# The Proper Motions of Globular Clusters in the Large Magellanic Cloud

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Illuminating Galaxy Formation with Ancient Globular Star Clusters and their Progenitors - 17th March 2022

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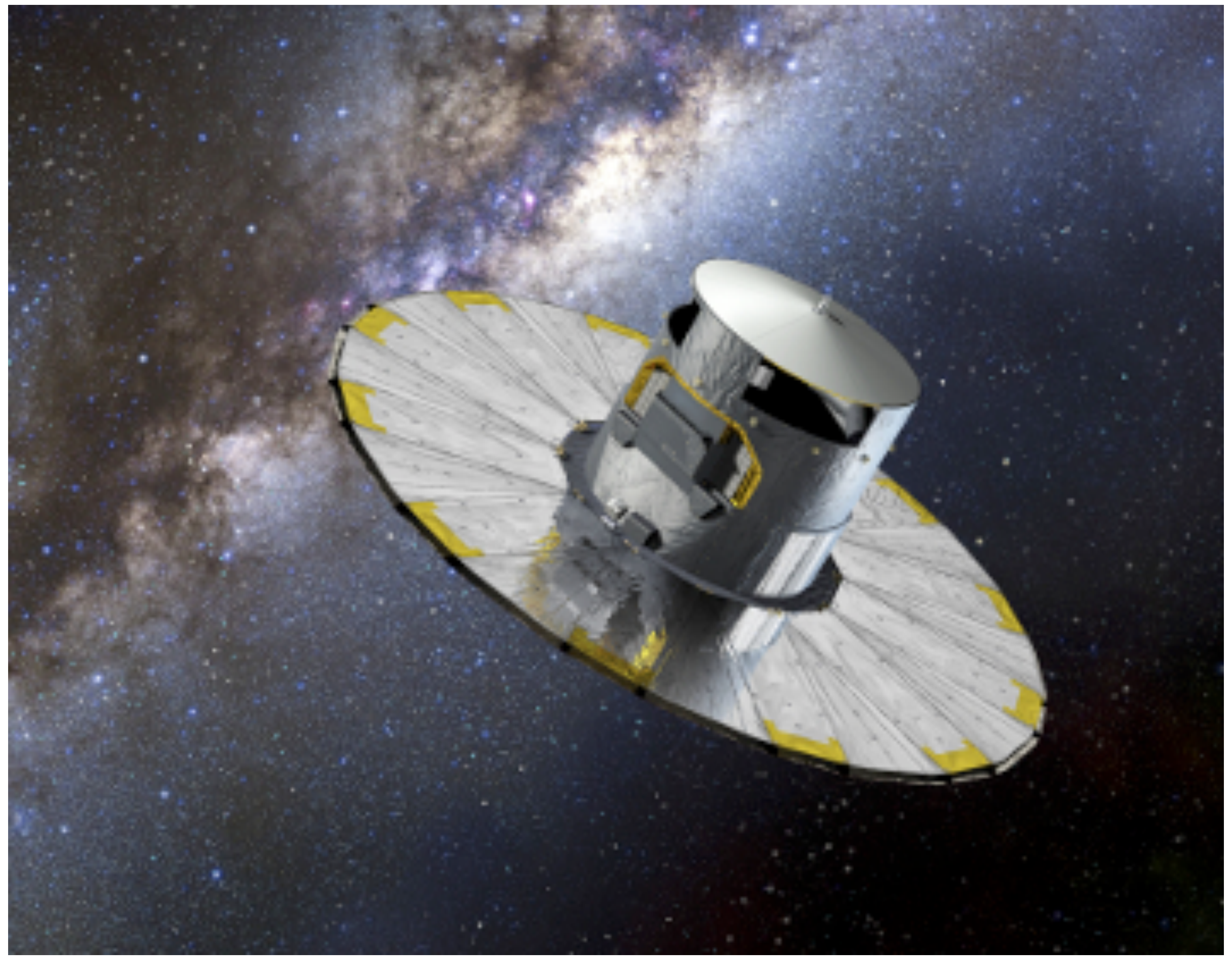
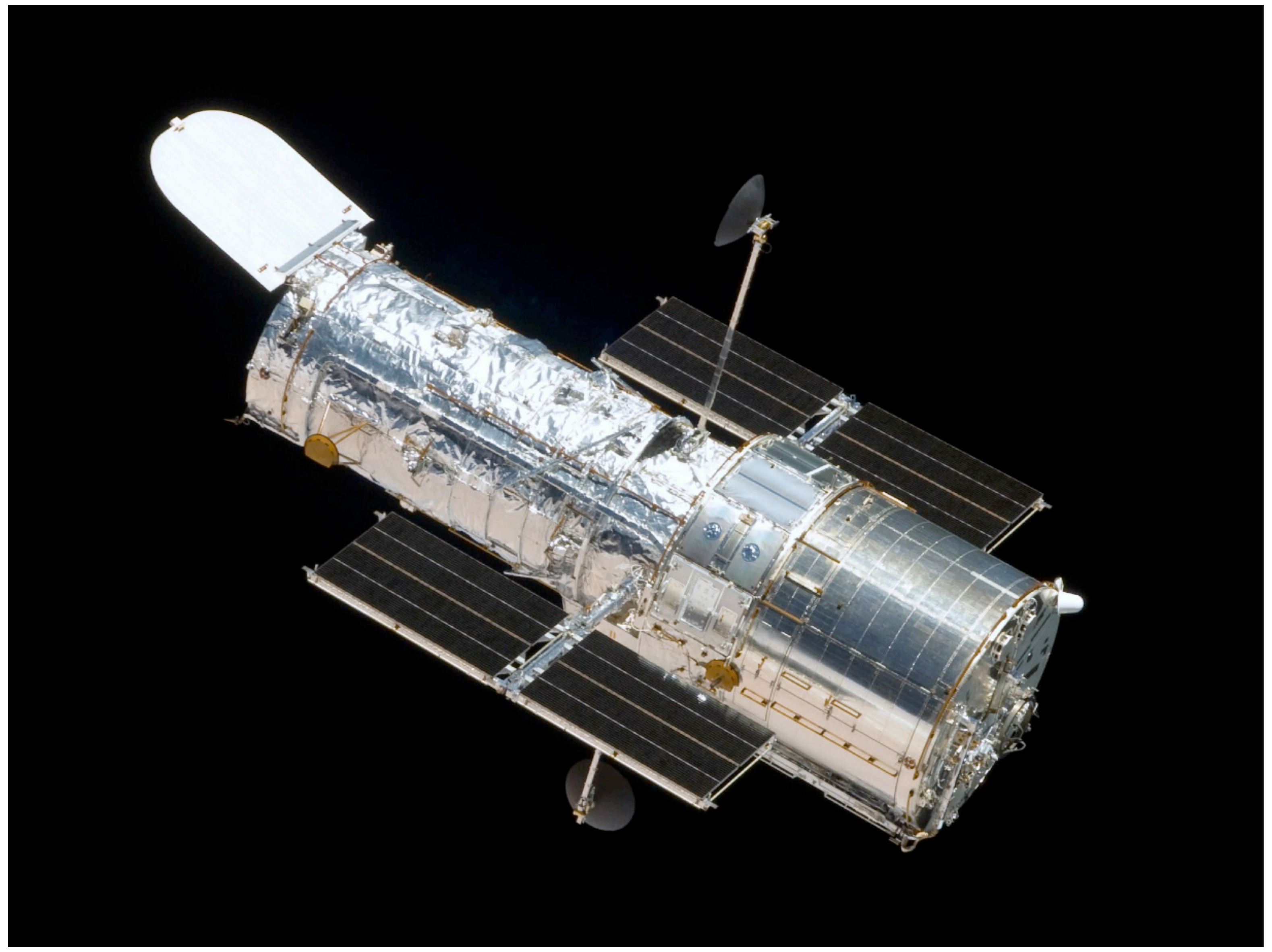
HSTPROMO

