The LISCA systems: hierarchical cluster assembly and early evolution

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ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

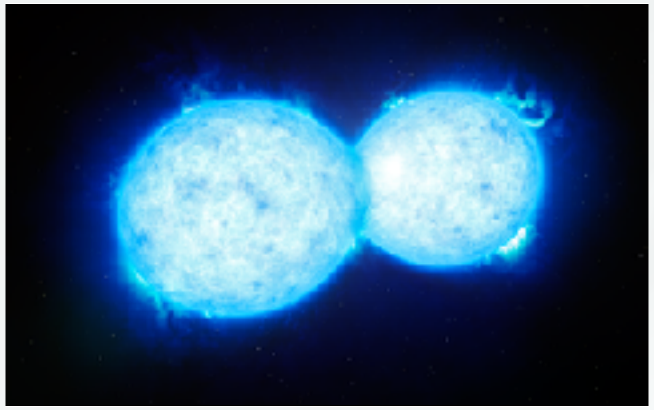
INAF OAS

SPA-OC Workshop (Bologna)

“Clustered” star formation

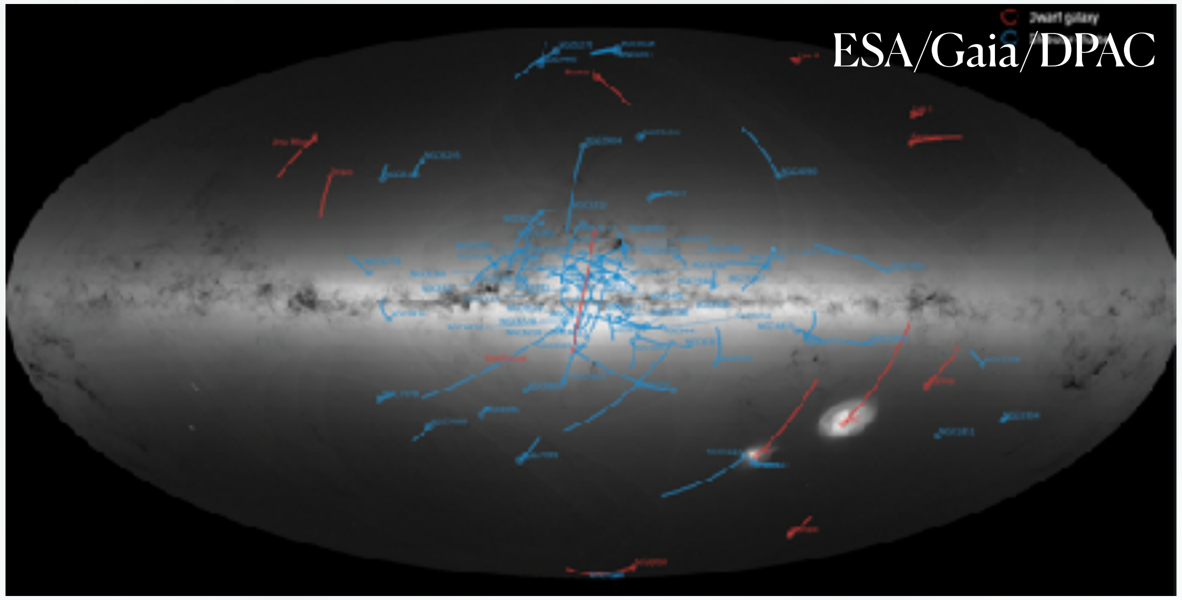
The majority of stars form in “groups” (70% - 90%) (e.g. Lada & Lada 2003)

Star formation,
gas and stellar dynamics

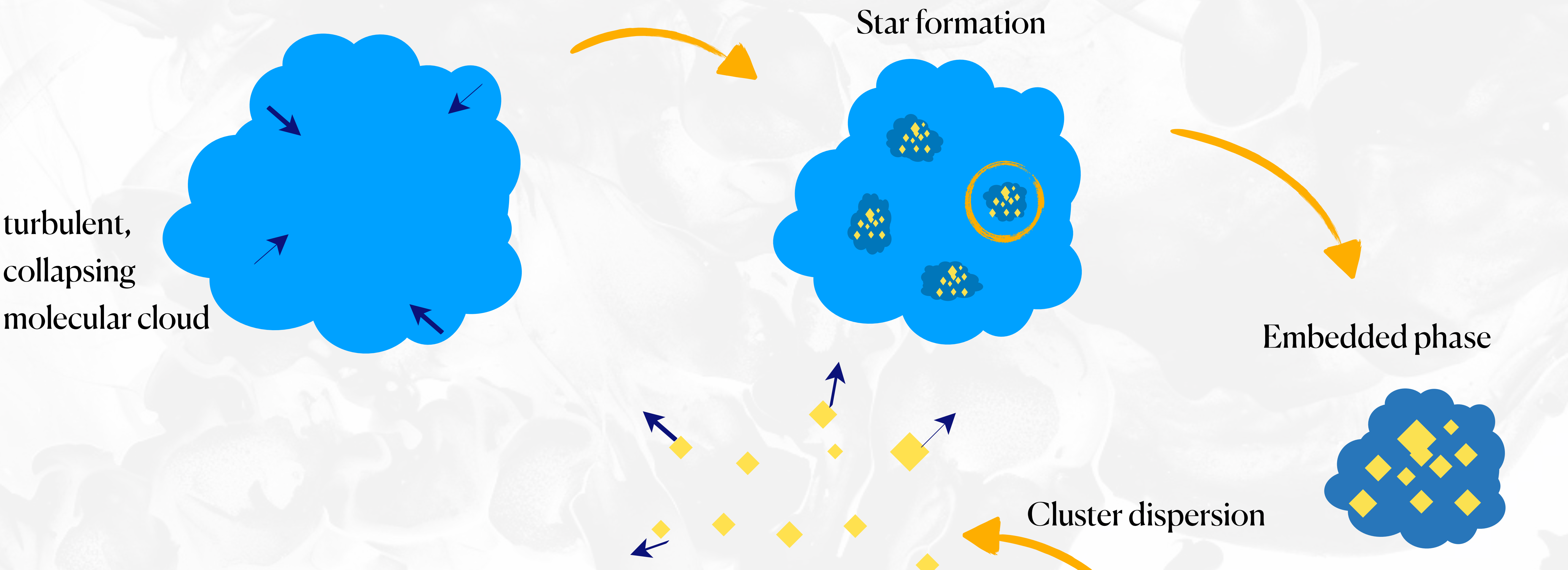


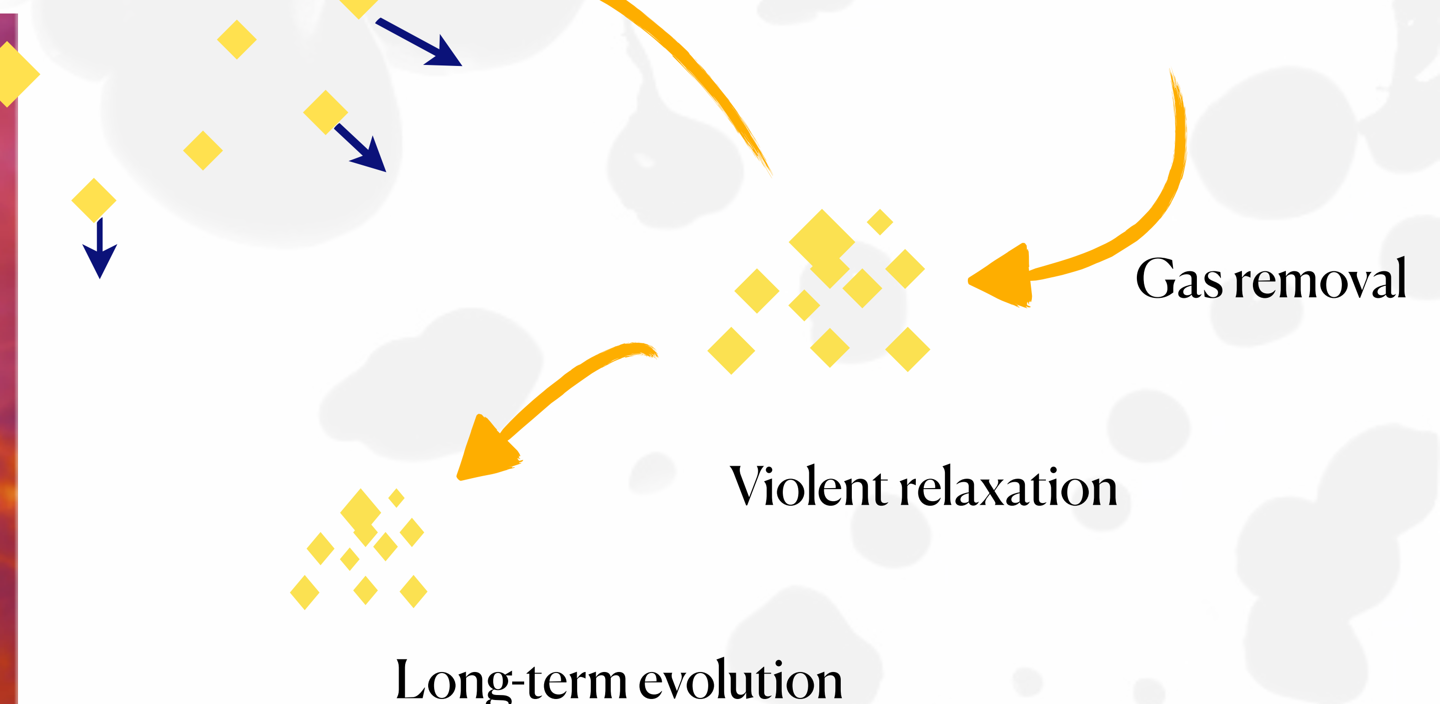
Star clusters:

- ✦ Stellar dynamics and evolution (binaries, GW sources)
- ✦ Galactic properties (disc, DM halo, assembly)



Cluster formation in a nutshell

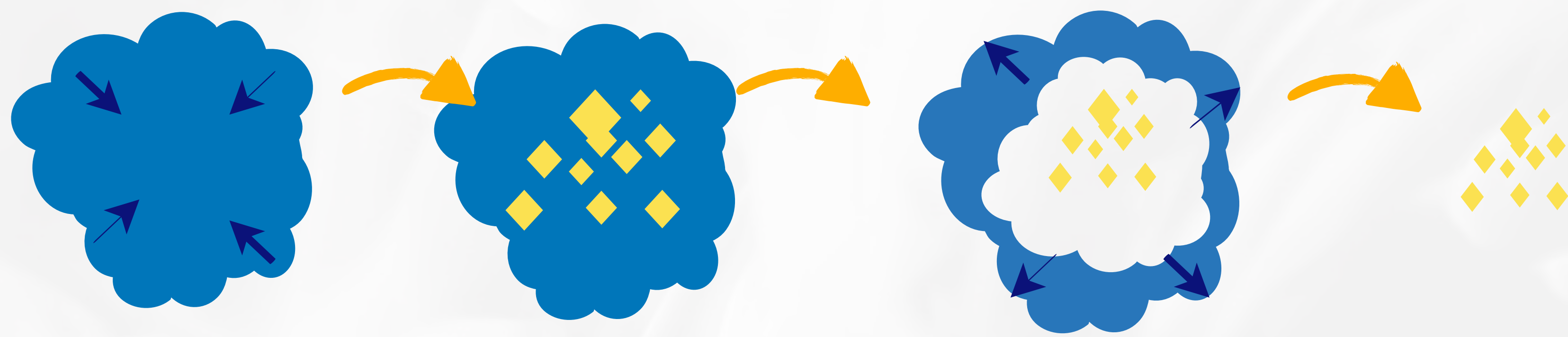




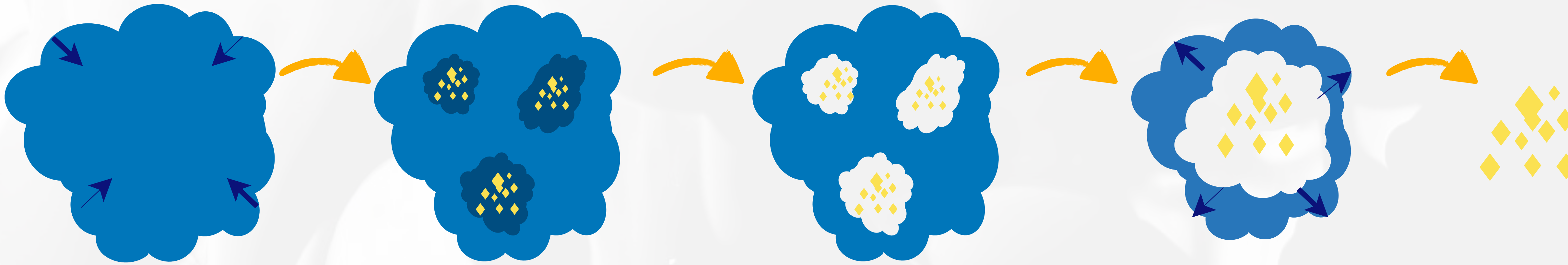

credits: STARFORGE group

Cluster formation scenarios

Monolithic formation



Hierarchical formation



Different early cluster properties

e.g. mass segregation, dynamics, feedback, etc.

