How could super-precision astrometry change our view of dwarf galaxies?

Eduardo Vitral

STScI | SPACE TELESCOPE SCIENCE INSTITUTE

HSTPROMO

A future space mission with very high precision astrometry.
IAP, Paris.
11th Sep 2024

Images' credits:
Elena Montuschi
NASA, ESA

Background and interests

Hello world!

Background and interests

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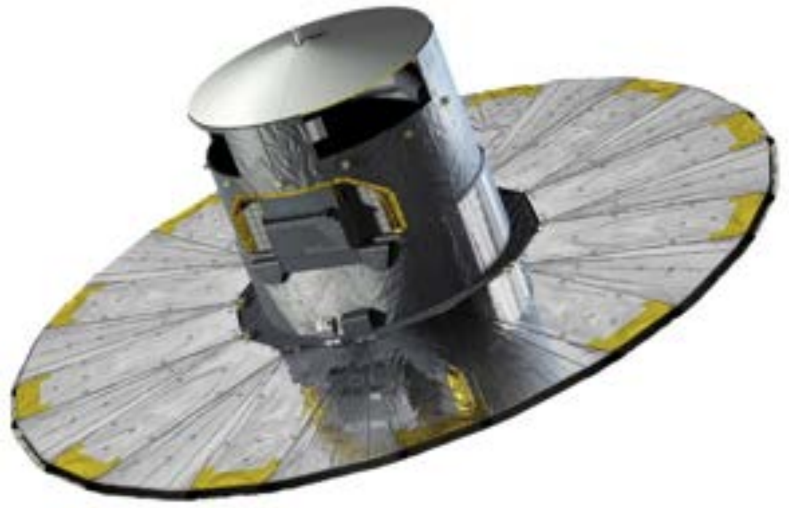

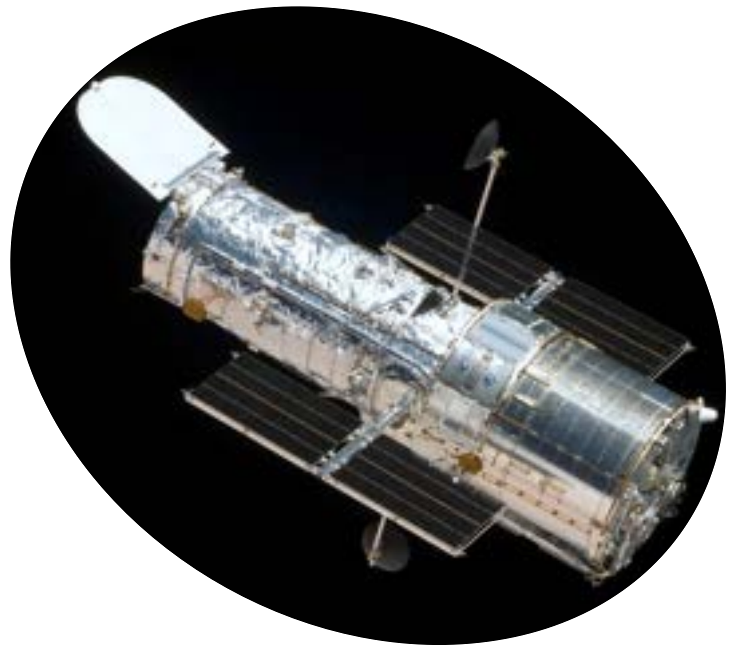

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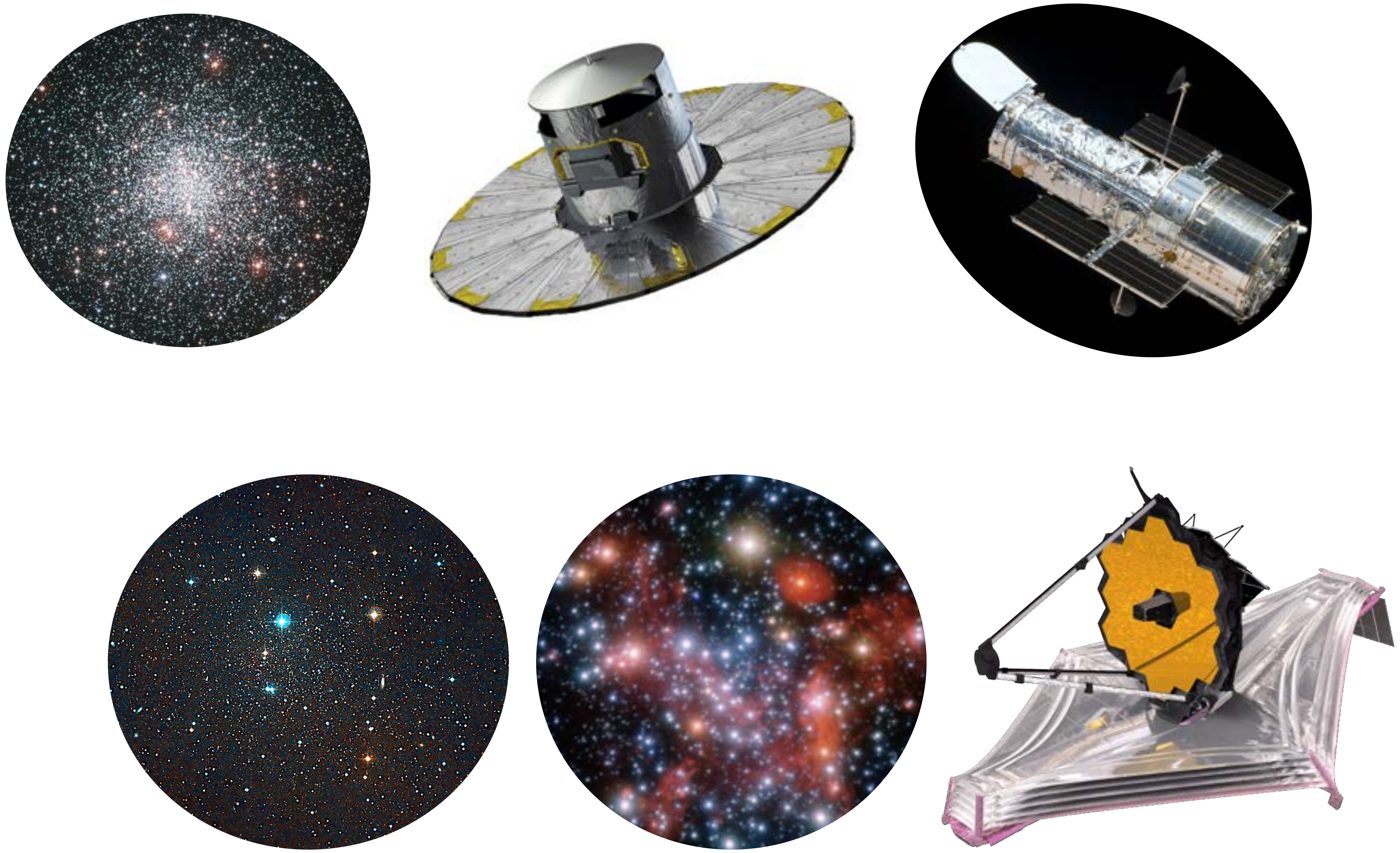

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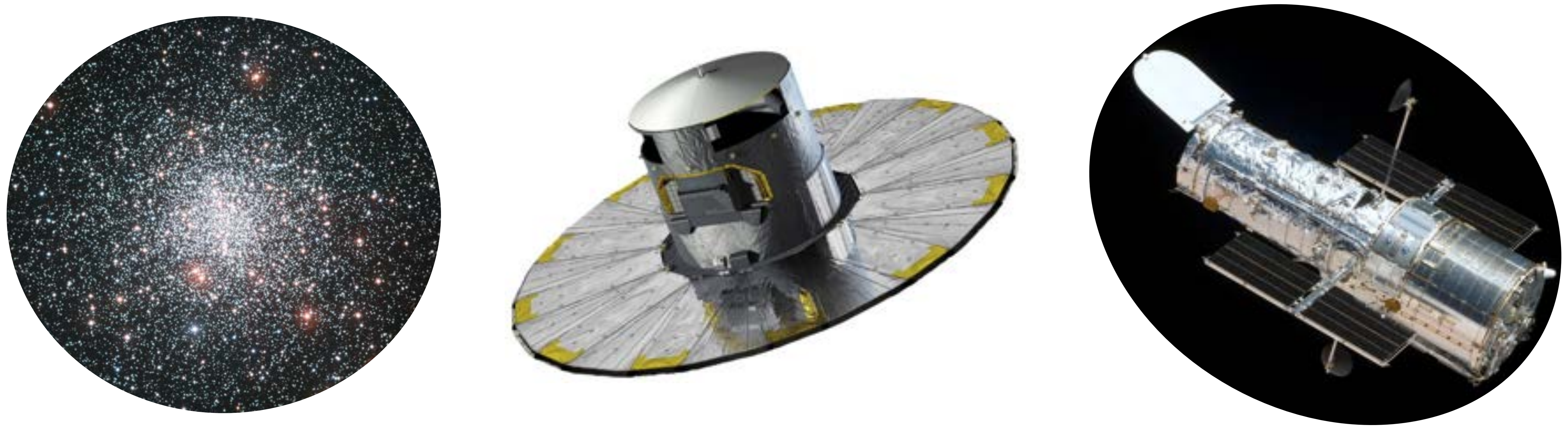

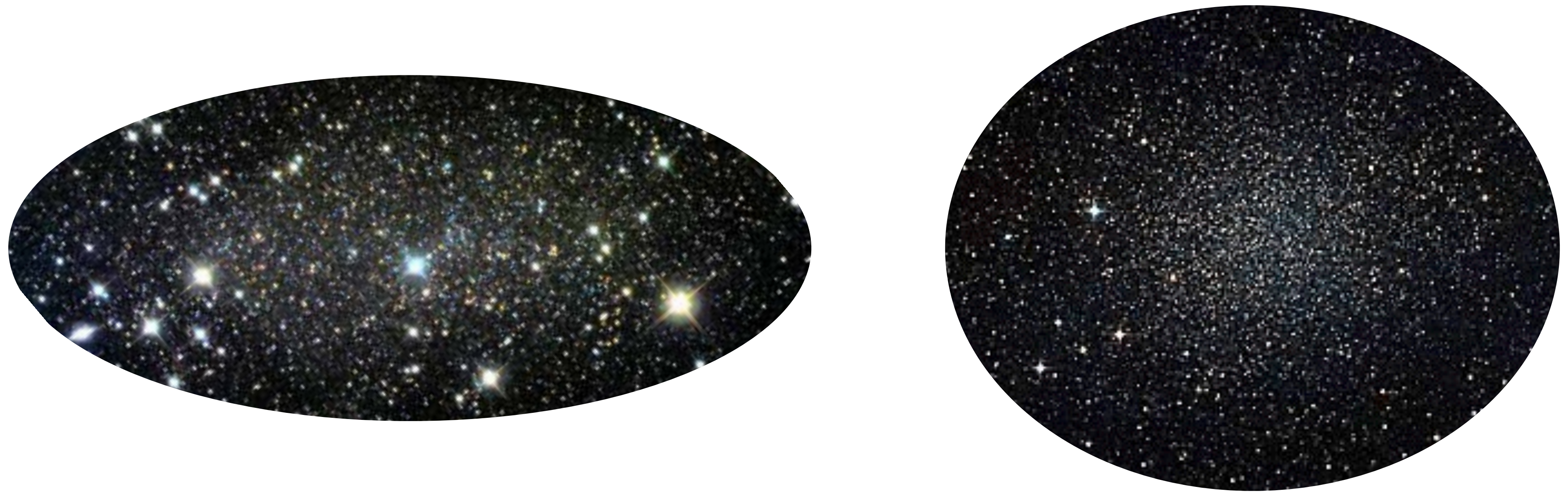

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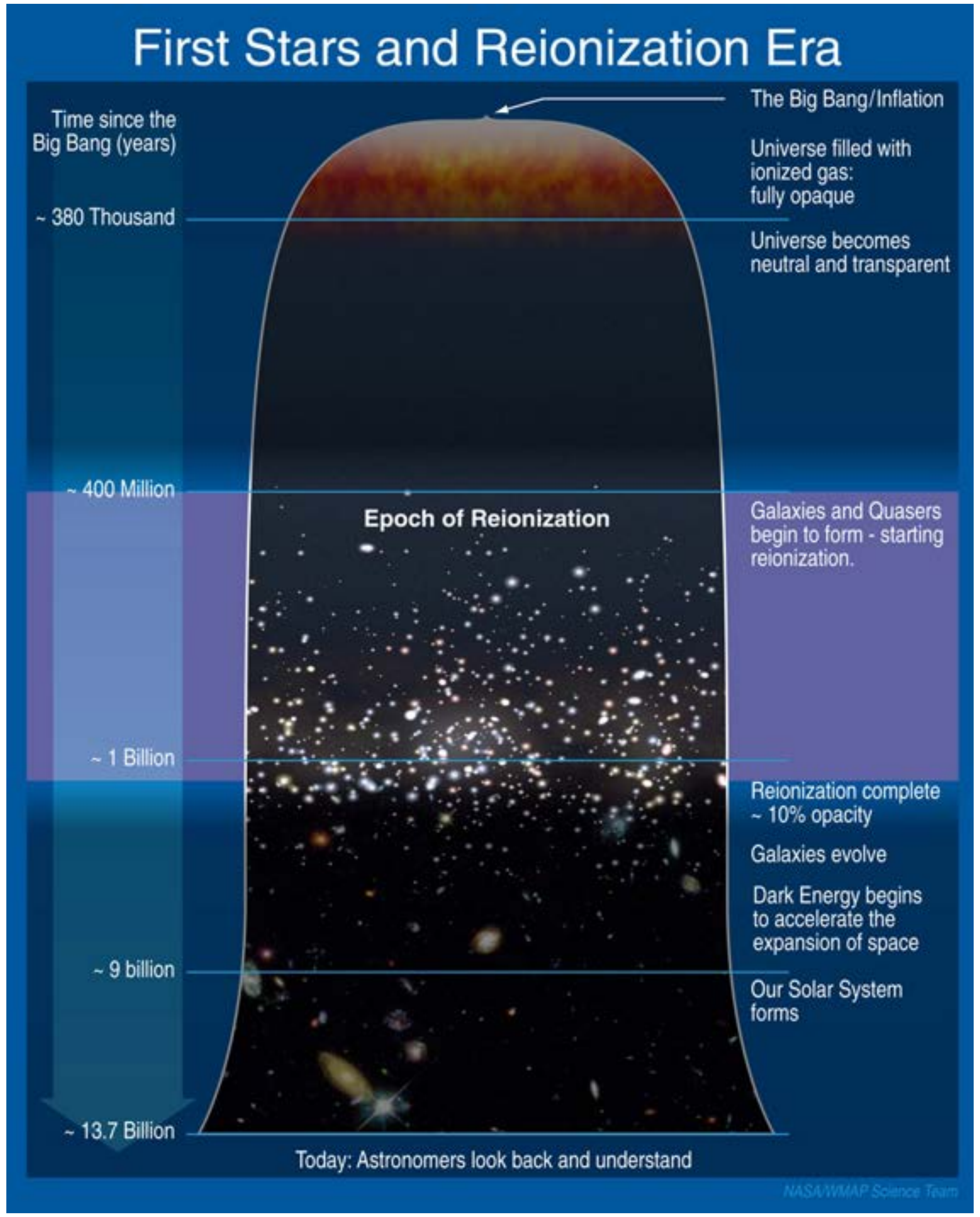
Why study dwarf galaxies?

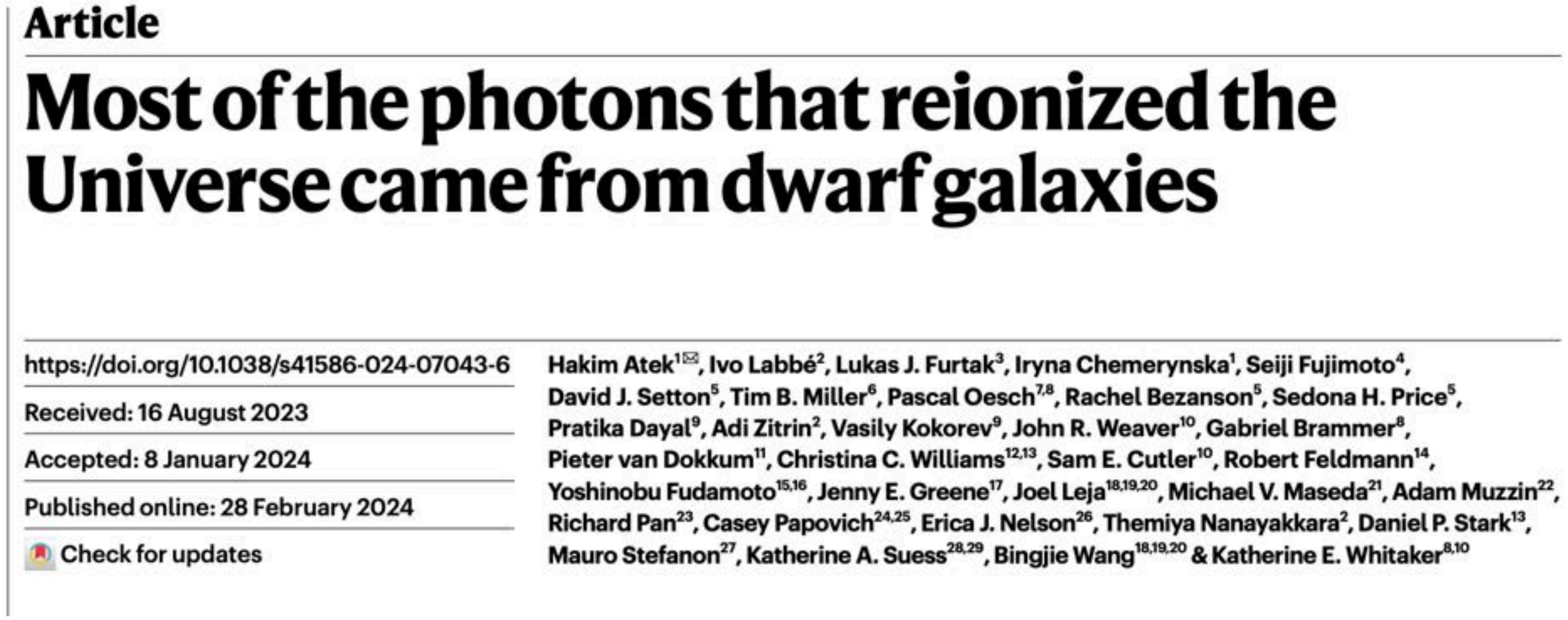
Dwarf galaxies

See Laura Watkins talk on globular clusters!

ESO/DSS

Dwarf galaxies: reionization





Article

Most of the photons that reionized the Universe came from dwarf galaxies

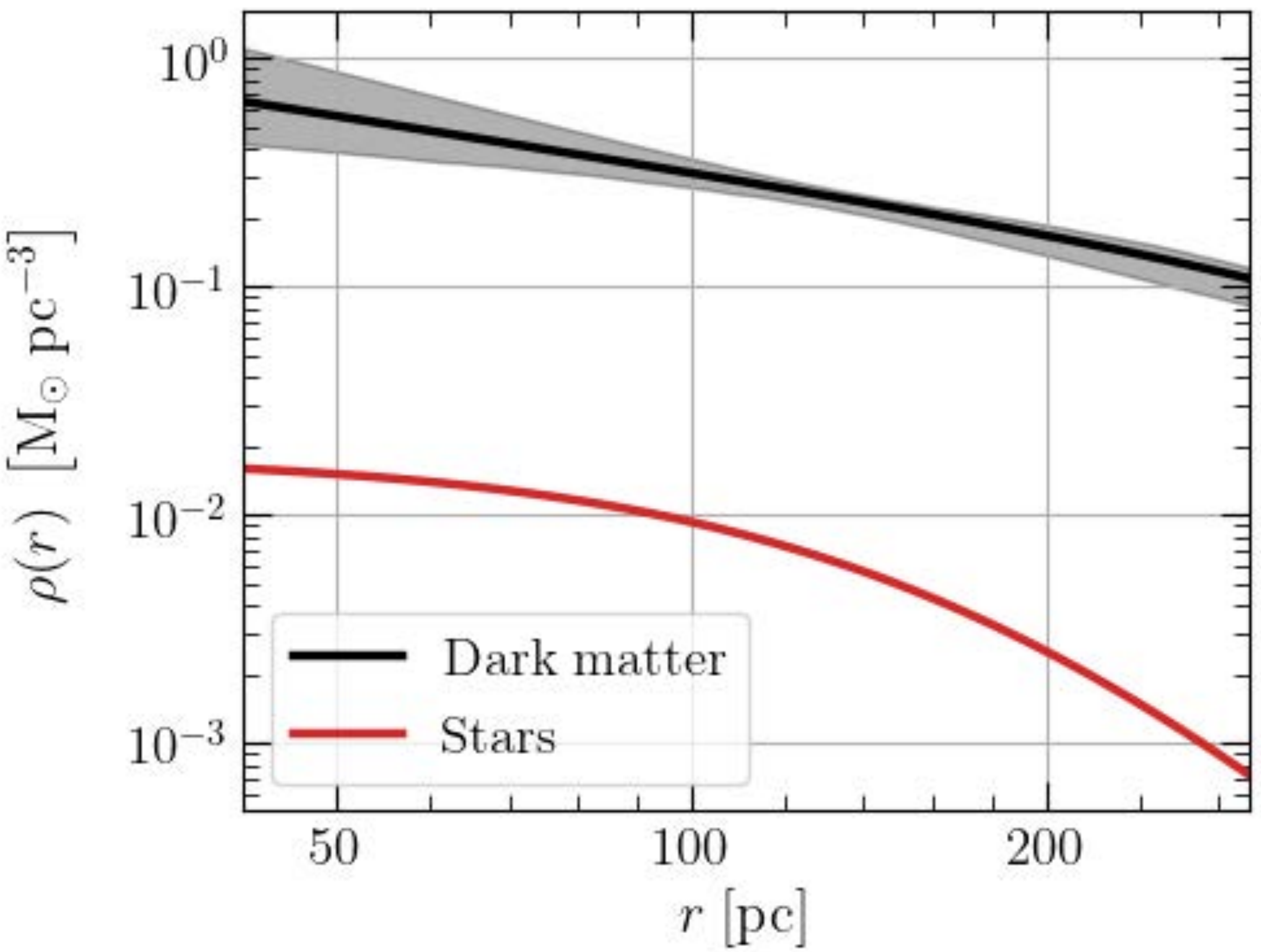
https://doi.org/10.1038/s41586-024-07043-6
Received: 16 August 2023
Accepted: 8 January 2024

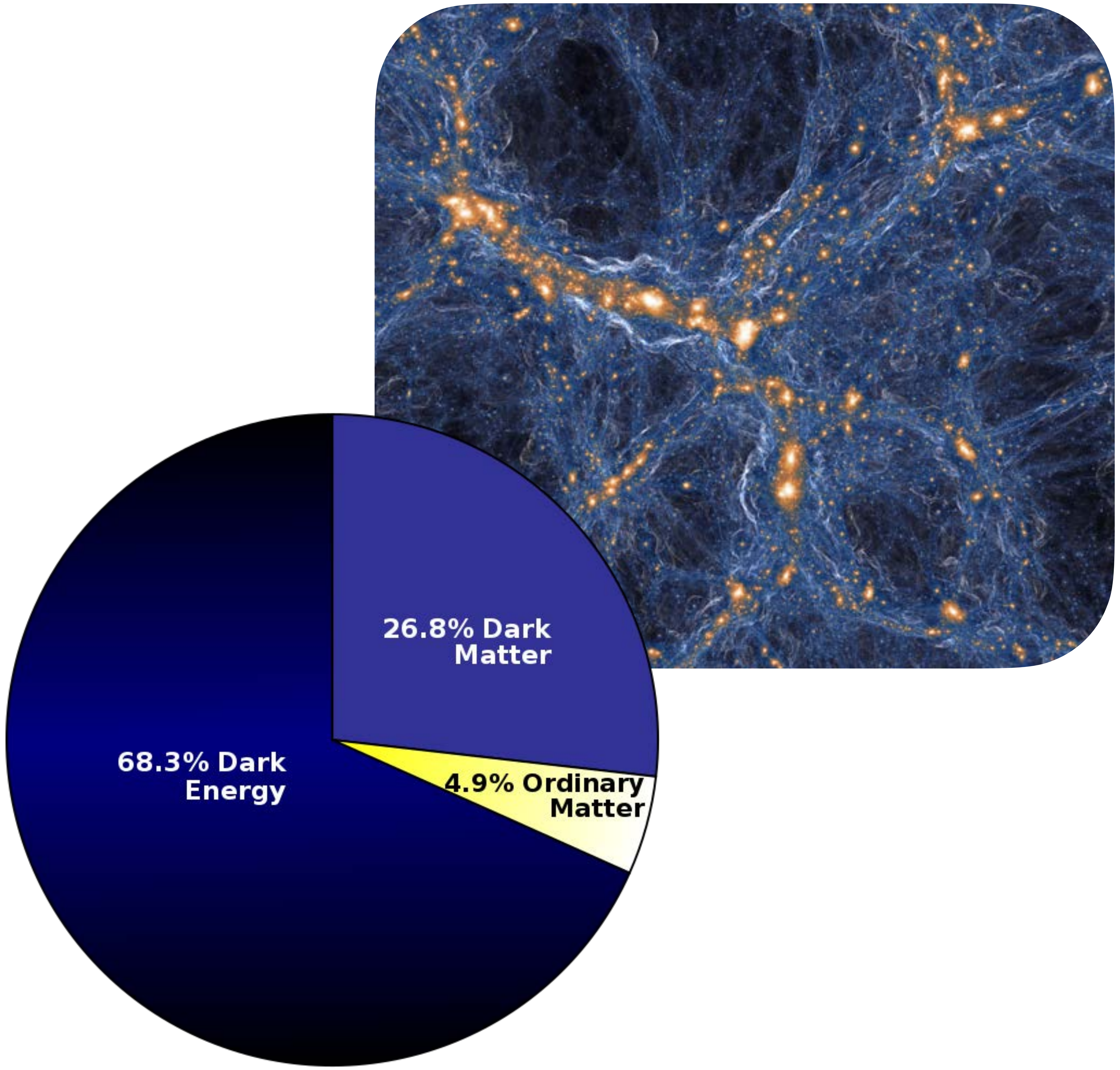
Hakim Atek[1]✉, Ivo Labbé[2], Lukas J. Furtak[3], Iryna Chemerynska[1], Seiji Fujimoto[4], David J. Setton[5], Tim B. Miller[6], Pascal Oesch[7,8], Rachel Bezanson[5], Sedona H. Price[5], Pratika Dayal[9], Adi Zitrin[2], Vasily Kokorev[9], John R. Weaver[10], Gabriel Brammer[8], Pieter van Dokkum[11], Christina C. Williams[12,13], Sam E. Cutler[10], Robert Feldmann[14], Yoshinobu Fudamoto[15,16], Jenny E. Greene[17], Joel Leja[18,19,20], Michael V. Maseda[21], Adam Muzzin[22], Richard Pan[23], Casey Papovich[24,25], Erica J. Nelson[26], Themiya Nanayakkara[2], Daniel P. Stark[13], Mauro Stefanon[27], Katherine A. Suess[28,29], Bingjie Wang[18,19,20] & Katherine E. Whitaker[8,10]

