Title: Strong Constraints on Superfluid Dark Matter from Milky Way Dynamics

Speakers: Oren Slone

Series: Particle Physics

Date: December 06, 2019 - 11:00 AM

URL: http://pirsa.org/19120049

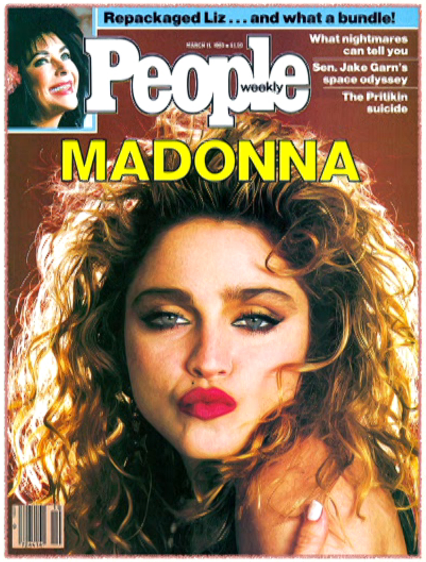
Abstract: Many well-known correlations between dark matter and baryons exist on galactic scales. These can essentially be encompassed by a simple scaling relation between observed and baryonic accelerations, historically known as the Mass Discrepancy Acceleration Relation (MDAR). This relation has prompted many theories that attempt to explain the correlations by invoking additional fundamental forces on baryons. Since a collisionless cold dark matter (CDM) model is desirable on scales of clusters and above, the standard lore has been that a theory which reduces to the MDAR on galaxy scales but behaves like CDM on larger scales provides an excellent fit to data. However, this statement should be revised in light of recent results showing that a fundamental force that reproduces the MDAR is often challenged at accommodating Milky Way dynamics. In this study, we test this claim on the example of Superfluid Dark Matter. We find that a standard CDM model is strongly preferred over a static superfluid profile. This is due to the fact that the superfluid model over-predicts vertical accelerations, even while reproducing galactic rotation curves. Our results establish an important criterion that any dark matter model must satisfy within the Milky Way.

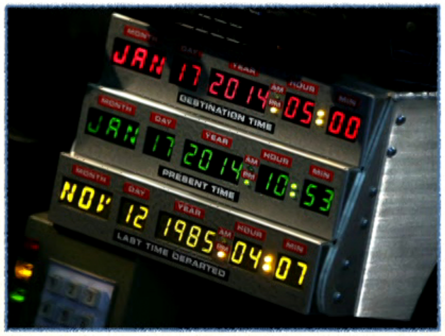
Inconsistency of SuperFluid DM with Milky Way Observables

Oren Slone, Princeton University

arXiv: 1812.08169 and 1911.12365 - M. Lisanti, M. Moschella, N. Outmezguine and O. Slone

Great things from the 80's





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Great things from the 80's

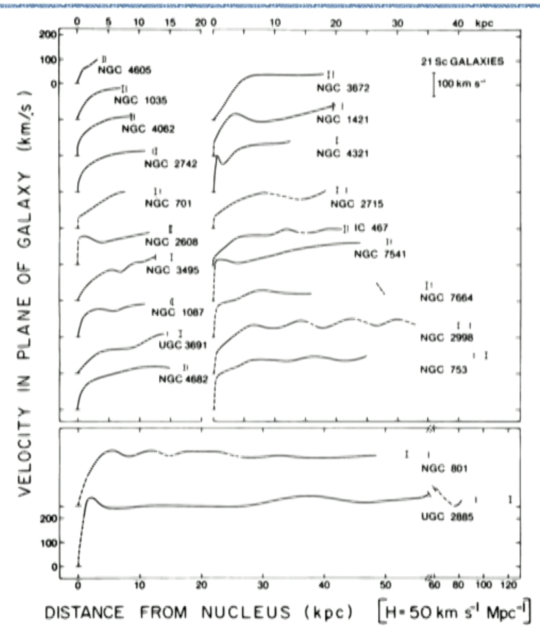
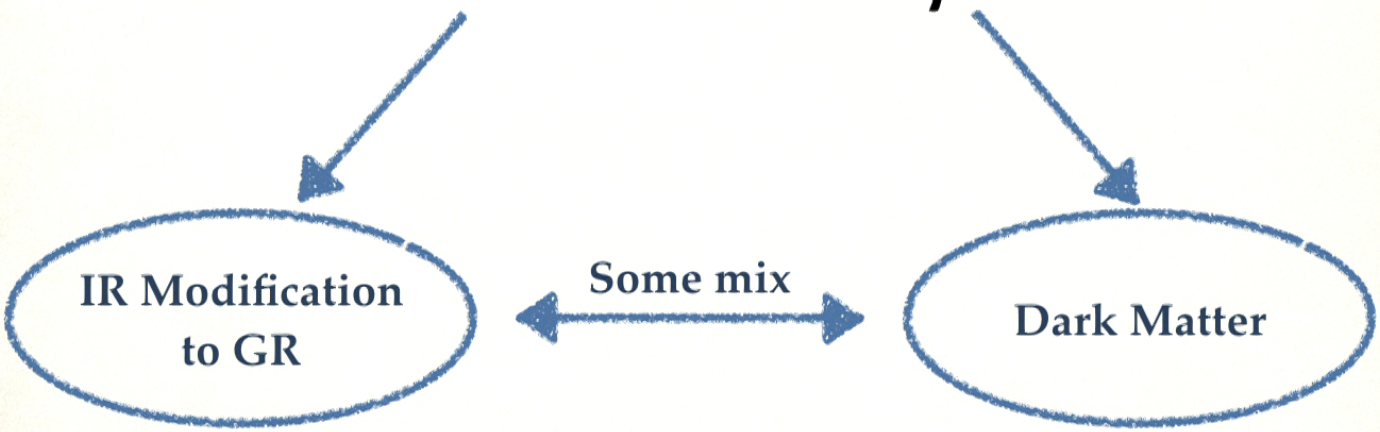


Fig. 5.—Mean velocities in the plane of the galaxy, as a function of linear distance from the nucleus for 21 Sc galaxies, arranged according to increasing linear radius. Curve drawn is rotation curve formed from mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, the isophote of 25 mag arcsec^{-2}; those with upper and lower extensions mark $R^{i,b}$, i.e., R_{25} corrected for inclination and galactic extinction. Dashed line from the nucleus indicates regions in which velocities are not available, due to small scale. Dashed lines at larger R indicates a velocity fall faster than Keplerian.

