

# Rotation and expansion in open clusters using simulations and Gaia DR3

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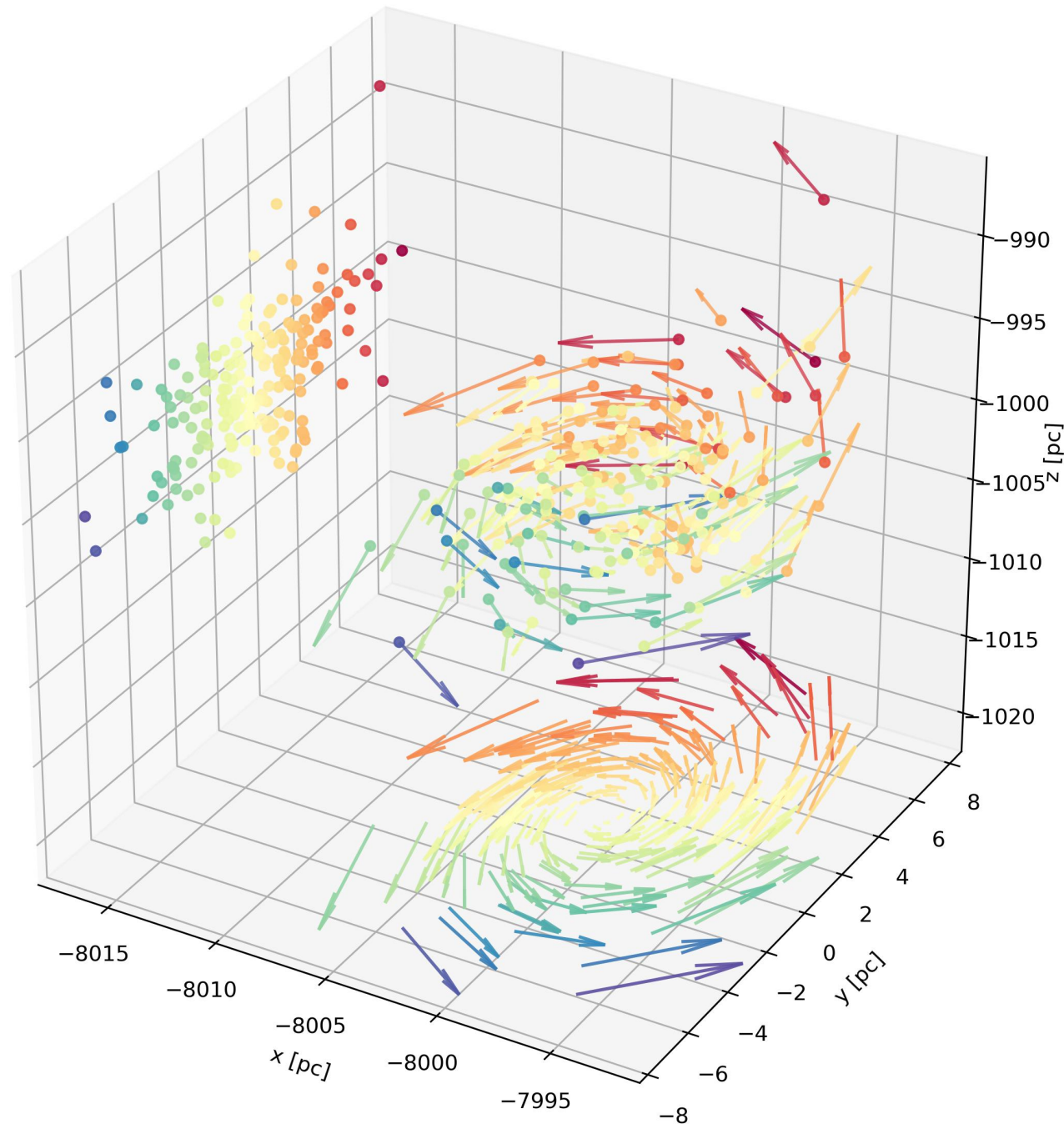
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# Background

- ◆ Rotation seen in >20 GCs (van Leeuwen+2000, Bianchini+2018, Szigeti+2021)
- ◆ Rotation in MW nuclear cluster (Schödel+2009)
- ◆ Linked with –
  - ◆ Cluster flattening (Kacharov+2014)
  - ◆ Multiple stellar populations (Carretta+2009)
- ◆ Slower rotating GCs: Bluer HBs and lower [Fe/H] (Bellazzini+2012)
- ◆ ~10 OCs with rotation patterns (Guilherme-Garcia+2023, Hao+2024)
- ◆ Spin of cluster and its stars are aligned\* in OC NGC 6791 (Kamann+2019)
  - ◆ Likely residual of GMC rotation
- ◆ High precision data availability: Gaia, APOGEE, LAMOST, GALAH... 4MOST, LSST...

