The VDAR in the Milky Way

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The VAR in the Milky Way

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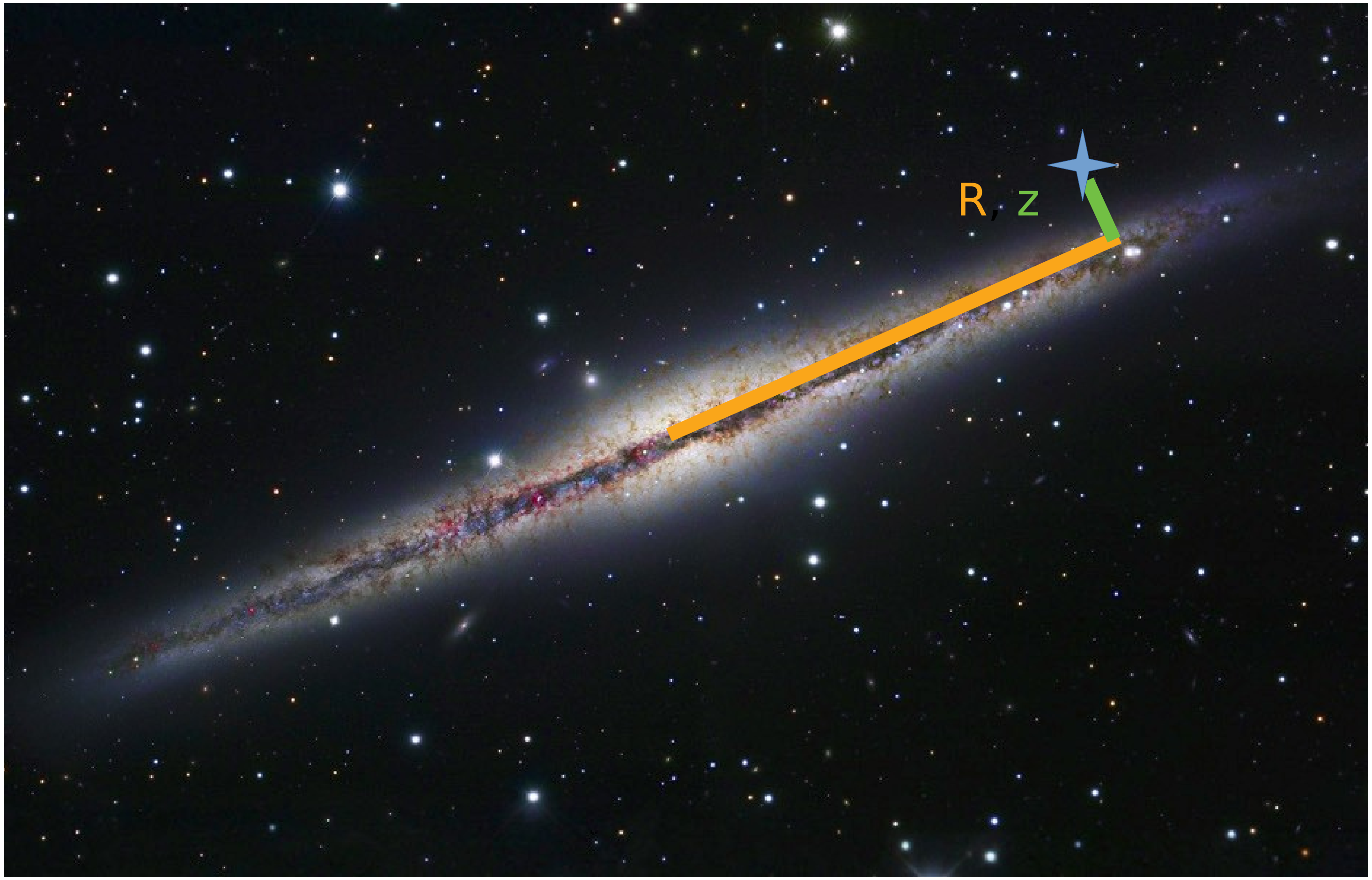
Coordinates

