

Structure and Dynamics of Giant Low Surface Brightness Galaxies

Federico Lelli

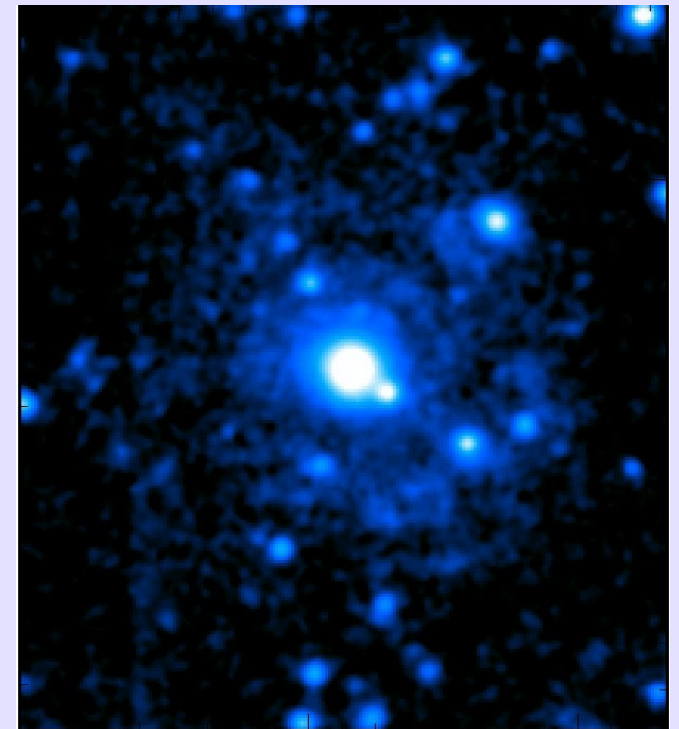
Kapteyn Institute, Groningen, NL

Filippo Fraternali

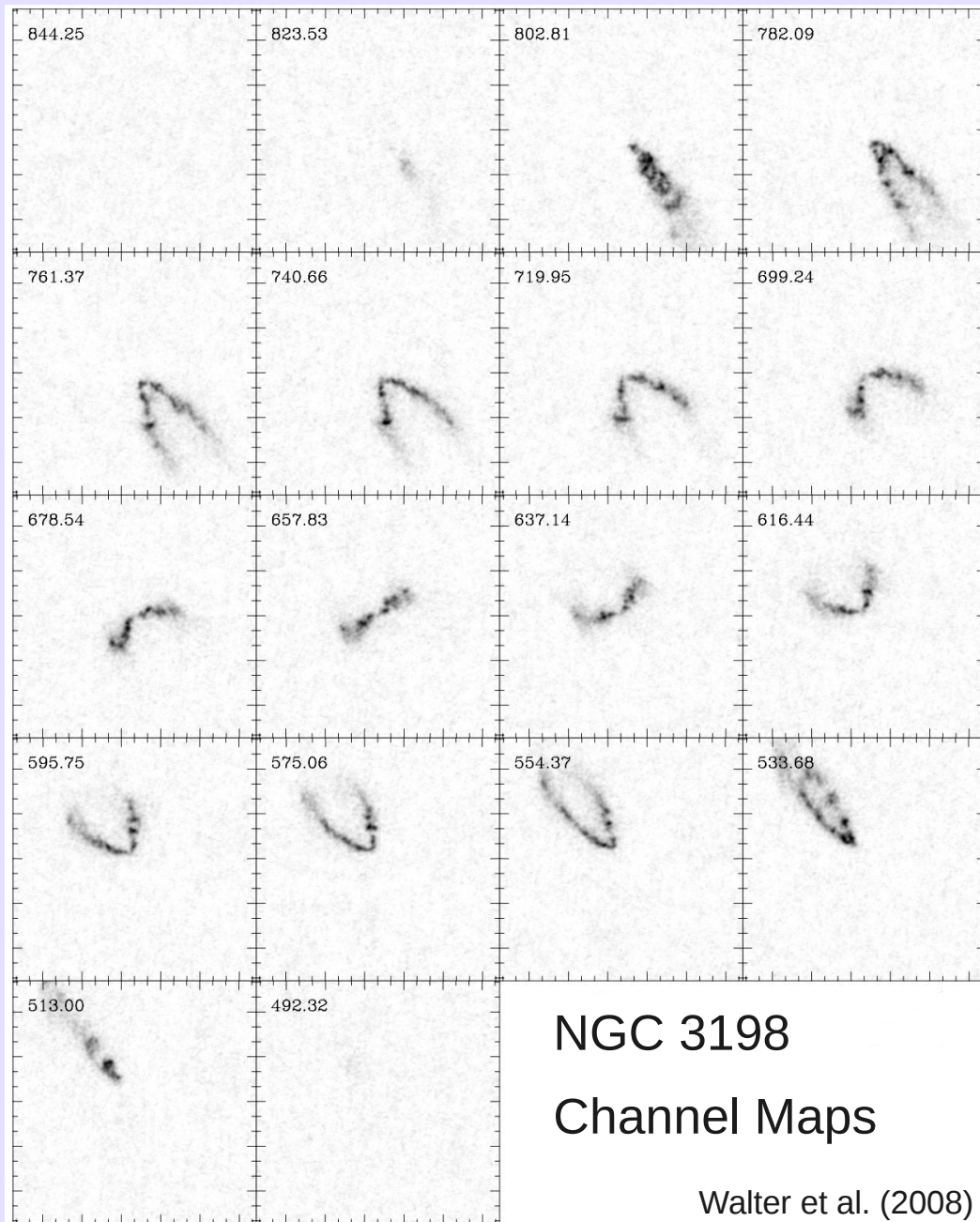
University of Bologna, Italy

Renzo Sancisi

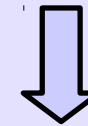
INAF – Observatory of Bologna, Italy



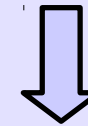
HI Observations of Spiral Galaxies



Hyperfine transition
at 21 cm (1.4 GHz)

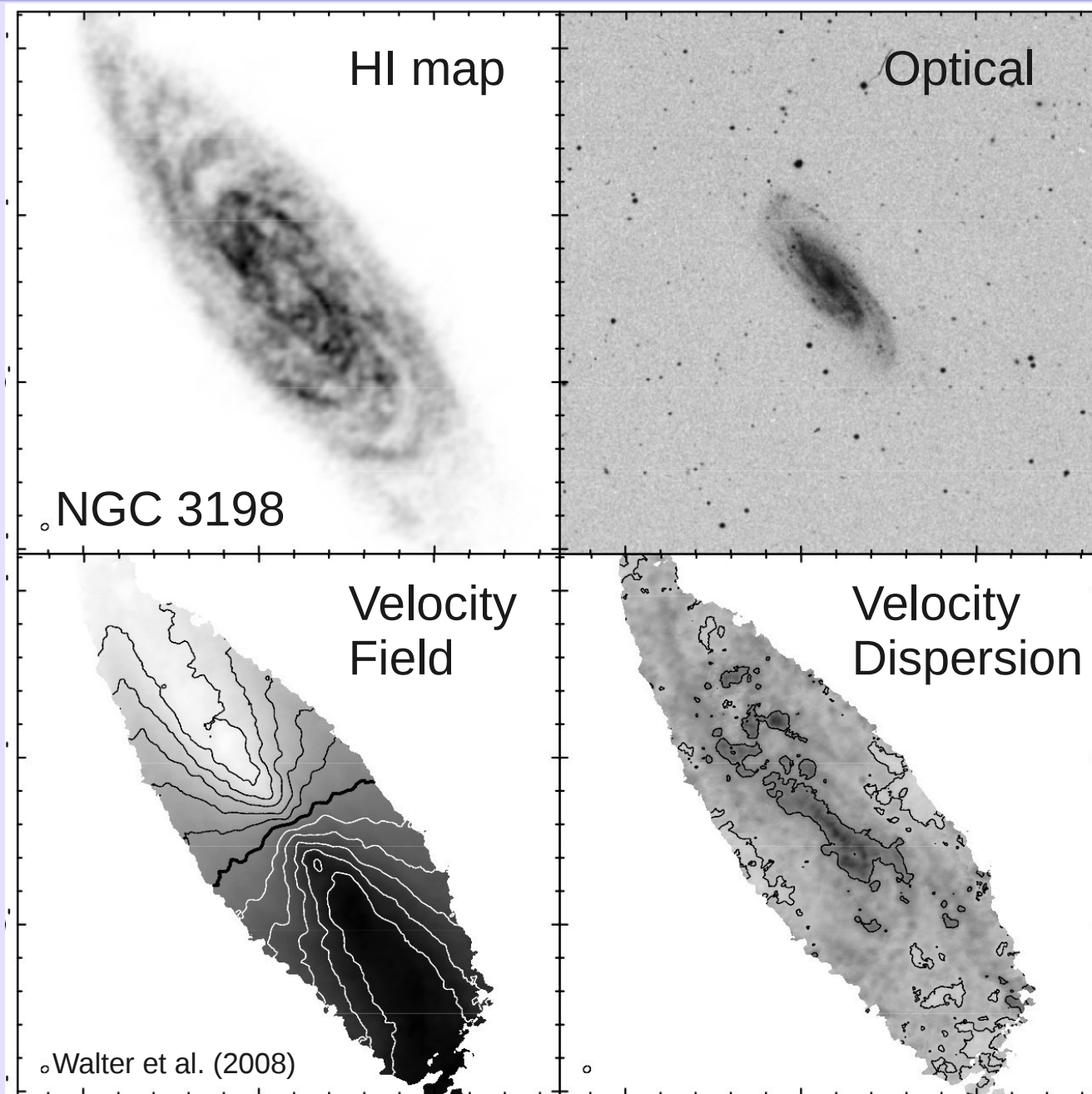


Interferometric observations
(e.g. VLA, WRST, GMRT)

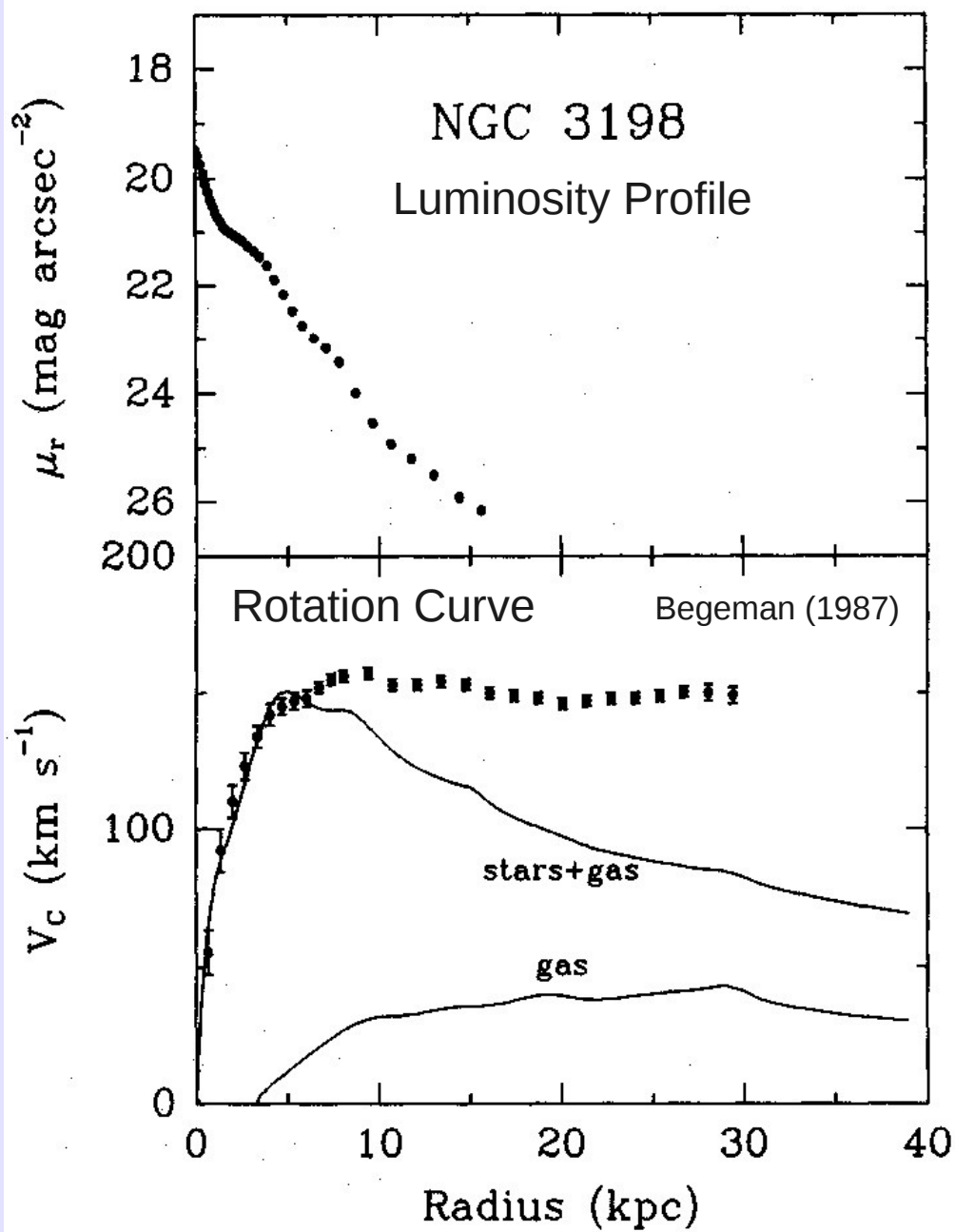


Spatially resolved
gas kinematics

HI Observations of Spiral Galaxies

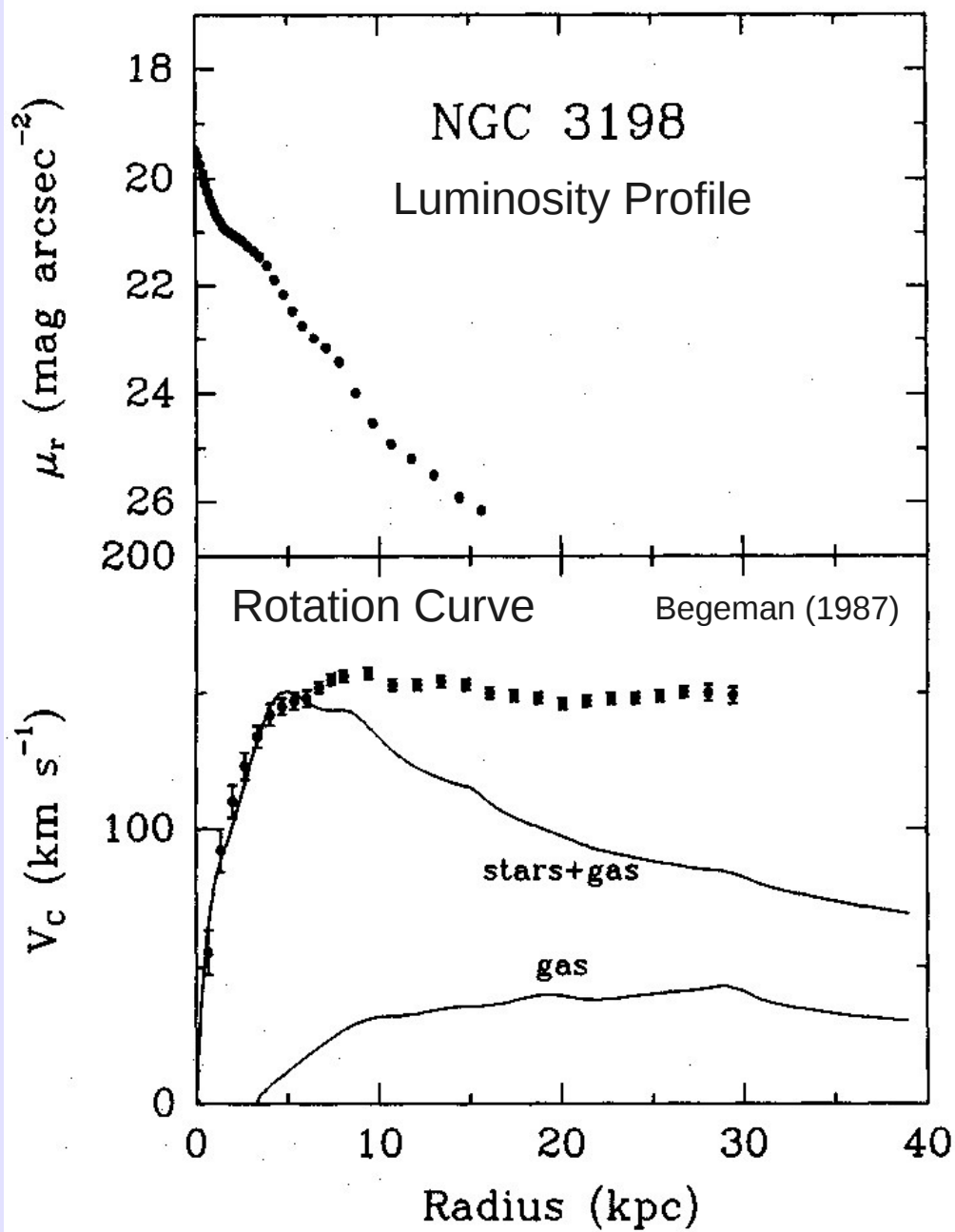


Rotation Curves of Spiral Galaxies



$$\frac{V_c(R)^2}{R} = -\frac{\partial \phi(R)}{\partial R}$$

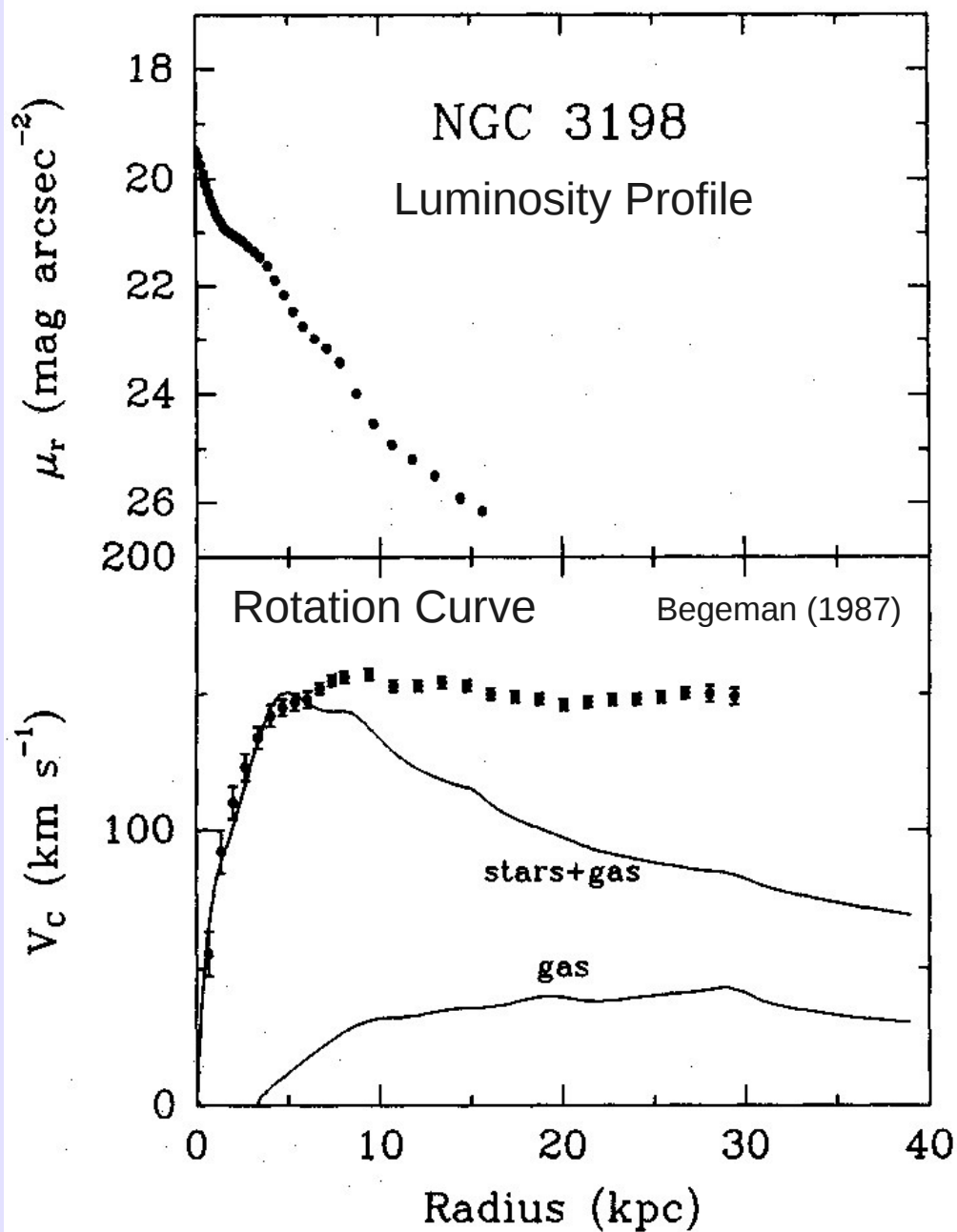
Rotation Curves of Spiral Galaxies



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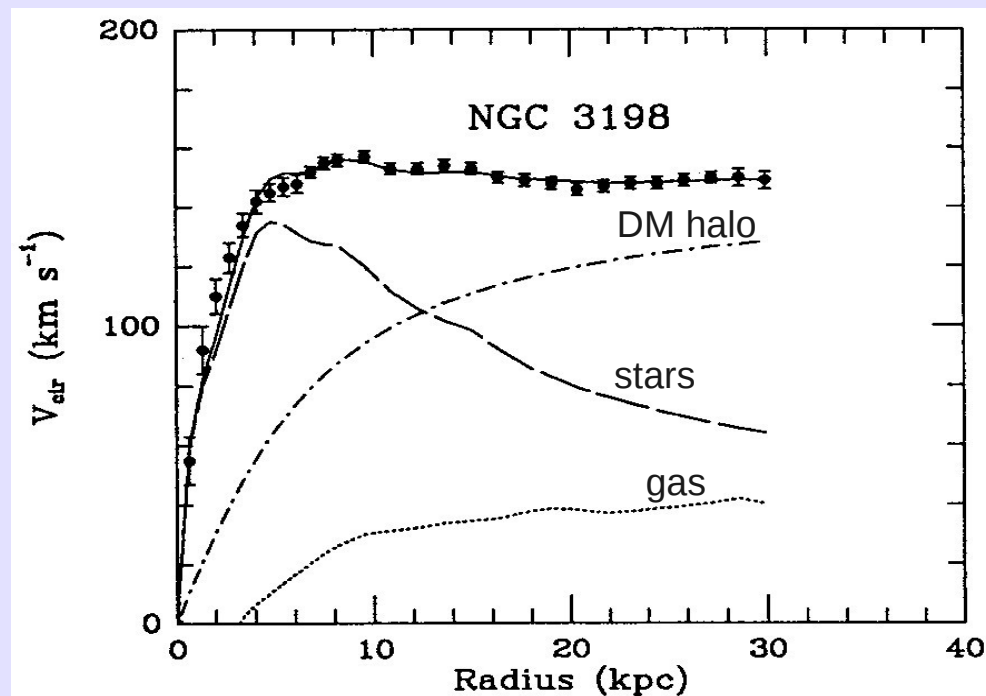
$$V_c(R)^2 = V_{\text{gas}}(R)^2 + (M_*/L) \times V_*(R)^2$$

