

Kinematic Identification of Stellar Groups and Associations with Coherent Ages

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Vanderbilt University

What are clusters?

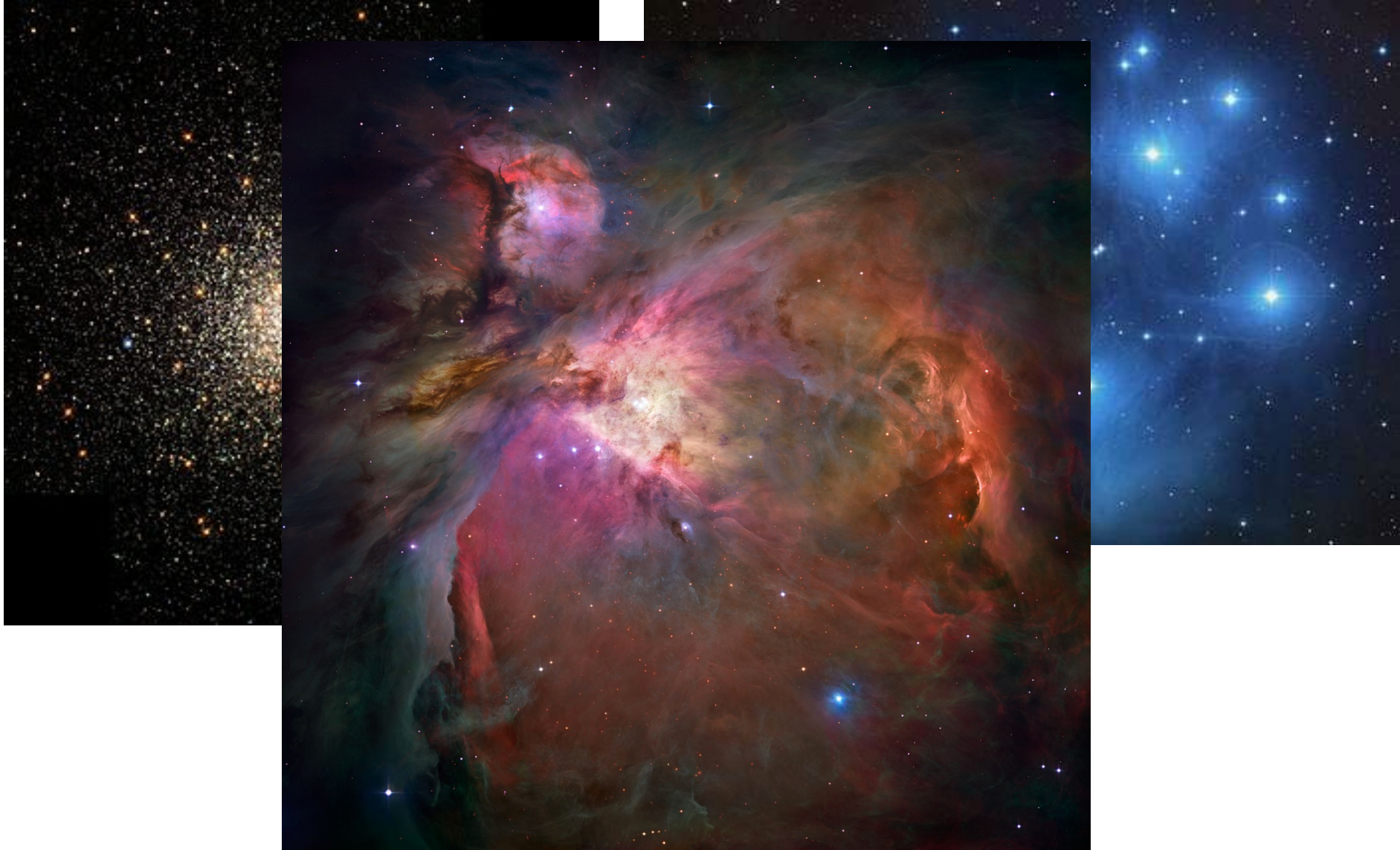
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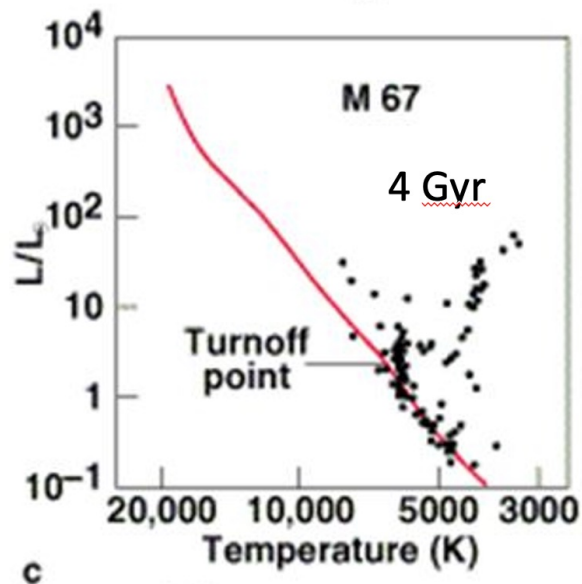
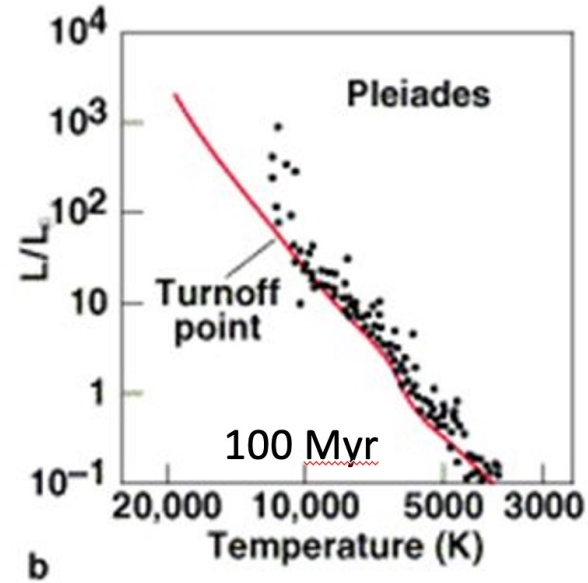
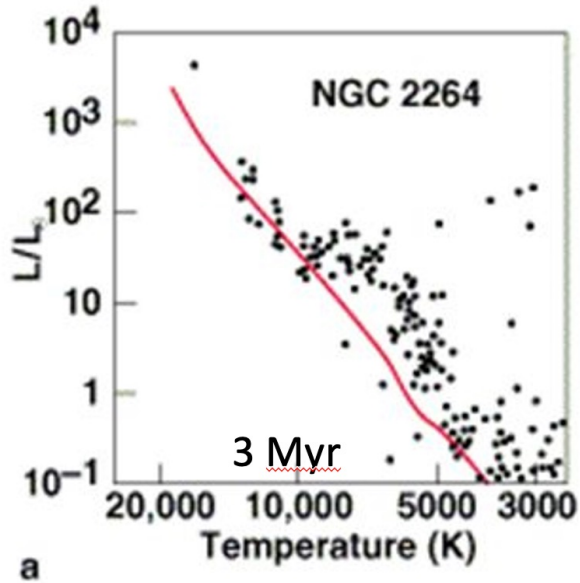
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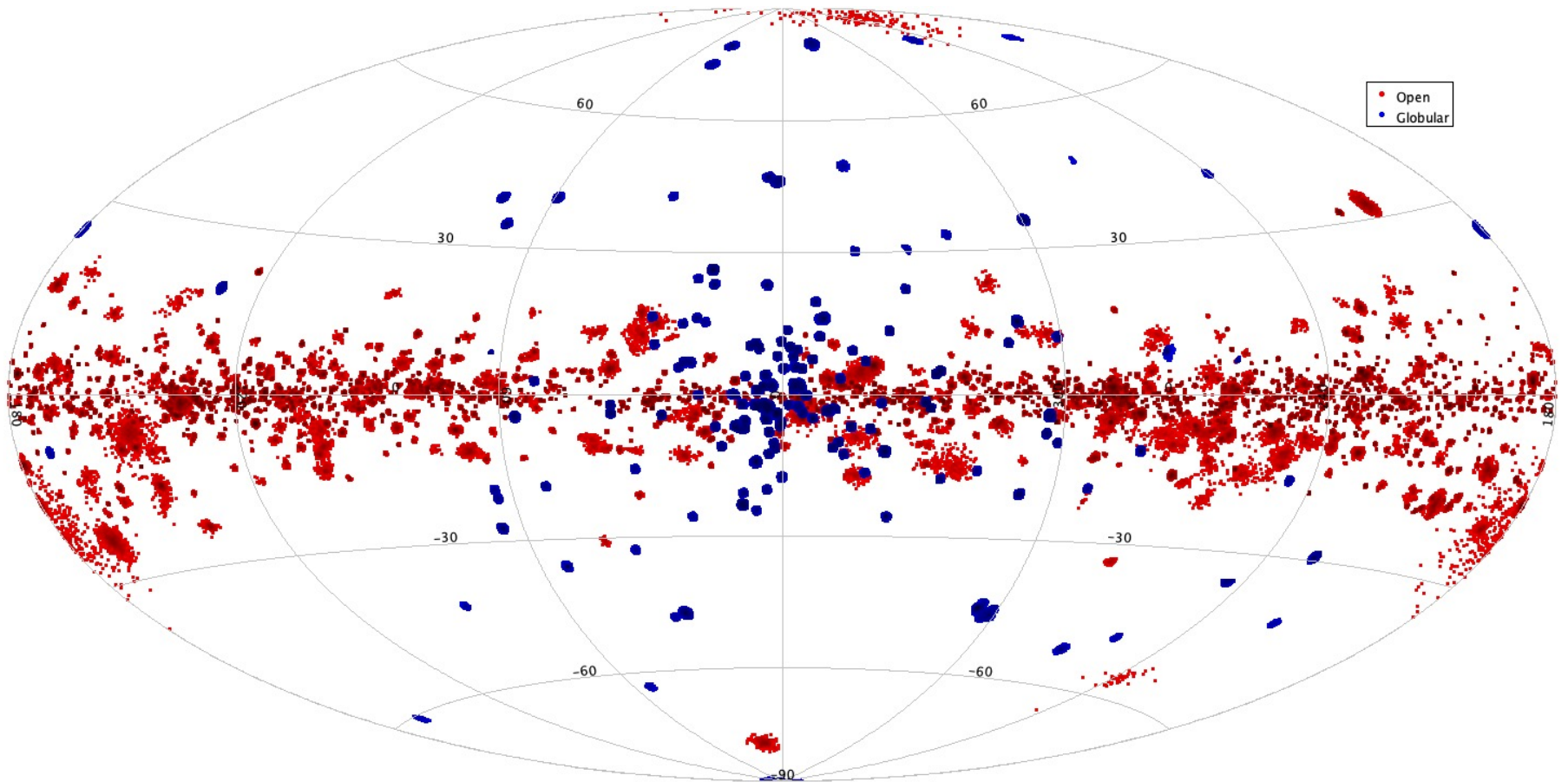
What are clusters?



Cluster HR diagram



Distribution of clusters



How to find a cluster

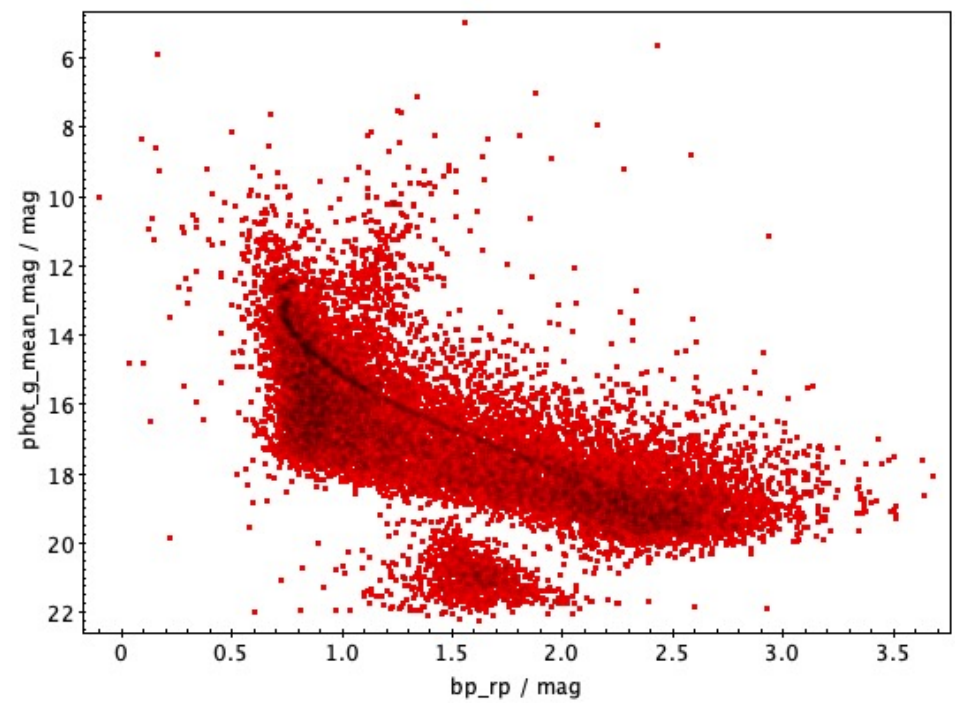
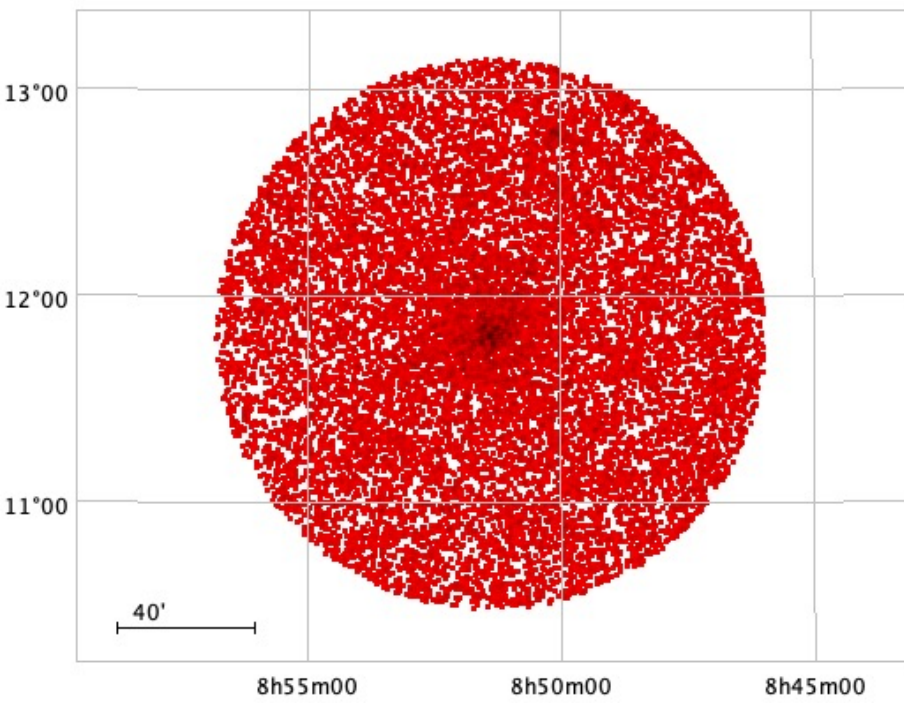


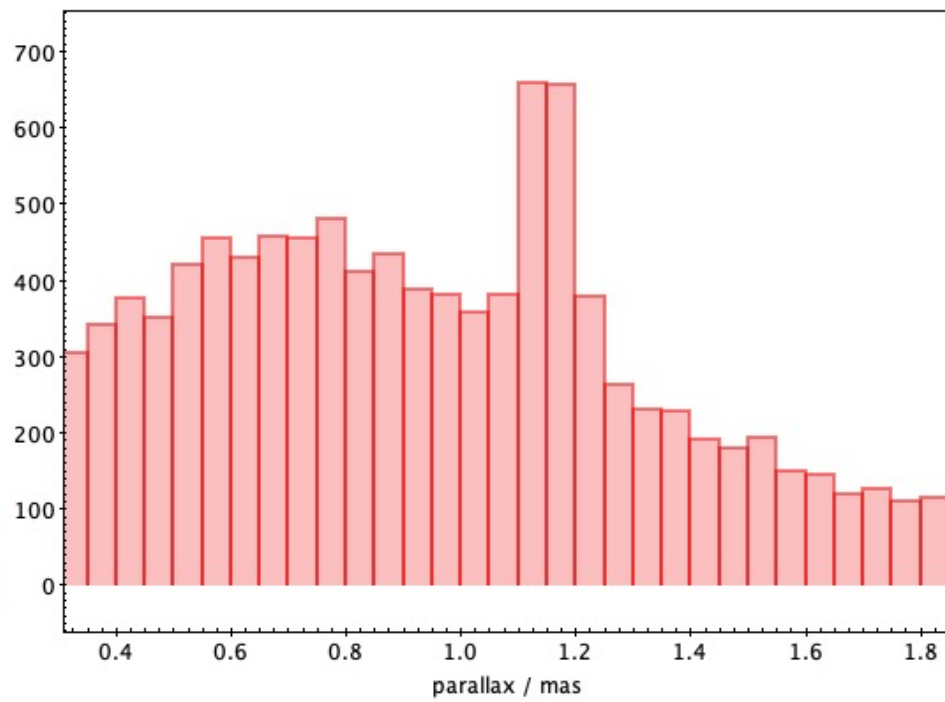
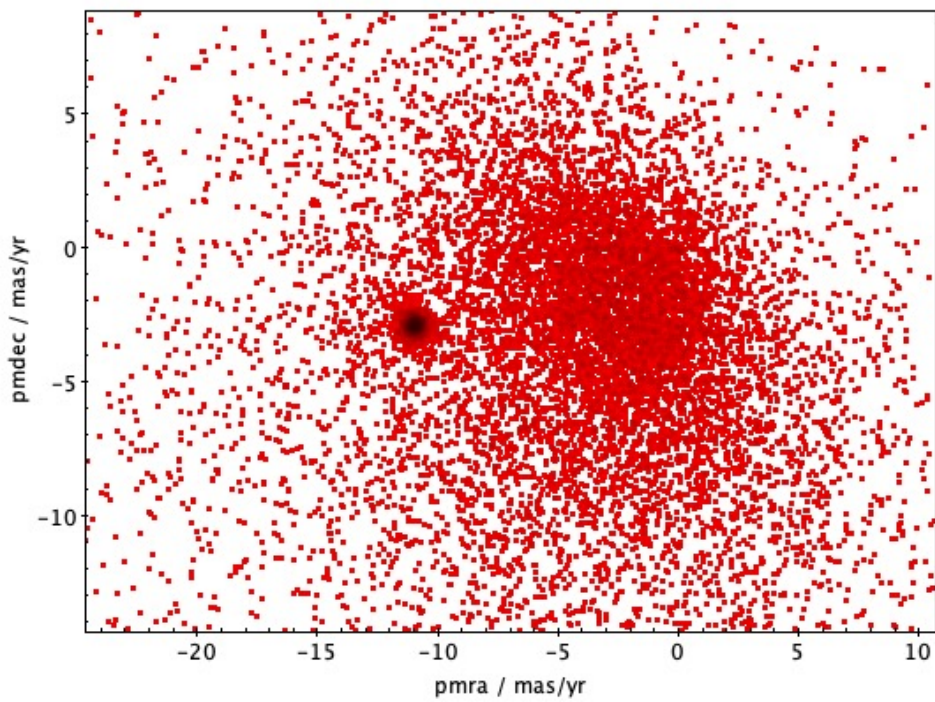
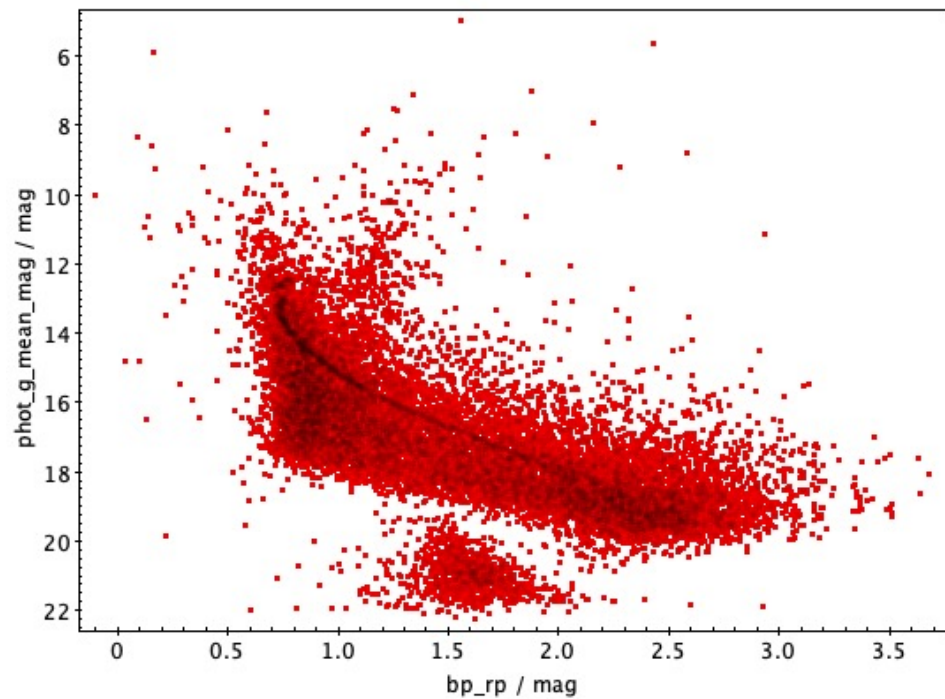
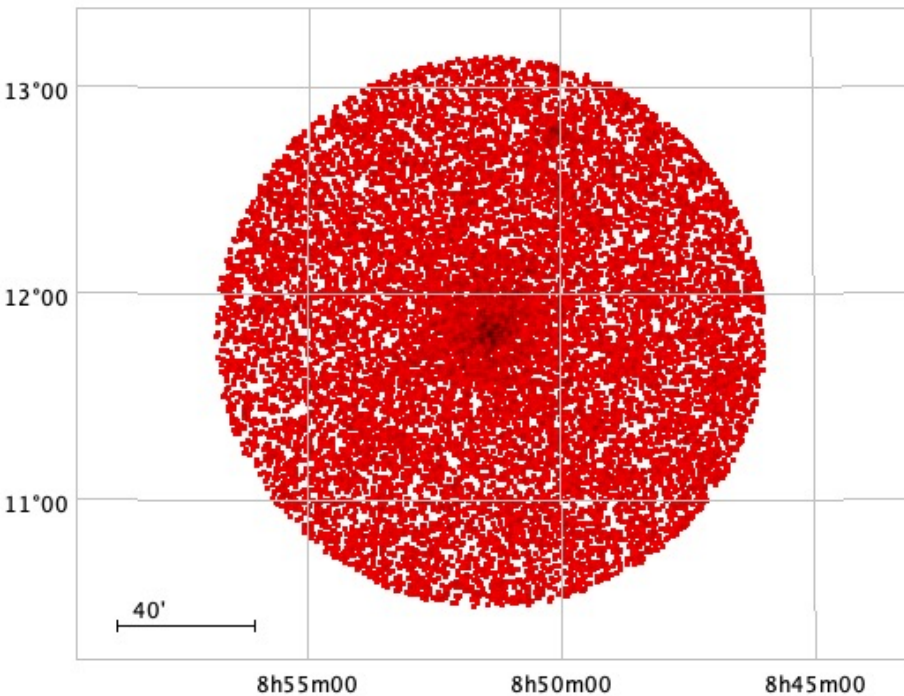
NGC 2682

