STRUCTURE AND DYNAMICS OF MALIN 1

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JENAM-2011 "Minor merging as a driver of galaxy evolution"

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Outline

What was known before

- Photometry and structural features of Malin 1
- Kinematics (HI rotation curve)

Our observations (Alexei Moiseev, SAO)

- A stellar rotation curve and velocity dispersion profiles

Data analysis

- The discovery of a satellite; an explanation of the structural features
- A “cold” rotation curve and the dark halo of Malin 1

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DISCOVERY OF A HUGE LOW-SURFACE-BRIGHTNESS GALAXY: A PROTODISK GALAXY AT LOW REDSHIFT?

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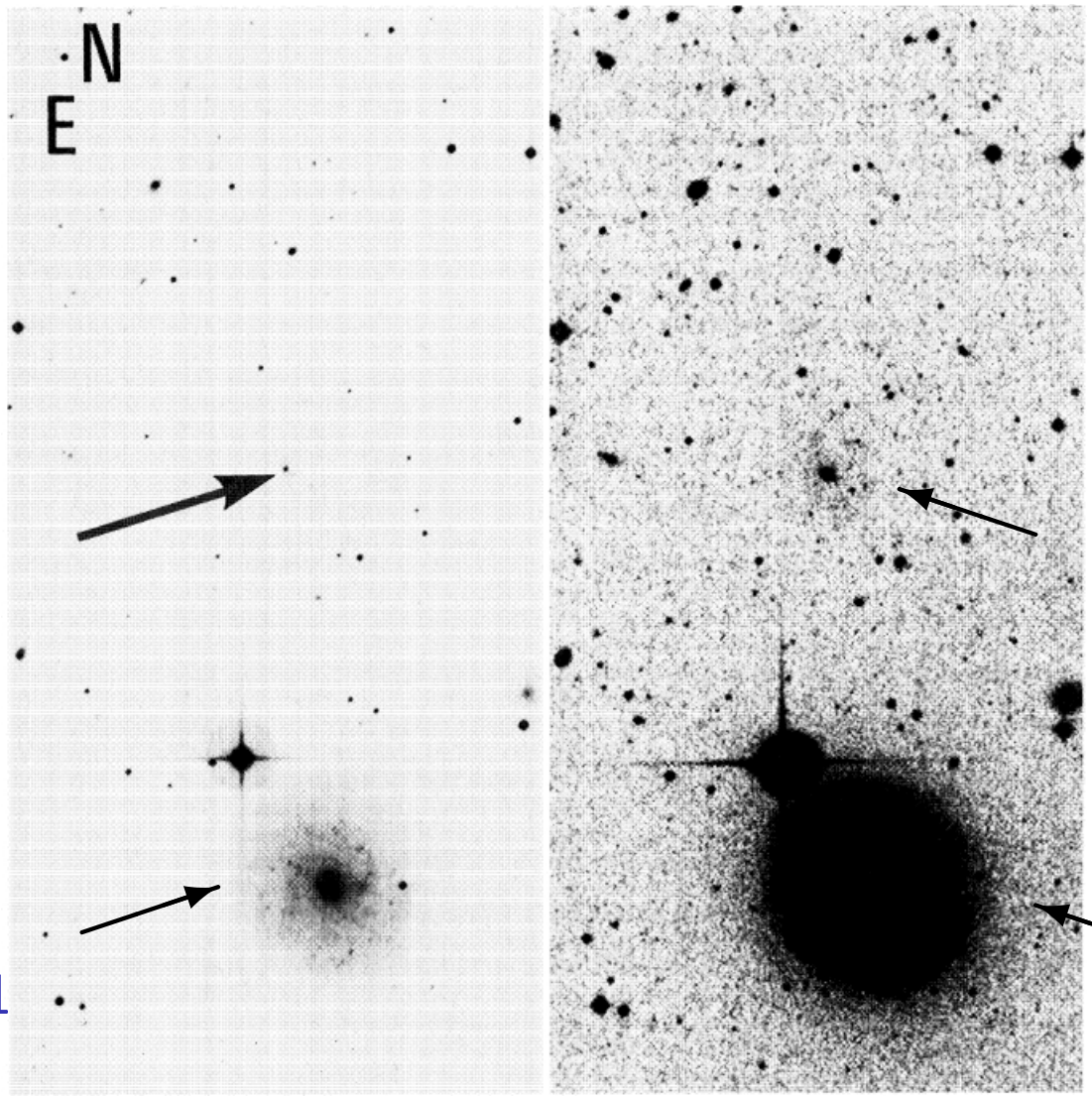
"The galaxy of interest which we christen Malin 1..."

