Dark gas in the disc of the giant low surface brightness galaxy Malin 2

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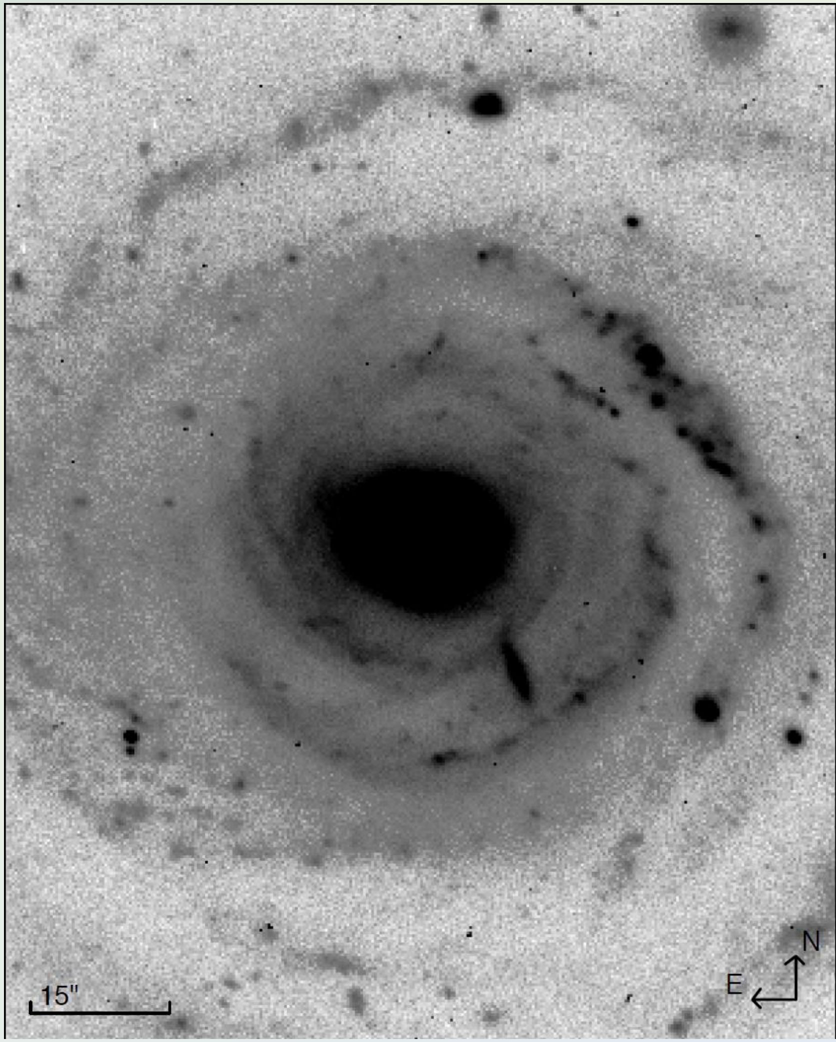

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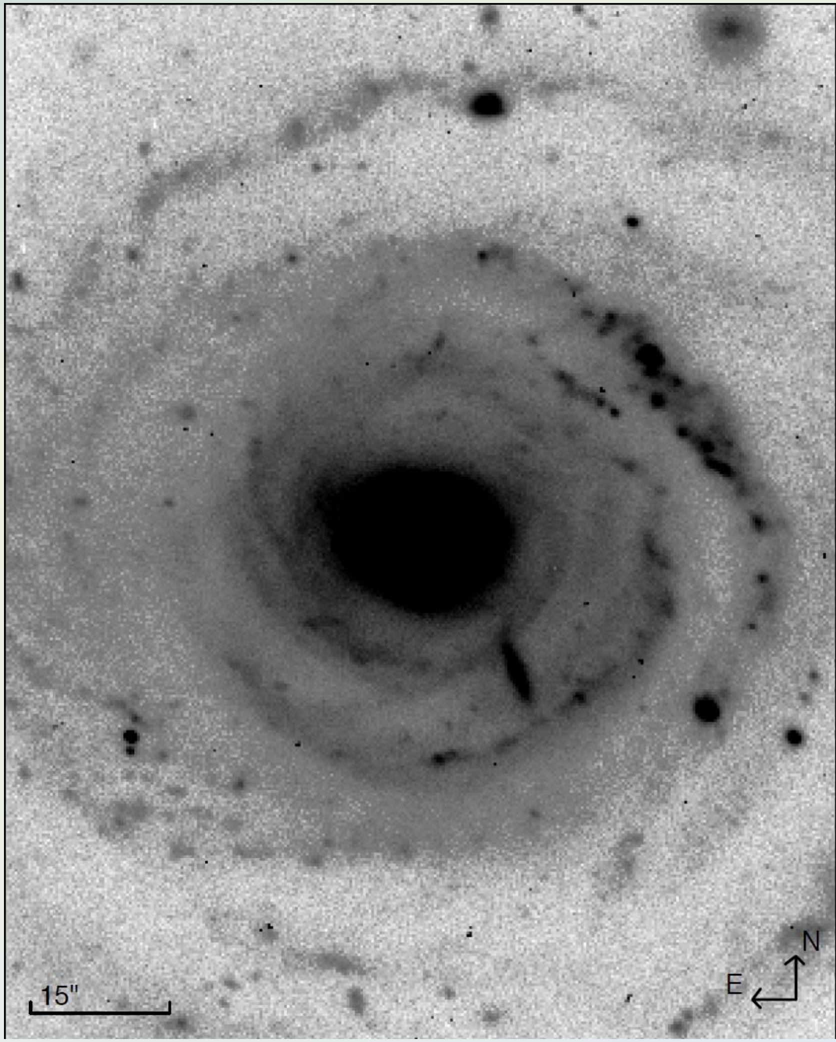
The main properties of Malin 2