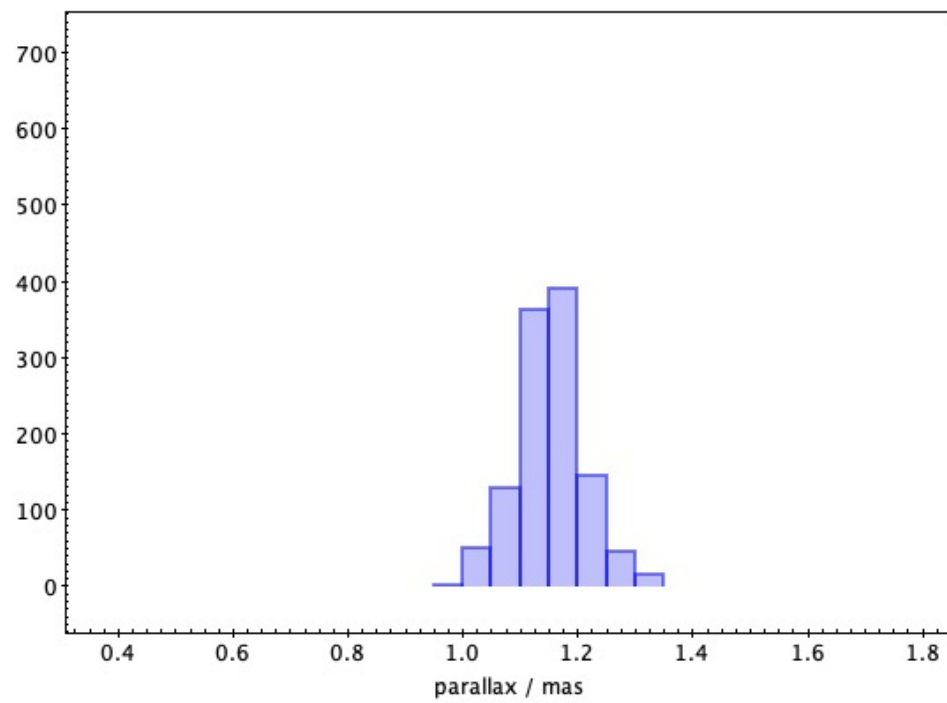
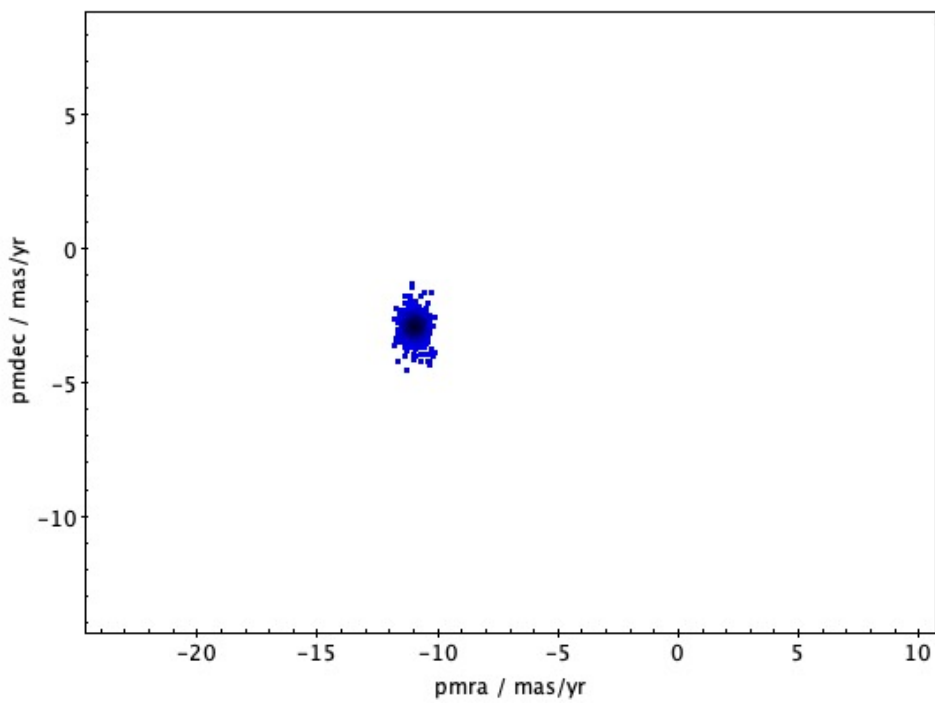
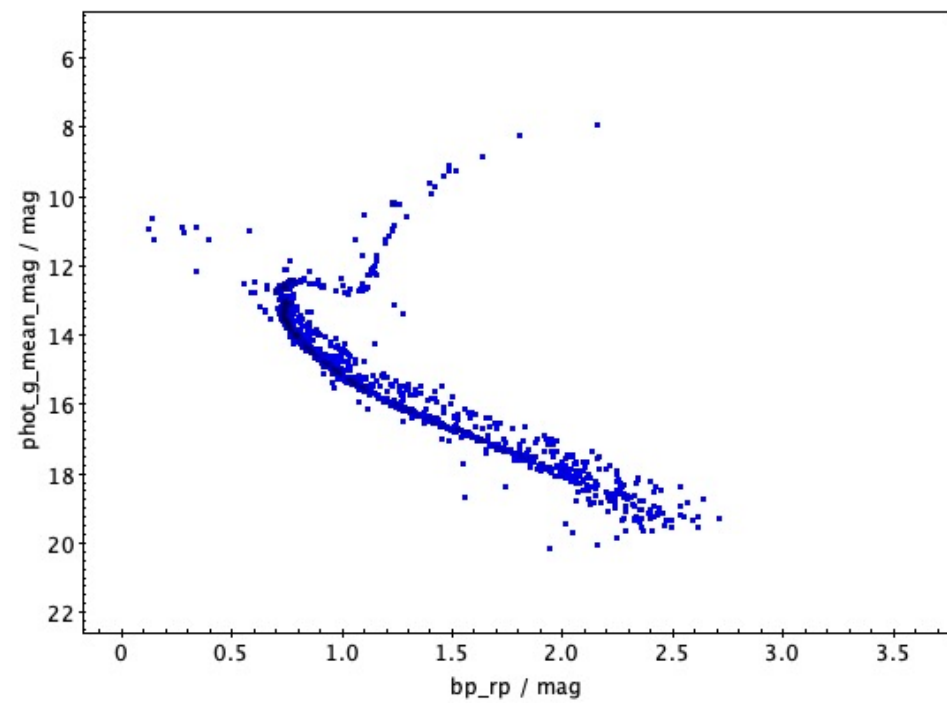
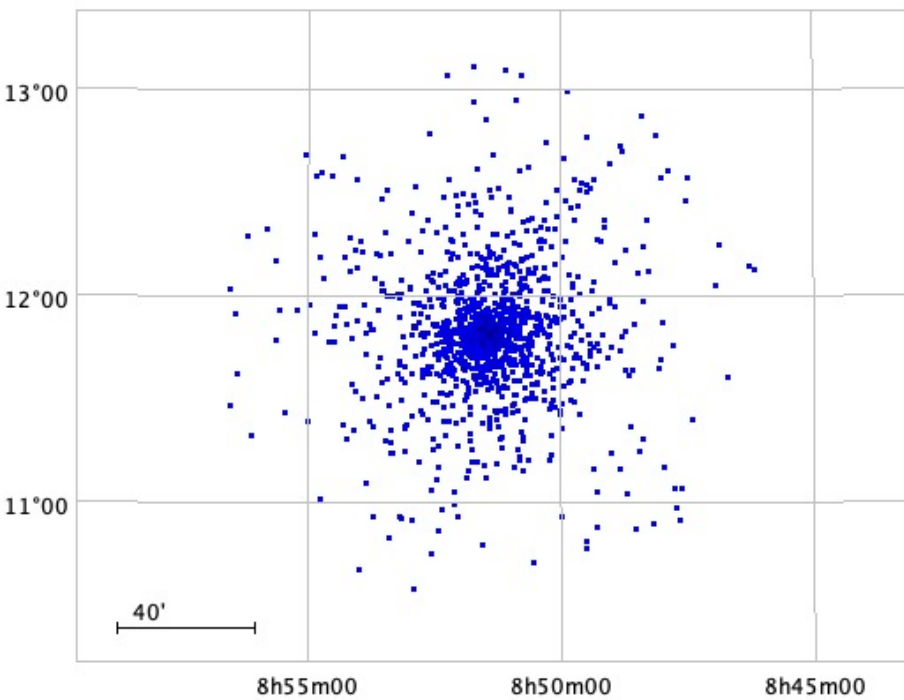
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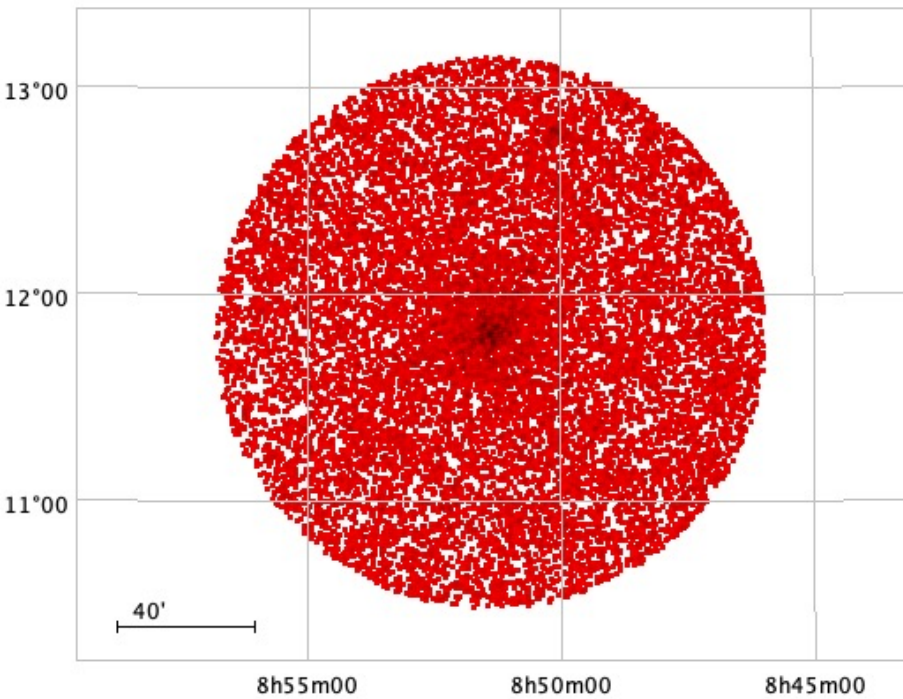
NGC 2682



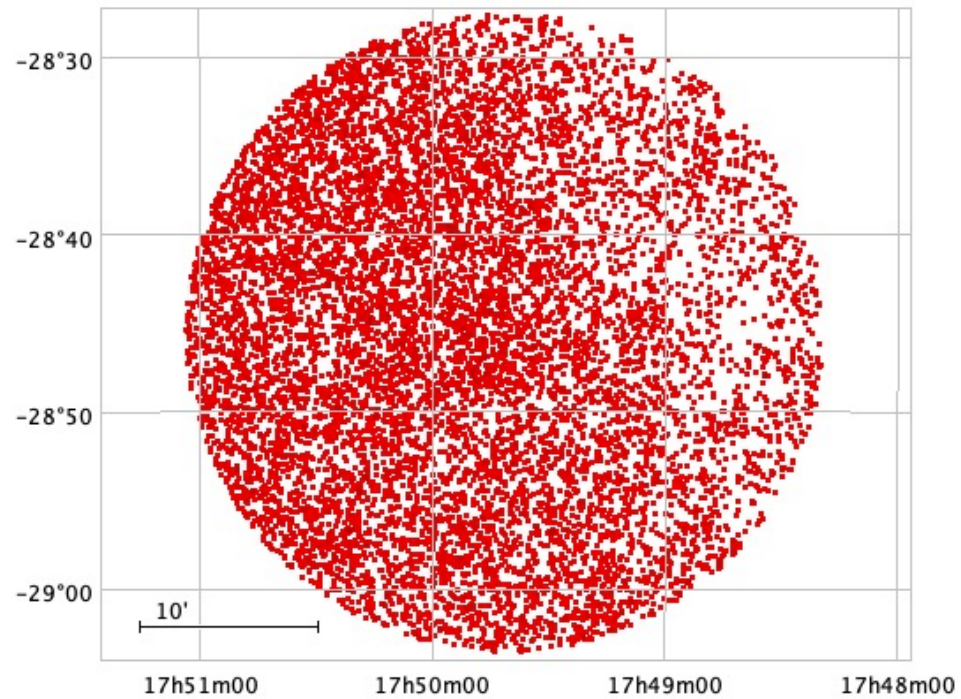




Gaia allows finding new clusters

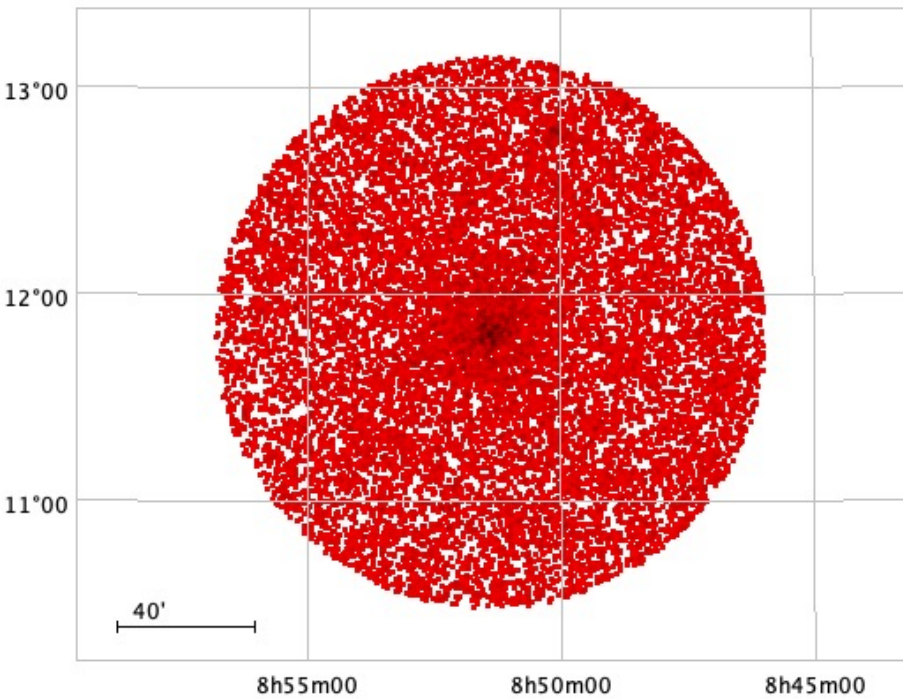


NGC 2682

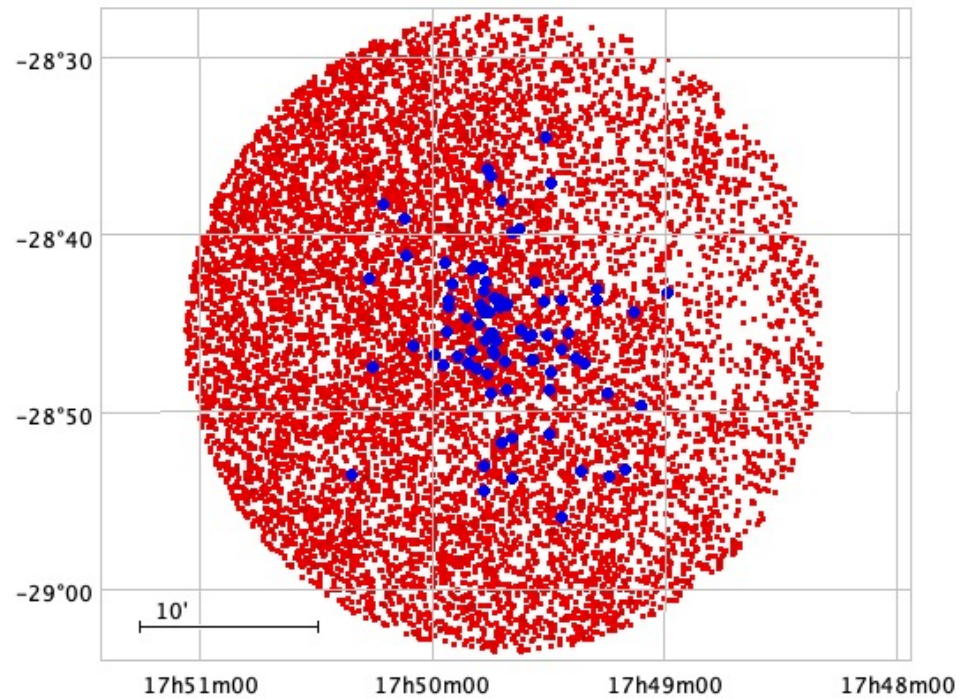


UBC91

Gaia allows finding new clusters

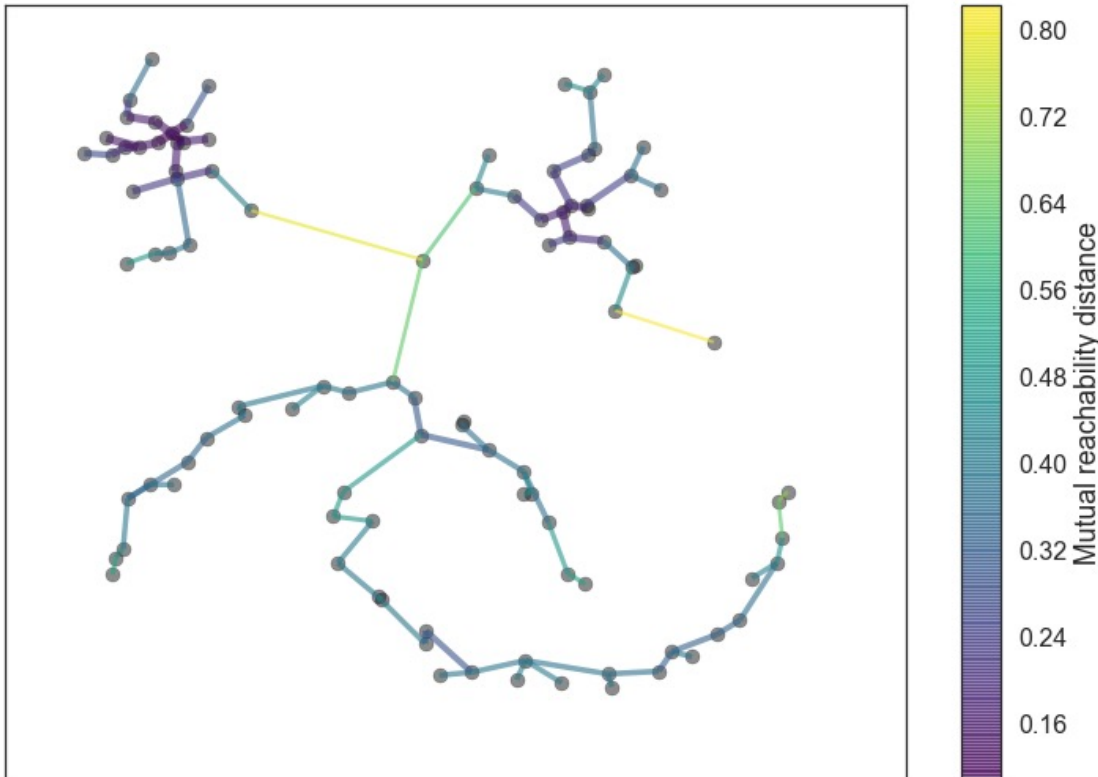


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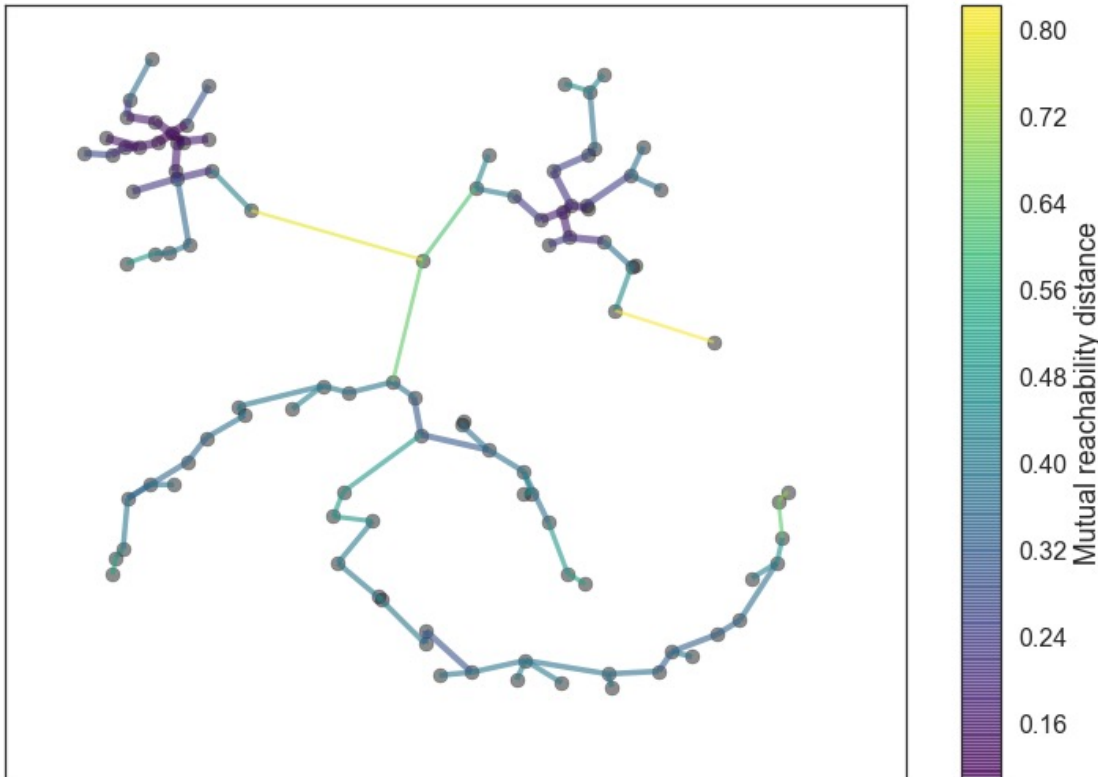
UBC91

