The Gaia space astrometry mission and the structure of our Galaxy

… with an emphasis on dark matter

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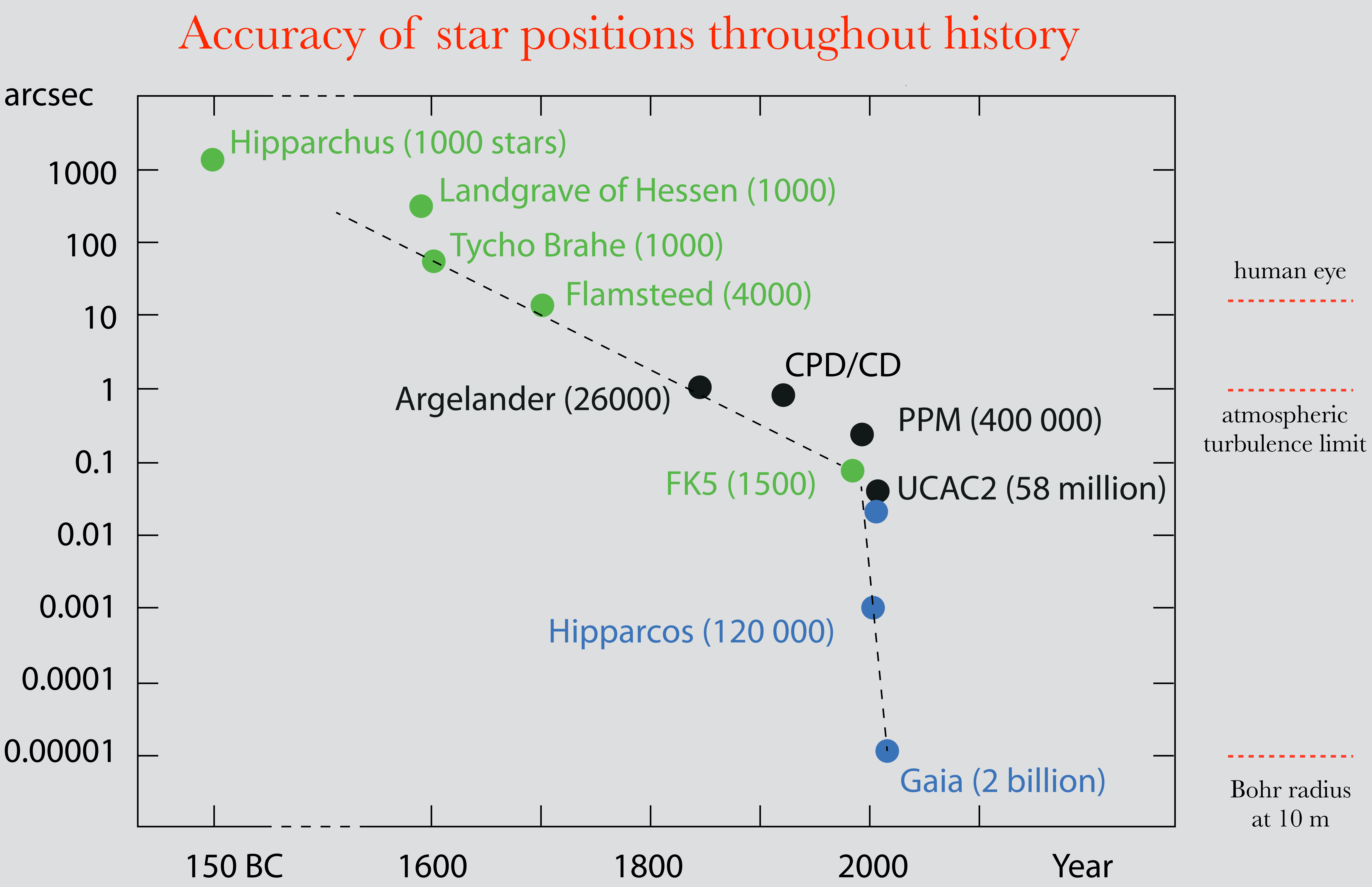
…and with thanks to Konstantin Zioutas

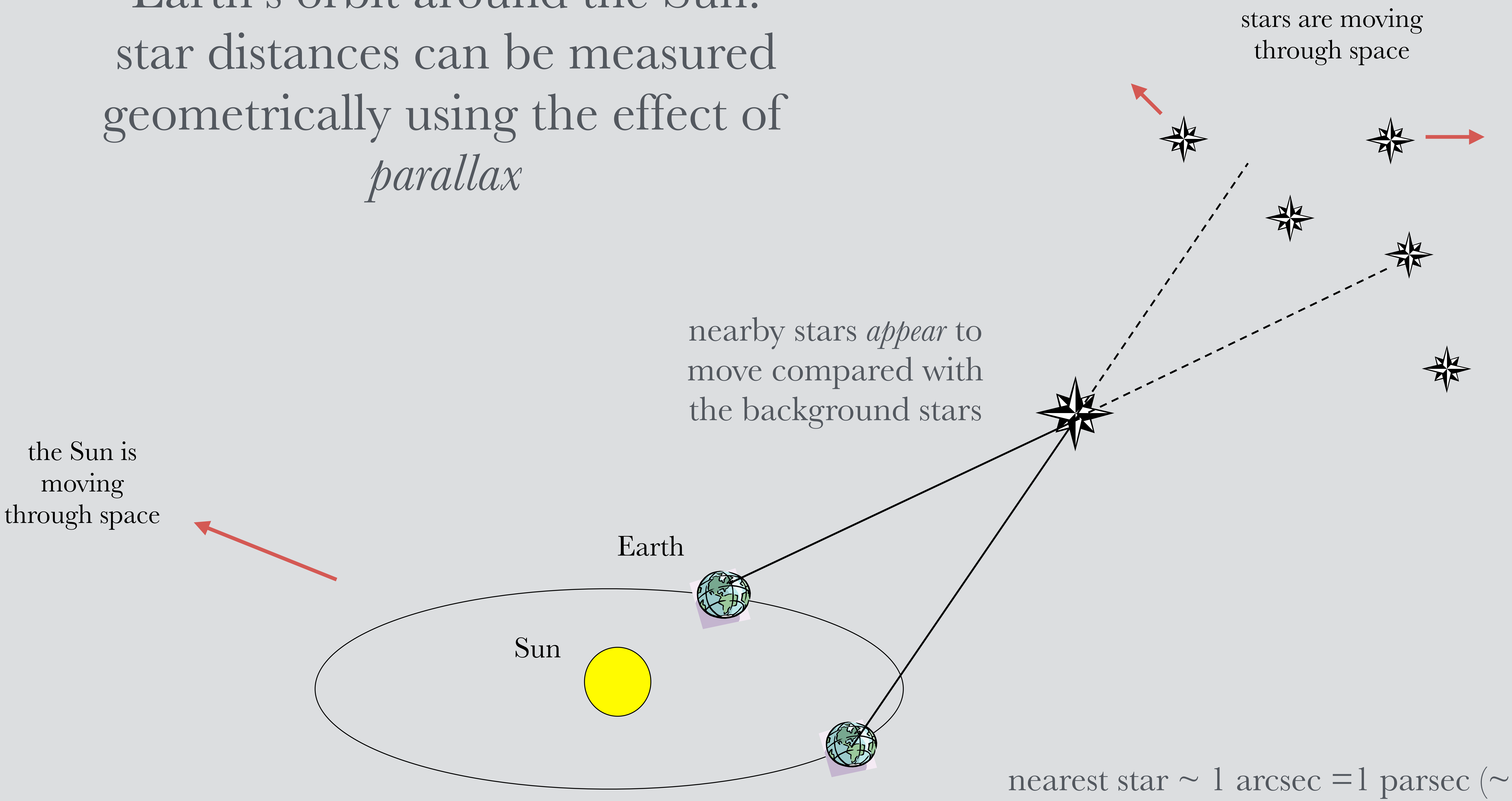


Accuracy of star positions throughout history
arcsec
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
Hipparchus (1000 stars)
Landgrave of Hessen (1000)
Tycho Brahe (1000)
Flamsteed (4000)
CPD/CD
Argelander (26000)
PPM (400 000)
FK5 (1500)
UCAC2 (58 million)
Hipparcos (120 000)
Gaia (2 billion)
150 BC
1600
1800
2000
Year
human eye
atmospheric turbulence limit
Bohr radius at 10 m

Understanding the stars from their positions

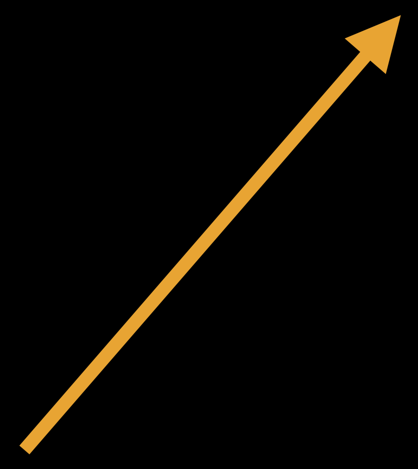
- 200 BC (ancient Greeks): size/distance of Sun and Moon; planet motions
- 900 – 1200: Islamic culture: direction of Mecca and the timing of Ramadan
- 1500 – 1700: resurgence of scientific enquiry in Europe
  - Earth moves around the Sun (Copernicus), better observations (Tycho Brahe)
  - planetary motion (Kepler); laws of gravity and motion (Newton); navigation at sea
- 1718: Edmond Halley: the movement of stars through space
- 1725: James Bradley: stellar aberration; Earth's motion; finite speed of light
- 1783: William Herschel: inferred the Sun's motion through space
- 1838: Friedrich Bessel: first star distances, direct proof of the immensity of space
- 1989 – 1993: *Hipparcos*: first measurements from space: 100,000 stars at 1 milli-arcseconds
- 2013 – 2023: *Gaia*: 2,000,000,000 stars at 10 – 20 micro-arcseconds

Earth’s orbit around the Sun: star distances can be measured geometrically using the effect of *parallax*



