# The 3D Dynamics of Young Star Clusters From GES and Gaia DR3


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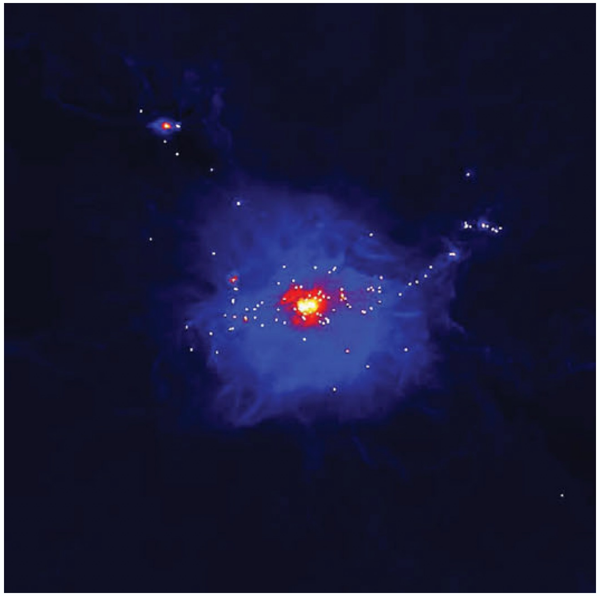
**Rob Jeffries, Richard Jackson, Germano Sacco and the Gaia-ESO Survey team**

# How do star clusters form?



Monolithic Formation

Hierarchical Collapse / Mergers

Forms ‘in situ’ at high densities (Banerjee & Kroupa 2014, Longmore 2014)

Stars form over extended area, then collapse to form cluster (Bonnell+ 2003, Fujii+ 2012, Vazquez-Semadeni+ 2017)

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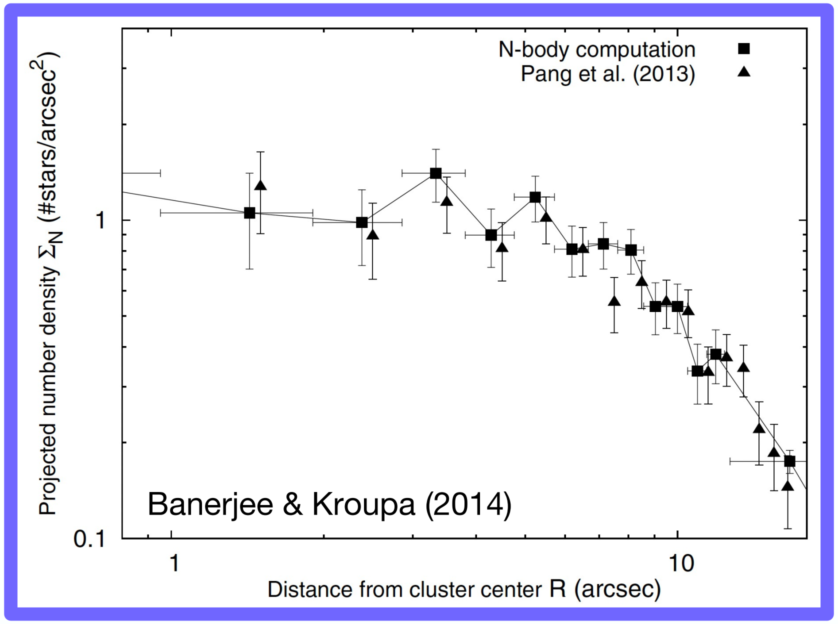


Monolithic Formation

- No strong spatial substructure (Banerjee & Kroupa 2014, 2018).

Forms 'in situ' at high densities (Banerjee & Kroupa 2014, Longmore 2014)

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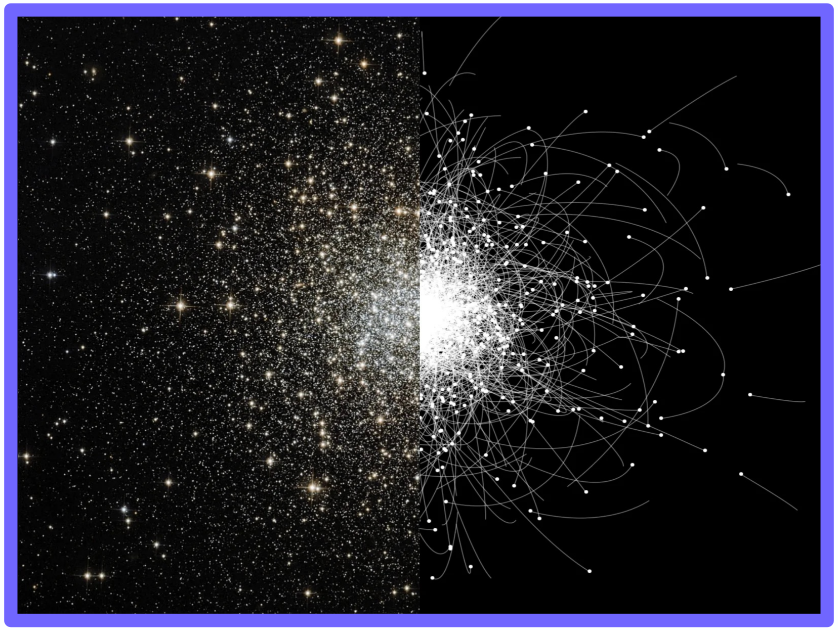
Forms ‘in situ’ at high densities (Banerjee & Kroupa 2014, Longmore 2014)



- Clusters should be spherical and dynamically evolved (Kroupa 2008)

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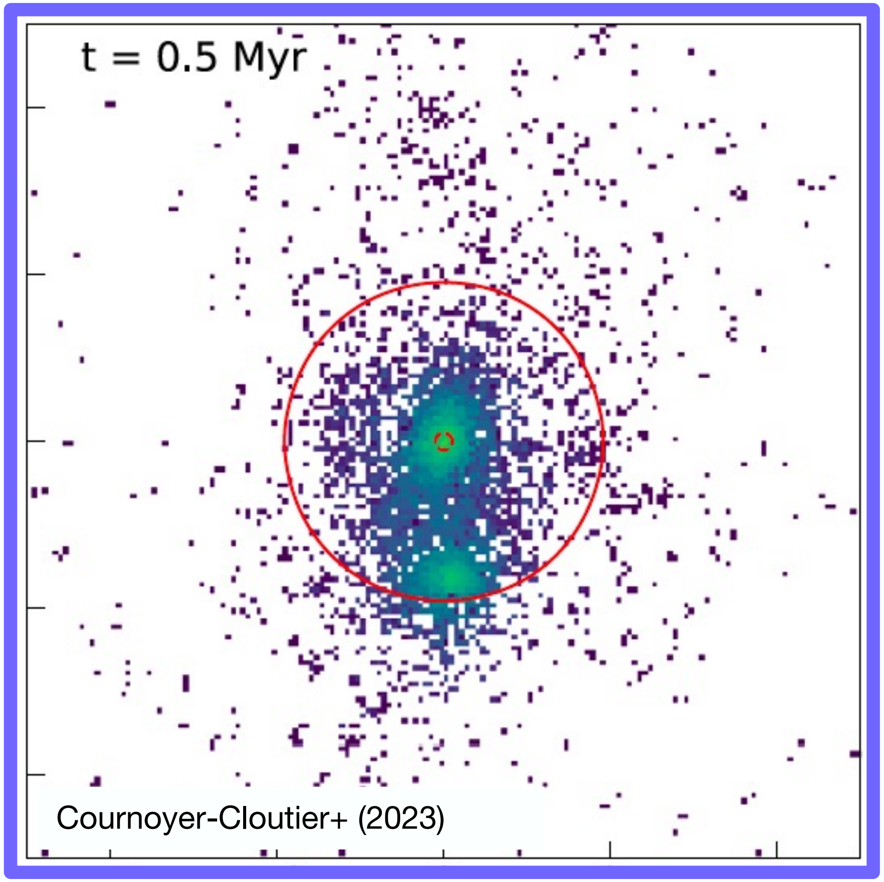
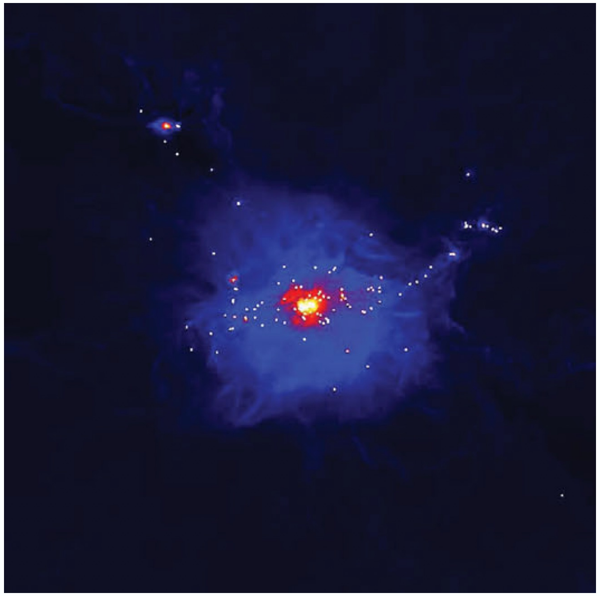



- Cluster elongated during mergers (Cournoyer-Cloutier+ 2023)



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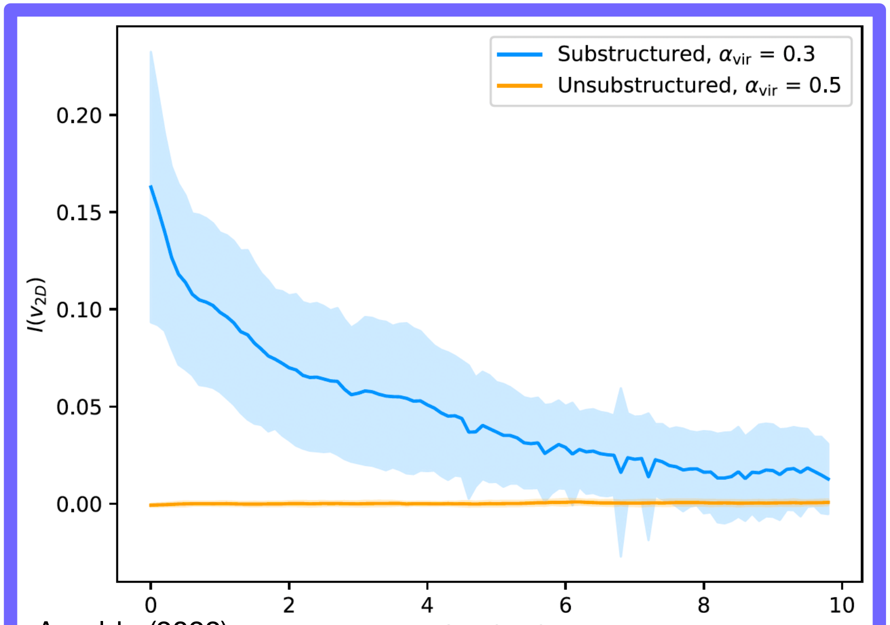
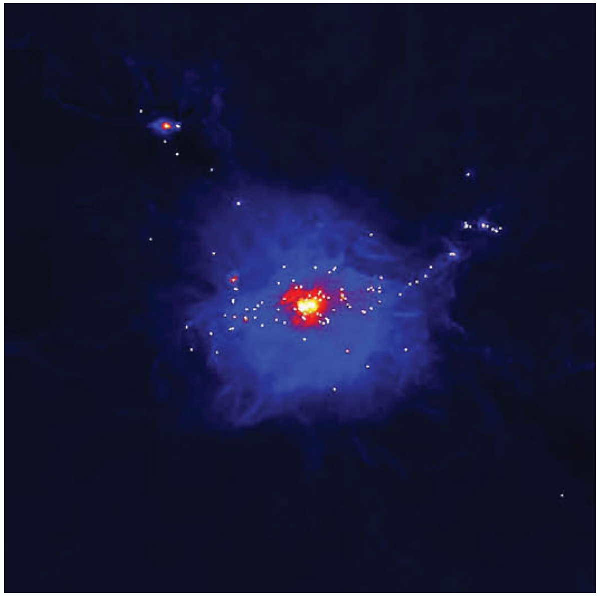


Arnold+ (2022)

- Kinematic substructure from mergers survives for multiple crossing times and is measurable (Arnold+ 2022)



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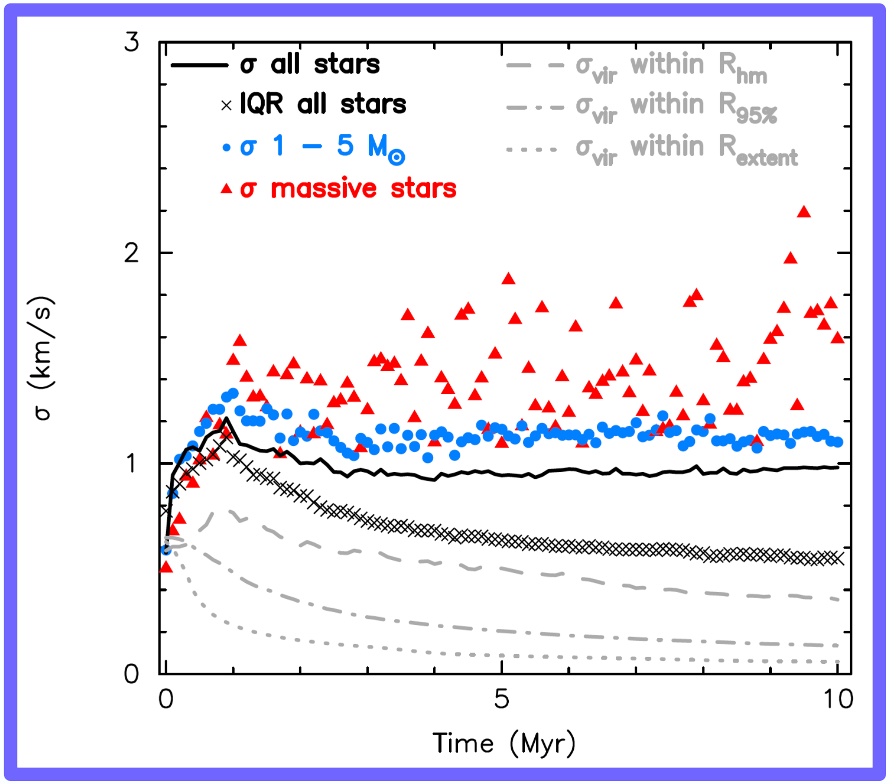
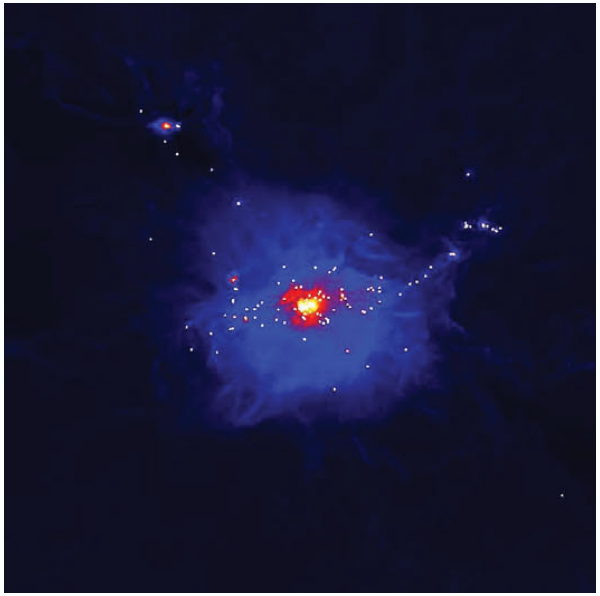



- Inverse energy equipartition develops from cool collapse due to the Spitzer Instability (Parker & Wright 2016)



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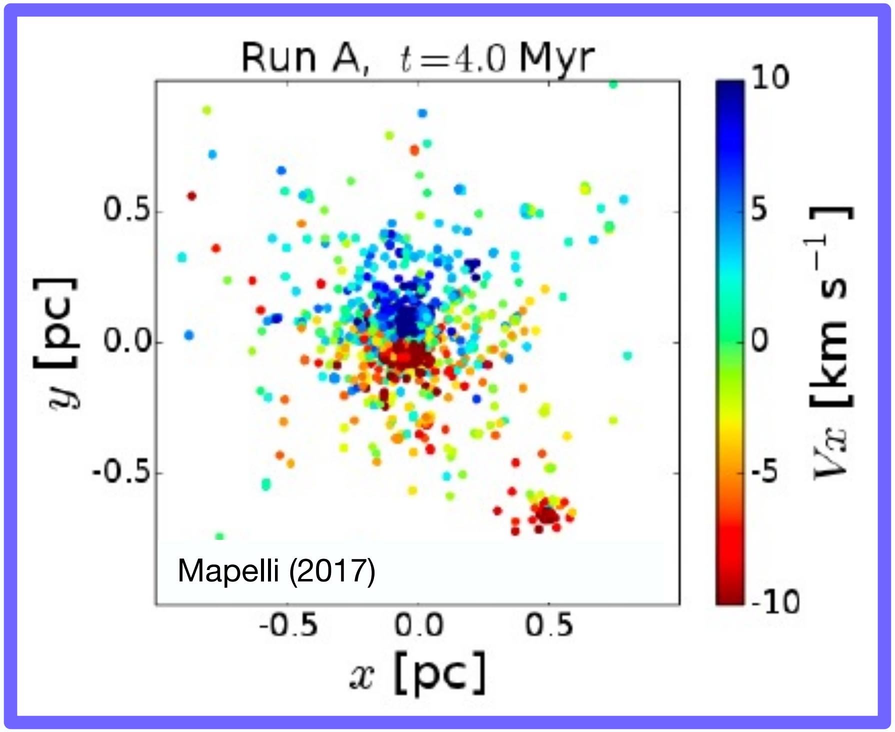
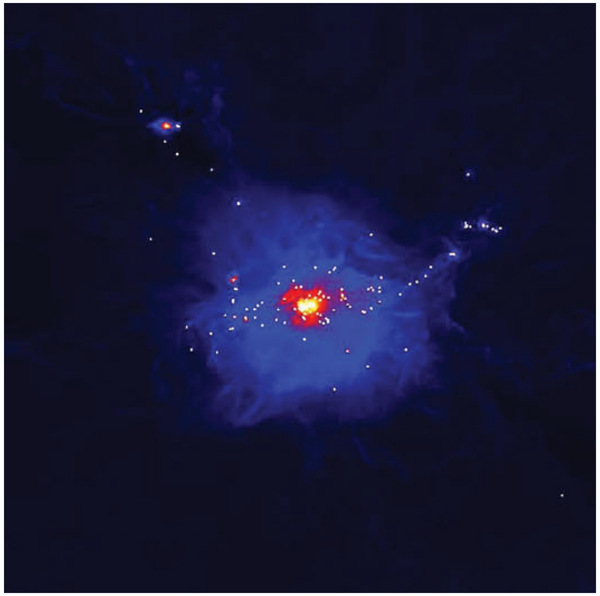