# Proper Motions with Gaia and HST



Gaia, image credit: ESA–D. Ducros, 2013

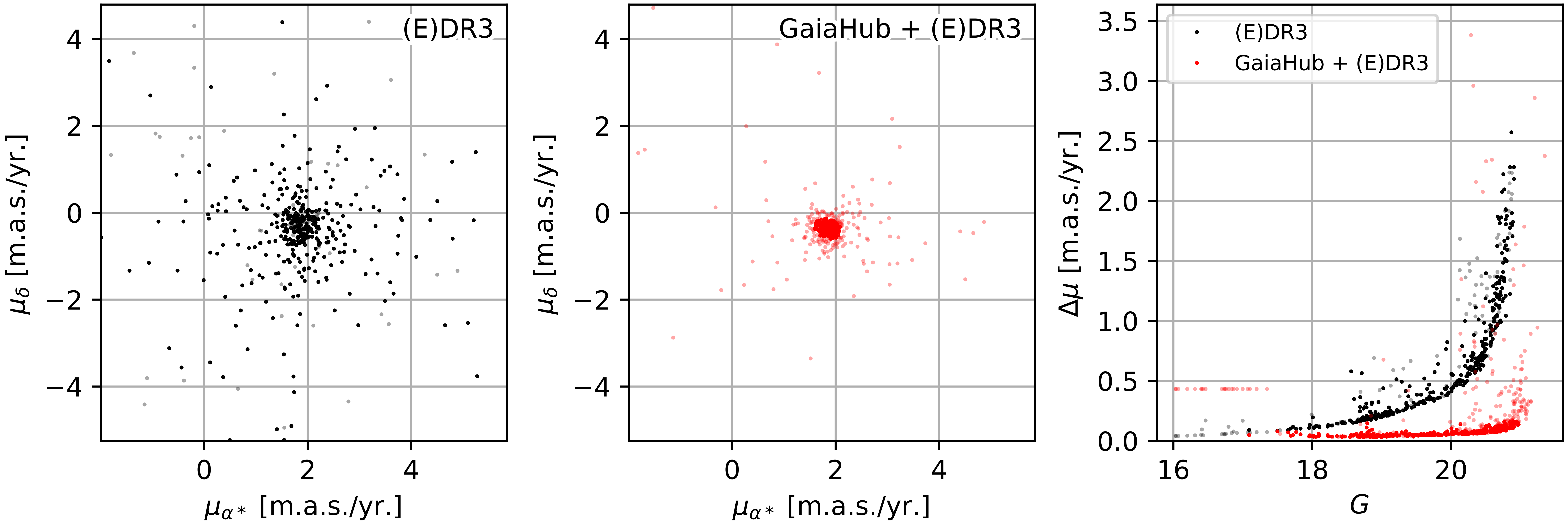
- Whole sky coverage
- ~3 year time baseline
- Less photometric sensitivity



Hubble Space Telescope, image credit: Crew of STS-125

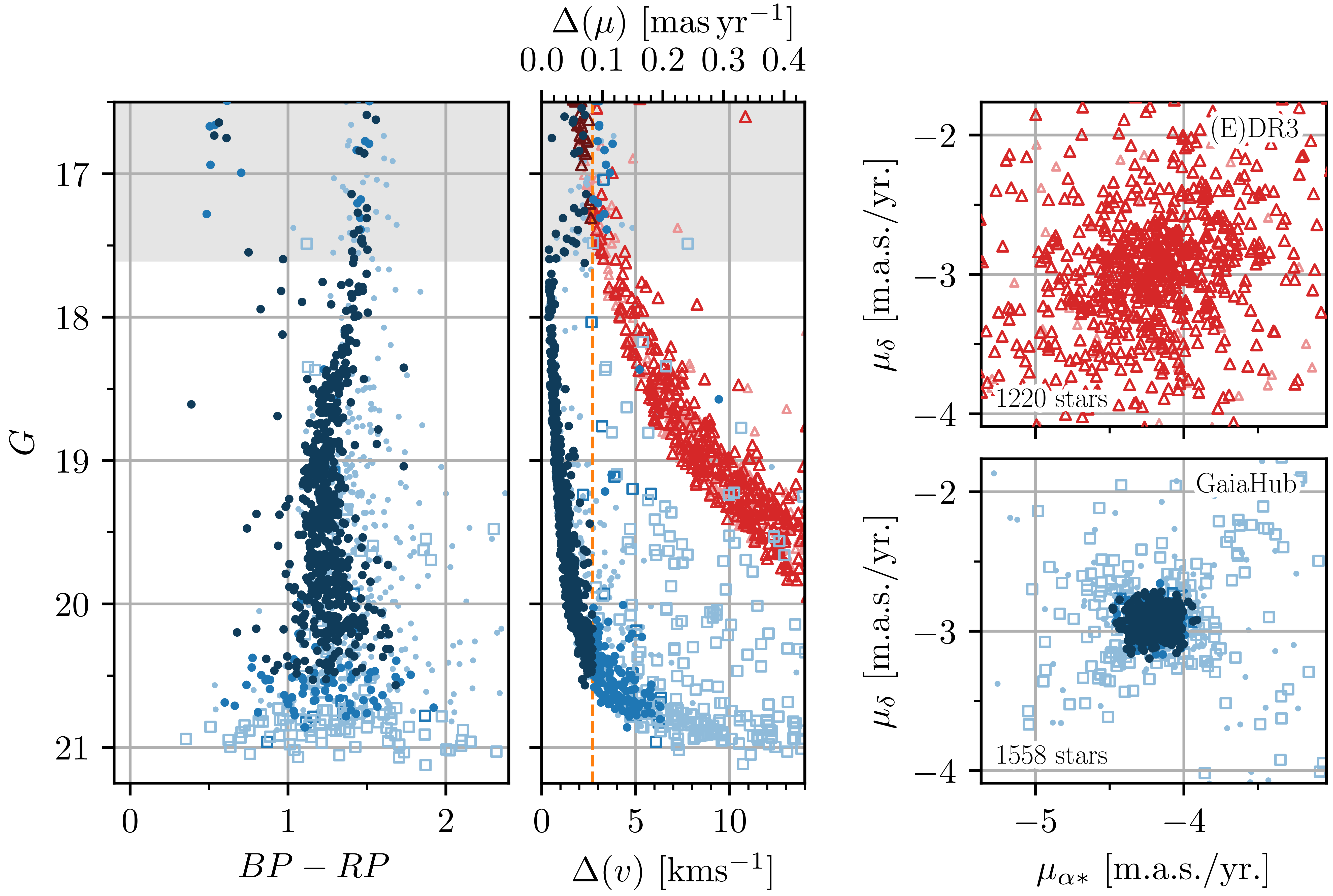
- Narrow field of view
- Needs two suitable observations
- Up to ~20 year time baseline
- Greater photometric sensitivity

# GaiaHub




- Combines Gaia and HST, using HST as the first epoch and Gaia as the second
- Provides greater accuracy and precision than can be achieved by Gaia alone
- Doesn't require more than one HST observation
- NGC 1783, young LMC GC

