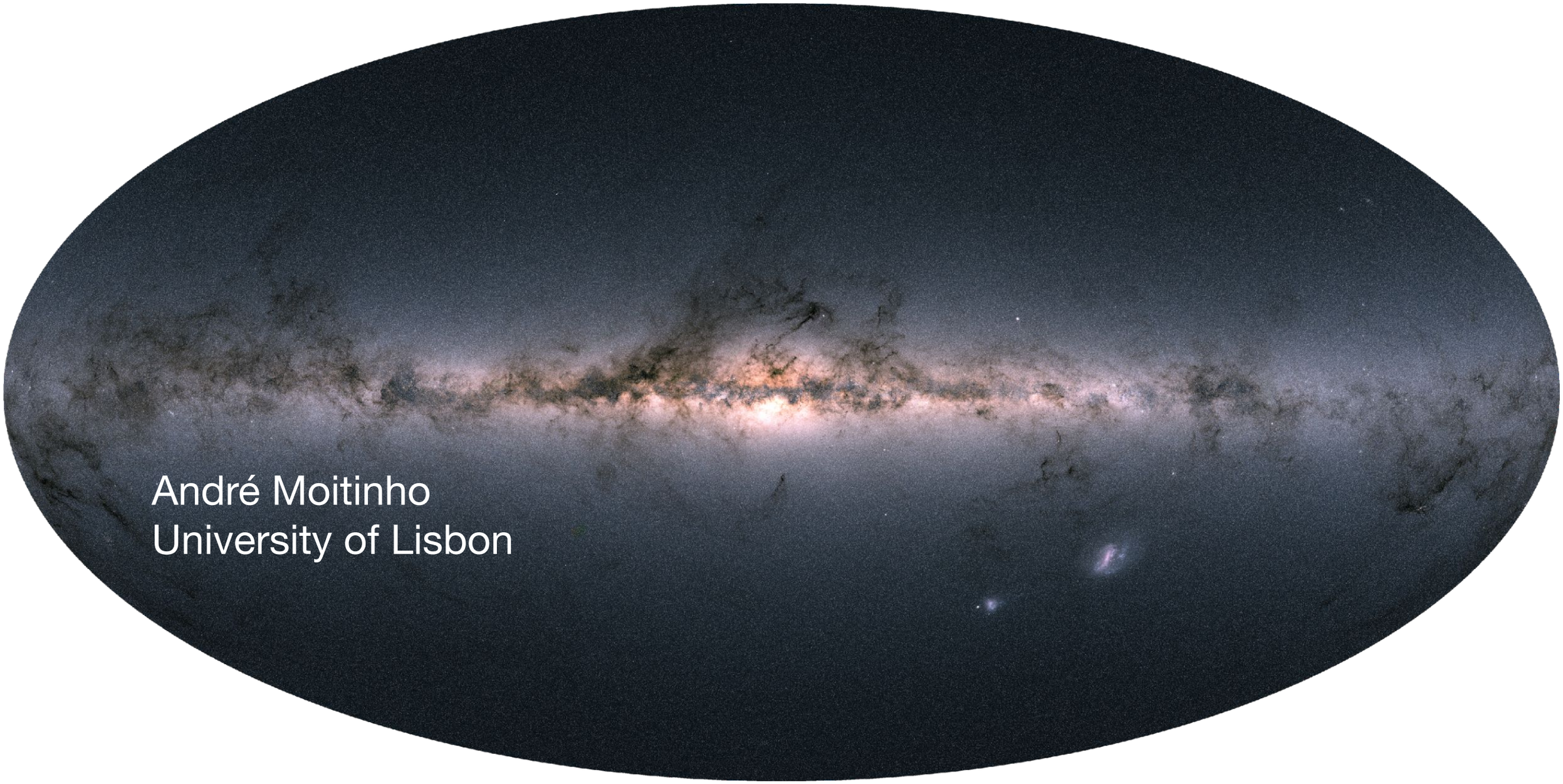
The Milky Way



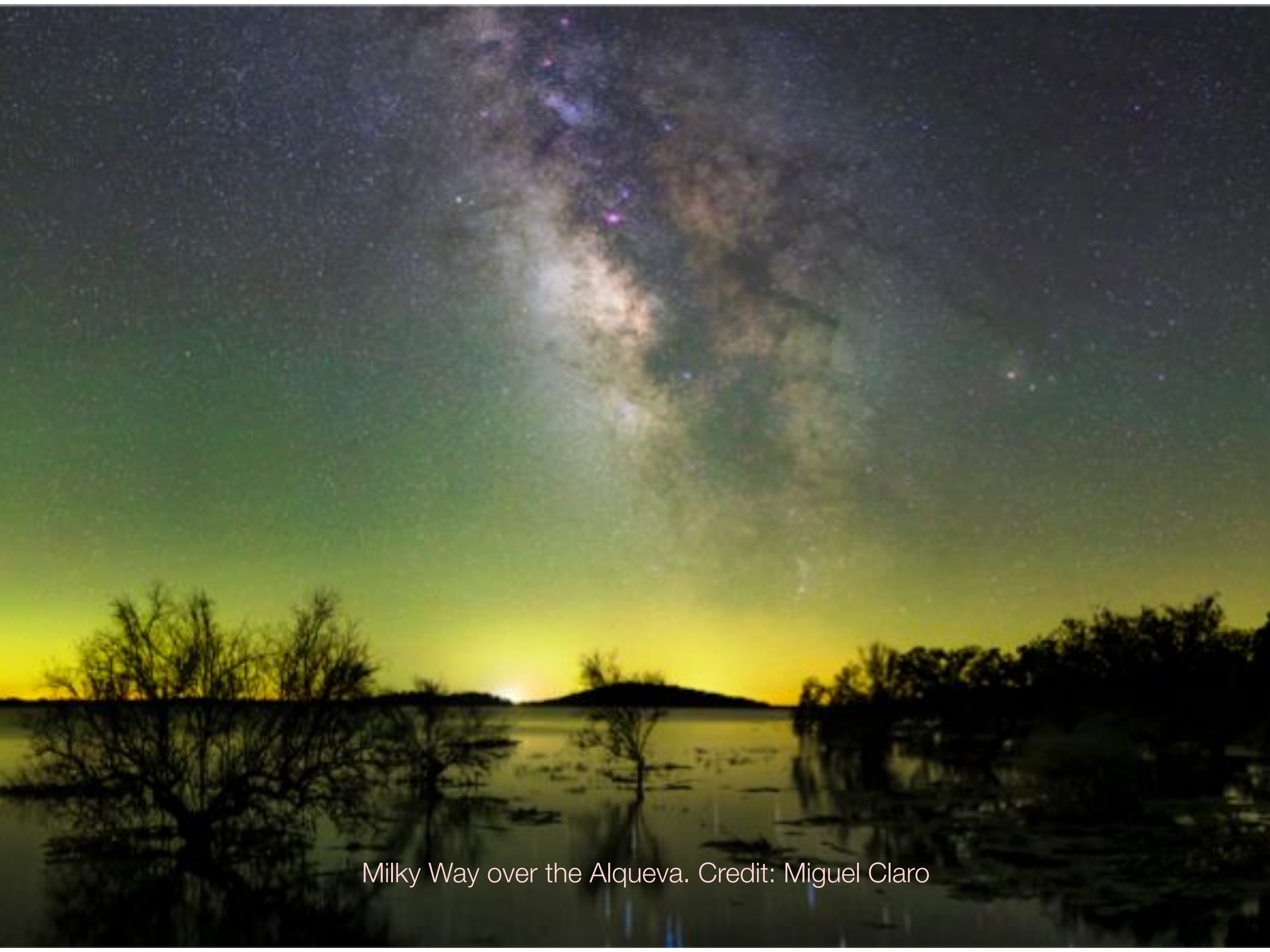
André Moitinho
University of Lisbon

Ciências ULisboa

centra
centre for astrophysics and gravitation

10th Astrophysics and Gravitation School
(EAG10) September, 2-7 2021

Preamble



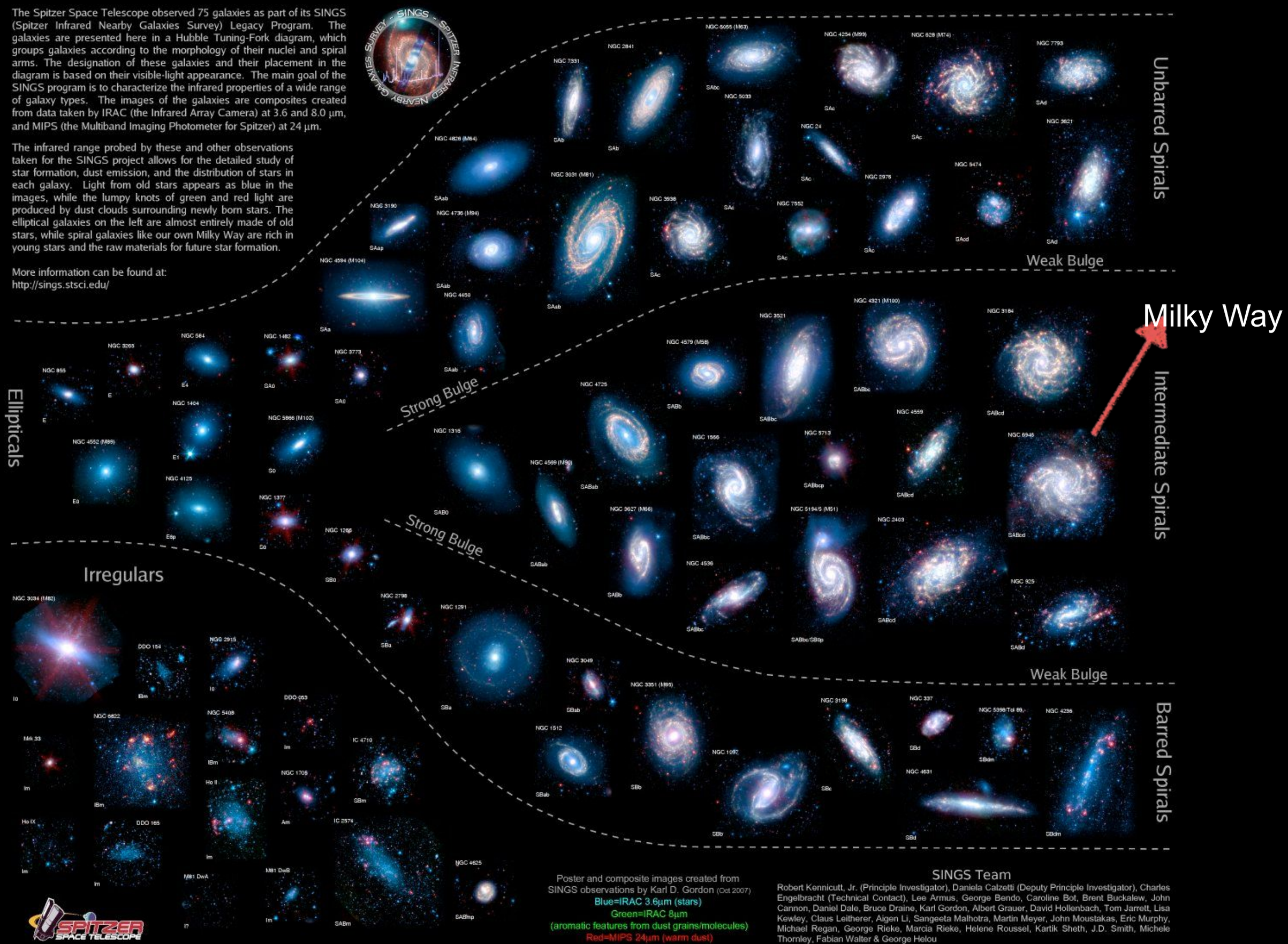
Milky Way over the Alqueva. Credit: Miguel Claro

The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork

The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm.

The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.

More information can be found at:
http://sings.stsci.edu/

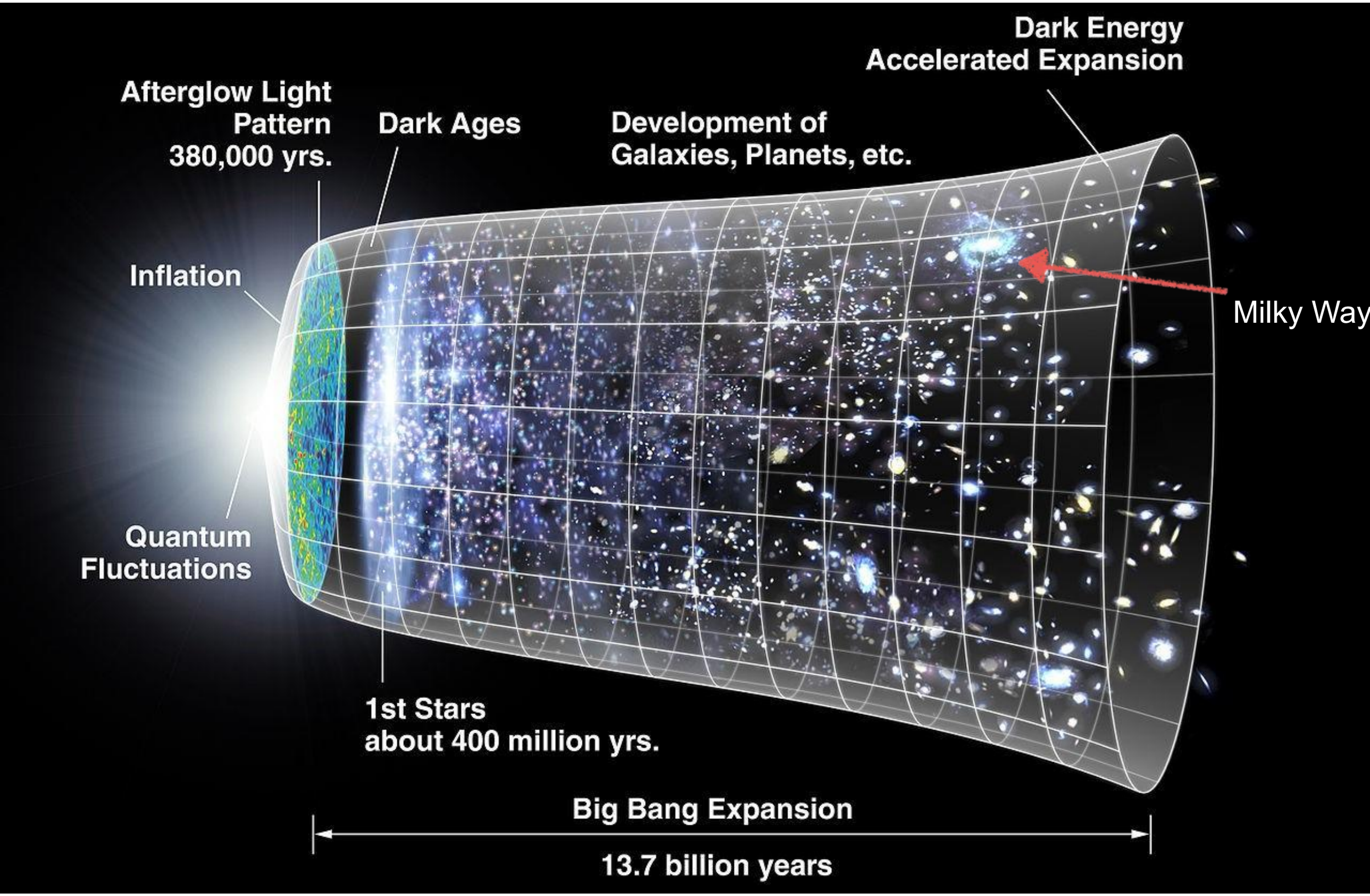


Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)

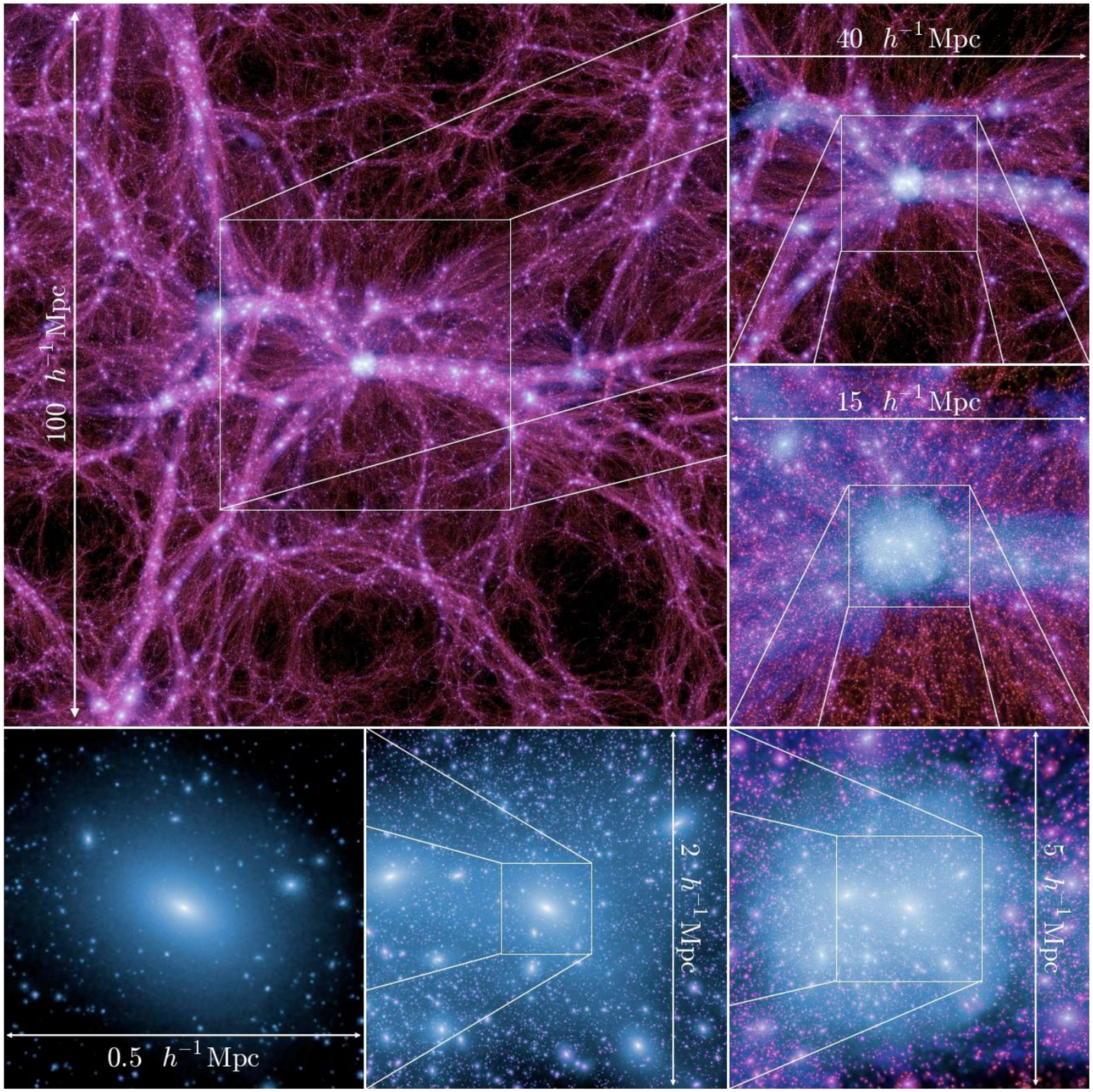
SINGS Team

Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou

Cosmological context (LCDM)



Cosmological context (LCDM)



Boylan-Kolchin et al. (2009)

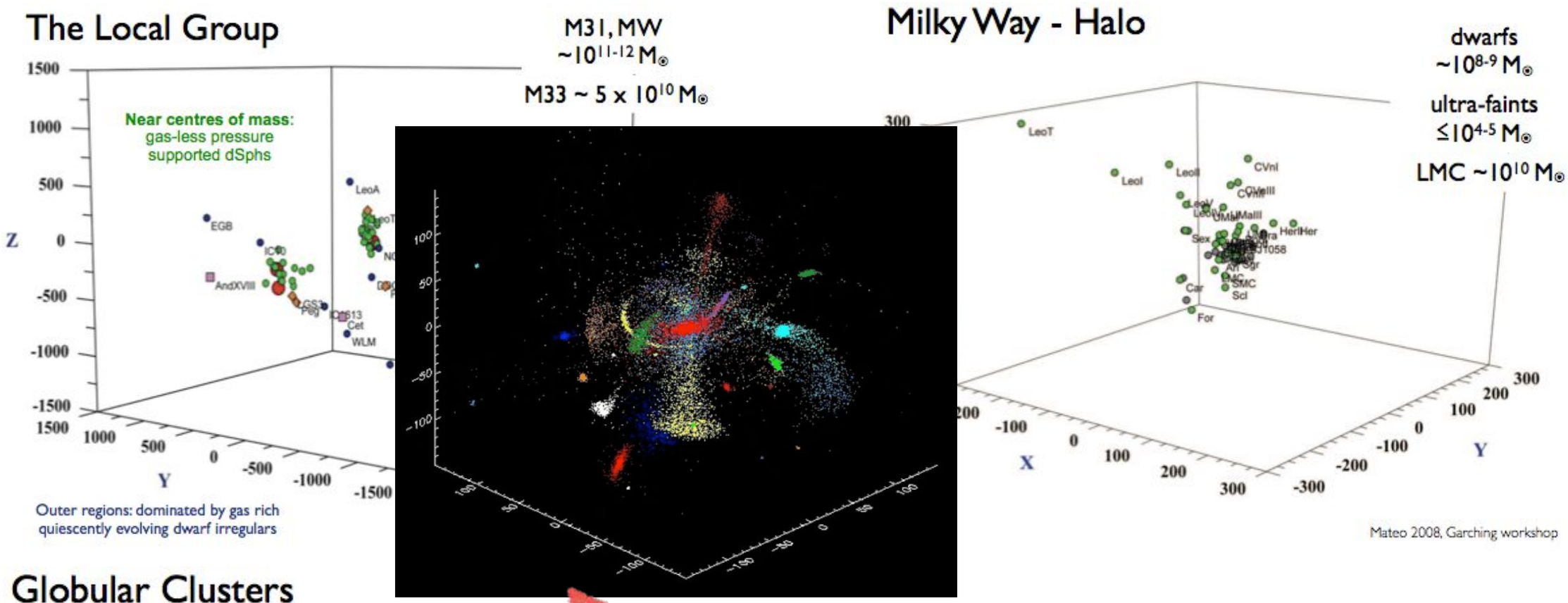
Seems to work…
but does it?

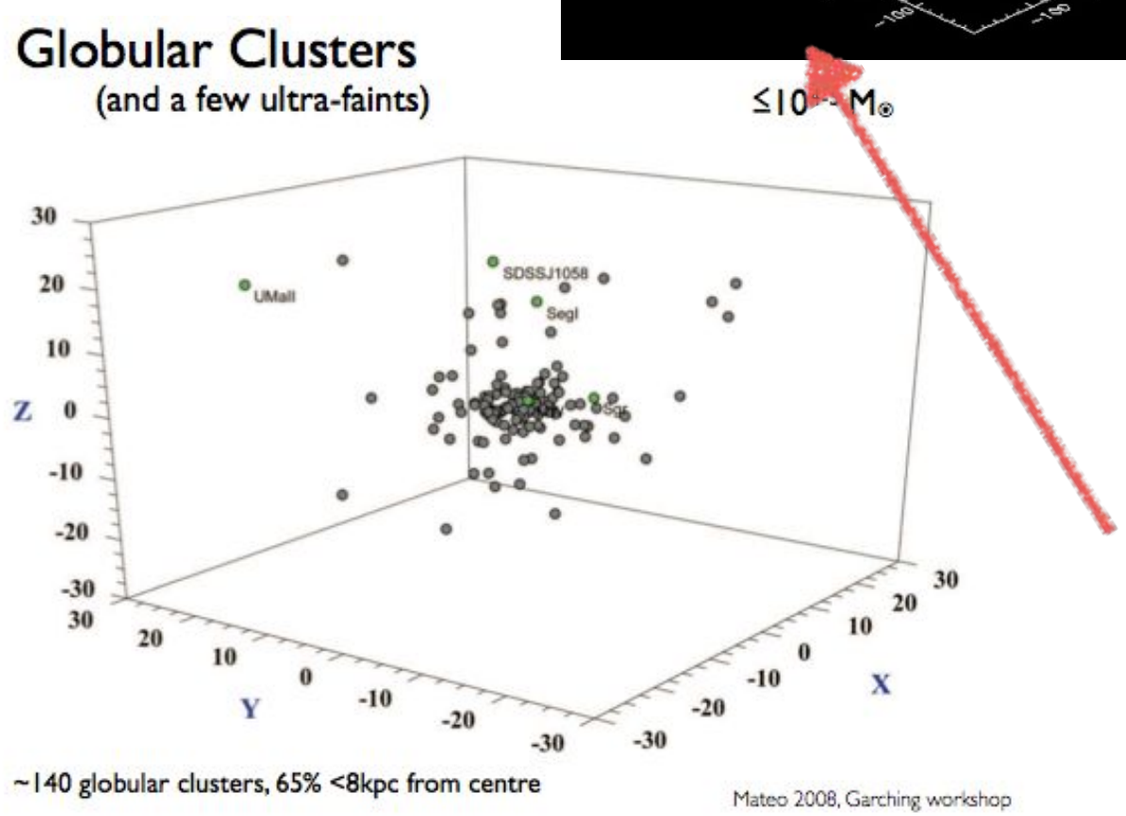
nice large scale structure and (qualitative) hierarchical galaxy build up

ad-hoc normalisation of scales

problems in reproducing smaller scales: different DM and visible mass distributions, missing satellites (near field cosmology)

Cosmological context (LCDM)

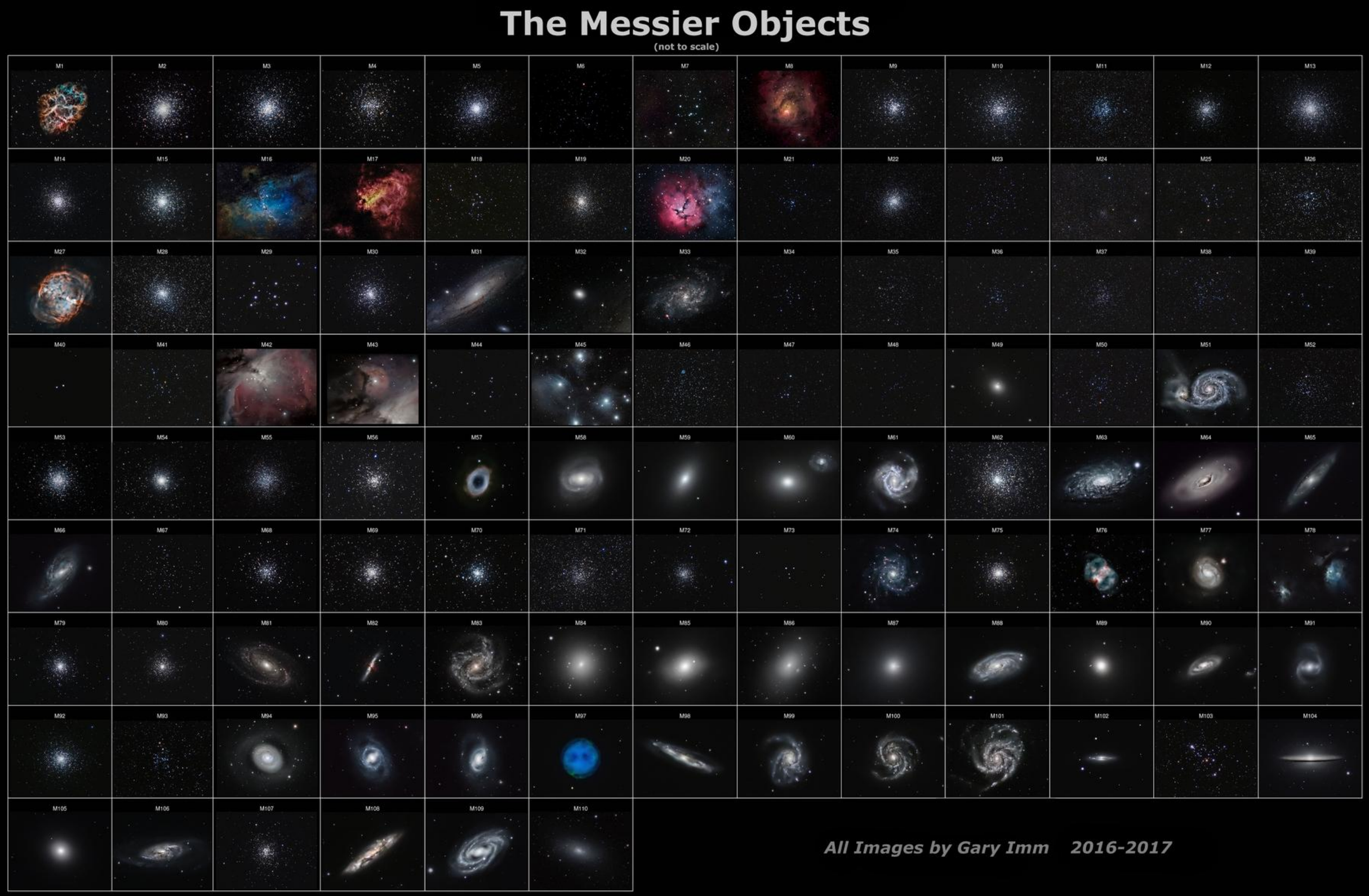




Detailed studies of the Milky Way are essential (see halo). Also, DM distribution will affect the Disc (rotation, ..)

