

# Testing Self-Interacting Dark Matter with Spiral & Early-Type Galaxies

Tao Ren

University of California, Riverside

Wednesday, May 22, 2019  
10:15am in Conference Room



## Committee:

Dr. Hai-Bo Yu, Chair  
Dr. Yanou Cui  
Dr. Flip Tanedo



Paper 1: Ren, Kwa, Kaplinghat, Yu, arXiv:1808.05695 (PRX, under review)  
Paper 2: Ren, Kaplinghat, Yu, (2019, in preparation)  
Paper 3: Ren, Kaplinghat, Yu, (in progress)

# Content

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- Research Background
- { Diversity of Galactic Rotation Curves  
Uniformity }
- Comparison with Cold Dark Matter Simulations
- Applications in Early-Type Galaxies
- Summary & Outlook

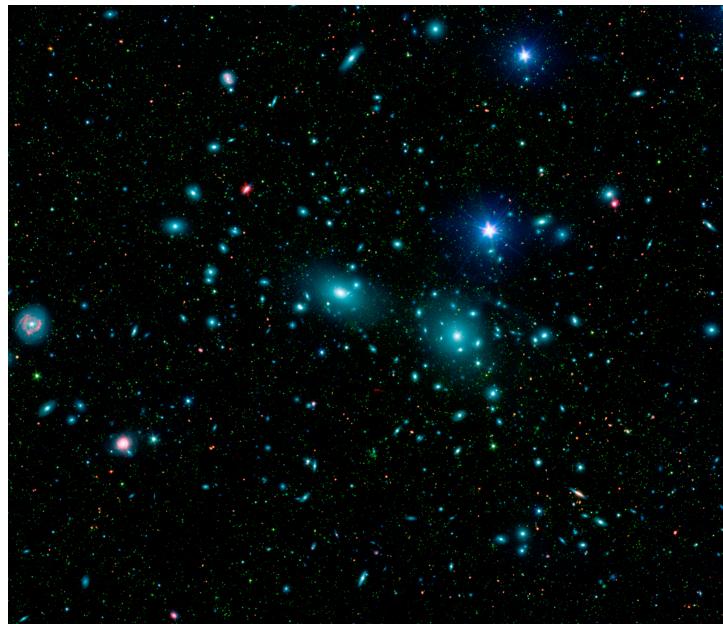
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# Why Dark Matter?

## Coma Cluster



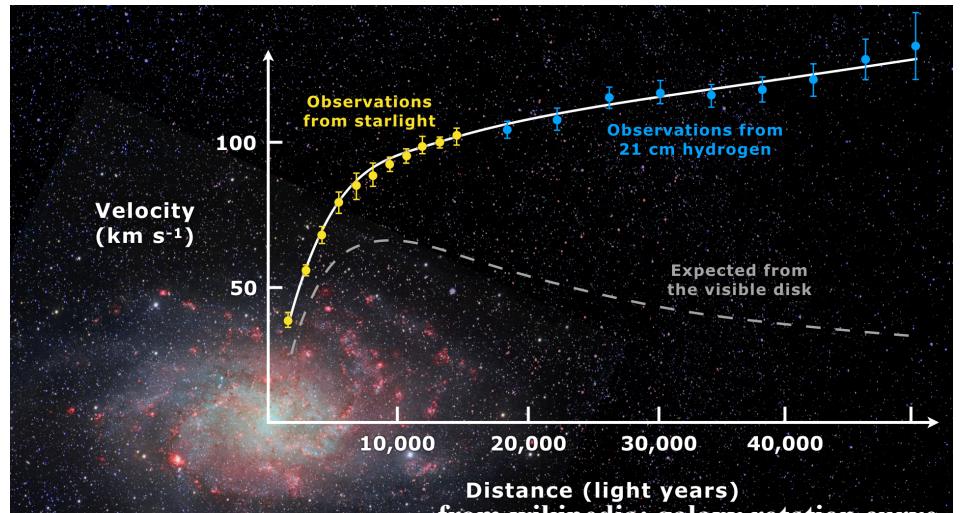
Credit: NASA/JPL-Caltech/SDSS

↔ long-wavelength infrared (red), short-wavelength infrared (green), and visible light.

- In 1933, Fritz Zwicky found the galaxies were moving too fast (line-of-sight velocity) to be bound by observed mass.  $\leftarrow L \times (M/L)$
- Virial theorem implied huge dynamical mass. Zwicky commented “*dunkle Materie*”.  $\uparrow$

$$\frac{GM_{dym}}{R} \approx \sigma^2$$

## Galaxy



Rotation curve of Messier 33

- Observations of rotation curves illustrated striking non-declining feature. (*Astronomer: e.g. Oort, Bosma, Rubin.*)

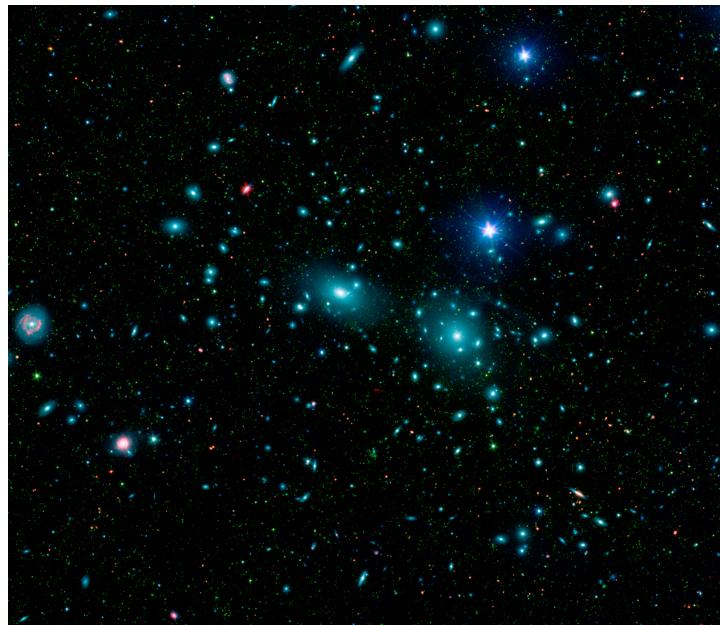
- Keplerian decline VS Flat rotation curve

$$\frac{GM_{obs}}{R^2} \Leftrightarrow \frac{V_{flat}^2}{R} \quad (F = ma)$$

- Ostriker, Peebles, and others (1970s) showed the instability of stellar-only disk and embedding the disk in a dark halo would help.

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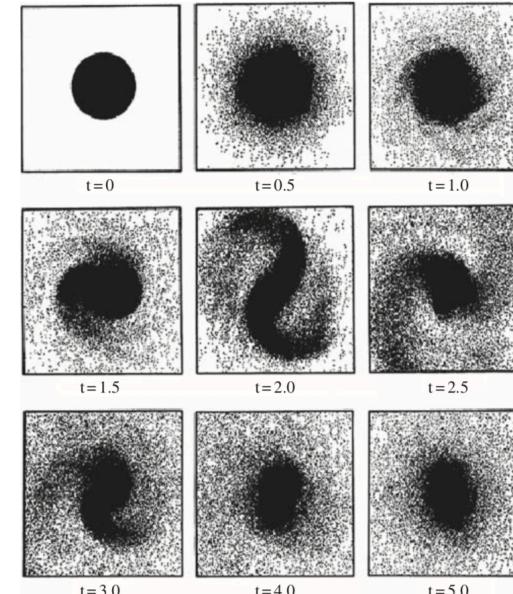
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## Galaxy



A cold disk of stars.

(Frank Hohl, 1971)

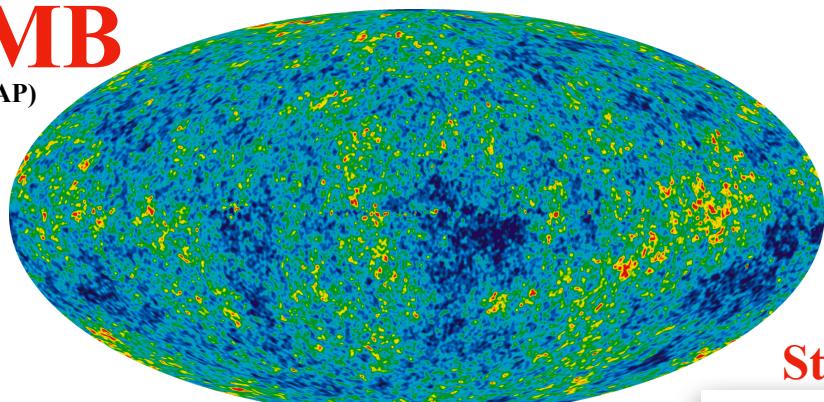
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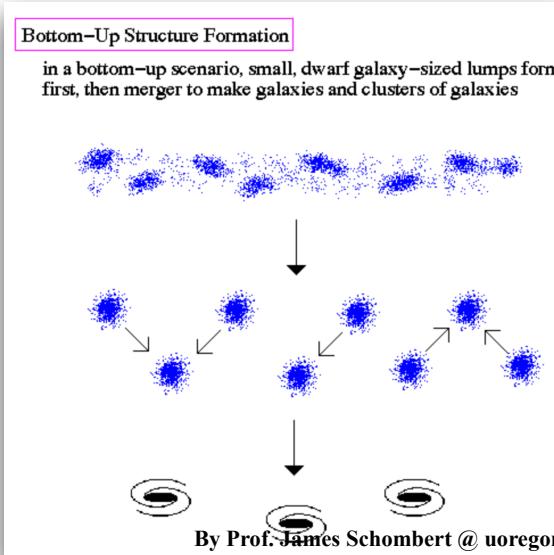
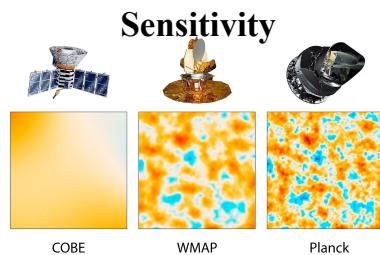
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# Why Dark Matter?

CMB  
(WMAP)



Structure Formation



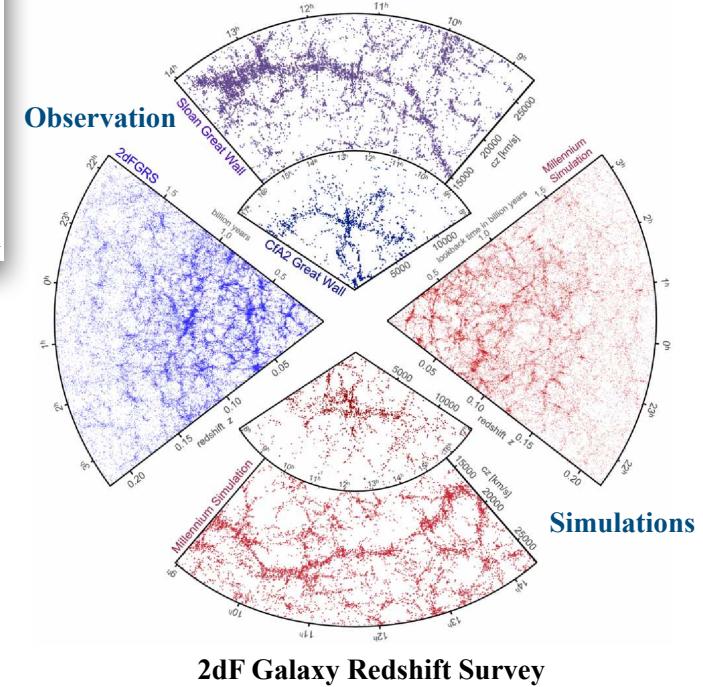
- Dark matter come to rescue. Freeze out and start structure formation earlier.
- Cold Dark Matter VS Hot Dark Matter (e.g. neutrinos)
- Cold Dark Matter paradigm successfully explained large-scale structure of the Universe.

