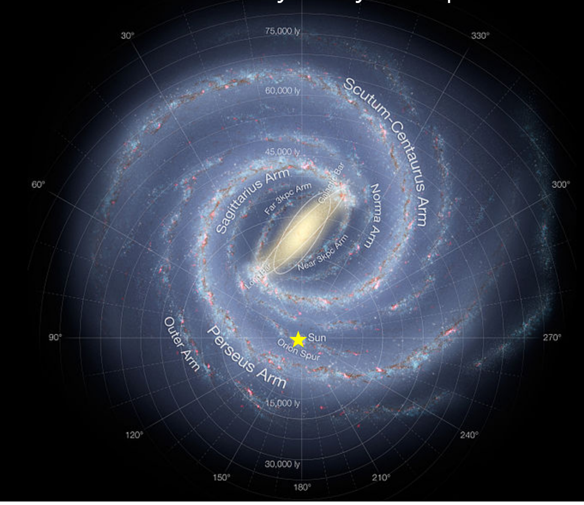
The Structure of our Milky Way Disk:

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

1

A Model of the Milky Way: A Spiral Galaxy



2

Thick/Thin Disk

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

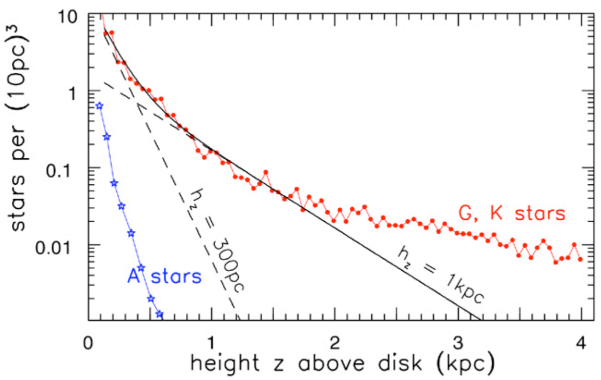


Fig 2.8 (Reid, Knude) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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

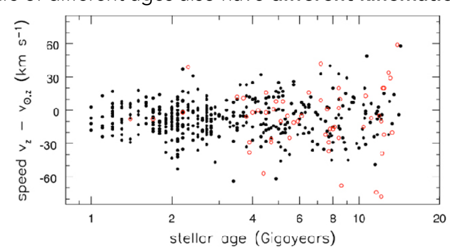
Sloping dashed lines show
n(z) α exp(-z / 300 pc) (thin disk)
And
n(z) α exp(-z/1 kpc) (thick disk);
the solid curve is their sum.

At z > 2 kpc, most stars belong to the metal poor halo. A dwarfs (star symbols) lie in a very thin layer.

3

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:

$$\sigma_z^2 \equiv \langle v_z^2 - \langle v_z \rangle^2 \rangle$$

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

4

An aside: what is meant by [Fe/ H]

$$[A/B] = \log_{10}\left[\frac{(\text{number of A atoms/number of B atoms})_\star}{(\text{number of A atoms/number of B atoms})_\odot}\right]$$

$$[A/B] \equiv \log_{10}\left(\frac{A}{B}\right)_\star - \log_{10}\left(\frac{A}{B}\right)_\odot$$

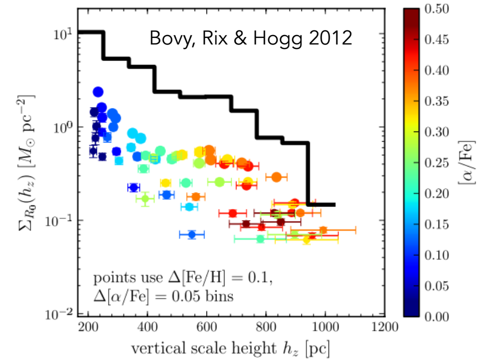
α refers to "alpha process elements" which are the result of a class of fusion processes involving helium. The α elements multiples of helium nuclei ("α particles"): integer multiple of 4 nucleons. The α elements are O, Ne, Mg, Si, S, Ar, Ca, Ti

An Evolving Picture: Thick Disk

How much of the total stellar surface mass density at R0 comes from stars with a scale-height hz ?