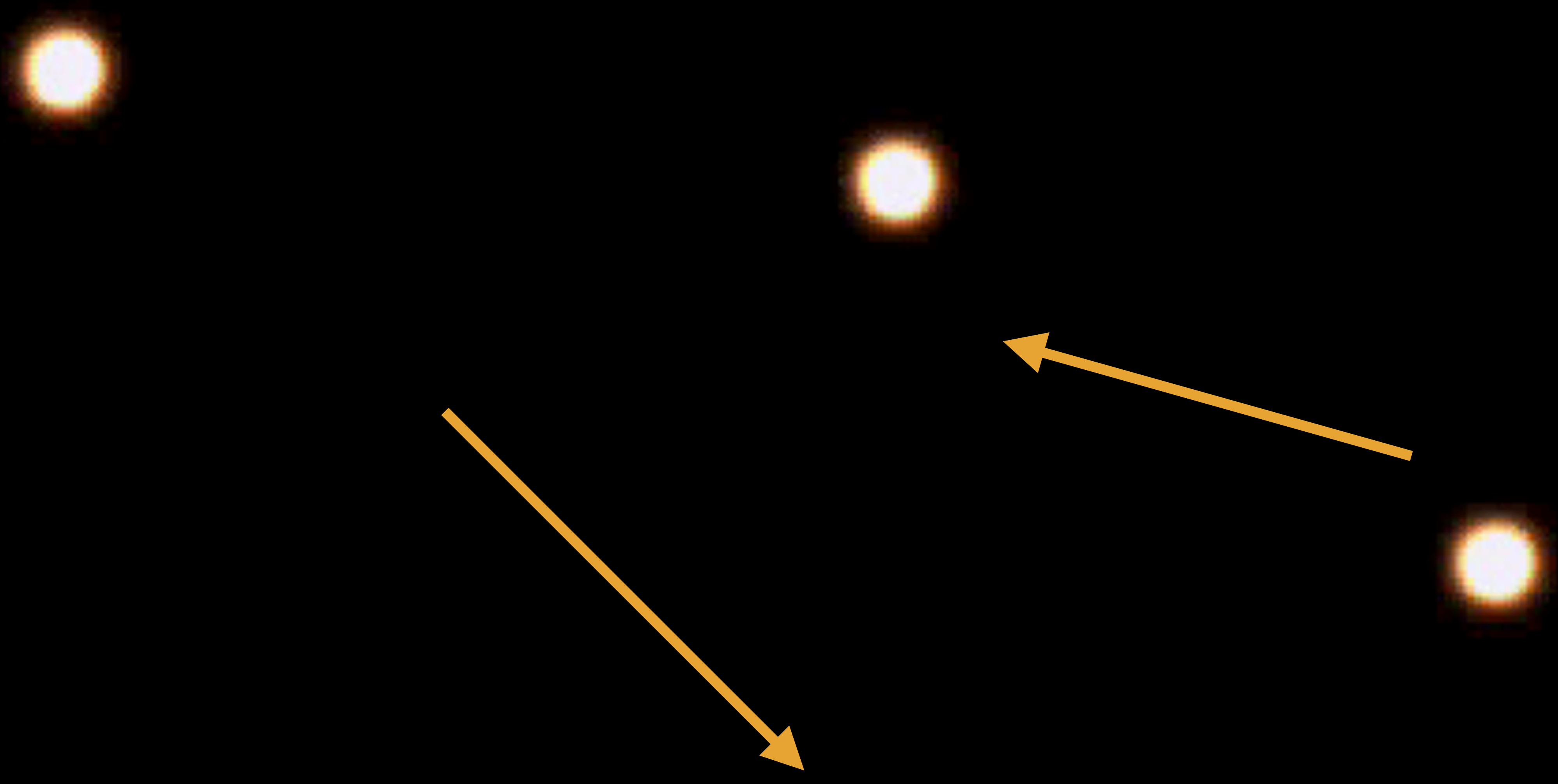
nearest star ~ 1 arcsec =1 parsec (~3.2 l-y)
Galactic centre ~ 8,000 pc ~ 30,000 l-y (100 microarcsec)

Principle: three stars in same region of sky



the stars are moving in different directions

and are at different distances (parallaxes)




Hyades Cluster:
6 degrees × 4 degrees
over 60,000 years
proper motions only

Hyades Cluster:
effect of
parallaxes only


Hyades Cluster:
over 60,000 years
motions and parallaxes

Cosmology: Big Bang/Lambda CDM

- a model of the observable Universe from its earliest periods
- expansion from a high-density and high-temperature state
- **normal matter (5%), dark matter (27%), dark energy (68%)**
- explains:
  - origin and abundance of the light elements (H, He, Li…)
  - cosmic microwave background radiation
  - large-scale structure of the Universe and Hubble's law

- it gives an age of the Universe of about 13.7 billion years
- it predicts a 'singularity' just before its emergence
- it does not explain how energy, time, and space emerged

Hubble: Ultra Deep Field, 2009

The Millennium Simulations used 10 billion 'particles' to trace the evolution of matter in a cubic region 2 billion light-years on a side

Millennium Simulations

(Volker Springel et al, 2005)

Illustris TNG50

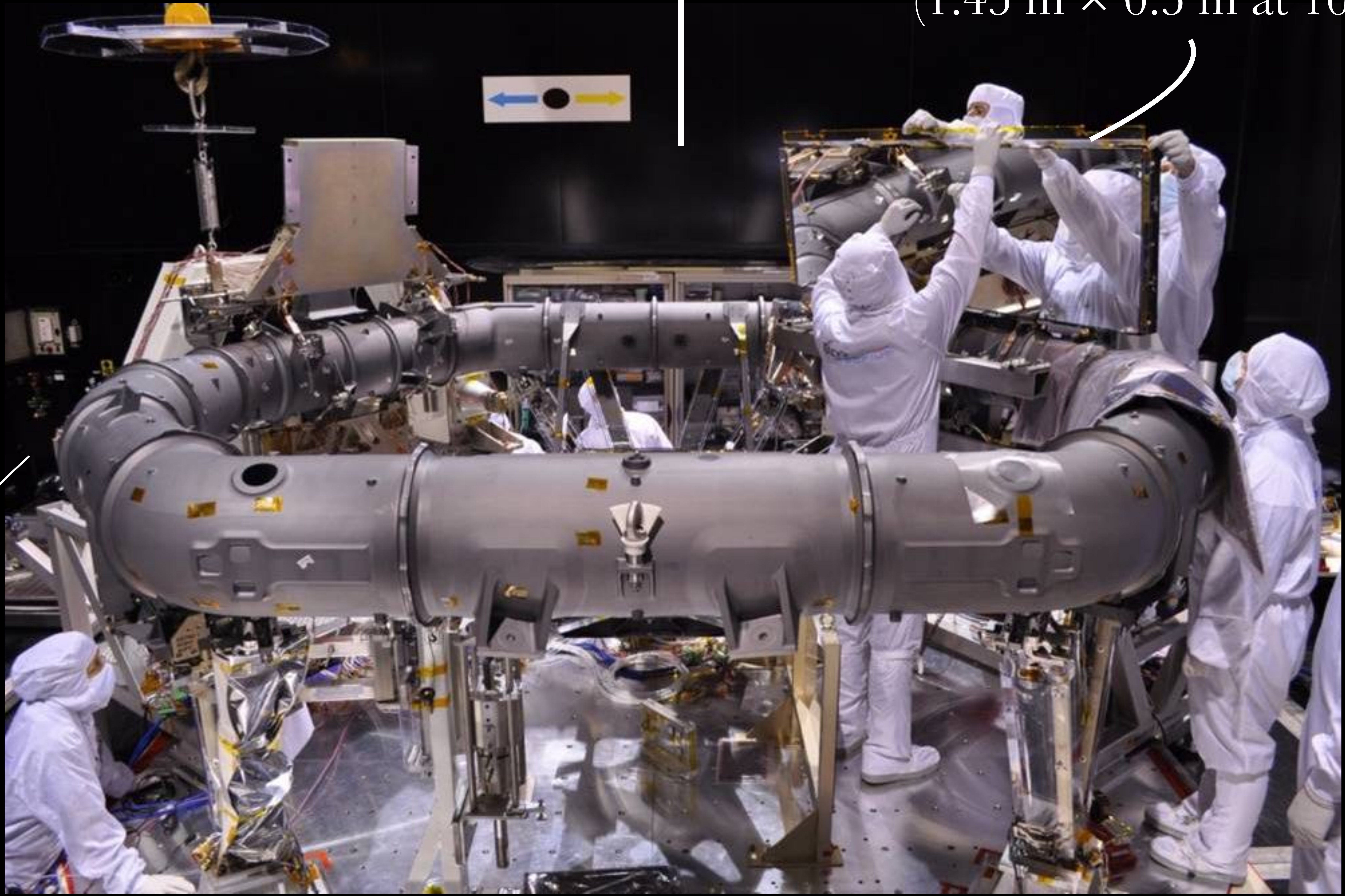
(Volker Springel et al, 2019)

Simulations of galaxy formation
100 ‘Milky Ways’
(2160^3 gas cells)


Hipparcos (1989)
measured this far:
1 milliarcsec
If we could see our
Galaxy from a distance
it would look something
like this (Andromeda)
we are here
Gaia (2013) measures out to
here (and more): 20 microarcsec

rotation axis

SiC primary mirrors
(1.45 m × 0.5 m at 106 degrees)



Silicon Carbide toroidal support structure

…protected by a
deployable 10-m diameter
combined solar array and sunshield

Improving Catalogues…

(launch 2013, operating to 2023, final results 2029)

Data release 1: Sep 2016 (14 months)
Data release 2: Apr 2018 (22 months)
Data release 3: Dec 2020 (34 months)

most recent: 1,811,709,771 stars

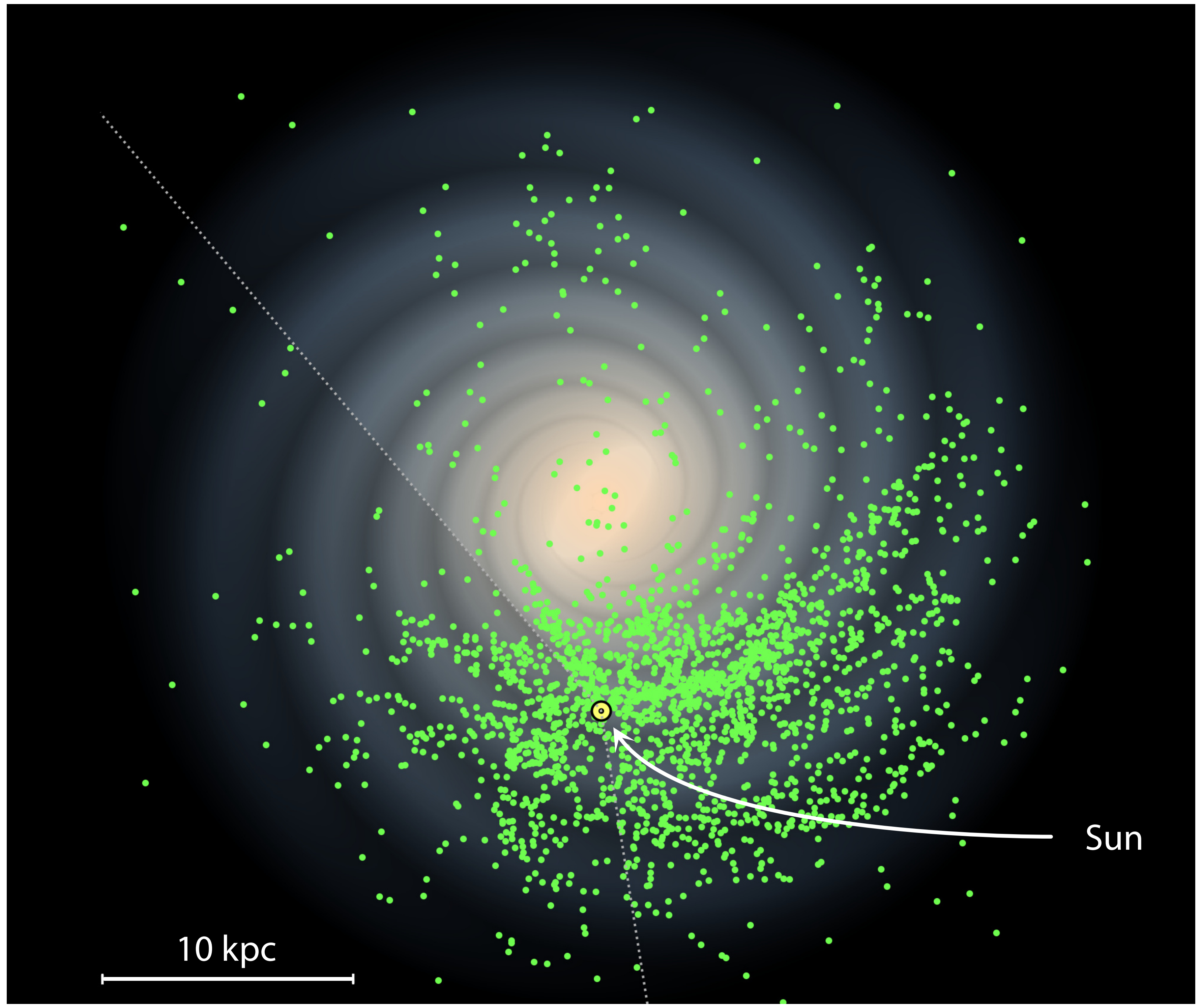

Gaia 200 pc sample
over 1.5 million years
(25,000 years per second)
Jacqueline Flaherty (AMNH)