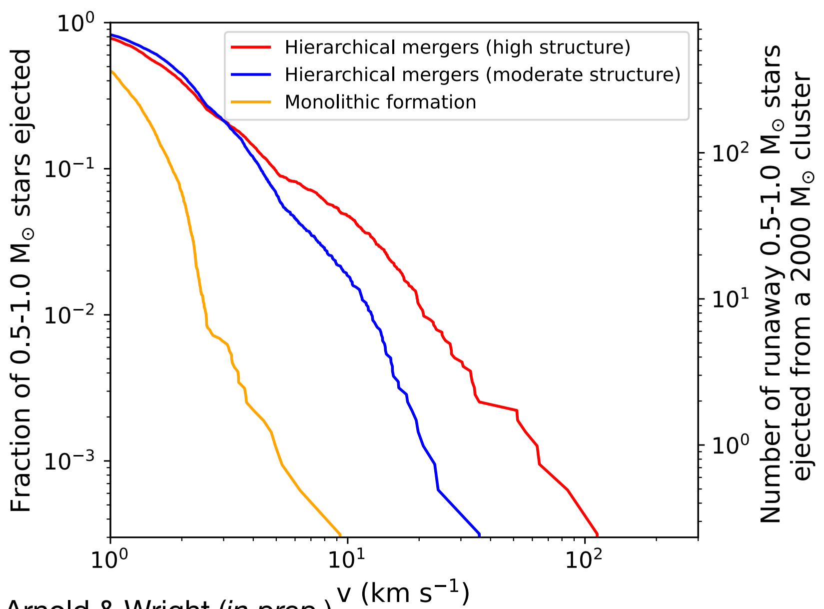



Hierarchical Collapse / Mergers

- Hierarchical collapse and mergers leads to considerable levels of angular momentum and rotation (Lee & Hennebelle 2016, Mapelli 2017, Smilgys & Bonnell 2017, Tiongco+ 2021).

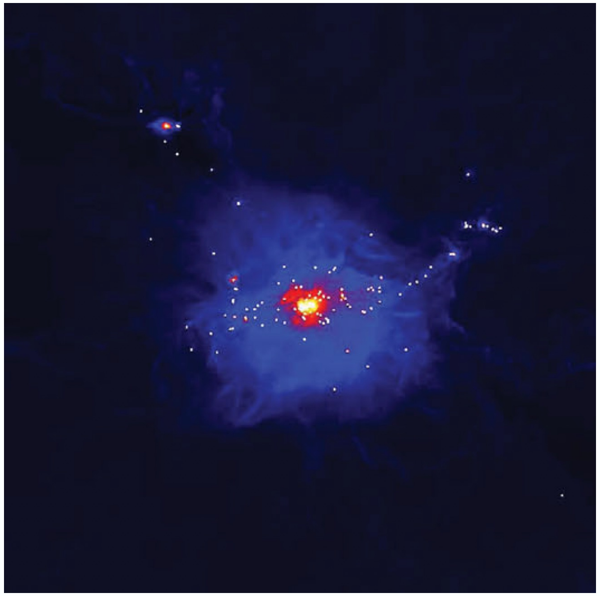
Stars form over extended area, then collapse to form cluster (Bonnell+ 2003, Fujii+ 2012, Vazquez-Semadeni+ 2017)

# How do star clusters form?




Arnold & Wright (*in prep.*)

- Clusters that form by mergers produce more runaway stars (Schoettler+ 2019, 2020, Farias+ 2019, Arnold & Wright *in prep).*



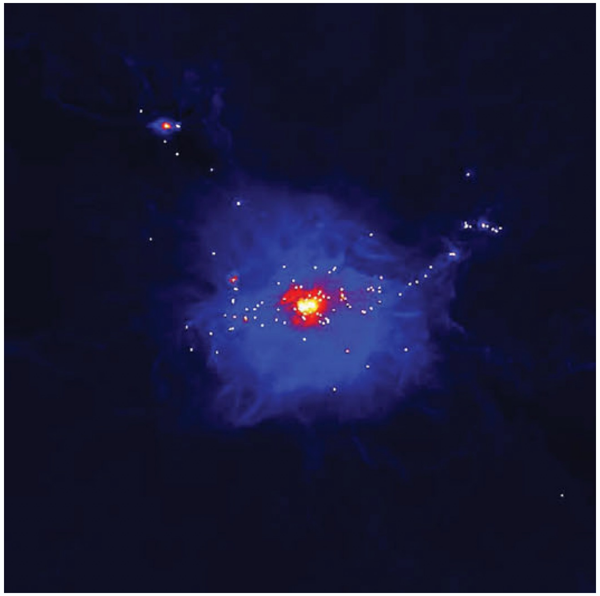
Hierarchical Collapse / Mergers

Stars form over extended area, then collapse to form cluster (Bonnell+ 2003, Fujii+ 2012, Vazquez-Semadeni+ 2017)

# How do star clusters form?

Monolithic Formation

- No strong spatial substructure.
- Spherical and dynamically evolved.

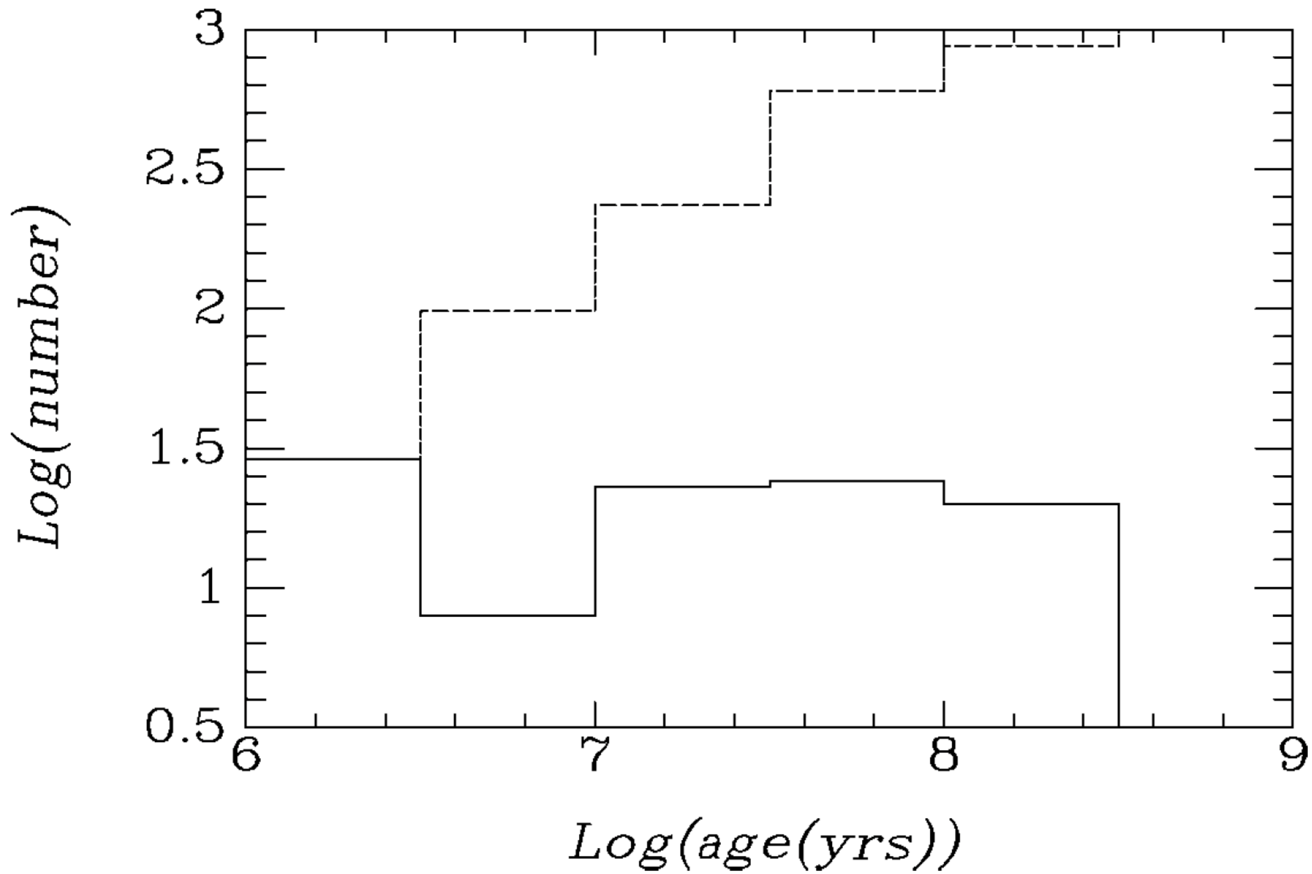


Hierarchical Collapse / Mergers

- Cluster elongated during mergers.
- Kinematic substructure measurable.
- Considerable levels of rotation.
- Many runaway stars.

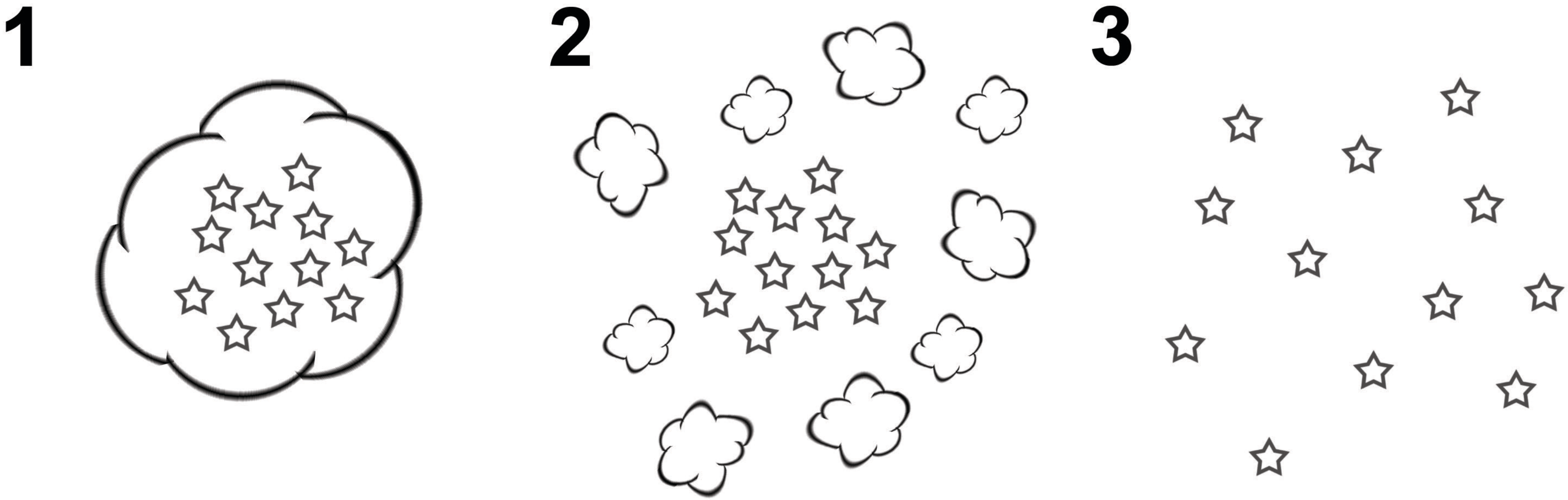
# What disperses star clusters?

90% of young star clusters don’t survive beyond 10 Myrs (Lada & Lada 2003).




Lada & Lada (2003)

# Classical Picture: Residual Gas Expulsion



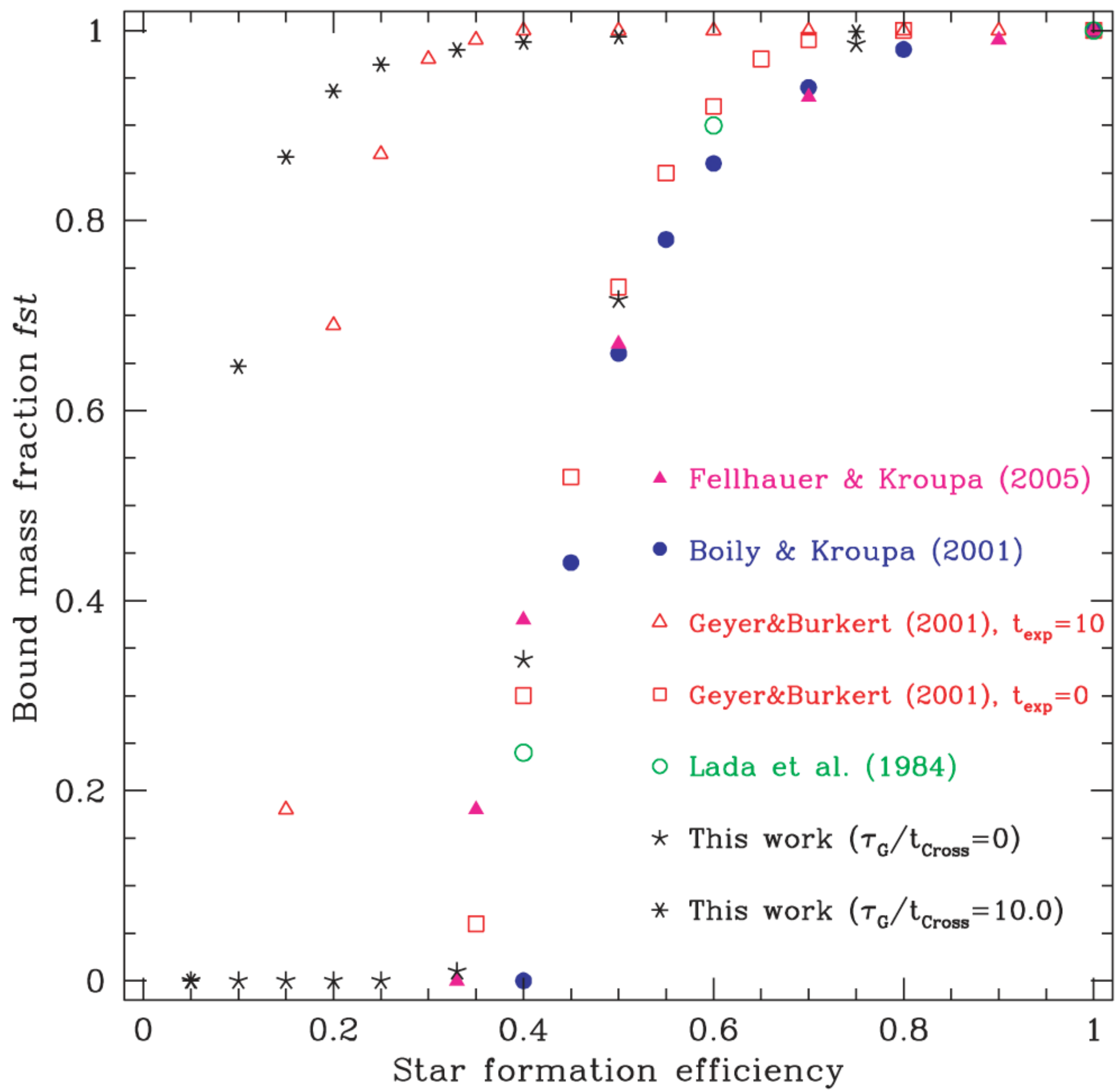

Star cluster born embedded within a molecular cloud.

Feedback disperses residual gas (removing gravitational potential)

Star cluster expands, possibly dispersing.

# Classical Picture: Residual Gas Expulsion

To first order, star formation efficiency determines the eventual fate of the cluster (e.g., Baumgardt & Kroupa 2007).