Names	Malin 2 F 568-06 PGC 086622
Distance	201 Mpc
Morph. type	Scd
Inclination	38^0
PA	75^0
M_B	-21.38 mag.
Disc radius ($4h_d$)	101 kpc (!)

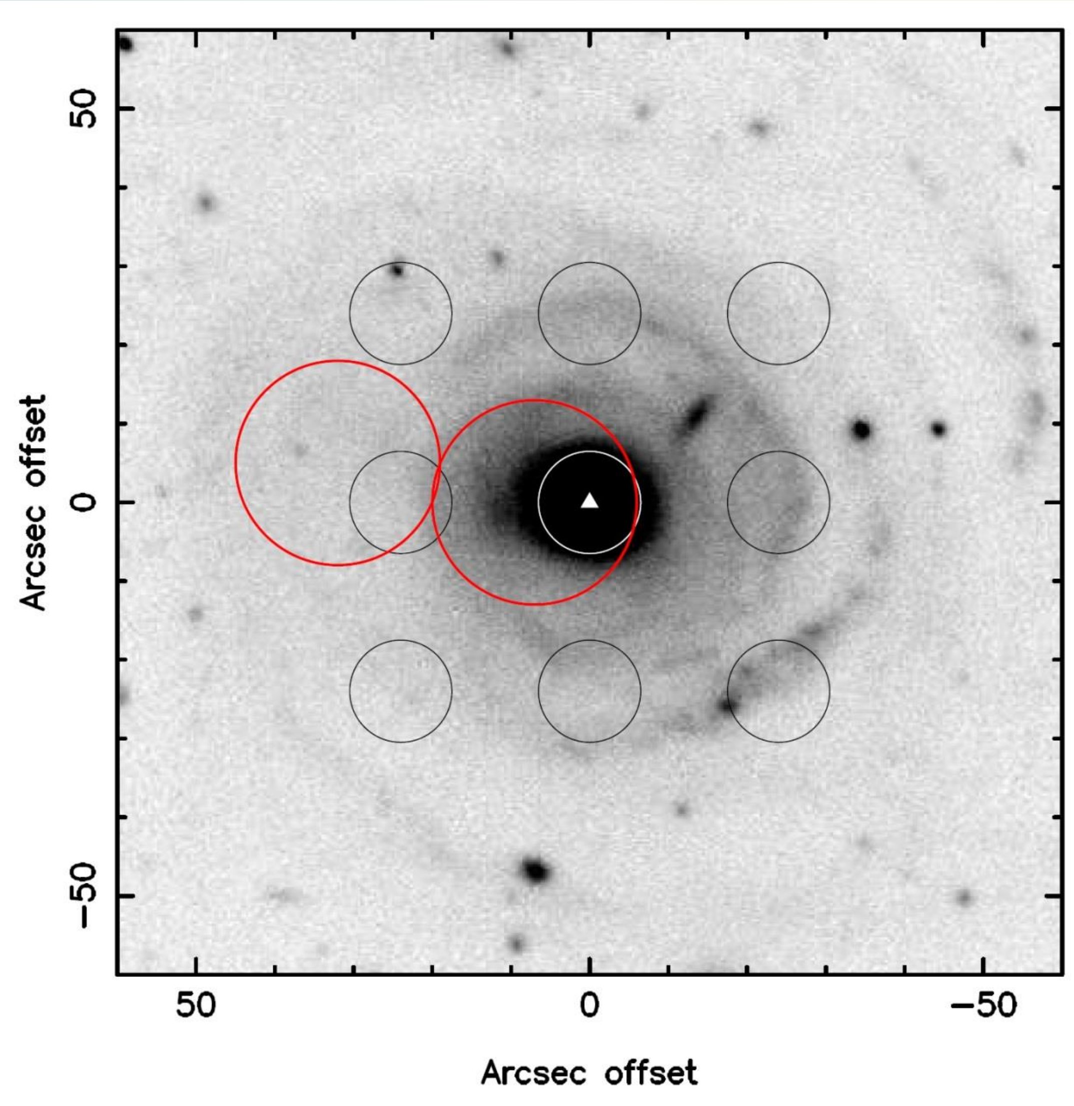


CO(2–1) line observations of Malin 2

Das et al. (2010): Observations with HERA beam array on the IRAM 30m telescope.

