Modified gravity under scrutiny – testing MOND with pairs of SDSS MaNGA galaxies

Özgen Tunç Türker

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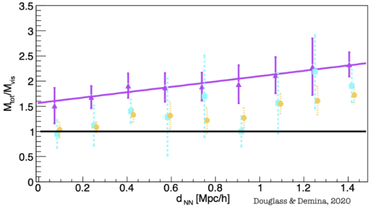
Observatoire astronomique de Strasbourg | ObAS

Goal of The Project

A Systematic Behaviour



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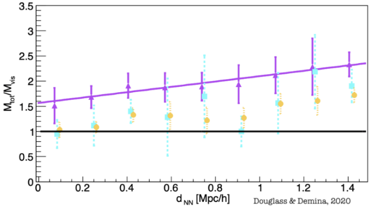
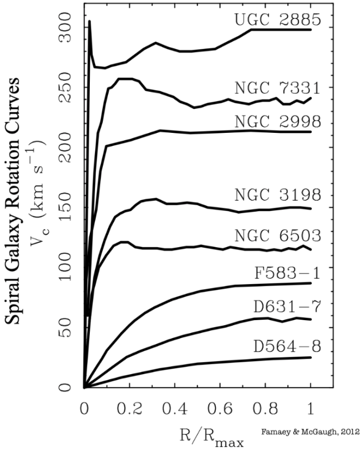


Observed by Galaxy Rotation Curves



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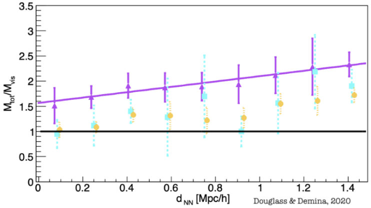
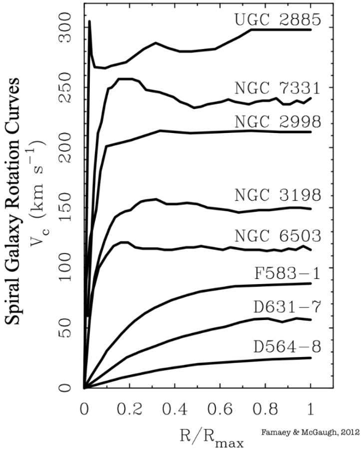
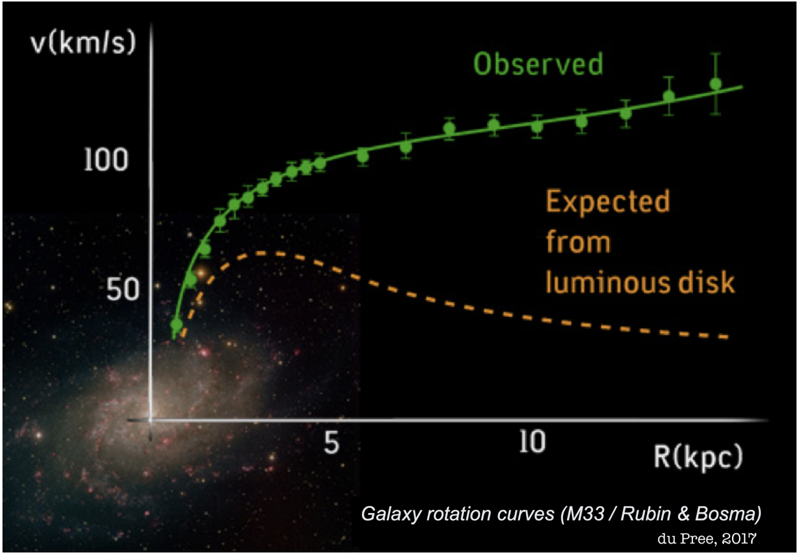




Is it explainable in Modified Gravity Context?

Missing Mass:
Dark Matter & It's Challenges

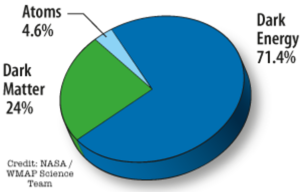
Missing Mass Problem



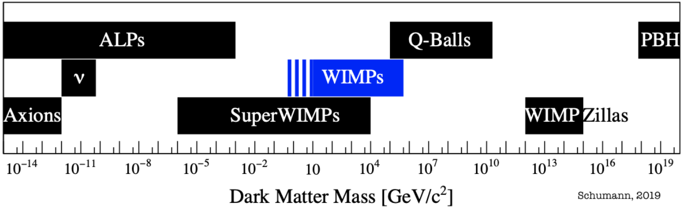
- 1930s
- Dynamic vs. Content
- Unvisible Matter
- Rubin & Bosma
- late '70s

Dark Matter Puzzle

Dark Matter: **Cold** & **Non-Baryonic**

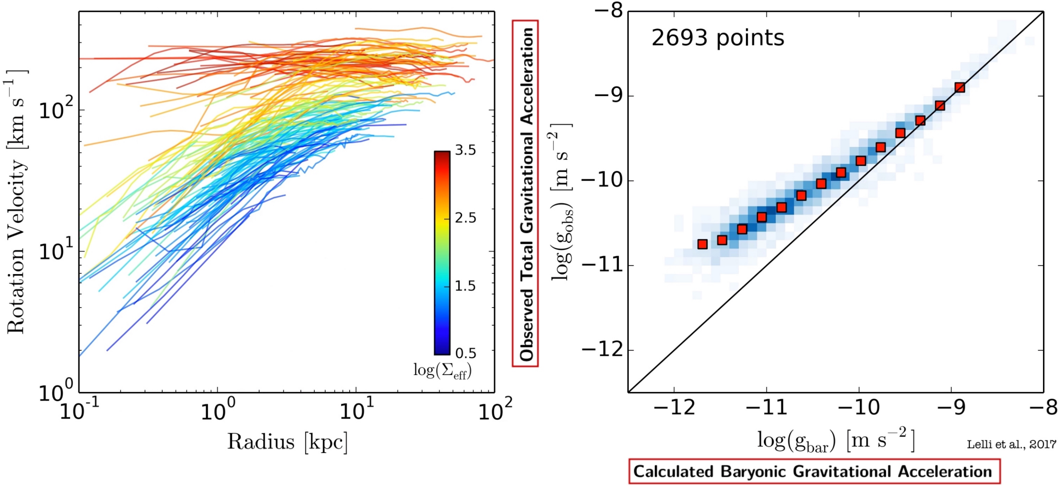


Content of the universe today



Different dark matter candidates on a many order of magnitude mass range.

