The Milky Way rotation curve and its accretion history from Gaia DR3: consequences on its mass determination

By François Hammer

LIRA

Observatoire de Paris | PSL

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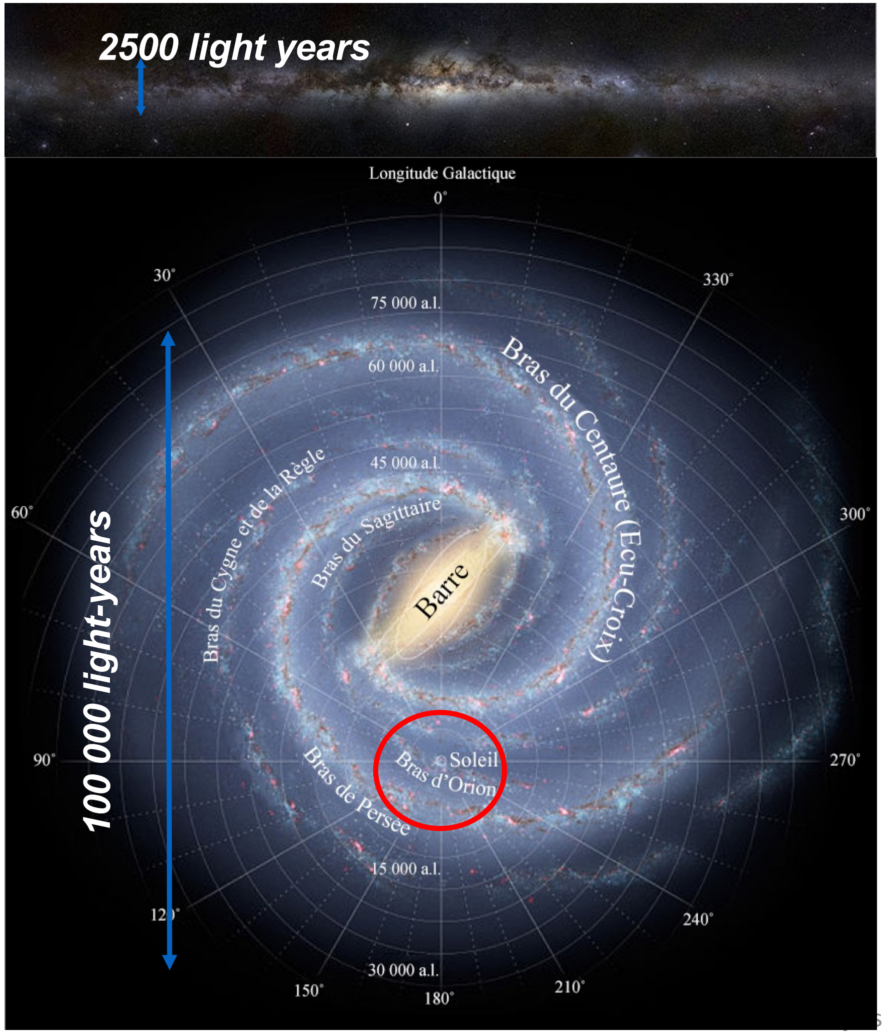
1- Context: Milky Way rotation curve and *Gaia*

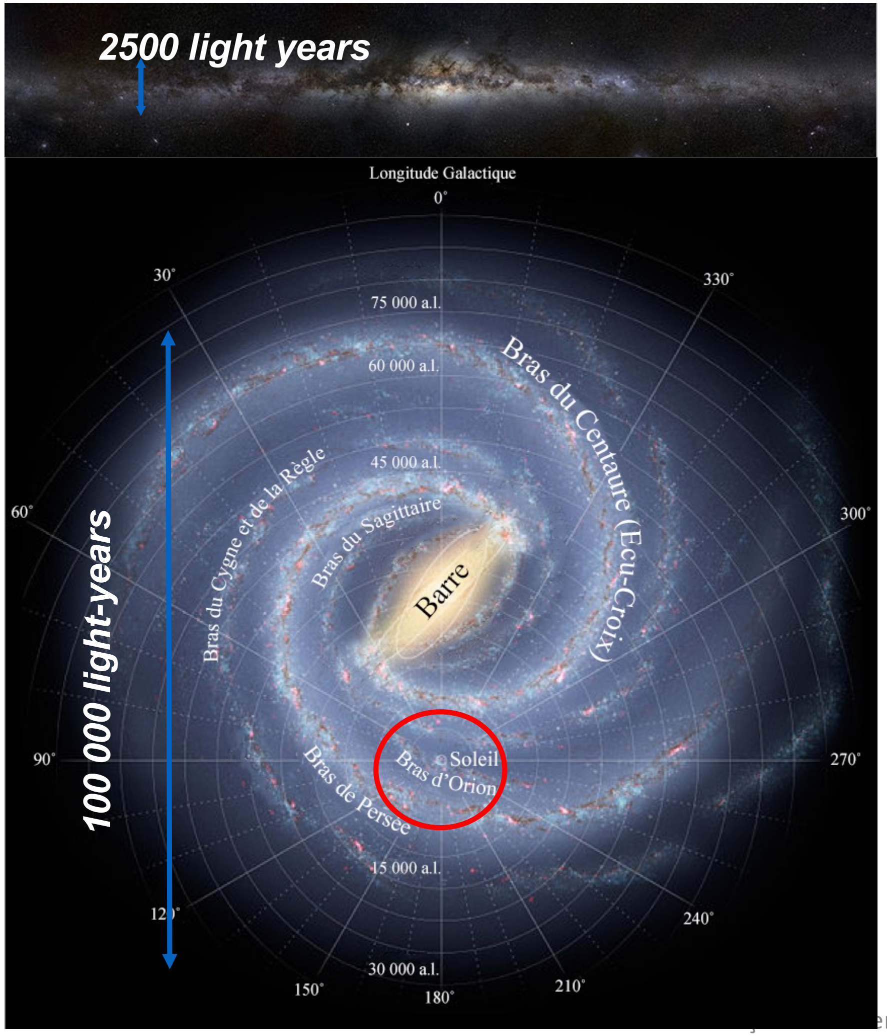
Milky Way rotating disk



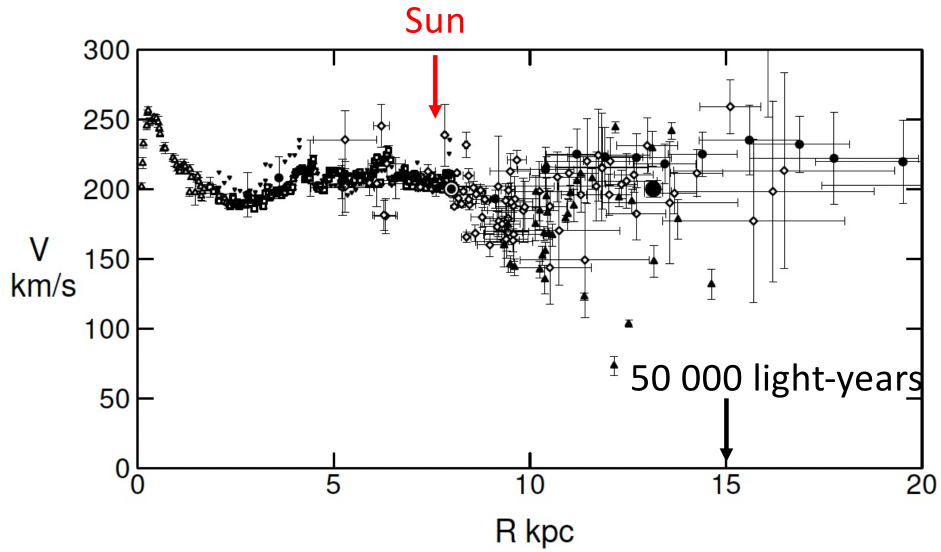
BEFORE Gaia:

- Rotation curve represents rotational velocities against galactocentric radii;
- We are part of the Milky Way disk;
- Rotational motions of disk stars are mostly in the sky plane and were difficult to detect, **before Gaia**;
- Rotation curve of the Milky Way was the less accurate among other spiral galaxies.

Milky Way rotation curve



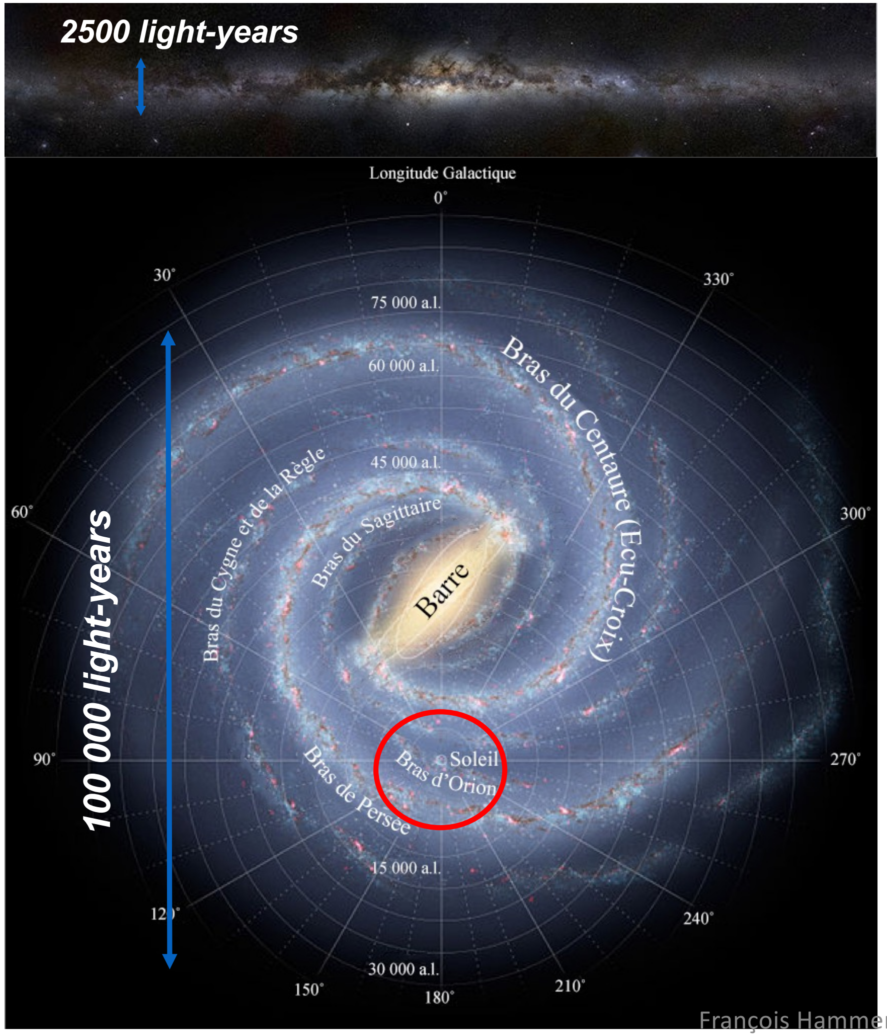
BEFORE Gaia:



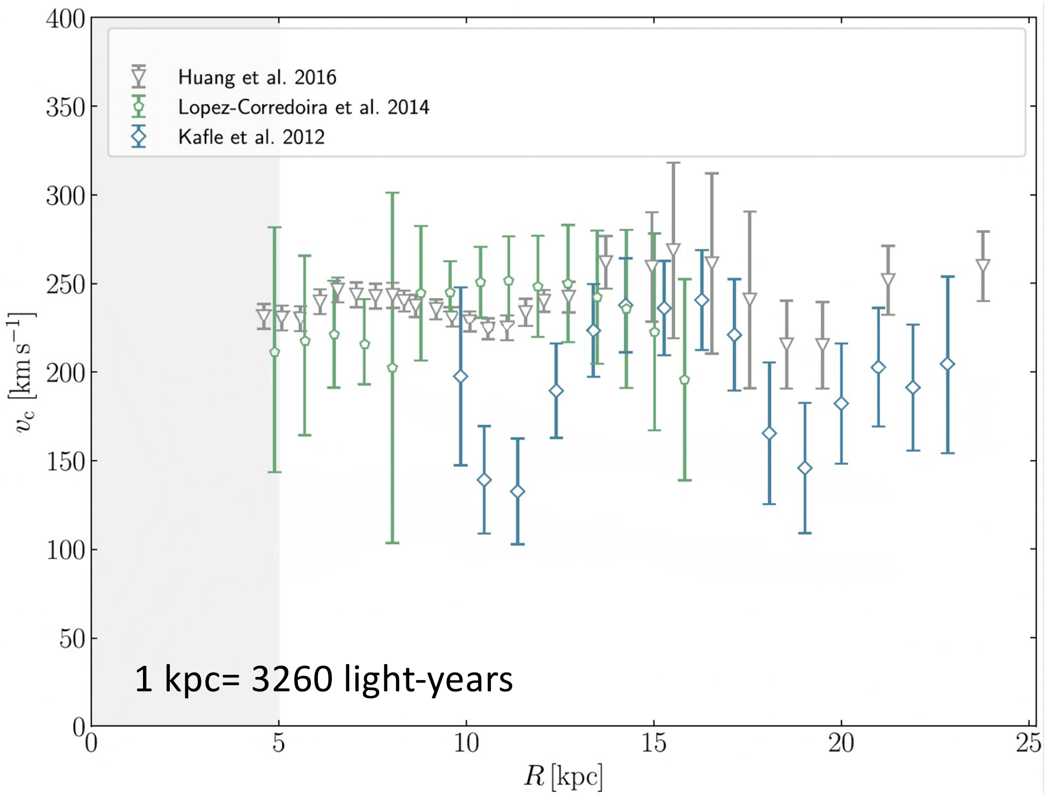
1 kpc= 3260 light-years

« *The crudeness of the fitting in the outer Galaxy, particularly at R > 10 kpc, is mainly due to the large scatter of the observed data*» Y. Sofue 2009, PASJ, 61, 227

