Detection of open cluster rotation fields from Gaia DR3 proper motions

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Context

- Open clusters and associations have been continuously forming in the disk, dissolving, and building the field population.
- **Theory** shows how encounters with GMCs and spiral arms, galactic tidal forces and secular evolution lead to quick disruption or gradual dissolution of star clusters. (talks by Duarte Almeida and Sandro Moreira).
- The **observational** study of cluster internal dynamics and dispersal has proved much **harder:**
    - Kinematic measurements **limited by small proper motions**. Until Gaia most studies have been LOS RV (1D view).
- We need PMs for full spatio-kinematic characterisation.

Previous work - rotation of clusters in proper motions

- **Rotation** of **GCs** seen in proper motions for > 20 objects, pre* and post** Gaia.
- But **OCs** have few members, sparse distributions seen against crowded fields in the disk: poorly sampled and contaminated of velocity maps.
- Very few detections of OC rotation in proper motions:
  - Kuhn+ 2019: 28 OCs with Gaia DR2, find only one rotating (Tr 15)
  - Loktin & Popov 2020 also DR2 measured rotation of Praesepe.

* e.g. van Leeuwen+ 2000; Anderson & King 2003; van de Ven+ 2006; Massari+ 2013; Bellini+ 2017
** e.g. Bianchini+ 2018; Sollima+ 2019; Vasiliev & Baumgardt 2021; Dalessandro+ 2021; Szigeti+ 2021

This work

Goal: Detect OC kinematic profiles, especially rotation

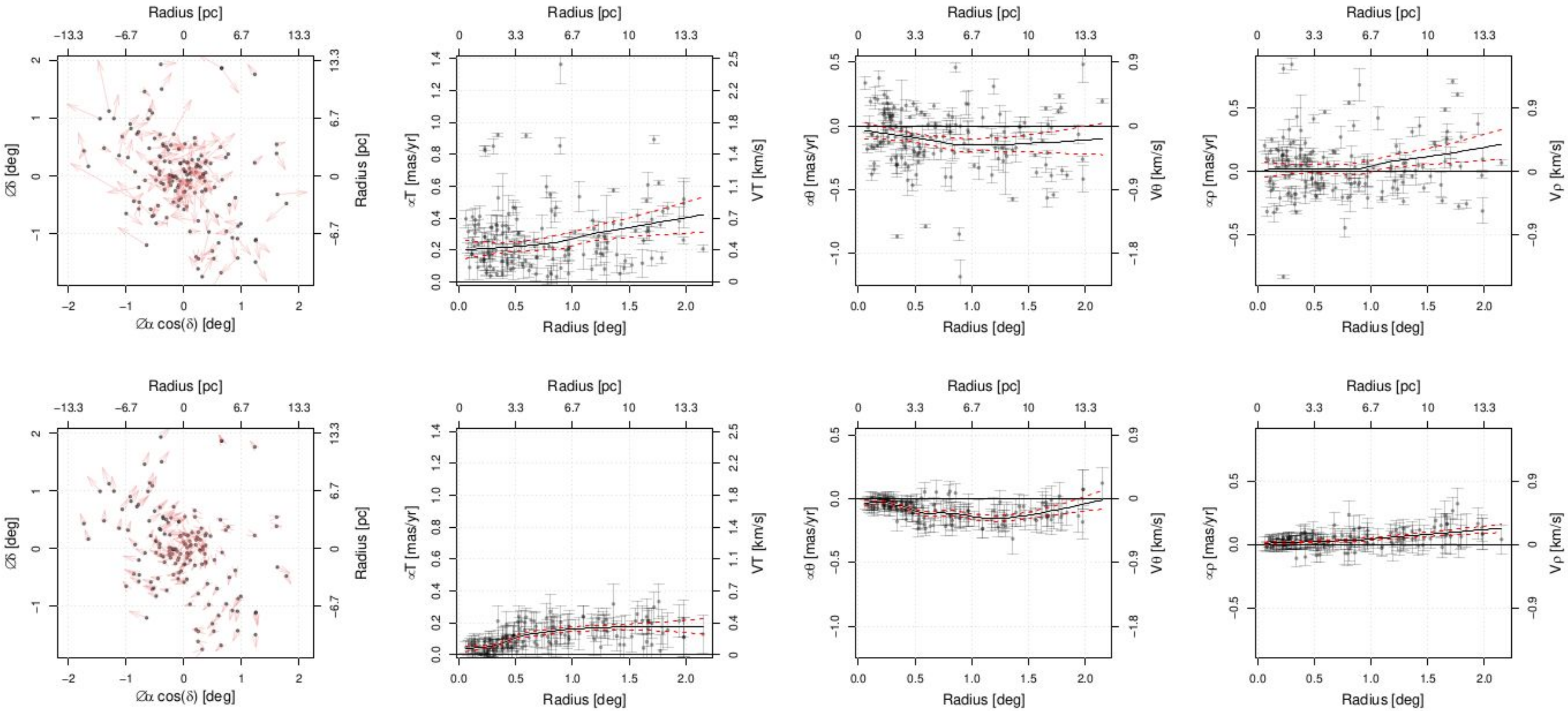
Data: 1275 clusters, with

- Coordinates, distances and membership lists: Cantat-Gaudin+ 2018, 2019
- Bulk RVs: Dias+ 2021, Gaia DR3, LAMOST (DR4), RAVE (DR5), APOGEE (DR14)
- Stellar coordinates, proper motions, parallaxes, errors and correlations: Gaia DR3

Method: Build and analyse maps of **inferred** OC velocity fields.

- Inference with INLA: Integrated Nested Laplace Approximation (Rue+ 2009)
- Bayesian inference alternative to MCMC
- 10s to 10.000s times faster with 100s typical

