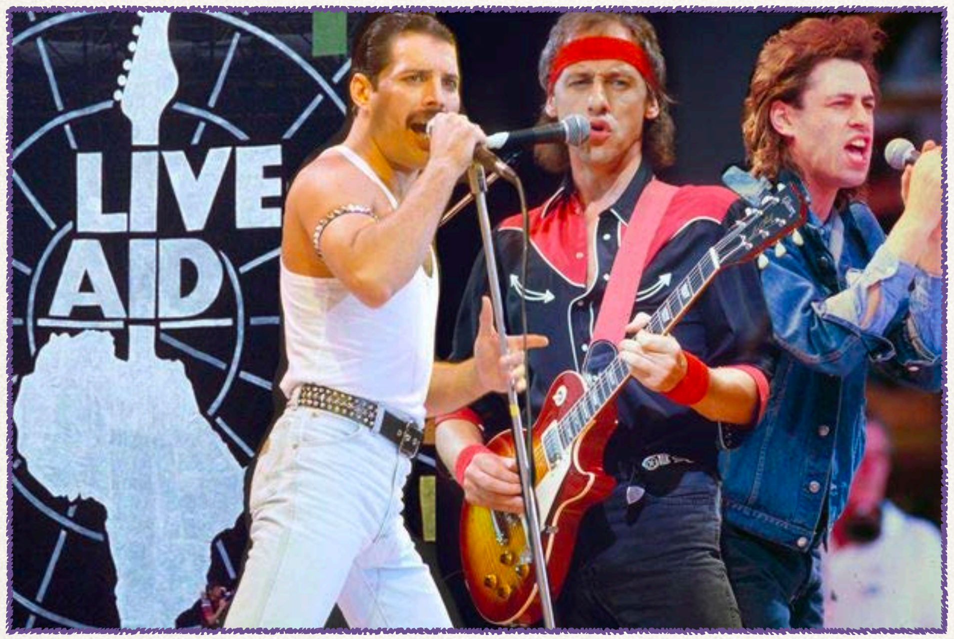
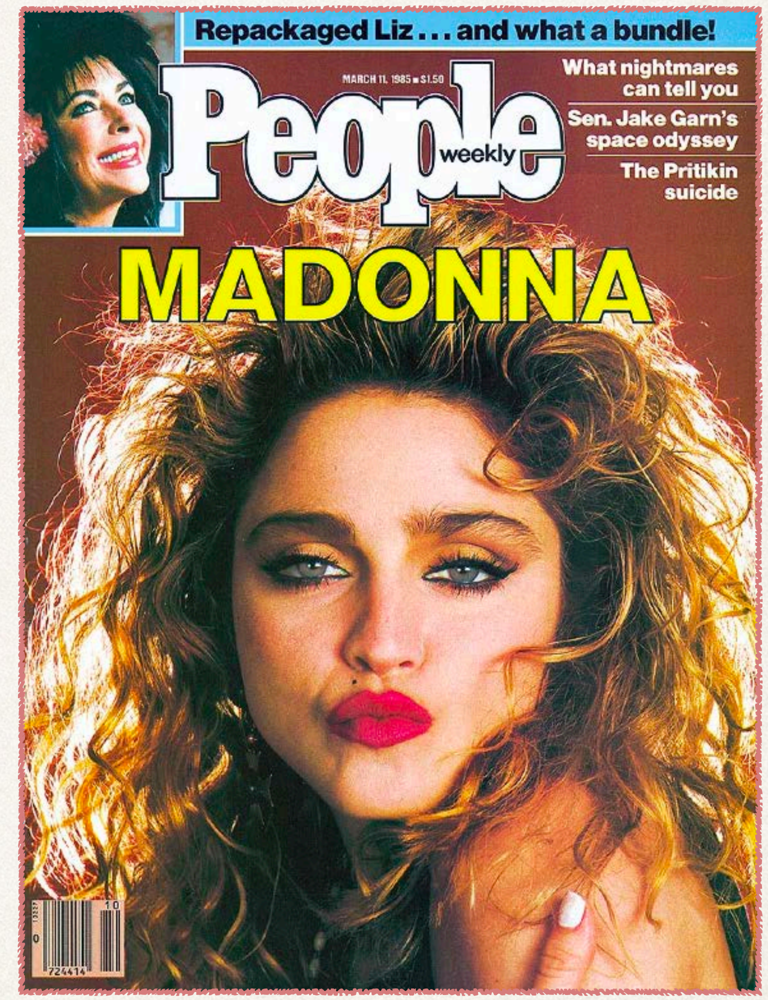
Inconsistency of SuperFluid DM with Milky Way Observables

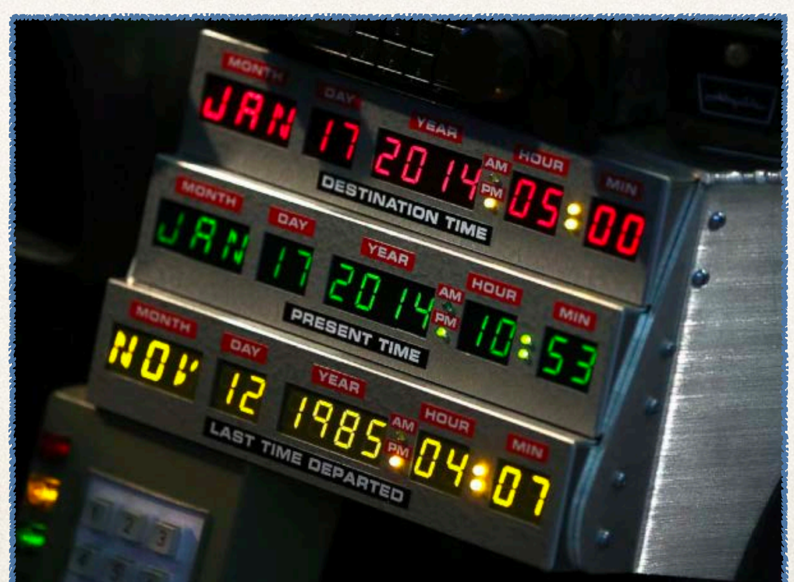
Oren Slone, Princeton University

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

Great things from the 80’s







Great things from the 80's

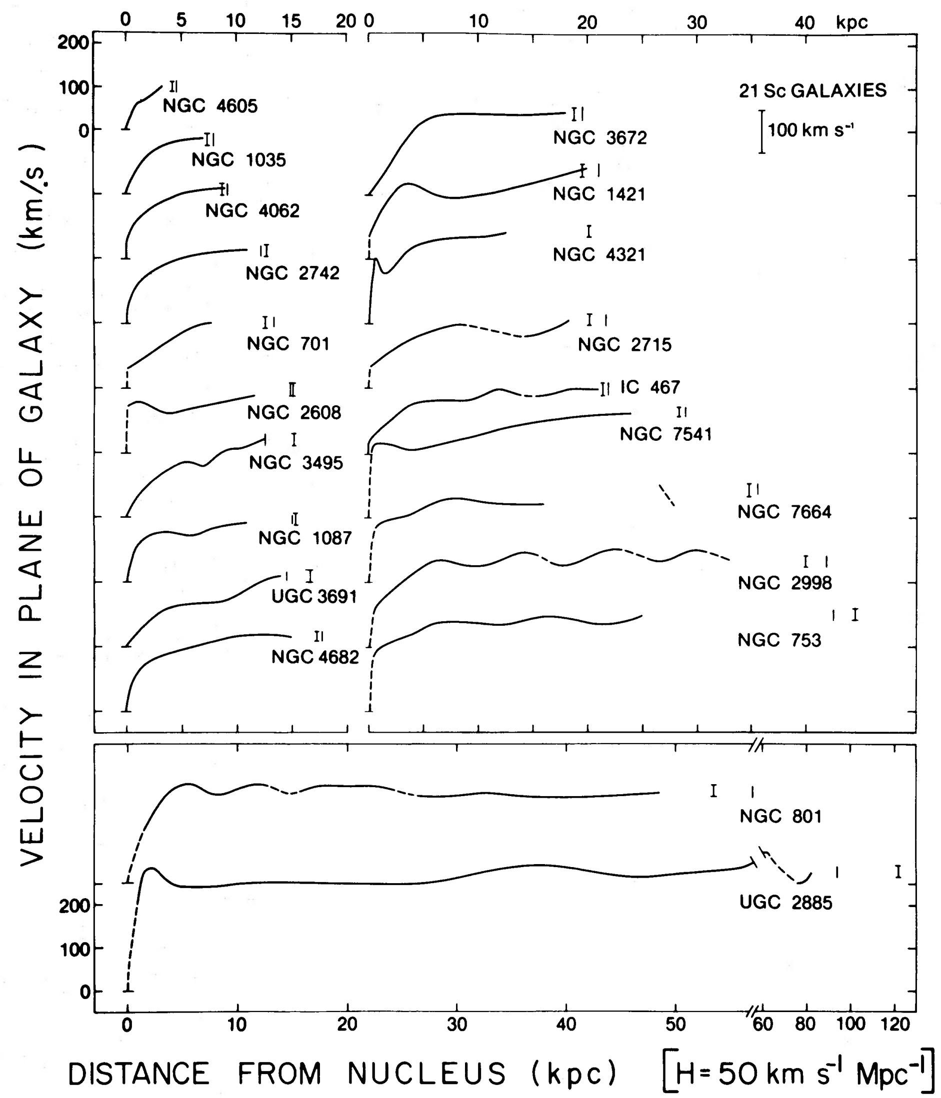
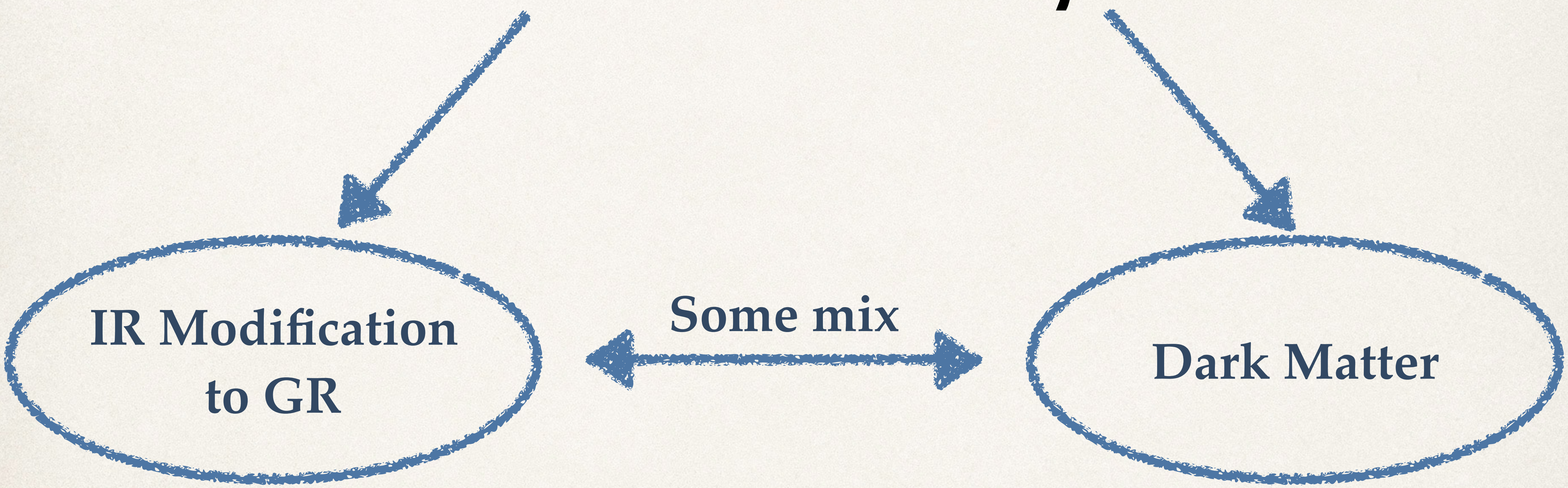


FIG. 5.—Mean velocities in the plane of the galaxy, as a function of linear distance from the nucleus for 21 Sc galaxies, arranged according to increasing linear radius. Curve drawn is rotation curve formed from mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25},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

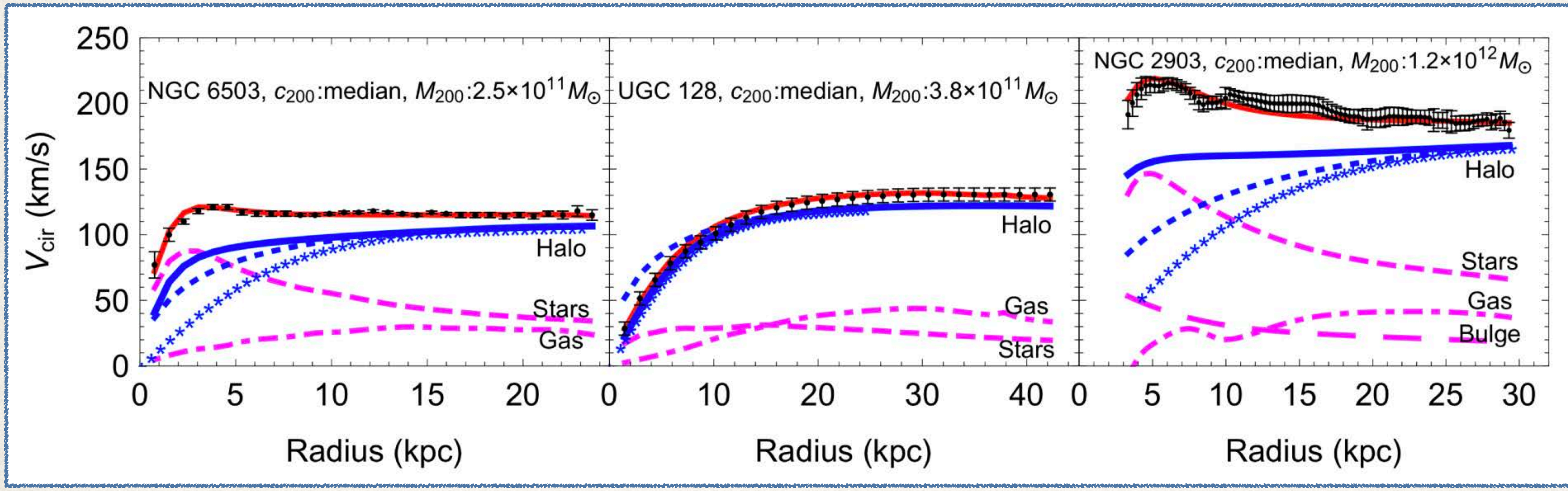
- Missing Mass and Galaxy Scale Observables
- Features of Various Classes of Solutions
- Superfluid Dark Matter
- Framework to Test Various Models using MW data
- Results and Conclusions