Challenges: left-overs can have large spatial scales, faint magnitudes, … precise kinematics

The Milky Way is the only big galaxy we can observe in high detail

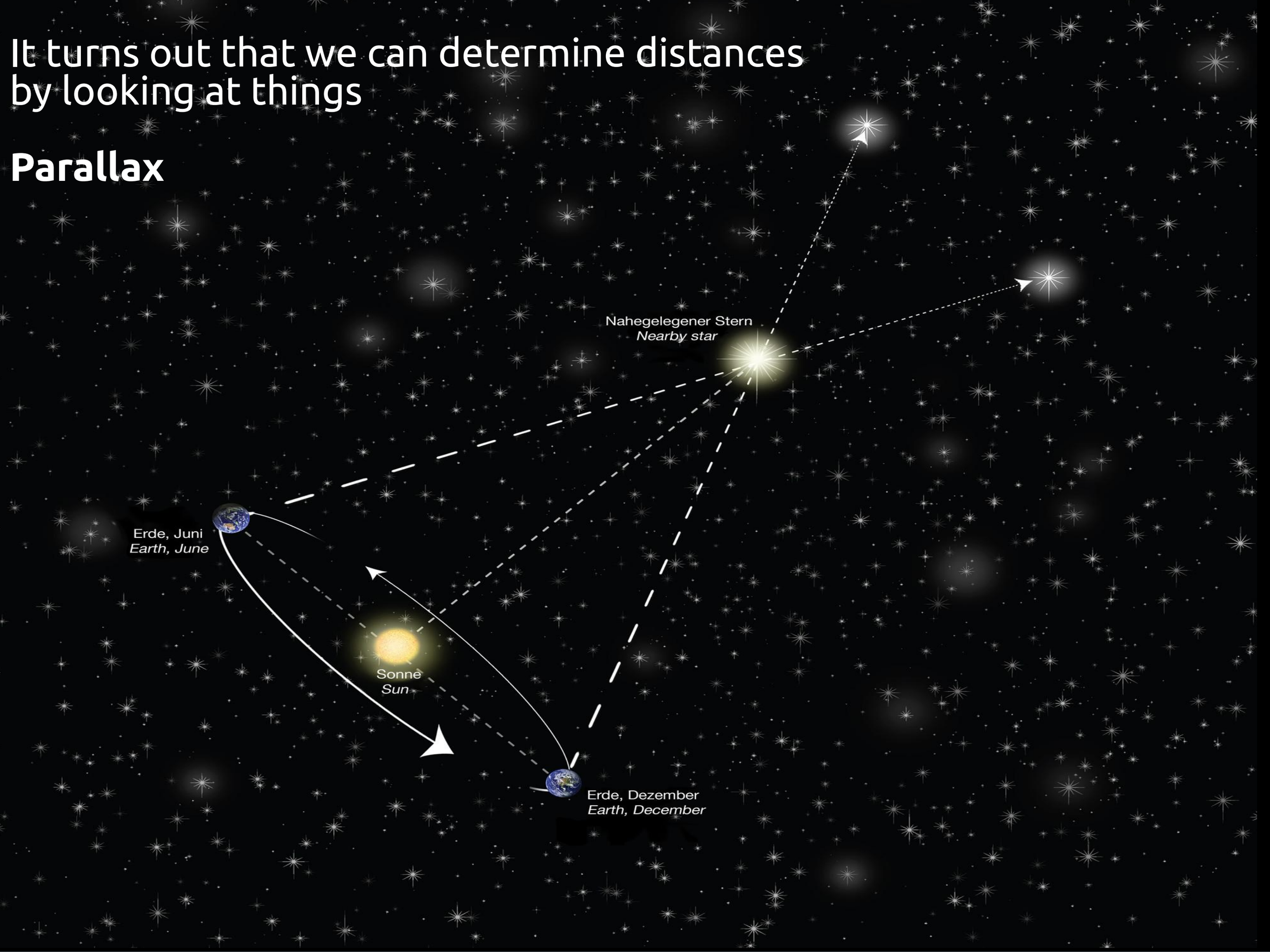


THE BIG TASK : build a map

Lundt representation of the Milky Way built from 7000 of the brightest stars (1955)

It turns out that we can determine distances by looking at things

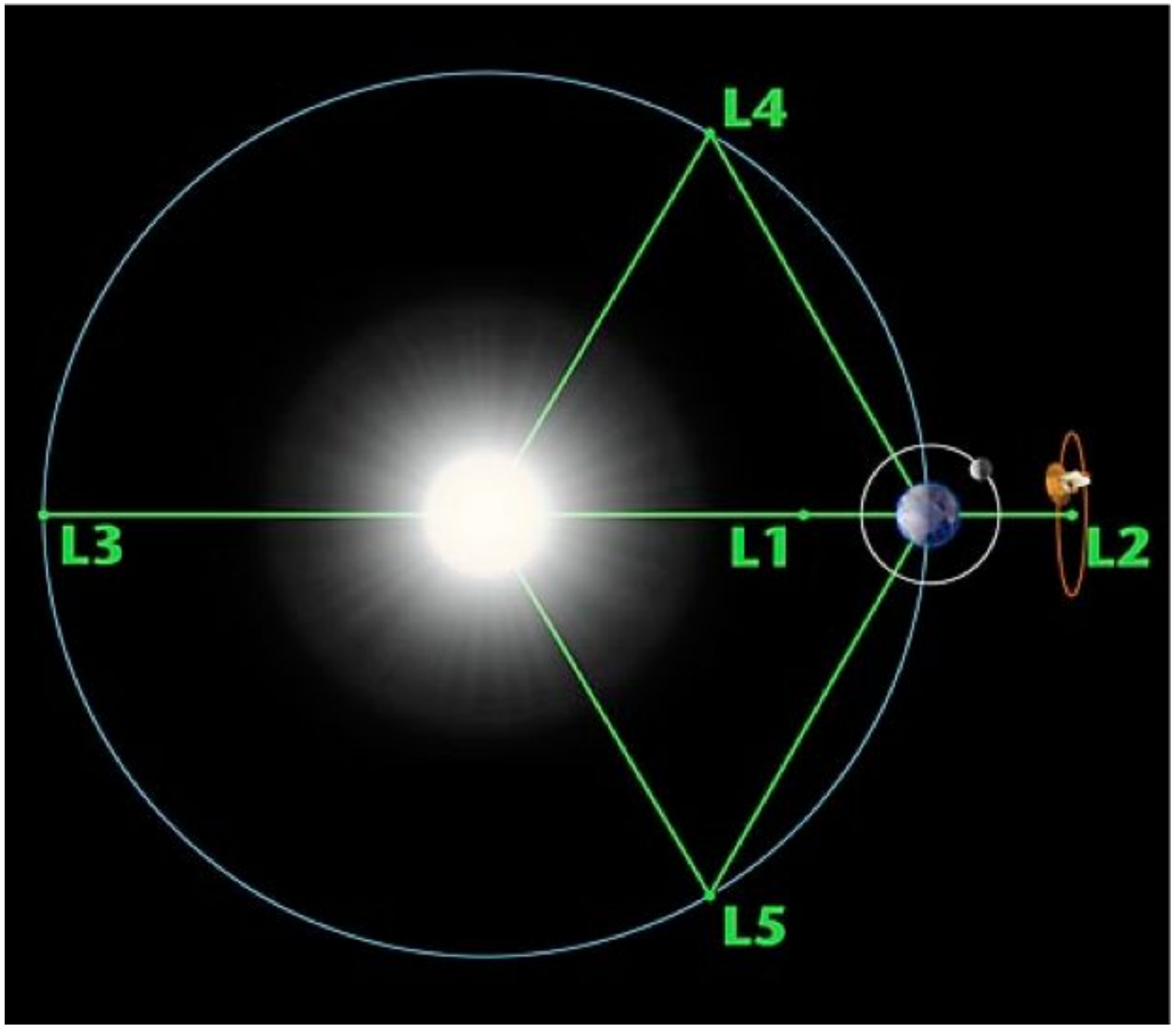
Parallax



Gaia

Lauched Dec 19, 2013.

Gaia



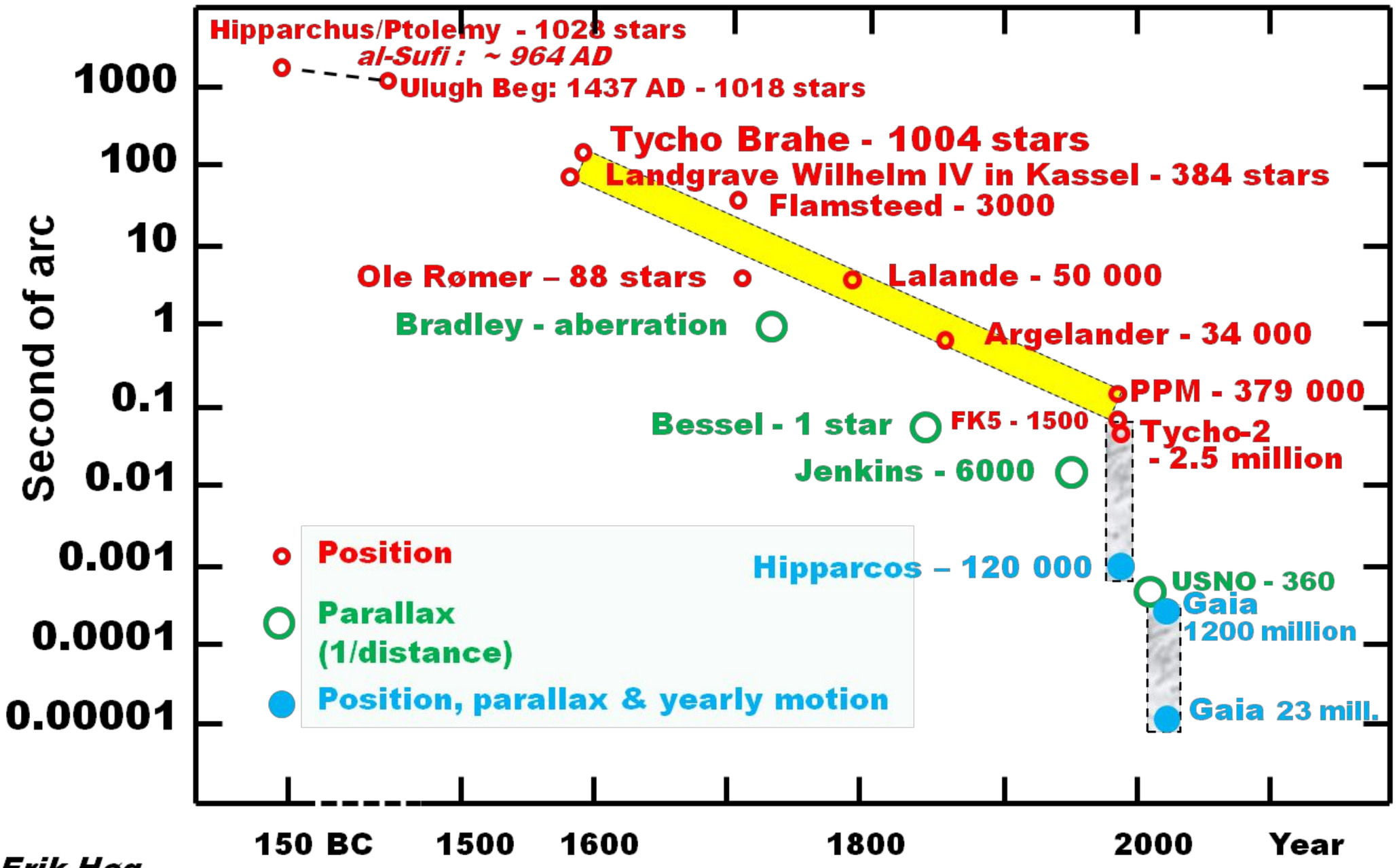
~7 micro-arcsec parallaxes

1st ESA mission with scientific participation of a Portuguese team

implications outside astronomy (GPS)

Astrometry and spectrophotometry for ~1.9 billion objects

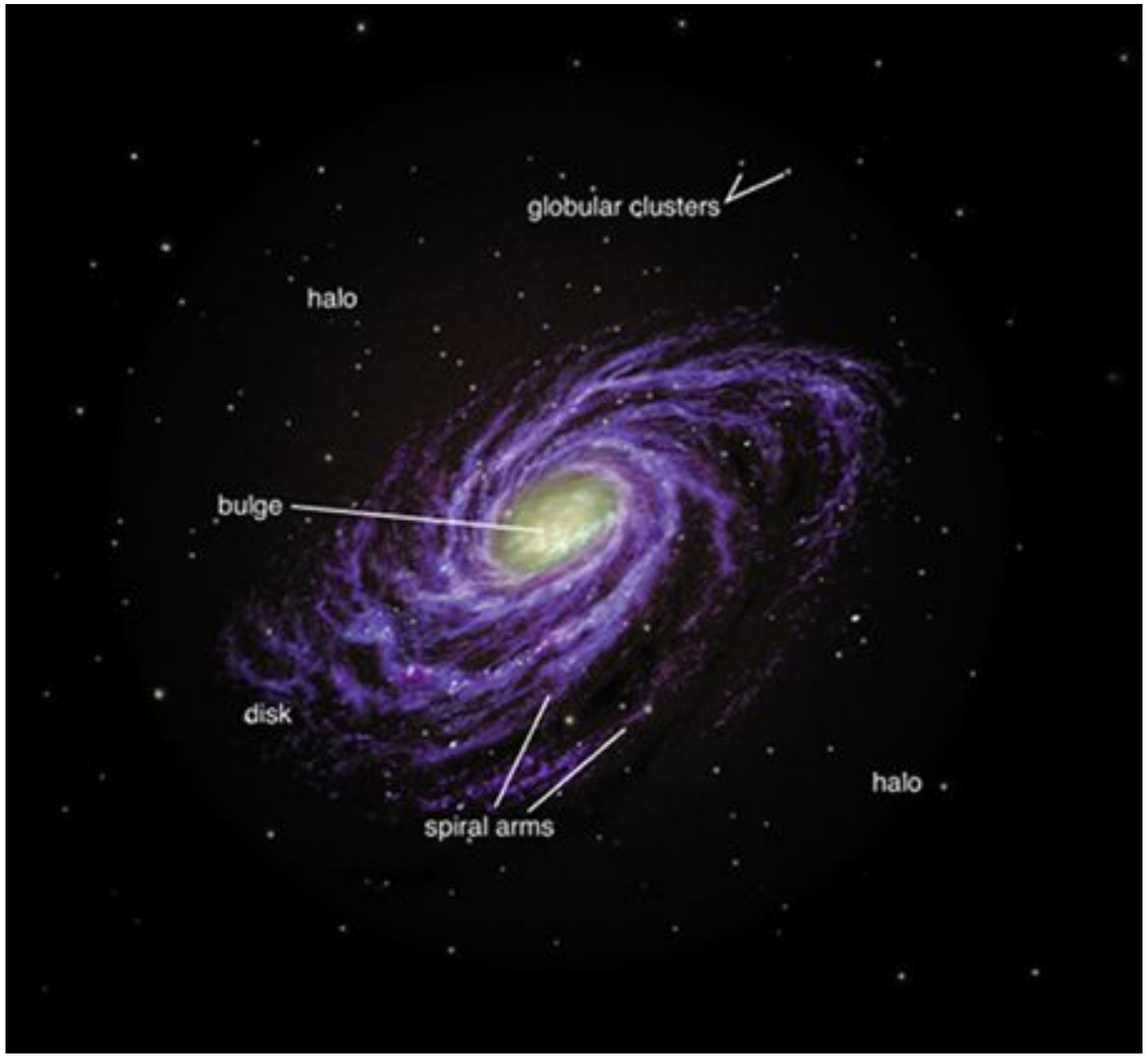
Astrometric Accuracy during 2000 Years

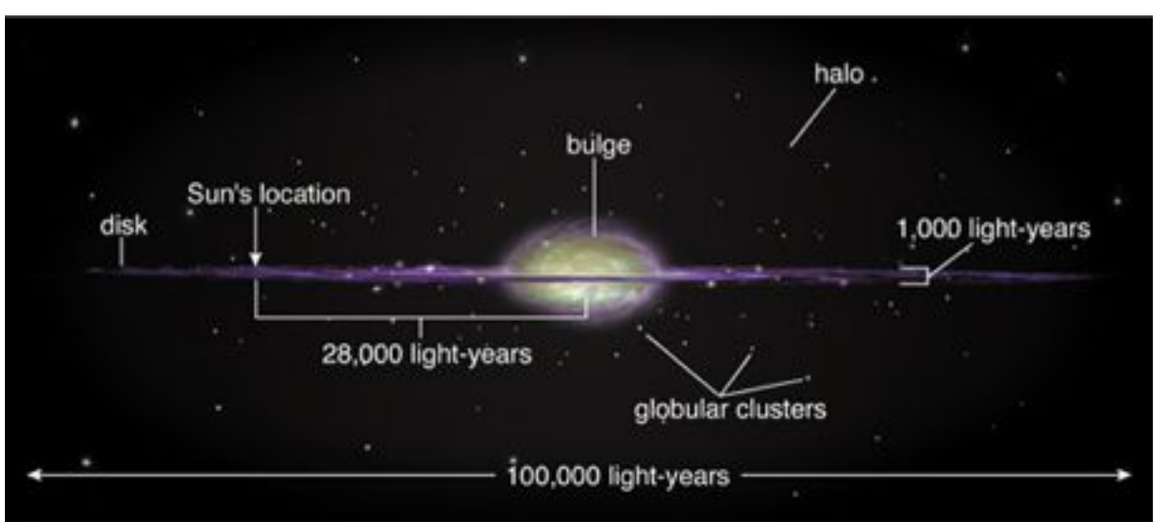


Erik Høg
1995/2016

Overview

The *canonical* Milky Way





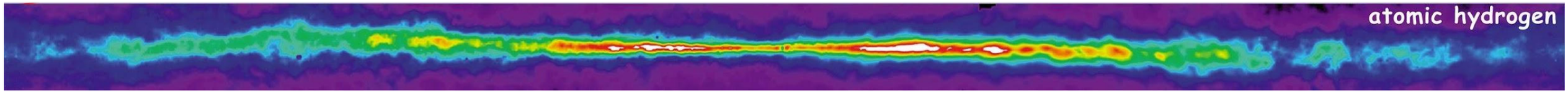
Components

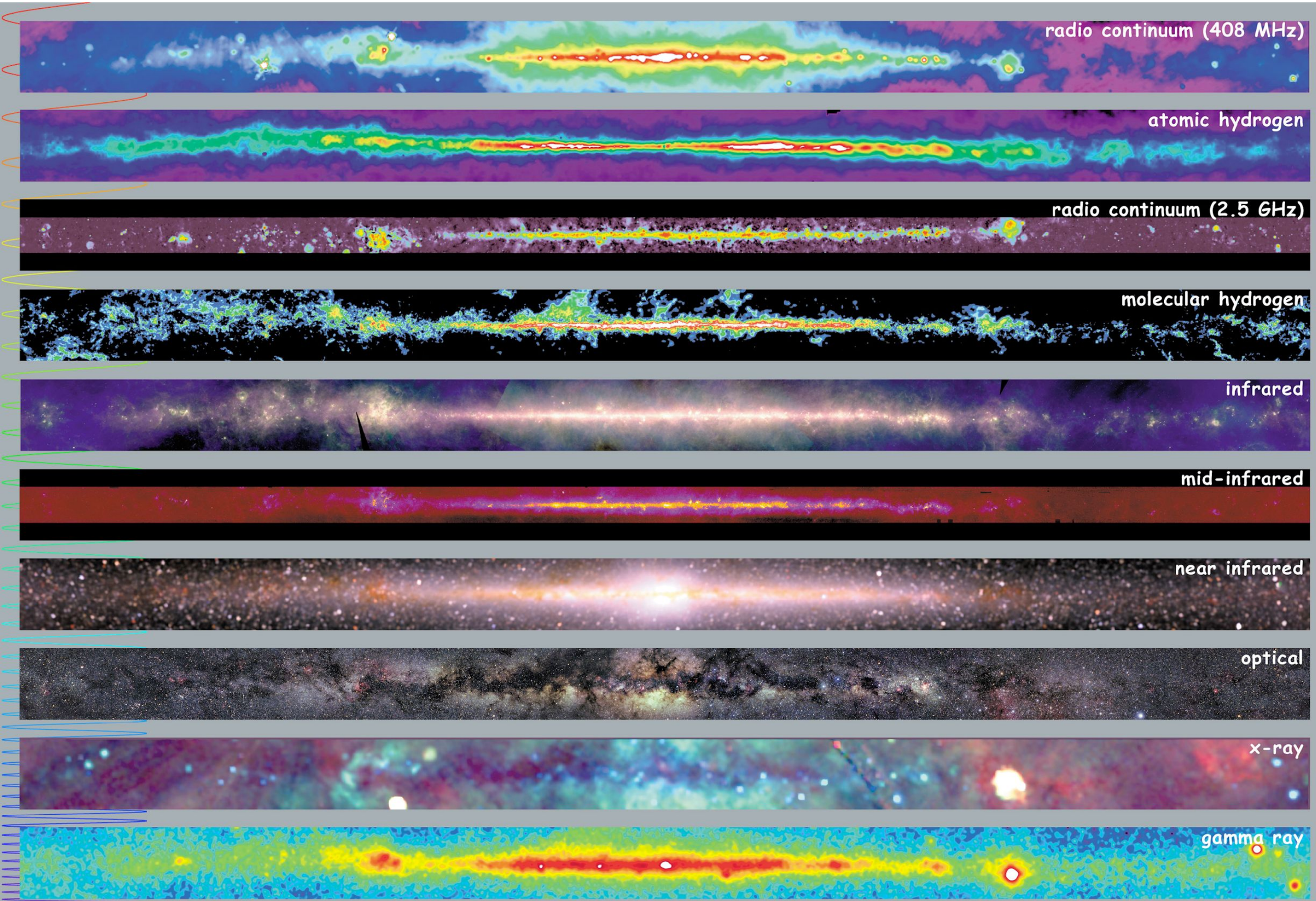
- Bulge
- Thin disc. 4 main spiral arms
- Thick disc
- Halo: glob + stars
- Dark matter halo (95% mass)

ISM: Dust, gas

~200,000,000,000 stars
d ~ 30 kpc (100.000 lyr)
P ~ 240.000.000 yr

The Discs





Multiwavelength Milky Way

http://adc.gsfc.nasa.gov/mw

Structure

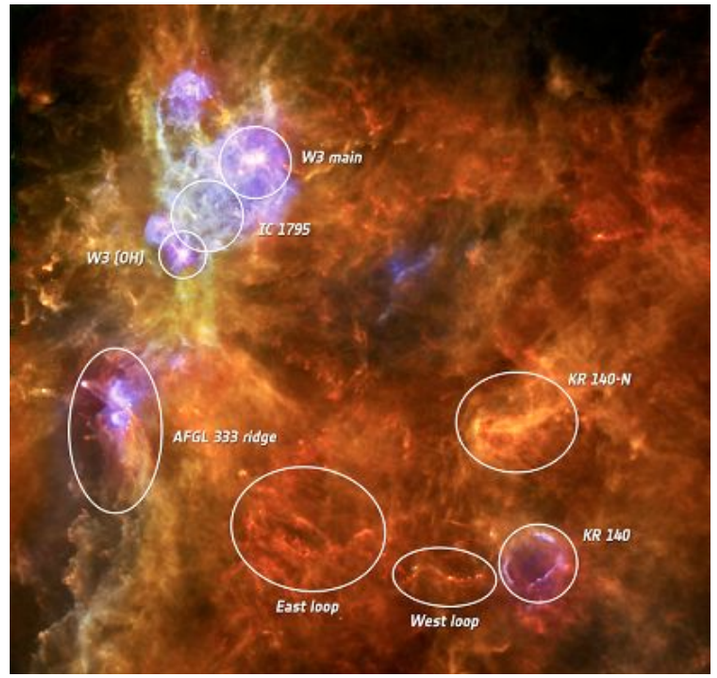
- Morphology
  - Scale heights
  - Scale lengths
  - Truncation?
  - Warp
  - Flare
  - Corrugations