(e.g. McMillan, Vesperini & Portegies Zwart 2007;
Moeckel & Bonnell 2009; Allison+09; Krumholz+19;
Krause+20; Livernois+21; Karam & Sills 2022; Rantala et al. 2024)

Nearby star-forming regions

Gaia DR3 data → Sky position, parallax, and proper motions

G, G_{BP}, G_{RP}

1.8 billion sources

High-resolution spectroscopy SPA @ TNG → ~ 70 nights (PI Origlia)

Optical (R=115,000)

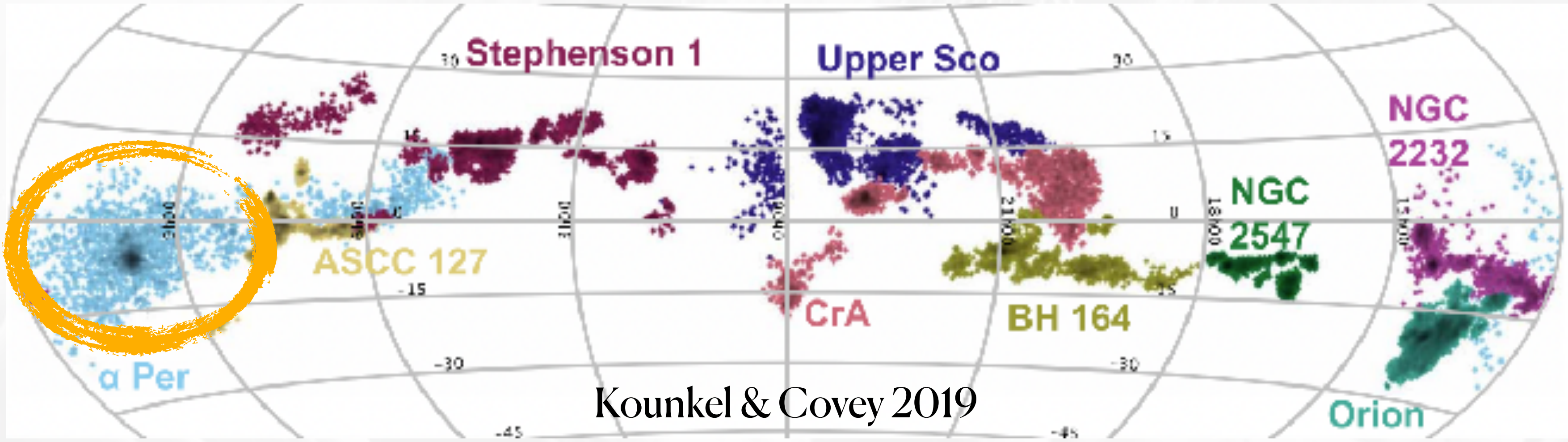
NIR (R=50,000)

LOS velocity + chemistry

N-body simulations → 10^5 particles

violent relaxation

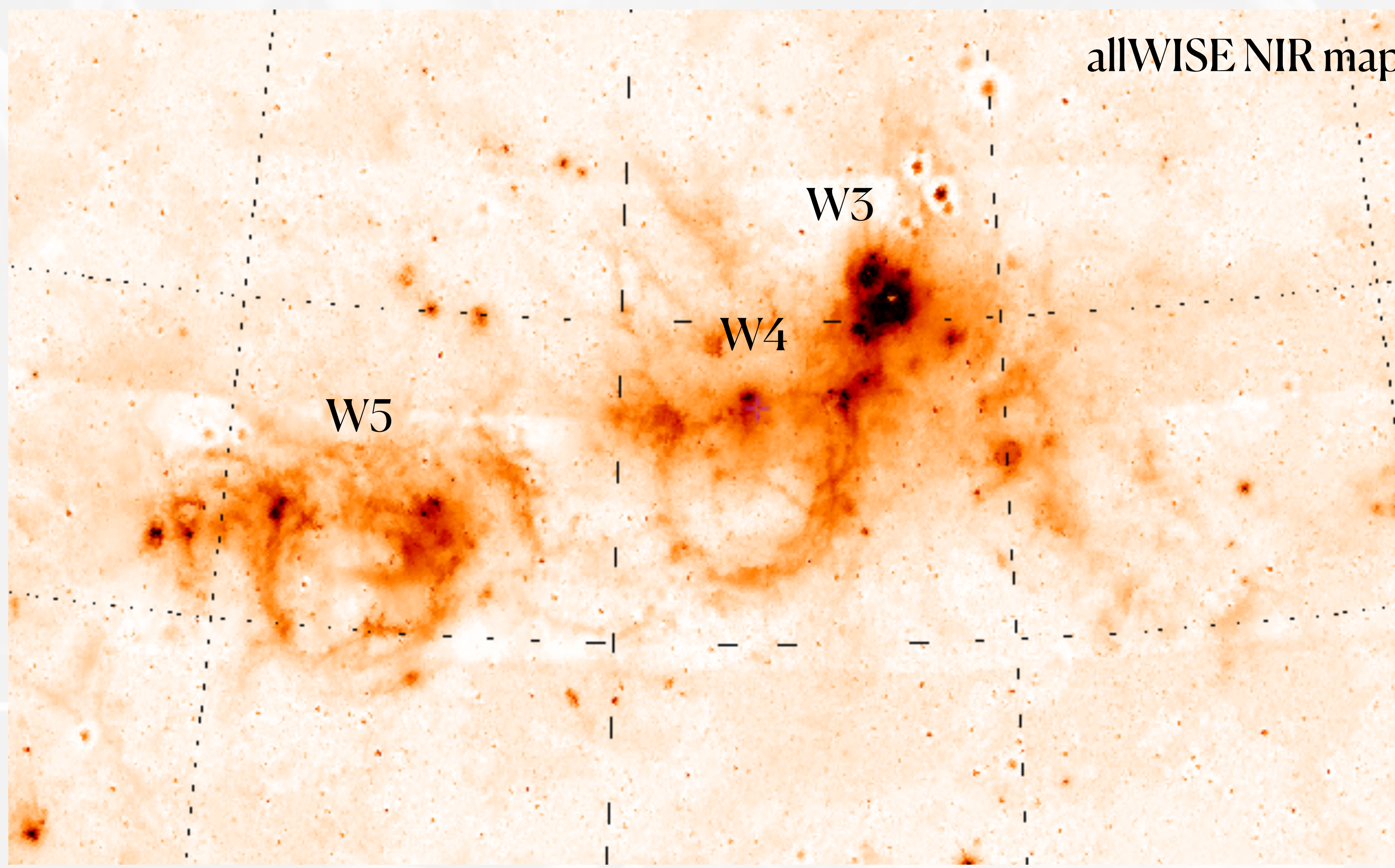
The Perseus complex



Perseus spiral arm
2.5 kpc away
major star-forming site

Several young star clusters

(Goudis & White 1980; Sugitani+1991; Massey+1995; Straizys+2013; Jose+2016; Panwar+2017, 2019; Roman-Zuniga+2019; Roman-Lopes+2019; Lim+2020)



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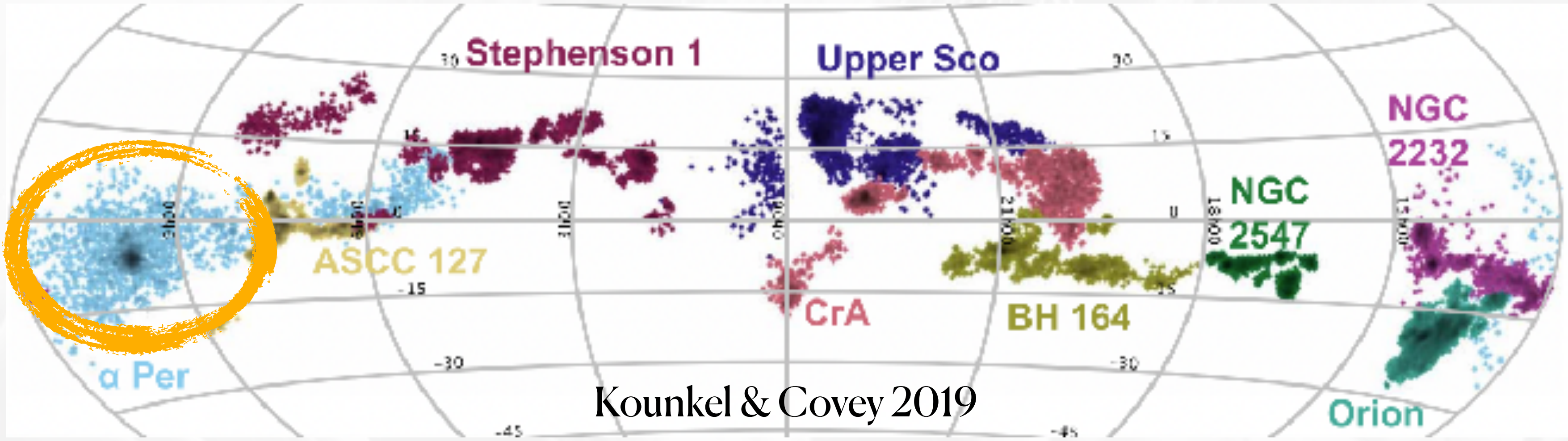
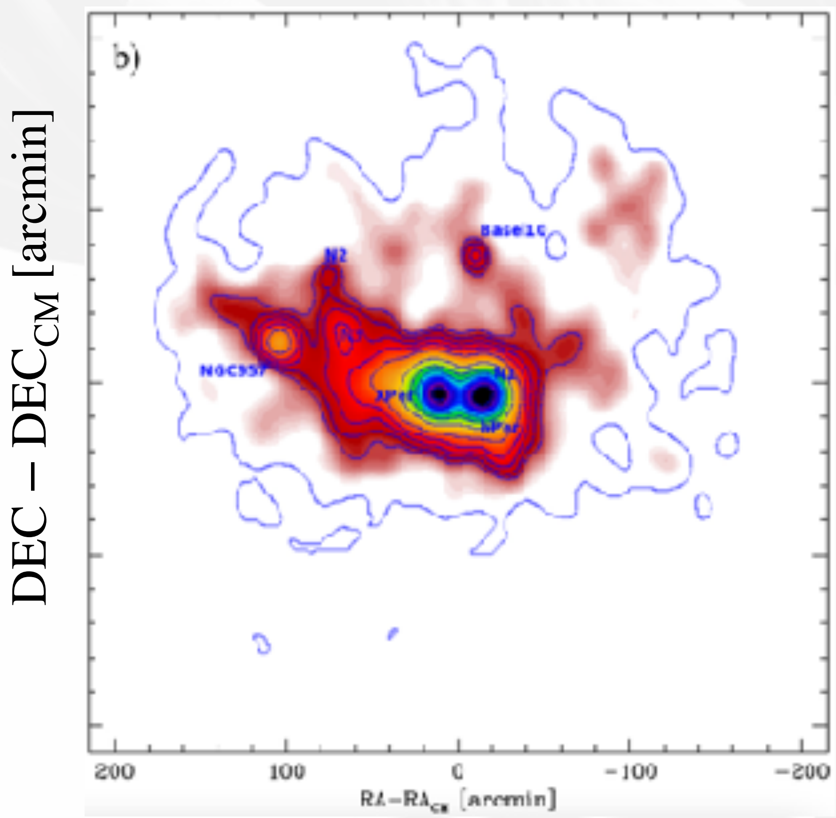


Kounkel & Covey 2019

Perseus spiral arm
2.5 kpc away
major star-forming site



Dalessandro et al. 2021, ApJ, 909, 90

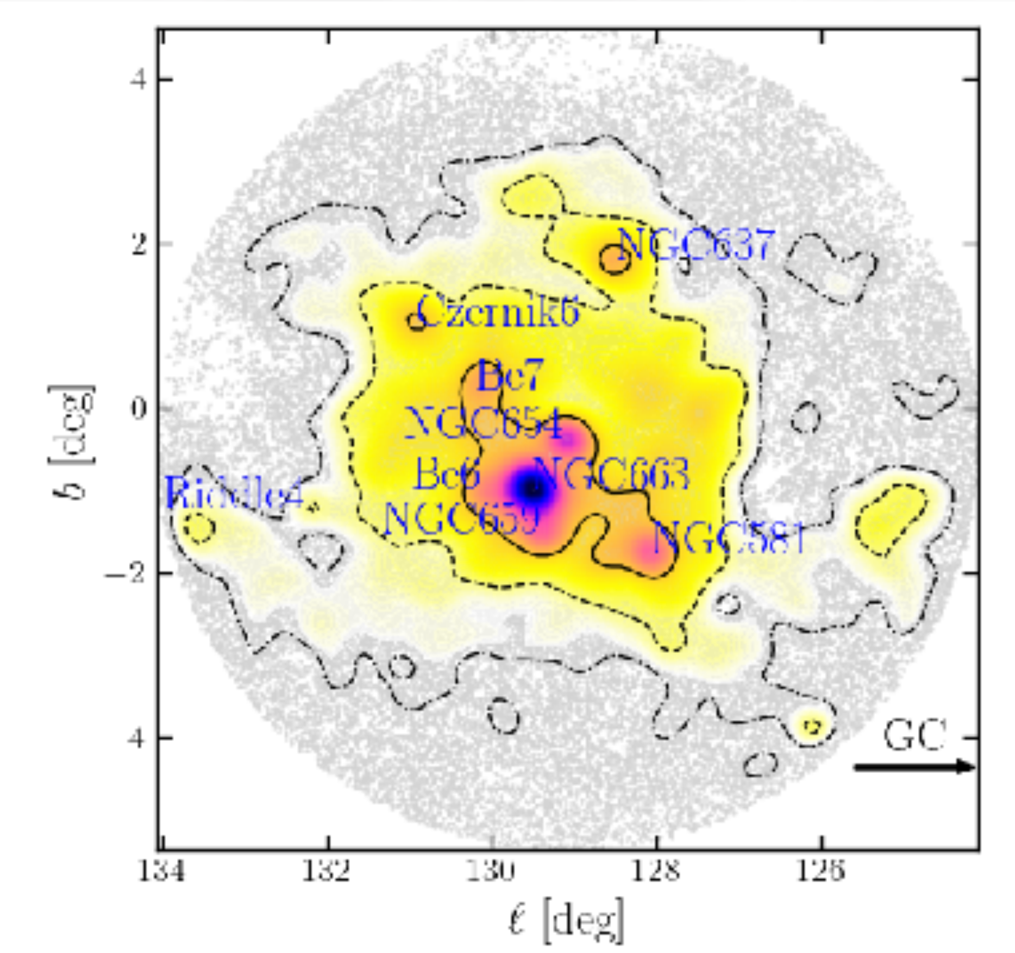
The first hierarchical structure
(h- and chi-Persei)
about $10^5\,M_\odot$