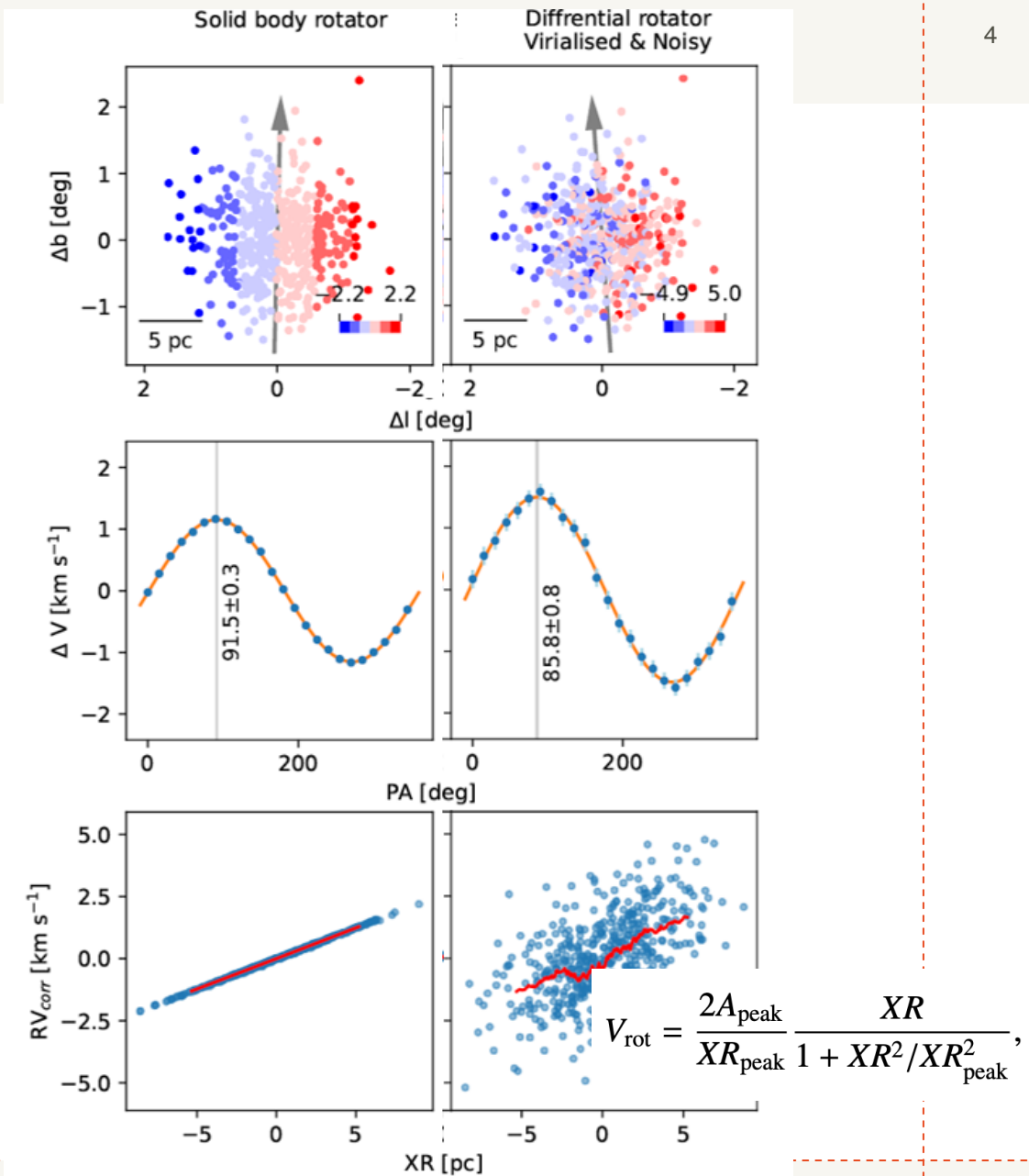


# Spinning cluster

- ◆ Pole on view
  - ◆ The proper motion shows rotation
  
- ◆ Edge on view
  - ◆ Half of the cluster is red/blue shifted

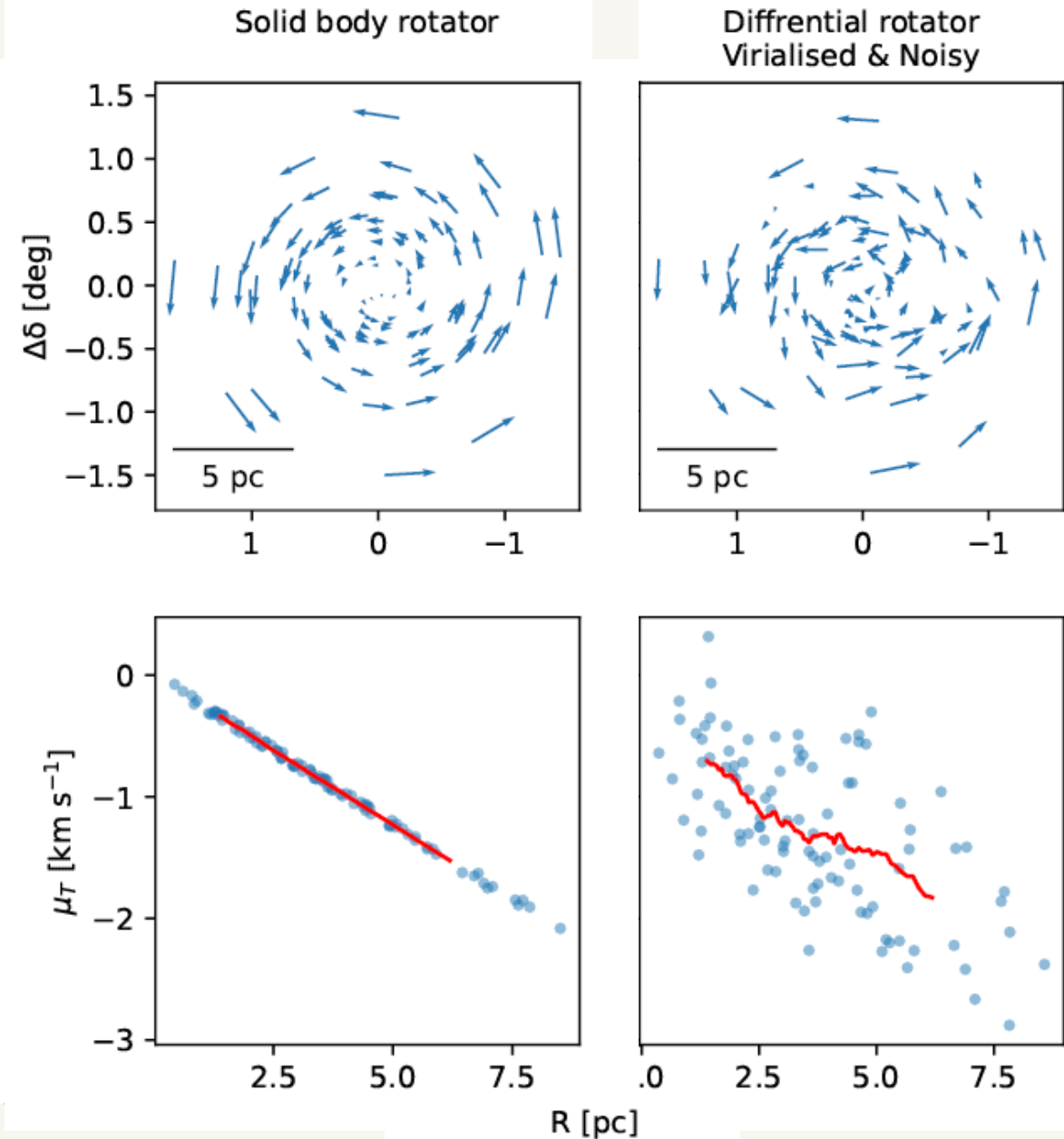
# Spin using RV

- ◆ Edge on view
- ◆ Assume a spin axis with  $PA$
- ◆ Divide the cluster using the axis and calculate difference between the mean RV of two halves ( $\Delta V$ )
