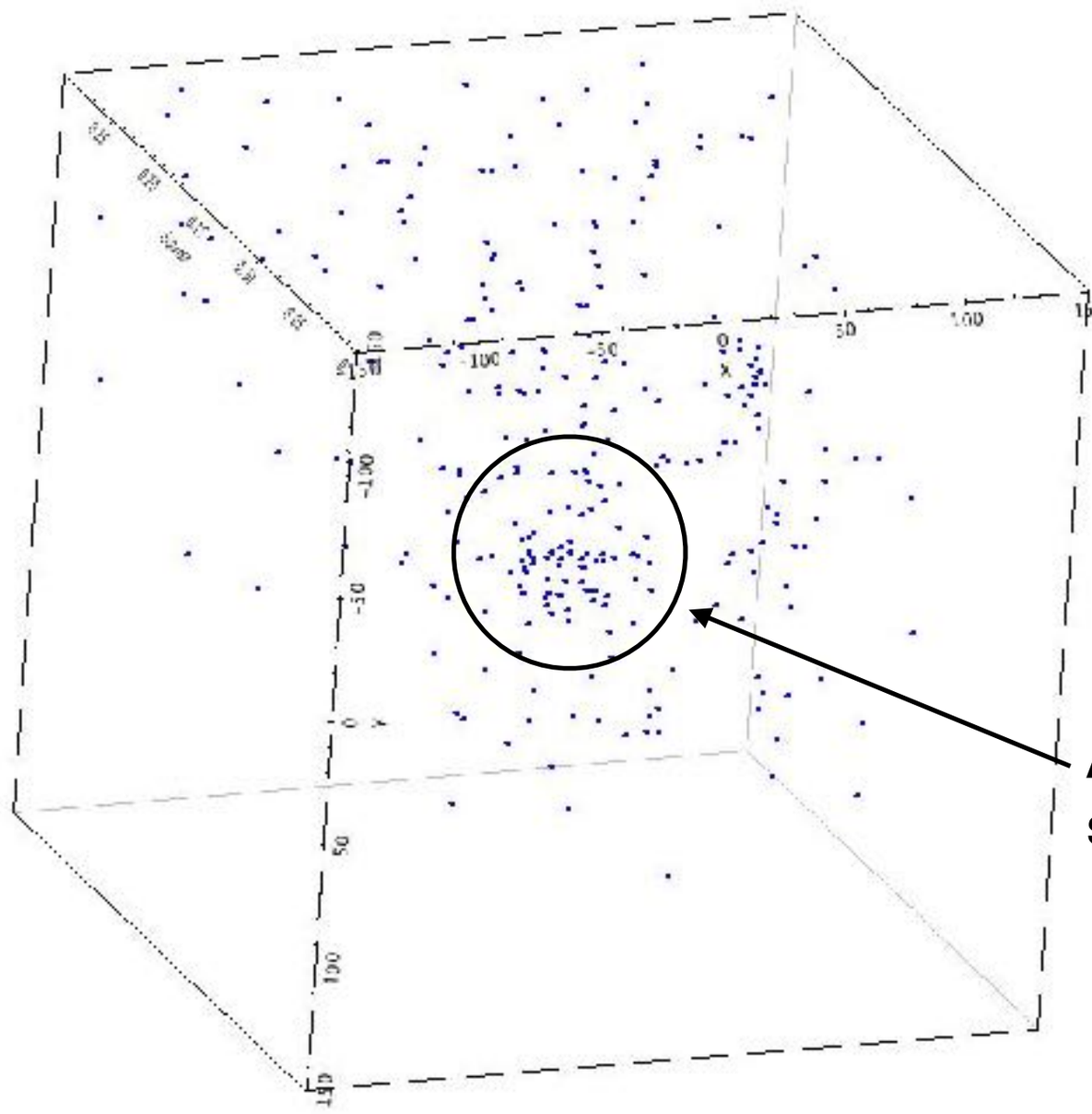
ESA/ATG medialab; background: ESO/S. Brunier

Association membership selection

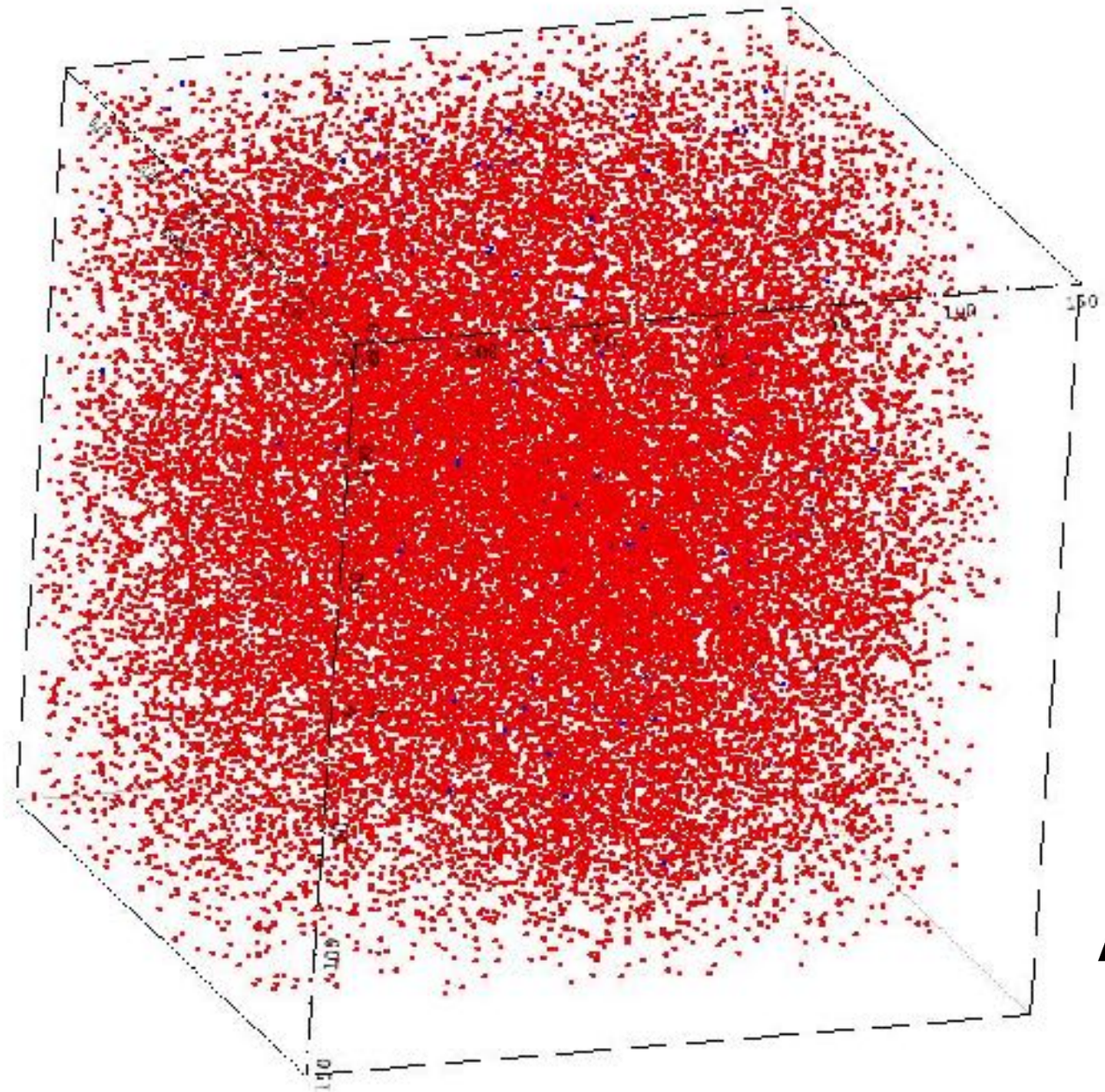
OB stars in a 300 pc box around where an OB association should be



