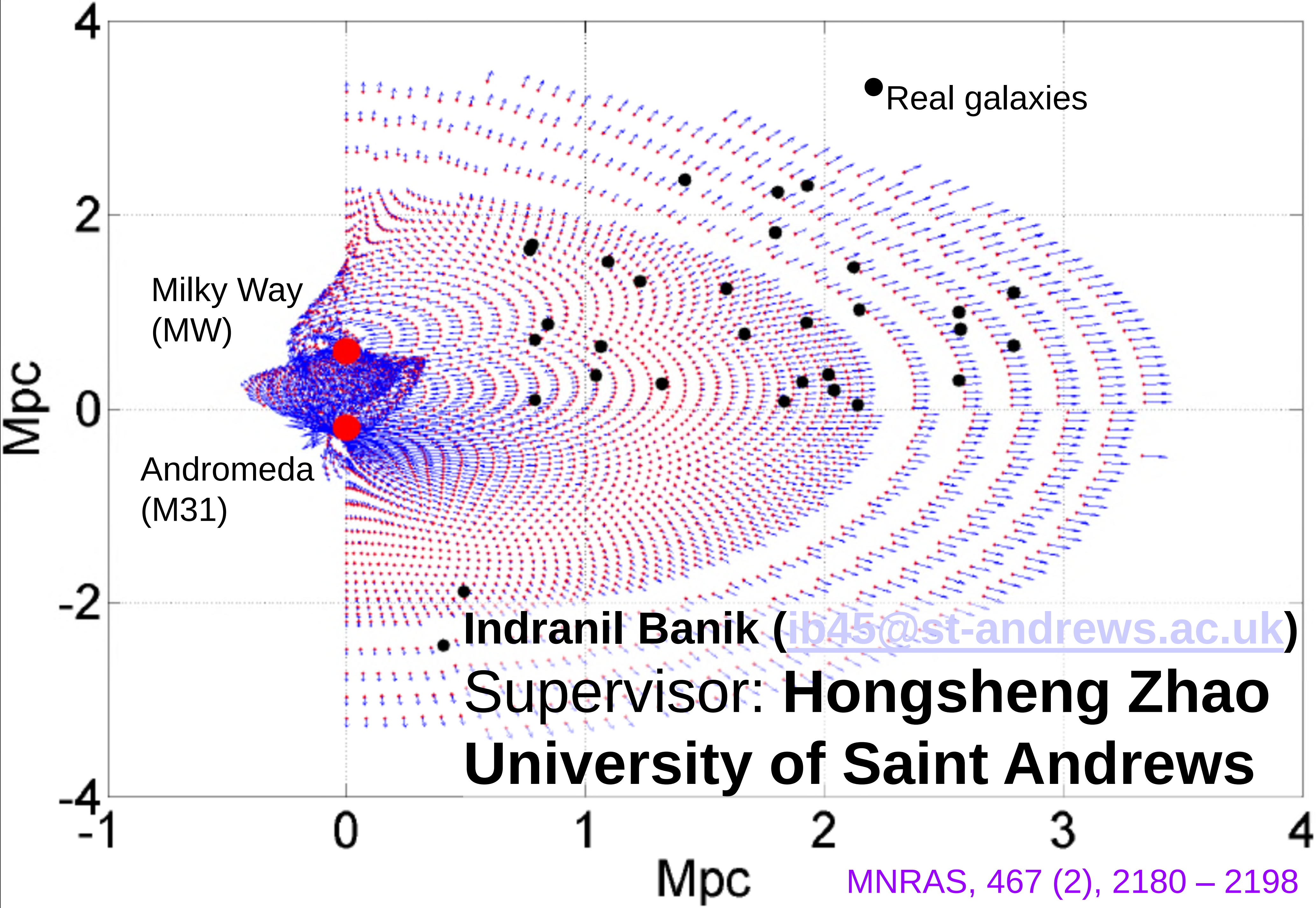
The Local Group Timing Argument



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MNRAS, 467 (2), 2180 – 2198

Basic idea

- Galaxies in Local Group (LG) and its surroundings evolved backwards from present conditions
- Try to get them on smooth Hubble flow at early times as Universe almost homogeneous then (peculiar velocities ~3 km/s at redshift 1000 but ~ 100 km/s now)
- Adjust masses and distances until best fit obtained, one parameter at a time

Governing Equations

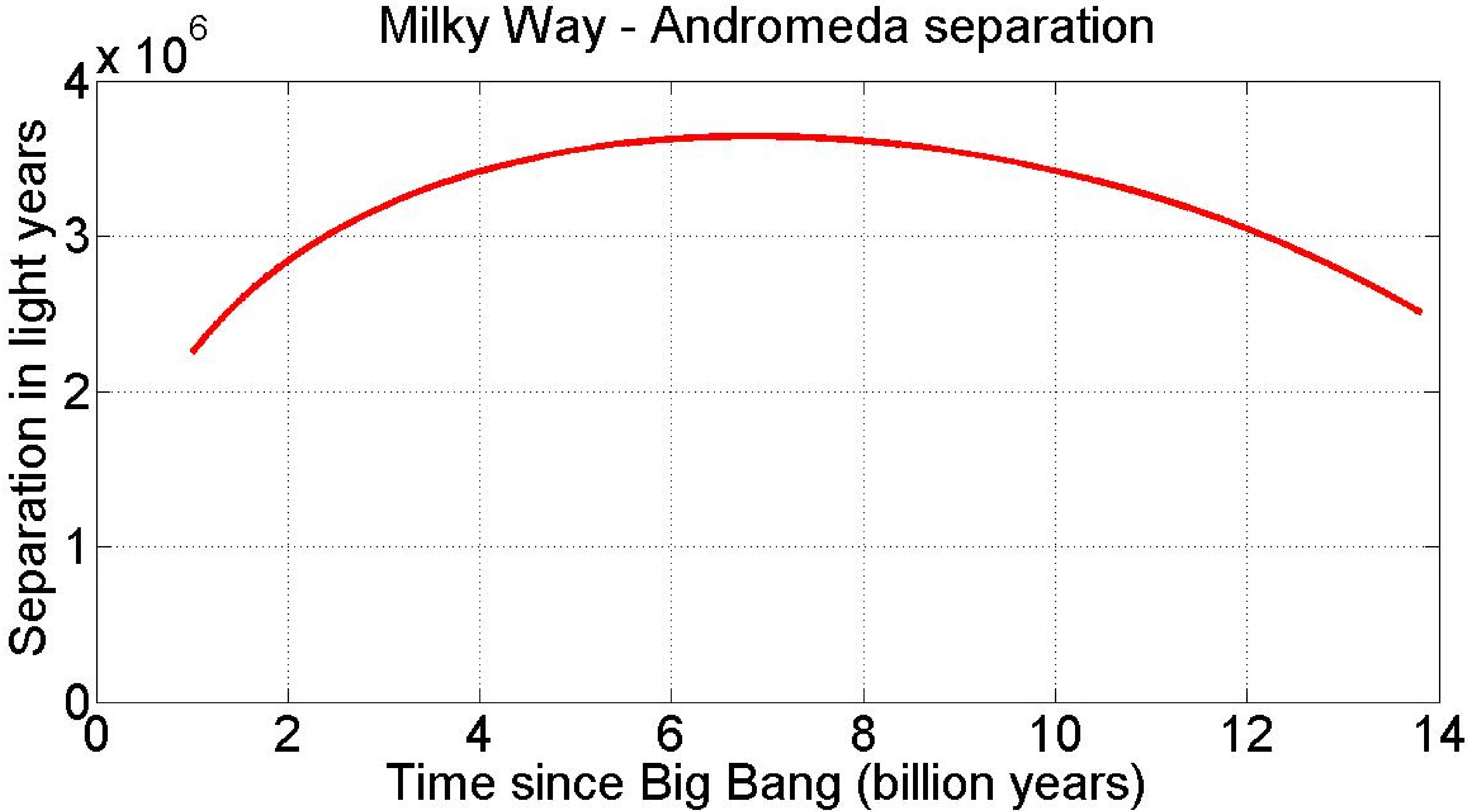
$$\ddot{\mathbf{r}} = \underbrace{H_0{}^2\Omega_\Lambda \mathbf{r}}_{\text{Dark energy}} - \sum_{\substack{\text{j=Nearby} \\ \text{massive} \\ \text{particles}}} \frac{GM_j\left(\mathbf{r}-\mathbf{r_j}\right)\left(r_c{}^2 + r_{S,j}{}^2\right)}{\left(\left|\mathbf{r}-\mathbf{r_j}\right|^2 + r_c{}^2\right) r_{S,j}{}^3} - \sum_{\substack{\text{j=Distant} \\ \text{massive} \\ \text{particles}}} \frac{GM_j\left(\mathbf{r}-\mathbf{r_j}\right)}{\left|\mathbf{r}-\mathbf{r_j}\right|^3}$$

- $r_c << r_{S,j}$ used to provide a constant density core, for numerical reasons
- $|r – r_j| < r_c$: Harmonic force law (irrelevant)
- $|r – r_j| > r_c$ but $< r_{S,j}$: Inverse r law, need to choose $r_{S,j}$ appropriately so rotation curve flatlines at correct level
- $|r – r_j| > r_{S,j}$: Usual inverse square law for forces from ‘distant’ bodies (outside halo)

List of galaxies

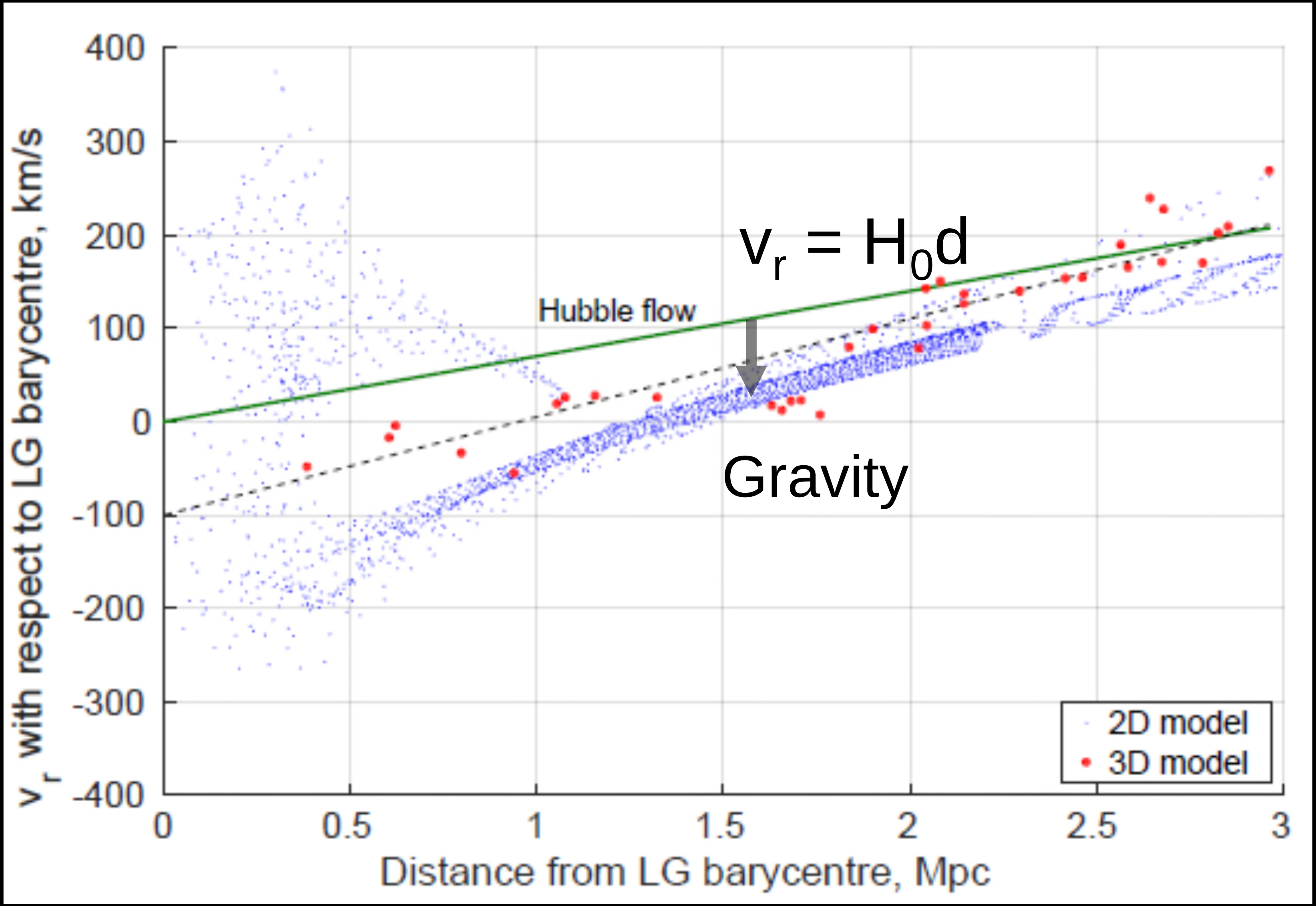
Galaxy	Distance, Mpc	Mass, 10^{12} $M_\odot$
Milky Way	0.008	1.83
Andromeda (M31)	0.707	2.06
Centaurus A	3.74	5.88
M101	7.39	9.31
M94	4.366	8.84
Sculptor	4.10	6.93
NGC 6946	5.86	4.61
M81	3.63	4.06
Maffei	3.99	3.49
IC 342	3.35	1.30
M33	0.948	0.22
LMC	0.065	0.20
NGC 55	2.04	0.13
NGC 300	1.96	0.11

