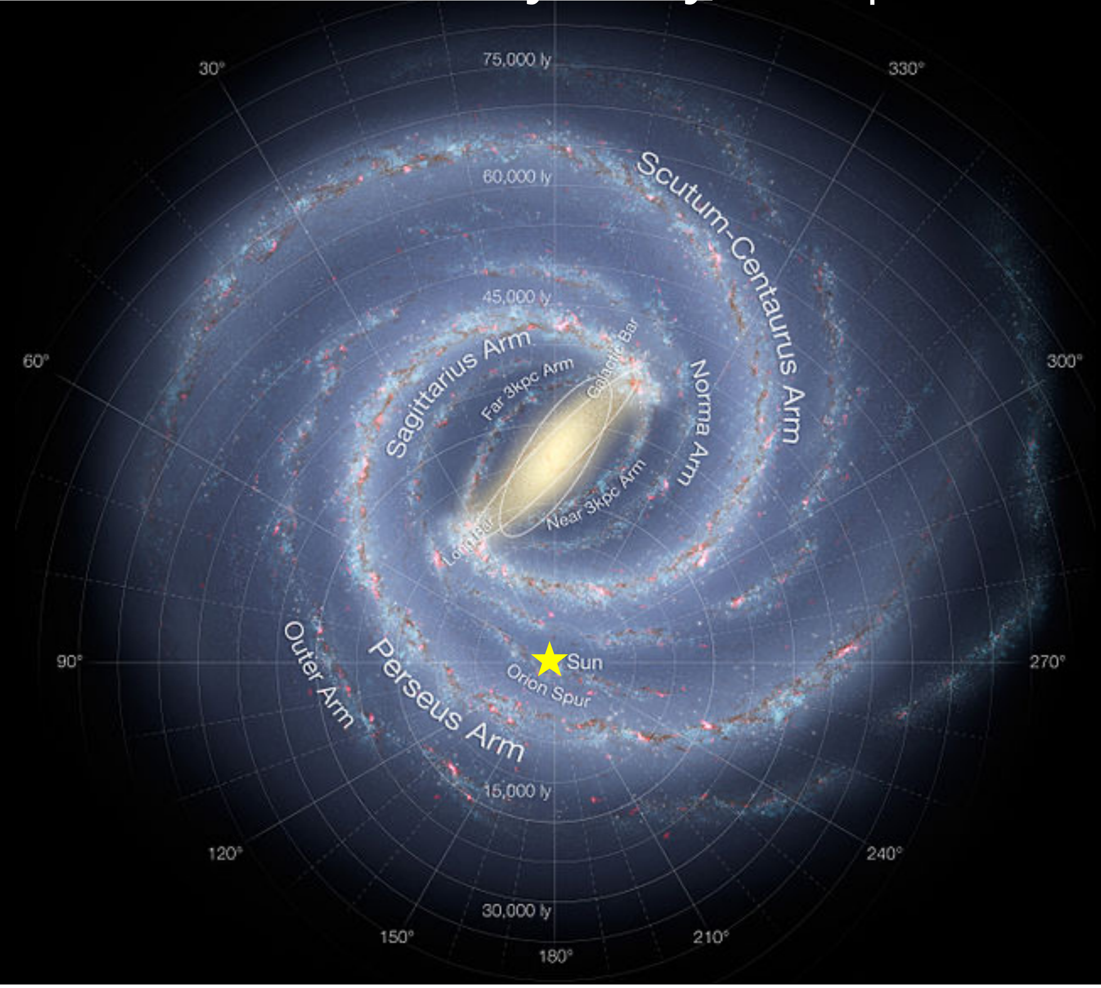

ASTR 400B Lecture 2: The Structure of the Milky Way

A Model of the Milky Way: A Spiral Galaxy

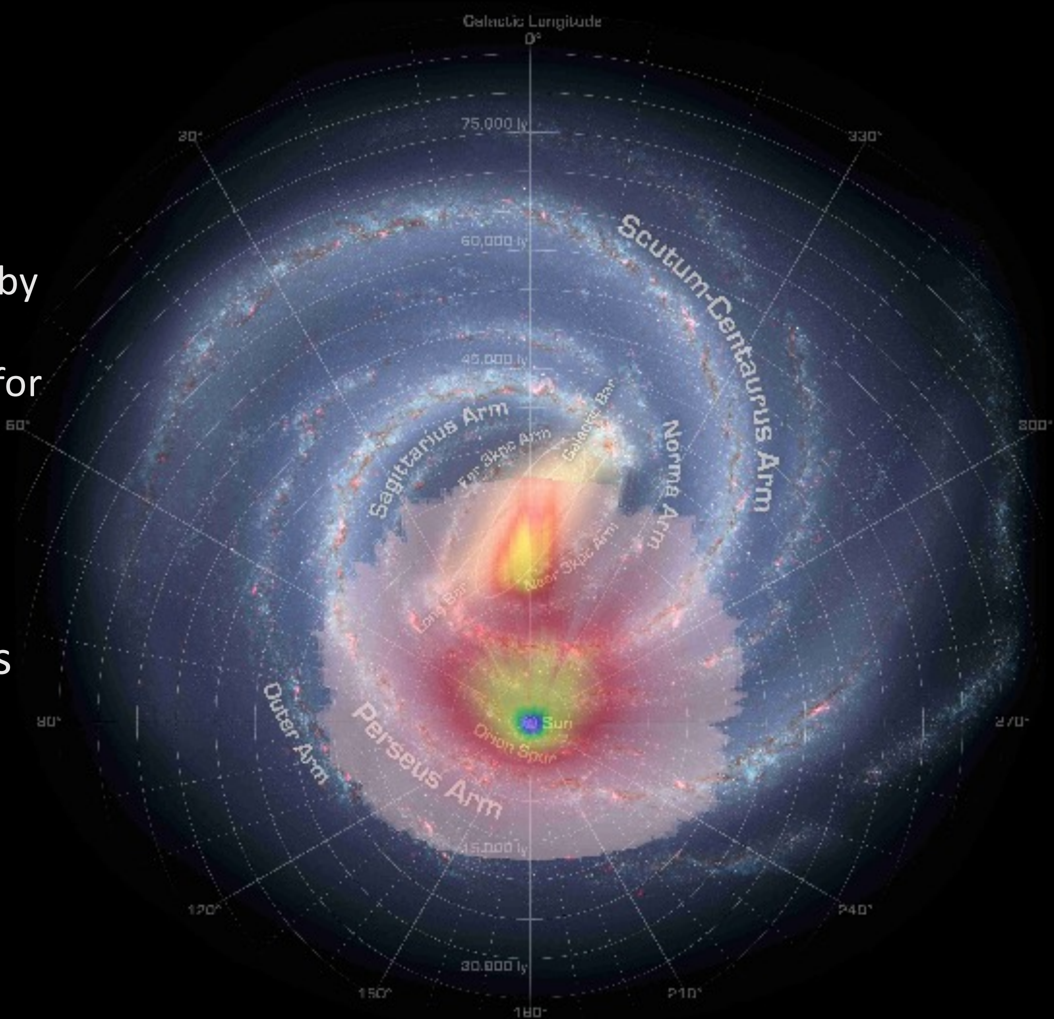


older

GAIA

Gaia is a space observatory operated by the European Space Agency. It is designed for **astrometry**.

ASTROMETRY: measuring the positions, distances and velocities of stars with unprecedented precision.