Milky Way rotation curve



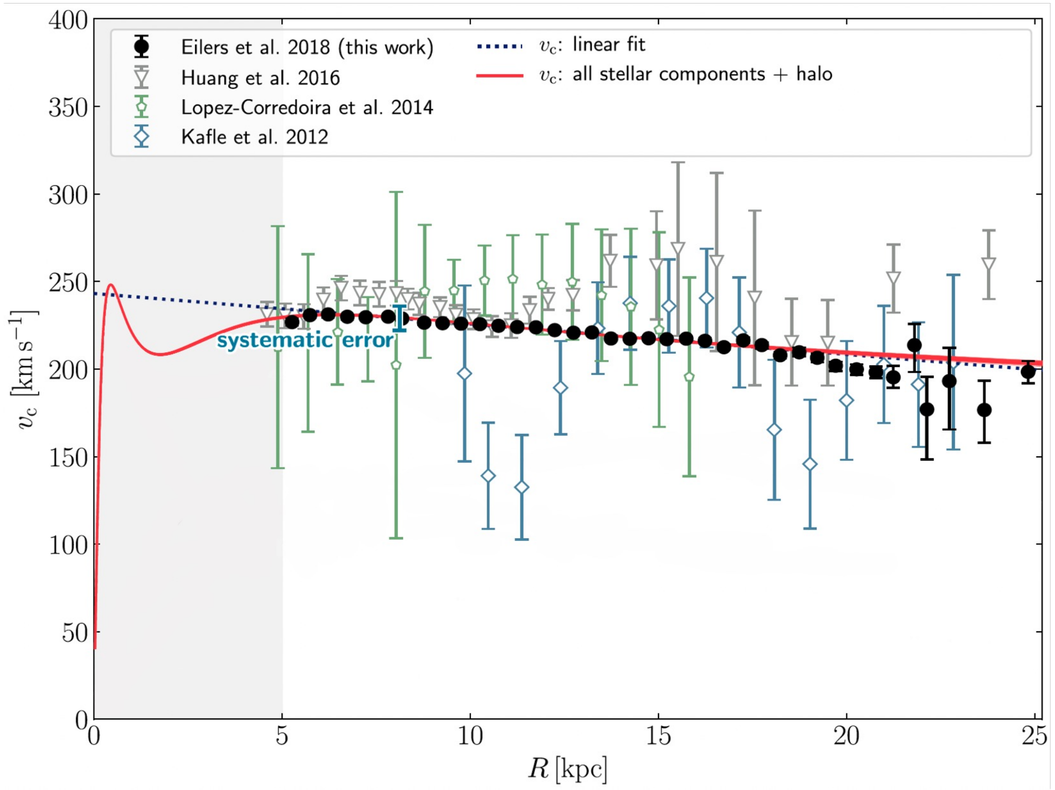
JUST BEFORE Gaia:



First Gaia revolution (DR2)

With Gaia 2nd data release (DR2)

- Most of the rotating star motions are in the sky plane and can be only measured by Gaia proper motions;
- In 2019, first paper by Christina Eilers et al. with Gaia DR2, and the Milky way rotation curve became the most accurate among those of all galaxies !
- Based on 23 000 red giant stars;
- Accuracy has increased by factor 10 to 100;
- A slightly declining rotation curve: « no evidence for bumps» Christina Eilers.



Gaia: unique measurements in physics

- With *Gaia* one may know 3D position and 3D velocity, which combination (phase-space diagram) is fundamental in all fields of physics;

- This allows to know stellar orbits, and then star’s past and future location;

- If a disk star is at equilibrium with the Galactic gravitational potential, one may derive the Galactic mass encircled by its circular orbit.

From *Gaia* DR2 to DR3

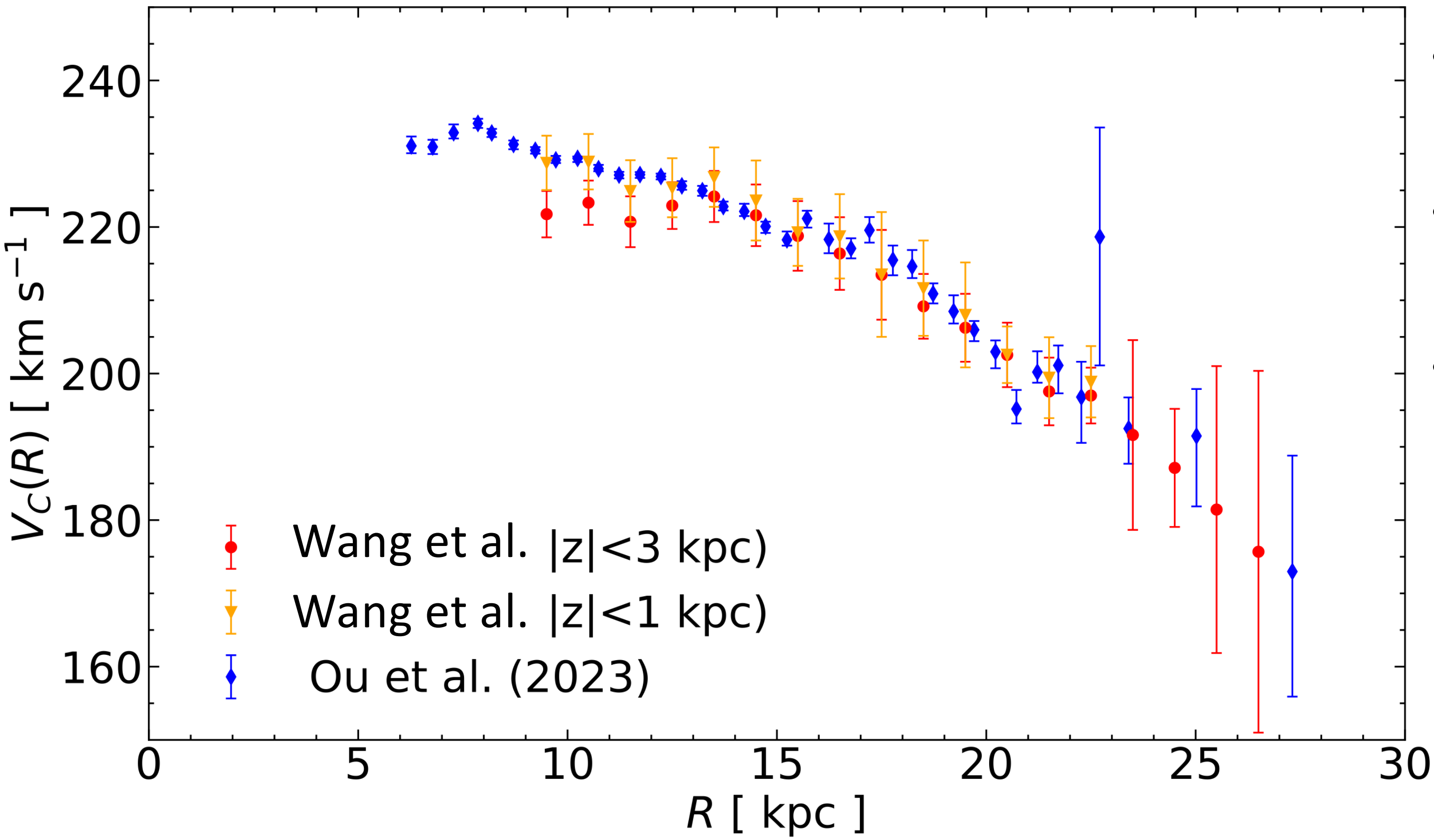
- The number of stars that have combined radial velocities & proper motions (3D): increases from 7 224 631 to 33 812 183
- Proper motion uncertainty is divided by ~ 2
- Parallax uncertainty is divided by ~ 1.3

Two rotation curve measurements based on *Gaia* DR3:

Wang et al. (2023): full *Gaia* DR3 sample (1.8 million stars)
Distance from *Gaia* parallaxes
Lucy's Inversion Method (LIM)

Ou et al. (2023): 33 342 luminous red giant branch (RGB) stars
Distance from spectrophotometric parallaxes

Two rotation curve studies using *Gaia* DR3 :



- Similar rotation curves at the outskirts;
- However, both lack systematic error analyses;
- It needs to evaluate the uncertainties related to the Jeans equation, which include the distribution function of stars and the equilibrium conditions

The Gaia DR3 rotation curve of the Milky Way : full analysis of systematic uncertainties (Jiao et al. 2023)

- Assumption of equilibrium: Jean equation;
- Difficulty to know the distribution function of stars especially in the outer disk;
- Uncertainties on radial and azimuthal velocities;
- Effects due to the disk warping and flaring.

➔ To account for these effects, we have divided the star samples into two parts as well as tested uncertainties from the Jeans equation, including the distribution function of stars

The Milky Way rotation curve with Gaia DR3

Yongjun Jiao (3rd-year Ph.D. student at Paris Observatory)
François Hammer (Paris Observatory)
Haifeng Wang (Centro Ricerche Enrico Fermi, Italy)
Jianling Wang (National Astronomical Observatories, Chinese Academy of Sciences)
Philippe Amram (Laboratoire d'Astrophysique de Marseille)
Laurent Chemin (Instituo de Astrofisica, Universidad Andres Bello, Chile)
Yanbin Yang (Paris Observatory)

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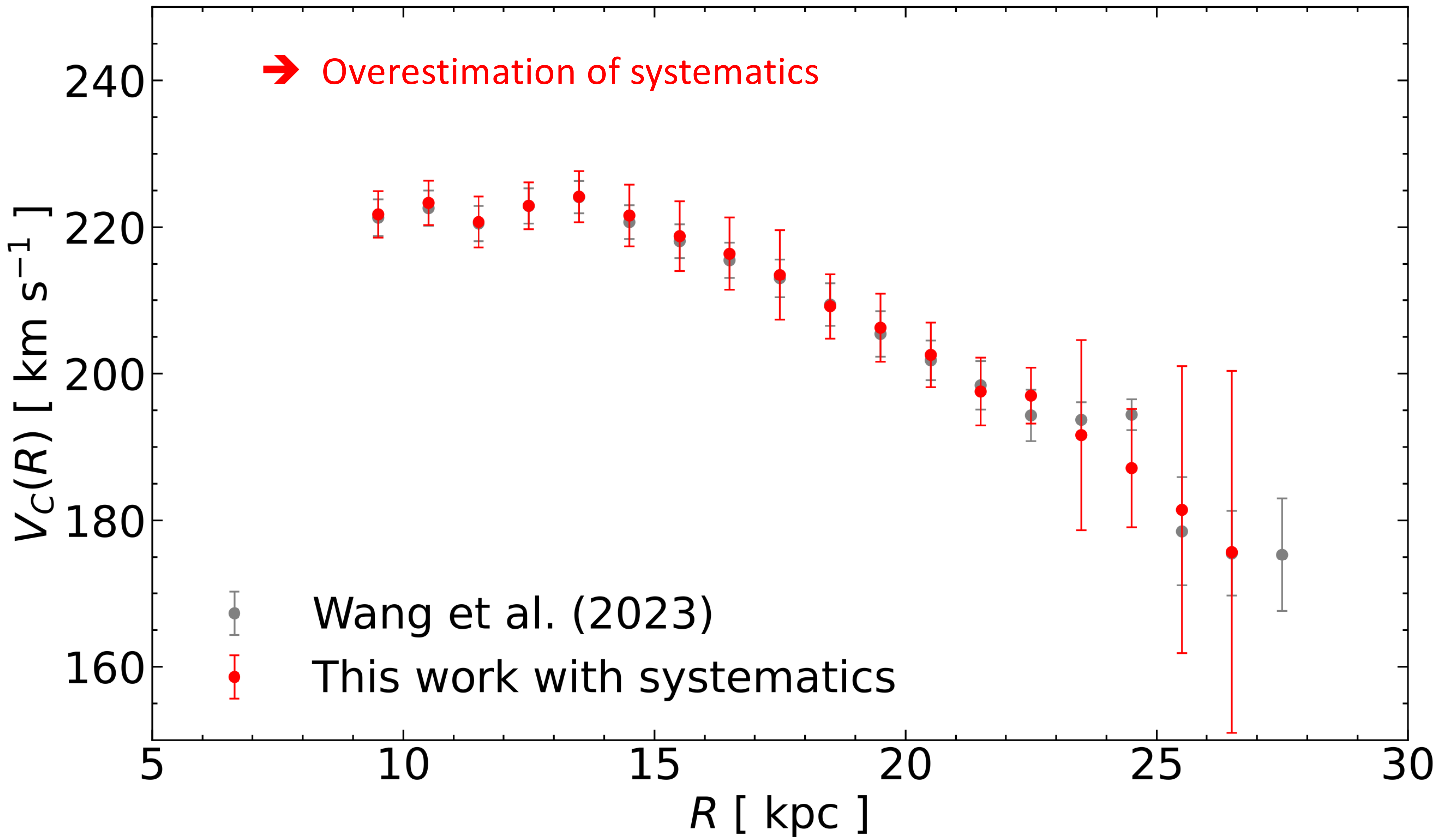
arXiv:2309.00048

Establishing the Gaia DR3 Milky Way rotation curve

Comparison of Jiao et al. (2023, this work) and previous measurements without systematics by Wang et al. (2023)

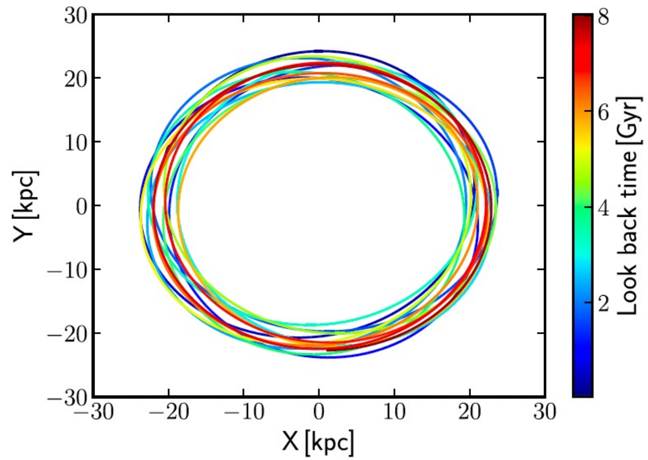


The Milky Way disk is relatively well at equilibrium!

Its last major merger occurred **9-10 billion years ago** (Gaia-Sausage-Enceladus, GSE, Haywood et al. 2018, Belokurov et al 2018), while for most spiral galaxies it occurred, on average, **6 billion years ago** (Hammer et al. 2009; Hopkins et al. 2010).

- Dynamical equilibrium requires that stars have had the time to perform at least 3-4 orbits after the last major merger event (GSE);
- The outer MW disk (> 20 kpc) is at equilibrium: stars have circular velocities (radial and azimuthal velocities are found very small by Gaia DR3) and they have performed at least 6 orbits at 26.5 kpc;
- The warp and flare result from ancient interactions.

