The “Bosma Effect” Revisited

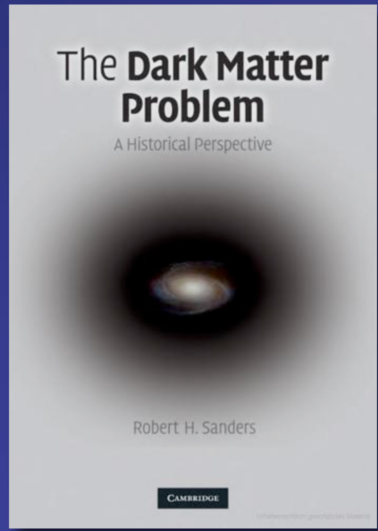
Correlations between the ISM and DM in Galaxies

F. V. Hessman & M. Ziebart
Institut für Astrophysik
Georg-August-Universität Göttingen

A Brief History of DM in Galaxies

- "Dark matter" needed to explain local stellar kinematics (Kapteyn 1922, Oort 1932)
- Flat rotation curve of M31 (Babcock 1939, Mayall 1951)
- MW globular cluster kinematics (Kurth 1950)
- Local Group kinematics (Kahn & Woltjer 1959)
- Problem with stability of massive discs (Toomre 1964)
- CDM halo provides stability (Ostriker & Peebles 1973)
- Ubiquity of "flat" rotation curves

  (Rogstad & Shostak 1972, Bosma 1978, Rubin, Ford & Thonnard 1980)



- Stellar disc-halo "conspiracy" (van Albada & Sancisi 1986)
- "Galaxies are irrelevant": CDM needed for LSS, ΛCDM cosmology (1990's-present)
- Bullet cluster: DM not in baryonic intracluster medium stripped from galaxies
- CDM halos can't be cuspy, so add toy gastrophysics until it fits

Classical Lines of Evidence for **Cold** DM

- Galaxy Dynamics
  - Stellar dynamics in the solar neighborhood
  - Spiral galaxy rotation curves
  - Stability of galaxy disks, spiral density waves
  - Projected kinematics of elliptical galaxies
  - Local Group kinematics
  - X-ray gas in elliptical galaxies
  - Strong gravitational lensing
- Galaxy Clusters
  - X-rays
  - Strong gravitational lensing
  - Weak gravitational lensing (e.g. “bullet cluster”)
  - Sunyaev-Zeldovich Effect
- Cosmic Background Radiation (e.g. WMAP)
- Large-scale structure formation
  - Baryonic acoustic oscillations
  - Galaxy correlation functions
  - Number and distribution of galaxy masses

WDM

Baryons matter (not just the stars)!

- Tully-Fisher relation
  (Tully & Fisher 1977)
- $V_{DM}^2 \propto V_{gas}^2$
  (Bosma 1978, 1981)
- Stellar disc - halo conspiracy (URC)
  (Bahcall & Casertano 1985; van Albada & Sancisi 1986)
- Maximum discs
  (van Albada & Sancisi 1986)
- MOdified Newtonian Dynamics
  (Milgrom 1983)
- Baryonic Tully-Fisher relation
  (McGaugh et al. 2000, Pfenniger & Revaz 2005)
- Mass discrepancy - acceleration relation
  (McGaugh 2004)
- Galaxies are a 1-parameter family
  (Disney et al. 2008)
- Constant mean DM & baryonic mean surface densities
  (Donato et al. 2009; Gentile, Famaey & Zhao 2009)

MOdifed Newtonian Dynamics (MOND)

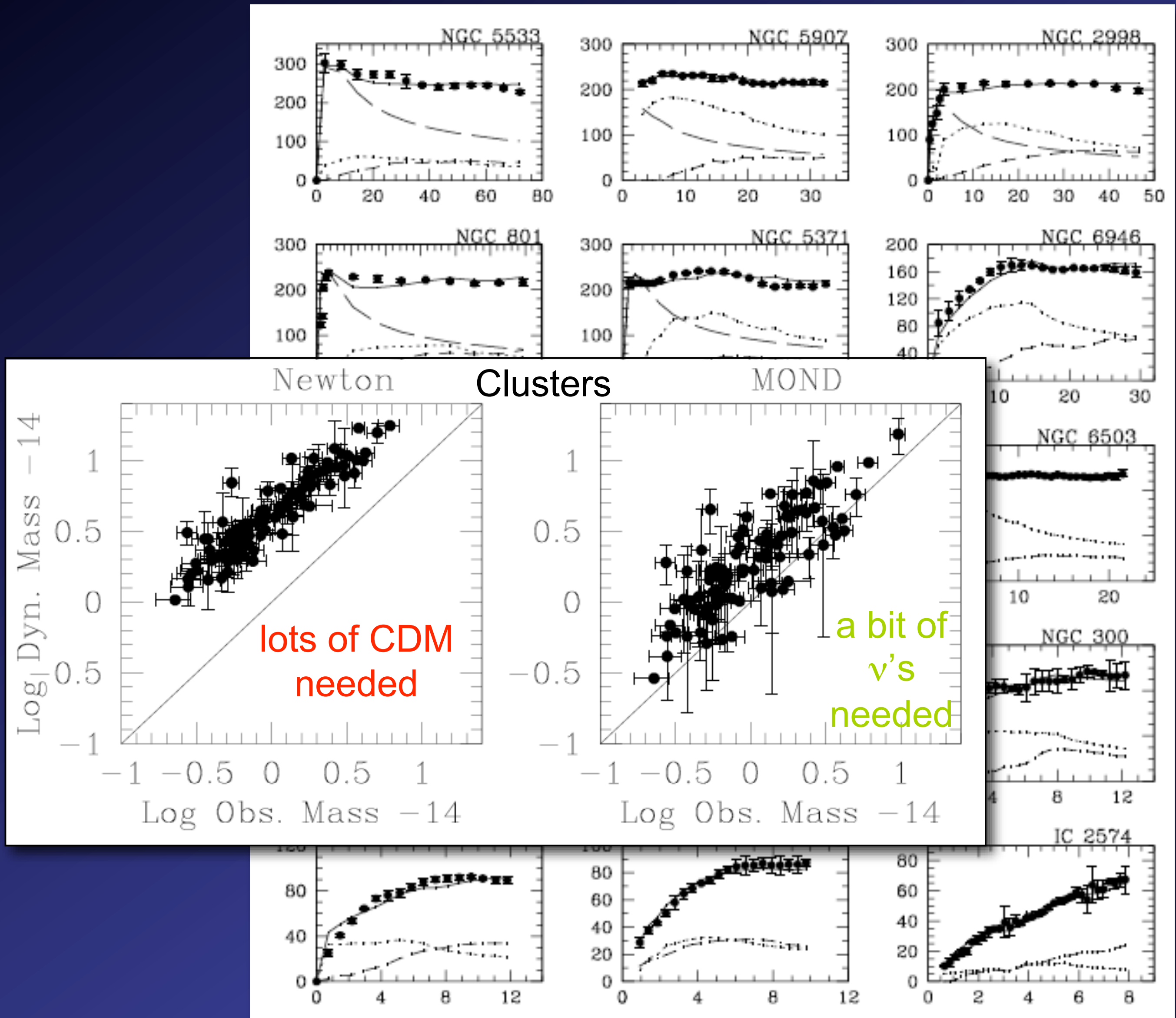
- Milgrom (1983)
- Fundamental universal acceleration scale a_0 due to
  - modified inertia $F = [m^* \mu(a/a_0)] * a$
  - modified gravity $a = a_{Newton} / \mu(a/a_0)$

  where $\mu(x>>1)=1$, $\mu(x<<1)=x$
- For modified gravity, Poisson equation is

$$\nabla \cdot [\mu(|\nabla\phi|/a_0)\nabla\phi] = 4\pi G\rho$$

- Fits to rotation curves yield $a_0 = 1.2 \times 10^{-10}$ m s^{-2} h_{75}^2 ~ 0.1 nm s^{-2}
- Many successful predictions for properties of galaxies
- Theoretical basis could be TensorVectorScalar gravity
- Can also explain "bullet cluster", WMAP angular power, gravitational lensing, …
- Functions so well, that - if not an alternative to Einstein gravity - then MOND says DM physics produces really bizzare correlations with baryons.

MOND Successes

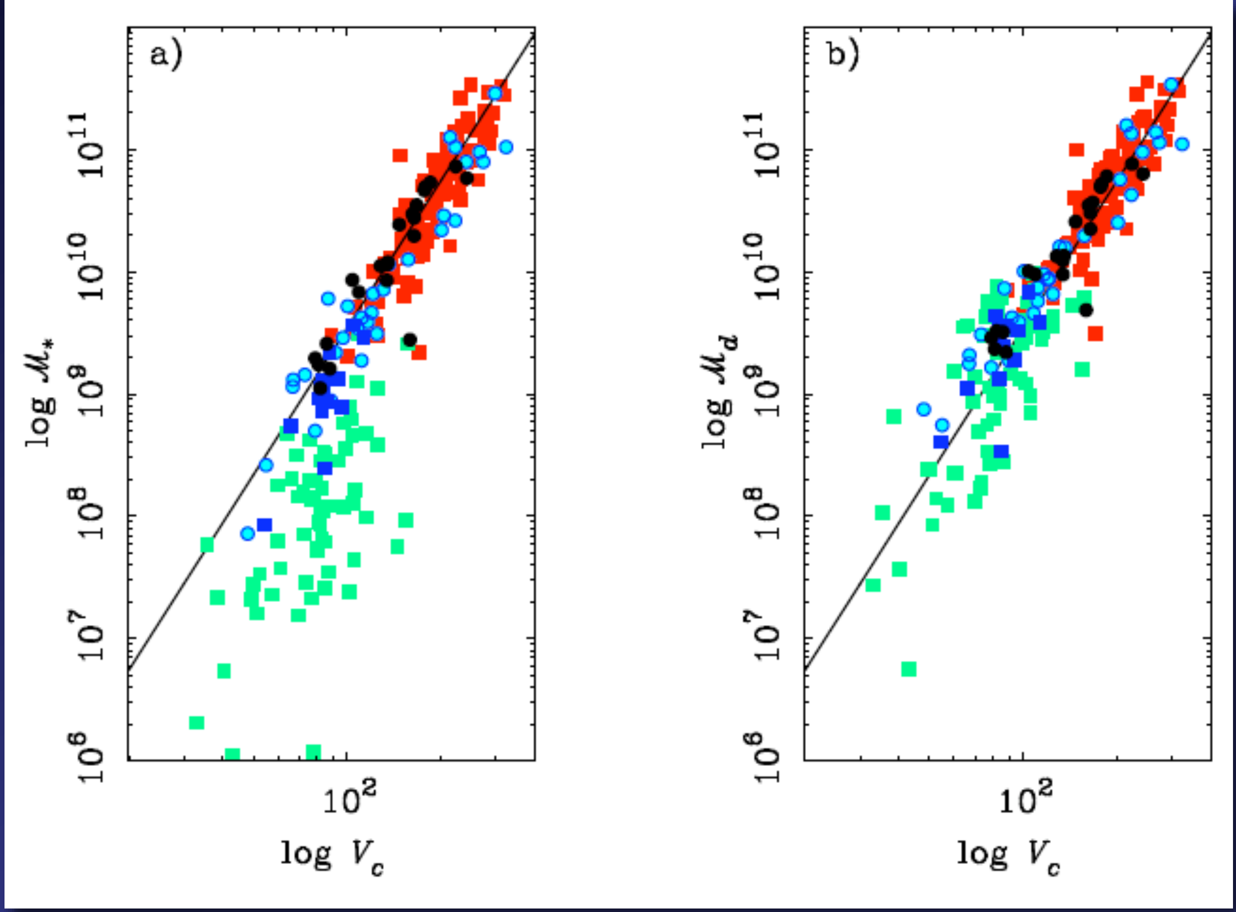


The Problem with MOND

- Basically pure (though spectacularly successful) phenomenology
- MOND-ish theories (TeVeS, conformal gravity) are inelegant
- No laboratory / Solar system tests