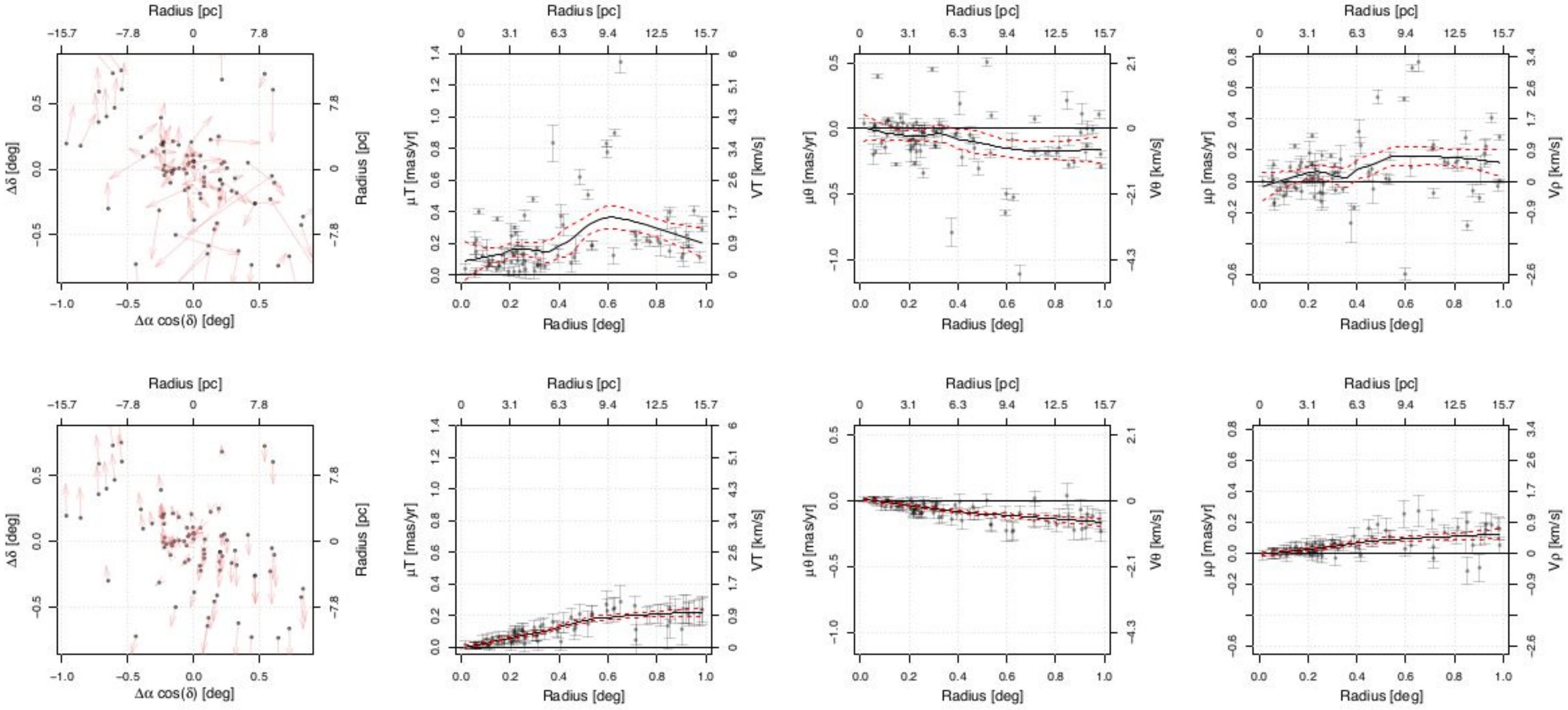
Results: Collinder 140 - rotation



Top: Gaia DR3. Bottom: reconstructed field.
Col 1: positions and their proper motion vectors.
Cols 2, 3, and 4: Total/angular/radial proper motion vs radius to cluster center.
(positive counter-clock-wise/expansion); negative (clockwise/contraction)

Criteria:
1 - Area under the curve
2 - $|\boldsymbol{\mu}|$ of 50%
Sort and threshold

Ruprecht 161 - rotation, expansion



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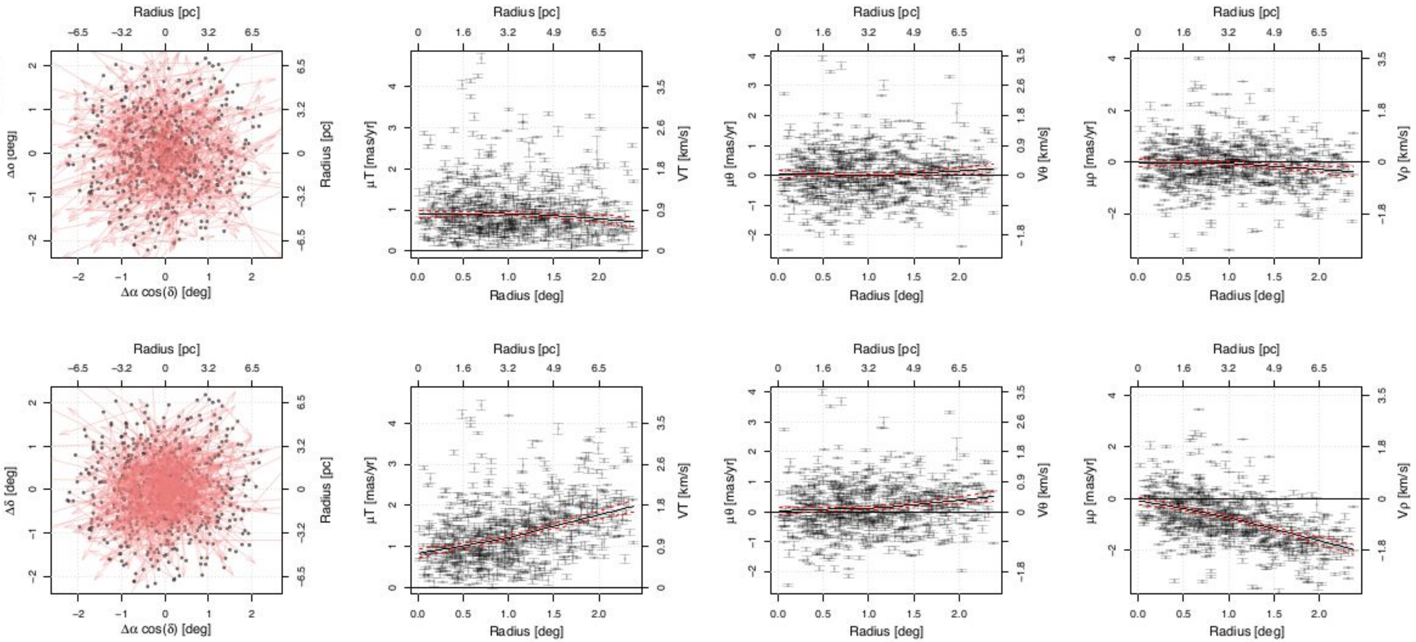
Perspective expansion/contraction corrections

$$\Delta\mu_{\alpha*,i} \approx \Delta\alpha_i\left(\mu_{\delta,0}\sin\delta_0 - \frac{V_{\mathrm{rad},0}\varpi_0}{\kappa}\cos\delta_0\right)$$

$$\Delta\mu_{\delta,i} \approx -\Delta\alpha_i\mu_{\alpha*,0}\sin\delta_0 - \Delta\delta_i\frac{V_{\mathrm{rad},0}\varpi_0}{\kappa}$$

$$\Delta V_{\mathrm{rad},i} \approx \Delta\alpha_i\frac{\kappa\mu_{\alpha*,0}}{\varpi_0}\cos\delta_0 + \Delta\delta_i\frac{\kappa\mu_{\delta,0}}{\varpi_0}$$