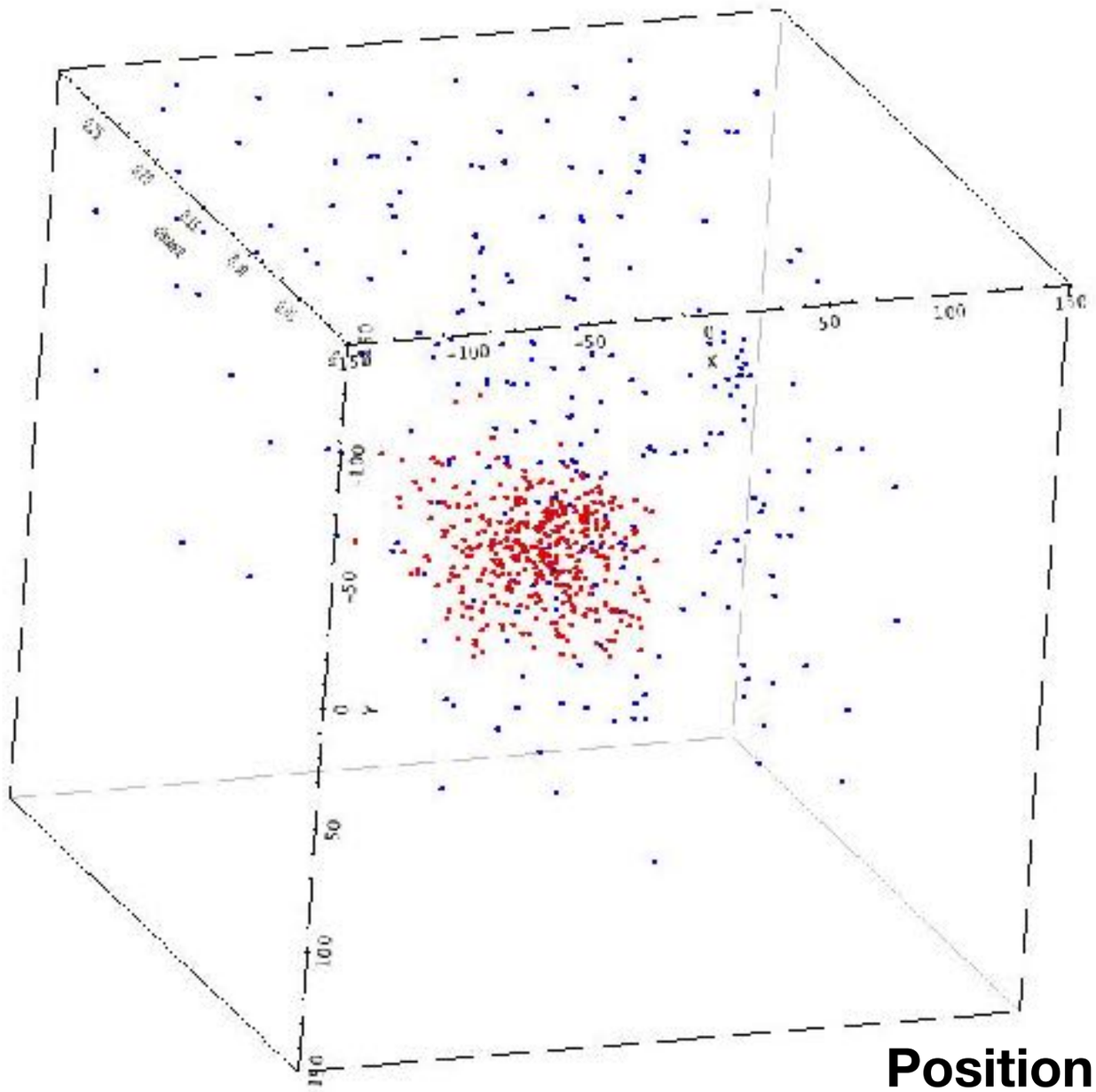
Association membership selection



An over-density of OB stars



All stars in the box

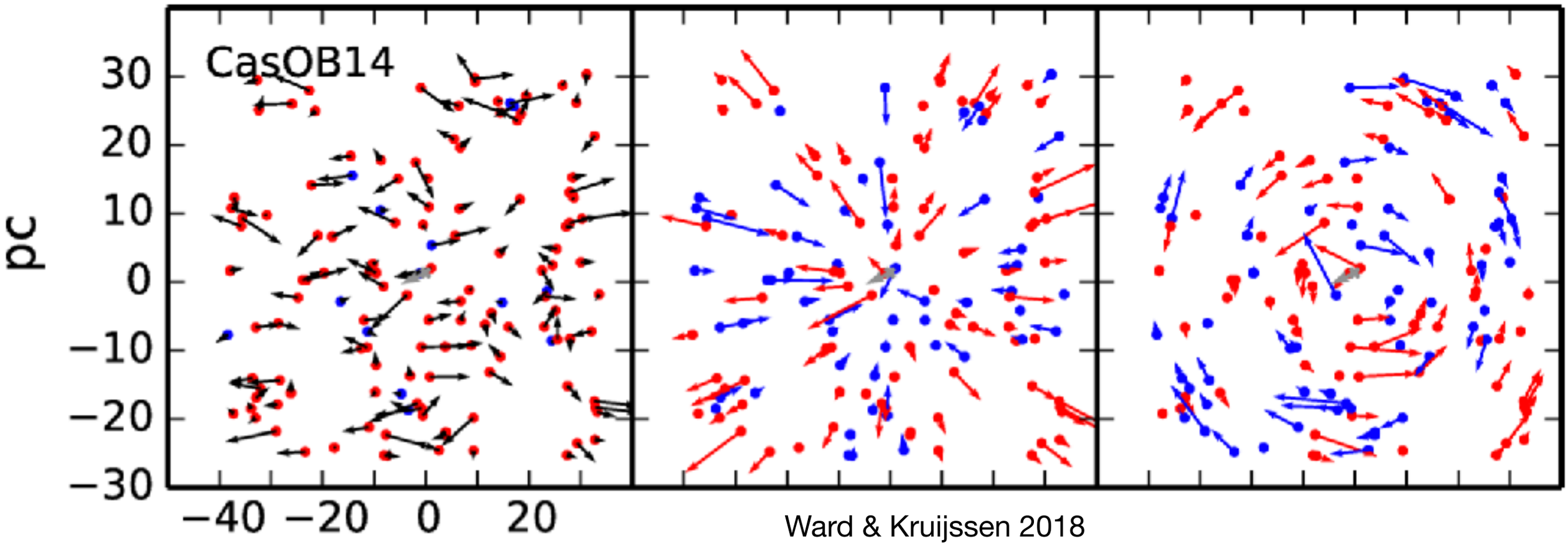


Position selected members of the association

$$|v_x| < 3\sigma_{v_X} \text{ and } |v_y| < 3\sigma_{v_Y}$$

$$v_x \equiv v_X - \mu_{v_X} \text{ and } v_y \equiv v_Y - \mu_{v_Y}$$

This helps to ensure that we do not include any stars which are on very different orbits to the OB association.



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What can we expect from an OB association formed from monolithic star formation?

- The majority of its members should be moving outwards from one or more sites of formation.

- On average stars should exhibit positive radial velocities with respect to the centre of the association. This should be true regardless of the number of initial clusters.

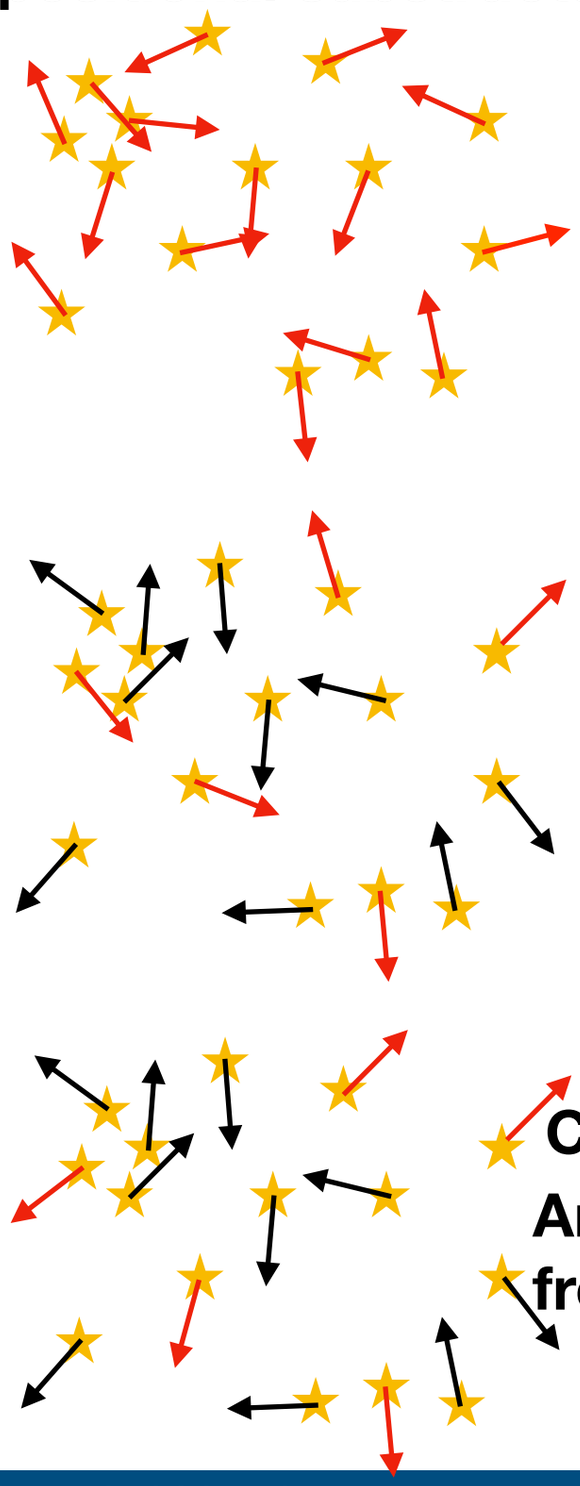
- The velocity field should remain radially anisotropic over many crossing times (several tens Myr)
  Baumgardt & Kroupa 2007

What do we test?

- Number ratio: $N_{v_r > 0} / N_{v_r < 0}$
- Median radial velocity
- Median radial velocity normalised by tangential velocity
- Radial anisotropy $\beta = 1 - \frac{< v_t^2 >}{< v_r^2 >}$

Model associations

Includes any observed positional substructure



Case I

Random directions observed velocity magnitudes

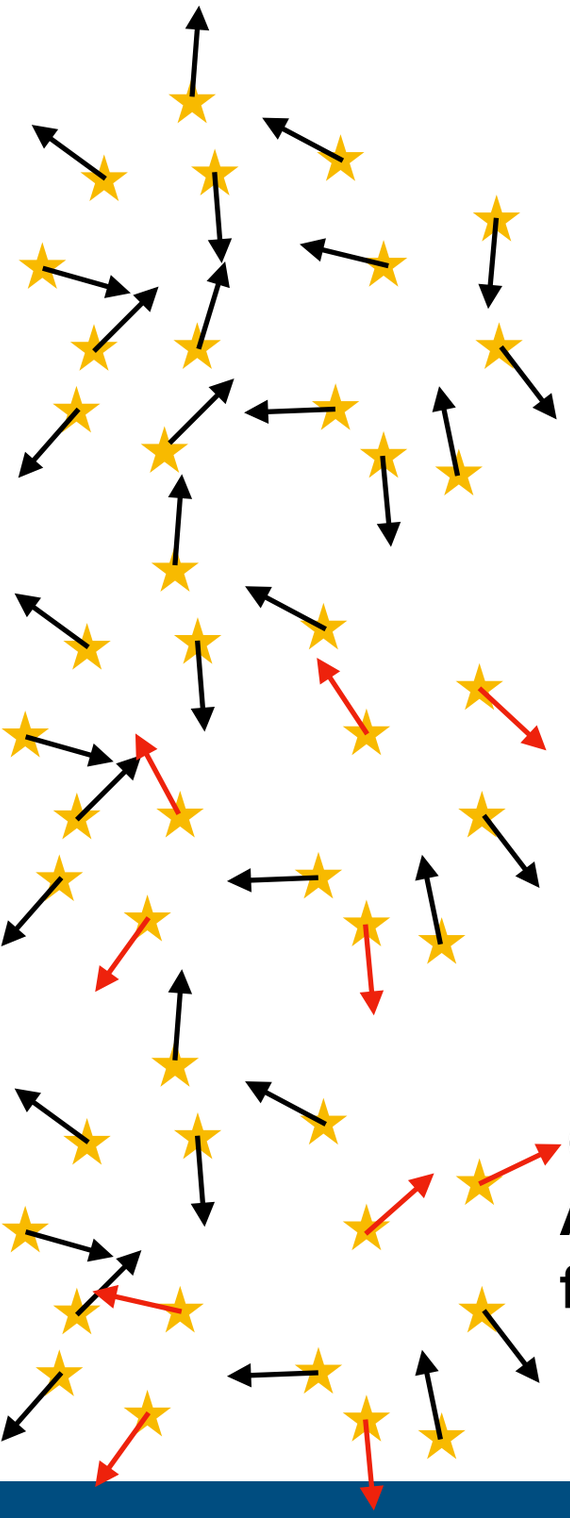
Case II

Expansion from multiple points

Case III

Anisotropic expansion from multiple points

Randomised positions



Case IV

Random velocity field

Case V

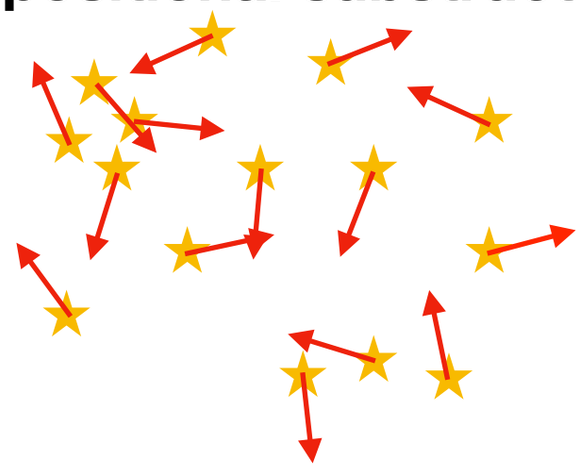
Expansion from a single point

Case VI

Anisotropic expansion from a single point

Model associations

Includes any observed positional substructure



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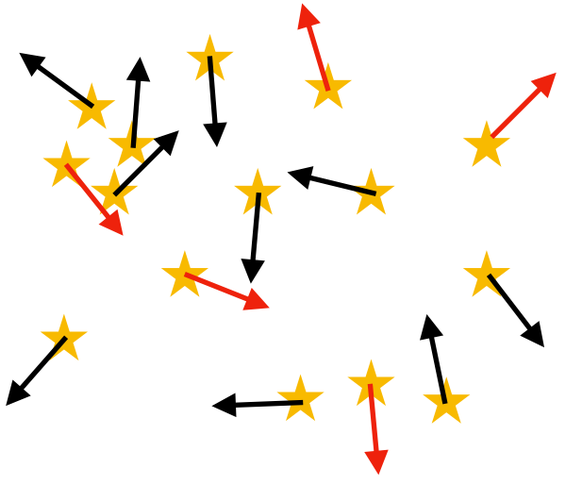
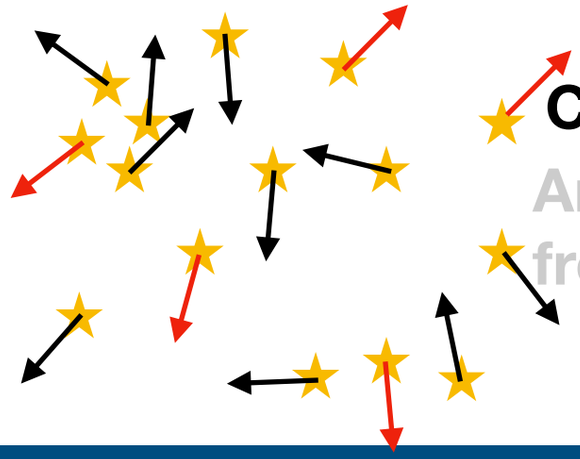
Random directions observed velocity magnitudes



