Galactic Archaeology for Near-Field Cosmology

Introduction: Local Answers to Difficult Galaxy Questions

Vasily Belokurov
IoA, Hoyle 20, vasily@ast.cam.ac.uk

Data Intensive Science **MPhil** Minor Module

Galactic Archaeology for Near-Field Cosmology

- **Introduction and big picture** (you are here)
  Vasily Belokurov

- **Stars as probes of Galactic Archaeology**
  Anke Ardern-Arentsen

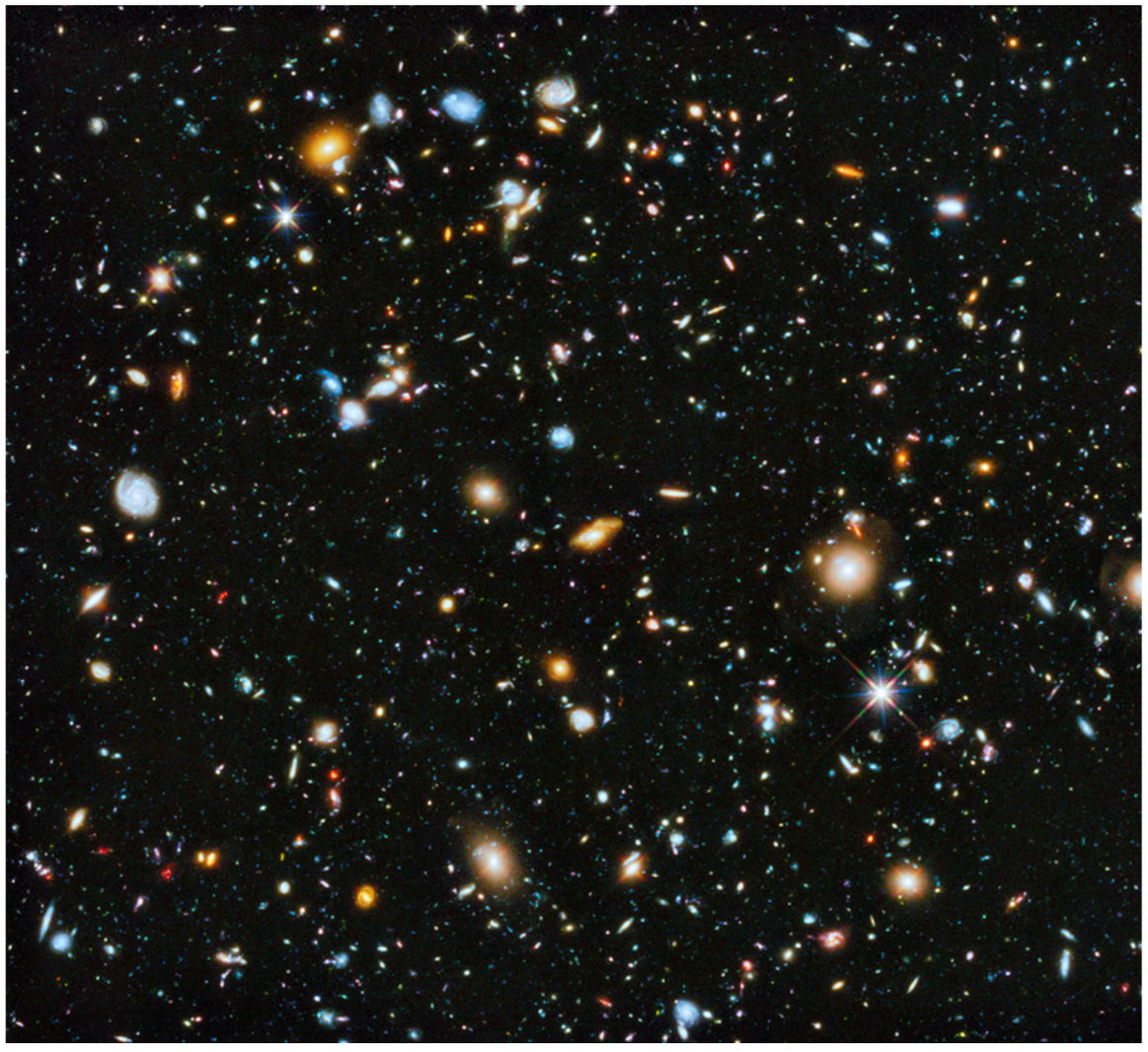
- **The Milky Way and Galactic Dynamics**
  GyuChul Myeong

- **Galaxy evolution in the local Universe**
  Elisabeth Sola

- **Wrap-up**
  Vasily Belokurov

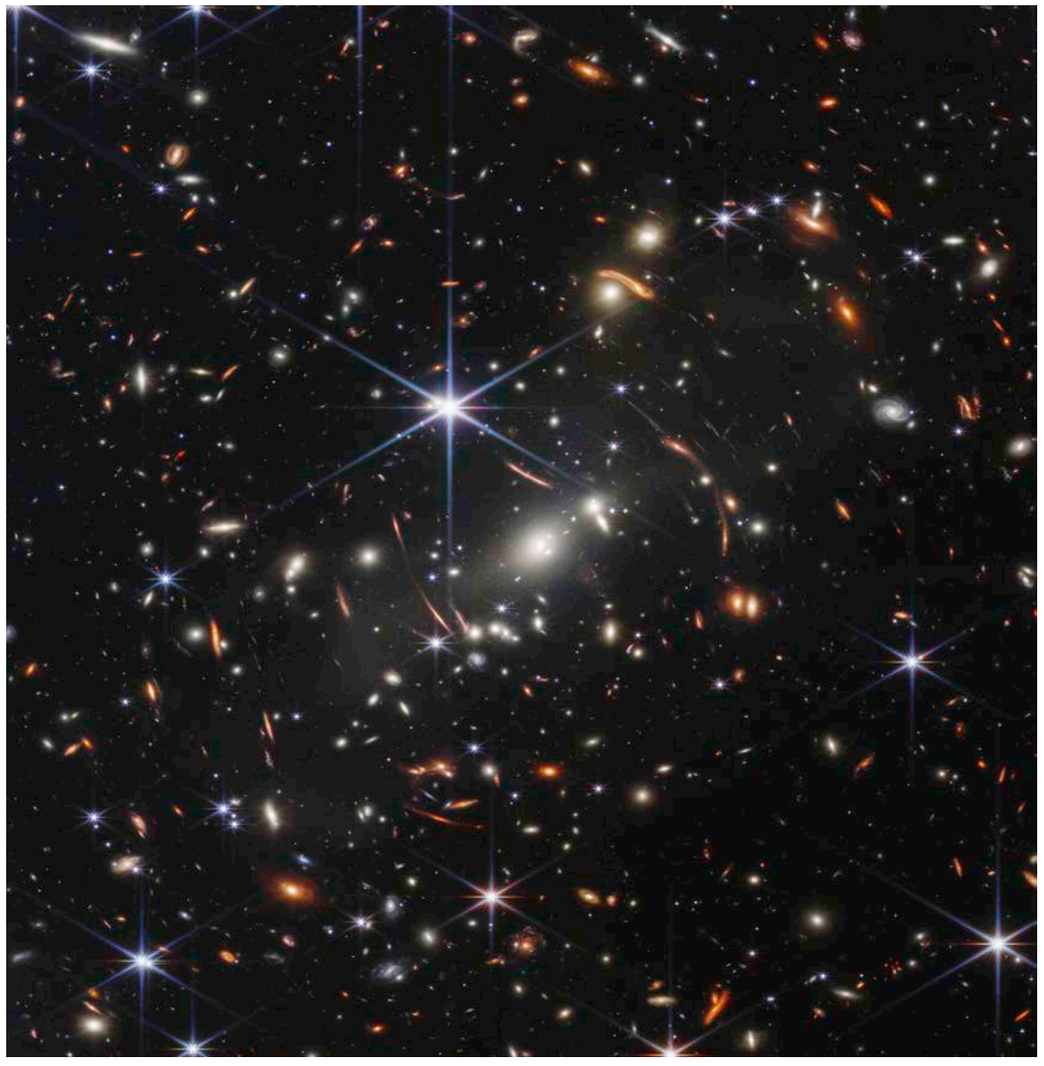
What is a galaxy?

Hubble' Ultra Deep Field



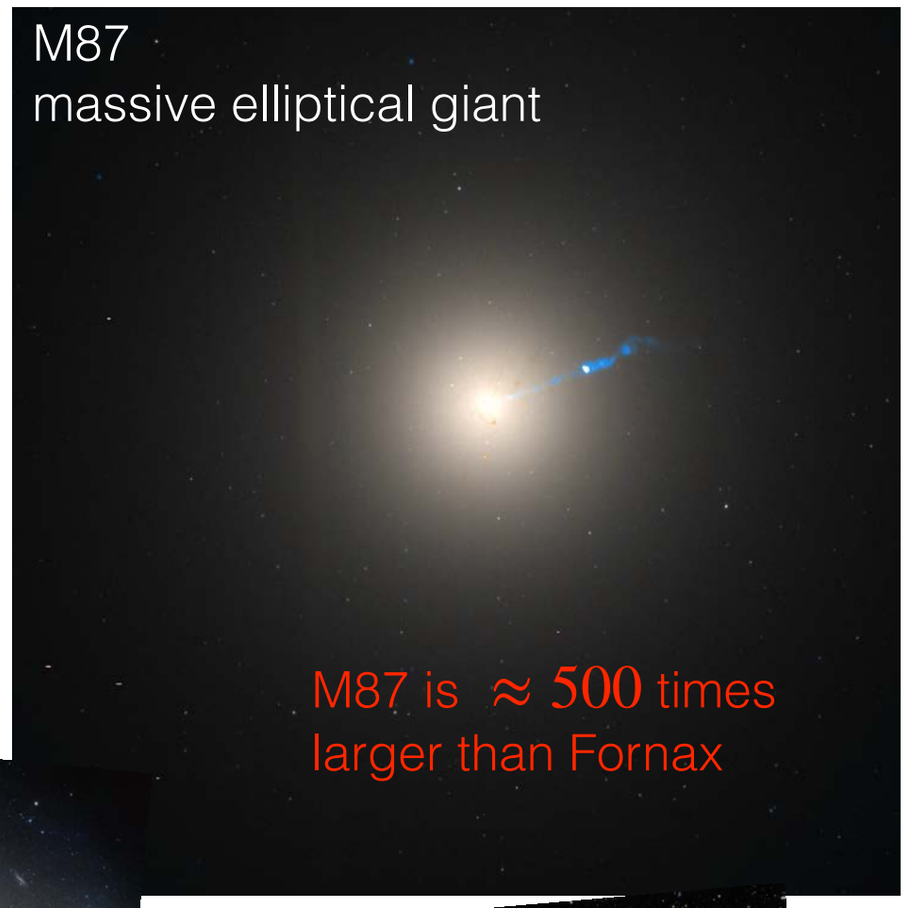
1000 HST orbits 10,000 galaxies

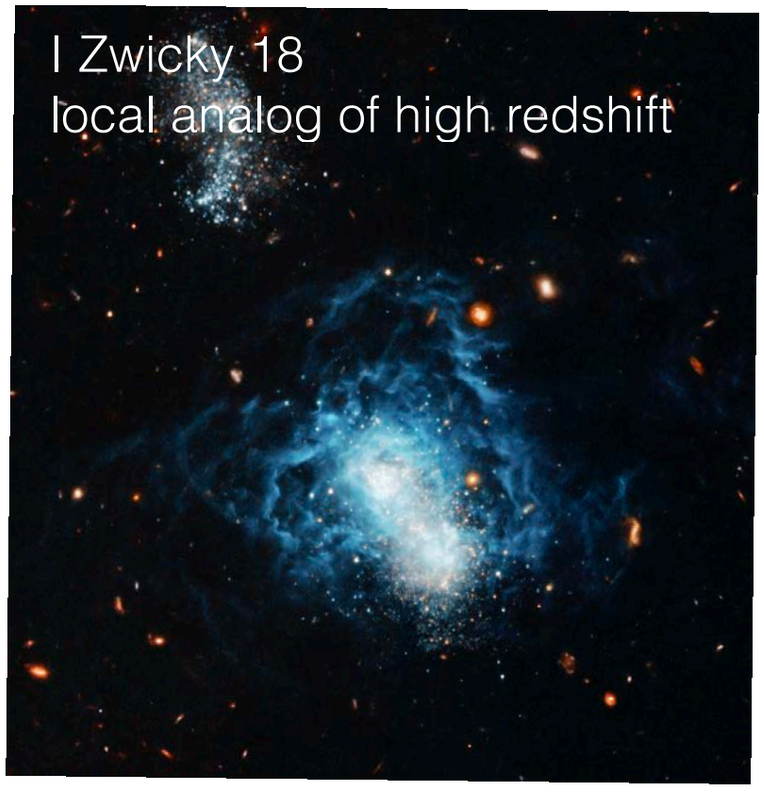
JWST's first Deep Field



12.5h exposure 1000s of galaxies

What is a galaxy?





What is a galaxy?

A shocking truth

Video clip of BBC's QI panel show with Stephen Fry

What is a galaxy?

A working definition

- A stellar system dominated by **Dark Matter**

The object needs to have most of its mass locked in Dark Matter and it needs to have formed some stars.

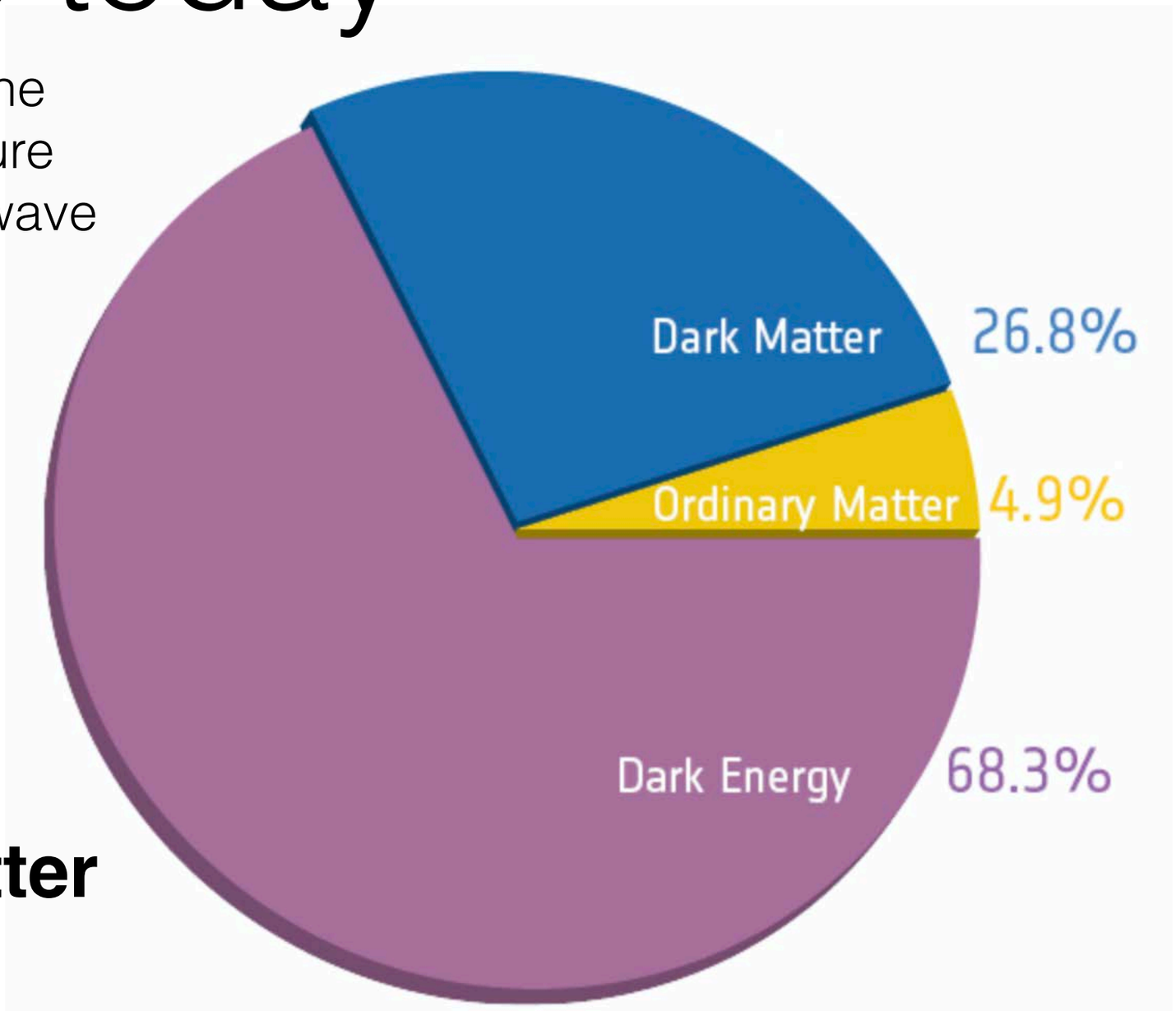
According to this ad-hoc definition, a cloud of Dark Matter mixed in with hydrogen gas is not a galaxy, neither is a cluster of stars

Questions about galaxies are questions about the nature of **Dark Matter** and the **physics of star formation**

Dark Matter???

