The Early Evolution of Young Star Clusters and Associations

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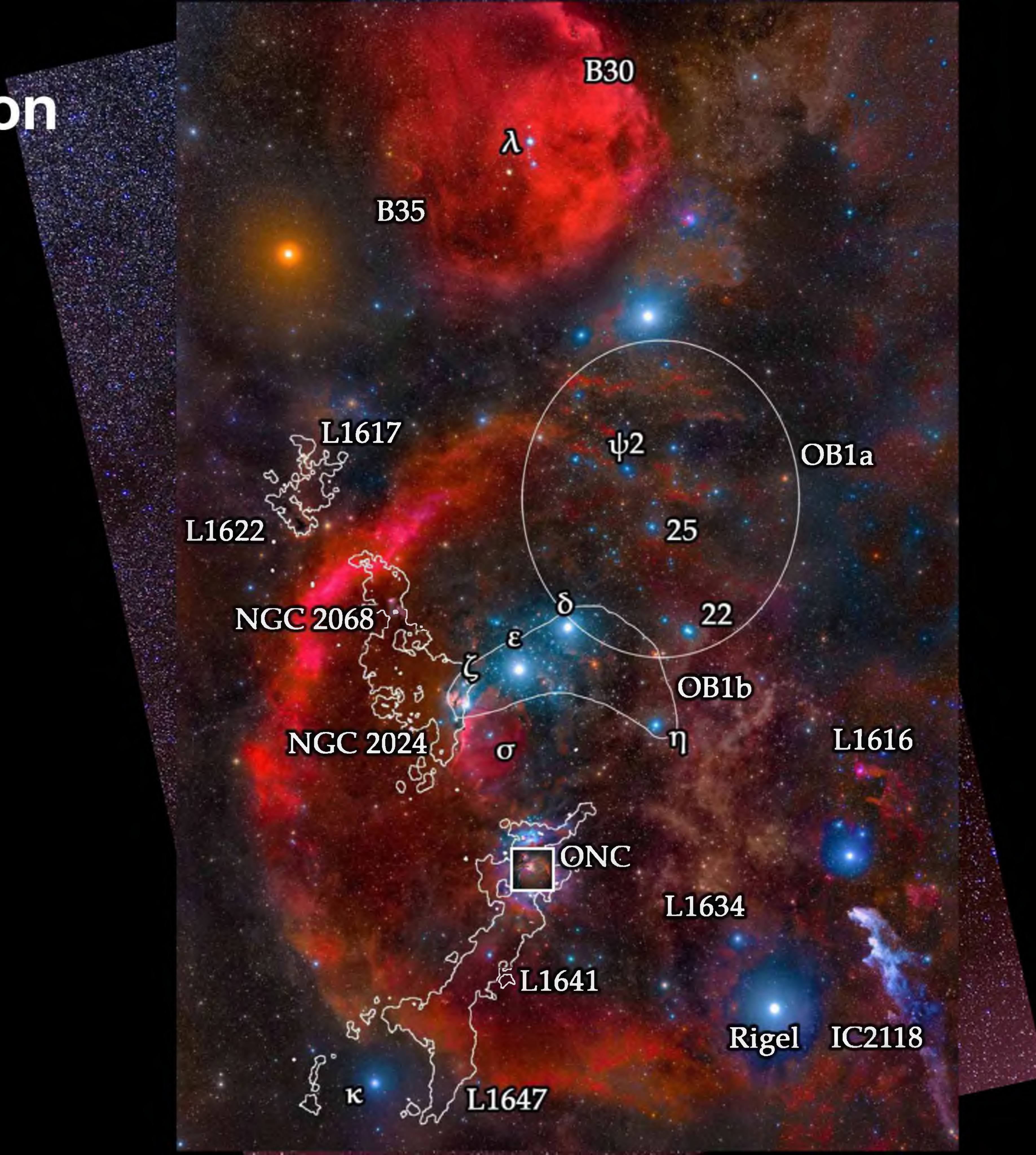
Background

- Most stars are born in groups in massive star-forming regions but most groups do not survive as bound clusters (e.g. Lada & Lada 2003)

- It has long been suspected that OB associations dispersed over degrees on the sky could have originated from more compact initial configurations (e.g. Blaauw 1964)

- With the ONC being the nearest progenitor of a possible bound open cluster, there is much interest in its dynamical state and future evolution

Orion



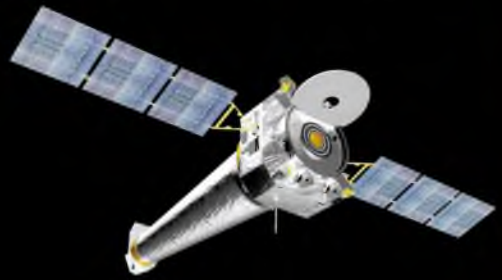
B30
λ
B35
L1617
ψ2
OB1a
L1622
25
NGC 2068
δ
22
ε
ζ
OB1b
NGC 2024
σ
η
L1616
ONC
L1634
L1641
Rigel
IC2118
κ
L1647

HST

VLT

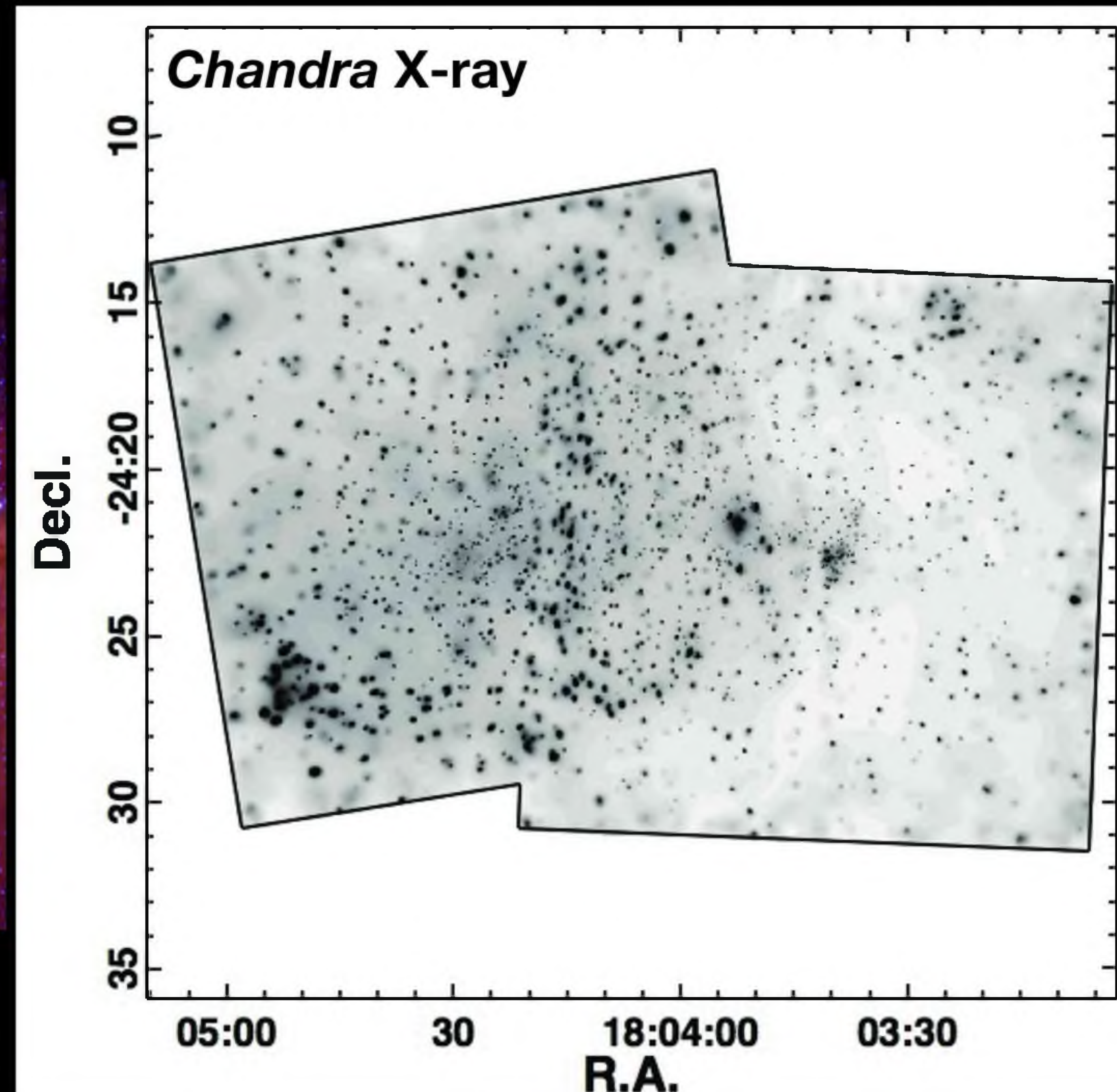
CXO

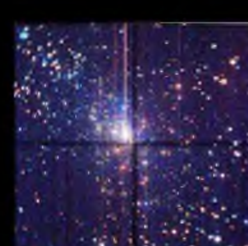
CXO



NGC 6530 – Lagoon Nebula

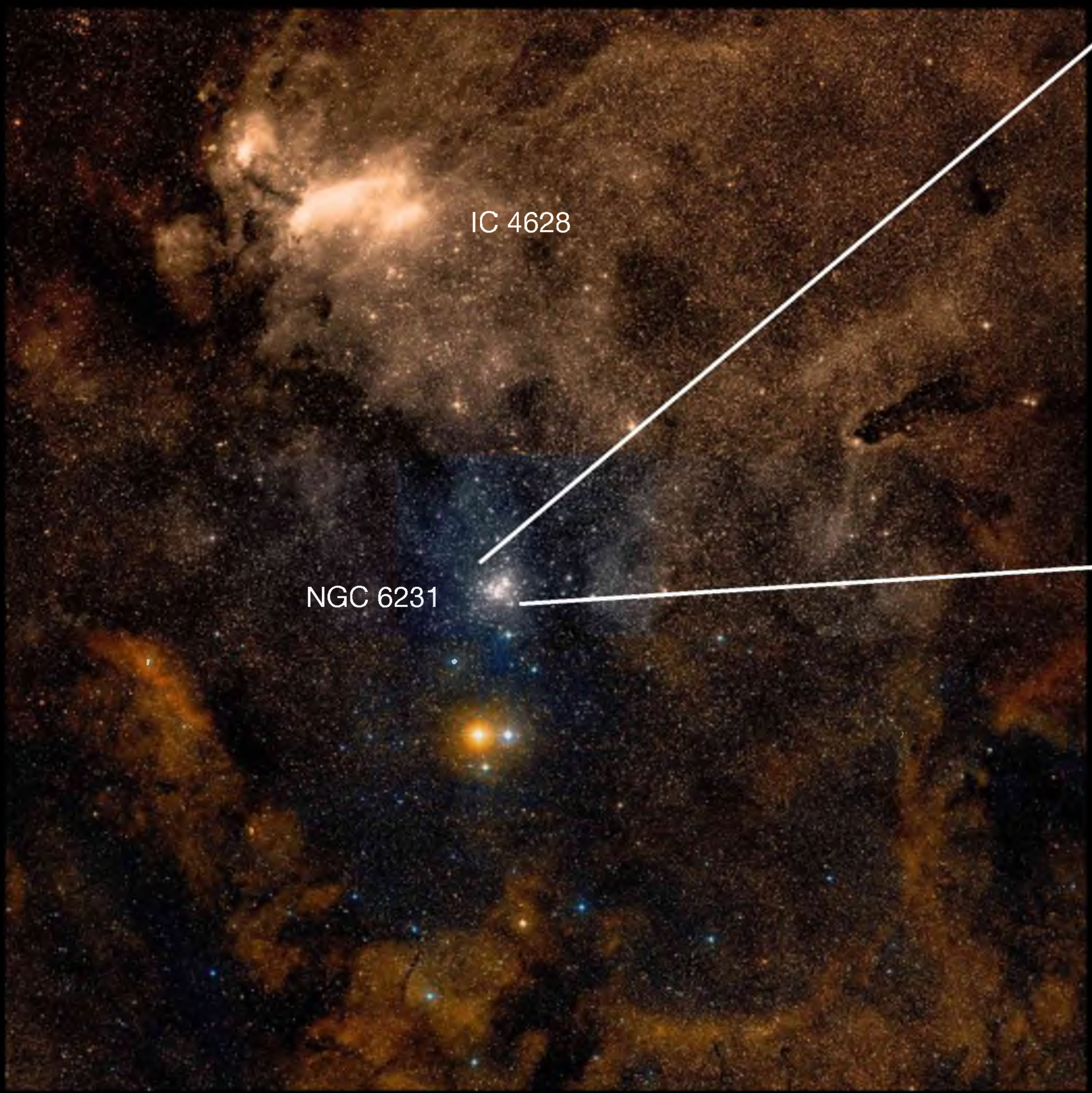
Spitzer IRAC



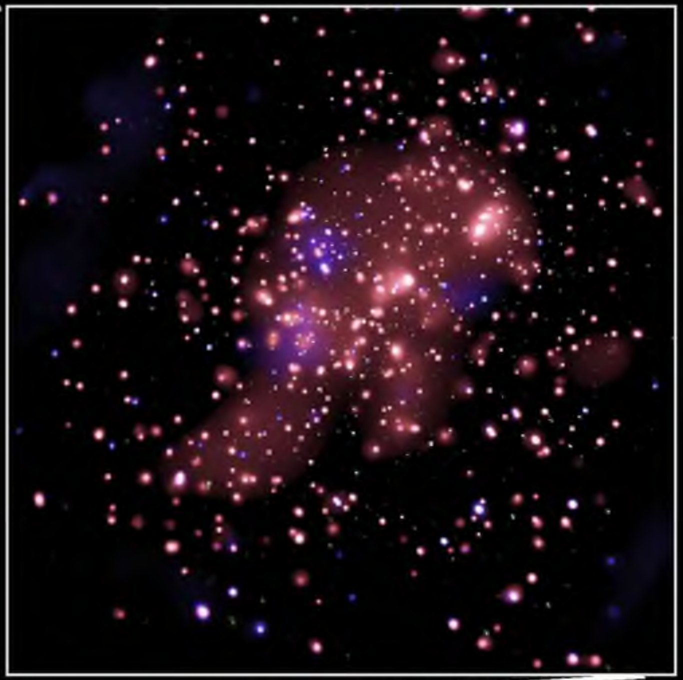


<- ONC *Chandra* image for comparison of physical size

NGC 6231 – nice testbed

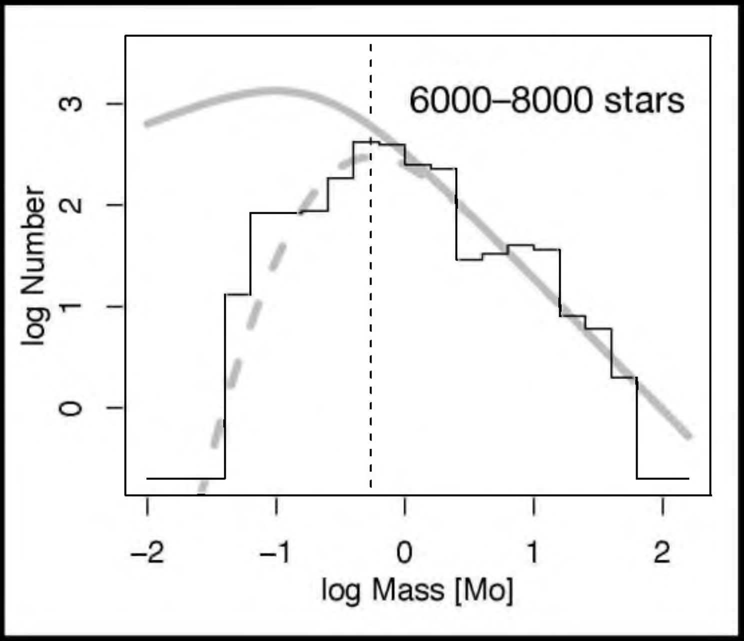


DSS image of Sco OB1



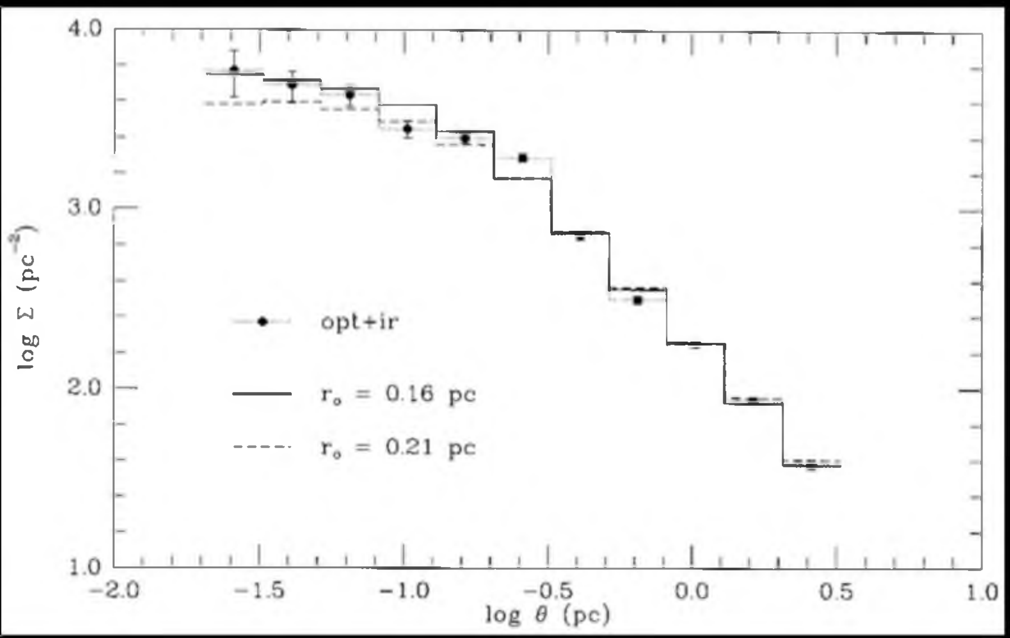
Chandra X-ray

3.2–6.4 Myr old
Nearly completely devoid of gas



See Damiani et al. (2016, 2018); Kuhn et al. (2017a, b)

Surface Density Profiles



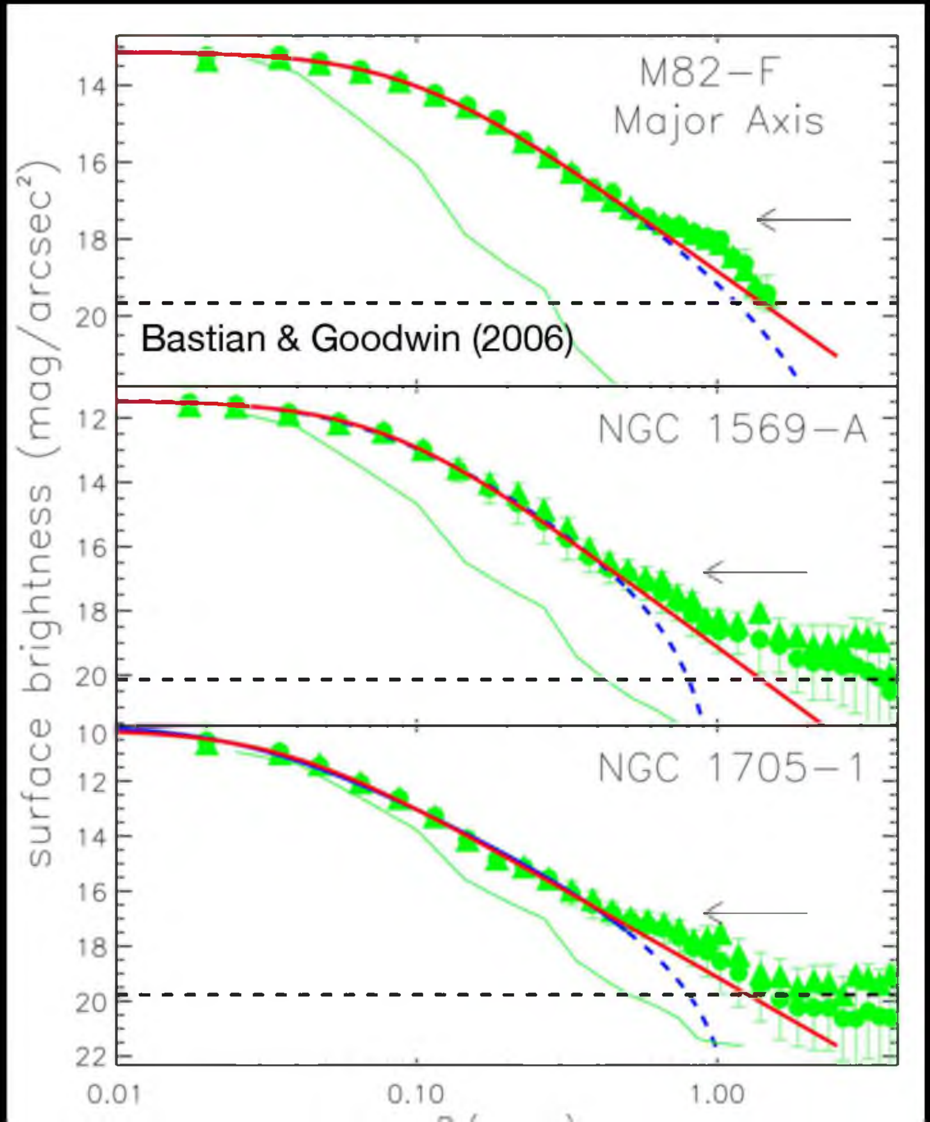
- Hillenbrand & Hartmann (1998) show the central region of the ONC is can be described by a King profile with r_0 ~ 1.6-0.2 pc