Hierarchical clustering

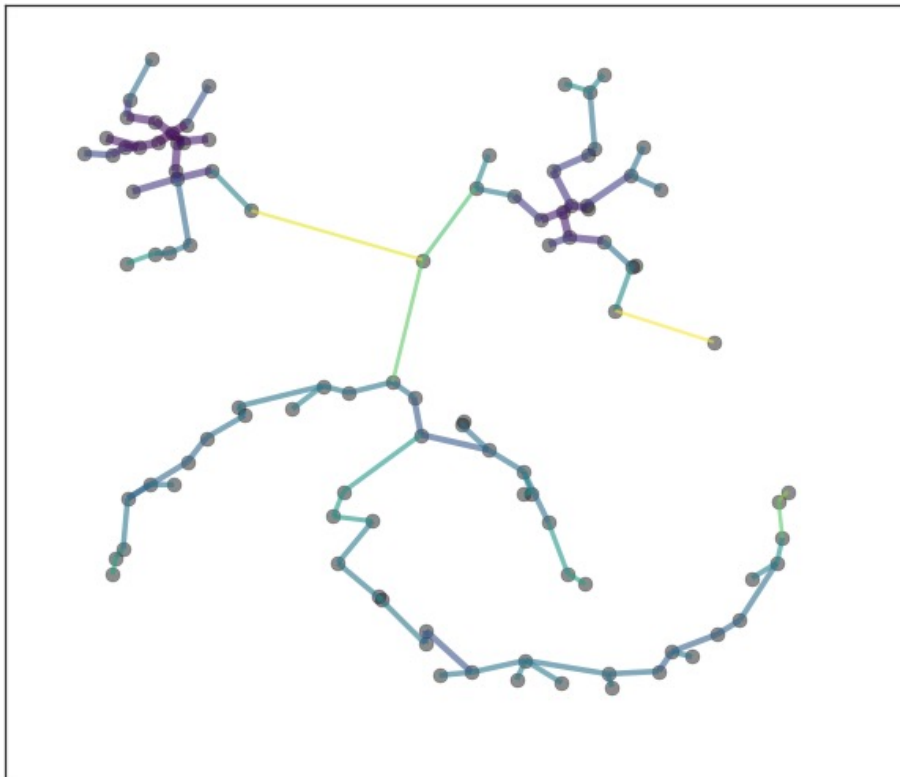


Hierarchical clustering

- Measure distance between all points

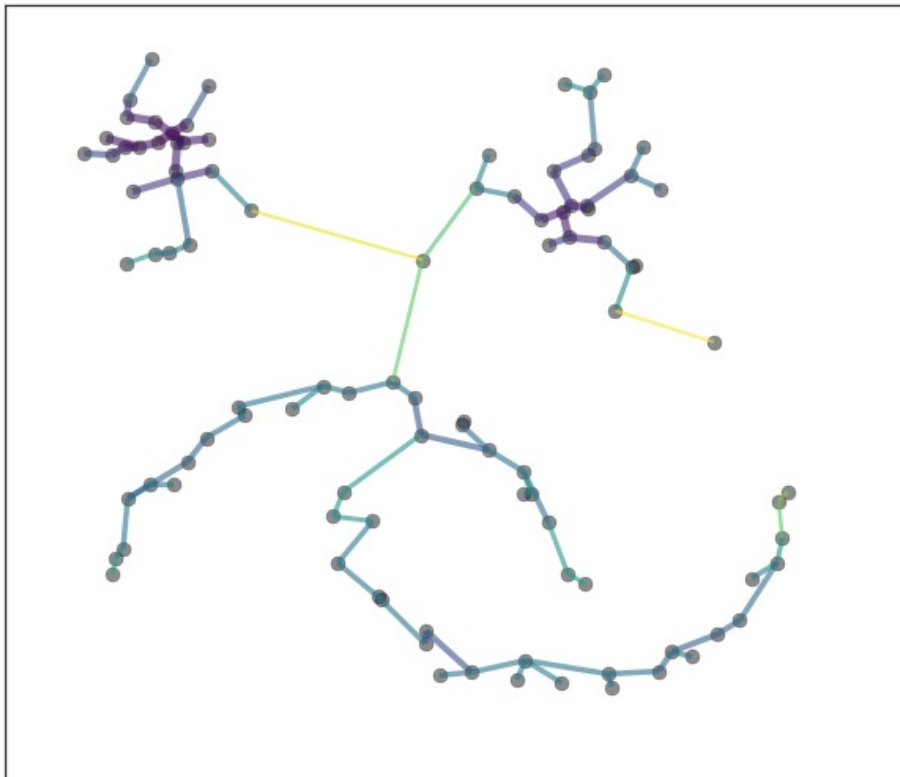


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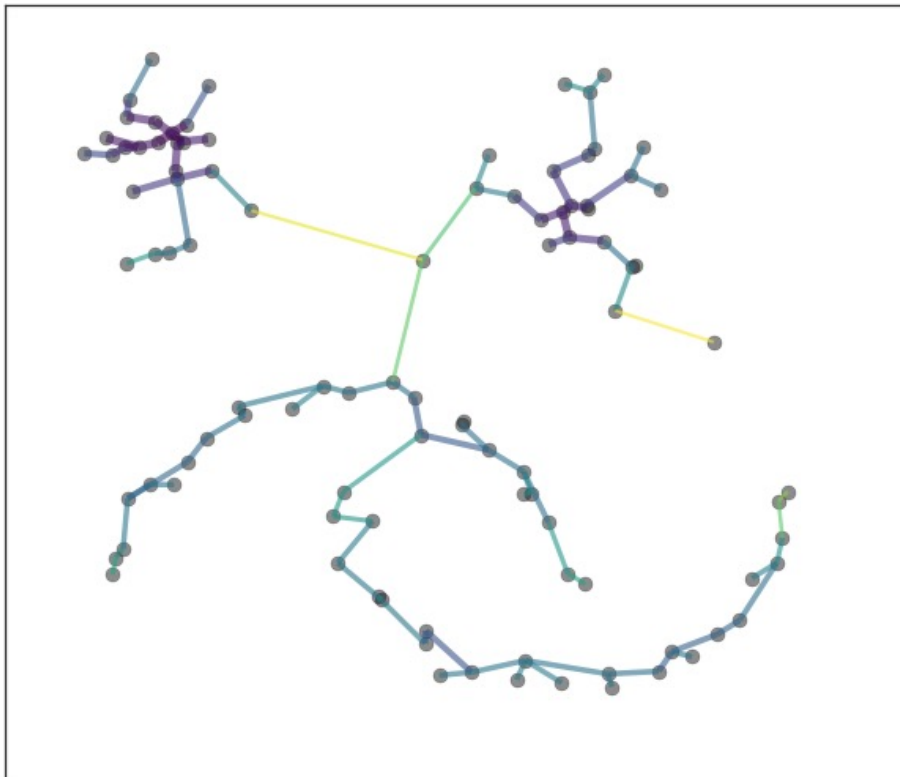
- Measure distance between all points
- Construct a minimum spanning tree

Hierarchical clustering



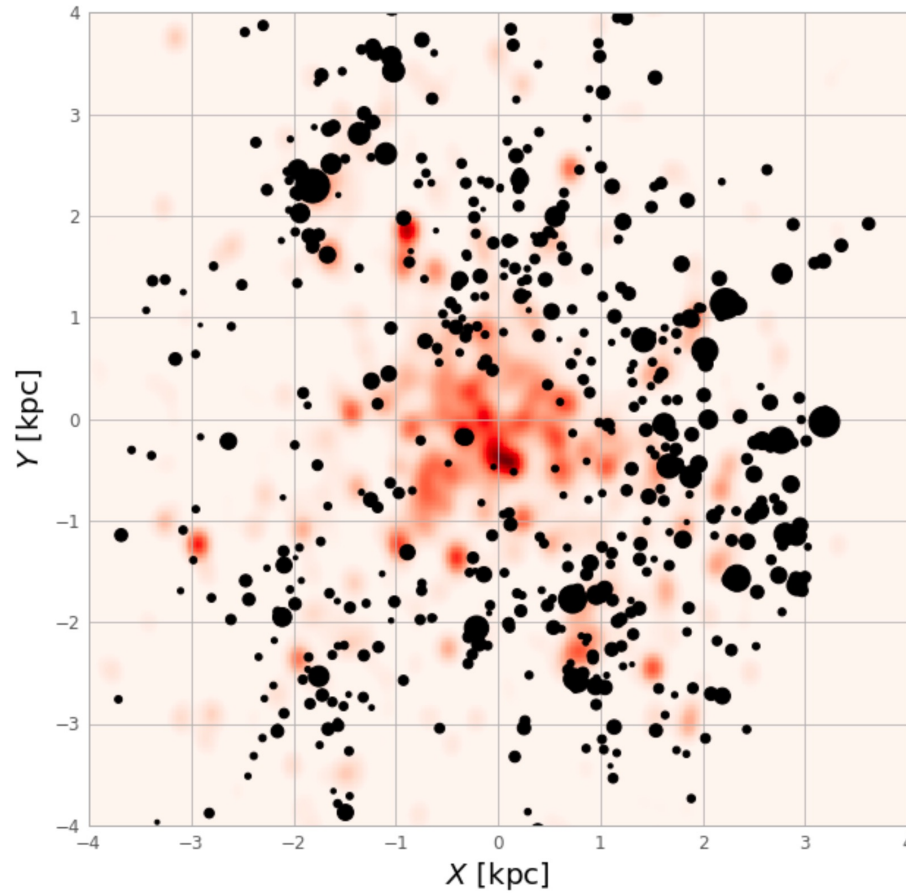
- Measure distance between all points
- Construct a minimum spanning tree
- Determine the appropriate place to cut the branches

Hierarchical clustering



- Different clustering algorithms may have differences in outputs, but trace the same underlying structure

Gaia allows finding new clusters



Castro-Ginard+20

“Common knowledge”

- Most stars form in **clusters**
- About half of all clusters do not **survive** past 10 Myr, only a few make it to 100 Myr

“Common knowledge”

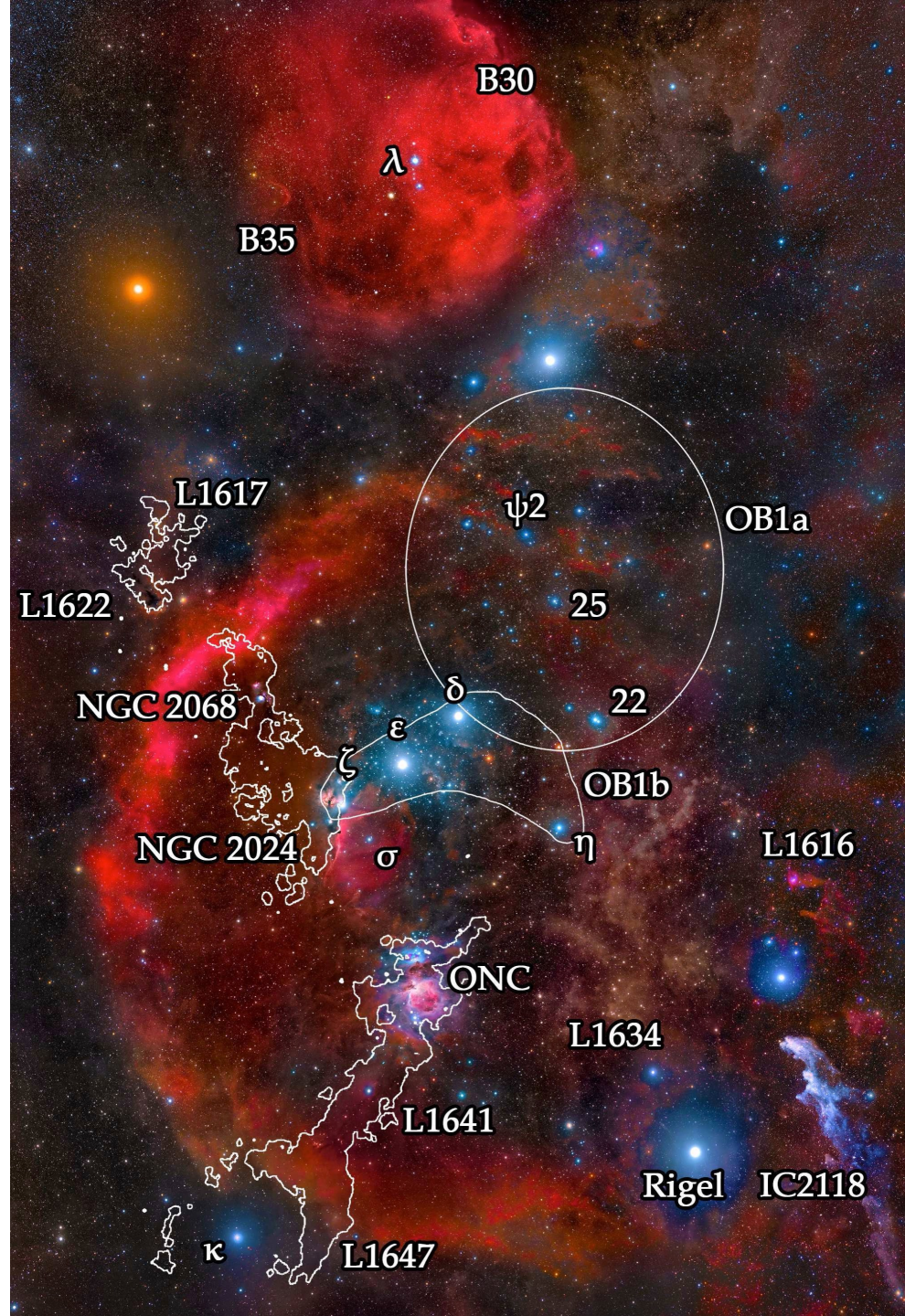
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 - What does it mean to survive?

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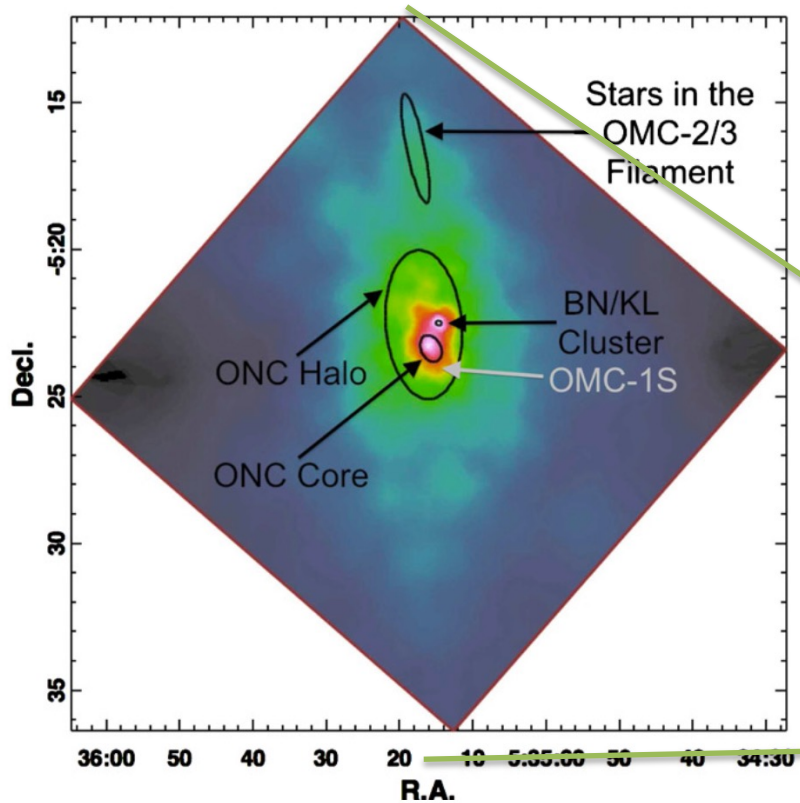
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 - What are clusters?
- About half of all clusters do not **survive** past 10 Myr, only a few make it to 100 Myr
 - What does it mean to survive?
- 16% of stars are born in **bound** clusters (Anders+21)

How does one define
a “star cluster”?

