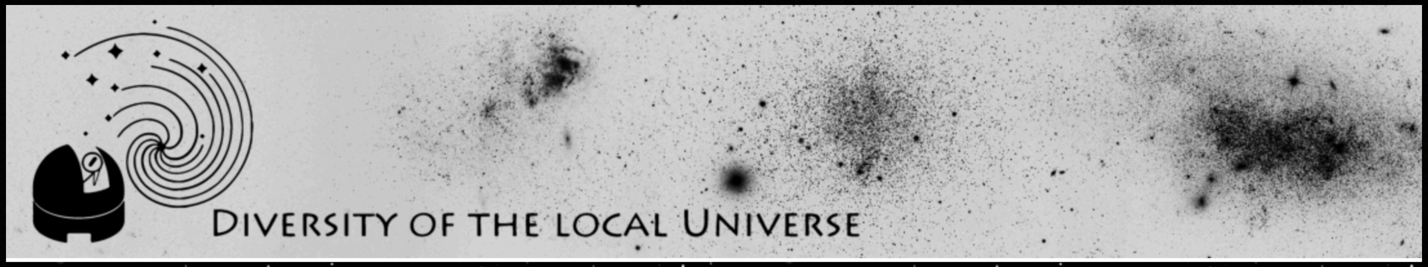


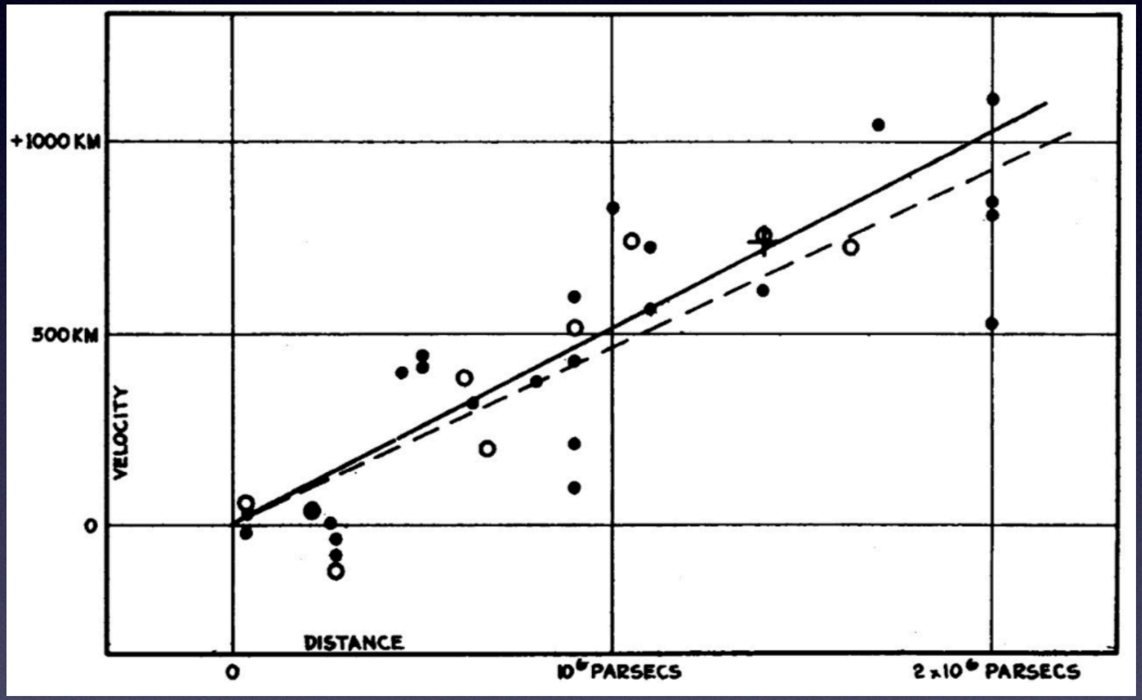
THE SPECIAL ASTROPHYSICAL OBSERVATORY OF THE RUSSIAN ACADEMY OF SCIENCES, NIZHNIJ ARKHYZ, RUSSIA
30 SEPTEMBER - 4 OCTOBER 2019

Revisiting the Local Hubble flow

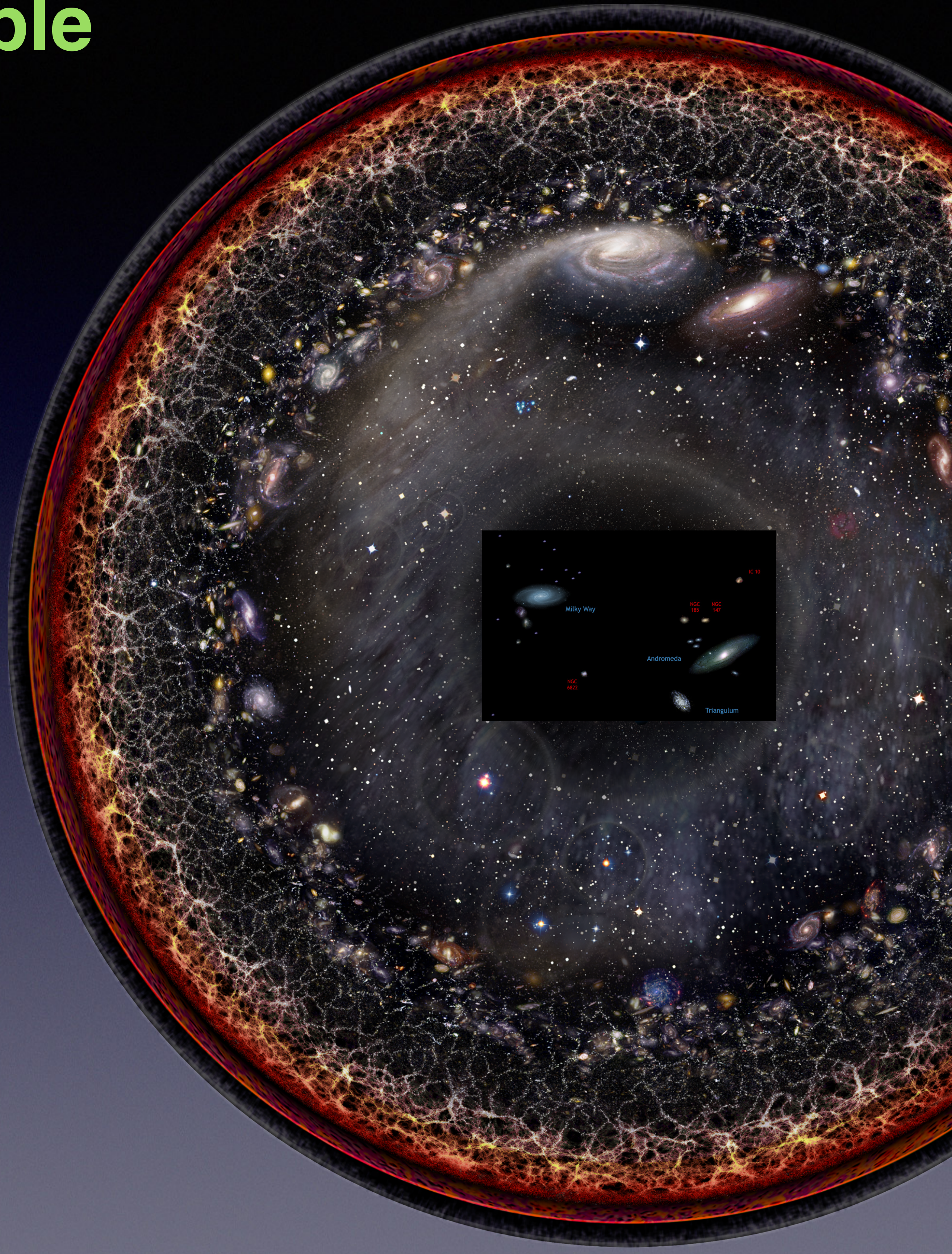
Jean-Baptiste SALOMON

Observatoire de Besançon, Institut UTINAM, FRANCE

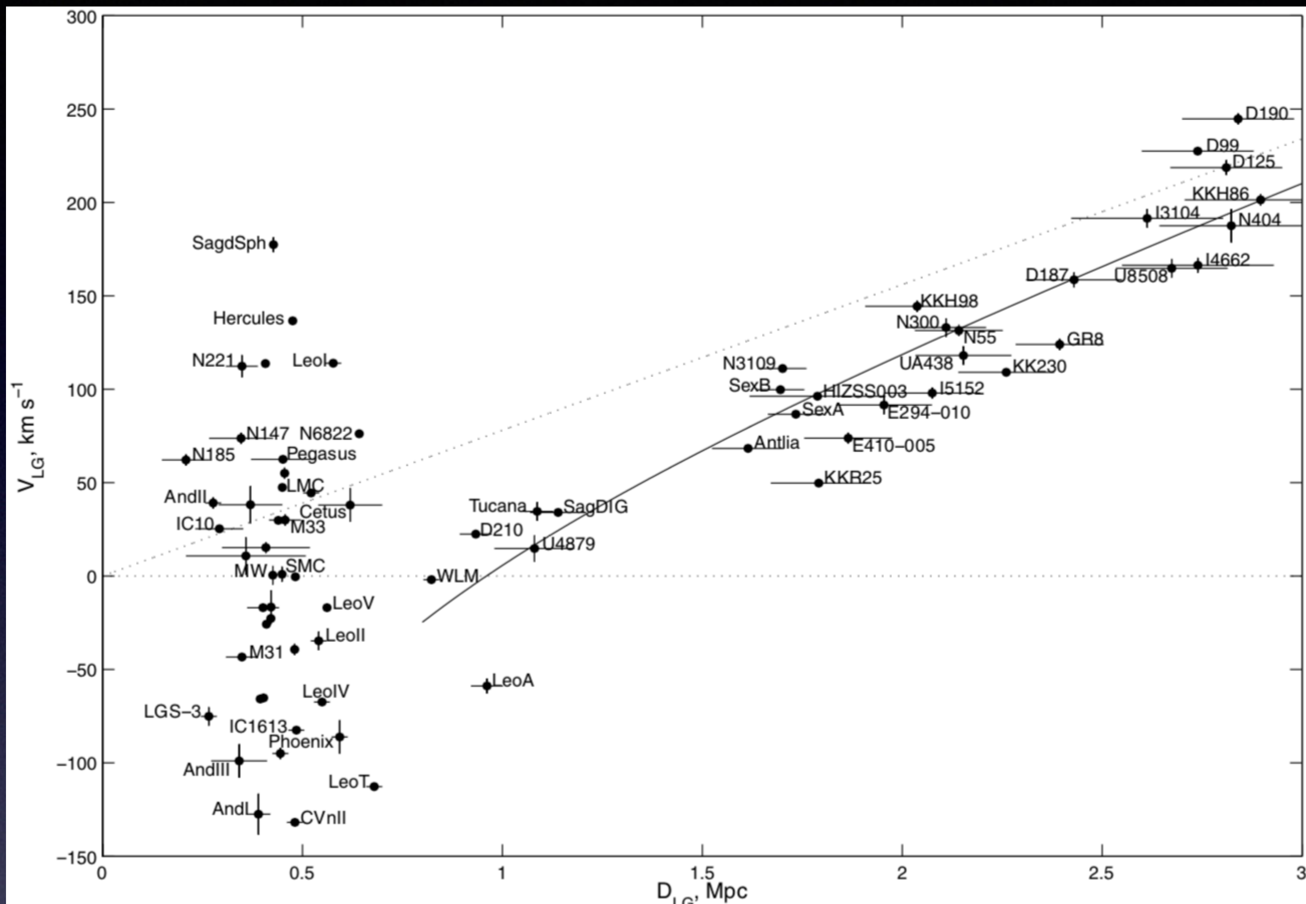
Hubble



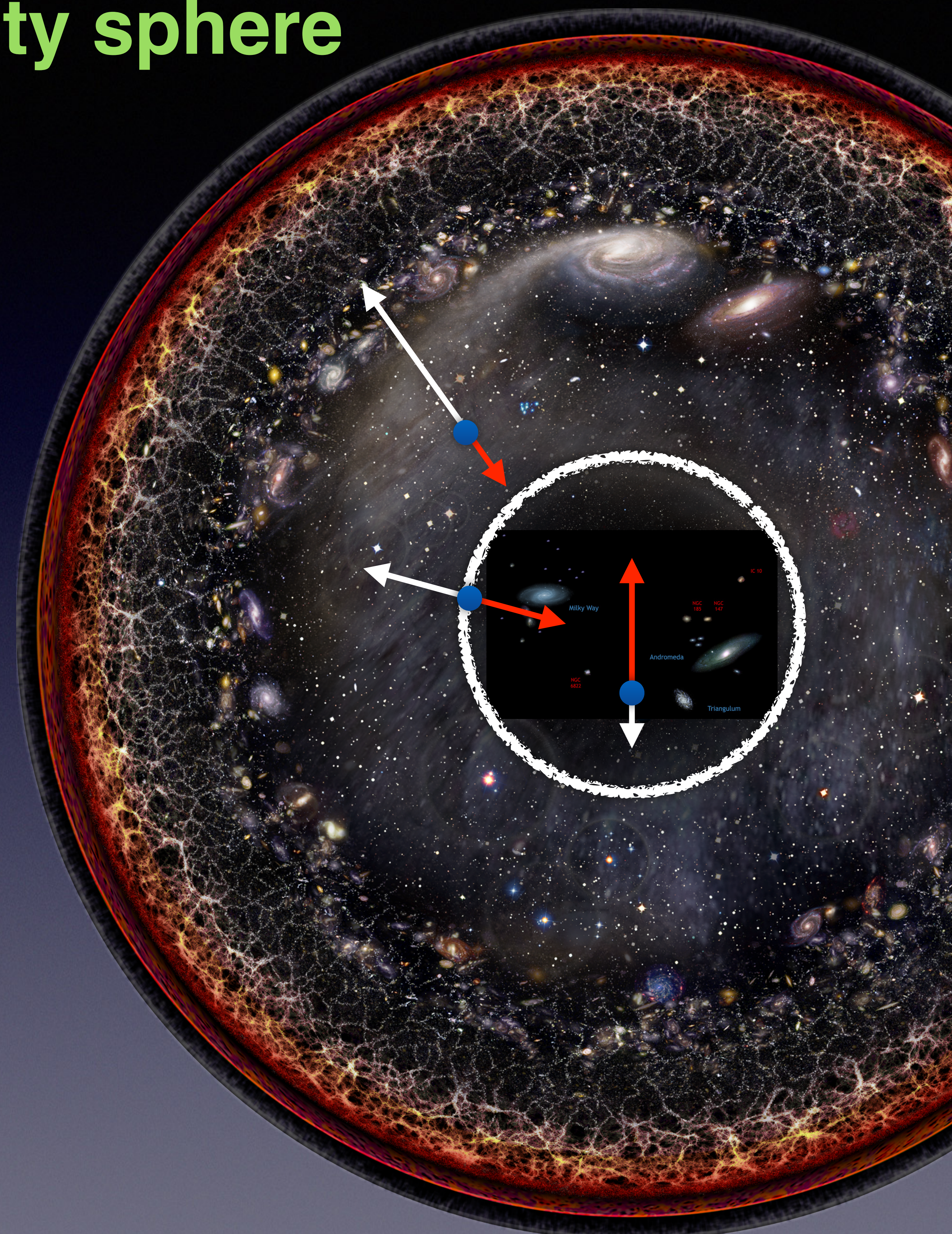
Hubble (1929)



Zero velocity sphere



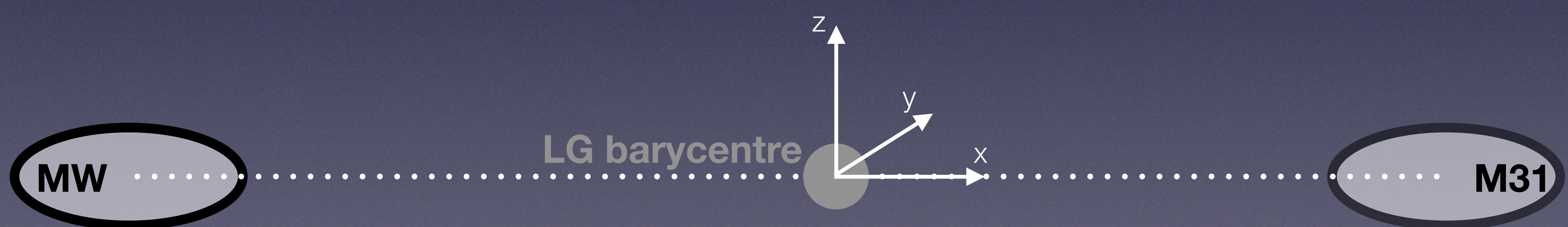
Karachentsev et al. (2009)



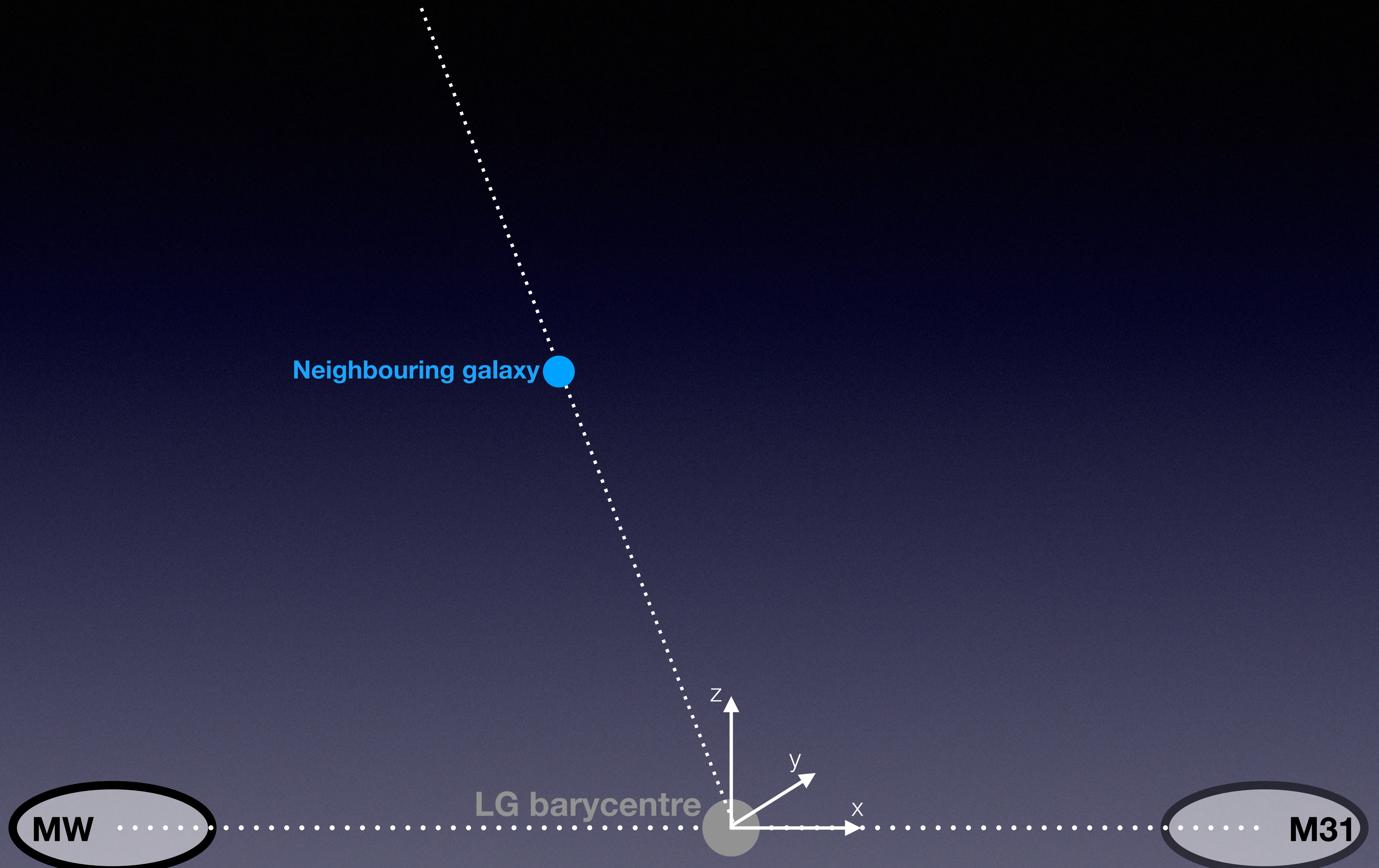
Radius = 0.96 Mpc
Hubble local flow of 78 ± 2 km/s/Mpc
Mass = 1.9 ± 0.2 10^{12} M_{Sun}