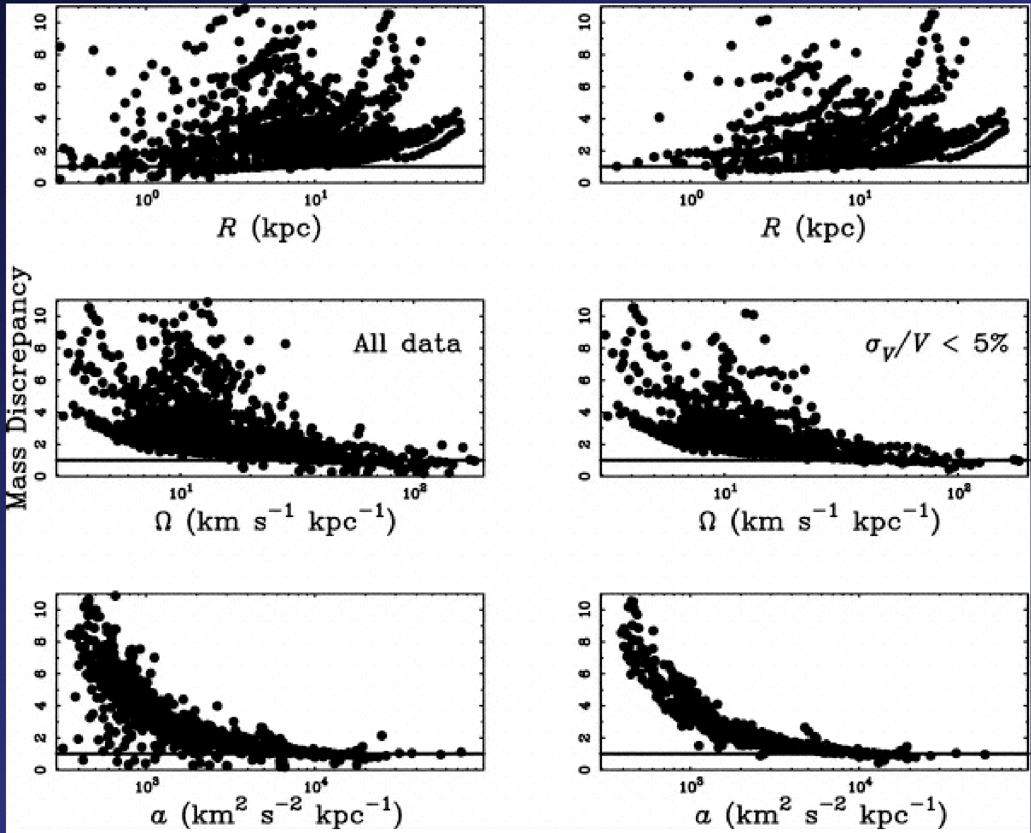
MOND is telling us that baryons are more important than we thought.

Baryonic Tully-Fisher Relation



McGaugh et al. (2000)

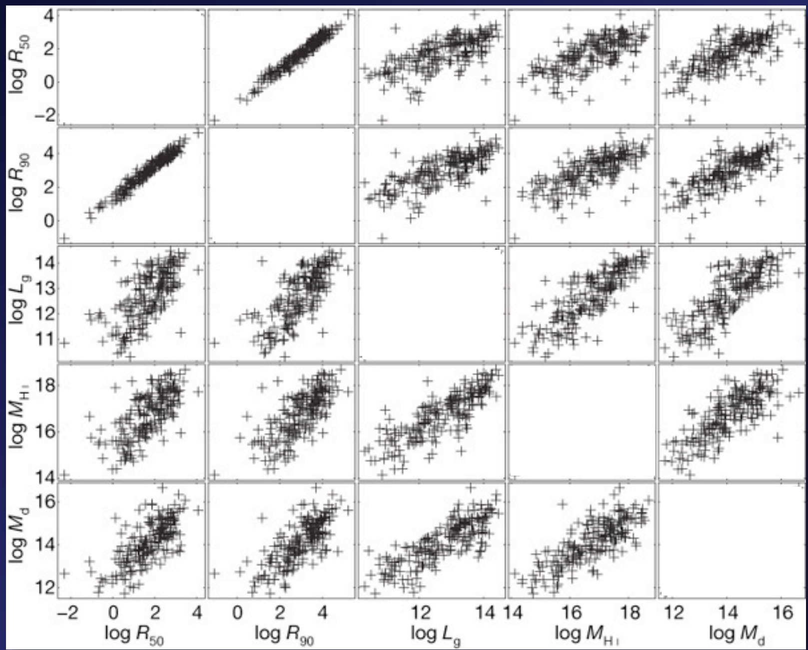
Mass Discrepancy - Acceleration Relation

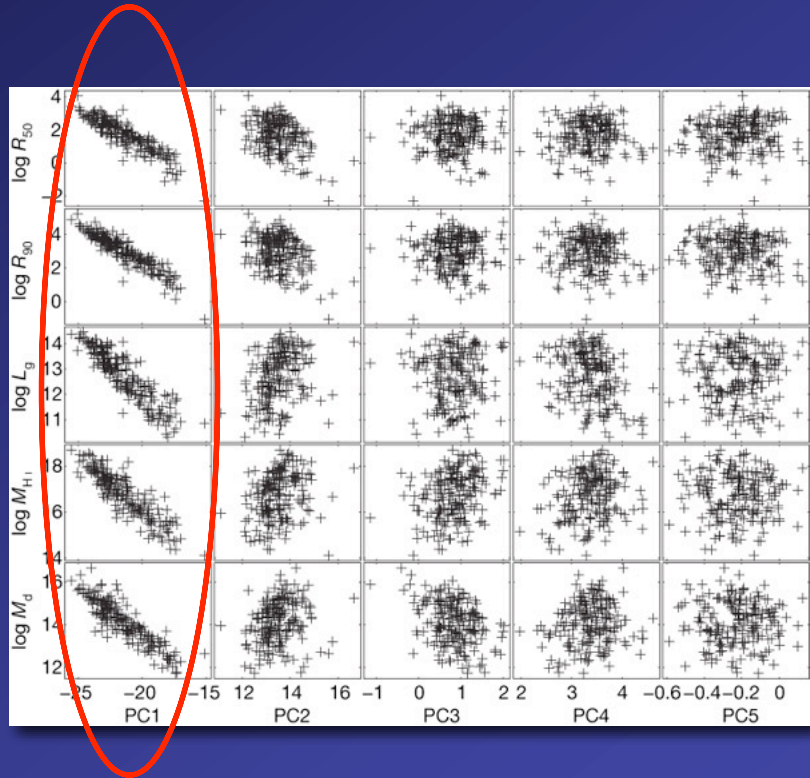


$$\mathcal{D} = \frac{V^2}{V_b^2} = \frac{V^2}{\Upsilon_* v_*^2 + V_g^2} = 1/\mu_{\mathrm{MOND}}$$

McGaugh (2004)