Rotation Curves of Spiral Galaxies

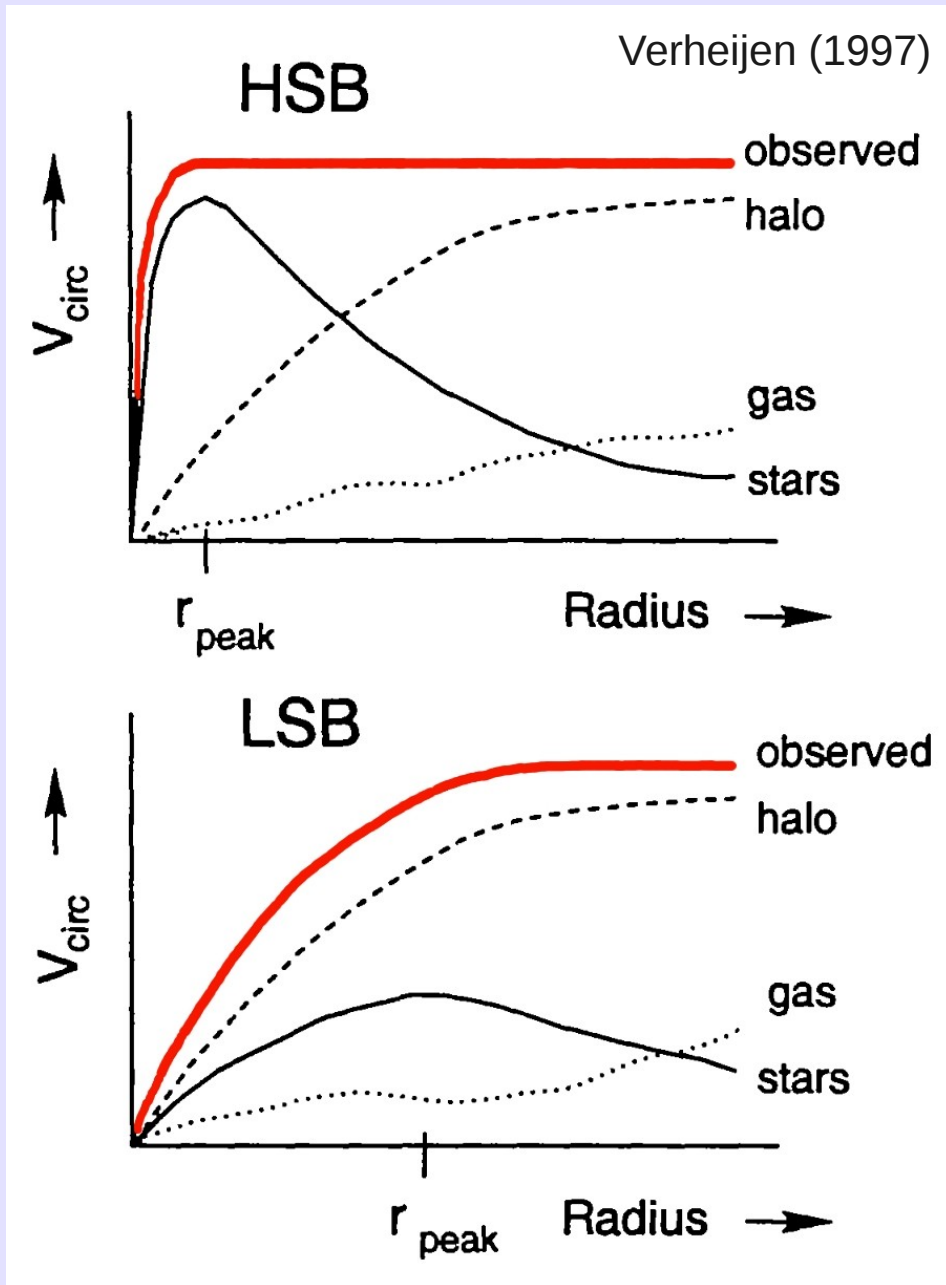


$$\frac{V_c(R)^2}{R} = -\frac{\partial \phi(R)}{\partial R}$$

$$V_c(R)^2 = V_{\text{gas}}(R)^2 + (M_*/L) \times V_*(R)^2 + V_{\text{DM}}(R; \rho_0, r_c)^2$$



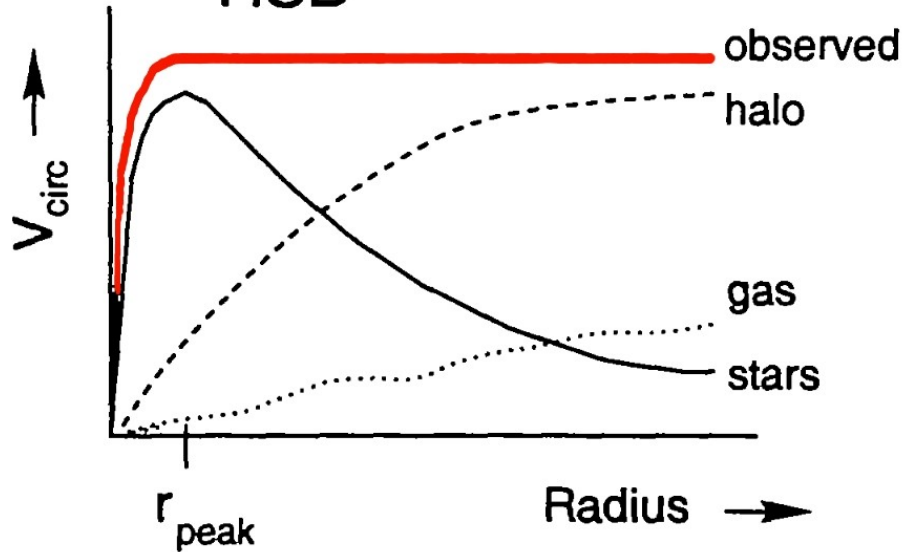
The HSB/LSB dichotomy



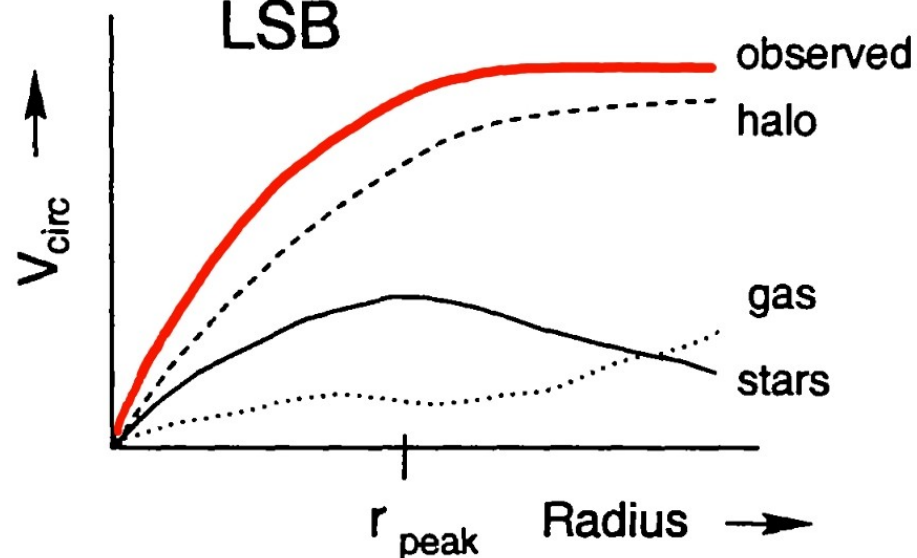
The HSB/LSB dichotomy

HSB

Verheijen (1997)



LSB



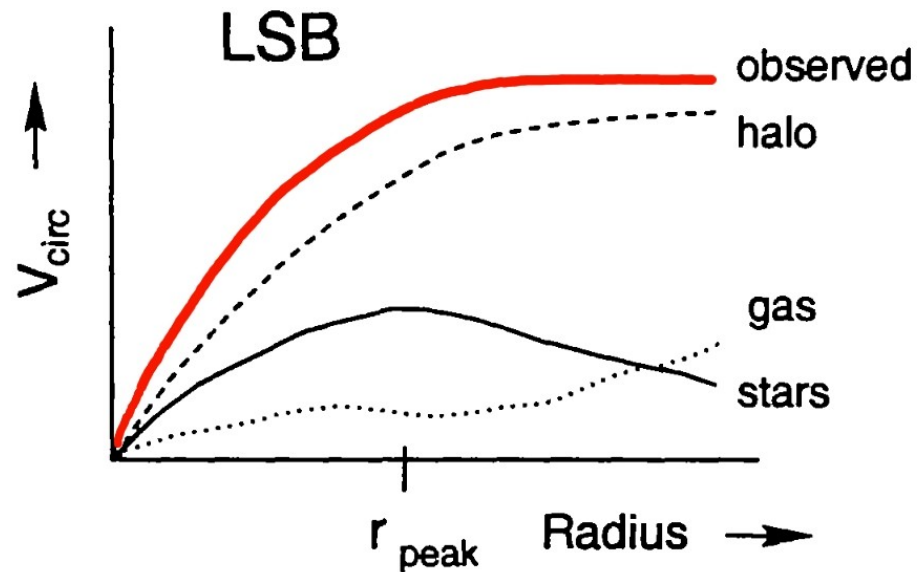
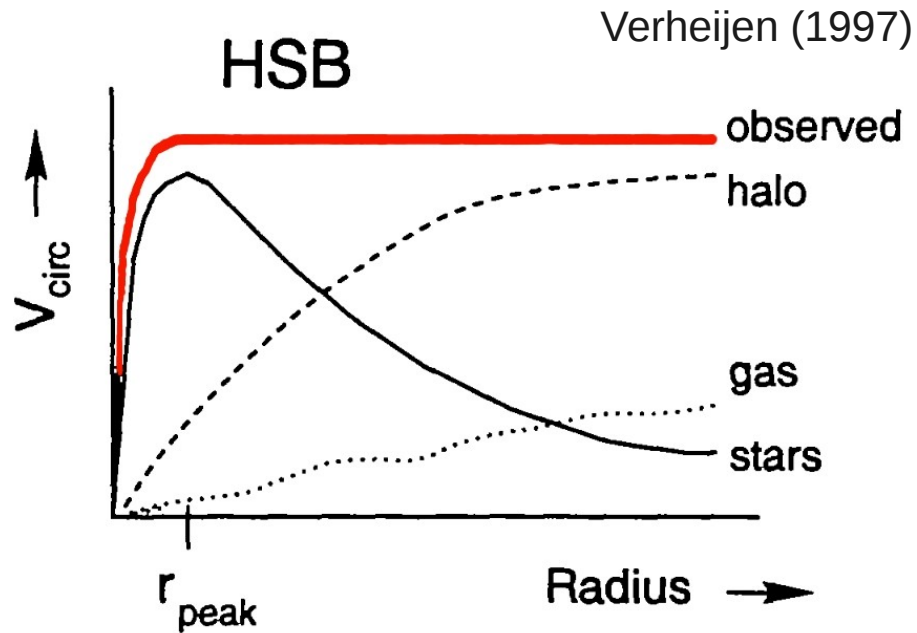
HSB galaxies:

- ✓ Steeply rising rotation curves
- ✓ Maximum disk hypothesis



Baryons dominate
inner galaxy regions

The HSB/LSB dichotomy



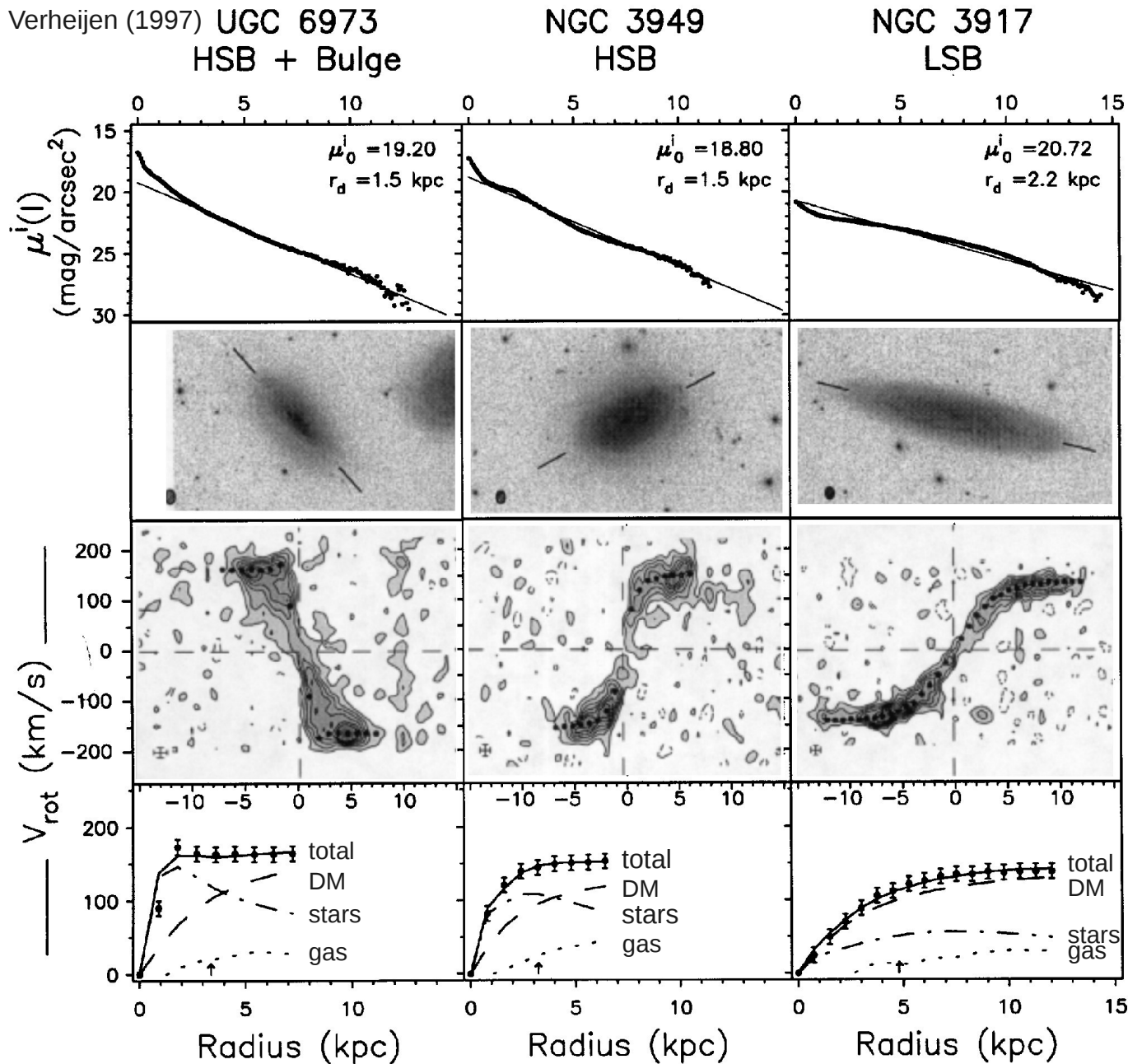
HSB galaxies:

- ✓ Steeply rising rotation curves
 - ✓ Maximum disk hypothesis
- ➔ Baryons dominate inner galaxy regions

LSB galaxies:

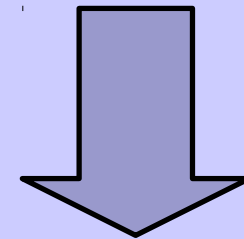
- ✓ Slowly rising rotation curves
- ✓ DM dominates everywhere

The HSB/LSB dichotomy



“RULE”:

Light Concentration
(HSB systems)



Steeply Rising
Rotation Curve
(Maximum Disk
works!)

What are Giant Low Surface Brightness Galaxies?

Why are they interesting?

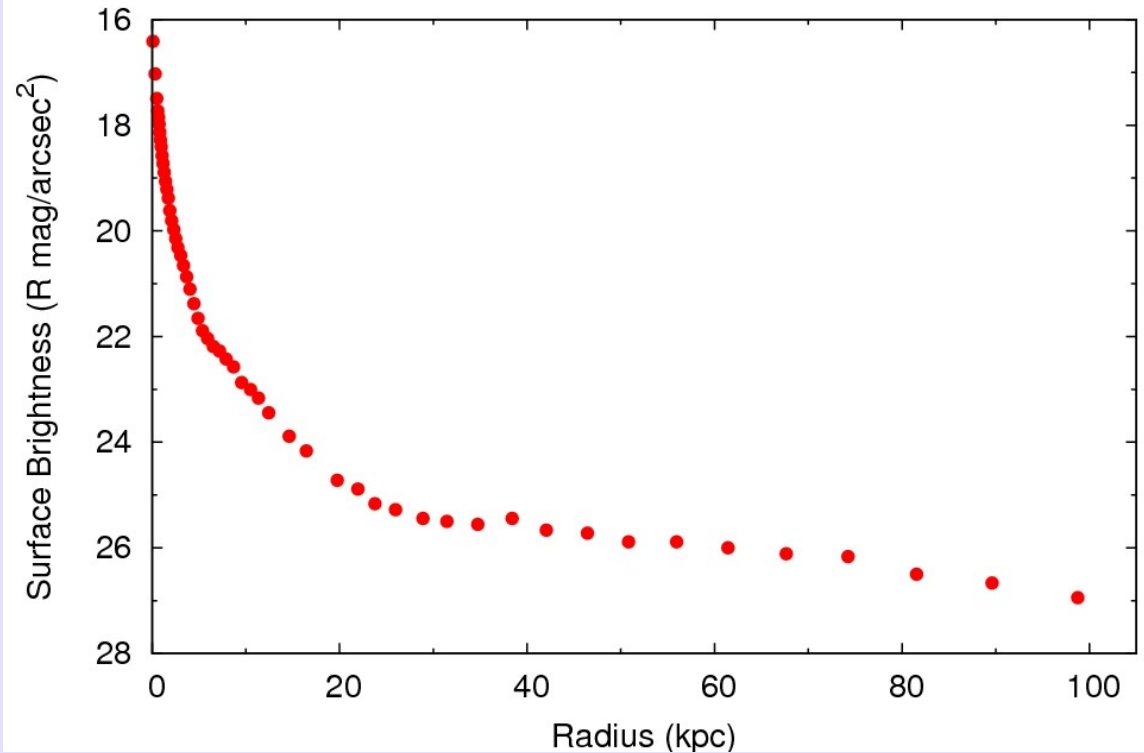
The GLSB prototype: Malin 1

R band (Moore & Parker 2006)

~100 kpc

$D_A = 322 \text{ Mpc}$ ($z = 0.083$)

MALIN 1 SURFACE BRIGHTNESS - R BAND



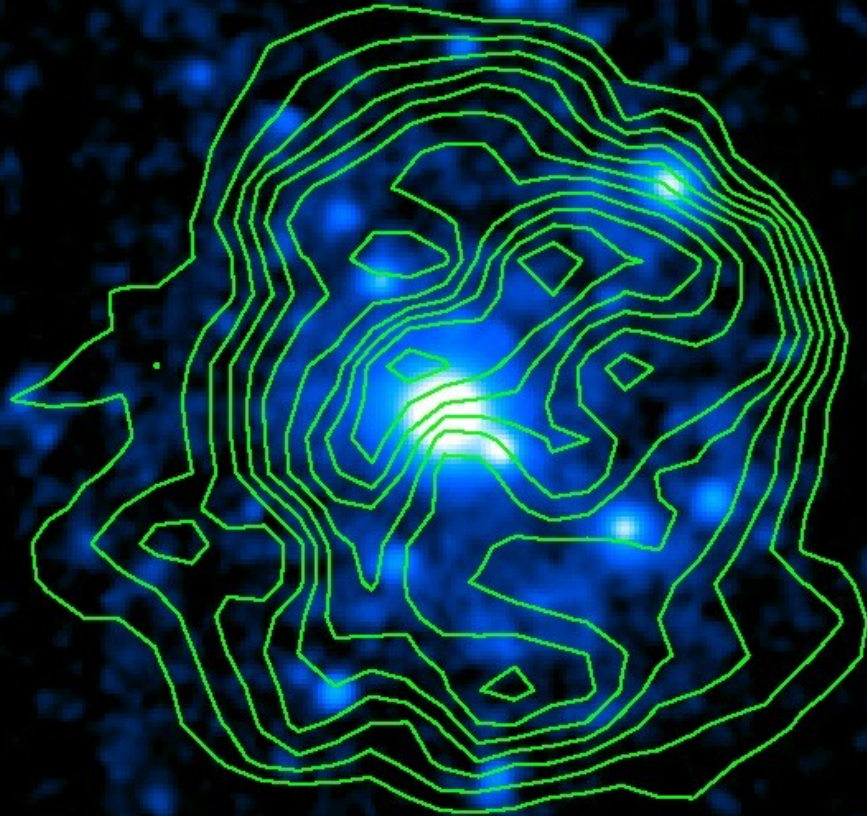
LSB disk from ~20 to ~100 kpc!

$M_B = -22 \text{ mag}$

$M_{\text{HI}} = 6.7 \times 10^{10} \text{ Msun}$

The GLSB prototype: Malin 1

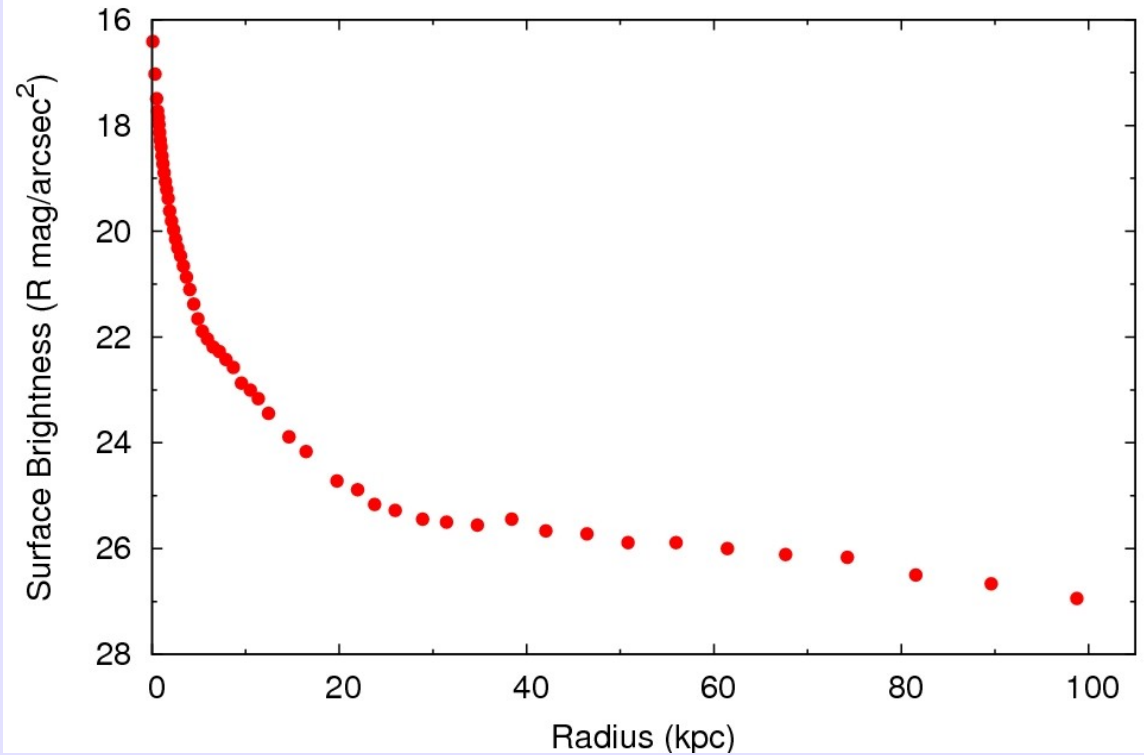
HI map



~100 kpc

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MALIN 1 SURFACE BRIGHTNESS - R BAND