The Radial Acceleration Relation



Why do mass discrepancies correlate with acceleration?

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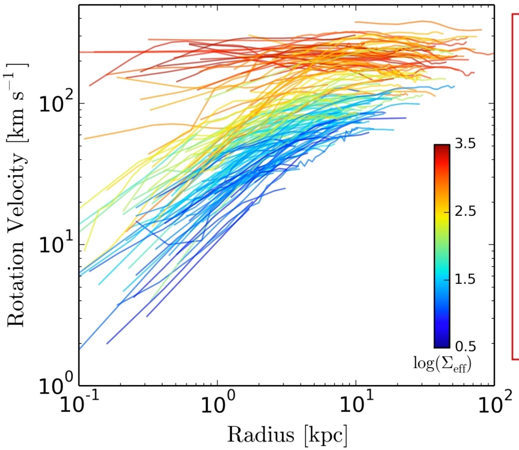

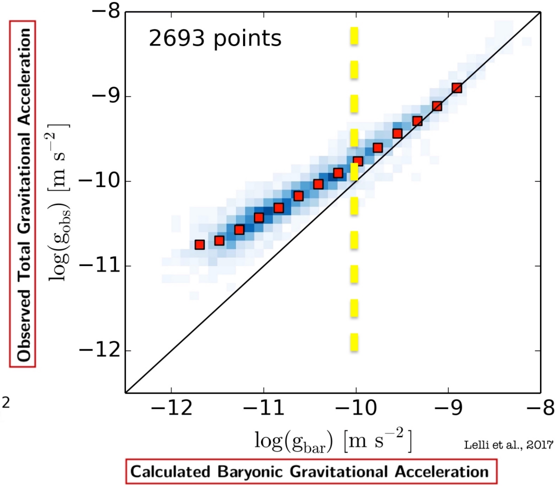

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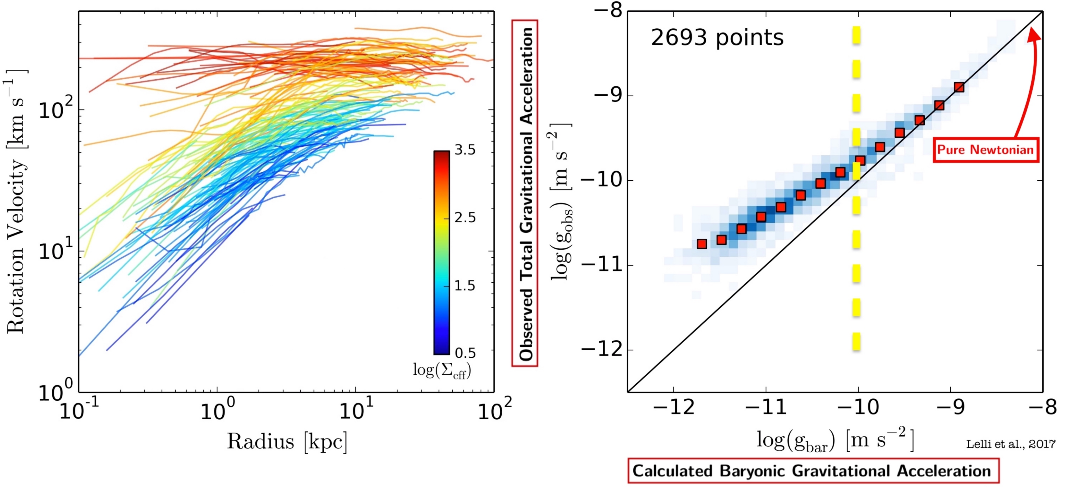

Why do mass discrepancies correlate with acceleration?

An alternative World: Modified Newtonian Dynamics

Introduction to MOND

- Mordehai Milgrom in 1983 ($\sim$ Dark Matter gets widely accepted.)

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- **The Universal Critical Acceleration Constant**

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- When the acceleration is less than the constant $(F/m = g << a_0)$

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- Milgrom's law: $$g\,\mu\left(\frac{g}{a_0}\right) = g_N$$

$$\mu\left(\frac{g}{a_0}\right) \to 1 \quad \text{for } g >> a_0 \quad \& \quad \mu\left(\frac{g}{a_0}\right) \to \frac{g}{a_0} \quad \text{for } a_0 >> g$$

External Field Effect (EFE)

- MOND breaks fundamental principle of **GR**: Strong Equivalence Principle.
- When the galaxy is not **isolated** then **total acceleration** matters

isolated systems

Newtonian Regime

$g_{in} > a_0$

$$M = \frac{RV^2}{G}$$

e.g., surface of the Earth

MOND Regime

$g_{in} < a_0$

$$M = \frac{V^4}{a_0 G}$$

e.g., remote dwarf Leo 1

non-isolated systems

External Field Dominant Newtonian Regime

$g_{in} < a_0 < g_{ex}$

$$M = \frac{RV^2}{G}$$

e.g., globular Cluster M13

External Field Dominant Quasi-Newtonian Regime

$g_{in} < g_{ex} < a_0$

$$M = \frac{g_{ex}}{a_0}\frac{RV^2}{G}$$

e.g., nearby Sgr dwarf

McGaugh, 2007

SDSS & MaNGA

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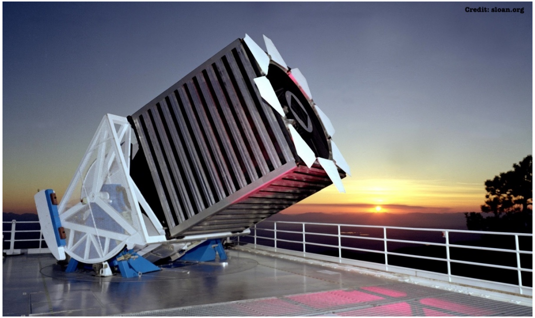
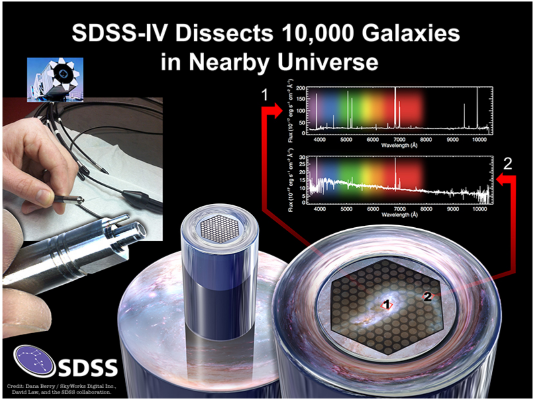