Schematic view

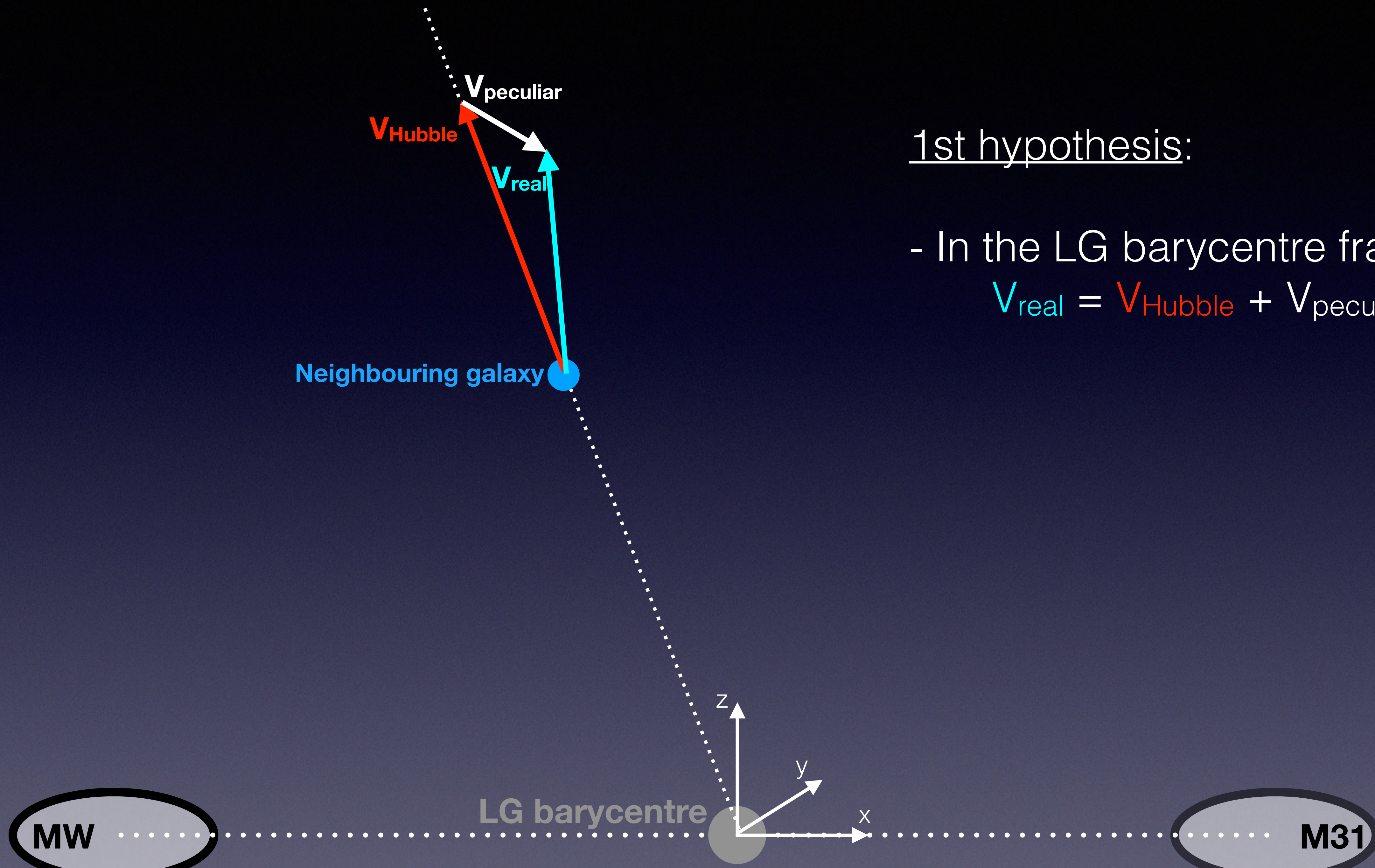
Schematic view



Schematic view



Schematic view

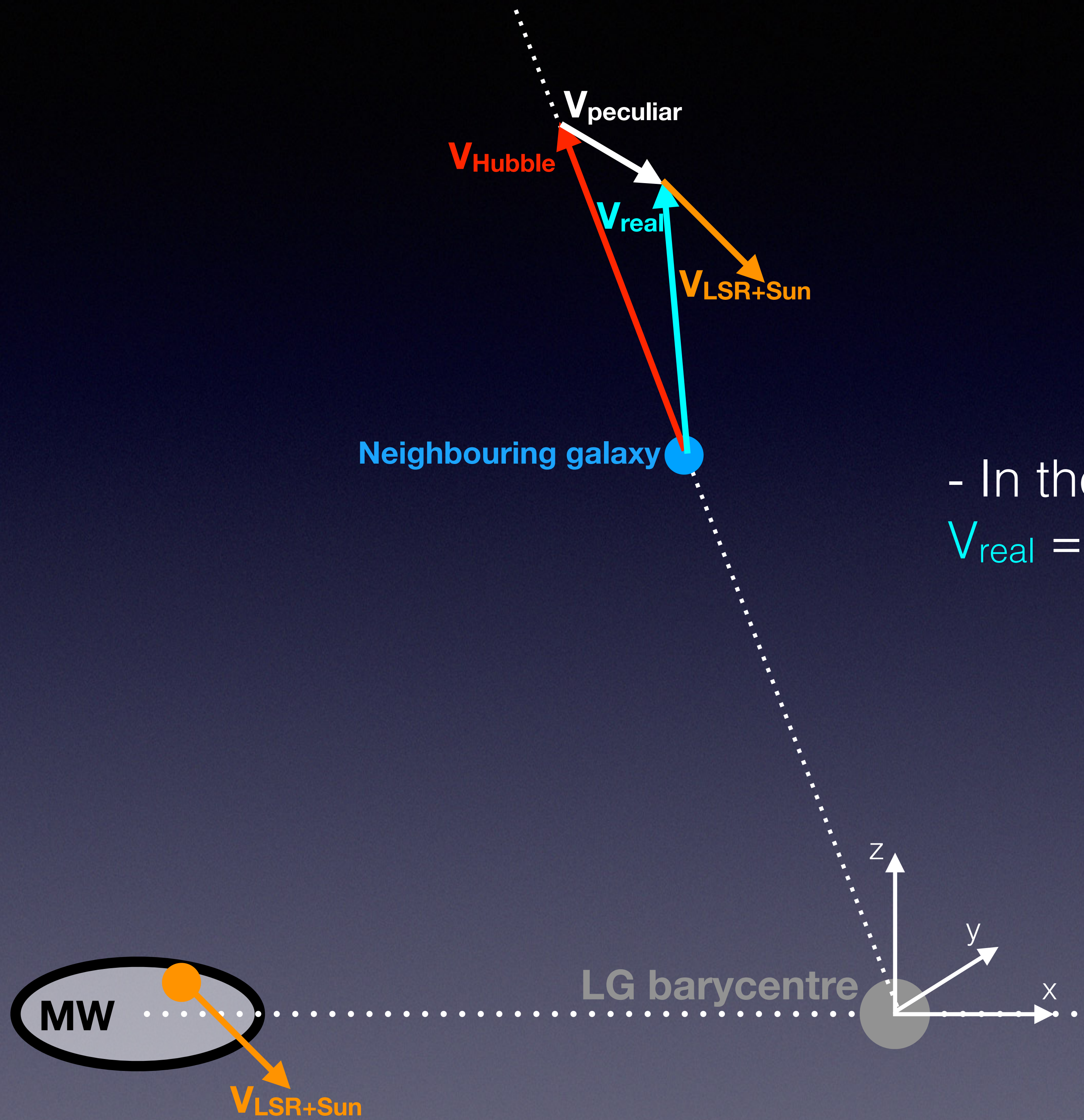


1st hypothesis:

- In the LG barycentre frame

$V_{real} = V_{Hubble} + V_{peculiar}$

Schematic view



1st hypothesis:

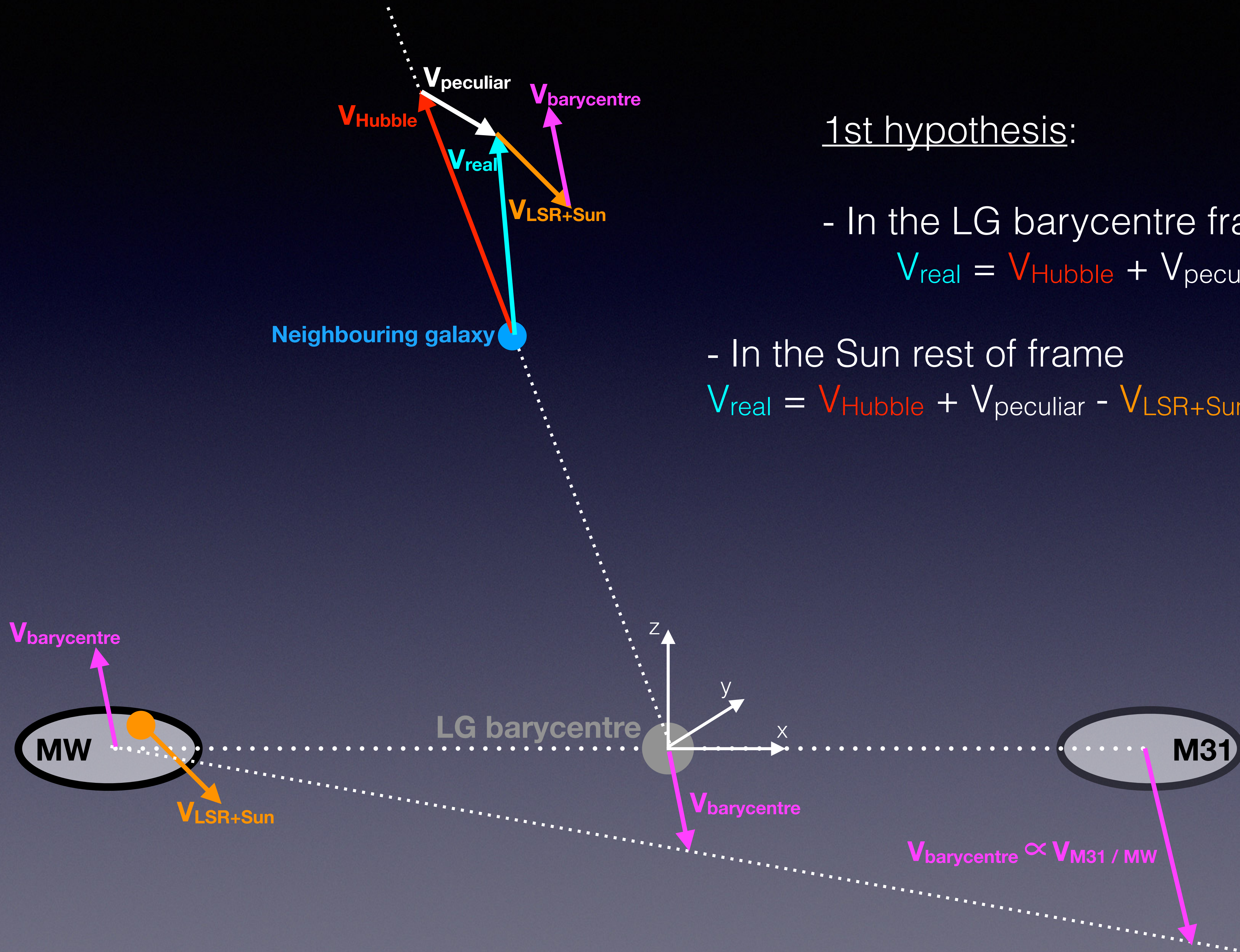
- In the LG barycentre frame

$$V_{real} = V_{Hubble} + V_{peculiar}$$

- In the Sun rest of frame

$$V_{real} = V_{Hubble} + V_{peculiar} - V_{LSR+Sun}$$

Schematic view



<u>1st hypothesis</u>:

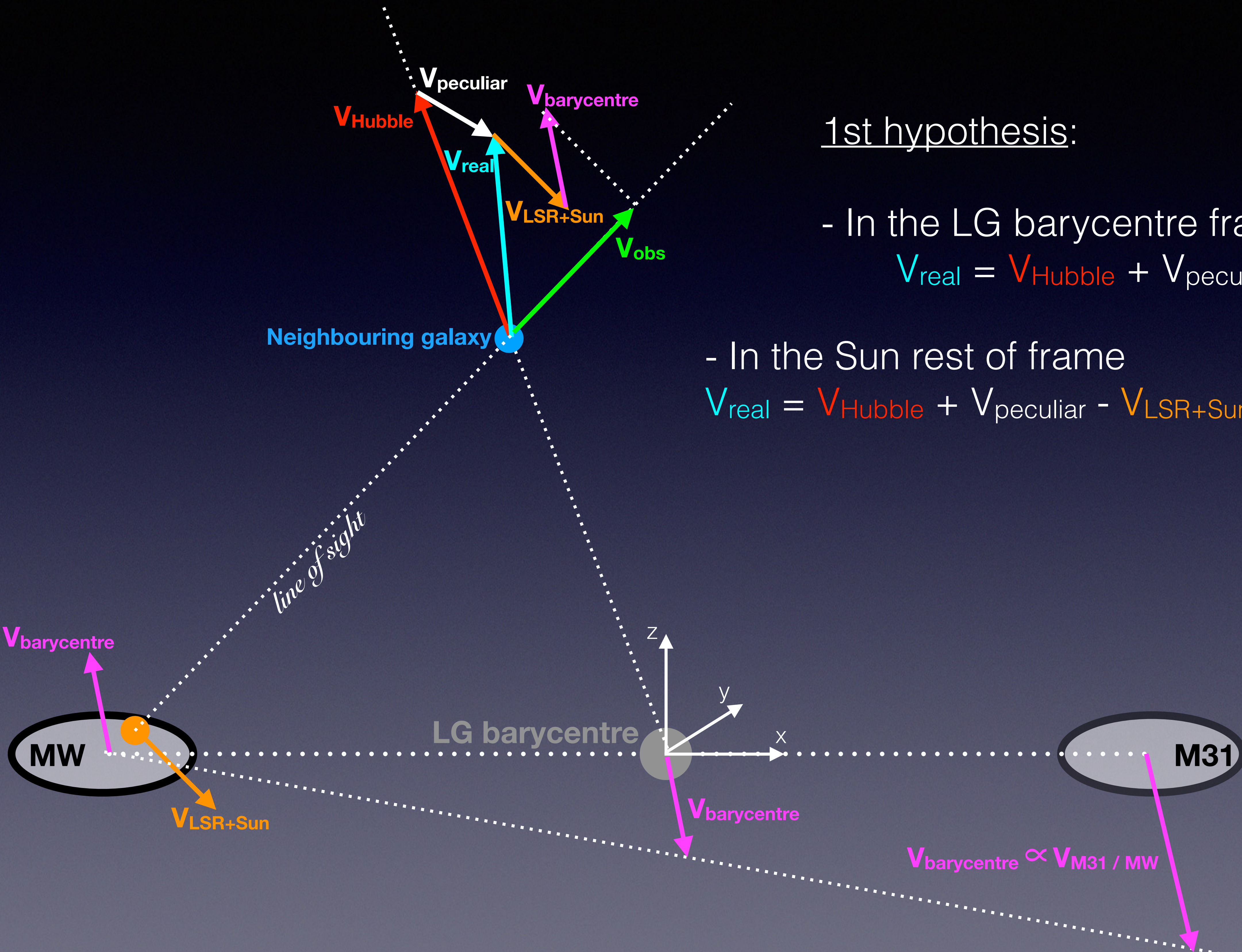
- In the LG barycentre frame

$$V_{real} = V_{Hubble} + V_{peculiar}$$

- In the Sun rest of frame

$$V_{real} = V_{Hubble} + V_{peculiar} - V_{LSR+Sun} - V_{barycentre}$$

Schematic view



1st hypothesis:

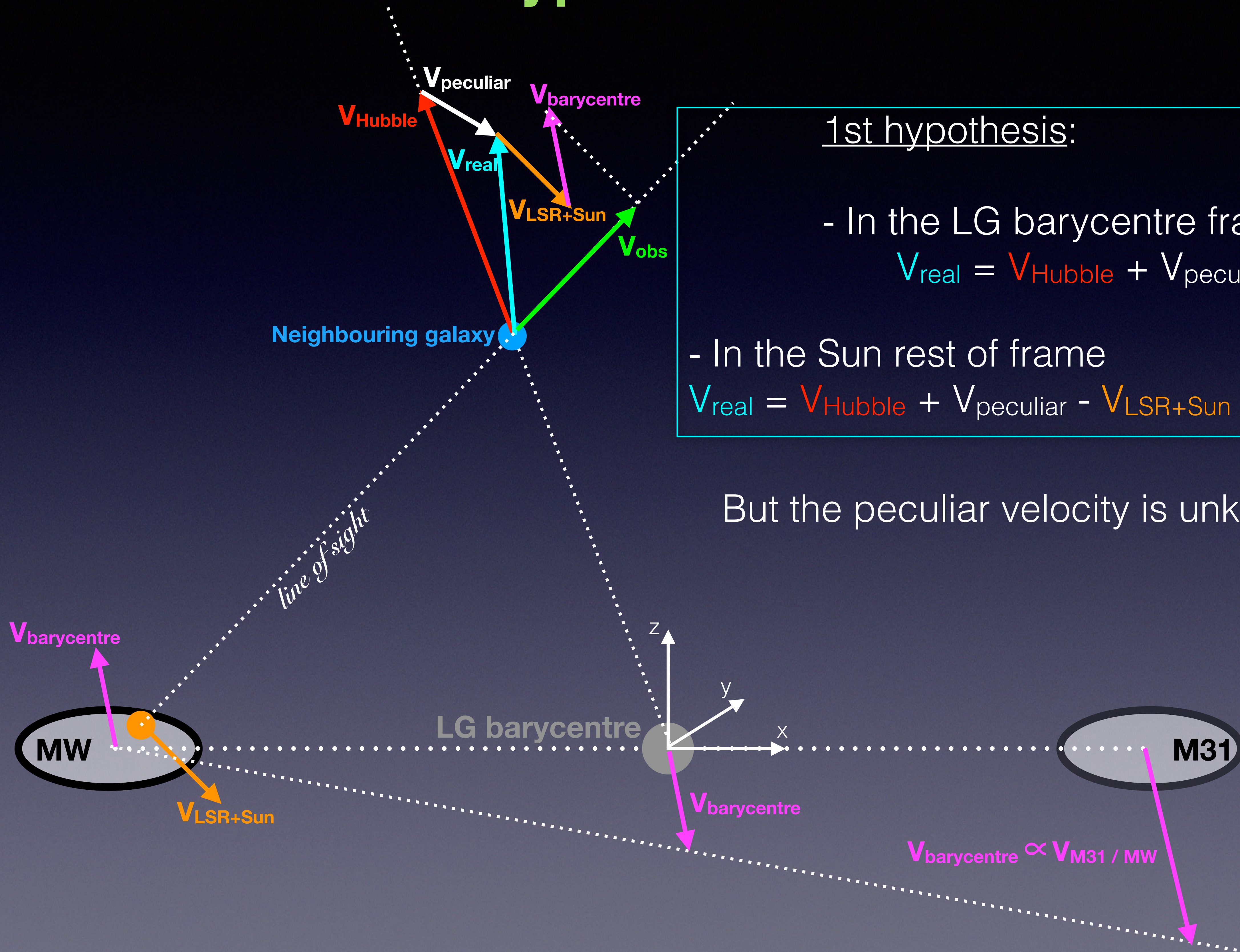
- In the LG barycentre frame

$$V_{real} = V_{Hubble} + V_{peculiar}$$

- In the Sun rest of frame

$$V_{real} = V_{Hubble} + V_{peculiar} - V_{LSR+Sun} - V_{barycentre}$$

Hypothesis 1



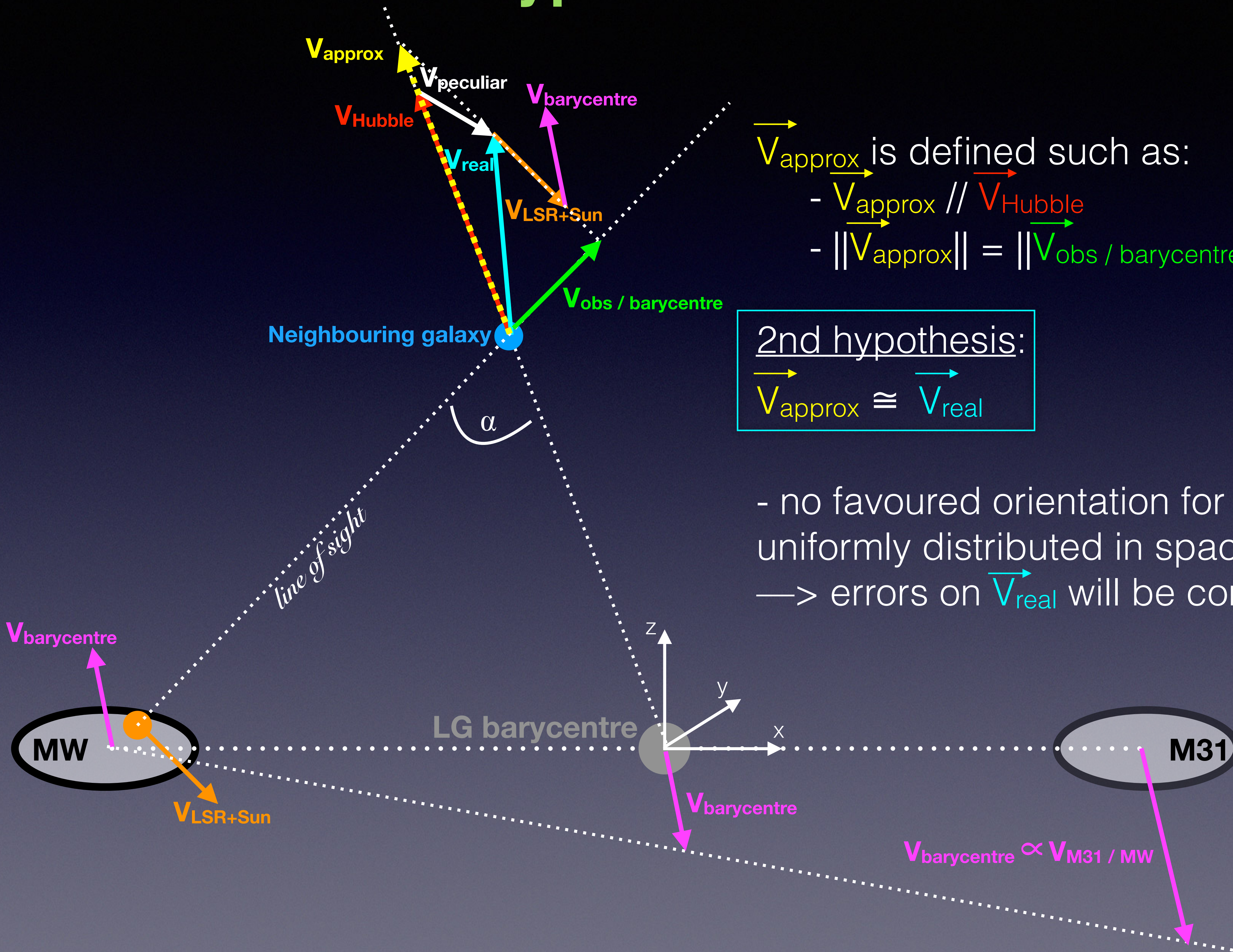
1st hypothesis:

- In the LG barycentre frame
  $V_{real} = V_{Hubble} + V_{peculiar}$

- In the Sun rest of frame
  $V_{real} = V_{Hubble} + V_{peculiar} - V_{LSR+Sun} - V_{barycentre}$

But the peculiar velocity is unknown

Hypothesis 2



$\vec{V}_{approx}$ is defined such as:

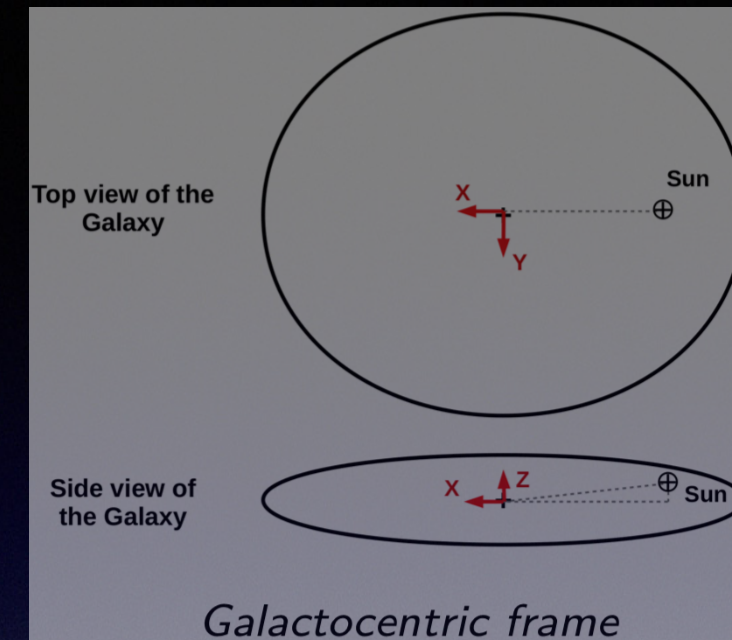
- $\vec{V}_{approx}$ // $\vec{V}_{Hubble}$
- $||\vec{V}_{approx}|| = ||\vec{V}_{obs\ /\ barycentre}|| / \cos\alpha$

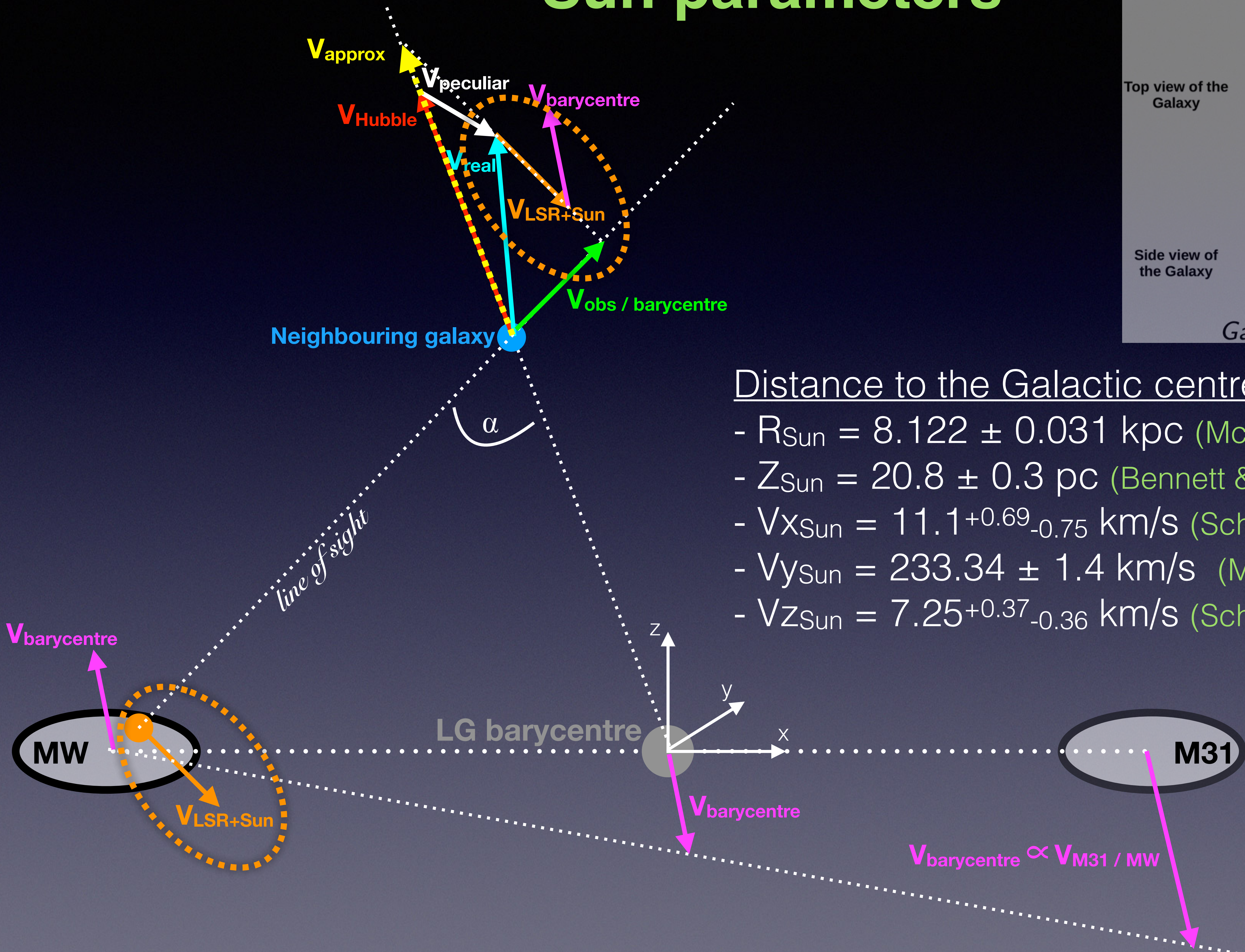
<u>2nd hypothesis</u>:

$\vec{V}_{approx} \cong \vec{V}_{real}$

- no favoured orientation for $V_{peculiar}$, uniformly distributed in space
—> errors on $\vec{V}_{real}$ will be compensated

Sun parameters

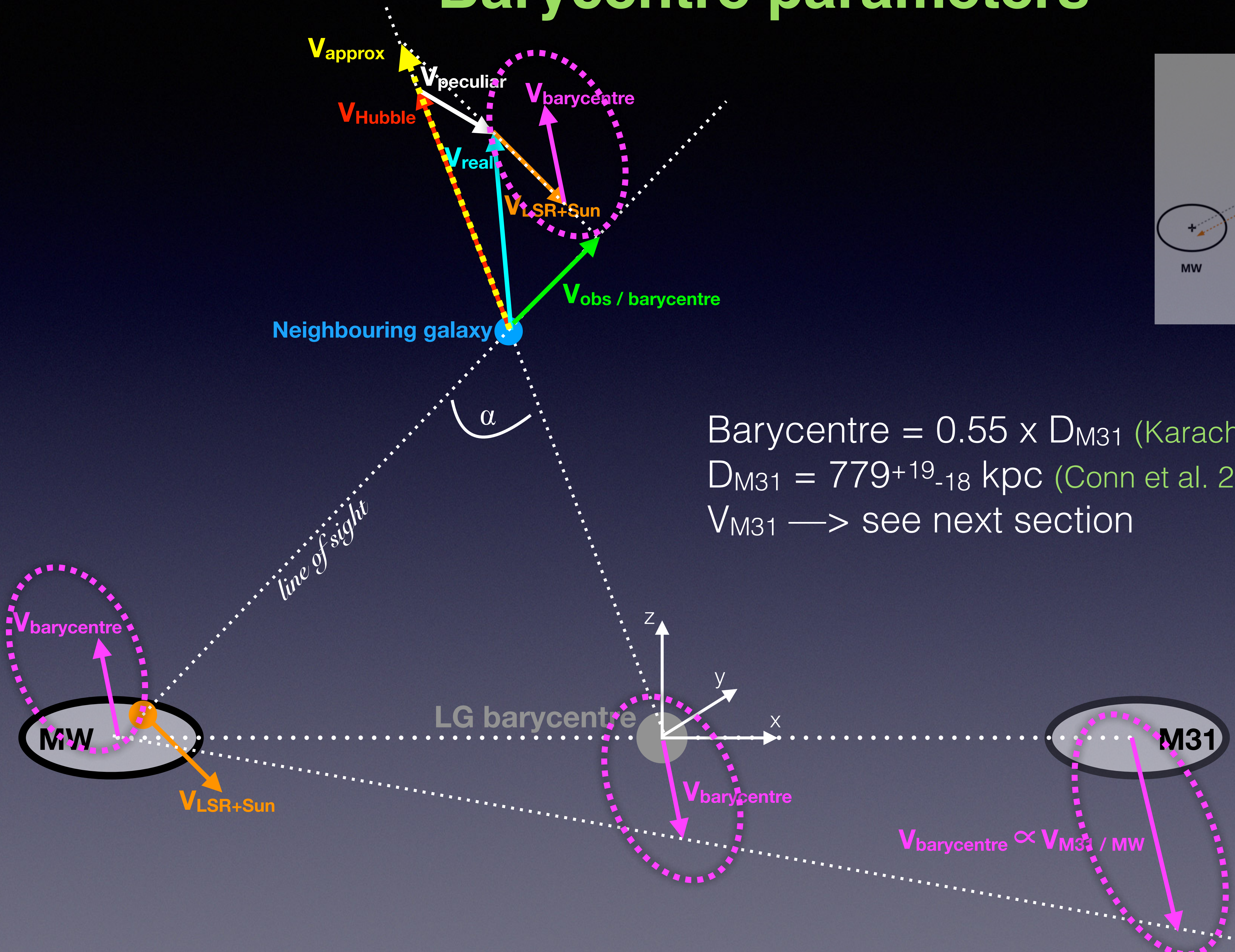


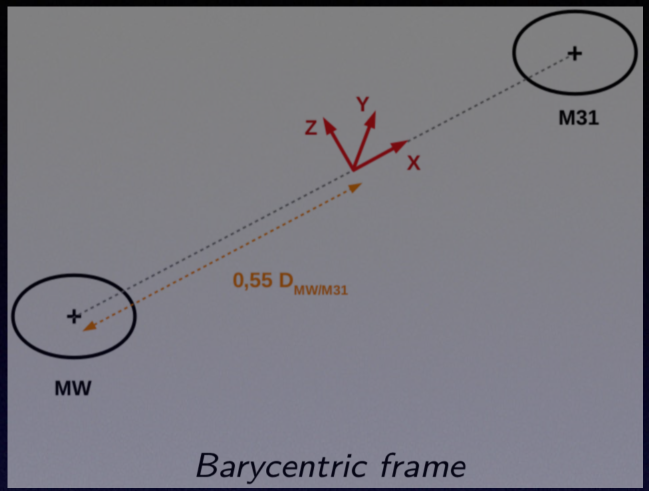


<u>Distance to the Galactic centre</u>:

- R_{Sun} = 8.122 ± 0.031 kpc (McGaugh 2018)
- Z_{Sun} = 20.8 ± 0.3 pc (Bennett & Bovy 2019)
- $Vx_{Sun} = 11.1^{+0.69}_{-0.75}$ km/s (Schönrich et al. 2010)
- Vy_{Sun} = 233.34 ± 1.4 km/s (McGaugh 2018)
- $Vz_{Sun} = 7.25^{+0.37}_{-0.36}$ km/s (Schönrich et al. 2010)

Barycentre parameters

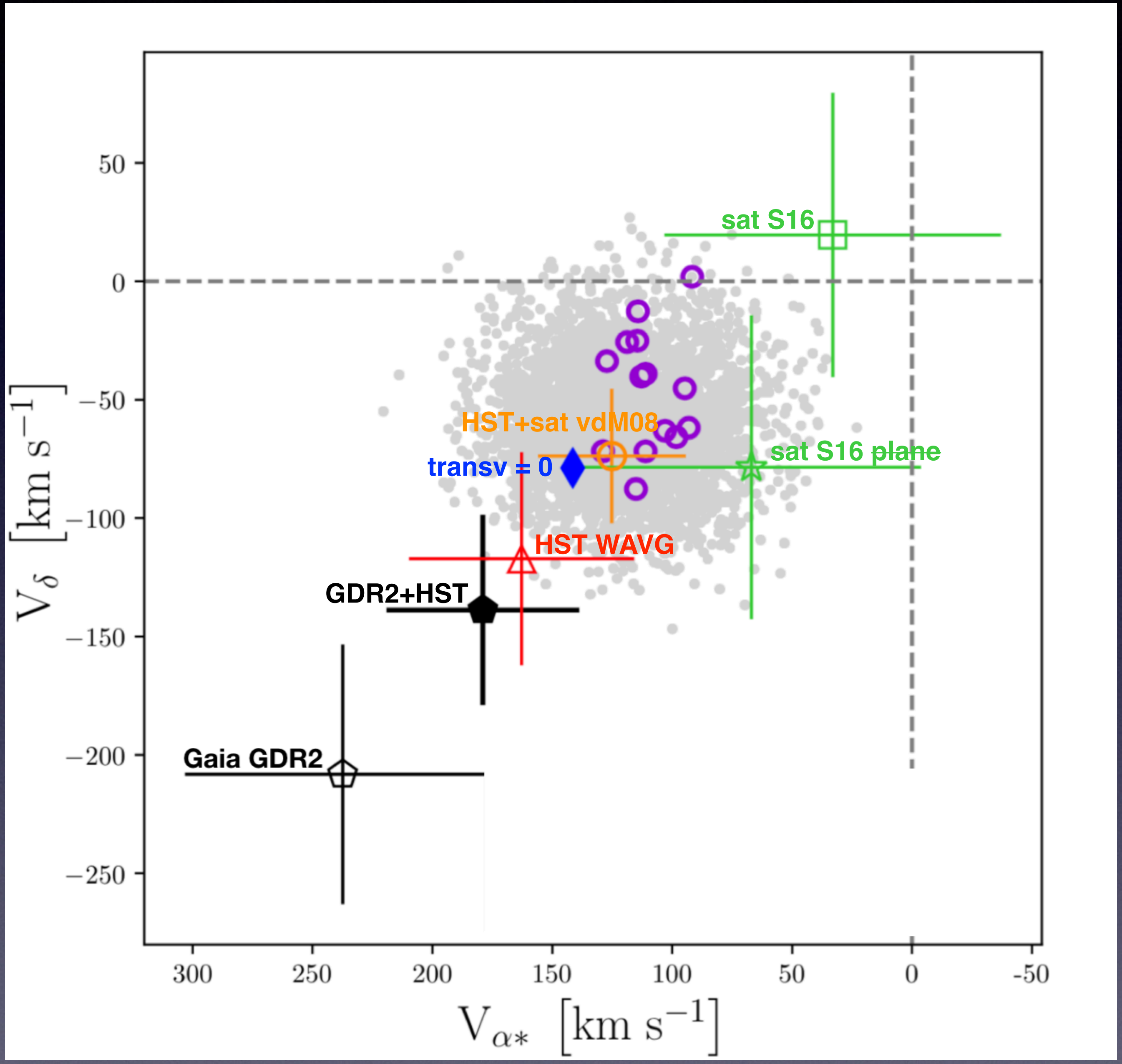




Barycentre = 0.55 x D_{M31} (Karachentsev et al. 2009)
D_{M31} = 779^{+19}_{-18} kpc (Conn et al. 2012)
V_{M31} —> see next section

M31 proper motion

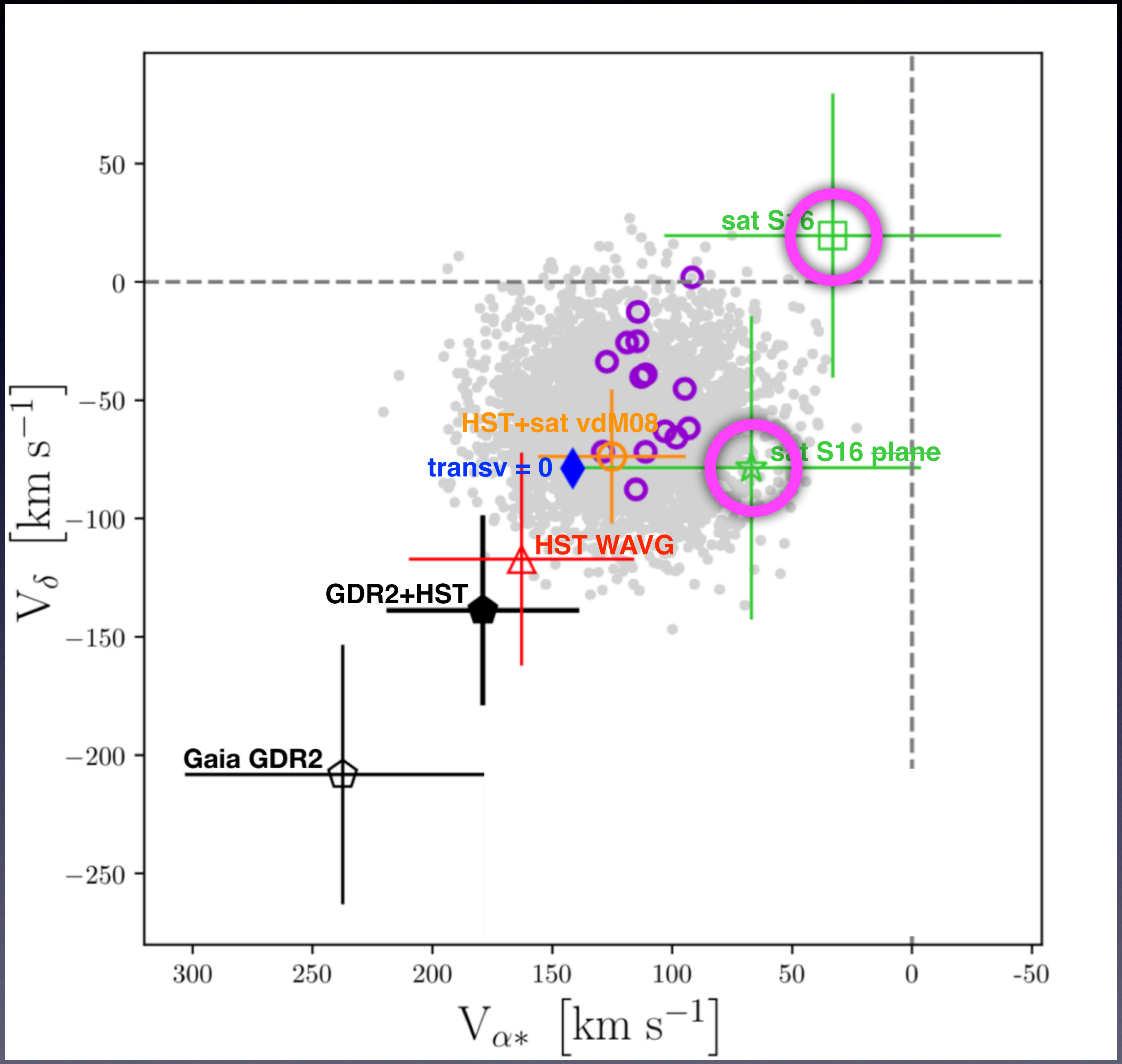
Heliocentric M31 transverse velocity



adapted from van der Marel et al. (2019)