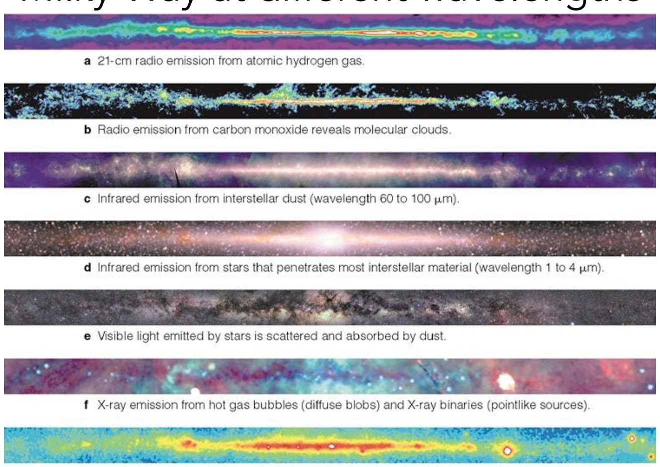
If there were a distinct 'thin' and 'thick' disk, one would expect a bimodal distribution in $\Sigma_{R_0}(h_z)$, with ≃85% of it in a thin disk peak (with scale heights covering the range $h_z \simeq$ 100 to 250 pc) and ≃15% in a thick disk (with $h_z \simeq$ 700 pc) for a canonical disk decomposition (e.g., Juric et al 2008). However, the Figure shows a different picture. There is a continuous distribution of $\Sigma_{R_0}(h_z)$, with no sign of bimodality, a distribution that is quite well-approximated by $\Sigma_{R_0}(h_z) \propto \exp(-h_z/280\text{ pc})$. Rix & Bovy 2013

Some recent work questions whether there is a distinction between the "thin" and "thick" disks.



No bimodality in scale height with age or metallicity?

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).

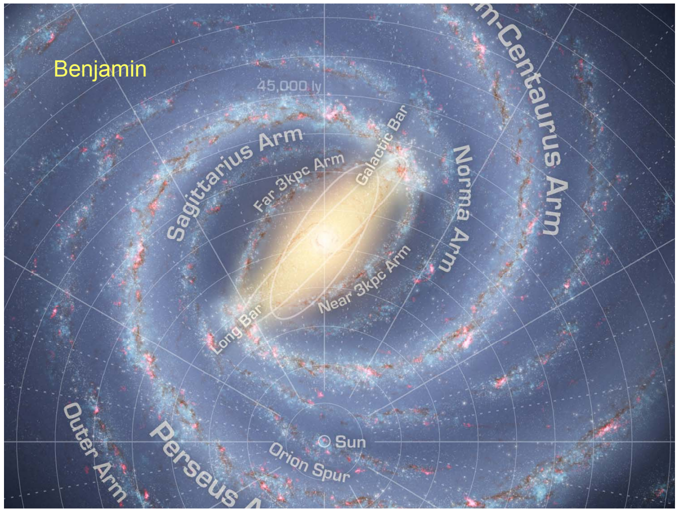
e Visible light emitted by stars is scattered and absorbed by dust.

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.

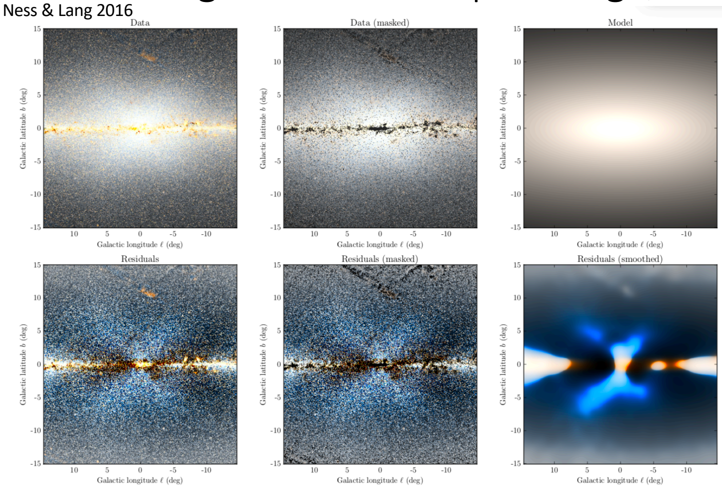
The MW Bar

Short ~3.0 kpc (Freudenreich 1997)
Long ~4.5 kpc (Cabrera-Lammers et al 08, Benjamin 2009)



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 (~ 1.7°) median filter of masked residuals (median of unmasked pixels).