Case II

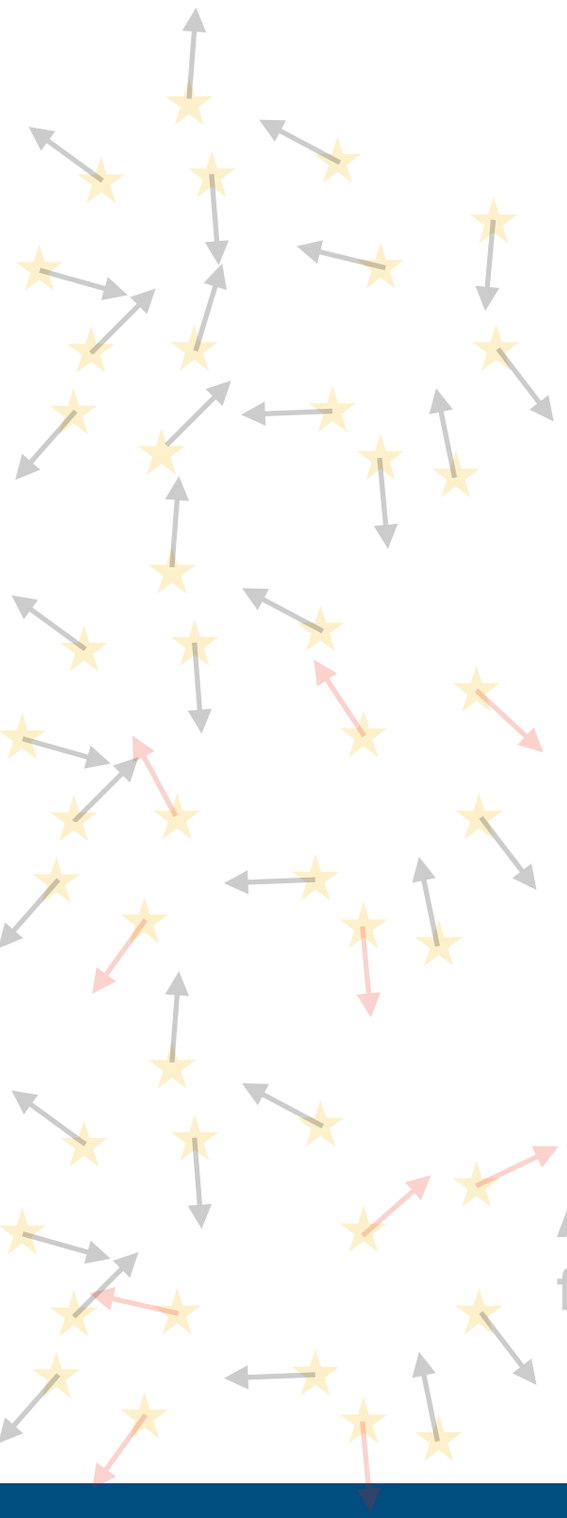
Expansion from multiple points



Case III

Anisotropic expansion from multiple points

Randomised positions



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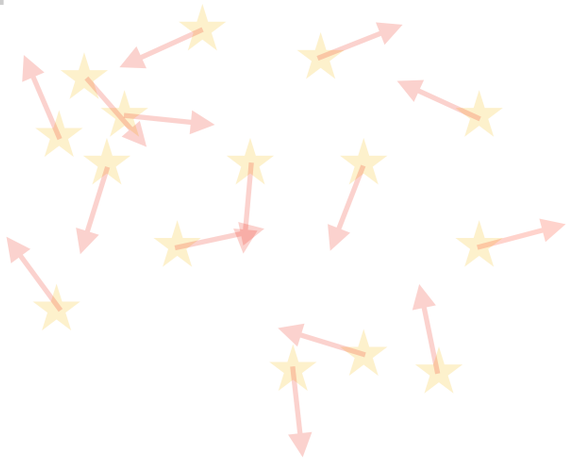

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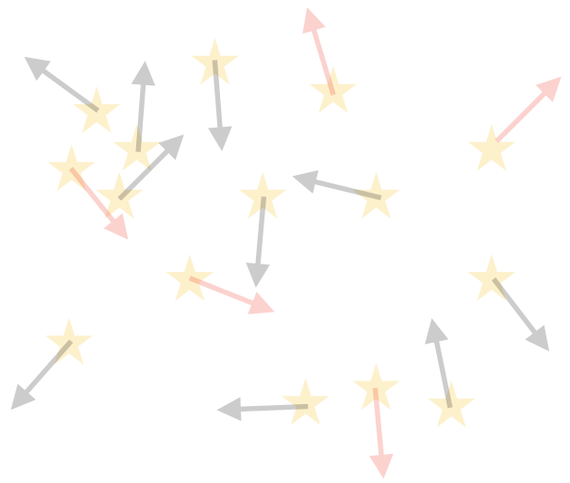
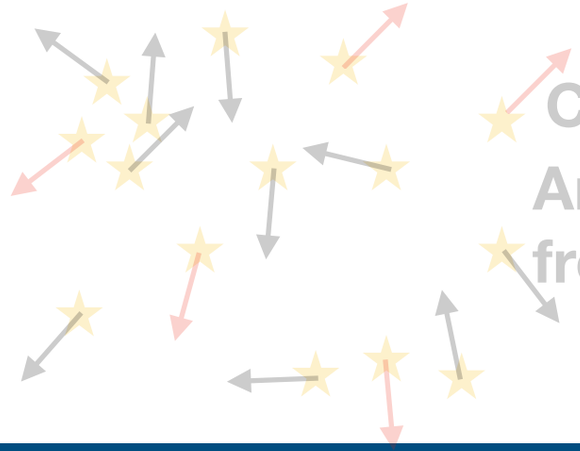


Case II

Expansion from multiple points



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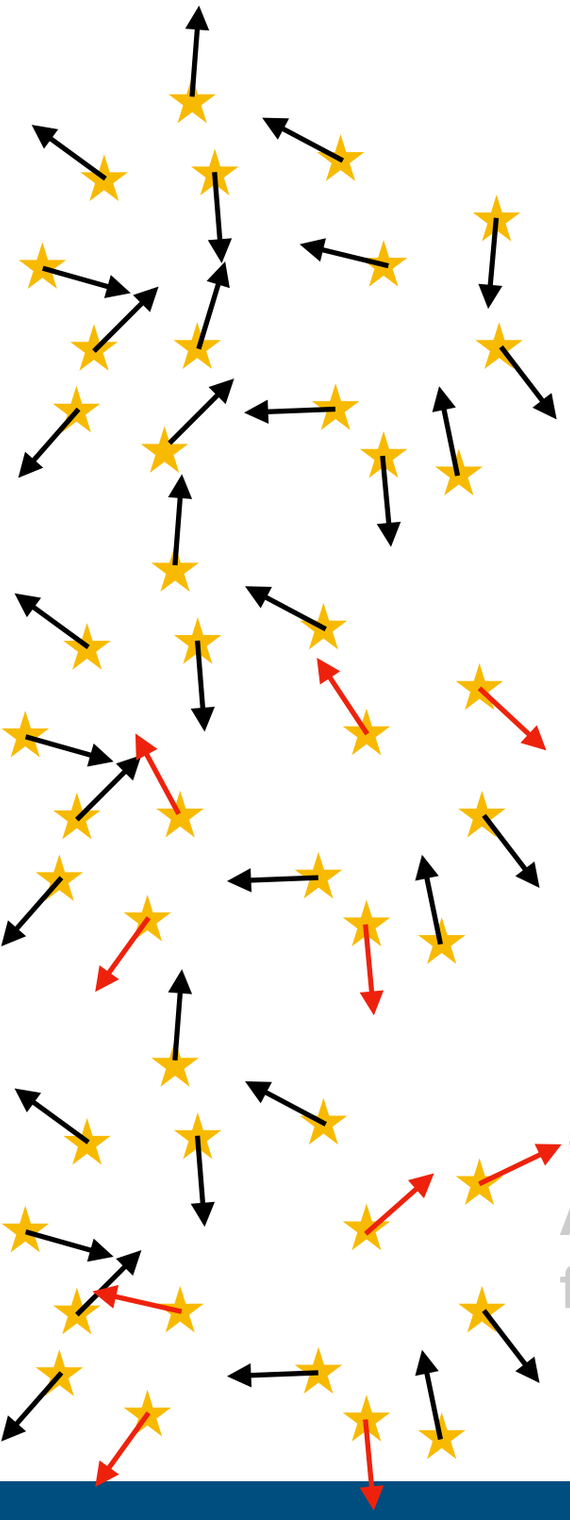

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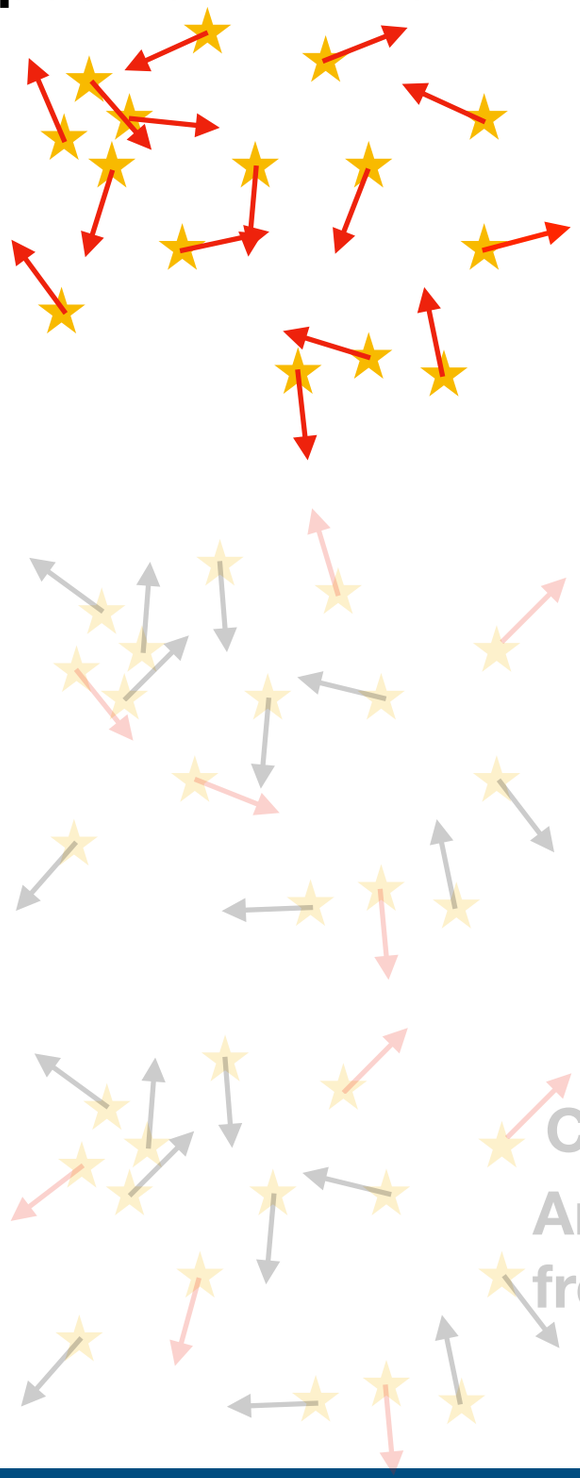