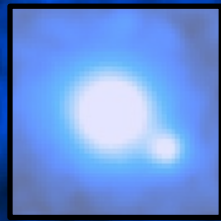
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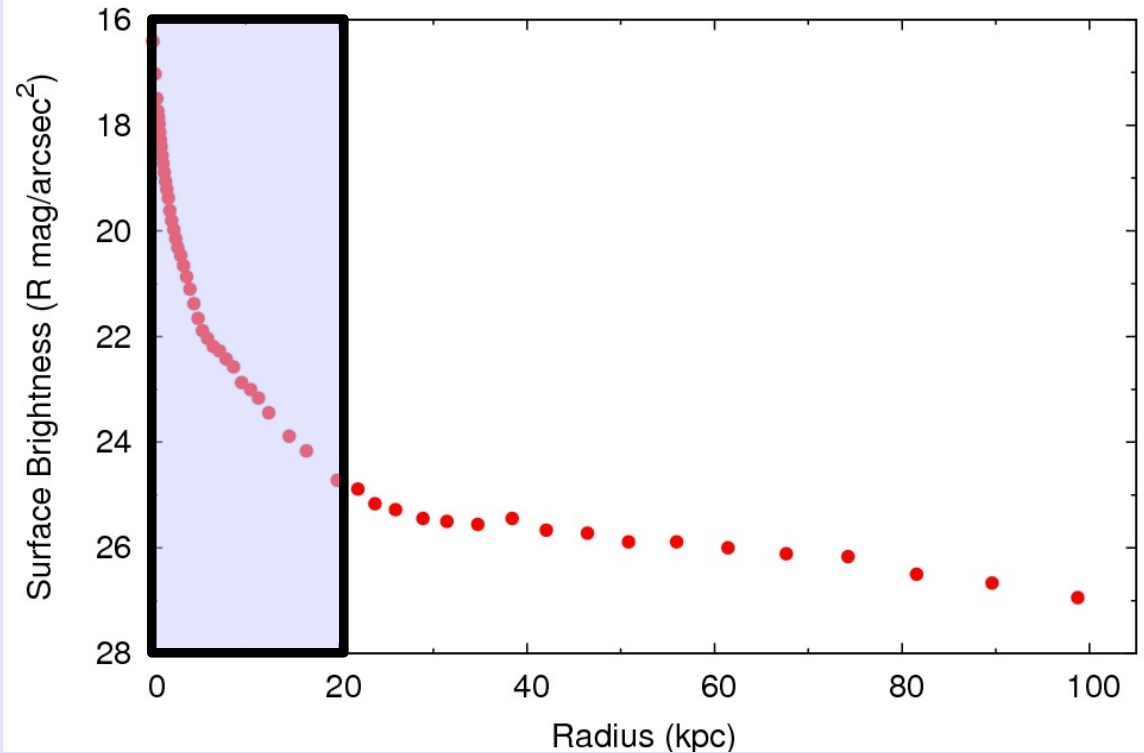
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MALIN 1 SURFACE BRIGHTNESS - R BAND



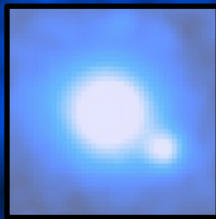
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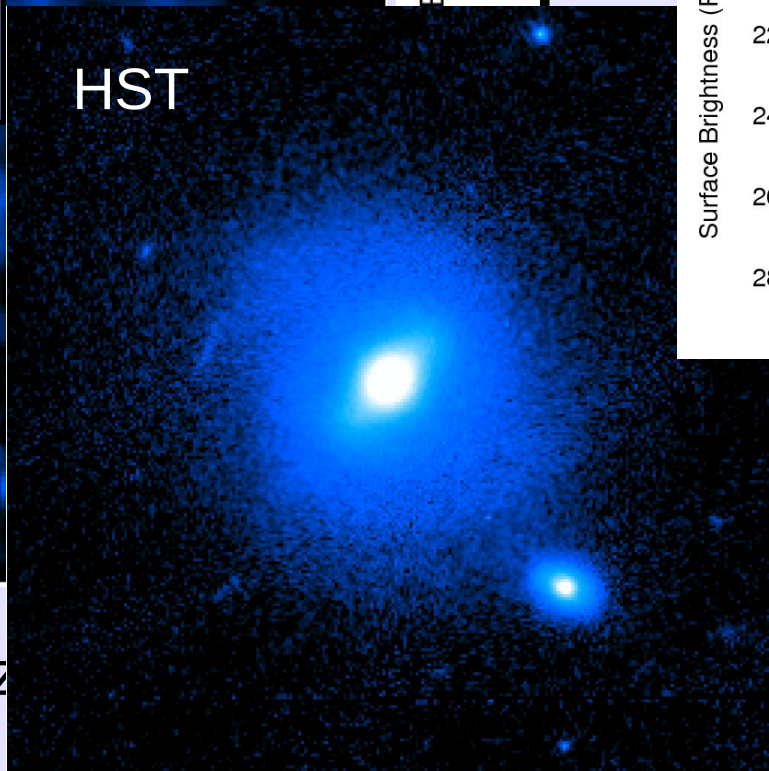
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The GLSB prototype: Malin 1

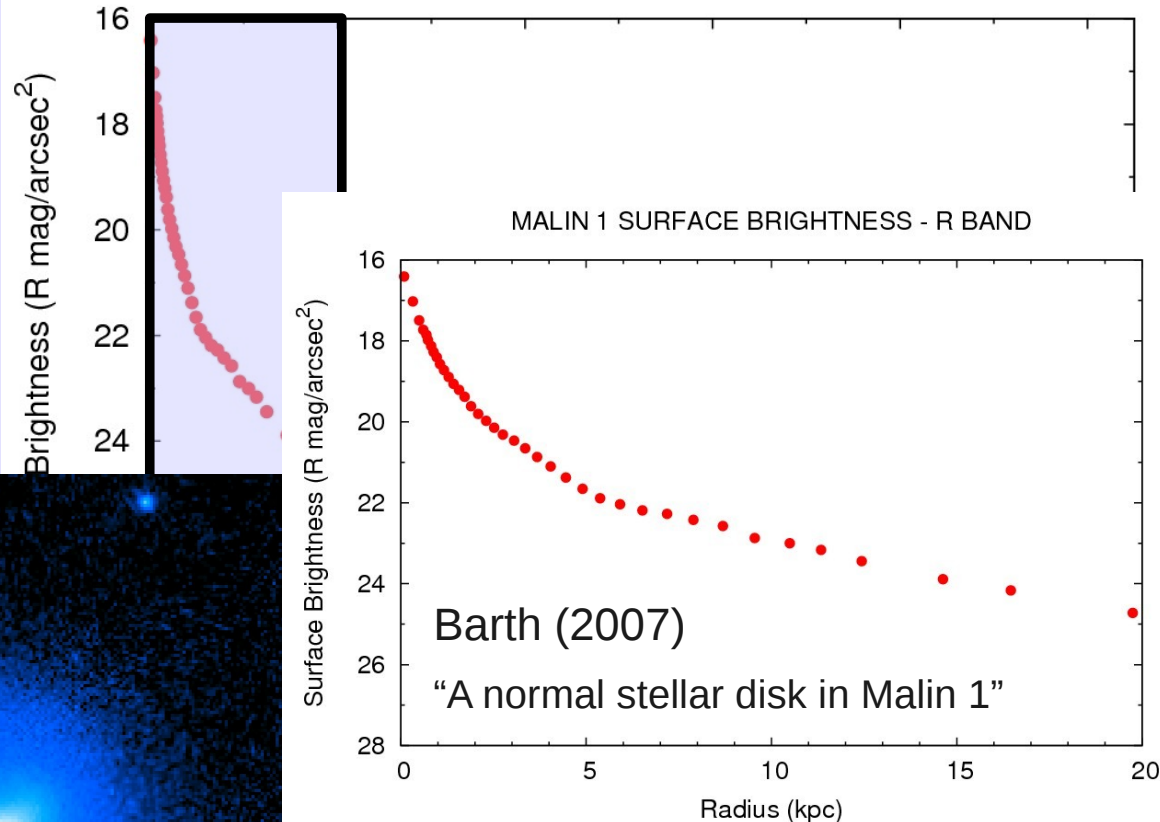
R band (Moore & Parker 2006)



HST



MALIN 1 SURFACE BRIGHTNESS - R BAND



Barth (2007)

“A normal stellar disk in Malin 1”

from ~20 to ~100 kpc!

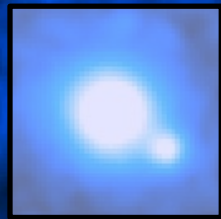
mag

$$D_A = 322 \text{ Mpc} \quad (z = 0.025)$$

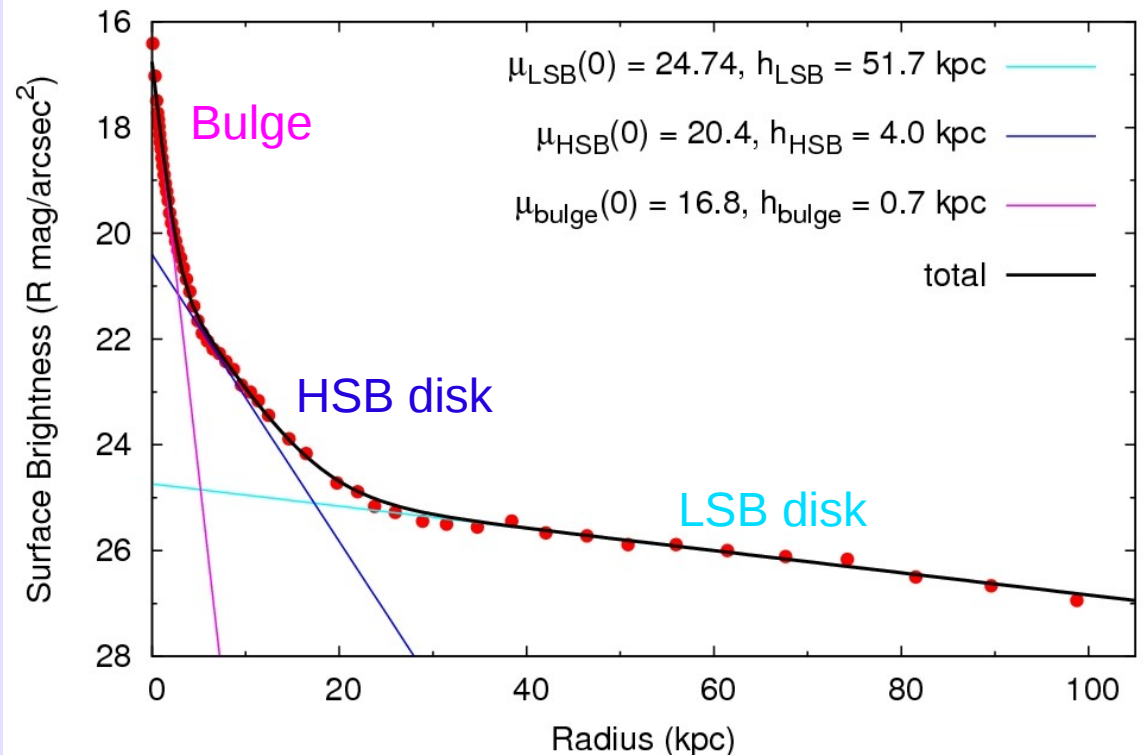
$$7 \times 10^{10} \text{ Msun}$$

The GLSB prototype: Malin 1

R band (Moore & Parker 2006)



MALIN 1 SURFACE BRIGHTNESS - R BAND



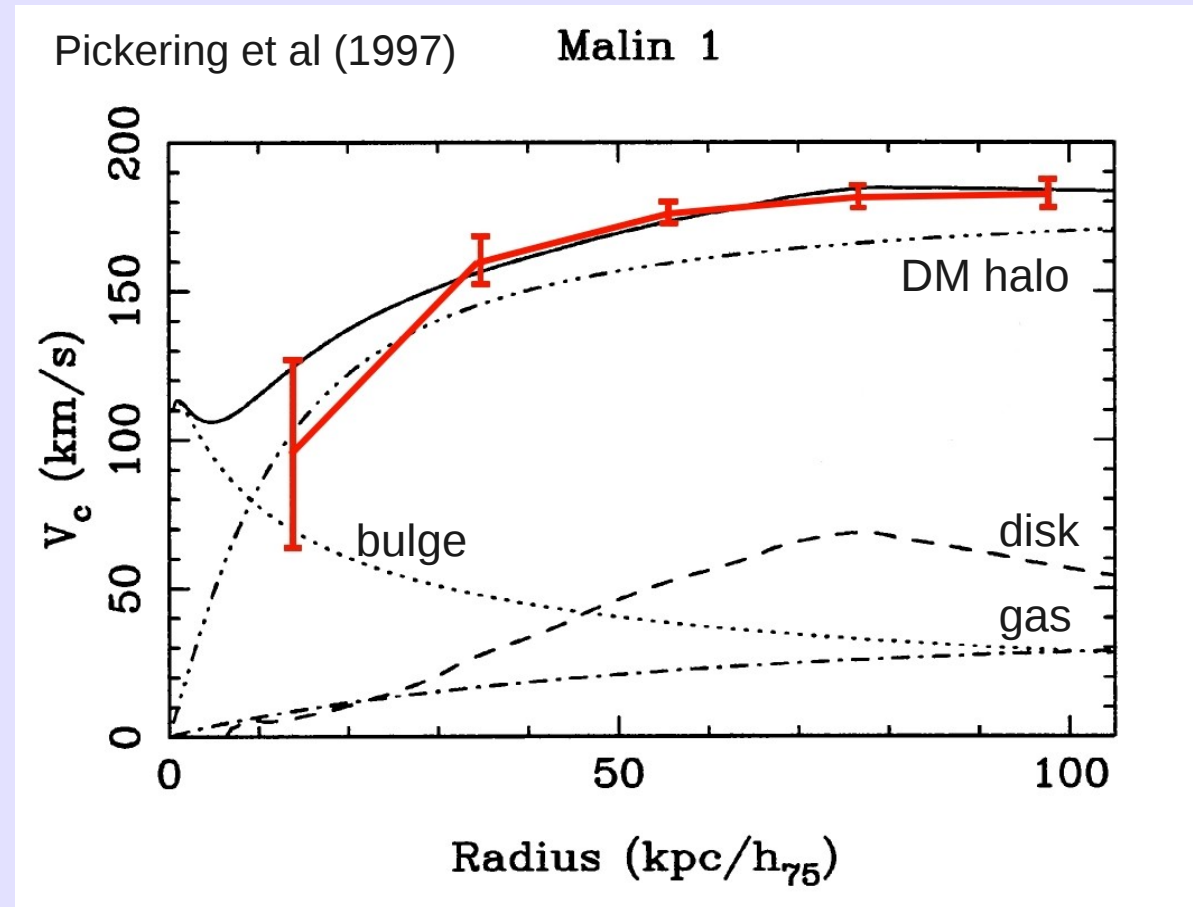
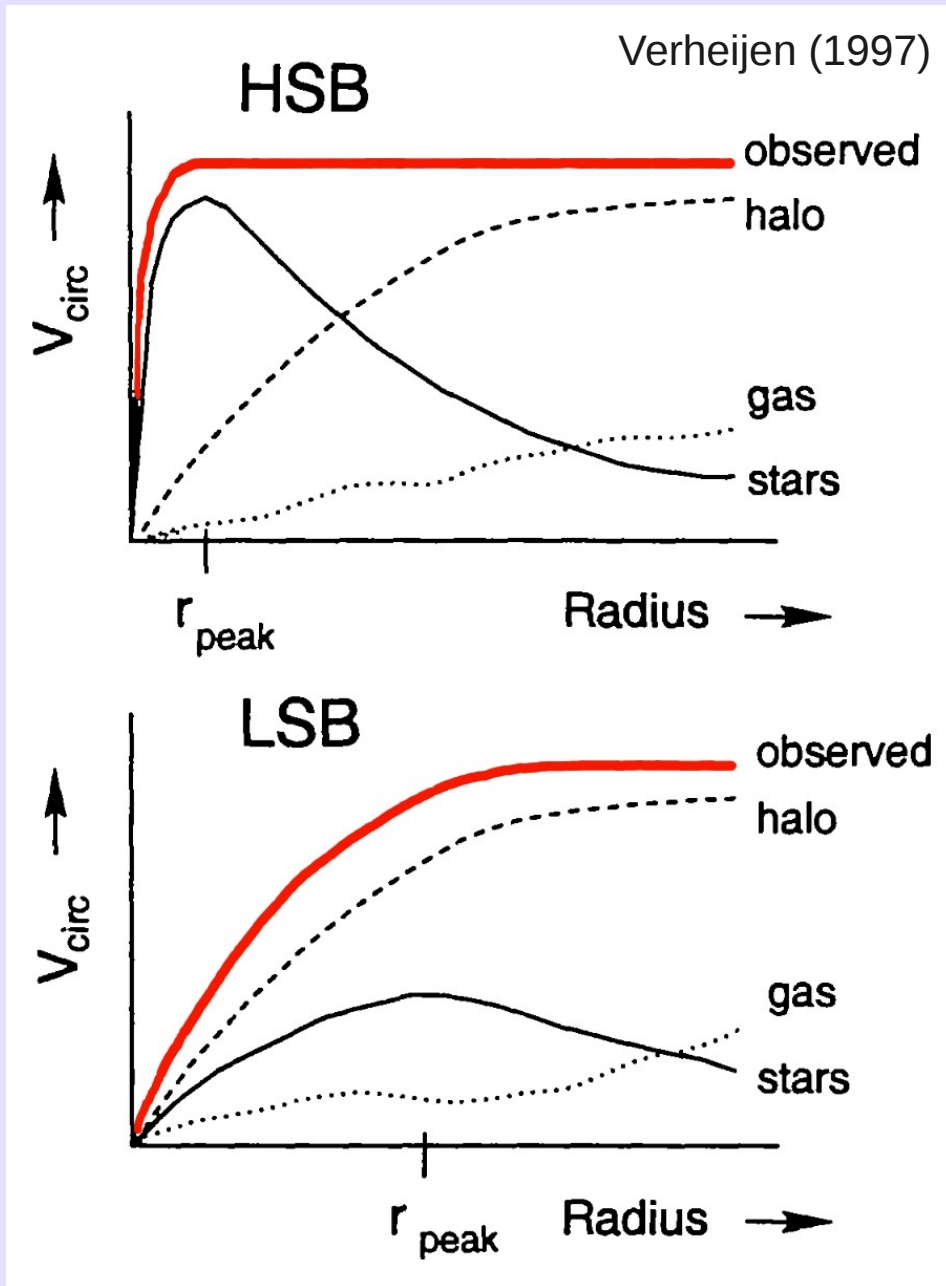
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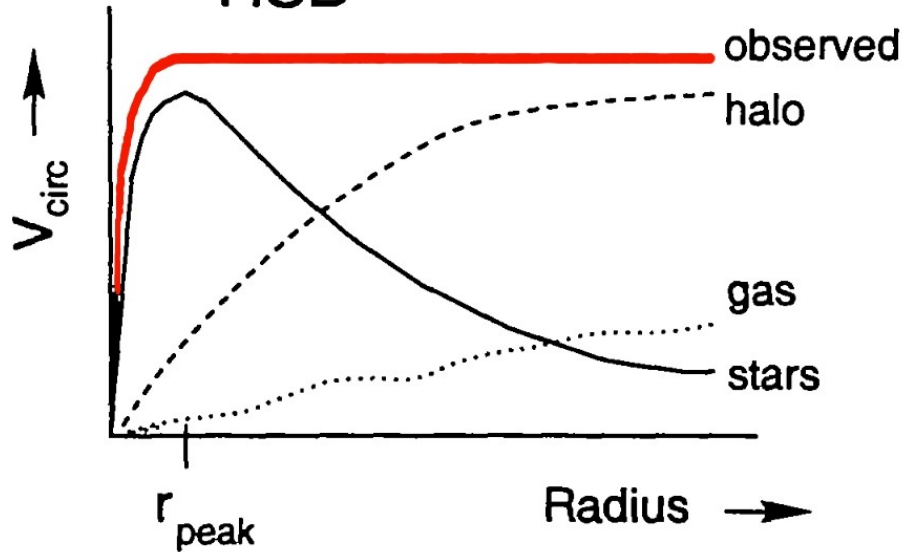
Previous Dynamical Studies



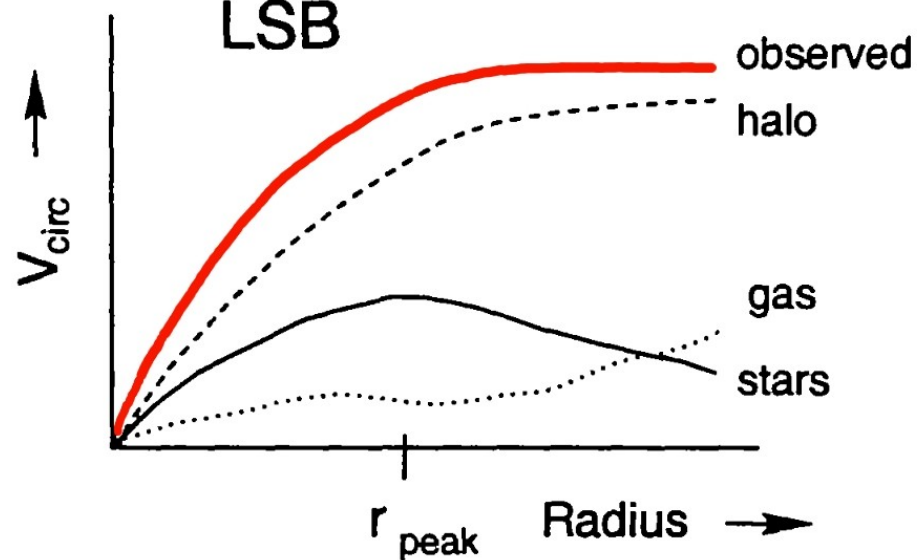
Previous Dynamical Studies

HSB

Verheijen (1997)

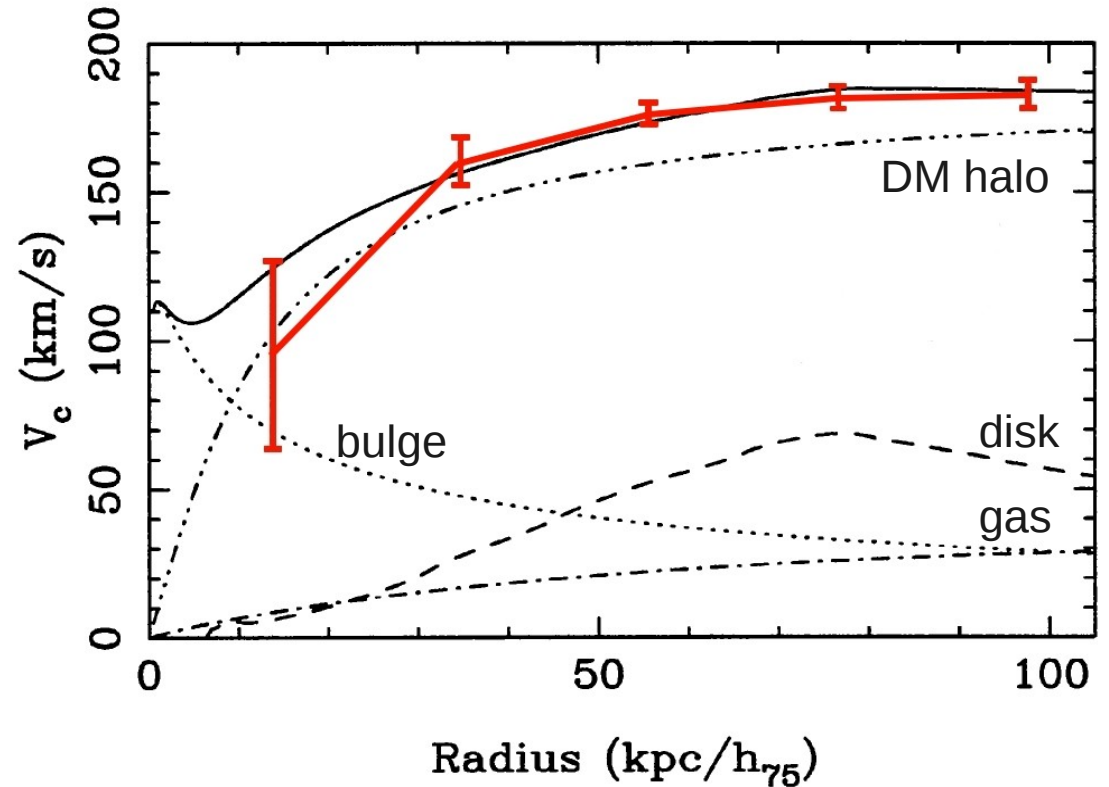


LSB



Pickering et al (1997)

Malin 1



Exception to the rule???