- ◆ Maximize  $\Delta V$  for various  $PA$
- ◆ The  $RV$  vs radius gives  $\sim v \cos(i)$



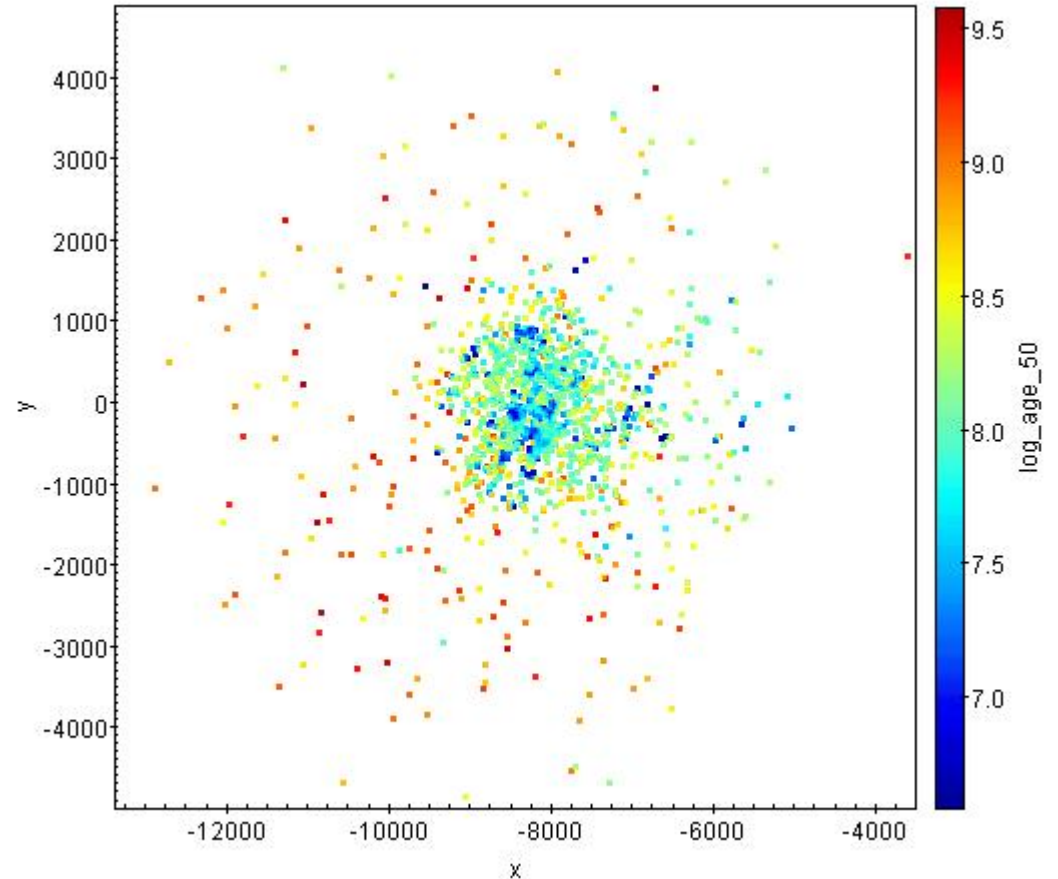
# Spin using PM

- ◆ Split the PM in  $\mu_T$  and  $\mu_R$
- ◆ Suited for **polar** view
- ◆ Change in  $\mu_T$  with radius gives measure of  $\sim v \sin(i)$
- ◆ More error sensitive than RV