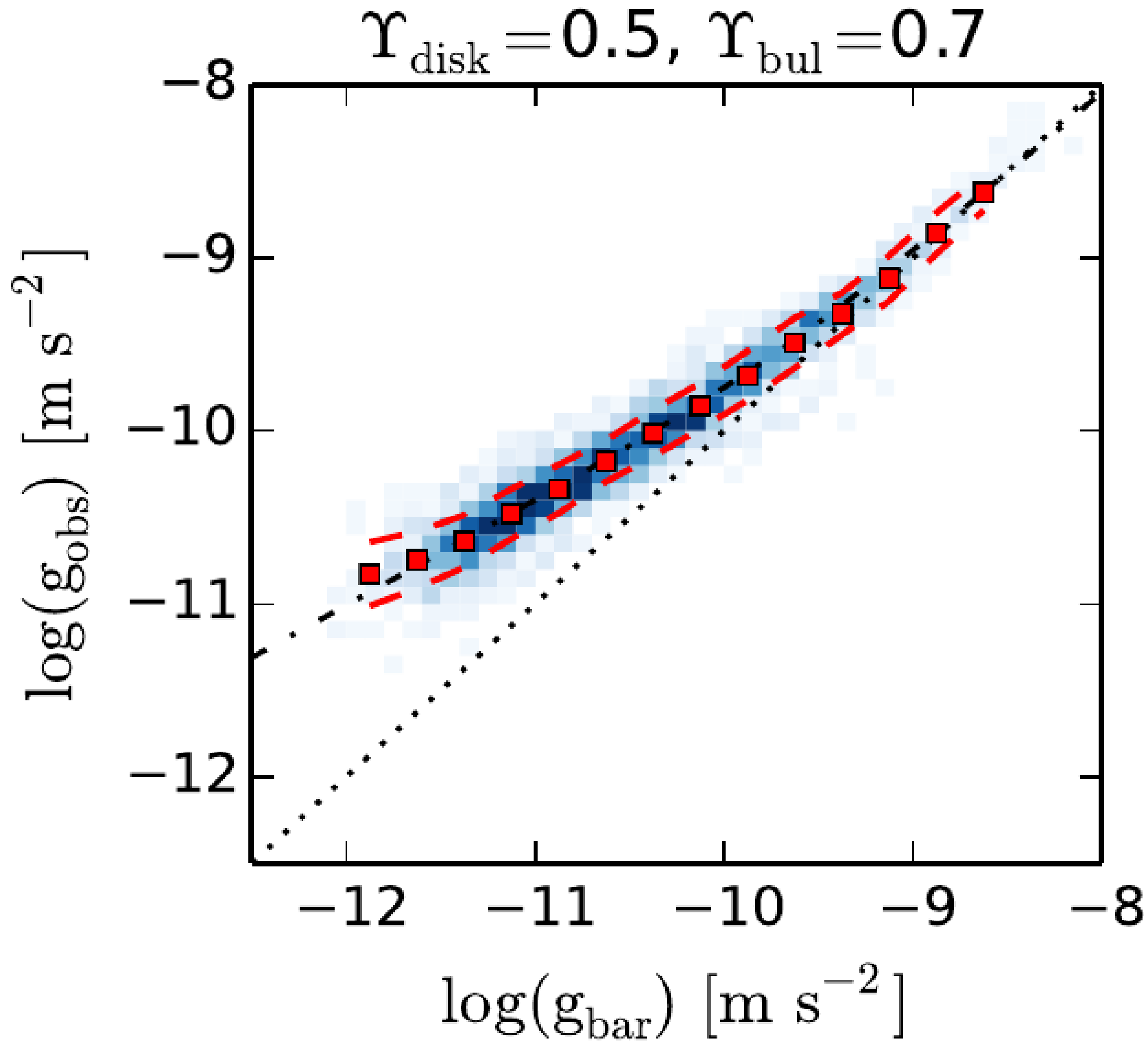


The RAR

RAR = ‘Radial Acceleration Relation’

