A Test of 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


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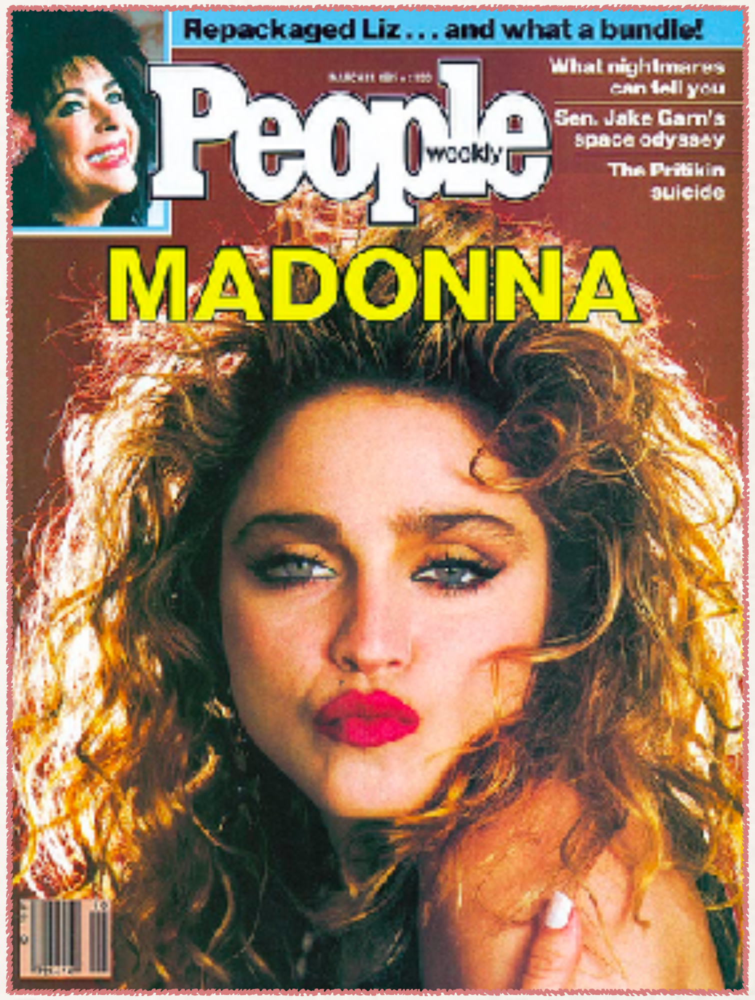
Prelude

Back to the 80’s



Prelude

Back to the 80's

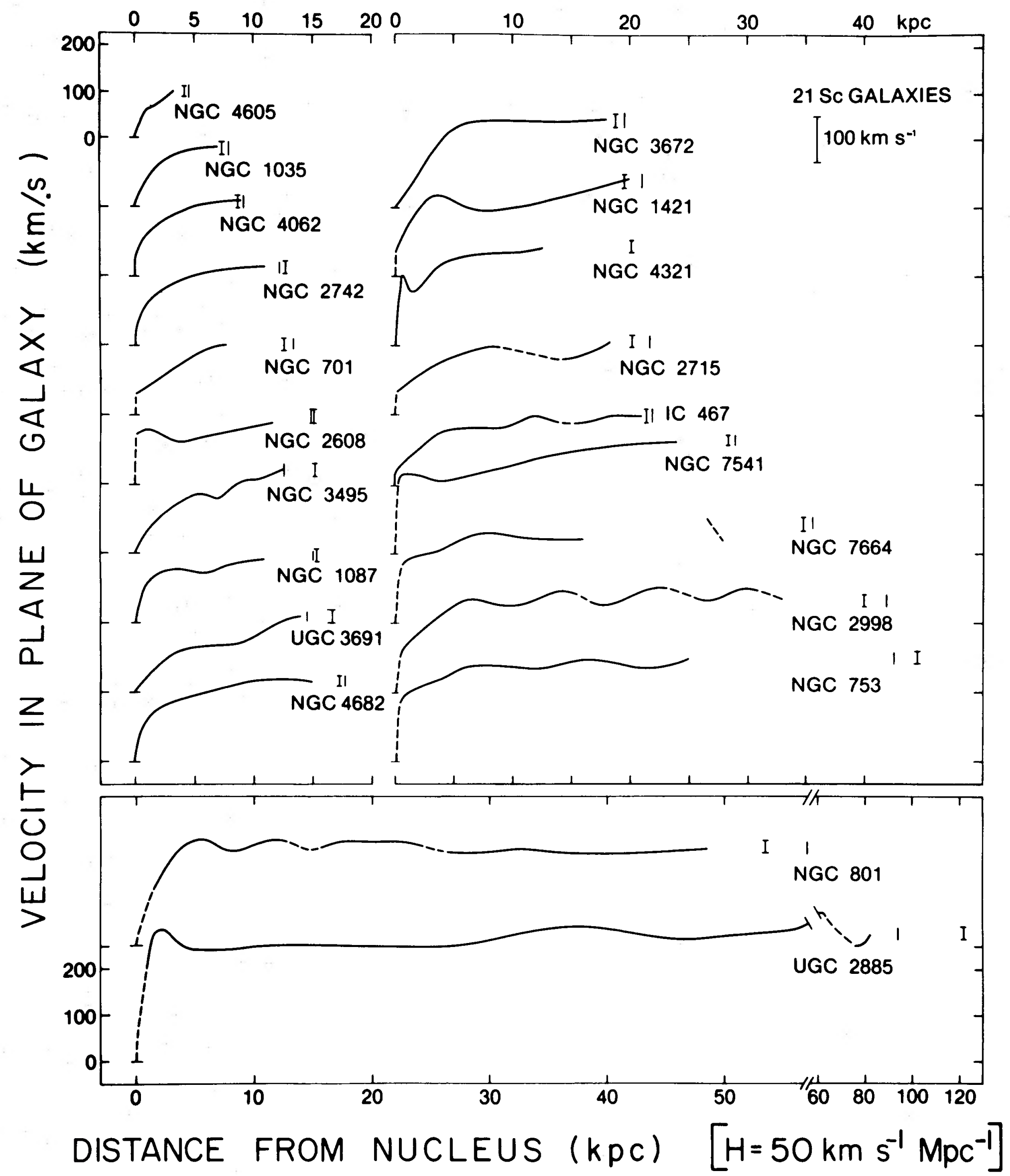


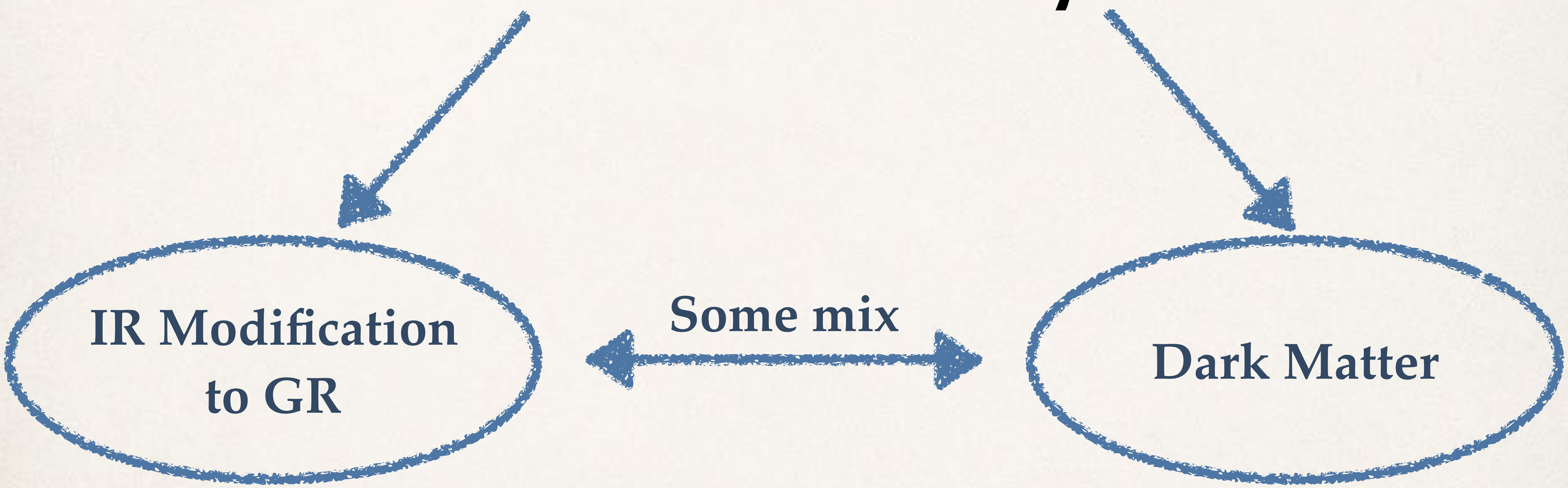
FIG. 5.—Mean velocities in the plane of the galaxy, as a function of linear distance from the nucleus for 21 Sc galaxies, arranged according to increasing linear radius. Curve drawn is rotation curve formed from mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25},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

2018:

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

↓

CAN THESE THEORIES FIT
ALL MILKY WAY OBSERVABLES?

↓

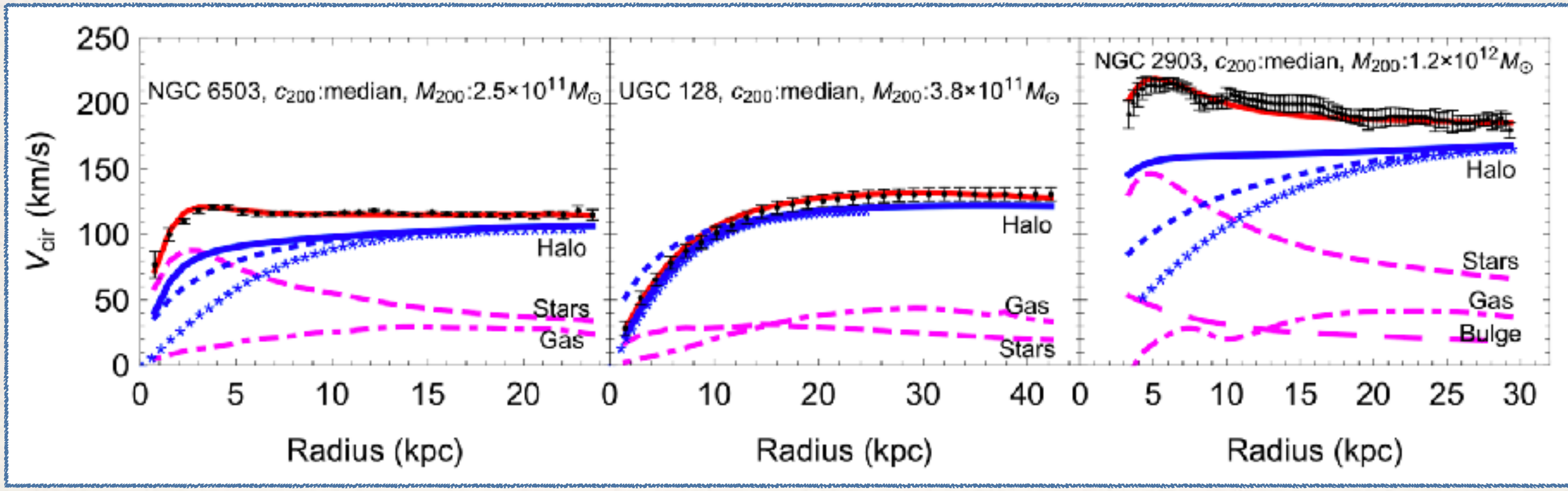
Learn about important properties of the MW

Outline

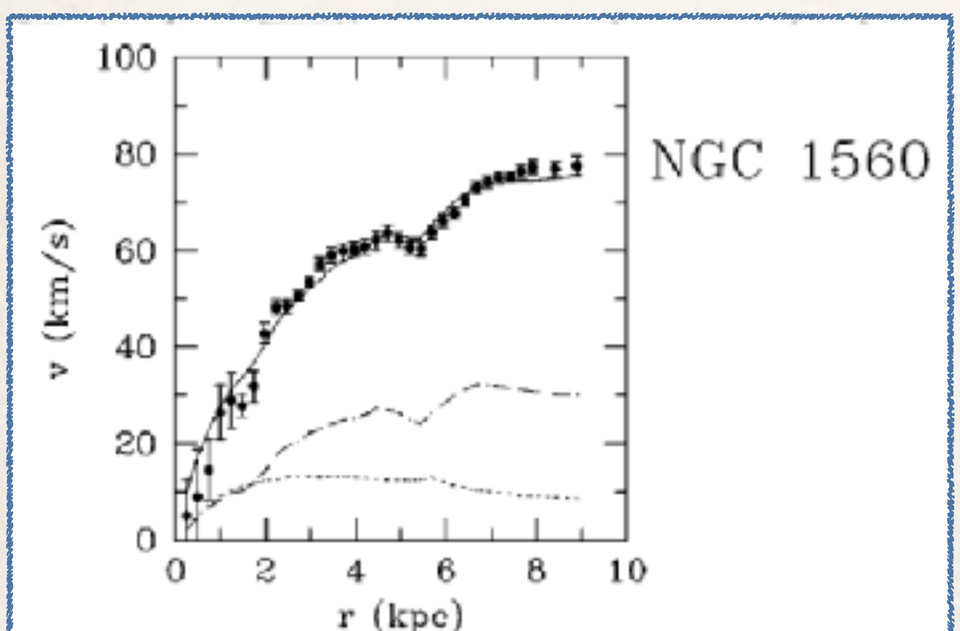
- Missing Mass and Galaxy Scale Observables
- Features of Dark Matter vs IR Modification to Gravity
- A Robust and Model Independent Test using MW data
- Results and Conclusions of our Study