- Massive young clusters well fit by core-power law EFF profiles (Elson et al. 1987)

$$\mu \sim \mu_0 \qquad \mu \propto R^{-\gamma}$$

- Bastian & Goodwin (2006) note that excess stars at large radii could be an effect of escaping stars

- Grudič et al. (2018) show that the EFF profile would be expected for clusters built from the merger of subclusters



NGC 6231

Isothermal sphere

$$\Sigma(R) = \Sigma_0 \left[1 + (R/r_c)^2\right]^{-1}$$

Plummer ellipsoid

$$\Sigma(R) = \Sigma_0 \left[1 + (R/r_c)^2\right]^{-5/2}$$

Gaussian distribution

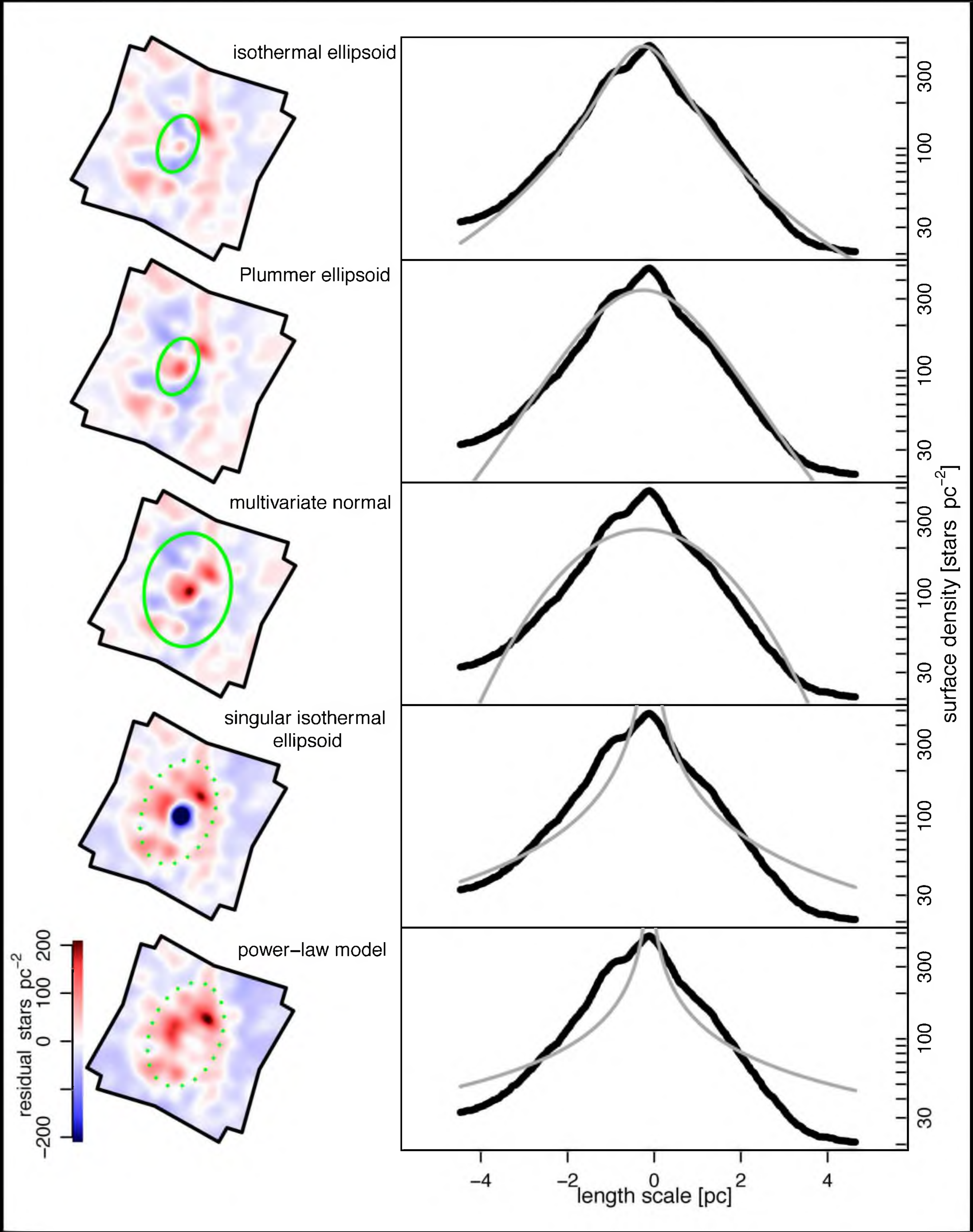
$$\Sigma(R) = \Sigma_0 \exp\left(-R^2/2r_c^2\right)$$

Singular isothermal sphere

$$\Sigma(R) = AR^{-1}$$

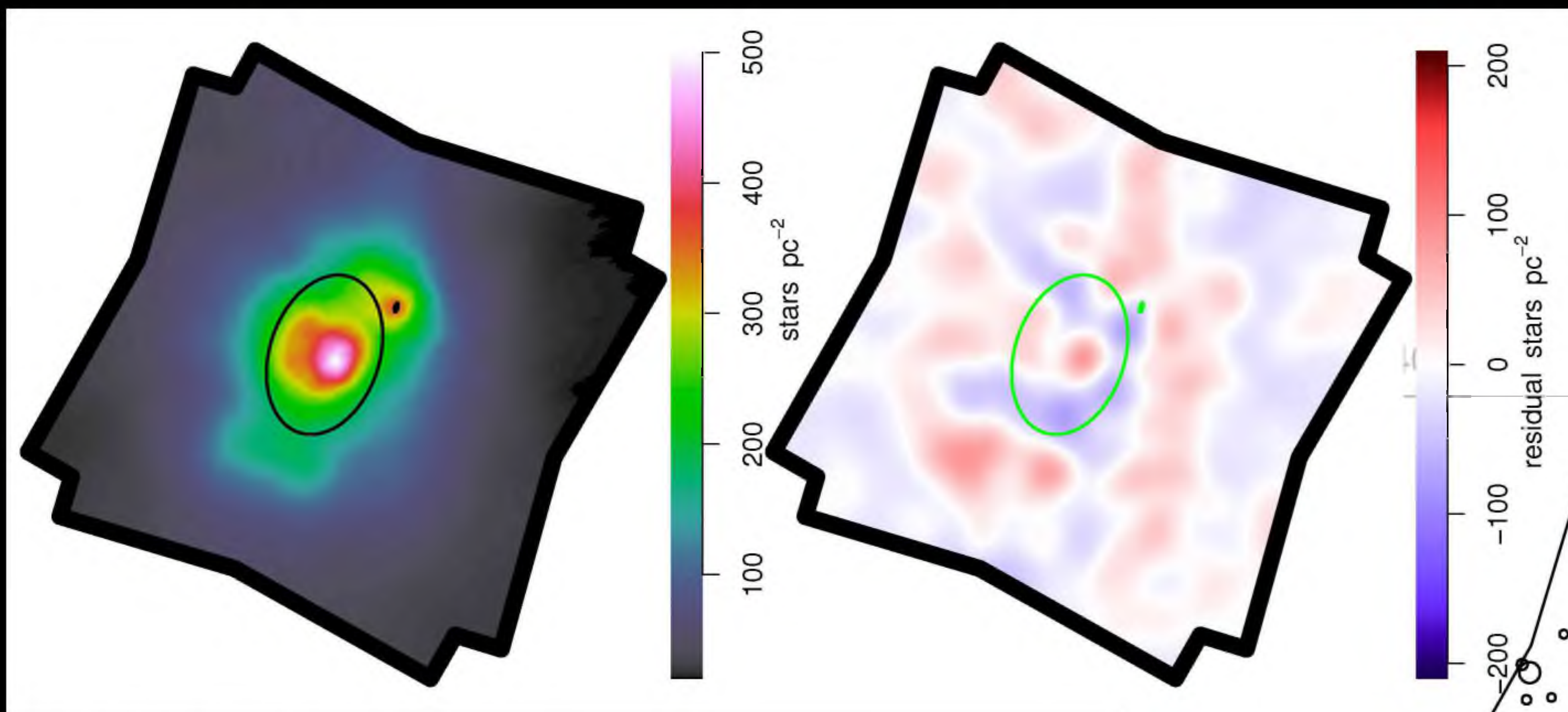
Power law

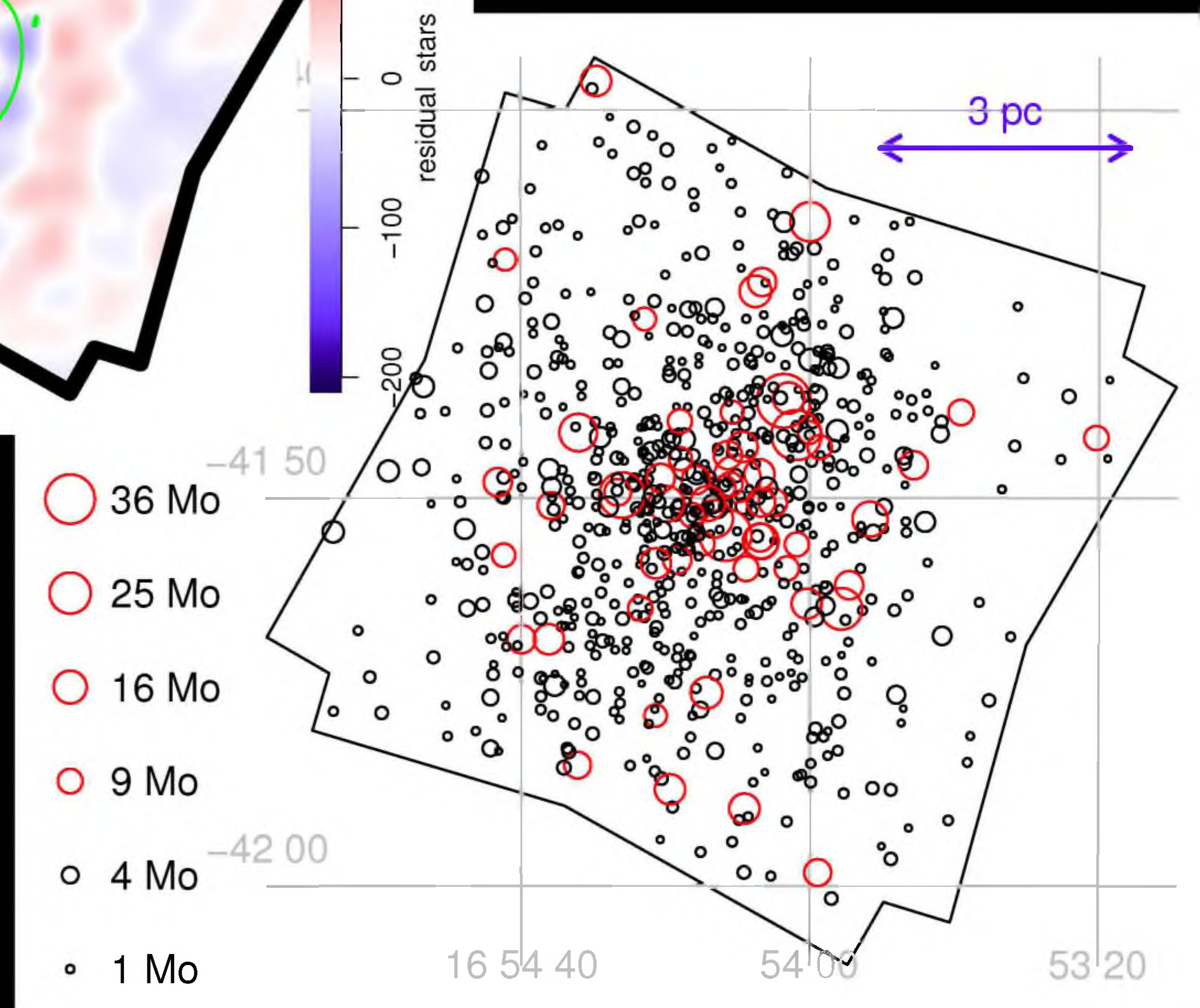
$$\Sigma(R) = AR^{\alpha}$$



Kuhn et al. (2017)

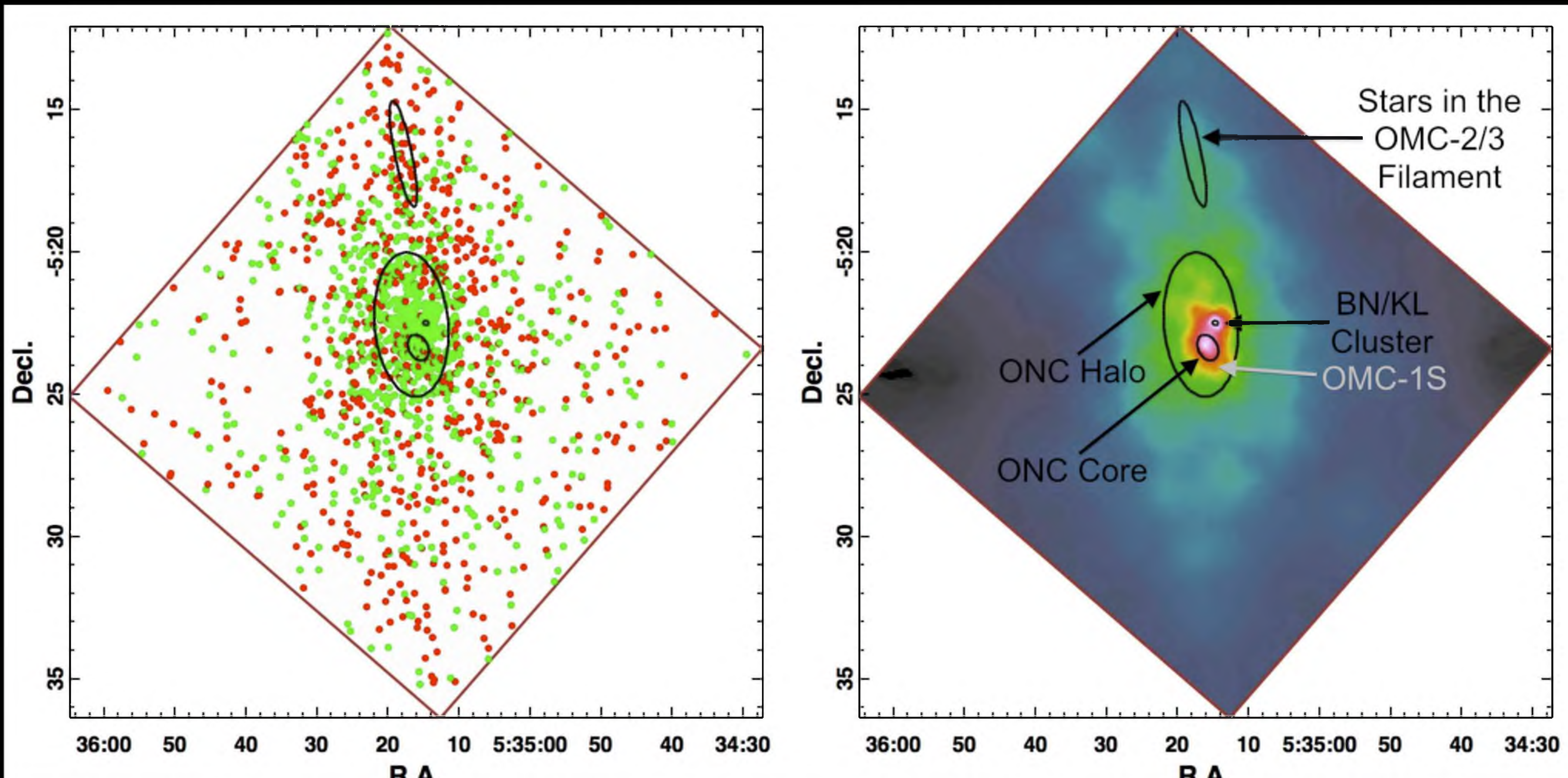
Even NGC 6231 has some substructure.





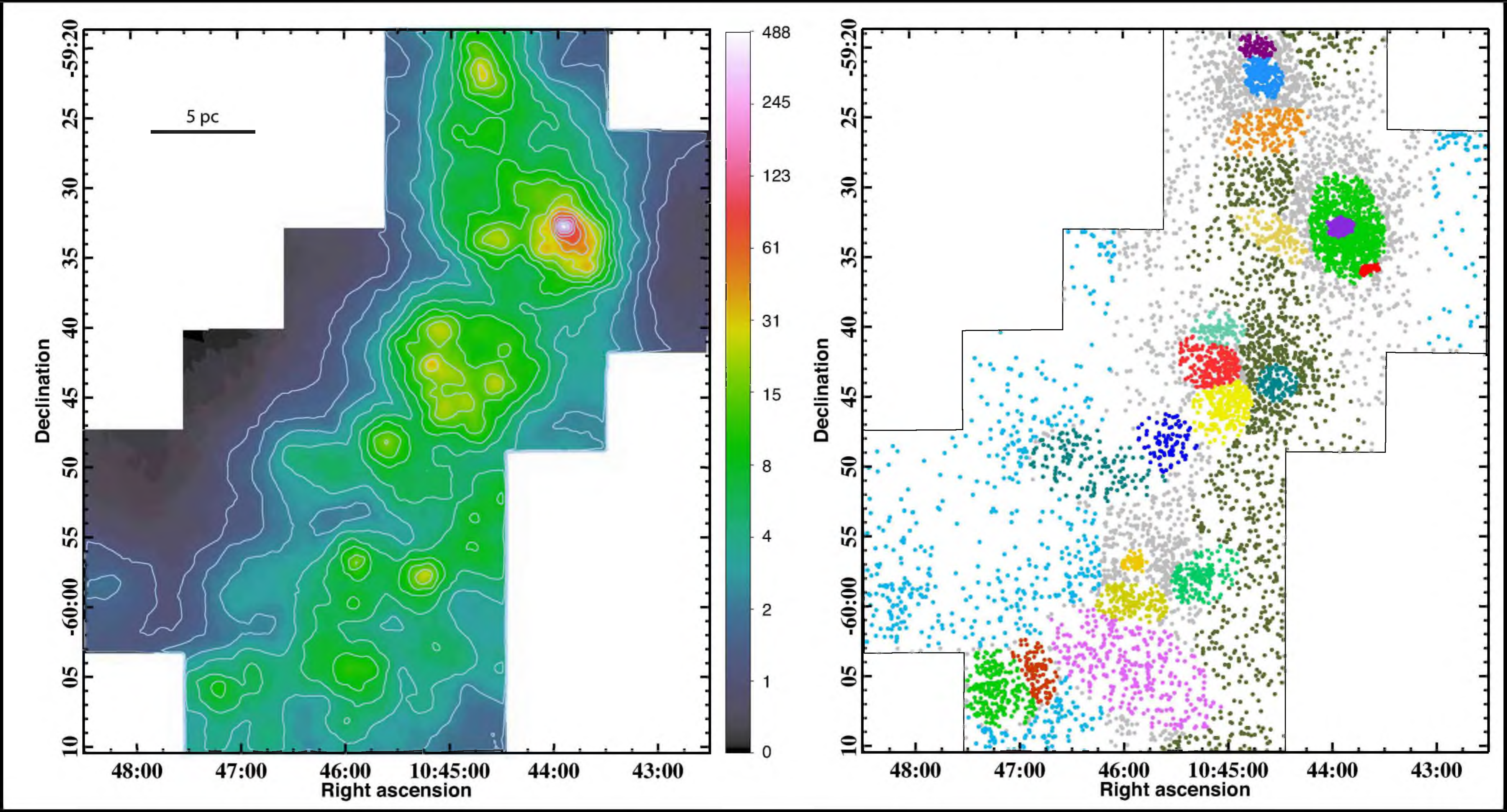
Kuhn et al. (2017)

Central portion of the Orion Nebula Cluster (ONC)
(X-ray selected and IR excess selected)