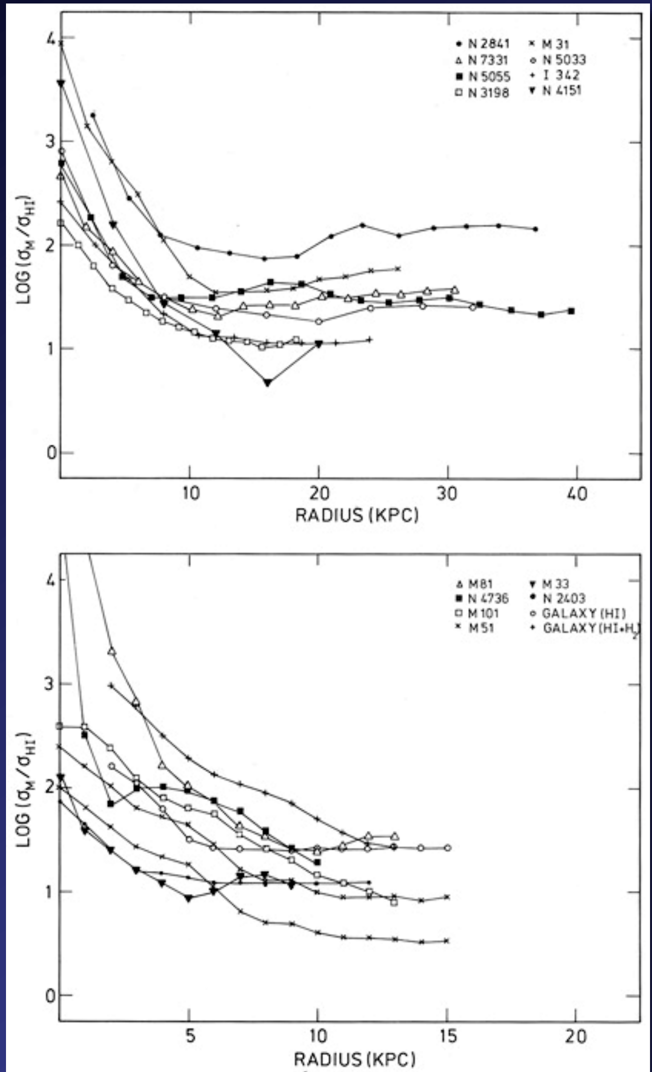
Galaxies are a 1-Parameter Family

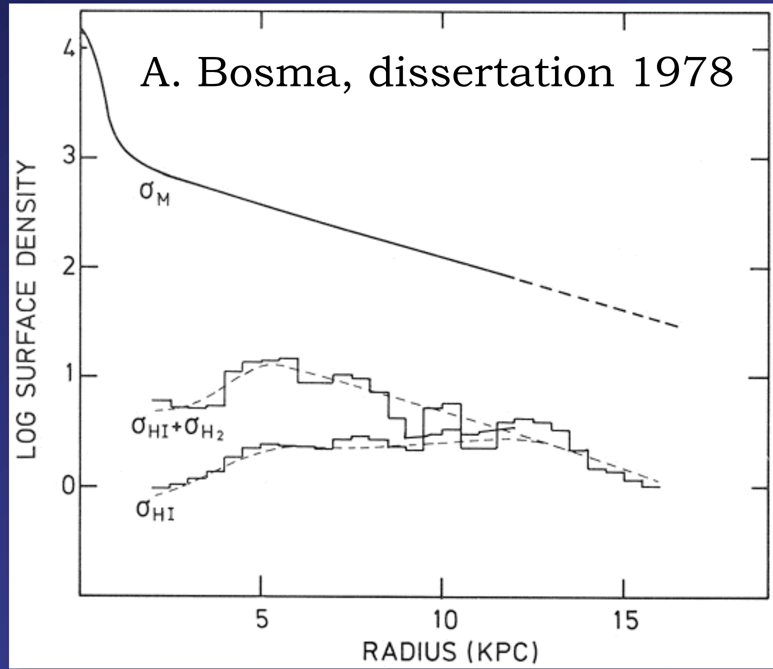




Disney et al. 2008

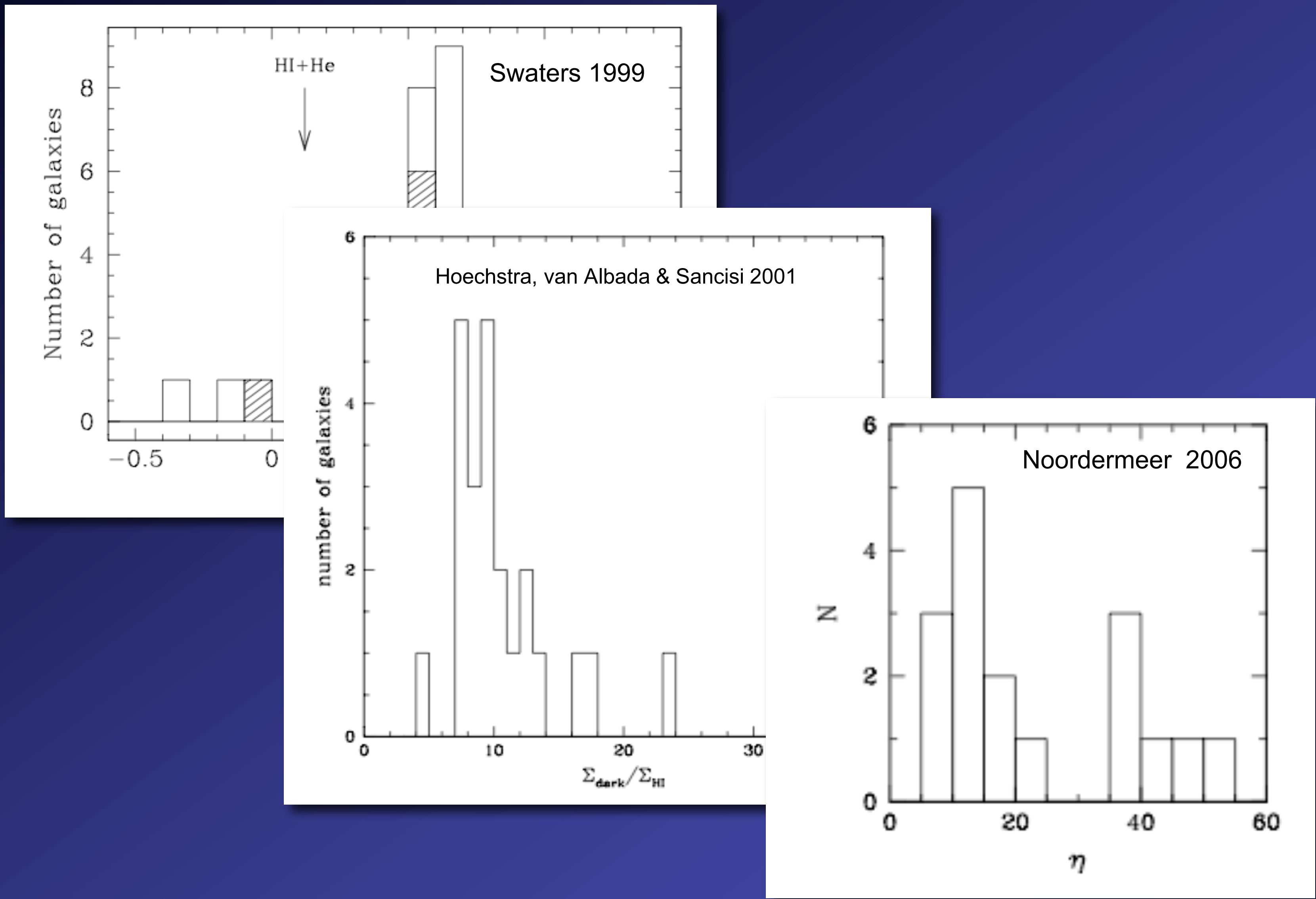
The “Bosma Effect”



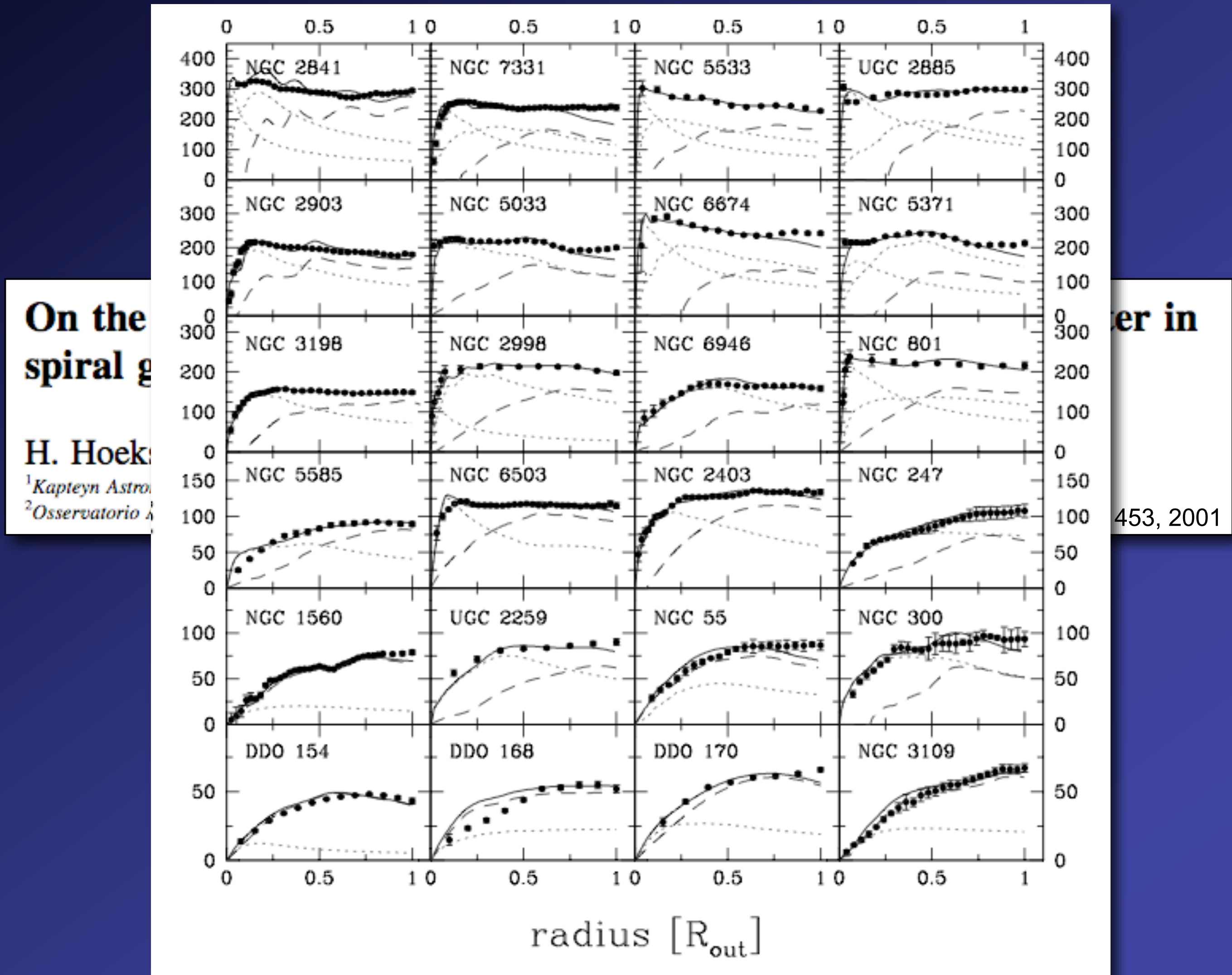


“… the ratio [of dynamic to gas surface densities] *… is more or less constant beyond about one-third of the optical radius, with HI being the dominant contributor … in the outer parts”*

Dependence on Galaxy Parameters



Testing the Bosma Effect



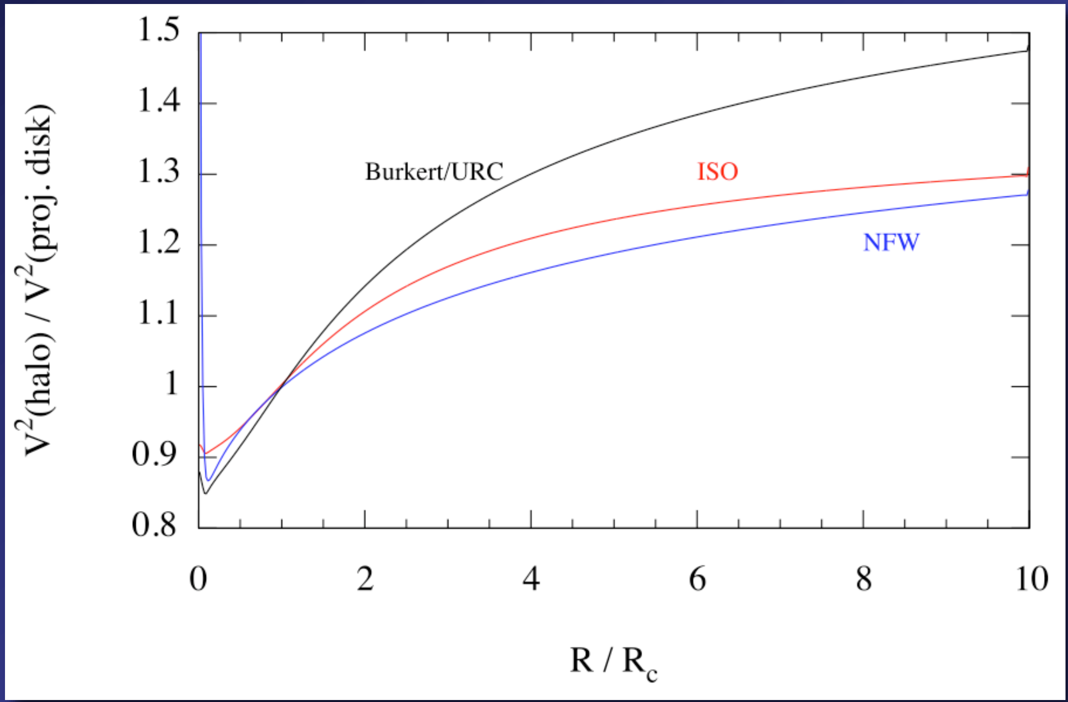
Conclusions of HvA&S

- "*The model curve* [of the poorer fits] *does not agree with the observed rotation curve in the inner region.*"
- There are "… *large wiggles that are not present in the observed rotation curve.*"
- "*The model rotation curve drops below the observed rotation curve at large radii.*"
- "… *scaling of HI to represent the dark component only works in combination with maximal discs.*"
- "… *our sample is biased against galaxies with* R_{out}/h_{HI} *substantially larger than 3.*"
- "… *for about two-thirds of the galaxies we obtain good fits to the data.*"
- "… *the good fits are somewhat coincidental.*"

Simply the Effects of CDM?