Sloan Digital Sky Survey at Apache Point Observatory in New Mexico, United States

- "Multi-color images of 1/3 of the sky, and spectra for more than three million astronomical objects"

- "17 simultaneous 'integral field units', each composed of tightly-packed arrays of optical fibers"

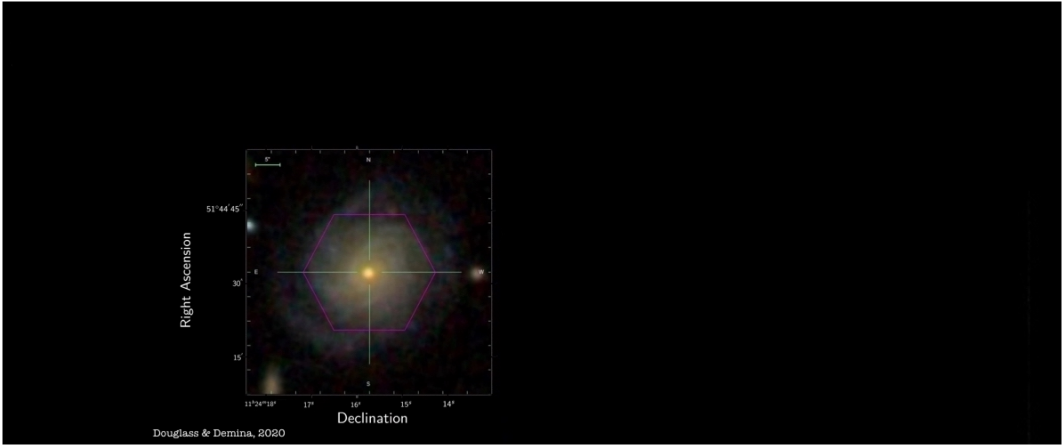
Mapping Nearby Galaxies (MaNGA) at APO



Pairs of SDSS MaNGA galaxies

Dependence of the ratio of total to visible mass on observable properties of SDSS MaNGA galaxies

KELLY A. DOUGLASS[1] AND REGINA DEMINA[1]



The relation between the ratio of masses and the nearest neighbor distance.

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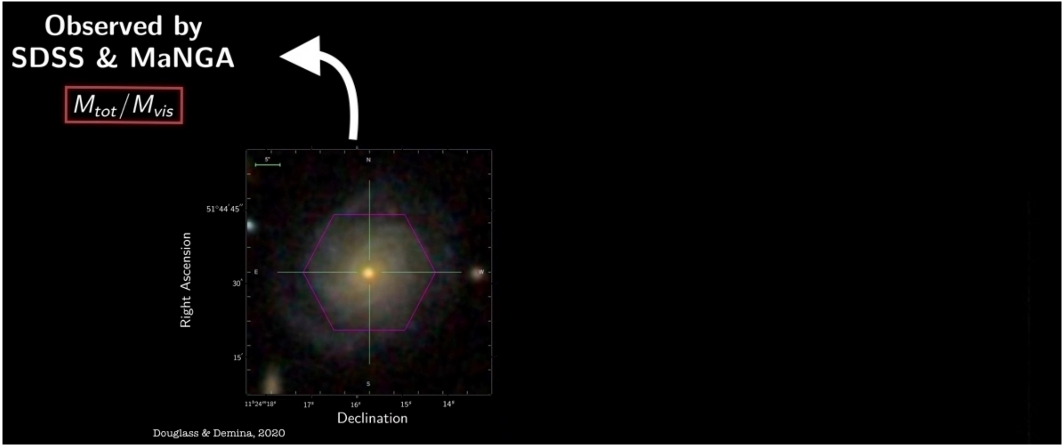

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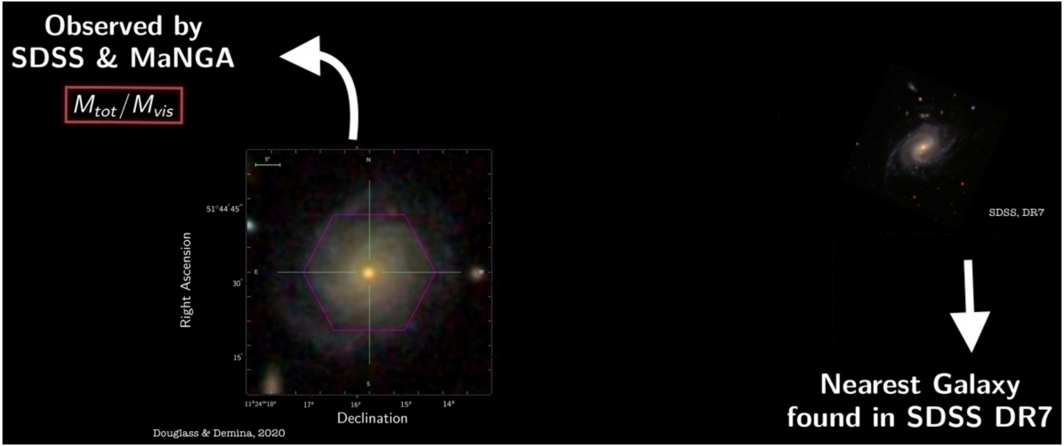

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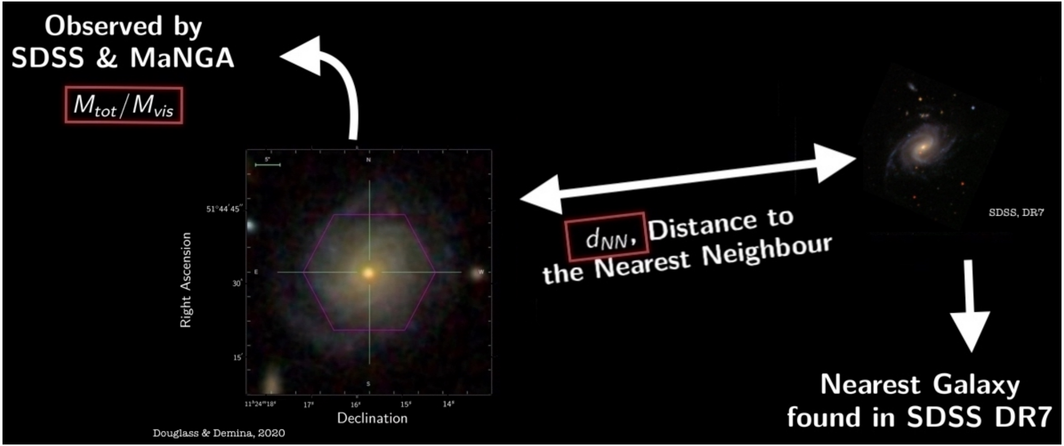