Vera Rubin, Ford and Thonnard, June 1980

A Naive Solution

$$\nabla^2 \Phi = 4\pi G \rho$$



Amazingly: Still not clear-cut on galactic scales

Outline

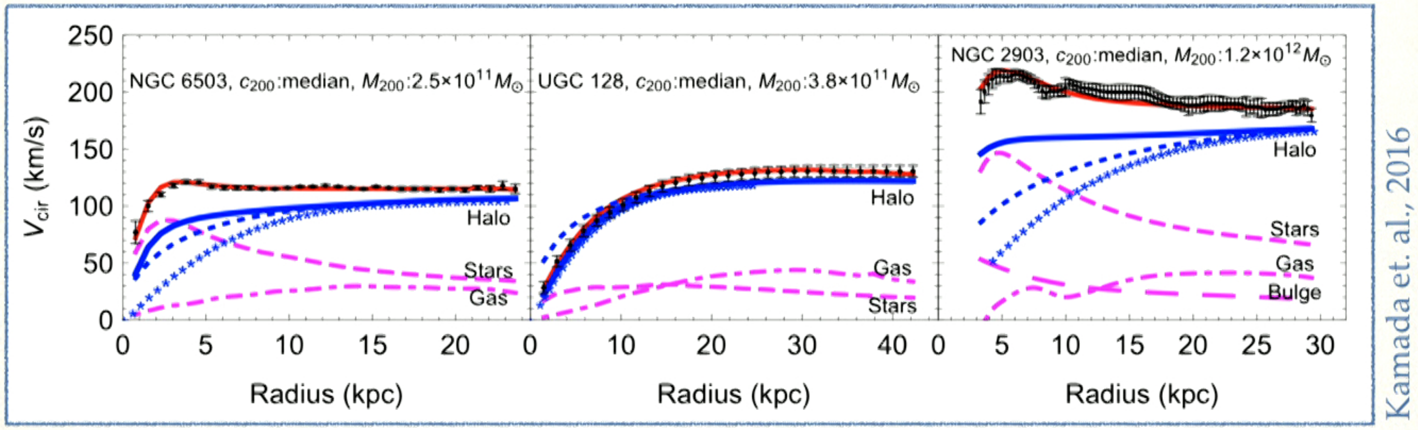
- Missing Mass and Galaxy Scale Observables
- Features of Various Classes of Solutions
- SuperFluid Dark Matter
- Framework to Test Various Models using MW data
- Results and Conclusions

The Missing Mass Problem on Galactic Scales, 2019

- **Flat Rotation Curves**
- **Issues with Small Scales:**
  - Missing Satellites (maybe solved)
  - Too Big To Fail
  - Core vs Cusp
- **DM Correlates with Baryons:**

Galaxy Scale Observables

The Diversity Problem

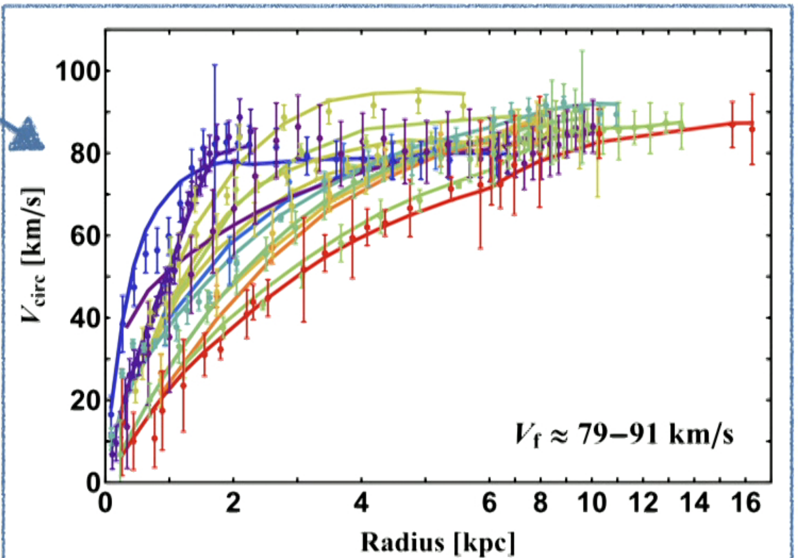


- Diversity of inner rotation curves even for galaxies with similar halo and stellar mass.
- Rotation curves correlate with baryons

Galaxy Scale Observables

The Diversity Problem

DM dominated galaxies!

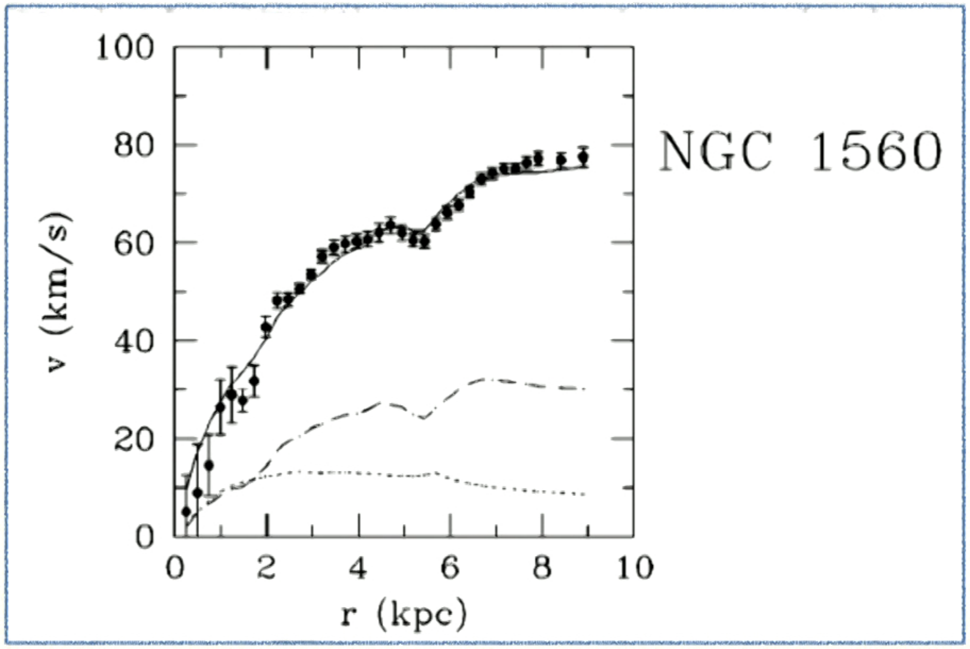


Kamada et. al., 2016

- Low surface brightness - halo is cored
- High surface brightness - halo is cusped
- Self similar if scaled to baryonic scale radius