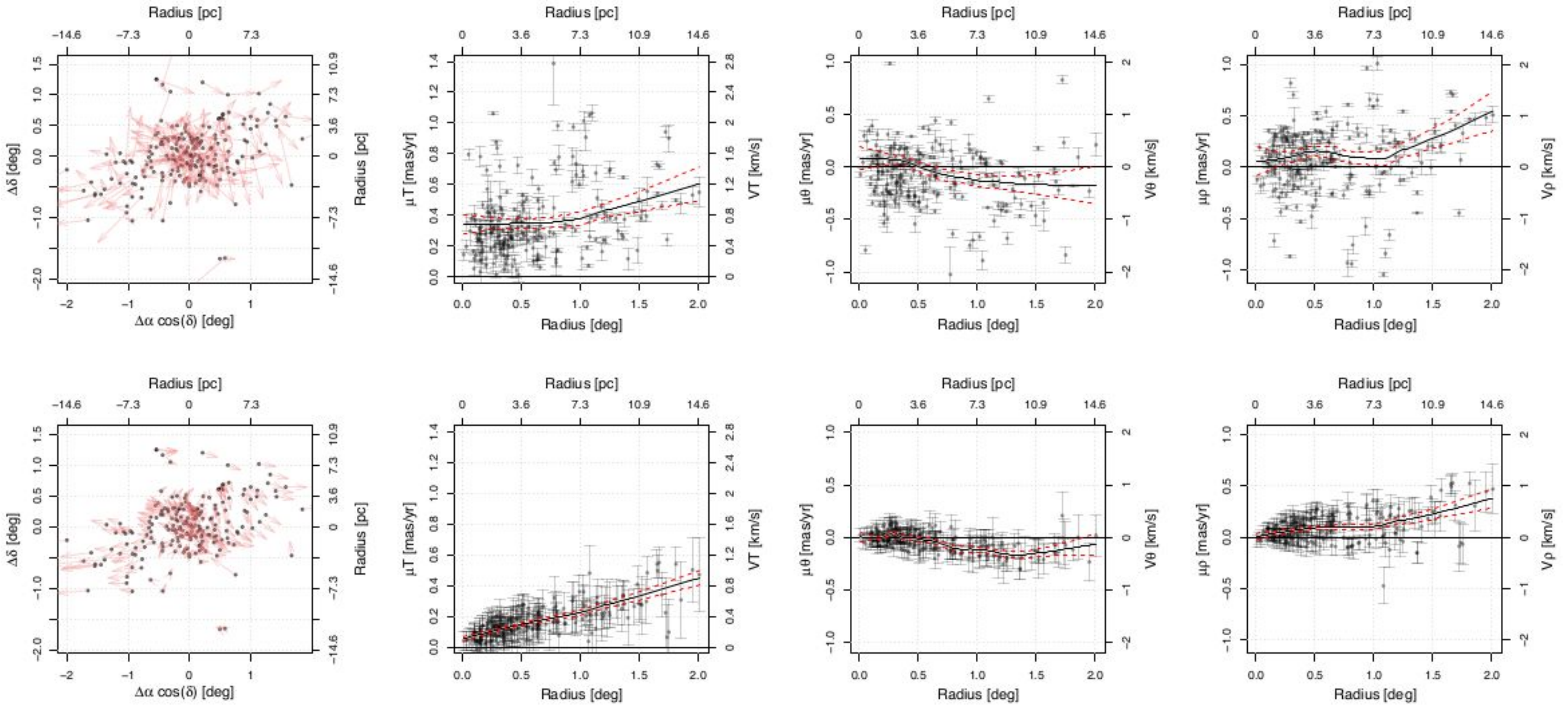


Follow Van Leeuwen (2018)

e. g. Praesepe/NGC2632

Up: corrected
Down: uncorrected

vdBH 164 - expansion, tails, (rotation?)



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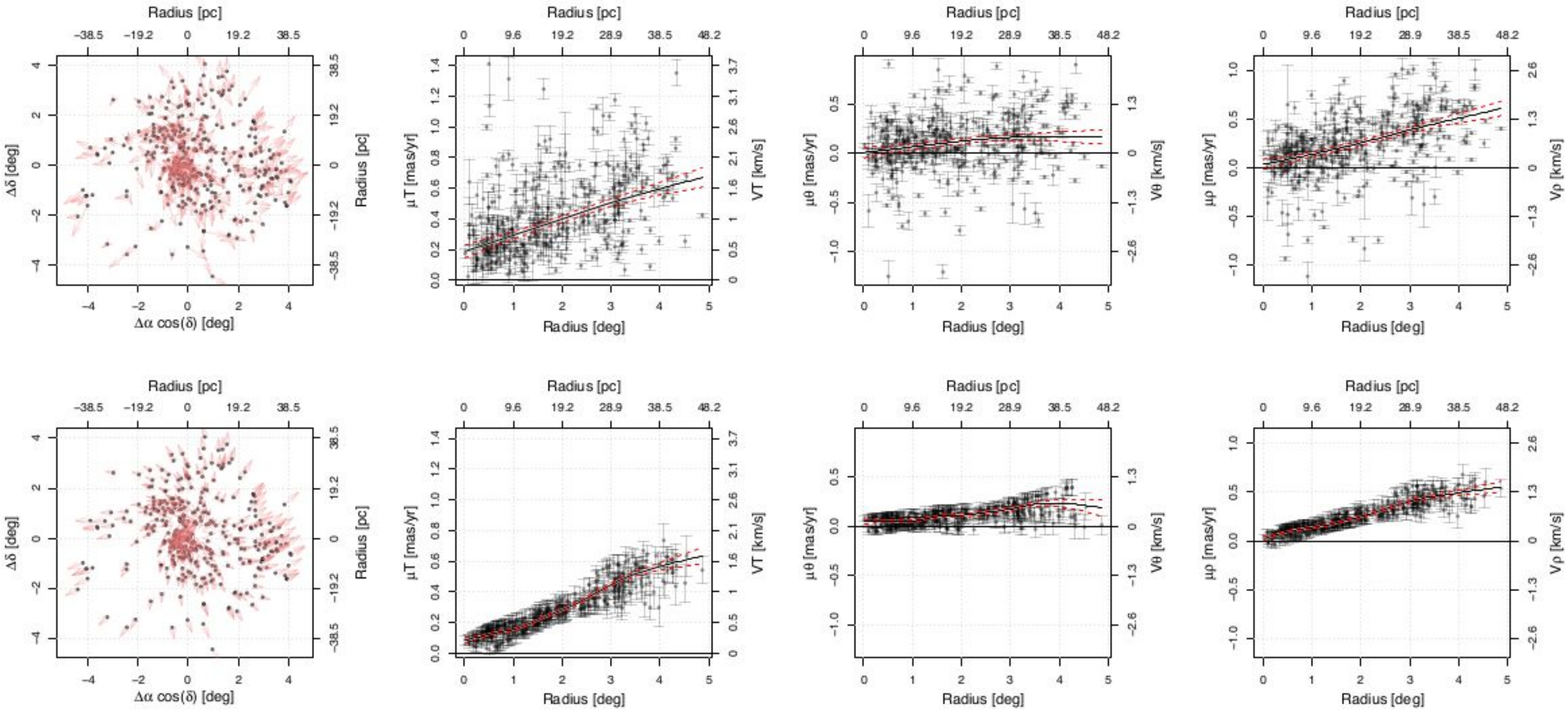
Collider 359 - rotation, expansion



