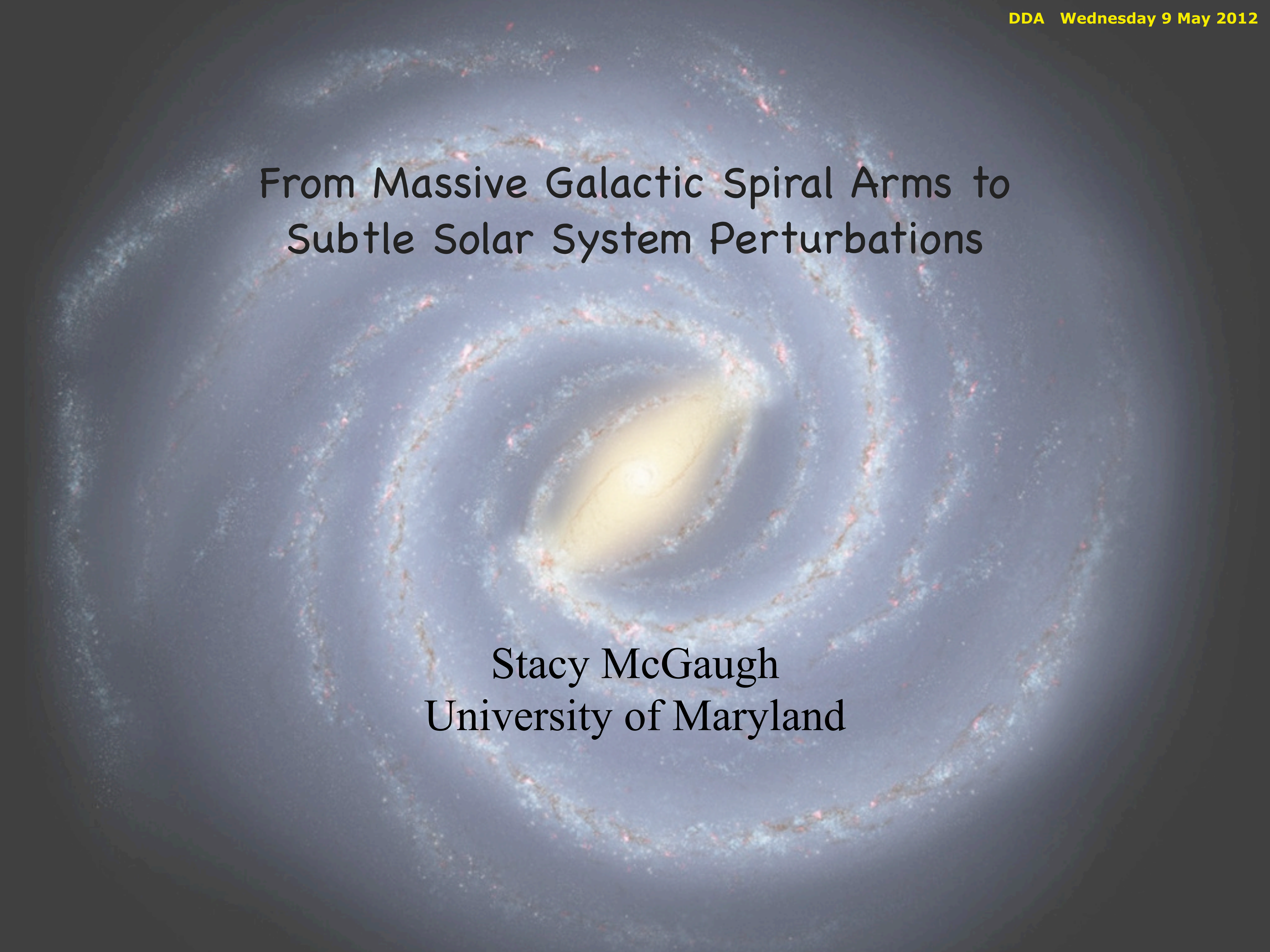
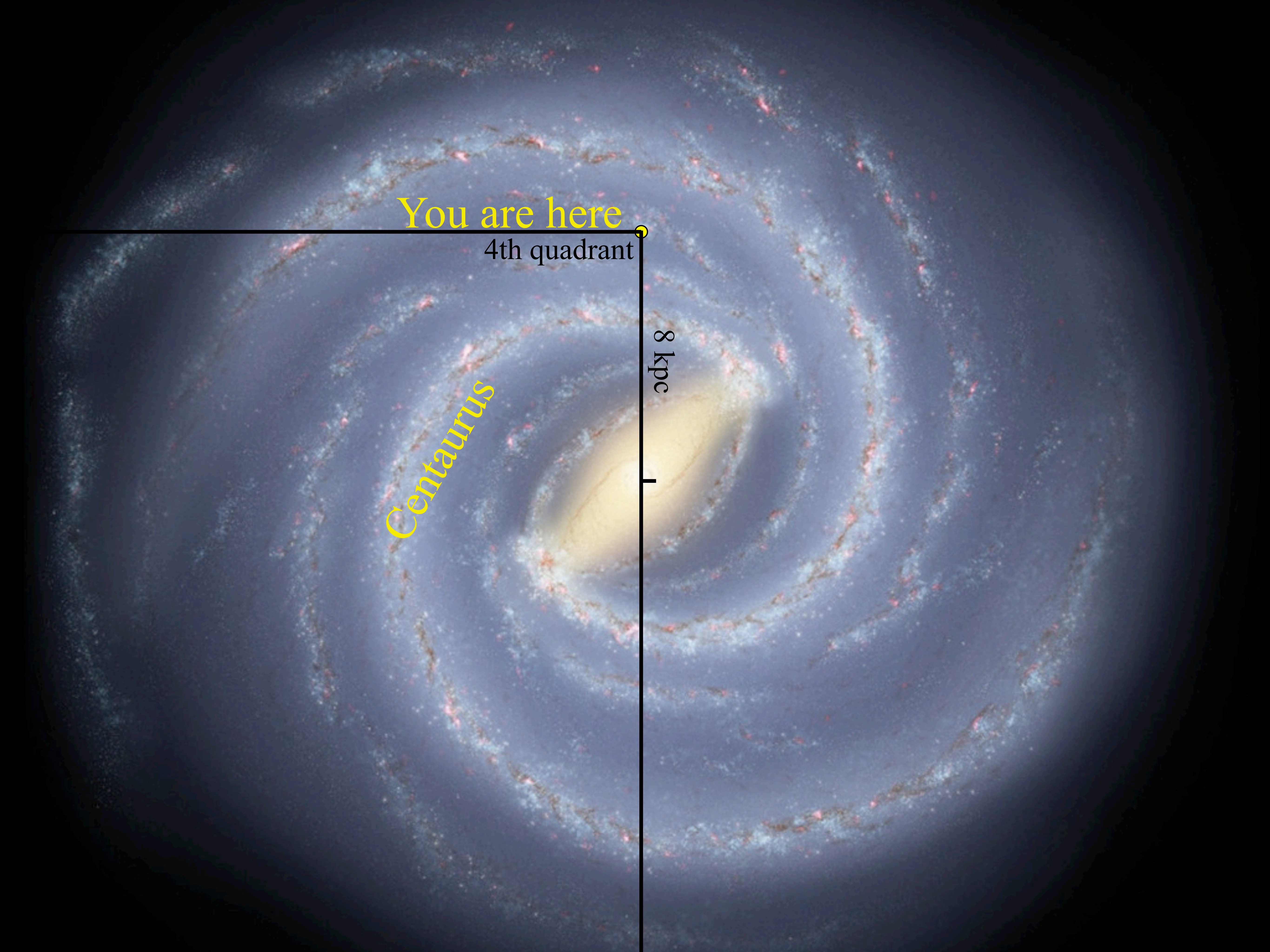


