A Test of Collisionless DM vs IR Modifications to Gravity with Local MW Observables

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arXiv 1812:08169 - M. Lisanti, M. Moschella, N. Outmezguine and O. Slone

arXiv 1906.xxxxx - Constraining Superfluid DM with MW Dynamics, Same authors

Prelude
Back to the 80's

Prelude

Back to the 80's

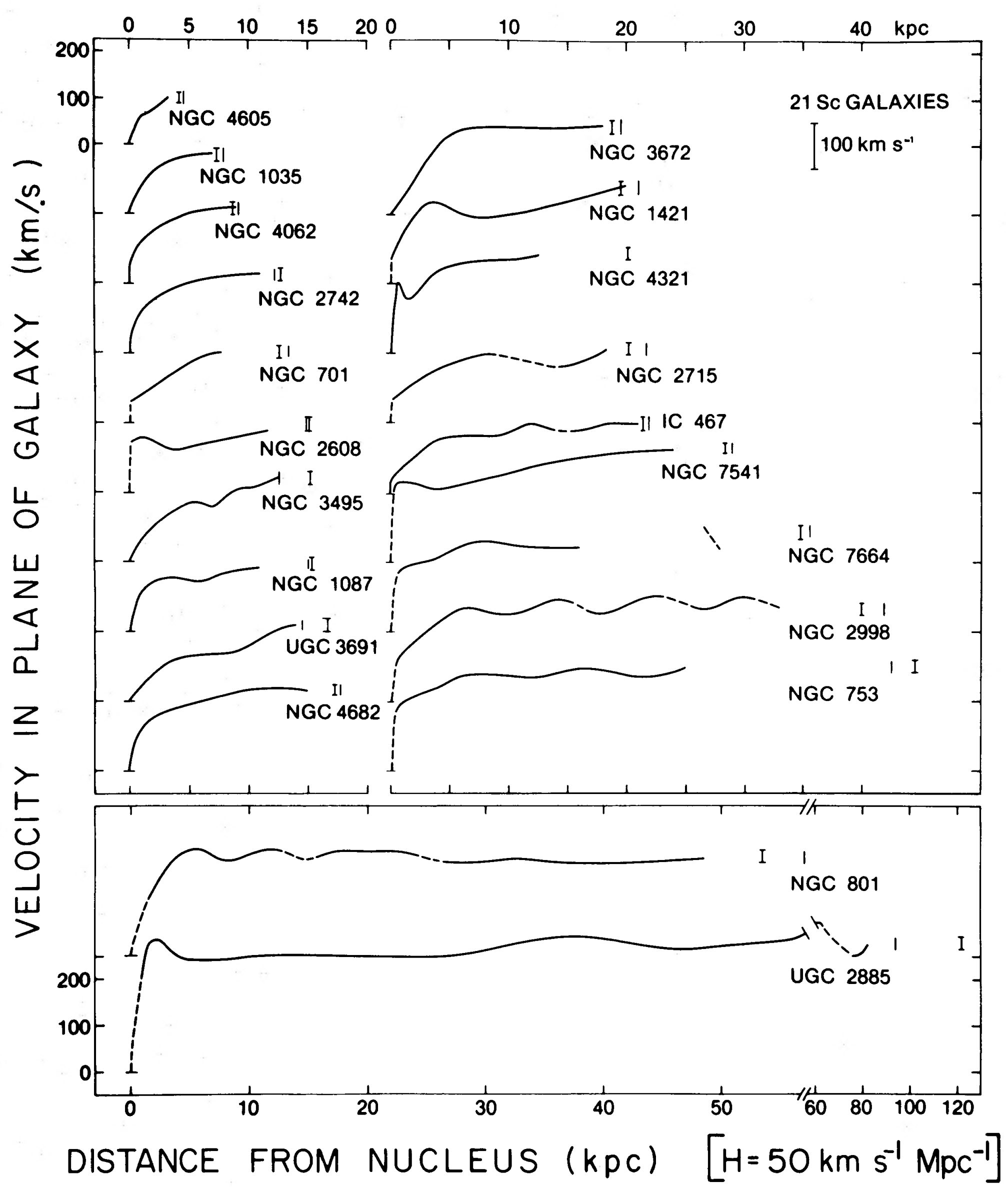


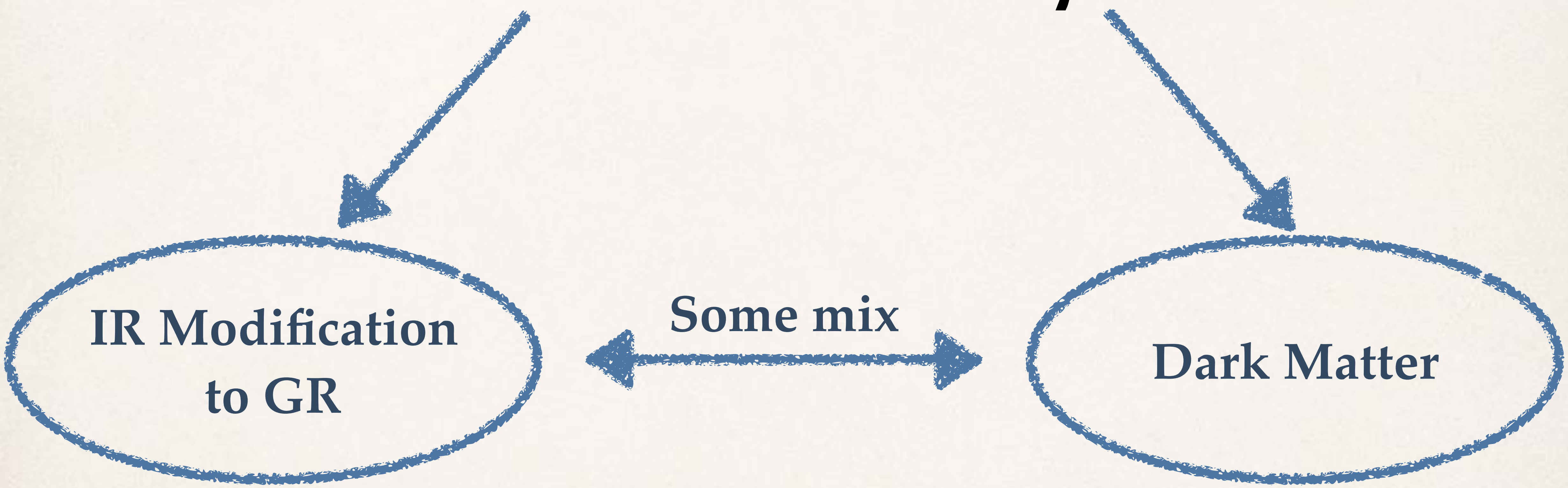
FIG. 5.—Mean velocities in the plane of the galaxy, as a function of linear distance from the nucleus for 21 Sc galaxies, arranged according to increasing linear radius. Curve drawn is rotation curve formed from mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, 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

Prelude

A Naive Solution

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



Amazingly: Still not clear-cut on galactic scales

2019:

Turns out there is still motivation to think about the problem in a similar fashion.

↓

CAN THESE THEORIES FIT
ALL MILKY WAY OBSERVABLES?

↓

Learn about important properties of the MW

Outline

- Missing Mass and Galaxy Scale Observables
- Features of Dark Matter vs IR Modification to Gravity
- A Framework to Test Various Models using MW data
- Results and Conclusions of our Study

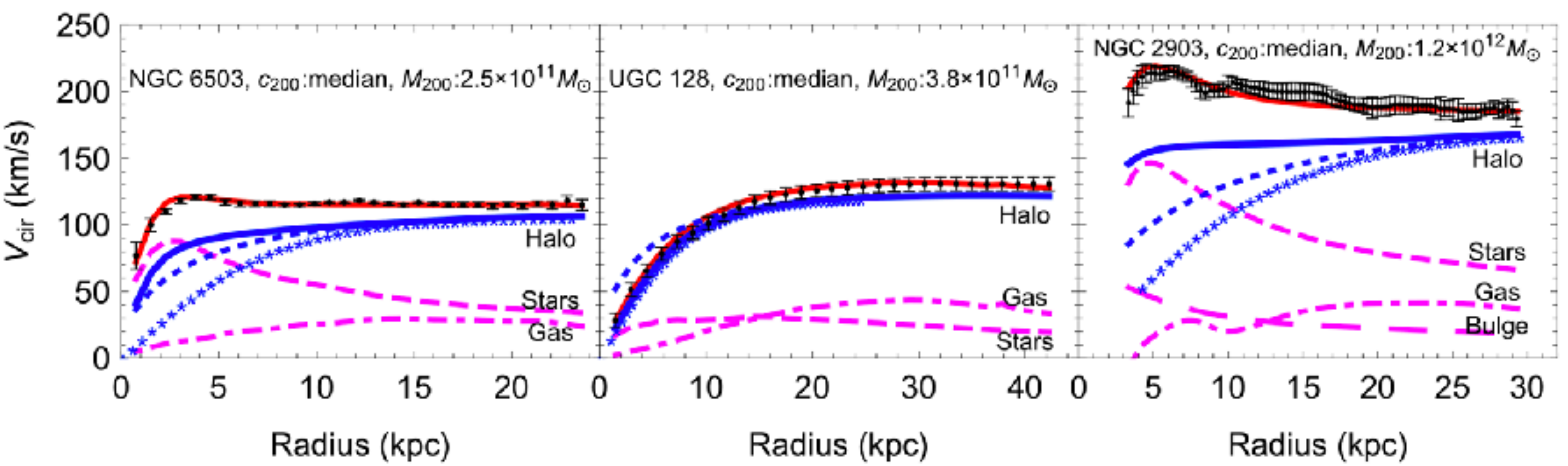
Galaxy Scale Observables

Issues with Small Scales

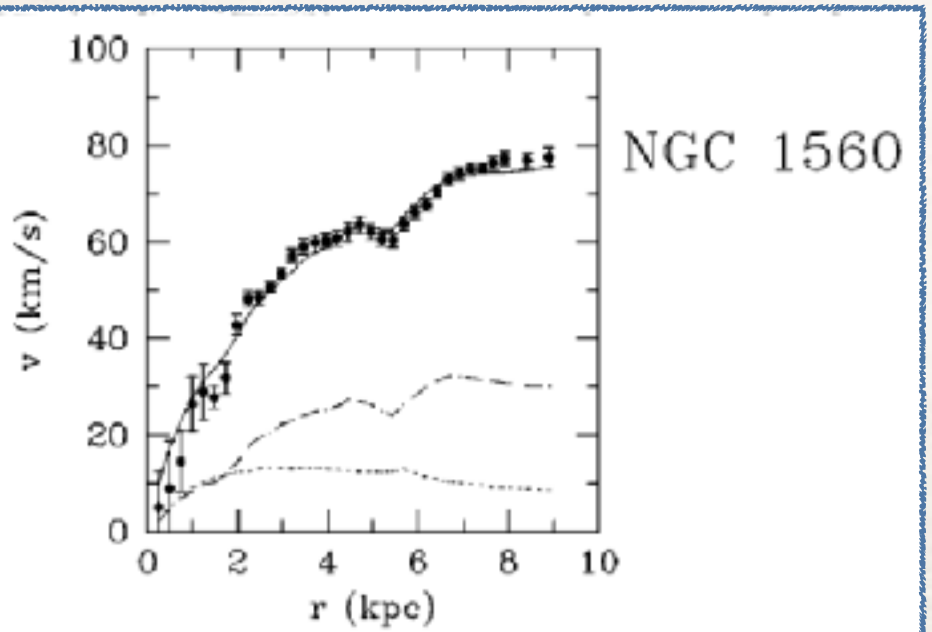
- Missing Satellites
- Too Big To Fail
- Core vs Cusp
- and also…

