No Evidence of Dark Matter in the Galactic Disk

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Moni Bidin et al. (2010, ApJ, 724, L122) - M10

Moni Bidin et al. (2011, in prep.) - PII

The spatial distribution of Galactic Dark Matter (DM) provides information about its nature

Examples:

Models dominated by hot DM predict round halo ($q=c/a\approx0.8$)

(Peebles 1993, Princeton Univ. Press)

Cold DM simulations result in triaxial DM halo

(Warren et al. 1992, ApJ, 399, 405)

Inclusion of gas dynamics result in flat oblate halo ($q=0.5$)

(Dubinski 1994, ApJ, 431, 617)

Massive decaying neutrino models require very flat halo ($q=0.2$)

(Sciama 1990, MNRAS, 244, 1)

The direct detection experiments need to compare with estimates of the DM local density

(e.g.: deriving WIMP interaction cross-section requires local density, Gaitskell 2004, ARNPS, 54, 315)

In ΛCDM cosmology, spiral galaxies form great part of their spheriodal component through accretion of smaller building blocks, but also accrete satellites into their disk

Lake (1989, AJ, 98, 1554) first proposed that, as satellites are torn apart, they deposit their DM in a dark disk

Read et al. (2008, MNRAS, 389, 1041) and Purcell et al. (2009, ApJ, 703, 2275) showed that a DM disk is a natural expectation of the ΛCDM model

"If the CDM cosmology represents the correct model of structure formation in the universe, it is certain that dark disks are virtually ubiquitous in disk galaxies." [Purcell et al. 2009]

The DM disk is strongly related to the debated merging origin of the stellar Thick Disk (TkD)

Alternative models (e.g. Bournaud et al. 2009, ApJ, 707, L1) do not expect a DM disk

Milgrom (2001, MNRAS, 326, 1261) argues that a *"phantom disk"* is also an expectation of MOND

The DM disk has become a benchmark for many theories, from cosmological galaxy formation to gravitational law (Bienaymé et al. 2009, A&A, 500, 781), and TkD origin

“Weighting” the Galactic disk by means of stellar kinematics is an ancient art

(Kapteyn 1922, ApJ, 588, 823; Oort 1932, BAN, 6, 249)

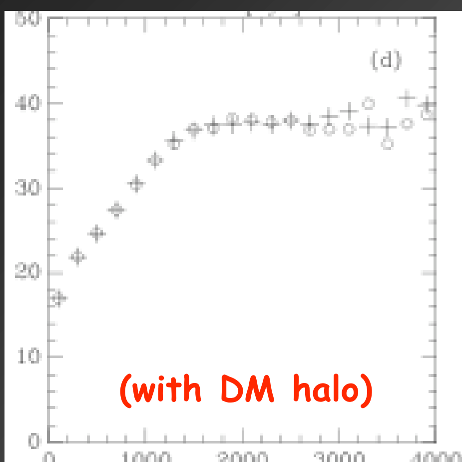
Solution of the Poisson-Boltzmann/Jeans equations:

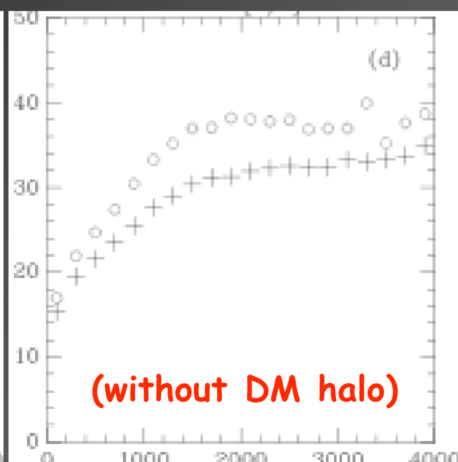
1) Surface mass density Σ at distance z from the plane (M_o pc^{-2})
(mass per unit area within ±z from the plane)

2) Local mass density ρ_0 (M_o pc^{-3})

Virialized system in steady state is required!
the conditions are satisfied in the Galactic disk

(see recent discussion by
Garrido Pestaña et al. 2010, ApJ, 722, L70;
Sánchez-Salcedo et al. 2011, ApJ, 731, L35)





The DM halo is detectable with this method
(see M10)

(Sánchez-Salcedo et al. 2011)

Rich literature:

Bahcall (1984, ApJ, 276, 169)
Kuijken & Gilmore (1989, MNRAS, 239, 605)
Kuijken & Gilmore (1991, ApJ, 367, L9)
Bahcall et al. (1992, ApJ, 389, 234)
Flynn & Fuchs (1994, MNRAS, 270, 471)
Crézé et al. (1998, 329, 920)
Holmberg & Flynn (2000, MNRAS, 313, 209)
Korchagin et al. (2003, AJ, 126, 2896)
Siebert et al. (2003, A&A, 421, 241)
Holmberg & Flynn (2004, MNRAS, 352, 440)
Bienaymé et al. (2006, A&A, 446, 933)
Moni Bidin et al. (2010, ApJ, 724, L122)

All investigations but two draw the same conclusion:

"No evidence for a significant amount of DISK DM"

"No evidence for a significant amount of DISK DM":

expected: Σ(1.1 kpc)= 75 M_o pc^{-2}

53 (VM, Holmberg & Flynn 2004) + 22 (DM halo, Olling & Merrifield 2001, MNRAS, 326, 164)

expected: ρ_0 = 95 mM_o pc^{-3} (85 VM + 10 DM halo)

1- results account for visible matter (VM) + "classical" DM halo only

(but the DM halo is always somehow less massive than expectations)

e.g.:

Σ(1.1 kpc)= 71±6 M_o pc^{-2} (Kuijken & Gilmore 1989)

Σ(1.1 kpc)= 74±6 M_o pc^{-2} (Holmberg & Flynn 2004)

Σ(1.1 kpc)= 68±11 M_o pc^{-2} (Bienaymé et al. 2006)

2- results account for VM only

(but within errors a round DM halo is allowed)

e.g.:

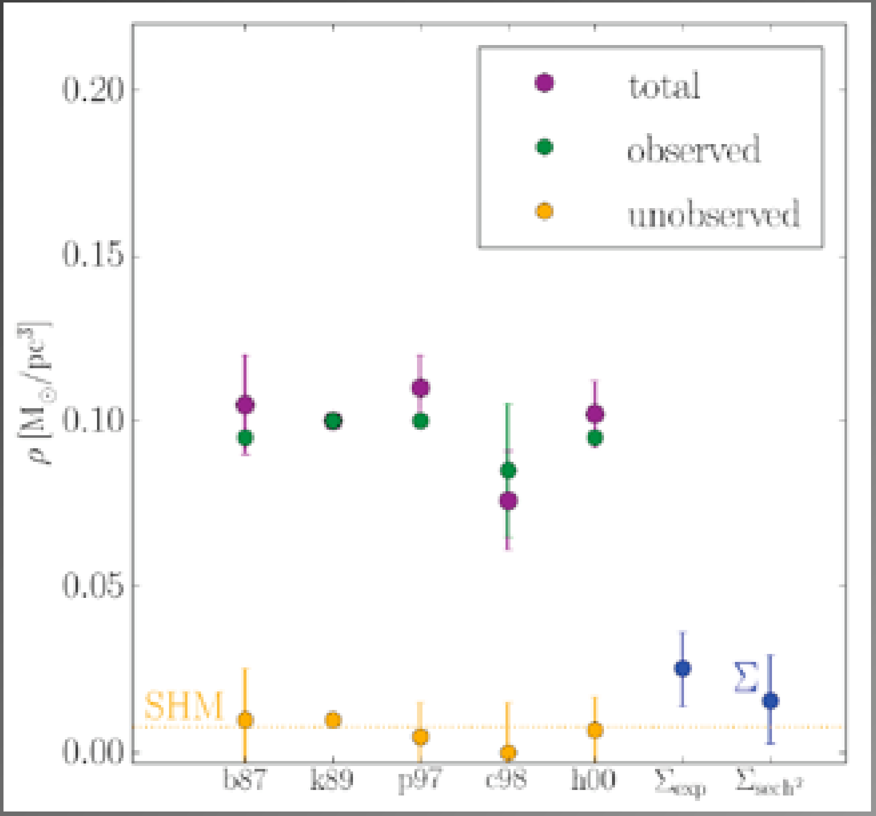
ρ_0 = 76±15 mM_o pc^{-3} (Crézé et al. 1998)

$\rho_0 - \rho_{0,VM}$= 3±8 mM_o pc^{-3} (Garbari et al. 2011, arXiv:1105.6339)

Some further constraints:

Crézé et al. (1998):
"there is just room for a spherical DM halo. Extreme changes of the parameters are needed to permit a significantly flatter halo"

Bienaymé et al. (2006):
"Flattenings larger than q=0.51 are excluded"



(Garbari et al. 2011)

Limited results:

1- Great observational effort required

2- Only vertical velocity component considered

(non-diagonal terms of dispersion matrix and radial component of Poisson equation neglected)

$$-2\pi G\Sigma(z) = \int_0^z \frac{1}{R}\frac{\partial}{\partial R}(RF_R)dz + F_z(z)$$

$$F_z = \frac{1}{\rho}\left[\frac{\partial(\rho\overline{W^2})}{\partial z} + \frac{\rho\overline{UW}}{R} + \frac{\partial}{\partial R}(\rho\overline{UW})\right]$$

$$F_R = \frac{1}{\rho}\frac{\partial(\rho\overline{U^2})}{\partial R} + \frac{1}{\rho}\frac{\partial(\rho\overline{UW})}{\partial z} + \frac{\overline{U^2} - \overline{V^2}}{R}$$