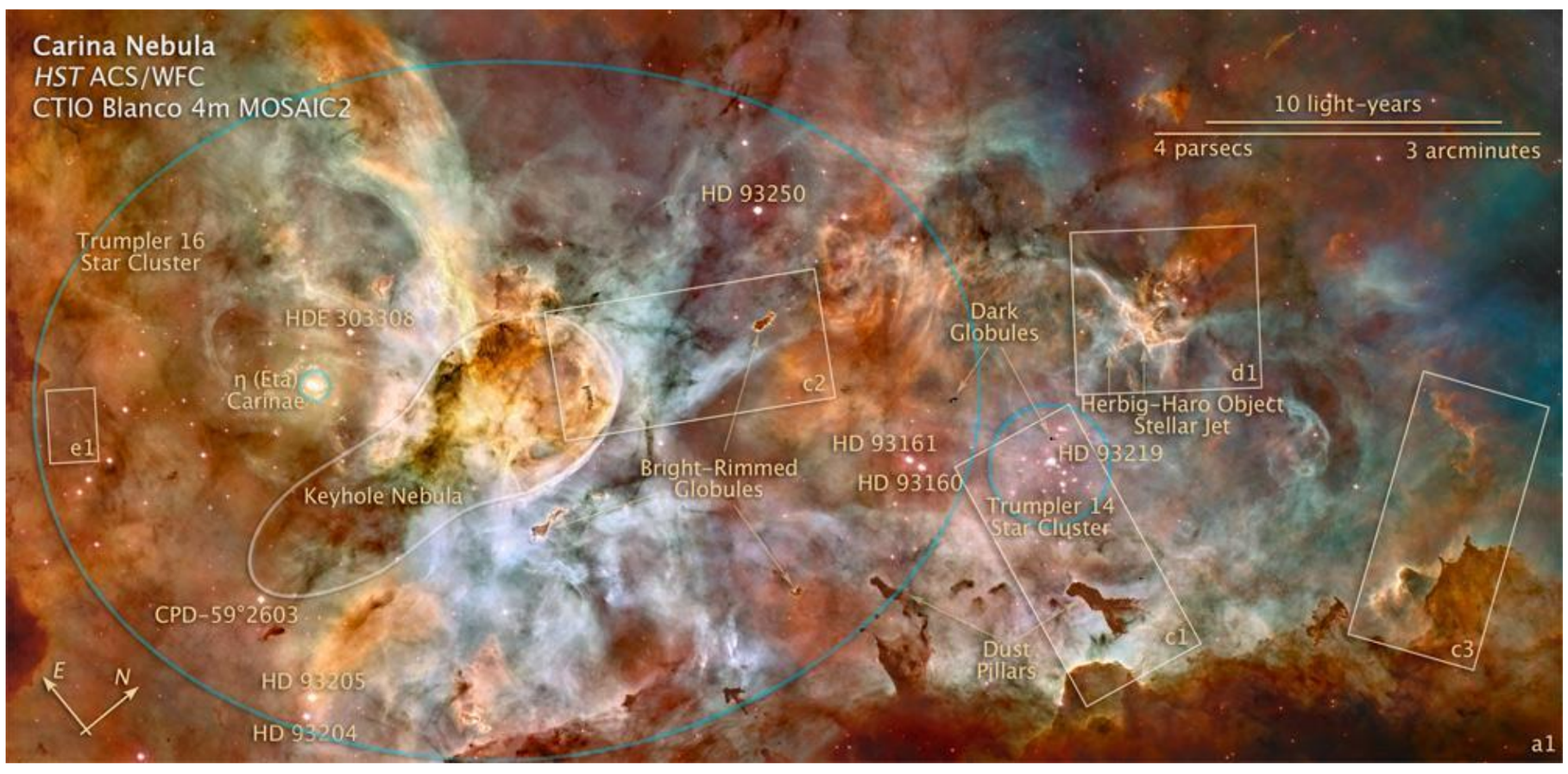
- Features
  - Spirals
  - Bar(s)
  - Streams

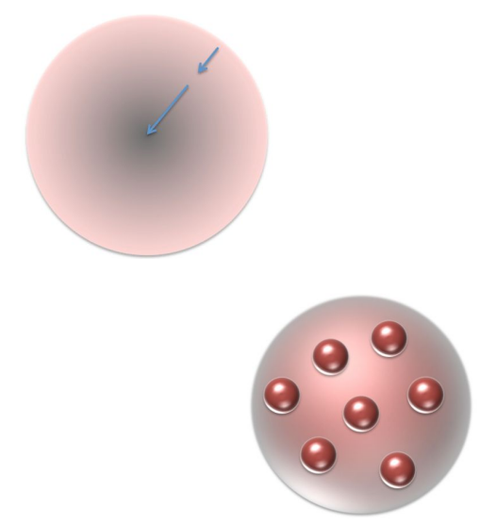
Tools

- Everything we can lay our hands (and heads) on. And a lot of it, if possible
  - Star counts
  - Photometry
  - Spectroscopy
  - Multi-wavelength (stars, gas)
  - Modelling (N-body, MHD,..)
  - Advanced Statistics (astrostatistics)
  - Machine learning (astroinformatics)

it turns out that star formation occurs mostly in star clusters in spiral arms

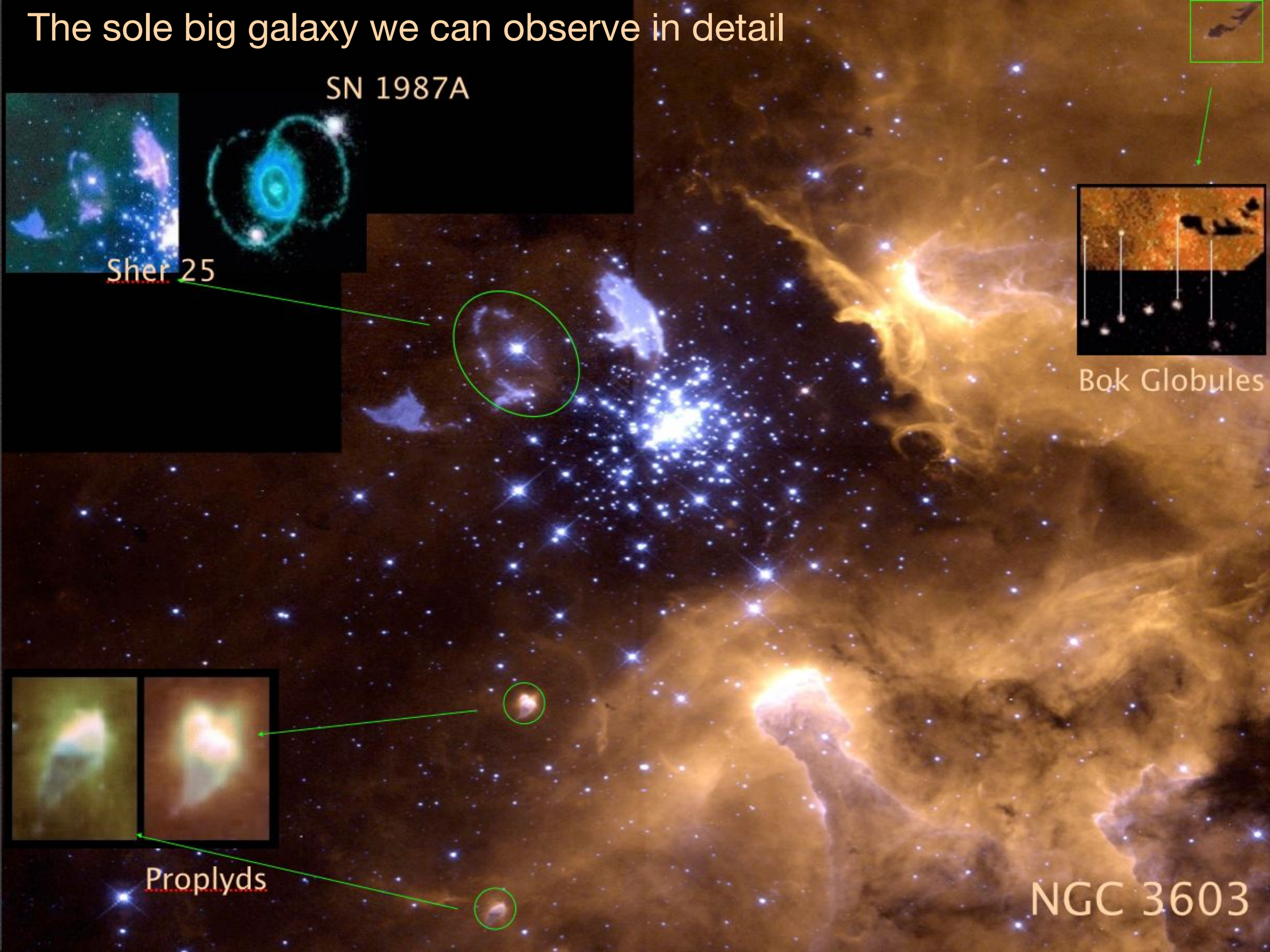






$$M_J \simeq \left(\frac{5kT}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

The sole big galaxy we can observe in detail

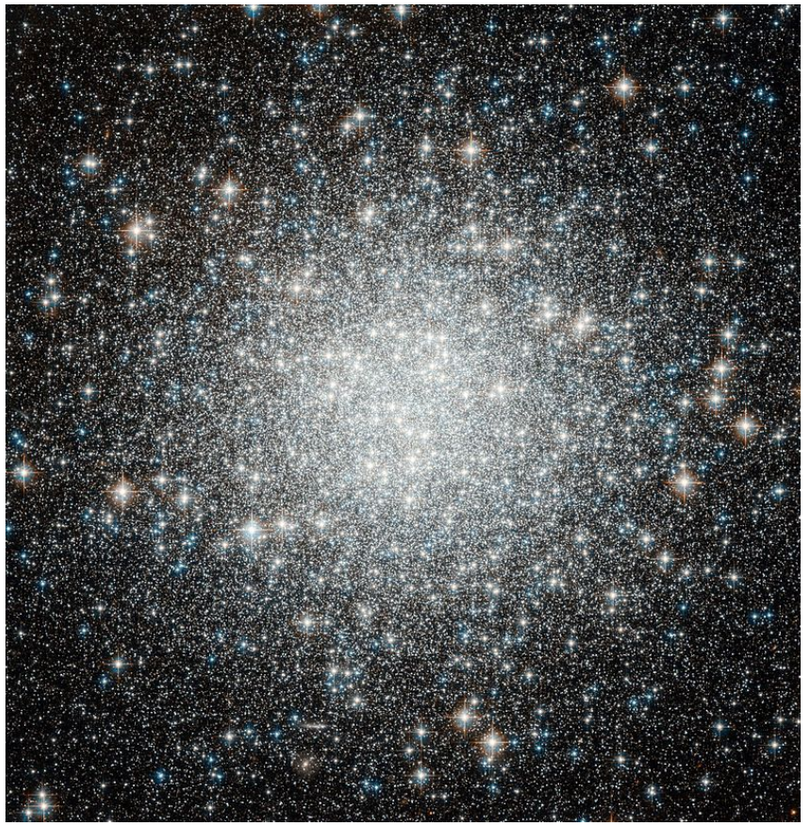


The sole big galaxy we can observe in detail

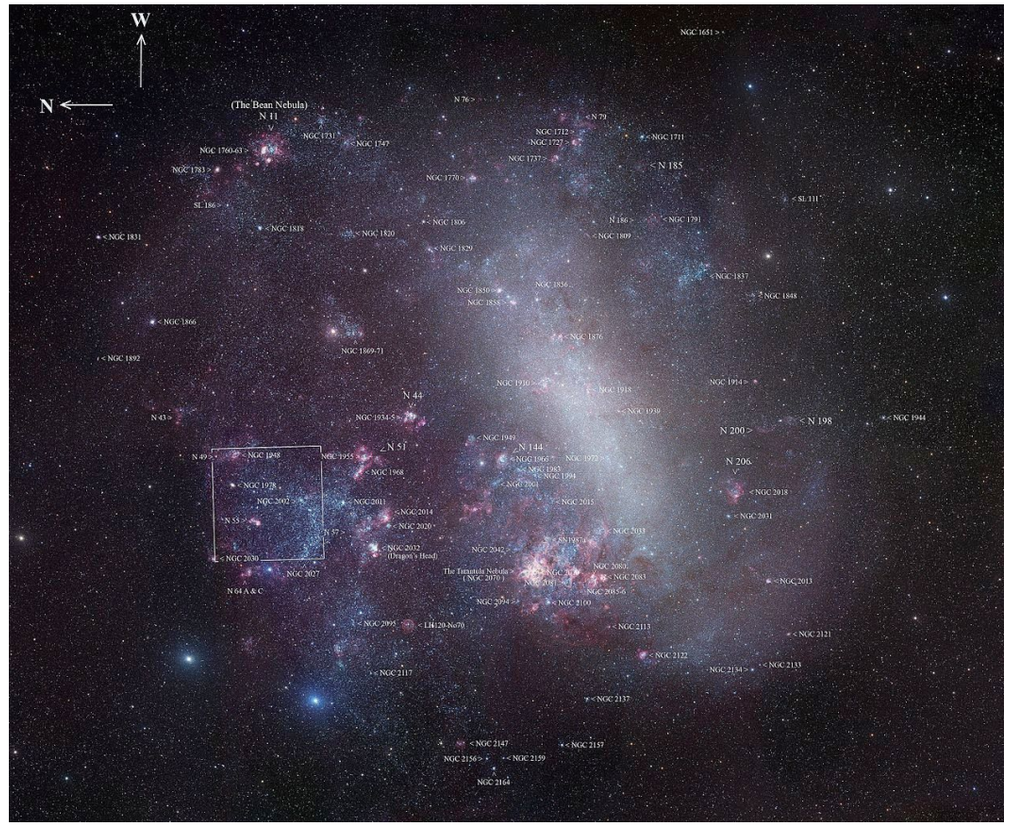
pocket physics:

Most of these clusters will puff up and suffer infant mortality.

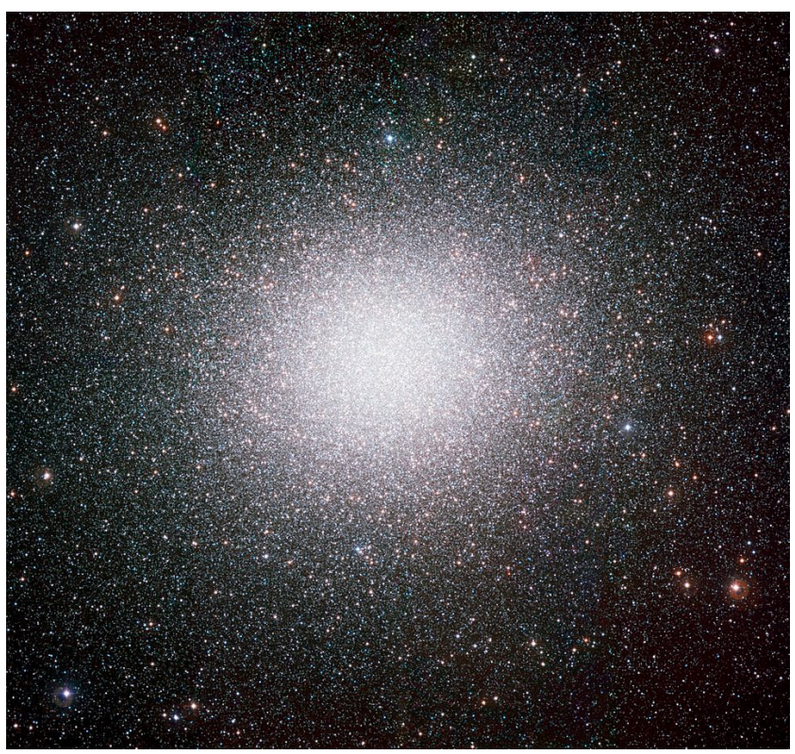
This is because stellar winds will blow away remaining gas which is acting as gravitational glue.



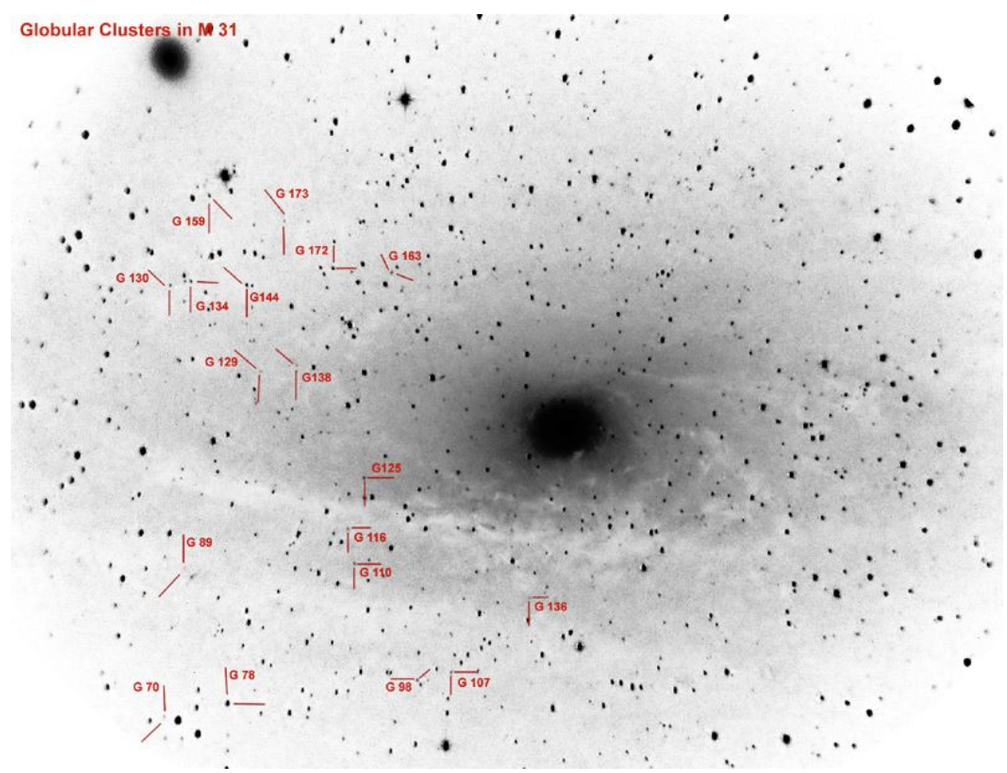
M53



Large Magellanic Cloud (young)



ωcen



M31 - Andromeda (old halo)

M53

ωcen

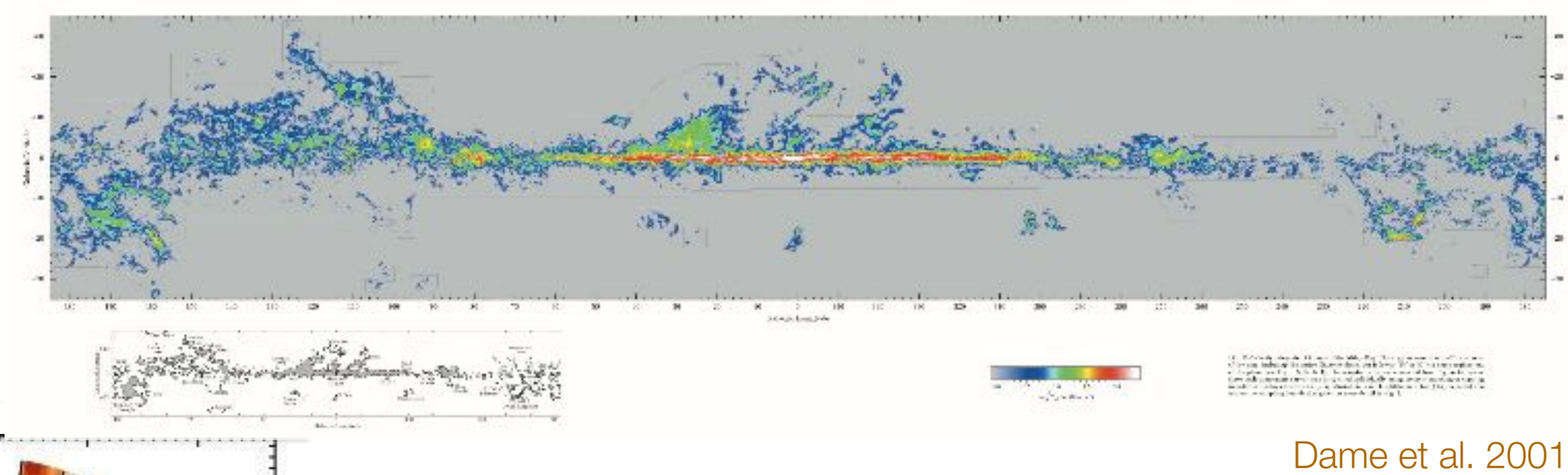
More pocket physics:

Star clusters tend to dissolve over time:

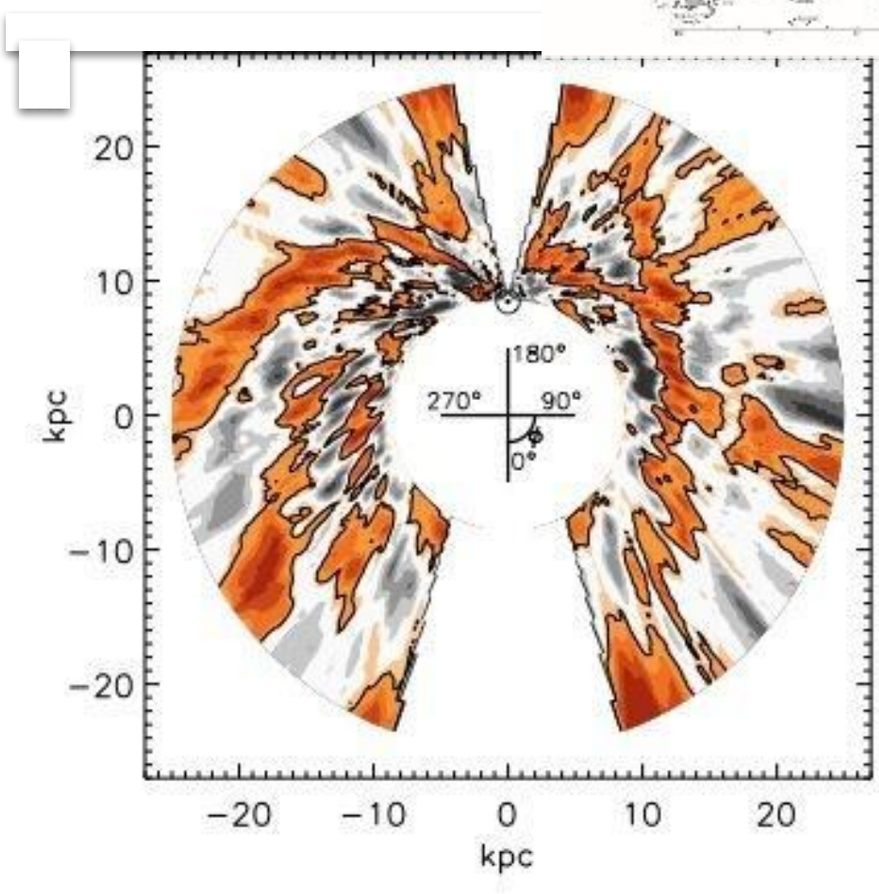
- Stars are like particles in a classic gas: Maxwell- Boltzmann velocity distribution
- Energy equipartition -> same Ec for massive and lighter stars -> higher speeds for lighter stars -> some speeds higher than escape vel.
- Stars escape -> mass loss -> escape vel decreases ($v = \sqrt{2GM/r}$) -> more stars escape