NASA/Nature

Dwarf galaxies: dark matter

Density of matter in the Draco dwarf spheroidal galaxy

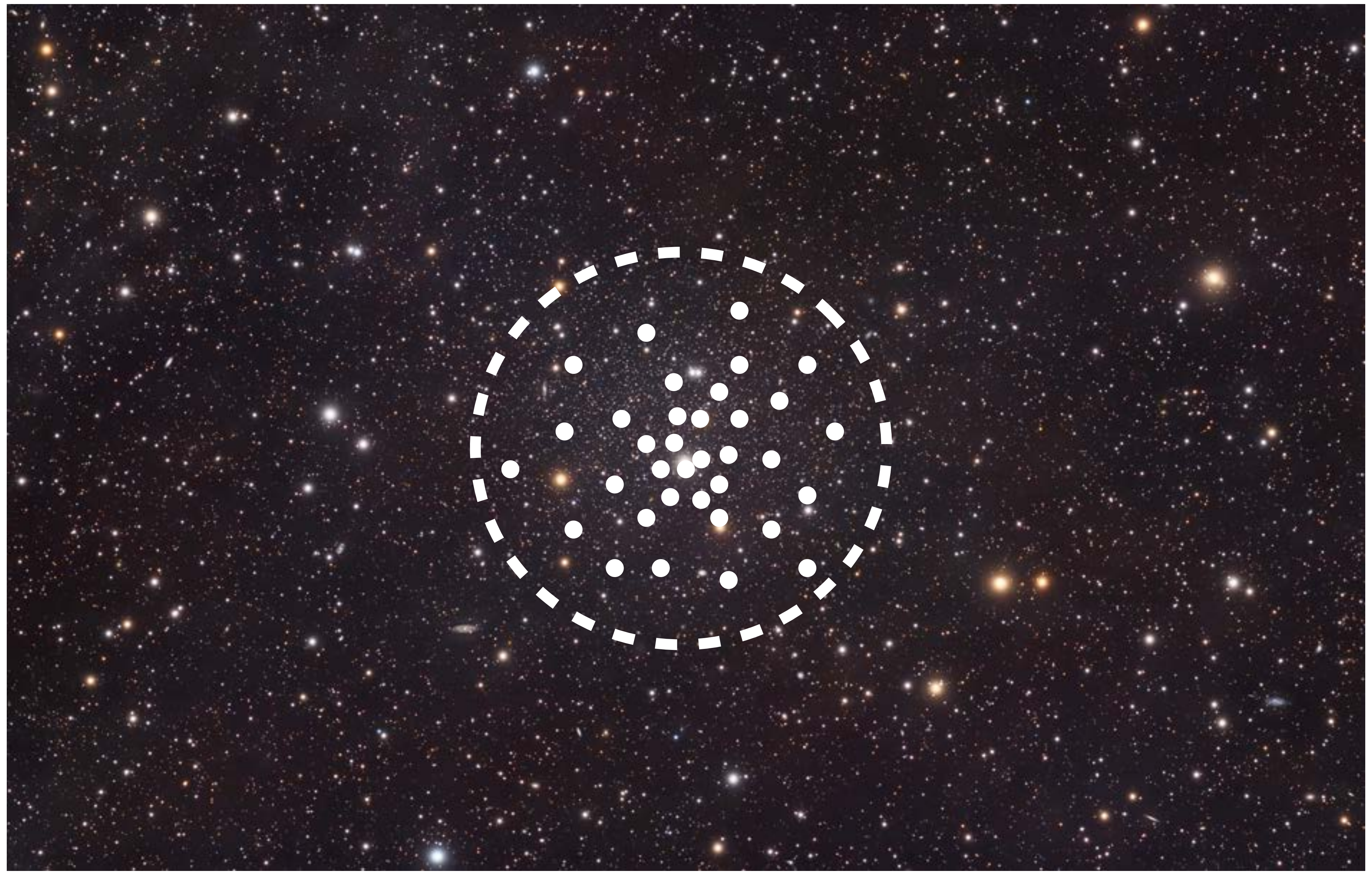




Vitral et al. 2024/IllustrisTNG/Wikimedia commons

Dwarf galaxies: dark matter

Core

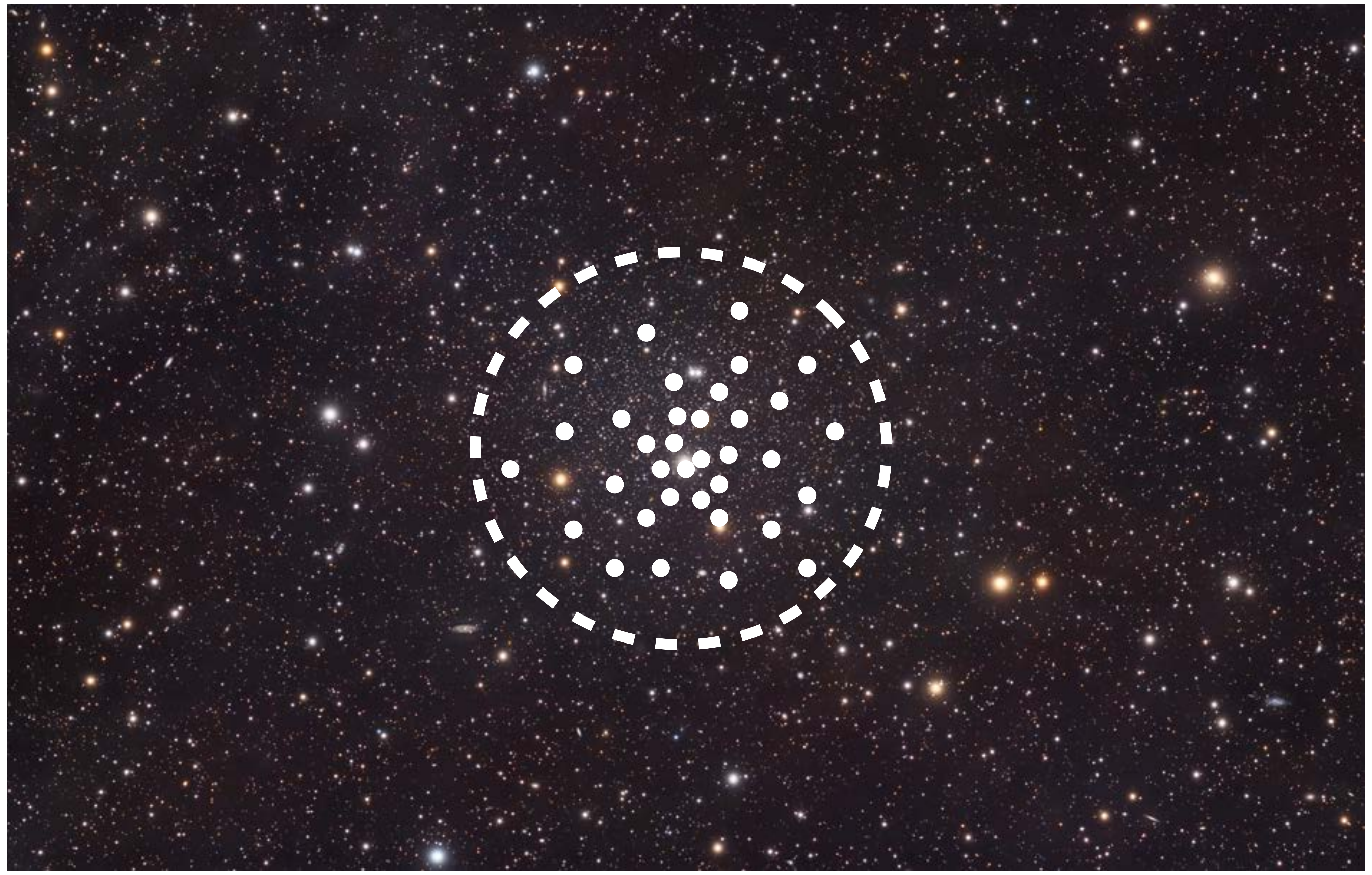


Self-interacting or warm dark matter

Draco image: Andrew Barton, AstroBin

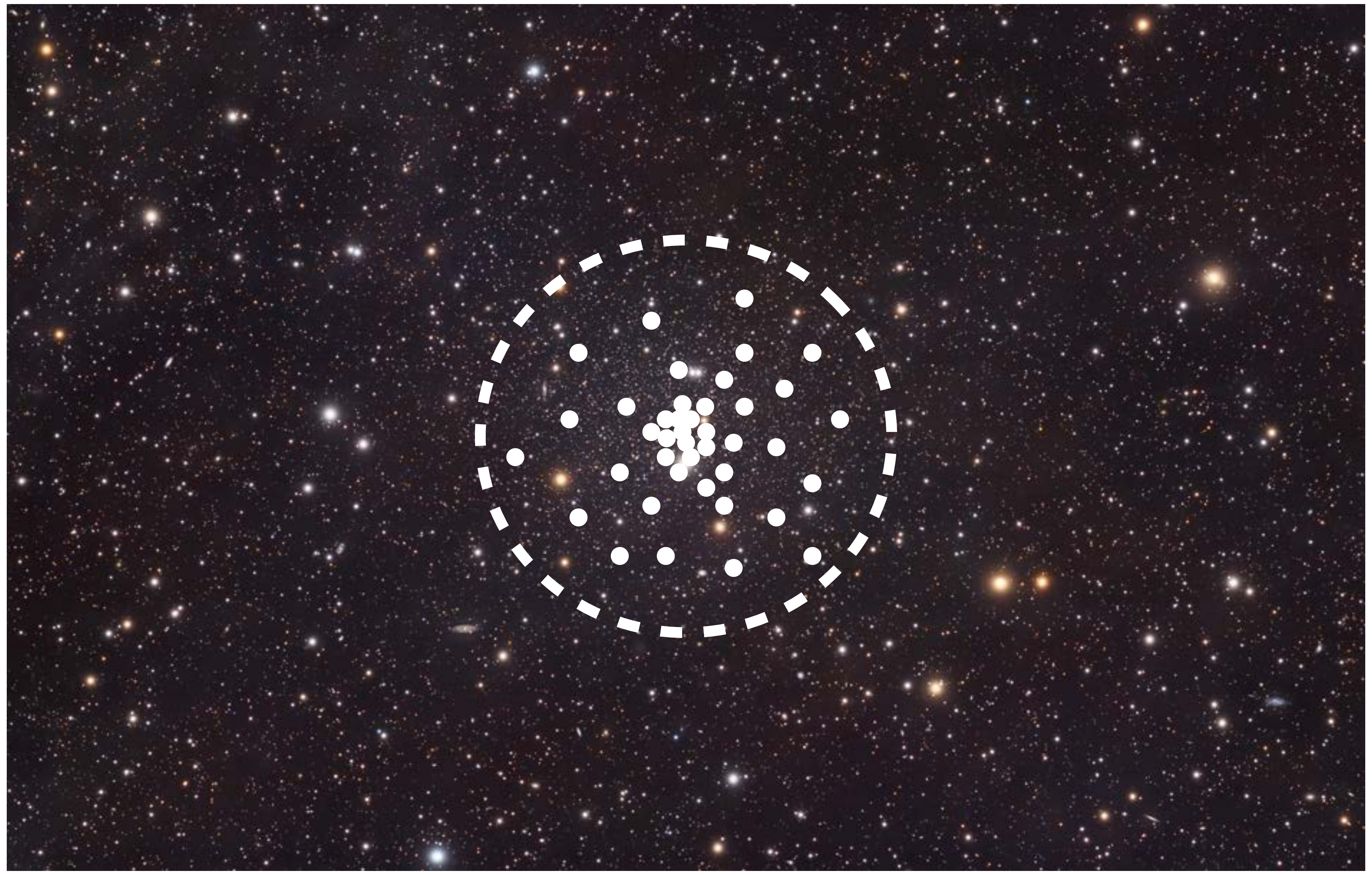
Dwarf galaxies: dark matter

Core



Self-interacting or warm dark matter

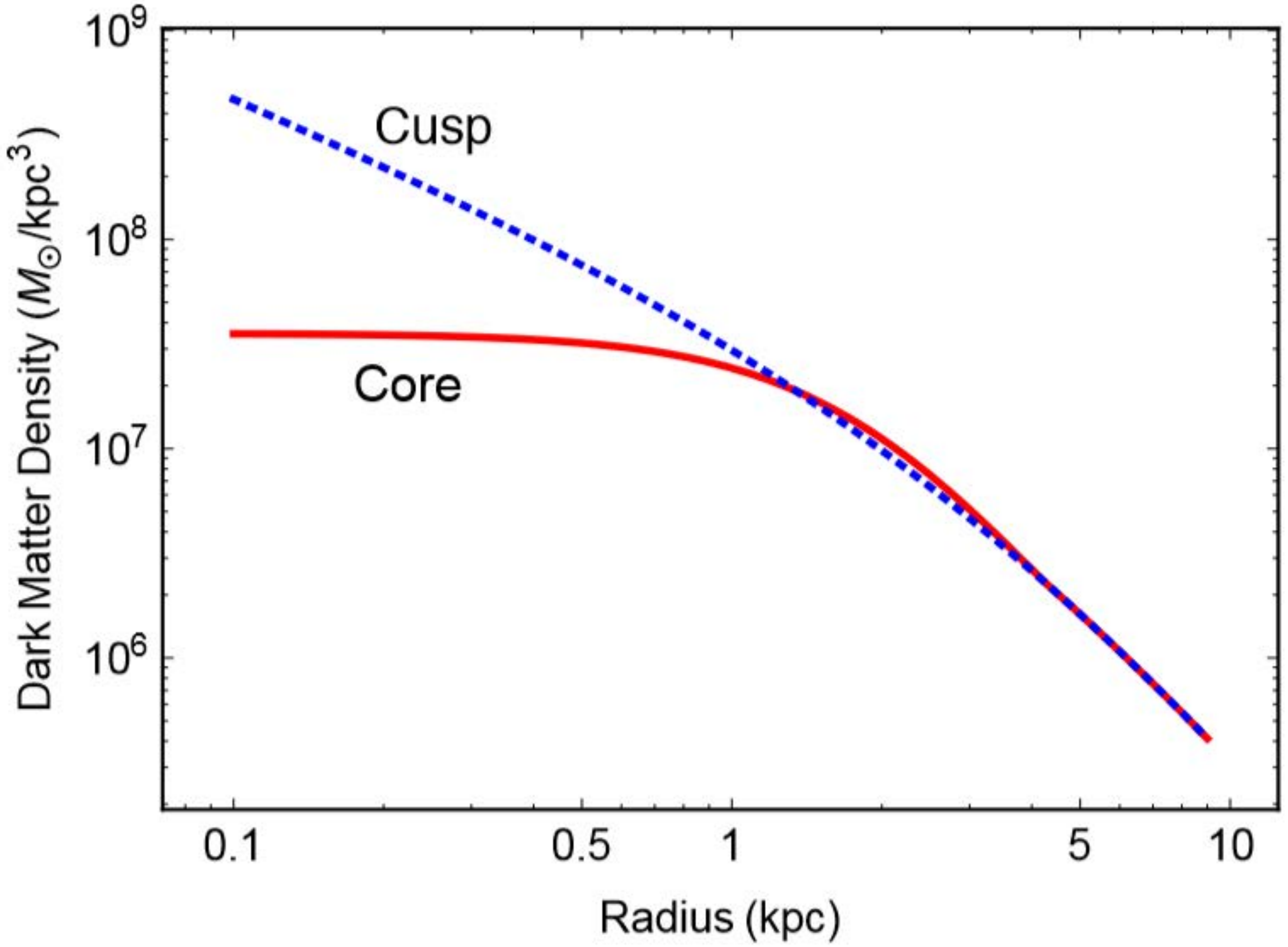
Cusp



Cold Dark Matter

Draco image: Andrew Barton, AstroBin

Dwarf galaxies: dark matter



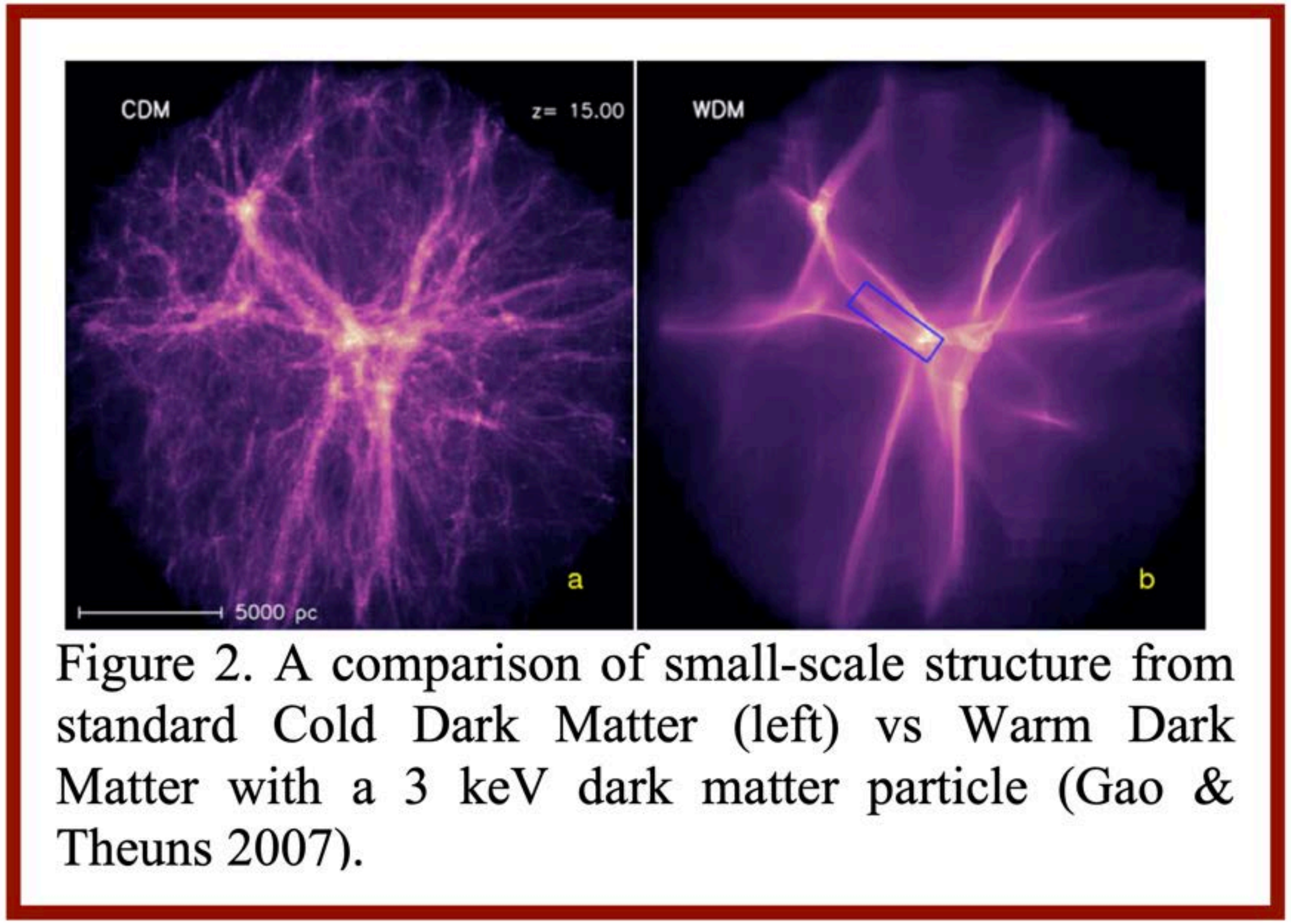
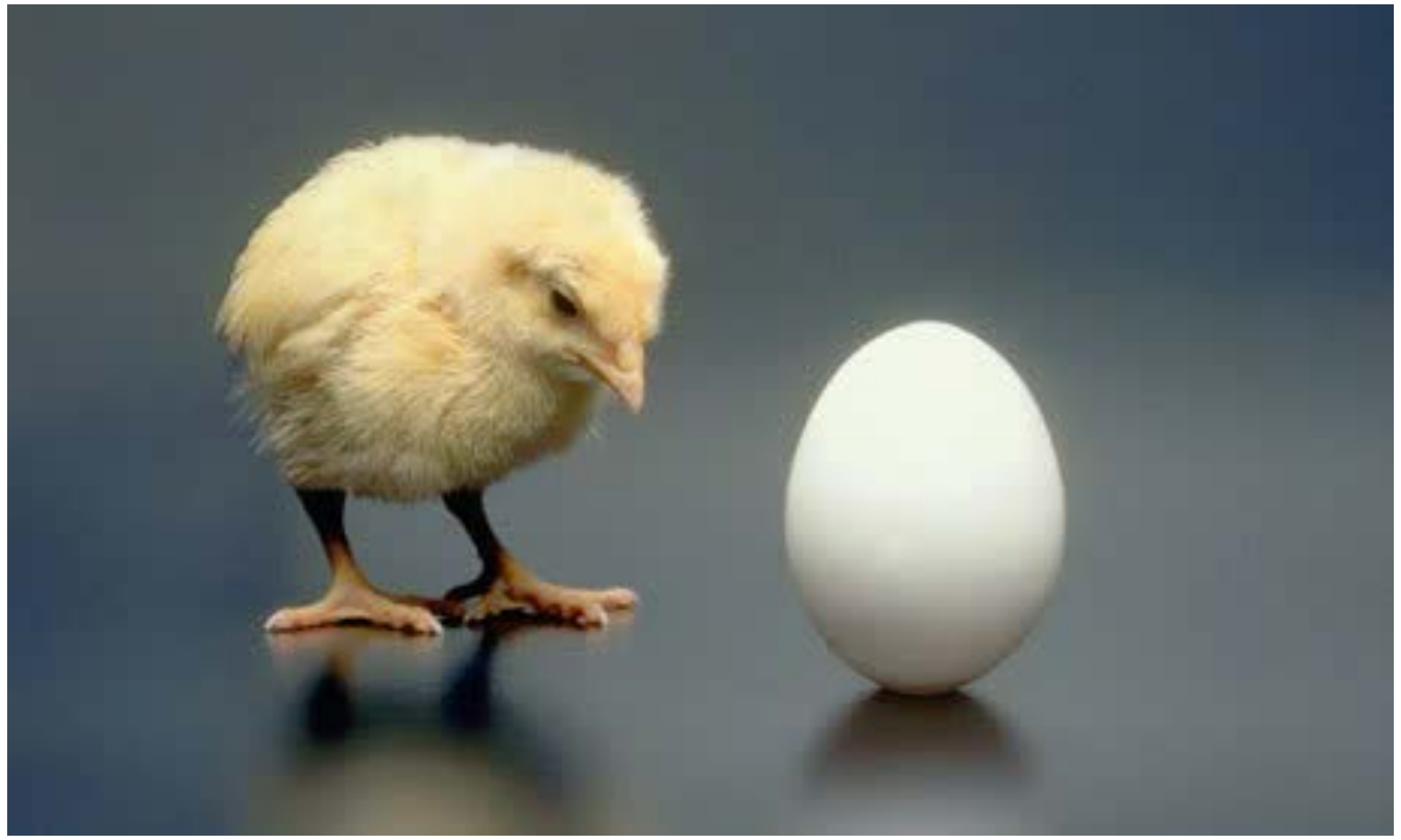
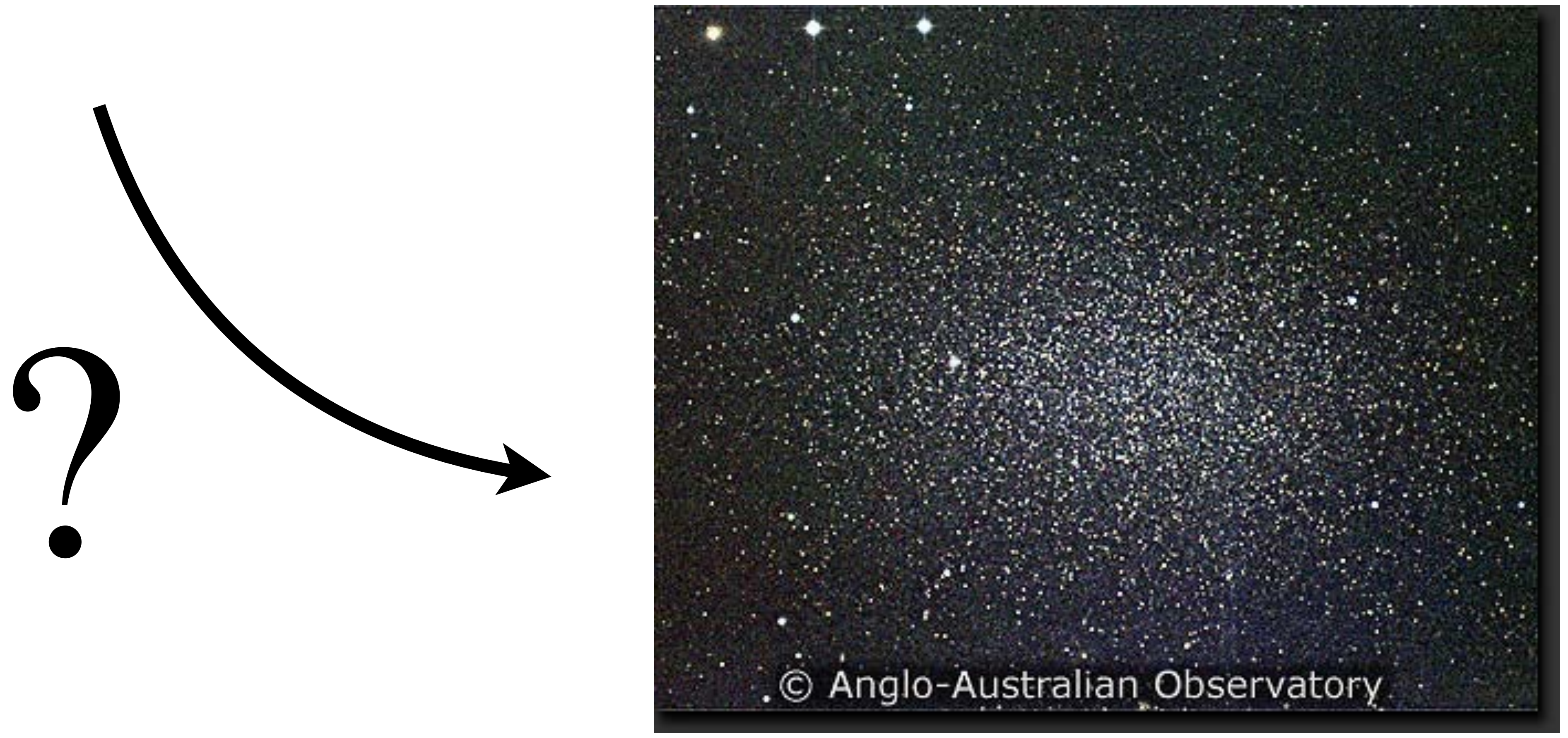


Figure 2. A comparison of small-scale structure from standard Cold Dark Matter (left) vs Warm Dark Matter with a 3 keV dark matter particle (Gao & Theuns 2007).