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



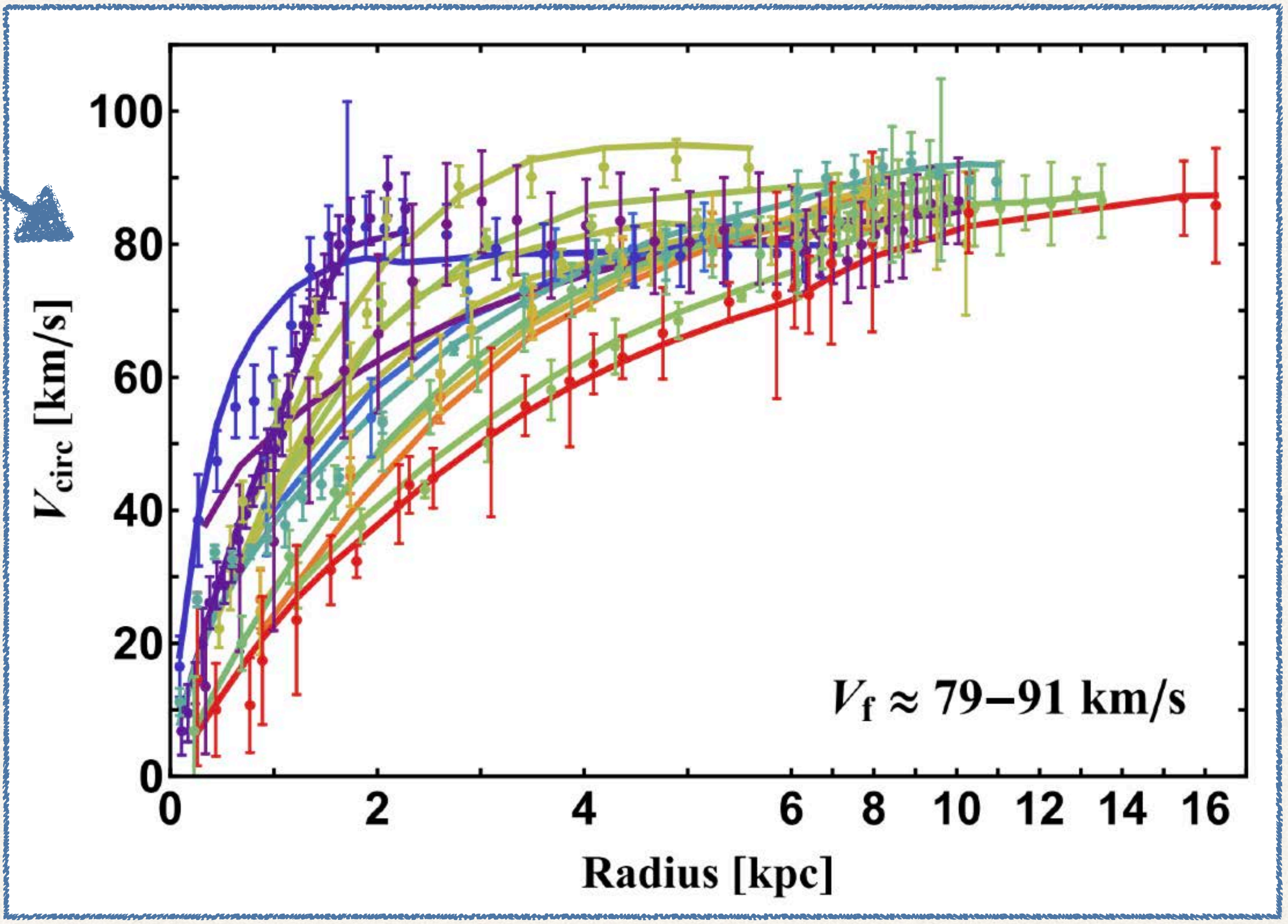
Kamada et. al., 2016

- 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!

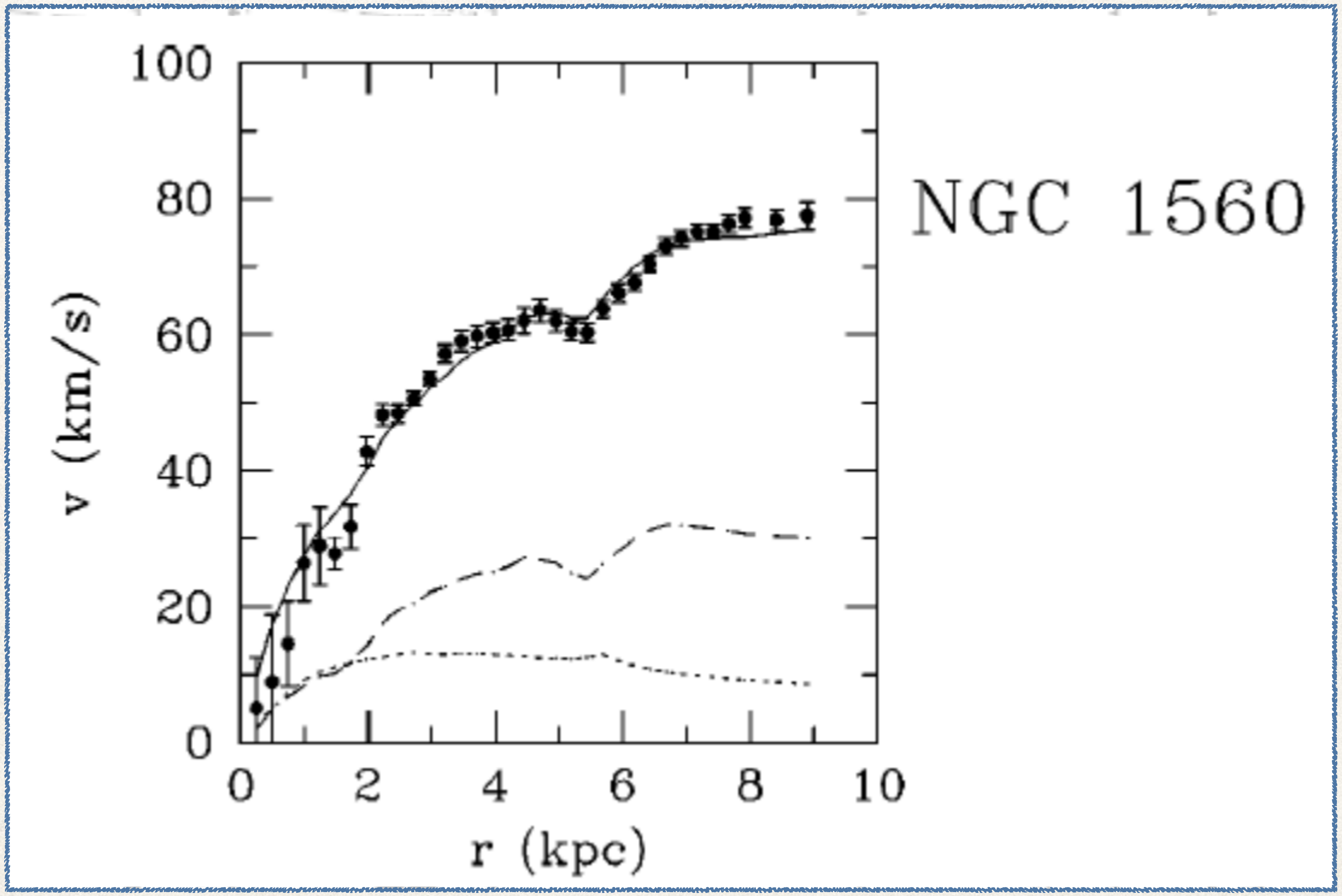


Kamada et. al., 2016

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

Galaxy Scale Observables

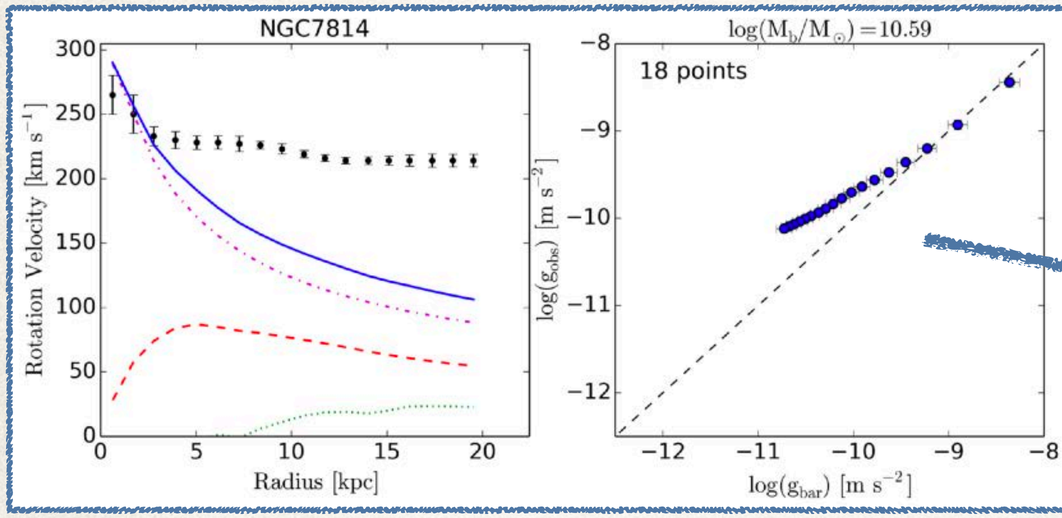
Renzo's Rule



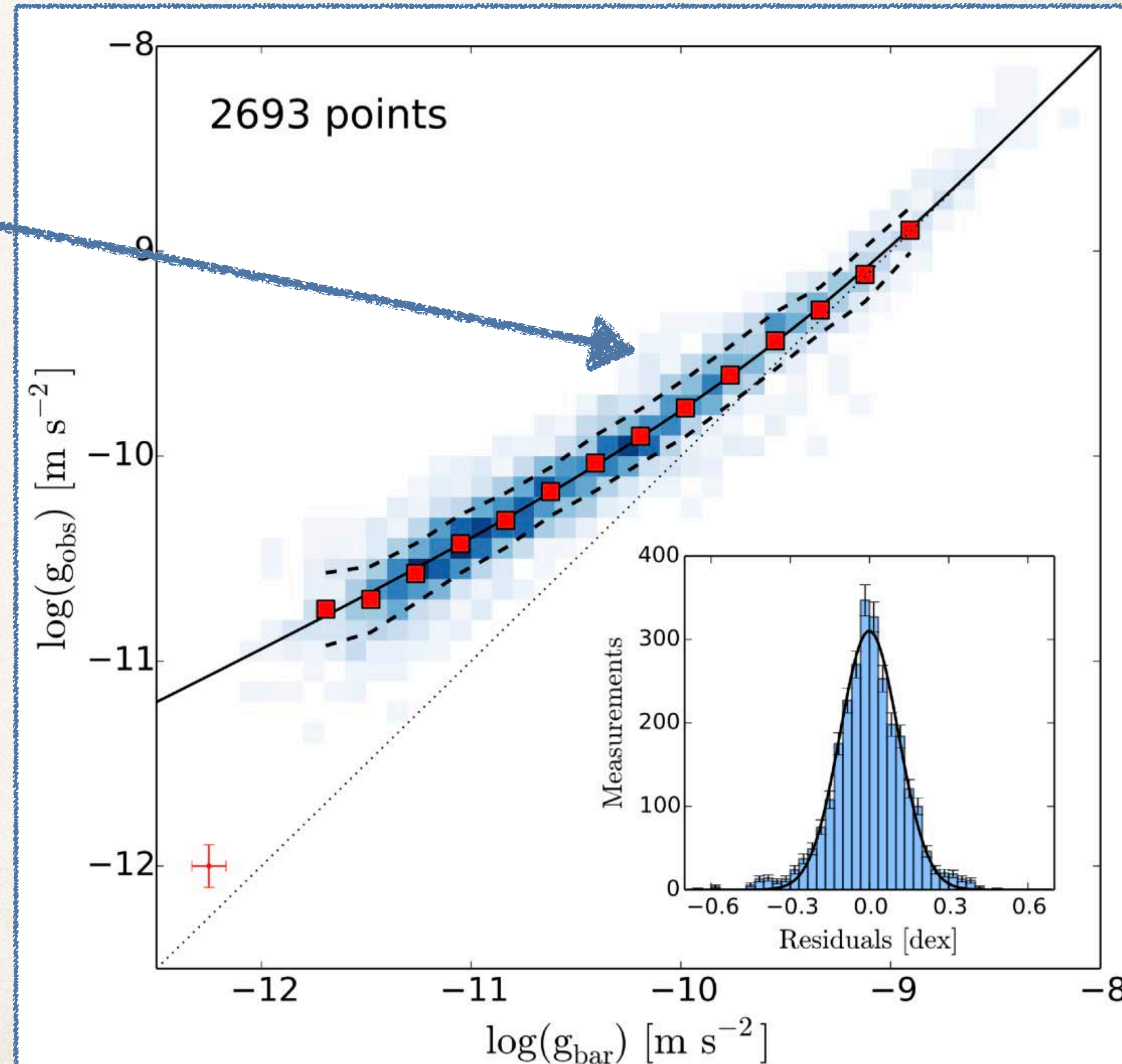
Sancisi, 2003

Galaxy Scale Observables

The Radial Acceleration Relation (RAR)



Lelli et. al, 2017



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

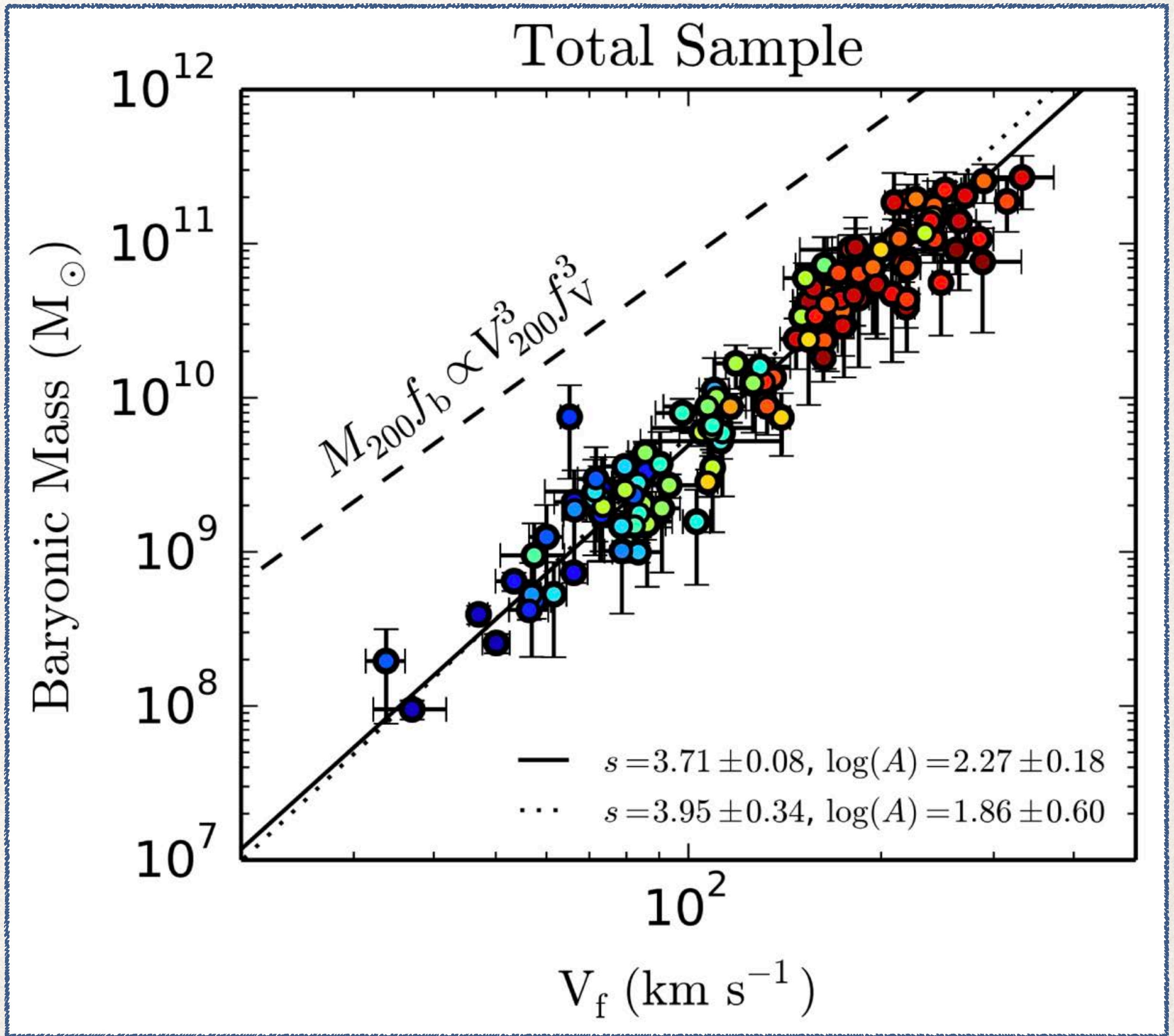
McGaugh, Lelli, 2017

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

A Universal Scaling Relation

A Mass Discrepancy Acceleration Relation (MDAR) appears to be a feature of galaxies:

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

An acceleration scale appears in the data

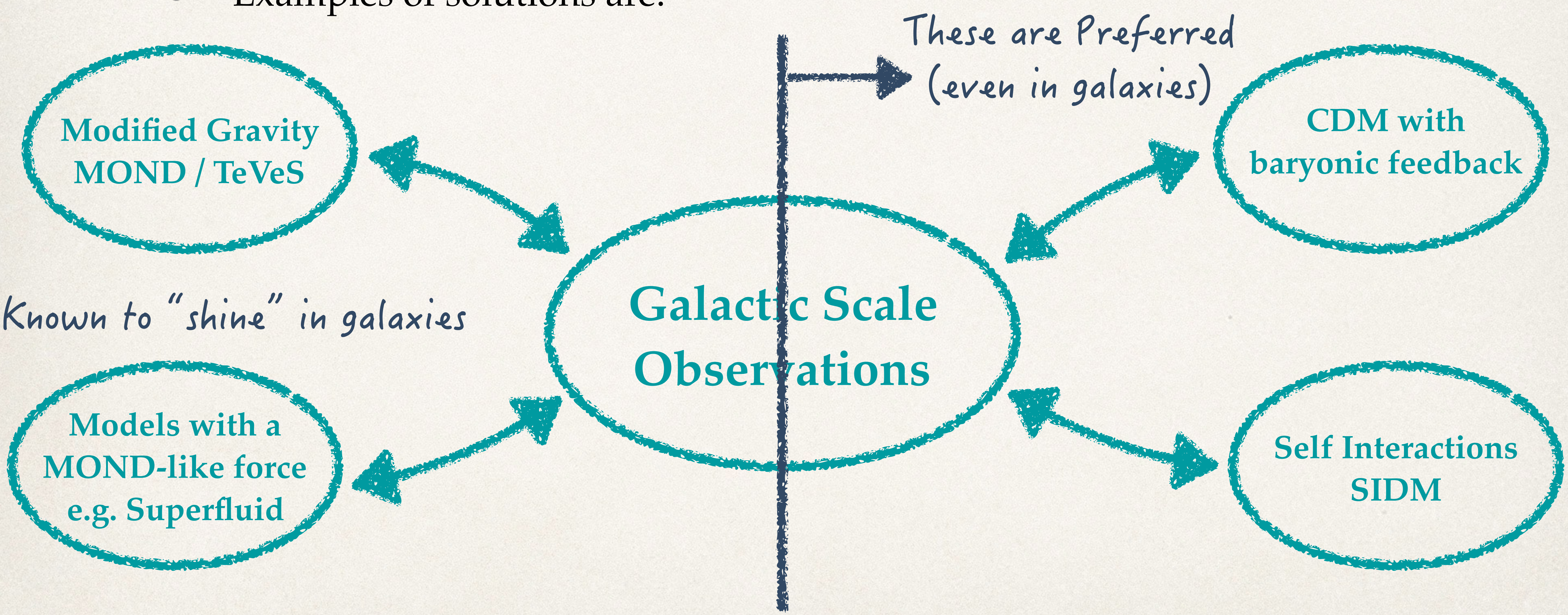
$$a_0 \sim 1.2 \times 10^{-10}\ \textbf{m/sec}^2 \sim \frac{1}{6} H_0$$

Galaxy Scale Observables

What models resolve these issues?

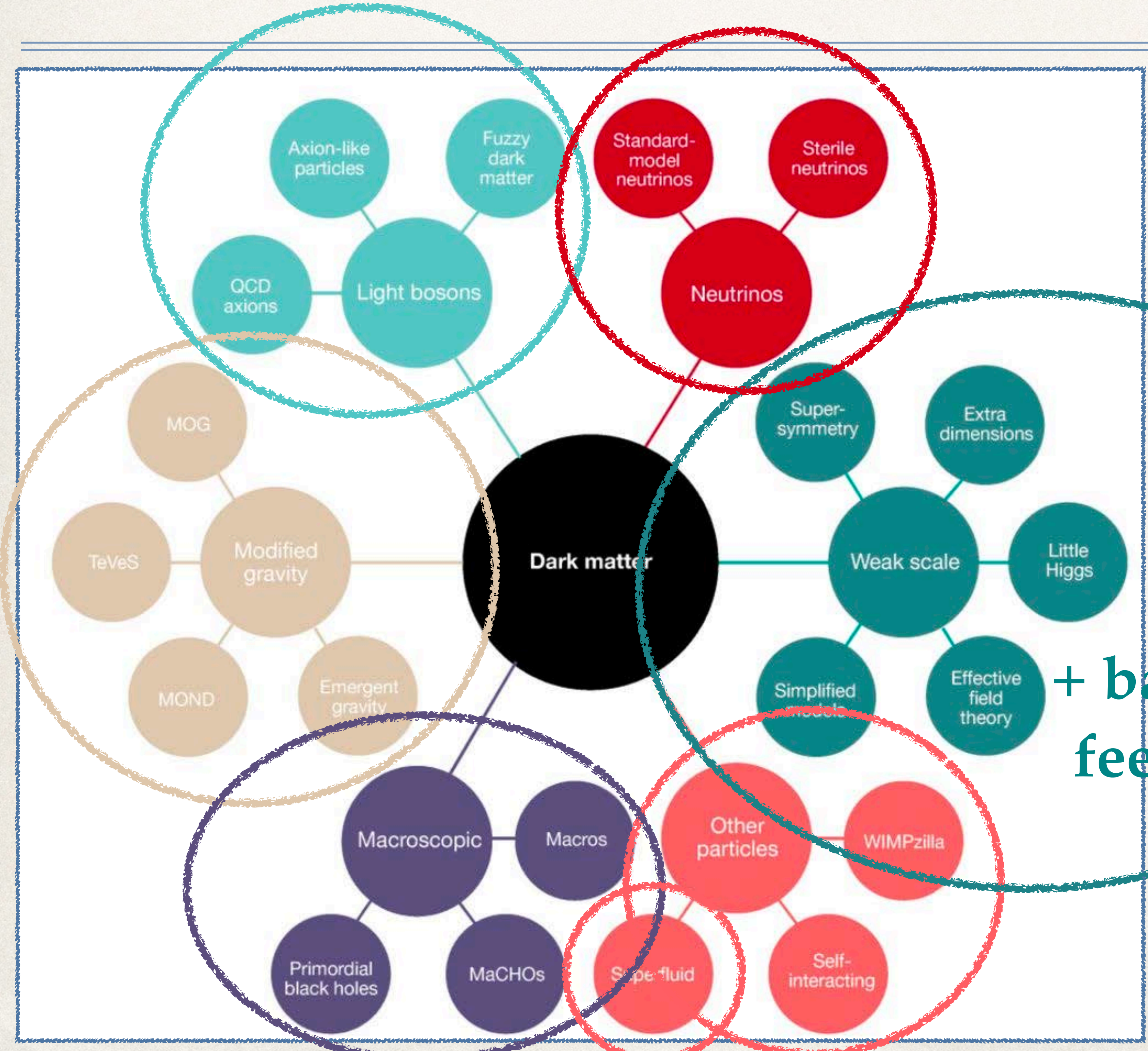
- Galaxies provide clues that DM correlates with baryons.
- Examples of solutions are:

SUMMARY OF THIS TALK



Or maybe DM mimics MOND on galactic scales?

Solutions?



Bertone and Tait, 2018

We should think broadly about the possible solutions

Fitting the MDAR with a Fundamental Force

- Produce flat rotation curves: $\Phi \propto \log r \to a \propto \frac{1}{r} \to v_c \propto \text{const}$
- 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: $a = \begin{cases} a_\mathrm{N} & a \gg a_0 \\ \sqrt{a_0 a_\mathrm{N}} & a \ll a_0 \end{cases}$

Fitting the MDAR with a Fundamental Force

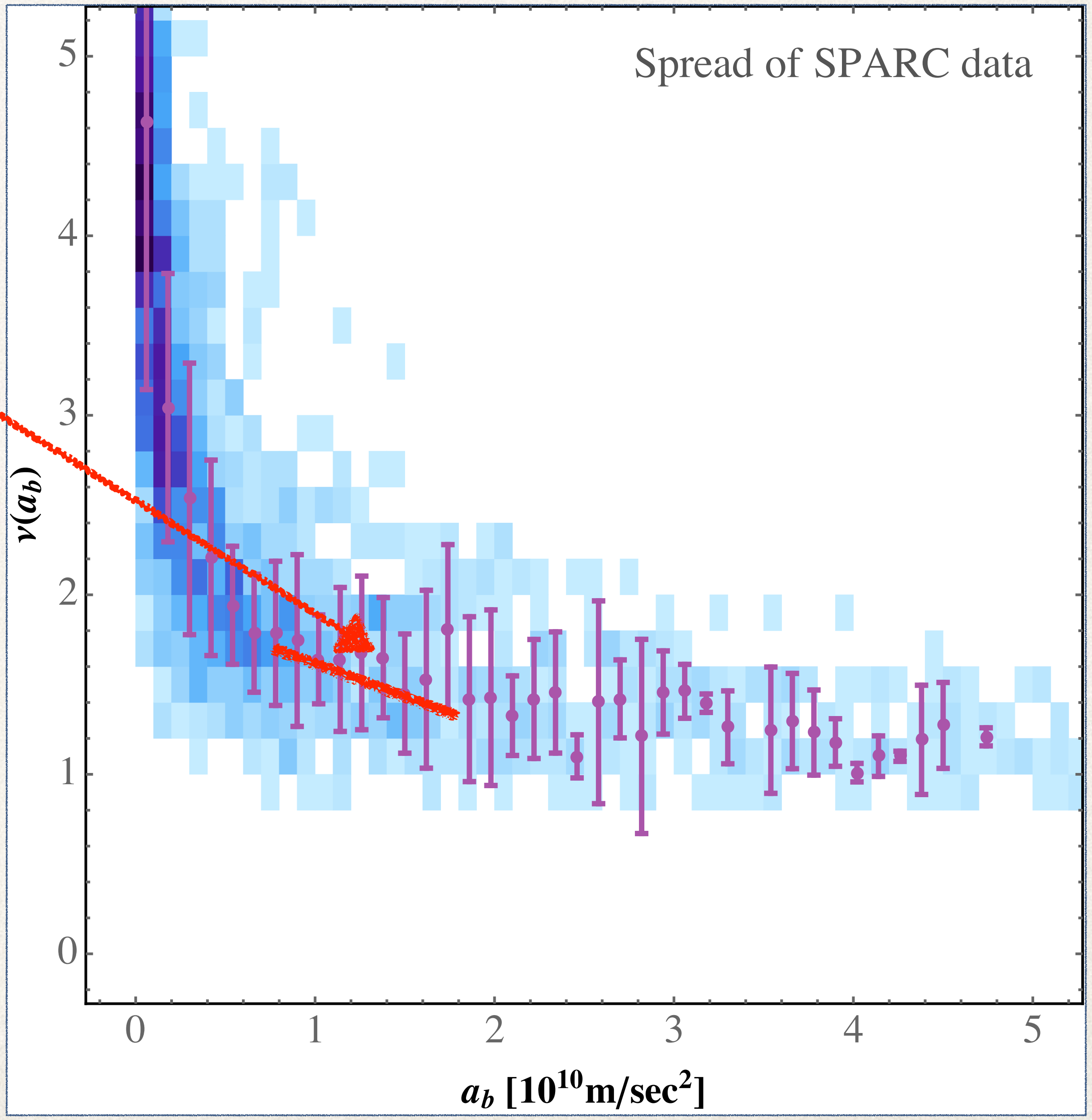
For example:
Solar acceleration happens to live here

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

McGaugh, et. al. 2016

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

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

Justin Khoury, Lasha Berezhiani

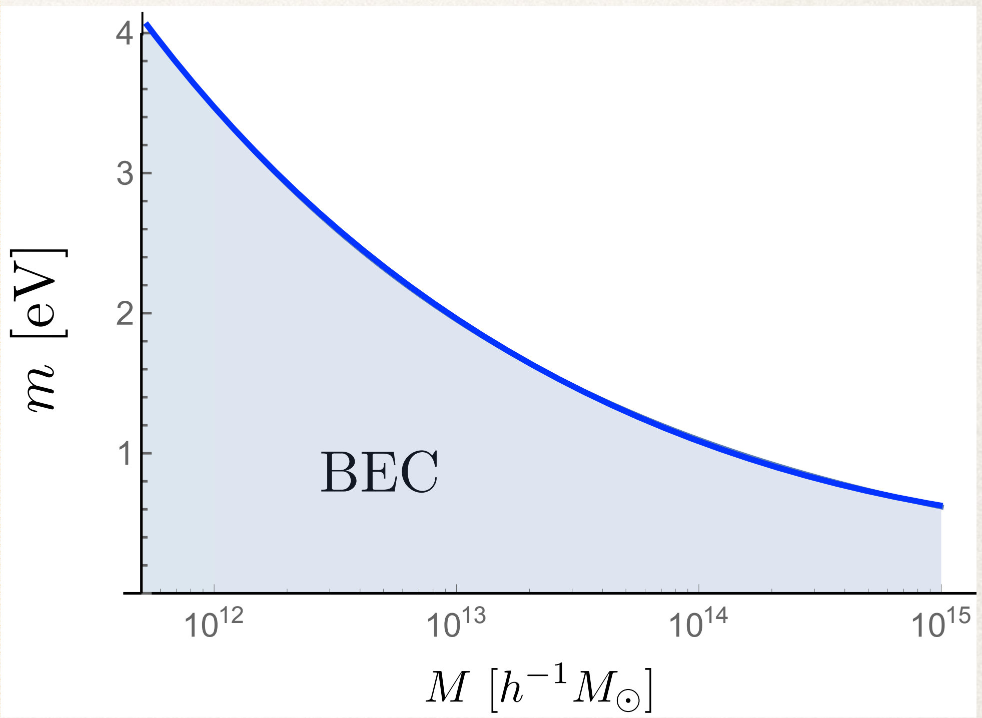
- Consider a light scalar DM particle with mass m.
- Require condensation to a state where the relevant DOF are phonons:
- An overlapping de Broglie wavelength:

$$\frac{1}{mv} \geq \left(\frac{m}{\rho_{\rm vir}}\right)^{1/3} \quad \Rightarrow m \lesssim 2\text{eV}$$