Energy density make-up of the Universe today

Based on the measurements of the power spectrum of the temperature fluctuations in the Cosmic Microwave Background

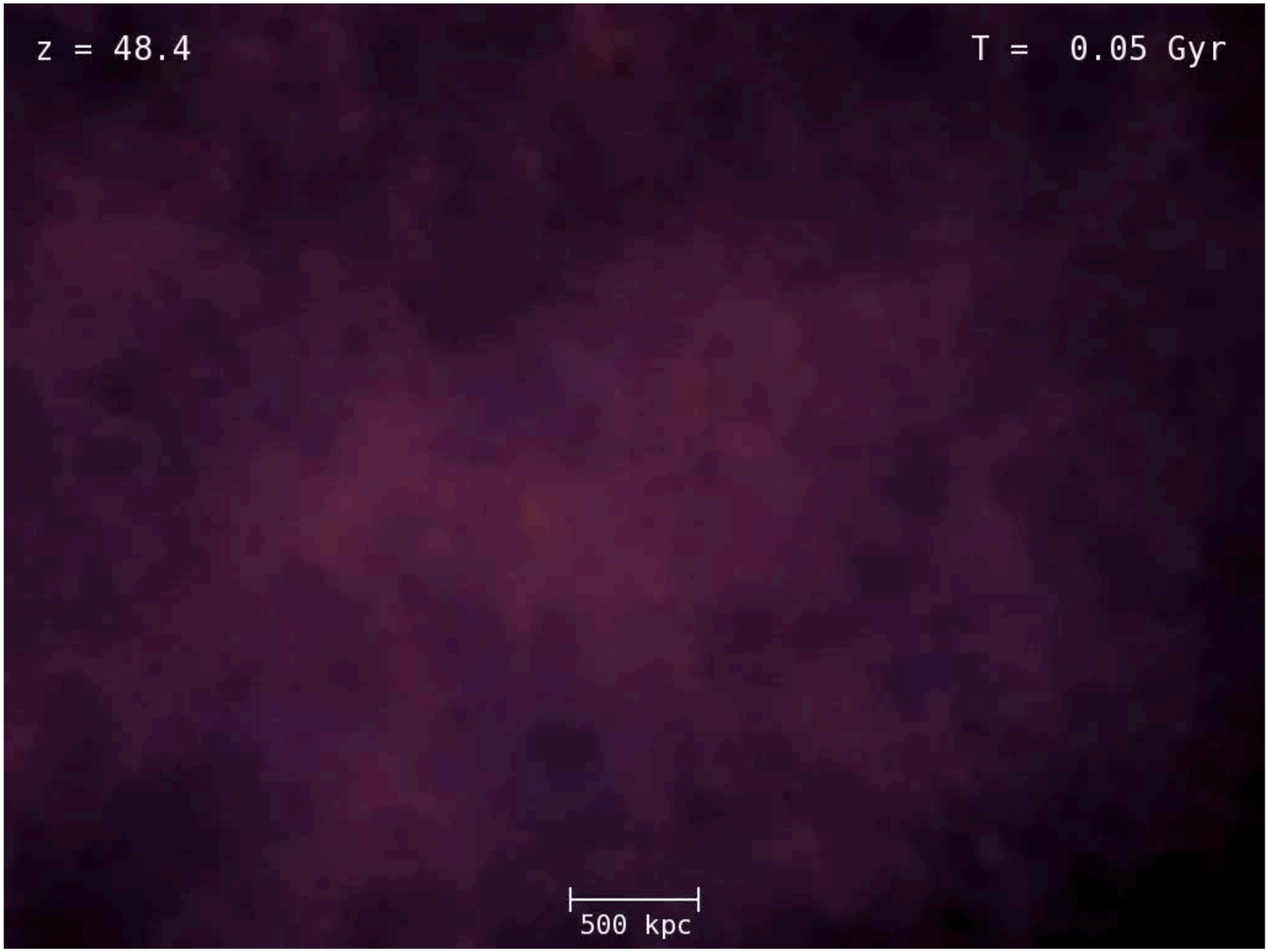


Based on ESA Planck measurements

The ratio of (Universe average) **Dark Matter density** to (Universe average) **ordinary matter density** is $\approx 5/1$

Dark Matter halo formation

this halo would host a typical galaxy like our own Milky Way



Animation of computer simulation of the Milky Way DM halo formation by Aquarius, Springel et al 2008

Dark Matter assembles into an **enormous** diffuse cloud, known as **halo**

The extent of the DM halo is ~500 kpc, 10-20 times larger than the extent of the MW disc

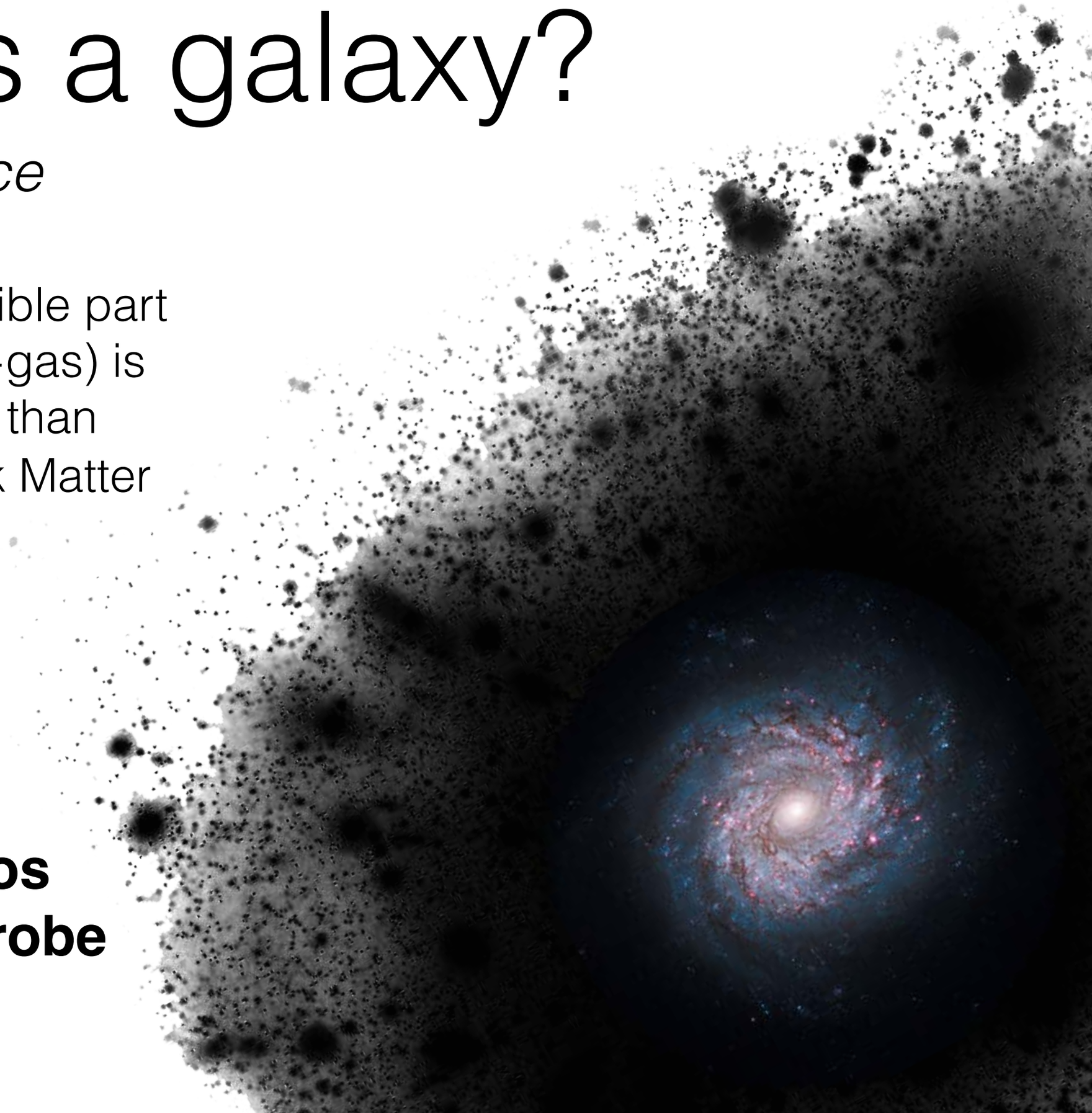
The halo's mass distribution is established early (by $z \approx 1$) and changes little subsequently

Dense lumps of DM form early and survive to redshift $z = 0$

What is a galaxy?

An empty space

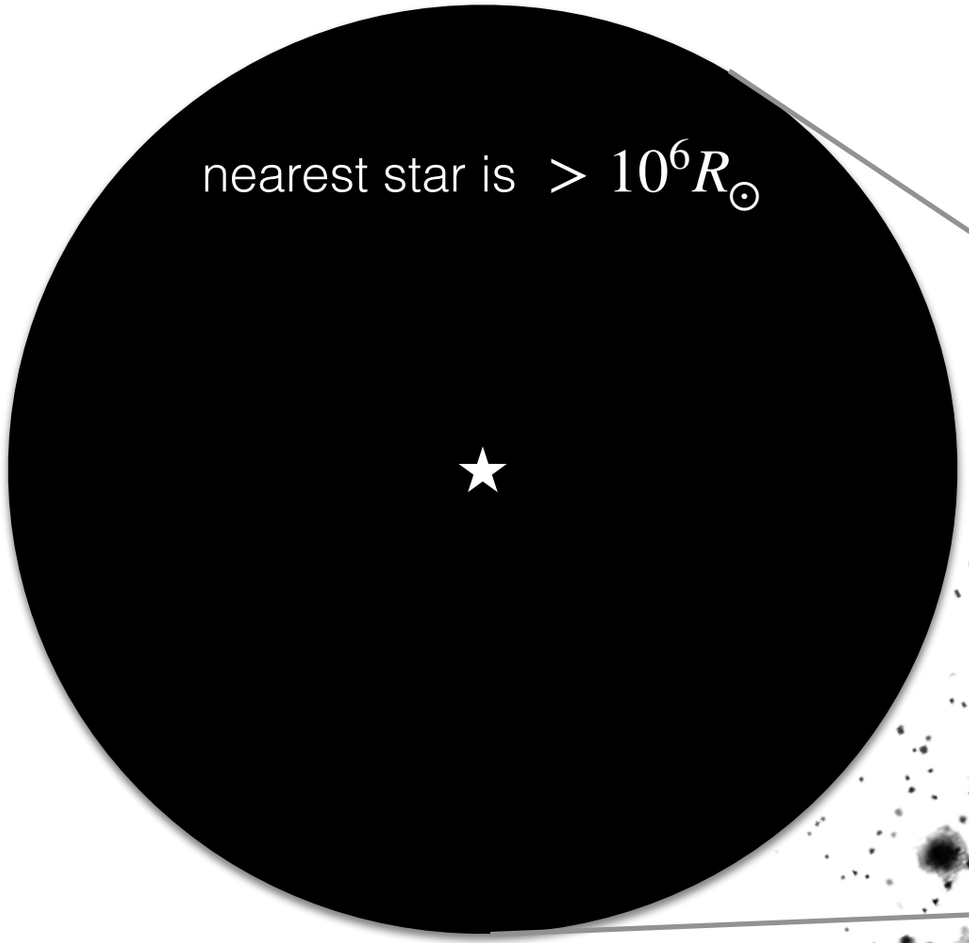
The extent of the visible part of the galaxy (stars+gas) is ≈ 10 times smaller than the extent of its Dark Matter “halo”



“empty” DM halos are difficult to probe

What is a galaxy?

An empty space



Typical distance between stars in a galaxy in relative terms is like distance between two rice grains on opposite sides of Cambridge

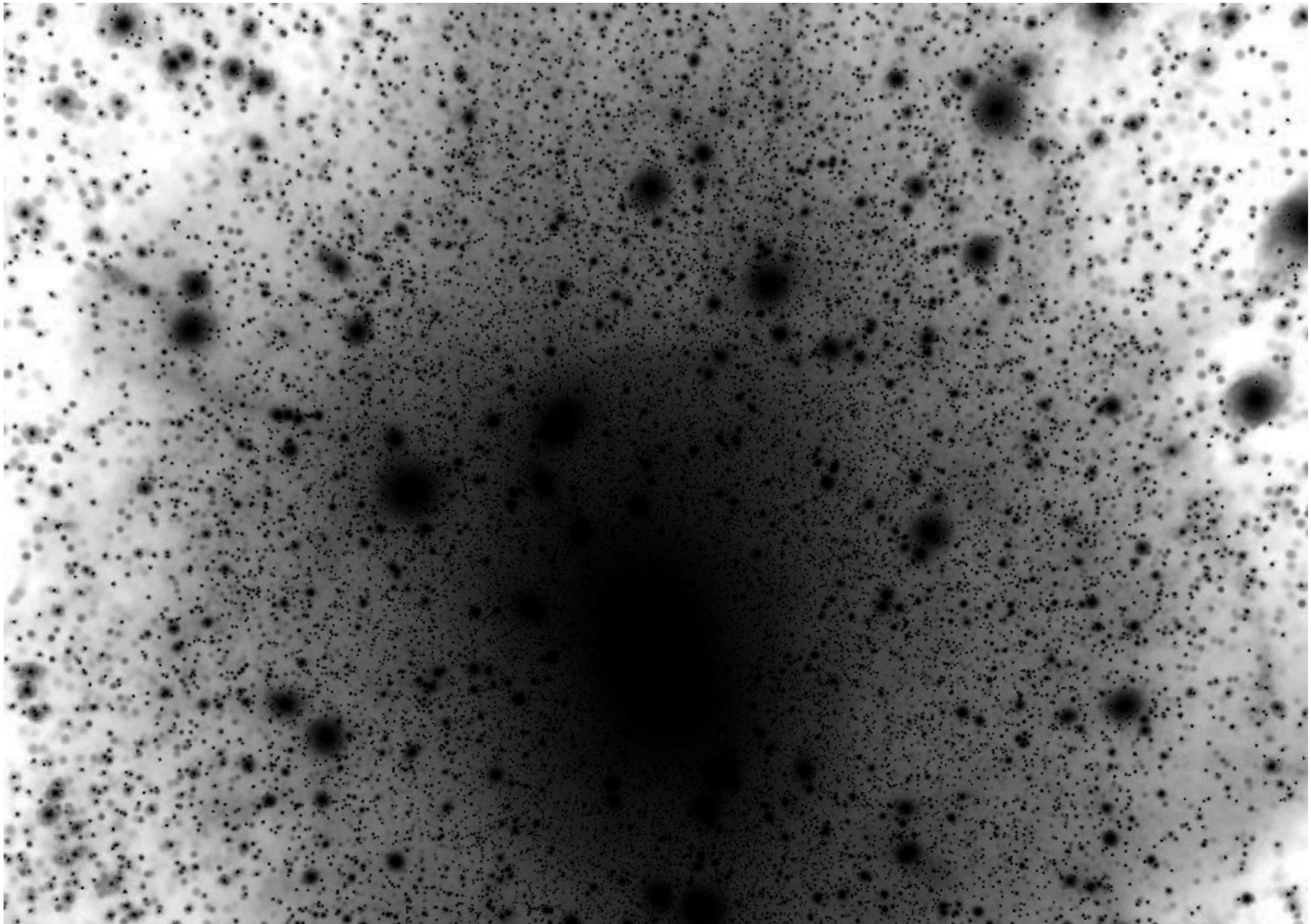
stars never interact

Unanswered galaxy formation and evolution **questions**

- **What is Dark Matter and is it Cold?**
  The 3D shape and the radial density profile of Dark Matter distribution, the lumpiness of Dark Matter, Dark Matter sub-halo mass function
- **How did first stars form?**
  Metal-free star formation, stellar Initial Mass Function and its universality and variations, re-ionisation of the Universe, nucleosynthetic sites and yields
- **How did first galaxies form?**
  Gas consumption in Early Universe, massive star clusters, disk emergence, super-massive black holes and their seeds

Dark Matter

Why have not we answered these questions already?