Malin – a man and a galaxy



Malin 1

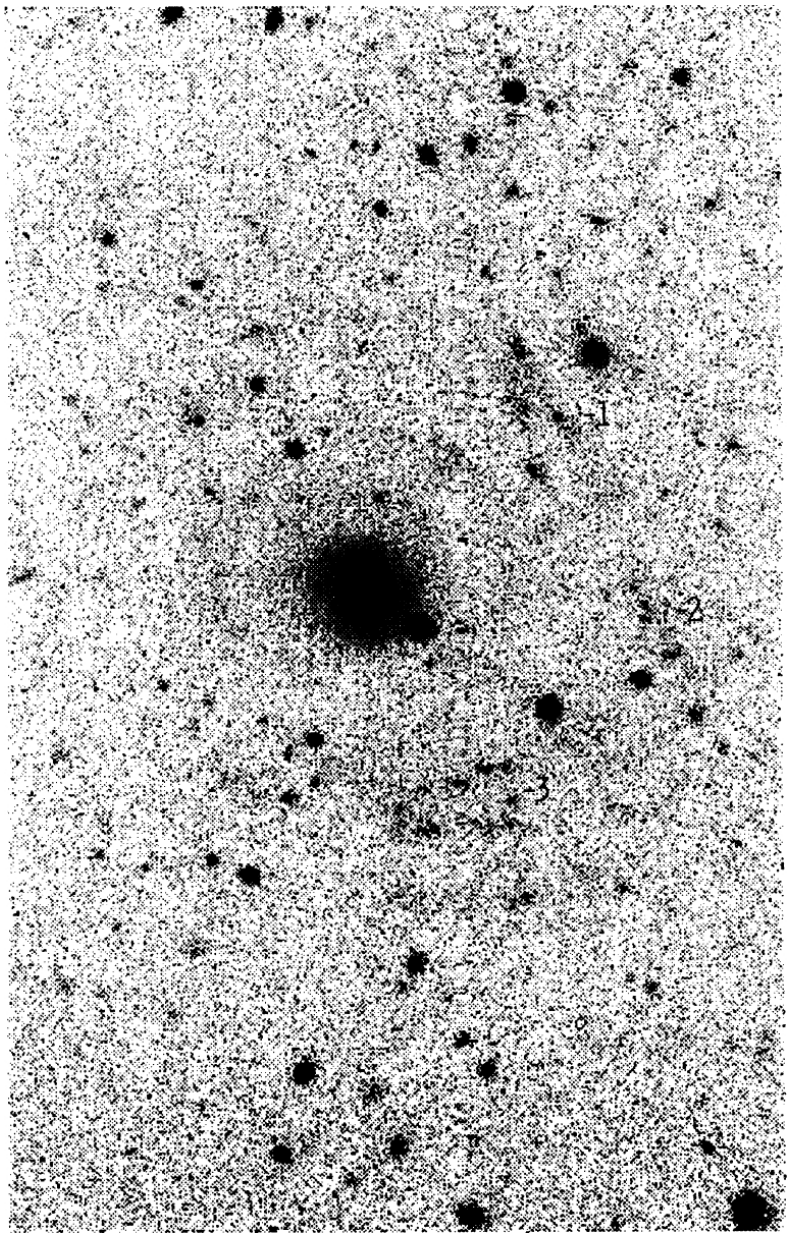
Malin 1

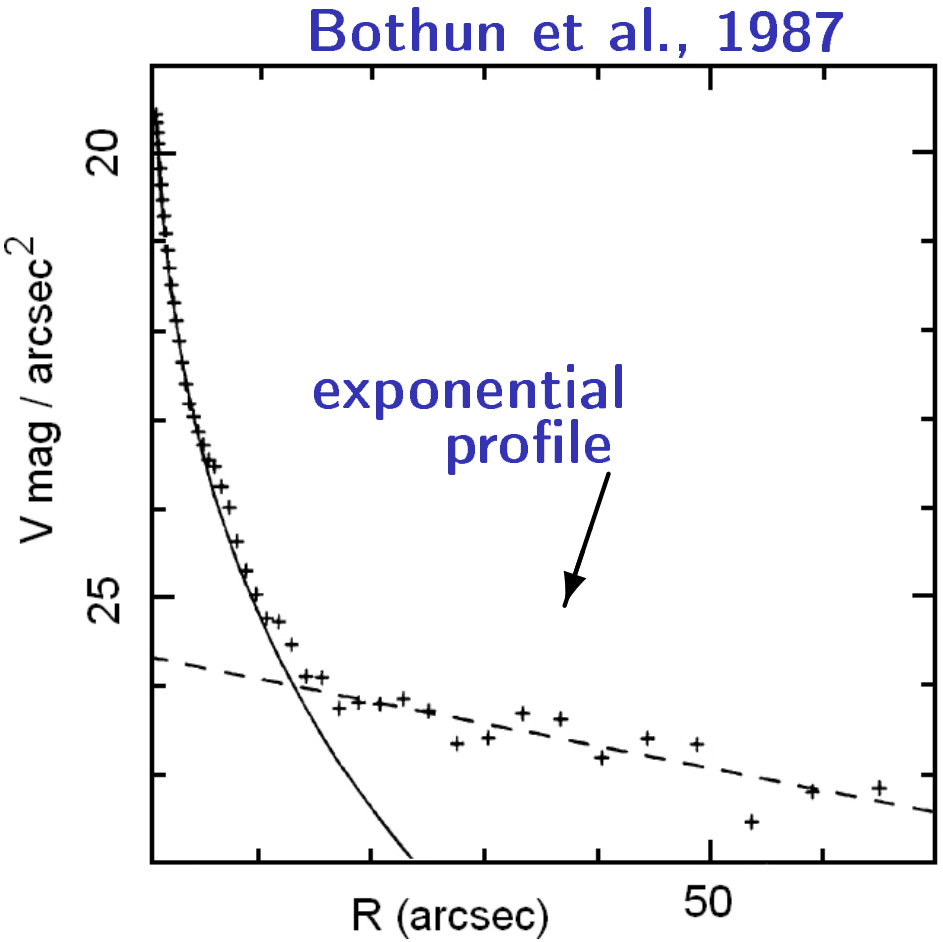
NGC 4571

NGC 4571

Bothun et al., 1987

Ground-based data. Giant stellar disc – the V band

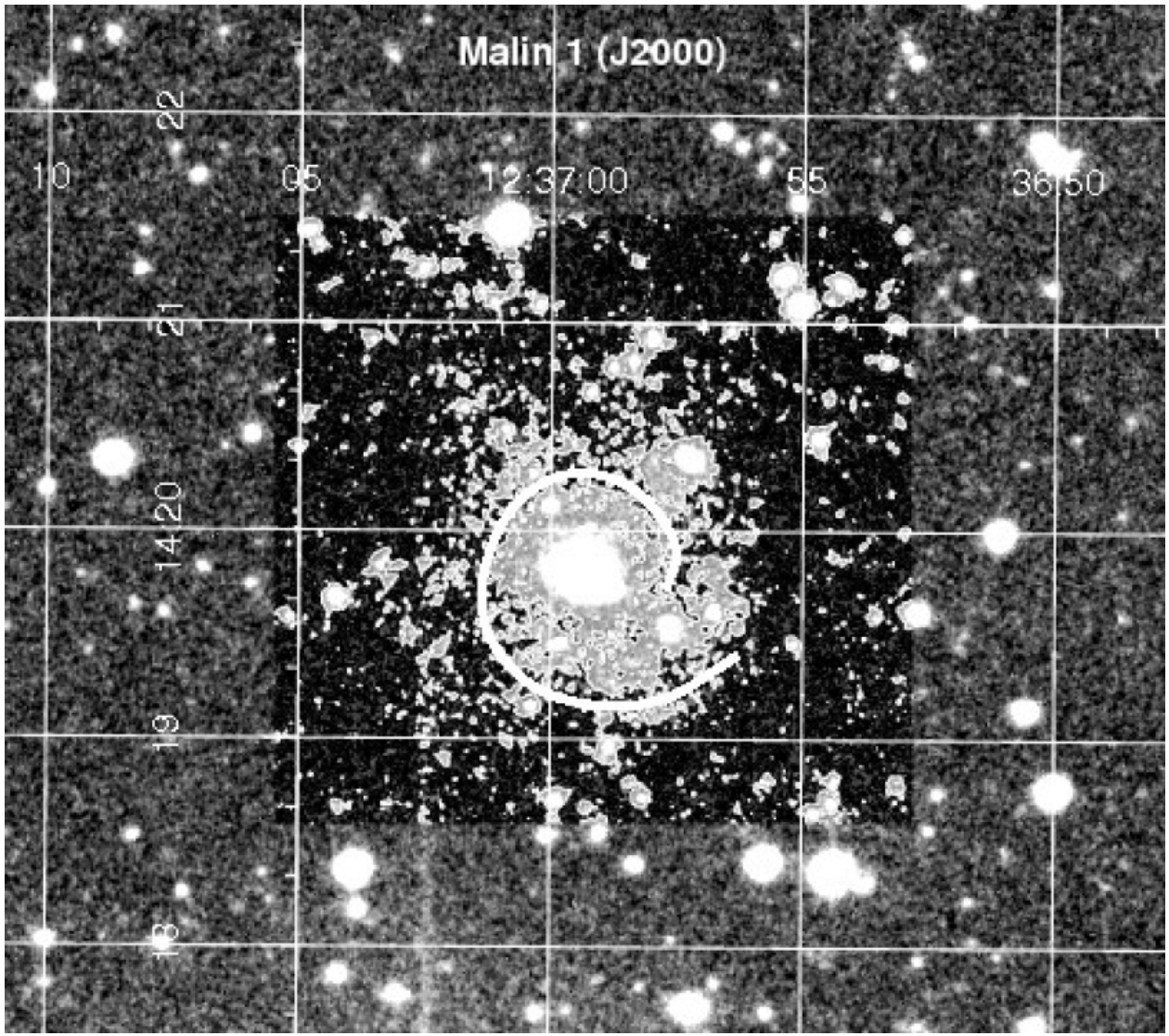




A surface brightness profile

scale : 1.53 kpc/arcsec

Outer one spiral arm – the R band



Moore and Parker, 2006

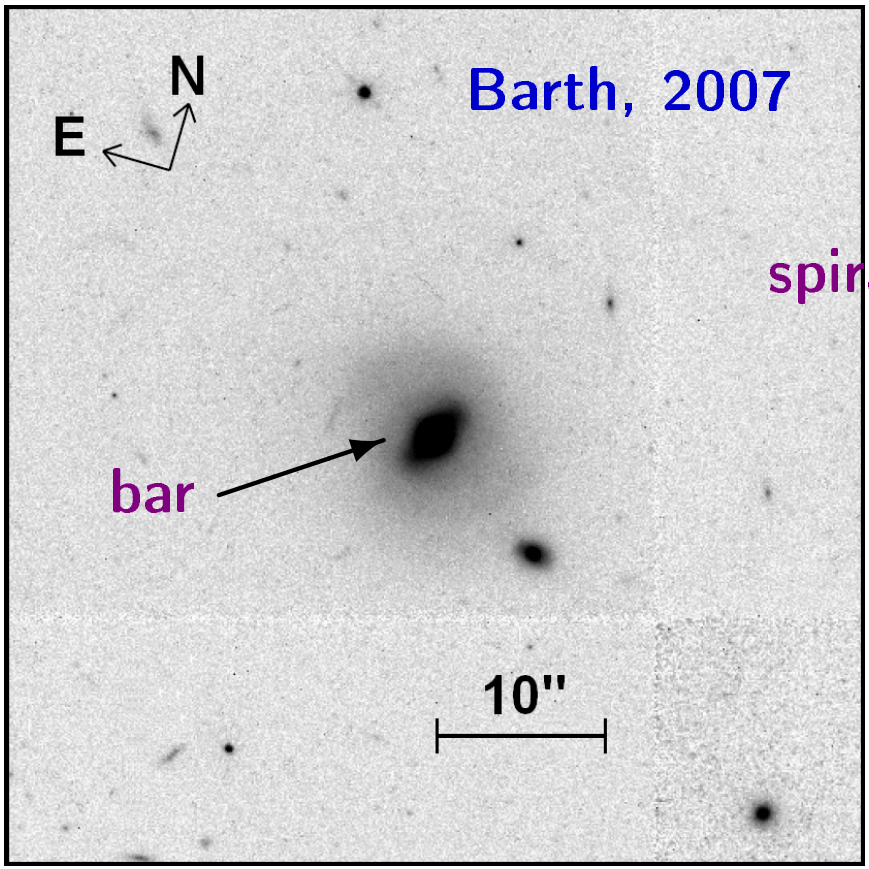
Giant stellar disc – main parameters

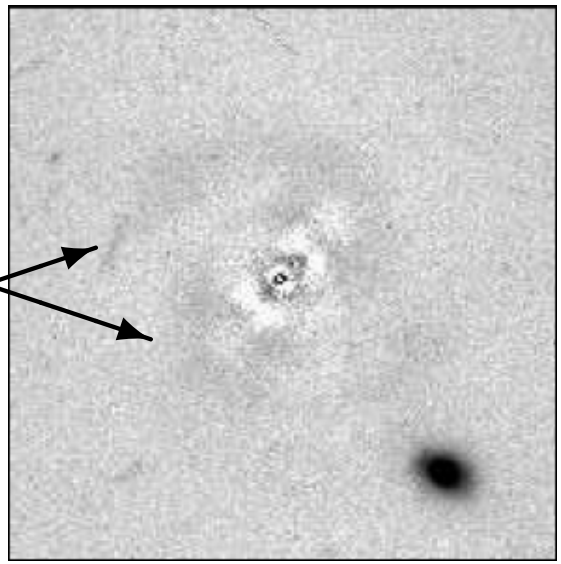