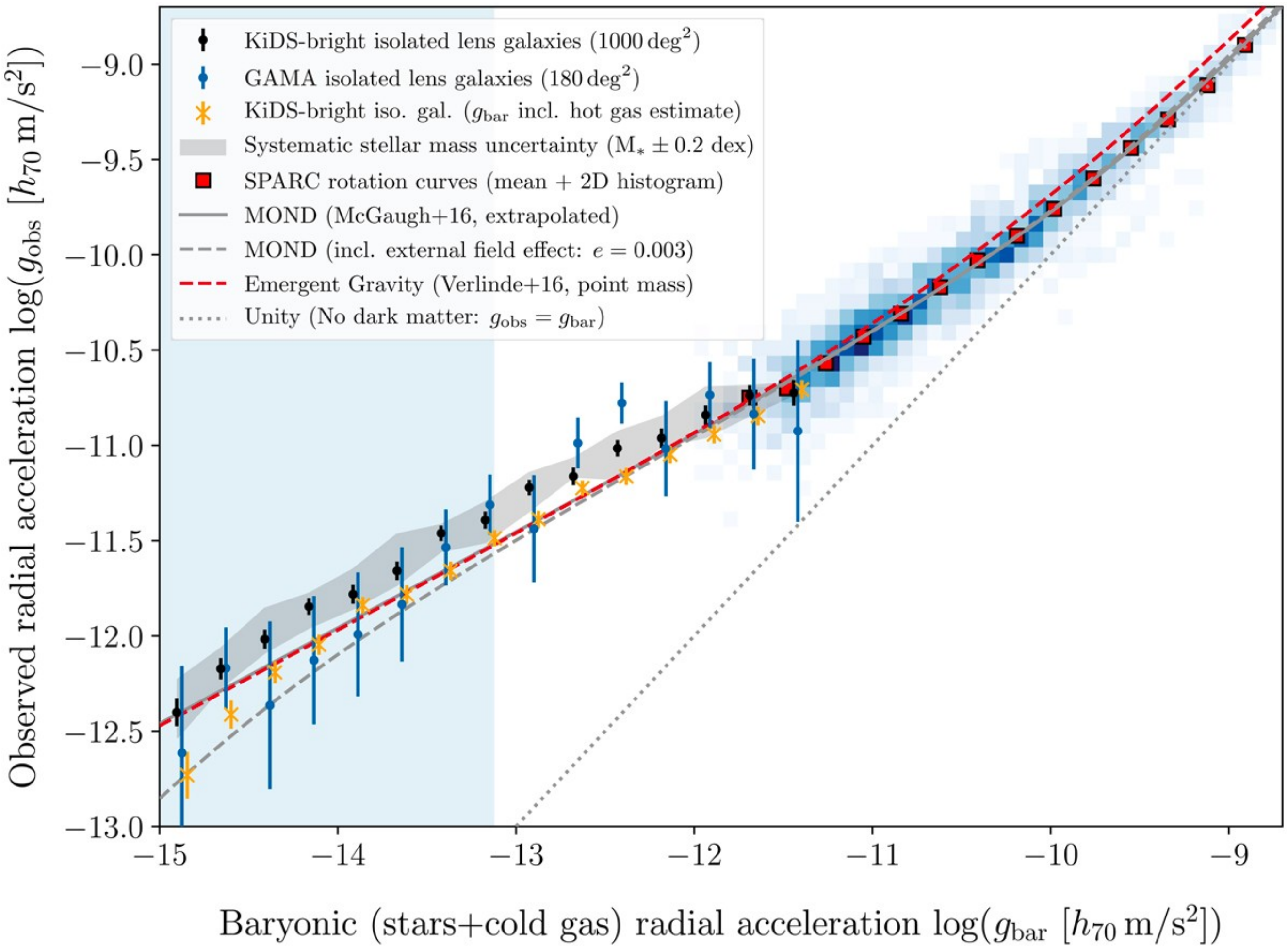
- $g_{\mathrm{obs}}(R) = v_{\mathrm{c}}^{2}(R)/R$
- g_{bar}(R) from models of luminous matter + Poisson eq.
- Tight correlation between the two

The RAR



Lelli et al. (2017)

The RAR



Brouwer et al. (2021)

The VAR

VAR = ‘Vertical Acceleration Relation’

- $a_{z,obs}(R,z)$ from Jeans eqs.
- $a_{z,bar}(R,z)$ from models of luminous matter + Poisson eq.
- What’s the relation between the two at different z?

‘Vertical’ Jeans equation

Assuptions

- Galaxy is stationary
- Galaxy is axisymmetric
- Ignore cross term in the v_R-v_z velocity DF
- Note: the acceleration here is NOT the gravitational force per unit mass.
- Plays the same role of $v_c^2(R)/R$ in RAR

$$a_{z,\mathrm{obs}} = \frac{1}{\nu}\frac{\partial}{\partial z}\left(\nu\sigma_z^2\right)$$

‘Vertical’ Jeans equation

Assuptions

- Galaxy is stationary
- Galaxy is axisymmetric
- Ignore cross term in the v_R-v_z velocity DF
- Note: the acceleration here is NOT the gravitational force per unit mass.
- If $\nu(R,z)=\nu_0(R)\exp(-|z|/h(R))$ with scale heigth h

$$a_{z,\mathrm{obs}}=\frac{-\mathrm{sgn}(z)\,\sigma_z^2}{h}+\frac{\partial\,\sigma_z^2}{\partial z}$$

Poisson equation

Assumptions:

- Galaxy is axisymmetric
- Integration over *z*
- Here the acceleration IS the gravitational force per unit mass; $g_{\mathrm{bar}}(R)=-a_{R,\mathrm{bar}}(R,z=0)$

$$a_{z,\mathrm{bar}}=2\pi G\Sigma_z+2\int_0^z \mathrm{d}z'\,\frac{1}{R}\frac{\partial\left(R\,a_{R,\mathrm{bar}}\right)}{\partial R}$$

Poisson equation

Assumptions:

- Galaxy is axisymmetric
- Integration over z
- Here the acceleration IS the gravitational force per unit mass; $g_{\mathrm{bar}}(R)=-a_{R,\mathrm{bar}}(R,z=0)$; $v_{\mathrm{c,bar}}^2(R) = \mathrm{R}\, g_{\mathrm{bar}}(R)$

$$a_{z,\mathrm{bar}} \approx 2\pi G \Sigma_z - 4 \frac{v_{\mathrm{c,bar}}}{R} \frac{\mathrm{d}\, v_{\mathrm{c,bar}}}{\mathrm{d}\, R} z$$