(1+2=) 3- Measurements limited to 1.1 kpc from the plane

(3->) - Small amount of DM in the considered volume

- uncertainties in the VM and observational errors

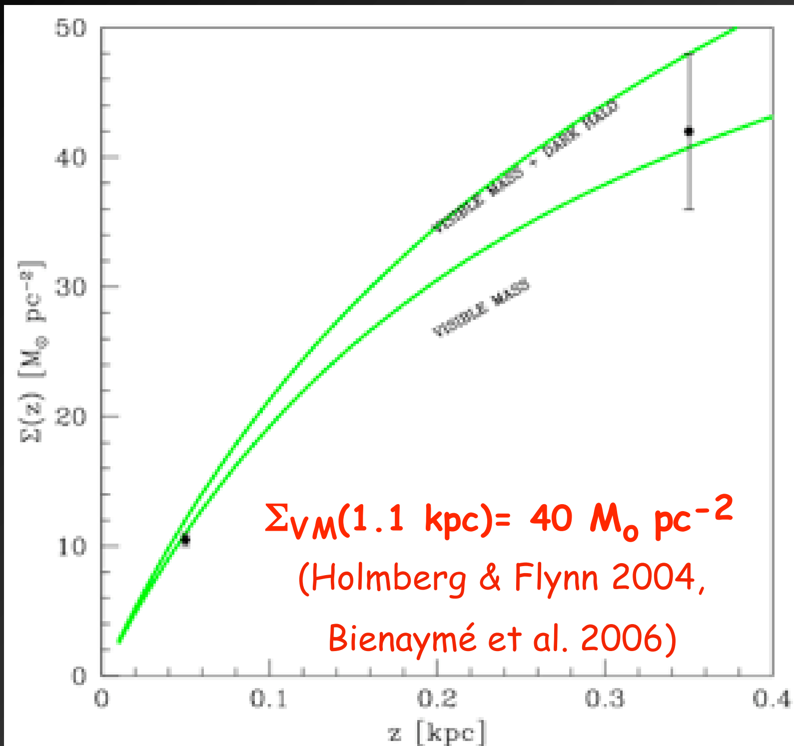
- No direct measurements

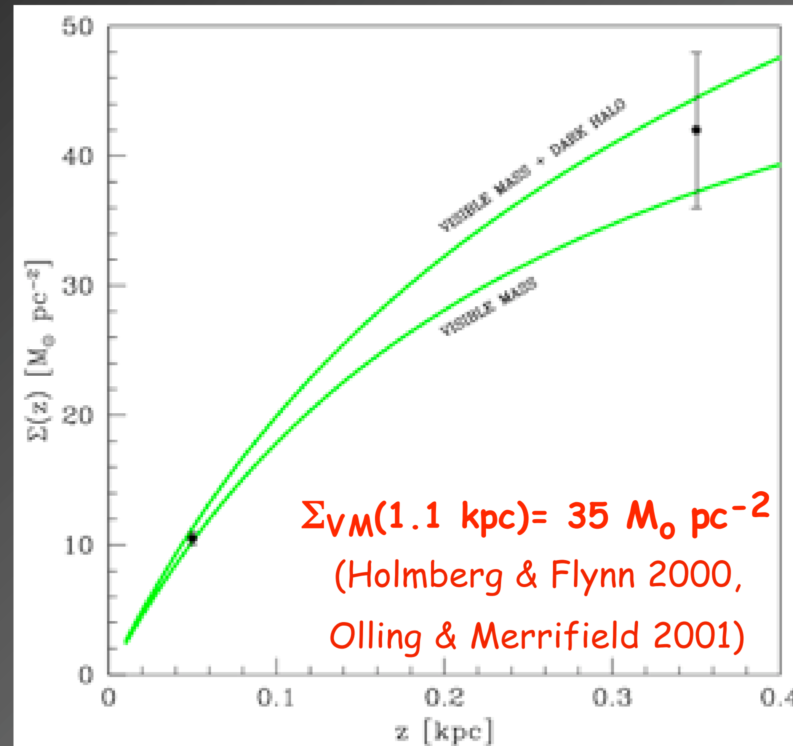
(fine-tuning of model parameters to fit observed quantitites)

Korchagin et al. (2003):

direct measurement by means of analytical expression

(cross-term of dispersion matrix neglected, radial component expressed through the Oort's constants)





M10:

First attempt to measure surface density beyond 1.1 kpc,

directly by means of an analytical expression, basing on full 3D kinematics

Set of very basic assumptions:

1- Virialized system in steady state

2- Exponential radial and vertical density fall-off (scale height-lenght: $h_{z\rho}, h_{R\rho}$)

(e.g., Juric et al. 2008, ApJ, 673, 864)

3- $h_{R\rho}$ is constant with z

(Cabrera-Lavers et al. 2005, A&A, 433, 173)

4- $\sigma^2_{uw}(z)$ antysimmetric ($\sigma^2_{uw}(0)=0$)

5*- Locally flat rotation curve

6*- No disk flaring

7- Symmetry: integral in ±z is twice the integral in 0-z

8- $F_z(0)=0$

9- No net radial and vertical stellar flux ($\langle U \rangle = \langle W \rangle = 0$)

*: hypothesis break-down considered

Inserting the Jeans equations in the Poisson equation, and integrating:

$$-2\pi G\Sigma(z) = \frac{\partial \sigma_W^2}{\partial z} - \frac{\sigma_W^2}{h_{z\rho}} - \int_0^z \frac{\sigma_U^2}{R h_{R\rho}} dz + \int_0^z \frac{\partial^2 \sigma_U^2}{\partial R^2} dz + \left(\frac{2}{R} - \frac{1}{h_{R\rho}}\right) \int_0^z \frac{\partial \sigma_U^2}{\partial R} dz - \frac{1}{R} \int_0^z \frac{\partial \sigma_V^2}{\partial R} dz + \sigma_{UW}^2 \left(\frac{2}{R} - \frac{1}{h_{R\rho}}\right) + 2\frac{\partial \sigma_{UW}^2}{\partial R} - \frac{1}{h_z \rho} \int_0^z \frac{\partial \sigma_{UW}^2}{\partial R} dz$$

Required:

- **Parameters: R, $h_{z\rho}$, $h_{R\rho}$**
- **Kinematical quantitites:**

$$\sigma^2_u(z),\ \sigma^2_v(z),\ \sigma^2_w(z),\ \sigma^2_{uw}(z)$$

- **The radial behavior of:** $\sigma^2_u(z)$, $\sigma^2_v(z)$, $\sigma^2_{uw}(z)$

Virialized population, large z-range, high above the plane

Modern surveys (e.g. SDSS, RAVE, Gaia) are providing such information

M10 and PII are "pioneering works":

(some information is still lacking)

the future is bright!

The data:

~400 red giant stars toward SGP (z=1.5-5 kpc)

Color cut (intermediate-metallicity stars)

Dwarf stars (d>63 pc) excluded with a cut in magnitude

Spectra: exclusion of residual low-metallicity ([Fe/H]<-1.5) or dwarf stars

cuts: |W|<150, |U|<300, -500<V<300 km s^{-1}

2MASS photometry

(Skrutskie et al. 2006, AJ, 131, 1163)

Absolute proper motions from SPM3

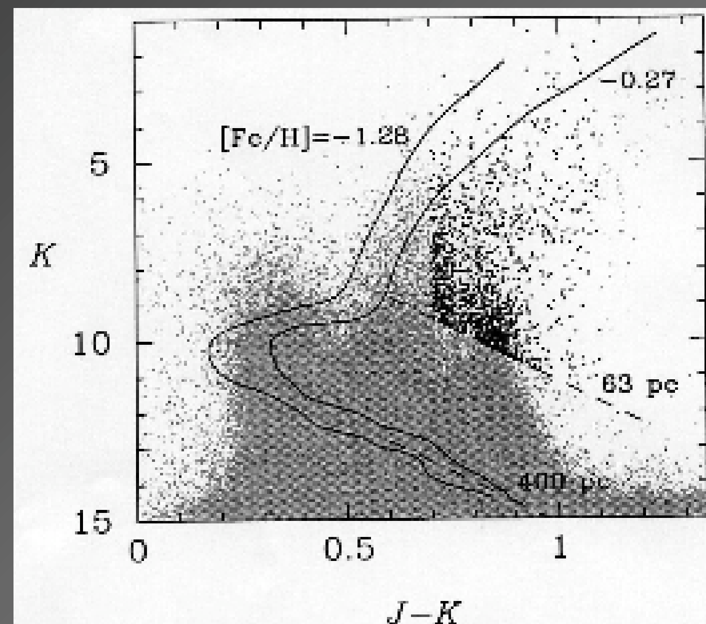
(Girard et al. 2004, AJ, 127, 3060)