•ESA/Gaia/DPAC, Stefan Payne-Wardenaar

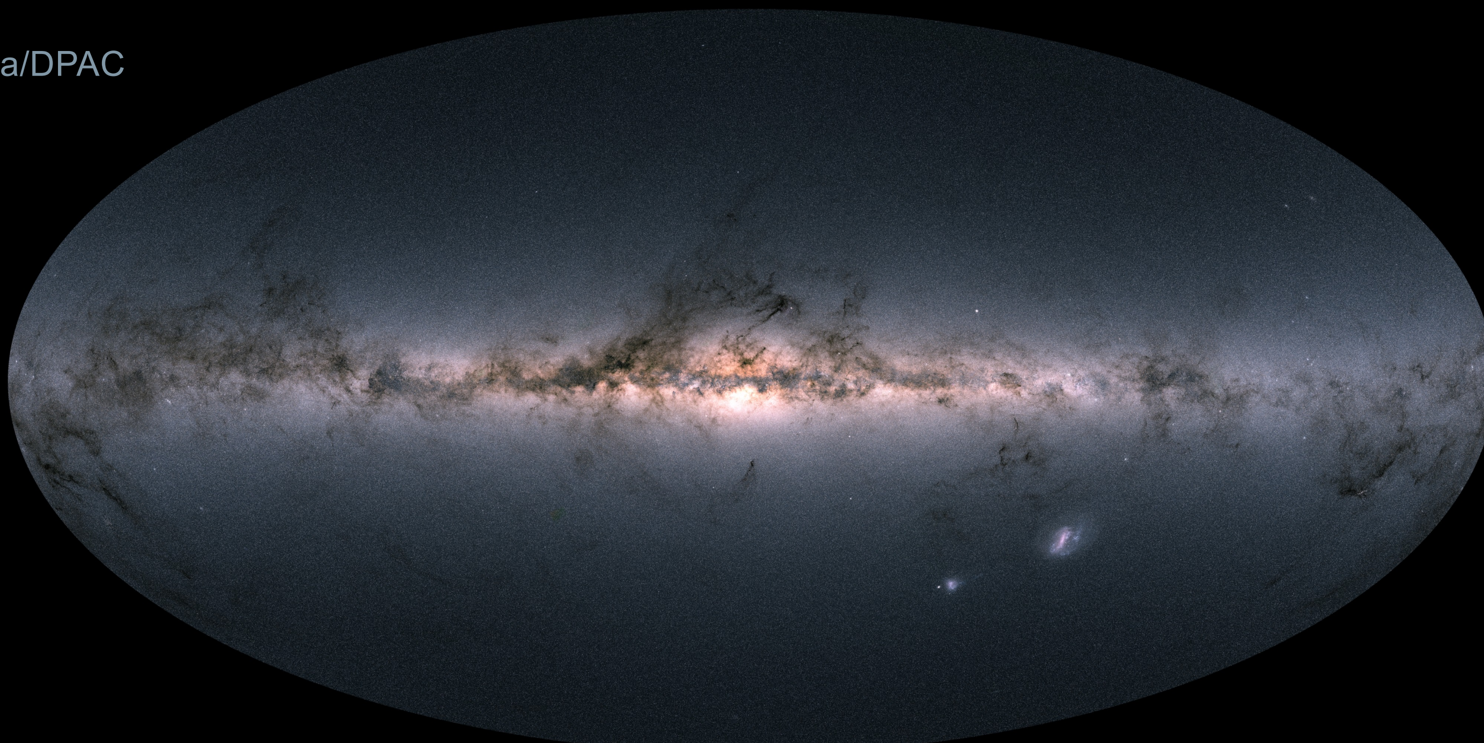
Artist Impression of our MW

Gaia: New View of the MW

- More than 2 spiral arms
- Less prominent

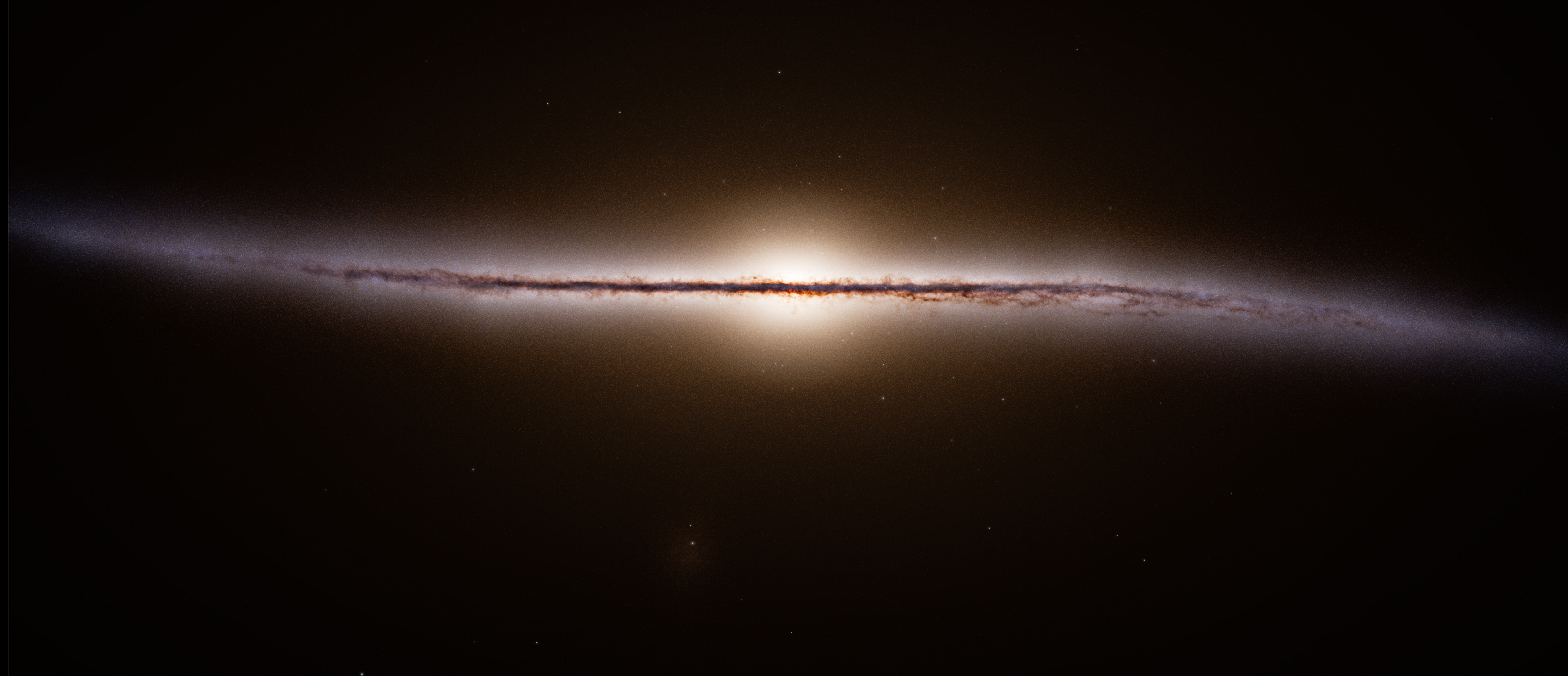
The Structure of our Milky Way Disk:

•ESA/Gaia/DPAC



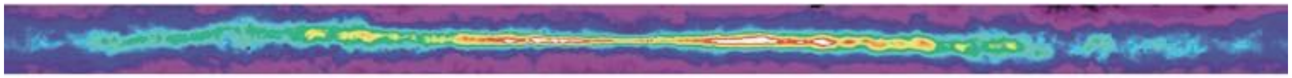
Gaia's all-sky view of our Milky Way Galaxy and neighboring galaxies, based on measurements of nearly 1.7 billion stars. The map shows the total brightness and color of stars observed by the ESA satellite in each portion of the sky between July 2014 and May 2016.

The Structure of our Milky Way Disk:



•ESA/Gaia/DPAC, Stefan Payne-Wardenaar
•Artist Impression: MW disk edge on is warped.

Milky Way at different wavelengths



a 21-cm radio emission from atomic hydrogen gas.

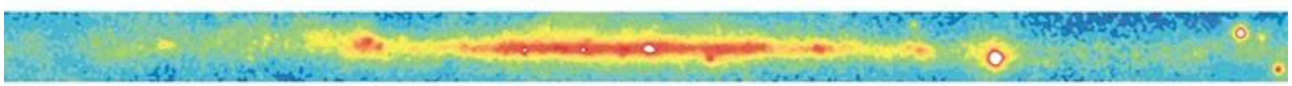
b Radio emission from carbon monoxide reveals molecular clouds.

c Infrared emission from interstellar dust (wavelength 60 to 100 μm).

d Infrared emission from stars that penetrates most interstellar material (wavelength 1 to 4 μm).

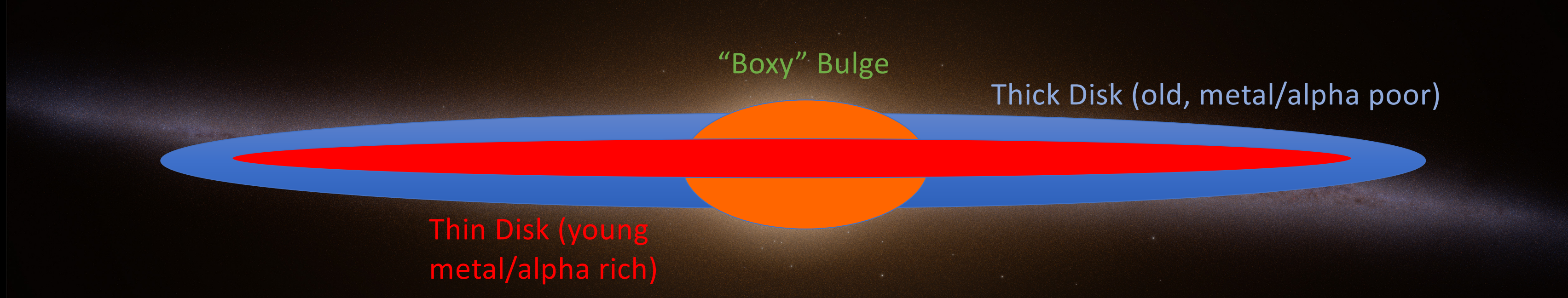
e Visible light emitted by stars is scattered and absorbed by dust.

f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).



g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

The Structure of our Milky Way Disk:

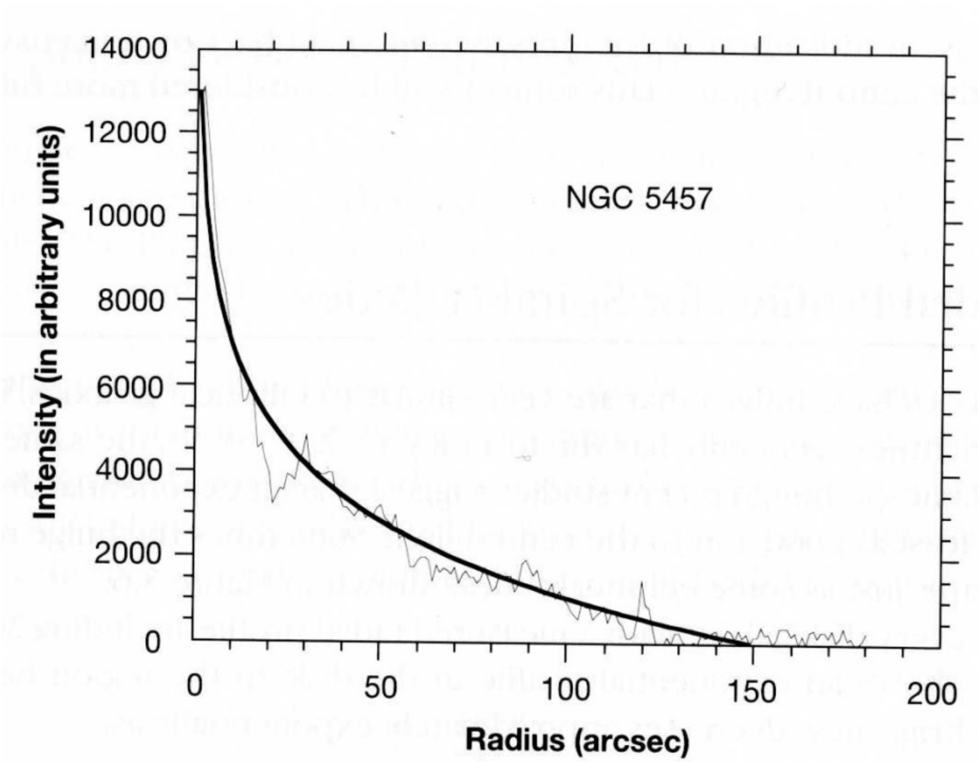


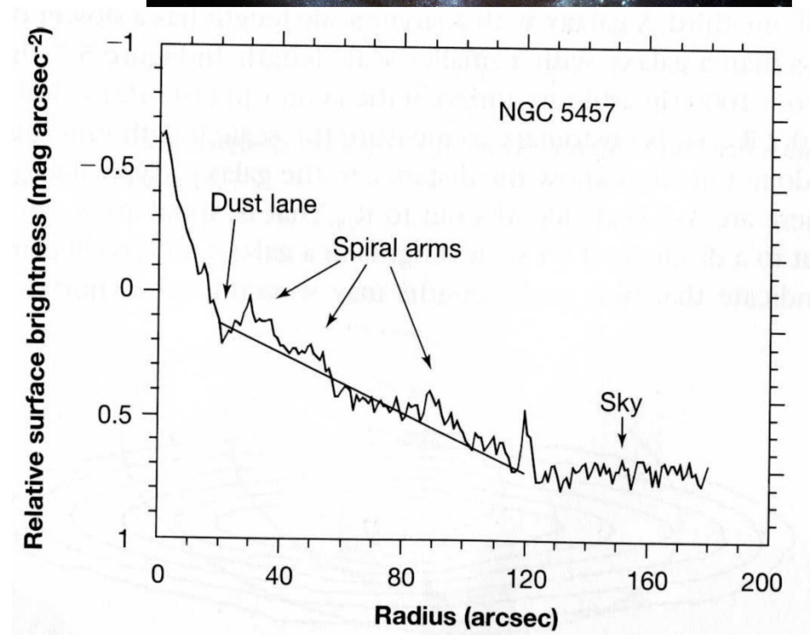
Diameter ~ 100,000 light years
Mass ~ 60 billion times the mass of the Sun

- ESA/Gaia/DPAC, Stefan Payne-Wardenaar
- Artist Impression: MW disk edge on is warped.