- $D_L = 370$ Mpc; scale $= 1.53$ kpc/arcsec

The band	V	R
Extension	$60''$, or 90 kpc	$80''$, or 120 kpc
Scale lenght h_{outer}	$45''$, or 68 kpc	$33''$, or 50 kpc
Central surface brightness $\mu_{0,\text{outer}}$	$\approx 25^{\text{m}}.5/\square''$	$\approx 24^{\text{m}}.7/\square''$

- $M_V \approx -22^{\text{m}}.9$ – **Extremely bright!!!**

HST data. Normal stellar disc in Malin 1 – the I band. Bar and two spiral arms





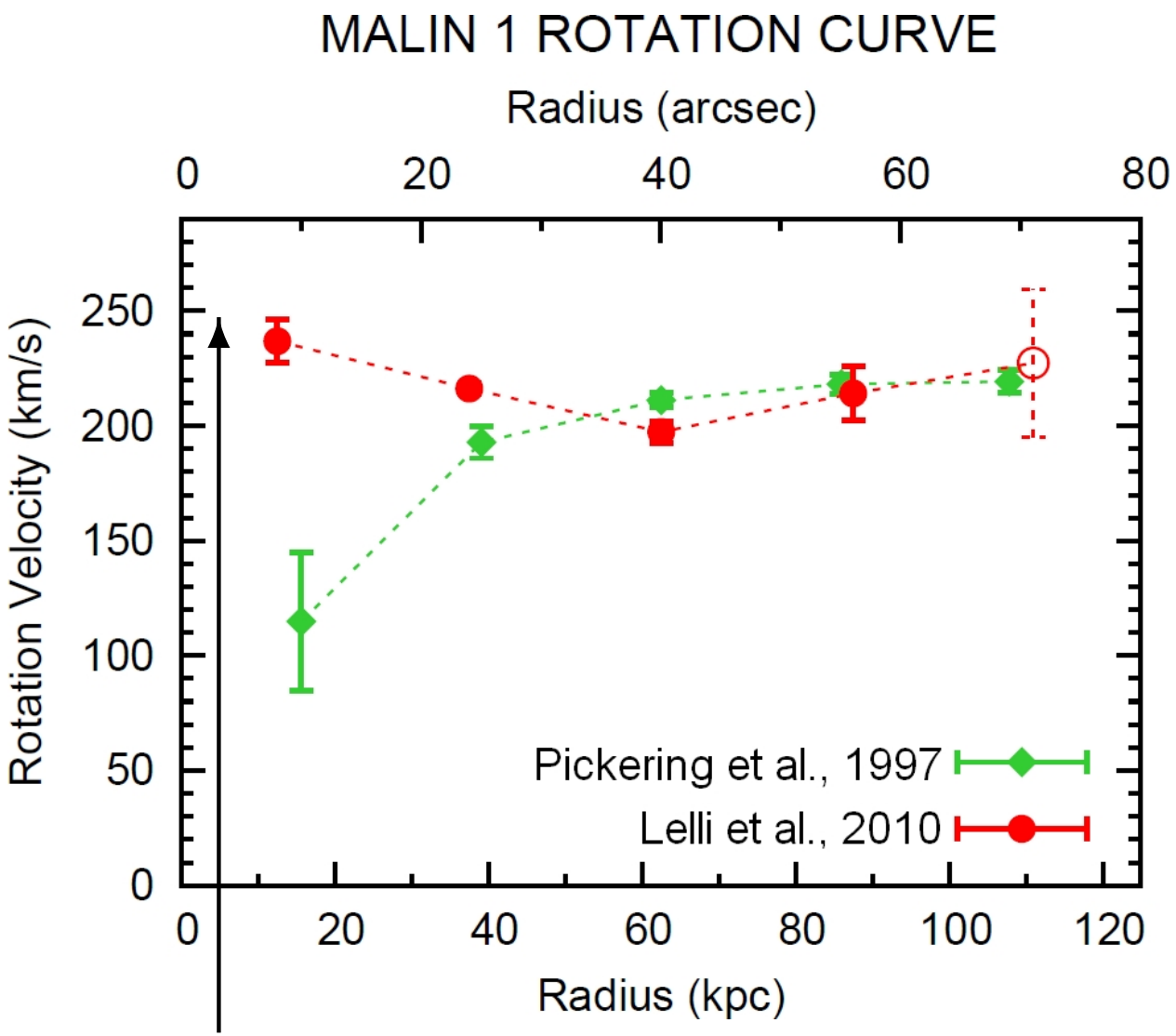
Bulge:	$r_{\rm e,b}$	0.6 kpc
	n	1.24
	$m_{\rm b}(I)$	$17^{\rm m}.0$