Aquarius, Springel et al 2008

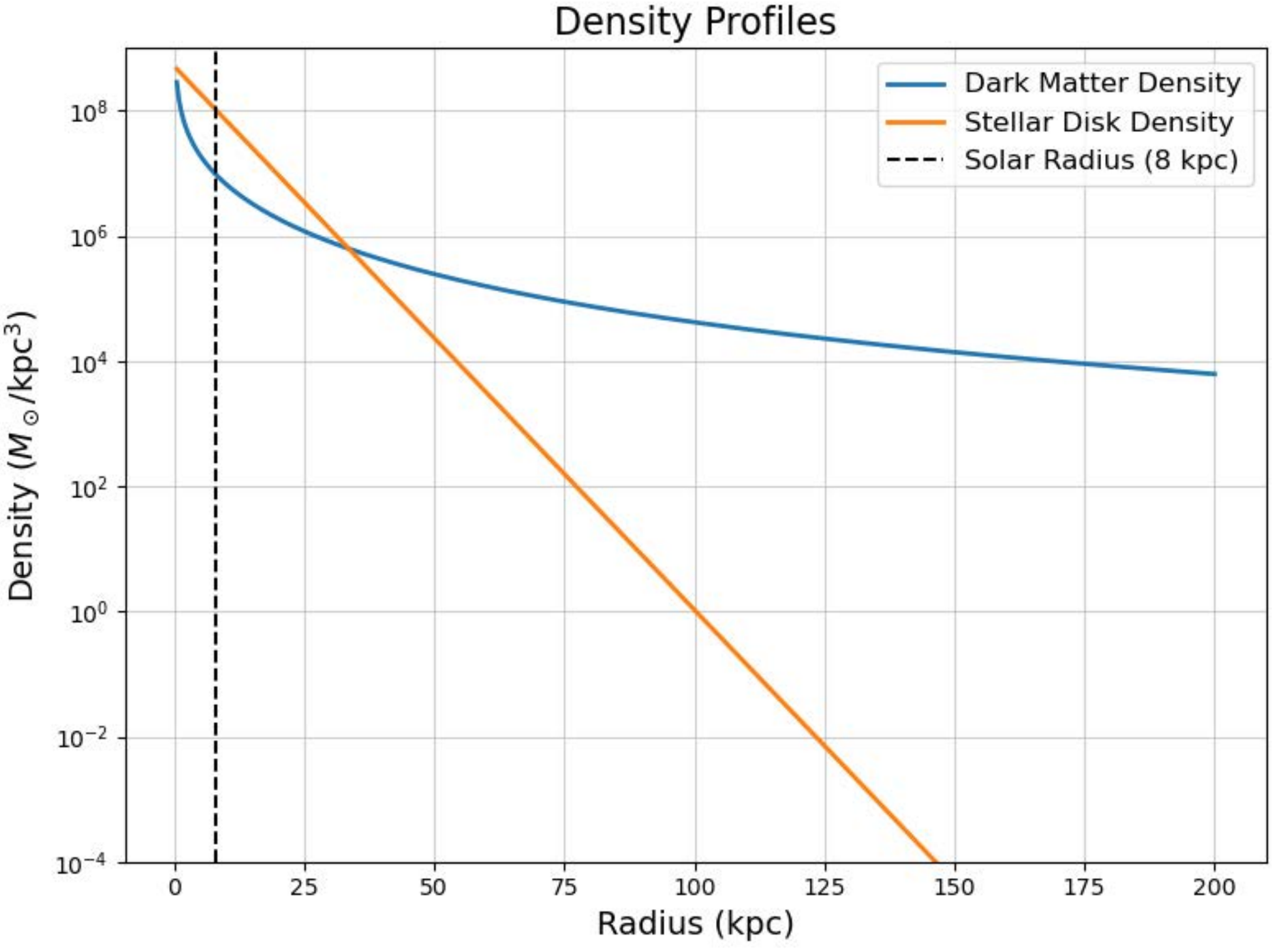
Most of the Dark Matter questions

are linked with the pragmatic issue

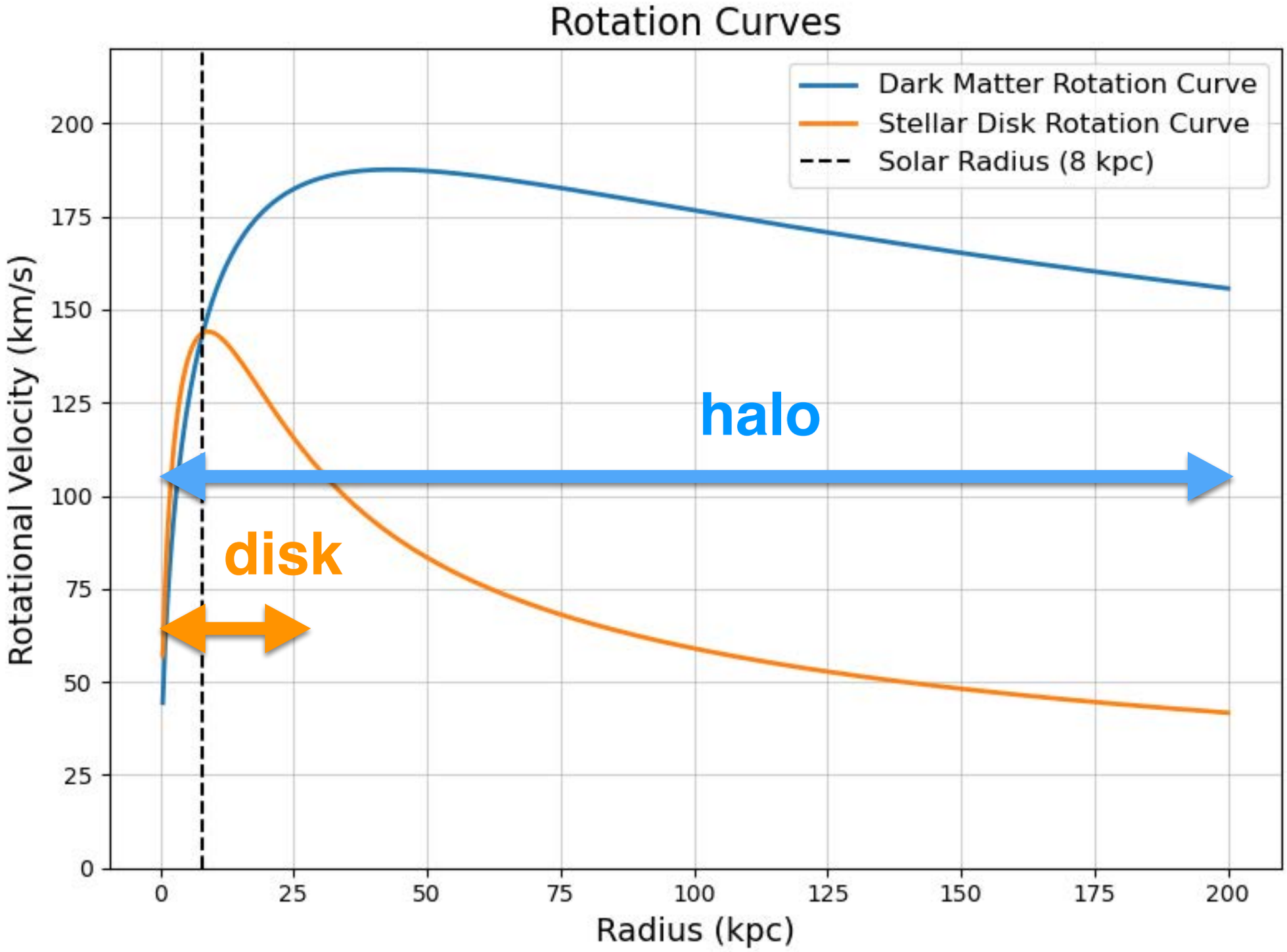
of surveying a vast structure

mostly **devoid** of baryons and light

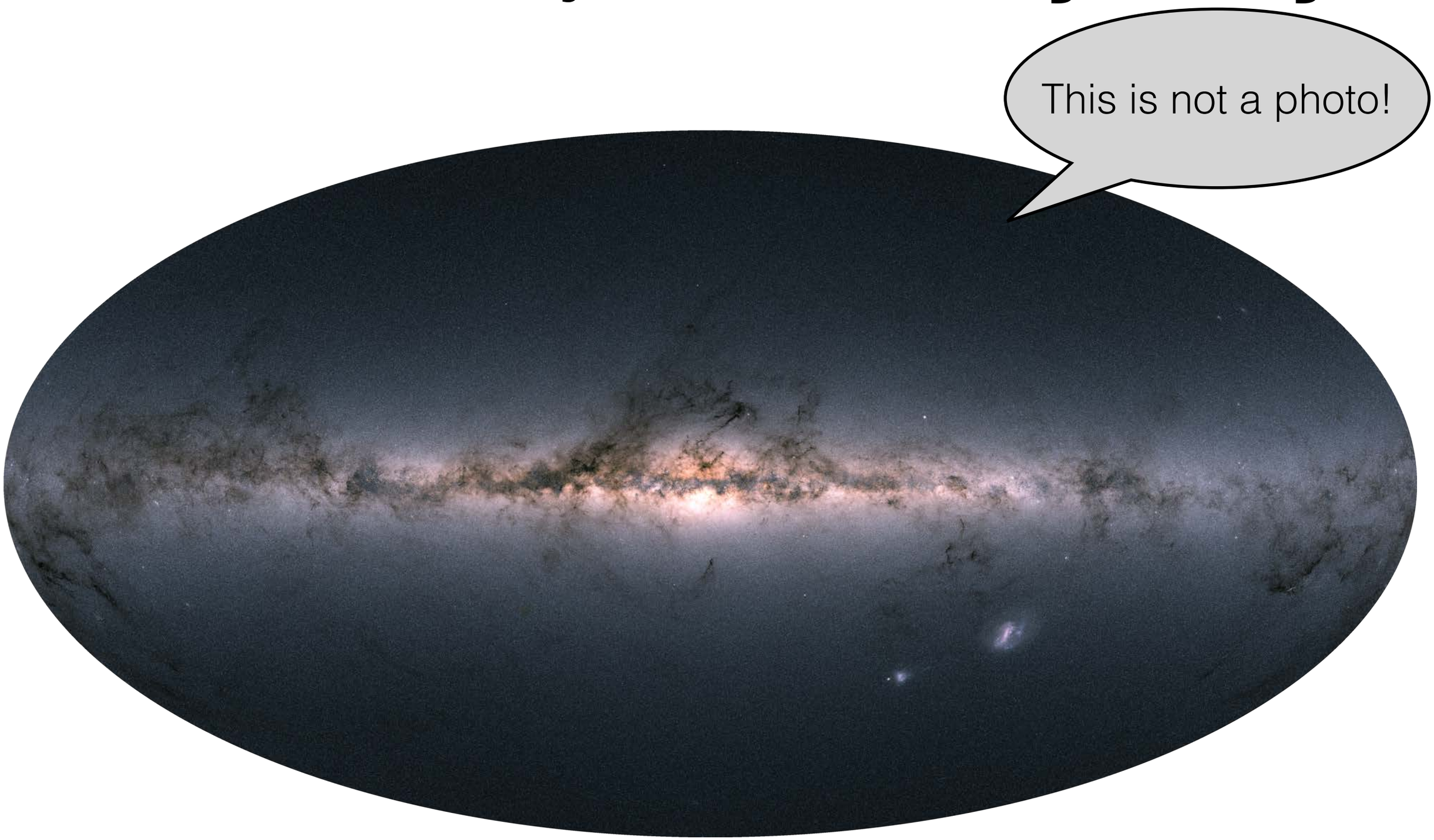
Mismatched coexistence



Mismatched coexistence



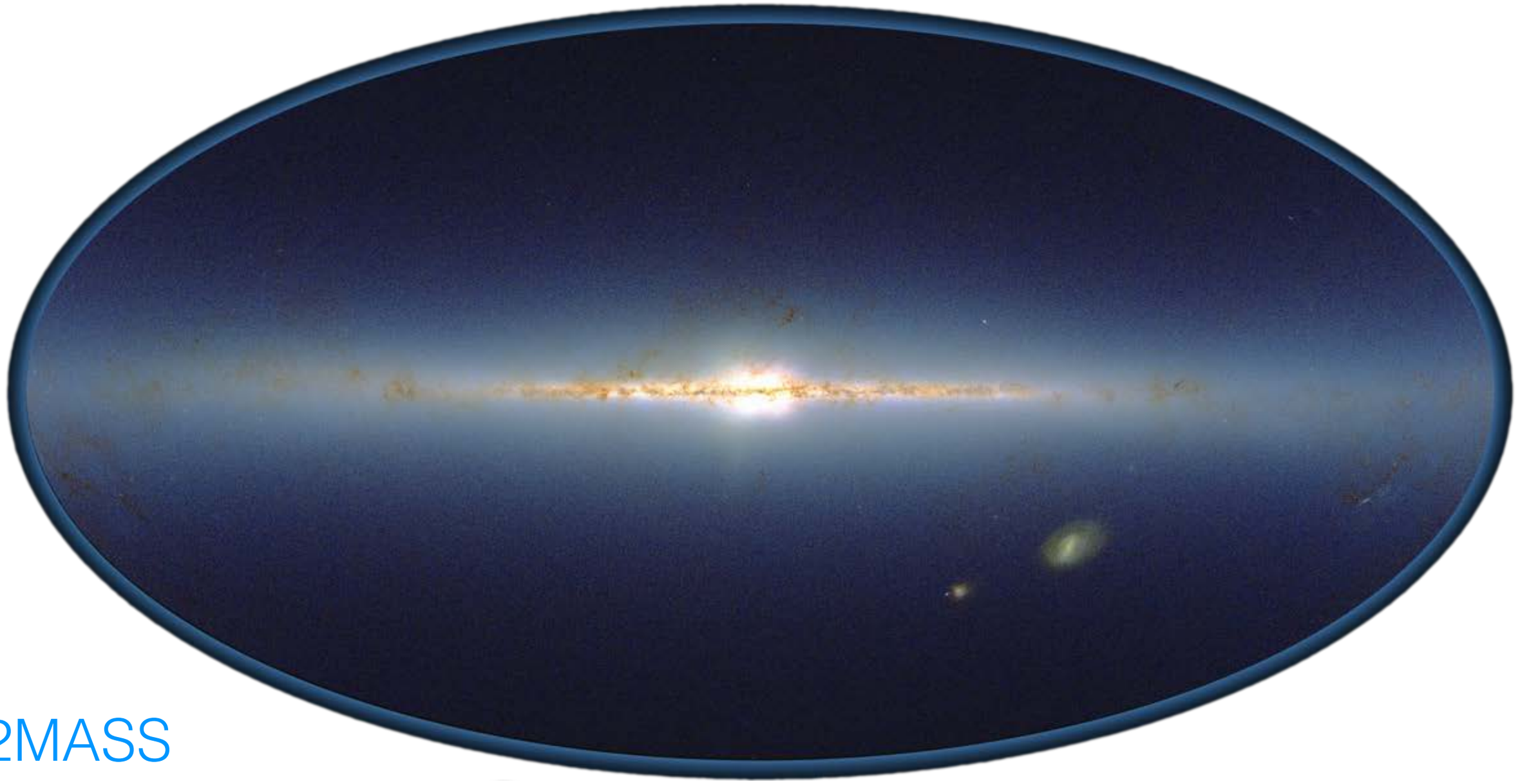
Our Galaxy, the **Milky Way**



ESA Gaia, Data Release 2

Our Galaxy, the **Milky Way**

This is a stitched-together panoramic **photo** of the entire sky in near-infrared