The case of the Milky Way

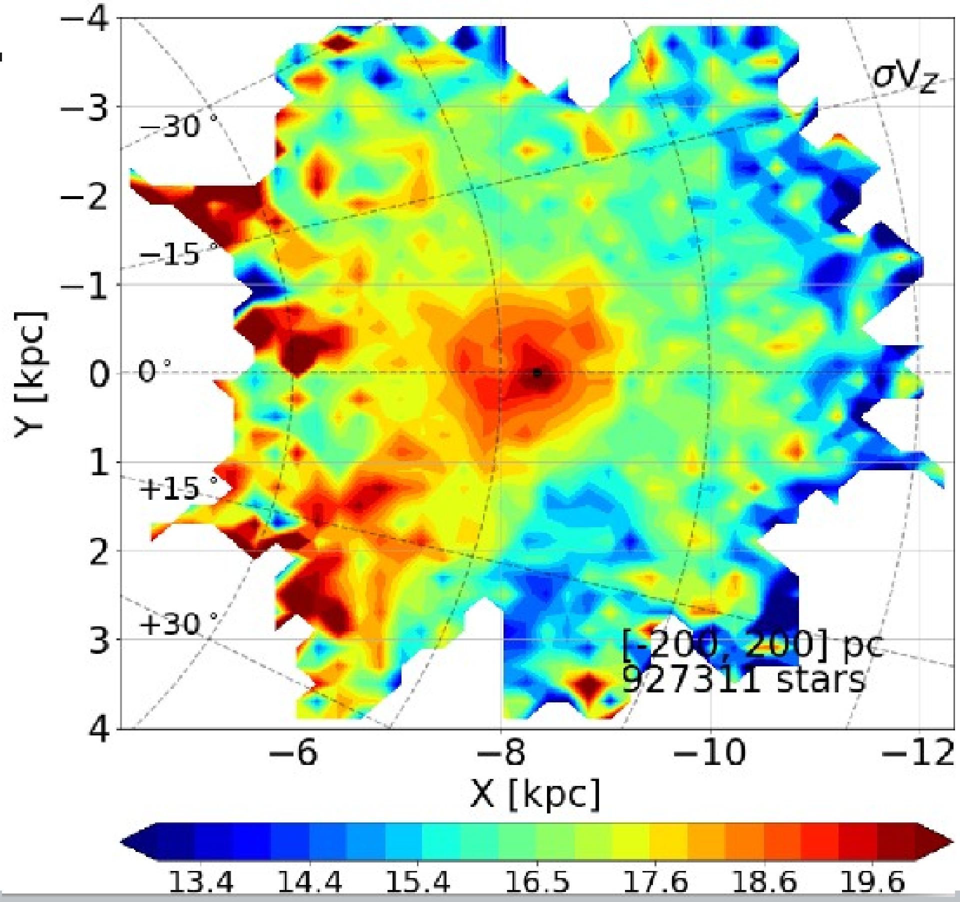
Check the VAR on the MW (Gaia DR3) before external galaxies

- ν and σ_z estimated from the number counts and v_z dispersion of Gaia data inside R and z bins
- $a_{z,\mathrm{bar}}$ from models of the baryonic content of the Galaxy ...

Ingredients: σ_z

- σ_z : measure it from std deviation of v_z for stars in Gaia at different R rings and z slices
- However ..

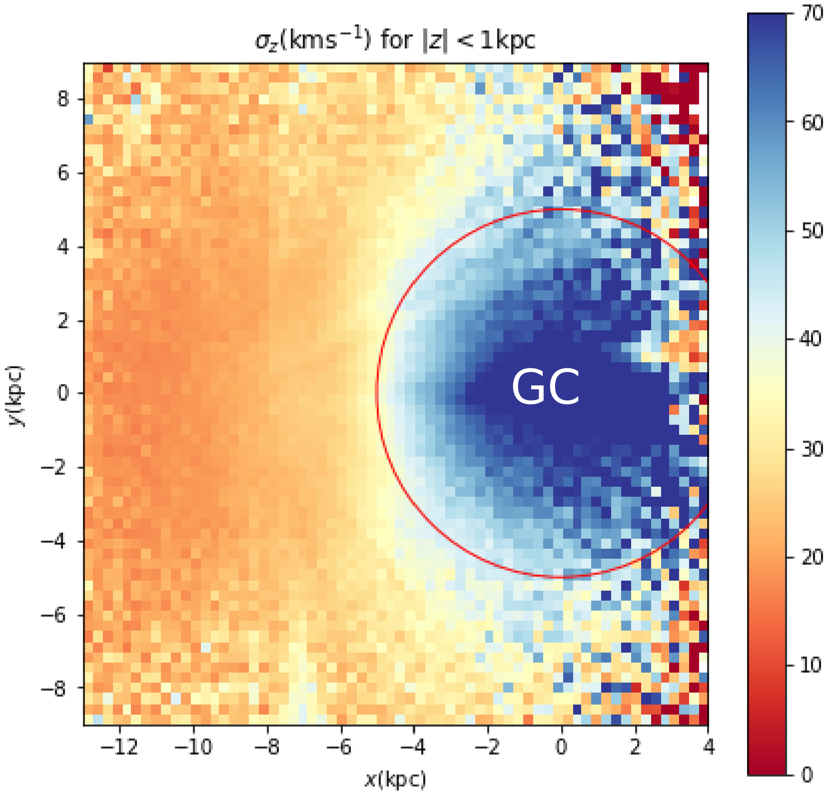
GC



From Gaia collab. (2018)