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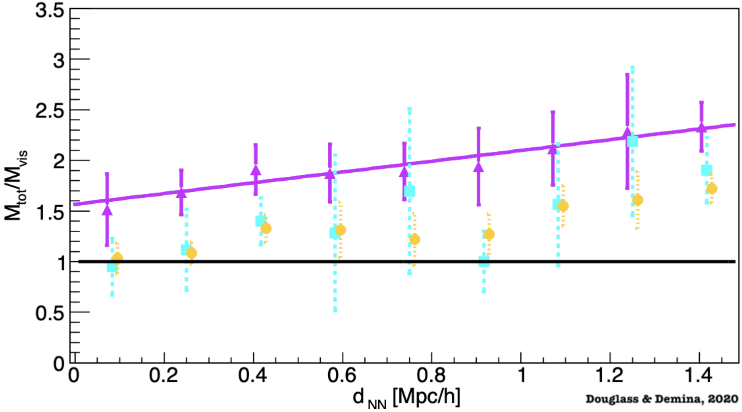

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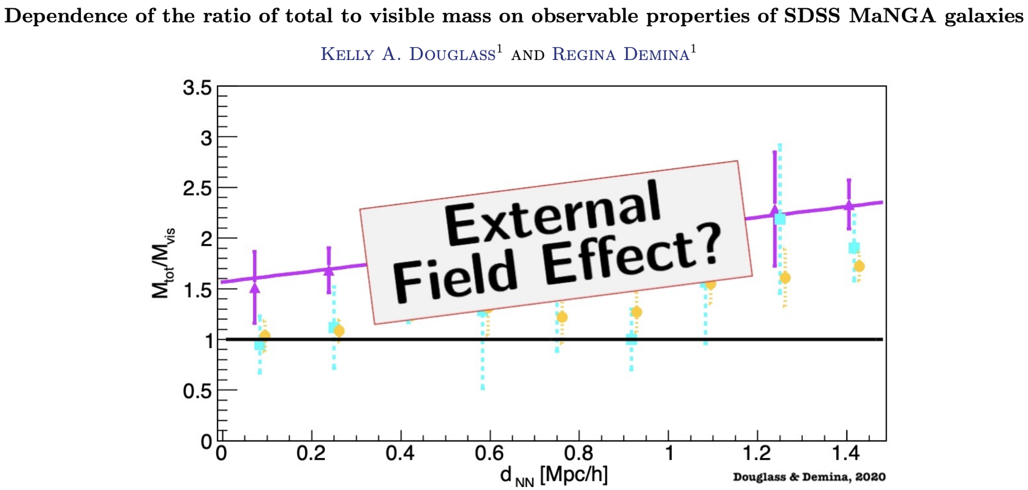

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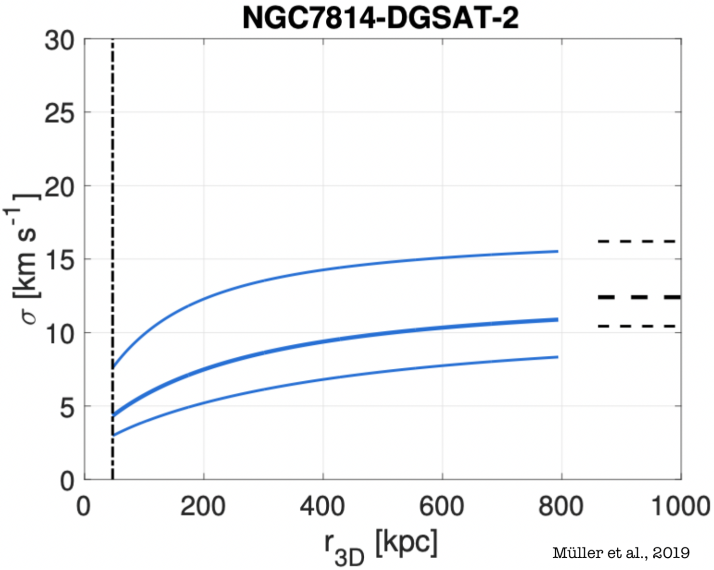
External Field Effect (EFE)



$\sim M_{tot} / M_{vis}$

Müller et al., 2019

Testing the External Field Effect

Spiral Galaxies

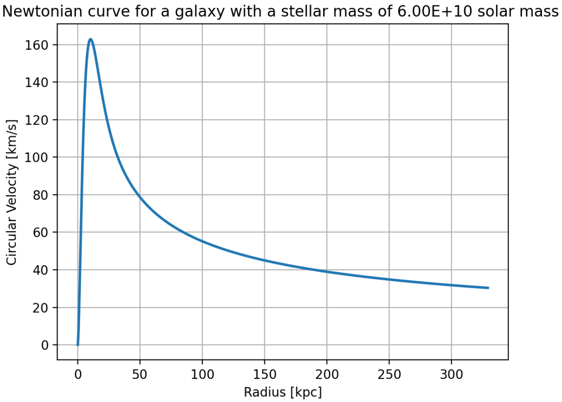
- Exponential & Infinitesimally Thin Disk

$$\Sigma(R) = \Sigma(0)e^{-R/R_d}$$

$$M(R) = M_b\left[1 - e^{-R/Rd}(1 + \frac{R}{Rd})\right]$$

$$V_c^2(R) = \frac{GM_d}{R_d} 2y^2 \left[I_0(y)K_0(y) - I_1(y)K_1(y)\right]$$

where $y = 2R/R_d$



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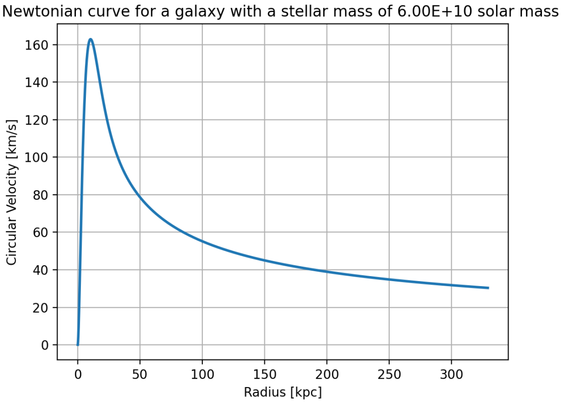
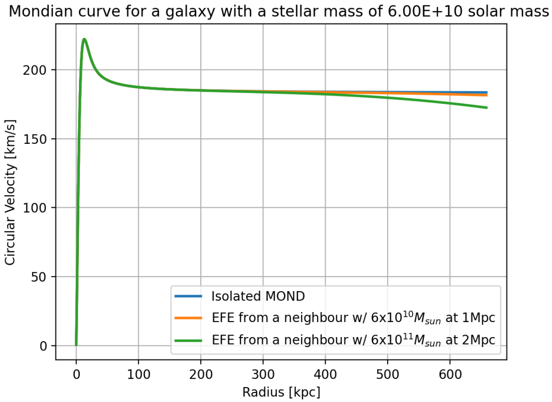