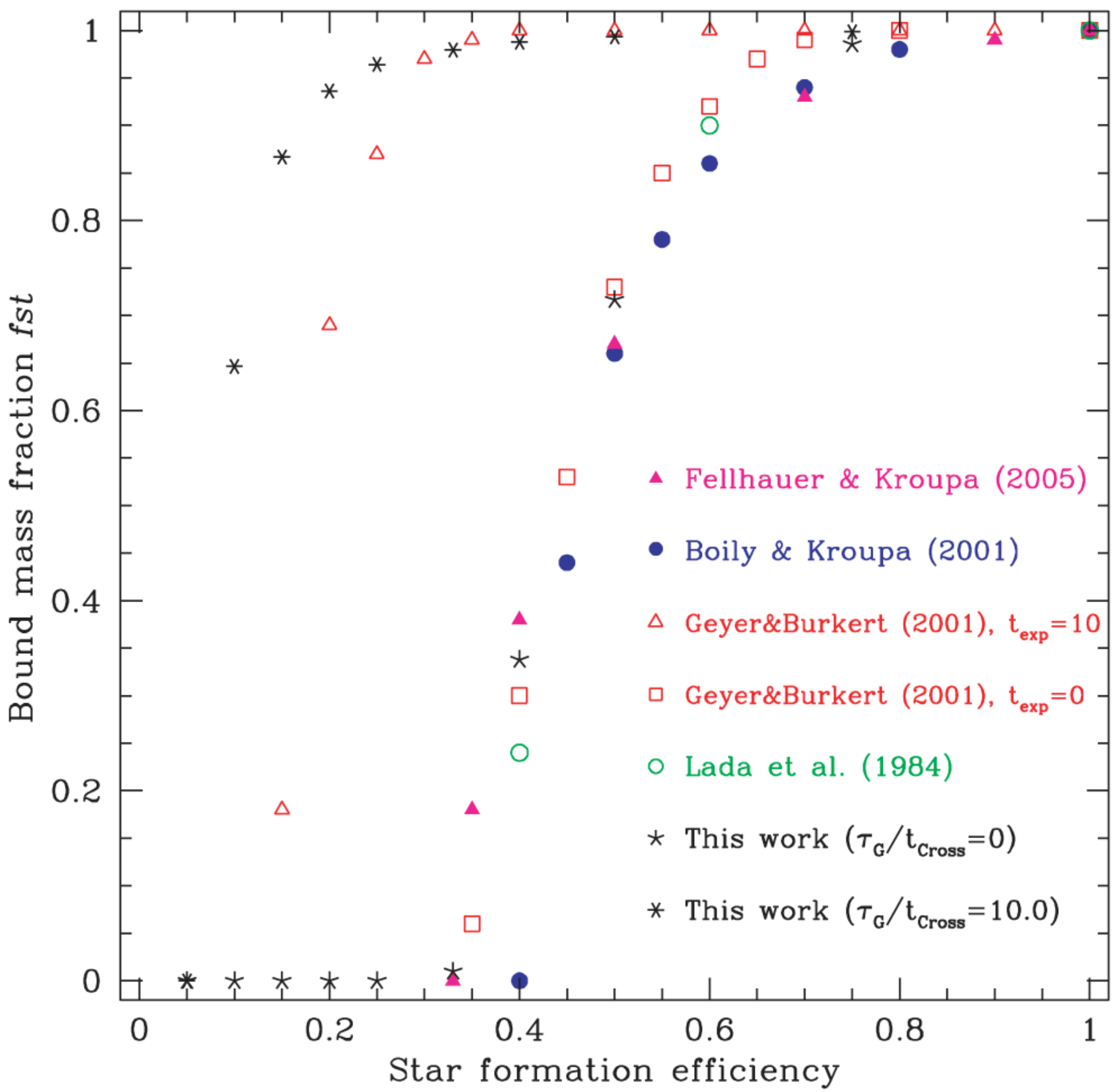



Baumgardt & Kroupa (2007)

# Classical Picture: Residual Gas Expulsion

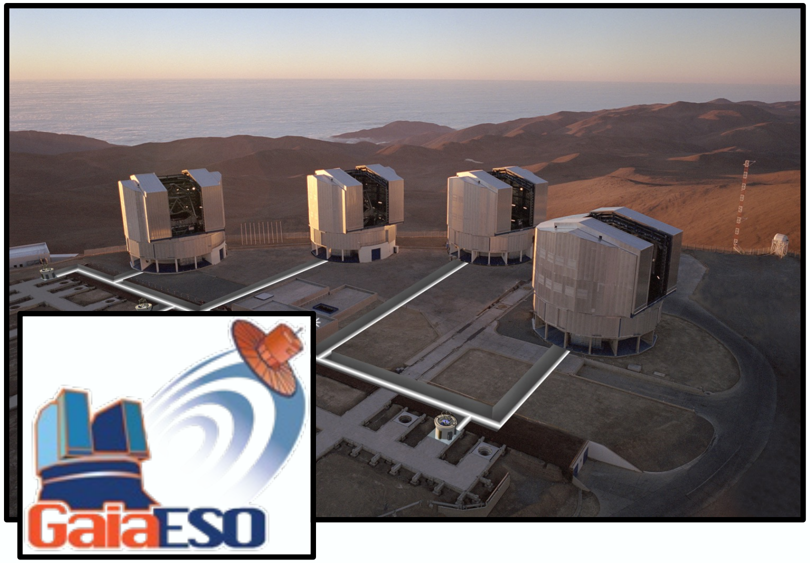
Picture begins to fall apart if:

- Cluster is not in virial equilibrium during gas expulsion (e.g., Offner+ 2009)
- Stars are highly substructured (Farias+ 2018)
- Stellar and gas components are decoupled (e.g., Kruijssen+ 2012)

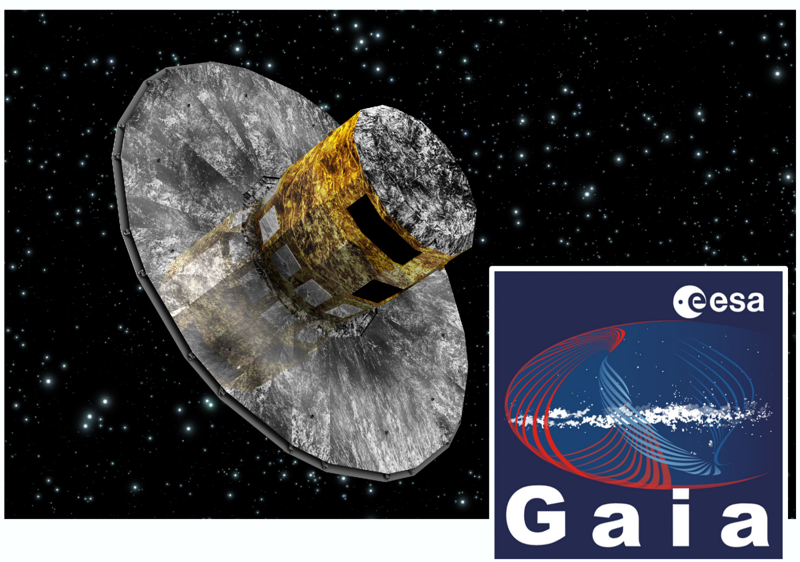



Baumgardt & Kroupa (2007)

# The kinematic data revolution




- Multi-object spectroscopic surveys providing RVs
- e.g., Gaia-ESO Survey, SDSS, WHT/WEAVE, 4MOST




- Gaia astrometry
- Positions, parallaxes, proper motions

# 3D Kinematics with GES and Gaia

3D kinematic study of ~2500 stars in 18 young (< 20 Myr) groups

(Wright+ *subm.*)

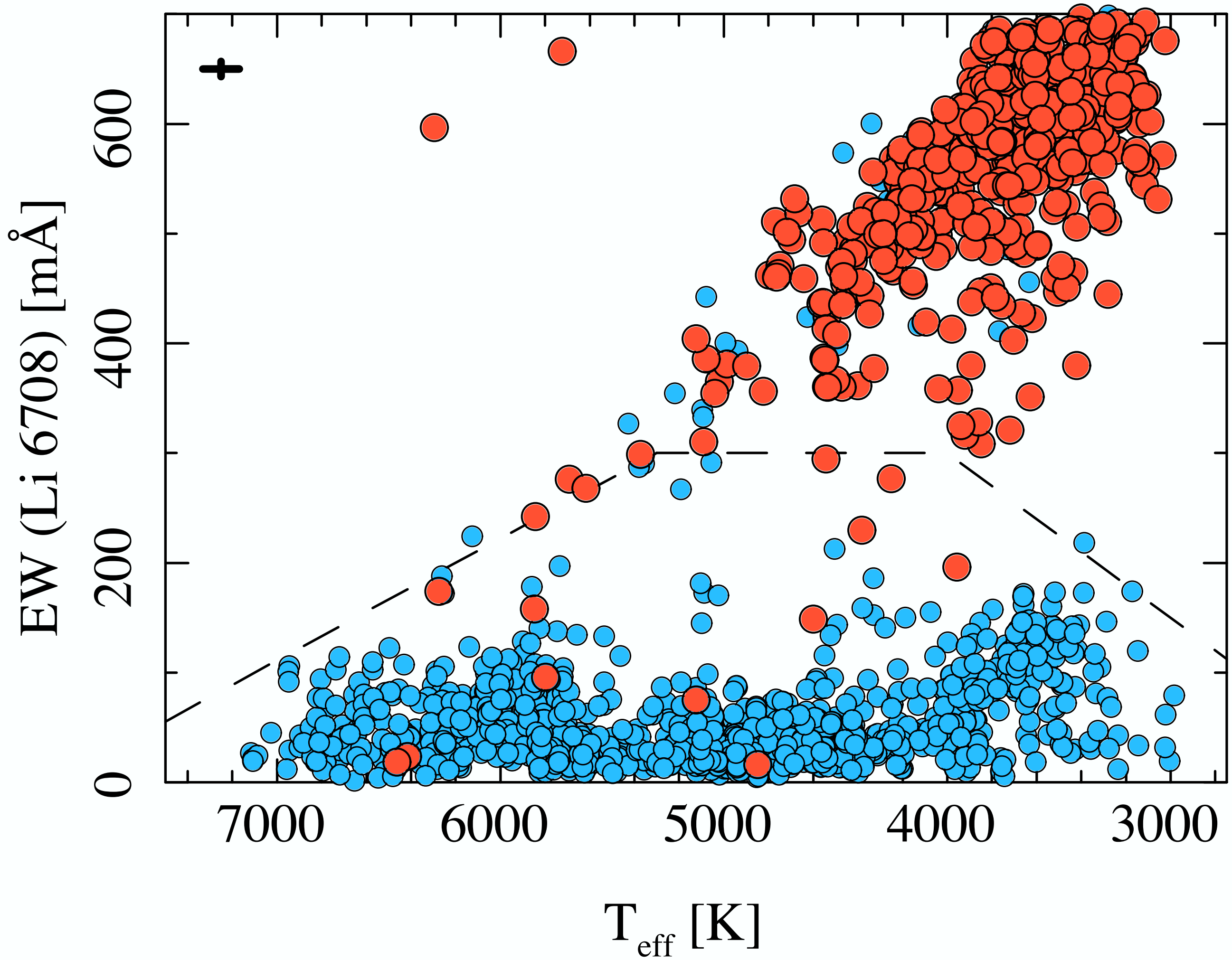
arxiv/2311.08358

Comments welcome!

# 3D Kinematics with GES and Gaia

All targets have spectroscopic signatures of youth:

- Li 6708 Å

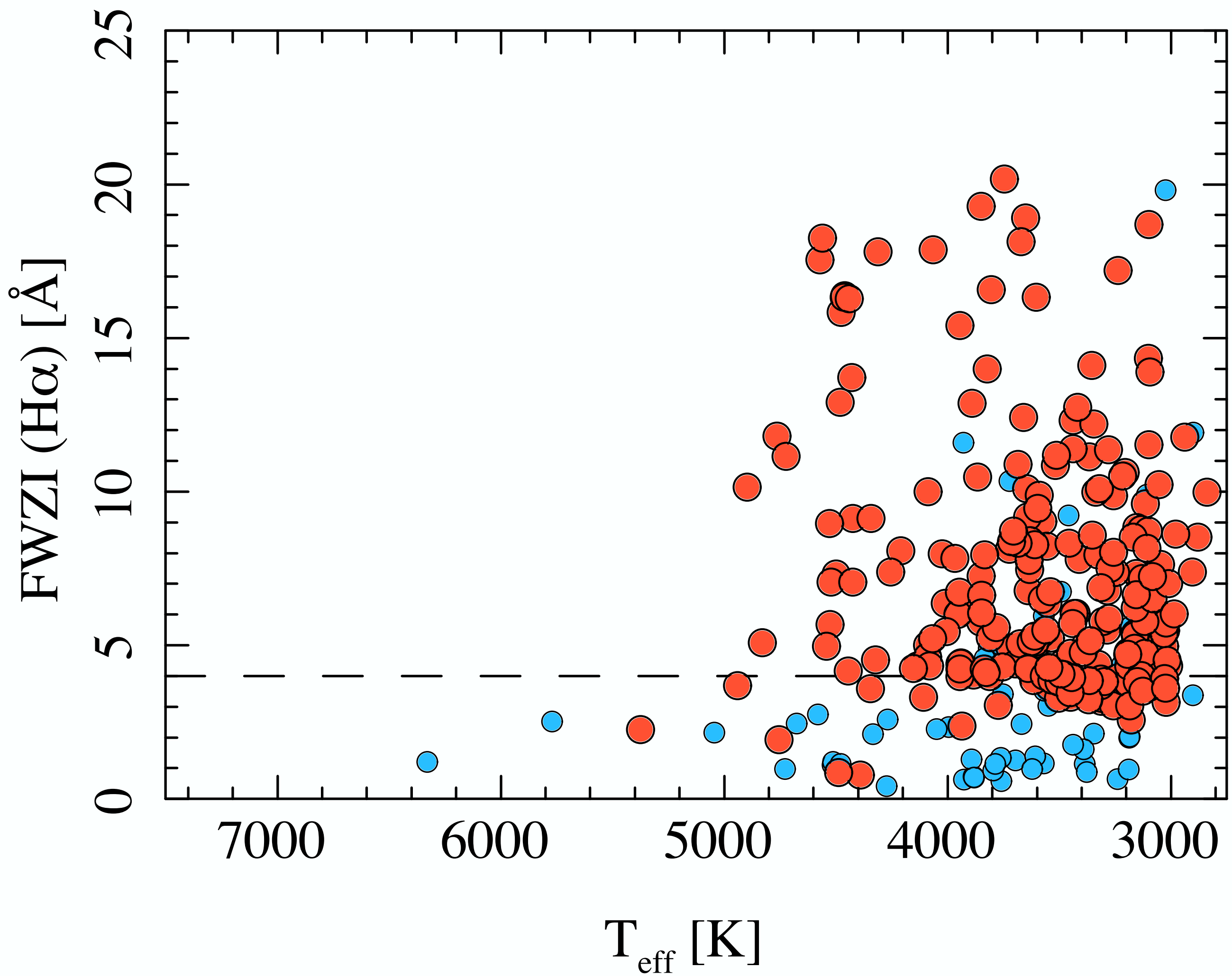



NGC 2264; Wright+ (subm)

# 3D Kinematics with GES and Gaia

All targets have spectroscopic signatures of youth:

- Li 6708 Å
- Hα excess

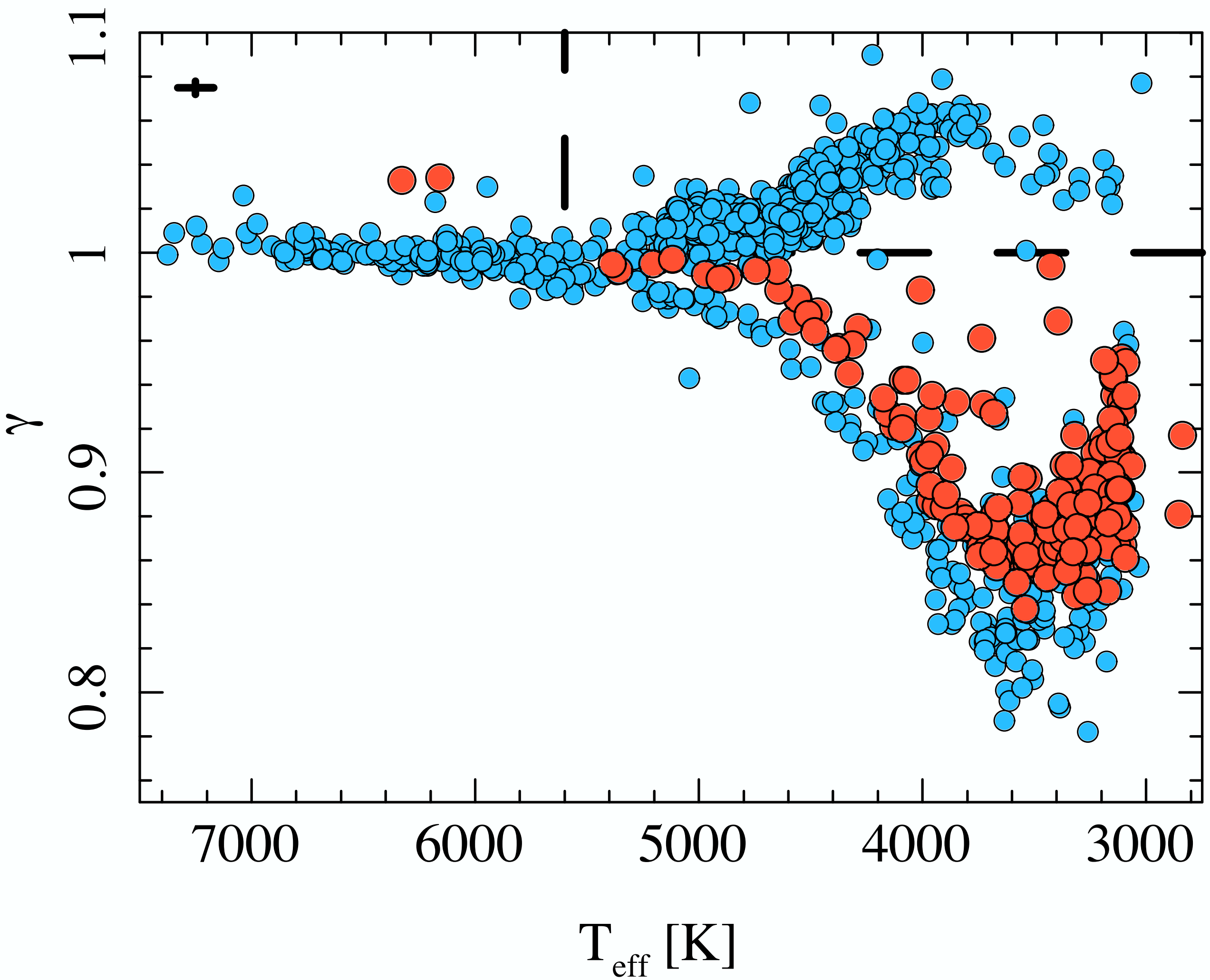



λ Ori; Wright+ (subm)