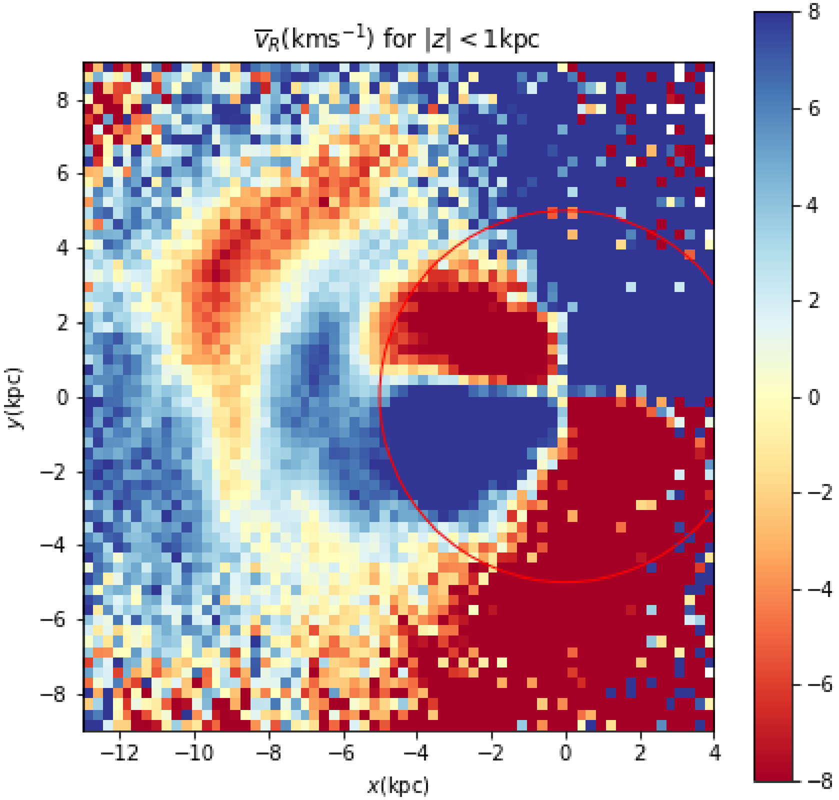
Ingredients: σ_z

- σ_z : measure it from std deviation of v_z for stars in Gaia at different R rings and z slices
- Pick tracer population: RGB stars (Gaia collab. 2023)



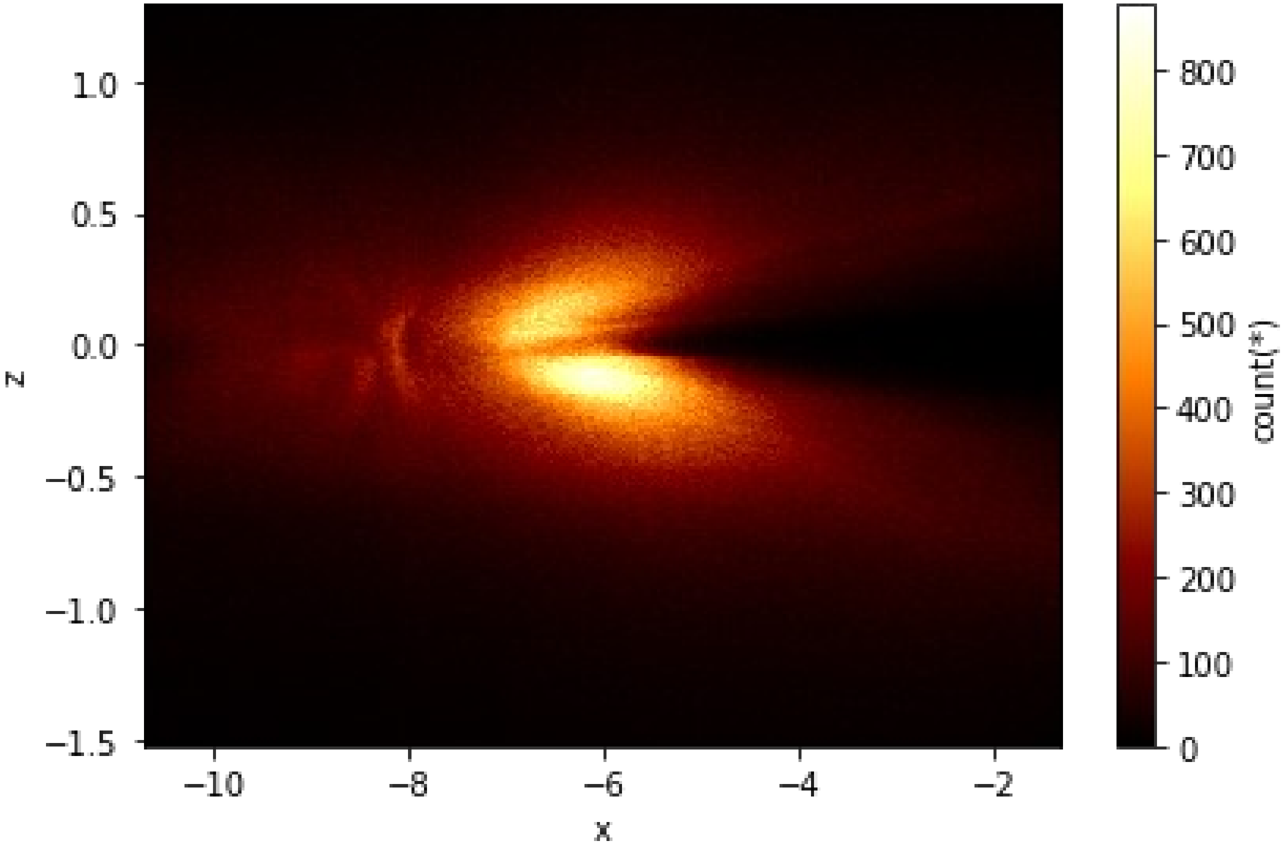
Avoid the bar!