- With a critical temperature:

$$T_c \approx \frac{1}{3}mv^2 \approx \text{few} \left(\frac{\text{eV}}{m}\right)^{5/3} \text{ mK}$$

(~ known values in cold atom systems)



Berezhiani, Khoury, 2015

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

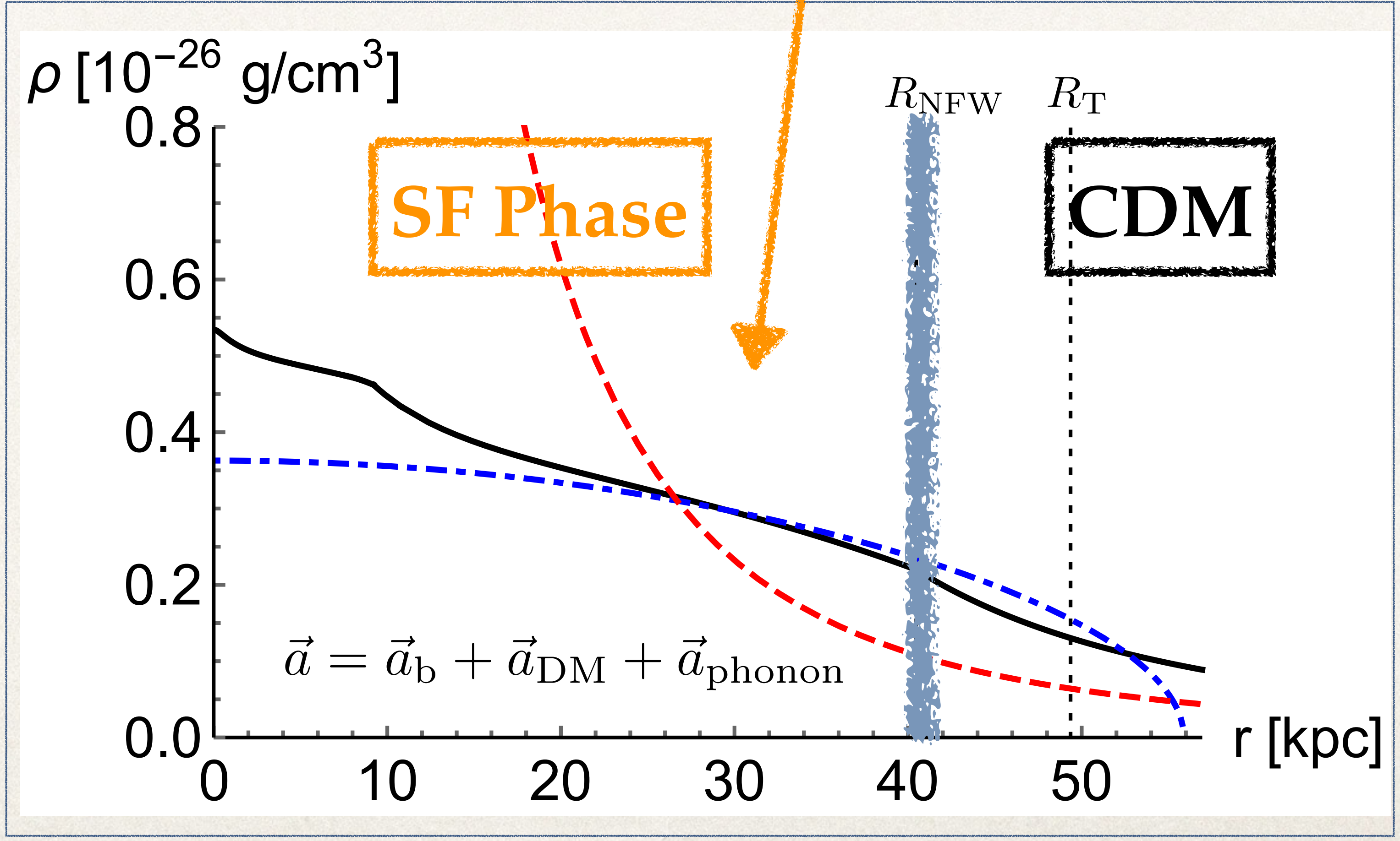
Standard DM Dynamics

Superfluid DM

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

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

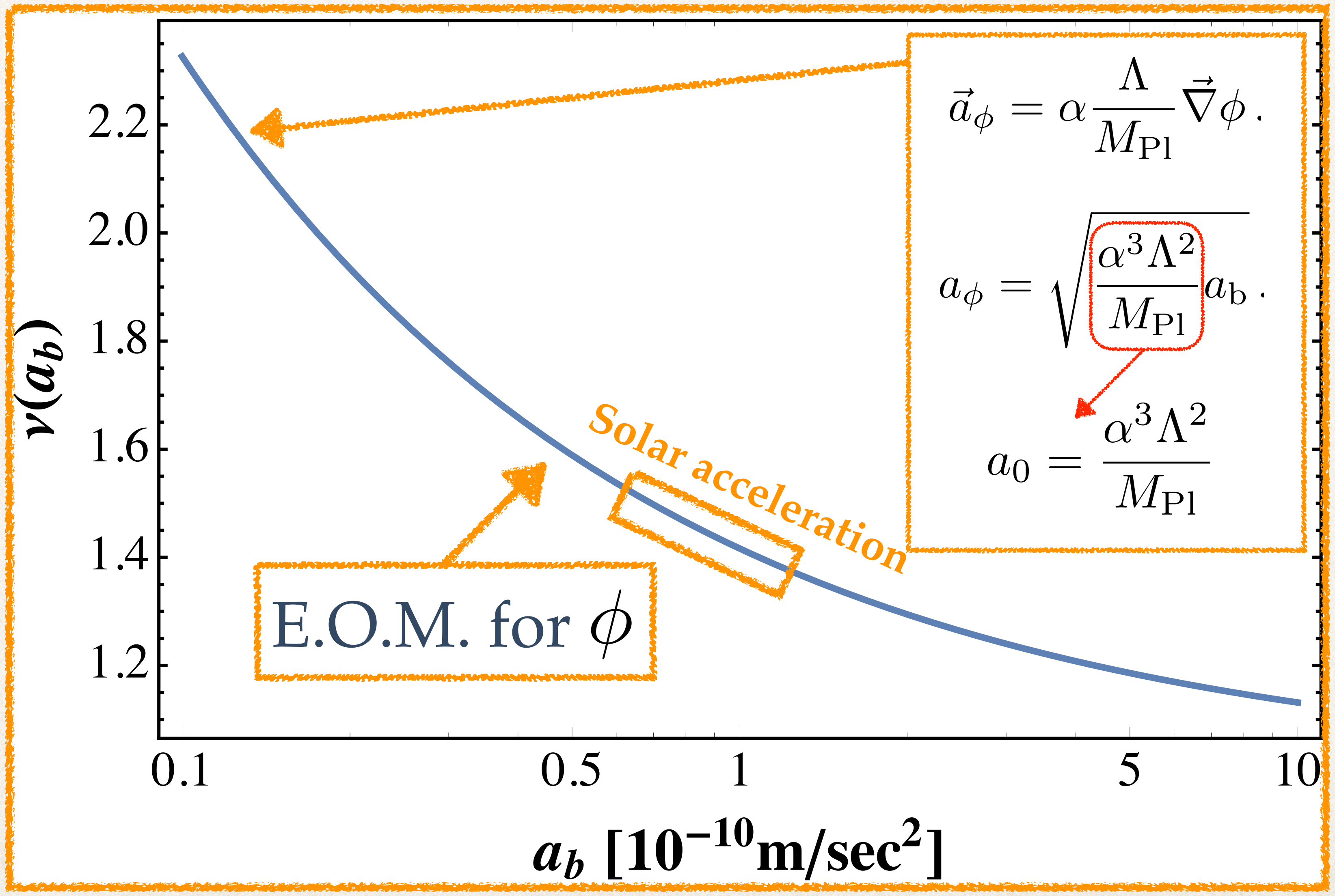
$$\rho_{\rm SF} = \frac{\partial\mathcal{L}}{\partial\Phi}$$



Berezhiani, Famaey, Khoury, 2017

Superfluid DM

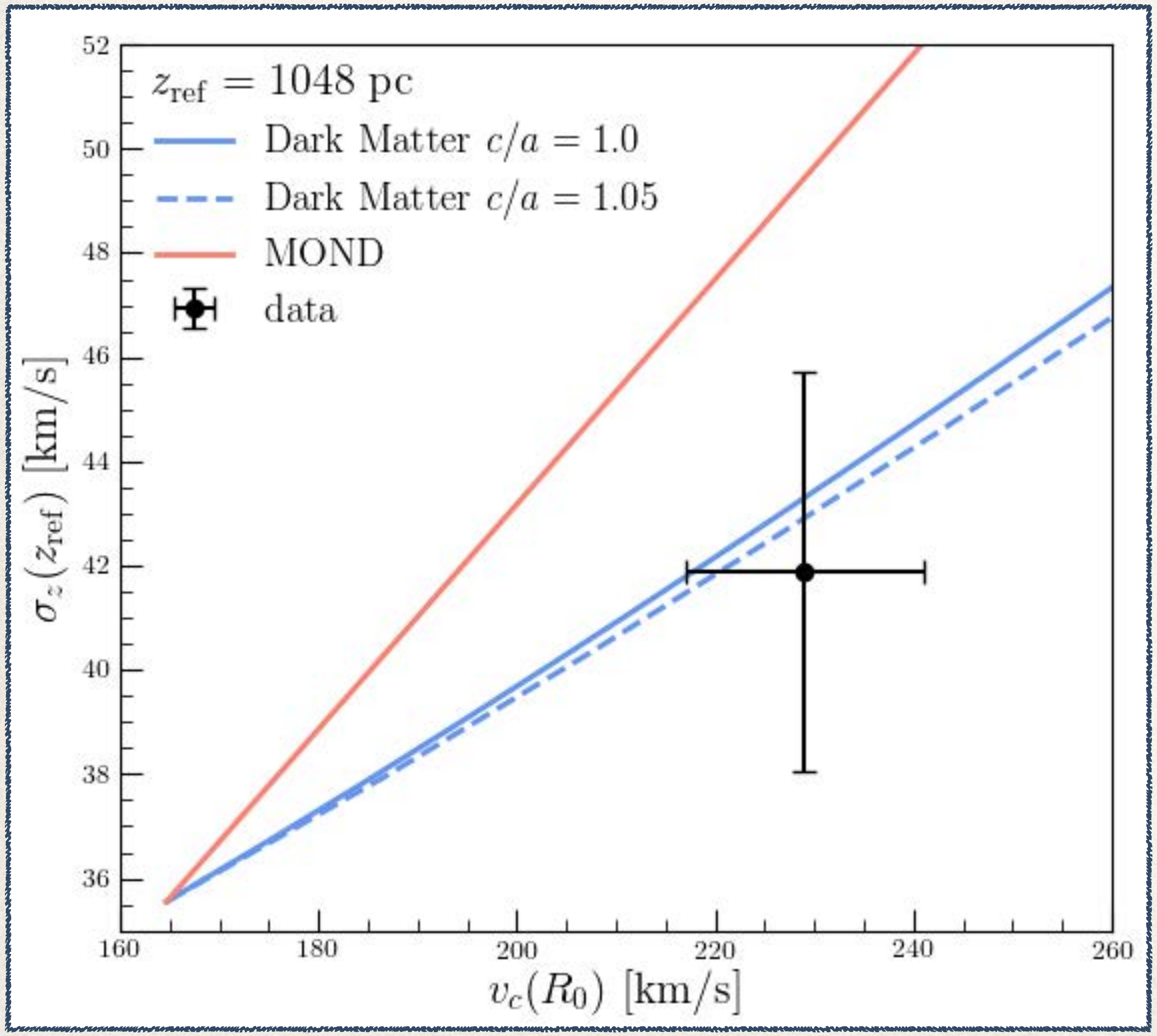
The SF Interpolation Function:



Constraining These Models

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:

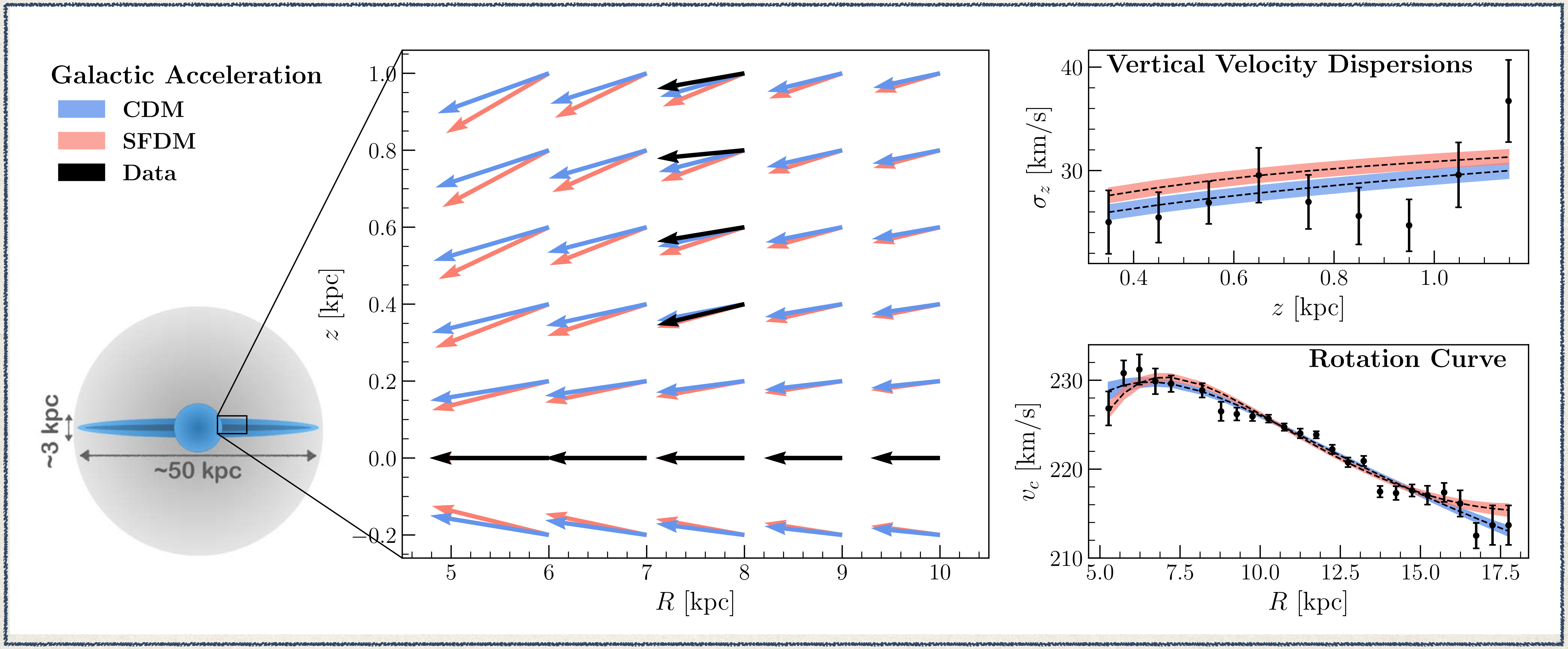
$$\boldsymbol{a}_{\rm DM} \approx -G\frac{M(R_0)}{R_0^2}\left(1, \frac{z}{R_0}\right)$$