Galaxy Scale Observables

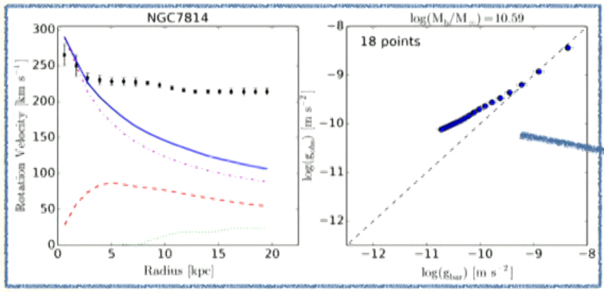
Renzo's Rule



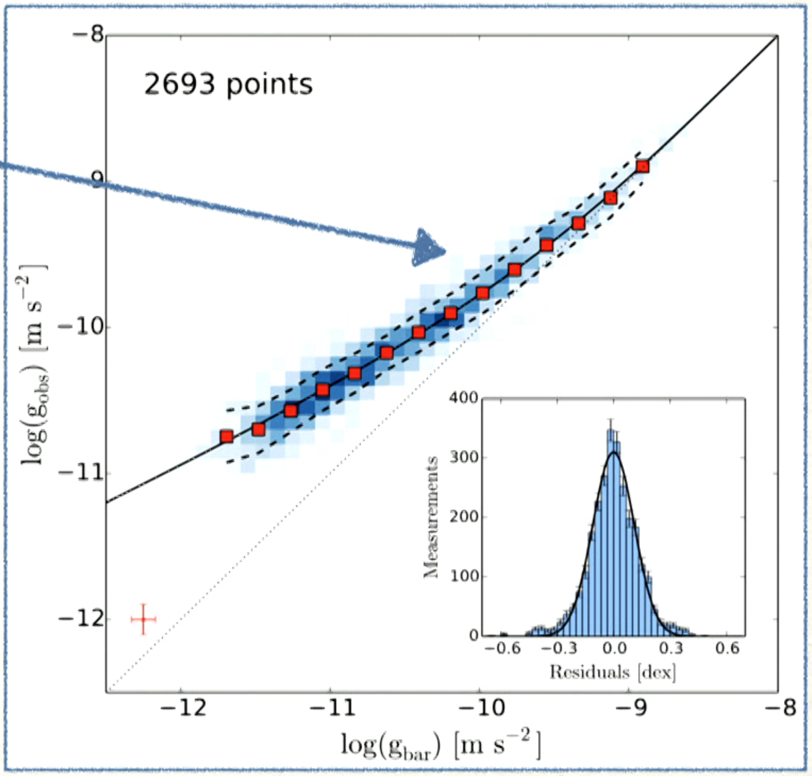
Sancisi, 2003

Galaxy Scale Observables

The Radial Acceleration Relation (RAR)



Lelli et. al, 2017



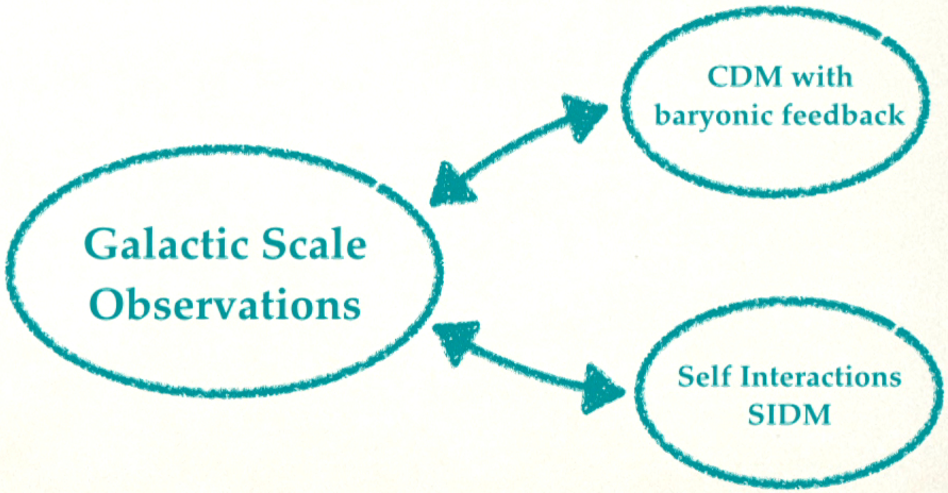
McGaugh, Lelli, 2017 10

A tight correlation and an acceleration scale appear in rotation curve data from the SPARC catalog

Galaxy Scale Observables

What models resolve these issues?

- Galaxies provide clues that DM correlates with baryons.
- Examples of solutions are:



Fitting the MDAR with a Fundamental Force

- Produce flat rotation curves: $\Phi \propto \log r \rightarrow a \propto \frac{1}{r} \rightarrow v_c \propto \text{const}$
- Different models do this in various ways
- They typically reduce to: $\boldsymbol{a} = \nu\left(\frac{a_\mathrm{N}}{a_0}\right)\boldsymbol{a}_\mathrm{N}$
- With an interpolation function with asymptotes: $\nu\left(x_\mathrm{N}\right) = \begin{cases} x_\mathrm{N}^{-1/2} & x_\mathrm{N} \ll 1 \\ 1 & x_\mathrm{N} \gg 1 \end{cases}$
- This reproduces the MDAR: $a = \begin{cases} a_\mathrm{N} & a \gg a_0 \\ \sqrt{a_0 a_\mathrm{N}} & a \ll a_0 \end{cases}$

What can we do?

1. Ask a **model independent** question:
   - Can local MW measurements fit a generic model that predicts the MDAR with a fundamental force?

Anything that mimics MOND

2. Test a **specific realization**:
   - e.g. A specific interpolation function
   - e.g. Superfluid dark matter

(Test these models where they're supposed to shine!)

Superfluid DM

$T \approx m v_{\text{vir}}$

Galaxies

$T_{\text{gal}} \approx 0.1\text{mK}$

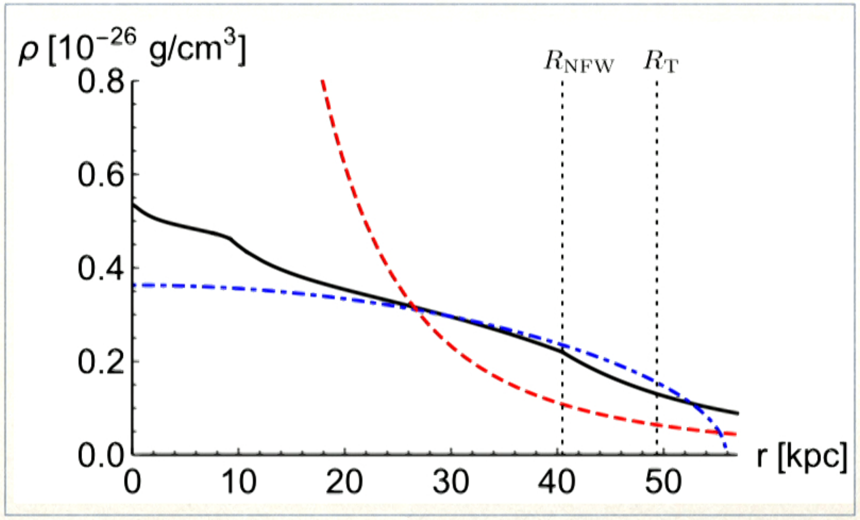
Super Fluid Phase
MOND-Like Emergent Force