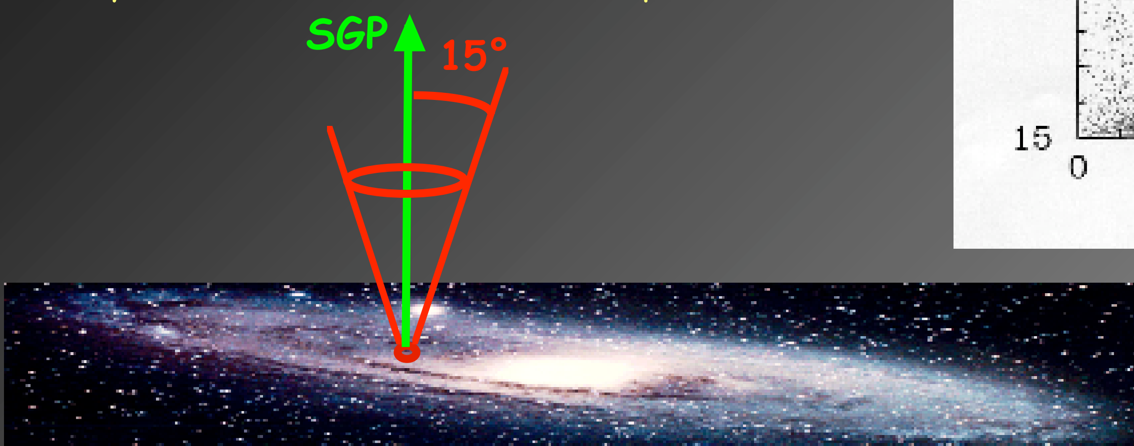
Radial velocities from spectra

(Moni Bidin 2009, PhD Thesis, U. de Chile)

distance: (J-K)-M_V relation calibrated on 47 Tuc

(Wyse & Gilmore 2005, arXiv:astro-ph/0510025)





Dispersions estimated fitting the probability plot

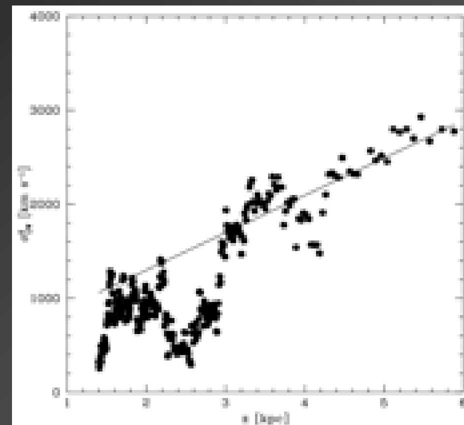
(Lutz & Hanson 1992, ASP Conf. Ser. 25, 257)

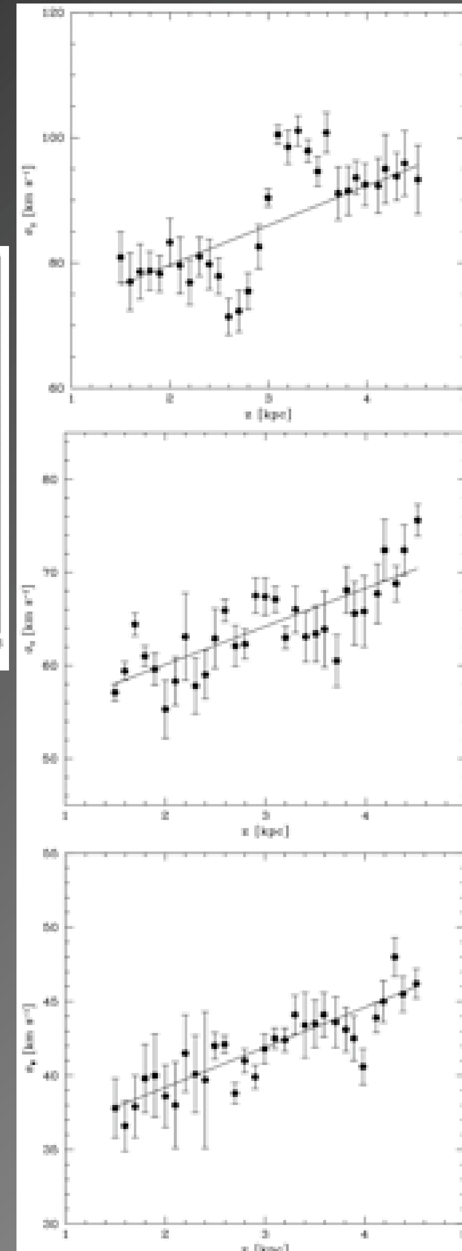
$\sigma_U=(67.1\pm3.2)+(6.3\pm1.1)\cdot z$ km s^{-1}

$\sigma_V=(51.9\pm3.1)+(4.1\pm1.0)\cdot z$ km s^{-1}

$\sigma_W=(33.8\pm0.8)+(2.7\pm0.3)\cdot z$ km s^{-1}

$\sigma^2_{UW}=(503\pm122)+(398\pm31)\cdot z$ km s^{-1}





$R_O= 8.0\pm0.3$ kpc

Weighted mean of the estimates of last decade:

$h_{R,\rho}= 3.8\pm0.2$ kpc (17 references)

$h_{z,\rho}= 0.90\pm0.08$ kpc (13 references)

No radial information

Additional hypothesis:

10- Dispersions exponentially decay with R, following the density (same $h_{R\rho}$)

- Observationally proven for σ^2_W
- Underlying hypothesis: constant anisotropy
  (constant dispersion ratios)
- Consistent with the scarce observations (Lewis & Freeman 1989, AJ, 97, 139)
- Numerical simulations show it is the best approximation for R<9 kpc
  (Cuddeford & Amendt 1992, MNRAS, 256, 166)

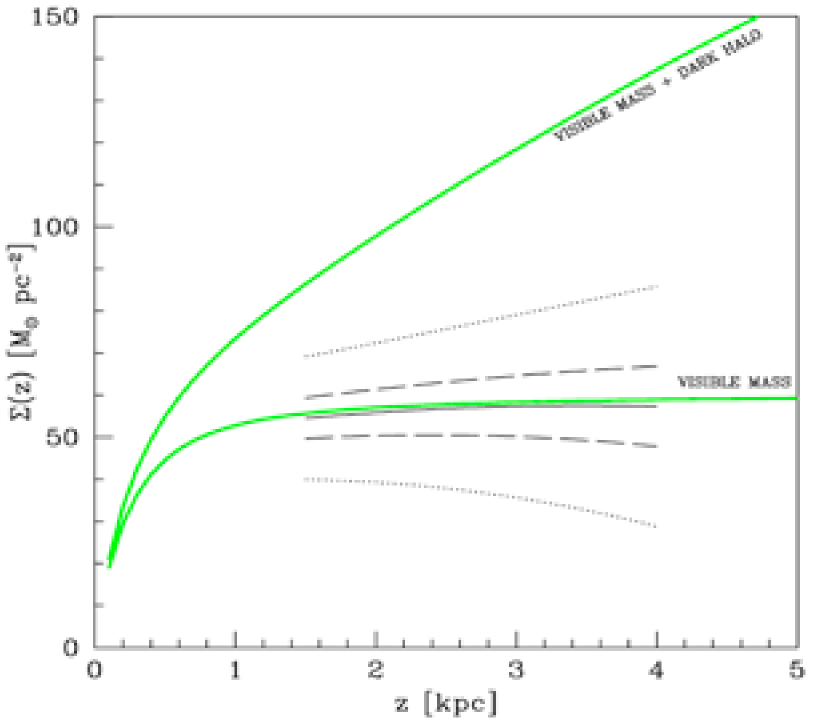
$$\Sigma(z) = \frac{1}{2\pi G}\Big[k_1 \cdot \int_0^z \sigma_U^2 dz + k_2 \cdot \int_0^z \sigma_V^2 dz + k_3 \cdot \int_0^z \overline{UW} dz + k_4 \cdot \overline{UW} + \frac{\sigma_W^2}{h_{z,\rho}} - \frac{\partial \sigma_W^2}{\partial z}\Big],$$