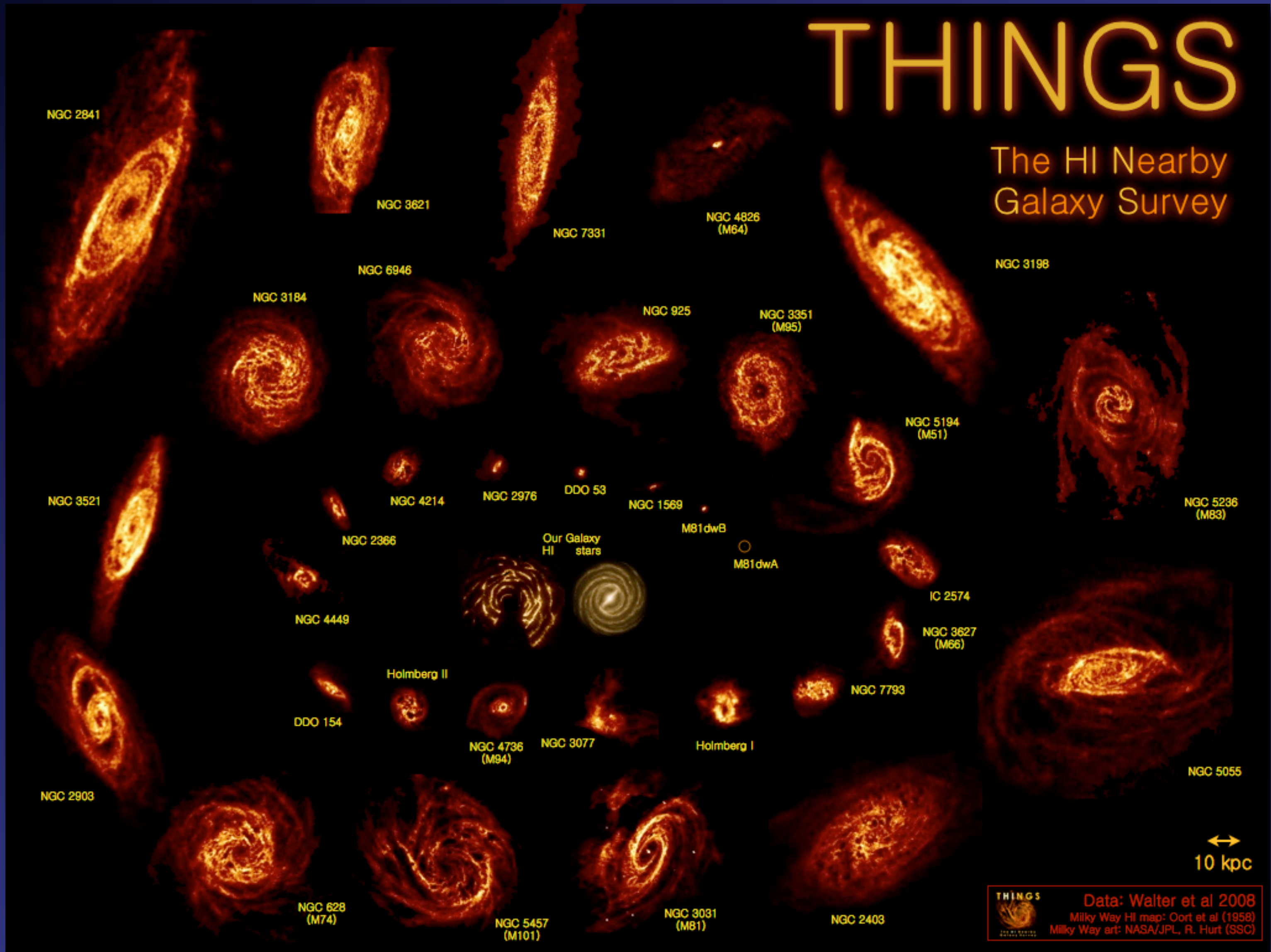
1978 : DM can be in the disc

2001 : CDM <u>must</u> be in the halo



$$V_{DM}(R)^2 \propto V_{gas}(R)^2$$

The Bosma Effect in Nearby Galaxies



Spitzer Infrared Nearby Galaxy Survey

Rotation Curve Models

Normally :

$$V^2_{tot} = \Upsilon_{disk} V^2_{disk} + \Upsilon_{bulge} V^2_{bulge} + V^2_{HI+He} + V^2_{DM} + V^2_{mol\text{-}H+He}$$

$$V^2_{DM} = f(\rho_0, r_c),\ f(V_{200}, c),\ f(V_{200}, c(V_{200})),\ \ldots$$

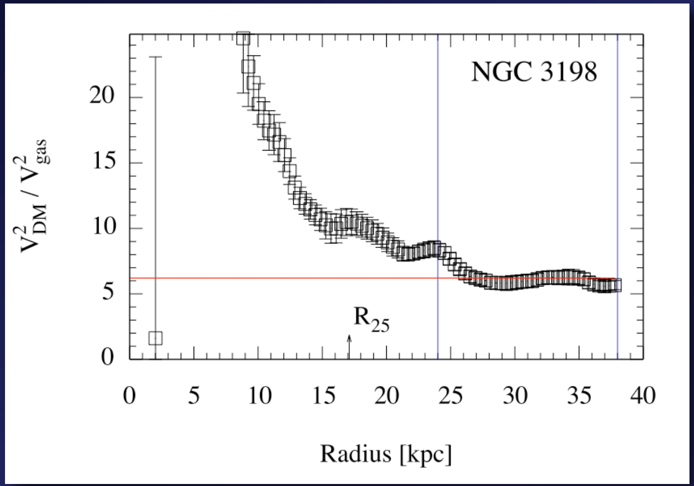
"Simple" Bosma effect = "HI-scaling" :

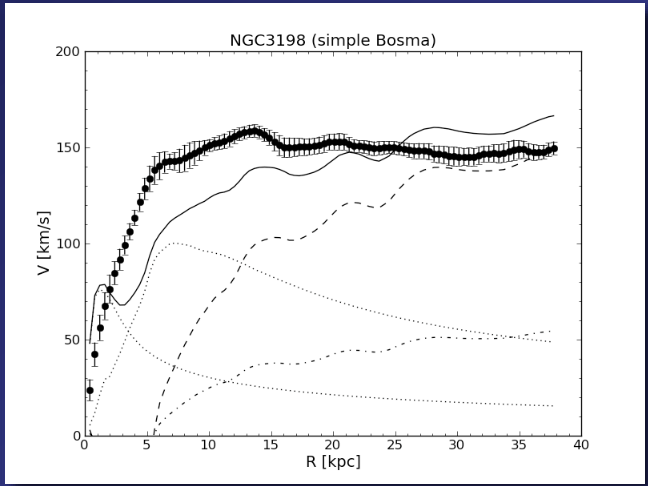
$$V^2_{tot} = \Upsilon_{d,IR} V^2_{disk} + \Upsilon_{b,IR} V^2_{bulge} + (1+f_{HI}) V^2_{HI+He}$$

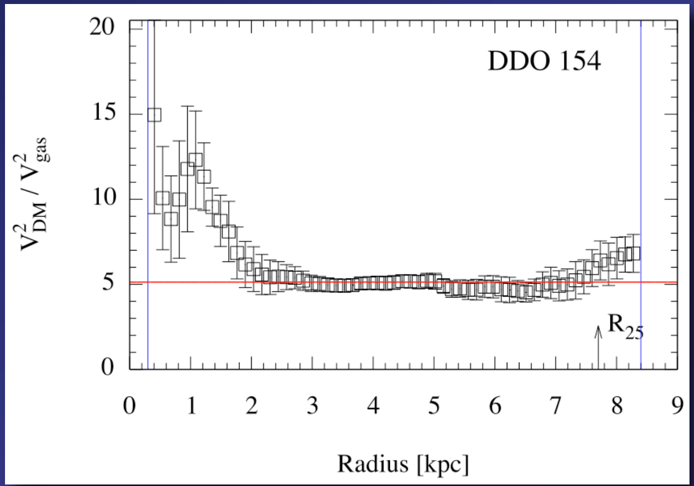
"Classic" Bosma effect :

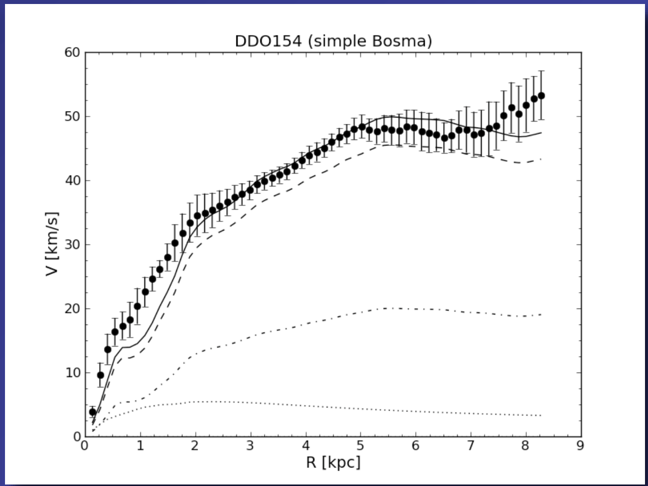
$$V^2_{tot} = (1+f_{disc}) \Upsilon_{d,IR} V^2_{disk} + \Upsilon_{b,IR} V^2_{bulge} + (1+f_{HI}) V^2_{HI+He}$$