The mean molecular gas surface density: $1.1 \pm 0.2 M_{sun}/pc^2$

$4.9 \times 10^8 M_{sun} < M_{mol.} < 4.9 \times 10^8 M_{sun}$



HERA footprint overlaid on the R-band image.
Das et al. (2010) FWHM=11.7’’

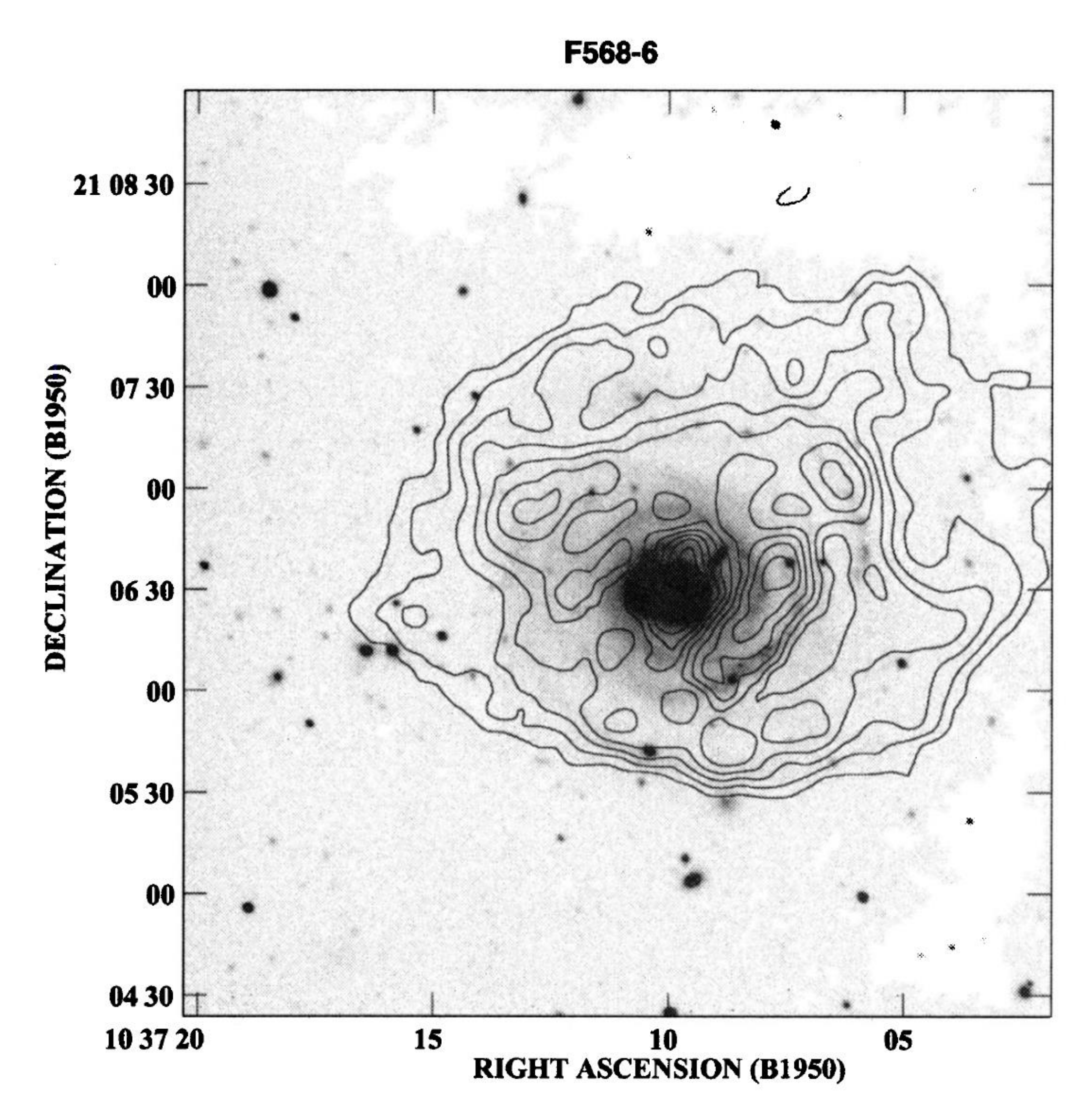
HI observations of Malin 2

Pickering et al. (1997):
Observations with VLA.