1st statistical estimation

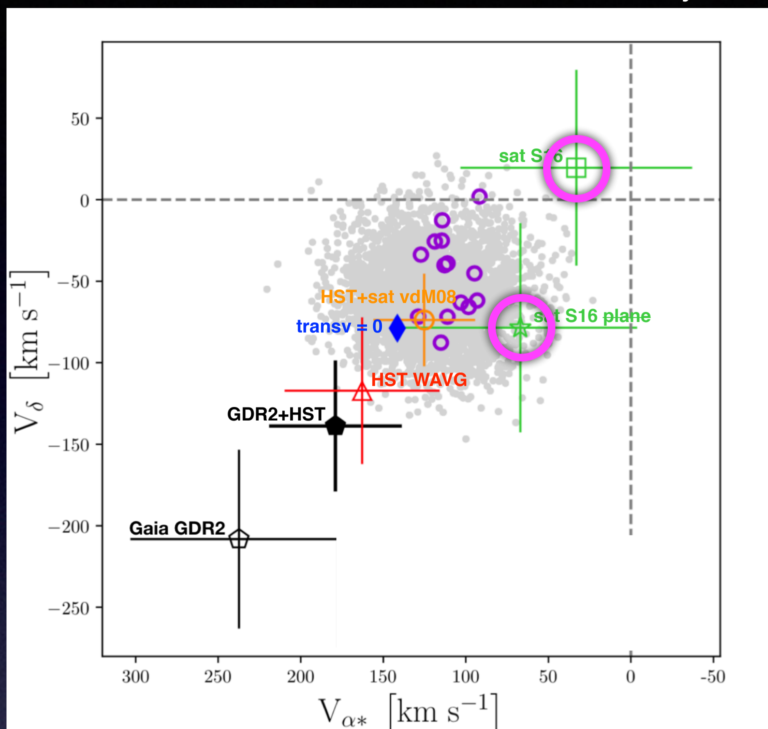
Heliocentric M31 transverse velocity



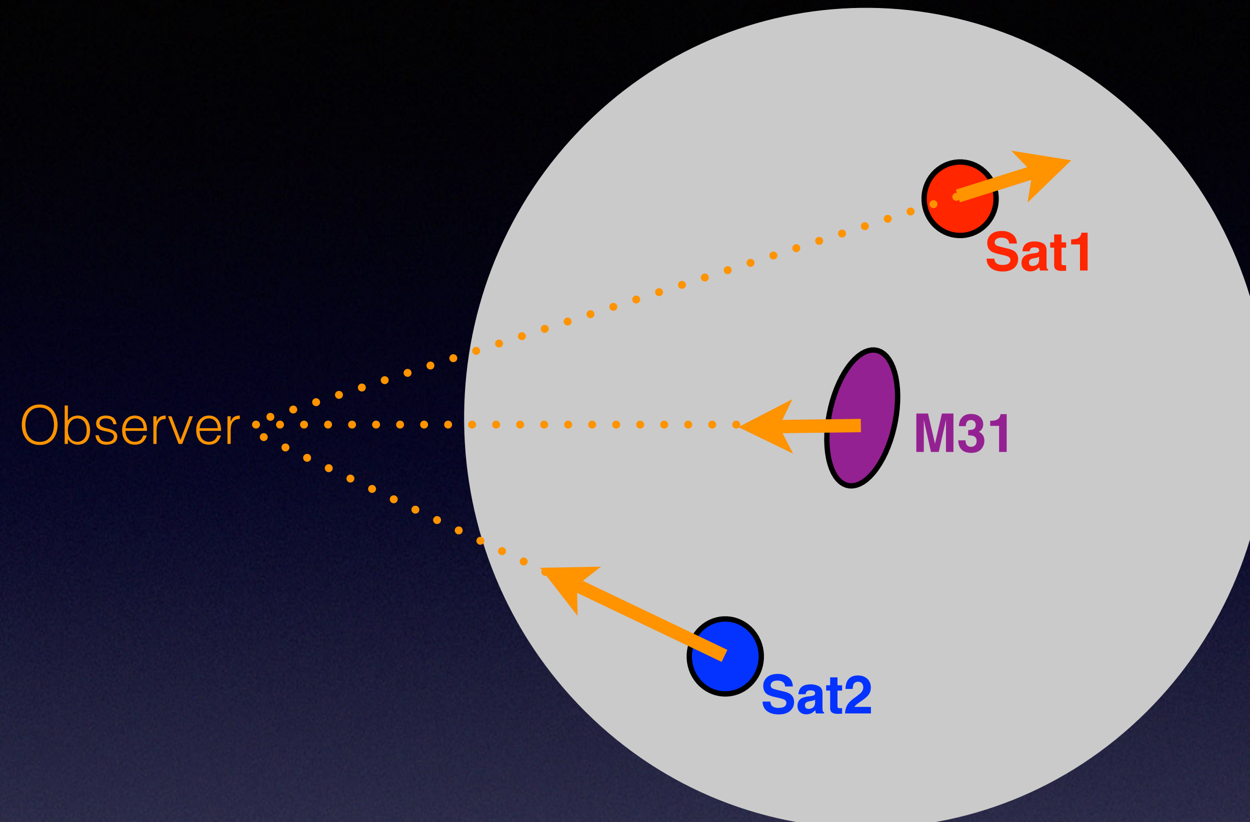
adapted from van der Marel et al. (2019)

1st statistical estimation

Heliocentric M31 transverse velocity



adapted from van der Marel et al. (2019)



<u>Assumption</u>:

M31 Satellites are embedded within its dark halo

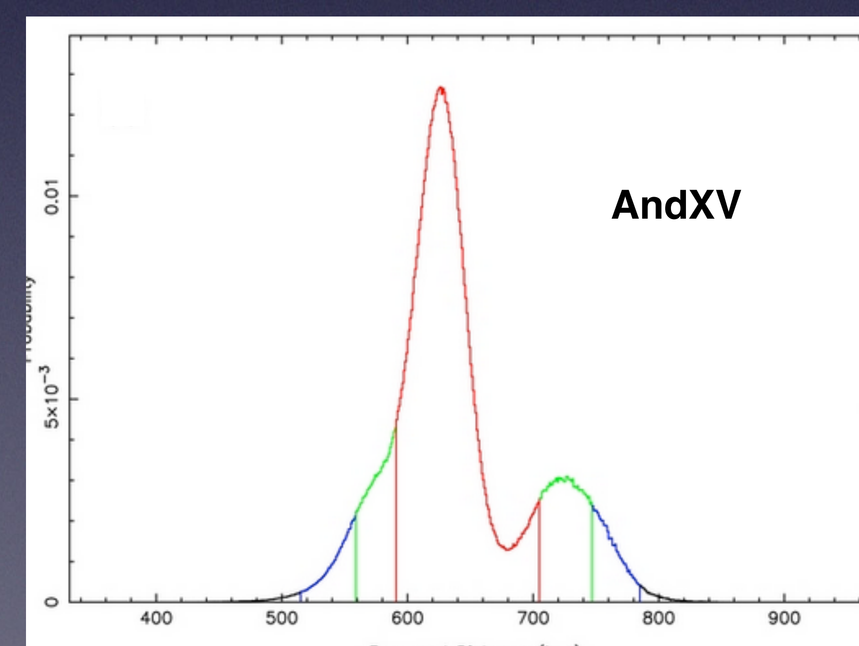
—> they are sharing a global proper motion

- $V_{sat} = V_{M31} + V_{peculiar}$
- NFW spherical halo (Navarro et al. 1997)
- peculiar velocities of satellites (Lokas & Mamon 2001)

$$\sigma_i = f(V_{200}, R_{200}, c, r_i)$$

R_{200} = 300 kpc, $M_{200} = 1.10^{12}\,M_{Sun}$, c =12

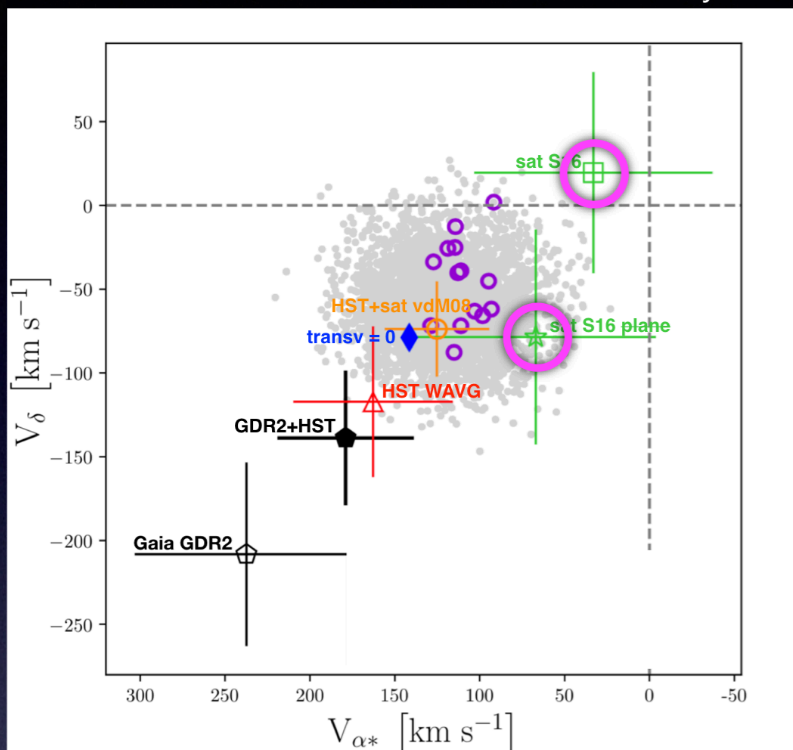
(Watkins et al. 2010, Fardal et al. 2013)



Conn et al. (2012)

1st statistical estimation

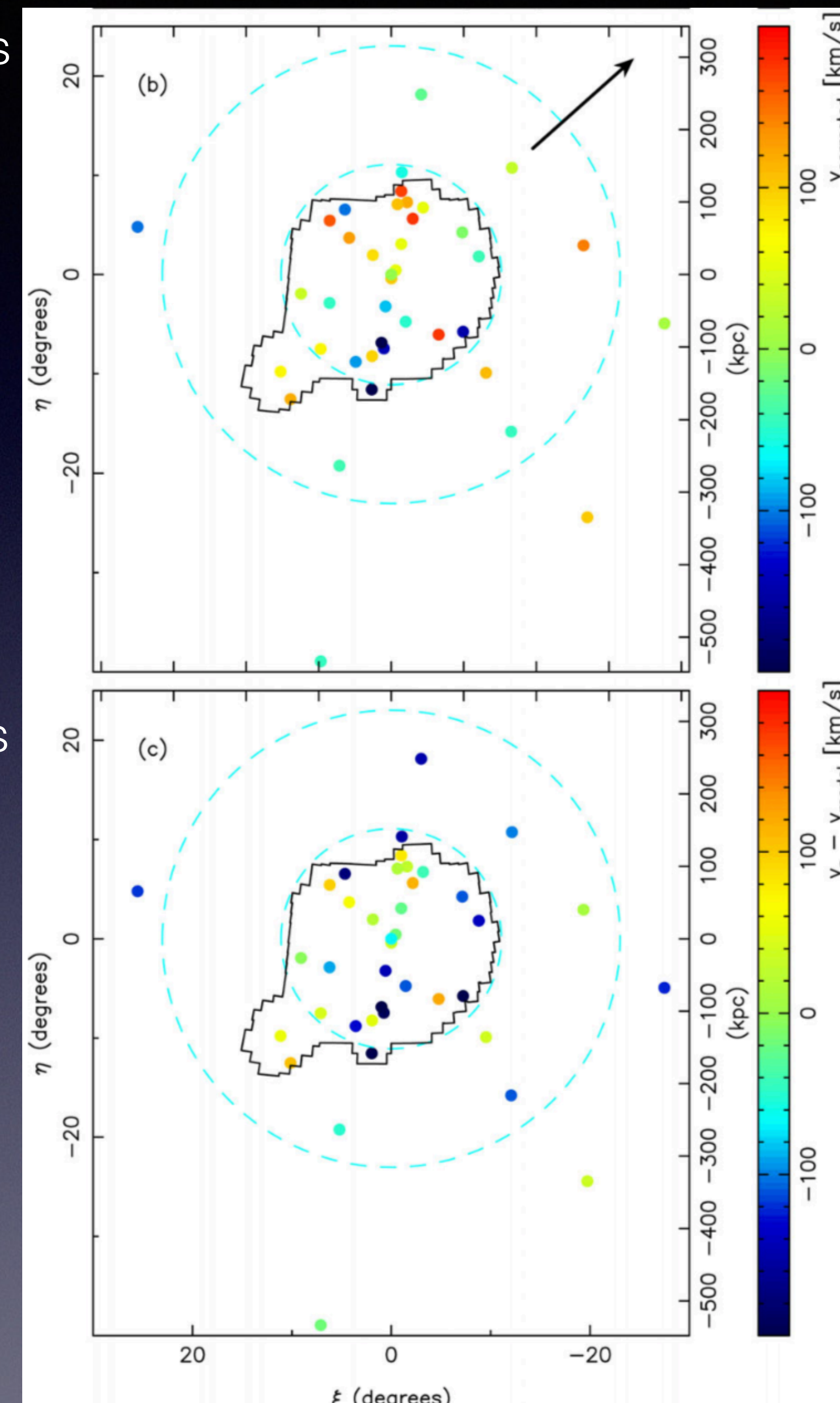
Heliocentric M31 transverse velocity



adapted from van der Marel et al. (2019)

Corrected velocities

Residuals



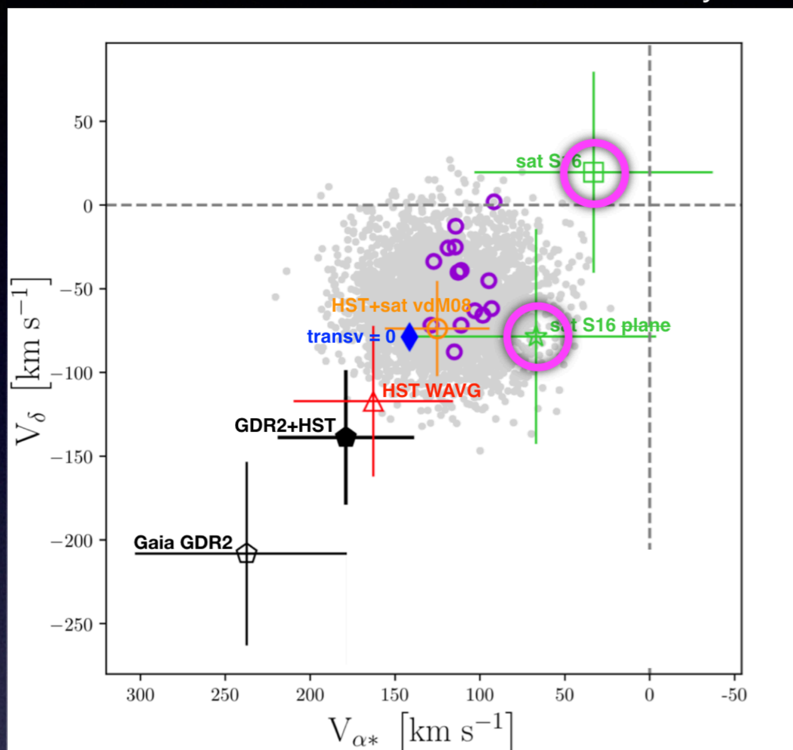
Velocities (km/s)

40 dwarf galaxies: 33 (-111) ± 70 km/s to the East
20 (99) ± 60 km/s to the North

Salomon et al. (2016)

1st statistical estimation

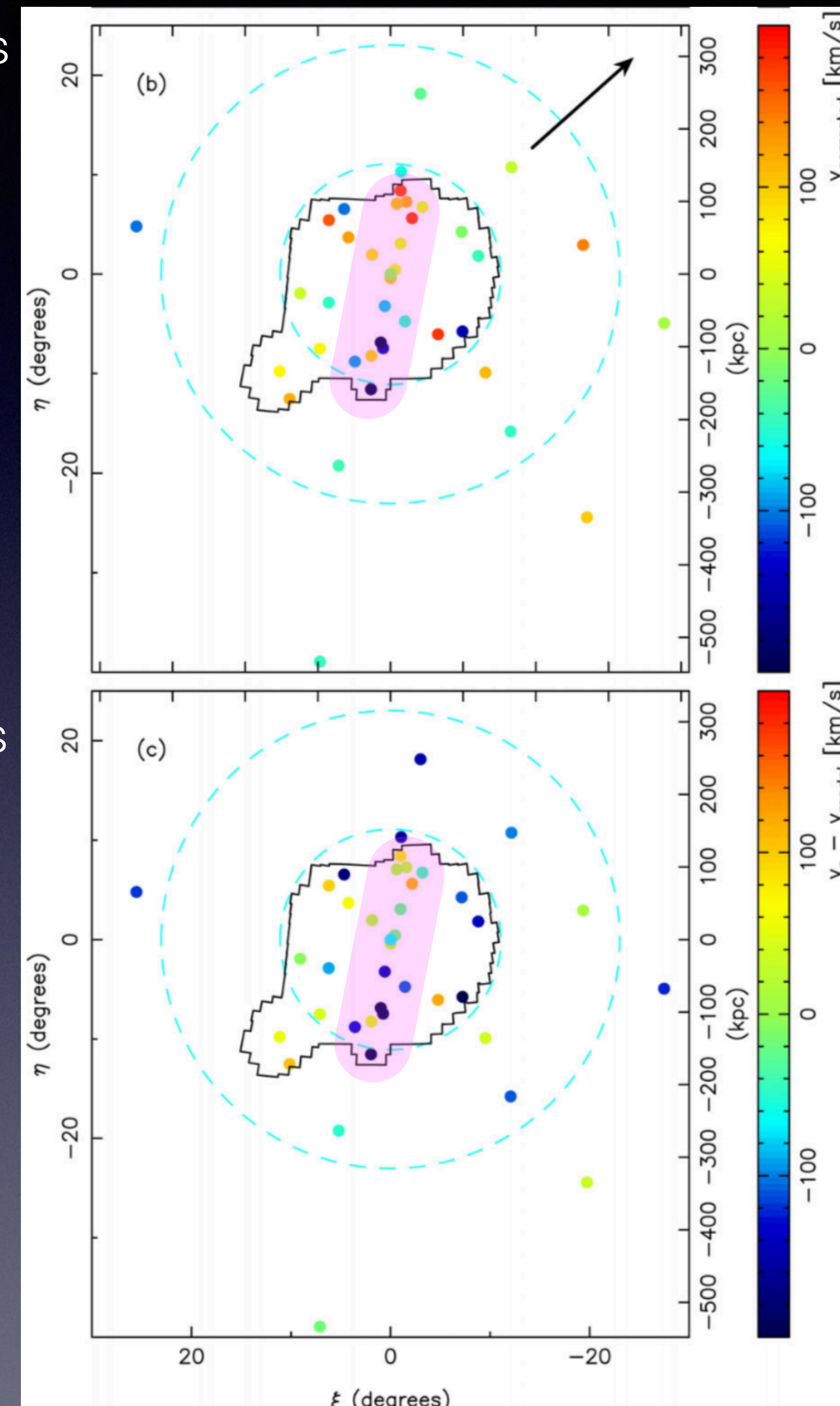
Heliocentric M31 transverse velocity



adapted from van der Marel et al. (2019)