2MASS

Our Galaxy, the Milky Way

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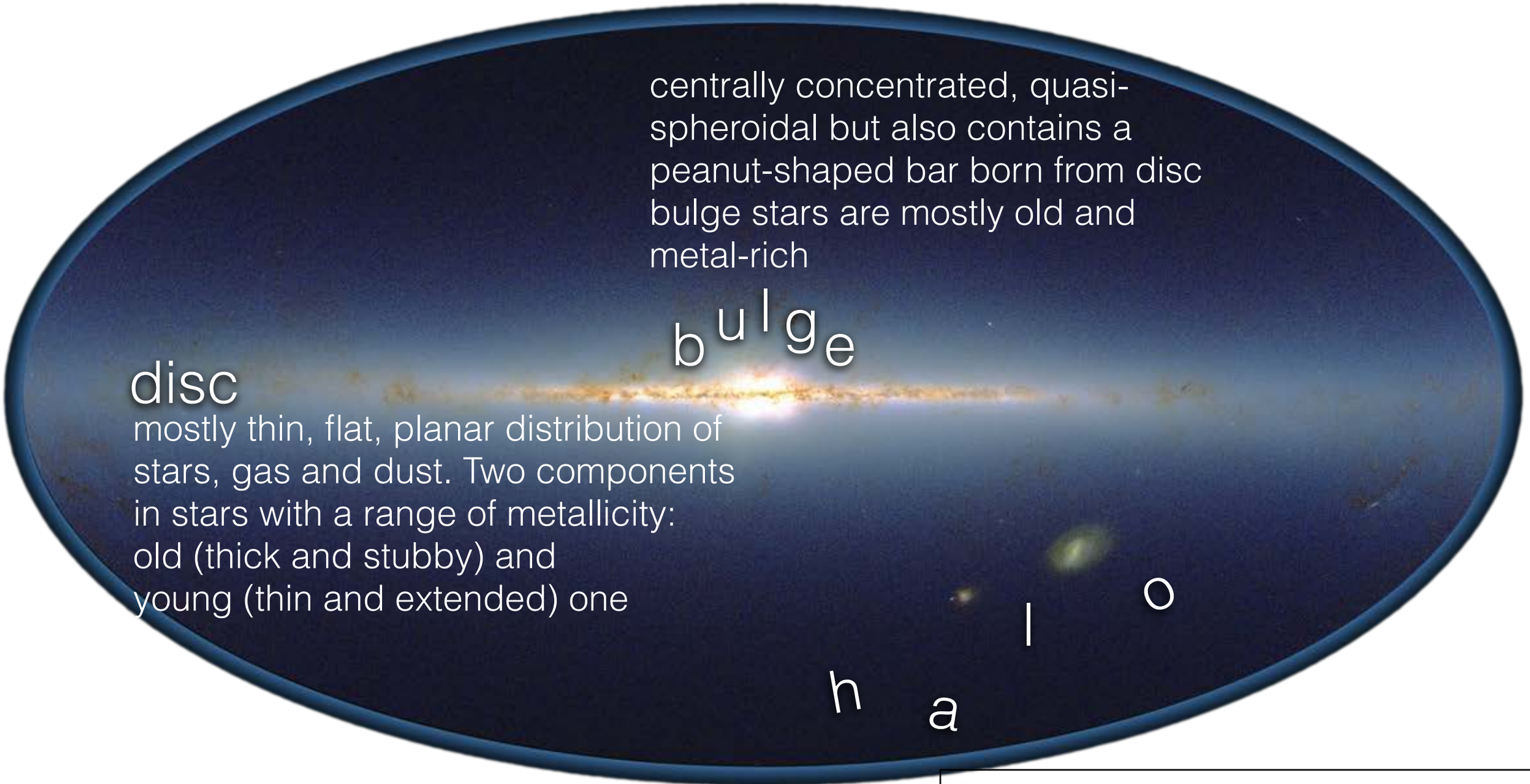
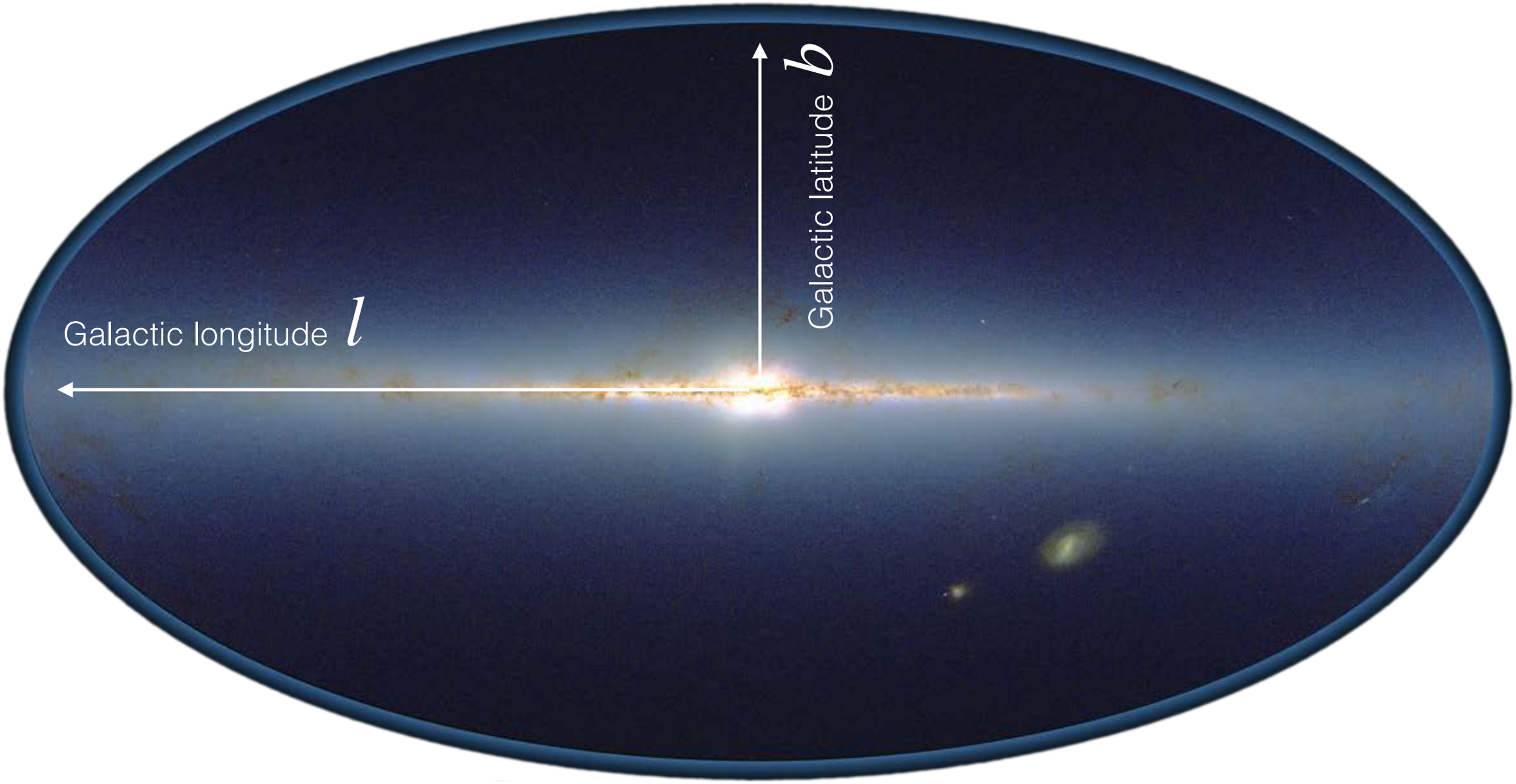


Note that the view of our Galaxy and any other galaxy as composed of fixed components is outdated as galaxies constantly evolve and transform

Galactic halo - any matter far away from the disc plane, it contains
$< 0.1\,\%$ of the Galaxy's mass but
$\approx 99\,\%$ of information on its evolution

Our Galaxy, the Milky Way

This is a stitched-together panoramic photo of the entire sky in near-infrared



This is also serves to explain one of the celestial coordinate systems which is aligned with the Galactic disc: the longitude l changes along the disc and the latitude b changes in a perpendicular direction

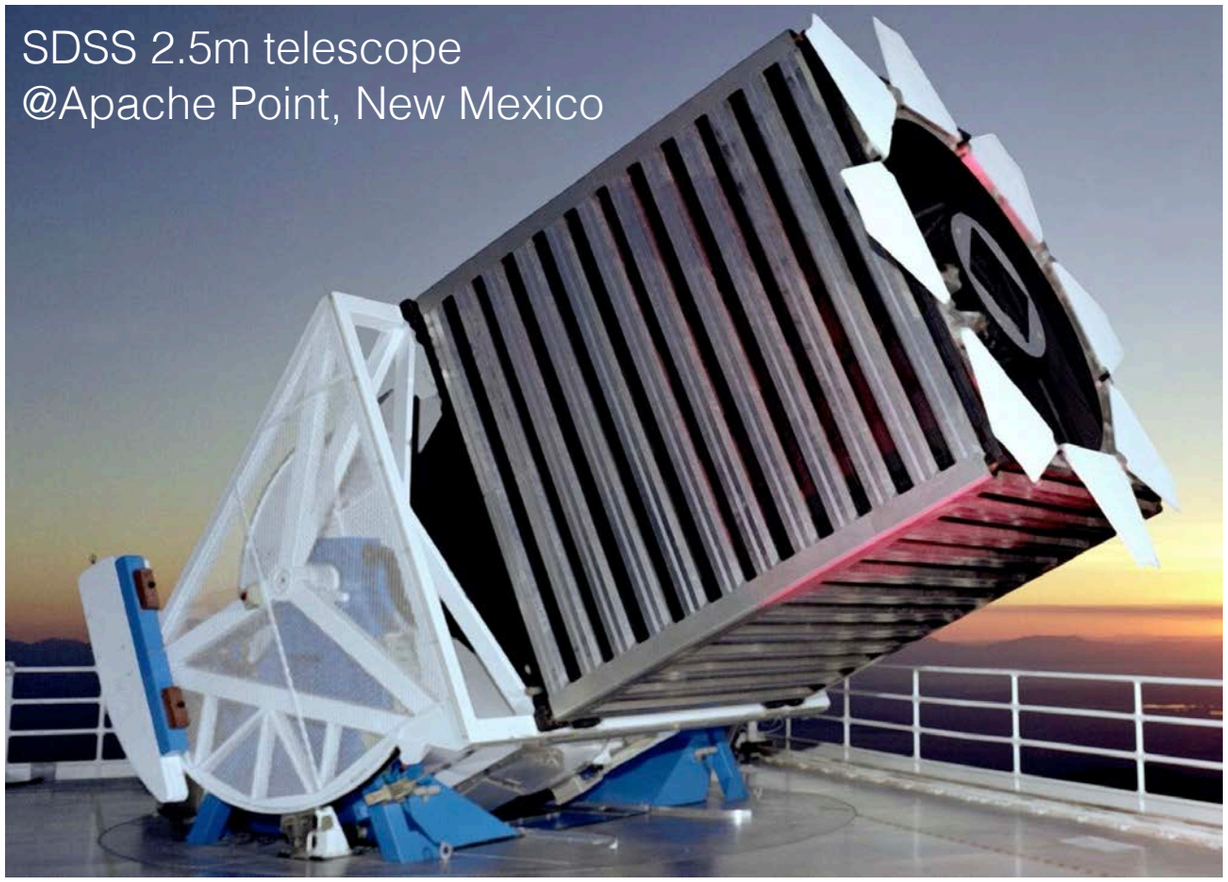
Recent breakthrough

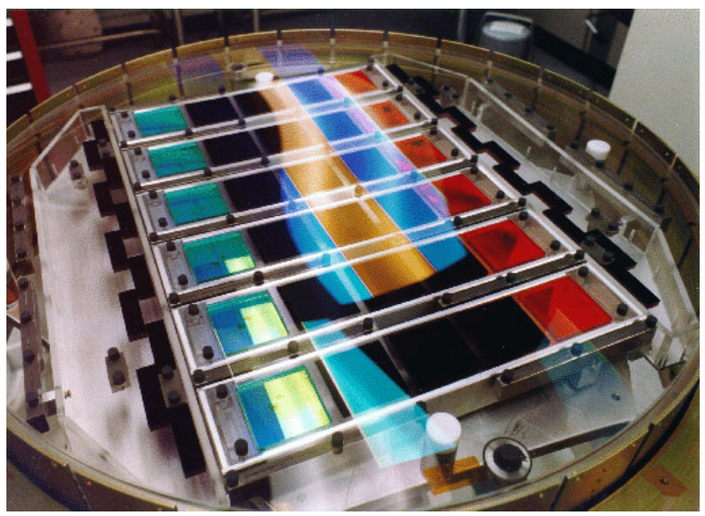
all-sky imaging
surveys

pushing galactic halo studies to
extreme surface brightness

Sloan Digital Sky Survey

pioneering all-sky robotic imaging





SDSS photometric system filters

	u	g	r	i	z
Mean wavelength (nm)	355.1	468.6	616.5	748.1	893.1
Magnitude limit	22.0	22.2	22.2	21.3	20.5

Sloan Digital Sky Survey

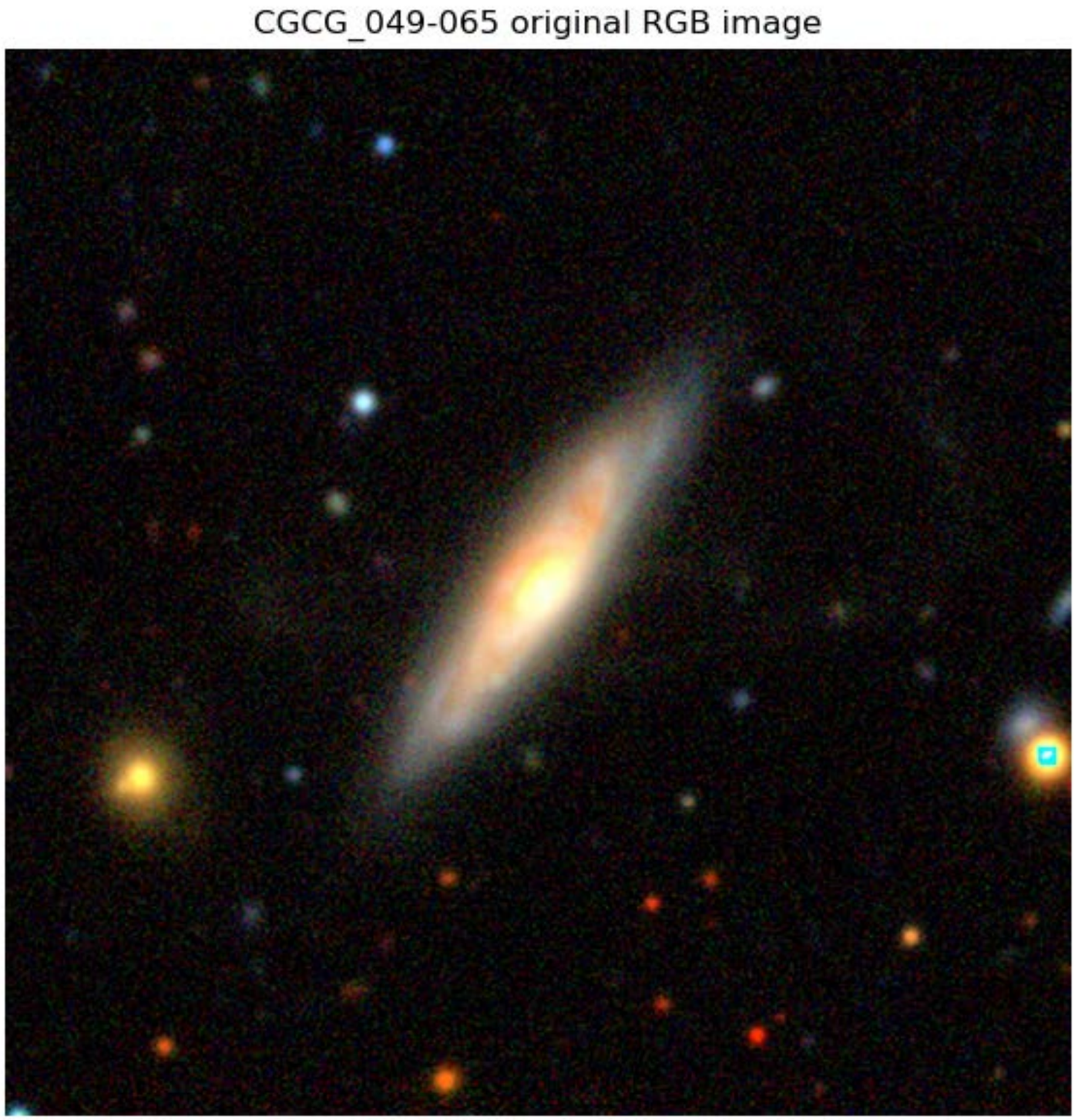
pioneering all-sky robotic imaging

- Used the drift-scanning techniques to get large portions of the sky quickly with consistent uniform quality

- Went both wide (1/4 of the sky) and deep (as faint as 23 mag in the r band)

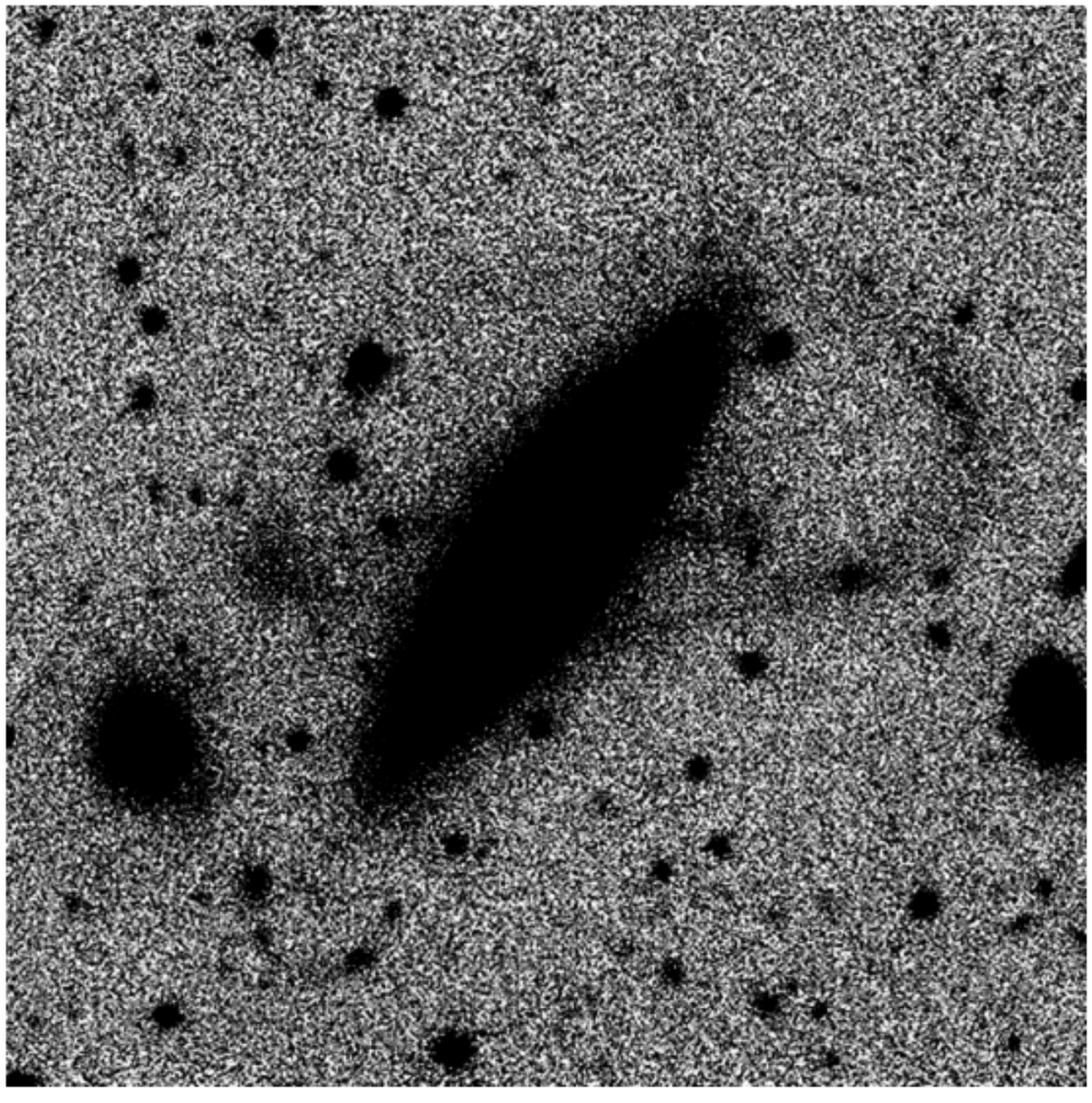
- Released all images (hundreds of millions of objects) and catalogues publicly through a queryable database

What lurks around galaxies?