From Massive Galactic Spiral Arms to Subtle Solar System Perturbations

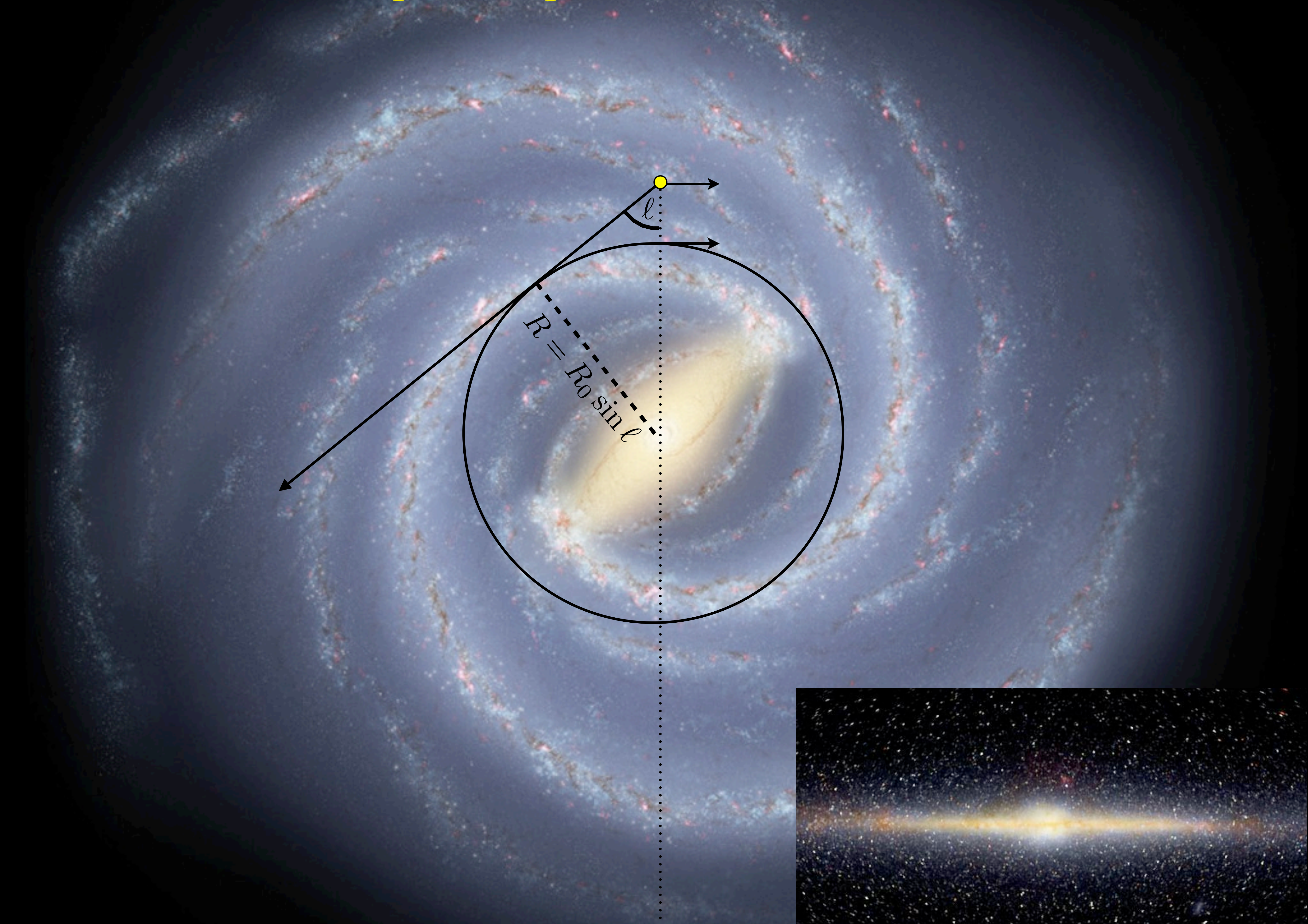
Stacy McGaugh
University of Maryland


You are here


You are here
4th quadrant
8 kpc


You are here
4th quadrant
8 kpc
Centaurus

Terminal velocities provide precise rotation curve inside solar circle



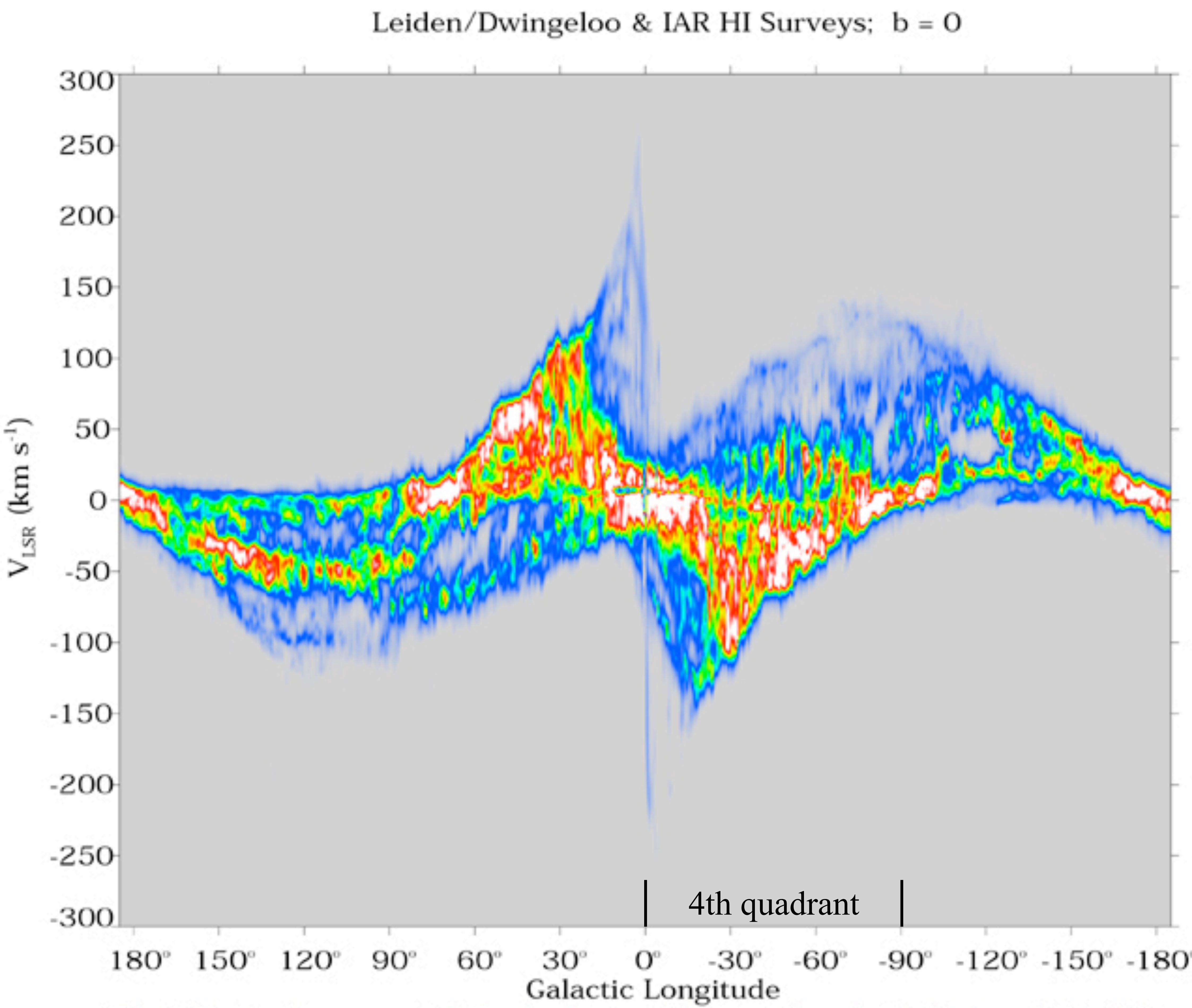


Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

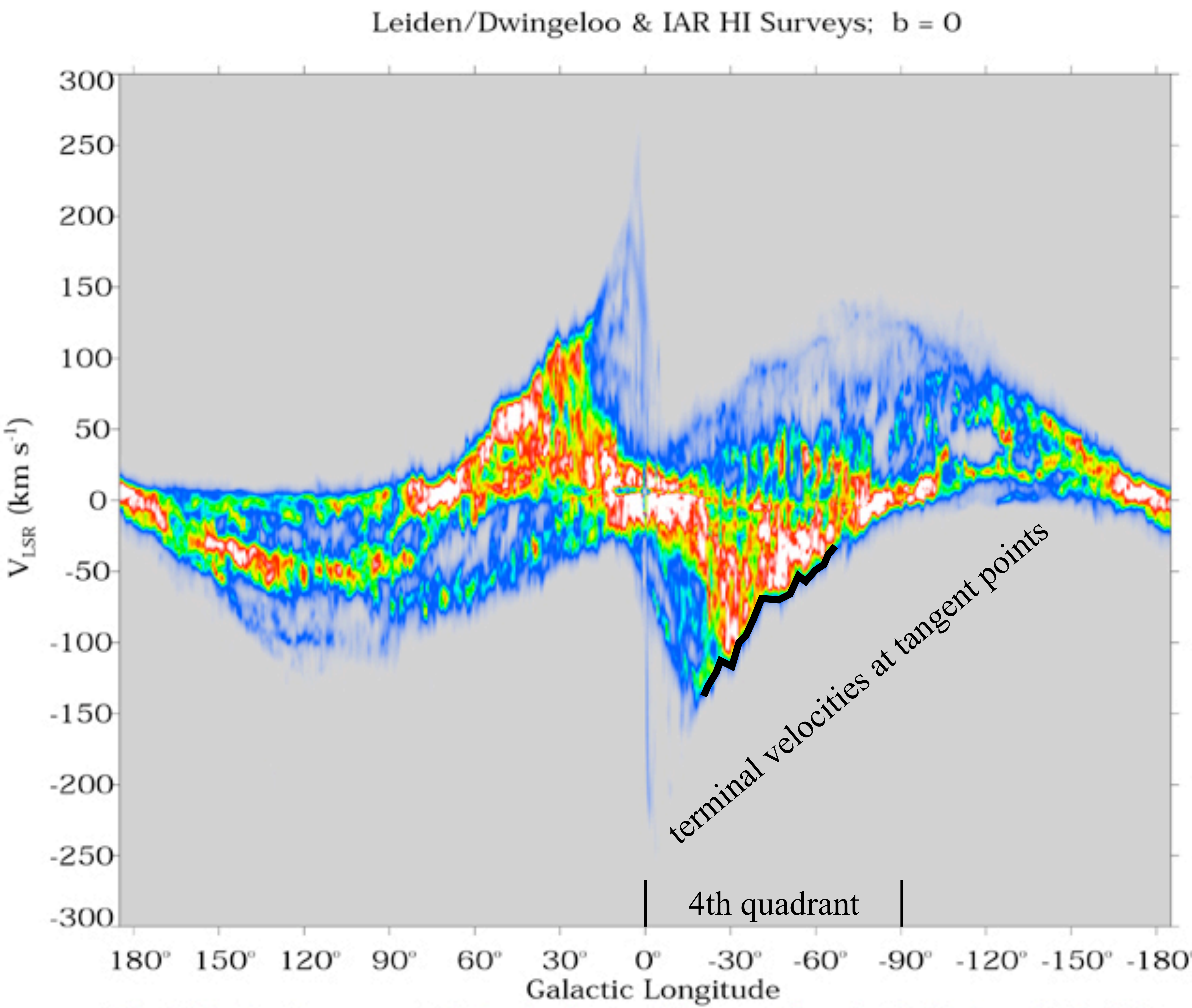
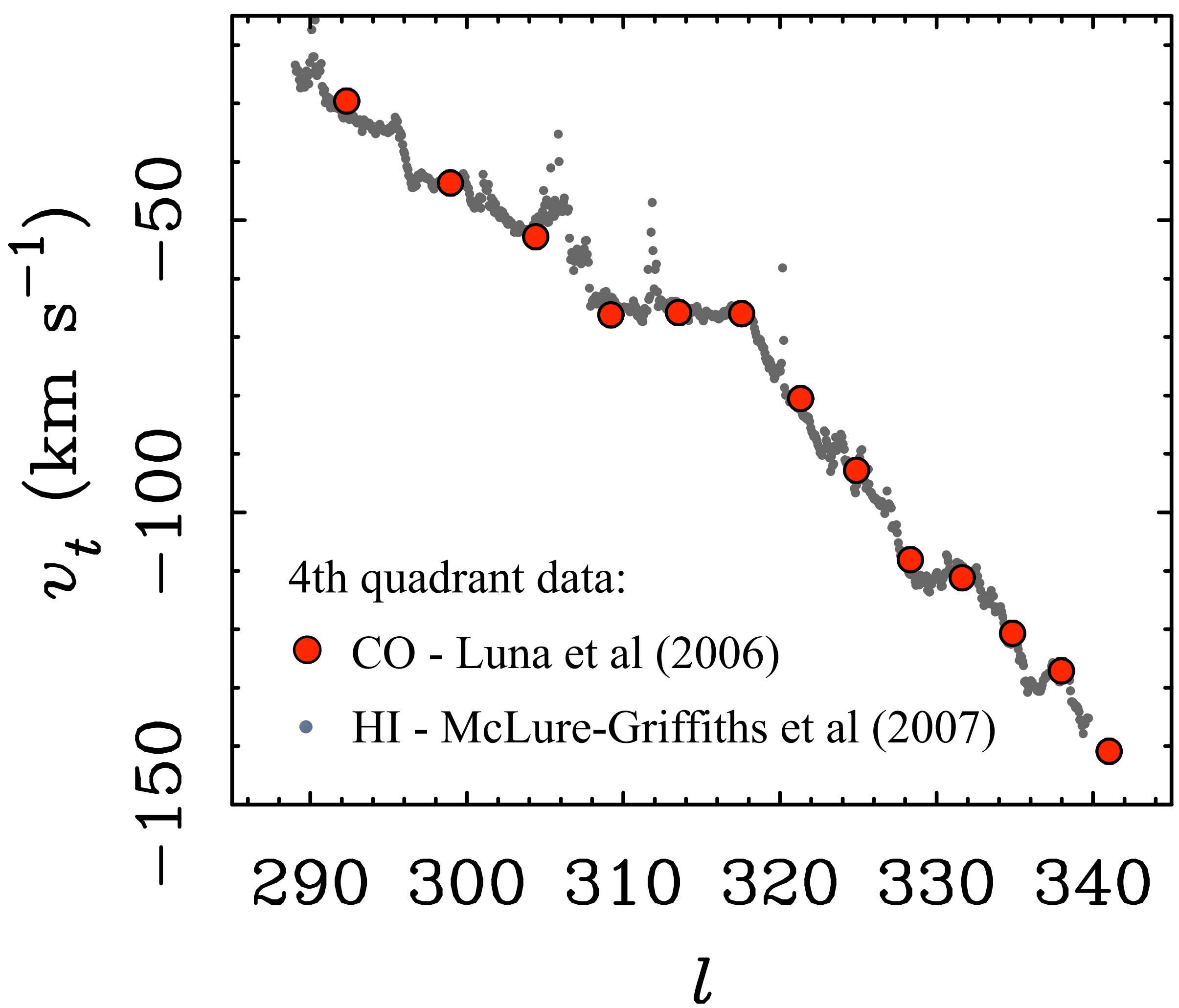
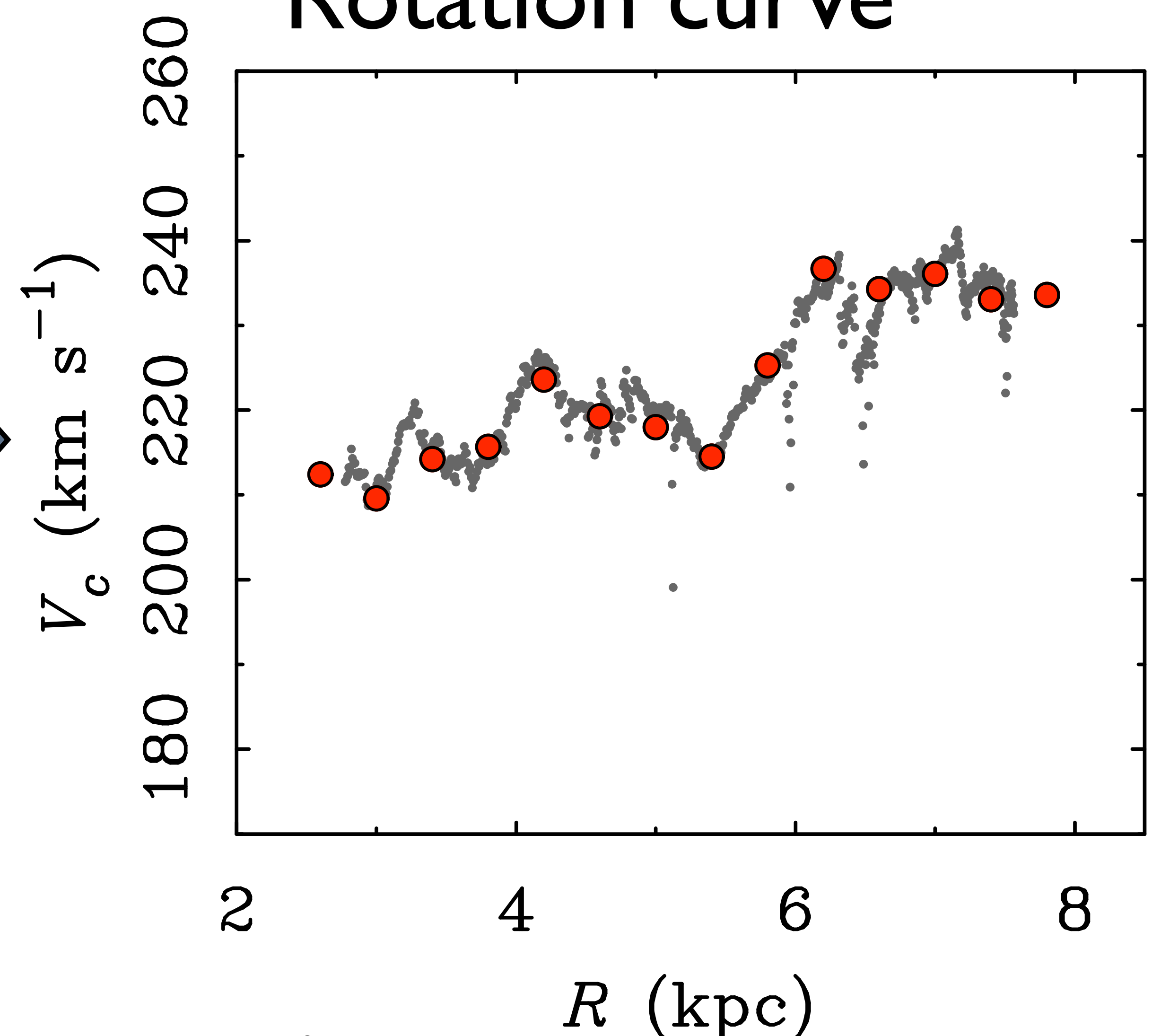


Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Terminal velocities



Rotation curve

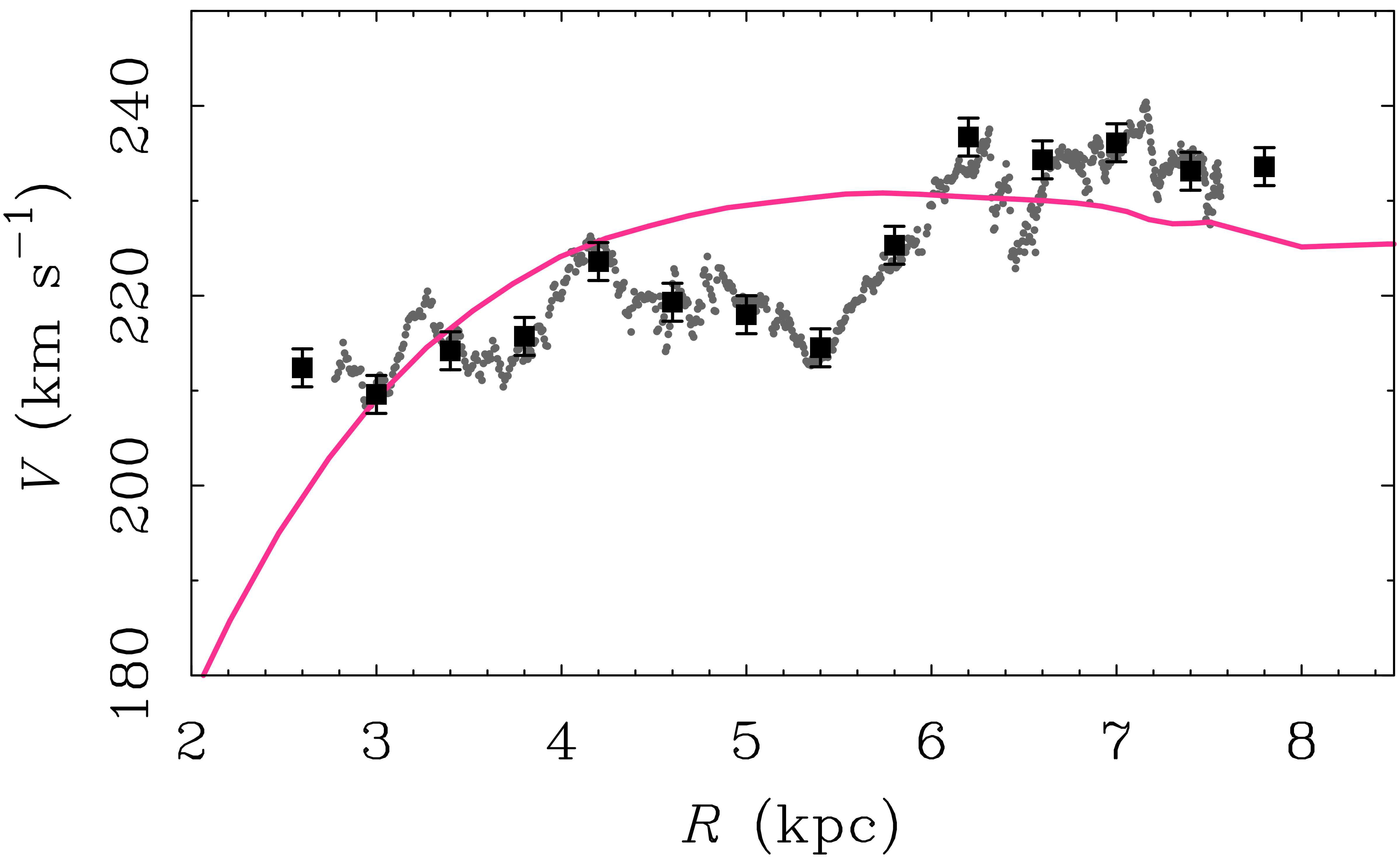


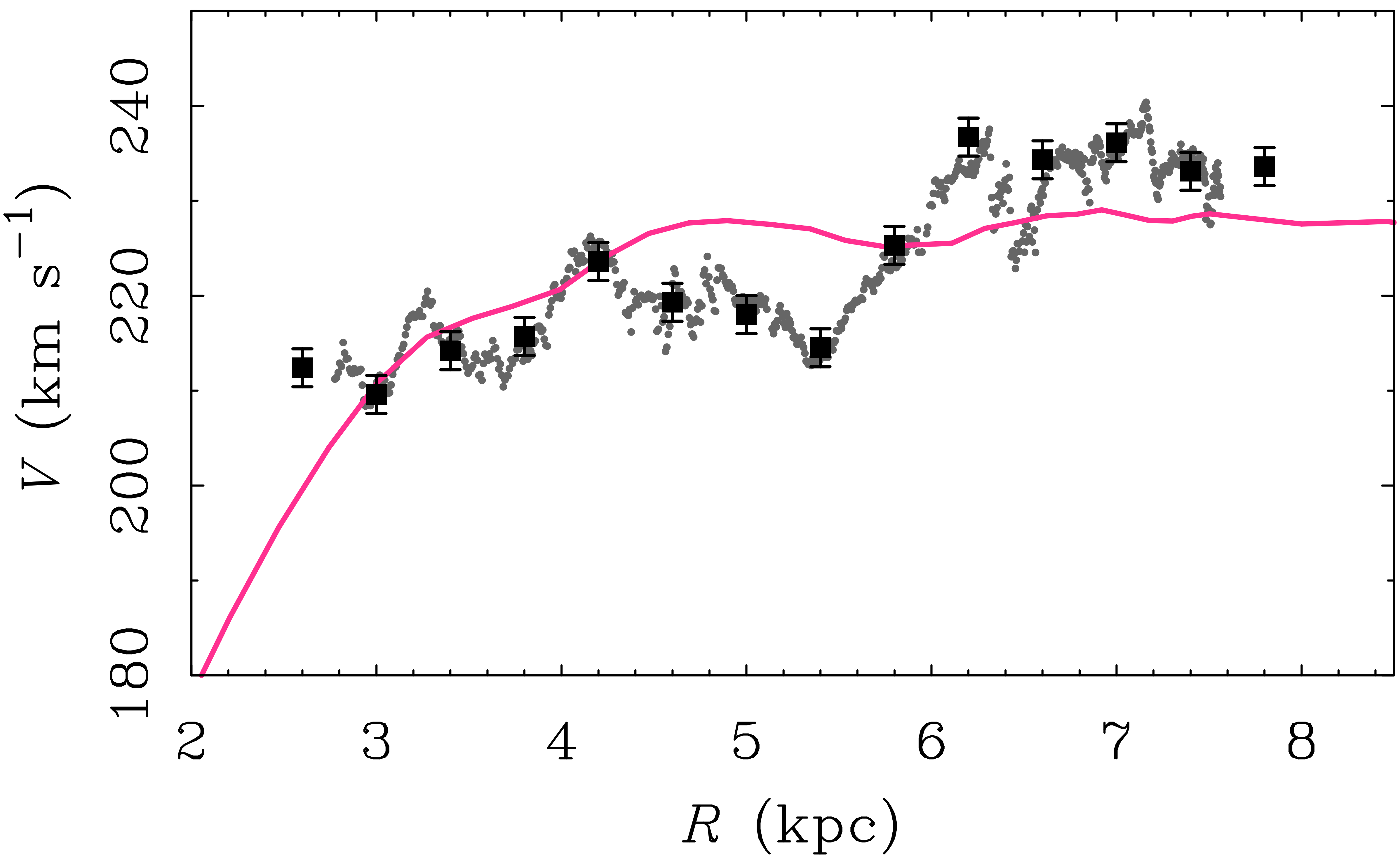
$$V_c = v_t + V_0 \sin \ell$$

$$R = R_0 \sin \ell$$

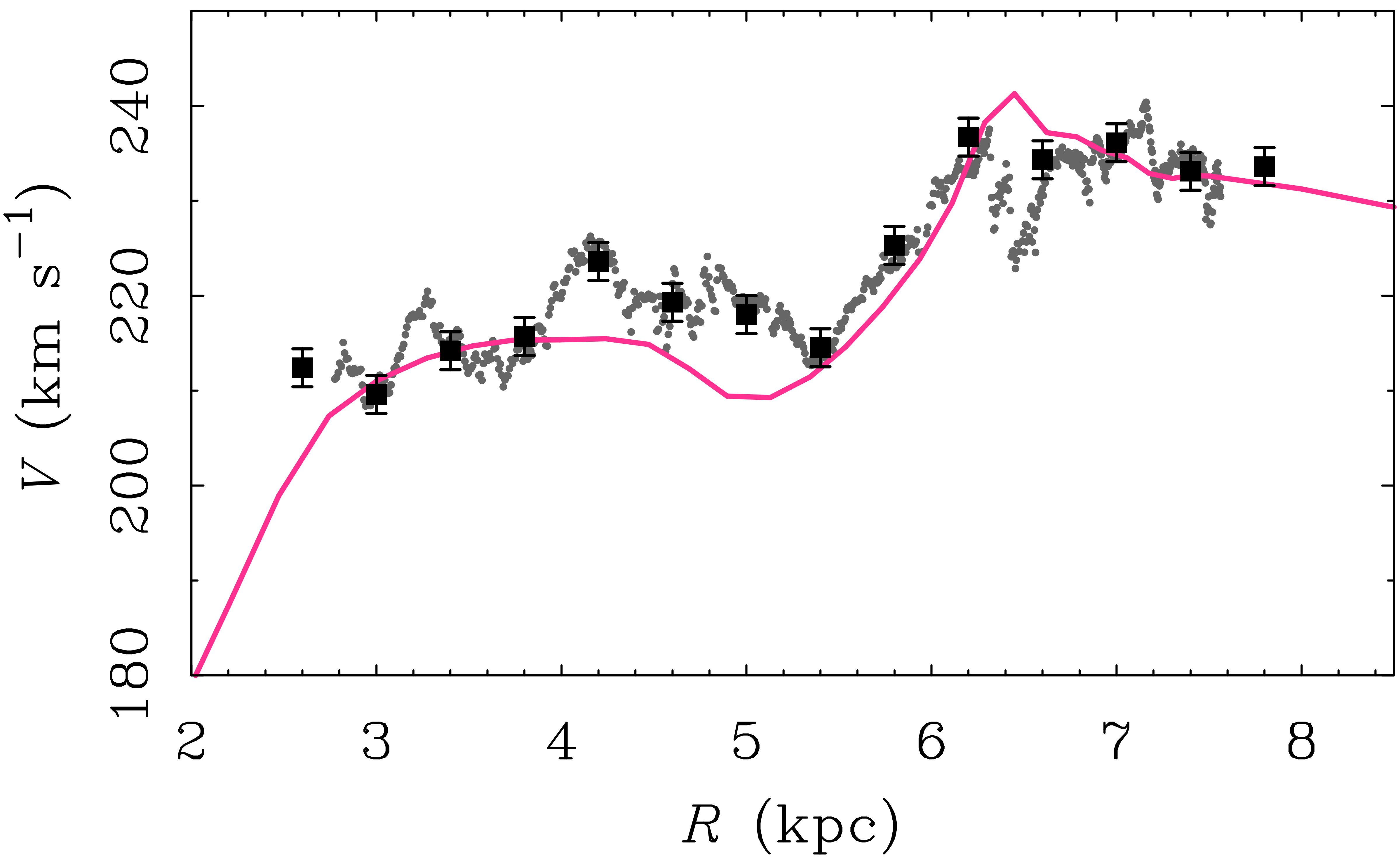
Terminal velocities give a precise measure of the rotation curve from $R \approx 3$ kpc to $R = R_0 \approx 8$ kpc. $V_0 = 235\ \mathrm{km\,s^{-1}} \left(\dfrac{R_0}{8\ \mathrm{kpc}}\right)$ (Sgr A*)

Start with smooth approximation; adjust mass in rings to fit data

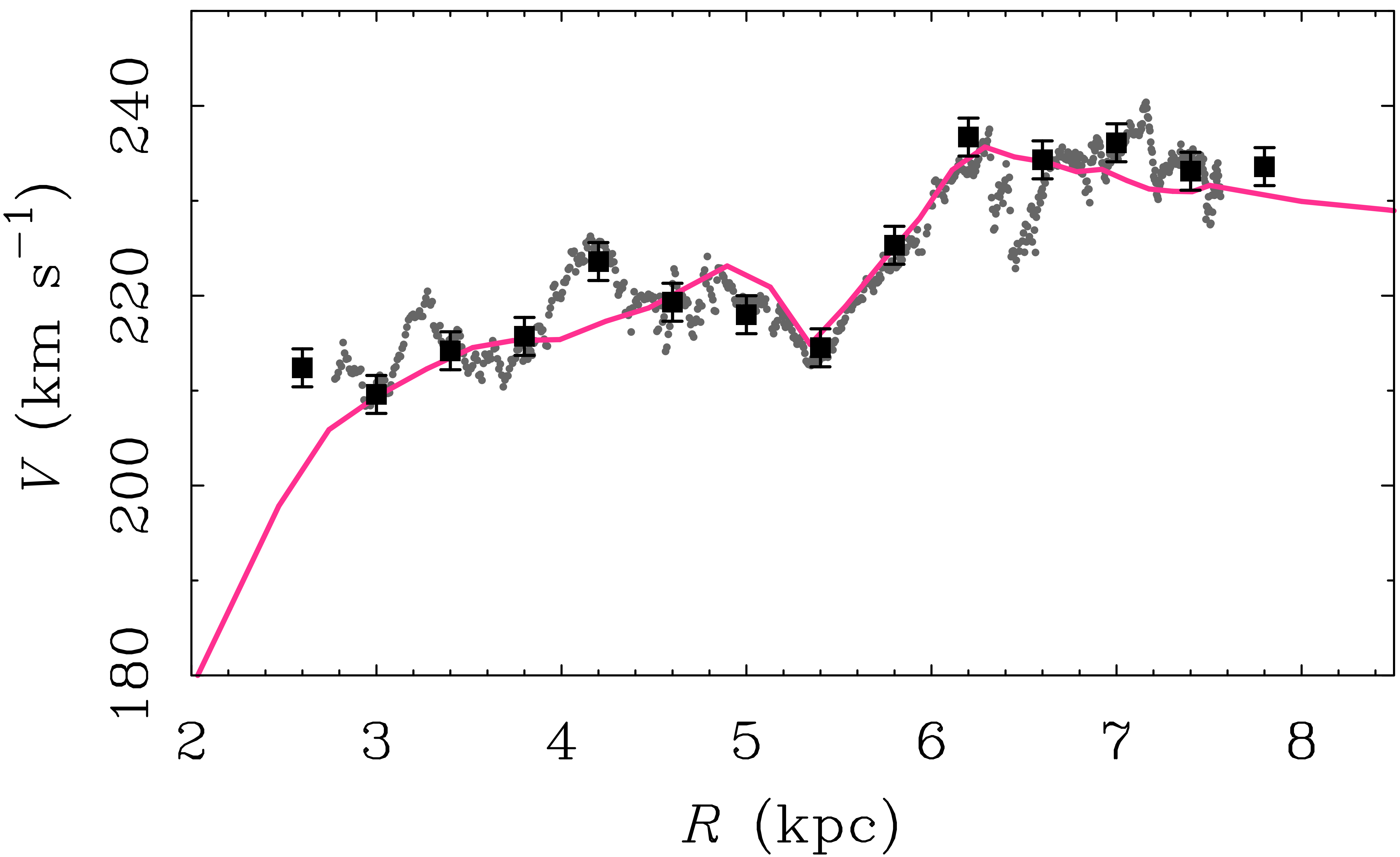




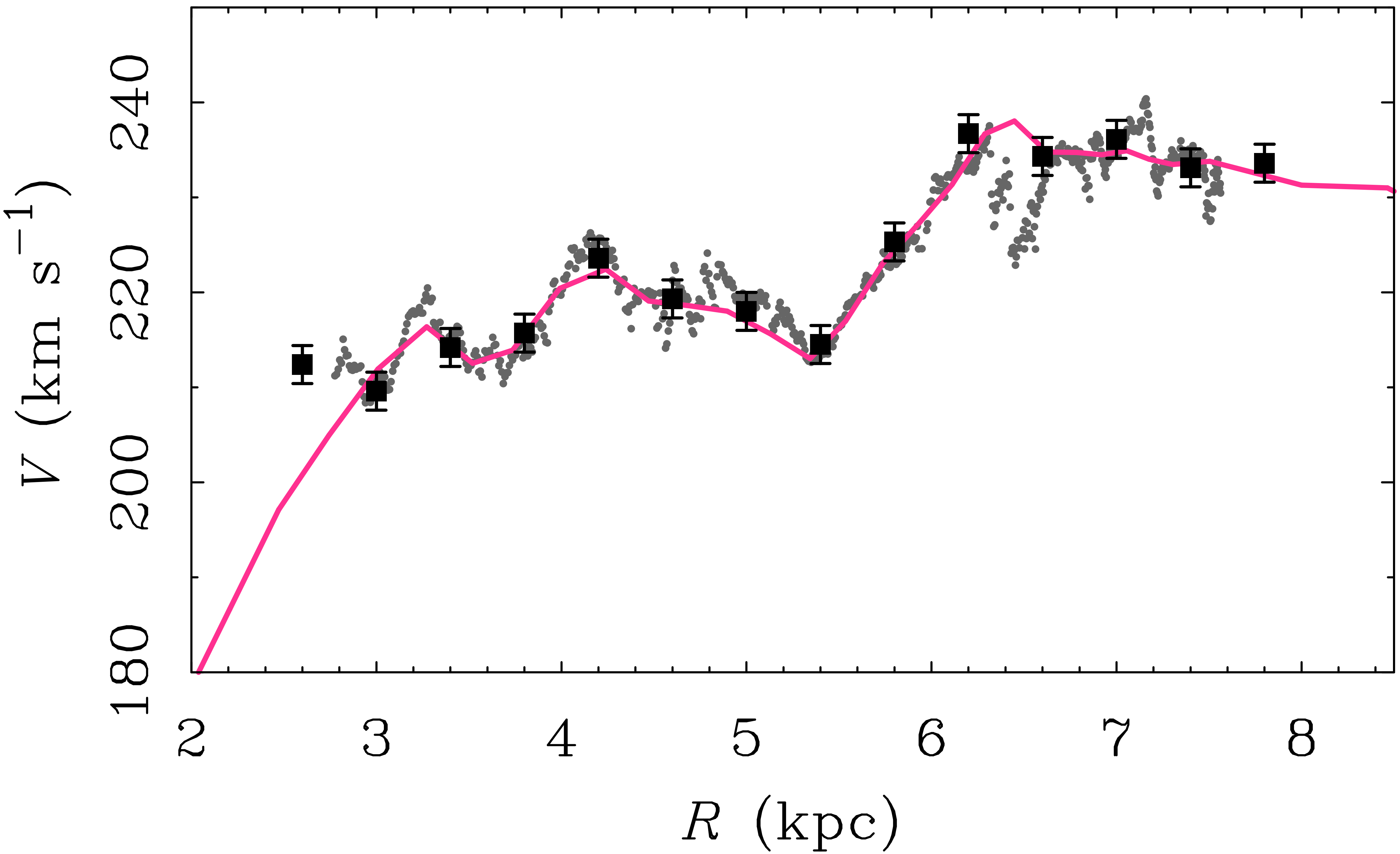
V (km s^-1)
180
200
220
240
2
3
4
5
6
7
8
R (kpc)