Corrected velocities

Residuals



Velocities (km/s)

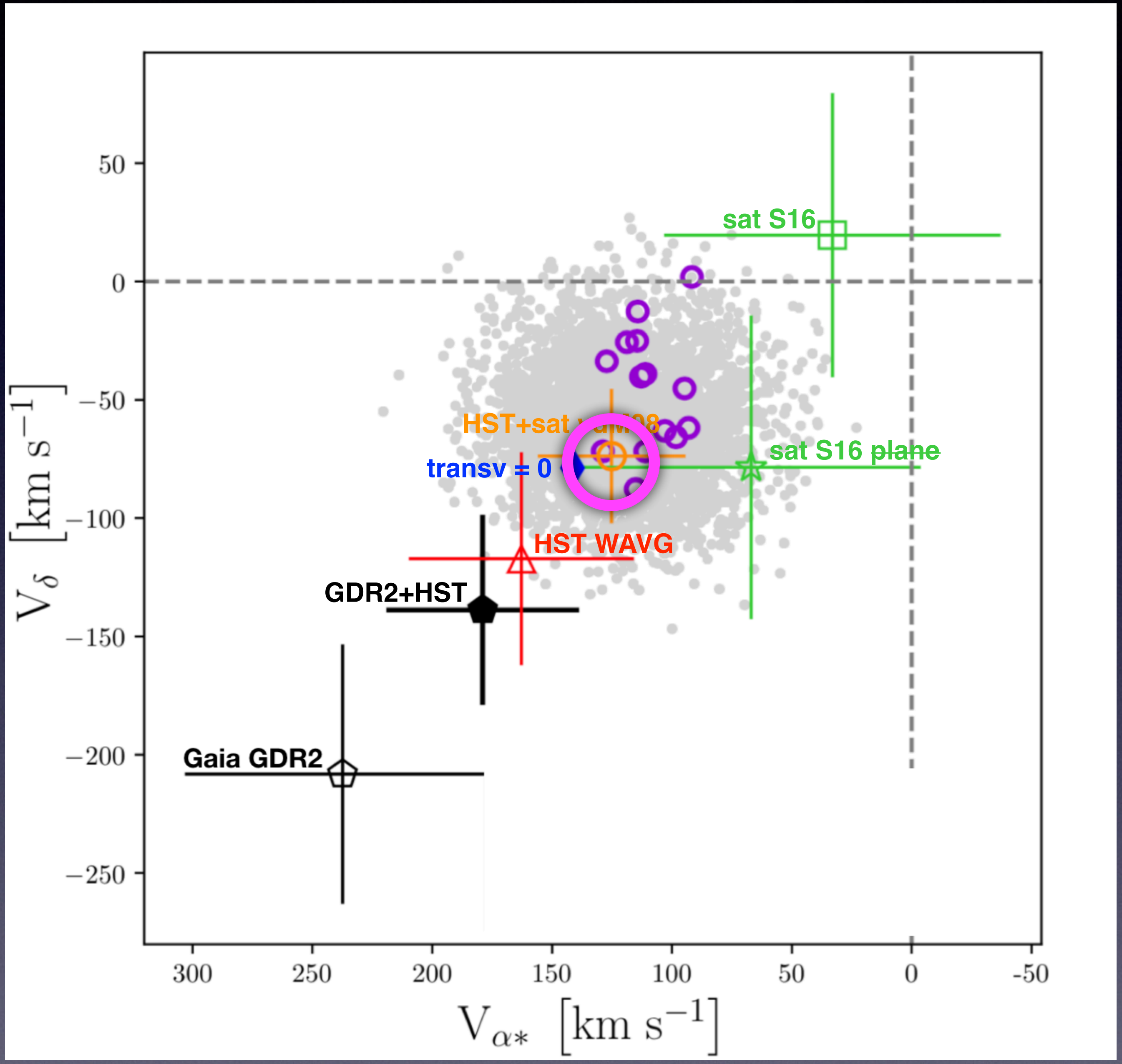
40 dwarf galaxies: 33 (-111) ± 70 km/s to the East
20 (99) ± 60 km/s to the North

26 (plane excluded): -78 ± 71 km/s to the East
1 ± 64 km/s to the North

Salomon et al. (2016)

2nd statistical estimation

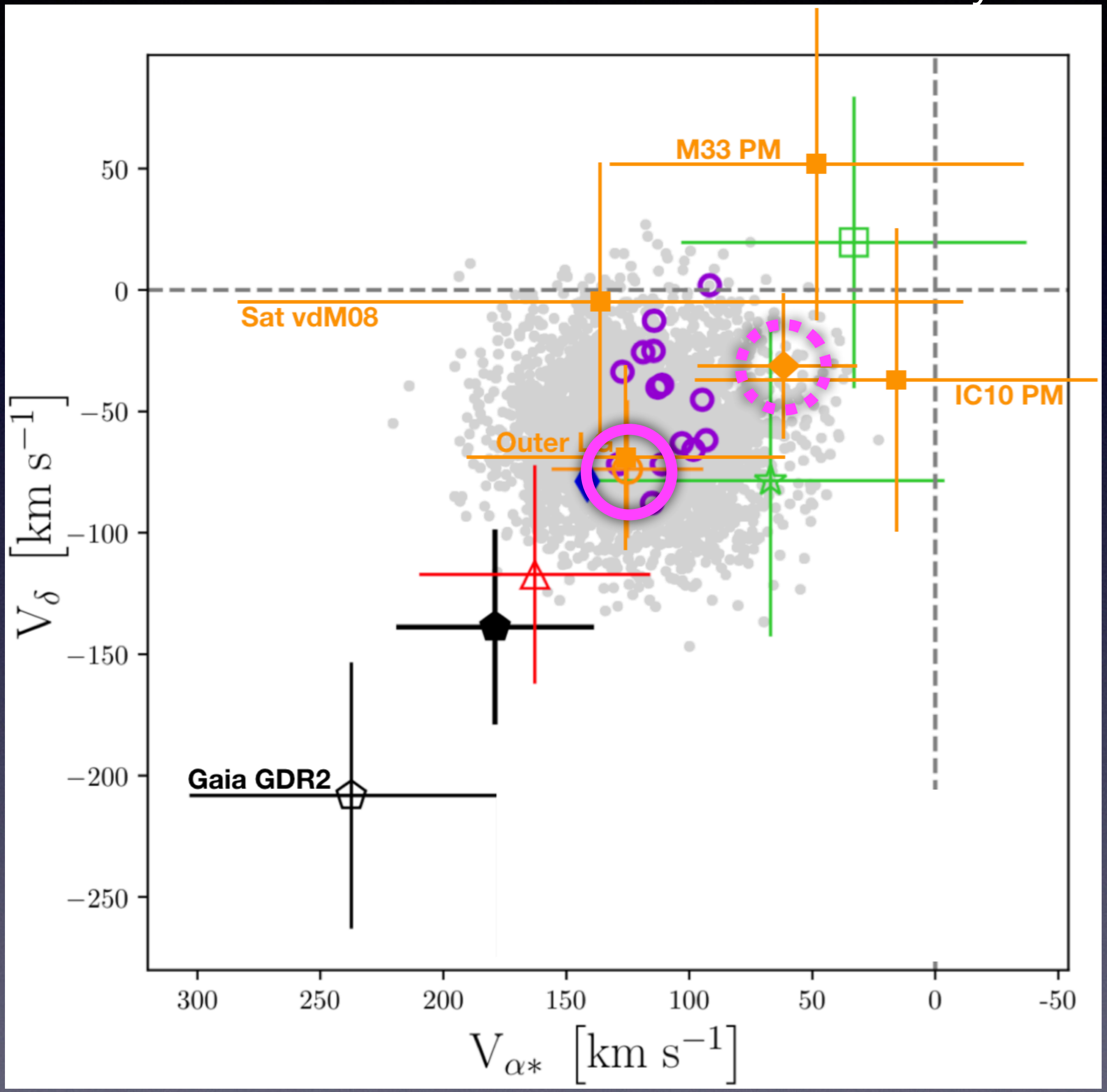
Heliocentric M31 transverse velocity



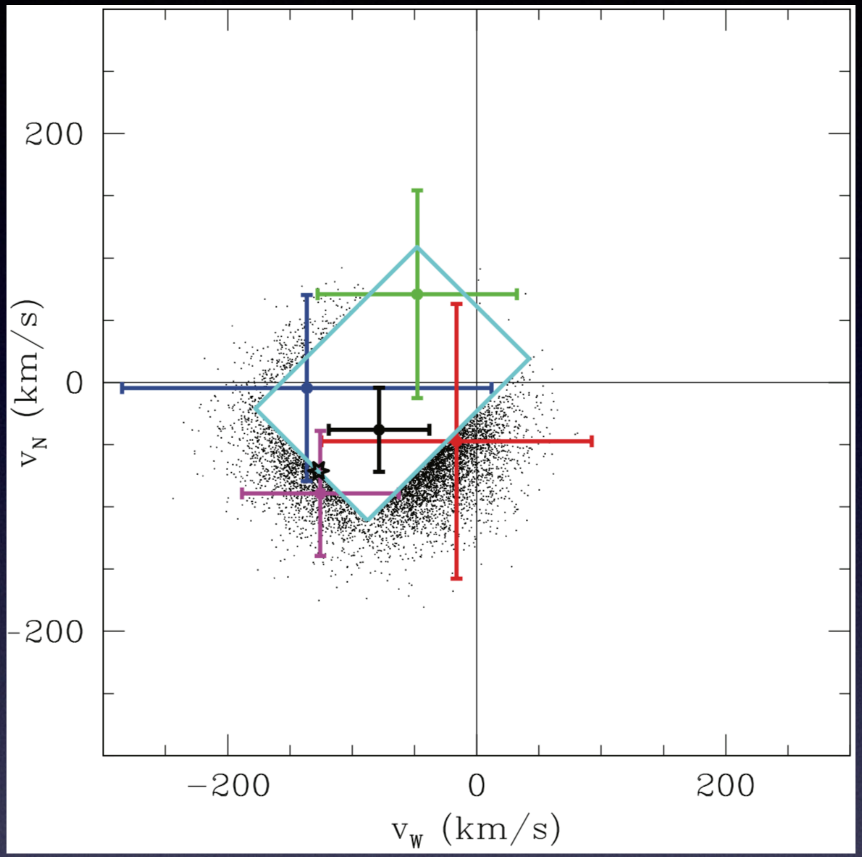
adapted from van der Marel et al. (2019)

2nd statistical estimation

Heliocentric M31 transverse velocity



adapted from van der Marel et al. (2019)

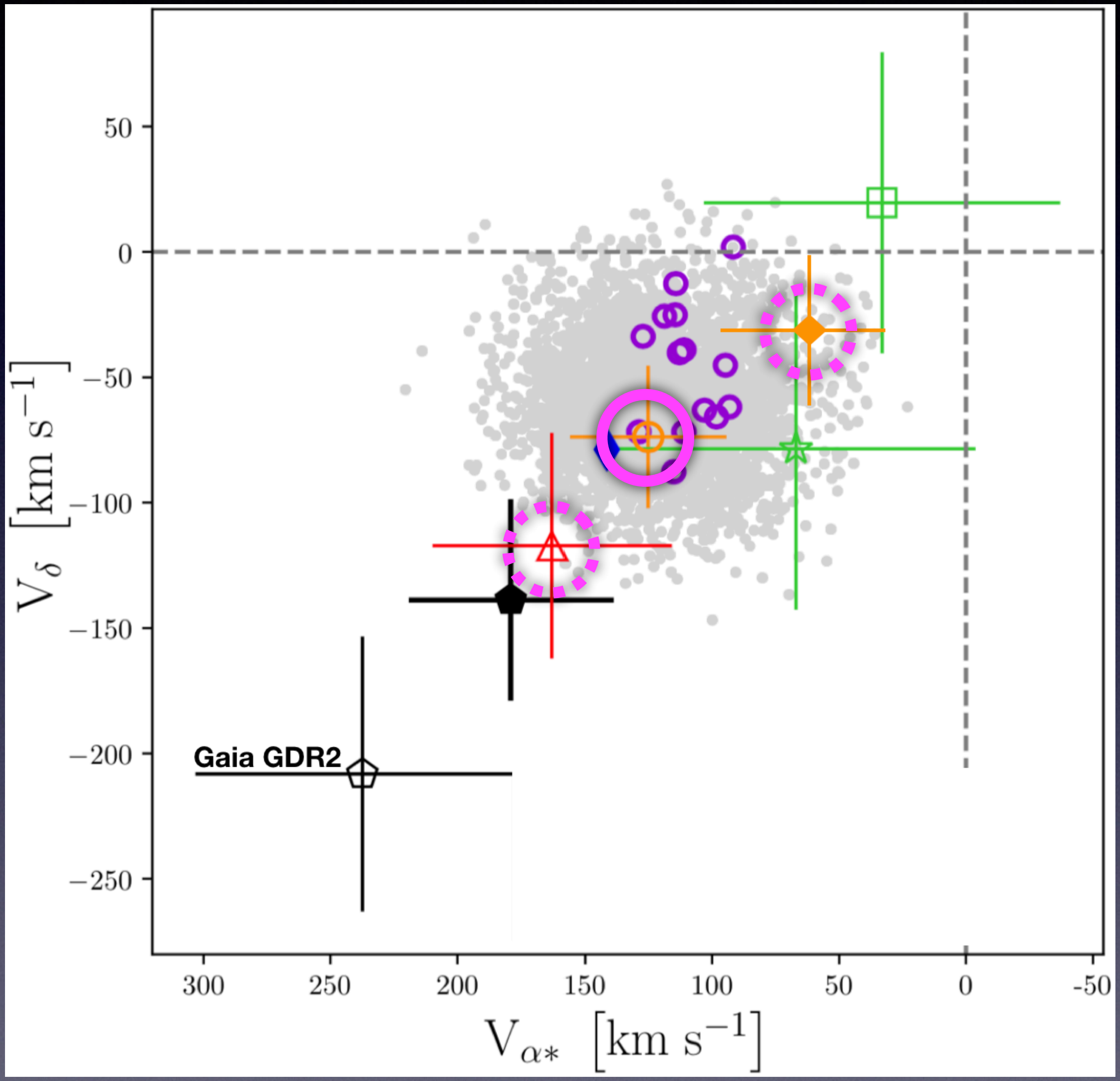


van der Marel & Guhathakurta (2008)

4 estimations:
- 17 M31 satellites
- M33 proper motion
- IC10 proper motion
- 5 outer LG satellites

1st observational estimation

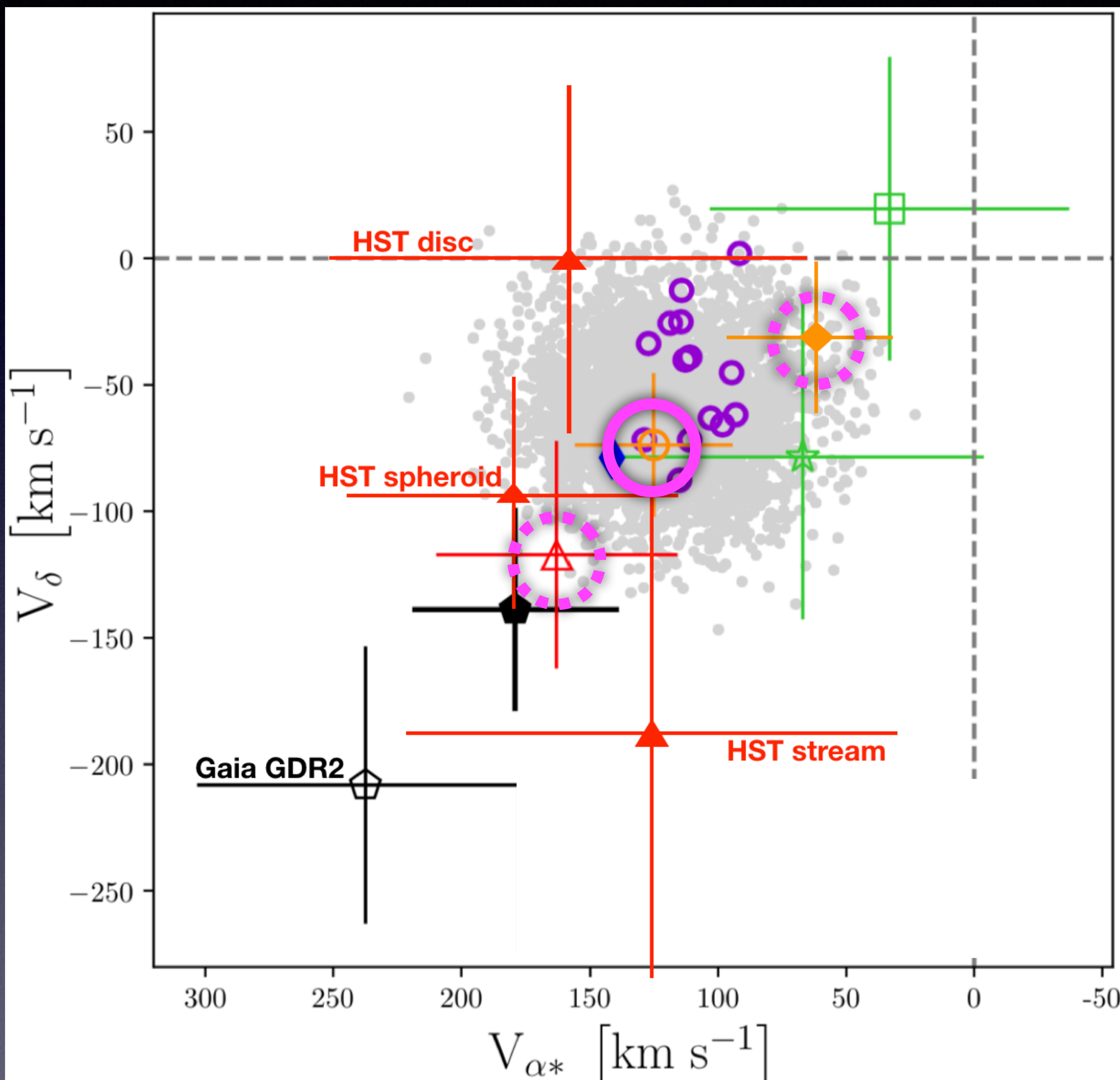
Heliocentric M31 transverse velocity



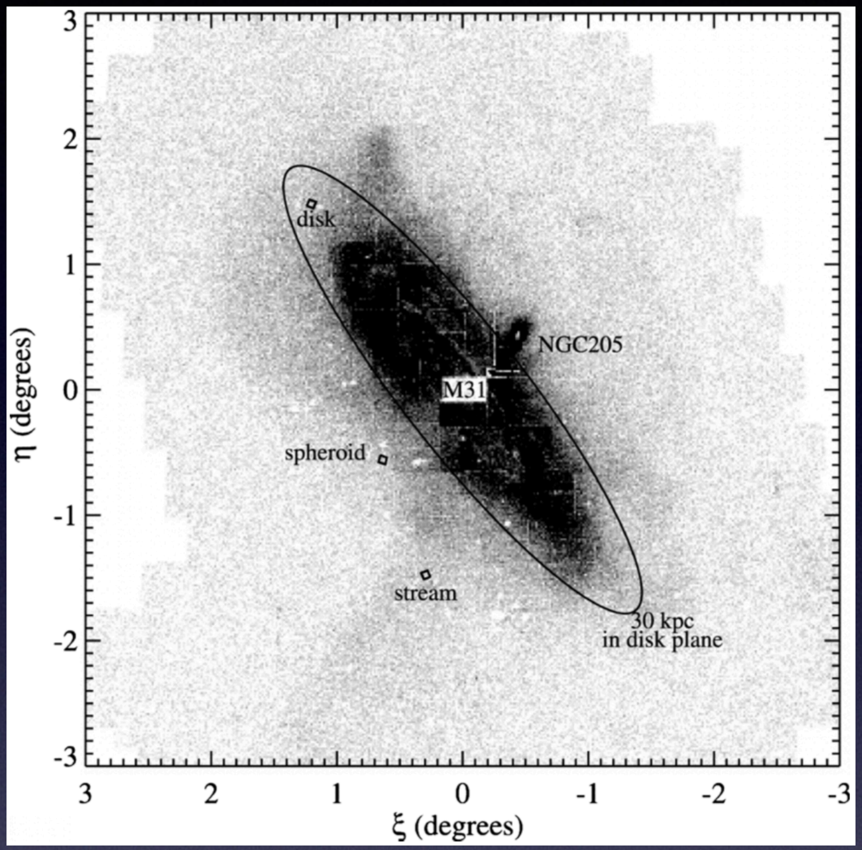
adapted from van der Marel et al. (2019)