LISCA I

detailed characterization of hierarchical assembly

The LISCA II structure

Della Croce et al. 2023, A&A, 674, A93

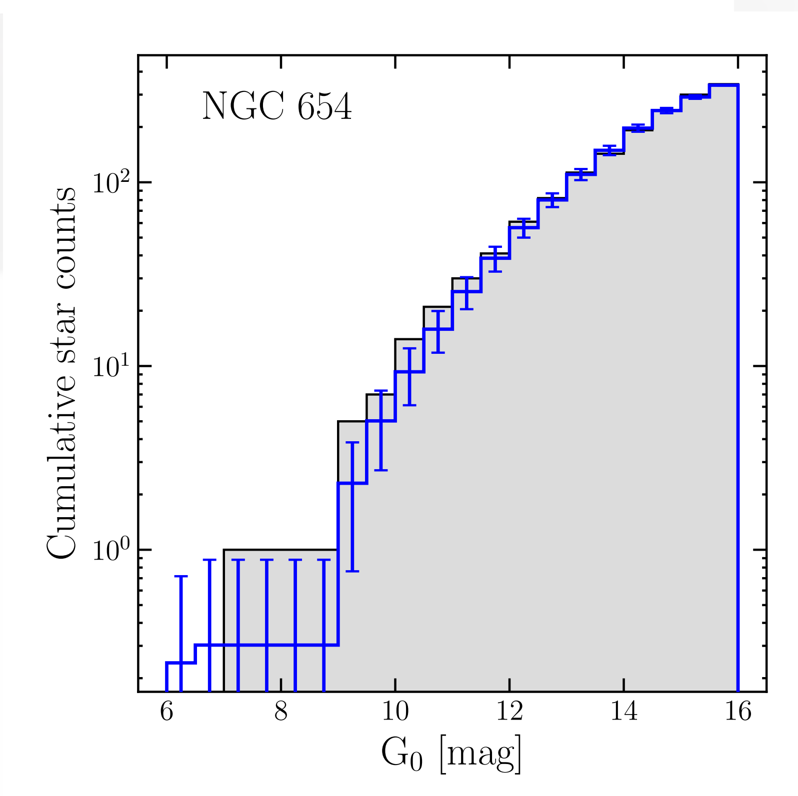


Nine stellar clusters

diffuse "*stellar halo*"

Co-moving (5.5 km/s)

Same 3D position (R_{hm} = 150 pc)

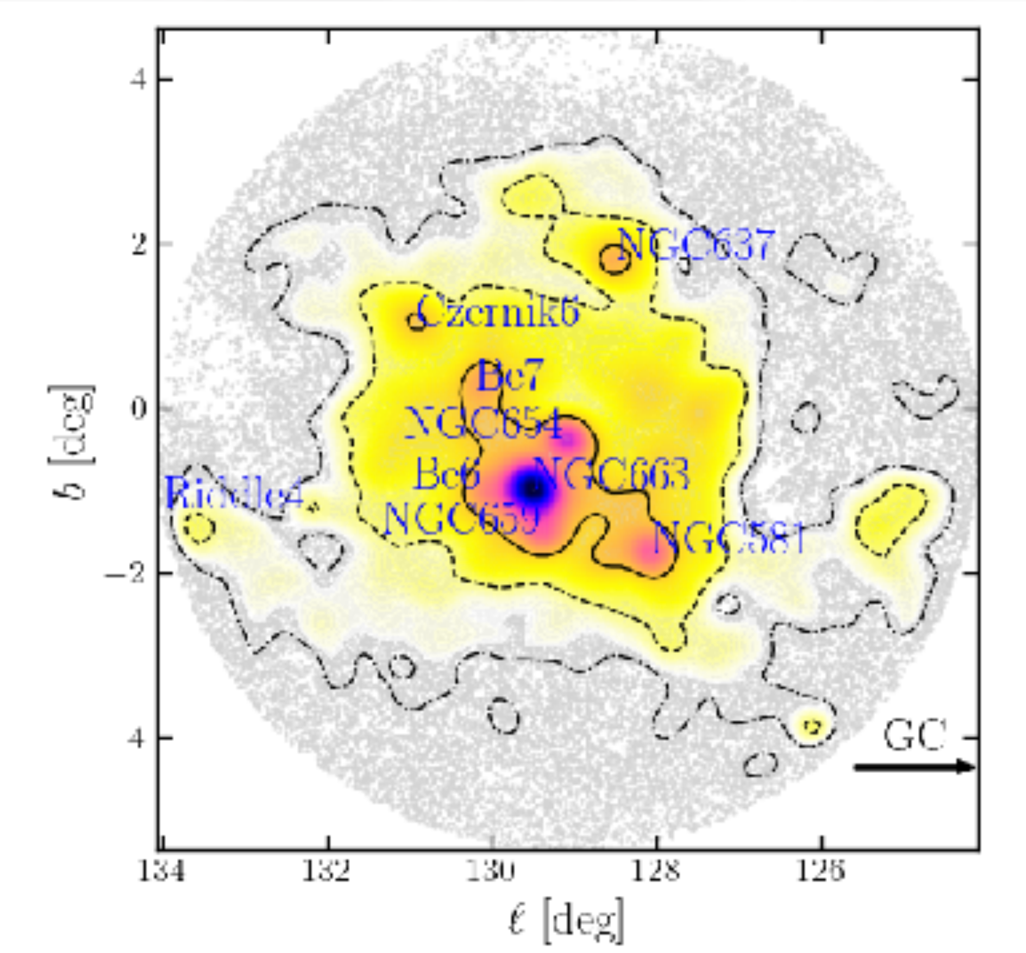


Age from LFs in the G_0 band

(statistical fluctuations at bright magnitudes)

The LISCA II structure

Della Croce et al. 2023, A&A, 674, A93



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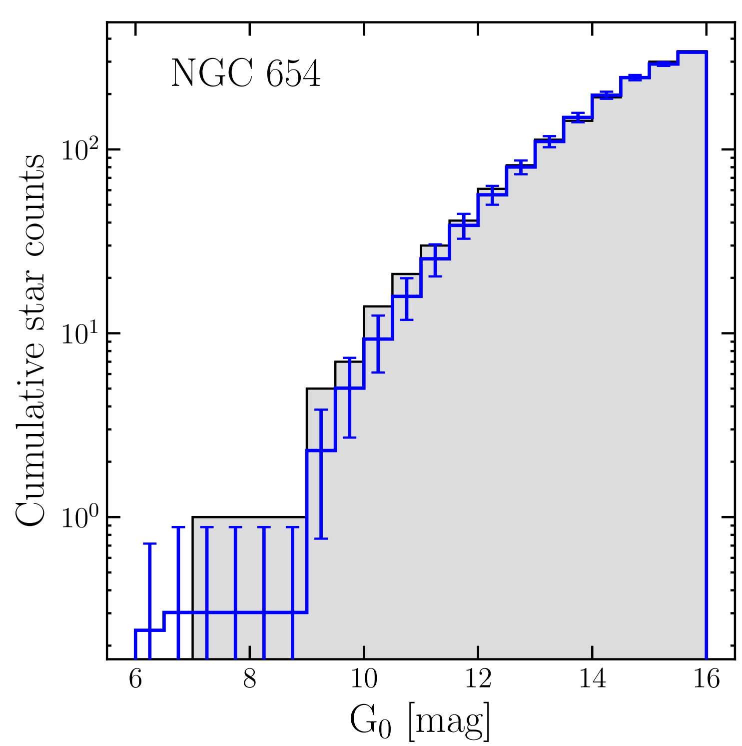
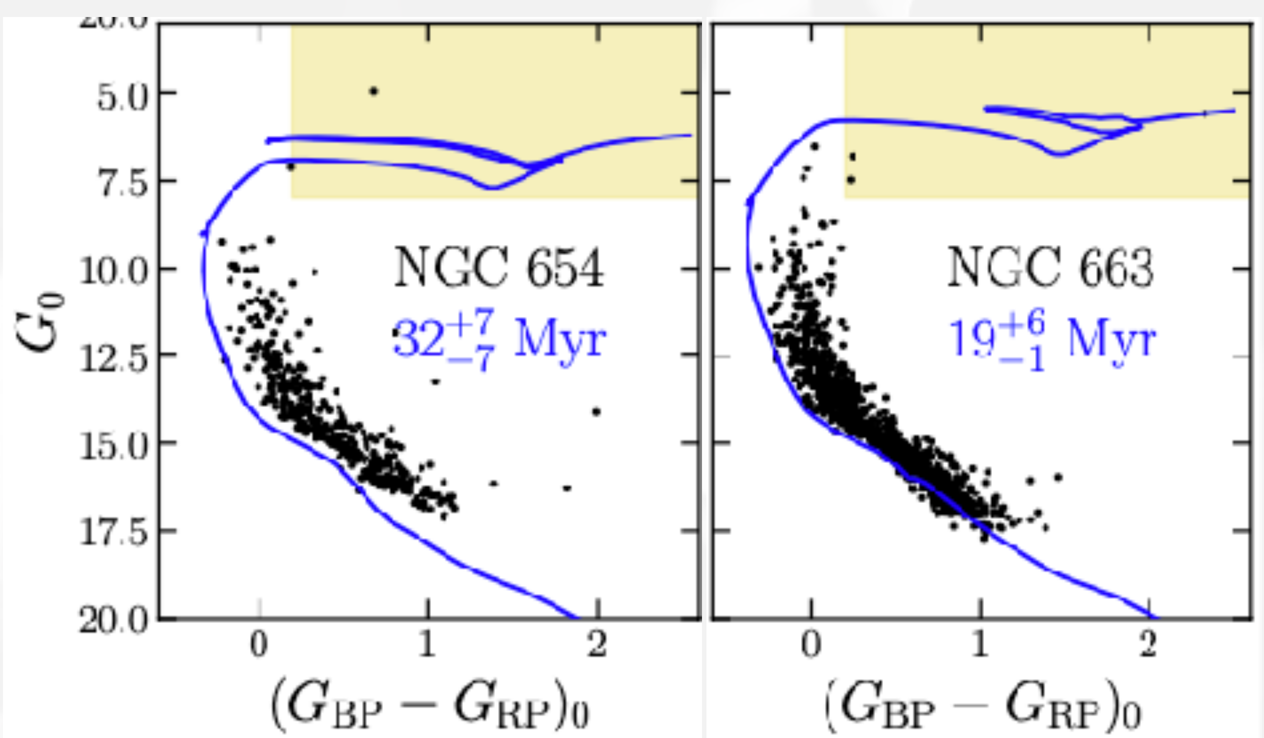


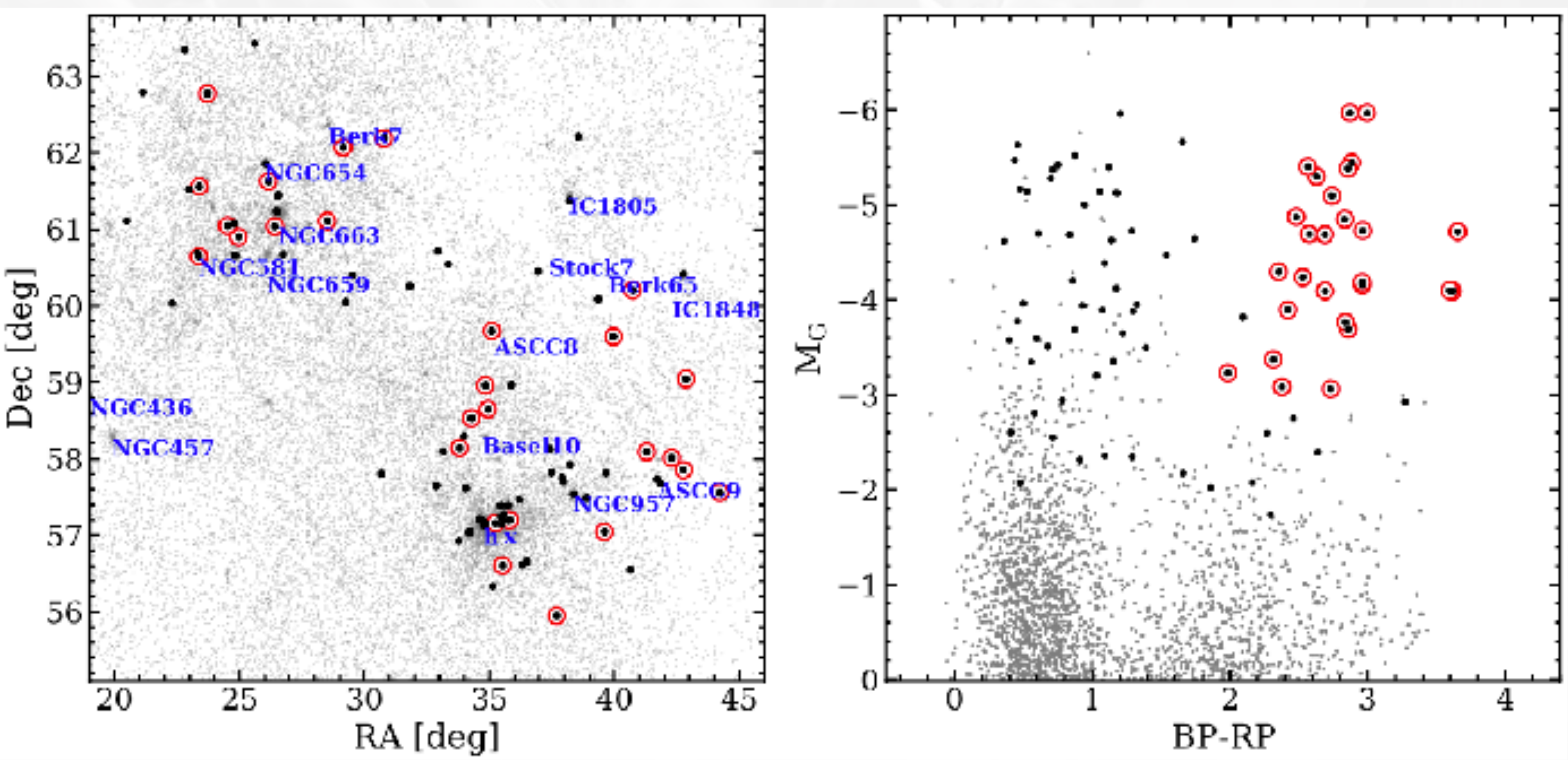
coeval (14-44 Myr)



High resolution spectra

High-resolution spectroscopy SPA @ TNG → ~ 70 nights (PI Origlia)
Optical (R=115,000)
NIR (R=50,000)