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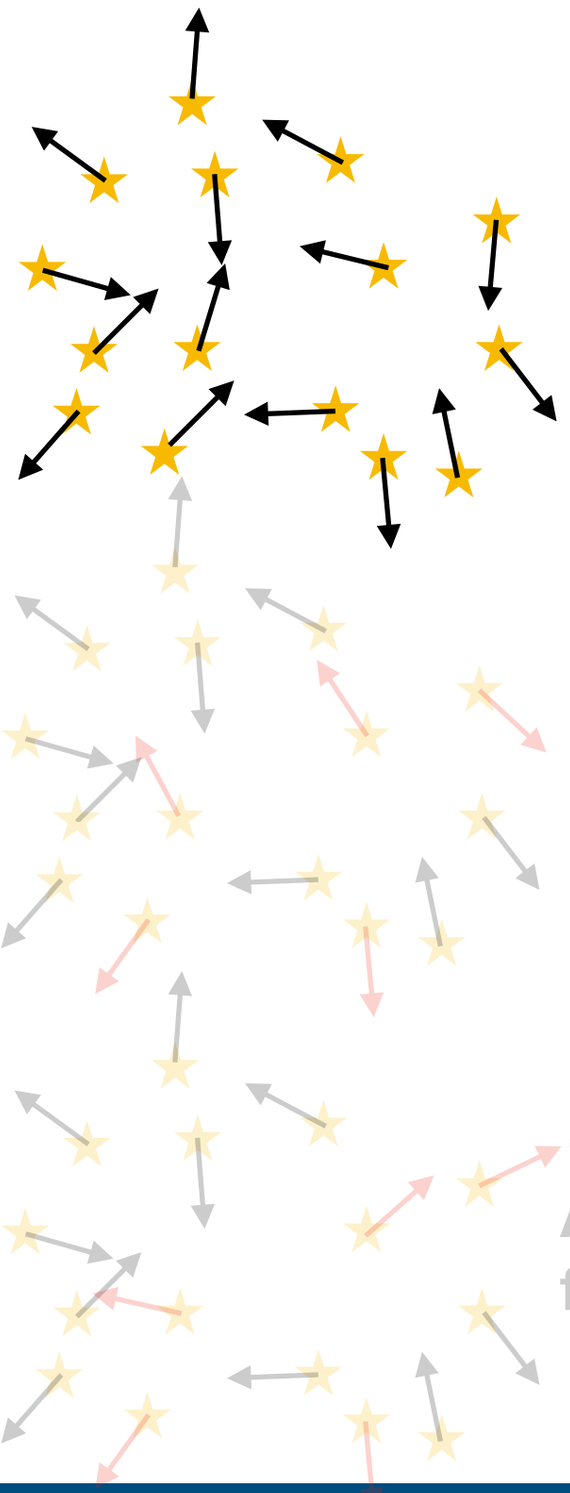

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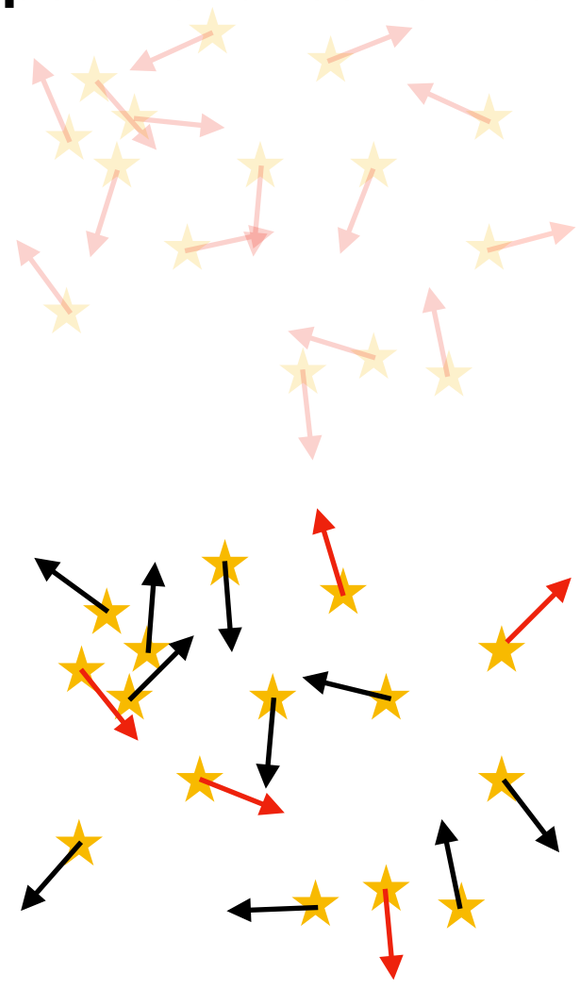

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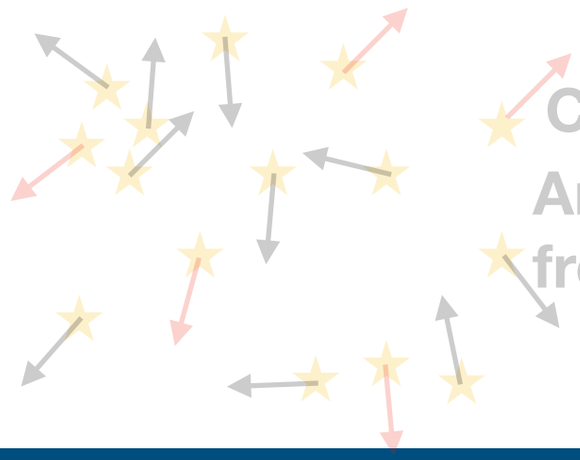

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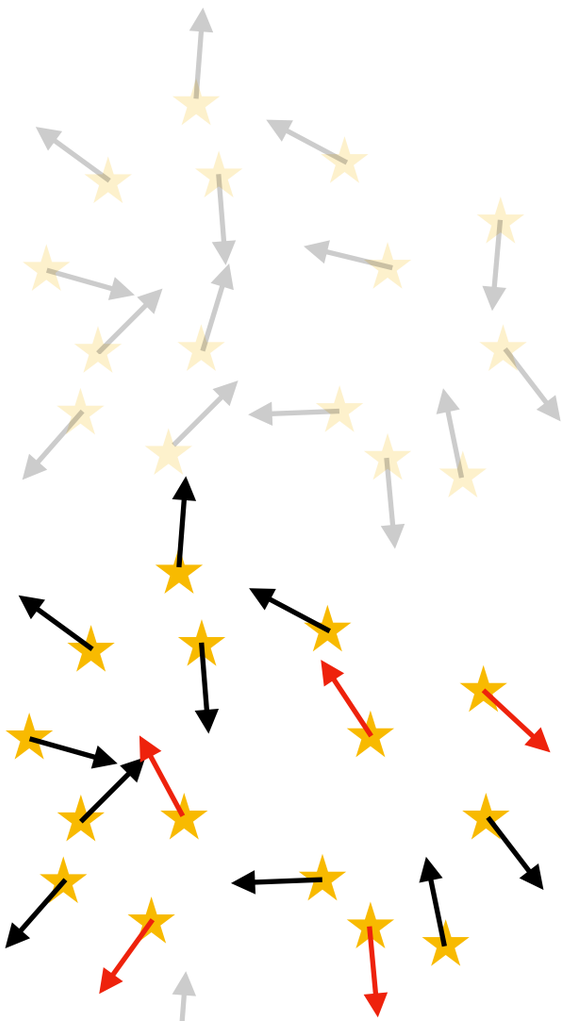
Randomised positions



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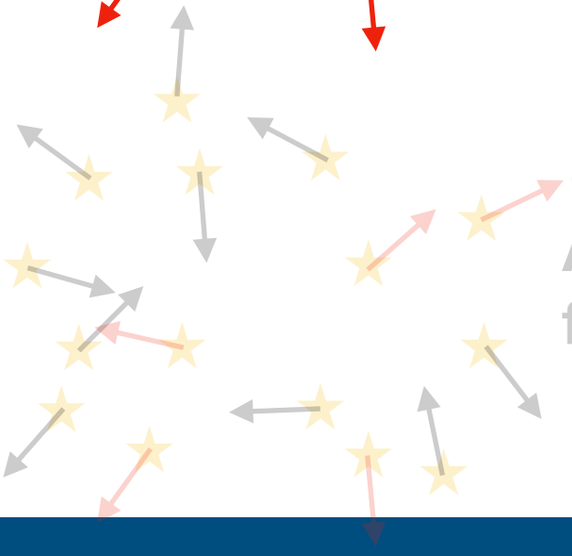

Case VI
Anisotropic expansion from a single point

Model associations

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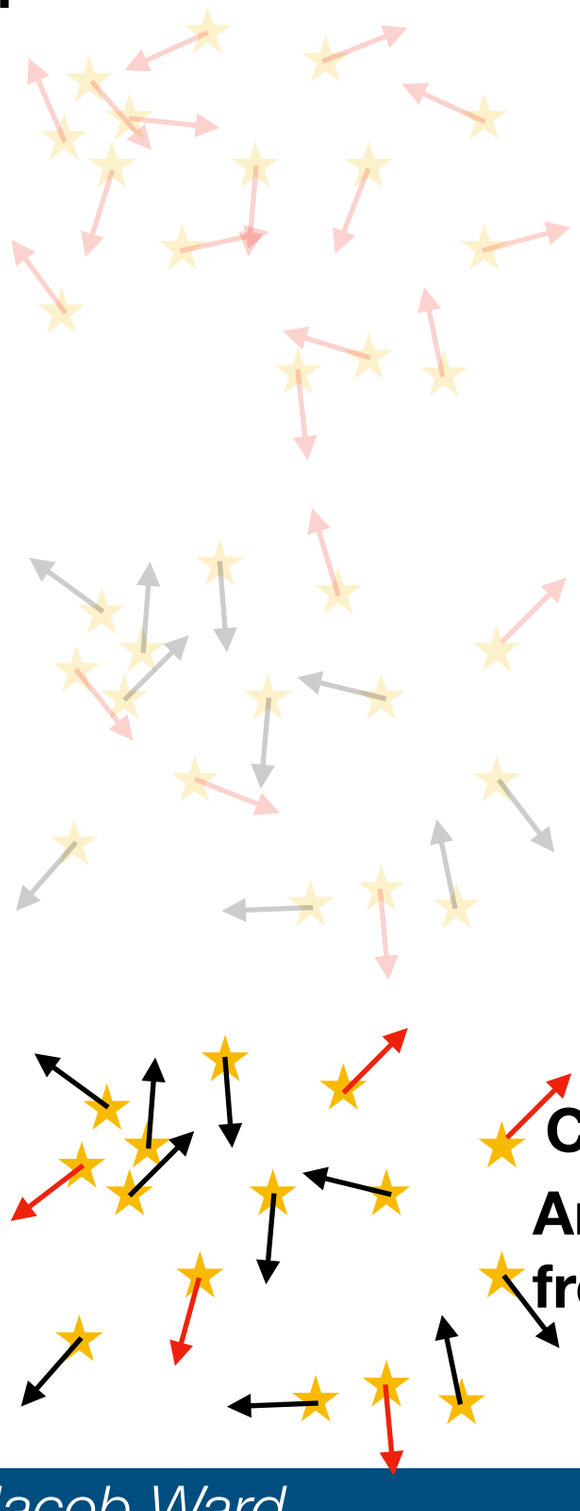