Tulin & Hai-Bo 2017

Dwarf galaxies: intermediate-mass black holes





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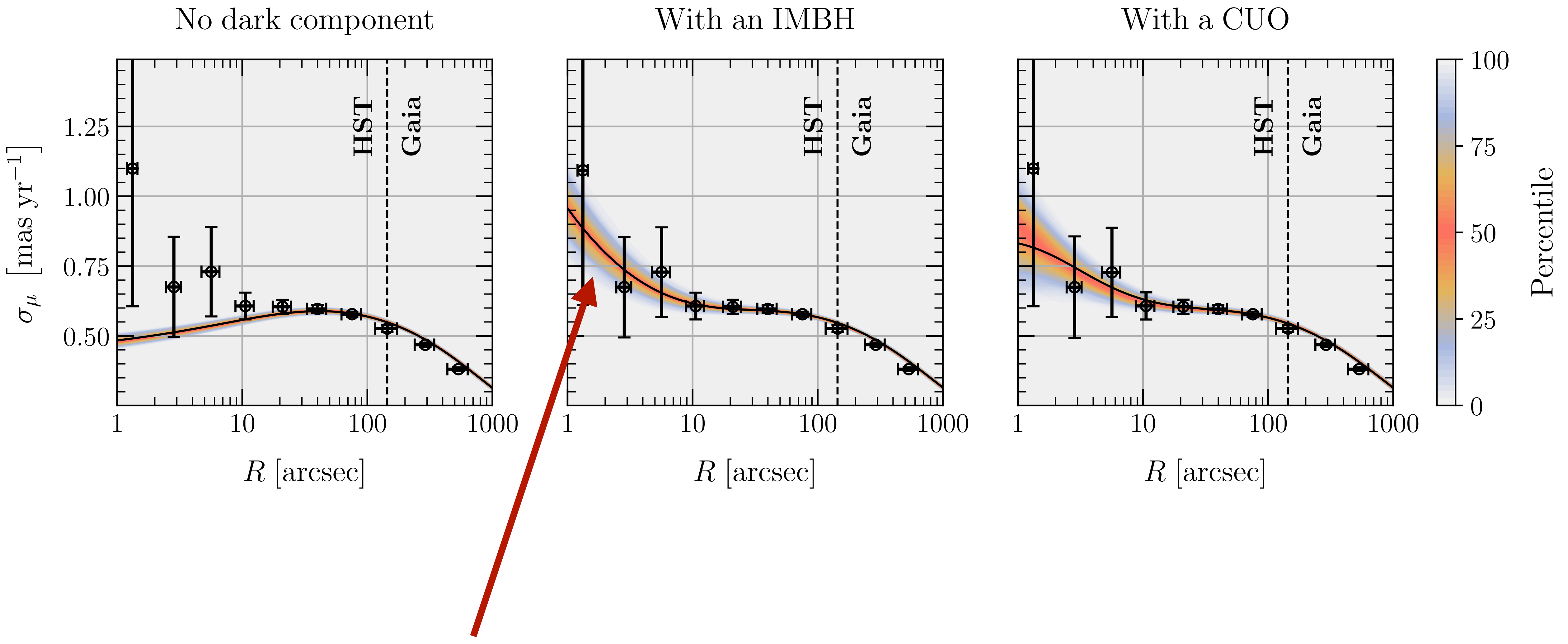
Dennis/ Novak for the Guardian/NASA/ Daniel Rutter

Dwarf galaxies: intermediate-mass black holes

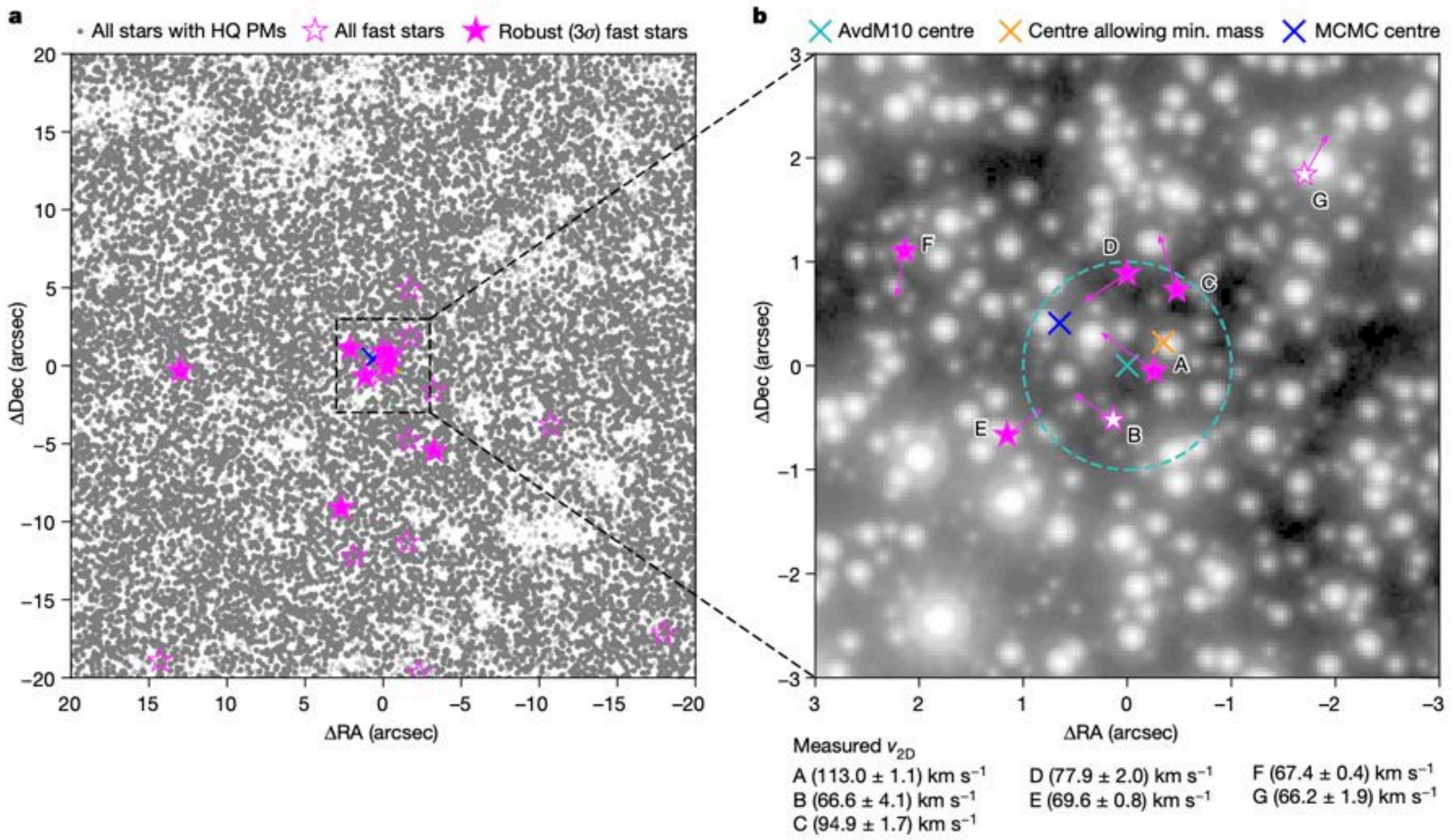
Knowledge from globular cluster previous analyses

Vitral, Libralato et al. (2023)



Rising velocity dispersion profiles

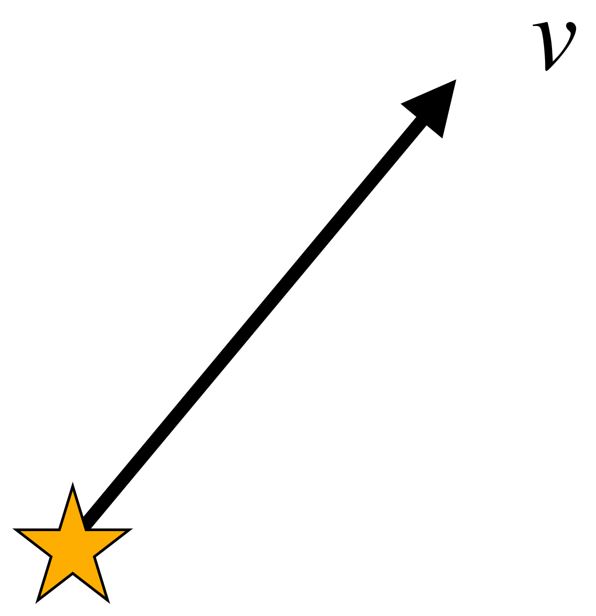
High-velocity stars (Häberle et al. 2024)



Some context on galactic dynamics

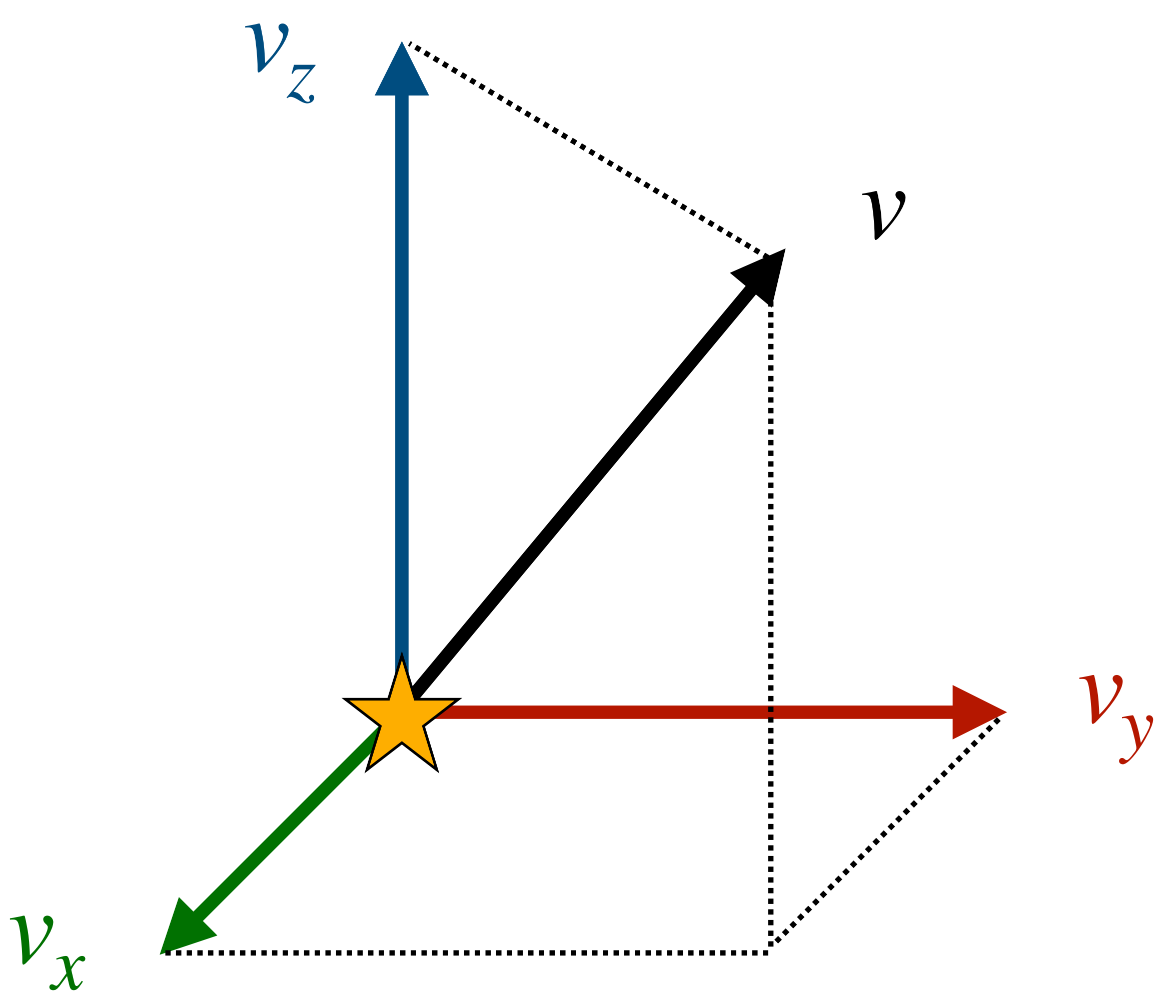
3D kinematics

Stellar velocities are among the main pathways to probe the distribution of mass around galaxies



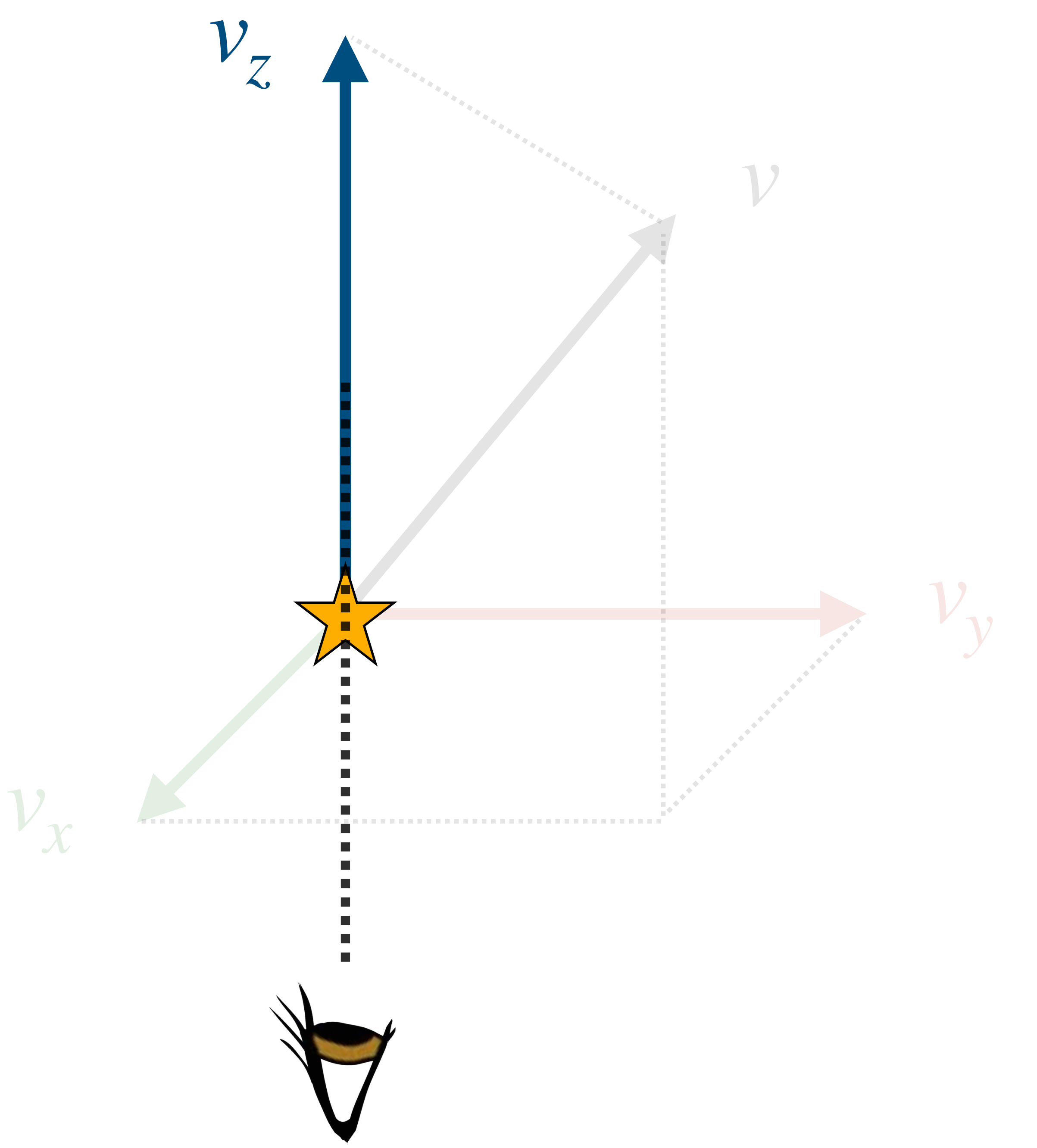
3D kinematics

Stellar velocities are among the main pathways to probe the distribution of dark matter around galaxies



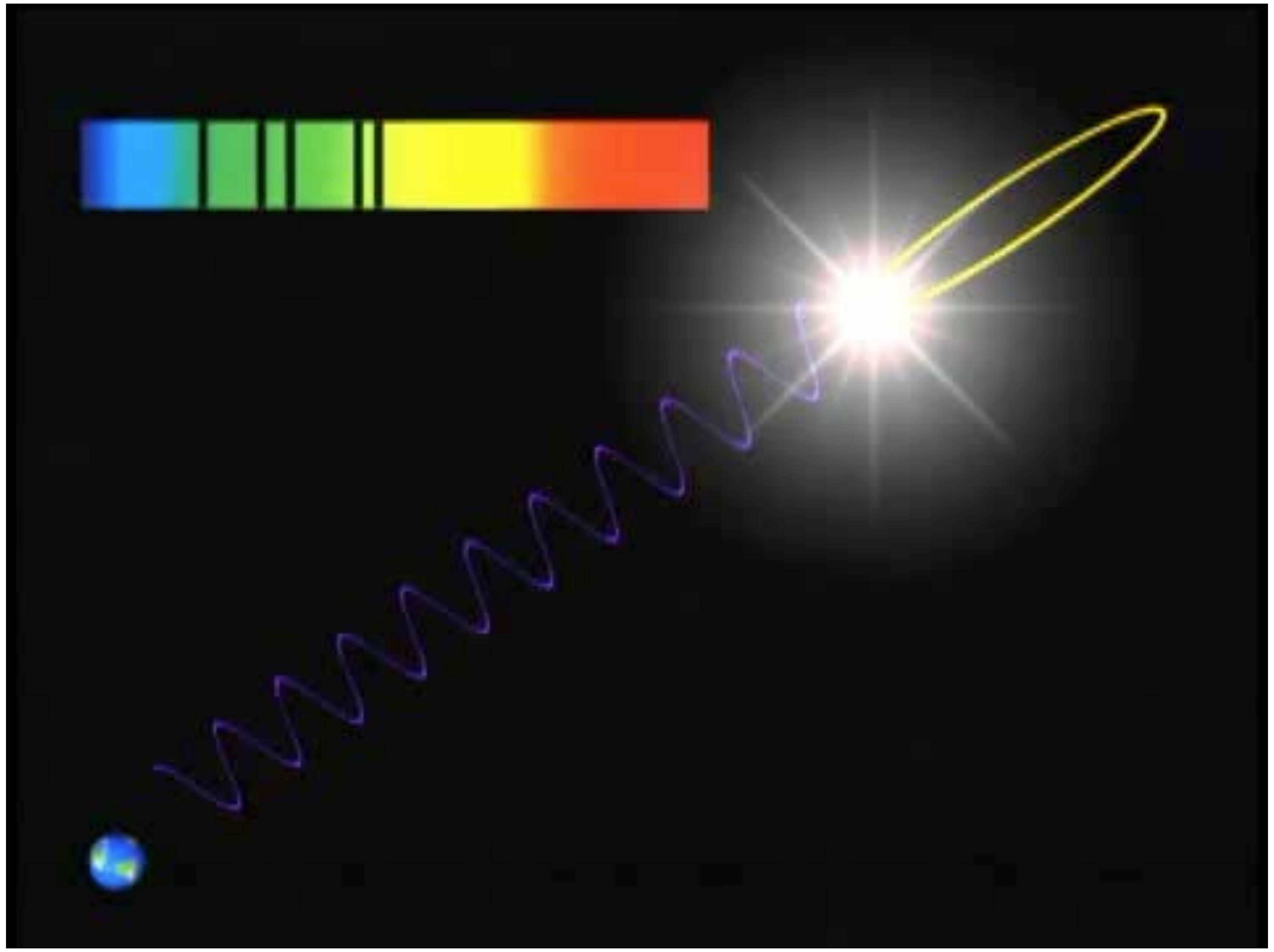
3D kinematics

Our knowledge of the internal velocities of galaxies comes mostly from a single dimension

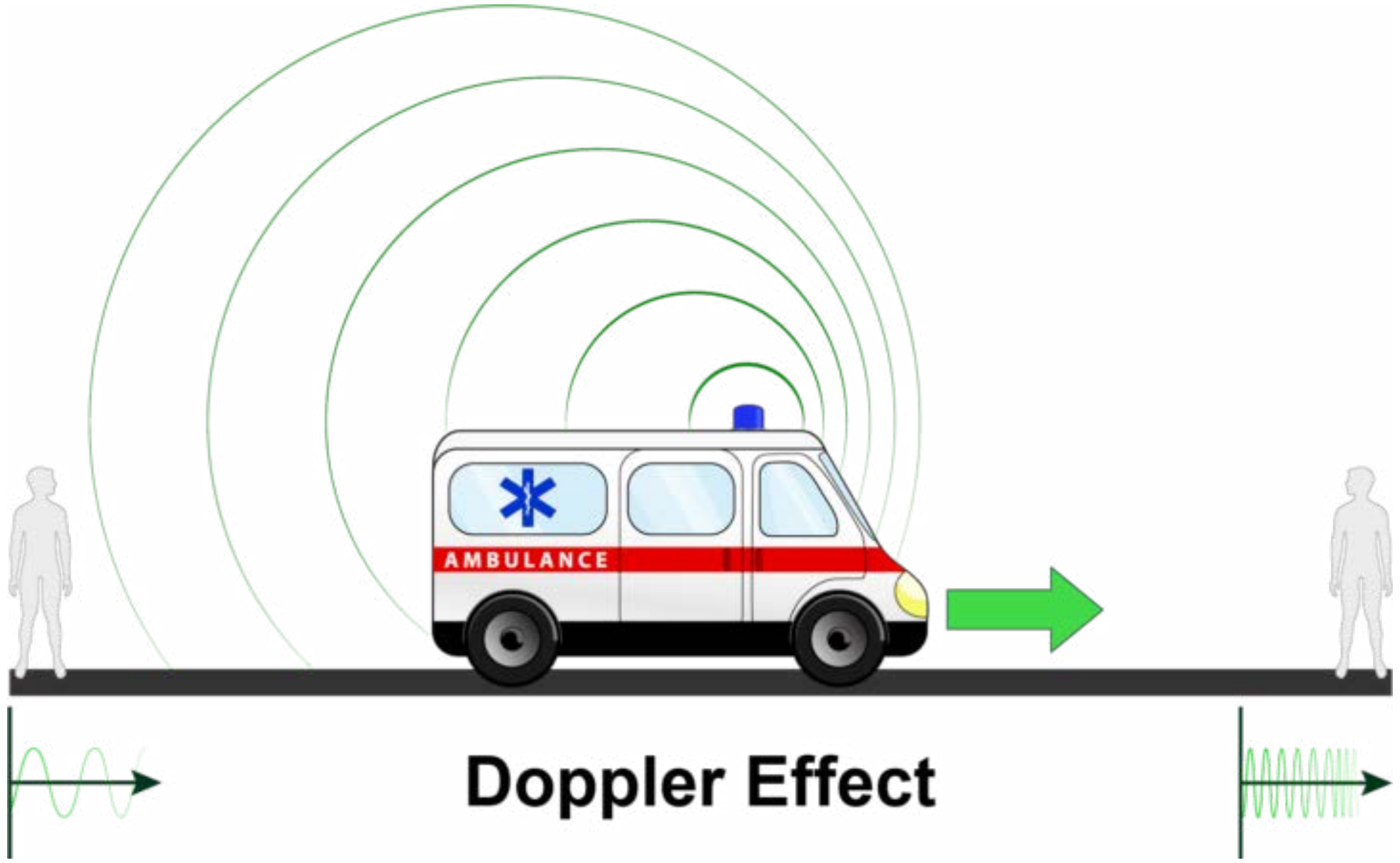


Madeleine Price Ball

3D kinematics



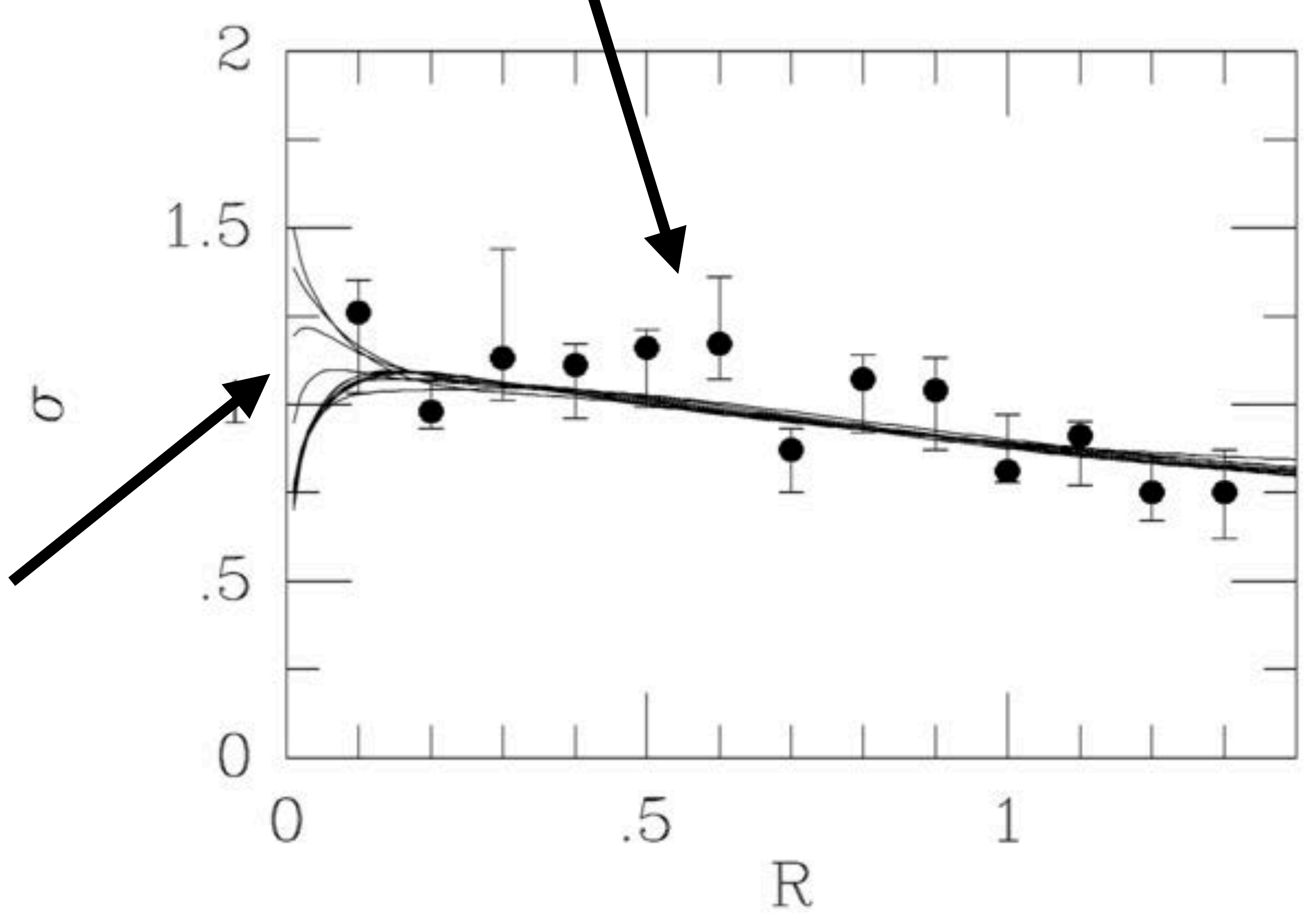
NASA/JPL



https://sciencetrek.org/topics/sound

3D kinematics

One dimensional velocity data (black dots)

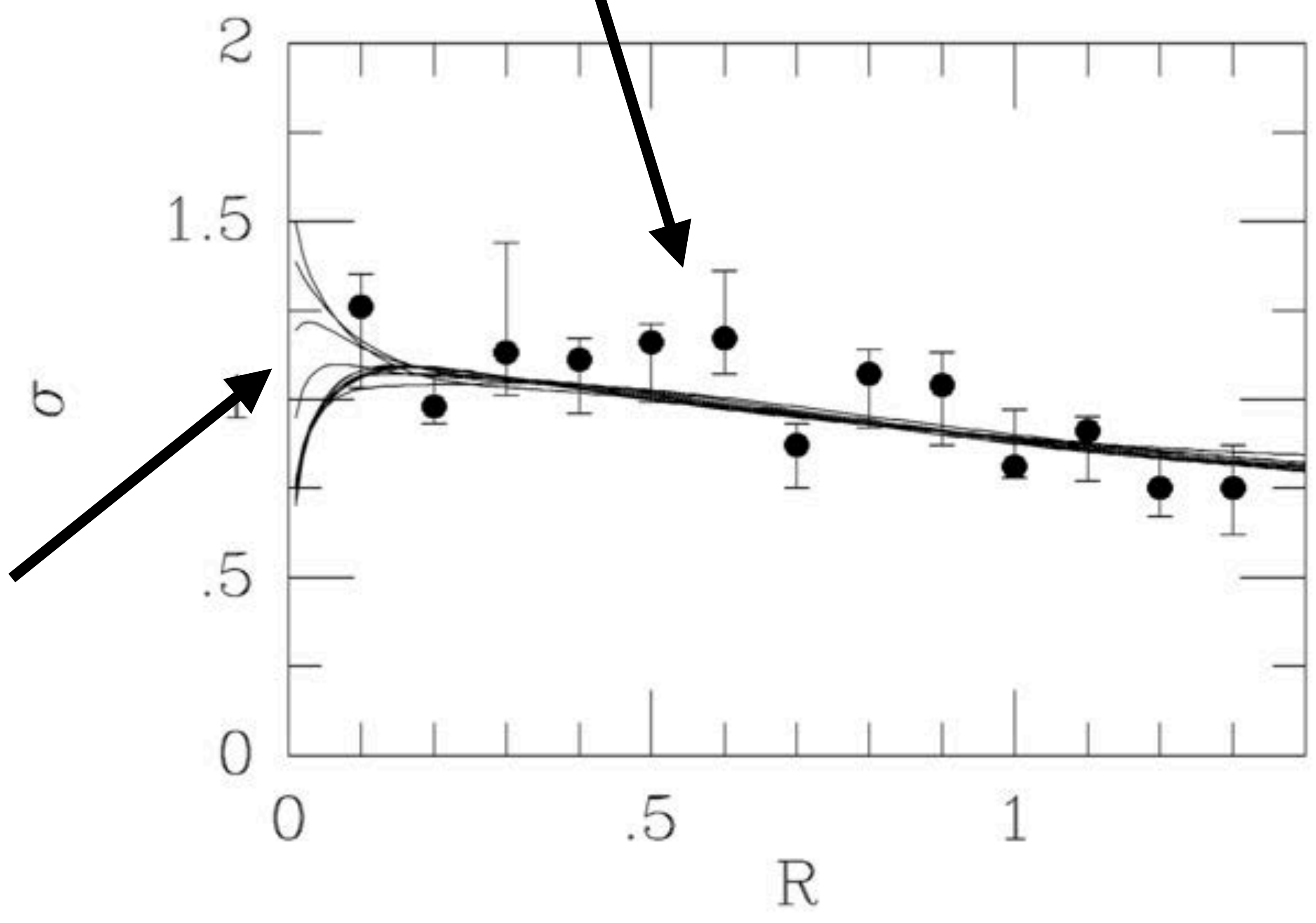


Many possible solutions that fit the data (Black lines)

van der Marel et al., 2000

3D kinematics

One dimensional velocity data (black dots)