Galaxy Clusters

$T_{\text{cluster}} \approx 10\text{mK}$

Cold DM
Standard DM Dynamics

Superfluid DM



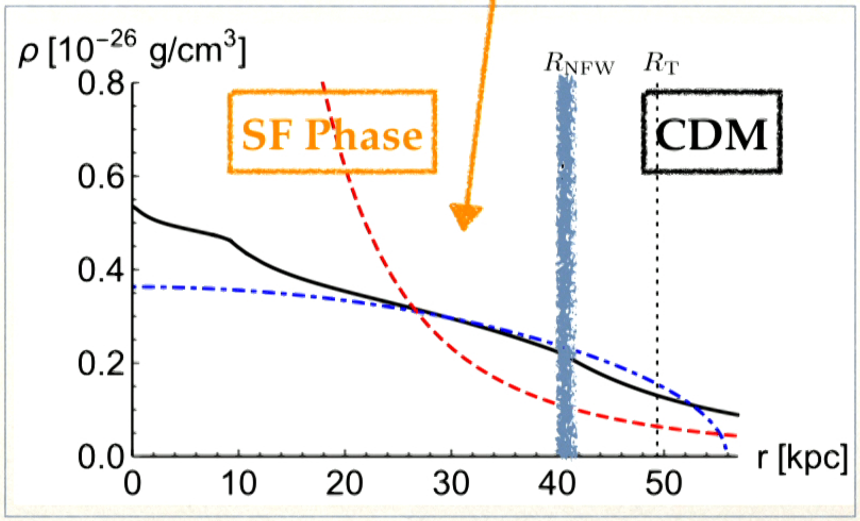
Berezhiani, Famaey, Khoury, 2017

Superfluid DM

$$\mathcal{L}_{\text{DM},\,T=0} = \frac{2\Lambda(2m)^{3/2}}{3} X\sqrt{|X|} - \alpha\frac{\Lambda}{M_{\text{Pl}}}\phi\rho_{\text{b}}$$

$$X = -m\Phi - (\vec{\nabla}\phi)^2/2m$$

$$\rho_{\text{SF}} = \frac{\partial\mathcal{L}}{\partial\Phi}$$



Berezhiani, Famaey, Khoury, 2017

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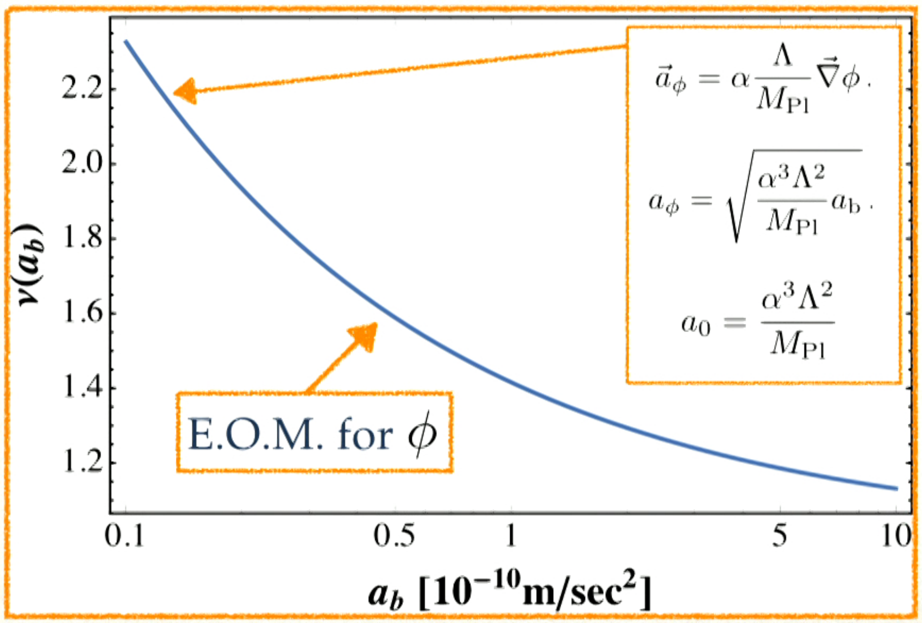
Superfluid DM

The SF Interpolation Function:



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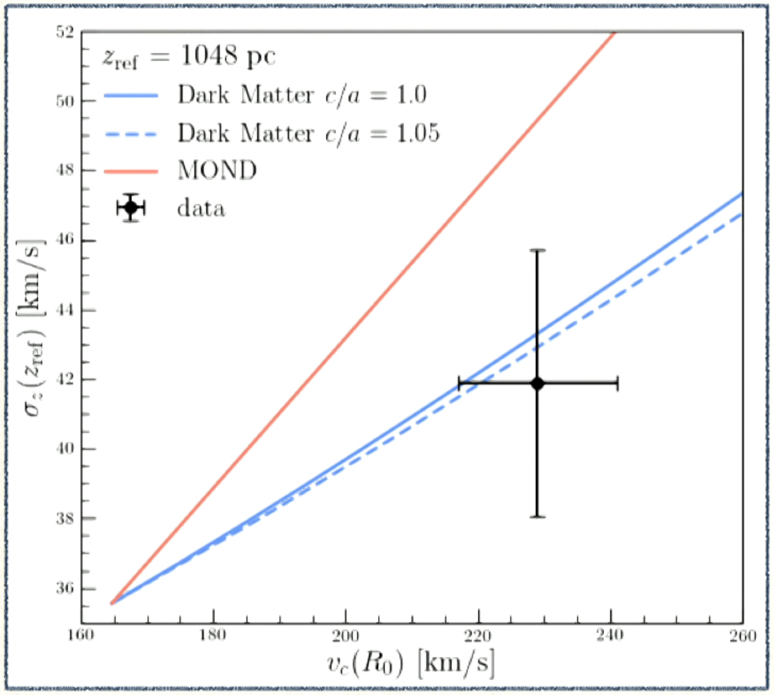
Local MW Observations Provide Differentiating Power

Compare accelerations in the R and z directions:



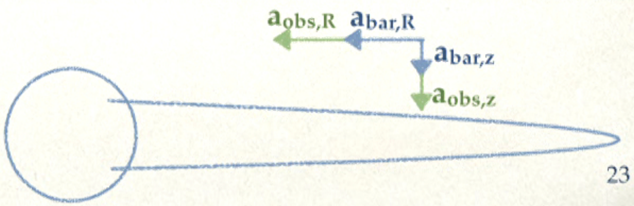
Lisanti, Moschella, Outmezguine, O.S., 2018

- Data requires amplification in a_R but essentially none in a_z.
- A spherical DM halo does precisely this:

$$\boldsymbol{a}_{\rm DM} \approx -G\frac{M(R_0)}{R_0^2}\left(1, \frac{z}{R_0}\right)$$