Fanelli et al., 2022, A&A, 660, A7
Fanelli et al., 2022, ApJ, 931, 61

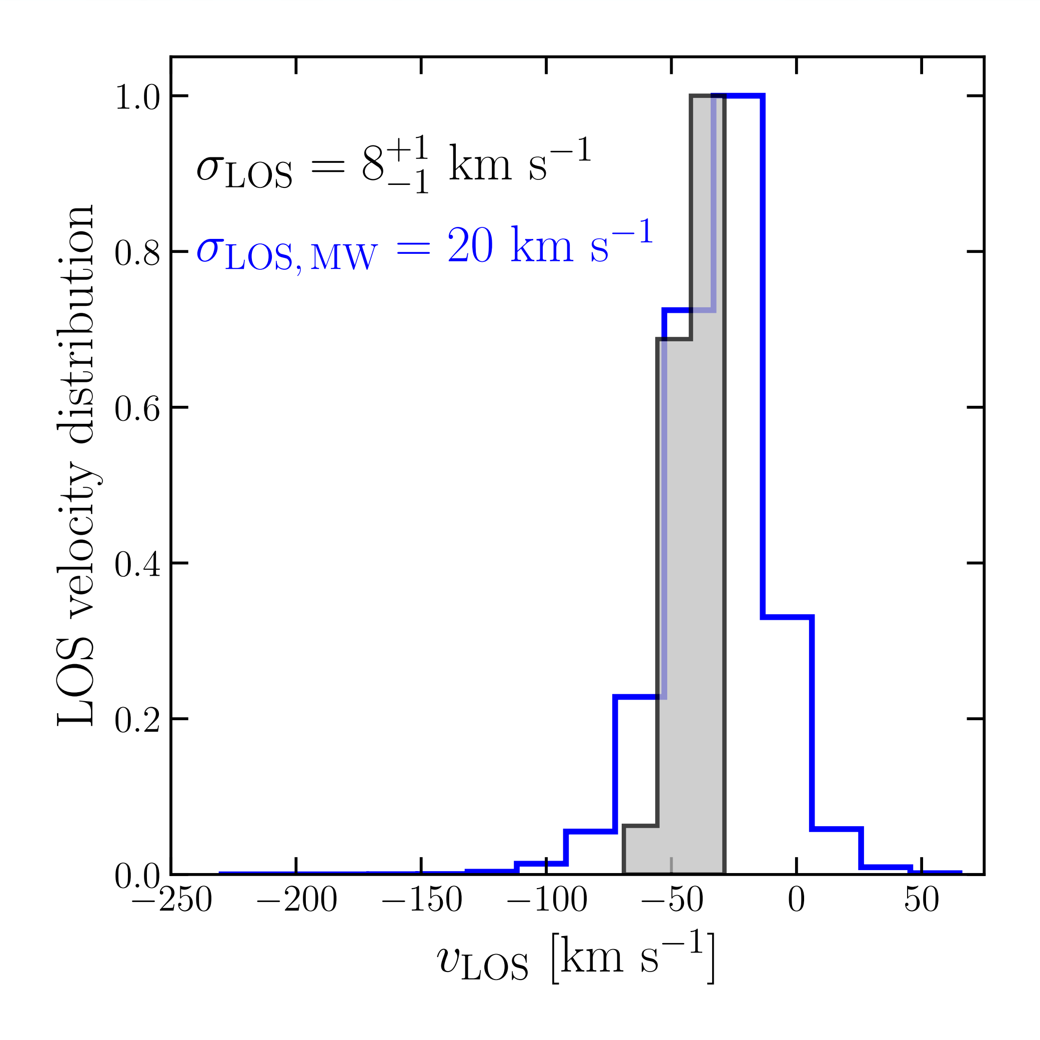


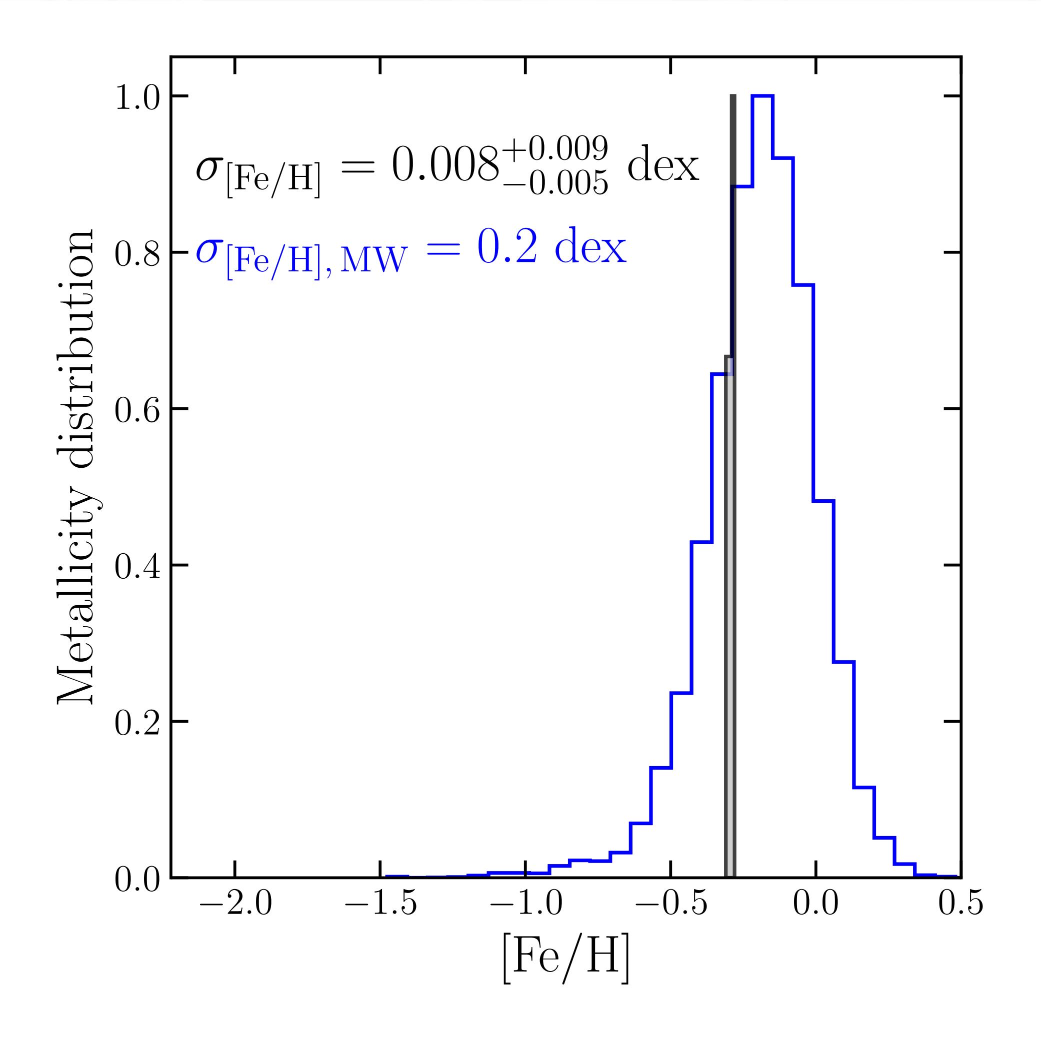
84 stars (27 RSG)

LOS velocity

abundances for 23 species (including Li)

The SPA view of LISCA II





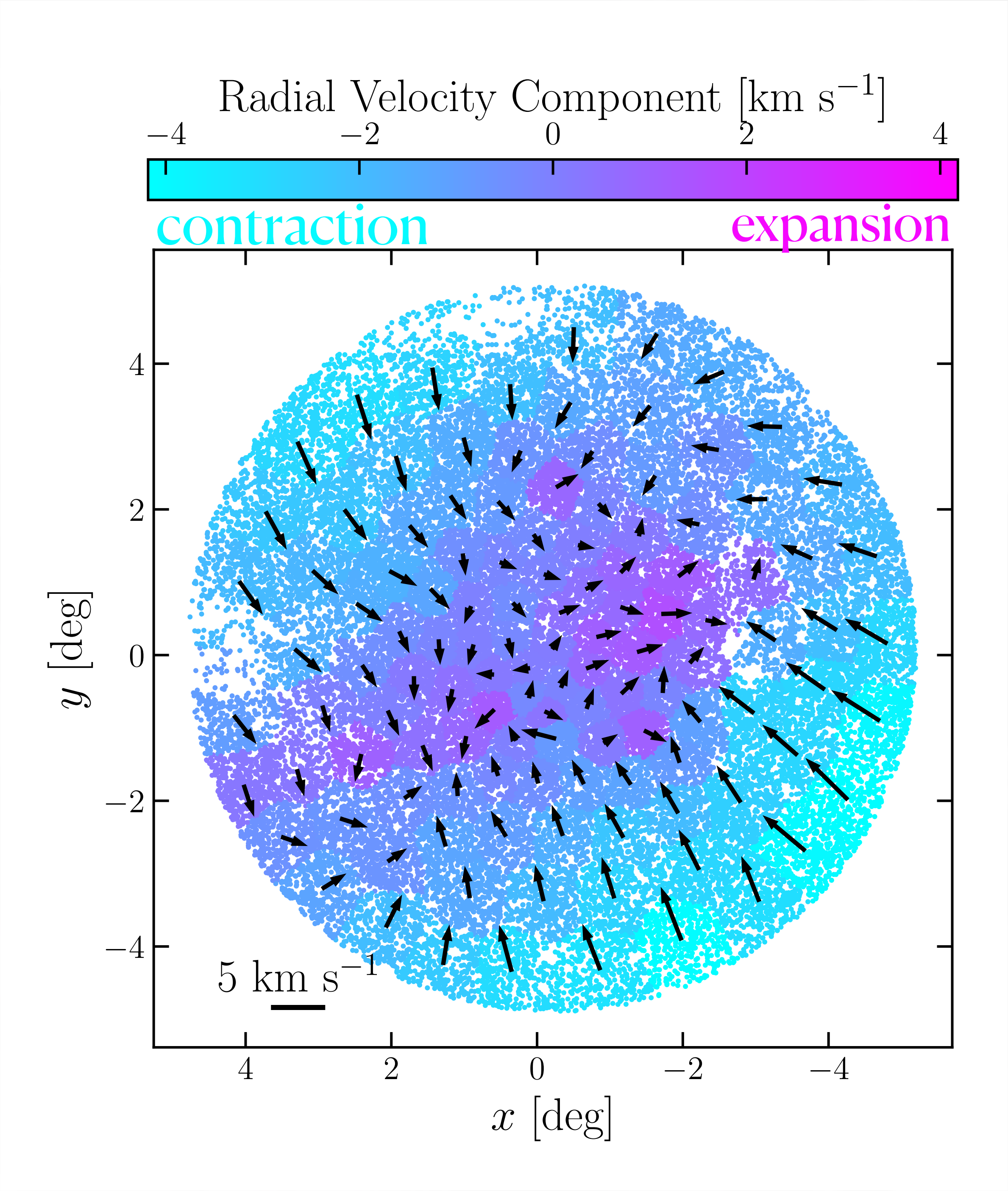
coherence in LOS vel

mono-metallic

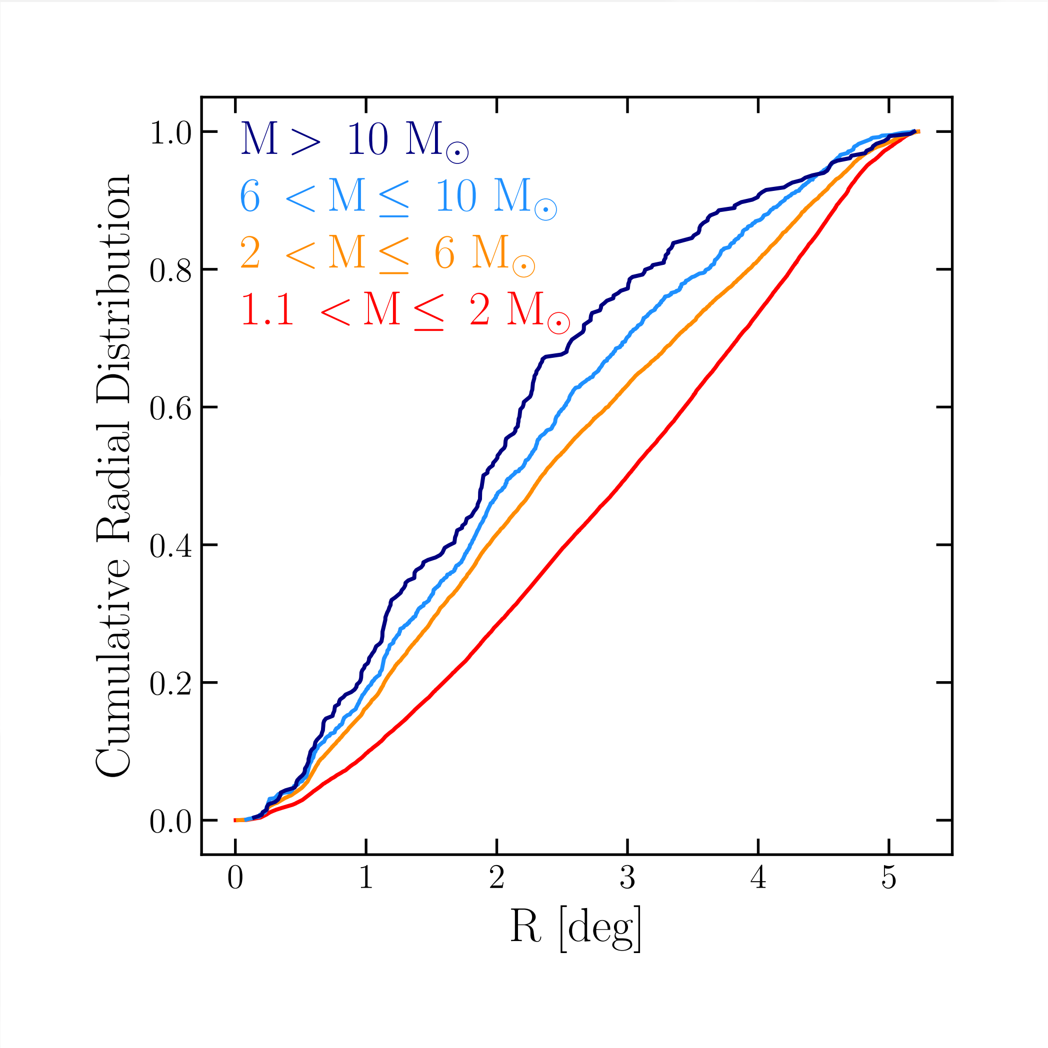
likely formed within the same molecular cloud