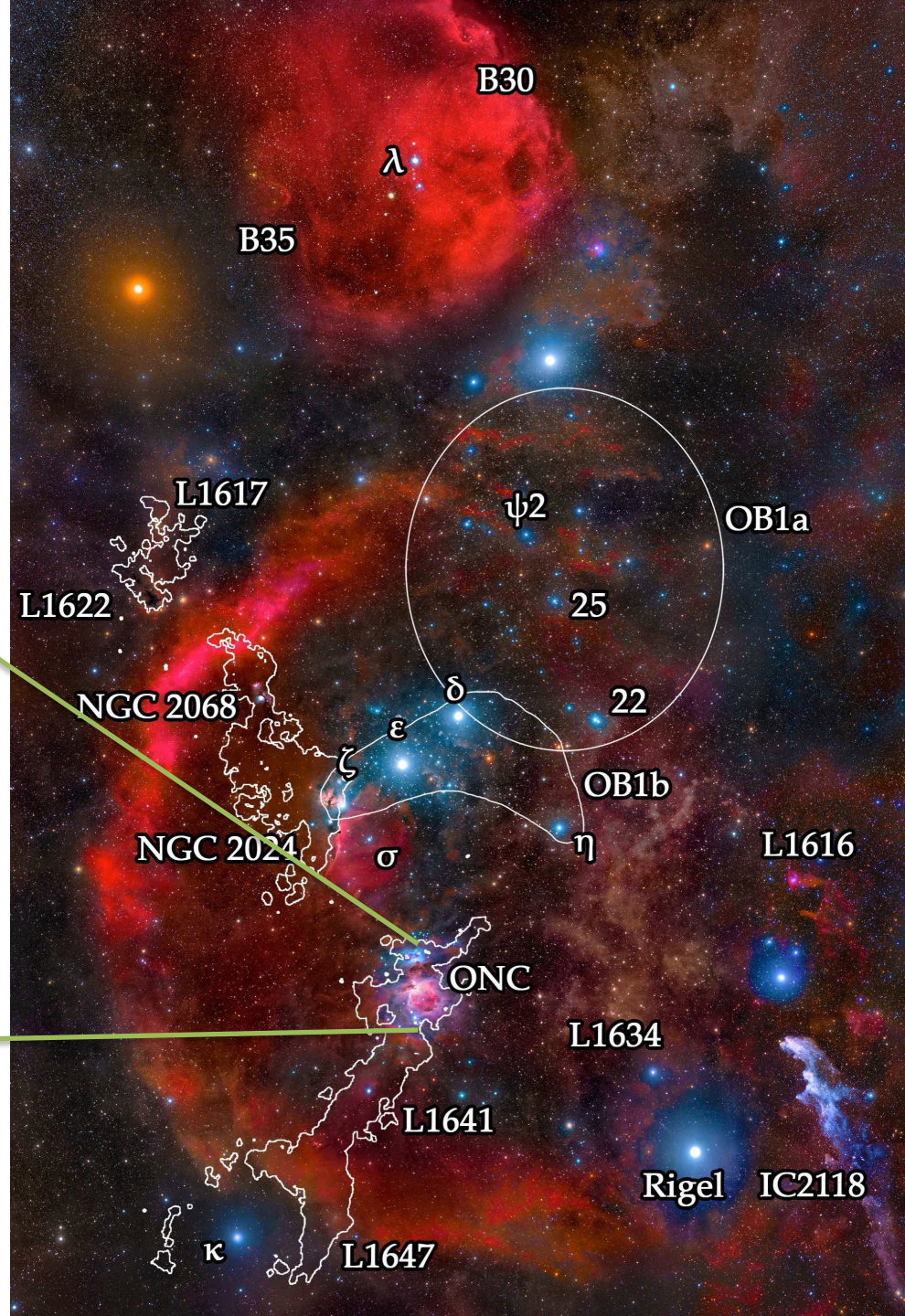
Star formation & clusters



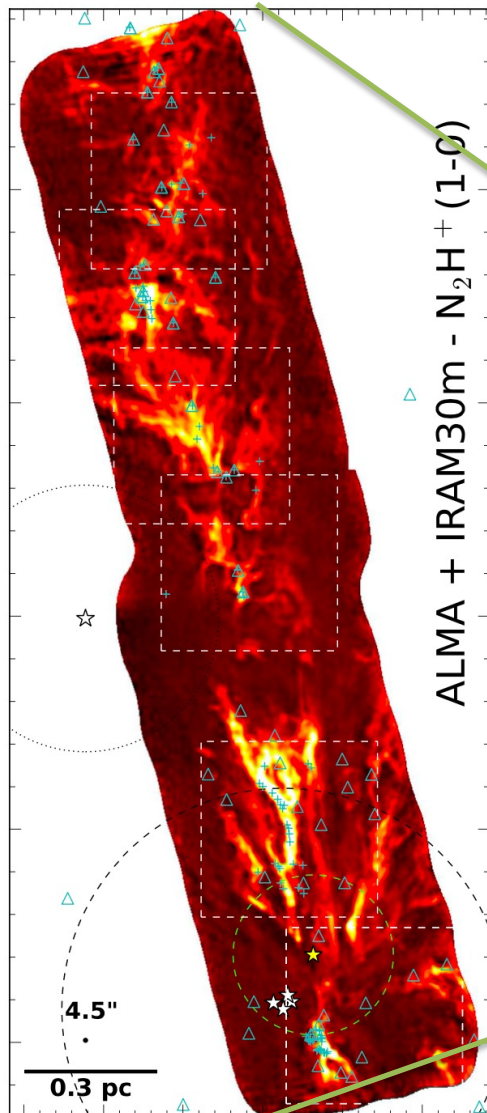
Star formation & clusters



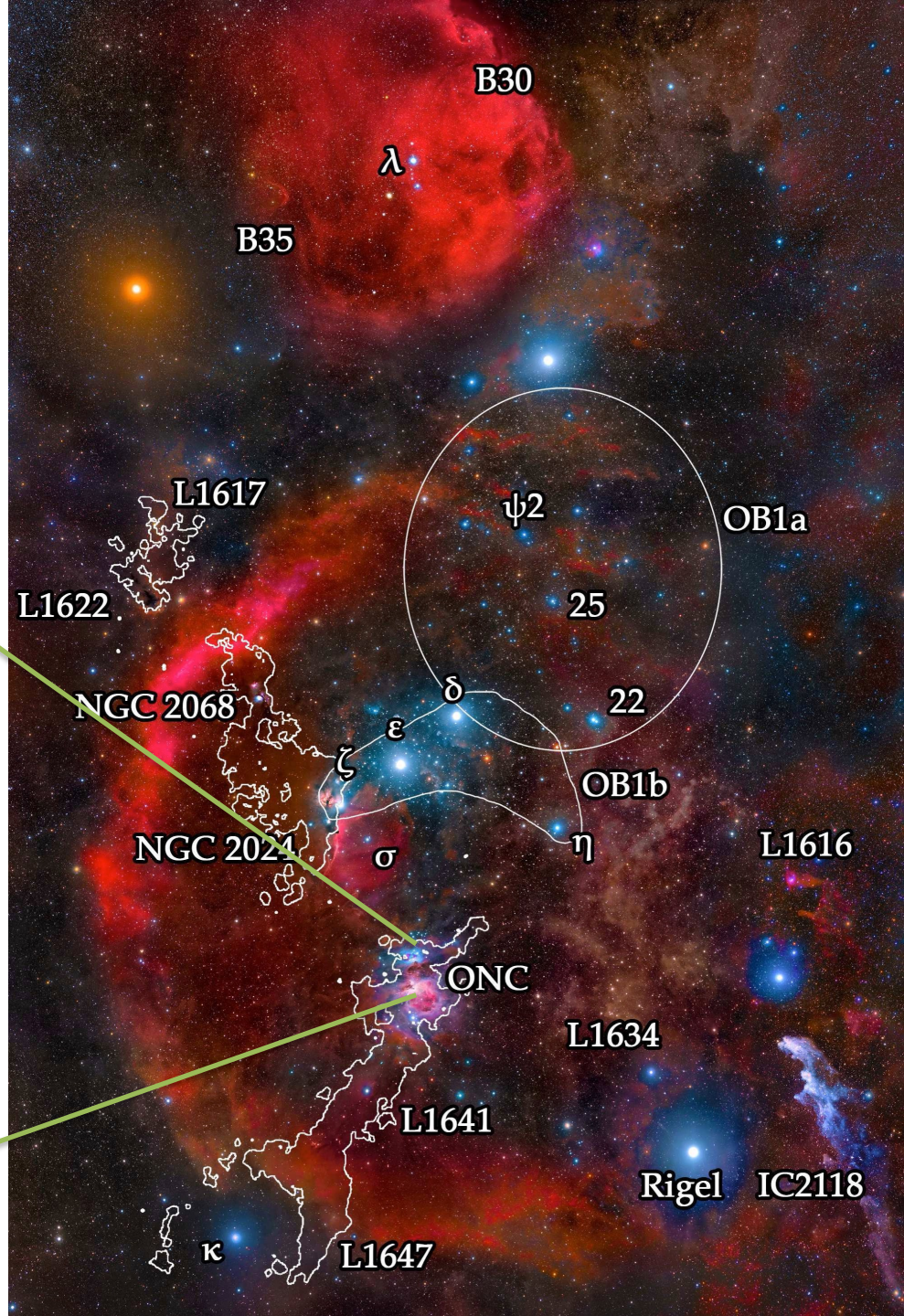
Kuhn+14



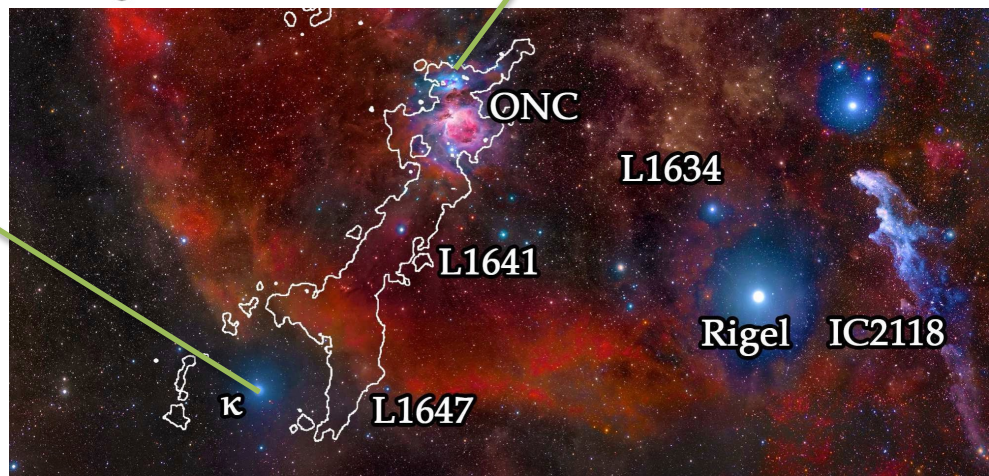
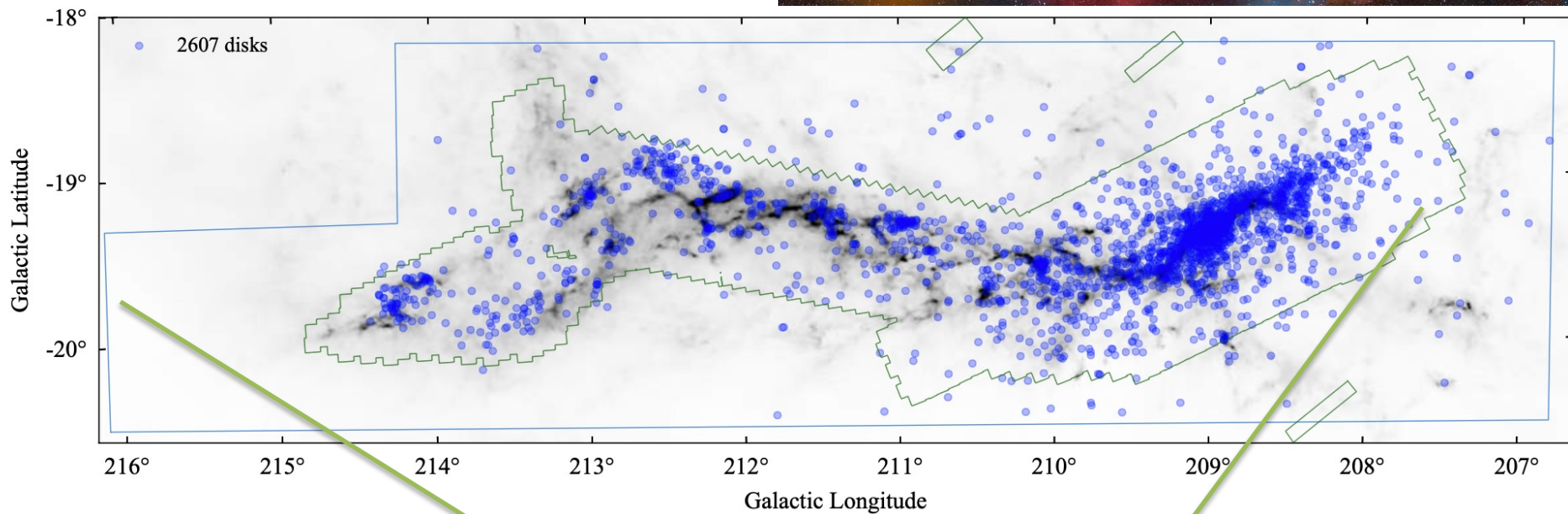
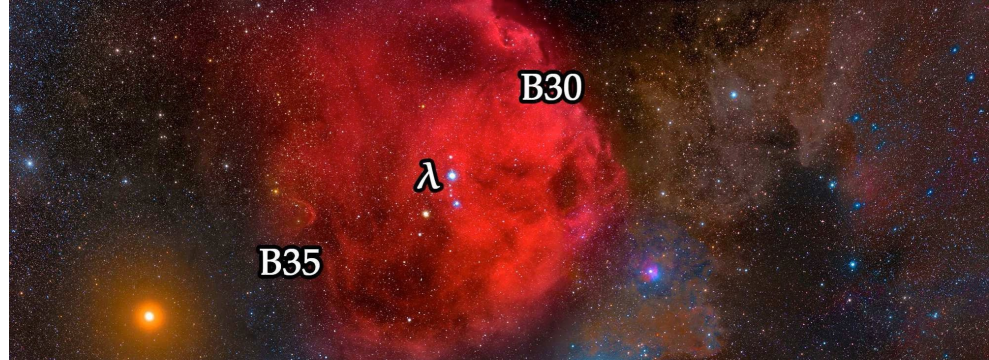
Star formation & clusters



Hacar+18



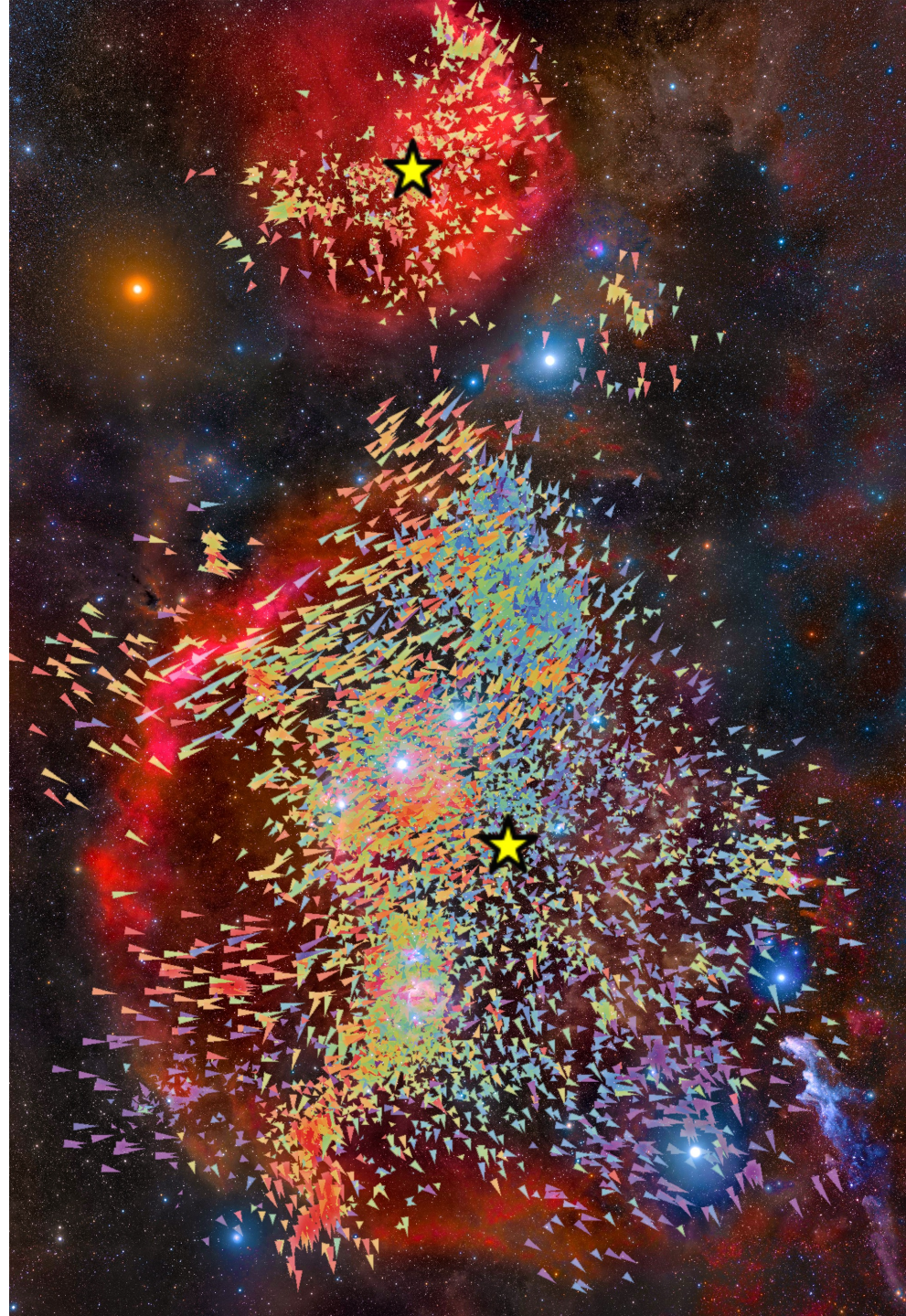
Star formation & clusters



Grosschedl+19

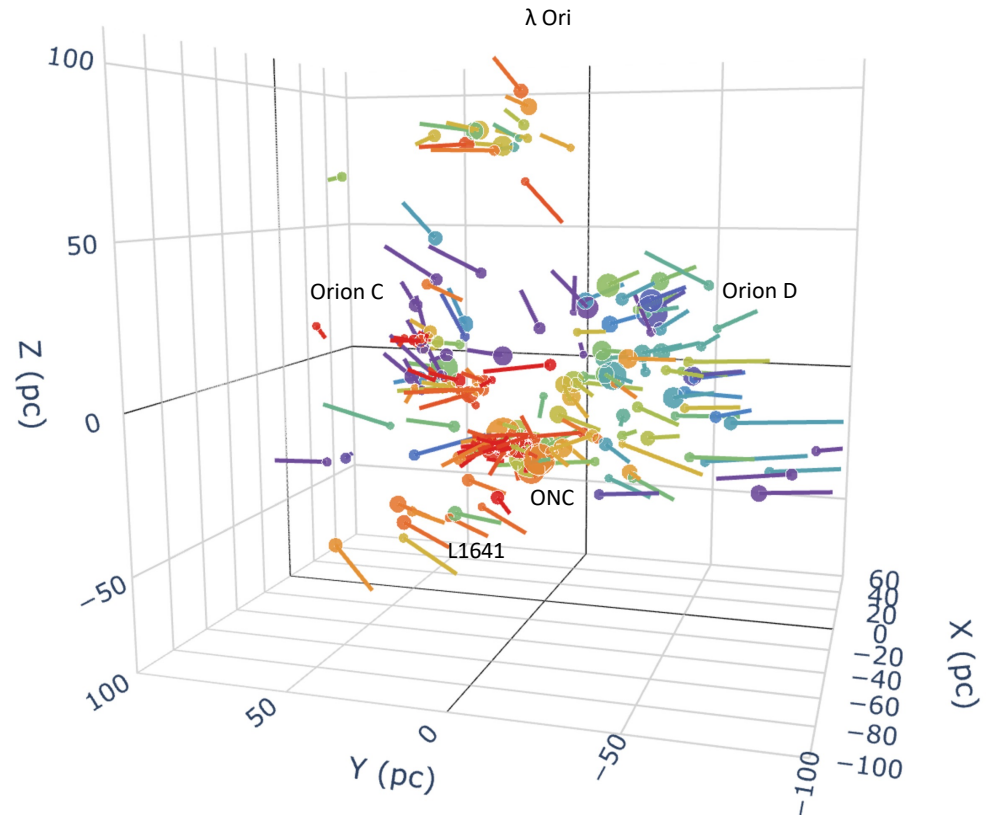
Star formation & clusters

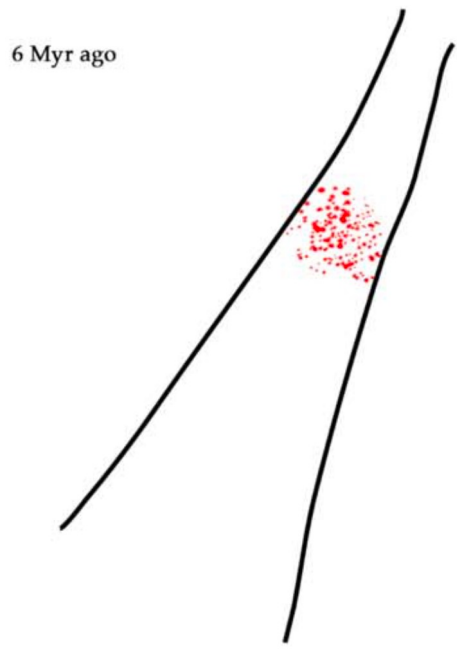
- Orion Complex spans 150+pc
- Age: 1-10 Myr
- Contains >10K stars



Orion Molecular Cloud Complex

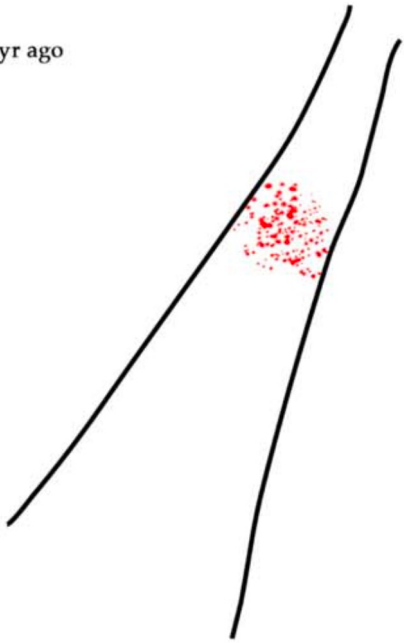
- Stars trace 3d expanding bubble
- Orion C & D projected on top of each other in the plane of the sky, have similar ages, but have different distances and RVs, moving away from each other
- ONC is moving inward into the Orion A filament
- Converge to the center 6 Myr ago
- Consistent with the supernova eruption





- Original cloud shaped as a long filament
- Population of stars starts forming towards the top ~8 Myr ago
- Bottom part of the cloud is not dense enough to form stars yet
- Supernova eruption ~6 Myr ago

6 Myr ago

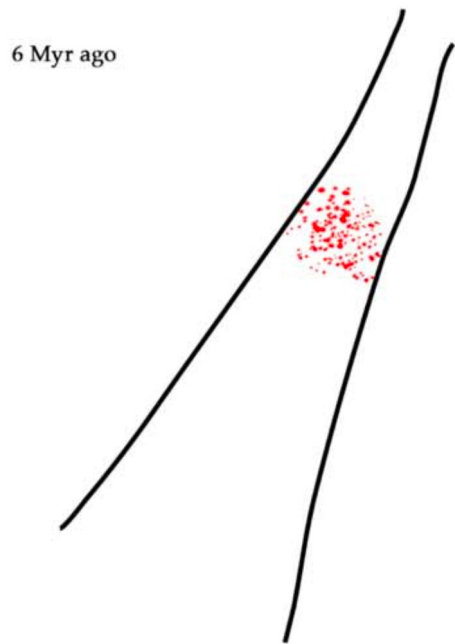


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4 Myr ago



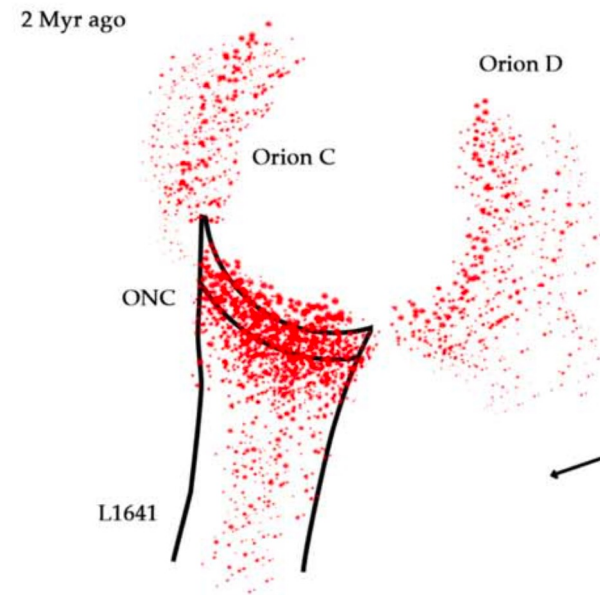
- Shockwave splits the cloud
- Triggered star formation in two directions perpendicular to the filament
- Gravitational feedback assists in the dispersal of stars near the center of the eruption
- Beginning of formation of the ONC along the shockwave



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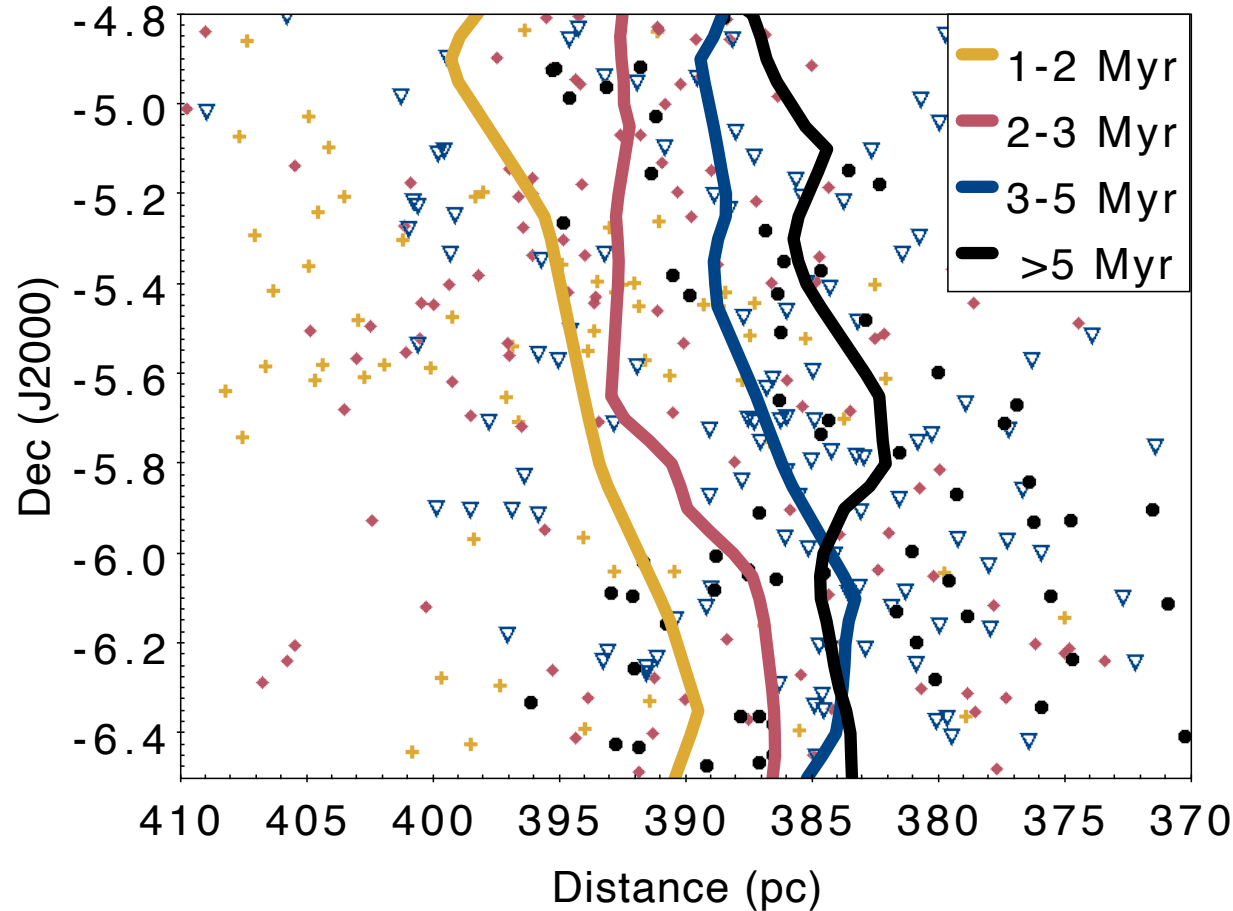
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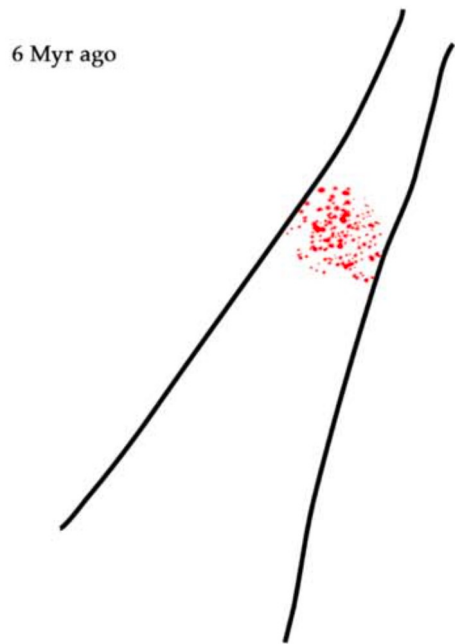