Galaxy Scale Observables

The Diversity Problem



Kamada et. al., 2016

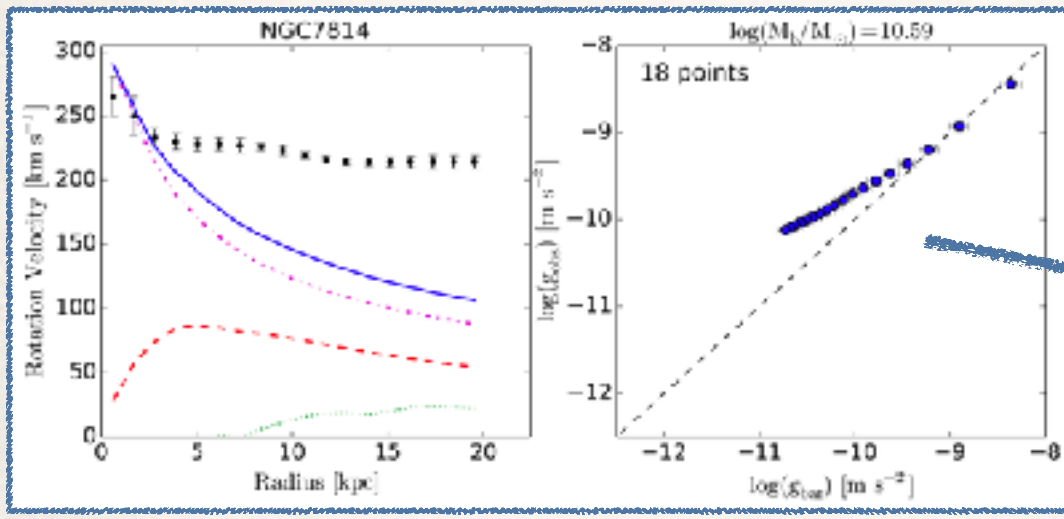


Sancisi, 2003

- Diversity of inner rotation curves even for galaxies with similar halo and stellar mass.
- Rotation curves correlate with galactic scale radius
- Some evidence points towards additional correlations between rotation curve shapes and baryonic distribution.

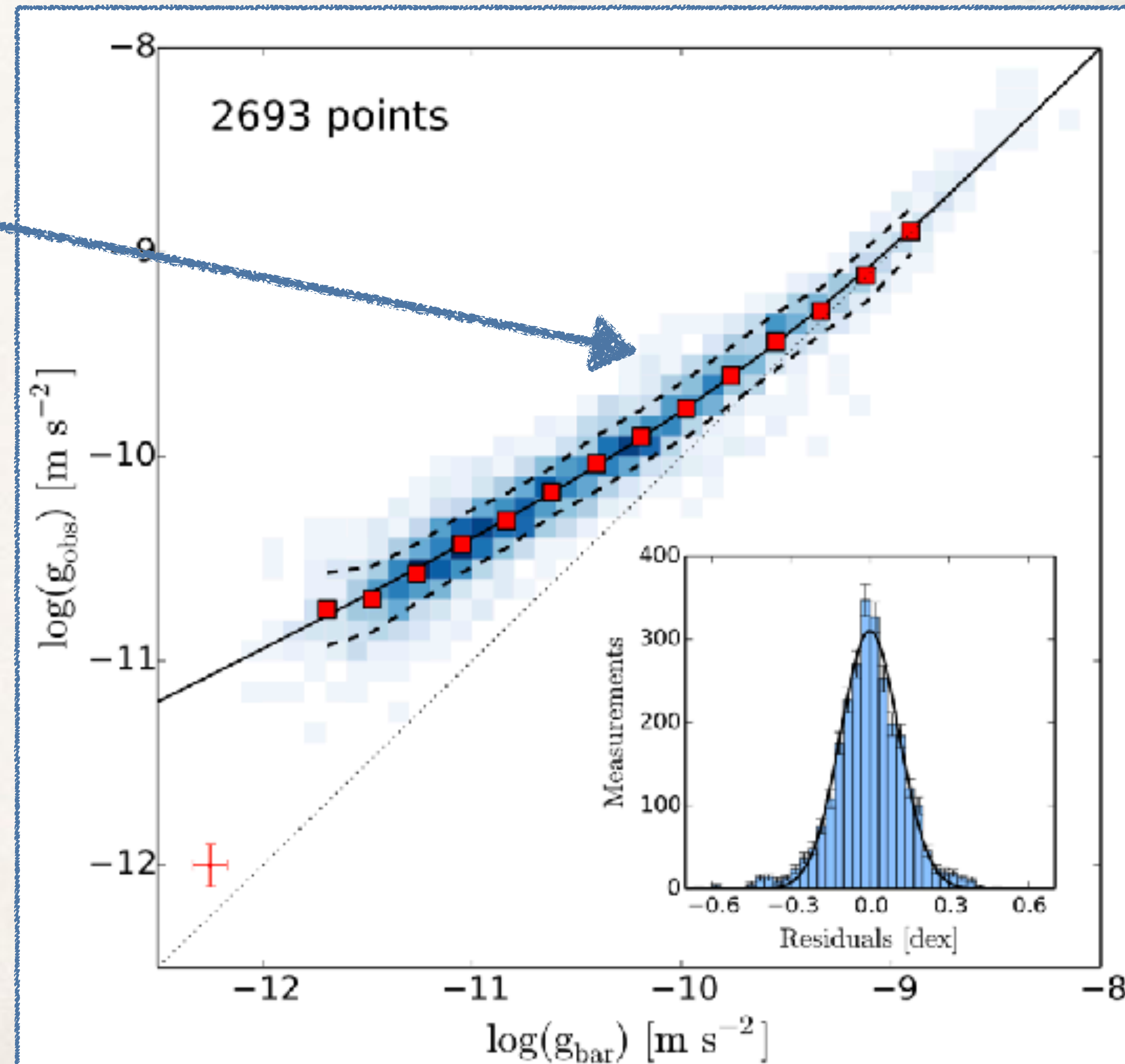
Galaxy Scale Observables

The Radial Acceleration Relation (RAR)



Lelli et. al, 2017

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



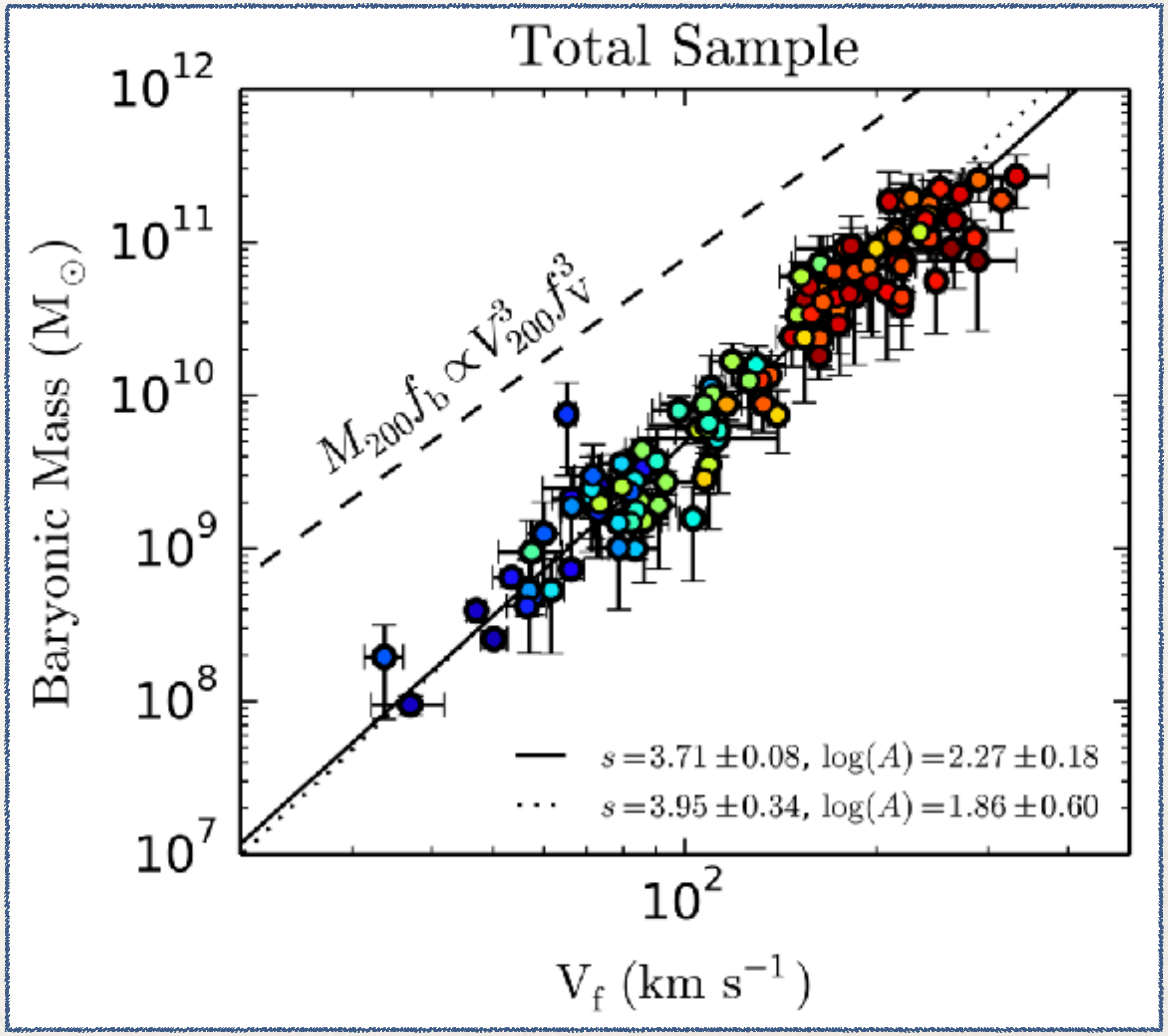
McGaugh, Lelli, 2017

Galaxy Scale Observables

The Baryonic Tully-Fisher Relation

A result of the information in the low end of the RAR

$$g_{\rm obs} \propto \sqrt{g_{\rm bar}} \quad \Rightarrow \quad \frac{V_{\rm f}^2}{R} \propto \frac{\sqrt{GM_{\rm bar}}}{R}$$



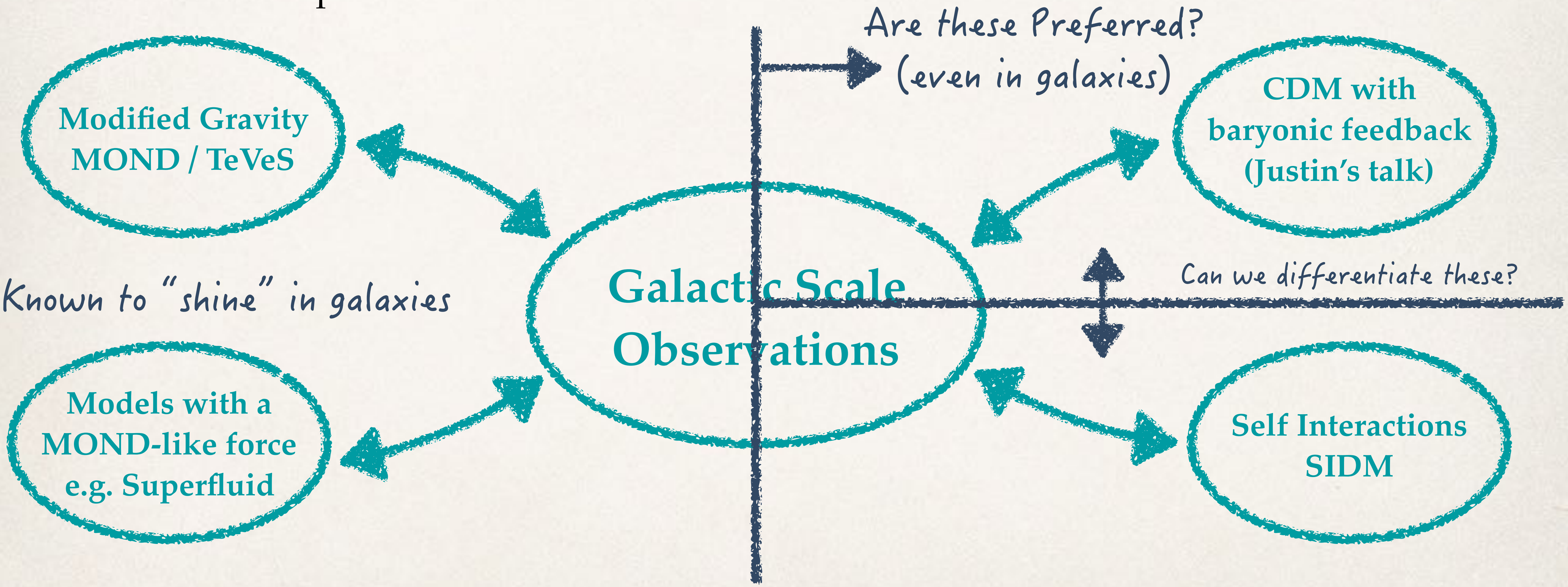
Lelli et. al., 2015

Galaxy Scale Observables

What models resolve these issues?