Some examples from Gaia

….more than 5000 papers since 2016

1. Dark matter halo from our Galaxy's rotation curve

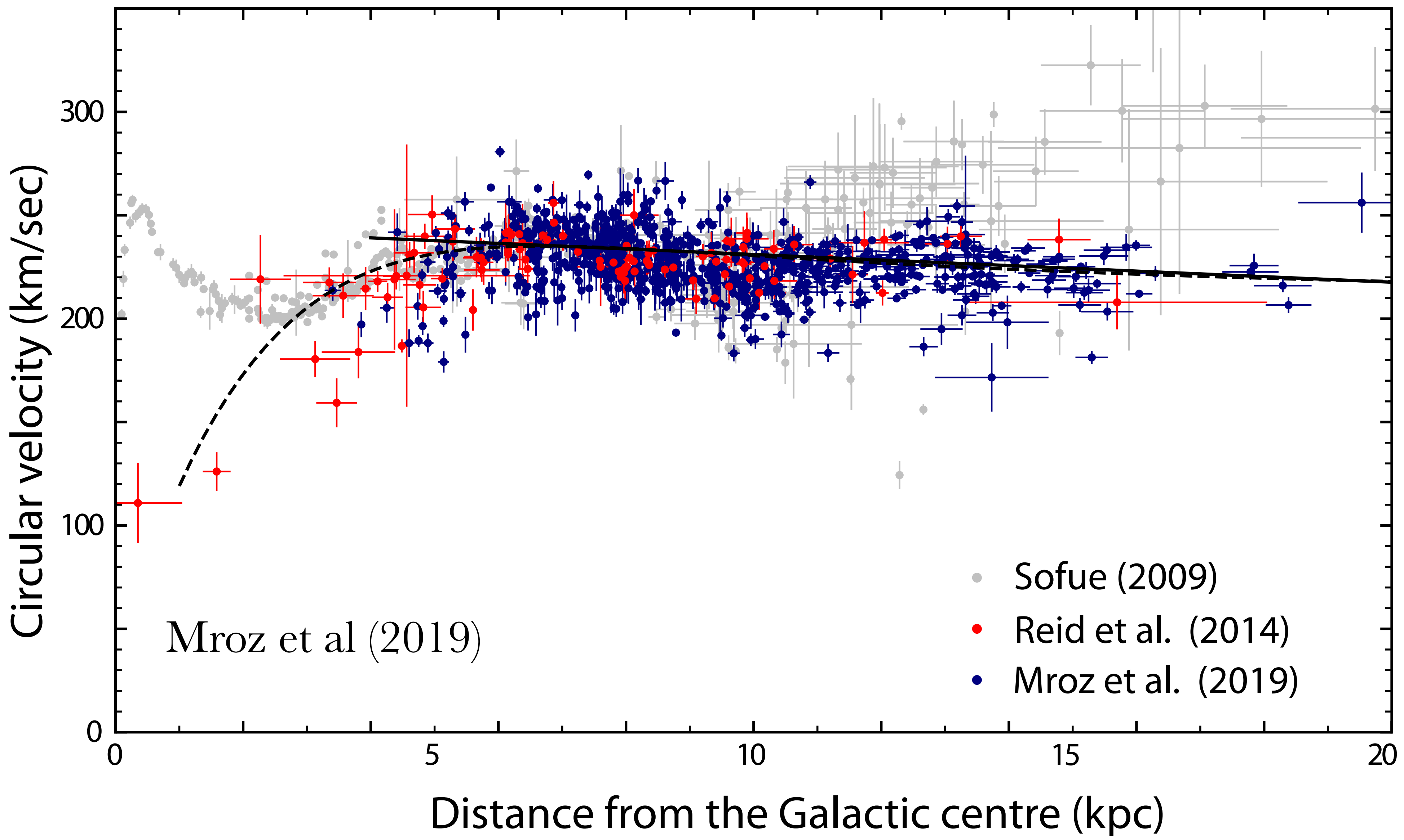
- stars rotate around the Galaxy with an orbital period of ~250 Myr
- luminous Cepheid stars are good 'tracers' of Galaxy rotation
- Ablimit et al (2020) use 3500 Cepheids from Gaia DR2, from which distances and angular motions yield velocities
- result: gently declining rotation curve, -1.33 ± 0.1 km/sec/kpc



Skowron et al (2019)

Conclusions:

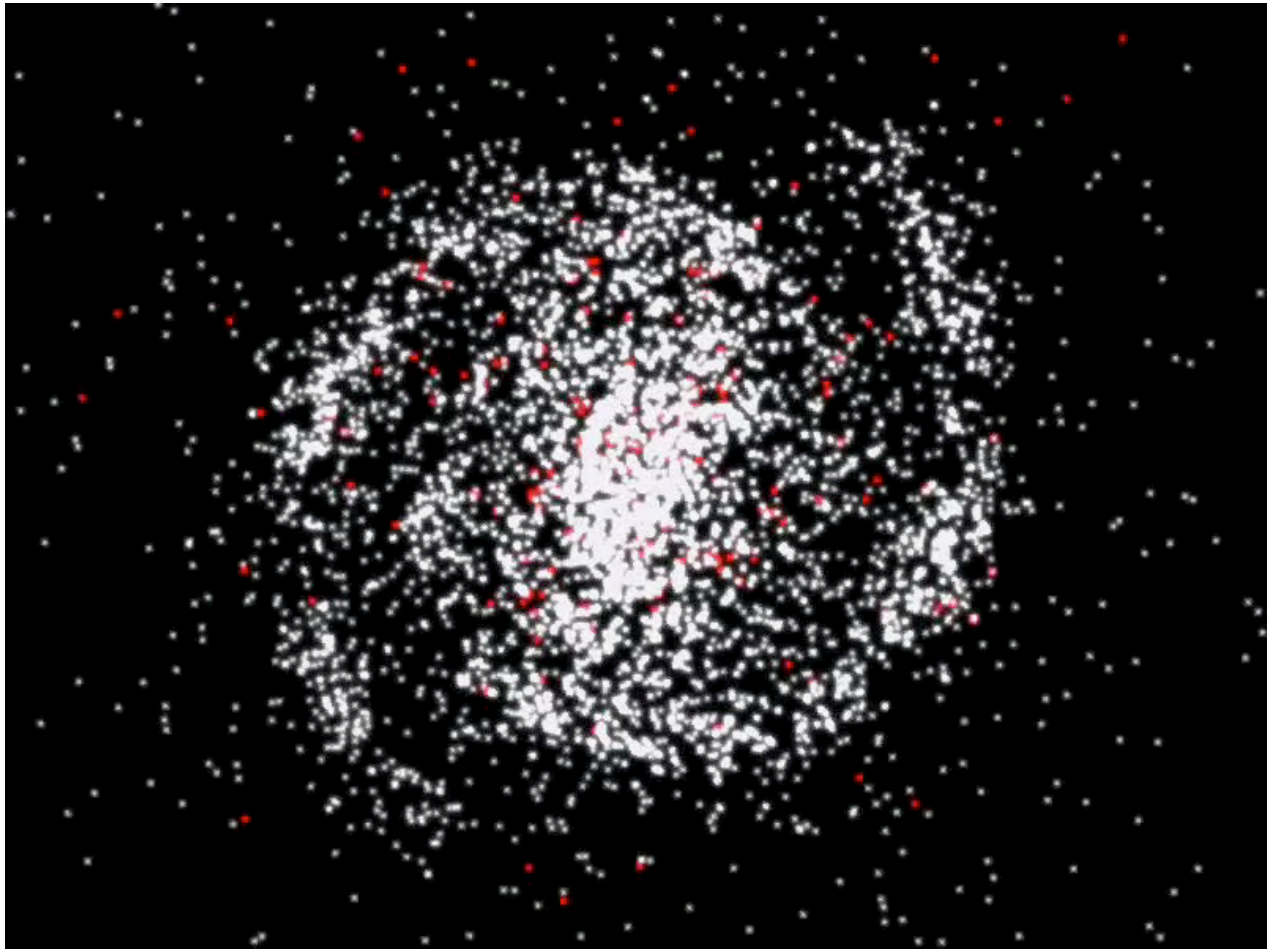
- our Galaxy's (virial) mass = $(0.822 \pm 0.052) \times 10^{12}\, M_{\odot}$ within the corresponding (virial) radius of ~200 kpc
- the local dark matter density is 0.33 ± 0.03 GeV cm^{-3}
- the dark matter halo is the main contributor to the Galaxy rotation curve beyond distances of about 12.5–14.5 kpc



Mroz et al (2019)

2. Mass density in the Galactic plane

- stars rotate *around* the Galaxy with an orbital period of ~250 Myr
- their *vertical* velocity is controlled by the mass of the Galactic plane
- the vertical force is reconstructed from the vertical velocity dispersion, and the vertical density profile (period ~50 Myr)
- comparison with the density of *visible* matter yields the *dark* matter



schematic only

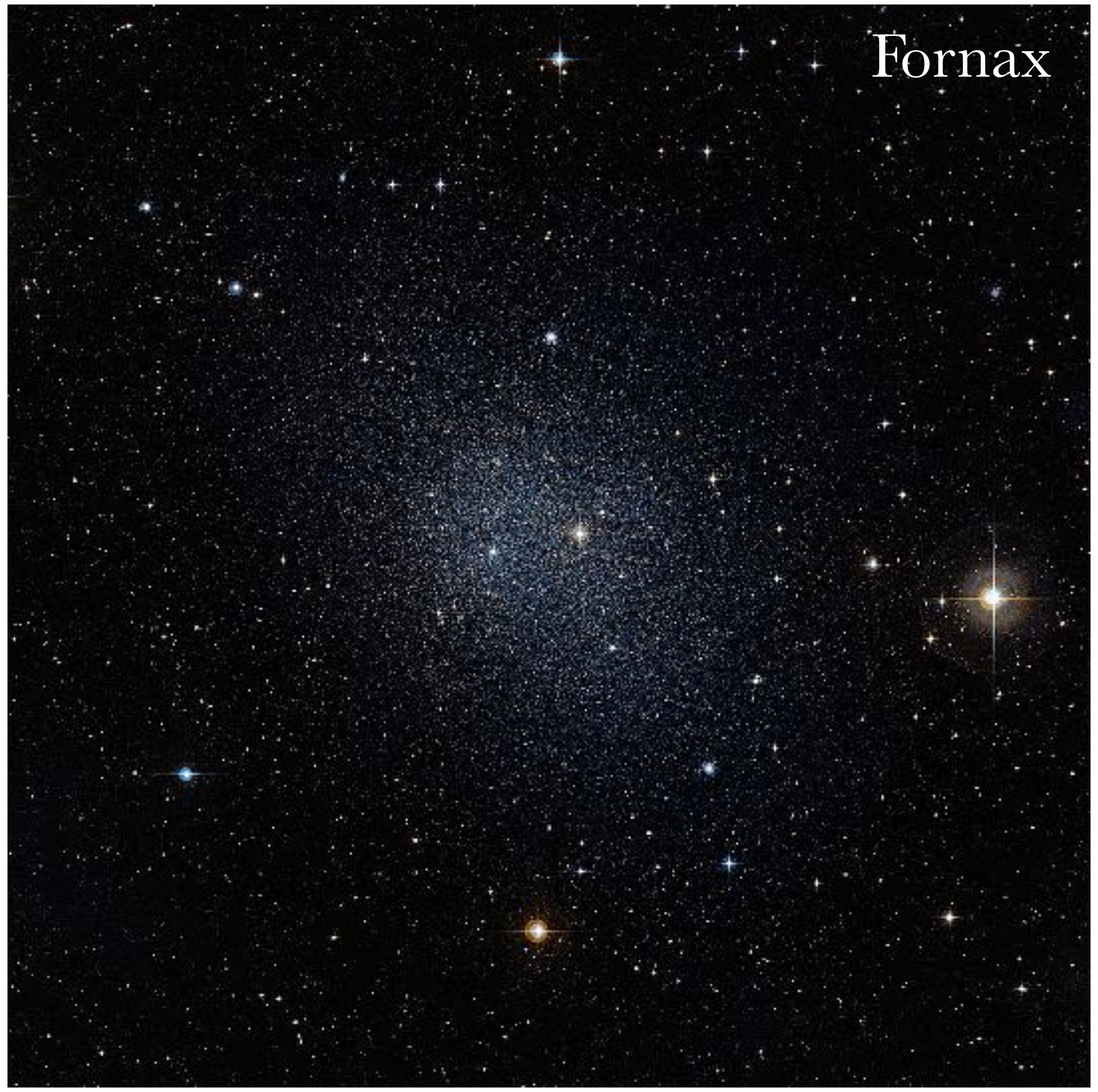
Hipparcos (~ 1998 – 2000) concluded: disk matter is well accounted for (by stars, and interstellar gas and dust)