238 among the 241 outer disk stars have circular orbits



2^{nd} Gaia revolution (DR3)

2- A small dynamical mass for the Milky Way

Method to derive Milky Way mass: adopted modeling

Baryonic model (Iocco et al. 2015, Jiao et al. 2023, Ou et al. 2024):

$$M_{\mathrm{disk}} = 4.0 \times 10^{10} M_{\odot}$$
$$M_{\mathrm{bulge}} = 1.95 \times 10^{10} M_{\odot}$$
$$M_{\mathrm{gas}} = 9.5 \times 10^{9} M_{\odot}$$
$$M_{\mathrm{dust}} = 7.02 \times 10^{7} M_{\odot}$$

Dark matter model:

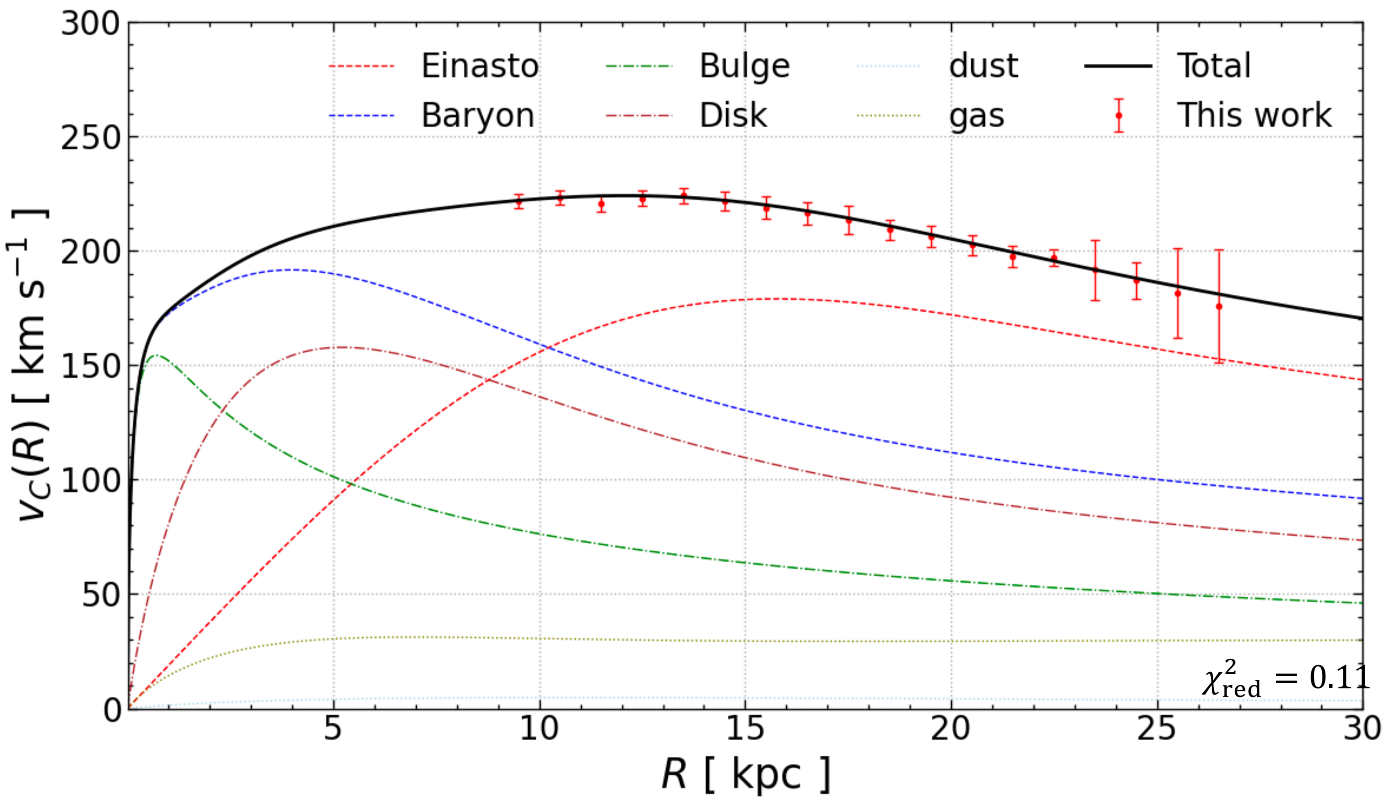
Einasto profile (Einasto 1965; Retana-Montenegro et al. 2012) :

$$\rho(r) = \rho_0 \exp\left[-\left(\frac{r}{h}\right)^{1/n}\right]$$

ρ_0: central density
n: Einasto index
h: scale length of halo (dark) matter

We do not consider the NFW (Navarro et al. 1997) profile because it cannot fit the significant declining rotation curve. (Jiao et al. 2021, Sylos Labini et al. 2023, Ou et al. 2023).

Milky Way mass model to fit the rotation curve



By applying Markov Chain Monte Carlo (MCMC) method, we estimated the MW dynamical mass: $M_{\rm dyn} = 2.06^{+0.24}_{-0.13} \times 10^{11} M_\odot$ within $R = 121.03^{+1.80}_{-1.23}$ kpc.

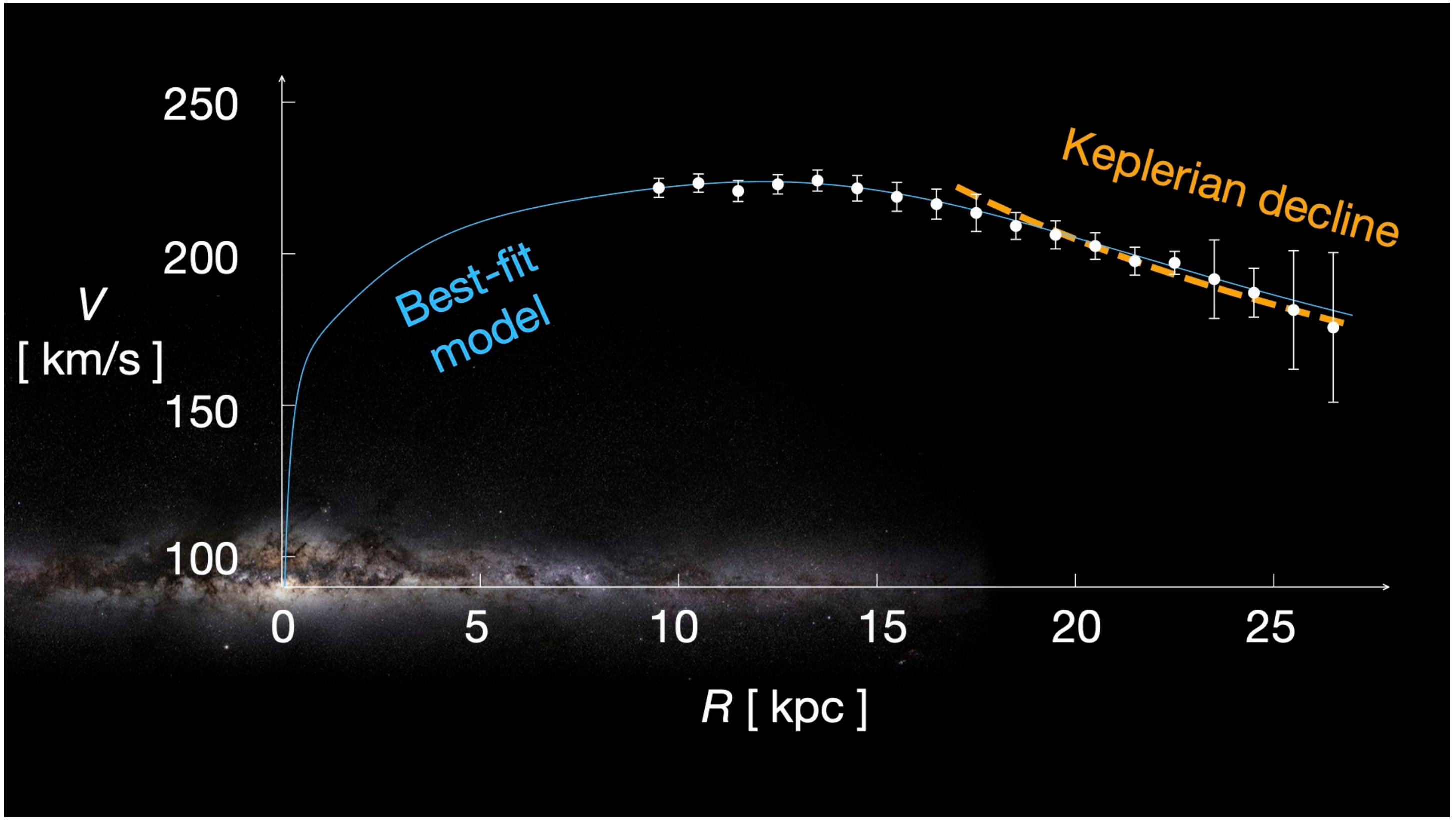
Much smaller than formerly thought! To be followed

3- Detection of a Keplerian decline of the Milky Way rotation curve

A Keplerian decline in the MW rotation curve

- We find a sharply decreasing MW RC, the decrease in velocity between 19.5 and 26.5 kpc is approximately 30 km/s.

- We identify a **Keplerian decline** ($V \sim R^{-1/2}$) , starting at about 19 kpc, very near to the edge of the optical disk, at 17 kpc.



The Milky Way rotation curve (Jiao et al. 2023)

The flat rotation curves of external spiral galaxies

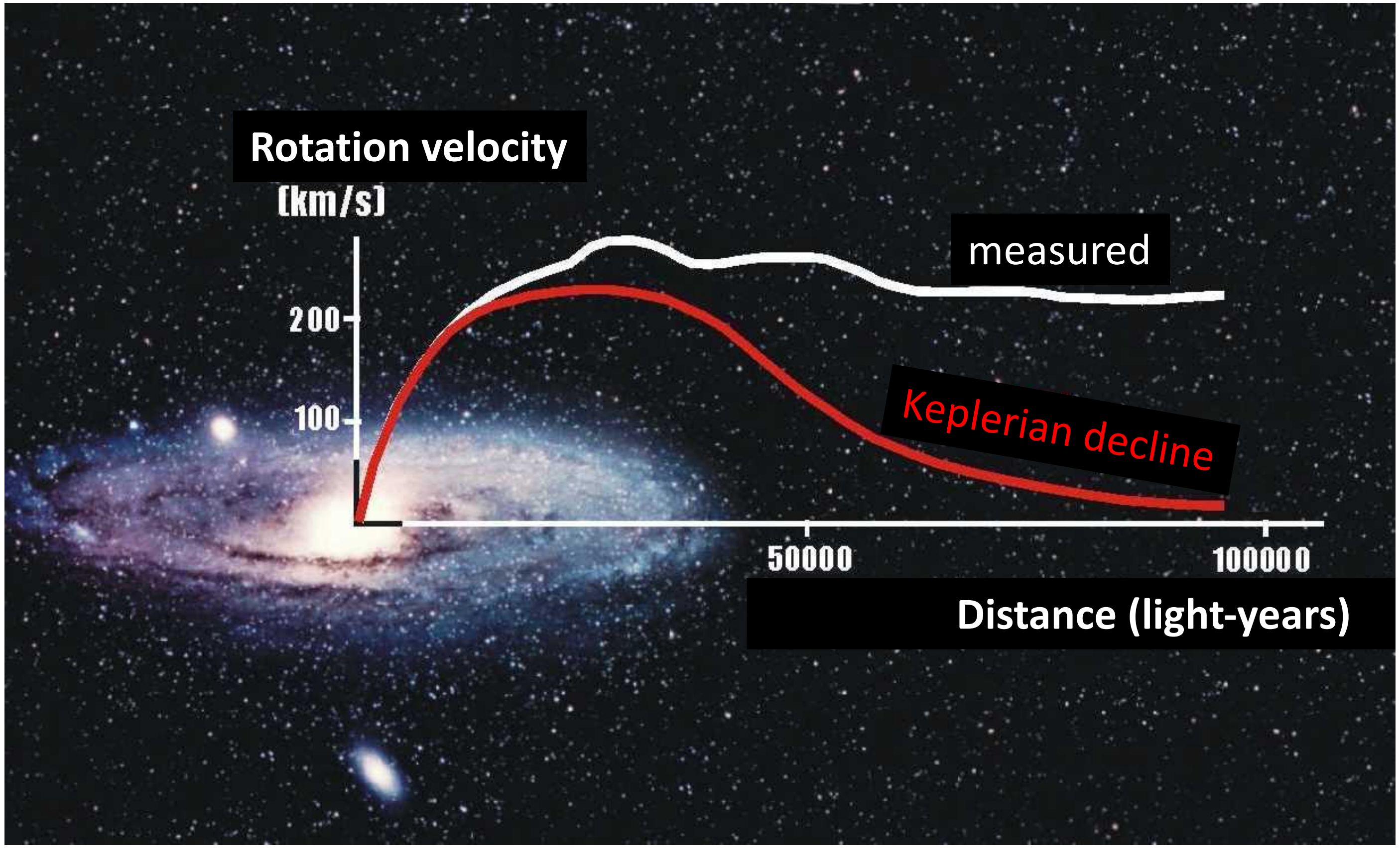
Lundmark (1925) was the first to identify the flat rotation curves of disc galaxies;

Babcock (1939, then Mayall 1951) reported that the RC of M31 shows no decrease up to 20 kpc from optical spectroscopy;

Rubin et al. (1978) and Bosma (1978, HI) found that several spiral galaxies, including Andromeda (M31) have flat rotation curves.

The first proof of dark matter within large halos surrounding galactic disks.

Rotation curve of M31



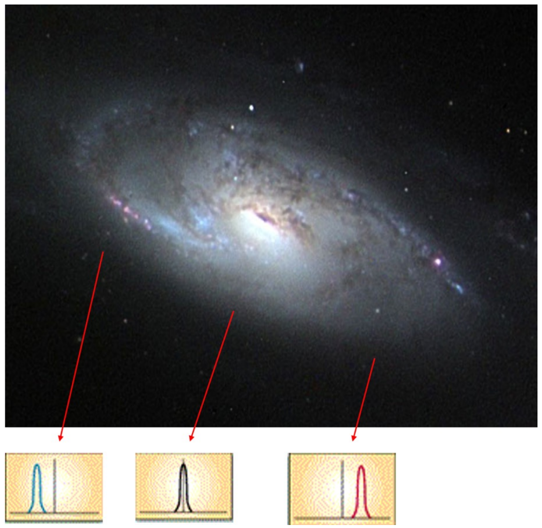
Why the Milky Way differs from other spiral galaxies?

A methodological problem?