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

SUMMARY OF THIS TALK

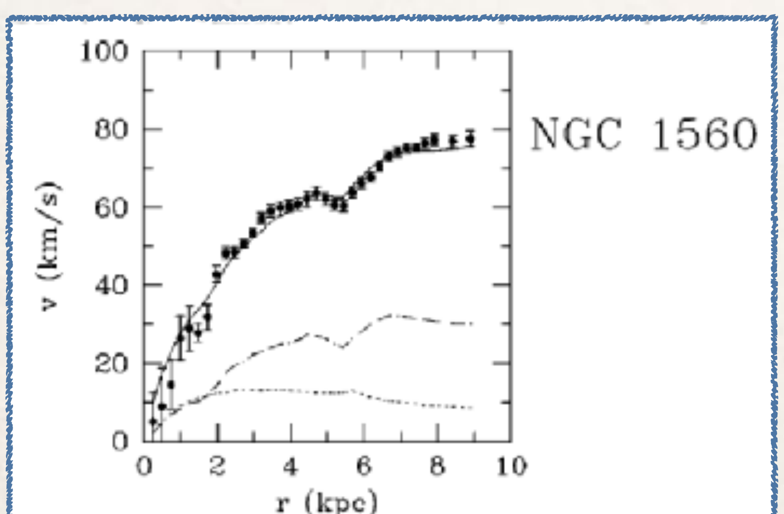


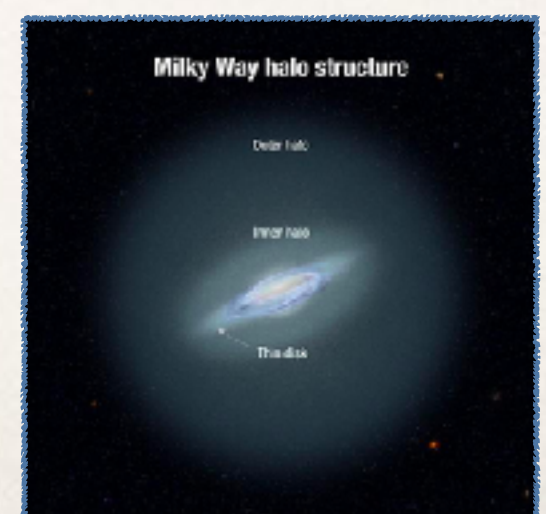
Or maybe DM mimics MOND on galactic scales?

Phenomenology of the Solutions

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

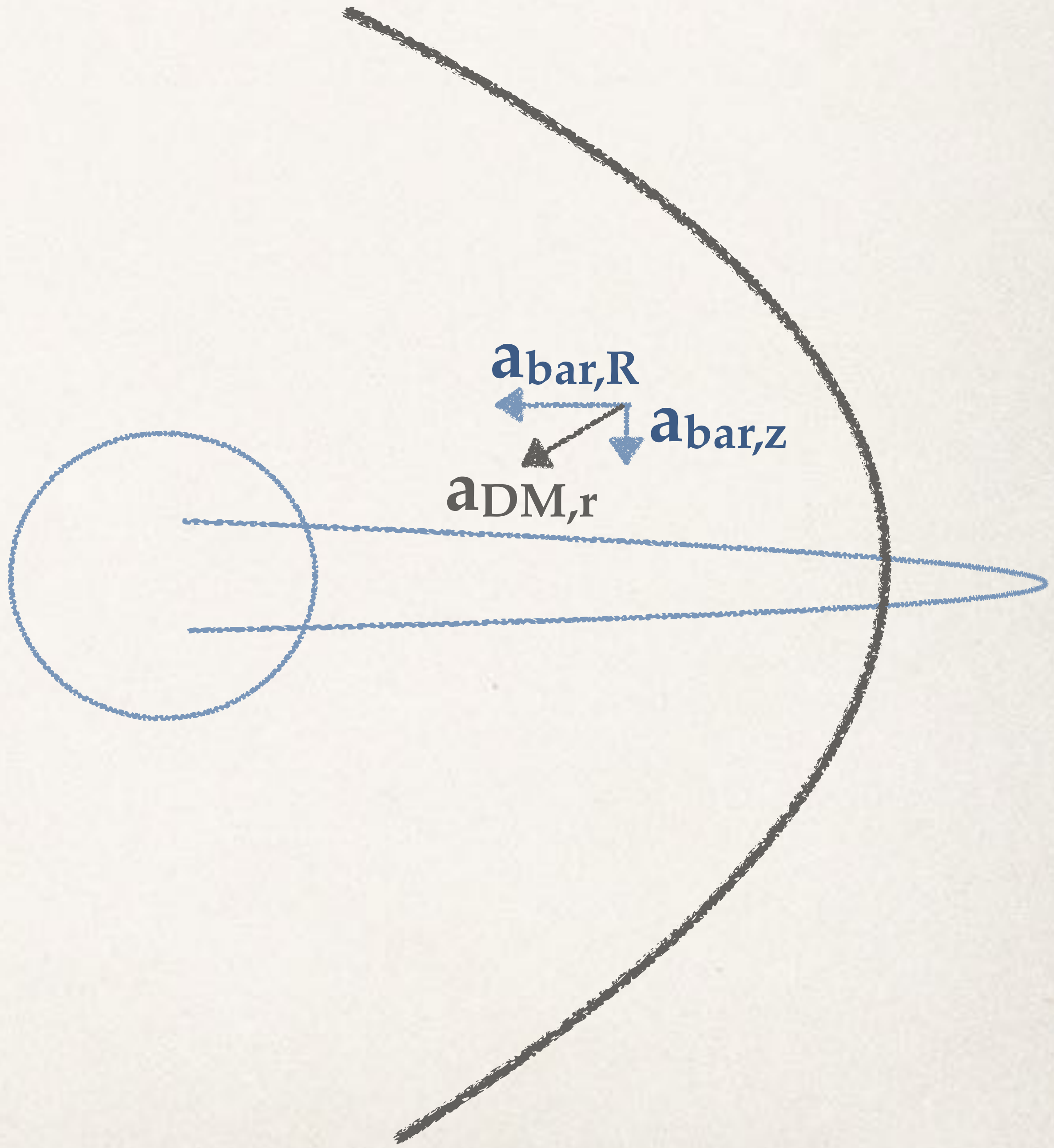
IR Modification to GR ⟷ **Some mix** ⟷ **Dark Matter**





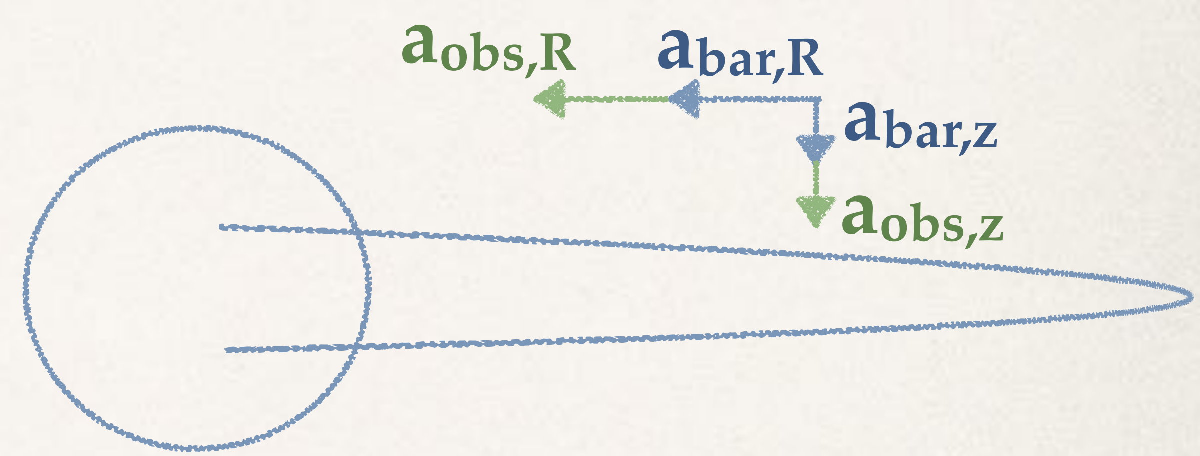
Dark Matter Pheno

- Galactic dynamics driven by an extended DM halo
- Halo shape is weakly constrained by measurements
- NFW-like profile probable from N-body simulations
- Amplifies acceleration via additional density profile



IR Modified Gravity Pheno

- **Galactic dynamics driven purely by baryons**
- Most simple example is a scalar enhancement to Newtonian gravity
- Designed to reproduce flat rotation curves:
- MOND-like forces amplify acceleration:



$$\Phi \propto \log r \to a \propto \frac{1}{r} \to v_c \propto \text{const}$$

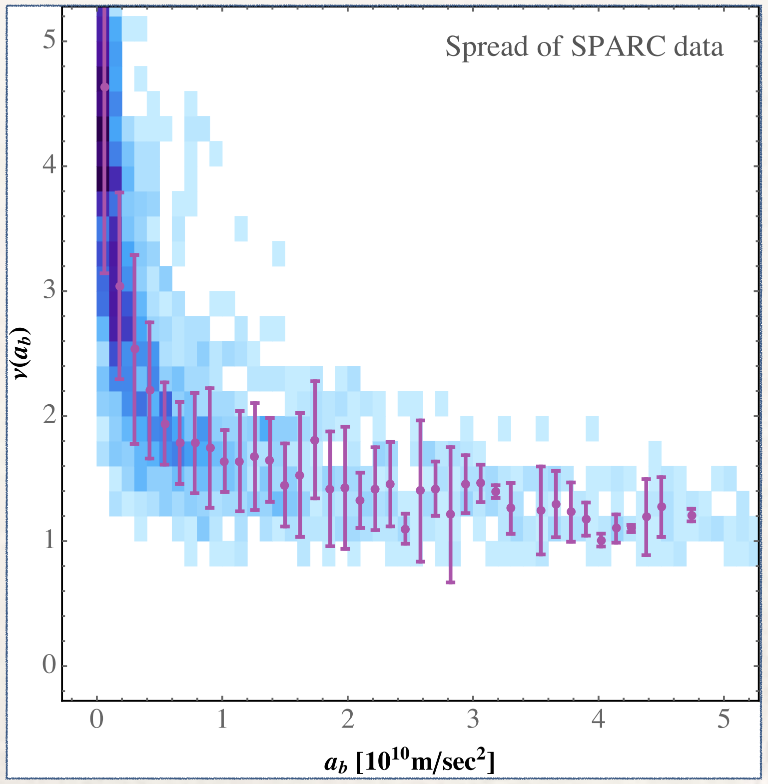
$$a = \begin{cases} a_{\rm N} & a \gg a_0 \\ \sqrt{a_0 a_{\rm N}} & a \ll a_0 \end{cases}$$