Radial Profile of stellar disks

$I(R) = I_o\, e^{-R/rs}$





Radial Profile for the Milky Way – Resolved Stars

$n(R) = n_o e^{-R/rs}$: Number density profile

$n_o = 0.02$ stars/pc^3

Scale Length ("total" disk) rs = 2-3 kpc
2.2 +/- 0.2 kpc (Bovy+ 2016 ApJ 823)
3.0 kpc (Klypin+ 2002 ApJ 573)

(geometric) Thick and Thin Disk

$$n(z,R) = n_o(e^{-z/z_{\rm thin}} + 0.085 \times e^{-z/z_{\rm thick}})e^{-R/rs}$$

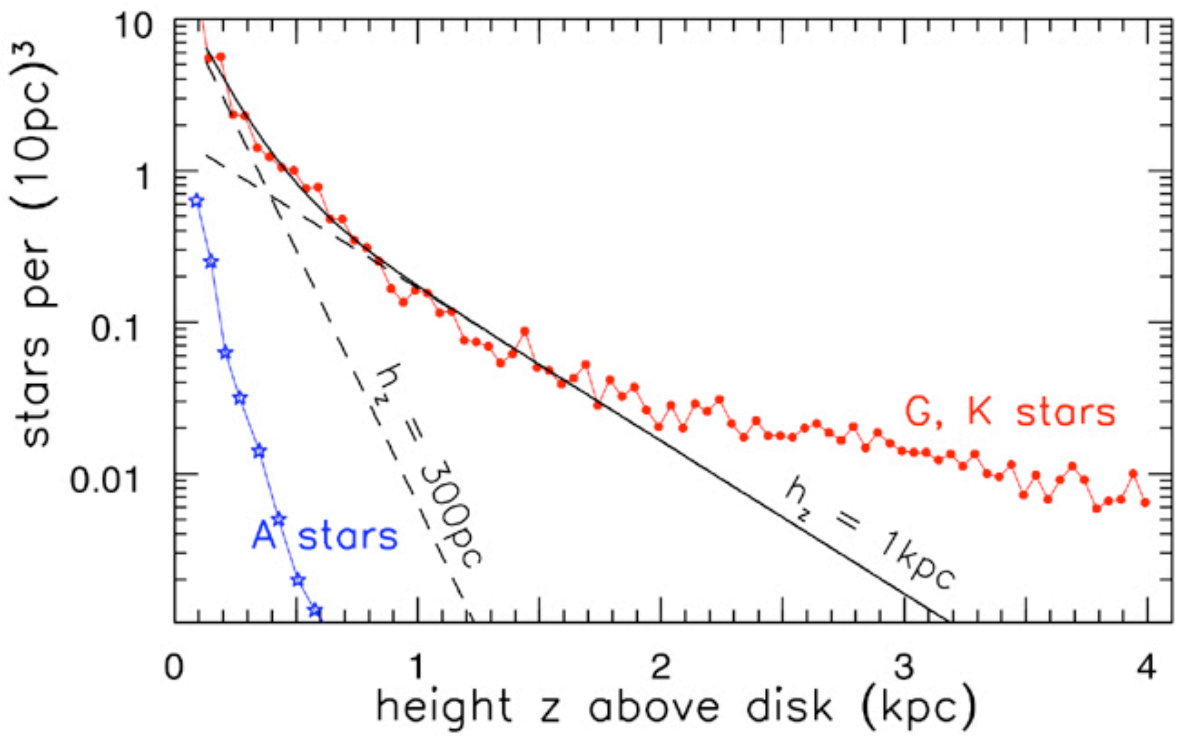


Fig 2.8 (Reid, Knude) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Looking toward the south Galactic pole, filled red circles show the density of stars with 5 < Mv < 6; these are late G and early K dwarfs.

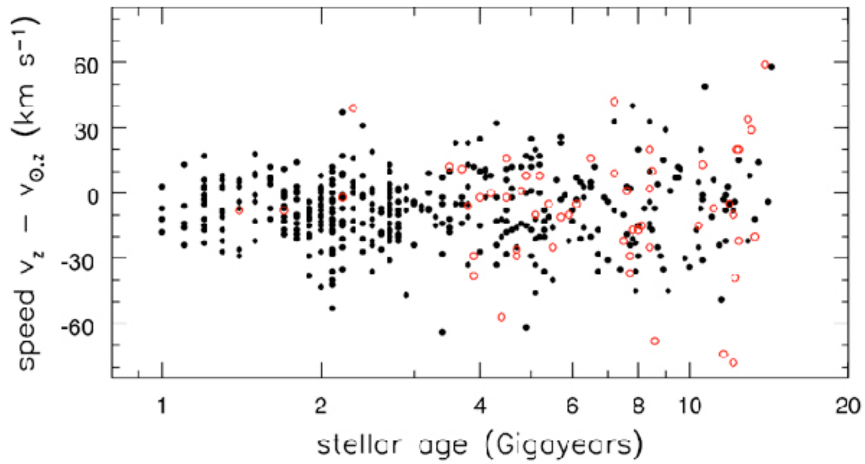
Sloping dashed lines show
n(z) α exp(-z / 300 pc) (thin disk)
And
n(z) α exp(-z/1 kpc) (thick disk);
The solid curve is their sum

At z > 2 kpc, most stars belong to the metal poor halo.

A stars (star symbols) lie in a very thin layer < 0.5 kpc.

Thick / Thin Disks

- Stars of different ages also have **different kinematics**:



red circles = low metallicity stars

- We can define 1 D velocity dispersion of a group of stars in a given direction:

$$\sigma_z^2 \equiv \left\langle v_z^2 - \langle v_z \rangle^2 \right\rangle \qquad \sigma = \sqrt{\frac{\sum_{i=0}^{N} (v_i - \bar{v})^2}{N}}$$

- Young stars (age < 3Gyr) have σz~15km/s while old, low metallicity, thick disk stars have σz~25-40km/s, σ_R is typically significantly larger!

But … this simple picture is evolving.

- Disk may be better described as a broken power law, rather than an exponential profile. In which case, the half light radius (5.75 ± 0.38 kpc) is **larger** than previously assumed.

  Lian+2024 Nature Astronomy, Volume 8, Issue 10, pp. 1302-1309

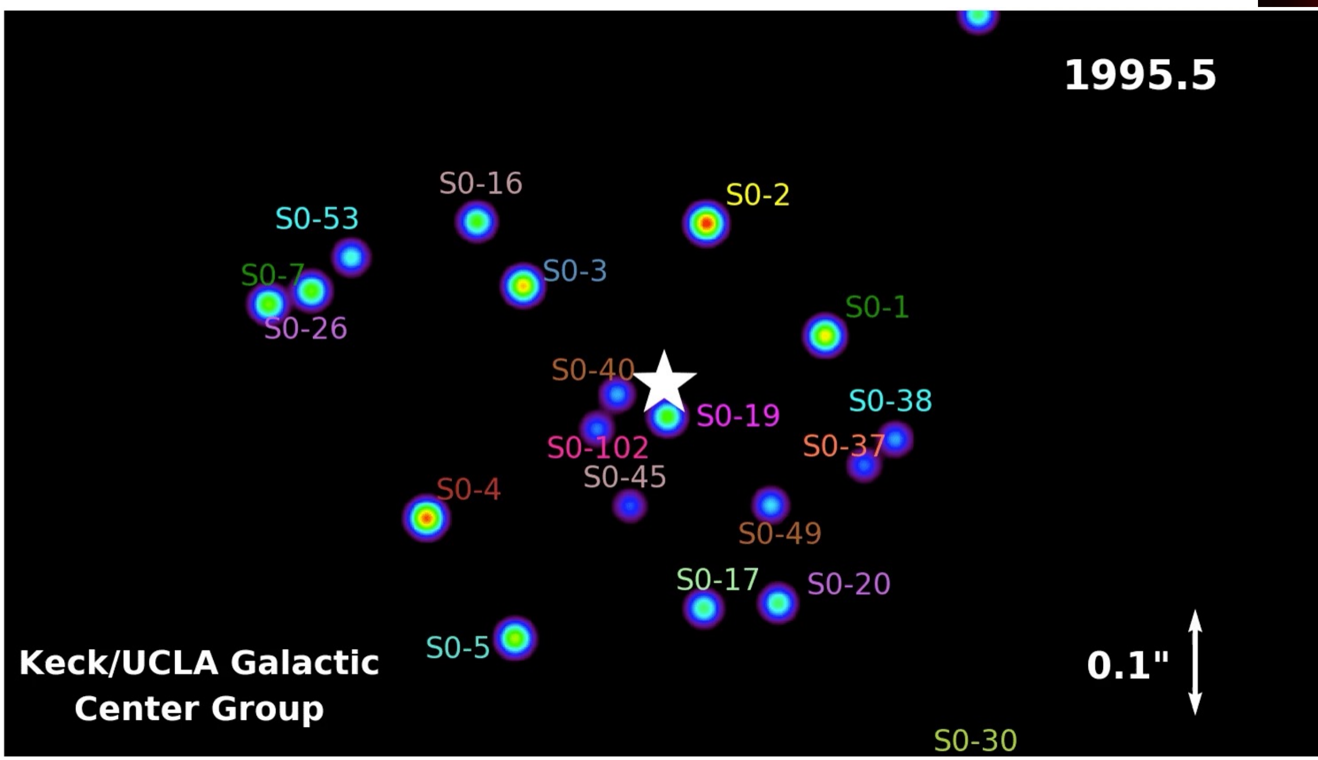
- Thick Disk might as much as ¼ of the total mass of the stellar disk

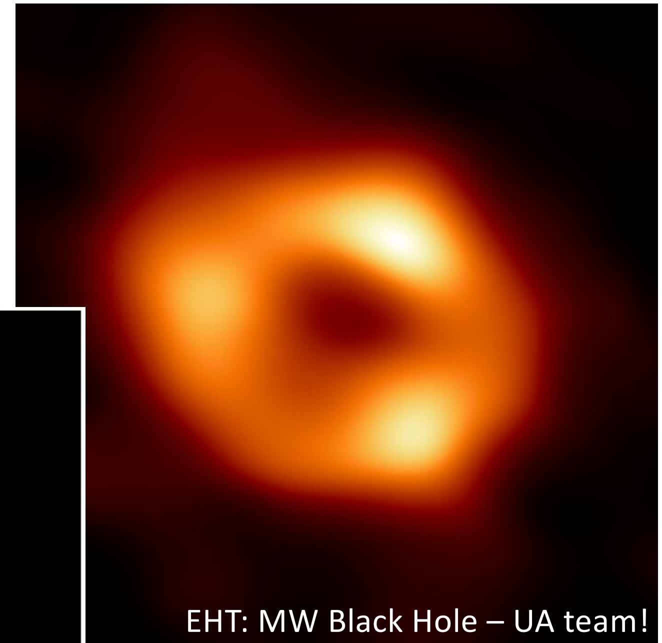
(Lian et al., 2022; Vieira et al., 2023; Khanna et al., 2024; Xiang et al., 2024)

- Others argue that there is only one disk and no true distinction between thick and thin → gradient of scale heights. (Rix & Bovy 2013)

The Super Massive Black Hole

- 4.1×10^6 Msun





Dr. Dan Marrone
Dr. Chi-Kwan Chan

The MW Bar

Elongated stellar structure in the central region of a disk galaxy. Stars in the bar are on non-circular orbits and the bar rotates rigidly