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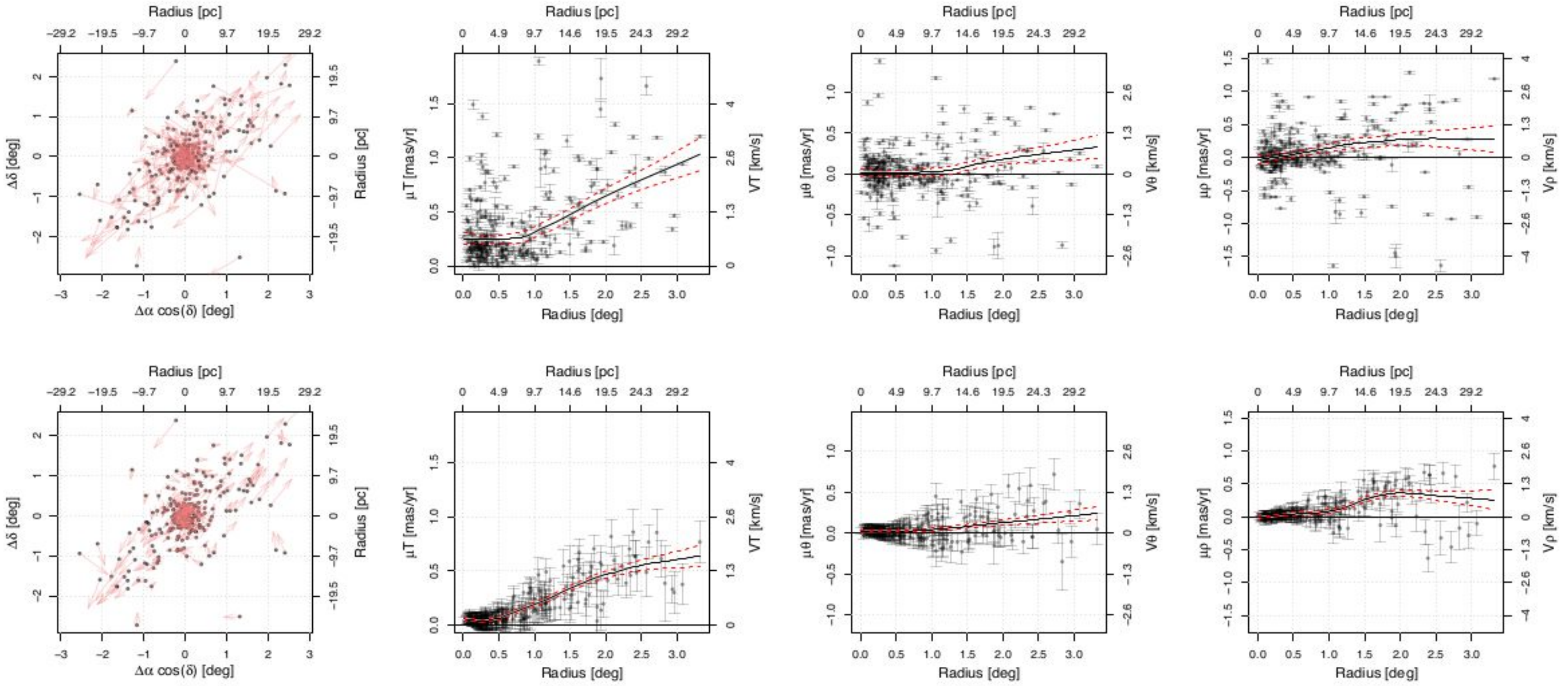
NGC 6991 - tail (expansion)



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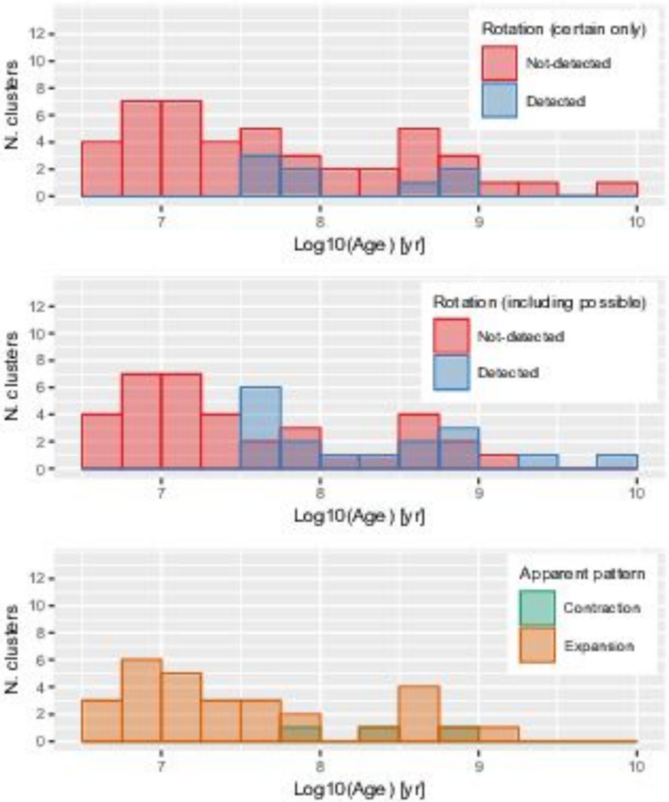
Results - Age distribution