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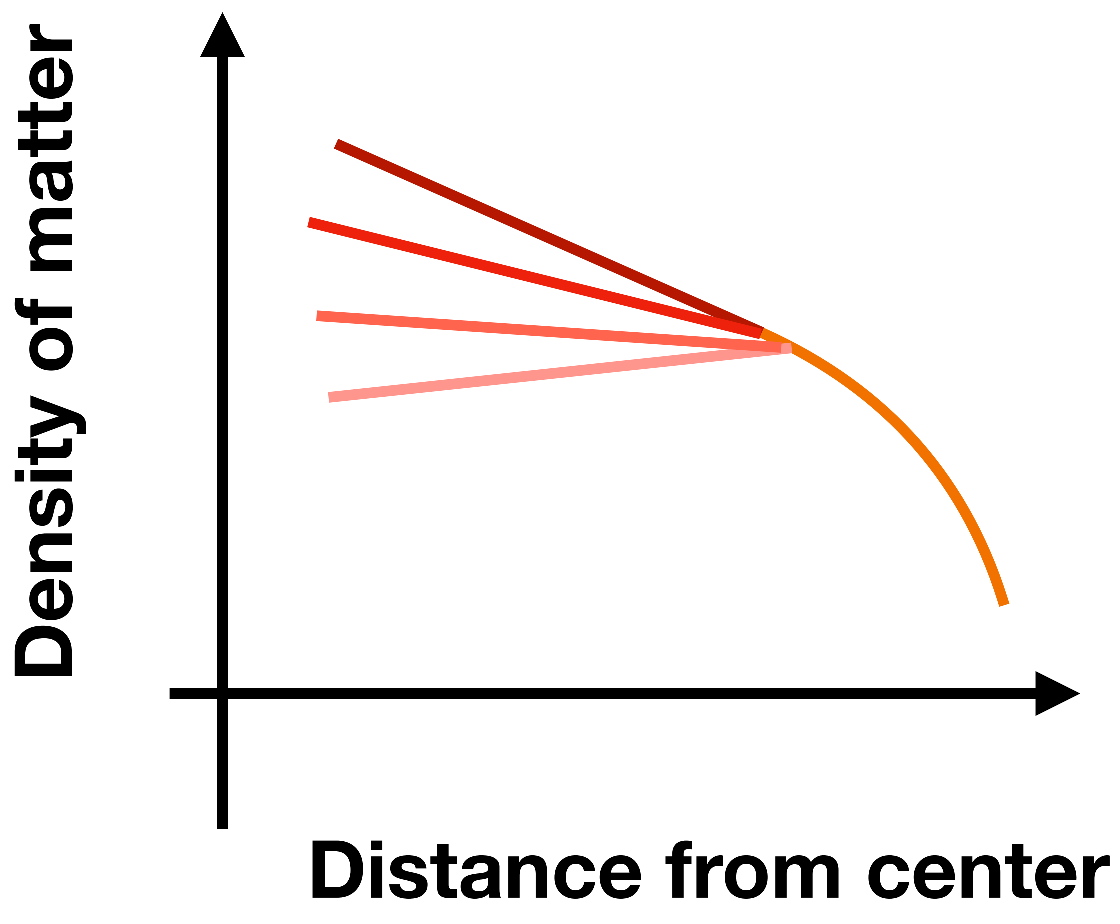


Several density
models possible with
just one velocity
dimension

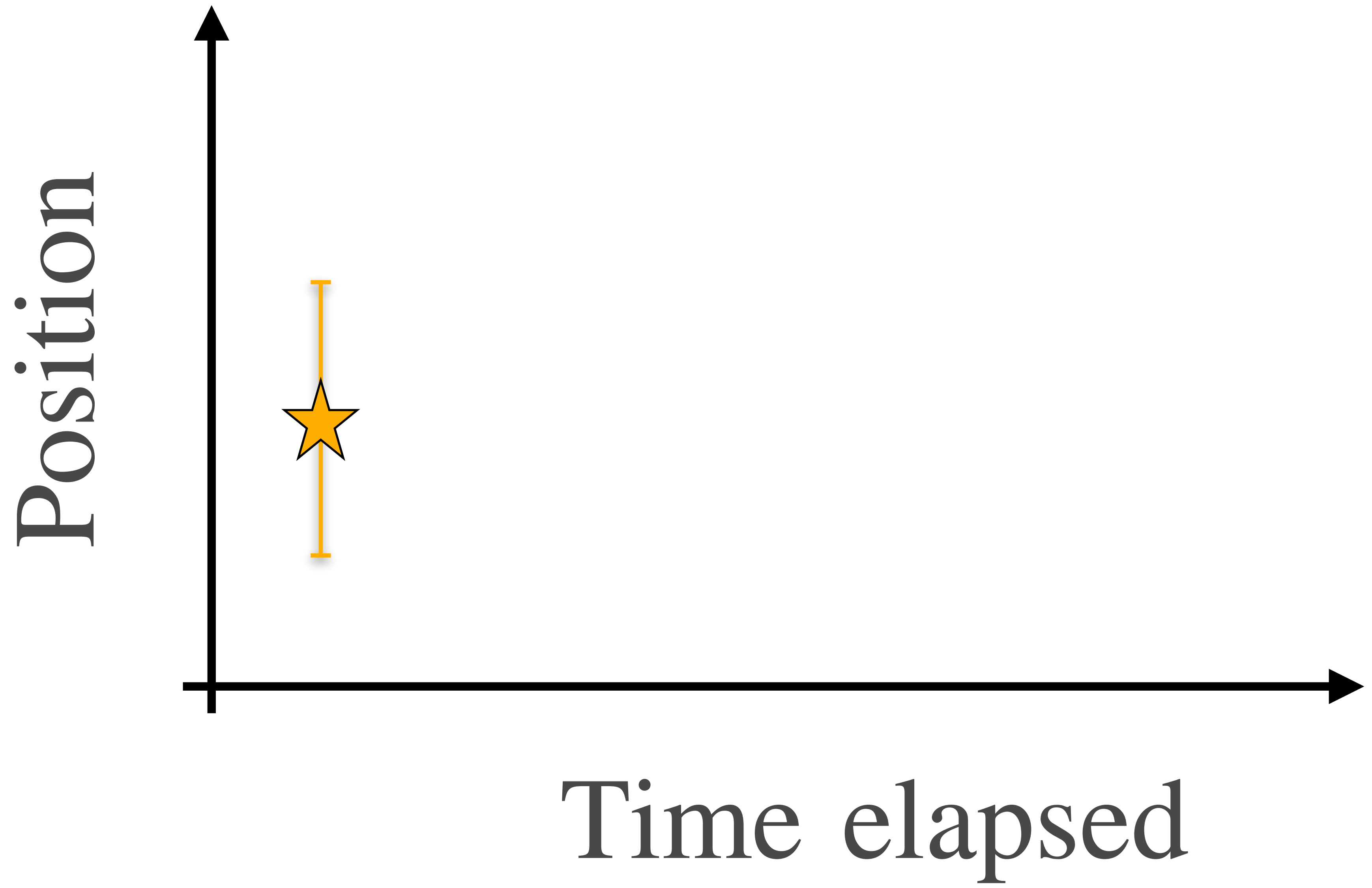
van der Marel et al., 2000

3D kinematics

We need the 2D motion on the sky-plane

HACKS catalog (M. Libralato)

3D kinematics



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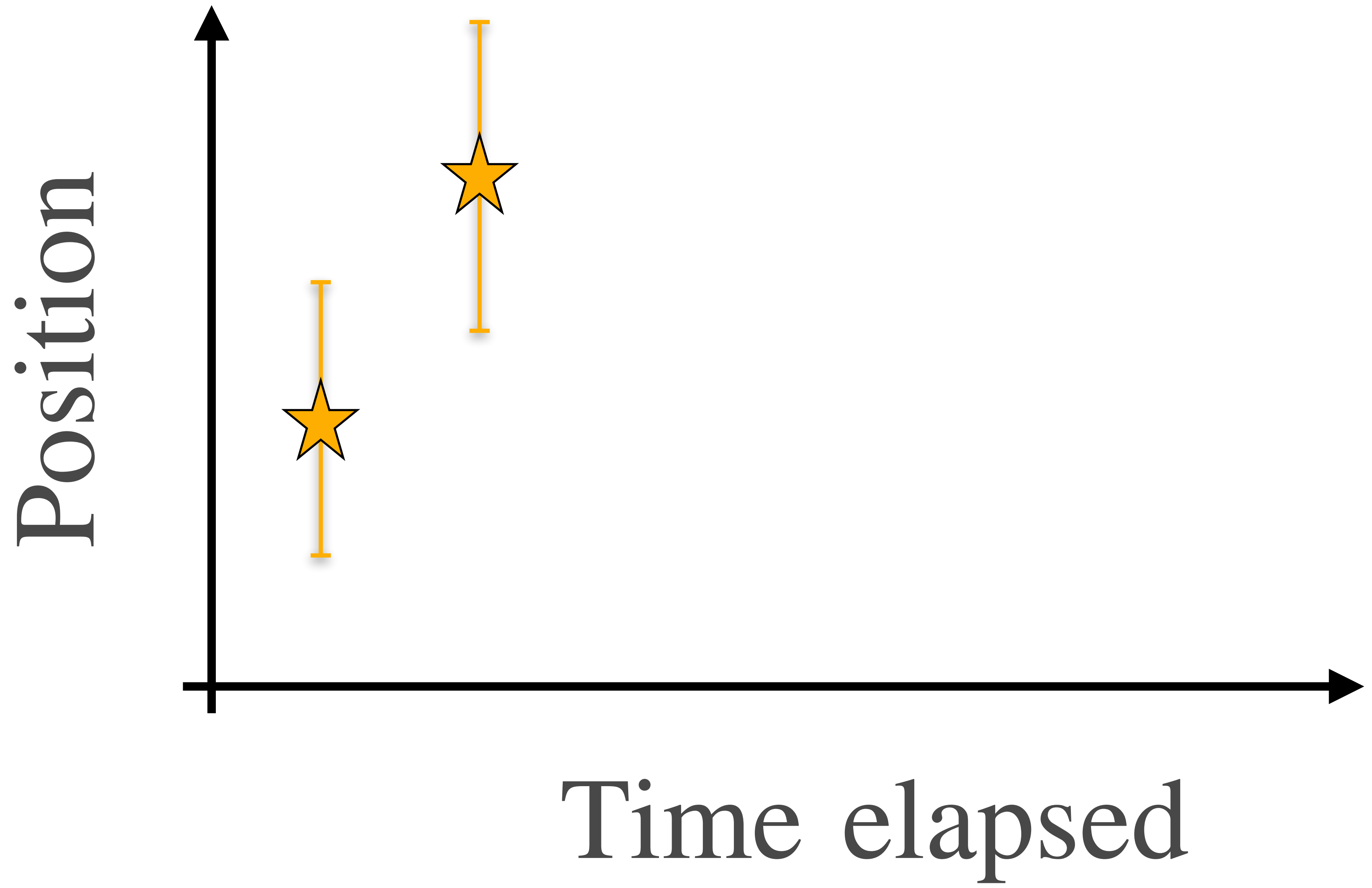
3D kinematics



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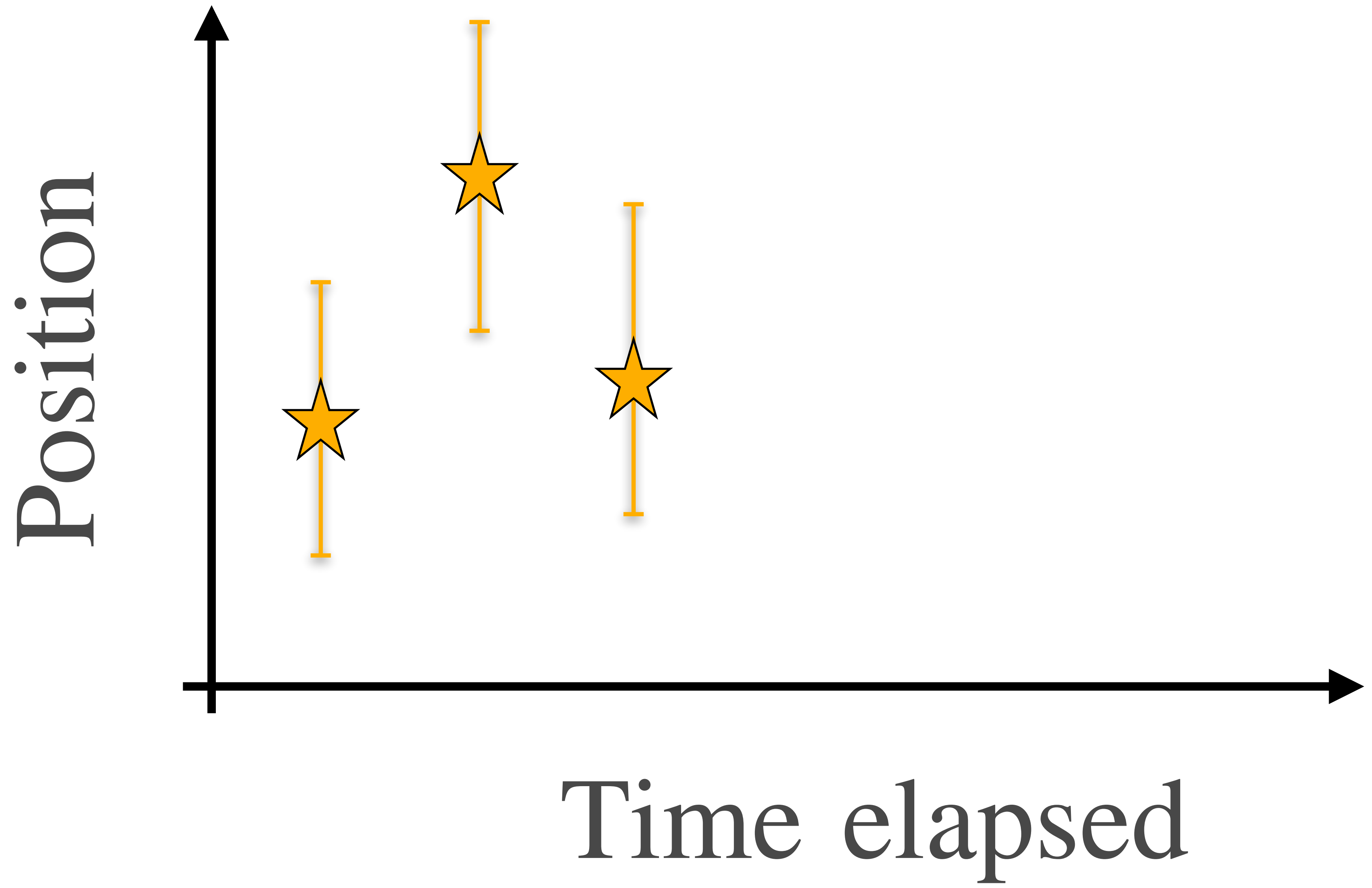

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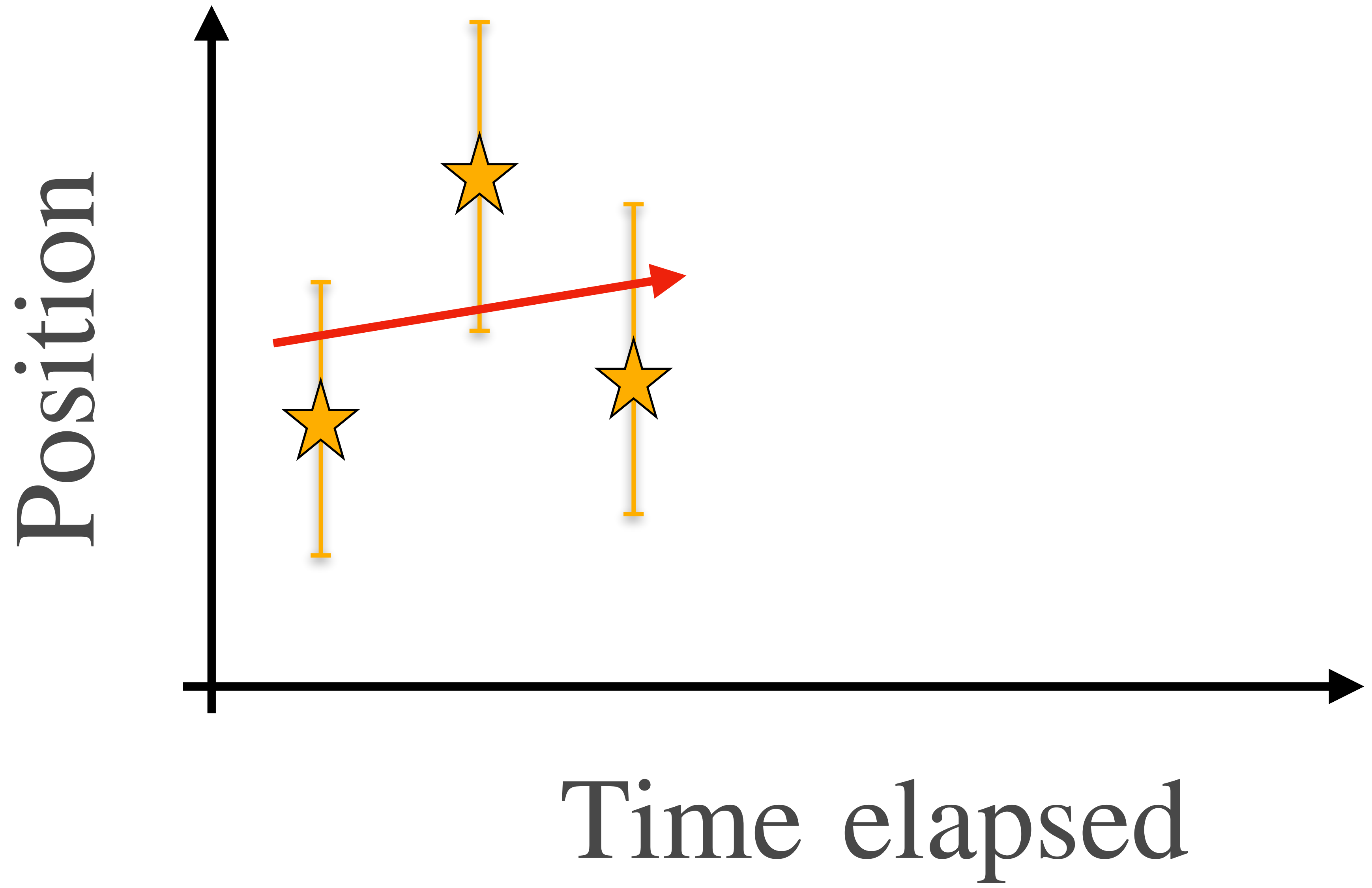

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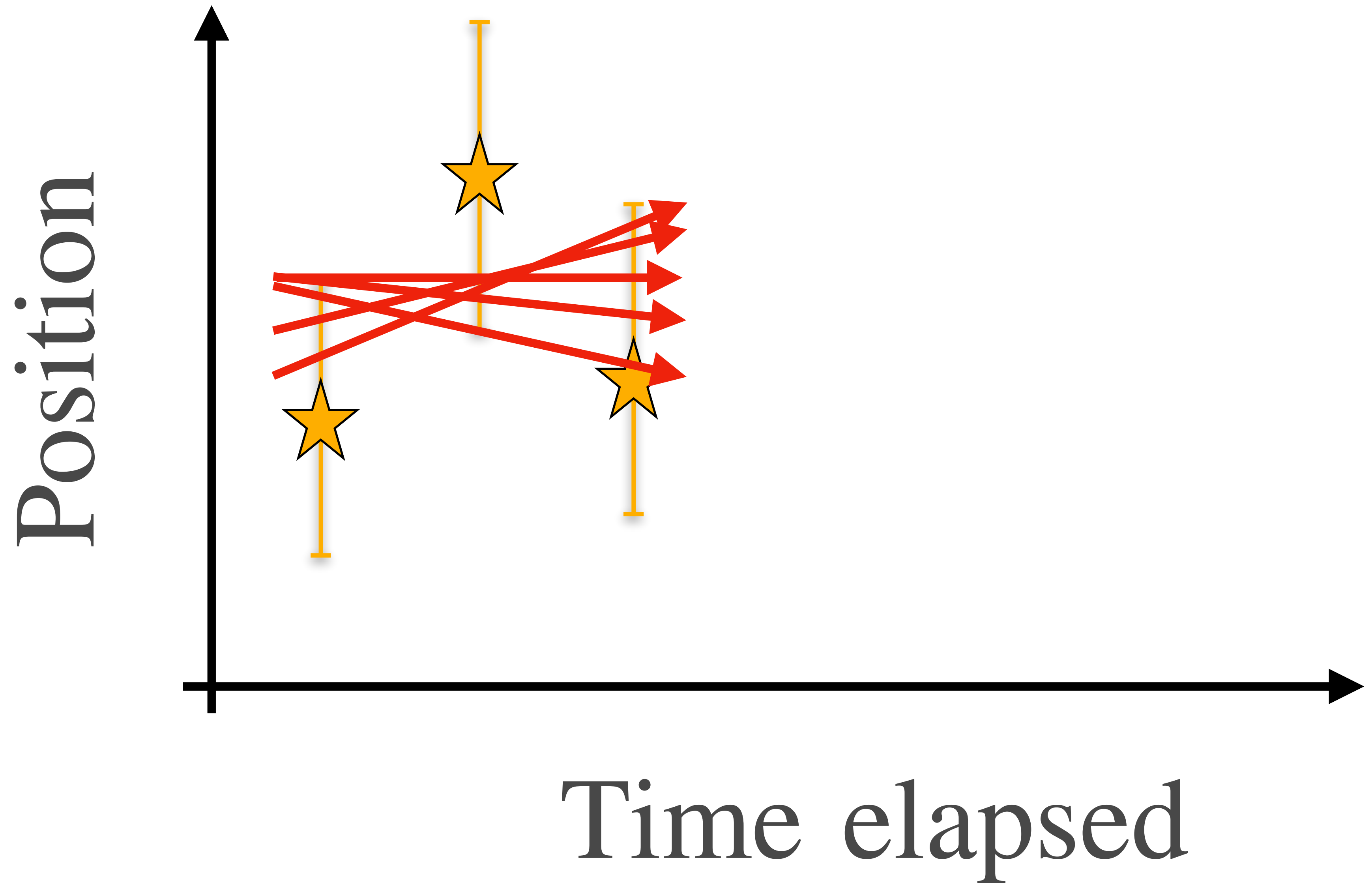
3D kinematics



We need the 2D motion on the sky-plane

HACKS catalog (M. Libralato)

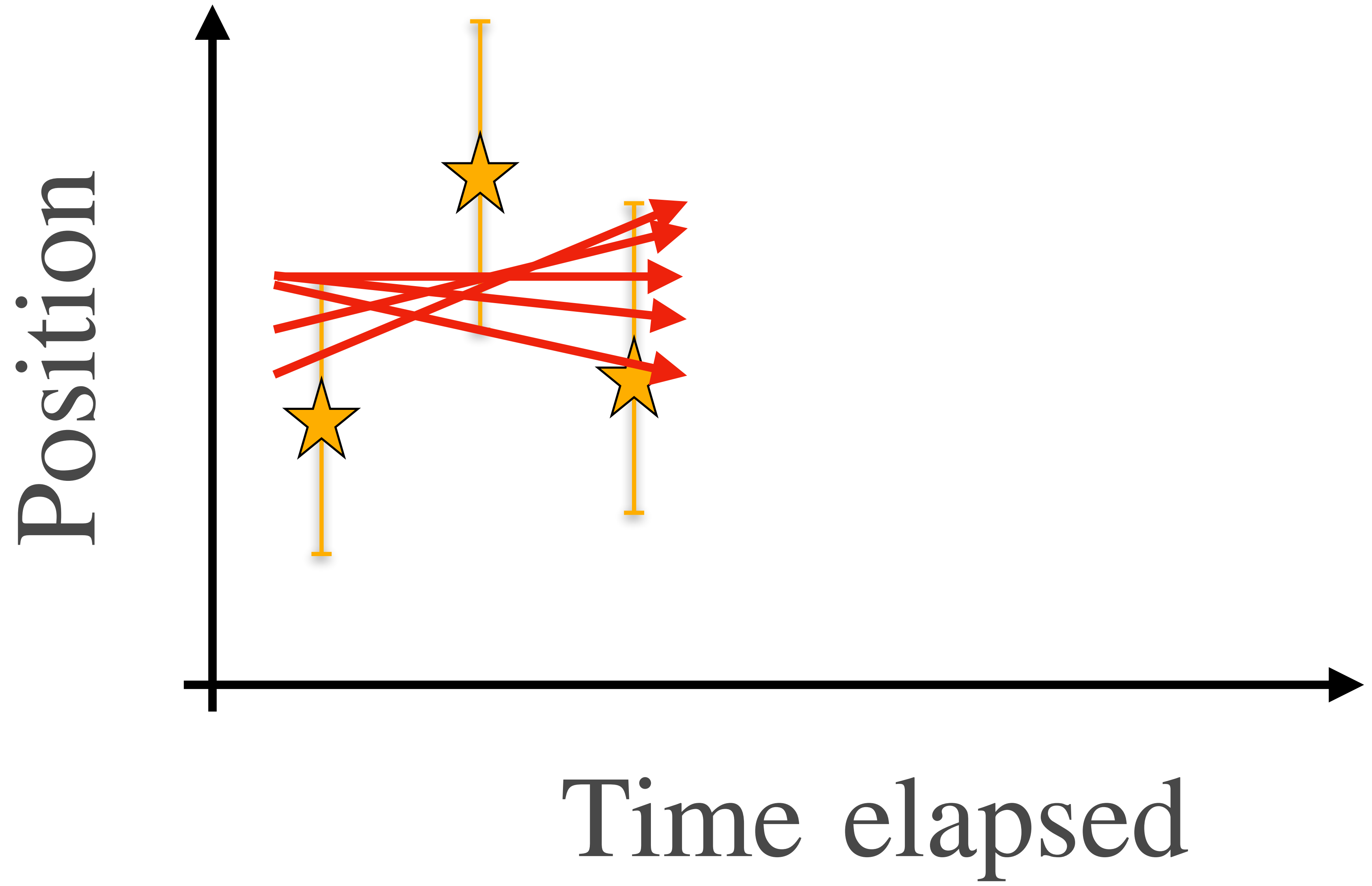
3D kinematics

$$M \propto \sigma_{\text{real}}^2$$

$$\sigma_{\text{data}}^2 = \sigma_{\text{real}}^2 + \epsilon_{\text{data}}^2$$

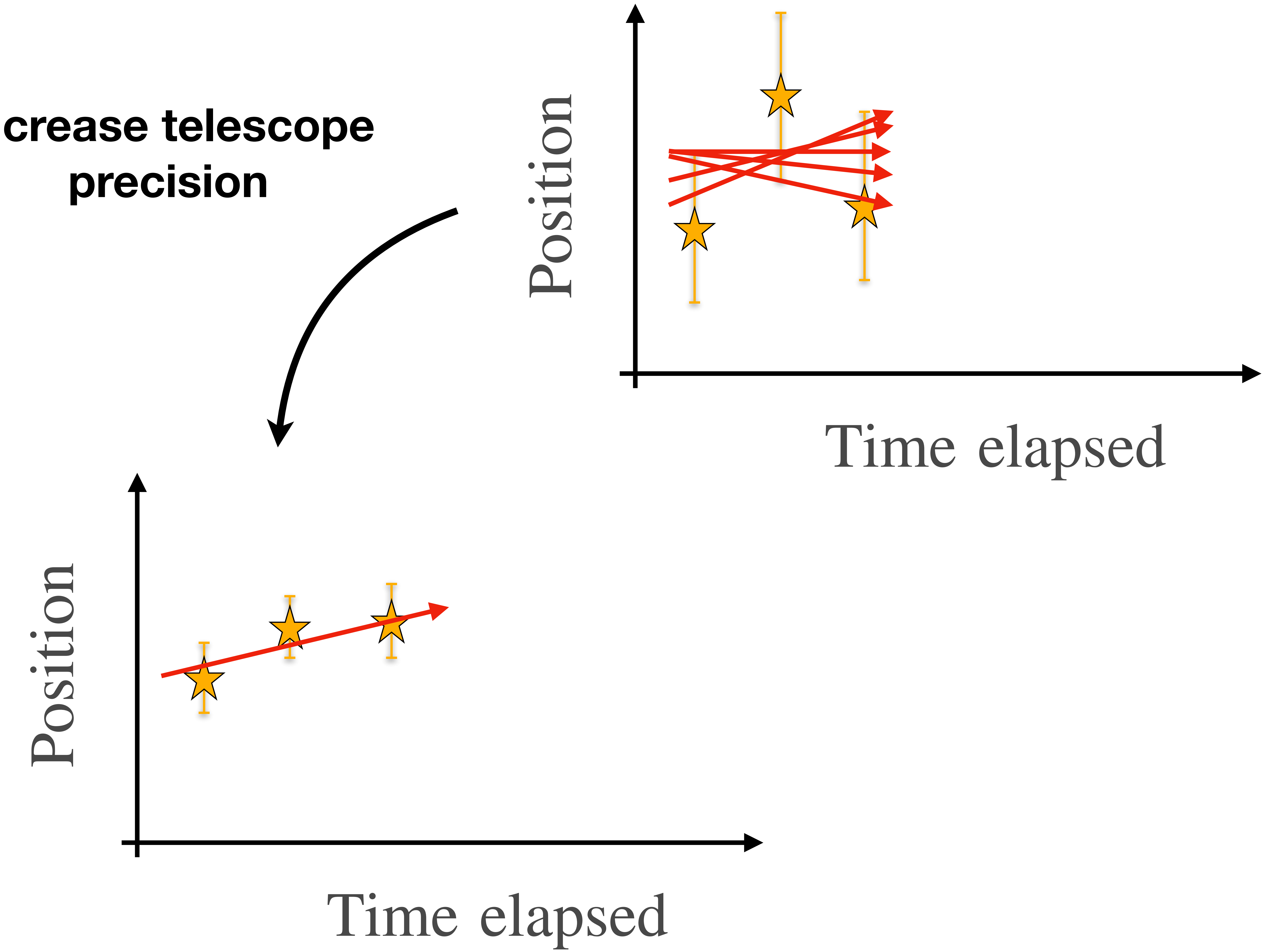
For robust mass modeling, one requires $\epsilon_{\text{data}} \lesssim \sigma_{\text{real}}$
and many tracers of the gravitational potential (stars)