$\Longrightarrow$ *dark matter* must be in the form of the spherical halo, with little concentrated in the disk

Much more will come from Gaia about the sub-structure of the disk and halo of our Galaxy

3. ΛCDM and dwarf spheroidal galaxies

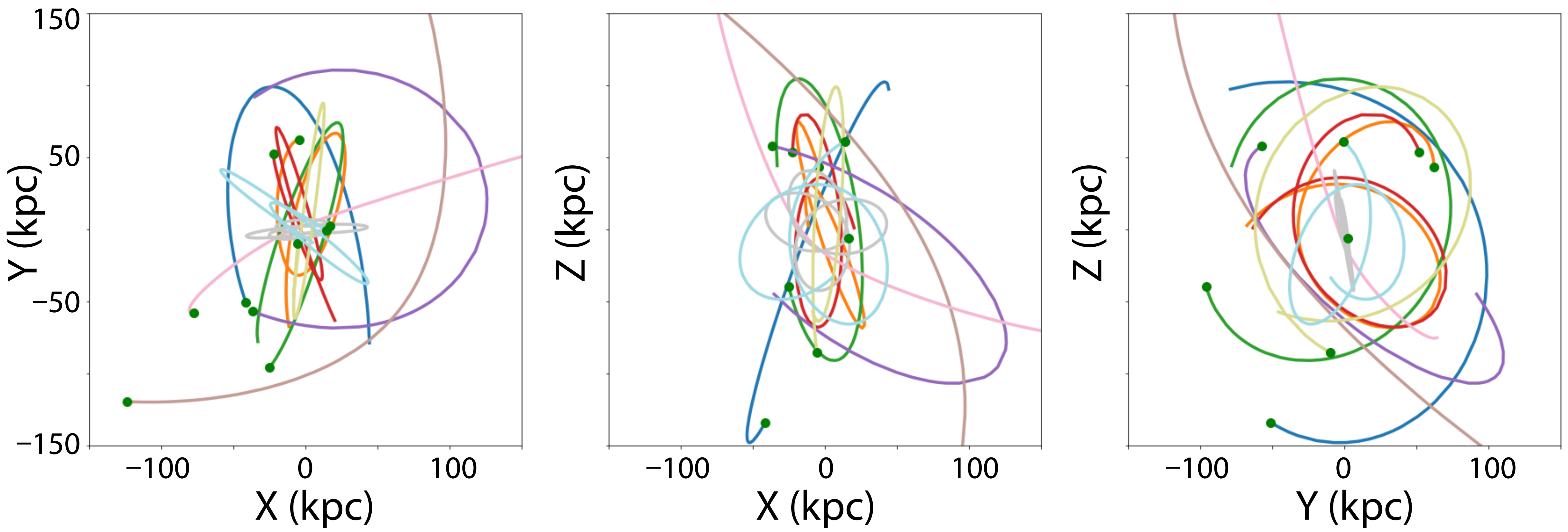
- small low-luminosity galaxies with an old stellar population and very little dust; they orbit the Milky Way at distances 25–250 kpc
- the first, Sculptor and Fornax, were discovered in the 1930s, while new discoveries are challenged by their low luminosities
- by the late 1990s their rarity seemed to be in conflict with ΛCDM, which predicted that massive galaxies (like ours) should be surrounded by many dark-matter dominated satellite halos
- this tension eased with the discovery of a dozen dSph from SDSS in 2000, and others from the Dark Energy Survey in 2015
- they provide key dynamical tracers of the mass distribution of the outer Milky Way, at distances larger than any other 'tracers'



Precise star distances and motions allow their orbits to be traced back over 250 Myr, using detailed mass models of the Galaxy

Most are on (slightly) prograde orbits, while Fornax is retrograde

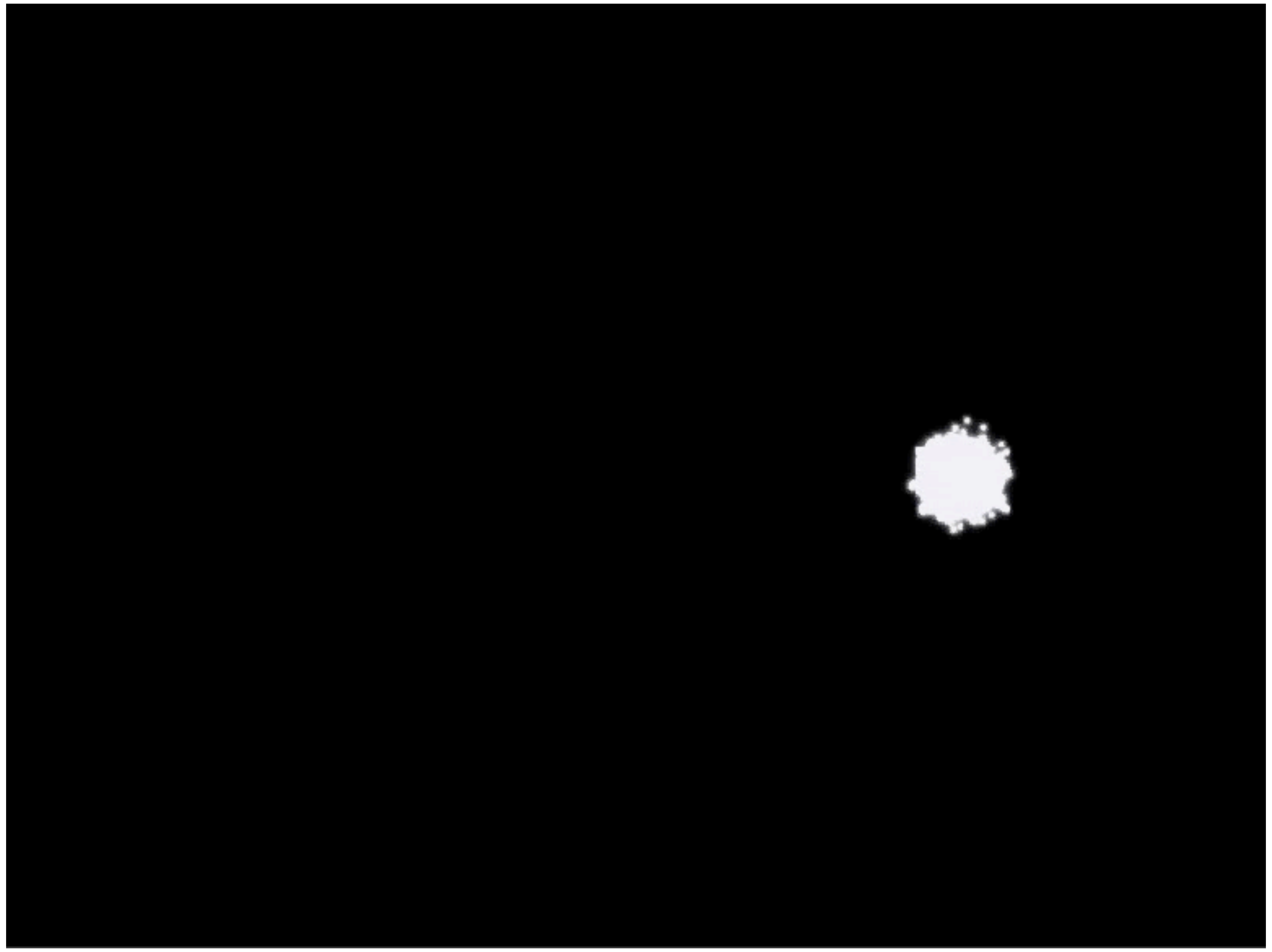
Their eccentricities are inconsistent with cosmological simulations, where they are predicted to be on radial orbits (Helmi et al 2018)



Orbits of 12 dwarf spheroidal galaxies in Galactic coordinates

4. Galaxy formation and tidal streams

- cosmological models inform us that galaxy halos are comprised of dark matter, and that larger galaxies like our Milky Way grew by a series of mergers, billions of years ago
- models suggest that our Galaxy's inner stellar halo should be dominated by the debris of just a few massive progenitor galaxies merging with our own early in its formation history
- these can be recognised by a combination of their orbital angular momentum and their primordial chemistry



schematic only

The inner halo is dominated by debris from one merger slightly more massive than the Small Magellanic Cloud (Helmi et al 2018)

The stars cover nearly the entire sky, and their motions reveal *the presence of streams* and slightly retrograde and elongated trajectories