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

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

Local MW Observations Provide Differentiating Power

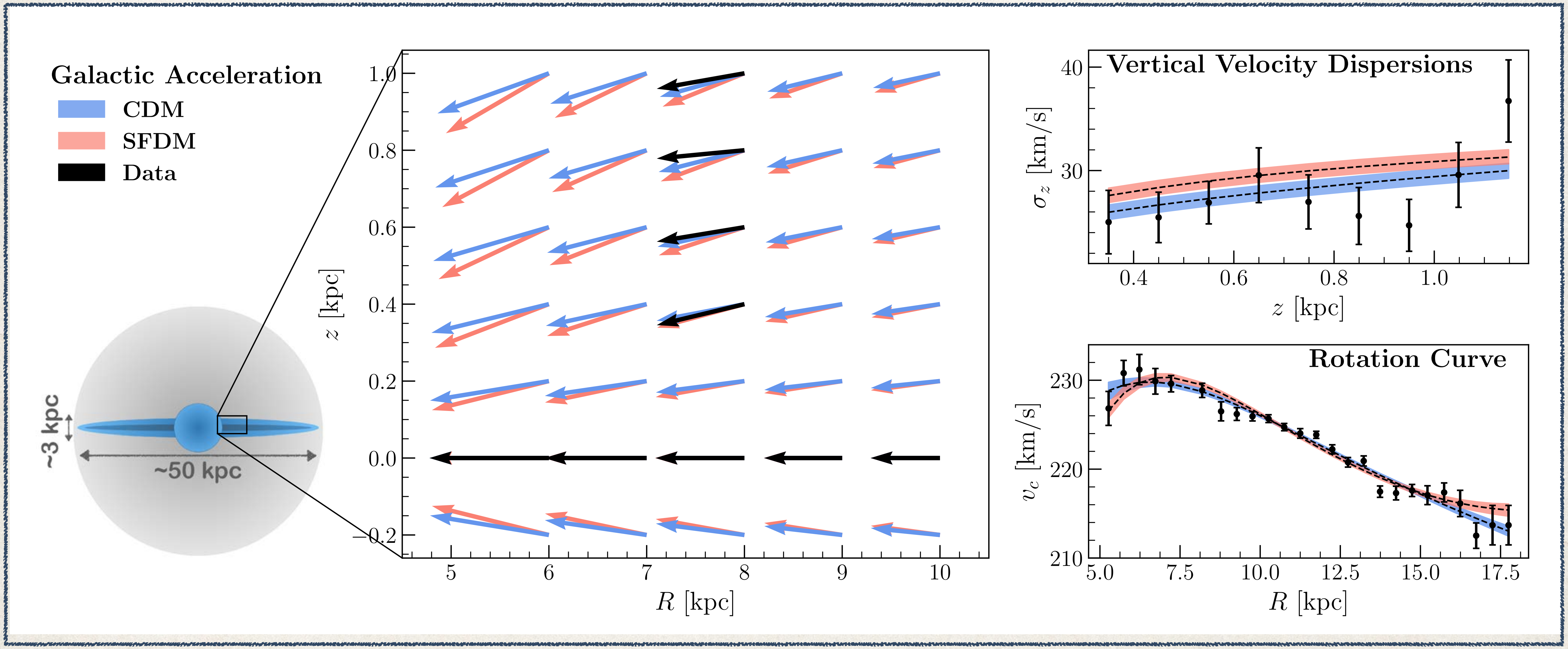
Superfluid Dark Matter is even more predictive:



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

Local MW Observations Provide Differentiating Power

A new criterion for any theory which attempts to reproduce the MDAR



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

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**

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:
Testing CDM vs SFDM / MOND-like

Analysis Procedure

Milky Way Model

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

Dark Matter
A generalized NFW profile

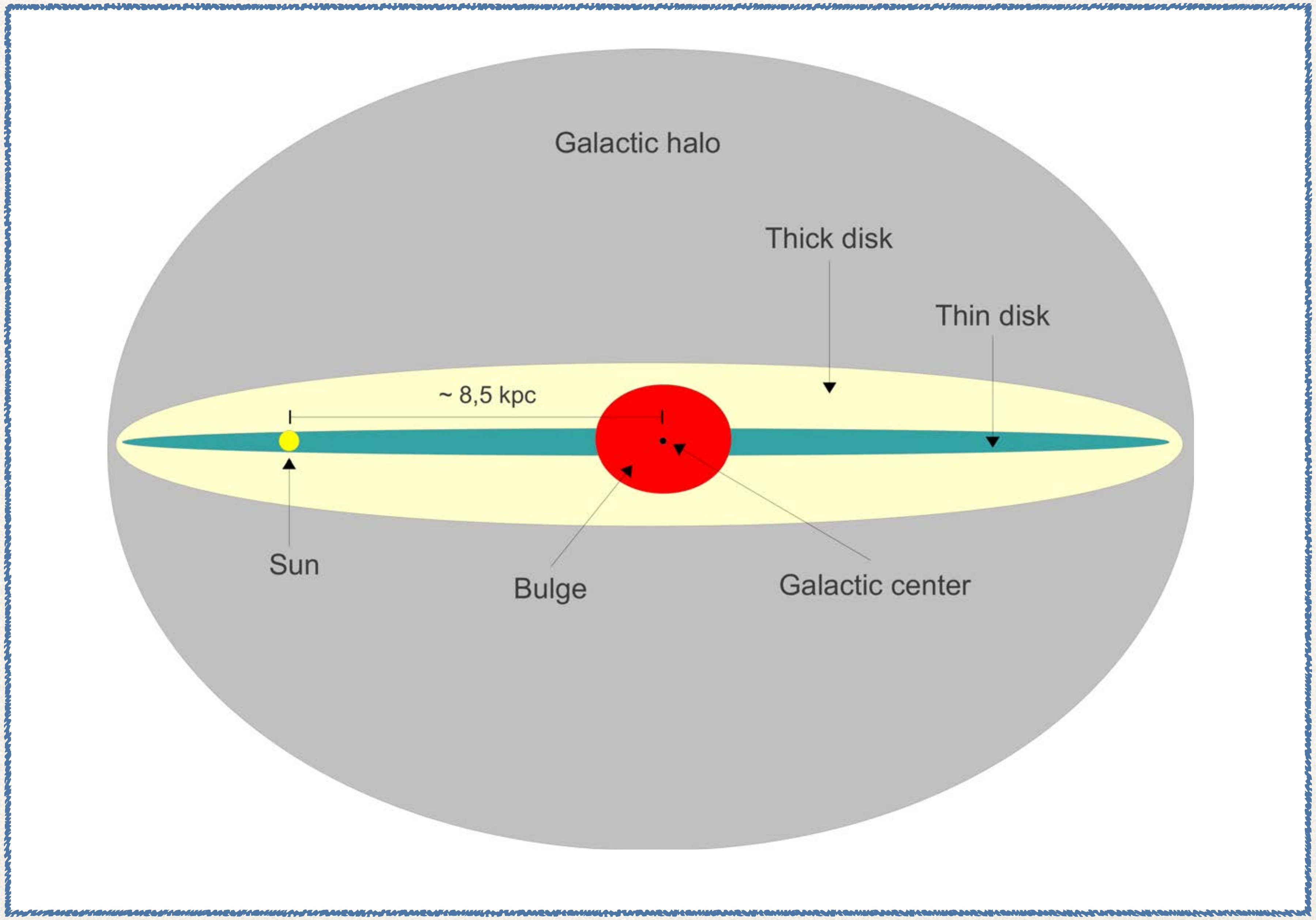
Model baryonic profile:

- 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

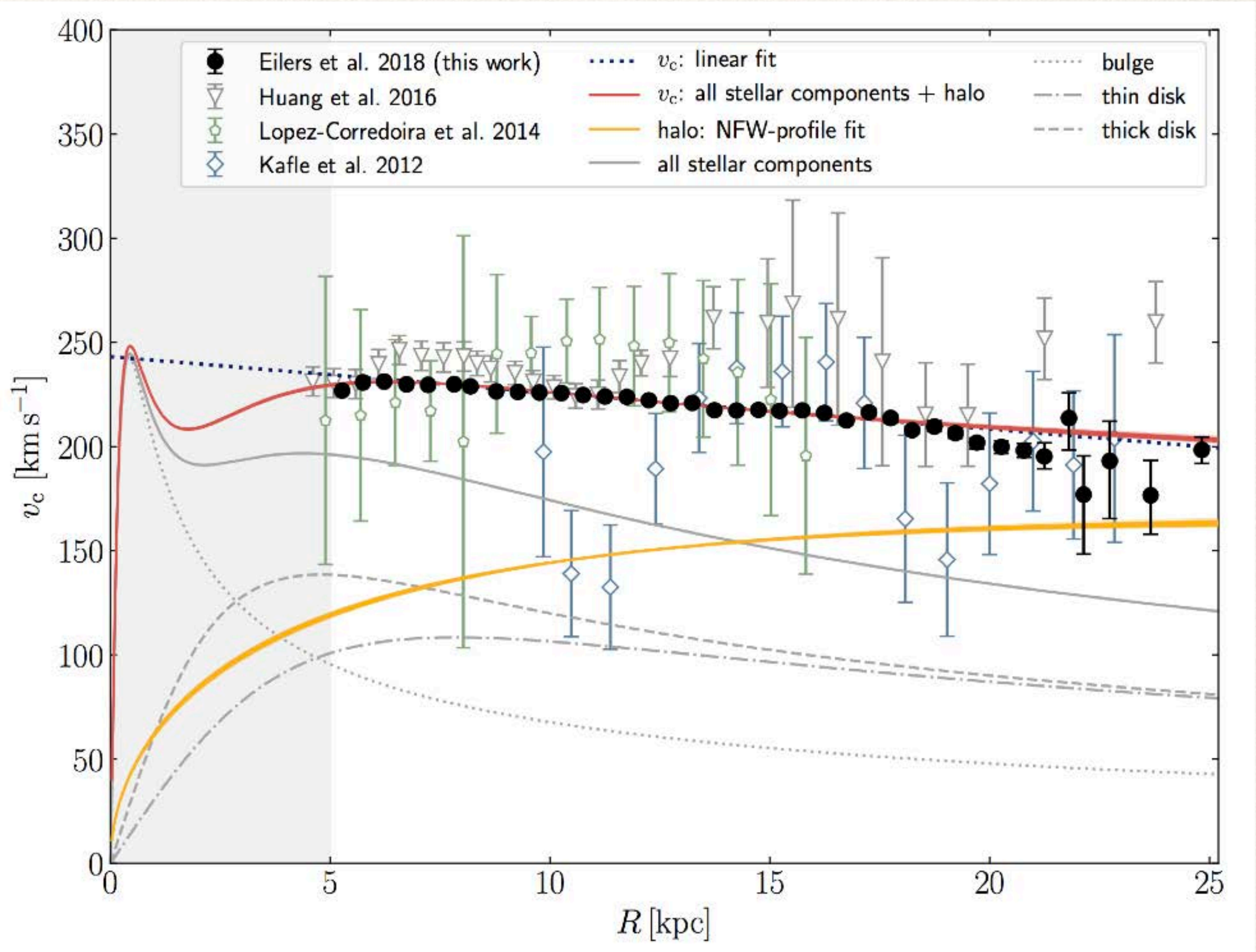
Milky Way Observables

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



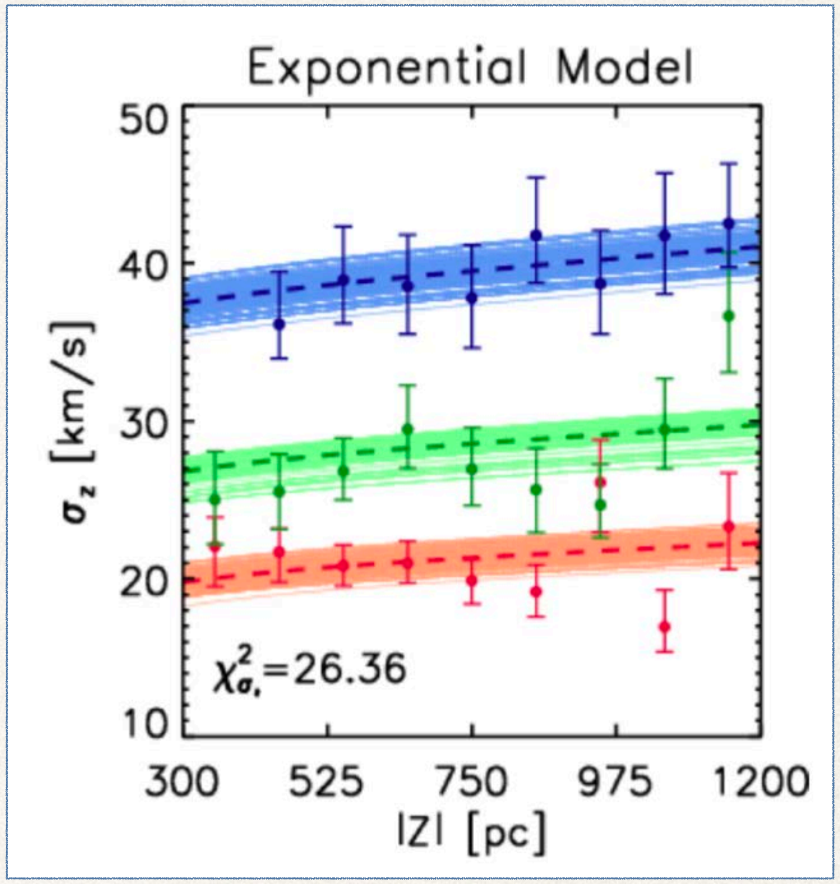
Eilers et. al., 2018

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

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



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

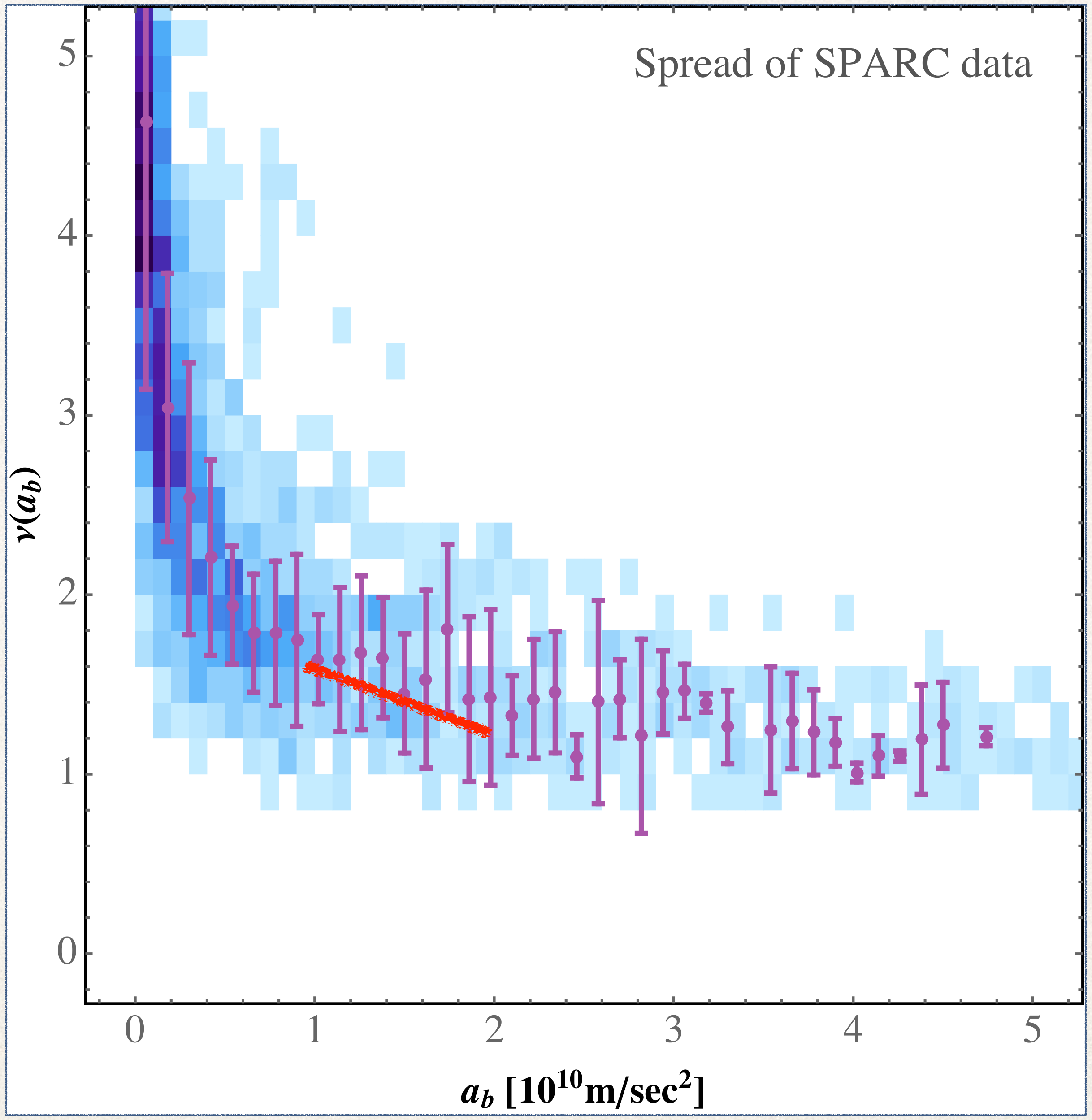
Ensure Self Consistency

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

RESULTS

Results for any MOND-like Model

FIT ONLY LOCAL ROTATION CURVE

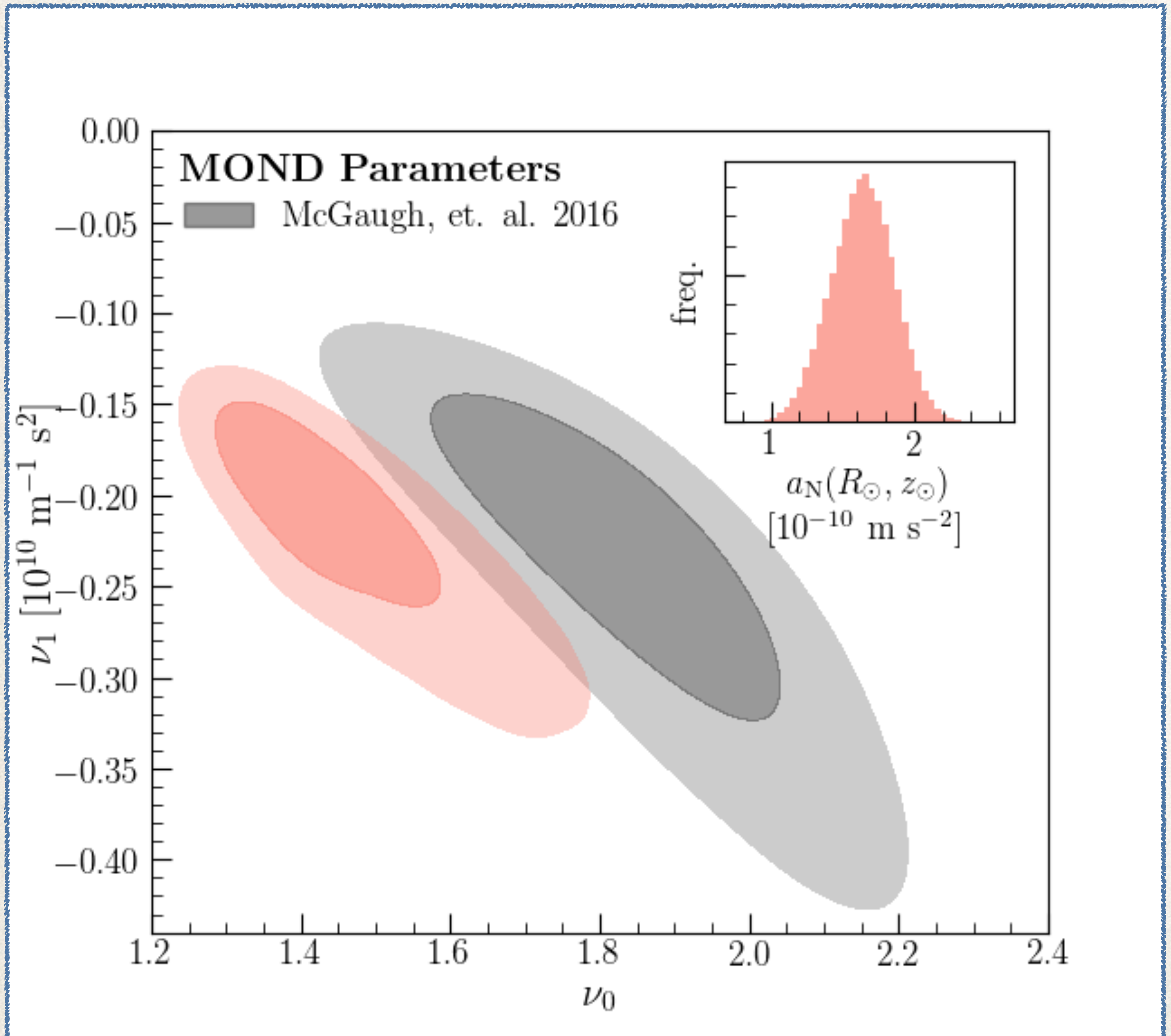


Lisanti, Moschella, Outmezguine, OS (PRELIMINARY)

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

Results of MCMC Scans

Interpolation Function Parameters



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

Interpolation function fitted to RAR:

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

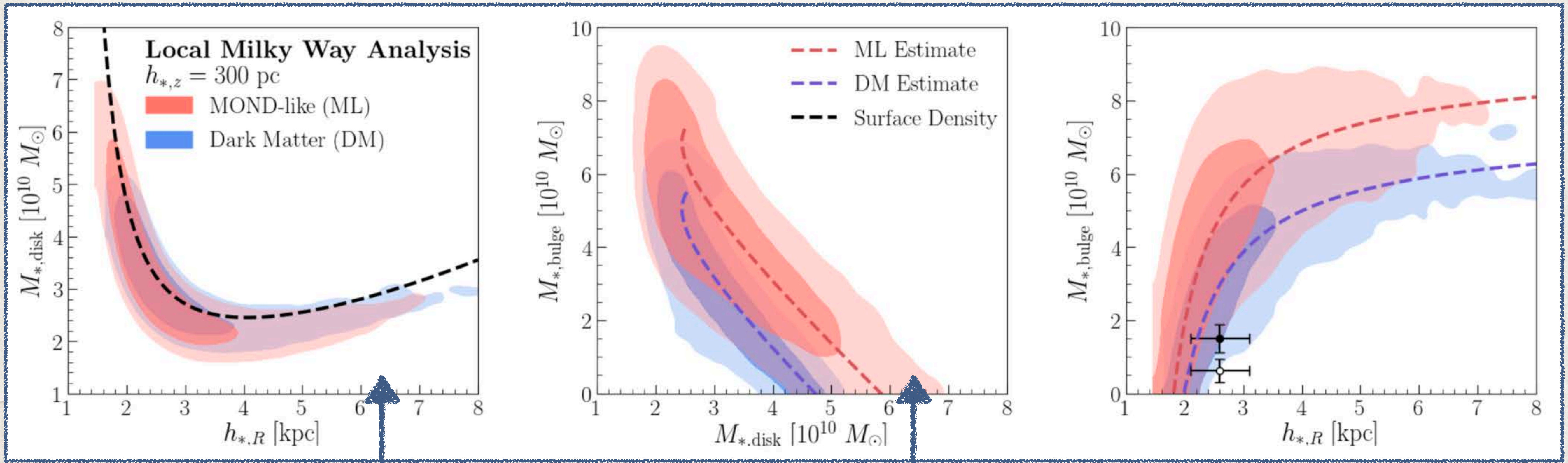
with

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

Excluded at 95% confidence

Results of MCMC Scans

Tension with MW Observations



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

Driven by stellar surface density constraint

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

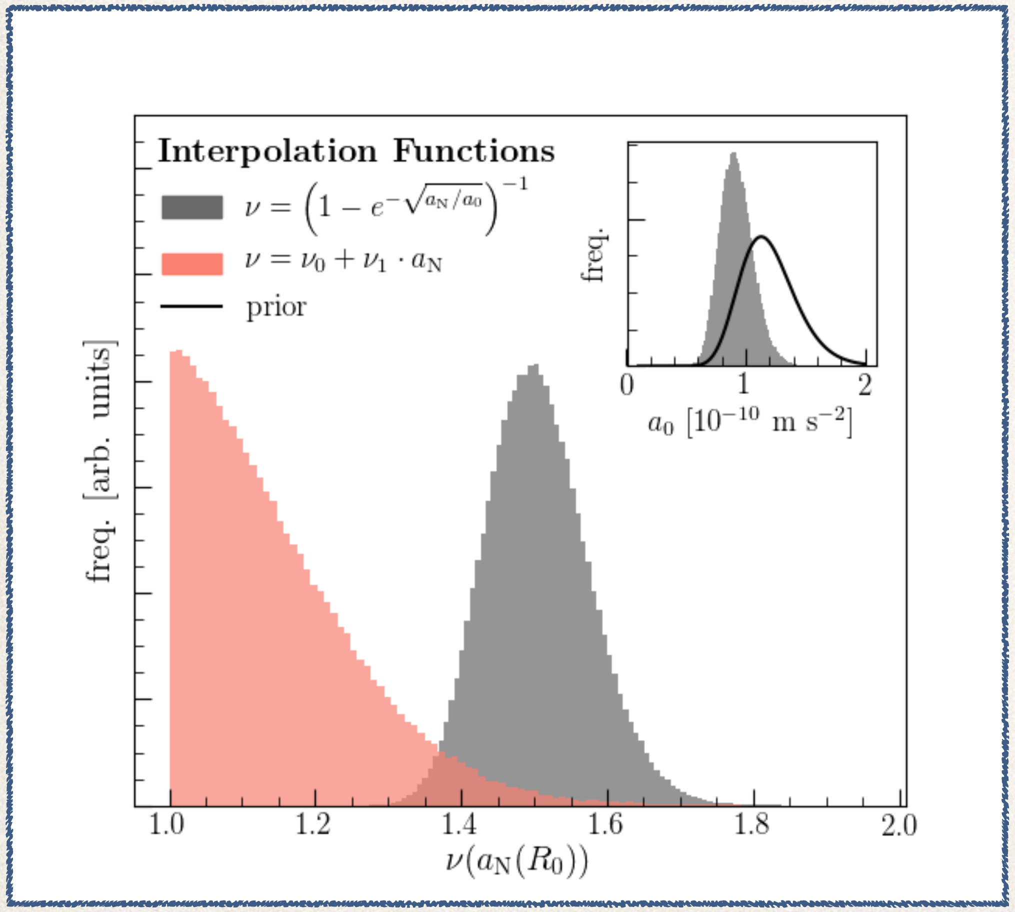
Driven by local value of rotation curve constraint