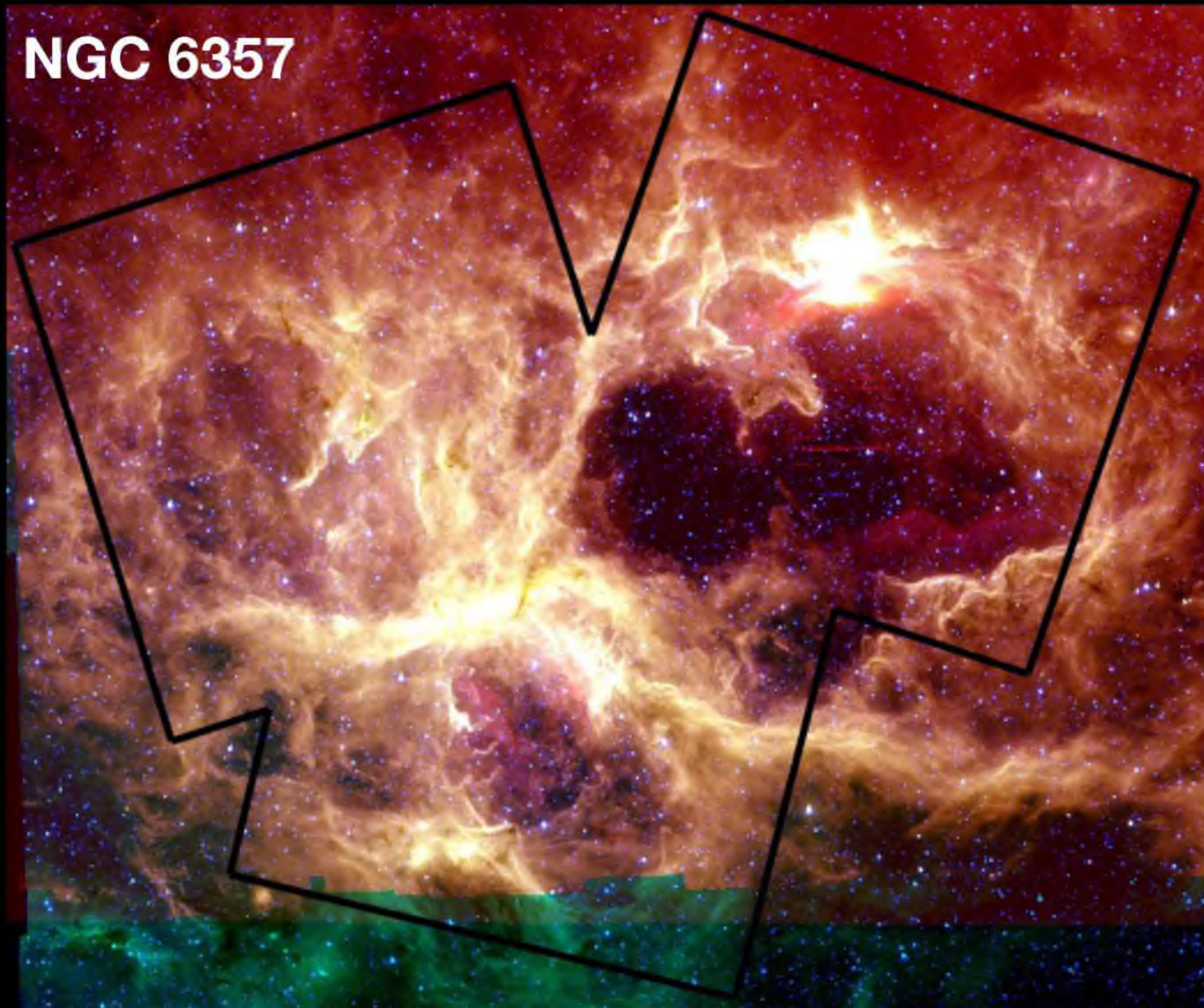
Stars from:
COUP (Getman et al. 2005; Feigelson et al. 2005)
Spitzer YSOs (Megeath et al. 2012)

Carina Nebula (Car OB1)

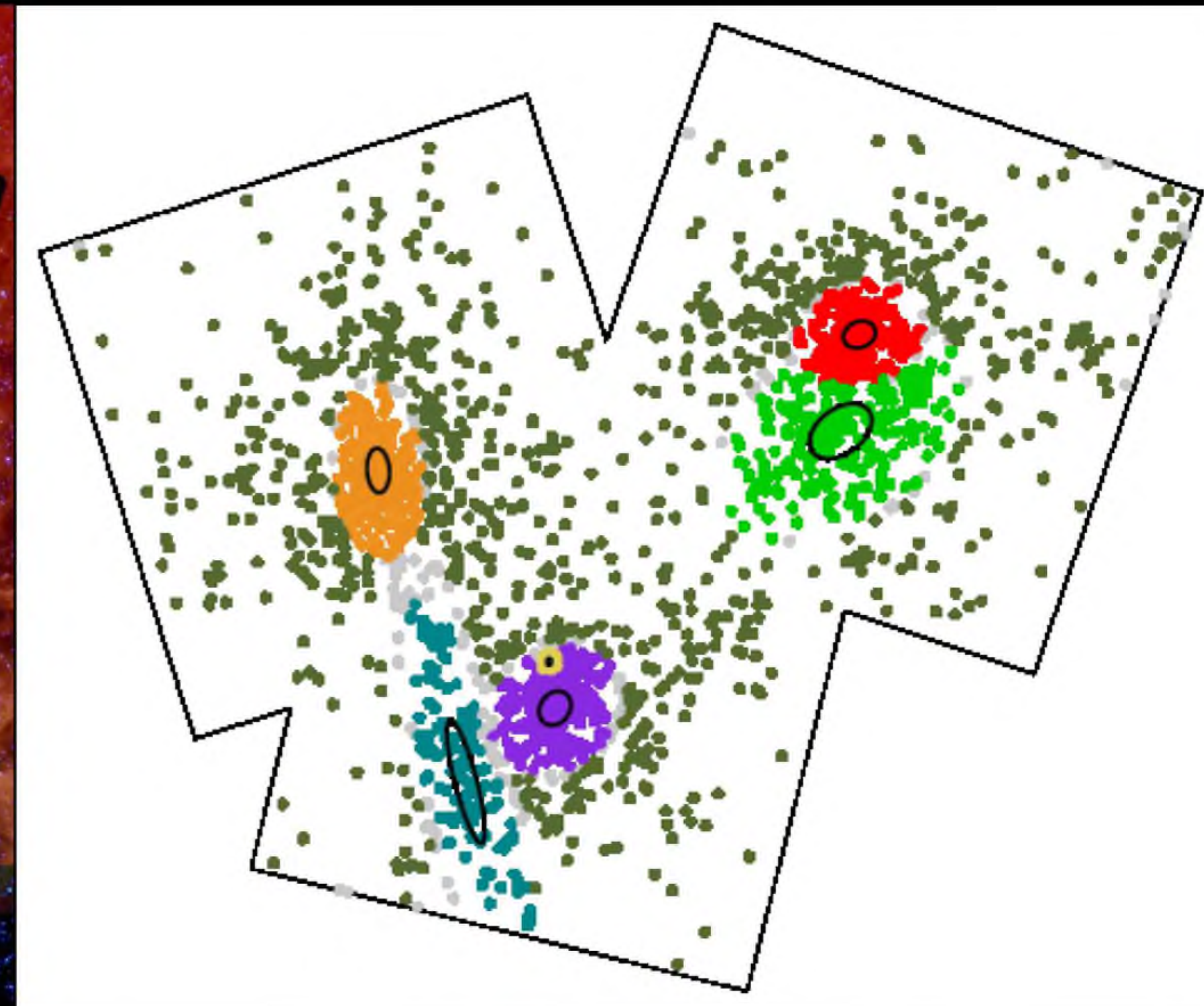


Stars from the *Chandra* Carina Complex Project (Townsley et al. 2011) and MYStIX (Broos et al. 2013)

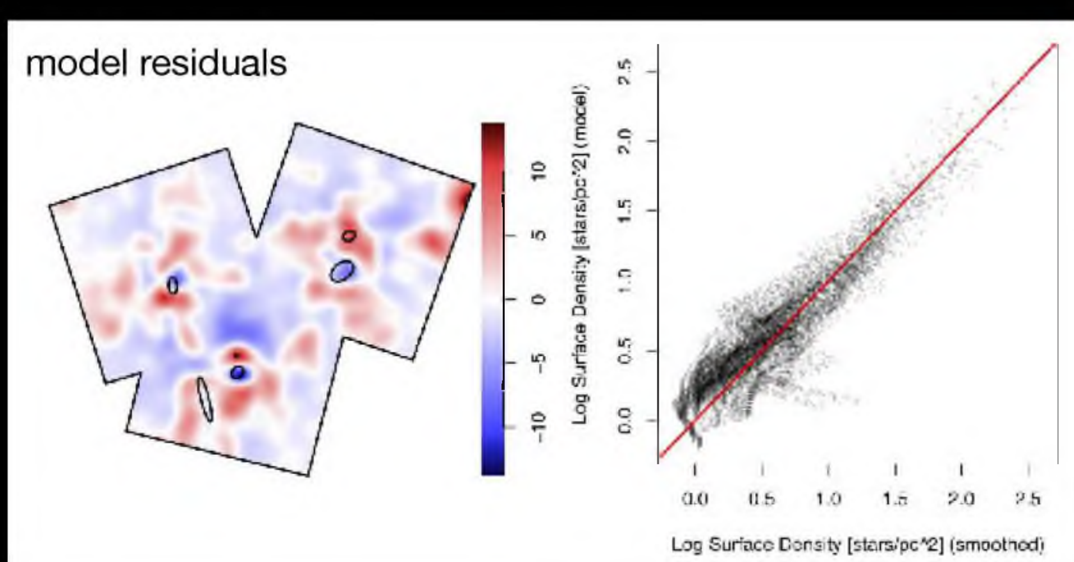
Surface densities on the left panel have been adjusted to correct for telescope sensitivity (Kuhn et al. 2014)

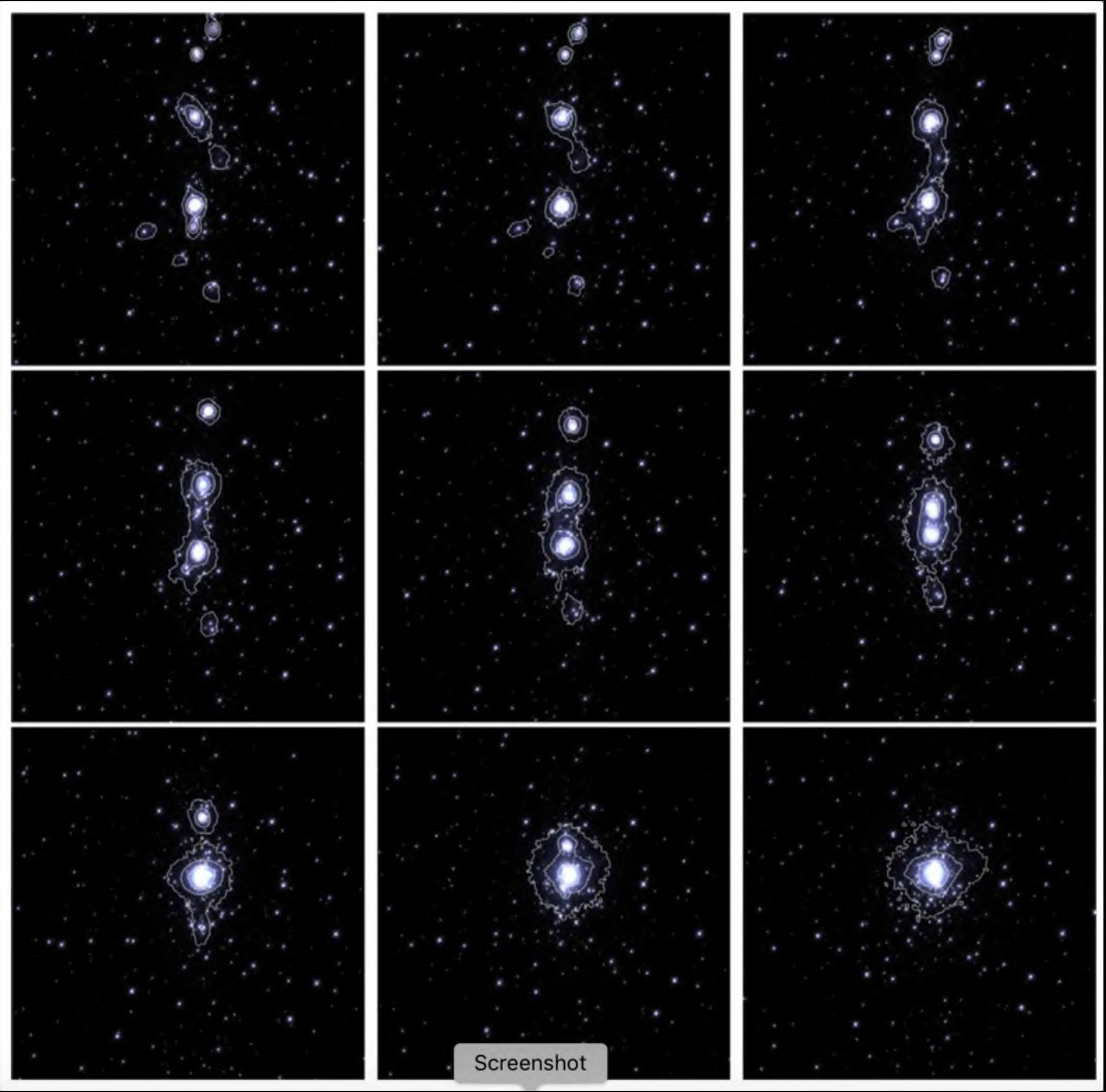


Spitzer IRAC 3.6 (blue), 5.8 (green), 8.0 (red) micron



Mixture model using “isothermal ellipsoid” components (Kuhn et al. 2014)

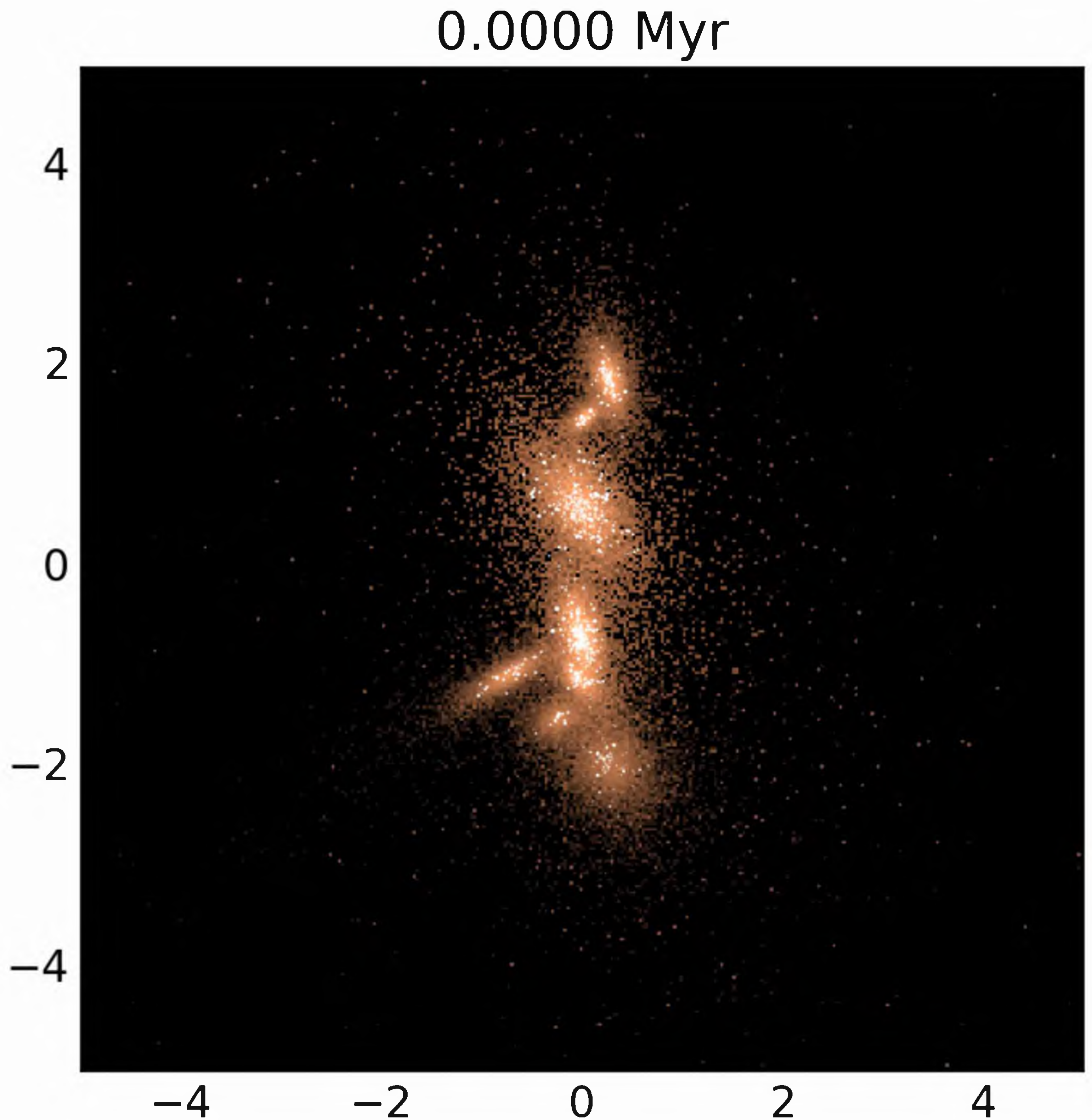




N-body +
Hydrodynamic
simulation

Based on spatial configurations of real stars in star-forming regions

Sills et al. (2018)



Sills et al. (2018)

1. The initial configuration is a chain of subclusters

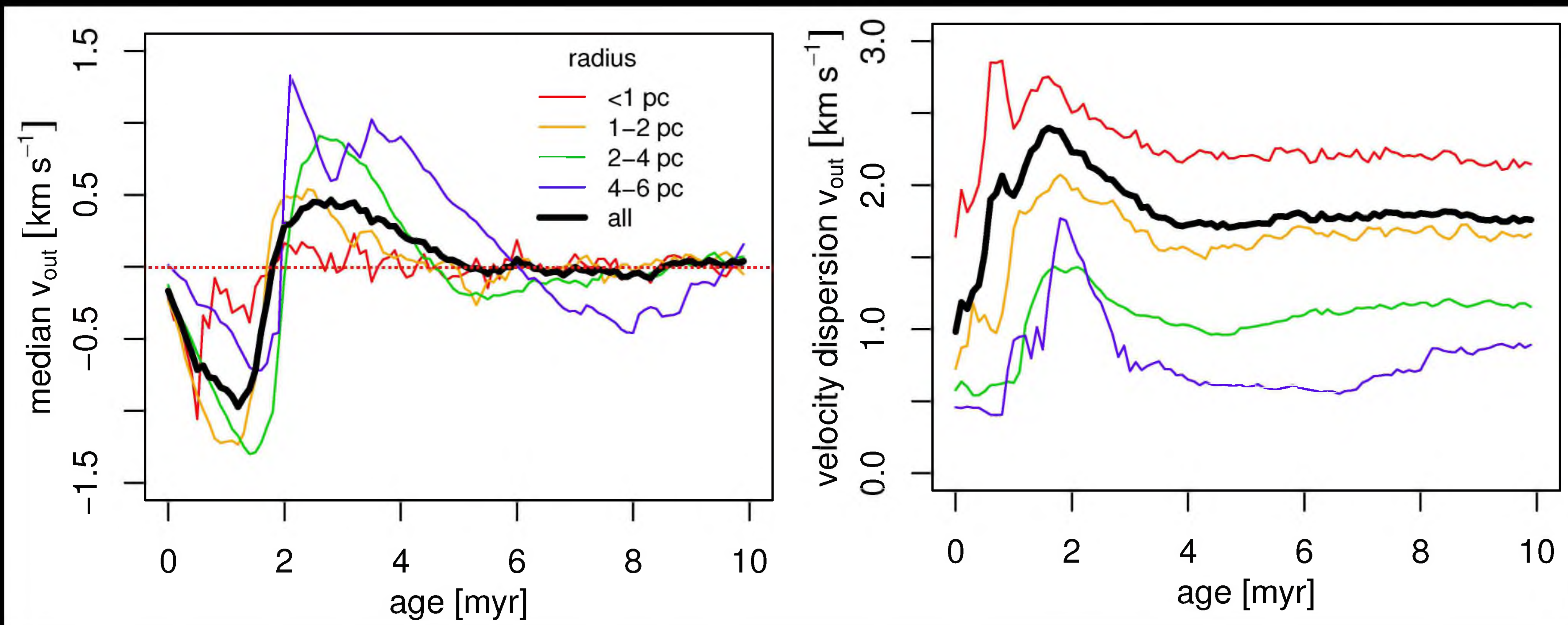
3. Simulation models gas flowing gently out of the cluster center