V (km s^{-1})
R (kpc)
180
200
220
240
2
3
4
5
6
7
8



240
220
200
180
V (km s^{-1})
2
3
4
5
6
7
8
R (kpc)



180
200
220
240
V (km s^{-1})
2
3
4
5
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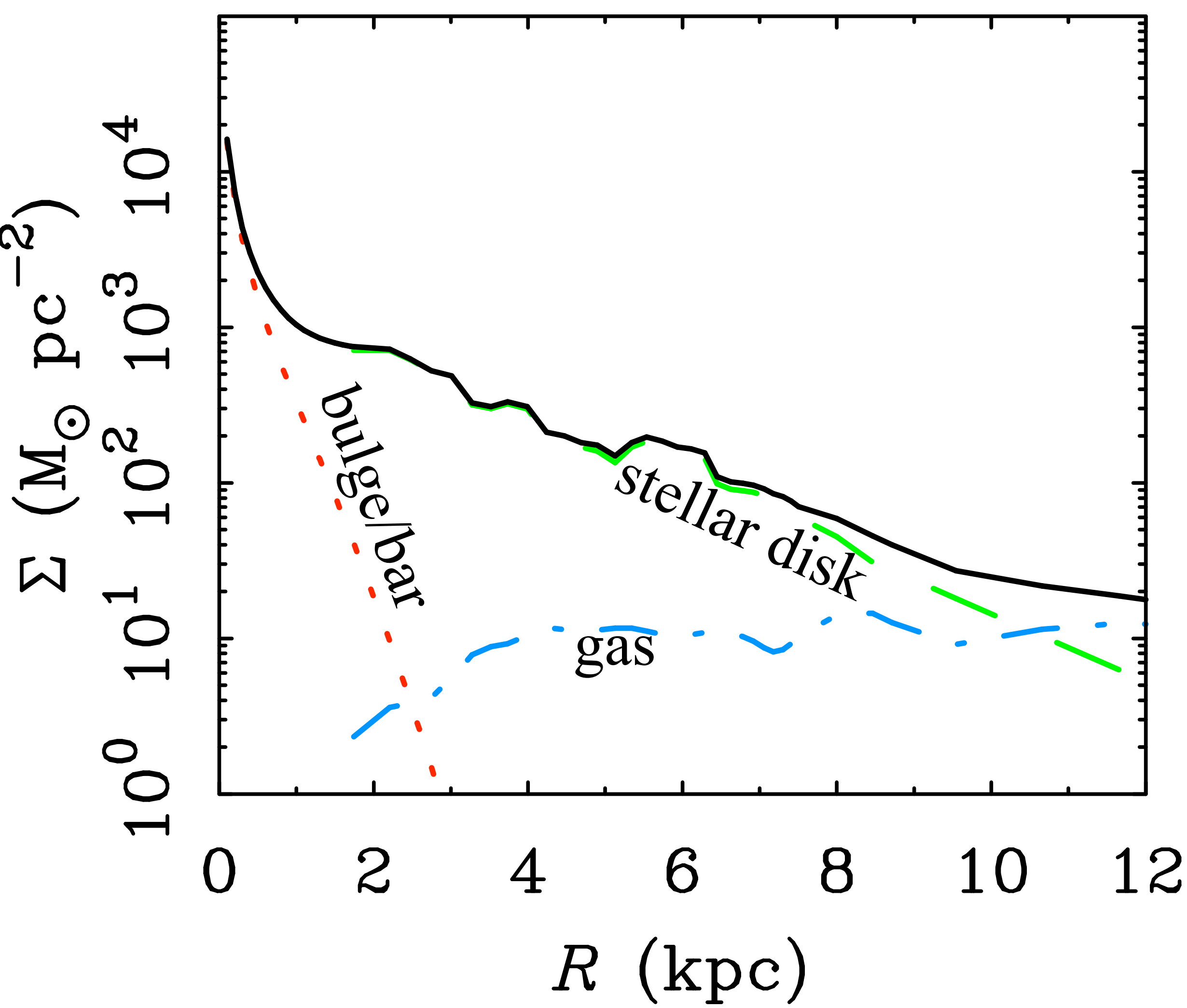
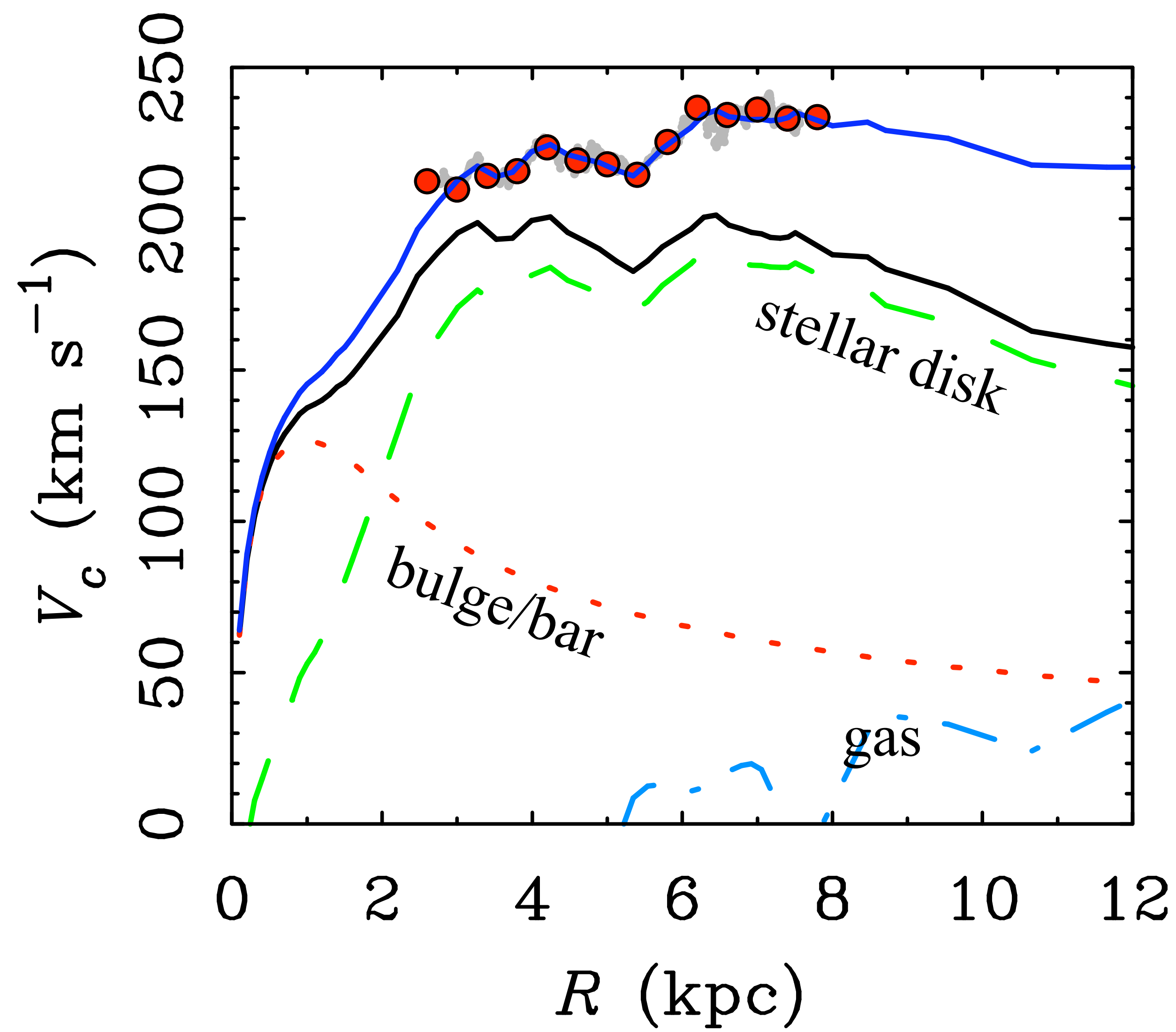
7
8
R (kpc)

Baryonic Surface Density

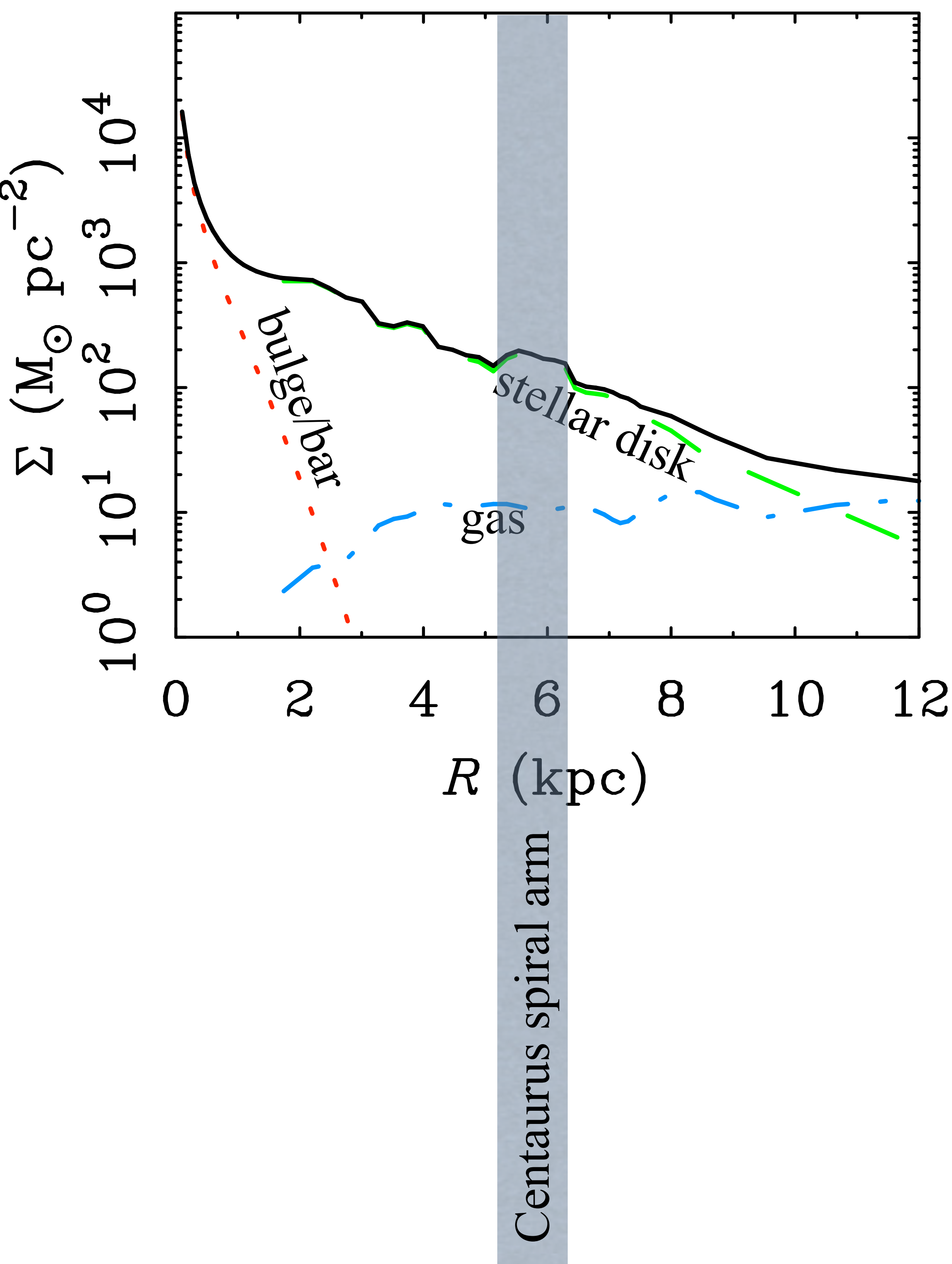


Rotation curve

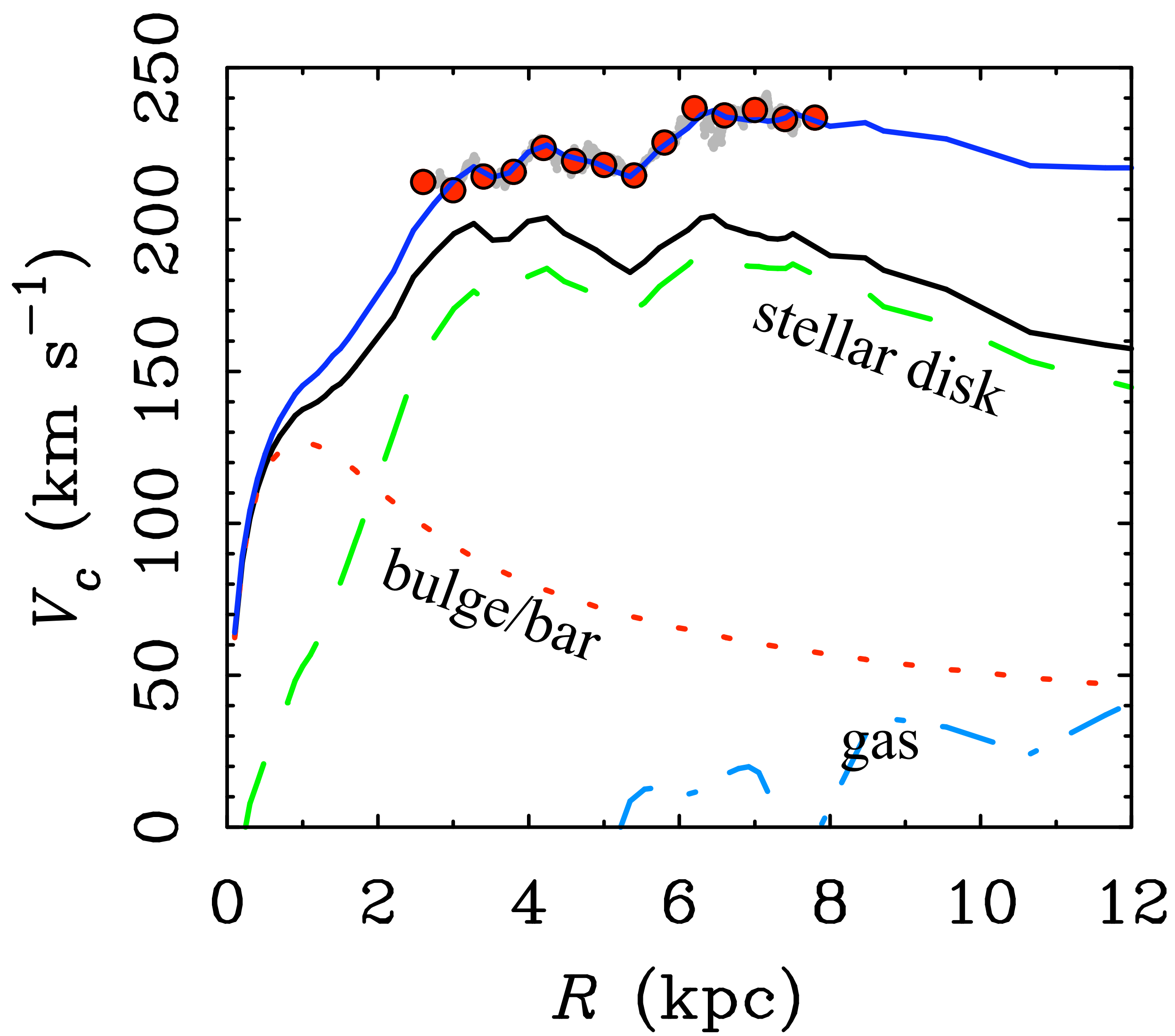


Bumps & wiggles in the rotation curve correspond to features in the mass distribution.