EFE Formulation



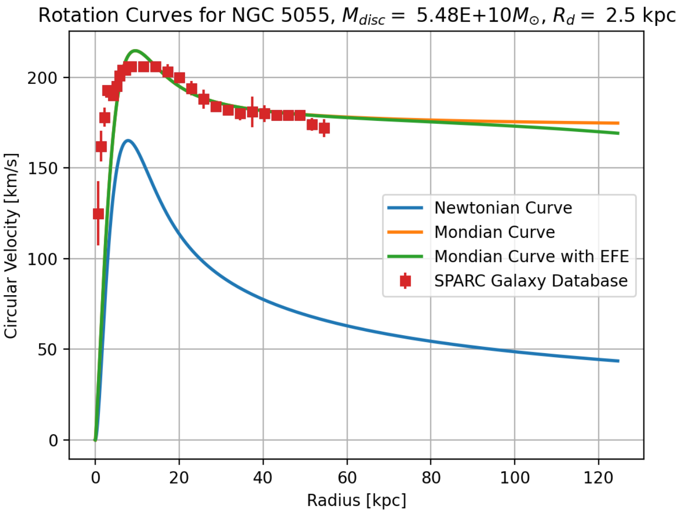
- EFE formulation

$$V_{rot}(r) = \sqrt{g_r(r)\, r}$$

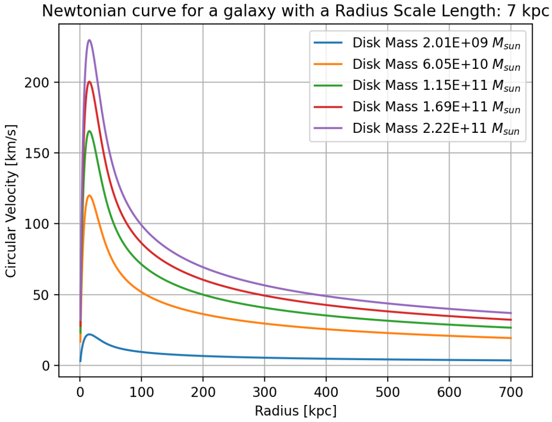
$$g_r(r) = \begin{cases} \nu\left(\frac{g_{N_i} + \frac{g_{N_e}^2}{3g_{N_i}(r)}}{a_0}\right), & g_{N_i}(r) > g_{N_e} \\ \nu\left(\frac{g_{N_e} + \frac{g_{N_i}(r)^2}{3g_{N_e}}}{a_0}\right), & g_{N_i}(r) < g_{N_e} \end{cases}$$

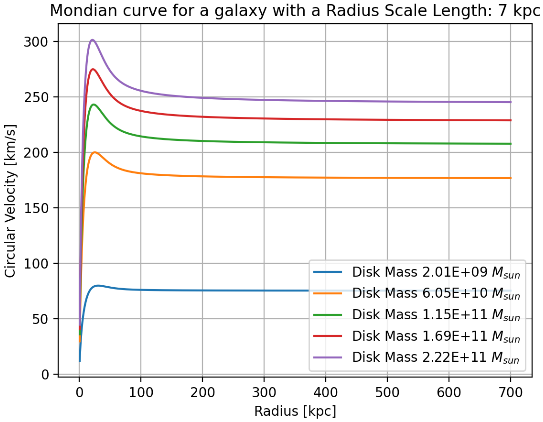
$$\nu(x) = \left(\frac{1}{4} + \frac{1}{x}\right)^{0.5} + \frac{1}{2}$$

Newtonian & MONDian Rotation Curves of NGC 5055

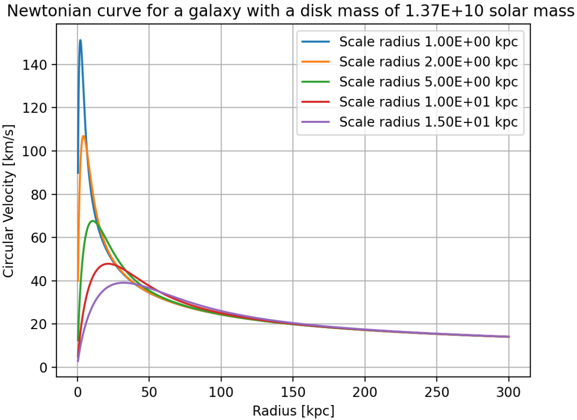


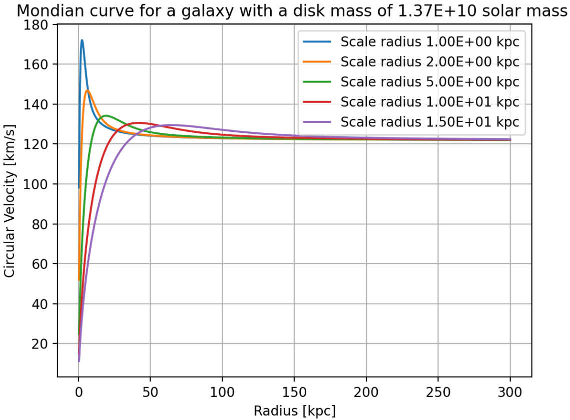
Rotation Curves with Different Disk Mass