- Orion C & D run out of gas, continue to expand outward
- Shockwave sweeping through the filament accumulates gas for the ONC, self-gravity, becomes important
- Bottom part of the filament continues to collapse naturally to form stars

Distance to ONC

- Older stars at 385 pc
- Younger stars at 395 pc
- No difference in RV between them, or stars and gas
- Star formation front being pushed back

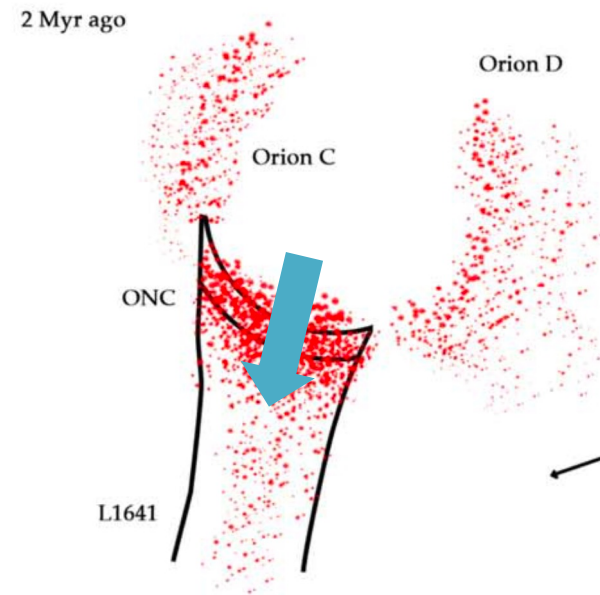




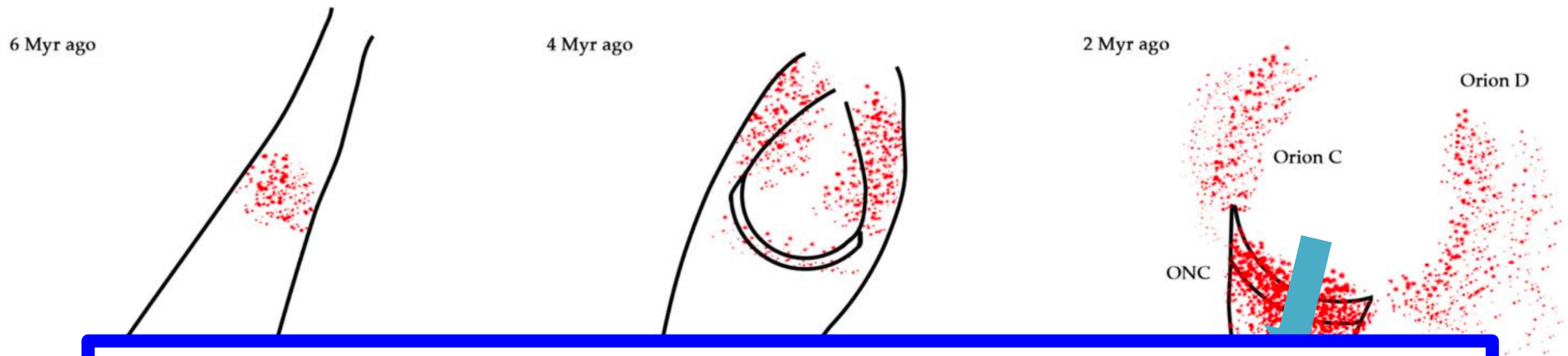
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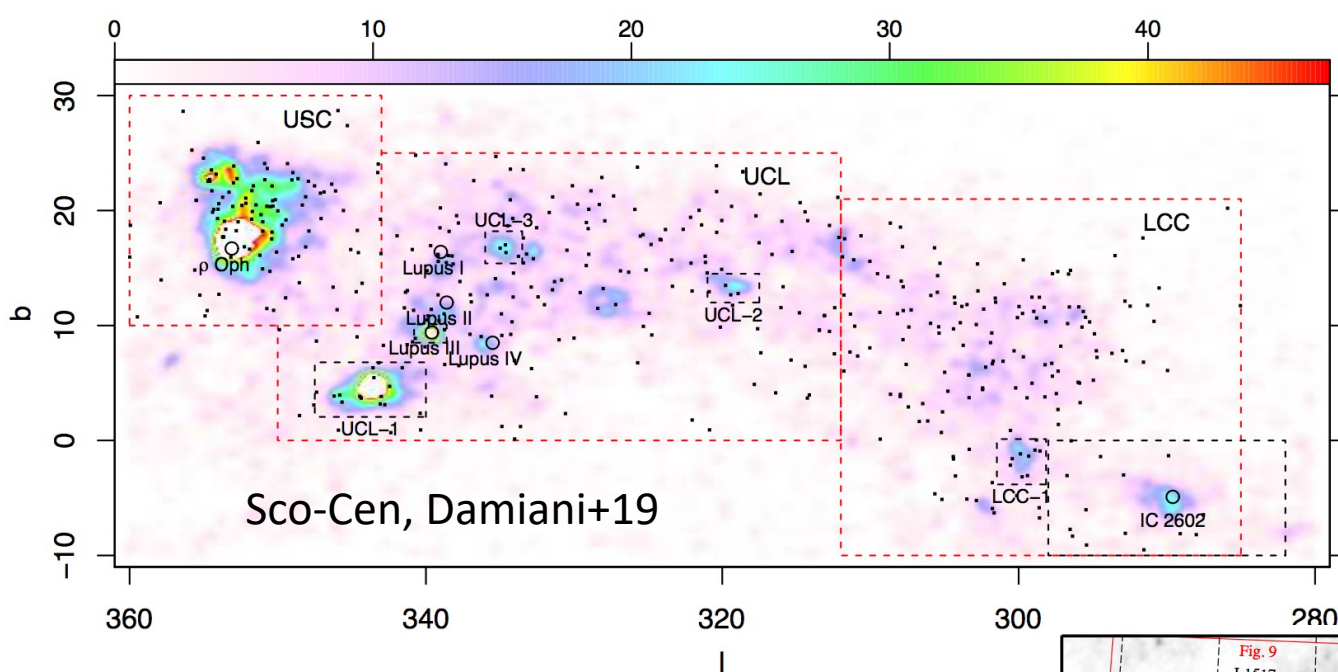


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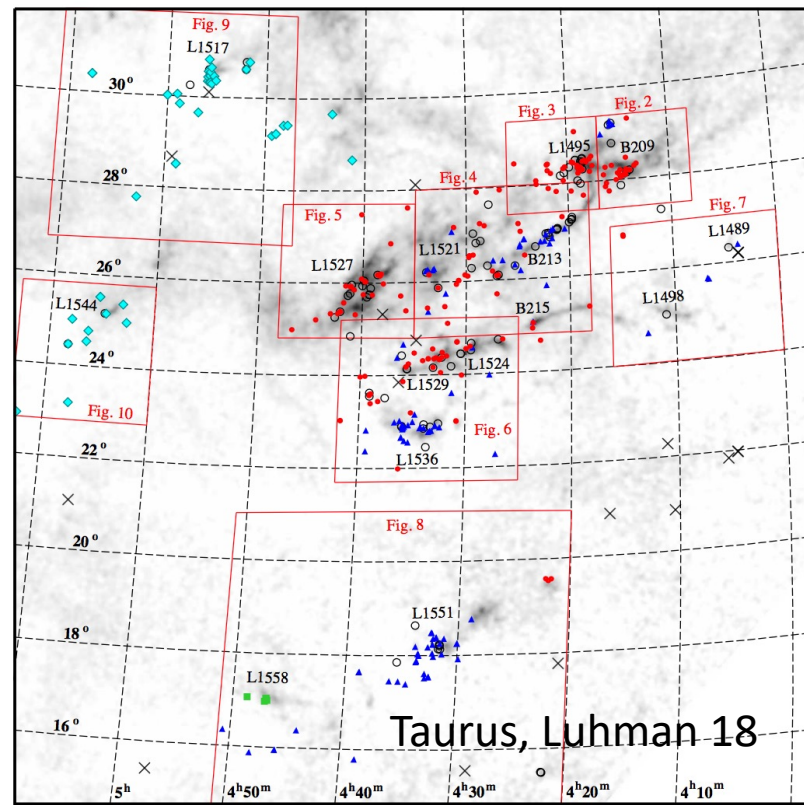
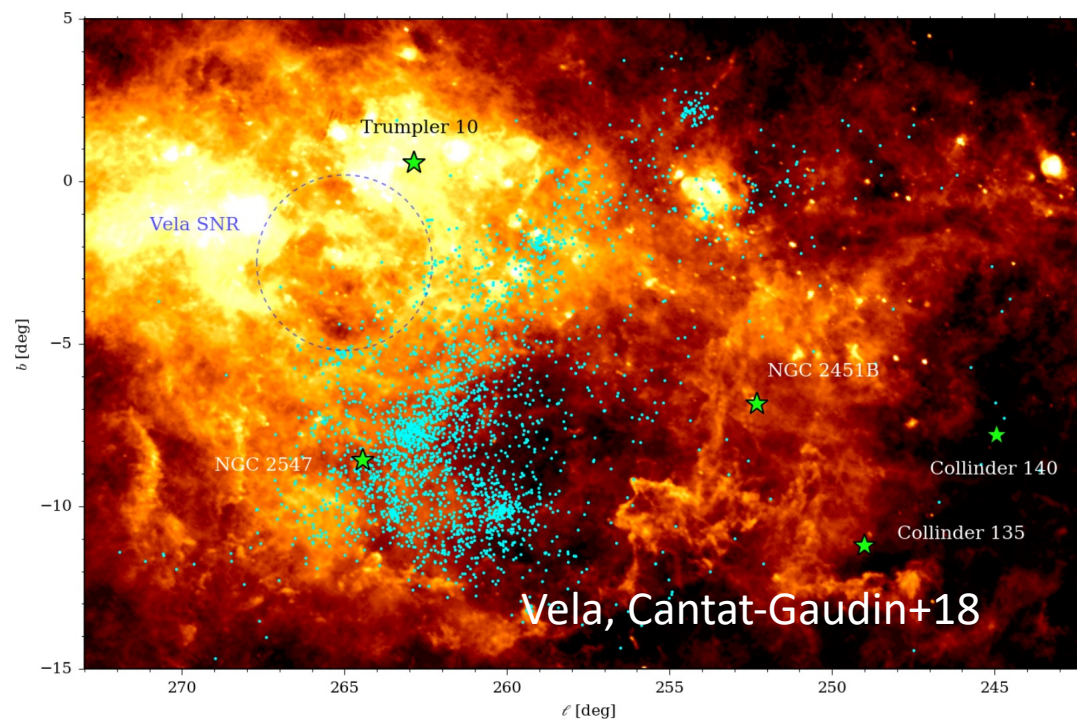


Despite large scale expansion,
velocity dispersion is $<4 \text{ km s}^{-1}$

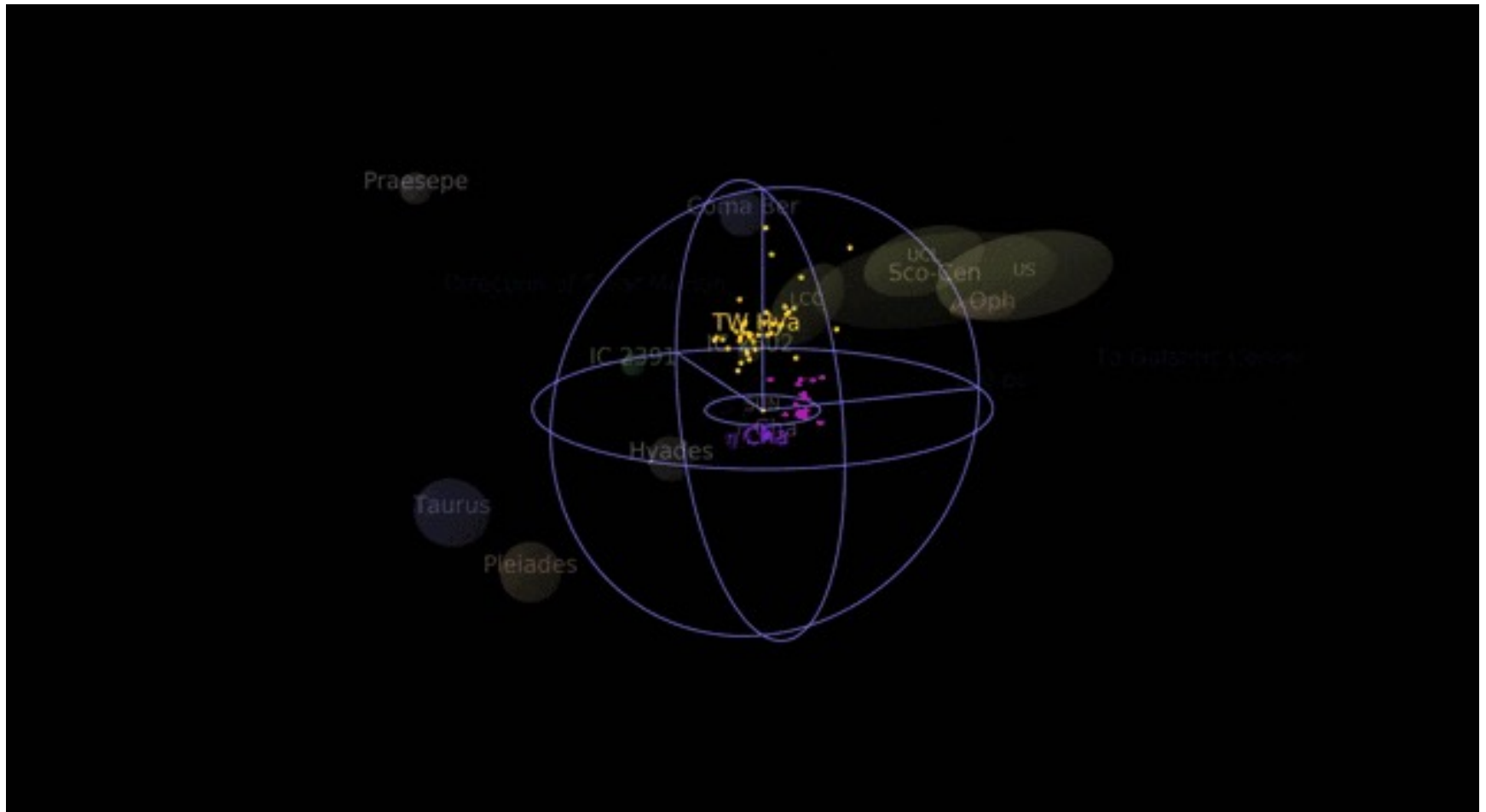
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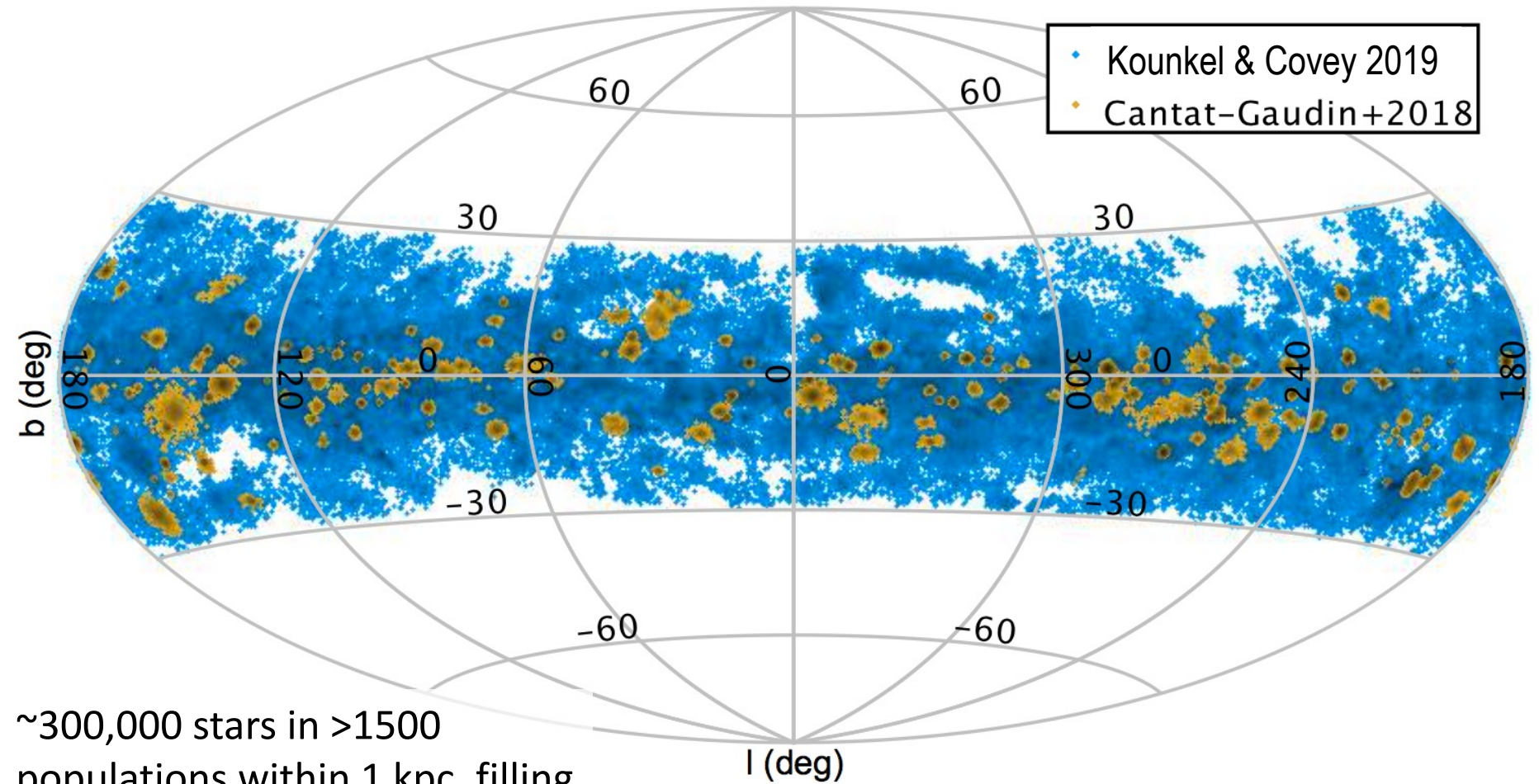
Most SFR are extended and dynamically cold