- A slightly prolate halo is slightly better.
- A MOND-like force amplifies a_R too little or a_z too much:

$$\frac{a_z}{a_R} = \frac{a_{z,\rm N}}{a_{R,\rm N}}\Big|_{\rm disk}$$



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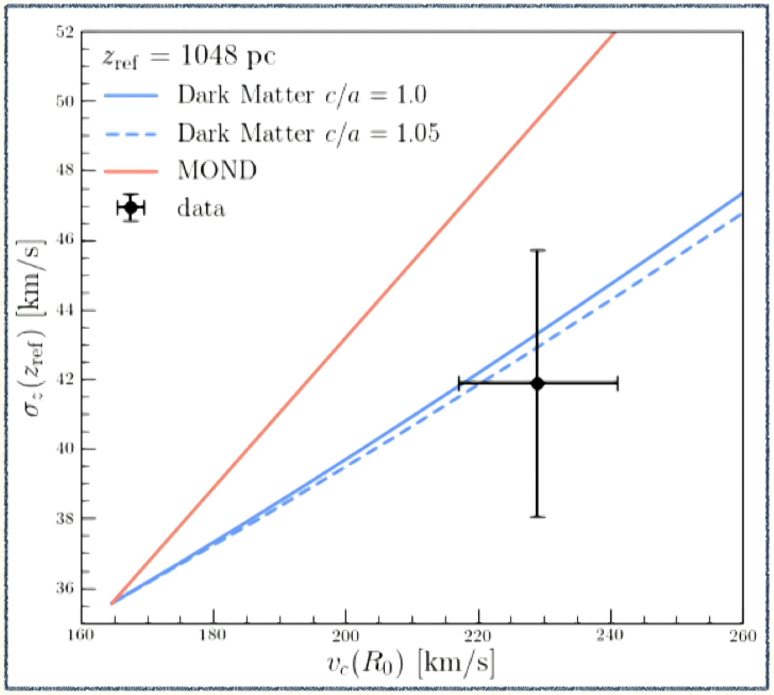

Lisanti, Moschella, Outmezguine, O.S., 2018

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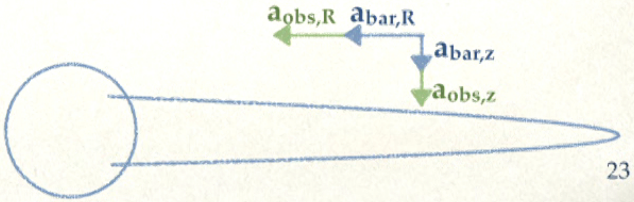
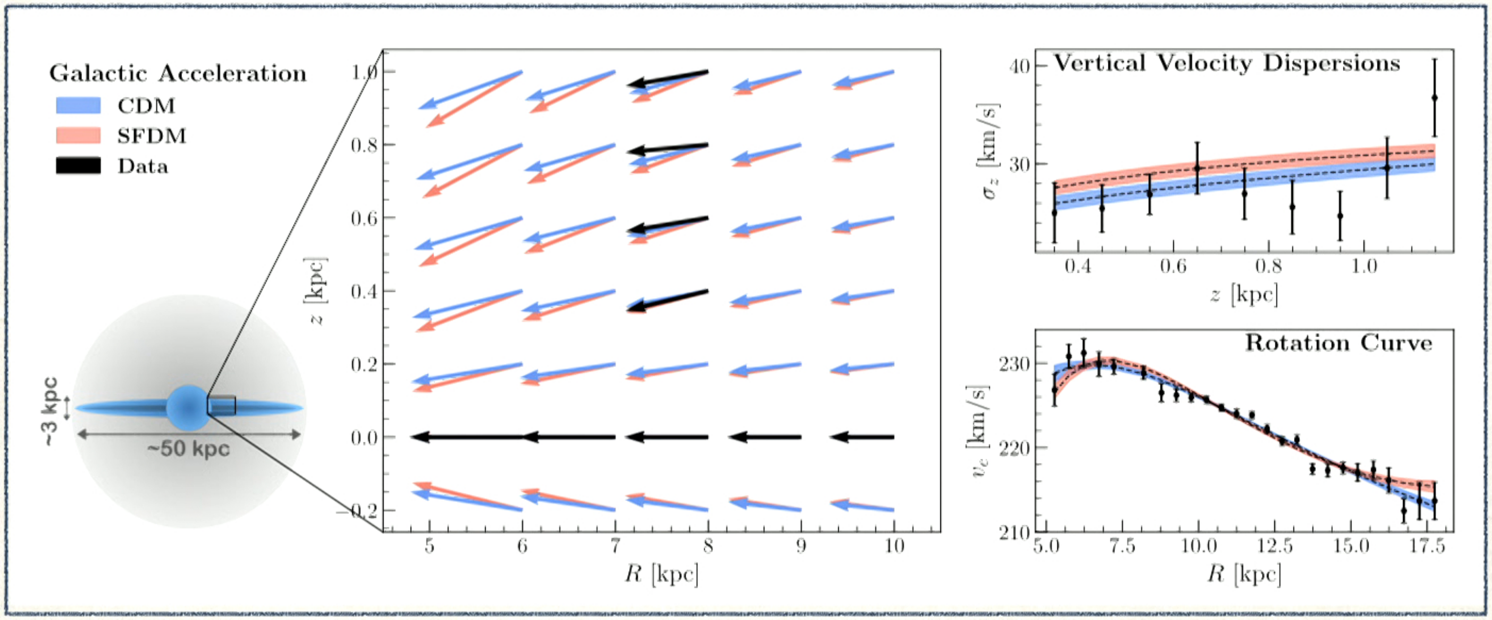


Local MW Observations Provide Differentiating Power

Superfluid Dark Matter is even more predictive:



Lisanti, Moschella, Outmezguine, O.S., 2019

Local MW Observations Provide Differentiating Power

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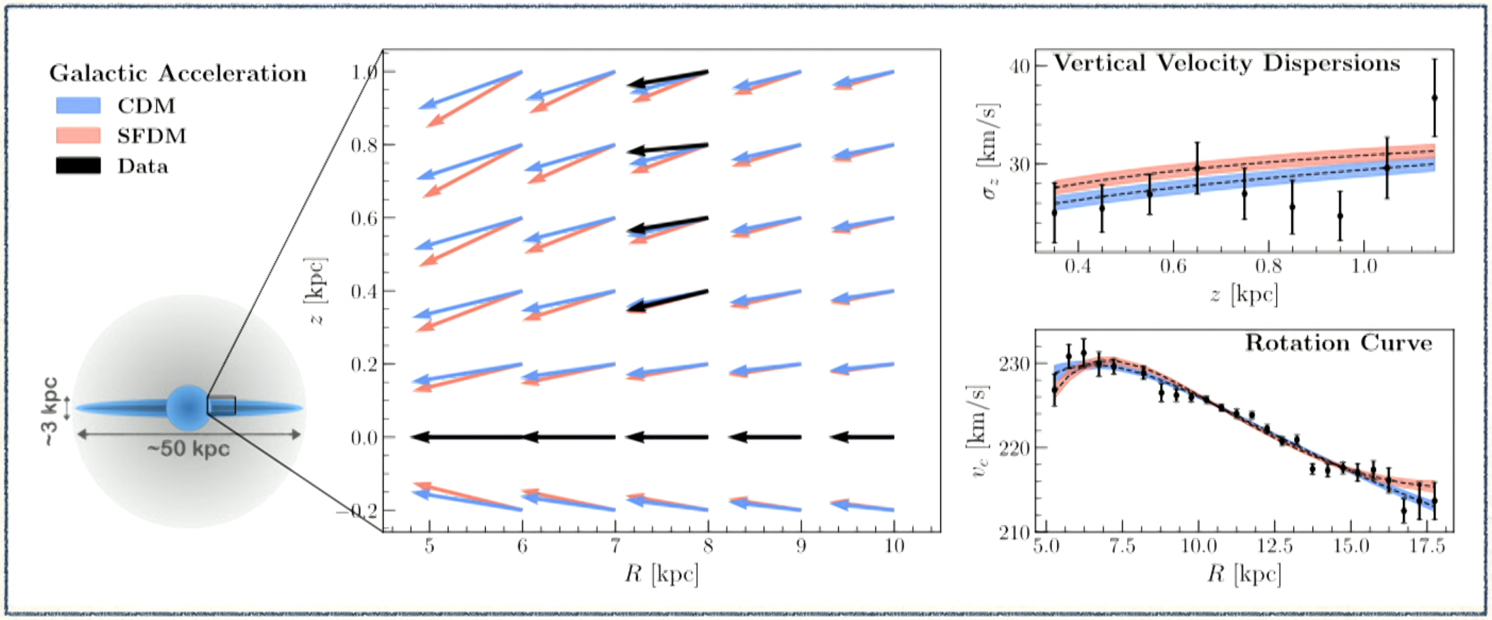


Lisanti, Moschella, Outmezguine, O.S., 2019

Local MW Observations Provide Differentiating Power

Bayesian Approach

- Given a model: $M =$ CDM vs SFDM / a generic MOND-like force
- With parameters: $\boldsymbol{\theta}_{\mathcal{M}}$
- Construct a likelihood function: $\mathcal{L}(\boldsymbol{\theta}_{\mathcal{M}}) \propto \exp\left[-\frac{1}{2}\sum_{j=1}^{N}\left(\frac{X_{j,\mathrm{obs}} - X_j(\boldsymbol{\theta}_{\mathcal{M}})}{\delta X_{j,\mathrm{obs}}}\right)^2\right]$
- $\mathbf{X}_{\mathrm{obs}}$: a set of measured values imposed as constraints
- $\mathbf{X}(\boldsymbol{\theta}_{\mathcal{M}})$: the corresponding model predictions
- Impose reasonable priors on $\boldsymbol{\theta}_{\mathcal{M}}$ and recover posterior distributions

Analysis Procedure

Milky Way Model

SFDM/MOND-like
For MOND use a Taylor expansion of the interpolation func

Dark Matter
A generalized NFW profile

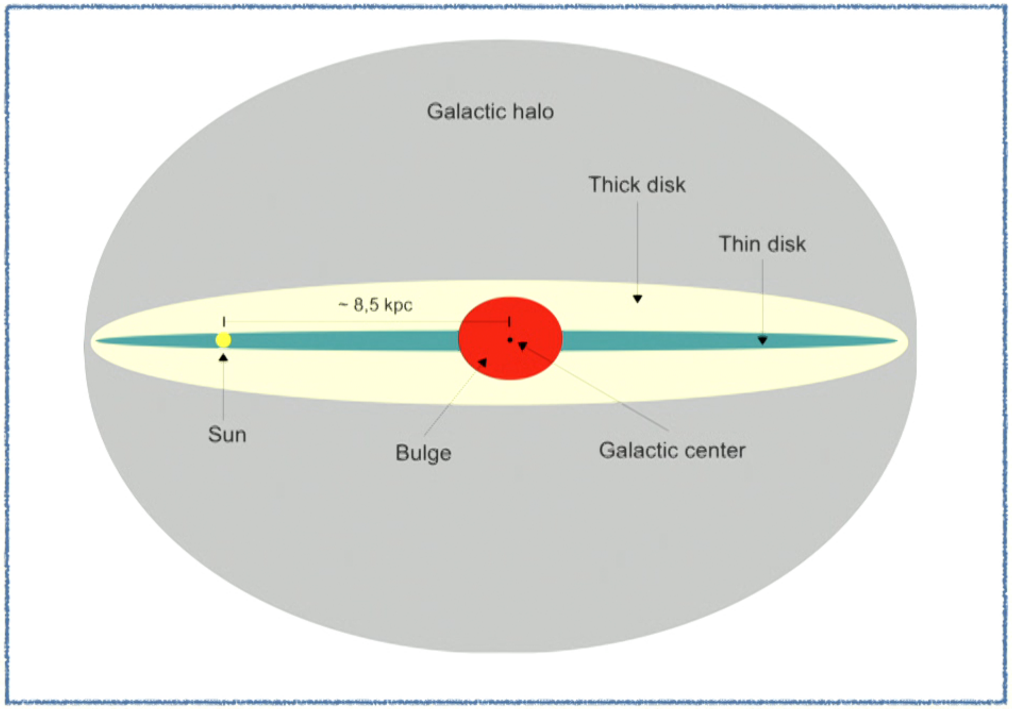
Model baryonic profile:

- Double exponential stellar disk
- Double exponential gas disk
- Hernquist stellar bulge

Perform a Markov Chain Monte Carlo analysis and fit parameters to MW measurements

Analysis Procedure

Baryonic Density Profiles



$$\rho_{\mathrm{B}} = \rho_{*,\mathrm{bulge}} + \rho_{*,\mathrm{disk}} + \rho_{g,\mathrm{disk}}$$

Analysis Procedure

Milky Way Observables

- Local stellar surface density
- Local gas surface density
- Disk scale radii (stars and gas)
- Disk scale heights (stars and gas)
- Bulge mass
- Rotation curve
- Vertical acceleration