- *Gaia* provides 3D spatial + 3D velocity coordinates (6D phase diagram) for MW disk stars, constraining, e.g., orbit circularity and stability;

- For external galaxies, the best RCs are from the neutral gas (HI), i.e., based on only 2 spatial and one (los) velocity coordinates (3D phase diagram). We can't constrain neither the orbits nor their stability;

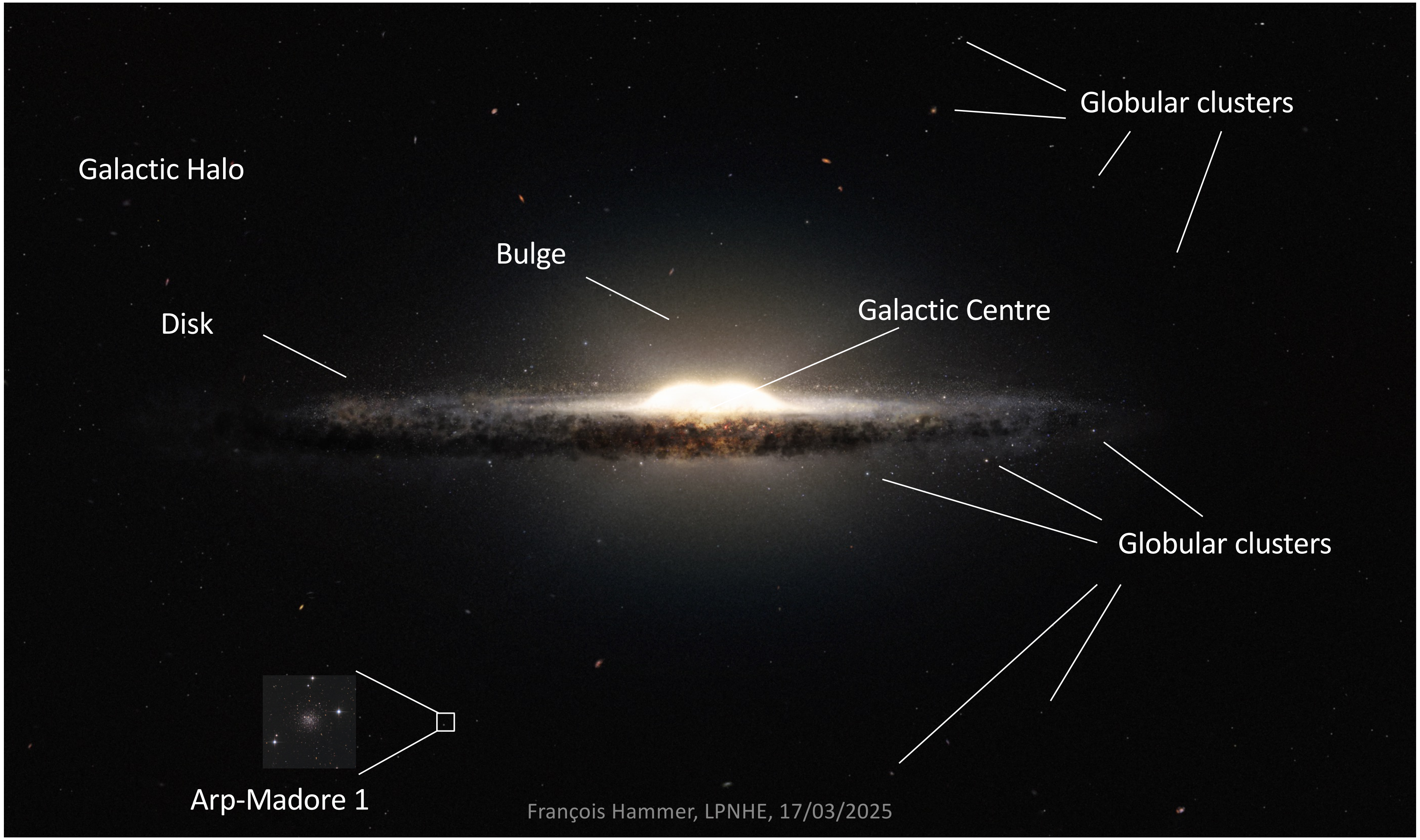
- Many other spiral galaxies have encounter more recent major mergers in their past history, which questions equilibrium conditions at their disk outskirts.



4- Why the Milky Way mass is revised downwards?

Why the Milky Way mass was believed to be large?

Before Gaia, astronomers found other ways to estimate the mass: **globular clusters or even dwarf galaxies**

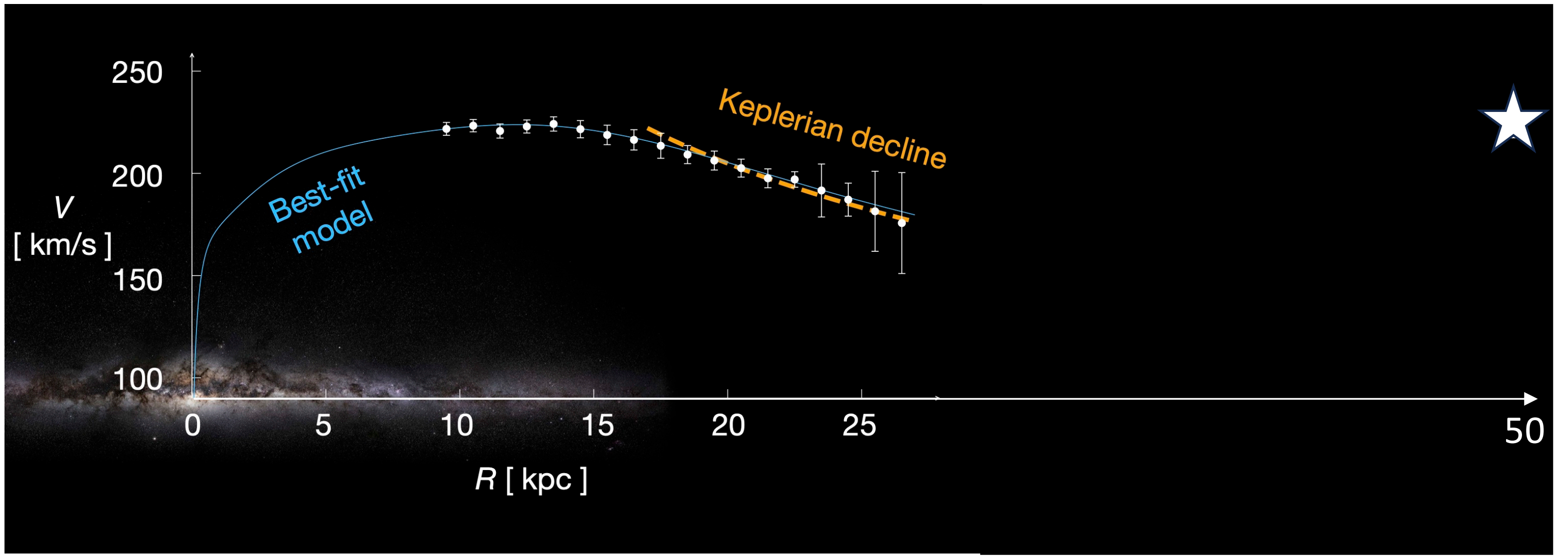


Why other methods predict a more massive Milky Way?

MW disk stars are sufficiently at dynamical equilibrium to allow mass determination.

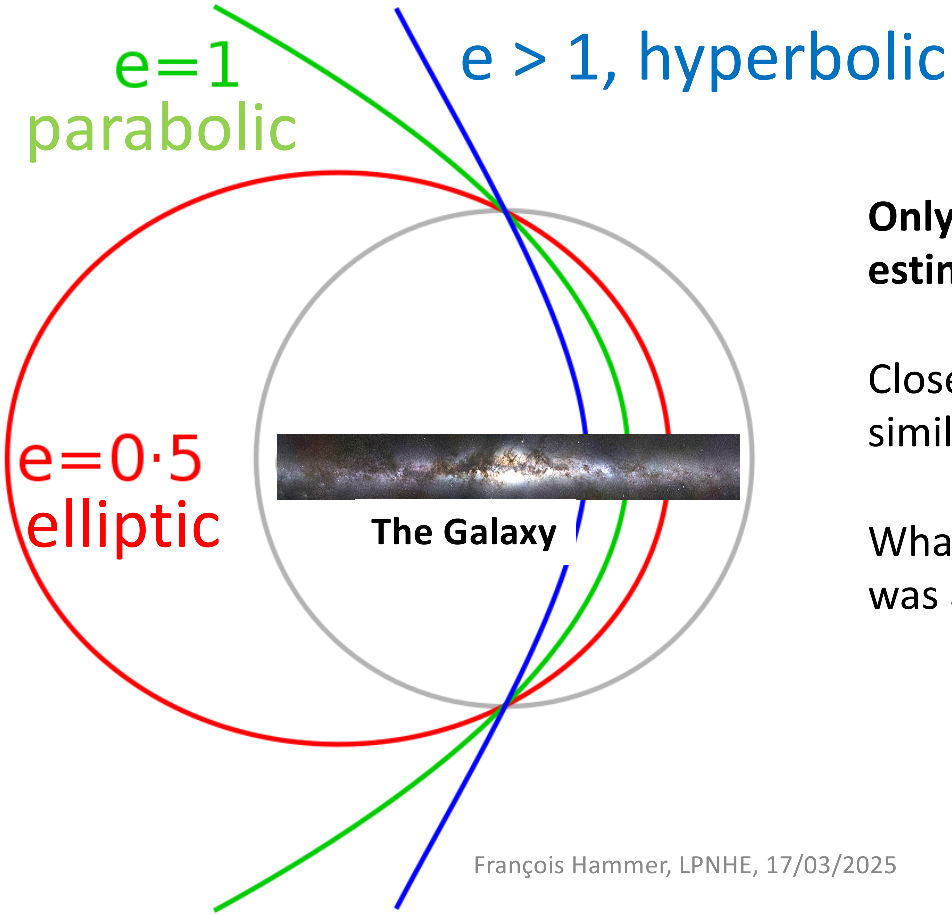
Other methods : are globular clusters and dwarf galaxies at equilibrium with the MW potential?

- <u>Example:</u> the LMC is at first passage (Kayavahill et al. 2007, 2013) from its large orbital eccentricity (e ~ 1.2), and assuming its equilibrium with the MW potential does not account for LMC initial velocity;
- In such a case, its 3D velocity (V_{3D}=321 +/- 24 km/s) has to be smaller than the MW escape velocity, leading to a circular velocity close to $V_{3D}/2^{1/2}$ =226 +/-17 km/s, i.e., a larger value at 50 kpc than at 15-26 kpc!



LMC assumed at equibrium

Can we use globular clusters and dwarf galaxies to constrain the Galactic dynamical mass?



Only circular & elliptical orbits can be used for estimating the mass of the Milky Way

Closer to us: Oumuamua eccentricity (e=1.2) is similar to that of the LMC

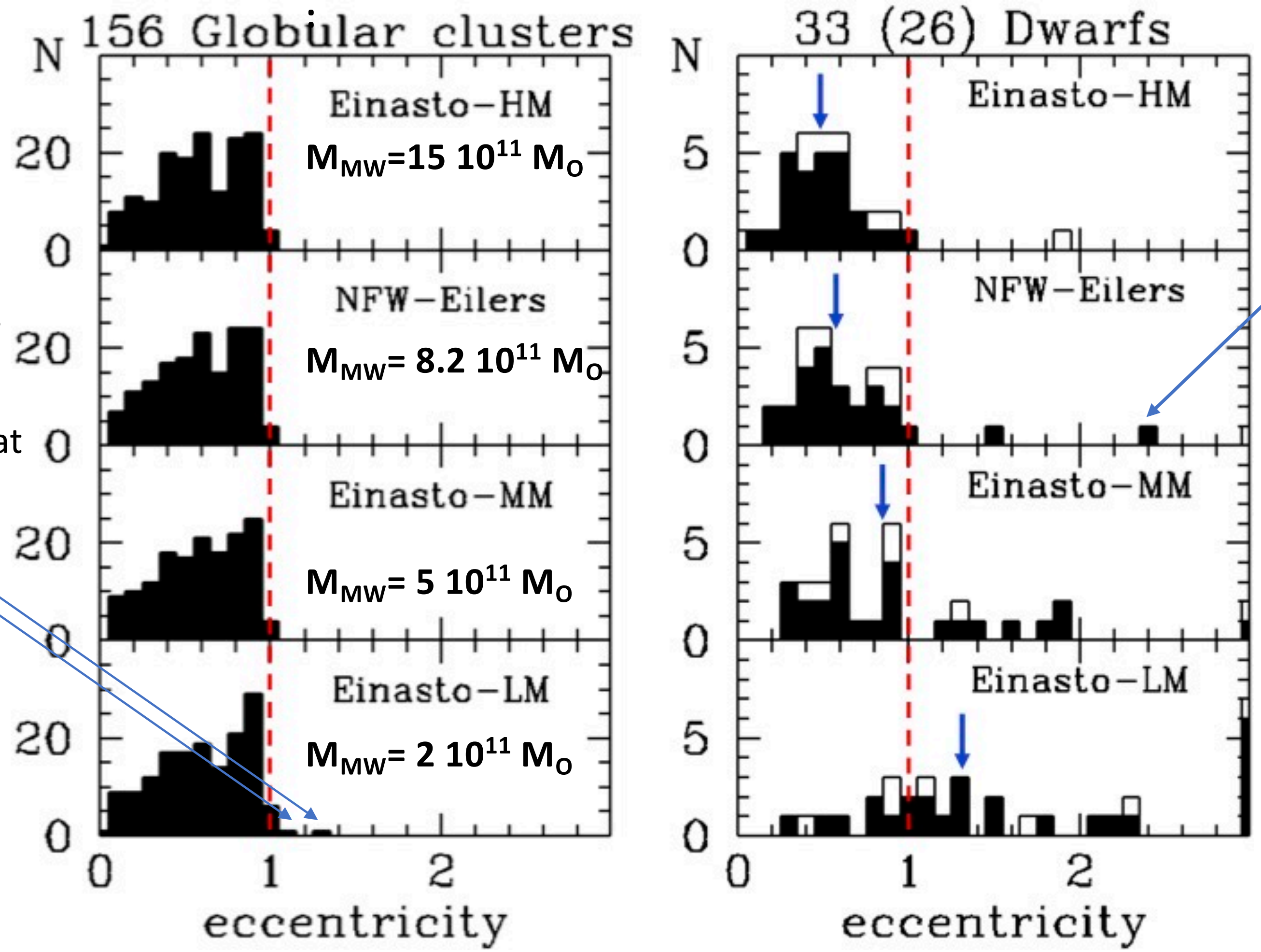
What would be the Sun's mass if Oumuamua was assumed to be at equilibrium?

Can we use globular clusters and dwarf galaxies to constrain the Galactic dynamical mass?

Counting Eridanus and Pyxis as satellites implies M ≥ **5 10^{11} M_O**

However, they could be at first infall!

Pyxis, Eridanus



Counting Leo I as satellites implies M_{MW} ≥ **1.5 10^{12} M_O**

However, Leo I likely escapes the Galaxy!

Hammer et al. 2023

Why other methods predict a more massive Milky Way?