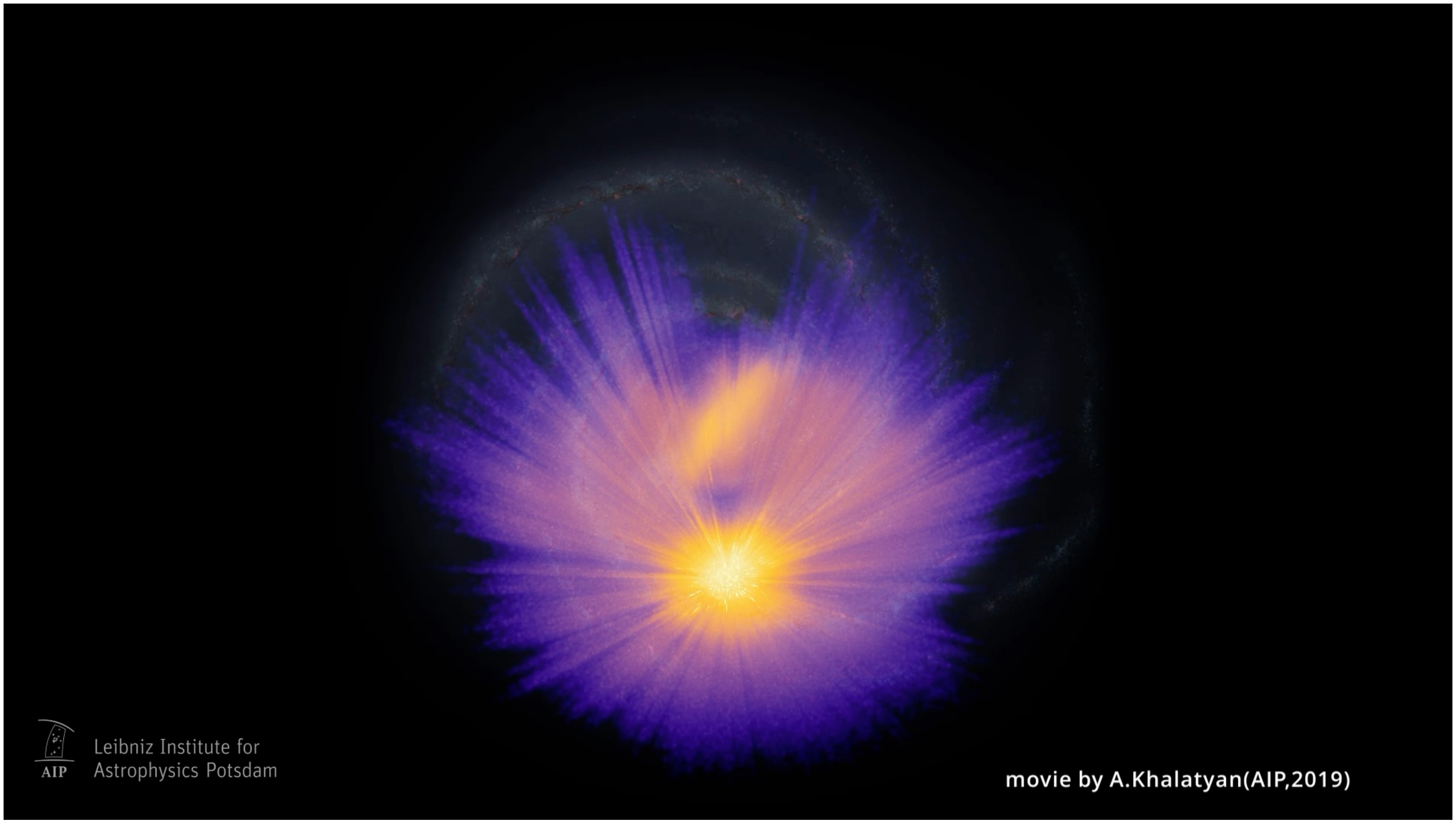
See Review: Juntai Shen and Xing-Wu Zheng 2020 *Res. Astron. Astrophys.* **20** 159

Old Debate: 1) Short ~3.0 kpc (Freudenreich 1997) ; or
2) Long ~4.5 kpc (Cabrera-Lammers et al 08, Benjamin 2009)

New → Single structure: long bar + boxy bulge

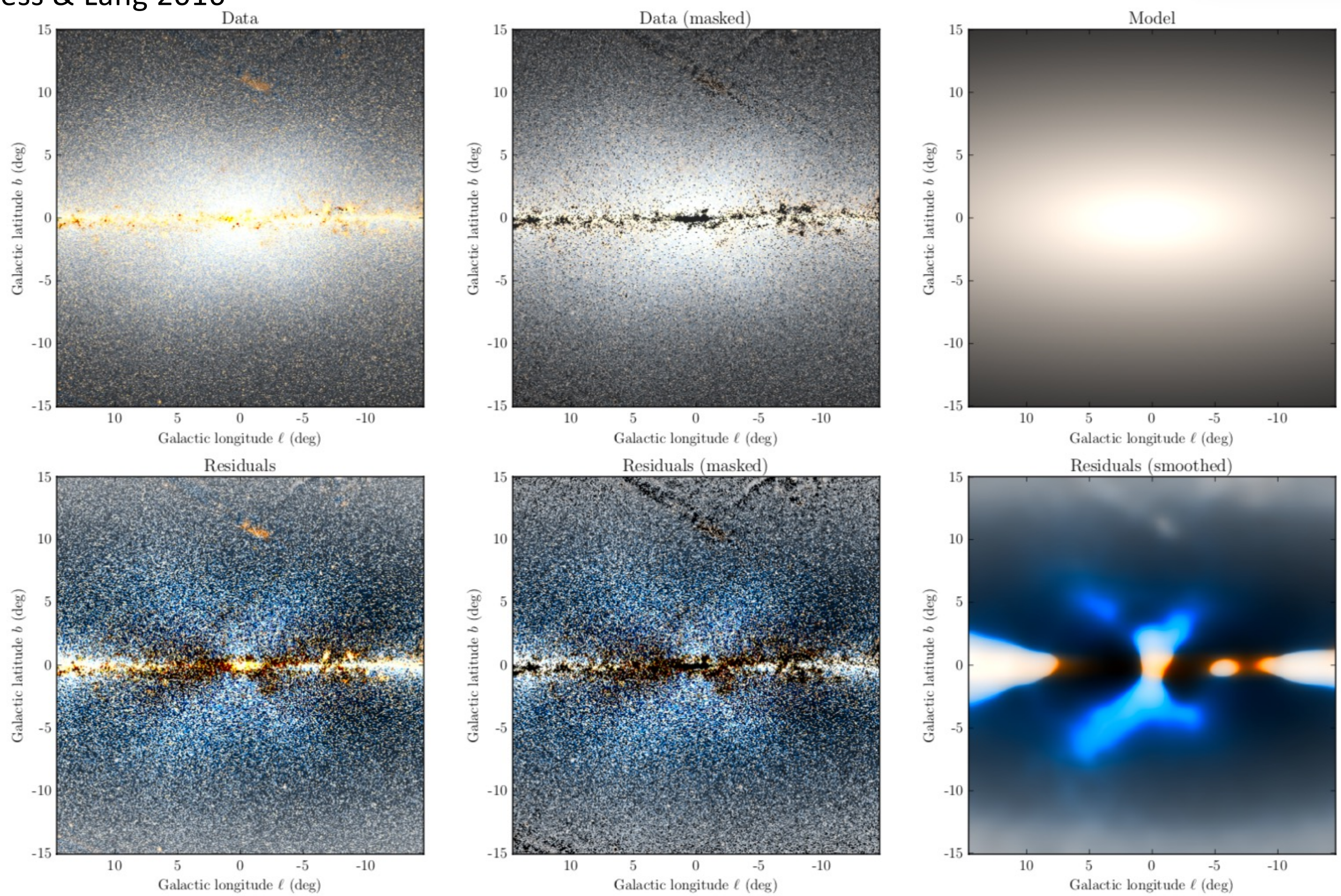
•ESA/Gaia/DPAC, Stefan Payne-Wardenaar
Artist Impression of our MW

Gaia: First Geometric Indication of the Galactic Bar

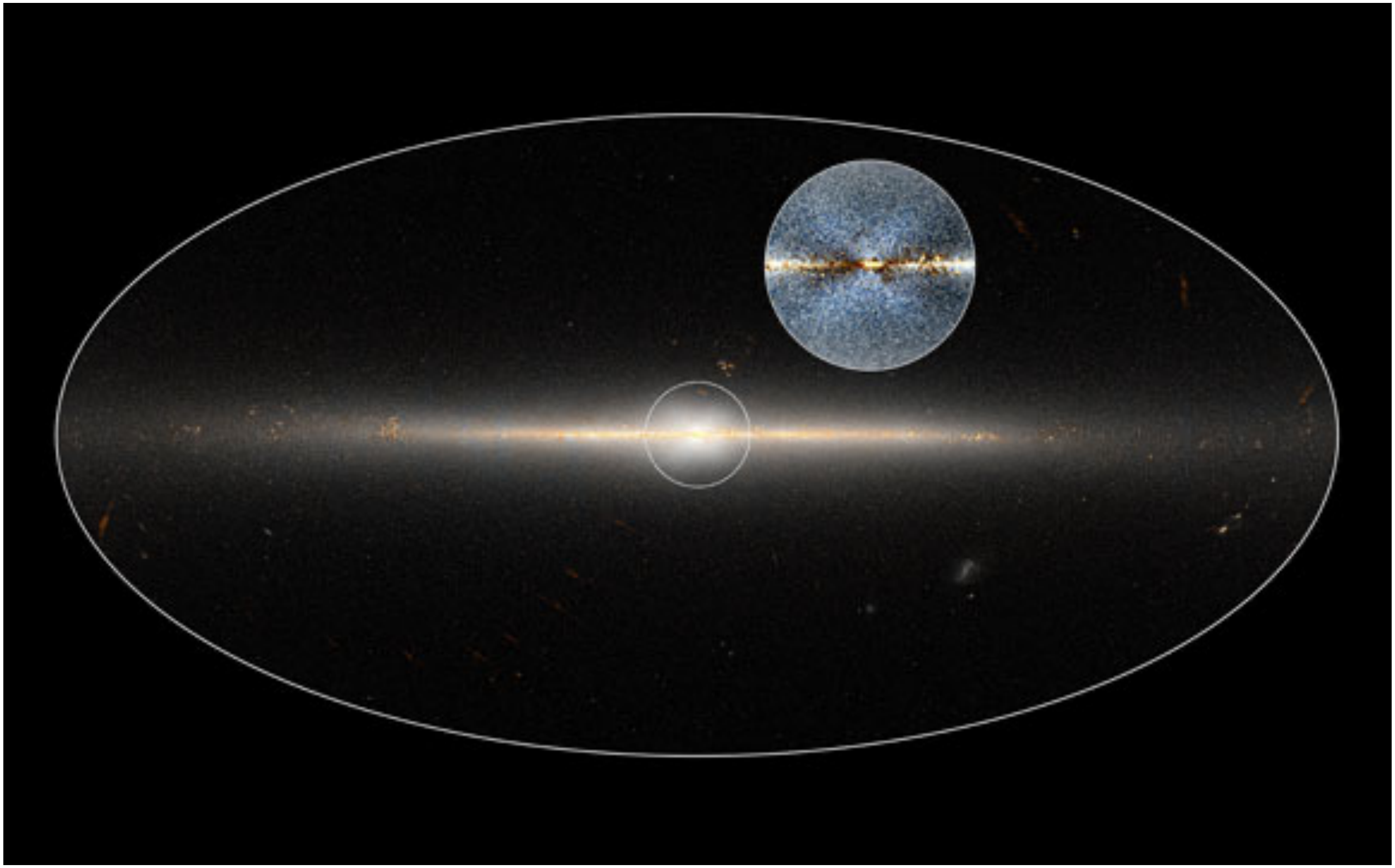


An Evolving Picture: X-Shaped Bulge/Bar

Ness & Lang 2016



The WISE W1 and W2 image fit by a simple exponential disk model, making the X structure more apparent. Top-left: Data. Top-middle: Data, masking out the top and bottom 5% of pixels based on W1 − W2 color, as well as pixels with negative flux. The diagonal structure at the top of the image is due to scattered light from the Moon in the unWISE coadds. Top-right: Exponential disk model fit. Bottom-left: Residuals (data minus model). Bottom-middle: Masked residuals. Bottom-right: 50-pixel ($\sim 1.7^{\circ}$) median filter of masked residuals (median of unmasked pixels).