First step: MW–M31 trajectory



Present radial velocity ~110 km/s, usually slower in past

Hubble diagram



Some dwarfs flung out by MW or M31, but only out to ~1 Mpc

Statistical analysis

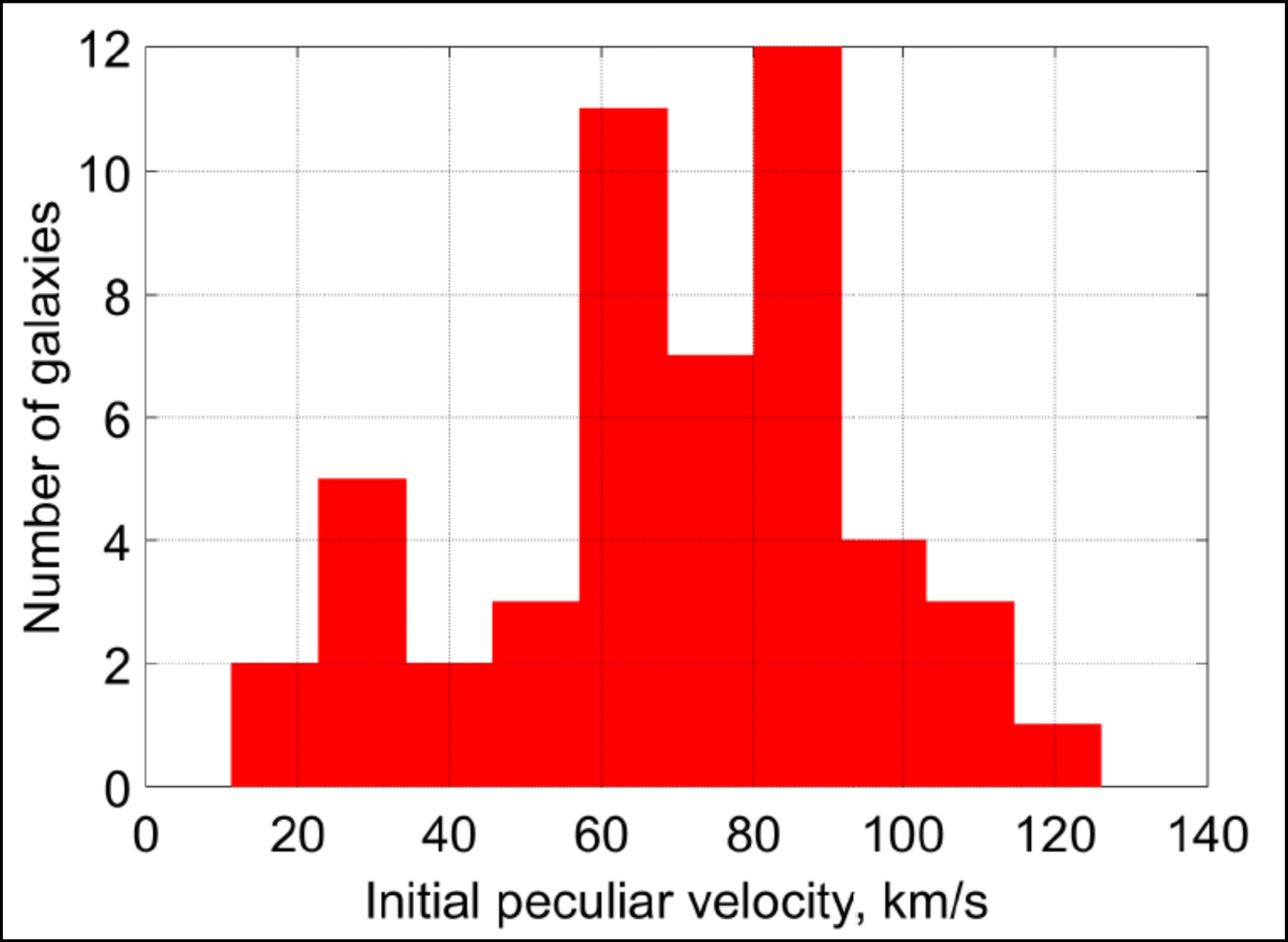
- Contributions to χ^2 from:
- Distance
- Radial velocity
- Proper motion (if known)
- Initial peculiar velocity

$$\Delta\chi^2 = \frac{\overbrace{\left|\mathbf{v}_i - H_i \mathbf{r}_i\right|}^{\mathbf{v}_{\mathbf{pec}}(t=t_i)}{}^2}{\sigma_v{}^2}$$

- Mass (guess based on M/L of 50 in K-band)

$$\Delta\chi^2 = \left[Ln\left(\frac{M}{M_{est}}\right) \div Ln\,1.5 \right]^2$$

Initial peculiar velocity



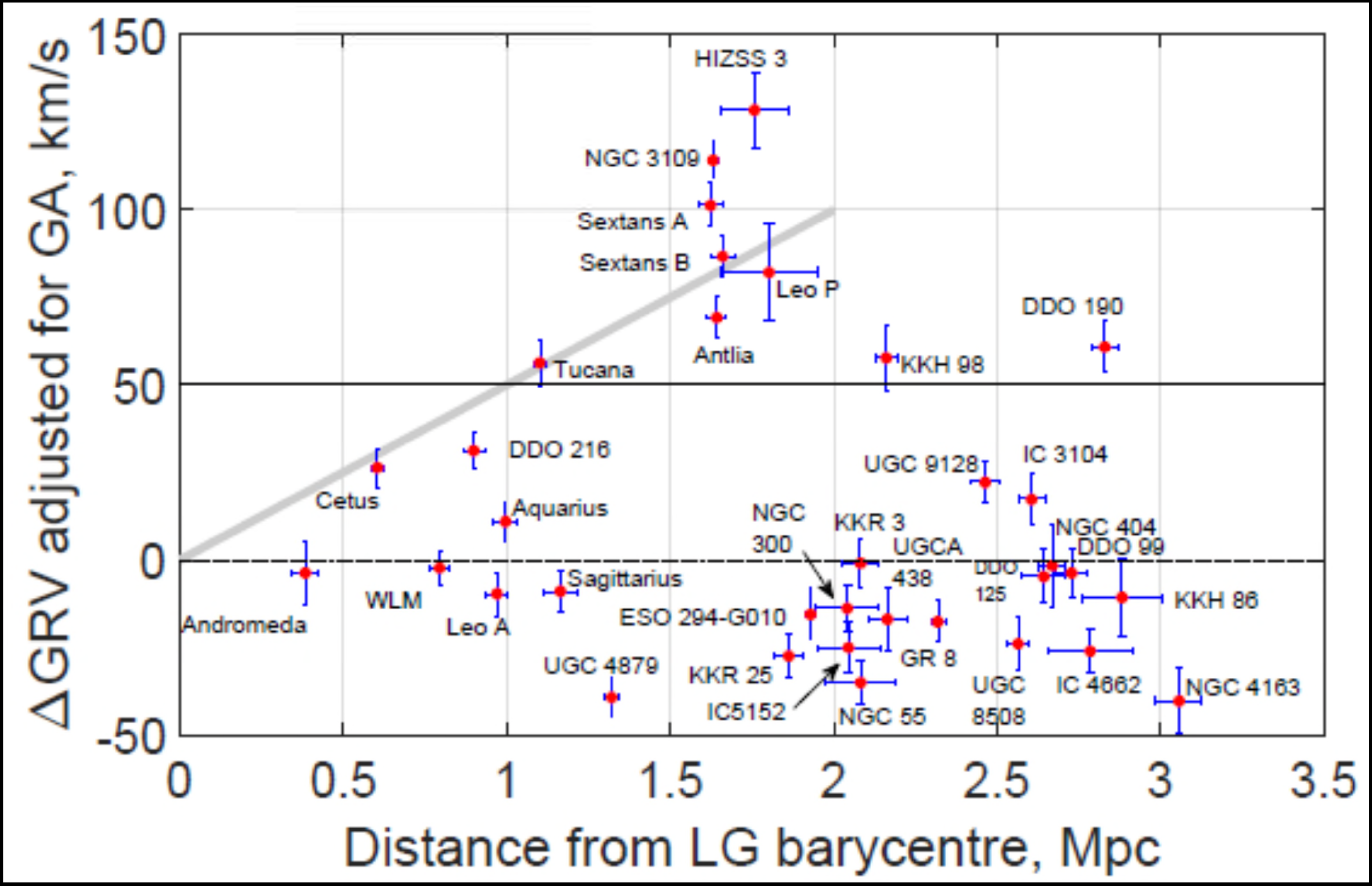
Allowance of 50 km/s used

Model uncertainties

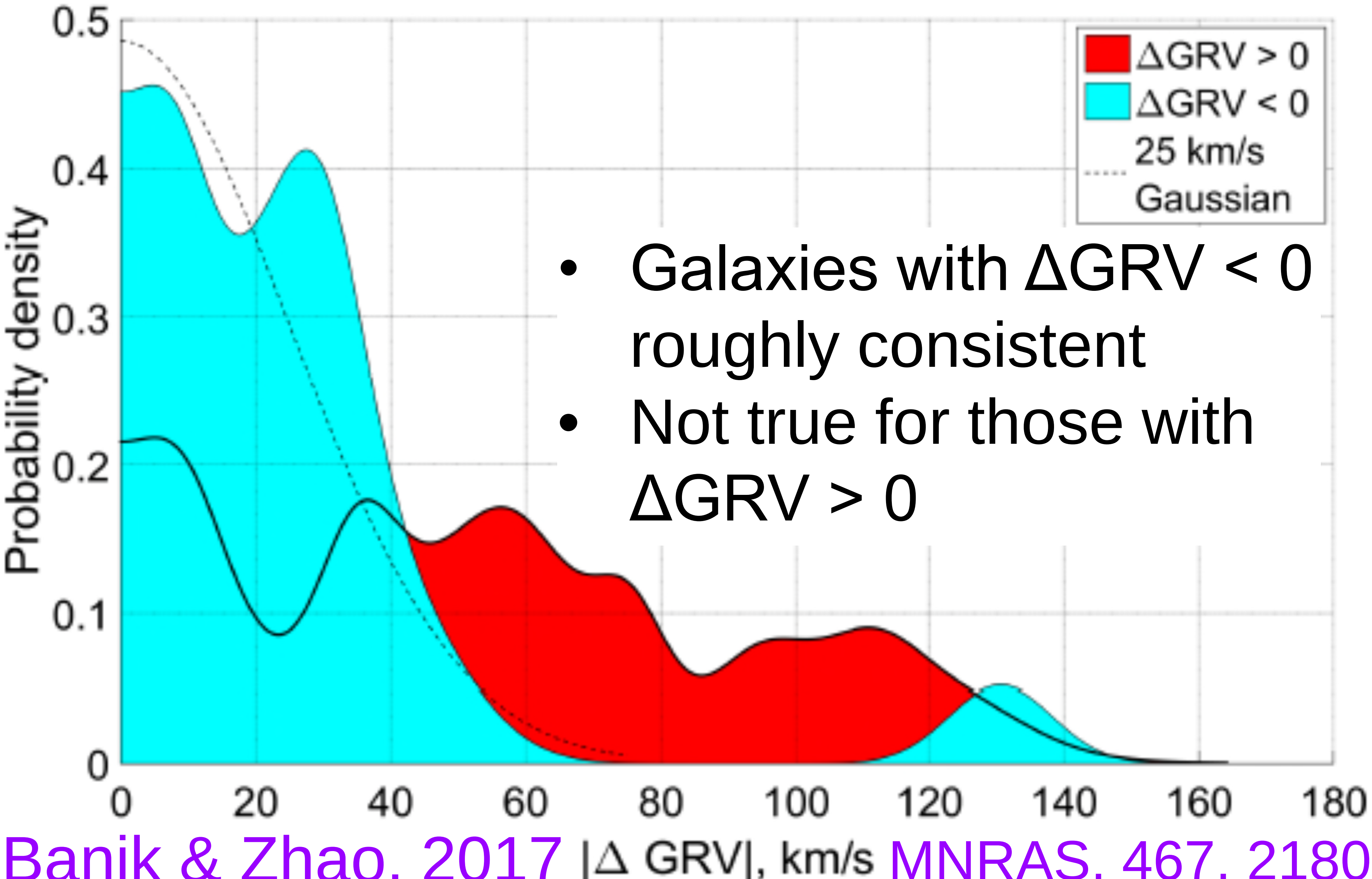
- Scatter about Hubble flow (1D model of LG) only ~30 km/s (MNRAS, 415, L16)
- 3D model should do much better
- LG galaxies rotate at ~15 km/s, so scatter should be more than this e.g. large-scale structure, but < 30 km/s as even a 1D model should be able to reach this accuracy