- CMB indicates structure formation in a *baryonic universe* began after  $z=1000$ .
- Density fluctuations were *too small* to develop the observed large-scale structure.

Required :  $\delta\rho/\rho \approx 10^{-4}$

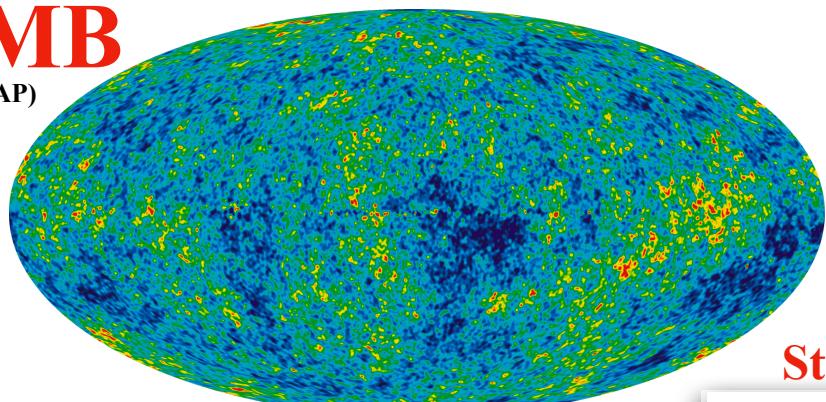
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Large-Scale Structure

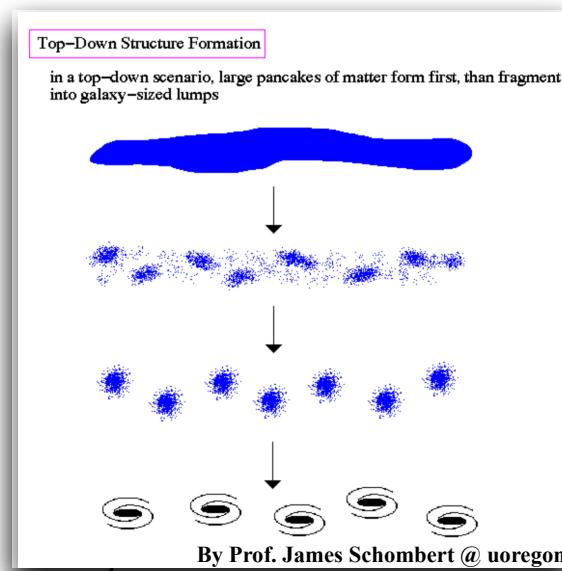
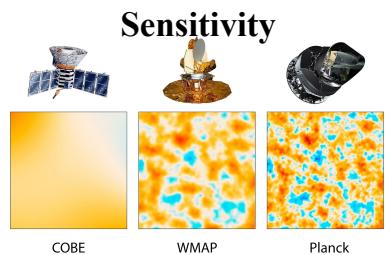


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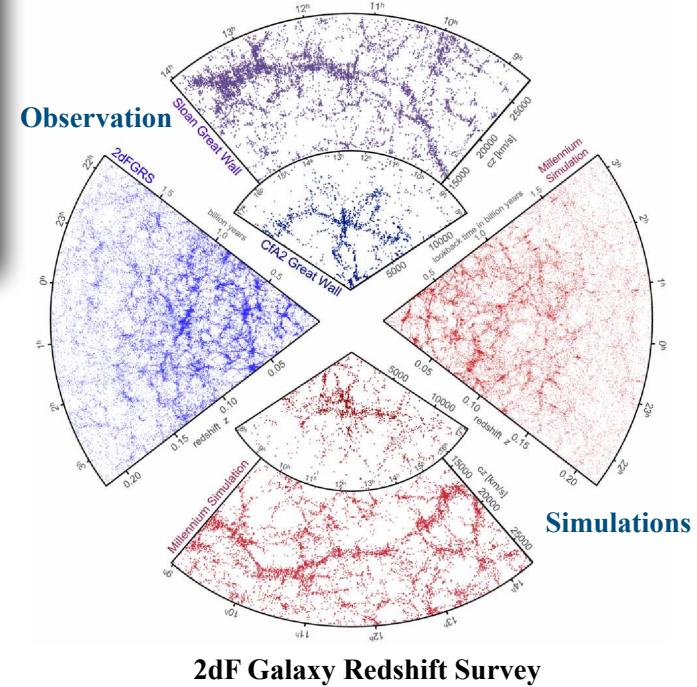


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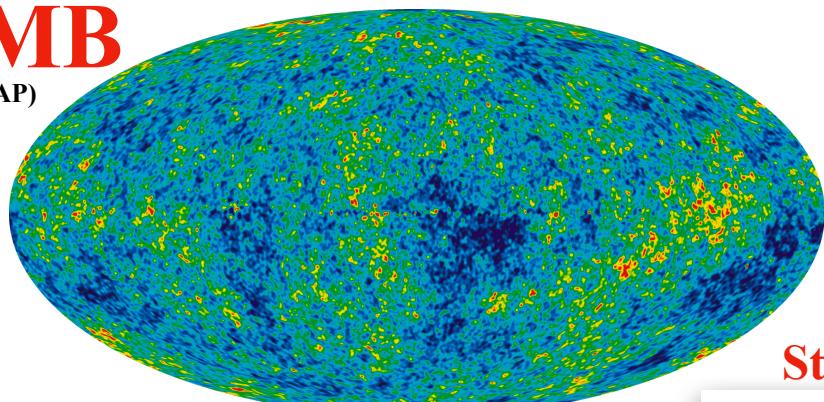
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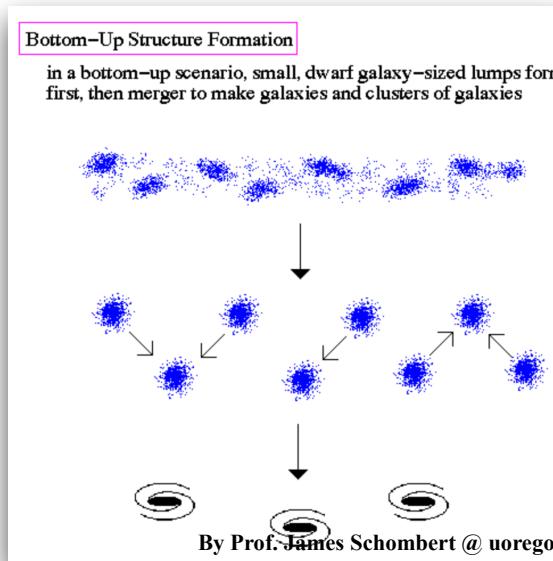
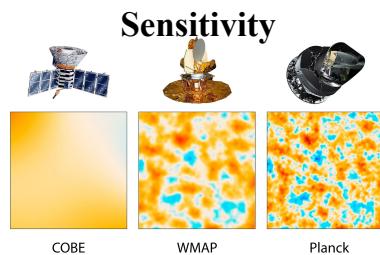


# Why Dark Matter?

CMB  
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Structure Formation

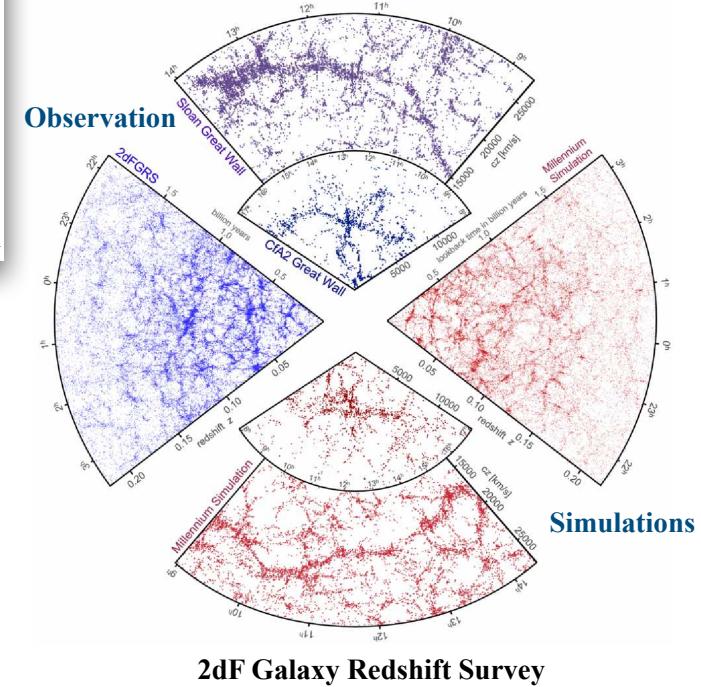


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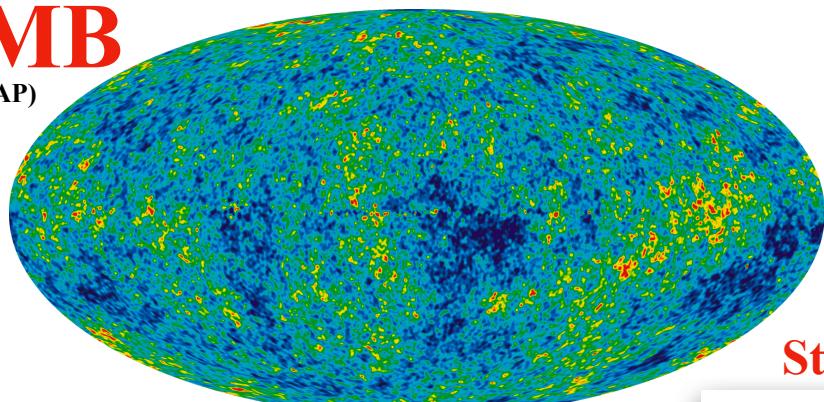
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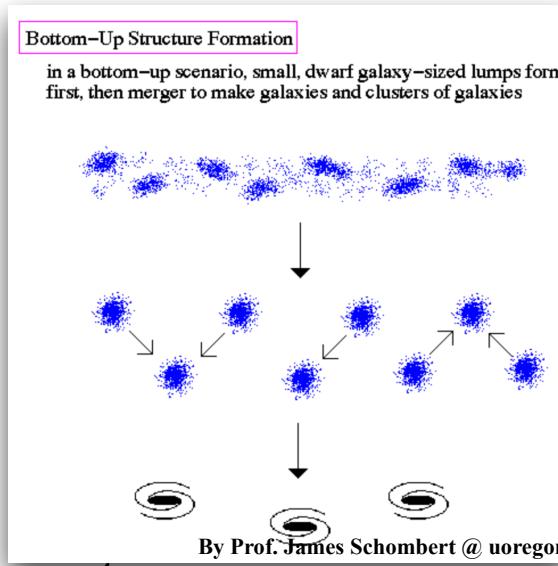
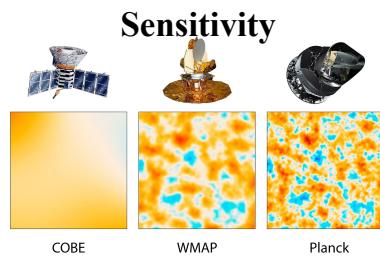


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**CMB**  
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Structure Formation