The properties of LISCA-like systems

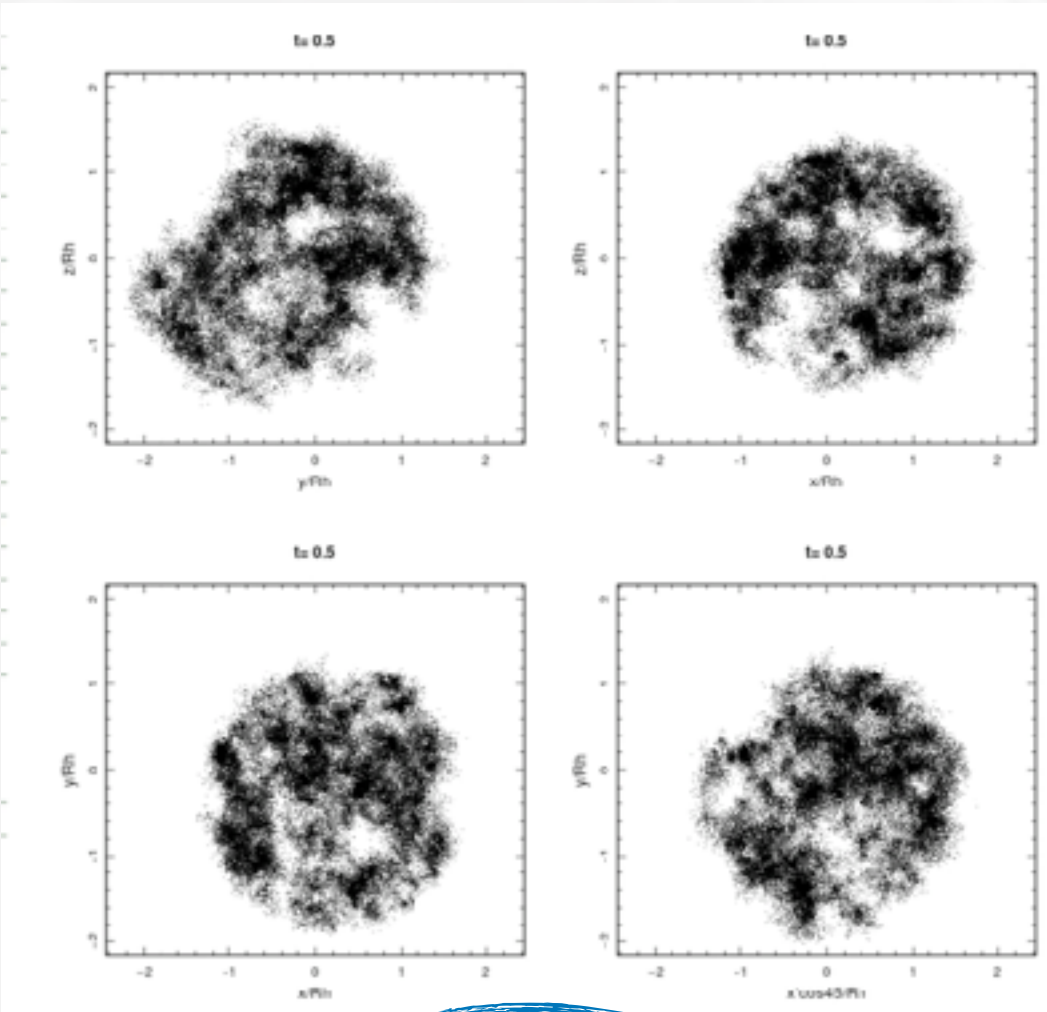
coherent contraction



mass segregation



Numerical simulations of LISCA systems



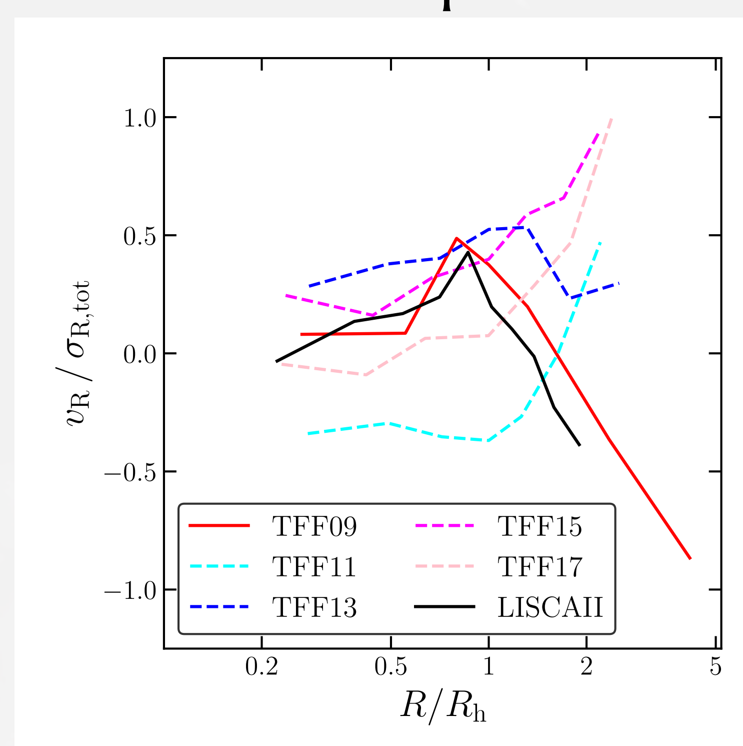
N-body following violent relaxation

Homogeneous and fractal configurations

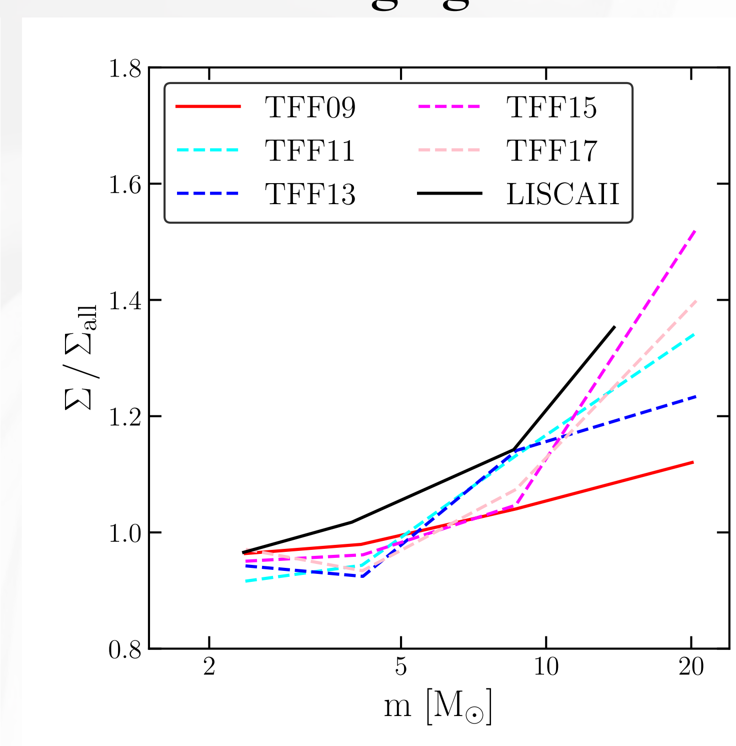
(Livernois et al. 2021, MNRAS, 506, 5781)

LISCA II in the early stages of massive ($10^5\,M_\odot$) hierarchical cluster assembly