➢ Assume model uncertainty of 25 km/s

$\Delta GRV \equiv GRV_{obs} - GRV_{model}$



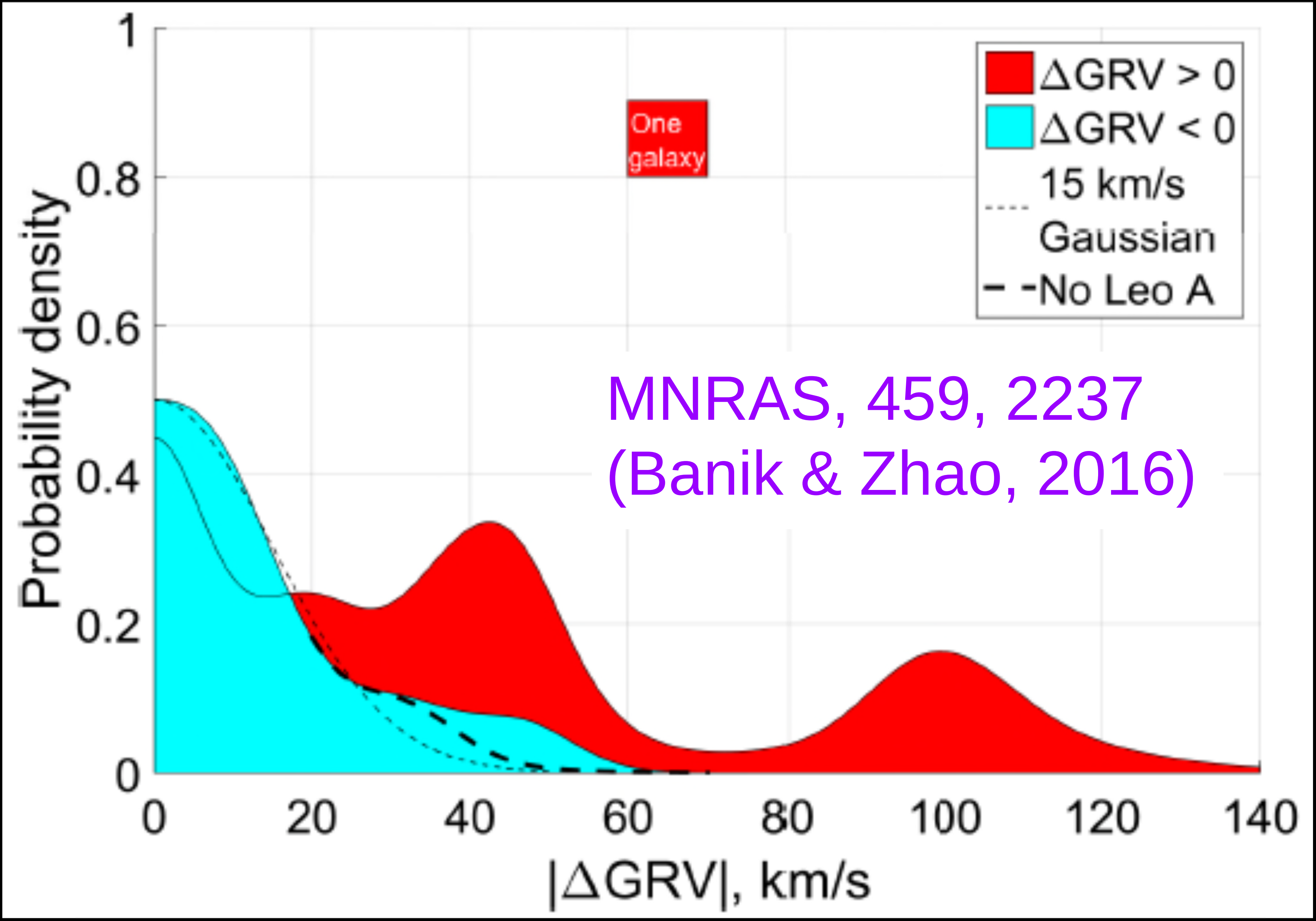
3D results



- Galaxies with ΔGRV < 0 roughly consistent
- Not true for those with ΔGRV > 0

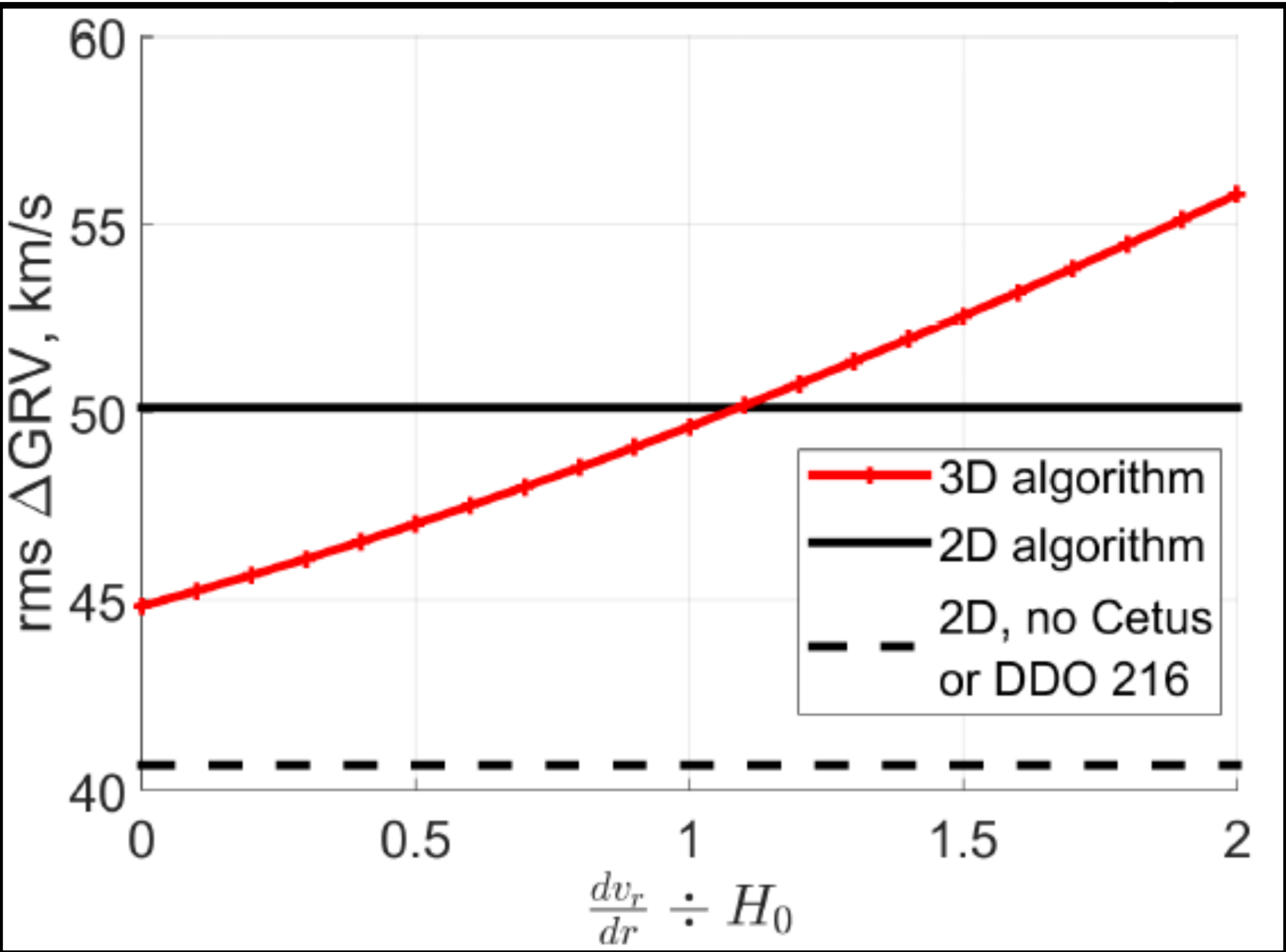
Banik & Zhao, 2017 MNRAS, 467, 2180

2D results



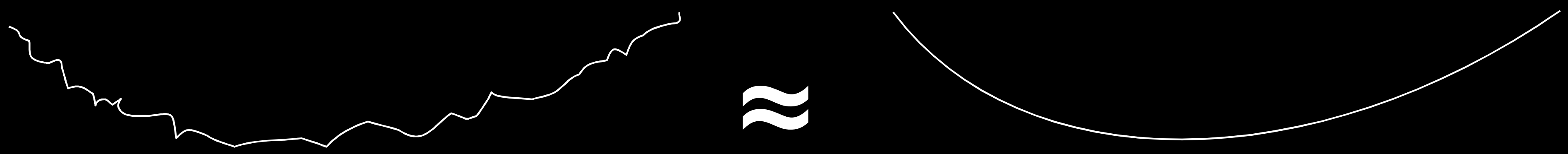
Probability density
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
|ΔGRV|, km/s
One galaxy
ΔGRV > 0
ΔGRV < 0
15 km/s Gaussian
No Leo A
MNRAS, 459, 2237
(Banik & Zhao, 2016)

2D and 3D models broadly agree



Is classical gravity appropriate?

- Arbitrarily high accuracy in position and velocity measurements impossible
- Classical theories assume this **is** possible



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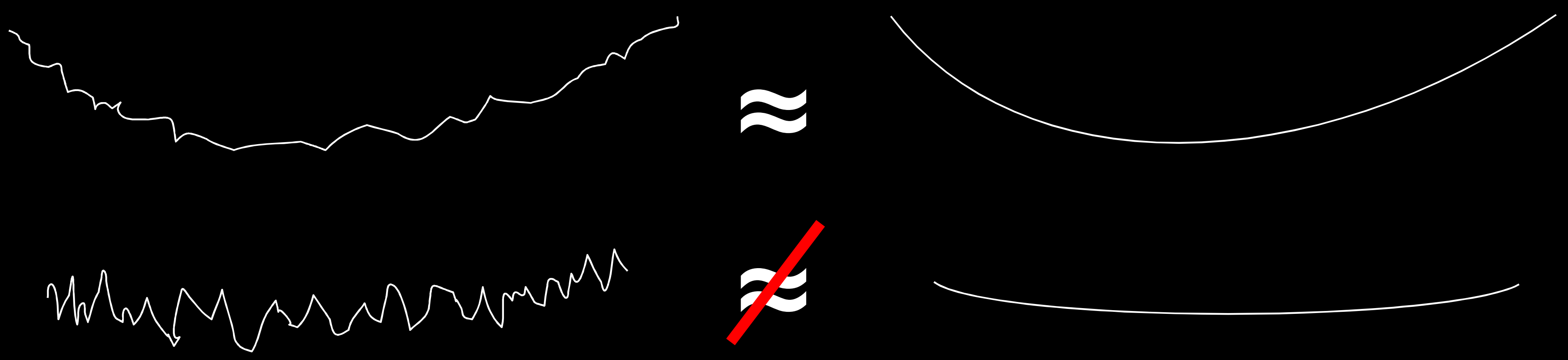
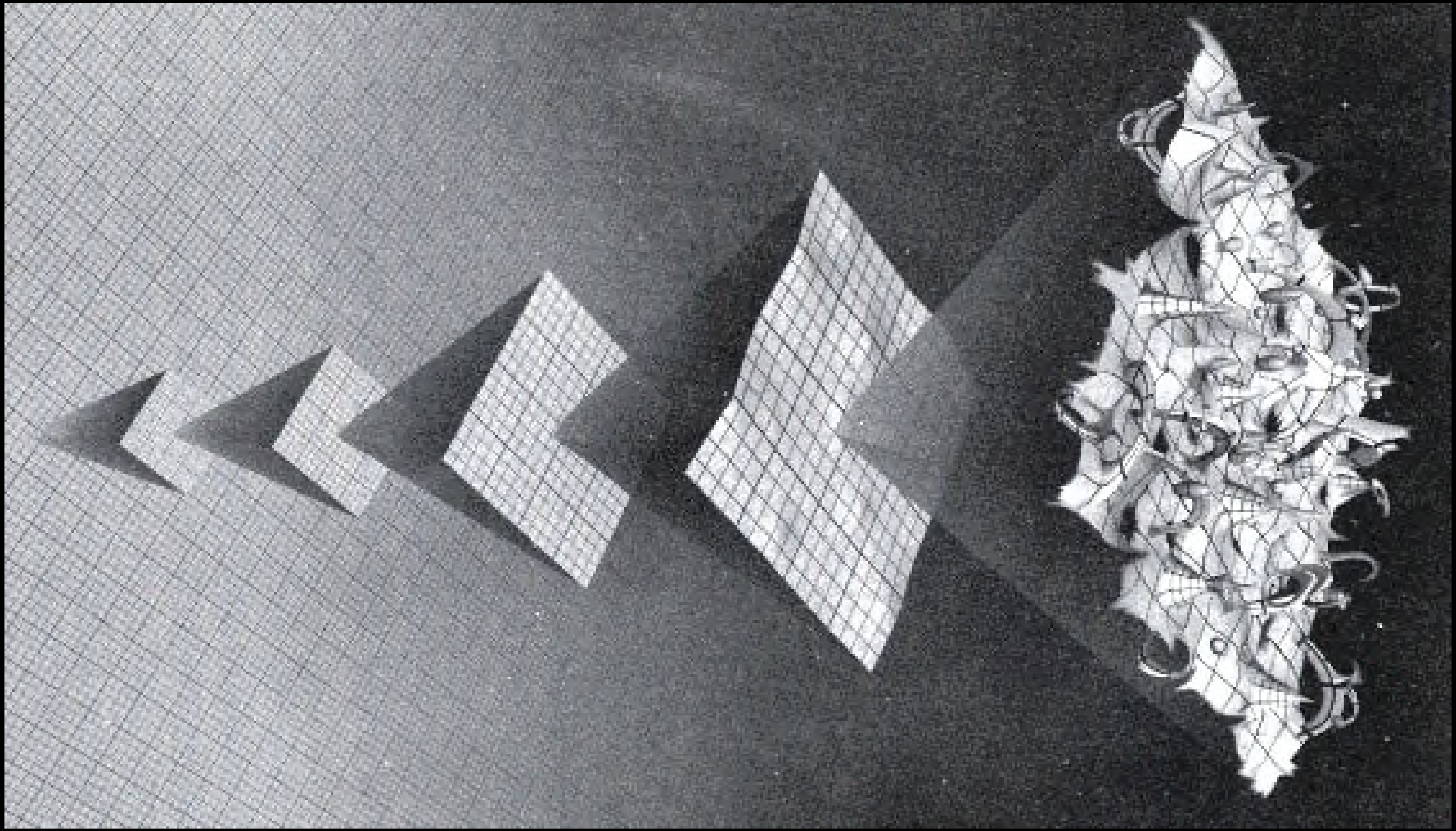


- Curvature (i.e. acceleration) so small in second panel that ignoring fluctuations iffy

Quantum Effects

- Curvature uncertain and not constant, like gravitational waves: vacuum carries energy



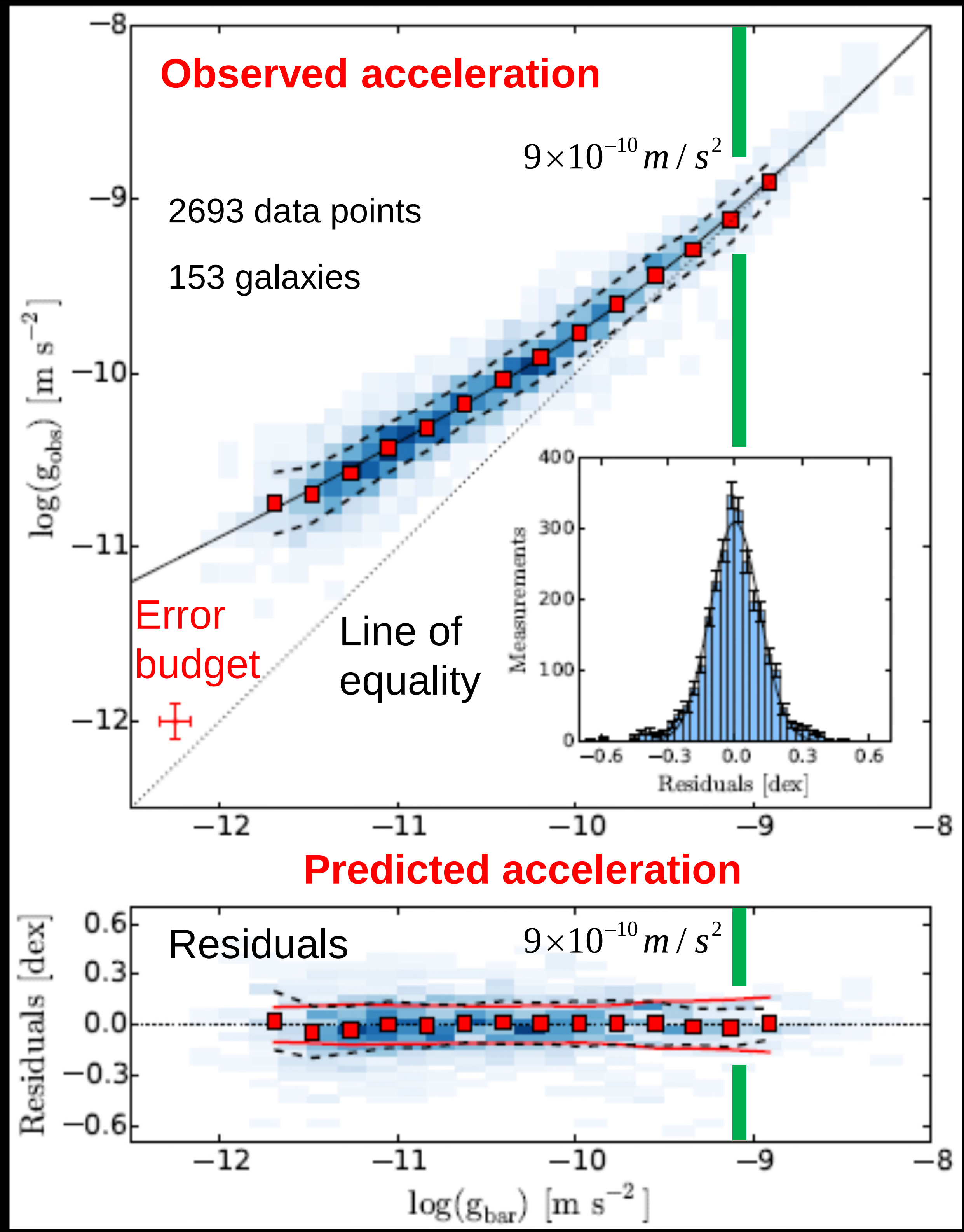
Quantum Spacetime

- Empty space has small but non-zero minimum energy $\rho_{\mathbf{vac}}$
- On large scales, this causes Universe to accelerate apart – dark energy (measurable)
- Use known energy density $\rho_{\mathbf{vac}}$ to estimate when quantum effects overwhelm classical (mean) gravitational field