Baryonic Surface Density

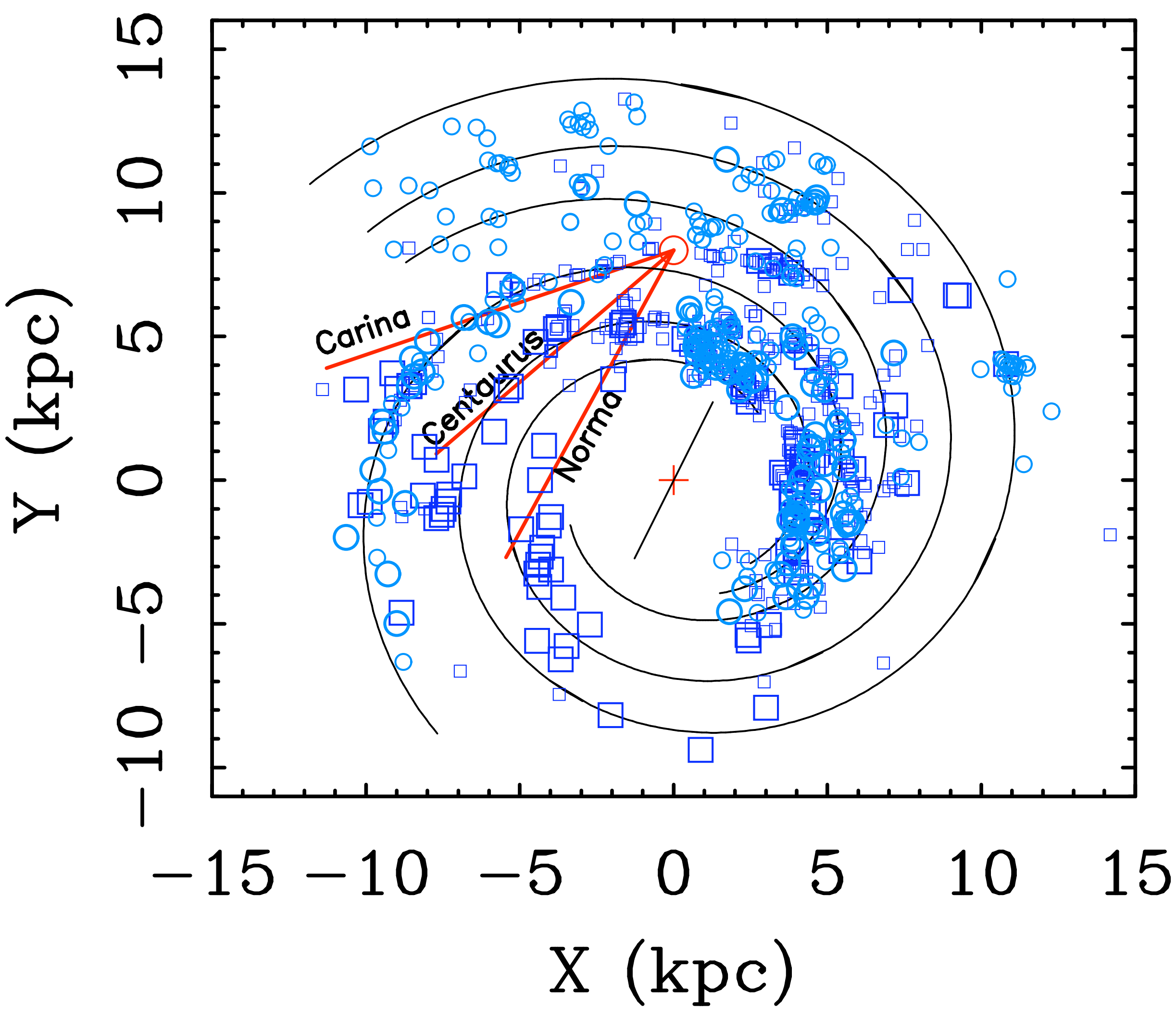


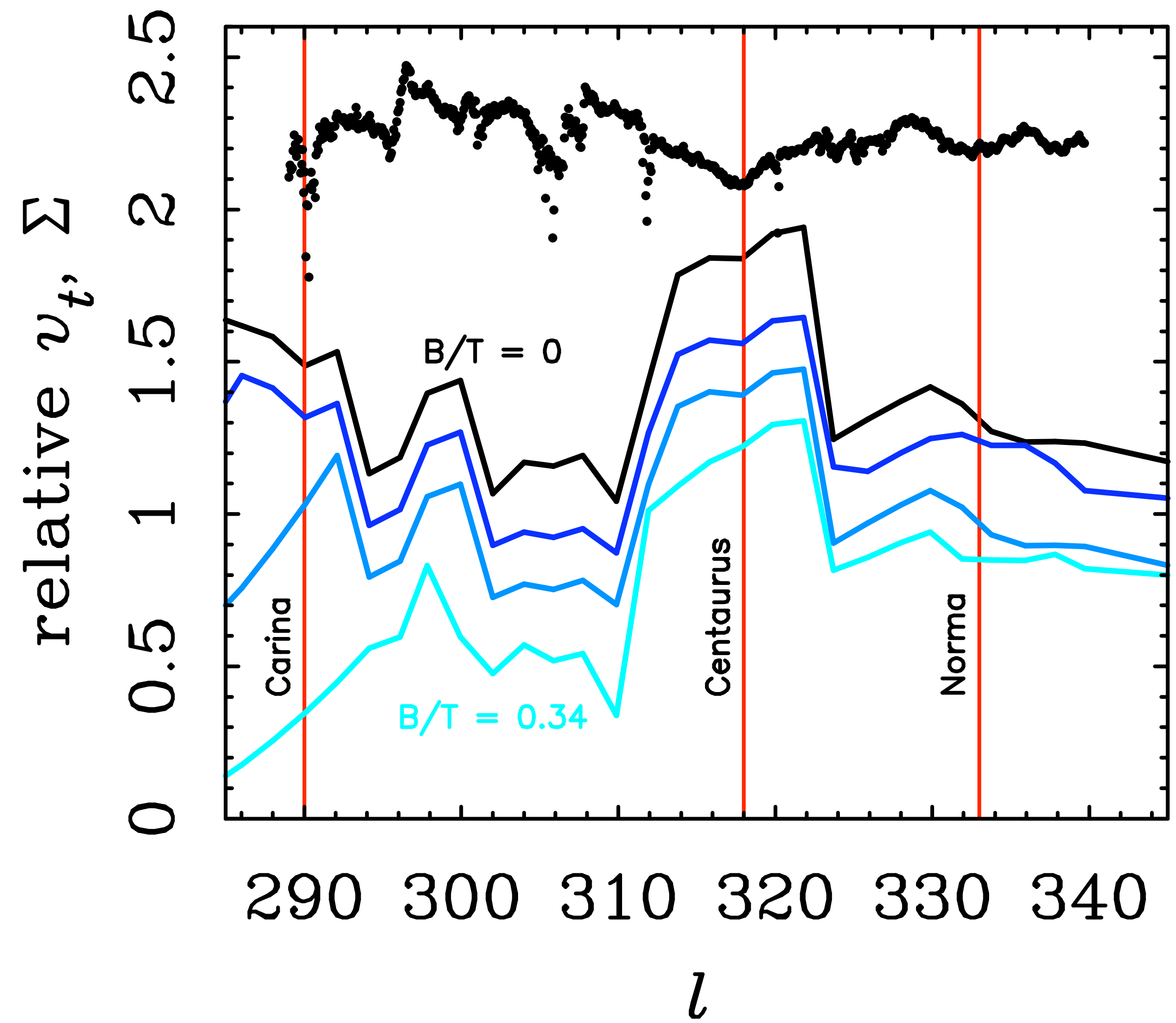
Rotation curve



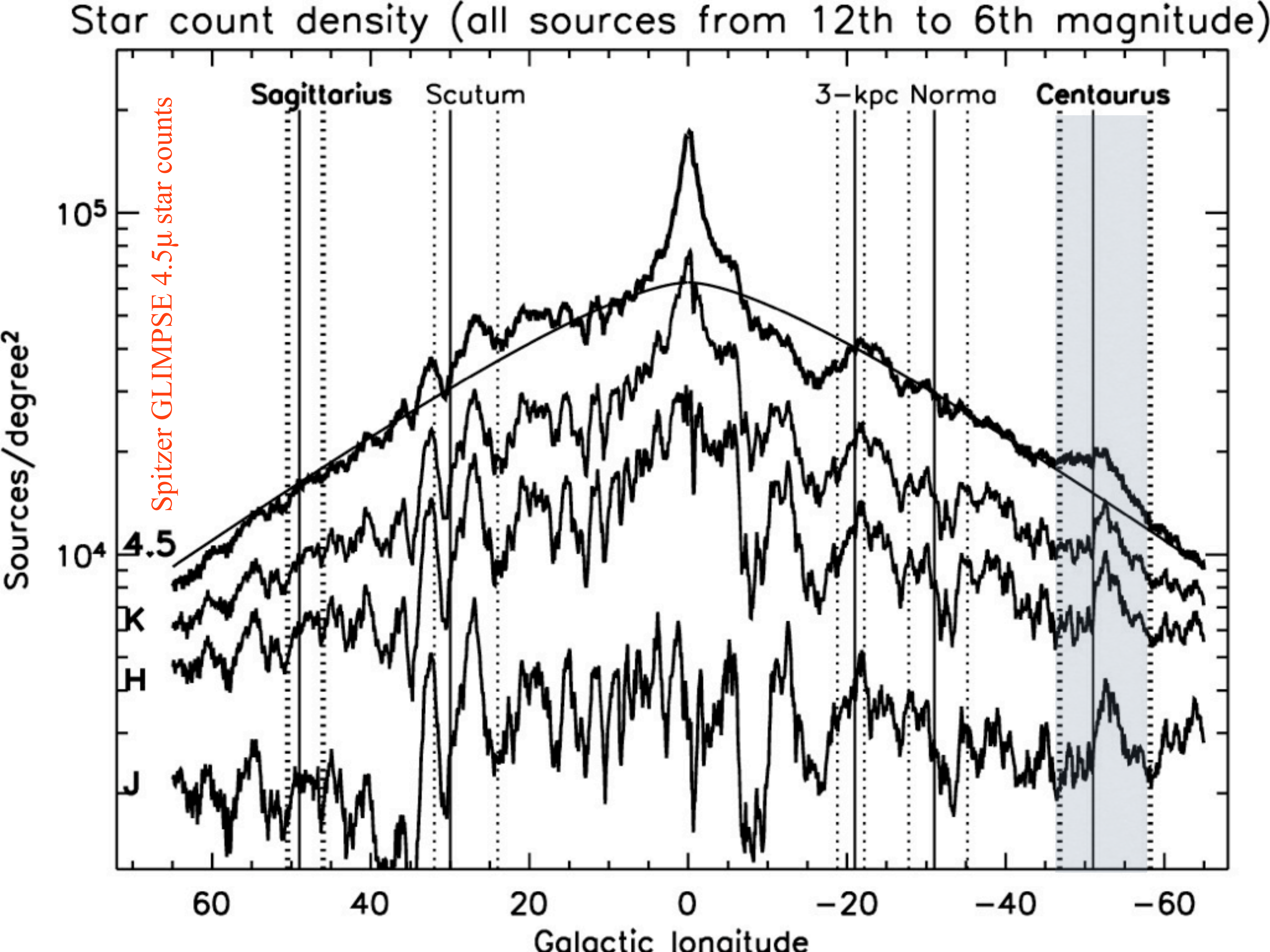
Bumps & wiggles in the rotation curve correspond to features in the mass distribution.