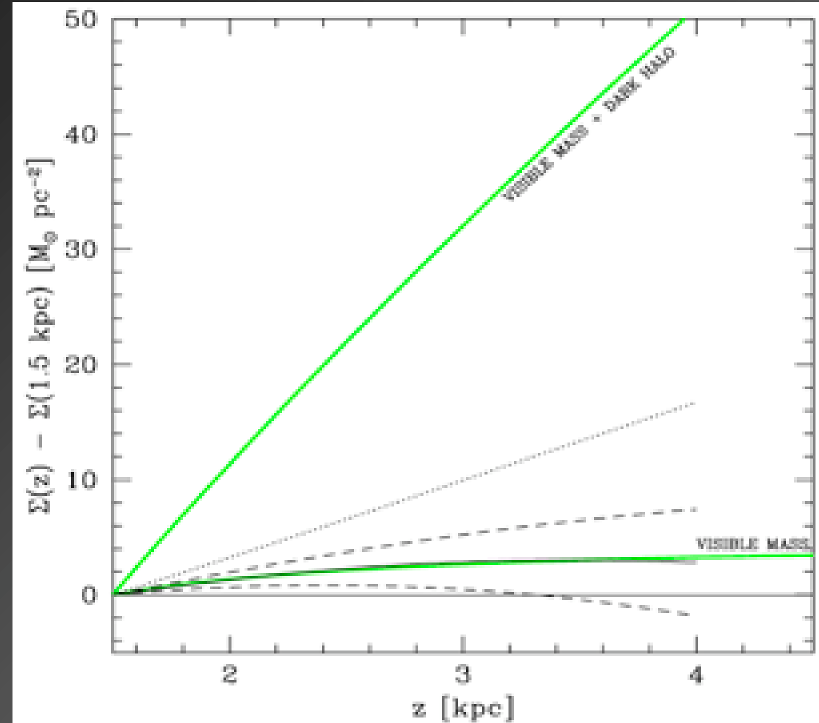
$$k_1 = \frac{3}{R_\odot \cdot h_{R,\rho}} - \frac{2}{h_{R,\rho}^2},$$

$$k_2 = -\frac{1}{R_\odot \cdot h_{R,\rho}},$$

$$k_3 = -\frac{1}{h_{z,\rho}} \cdot \Big(\frac{1}{R_\odot} - \frac{1}{h_{R,\rho}}\Big),$$

$$k_4 = \frac{3}{h_{R,\rho}} - \frac{2}{R_\odot}.$$





VM model:

Σ^*(1.1kpc)= 40 M_o pc^{-2}, Σ^{ISM}(1.1kpc)= 13 M_o pc^{-2} (Holmberg & Flynn 2004)

Parameters of Galactic components from Juric et al. (2009)

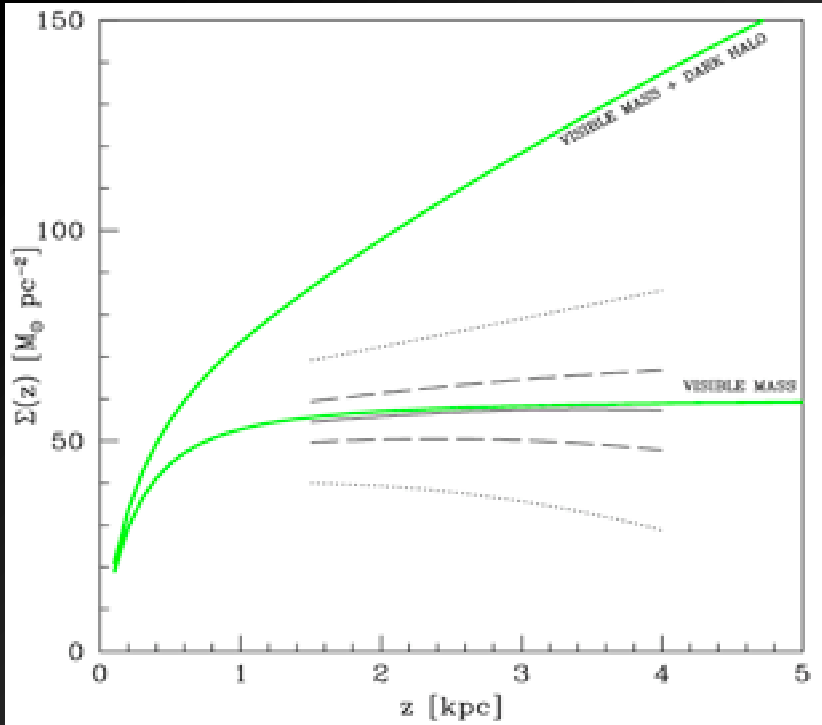
DM halo model:

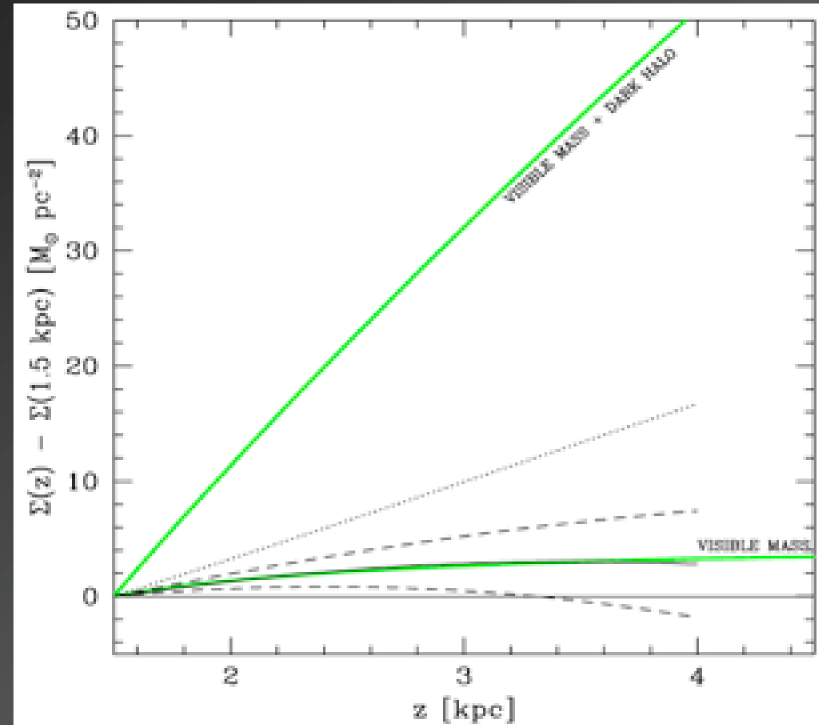
Olling & Merrifield (2001), normalized to $\rho_{0,DM}$= 10 mM_o pc^{-3}

1.5-4 kpc increment:

independent of Σ^{ISM}, Σ^* only introduces negligible uncertainty (<0.15 M_o pc^{-2})

no extrapolation to z<1.5 kpc





Results perfectly match the VM alone

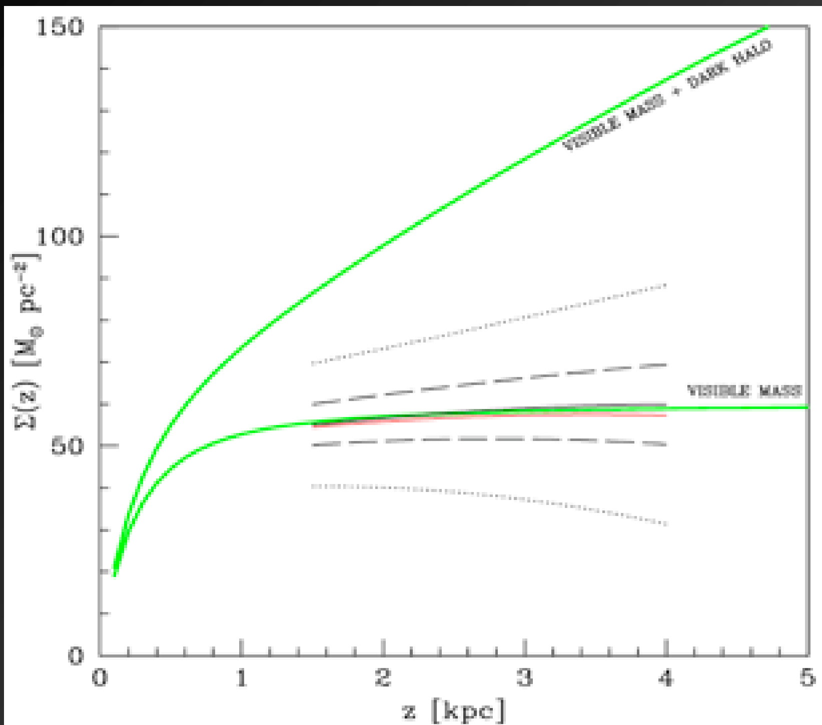
No need for any dark component

The space left for DM is negligible:

within 1σ, $\rho_{0,DM} < 1$ m$M_\odot$ pc^{-3}

Highly prolate DM halo?

Non-flat rotation curve -> additional term: $$\frac{1}{2\pi G}\int_0^z \frac{1}{R}\frac{\partial \overline{V}^2}{\partial R}dz$$



-0.085 km s^{-1} kpc^{-1}

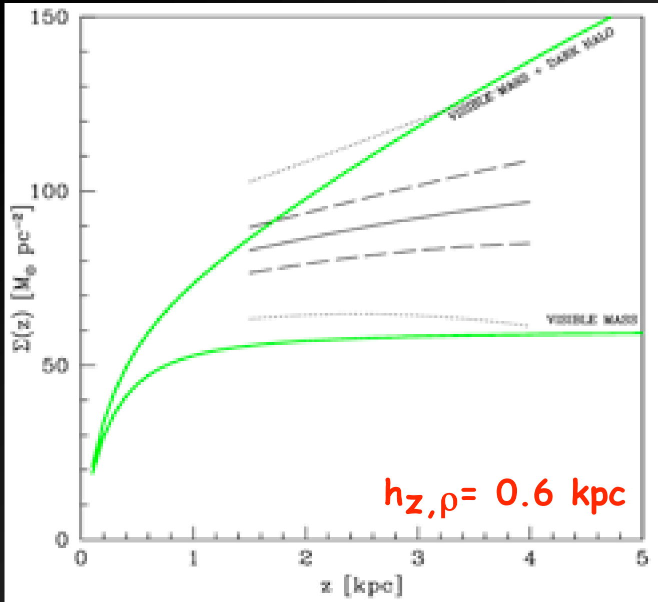
(Xue et al. 2008, ApJ, 684, 1143)

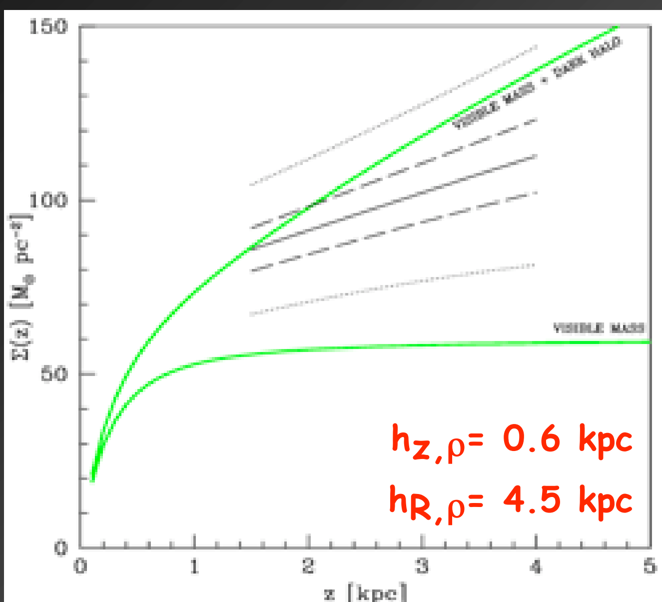
negligible effects

Increasing rotation

(e.g. +12 km s^{-1} kpc^{-1} Casetti-Dinescu et al. 2011, ApJ, 728, 7)

further decreases the observed mass





R_0 ininfluent

Results shift upward at decreasing $h_{z,\rho}$

(**$h_{z,\rho}$=0.62 kpc**, Bilir et al. 2008, PASA, 25, 69;