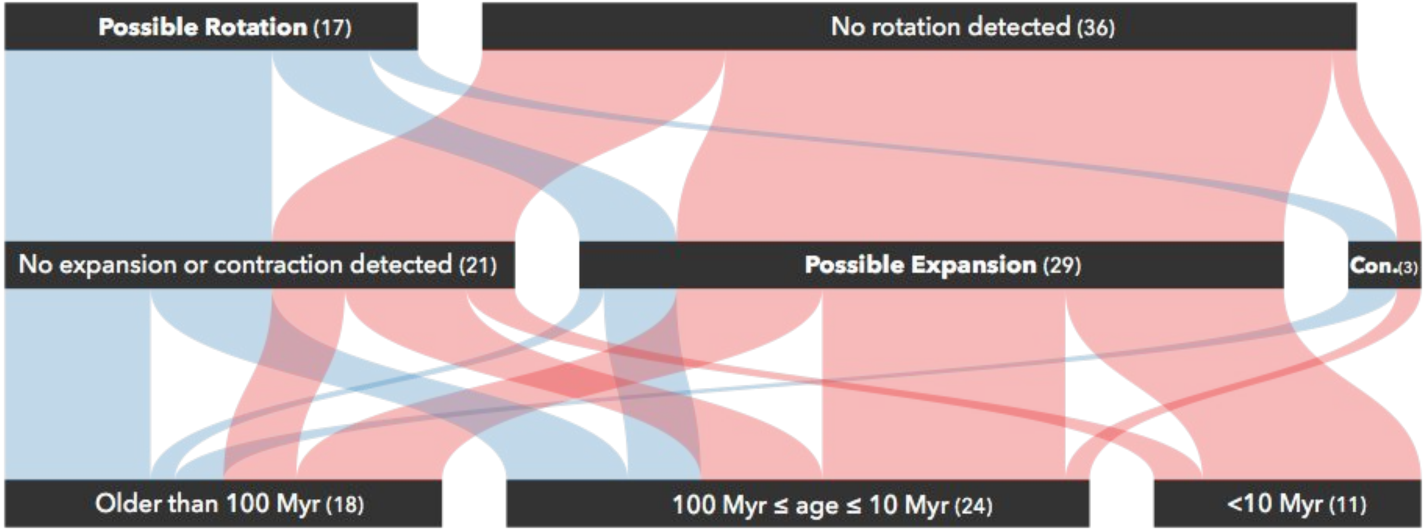
53 clusters with kinematic patterns detected

Rotation: 8 (+9)
Expansion: 14 (+15)
Contraction: 2 (+1)

5 of these with hints of tidal tails

These plots simply represent our results. They are not (necessarily) representing the age dependence of OC kinematic patterns in the Galaxy.

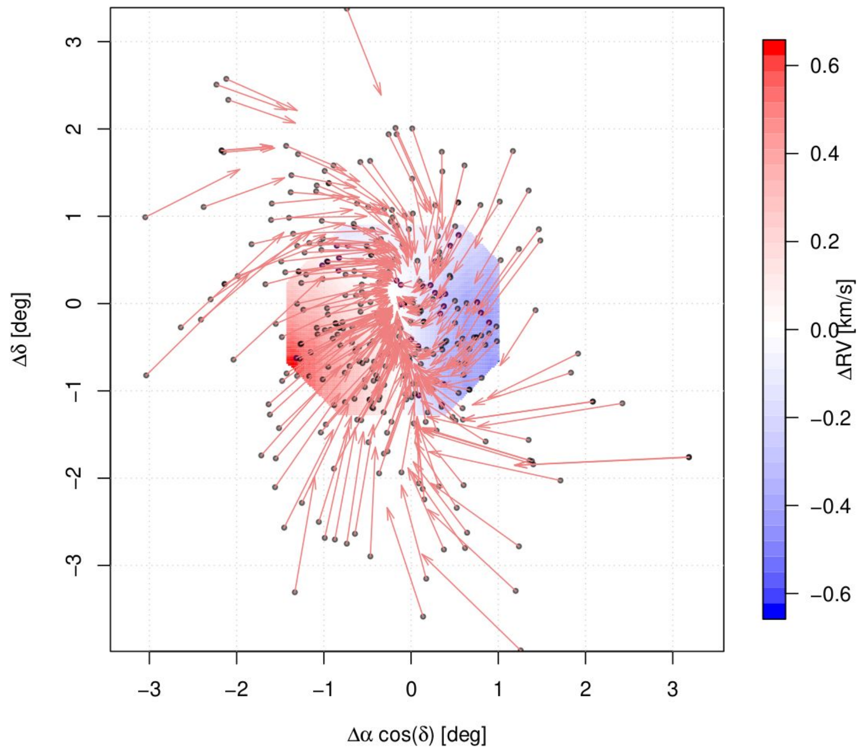
Results - Age/kinematic pattern correlations



- Blue: possible rotation; Red: no rotation detected.
- Band widths proportional to number of clusters with each pattern (e.g. about half of the clusters older than 100 Myr had a detectable rotation.
- Visualisation connects the different dimensions, revealing correlations in the patterns of the sample among the different dimensions (e.g. most clusters with possible rotation and possible expansion have ages between 10 and 100 Myr).

3D velocity maps - a peek into the future

- Gives inclination of rotation
- Mostly not yet possible
- More radial velocities needed



NGC 2451-A

Conclusions

- Kinematic patterns detected for 54 clusters. Possible with Gaia DR3
  - Rotation: 8 (+9)
  - Expansion: 14 (+15)
  - Contraction: 2 (+1)
- INLA reconstruction revealed internal cluster dynamical profiles.
- Profiles may reveal cluster limits and interface with galactic tidal field.
- May eliminate virial equilibrium assumption for dynamical mass determination.
- 2D projection. For full 3D map, more RVs needed.
- Gaia DR4 should greatly increase the number of velocity profile detections.

Questions?