# GaiaHub - MW GCs

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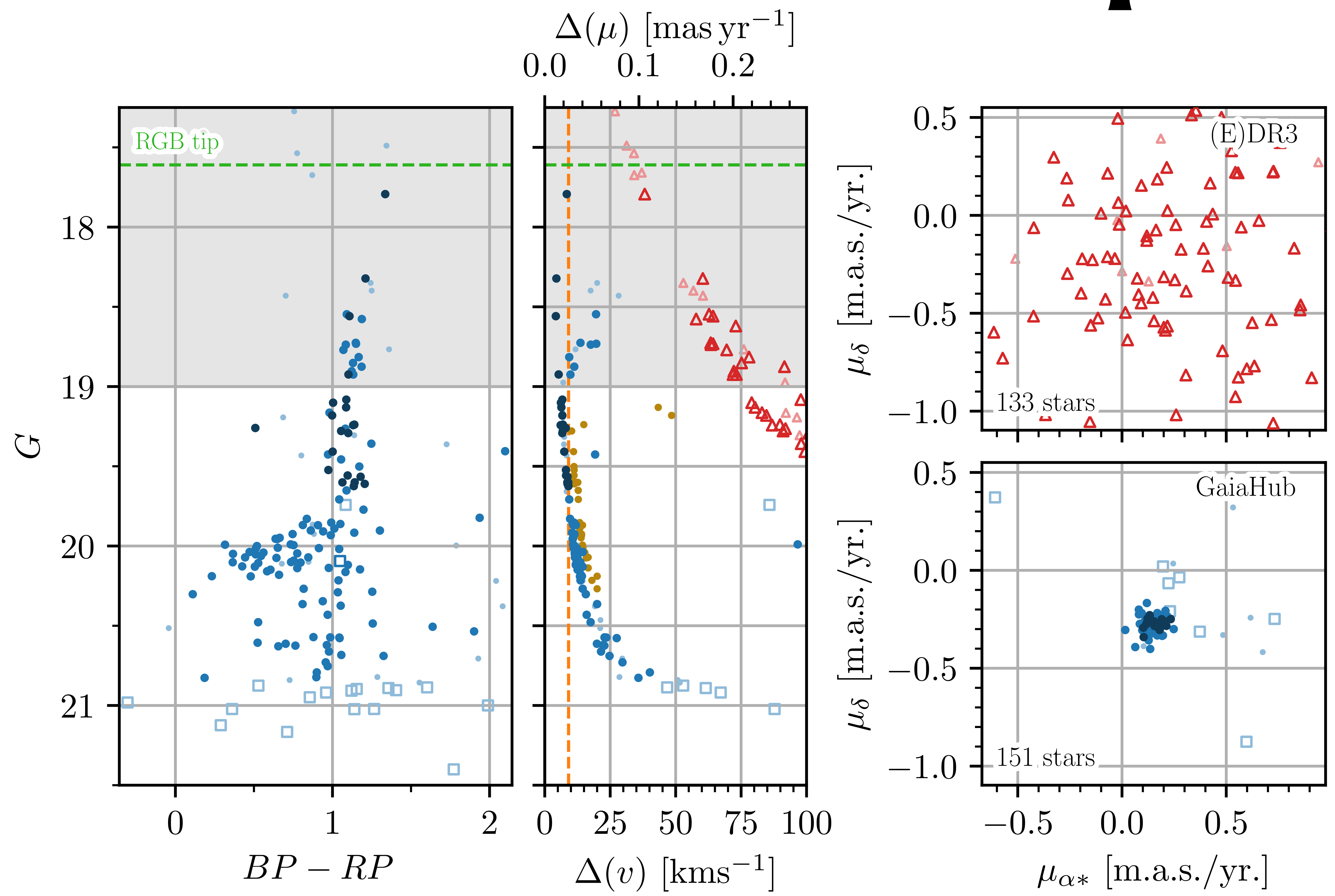
- NGC 6535
- MW GC, D~6.5 kpc
- Improves the proper motion uncertainty by over an order of magnitude over Gaia eDR3, 21.2 vs 1.9 kms$^{-1}$

# GaiaHub - Draco dSph

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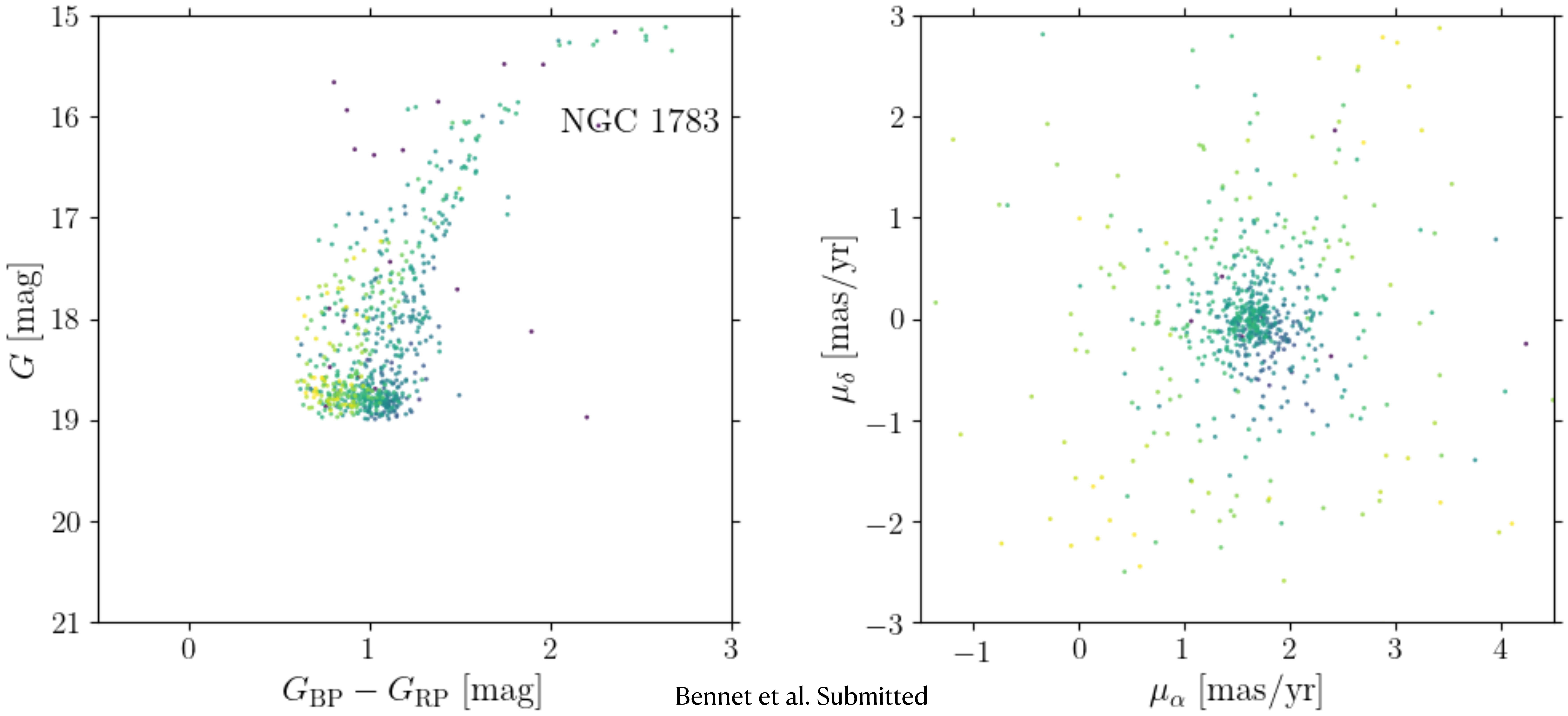
- Draco dSph
- MW Satellite Dwarf, D~76 kpc
- Improves proper motion uncertainty by over an order of magnitude compared to Gaia eDR3, 167 vs 11 kms$^{-1}$