Light and dark matter are not linked?

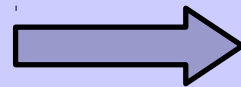
Re-Analysis of VLA data



Re-Analysis of VLA data

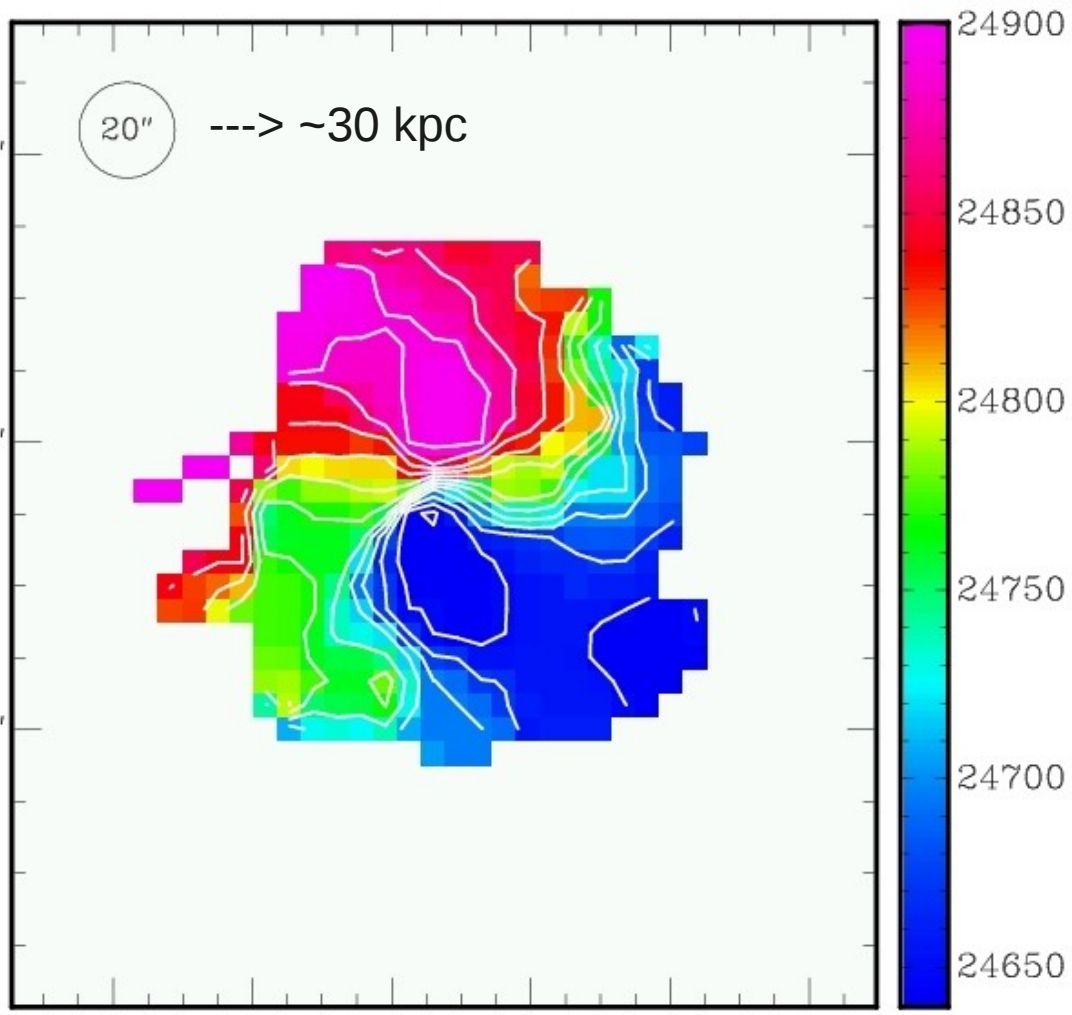


C-Array Config.



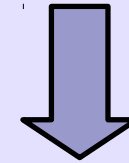
Low Spatial Resolution

New Velocity Field for Malin 1

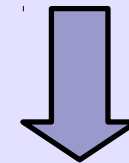


Velocity along the *line of sight*:

$$V(x,y) = V_{\text{sys}} + V_C(R)\sin(i)\cos(\vartheta)$$

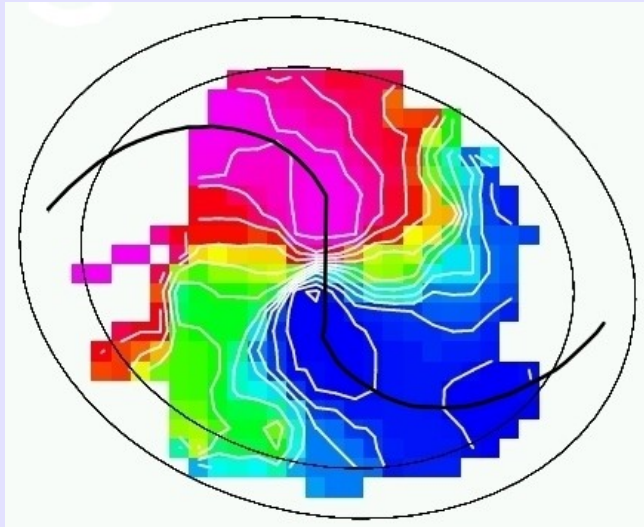


Tilted Ring Model

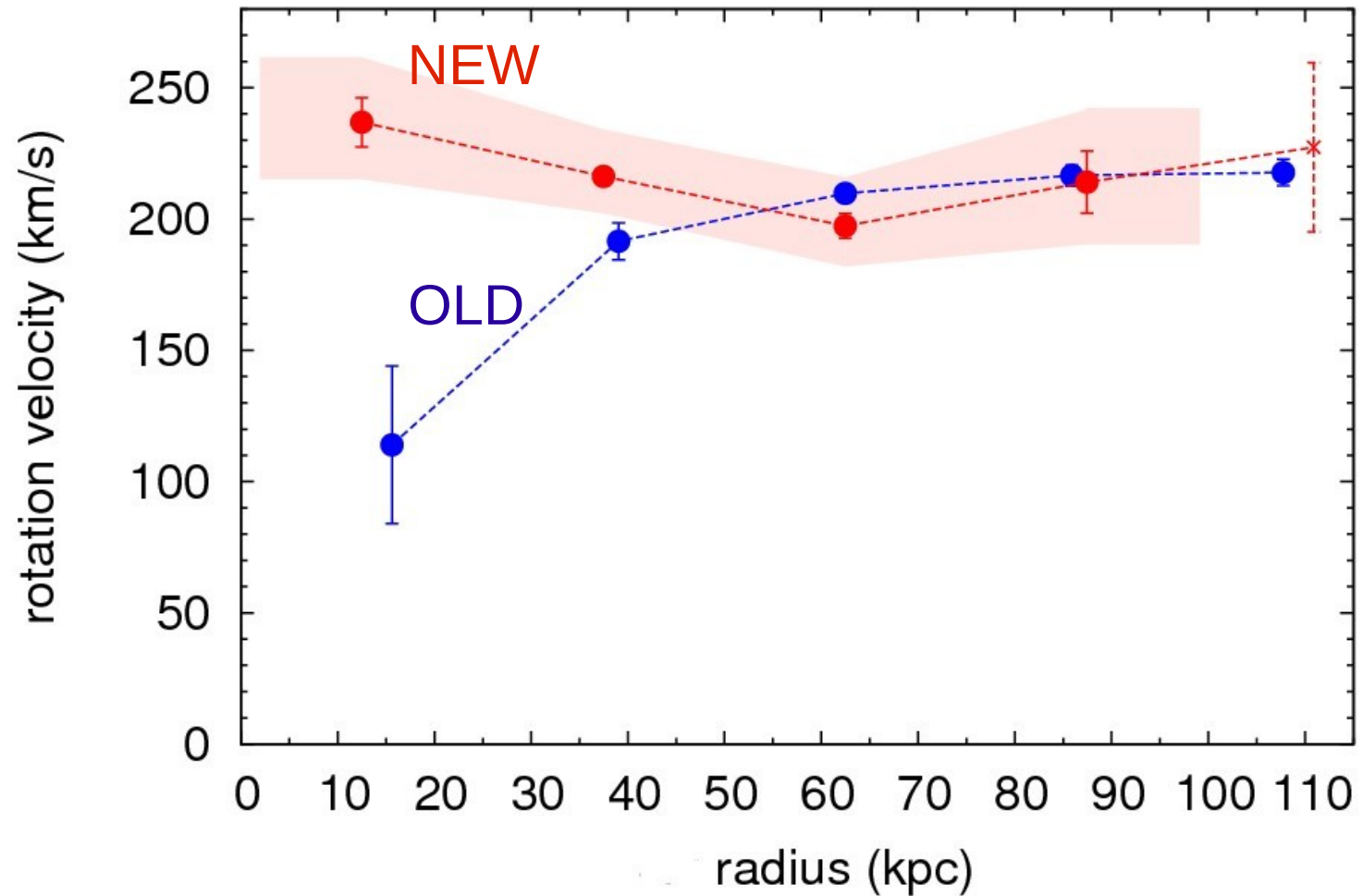


Rotation Curve

New Rotation Curve for Malin 1



$M_{\text{dyn}} \sim 2 \cdot 10^{12} \text{ Msun}$



3-D Kinematical Models

Main Ingredients:

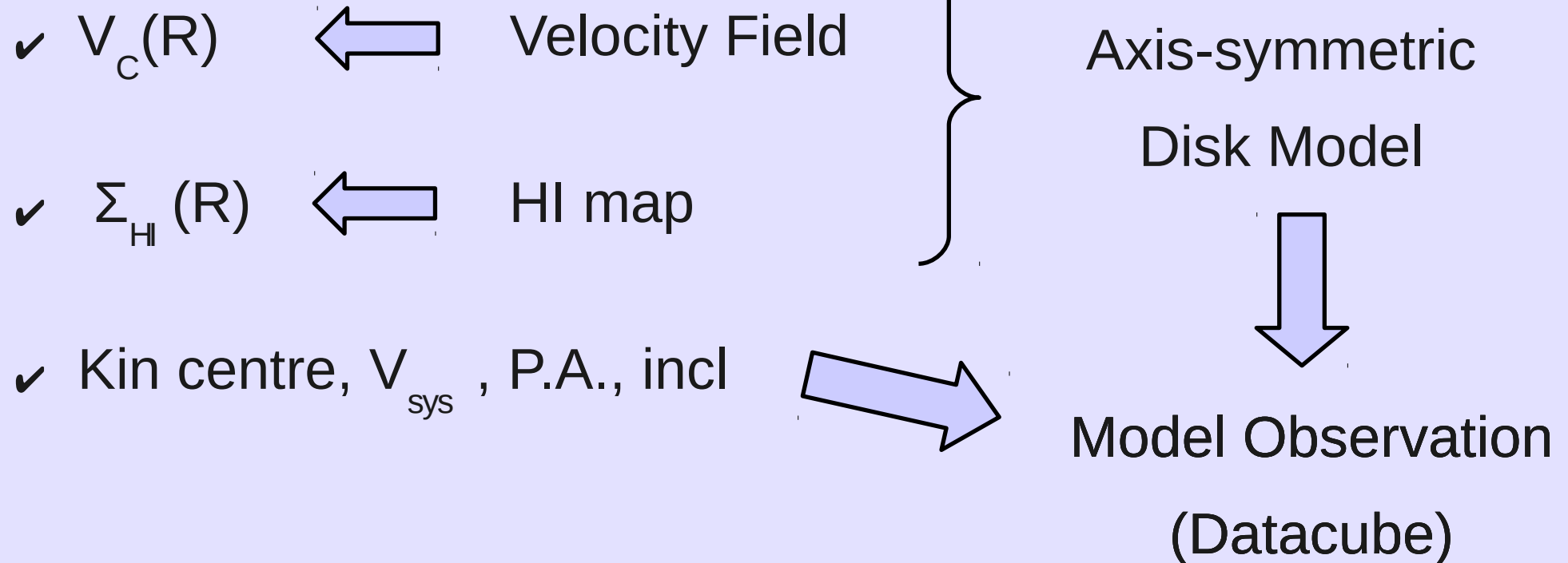
✓ $V_c(R)$ ← Velocity Field

✓ $\Sigma_H(R)$ ← HI map

✓ Kin centre, V_{sys} , P.A., incl

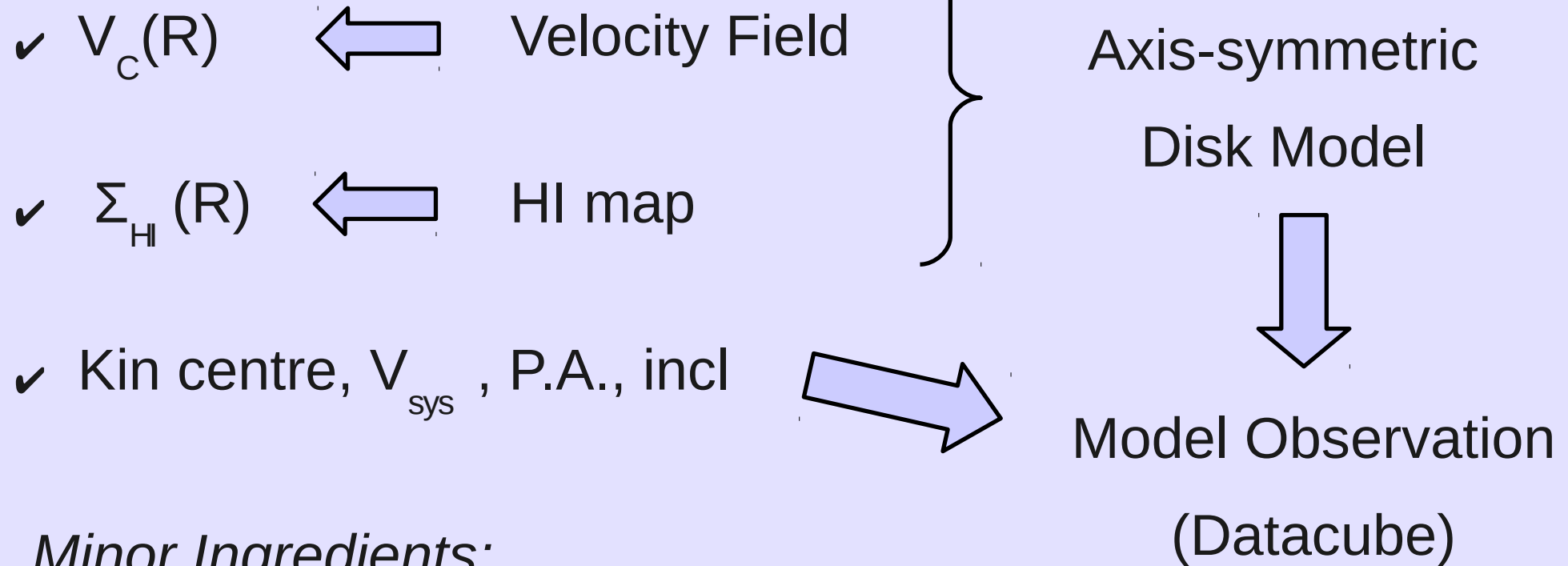
3-D Kinematical Models

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3-D Kinematical Models

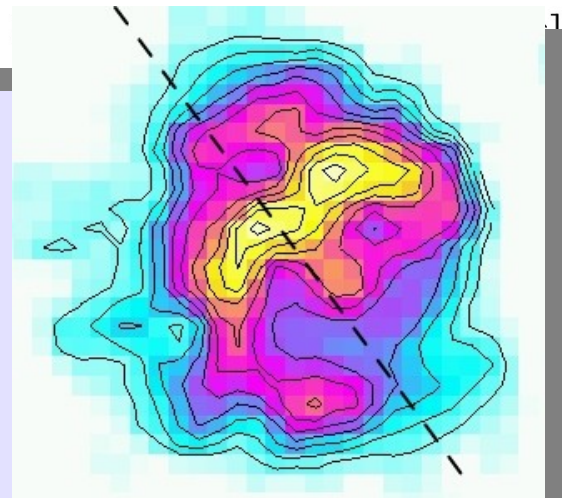
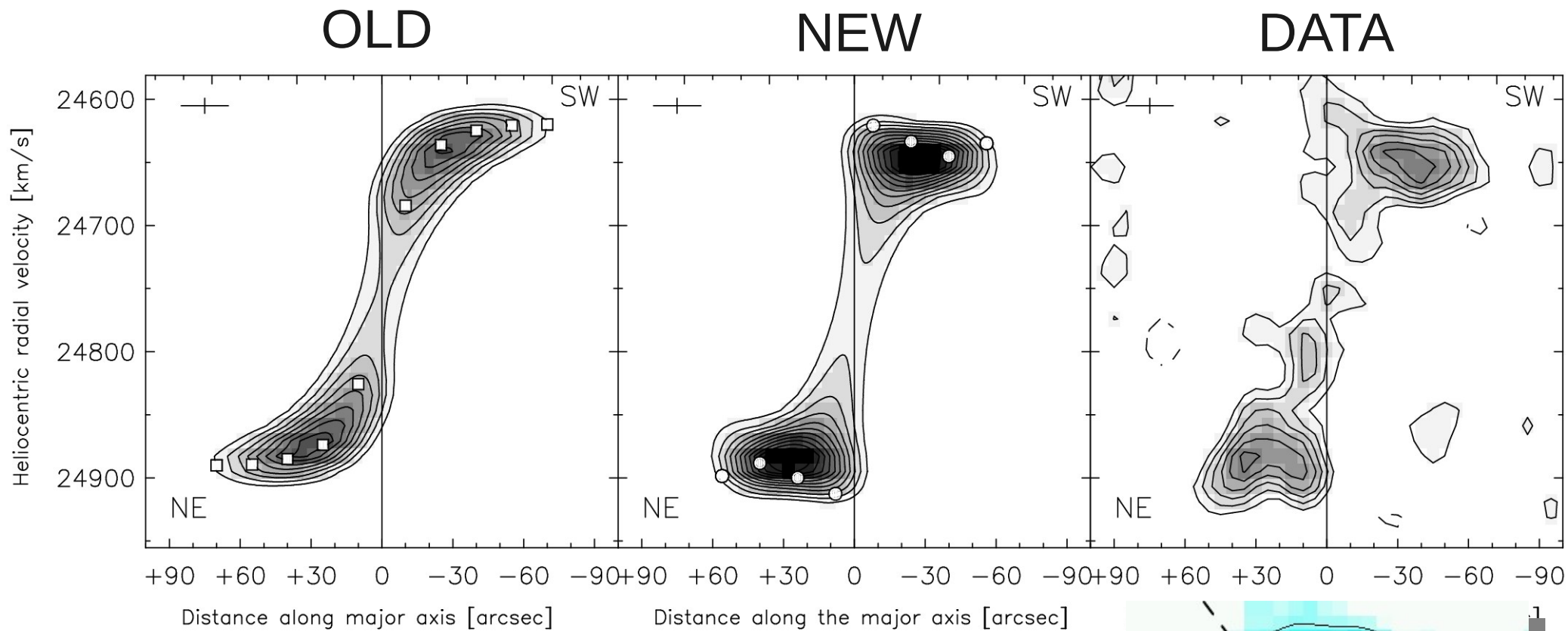
Main Ingredients:



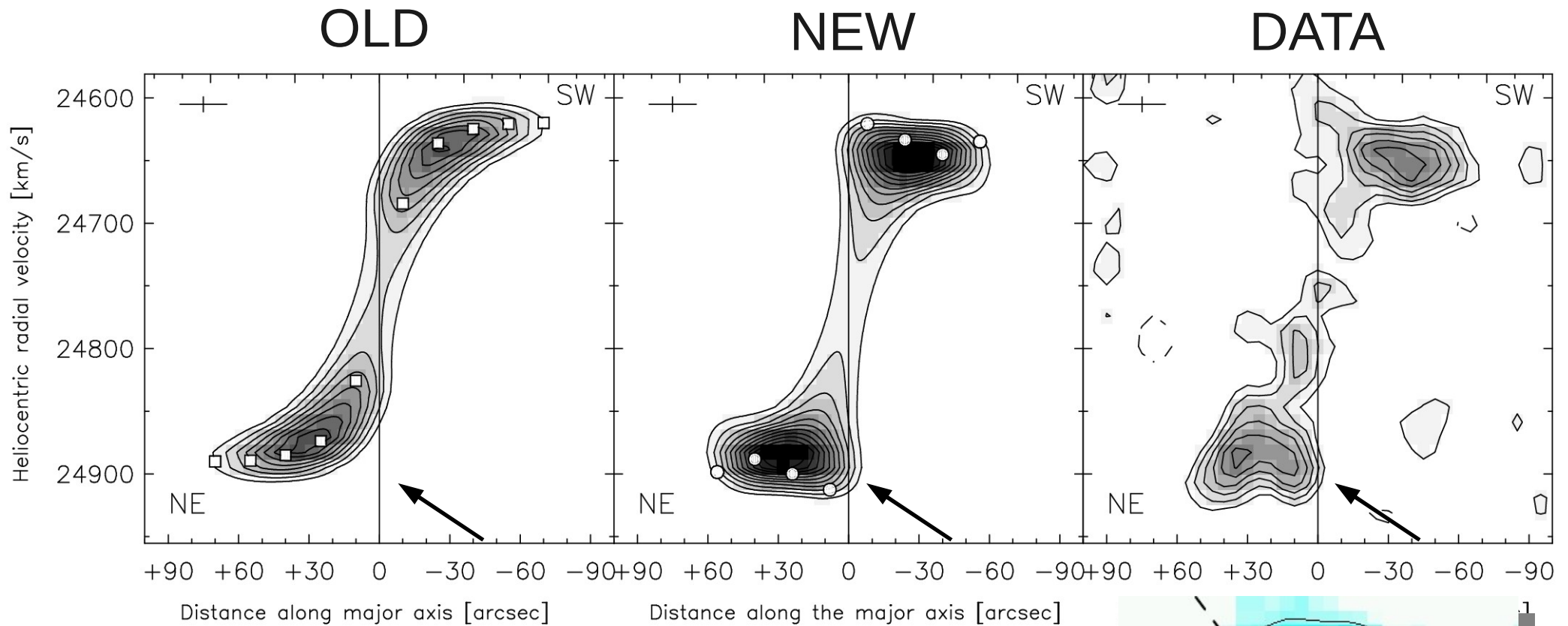
Minor Ingredients:

- ✓ $\sigma_H = 8 \text{ km/s}$
- ✓ $\rho_z(R, z) \sim \exp(z/h_z)$ $h_z = 200 \text{ pc}$