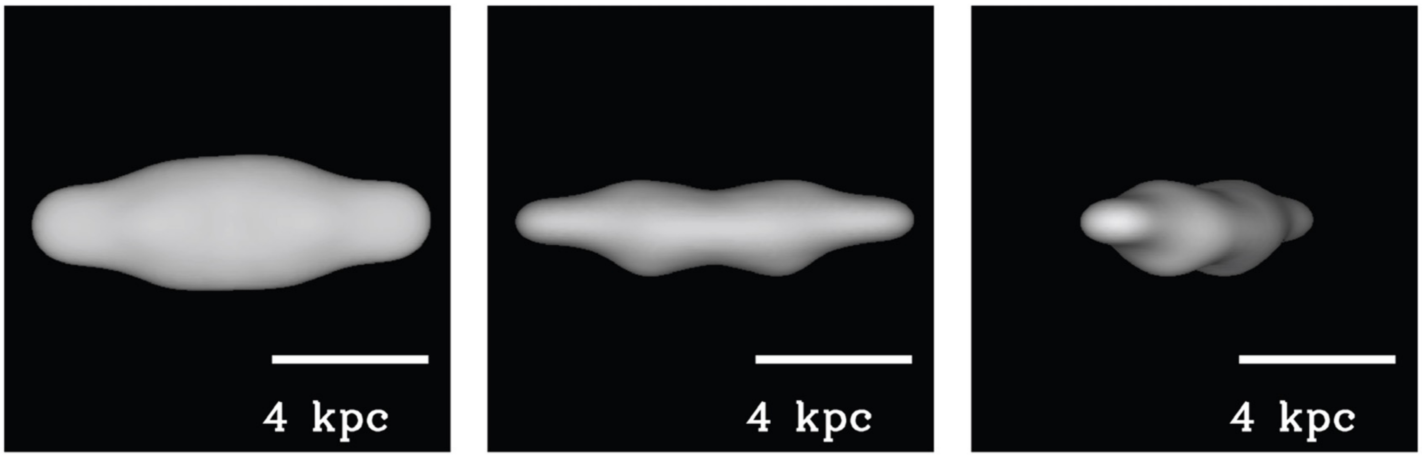
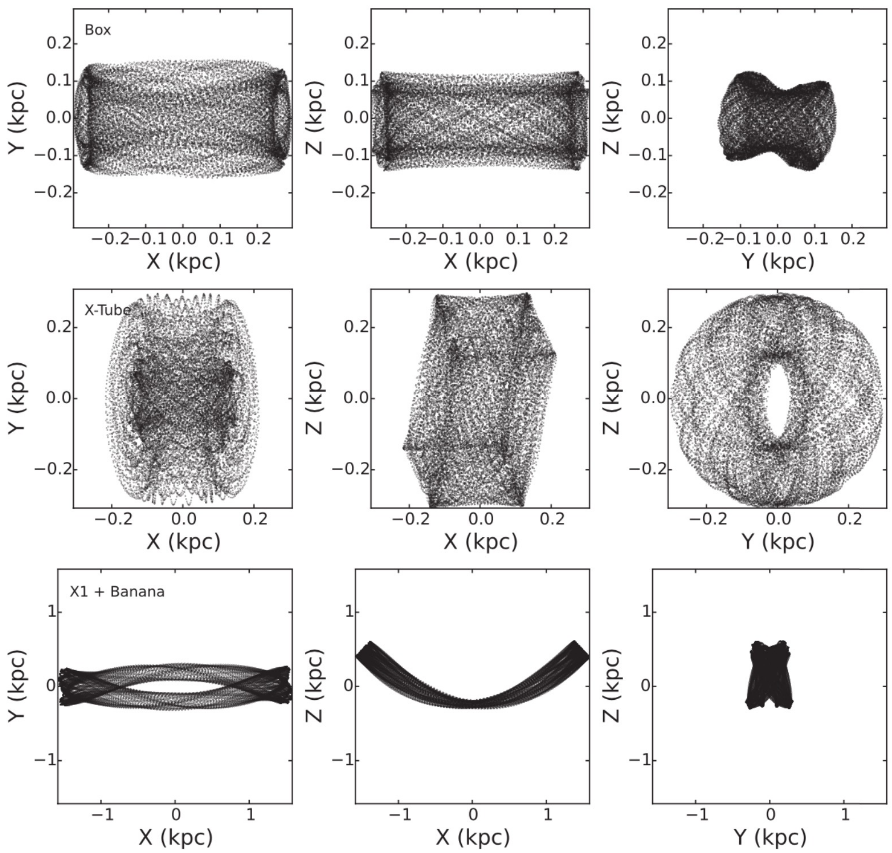
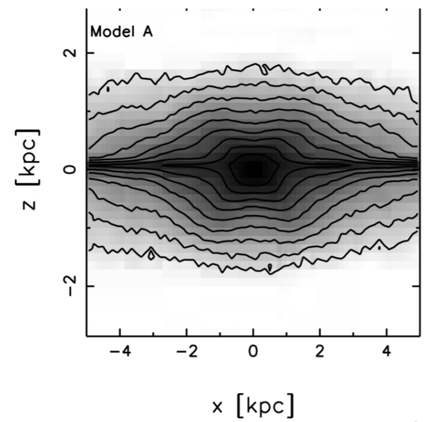


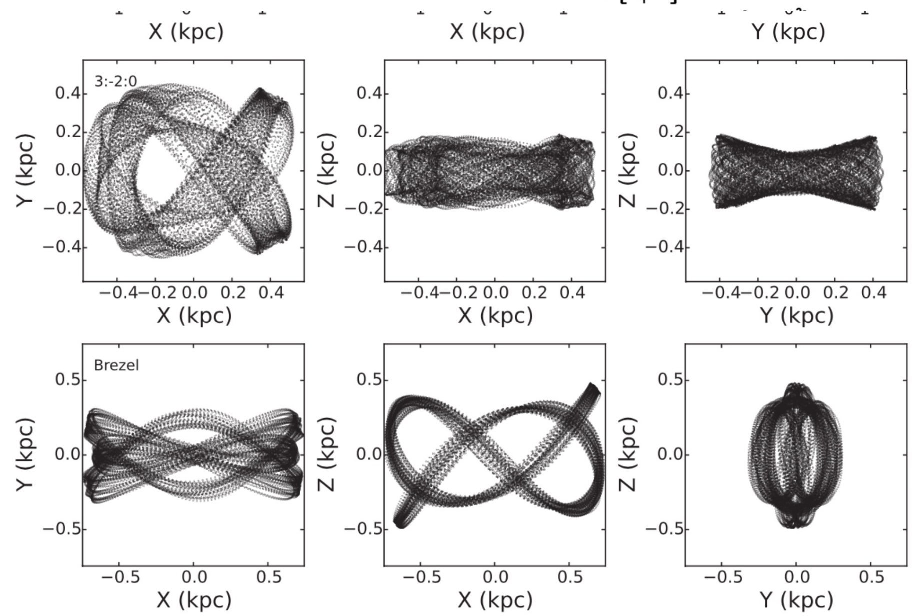
Fig. 4 3D isodensity surfaces of a strongly buckled bar in N-body simulations. The left and middle panels show the face-on and side-on appearance of the bar, respectively. The right panel shows an edge-on view at a bar angle of $25°$. Adapted from Li & Shen (2015).