Hou et al (2009) spiral model

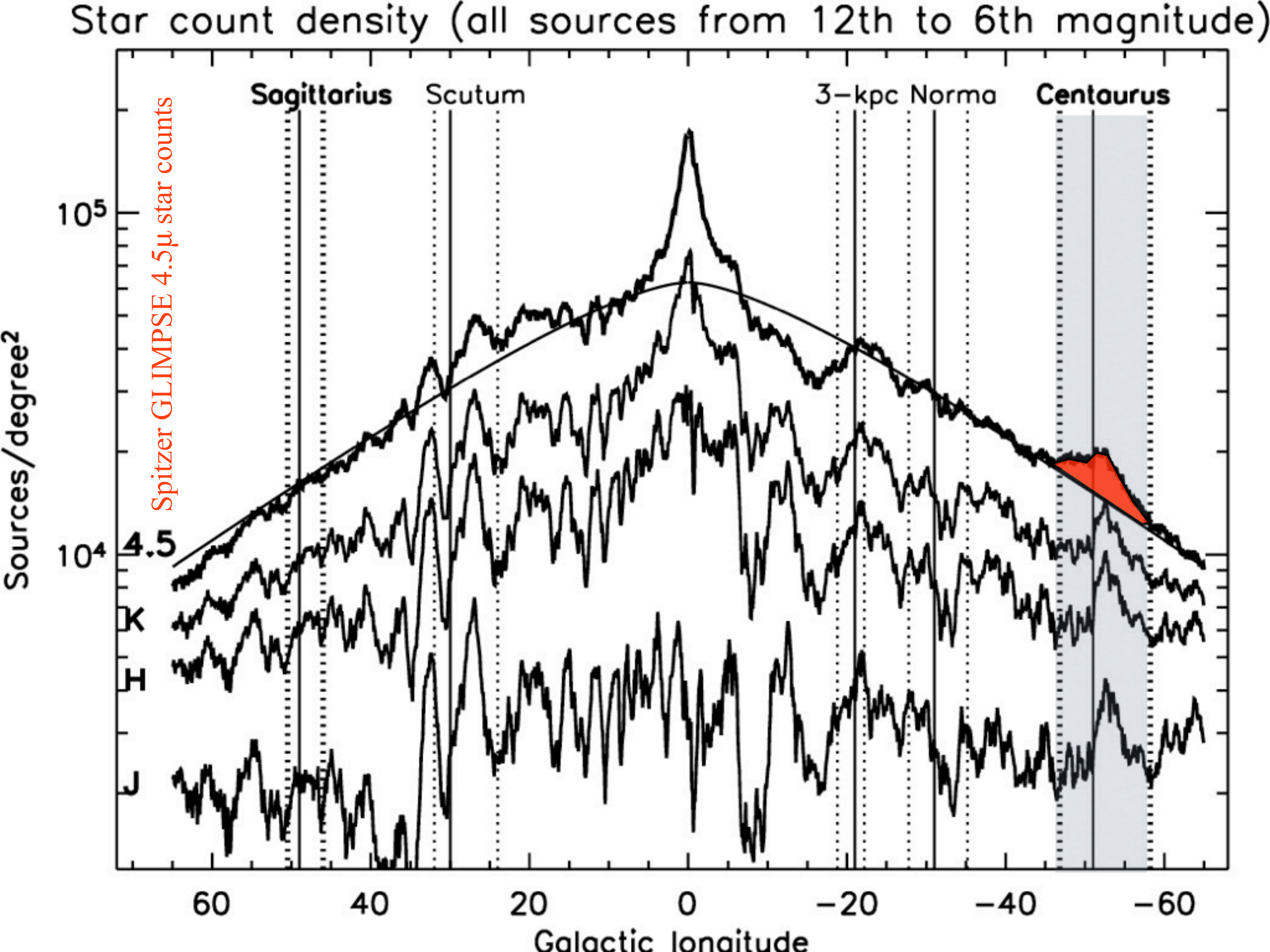




Fitting the terminal velocities recovers the same spiral arm features seen in tracers like GMCs and HII regions. The Centaurus arm is a ~60% over-density in a ring 1.3 kpc wide centered at R = 5.8 kpc.



Star count density (all sources from 12th to 6th magnitude)
Sagittarius
Scutum
3−kpc
Norma
Centaurus
Spitzer GLIMPSE 4.5μ star counts
Sources/degree²
10⁵
10⁴
4.5
K
H
J
60
40
20
0
−20
−40
−60
Galactic longitude



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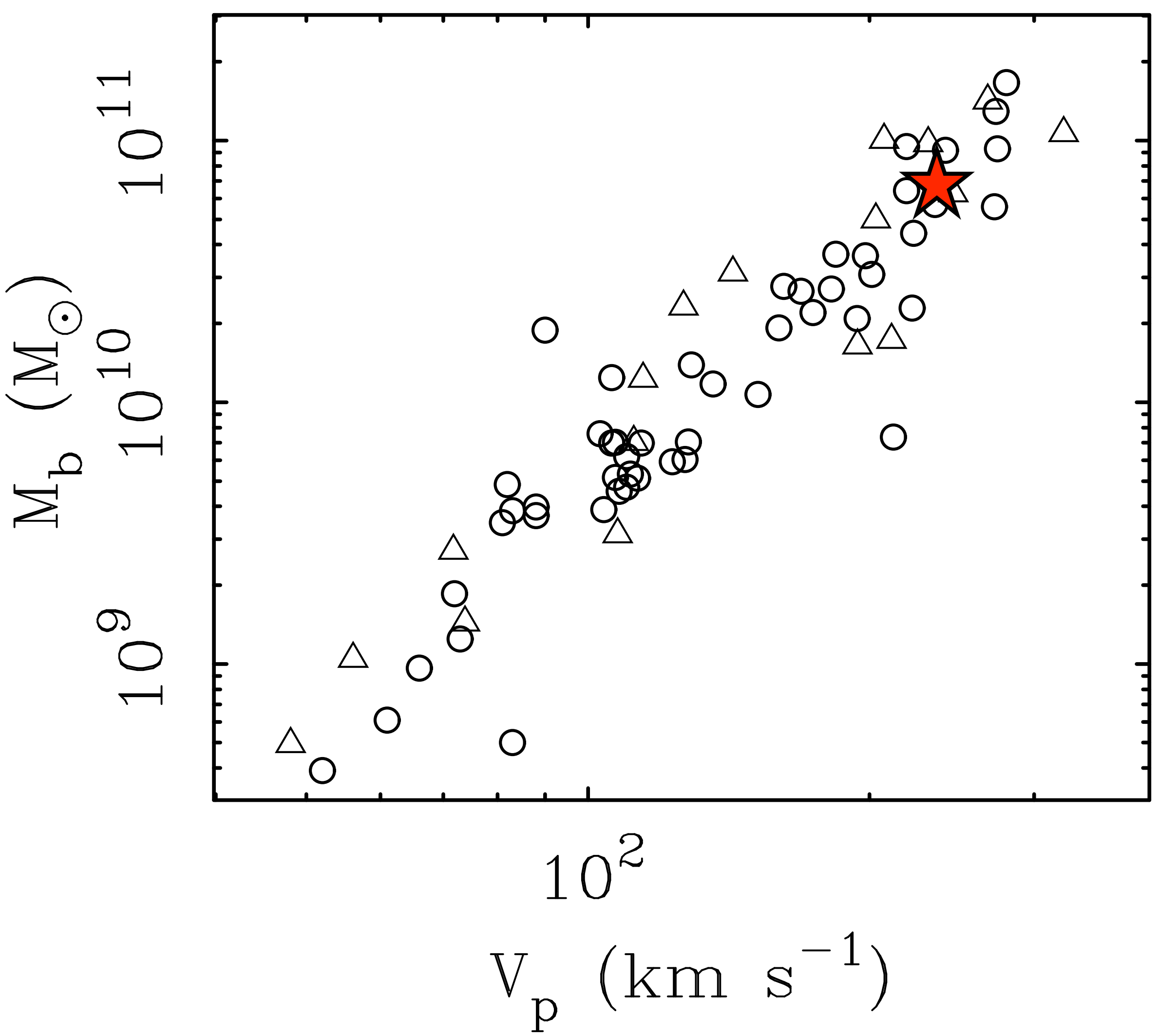
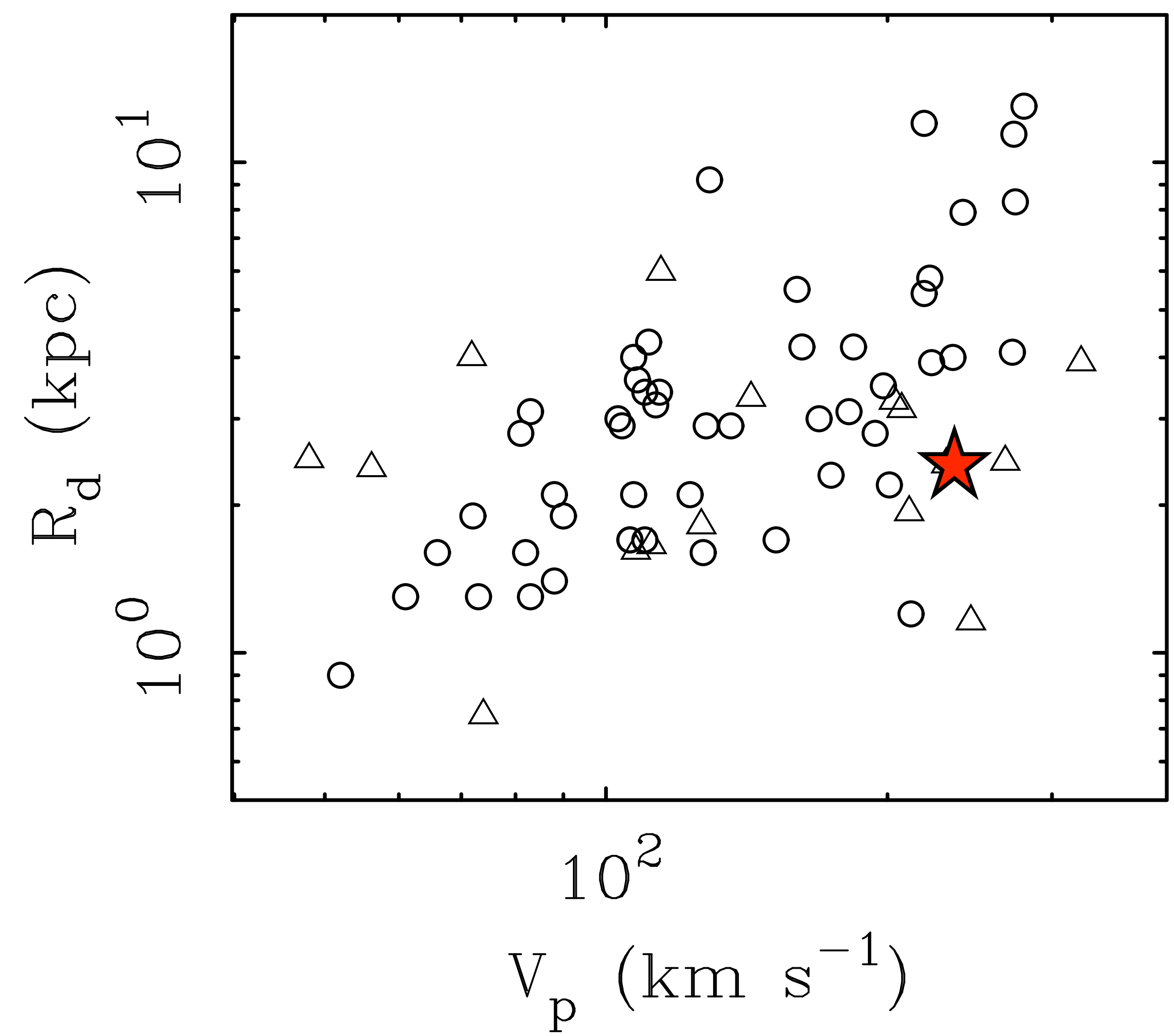
−20
−40
−60
Galactic longitude

Global Properties of Mass Models fit to Terminal Velocities

Baryonic Tully-Fisher



Disk size-rotation speed



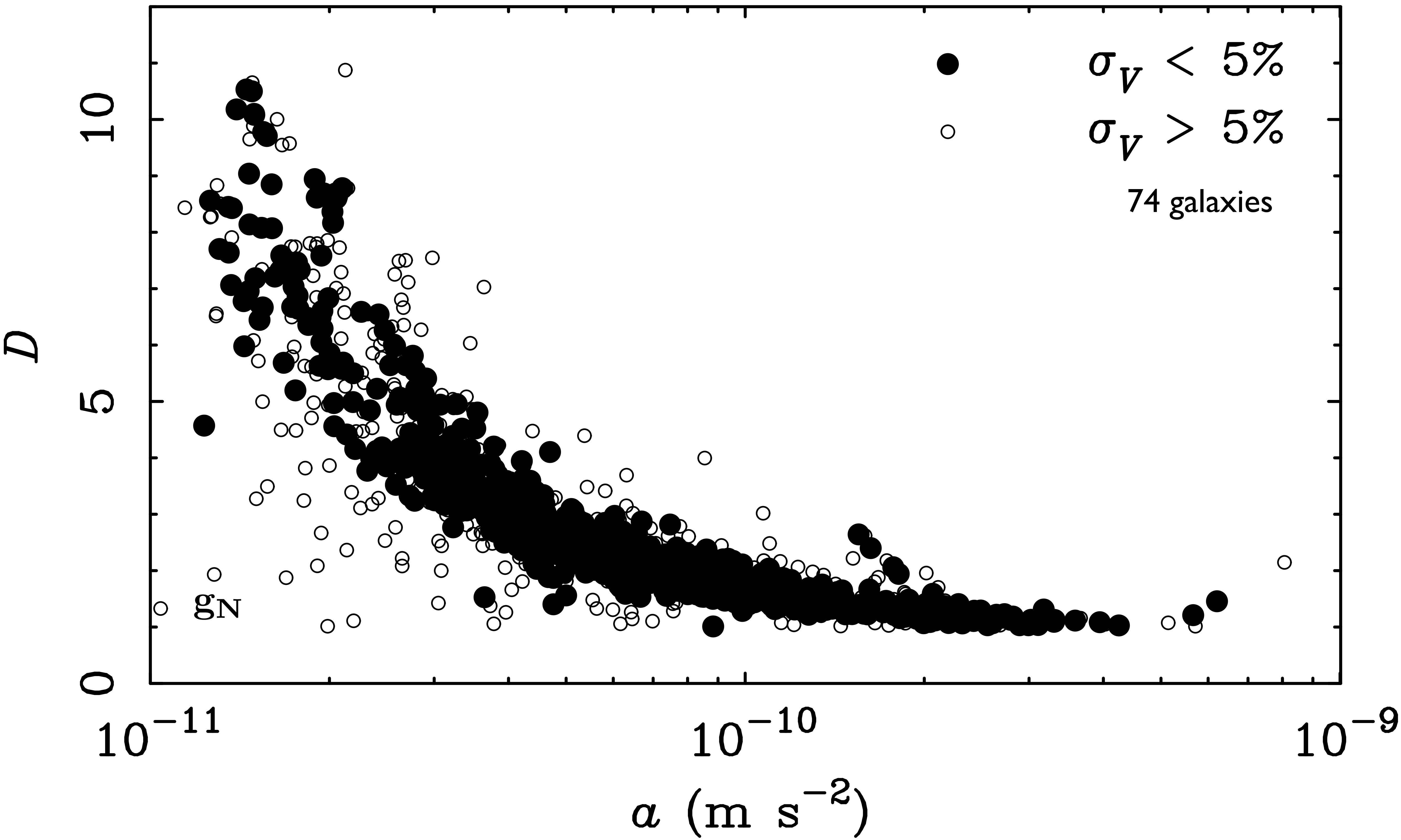
The Milky Way is a normal spiral galaxy.