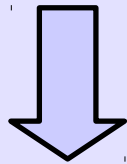
Malin 1 Model Datacubes



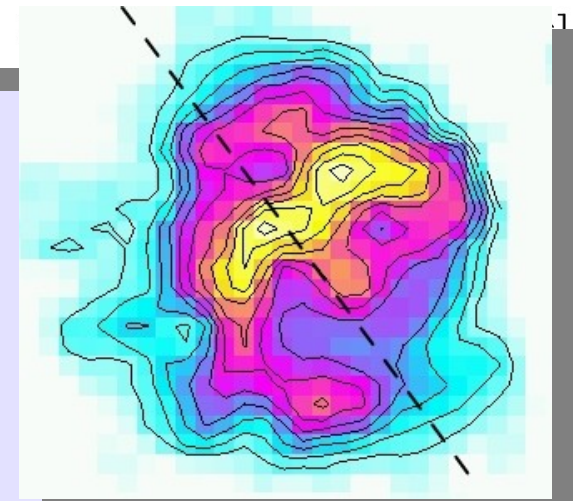
Malin 1 Model Datacubes



New Rotation Curve

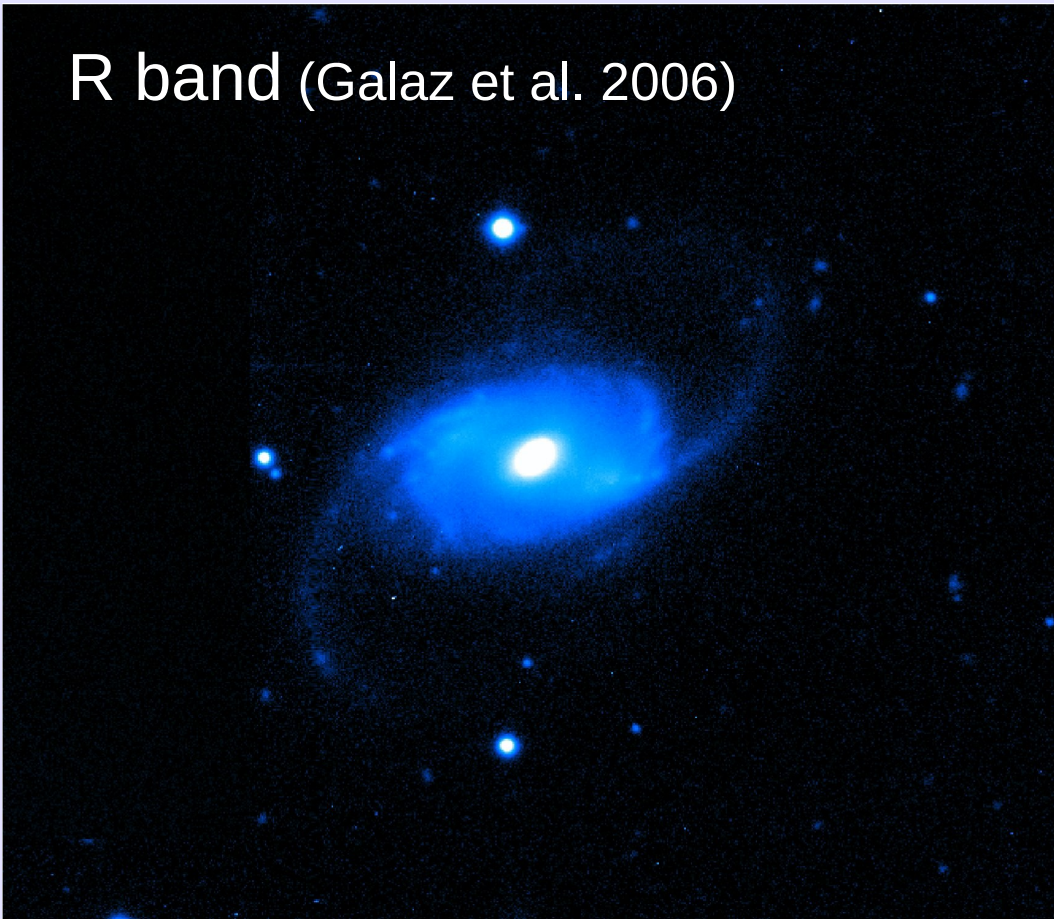


Better reproduction of the Data-Cube

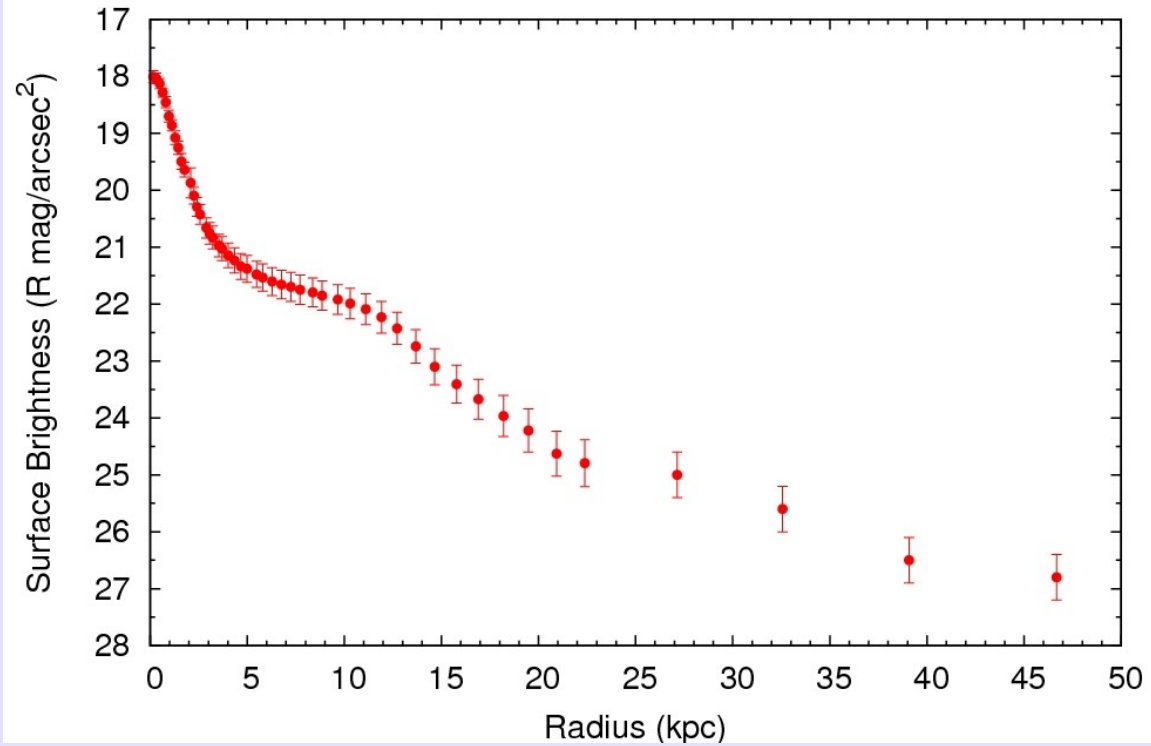


NGC 7589 – Optical Properties

R band (Galaz et al. 2006)



NGC 7589 SURFACE BRIGHTNESS - R BAND



$$V_{\text{sys}} = 8926 \text{ km/s}$$

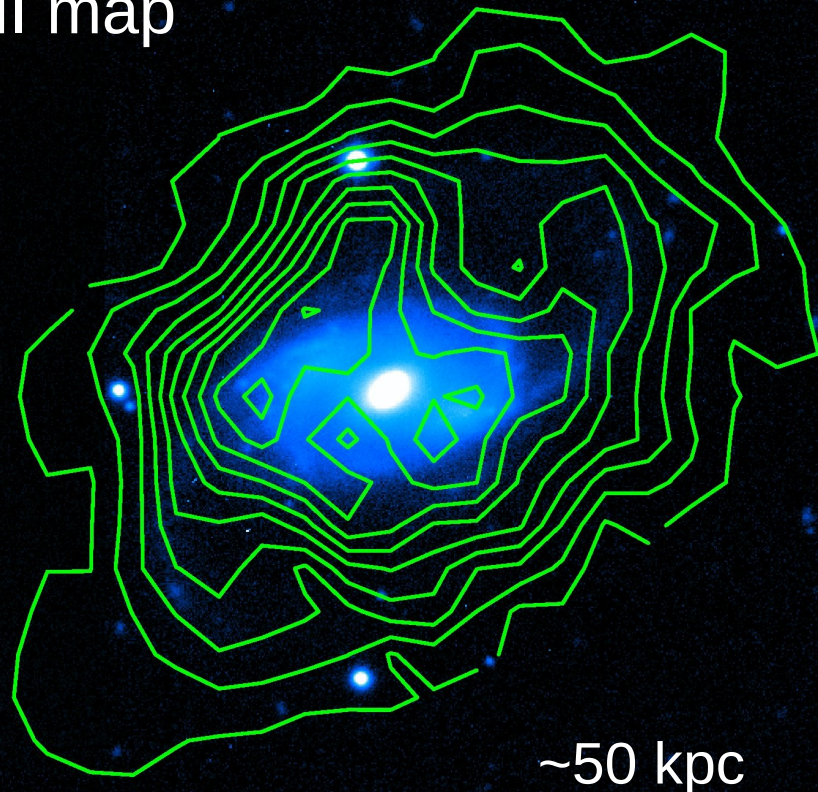
$$D_A = 122.7 \text{ Mpc} \quad (z = 0.03)$$

$$M_B = -19.87 \text{ mag} \quad (\text{Galaz et al 2006})$$

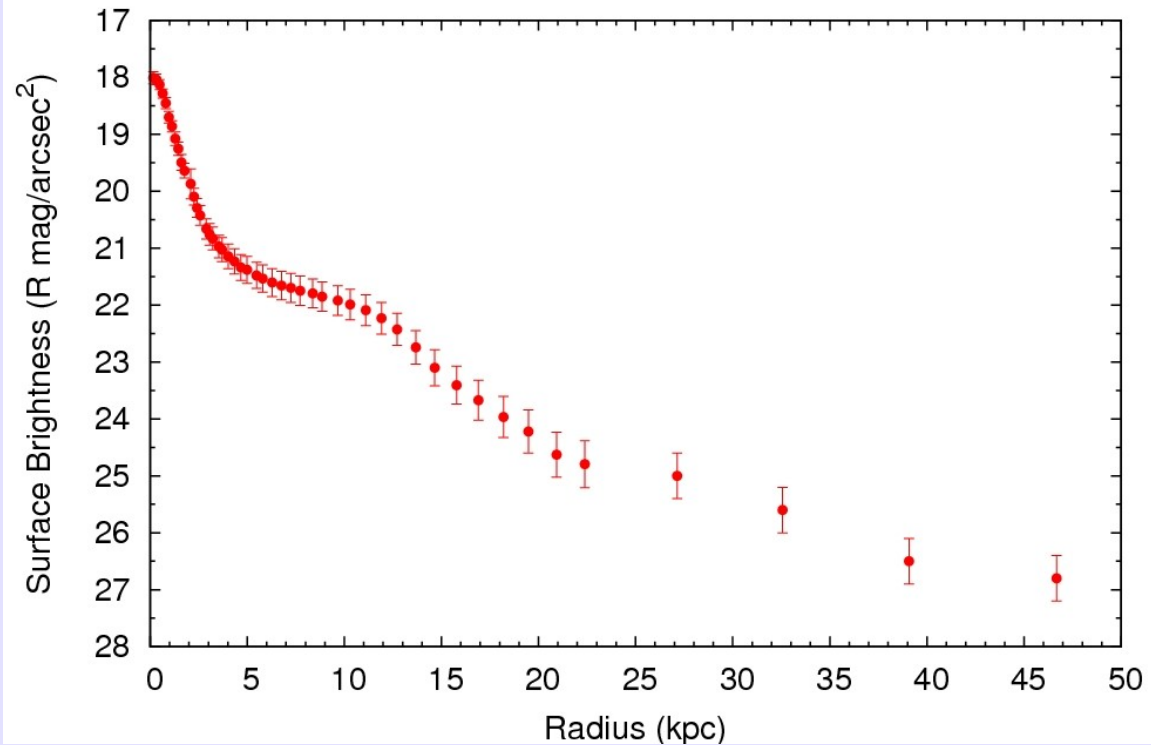
$$M_{\text{HI}} = 1.5 \pm 0.4 \times 10^{10} \text{ Msun}$$

NGC 7589 – Optical Properties

HI map



NGC 7589 SURFACE BRIGHTNESS - R BAND



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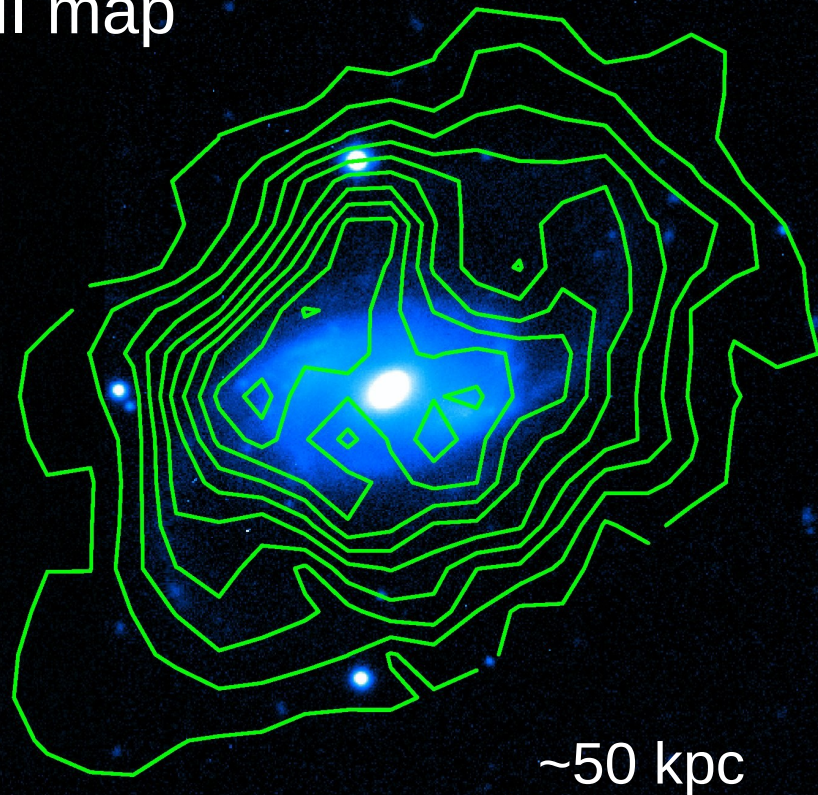
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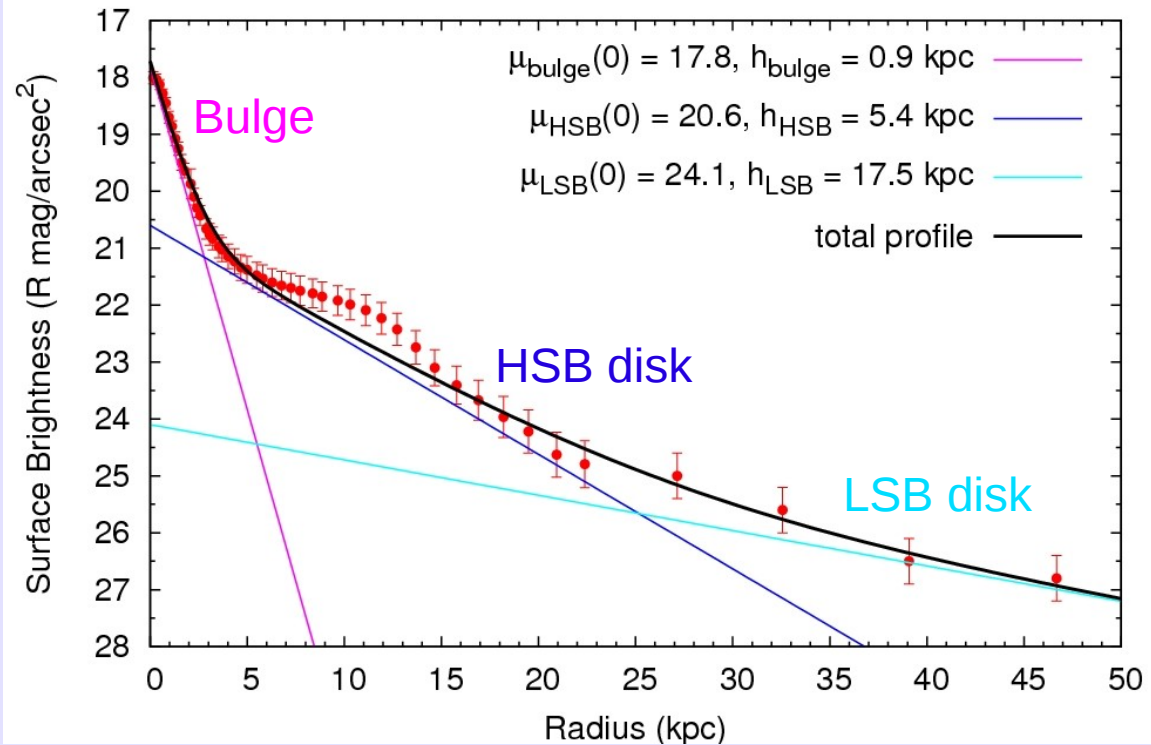
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NGC 7589 SURFACE BRIGHTNESS - R BAND



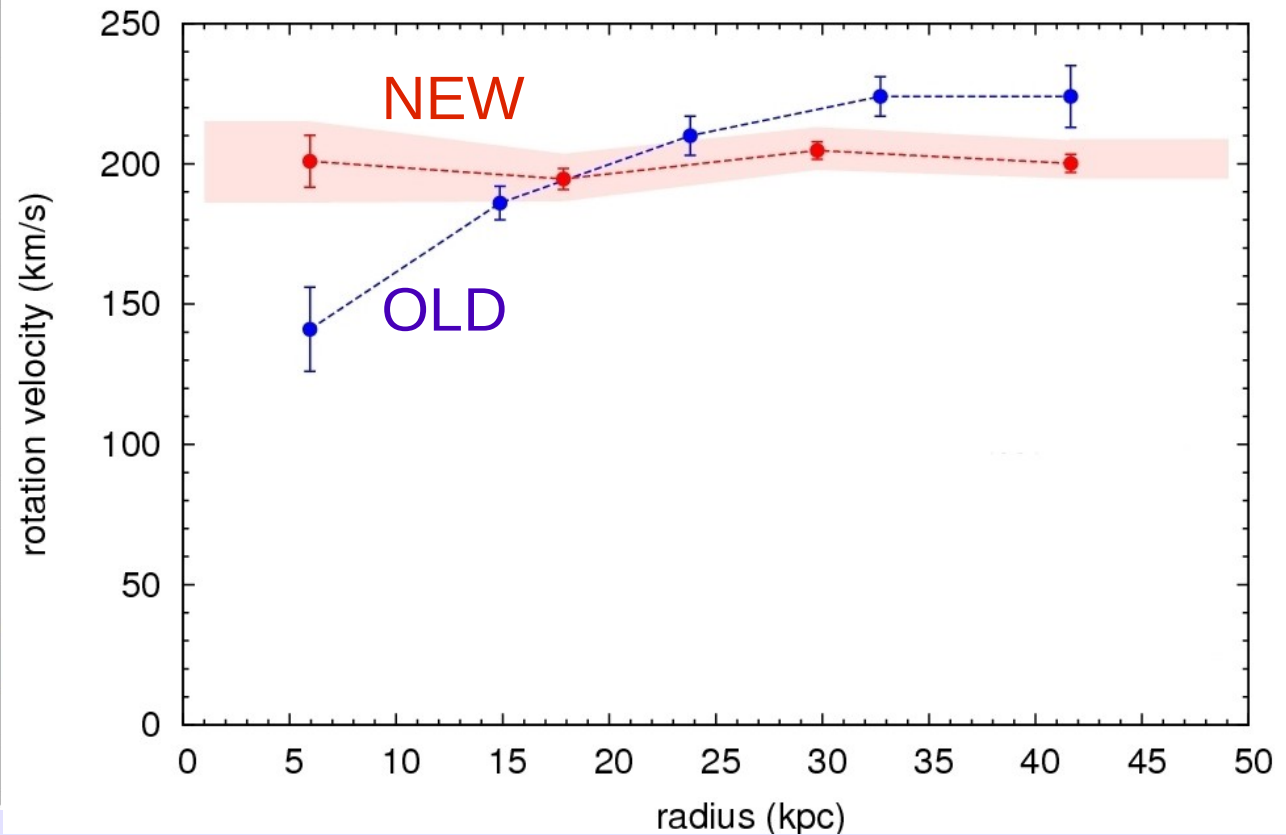
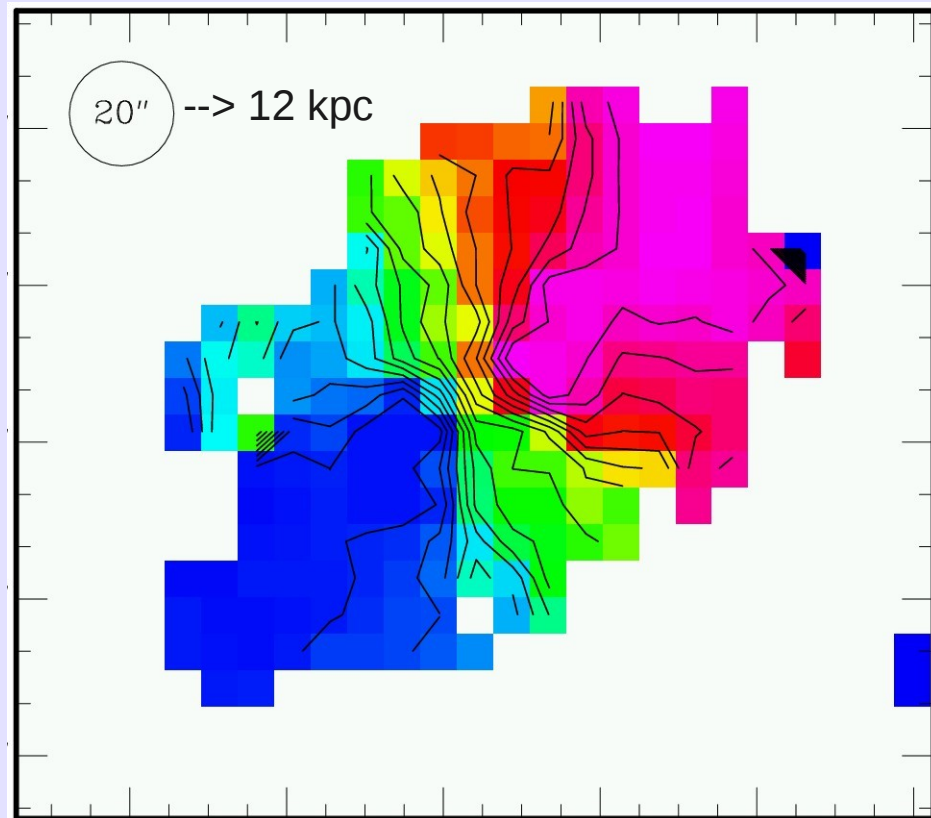
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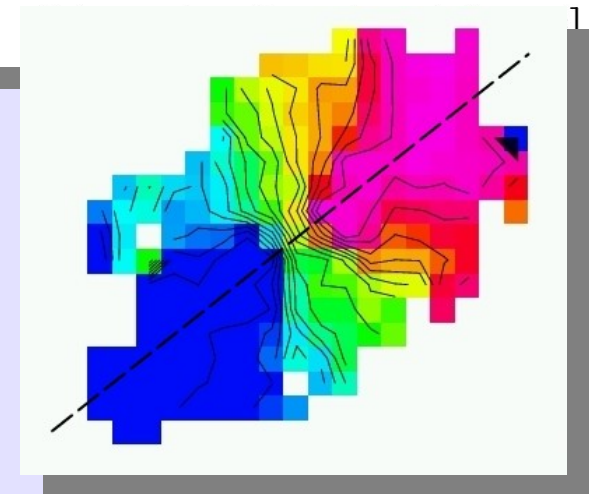
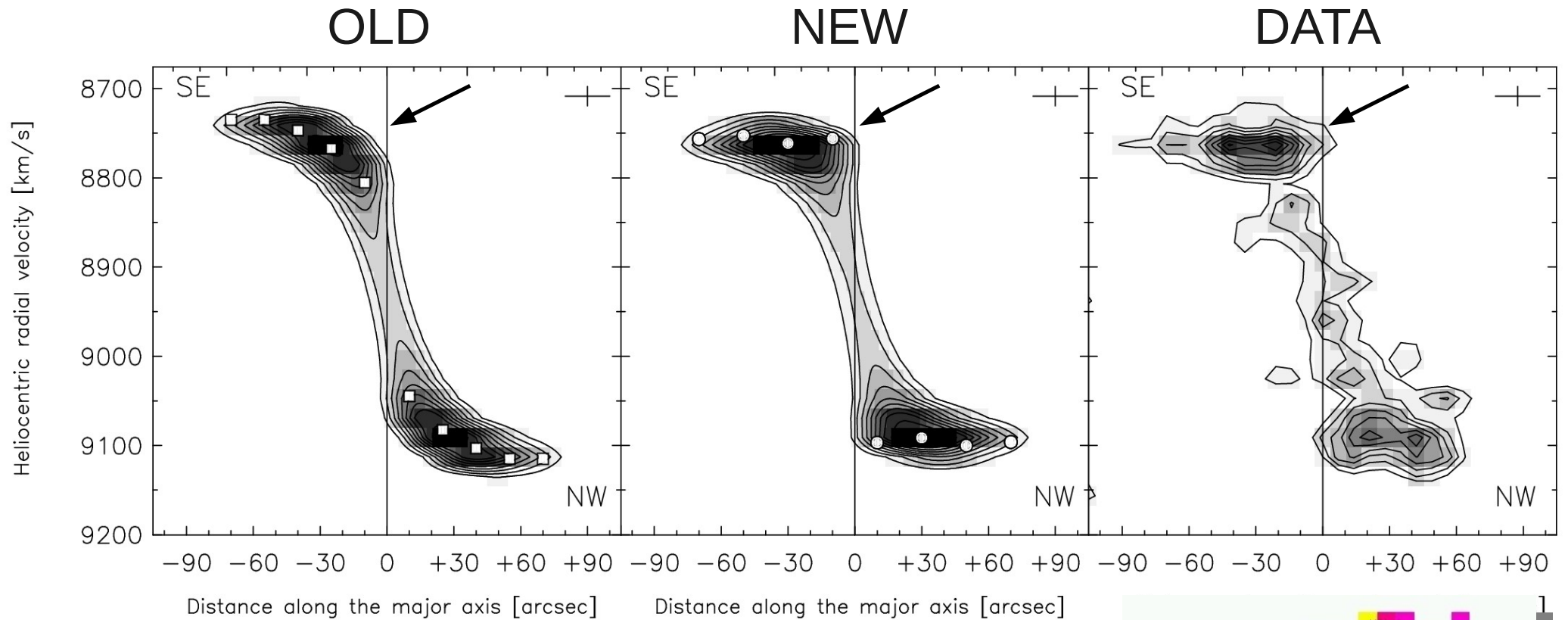
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NGC 7589 – Kinematics