- Non-axisymmetric effects strongest R<5kpc



Ingredients: ν

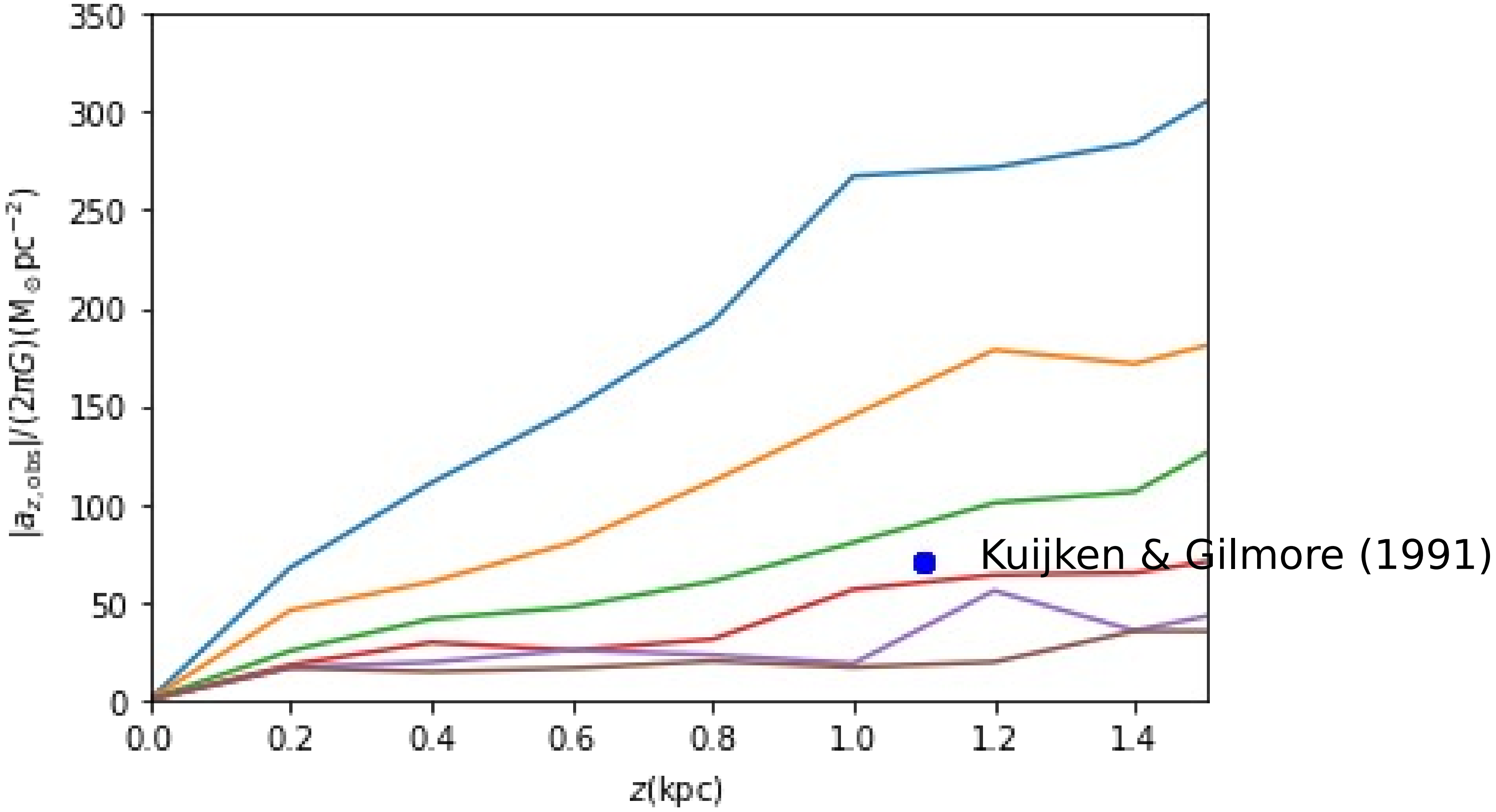
- ν : count stars in Gaia at different R rings and z slices?
- You’ll never make it this way ...