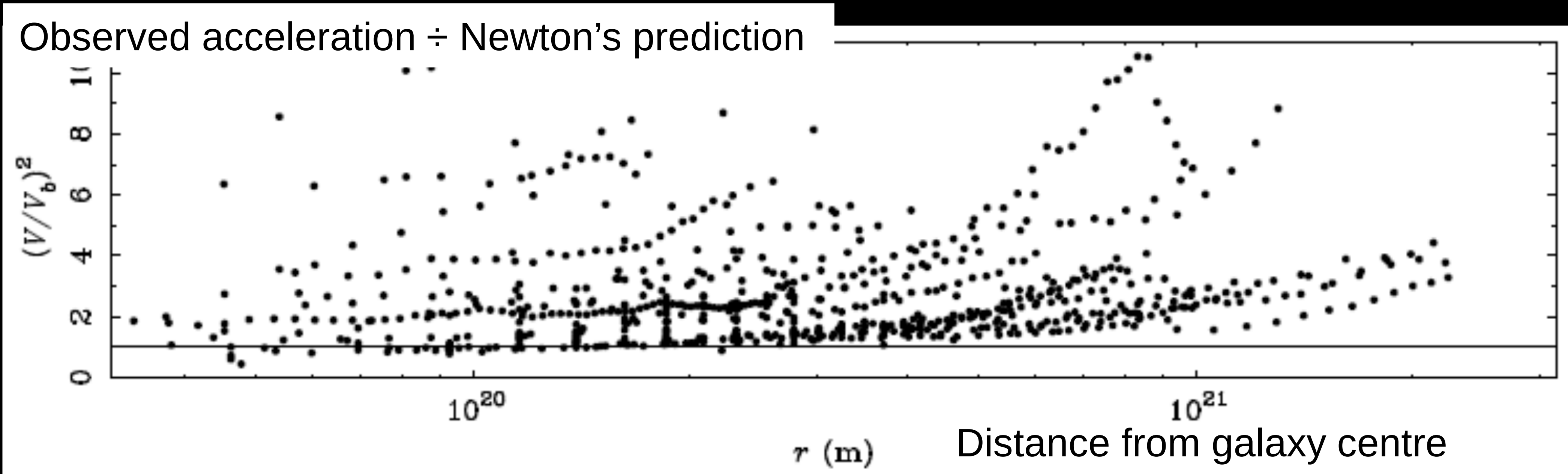
$$\frac{g^2}{8\pi G} = \rho_{vac} \Leftrightarrow g = 9\times 10^{-10}\, m/s^2$$

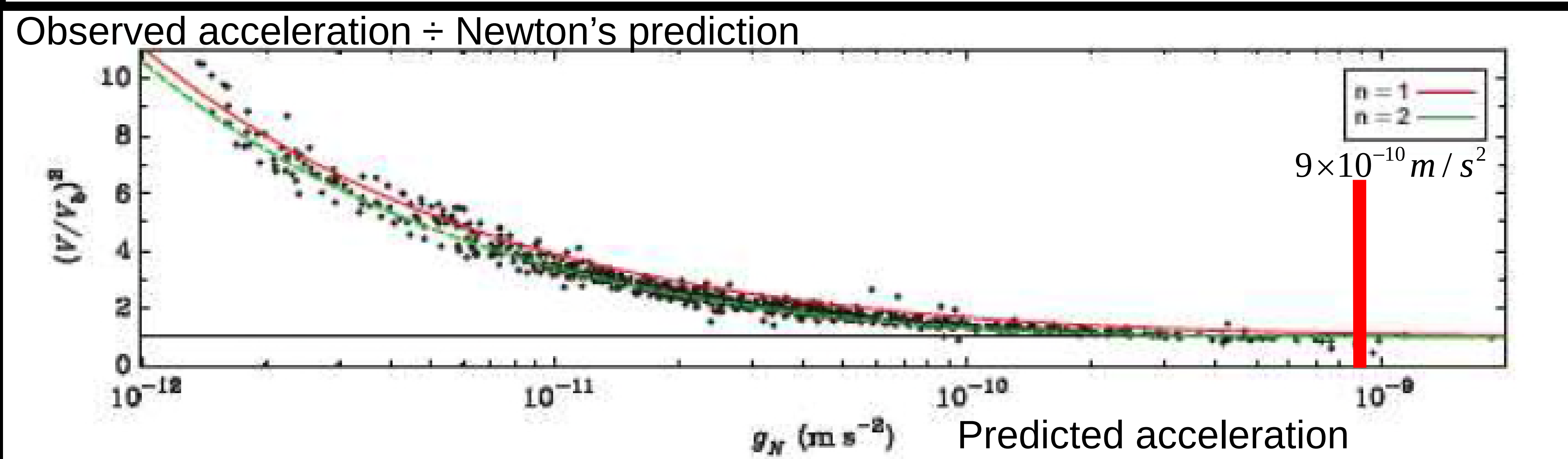
Latest data

Physical Review Letters 117, 201101, McGaugh+ (2017)



Acceleration, not distance

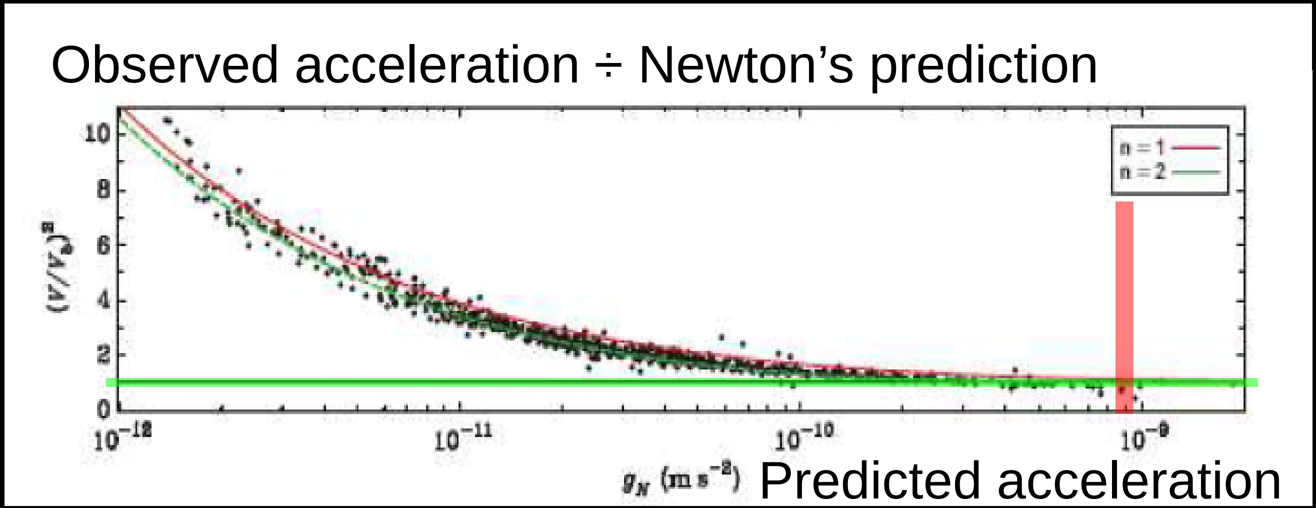




Basics Of MOND

$$\mu\left(\frac{|g|}{a_0}\right)\vec{g} = \vec{g}_N$$

(Spherical symmetry)



$$\mu(x) = 1 \text{ when } x >> 1$$

$$\mu(x) = x \text{ when } x << 1, \text{ so } g = \sqrt{g_N a_0}$$

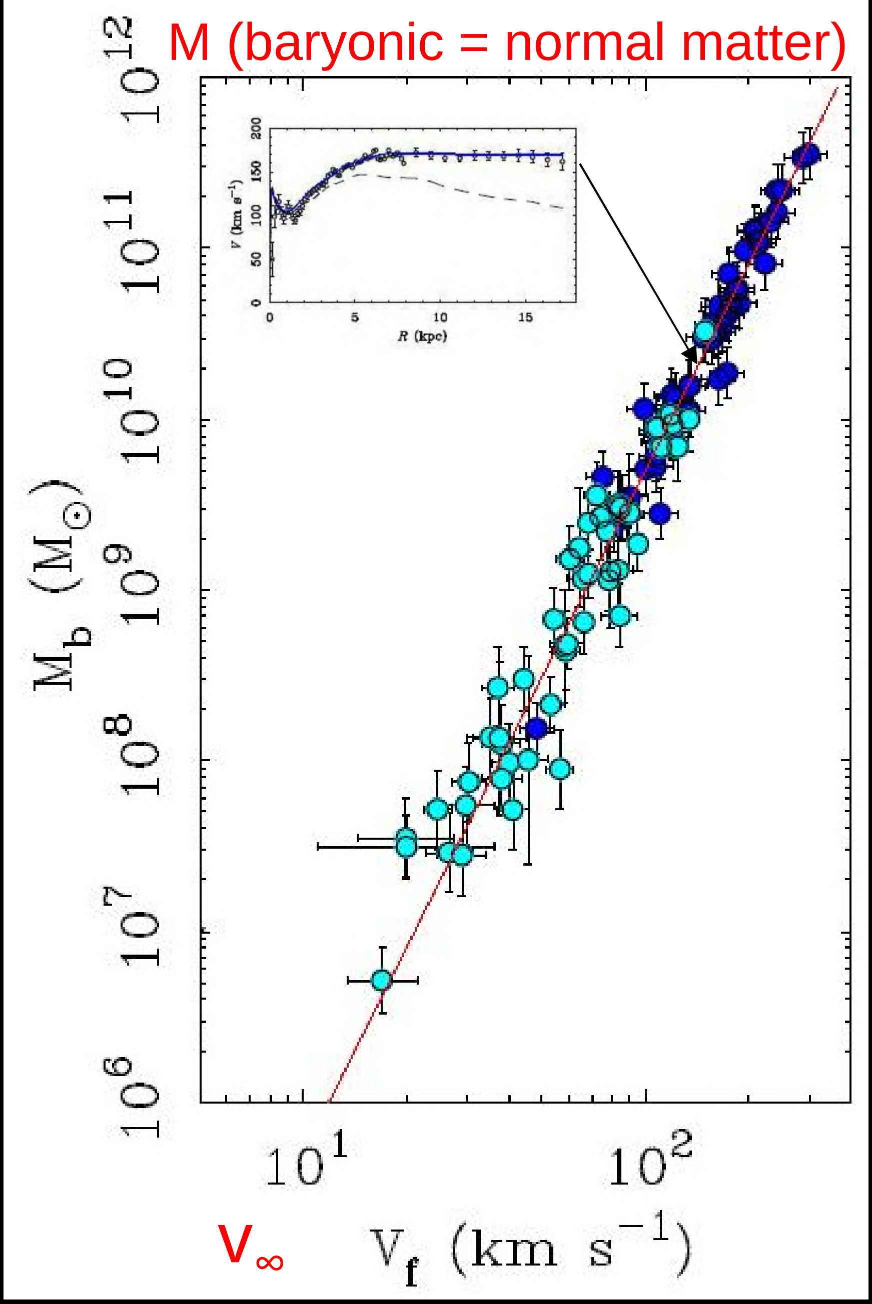
Far from an isolated point mass, $g = \frac{\sqrt{GMa_0}}{r}$

Tully-Fisher Relation

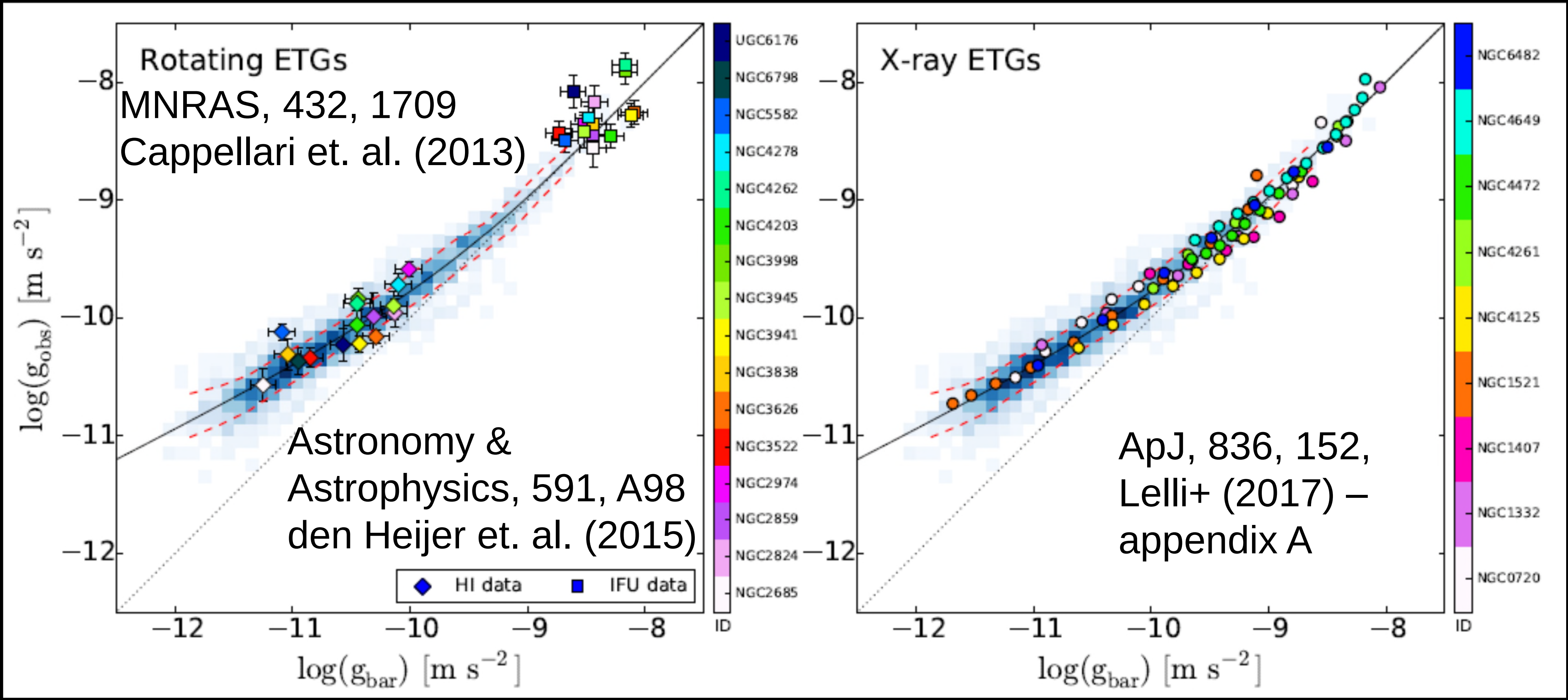
$$g = \frac{\sqrt{GMa_0}}{r} = \frac{v^2}{r}$$

$$v_\infty = \sqrt[4]{GMa_0}$$

- This works in both star and gas dominated galaxies (light and dark blue data points)
- MOND parameter a_0 set by observations outside Local Group