Disc:	$\mu_0^{\rm inner}(I)$	$20^{\rm m}.1/\Box''$
	$h_{\rm inner}$	4.8 kpc

$$I_{\rm bulge}(r) = I_{0,\rm b}\, e^{-\nu_{\rm n}[(r/r_{\rm e,b})^{1/n}]}$$

$$I_{\rm disc}^{\rm inner}(r) = I_{0,\rm d}^{\rm inner}\, e^{-r/h_{\rm inner}}$$

HI rotation curve



$\mathcal{M}(\mathrm{HI}) \approx 6.7 \cdot 10^{10} \mathcal{M}_{\odot}$

Decomposion of the rotation curve:

Pickering et al., 1997

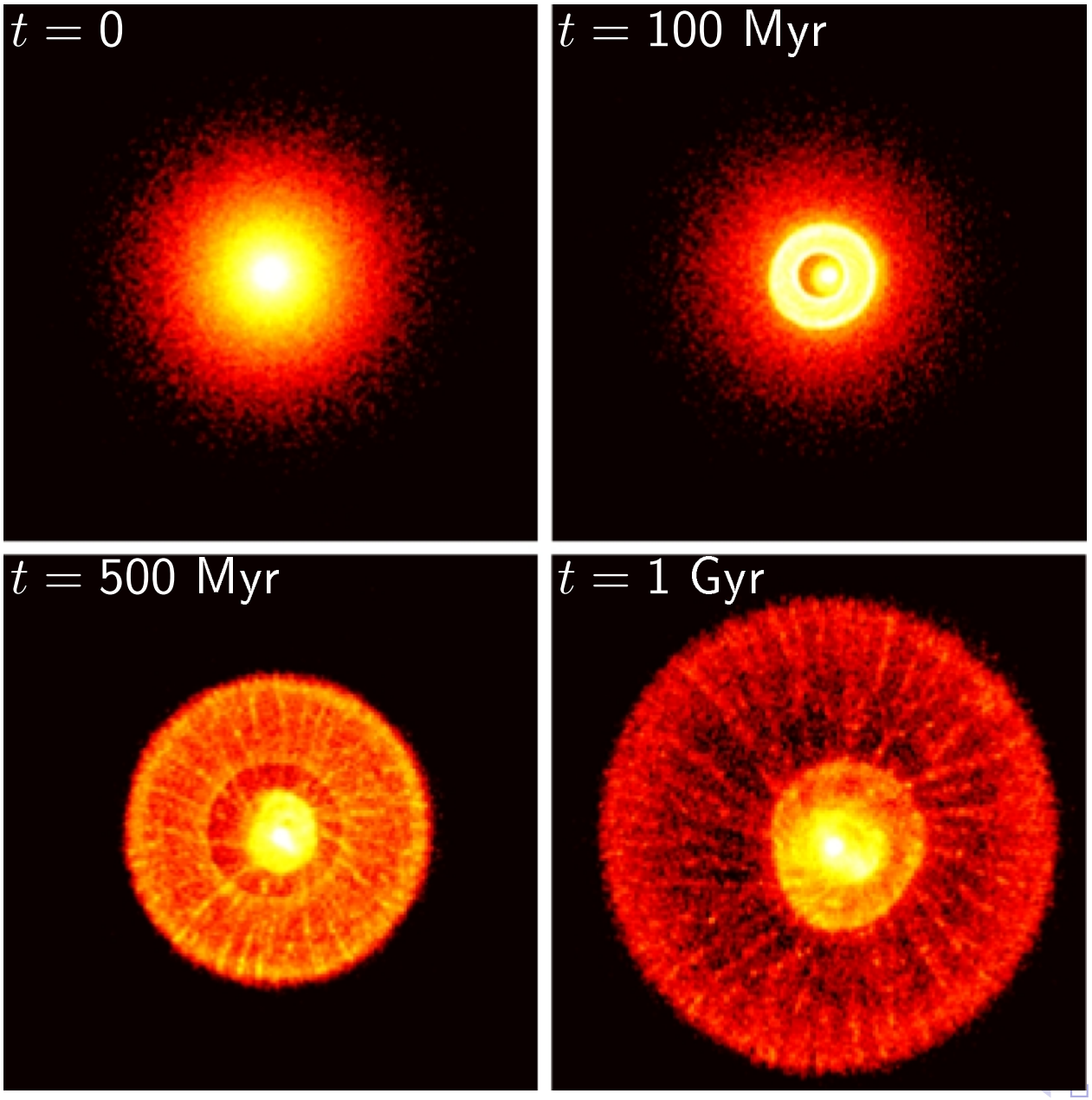
Sancisi & Fraternali, 2007

Seigar, 2008

Lelli et al., 2010

Inner disc, bar and bulge

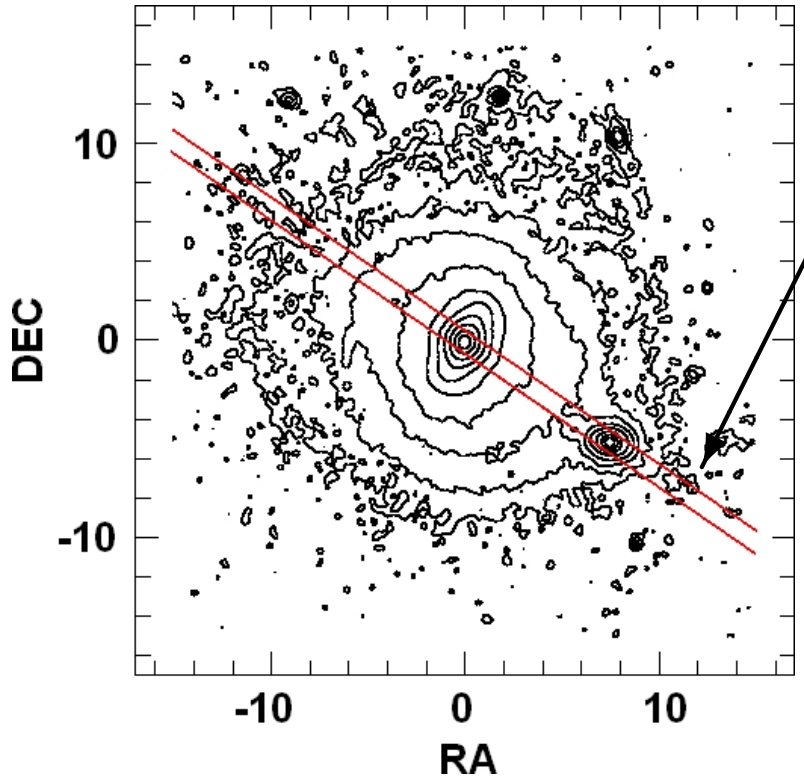
A collisional model. Where is a satellite?



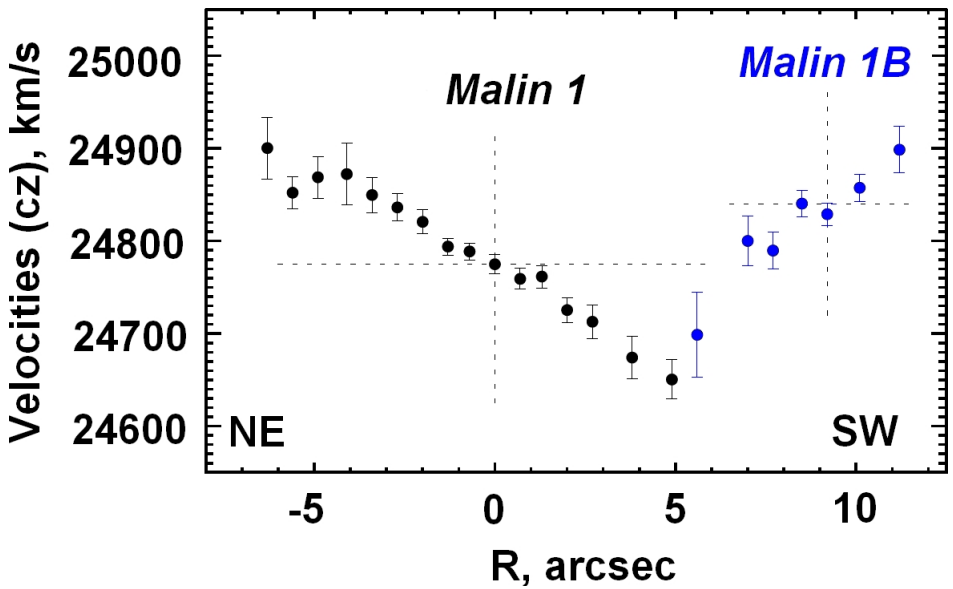
Mapelli et al., 2008

A very massive satellite is needed!!!