Nearby Moving Groups



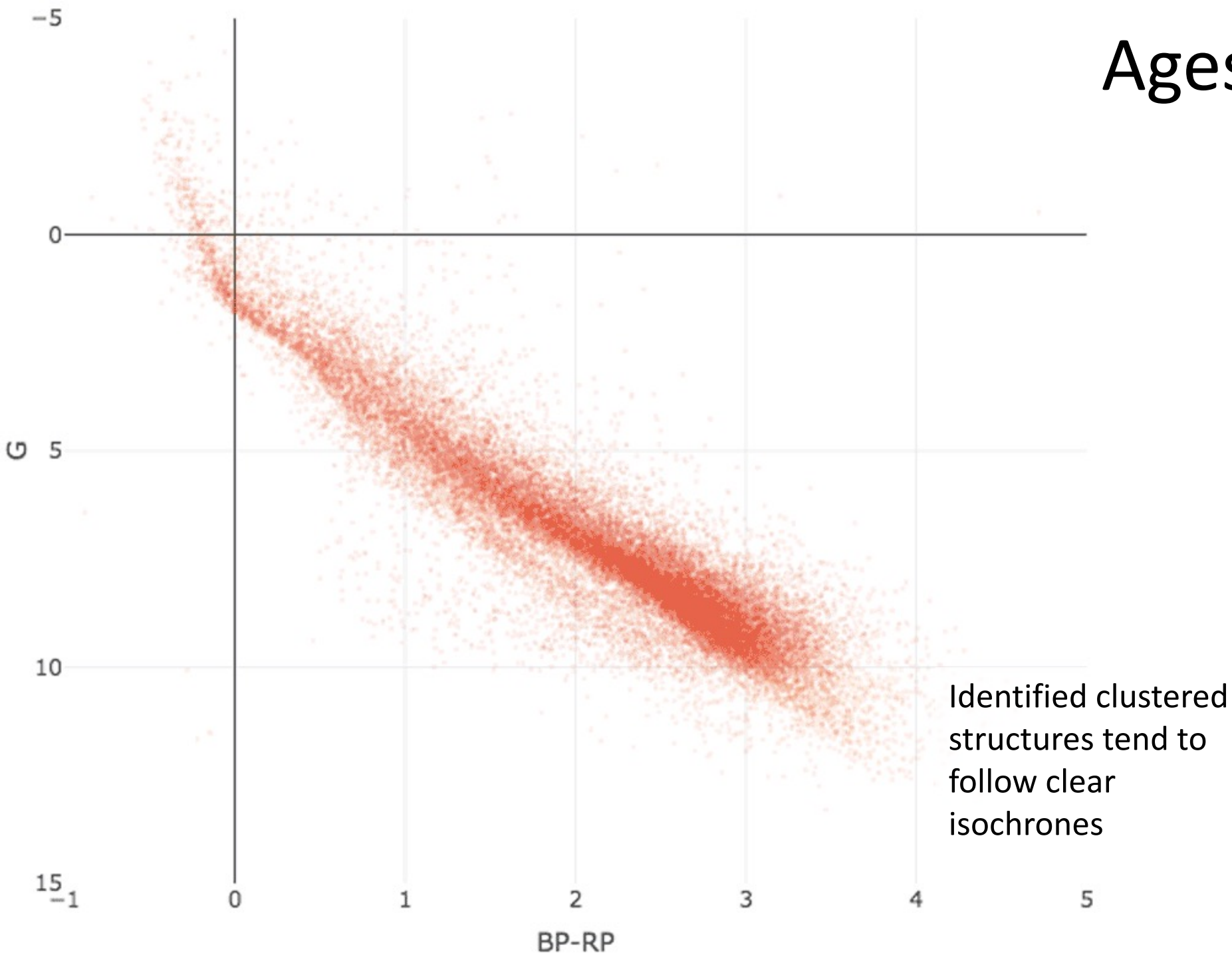
Identified Structures



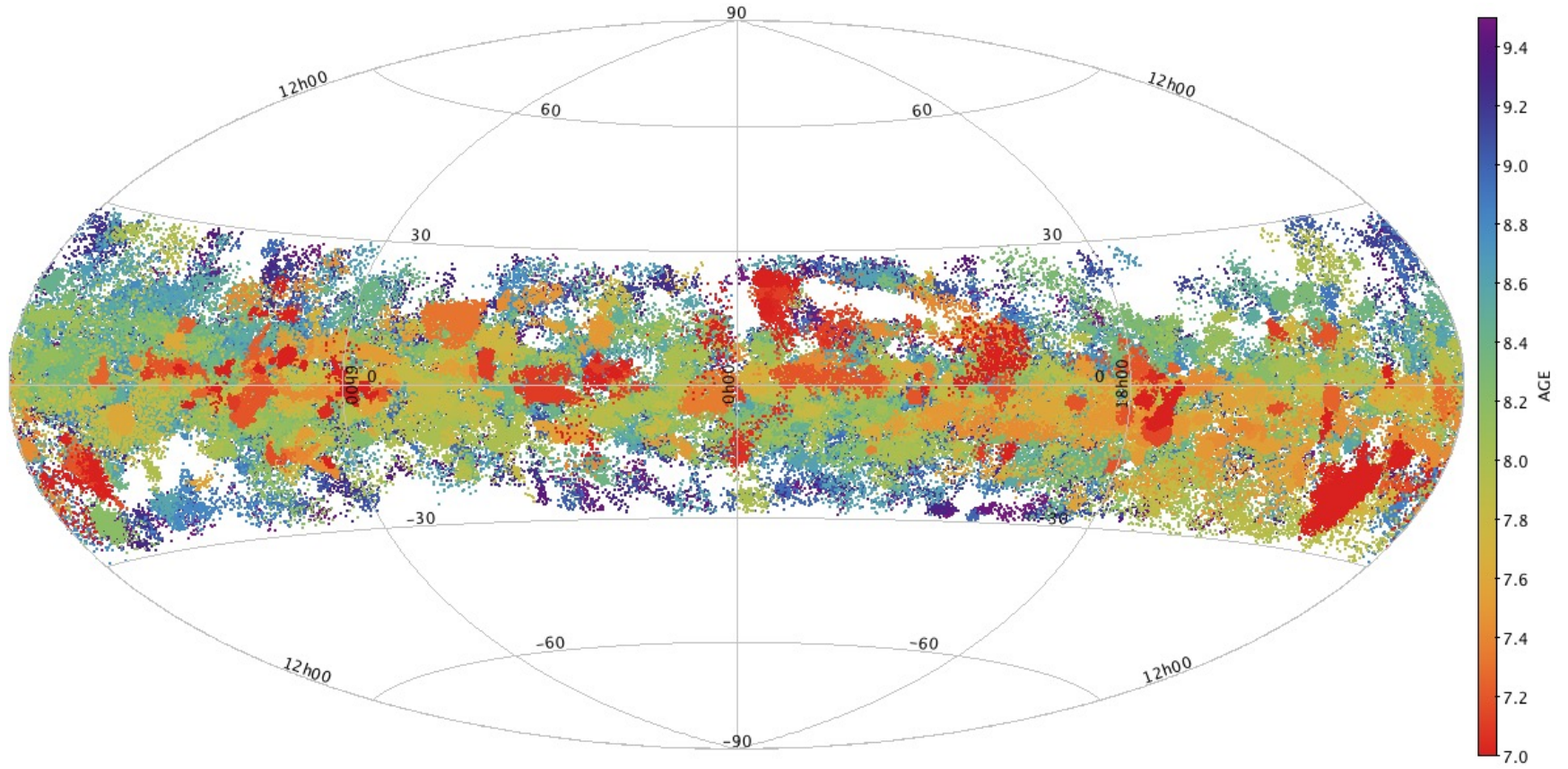
~300,000 stars in >1500
populations within 1 kpc, filling
a larger volume of the sky than
previously known clusters

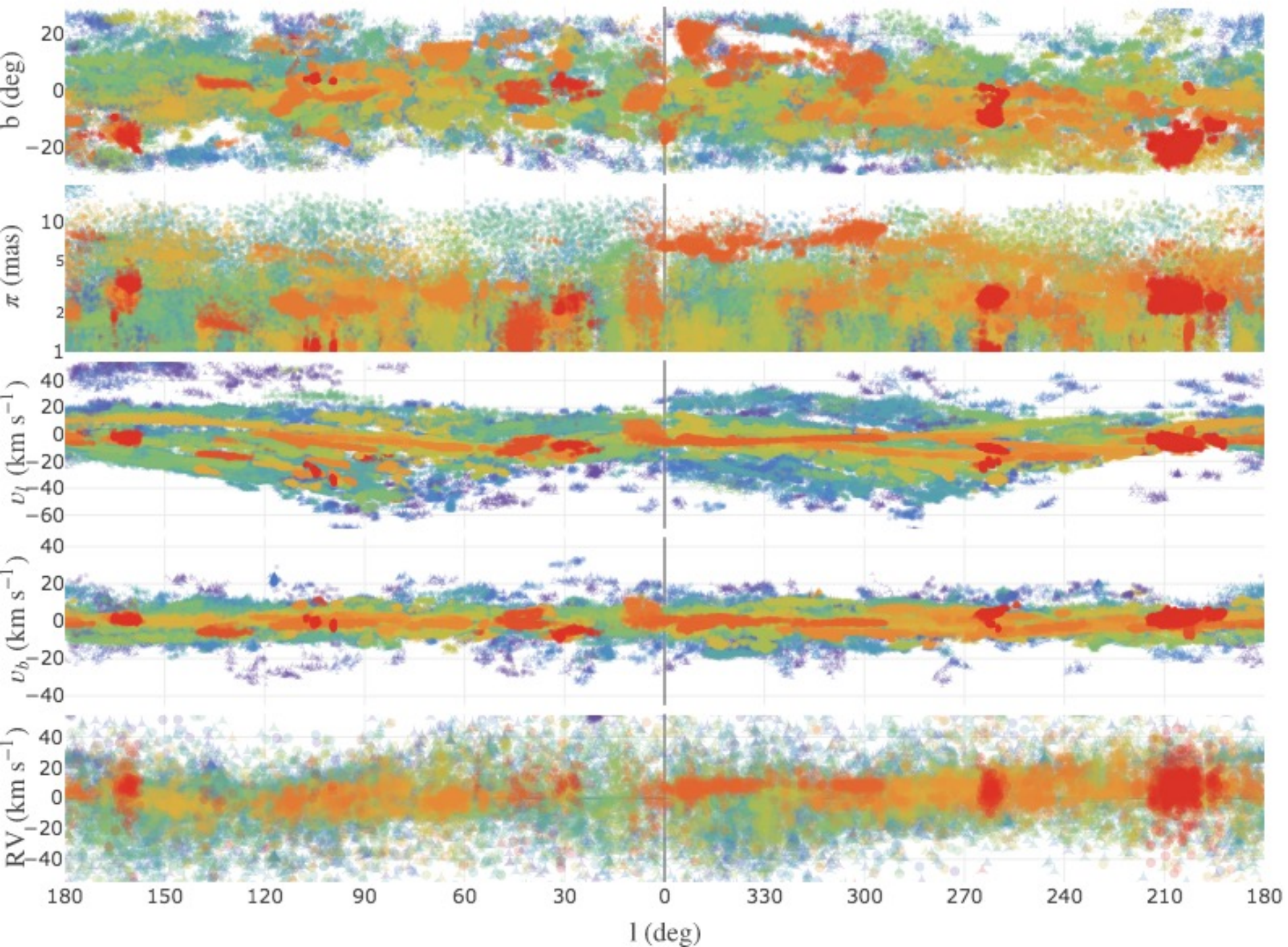
~1 million stars in >8000
populations within 3 kpc