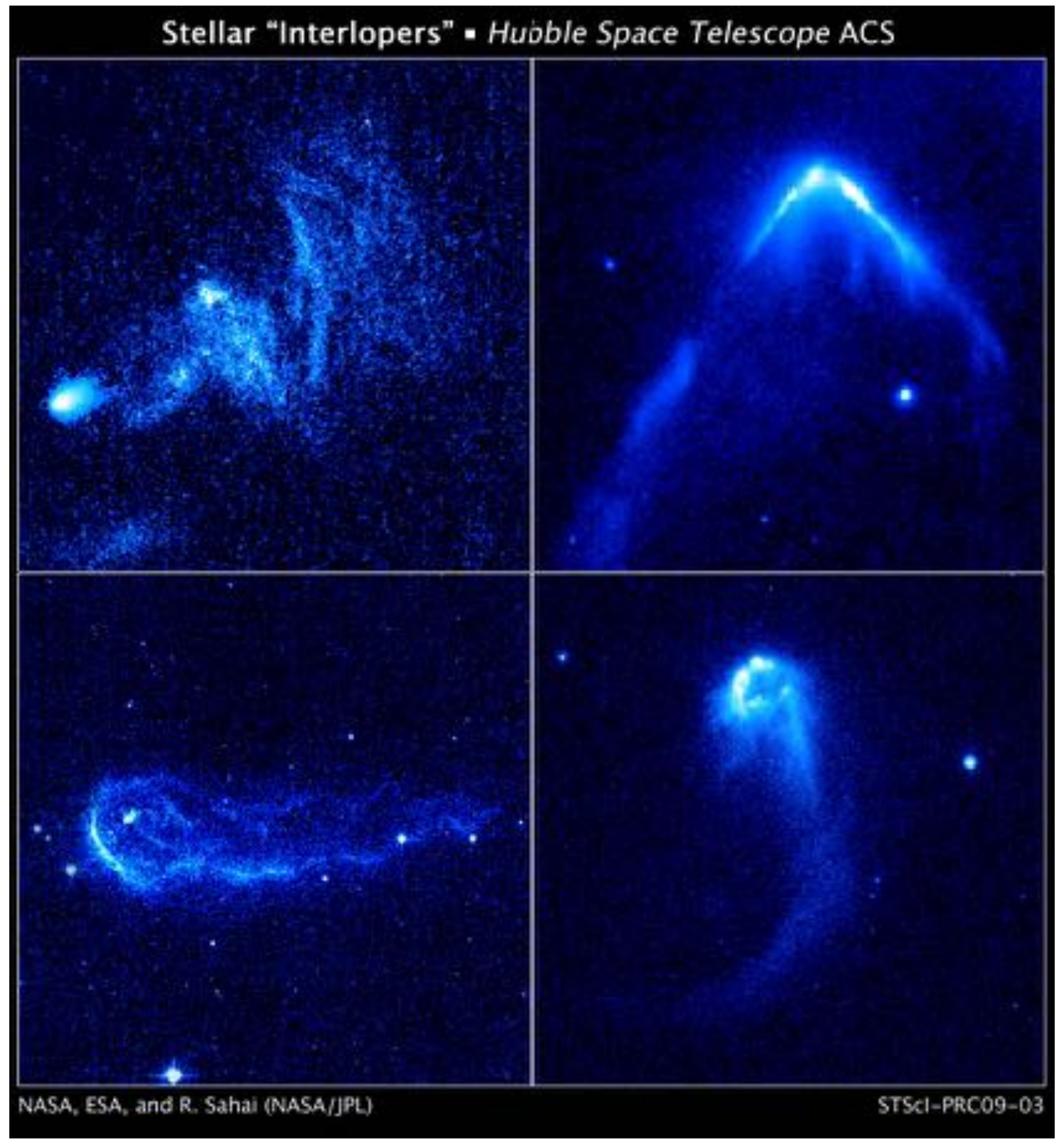
Hundreds of RR Lyrae stars and 13 globular clusters can be associated to the merger based on their orbits, age, and chemistry

This merger probably contributed to the formation of our Galaxy's thick disk component some 10 Gyr ago

Most probably, this was the last significant merger that our Galaxy experienced

5. Black holes and hypervelocity stars

- typical stars move through space at ~20-30 km/s
- runaway stars ~100 km/s were discovered half a century ago, hurled out of star clusters
- Gaia is discovering dozens of even more extreme stars escaping the Galaxy at 1000 km/s



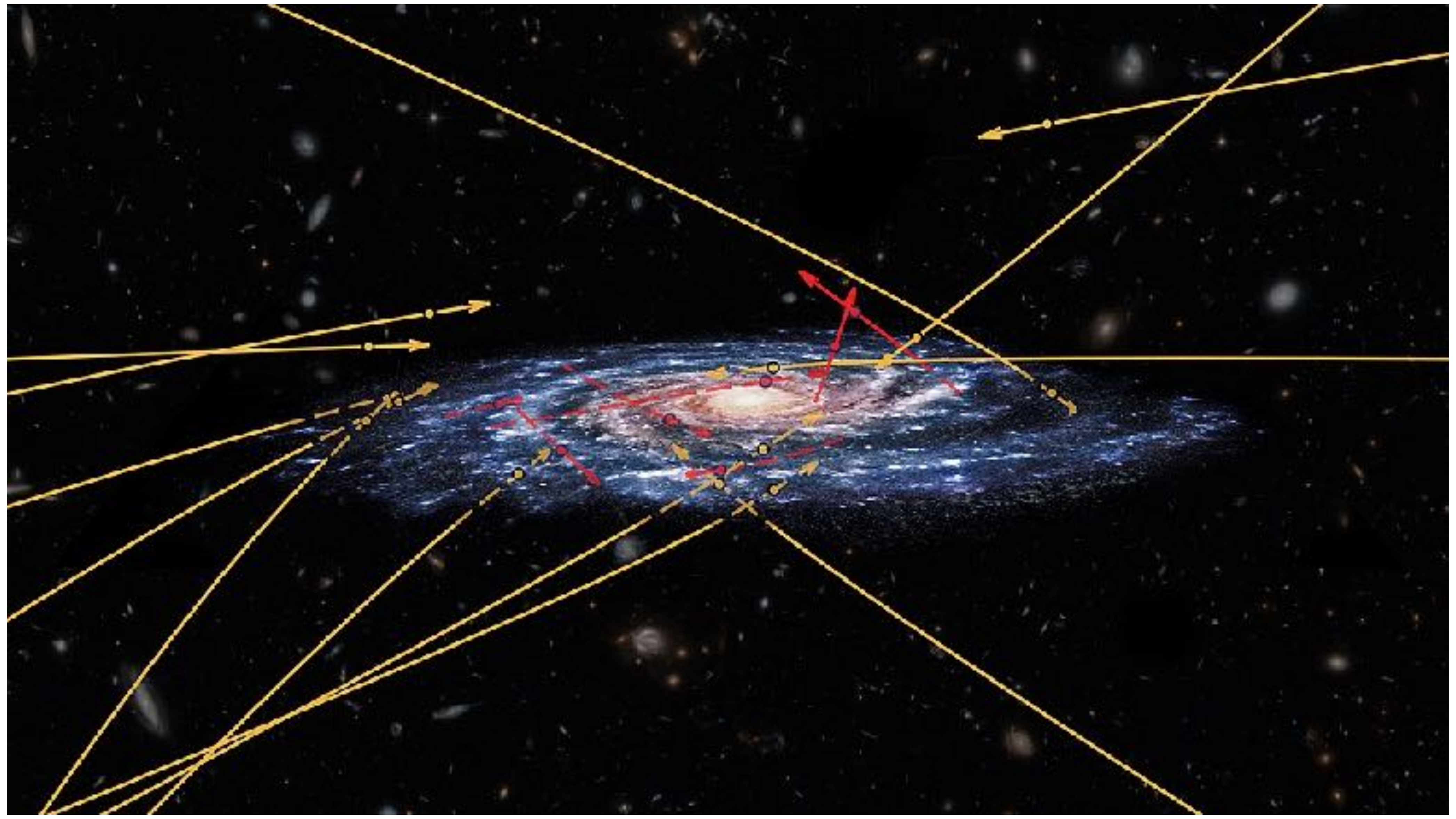
bow shocks in the interstellar medium due to high-velocity stars

Predicted by Hills (1988), stars can be ejected from the deep potential of a massive black hole, either from scattering with another star, or via tidal breakup of a binary system

In the 'concordance ΛCDM model', galaxies are embedded within extended halo structures, largely made of some 'non-viscous' dark matter, visible only through its gravitational effects

Over cosmic time, haloes grow in mass and size through hierarchical clustering (starting from initial perturbations), with resulting shapes and masses which depend on the model details

The motion of hypervelocity stars out through the Galaxy halo provides a unique probe of our Galaxy's gravitational potential

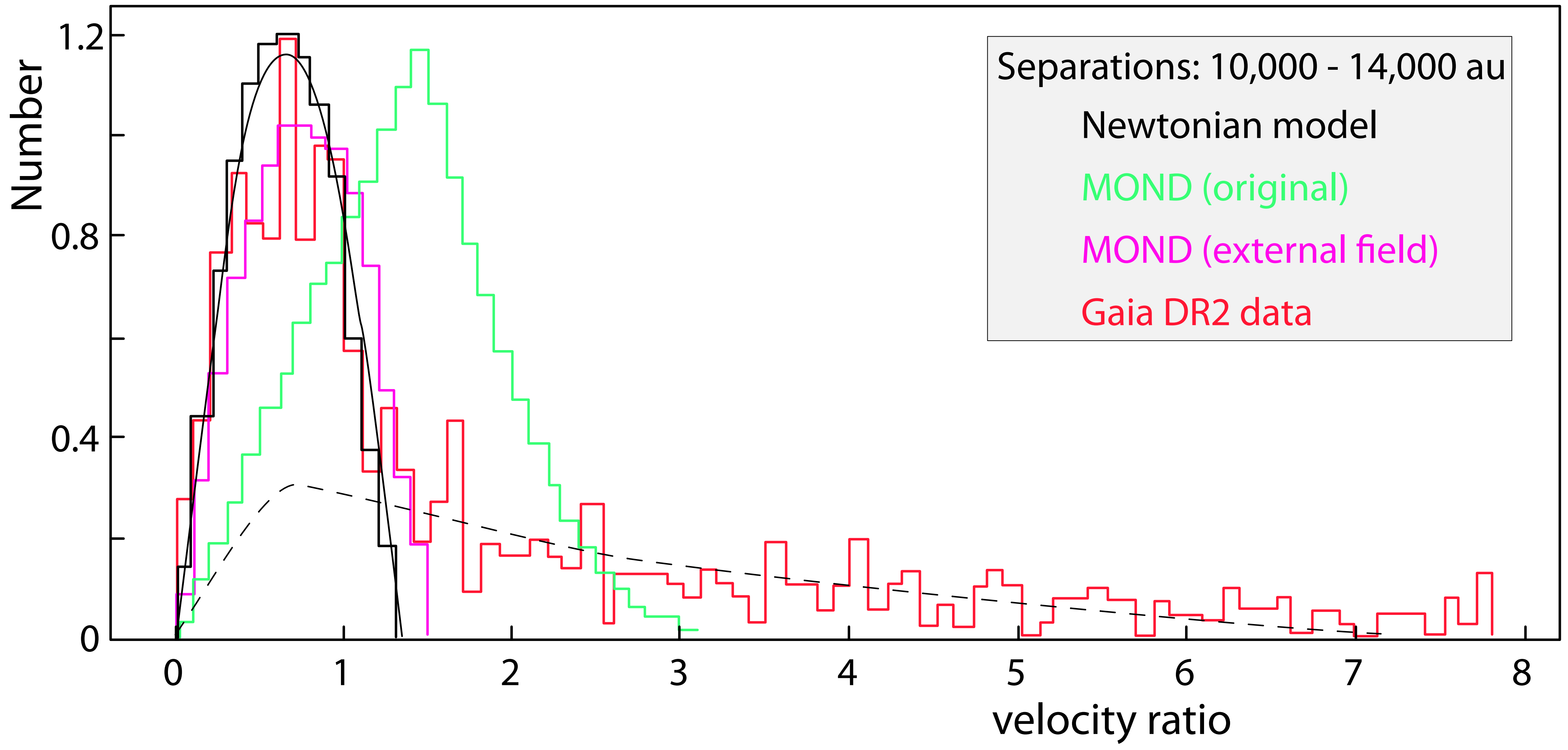


6. Tests of gravity (in principle)

- any tests which can further discriminate between dark matter and modified gravity are still desirable
- e.g. basic MOND is ruled out by precise timing effects in the neutron-star merger GW 170817 (Born et al 2018)
- one set of tests aims to probe the observational effects of gravity under conditions of very low accelerations
- binary stars can evolve out to ultra-wide separations, e.g. to 100,000 au, at which T(break-up) ~100 Myr
- for 5000 au, orbital accelerations are < 10^{-10} m s^{-2}, which can provide a direct probe of MOND-like theories
- such theories allow for bound binaries with relative velocities well above the Newtonian limit