Acknowledgement

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Fundação
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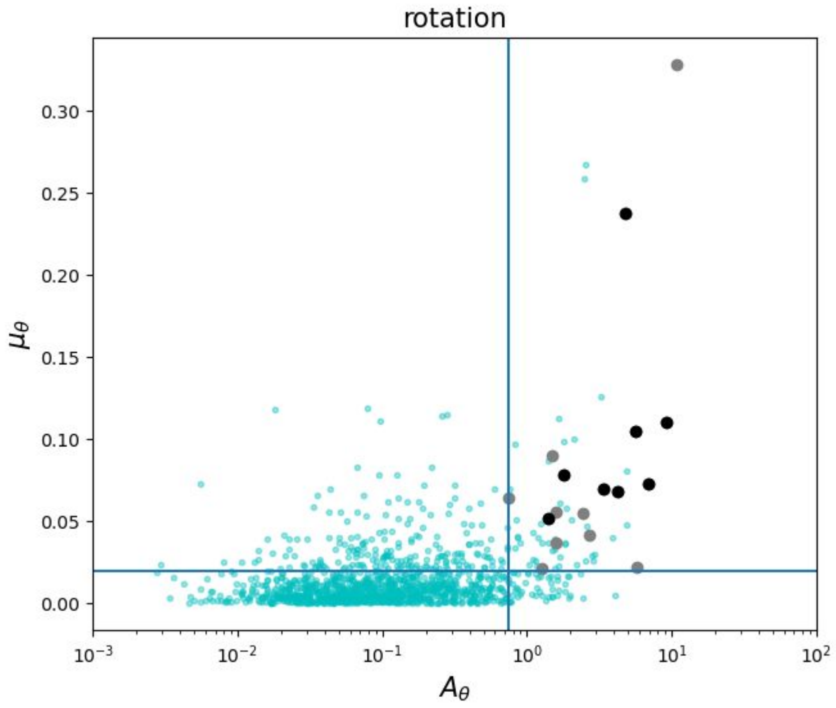
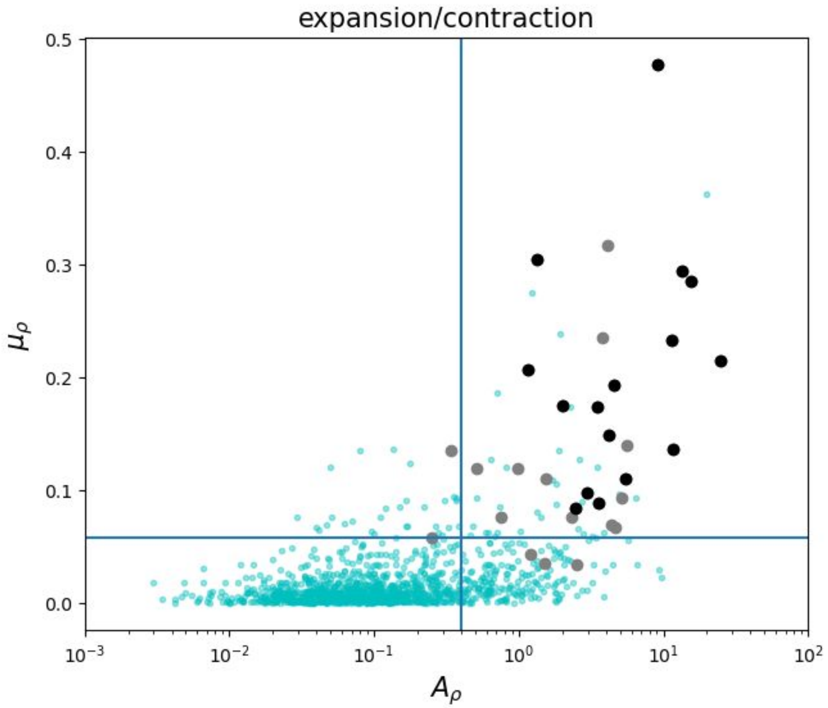
Extra slides

Selection



rotation
0.30
0.25
0.20
0.15
0.10
0.05
0.00
μ_θ
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
A_θ



expansion/contraction
0.5
0.4
0.3
0.2
0.1
0.0
μ_ρ
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
A_ρ

Method - Velocity field inference

INLA: Integrated Nested Laplace Approximation (Rue et al. 2009)

- Bayesian inference with alternative to MCMC
- Speed. 10s to 10.000s times faster with 100s typical
- Unlike MCMC, which relies on the convergence of a Markov chain to the desired posterior distribution, INLA uses a Laplacian approximation to estimate the individual posterior marginals of the model parameters.

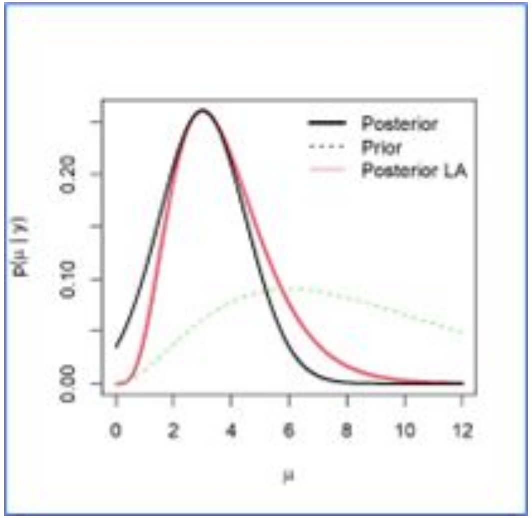
- R-INLA
- Few published astronomical works (more common in geology and medical)
- 1D Multivariate fields (need to adapt for vector fields)

Velocity field inference

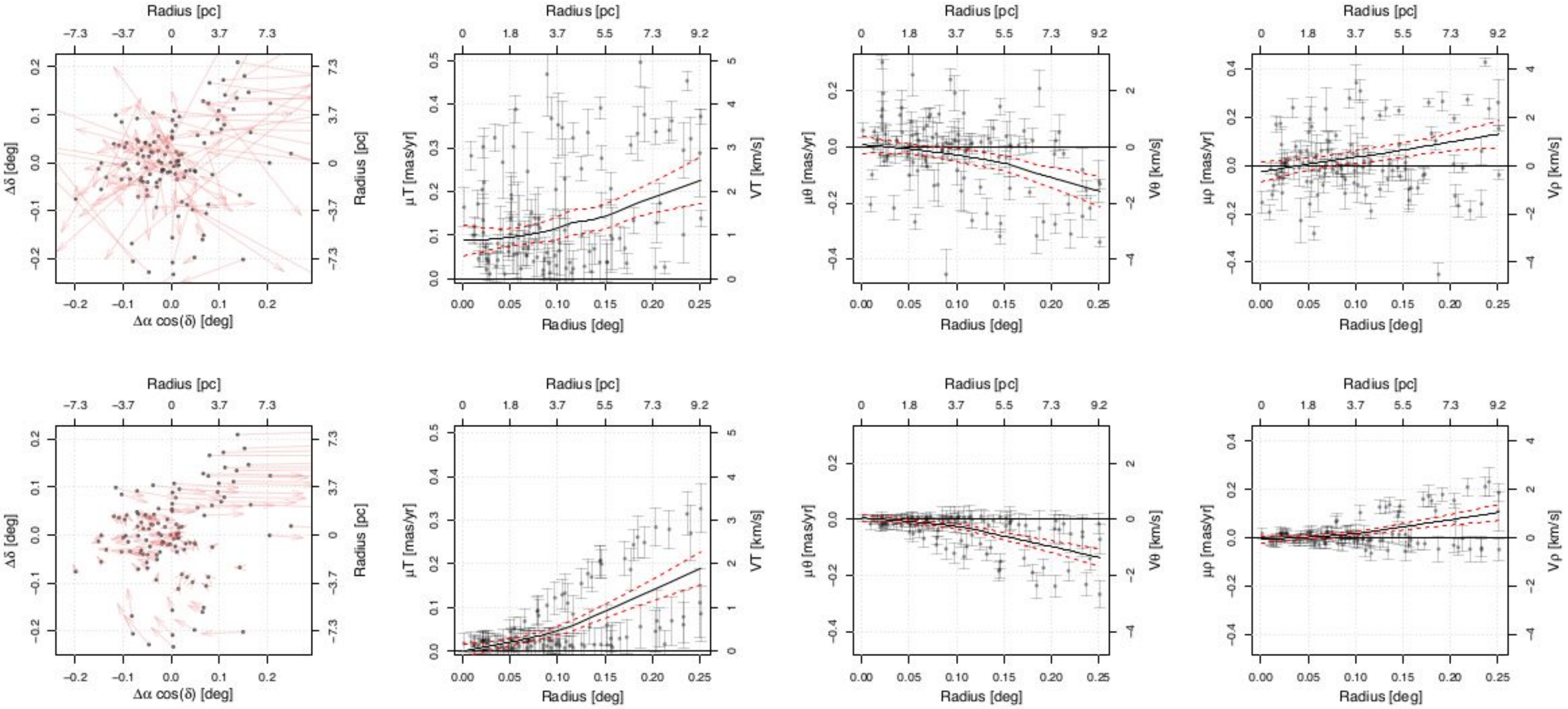
Application: Not as general as MCMC

INLA only works for Latent Gaussian Models, whose parameters form a Gaussian Markov Random Field. Typically achieved by setting normal priors to some transformation of the unknown parameters.
Still, it works for:

- Linear Models
- Generalized Linear Models
- Linear Mixed Models
- Generalized Linear Mixed Models
- Generalized Additive Models
- Time to Event (Survival) Models



FSR0904 - other (2 groups)



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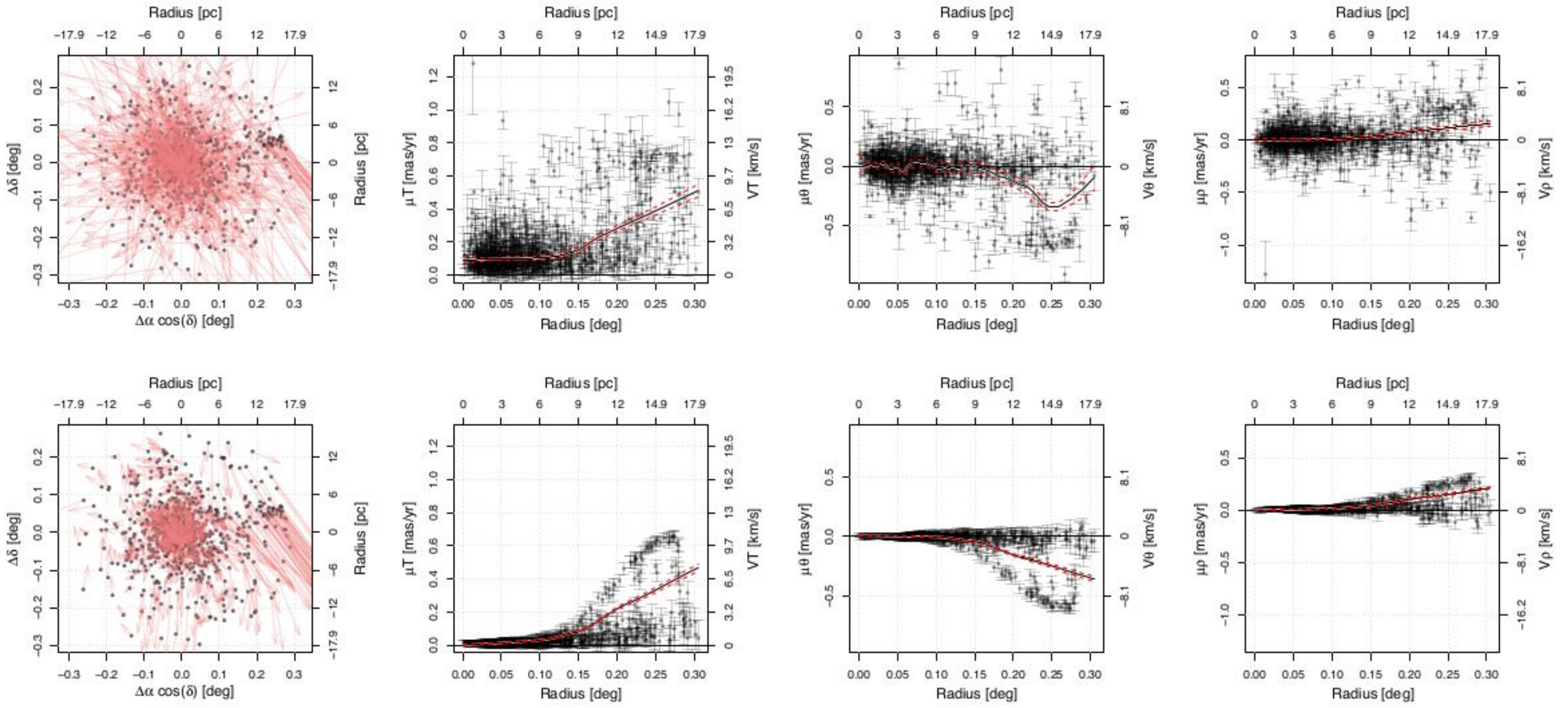
NGC 2194 - other (2 groups)



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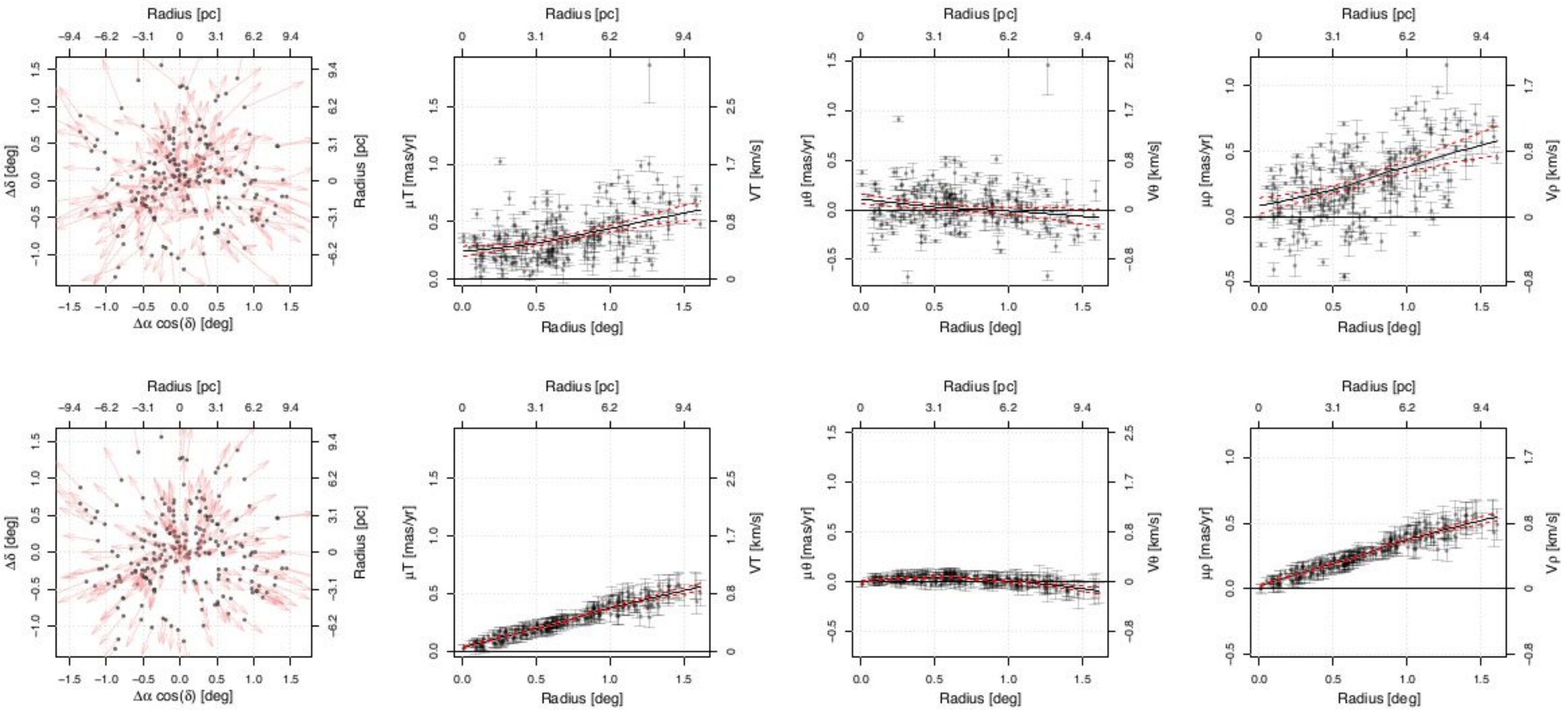
Alessi 19 - contraction