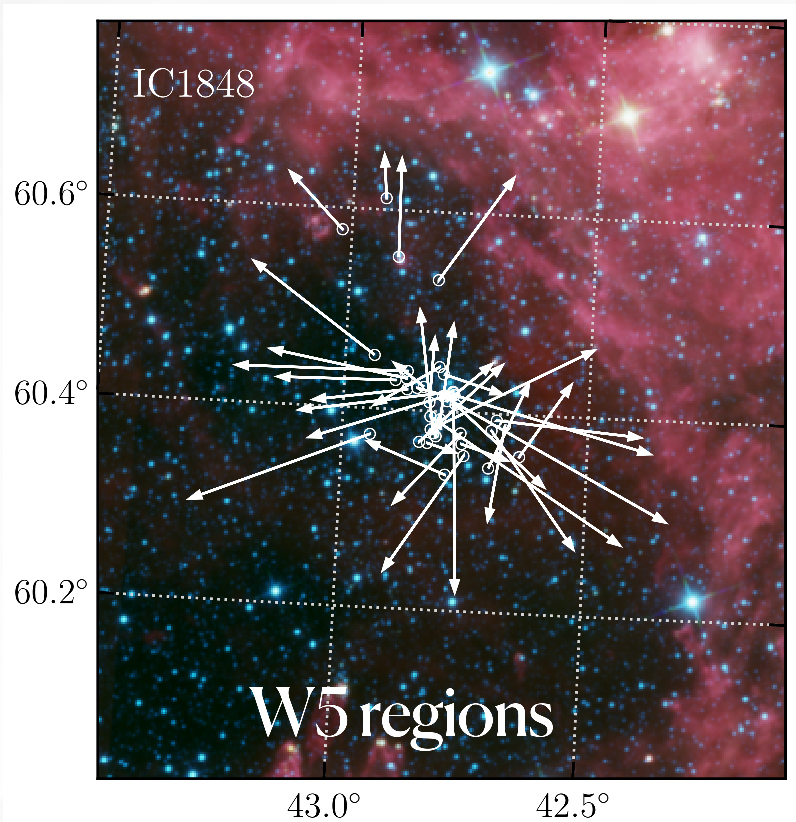
contraction pattern

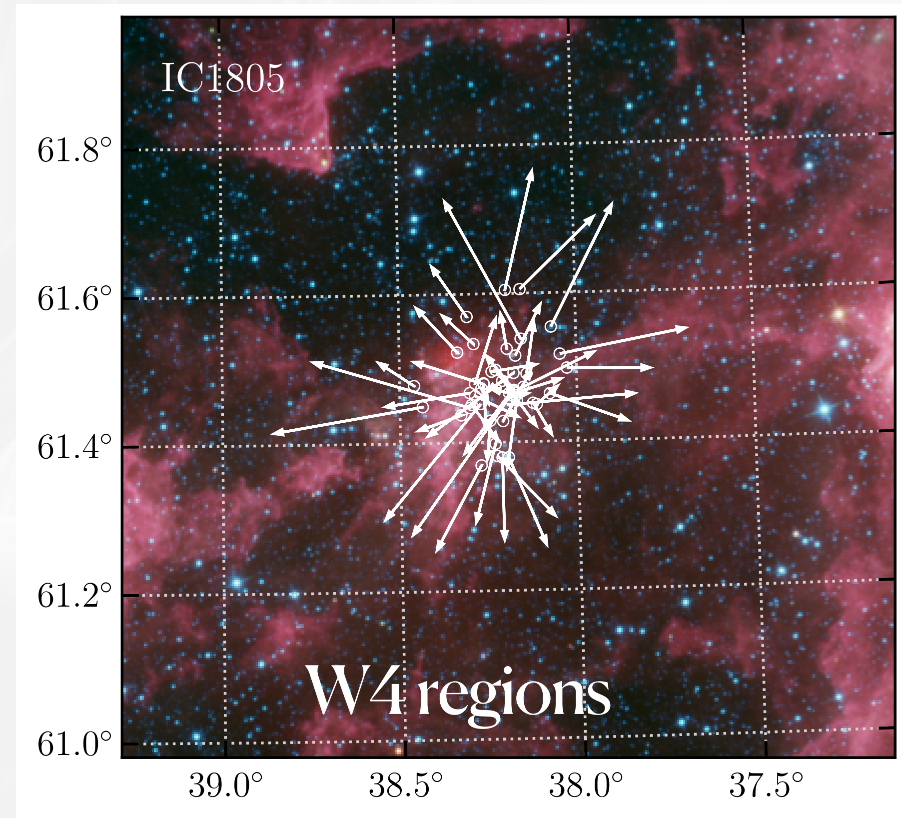


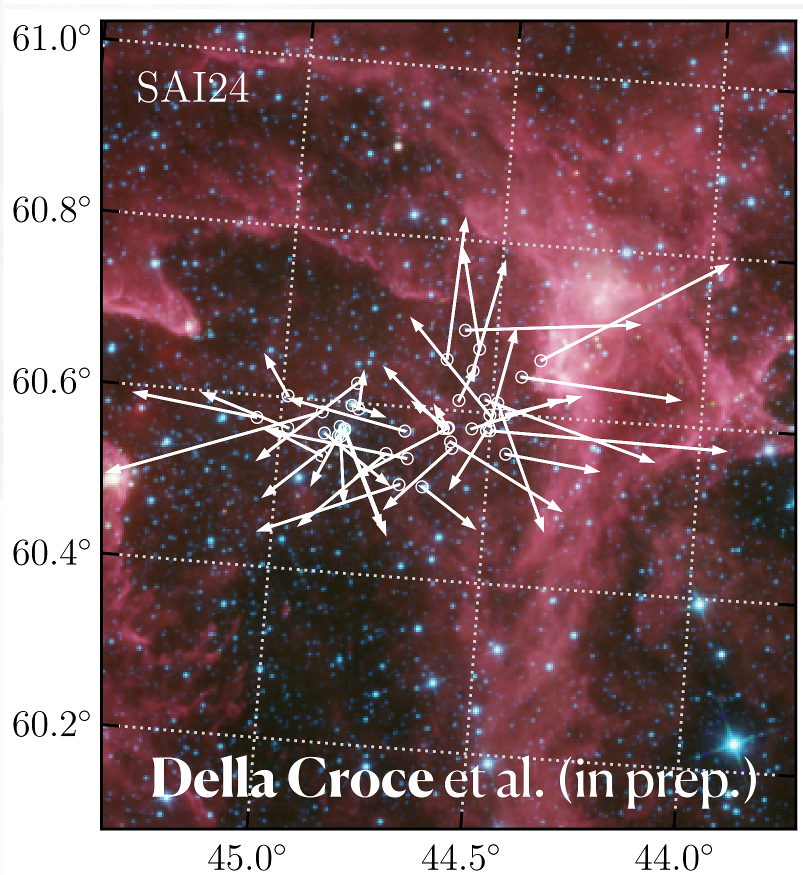
mass segregation



Cluster kinematics in hierarchies



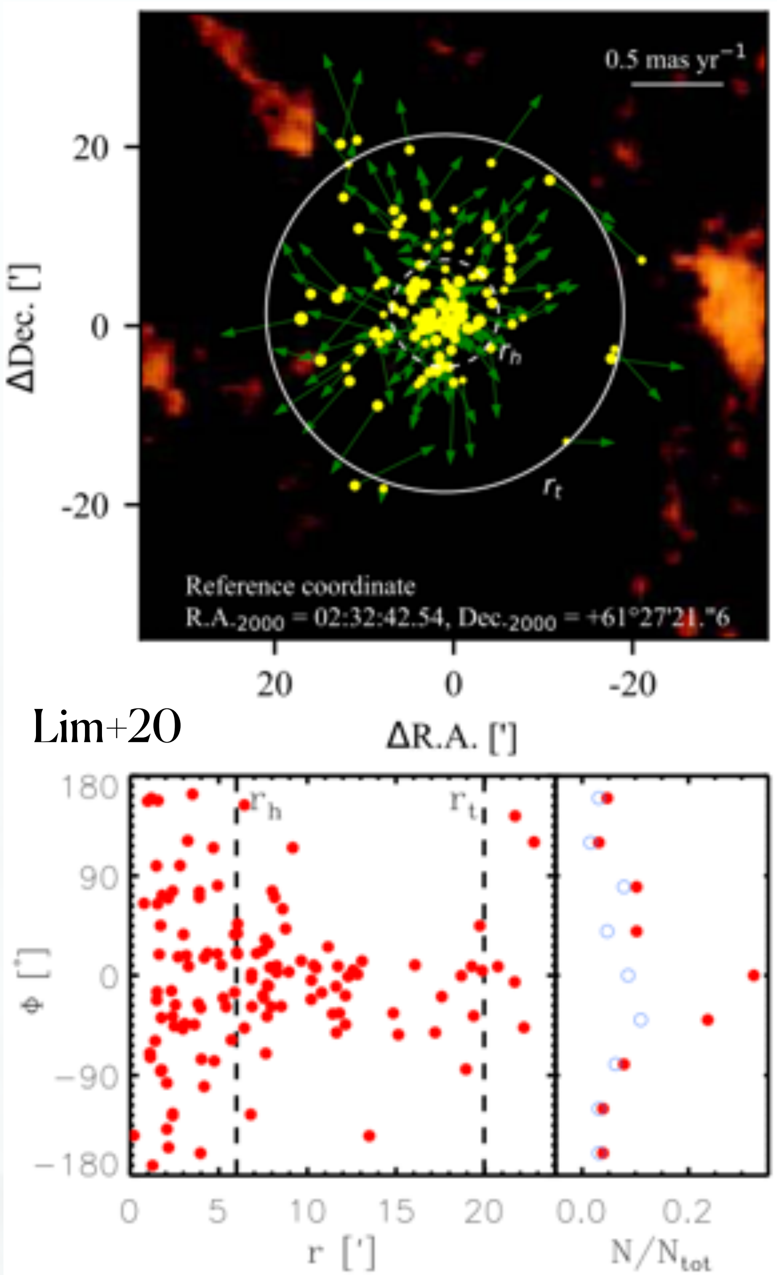


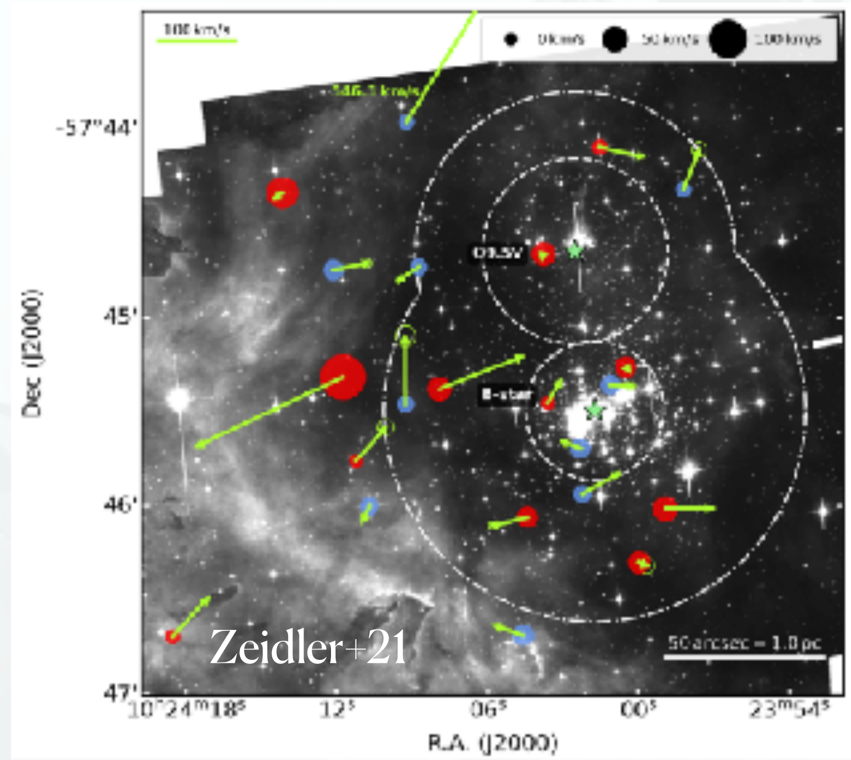


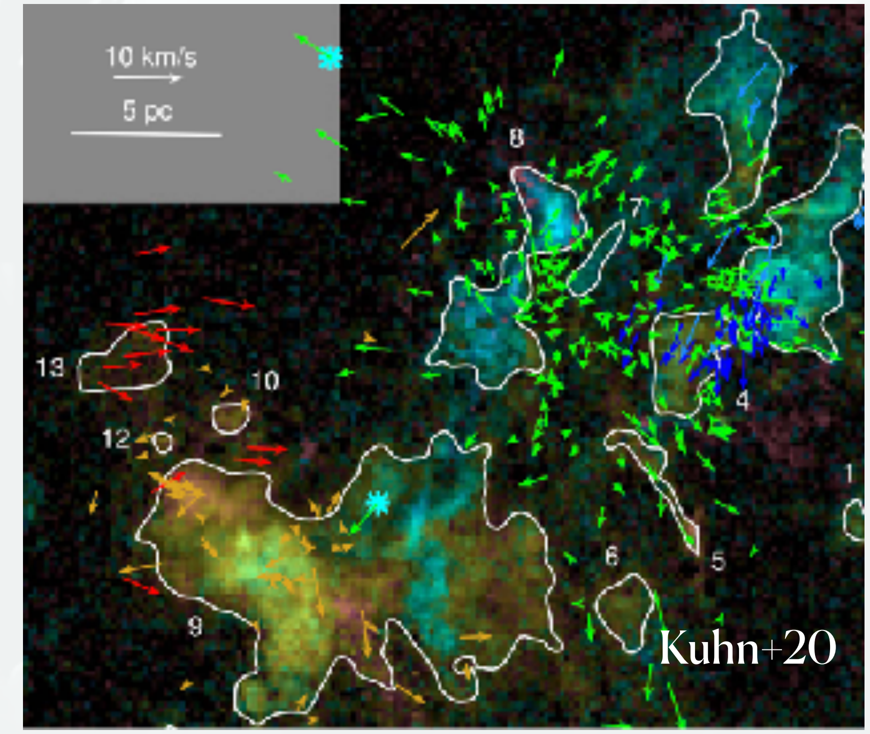
Study cluster kinematics for:

1. gas and stellar dynamics
   "infant mortality"
2. tidal interactions (environment)
   "cruel cradle"

Expanding young star clusters







Expansion in OB associations,
young clusters, and star-forming complexes

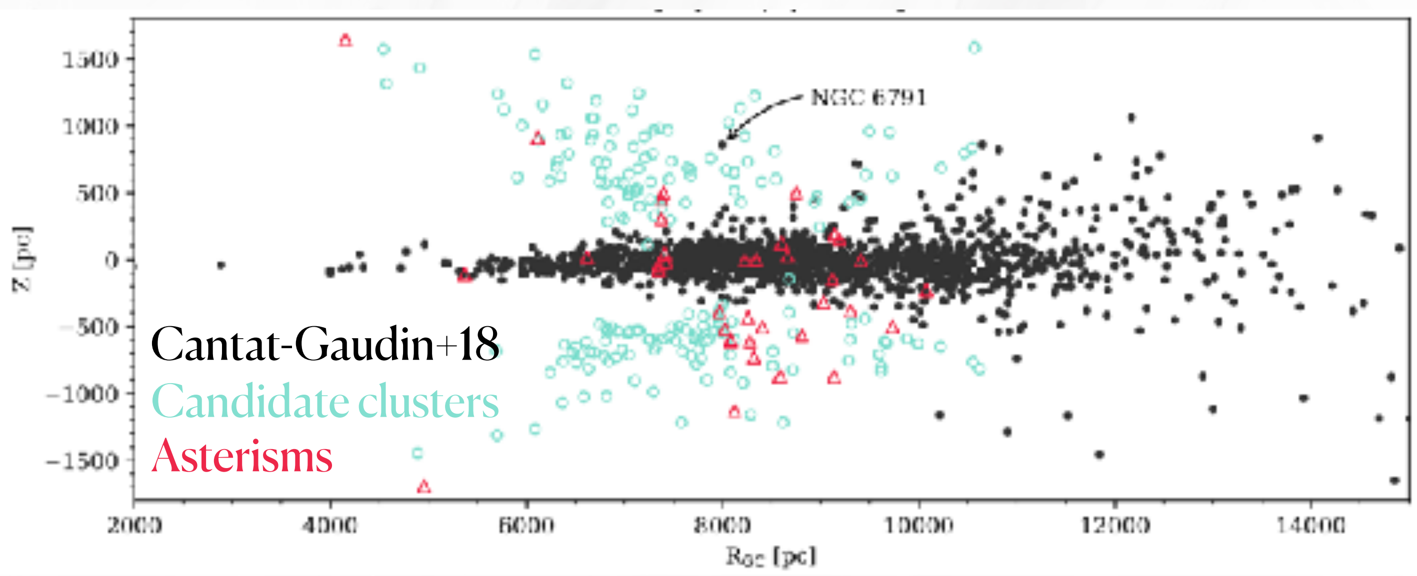
(Bravi+18; Cantat-Gaudin+19a,b; Roman-Zuniga+19; Karnath+19; Damiani+19; Kim+19; Wright+19; Lim+19,22; Buckner+20; Armstrong+20; Kuhn+20; Swiggum+21; Maiz Apellaniz+21)

large, homogeneous study

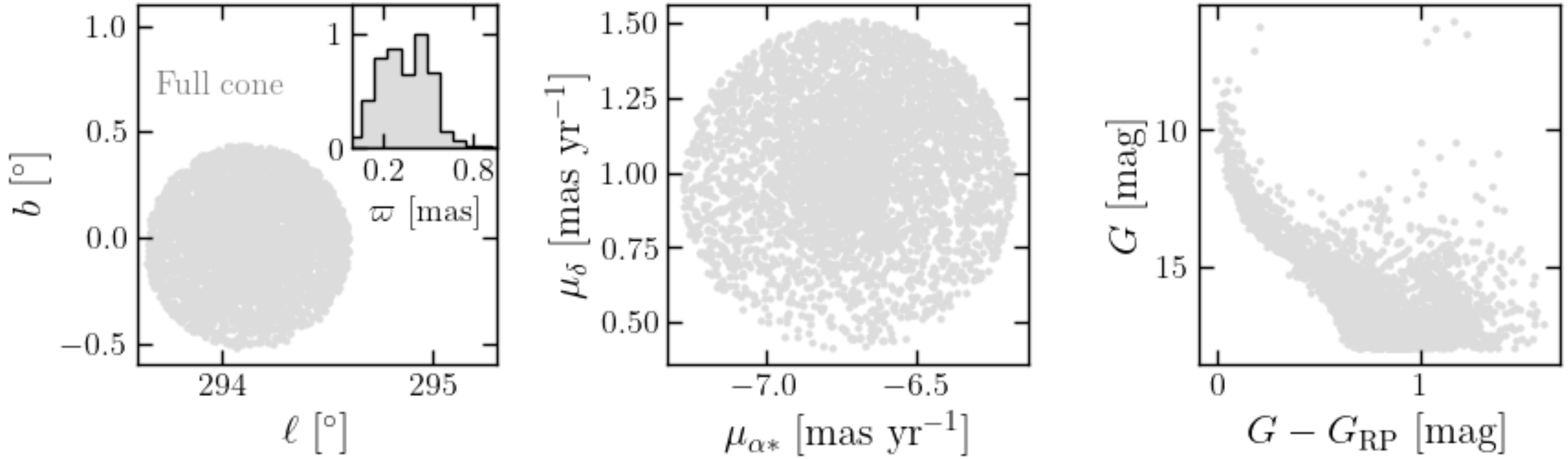
The starting catalog

The cluster catalog by Cantat-Gaudin+18,20

i. about 2000 clusters
ii. homogeneous parameters estimation
iii. membership lists based on Gaia DR2 → DR3