Ages

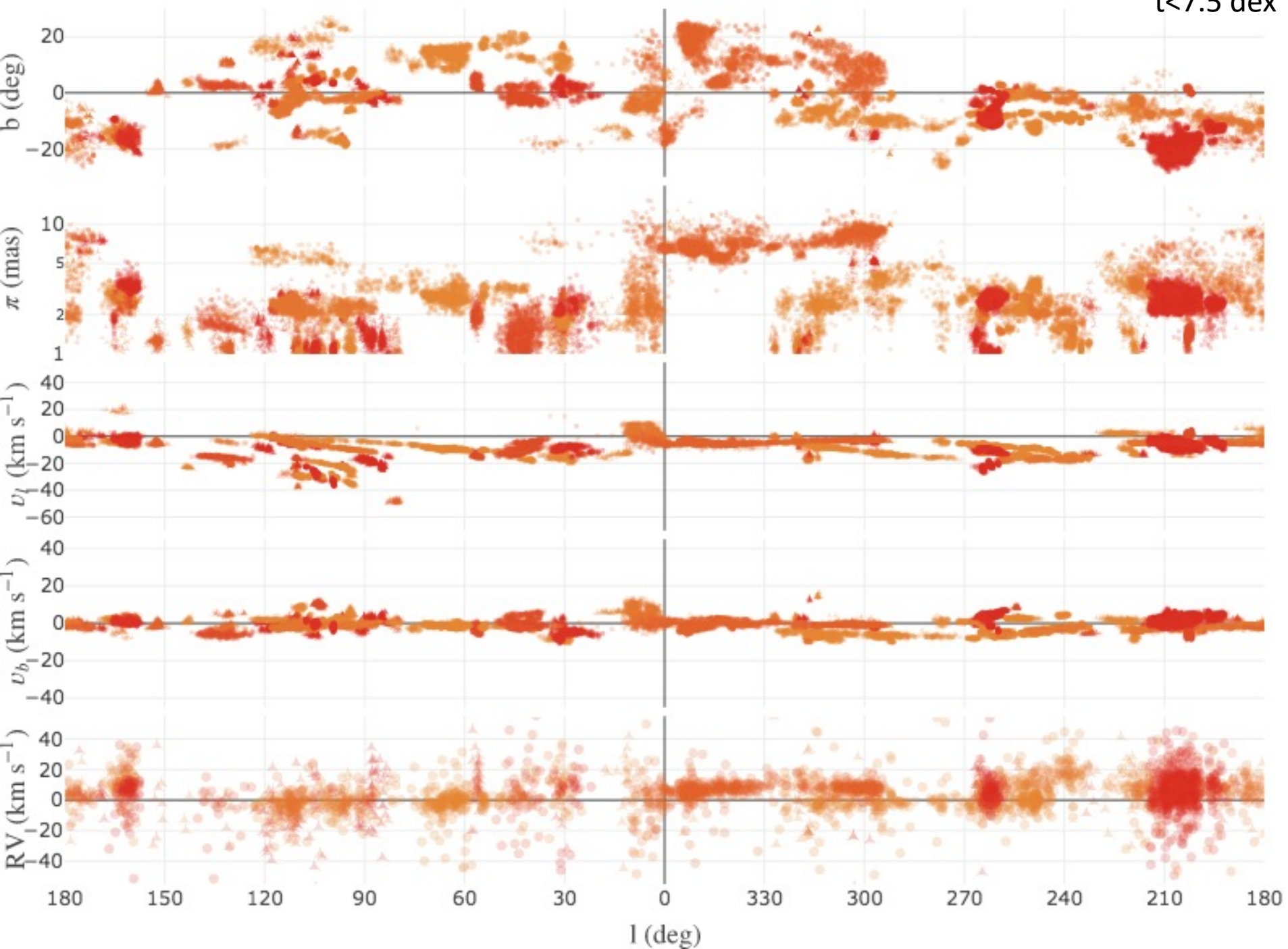


Ages



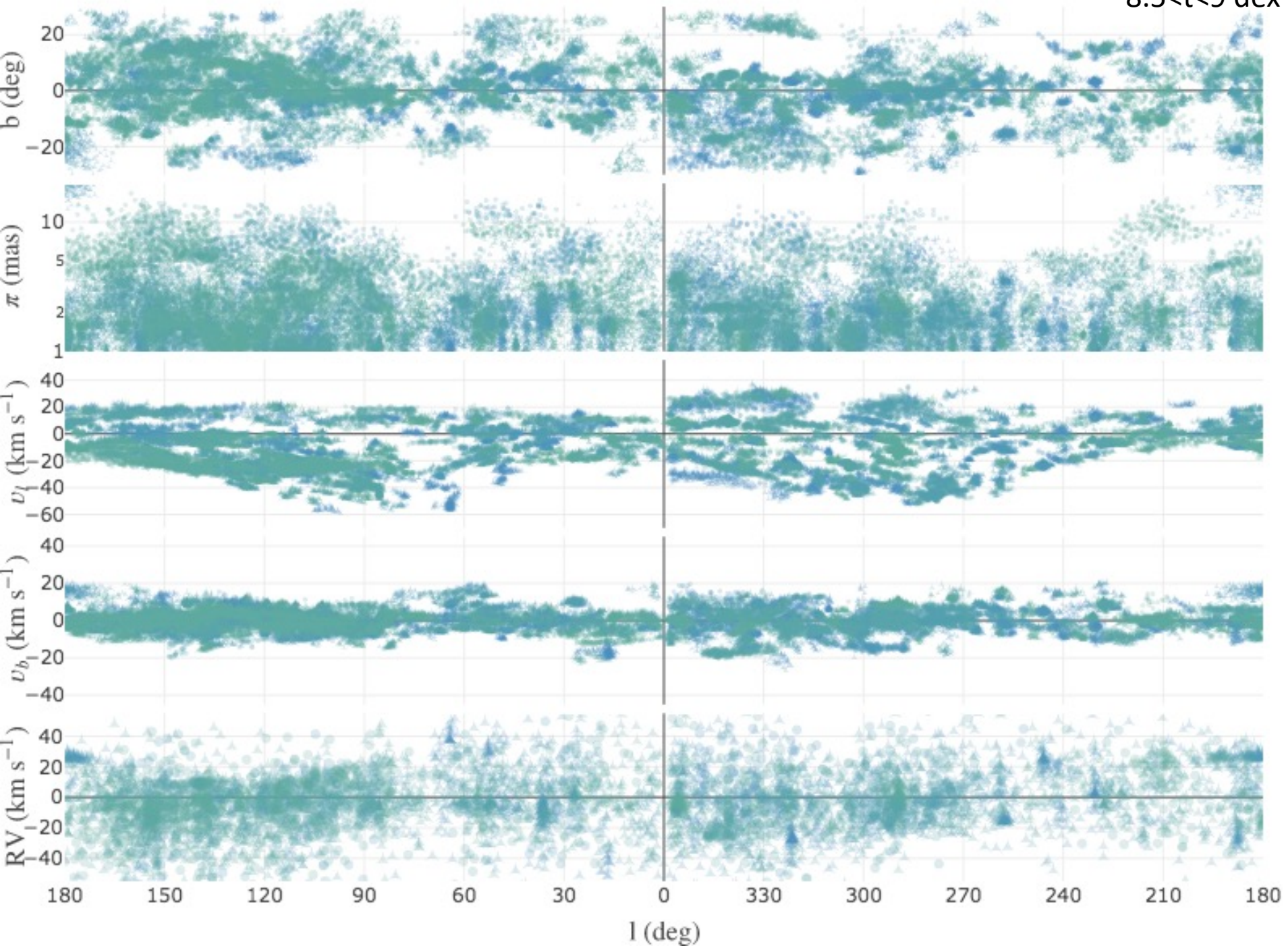


$t < 7.5$ dex

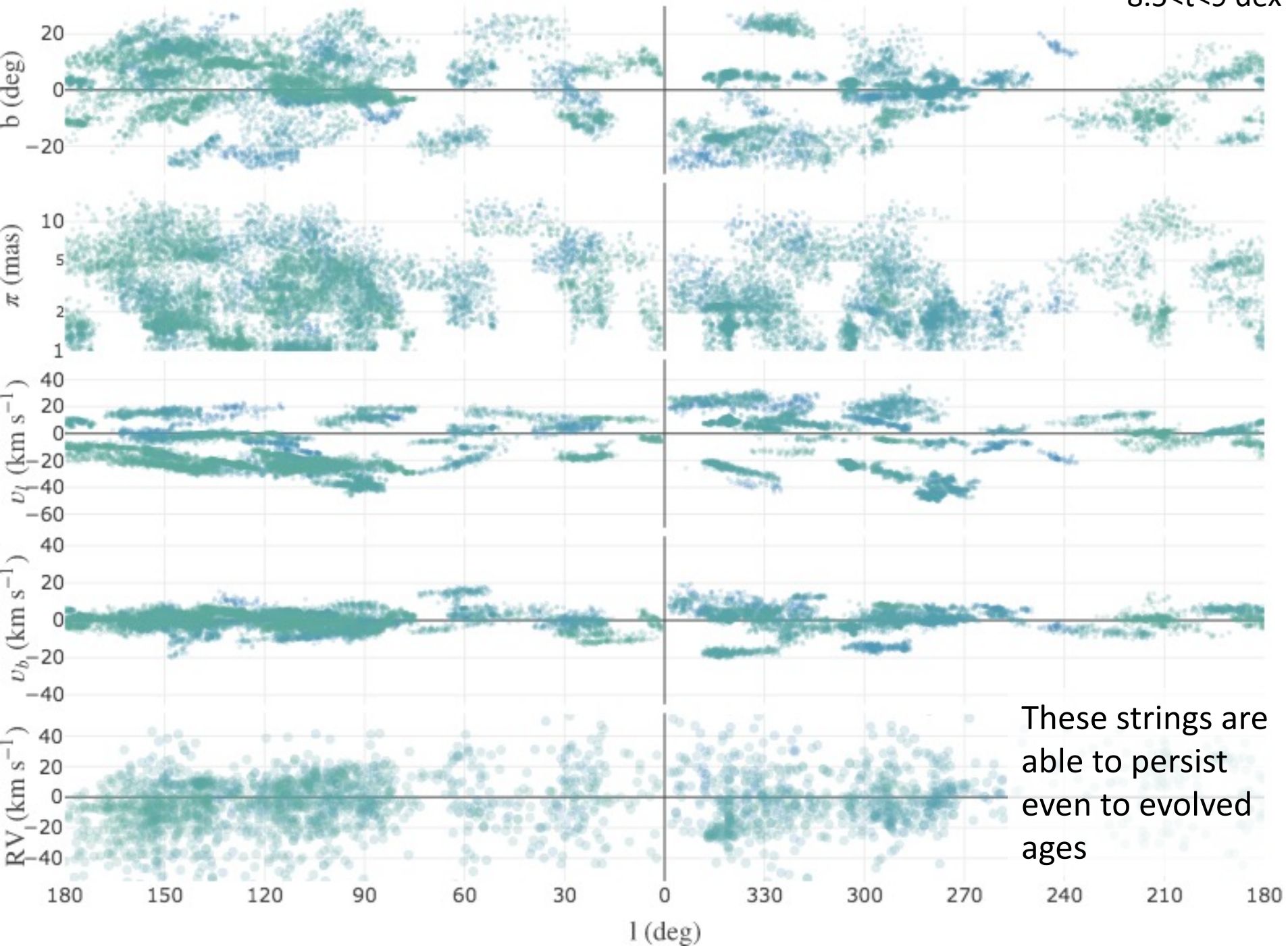




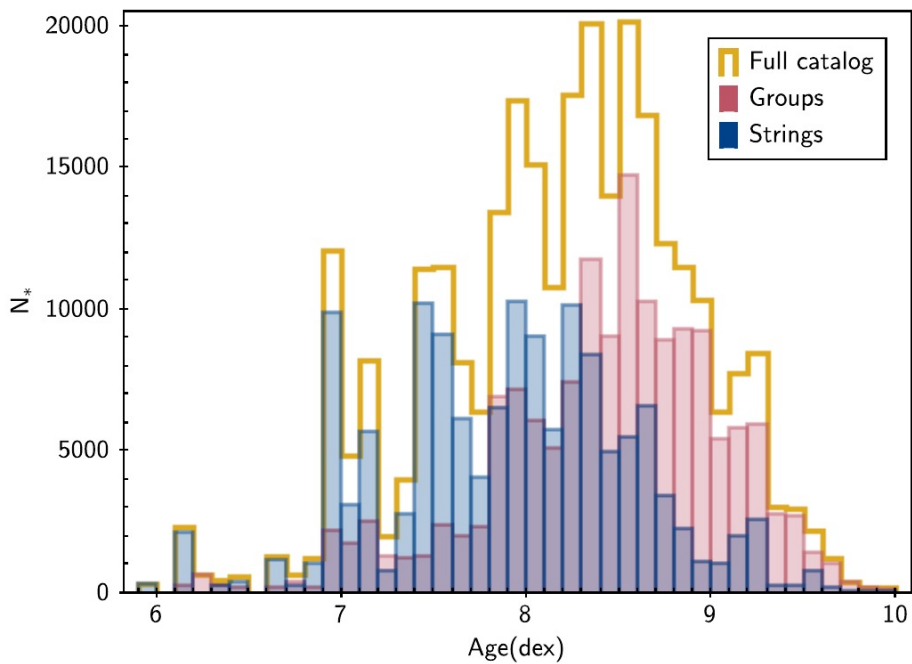
8.5 < t < 9 dex



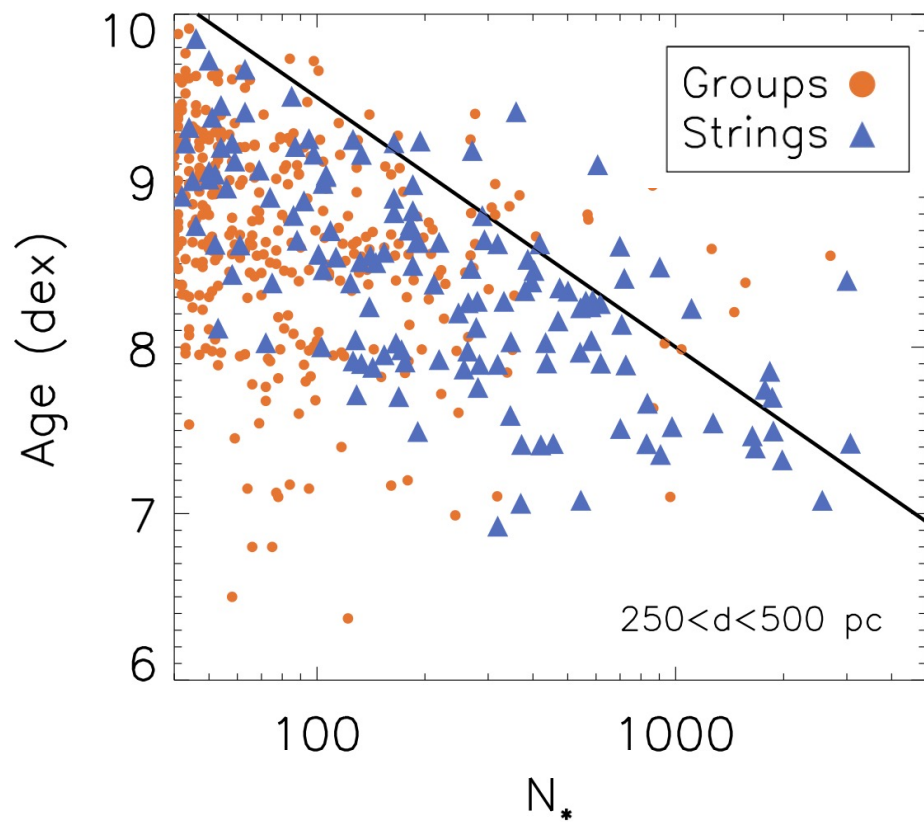
8.5 < t < 9 dex



Distribution of ages

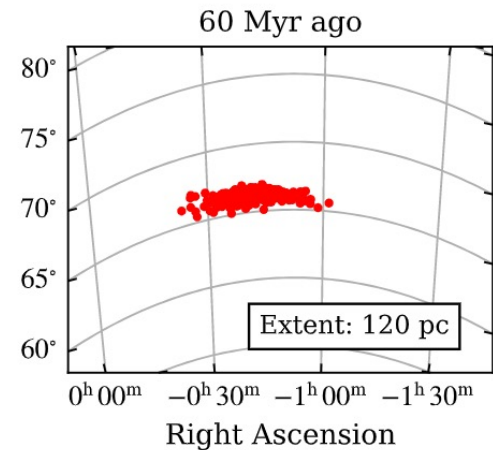
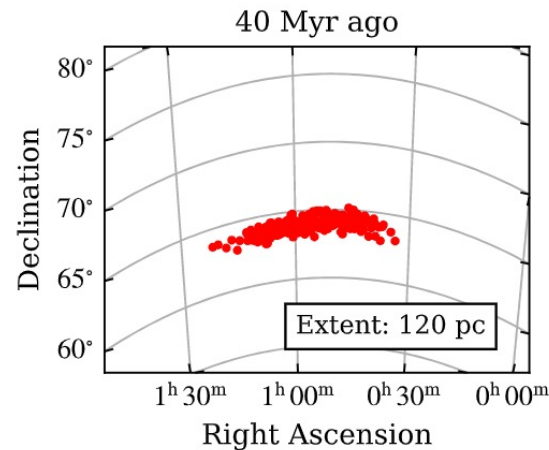
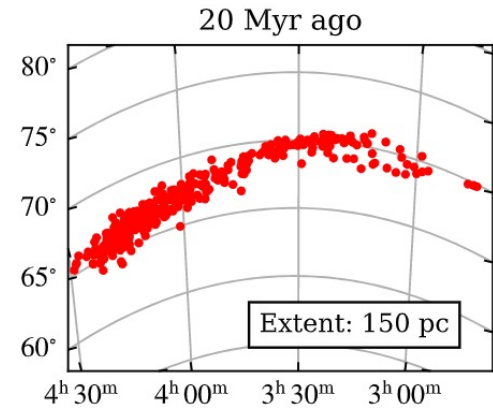
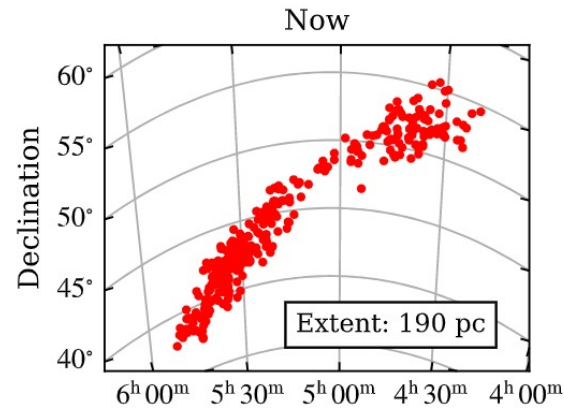


Number of stars as a function of age



Traceback of Theia 456

- Expanded by 50% over last 60 Myr
- Still has string-like morphology at younger ages

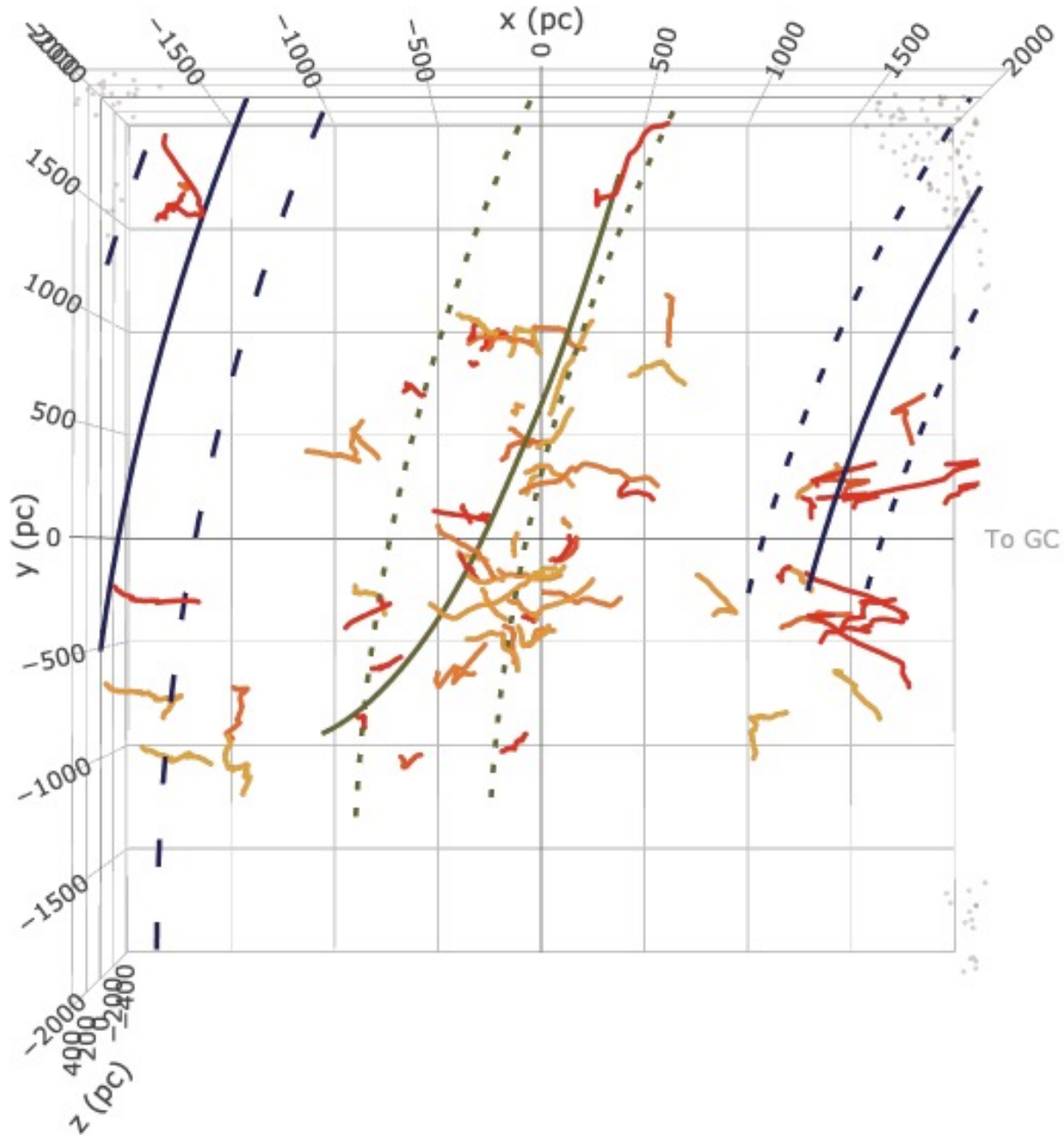


Origin of extended structure

- Not tidal stretching
 - Present ubiquitously in younger regions
 - Frequently not associated with a cluster at a center

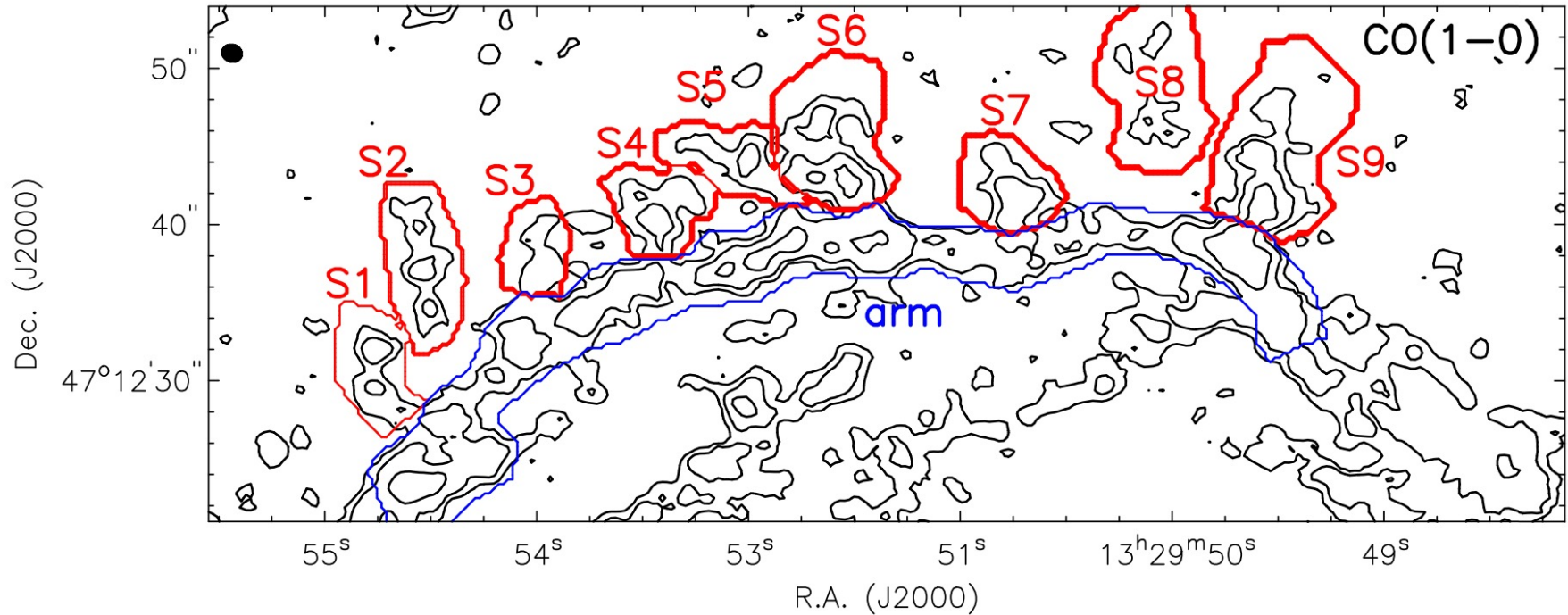
Origin of extended structure

- Not tidal stretching
 - Present ubiquitously in younger regions
 - Frequently not associated with a cluster at a center
- Primordial!
 - Remnants of the filamentary molecular clouds
 - Slowly dissolving over time
 - Only those that have been incredibly massive to begin with will survive for more than a few hundred Myr

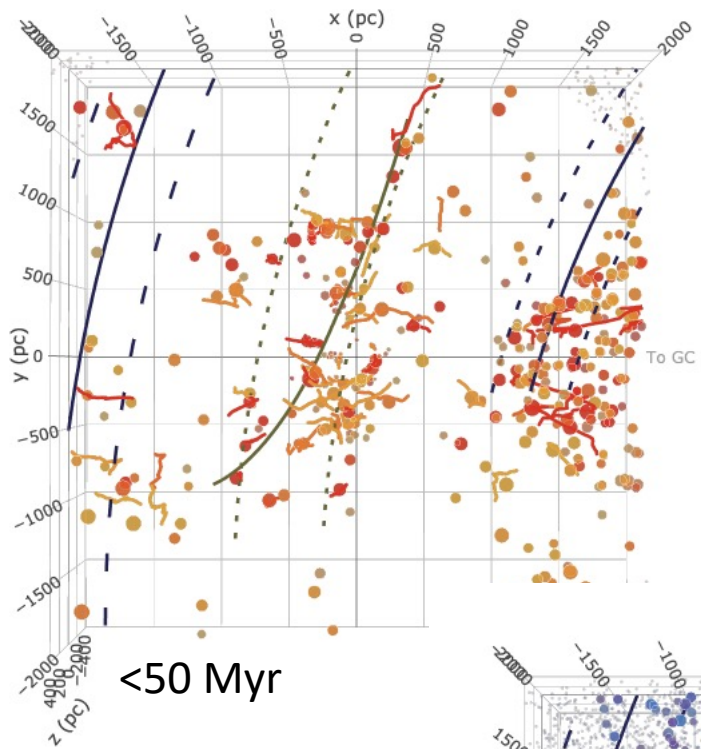


<50 Myr age

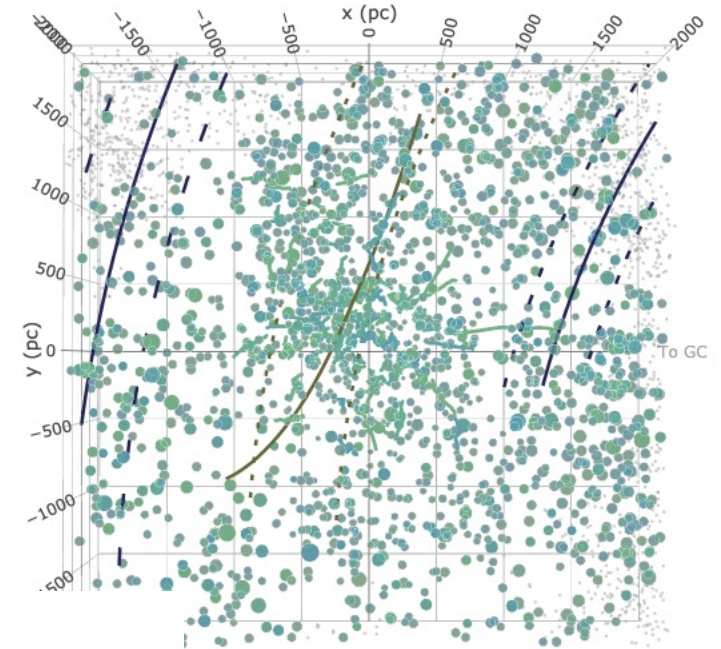
Strings are oriented largely in parallel to one another, perpendicular to the spiral arms



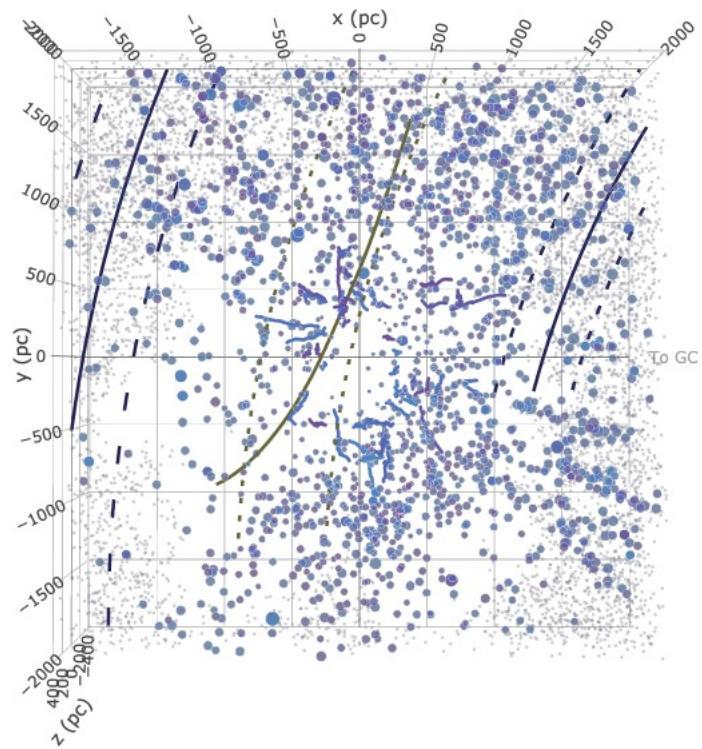
In extragalactic observations of molecular gas, there are various feathers that are oriented perpendicular to the spiral arm



< 50 Myr



200-600 Myr



> 1 Gyr

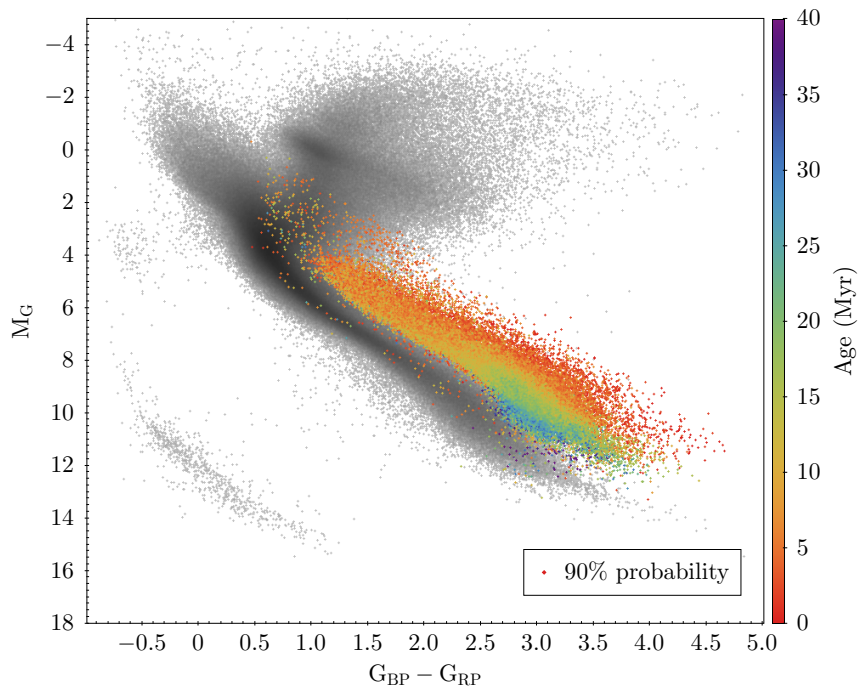
Substantial evolution in structure as a function of age

No star left behind

- As moving groups incrementally disperse, some stars would dissolve into the field
- Impossible to find *all* stars that have formed in a given group through clustering – even at the youngest ages
- What are the alternatives?