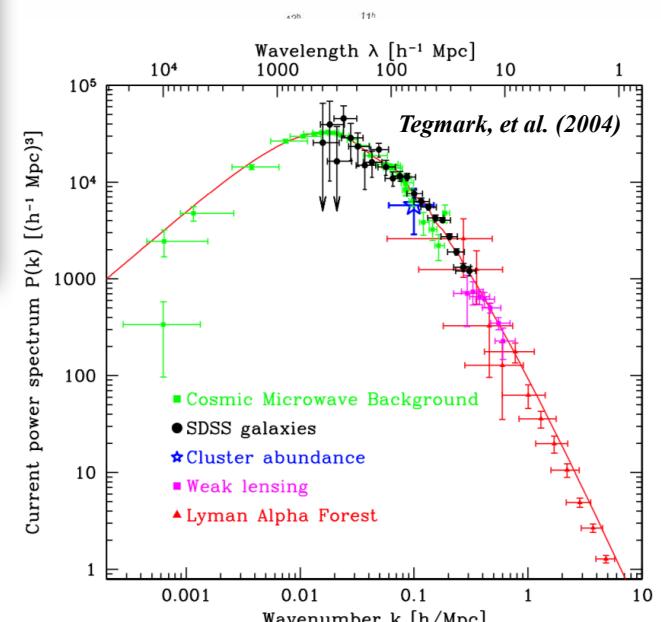
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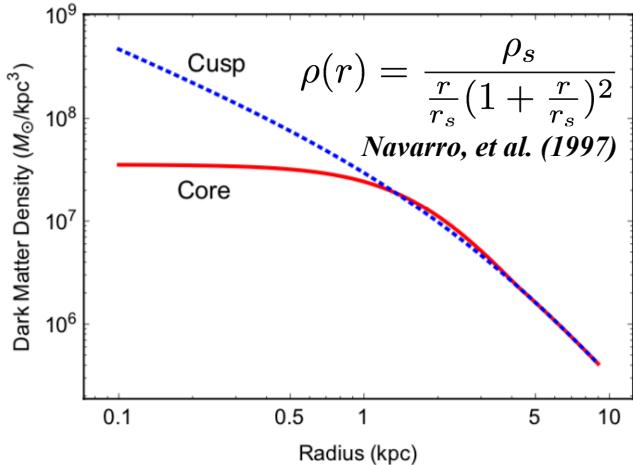
## Large-Scale Structure



2dF Galaxy Redshift Survey

# CDM Paradigm on Galactic Scales

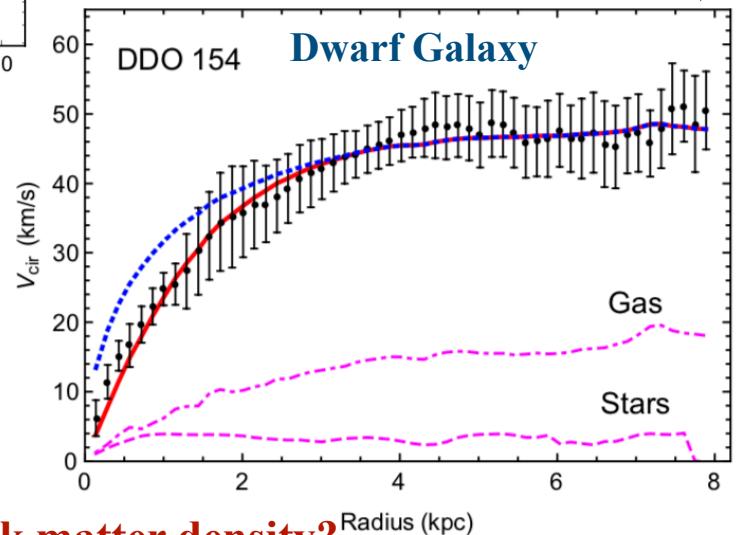
## NFW Profile



- CDM only simulation predicts cuspy NFW profiles on average from dwarf galaxies to galaxy clusters.
- NFW profiles usually contain too much dark matter in the central regions for the observations in dark matter dominated systems.

## Core vs Cusp Problem

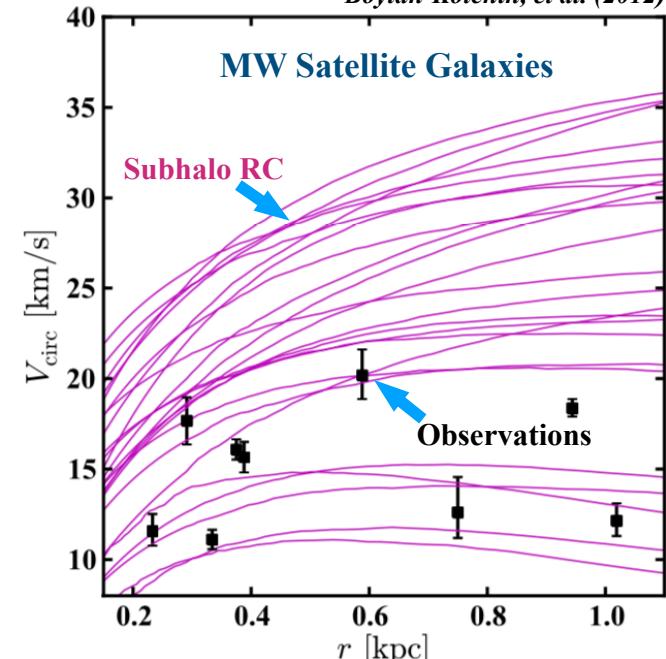
Tulin, et al.(2018)



- Some dwarf galaxies prefer cored profiles.
- How to lower the central dark matter density? Baryon physics may help.  
(e.g. feedback effect like the explosion of supernovae.)
- Alternative dark matter model beyond the collisionless scenario, e.g. Self-Interacting Dark Matter.

## Too-big-to-fail Problem

Boylan-Kolchin, et al. (2012)



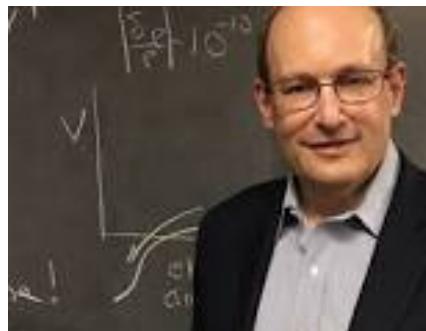
# The Rise of Self-Interacting Dark Matter

D. N. Spergel



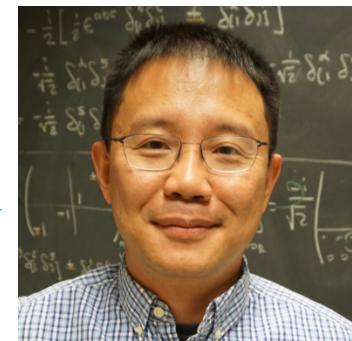
Princeton

P. J. Steinhardt



Princeton

Hai-Bo Yu



UC Riverside

Manoj Kaplinghat

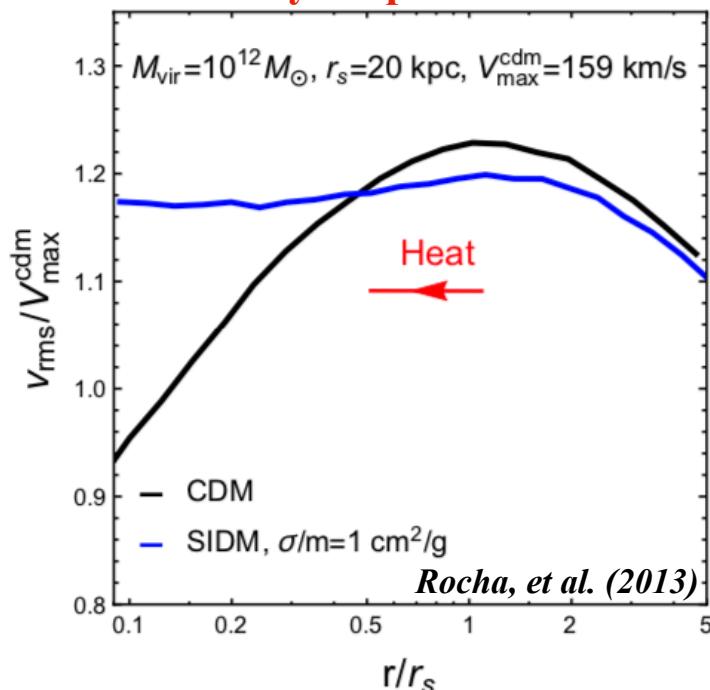


UC Irvine

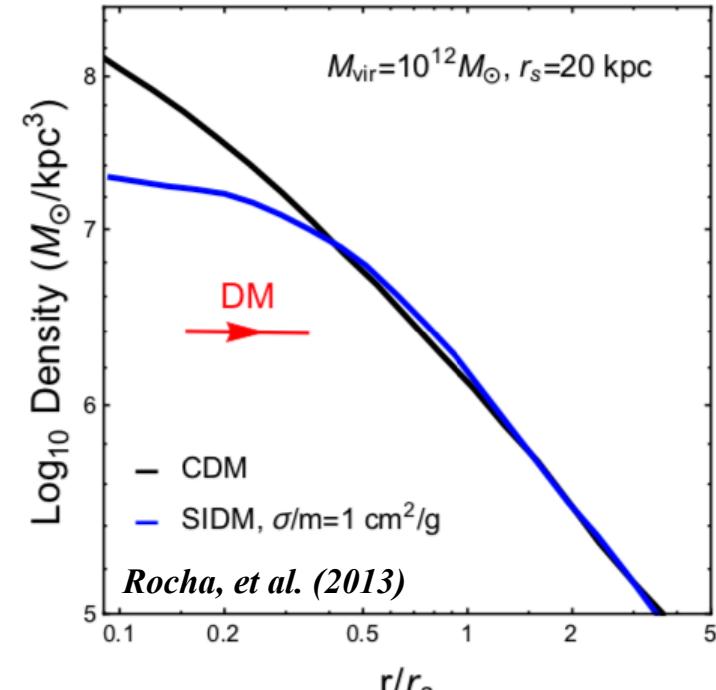
2000      Present

## Mechanism of SIDM

### Velocity Dispersion Profile



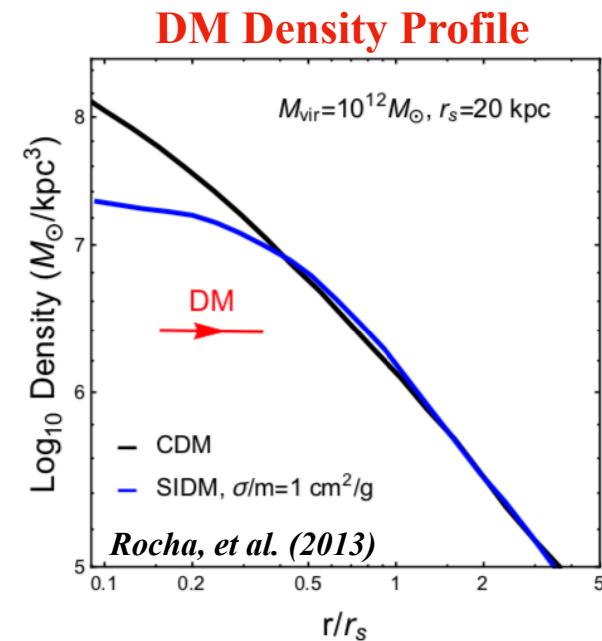
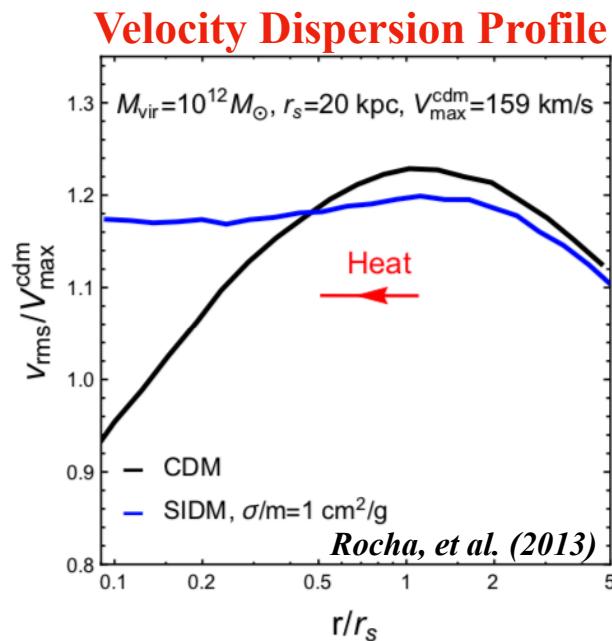
### DM Density Profile



- Heat is transferred from outer region to inner region through DM self-interactions.
- DM particles get higher energy and escape the bound of gravity from original cusp.