# Proper Motions with Gaia eDR3

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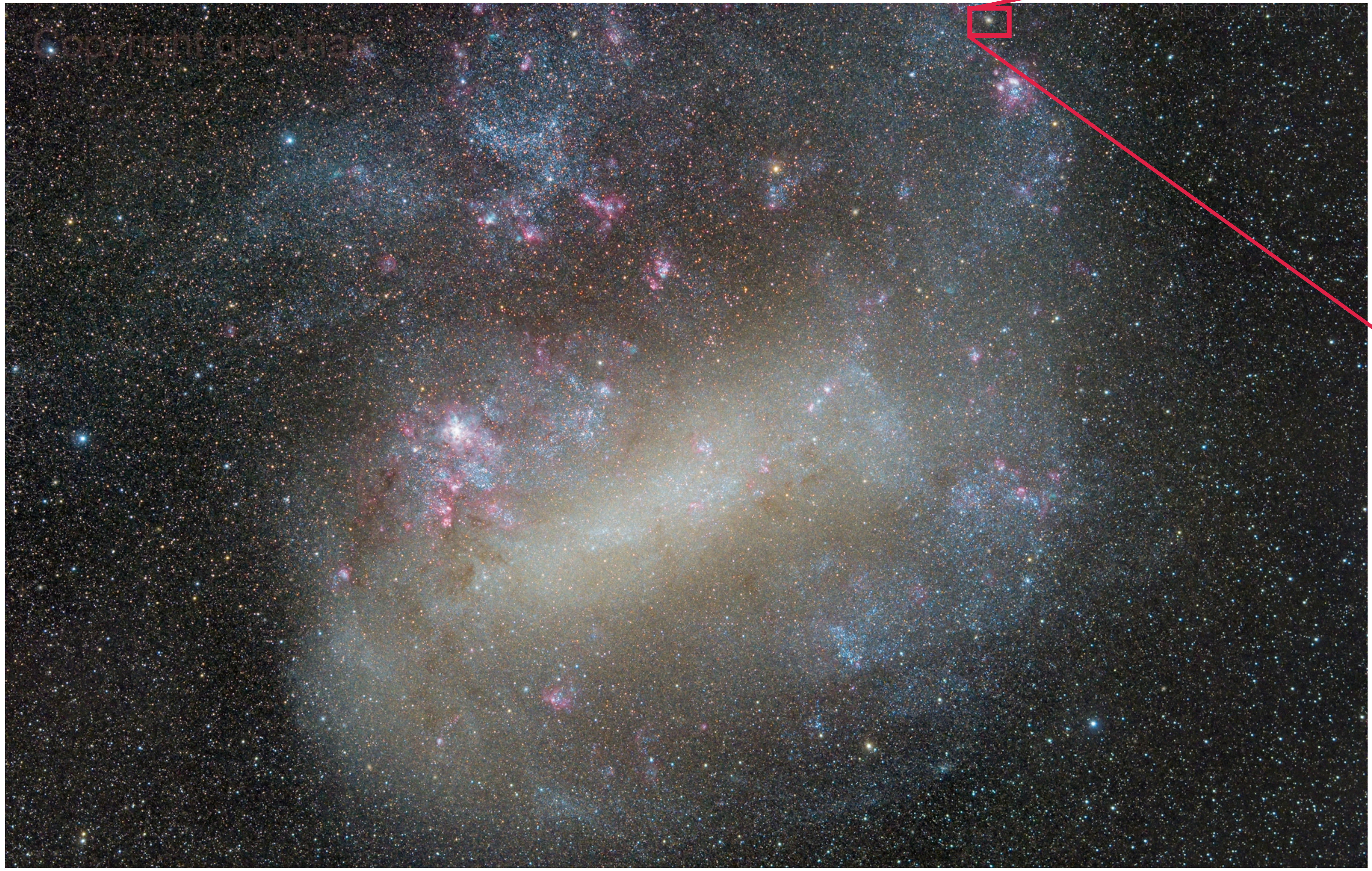
- We first have to separate the GC from the field population, in this case the LMC's stellar disk
- Once GC member stars are selected we can fit a 2D gaussian in proper motion space to determine the bulk proper motion of the GC

# LMC and Globular Clusters

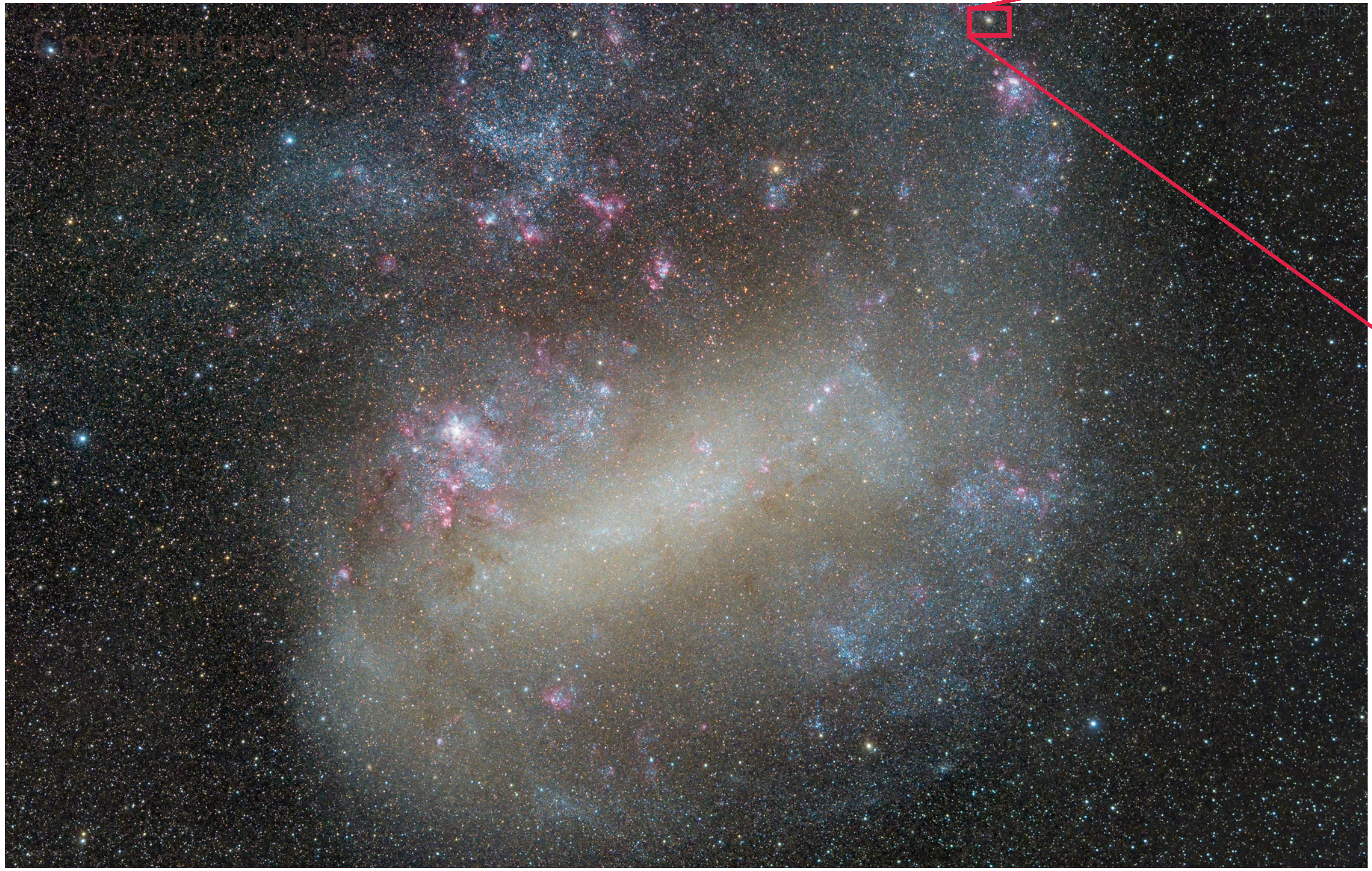
NGC 1783 Photo by ESA/Hubble & NASA; acknowledgement: Judy Schmidt