1st observational estimation

Heliocentric M31 transverse velocity



adapted from van der Marel et al. (2019)

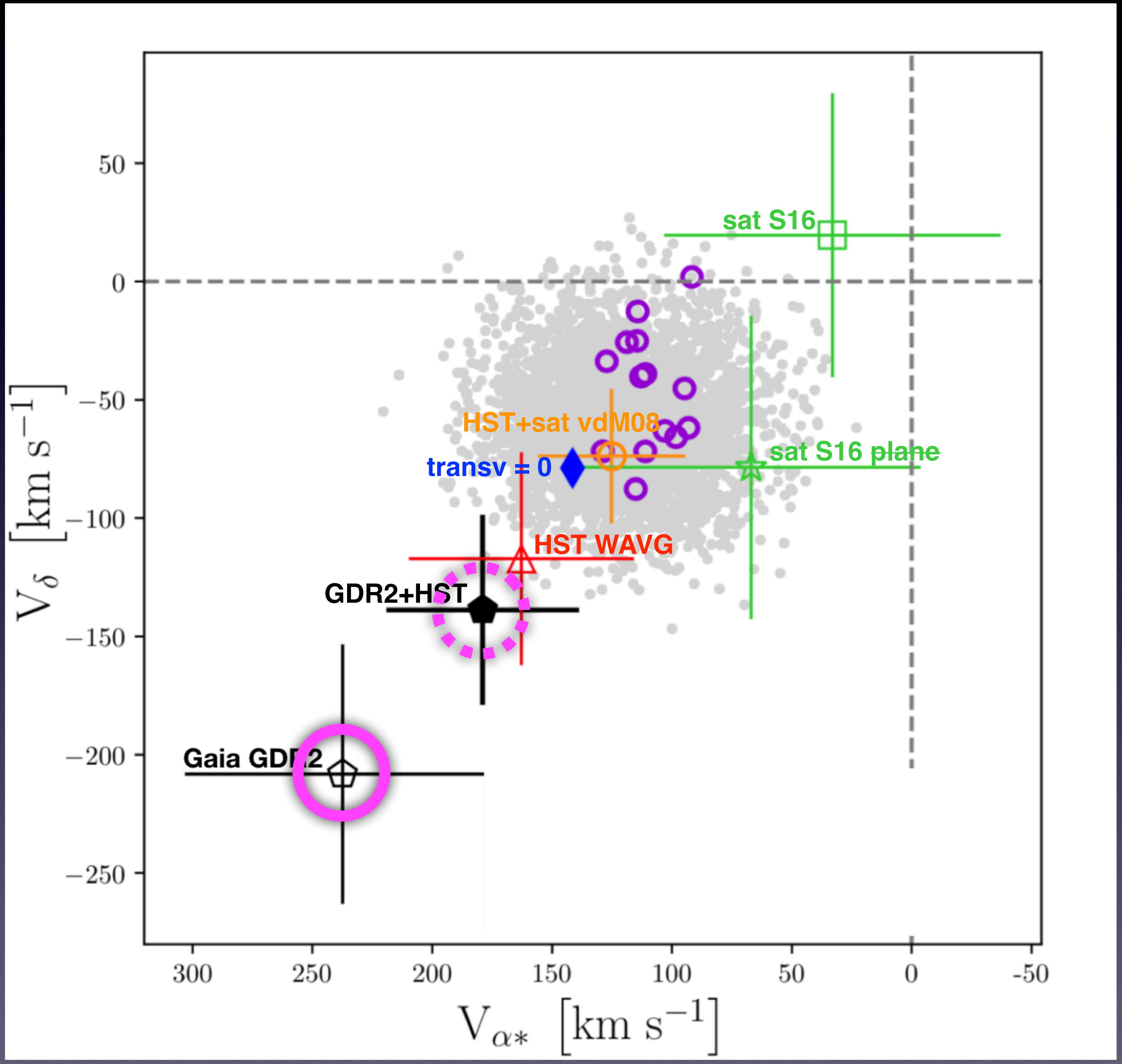


Sohn et al. (2012)

3 measurements:
- disk field
- bulge field
- stream field

2nd observational estimation

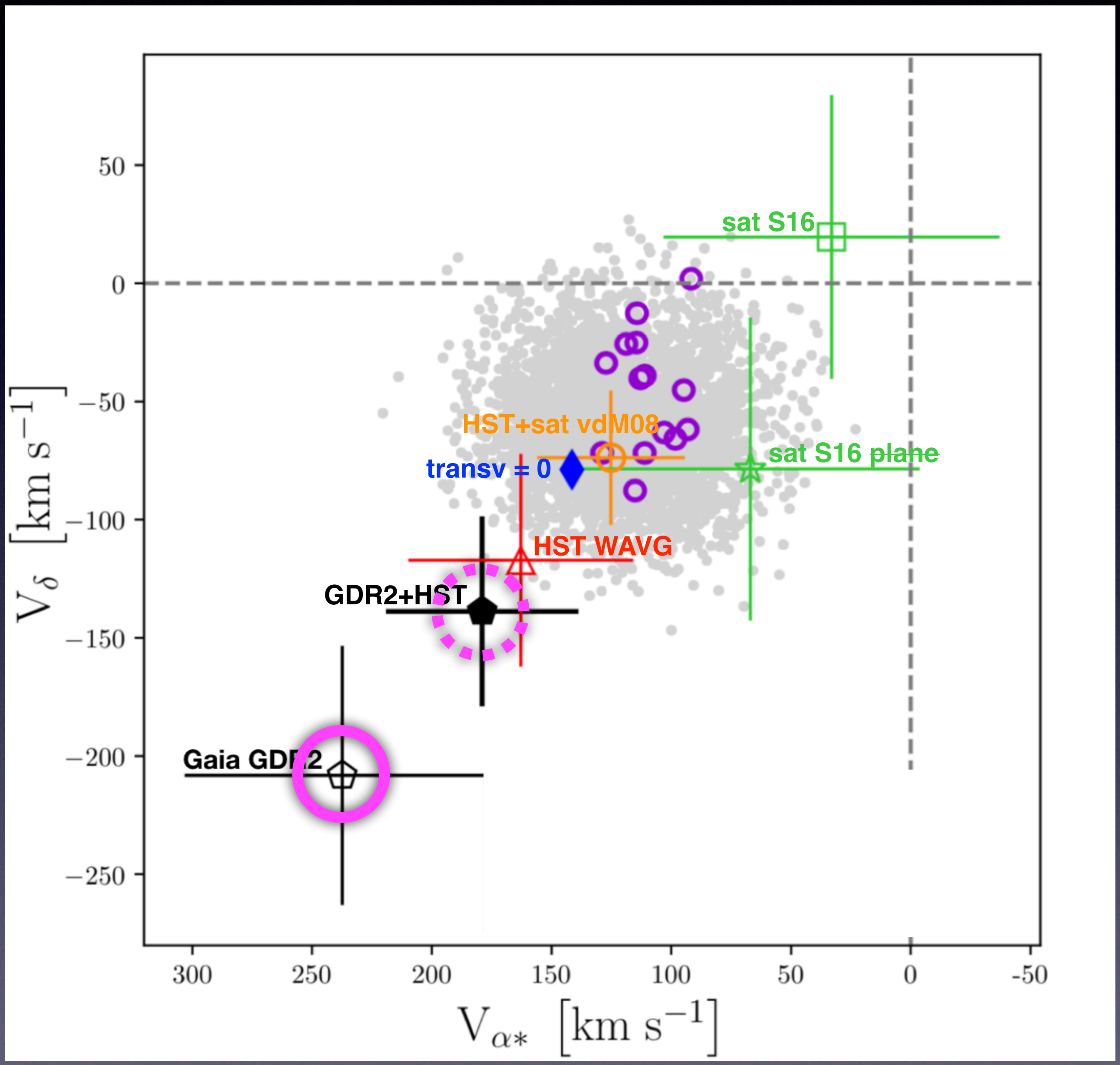
Heliocentric M31 transverse velocity



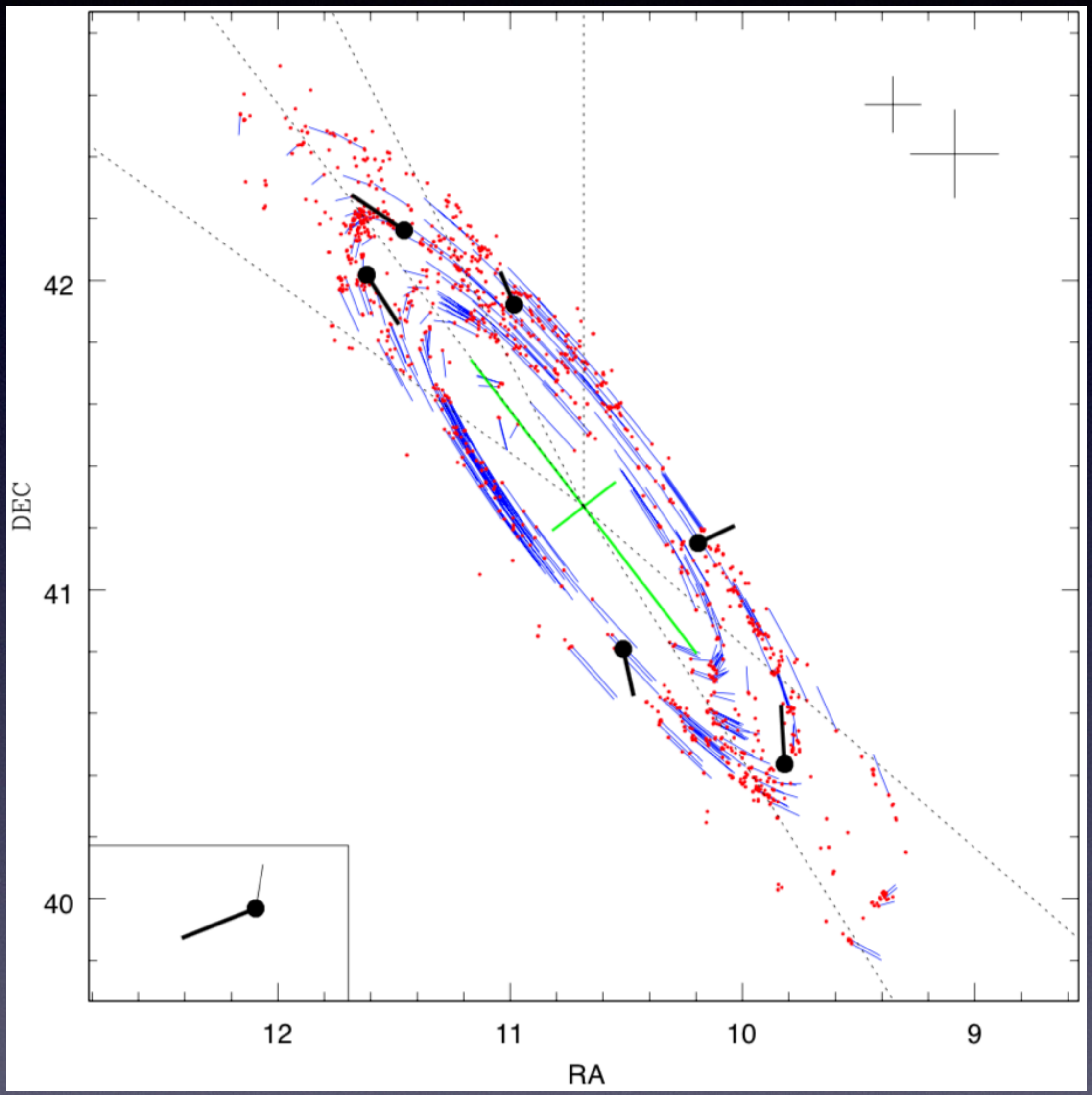
adapted from van der Marel et al. (2019)

2nd observational estimation

Heliocentric M31 transverse velocity



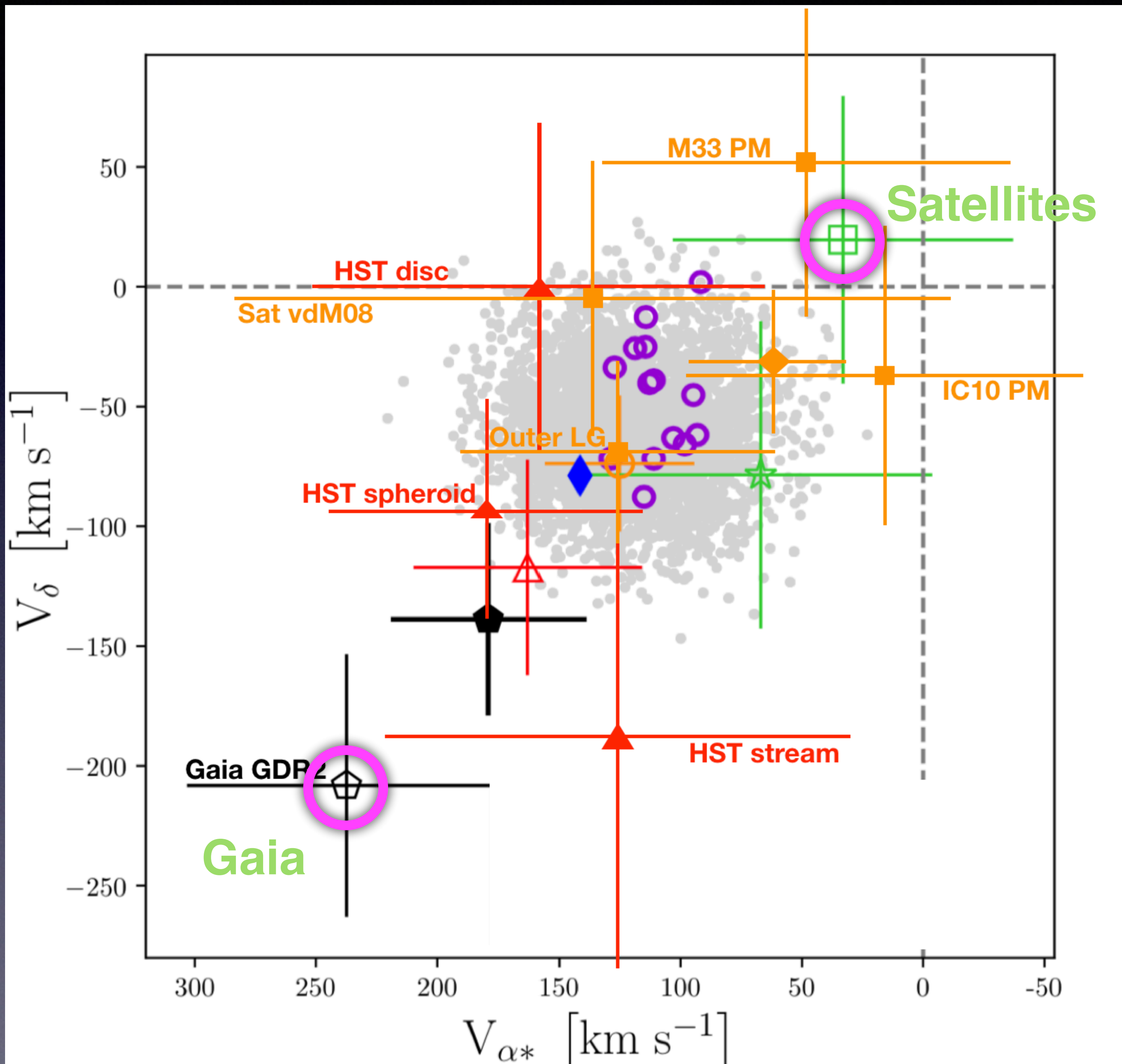
adapted from van der Marel et al. (2019)



van der Marel et al. (2019)

1084 sources

M31 proper motion



~ -75 km/s < V_{East} <~ 300 km/s
~ -290 km/s < V_{North} <~ 120 km/s

!!!

V_{East} = 113 ± 187 km/s
V_{North} = -85 ± 205 km/s

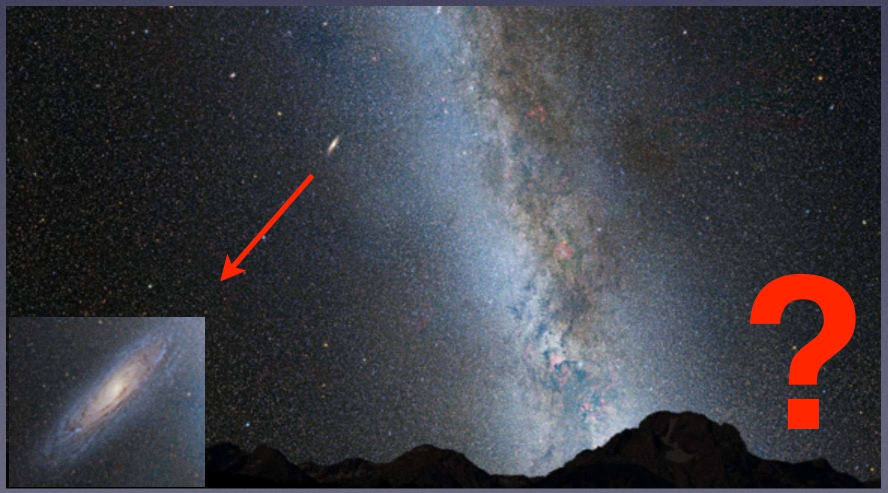
M31 proper motion

Present time

M31 proper motion

Present time

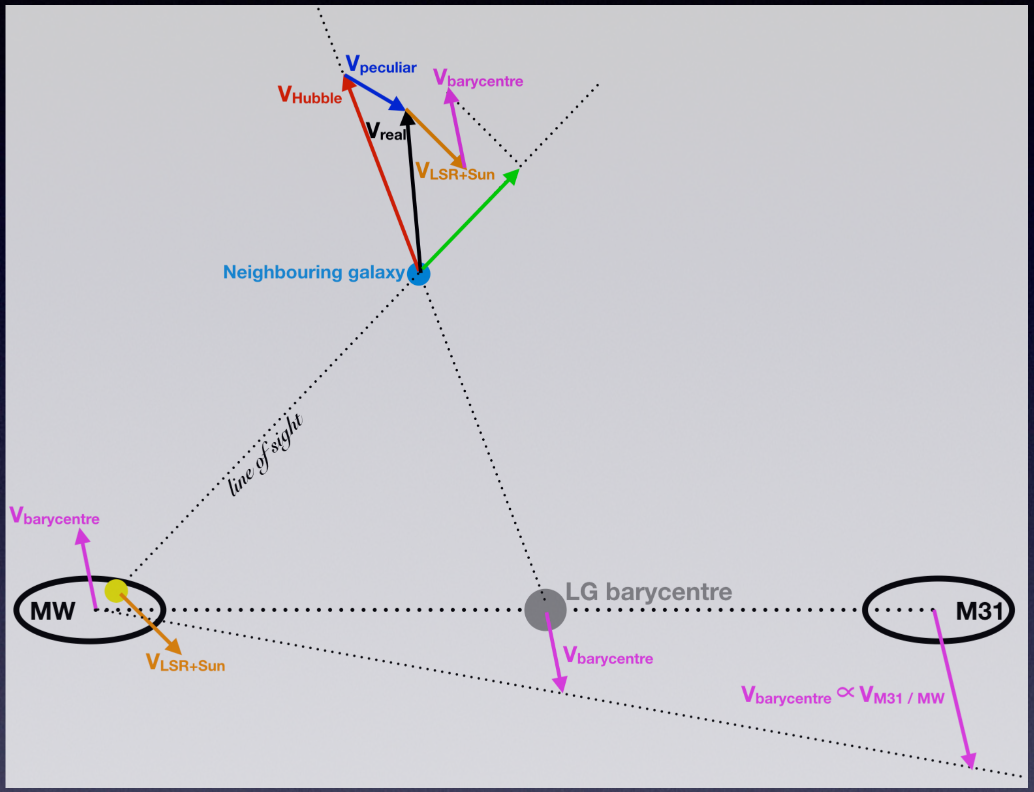
In 6 billion years



OR

OR

Validation

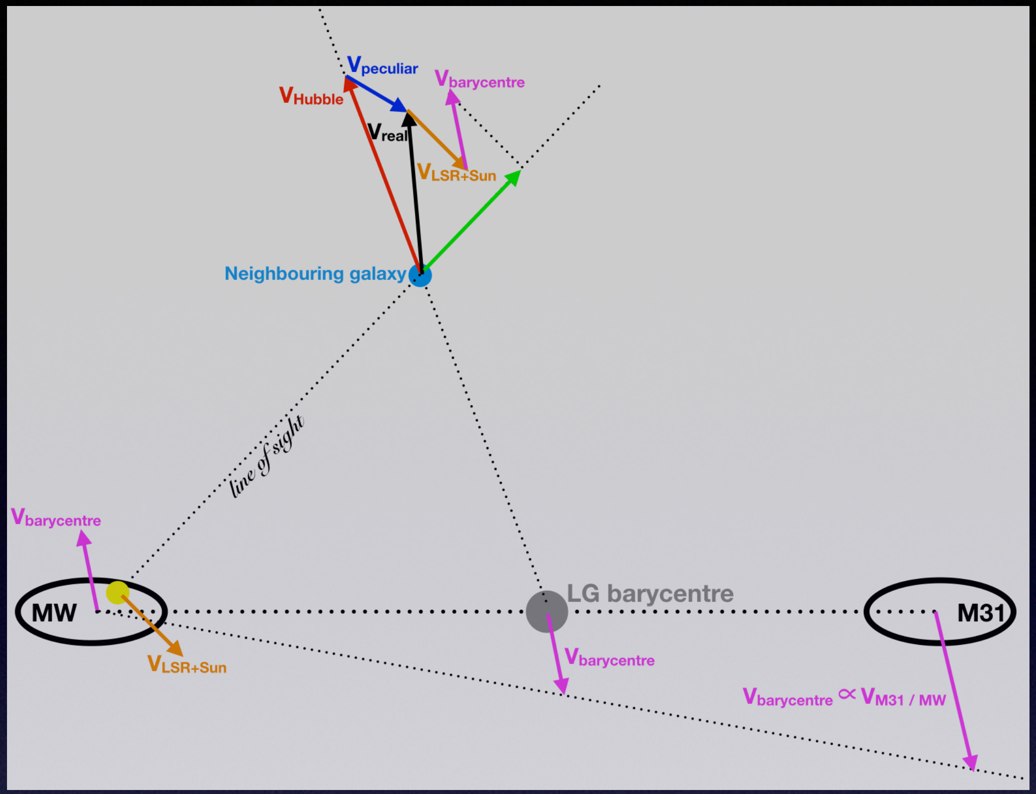


MOCK data:

- 30 galaxies uniformly distributed in space from 0,5 to 3 Mpc (d_{gal})
- $V = V_H + V_{peculiar}$ with
  $V_H = d \times 73$ (barycentre direction)
  $V_{peculiar} = 100 \pm 100$ km/s (random 3D)
- 100 of such sample
- observed from a Sun-like position
  $(R, z, vx, vy, vz, D_{LG}, vx_{M31}, vy_{M31}, vz_{M31}) =$
  (8, 20, 11, 233, 7, 430, 300, 30, 20)

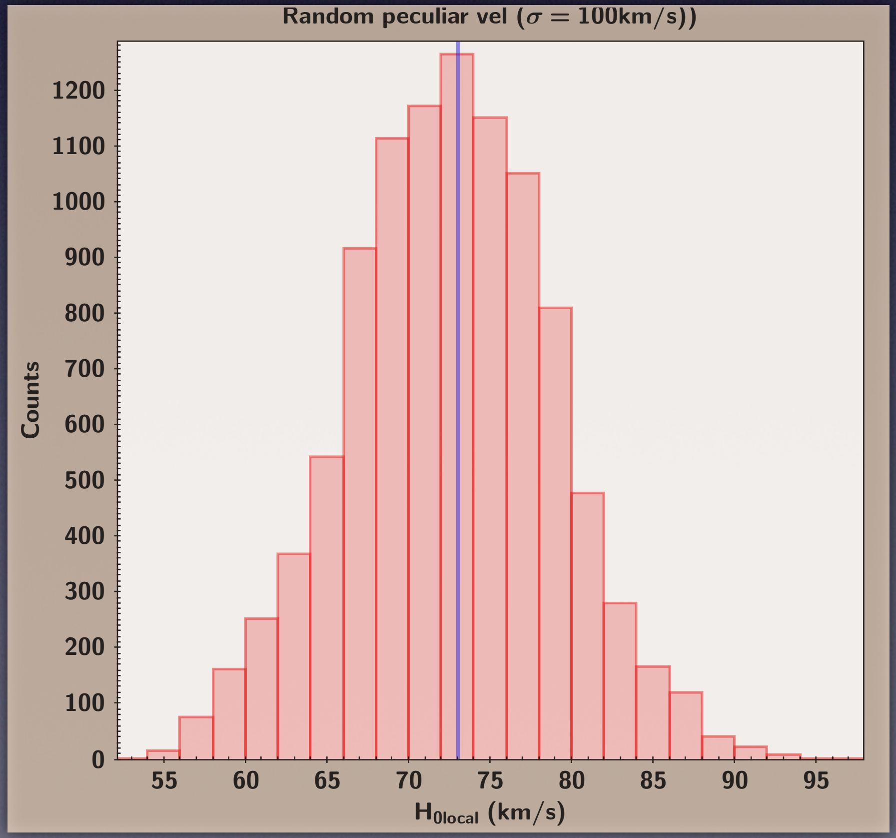
Guillaume Chaverot

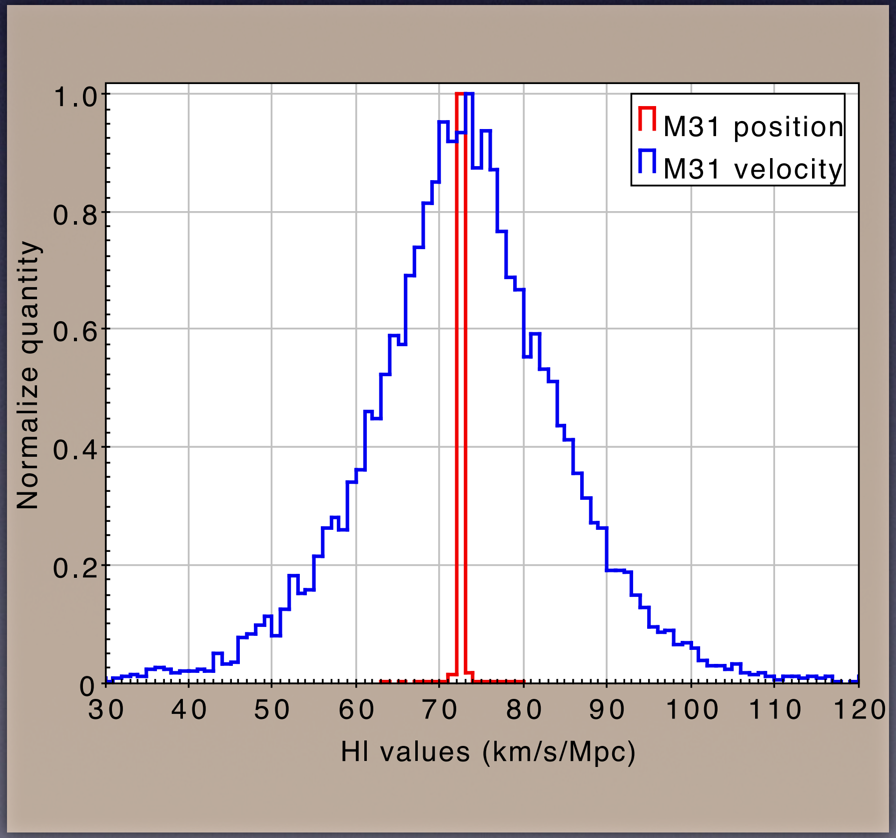
Validation

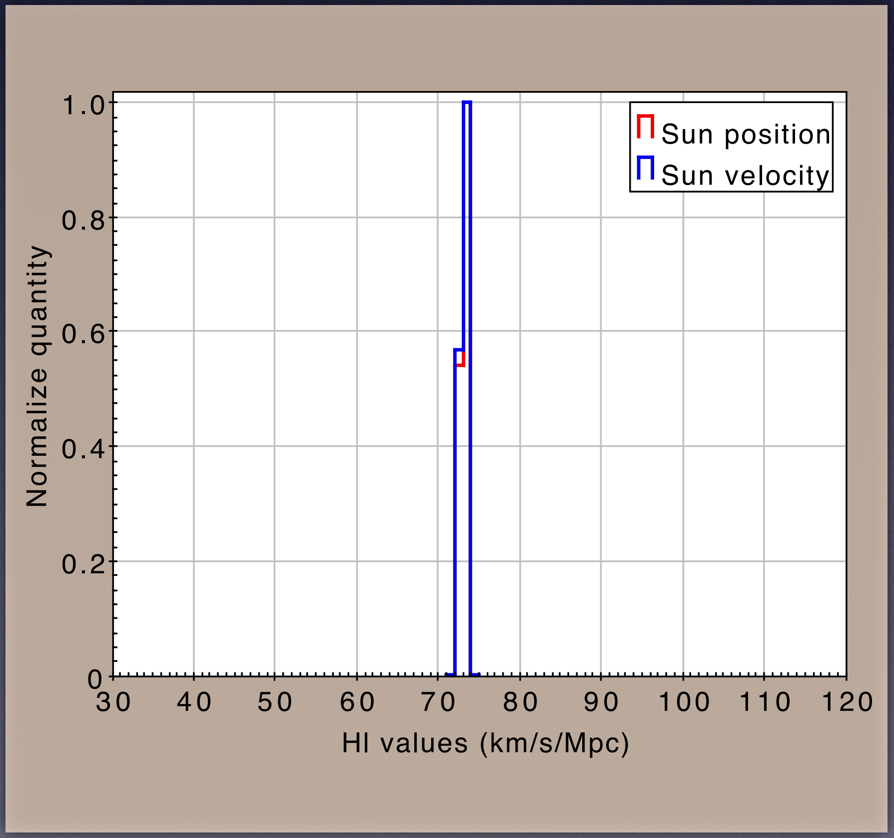


<u>Monte Carlo method</u>:

- for one “simulated local volume”, drawing of one set of parameters in the uncertainties range
- one distance per galaxy in distance uncertainty
- repeat 10000 times
- linear fitting to get the Hubble parameters

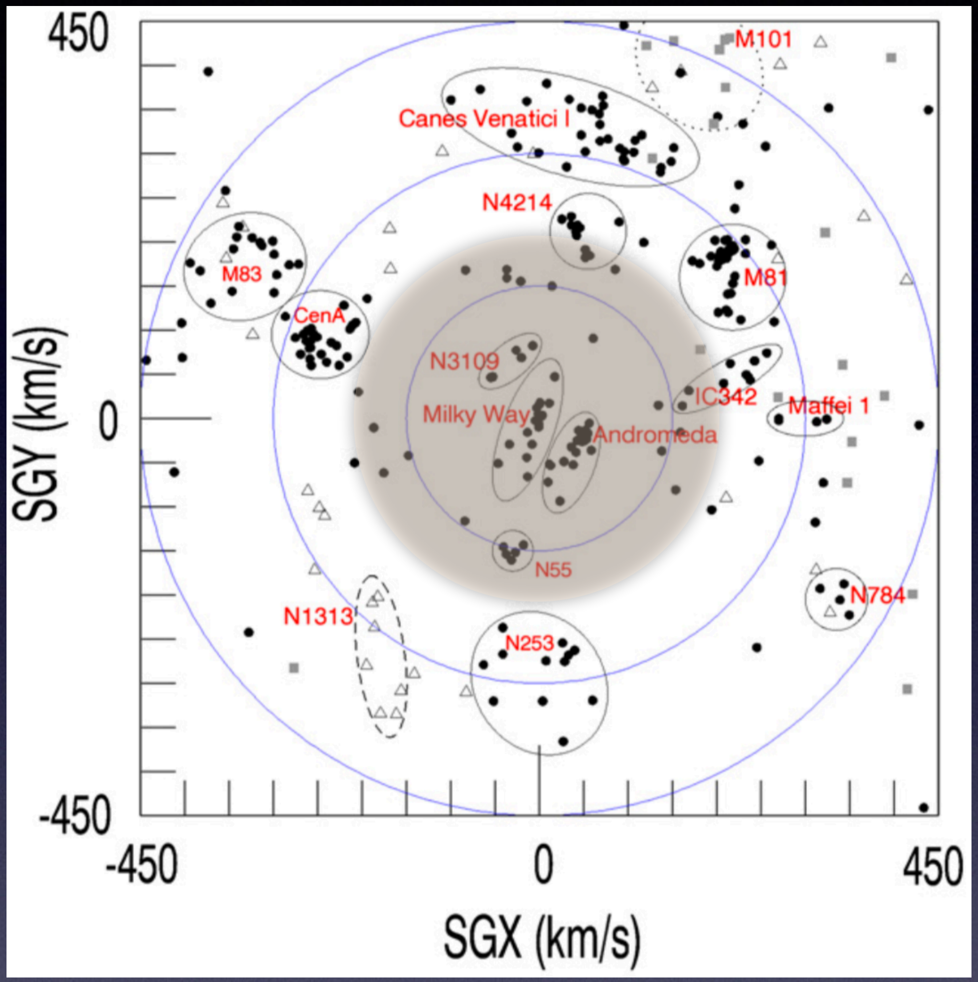


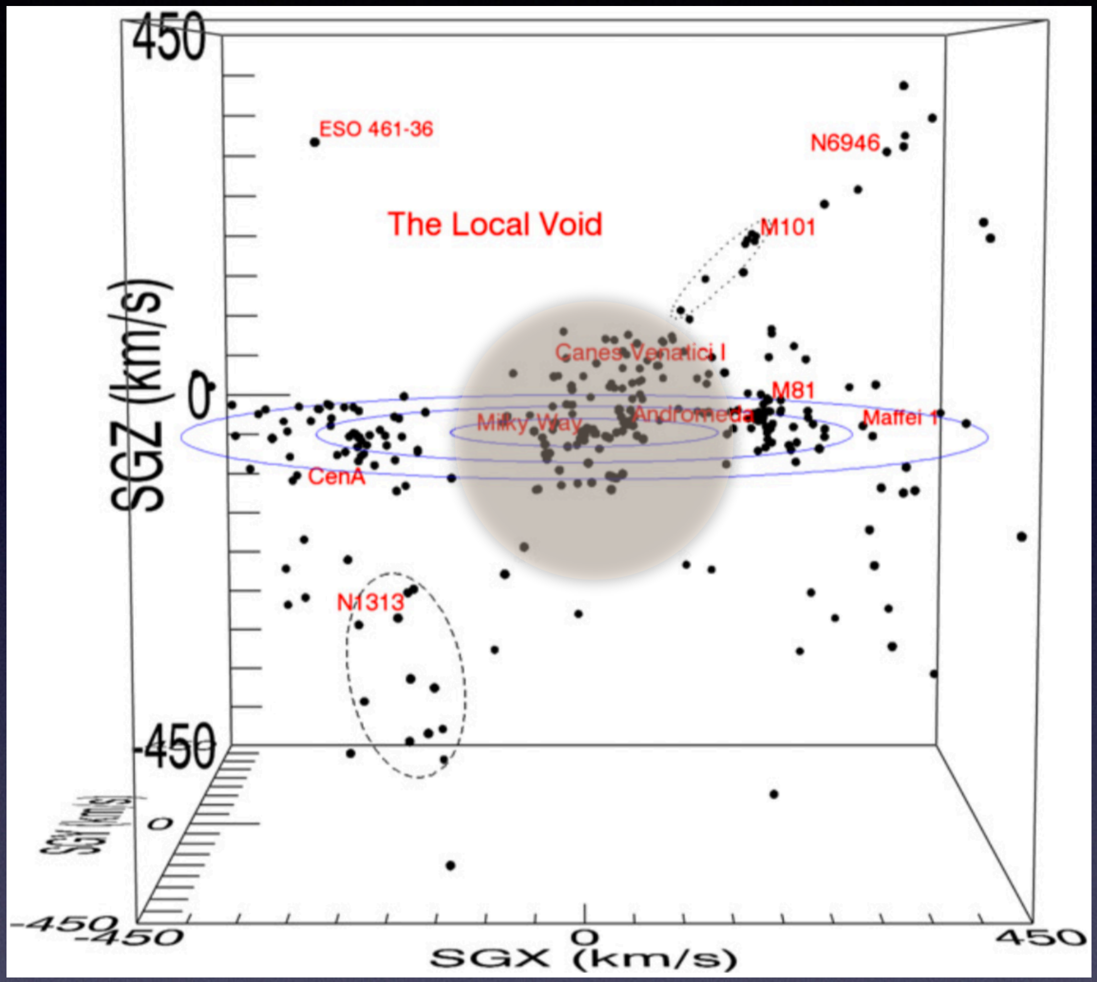




Guillaume Chaverot
Jean-Baptiste SALOMON

Sample





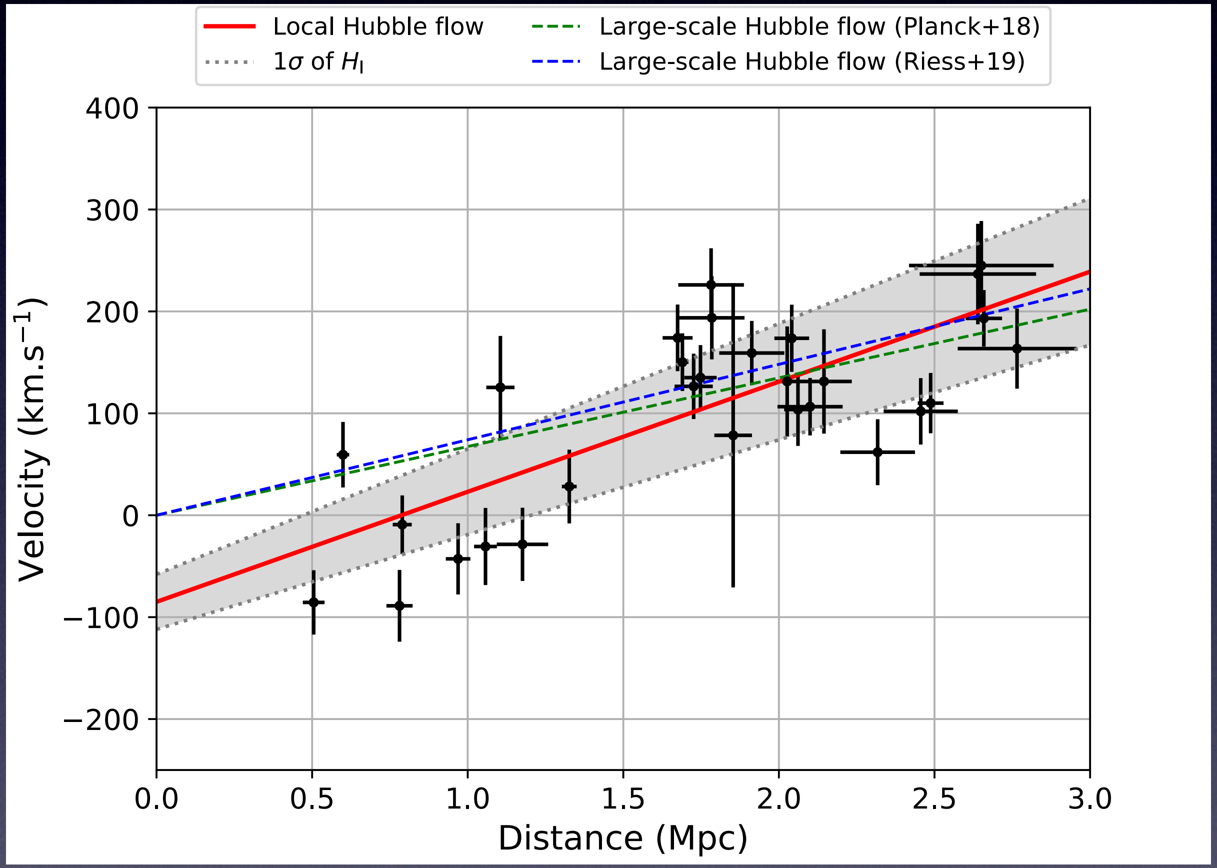
Courtois et al. (2013)

30 galaxies [0.5 - 3 Mpc] considered as not belonging to the MW or to the M31 system

McConnachie et al. (2012)