5. Subclusters merge following “conveyor belt” mechanism

7. Resulting cluster virializes dynamically

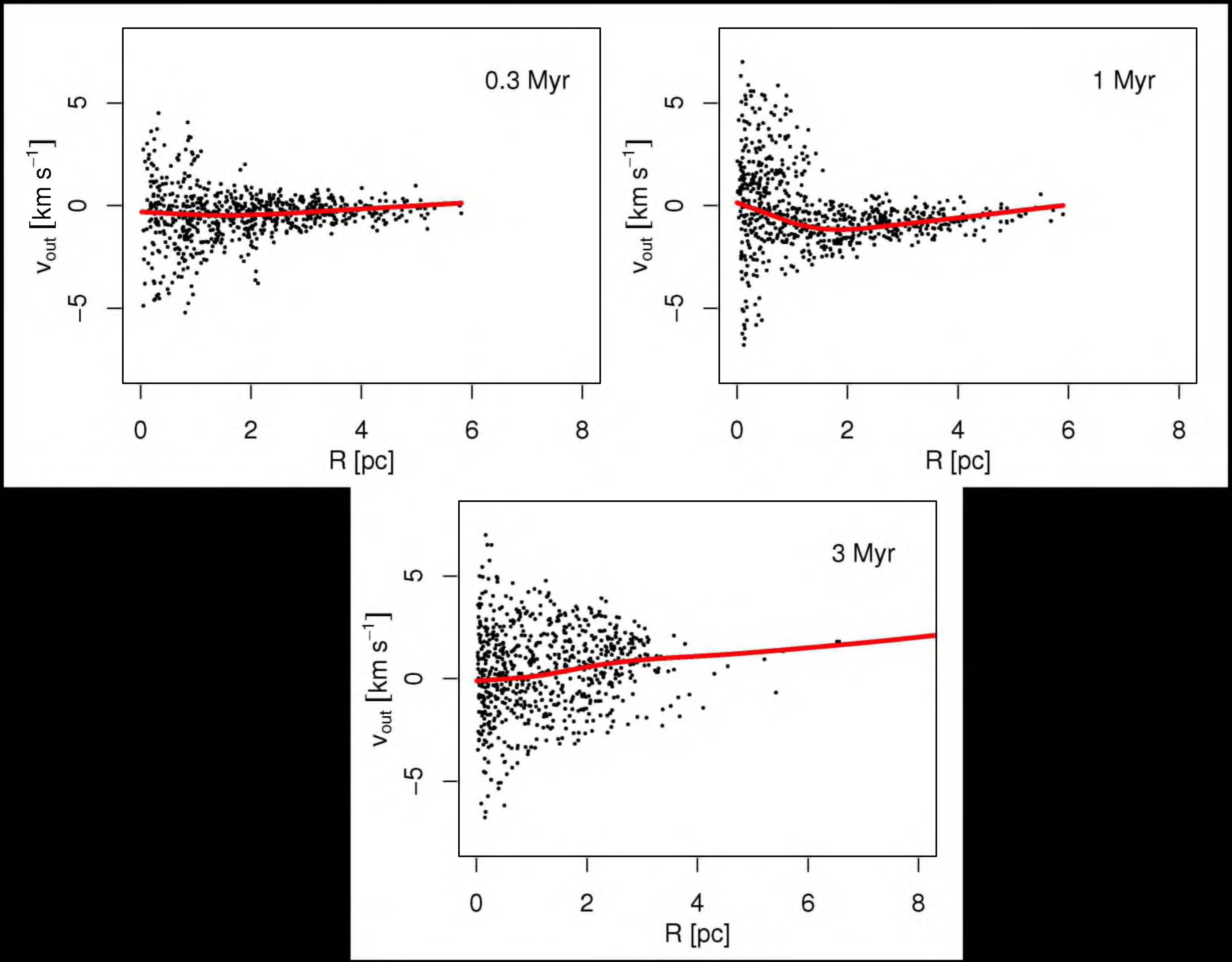
What kinematic properties to expect for bound cluster assembly:

Median Expansion Velocity **Velocity Dispersion**



Kuhn et al. (2019) based on simulations from Sills et al. (2018)

What kinematic properties to expect for bound cluster assembly:

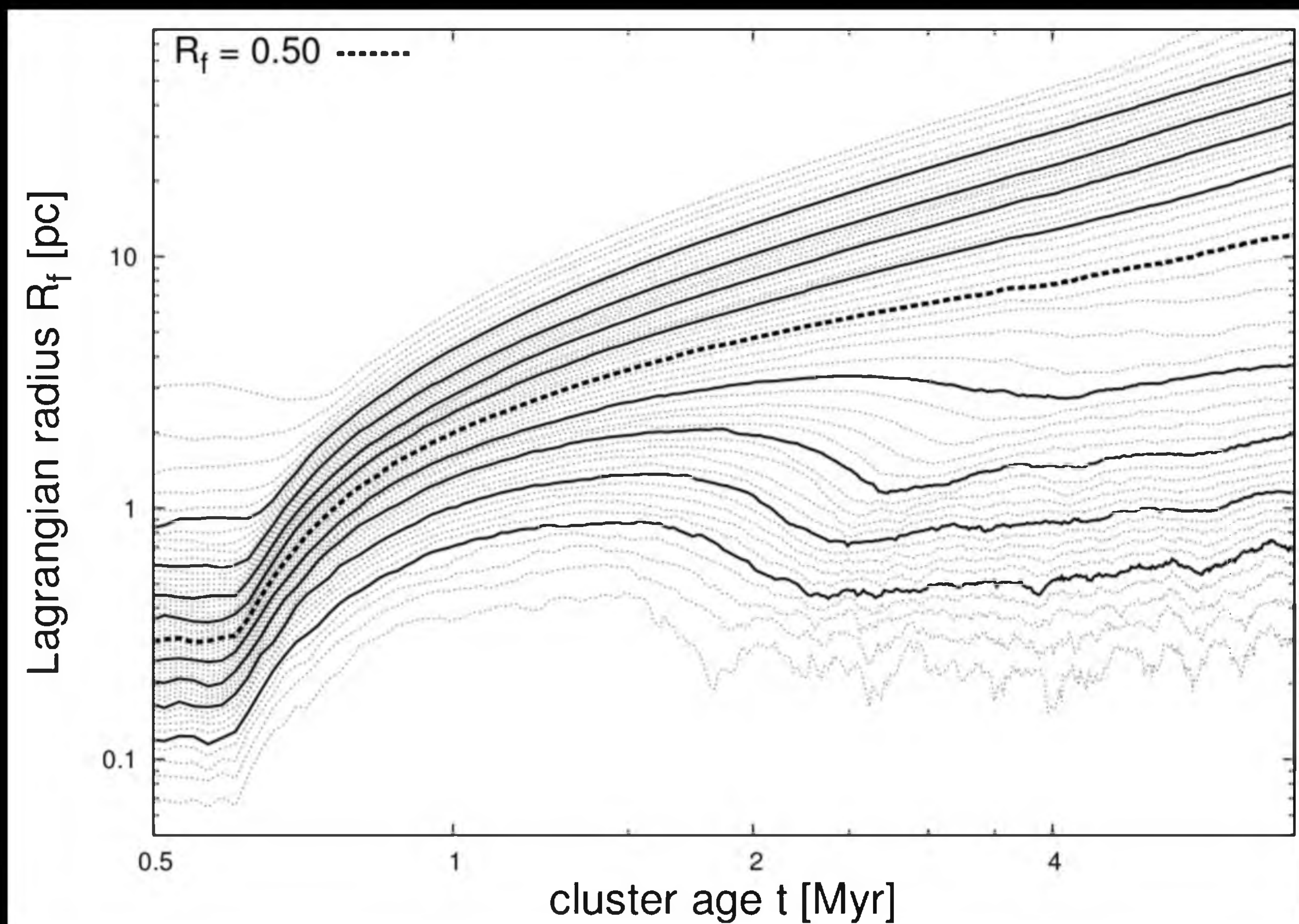


1. Higher velocity dispersions in inner regions at all stages

3. At ~1 Myr slightly negative velocity dispersions for stars streaming inwards

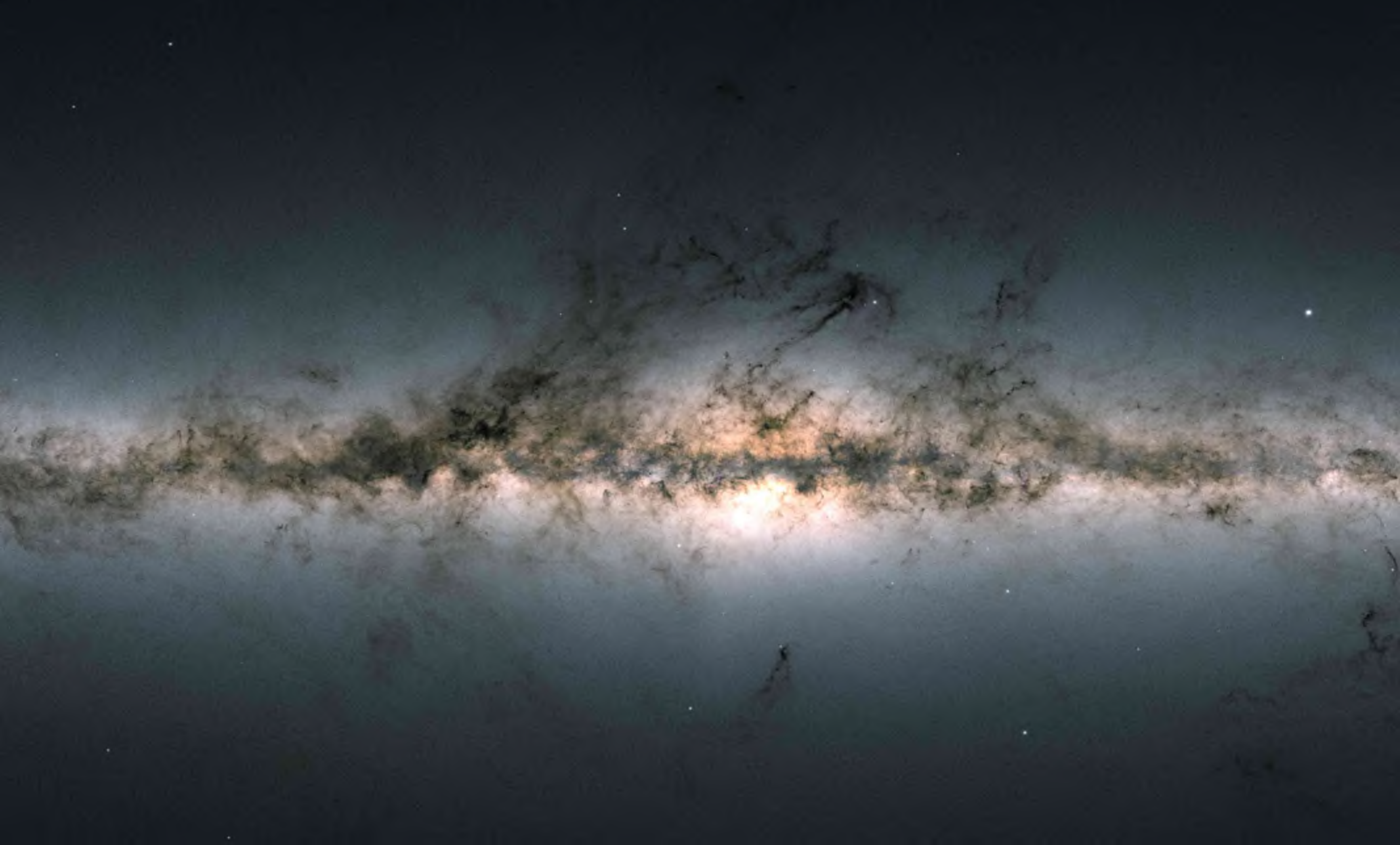
5. Slight positive outward velocity gradient at 3 Myr

Expectations for Cluster Expansion



Brinkmann et al. (2017)
$\varepsilon_{\rm SFE} = 0.33$

ESA's *Gaia* DR2!



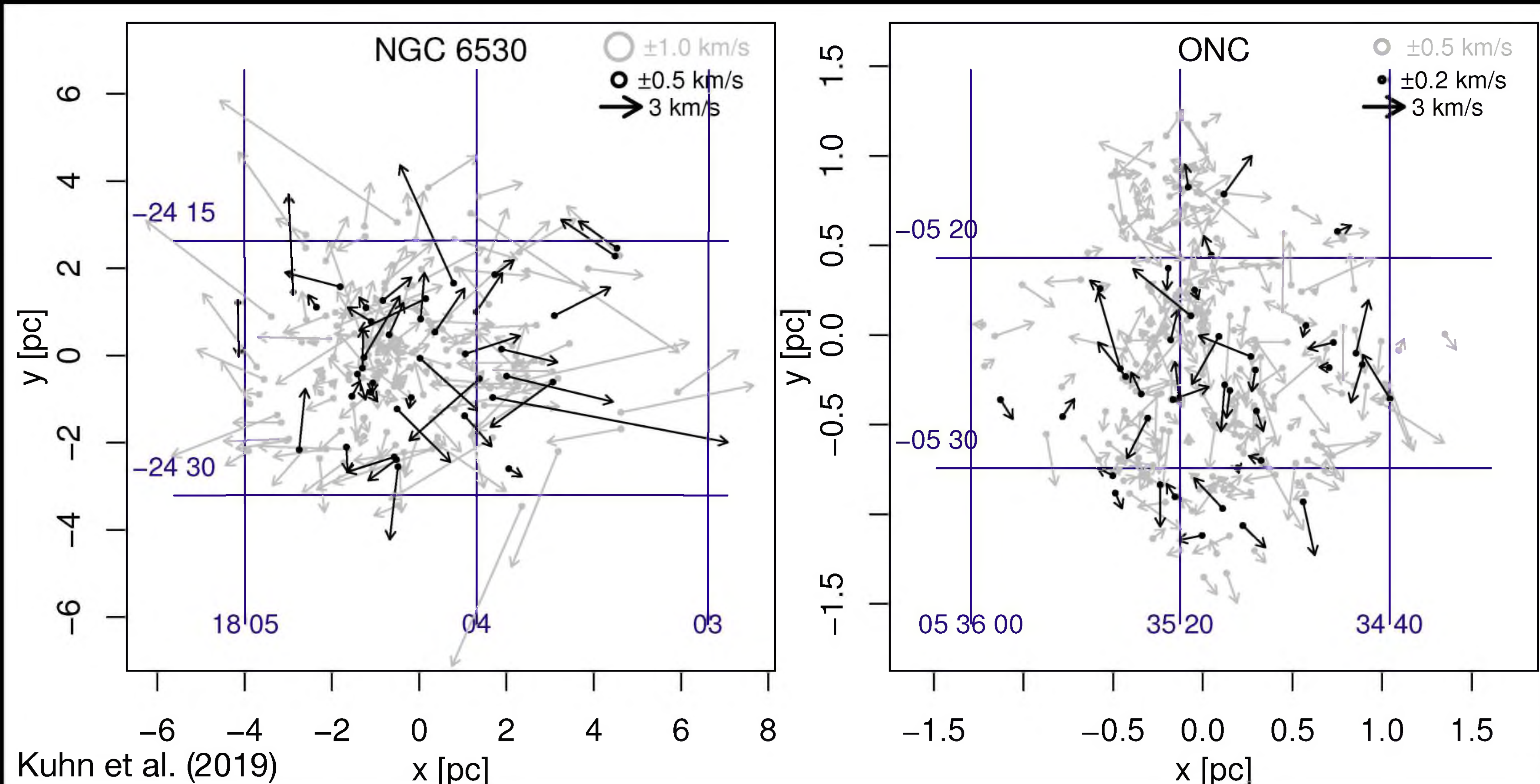
Are young star clusters expanding/contracting?

Is the ONC expanding?

Long history to this question.

- Jones & Walker (1988) suggested increasing radial velocity dispersion as a function of radius is evidence for expansion
- Fallon et al. (1977) argued for contraction, although results were later called into question
- Hillenbrand & Hartmann (1998) suggested that the velocity dispersion in the ONC is consistent with the cluster being in virial equilibrium

Projected Stellar Velocities from Gaia DR2

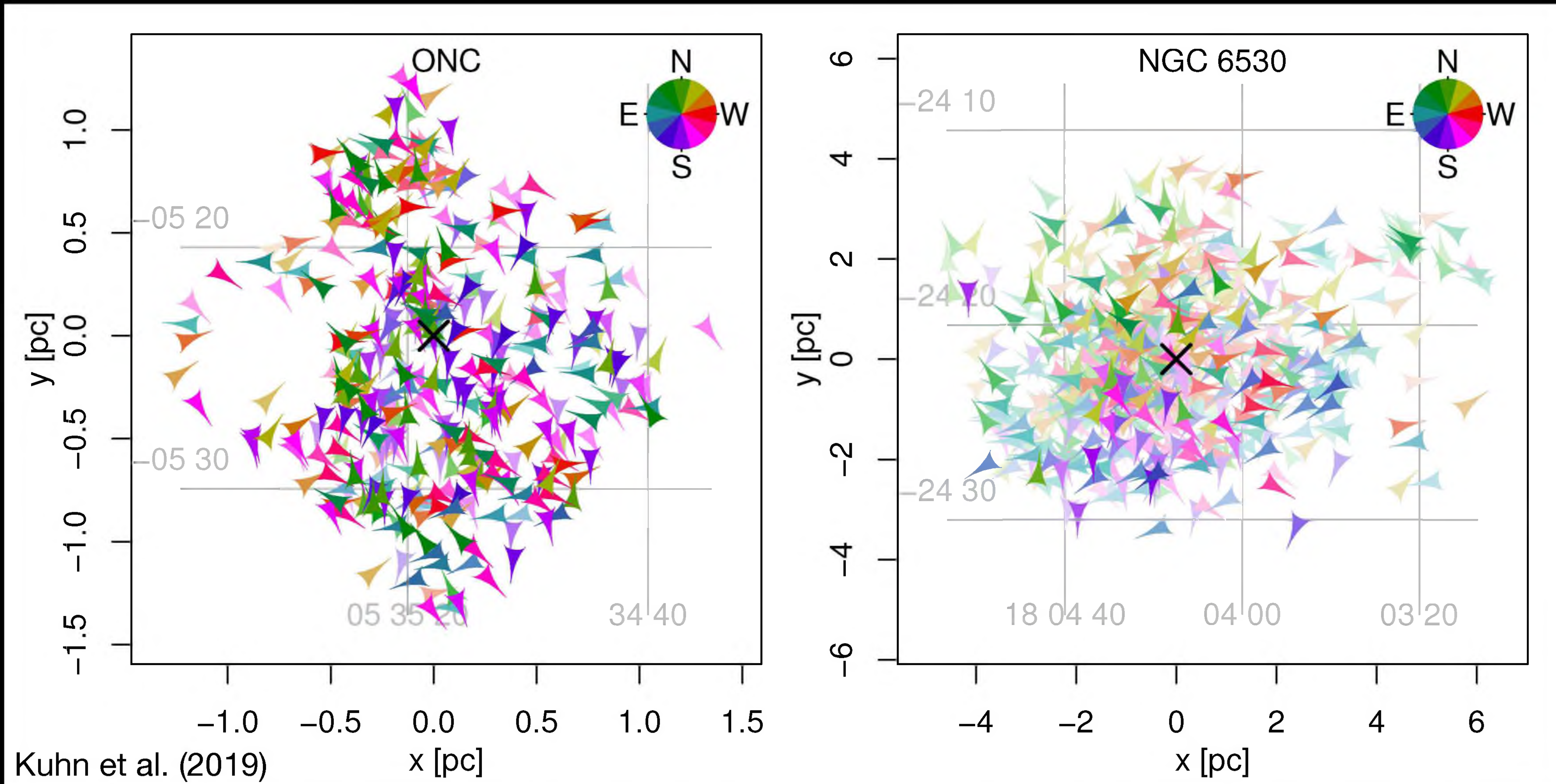


$$v_\alpha \approx -\kappa\left(\frac{\Delta\mu_{\alpha\star,\mathrm{obs}} - \Delta\mu_{\alpha\star,\mathrm{per}}}{\varpi_0}\right)$$

$$v_\delta \approx \kappa\left(\frac{\Delta\mu_{\delta,\mathrm{obs}} - \Delta\mu_{\delta,\mathrm{per}}}{\varpi_0}\right)$$

- Perspective expansion is a function of RV
- We based the RV for the center of mass of the cluster on previous spectroscopic studies

Color coded arrows by the direction of motion.