- The GCs of the LMC are very different to those of the MW
- They have a variety of ages and metallicities, with a large age gap
- Studies have been inconclusive about the kinematics of the LMC's GCs



The Large Magellanic Cloud. Image by Gabriel R. Santos

# LMC and Globular Clusters

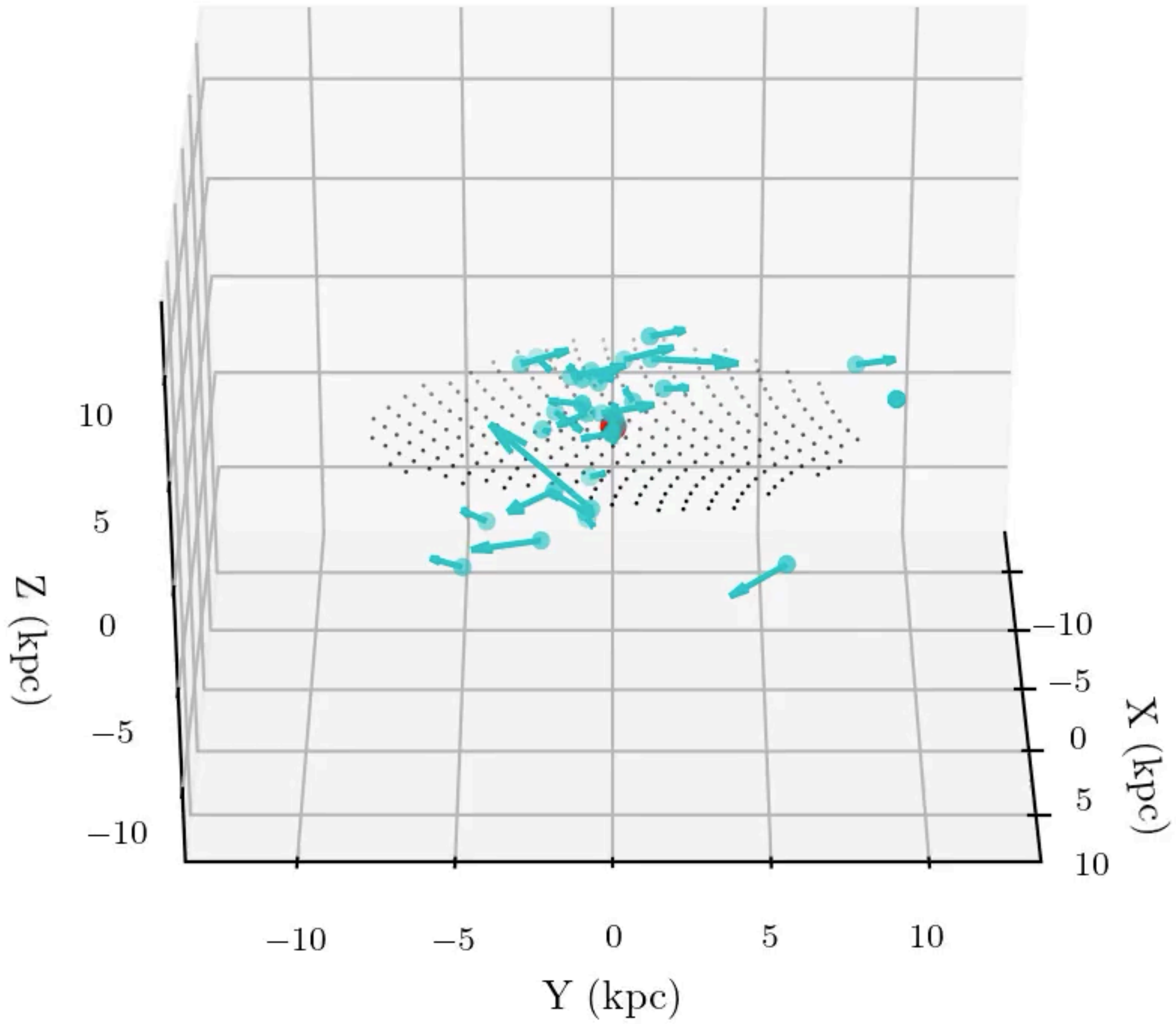


The Large Magellanic Cloud. Image by Gabriel R. Santos

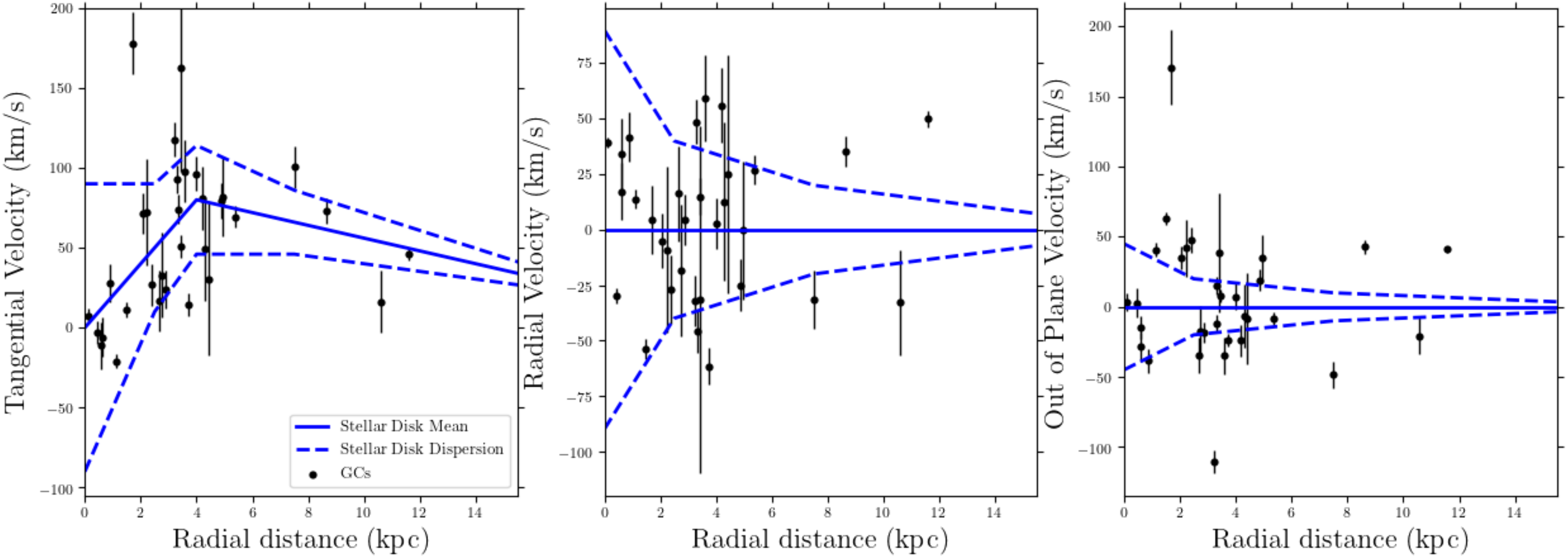
NGC 1783 Photo by ESA/Hubble & NASA; acknowledgement: Judy Schmidt