6-m telescope's data. A missing satellite? MN, 414, 3645, 2011



Slit 2



Slit 1 – PA = 200°

Slit 2 – PA = 235°

Slit 3 – PA = 333°

$\Delta v \sim 65 \pm 16$ km/s

$\Delta R_{\text{proj}} \sim 14$ kpc

$L_{\text{satellite}}(I) \approx 0.1\, L_{\text{Malin1}}(I)$

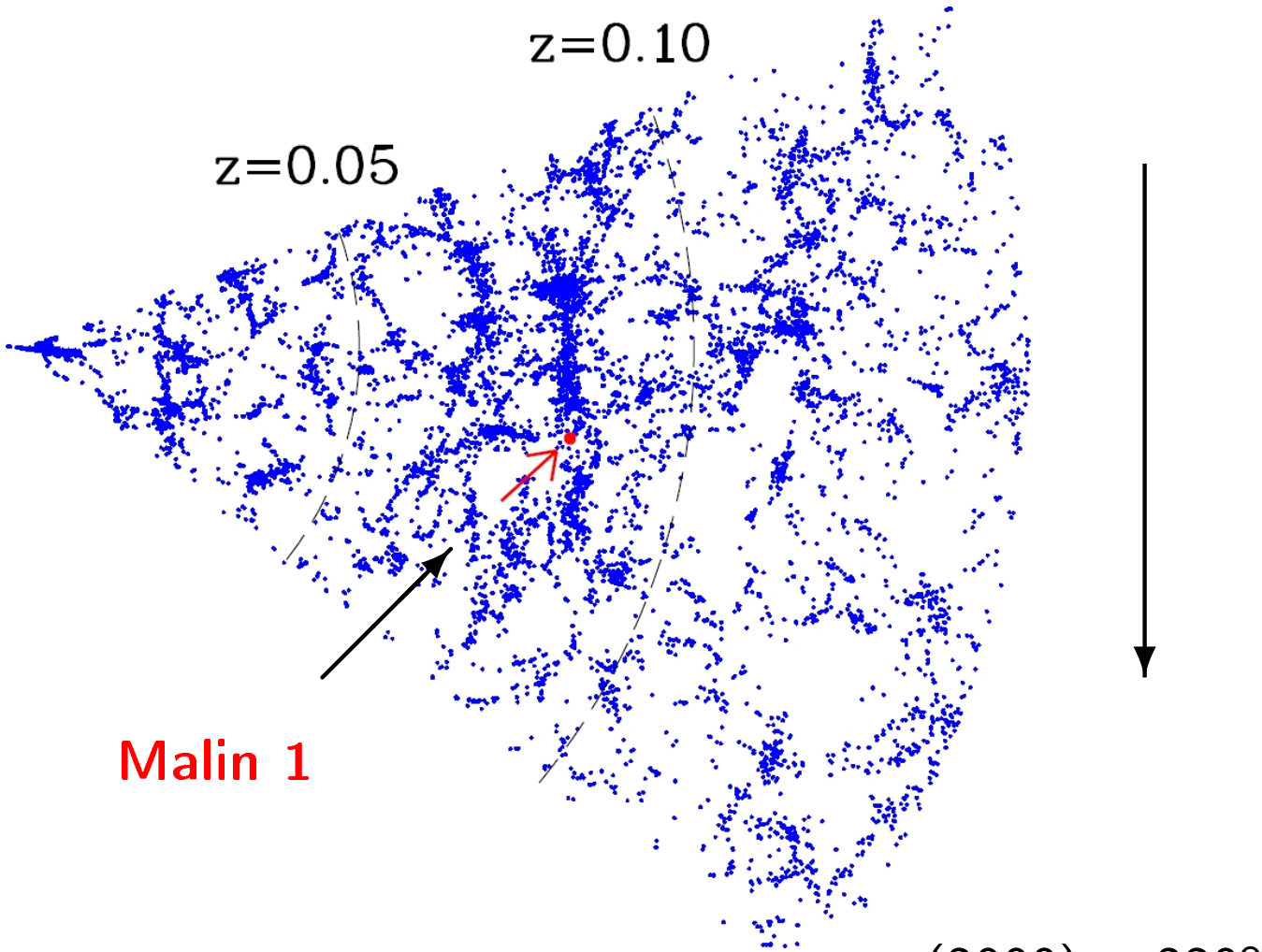
Too small

A close orbit rather than a flyby

Formation in the voids?

A slice within $13.1° \leq \delta(2000) \leq 15.6°$

$\alpha(2000) = 160°$



$\alpha(2000) = 220°$

A missing satellite?

The nearest bright galaxy:

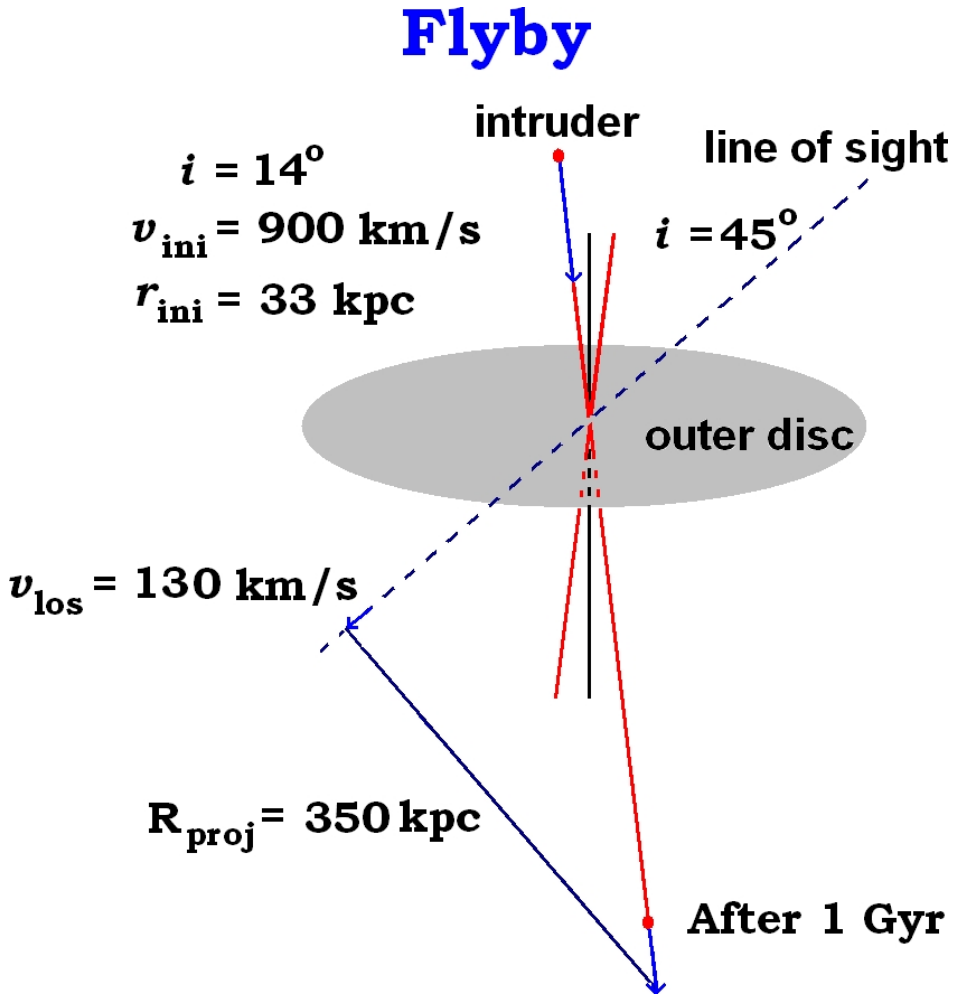
SDSS J123708.91+142253.2

$\Delta R_{\text{proj}} \sim 350$ kpc

$\Delta v \sim 132 \pm 29$ km/s

The g-band:

$$L_{\text{satellite}}/L_{\text{Malin1}} = 1/2.5$$

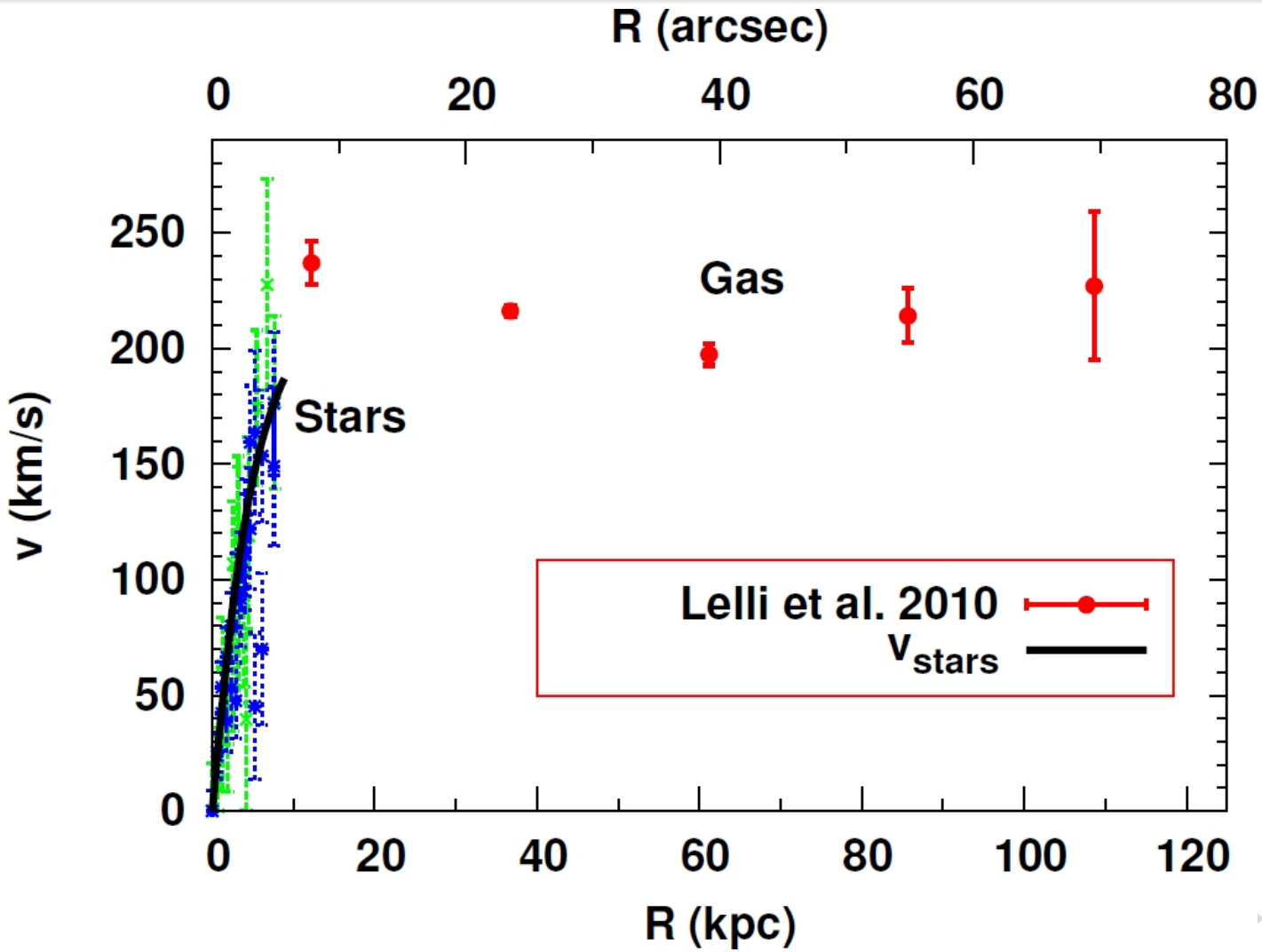


Can be reconciled with Mapelli's model!

Stellar rotation curve (two slits)

PA = 200° – was not used; data are very noisy

PA = 235° and PA = 333° $\Longrightarrow$ $i = 38°$, $\mathrm{PA}_{\mathrm{maj}} = 1.7°$



Stellar and gaseous rotation curves

The asymmetric drift equation – the in-plane steady state

$$v_{\mathrm{c}}^2 - \bar{v}_\varphi^2 = \sigma_\varphi^2 - \sigma_R^2 - R\frac{\partial \overline{v_R v_z}}{\partial z} - \frac{R}{\Sigma_{\mathrm{d}}}\frac{\partial \Sigma_{\mathrm{d}} \sigma_R^2}{\partial R}$$

$$\Sigma_{\mathrm{d}}(R) = \left(\frac{M}{L}\right) I_{\mathrm{d}}(R)$$

$R\frac{\partial \overline{v_R v_z}}{\partial z}$ – describes the tilting of the velocity ellipsoid;

essential only in the centre

LOS velocity dispersion

Profiles along slits

$$\sigma^2_{\rm los}(R') = \left[\sigma^2_R \sin^2\varphi + \sigma^2_\varphi \cos^2\varphi\right] \sin^2 i + \sigma^2_z \cos^2 i$$

$$R' = \frac{R\cos i}{\sqrt{1-\sin^2 i \cos^2\varphi}}; \qquad \varphi = PA - PA_{\rm maj}$$