It falls within the scatter of both

- the Baryonic Tully-Fisher relation and
- the disk size-rotation velocity relation

The disk must be nearly maximal: spiral arms influence kinematics

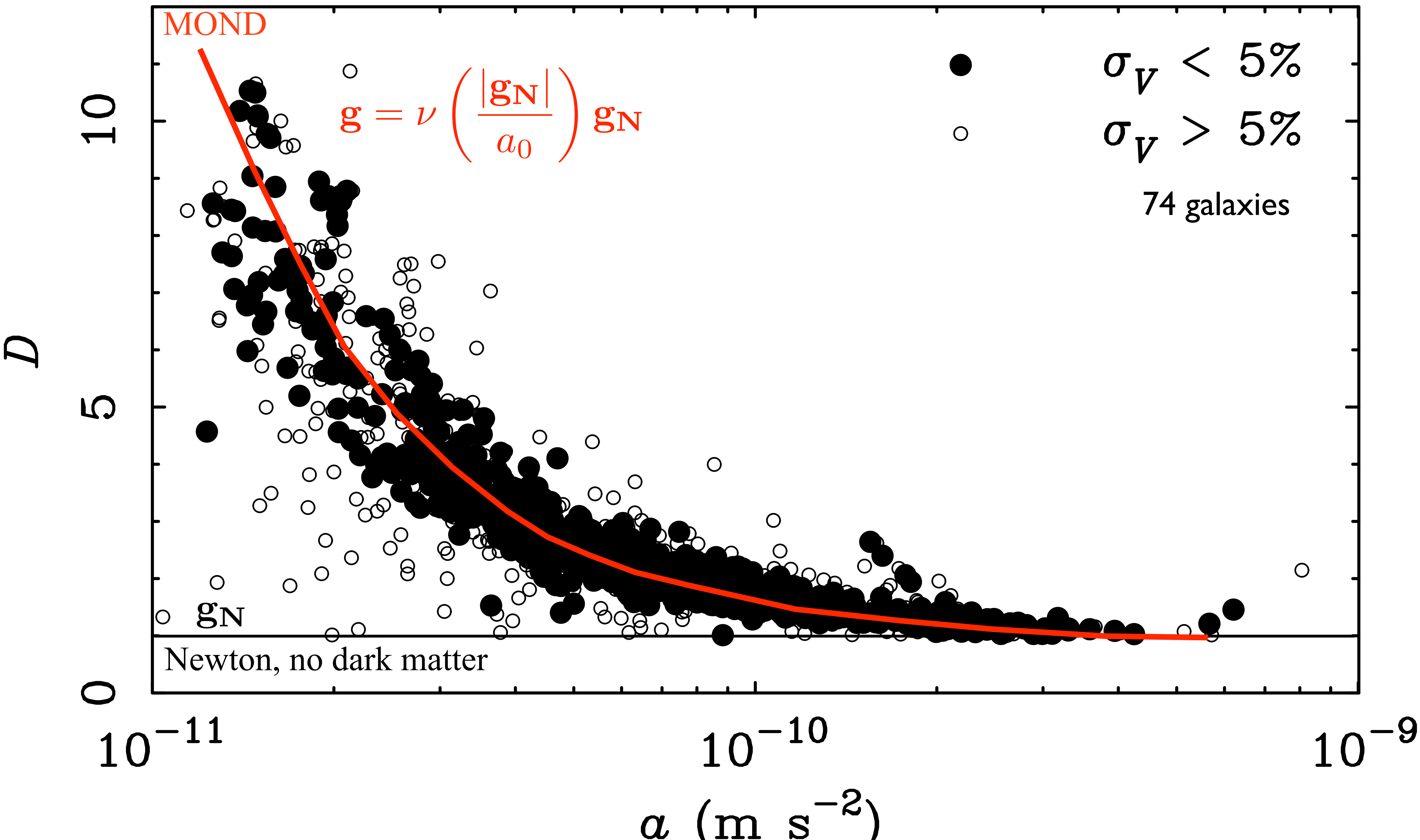
Mass discrepancy-acceleration relation



Mass discrepancy-acceleration relation:
just an empirical relation? or MOND?

Exhaustive review
Famaey & McGaugh
arXiv:1112.3960

Mass discrepancy-acceleration relation



Mass discrepancy-acceleration relation:
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MOND

Alternative to dark matter

Everything normal at high accelerations

$$g \rightarrow g_N \text{ for } g \gg a_0$$

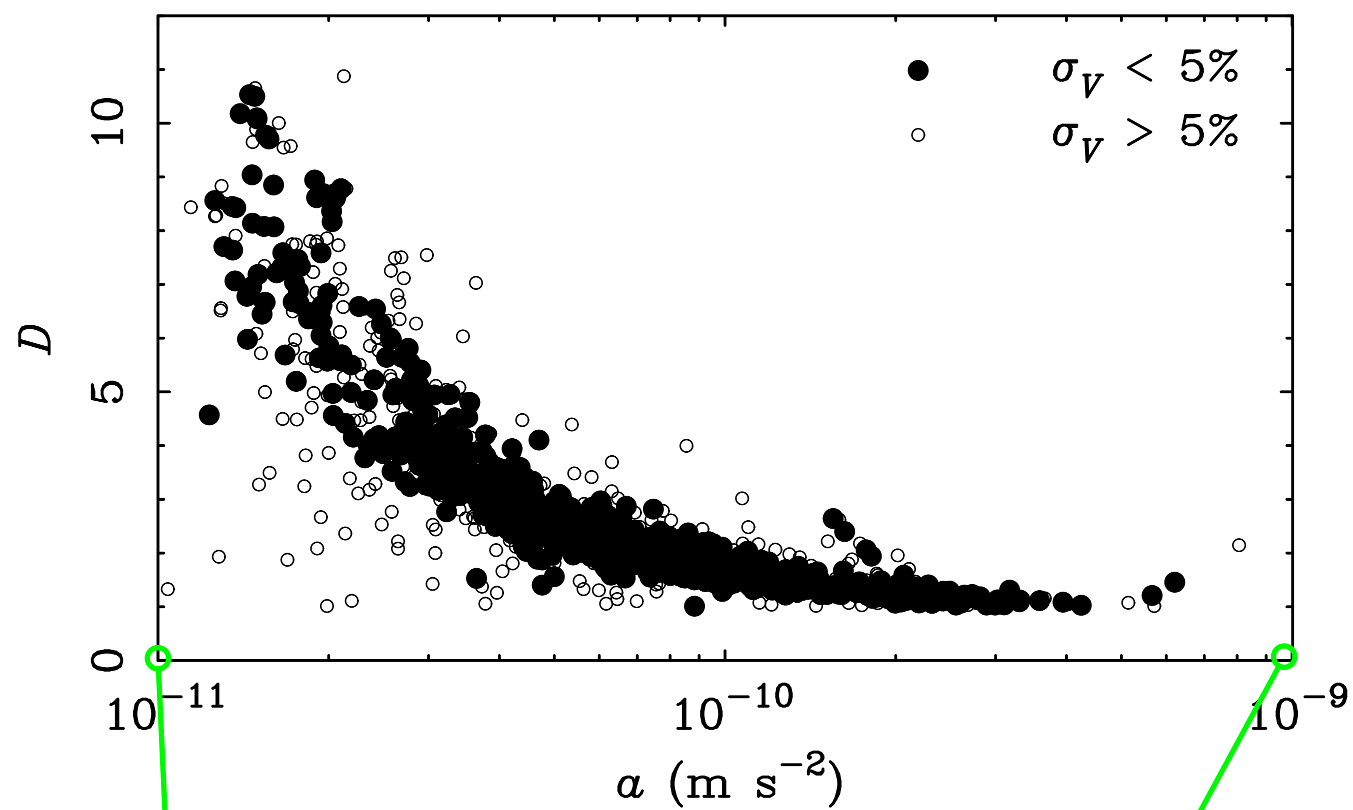
Modification applies at low accelerations

$$g \rightarrow \sqrt{g_N a_0} \text{ for } g \ll a_0$$

Regimes connected by smooth interpolation function $\nu(g/a_0)$

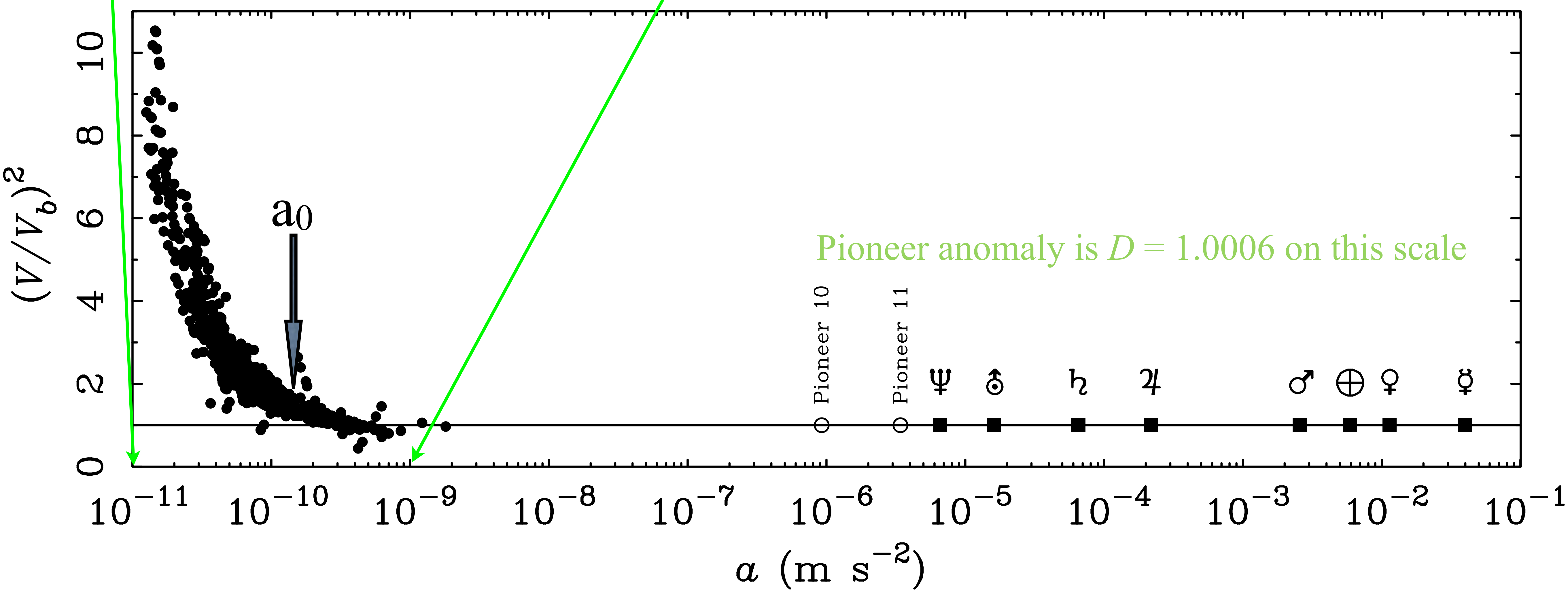
$$a_0 = 1.2 \times 10^{-10}\,\mathrm{m\,s^{-2}}$$

theory



The solar system is many orders of magnitude removed from the MOND regime.

Monopole terms negligible (or excluded!)
But there can also be quadrupole effects...



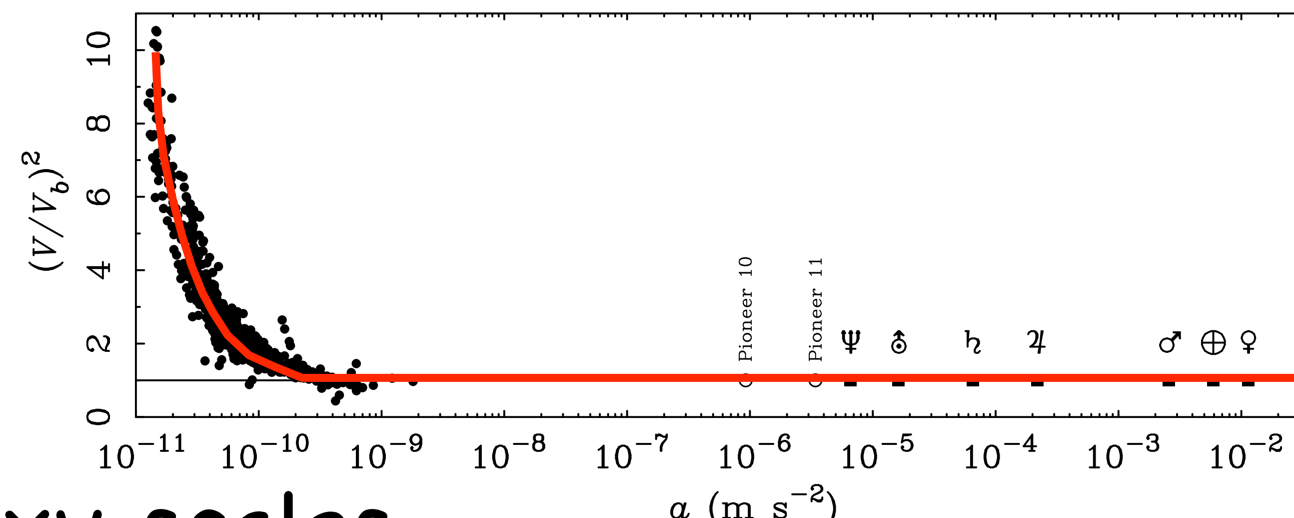
Direct MOND effects small in solar system.
Only sensitive to deviation of interpolation function from unity in limit $g \gg a_0$

A form like

$$\frac{x}{1+x} \qquad x = \frac{g}{a_0}$$

explains the Pioneer anomaly but is excluded by inner solar system data

(effect is 1 part in 10^8)



A form like

$$1 - e^{-x}$$

is indistinguishable on galaxy scales, but in the inner solar system has an **effect that is 1 part in $\exp(10^8)$**

There can be more subtle effects

- In some flavors of relativistic theories, e.g., TeVeS, what matters is the potential gradient.
  - Predicts strong effects at saddle points between massive bodies (e.g., sun-planet)
- MOND violates the Strong Equivalence Principle, leading to the External Field Effect - the Galactic field might matter in the Solar System.
  - Predicts modest precession of outer planets

$$\nabla\Phi \to 0$$

near saddle point, so

$$\frac{|\mathbf{g_N}|}{a_0}$$

becomes small, and strong MOND effects can occur

in a small region (theory specific, e.g., TeVeS - Bekenstein & Magueijo 2006)