# SIDM Modeling

## Mechanism of SIDM



**0th D-Order : Isothermal profile**

$$\rho_{iso}(\vec{x}) = \rho_0 \cdot \exp(-\Phi_{tot}(\vec{x})/\sigma_0^2)$$

The form of solution

**1st D-Order : Hydrostatic equilibrium**

$$p = \rho \cdot \sigma_0^2$$

$$\nabla p = -\rho \cdot \nabla \Phi_{tot}$$

Equation of state

**2nd D-Order : Poisson equation**

$$\nabla^2 \Phi_{tot} = 4\pi G(\rho_{iso} + \rho_b)$$

Solve for density profile

- The thermalization is caused by self-interactions between dark matter particles, specifically scatterings.
- The number of collisions can measure the level of scatterings.

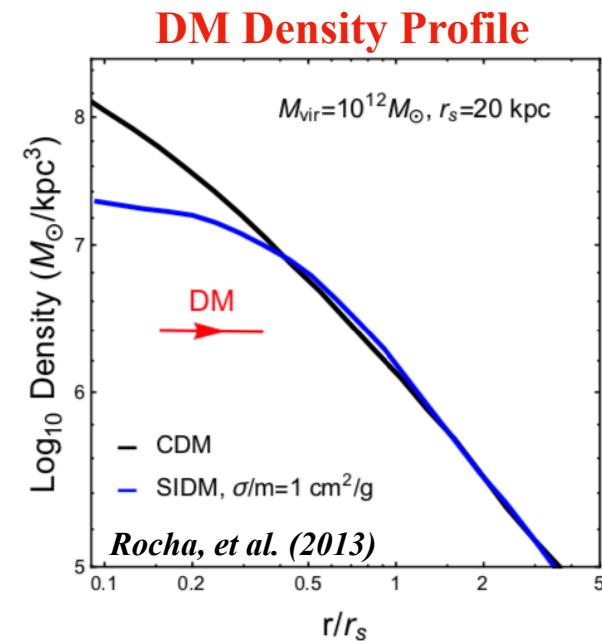
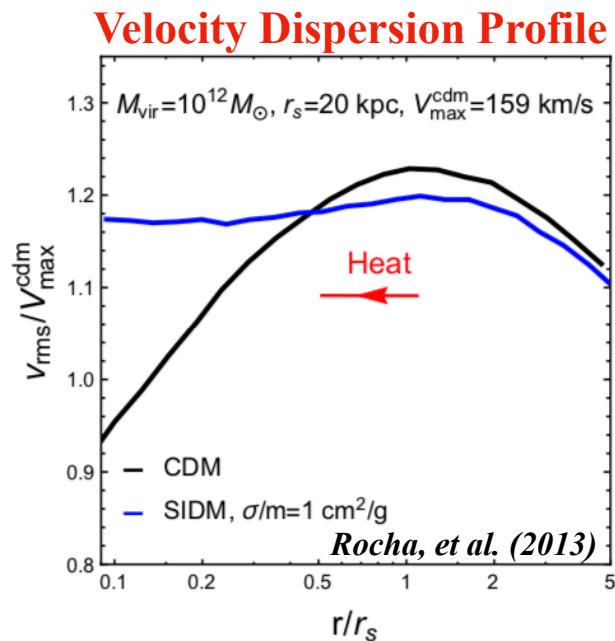
$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho_{iso}(r_1) t_{\text{age}} \approx 1$$

$$\rho_{\text{SIDM}}(r) = \begin{cases} \rho_{iso}(r), & r < r_1 \\ \rho_{\text{NFW}}(r), & r > r_1 \end{cases}$$

(Mass & density continuity at  $r_1$ )

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### 2nd D-Order : Poisson equation

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Solve for density profile

- The thermalization is needed to make interaction between dark matter and particle.
- The number of collisions can measure the level of scatterings.

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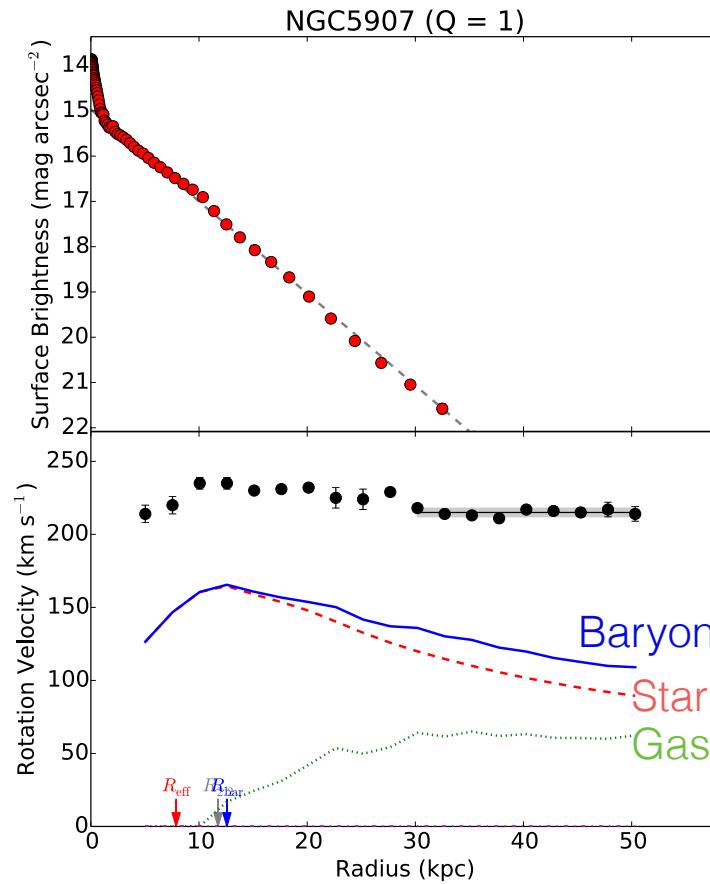
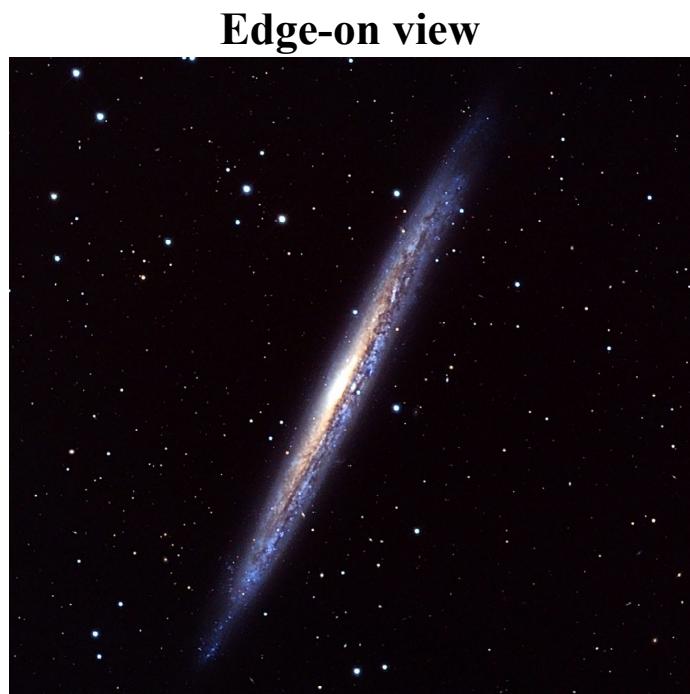
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# Spitzer Photometry & Accurate RCs (SPARC) Dataset

Lelli, et al. (2016)

- SPARC contains a sample of 175 nearby spiral galaxies with **homogeneous photometry** at  $3.6 \mu\text{m}$  and **high-quality RC data** from previous HI/H $\alpha$  studies.
- SPARC spans very **broad ranges** in luminosity, surface brightness, rotation velocity, and Hubble type, forming a representative sample of spiral galaxies in the nearby Universe.