Newtonian acceleration

$$a_{\rm N} \propto \frac{1}{r^2}$$

MOND-like forces

- MONDian theories: MOND, QuMOND, TeVeS, AQUAL
- Also some Newtonian DM theories: e.g. Superfluid DM
- All reduce to: $$\boldsymbol{a} = \nu\left(\frac{a_{\rm N}}{a_0}\right)\boldsymbol{a}_{\rm N}$$
- With an interpolation function with asymptotes: $$\nu\left(x_{\rm N}\right) = \begin{cases} x_{\rm N}^{-1/2} & x_{\rm N} \ll 1 \\ 1 & x_{\rm N} \gg 1 \end{cases}$$



Lisanti, Moschella, Outmezguine, OS (PRELIMINARY)

For example:

$$\hat{\nu}_\alpha(x_{\rm N}) = \left(1 - e^{-x_{\rm N}^{\alpha/2}}\right)^{-\frac{1}{\alpha}}$$

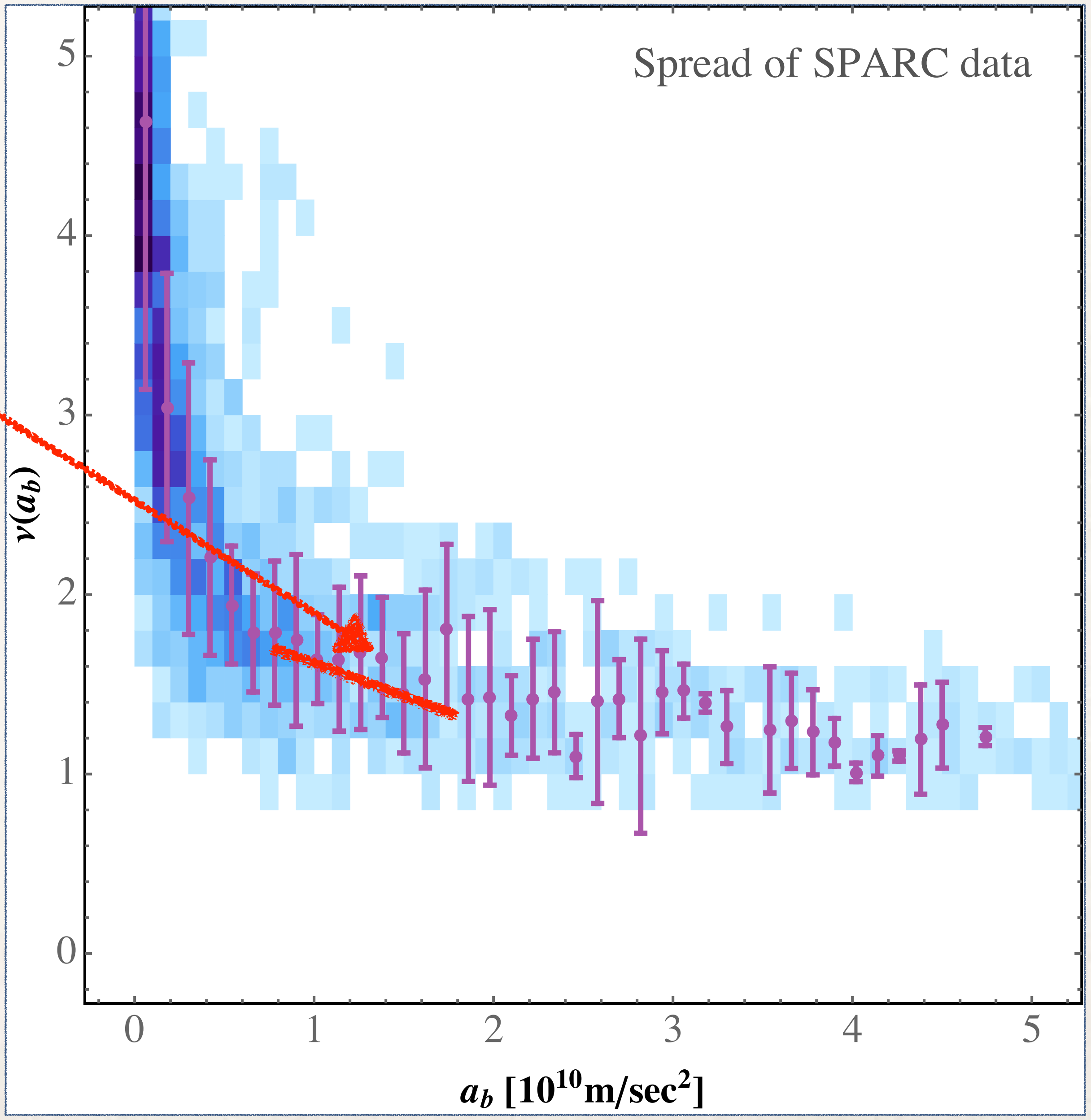
McGaugh, et. al. 2016

MOND-like forces

Solar acceleration happens to live here

Local measurements are sensitive only to small deviation in acceleration

$$\boldsymbol{a} = \nu\left(\frac{a_{\mathrm{N}}}{a_0}\right)\boldsymbol{a}_{\mathrm{N}} \rightarrow \mathbf{a} = (\nu_0 + \nu_1 a_{\mathrm{N}})\,\mathbf{a}_{\mathrm{N}}$$



Lisanti, Moschella, Outmezguine, OS (PRELIMINARY)

What can we do?

Anything that mimics MOND

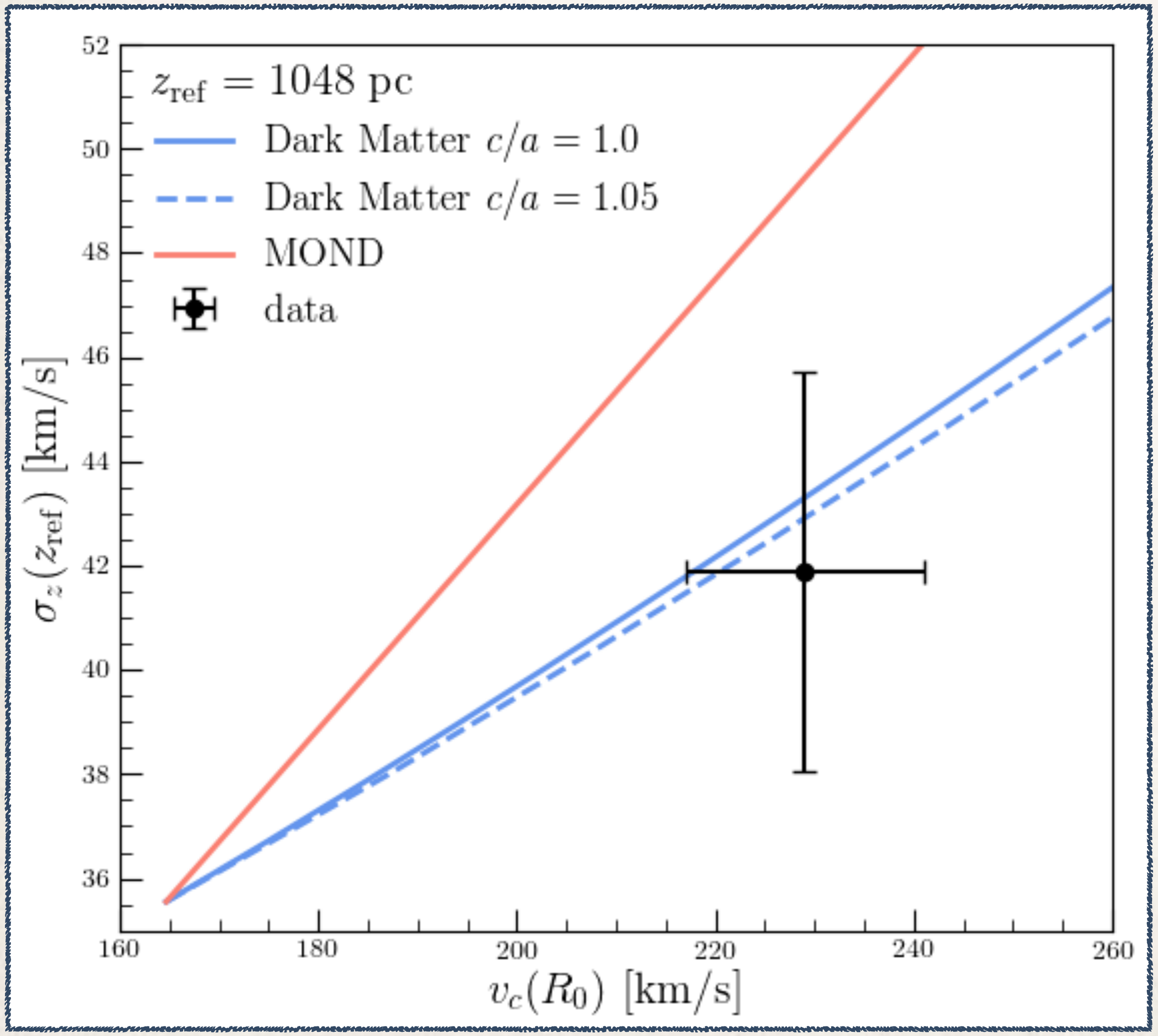
Ask a **model independent** question:

Can local MW measurements fit a generic model that results in a MOND-like force?

(Test MOND-like models where they're supposed to shine!)

Local MW Observations Provide Differentiating Power

Compare accelerations in the R and z directions:



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

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

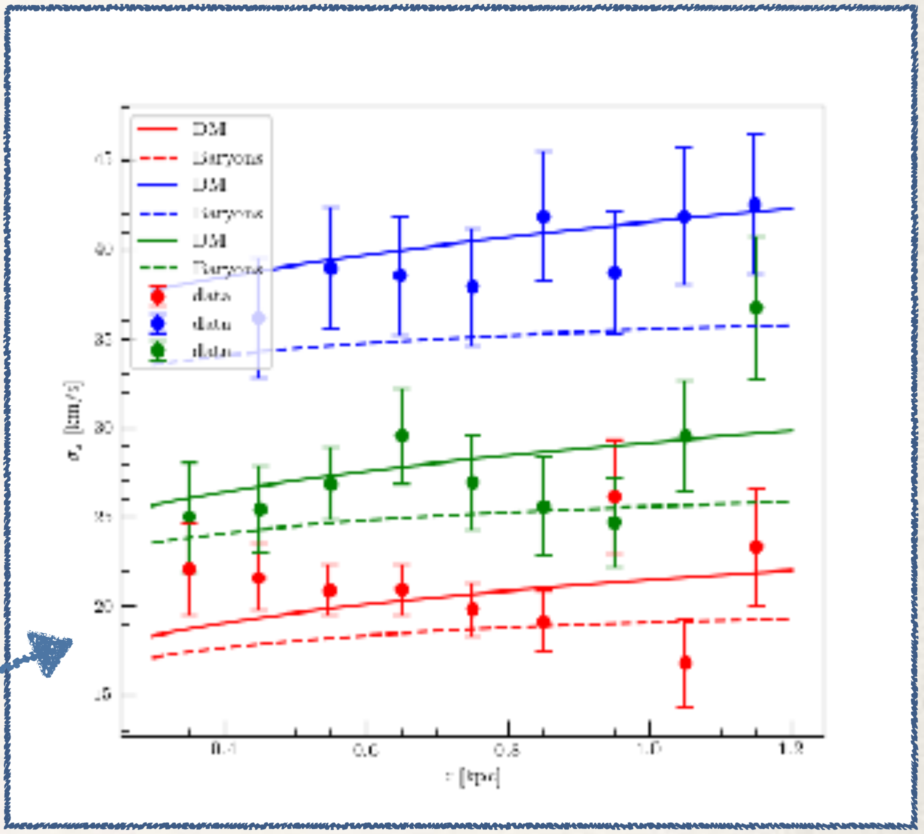
- A slightly prolate halo is slightly better.
- A MOND-like force amplifies a_R too little or a_z too much:

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

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

Local MW Observations Provide Differentiating Power

- In principle: measure **a** and $\mathbf{a_N}$ and you're done!
- However measurements are imperfect:
  - Baryonic profile is not perfectly measured.
  - Accelerations are not directly measured. Velocities and velocity dispersions are.
- Therefore: Adopt a **Bayesian Approach**