Galaxy Scale Observables

The Diversity Problem



Kamada et. al., 2016

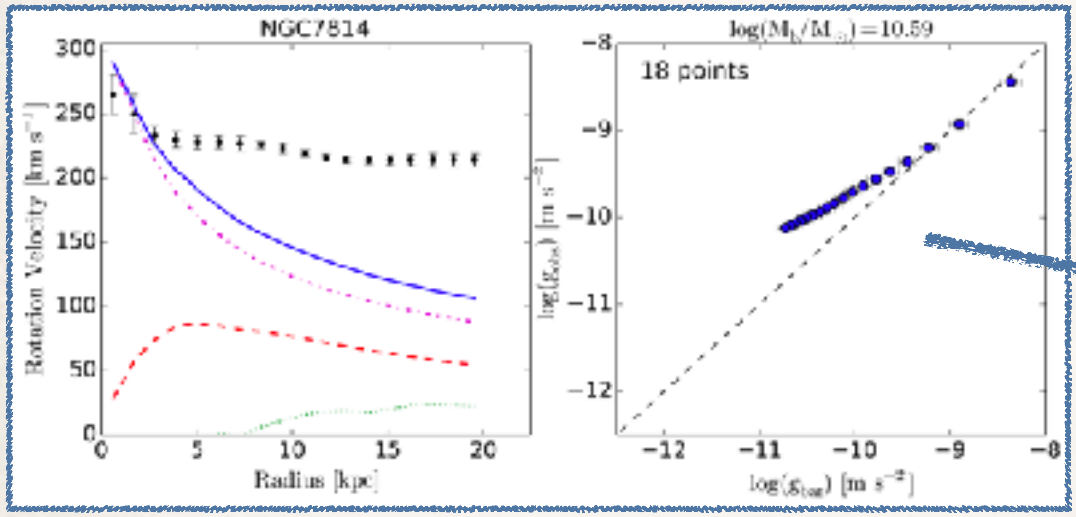


Sancisi, 2003

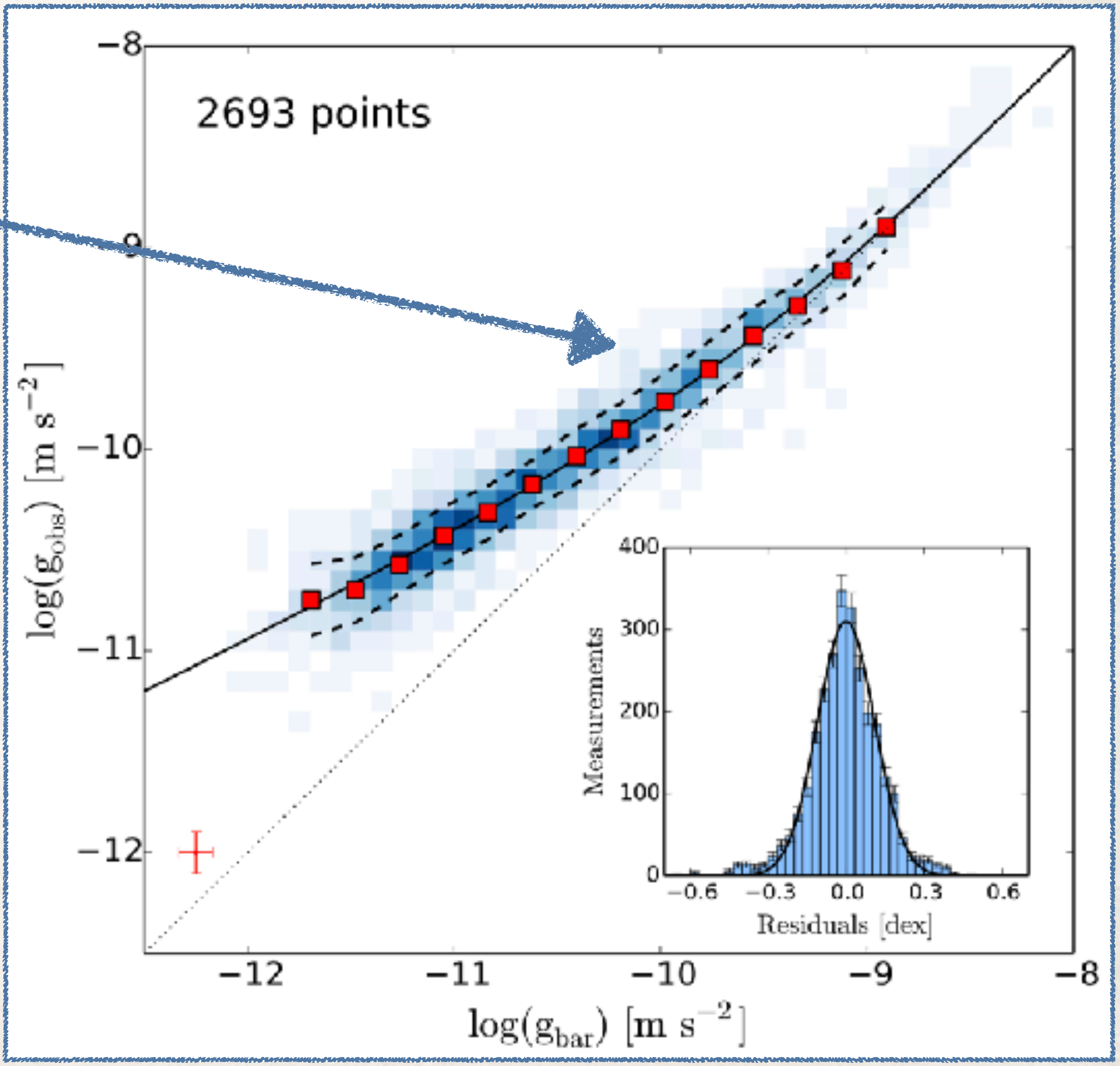
- Diversity of inner rotation curves even for galaxies with similar halo and stellar mass.
- Rotation curves correlate with galactic scale radius
- Some evidence points towards additional correlations between rotation curve shapes and baryonic distribution.

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

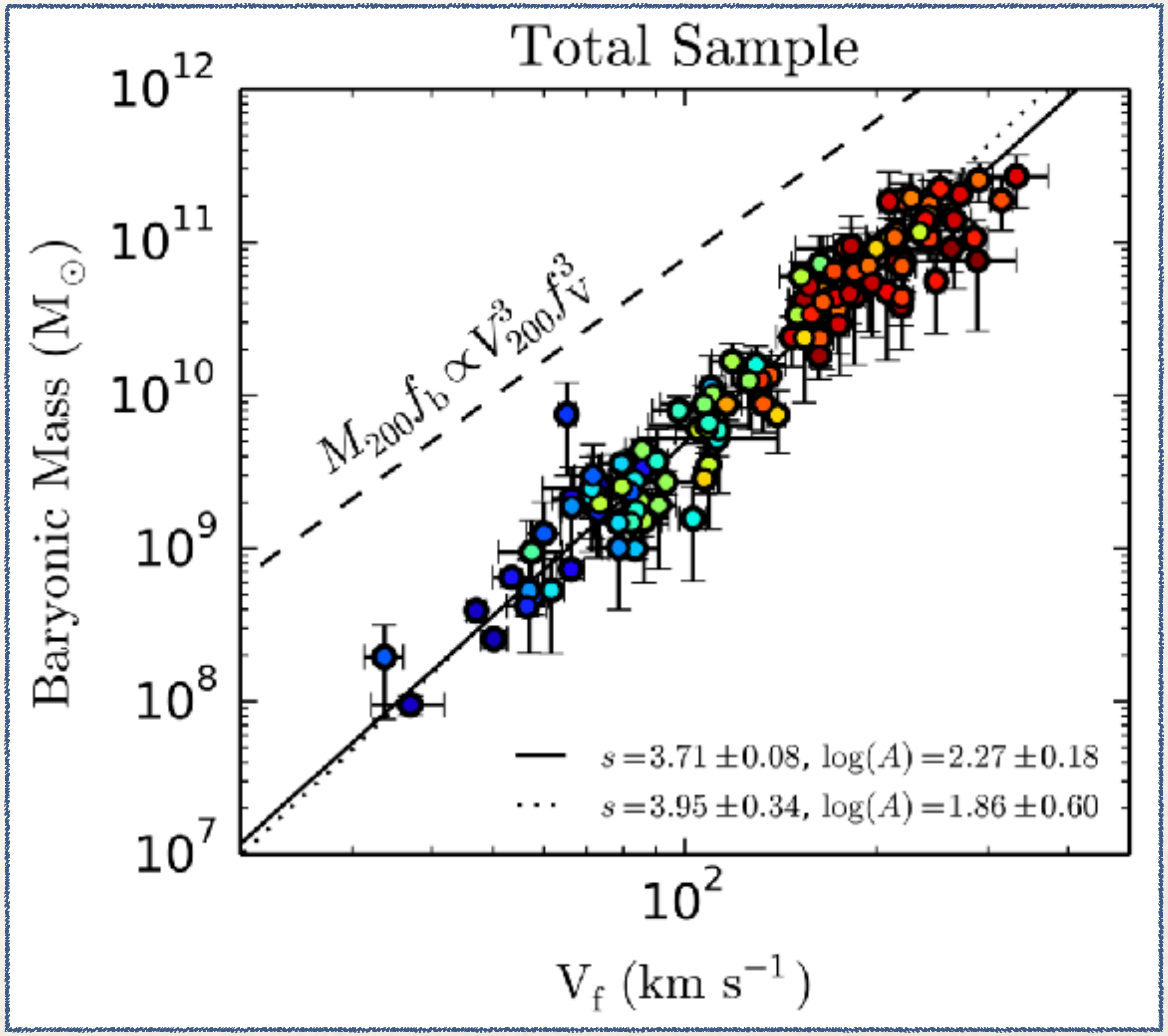
McGaugh, Lelli, 2017

Galaxy Scale Observables

The Baryonic Tully-Fisher Relation

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

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



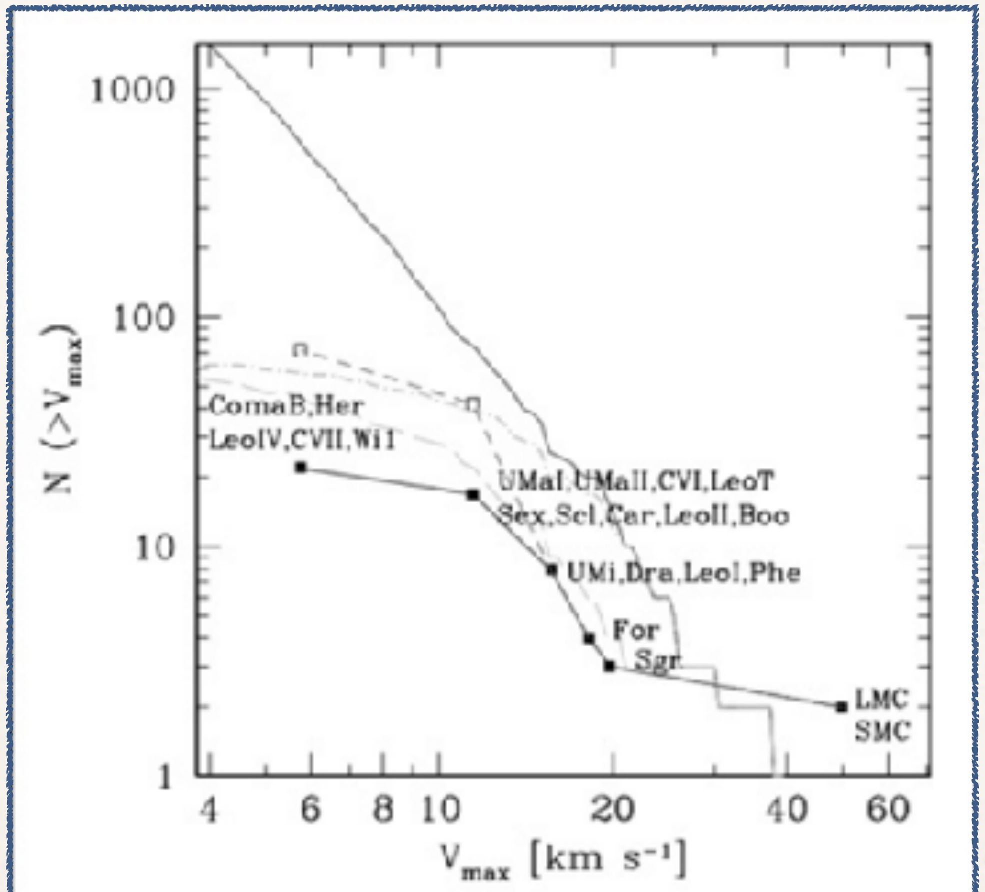
Lelli et. al., 2015

Galaxy Scale Observables

Issues with MW Satellites

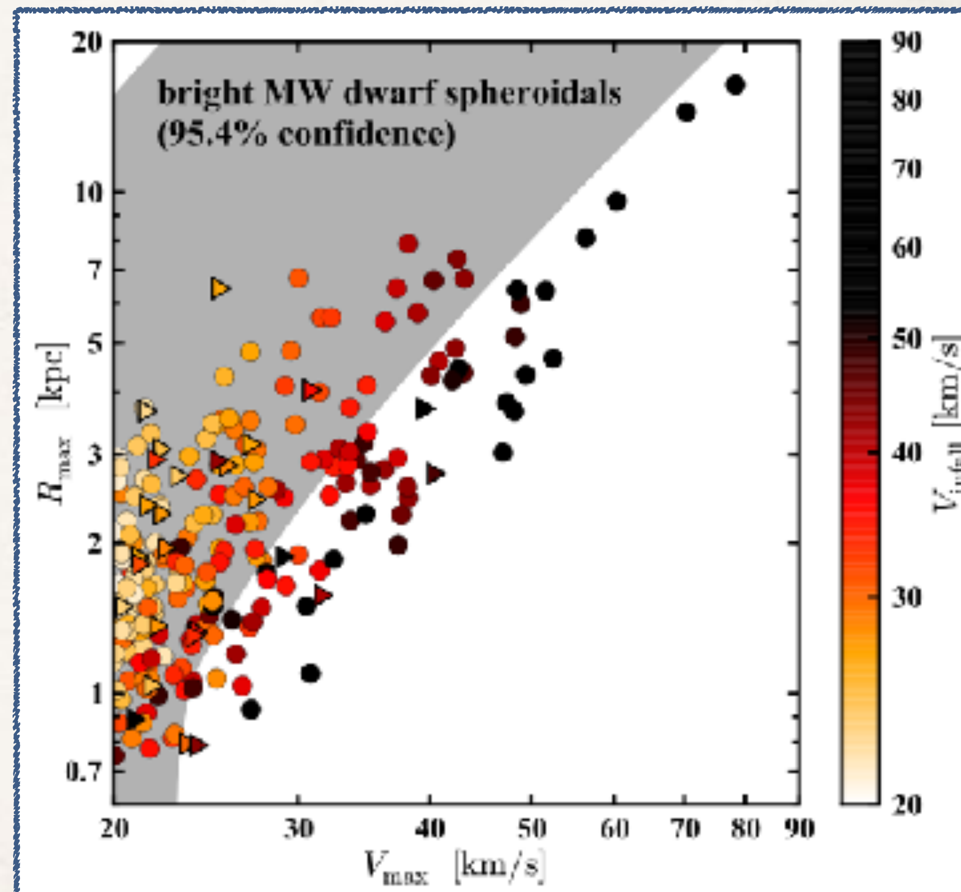
A lack of observed small scale structure with respect to expectations from DM simulations