**Abs. magnitude & Luminosity**

$$M \equiv -2.5 \log_{10} L + \text{const.}$$

$$M = a \times R + b$$

$$\rightarrow L \propto e^{-r/r_d}$$

$$\rightarrow \rho_b = \Sigma_0 e^{-r/r_d} \times \delta(z)$$

**Data Selection**

Goal: High quality + Large size

Criterion: measured flat velocity

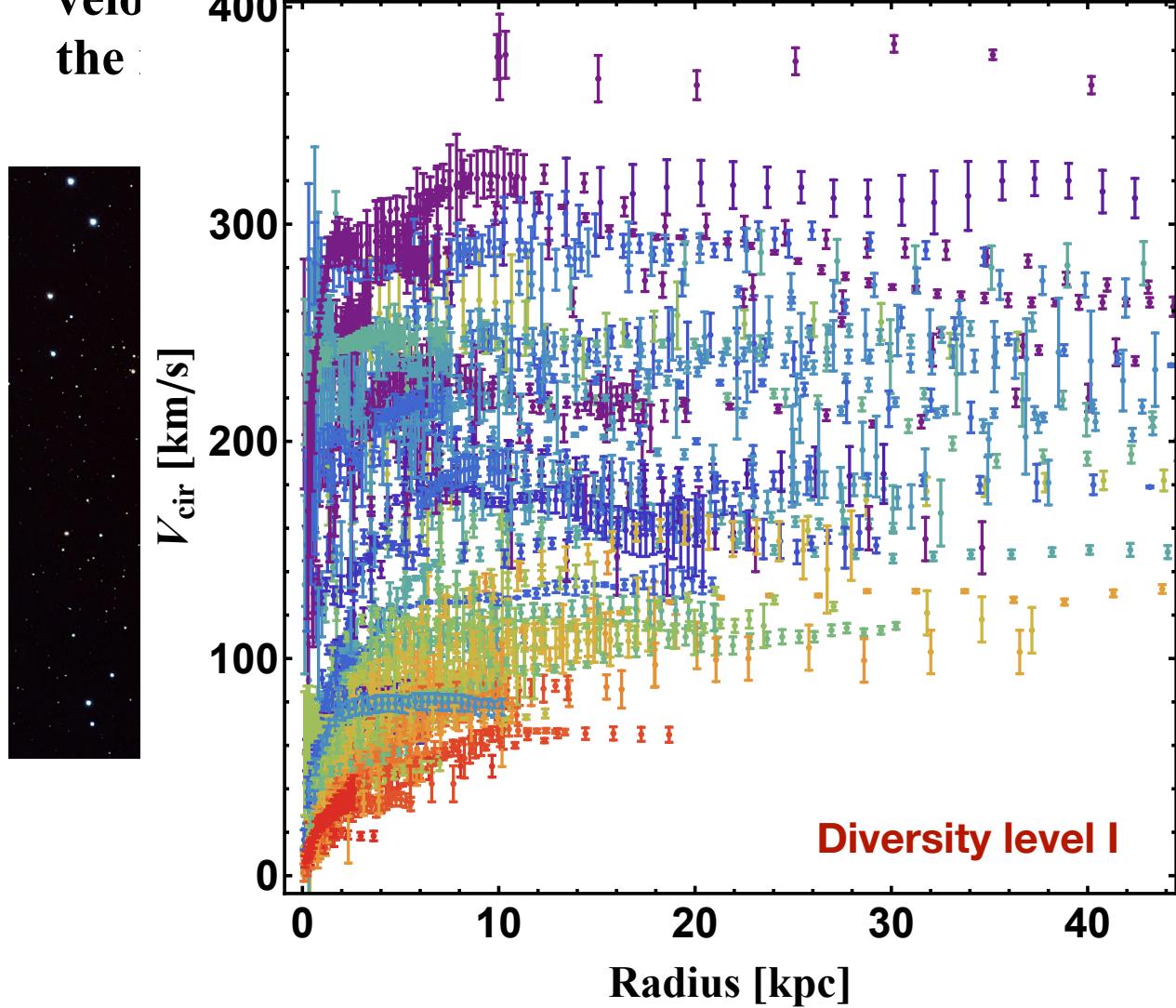
$\rightarrow$  135 galaxies

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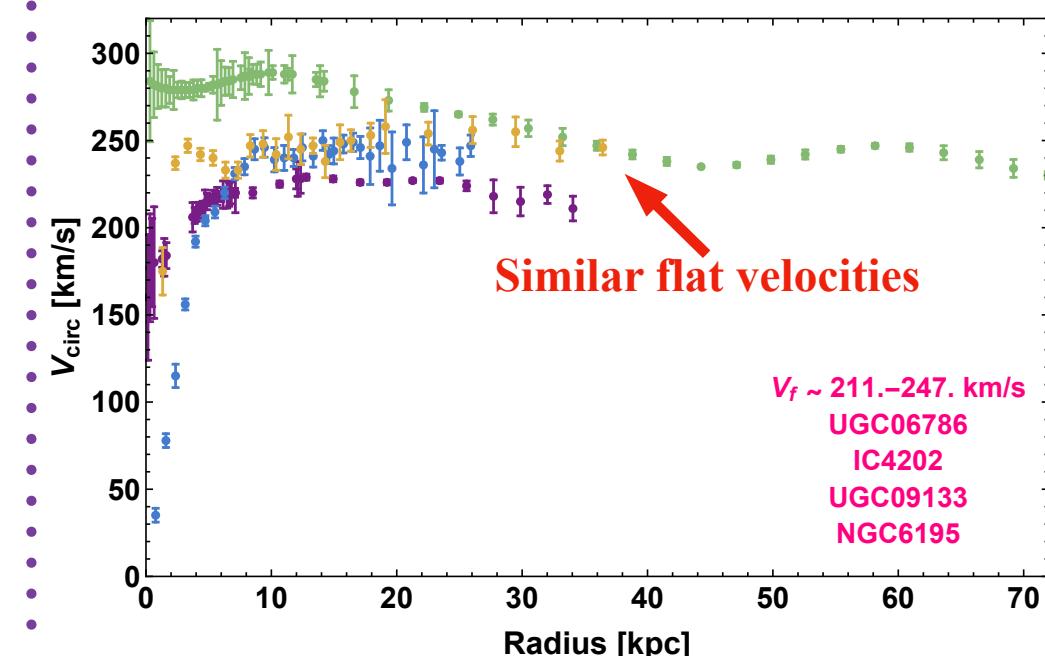
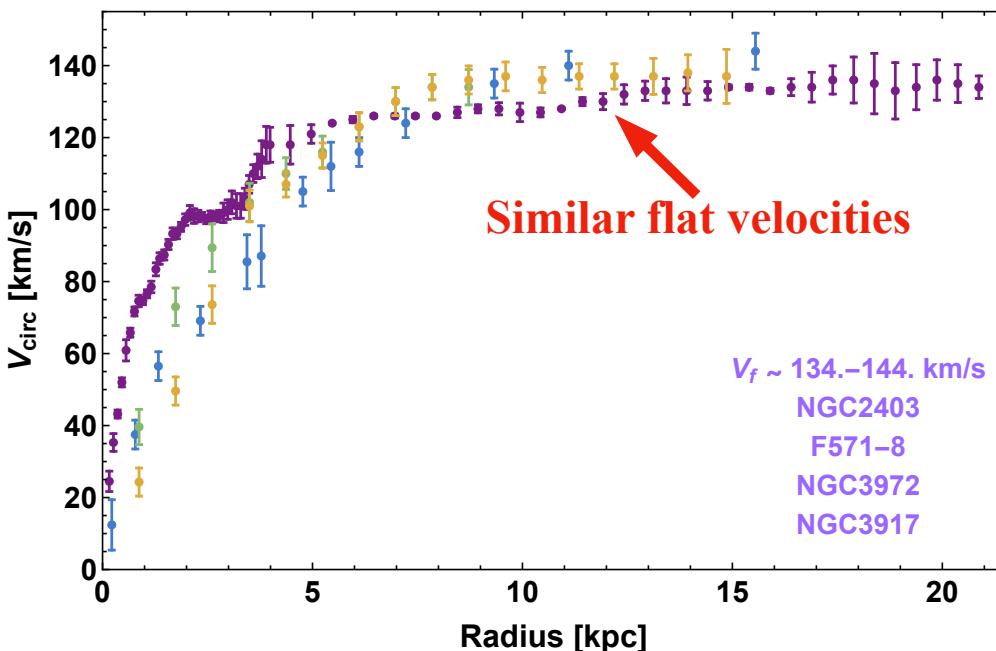
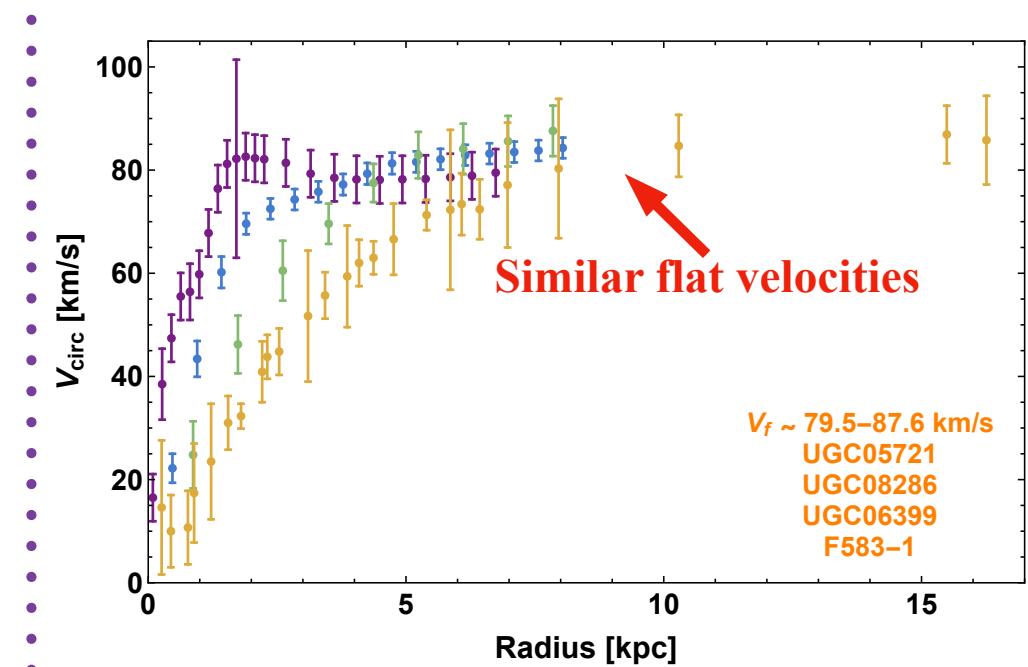
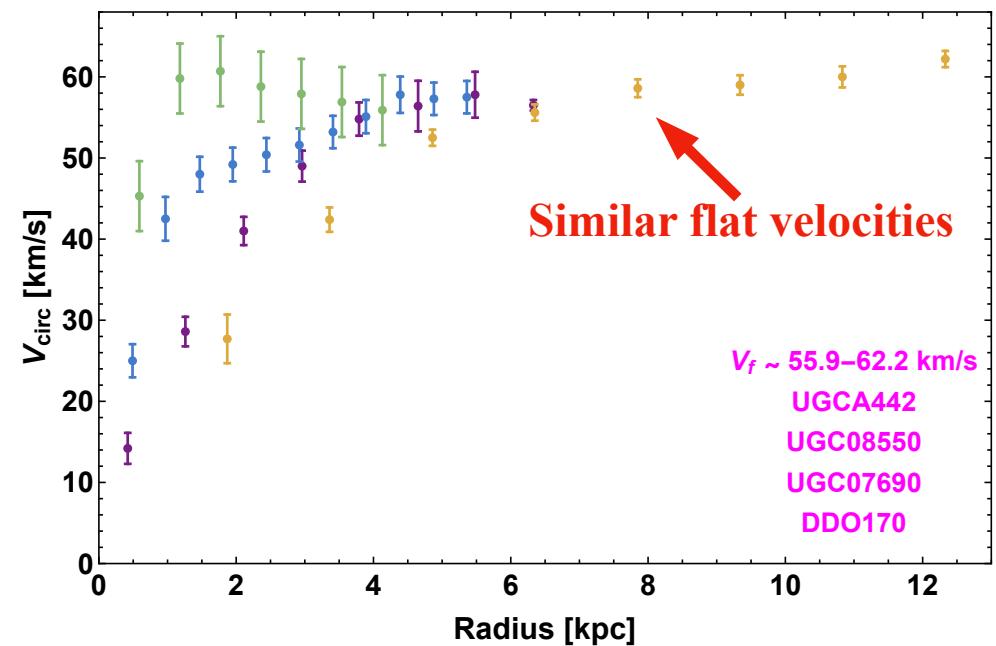