# 3D Kinematics with GES and Gaia

All targets have spectroscopic signatures of youth:

- Li 6708 Å
- H$\alpha$ excess
- Surface gravity indicators



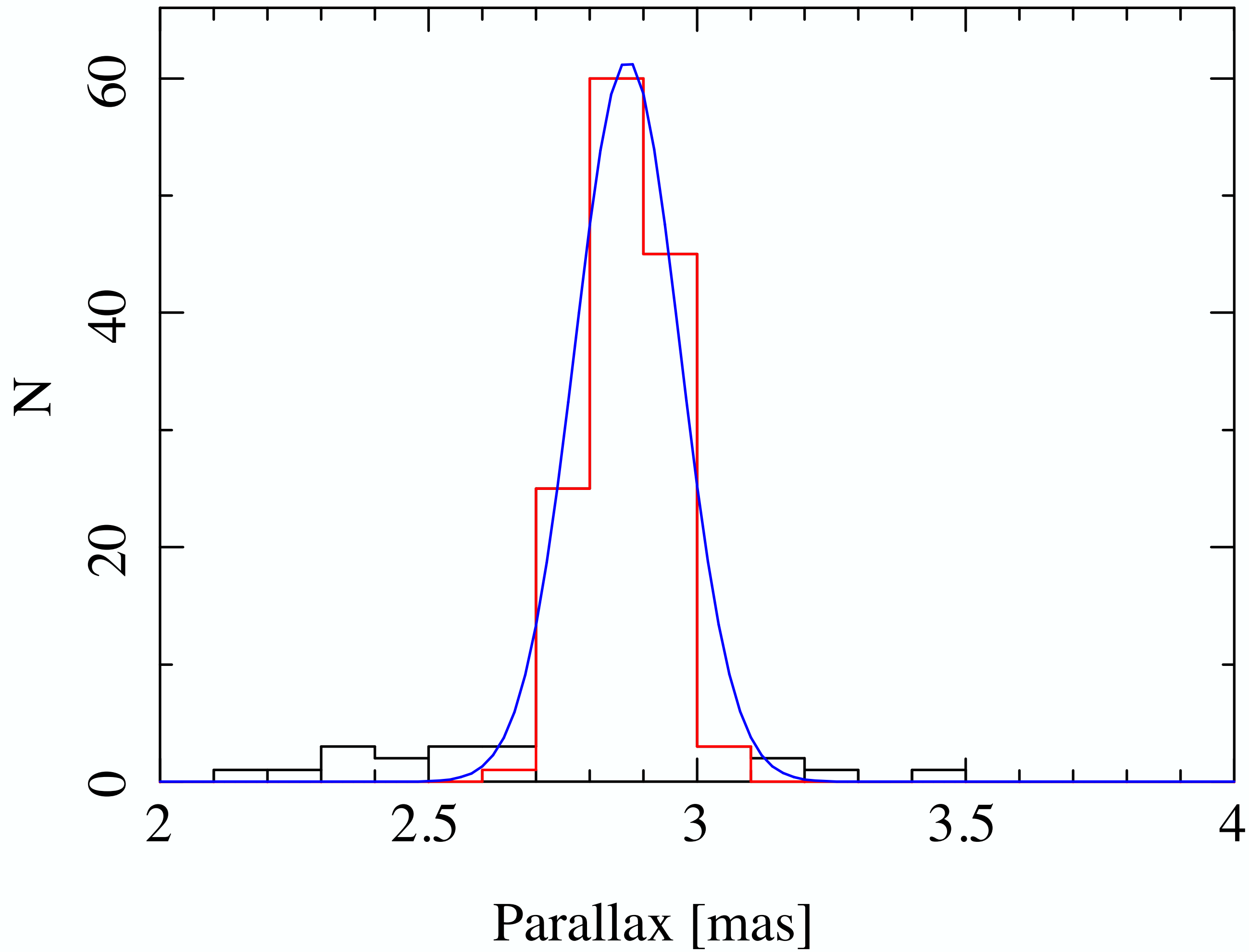

Gamma Vel; Wright+ (subm)

# 3D Kinematics with GES and Gaia

All targets have spectroscopic signatures of youth:

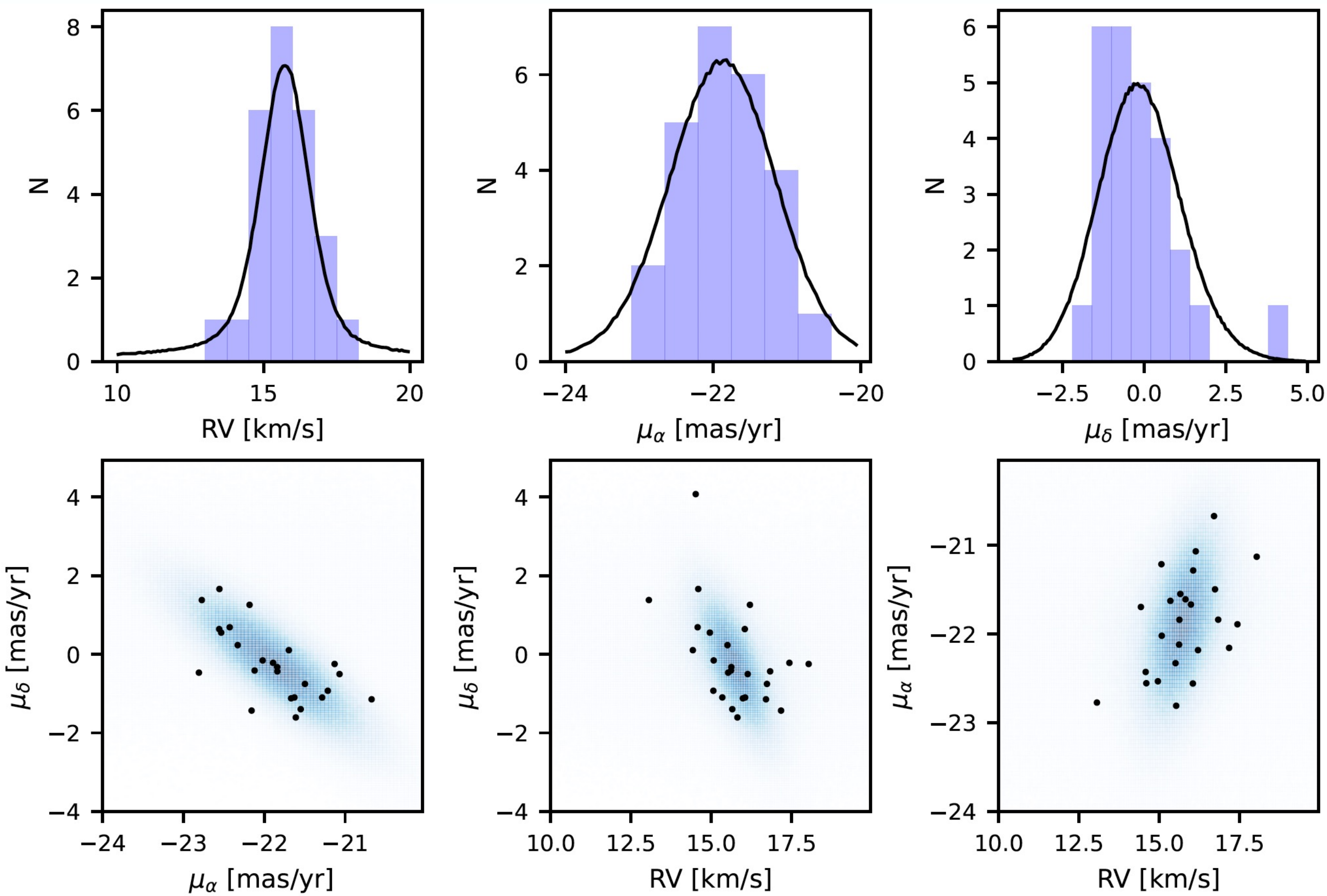
- Li 6708 Å
- Hα excess
- Surface gravity indicators

And parallax consistent with cluster membership.




25 Ori; Wright+ (subm)

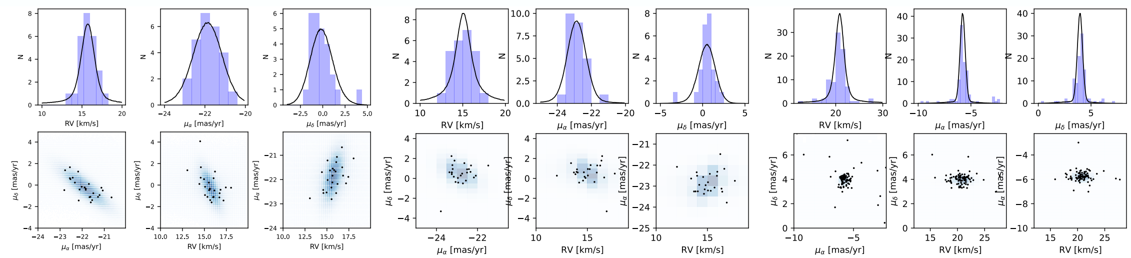
# Velocity dispersions

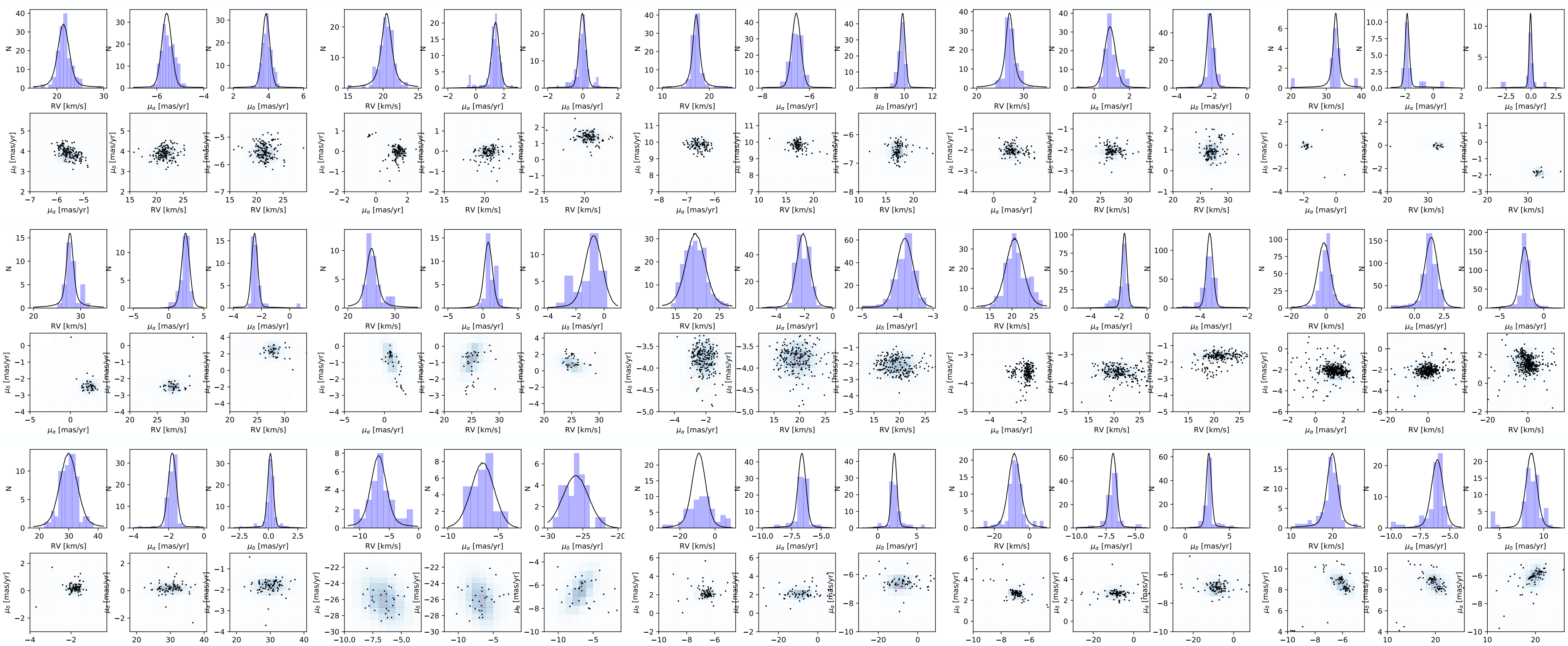



Cha I North; Wright+ (subm)

# Velocity dispersions

1D, 2D and 3D velocity dispersions calculated for all groups.

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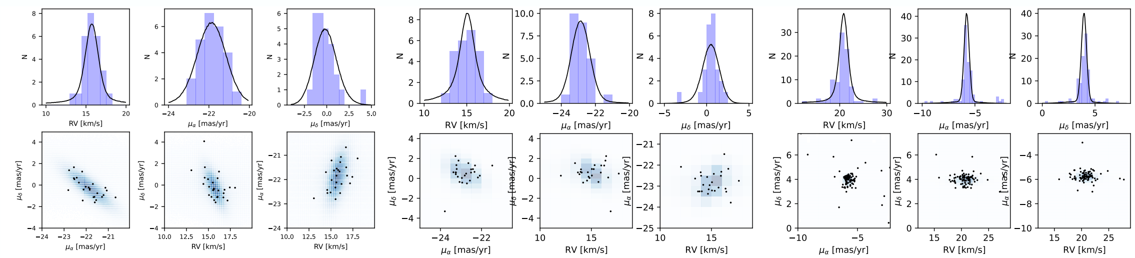
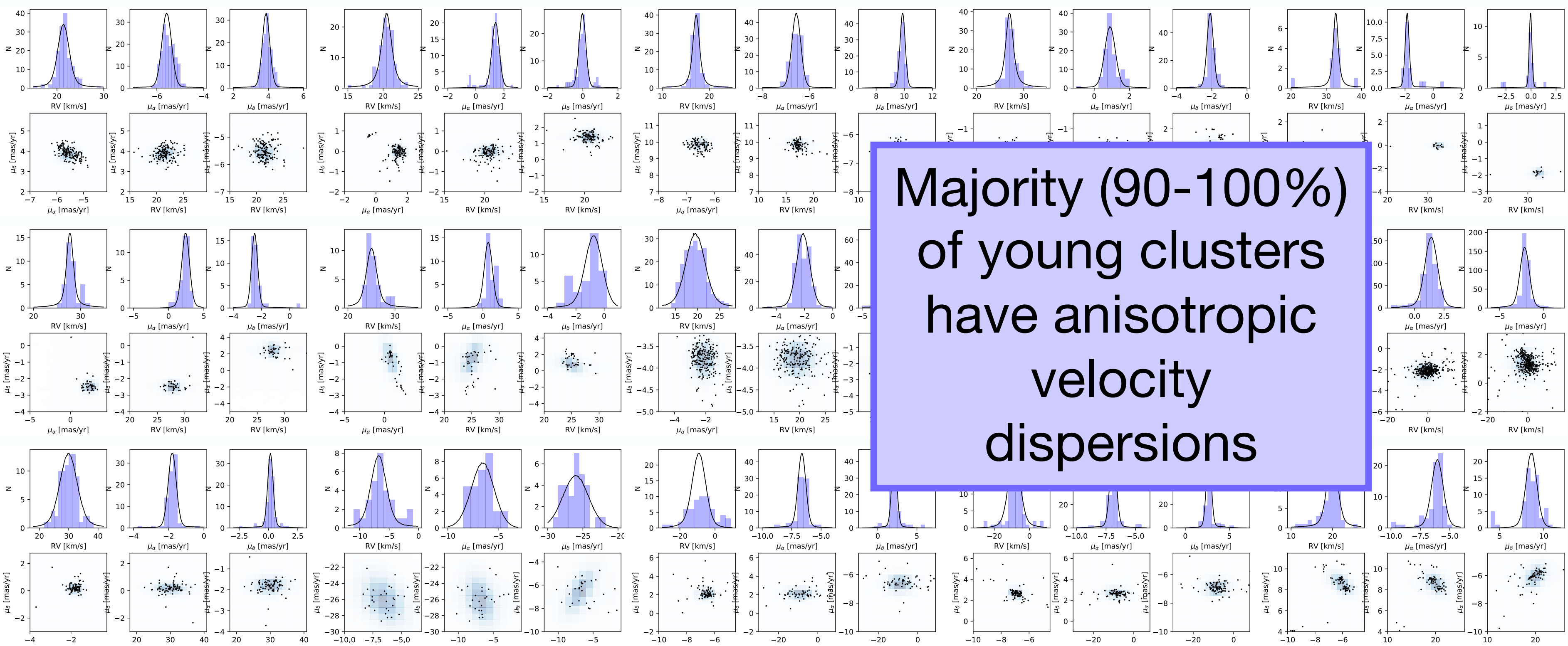
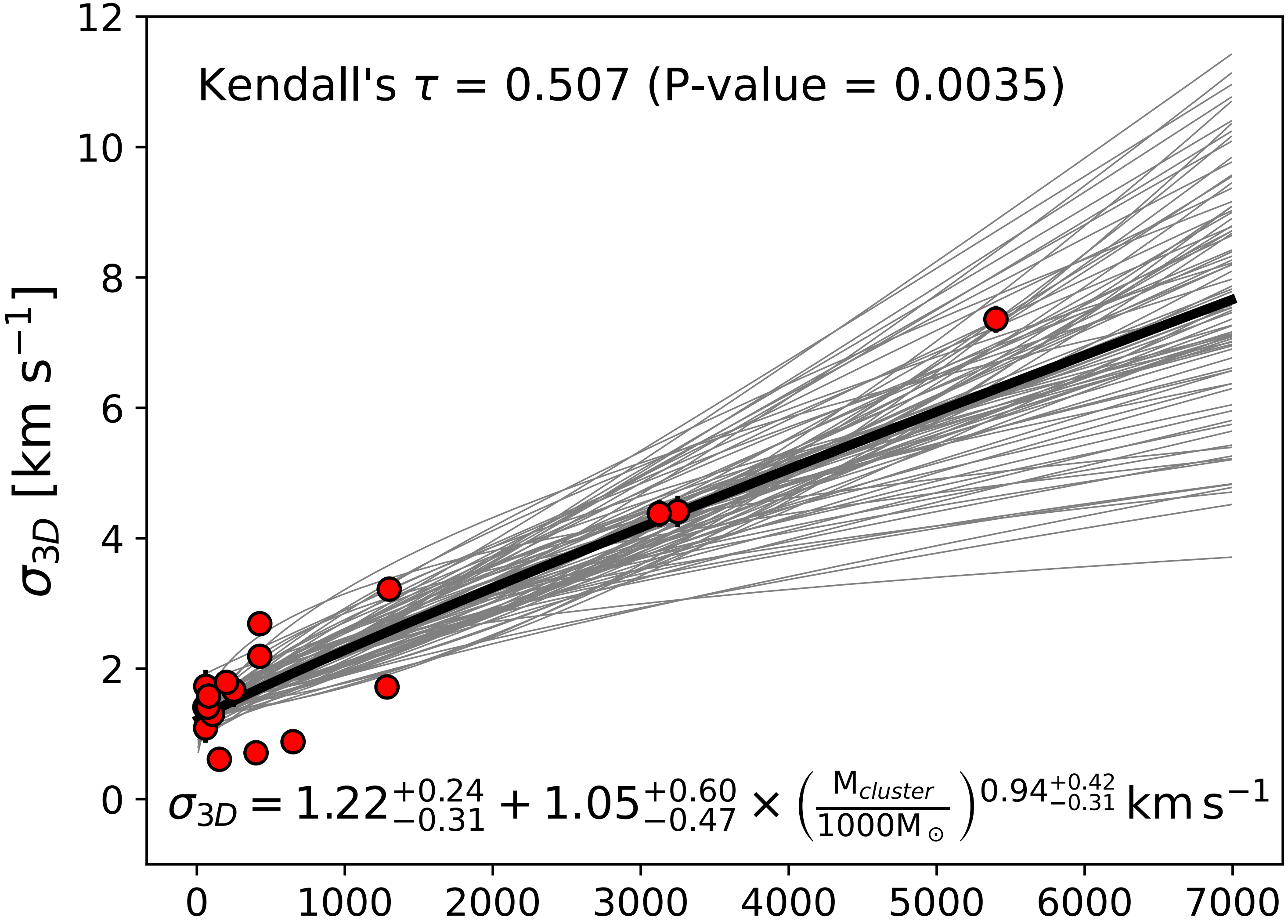