Morphology

Overall appearance: Gas



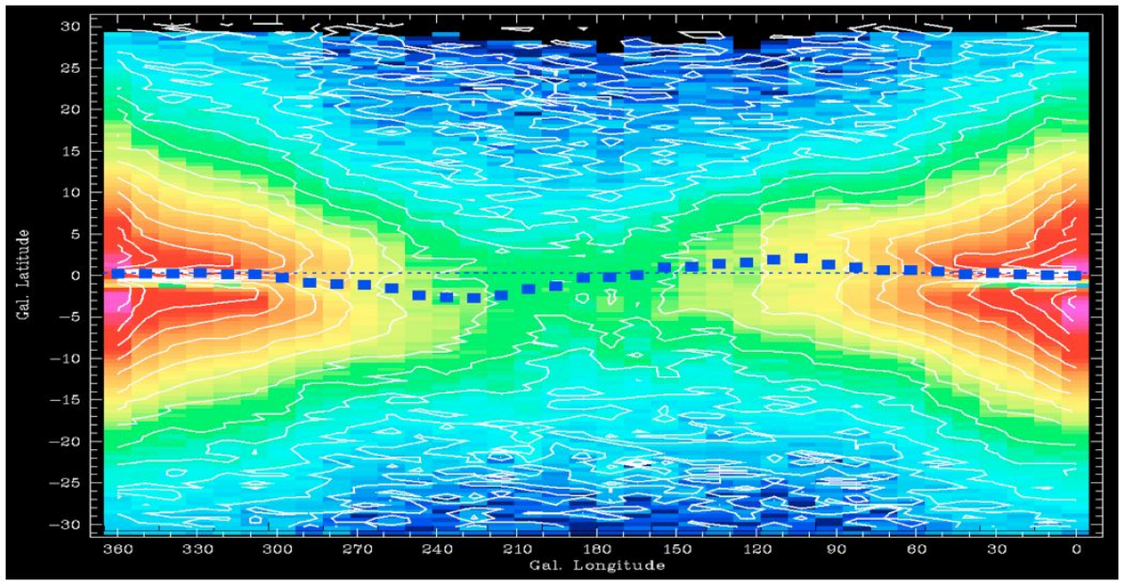
Dame et al. 2001



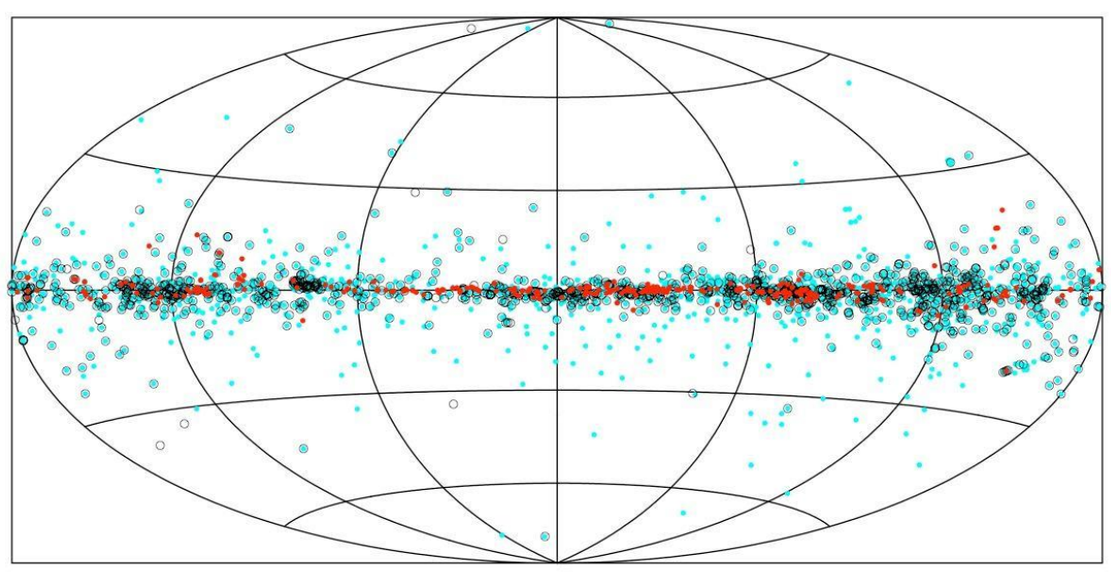
- H1: R> 25 kpc
- CO: Thin and fragmented

Levine et al. 2006

Overall appearance: Stars



Momany et al. 2006



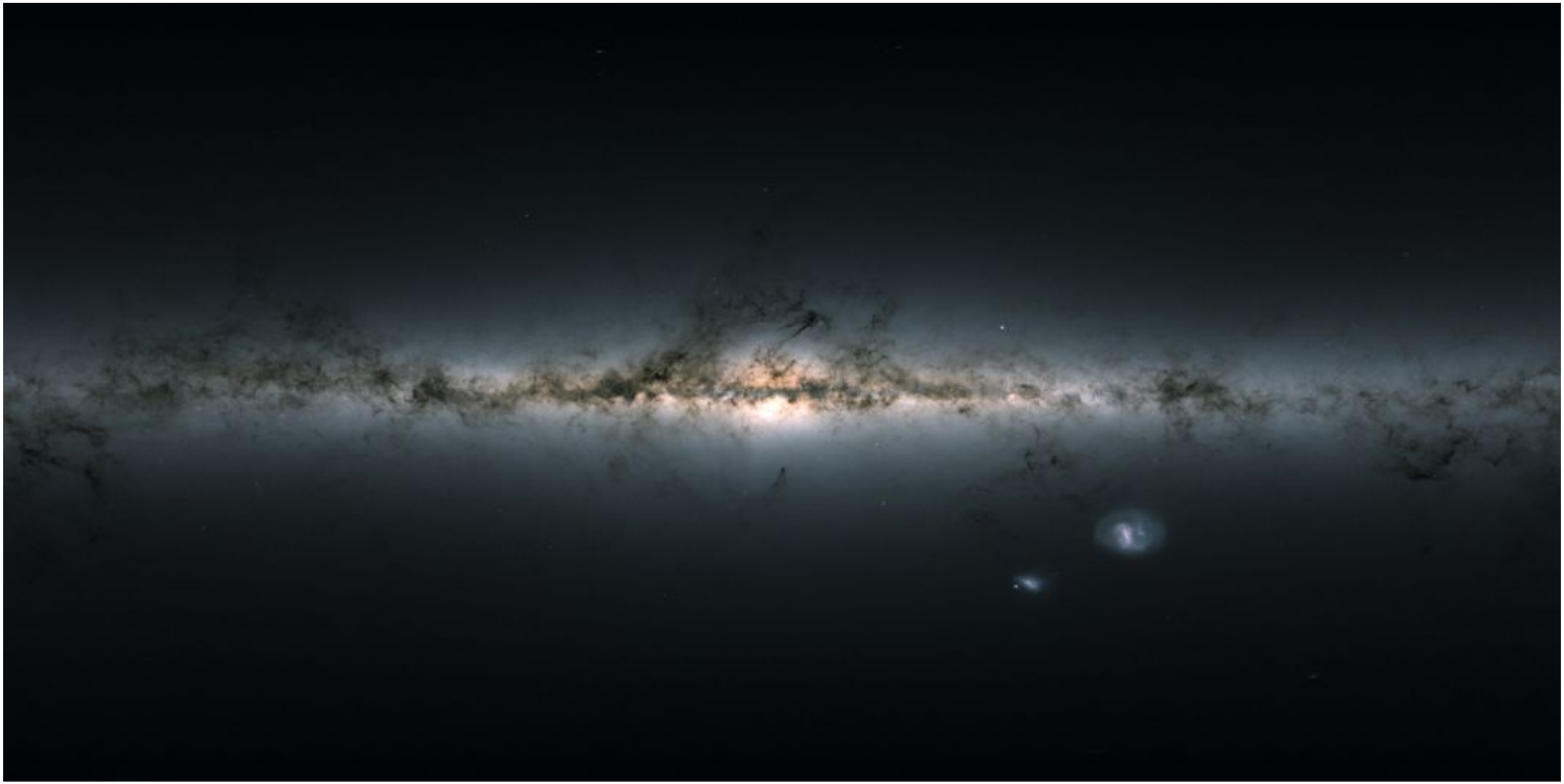
Star counts

- Pro: Infrared counts less affected by extinction
- Pro: Statistics. There are lots
- Con: Distances and reddenings not too precise.
- Con: Interpretation often model dependent

Clusters - Optical (& NIR)

- Pro: Precise distances and ages. Unique chronometer over a wide time interval
- Con: Very limited distance range (for the moment)

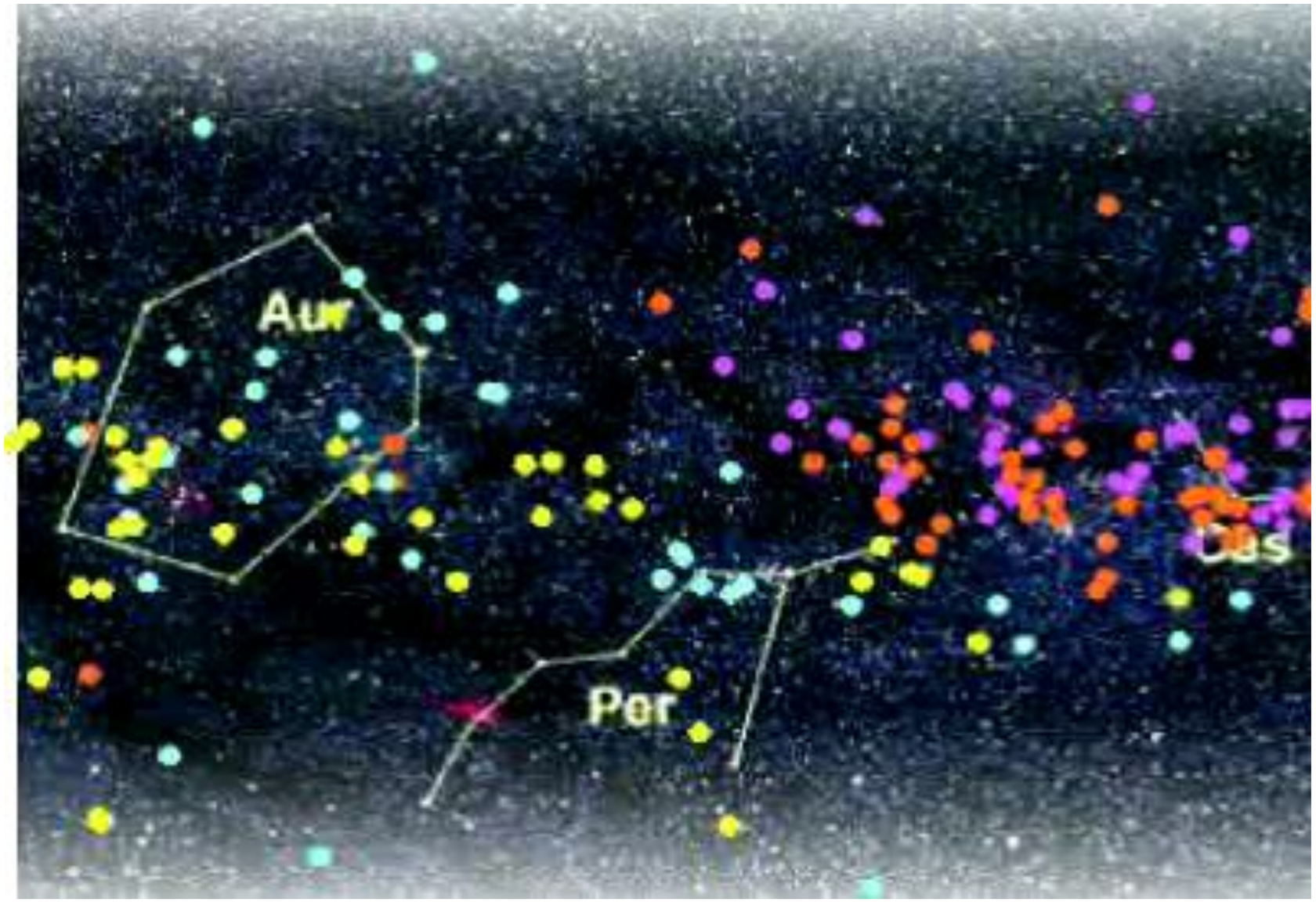
Selection effects



- Must really keep in mind that extinction will affect determination of Disc structural parameters when using optical observations:

  Cluster imaging, stellar spectroscopy, ...

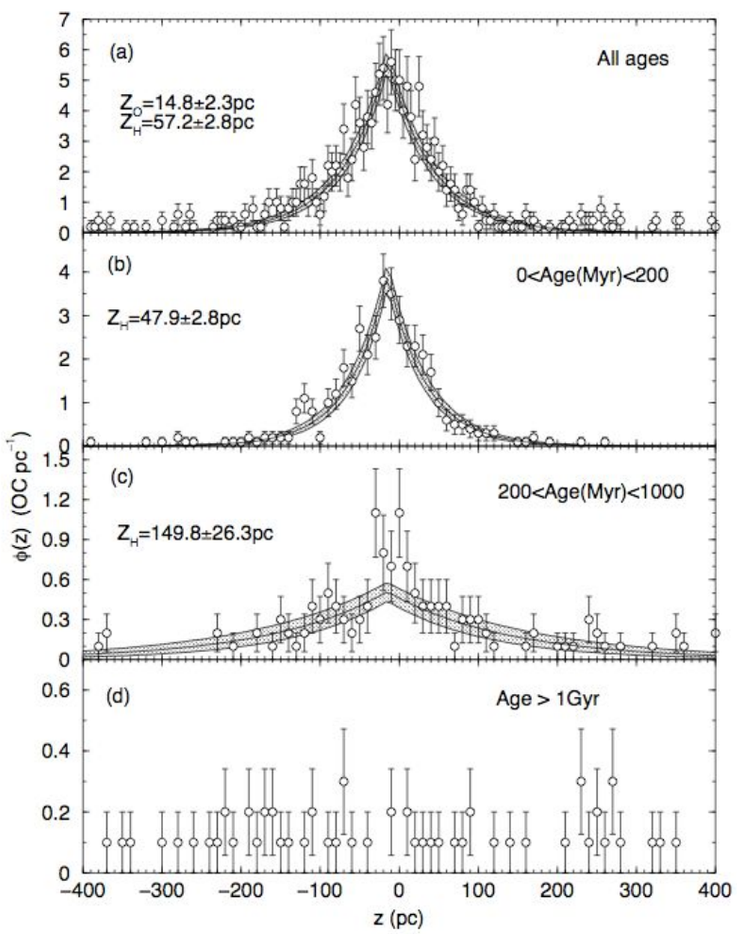
Selection effects

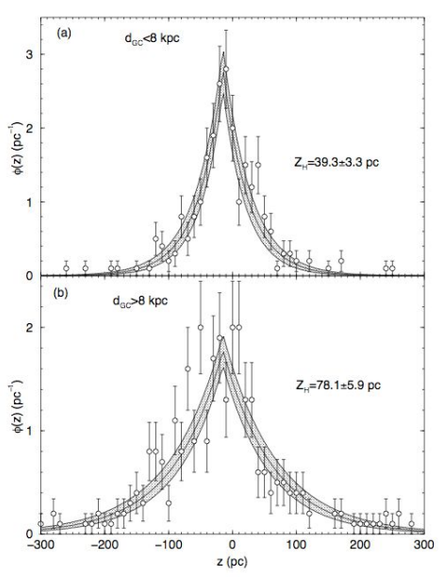


- Must really keep in mind that extinction will affect determination of Disc structural parameters when using optical observations:

  Cluster imaging, stellar spectroscopy, ...

Disc scale heights (SH)

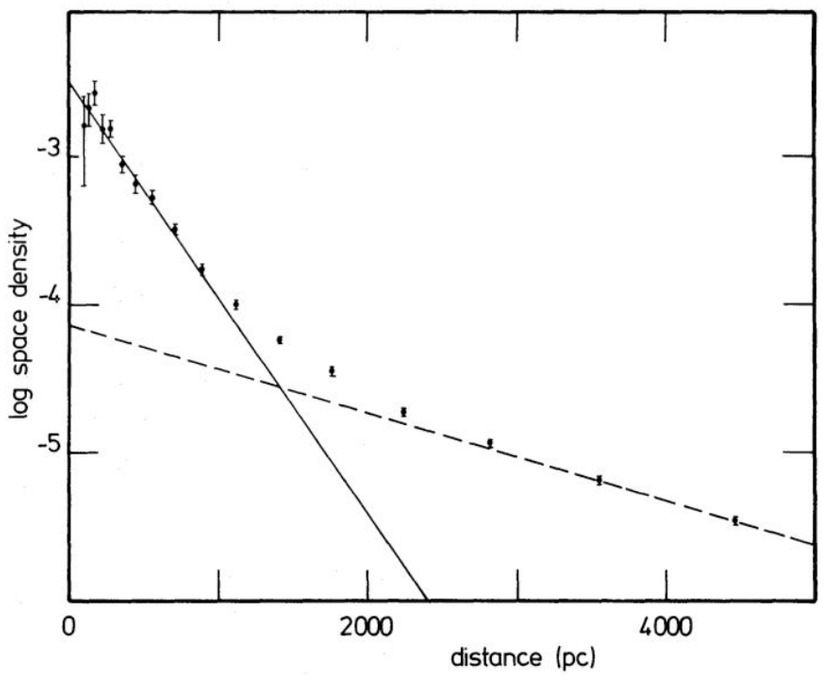




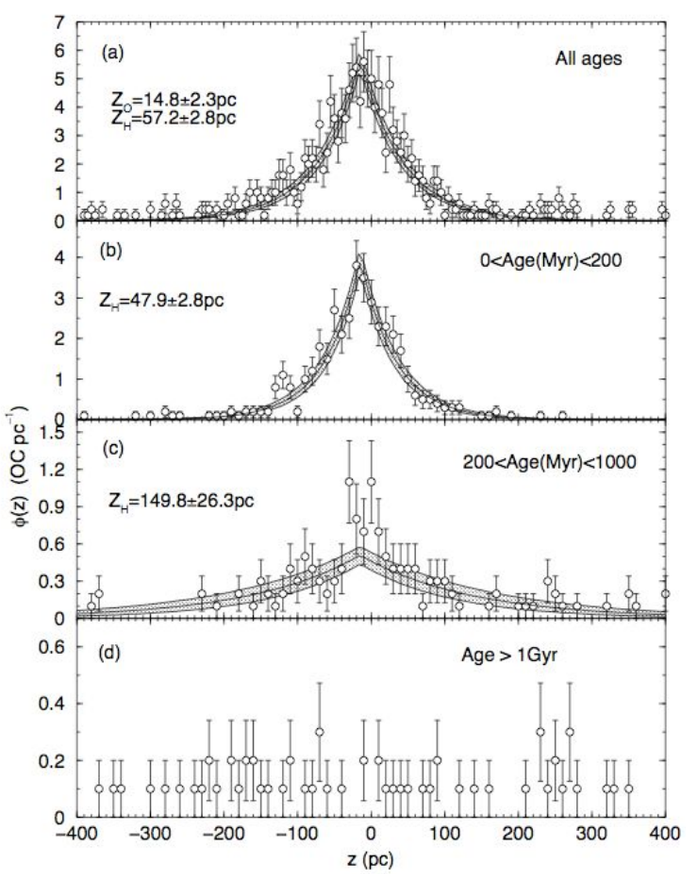
From Bonatto et al. 2006

- OB stars: 45 pc (Reed, 2000)
- Open clusters:
  - young: 47.9 pc
  - older: 149.8 pc
  - Young SH < Old SH
  - In SH < Out SH
  - Sun height ~15 pc (other studies 22 pc; 13-20 pc +/-4)
- H1: 140 pc
- Field stars: 300 pc

Disc scale heights (SH)



Gilmore & Reid 1983



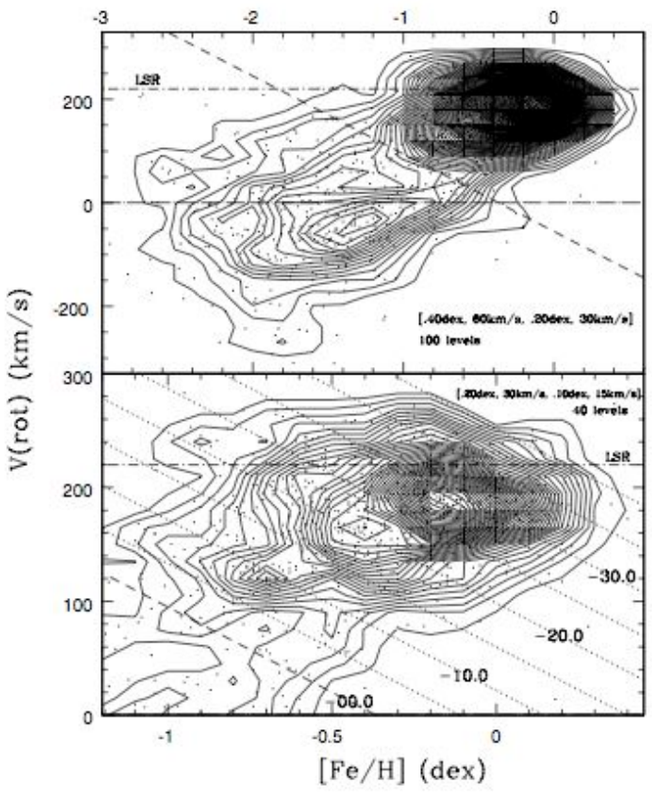
Bonatto et al. 2006

- Field stars
  - 300 pc - Thin Disc
  - 1350 pc - Thick Disc

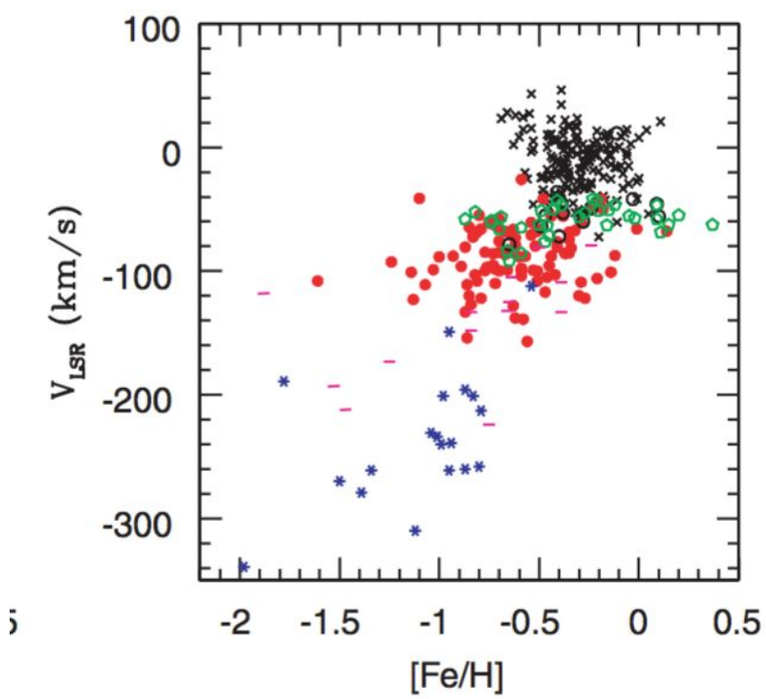
(see Chang 2011, for a compilation)

- Cluster SH much smaller than stars (48-150 vs 300 pc)
  - Signature of original scale heights? (young vs old)
  - Heating of cluster orbits?
  - Signature of disruption close to plane?
  - If thick disk forms from OC popping (Kroupa 2002) then TD OCs should not exist (except if captured).

Thick Disc



Schuster et al. 2006



Reddy et al. 2006

Thin disk stars: rapid rotation, higher metallicity

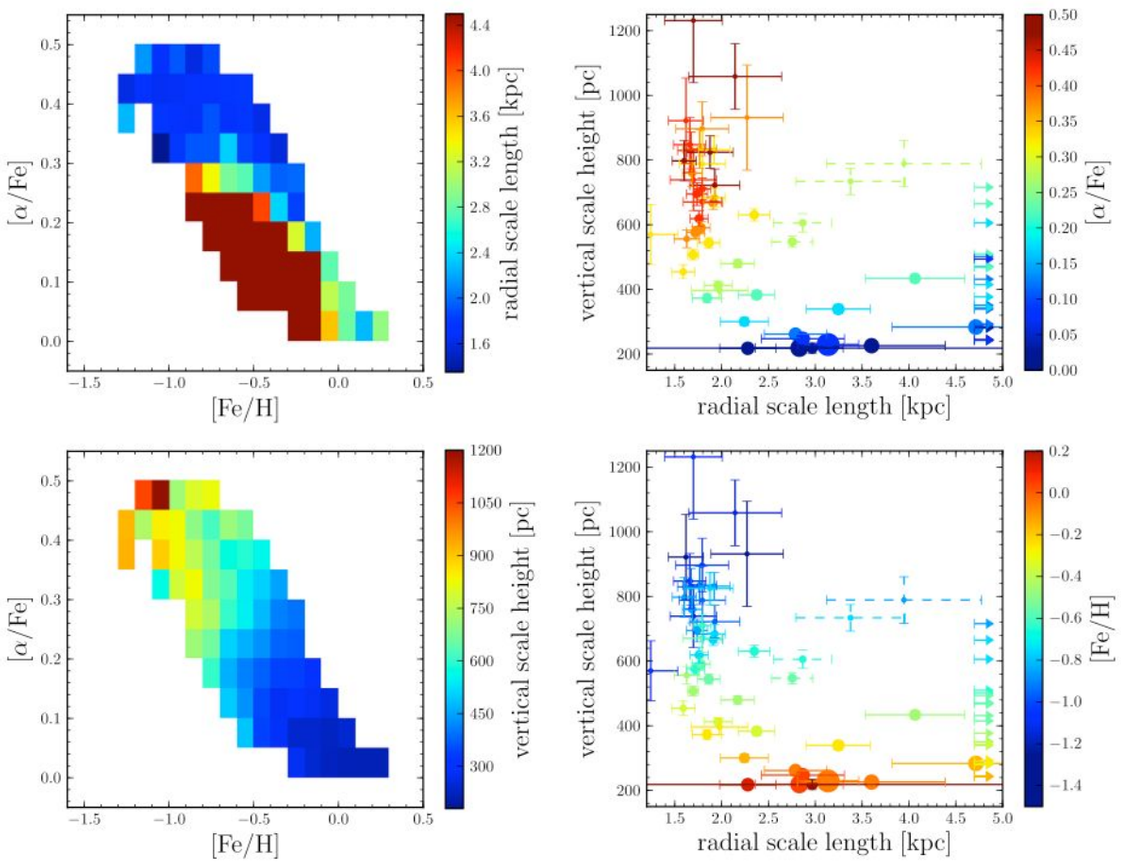
Thick disk stars

Halo stars: slow rotation, low metallicity

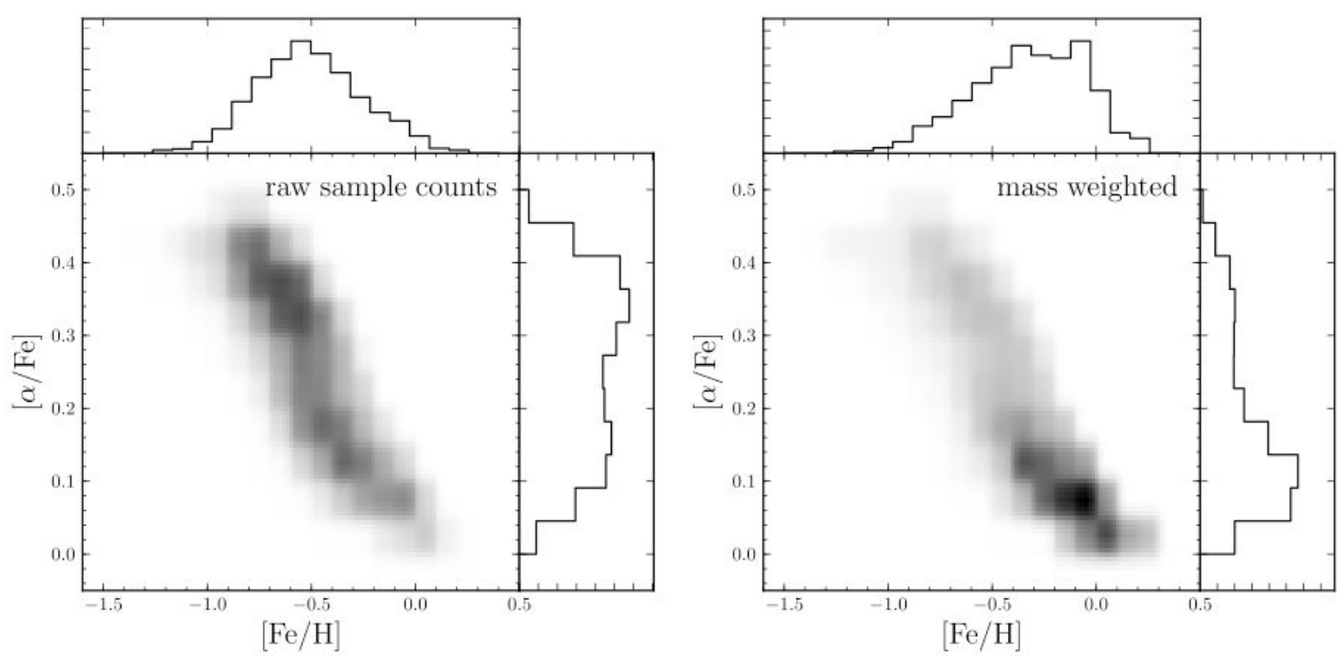
- Evidence for:
  - Different kinematics
  - Different abundances
  - Different ages
  - Substructure?