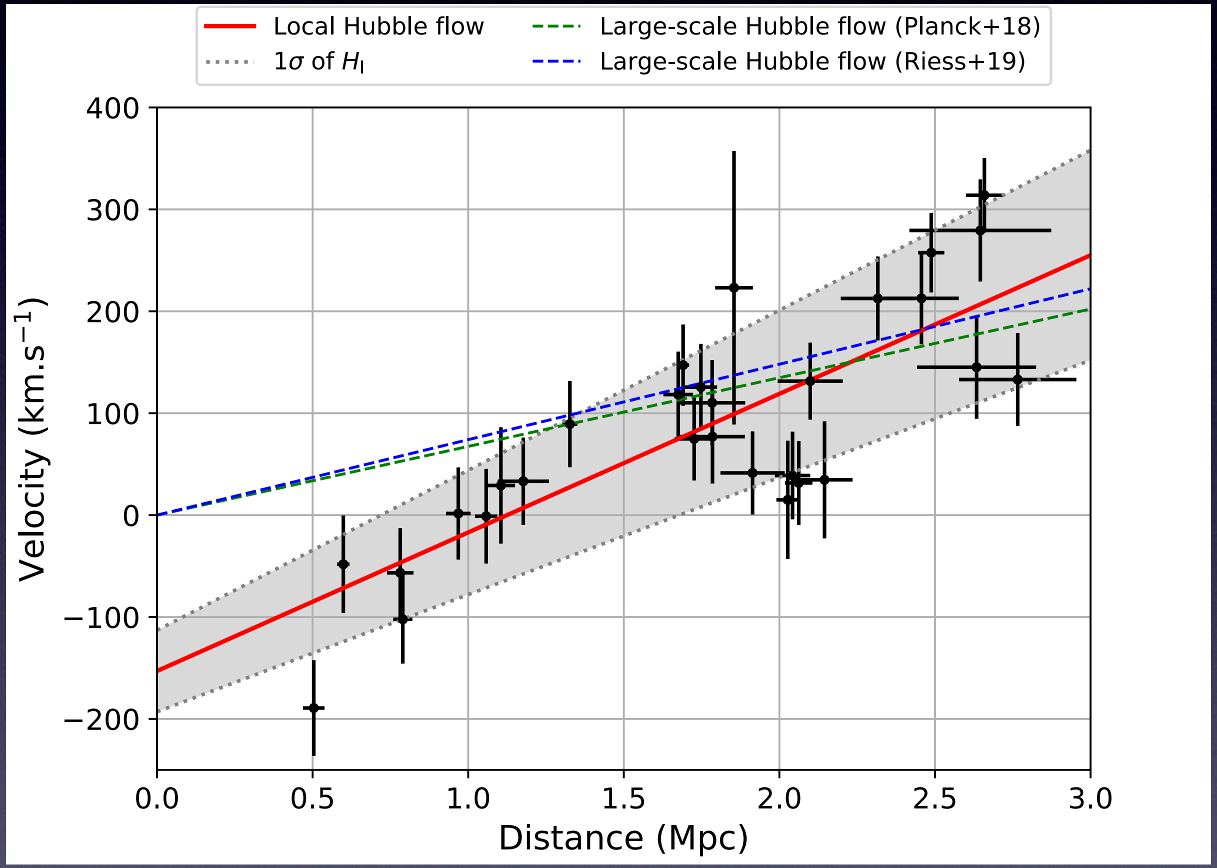
Impact of M31 proper motion

Satellites



H_L = 108 ± 15 km/s/Mpc
R ~ 780 kpc
(V = -85 ± 27 km/s)

Gaia



H_L = 136 ± 21 km/s/Mpc
R ~ 1120 kpc
(V = -153 ± 40 km/s)

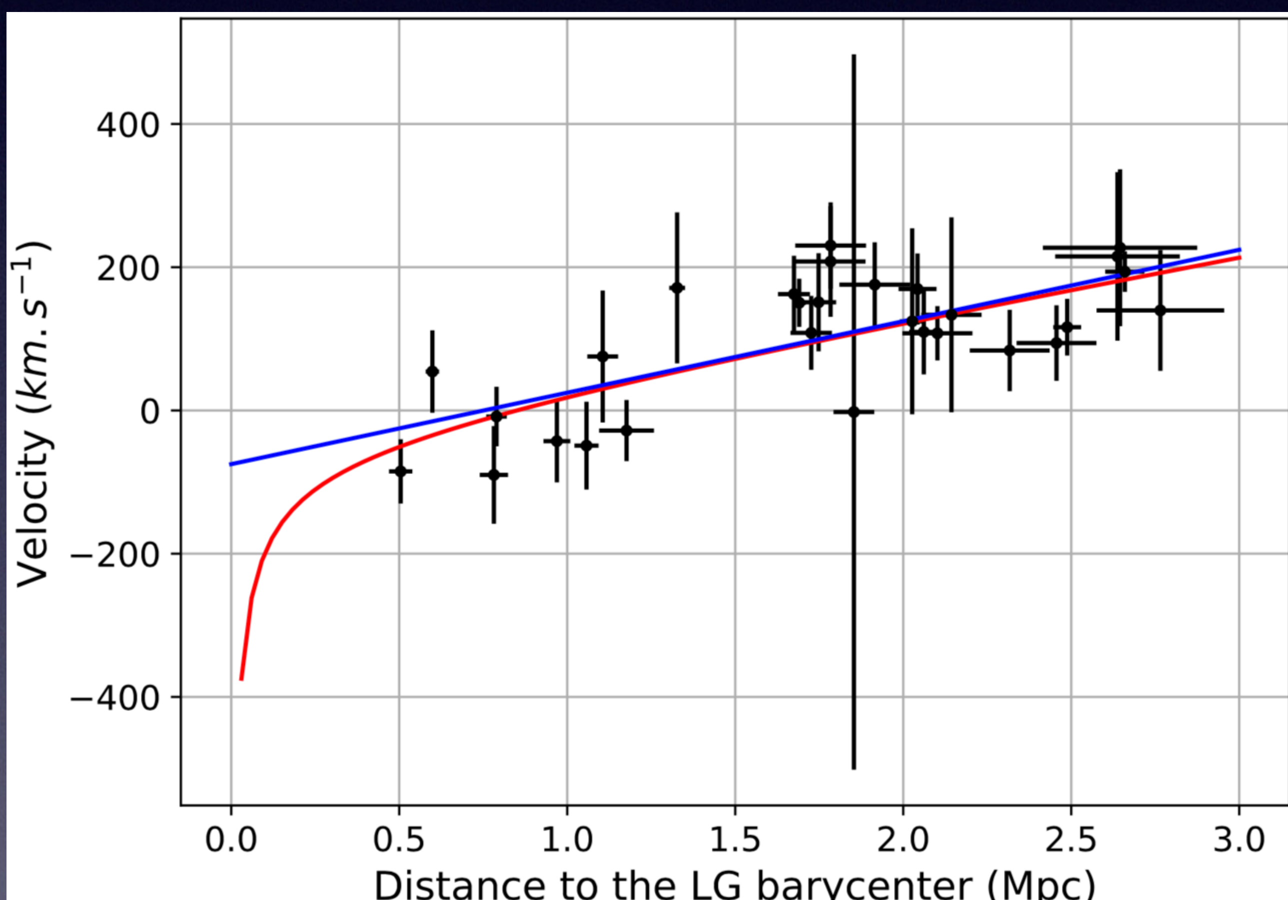
Mass

Peirani & Freitas Pacheo et al. (2008)

Canonical Lemaître Tolman model
with n = 0.627

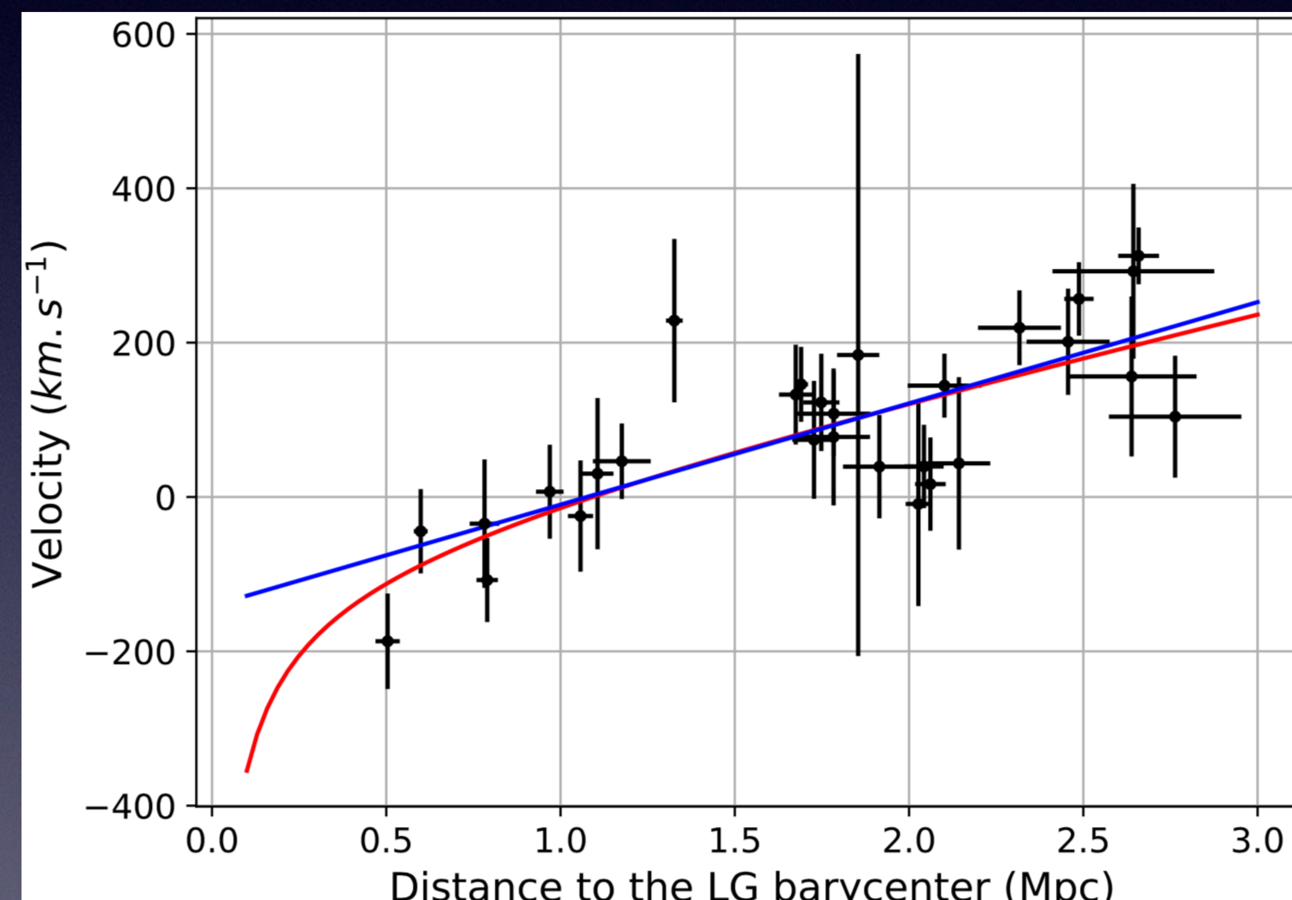
$$v(R) = -1.038 \left(\frac{GM}{R}\right)^{1/2} + 1.196 H_0 R$$

Satellites



H_L = 70.0 ± 16.0 km/s/Mpc
R ~ 810 kpc
9.3 ± 6.6 x 10^{11} M_{Sun}

Gaia



H_L = 84.4 ± 15.0 km/s/Mpc
R ~ 1120 kpc
2.9 ± 1.7 x 10^{12} M_{Sun}

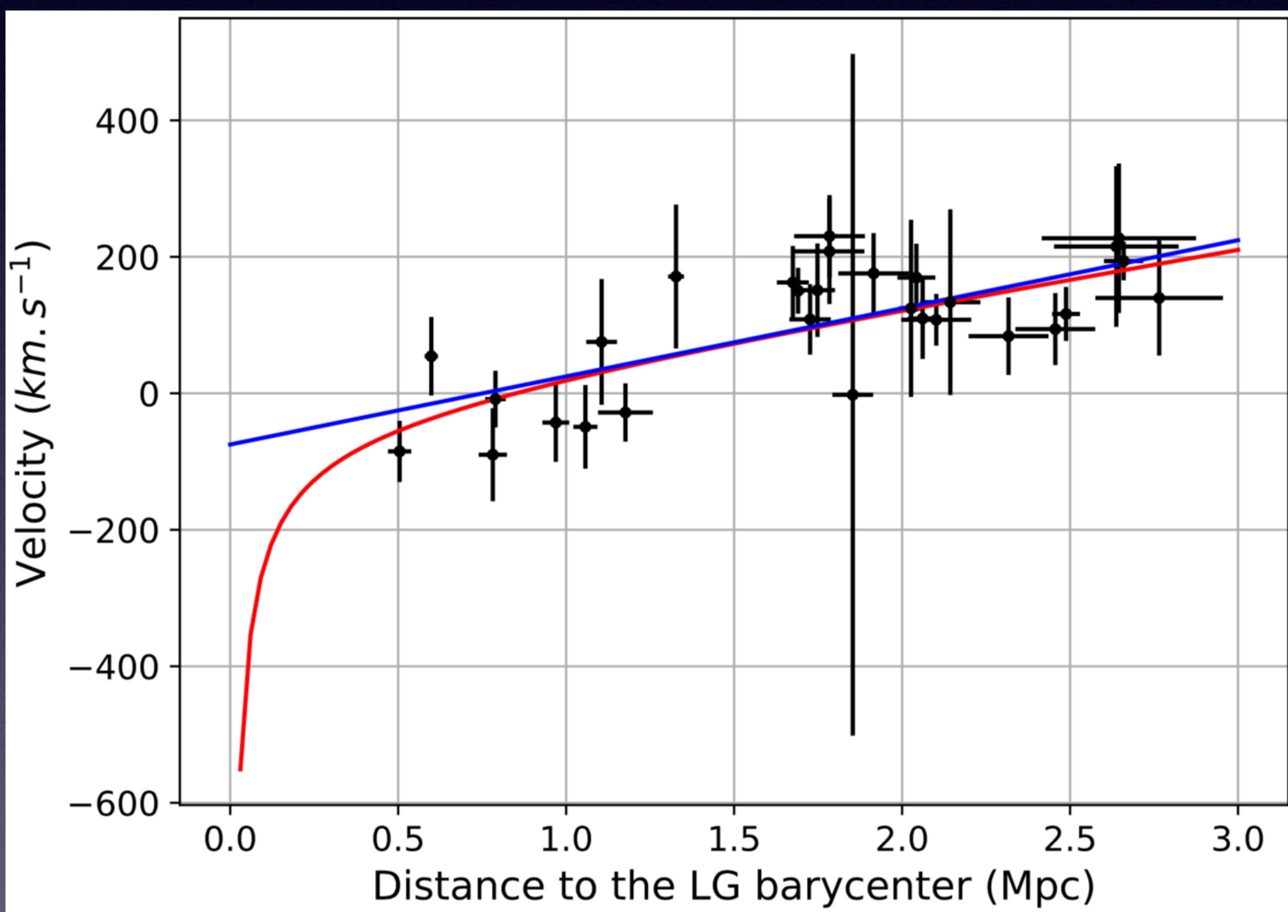
Mass

Peirani & Freitas Pacheo et al. (2008)

Modified Lemaître Tolman model
with n = 0.627

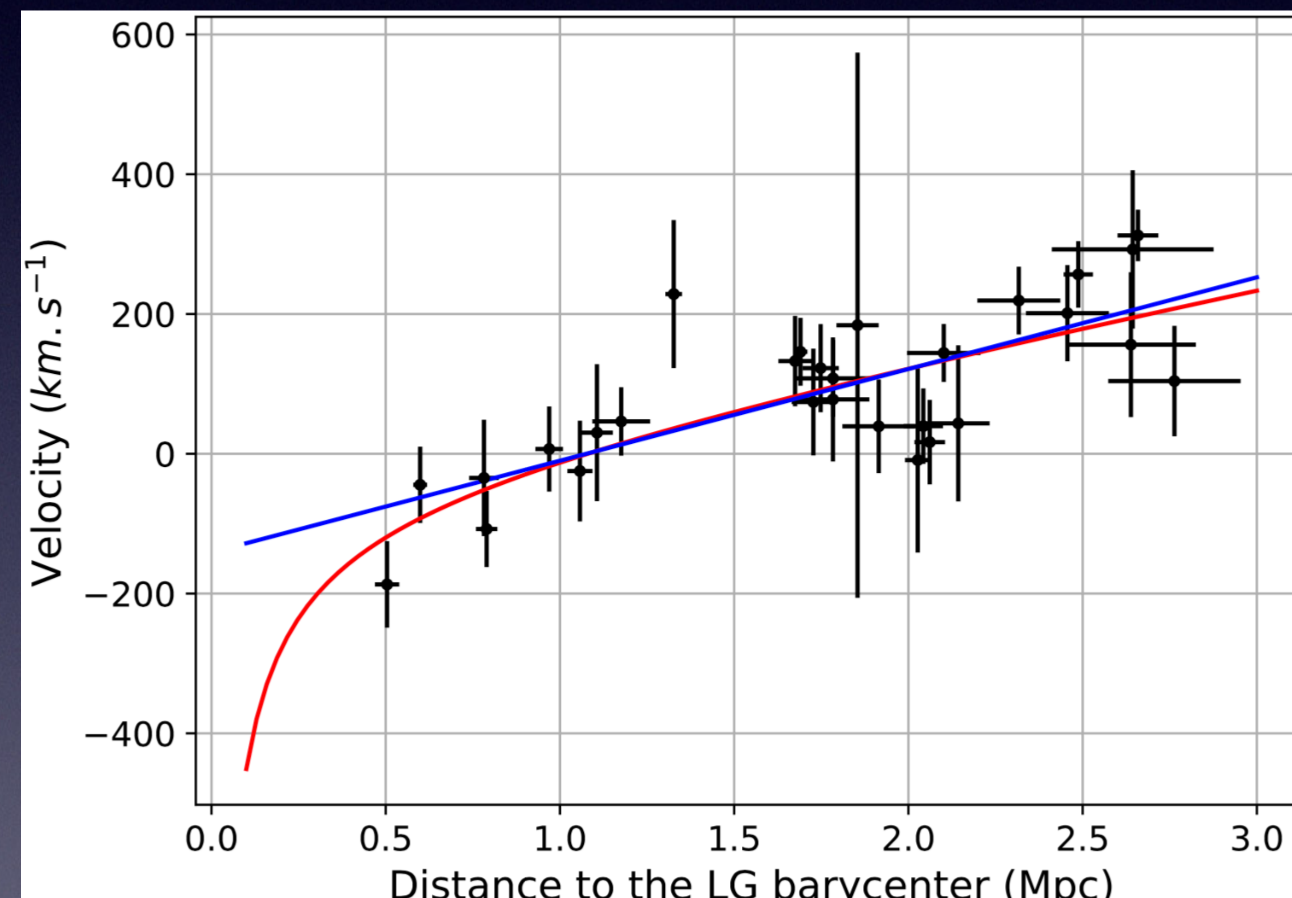
$$v(R) = -\frac{0.976 H_0}{R^n}\left(\frac{GM}{H_0^2}\right)^{(n+1)/3} + 1.377 H_0 R$$

Satellites



H_L = 58.4 ± 14.4 km/s/Mpc
R ~ 810 kpc
9.2 ± 6.3 x 10^{11} M_{Sun}

Gaia



H_L = 69.7 ± 12.4 km/s/Mpc
R ~ 1120 kpc
2.7 ± 1.5 x 10^{12} M_{Sun}

Conclusion

- **M31 proper motion is more than inaccurate for now**

—> almost 400 km/s of uncertainties along the 2 directions

- **It indeed has a strong impact in the LG frame**

—> [10 - 15] km/s/Mpc on the local Hubble flow
—> factor 3 in mass

Conclusion

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—> almost 400 km/s of uncertainties along the 2 directions

- **It indeed has a strong impact in the LG frame**

—> [10 - 15] km/s/Mpc on the local Hubble flow
—> factor 3 in mass

Ideas or Collaborations are welcome :-)

data,
method,
fit of the mass,
discussions…

thank you

Annexe 1

MCMC :
- $v_{M31_{x_k}}$
- $v_{M31_{y_k}}$
- $v_{M31_{z_k}}$

k + 1

$$\vec{v}_{Sat_{i_{MCMC}}} = \vec{v}_{M31_k} + \vec{v}_{LSR} + \vec{v}_{pec_\odot}$$

Projection on the line of sight i

Distance $d_{i_k} \xrightarrow{r_{i_k}, V_{200}, R_{200}, c} \sigma_{i_k}$ $(\vec{v}_{pec_{Sat_{i_k}}})$

$$\vec{v}_{Sat_{i_{obs}}}$$

Calculation of the likelihood :

$$\ln \mathcal{L} = \sum_{i=1}^{n_{sat}} \left[-\ln(\sigma_{i_k}\sqrt{2\pi}) - \frac{1}{2}\left(\frac{v_{Sat_{i_{MCMC}}} - v_{Sat_{i_{obs}}}}{\sigma_{i_k}}\right)^2 \right]$$

Annexe 2