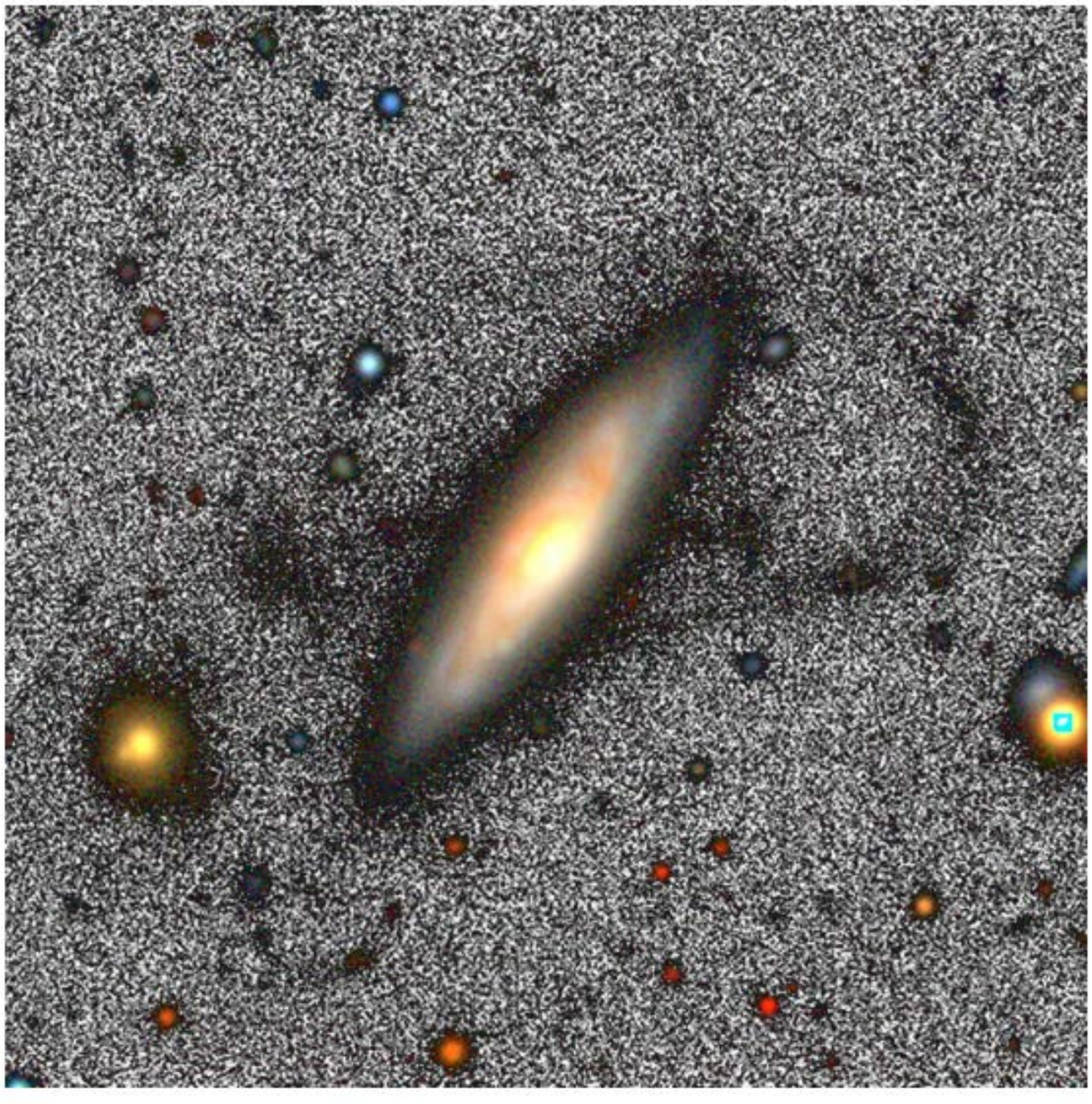


Ghostly streams!

CGCG_049-065 inverted stretched B&W image

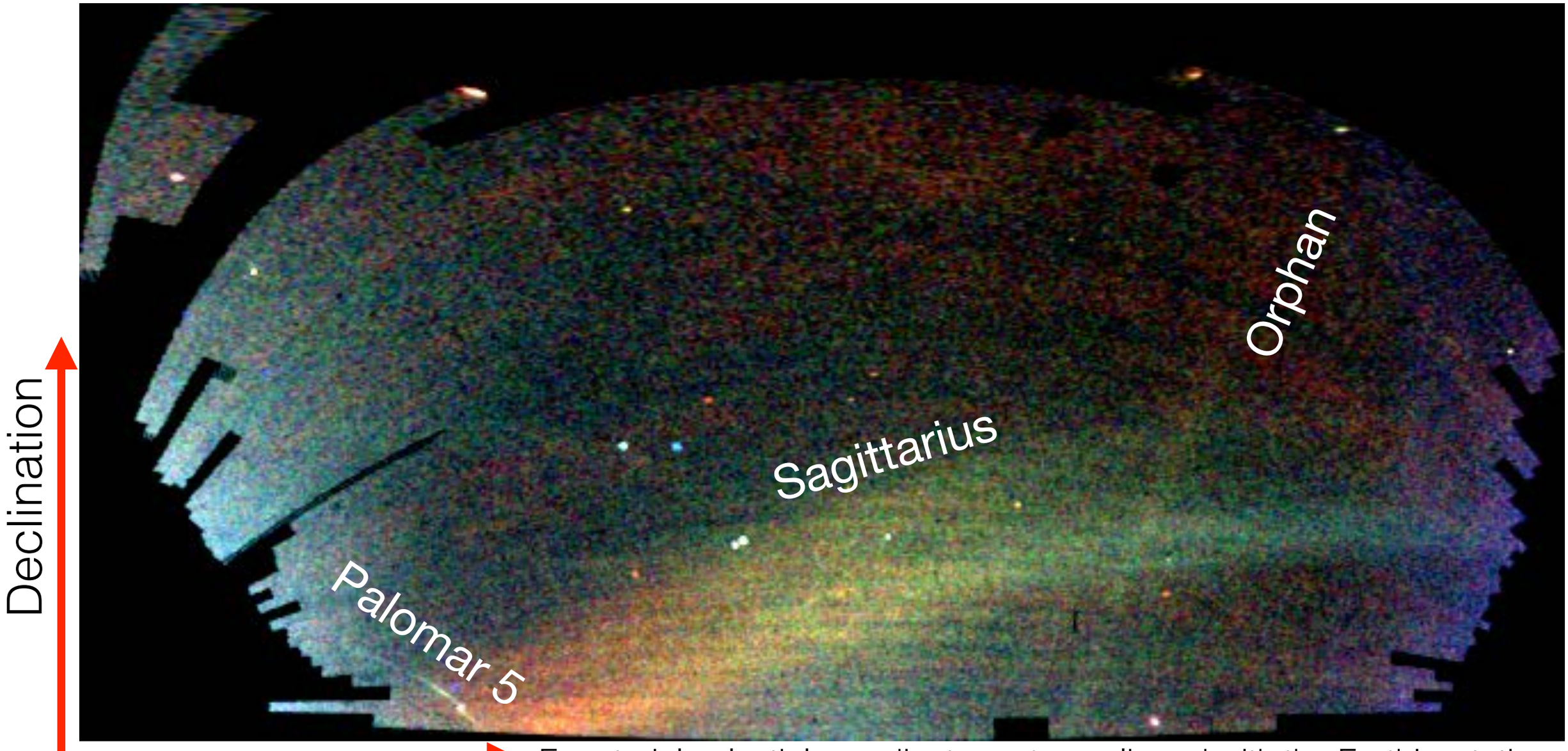


CGCG_049-065 combined RGB with inverted B&W (max mode)



In our own Galaxy: **the field of streams**

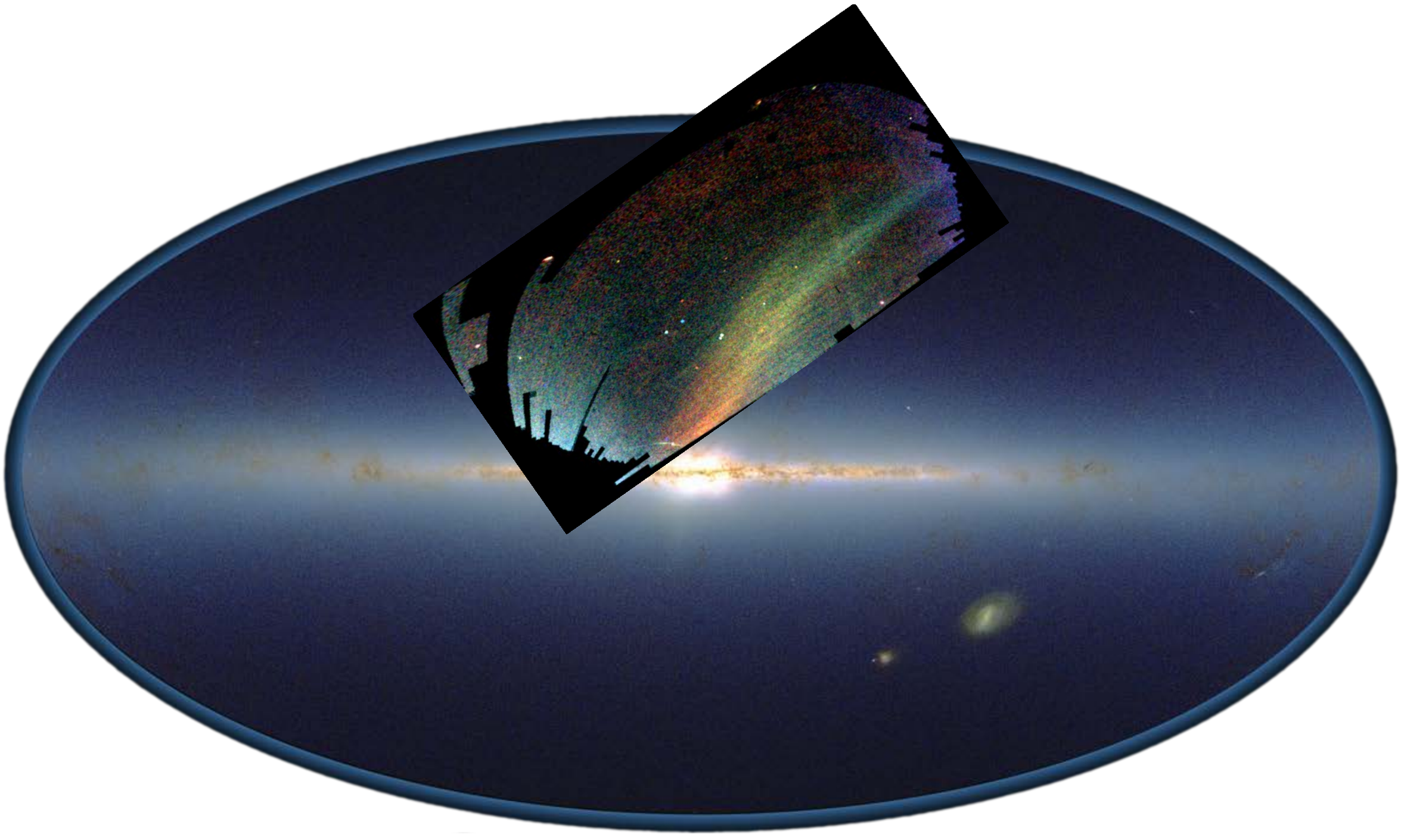
Dark regions are close to the Galactic disk, avoided by the SDSS which was primarily an extragalactic survey
This is a false colour RGB image of **density** map of Main Sequence Turn Off stars in three apparent magnitudes.
Because similar stellar spectral types are chosen, apparent magnitude is a proxy for heliocentric distance. Thus the image gives density of the stellar halo in three distance ranges: red=far, blue=close and green=intermediate
At least three streams are visible, they have names. You can tell by their appearance that they come from progenitors with very different properties: Pal 5 GC, Sagittarius big dwarf galaxy, Orphan from small dwarf galaxy



VB et al 2006

Equatorial celestial coordinate system, aligned with the Earth's rotation

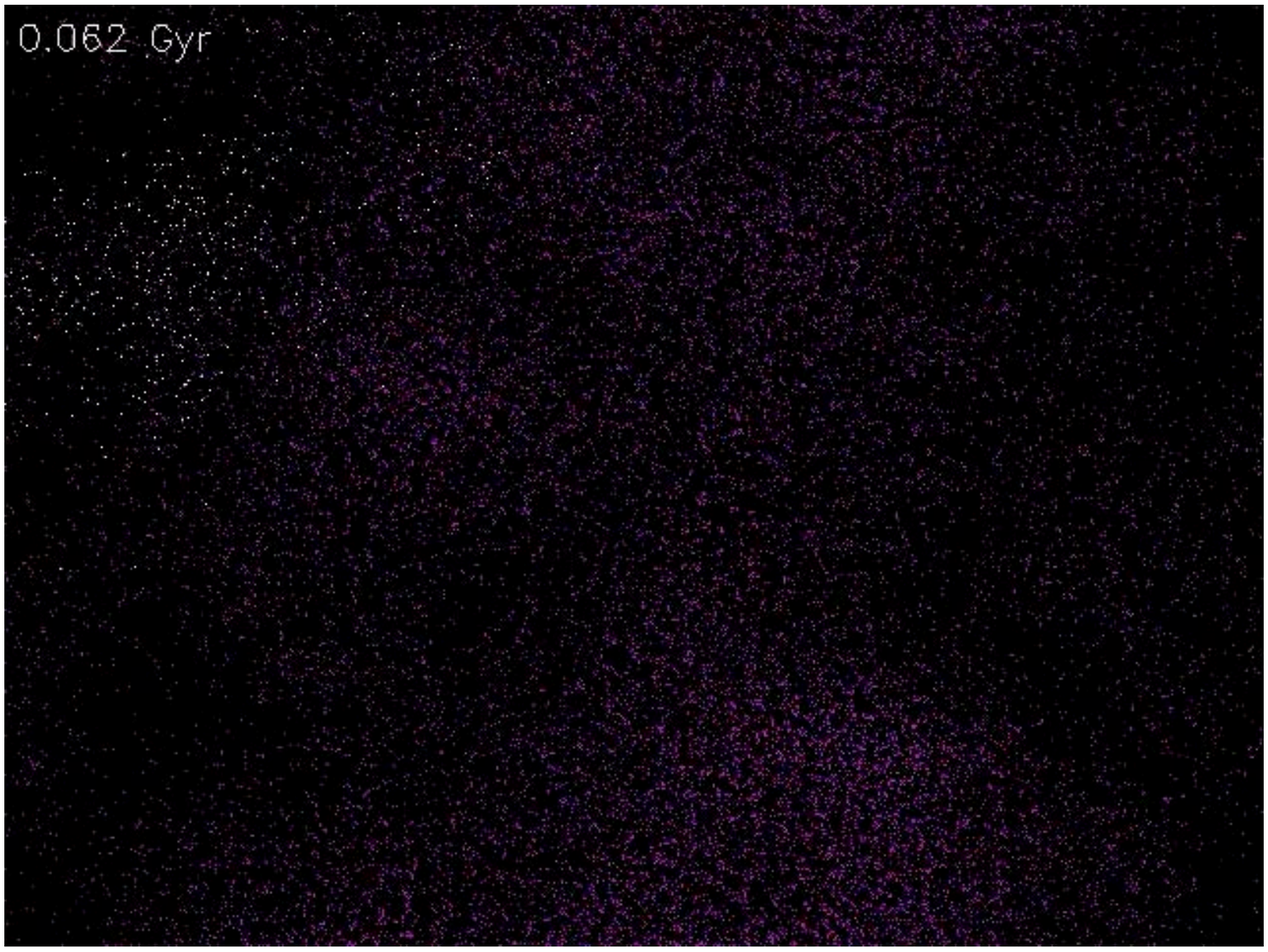
Field of streams in perspective



Where are these ghost from?