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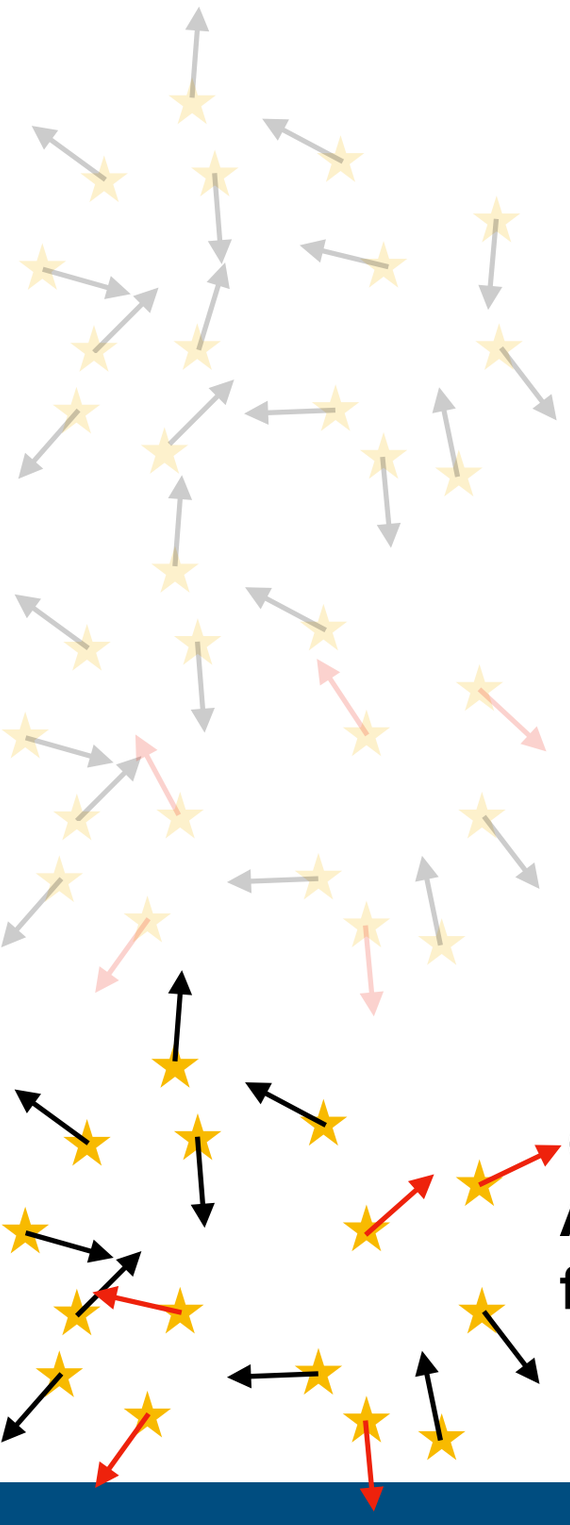
Case II
Expansion from multiple points

Case III
Anisotropic expansion from multiple points

Randomised positions



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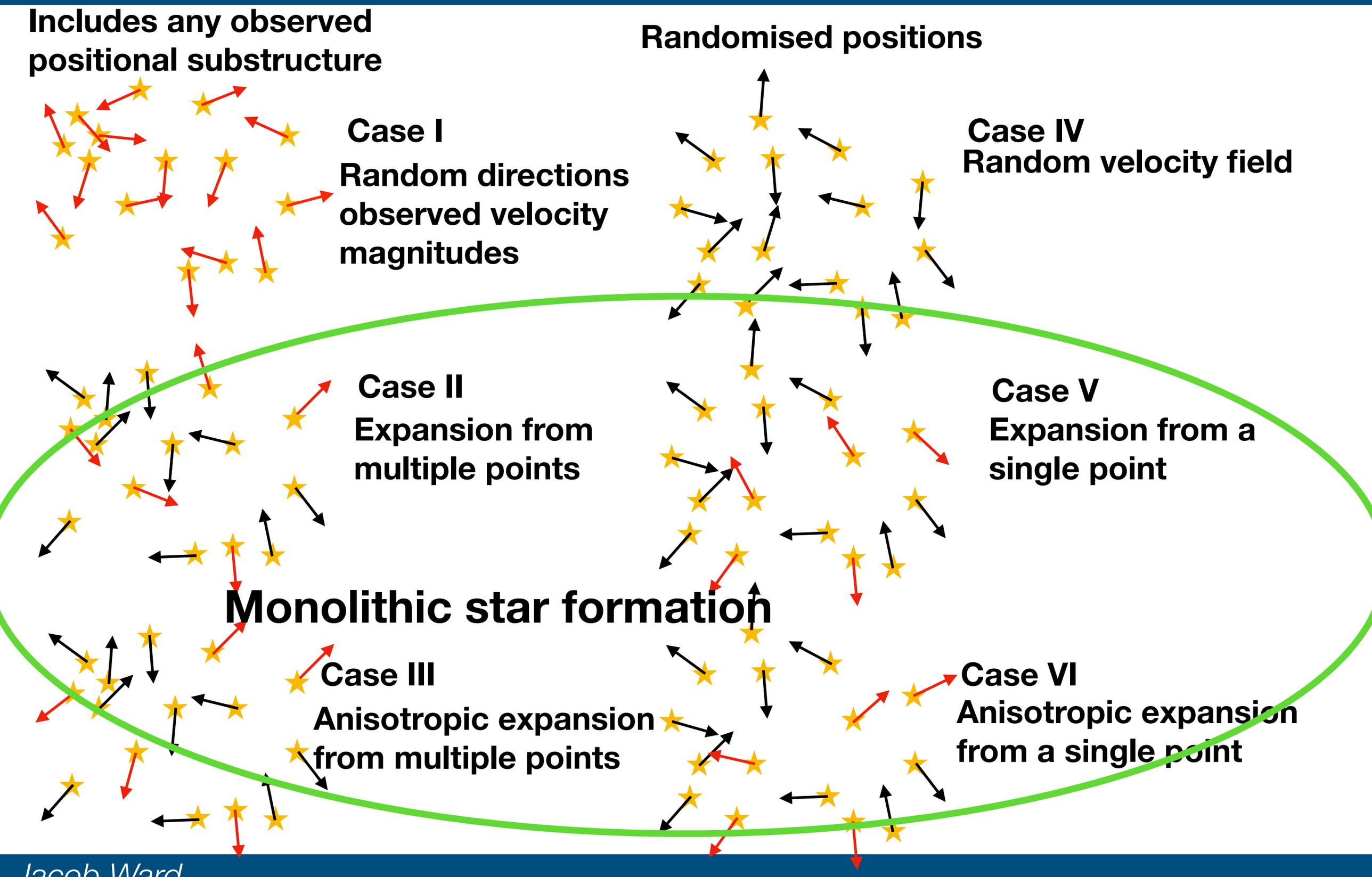

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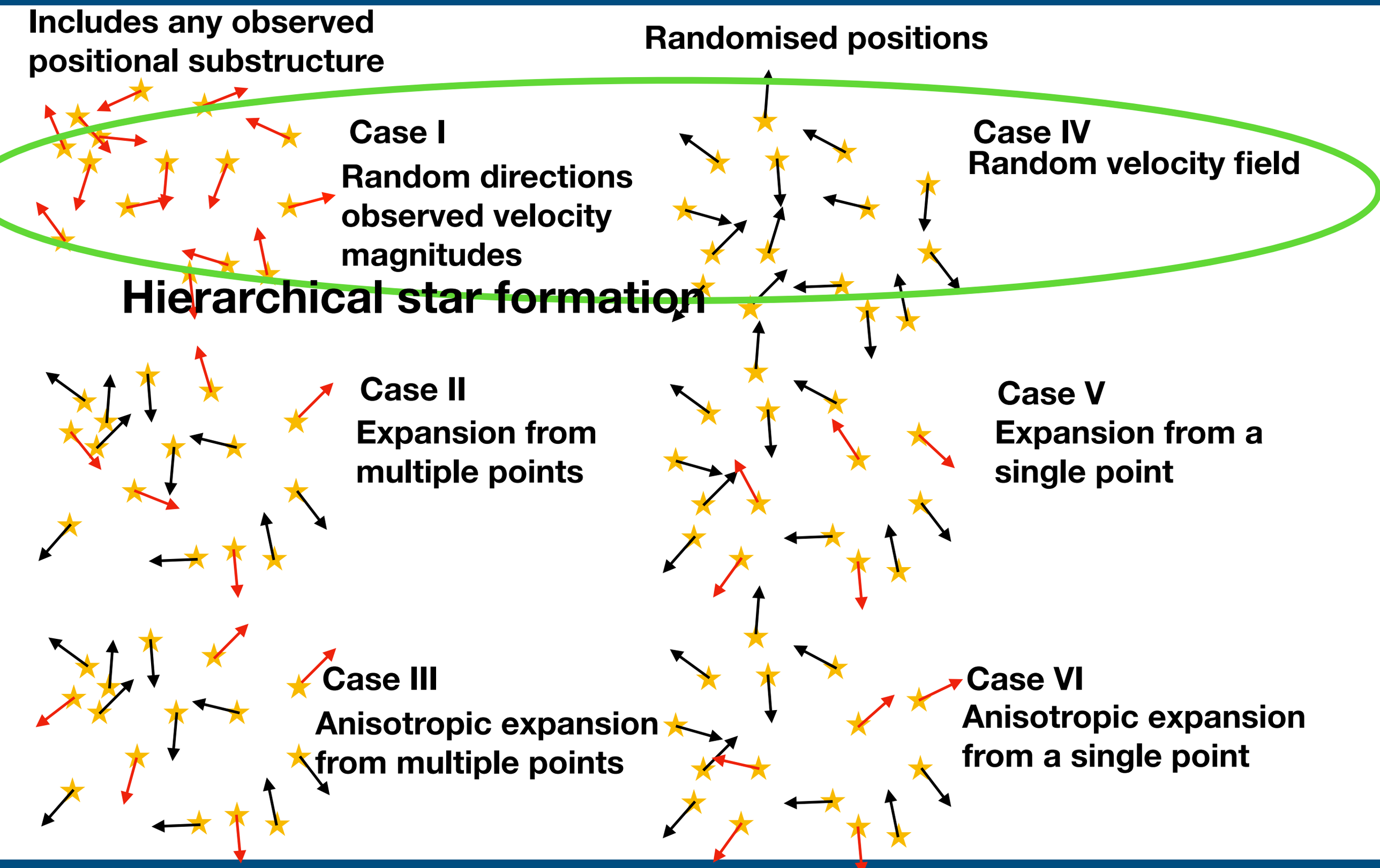
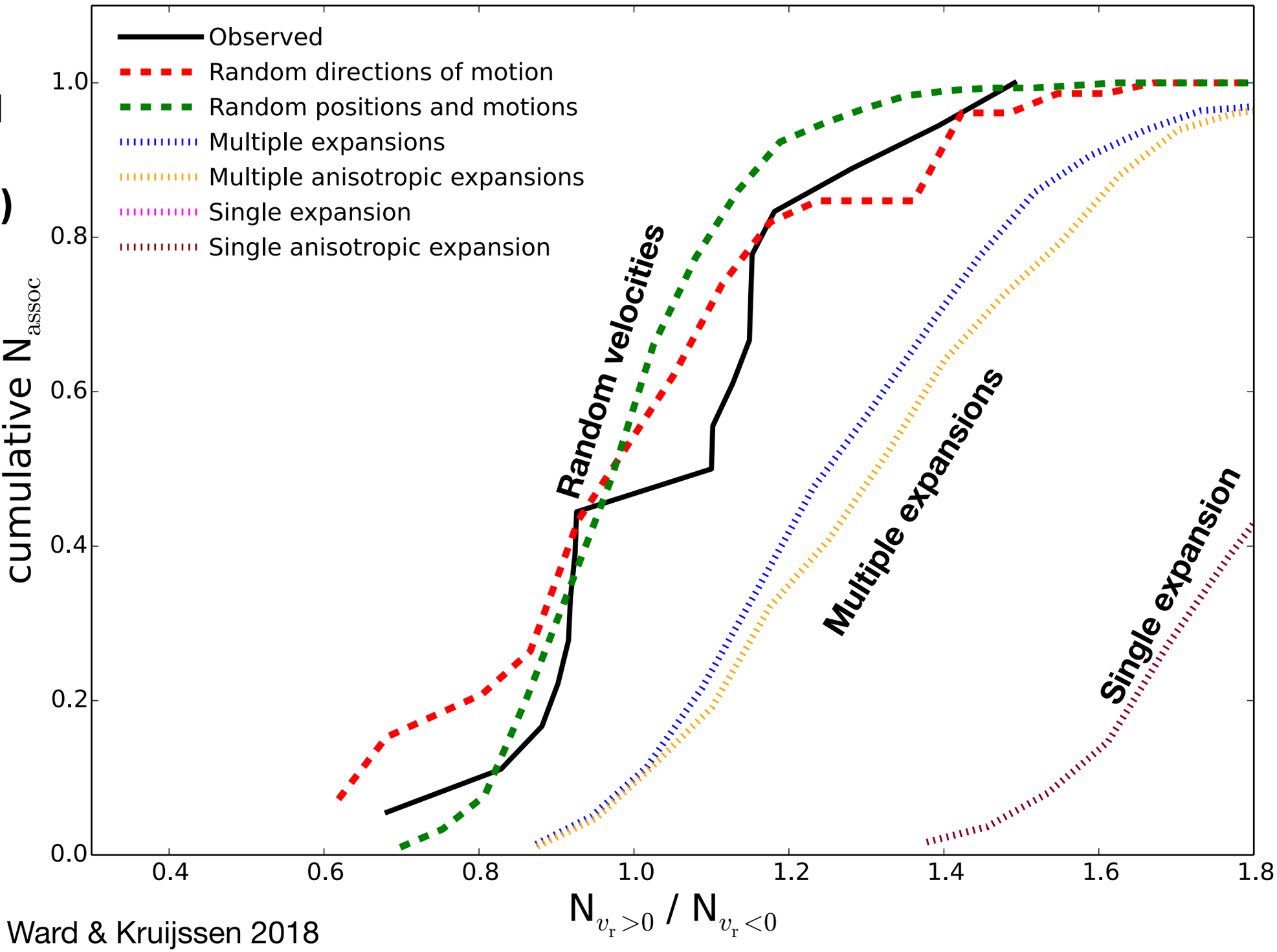