- Origin?
  - Accretion of dwarf galaxy?
  - Stellar migration?
  - Heating of DM sub-halos?
  - Gas-rich merger?
  - Puffed-up disc?

Thick Disc



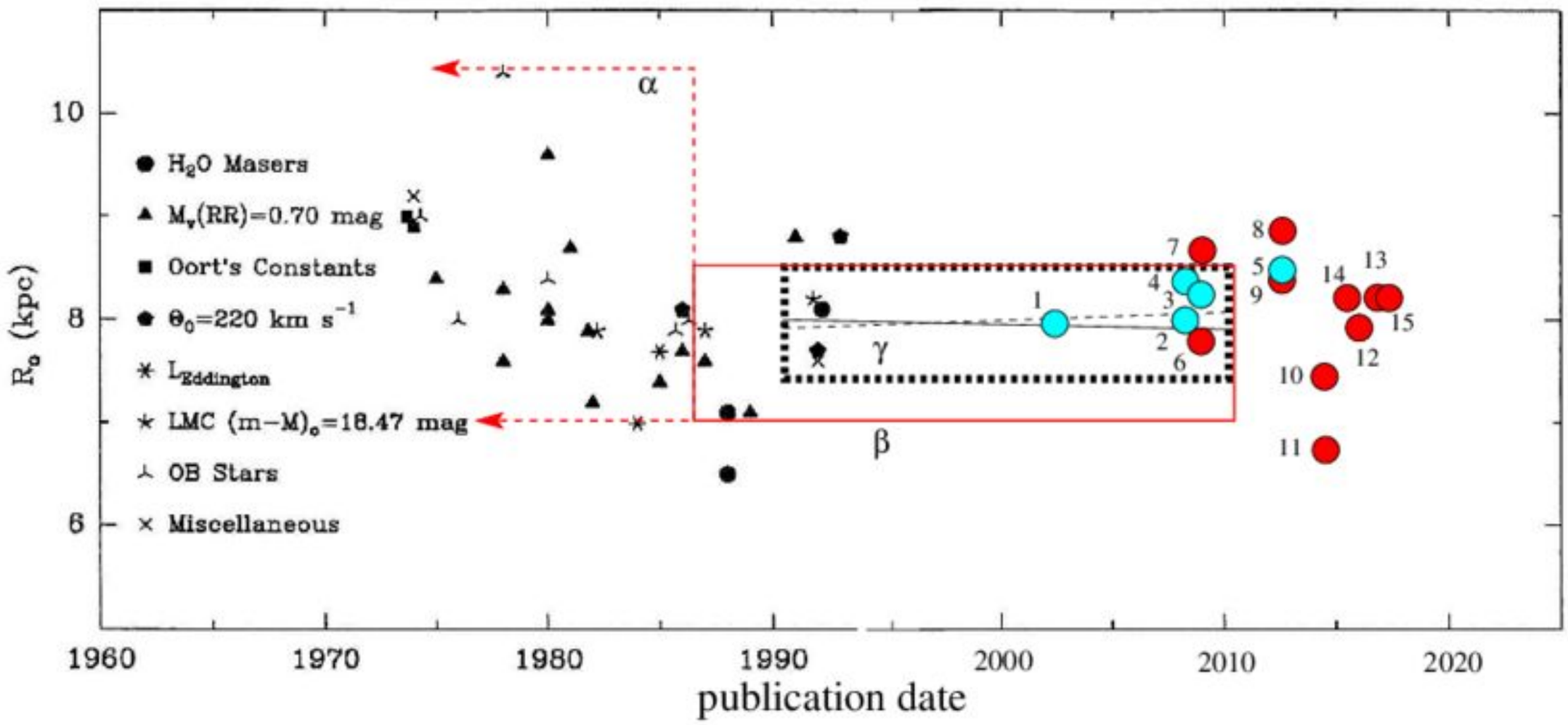
Bovy et al. 2011



- However:
  - New claims that distribution of SH of mono abundance samples doesn't show a break
  - Bi-modality as a sample selection effect?
  - Have served as base for challenging thick disc as an independent structure
  - Also some bayesian hype..

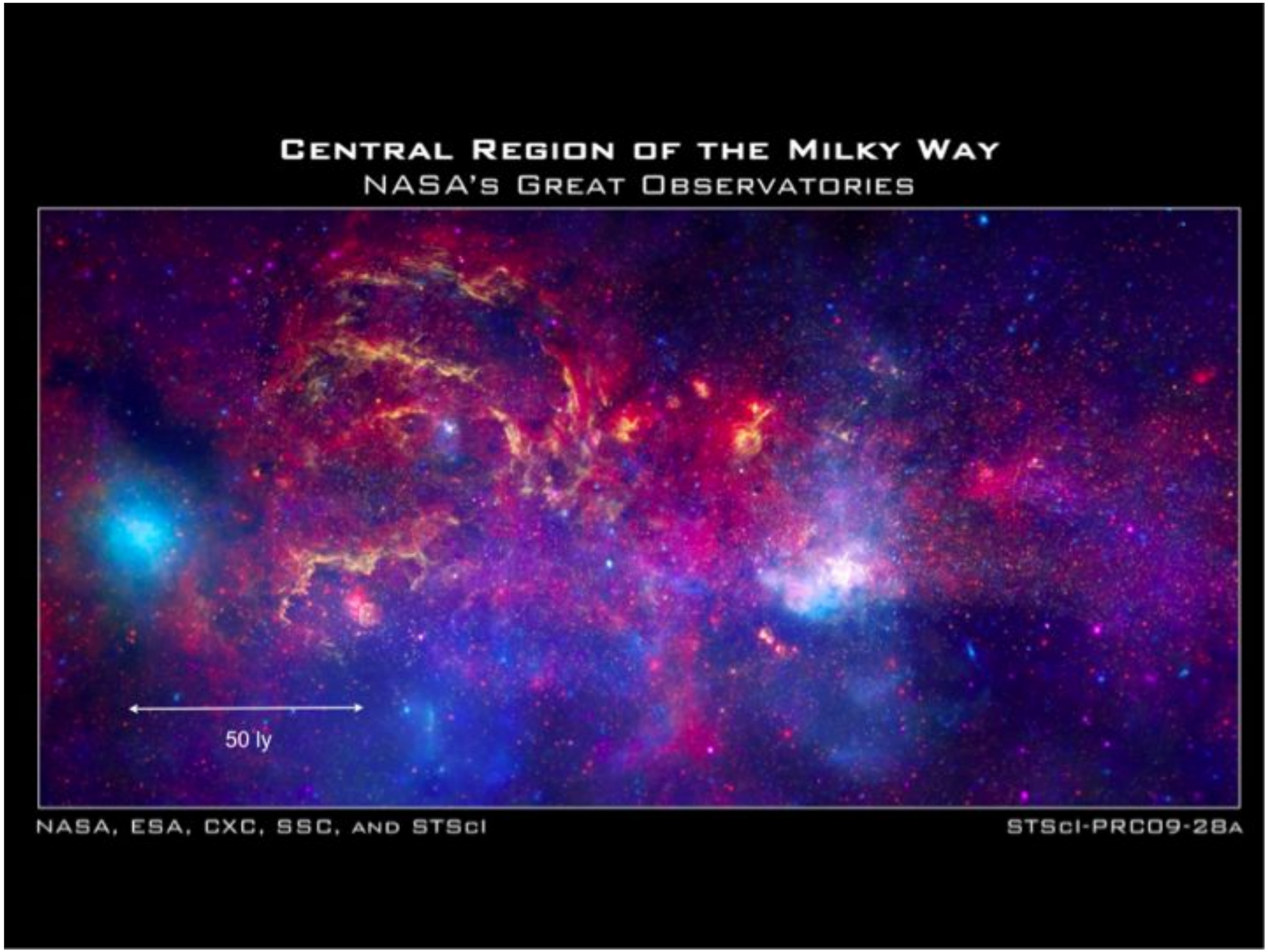
Bovy et al. 2012

Distance to Galactic Center



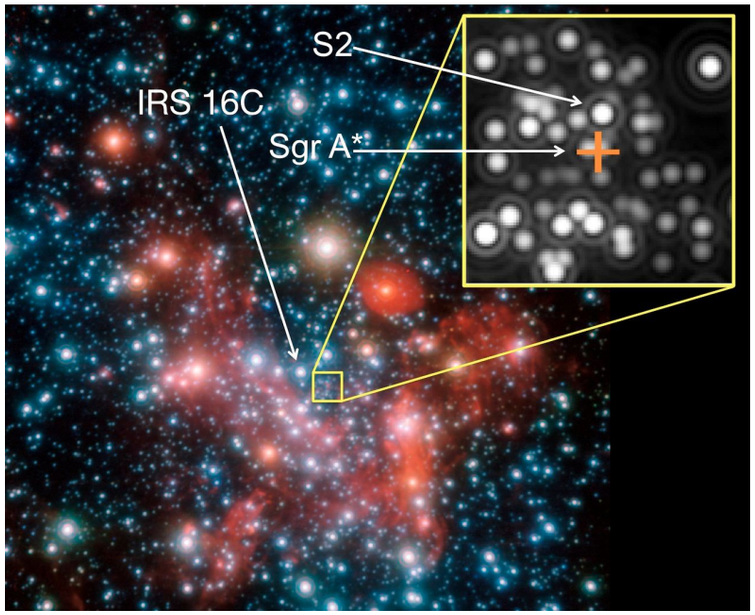
Distance to the Galactic Center: Black symbols and comments are taken from Reid (1993). The bulk of the data presented by Genzel et al (2010) is located in region α and β. The data used by Malkin (2013) is mostly located in region γ. The solid and dashed lines in region γ correspond to the weighted and unweighted versions of the calculated trends found by Malkin (2013). New and recent data points based on stellar orbital analyses are shown by turquoise filled circles and labeled: 1: Horrobin et al (2004); Eisenhauer et al (2003); Schödel et al (2002); 2: Ghez et al (2008); 3: Gillessen et al (2009a); 4: Ghez et al (2008); 5: Do et al (2013). Distance estimates based on stellar distributions in the global stellar cluster or Milky Way bulge are shown by red filled circles and labeled: 6 Majaess et al (2009); 7: Vanhollebeke et al (2009); 8: Do et al (2013); 9: Dékány et al (2013); 10:Francis and Anderson (2014); 11:Branham (2014); 12:Boehle et al (2016); 13:Parsa et al (2017); 14:Chatzopoulos et al (2015); 15:Gillessen et al (2017). [from Eckart et al 2019]

Galactic Center



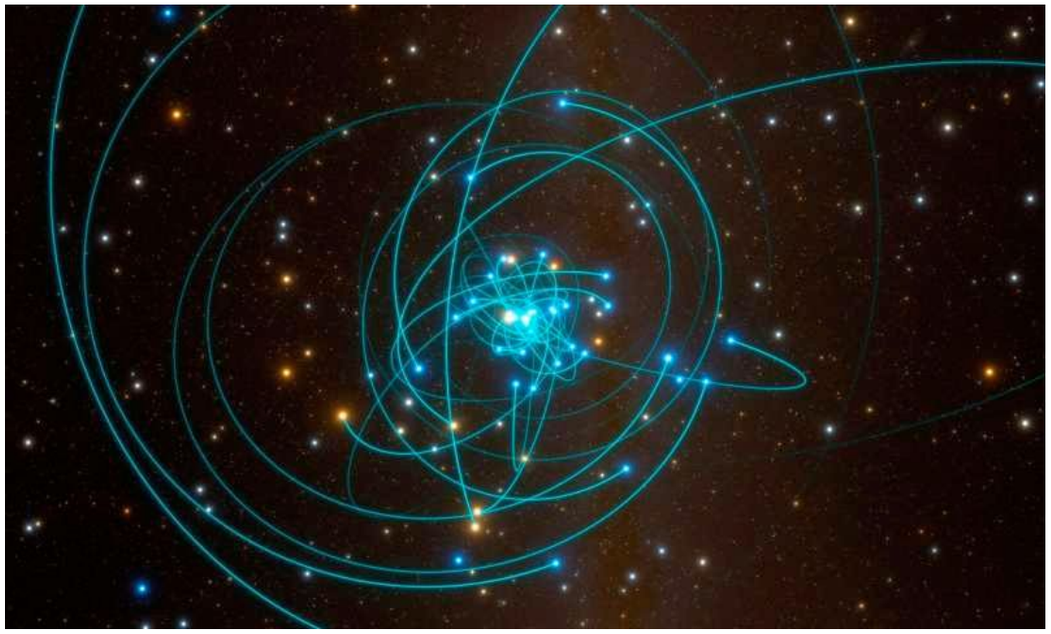

390 ly
Sgr B2 - 3.000.000 Msun
Ethyl formate (a major precursor to amino acids)
27 to -233 C

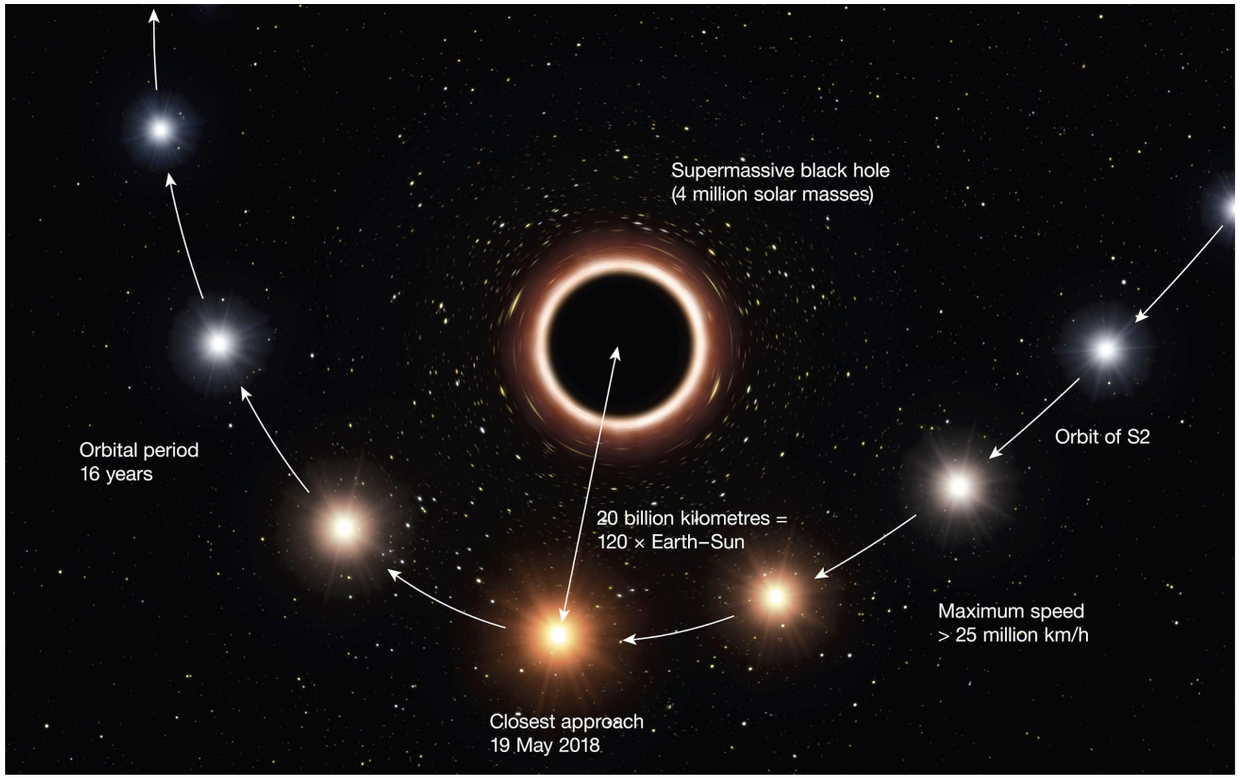
Galactic Center



- ~4.300.000 Msun (8.2 x 10^36 kg)

- CENTRA participates in the ESO VLTi Gravity instrument.
- gravitational redshift detected and measured in July 2018



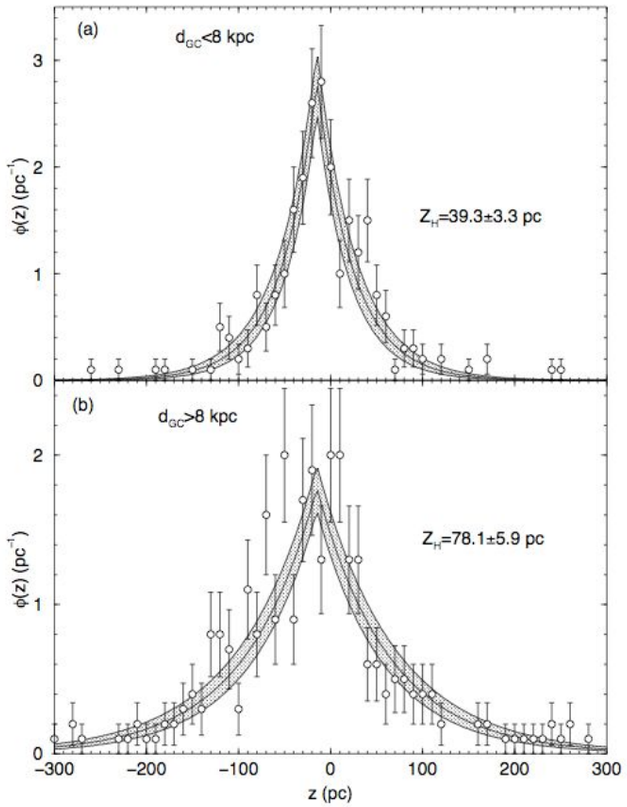


next opportunity in 16 years

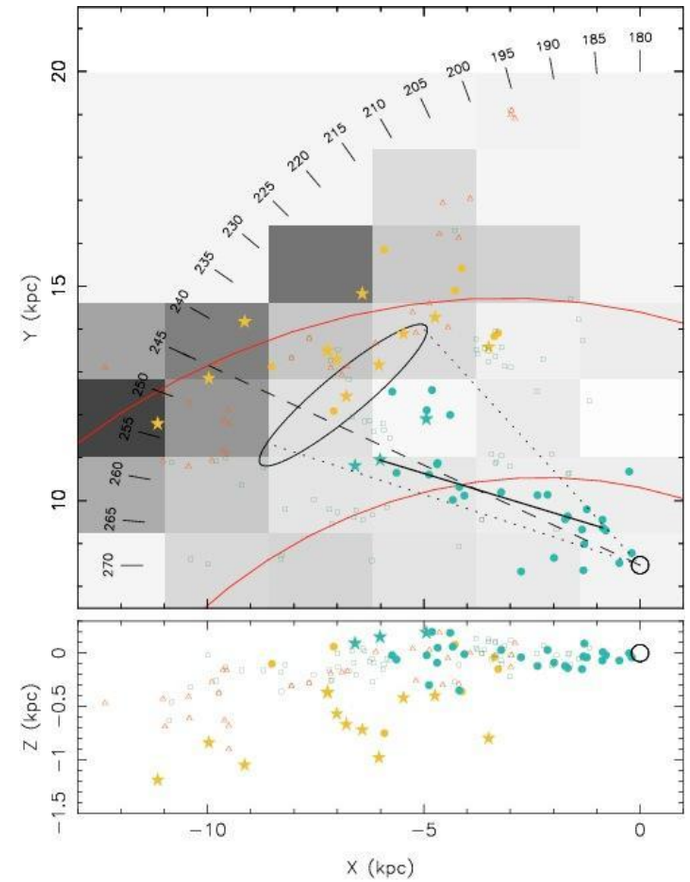
Warp and Flare

Galaxy ESO
510-G13

Warp & Flare

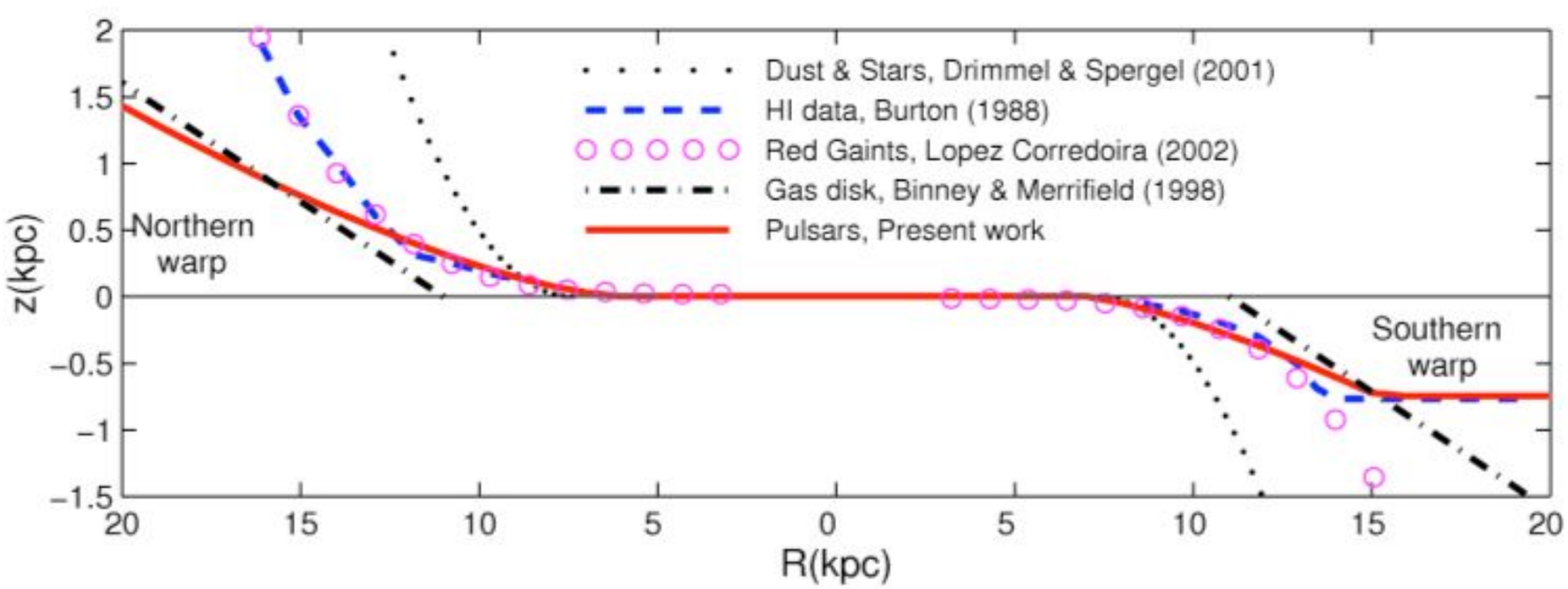


Bonatto et al. 2006

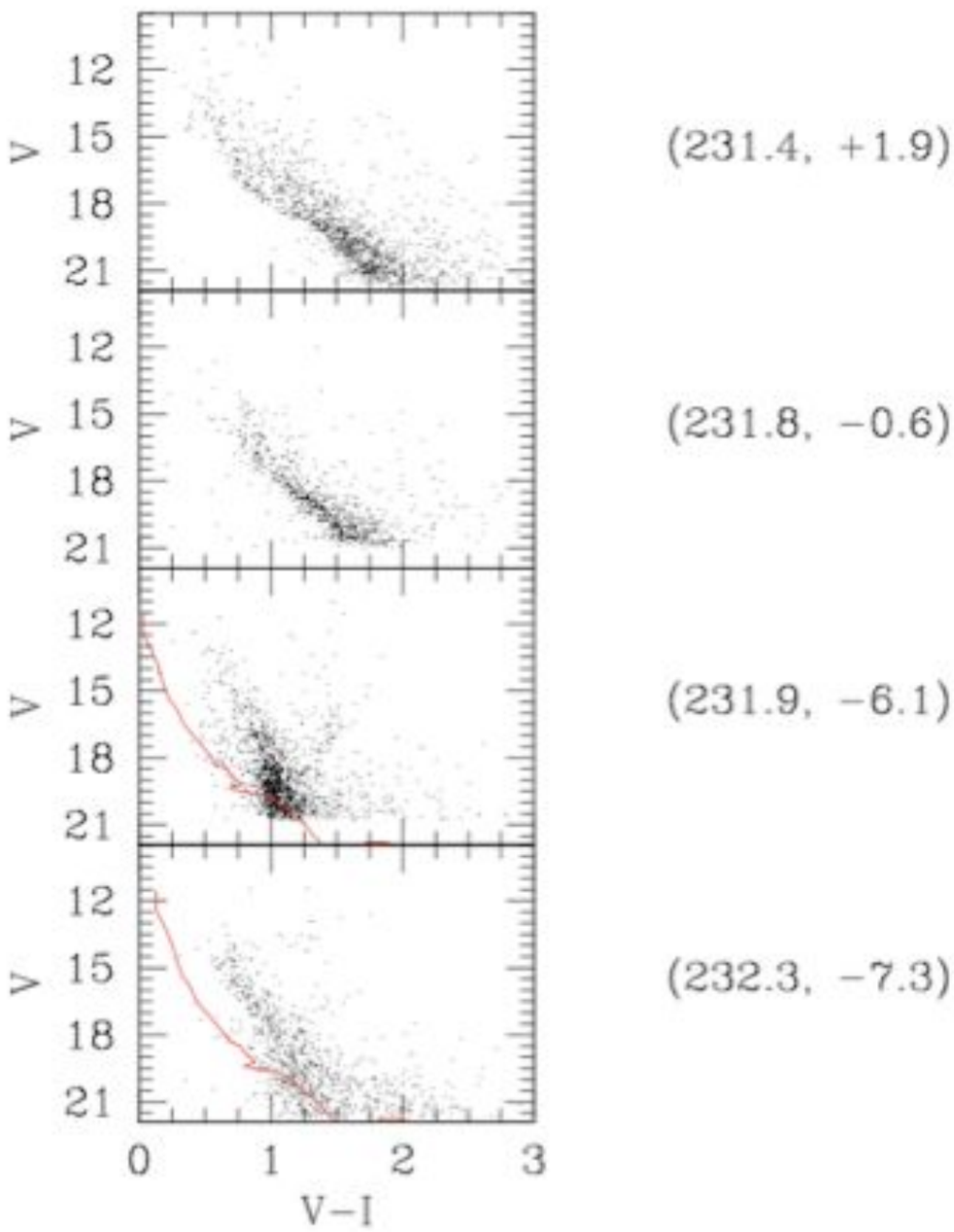


Moitinho et al. 2006

- Disc is not truncated at RGC ~ 12.5-15 kpc
- Illusion caused by the Warp and Flare