Lisanti, Moschella, Outmezguine, O.S., 2018
Data from Zhang et. al., 2013

Local MW Observations Provide Differentiating Power

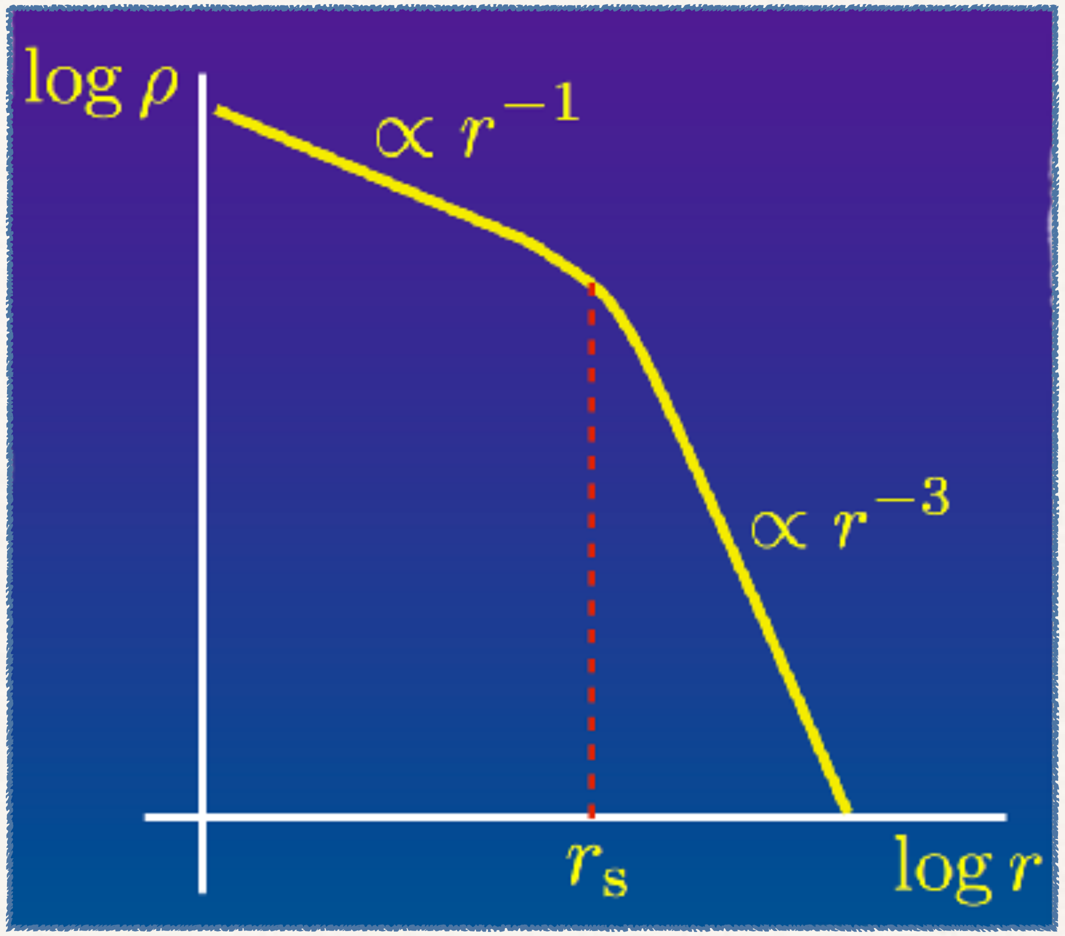
Bayesian Approach

- Given a model: $\mathcal{M} = \mathrm{DM, MG}$
- 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:
TESTING a MOND-like force vs DM

Analysis Procedure

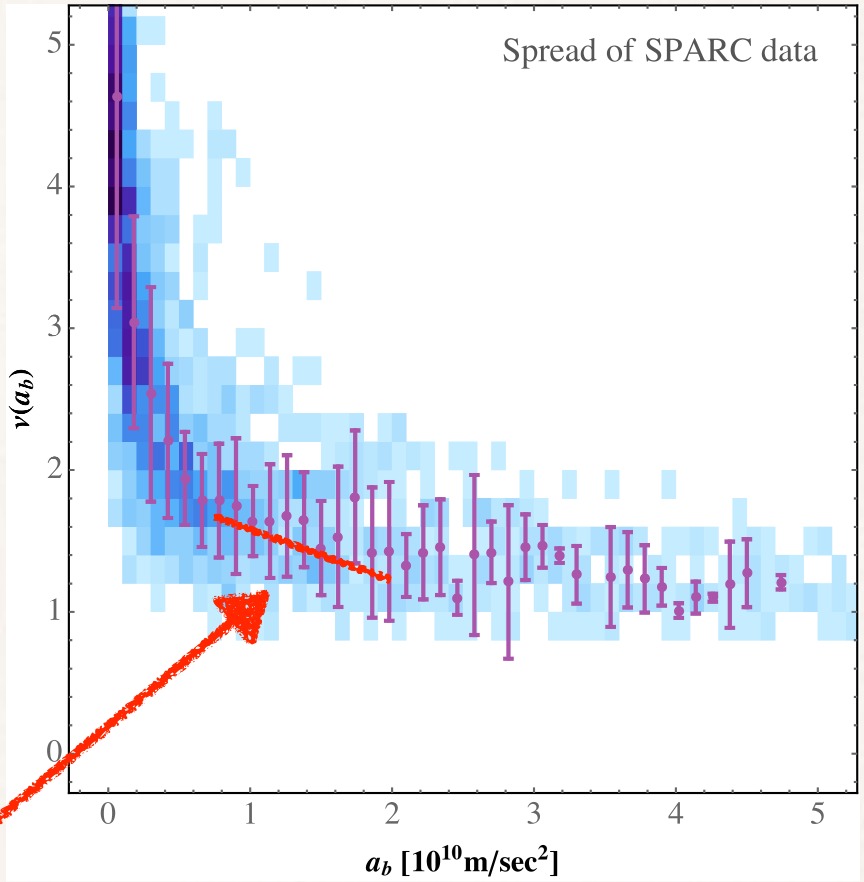
Dark Matter Parameters



$$\rho_{\rm DM}(r) = \frac{\tilde{\rho}_{\rm DM}}{(r/r_s)^{\alpha}\,(1+r/r_s)^{3-\alpha}}$$

Analysis Procedure

Modified Gravity Parameters

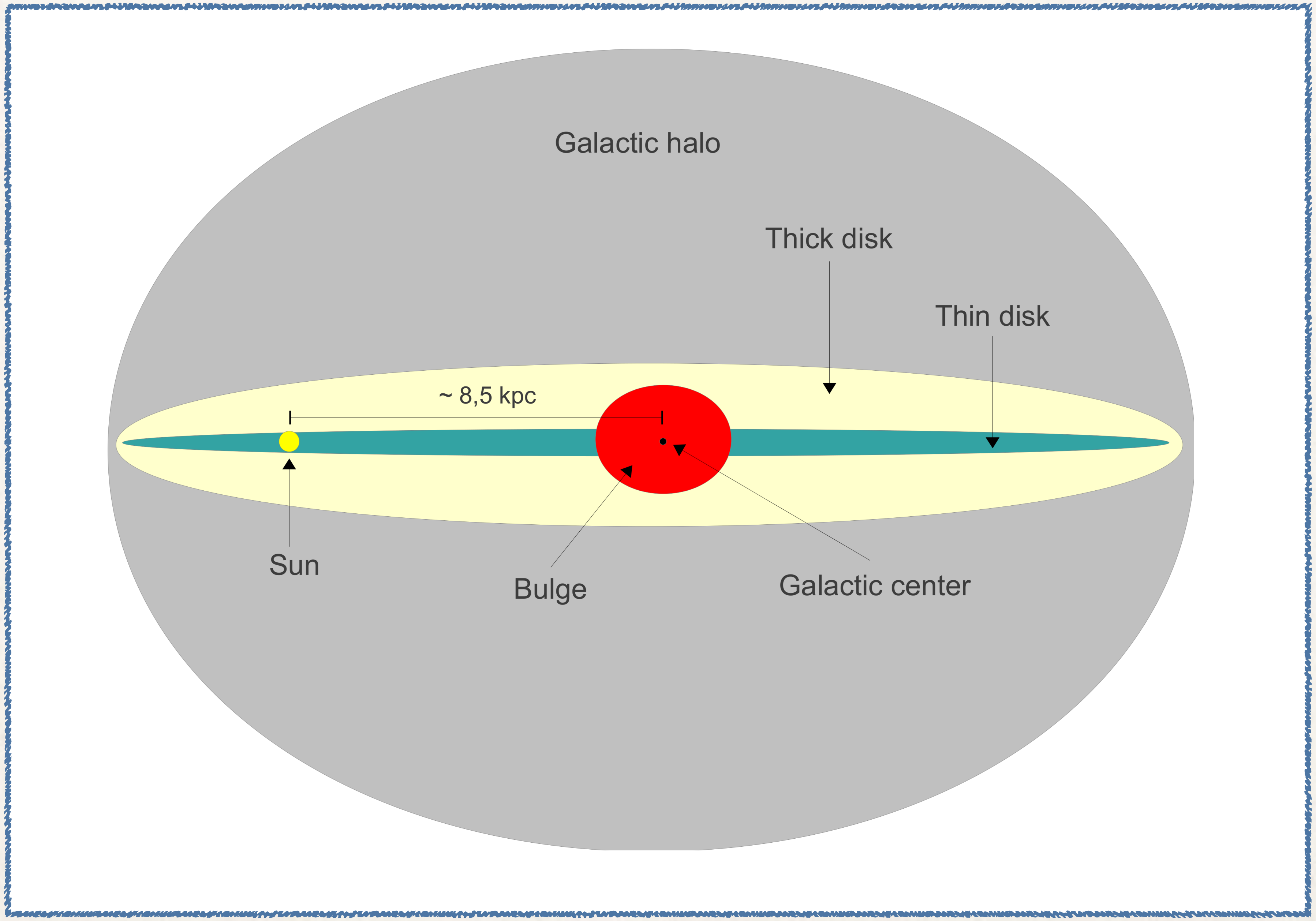


$$\nu(a_\mathrm{N}/a_0) = \nu_0 + \frac{\tilde{\nu}_1}{a_0} \cdot a_\mathrm{N} \equiv \nu_0 + \nu_1 \cdot a_\mathrm{N}$$