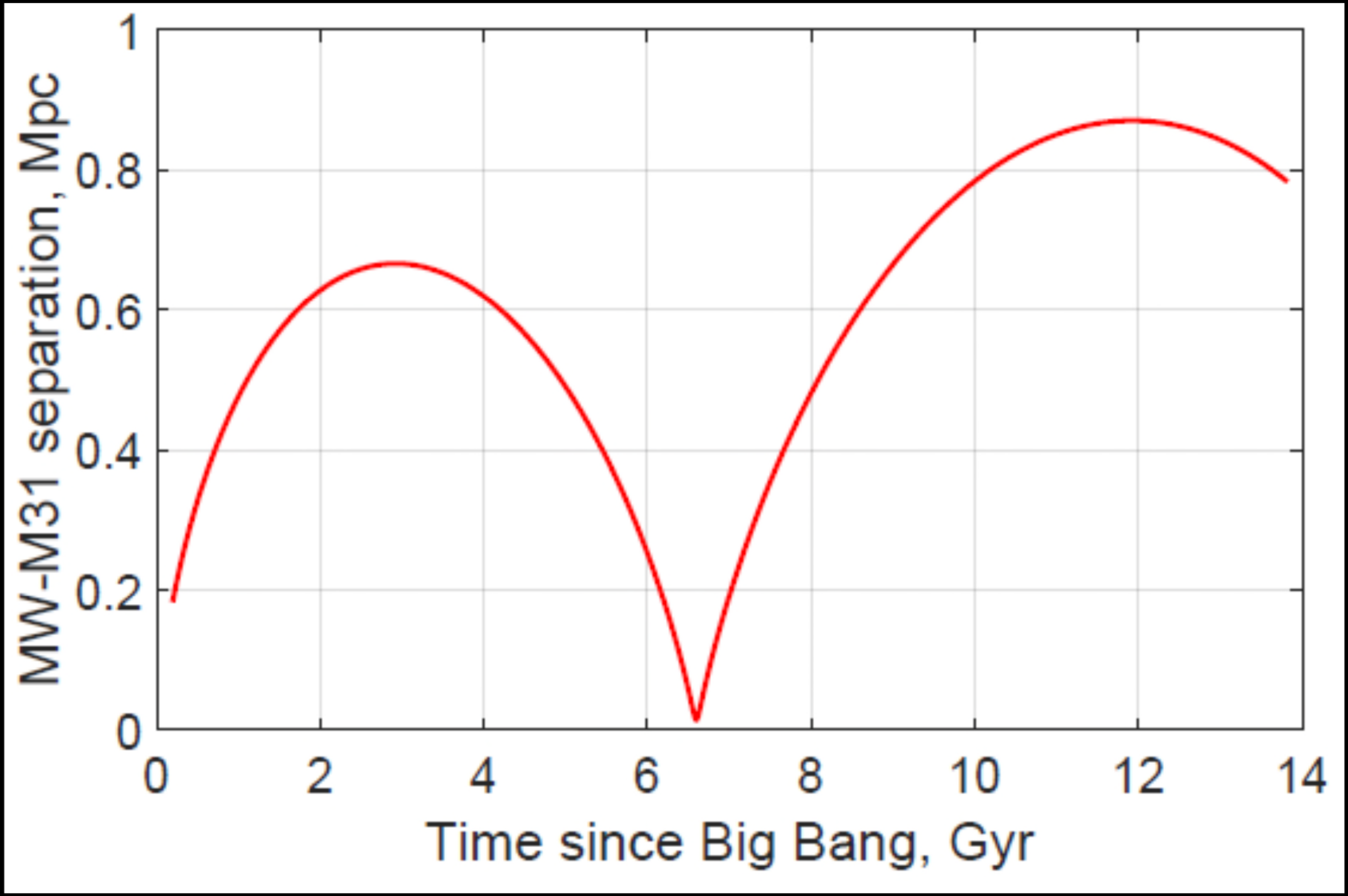


What about elliptical galaxies?



- The acceleration is tightly correlated with the distribution of baryons in elliptical galaxies, *in exactly the same way as in spirals!*

MW-M31 trajectory in MOND



Flyby inevitable under wide range of assumptions

Astronomy & Astrophysics 557, Letter 3 (Zhao+, 2013)

MOND

- In this model, there was a close encounter between the MW & M31 in the past
- This caused substantial dynamical heating of the Local Group

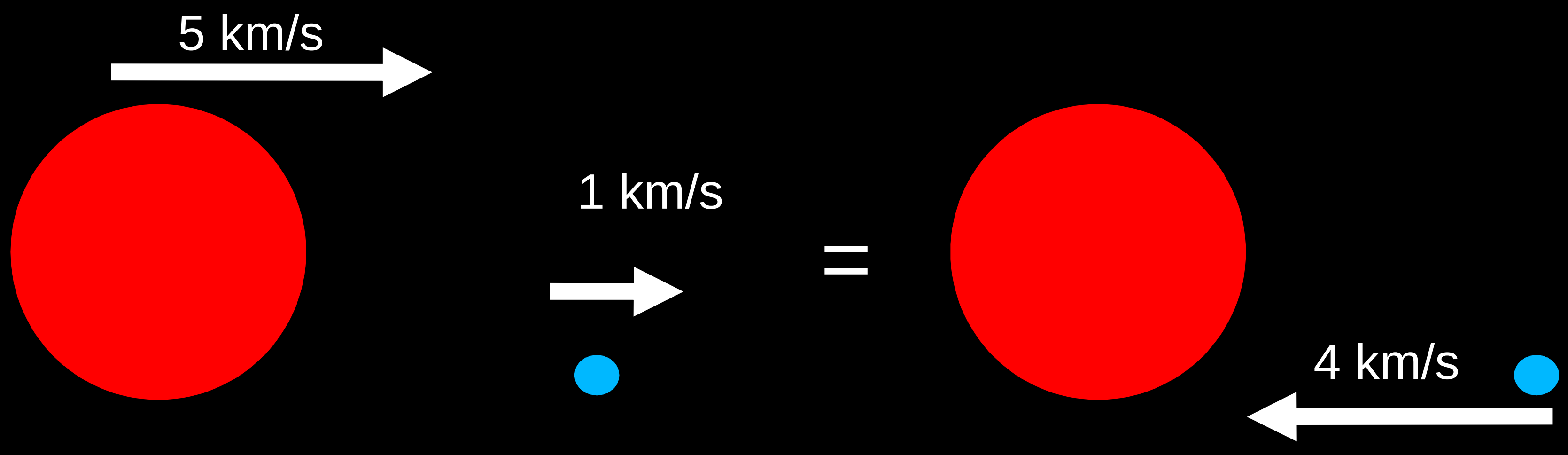
➢ Very high GRV's occur as some LG galaxies flung out at high speed by fast-moving MW / M31 (around time of their encounter)

- Process also occurs in ΛCDM, but MW–M31 relative motion much slower as no close flyby

Basic principle: gravitational slingshots

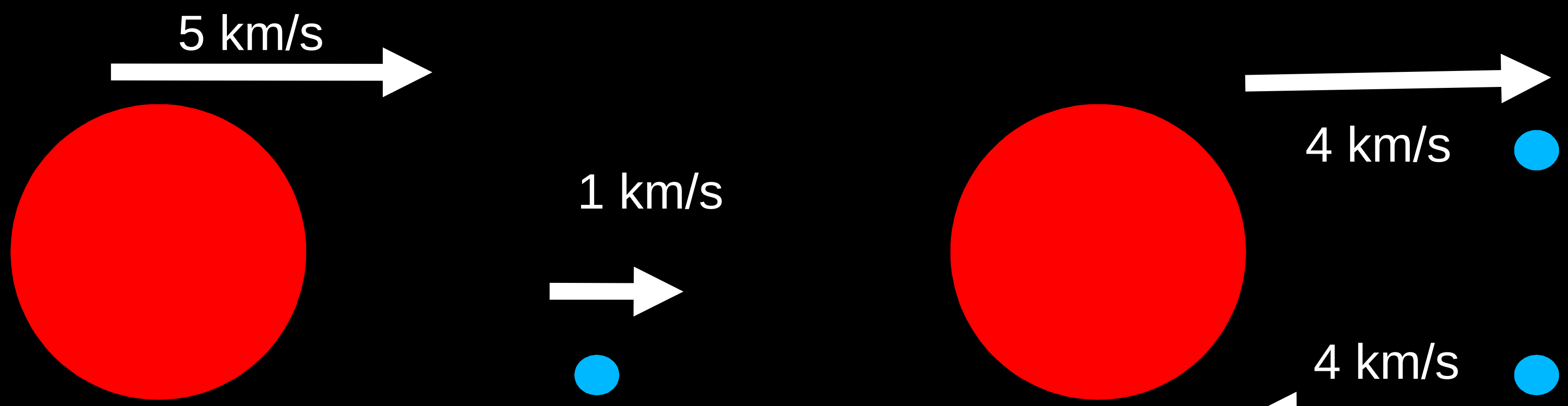
- Heavy galaxy (e.g. MW) moves right at 5 km/s
- Small object moving right at 1 km/s

➢ Relative speed = 4 km/s



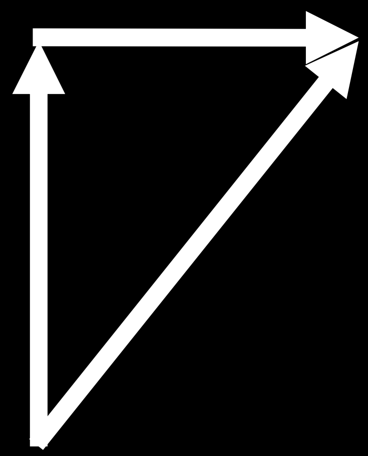
Basic principle: gravitational slingshots

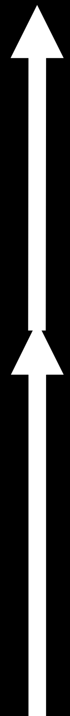
- Heavy galaxy (e.g. MW) moves right at 5 km/s
- Small object moving right at 1 km/s
  - ➢ Relative speed = 4 km/s
- MW reverses relative velocity of object
  - ➢ Object now moves at (5 + 4) km/s



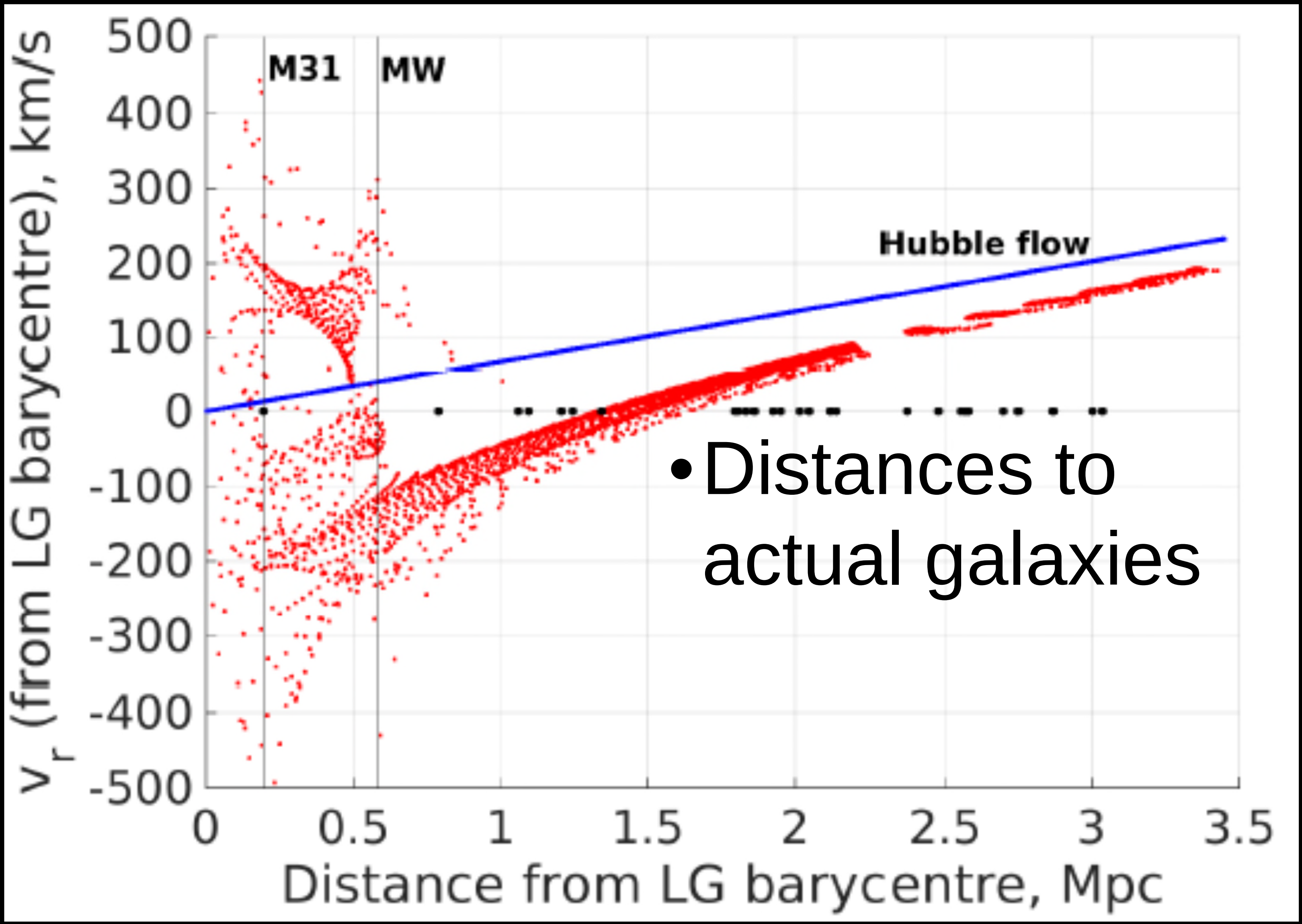
Lean in to go faster…

- Slingshots most efficient parallel to motion of perturber (adding vectors most efficient in parallel, not in quadrature)
- Objects flung out fastest from event fixed time ago would be furthest away now