3D kinematics

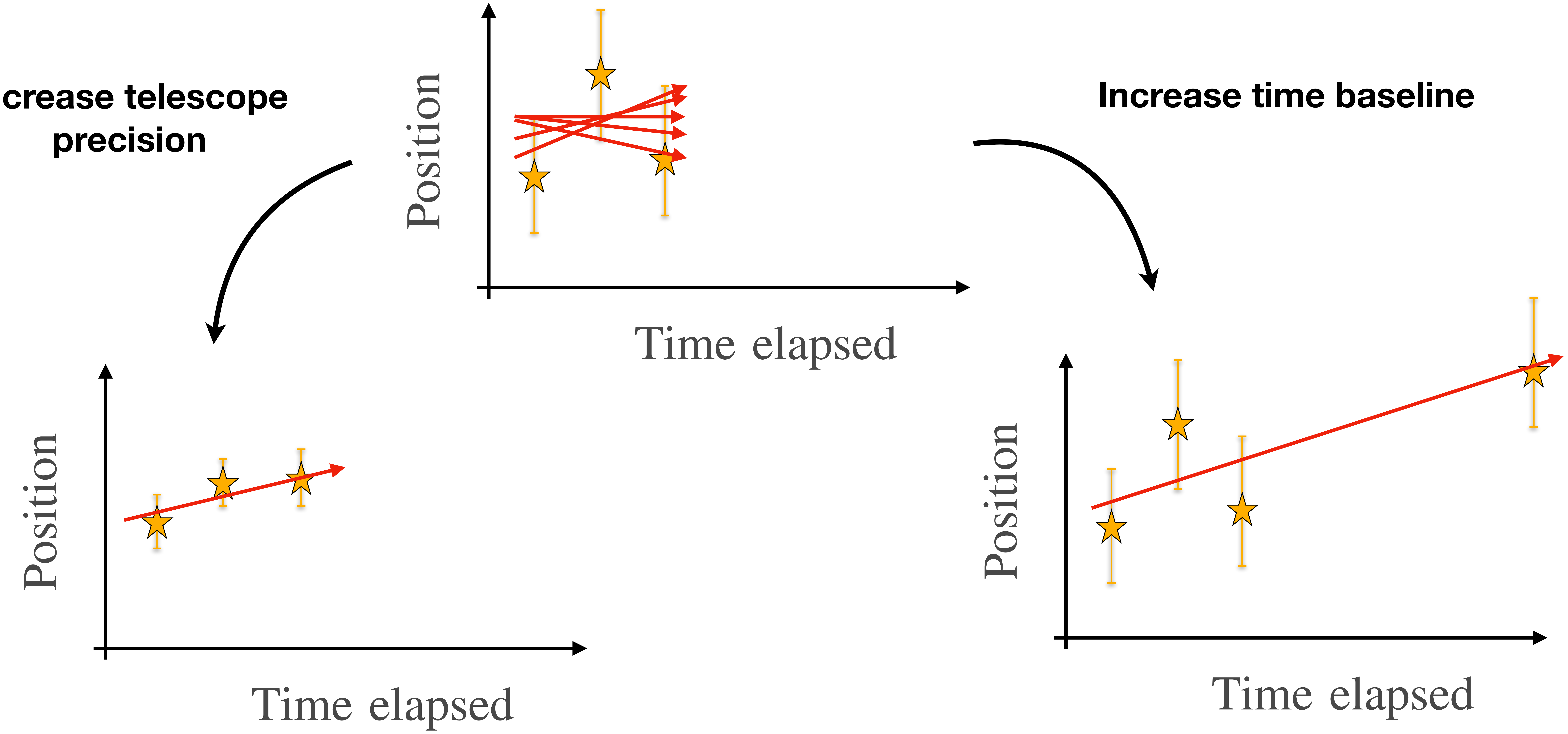


3D kinematics

Increase telescope precision



3D kinematics

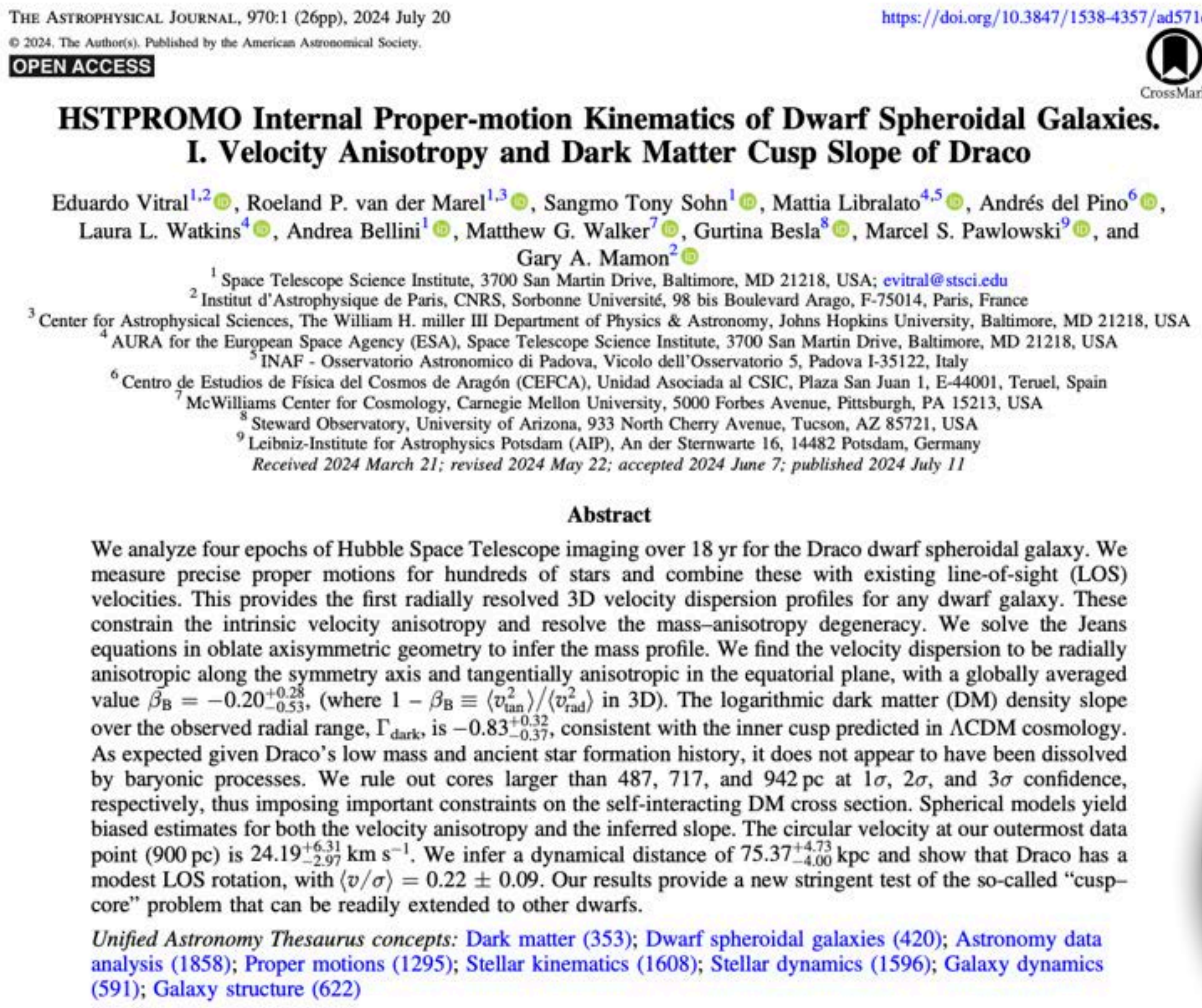


Increase telescope precision

Increase time baseline

How much precision and how much time?

Measuring proper motions



The Astrophysical Journal, 970:1 (26pp), 2024 July 20
https://doi.org/10.3847/1538-4357/ad571c

HSTPROMO Internal Proper-motion Kinematics of Dwarf Spheroidal Galaxies. I. Velocity Anisotropy and Dark Matter Cusp Slope of Draco

Eduardo Vitral[1,2], Roeland P. van der Marel[1,3], Sangmo Tony Sohn[1], Mattia Libralato[4,5], Andrés del Pino[6], Laura L. Watkins[4], Andrea Bellini[1], Matthew G. Walker[7], Gurtina Besla[8], Marcel S. Pawlowski[9], and Gary A. Mamon[2]

[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; evitral@stsci.edu
[2] Institut d'Astrophysique de Paris, CNRS, Sorbonne Université, 98 bis Boulevard Arago, F-75014, Paris, France
[3] Center for Astrophysical Sciences, The William H. miller III Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
[4] AURA for the European Space Agency (ESA), Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[5] INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, Padova I-35122, Italy
[6] Centro de Estudios de Física del Cosmos de Aragón (CEFCA), Unidad Asociada al CSIC, Plaza San Juan 1, E-44001, Teruel, Spain
[7] McWilliams Center for Cosmology, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA
[8] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
[9] Leibniz-Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany

Received 2024 March 21; revised 2024 May 22; accepted 2024 June 7; published 2024 July 11

Abstract

We analyze four epochs of Hubble Space Telescope imaging over 18 yr for the Draco dwarf spheroidal galaxy. We measure precise proper motions for hundreds of stars and combine these with existing line-of-sight (LOS) velocities. This provides the first radially resolved 3D velocity dispersion profiles for any dwarf galaxy. These constrain the intrinsic velocity anisotropy and resolve the mass–anisotropy degeneracy. We solve the Jeans equations in oblate axisymmetric geometry to infer the mass profile. We find the velocity dispersion to be radially anisotropic along the symmetry axis and tangentially anisotropic in the equatorial plane, with a globally averaged value $\tilde{\beta}_{\rm B} = -0.20^{+0.28}_{-0.53}$, (where $1 - \beta_{\rm B} \equiv \langle v_{\rm tan}^2 \rangle / \langle v_{\rm rad}^2 \rangle$ in 3D). The logarithmic dark matter (DM) density slope over the observed radial range, $\Gamma_{\rm dark}$, is $-0.83^{+0.32}_{-0.37}$, consistent with the inner cusp predicted in ΛCDM cosmology. As expected given Draco's low mass and ancient star formation history, it does not appear to have been dissolved by baryonic processes. We rule out cores larger than 487, 717, and 942 pc at 1σ, 2σ, and 3σ confidence, respectively, thus imposing important constraints on the self-interacting DM cross section. Spherical models yield biased estimates for both the velocity anisotropy and the inferred slope. The circular velocity at our outermost data point (900 pc) is $24.19^{+6.31}_{-2.97}$ km s^{-1}. We infer a dynamical distance of $75.37^{+4.73}_{-4.00}$ kpc and show that Draco has a modest LOS rotation, with $\langle v/\sigma \rangle = 0.22 \pm 0.09$. Our results provide a new stringent test of the so-called "cusp–core" problem that can be readily extended to other dwarfs.

Unified Astronomy Thesaurus concepts: Dark matter (353); Dwarf spheroidal galaxies (420); Astronomy data analysis (1858); Proper motions (1295); Stellar kinematics (1608); Stellar dynamics (1596); Galaxy dynamics (591); Galaxy structure (622)

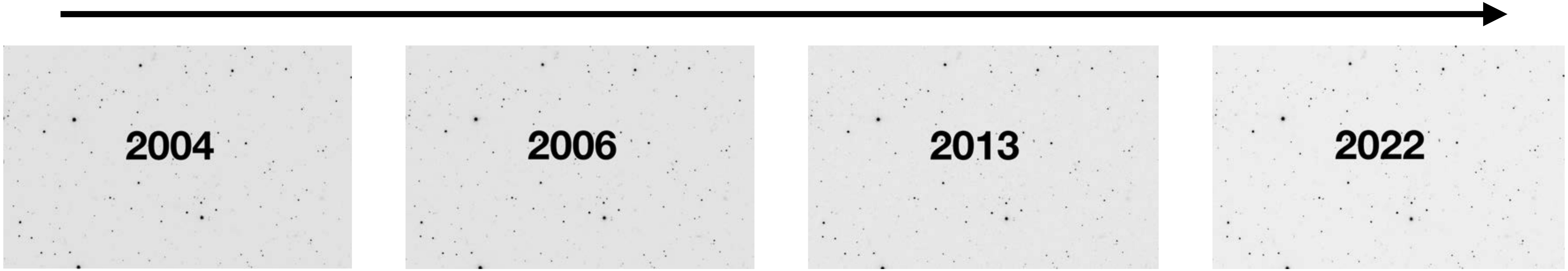
Draco dwarf spheroidal

HSTPROMO

Draco image: Andrew Barton, AstroBin / Elena Monstuschi

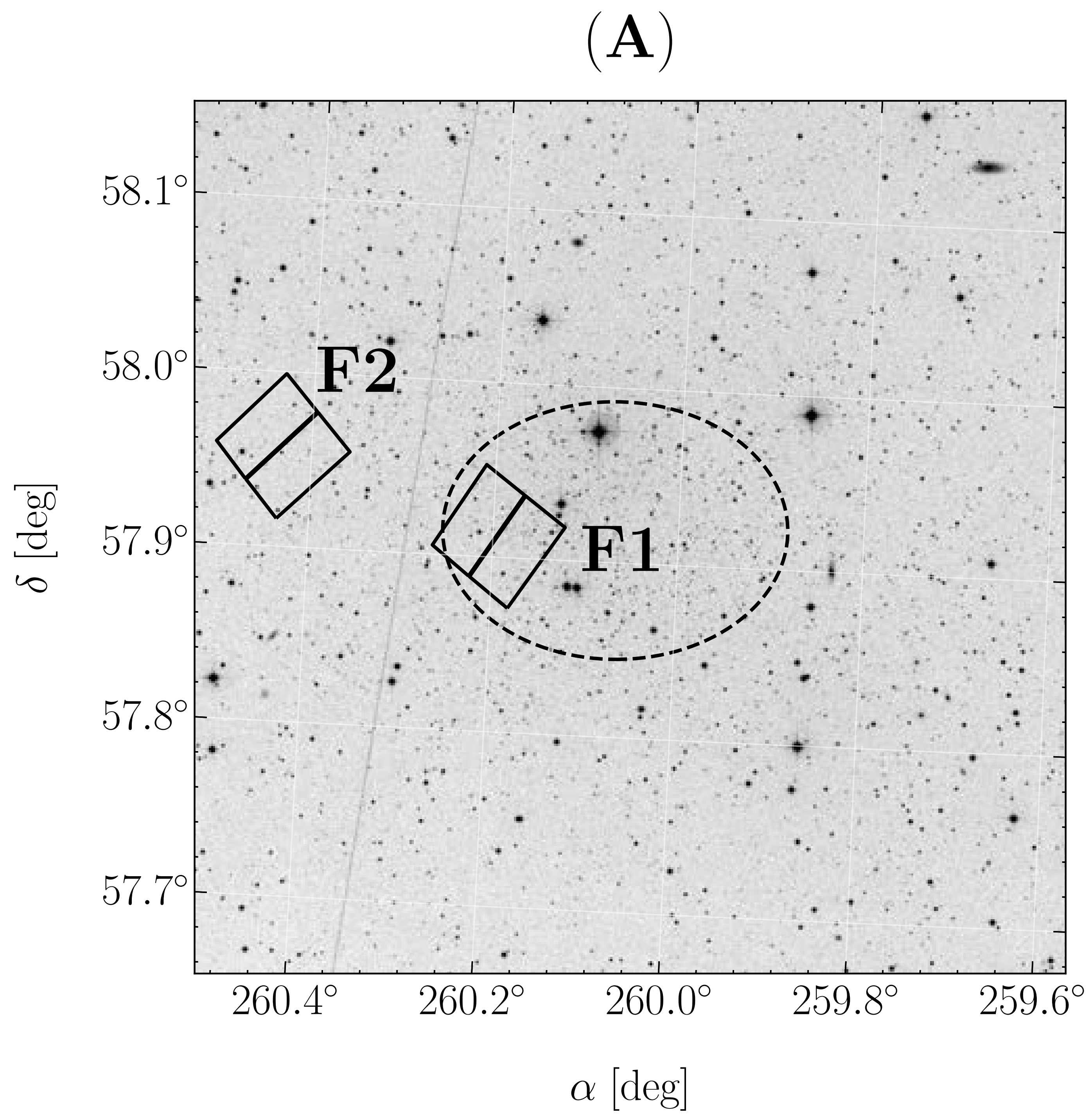
Measuring proper motions

HST observations: Galactic timescales



Sangmo Tony Sohn / Titanic Movie (1997)

Data



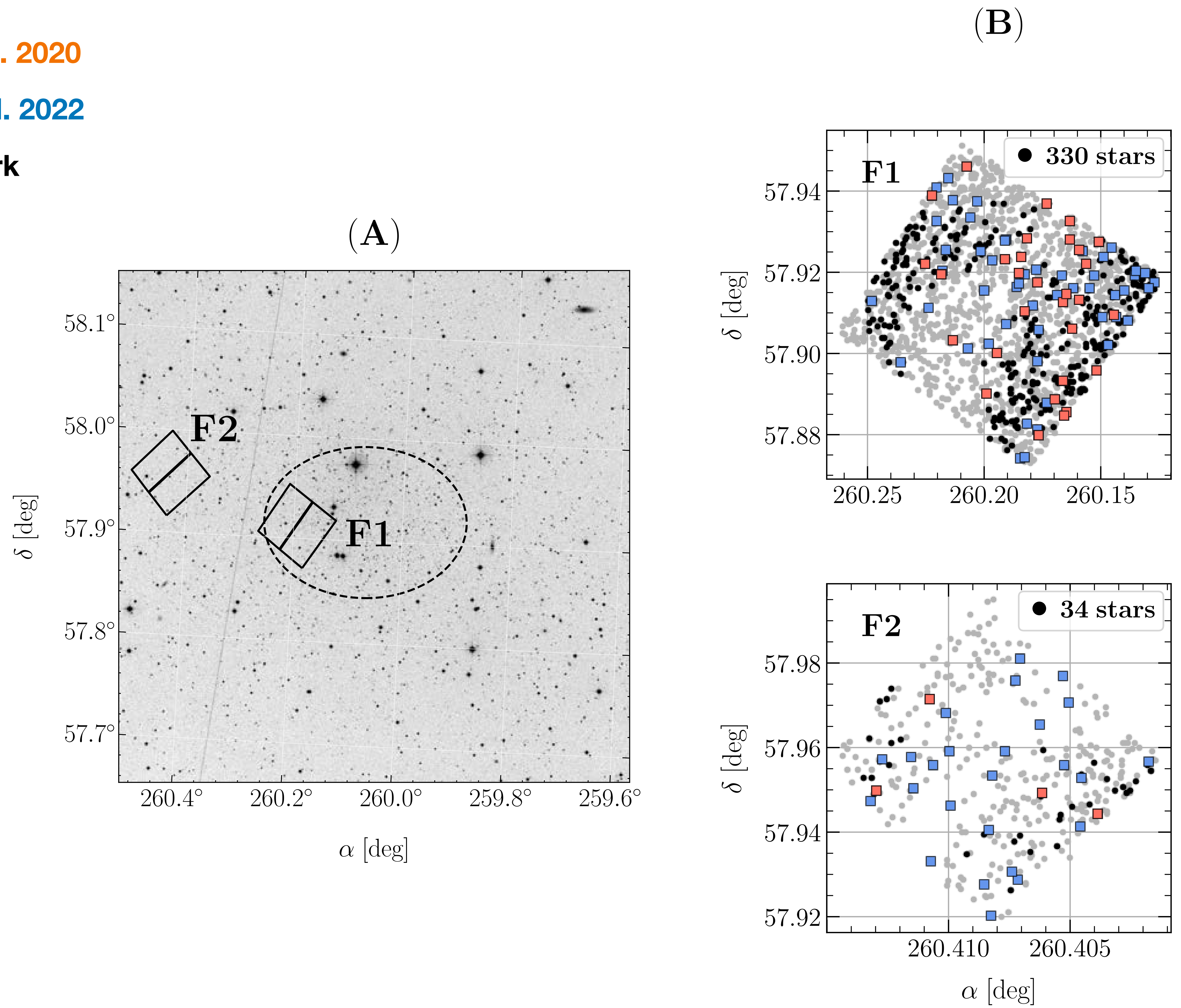
Vitral et al. 2024

Data

Massari et al. 2020

Del Pino et al. 2022

This work



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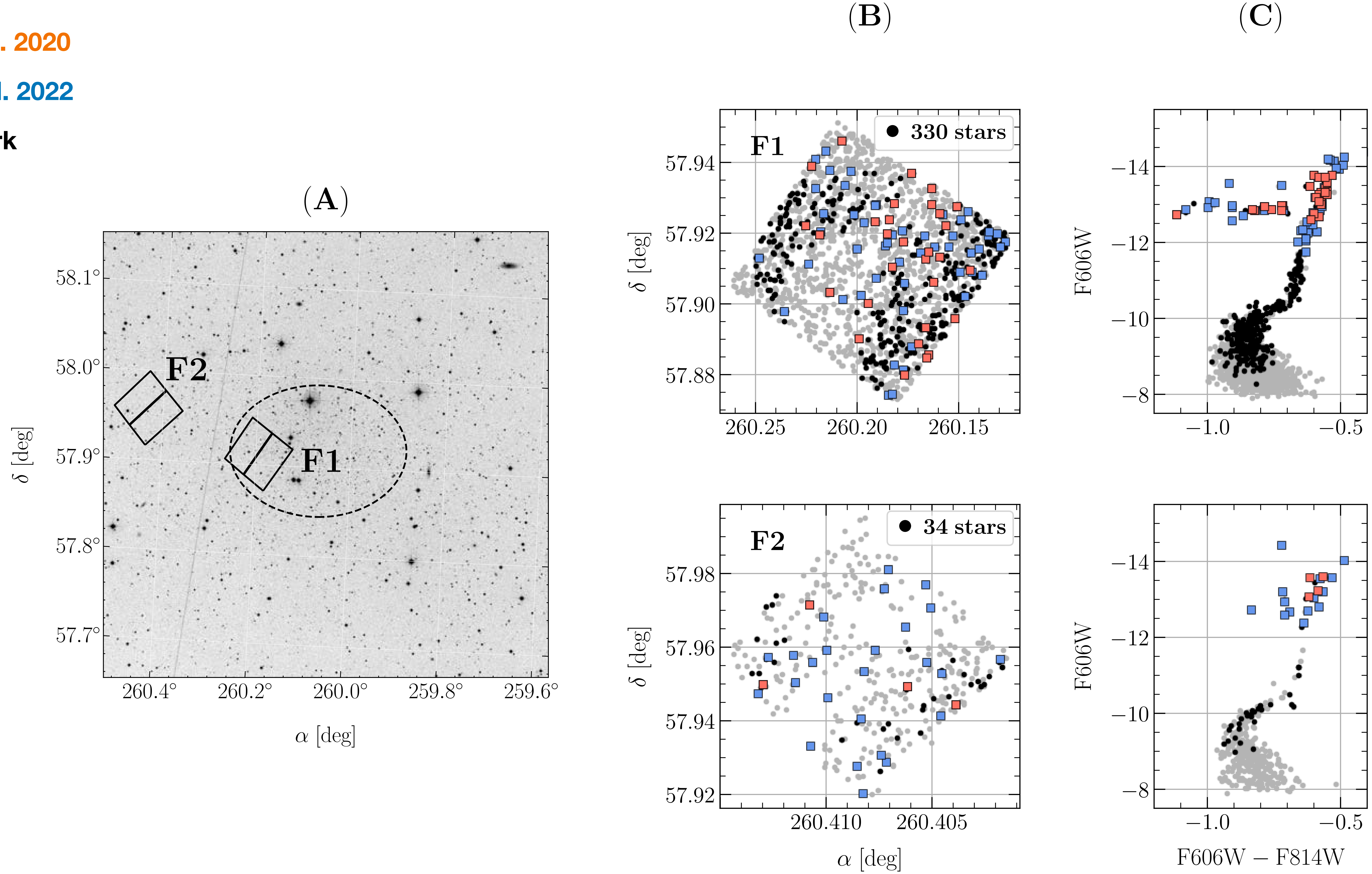