- We examined 42 LMC GCs
- 10 of these had HST images suitable for GaiaHub
- We used GaiaHub and two independent algorithms using Gaia data to derive proper motions
- From the initial 42 we find PMs for 32 GCs

# Globular Cluster Velocities



# Rotation Curves

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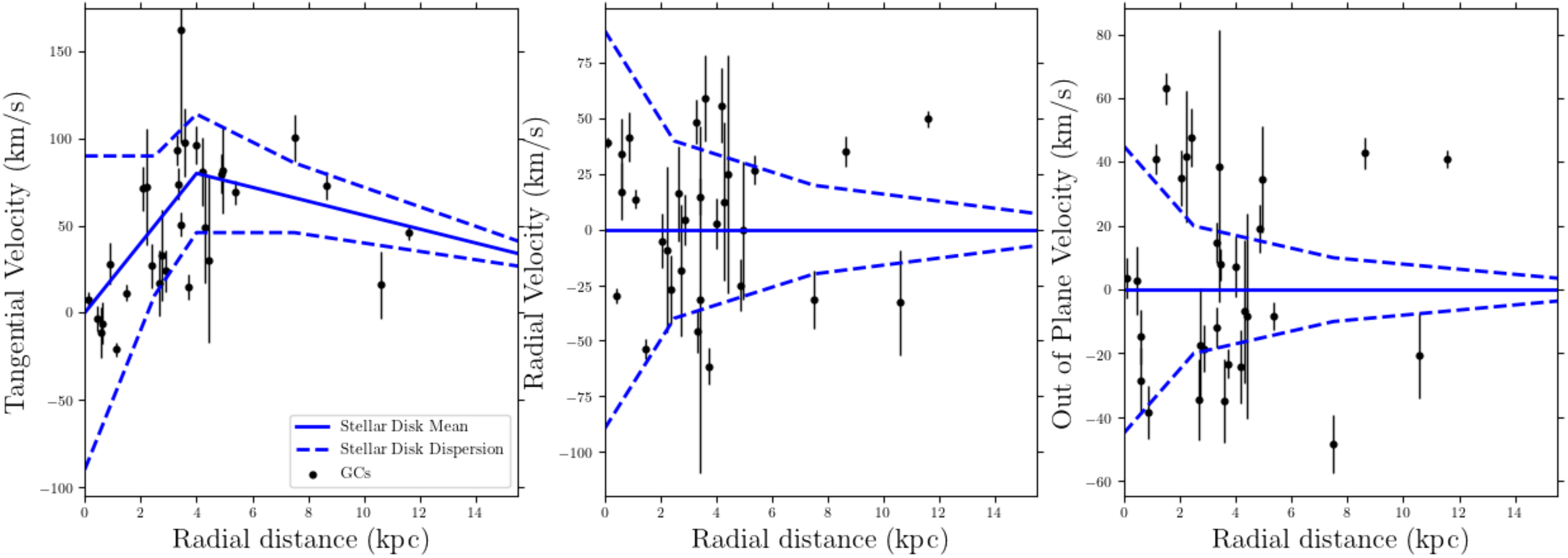
# Rotation Curves

# Rotation Curves

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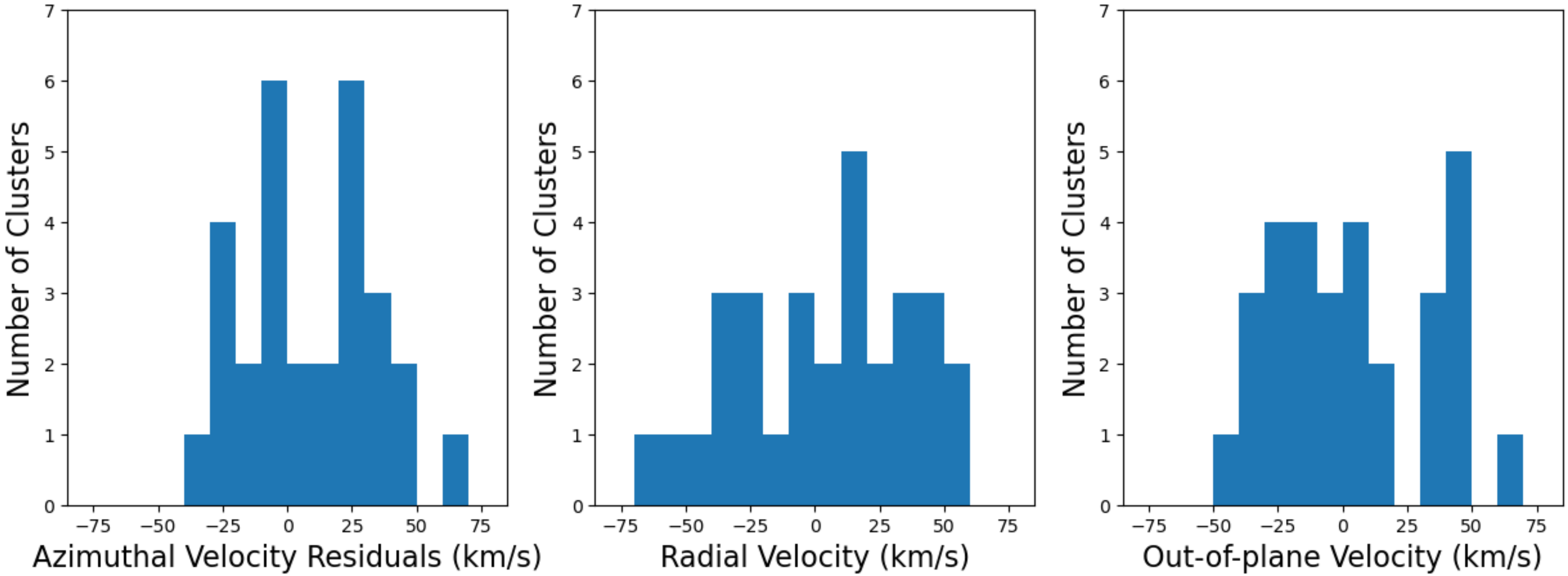
# GC kinematics

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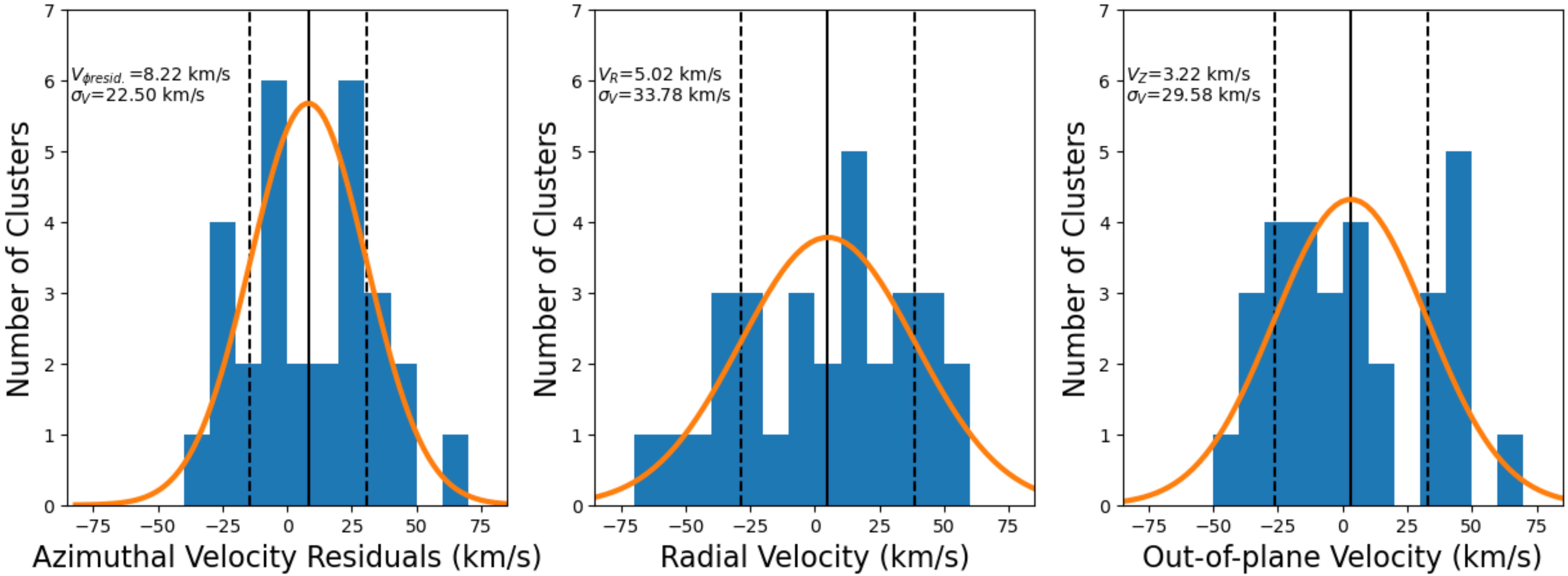
# GC kinematics