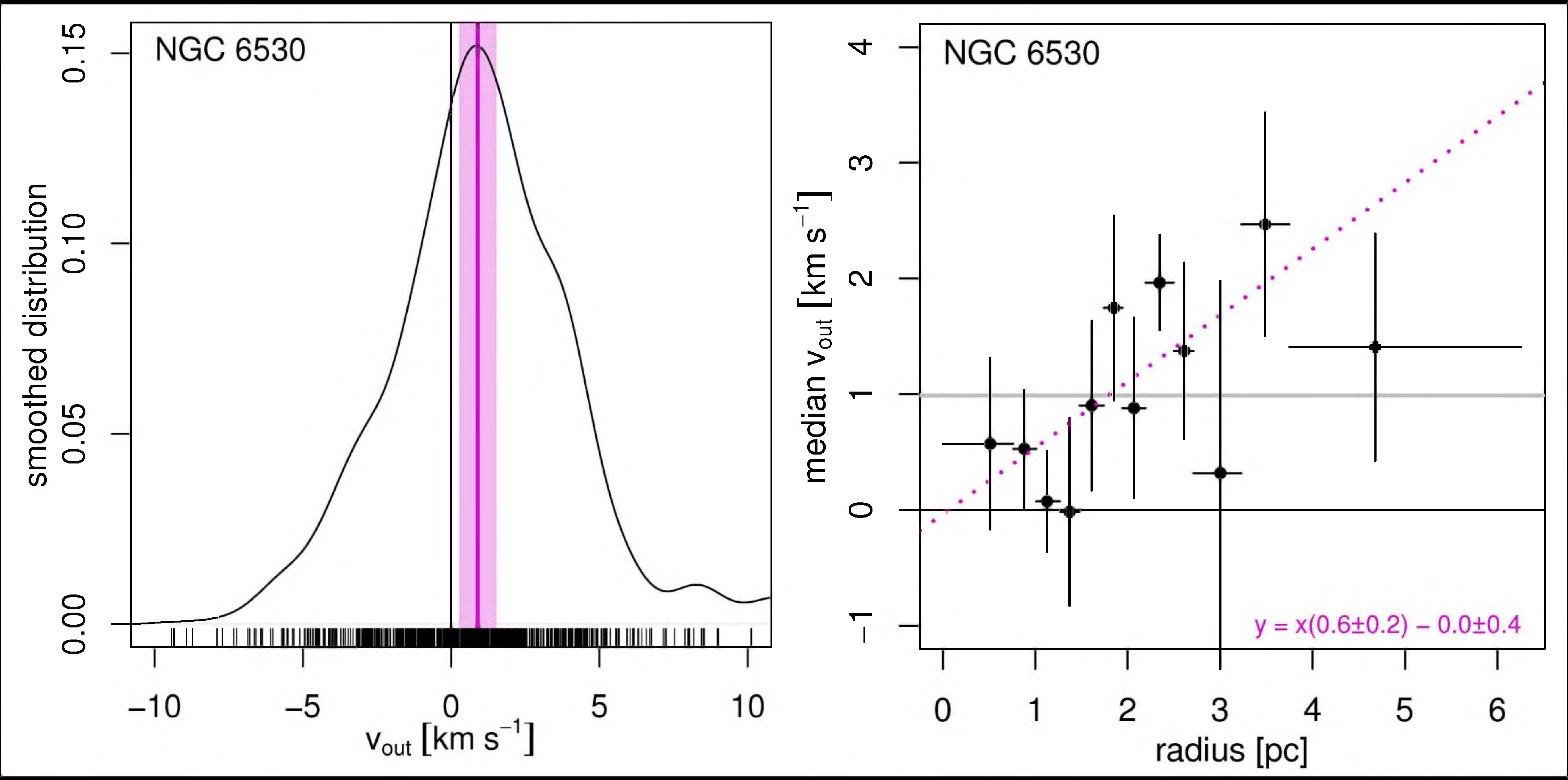


- Gradient patterns may become more apparent to the eye
- See also Wright & Mamajek et al. (2017)

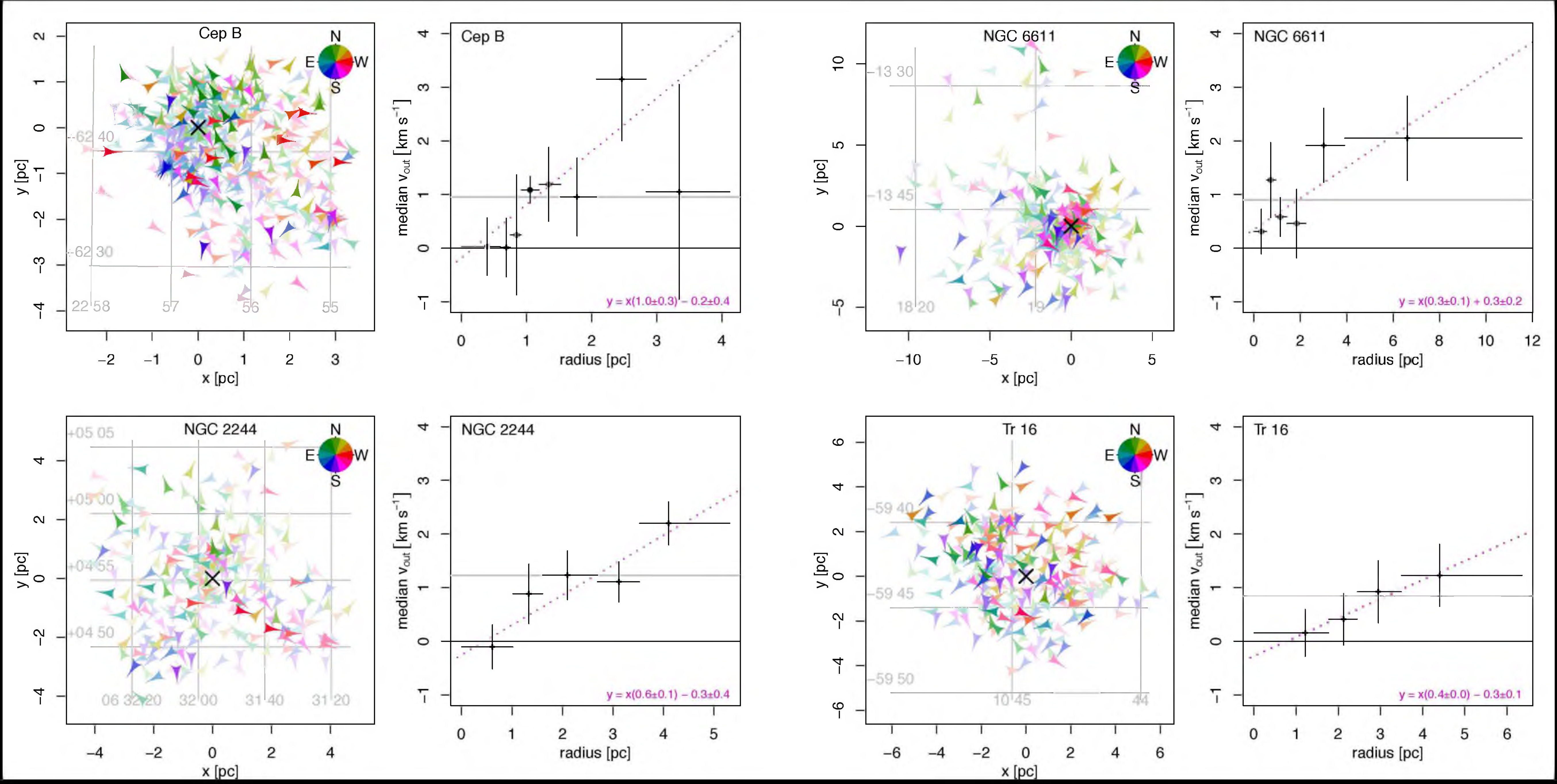
- No obvious pattern of expansion in the ONC
- Possible more N–S motion than E–W

- Some indication of a color variations with area in the cluster

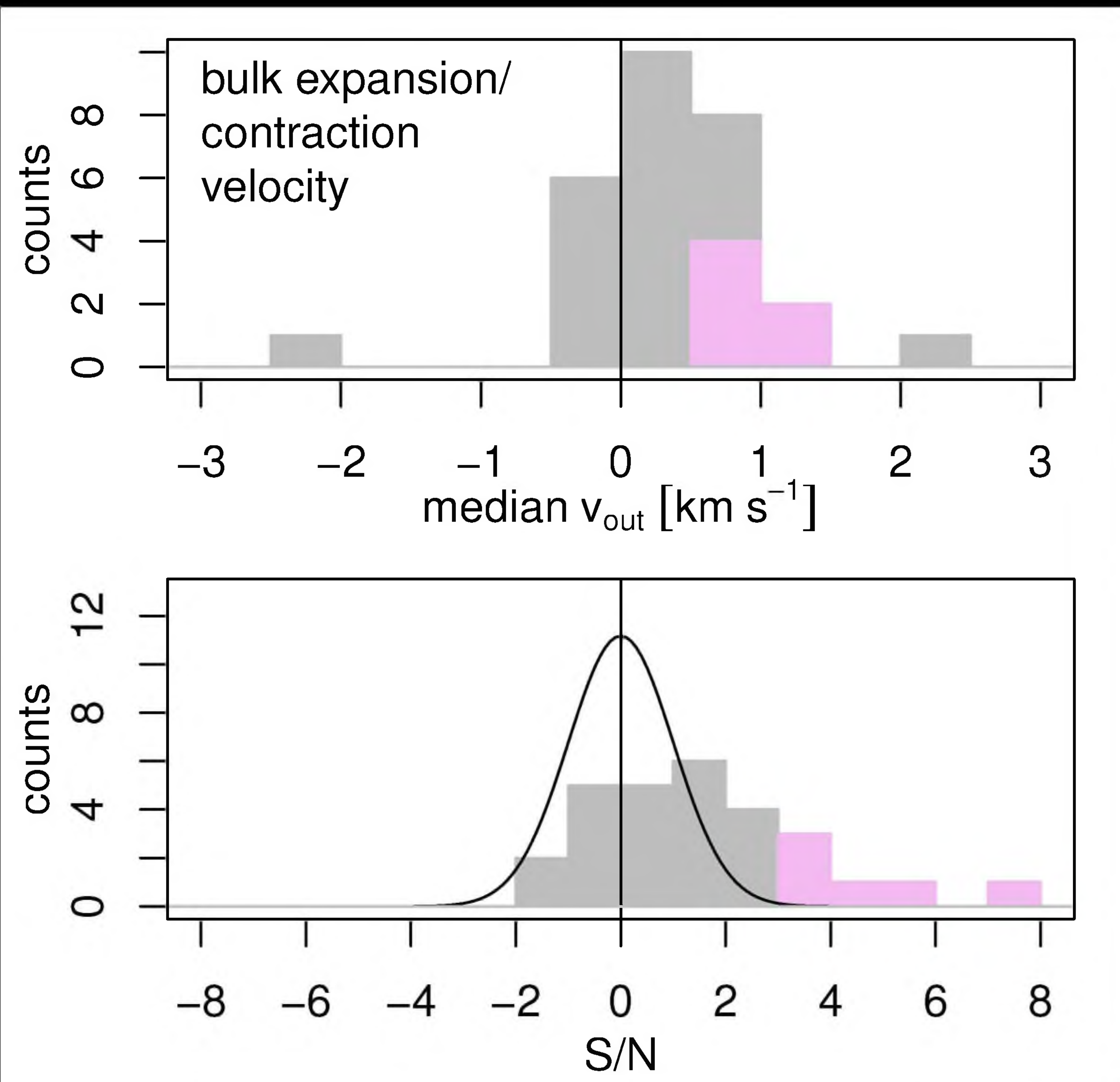
Outward-directed velocity component of stars in NGC 6530



Examples of other systems with signs of expansion



Is Expansion Typical?



- Out of a sample of 28 systems 21 have positive expansion velocities
  - 5 cases of strongly significant expansion
  - Precisely 0 expansion/ contraction is a set of measure zero
  - Bayesian analysis suggests that the effect of measurement error is to reduce the apparent effect of expansion
  - ***At least*** 75% of systems are in a state of expanding
- Our sample is dominated by systems where gas expulsion is either partial or complete
  - Does not constrain embedded systems

Is the ONC expanding?

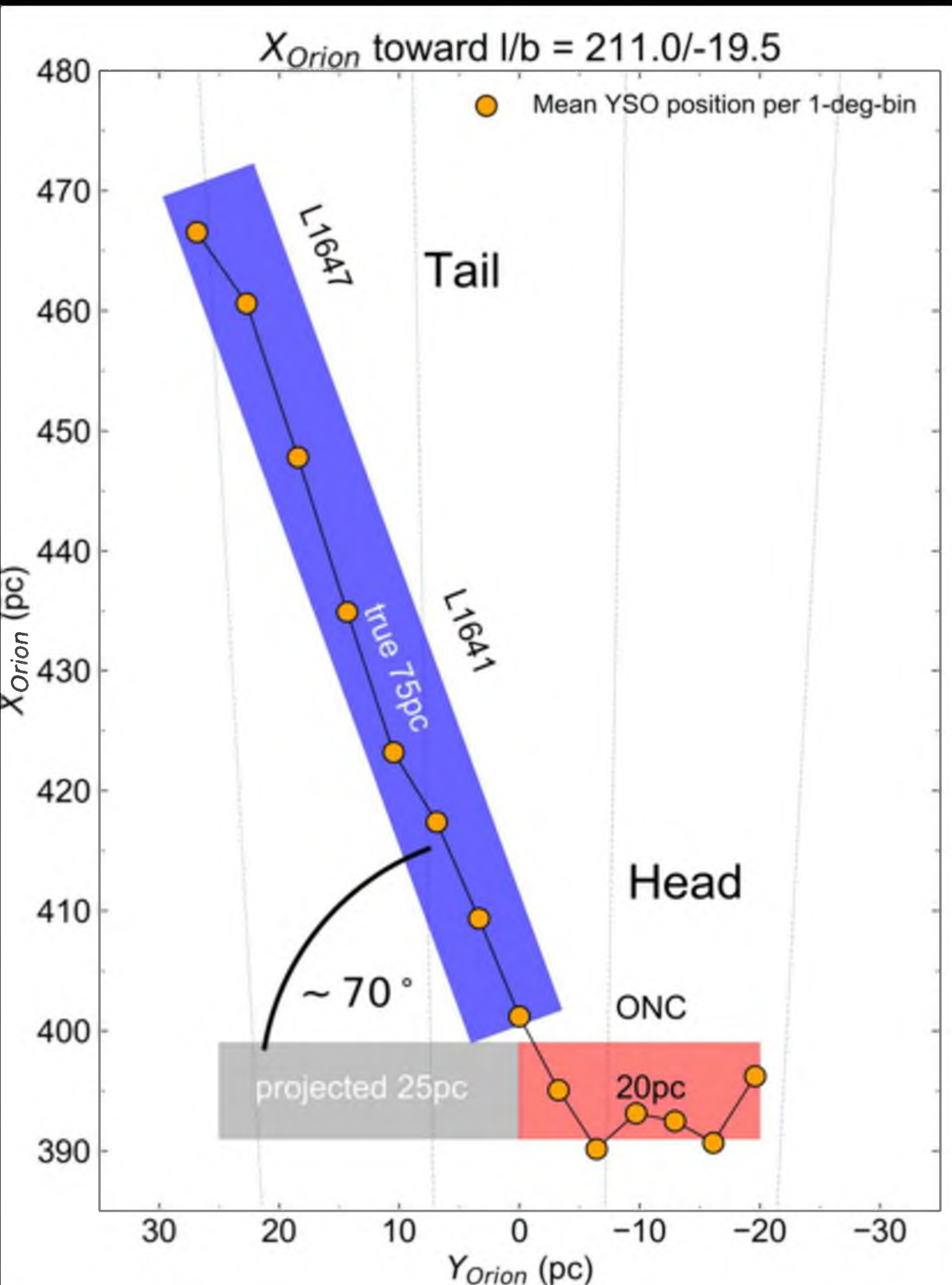
Maybe, but not rapidly.

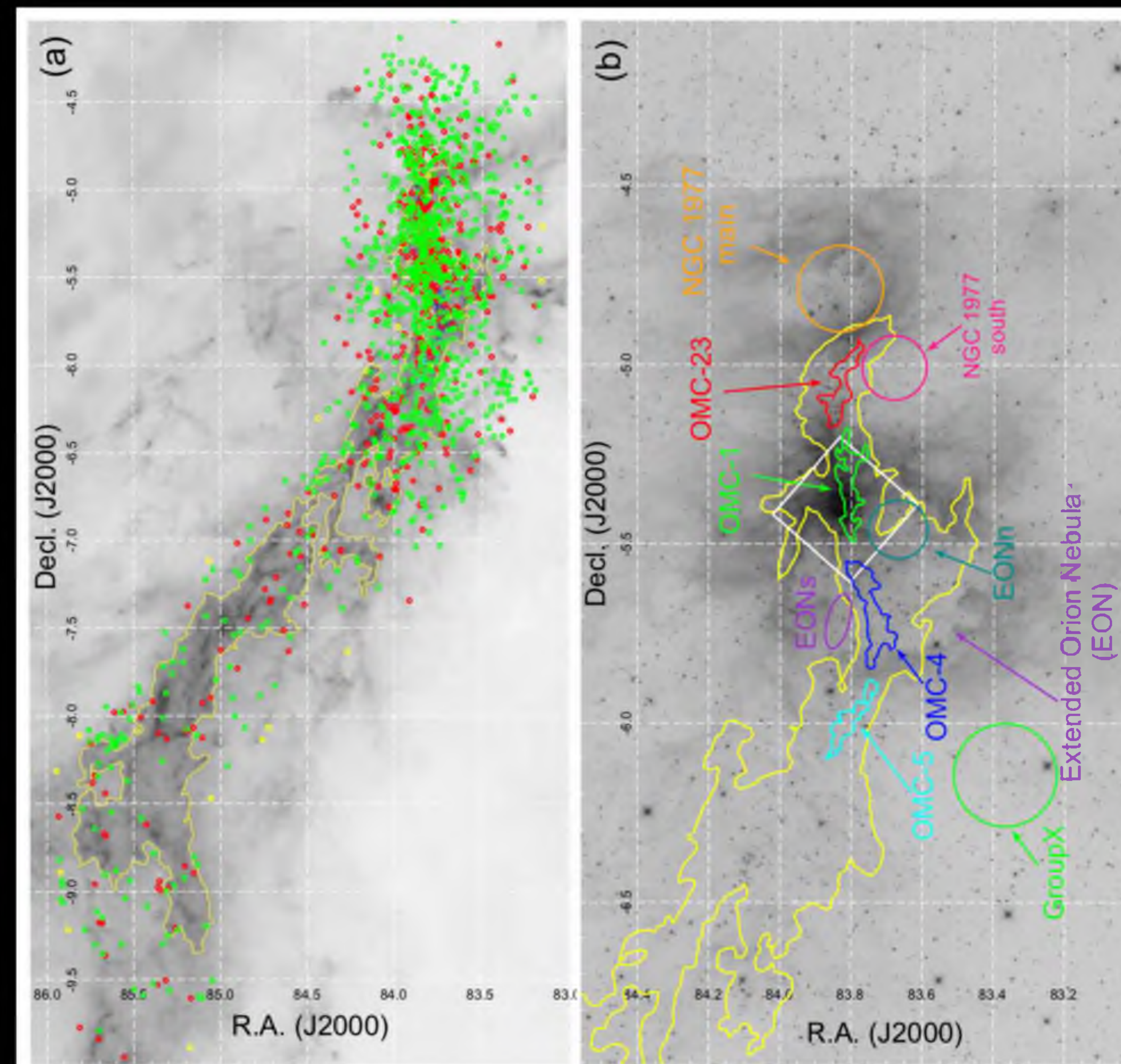
median *Gaia* v_{out} = 0.4±0.2 km/s

(~2σ result)

Kim et al. (2019) find similar velocity dispersions
but no evidence of expansion in proper motions
from NIR HST+Keck data

Global view of Orion A





Großschedl et al. (2018)

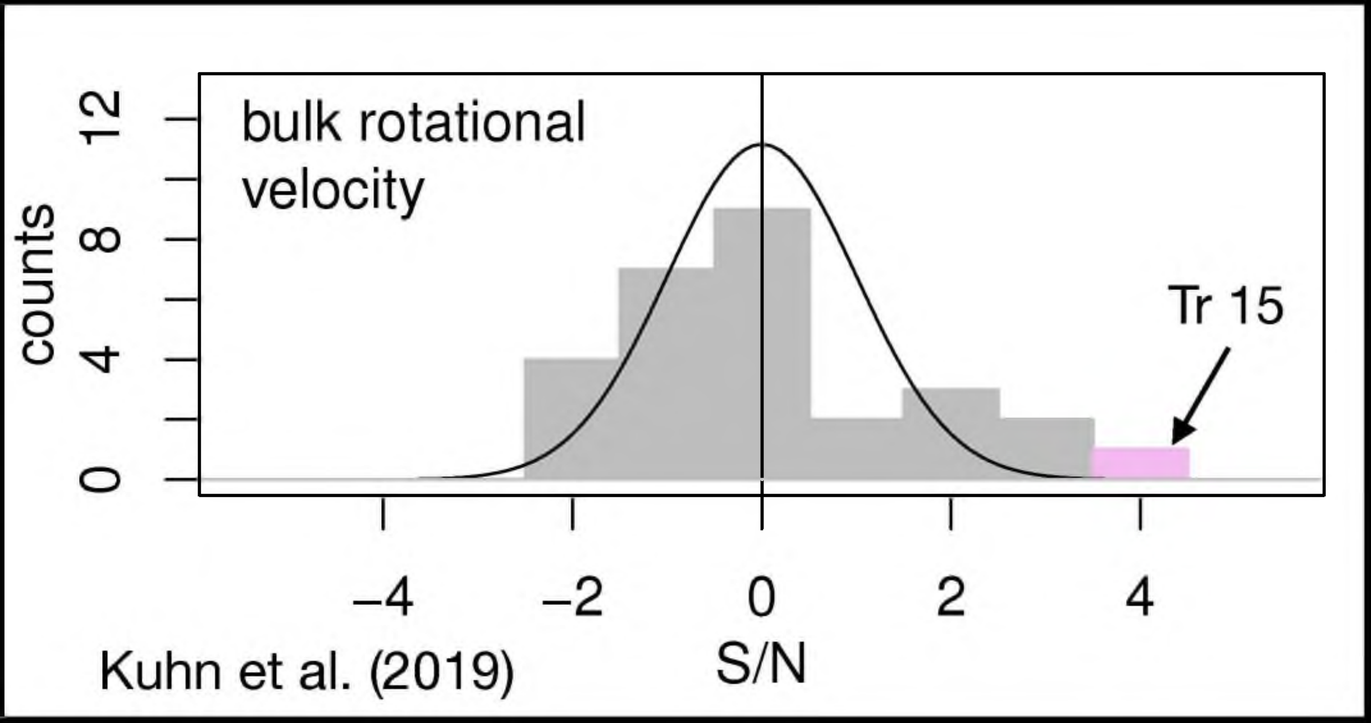
- Orion A is longer along the line of sight

Getman et al. (2019)