Vitral et al. 2024

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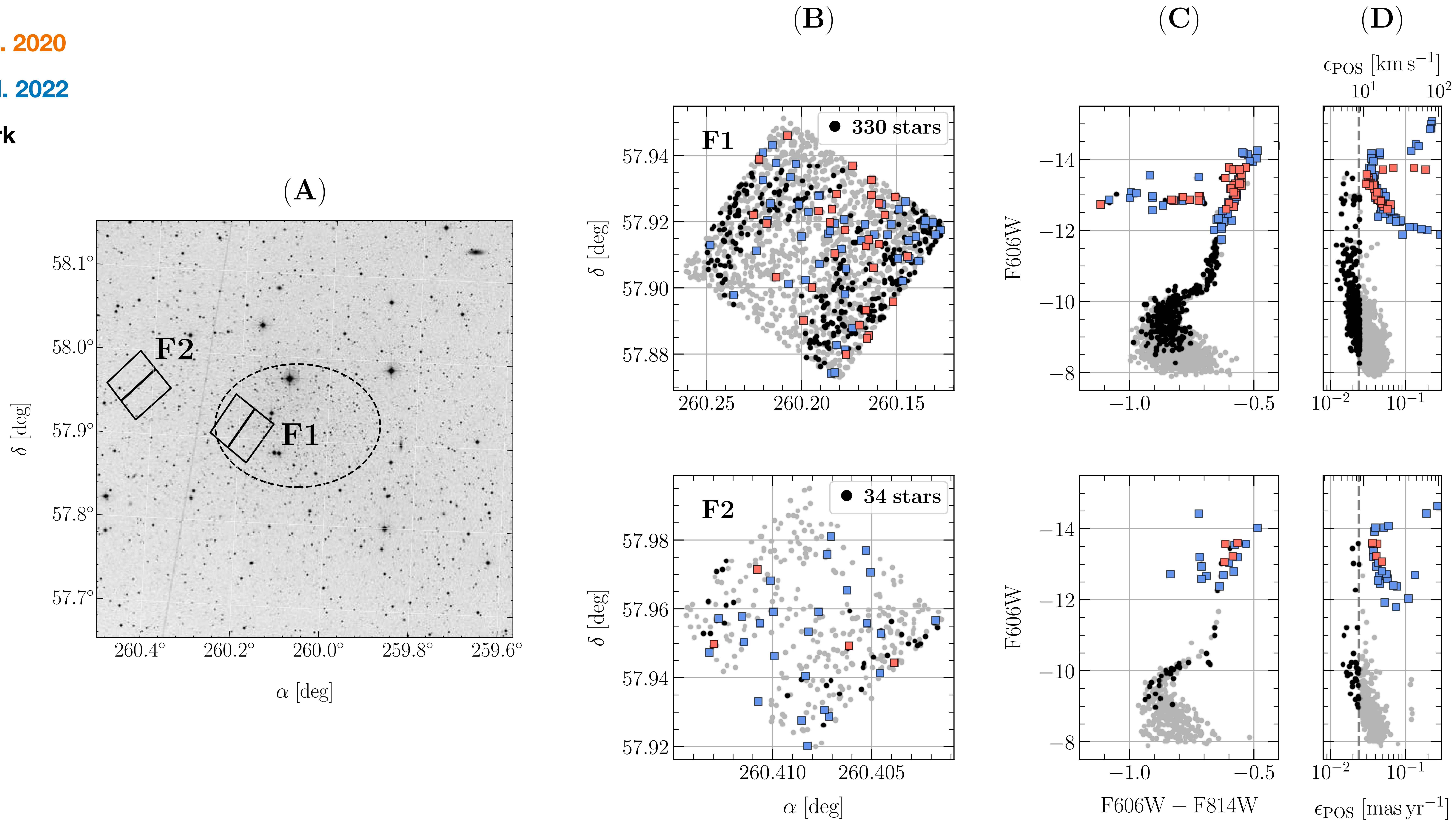
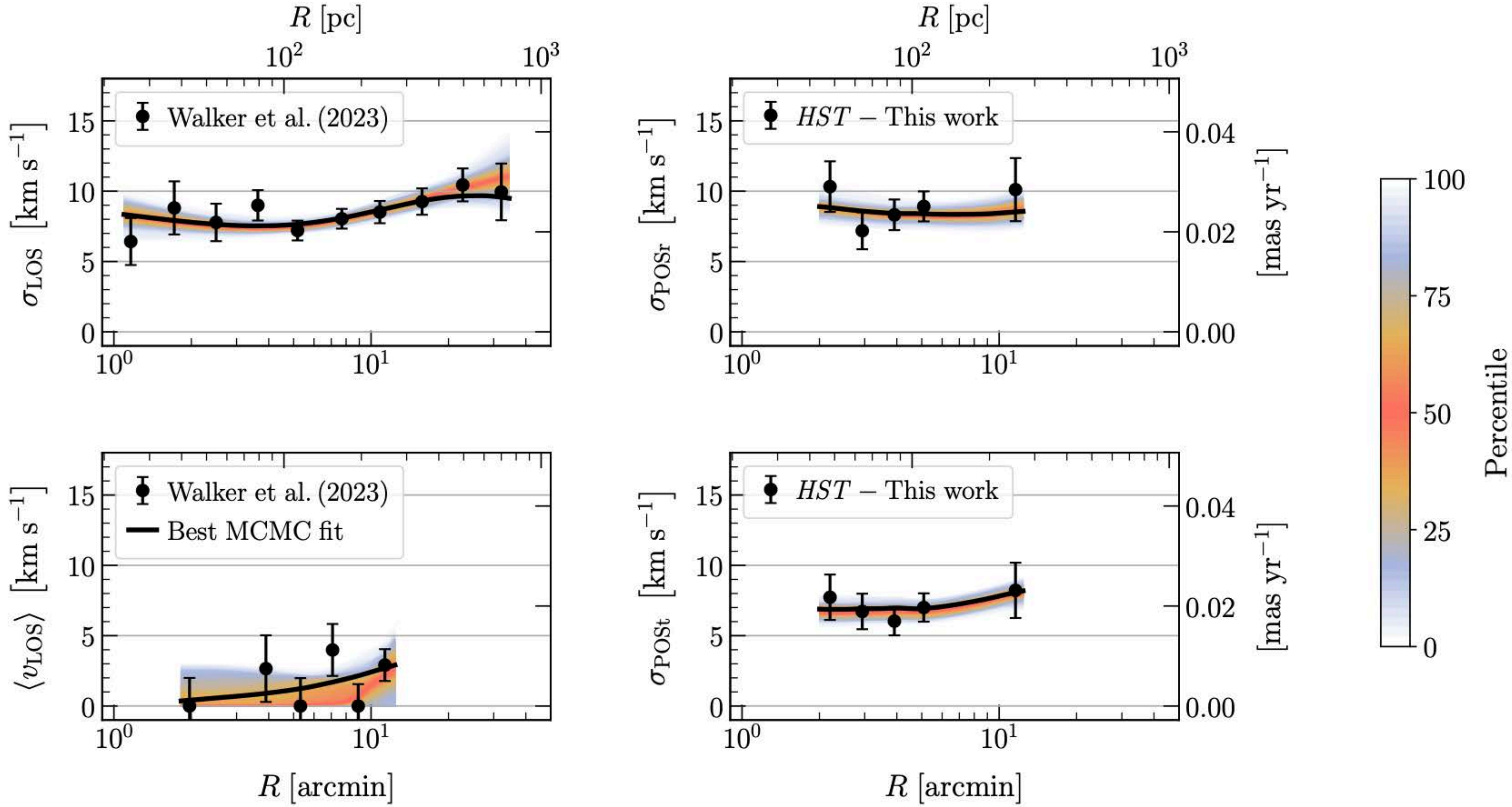


Vitral et al. 2024

Results

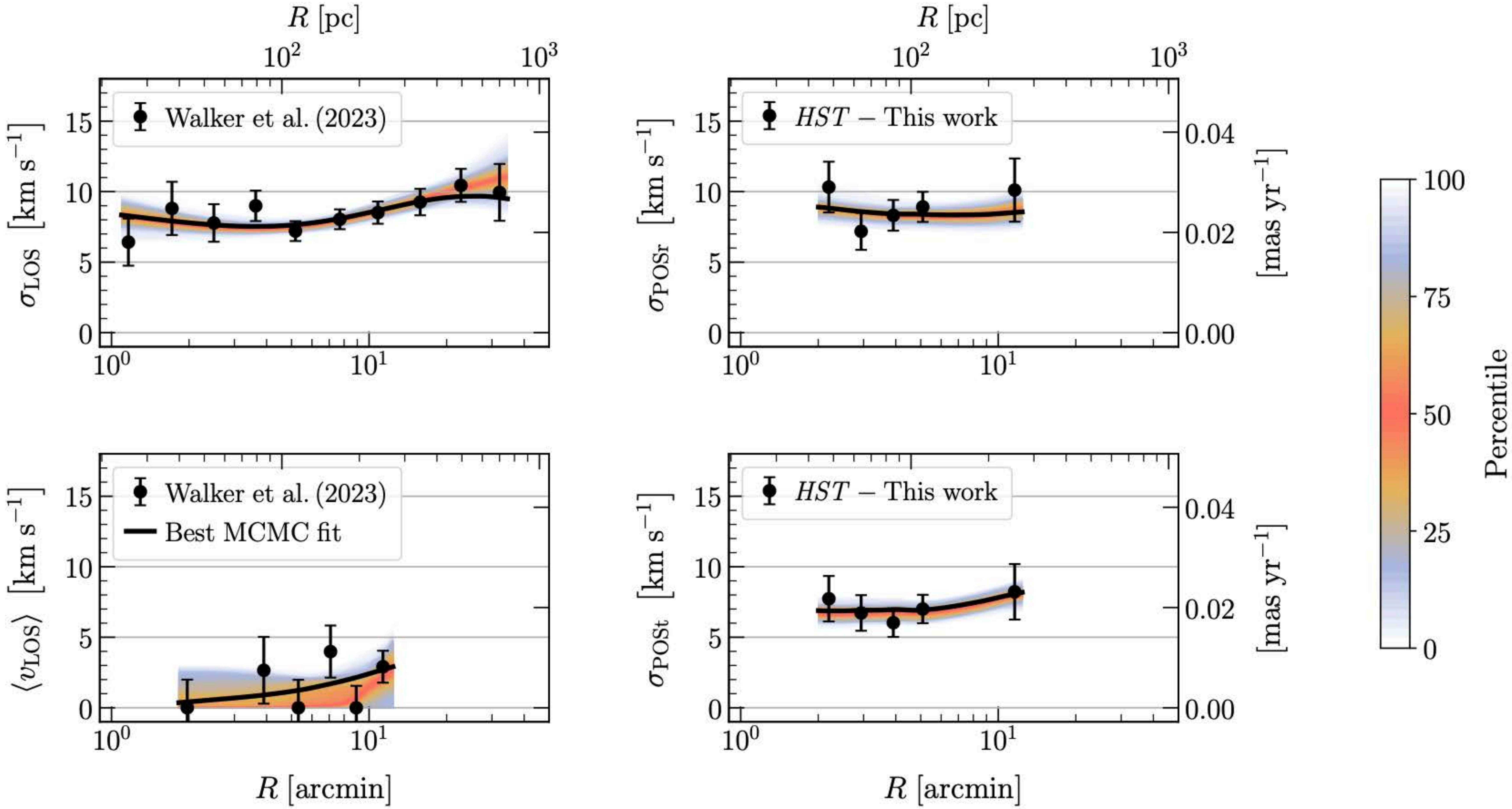


Vitral et al. 2024

Results

Line-of-sight velocity dispersion

Line-of-sight Rotation



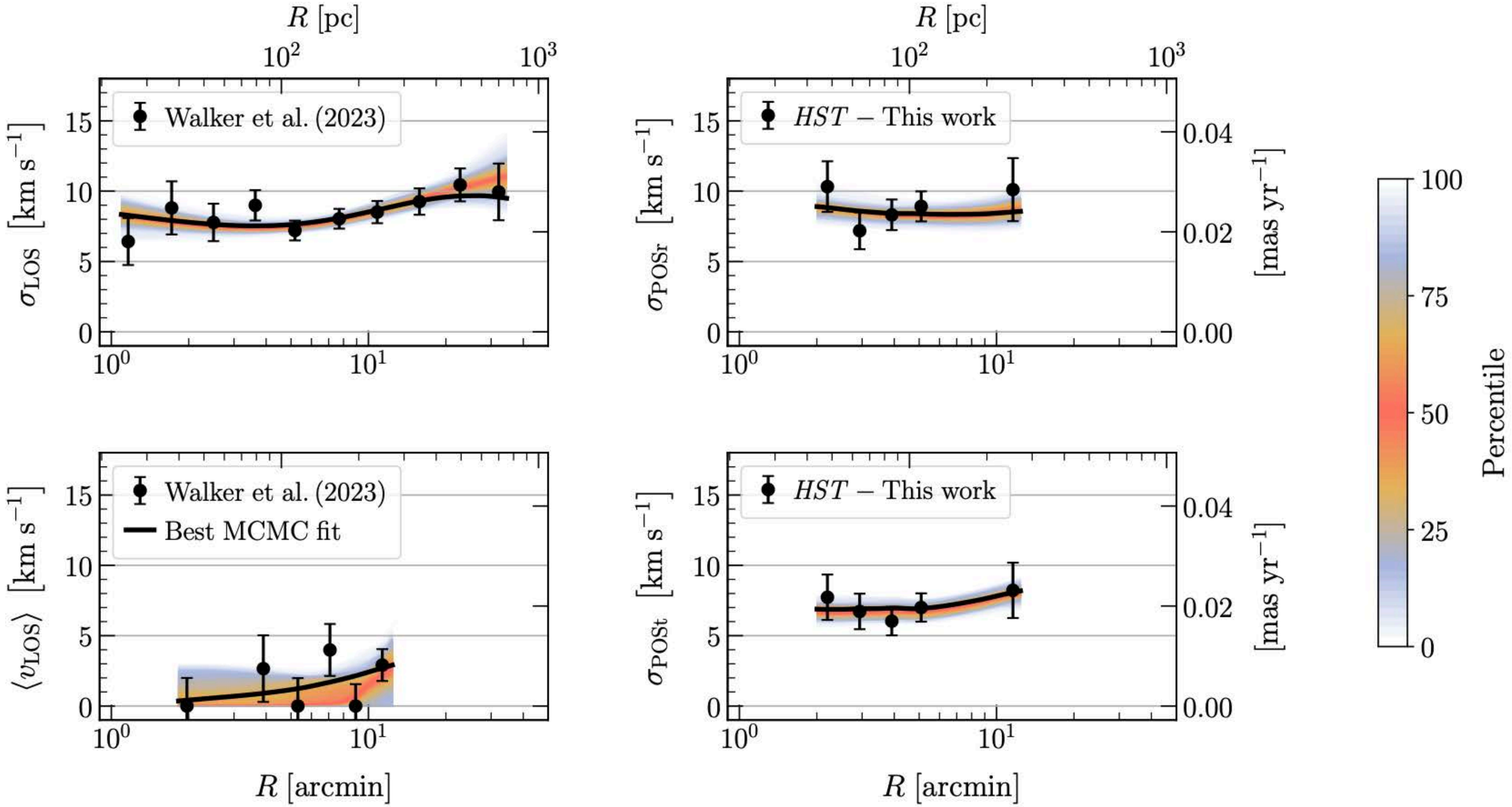
Vitral et al. 2024

Results

Proper motion dispersion profiles

Line-of-sight velocity dispersion

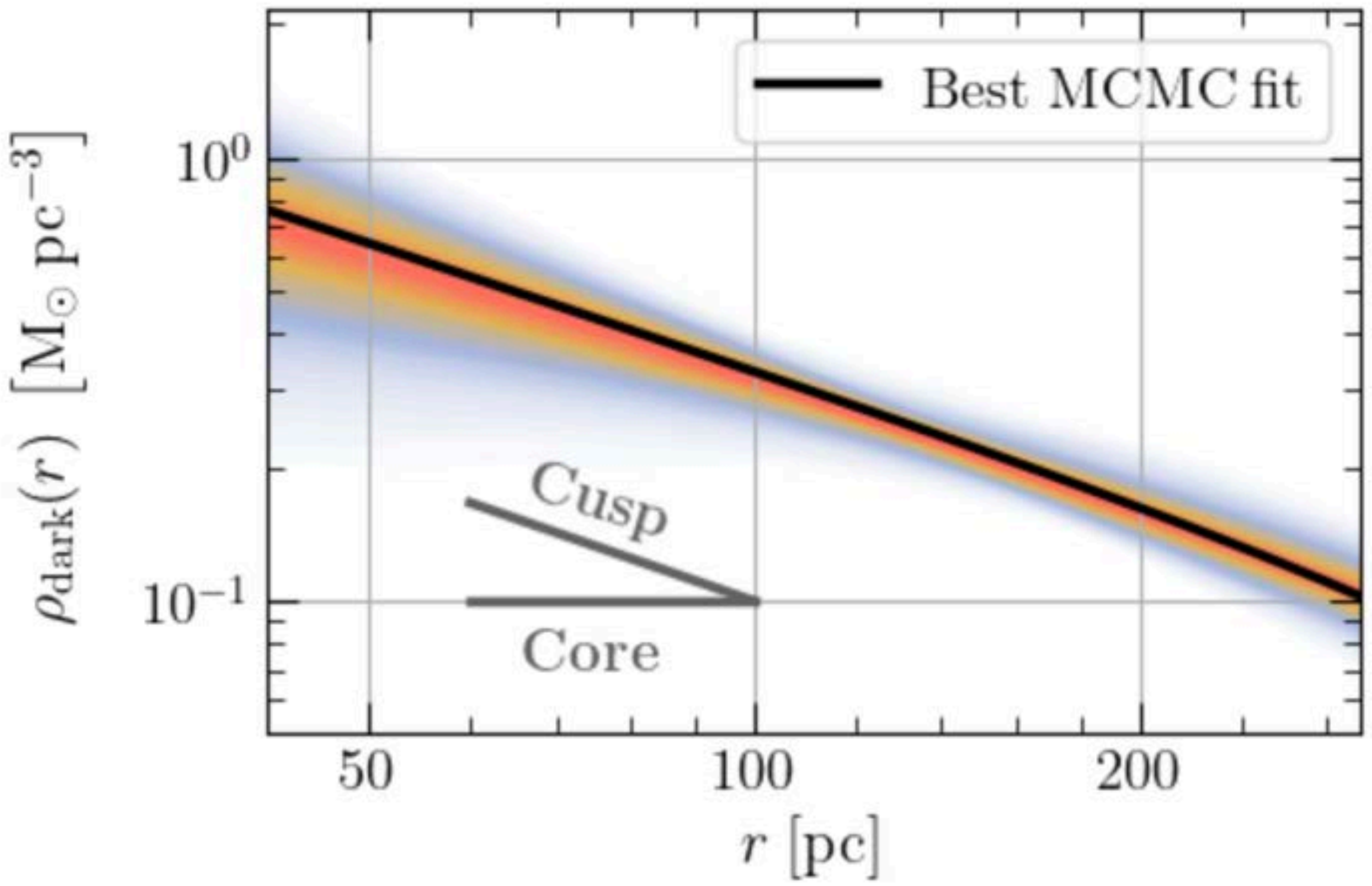
Line-of-sight Rotation



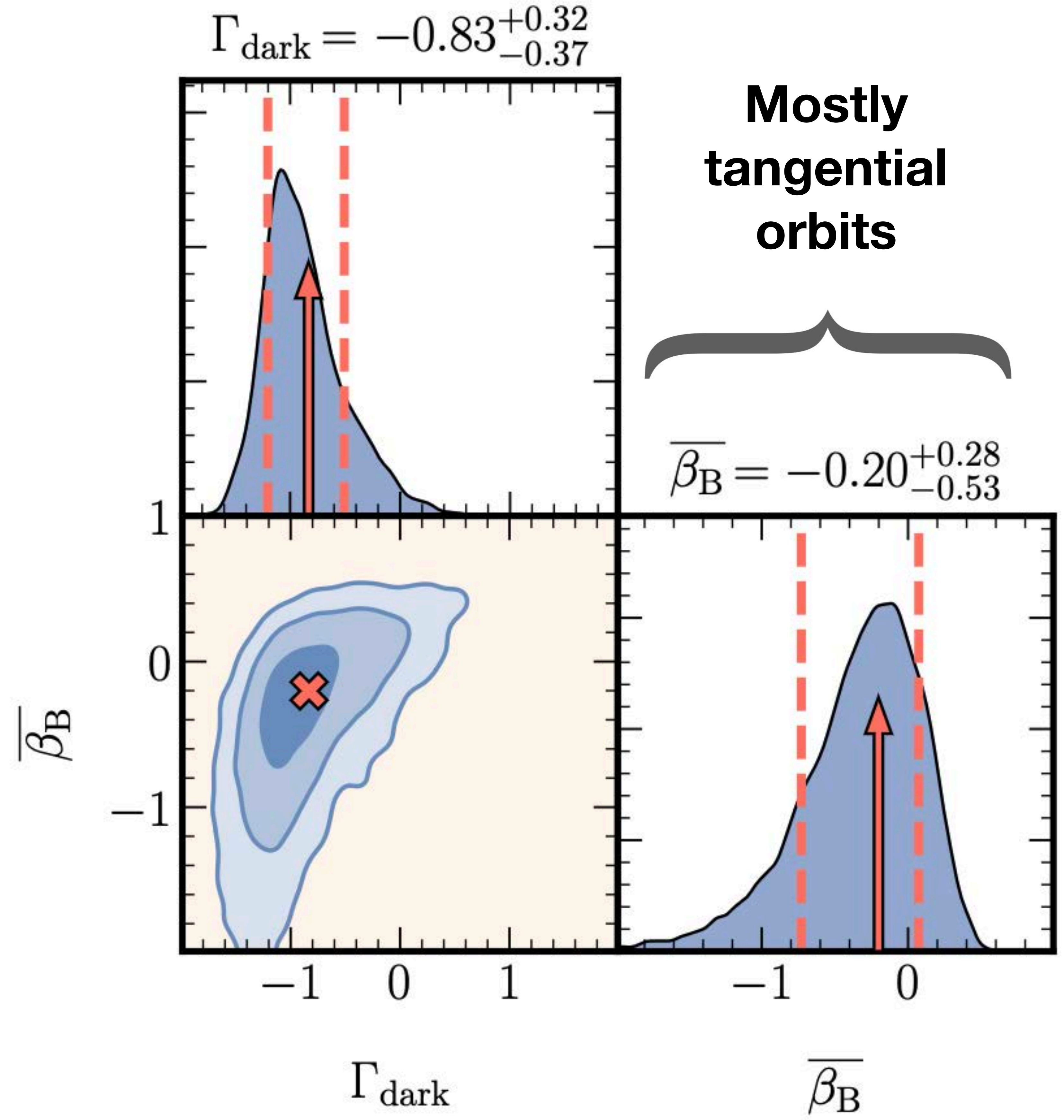
Vitral et al. 2024

Results

$$\Gamma_{\rm dark} \equiv \frac{\int_{r_{\rm min}}^{r_{\rm max}} \frac{{\rm d}\log\rho}{{\rm d}\log r}\,\rho(r)\,{\rm d}r}{\int_{r_{\rm min}}^{r_{\rm max}} \rho(r)\,{\rm d}r}$$



Agreement with ΛCDM



Mostly tangential orbits

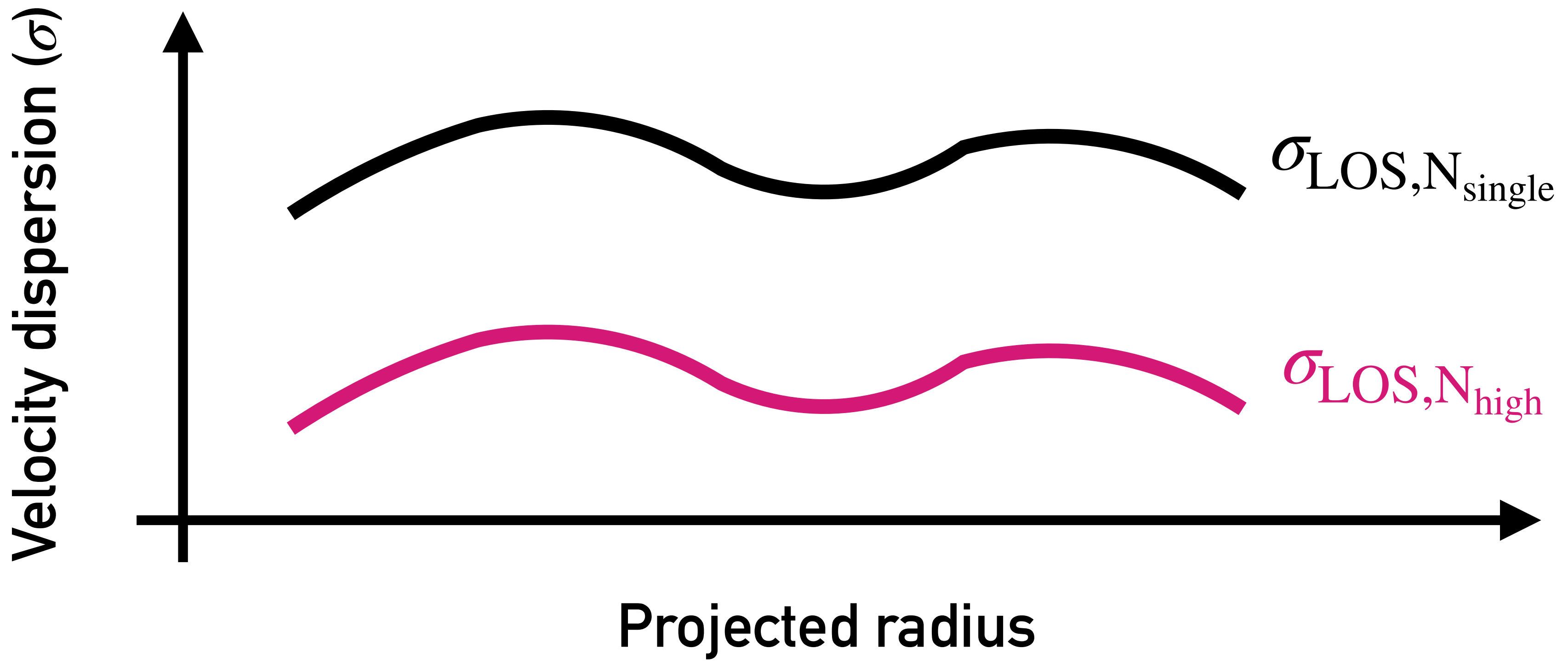
Vitral et al. 2024

Effect of binaries (case of Draco)

Tests with line-of-sight data

If binaries inflate the line-of-sight dispersion profile

$\sigma_{\mathrm{LOS,N_{high}}} \ll \sigma_{\mathrm{LOS,N_{single}}}$



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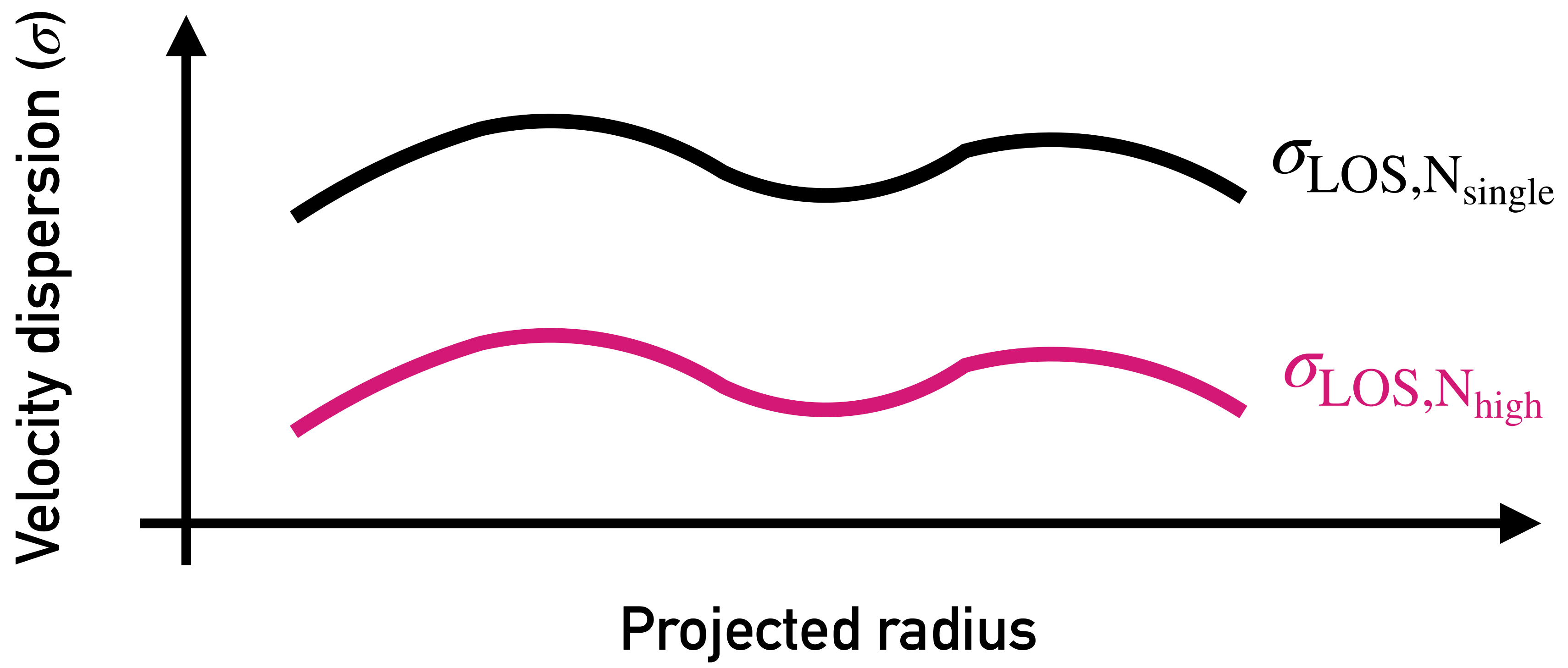
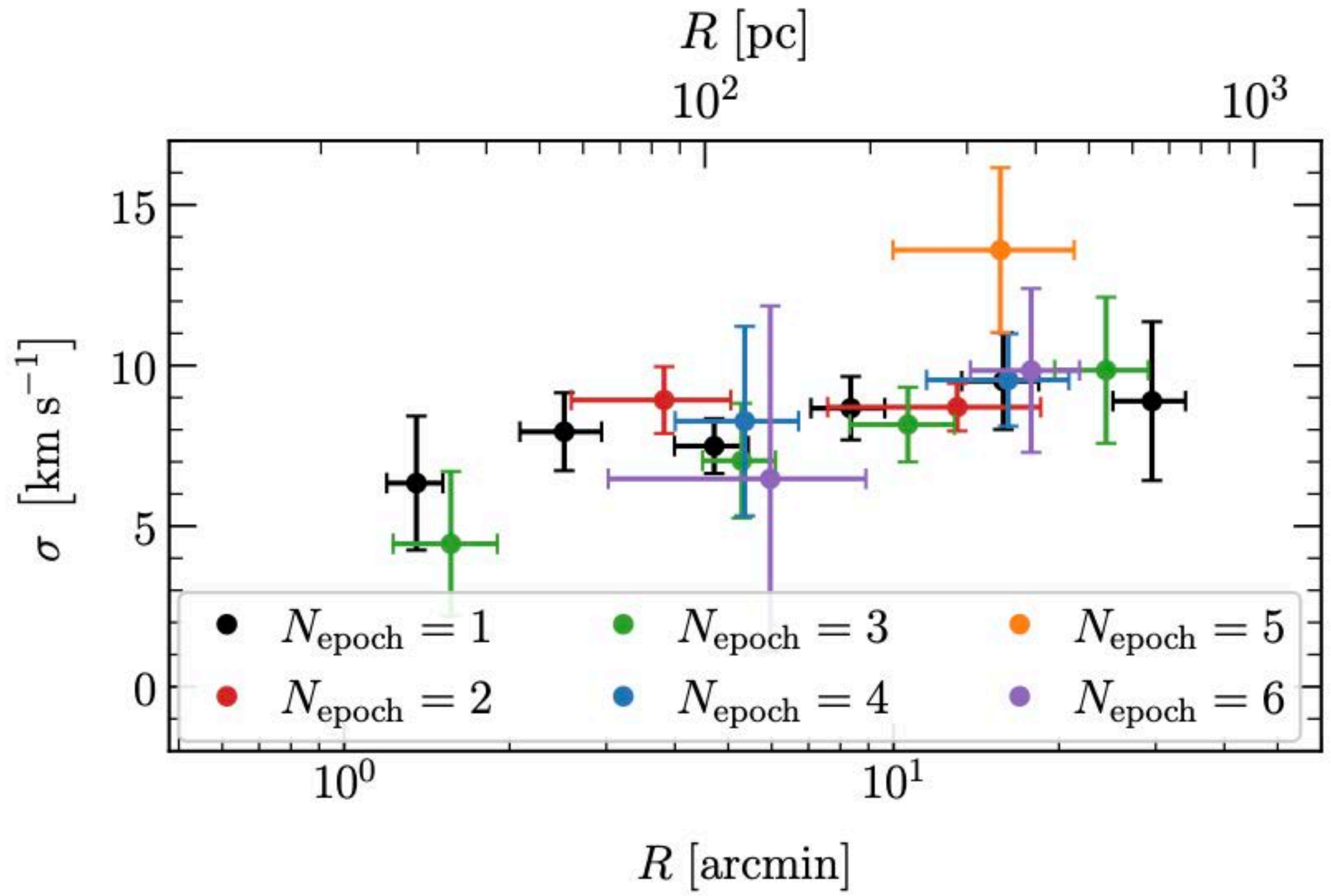