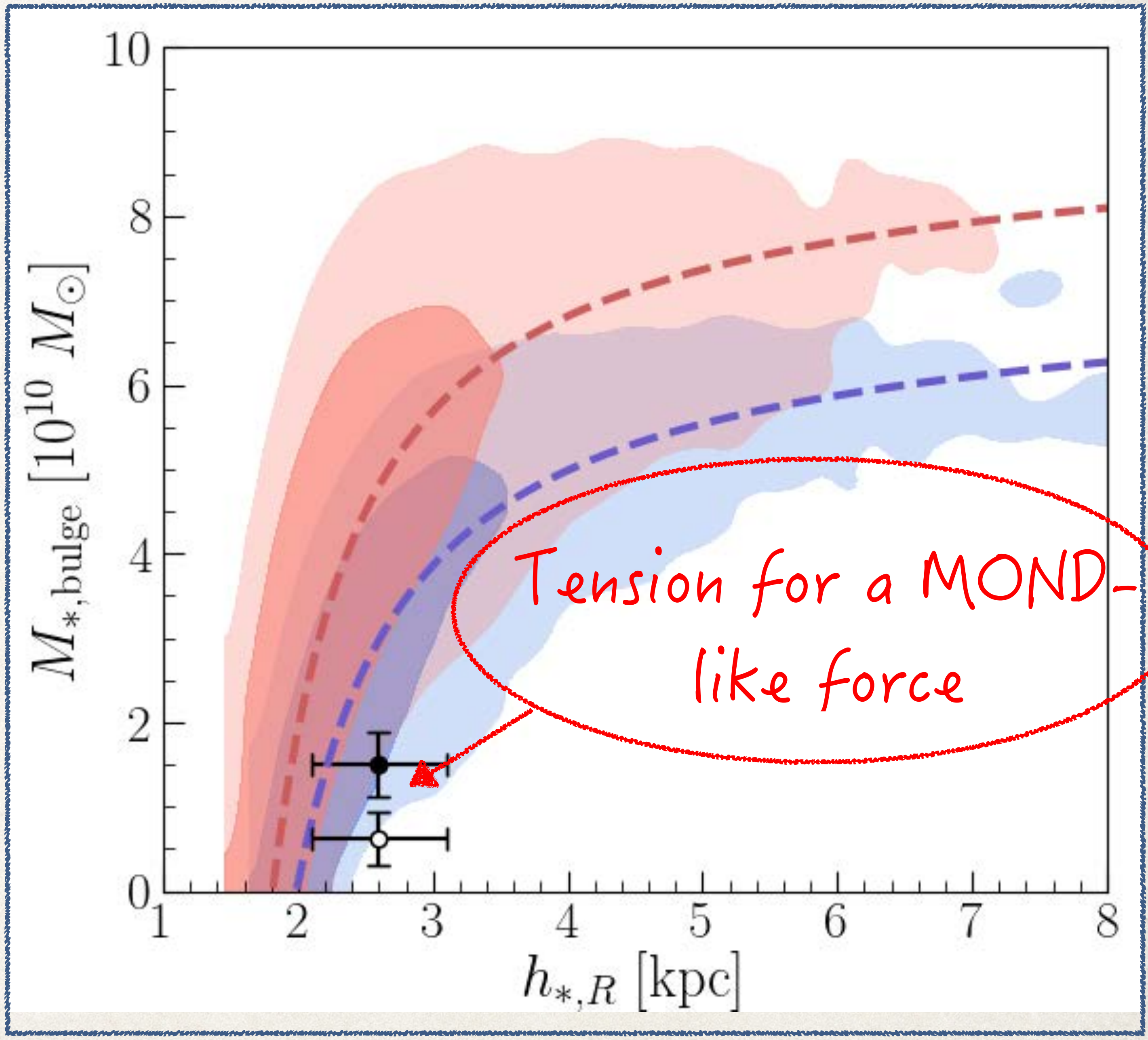
$$v_c(R) = \sqrt{R\cdot a(R)}\Big|_{z=0}$$

Results of MCMC Scans

Stellar Scale Radius *vs* Stellar Bulge Mass

Driven by local surface density and rotation curve





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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

Naming Convention	Functional Form	Prior for Scan	ΔBIC
Taylor Expansion	$\nu(a_{\rm N}) = \nu_0 + \nu_1 a_{\rm N}$	$\nu(a_{\rm N}) > 1$ or 1.3	4.1 or 7.5
RAR [7]	$\nu(a_{\rm N}) = \left(1 - e^{-\sqrt{a_{\rm N}/a_0}}\right)^{-1}$	$a_0 = \text{LOGNORMAL}\left(1.20, 0.24^2\right)$	10.4
Simple [27, 52]	$\nu(a_{\rm N}) = \frac{1}{2}\left(1 + \sqrt{1 + \frac{4}{a_{\rm N}/a_0}}\right)$	$a_0 = \text{LOGNORMAL}\left(1.2, 0.4^2\right)$	9.6
Standard [27, 52]	$\nu(a_{\rm N}) = \sqrt{\frac{1}{2}\left(1 + \sqrt{1 + \left(\frac{2}{a_{\rm N}/a_0}\right)^2}\right)}$	$a_0 = \text{LOGNORMAL}\left(1.2, 0.4^2\right)$	4.8

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

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

k: number of model parameters

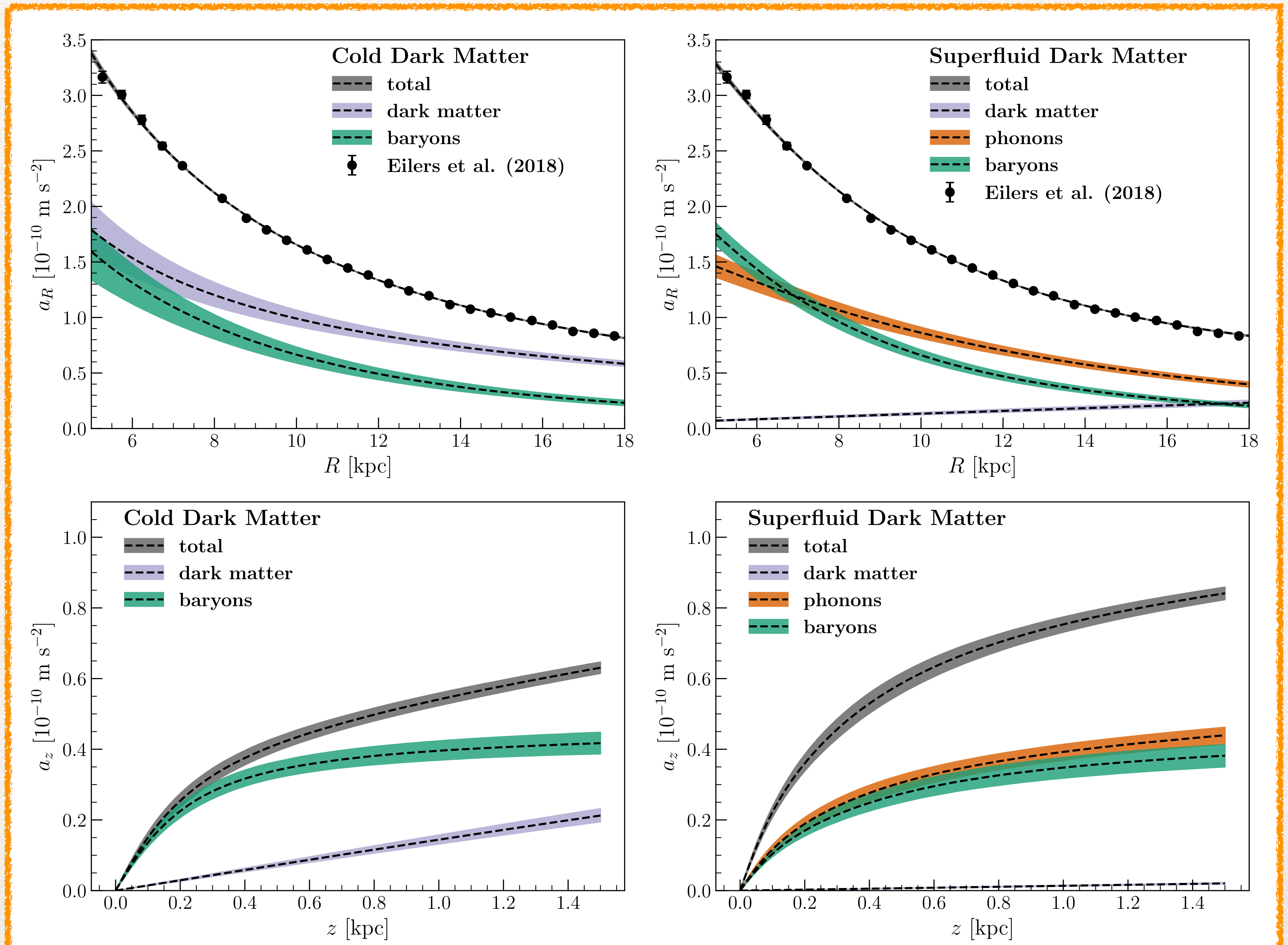
n: number of data points

$\hat{\mathcal{L}}$: maximum likelihood

Results for Superfluid DM

Results for SuperFluid DM

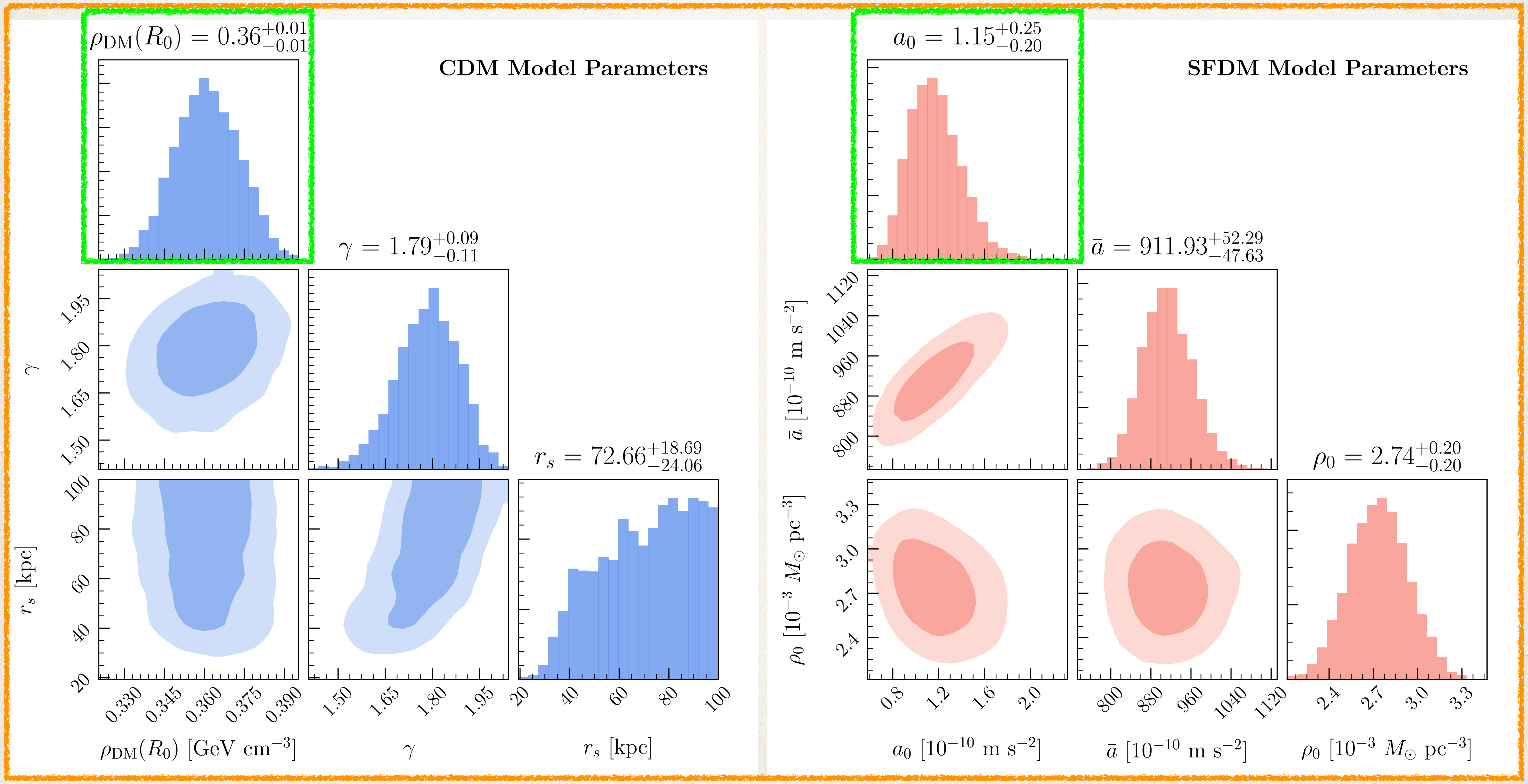
Full Rotation Curve and Vertical Accelerations



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

Results for SuperFluid DM

Model Parameters



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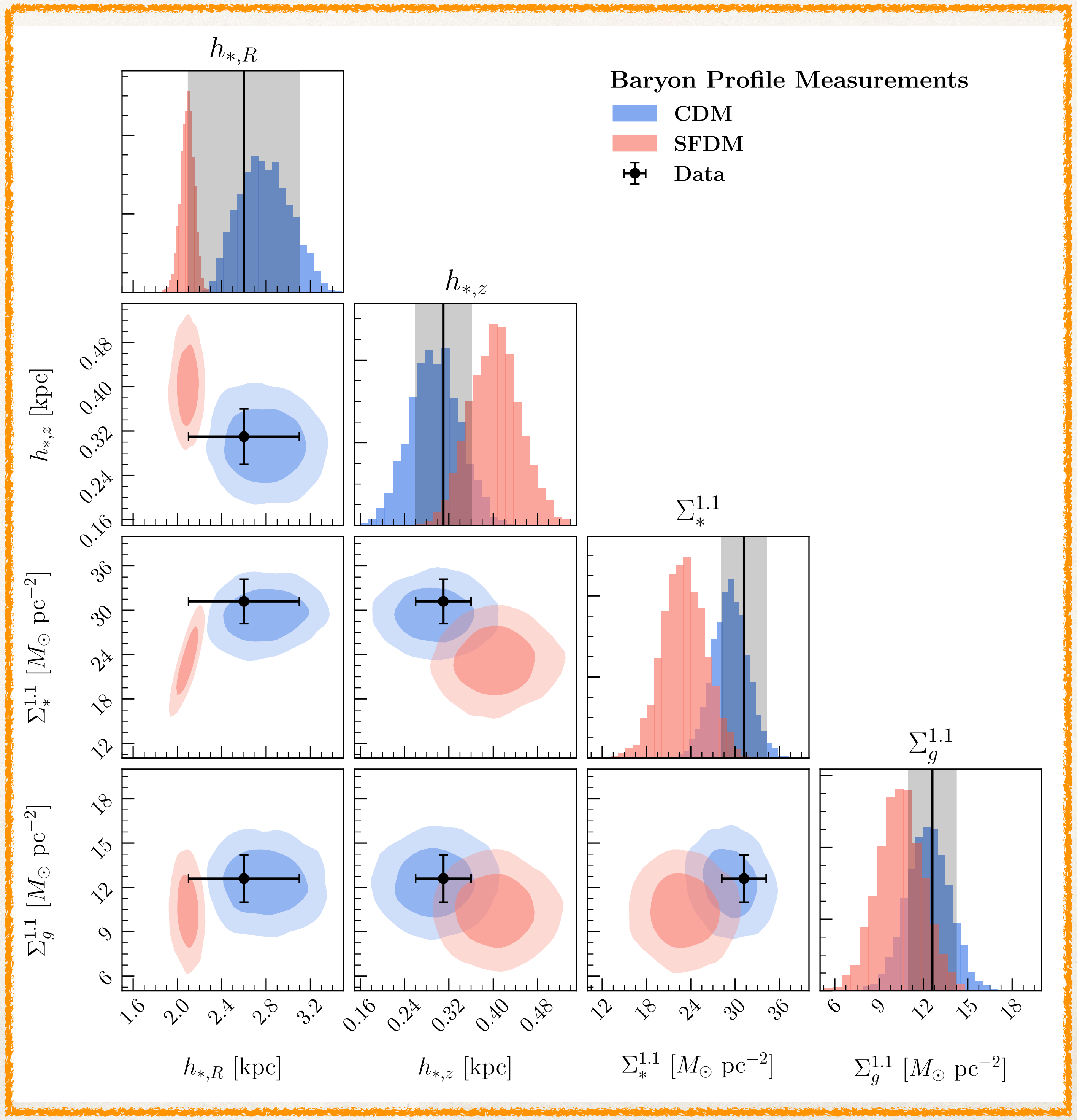
Results for SuperFluid DM