Hierarchical (random velocity field) I, IV

Monolithic (expanding) II,III,V,VI



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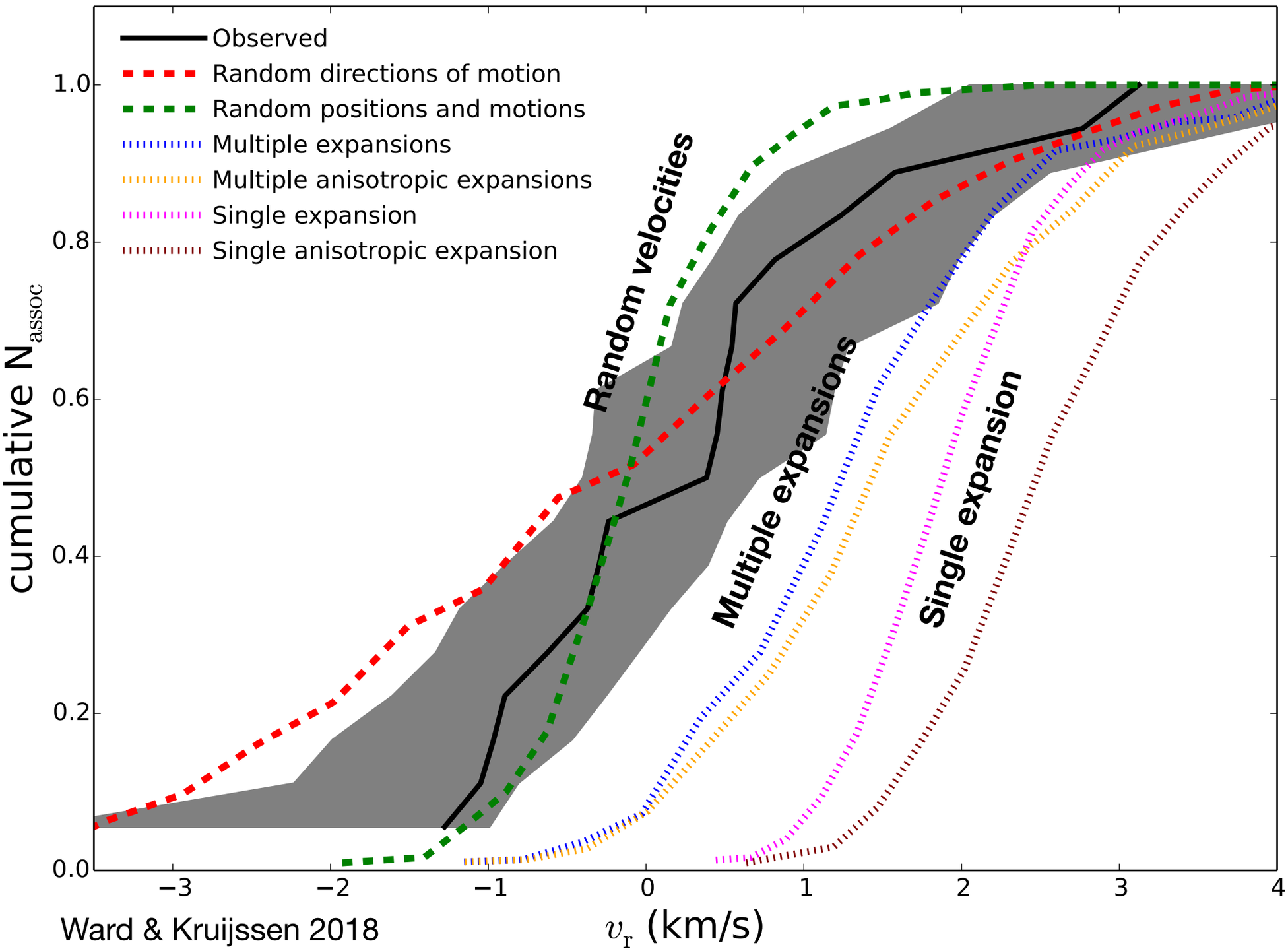

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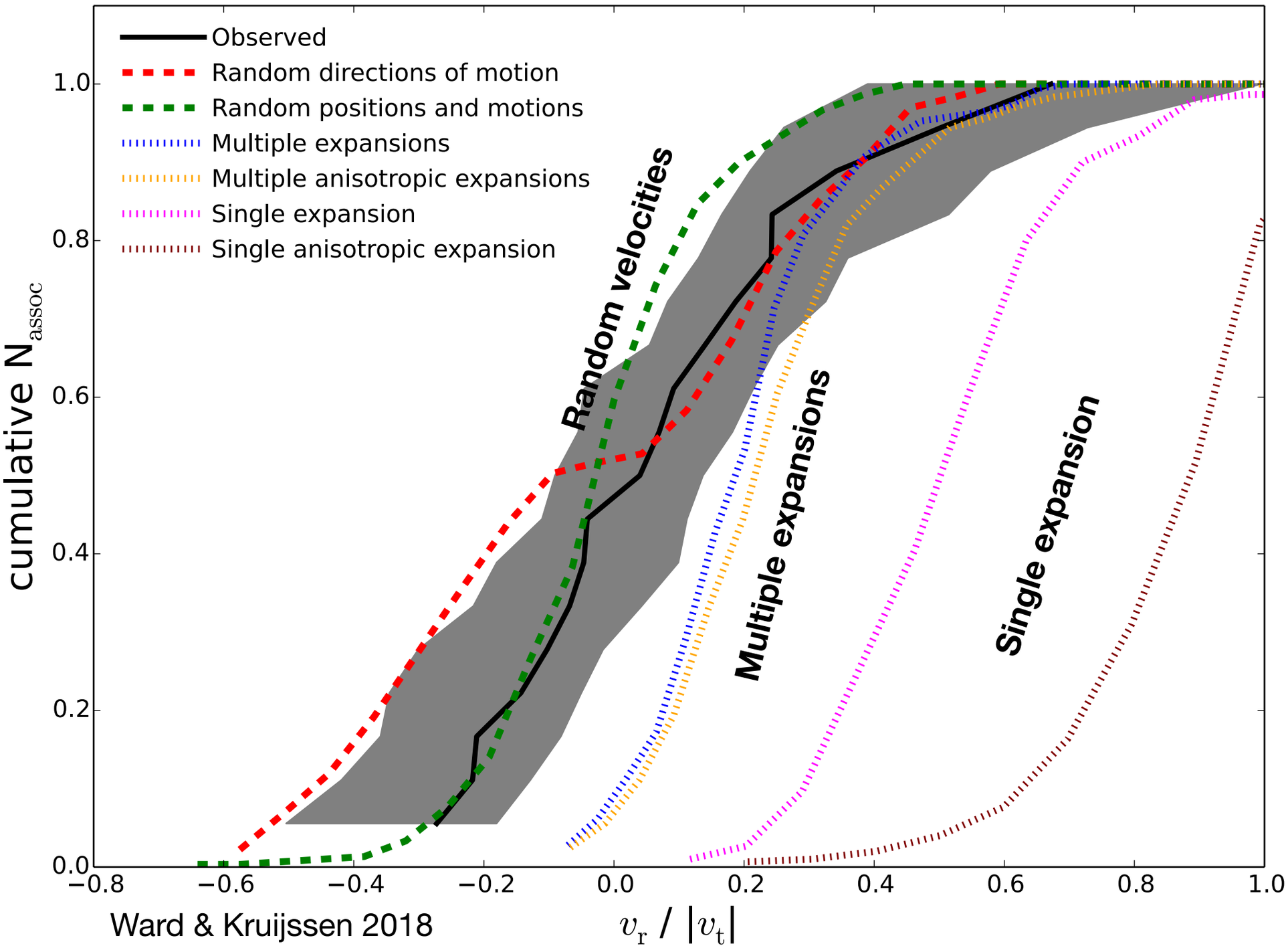