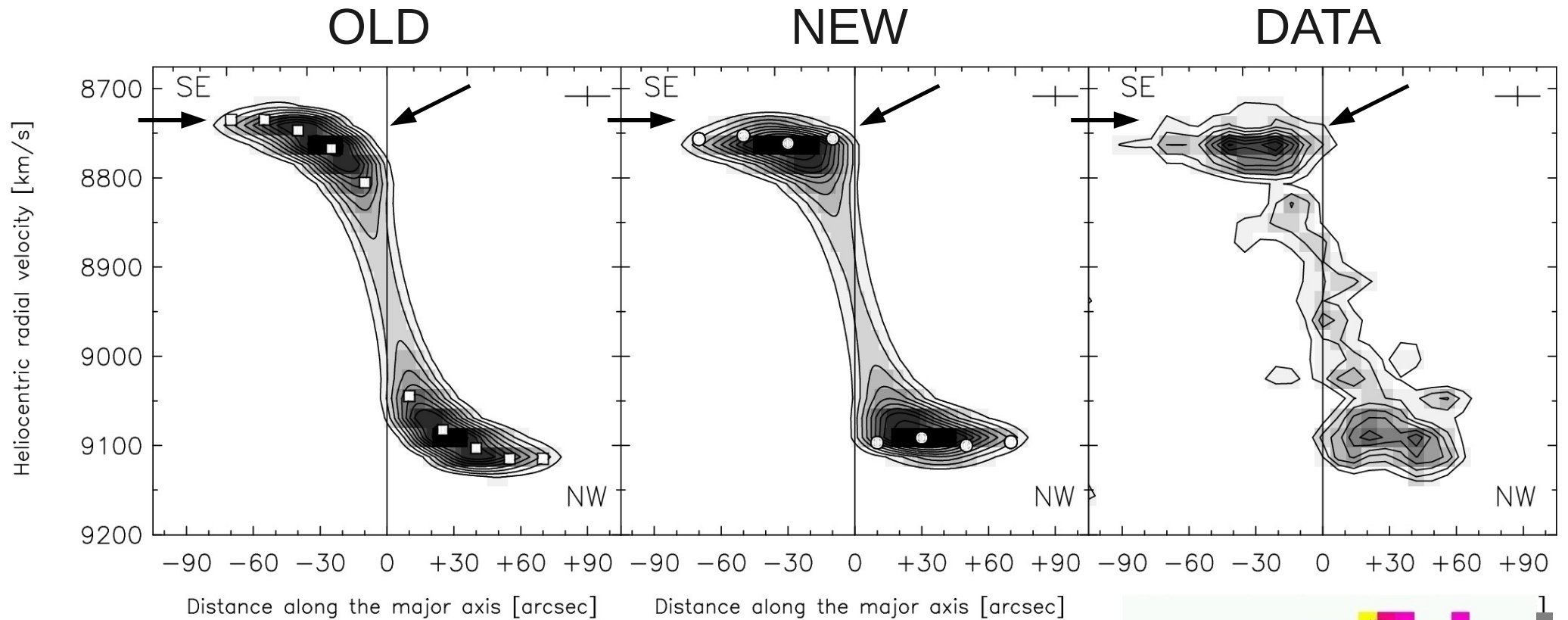


$$M_{\text{dyn}} \sim 8.5 \cdot 10^{11} \text{ Msun}$$

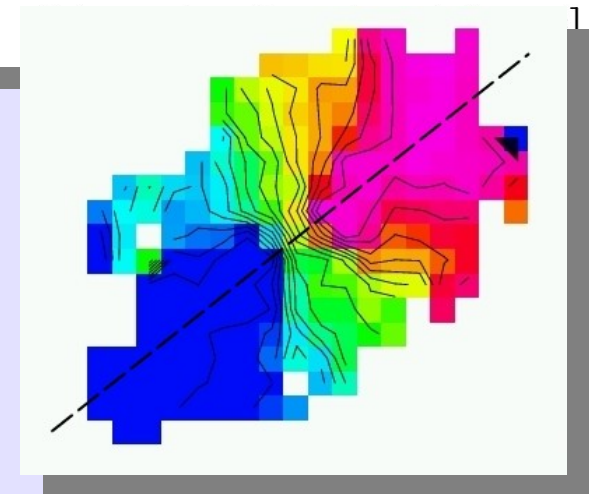
NGC 7589 Model Datacubes



NGC 7589 Model Datacubes



The RC by *Pickering et al* (1997) is under-estimated at small radii and over-estimated at large radii.



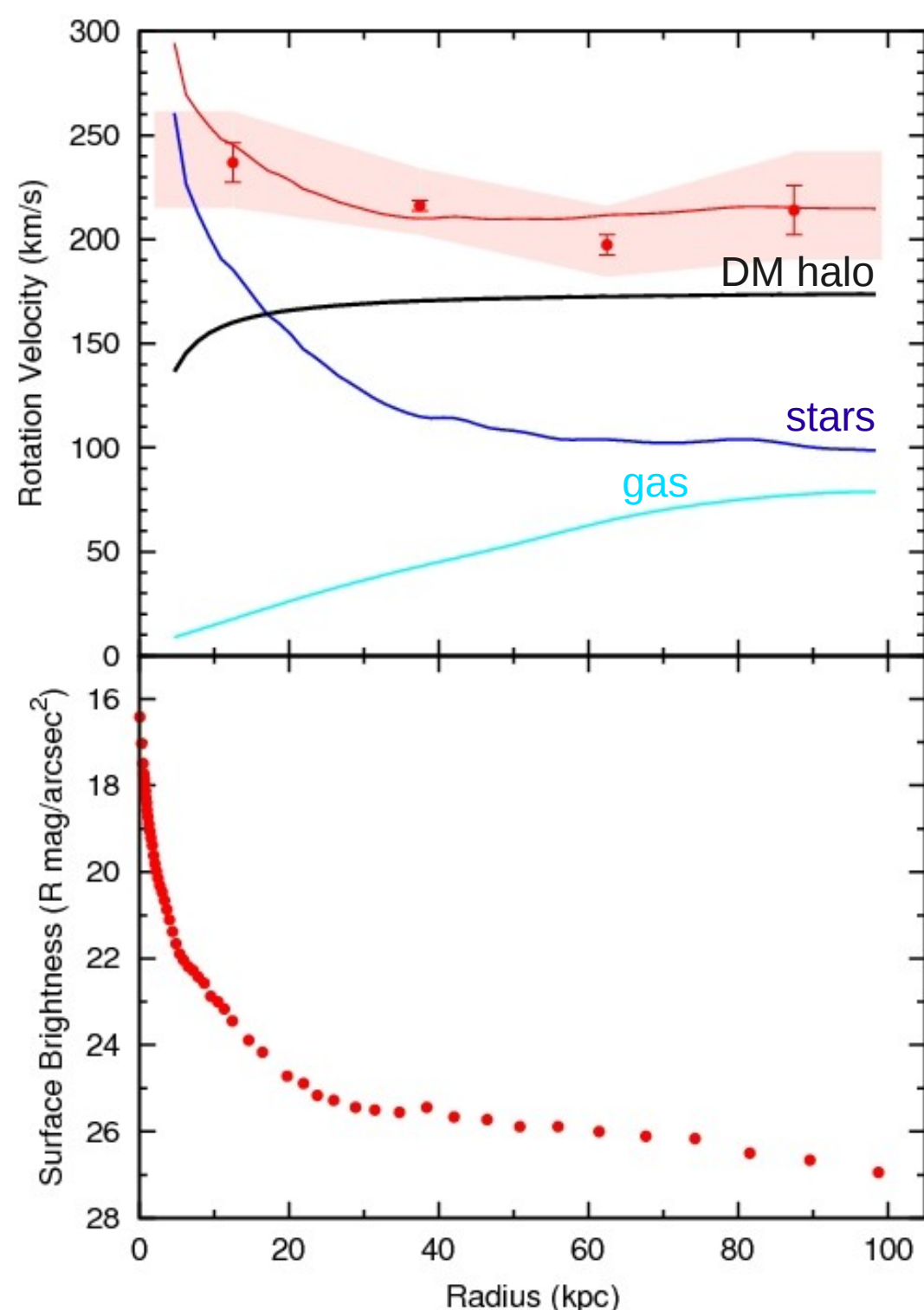
Malin 1 Mass Model

Pseudo-Isothermal Spherical DM Halo:

$$\rho(R) = \rho_0 \left[1 + \left(\frac{R}{R_c} \right)^2 \right]^{-1}$$

Maximum Disk works
(as in HSB galaxies)

➔ $M_*/L_R = 3.4$



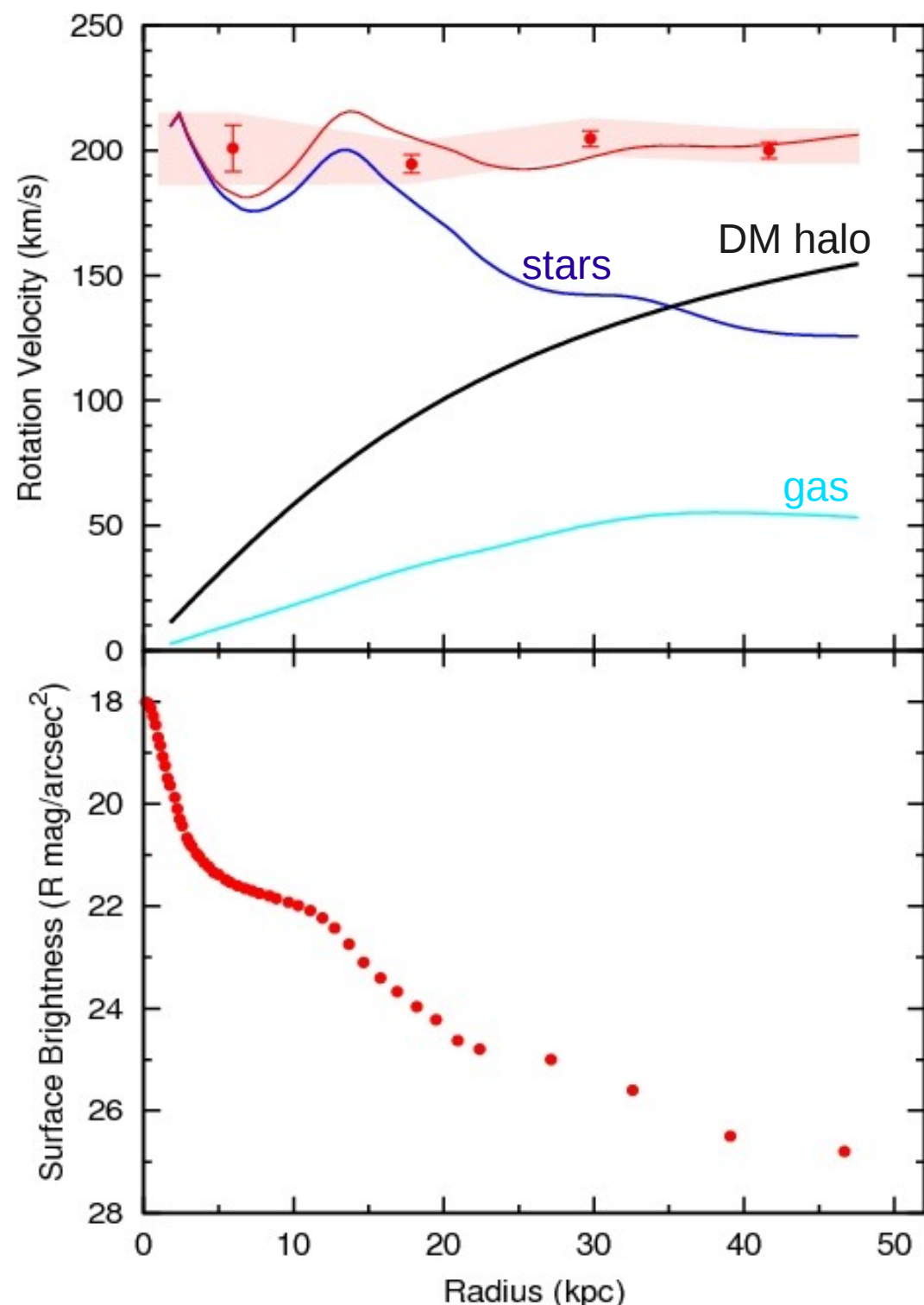
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Maximum Disk works
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➔ $M_*/L_R = 2.5$



Results on Malin 1 & NGC 7589

✓ Structure:

inner HSB early-type spiral galaxy

outer extended LSB disk

Results on Malin 1 & NGC 7589

✓ **Structure:**

inner HSB early-type spiral galaxy

outer extended LSB disk

✓ **Dynamics:**

typical of a HSB system (maximum disk works)

Dark Matter NOT dominating everywhere

Results on Malin 1 & NGC 7589

✓ Structure:

inner HSB early-type spiral galaxy

outer extended LSB disk

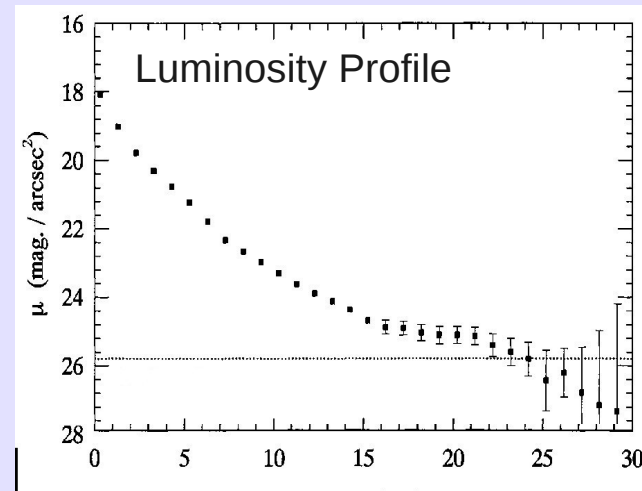
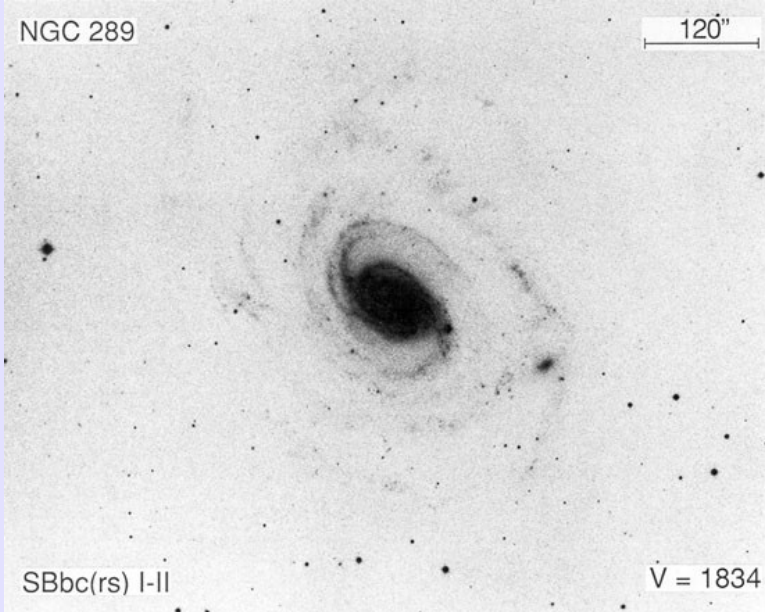
✓ Dynamics:

typical of a HSB system (maximum disk works)

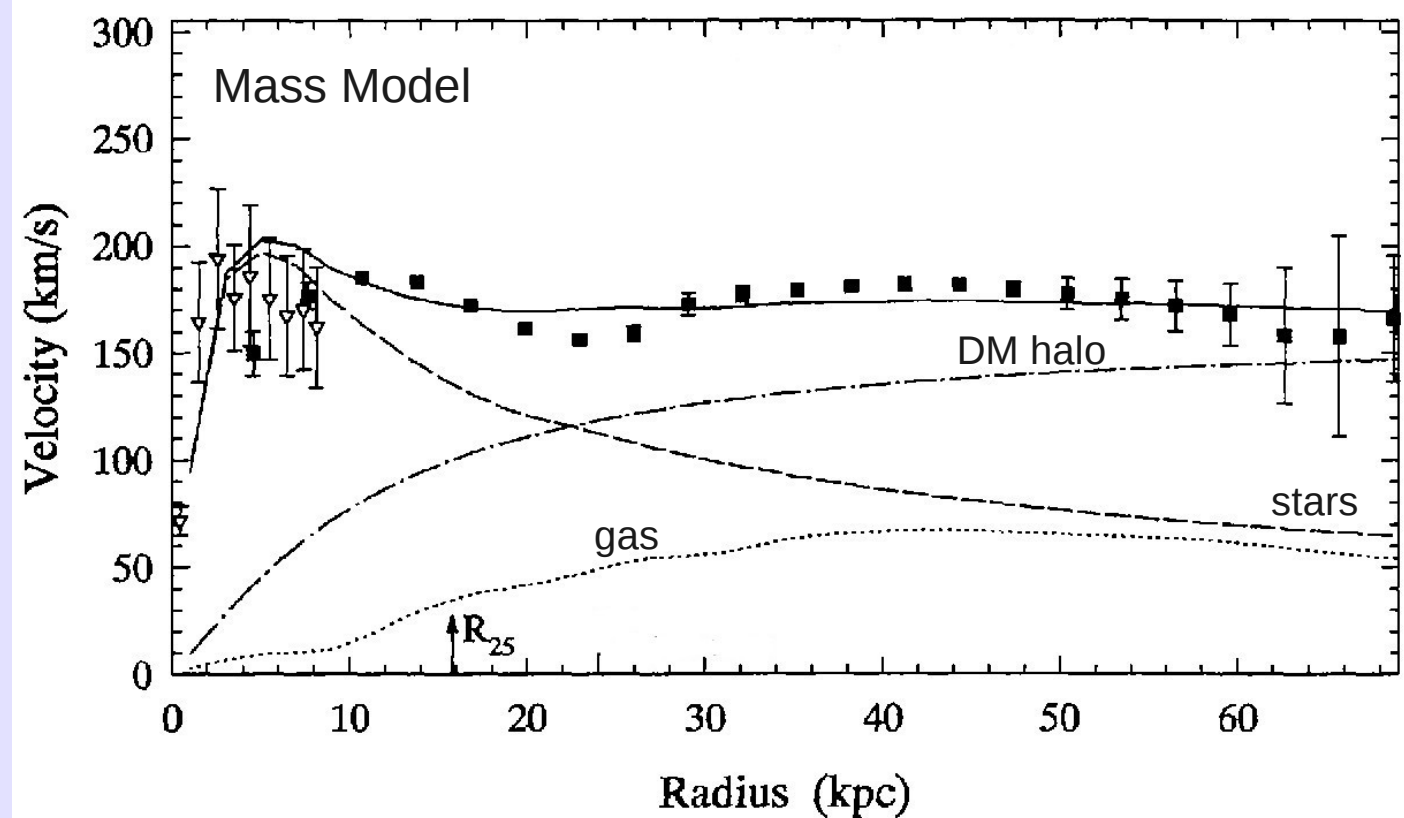
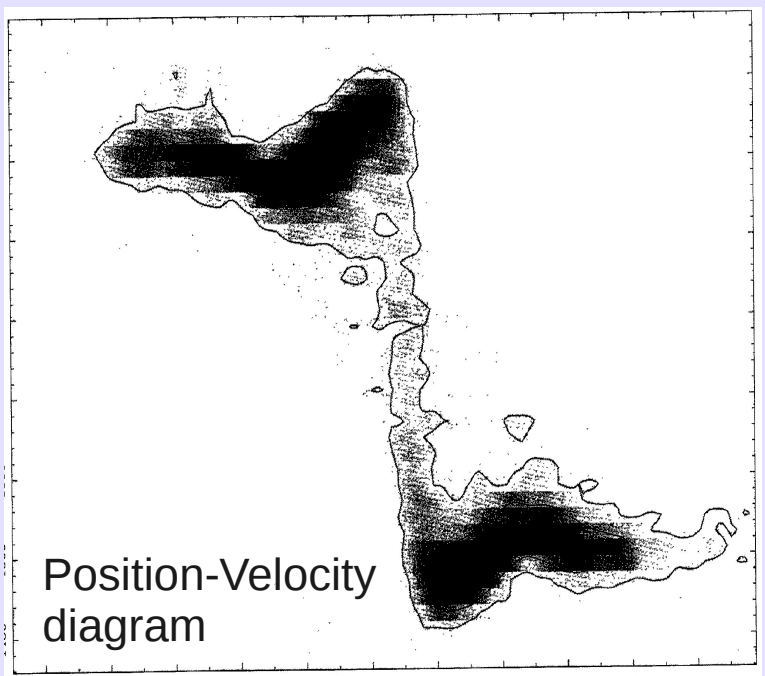
Dark Matter NOT dominating everywhere

and the other GLSB galaxies???