The mean surface density at the radii of CO observations: ~$2M_{sun}/pc^2$

Total HI mass:
$M_{HI}=3.6\pm0.4\times10^{10}\ M_{sun}$

FWHM of synthesized beam:
19.5''X18.4''



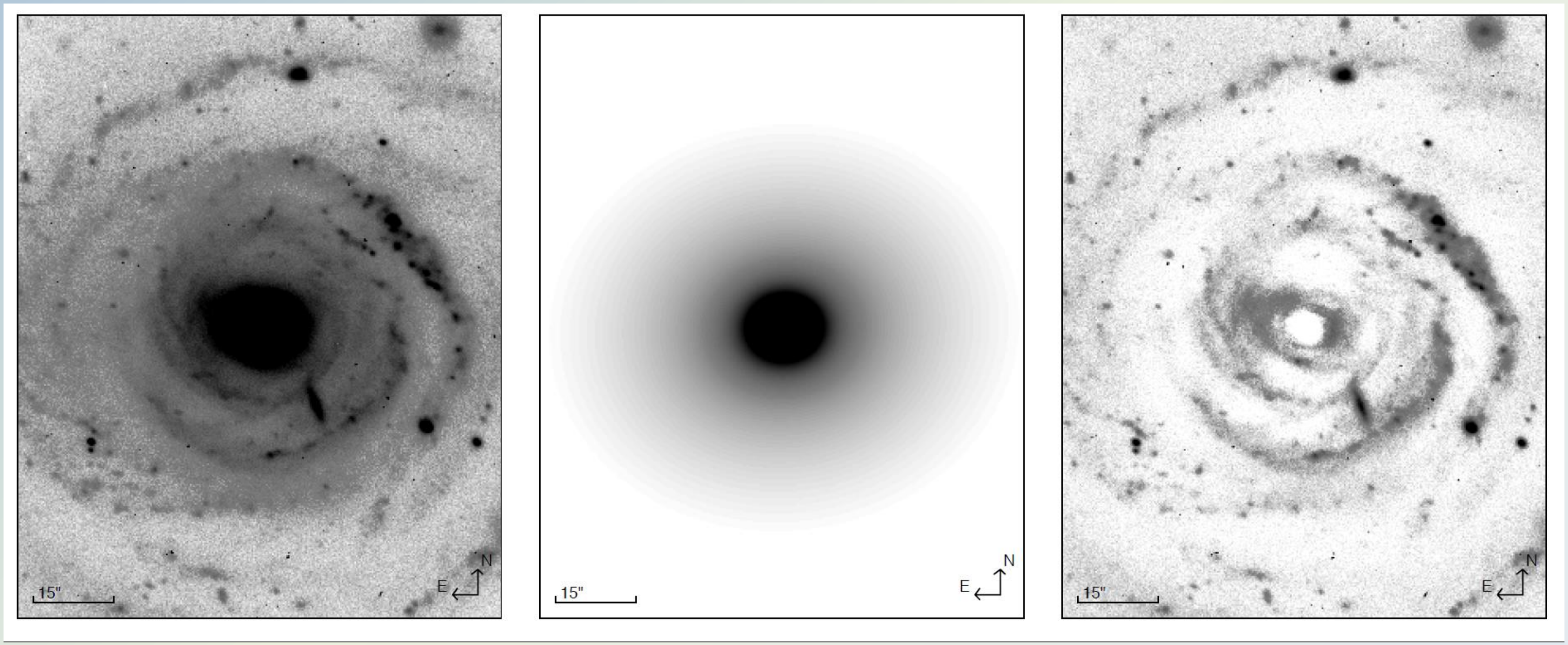
R-band image overlayed with HI intensity contours.
Pickering et al. (1997)

Other observational data:

- Long-slit spectral observations with GMOS-N spectrograph on the 8-m Gemini-North telescope *(under science program GN-2006B-Q-41 (P.I.: C. Onken) in January 2007)*

- Photometrical observations in BVR-bands with 0.5m Apache Point Observatory telescope; griz photometry from Sloan Digital Sky Survey; g-band photometry from GMOS-N; GALEX data.

To obtain the structural parameters of exponential disc and Sersic bulge we used 2D decomposition of the images.

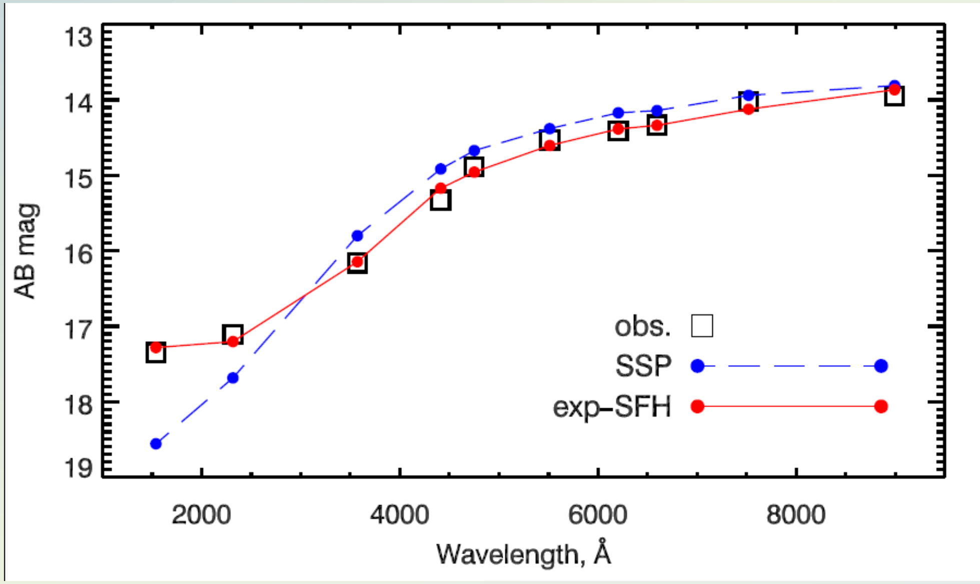


The results of 2D decomposition of Gemini g-band image using BUDDA code.