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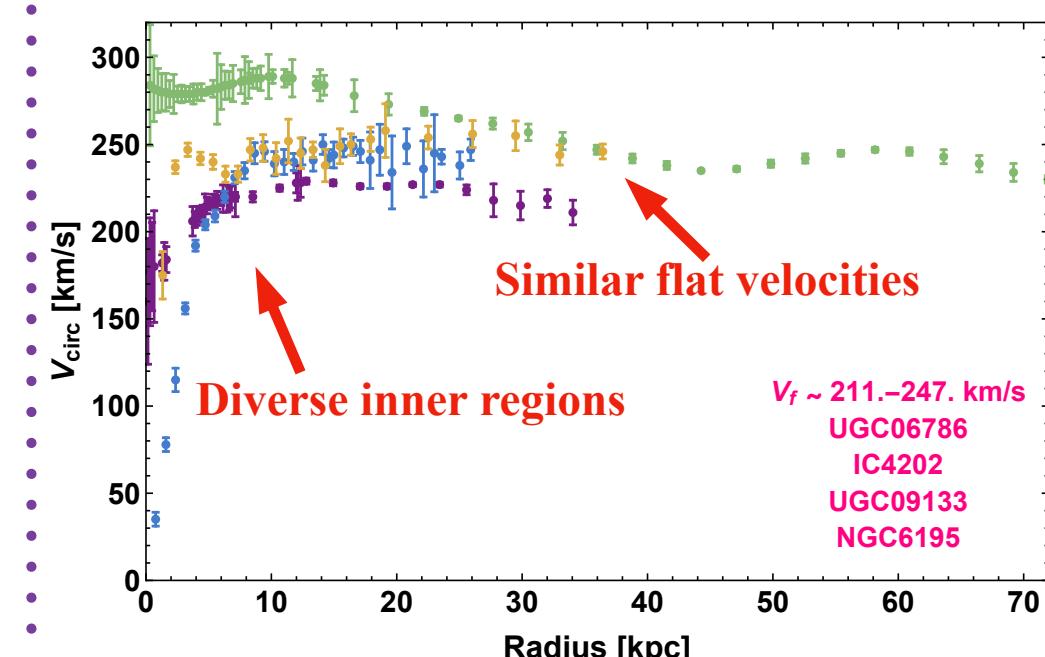
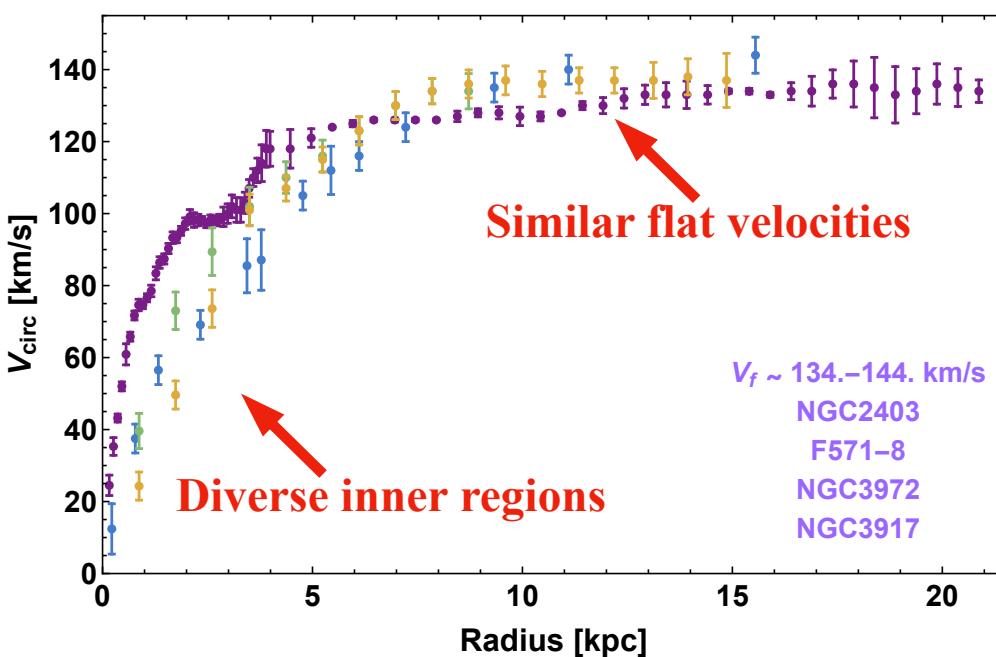
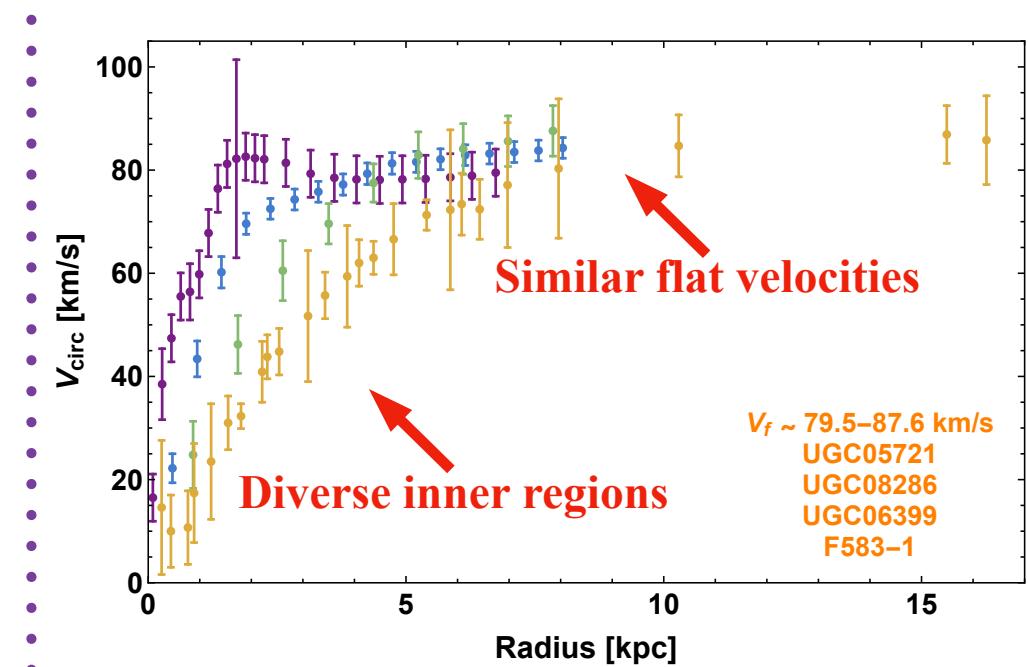
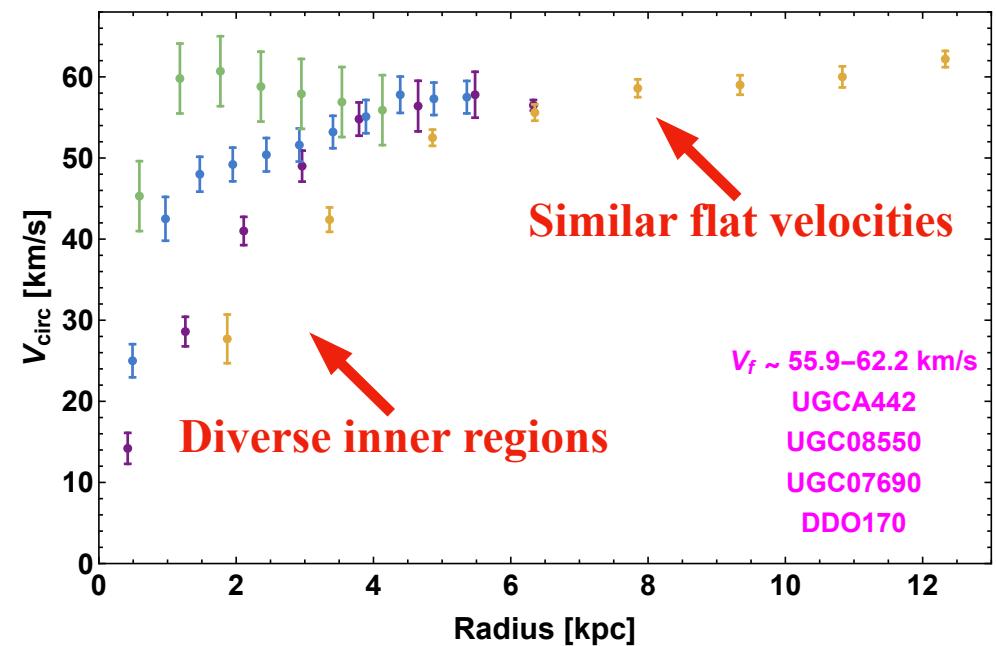
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Data Source: SPARC  
*Lelli, et al. (2016)*



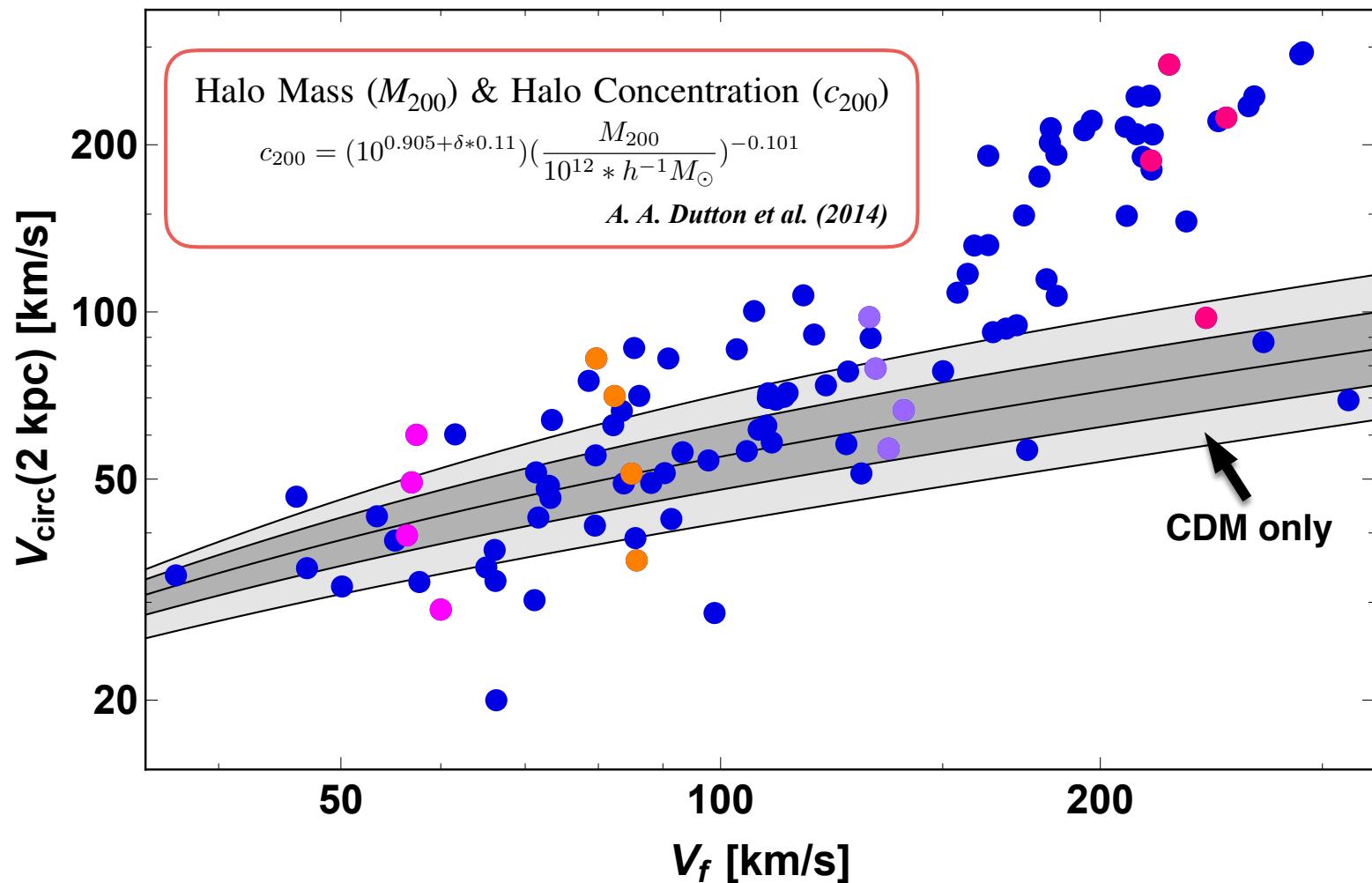
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# Challenges for Cold Dark Matter (CDM)