$$\mathbf{a} = (\nu_0 + \nu_1 a_\mathrm{N})\,\mathbf{a}_\mathrm{N}$$

Analysis Procedure

Baryonic Density Profiles



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

Analysis Procedure

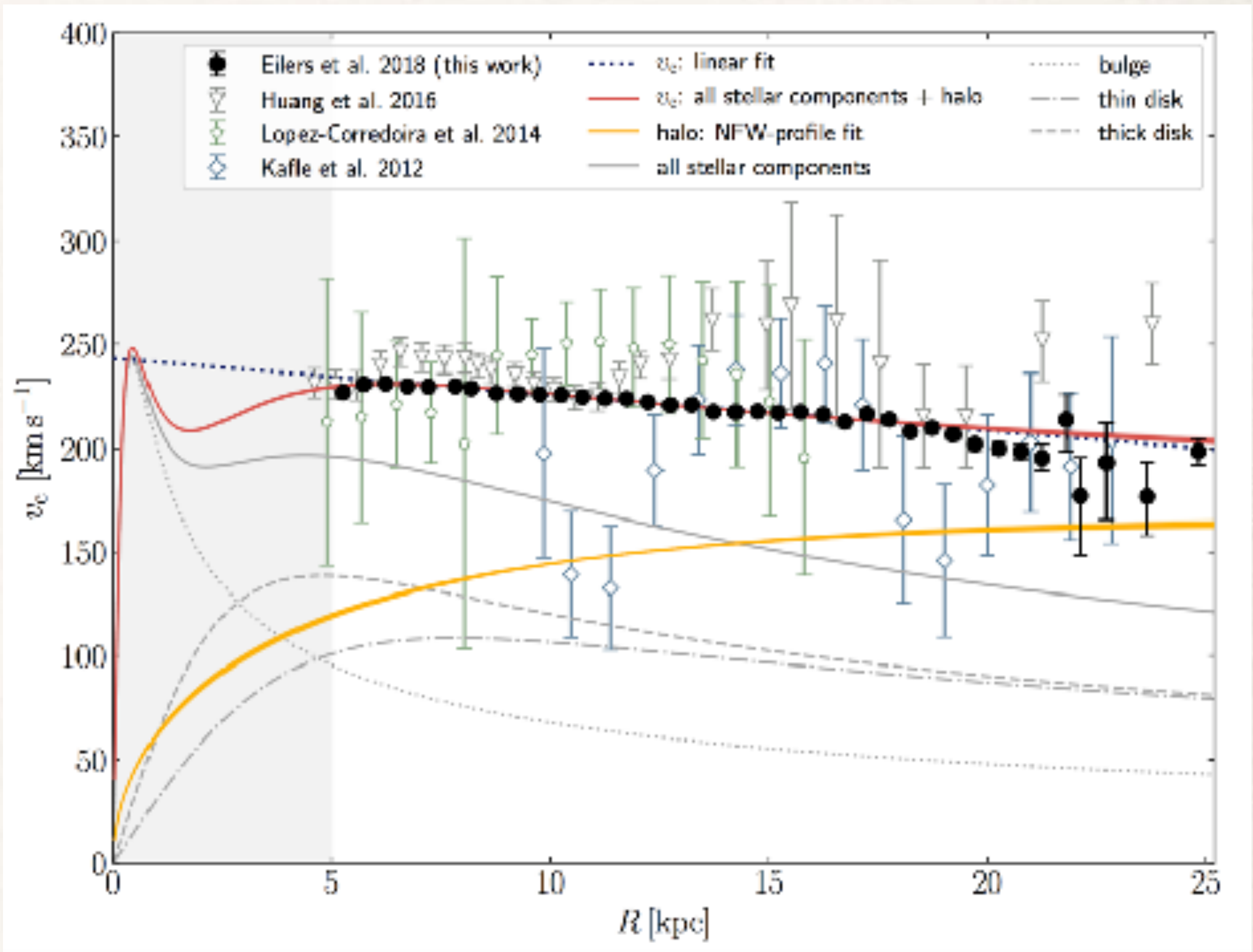
Milky Way Observables

- Local stellar surface density
- Local gas surface density
- Local value for rotation curve
- Slope of the rotation curve
- Vertical velocity dispersions

Analysis Procedure

Milky Way Observables

- Local stellar surface density
- Local gas surface density
- **Local value for rotation curve**
- **Slope of the rotation curve**
- The vertical acceleration



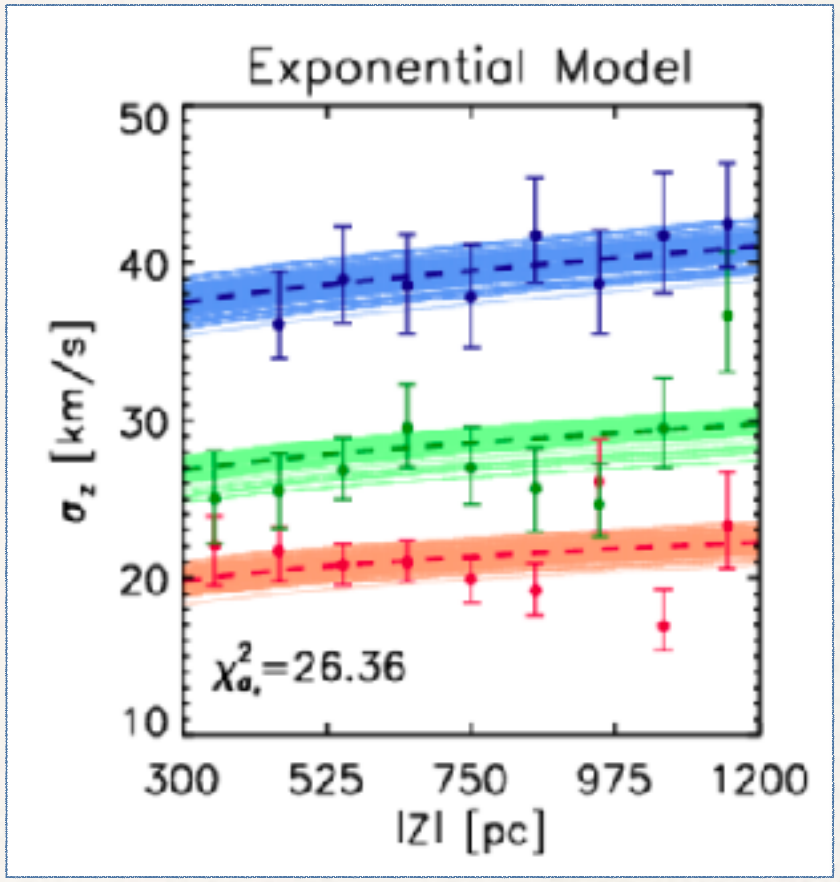
Eilers et. al., 2018

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

Analysis Procedure

Milky Way Observables

- Local stellar surface density
- Local gas surface density
- Local value for rotation curve
- Slope of the rotation curve
- **The vertical acceleration**
  Inferred from 9000 K-dwarfs in the SEGUE sub-survey of the SDSS



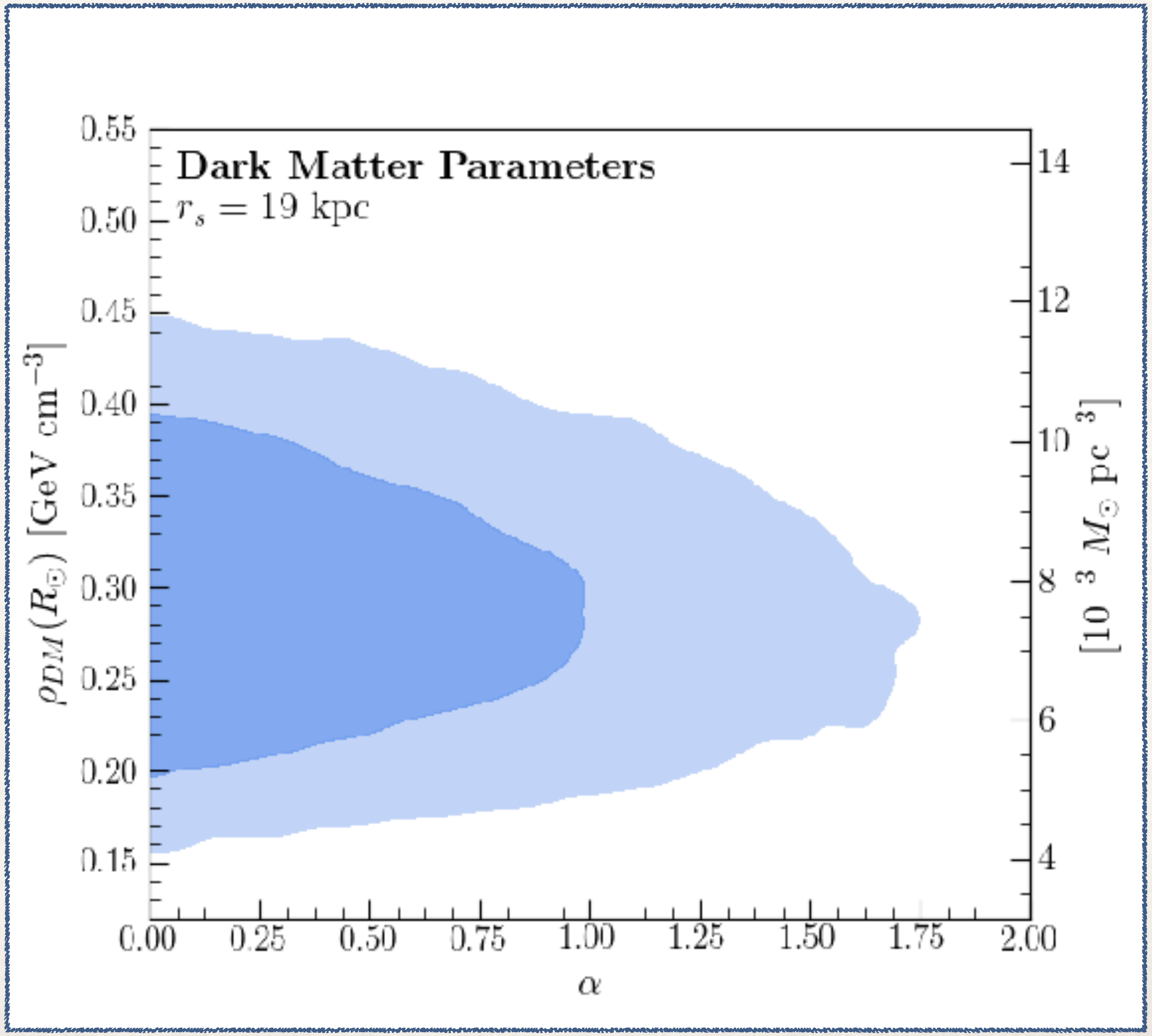
Zhang et. al., 2013

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

RESULTS

Results of MCMC Scans

Dark Matter Parameters



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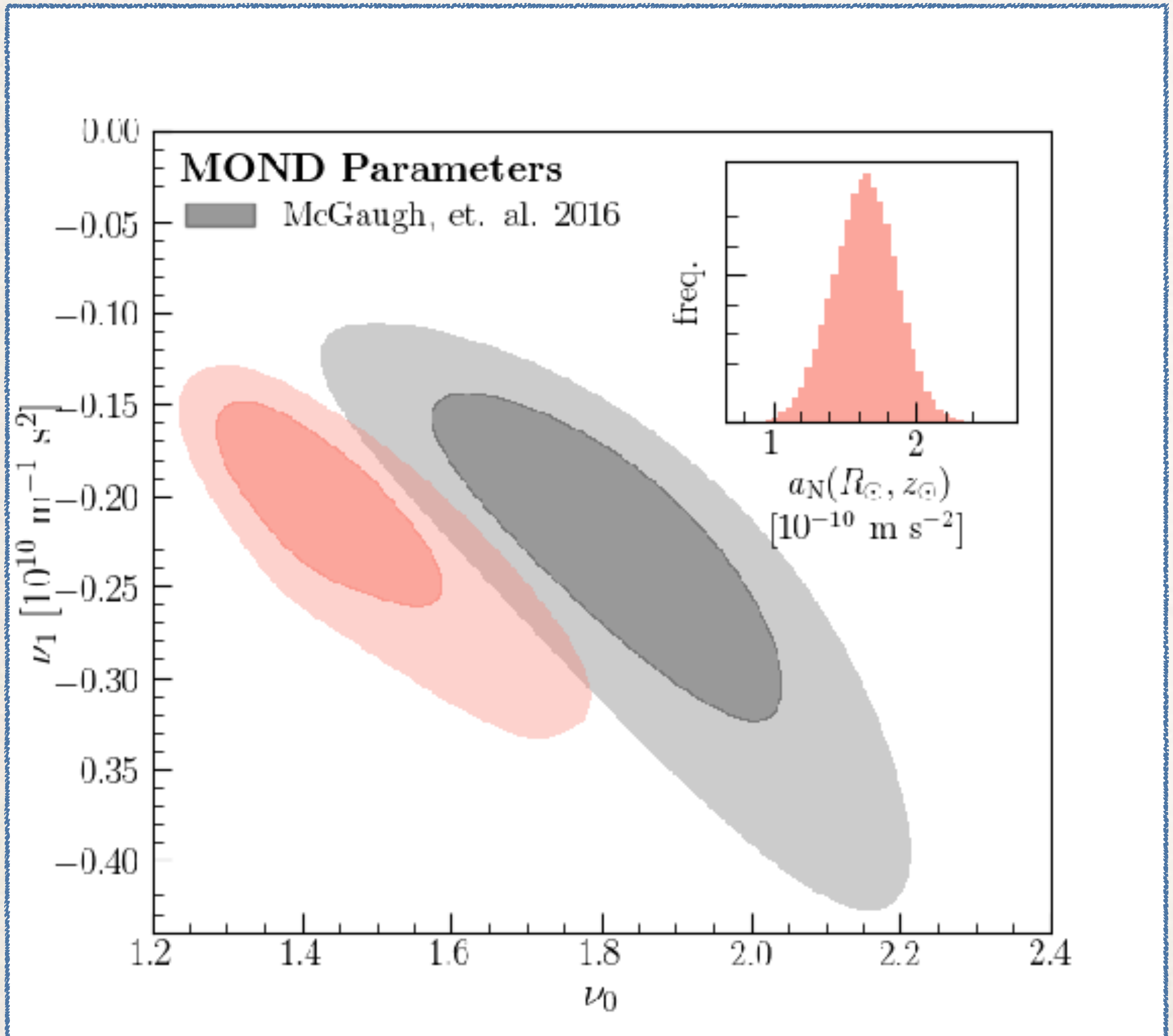
Results of MCMC Scans