Baryonic Parameters

Bayes Factor:
lnBF=32



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

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

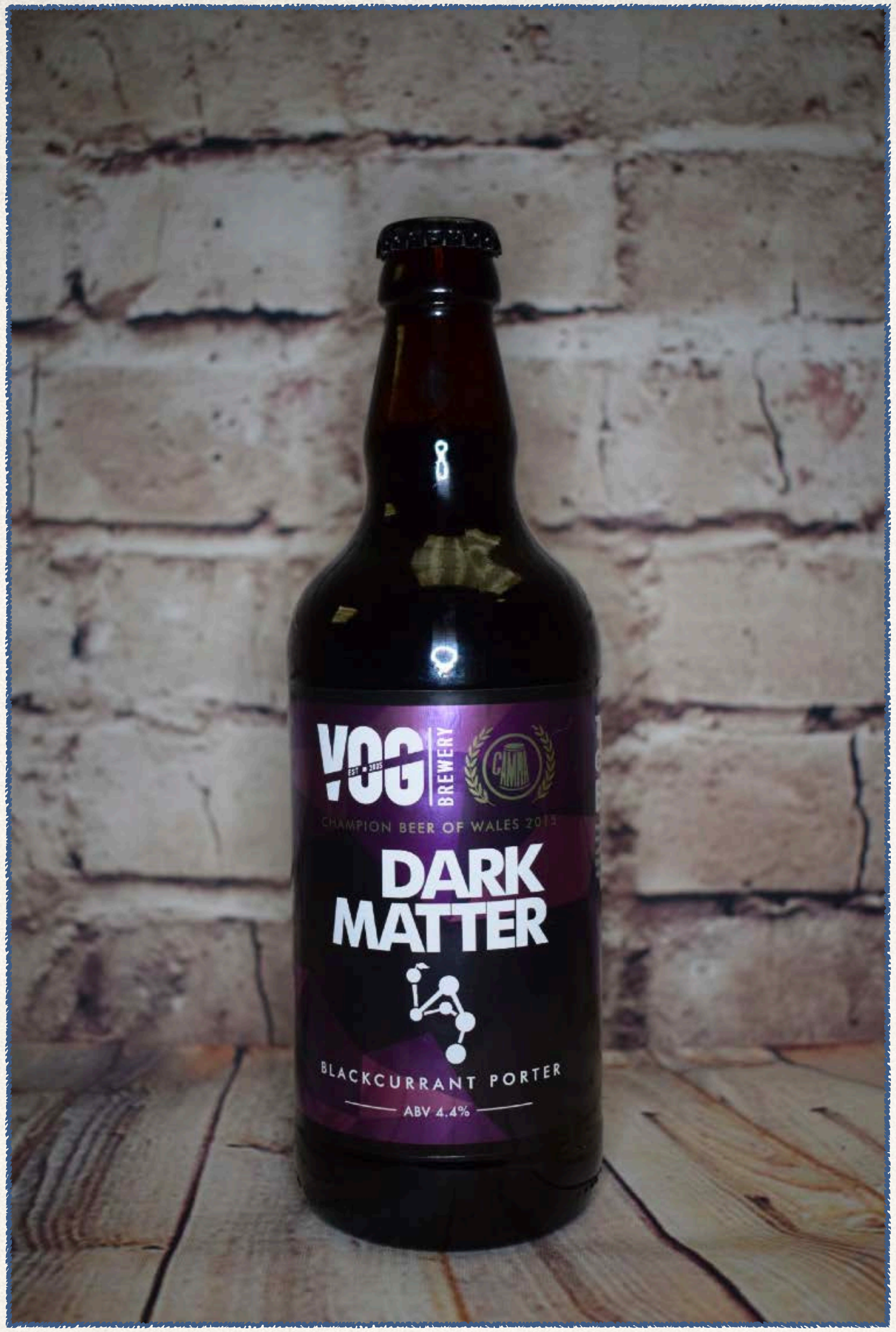
$\Longrightarrow$ Qualitatively same results for all cross checks

Summary of the Results

❖ Local accelerations only ❖ Taylor interpolation func	Δ**BIC** ≈ 4	**POSITIVE EVIDENCE (with** $\nu \approx 1$**)**
❖ Local accelerations only ❖ Specific interpolation func	Δ**BIC** ≈ 10	**STRONG EVIDENCE**
❖ All rotation curve and velocity dispersion data ❖ Superfluid DM	**lnBF** ≈ 30	**DECISIVE EVIDENCE**

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.



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

THANK YOU

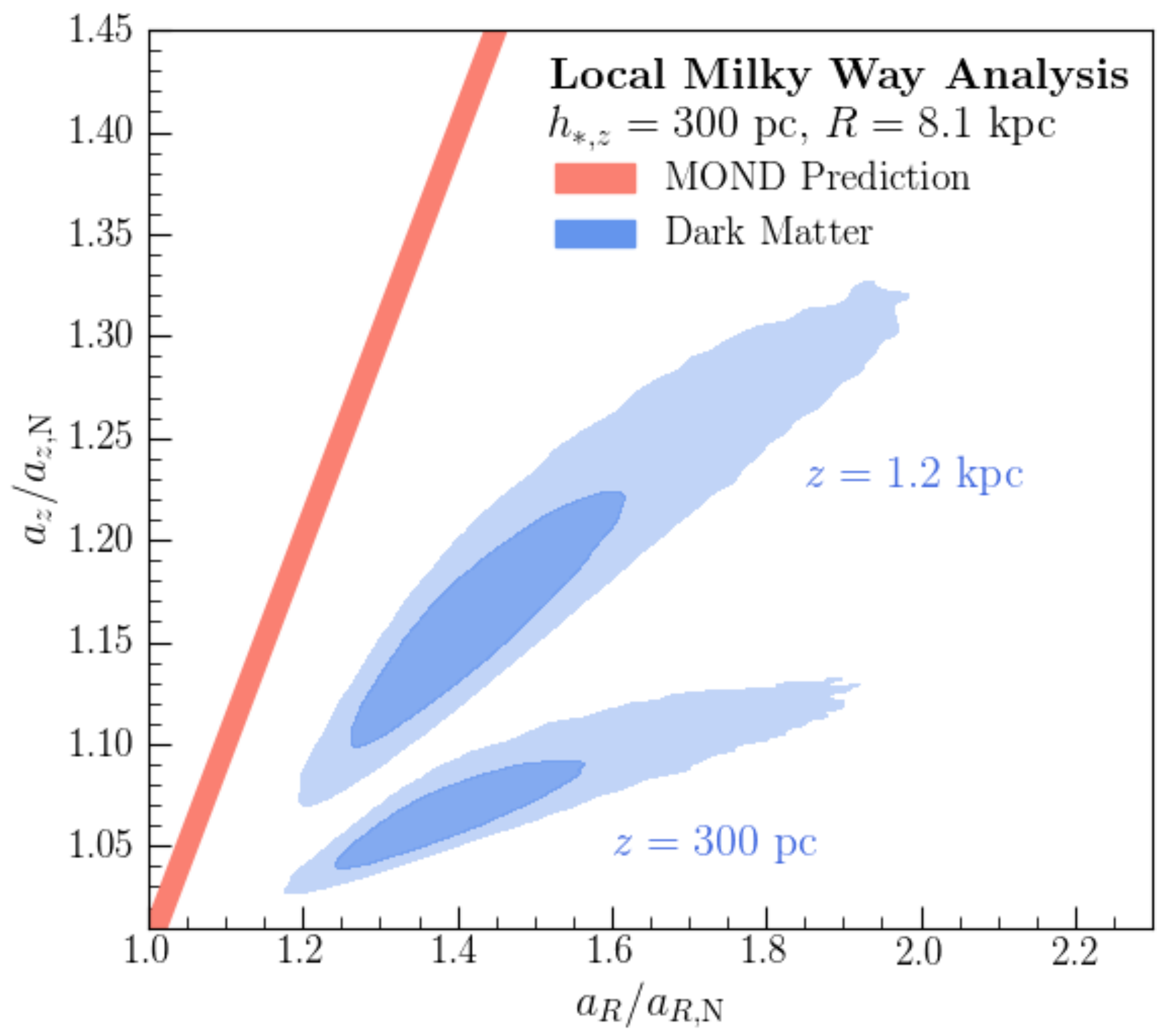
Results of MCMC Scans

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



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

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

Some Comments

- Could be done for any model where dynamics are predicted locally by baryons
- The starting point could have been something of the form:

Example of a MONDian Poisson Equation

$$\nabla \left(\mu \left(\frac{|\nabla \Phi|}{a_0} \right) \nabla \Phi \right) = 4\pi G \rho \quad \rightarrow \quad \Phi \propto \log r$$

Inverse of interp. func.

- This equation is non-linear and difficult to calculate
- Is VERY model dependent
- Starting from an acceleration relation can map onto other theories

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:

$$\Phi \propto \log r$$

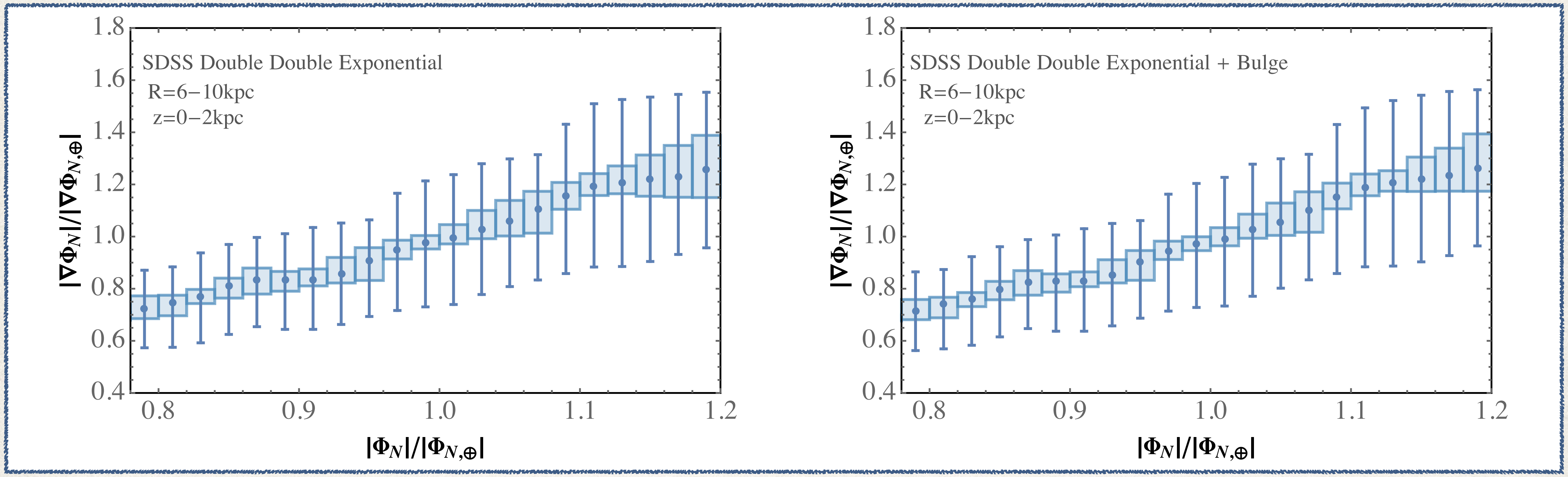
$$\nabla\left(\mu\left(\frac{|\nabla\Phi|}{a_0}\right)\nabla\Phi\right) = 4\pi G\rho$$

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
A Divergenceless Field

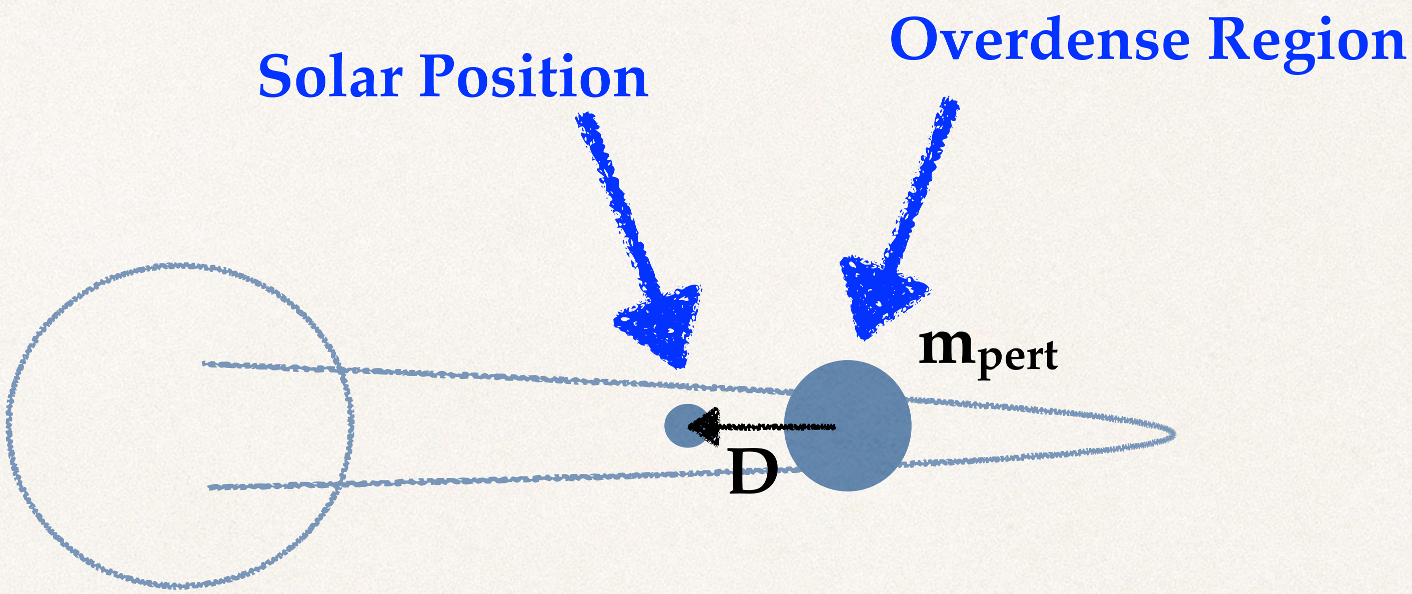


Can be shown that S=0 for 1D symmetrical potentials, or:

$$\nabla|\nabla\Phi_N| \times \nabla\Phi_N = 0$$

$$|\nabla\Phi_N| = f(\Phi_N)$$

MOND / Superfluid DM
Small Perturbations



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

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

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

MOND
So for a local MW study:

Using $$\boldsymbol{a} = \nu\left(\frac{a_{\rm N}}{a_0}\right)\boldsymbol{a}_{\rm N}$$

with $$\nu(x_{\rm N}) \rightarrow \nu_0 + \nu_1 \cdot x_{\rm N}$$

- A good local approximation.
- Holds for many MOND-like theories.
- Independent of specific interpolation function.