The “simple” Bosma Effect: Pure HI-scaling

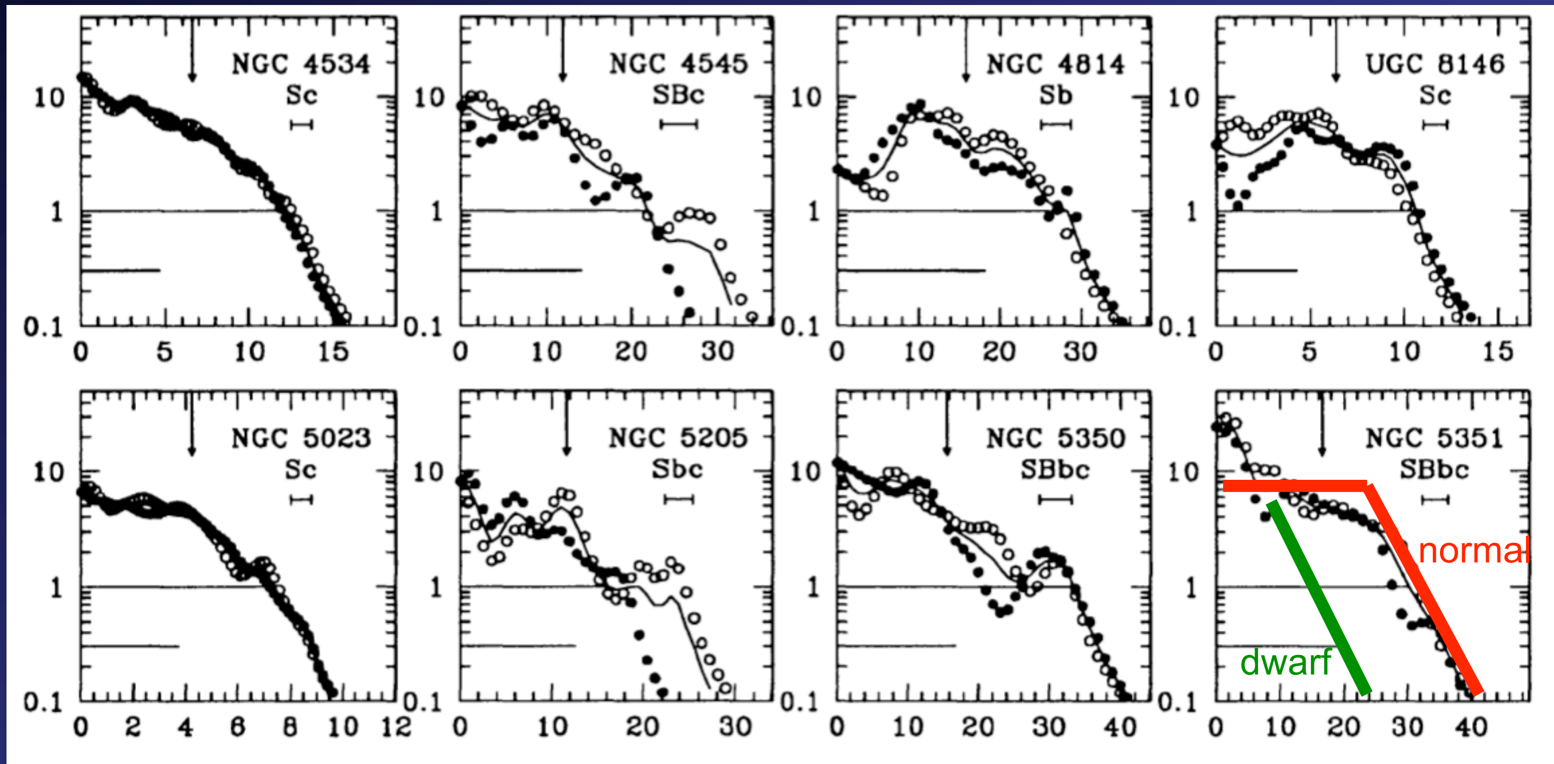






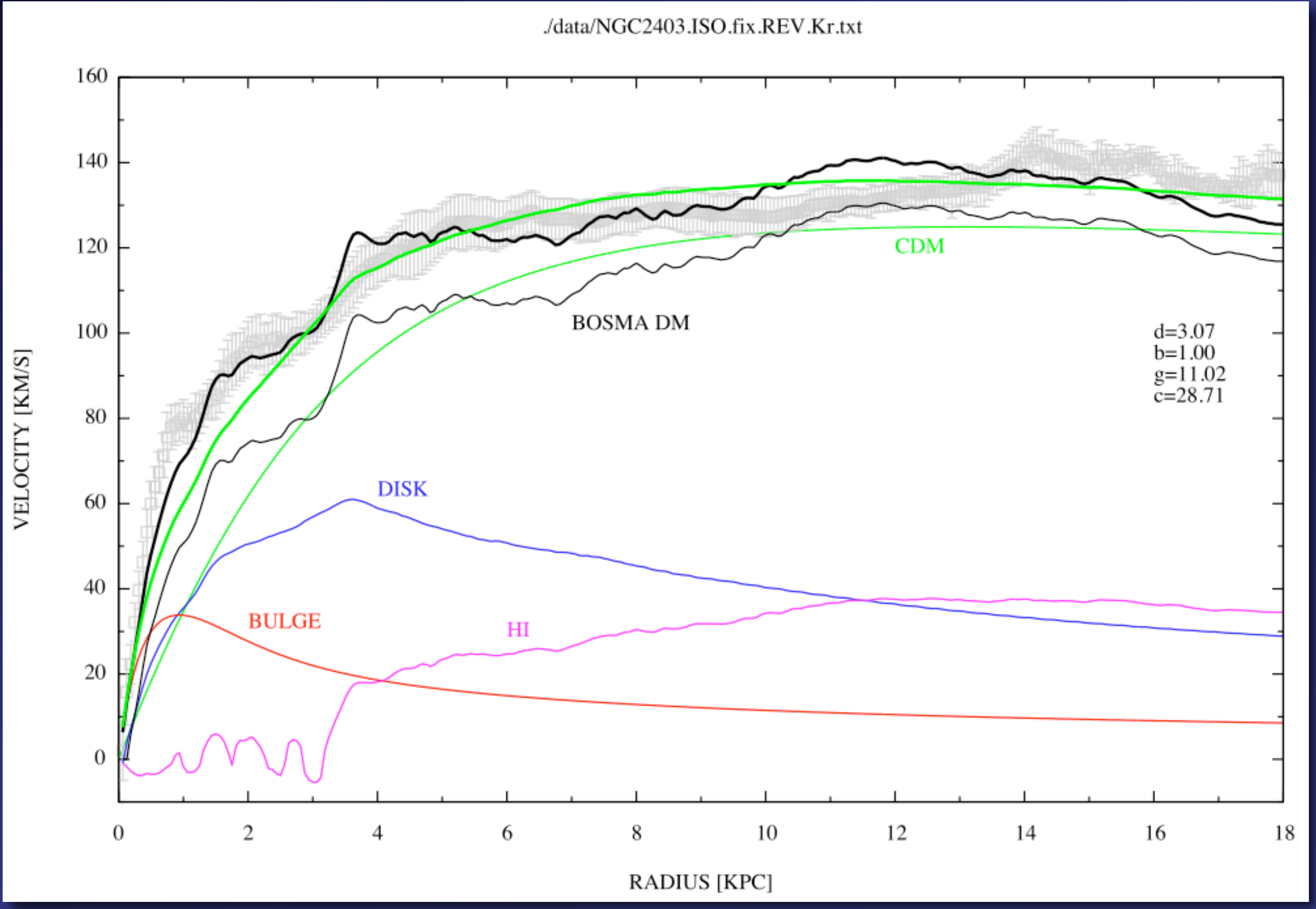


HI Distributions of Galaxies

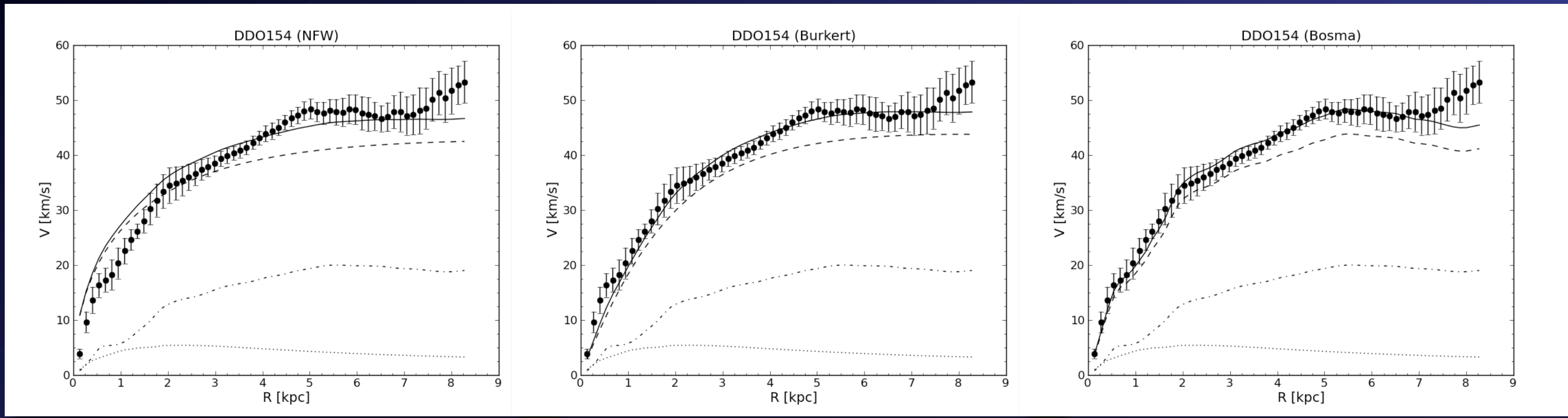


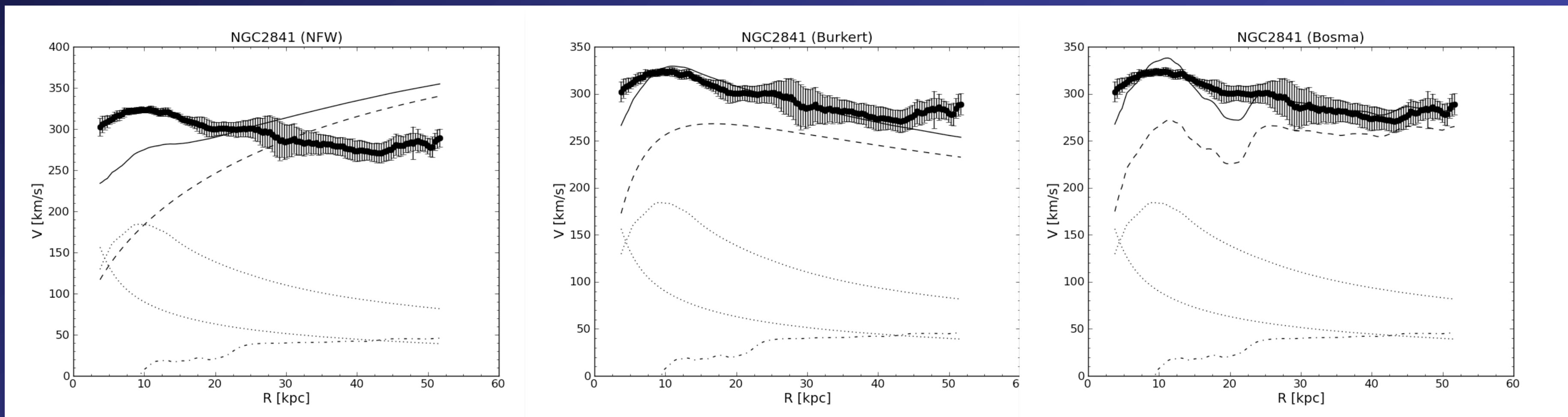
Rhee & van Albada (1996)