# Sample selection: clusters

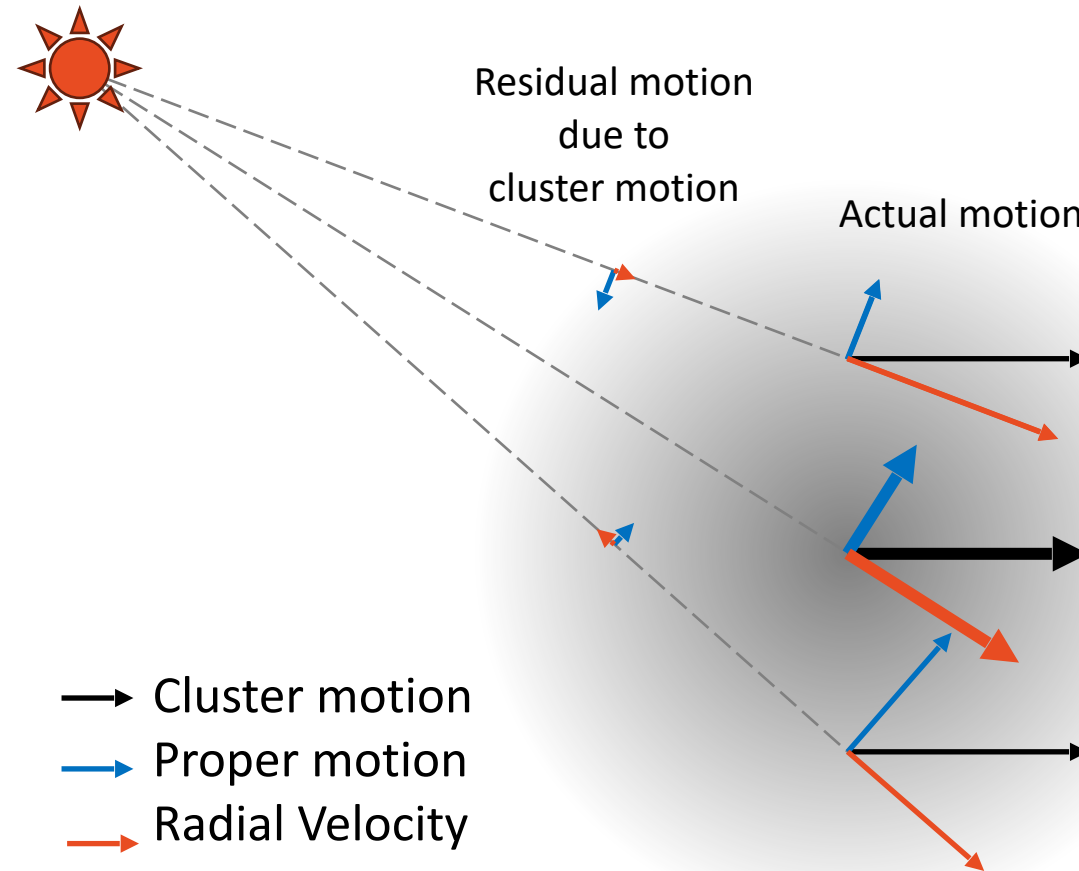
- ◆ Gaia DR3 OC catalog (Hunt+2023,2024)
  - ◆ Cluster identification using HDBSCAN
  - ◆ ~7000 star systems with members and parameters (age, mass, radius...)
- ◆ **1428** high quality **open clusters** with known space velocity
  - ◆  $N_{\text{stars}} = 15 - 4000$
  - ◆ Age = 3 – 4500 Myr
  - ◆ Distance = 50 – 9000 pc
- ◆ RV Data from Gaia DR3, APOGEE, GALAH, Gaia-ESO, LAMOST, RAVE



Spatial distribution of cluster sample

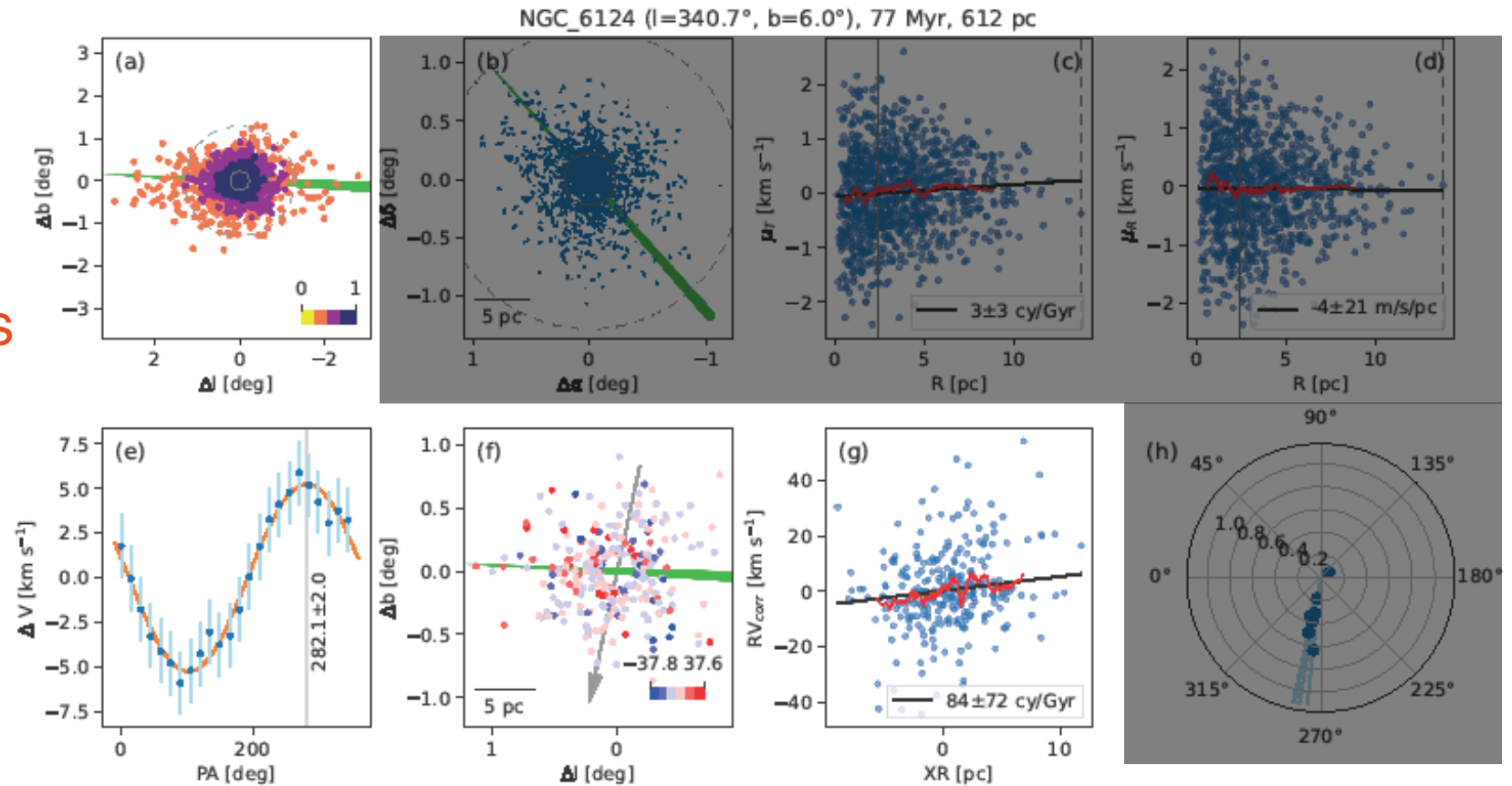
# Correction for Solar motion

- ◆ The cluster members are at slightly different distance from us
  - ◆ The projected PM and RV are affected
  - ◆ The cluster appears to spin and contract
- ◆ Corrections based on the relative motion  
(van Leeuwen+2009)