Galactic disk stars are rotating in circular orbits providing a mass of 2.06 10^{11} $M_{\odot}$ from Gaia DR3

Other methods should demonstrate that other probes are at equilibrium with the MW potential**:**

- *Gaia* motions of 154 (among 156) globular clusters are consistent with the MW RC mass (2.06 10^{11} $M_{\odot}$);
- However, if considered at equilibrium, most dwarf galaxies would lead to much larger mass estimates for the Milky Way (10^{12} $M_{\odot}$ to 2 10^{12} $M_{\odot}$ or even more).

Are dwarf galaxy orbits at equilibrium with the MW potential?

4- The Milky Way accretion history revealed by *Gaia*

From *Gaia* DR2 to DR3

- The number of stars that have combined radial velocities & proper motions (3D): increases from 7 224 631 to 33 812 183
- Proper motion uncertainty is divided by ~ 2
- Parallax uncertainty is divided by ~ 1.3

Two papers on dwarf galaxy orbits based on *Gaia* DR3:

Li, Hammer, Babusiaux et al. (2021):

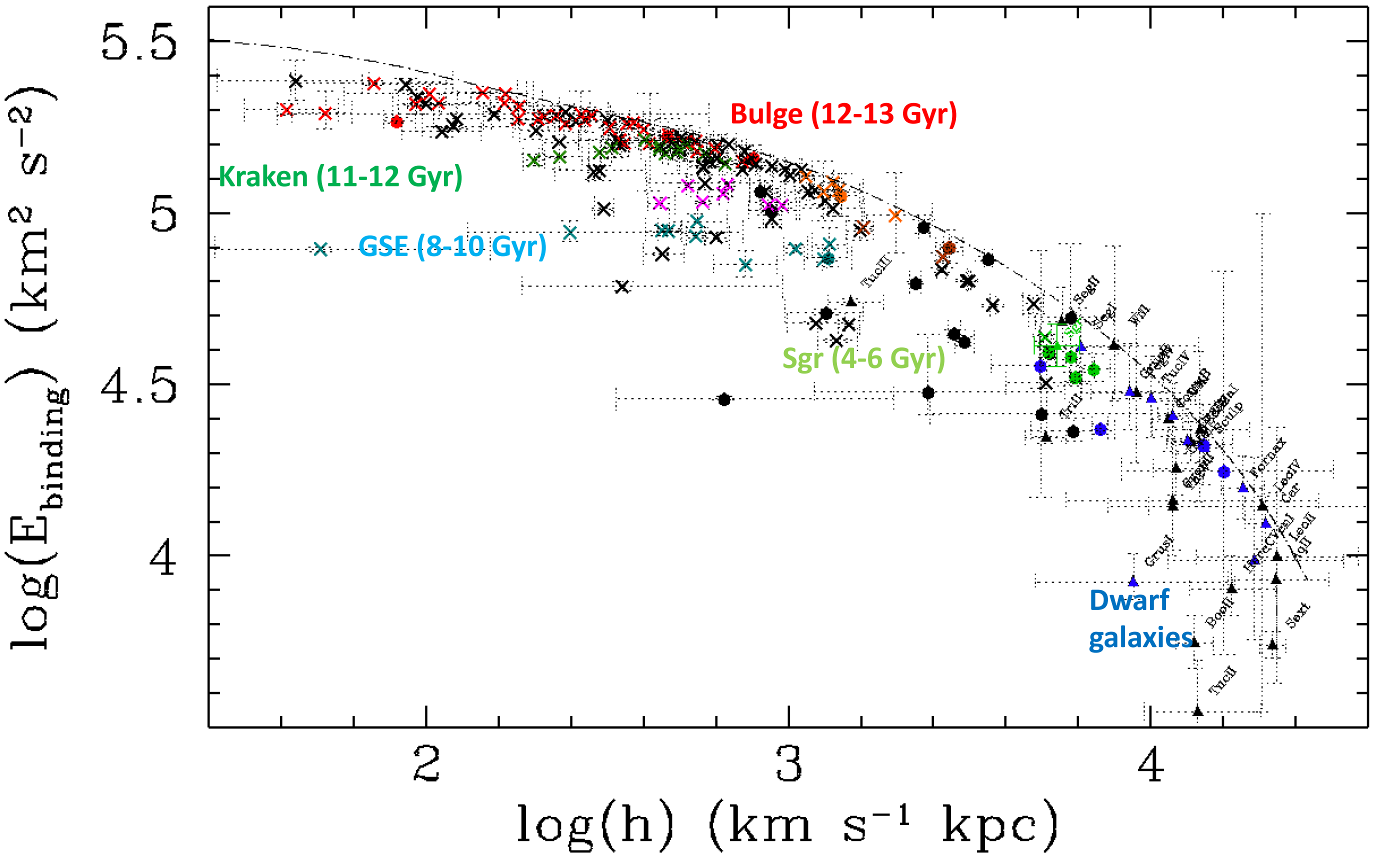
46 dwarf galaxies
full account of Gaia systematics

Battaglia, Taibi, Thomas et al. (2022):

66 dwarf galaxies with reliable measurements
Bayesian method

➔ **Angular momentum and binding energy of dwarf orbits with very good accuracy**

A fundamental relation between binding energy ($E_{binding}$) and total angular momentum (h) for globular clusters and dwarf galaxies from Gaia DR3



Crosses: globular clusters from Malhan et al. 2022; Kruijssen et al. 2019; see also Massari et al. 2019

Triangles: dwarf galaxies from Hammer et al. 2023

The halo accretion history

Prediction of the hierarchical scenario :

- Galaxy mass growth, the most recent newcomers are the lesser bound (Gott, 1975);
- Proben by all cosmological simulations, e.g., Rocha et al. 2012, Boylan-Kolchin et al. 2013.

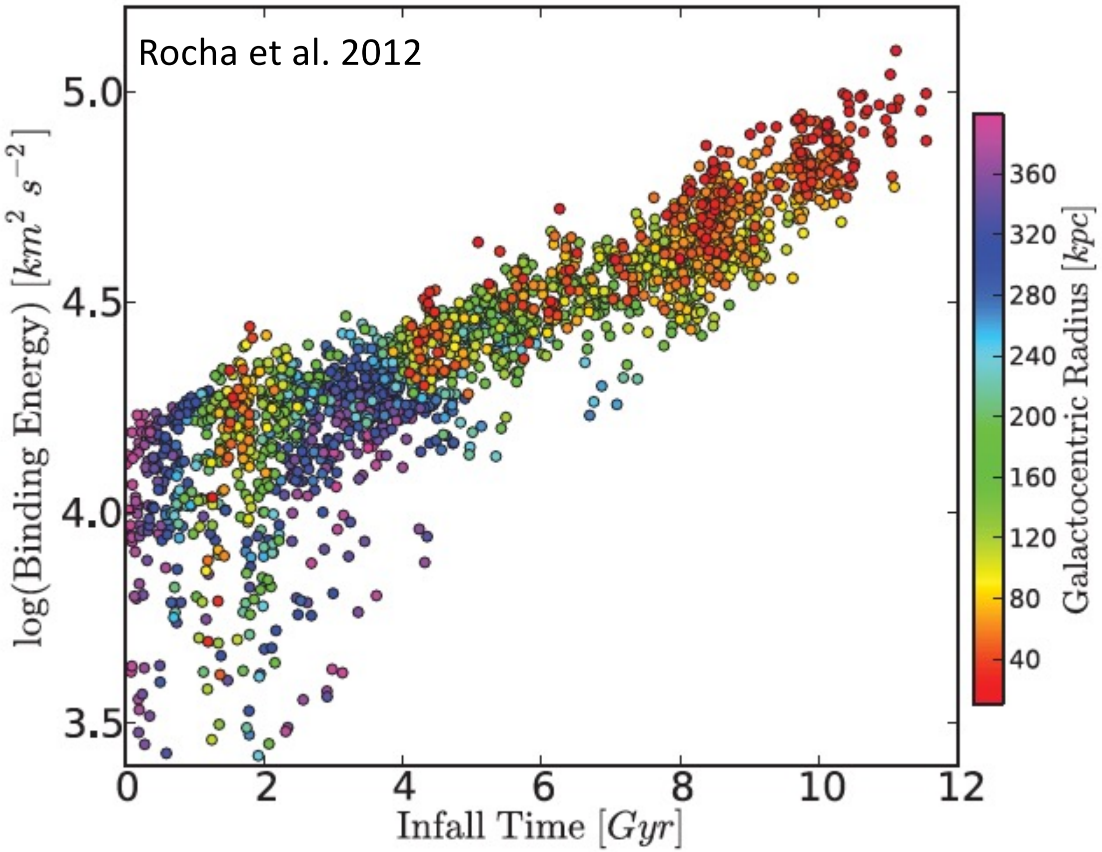
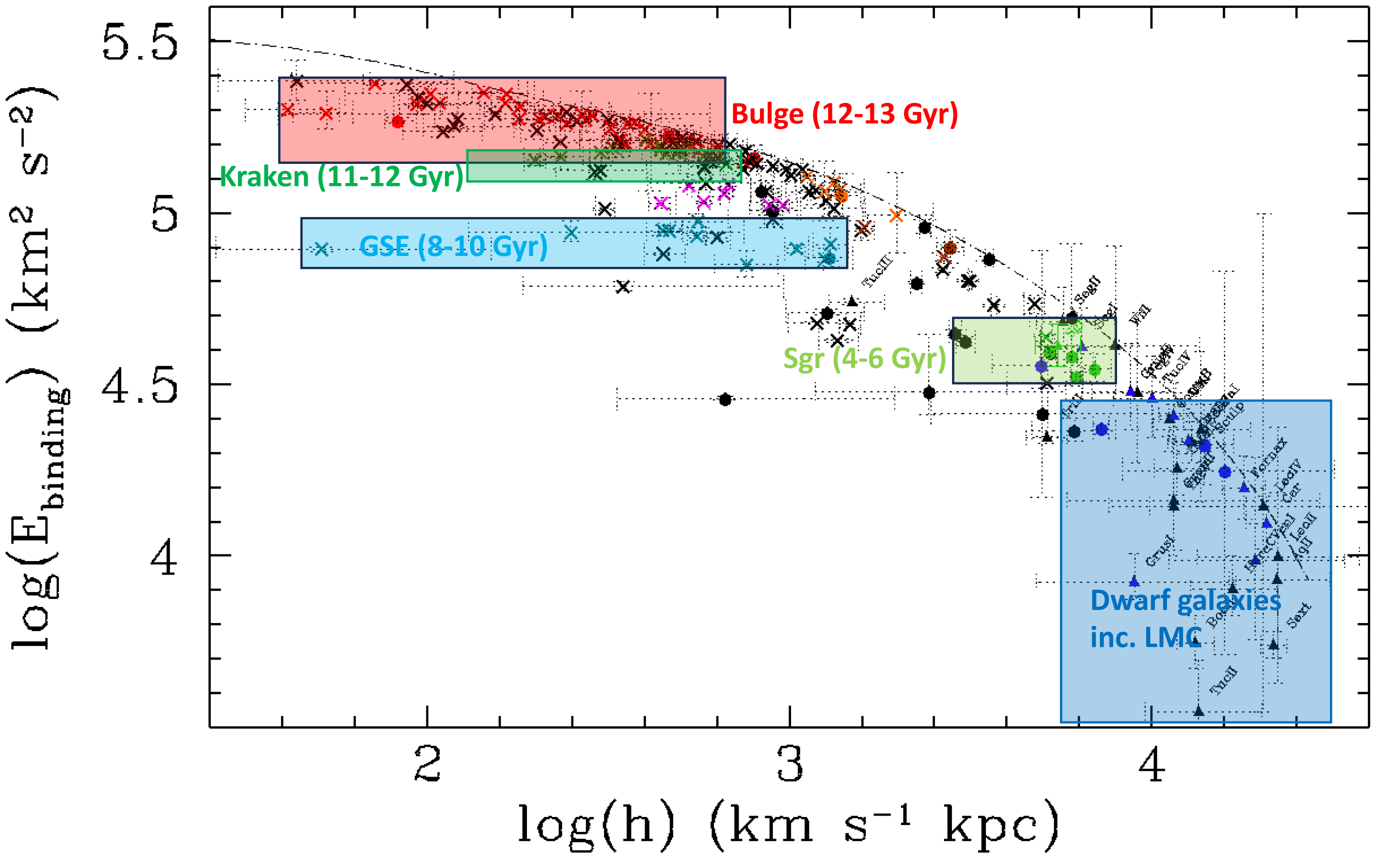


Figure 1. Binding energy versus infall time for the selected sample of VL2 subhaloes at $z = 0$. Colours indicate galactocentric distance. Notice how the least bound subhaloes are the ones accreted most recently and also the only ones with large galactocentric distances.