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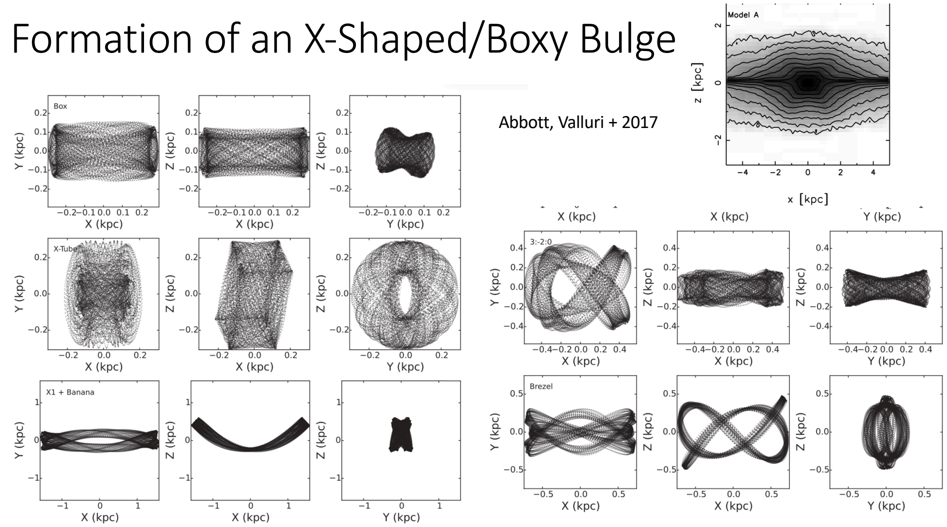
Formation of an X-Shaped/Boxy Bulge

Abbott, Valluri + 2017



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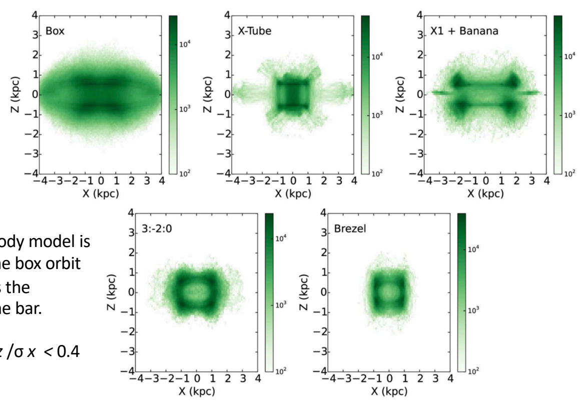
Formation of an X-Shaped/Boxy Bulge

Abbott, Valluri + 2017



BP/X shape in the *N*-body model is produced largely by the box orbit family that constitutes the majority of orbits in the bar.

Bar Buckling: when $\sigma_z/\sigma_x < 0.4$

Figure 8. Projected excess-mass density on the x–z plane for each of the five orbit families from Model A as labelled. The colour gradient as shown in the bar on the right of each plot is in units of $M_\odot\,kpc^{-2}$. The box orbits (top row left) and resonant 2:−2:1 x1+banana orbits (top row right) show a clear BP/X-shape at large radii. The x-tube orbits (top row middle) show a hint of an X-shape but at very low-density levels. Resonant boxlet 3:−2:0 fish/pretzel orbits (bottom row left) and resonant 3:0:−5 brezel orbits (bottom row right) show a BP/X-shape at small radii (≲2 kpc).

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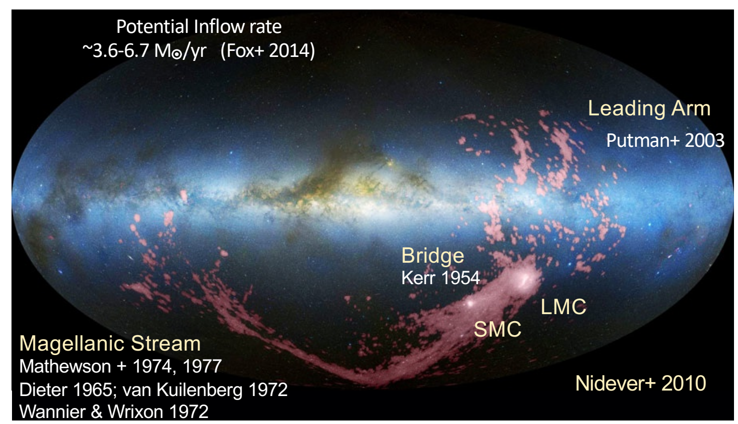
The Magellanic System & the CGM