Majority (90-100%) of young clusters have anisotropic velocity dispersions

Wright+ (subm)

# Velocity dispersions




Wright+ (*subm*)

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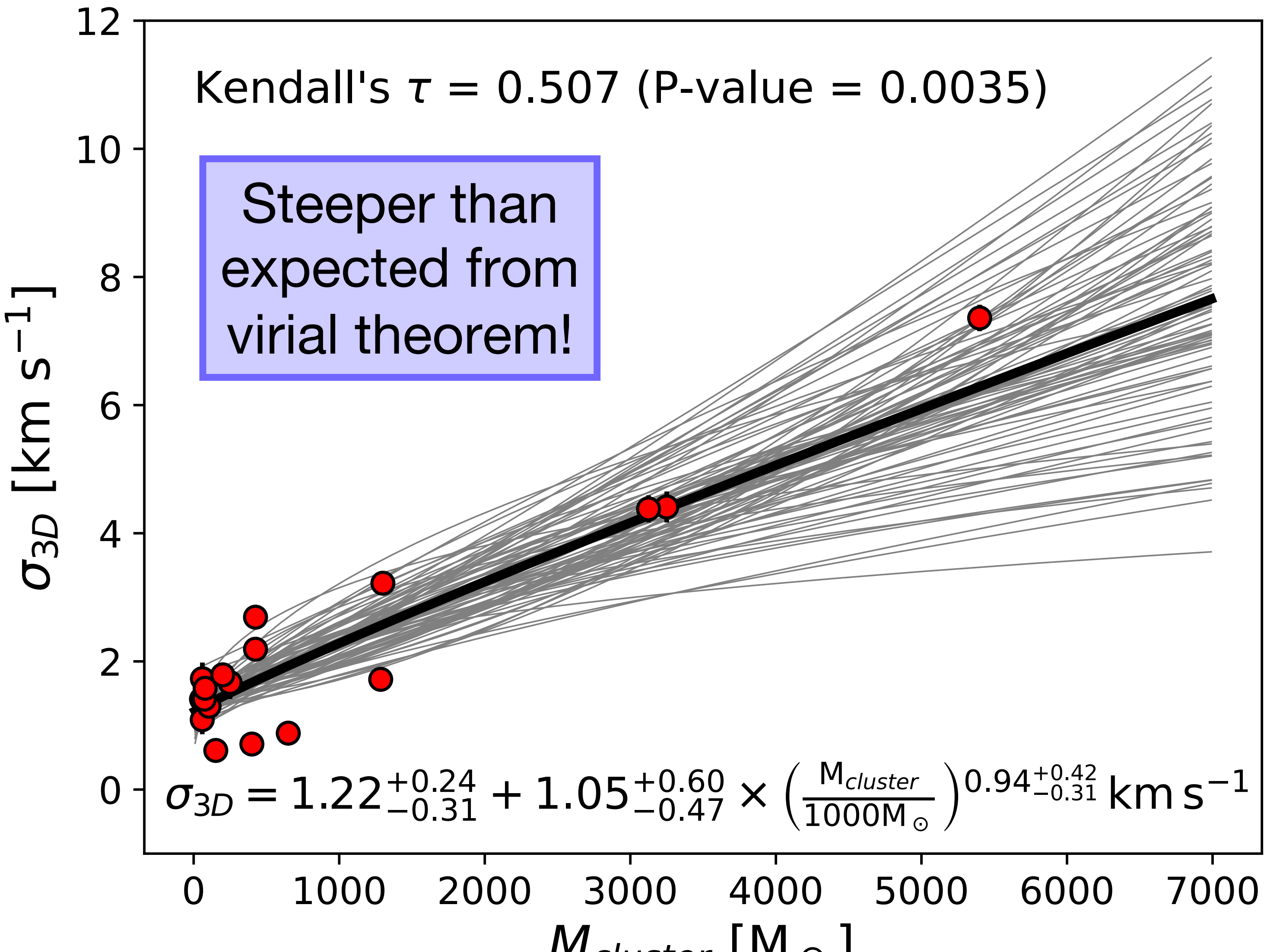


Wright+ (*subm*)

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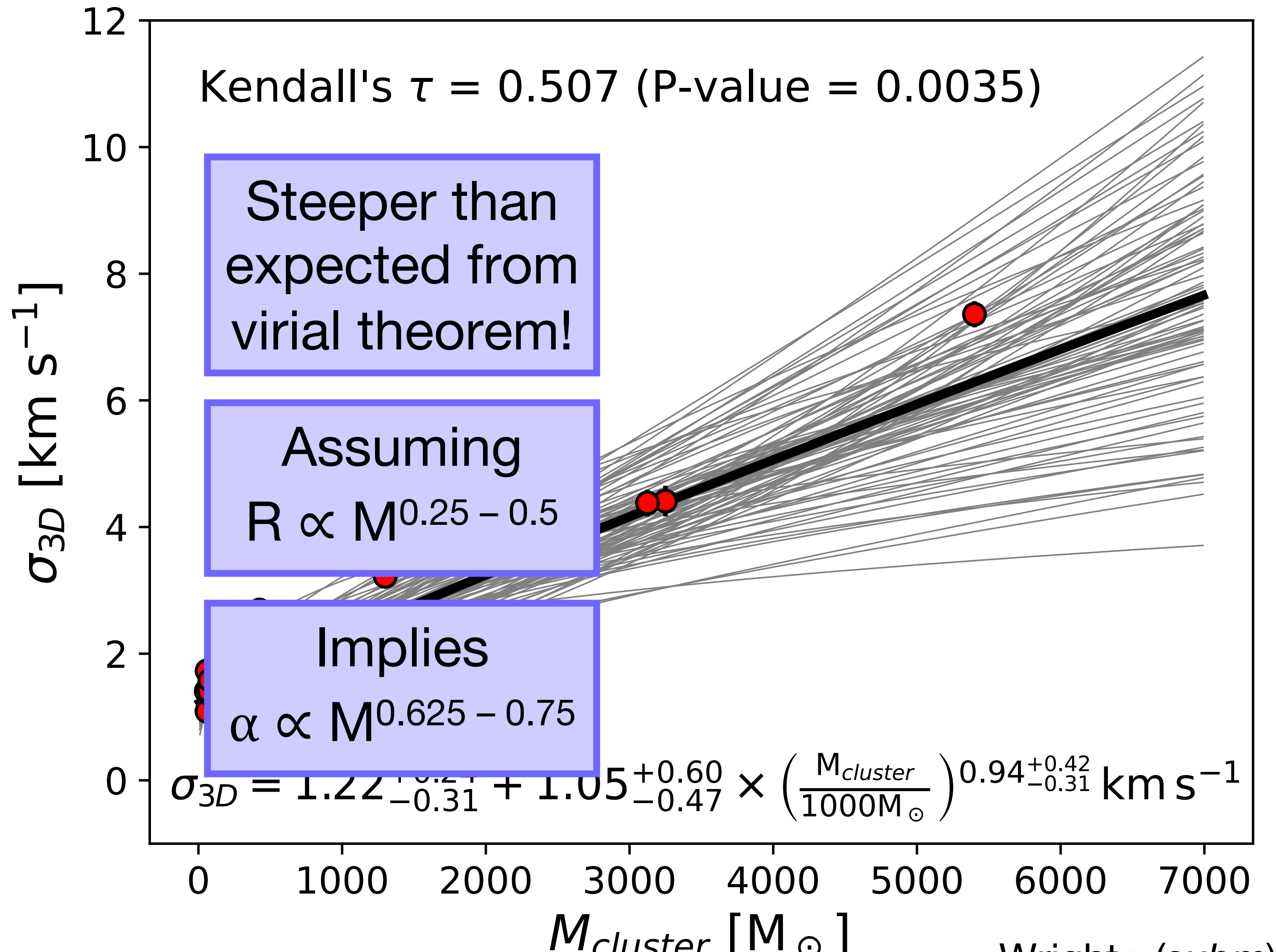
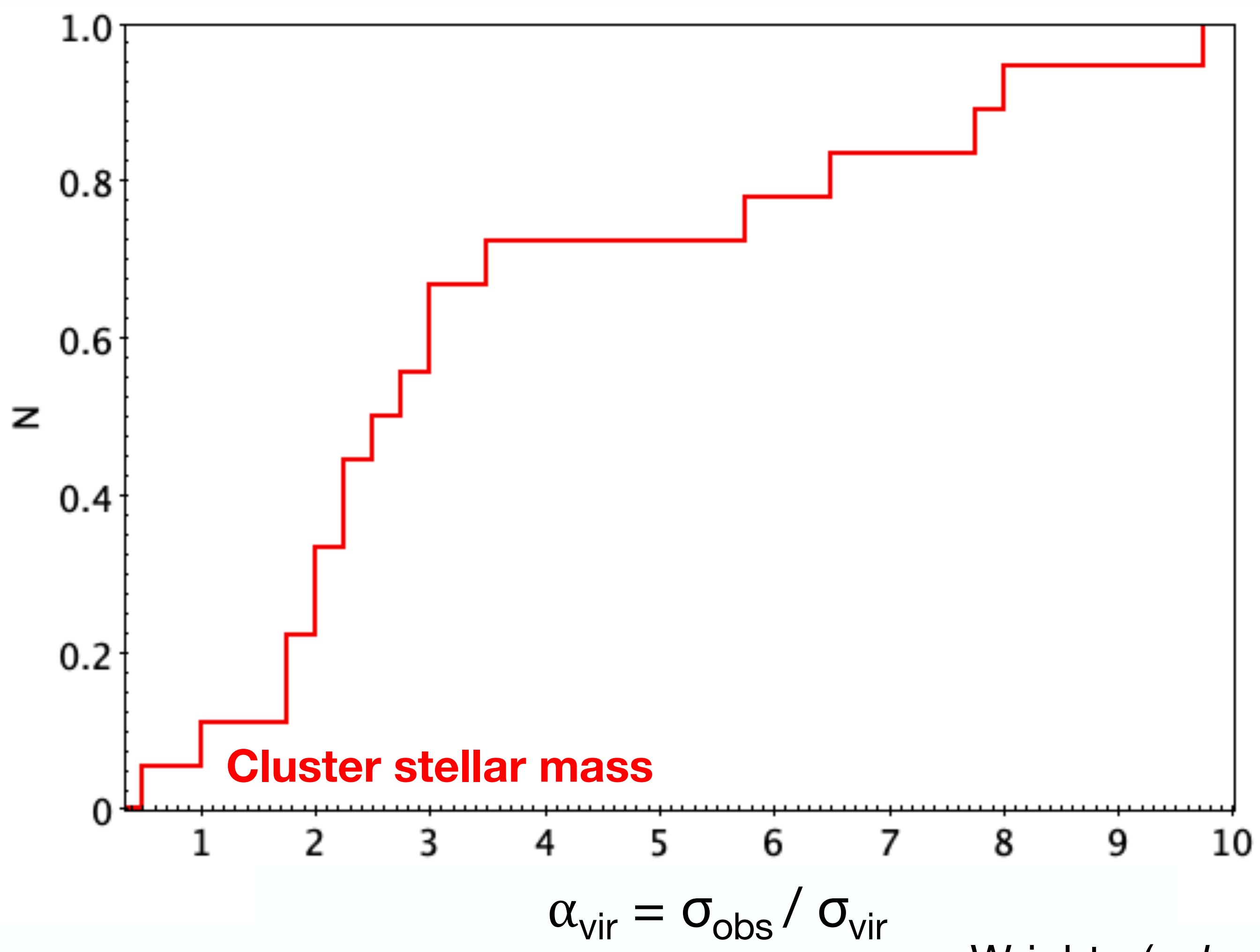



Wright+ (*subm*)

# Virial state

Most young star clusters not in virial equilibrium

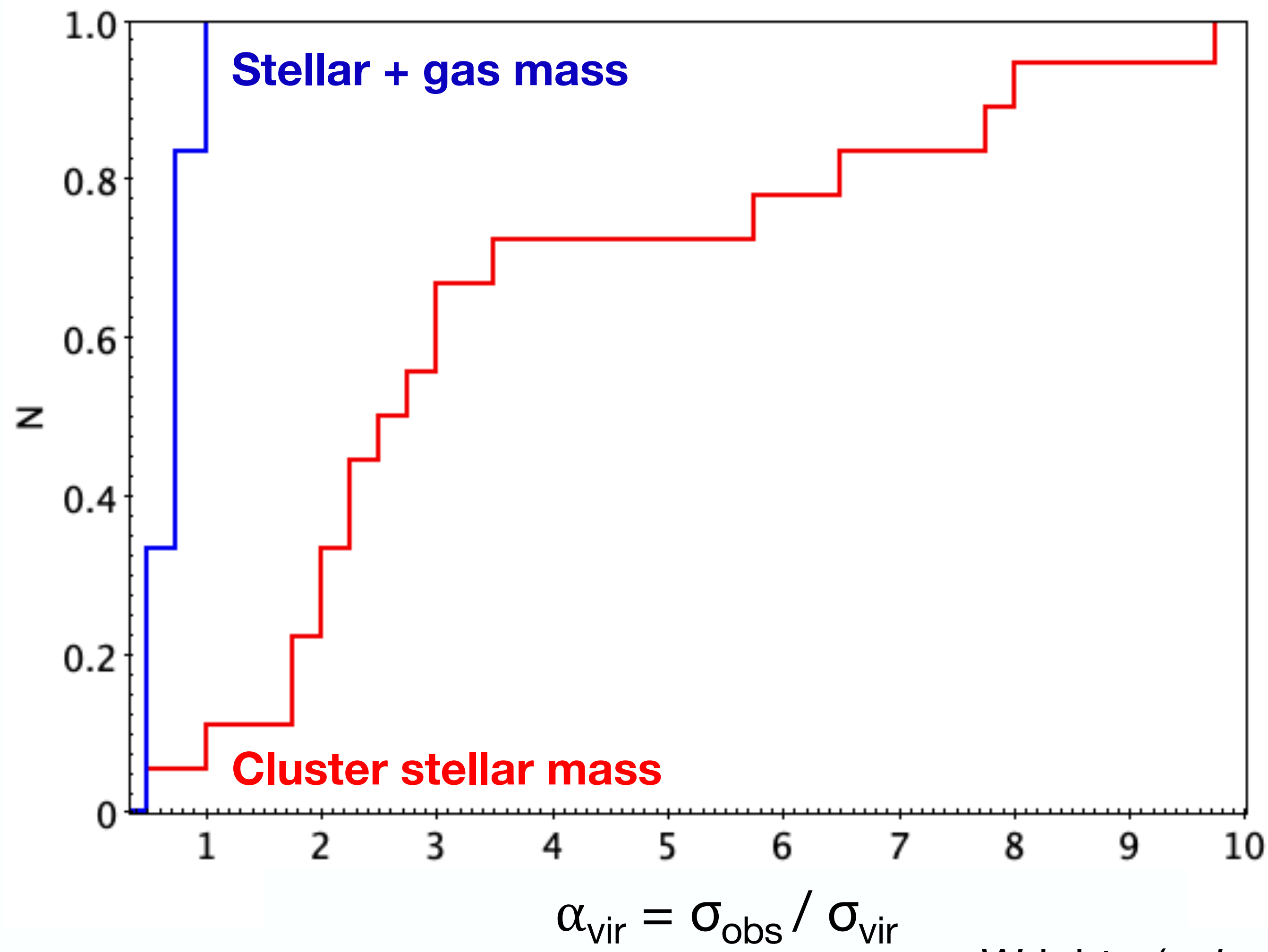



Wright+ (*subm*)