The mass-to-light ratios of disc and bulge

Disc: SED-modeling with exponentially declining star formation history.

$(M/L_R)_{disc}=1.7M_{sun}/L_{sun}$

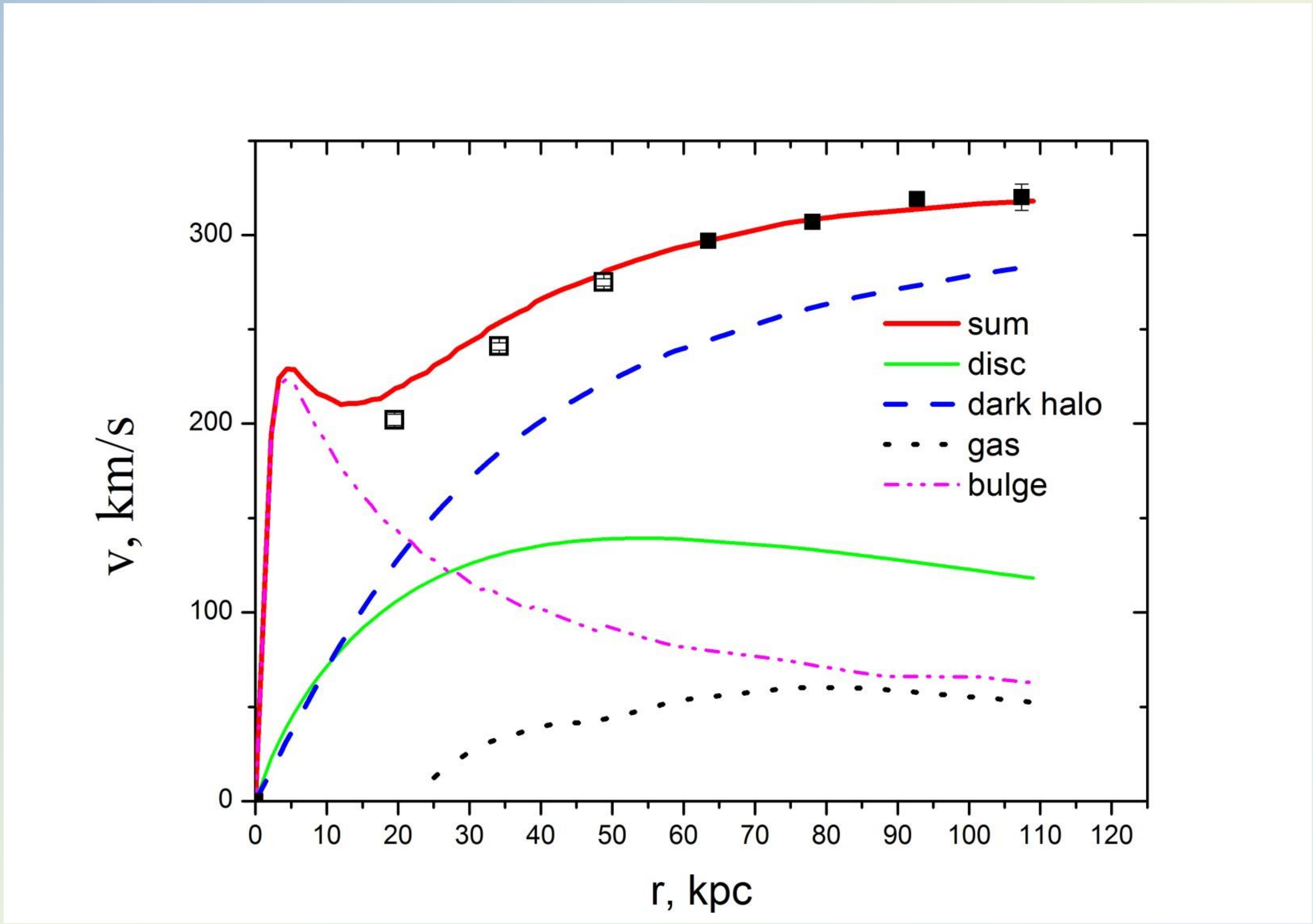


The results of SED modeling for the disc.