IR Modified Gravity 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

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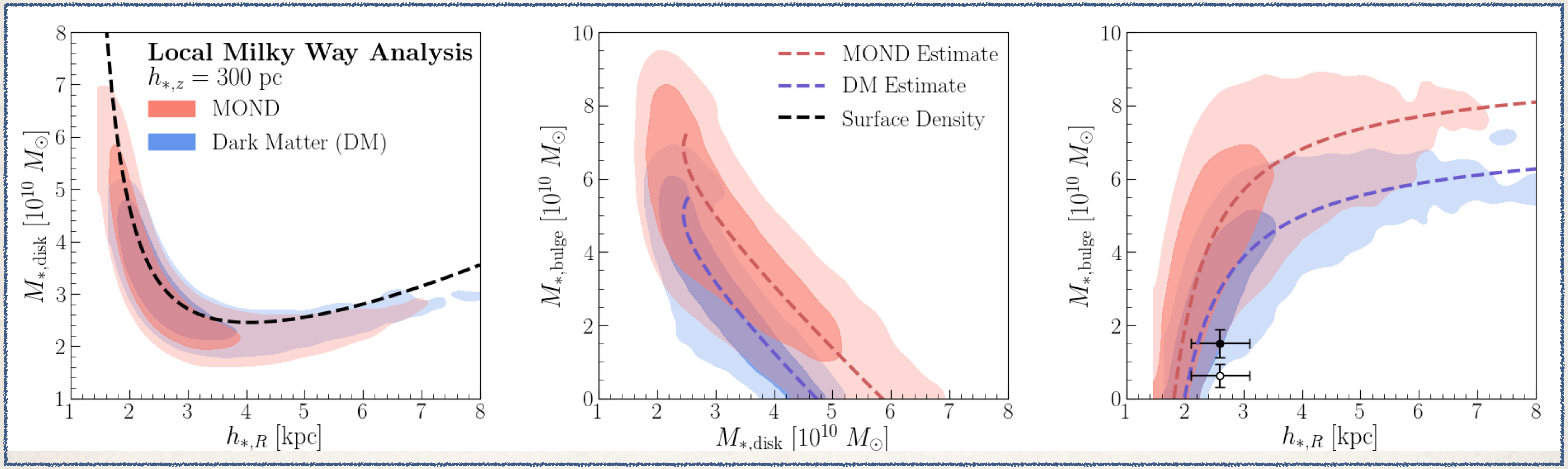
Results of MCMC Scans

Tension with MW Observations



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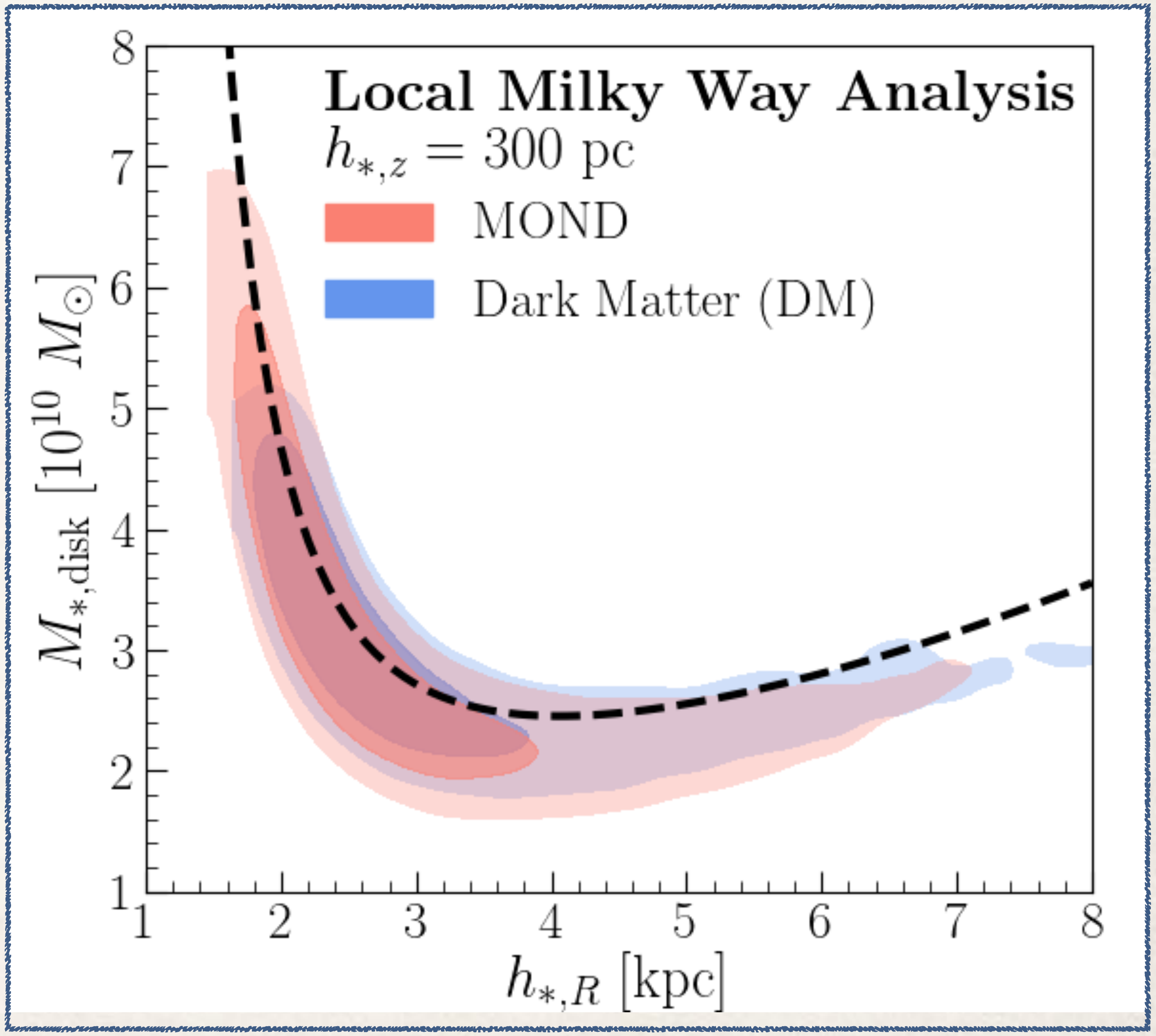
Results of MCMC Scans

Stellar Scale Radius *vs* Stellar Disk Mass

Driven by stellar surface density constraint

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



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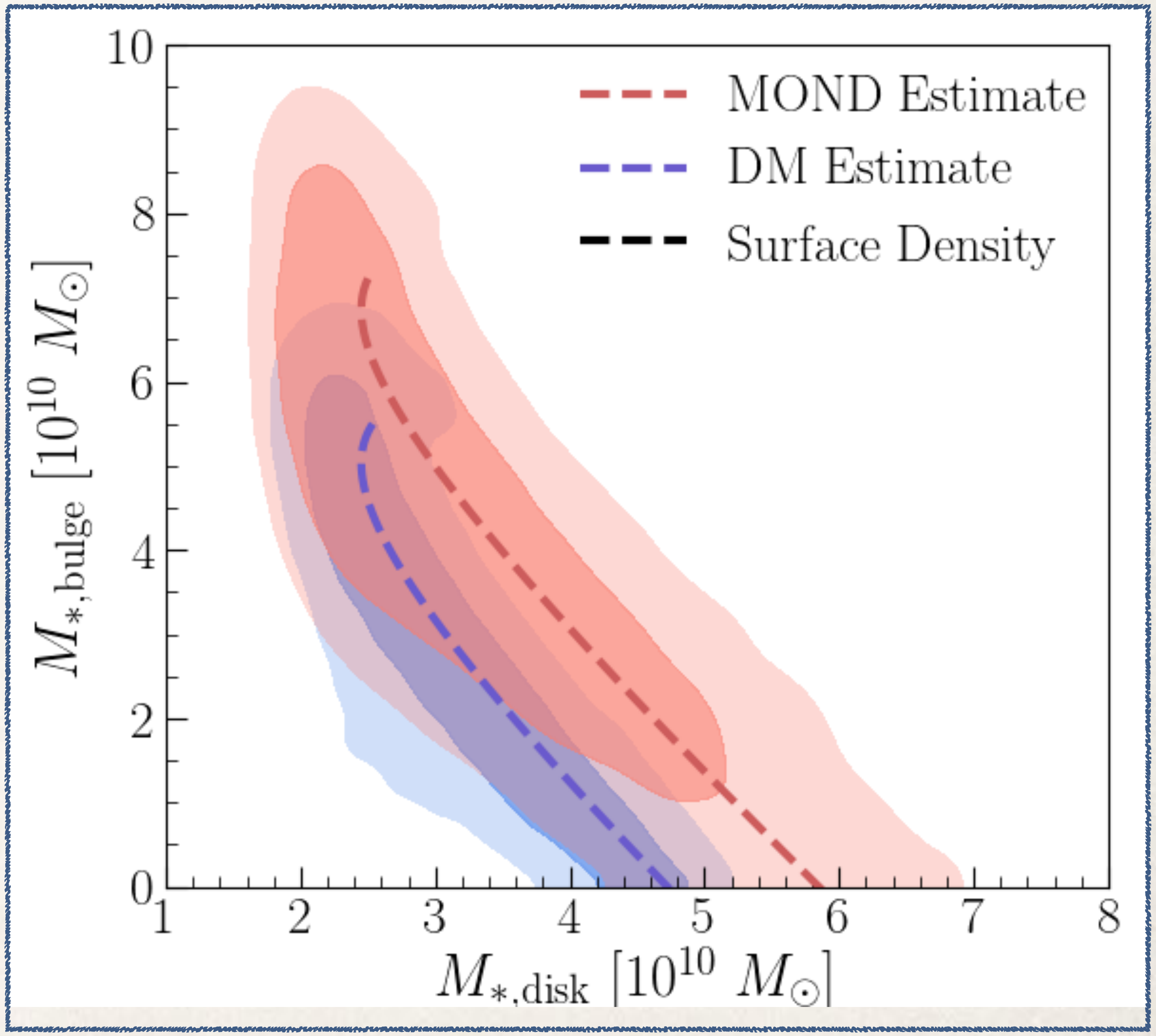
Results of MCMC Scans