A fundamental relation between binding energy ($E_{binding}$) and total angular momentum (h) for globular clusters and dwarf galaxies from Gaia DR3

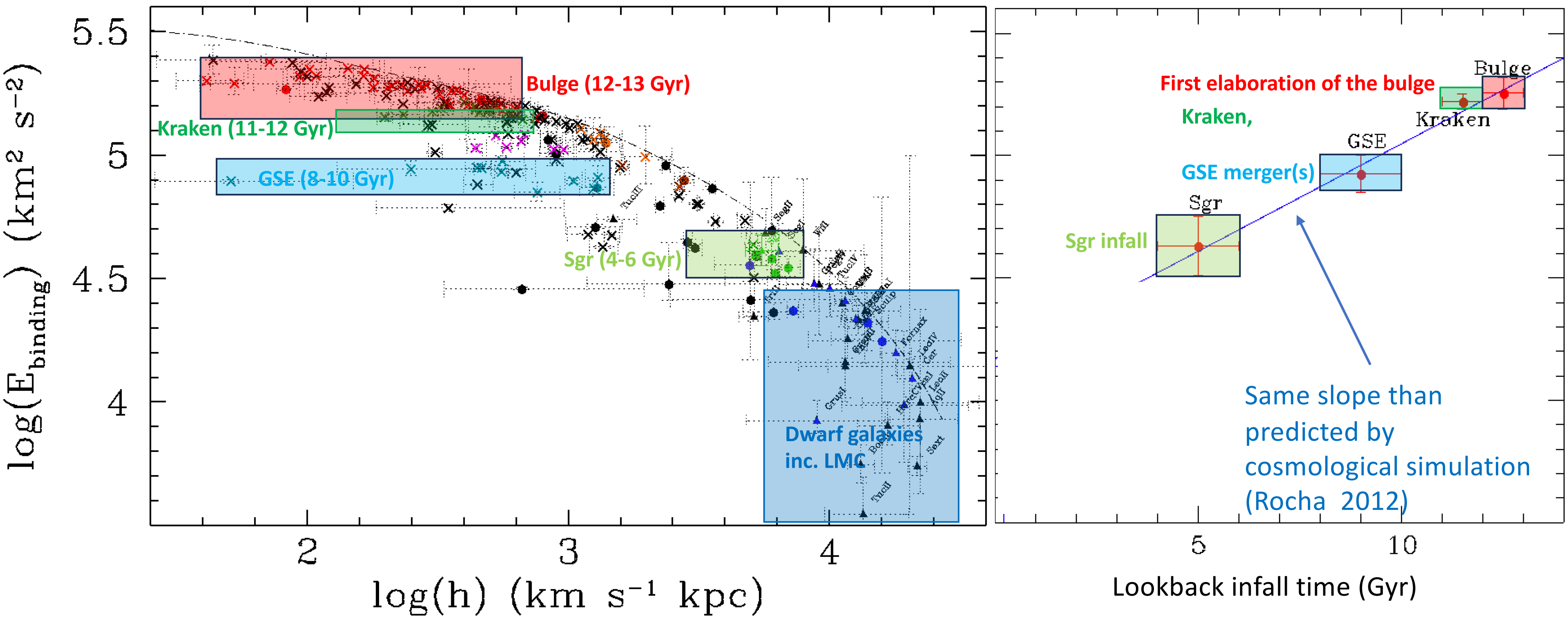


Crosses: globular clusters from Malhan et al. 2022; Kruijssen et al. 2019; see also Massari et al. 2019

Triangles: dwarf galaxies from Hammer et al. 2023

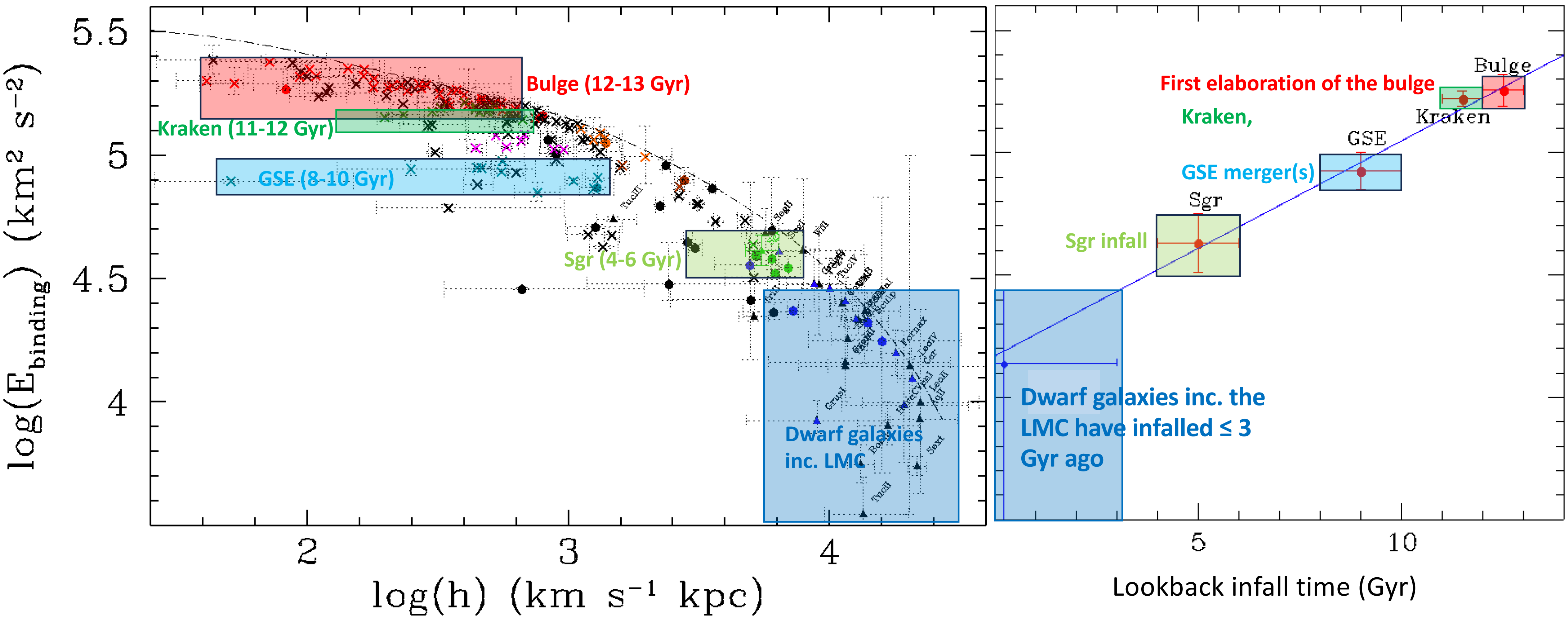
The Milky Way halo accretion history from Gaia DR3

Hammer, Li, Mamon et al. 2023

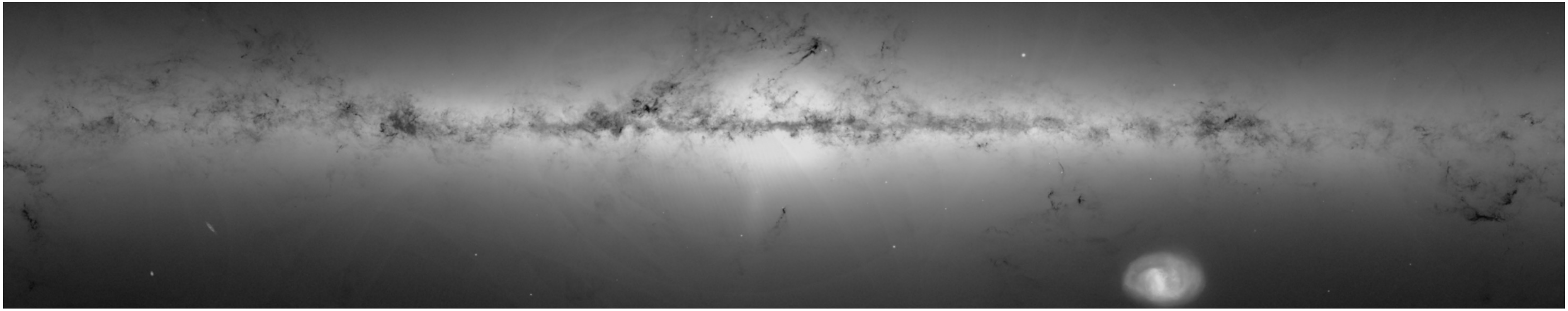


The Milky Way halo accretion history from Gaia DR3

Hammer, Li, Mamon et al. 2023



ESA news



SCIENCE & EXPLORATION

Gaia reveals that most Milky Way companion galaxies are newcomers to our corner of space

Why other methods predict a more massive Milky Way?

Galactic disk stars are rotating in circular orbits providing a mass of 2.06 10^{11} $M_{\odot}$ from Gaia DR3

Other methods should demonstrate that other probes are also at equilibrium with the MW potential**.**

- *Gaia* motions of 154 (among 156) globular clusters are consistent with the MW RC mass (2.06 10^{11} $M_{\odot}$);
- However, if considered at equilibrium, most dwarf galaxies would lead to much larger mass estimates for the Milky Way (10^{12} $M_{\odot}$ to 2 10^{12} $M_{\odot}$ or even more).

As the LMC, dwarf galaxies had no time to perform a single orbit and they can’t be used to estimate the Milky Way mass

Missing dark matter in the Milky Way

- The Milky Way has a quiet merger history since 8-10 Gyr (GSE);
- Its disk is relatively well at equilibrium: warp and flare effects have been tested;

- However, the baryonic matter (stars + neutral gas) represents 60 billion solar mass, almost **one third** of the dynamical mass (206 billion), a fraction much higher than expectations from other galaxies (**about one tenth**), or of the Universe (**about one sixth**).

- Can the outer parts of external galaxy disks be affected by non-equilibrium motions due to relatively recent past mergers?

➔ In course: studies of external galaxies with the best RC to determine if their past histories have influenced their dynamics

5- A new estimate of the M31 dynamical mass and its lack of missing matter

The flat rotation curve of M31

Lundmark (1925) was the first to identify the flat rotation curve of the Andromeda galaxy

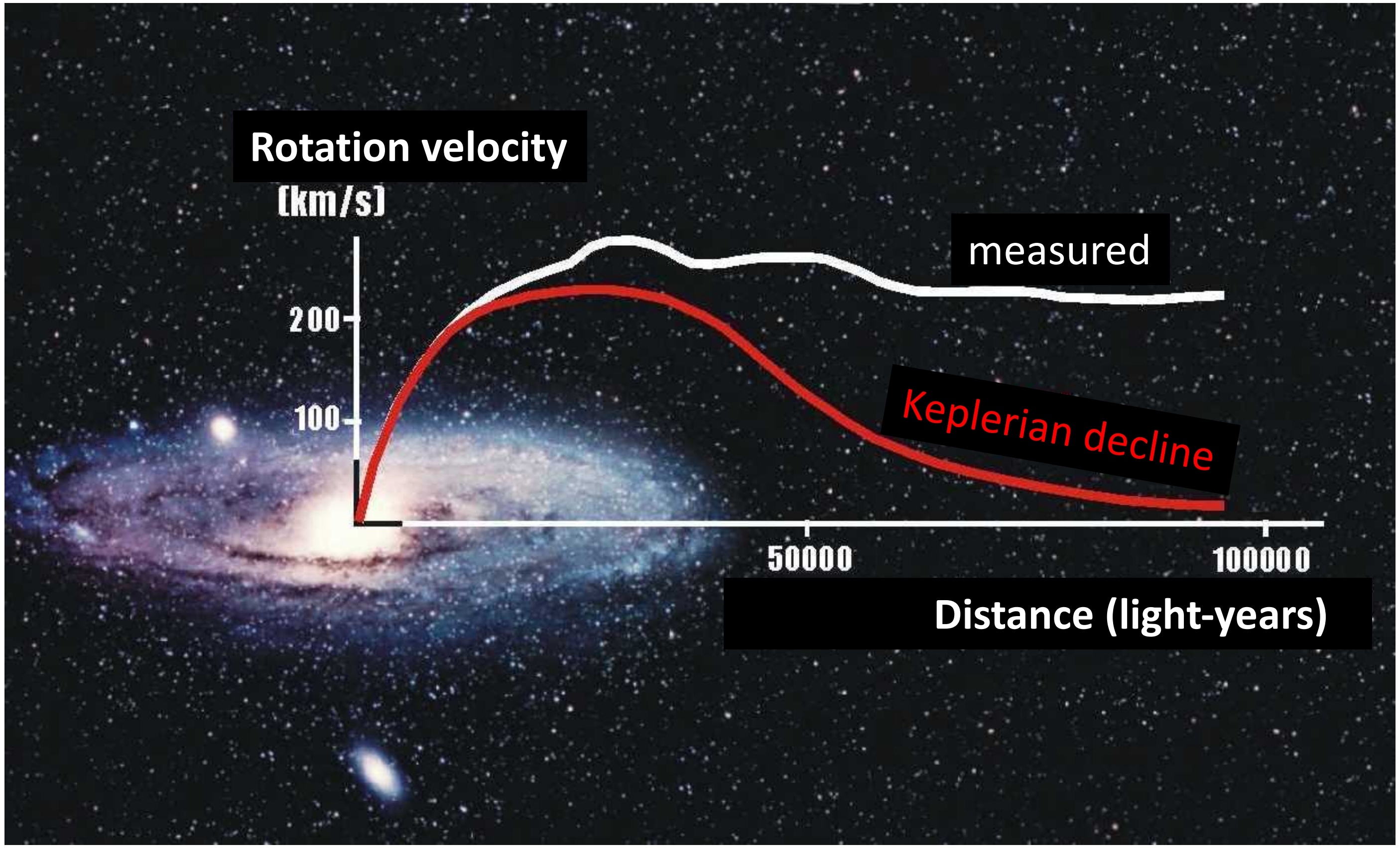
Babcock (1939, then Mayall 1951) reported that the rotation curve of M31 shows no decrease up to 20 kpc from optical spectroscopy.

Rubin et al. (1970) found M31 with a flat **extended** rotation curve (HI and HII).

The first proof of a massive dark matter halo surrounding a galactic disk

IS THAT CORRECT?

Rotation curve of M31



Differences between the Milky Way and M31

They have been longtime considered as twin galaxies!

The Milky Way is an exceptional quiet galaxy because:

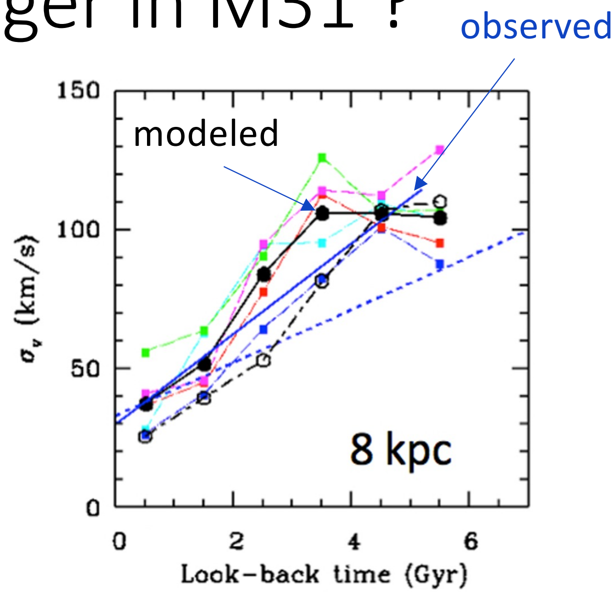
- Its halo is particularly poor and its disk angular momentum (and disk scalelength) is particularly small (Hammer et al. 2007);
- Its last major merger occurred **9-10 Gyr ago** (Gaia-Sausage-Enceladus, GSE, Haywood et al. 2018, Belokurov et al 2018, Helmi et al 2018).