Ingredients: ν

- ν : count stars in Gaia at different R rings and z slices?
- You'll never make it this way …
- Simple (simplistic?) solution: fit $\nu(R,z)=\nu_0(R)\exp(-|z|/h(R))$ in the Solar neighbourhood and extrapolate to the rest of the Galaxy
- Find $h(R)=aR+b$, a=0.05 and $h(R_0)=0.32$kpc
- Increasing scaleheight with R found by many authors (e.g. Binney & Vasiliev 2023)

$a_{z,obs}$



350
300
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$|a_{z,obs}|/(2\pi G)\,(M_\odot\,pc^{-2})$
z(kpc)
● Kuijken & Gilmore (1991)

Ingredients for $a_{z,bar}$

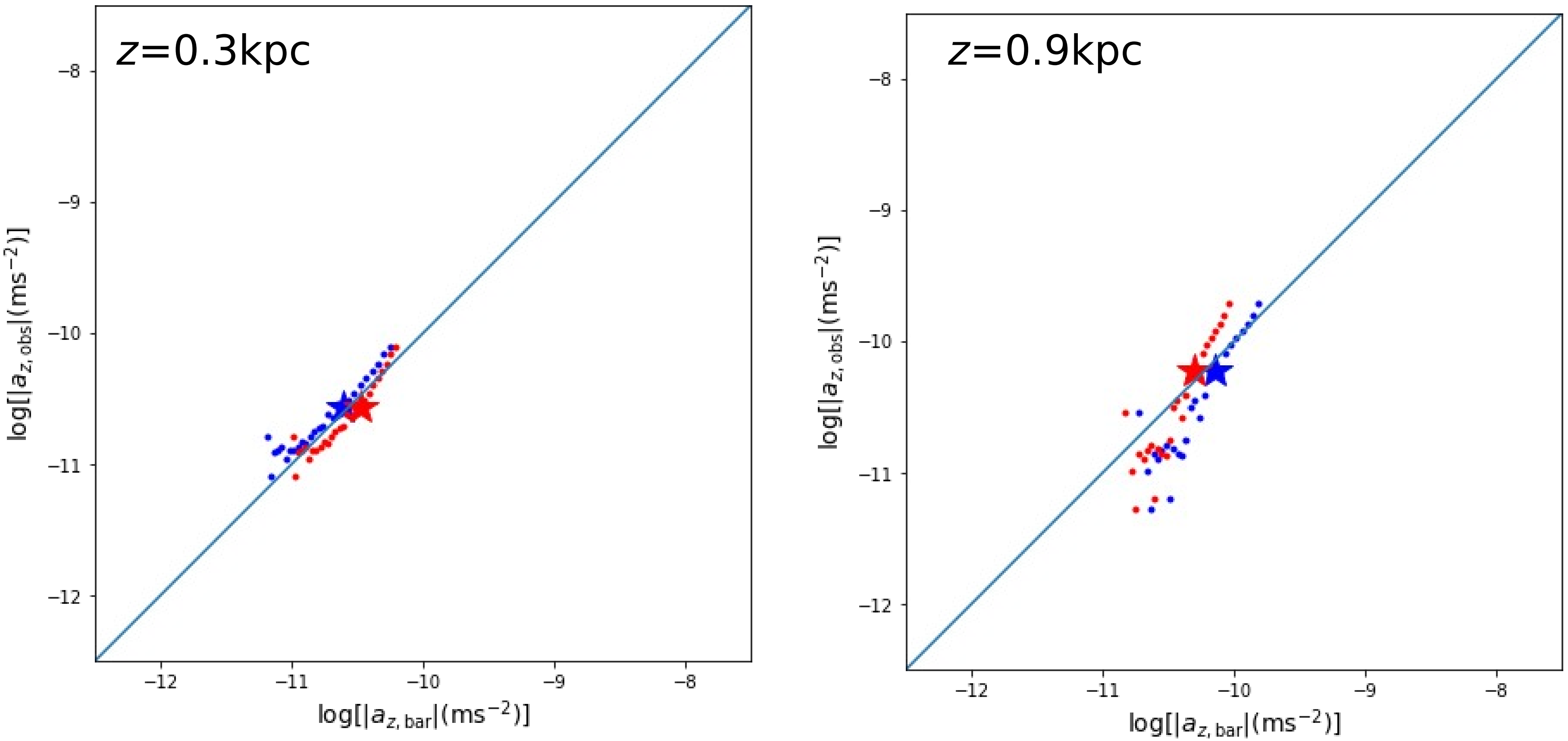
- Models for the baryons of the MW … Unfortunately for the stellar disk few and date back to >20 years ago (e.g. Freudenreich 1998, Drimmel & Spergel 2001). IR point source measurements are the most reliable (scale length ~ 2.6 kpc)
- Almost the same happens with gas