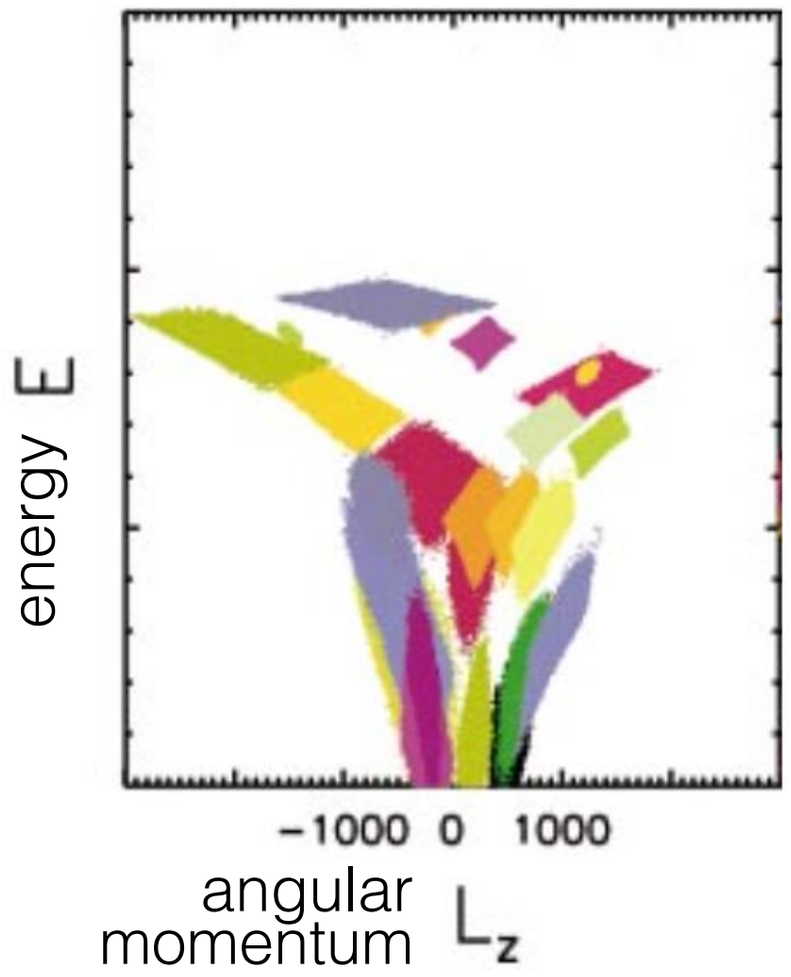
hierarchical build-up of galactic halos

Galactic halo formation in Cold Dark Matter Cosmology



Animation of computer simulation of stellar halo formation by Aquarius Collaboration

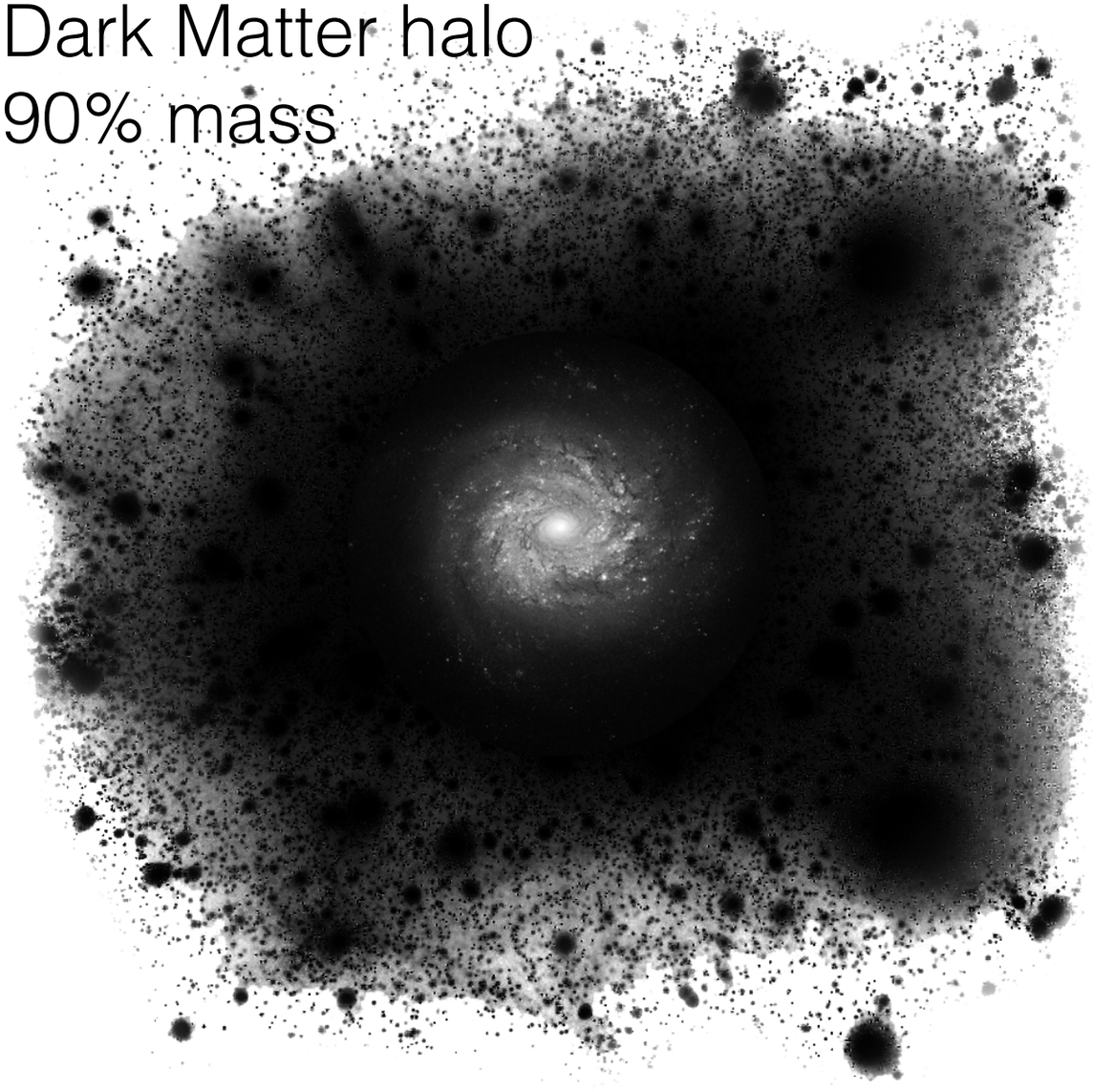
Even when completely phase-mixed and not discernible spatially the debris remain strongly **clumped in the Integrals-of-Motion space**

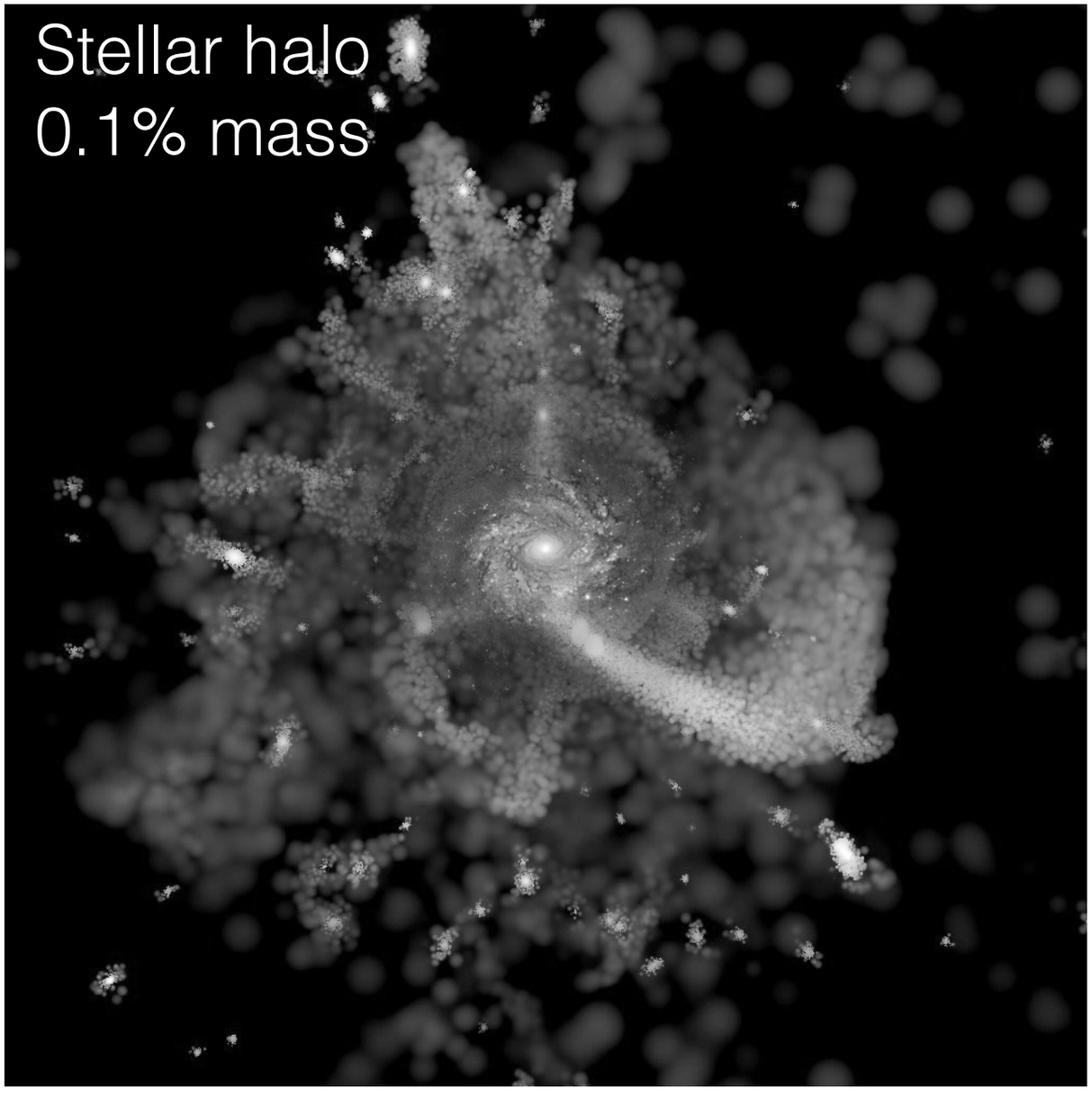


Helmi & de Zeeuw et al 2000

Stellar and Dark Halos are linked

Dark halo dominates the Galaxy's mass budget, the stellar halo on the other hand contributes a small fraction of a percent to the total mass. However (at least at large galactocentric distances) **they are formed through the same processes of accretion and phase mixing**. As a result, there are enough stars in the stellar halo at large distances to trace the properties of the dark matter halo. These stars are at ridiculously small surface brightness levels and are not accessible outside of the MW/LG





What can we learn

from stellar streams**?**

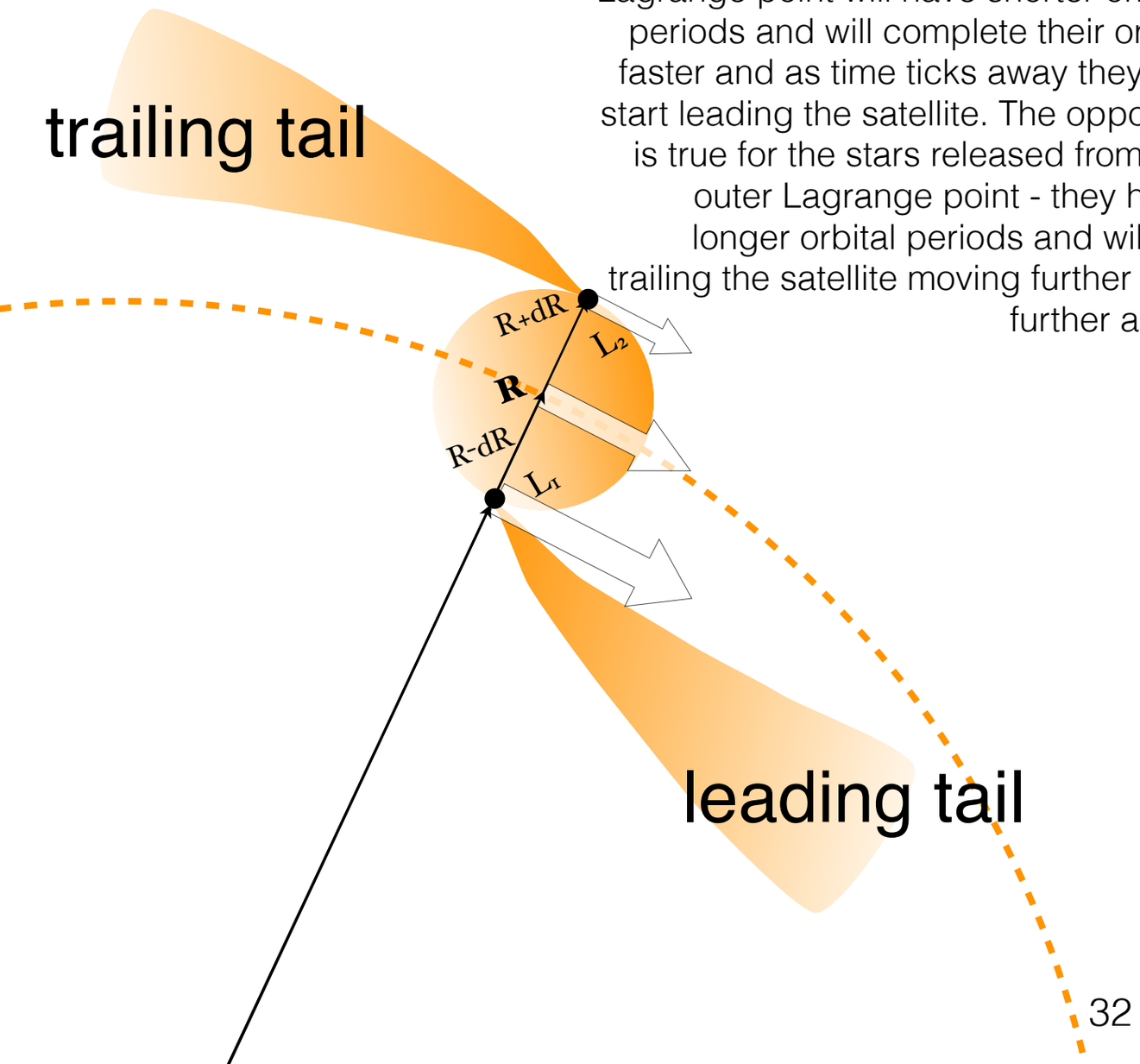
Stellar stream formation

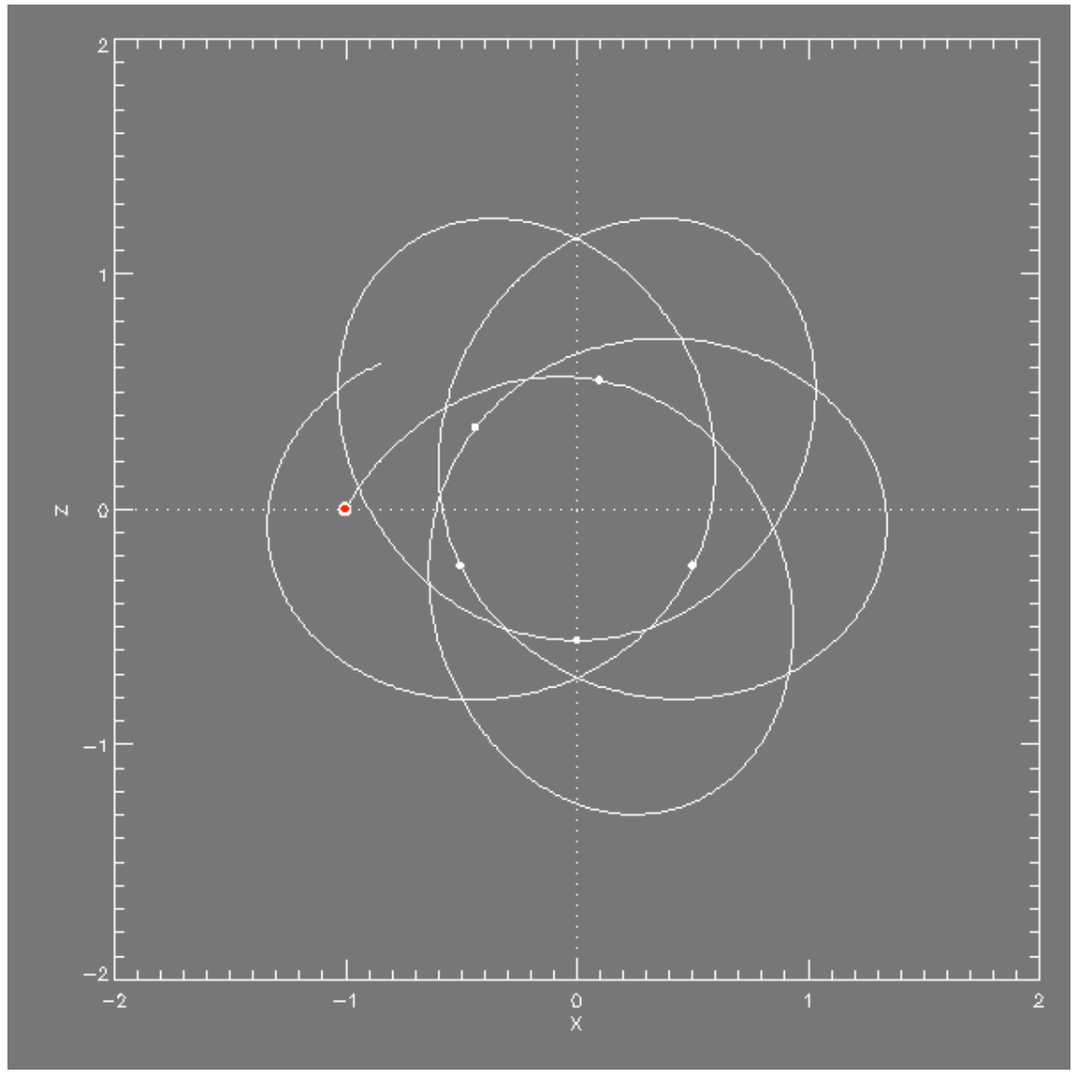
is a manifestation of phase mixing

linear growth with time of small differences in orbital frequencies into large orbital phase offsets

streams delineate orbits!