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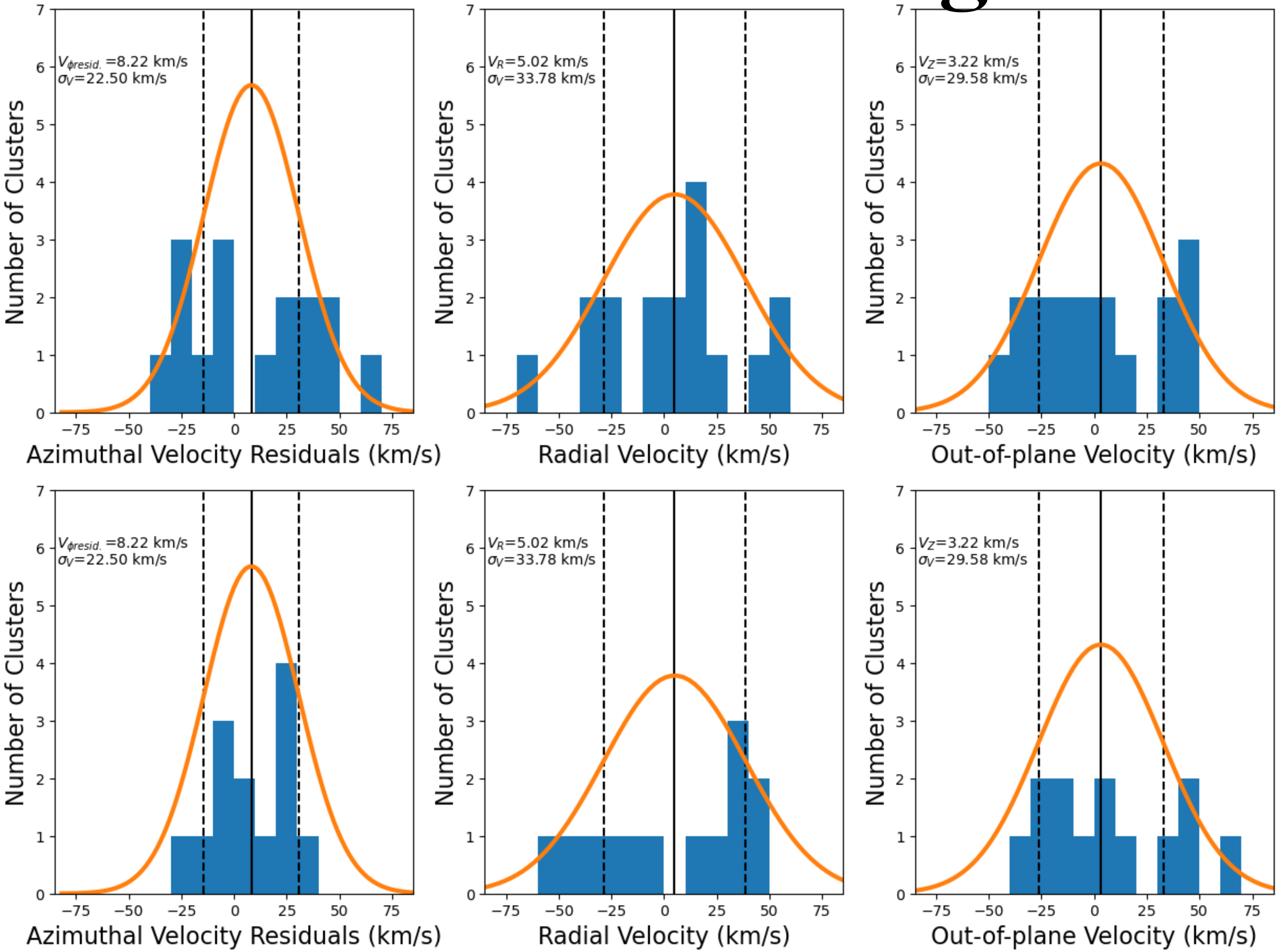
# GC kinematics - Age