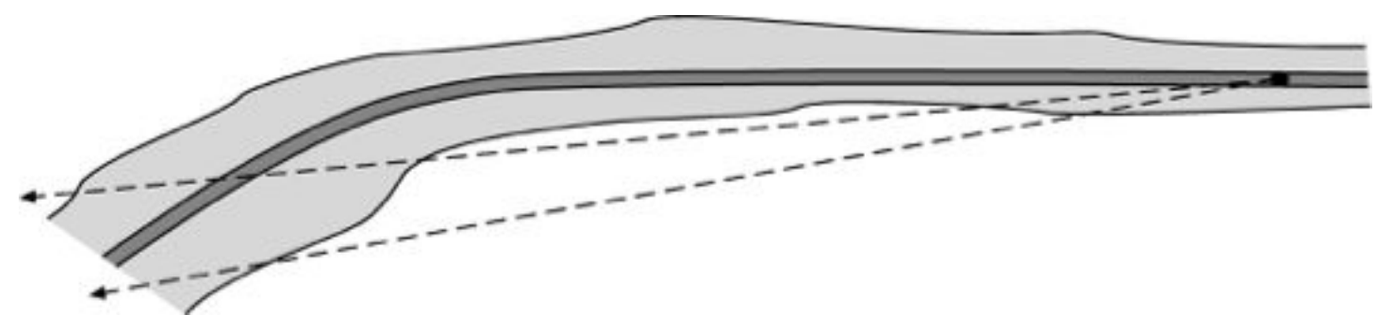


Seeing the Milky Way face-on



Carraro et al. 2007

- Disc is not truncated at RGC ~ 12.5-15 kpc
- Illusion caused by the Warp and Flare



- Photometric signature of the old metal-poor disc population (Thick Disc)
- Not all fields show TD hump

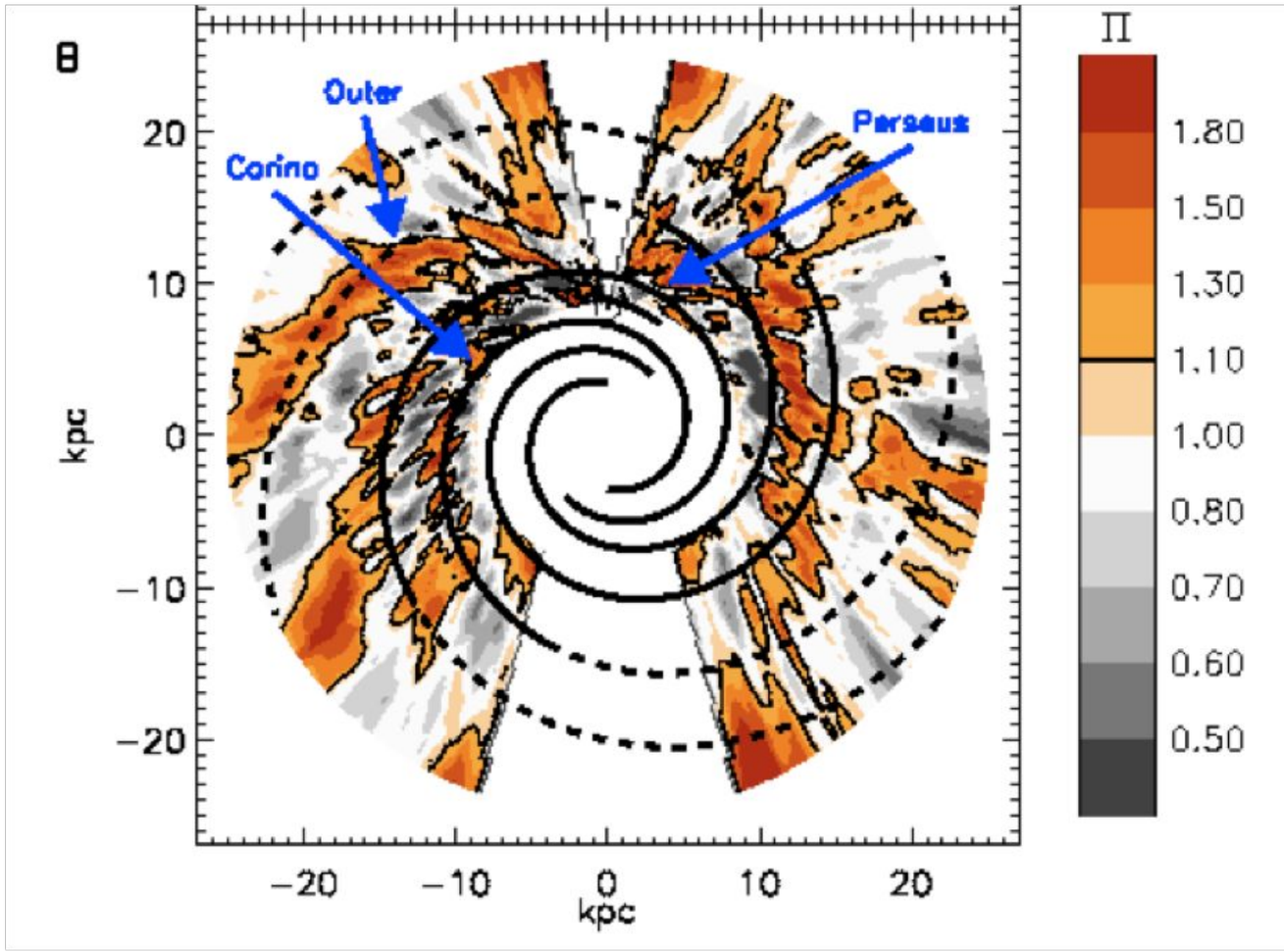
Spiral Structure

Incidentally, if you are looking for a good problem, the exact details of how the arms are formed and what determines the shapes of these galaxies has not been worked out.

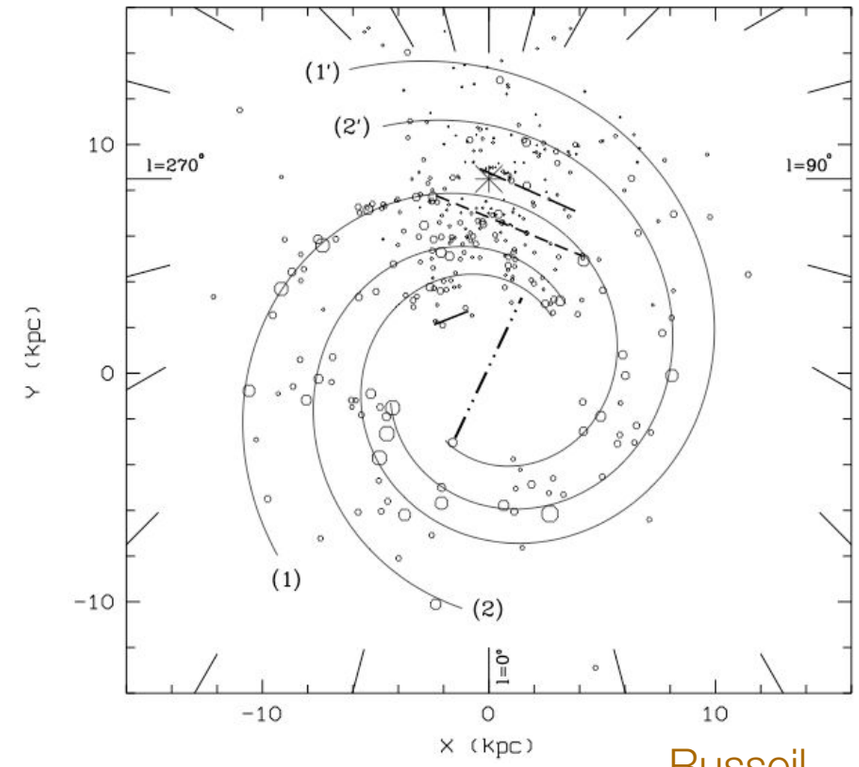
-R.P. Feynman

The Feynman lectures on physics, vol. 1, 1963

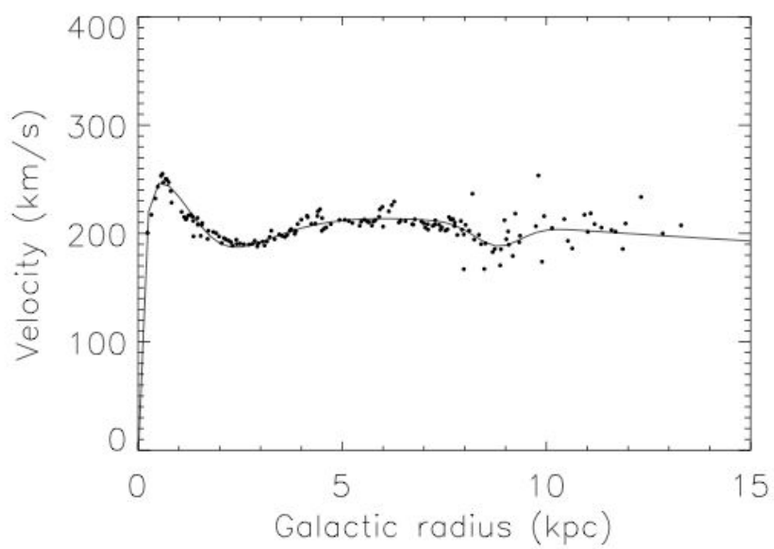
- HI, YOCs, SFR



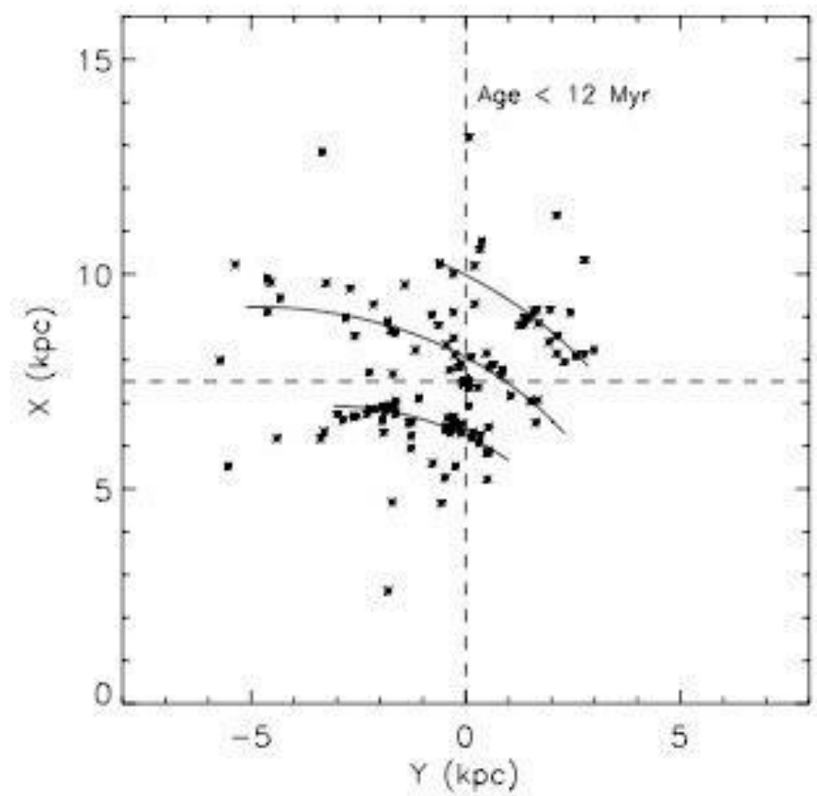
Levine et al 2006



Russeil 2003

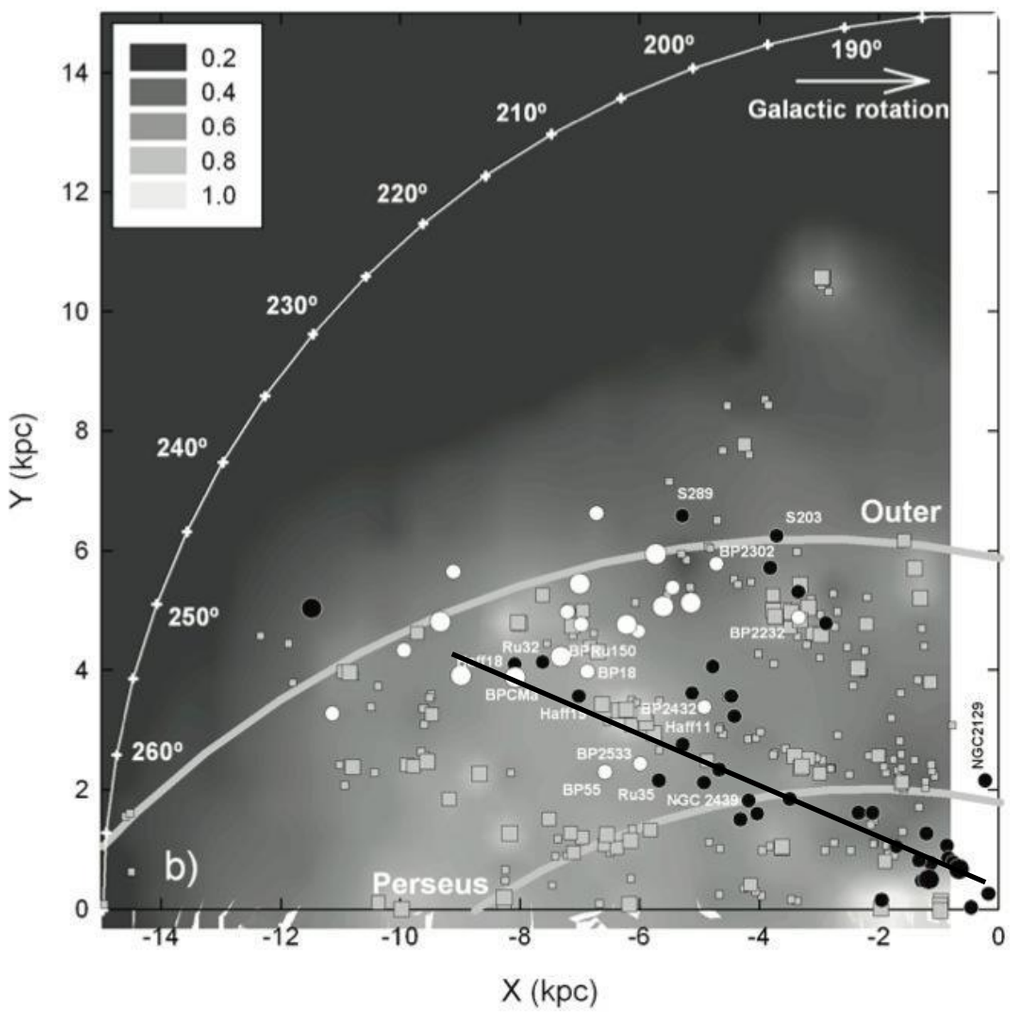


Amôres et al. 2009



Dias & Lépine 2005

- Perseus not traced by YOCs in the 3GQ (but, some YOCs in the right place in the 4GQ)
- Norma-Cygnus defined over the 3GQ up to 20 kpc RGC
- The Local arm reaches the Norma arm

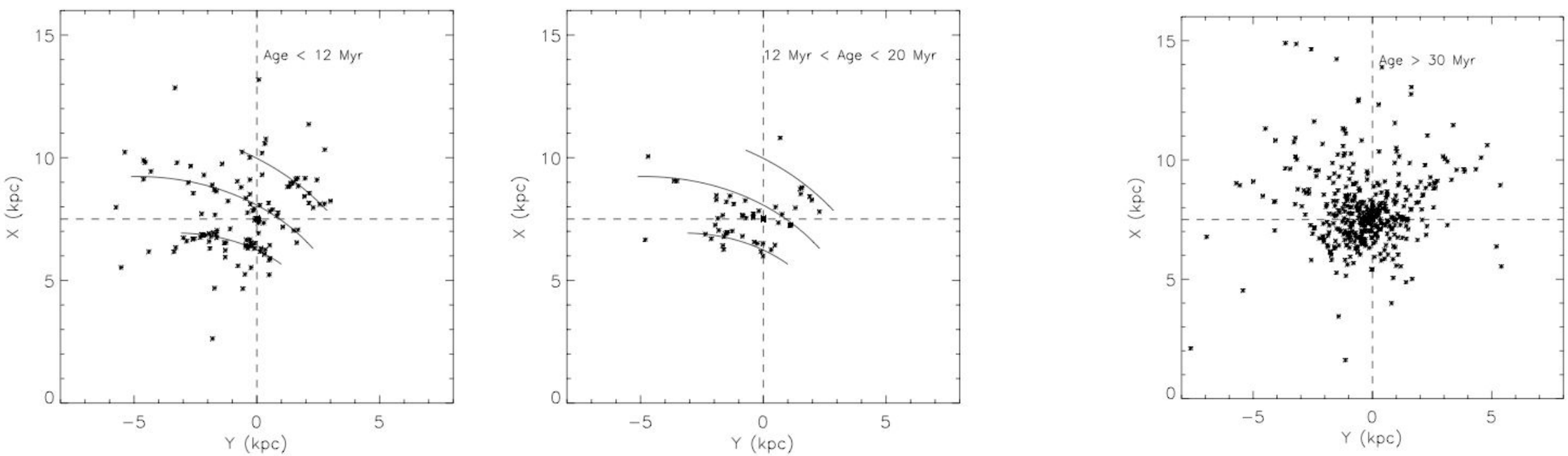


Vázquez et al 2008

M74

Spiral arms

- Young open clusters
- Leave arms between 20-30 Myr

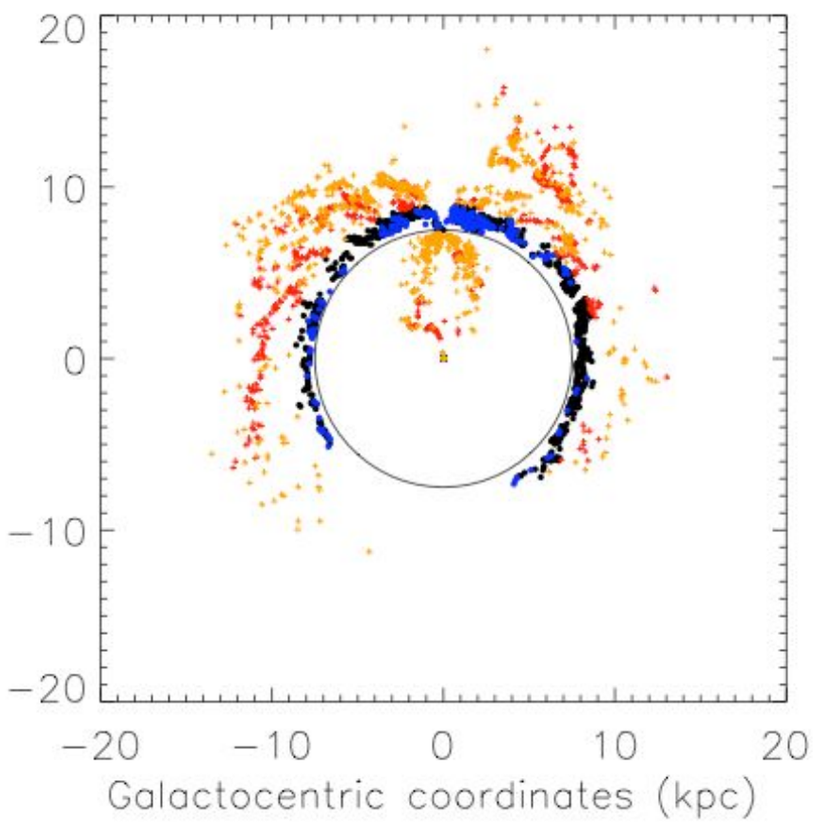


Dias & Lépine 2005

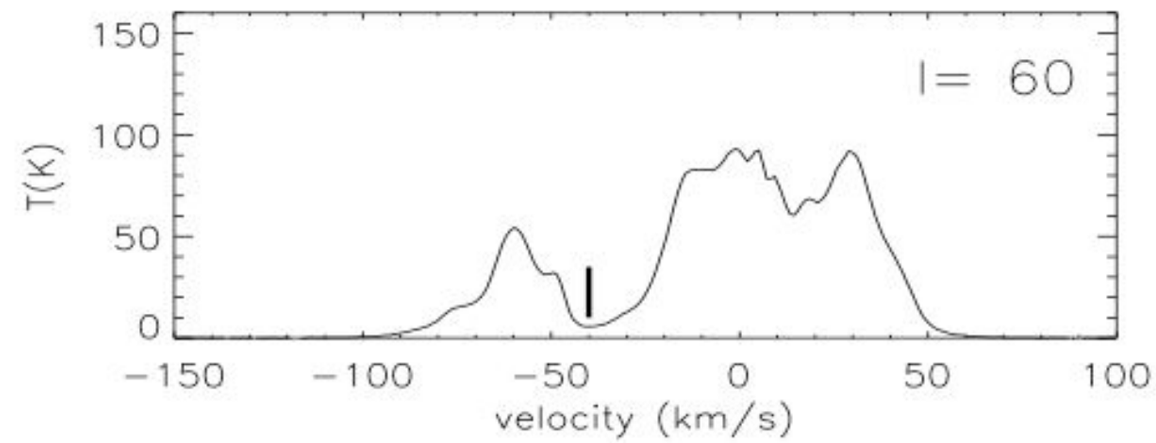
Method for determining pattern speed of spiral arms

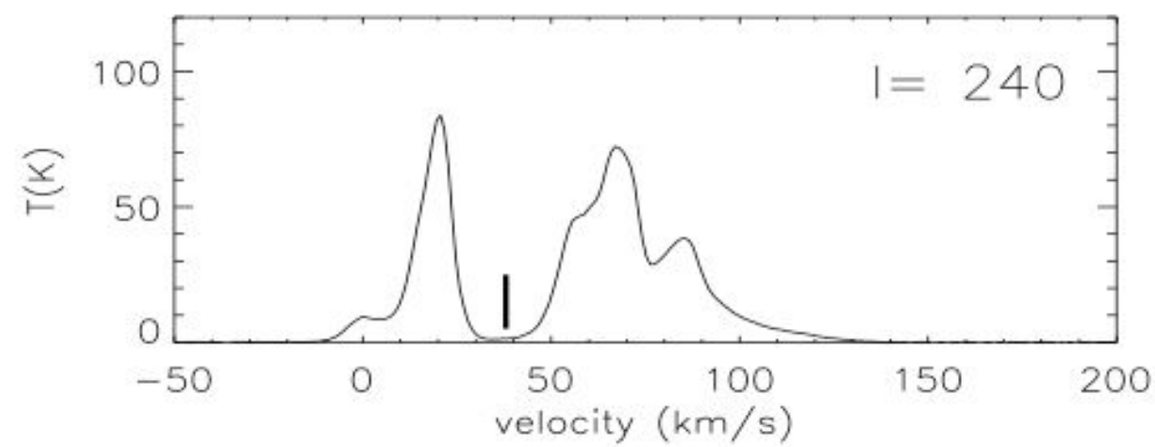
- Comparison of “arms” defined by different age groups
- Direct and doesn’t rely of rotation curve