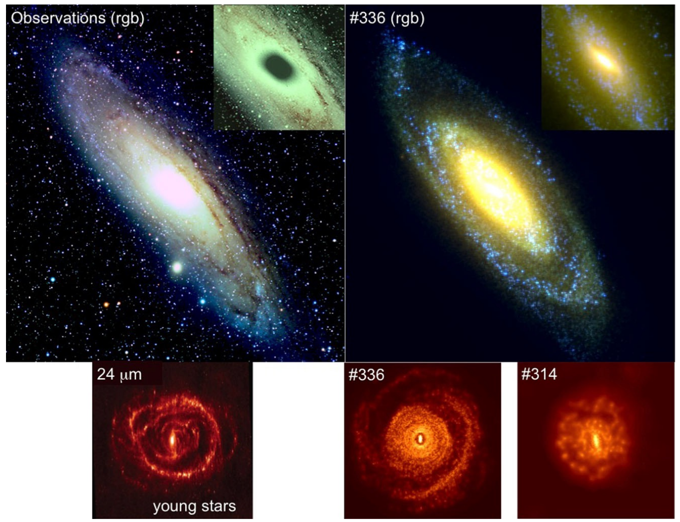
M31 is also exceptional but because it is a very perturbed galaxy :

- Its halo is particularly rich (Ibata et al. 2001, 2014) and its disk angular momentum (and disk scalelength) is particularly large (Hammer et al. 2007);
- Its last major merger occurred recently, **2-3 Gyr ago** (Hammer et al 2018, D'Souza & Bell, 2018).

Why a recent, 2-3 Gyr, major (4:1) merger in M31 ?

- Strong event of star formation in the disk, 2.5 Gyr ago (Williams et al. 2015);
- Very peculiar age-velocity relation (Dorman et al. 2015), e.g., a star like the Sun in M31 doesn't orbit circularly;
- A bar and a stable 10 kpc ring with time (Lewis et al. 2015);
- Complex structure of the Giant stream and shells (Conn et al. 2016, Dey et al. 2023, Tsakonas et al. 2024).





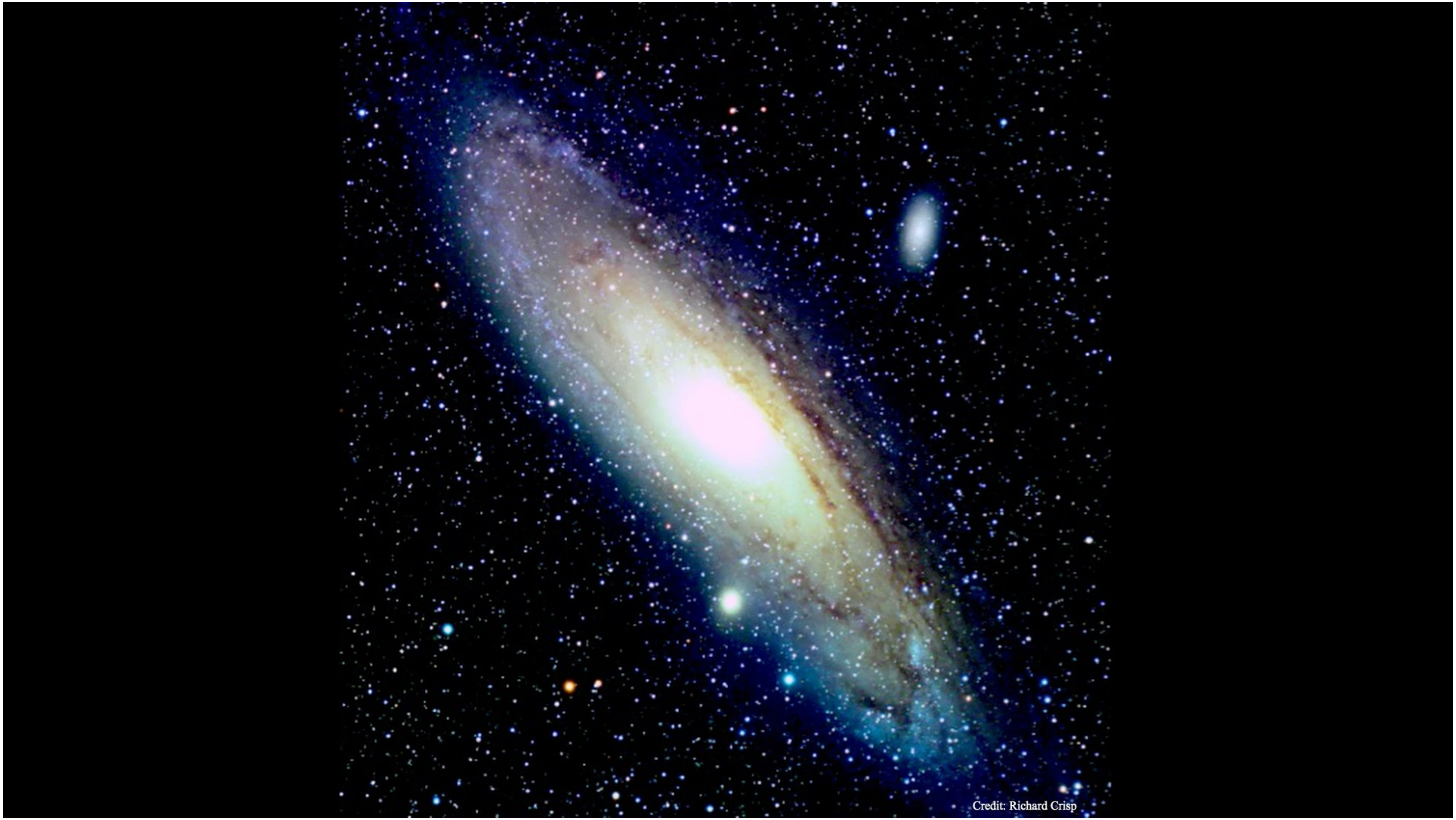

Credit: Richard Crisp

Table 1. Initial and adopted conditions for a major merger model for M31.

Ingredient	Tested range	Comments	Adopted range
Total mass	$8.25 \times 10^{11} M_\odot$	20 per cent of baryons	–
Mass ratio	2–5	To reform $B/T \sim 0.3$	4.0 (3.5–4.25)
f_{gas} Gal1	0.4–0.6	Expected at $z = 1.5$[a]	0.4–0.6
f_{gas} Gal2	0.6–0.8	Expected at $z = 1.5$	0.6–0.8
Orbit	Near polar	To form the ring	–
Gal1 θ'[b]	65–100	GS	35–75
Gal2 θ'[b]	−50 to −70	GS	−60 to −70
Gal1 ϕ'[c]	115 to 175	GS	165
Gal2 ϕ'[c]	75 to 110	GS	95–105
$r_{pericentre}$	28–40 kpc	See the text	32 kpc (31–33 kpc)
Feedback	1–5 × median[(d)]	To preserve gas	1–2.5 × median[d]

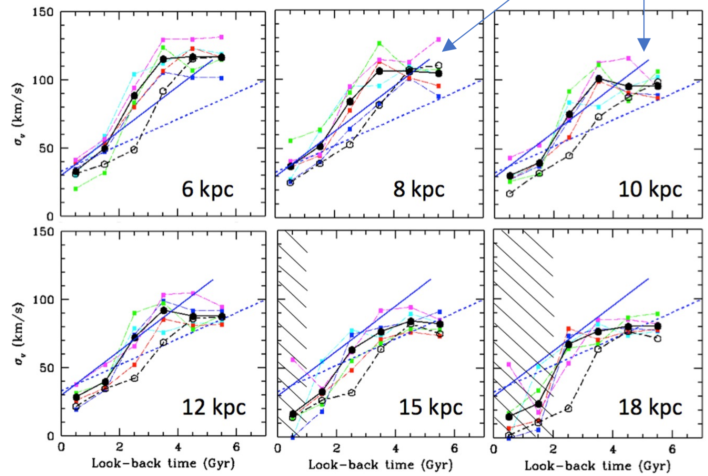
Dr Yanbin YANG

Dr Jianling WANG

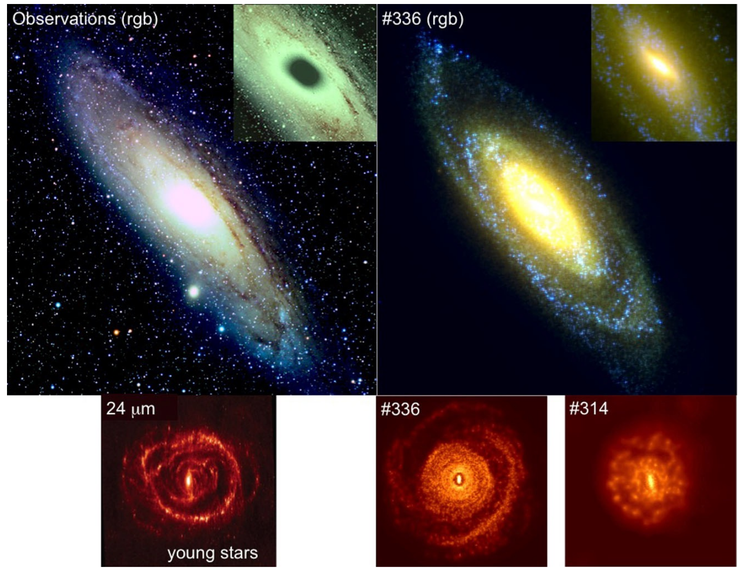
- Feedback and star formation from Cox et al. 2006
- Orbital parameters from Hammer et al. 2010
- Hydrodynamical solver: GIZMO (Hopkins 2014)
- r_{soft}= 0.16 kpc for 2 million particles (0.08 for 24 M particles)
- up to 500 models, half of them to retrieve the M31 bar


Credit: Richard Crisp

A recent, 2-3 Gyr, major (4:1) merger model for M31



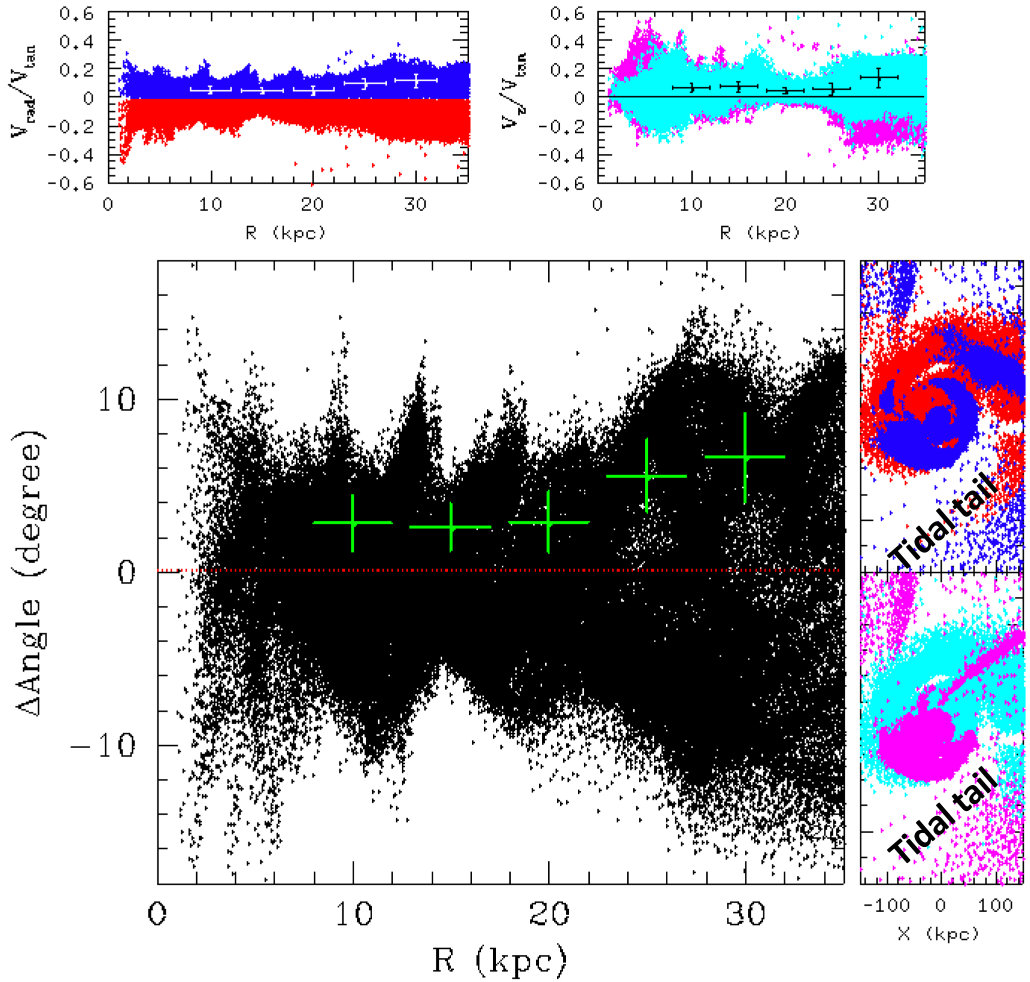
- Strong event of star formation in the disk, 2.5 Gyr ago (Williams et al. 2015);
- Very peculiar age-velocity relation (Dorman et al. 2015);
- A bar and a stable 10 kpc ring with time (Lewis et al. 2015);
- Complex structure of the Giant stream and shells (Dey et al. 2023, Tsakonas et al. 2024);
- Halo profile.



The major merger modeling reproduces them all (Hammer, Yang, Wang et al., 2018)

M31: signature of gaseous disk instabilities at outskirts

- Net increase of both V_{rad}/V_{tan} and V_z/V_{tan} , in the disk at R > 25 kpc;
- ΔAngle is the disk projected angle difference between V_{gas} and circular velocity: it significantly increases at R > 25 kpc;
- Fluctuations and oscillations are caused by gas particles returning from a tidal tail.