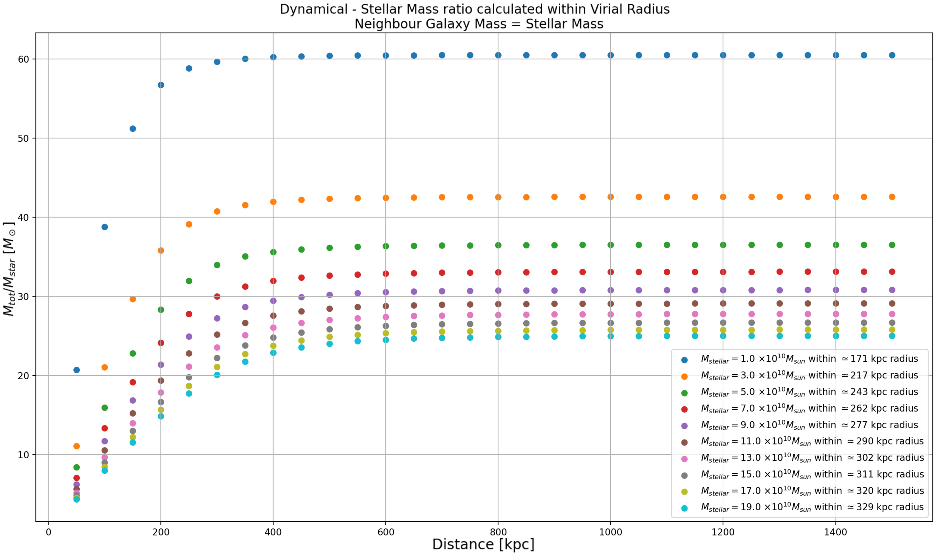


Rotation Curves with Different Radius Scale Length





External Field Effect on Dynamical Properties



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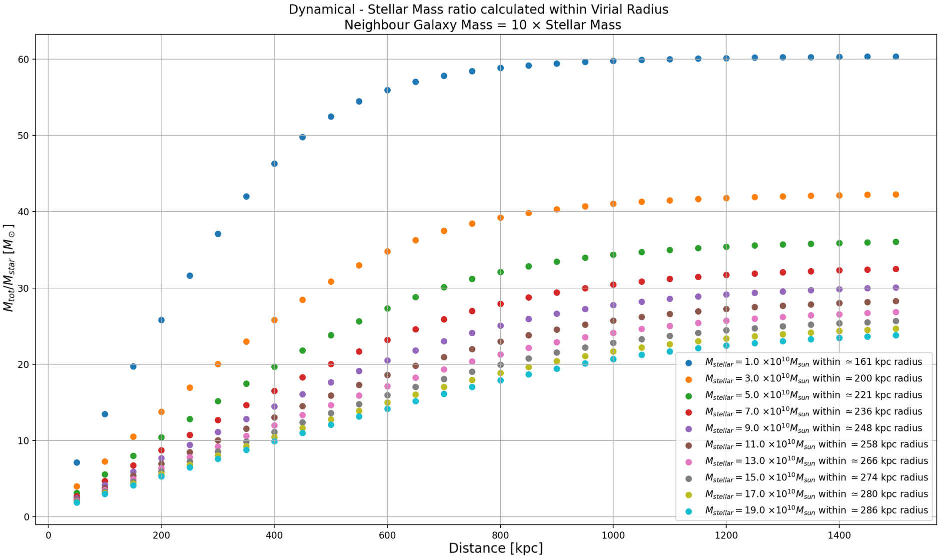

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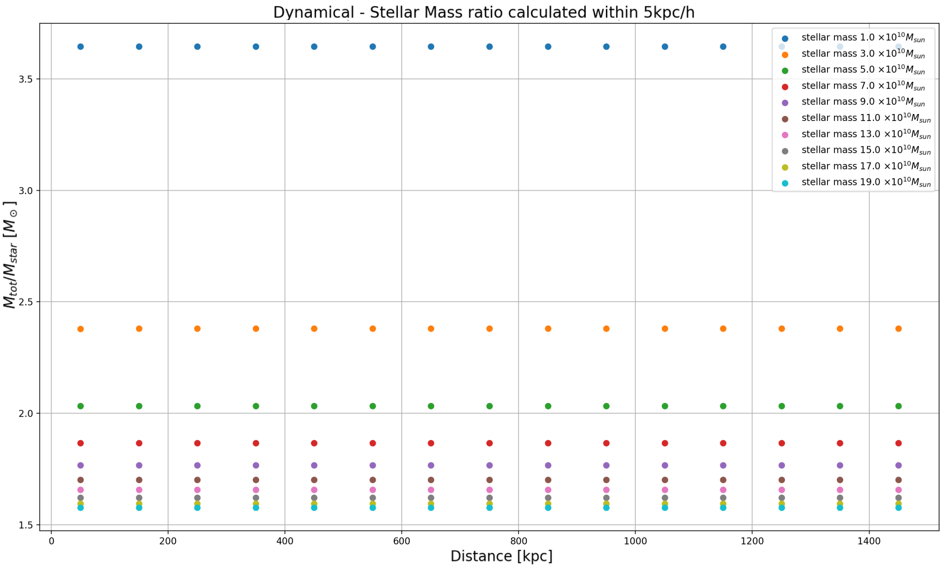


Results

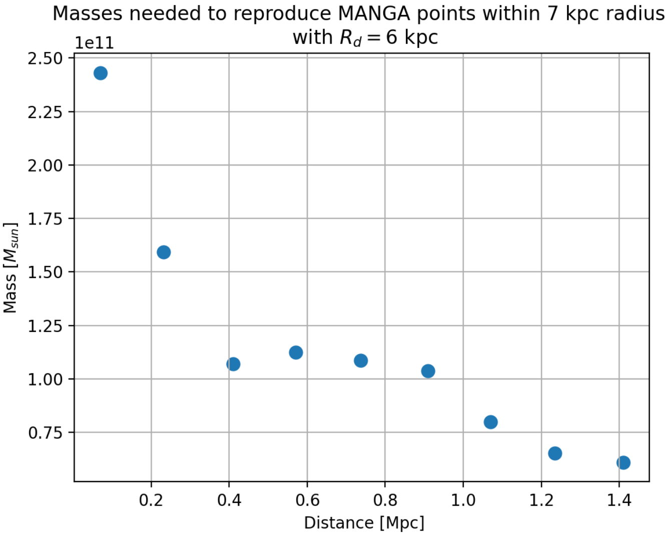
Result 1:

External Field Effects dynamics at outskirts of galaxies.

Result 2:

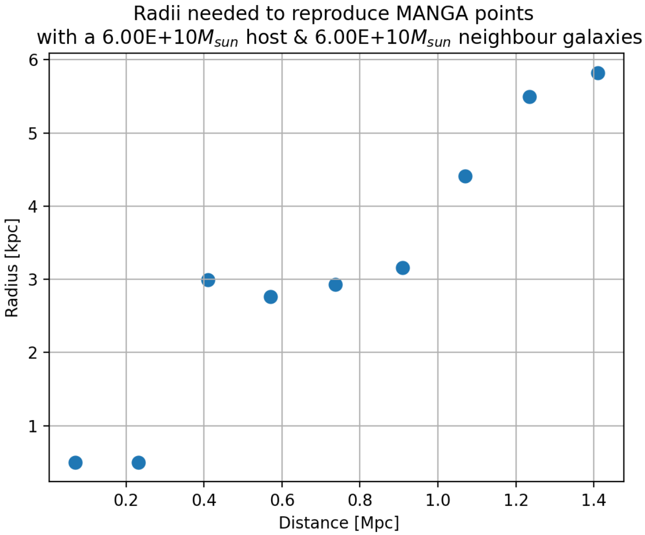
External Field Effect has no influence on the radii considered!