Missing Satellites



Kauffmann 1993, Bullock 2010

TBTF



Kolchin et. al., 2011

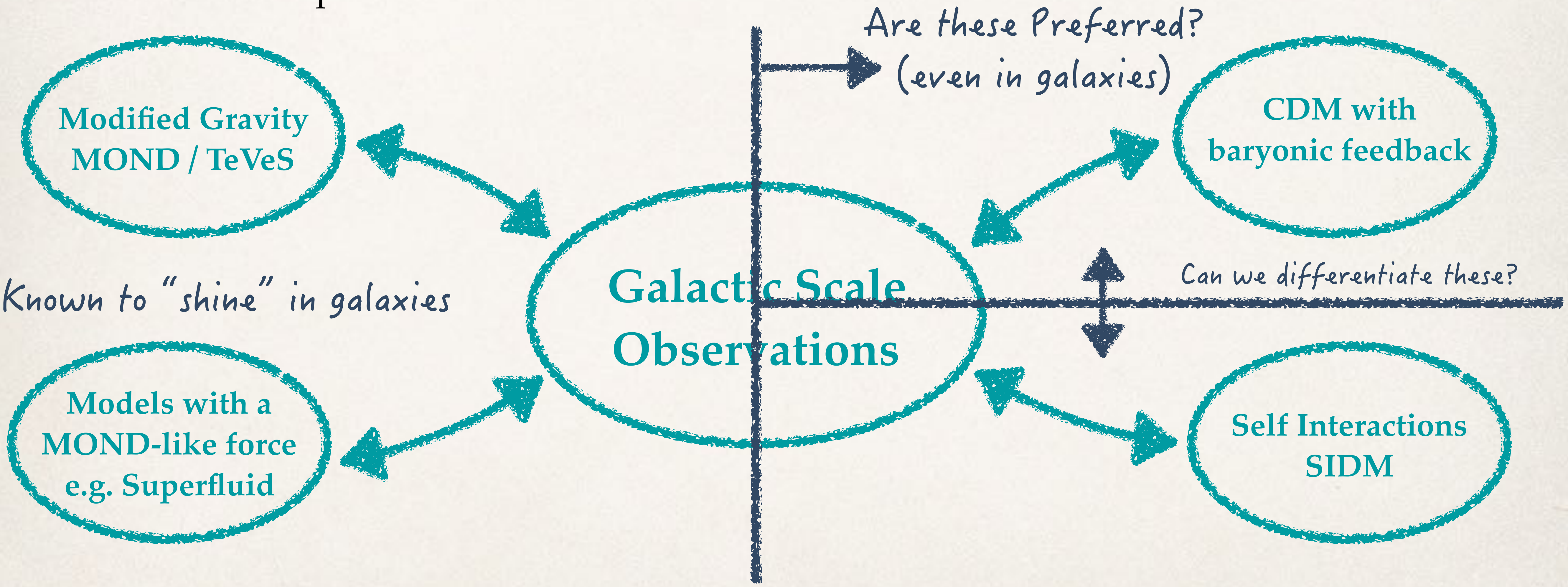
Galaxy Scale Observables

What can we learn?

- Galaxies provide clues that DM correlates with baryons.

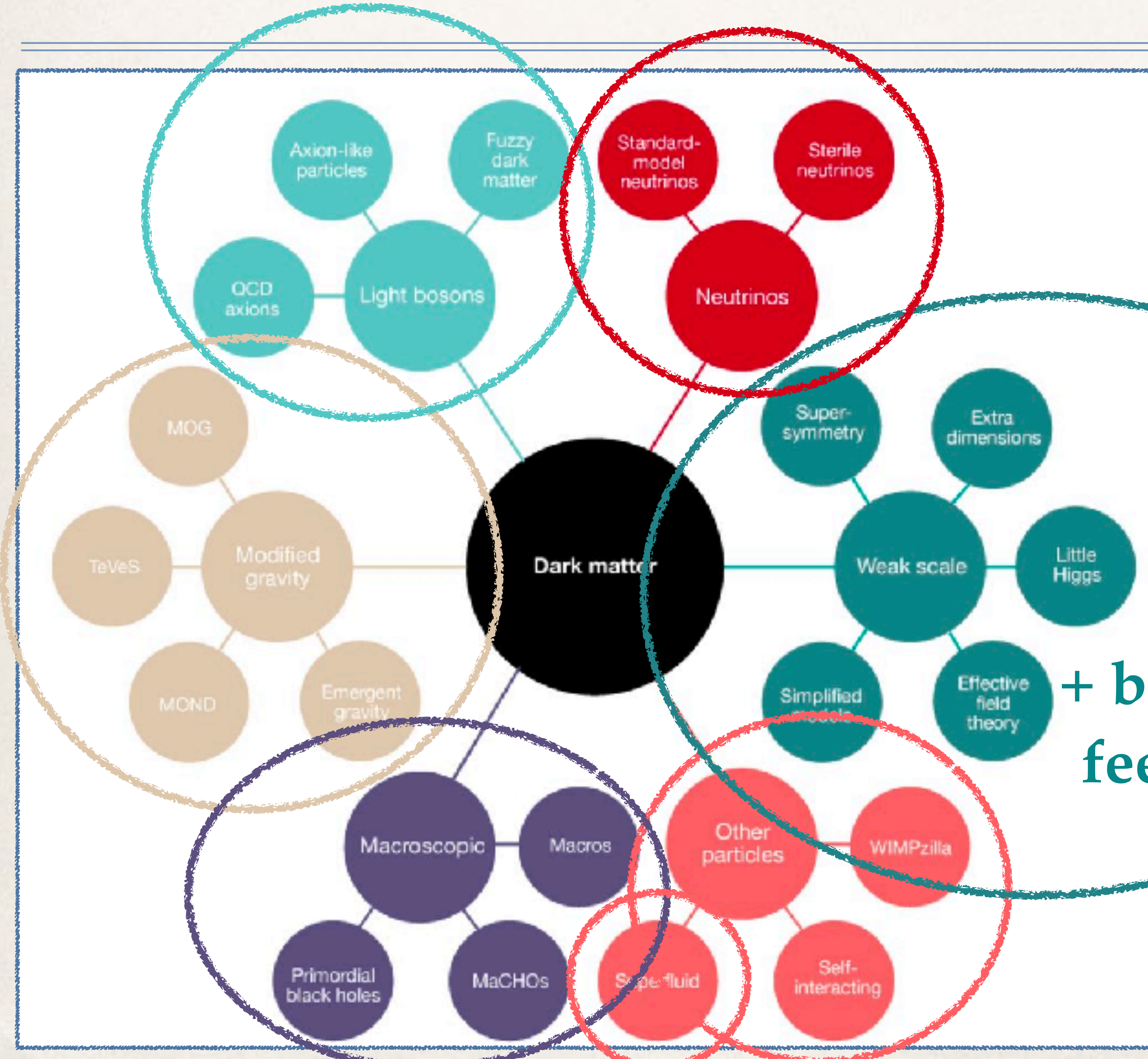
- Examples of solutions are:

SUMMARY OF THIS TALK



Or maybe DM mimics MOND on galactic scales?

Solutions?



We should think broadly about the possible solutions

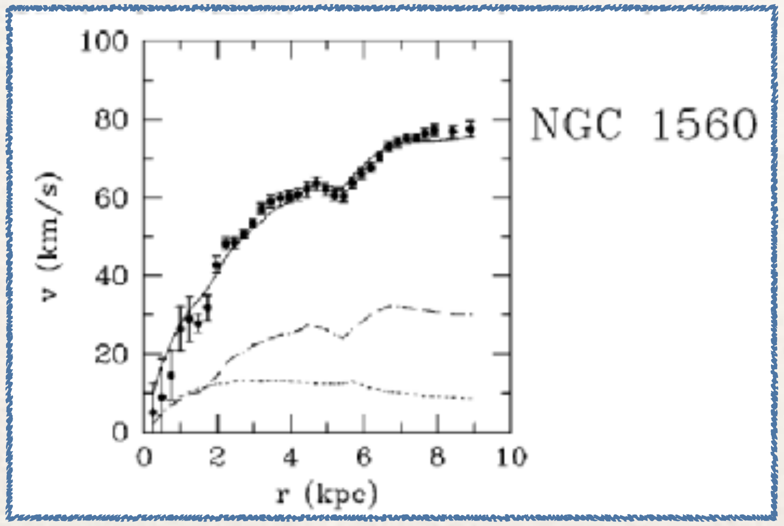
+ baryonic feedback

Bertone and Tait, 2018

Phenomenology of the Solutions

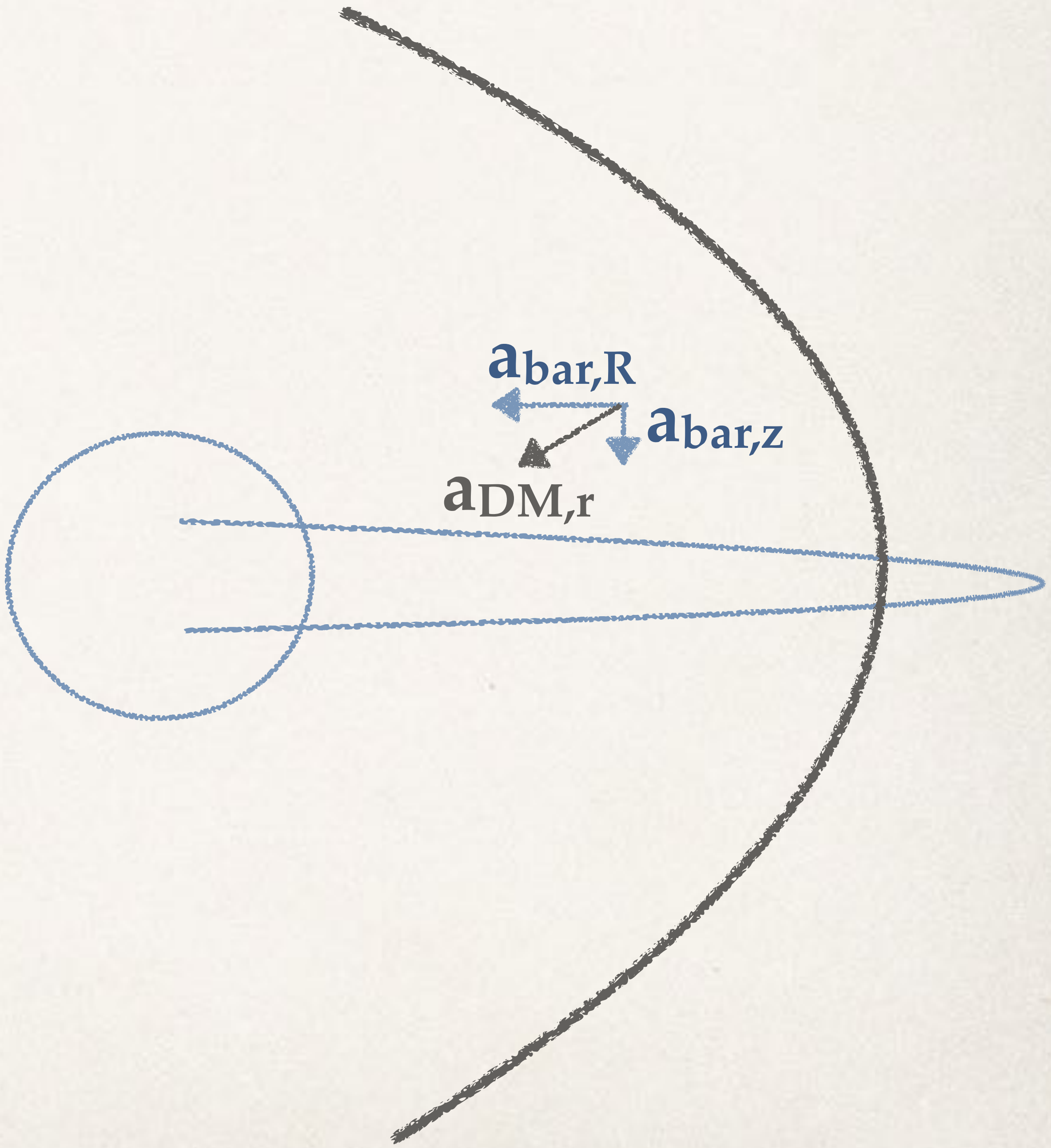
$$\nabla^2\Phi = 4\pi G\rho$$

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



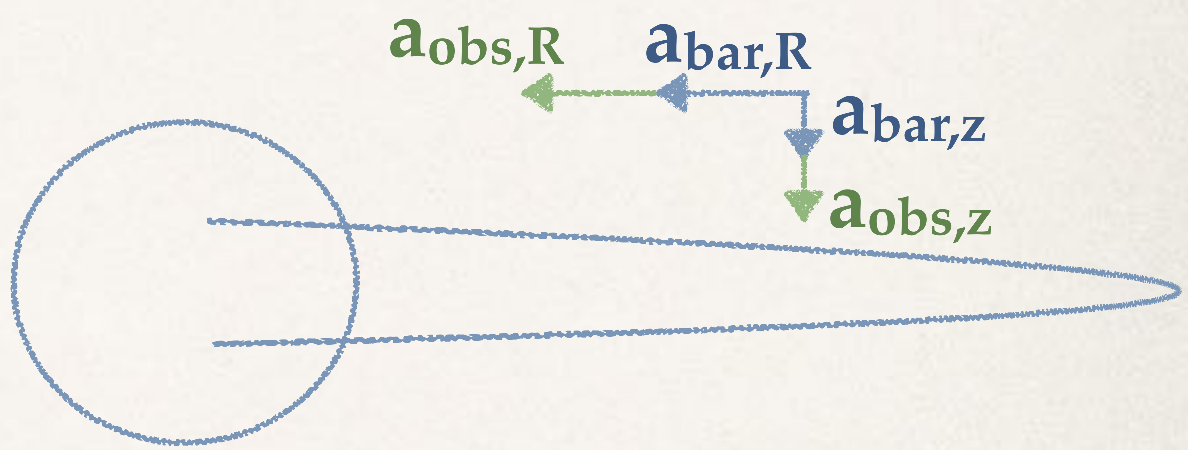
Dark Matter Pheno

- 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**
- Often exhibit a non-linear response to matter (no superposition principle)
- Most simple example is a scalar enhancement to Newtonian gravity
- Designed to reproduce flat rotation curves:
- MOND-like forces amplify acceleration:



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

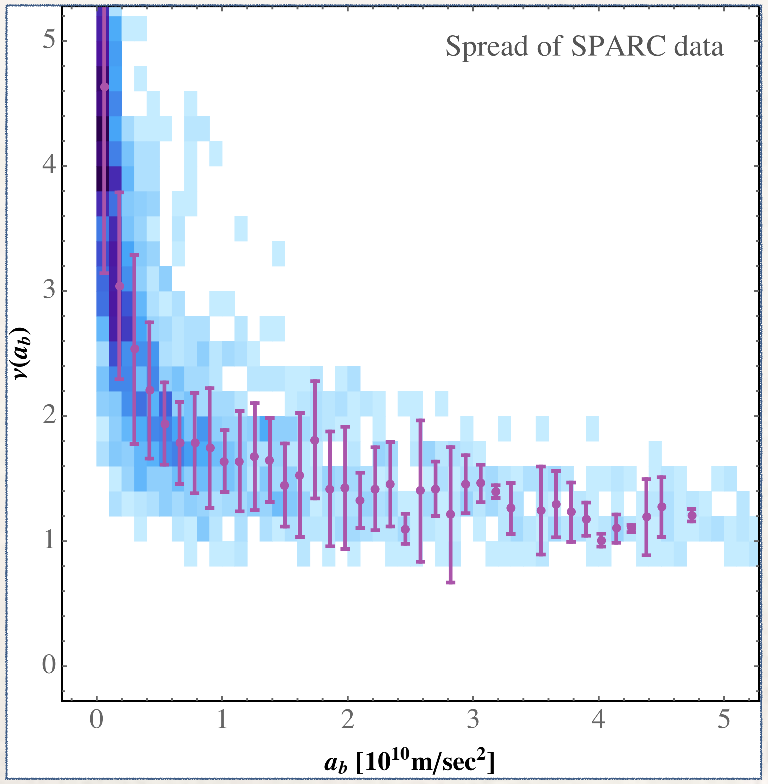
$$a = \begin{cases} a_{\mathrm{N}} & a \gg a_0 \\ \sqrt{a_0 a_{\mathrm{N}}} & a \ll a_0 \end{cases}$$

Newtonian acceleration

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

MOND-like forces

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



Lisanti, Moschella, Outmezguine, OS (PRELIMINARY)

For example:

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

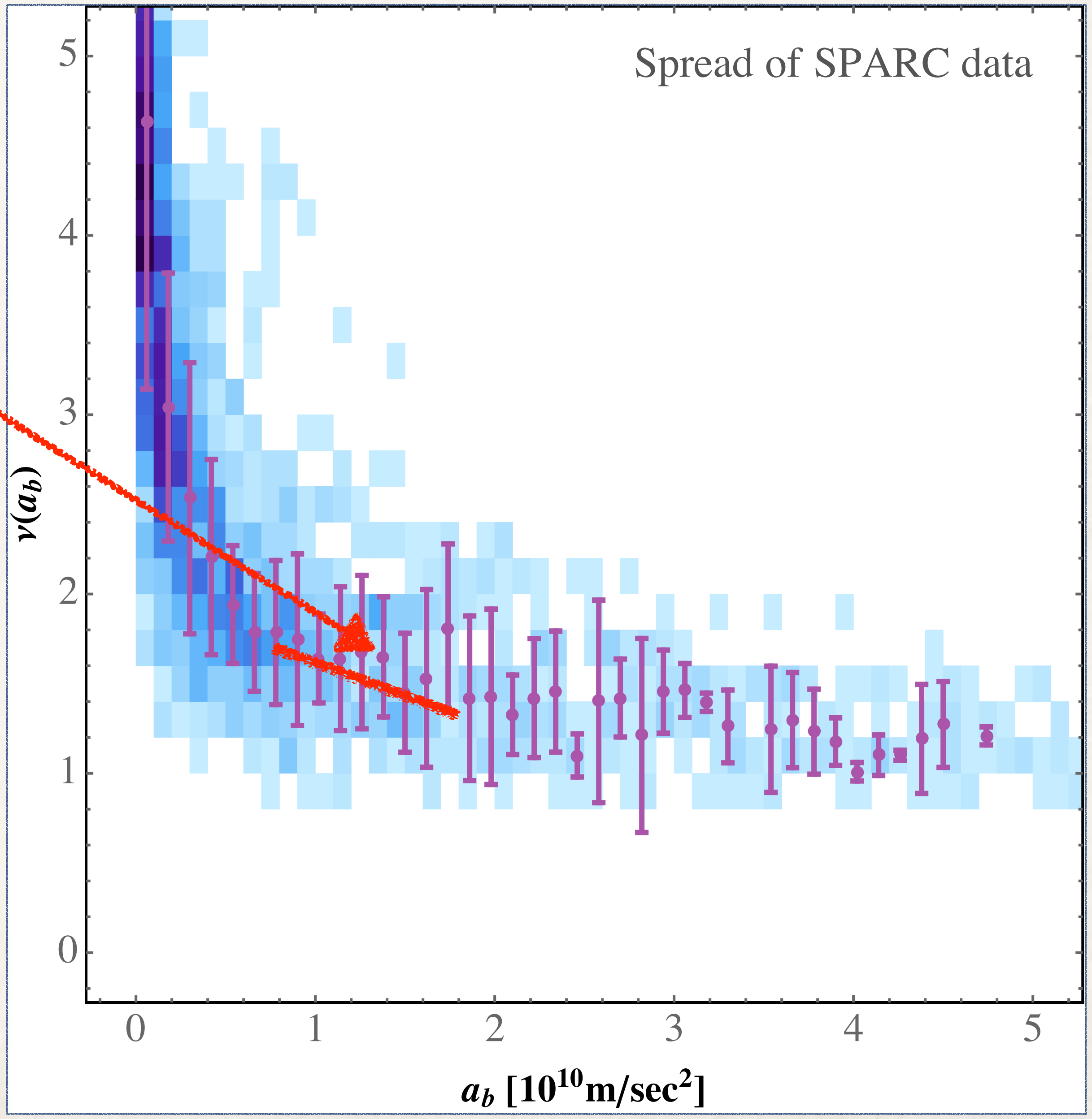
McGaugh, et. al. 2016

MOND-like forces

Solar acceleration happens to live here

Local measurements are sensitive only to small deviation in acceleration

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



Lisanti, Moschella, Outmezguine, OS (PRELIMINARY)

Observe the following:

The Solar neighborhood happens to be at the acceleration scale a_0

Local MW measurements are sensitive to a small range of acceleration

Anything that mimics MOND

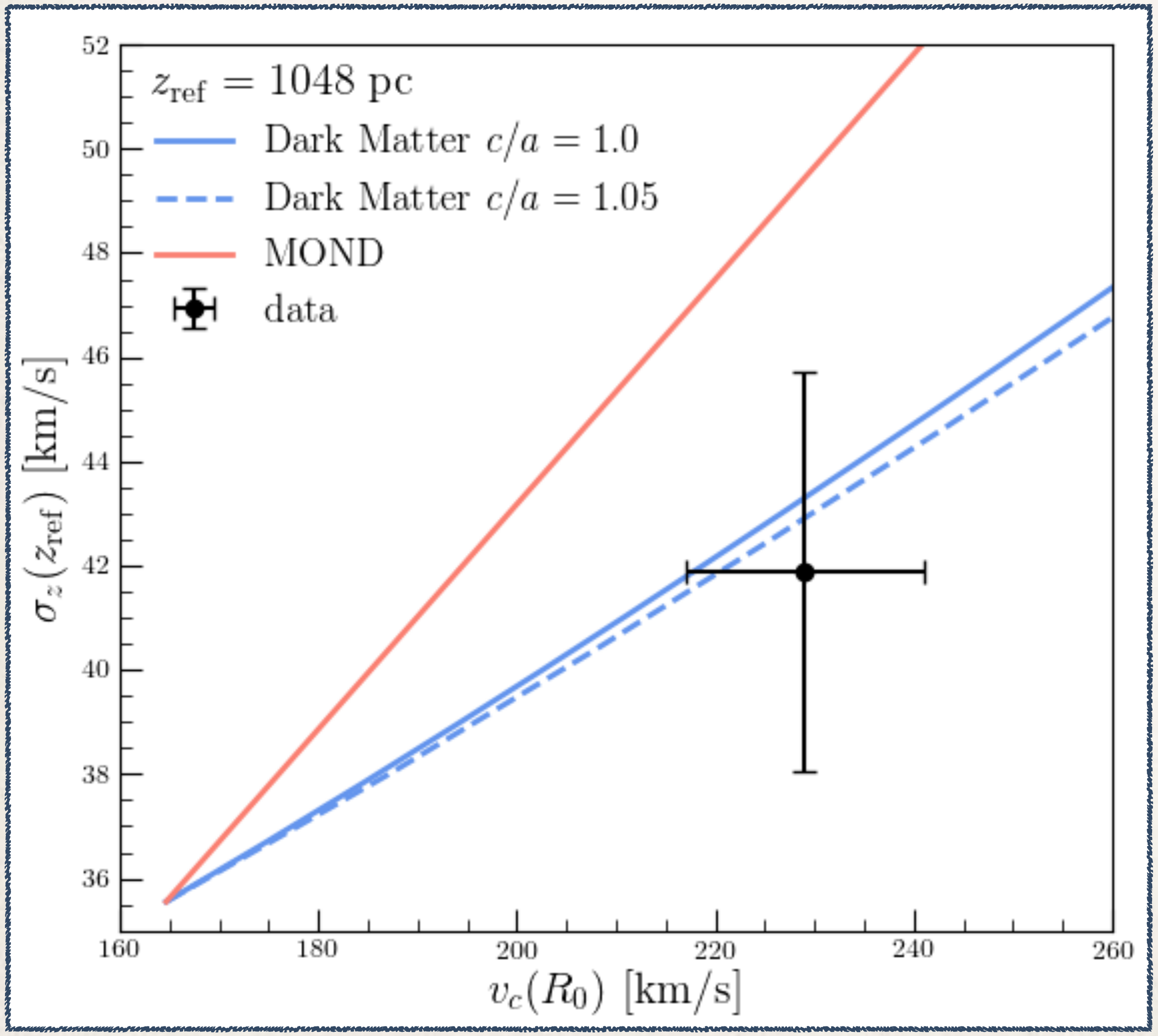
Ask a **model independent** question:

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:

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

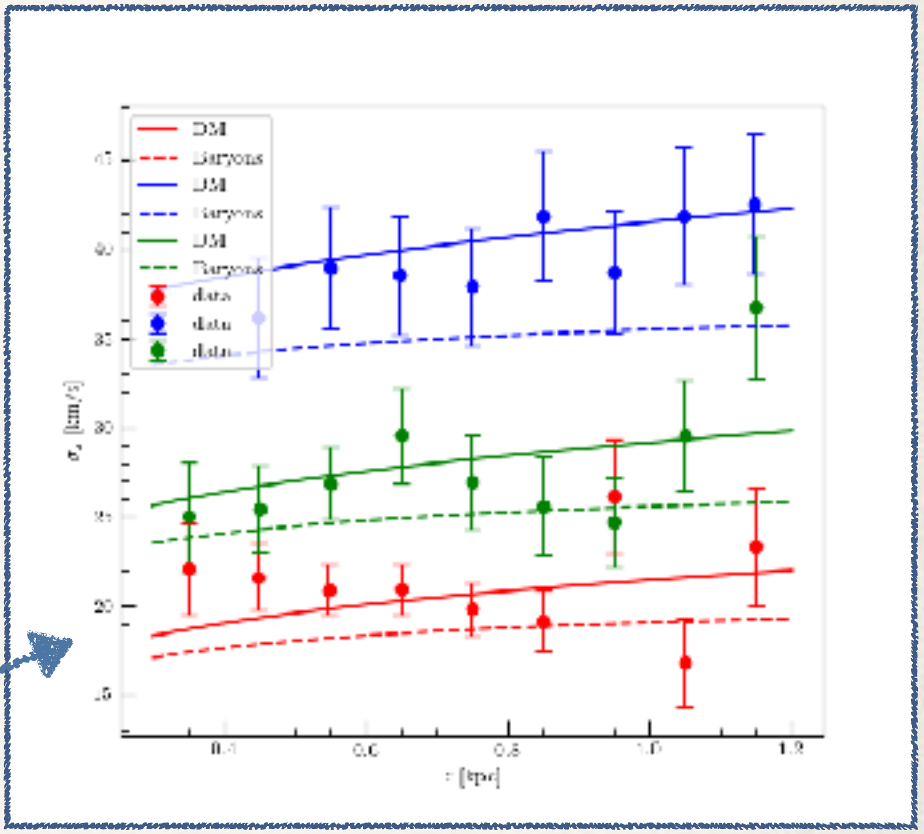
- A slightly prolate halo is slightly better.
- A MOND-like force amplifies a_R too little or a_z too much:

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

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: $\mathcal{M} = \mathrm{DM}, \mathrm{MG}$
- 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

Some general comments (and more on MOND-like forces)

MOND / Superfluid DM
Non-Linear Effects

- Non-linear effects must be accounted for!
- Potential problems include:
  - A possible non-trivial correction to the acceleration relation.
  - Small perturbations to a smooth potential can cause large effects.