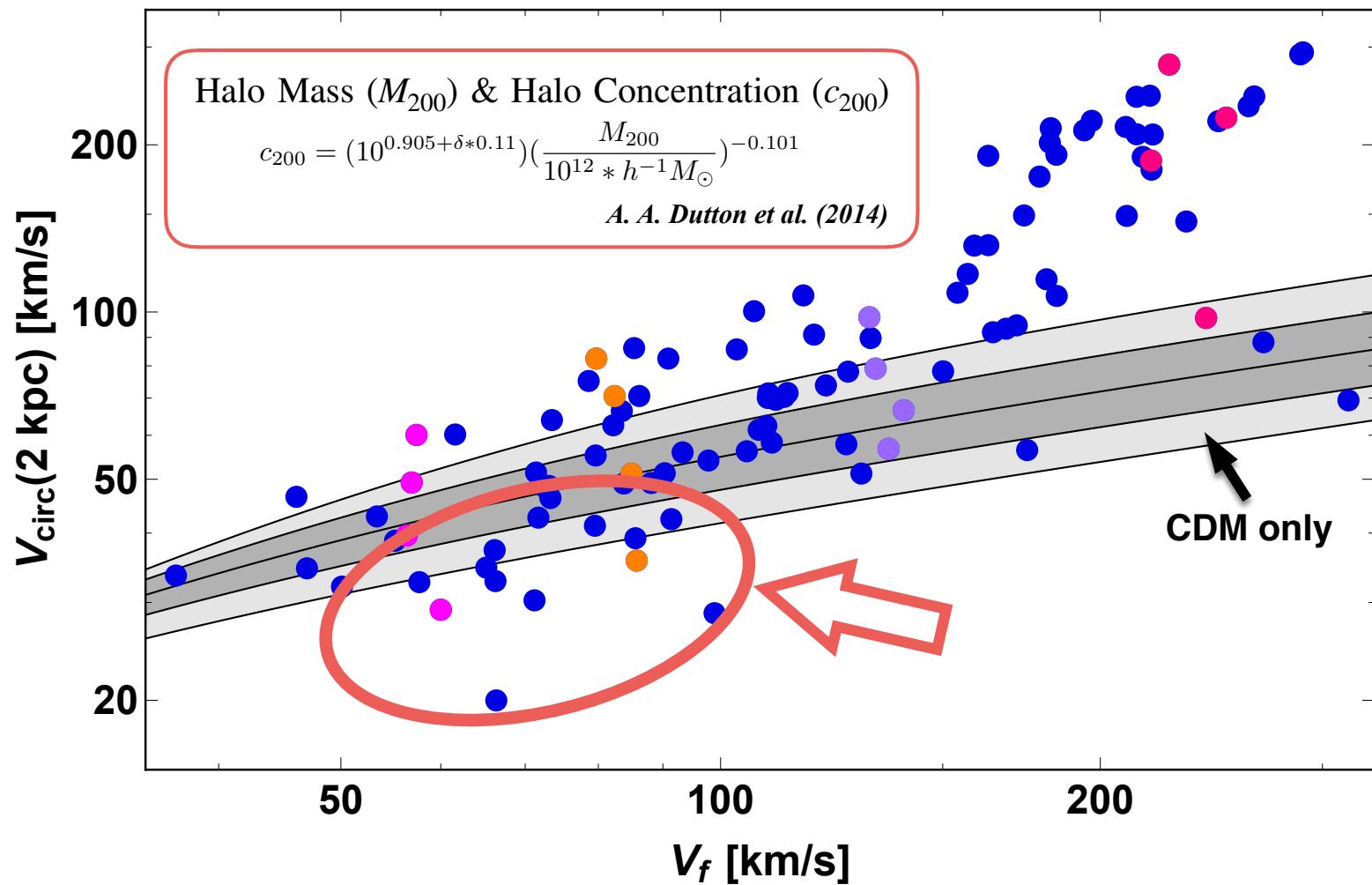
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+  
Baryon



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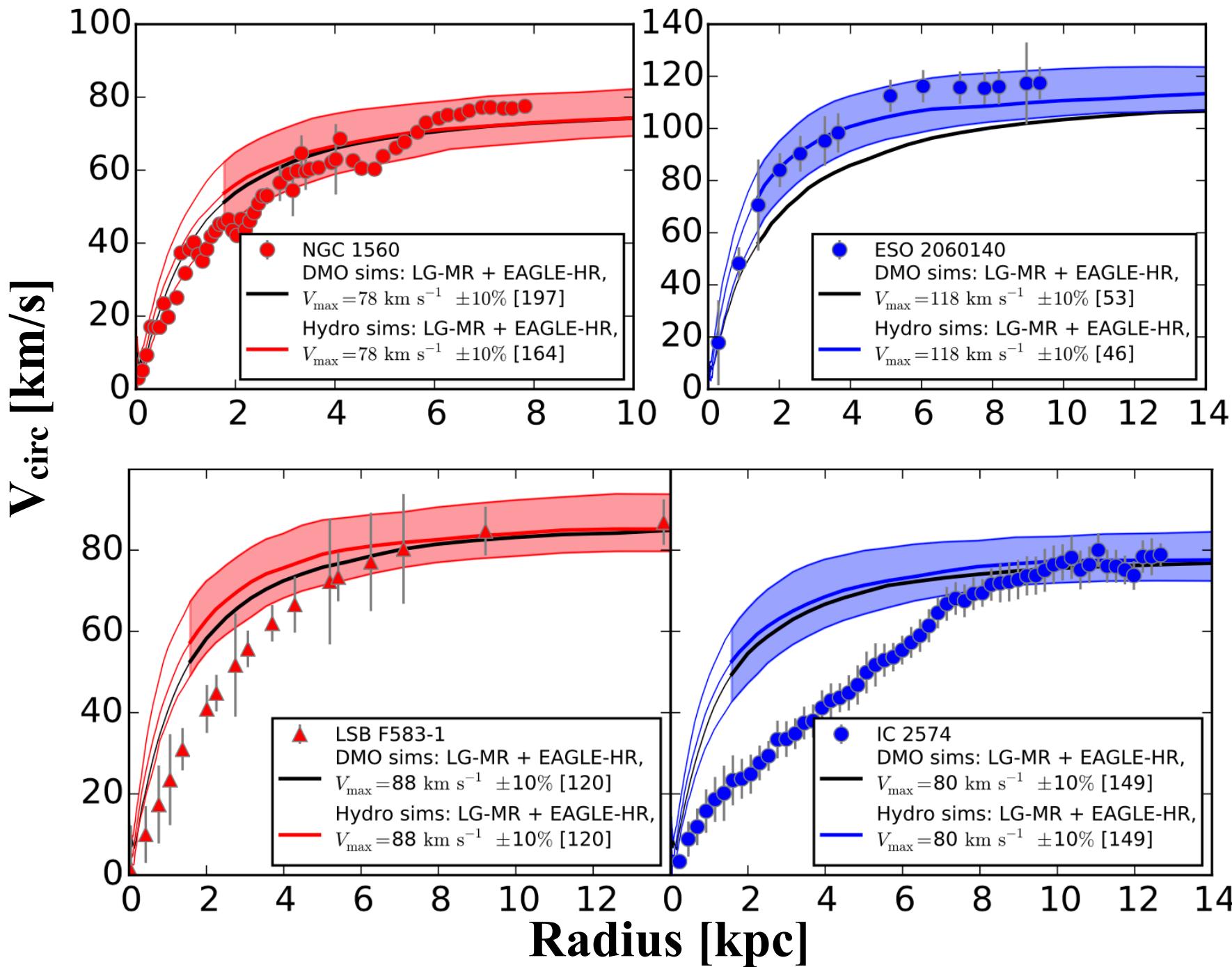
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- Diversity is the scatter of the data points at a fixed  $V_f$  value.
- The obvious challenge is from dwarf galaxies.