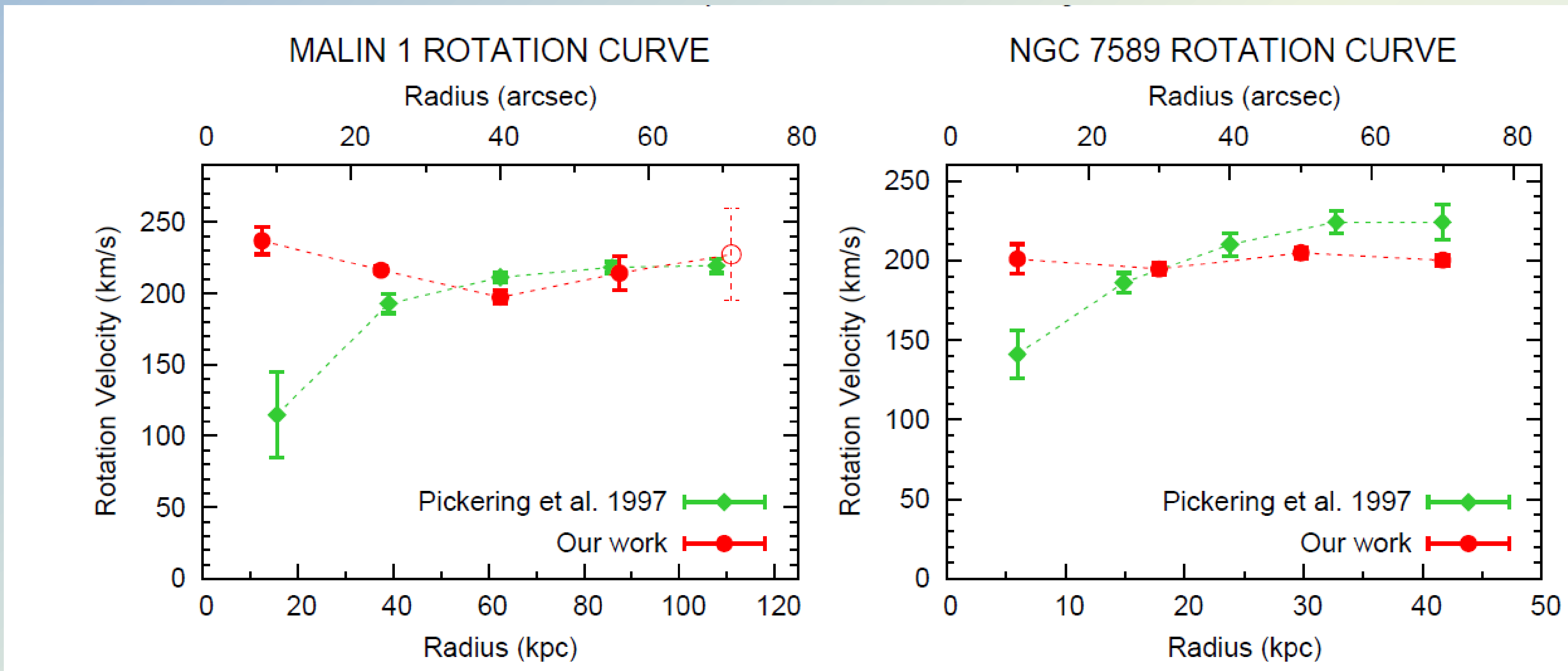
Bulge: Spectral fitting using SSP model (a single instantaneous burst of star formation).

$(M/L_R)_{bulge}=3.25M_{sun}/L_{sun}$

The results of mass-modelling



The central points of the rotation curve are uncertain due to the beam smearing effect:



A comparison of the rotation curves obtained from reanalyzed HI data from Pickering et al (1997) with the old ones for two other giant LSBs. **Lelli et al. (2010)**

The results of mass modeling

	M_{bulge}/M_{tot}	M_{disc}/M_{tot}	M_{halo}/M_{tot}	M_{gas}/M_{tot}	M_{tot}
r=h	0.30	0.25	0.43	0.02	$3.1 \cdot 10^{11}$
r=4h	0.04	0.12	0.81	0.02	$2.2 \cdot 10^{12}$

The dark halo is not dominating in the inner region.
The mass model is close to the maximum disc model.
In good agreement with results of Lelli et al. (2010).

The parameters of the dark matter halo:

ρ_0=0.0029 M_{sun}/pc^3
r_c=27.3 kpc

for a comparison in MW:
ρ_0=0.036M_{sun}/pc^3 , r_c=5 kpc (Mera et al., 1998)

From the condition of the vertical hydrostatic equilibrium and the Poisson equation it follows:

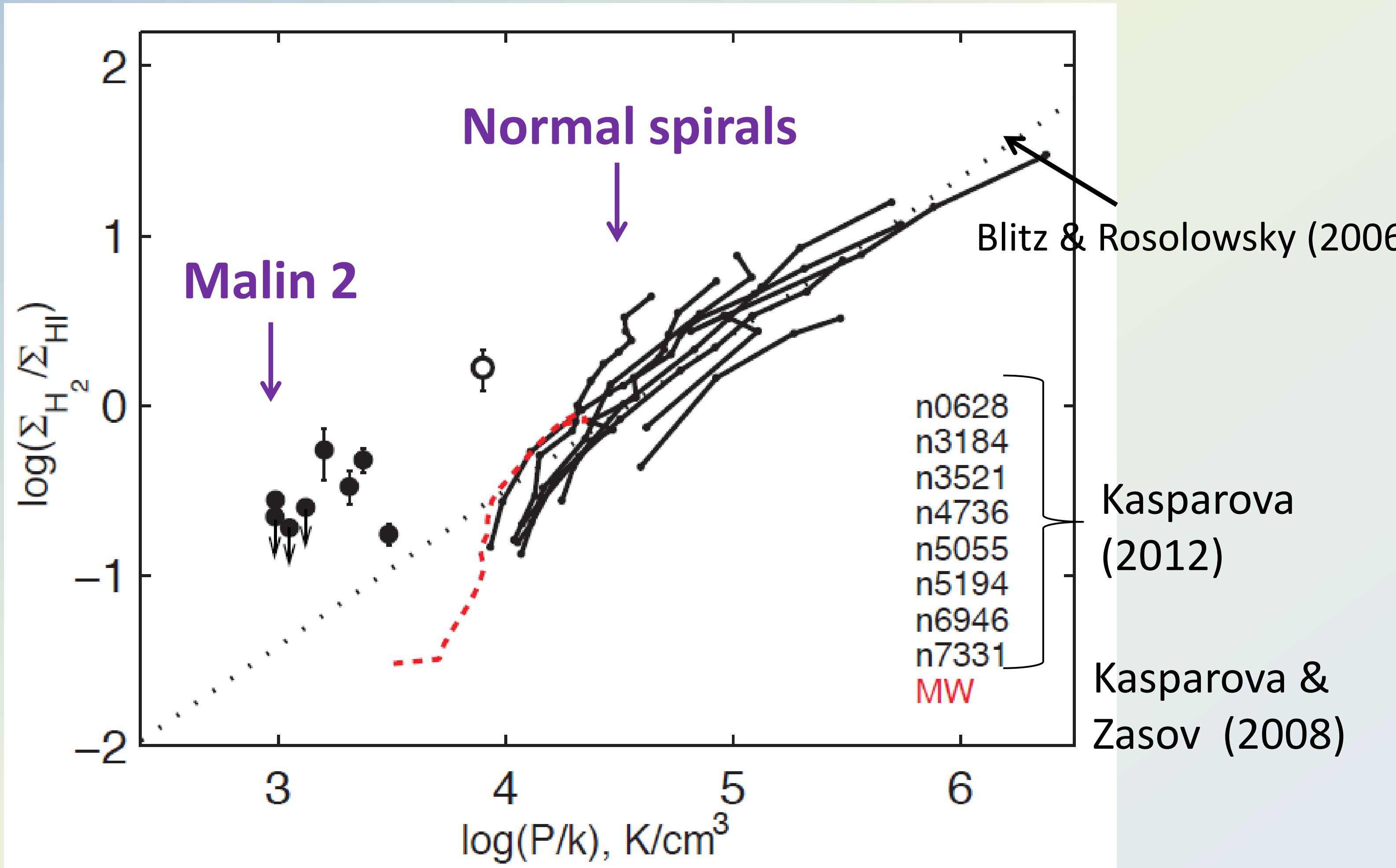
$$\frac{d^2\rho_i}{dz^2} = \frac{\rho_i}{\langle(\sigma_i)_i^2\rangle}\left[-4\pi G\sum_{i=1}^{3}\rho_i - \frac{\partial^2\phi_d}{\partial z^2}\right] + \frac{1}{\rho_i}\left(\frac{d\rho_i}{dz}\right)^2$$

The potential of the 3-component disc in dark matter halo, *i* denotes each of the disc components (stars, HI, H_2).

In the disc midplane (Z=0): $$\rho_i = (\rho_0)_i \quad \text{and} \quad \frac{d\rho_i}{dz} = 0.$$

ρ is the volume density, σ is the turbulent velocity along Z axis.
σ_{HI}=10 km/s, σ_{H2}=13 km/s

The molecular gas fraction of Malin 2 is higher by a factor of ten than expected for given equilibrium turbulent pressure for normal spirals



The equilibrium hydrostatic pressure of the interstellar medium:

$$P=(\sigma_{HI})^2\rho_{HI}+(\sigma_{H2})^2\rho_{H2}$$

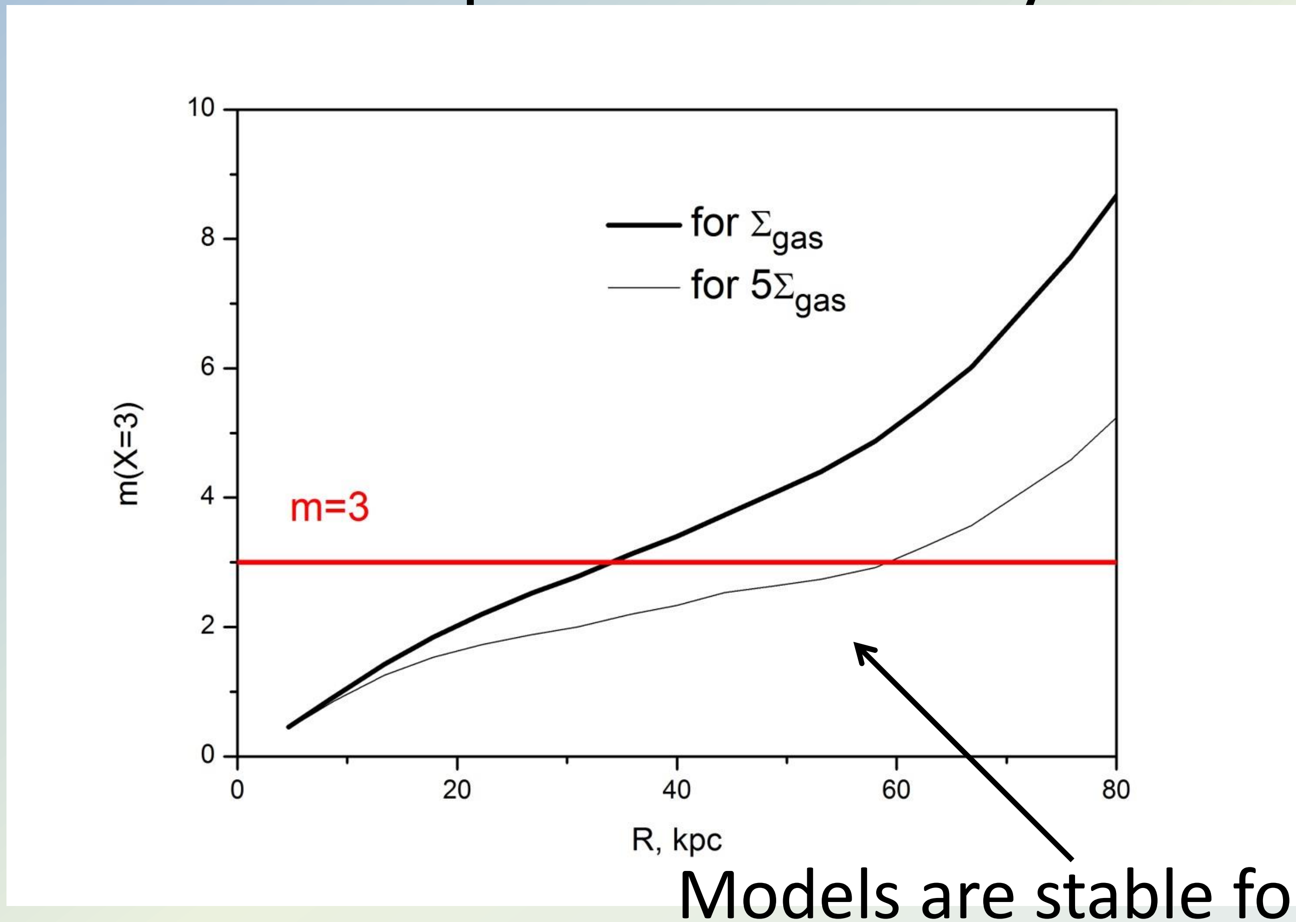
Possible reasons for the imbalance:

The additional pressure due to environmental impact such as ram pressure from the intergalactic medium. – **Unlikely.**

The overestimation of the conversion factor $X \sim Z^{-1}$. – **Unlikely.**

Additional fraction of gas invisible in CO and HI lines which is higher than in normal galaxies due to particular structure of ISM in Malin 2. – **Most likely**.

The observed spiral structure in the frame swing amplification theory



Models are stable for m<m(X=3)

$$m(X=3) = \frac{R\,\kappa^2}{6\,\pi\,G\,\Sigma_{\rm disk}}$$

Where X is the ratio between the perturbation and critical wavelengths, κ is epicyclic frequency, R is radius.

Additional arguments in favor of the presence of dark gas in Malin 2

- The presence of dark gas provides additional shielding of H_2 molecules from UV radiation preventing it from dissociation.

- Taking into account of dark gas increases the total gas density allowing it **to reach the gravitational stability threshold** needed for the ongoing star formation.

Notes on the formation scenario

- Bygone head-on collision with the massive intruder (Mapelli et al. 2008). – **Unlikely** *(no massive candidate intruder around Malin 2, the progenitor in the model is massive LSB-galaxy).*
- The disc of Malin 2 was formed by tidally disrupted dwarf galaxies (Peñarrubia et al. 2006). – **Unlikely** *(no traces of the recently accreted satellites in the color map, satellites should have the same angular momentum to form disc).*
- Initial peculiarities (high core radius and low central density) of dark halo together with the poor gas environment. – **Most likely.**

Conclusions:

- We performed the dynamical modeling of the rotation curve of Malin 2. Our model implies the massive and rarified dark halo which dominates by mass within 4 disc scales but does not dominate in the inner region.
- The observed molecular to atomic hydrogen surface density ratio is significantly higher than expected for given low value of turbulent gas pressure. The presence of dark gas which doubles the total gas density could explain this imbalance.
- Peculiar properties of the disc of Malin 2 could be explained by shallow potential well of the host halo and poor gas environment when the disc was formed.


Thank you!