# Virial state

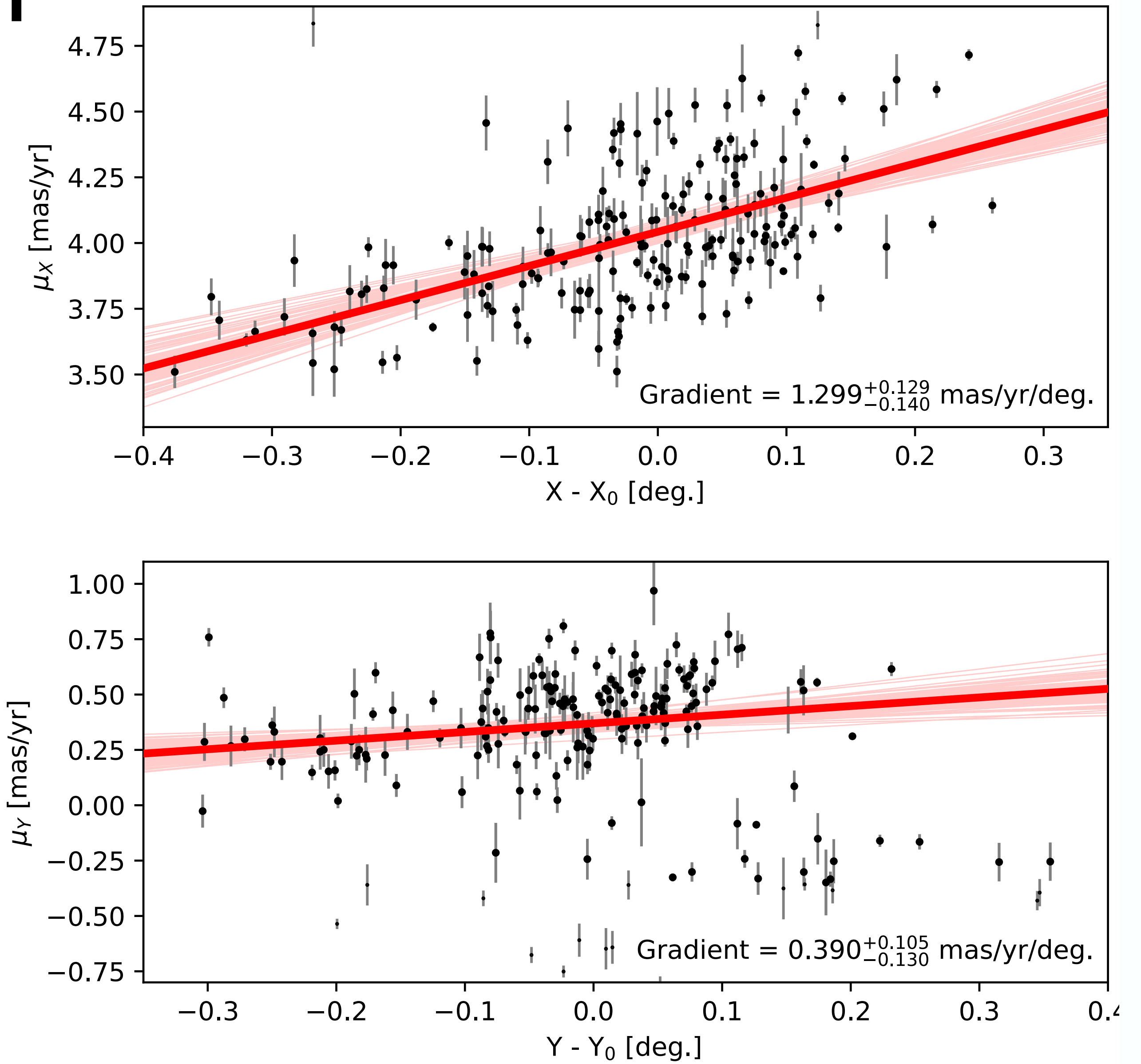
Most young star clusters not in virial equilibrium

But subvirial when mass of molecular cloud included




Wright+ (*subm*)

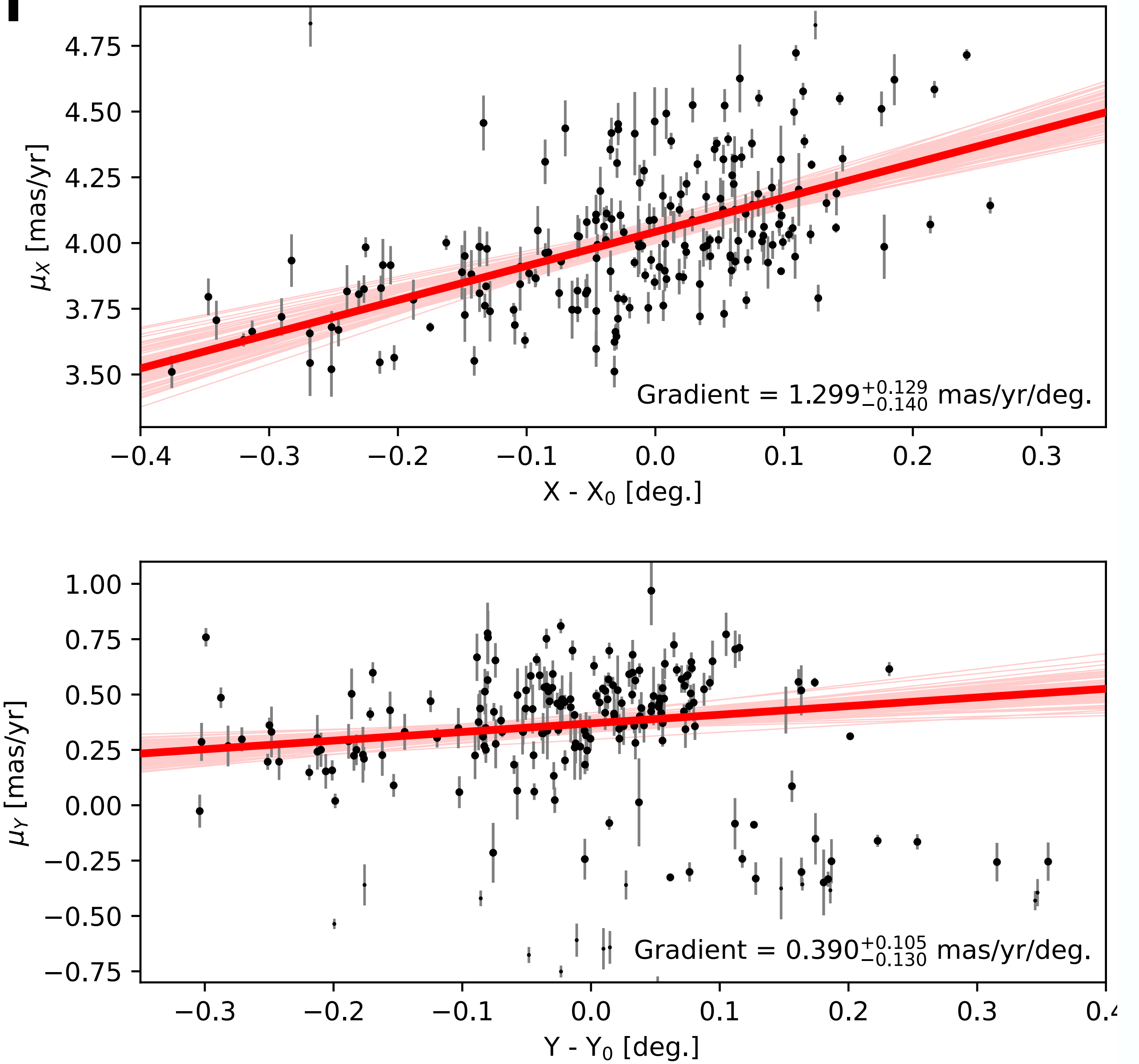
# Expansion




S Mon cluster (NGC 2264); Wright+ (*subm*)

# Expansion

94% of young clusters are expanding




S Mon cluster (NGC 2264); Wright+ (*subm*)

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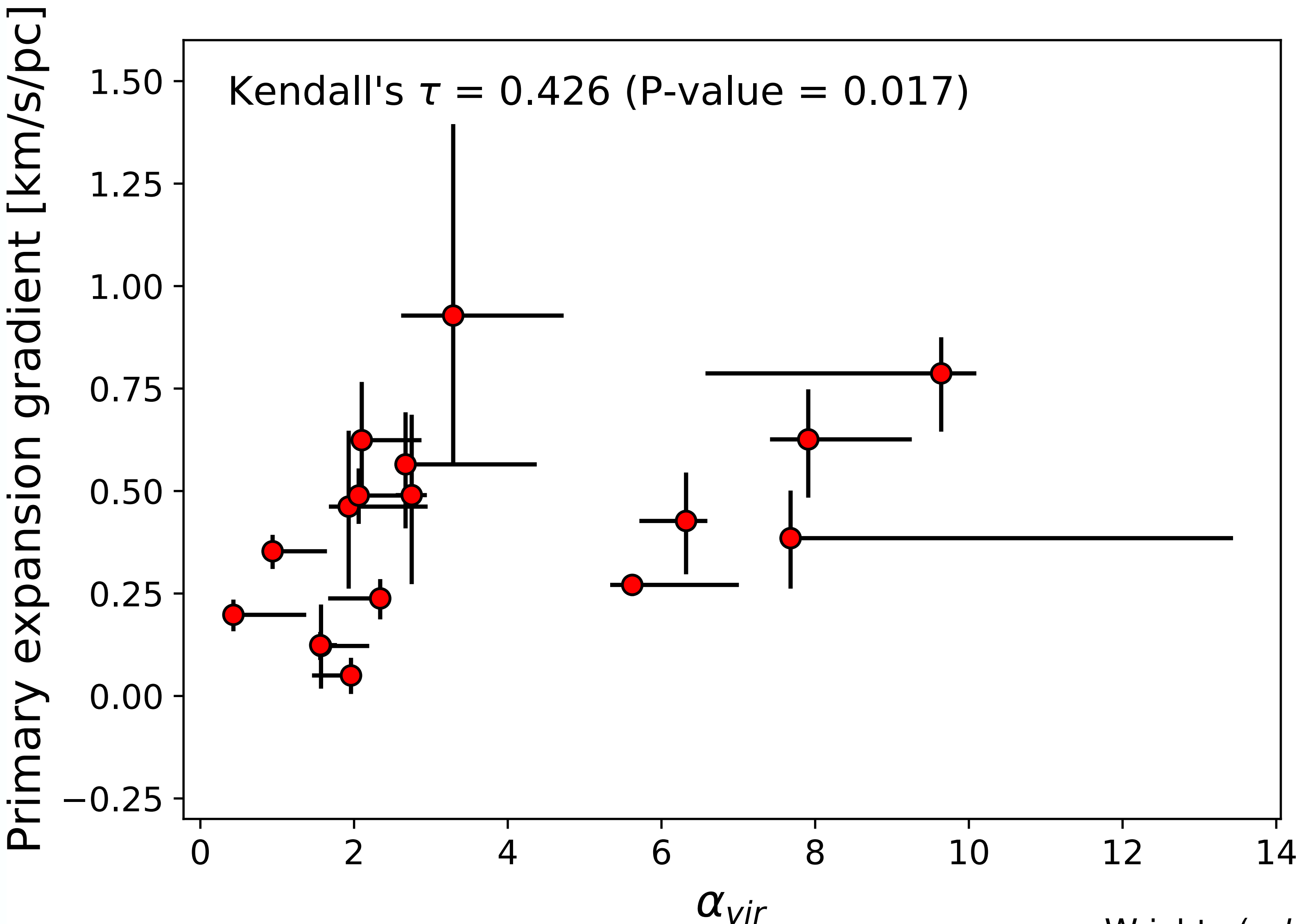
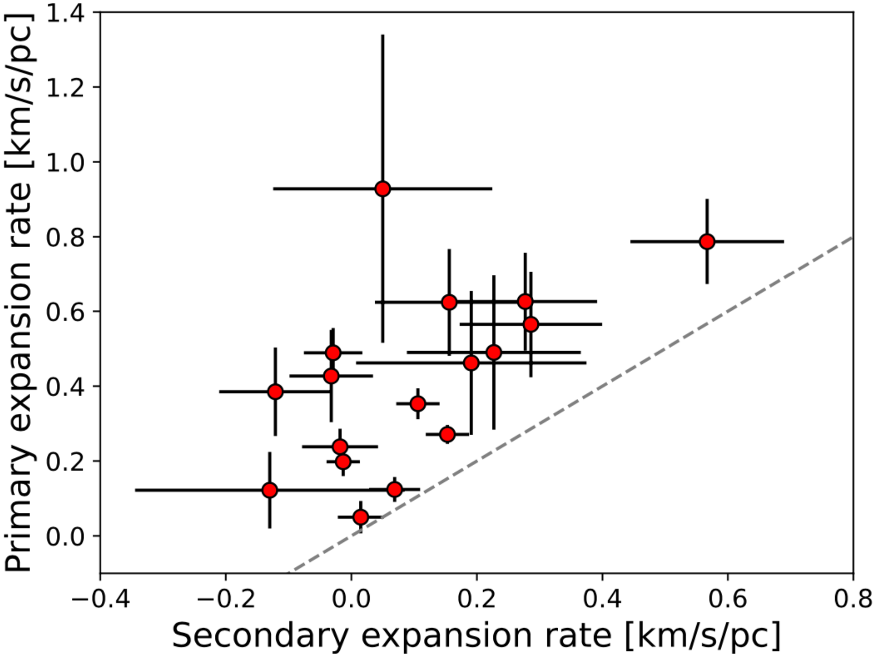
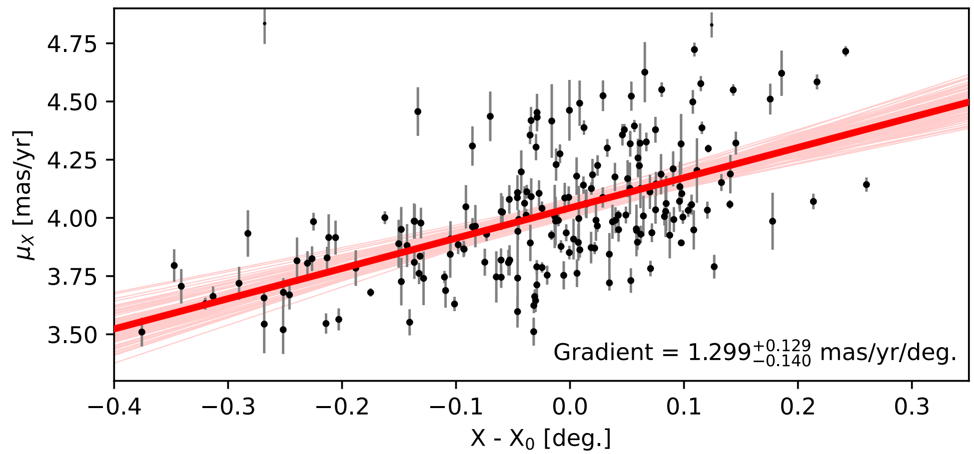


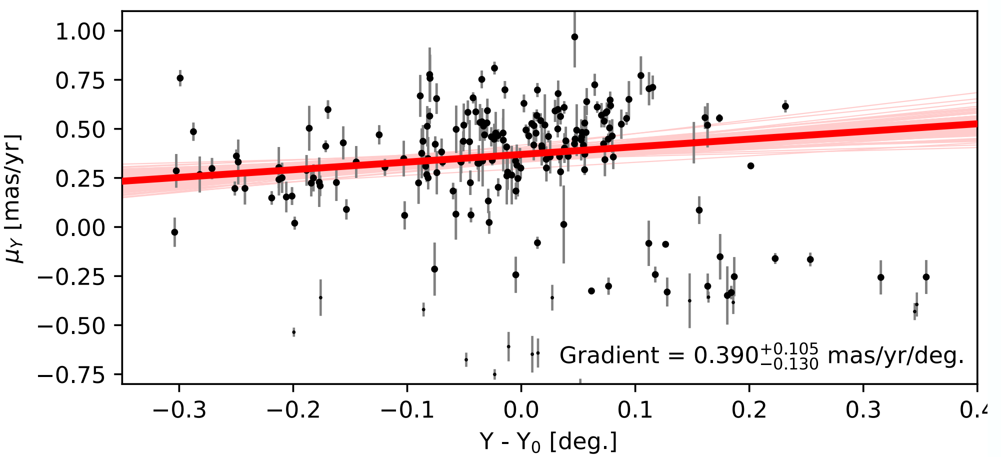

Wright+ (*subm.*)

# Asymmetric Expansion

- Most systems expanding asymmetrically
- Same as OB associations (Wright+ 2023, P&PVII).