Analysis Procedure

Milky Way Observables

- Local stellar surface density
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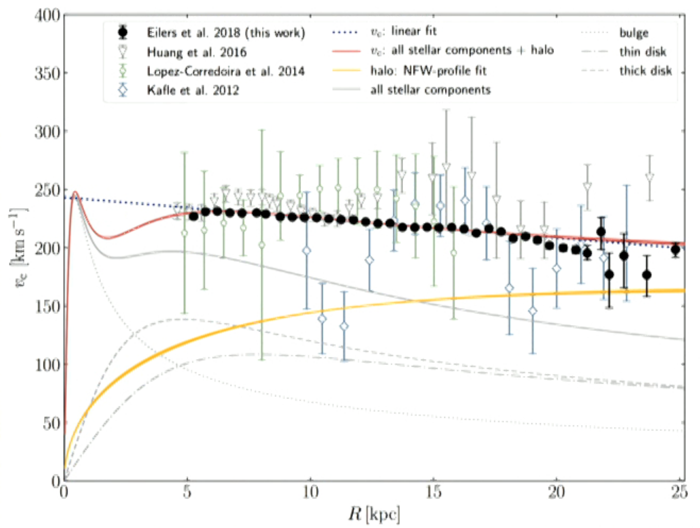
- Disk scale radii (stars and gas)
- Disk scale heights (stars and gas)
- Bulge mass
- **Rotation curve**
- Vertical acceleration



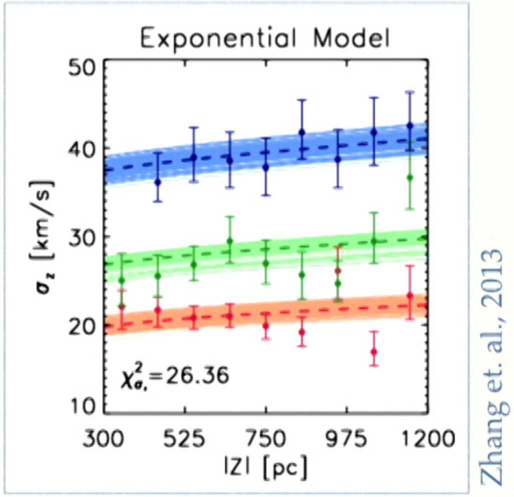
Eilers et. al., 2018

$$v_c(R) = \sqrt{R \cdot a(R)}\Big|_{z=0}$$

Analysis Procedure

Milky Way Observables

- Local stellar surface density
- Local gas surface density
- Disk scale radii (stars and gas)
- Disk scale heights (stars and gas)
- Bulge mass
- Rotation curve
- **Vertical acceleration**
  Inferred from 9000 K-dwarfs in the SEGUE sub-survey of the SDSS



$$\sigma_{i,z}(z)^2 = \frac{n_i(0)\,\sigma_{i,z}(0)^2}{n_i(z)} + \frac{1}{n_i(z)}\int_0^z n_i(z')\,a_z(z')\,dz'$$

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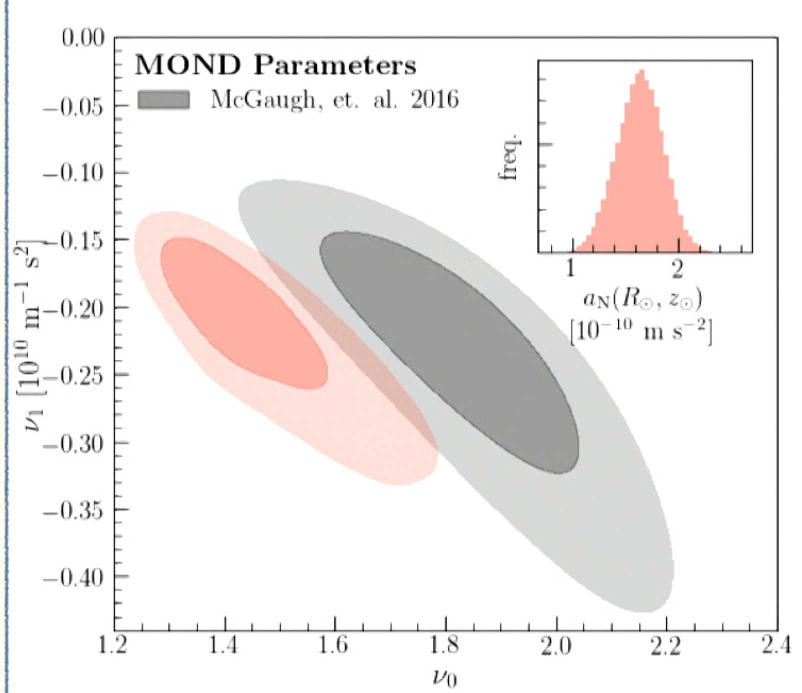
Results of MCMC Scans

Interpolation Function Parameters



Interpolation function fitted to RAR:

$$\nu(a_N/a_0) = \frac{1}{1 - e^{-\sqrt{a_N/a_0}}}$$

with

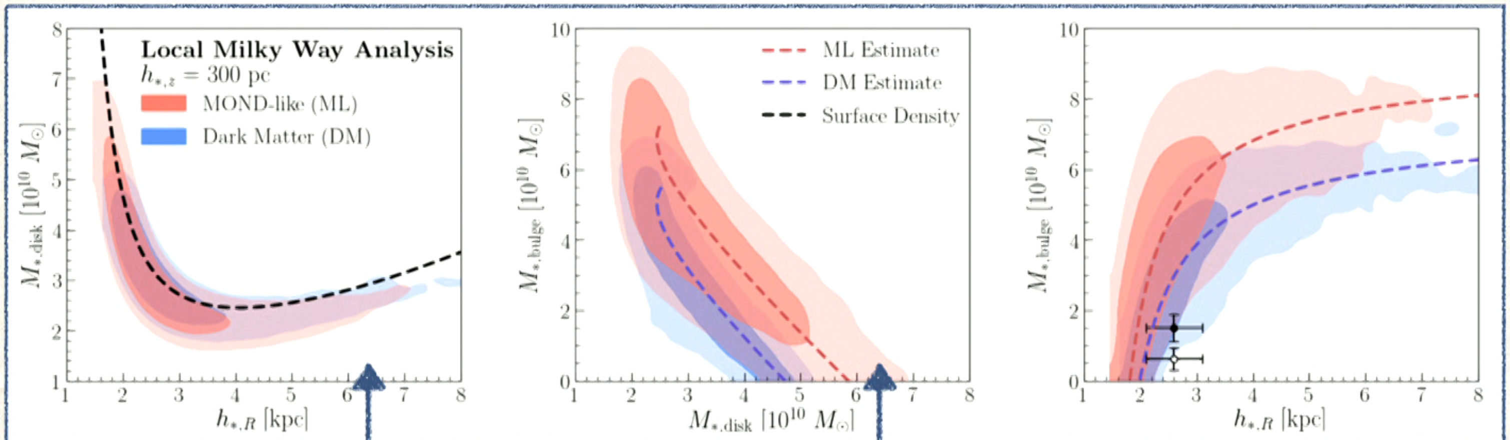
$$a_0 = 1.20 \pm 0.24 \times 10^{-10} \text{ m s}^{-2}$$

Excluded at 95% confidence

1812.08169 - Lisanti, Moschella, Outmezguine, O.S.