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

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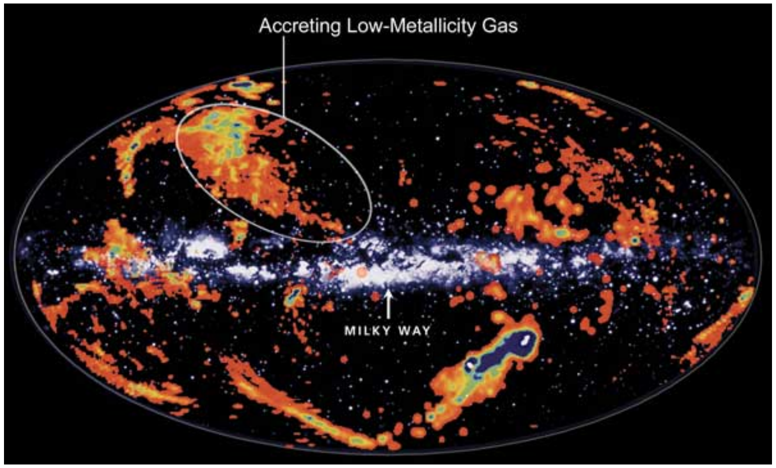
Circumgalactic Medium (CGM) in Cold Gas (HI)



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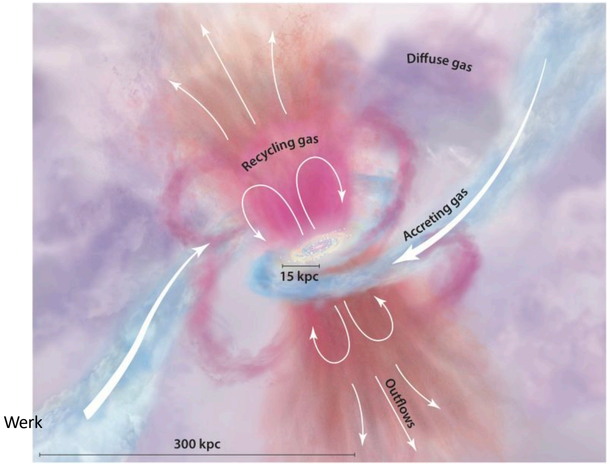
Circumgalactic Medium (CGM): Baryon Cycle



Tumlinson, Peeples, Werk 2017

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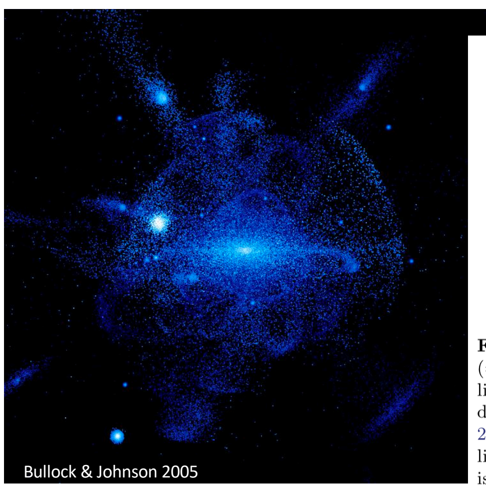
Stellar Halo



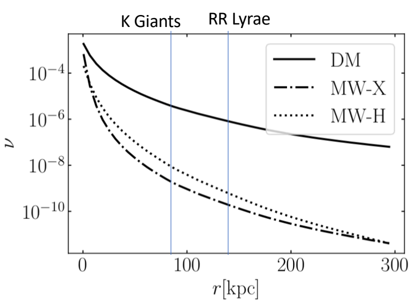


Figure 4. Initial number density profiles of the stellar halo (#/kpc^3), built by applying the stellar tracer method, outlined in Laporte et al. (2013a,b), and using the observed density profiles for K-giants (MW-X; dashed line Xue et al. 2015) and RR Lyrae (Hernitschek et al. 2018, MW-H; dotted line).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

Garavito-Camargo + 2019

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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).