Stellar Disk Mass *vs* Stellar Bulge Mass

Driven by local value of rotation curve constraint

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



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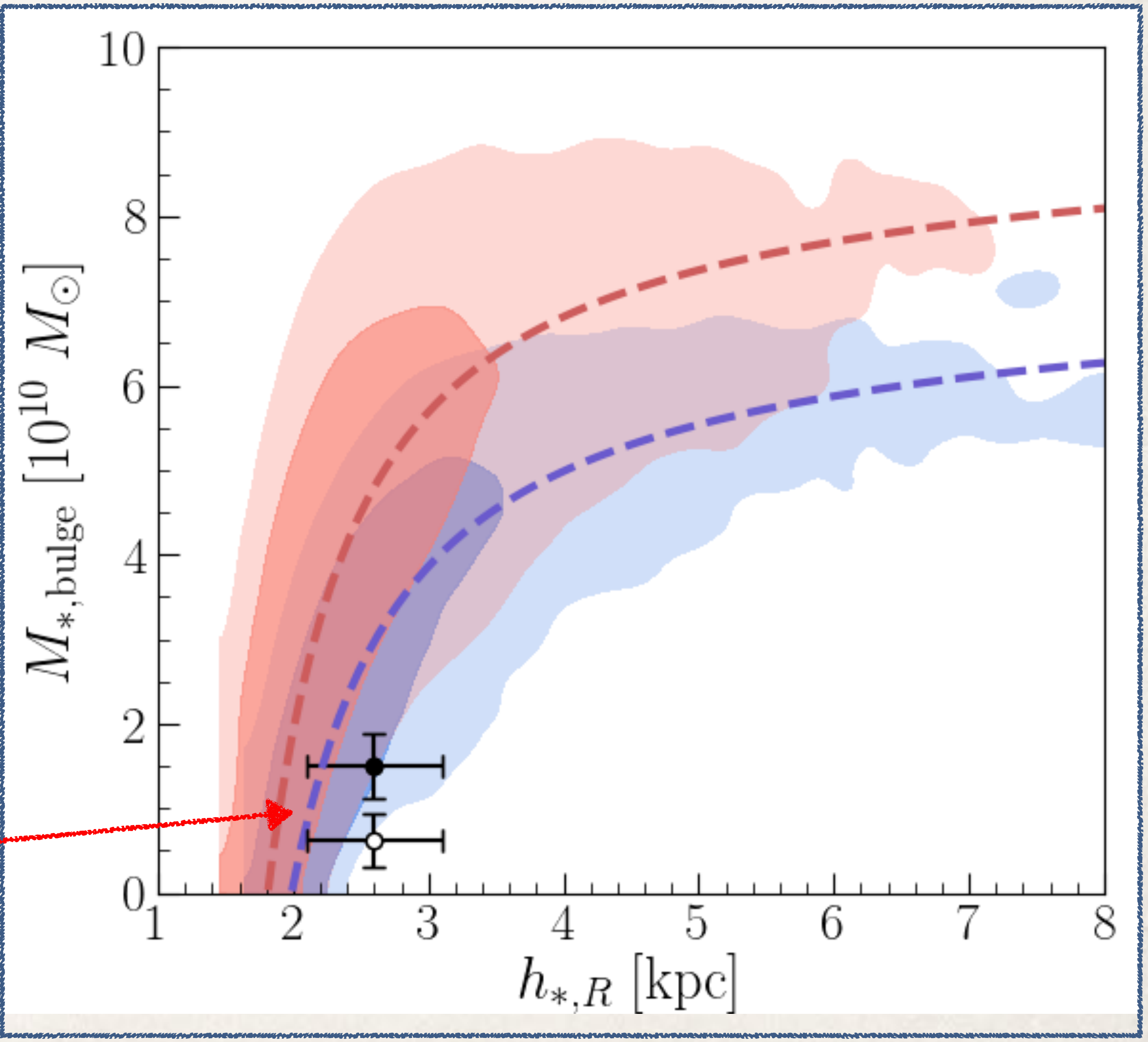
Results of MCMC Scans

Stellar Scale Radius *vs* Stellar Bulge Mass

Driven by combination of previous correlations

Tension for a MOND-like force



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Results of MCMC Scans

Bulge Mass is Poorly Constrained

Reference	$M_\star^B \pm 1\sigma$ (10^{10} $M_\odot$)	R_0 assumed (kpc)	Constraint type	β[a]	$M_\star^B \pm 1\sigma(R_0 = 8.33\text{kpc})$ (10^{10} $M_\odot$)
Kent (1992)	1.69 ± 0.85	8.0	Dynamical	1	1.76 ± 0.88
Dwek et al. (1995)	2.11 ± 0.81	8.5	Photometric	2	2.02 ± 0.78
Han & Gould (1995)	1.69 ± 0.85	8.0	Dynamical	1	1.76 ± 0.88
Blum (1995)	2.63 ± 1.32	8.0	Dynamical	1	2.74 ± 1.37
Zhao (1996)	2.07 ± 1.03	8.0	Dynamical	1	2.15 ± 1.08
Bissantz et al. (1997)	0.81 ± 0.22	8.0	Microlensing	0	0.81 ± 0.22
Freudenreich (1998)[b]	0.48 ± 0.65	...	Photometric	...	0.48 ± 0.65
Dehnen & Binney (1998)	0.61 ± 0.38	8.0	Dynamical	1/2	0.62 ± 0.38
Sevenster et al. (1999)	1.60 ± 0.80	8.0	Dynamical	1	1.66 ± 0.83
Klypin et al. (2002)	0.94 ± 0.29	8.0	Dynamical	1	0.98 ± 0.31
Bissantz & Gerhard (2002)[c]	0.84 ± 0.09	8.0	Dynamical	1	0.87 ± 0.09
Han & Gould (2003)	1.20 ± 0.60	8.0	Microlensing	0	1.20 ± 0.60
Picaud & Robin (2004)	0.54 ± 1.11	8.5	Photometric	0	0.54 ± 1.11
Hamadache et al. (2006)	0.62 ± 0.31	None	Microlensing	0	0.62 ± 0.31
Wyse (2006)	1.00 ± 0.50	None	Historical review	0	1.00 ± 0.50
López-Corredoira et al. (2007)	0.60 ± 0.30	8.0	Photometric	2	0.65 ± 0.33
Calchi Novati et al. (2008)	1.50 ± 0.38	8.0	Microlensing	0	1.50 ± 0.38
Widrow et al. (2008)	0.90 ± 0.11	7.94	Dynamical	1	0.95 ± 0.12

Bland-Hawthorn, Gerhard (2016), Licquia, Newman (2015)

Conservative Range: $0 < M_{*,\text{bulge}} < 2 \times 10^{10} M_\odot$

Reference Value: $M_{*,\text{bulge}} = 1.50 \pm 0.38 \times 10^{10} M_\odot$

Results of MCMC Scans

Comparison between the Theories

Bayes Evidence: $$\mathrm{BF} \equiv \frac{\mathrm{BE}_{\mathrm{DM}}}{\mathrm{BE}_{\mathrm{G}}}$$

Bayesian Information Criterion:
(a proxy for the Bayes Evidence)

$$\mathrm{B.I.C.} = k \log n - 2 \log \hat{\mathcal{L}}$$

k: number of model parameters
n: number of data points
$\hat{\mathcal{L}}$: maximum likelihood

For baseline study: $\Delta\mathrm{BIC} = 4.1$ **(positive evidence)**

No sys. uncertainty on v_c: $\Delta\mathrm{BIC} = 7.1$ **(strong evidence)**

Outlook

Future Work

- Do the Superfluid case (very slight differences) - same result is expected.
- Extend analysis to any theory for which baryons predict accelerations, e.g.:
  - Strongly Interacting DM (Famaey, Khoury & Penco, 2018)
  - Emergent Gravity (Verlinde, 2016)
  - SIDM (Kamada, Kaplinghat, Pace and Yu, 2017)
- Extend the analysis to more precise data-sets (Gaia)
- Understand how robust our analysis is to recent observations of dis-equilibrium within the MW

Conclusions

- Precision astrometry can be a powerful probe of New Physics.
- Standard lore is "MOND-like forces work on Galactic Scales". This is not precisely true.
- Local MW measurements seem to prefer a Dark Matter theory over a scalar enhancement of gravity (e.g. MOND or Superfluid DM).
- Better measurements will make this statement more precise.

A strictly MOND-like force has trouble simultaneously explaining rotation curves and velocity dispersions… so, probably something else

THANK YOU

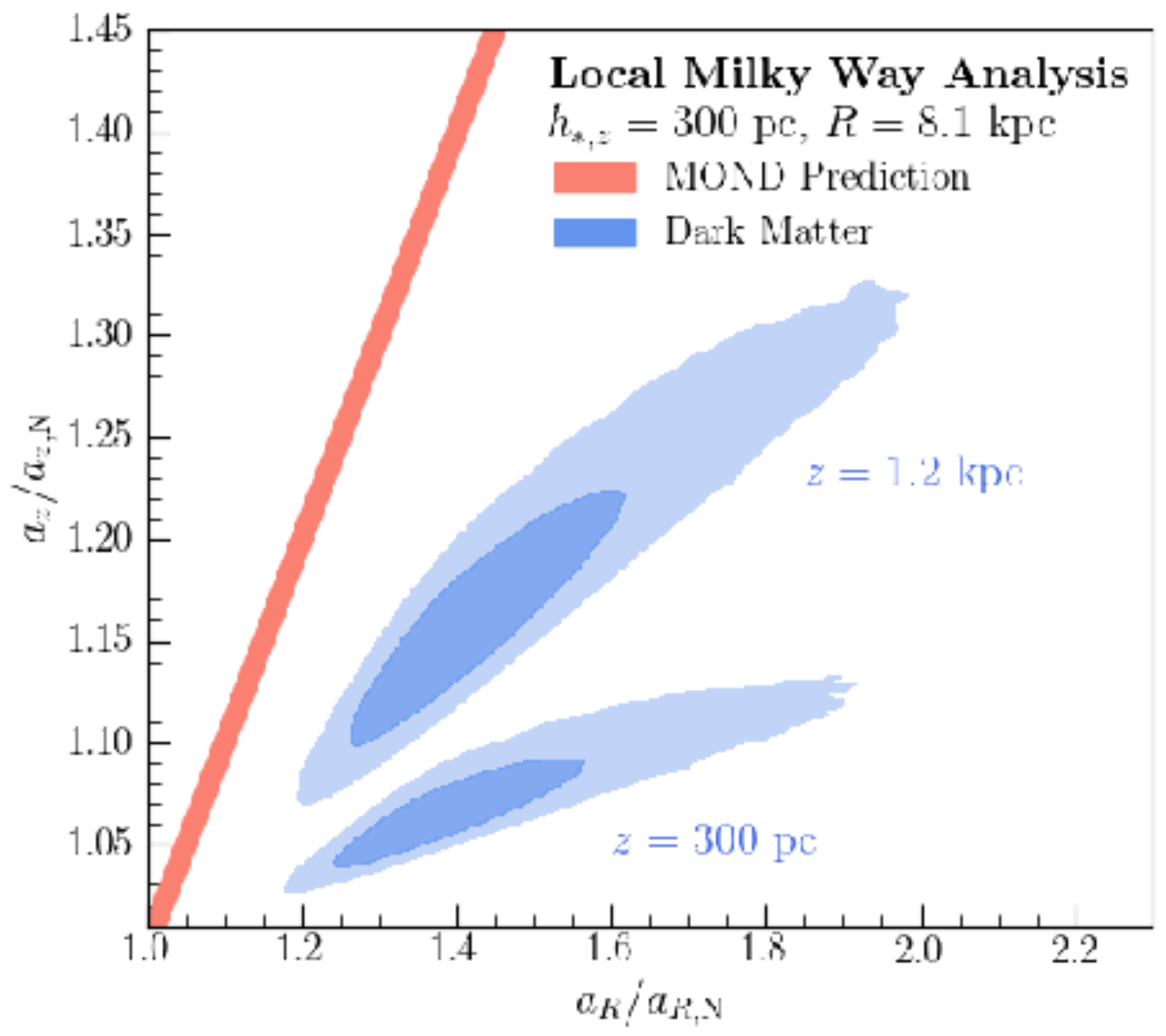
Results of MCMC Scans

Tension between models for **any** Scalar Enhancement

Each axis is the local enhancement of acceleration in the R/z directions

or

an independent measurement of the local value of the interpolation function



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