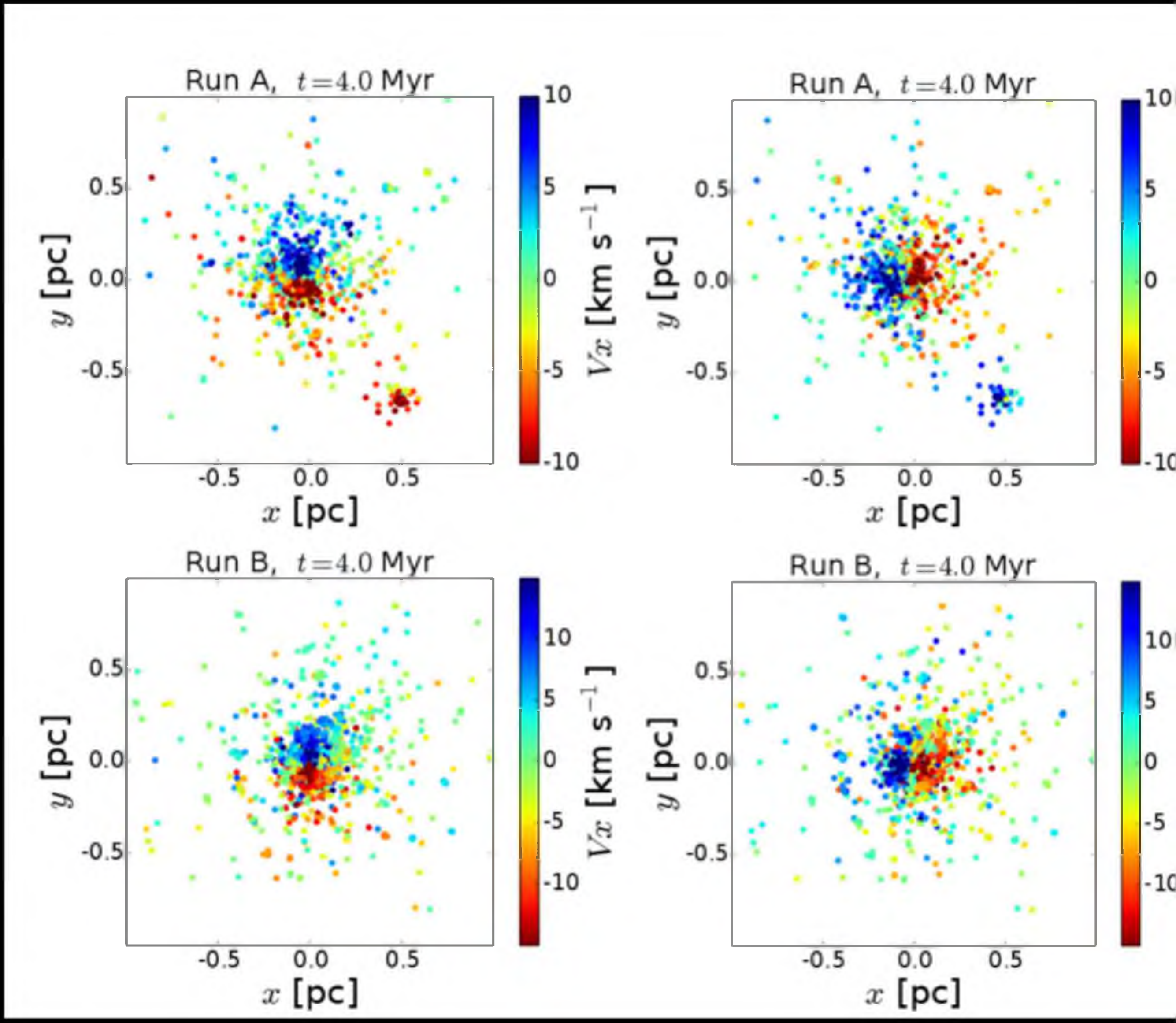
- Gaia parallaxes + gas kinematics suggests contraction along the length of the cloud in the head
- Gaia proper motions shows stars drifting away perpendicular to the cloud
- Pecular velocities of NGC 1977 (3 km/s), Group X, EON groups

Rotation of Stellar Groups

Same sort of analysis as for expansion, using the azimuthal velocity component instead.



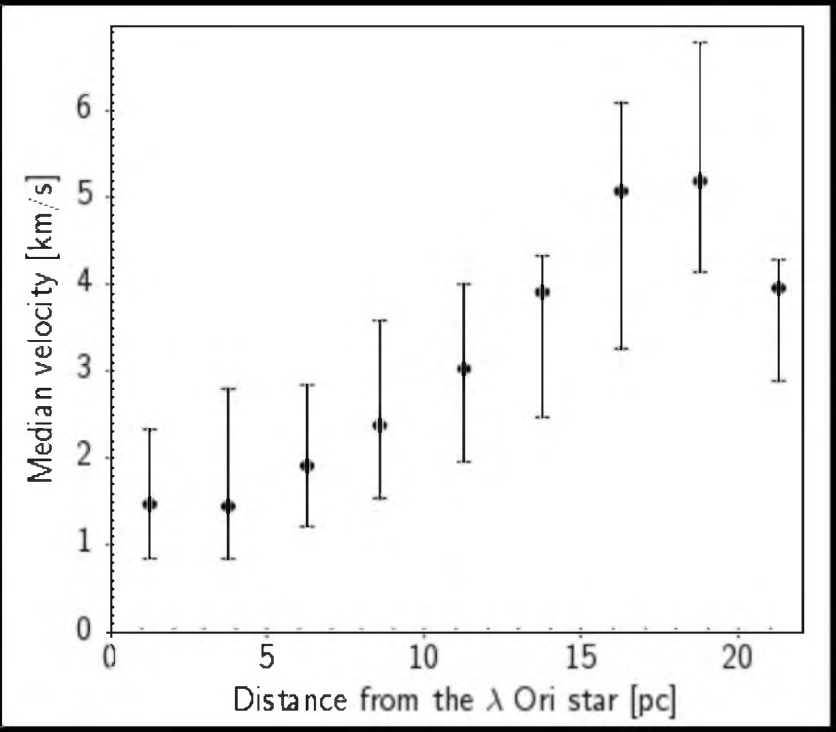
Only sensitive to rotations that produce velocities greater than ~0.3 km/s.



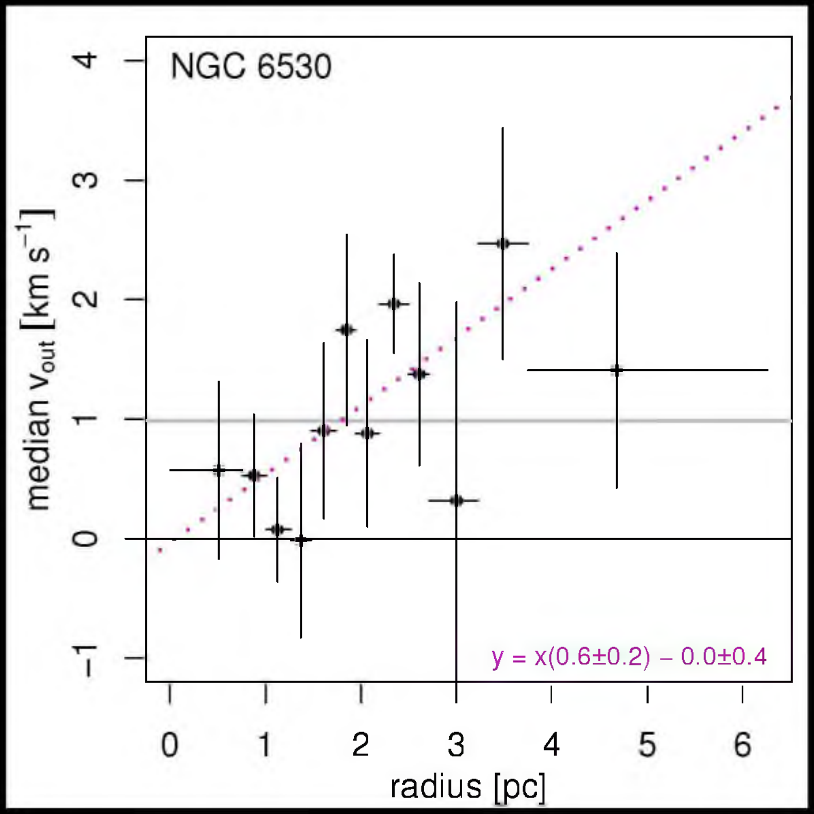
Cluster rotation is an expected consequence of cluster assembly through hierarchical mergers (e.g. Mapelli et al. 2017)

Homologous Expansion

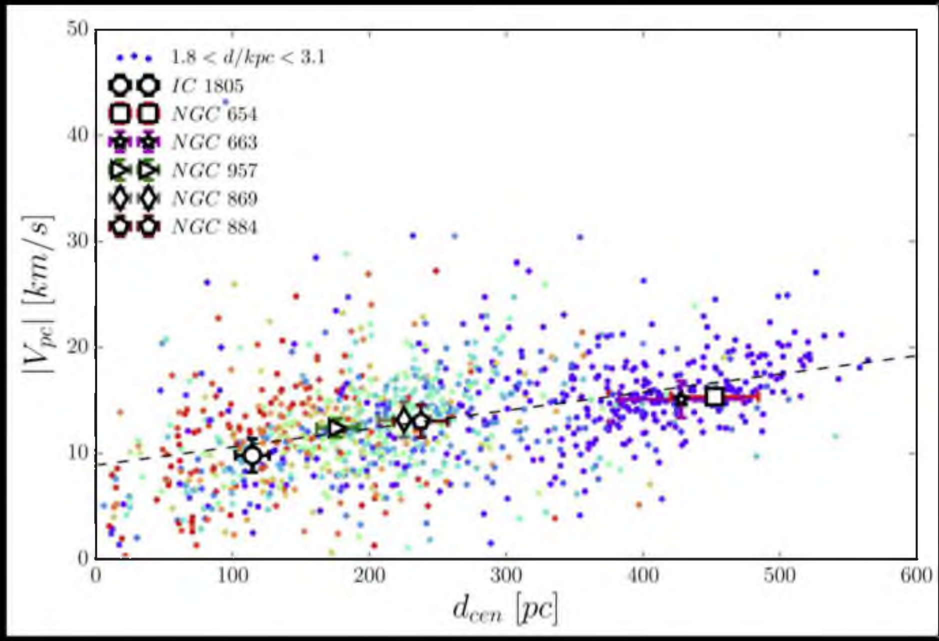
$v \propto d$, where d is the distance to the center of the system



Zamora-Avilés et al. (2019) λ Ori based on Kounkel et al. (2018)data



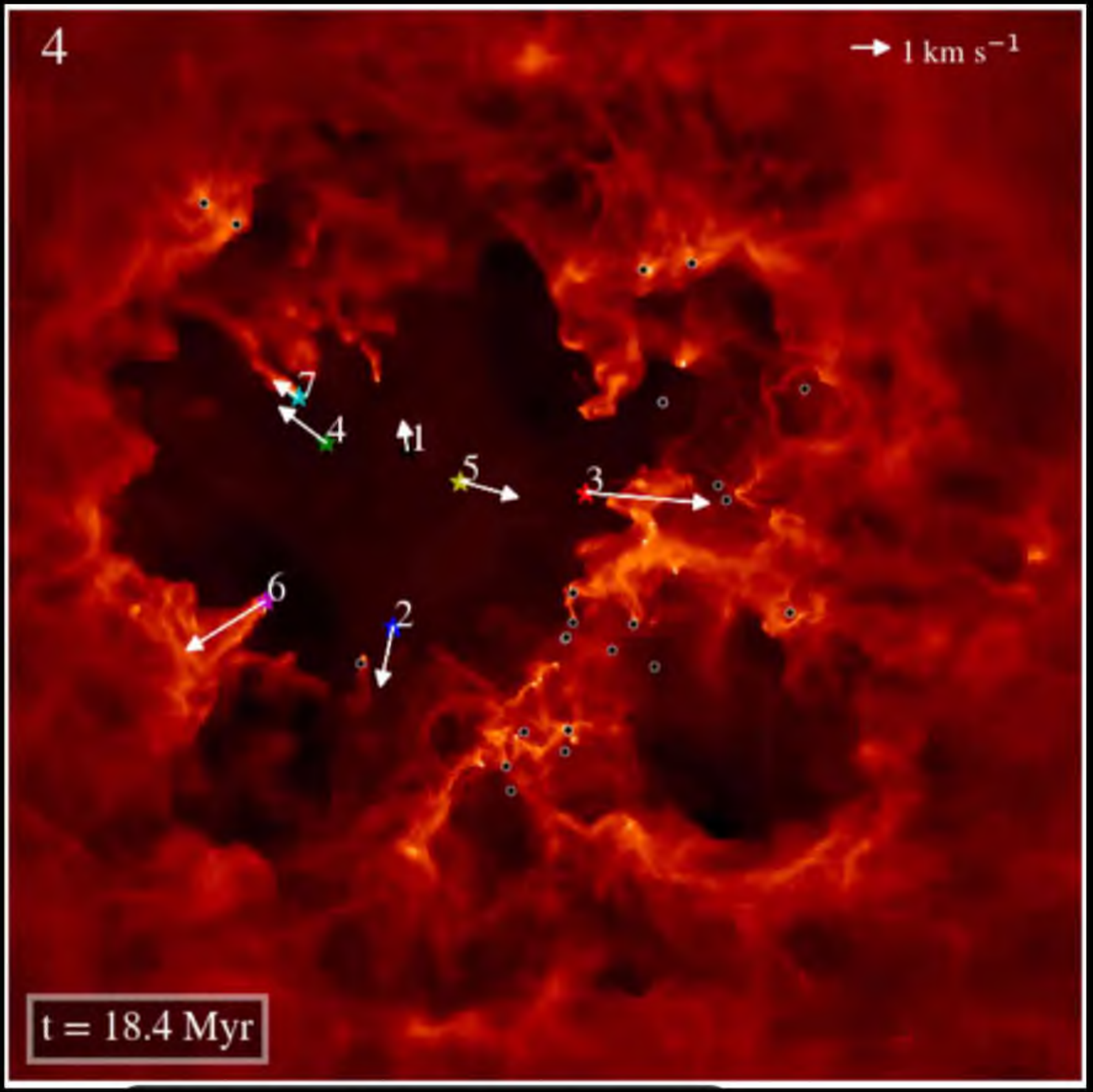
Kuhn et al. (2019)



Román-Zúñiga et al. (2019) Young stellar groups in the Perseus Arm

Explanations for Homologous Expansion

- Stars that are faster travel further
- Tidal disruption
- Triggered star formation

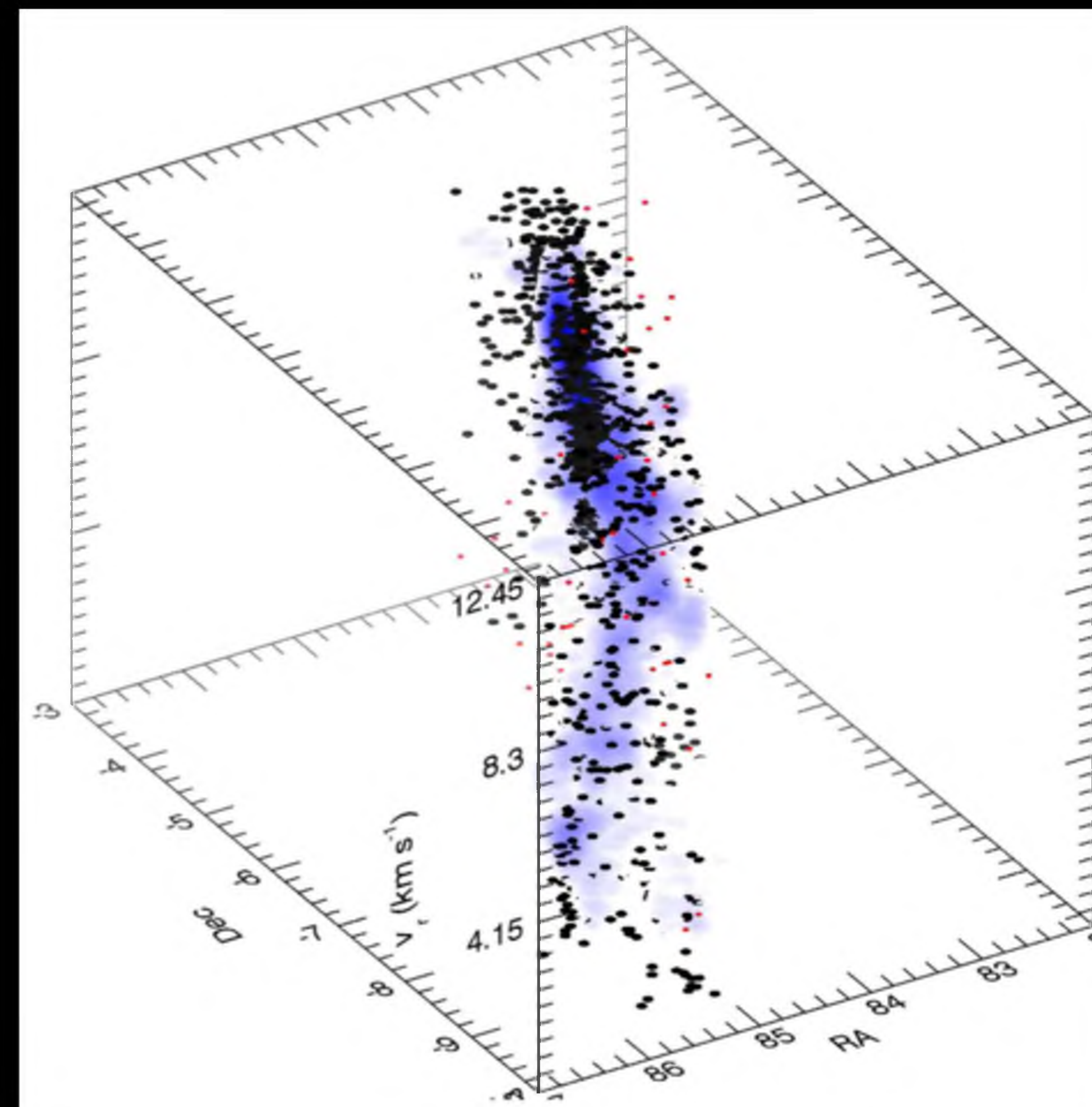


Zamora-Avilés et al. (2019) propose a scenario in which feedback displaces the cloud mass from the stars

Velocity dispersions in star-forming regions

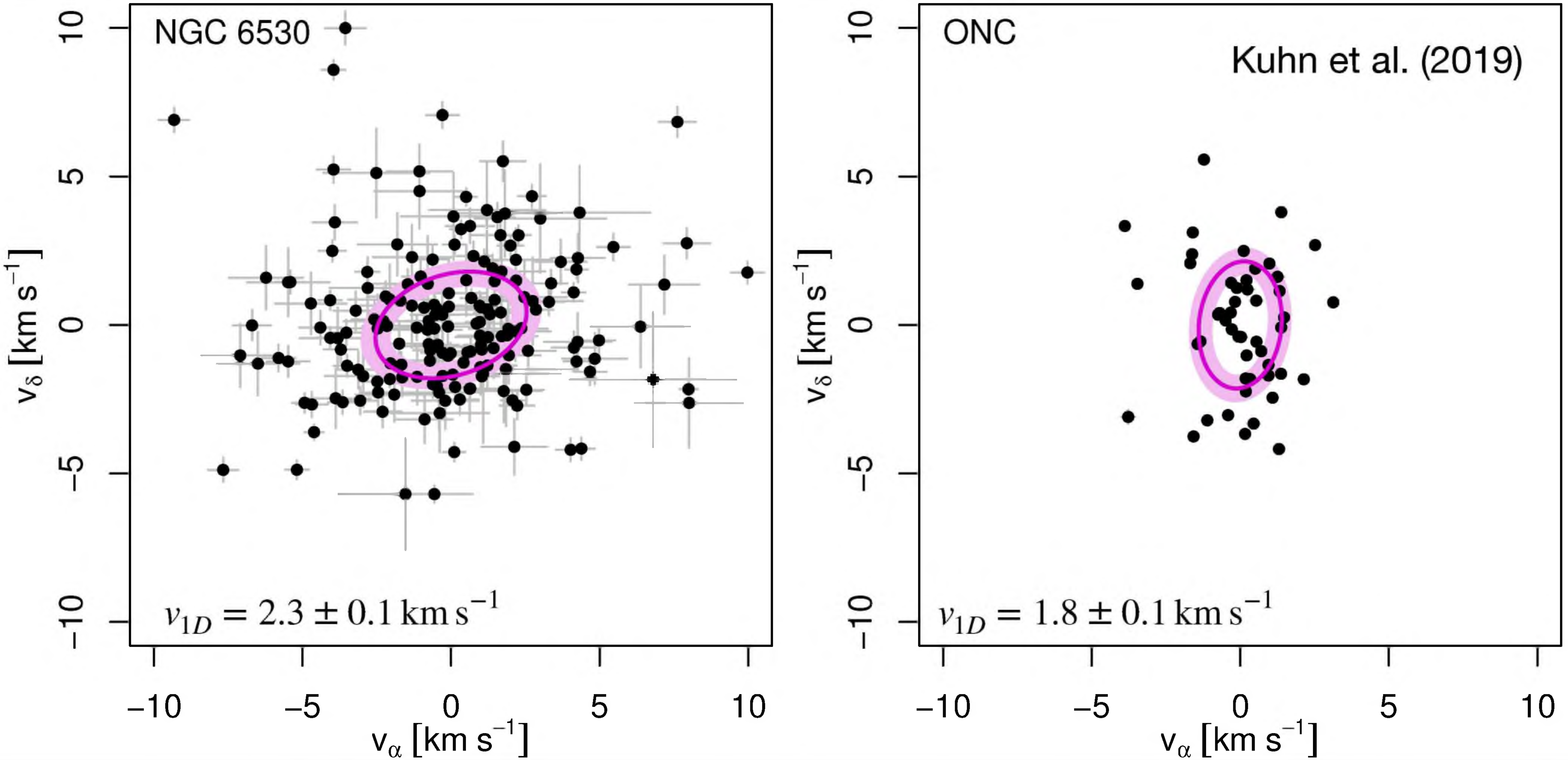
Select Pre-*Gaia* Measurements

- ONC
  - ~2.3 km/s (Jones & Walker 1988)
  - More recent pre-Gaia measurements: 3.1 km/s (Furesz et al. 2008); ~2.5 km/s (Kounkel et al. 2016); 1.7 km/s (da Rio et al. 2017)
- Low-mass clusters
  - Chameleon I – 1.0 km/s (Sacco et al. 2017)
  - NGC 1333 – 0.9 km/s (Foster et al. 2015)
- Massive clusters
  - Wd 1 – 2.1 km/s (Cottaar et al. 2012)
  - R136 – 4-5 km/s (Hénault-Brunet et al. 2012)
- OB Associations
  - Cyg OB2 – 9-13 km/s (Wright et al. 2013)