# Example of NGC 6124

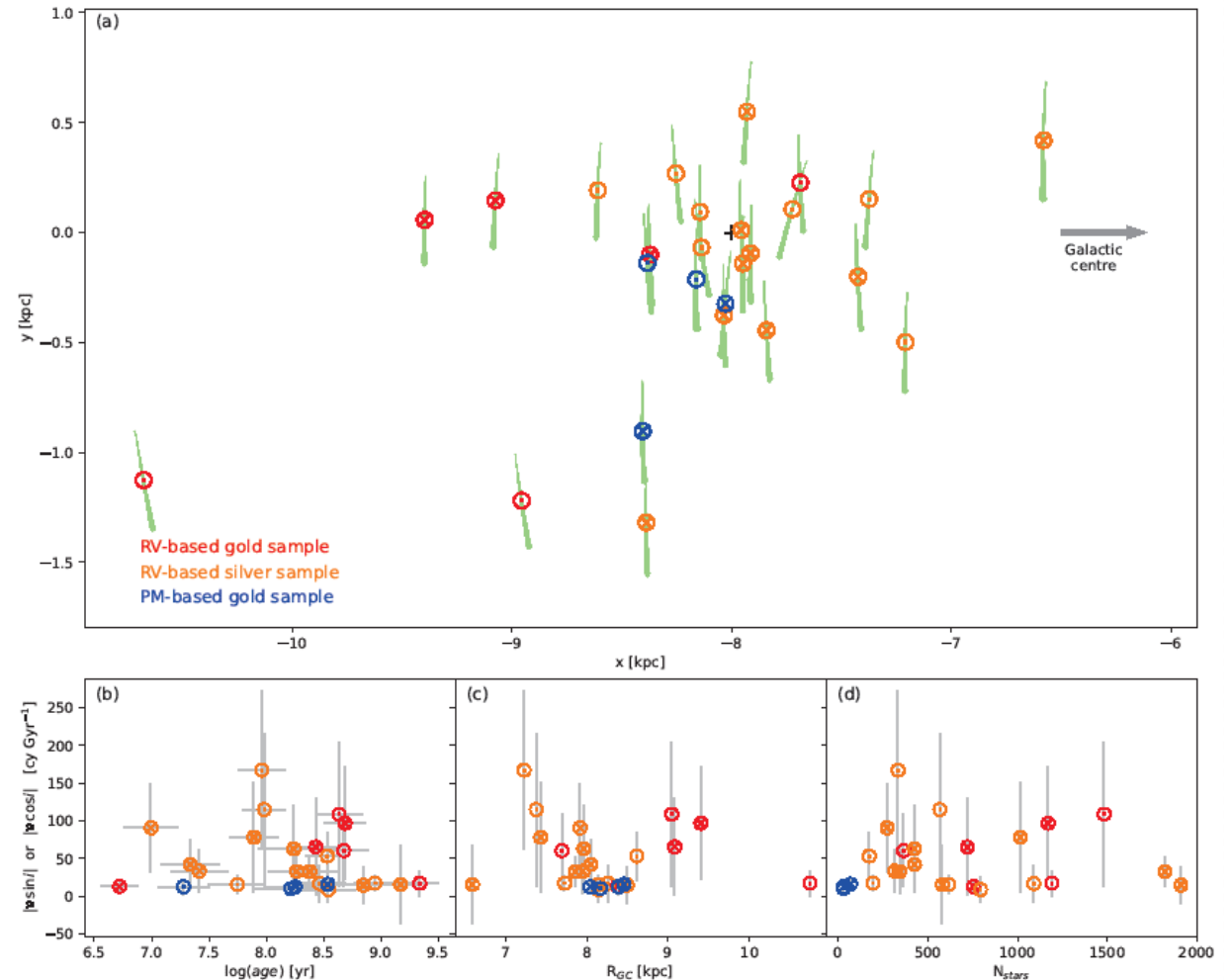
- Spin signature in RV distribution of NGC 6124
- Spin seen in 10 clusters (6 RV, 4 PM based) +16 candidates
- Spin rates: 10–170 cycles/Gyr