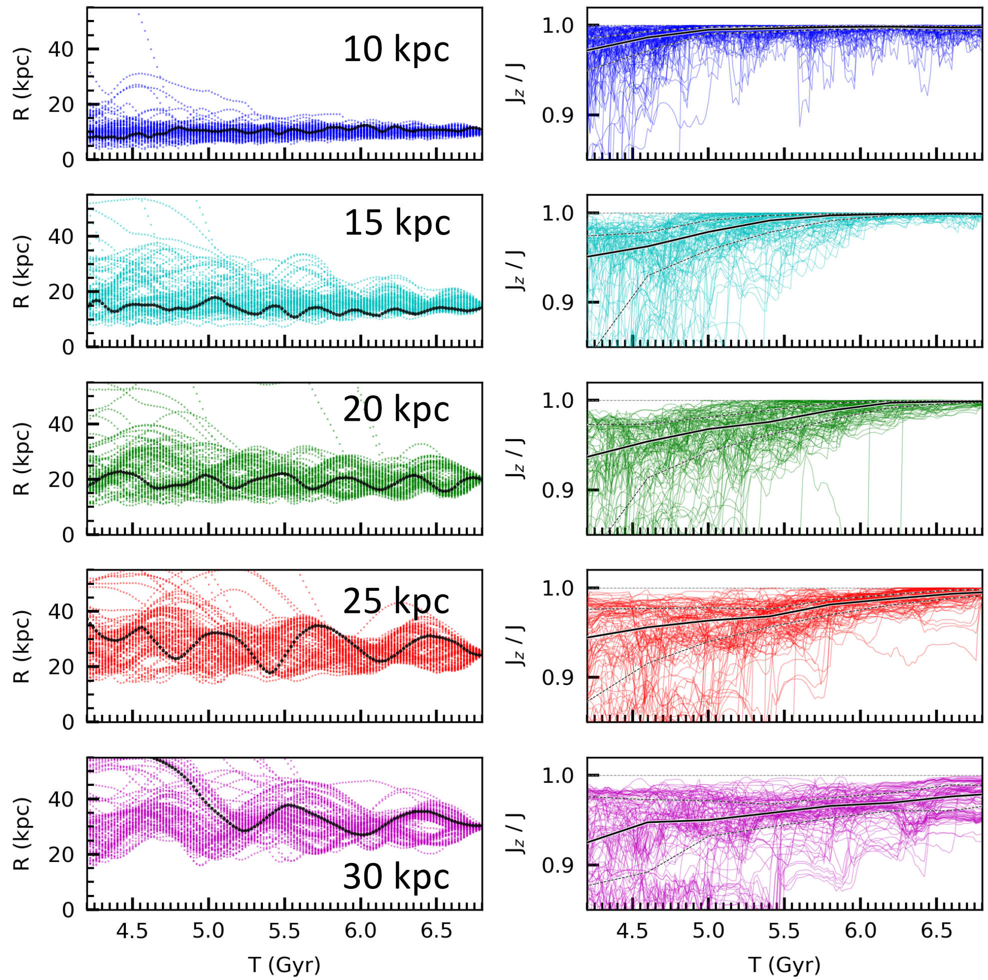


Signature of gaseous disk instabilities at outskirts

- Orbital motions of gas particles during the 2.6 Gyr elapsed time after the merger (4.2 Gyr) to the present time (6.8 Gyr);

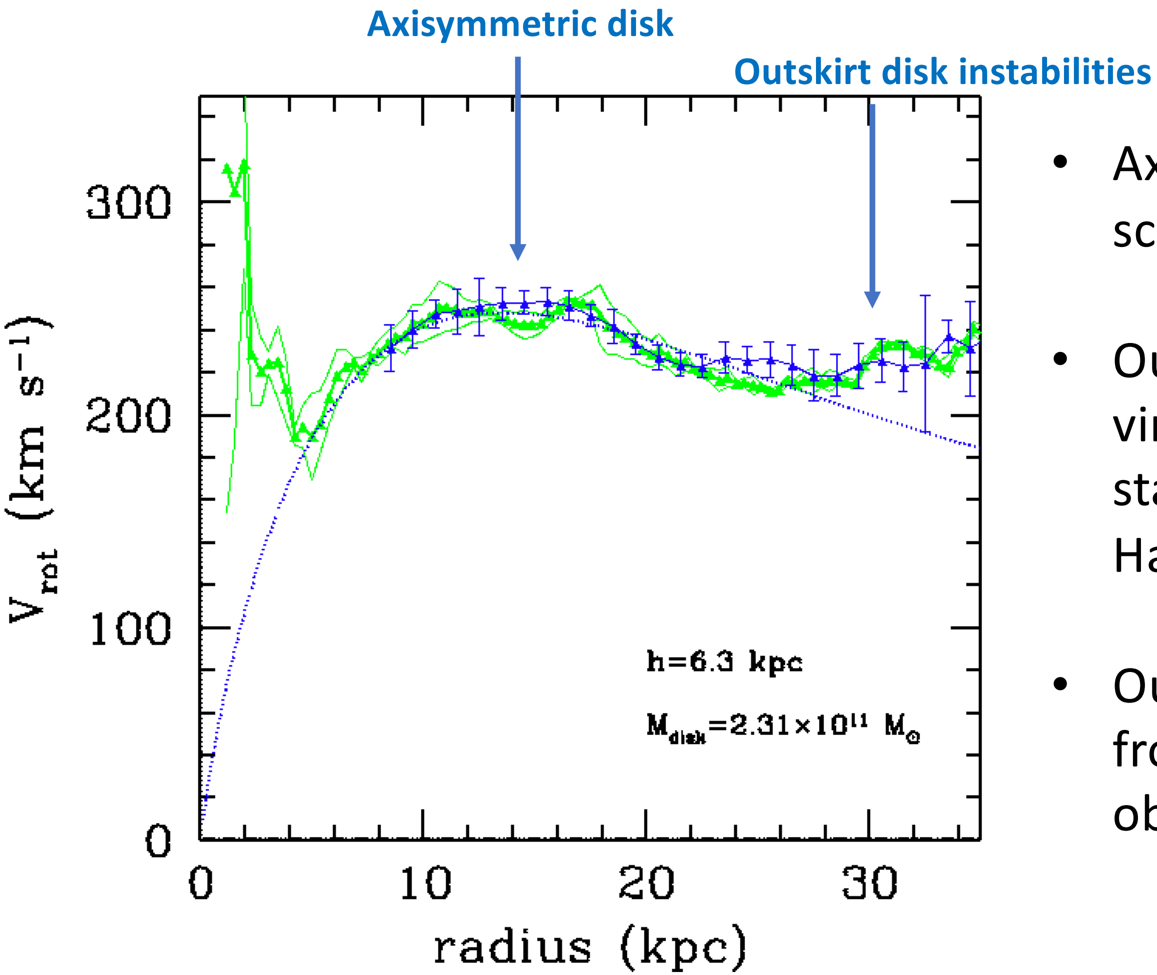
- Gas particles selected at ≤ 20 kpc show almost circular orbits, with ≥ 6 full orbits and the angular momentum is aligned;

- Beyond 25 kpc, gas follows only few (≤ 4) eccentric orbits, i.e., not sufficient to warrant equilibrium, and the angular momentum is not well aligned with the disk.



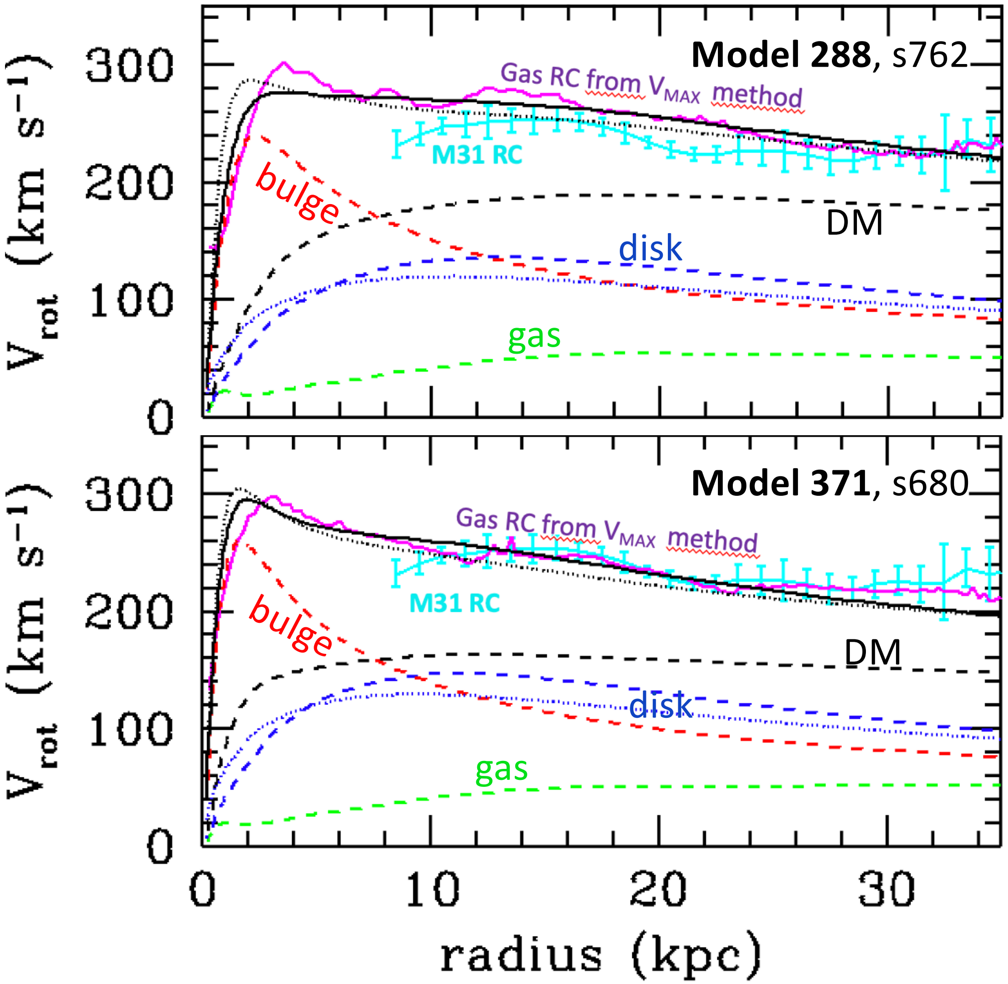
François Hammer, LPN

Signatures of disk and of outskirt disk instabilities



- Axisymmetric disk results in a bump at 2.2 x scalelength, i.e., at 14 kpc;
- Outskirts, for R > 25 kpc the gas is not at virial equilibrium: it requires > 3-5 orbits (for stars: Gnedin & Ostriker, 1999; for gas: Hammer et al. 2025);
- Ouskirt instabilities are due to incoming gas from a tidal tail: it affects (increases) the observed HI velocities.

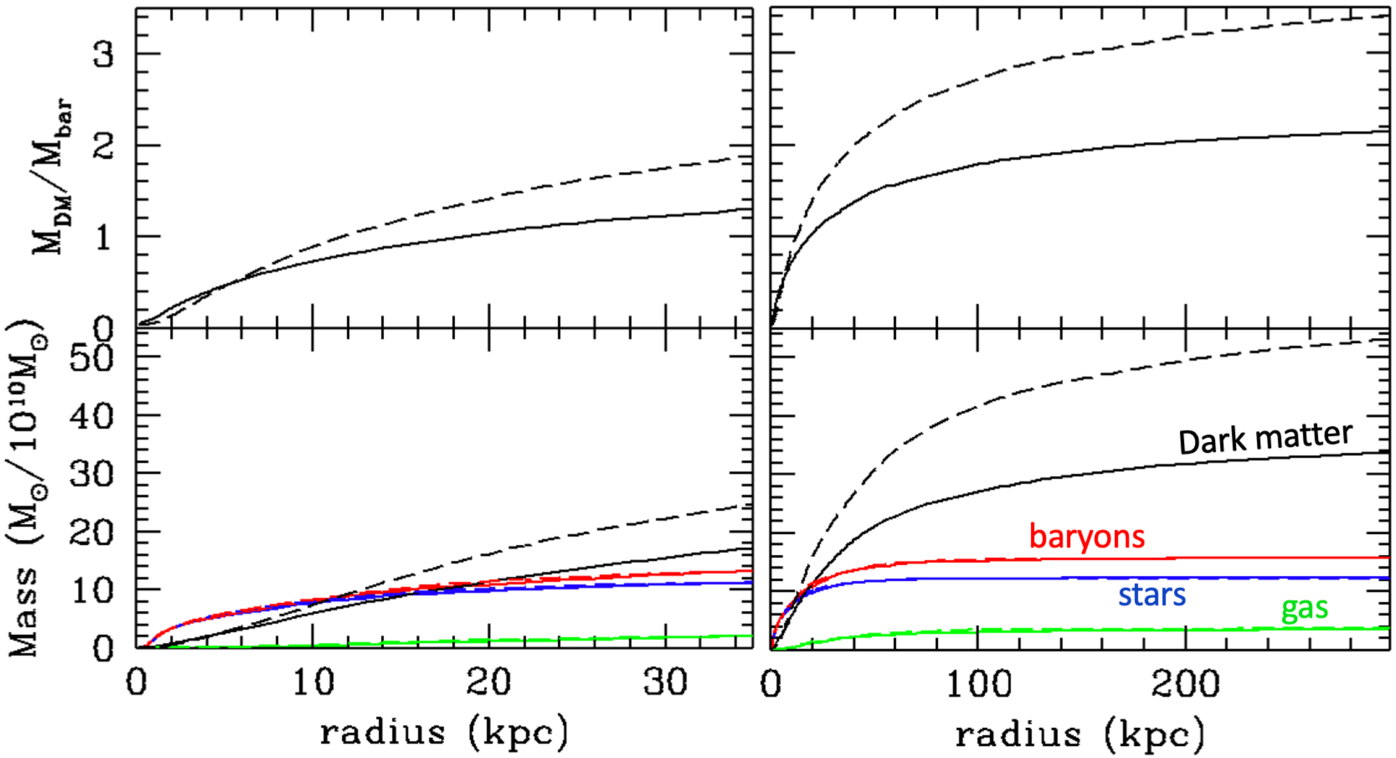
Calibrating the mass of M31 from its rotation curve



- Former models (e.g., **288**) from Hammer et al. 2018 overestimated the M31 rotation curve;
- This requires to decrease the dark-matter mass by a factor 1.6 to derive **model 371**;
- This well reproduces the whole rotation curve, including axisymmetric disk and non-equilibrium features.

➔ The dynamical modelling of M31 reveals its mass and dark matter content.

M31 mass component distribution



- DM profile of the M31 model follows a Dehnen profile, which is limited at 200 times the critical density.
- M_{200}= 2.95 10^{11} M_{sun} and a total mass of M_{tot}= 4.5 10^{11} M_{sun} within R_{200}= 137 kpc, i.e., 2 times more DM than baryons.
- M31 mass is much smaller than M_{tot} > 10^{12} M_{sun} expectations based on orbits of globular clusters or satellite galaxies. These probes are lying at much larger distances (50 to 300 kpc) and have had no time to perfom even a single orbit since the merger.

Conclusions

Gaia revises our knowledge of the Milky Way mass and size:

- Detection of a Keplerian decline in the Milky Way rotation curve;
- Dwarf galaxies are newcomers (< 3 Gyr ago) and cannot be used to derive the MW mass;
- Only 2-2.5 times missing (dark) matter than ordinary matter instead of ≥ 5 (Planck);
- Either the Milky Way is special, or rotation curves of external galaxies have methodological problems.

A full dynamical modeling of M31, reproducing all observed features :

- Total mass within R_{200}= 137 kpc is M_{tot}= 4.5 10^{11} M_{sun} with M_{200}= 2.95 10^{11} M_{sun} of DM;
- Only ≤ 2 times missing (dark) matter than ordinary matter instead of ≥ 5 (Planck);
- Estimating M31 mass with probes at distances >> 30 kpc : these probes have experimented one orbit or less since the major merger!

A too large fraction of baryons inside the main Local group galaxies vs cosmological models ?