The “classic” Bosma Effect

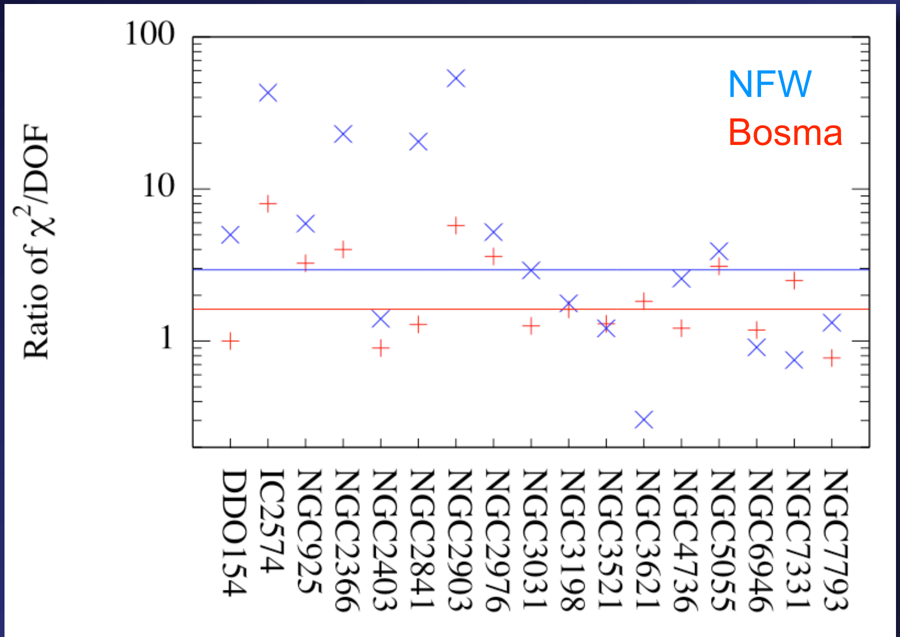


Bosma effect vs. CDM



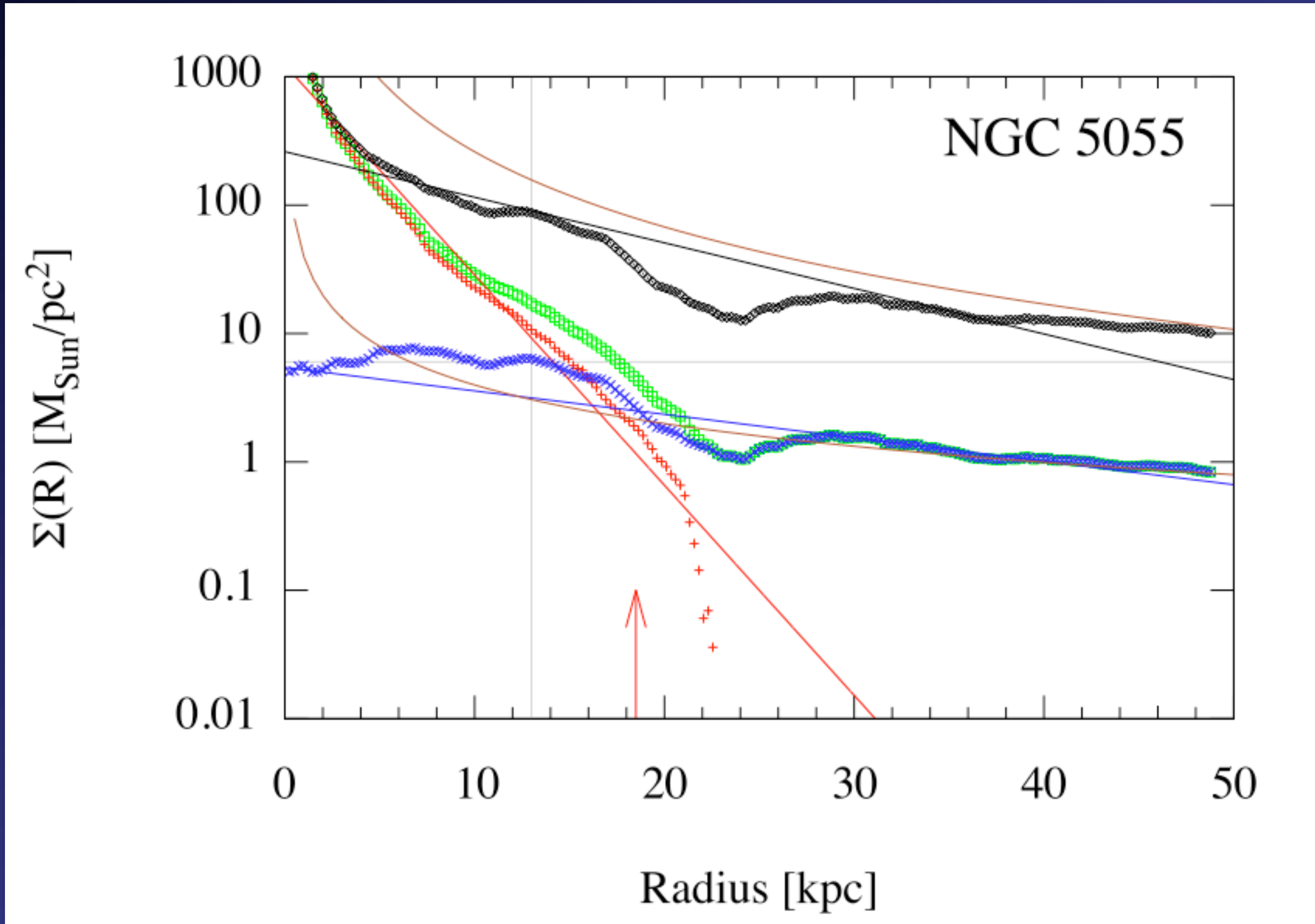


Results

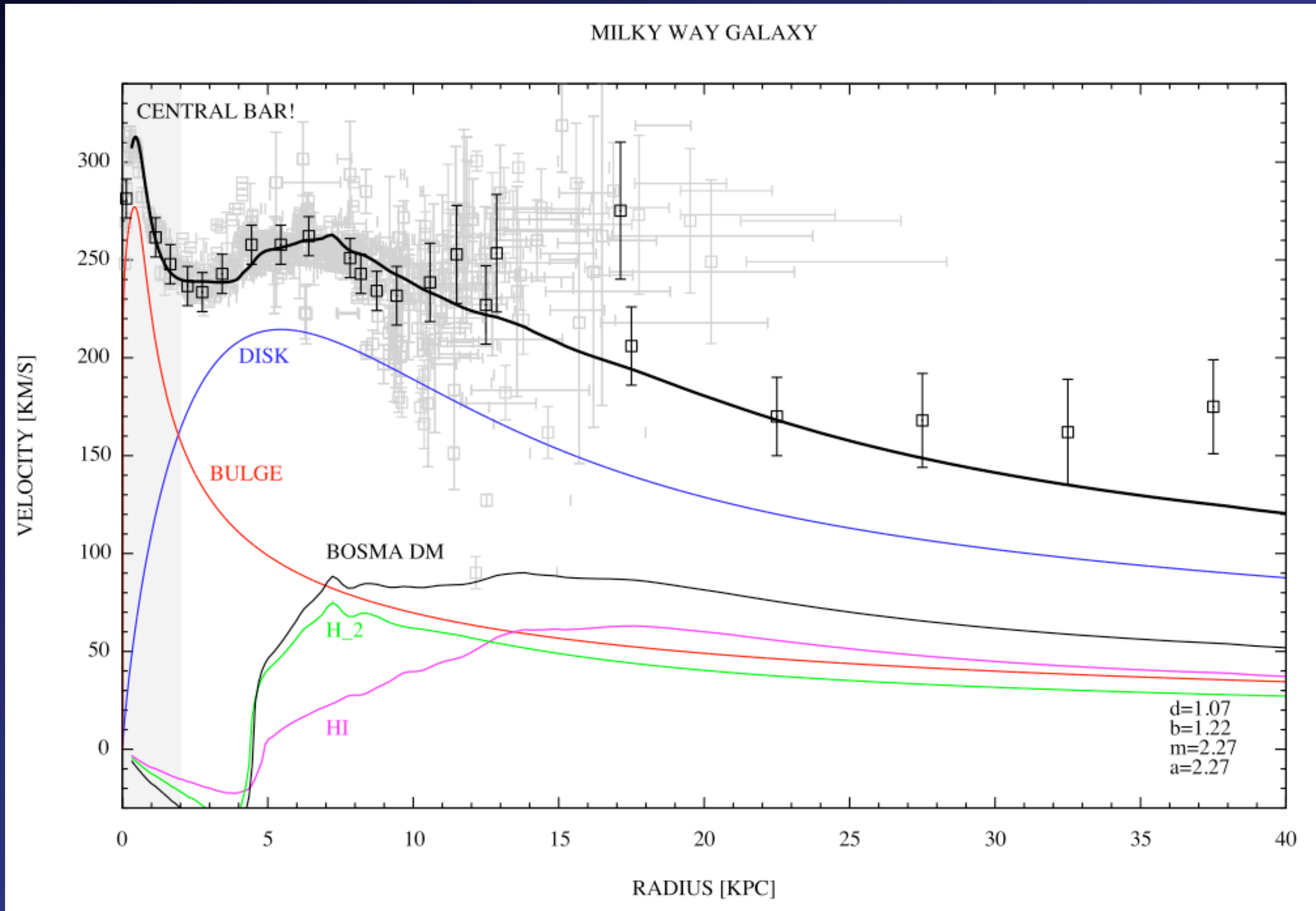


- Self-consistent NFW model ruled out
- “Simple” Bosma effect = “HI scaling” only works outside of the stellar disk
- “Classical” Bosma effect with stellar proxy nearly as good as URC/Burkert

Implied Surface Densities

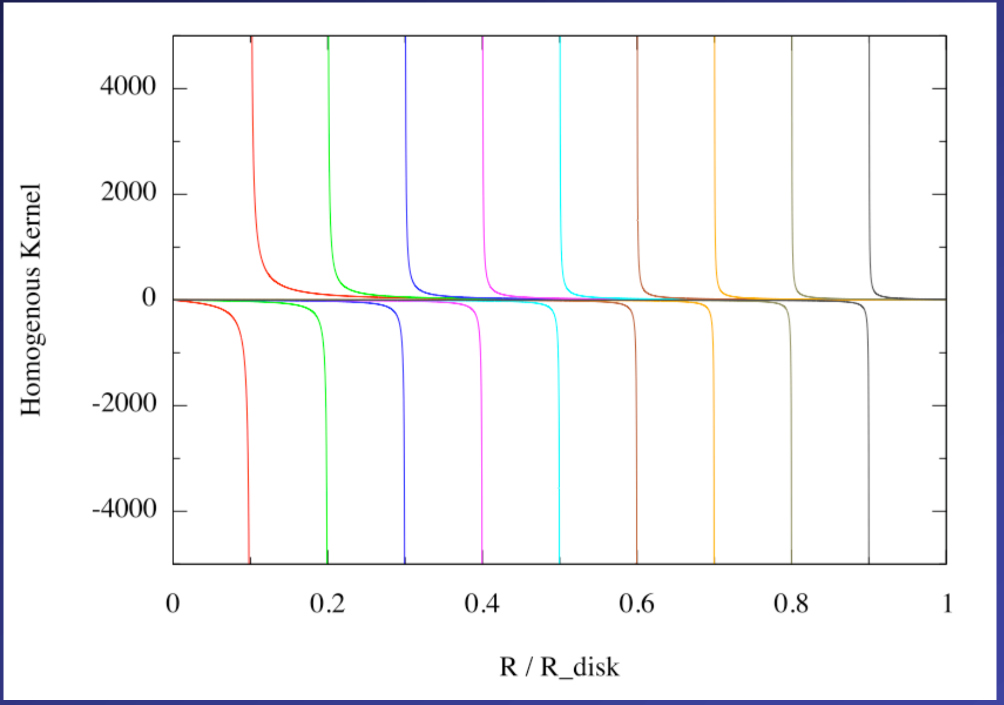


Paper II: Including More of the ISM



Paper III: What does the Bosma effect mean?

- CDM? : disk potential fundamentally different from that of a spherical distribution

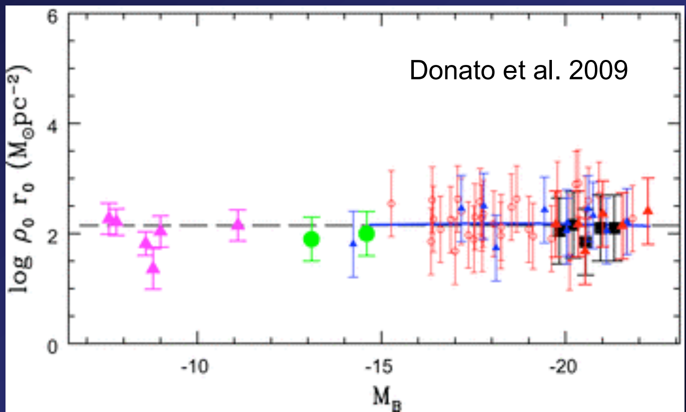


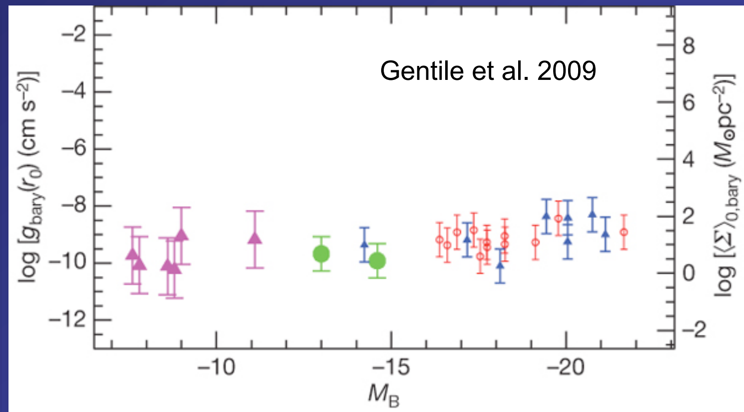
CCM has no means of teaching small amounts of gas in a disk to behave as if it was distributed exactly as a spherical CDM halo - is galactic DM then baryonic??