The stars that leave thought the inner Lagrange point will have shorter orbital periods and will complete their orbits faster and as time ticks away they will start leading the satellite. The opposite is true for the stars released from the outer Lagrange point - they have longer orbital periods and will be trailing the satellite moving further and further away





animation of tidal tail formation by particles released from Lagrange points around the orbiting satellite

Orbits - most precise mass determination

Orbits are defined by a system of simple differential equations

1) $\mathbf{v} = \dot{\mathbf{r}} = (\dot{r}, r\dot{\phi})$

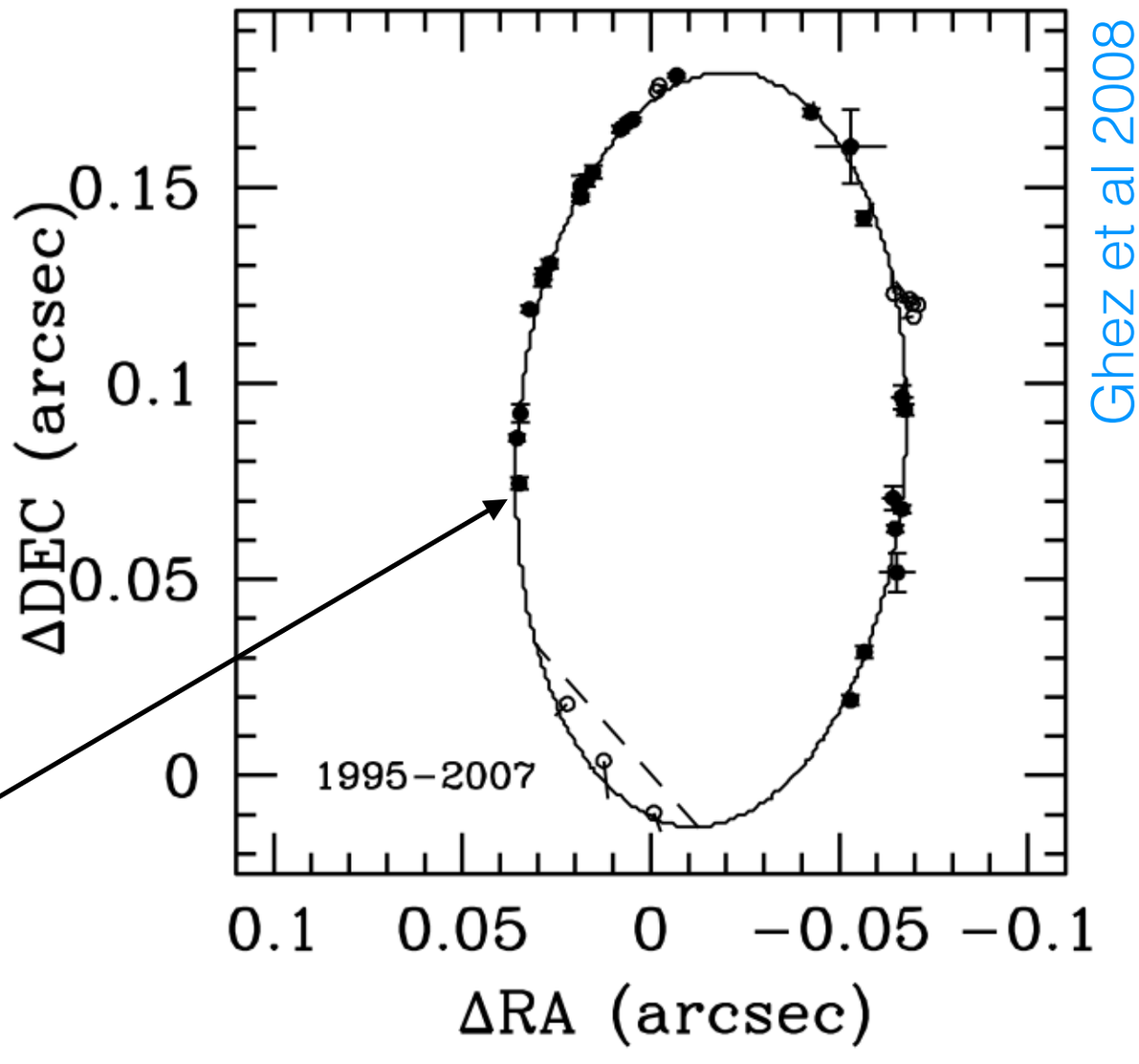
2) $\mathbf{a} = \ddot{\mathbf{r}} = [\ddot{r} - r\dot{\phi}^2, \frac{1}{r}\frac{d}{dt}(r^2\dot{\phi})]$

$f_r = \ddot{r} - r\dot{\phi}^2 \qquad f_r = -\frac{GM}{r^2}$

$f_\phi = 0 \qquad r^2\dot{\phi} = \text{const}$

S02 star, 0.0005 pc
away from the Galactic BH

point mass
$4.1 \pm 0.6\ 10^6\ M_\odot$

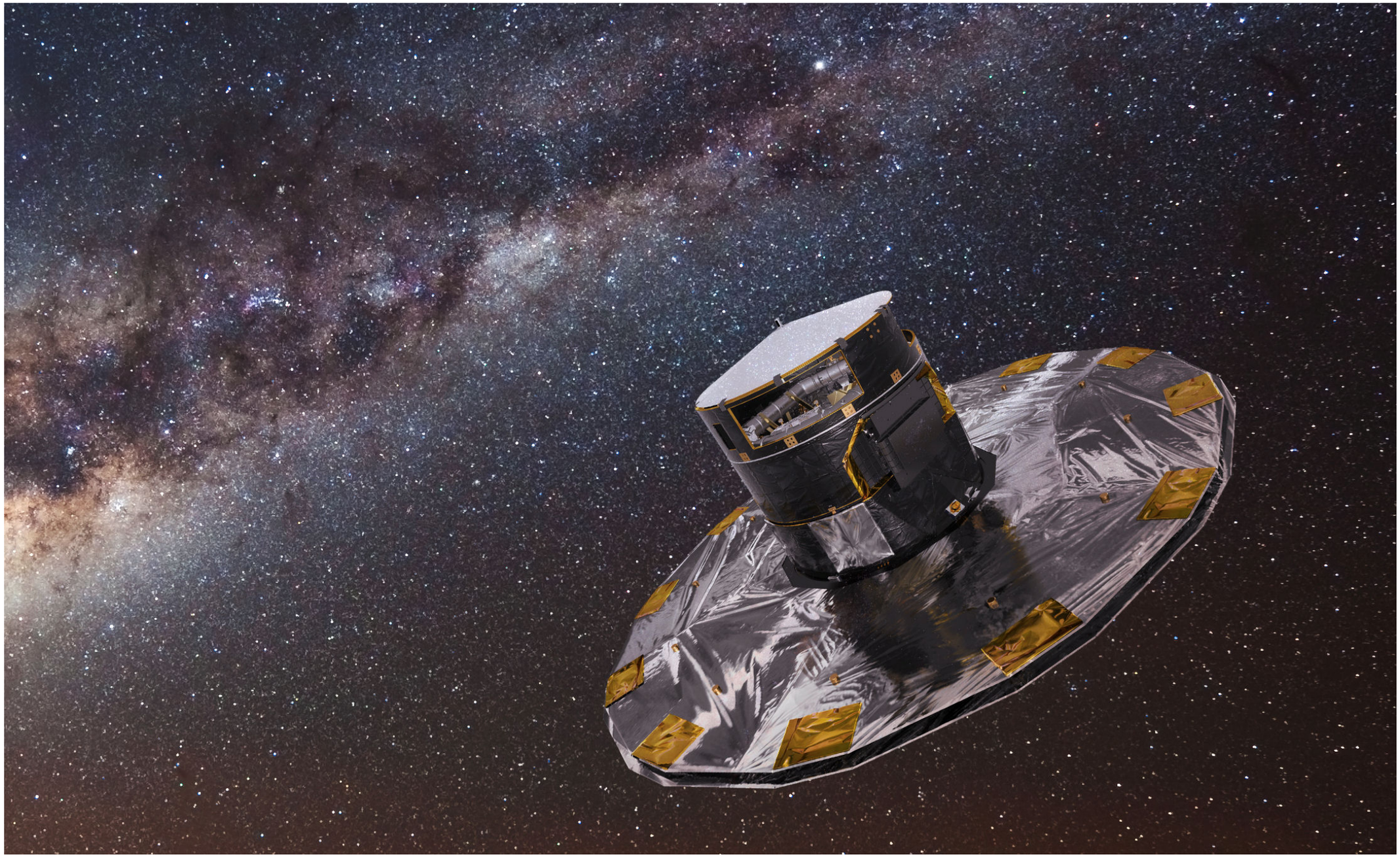


Recent breakthrough

Gaia
space observatory

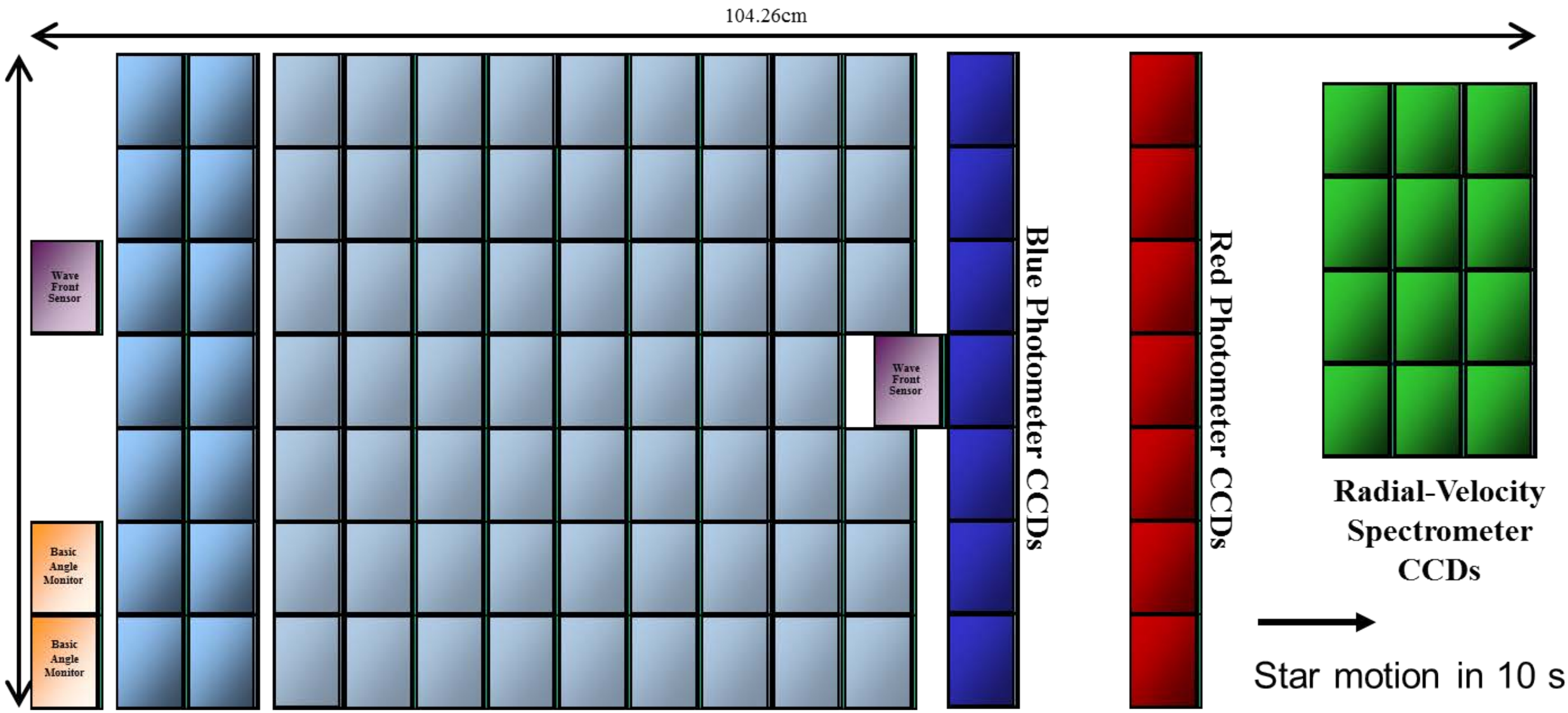
motions and distances
f**or 1.5 billion stars**