Radial and azimuthal profiles

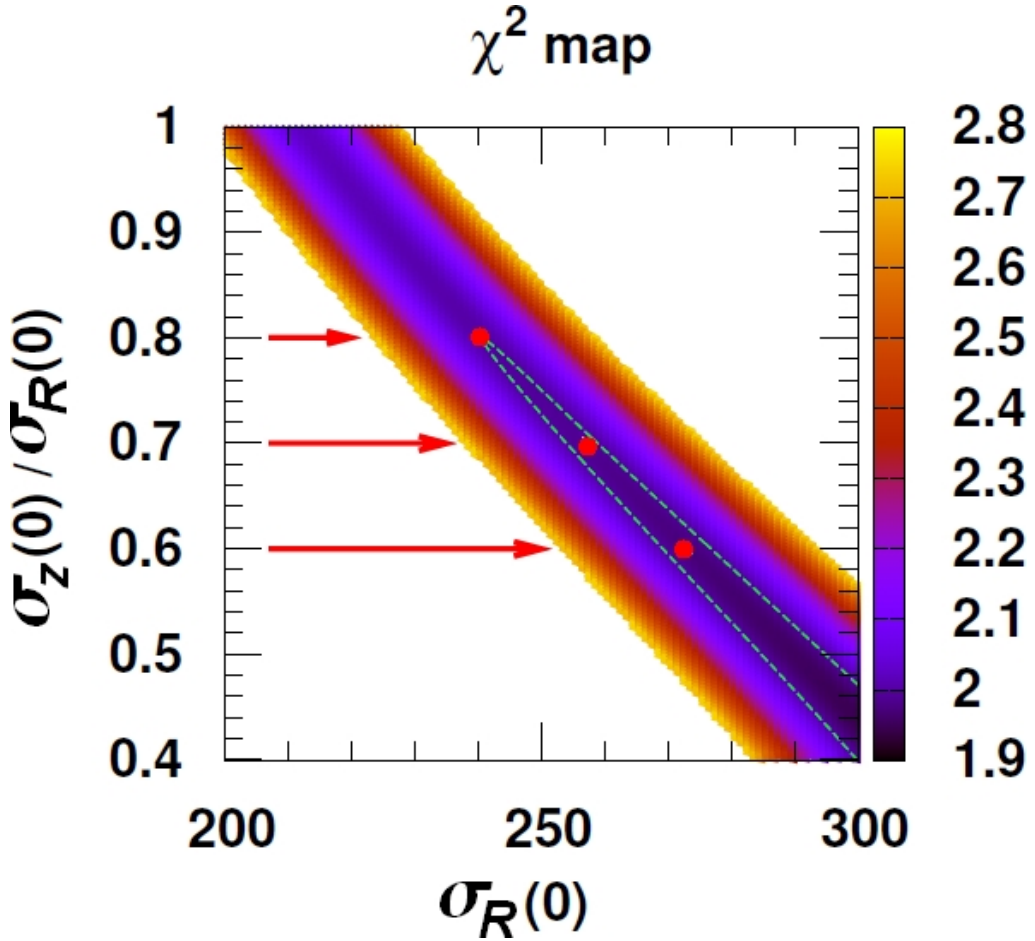
$$\frac{\sigma^2_\varphi}{\sigma^2_R} = \frac{1}{2}\left(1 + \frac{\partial \ln \bar{v}_\varphi}{\partial \ln R}\right)$$

Solid body rotation

$$\sigma_\varphi \approx \sigma_R$$

$\sigma_{\rm los}(R)$ doesn't depend on PA!!!

Velocity dispersion profiles. Degeneracy

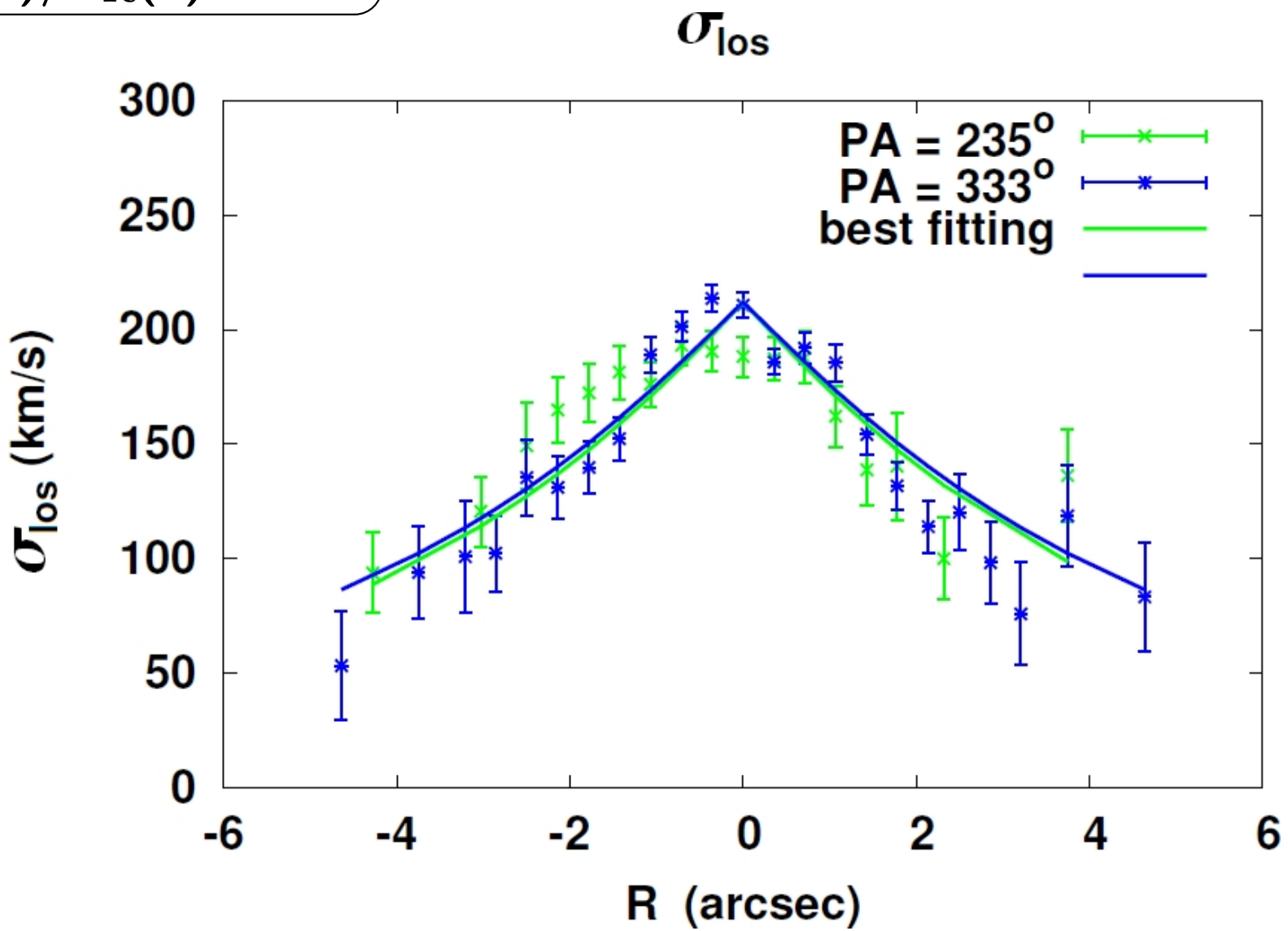


$$\sigma^2_{\text{los}}(R) \approx \sigma^2_R \,\sin^2 i + \sigma^2_z \,\cos^2 i$$

$$\sigma_z(R) \propto \sigma_R(R) = \sigma_{R,0}\, e^{-R/h_{\text{kin}}}\,; \quad h_{\text{kin}} \approx 2\,h$$