What does the literal Bosma effect mean?

- Only about 10-70% of the baryons are visible
- The Utility of “maximal disks” is explained
- The relative mean surface density constancy is explained

$$<\Sigma>_{DM} / <\Sigma>_{baryons} \approx <g>_{DM} / <g>_{baryons} \approx 5$$





- The extended baryonic Tully-Fisher relation (Pfenniger & Revaz 2005)

$$\log (M_{*} + c\ M_{HI+He}) = a + b * V_{rot} \qquad c \sim 3$$

Discs are More Efficient Sources of V^2

DM sphere with flat rotation curve:

$$\rho(r) = (M_{vir}/4\pi r_{vir})(r_{vir}/r)^2$$

$$V(r)^2 = G\, M_{vir}/r_{vir} = \text{const}$$

Mestel disc:

$$\Sigma(R) = (M_{disc}/(2\pi R_{disc}{}^2))\ (R_{disc}/R)\ \text{acos}(R_{disc}/R)$$

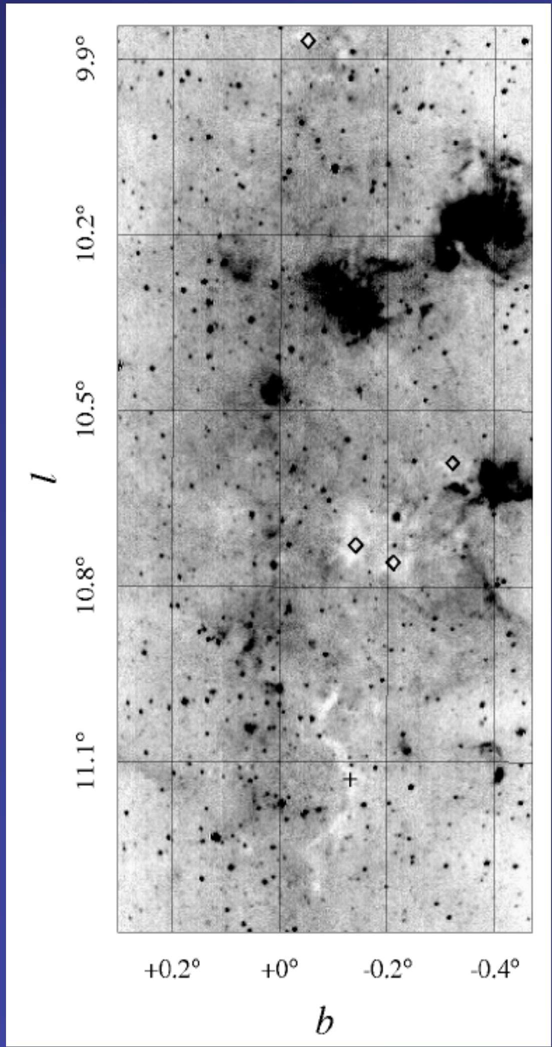
$$V(r)^2 = \pi G\, M_{vir}/2r_{vir} = \text{const}$$

$M_{disc}/M_{vir} = (2R_{disc}/\pi r_{vir}) \approx 10$ kpc / 100 kpc = 0.1

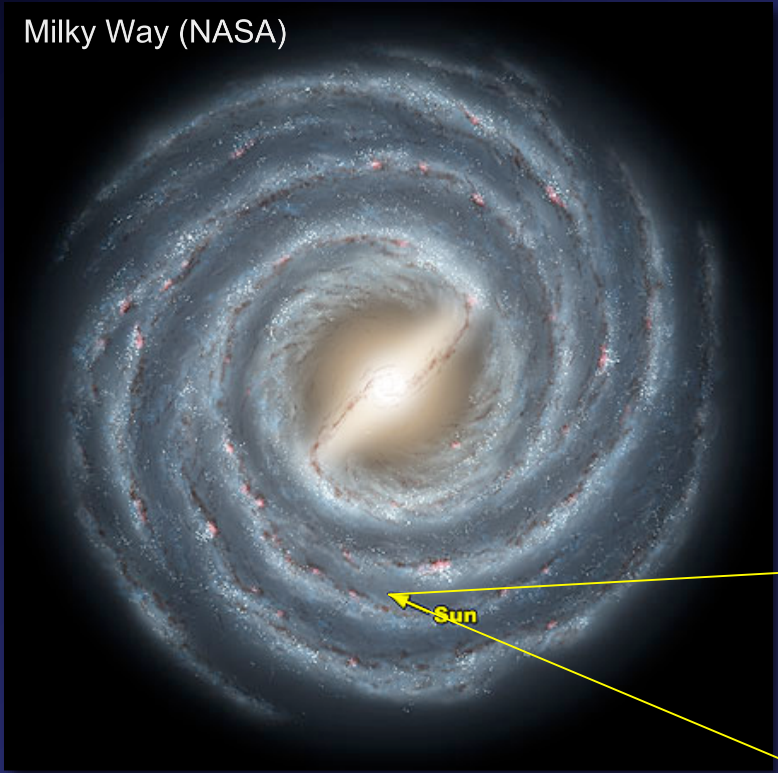
Are there other Signs of a Hidden ISM?

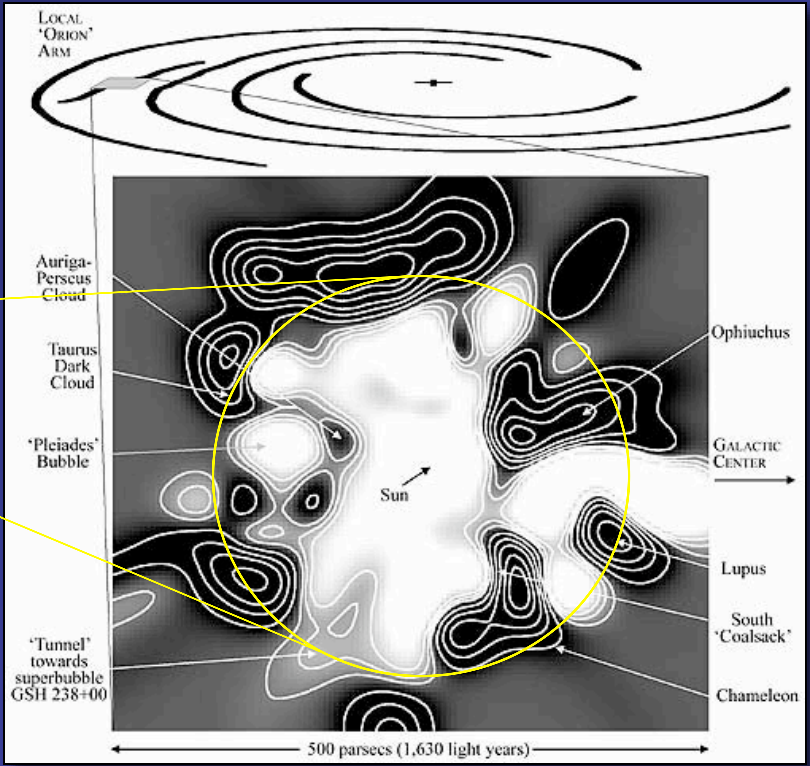
- Cold H_2 "clumpescules"
  (Pfenniger & Combes 1994)
- "Extreme Scattering Events", l~AU
  (Walker & Wardle 1998)
- MSX, PLANCK "cold cores", l~pc
  (Egen et al. 1998, Ade et al. 2011a)
- EGRET "dark gas"
  (Grenier et al. 2005)
- Dwarf galaxies from collisional debris
  (Bournaud et al. 2007)
- PLANCK "dark gas" phase
  (Ade et al. 2011)
- HERSCHEL dwarf galaxy survey
  (Madden et al. 2011)

Egen et al. 1998

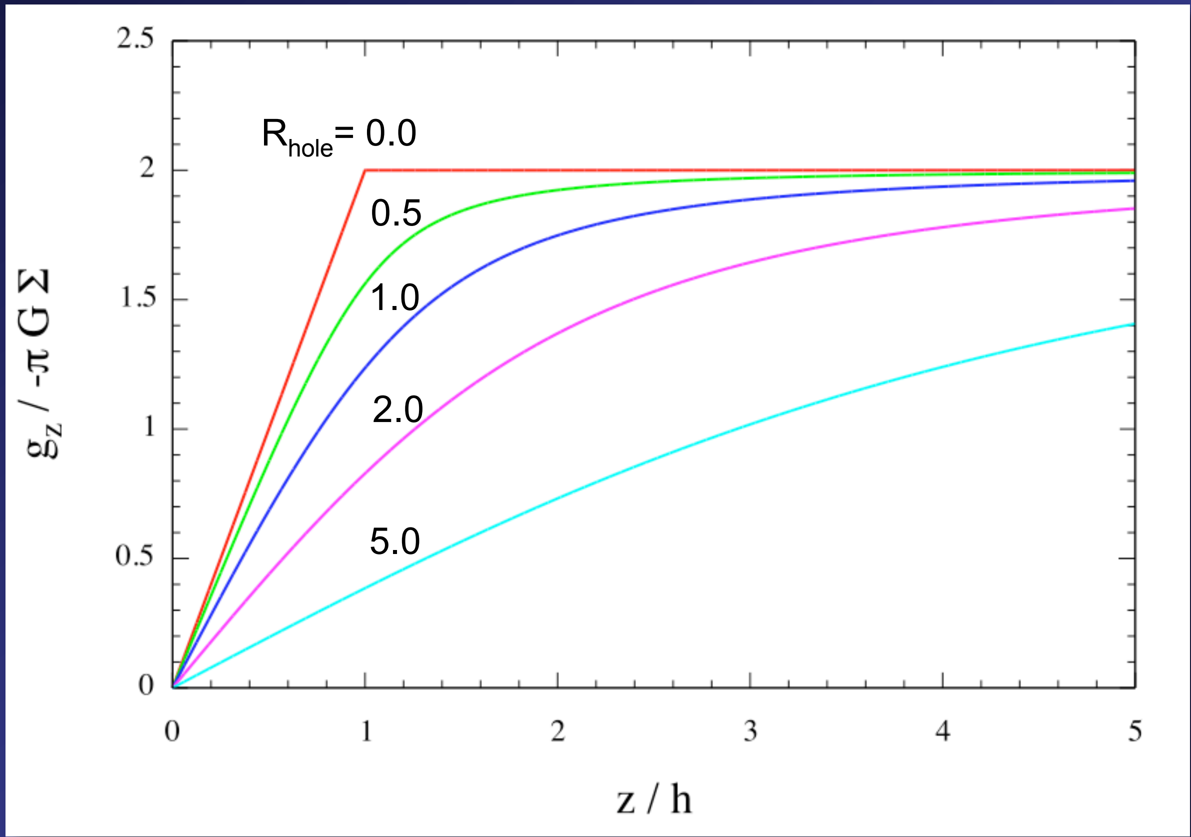


Local Stellar Dynamics Revisited





The Local Mass-Density Revisited



The Bosma Effect & MOND

Define :

$$g_{tot} = g_* + g_{gas} + g_{dDM}$$
$$= g_{vis} + g_{dDM} = g_* + g_{ISM} = g_* + (1+f_B)\ g_{gas}$$