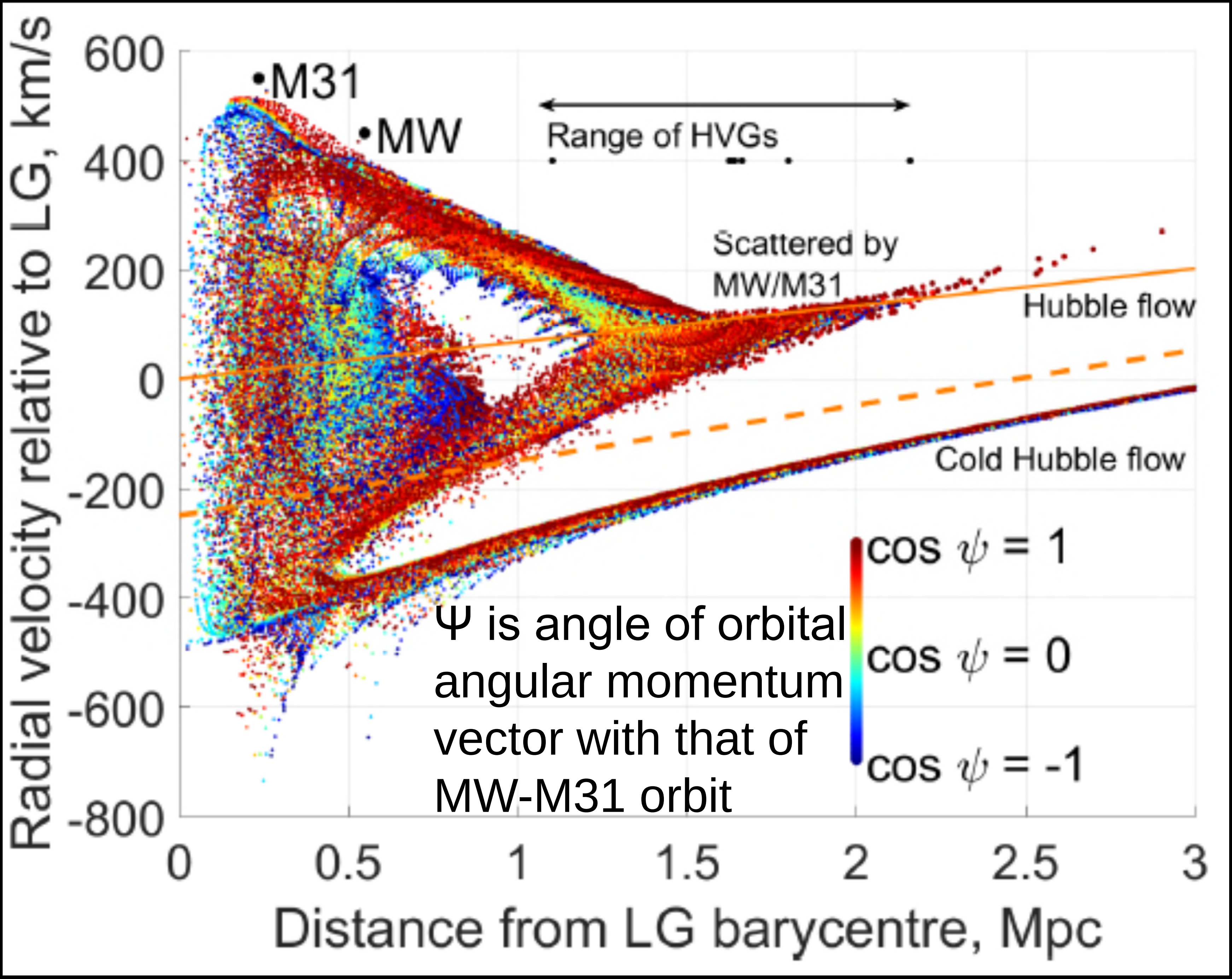


Hubble diagram in ΛCDM

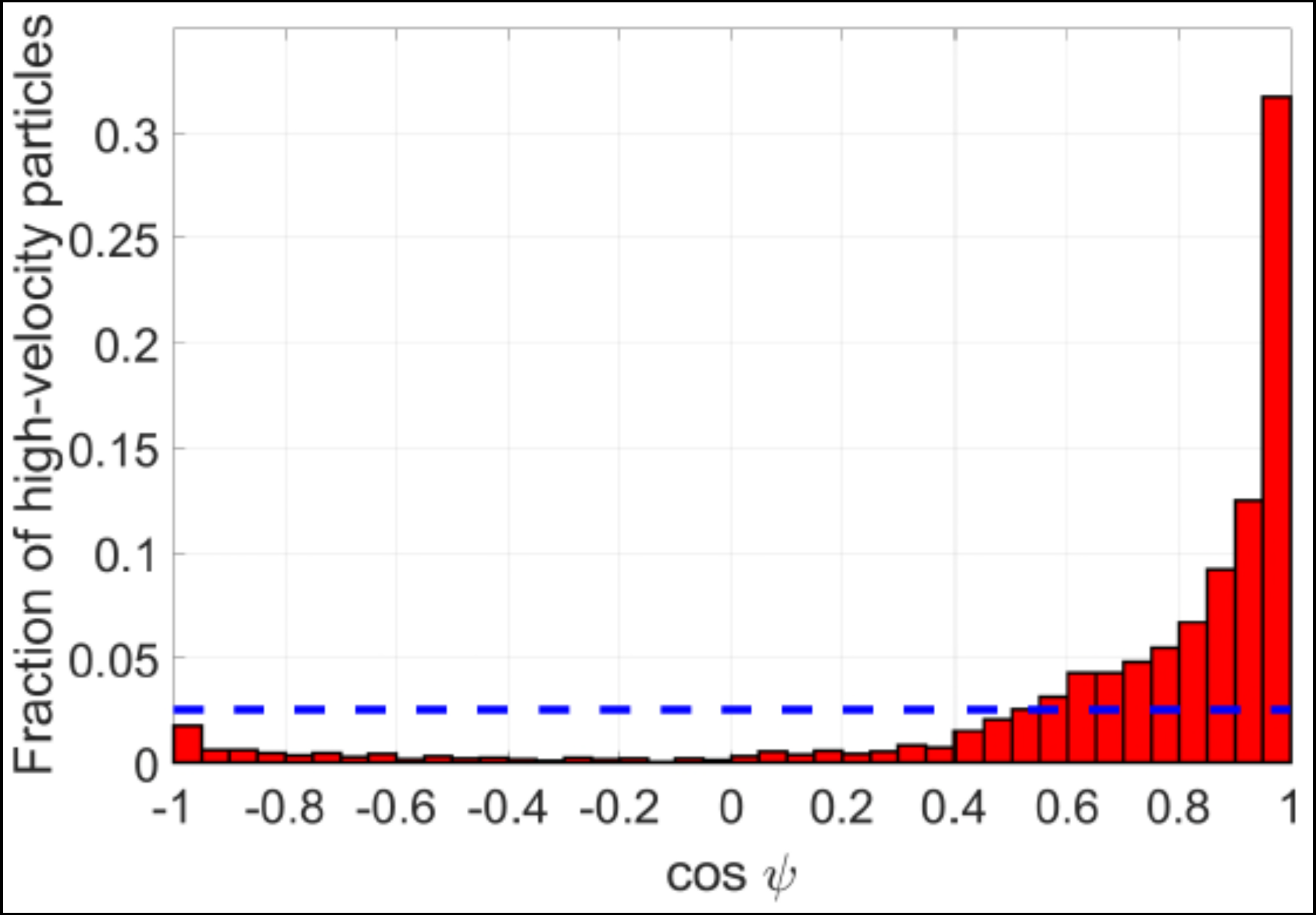


- Distances to actual galaxies

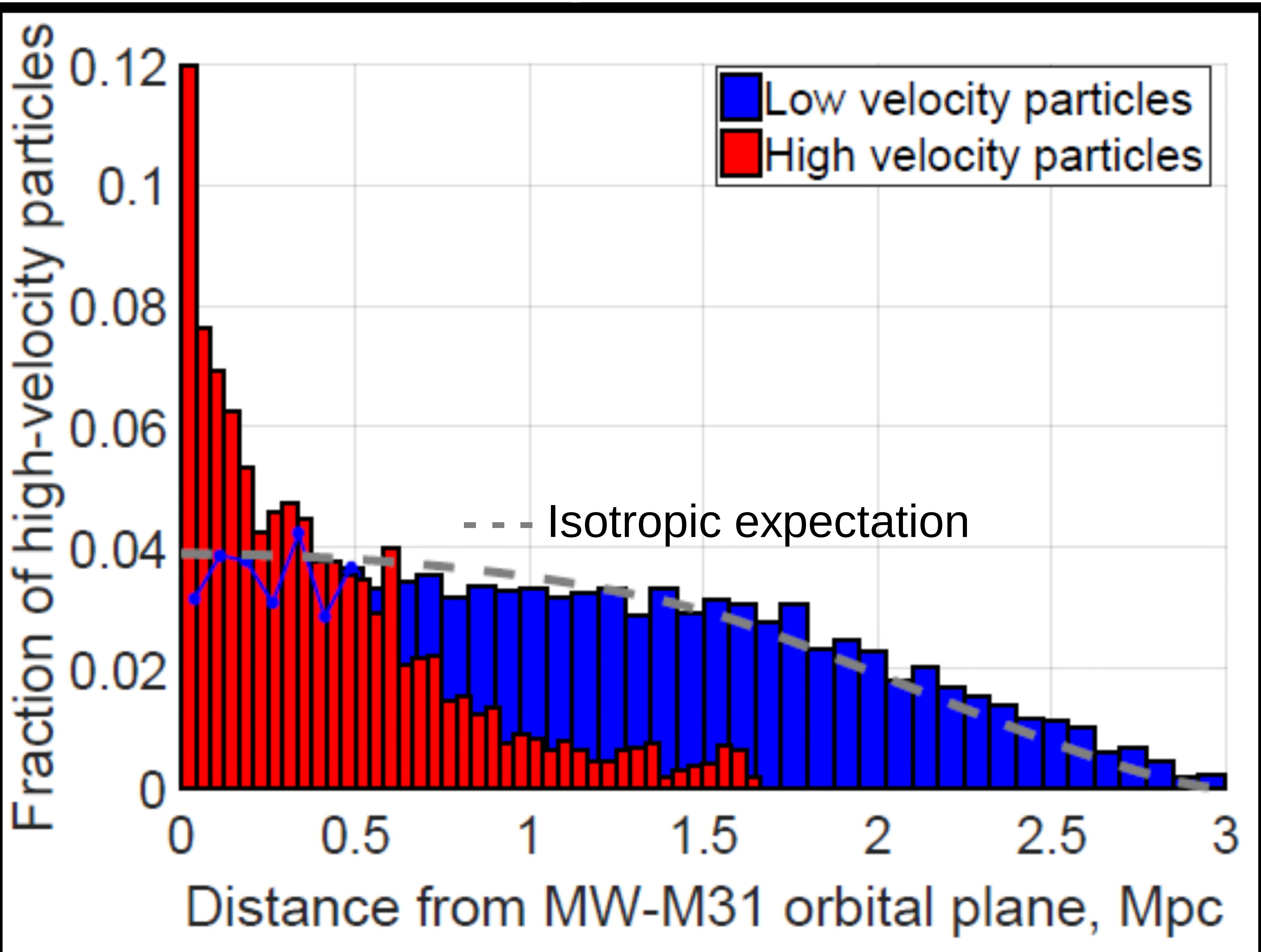
Hubble diagram in MOND



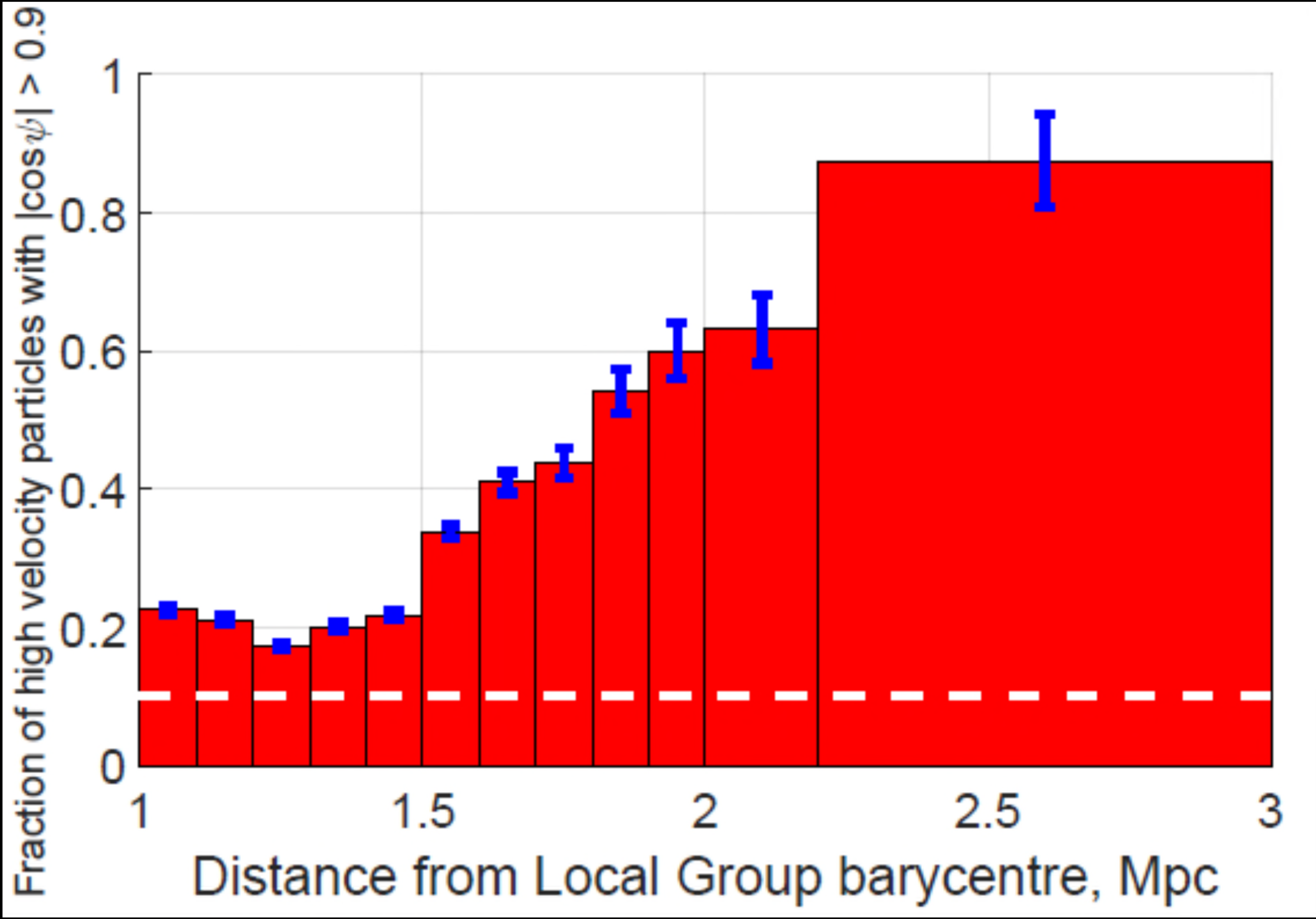
Orbital planes of flung-out particles



Distribution of high-velocity particles



Different radial cuts

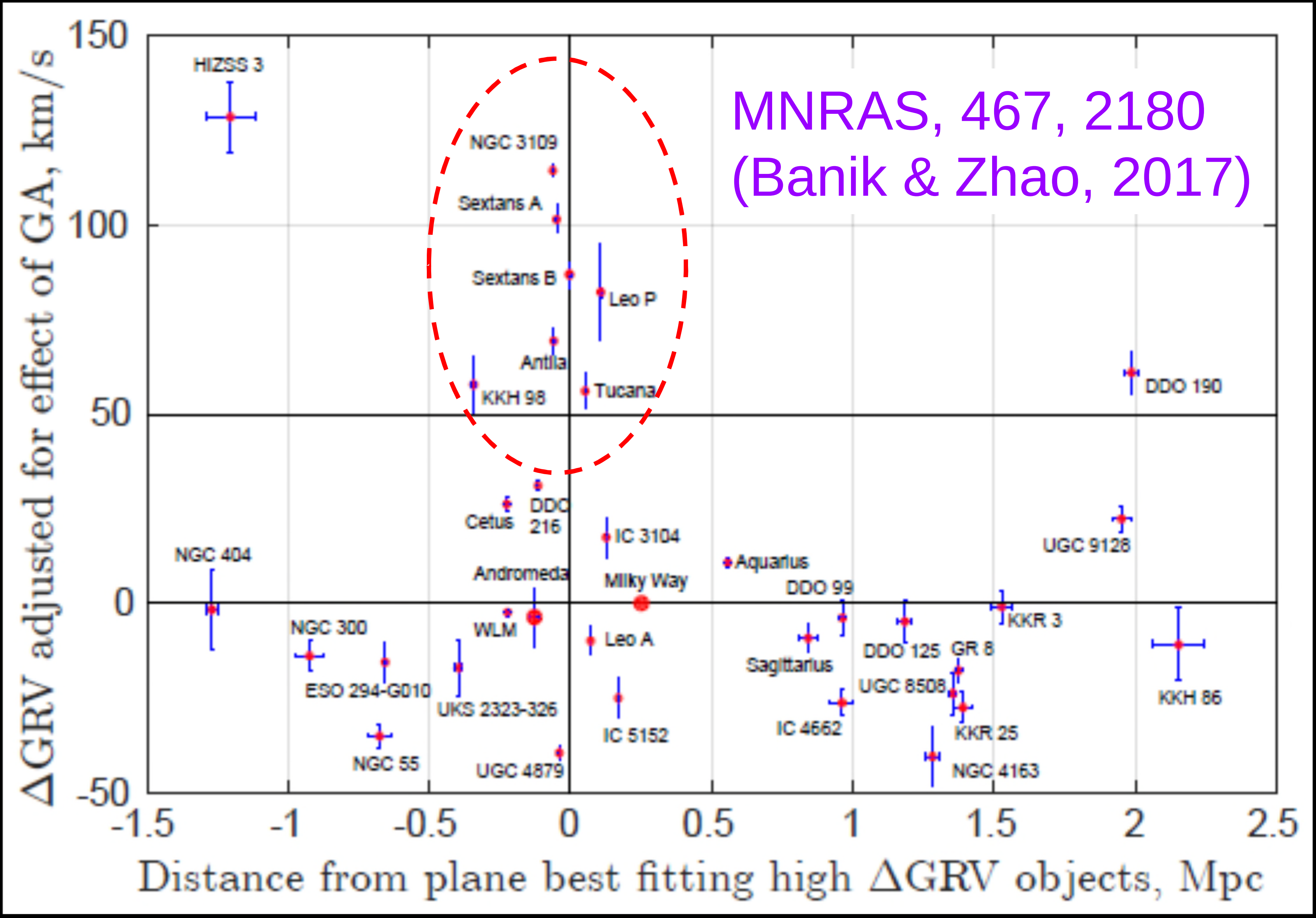


Plane fitting

$$f \equiv N z_{rms}{}^{2} = \sum_{i=1}^{N} \left[\left(\mathbf{r}_i - \mathbf{v} \right) . \hat{\mathbf{n}} \right]^2$$

- **v** found analytically
- Minimise f using gradient descent method
- Gradient **∇f** found by finite differencing
- Step length raised normally (over-relaxation)
- Reduced if minimum overshot (either f rises or **∇f** reversed) or if |**∇f**| falls substantially