MOND / Superfluid DM
A Divergenceless Field

Poisson Equation:

$$\nabla\left(\nabla\Phi_{\mathrm{N}}\right) = 4\pi G\rho$$

MONDian Poisson Equation:

$$\nabla\left(\mu\left(\frac{|\nabla\Phi|}{a_0}\right)\nabla\Phi\right) = 4\pi G\rho$$

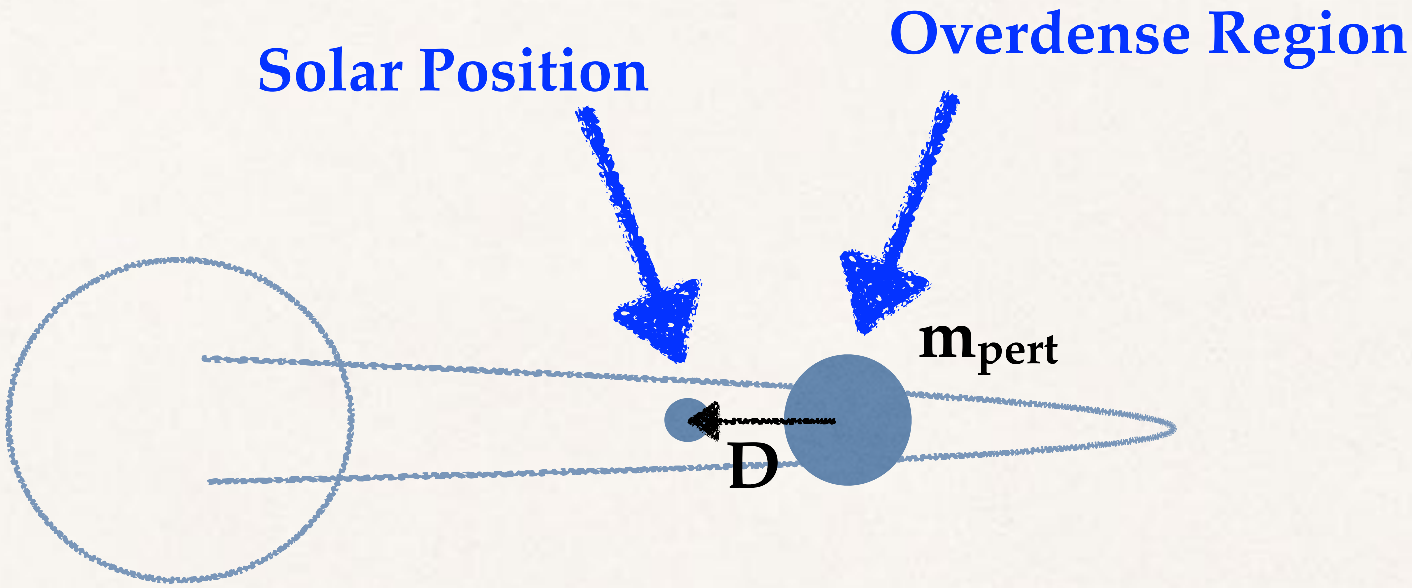
$$\Phi \propto \log r$$

Inverse of

Acceleration Relation known up to a divergenceless field:

$$\boldsymbol{a} = \nu\left(\frac{a_{\mathrm{N}}}{a_0}\right)\boldsymbol{a}_{\mathrm{N}} + \boldsymbol{S}$$

MOND / Superfluid DM
Small Perturbations



The External Field Effect (EFE) is small as long as:

$$D \gg 0.1\ \mathrm{kpc} \times \left[\nu\left(\frac{a_{\mathrm{N,BG}}}{a_0}\right) \cdot \frac{m_{\mathrm{pert}}}{10^7\, M_\odot} \cdot \frac{2 \cdot 10^{-10}\ \mathrm{m/s^2}}{a_{\mathrm{loc}}} \right]^{1/2}$$

$$a_{\mathrm{loc}} = \frac{v_c^2}{R_0} \approx 2 \cdot 10^{-10}\ \mathrm{m/s^2}.$$

Analysis Procedure:
TESTING a MOND-like force vs DM

Analysis Procedure

Milky Way Model

<u>MOND-like Force</u>
A Taylor expansion of ν

<u>Dark Matter</u>
A generalized NFW profile

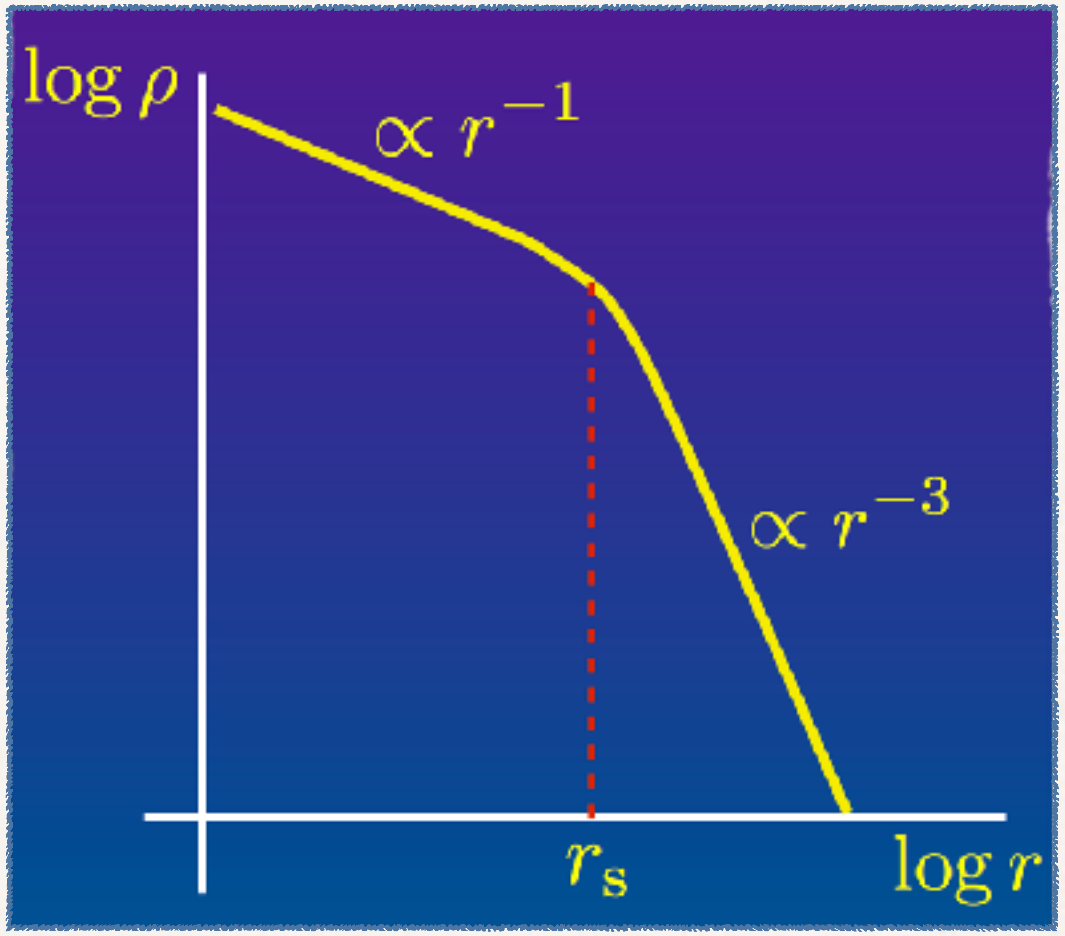
<u>Model baryonic profile:</u>

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

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

Analysis Procedure

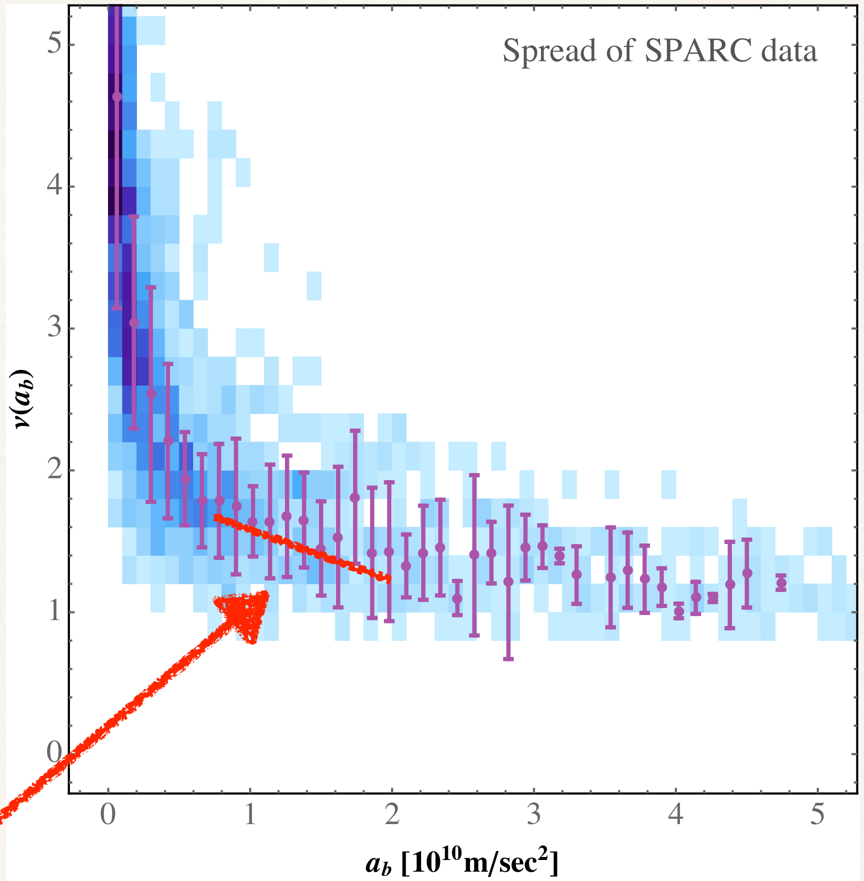
Dark Matter Parameters



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

Analysis Procedure

Modified Gravity Parameters

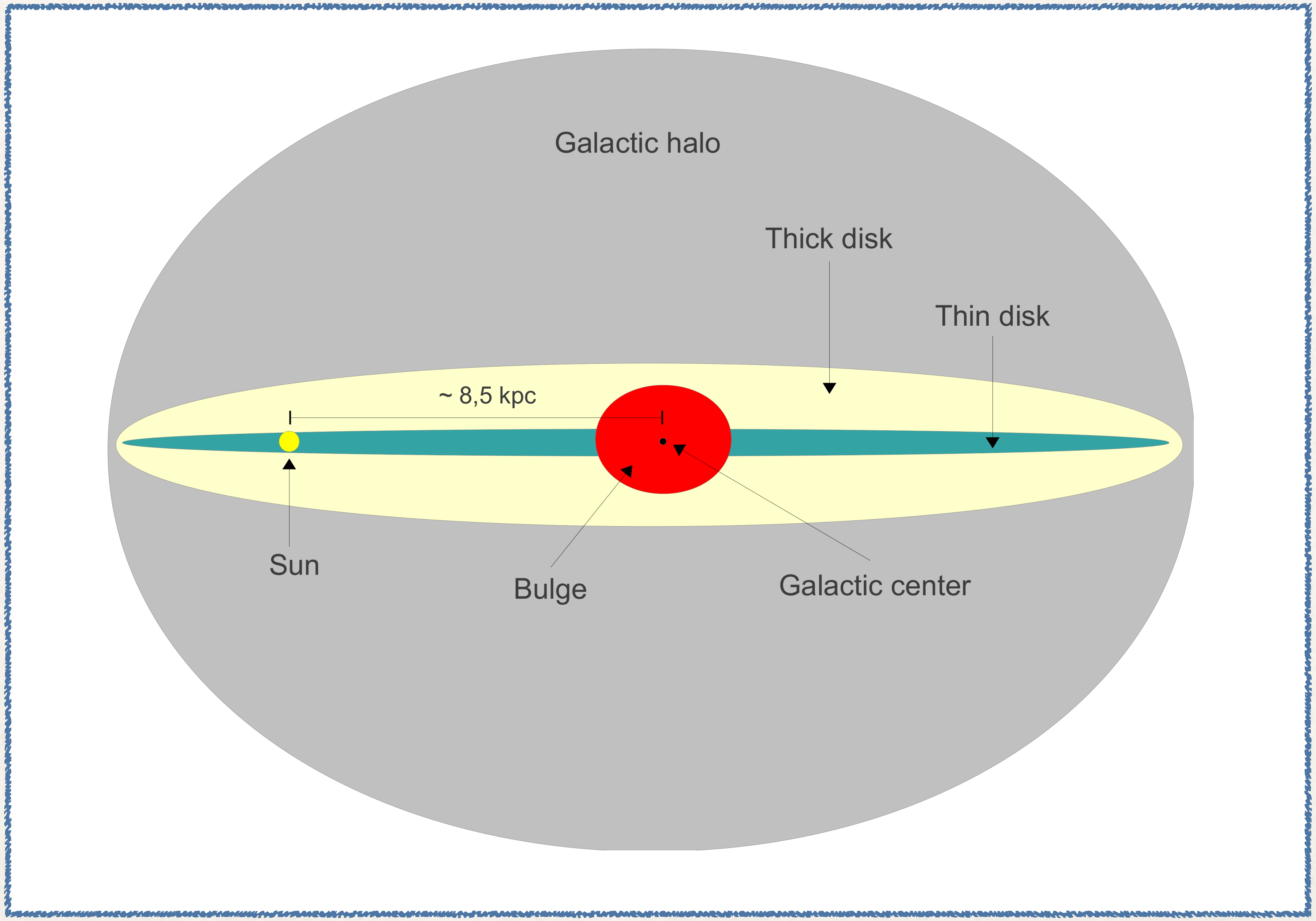


$$\nu(a_N/a_0) = \nu_0 + \frac{\tilde{\nu}_1}{a_0} \cdot a_N \equiv \nu_0 + \nu_1 \cdot a_N$$

$$\mathbf{a} = (\nu_0 + \nu_1 a_N)\,\mathbf{a}_N$$

Analysis Procedure

Baryonic Density Profiles



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

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

$$\Sigma_j^{z_{\rm max}} = 2\int_0^{z_{\rm max}} \rho_j(R_\odot, z')\, dz'$$

Table 1. Local Stellar Surface Densities (Excluding Halo Stars with $z > 3$ kpc)[a]

Description	Σ_*(F06)[b] ($M_\odot$ pc^{-2})	ρ_{*0} ($M_\odot$ pc^{-3})	h (pc)	Σ_* ($M_\odot$ pc^{-2})	$\Sigma_{*,1.1}$ ($M_\odot$ pc^{-2})
$M_V < 3$	1.5	0.0018	140	0.5	0.5
$3 < M_V < 4$	1.1	0.0018	236	0.8	0.8
$4 < M_V < 5$	2.2	0.0029	384	2.2	2.1
$5 < M_V < 8$	7.2	0.0072	400	5.8	5.4
$8 < M_V$ (M dwarfs)	13.8	0.0216	400	17.3	16.2
Giants	0.6	0.0006	344	0.4	0.4
Halo ($z < 3$ kpc)[e]	0.4	...	...	0	0
Visible stars	23.7	0.036	...	27.0	25.4
Brown dwarfs (BD)	2.3	0.0015	400	1.2	1.1
White dwarfs (WD)	6.9[d]	0.0056	430	4.9	4.6
Neutron stars (NS)	...	0.0001	...	0.2	0.1
Black holes (BH)	...	0.0001	400[f]	0.1	0.1
Total	35.8	0.043	...	33.4 ± 3	31.2 ± 3