$$\beta = 1 - \frac{< v_t^2 >}{< v_r^2 >}$$

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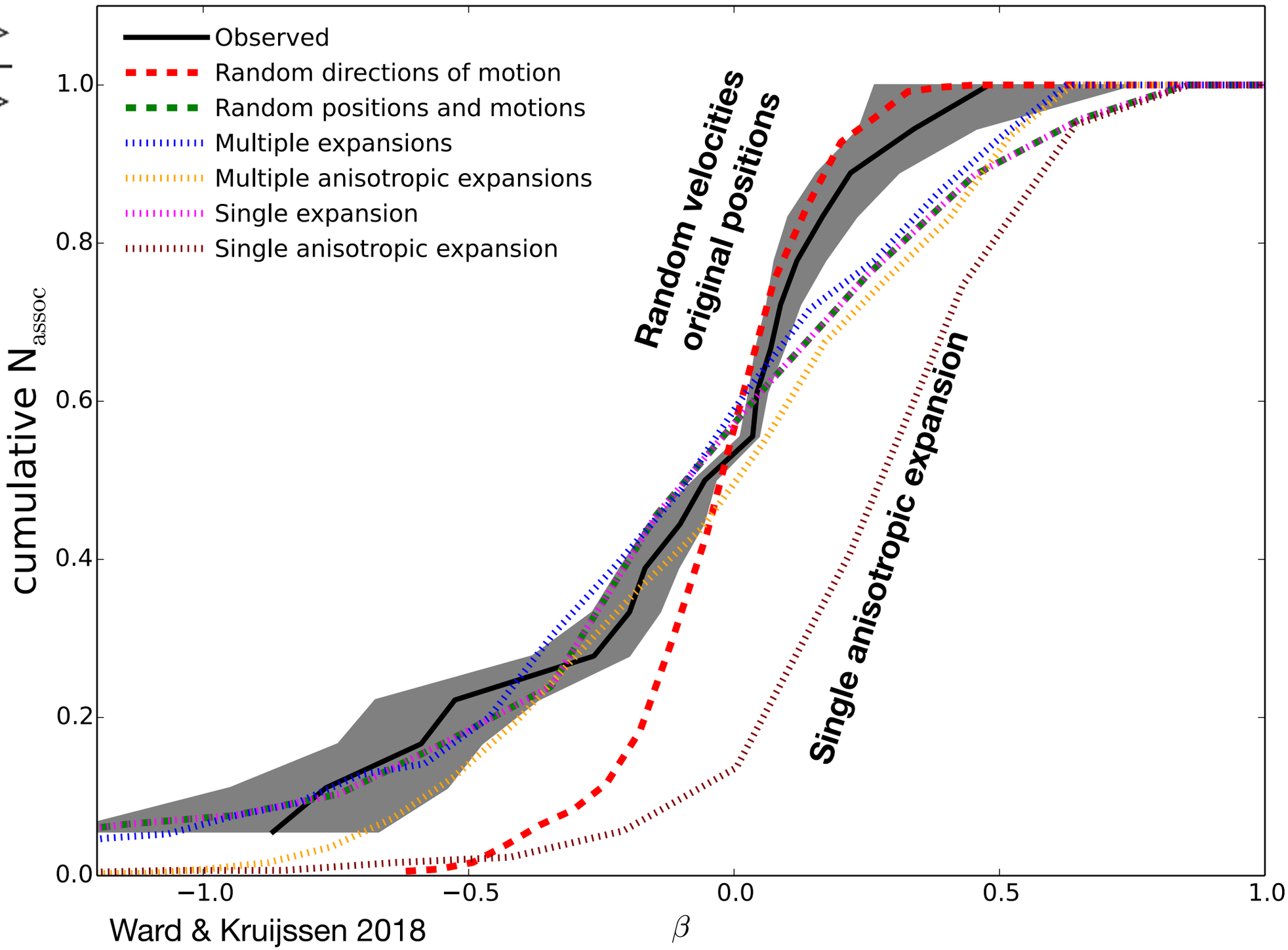


Not all stars form in clusters.

The results of this study are totally inconsistent with the predictions of a monolithic model of star formation

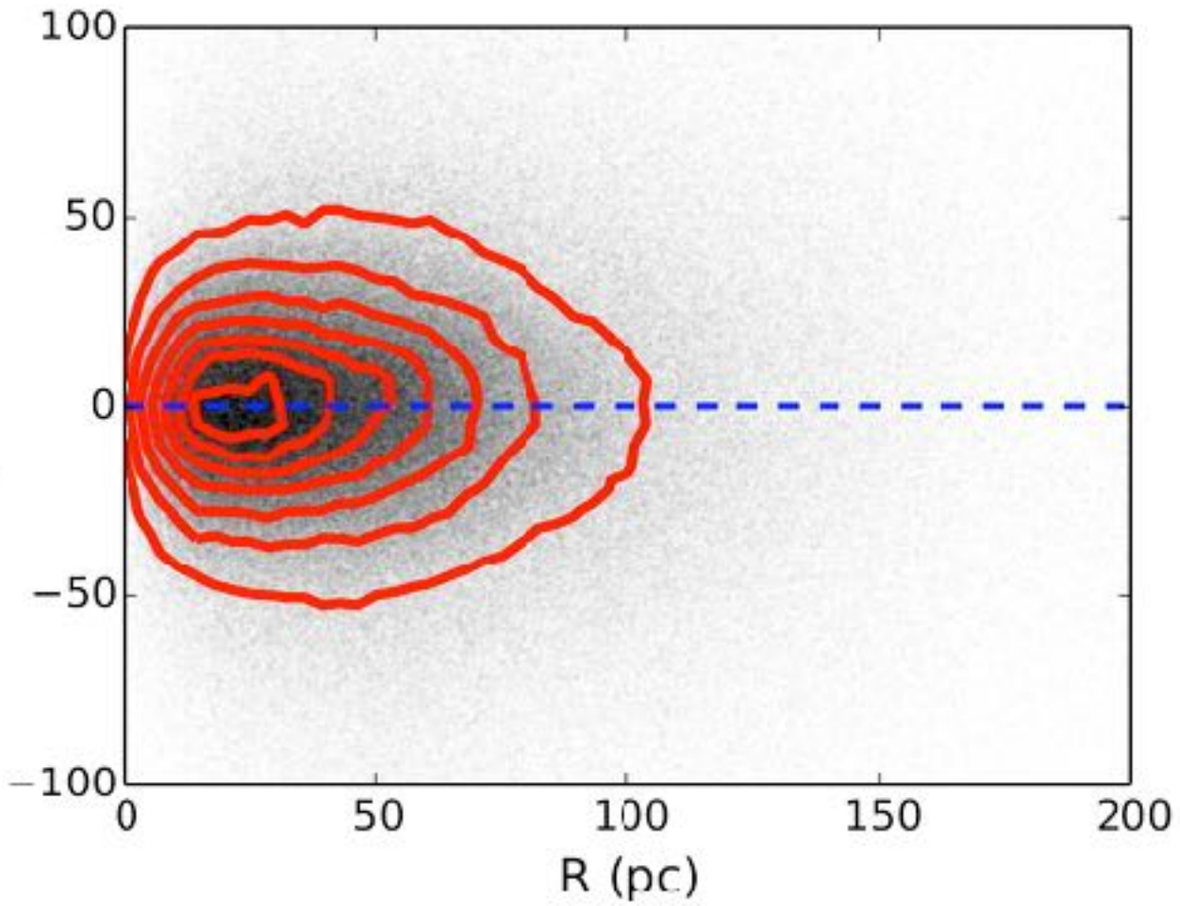
These results favour a hierarchical picture of star formation in which OB associations can form as large, scale-free structures following the structure of the molecular cloud

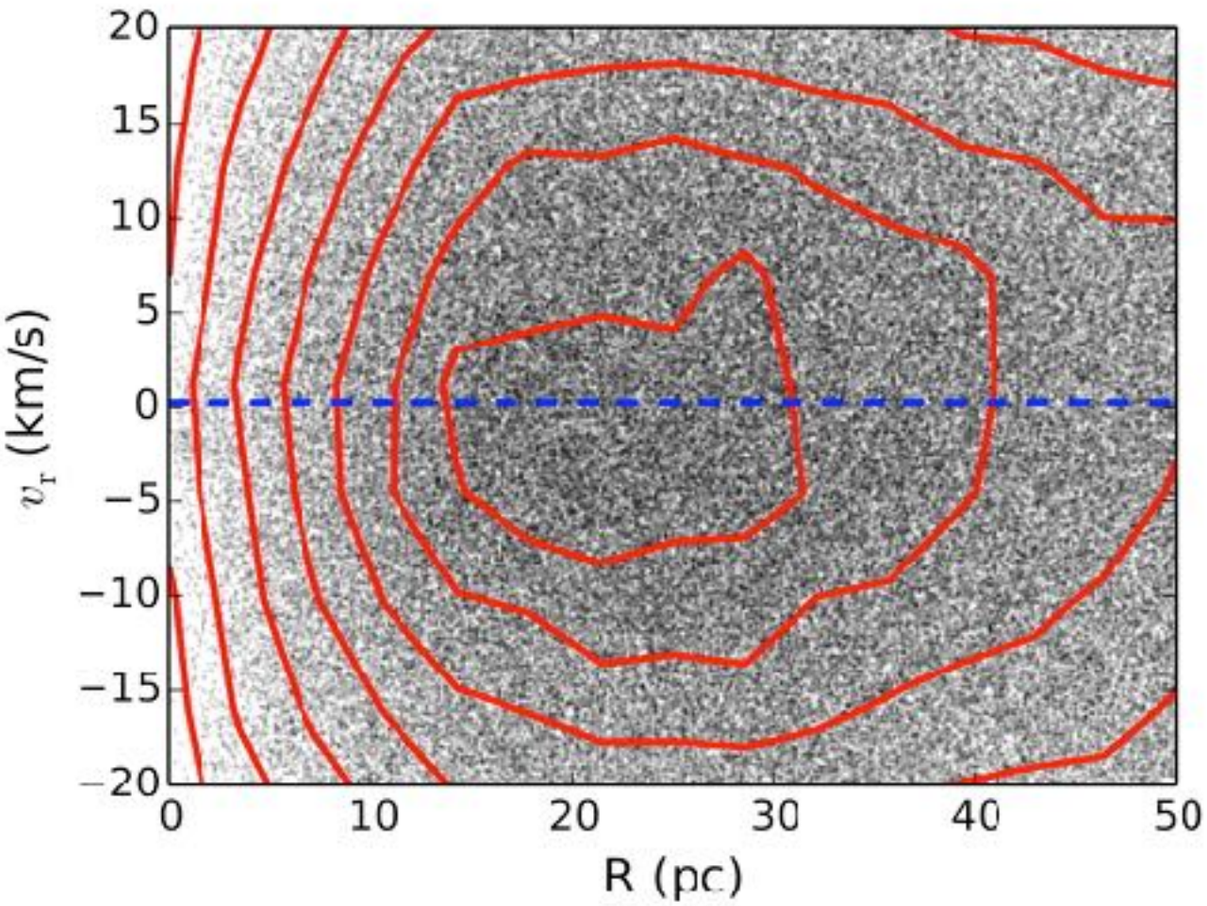
(e.g. Elmegreen 2002, 2008, Bastian et al. 2007, Bonnell et al. 2011, Kruijssen 2012)

	Gaia DR1/TGAS	*Gaia DR2*
5 parameter sources	~2,000,000	>1,300,000,000
6 parameter sources	0	>6,000,000
Parallax uncertainty	0.32 mas	<0.04(G<15), <0.1 (G=17)
PM uncertainty	1.32 mas/yr	<0.06(G<15), <0.2(G=17)