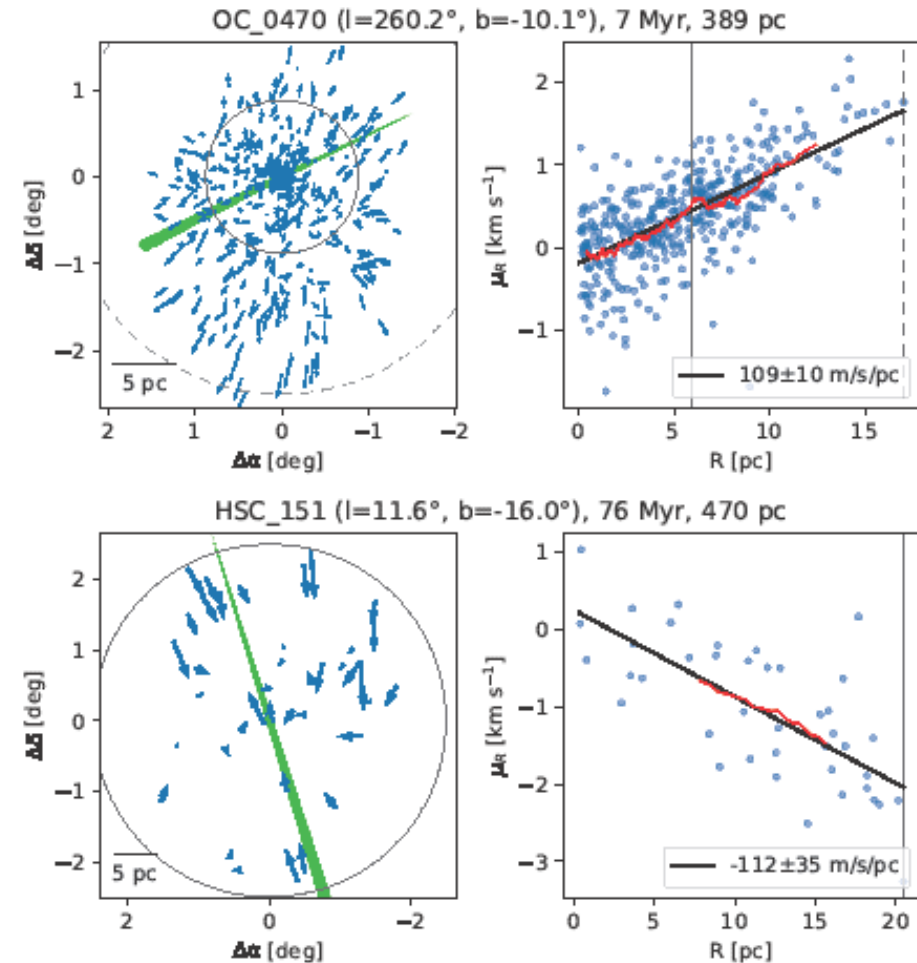
# Spin and its Orientation

- ◆ If the Galactic orbit/interaction is the main cause, the spin should have some correlation with the **orbital angular momentum**
  - ◆ There is **no correlation**
- ◆ No dependence on age,  $R_{GC}$  or number of stars

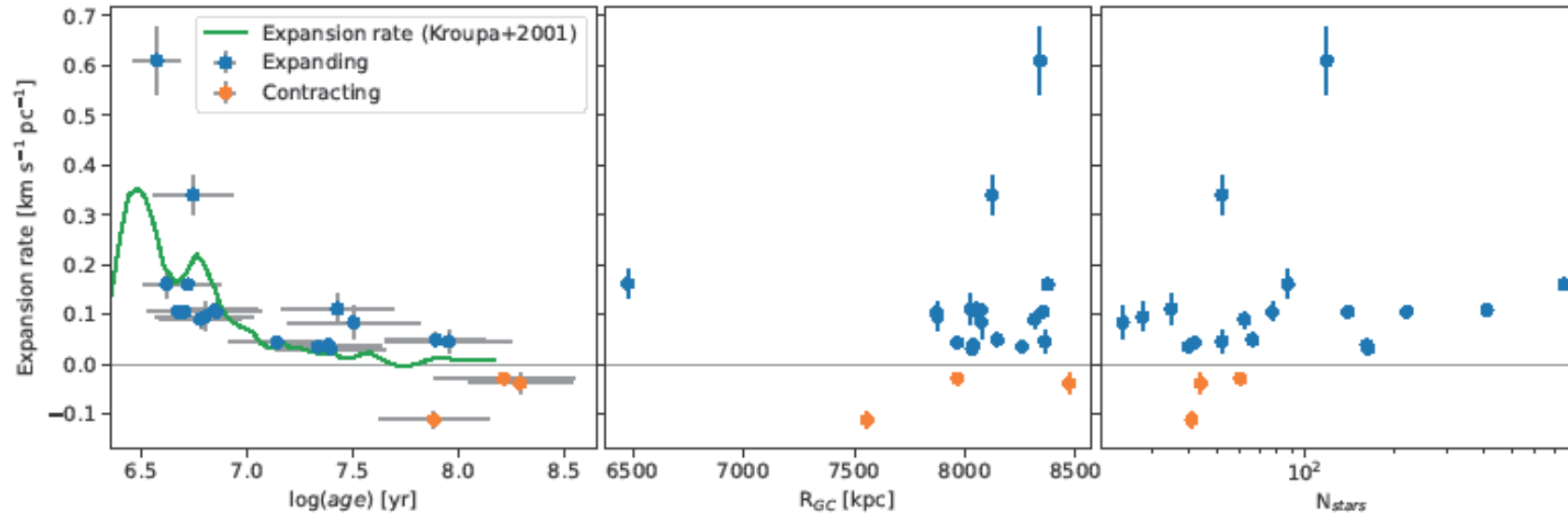


# Cluster Expansion/Contraction

- ◆ Changes in  $\mu_R$  with radius
- ◆ **18 expanding** clusters  
(4% of clusters younger than 100 Myr)
- ◆ **3 contracting** clusters – Why?
  - ◆ Expansion cycles during the Virialization?
  - ◆ Ejection of stars in dense clusters (King1958)