Conclusion



Masses needed to reproduce MANGA points within 7 kpc radius
with $R_d = 6$ kpc
1e11
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
Mass [M_{sun}]
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Distance [Mpc]

Conclusion



Radii needed to reproduce MANGA points
with a 6.00E+10M_{sun} host & 6.00E+10M_{sun} neighbour galaxies
Radius [kpc]
Distance [Mpc]
6
5
4
3
2
1
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Results

Result 1:
External Field Effects dynamics at outskirts of galaxies

Result 2:
External Field Effect has no influence on the radii considered!

Result 3:
Higher R_d $\rightarrow$ Low Surface Density $\rightarrow$ Higher M_{tot}/M_{vis}

References I

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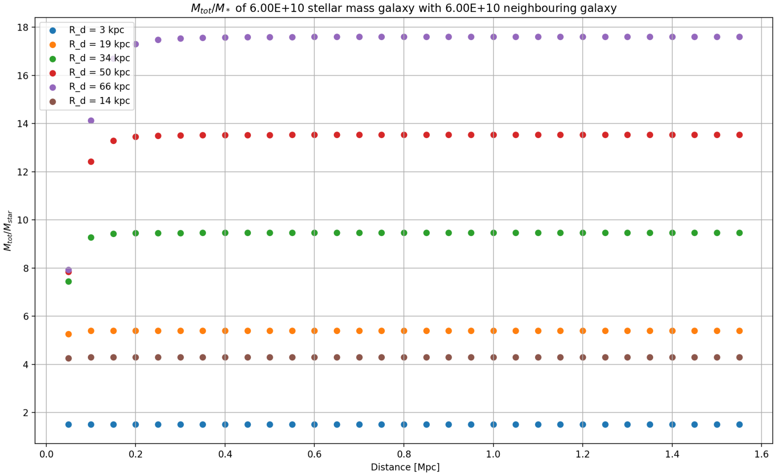
Where to look?

Dwarf Spheroidals

- Dwarf Galaxies with Low Surface Brightness $\rightarrow$ Inner regions can be EFE dominant.

Back-up - Milky Way Like Galaxy



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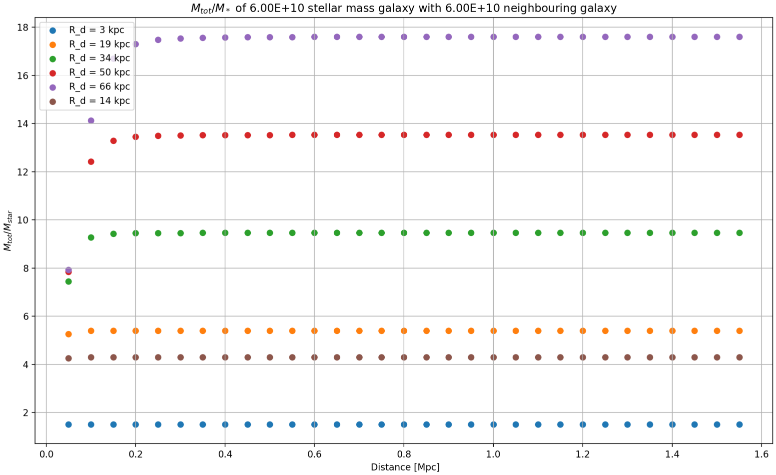

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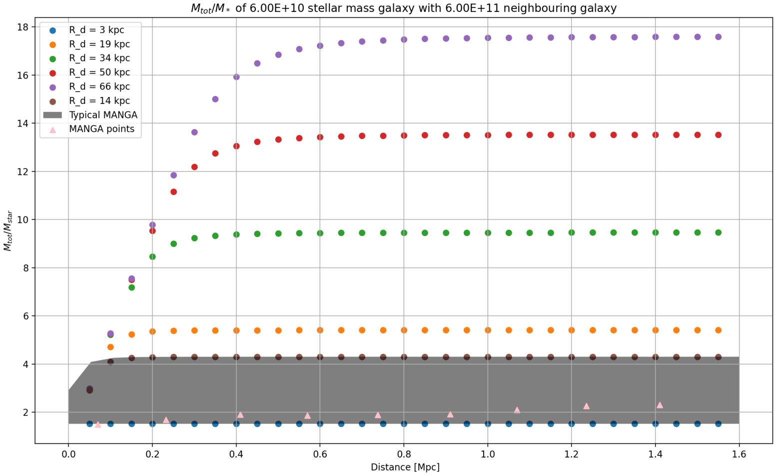

Back-up - Dark Matter Candidates

Axions: Hypothetical particle (Peccei–Quinn theory) introduced to solve *strong CP problem*.
ν: Heavy righ-handed neutrinos
WIMPs: Weakly interacting massive particles
SuperWIMPs: Decay product of WIMPs (Feng, Su & Takayama, 2006)
Q-Balls: arised from supersymmetric extensions of the standard model, stable localised field, which carry baryon or lepton number. (Kusenko & Shaposhnikov, 1997)
WIMPZillas: nonthermal WIMPs, not in qeuilibrium when it froze out. (Kolb, Chung & Riotto, 1998)
PBH: Primordial black holes

One Law to Rule Them All: The Radial Acceleration Relation of Galaxies

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[2] European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748, Garching, Germany
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Abstract

We study the link between baryons and dark matter (DM) in 240 galaxies with spatially resolved kinematic data. Our sample spans 9 dex in stellar mass and includes all morphological types. We consider (1) 153 late-type galaxies (LTGs; spirals and irregulars) with gas rotation curves from the SPARC database, (2) 25 early-type galaxies (ETGs; ellipticals and lenticulars) with stellar and H I data from ATLAS^{3D} or X-ray data from *Chandra*, and (3) 62 dwarf spheroidals (dSphs) with individual-star spectroscopy. We find that LTGs, ETGs, and "classical" dSphs follow the same radial acceleration relation: the observed acceleration ($g_{\rm obs}$) correlates with that expected from the distribution of baryons ($g_{\rm bar}$) over 4 dex. The relation coincides with the 1:1 line (no DM) at high accelerations but systematically deviates from unity below a critical scale of $\sim 10^{-10}$ m s^{-2}. The observed scatter is remarkably small ($\lesssim$0.13 dex) and largely driven by observational uncertainties. The residuals do not correlate with any global or local galaxy property (e.g., baryonic mass, gas fraction, and radius). The radial acceleration relation is tantamount to a natural law: when the baryonic contribution is measured, the rotation curve follows, and vice versa. Including ultrafaint dSphs, the relation may extend by another 2 dex and possibly flatten at $g_{\rm bar} \lesssim 10^{-12}$ m s^{-2}, but these data are significantly more uncertain. The radial acceleration relation subsumes and generalizes several well-known dynamical properties of galaxies, like the Tully–Fisher and Faber–Jackson relations, the "baryon-halo" conspiracies, and Renzo's rule.