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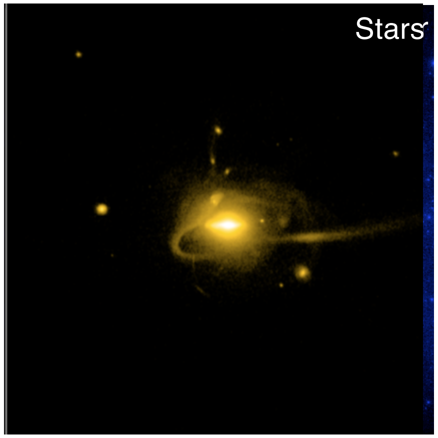
Dark Matter vs. Stars



Wetzel+2016

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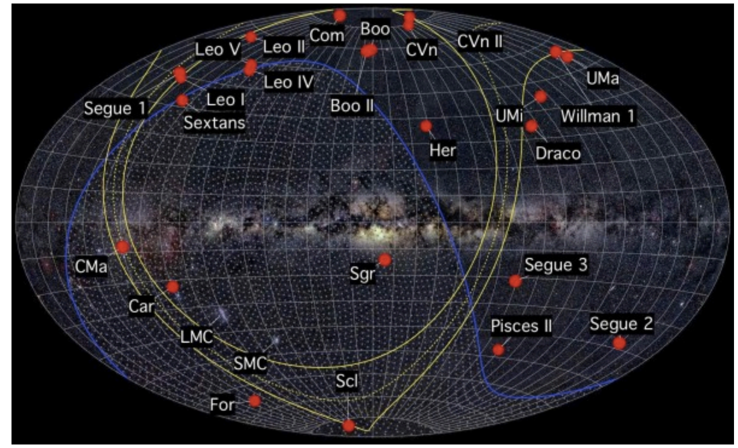
Our Milky Way has many Neighbors



26 Satellites as of Feb 2015

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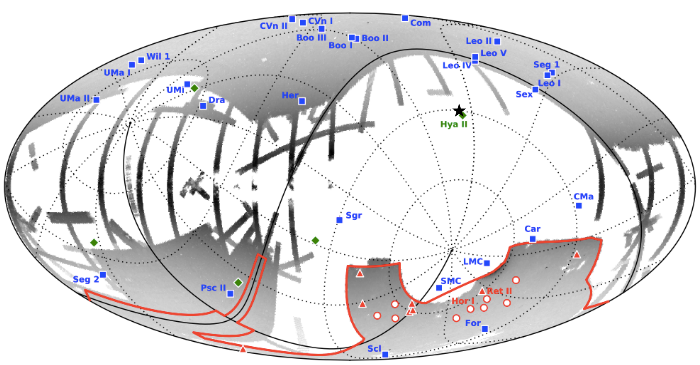
Possible New Dwarfs found by DES Survey +PANSTARRS +SMASH survey = ~ 50 ?



Bechtol + 2015 (DES); Koposov+2015; Laevens +2015; Martin, Nidever, Besla+ 2015 (SMASH), Drlica-Wagner+2015 (DES), Homma+2016 … more to come with LSST!

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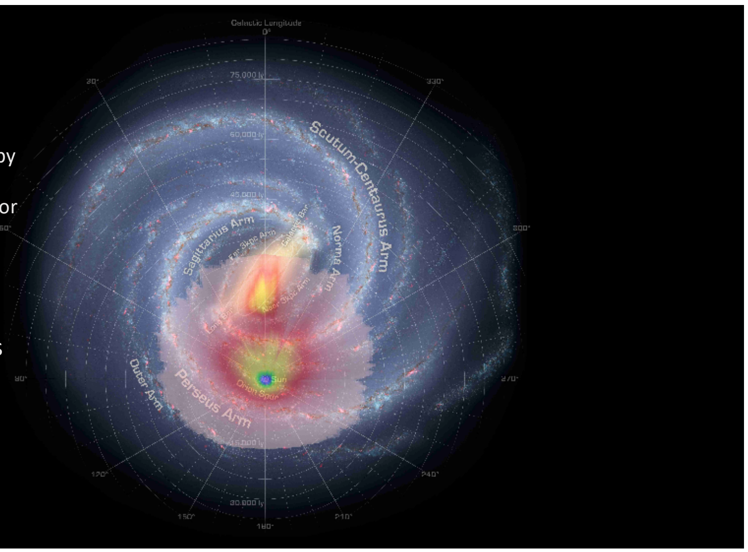
GAIA

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.