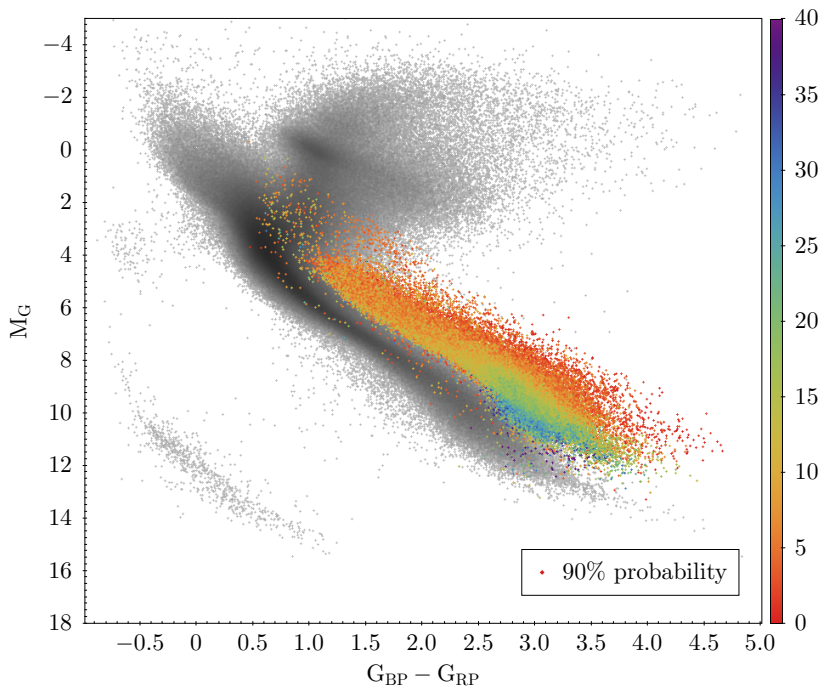
Age estimate outside of clustering

Pre-main sequence HR diagram

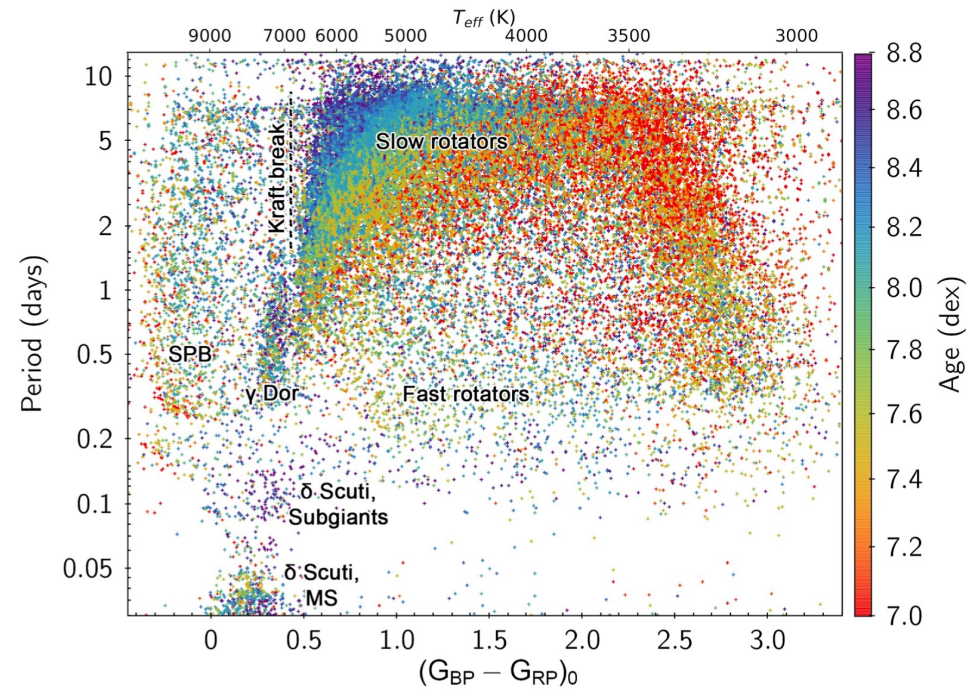


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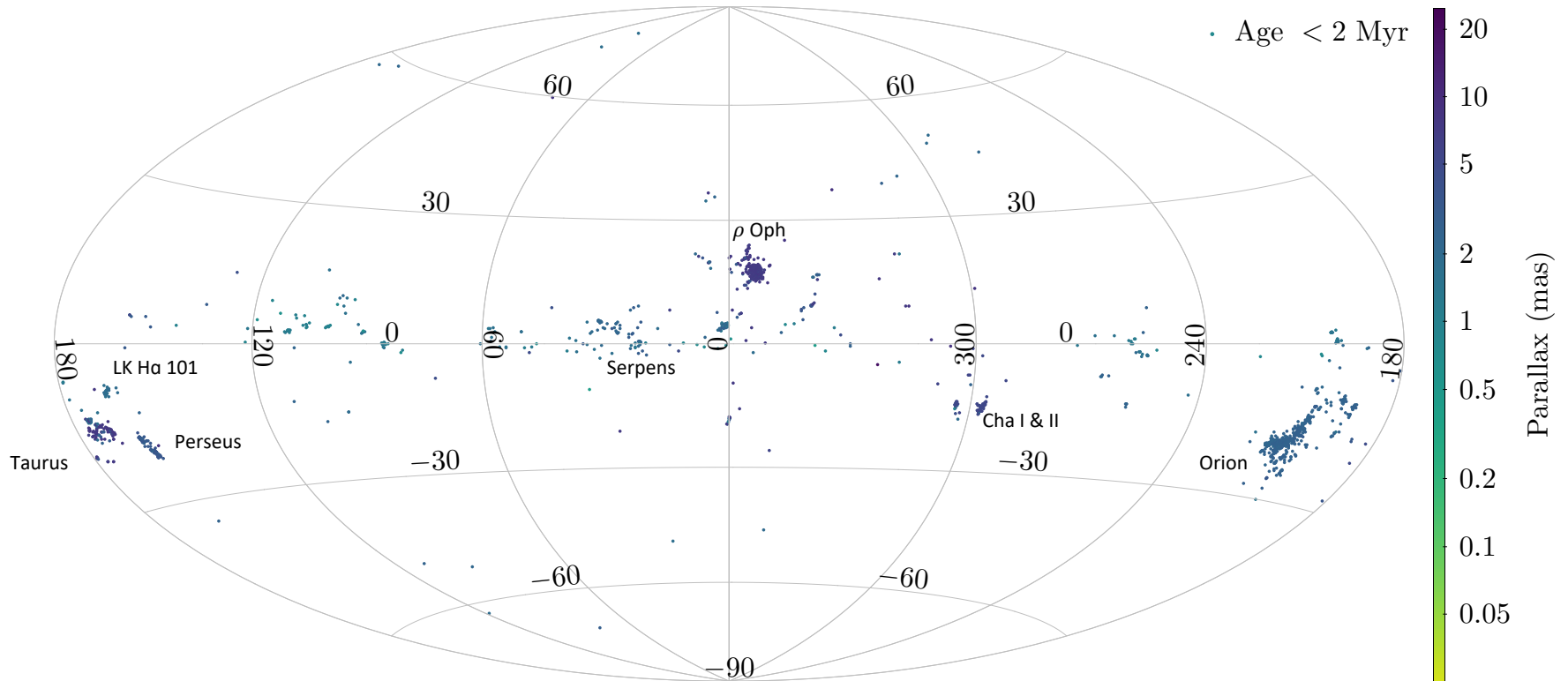
Pre-main sequence HR diagram



Gyrochronology

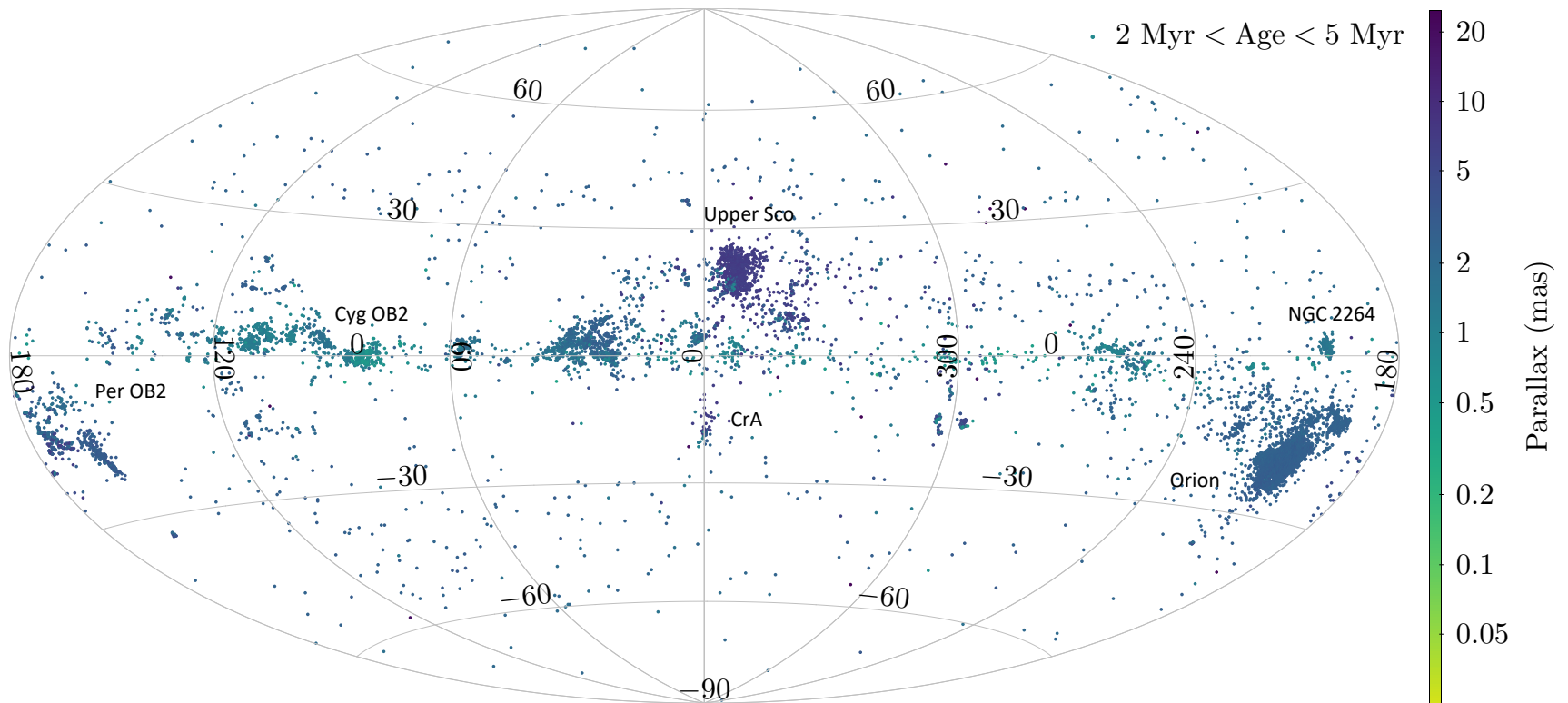


Map of star forming regions

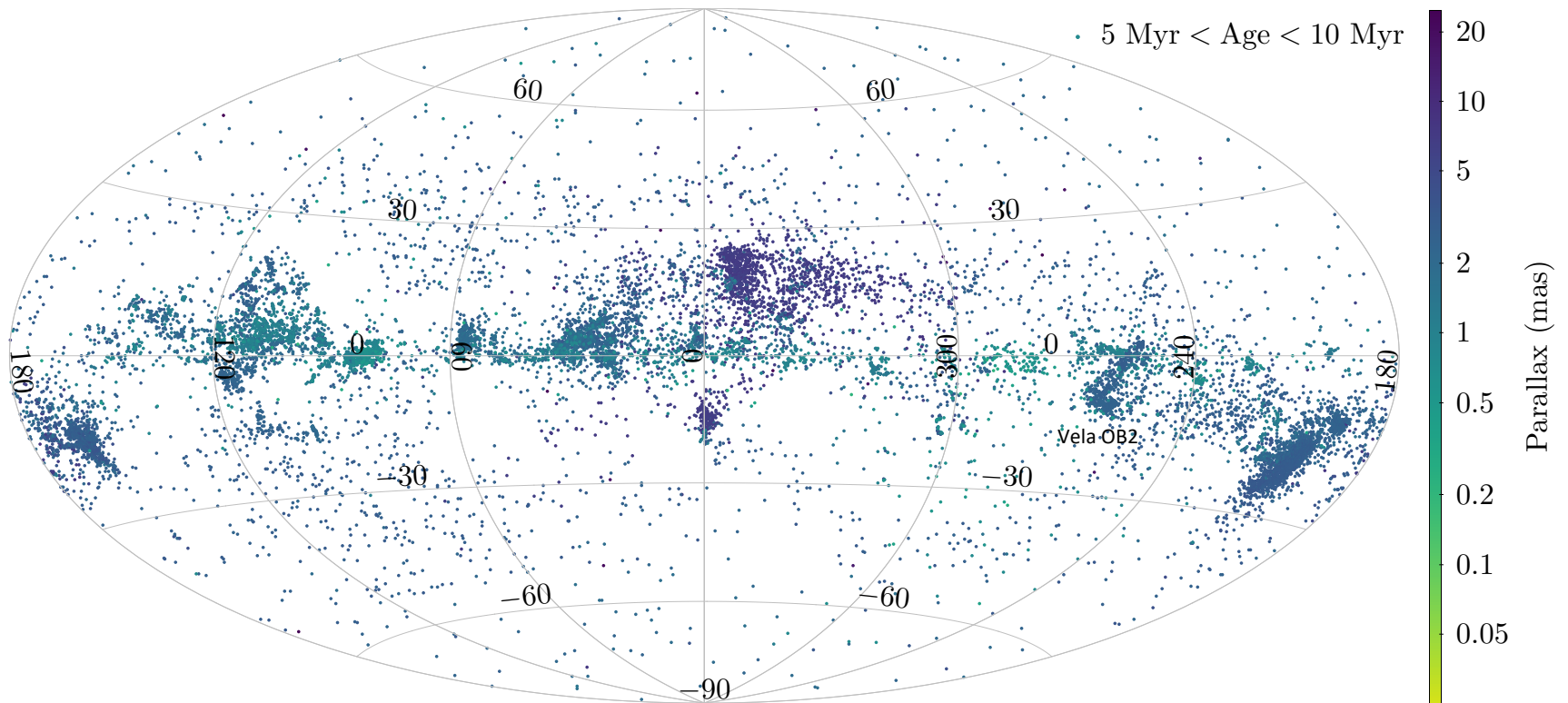


The bulk of our understanding of star-forming history of the Solar Neighborhood

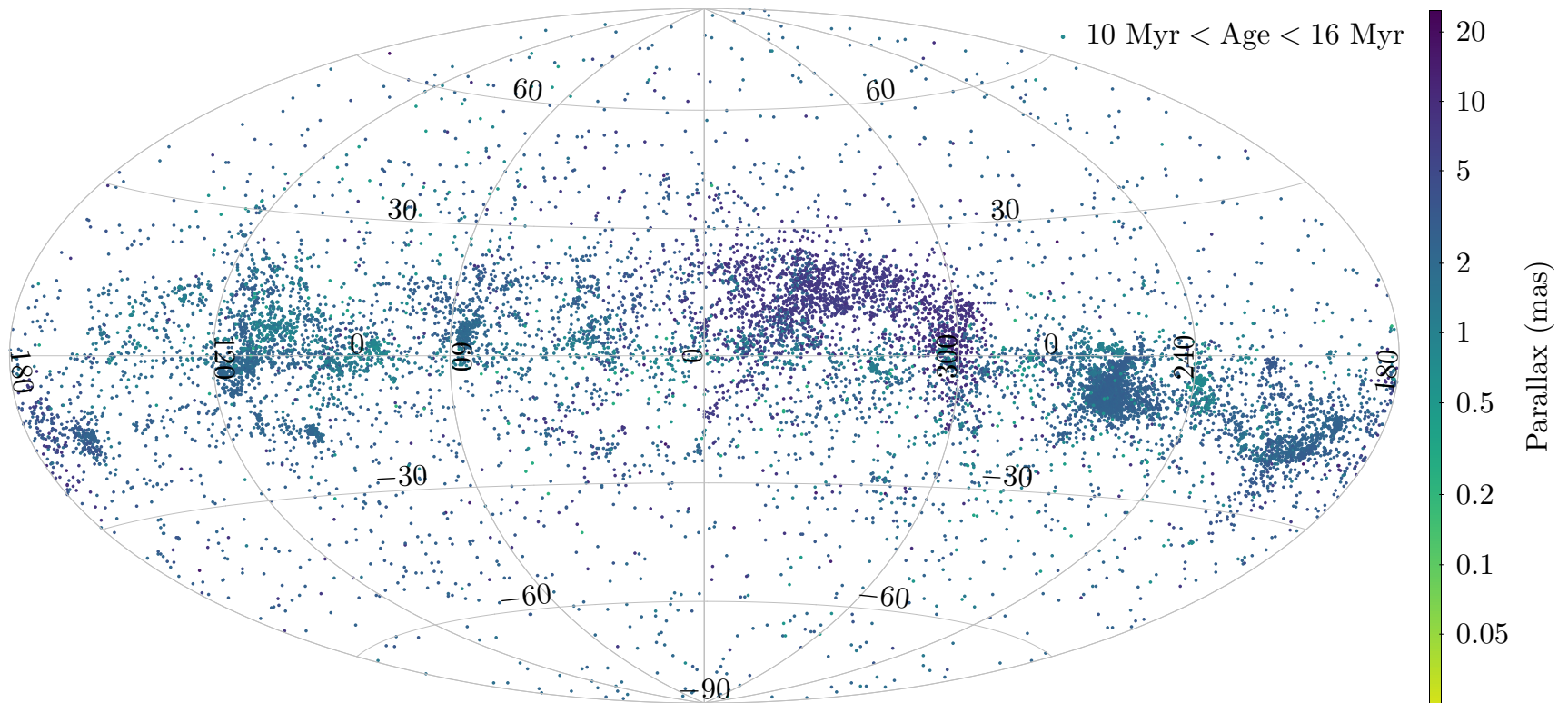
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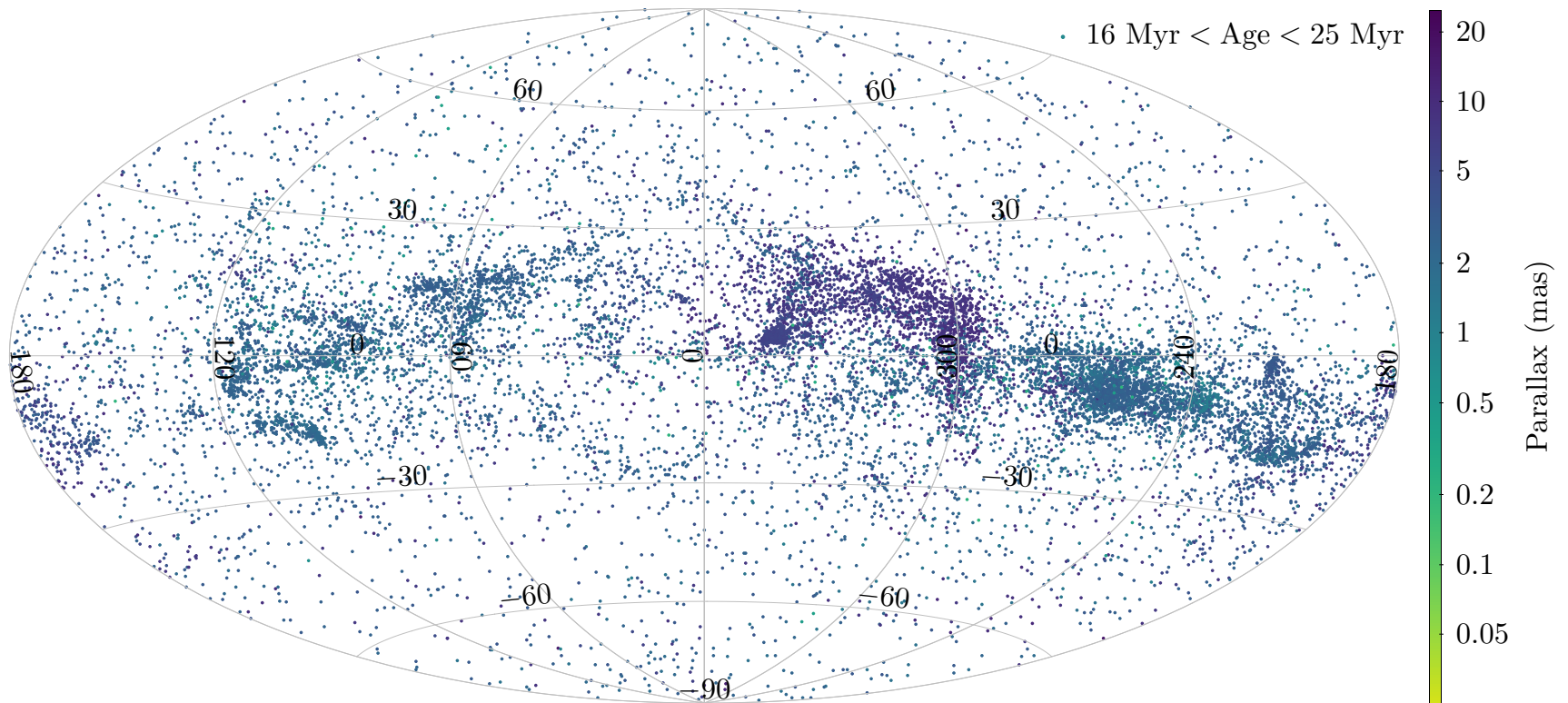
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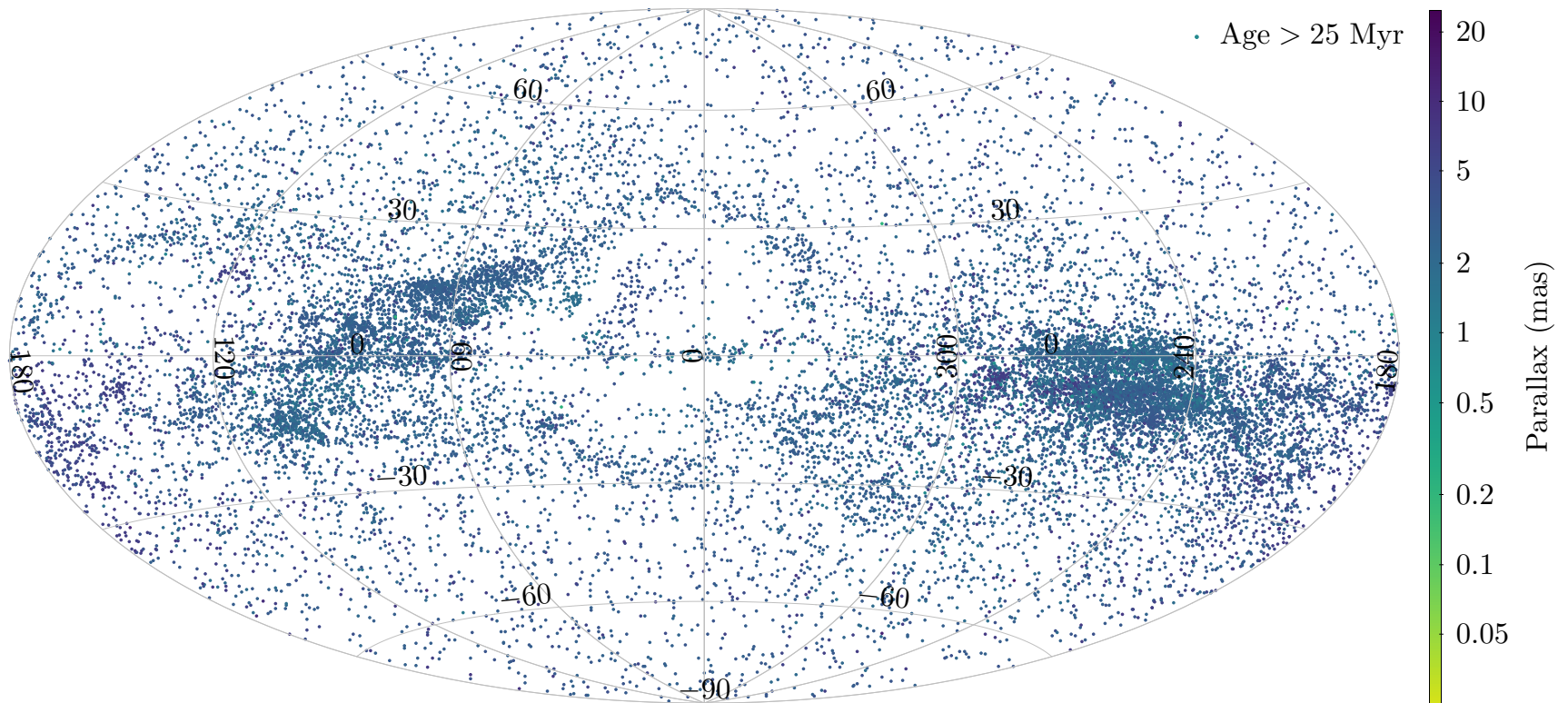
Map of star forming regions



Map of star forming regions



Map of star forming regions



Summary

- In 10 years, we've progressed from crude estimates of stellar properties of a handful of stars, to having a wealth of data for detailed characterization of both stellar and galactic evolution
- Another order of magnitude increase is possible in the next decade