Results of MCMC Scans

Tension with MW Observations



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Driven by stellar surface density constraint

$$M_{*,\rm disk} = \frac{2\pi h_{*,R}^2 \Sigma_{*,\rm obs}^{z_{\rm max}} \exp(R_\odot/h_{*,R})}{1 - \exp(-z_{\rm max}/h_{*,z})}$$

Driven by local value of rotation curve constraint

$$v_c(R) = \sqrt{R \cdot a(R)}\Big|_{z=0}$$

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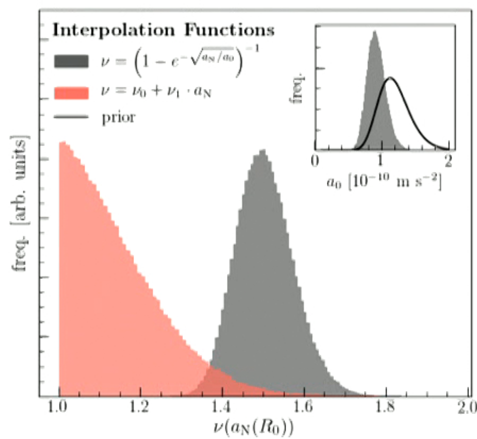
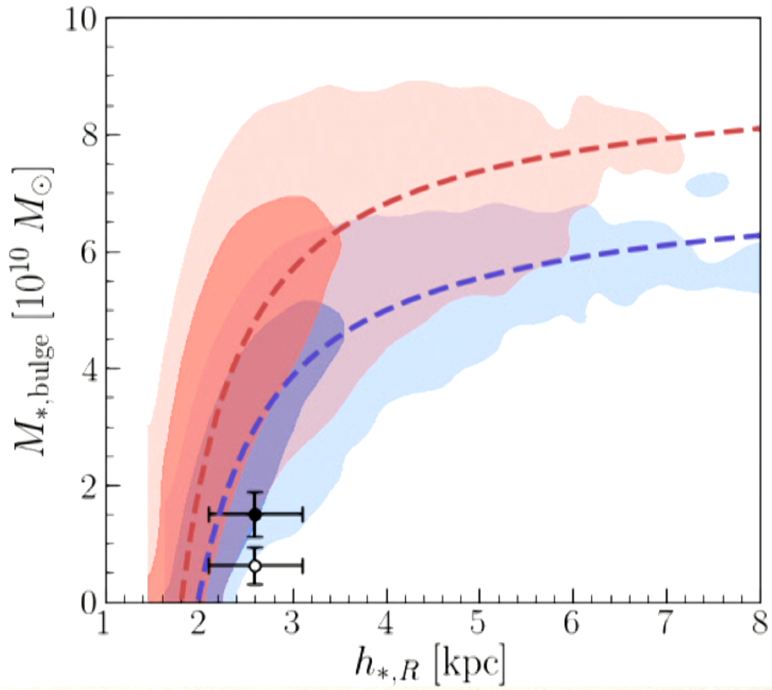
Results of MCMC Scans

Stellar Scale Radius *vs* Stellar Bulge Mass

Driven by local surface density and rotation curve





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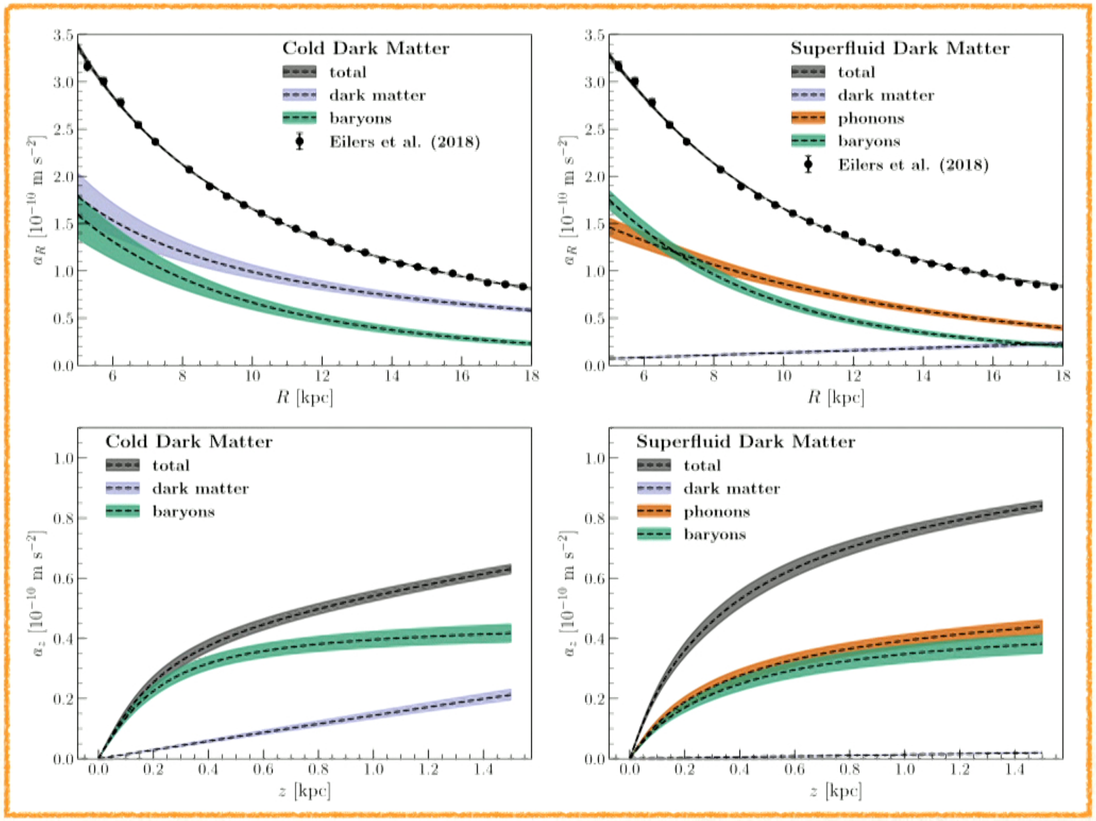
Results for SuperFluid DM

Full Rotation Curve and Vertical Accelerations



Lisanti, Moschella, Outmezguine, O.S., 2019

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Additional Tests

Redo analysis with:

- Only one mono-abundance population for velocity dispersions
- Various choices of priors for all parameters
- Artificially enhanced errors by factor of 2

$\Longrightarrow$ Qualitatively same results for all cross checks

Conclusions

- Standard lore is that "MOND-like forces work on Galactic scales". This is not precisely true.
- Our results establish a new criterion for any DM model which attempts to reproduce the MDAR.
- SFDM is a representative example of a broad class of such theories.
- MW measurements seem to prefer CDM over these models.