Back-up - Radial Acceleration Relation

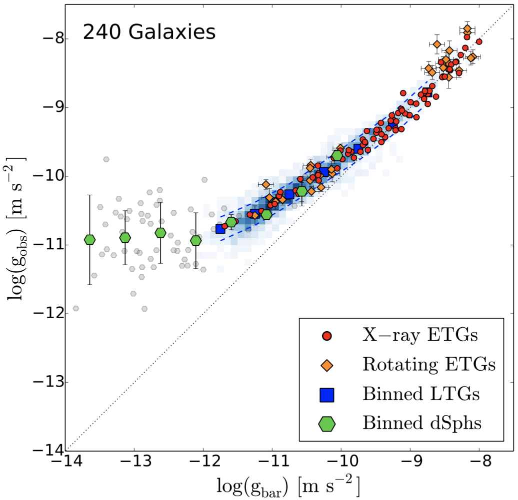
Table 1
Fiducial Stellar Mass-to-light Ratios

Galaxy Component	$\Upsilon_\star$
Disks of LTGs (Sa to Irr)	$0.5\ M_\odot/L_\odot$
Bulges of LTGs (Sa to Sb)	$0.7\ M_\odot/L_\odot$
Rotating ETGs (S0 and disky E)	$0.8\ M_\odot/L_\odot$
X-ray ETGs (Giant metal-rich E)	$0.9\ M_\odot/L_\odot$
Dwarf Spheroidals (V-band)	$2.0\ M_\odot/L_\odot$

Note. The values of $\Upsilon_\star$ refer to 3.6 μm apart for dwarf spheroidals (V-band). We adopt a Chabrier (2003) IMF and the SPS models of Schombert & McGaugh (2014).

(Lelli et al., 2017)

Back-up - Radial Acceleration Relation

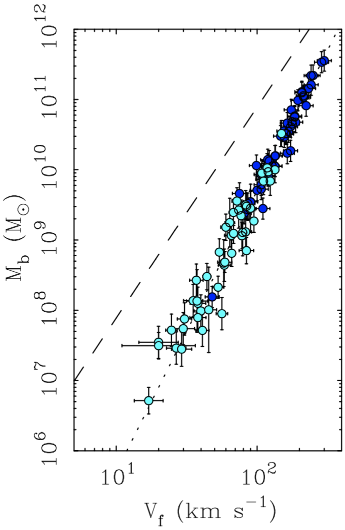


(Lelli et al., 2017)

Back-up - Some ΛCDM Challenges

Missing Satellite Problem: "model predicts overabundance of dark subhalos" (Famaey & McGaugh, 2012)
Local Void Challenge: structure formation, faster than model predicts (Famaey & McGaugh, 2012)
Cusp-Core Problem: Do DM halos have a density profile which is constant at the small radii or steeply increasing?

Back-up - Baryonic Tully-Fisher

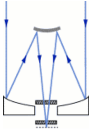


"The dotted line has slope 4 corresponding to a constant acceleration parameter, 1.2 $\times$ 10^{10} m s^2. The dashed line has slope 3 as expected in ΛCDM with the normalization expected if all of the baryons associated with dark matter halos are detected." (Famaey & McGaugh, 2012)

Back-up - SDSS

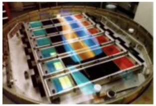
Key Components of the Survey Telescope

Channeling the light



The telescope's optical system is dominated by two reflecting mirrors. The focusing system includes two corrective lenses that minimize distortion. The diagram at right shows how that incoming starlight strikes the 2.5-meter primary mirror, bounces back and strikes the smaller secondary mirror, then is reflected back through a hole in the primary mirror. The light passes through the first correcting lens and then through the second lens on top of the camera. Images from the system appear in good focus from an area of sky equal to about 30 full moons.

Making the two-dimensional image



The inner sanctum of the SDSS telescope contains what may be the most complex camera ever built. It includes 30 silicon electronic light sensors called charge-coupled devices, or CCDs (seen at left), that are each two inches square. Scientists encase each column of five devices in a vacuum-sealed chamber. In order to enhance sensitivity, liquid nitrogen cools each chamber to -80 degrees Celsius. Each CCD is made up of more than four million picture elements, which release electrons as light is absorbed. The electrons in turn are amplified into electronic signals that can be digitized, recorded on tape and ultimately fed into a computer. A night's observing will produce up to 200 gigabytes of data on a dozen tapes. Each of the five rows of CCDs receives the light through a different colored filter, so each row records the brightness of objects in a different color.

Into the third dimension

A spectrograph, a device that disperses light into many colors so the spectrum can be recorded, analyzes the distance, composition and age of each celestial object. Astronomers drill 640 holes in an aluminum plate, with each hole corresponding to the position of a selected galaxy, quasar or star in the sky. Scientists plug the holes with optical fiber cables (right). The fibers simultaneously capture light from the 640 objects and record the results in CCDs. The plug plates are interchangeable with the CCD camera at the focal plane of the telescope. On a good night, observers will use six to nine plates.

http://classic.sdss.org/background/telescope.html

Back-up - Interpolating Function

Written like this, the analogy between Milgrom's law and Coulomb's law in a dielectric medium is clear, as noted in [56]. Indeed, inside a dielectric medium, the amplitude of the electric field E generated by an external point charge Q located at a distance r obeys the following equation:

$$\mu(E)E = \frac{Q}{4\pi\epsilon_0 r^2}, \tag{9}$$

where μ is the relative permittivity of the medium, and can depend on E. In the case of a gravitational field generated by a point mass M, it is then clear that Milgrom's interpolating function plays the role of " gravitational permittivity". Since it is smaller than 1, it makes the

(Famaey & McGaugh, 2012)

Back-up - Acceleration