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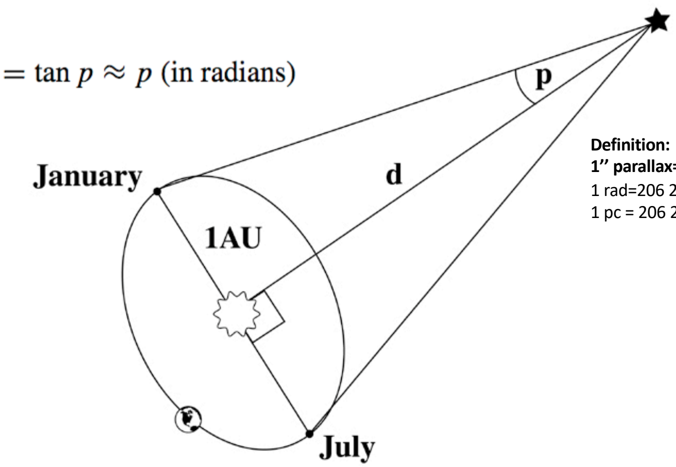
$$\frac{1\ \mathrm{AU}}{d} = \tan p \approx p \text{ (in radians)}$$

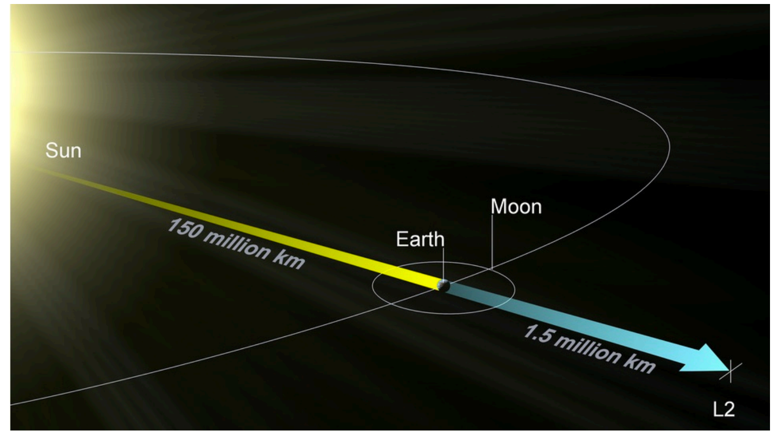


Definition:
1'' parallax=1pc distance
1 rad=206 265''
1 pc = 206 265 AU = 3.086e18 cm

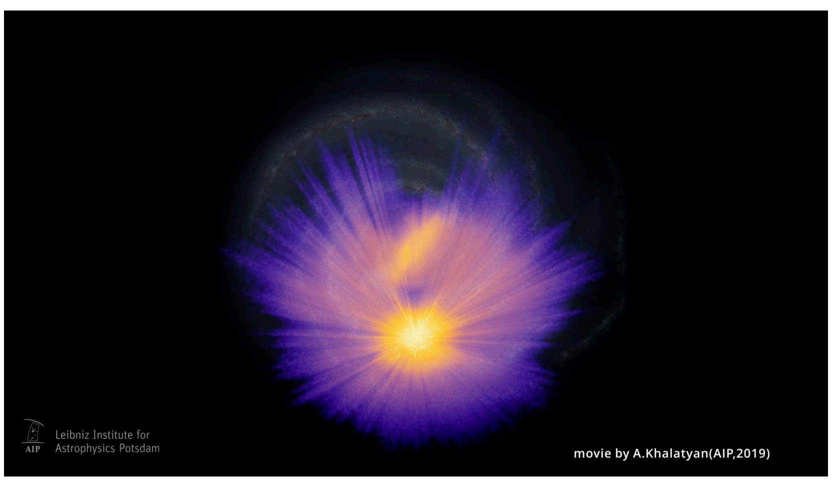
Fig 2.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Gaia is orbiting L2

Positions to 20 micro arc second! Each star is observed 70 times: parallaxes and proper motions (motion on the sky).
Hipparcos: measured positions of bright stars to only 0.001''