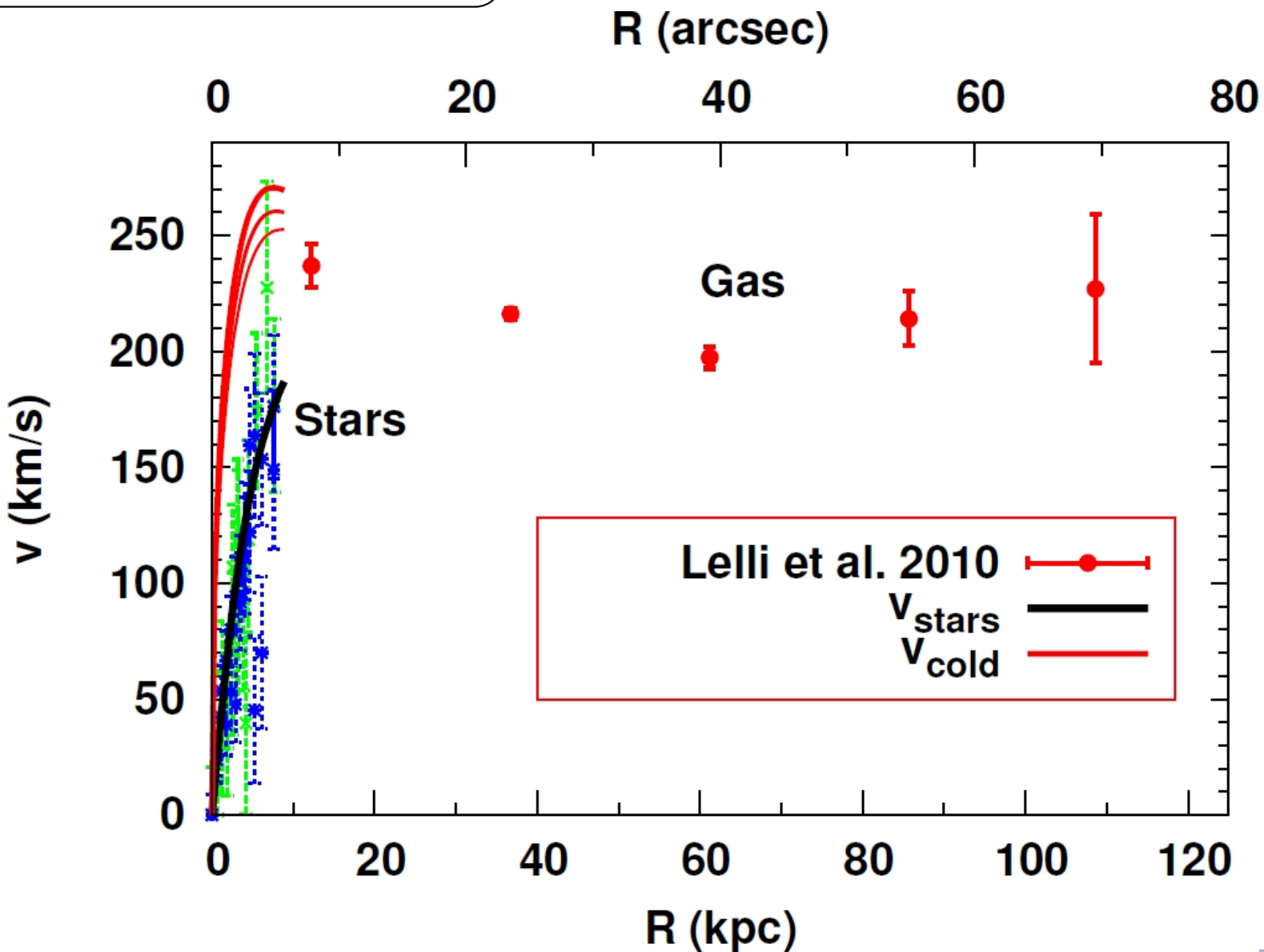
Velocity dispersion profiles

$\sigma_z(0)/\sigma_R(0) = 0.6$



Recovered "cold" rotation curve

$\sigma_z(0)/\sigma_R(0) = 0.6,\ 0.7,\ 0.8$



Decomposition of the rotation curve

$(\mathcal{M}/L_{\text{band}})$ – **Bell et al., 2003**: $\lg(\mathcal{M}/L_{\text{band}}) = a_{\text{band}} + b_{\text{band}} \times Color$

Inner disc – exponentional profile; $h_z/h_{\text{inner}} = 0.2$

Bar – Sersic profile

$$B - V = 0.9 \Longrightarrow 1.7 < (\mathcal{M}/L_I) < 2.8 \text{ (up to 3.5)}$$

Bulge – Sersic profile

$(\mathcal{M}/L_I)$ – free

Outer disc – exponential profile

$(\mathcal{M}/L_R) \approx 0.9$

+ HI

Dark halo – NFW model

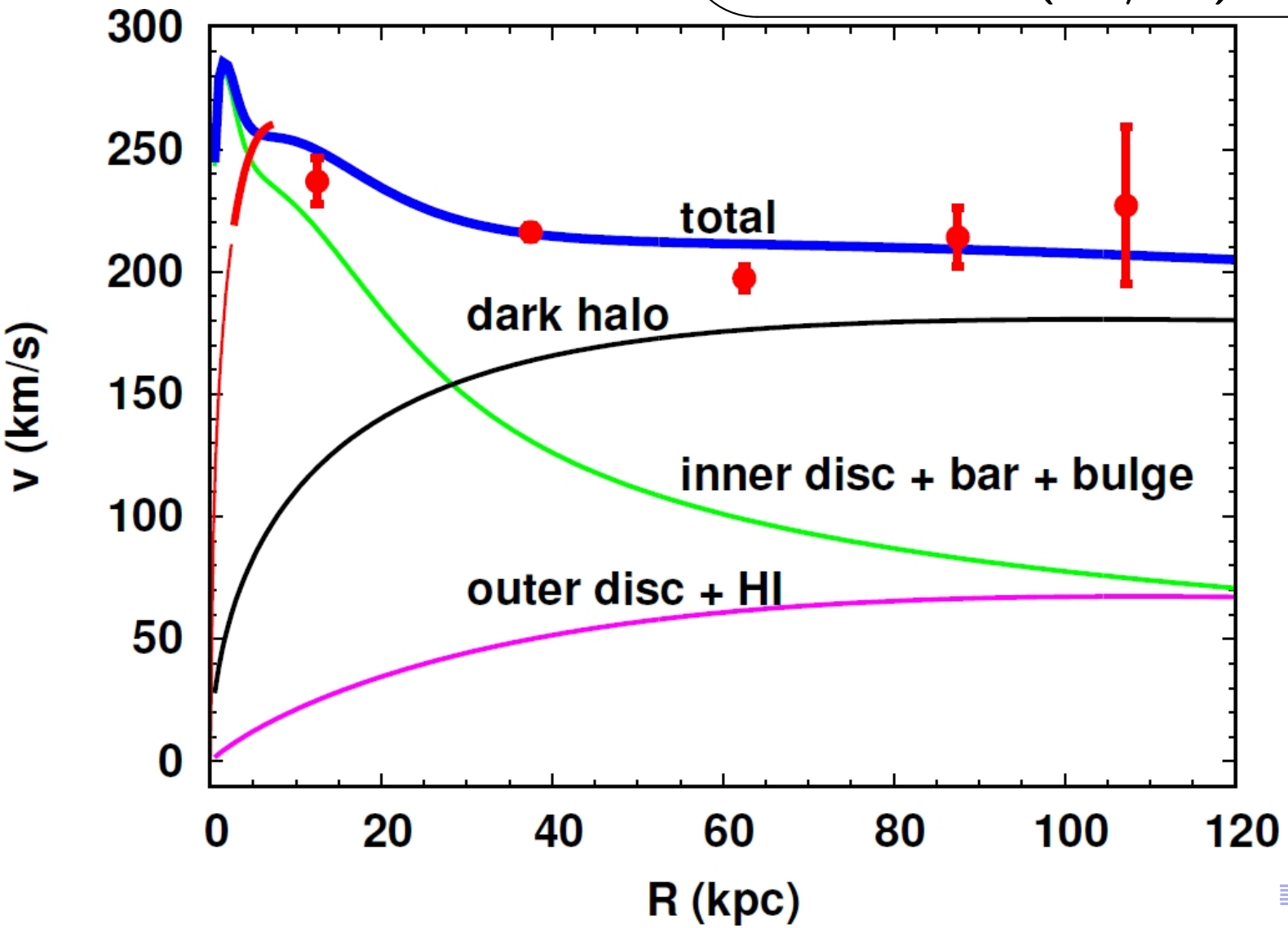
Two parameters:

$c = r_s/r_{200}$ – concentration

v_{200} – the velocity at the virial radius

"Maximal" disc, "minimal" bulge

inner disc: $\sigma_z(0)/\sigma_R(0) = 0.7$
$(\mathcal{M}/L_I) = 3.0$



Summary

The discovery of a small satellite Malin 1B interacting with Malin 1

The location and the speed of the galaxy SDSS J123708.91+142253.2 can be reconciled with the collisional model of the outer disc

The "cold" rotation curve was recovered

If the inner disc is maximal dark matter begin to dominate only in the outermost regions