Table 2 The Vertical Distribution of the Local Interstellar Medium[a]

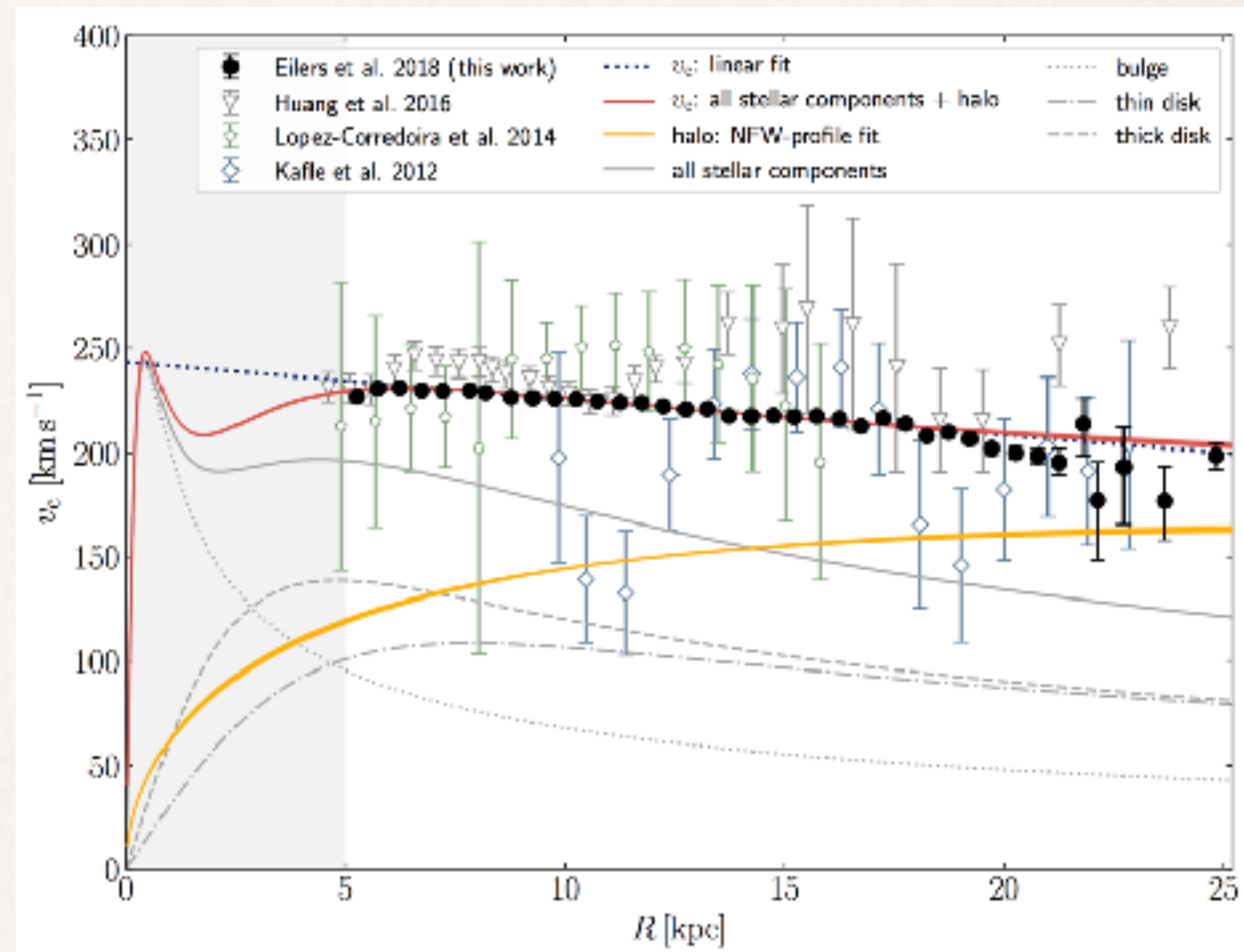
	$\bar{n}_H(z)$ (cm^{-3})	$N_{H,1.1}$ (10^{20} cm^{-2})	Σ_g[b] ($M_\odot$ pc^{-2})	$\Sigma_{g,1.1}$[b] ($M_\odot$ pc^{-2})
H_2	0.15 exp $-(z/105\ \rm pc)^2$	0.9 ± 0.3	1.0 ± 0.3	1.0 ± 0.3
HI: CNM[c]	0.80 exp $-(z/127\ \rm pc)^2$	5.54	6.21	6.21
WNM$_1$	0.13 exp $-(z/318\ \rm pc)^2$	2.24	2.51	2.51
WNM$_2$	0.077 exp $-(z/403\ \rm pc)$	1.91	2.14	2.00
Total HI	$z_{HI,e}$ = 1.01	9.7 ± 1.5	10.9 ± 1.6	10.7 ± 1.6
HII[d]	0.0154 exp $-(z/1500\ \rm pc)$	1.6 ± 0.1	1.8 ± 0.1	0.9 ± 0.1
Total	—	12.2 ± 1.5	13.7 ± 1.6	12.6 ± 1.6

McKee, Parravano, Hollenback, 2015

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

Tracer stellar populations modeled by a steady-state collisionless system

Solve Jeans Equation assuming cylindrical symmetry and negligible tilt term

$$n_i(z) = \tilde{n}_i \exp(-z/h_i)$$

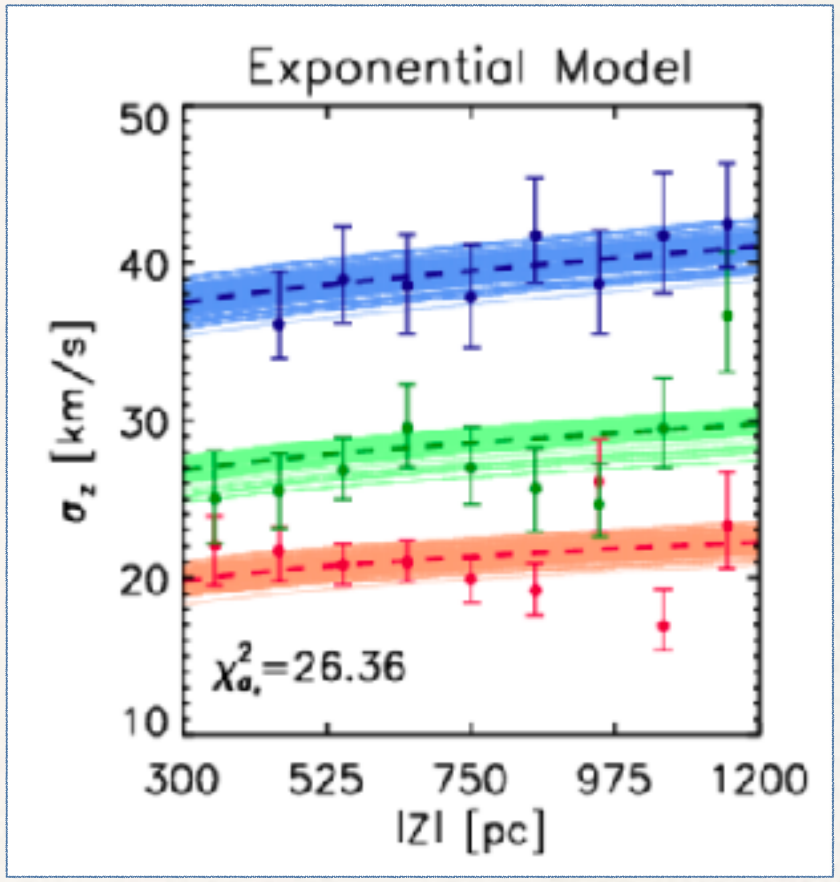
$$\sigma_{i,z}(z)^2 = \frac{n_i(0)\,\sigma_{i,z}(0)^2}{n_i(z)} + \frac{1}{n_i(z)} \int_0^z n_i(z')\,a_z(z')\,dz'$$

Zhang et. al., 2013

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



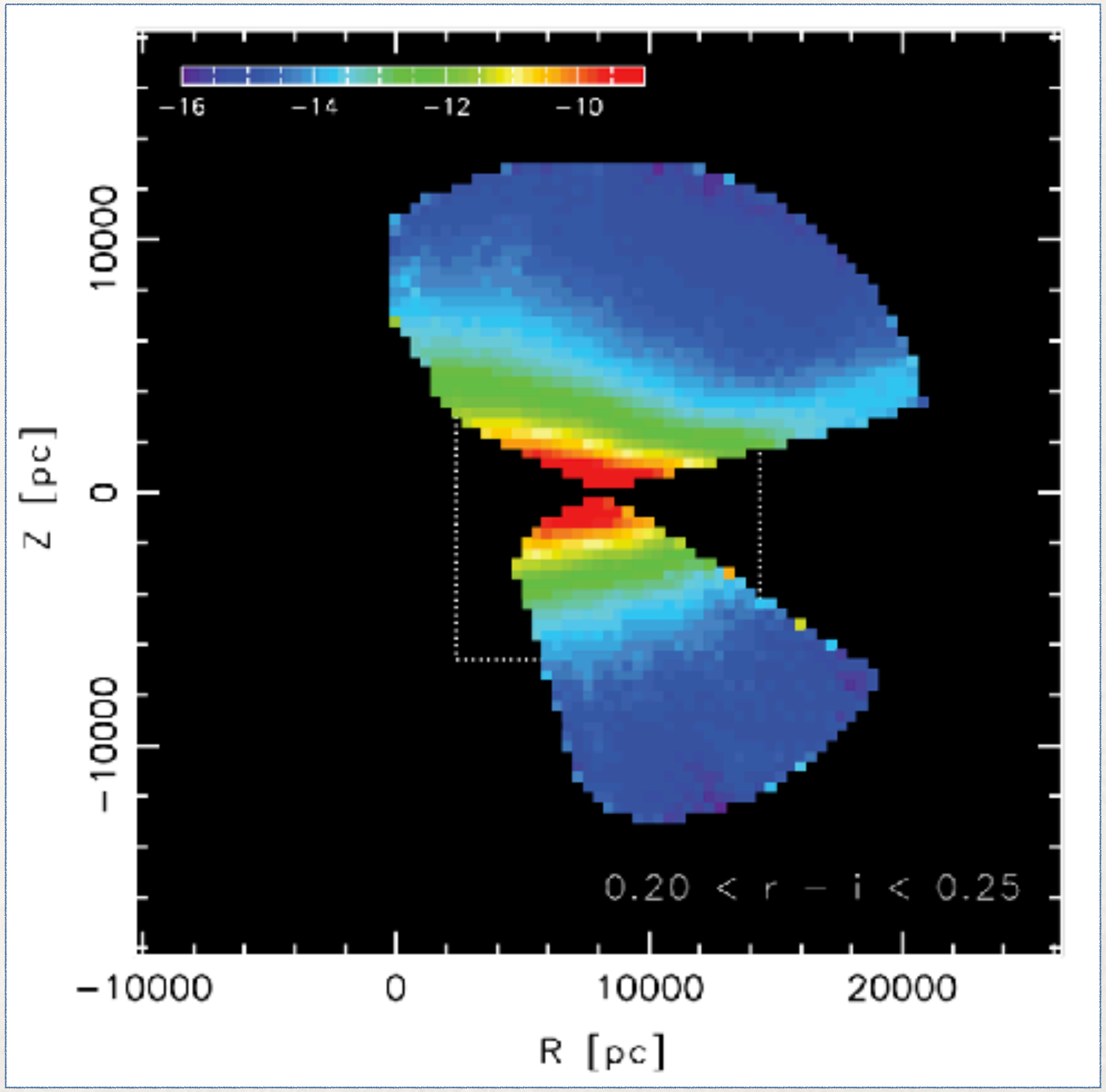
Zhang et. al., 2013

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

Analysis Procedure

Milky Way Observables

- Stellar scale radius
- Stellar disk mass
- Stellar bulge mass



Juric et. al., 2008

Analysis Procedure

Ensure Self Consistency

- Only use measurements from locations where non-linear effects are negligible
- Only use measurements which were not inferred dynamically under the assumption of DM

A Test of Isotropic Theories vs DM

MCMC Analysis

Free parameters of each theory:

$$\boldsymbol{\theta}_{\mathrm{G}} = (\tilde{n}_i,\ h_i,\ \tilde{\rho}_*,\ h_{*,R},\ M_{b,0},\ \tilde{\rho}_g,\ \nu_0,\ \nu_1)$$
$$\boldsymbol{\theta}_{\mathrm{DM}} = (\tilde{n}_i,\ h_i,\ \tilde{\rho}_*,\ h_{*,R},\ M_{b,0},\ \tilde{\rho}_g,\ \tilde{\rho}_{\mathrm{DM}},\ \alpha)$$