Other GLSB galaxies: NGC 289



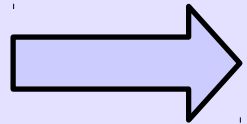
Maximum-Disk Fit:
 $M_*/L_I = 2.3$
(Walsh et al 1997)



Conclusions on Giant LSB galaxies

Photometry + Gas Dynamics =

Double HSB/LSB nature



Link between light and gravitational potential

Conclusions on Giant LSB galaxies

Photometry + Gas Dynamics =

Double HSB/LSB nature



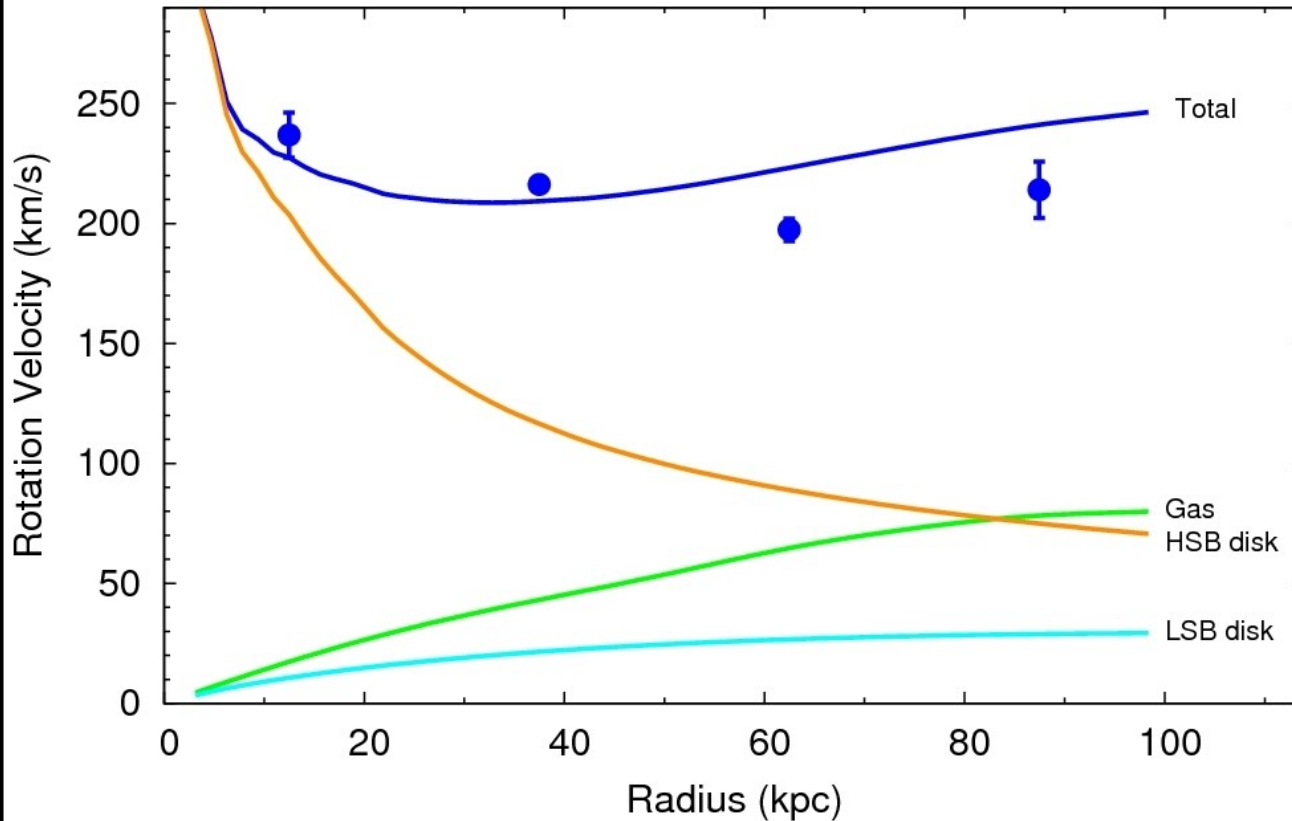
Link between *light* and *gravitational potential*

**The distribution of baryons
predicts the dynamics of a galaxy!?**

More Slides

Malin 1 - MOND

$$a_{\text{Newton}} = \mu(x) a \text{ where } x = a/a_0 \text{ (Milgrom 1983)}$$

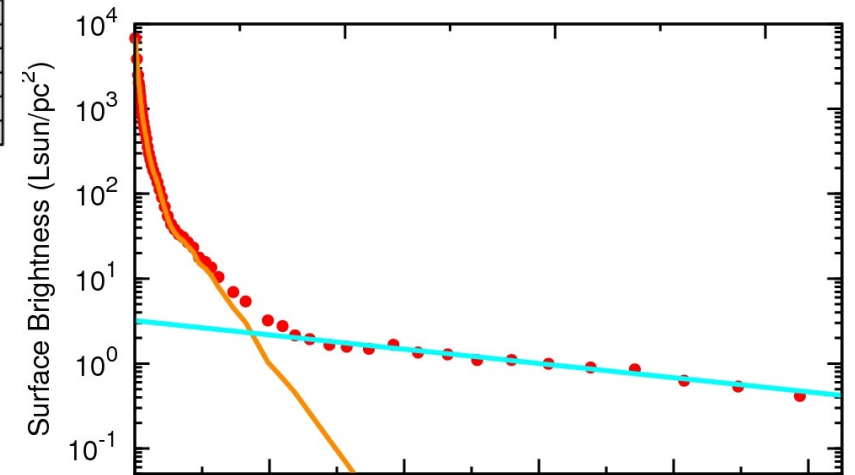


$$M/L_{\text{LSB}} = 0.5 \quad M/L_{\text{HSB}} = 3.7$$

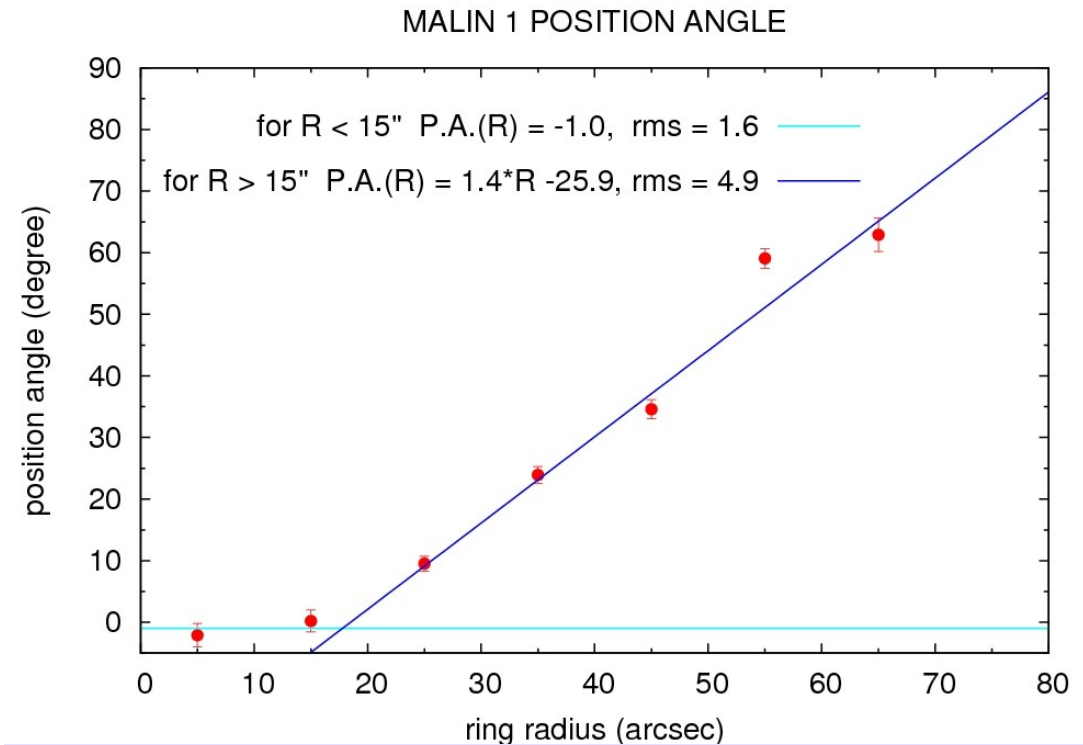
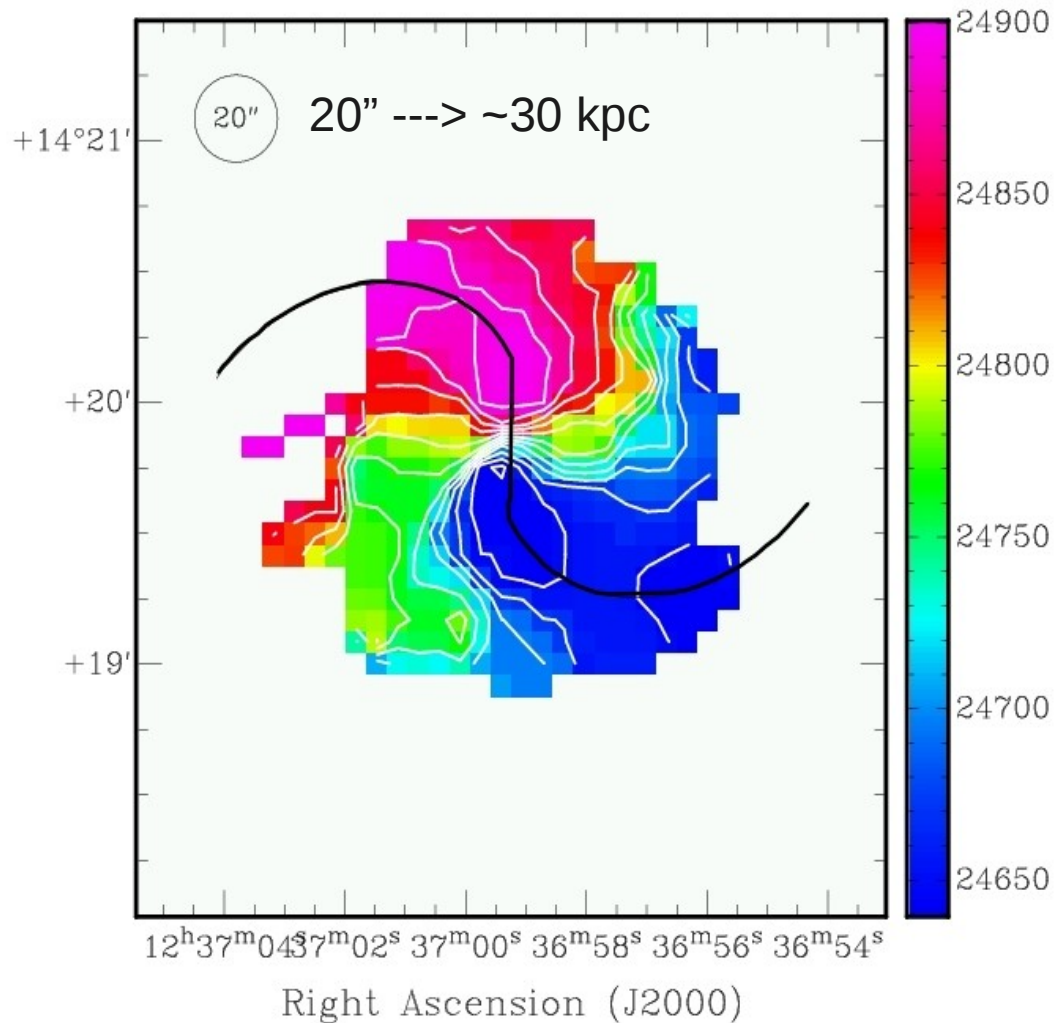
$$a_0 = 3000 \text{ km}^2 \text{ s}^{-2} \text{ kpc}^{-1} \text{ (Bottema et al. 2002)}$$

✓ Very Low Acceleration:
Deep MONDian regime
($a/a_0 \sim 0.15$)

✓ Very Gas Rich
Fit independent on M_*/L



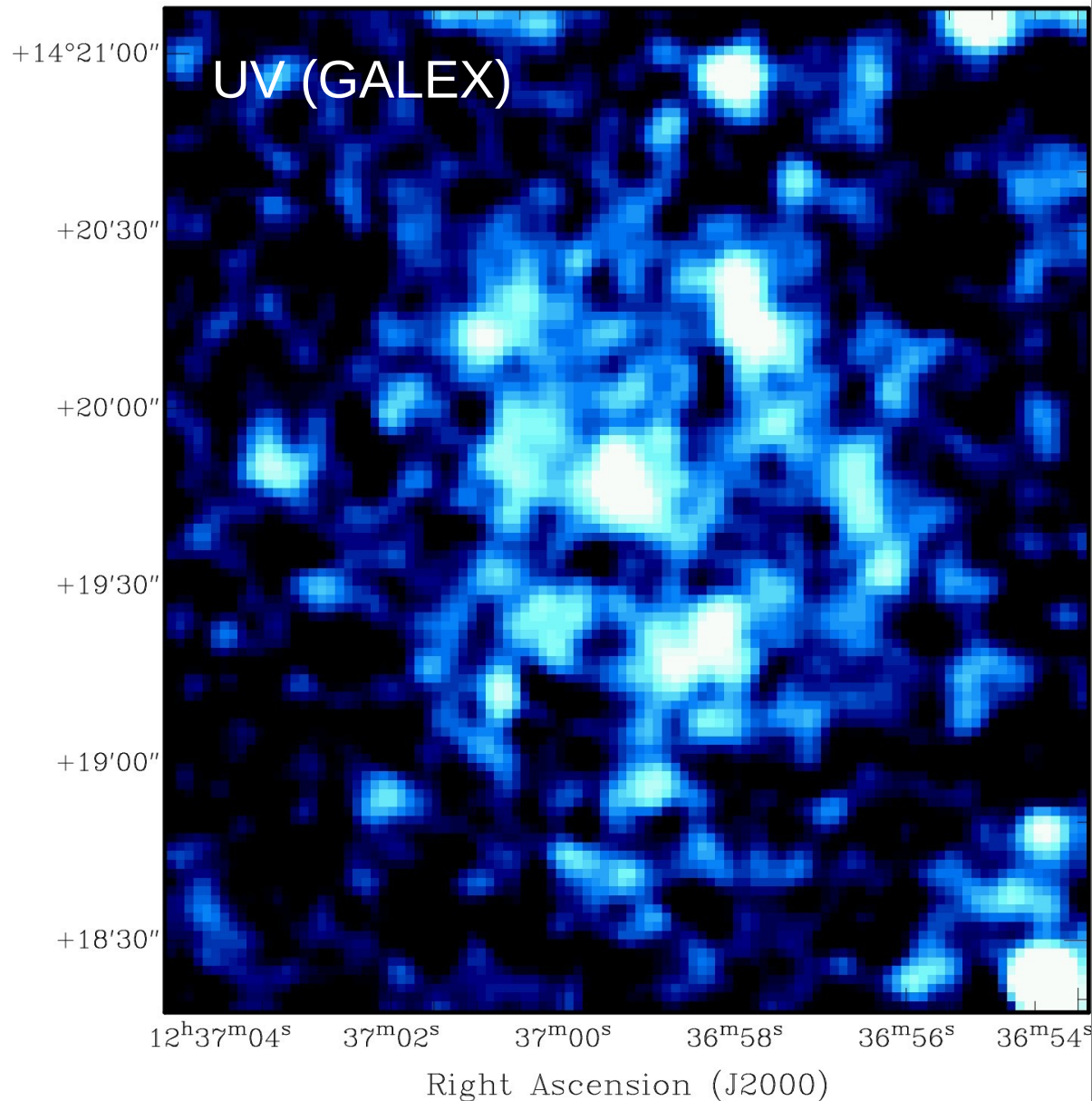
Malin 1 - Warp



$$\text{Incl}_{\text{qt}} = 45^\circ \pm 15^\circ \text{ (Pickering et al 1997)}$$

$$\text{Incl}_{\text{qt}} = 38^\circ \pm 3^\circ \text{ (Moore \& Parker 2007)}$$

Spiral Structure in Malin 1?



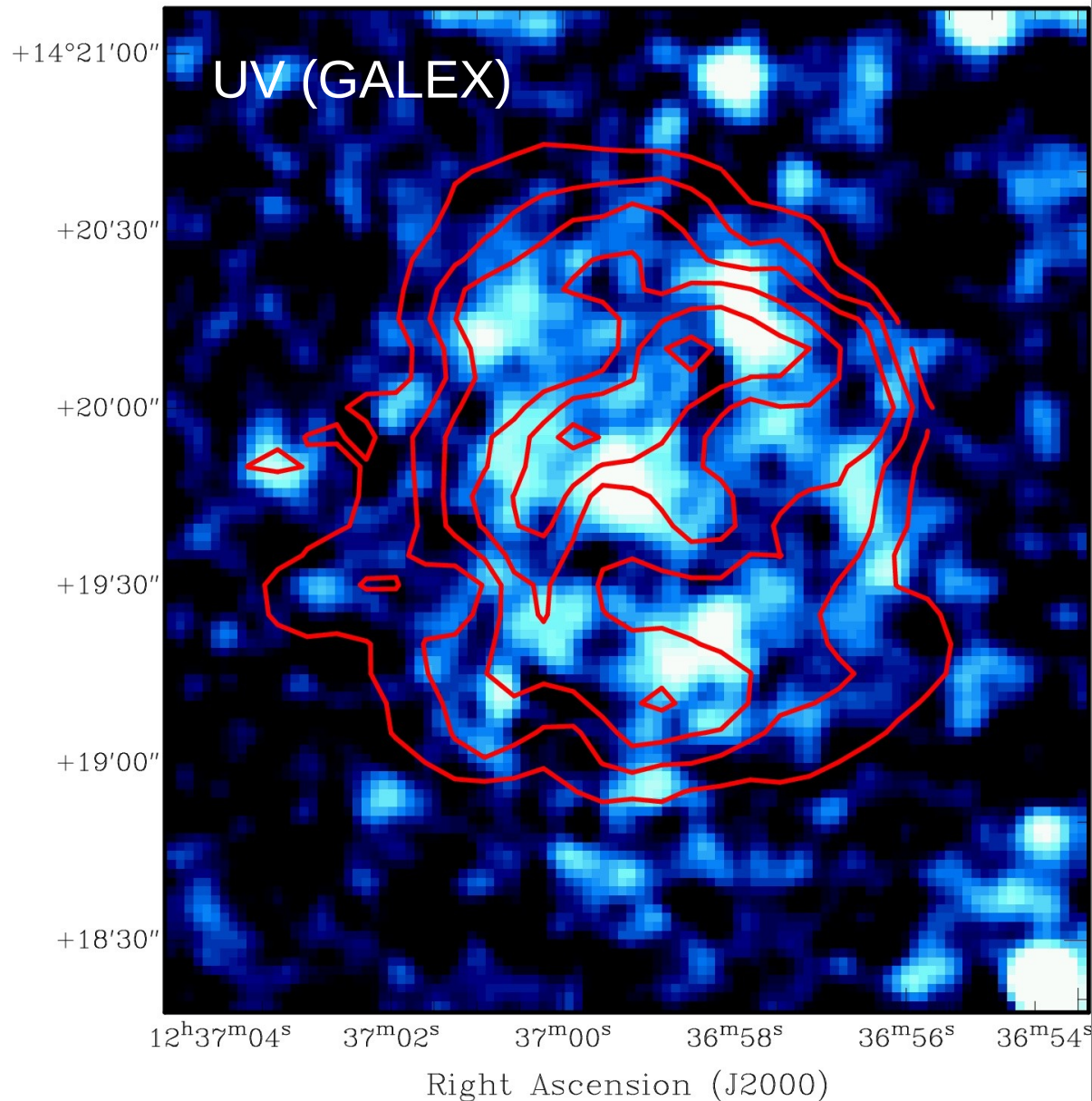
NEW OBSERVATIONS!

GMRT, India, 5-9 Sep. 2009

Goals:

- High resolution HI map
spiral structure out to 80 kpc?
- Modelling the warp
long-lived (~ 3 Gyr) structure?
- High quality rotation curve
test MOND at very low a/a_0
trace DM halo out to 100 kpc

Spiral Structure in Malin 1?



NEW OBSERVATIONS!

GMRT, India, 5-9 Sep. 2009

Goals:

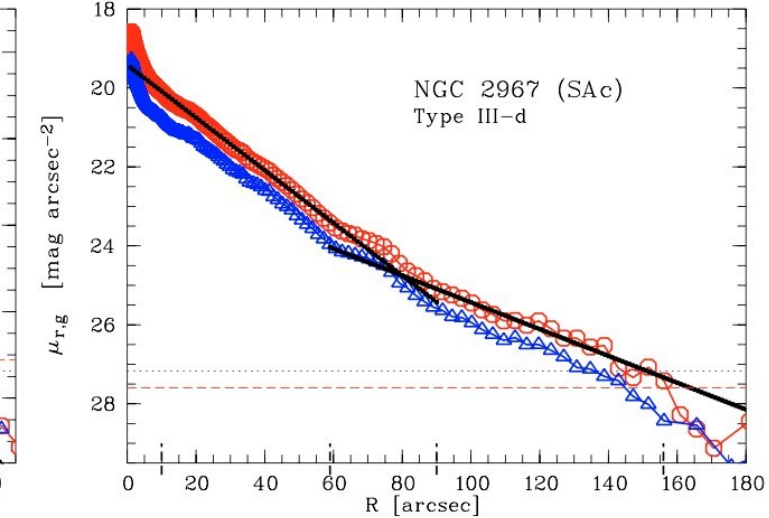
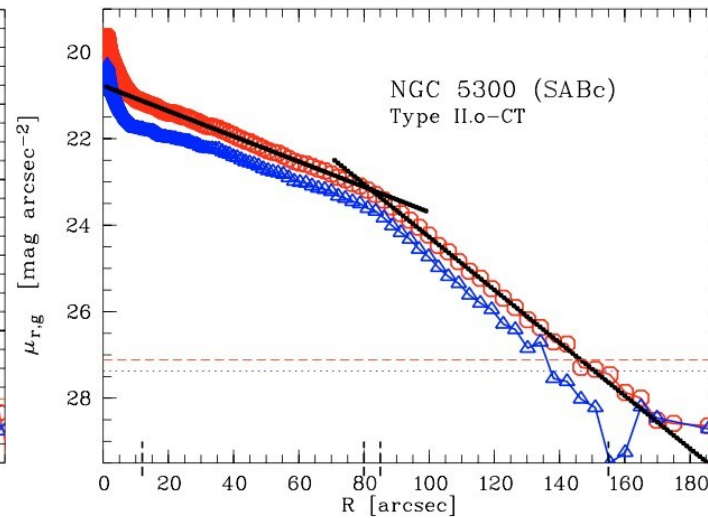
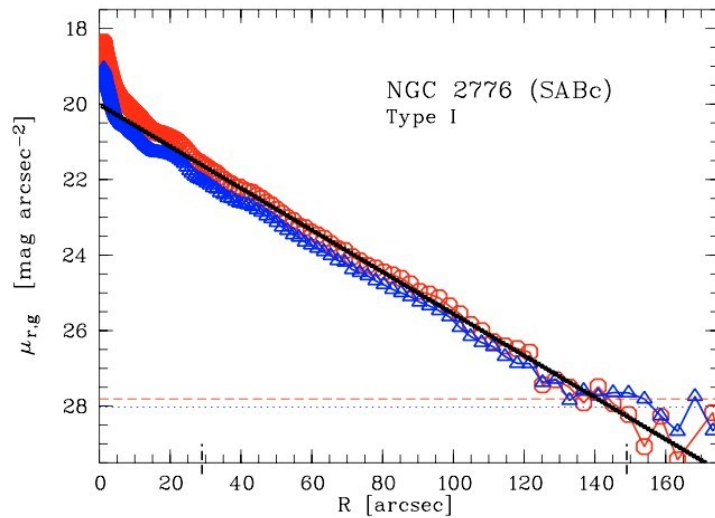
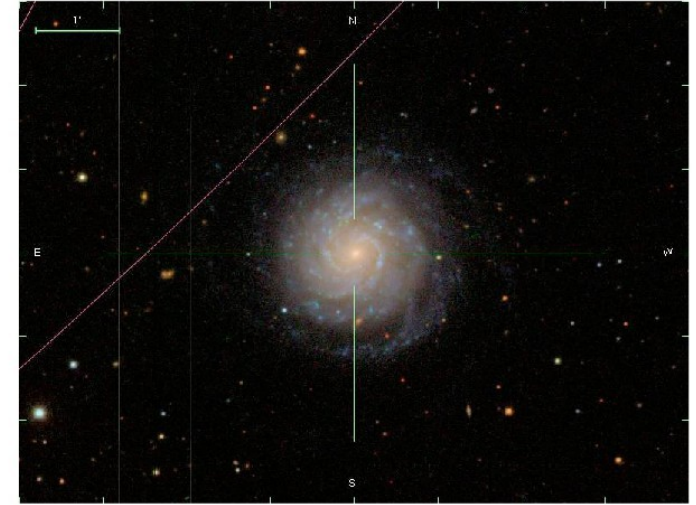
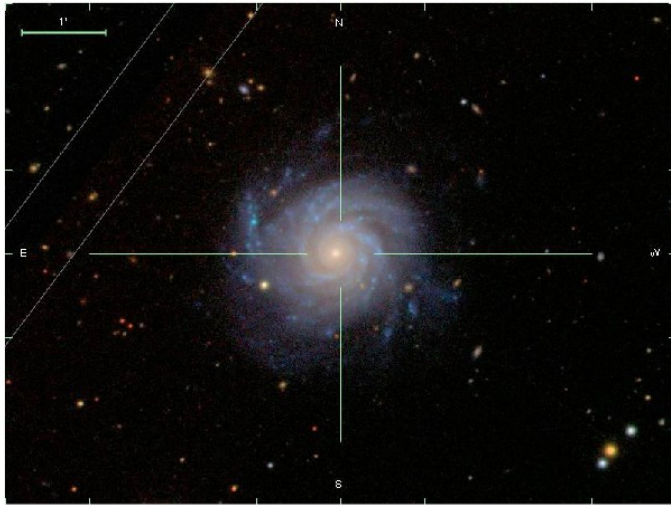
- High resolution HI map
spiral structure out to 80 kpc?
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test MOND at very low a/a_0
trace DM halo out to 100 kpc