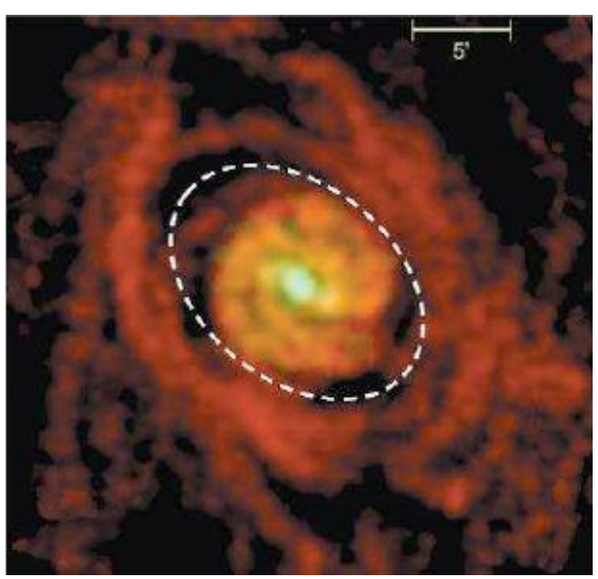
Corotation Gap



Amôres et al. 2009



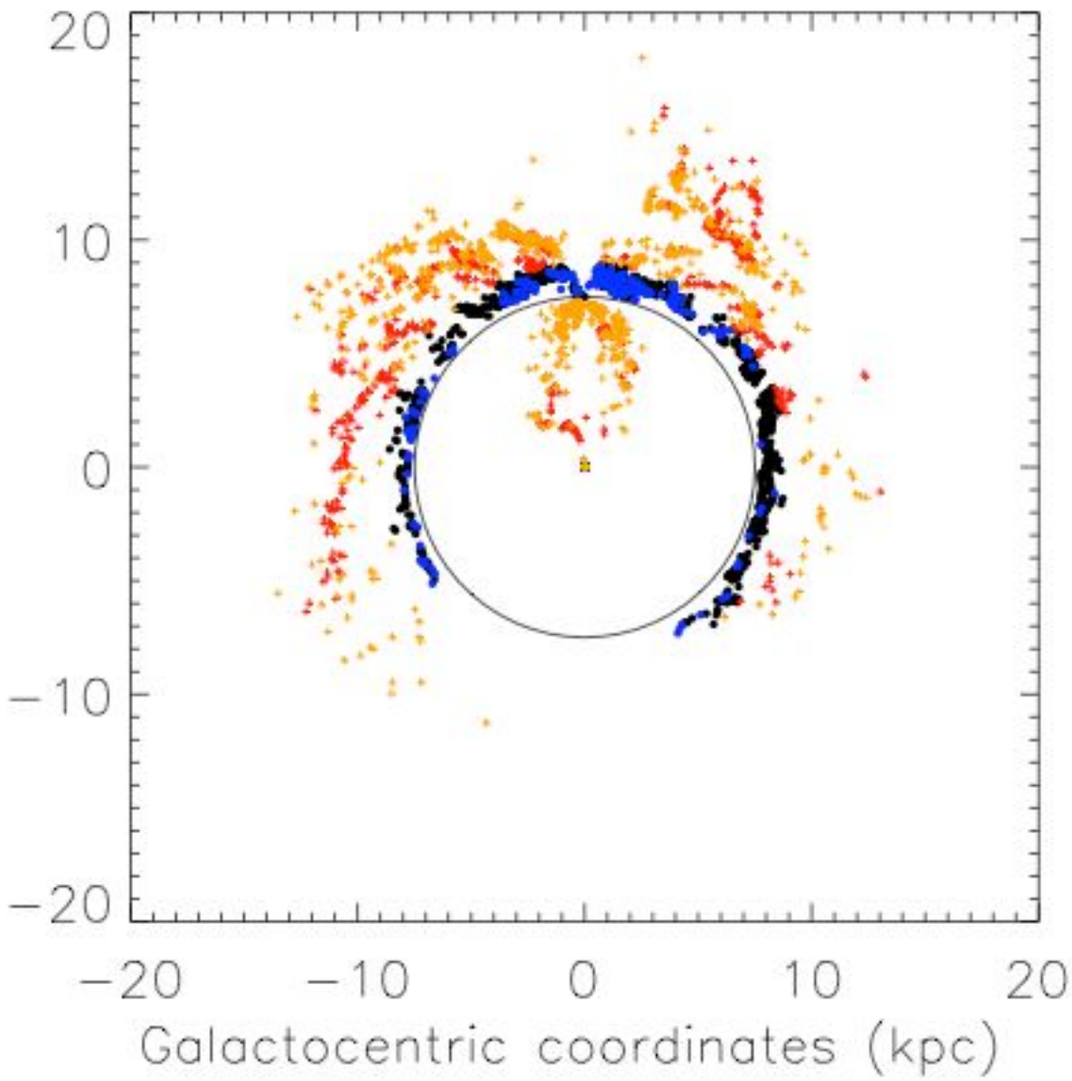




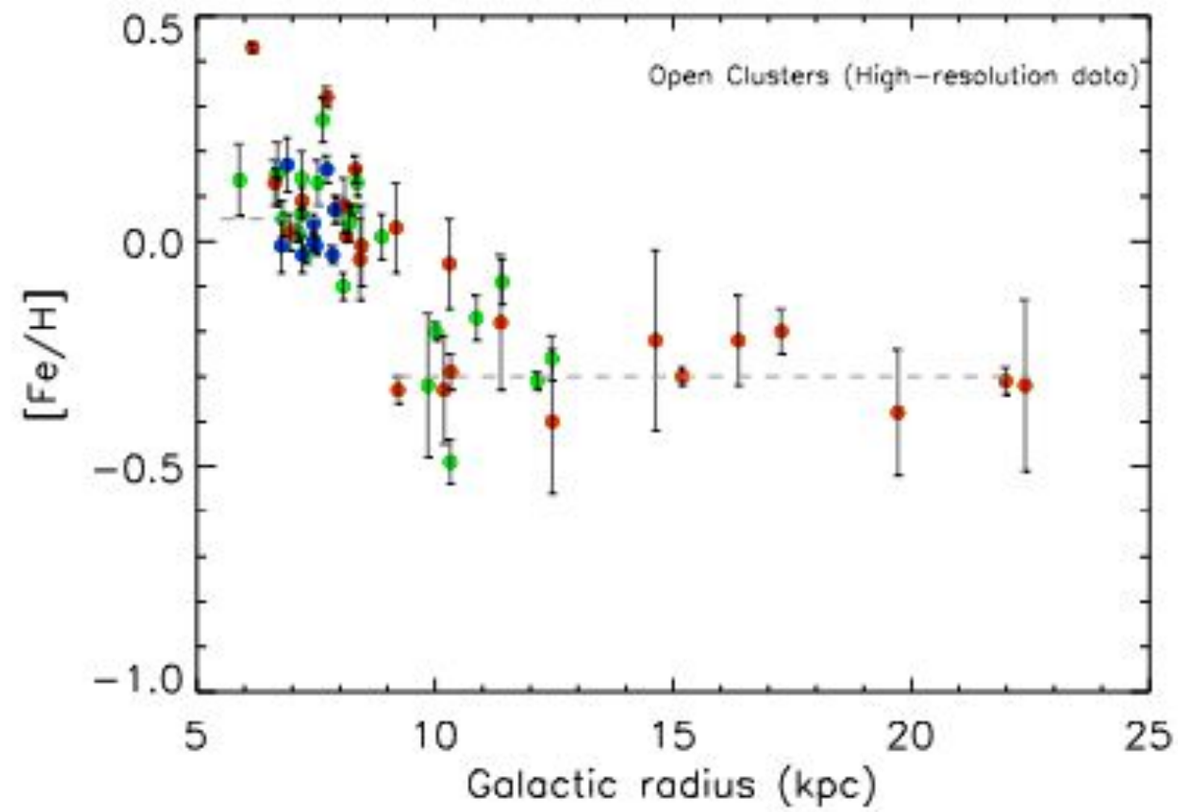
- Here RGC=7.5 kpc
- Rc= 8.3 kpc

- Spiral arms and disk material move at different speeds
- Co-rotation acts as hydrostatic pump!

Corotation Gap



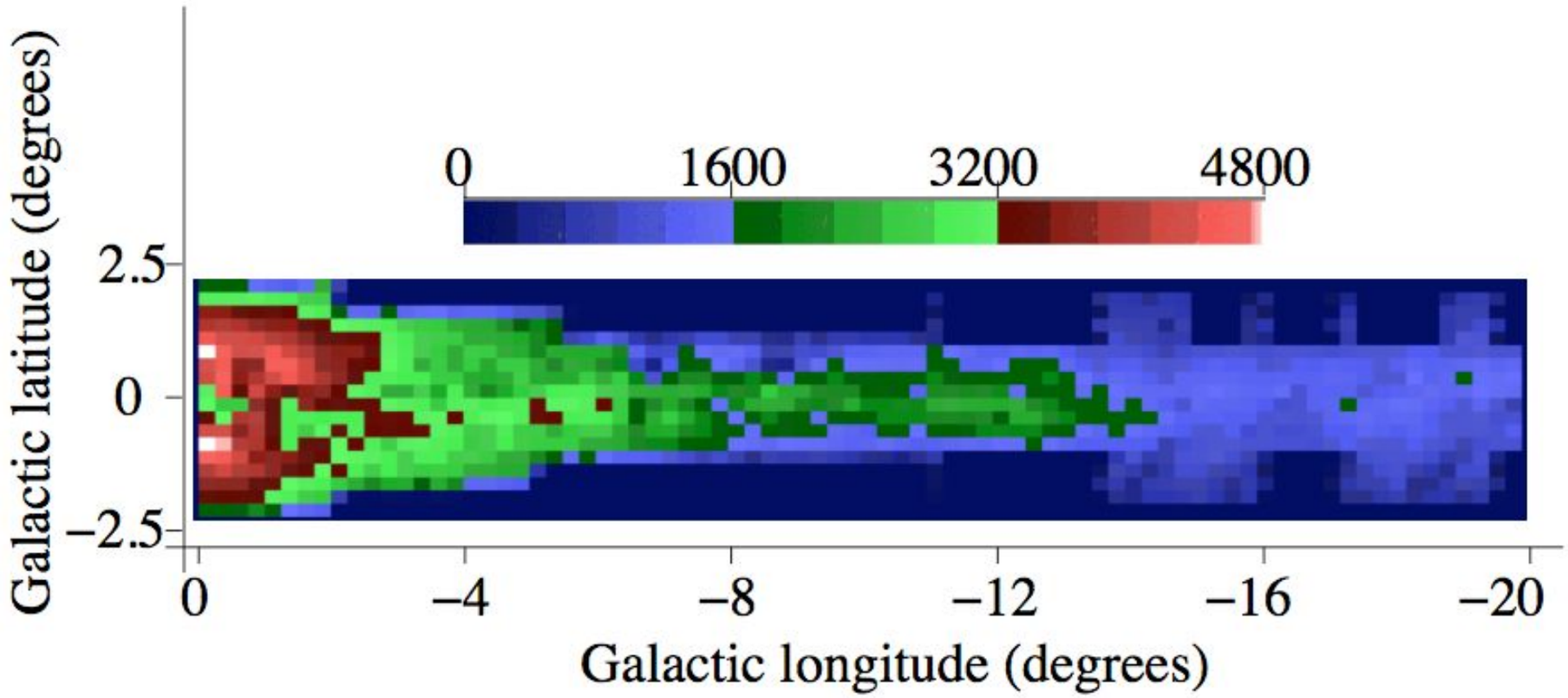
Amôres et al. 2009



Lépine et al. 2011

- Hints at persistent pattern: Building a 0.3dex "gradient step" takes > 3Gyr

Bar



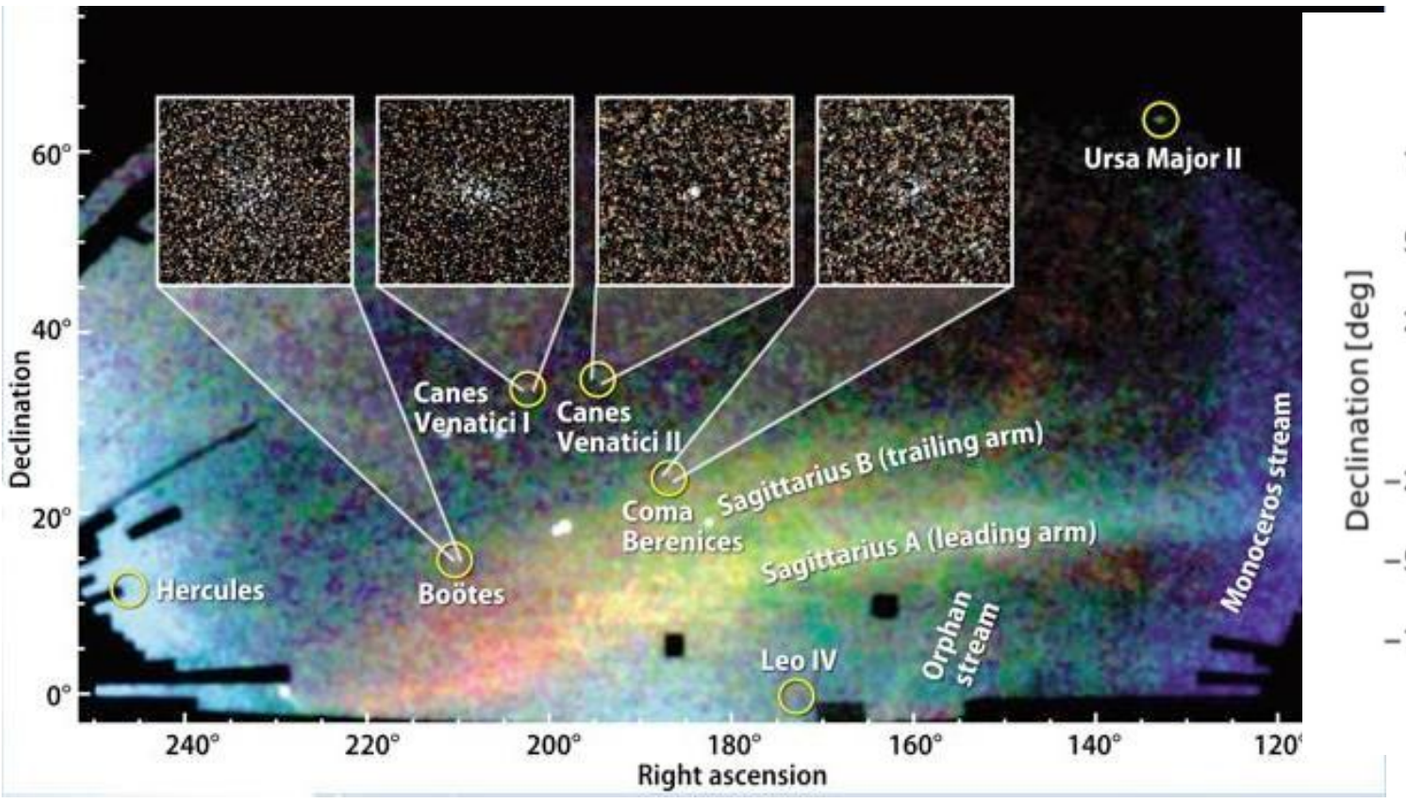
Amôres et al. 2012

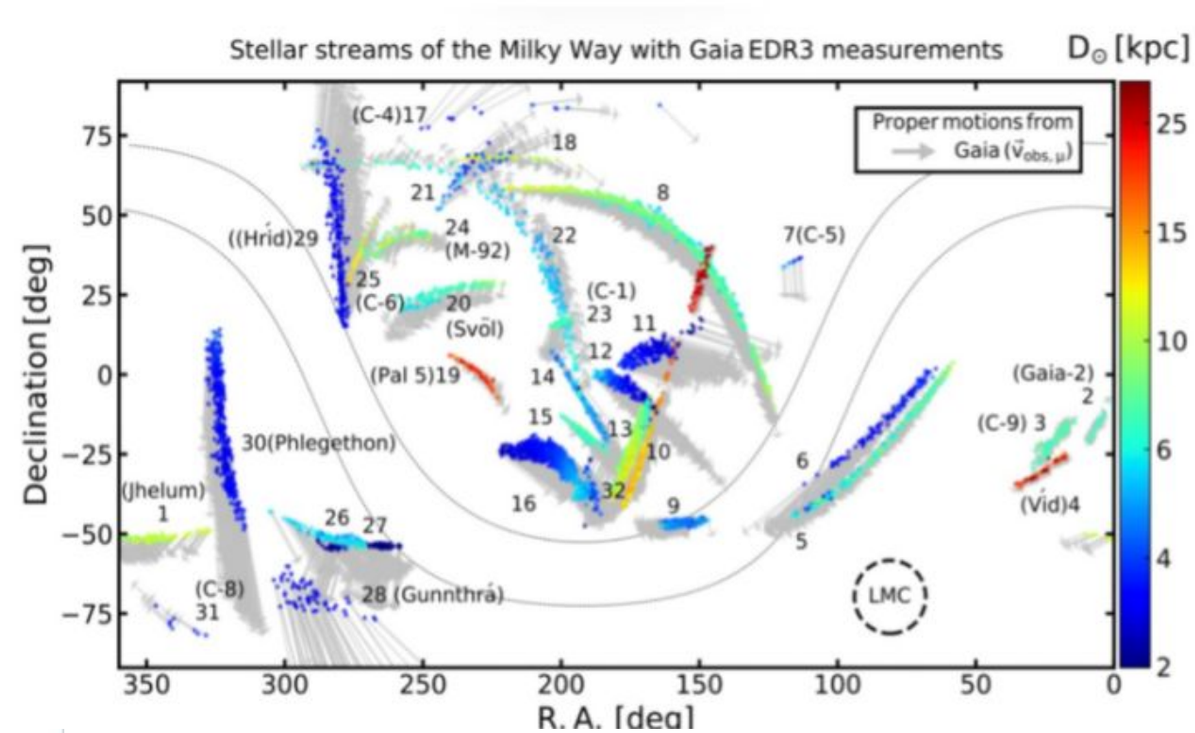
- Star counts. GLIMPSE + 2MASS + VVV
  - 7.8 kpc x 1.2 kpc x 0.2 kpc
  - Inclination 43°

The Halo

Substructure

tails and streams (possibly) of disrupted galaxies: SDSS and 3D in Gaia eDR3

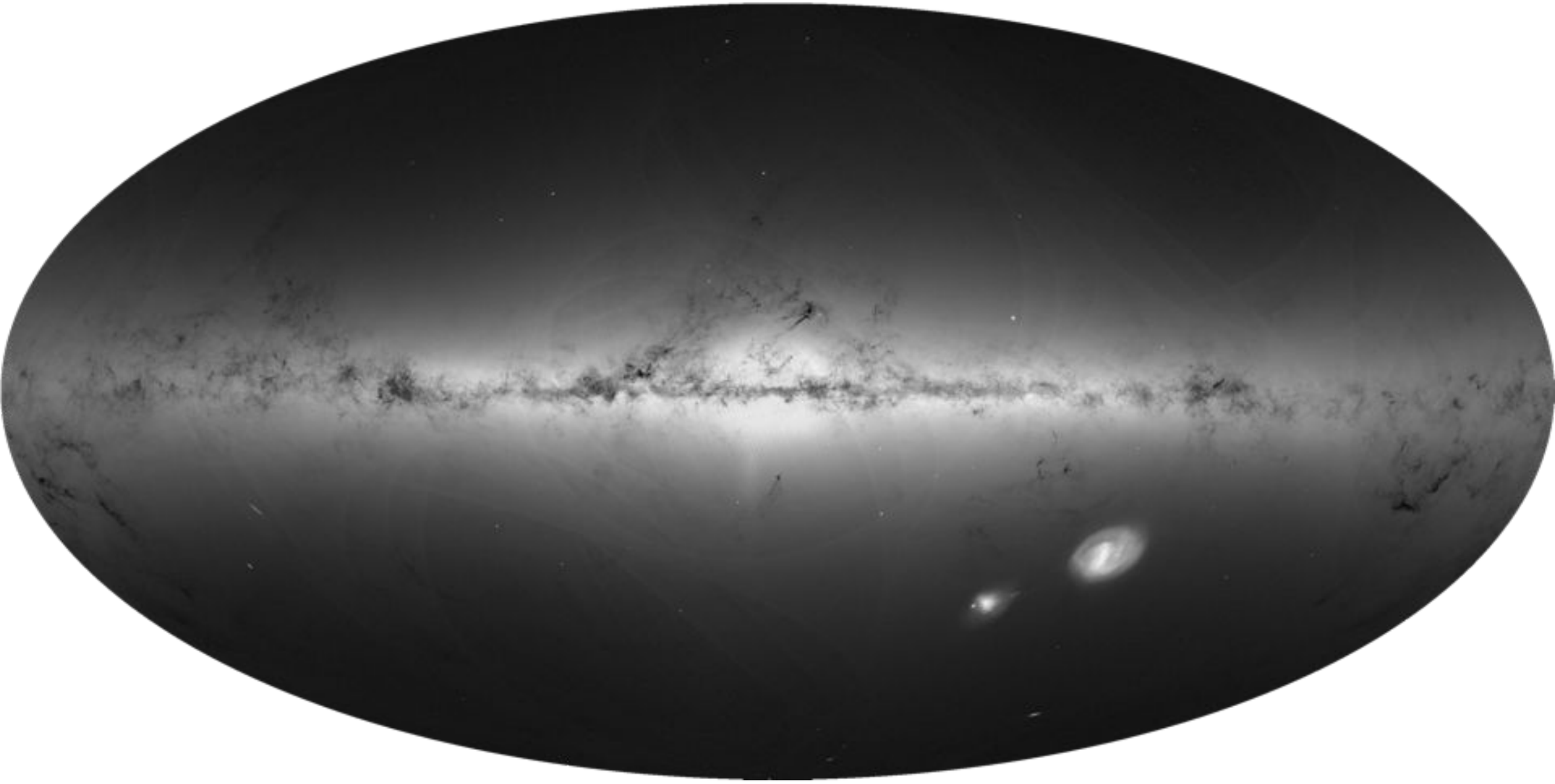




Belokurov et al. (2006)

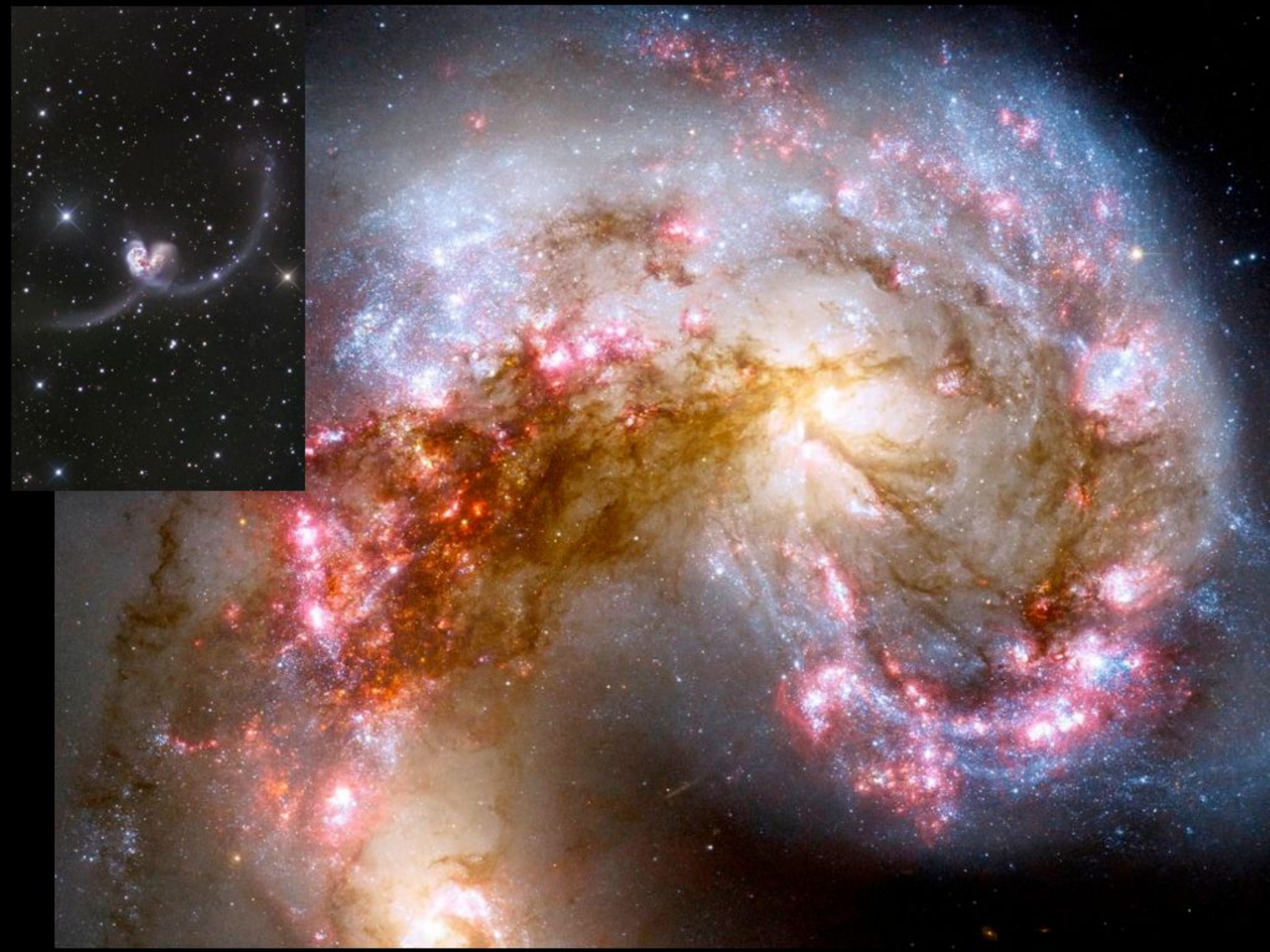
- Shape and kinematics probe the gravitational potential of the Galaxy.
- Need more (!), deeper and accurate data. Gaia, LSST (8.4m)

Substructure - Gaia DR2



Big structures: Sgr dSph/dE (1994 ~0.3-0.9 Gyr), Gaia Encedalus/Sausage (2018 ~10Gyr)