Current results are <u>inconsistent</u> with a Newtonian model, and also with a MOND-like model (even with external field effect)

The long-tail in the observed distribution suggests some other (probably quite classical effect, like cluster ejection) at work



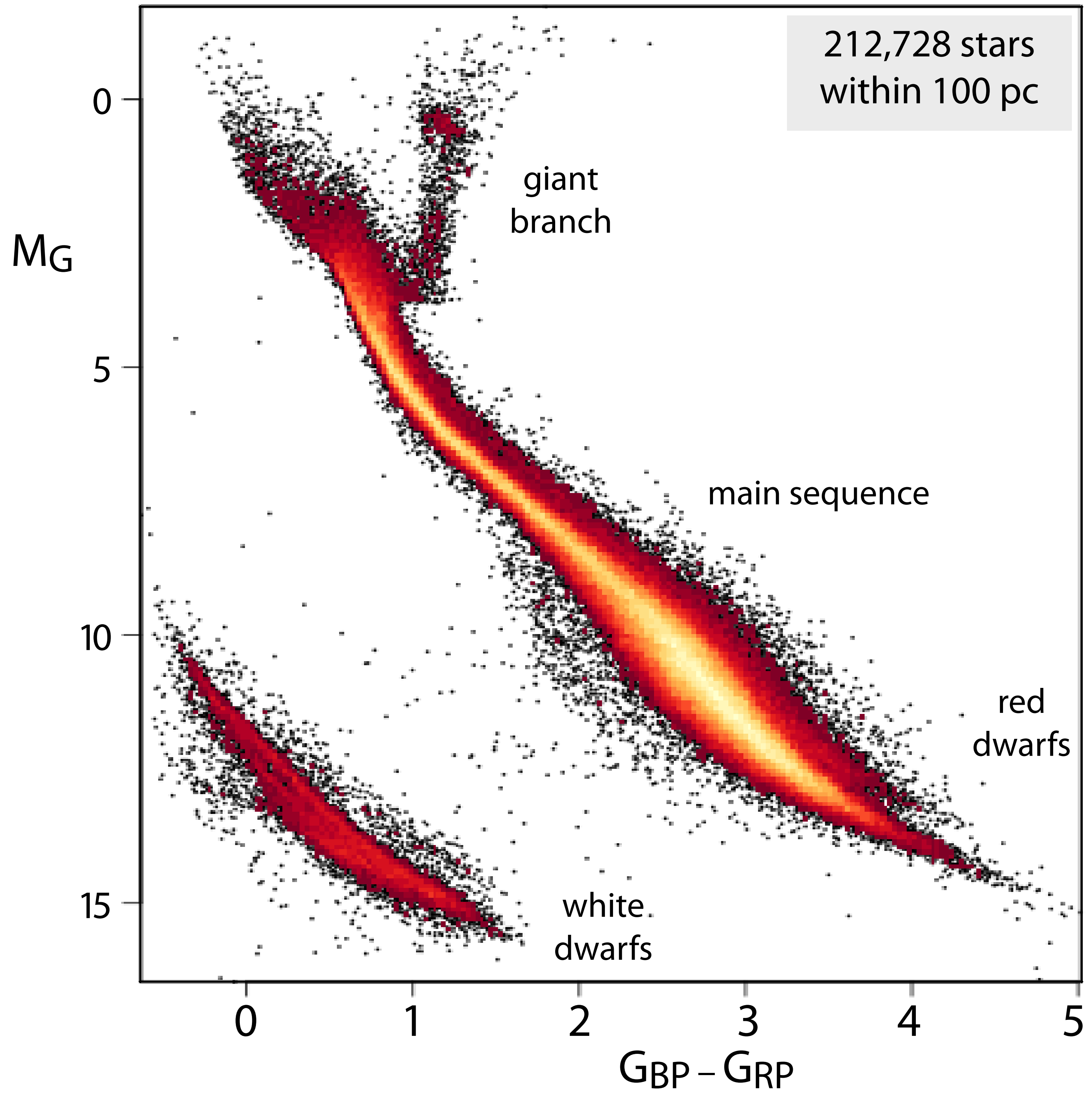
* au = astronomical unit = Sun-Earth distance

Could Gaia assist astrophysical axion searches, e.g. via their interaction with photons in strong magnetic fields?

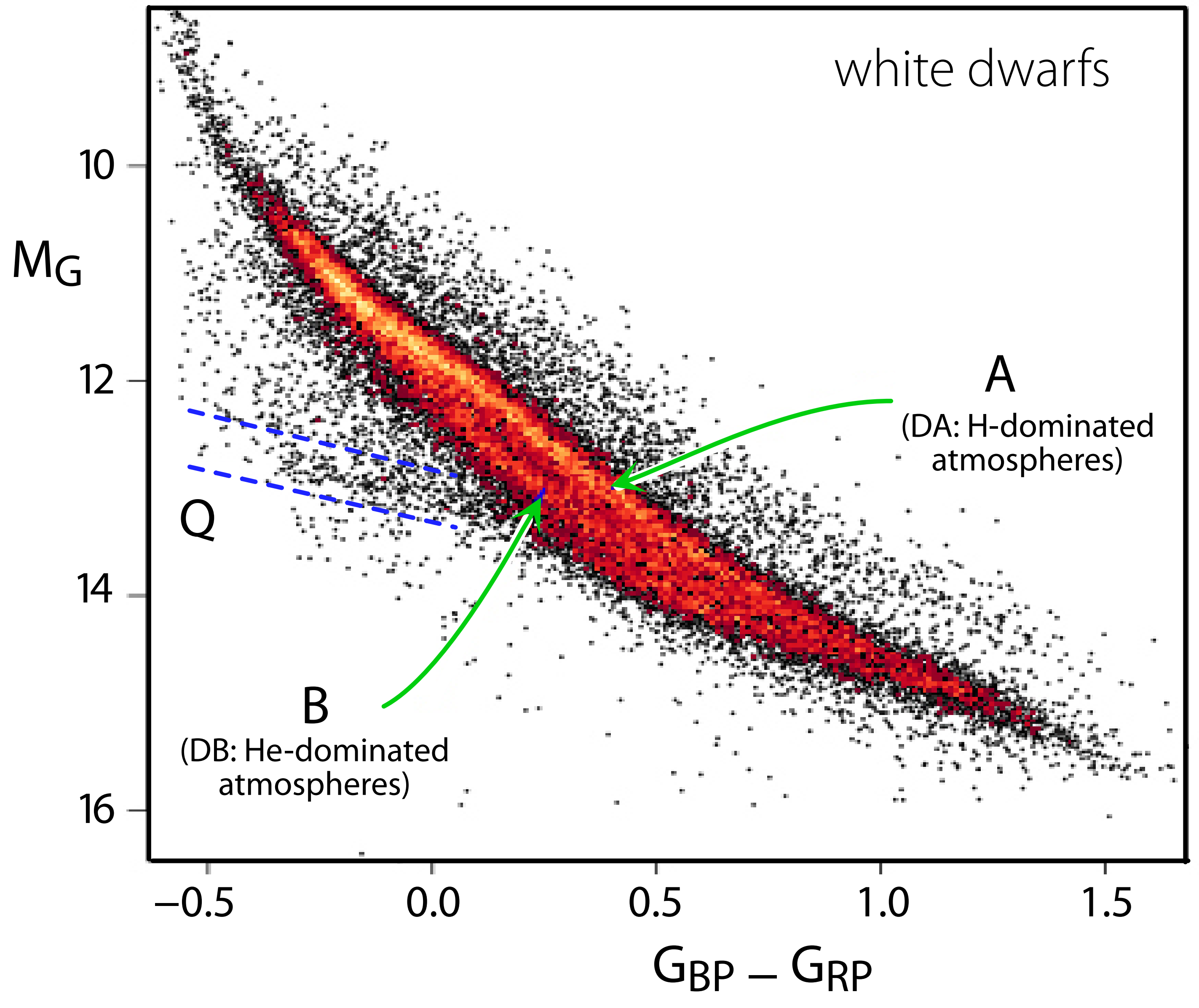
I do not know, but see the following….

7. Physics of white dwarf interiors

- end point of stellar evolution for 97% of stars
- faint objects, dominated by C or C/O cores
- they cool slowly over billions of years
- Gaia is finding tens of thousands out to 100 pc



Hertzsprung-Russell diagram



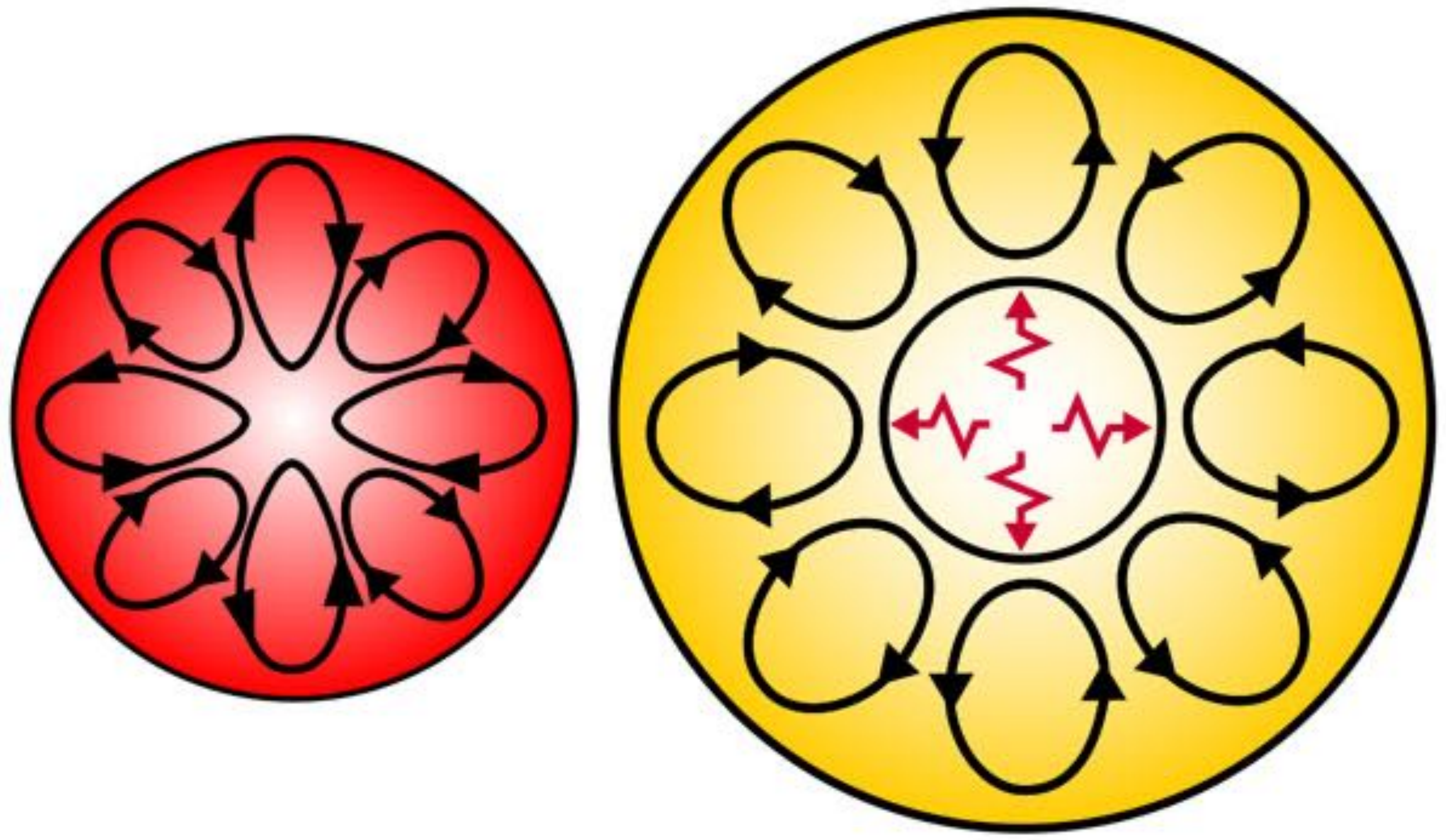
In the early 1960s, it was predicted that their cores should slowly crystallise as they cool, resulting in a lattice rather than a gas