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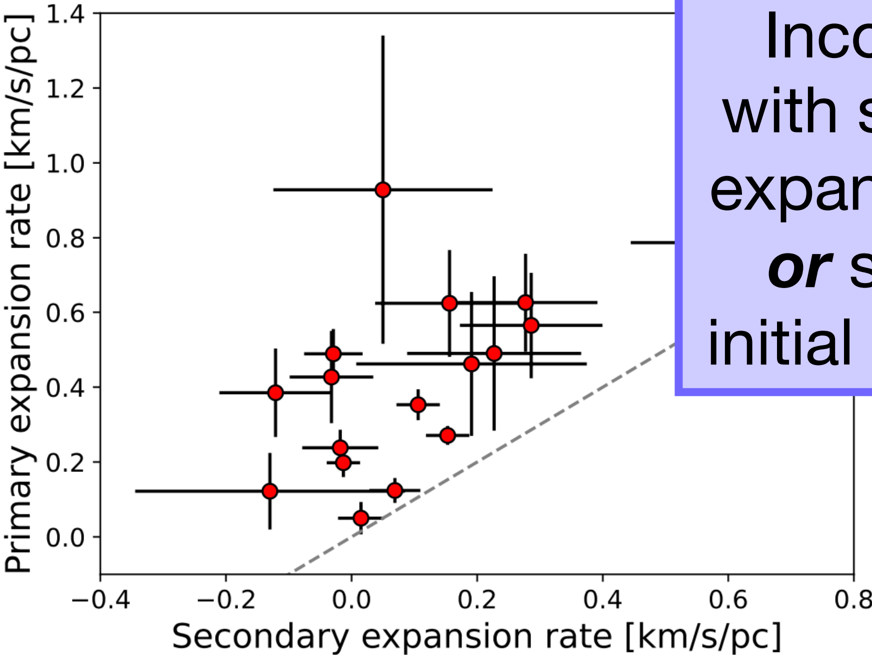
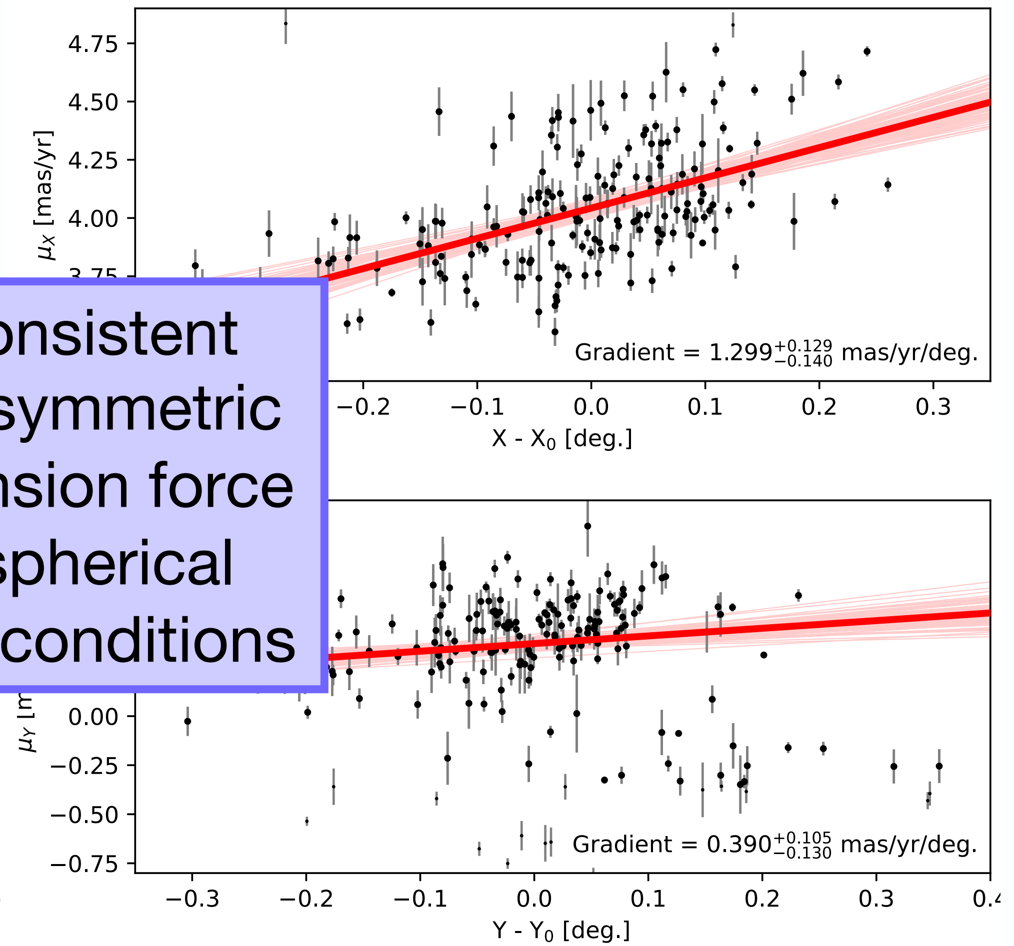



Inconsistent with symmetric expansion force ***or*** spherical initial conditions

Wright+ (*subm.*)

# Contracting: Rho Ophiuchus

Contracting according to all measures:

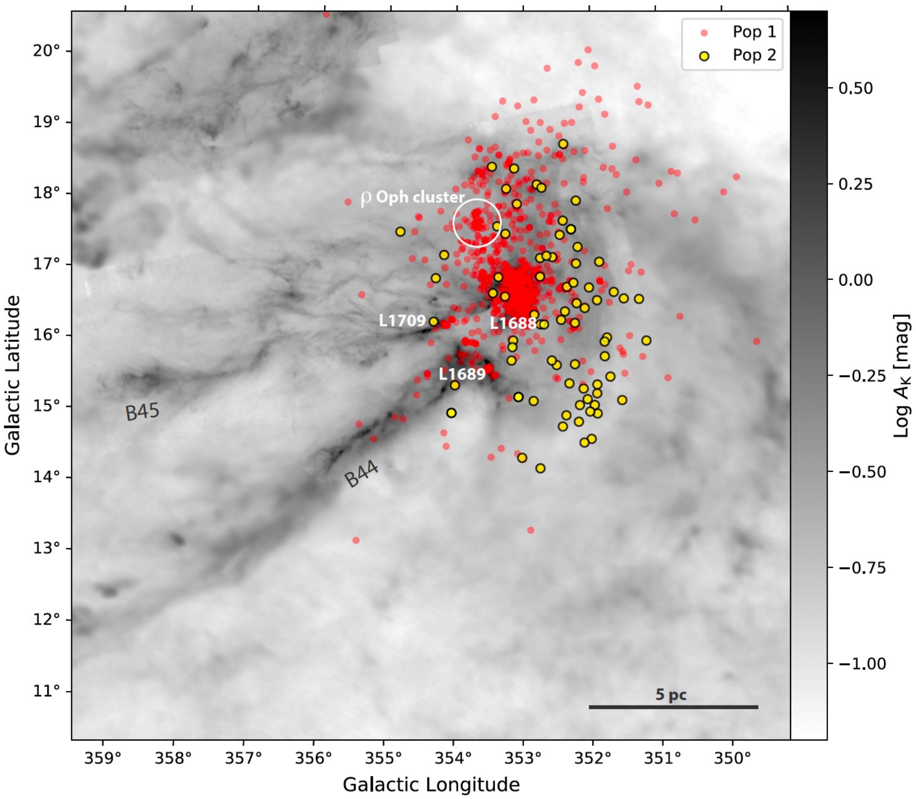
- 2D expansion gradients $= -0.18^{+0.22}_{-0.20}, -0.53^{+0.24}_{-0.21}$ km/s/pc
- Median outward velocity = $-0.34^{+0.01}_{-0.12}$ km/s

In virial equilibrium:

$$\alpha = 0.70^{+0.09}_{-0.03}$$

(when considering mass of L1688, which these stars surround)

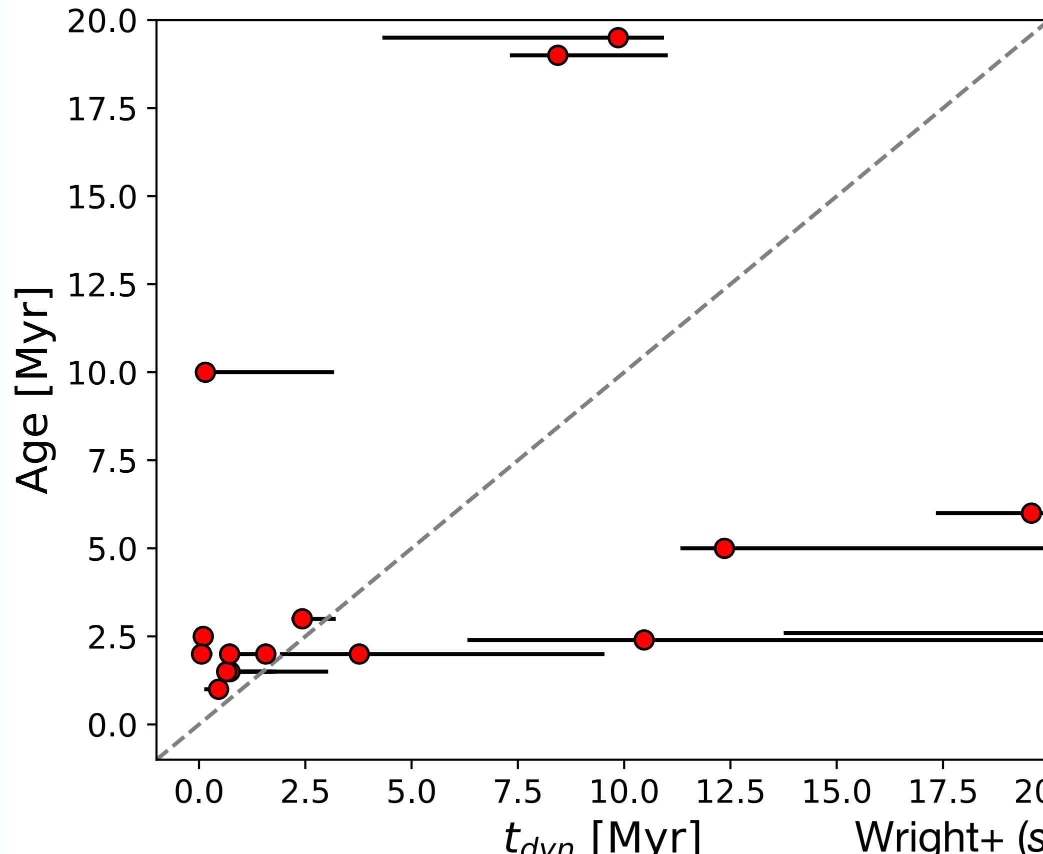
- First kinematic evidence for a young, contracting group of stars.
- Could lead to accretion of stars onto the forming cluster in L1688.




Grasser+ (2021)

# Star Cluster Formation

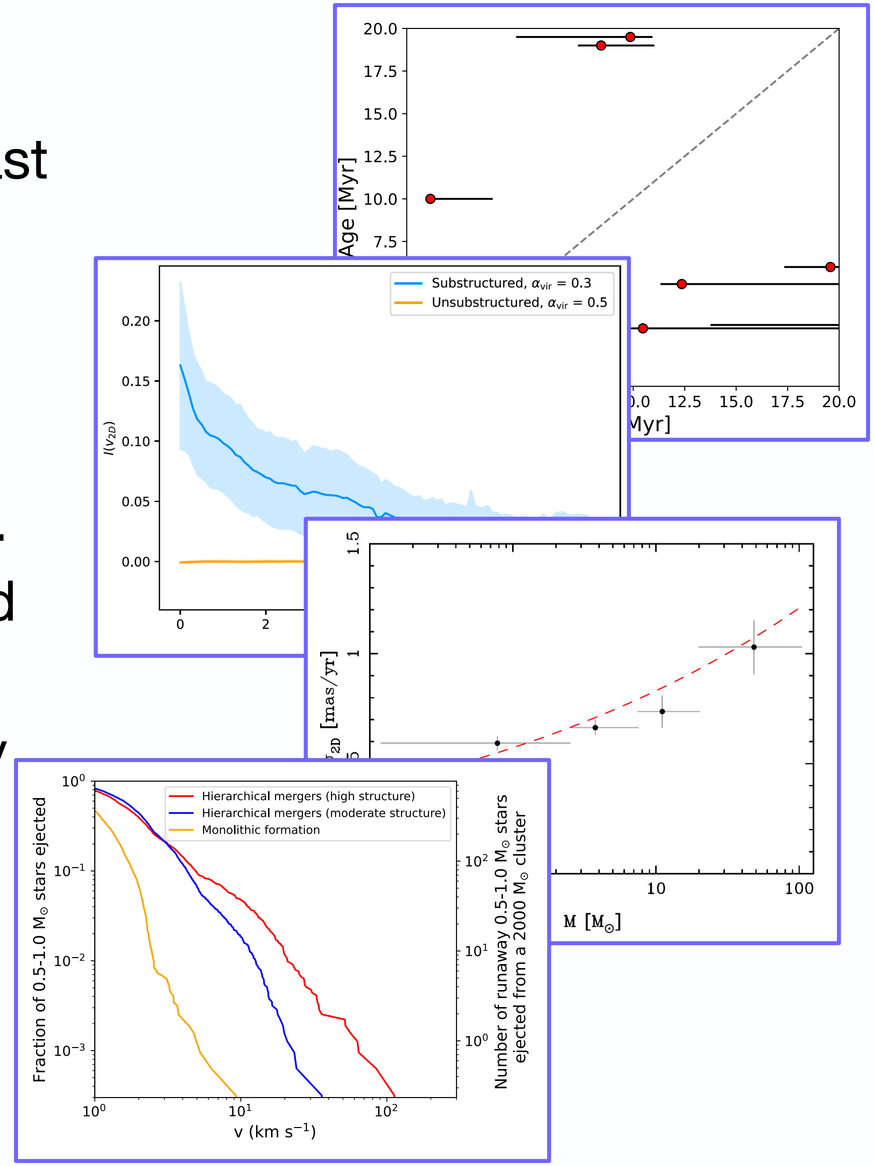
- Majority of groups older than their dynamical timescale (66-75%).
- Nearly all groups not dynamically evolved.
- Must have been less dense in the past.




Wright+ (*subm*)

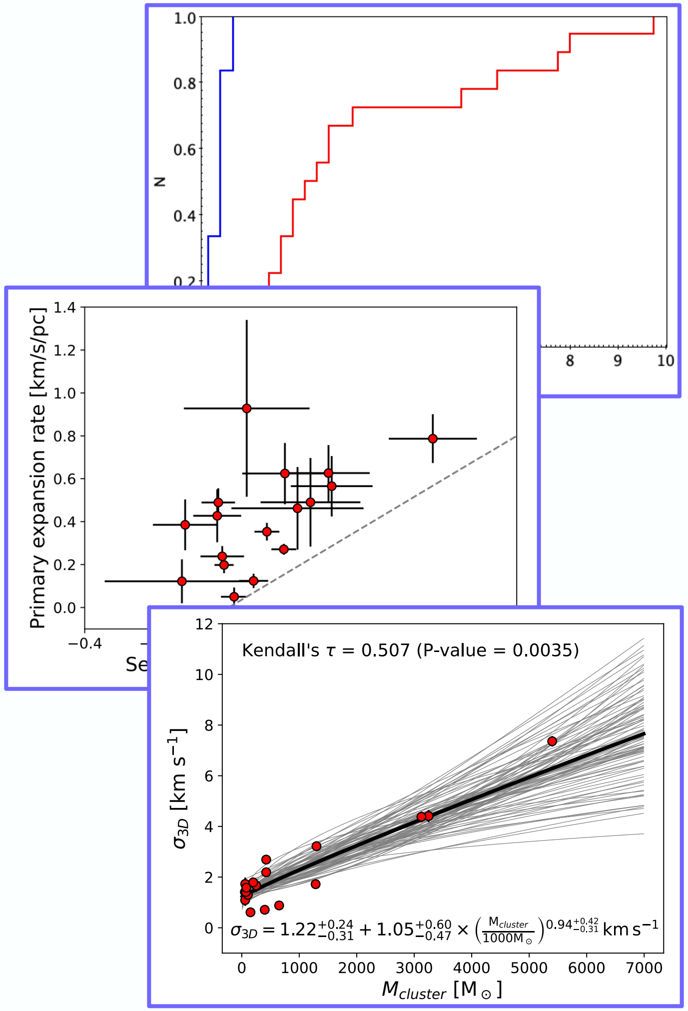
# Implications for star cluster formation

- Young clusters not dynamically evolved, suggesting a low-density past (Wright+ *subm*).
- Rho Ophiuchus observed to be contracting (Wright+ *subm*).
- Kinematic substructure detected in young clusters (Arnold+ 2022, *subm*).
- Inverse energy equipartition observed in NGC 6530 (Wright & Parker 2019).
- Large number of (candidate) runaway stars (Schoettler+ 2020, 2022).
- Most young clusters structurally elongated (Kuhn+ 2014).