The Future

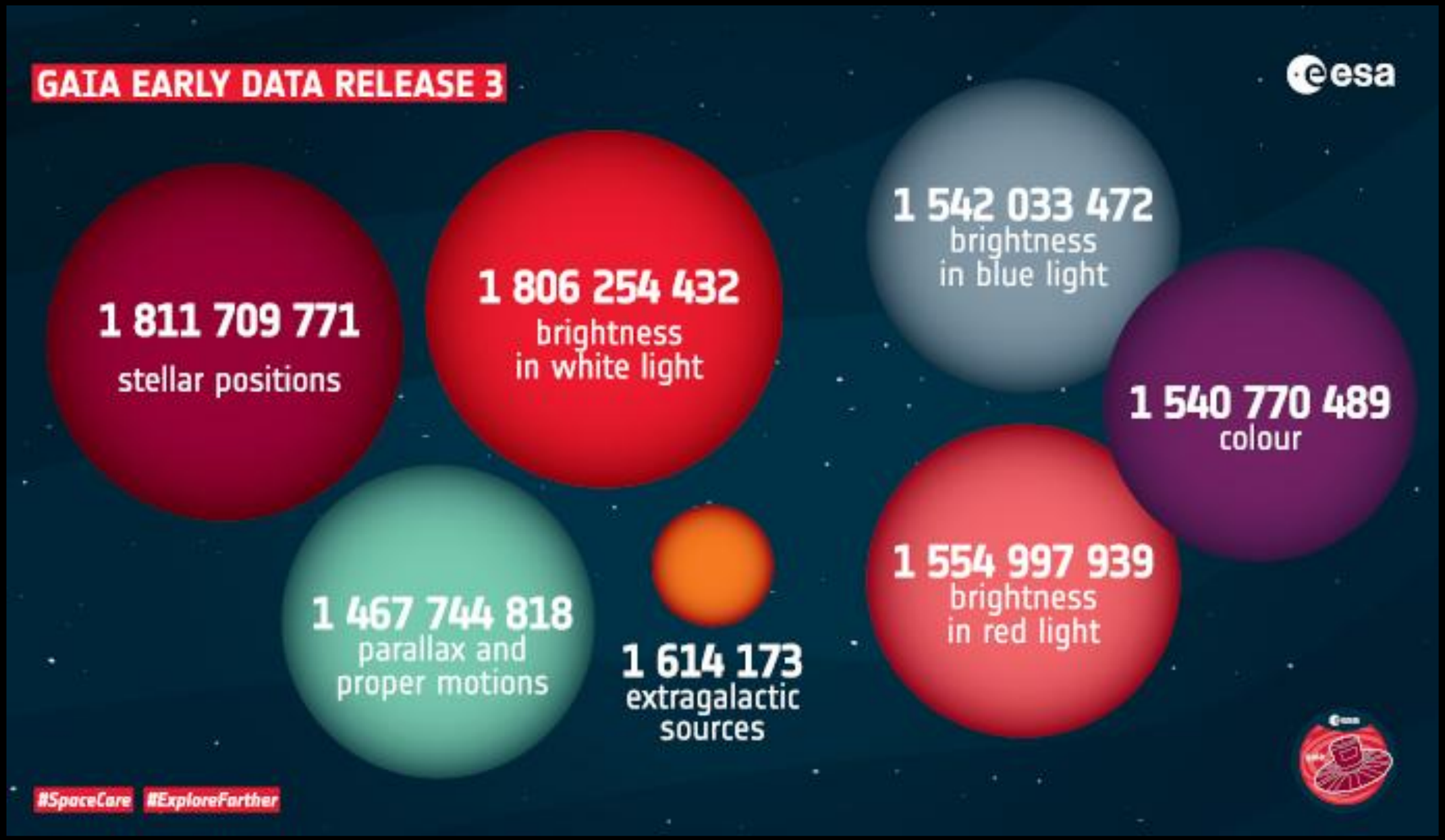


Gaia

Gaia

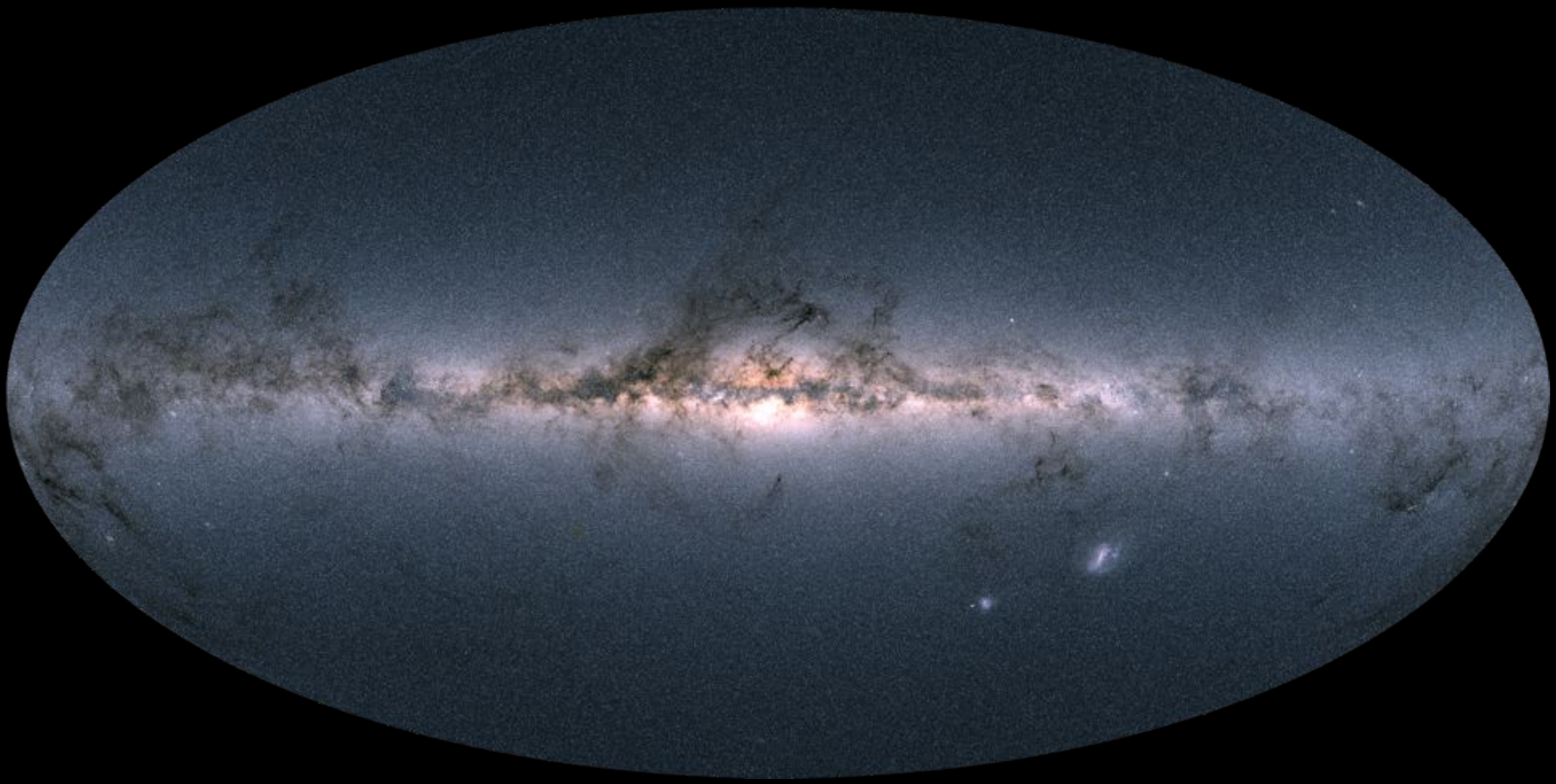
Lauched Dec 19, 2013.

Great!!! Now we will solve almost everything and who knows what else!



Ooops!! But how can I handle and make sense of this huge data volume?

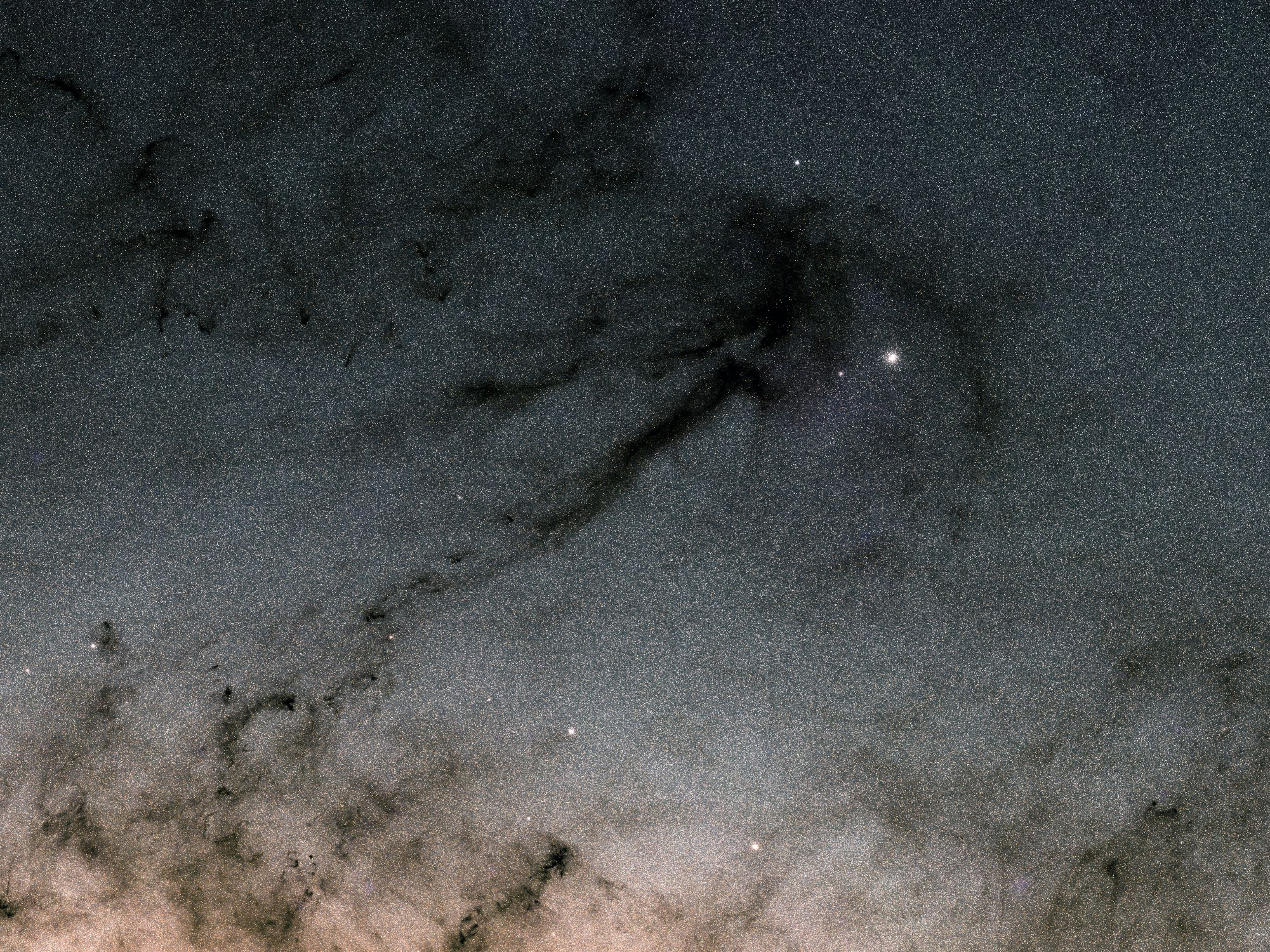
eDR3: 1.8 billion sources



source brightness map

Gaia: already an allsky catalogue at HST resolution

Footprint of Hubble Space Telescope observations



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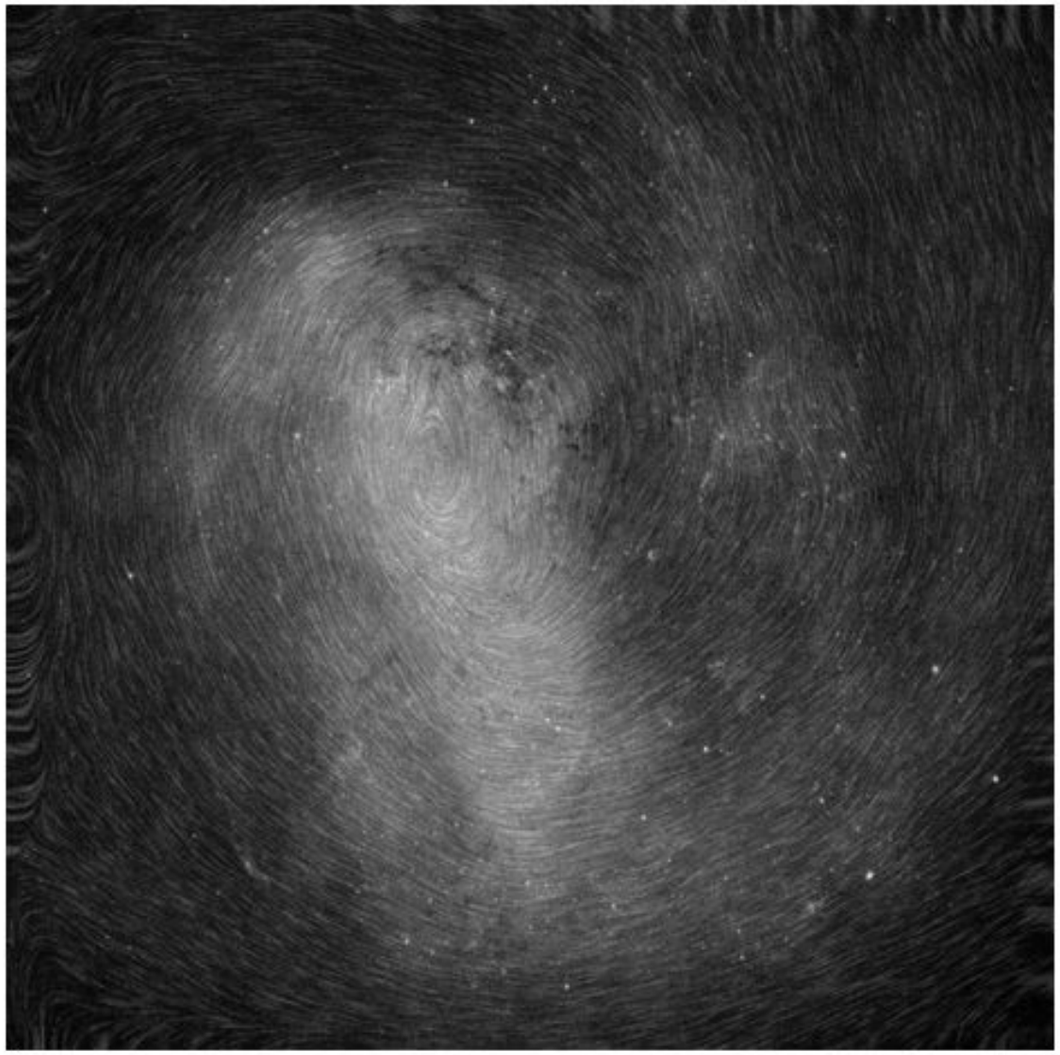

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Title Rotation of the Large Magellanic Cloud

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ESA > Space in Images > 2018 > 04 > Rotation of the Large Magellanic Cloud

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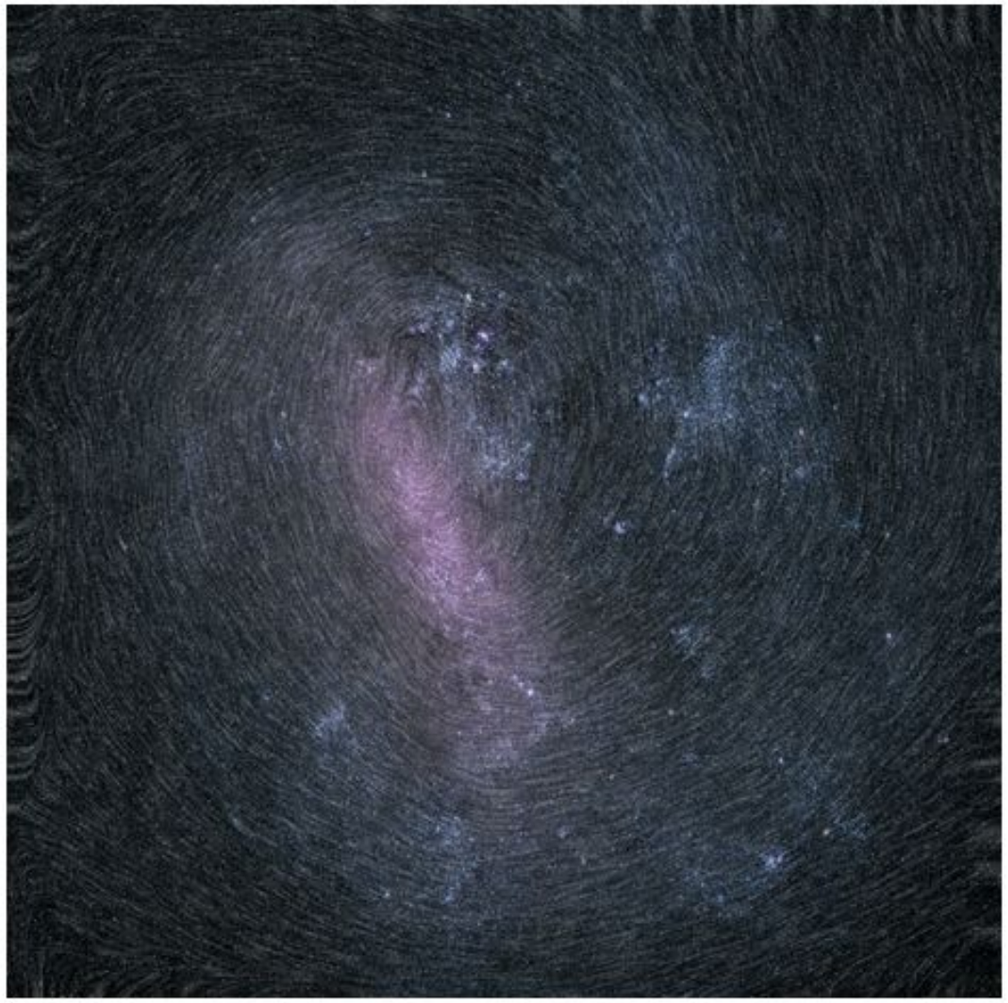

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DETAILS ▼

Title Rotation of the Large Magellanic Cloud

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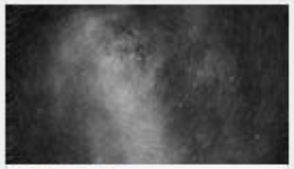

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How 1.7 Billion Stars Were Mapped

CNN Today @cnntoday · 25 de abr

"We're viewing the galaxy in a way that we've never been able to view it before." - @jfaherty Astrophysicist at @AMNH on #GaiaMission by @esa @ESAGaia #GaiaDR2 #ESAC #Gaia #MilkyWay

CNN International

Gaia Space Telescope Maps Milky Way

See more at edition.cnn.com

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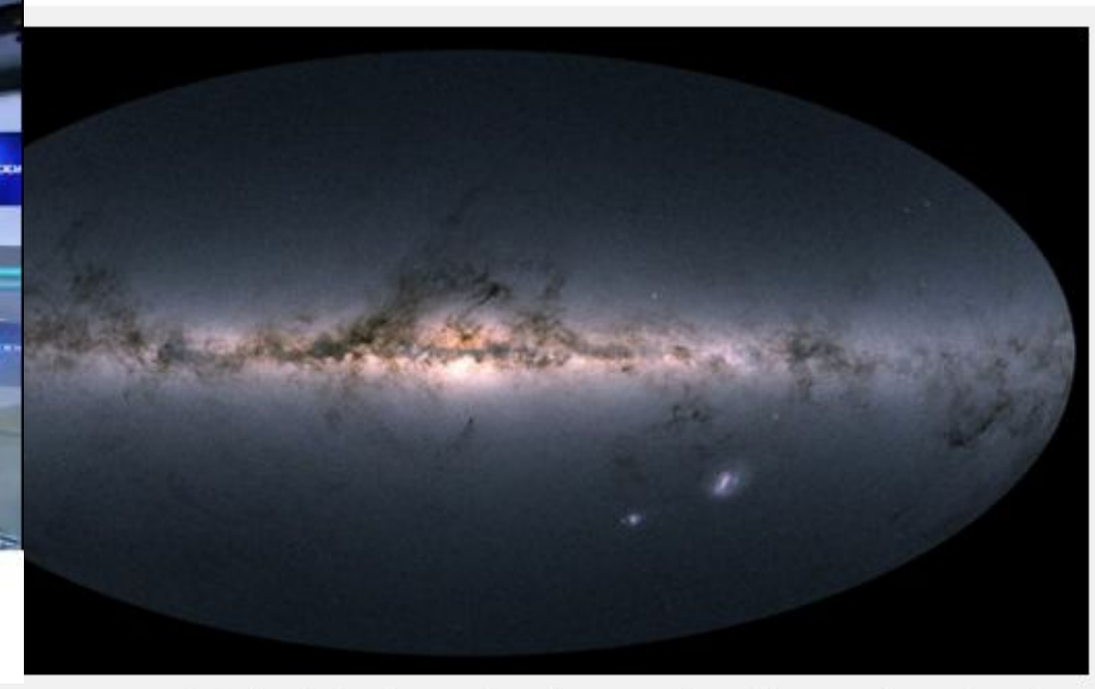
NEWS · 25 APRIL 2018

Billion-star map of Milky Way set to transform astronomy

European Gaia spacecraft's first major data dump — the most detailed 3D chart yet of our Galaxy — will keep researchers busy for decades.



A graphical representation of Gaia's all-sky data on the Milky Way and neighboring galaxies, based on measurements of nearly 1.7 billion stars. The map shows the total brightness and color of stars observed by the ESA satellite in each portion of the sky between July 2014 and May 2016. Thanks to additional data in the 2nd data release, this representation has fewer artifacts than the DR1 image, and it also additional color information. Read more about the image here.
Gaia Data Processing and Analysis Consortium (DPAC) / A. Moitinho / A. F. Silva / M. Barros / C. of Lisbon, Portugal) / H. Savietto (Fork Research, Portugal)

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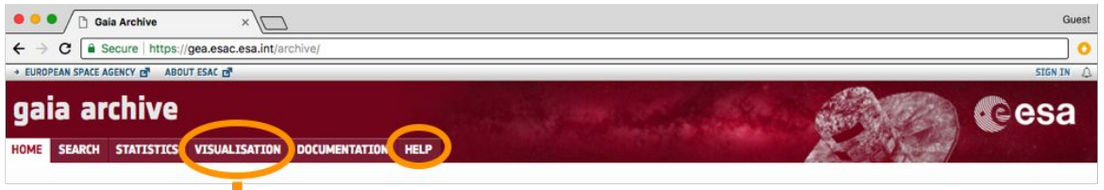
Gaia - web data visualisation



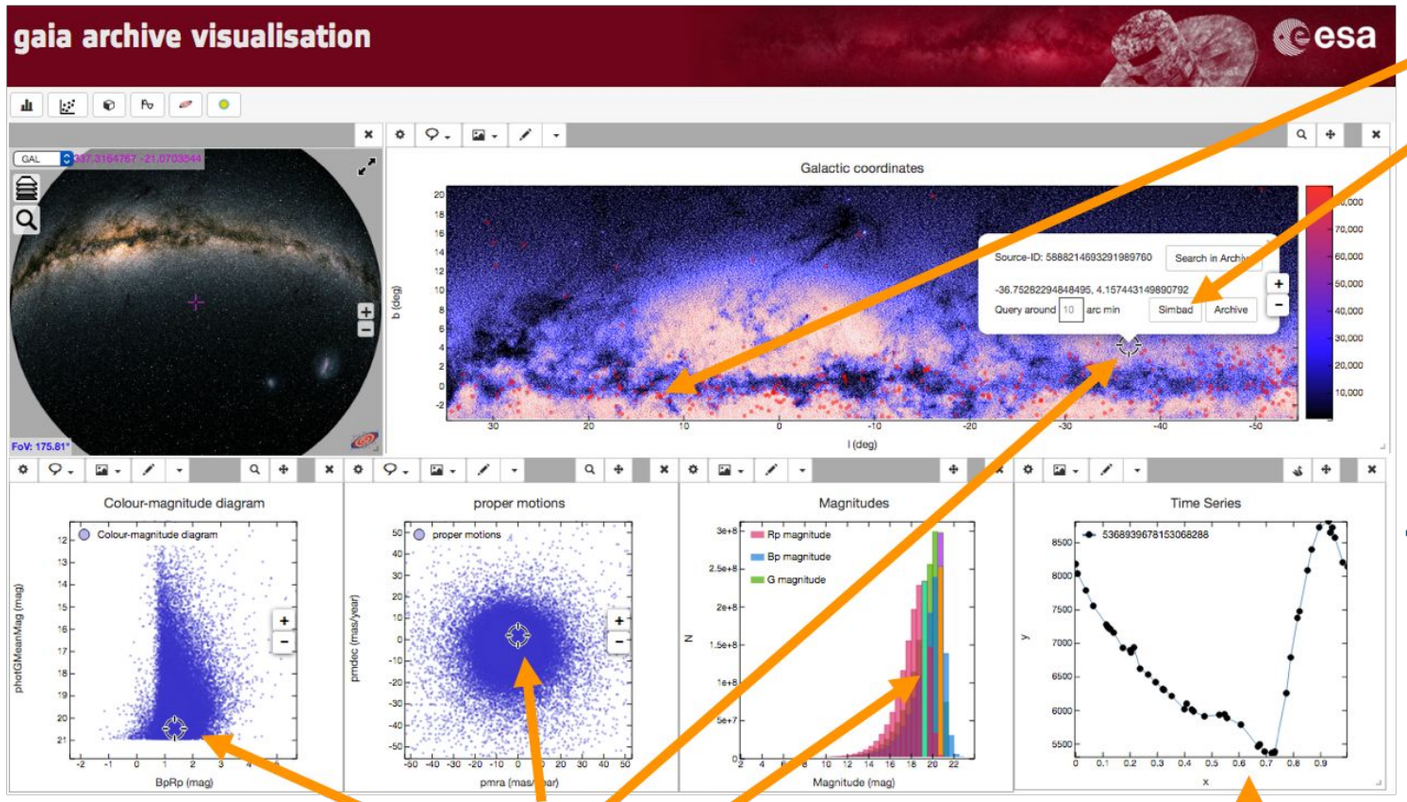
web service https://gea.esac.esa.int/archive/visualization/

help/tutorial http://gea.esac.esa.int/archive-help/index.html

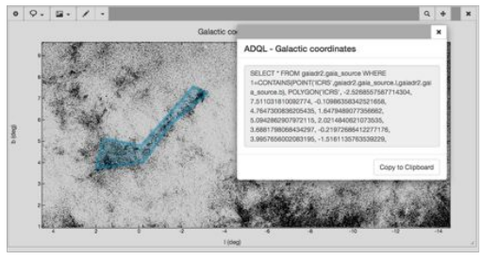
GAVS provides a multi-panel visualisation desktop in a browser tab. The panels are resizeable, moveable and their plots can be panned and zoomed. The figure on the right illustrates how a working setup might look.

Behind the scenes, the GAVS server software running at ESAC indexes the data and pre-computes views for offering detail on demand. This allows the complexity and volume of the Gaia data from the user interface

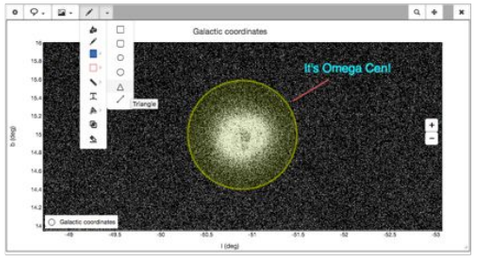
Some capabilities are illustrated. More info in the help/tutorial page



- **overlay catalogues**
- **identify sources in Simbad**
- **visual ADQL queries**



- **annotate and save hard copies**



- **linked views**
- **time series analysis**

Now is when it gets good!