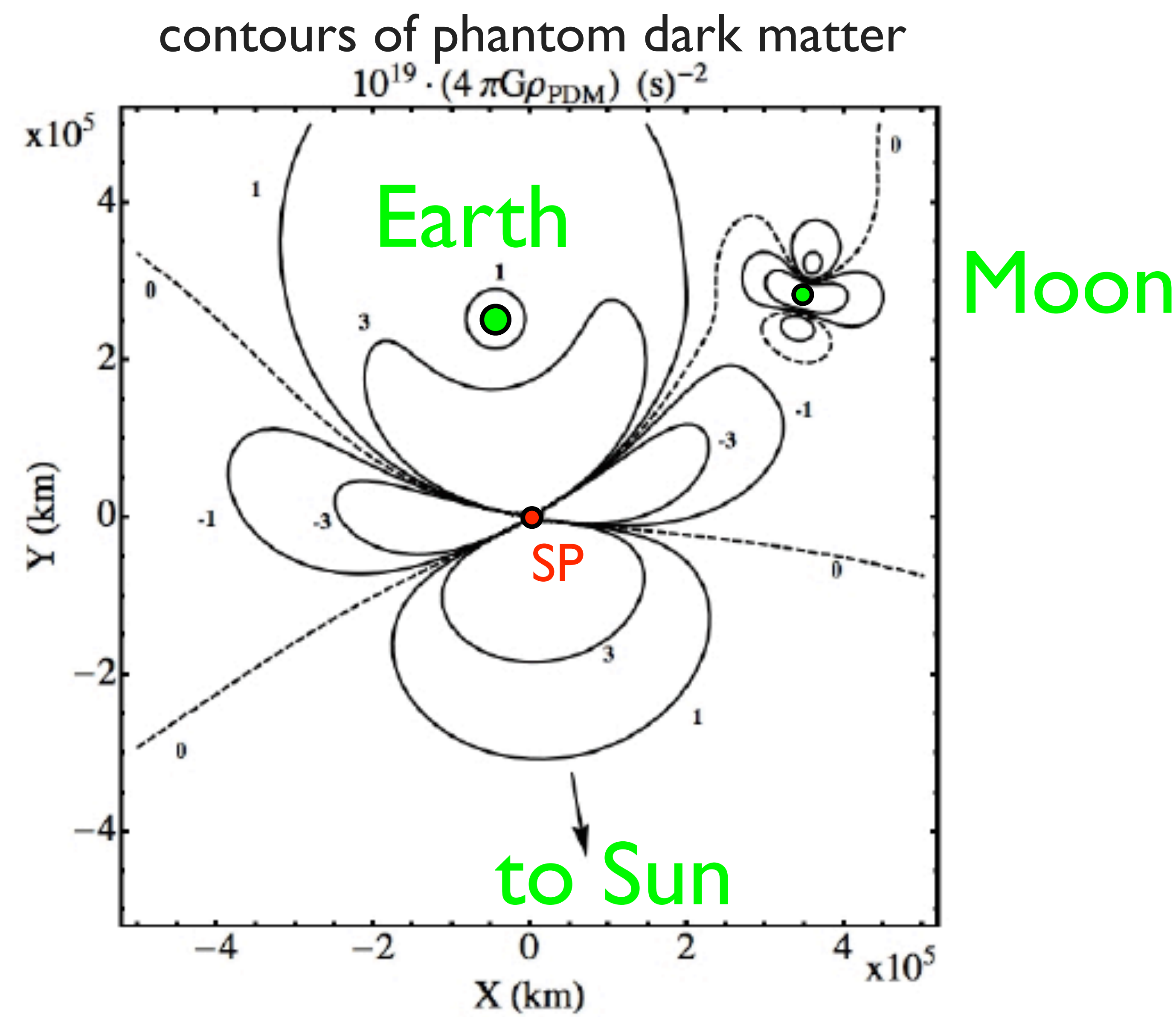


FIG. 13. PDM isodensity contours inside in a box of 5×10^5 km centered on the Earth-Sun SP along the $z = 0$ plane and assuming ν given by Eq. (12): The positions of the Earth and the Moon-Sun SP are marked with a large and a small dot, respectively. The arrow points towards the Sun and the dashed line indicates the $\rho_{PDM} = 0$ contour. The PDM density is negative within a conic region (deformed by the Moon's presence), with the symmetry axis perpendicular to the Earth-Sun direction, and positive elsewhere. The Earth is embedded into a halo of positive PDM. Moreover, the PDM density gradient is bigger near the Moon-Sun SP.

Galianni et al. arXiv:1111.6681

The saddle point moves around:

Might detect strong effects with a satellite probe (e.g., LISA - Bekenstein & Magueijo 2006) or weak effects in the motions of outer moons, e.g. Norse satellites of Saturn:

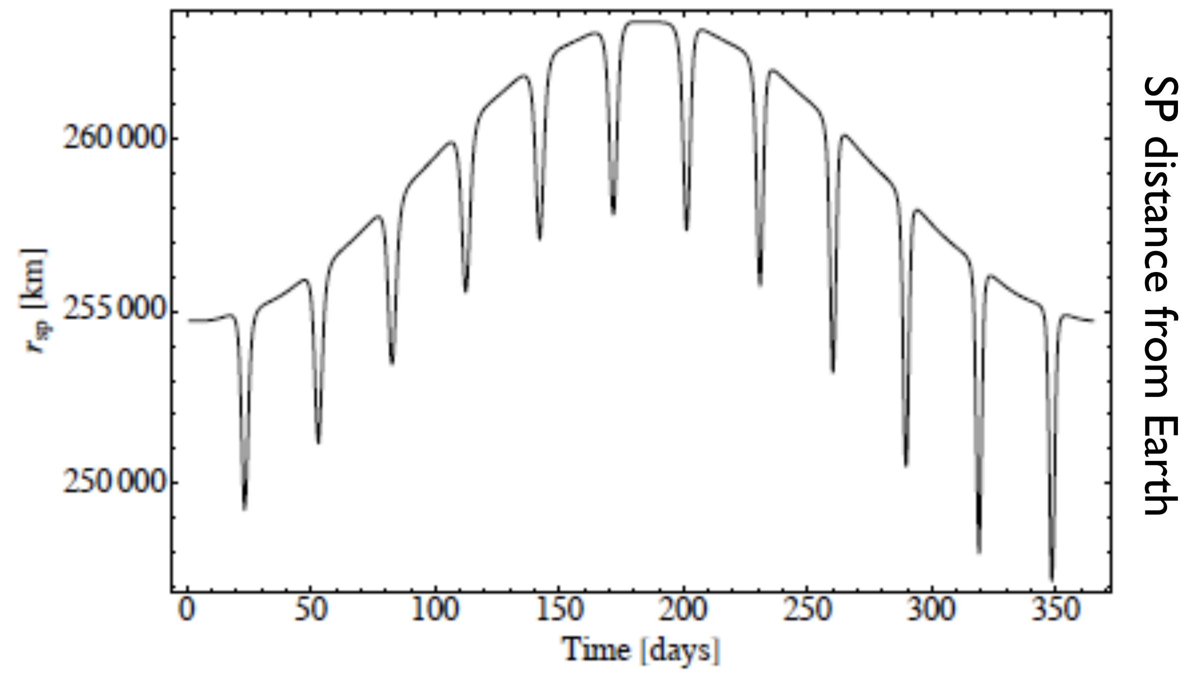
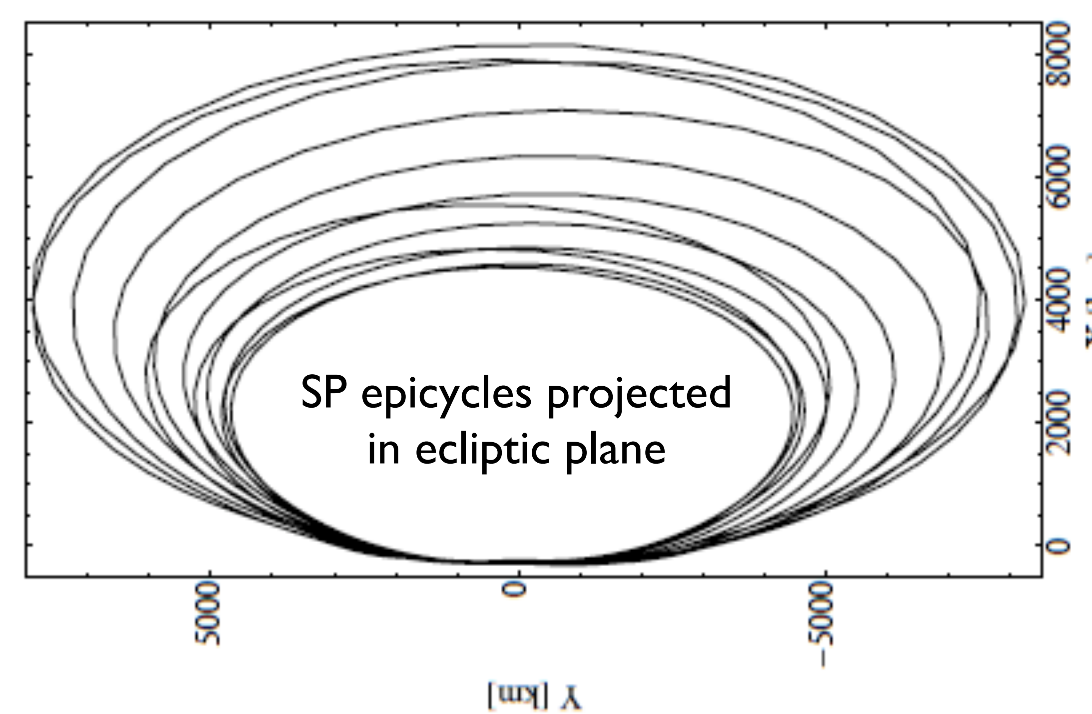


FIG. 1. Distance of the Earth-Sun SP from the Earth during a year: The gentle yearly variation is due to the eccentricity on the Earth's orbit and its amplitude is (measured on the picture) around Δr_{sp} = 8800 km. The vertical peaks are due to the moon's perturbation. Their measured amplitudes oscillate between 4700 km < a < 9000 km.

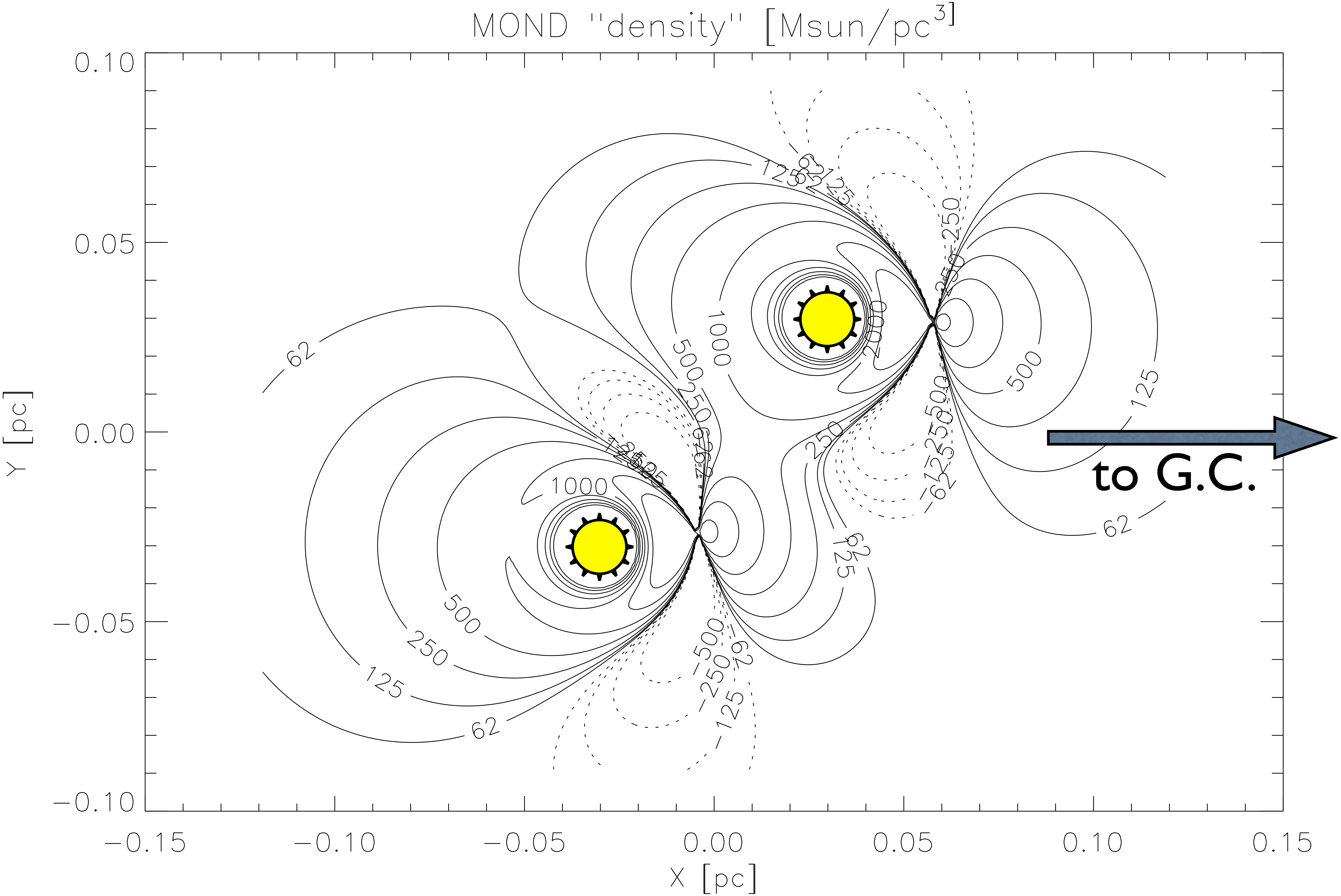
Galianni et al. arXiv:1111.6681

TABLE II. Norse's satellites minimum distances to the Saturn-Sun MOND weak bubble.

Satellite	$d_{\min}$ (10^6km)	$d_{\min}/r_{\mathrm{TEV}}$	Date (dd/mm/yyyy)	Crossing time (days)
Surtur	2.00	0.48	24/06/2015	64
Ymir	0.65	0.16	09/02/2013	68
Fenrir	1.43	0.43	03/01/2029	49
Loge	0.60	0.17	16/03/2026	58



EFE: Phantom DM around binary stars embedded in Galactic field



Credit: Ed Shaya (U Maryland)

The Galactic field exerts a torque that might result in precession of order $\sim 10^{-3}$ arcesec/century

details depend on the interpolation function

Milgrom (2009) MNRAS, 399, 474

	Merc.	Ven.	Ea.	Mar.	Jup.	Sat.	Uran.	Nept.	Plut.	Icar.
$\kappa\lambda$	2.1	.38	1.98	-1.0	-1.1	2.2	-1.5	.56	.50	$-.18$
$\langle\dot{\omega}\rangle$	.13	.065	.53	$-.53$	-3.8	18	-34	26	31	$-.054$
$\|g^a\|$	.048	.094	.13	.20	.67	1.2	2.5	3.9	4.8	.14
$-\langle\dot{\omega}^h\rangle$	.60	1.7	2.7	5.1	32	80	230	450	590	1.7
$\|g^h\|$	.32	.62	.86	1.3	4.5	8.2	17	26	32	.93
$\|\Delta\dot{\omega}\|$	$50^{(a)}$	$5^{(b)}$	$4^{(a)}$	$5^{(a)}$	$2000^{(c)}$	$100^{(c)}$	$2\cdot 10^5$ $^{(c)}$	$2\cdot 10^5$ $^{(c)}$		

Table 2: Characteristics relating to the perihelion precession rates produced by the EFE quadrupole anomaly, and the harmonic anomaly: $\kappa\lambda$ as defined in eq.(38); the predicted precession rate $\langle\dot{\omega}\rangle$ for the quadrupole anomaly (calculated assuming that the orbit is in the ecliptic–not a very good approximation for Pluto and Icarus.); the mean anomalous quadrupole acceleration on the orbit, $|g^a| = |q_{zz}|a$; the precession rate due to the harmonic anomaly $\langle\dot{\omega}^h\rangle$; its mean acceleration $|g^h| = Aa_0a/R_M$; and an indication of existing tightness of conventional fits, $|\Delta\dot{\omega}|$, that I was able to find in the literature: from (a) Pitjeva (2005), (b) Pitieva as quoted in Fienga & al. (2009), (c) Fienga & al. (2009). All precession rates in units of 10^{-4}"/c. All accelerations in units of 10^{-12}cm s^{-2}. All values are calculated for $a_0 = 10^{-8}$cm s^{-2}, $q = -0.1$, and $A = 2/3$.

Conclusions

- Features in the terminal velocity curve of the Milky Way correspond to real physical structures like the Centaurus sprial arm
- MOND might cause tiny but detectable effects like precession of outer planets
- Do not attempt to cram this much into a short talk