Formation of an X-Shaped/Boxy Bulge

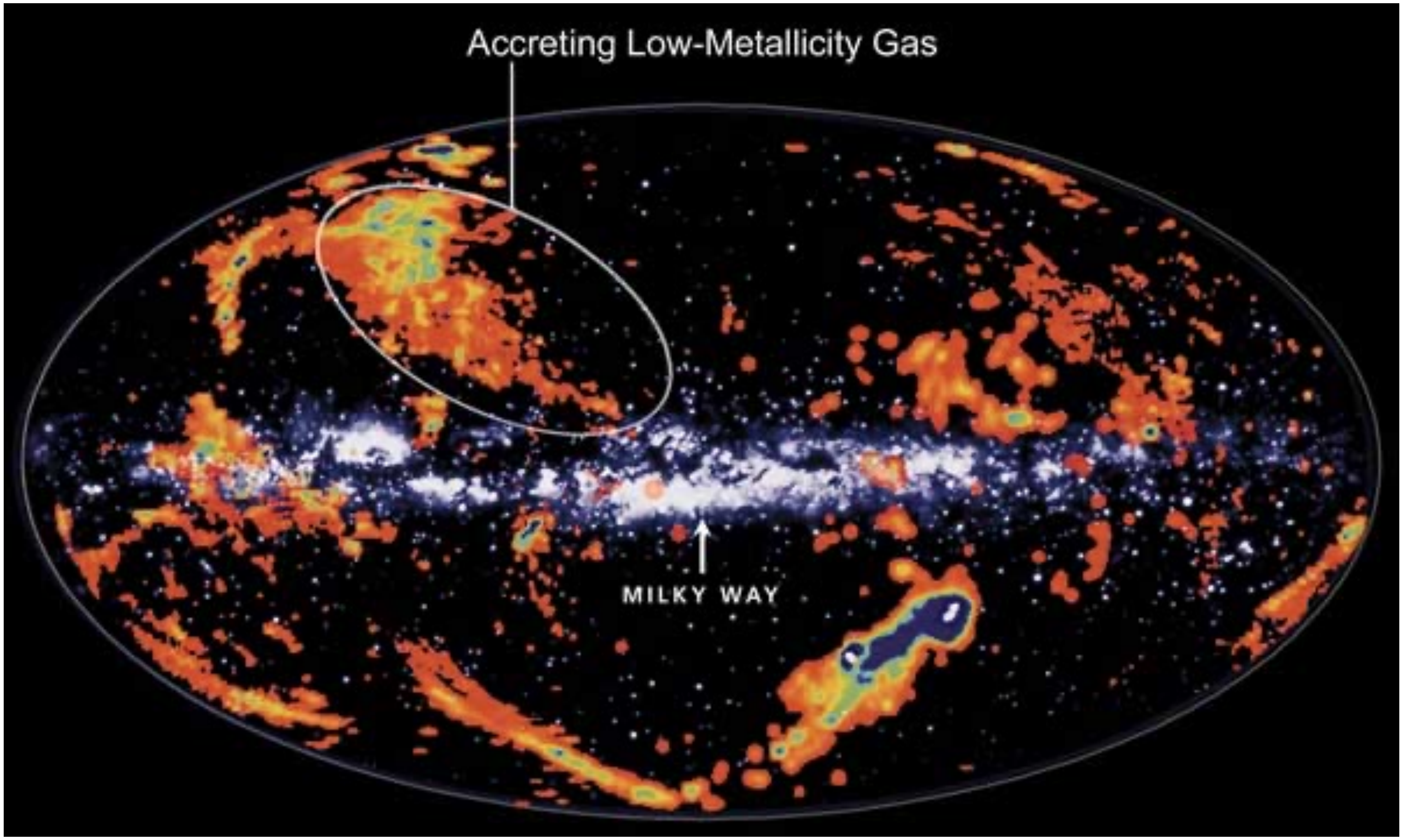


Abbott, Valluri + 2017

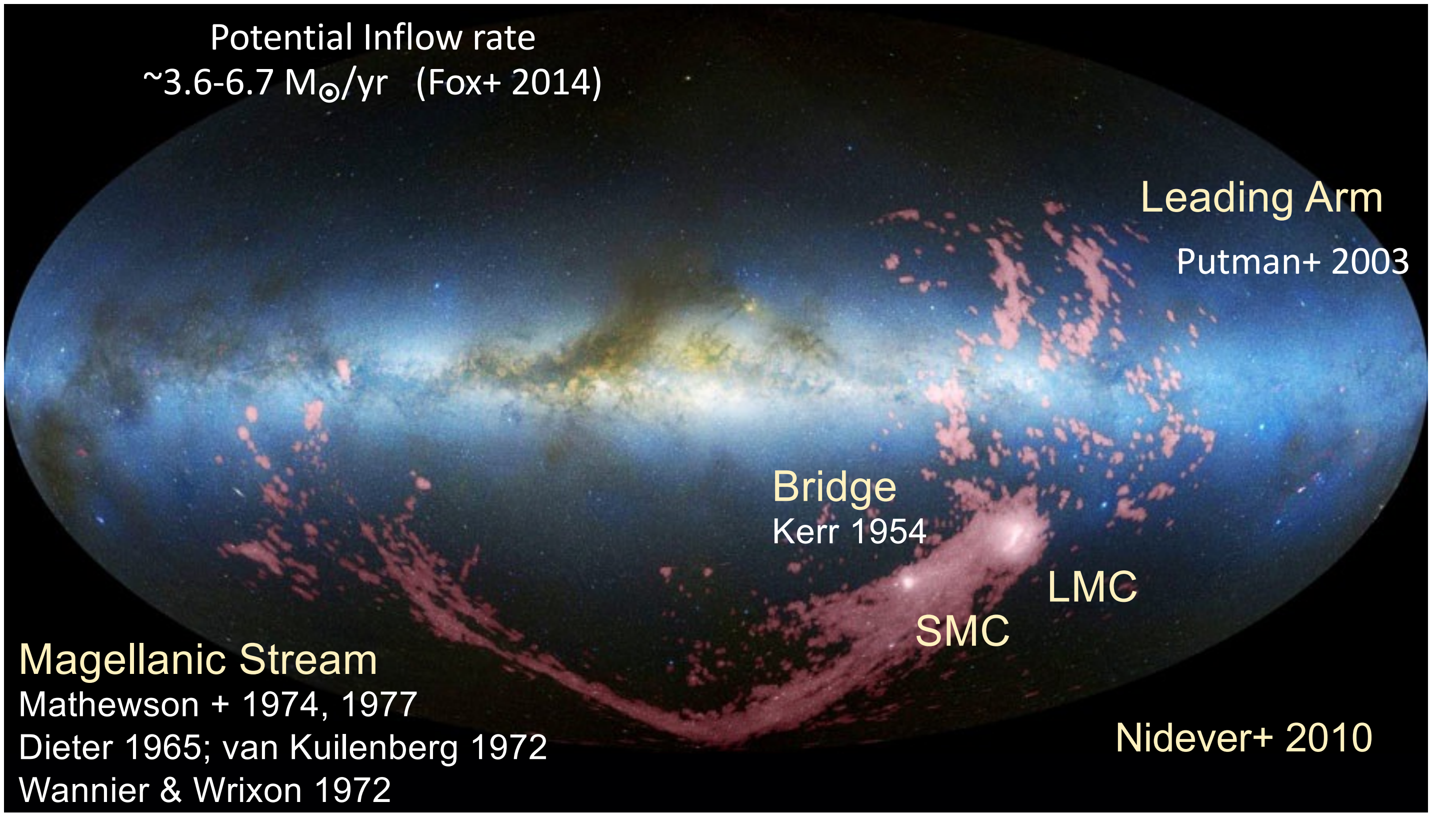




Circumgalactic Medium (CGM) in Cold Gas (HI)

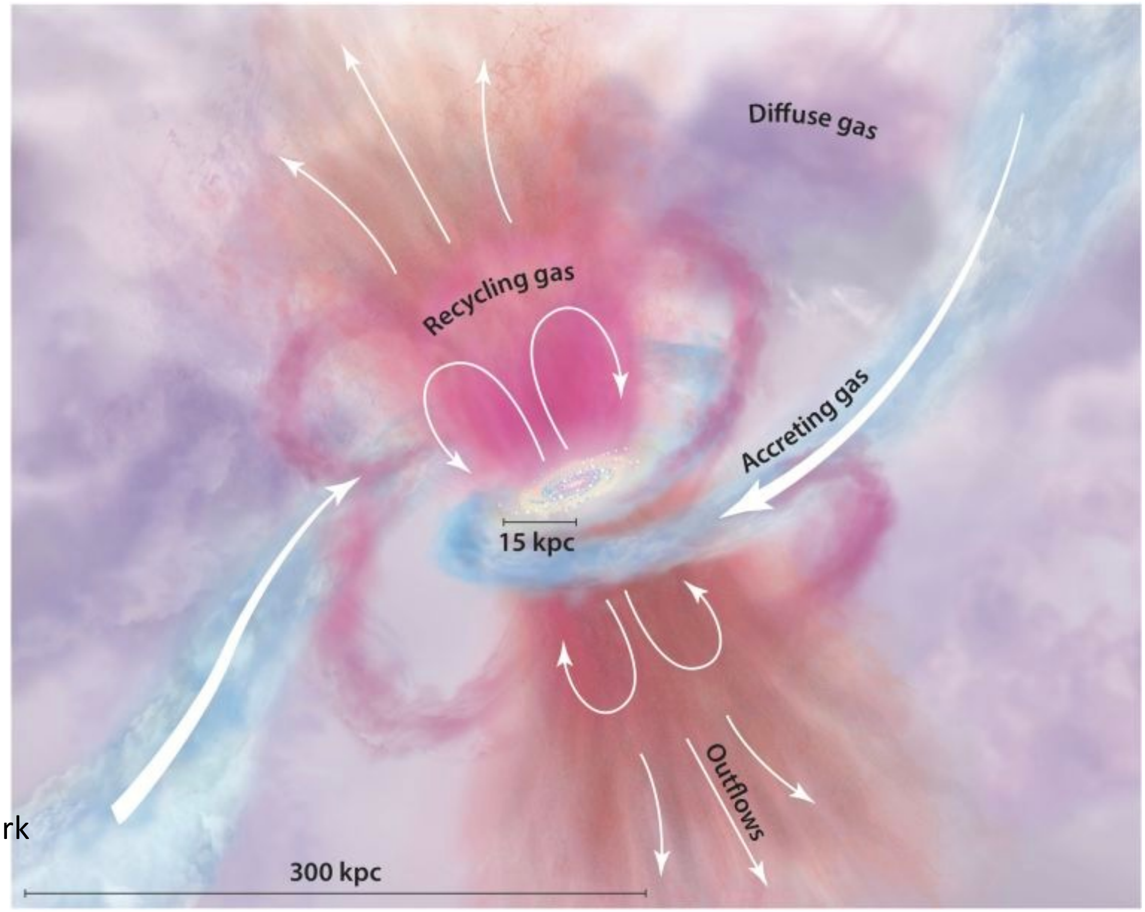


The Magellanic System & the CGM



$M_{\text{Gas outside}} \sim \mathbf{2\ x10^9\ M_\odot}(d/55\ \text{kpc})^2 > 2 \text{ x } M_{\text{Gas LMC+SMC}}$ Fox + 2014

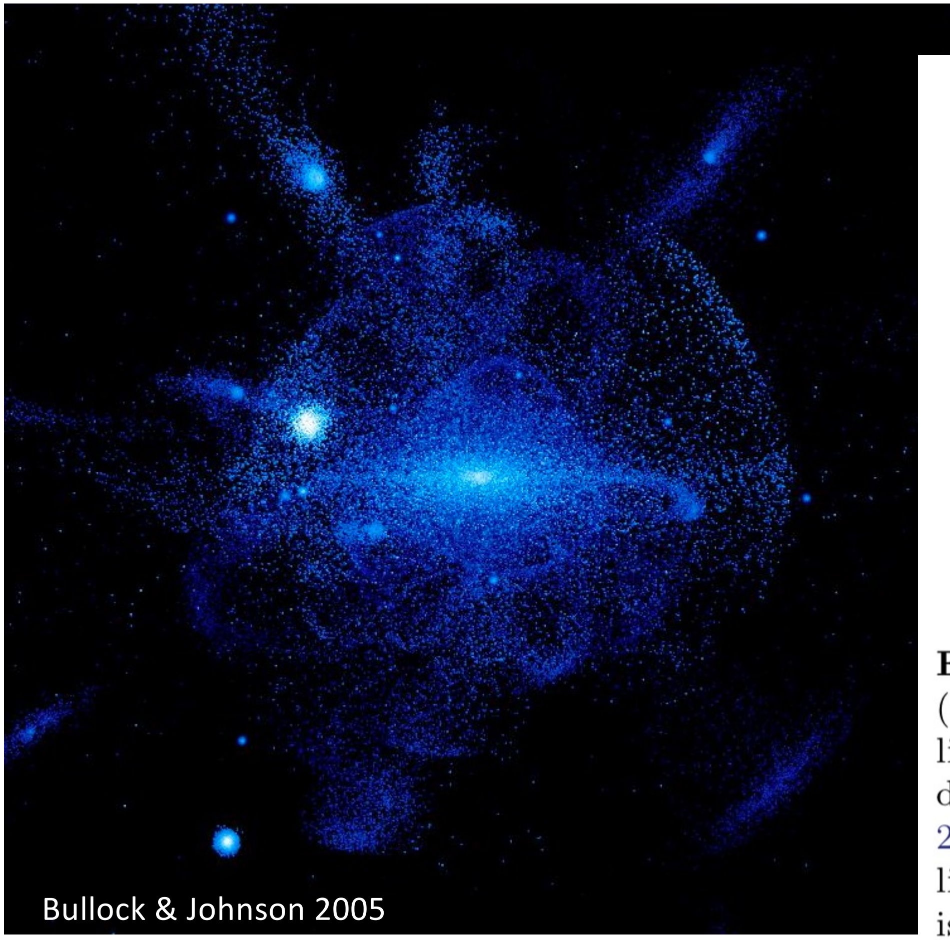
Circumgalactic Medium (CGM): Baryon Cycle



Tumlinson, Peeples, Werk 2017

Stellar Halo

Video Link: DC Halos



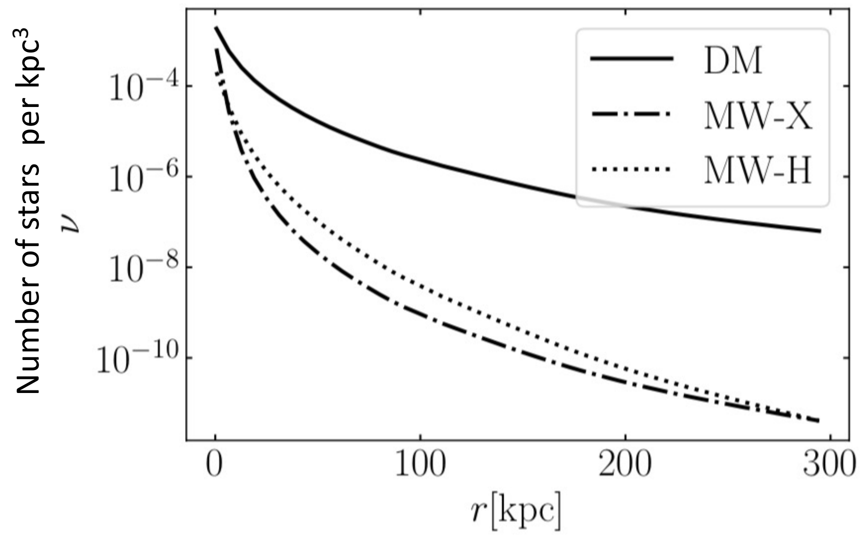


Figure 4. Initial number density profiles of the stellar halo (#/kpc^3), built by applying the stellar tracer method, outlined in Laporte et al. (2013a,b), and using the observed density profiles for K-giants (MW-X; dashed line Xue et al. 2015) and RR Lyrae (Hernitschek et al. 2018, MW-H; dotted line). The DM density profile for the MW halo (solid line) is shown for comparison.