Arnadottir et al. 2008, IAU symp., 254, 5)

Gradient increases with $h_{R,\rho}$

An unrealistic thin and extended Thick Disk

(**$h_{z,\rho}$≈ 0.6 kpc**, **$h_{R,\rho}$>** 4.5 kpc),

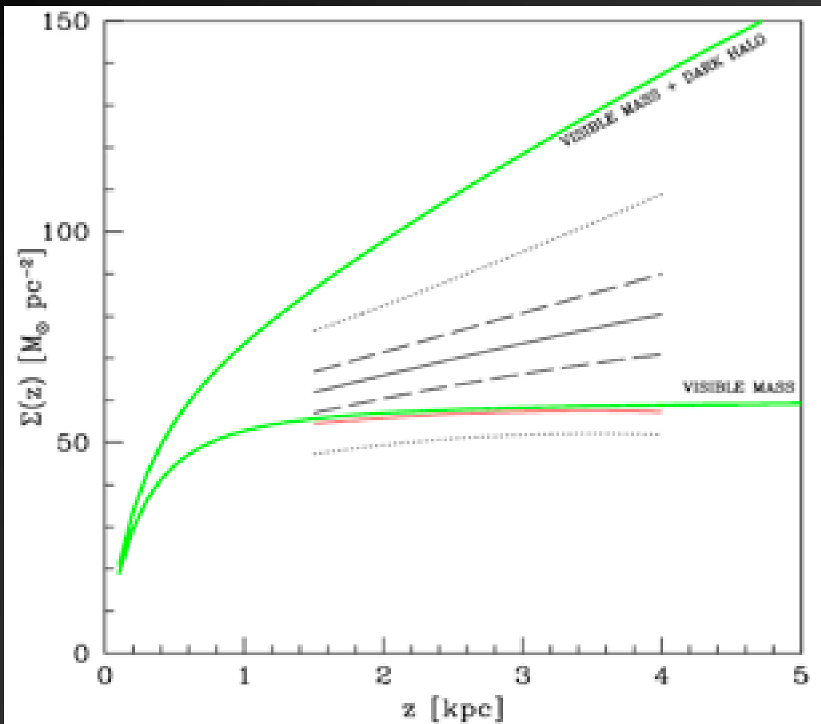
excluded by observations,

is needed to push the results toward the

VM+DM halo model

Radial decay of σ^2_u: constant Toomre Q-parameter

(exluded by Cuddeford & Amendt (1992))



$$\sigma^2_{RR}(R) \propto R^2 \exp(-2R/h).$$

σ^2_v and σ^2_{uw} irrelevant

The change in $\partial\sigma^2_x/\partial R$ is tiny

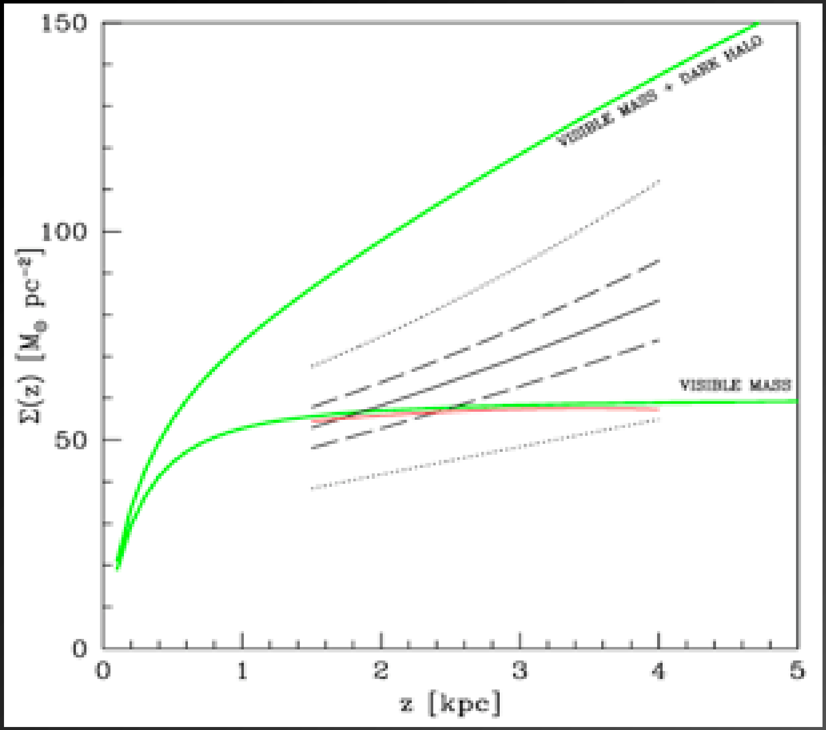
but not for $\partial^2\sigma^2_x/\partial^2 R$

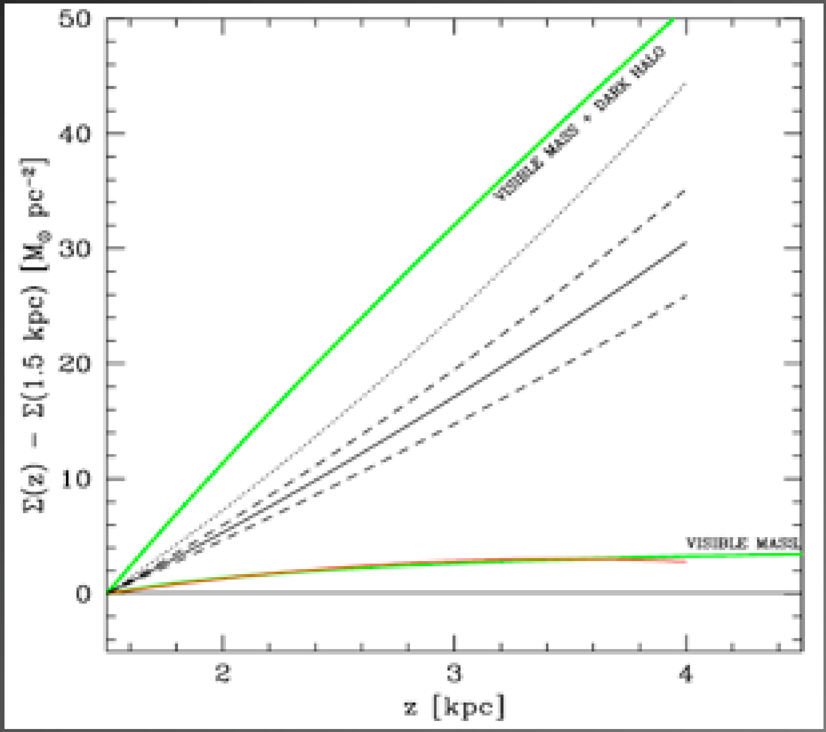
Some DM is required but, within 1σ :