Gaia space observatory



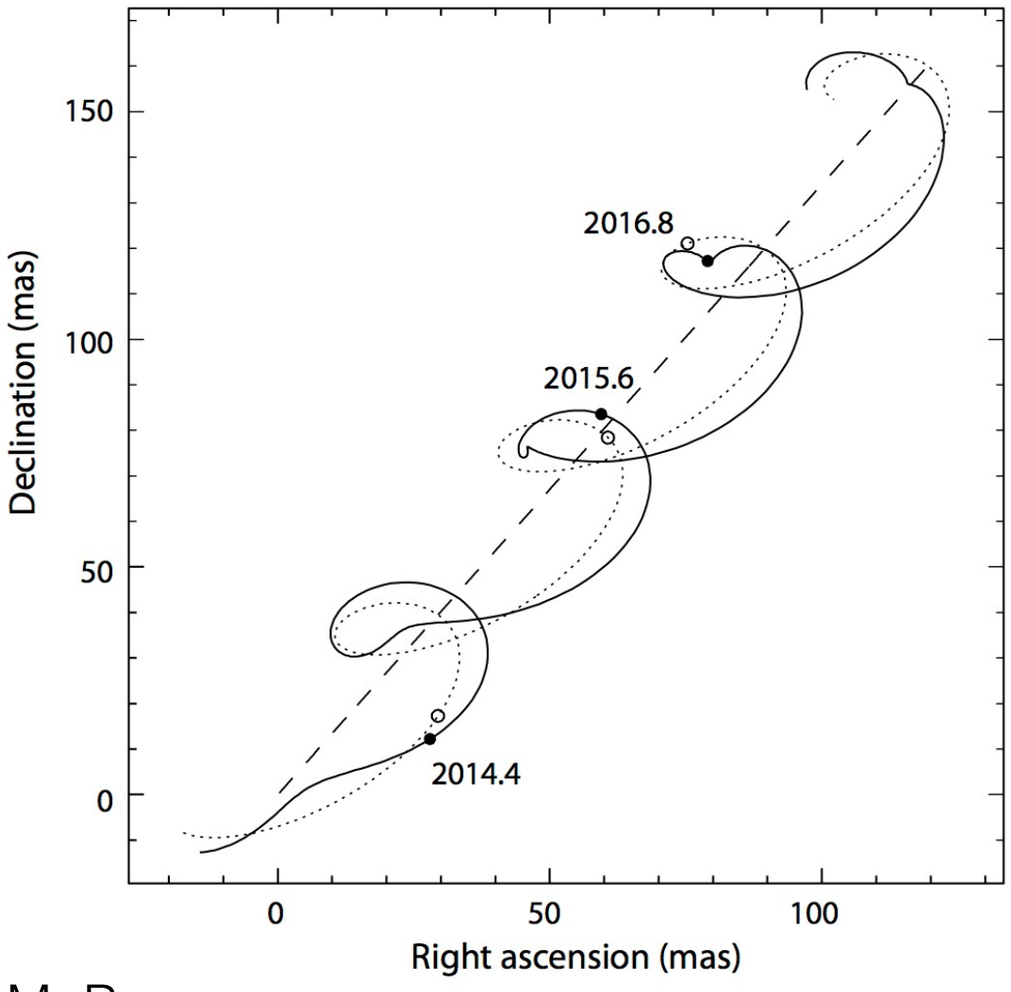
ESA

Gaia space observatory



Gaia space observatory

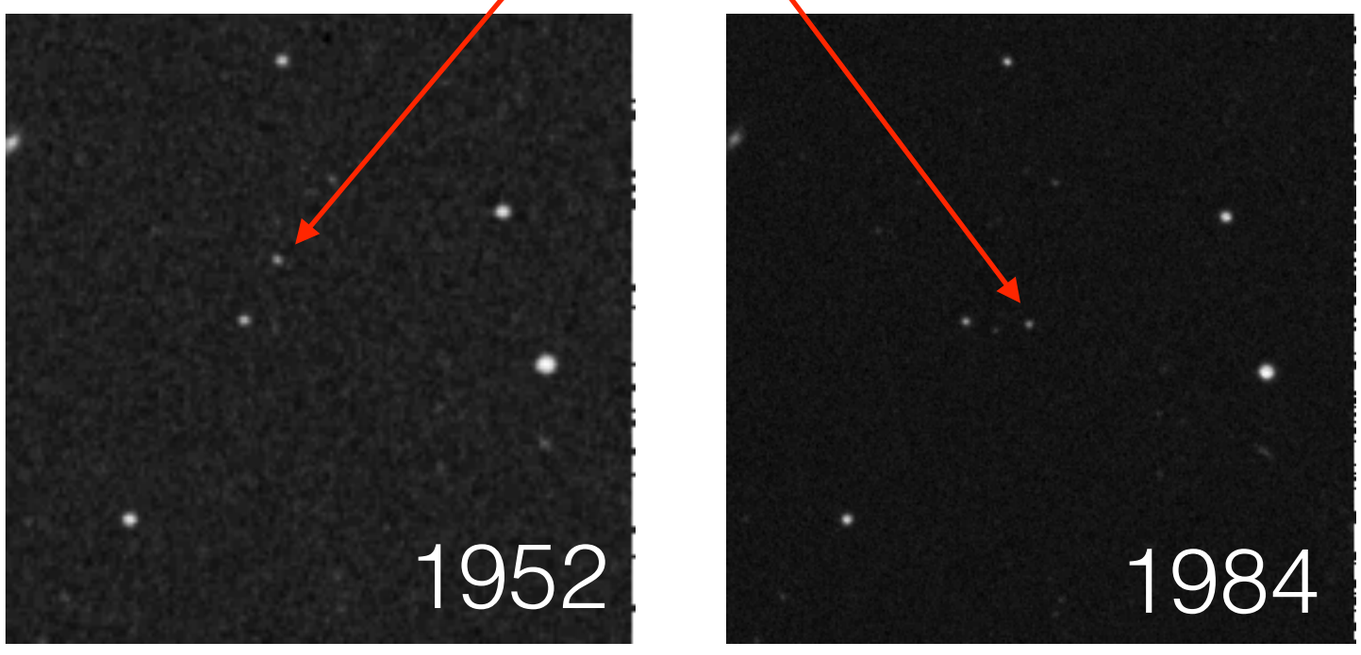
- stare at the sky
- wait a few years
- stare at the sky again



M. Perryman

Has anything moved?

same star



Neil Reid

Gaia can resolve angles corresponding to 1 pound coin at the distance of the Moon

Gaia space observatory

1.5 billion stars in a
publicly accessible database

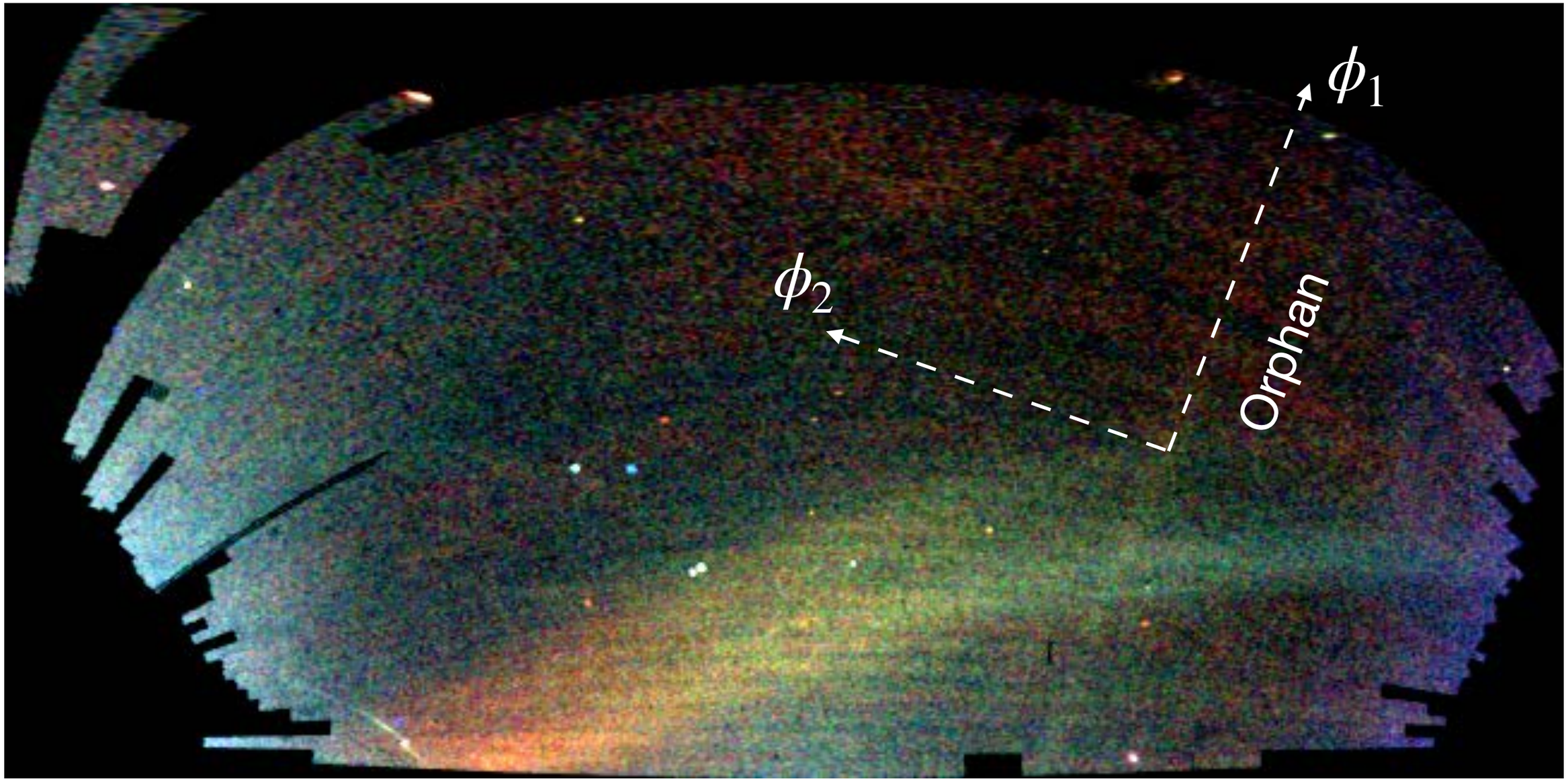
- Proper motions
- Distances
- Low-resolution spectra as a function of time
- Brightness as a function of time
- Astrometry as a function of time

Recent breakthrough

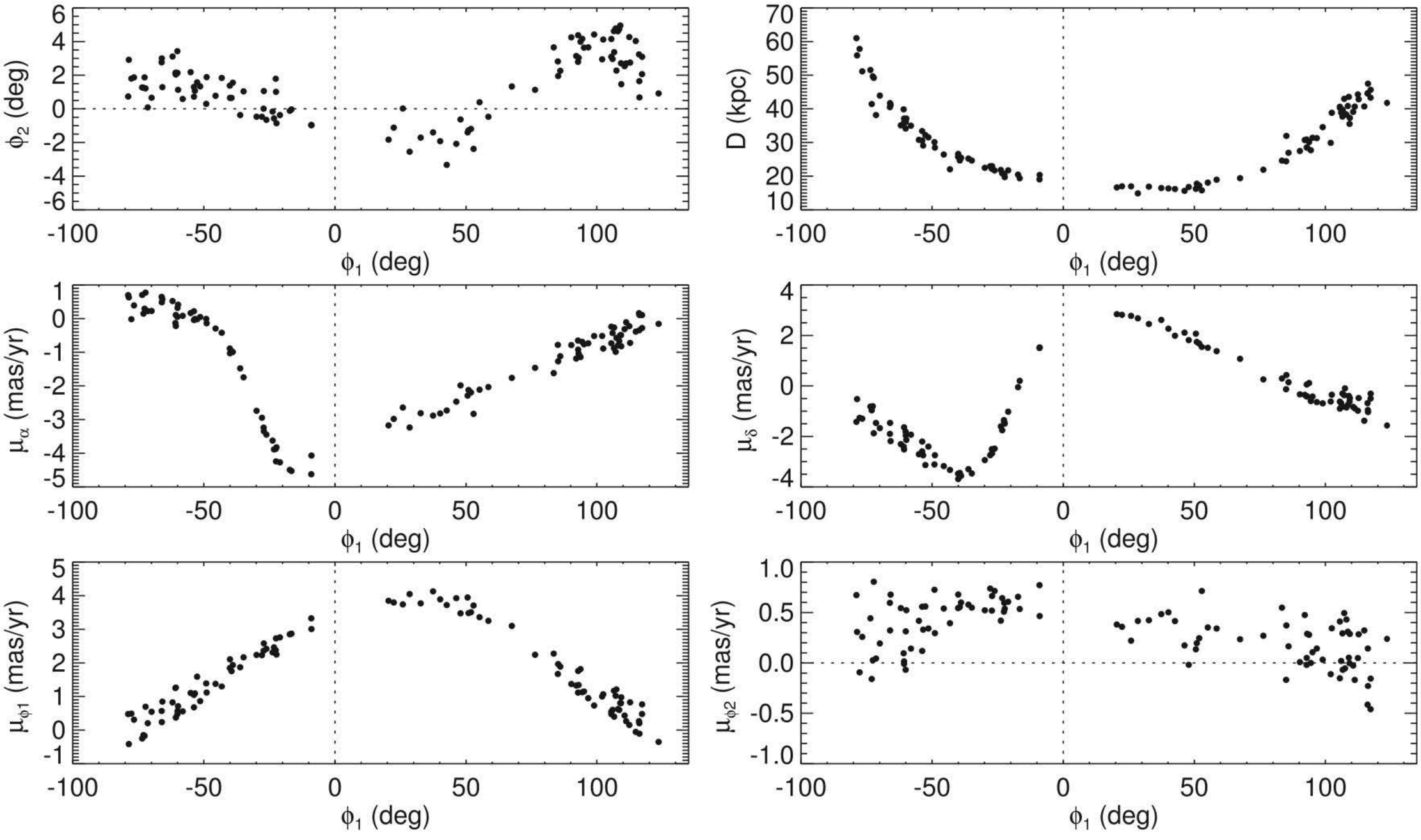
stream

perturbations

Orphan stream perturbation

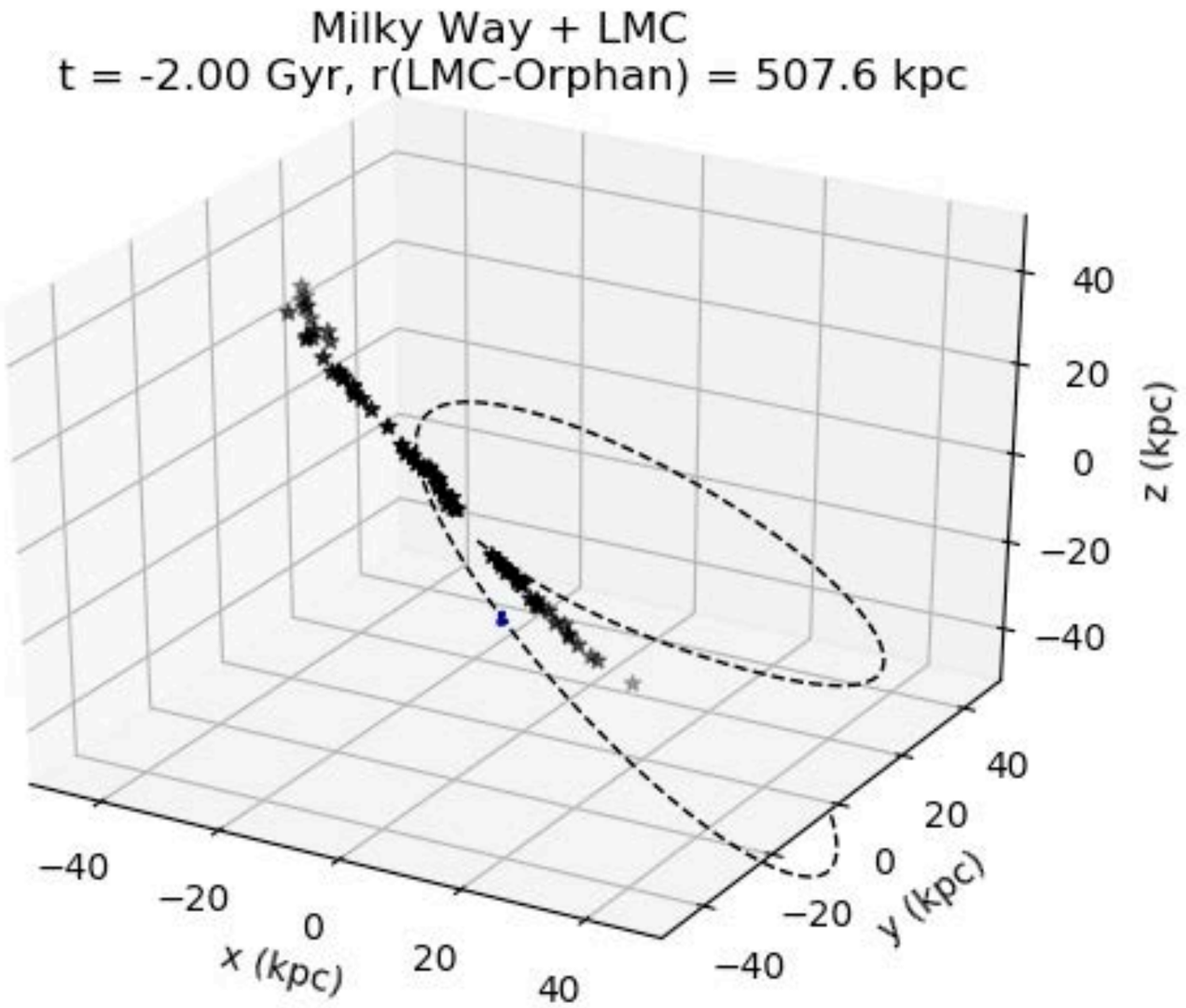


Orphan stream perturbation



Koposov et al 2019

Orphan stream perturbation



Measurement of the mass and shape of deforming and recoiling Milky Way

Measurement of the <u>total</u> mass of a dwarf galaxy

M_{LMC}=1.5x10^{11} M_{Sun}

Erkal et al 2019

Galactic Archaeology for Near-Field Cosmology

Galactic Archaeology finds, measures properties of and carries out inference with ancient (early formed) and under-represented (rate, difficult to find) portions of galaxies

Near-Field Cosmology links Local Group observations and the Early Universe to pin down the physics of structure formation at high redshift as well as the properties of Dark Matter on small scales

What is unique about the Milky Way?

Resolving stars turns out to be a big deal as it allows us to study components of our Galaxy usually not seen in great detail in others such as the stellar halo

- **You can see individual stars**
- You can see extremely low mass galactic sub-systems
- You can see in 3D!
- Hell, you can even see in 6D!!!
- You can measure precise elemental abundances and ages
- You can resolve gas distribution across a wide range of densities and temperatures

What is unique about the Milky Way?

- **Compute detailed star-formation histories and connect them do dynamics**
- **Resolve ongoing star-formation in a wide range of environments**
- **Measure orbits**
- **Measure the shape of the Dark Matter distribution**
- **Measure the lumpiness of the Dark Matter distribution**
- Measure the stellar Initial Mass Function and its variations
- Study “invisible” objects (Brown Dwarfs, White Dwarfs, other dark stellar remnants)

What is unique about the Milky Way?

- Turn back time and reconstruct the formation history of the Galaxy

- Measure the small-scale properties of Dark Matter along the way

- Test all of the assumptions that go into Galaxy Formation and Evolution theory

Follow-up questions for those who were paying attention

- What's the blue streak sticking out of the M87's centre?
- What is "phase-mixing"?
- How does SDSS "know" what is a star and what is not?
- Is binning stars in "boxes" of RA, Dec sensible/correct?
- Why Gaia's all-sky view of the Galaxy is not a photograph?
- Why does the S02 star's orbit around the Galactic (super-massive) Black Hole close and the stream progenitor's does not?