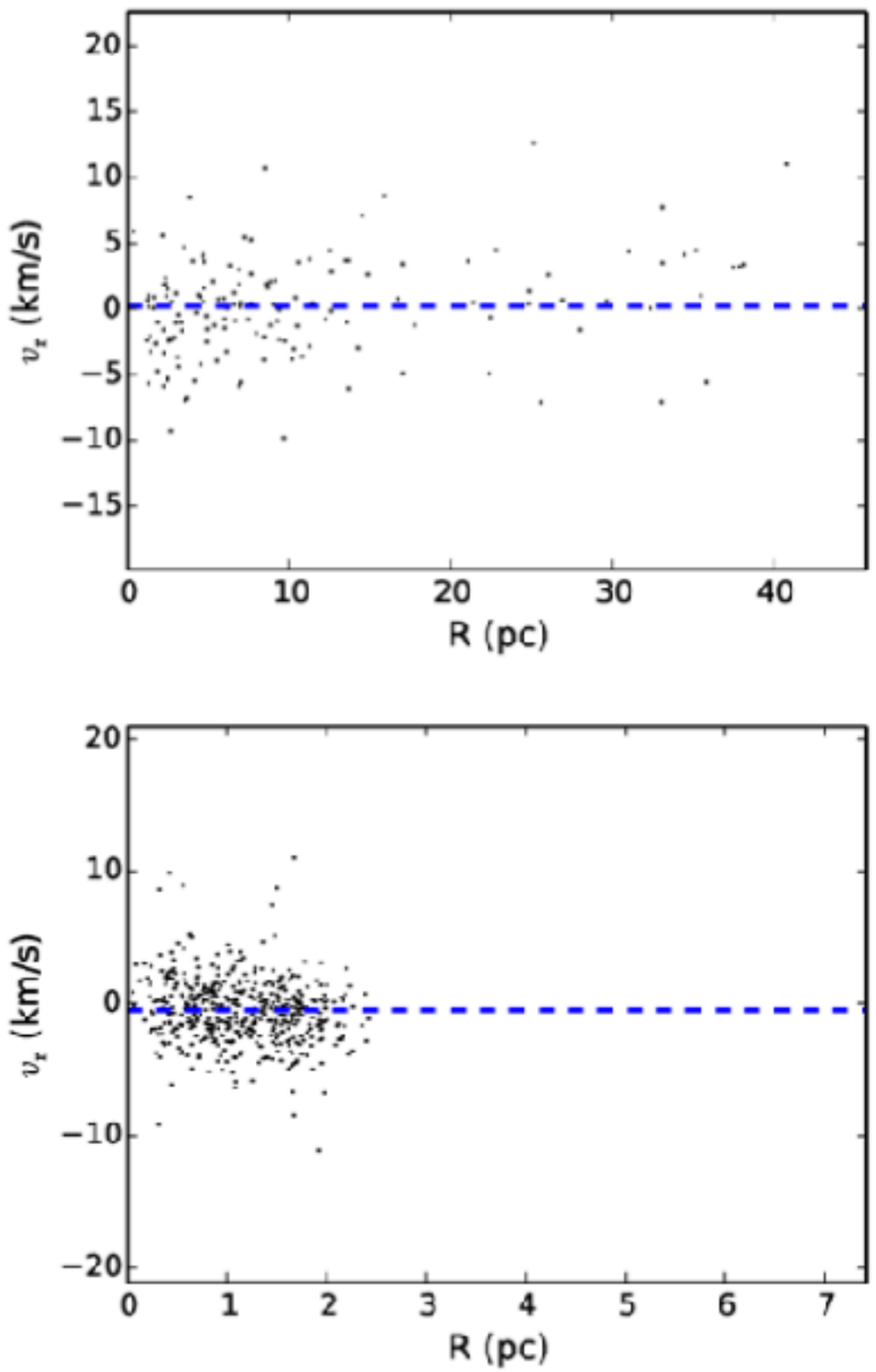
With DR2 we can independently identify OB associations without prior information on their positions and distances

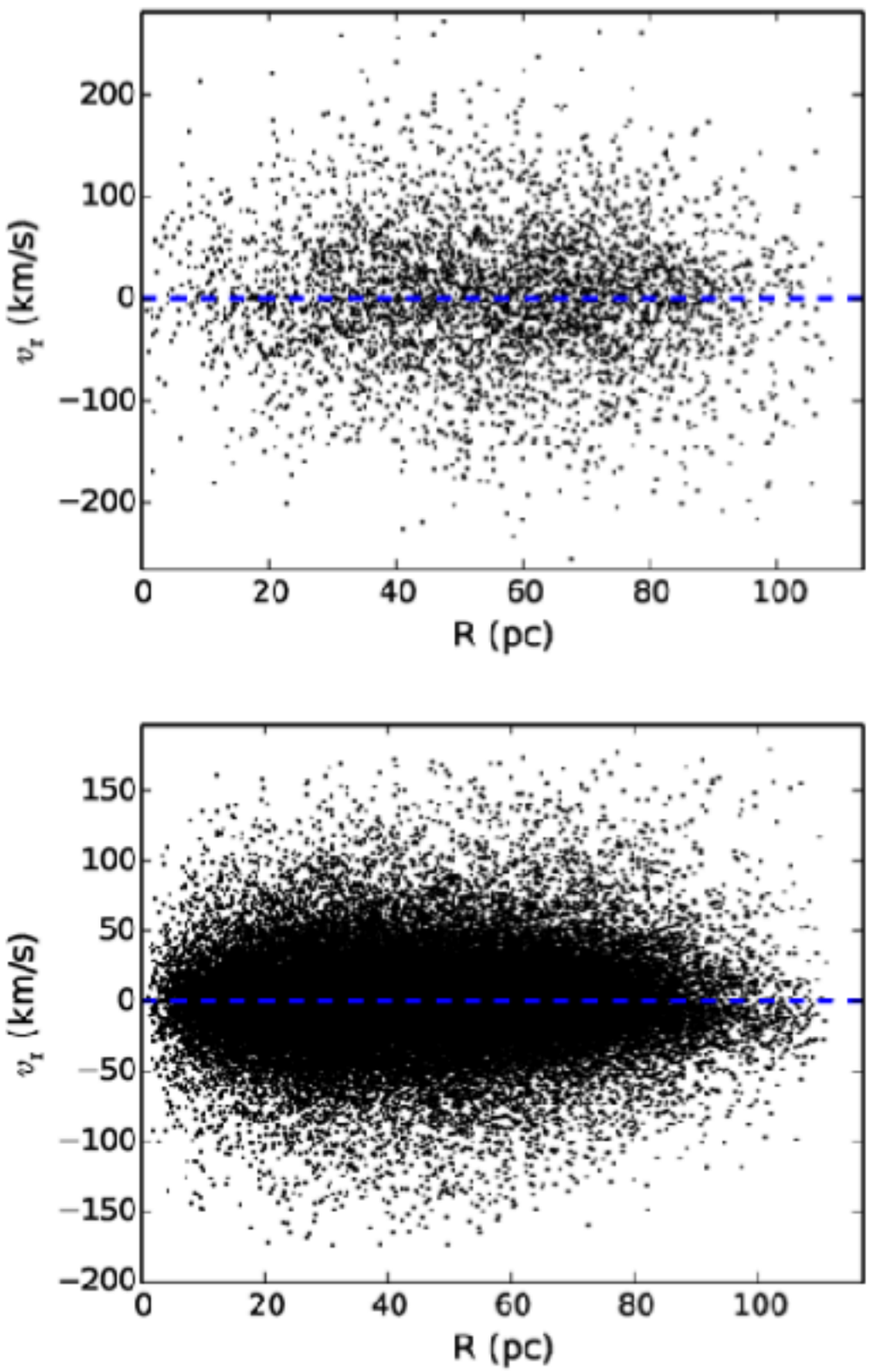
ESA/ATG medialab; background: ESO/S. Brunier



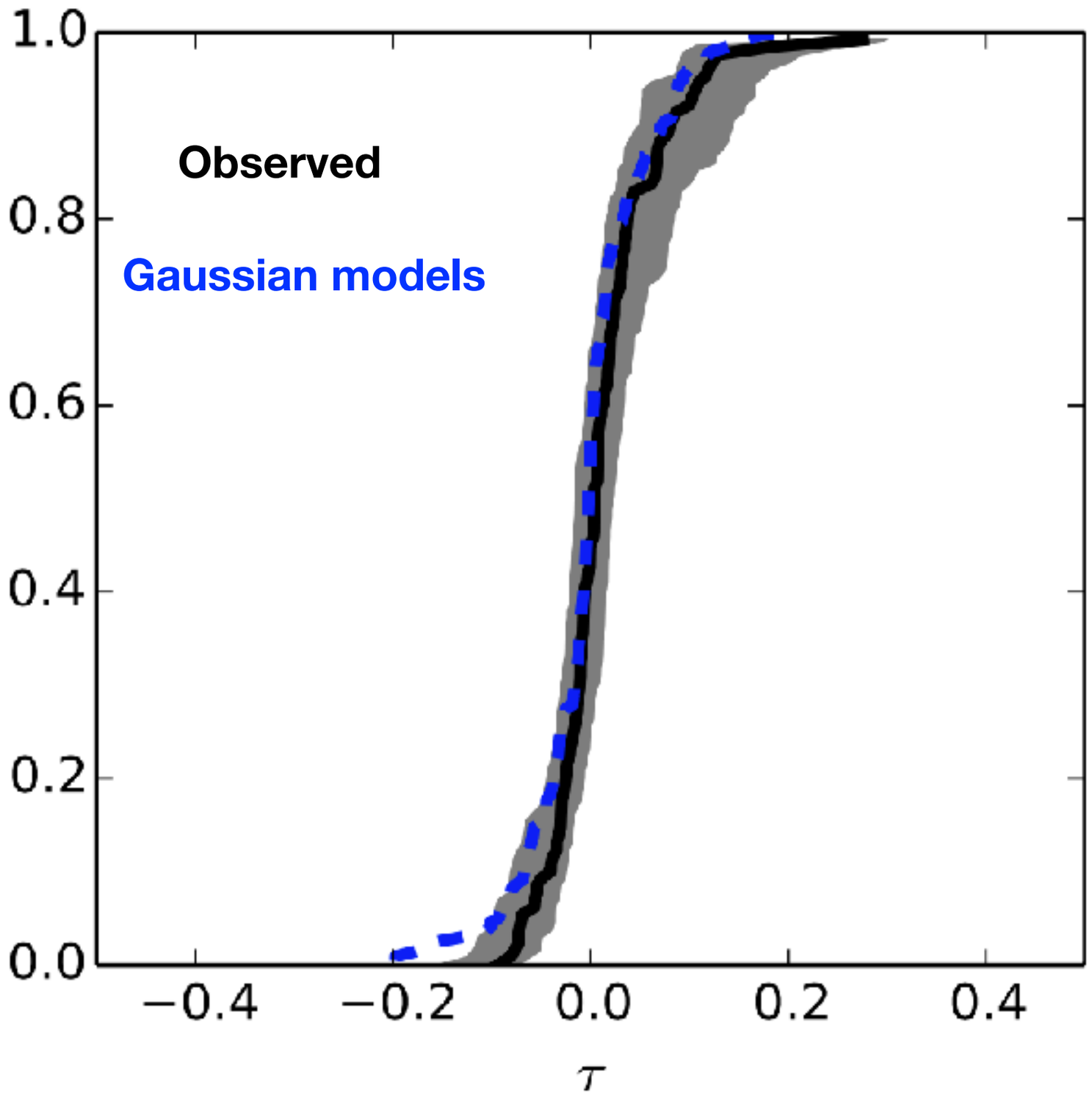


Median v_r = 0.23 km/s


v_r (km/s)
R (pc)


v_r (km/s)
R (pc)

$$\tau = \frac{n_{concordant} - n_{discordant}}{n(n-1)/2}$$



Key points

- The dynamics of OB associations are inconsistent with expanding velocity fields

- Clusters are a possible outcome of star formation rather than a fundamental unit and star formation most likely proceeds in a scale-free fashion, following the hierarchical structure of the parent cloud

- Gaia DR2 now allows us to measure the kinematics for an unprecedented number of OB associations, out to distances ~3 kpc

- Early results from Gaia DR2 also suggest that OB associations could not have formed from the expansion of compact clusters