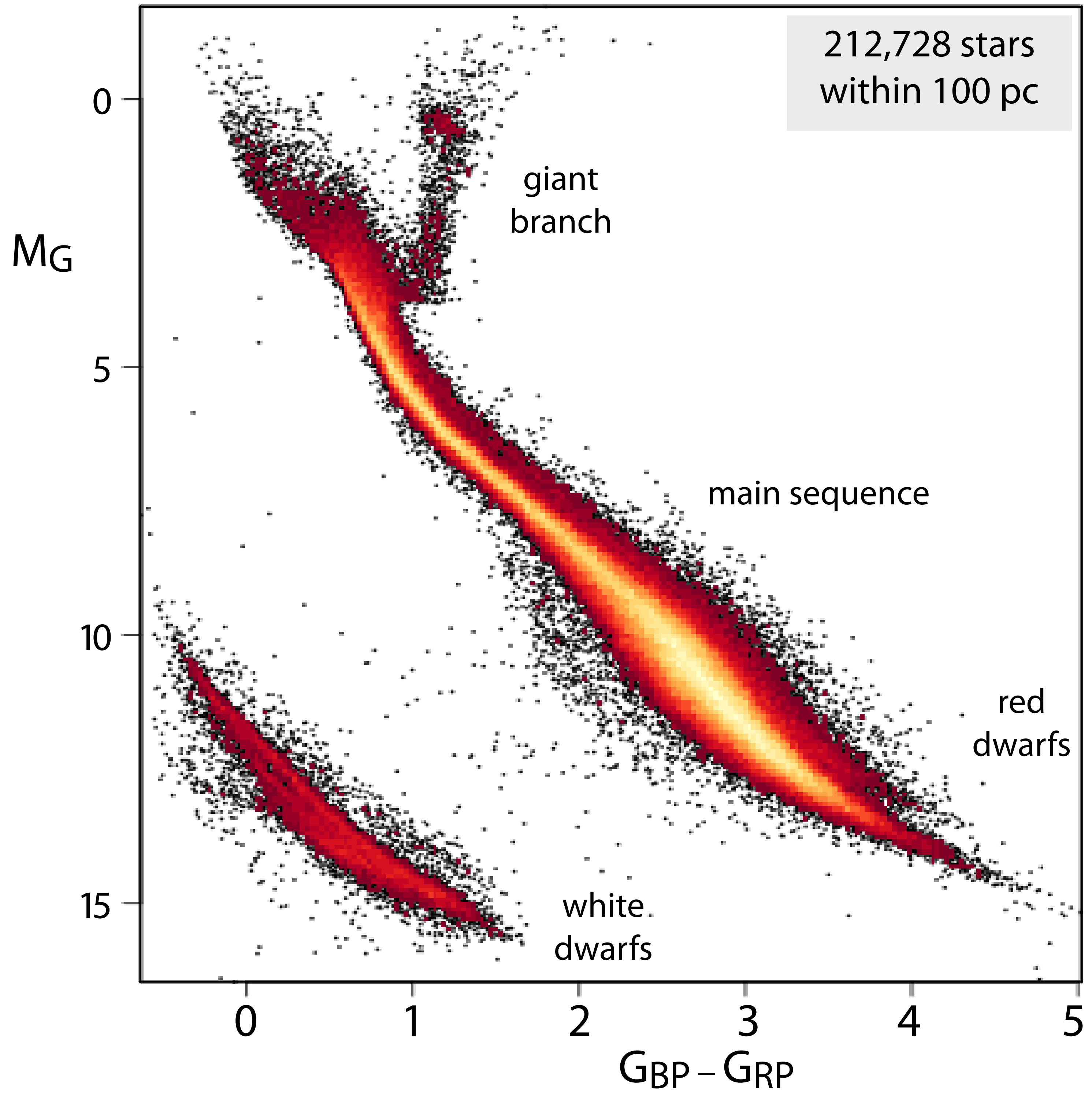
The hot plasma (of nuclei and electrons) releases its latent heat, providing a new source of energy that delays the object's cooling

Gaia reveals the crystallisation as a mass-dependent pile-up in the HR diagram while they release their latent heat

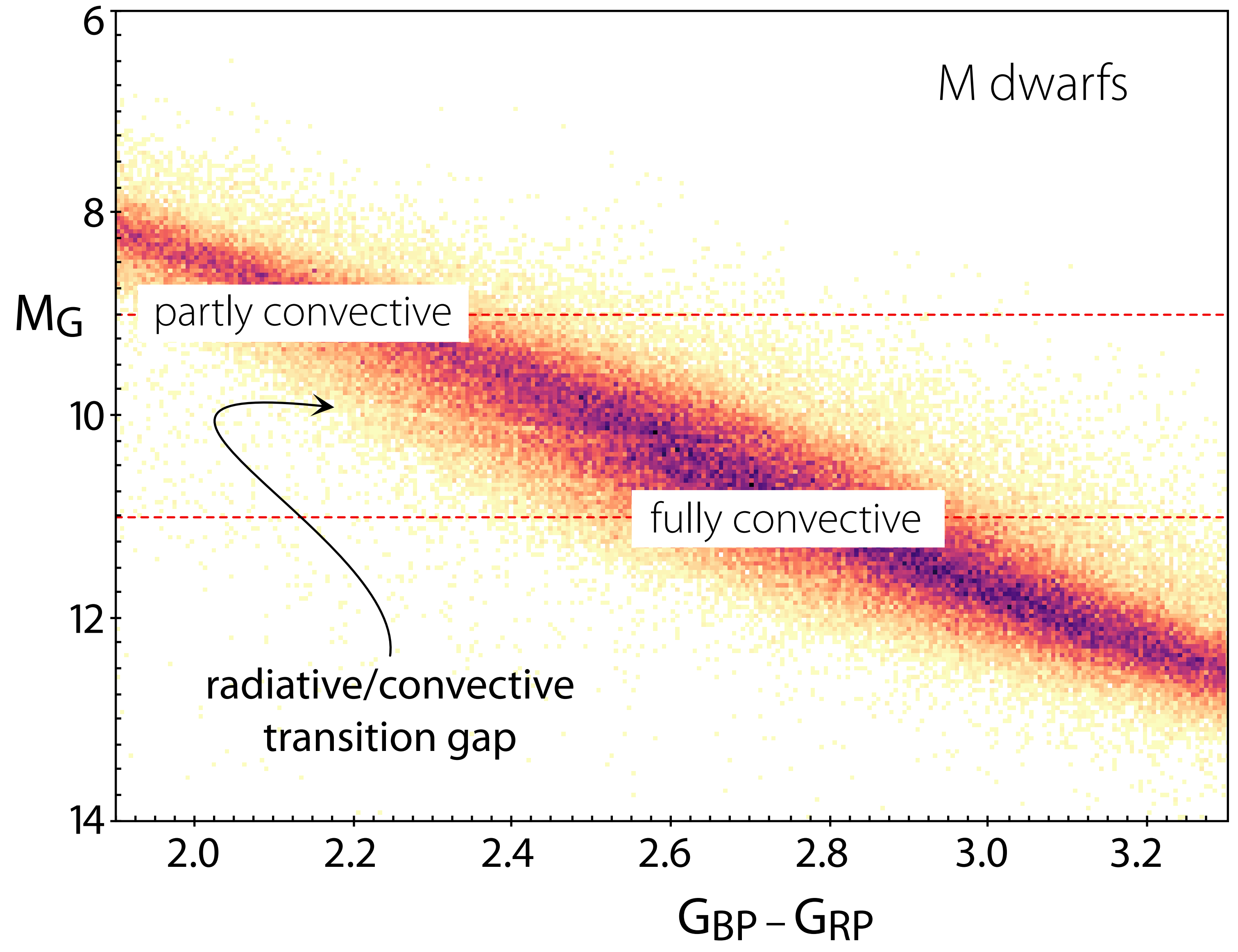
8. Physics of M dwarf interiors

- for M dwarfs, there is another small but significant discontinuity in the Hertzsprung-Russell diagram
- it corresponds to a fundamental transition in interior structure between purely convective (low mass stars), and convective outer + radiative inner
- the mixing affects the rate of nuclear reactions





Hertzsprung-Russell diagram

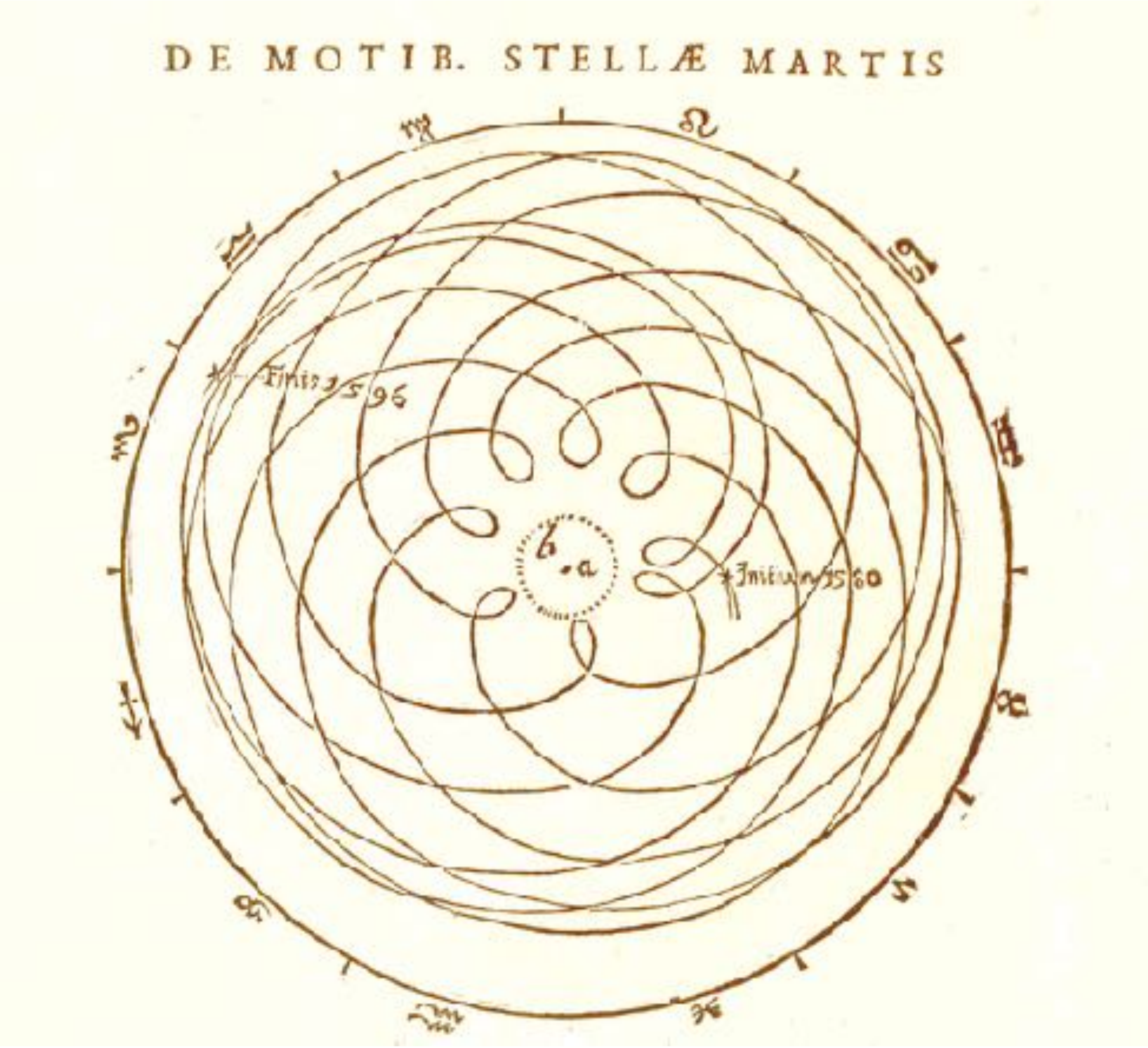


Jao et al. (2018)