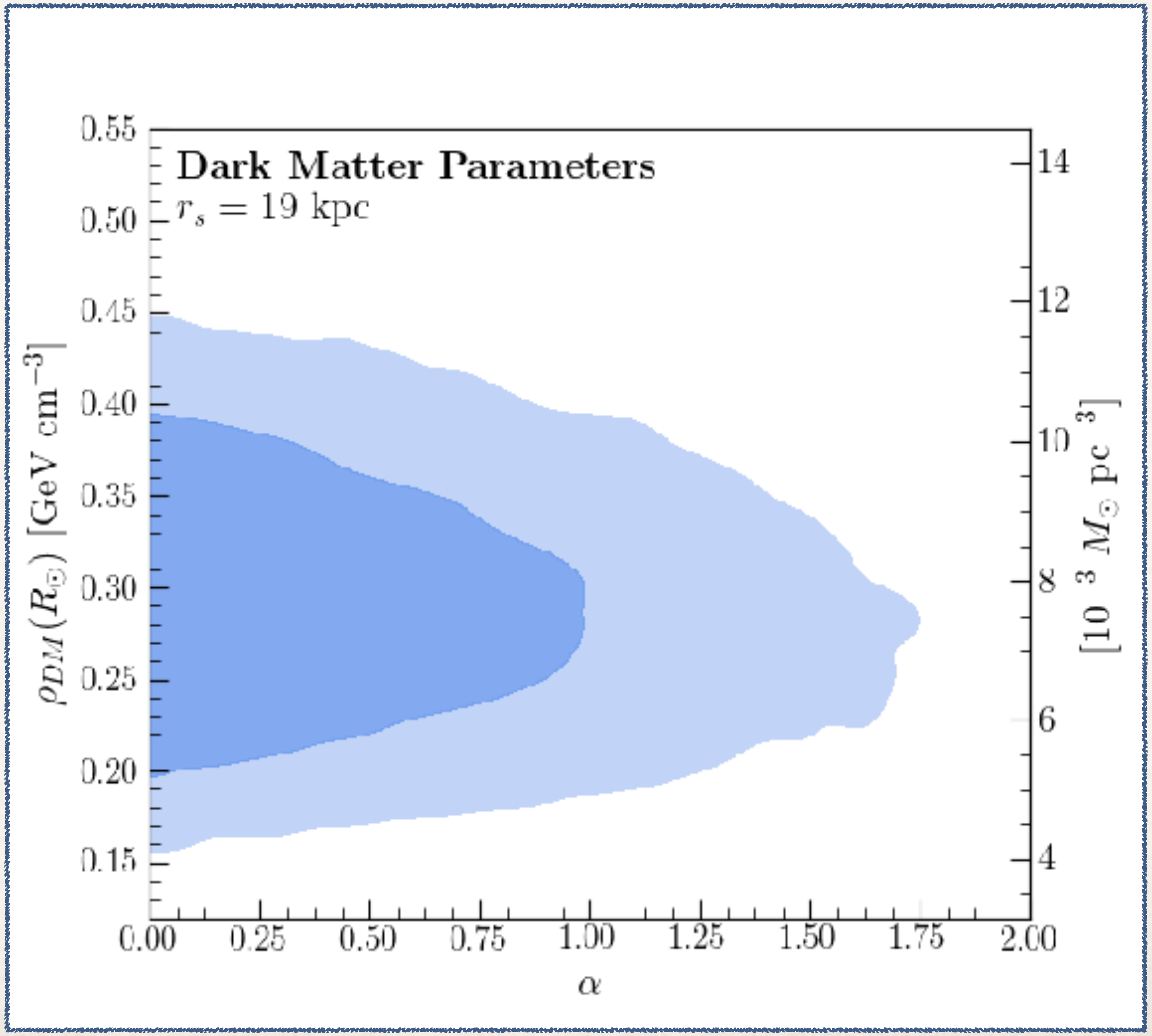
Bayesian Evidence calculated numerically by:

$$\mathrm{BE}_{\mathcal{M}} = \int_{\mathrm{prior}} \mathrm{d}\boldsymbol{\theta}\, \mathcal{L}_{\mathcal{M}}(\boldsymbol{\theta}|\mathbf{X}_{\mathrm{obs}}) \approx \left(\sum_{\mathrm{i}} \frac{1}{\mathcal{L}_{\mathcal{M},\mathrm{i}}} \right)^{-1}$$

RESULTS

Results of MCMC Scans

Dark Matter Parameters



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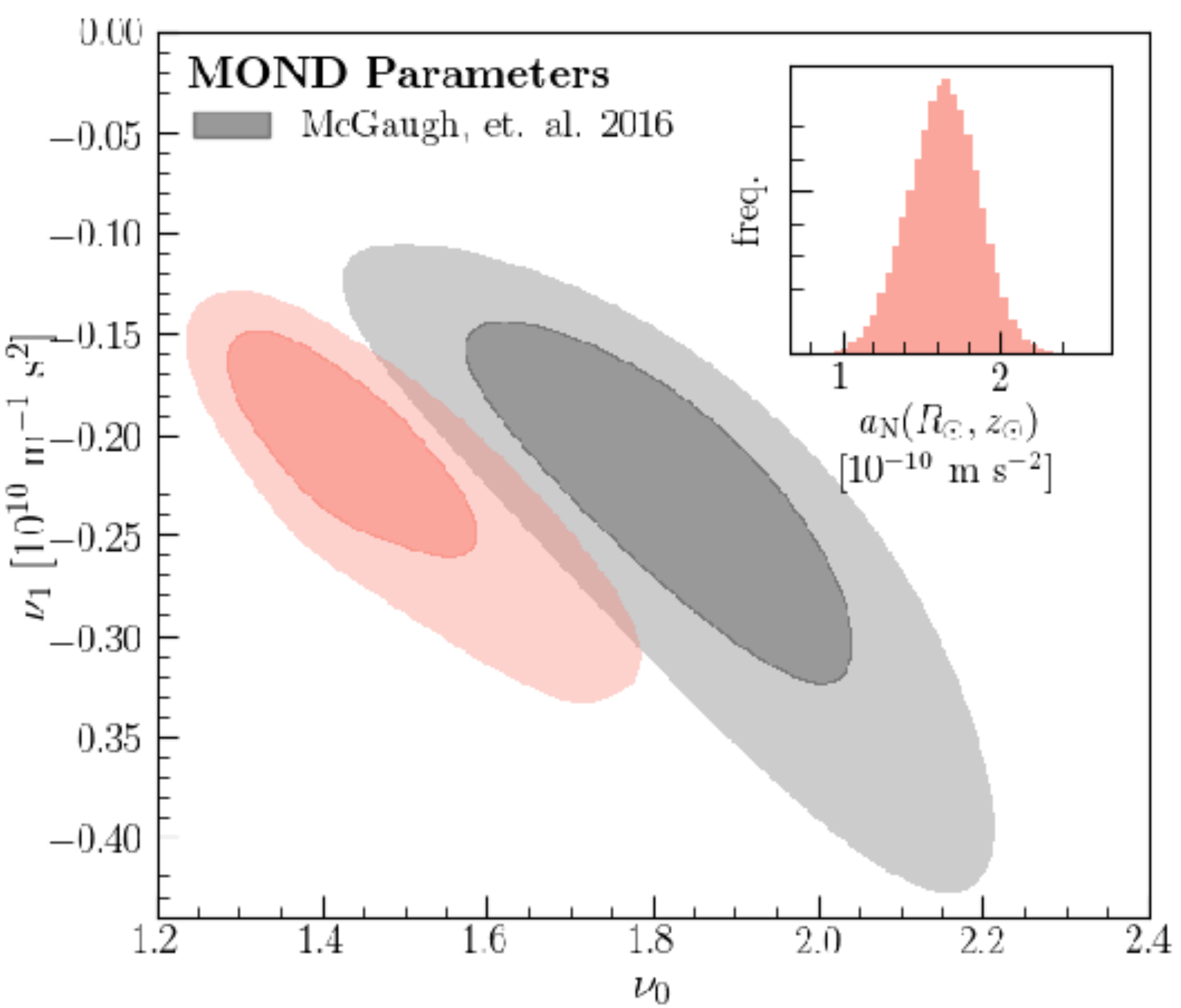
Results of MCMC Scans

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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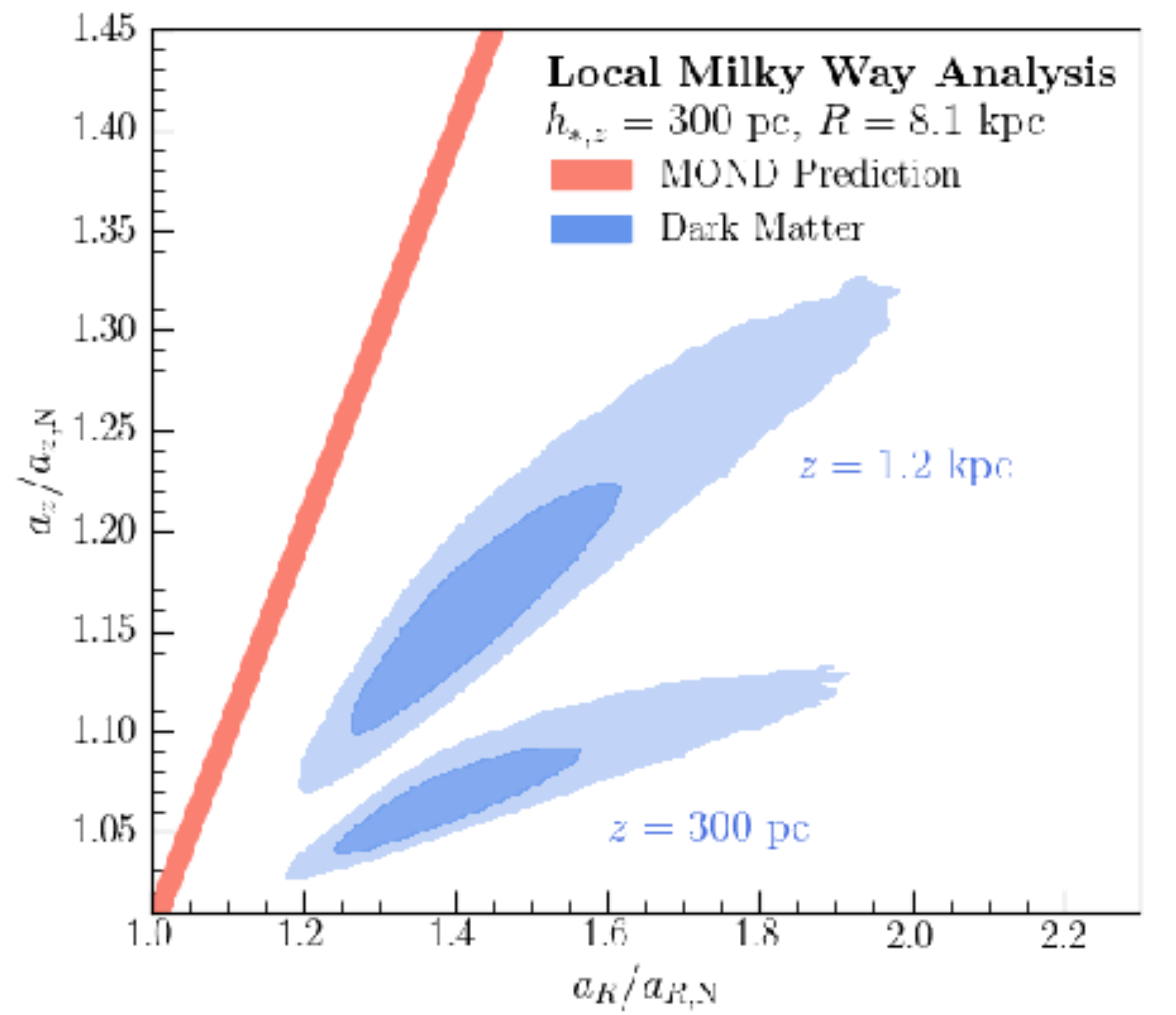
Results of MCMC Scans

Tension between models for <u>any</u> 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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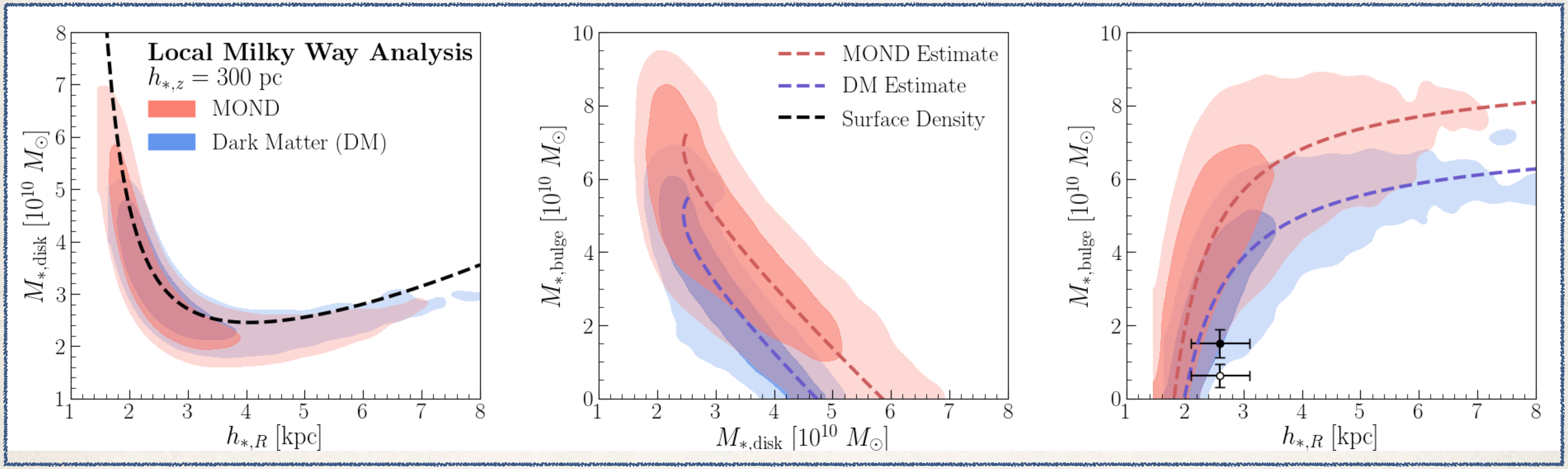
Results of MCMC Scans