Ingredients for $a_{z,\mathrm{bar}}$

- **Baryonic model 1)**: McMillan (2017) without the dark halo (beware: the fit was done WITH the halo!)
- **Baryonic model 2)**: McGaugh (2019) with gas data from Olling & Merrifield (2001), disk obtained inverting RAR
- Beware! R_0 = 8.2 kpc for McMillan, but was 8.122 kpc for McGaugh. I use R_0=8.277 (Gravity 2022).
- I stretched McGaugh model which is now ~ 2x more massive than McMillan.

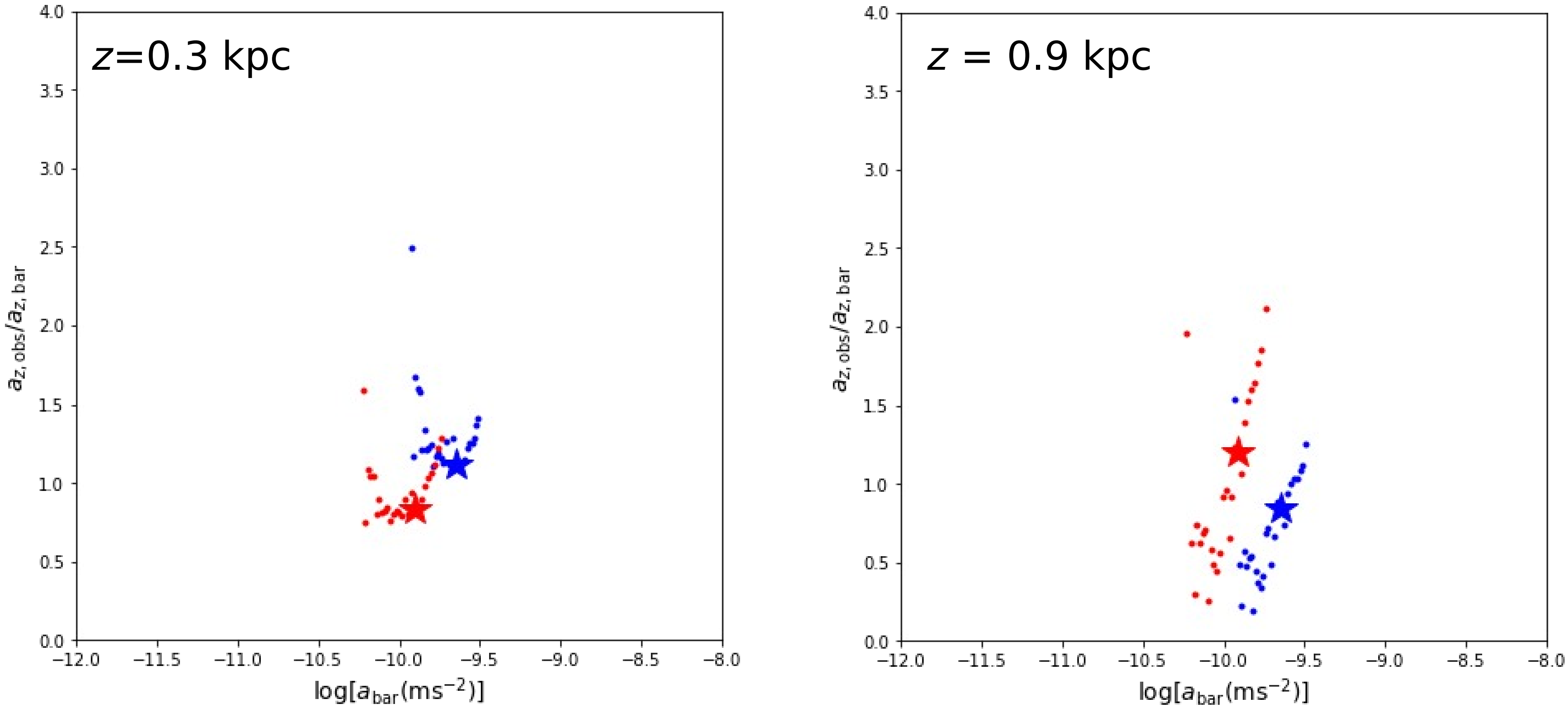
Results

McGaugh and **McMillan**



Results (with a_{bar}=|total acceleration|)

McGaugh and **McMillan**



No conclusions but caveats

- Is the velocity dispersion from Gaia still biased?
- Are we getting the vertical density of the RGBs right?
- Cross terms / Galactic wobbling and phase-spiral?
- Non-axisymmetric effects?
- Baryonic models. Which one is ‘right’?
- What’s the detailed prediction from MOND?