Thus (Dunkel 2004) :

$$\varepsilon \equiv g_{tot}/g_{dDM} - 1 = g_{vis}/g_{dDM}$$
$$\varepsilon/(\varepsilon+1) = g_{vis}/g_{tot} = \mu(\varepsilon)$$
$$g_{vis} = \mu(\varepsilon)\ g_{tot}$$

MOND :

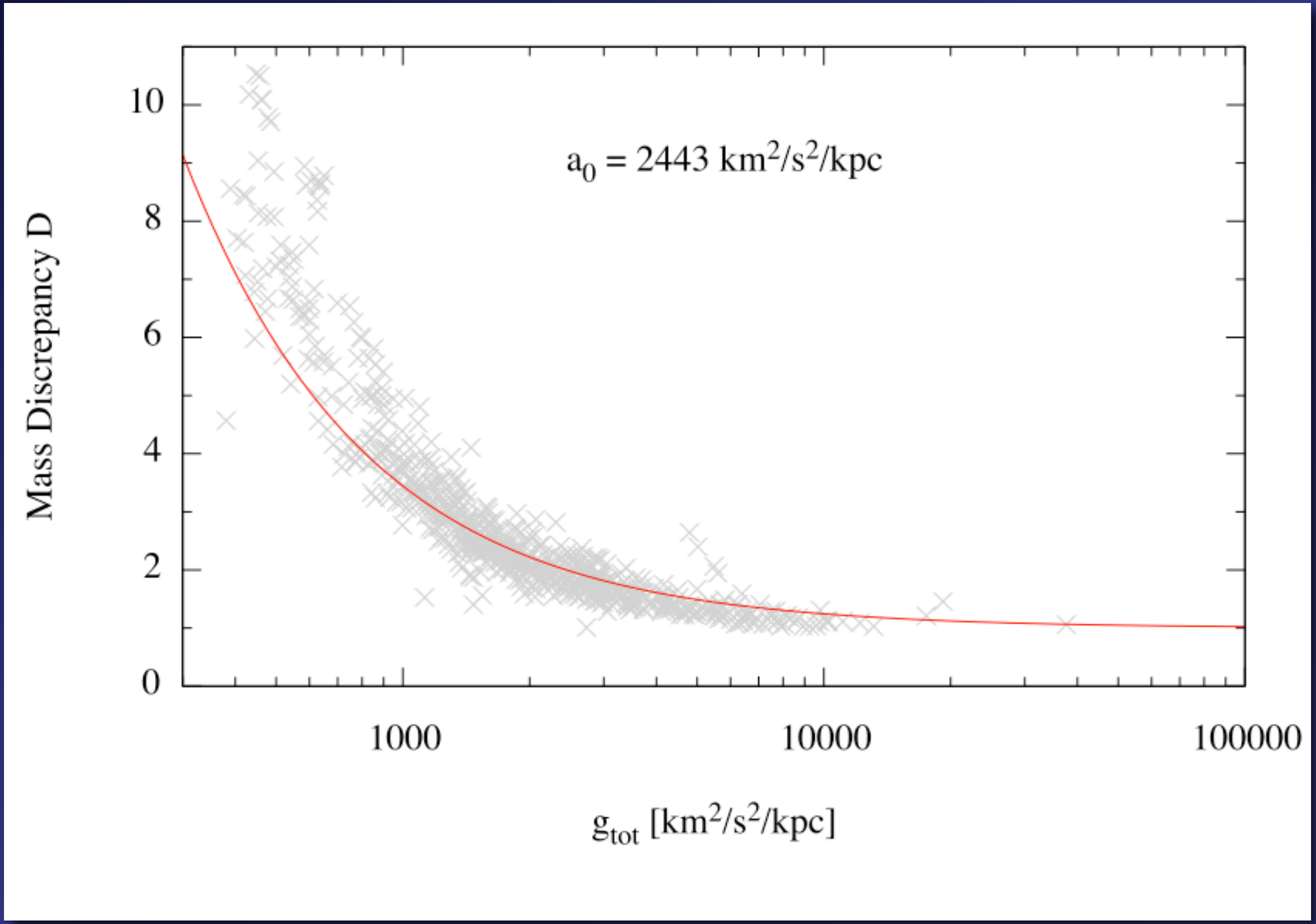
$$g_{vis} = \mu(x)\ g_{tot}$$
$$x/(x+1) = \mu(x)$$
$$x = g_{tot}/a_0,$$

If $x = \varepsilon$:

$$g_{tot}/g_{dDM} - 1 = g_{tot}/a_0$$
$$1/a_0 = 1/g_{dDM} - 1/g_{tot}$$
$$g_{tot}/a_0 = g_{vis}/g_{dDM} = g_*/g_{dDM} + 1/f_B$$
$$\approx g_*/g_{dDM}$$

The local gravitational field (and approximately the total local surface density) determines how much mass is in stars vs. in dDM

The Mass Discrepancy-Acceleration Relation

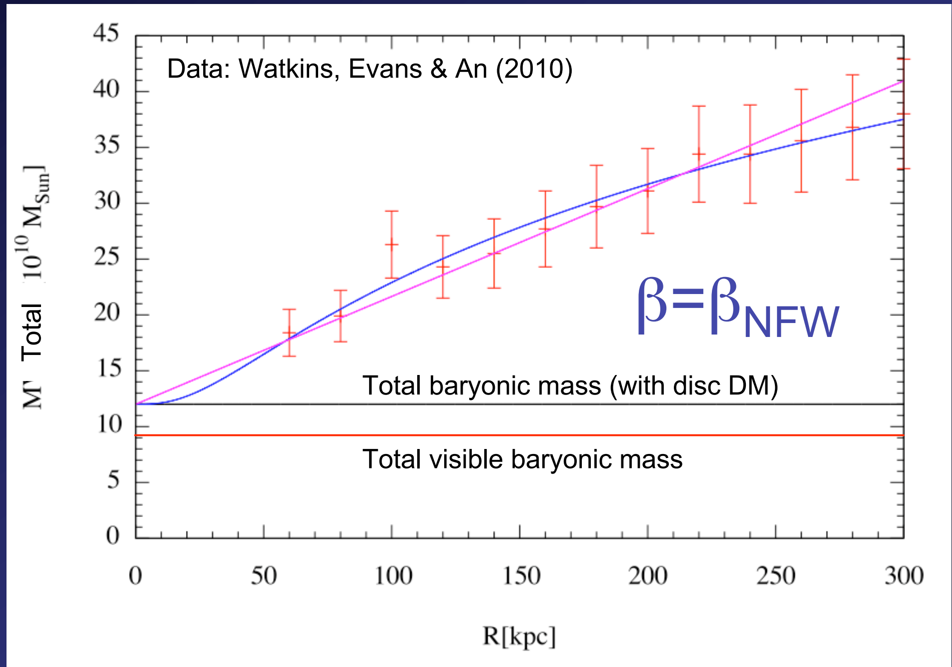


Halo Mass of the Milky Way Revisited

- Estimates for total baryonic mass
  $M_b+M_d+M_g+M_{dDM} \approx (0.1+0.7+0.1+0.3)\ 10^{11}\ M_{Sun} \approx 1.2 10^{11}\ M_{sun}$
- Concordance assumptions & result (Watkins, Evans & An 2010)
  - Most of mass in NFW halo with scales >> r_{vis}, all satellite galaxies observed are bound
  - Result: $M_{halo}(r<300\ kpc) \sim 13\ 10^{11}\ M_{Sun}$ ~ 15x visible disc
- Non-standard assumptions & result
  - Kinematics of satellite galaxies with r > 40 kpc
  - Isotropy parameter $\beta \sim 0$
  - Leo I & Hercules are not bound (2 most extreme outliers from 28)
  - Result: $M_{halo}(r<300\ kpc) \sim 4\ 10^{11}\ M_{Sun}$ ~ 3x total disc

The results of satellite kinematics depends upon poor statistics & what one assumes, but one needs a modest (W?)DM halo at scales of the Local Group.

The Bosma Effect & Warm DM



- Disk DM cannot explain kinematics at large distances (e.g. Milky Way & M31 satellites, massive ellipticals)
- Disk DM cannot explain galaxy clusters
- WDM naturally fills in the gap at large radii.

Disk Stability?

- Increase Σ(R) by a factor of ~3, $Q = \sigma\kappa/\pi G\Sigma < 1$
- Real discs are not uniform, axisymmetric, thin
- Real ISM chemistry complicated
- Read ISM is fractal
- Stability of turbulent media complicated
  (Romero, Burkert, Agertz 2010)
- Spiral structure is non-stationary
  (Sellwood 2010)
- m=1 structure seen in 56% of non-interacting galaxies
  (Van Eymeren et al. 2011)
- m=1 structure seen in inner galaxies
  (Rix & Zaritsky 1995)
- Dark component in discs are stabler than one expects
  (Revaz, Pfenniger, Combes & Bournaud 2009)

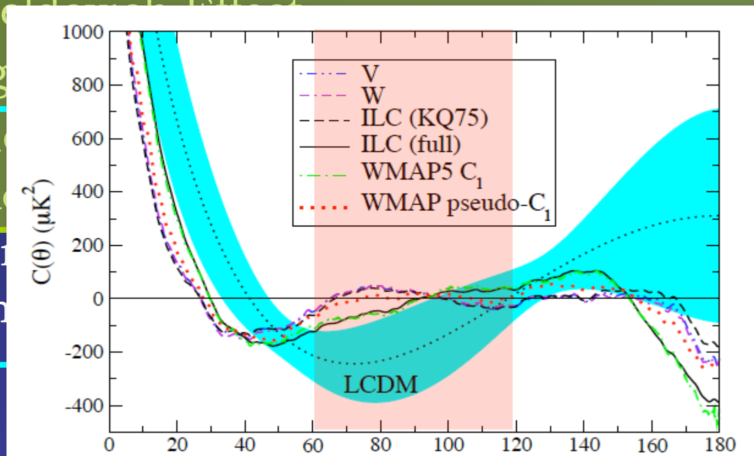
Q > 1 keeps galaxies from looking like galaxies

The Lines of Evidence for Cold DM

- Galaxy Dynamics
  - Stellar dynamics in the solar neighborhood
  - Spiral galaxy rotation curves
  - Stability of galaxy disks, spiral density waves
  - Projected kinematics of elliptical galaxies
  - Local Group kinematics
  - X-ray gas in elliptical galaxies
  - Strong gravitational lensing
- Galaxy Clusters
  - X-rays
  - Strong gravitational lensing
  - Weak gravitational lensing (e.g. “bullet cluster”)
  - Sunyaev-Ze
- Cosmic Backg
- Primordial nu ... ure formation
  - Baryonic a
  - Galaxy cor
  - Number an

WDM

CDM



Copi et al. 2010

Summary

- The "Bosma effect" - the correlation between the centripetal contribution of the dynamically unimportant visible gas and DM is clearly seen in the THINGS+SINGS data.
- It is physically implausible for DM in a spherical halo to force the ISM in a disk to show exactly the same centripetal signature, despite different geometries.
- The Bosma effect appears to be telling us that there is more baryonic matter in the discs of spiral galaxies and no need for a halo of COLD DM.
- The Bosma effect explains lots (but not all) of the baryon-DM correlations
- The theory and implications of disc DM need to be re-considered.
- A non-cold DM component is still needed for the Local Group, massive galaxies, clusters, and LSS
- W/HDM and baryonic disc DM seem to be a perfect match.