$\rho_{0,DM} <$ 3.5-4 mM_o pc^{-3}

below the minimum allowed by flat rotation curve

(5-15 mM_o pc^{-3})



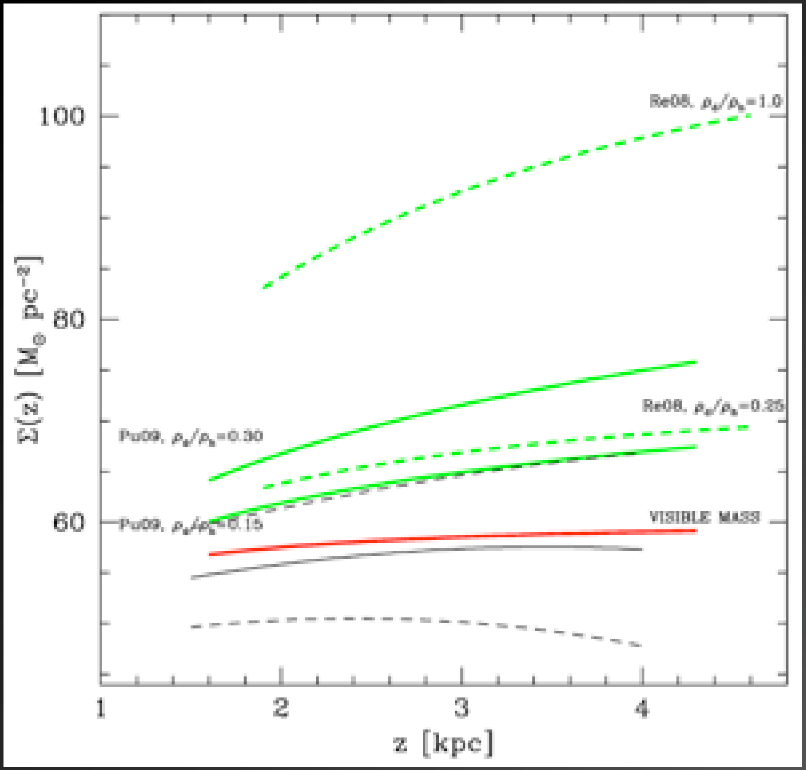


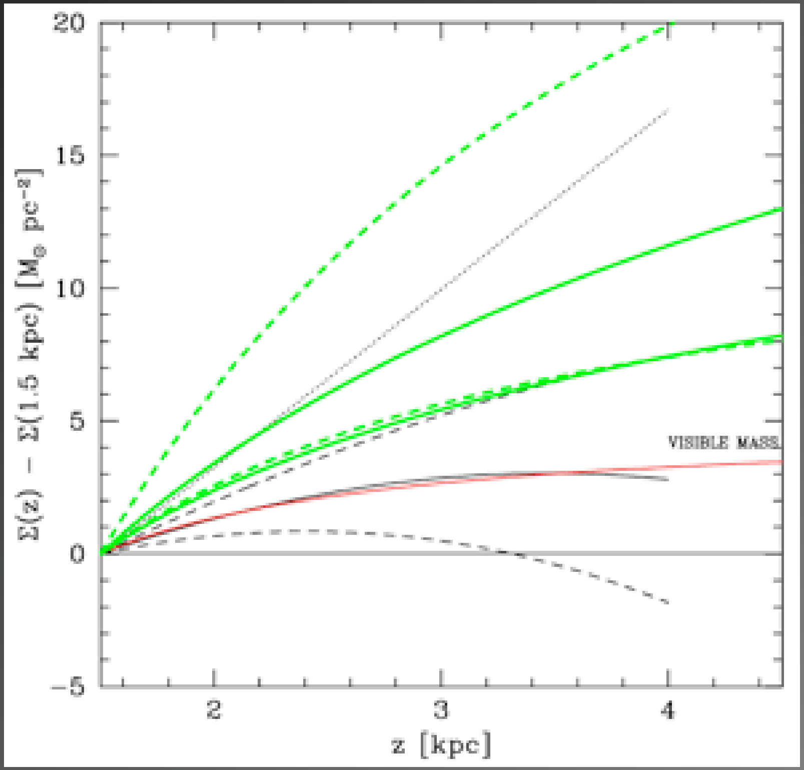
Linear decay of σ^2_u with R (unjustified)

-3.8 km s^{-1} kpc^{-1} (Neese & Yoss 1988, AJ, 95, 2; Casetti-Dinescu et al. 2011)

increment consistent (1σ) with $\rho_{0,DM}$= **7.5 mM$_o$ pc^{-3}**

but huge offset of 30 **M$_o$ pc^{-2}**





DM disk models:

Results of M10 fully confirmed

DM disk models (Read et al. 2008; Purcell et al. 2009) is excluded within 1σ

Only low-density, thin models are allowed

Conclusions

- Disk density measurements:
    - **Limited to z<1.1 kpc, approximated formulae, model-dependent fit**
    - **Weak constraints**
    - **"No evidence of DM in the Galactic disk"**

- With full 3D kinematics: analytical estimate at any z

- Our results:
    - **No information on radial behavior: assumptions required**
    - **No evidence of any DM component $\rho_{0,DM}$ < 1 m$M_\odot$ pc^{-3}**
    - **Some DM can be allowed under non-standard assumptions**
    - **DM density required for a flat rotation curve is excluded**
      Except under more than one non-standard hypothesis

- Future surveys will provide extensive data to expand our investigation

- DM disk not observed, and only low-density, thin models are allowed
  (see M10 for complete discussion)