Membership analysis



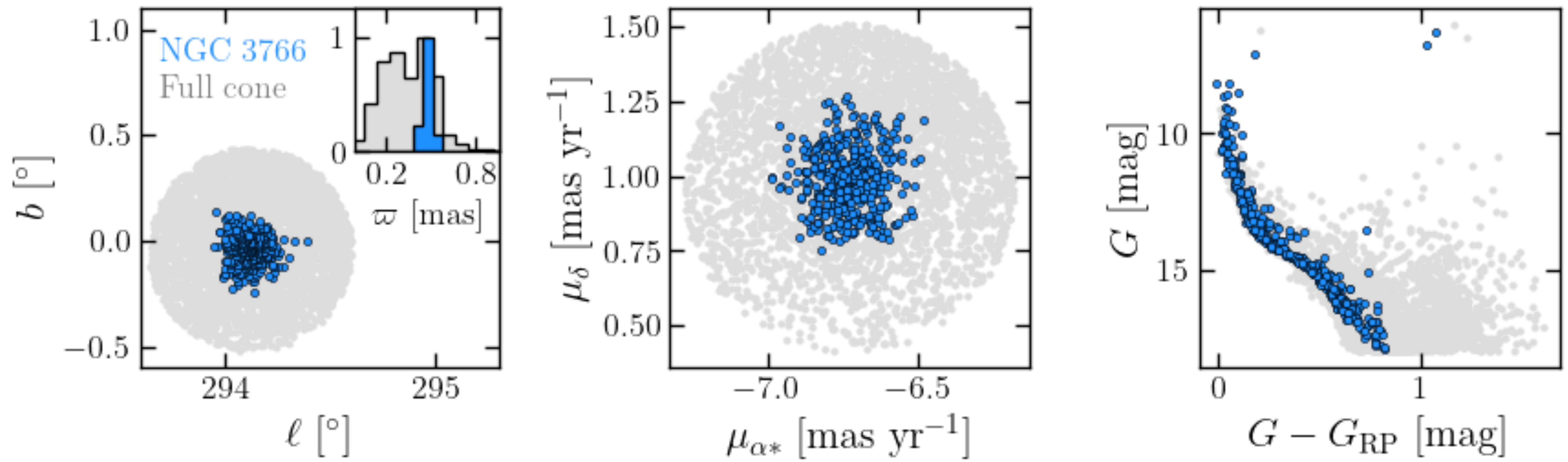
5 parameters solution

$G \leq 18$ mag

$R_{\text{search,sky}} = 2R_{95,\text{sky}}$

$R_{\text{search,PM}} = 2R_{95,\text{PM}}$

Membership analysis



5 parameters solution

$G \leq 18$ mag

$R_{\text{search,sky}} = 2R_{95,\text{sky}}$

$R_{\text{search,PM}} = 2R_{95,\text{PM}}$

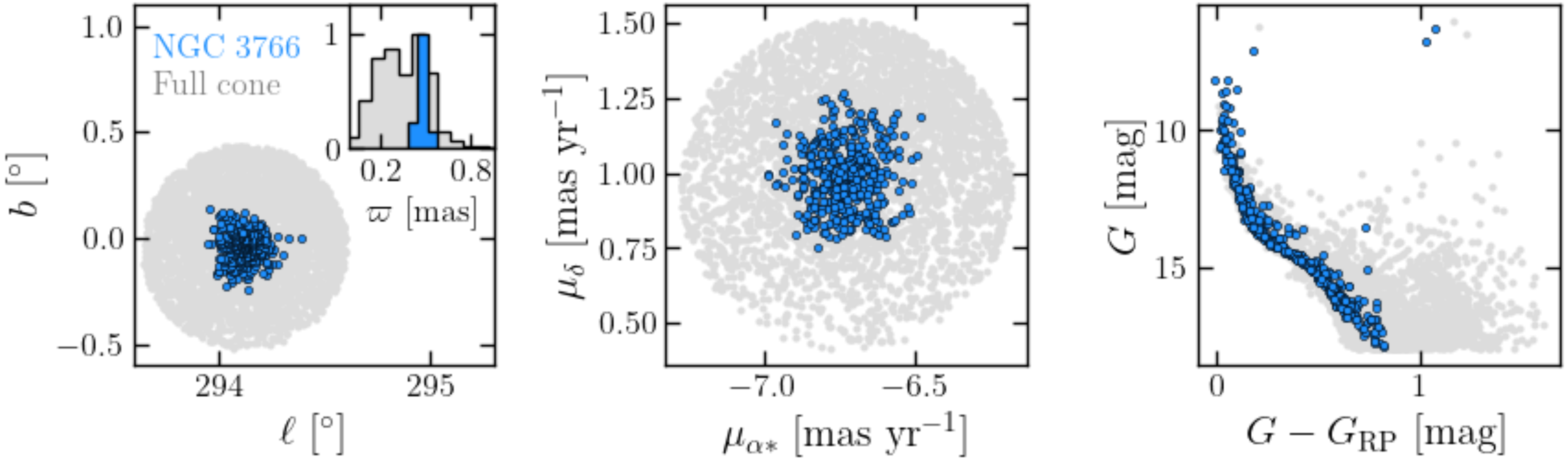
Clustering with HBDSCAN in $(\ell, b, \mu_{\alpha*}, \mu_\delta, \varpi)$ space

NGC 3766

age $\sim$ 22 Myr

d $\simeq$ 2 Kpc

Membership analysis

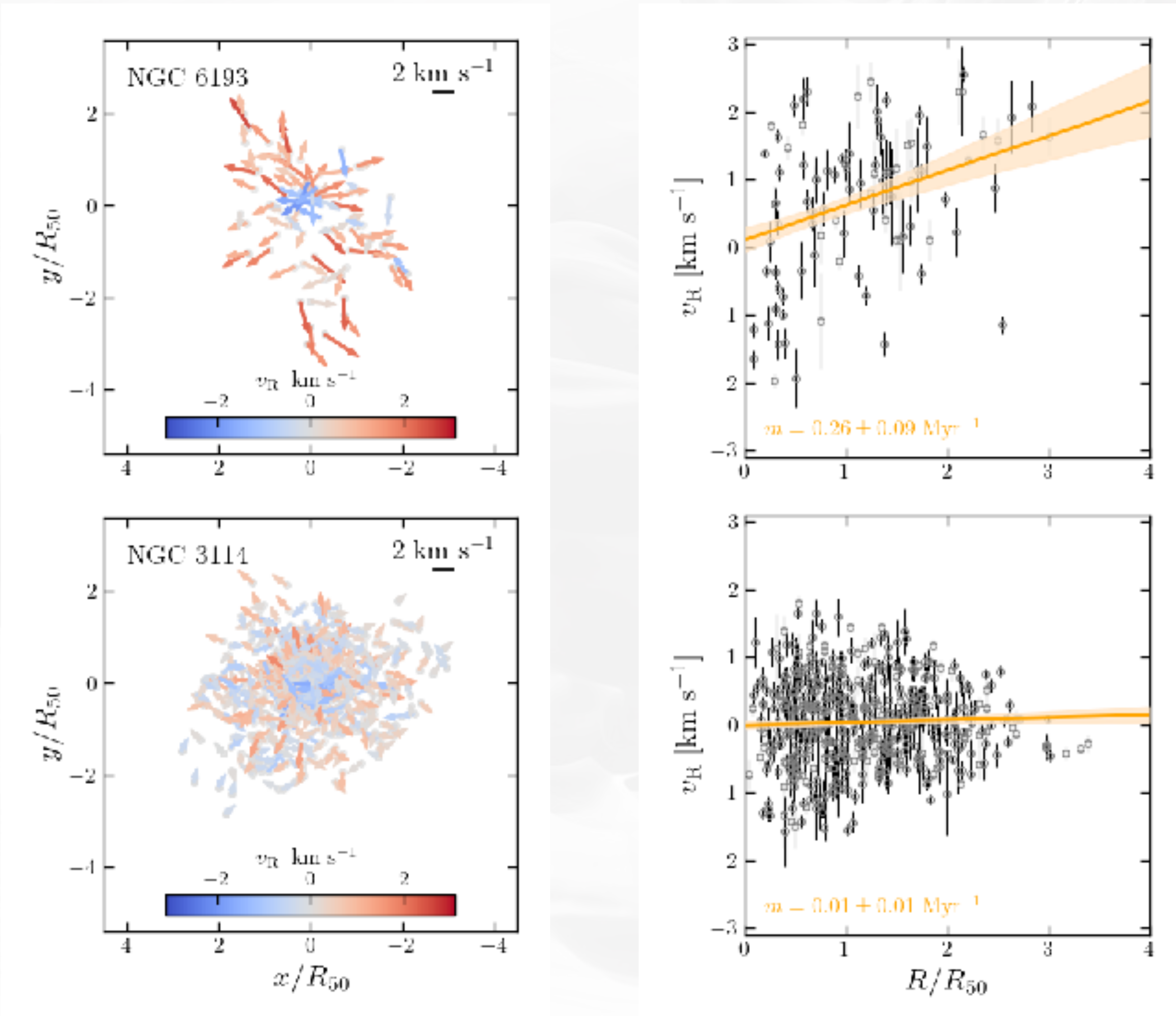


All clusters younger than 300 Myr in CG20

Cluster internal kinematics

Estimated the $\langle v_R \rangle / \sigma_R$ (direct indicator of expansion) by MCMC

perspective corrections (van Leeuwen+2009, LOS velocities from Tarricq+21)



NGC 6193

age ~ 5 Myr

$\langle v_R \rangle / \sigma_R = +0.62^{+0.12}_{-0.13}$

$R_{50} \simeq 2$ pc

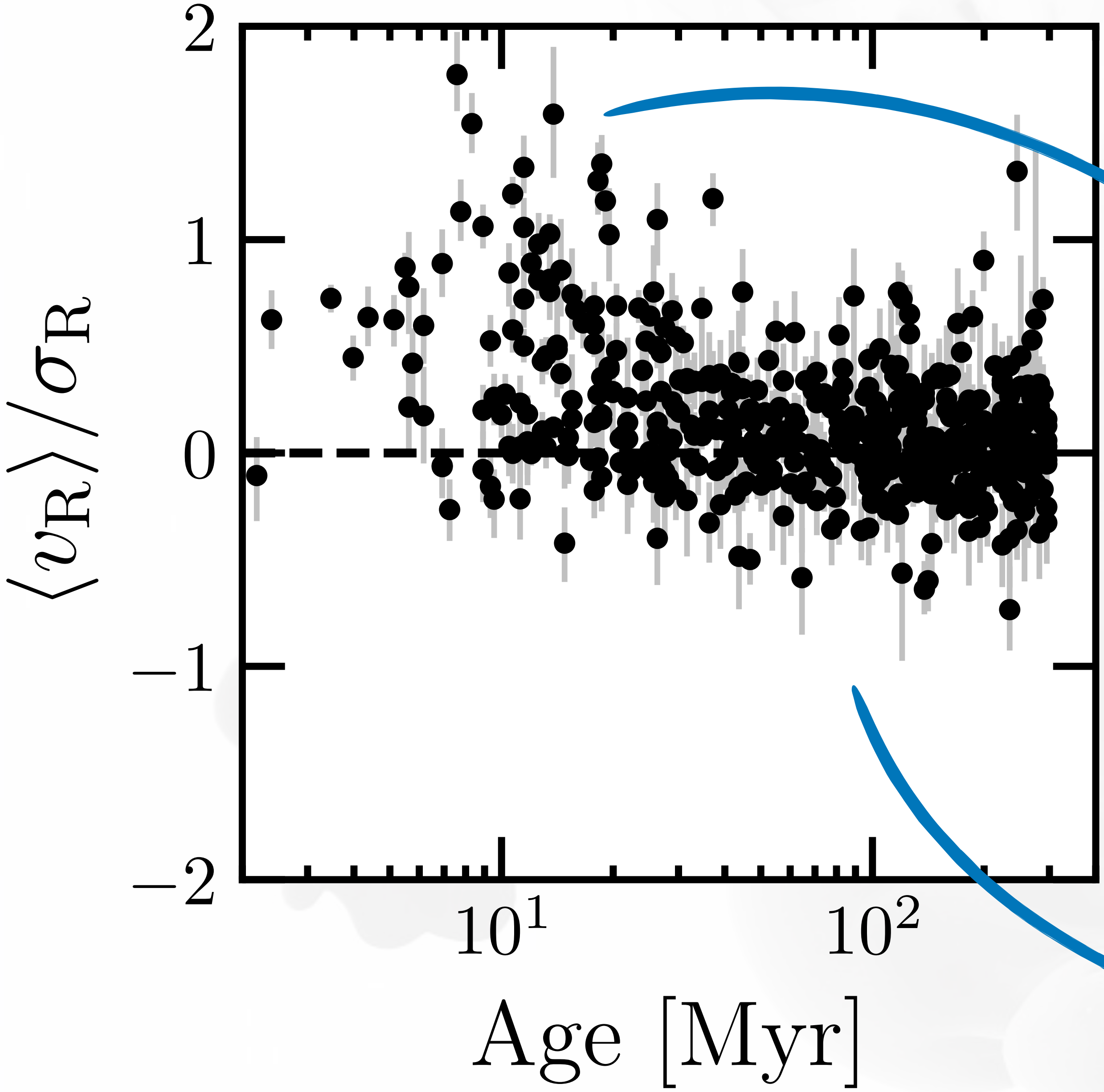
NGC 3114

age ~ 150 Myr

$\langle v_R \rangle / \sigma_R = +0.08^{+0.05}_{-0.05}$

$R_{50} \simeq 4.5$ pc

Expansion of young stellar clusters



509 clusters

with an estimated $\langle v_R \rangle / \sigma_R$

Della Croce et al. 2024, A&A, 683, A10

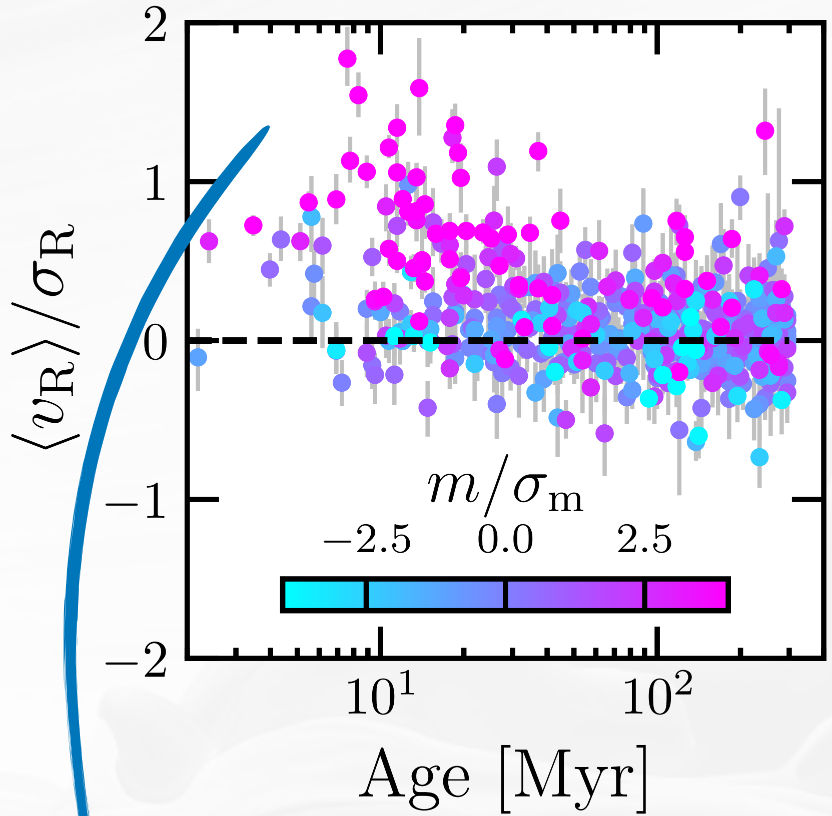
$<$ 30 Myr, 58/138 (43%)