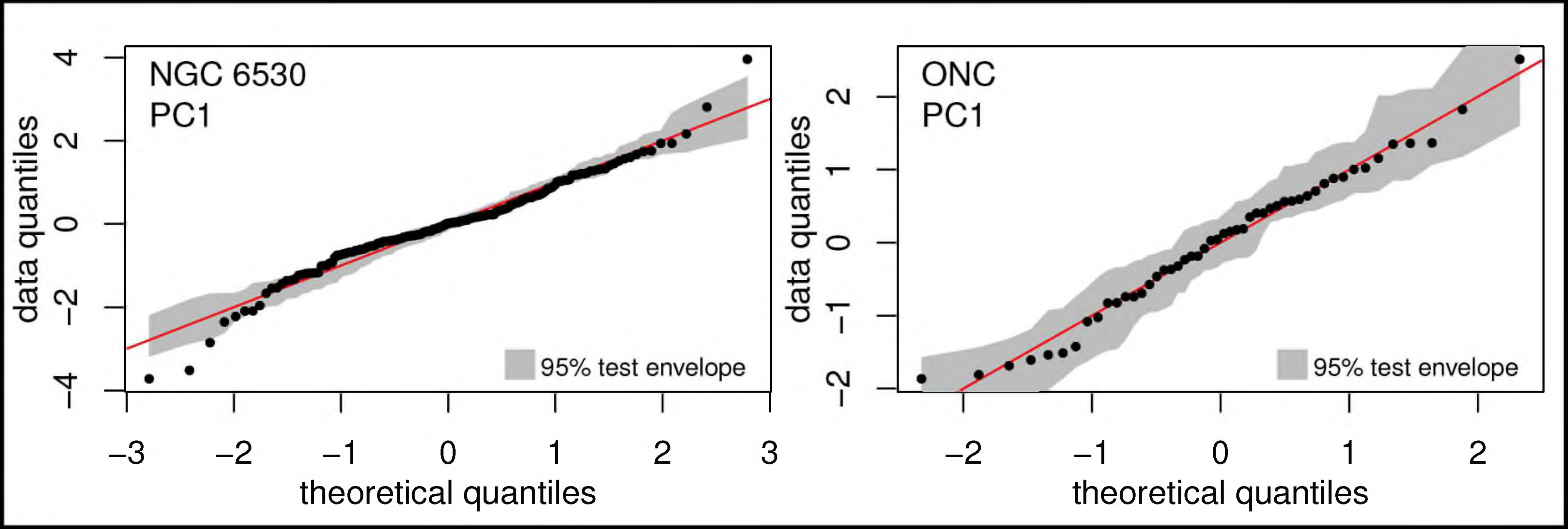
Velocity gradient in Orion A from da Rio et al. (2107)

Velocity Dispersions with Gaia DR2



Velocity Dispersions

In an isothermal cluster, stars would follow a Maxwell–Boltzmann (Gaussian) velocity distribution



$$Q_{\mathrm{data},i} = \frac{v_{\mathrm{obs},i} - \mu}{\sqrt{\sigma_v^2 + \sigma_{\mathrm{err},i}^2}}$$

$$Q_{\mathrm{theo},i} = \sqrt{2}\,\mathrm{erf}^{-1}\left(2(r_i - 0.5)/n - 1\right)$$

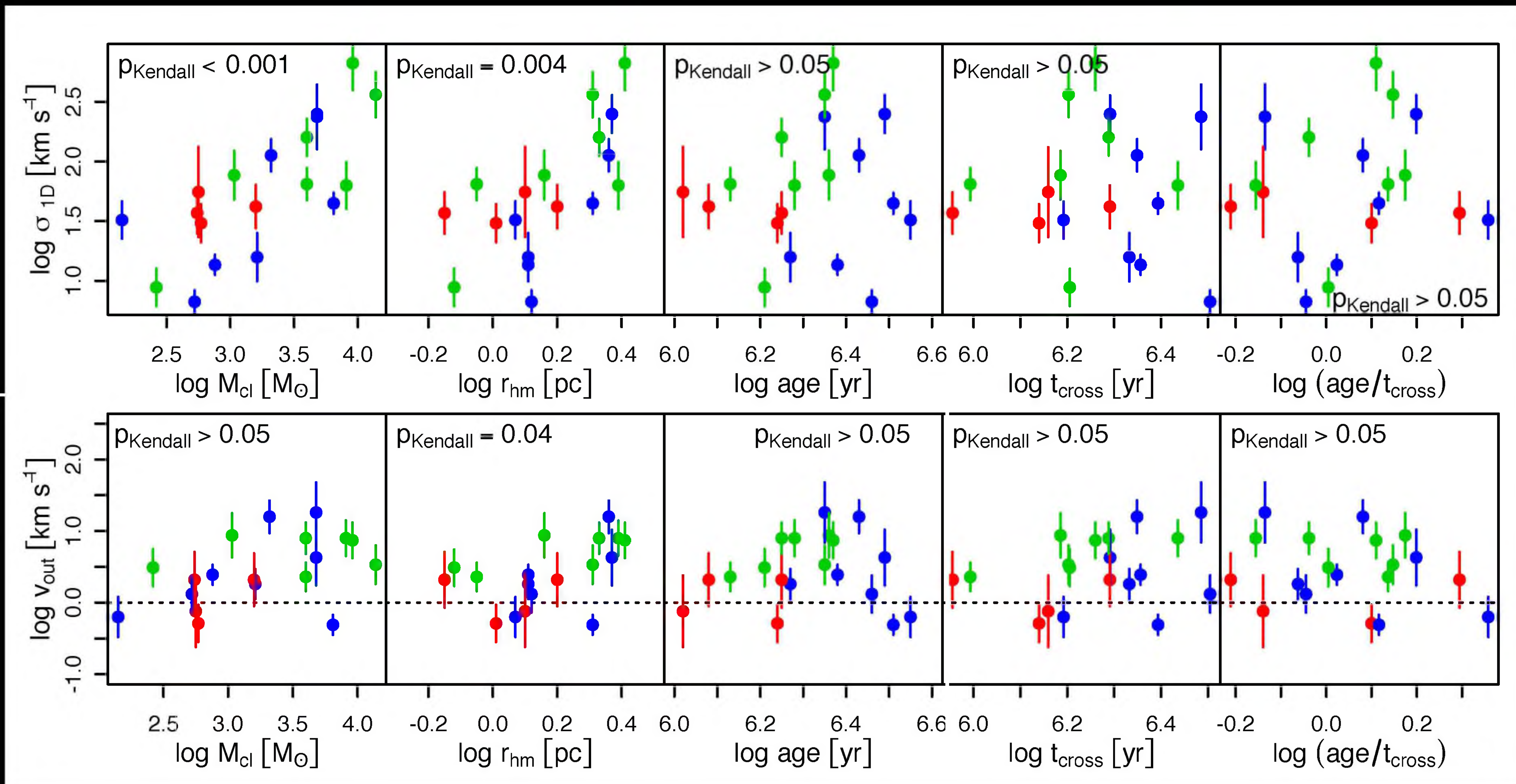
- Gaussian distribution does relatively well at describing velocity dispersions
- Some systems have slight excesses of high velocity stars (unclear if real or an effect of errors/contaminants)

Relations to other physical properties:

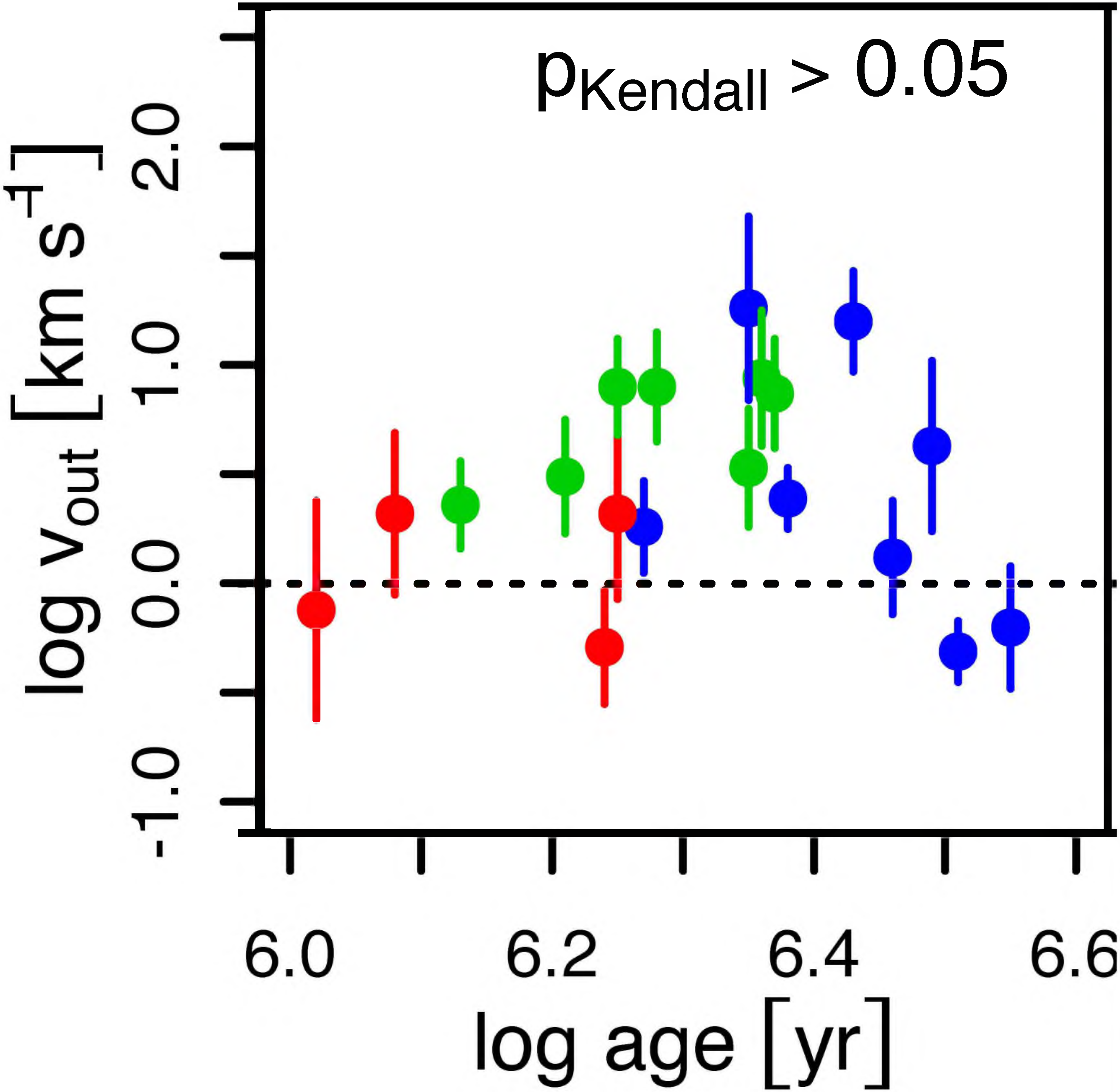
Embedded
Partially Embedded
Revealed

velocity dispersion

expansion velocity



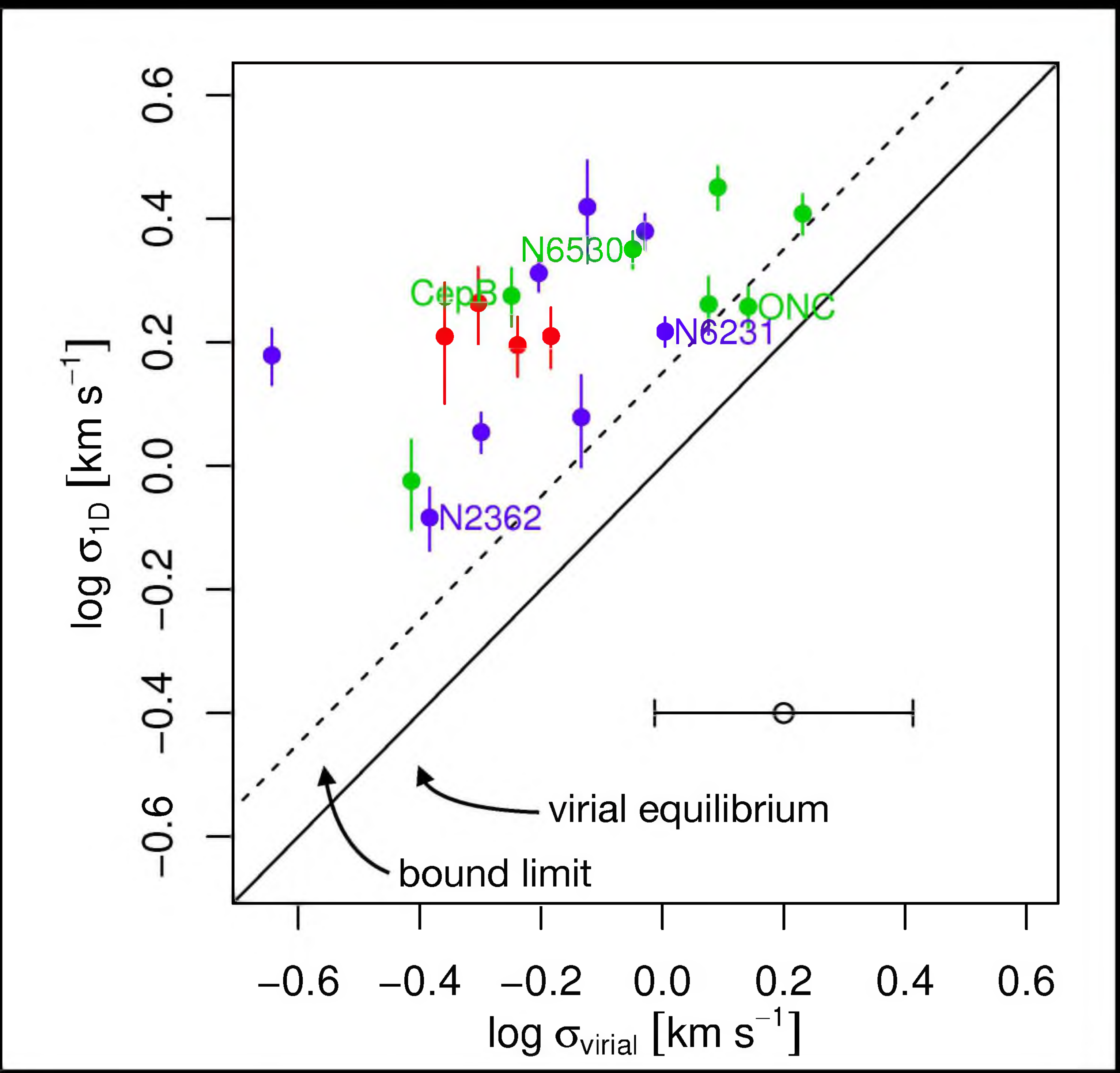
cluster mass | **half mass radius** | **median stellar age** | **crossing timescale** | **age/t_{cross}**



Embedded
Partially Embedded
Revealed

- Stellar populations in regions with regions with partial or complete gas expulsion tend to be older
- Embedded clusters tend not to be expanding