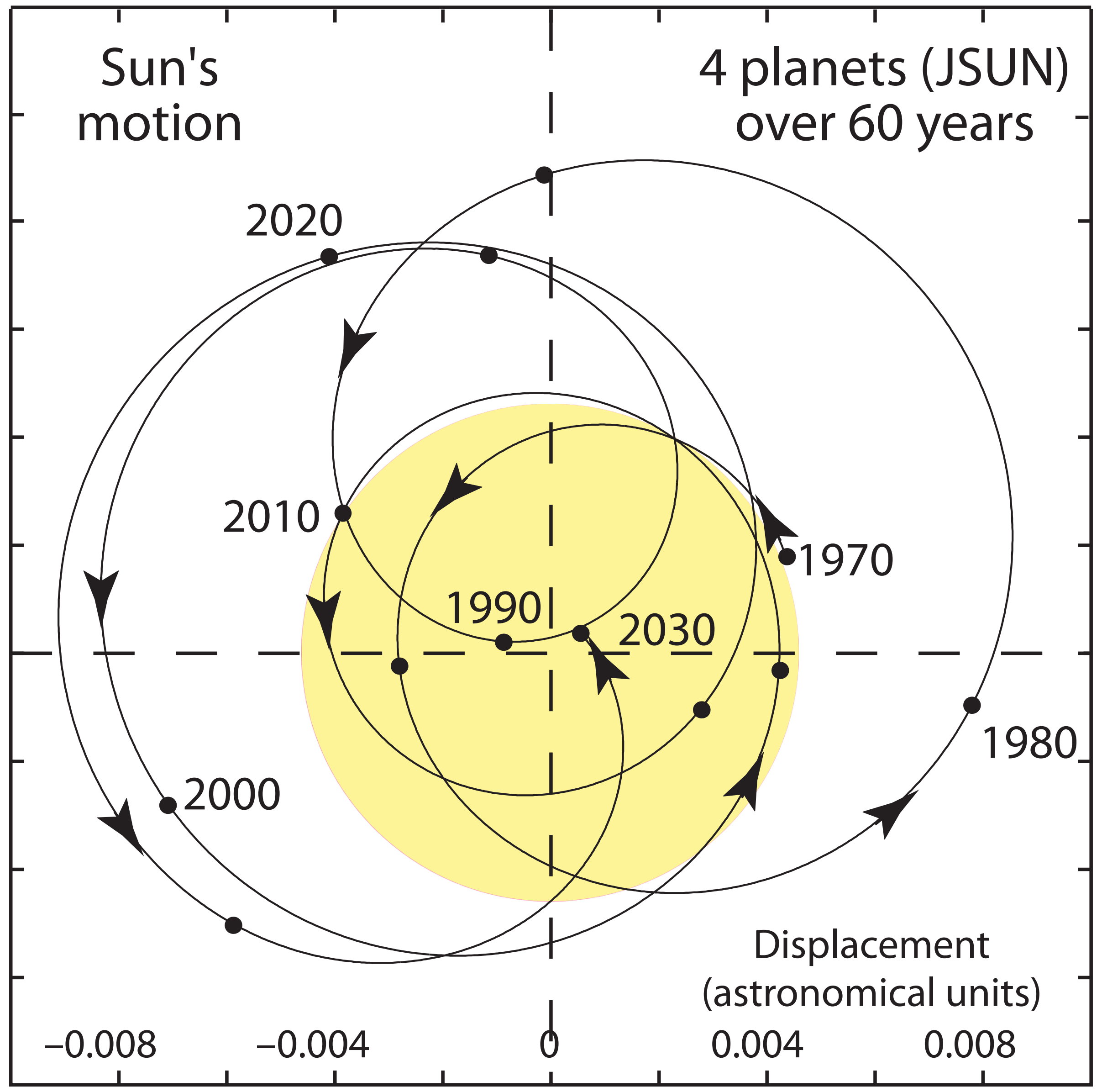
9. Exoplanet mandalas

- the first exoplanets were discovered in 1995
- more than 4000 are known today
- Gaia is expected to discover 30,000 or more from their host star motion (Perryman et al. 2013)
- two or more massive planets result in a complex pattern of the host star motion around the system barycentre, termed ‘mandalas’

Preamble to next slide: Solar rotation is central to the two main hypotheses for the 11-year solar activity cycle: that it is related either to a turbulent dynamo operating in or below the Sun’s convection envelope, or to large-scale oscillations of a fossil magnetic field in its radiative core



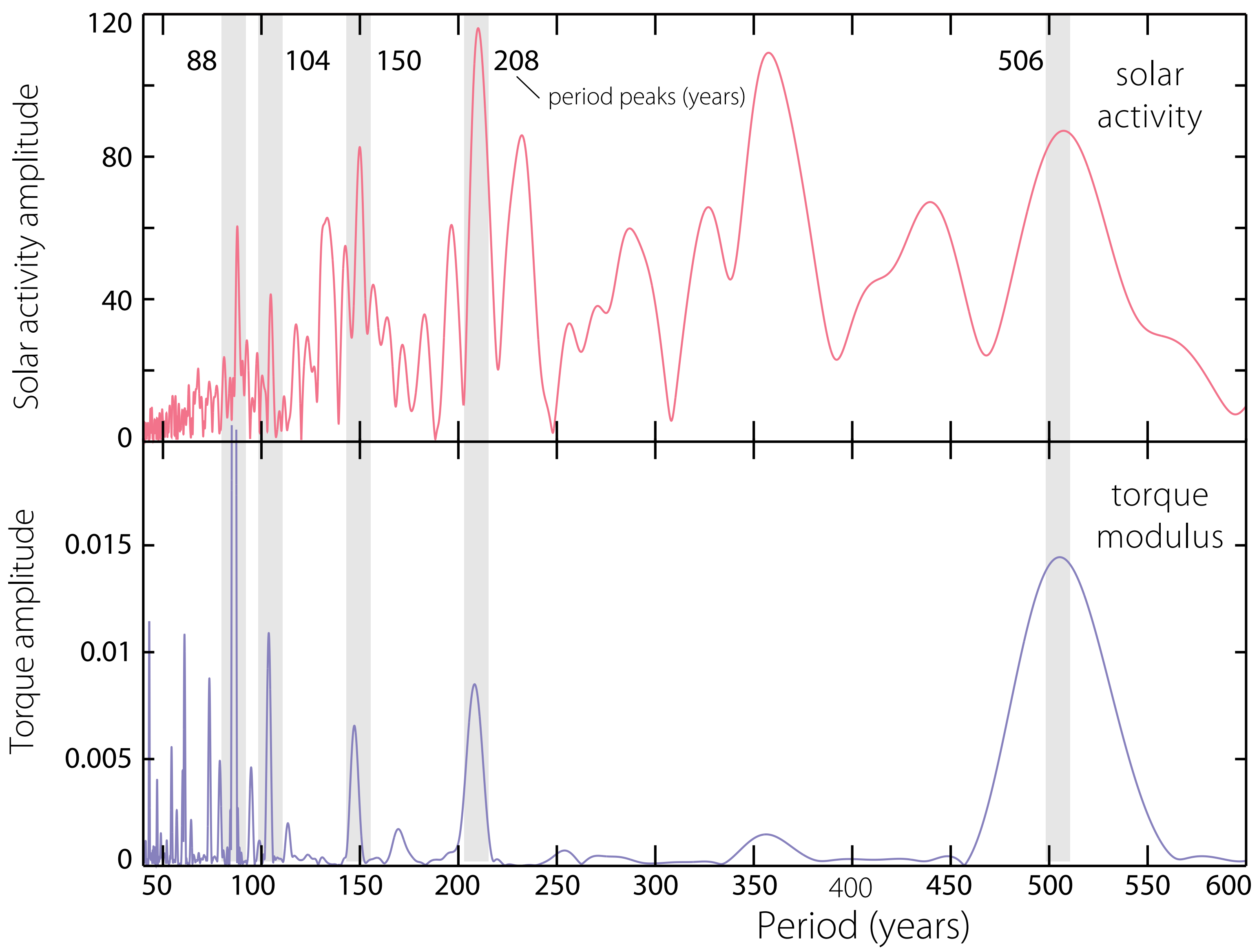
Kepler’s orbit of Mars seen from Earth



The Sun’s orbit wrt solar system barycentre

10. Planets as dark energy detectors ???

- various investigations (since the 1850s) have hinted at a link between the Sun's motion and variability indices
- one suggestion is that activity correlates with intervals of retrograde angular momentum (1632, 1811, 1990)
- one hypothesis: due to tidal forcing at the tachocline ?
- but no clear physical origin has been offered/accepted
- it could be tested using other exoplanet systems (Perryman & Schulze-Hartung 2011)



Two recent papers offer a very different possibility:

- Bertolucci et al. (2017)
  The Sun and its planets as detectors for invisible matter
- Leane & Smirnov (Physical Review Letter, 2021)
  Exoplanets as sub-GeV dark matter detectors

The idea:

- for matter (including dark matter) streaming towards the Sun with velocities $10^{-4} - 10^{-3}\ c$, particles would be gravitationally focused by any planet along its path
- Bertolucci et al. (2017) found a correlation between solar activity and heliocentric longitude of Mercury and Venus, perhaps consistent with preferred directions in the dark matter streams

This can be tested:

- by exoplanet scientists: are other nearby planetary systems affected at the same phases of Galactocentric longitude ?
- by Gaia researchers: is the preferred streaming direction consistent with any known stellar tidal stream ?

Several ongoing experiments in astronomy target a better understanding of dark matter and dark energy (Dark Energy Survey, Euclid 2022)

These are some first ideas about how the Gaia results (for our Galaxy, and our Local Group of galaxies) might advance the understanding of dark matter, both in its spatial distribution, and in its possible interactions with ordinary matter

Is it plausible that within Gaia's huge and accurate data set (which probes fundamental physics across many domains) there is *nothing* which characterises dark matter physics more securely?

Thank you!