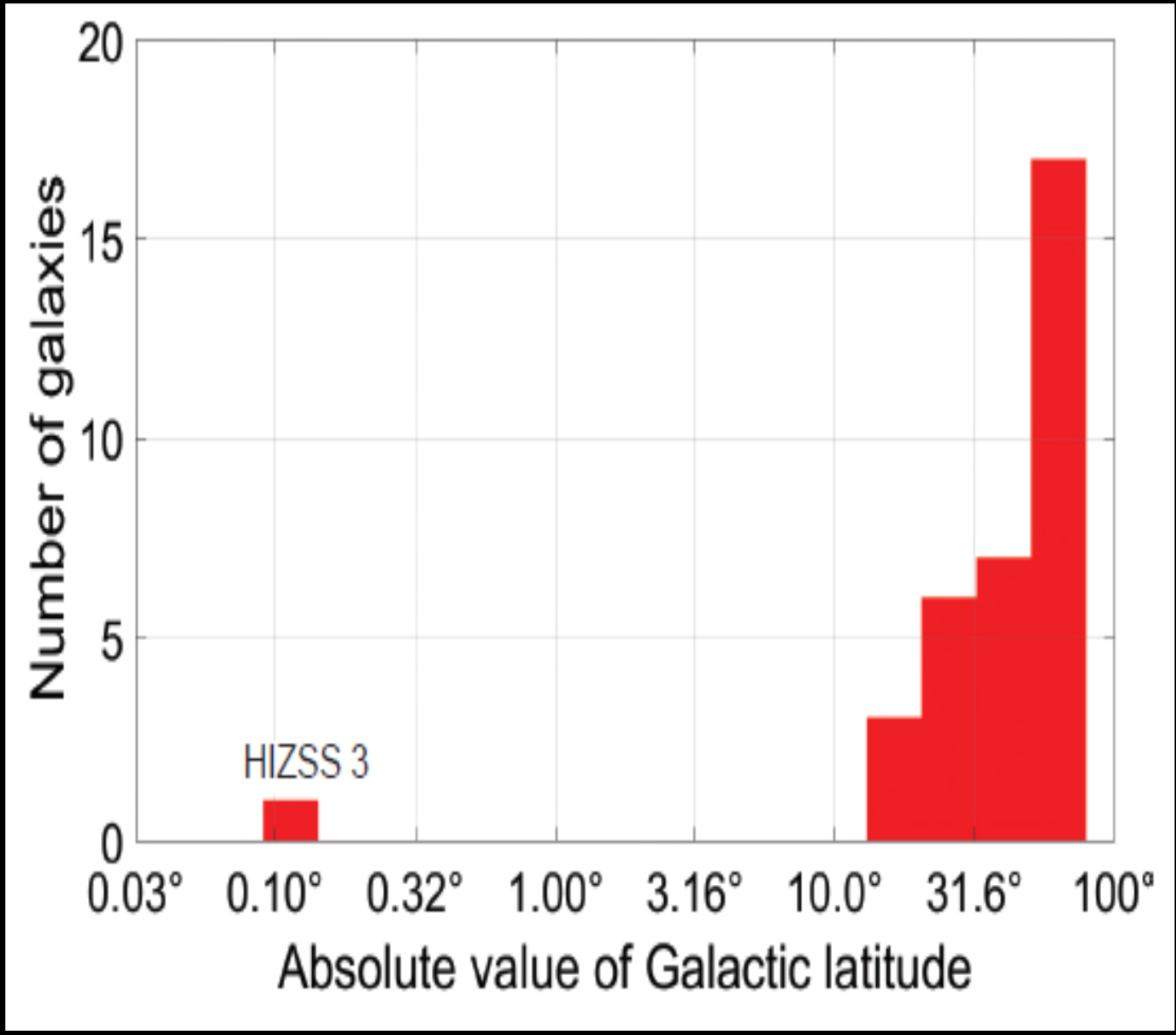
Where are the high-velocity galaxies?



HIZSS 3: a closer look

- Very high contamination fraction by foreground stars
- Very uncertain extinction estimate

➢ Old observations rather unreliable, likely further away than thought (so predicted GRV higher and ΔGRV lower)



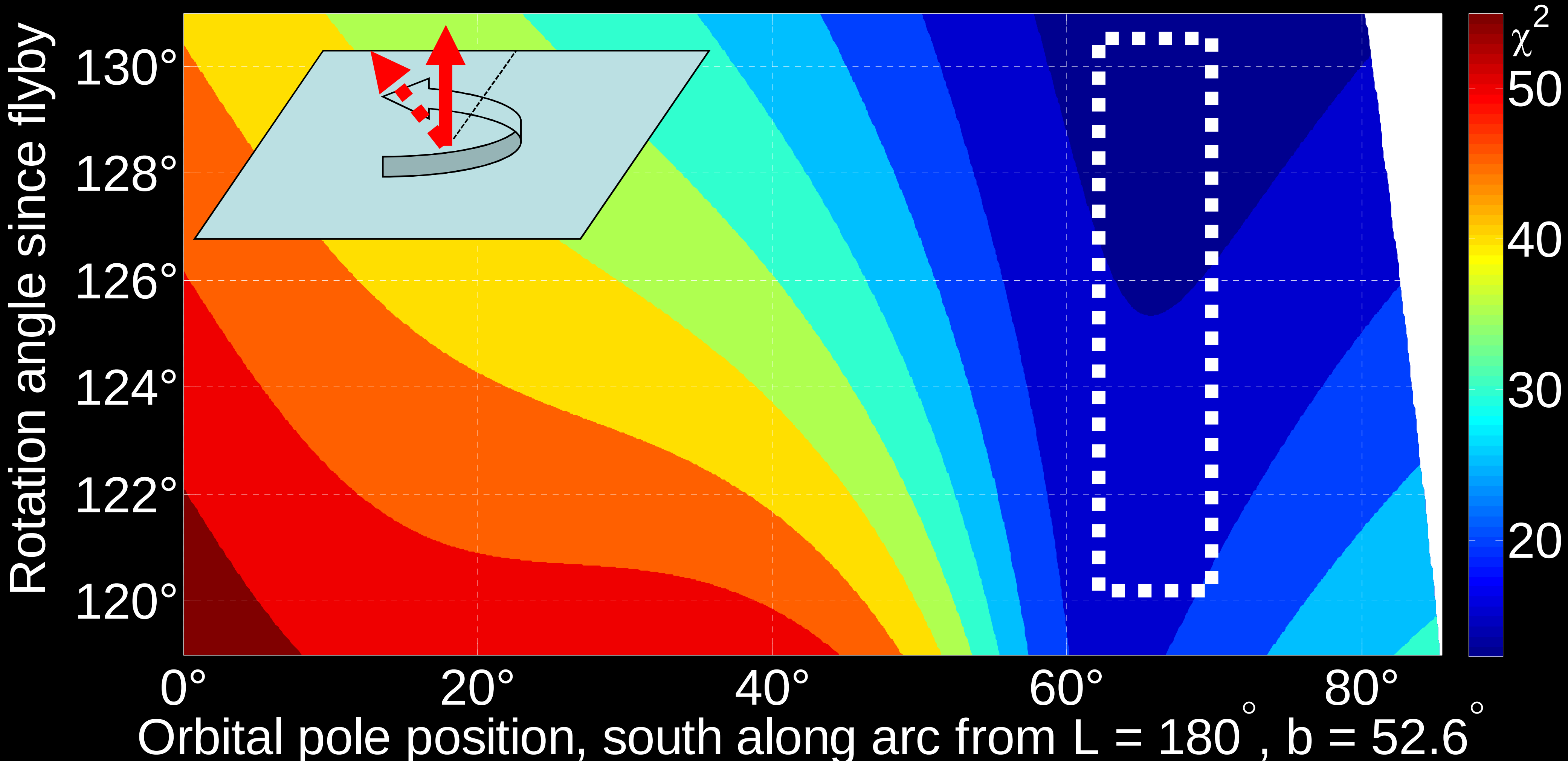
ApJ, 623, 148
(Silva+, 2005)

Quantifying the probability

- Monte Carlo trials used, with randomly selected:
  - Directions towards the high-velocity galaxies
  - Distances (observational uncertainties used)
- Remove whichever galaxy leads to lowest rms thickness (to mimic removing HIZSS 3 in actual LG to get better plane fit)

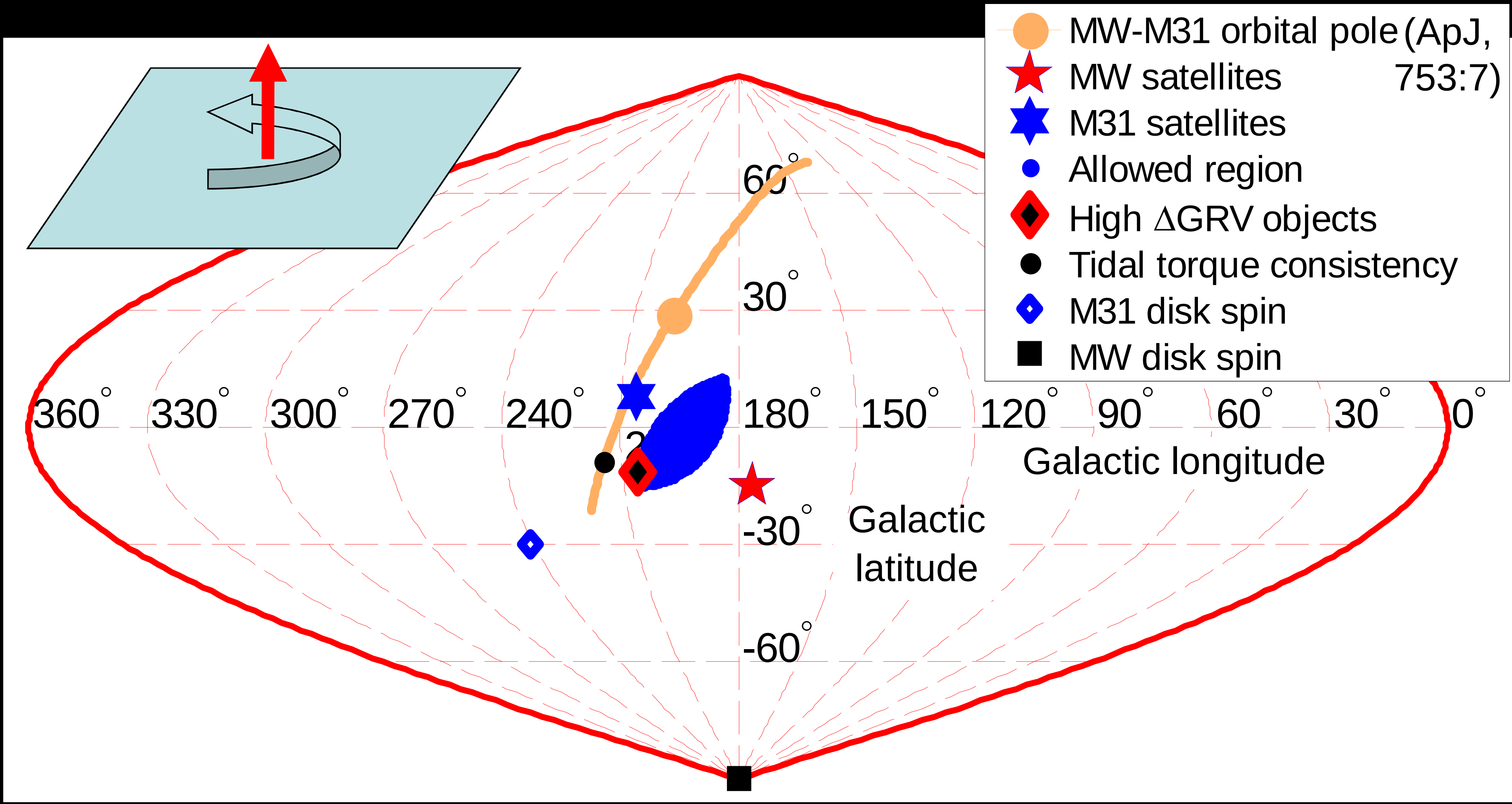
Where should the plane be?