Gaia: First Geometric Indication of the Galactic Bar



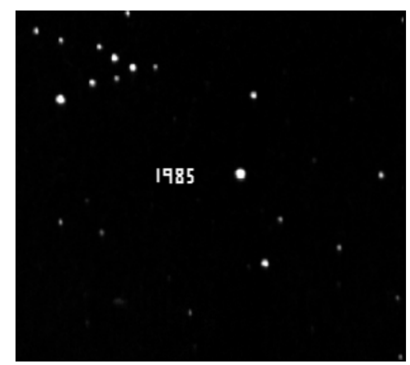
V_{tan} --> Proper Motion

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

GAIA

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

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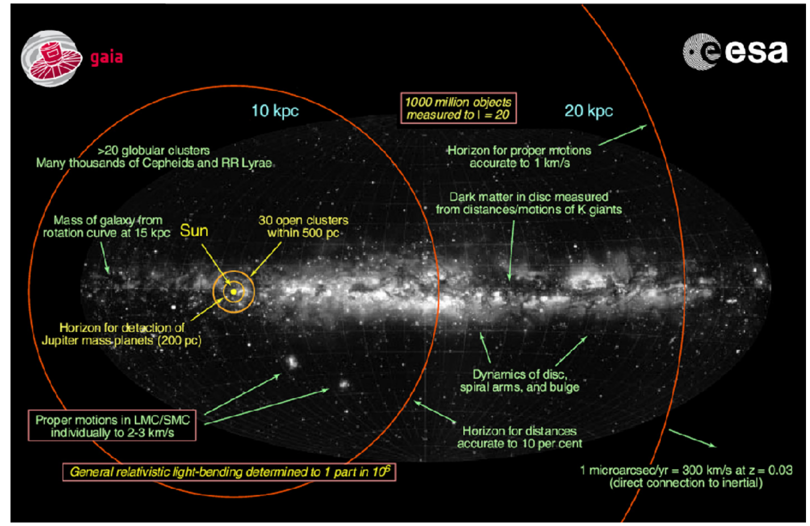

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HSTPROMO

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

HSTPROMO

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The Need for HST:

Both Gaia & HST in concert are needed to develop a model for the dynamics of our Local Group.

Galaxy	ΔPM (km/s) HST	ΔPM (km/s) Gaia (2017)/2018
Horologium I	23	45
Pictoris II	24	119
Phoenix II	25	125
Hydra II	27	138
Grus I	26	138
Eridanus III	23	151
Tucana II	24	59

< 30 kpc: Gaia
30-80 kpc: Gaia & HST
> 80 kpc: HST

HSTPROMO

HST Cycle 23 Large
PI Kallivayalil

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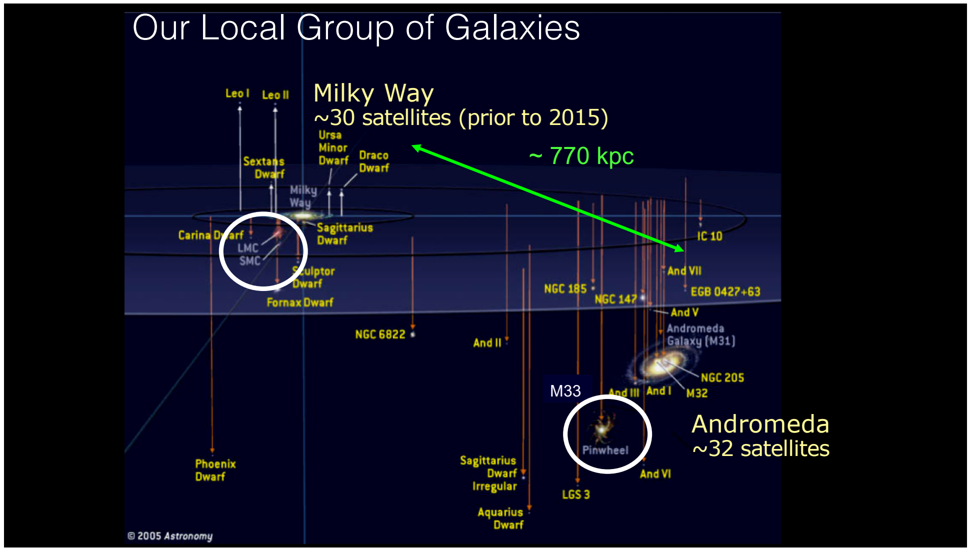