Not the case…



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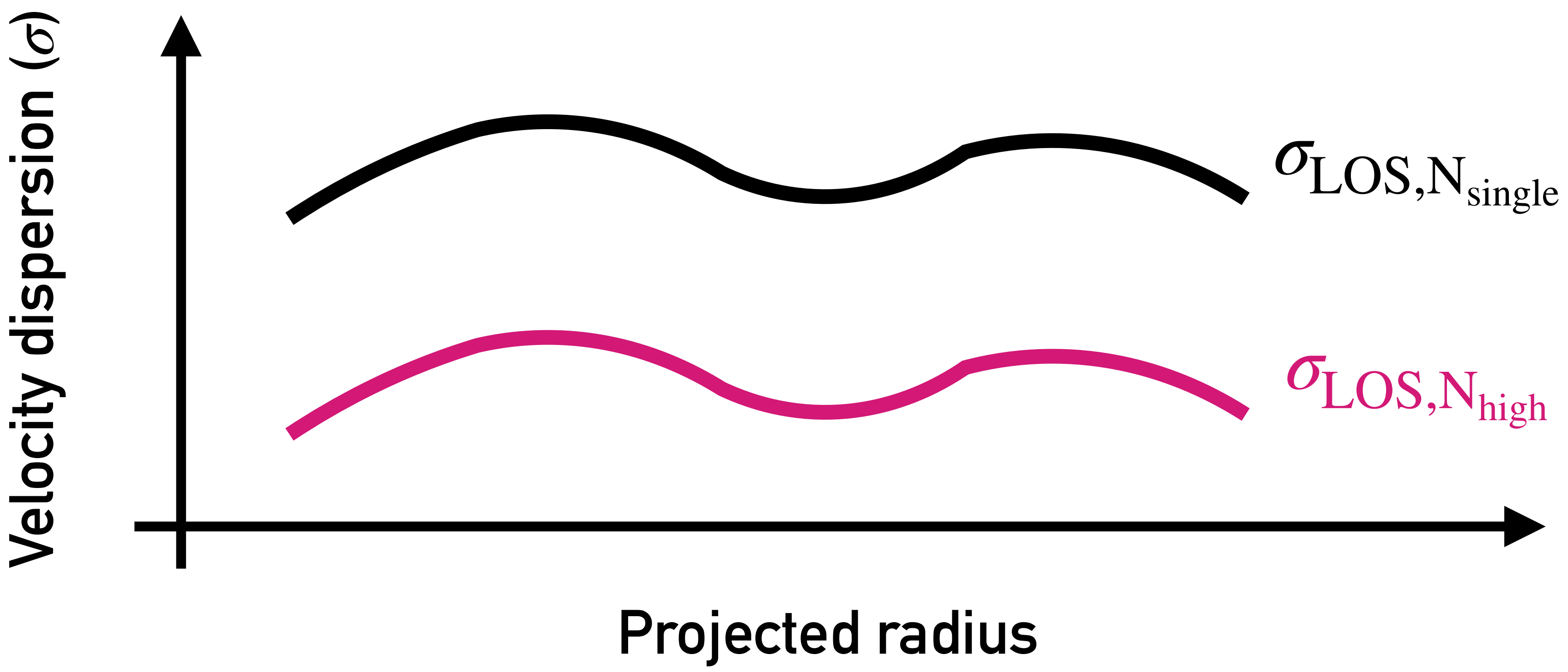
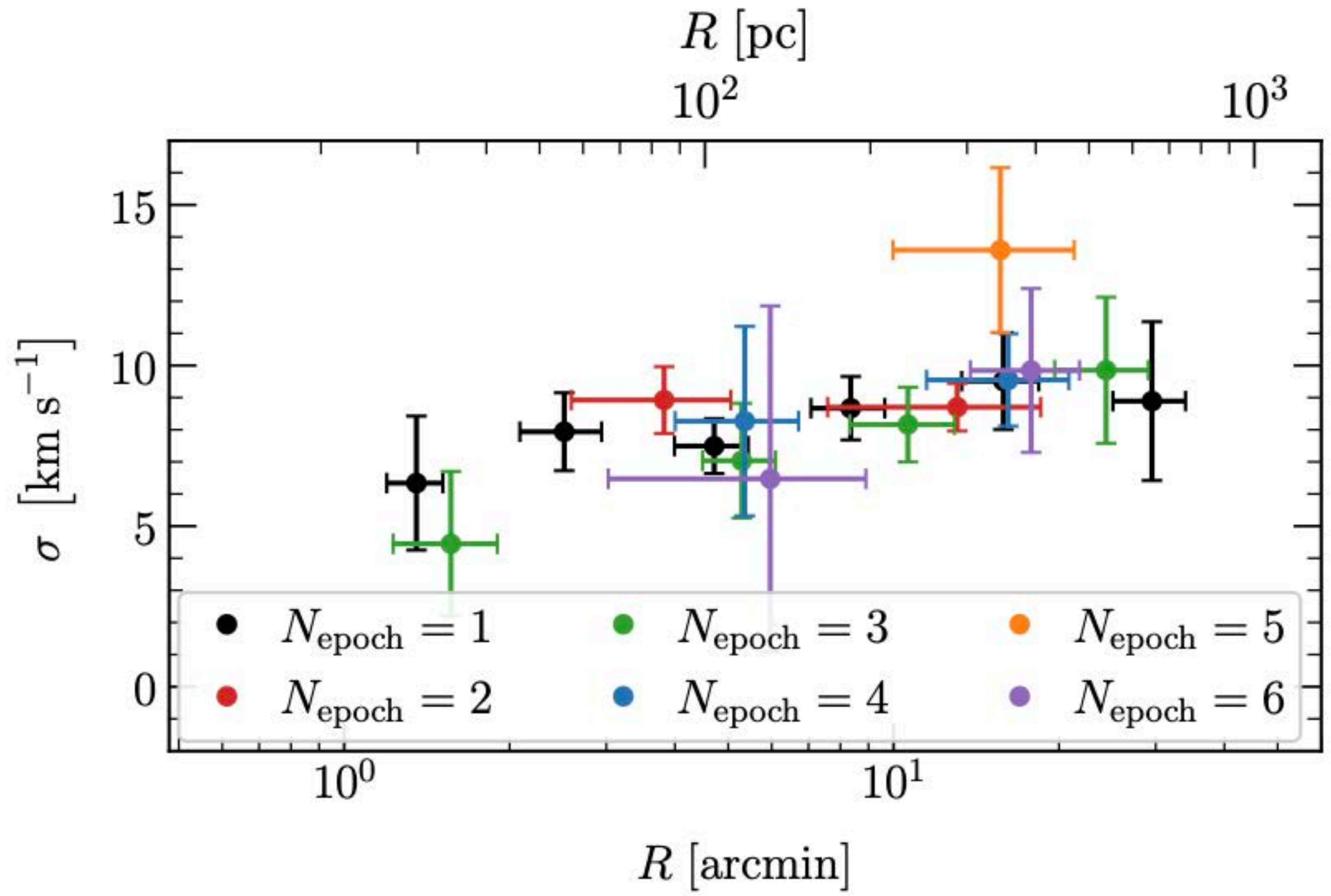
If binaries inflate the line-of-sight dispersion profile

$\sigma_{\mathrm{LOS,N_{high}}} \ll \sigma_{\mathrm{LOS,N_{single}}}$



Not the case...



Tests with proper motion data

1σ agreement between PM only and 3D mass modeling fits.

Comparison with other telescopes

Comparison between telescopes

***Disclaimer: numbers are approximative and depend on multiple factors (magnitude, exposure time, analyzed source, etc)**

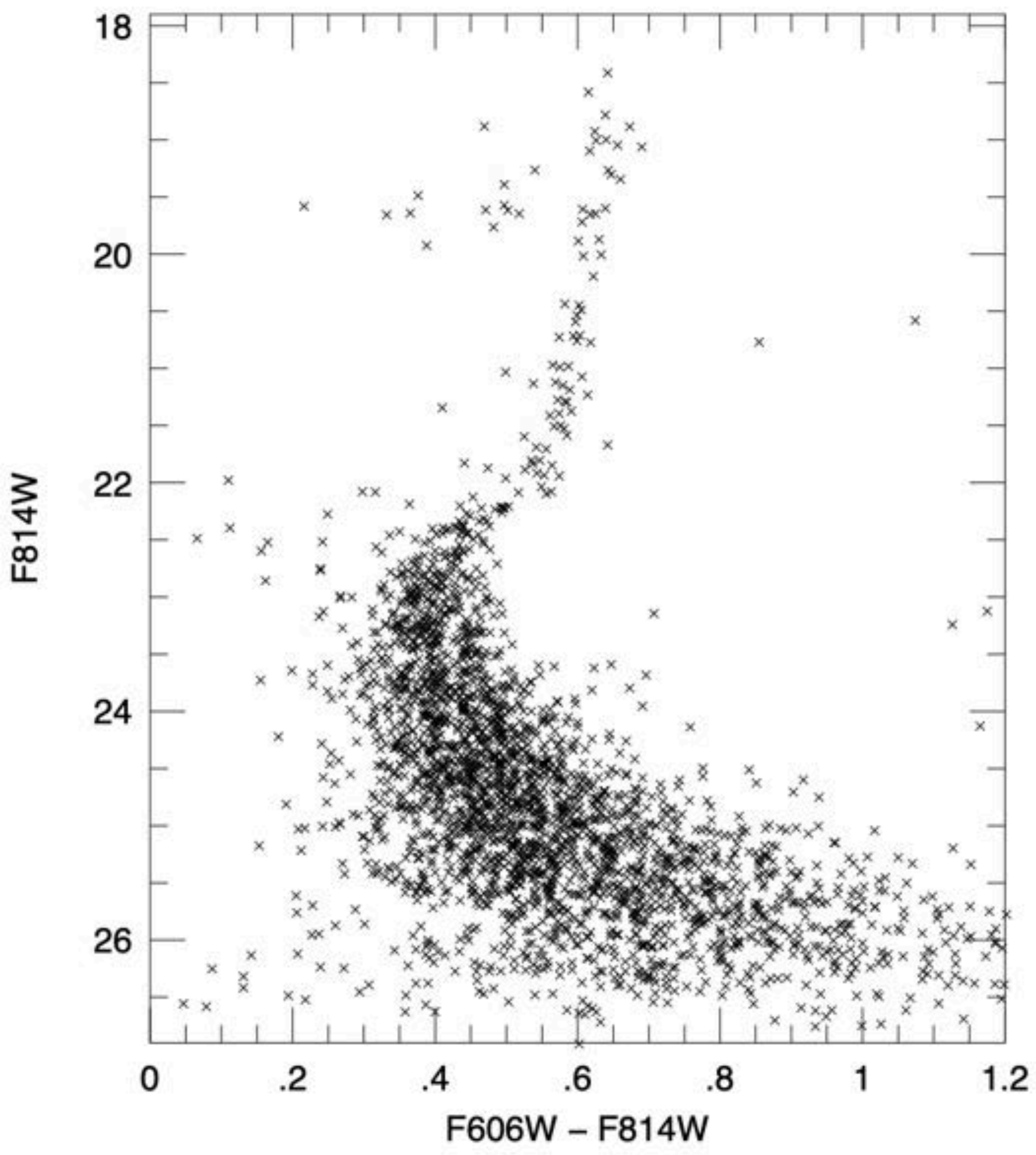
	Magnitude limit	**Field of view**	**PM precision (end of mission or 20 yr baseline)**	**Number of stars with PM errors < 0.02 mas/yr (Per field/galaxy)**
HST	~ 28	~ 3’ x 3’	~ 0.01 mas/yr	O(10^2)
JWST	~ 30	~ 2’ x 2’	~ 0.01 mas/yr	O(10^2)
Gaia	~ 21	All-sky	~ 0.1 mas/yr	O(0)
Euclid	~ 26	~ 45’ x 45’	~ 0.03 mas/yr	O(0)
Roman	~ 28	~ 40’ x 25’	~ 0.05 mas/yr	O(0)
Theia	~ 22	~ 30’ x 30’	~ 0.01 mas/yr	O(10^3)
HWO	~ 30	~ 3’ x 3’	~ 0.003 mas/yr	O(10^4)

Comparison between telescopes

*Disclaimer: numbers are approximative and depend on multiple factors (magnitude, exposure time, analyzed source, etc)

	Magnitude limit
HST	~ 28
JWST	~ 30
Gaia	~ 21
Euclid	~ 26
Roman	~ 28
Theia	~ 22
HWO	~ 30

Draco's CMD (Grillmair+98)

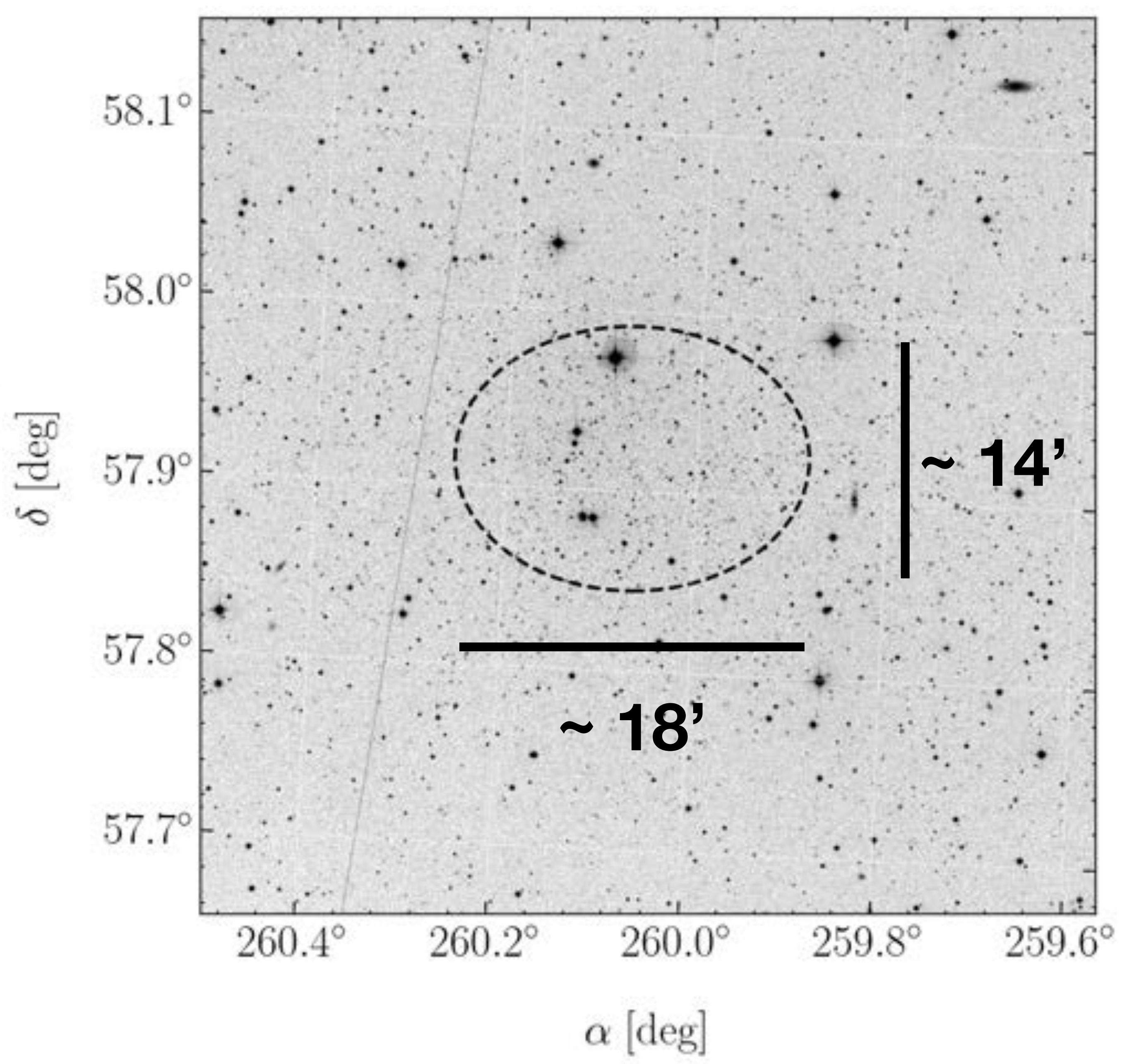


Comparison between telescopes

***Disclaimer: numbers are approximative and depend on multiple factors (magnitude, exposure time, analyzed source, etc)**

	Magnitude limit	Field of view
HST	~ 28	~ 3’ x 3’
JWST	~ 30	~ 2’ x 2’
Gaia	~ 21	All-sky
Euclid	~ 26	~ 45’ x 45’
Roman	~ 28	~ 40’ x 25’
Theia	~ 22	~ 30’ x 30’
HWO	~ 30	~ 3’ x 3’

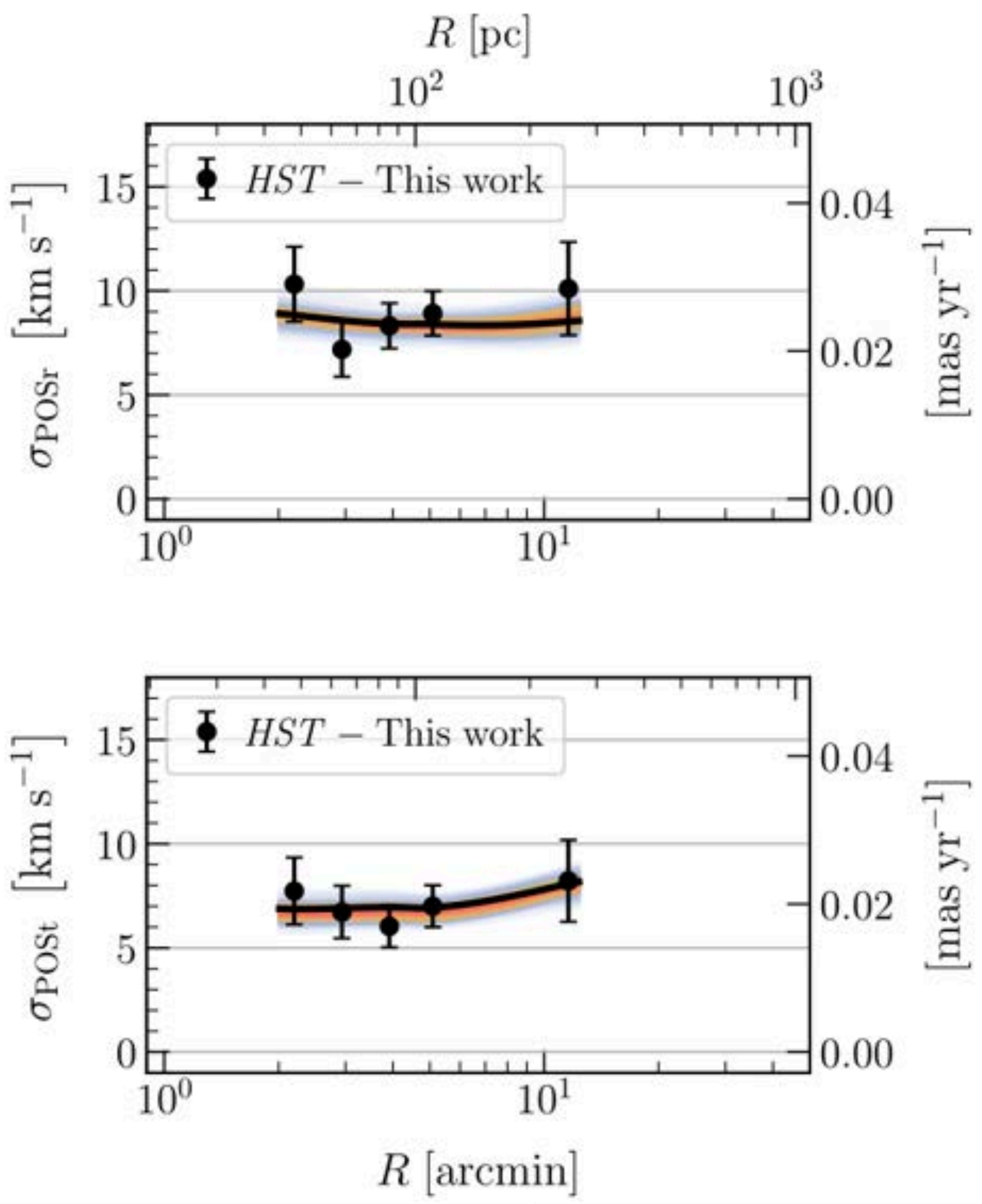
Draco’s FOV (Vitral+24)



Comparison between telescopes

*Disclaimer: numbers are approximative and depend on multiple factors (magnitude, exposure time, analyzed source, etc)

Draco's PM dispersion profile (Vitral+24)

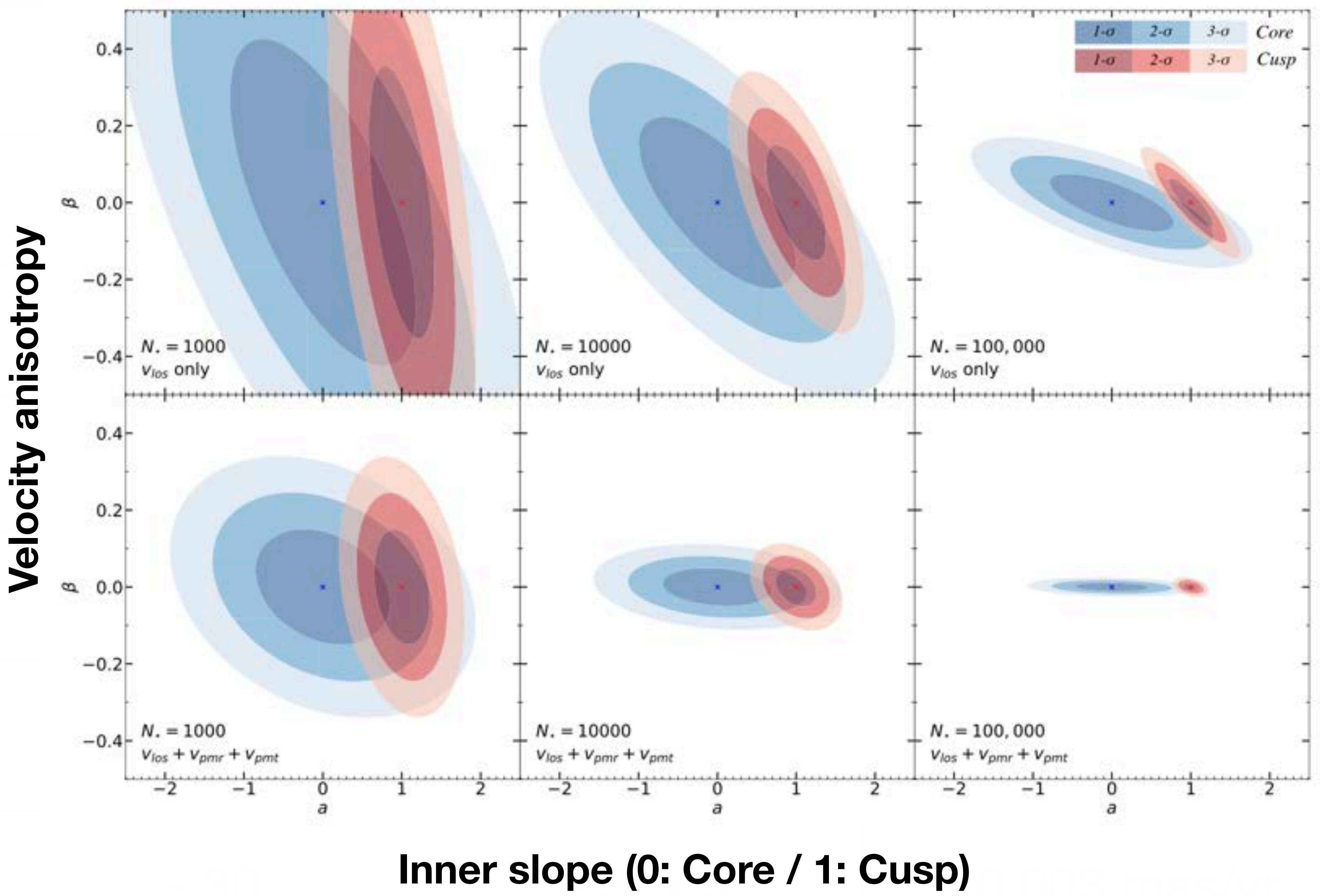


	Magnitude limit	Field of view	PM precision (end of mission or 20 yr baseline)	Number of stars with PM errors < 0.02 mas/yr (Per field/galaxy)
HST			~ 0.01 mas/yr	O(10^2)
JWST			~ 0.01 mas/yr	O(10^2)
Gaia			~ 0.1 mas/yr	O(0)
Euclid			~ 0.03 mas/yr	O(0)
Roman			~ 0.05 mas/yr	O(0)
Theia			~ 0.01 mas/yr	O(10^3)
HWO			~ 0.003 mas/yr	O(10^4)

Comparison between telescopes

***Disclaimer: numbers are approximative and depend on multiple factors (magnitude, exposure time, analyzed source, etc)**

Confidence intervals from Jeans modeling (Guerra+23)



	Number of stars with PM errors < 0.02 mas/yr (Per field/galaxy)
HST	O(10^2)
JWST	O(10^2)
Gaia	O(0)
Euclid	O(0)
Roman	O(0)
Theia	O(10^3)
HWO	O(10^4)