- Assume tidal torque exerted only at closest approach and only on material closest to perturber
- Try to get material in MW to gain angular momentum in direction of its disk of satellites
- Same for M31
- In MOND, the MW–M31 line has rotated ~120° since closest approach



- Orbital pole of MW–M31 system must be orthogonal to direction in which we observe M31
- Orbital pole must lie in a small part of this Great Circle for the MW–M31 flyby scenario to work

Directions of the key vectors



- Agreement between pole suggested by satellite galaxies and distant high ΔGRV non-satellites

Finding a ‘matching’ mock system

Criterion	Meaning
Plane thickness	rms thickness should be below observed value
Aspect ratio	Aspect ratio (rms thickness ÷ rms in-plane radial extent) should be below observed value
Barycentre offset	MW-M31 barycentre closer to plane than observed situation
Direction	Plane normal must be closer than observed to the direction indicated by our toy model (based on MW and M31 disk and satellite plane orientations)

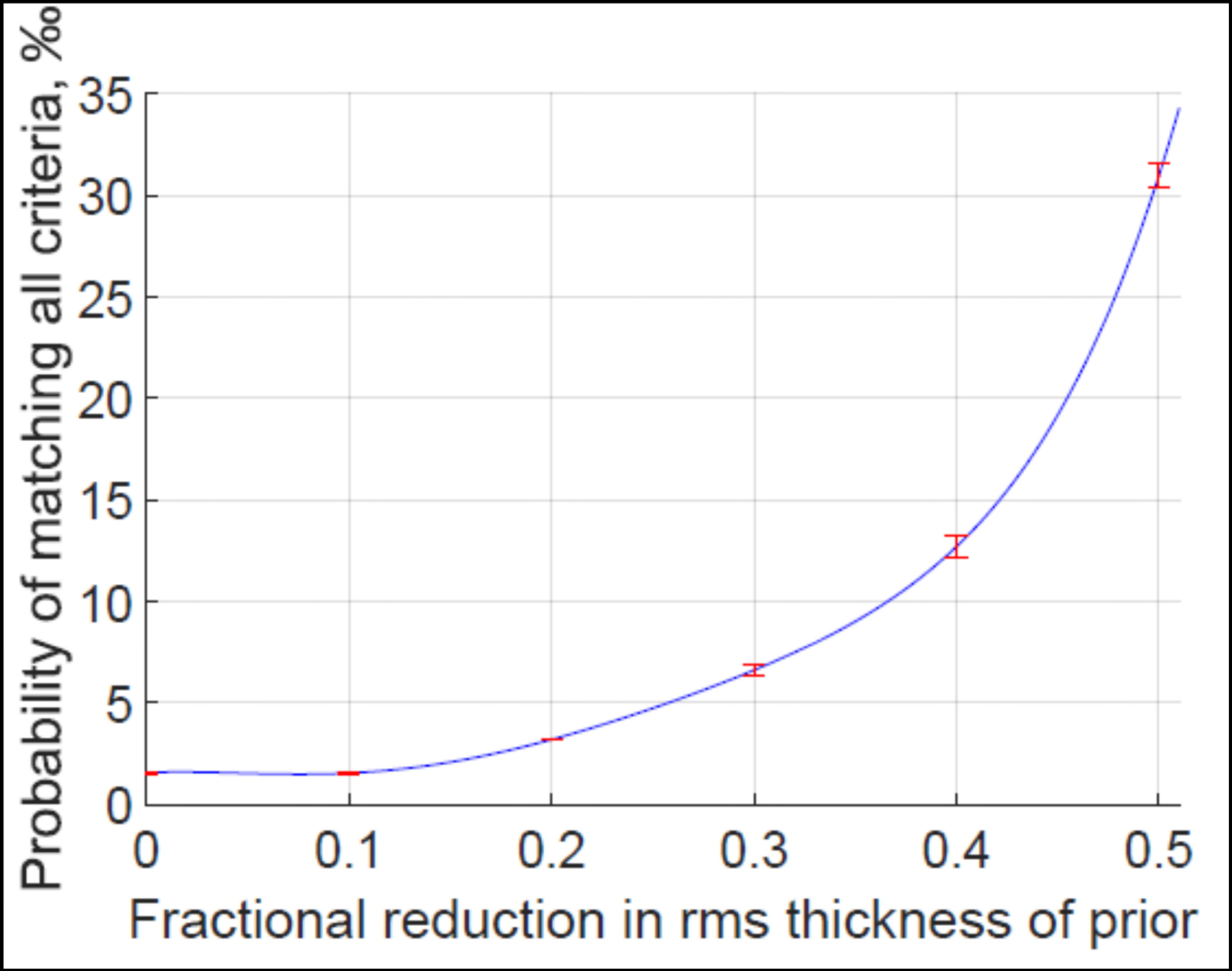
Probability, ‰	Thickness	Orientation	Barycentre offset
Thickness	5.2 ± 0.2		
Orientation	2.7 ± 0.1	442.7 ± 0.3	
MW-M31 barycentre offset	2.4 ± 0.1	76.7 ± 0.5	158.8 ± 0.9

Probability of matching all criteria

Investigation	Sample	Probability, ‰
Nominal (physical thickness)	All	1.56 ± 0.06
MW-M31 orbital plane rotated 5° south	All	1.59 ± 0.06
Distances fixed	All	1.22 ± 0.01
Nominal	~~HIZSS 3~~ (low latitude)	0.42 ± 0.02
Nominal	~~Antlia~~ (satellite of NGC 3109)	5.37 ± 0.24
Nominal	+KKH 98	0.24 ± 0.01
Aspect ratio	All	2.68 ± 0.01
Aspect ratio	~~Antlia~~	8.43 ± 0.03

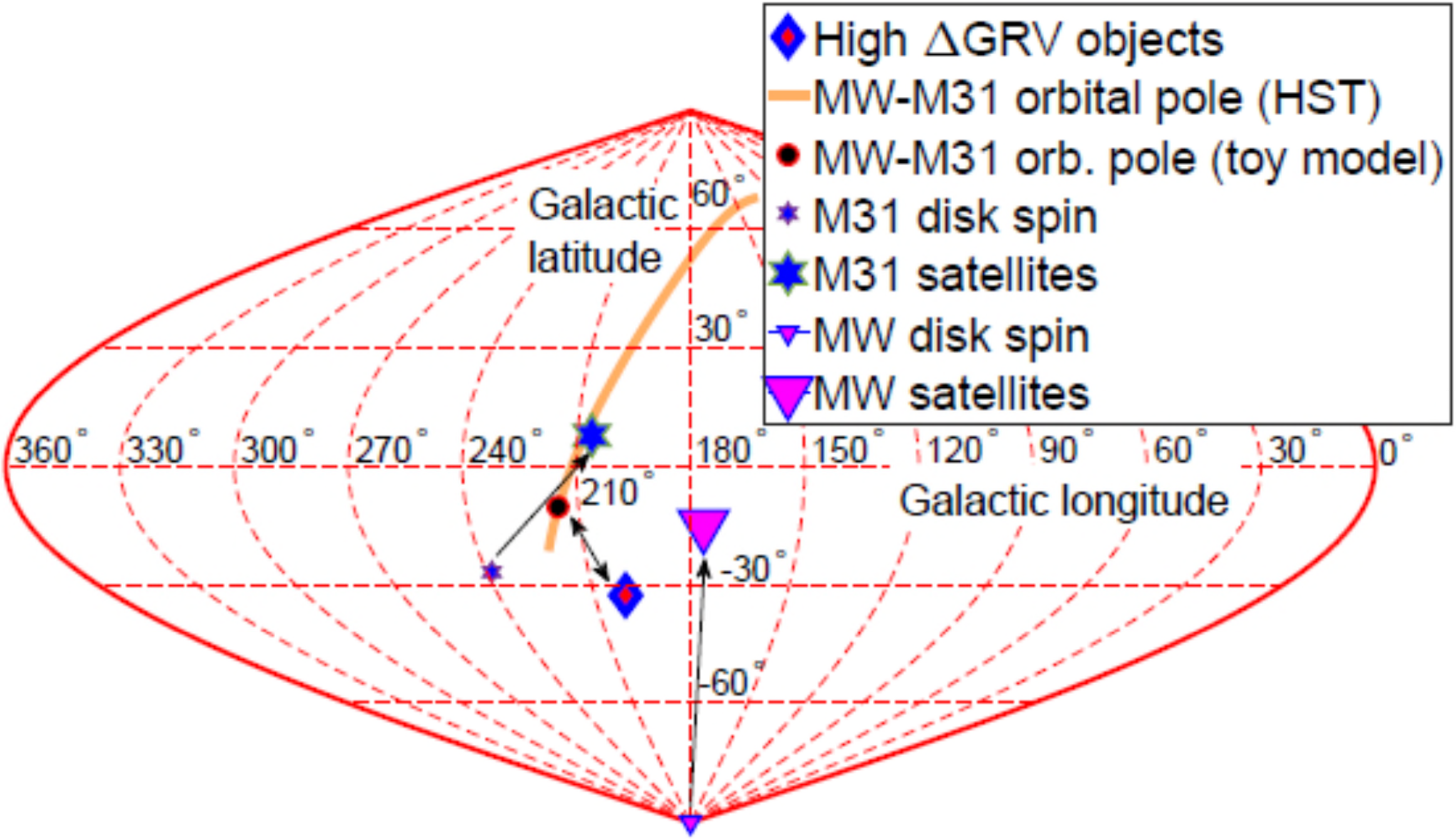
- Extremely unlikely that random system of HVGs matches expected characteristics in MOND as well as observed system

Aspect ratio = 0.1, so…

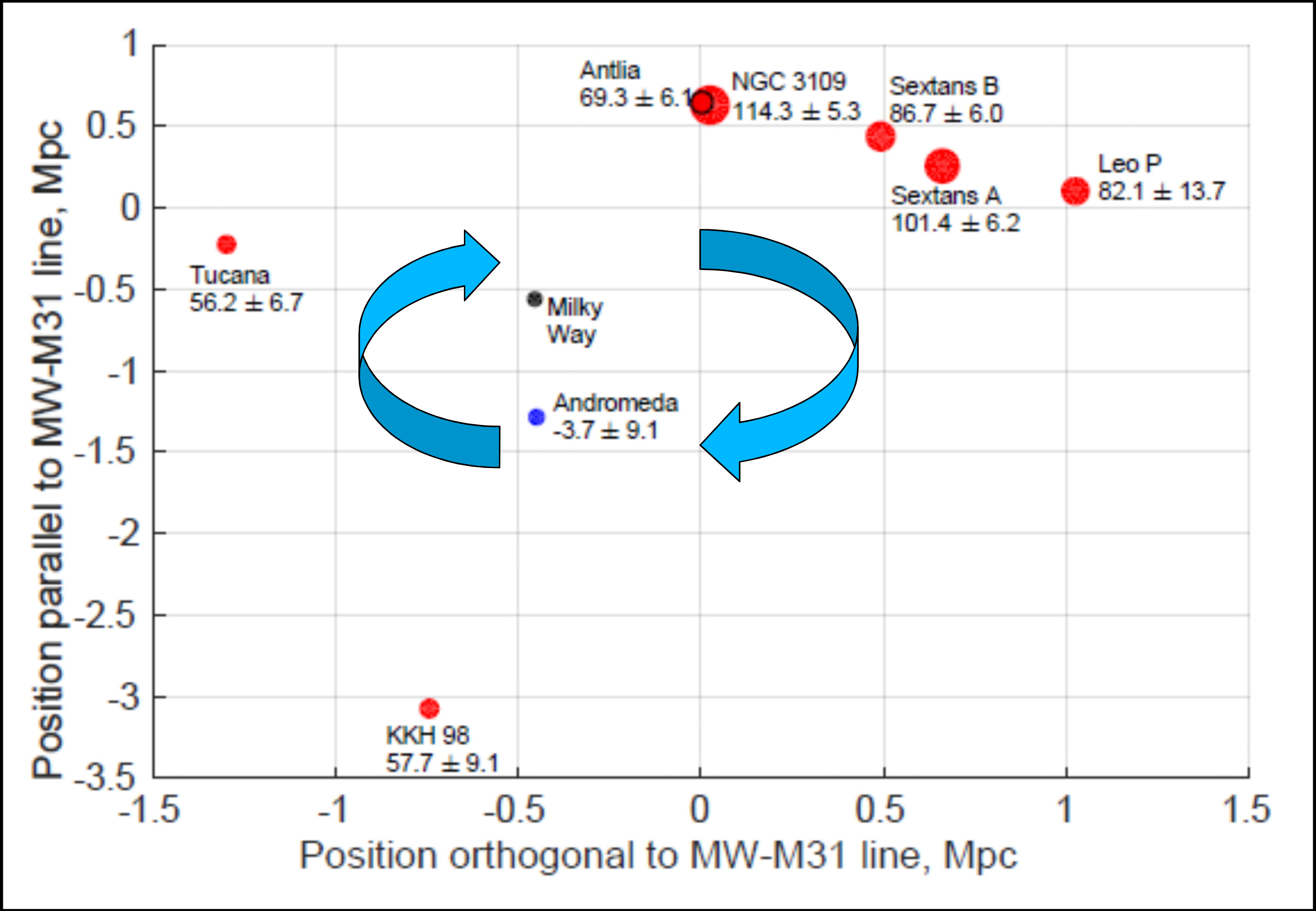


- System not mildly flattened

Directions of relevant vectors



Geometry within the HVG plane



Local Group galaxies flying outwards at high speeds

Only Milky Way or Andromeda could fling them out, if they were fast-moving

In Newtonian gravity, they were always moving slowly if given reasonable masses

Gravity is modified

MNRAS: 459, 2237 (Banik & Zhao, 2016)

MNRAS: 467, 2180 (Banik & Zhao, 2017)

Local Group galaxies flying outwards at high speeds

↓

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↓

Gravity is modified

In Newtonian gravity, they were always moving slowly if given reasonable masses → Gravity is modified

↓

Try very high mass: a close flyby leads to high speeds

↓

Galaxies merge as dark matter halos overlap

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Conclusions

- In ΛCDM, several Local Group galaxies have very high radial velocities: MNRAS, 459, 2237 and 467, 2180 (3D)
- In MOND, a past MW-M31 flyby provides a mechanism to fling LG dwarfs out at high speeds
- The dwarfs flung out fastest should lie close to the MW-M31 orbital plane (Arxiv: 1701.06559)
- Indeed, actual HVGs lie close to a plane (rms thickness 88 kpc, max. radial extent ~3 Mpc, aspect ratio 0.09)
- Orientation of HVG plane ~agrees with toy model based on MW & M31 satellite plane & disk orientations
- MW-M31 barycentre lies close to this plane (~50 kpc off)
- MW-M31 flyby infeasible in ΛCDM (dynamical friction)

The high-velocity galaxies

Galaxies included in plane fit	Distance from MW-M31 mid-point, Mpc	ΔGRV, km/s
Milky Way	0.382 ± 0.04	Not applicable
Andromeda	0.382 ± 0.04	-3.7 ± 9.1
Tucana	1.102 ± 0.016	56.2 ± 6.7
Sextans A	1.624 ± 0.036	101.4 ± 6.2
Sextans B	1.661 ± 0.037	86.7 ± 6.0
NGC 3109	1.631 ± 0.014	114.3 ± 5.3
Antlia	1.642 ± 0.030	69.3 ± 6.1
Leo P	1.80 ± 0.15	82 ± 14
KKH 98	2.160 ± 0.033	57.7 ± 9.1