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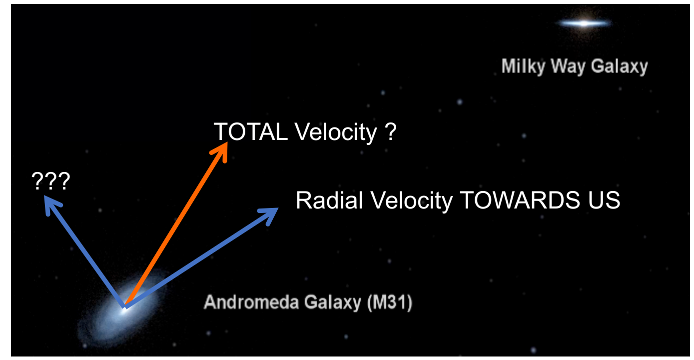
What is the 3D velocity of M31?



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HSTPROMO: The First Direct Proper Motion Measurement of M31

Sohn + 2012 (12 μas accuracy) - M31 is coming straight at us!

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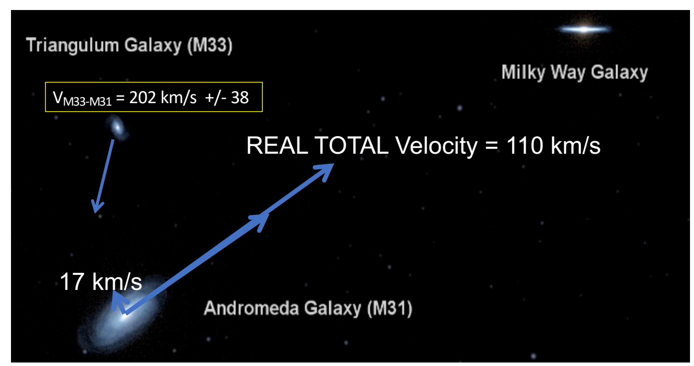
Andromeda is heading DIRECTLY towards us!



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With the new M31 proper motion measurement we can predict the timing of the collision between the MW & M31: $3.87^{+0.42}_{-0.32}$ Gyr   van der Marel,Besla+2012

Artistic License: Z. Levay and R. van der Marel (STScI), T.Hallas, and A. Mellinger

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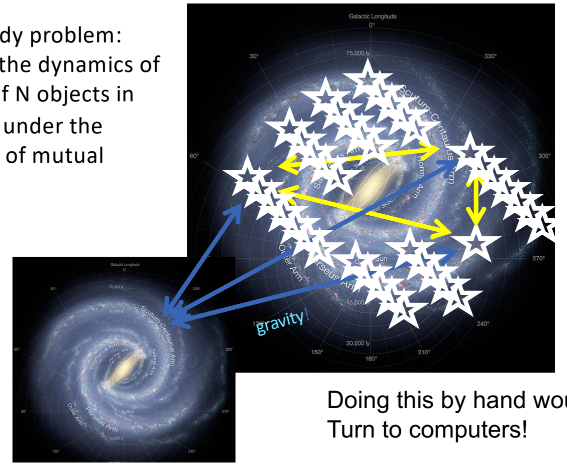
Simulating a Galaxy Collision

The N-body problem: solve for the dynamics of a group of N objects in 3D space under the influence of mutual gravity.



Doing this by hand would suck!
Turn to computers!

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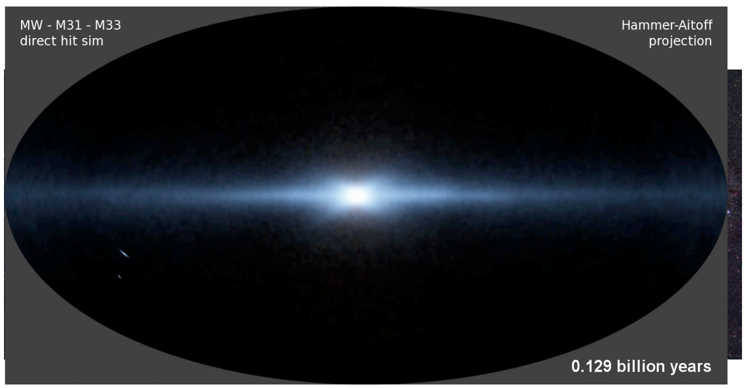
How might the night sky change?



Credit: Besla, Frank Summers

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Q: What are the Future Prospects for Astronomy in 6 Billion Years?

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