# Implications for star cluster dispersal

- Clusters associated with molecular clouds are gravitationally bound, but clusters not associated with molecular clouds are mostly unbound (Wright+ *subm*).
- Most clusters and associations expanding asymmetrically (Wright+ 2023 P&PVII, Wright+ *subm*).
- Clusters not relaxed prior to expansion: asymmetric spatially & kinematically (Kuhn+ 2014, Wright+ *subm*).
- More massive clusters more likely to be out of virial equilibrium? (Wright+ *subm*).



# Summary: arxiv/2311.08358

- 3D kinematic study of ~2500 young stars in 18 young clusters and associations, all with spectroscopically-verified youth.
- Implications for star cluster formation: growing picture favours formation via collapse and mergers.
- Implications for star cluster dispersal: consistent with residual gas expulsion, but some asymmetric force at work **and** clusters not dynamically relaxed prior to expansion.

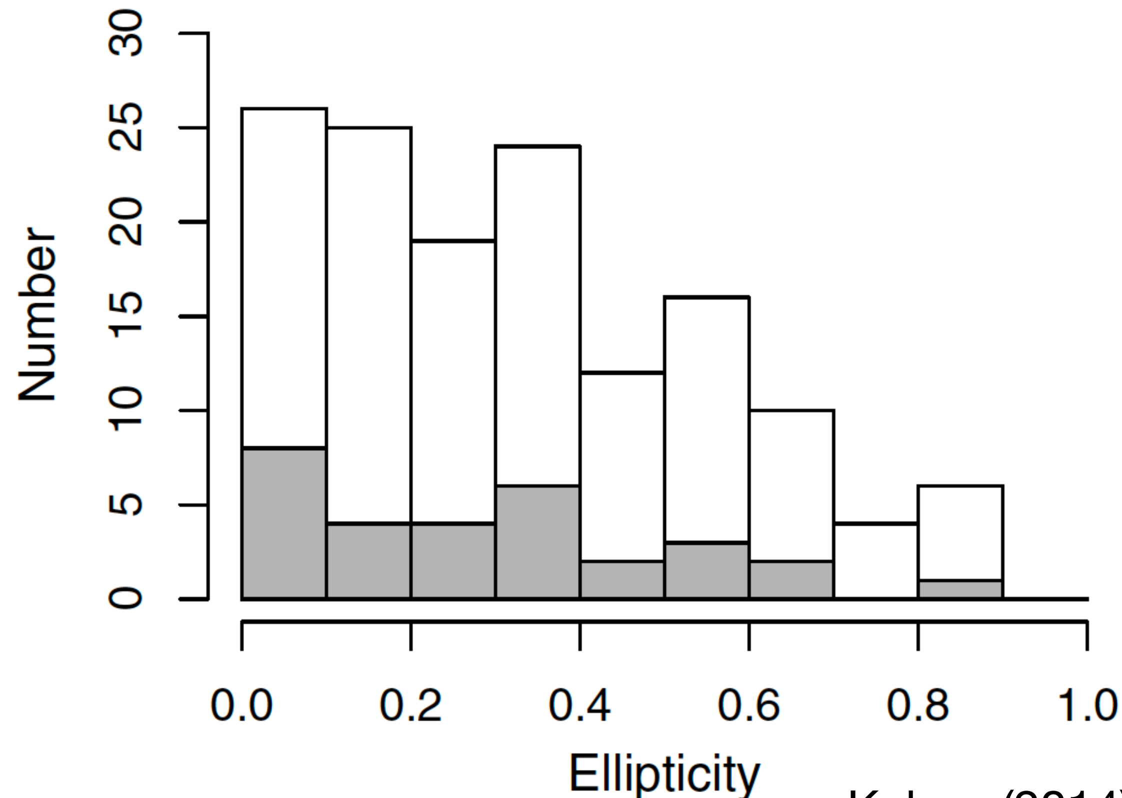
Thank you for listening

# Summary: arxiv/2311.08358

- 3D kinematic study of ~2500 young stars in 18 young clusters and associations, all with spectroscopically-verified youth.
- Linear correlation between 3D velocity dispersion and mass, implying $\alpha \propto M^{0.625-0.75}$ (i.e., more massive clusters are more super-virial).
- Majority of groups are super-virial, but sub-virial when the mass of the molecular cloud is considered.
- Majority of systems are expanding, anisotropically (implying either a non-isotropic force is at work ***or*** clusters are not spherical prior to expansion).
- Rho Ophiuchus is contracting: optically visible stars will accrete onto or merge with embedded cluster in L1688.
- Majority of clusters are older than $t_{dyn}$ yet are dynamically unevolved, implying they were less dense in the past.

# Morphology and ellipticity

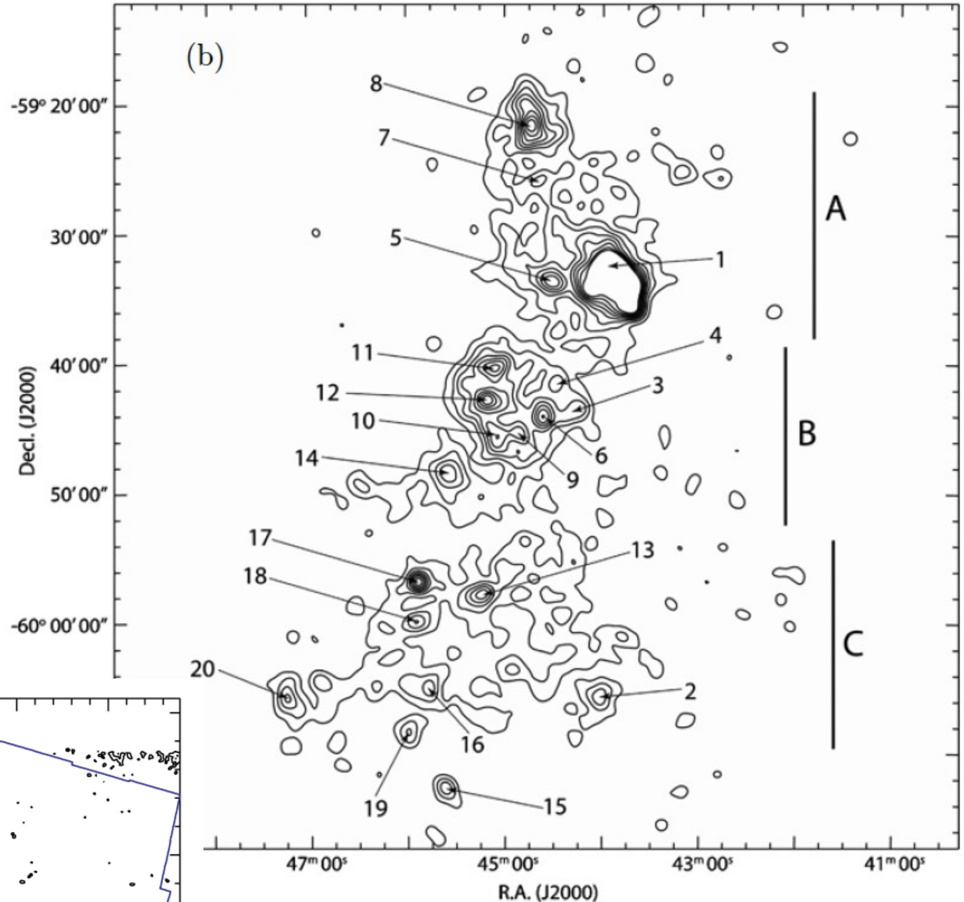
- Most young clusters are non-spherical.
- Ellipticity is higher for embedded clusters than non-embedded clusters (Getman+ 2018).



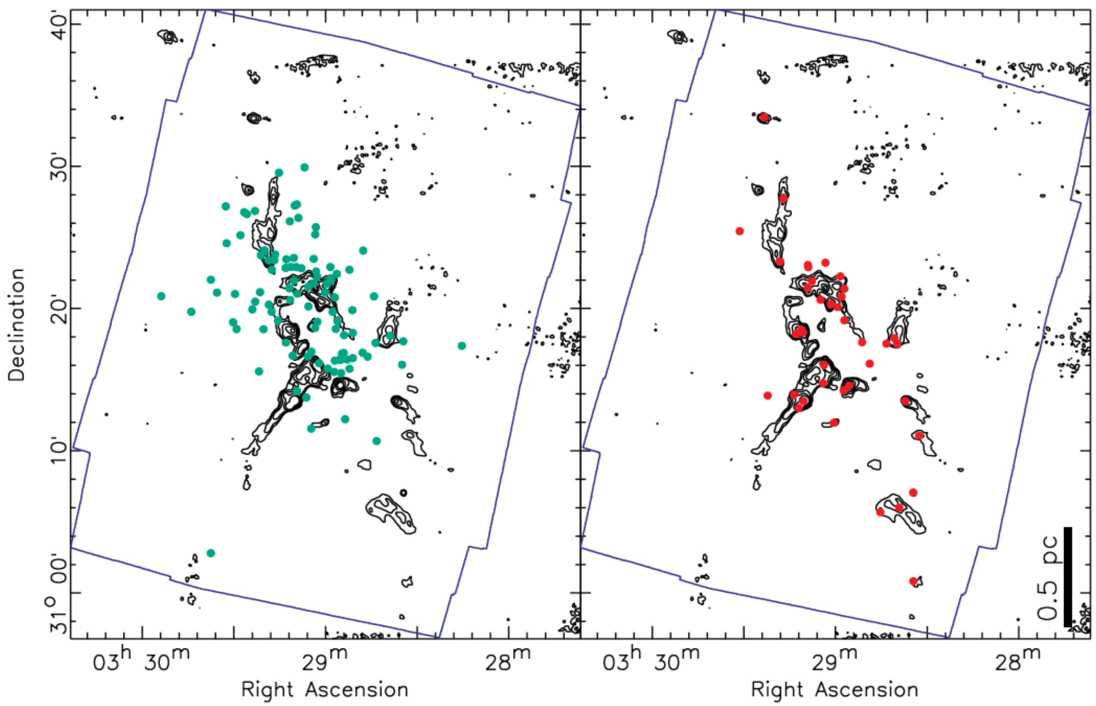

Kuhn+ (2014)

# Substructure

Substructure is common in star forming regions.

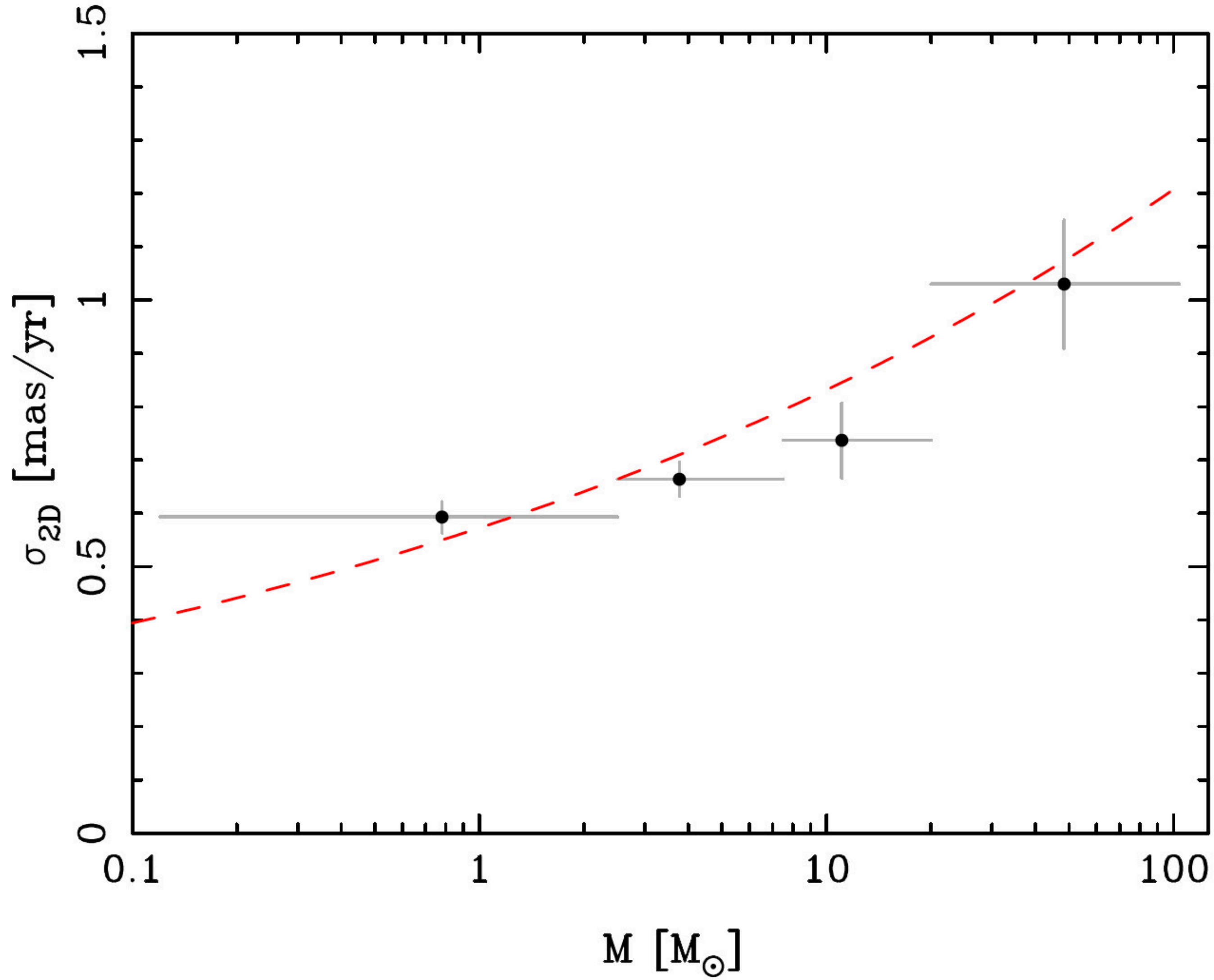



Feigelson+ (2011)



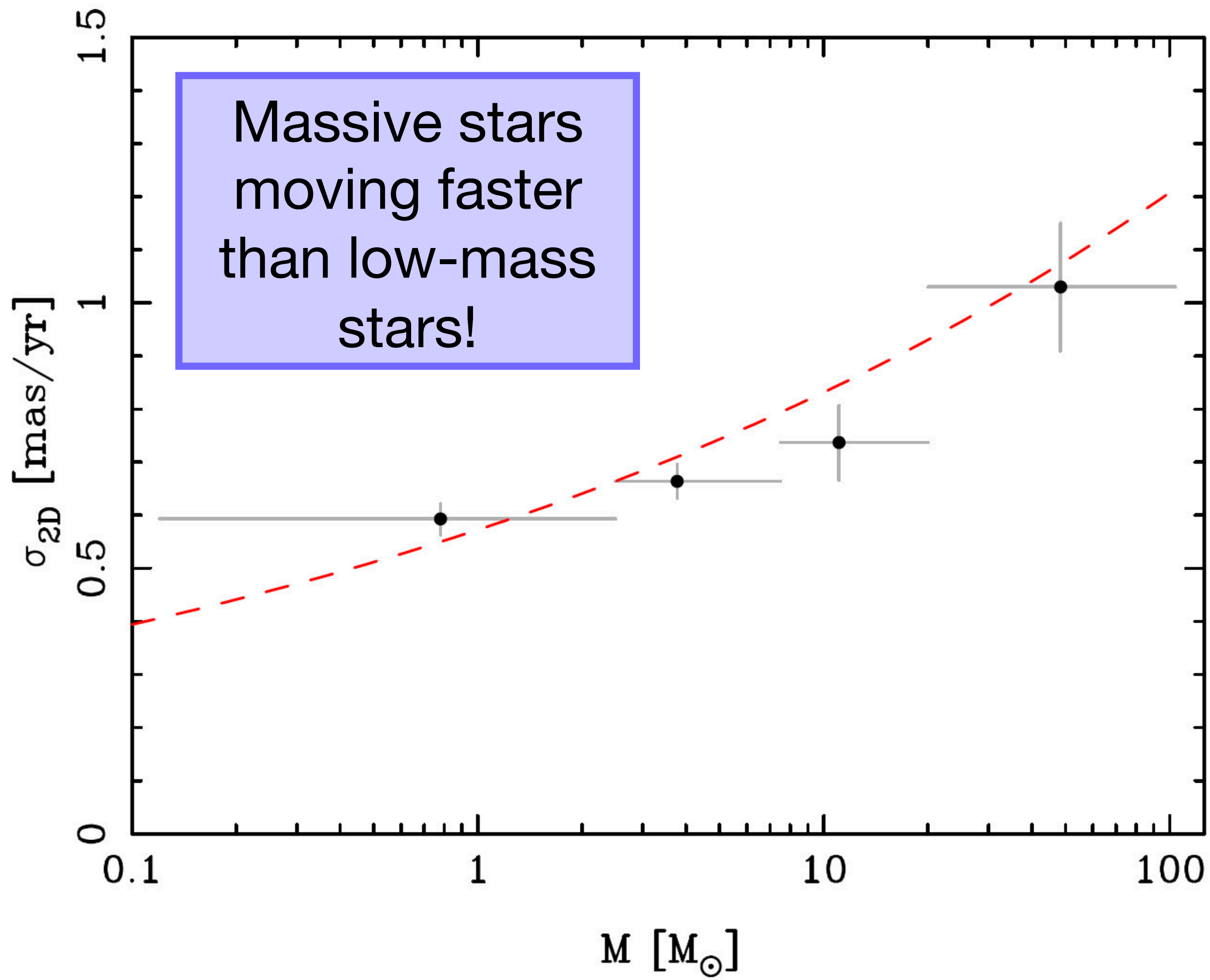

Gutermuth+ (2008)

# Velocity dispersions




Wright & Parker (2019)

# Velocity dispersions




Wright & Parker (2019)