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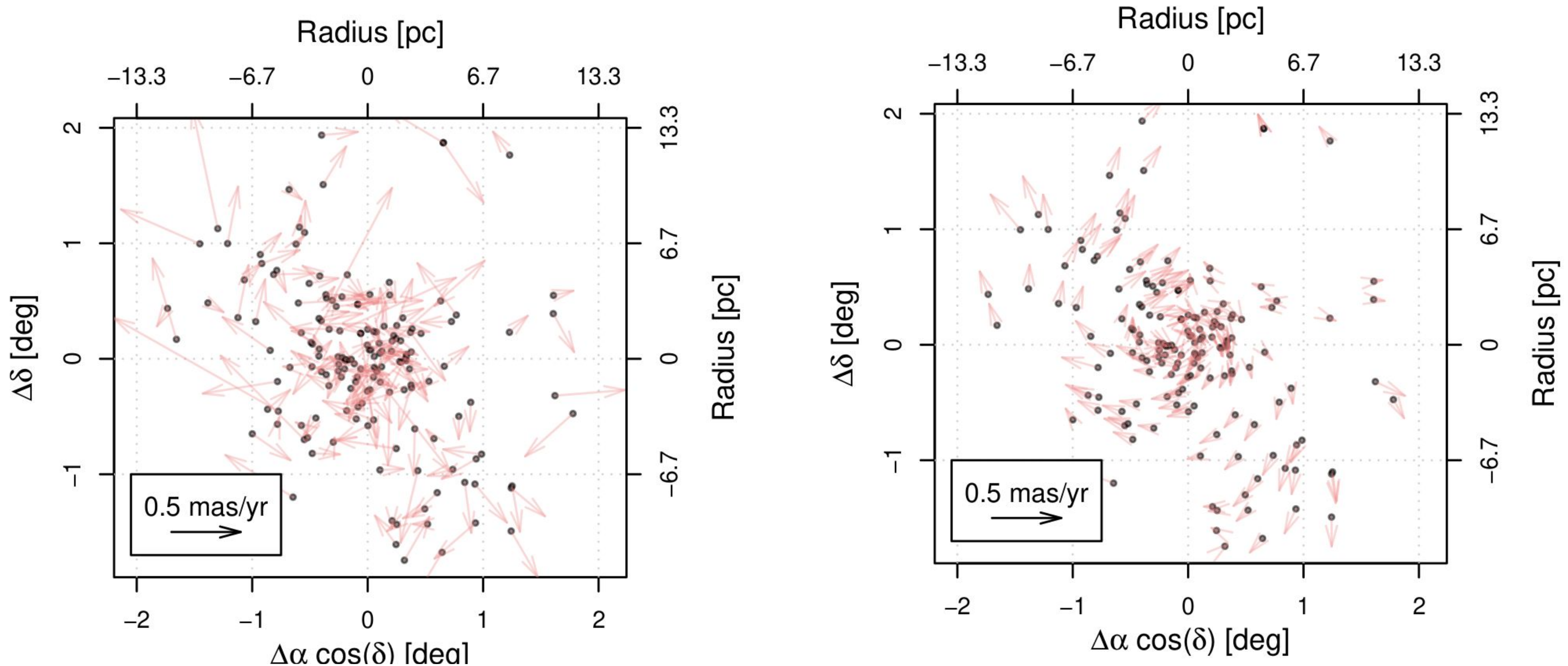
Results



Positions and proper motions of Collinder 140 members. Left: Gaia DR3 proper. Right: INLA inferred field. The inferred field, reaches a maximum angular component $\mu\theta = -0.16 \pm 0.01$ mas/yr and a maximum radial component $\mu\rho = 0.13 \pm 0.02$ mas/yr, indicating clockwise rotation.

Results - overview

Cluster	Rotation	Expansion	Contraction	Other
Alessi 3	●			
Alessi 6	○			
Alessi 9		○		
Alessi 13	●	●		
Alessi 19			●	
Alessi 37		○		
Alessi 43		●		
Alessi 44				●
ASCC 13		○		
ASCC 16		●		
ASCC 19		●		
ASCC 58	●			
ASCC 71	○			
ASCC 73	○			
ASCC 114	○			
ASCC 127		○		
Aveni Hunter 1		●		
BDSB96		○		
BH 99		○		
BH 164	○	●		
Collinder 69		●		
Collinder 132		●		
Collinder 140	●			
Collinder 197		○		
Collinder 359	●	●		
FSR 0904				●
Gulliver 9		●		○
IC 1396		●		○
IC 1805		○		
IC 2602	○			
IC 4665	●			
Mamajek 4		○		
NGC 188	○			
NGC 2194				●
NGC 2244				●
NGC 6193				●
NGC 6531				●
NGC 6871		●		●
NGC 6991		○		
NGC 7380		○		
Platais 3	○		○	●
Platais 8				○
Roslund 2		○		
Ruprecht 41				●
Ruprecht 98		●		
Ruprecht 147	○			
Ruprecht 161	●	○		
Stock 1		●		
Stock 2	●		●	○
Stock 8				●
Trumpler 16		○		○
Trumpler 22				●
vdBergh 92		○		○

98 above threshold

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Rotation: 8 (+9)
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None of above: 9 (+1)

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