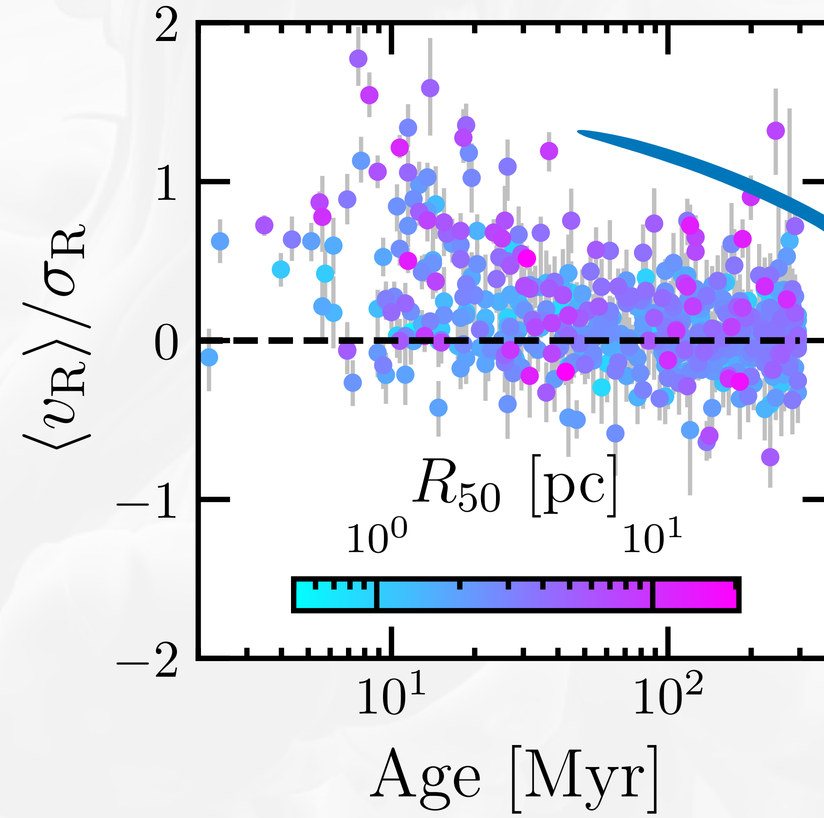
30 – 50 Myr, 5/53 (<10%)

"Constrain the time scale"

mostly consistent with no expansion

Expansion of young stellar clusters



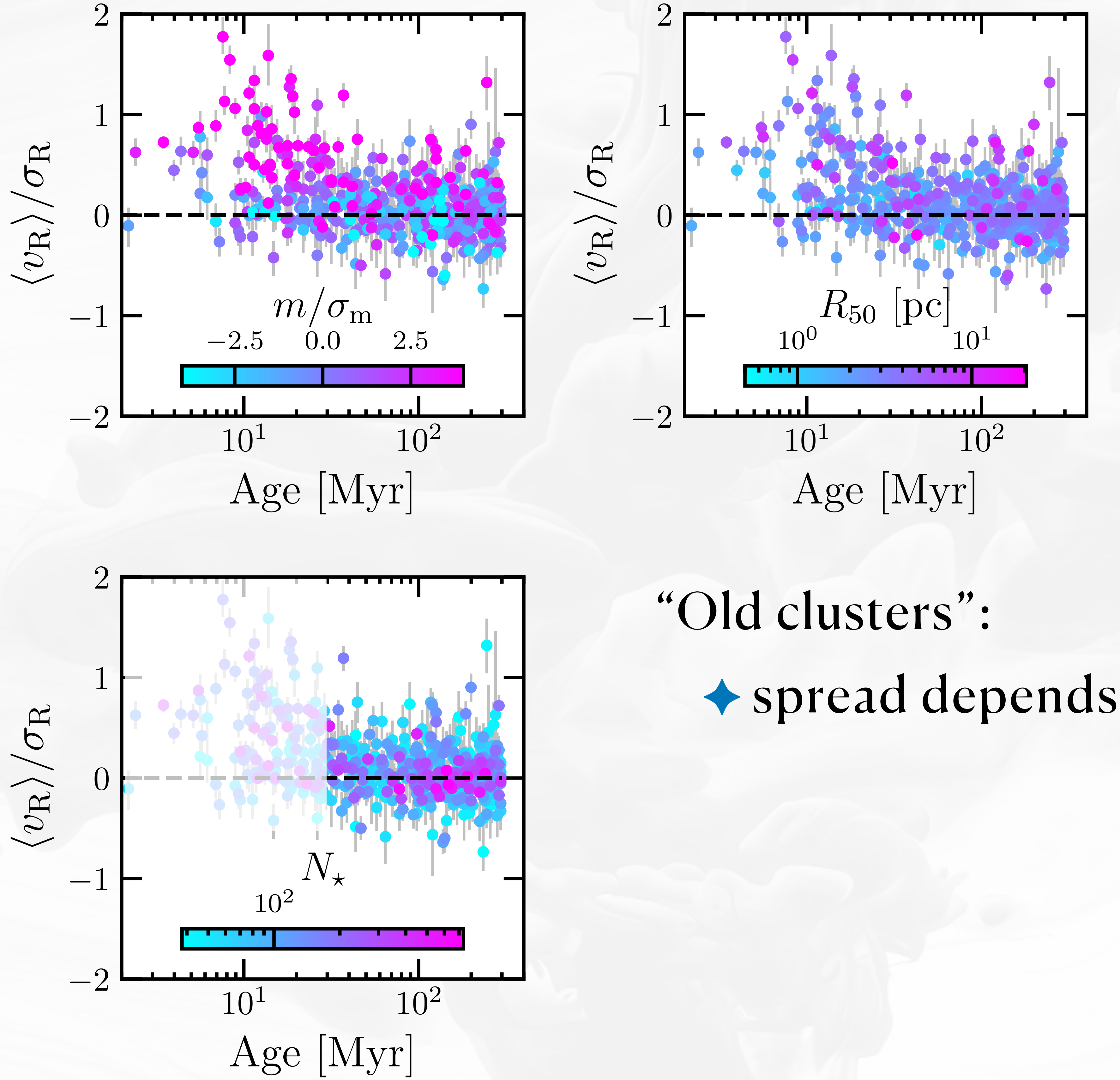


Expanding systems have $m/\sigma_m \gtrsim 3$

expanding systems exhibit larger extensions

mass loss,
eventually disperse

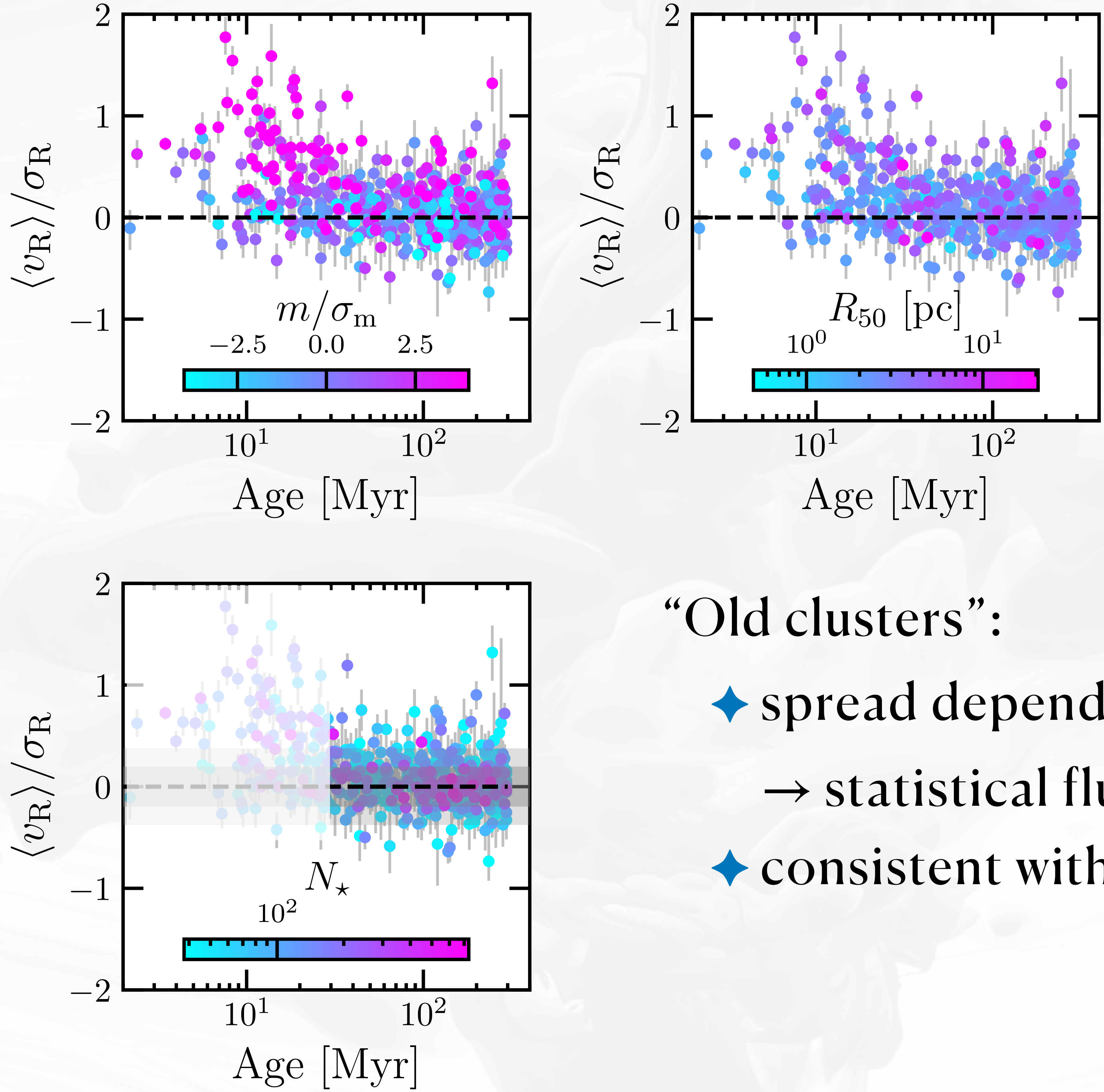
Expansion of young stellar clusters



"Old clusters":

- spread depends on $N_\star$

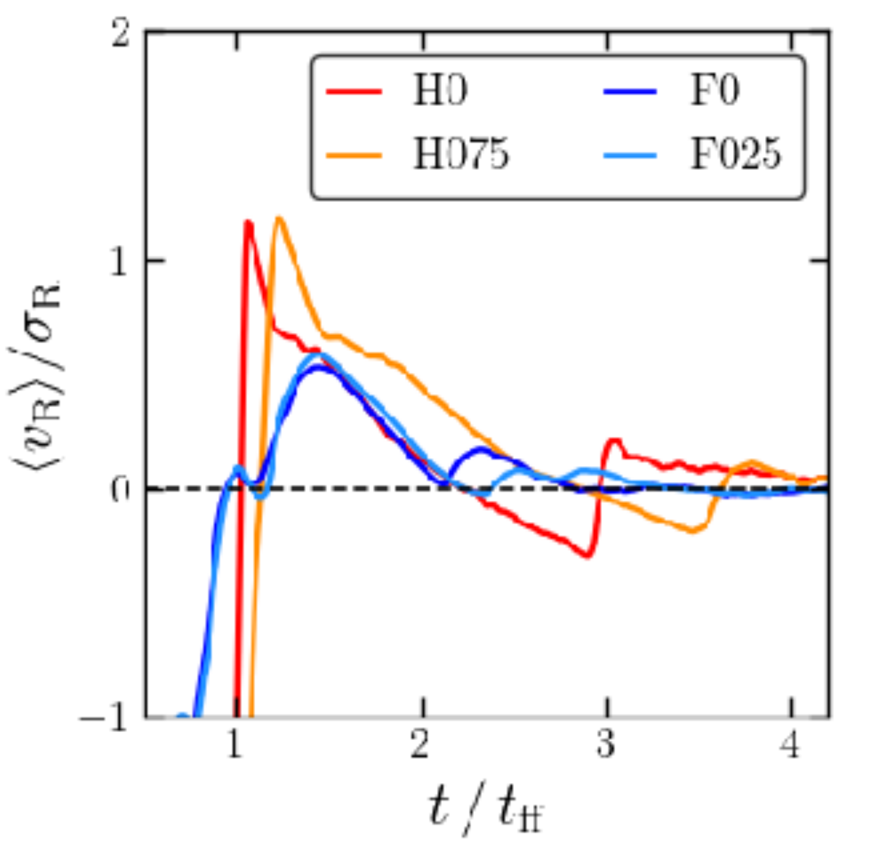
Expansion of young stellar clusters



"Old clusters":

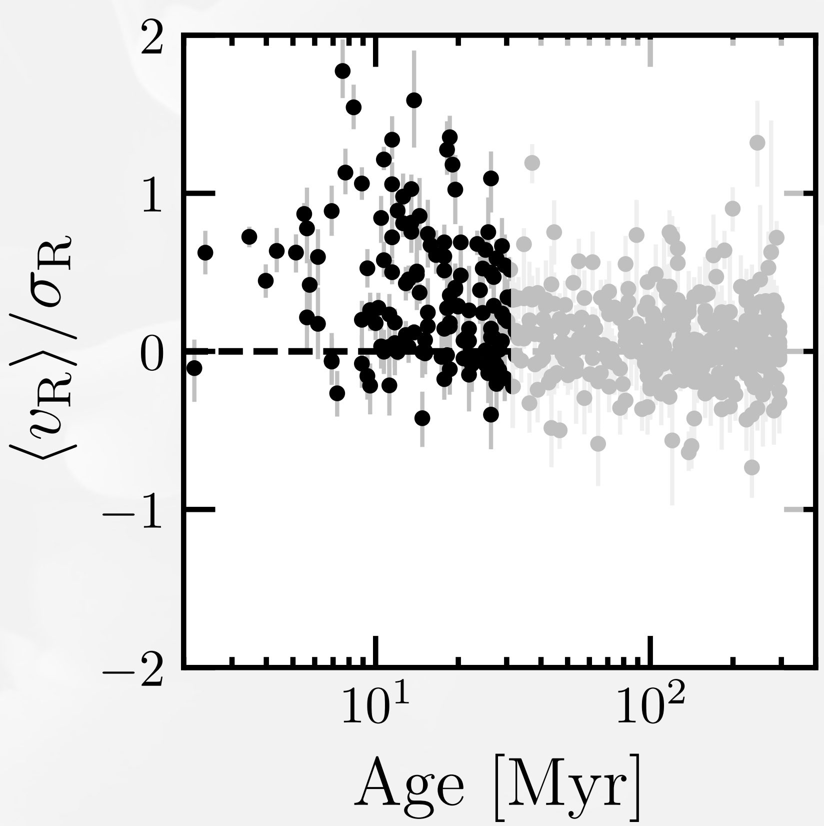
- spread depends on $N_\star$
  → statistical fluctuations
- consistent with equilibrium

N-body simulations of cluster formation



N-body simulations following the violent relaxation phase

(Livernois et al. 2021, MNRAS, 506, 5781)



$t_{ff} \sim 2 - 10$ Myr

expansion up to ~ 25 Myr

Conclusions

Nearby star-forming regions:

to study cluster formation

Gaia in synergy ***with spectroscopic surveys***

LISCA I and LISCA II:

hierarchical structures

in the process of forming a ***massive cluster***

Early cluster kinematics:

large and ***homogeneous*** study for 509 clusters

expansion plays a key role in the first ***30 Myr***

Cluster kinematics in hierarchies:

stay tuned!