Tension with MW Observations



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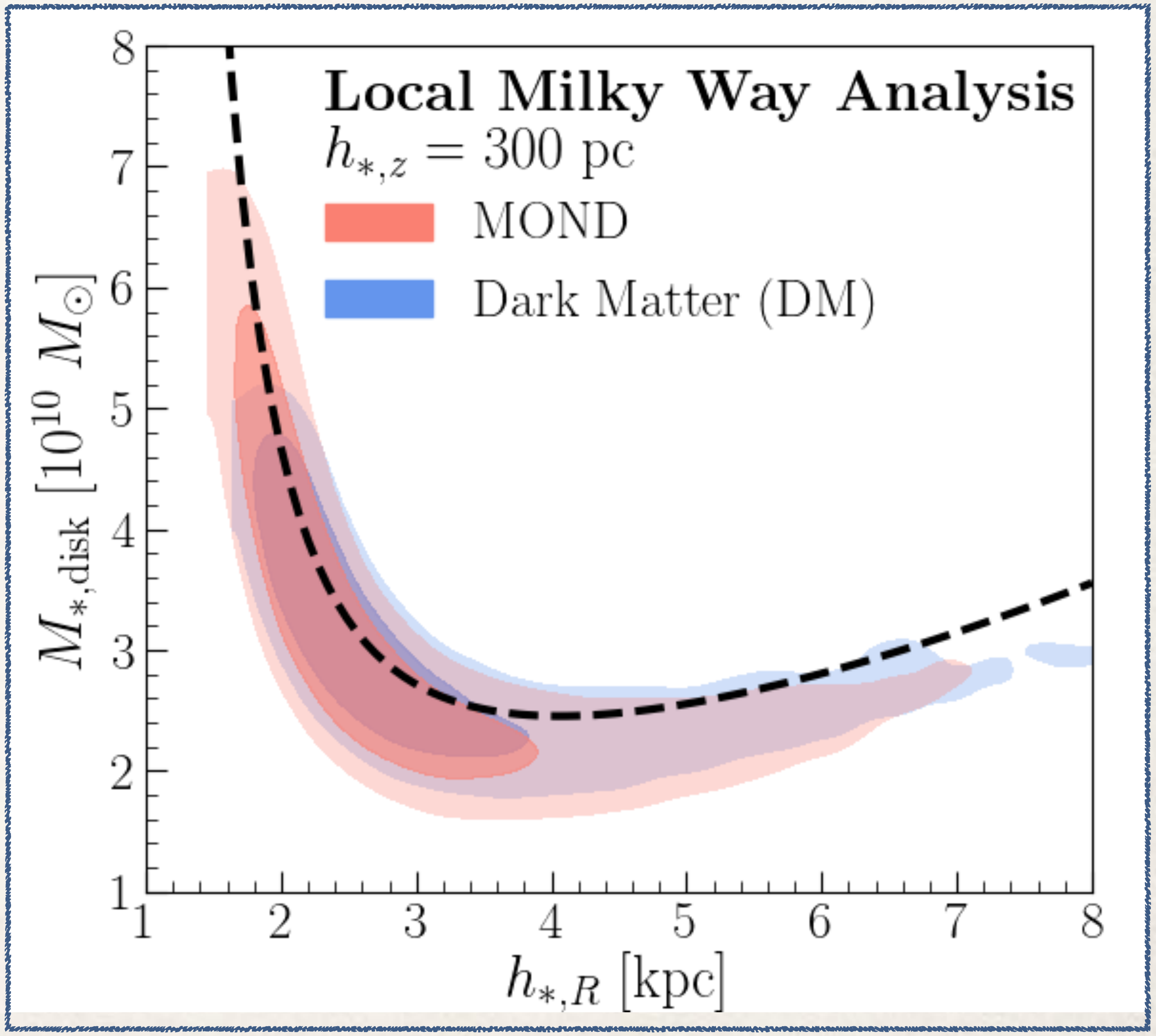
Results of MCMC Scans

Stellar Scale Radius *vs* Stellar Disk Mass

Driven by stellar surface density constraint

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



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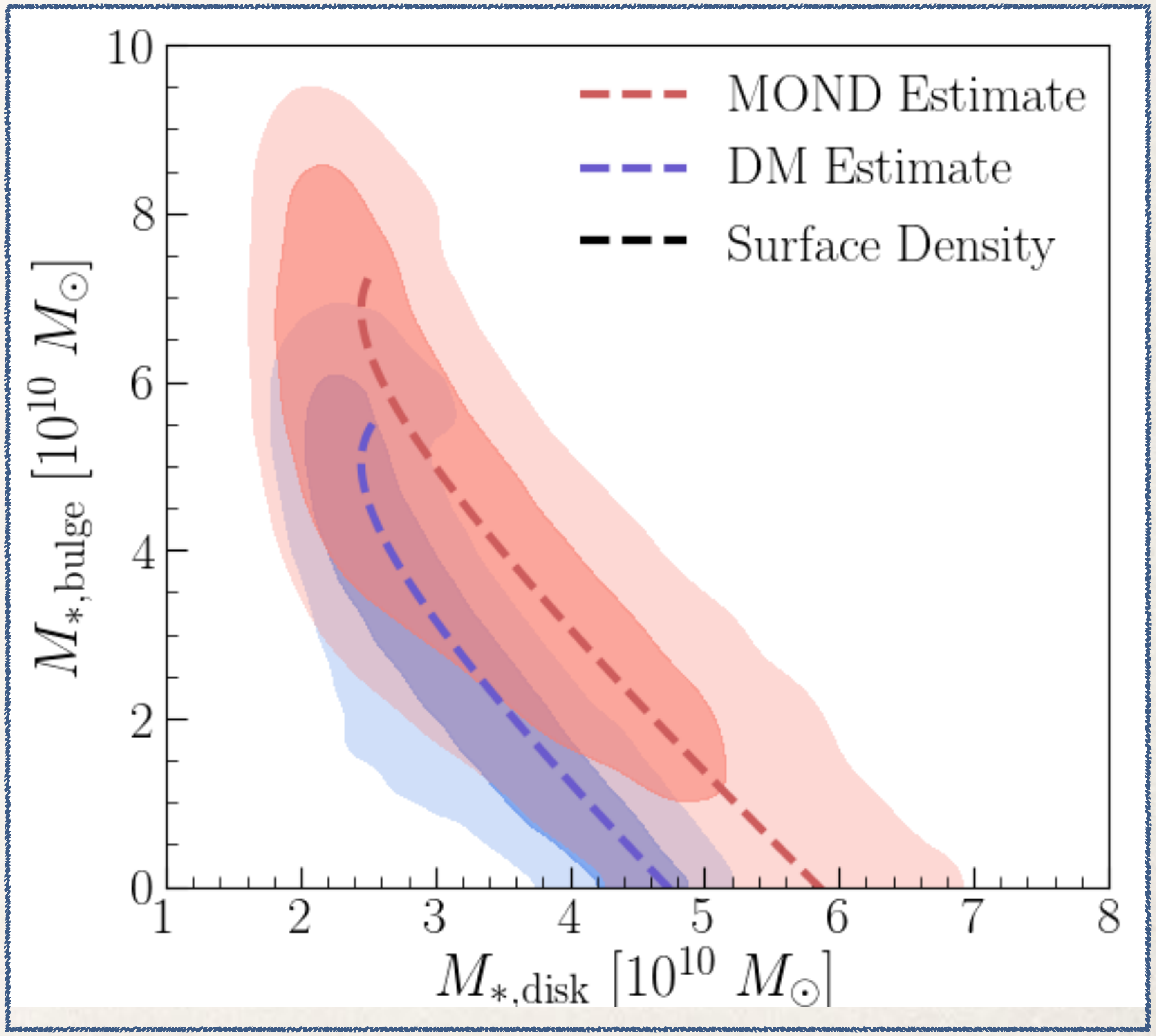
Results of MCMC Scans

Stellar Disk Mass *vs* Stellar Bulge Mass

Driven by local value of rotation curve constraint

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



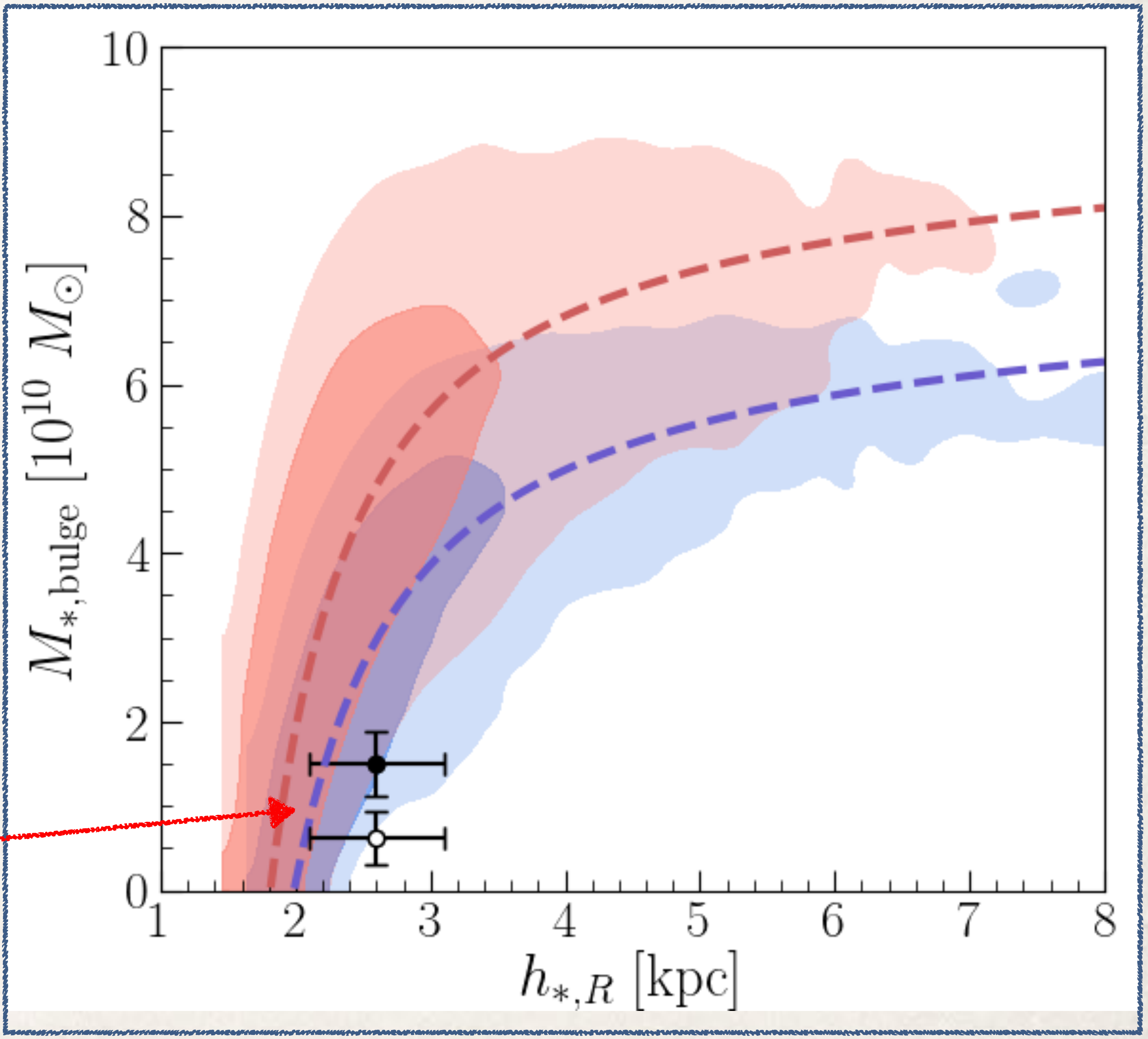
1812.08169 - Lisanti, Moschella, Outmezguine, O.S.

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	$M^B_\star \pm 1\sigma$ (10^{10} $M_\odot$)	R_0 assumed (kpc)	Constraint type	β^a	$M^B_\star \pm 1\sigma (R_0 = 8.33\text{kpc})$ (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

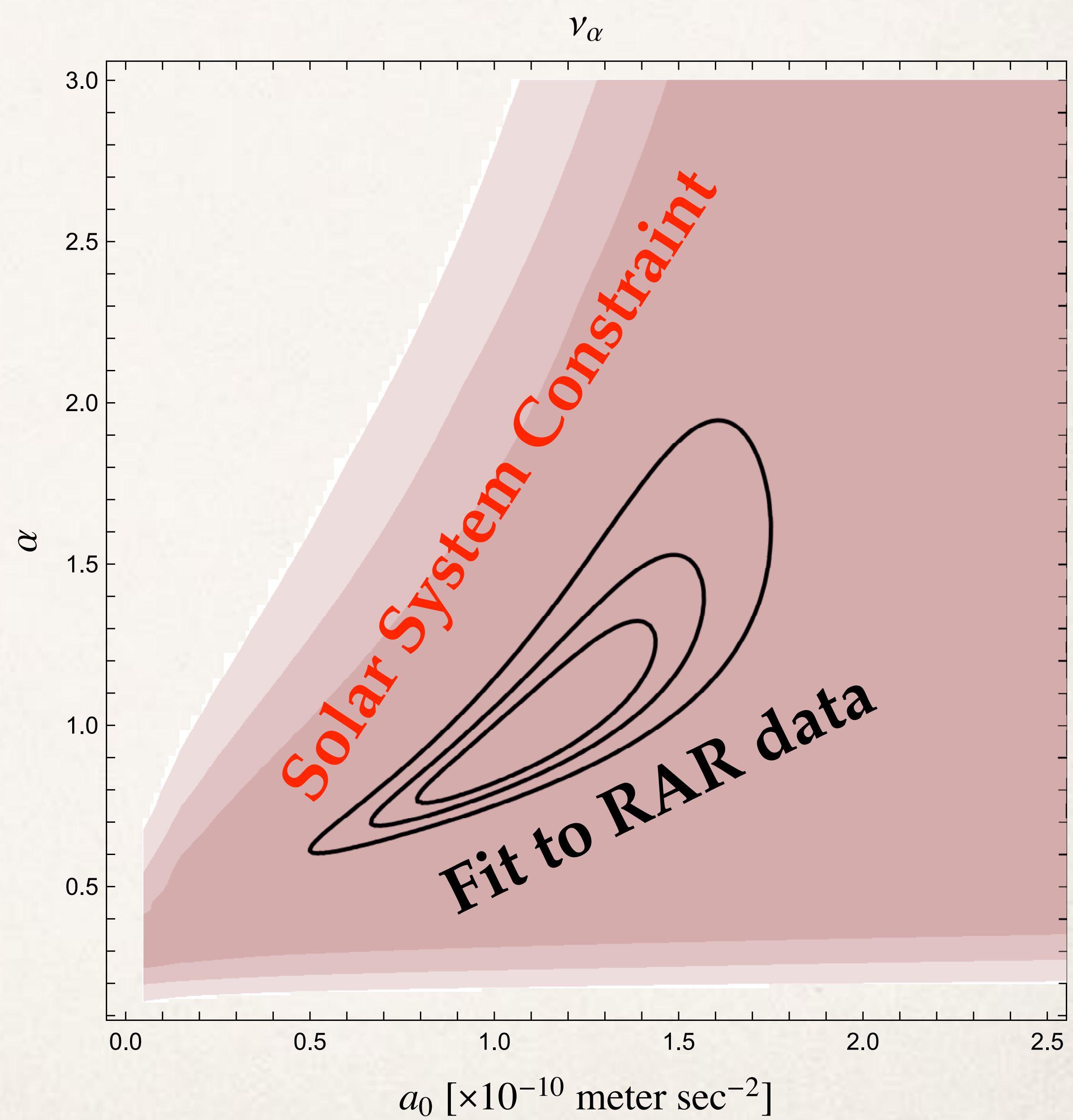
Future Work

- 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

Outlook

More results for "standard" MOND

- Results can be mapped onto specific interpolation functions which exist in the literature.
- Consistent with RAR results.
- VERY INCONSISTENT with Solar System constraints (upcoming study).



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(VERY PRELIMINARY)

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

Conclusions

- Precision astrometry can be a powerful probe of New Physics.
- Developed a Bayesian framework to compare theories of baryonic acceleration to Dark Matter.
- 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.
- Standard MOND is inconsistent with the combination of MW data, RAR and Solar System constraints.

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

THANK YOU