Garavito-Camargo + 2019

Stellar Halo: Einasto Profiles

Number of stars per kpc^3

$$\nu(r) = \nu_e e^{-dn(r/r_{eff})^{(1/n)-1}}$$

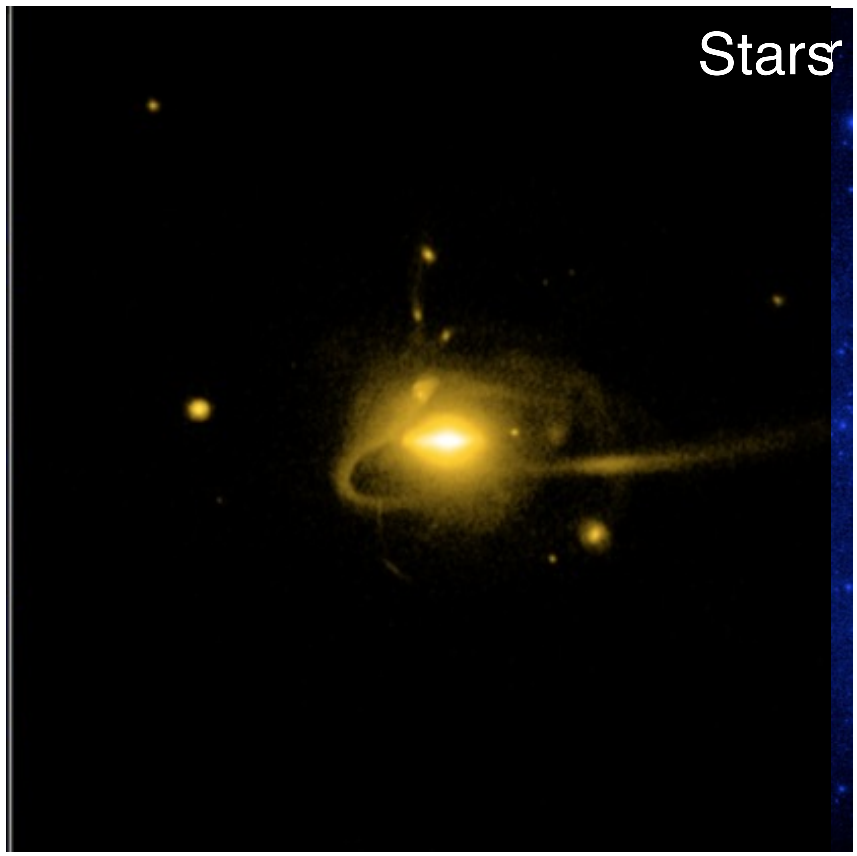
$$dn = 3n - 1/3 + 0.0079/n.$$

	MW-X	MW-H
Density profile	Einasto	Einasto
$(n;\, r_{eff})$	(3.1; 15 kpc)	(9.53; 1.07 kpc)
Distances (kpc)	10−80	20−131
Tracers	K-giants	RRLyr
Reference	Xue et al. (2015)	Hernitschek et al. (2018)

Table 4. MW stellar halo model parameters from observations of K-giants and RR Lyrae (RRLyr).