Young GCs
Age < 4 Gyr

Old GCs
Age > 9 Gyr



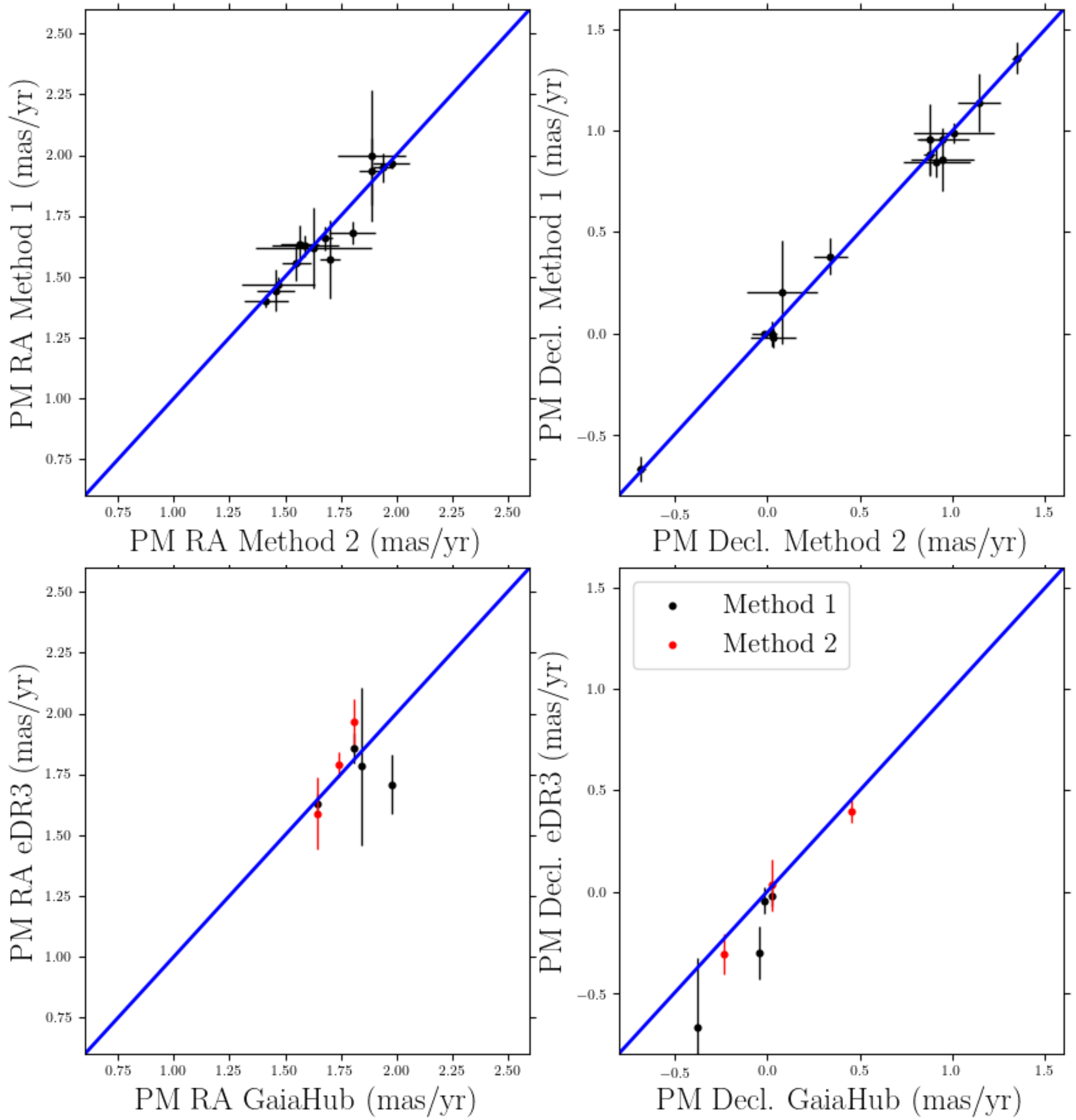
# Single Population

- From the 30 LMC GCs we examine we find that they are explained by a single kinematic population that is consistent with the LMC's stellar disk
- However, we can not statistically rule out two populations, i.e. Halo and Disk due to the small total number of clusters
- A single kinematic population of GCs would indicate they all formed via the same or similar mechanisms
- This would have to explain both old clusters (>10 Gyrs) and very young clusters (~100 Myrs)

# Summary and Conclusions

- We have created a software pipeline to combine HST and Gaia data to find proper motions more effectively than Gaia alone and without the need for additional HST data
- We have found the Proper Motion of 32 Globular clusters around the LMC, 30 of which are associated with the LMC
- These show evidence of a single kinematic population with no compelling differences based on kinematic or observational properties
- This would require a single formation mechanism that can form Globular clusters both in the early universe and more recently or multiple mechanisms that produce kinematically similar GCs
- Why are the LMC's Globular clusters so different from the Milky Way's?

# GaiaHub vs. Gaia eDR3

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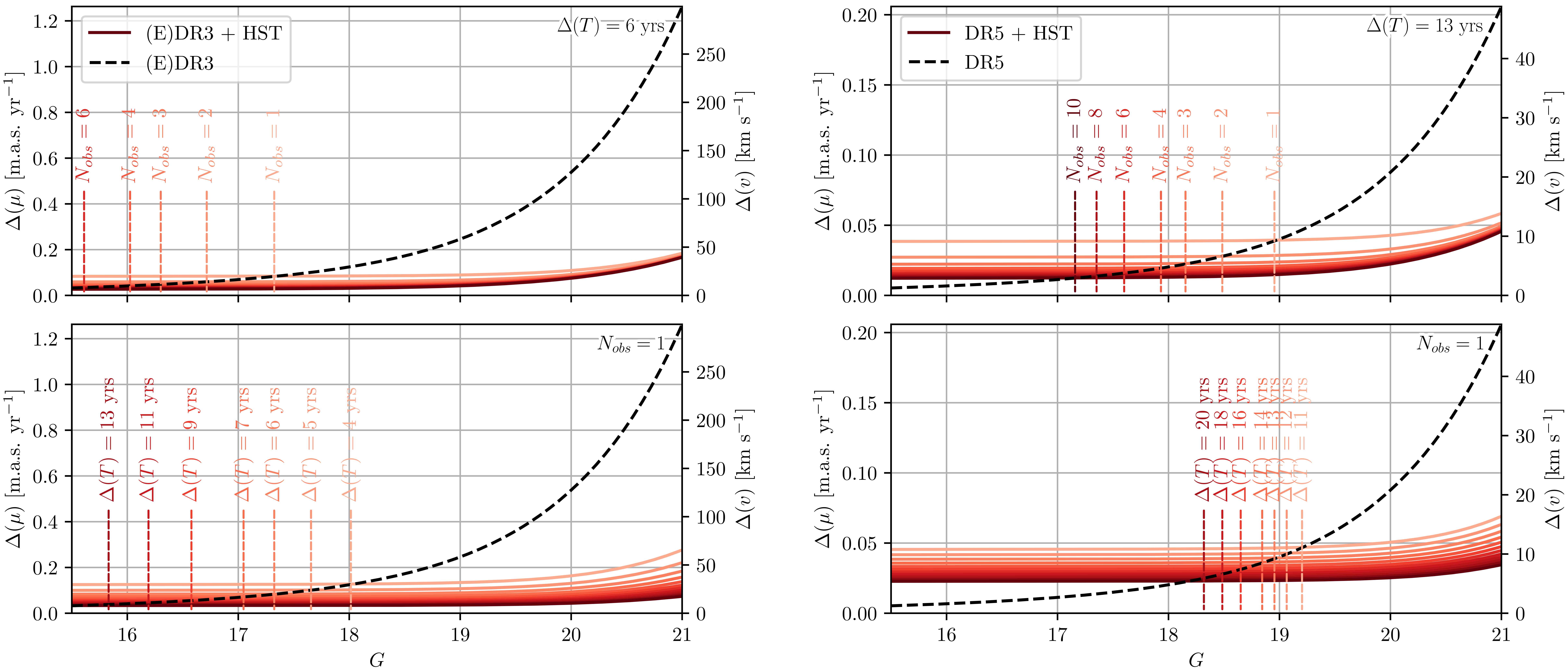
- Strong agreement between the PMs derived from the 2 Gaia based methods
- Also good agreement between GaiaHub and Gaia eDR3
- Far smaller uncertainty for GaiaHub due to the greater photometric sensitivity and time baseline of HST



(E)DR3 + HST
(E)DR3
$\Delta(T) = 6$ yrs
$N_{obs} = 6$
$N_{obs} = 4$
$N_{obs} = 3$
$N_{obs} = 2$
$N_{obs} = 1$
DR5 + HST
DR5
$\Delta(T) = 13$ yrs
$N_{obs} = 10$
$N_{obs} = 8$
$N_{obs} = 6$
$N_{obs} = 4$
$N_{obs} = 3$
$N_{obs} = 2$
$N_{obs} = 1$
$N_{obs} = 1$
$\Delta(T) = 13$ yrs
$\Delta(T) = 11$ yrs
$\Delta(T) = 9$ yrs
$\Delta(T) = 7$ yrs
$\Delta(T) = 6$ yrs
$\Delta(T) = 5$ yrs
$\Delta(T) = 4$ yrs
$N_{obs} = 1$
$\Delta(T) = 20$ yrs
$\Delta(T) = 18$ yrs
$\Delta(T) = 16$ yrs
$\Delta(T) = 14$ yrs
$\Delta(T) = 13$ yrs
$\Delta(T) = 12$ yrs
$\Delta(T) = 11$ yrs
$\Delta(\mu)$ [m.a.s. yr$^{-1}$]
$\Delta(v)$ [km s$^{-1}$]
$G$

# LMC and Globular Clusters