Dynamical State

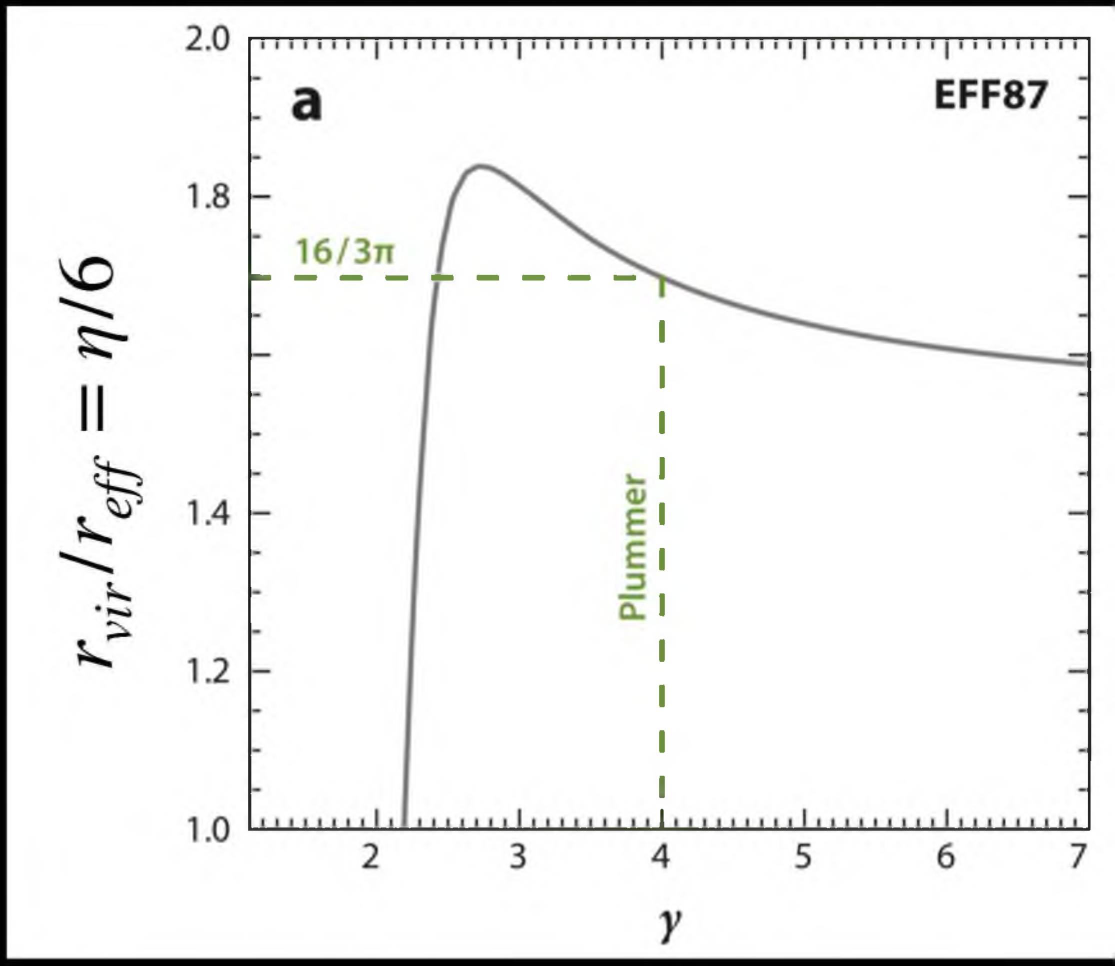


Embedded

Partially Embedded

Revealed

$$\sigma_{virial} = \left(\frac{G M_{cl}}{\eta \, r_{hm}} \right)^{1/2}$$

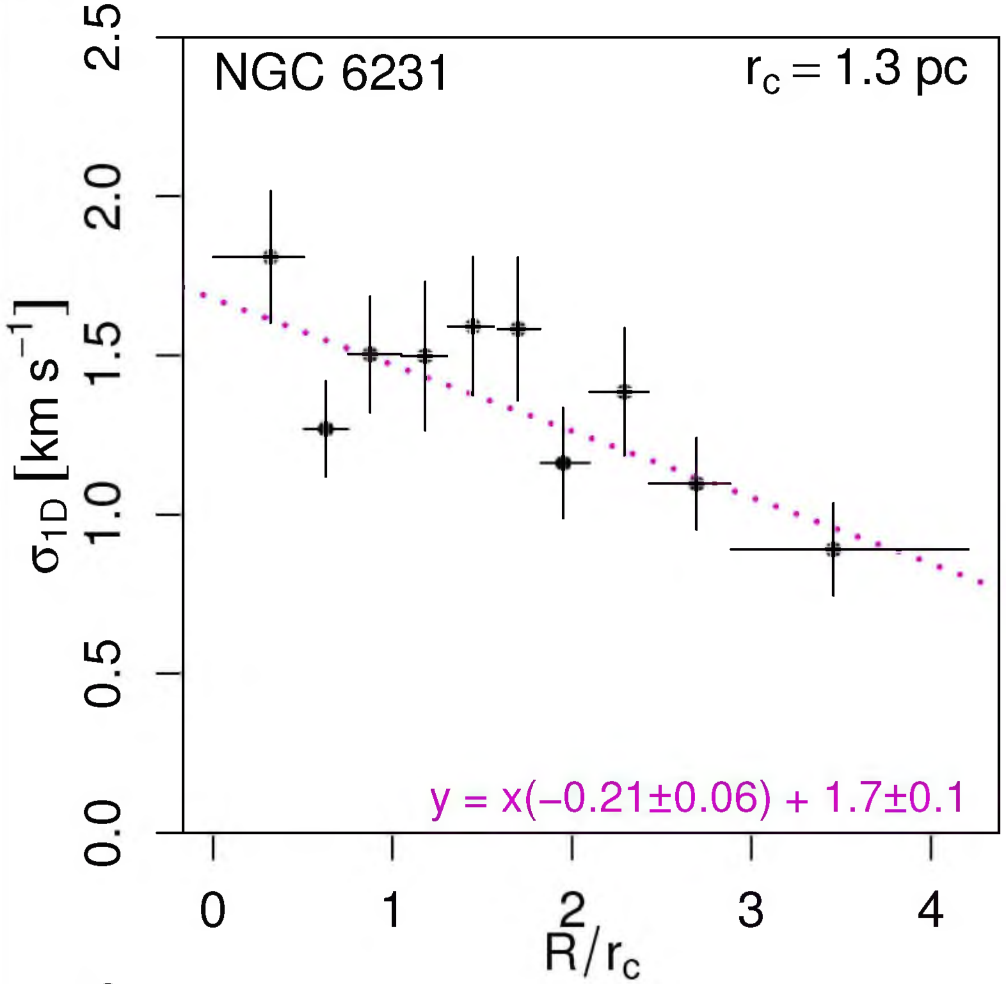


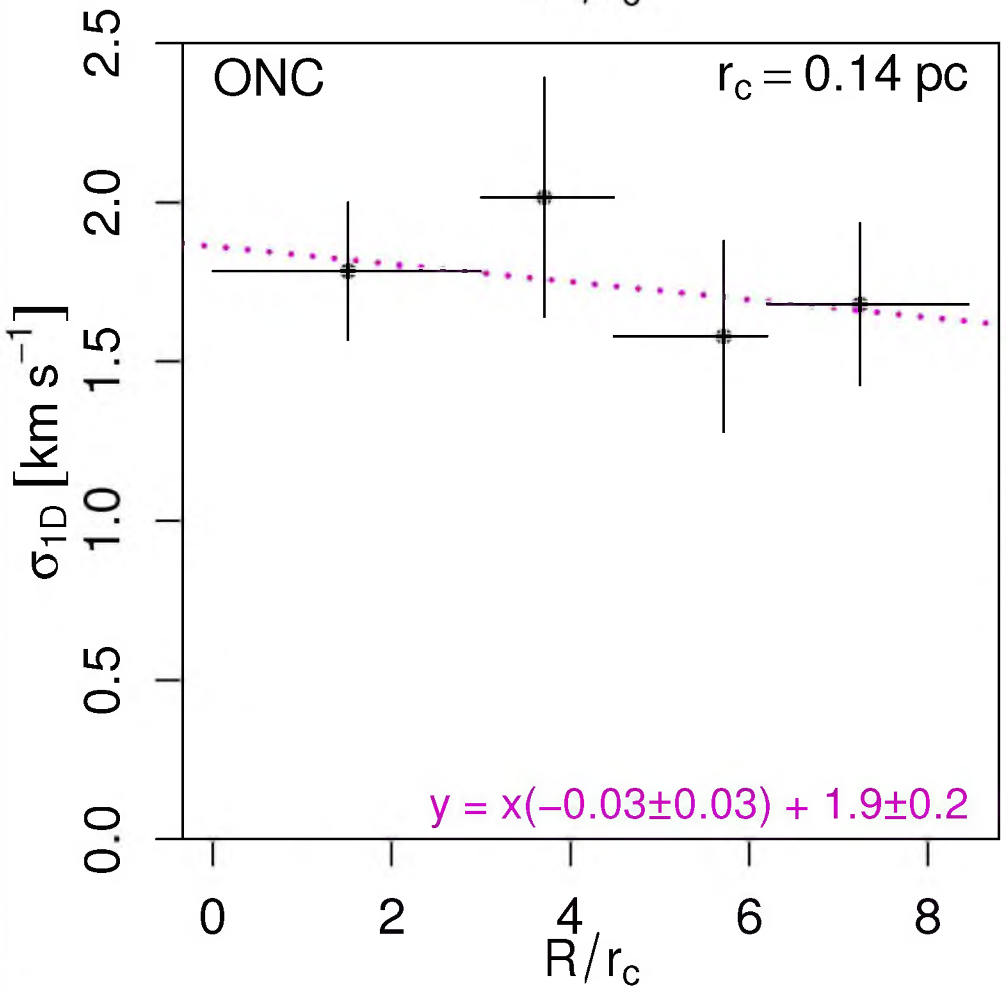
Kuhn et al. (2010) assume $\eta = 10$

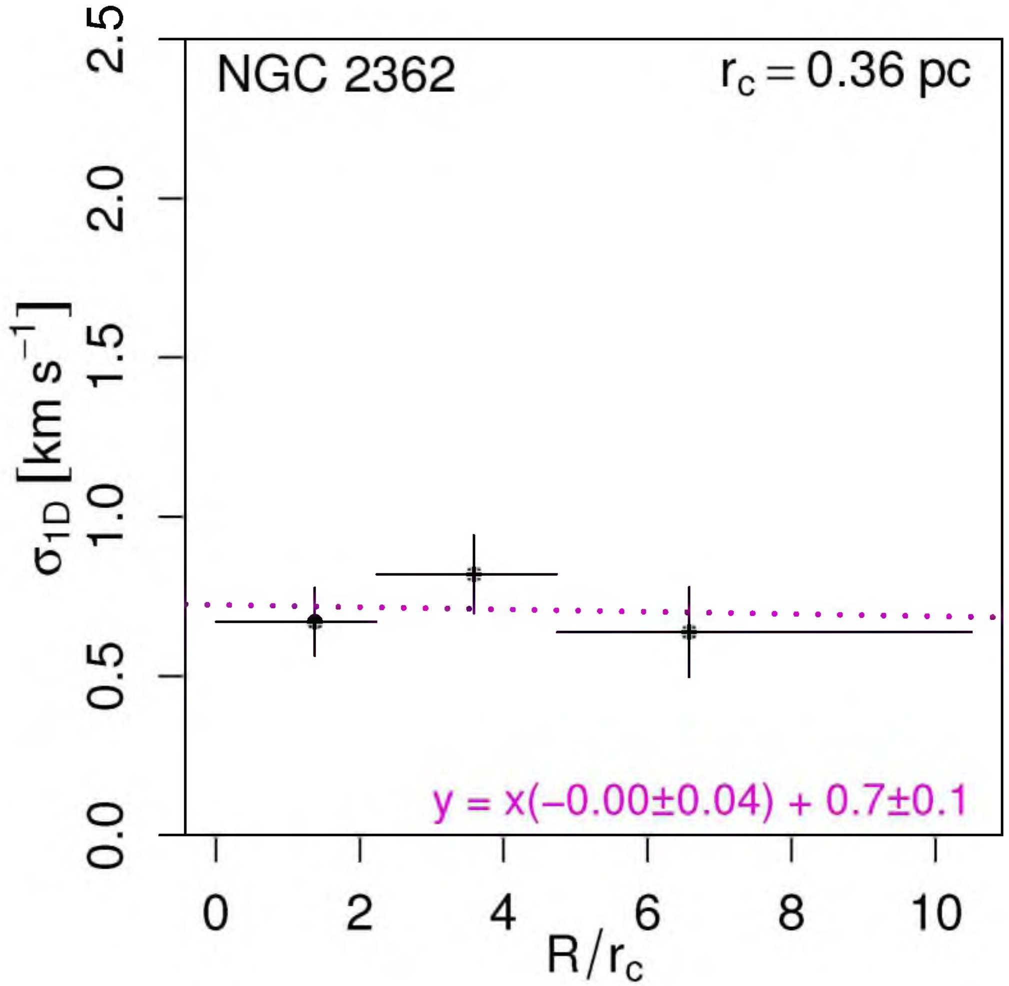
Portegies Zwart et al. (2010)

Three systems show are most likely to be gravitationally bound.

Velocity dispersions are either approximately constant (isothermal) or declining with radius (i.e. Plummer sphere or lowered isothermal sphere)



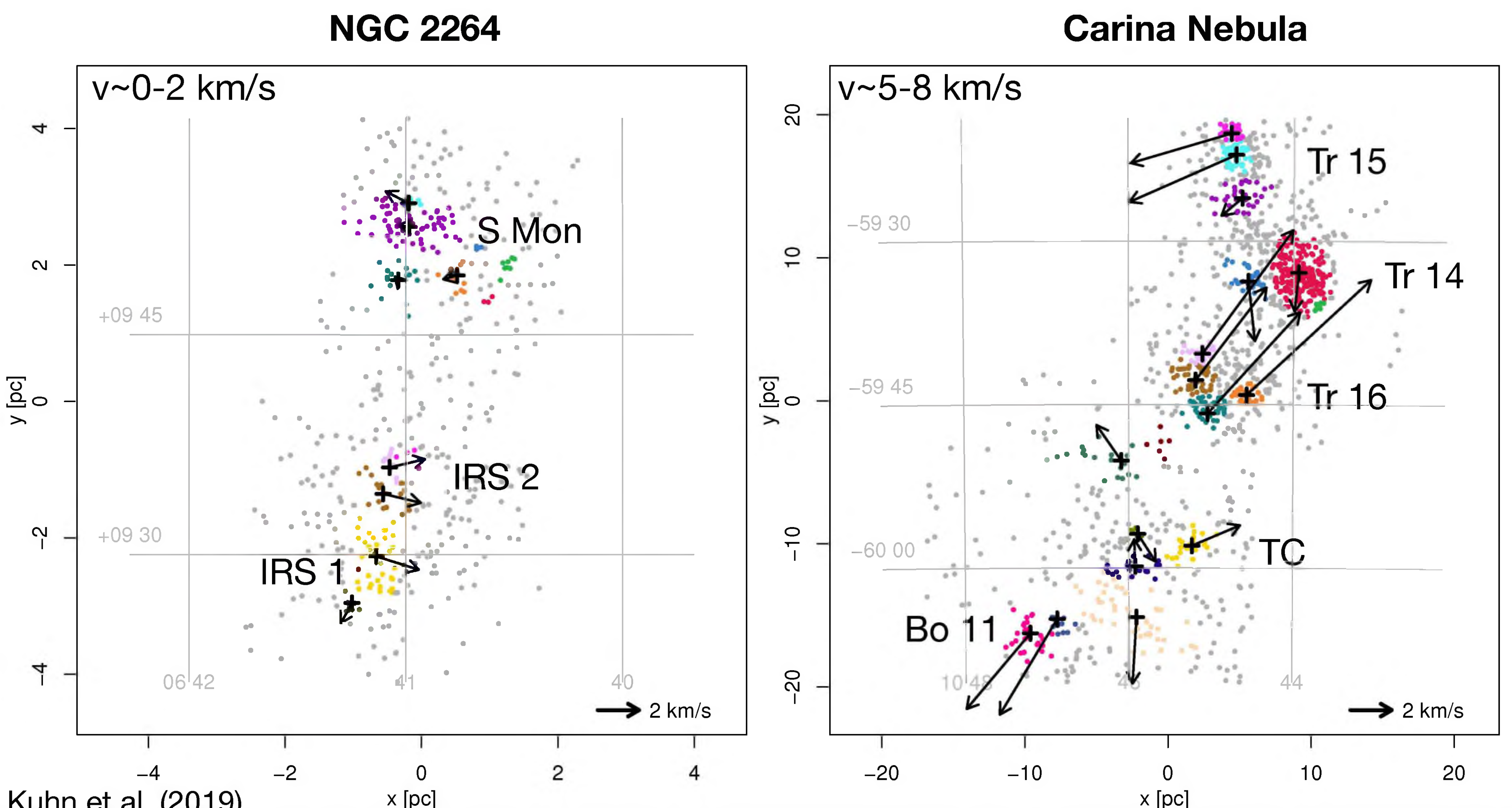




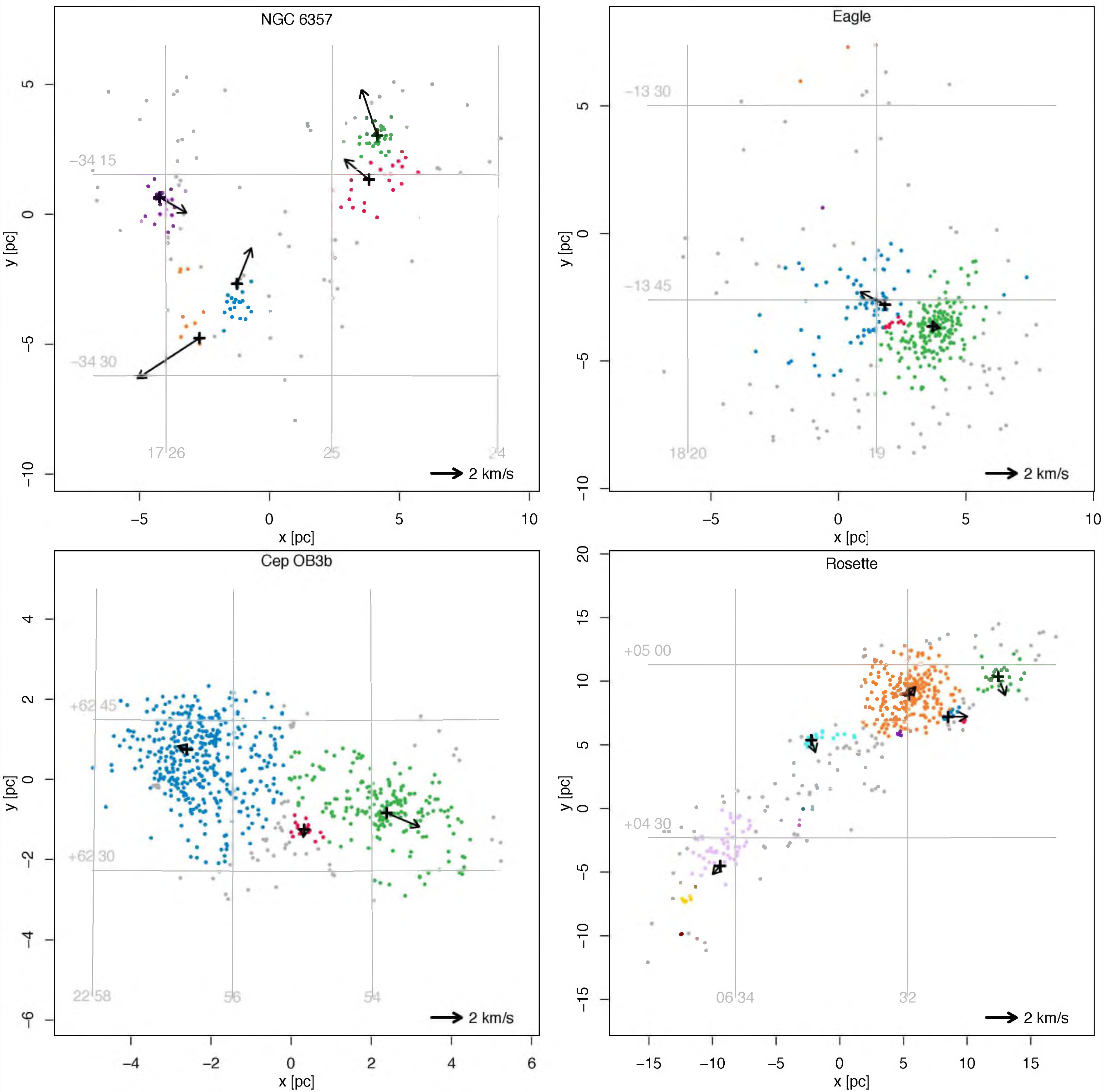
Cluster Formation Scenarios

- Star formation in a free-fall time (Elmegreen 2000)
- Gradual star formation (Tan et al. 2006)
- Hierarchical cluster assembly (Fellhouer et al. 2009)
- Monolithic cluster formation (Banerjee & Kroupa 2015)
- Conveyor Belt (Longmore et al. 2012)
- Global hierarchical collapse (Vázquez-Semadeni et al. 2019)
- Increasing efficiency (Lee et al. 2015; Murray & Chang 2015)

Are clusters built up by the mergers of subclusters?

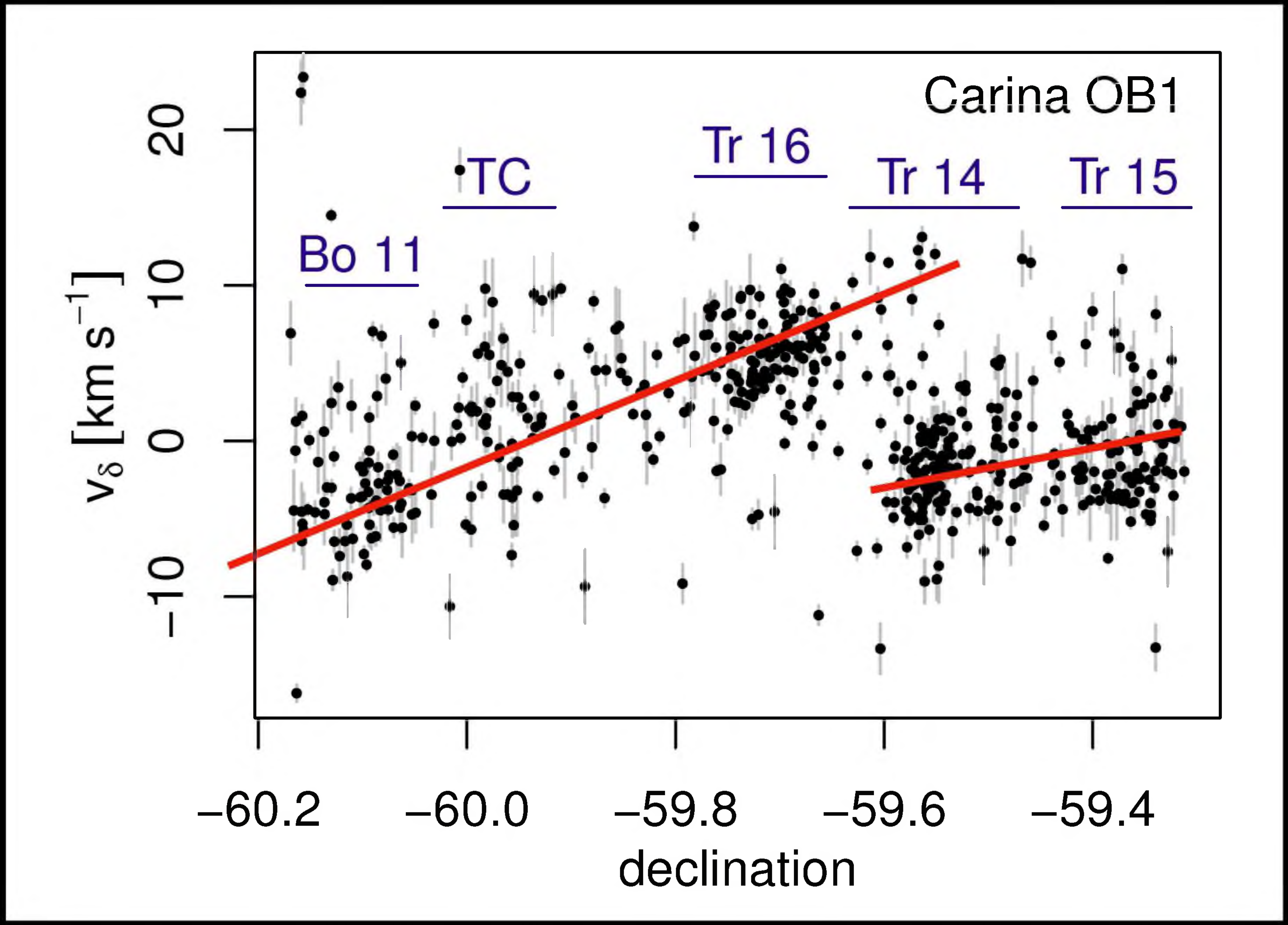


Kuhn et al. (2019)



NGC 6357
Eagle
Cep OB3b
Rosette
x [pc]
y [pc]
2 km/s
−34 15
−34 30
17 26
25
24
−13 30
−13 45
18 20
19
+62 45
+62 30
22 58
56
54
+05 00
+04 30
06 34
32

Motions of subgroups



Implications for Hierarchical Cluster Assembly

- Our sample shows no sign of on-going cluster assembly
  - It could be that this is because the included systems are too evolved, having either partially or completely expelled their gas (e.g. conveyor belt + dispersal; Goldbaum et al. 2011)
  - Hierarchical assembly (if it occurs) must be prompt (<1 Myr)
- Subcluster motions likely inherited from the natal molecular cloud

Summary

- Gaia DR2 clearly detects expansion of stellar groups in star-forming regions
    - >75% of the groups in our sample are in a state of expanion
    - Homologous expansion is common
    - Embedded systems are less likely to be in a state of expansion than systems where the cloud has been partially or completely dispersed
- Cluster rotation detected only in one case
- Stellar velocity distributions are often approximately Gaussian
- No evidence of subcluster mergers (hierarchical assembly) in the star-forming regions we examined