Comparison between telescopes

*Disclaimer: numbers are approximative and depend on multiple factors (magnitude, exposure time, analyzed source, etc)

	Magnitude limit	Field of view	PM precision (end of mission or 20 yr baseline)	Number of stars with PM errors < 0.02 mas/yr (Per field/galaxy)
HST	~ 28	~ 3’ x 3’	~ 0.01 mas/yr	O(10^2)
JWST	~ 30	~ 2’ x 2’	~ 0.01 mas/yr	O(10^2)
Gaia	~ 21	All-sky	~ 0.1 mas/yr	O(0)
Euclid	~ 26	~ 45’ x 45’	~ 0.03 mas/yr	[illegible]
Roman	~ 28	~ 40’ x 25’	~ 0.05 ma	
Theia	~ 22	~ 30’ x 30’	~ 0.01 m	
HWO	~ 30	~ 3’ x 3’	~ 0.003 mas/yr	

- Fields limited by existing observations.
- New funding cuts from NASA
- Increasing systematics with time

ESA/NASA, Edited

Comparison between telescopes

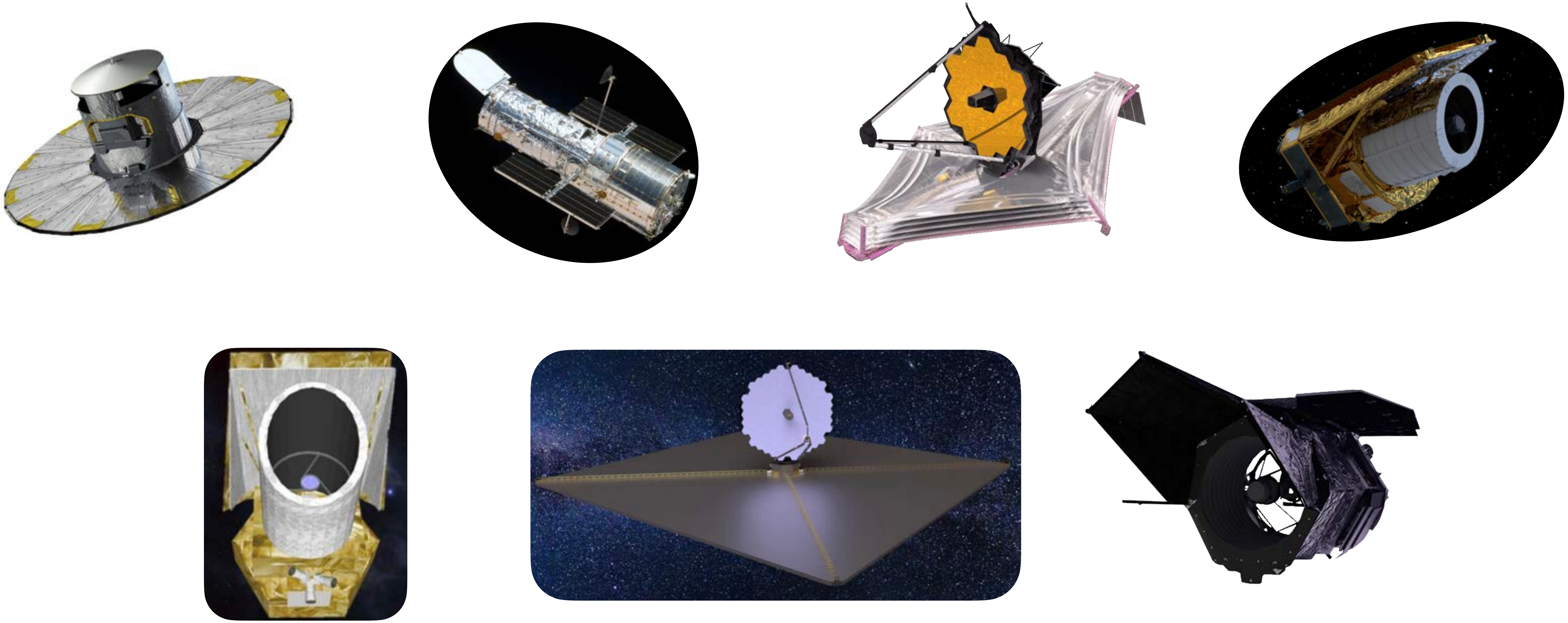
*Disclaimer: numbers are approximative and depend on multiple factors (magnitude, exposure time, analyzed source, etc)

	Magnitude limit	**Field of view**	**PM precision (end of mission or 20 yr baseline)**	**Number of stars with PM errors < 0.02 mas/yr (Per field/galaxy)**	
HST	~ 28	~ 3’ x 3’	~ 0.01 mas/yr	$O(10^2)$	**Currently available**
JWST	~ 30	~ 2’ x 2’	~ 0.01 mas/yr	$O(10^2)$	**20 yr wait**
Gaia	~ 21	All-sky	~ 0.1 mas/yr	O(0)	**-**
Euclid	~ 26	~ 45’ x 45’	~ 0.03 mas/yr	O(0)	**-**
Roman	~ 28	~ 40’ x 25’	~ 0.05 mas/yr	O(0)	**-**
Theia	~ 22	~ 30’ x 30’	~ 0.01 mas/yr	$O(10^3)$	**>10 yr wait (If approved)**
HWO	~ 30	~ 3’ x 3’	~ 0.003 mas/yr	$O(10^4)$	**>50 yr wait**

What is the best telescope for dwarf galaxies' kinematics?

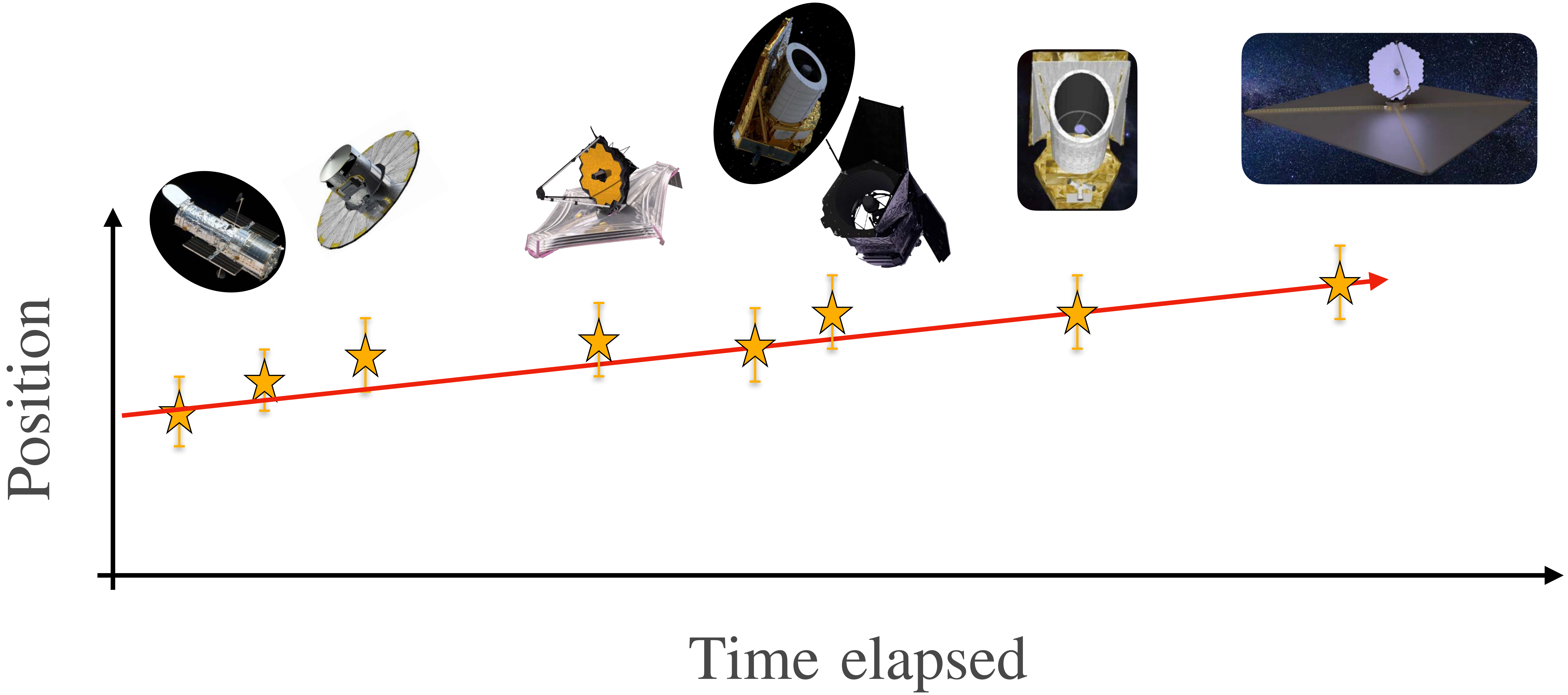
Combining different telescopes

All of them!

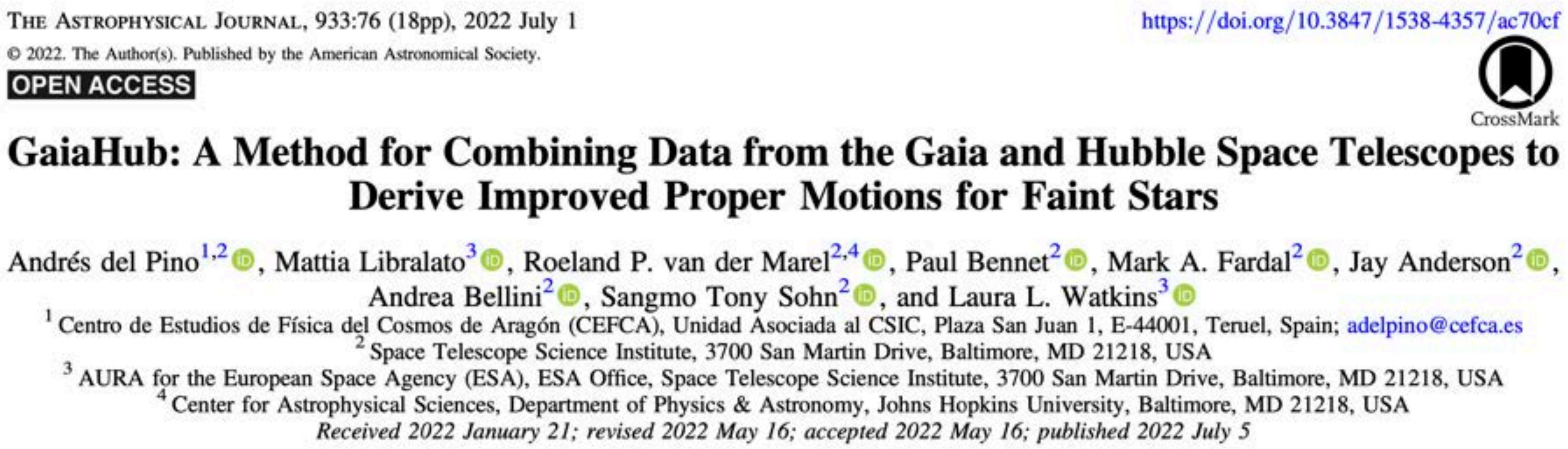


Combining different telescopes

All of them!



Combining different telescopes



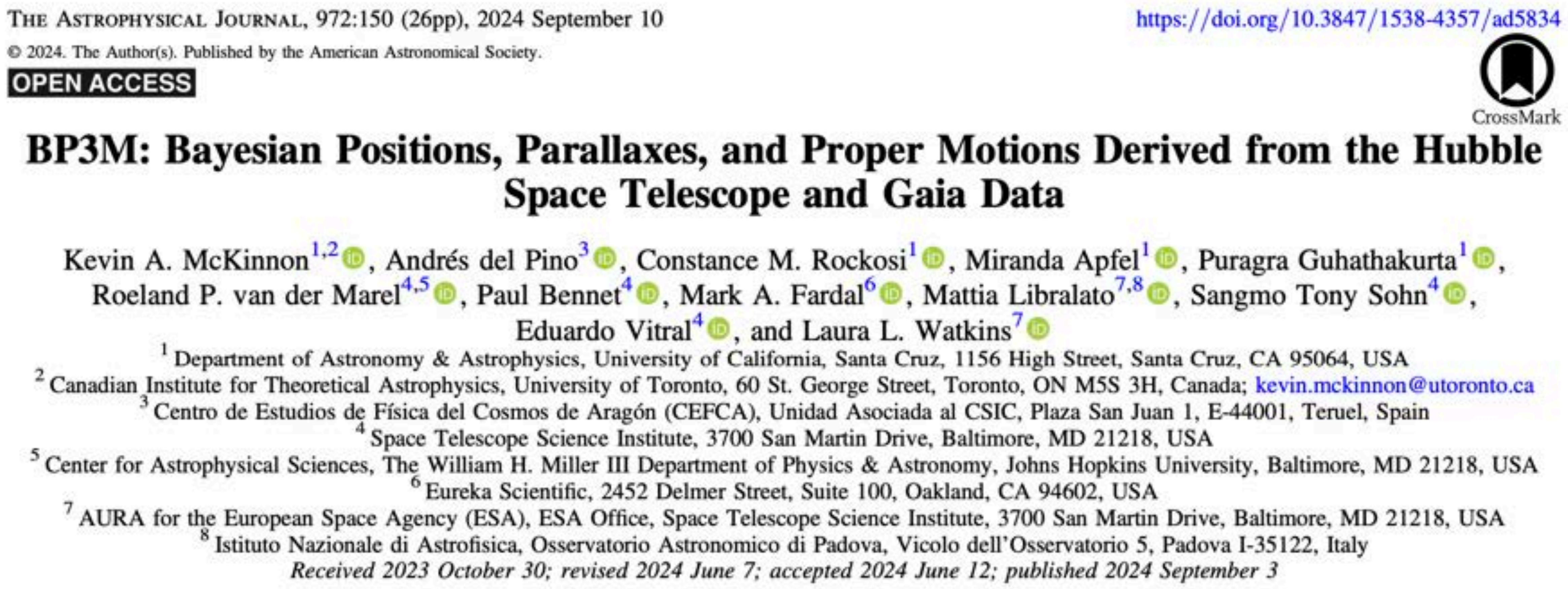
The Astrophysical Journal, 933:76 (18pp), 2022 July 1 https://doi.org/10.3847/1538-4357/ac70cf

GaiaHub: A Method for Combining Data from the Gaia and Hubble Space Telescopes to Derive Improved Proper Motions for Faint Stars

Andrés del Pino[1,2], Mattia Libralato[3], Roeland P. van der Marel[2,4], Paul Bennet[2], Mark A. Fardal[2], Jay Anderson[2], Andrea Bellini[2], Sangmo Tony Sohn[2], and Laura L. Watkins[3]

[1] Centro de Estudios de Física del Cosmos de Aragón (CEFCA), Unidad Asociada al CSIC, Plaza San Juan 1, E-44001, Teruel, Spain; adelpino@cefca.es
[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[3] AURA for the European Space Agency (ESA), ESA Office, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[4] Center for Astrophysical Sciences, Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

Received 2022 January 21; revised 2022 May 16; accepted 2022 May 16; published 2022 July 5



The Astrophysical Journal, 972:150 (26pp), 2024 September 10 https://doi.org/10.3847/1538-4357/ad5834

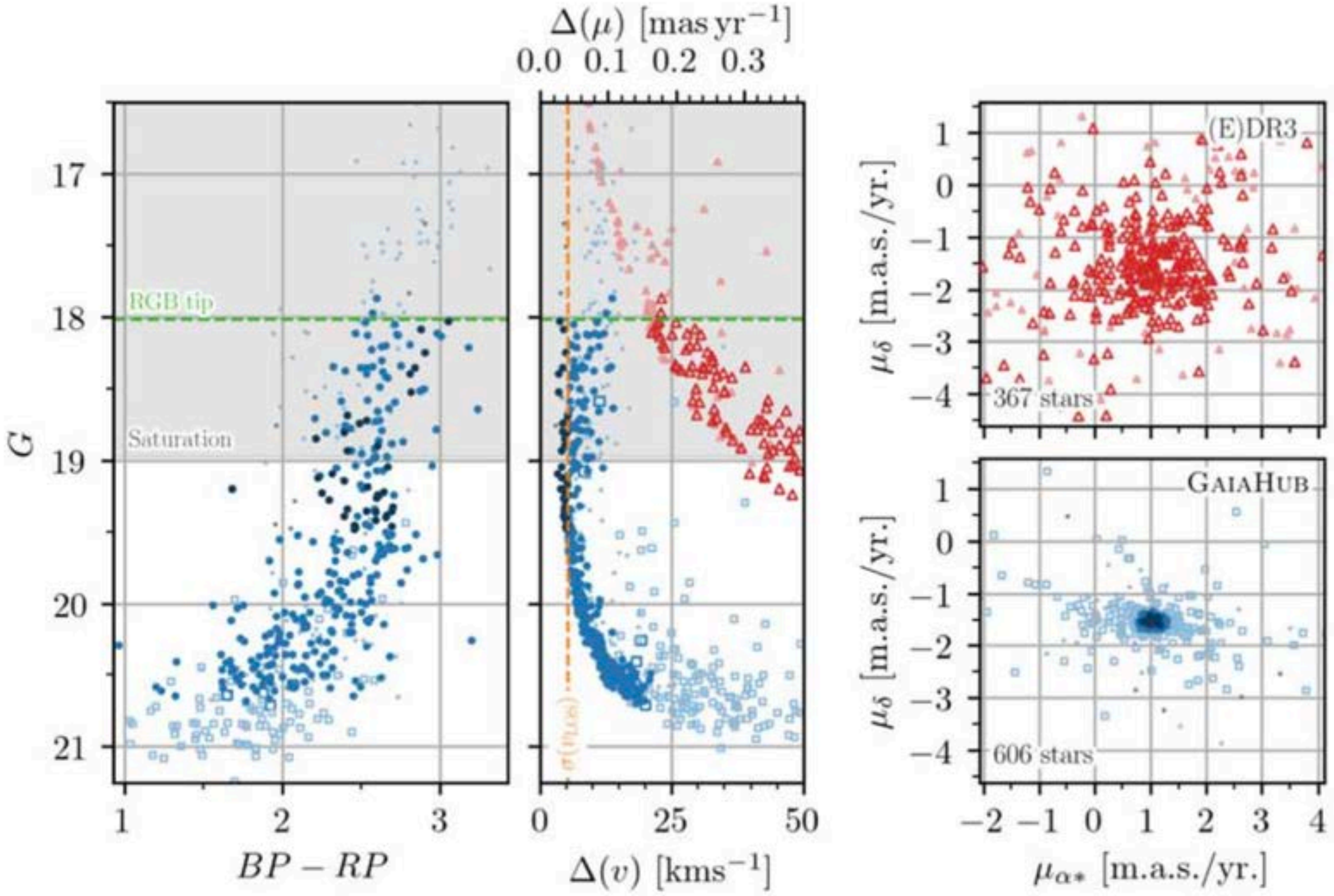
BP3M: Bayesian Positions, Parallaxes, and Proper Motions Derived from the Hubble Space Telescope and Gaia Data

Kevin A. McKinnon[1,2], Andrés del Pino[3], Constance M. Rockosi[1], Miranda Apfel[1], Puragra Guhathakurta[1], Roeland P. van der Marel[4,5], Paul Bennet[4], Mark A. Fardal[6], Mattia Libralato[7,8], Sangmo Tony Sohn[4], Eduardo Vitral[4], and Laura L. Watkins[7]

[1] Department of Astronomy & Astrophysics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
[2] Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H, Canada; kevin.mckinnon@utoronto.ca
[3] Centro de Estudios de Física del Cosmos de Aragón (CEFCA), Unidad Asociada al CSIC, Plaza San Juan 1, E-44001, Teruel, Spain
[4] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[5] Center for Astrophysical Sciences, The William H. Miller III Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
[6] Eureka Scientific, 2452 Delmer Street, Suite 100, Oakland, CA 94602, USA
[7] AURA for the European Space Agency (ESA), ESA Office, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[8] Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, Padova I-35122, Italy

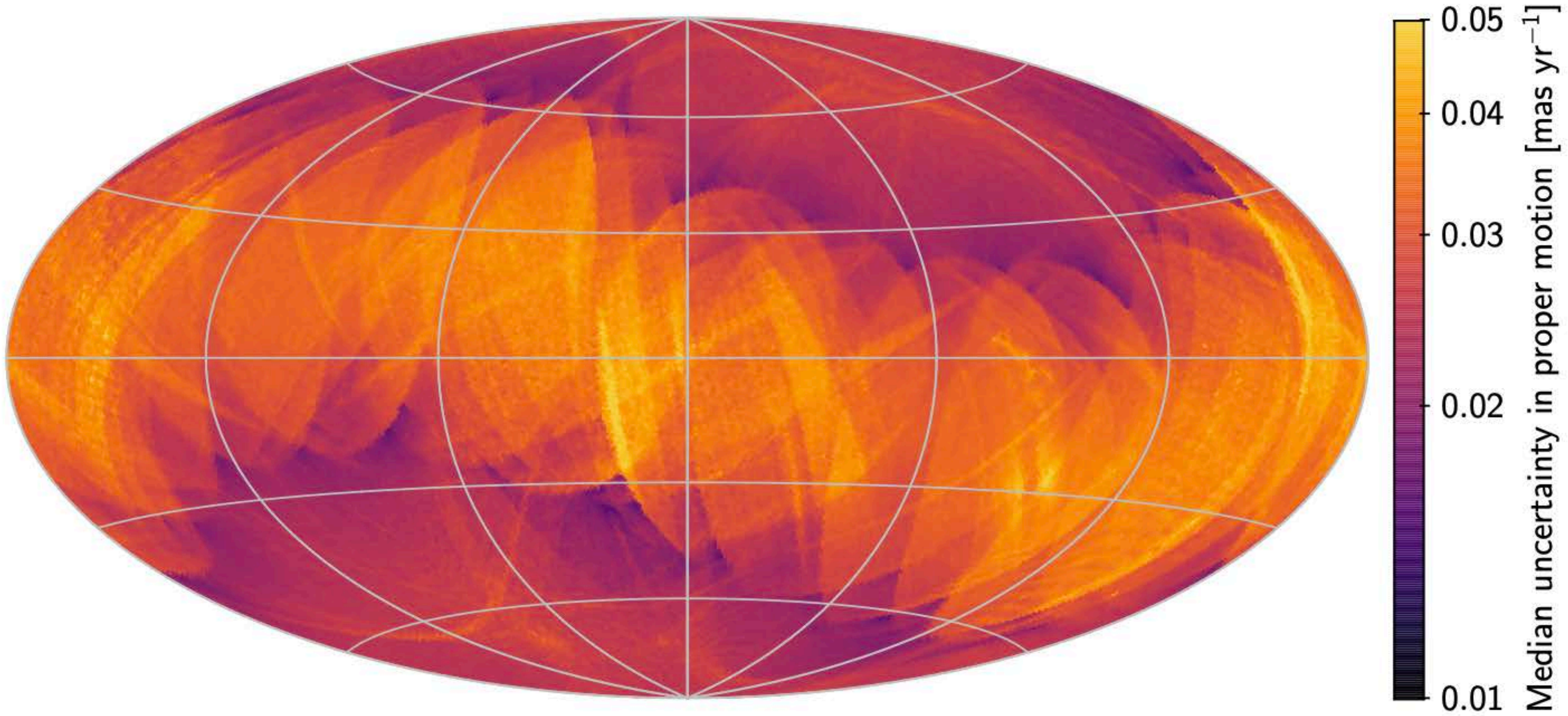
Received 2023 October 30; revised 2024 June 7; accepted 2024 June 12; published 2024 September 3

HSTPROMO



Future challenges

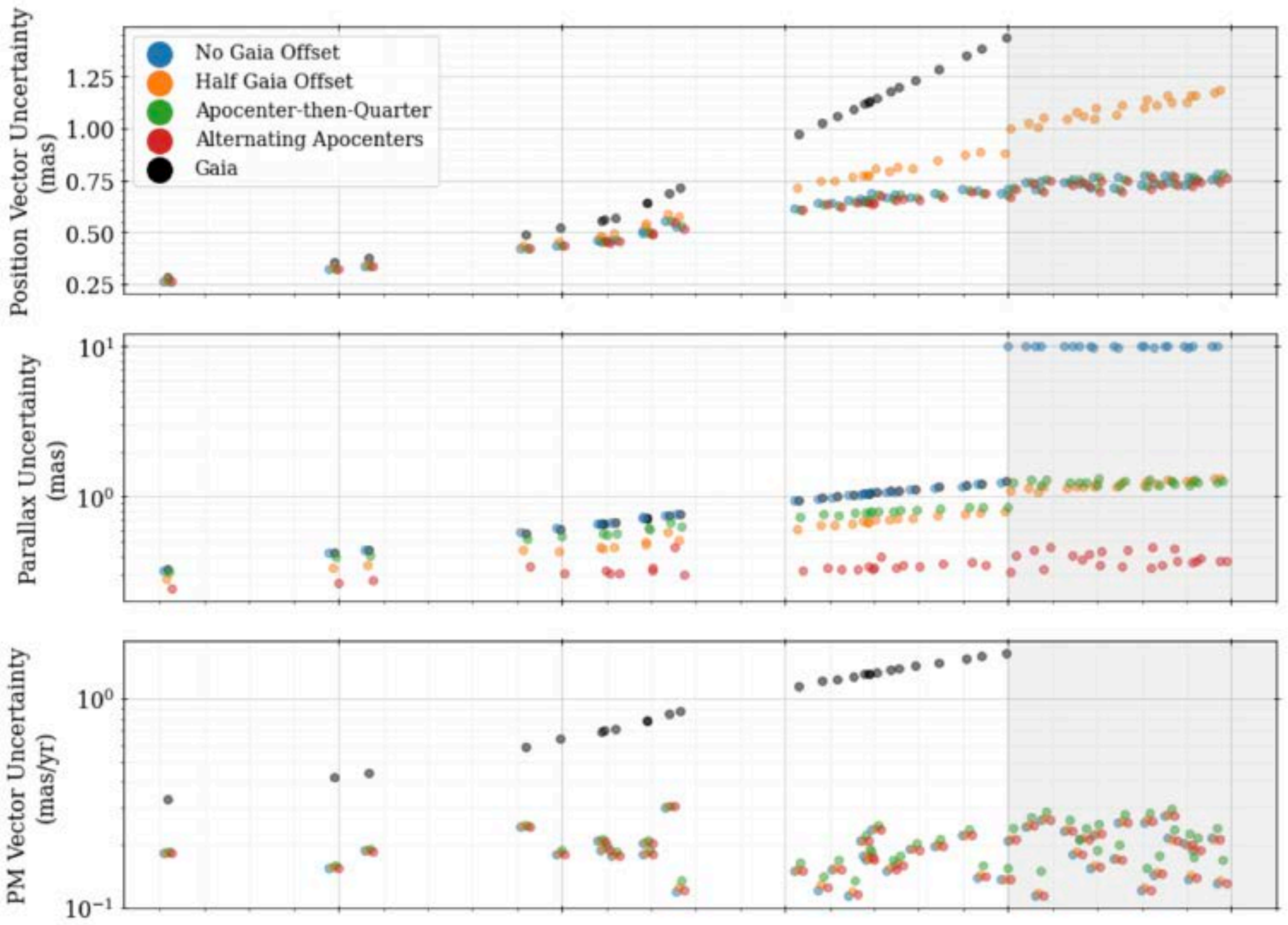
- **Identify and constrain/characterize systematics from each telescope.**



Lindegren et al. 2021, Gaia Collaboration

Future challenges

- **Identify and constrain/characterize systematics from each telescope.**
- Wisely choose observation strategies (see McKinnon+24, sect. 5).



McKinnon et al. 2024

Future challenges

- **Identify and constrain/characterize systematics from each telescope.**
- Wisely choose observation strategies (see McKinnon+24, sect. 5).
- Measure first epochs with wide-field telescopes (e.g., Roman, Euclid and Theia)

Summary

Thank you!

- Dwarf galaxies help us to probe the **nature of dark matter**, as well as **galaxy evolution**.

- Most of our knowledge of their internal kinematics comes from a single velocity dimension (line-of-sight), which leads to many degeneracies.
  →**Proper motions** (transverse velocities in the sky) are needed to **lift these degeneracies**.

- Currently, **only Hubble** is able probe dwarf galaxy proper motions (on a stellar level) with **trustworthy uncertainties**.

- **Future missions** will target **different important goals** (field of view, magnitude depth, different wavelengths, etc), but none fills all the check points for an ideal proper motion subset.

- The solution might be to **combine different epochs from different observatories**, which will require **better handling of current telescope systematics**.