Outer Disk Structure

Type I – Single Exponential

Type II – Truncated
(down-bending profile)

Type III – Anti-Truncated
(up-bending profile)



Pohlen & Truillo (2006); Erwin et al. (2008)

Giant LSB Galaxies

Defining Properties:

✓ $\mu_{0,disk} (B) \geq 23 \text{ mag arcsec}^{-2}$

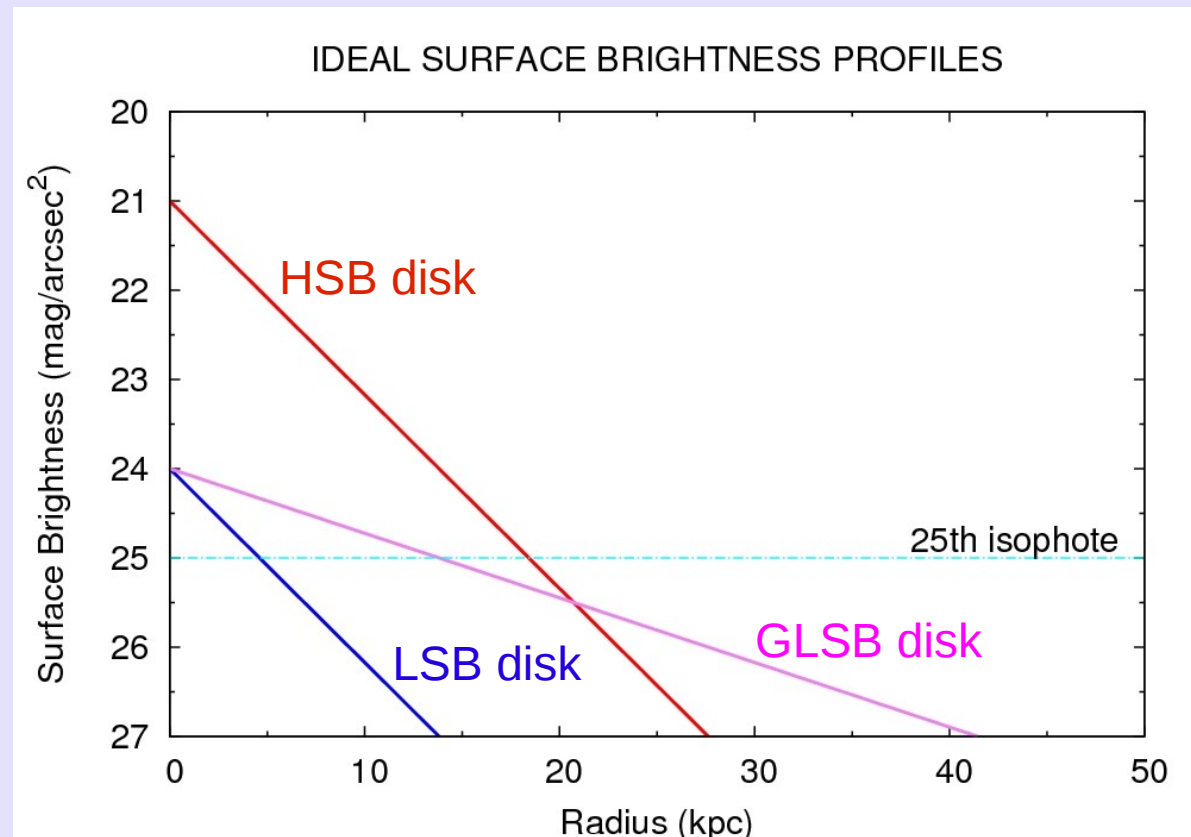
✓ $h_{disk} \geq 10 \text{ kpc}$

✓ Massive ($M_B \leq -19 \text{ mag}$)

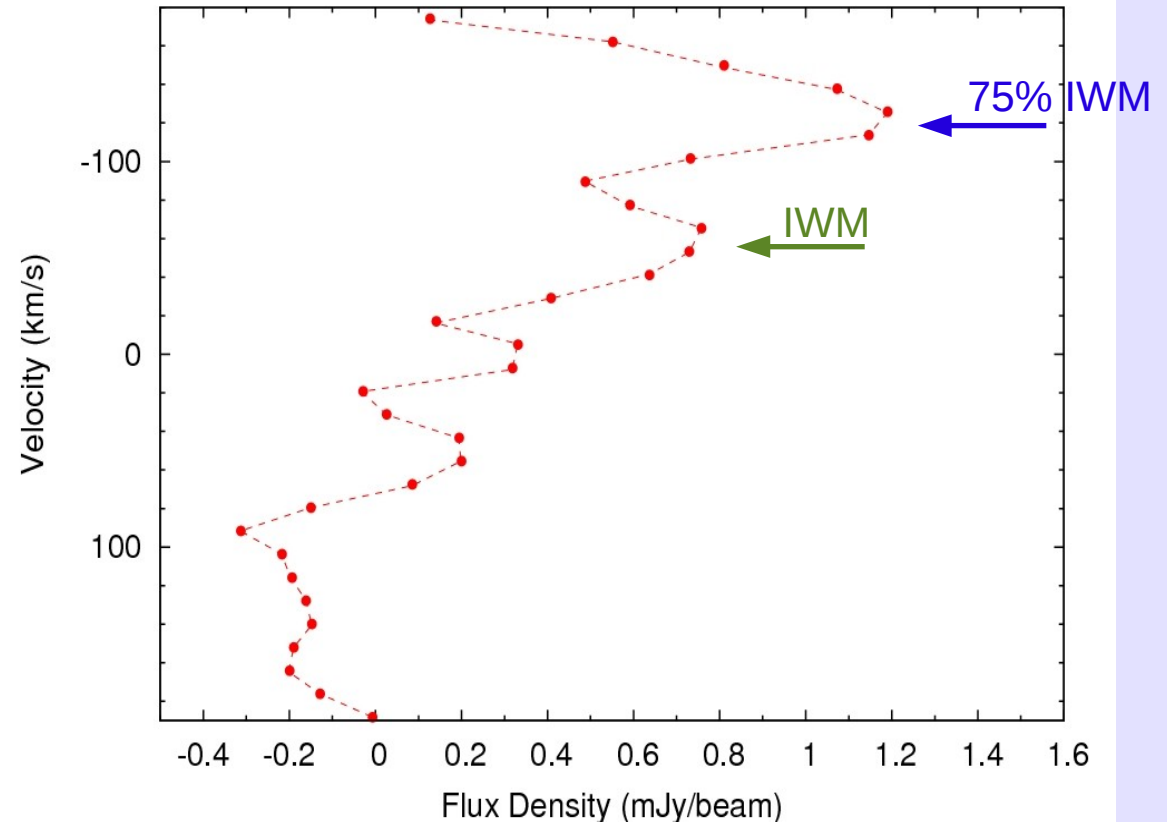
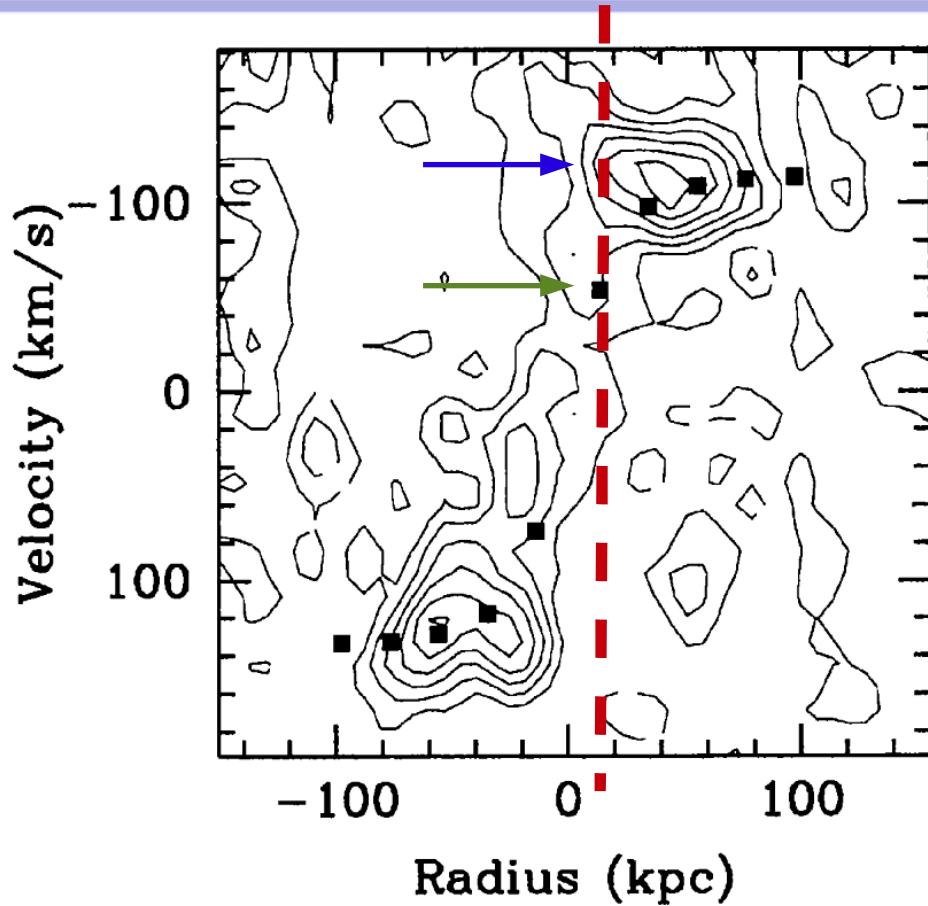
✓ Gas Rich ($M_{HI} \geq 10^9 \text{ Msun}$)

✓ Inner Light Concentration

$$\mu_{disk}(r) = \mu_{0,disk} + 1.086 \left(r / h_{disk} \right)$$

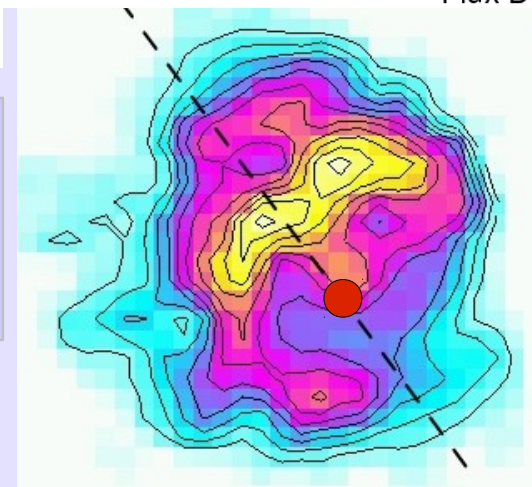


Does Malin 1 have a slowly rising RC?



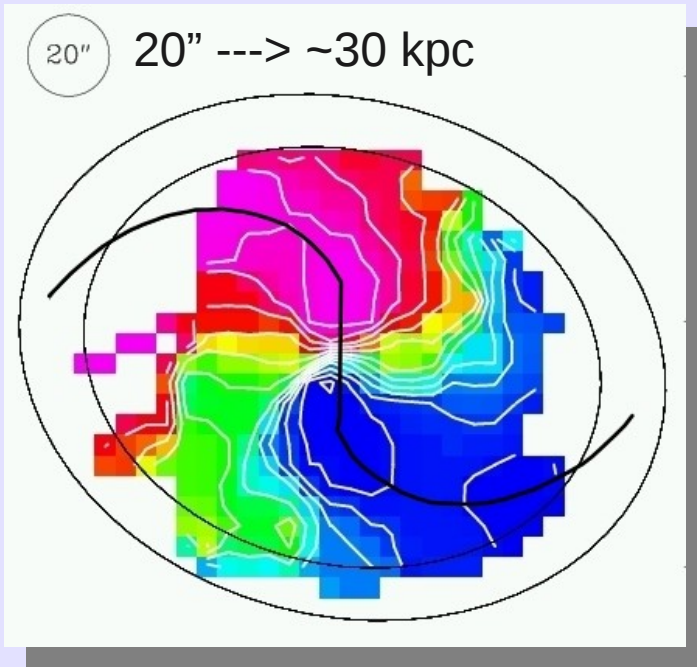
Position – Velocity diagram
from *Pickering et al (1997)*

Beam = 20" ~ 30 kpc!!!

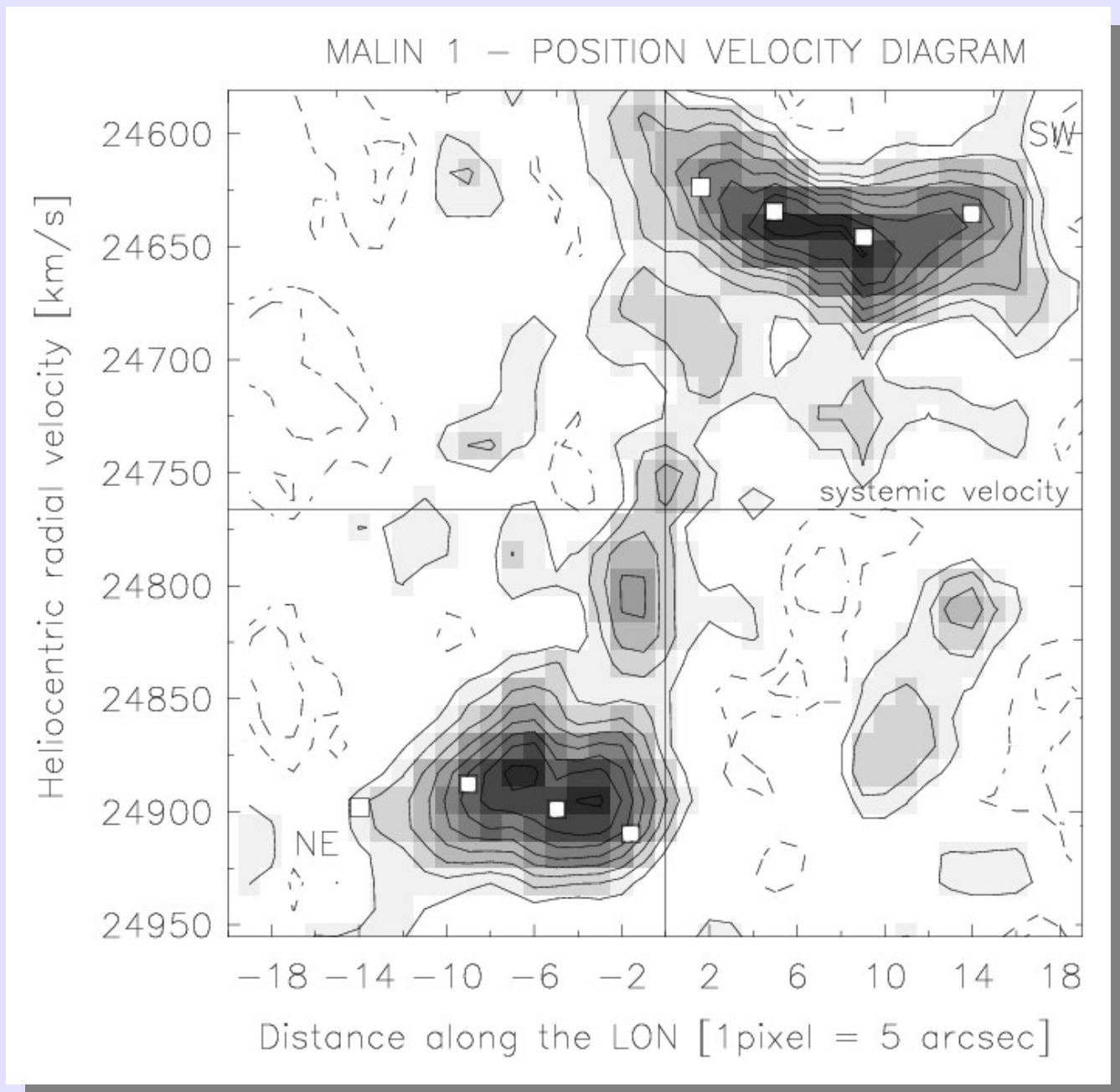


21 cm line profiles
strongly affected
by *beam smearing*.

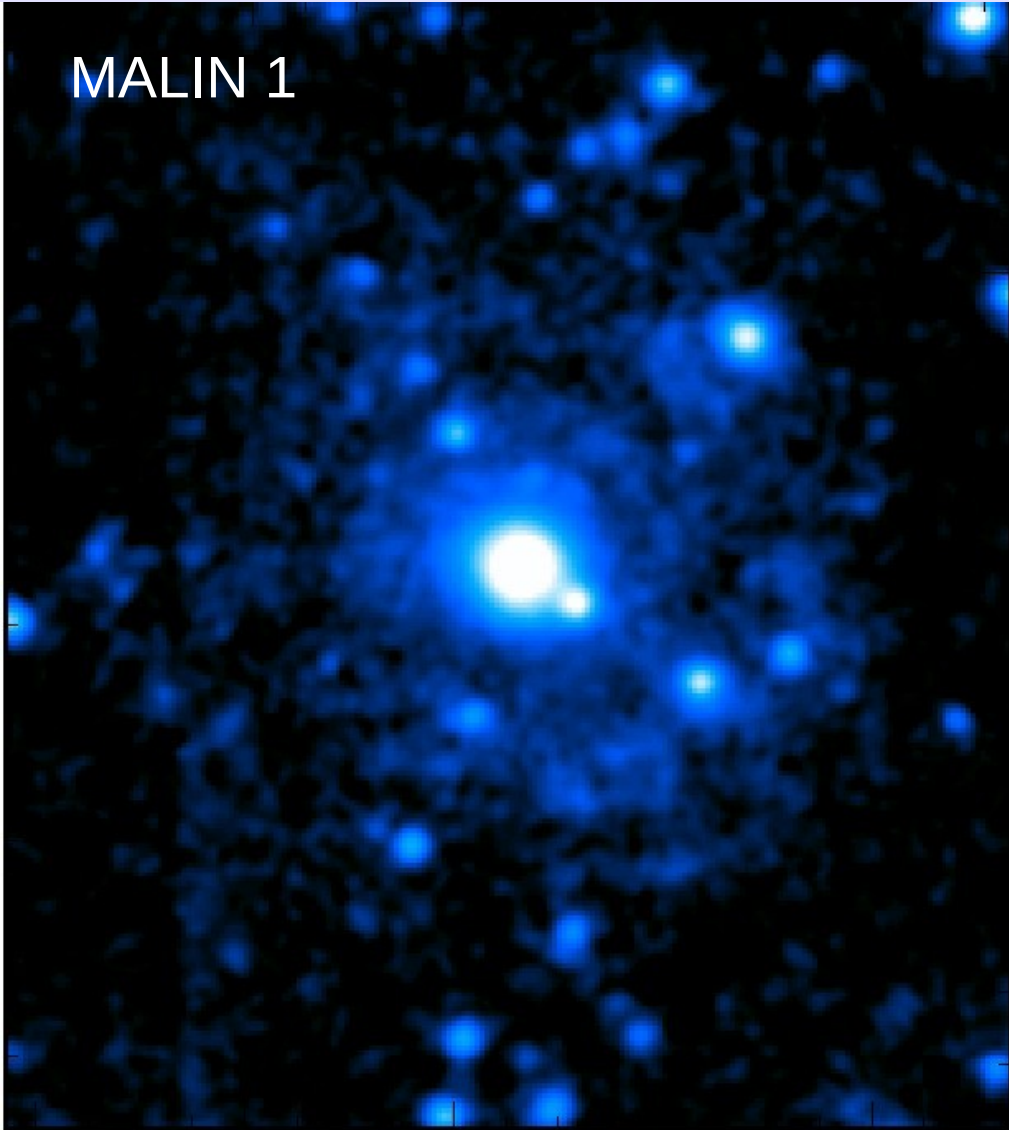
Position Velocity Diagram for Malin 1



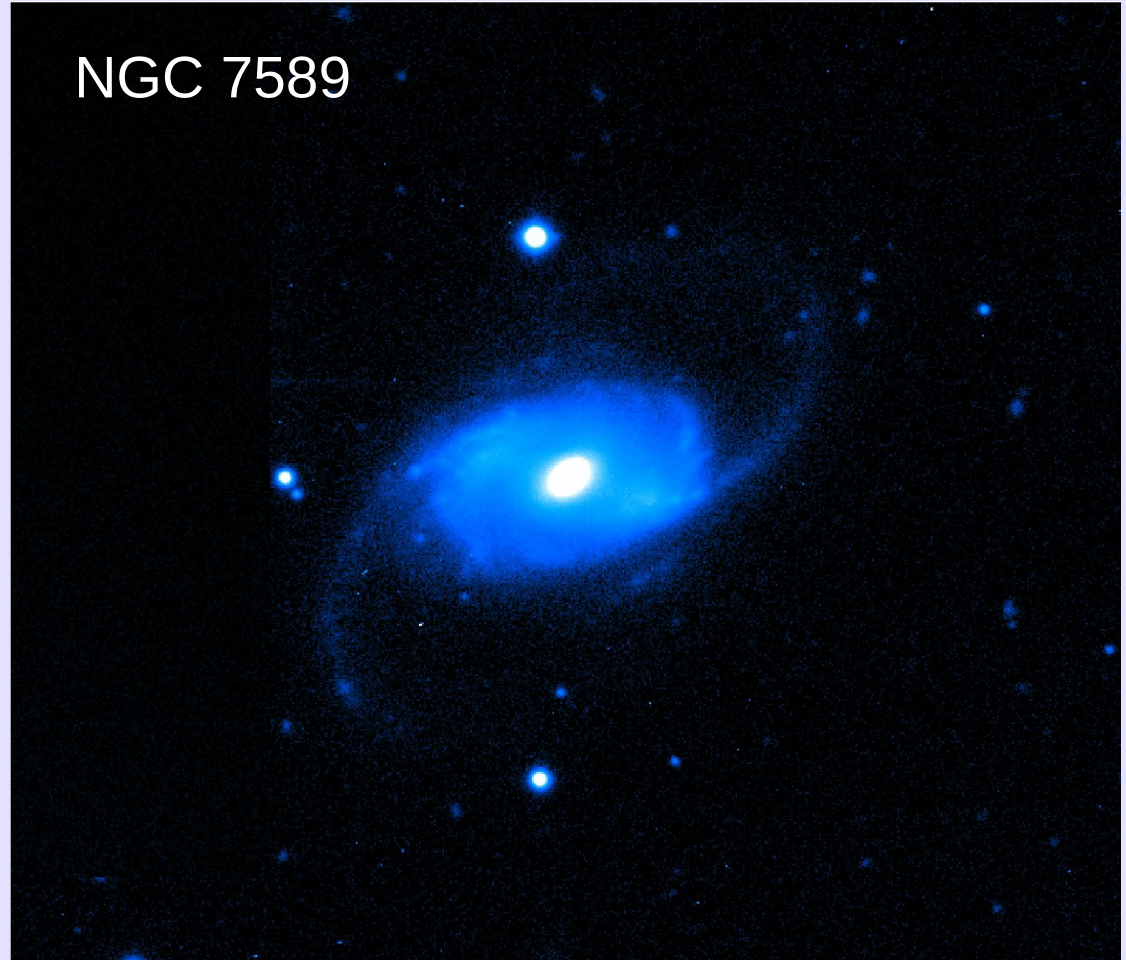
$$M_{\text{dyn}} \sim 2 \cdot 10^{12} \text{ Msun}$$



MALIN 1



NGC 7589



END