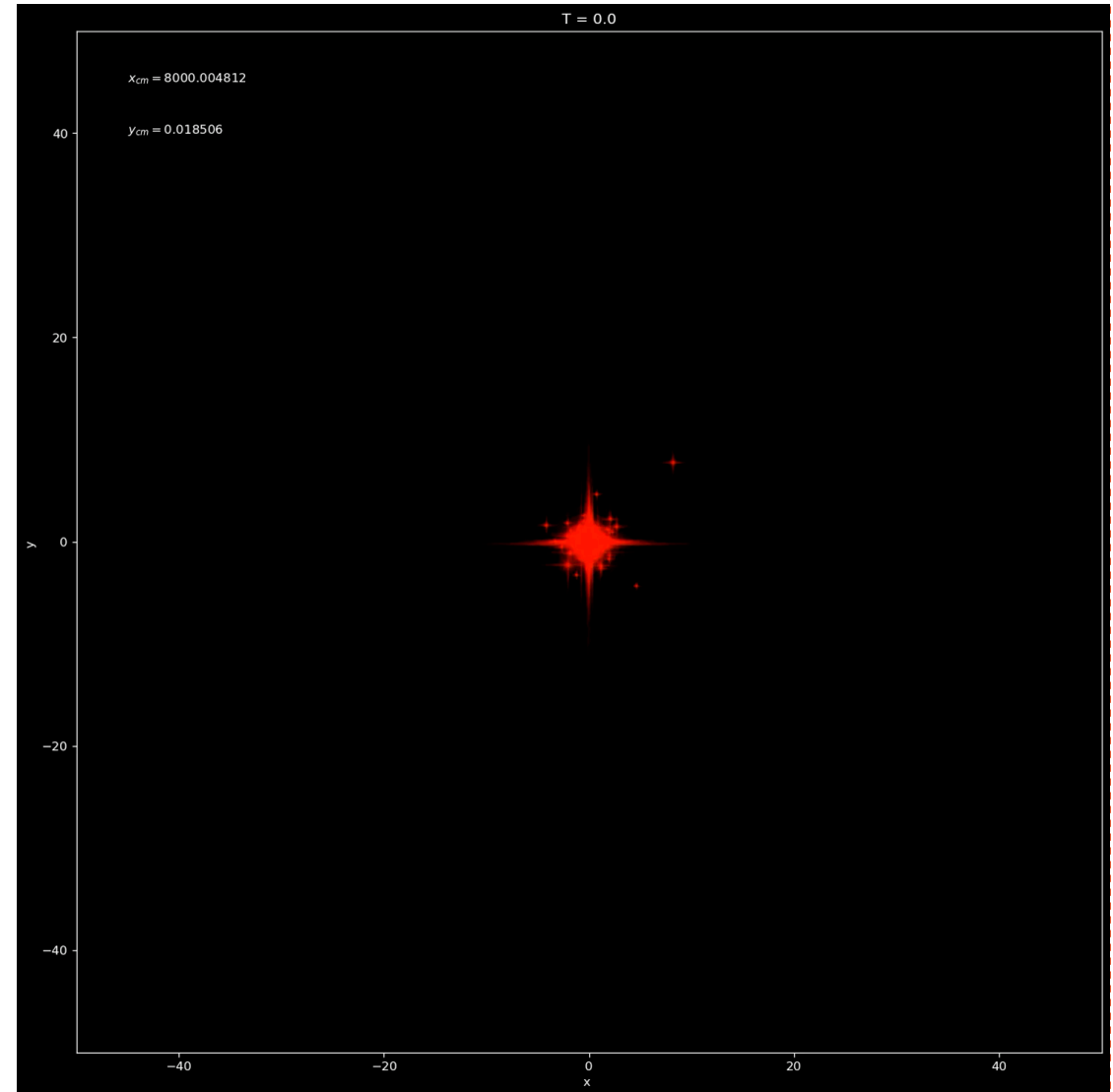
# Cluster Expansion/Contraction...



- ◆ Expansion rate-Age matches with simulations (Kroupa+2001)
  - ◆ Gas expulsion and mass loss through evolving stars
- ◆ No other dependence observed

# N-body simulations

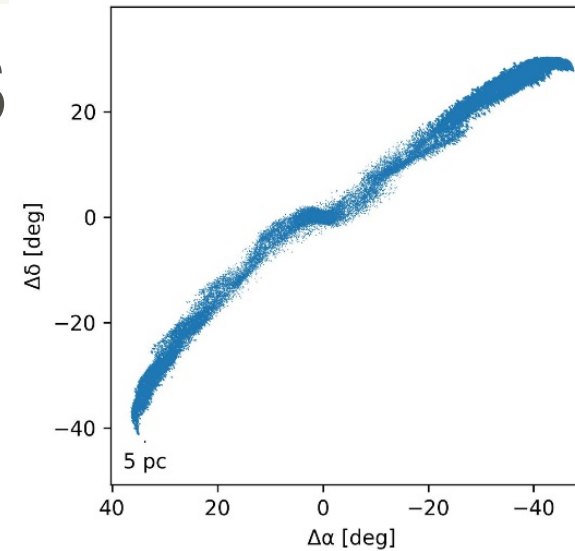
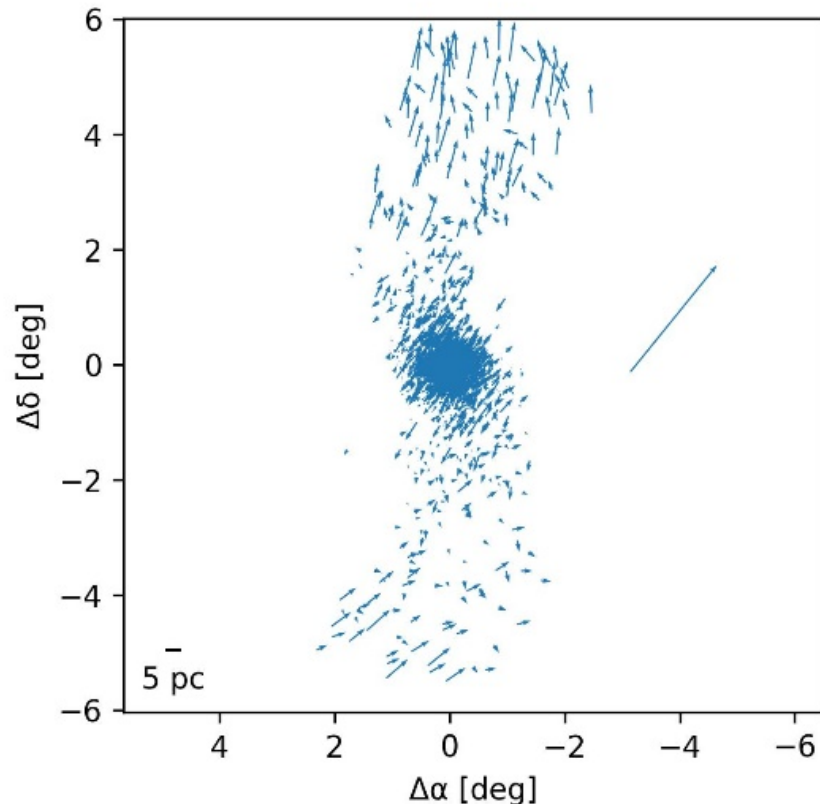
- ◆ Simulated  $\sim 2000 M_{\odot}$  OCs  $\sim 1$  Gyr
- ◆ Including stellar evolution, pair instability, SNs, Galactic potential
- ◆ Synthetic observations of simulated clusters to identify spin
  - ◆ Recovering rotation signatures
  - ◆ Tidal tails always rotating, so stars within the tidal radius ( $\sim 10$  pc) are analyzed



# Simulated clusters

PeTar ([Wang+2020](#))