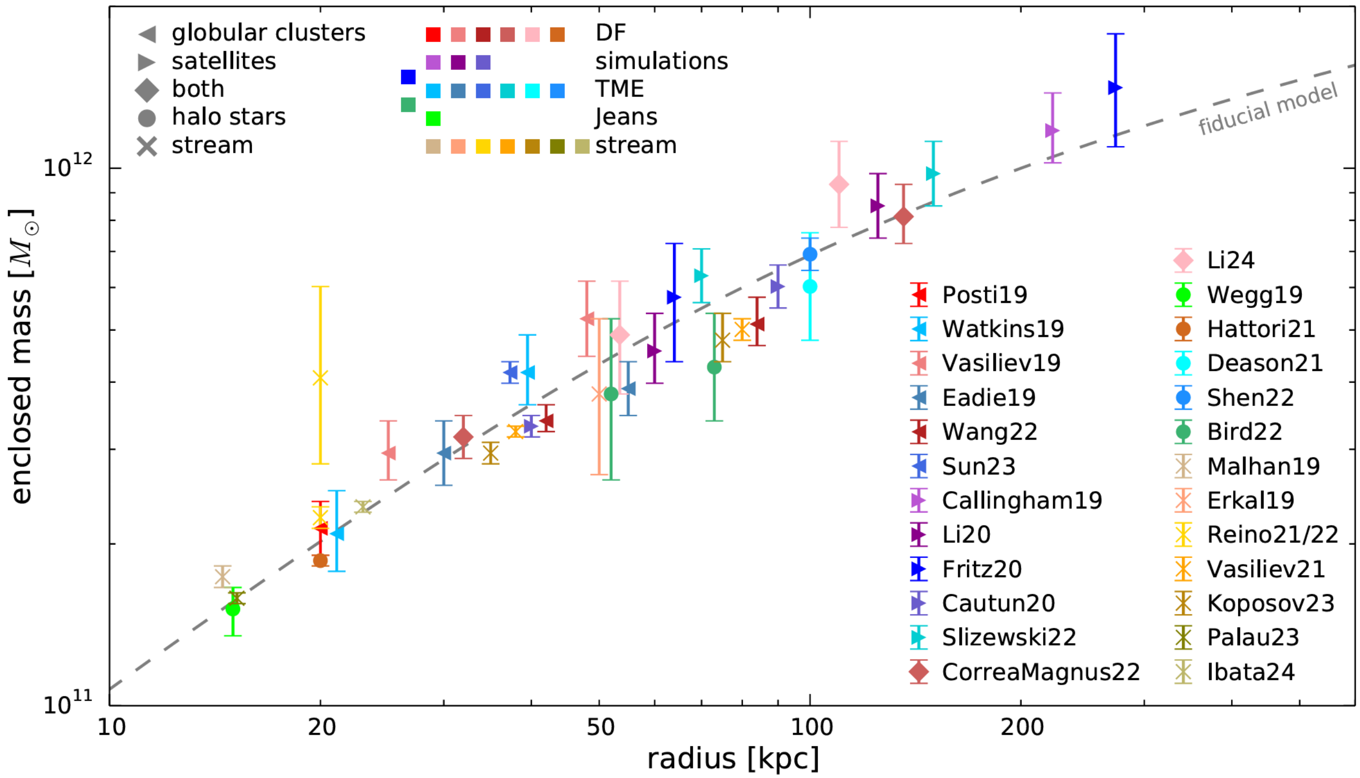
Garavito-Camargo + 2019

Dark Matter vs. Stars



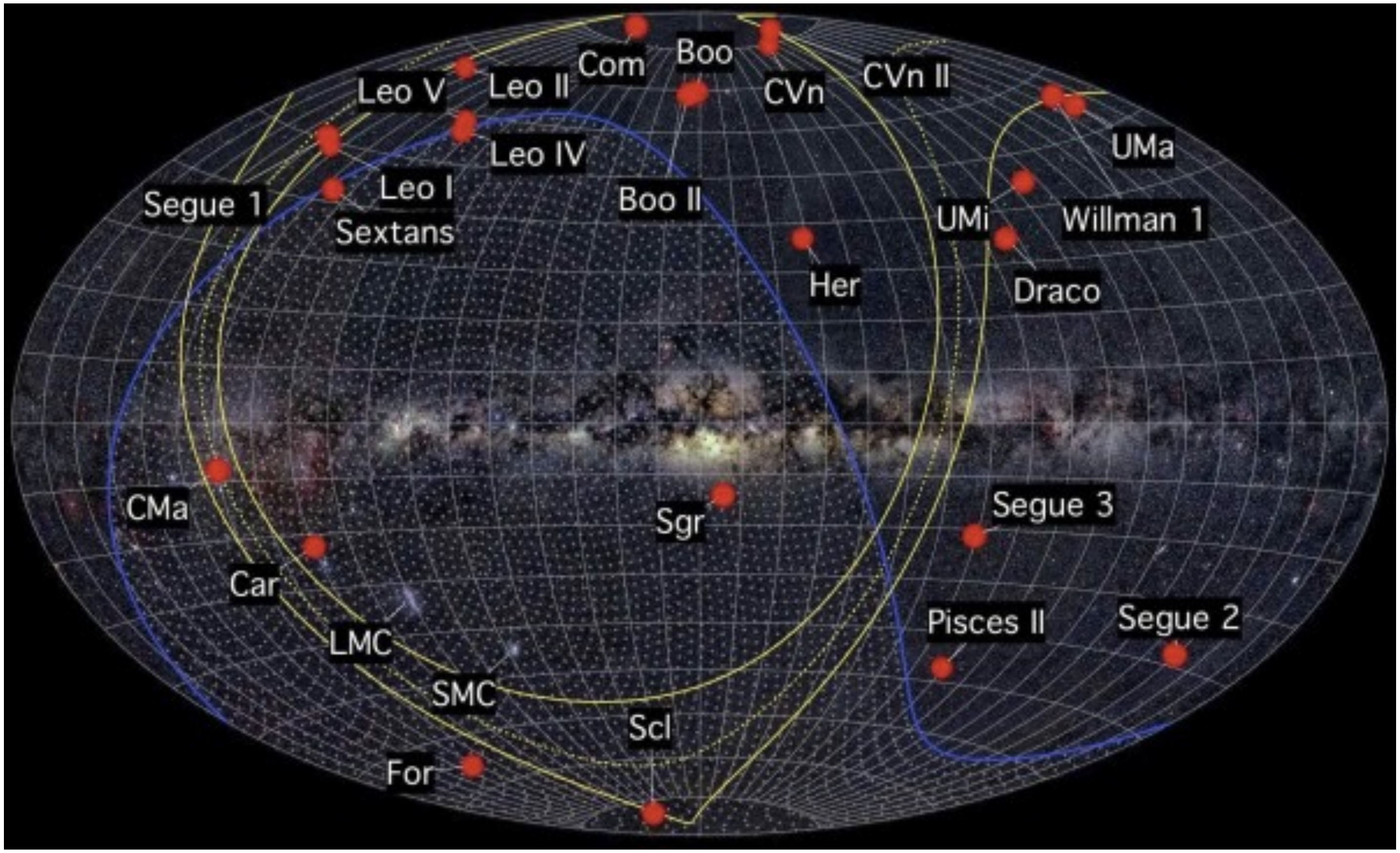
Wetzel+2016

Mass Enclosed at Large Radii
>> Baryonic Mass = Dark Matter



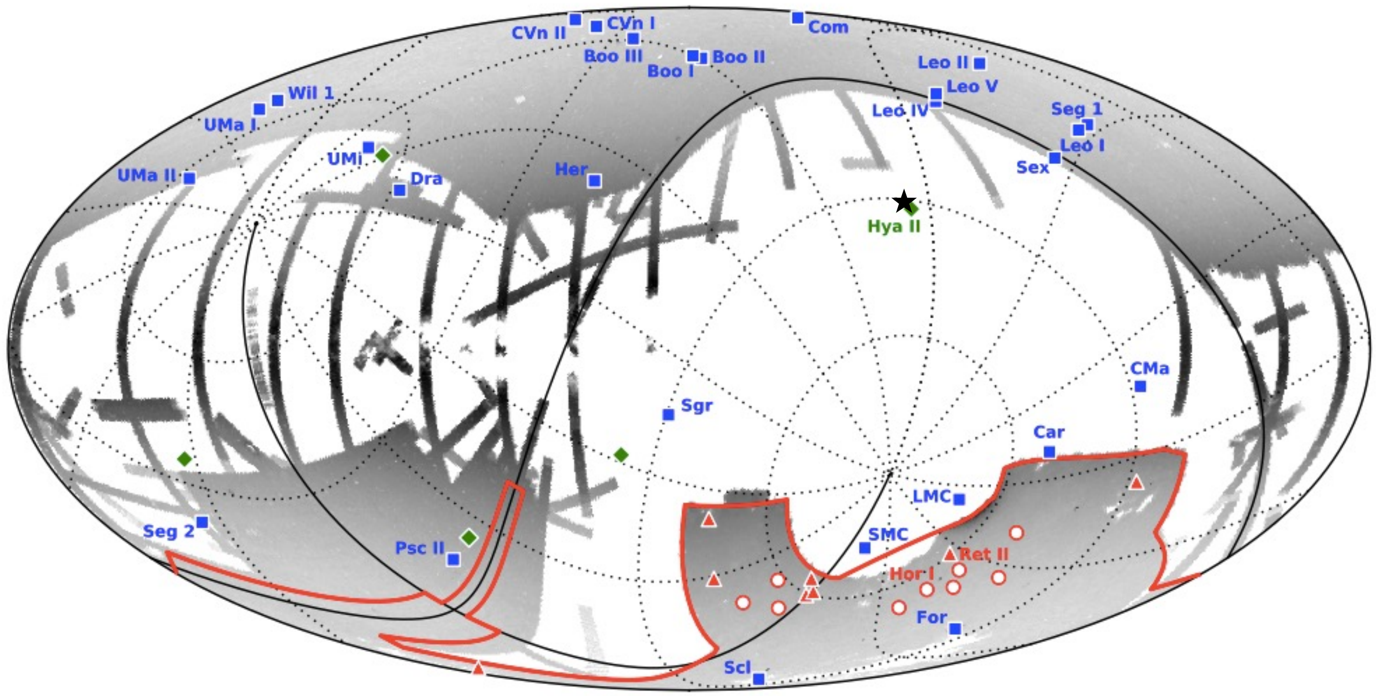
Hunt & Vasiliev 2025 Review ArXiv 2501.04075

Our Milky Way has many Neighbors



26 Satellites as of Feb 2015

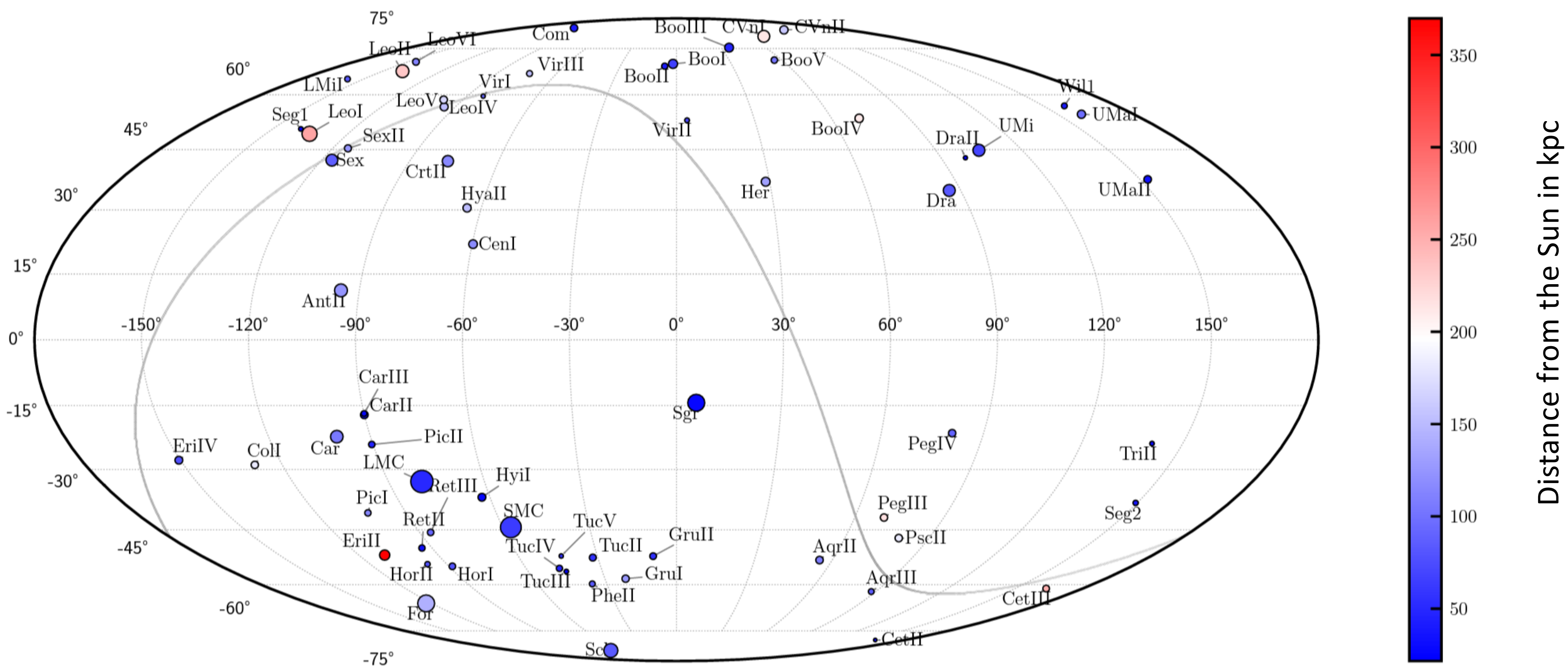
Possible New Dwarfs found by DES Survey +PANSTARRS +SMASH survey = ~ 50 (2016)



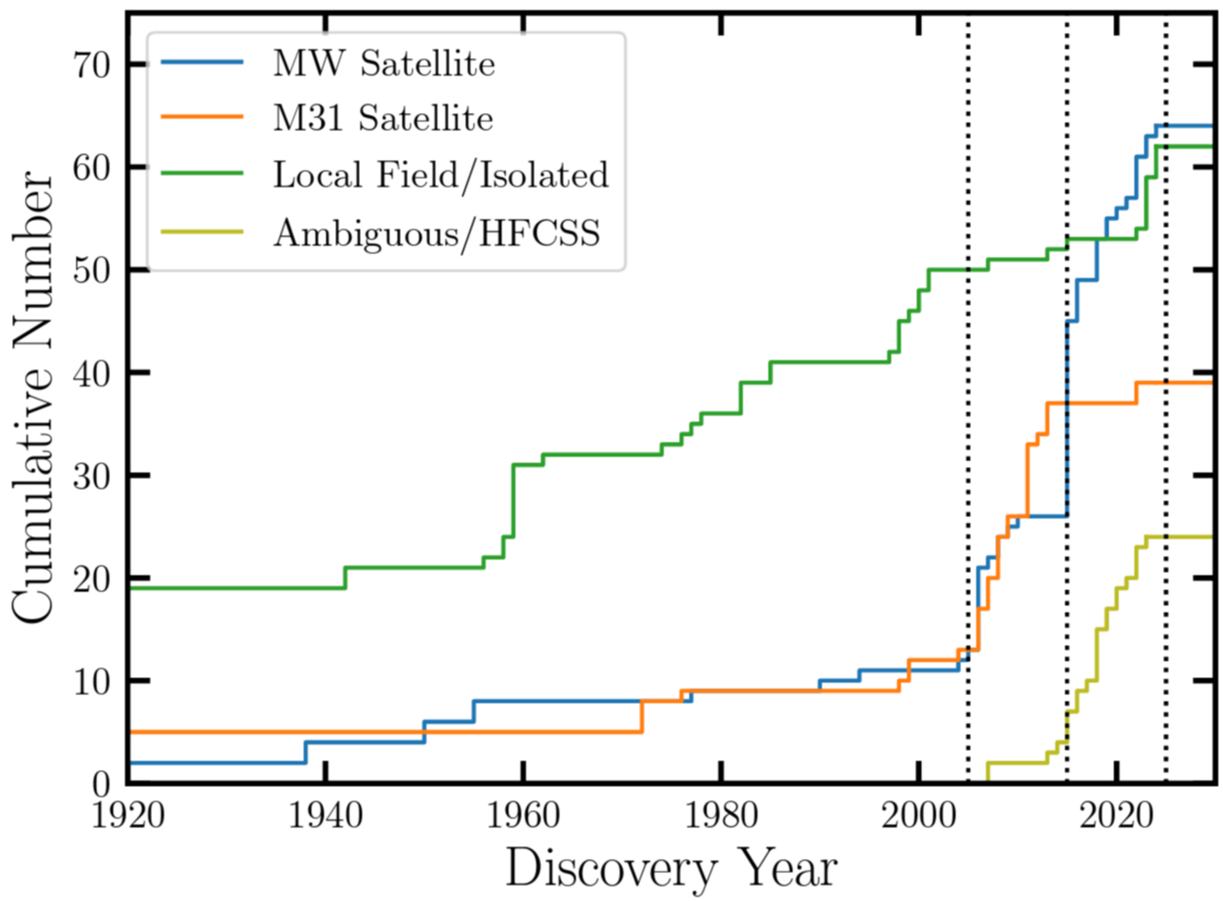
Bechtol + 2015 (DES); Koposov+2015; Laevens +2015; Martin, Nidever, Besla+ 2015 (SMASH), Drlica-Wagner+2015 (DES), Homma+2016

Number of Satellites in the Era of Gaia

- 58 satellites with measured tangential velocities
- > 65 (not all confirmed) Pace 2024 arXiv 2411.07424



Satellite Discovery Timeline Pace 2024 arXiv 2411.07424



Dotted lines at :

2005 = SDSS Era

2015 = Blanco/DECam, Pan-STARRS, ATLAS, Gaia, Subaru/HSC, CFHT/Megacam

2025 = UPCOMING ERA OF Vera Rubin/LSST (2026 release!!), Euclid, and Nancy Grace Roman Space Telescope

V_{tan} --> Proper Motion

The **proper motion** of an object is the measurement of its angular change in position on the sky over time**.**

Barnard's Star:

Highest proper motion of any star visible from the Earth.

True motion: 140 km/s

Credit: Steve Quirk

HSTPROMO

The HST Proper Motion Collaboration

(http://www.stsci.edu/~marel/hstpromo.html)

- Characteristic velocity accuracy necessary
  ~10 km/s at 70 kpc   (Milky Way halo/satellite dynamics)

- Corresponding PM accuracy
  ~ 30 μas / yr

  (~ speed of human hair growth
  at distance of the Moon)

With HST we can measure a change of 0.006 ACS/WFC pixels over a 10 yr baseline

GAIA

Data Release 1: Sep. 2016
Data Release 2 : April 2018
Data Release 3: late 2020/early 2021
Mission Duration: Until 2022