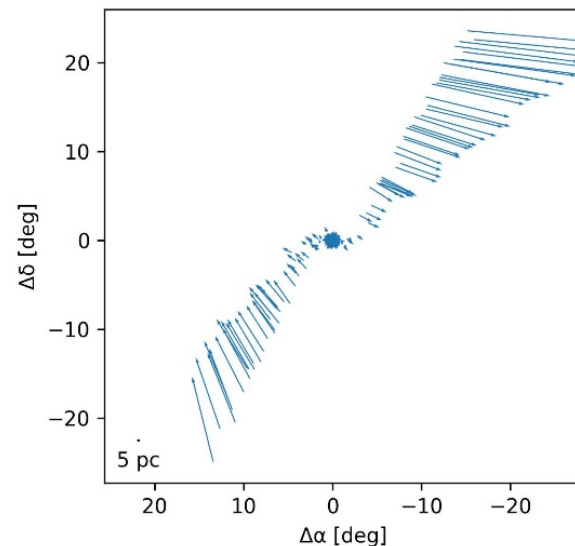
Binaries, IMF,  $N \sim 2000$ , Stellar evo., SN kicks...



Phantom of Ramses

([Lügghausen+2015](#),  
[Kroupa+2022](#))

Equal mass particles,  
 $N \sim 20000$ , Newtonian  
& MOND dynamics

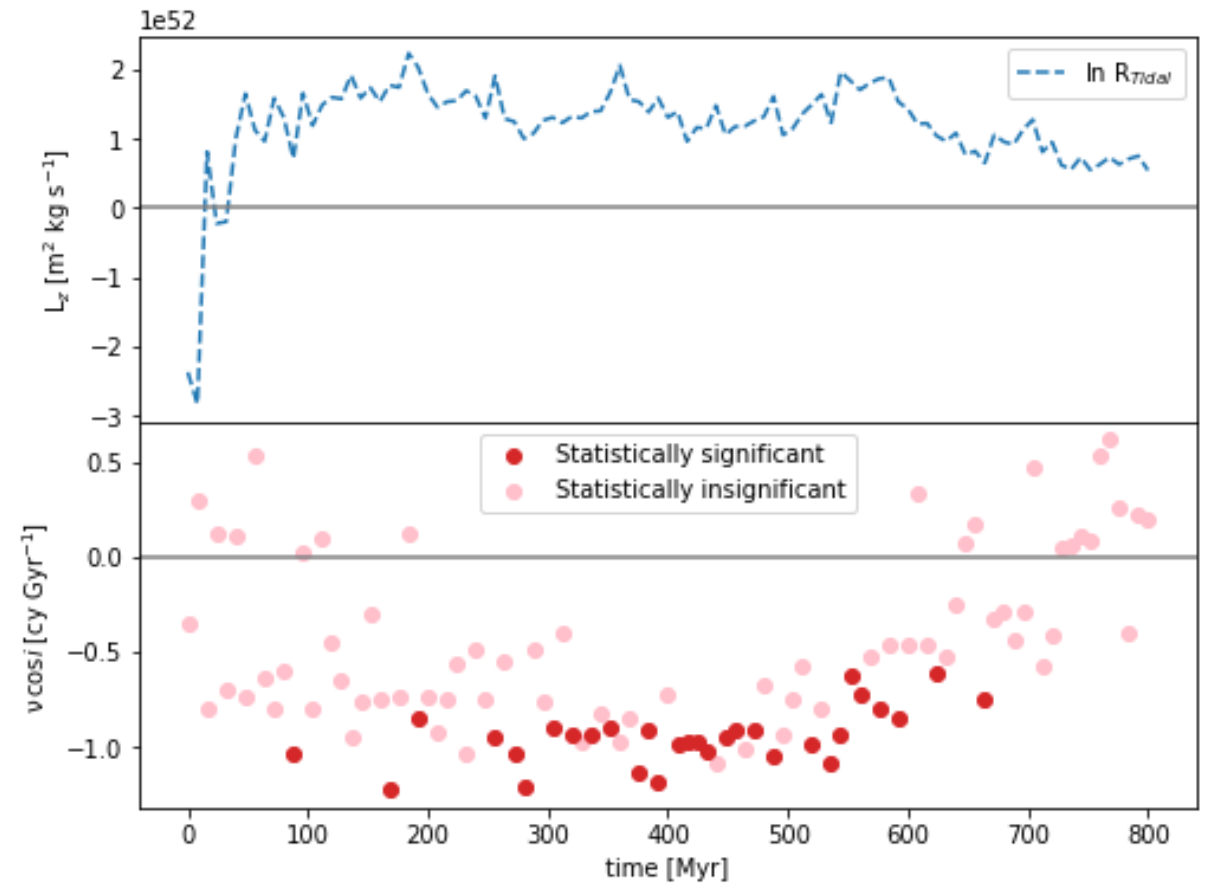


Milgromian Law  
Dynamics (MLD;  
[Pflamm-Altenburg+2024](#))

Equal mass particles,  
 $N \sim 1000$ , MONDian  
dynamic

# Spin in Simulations

- ◆ Initial  $L_z$  is negligible
- ◆ The clusters *slightly* spin aligned with the Galactic orbit
  - ◆  $|v \cos(i)| \sim 0-5$  cycle/Gyr
- ◆ Other mechanisms required to get the observed  $\sim 100$  cy/Gyr spin



# Source of spin

- ◆ **>0.6%** open clusters have **detectable spin**
  - ◆ Actual number would be higher –
    - ◆ poor statistics; unsuitable inclination; limitation of the detection method
  - ◆ For comparison: 20–30 (~15%) GCs have rotation signatures
- ◆ Observed spin rate: 10–170 cy/Gyr
  - ◆ Rotation around the MW and tidal tails have minimal effect (~ 5 cy/Gyr)
  - ◆ **Molecular clouds** have velocity gradients of ~30 cy/Gyr (Braine+2020)
  - ◆ **Initial spin** is integral
- ◆ **Collisions** with other clusters/GMCs/Spiral arms?

# Outlook

- ◆ **RV precision** (and availability) is the primary limitation
- ◆ Better sample (waiting for **Gaia DR4/5, LSST, WEAVE, 4MOST...**)
- ◆ Simulations based on **primordial spin** and **cluster-cluster interactions**

Questions?