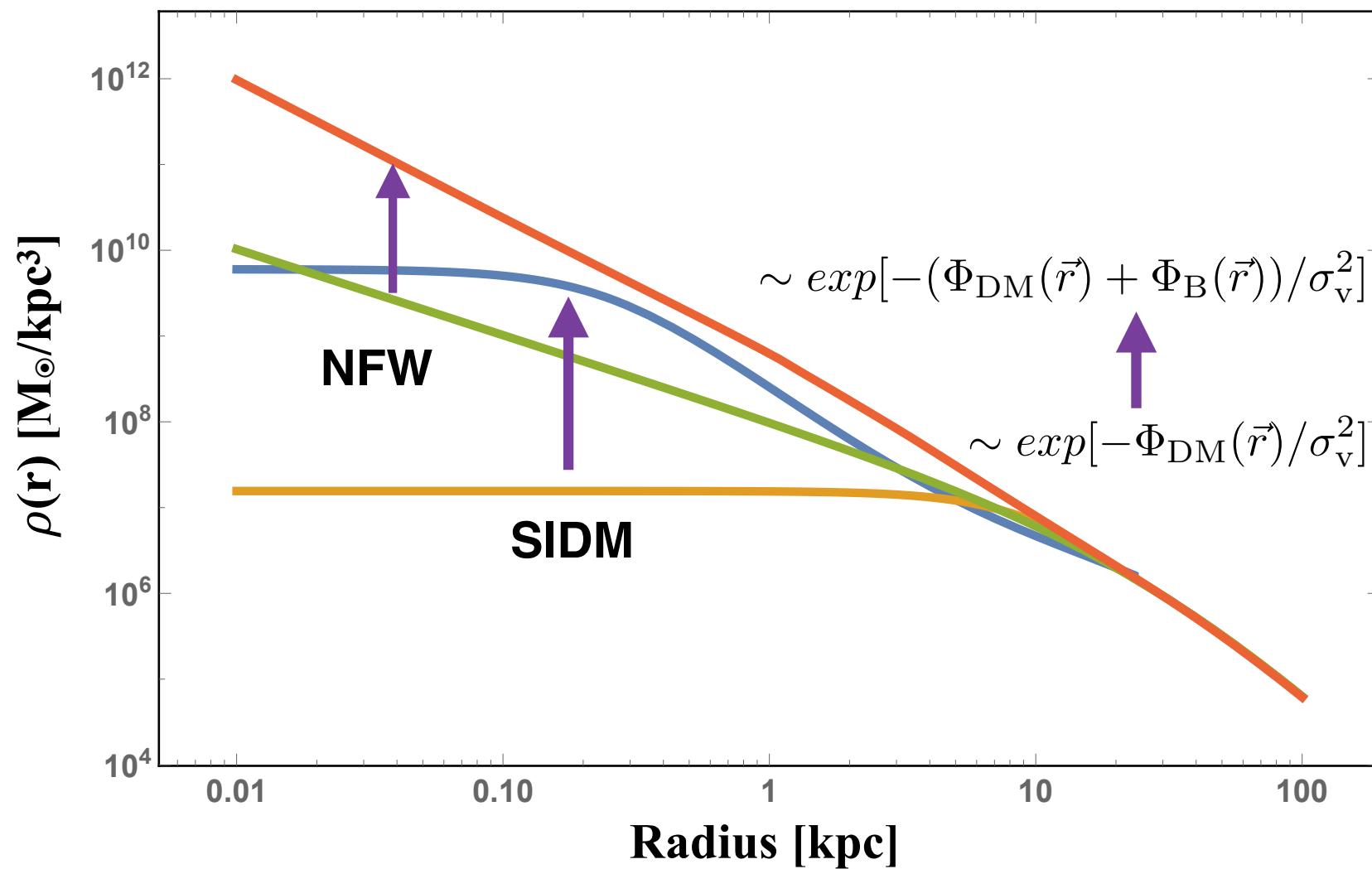
# Examples

*Oman et al. (2015)*



# SIDM & CDM Density Profiles w/ Baryons

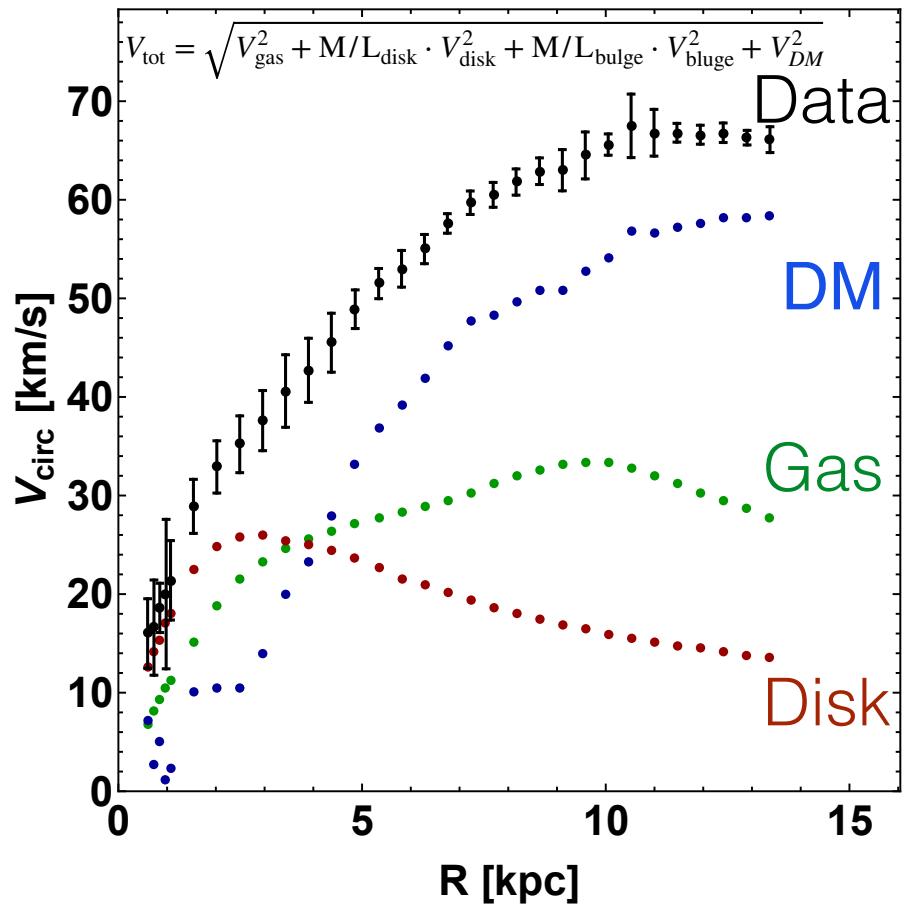
Amorisco, et al. (2010)  
Kaplinghat, et al. (2014)  
Kamada, et al. (2017)



How SIDM works:

**Self-Interaction + Baryon Effect + M<sub>200</sub>-c<sub>200</sub> Relation**

# SIDM: Fit to the Rotation Curves



## Parameters in SIDM model

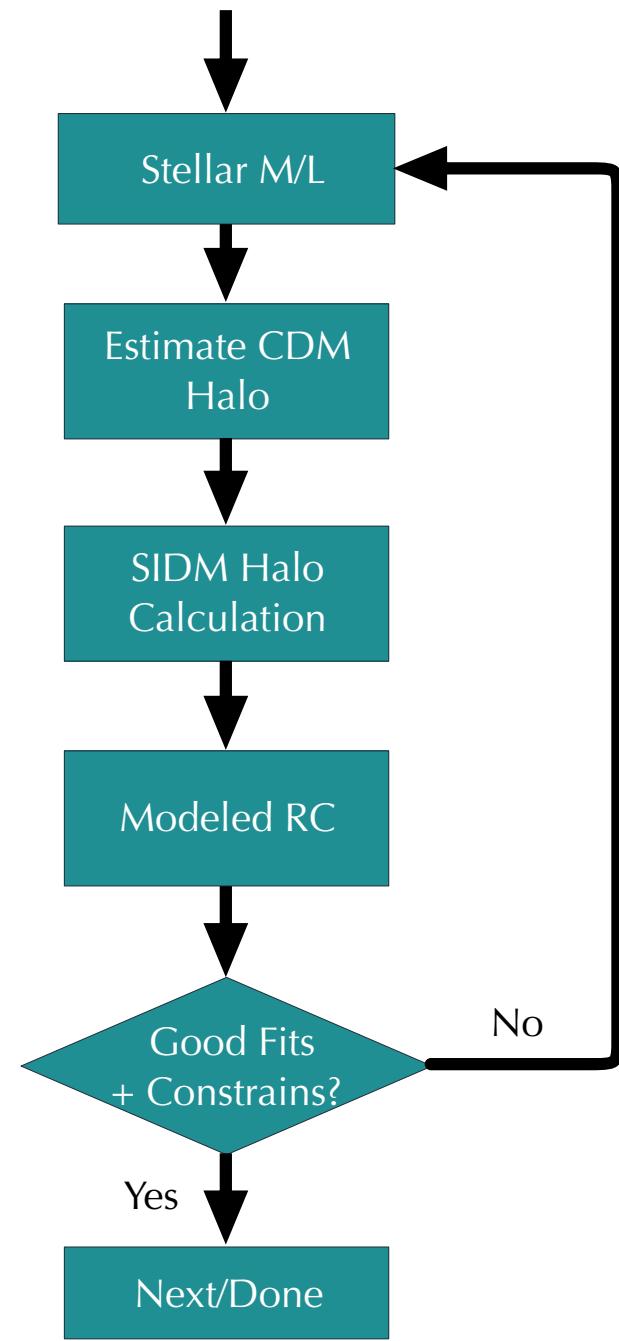
$(M/L_{\text{Disk}}, M/L_{\text{Bulge}}, M_{200}, c_{200} (V_{\text{max}}, R_{\text{max}}))$

Baryon

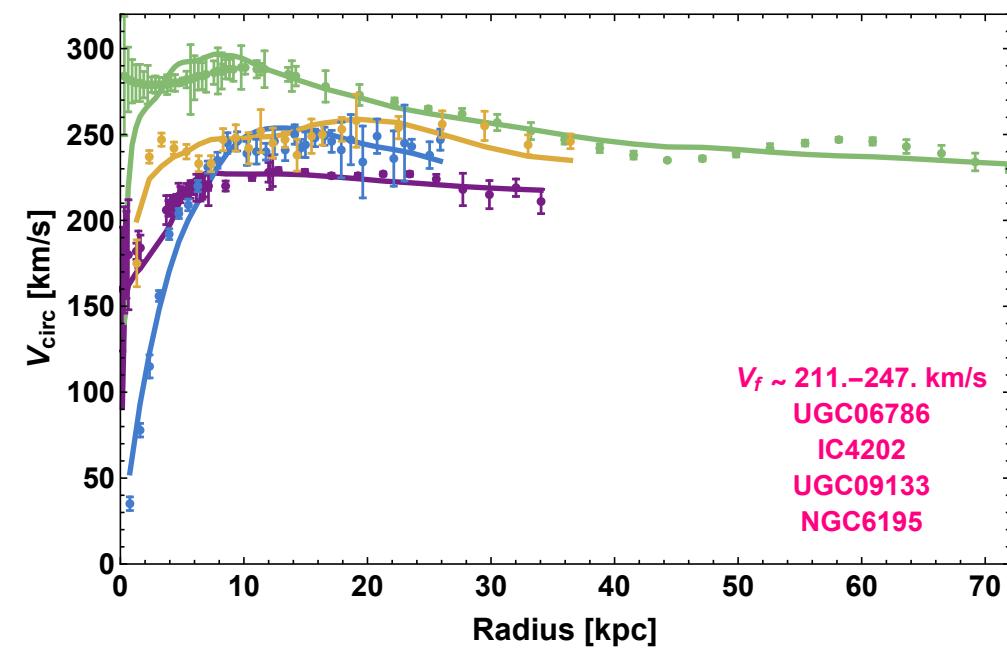
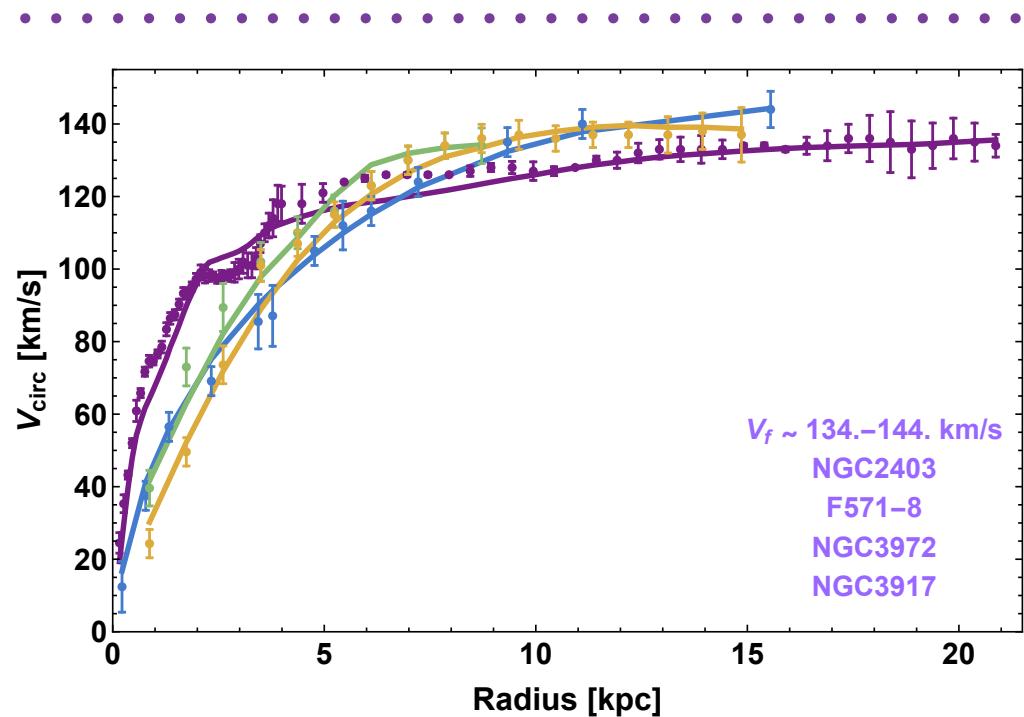
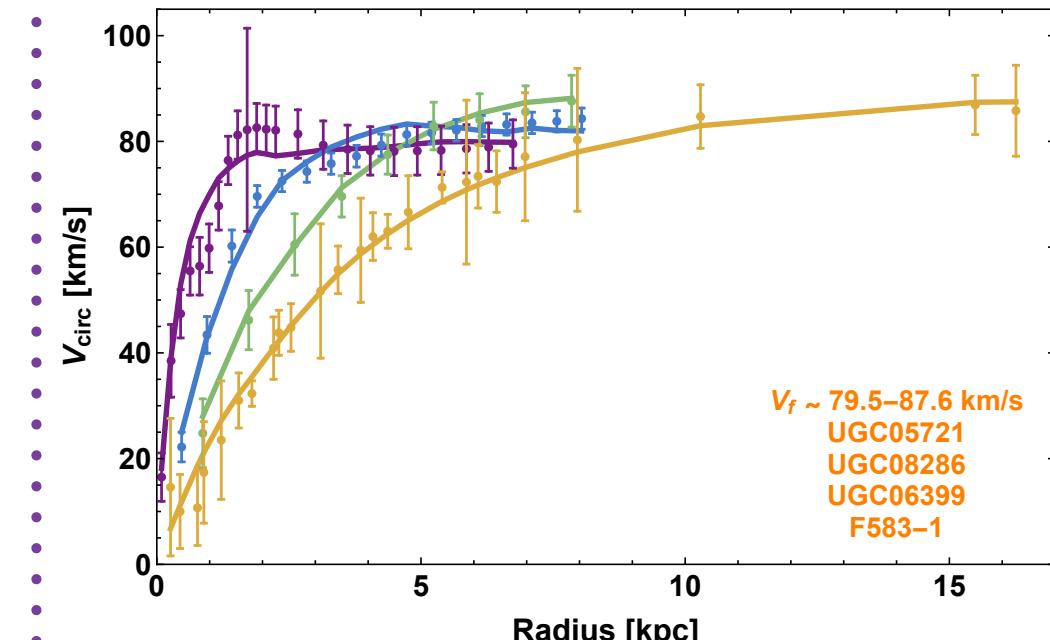
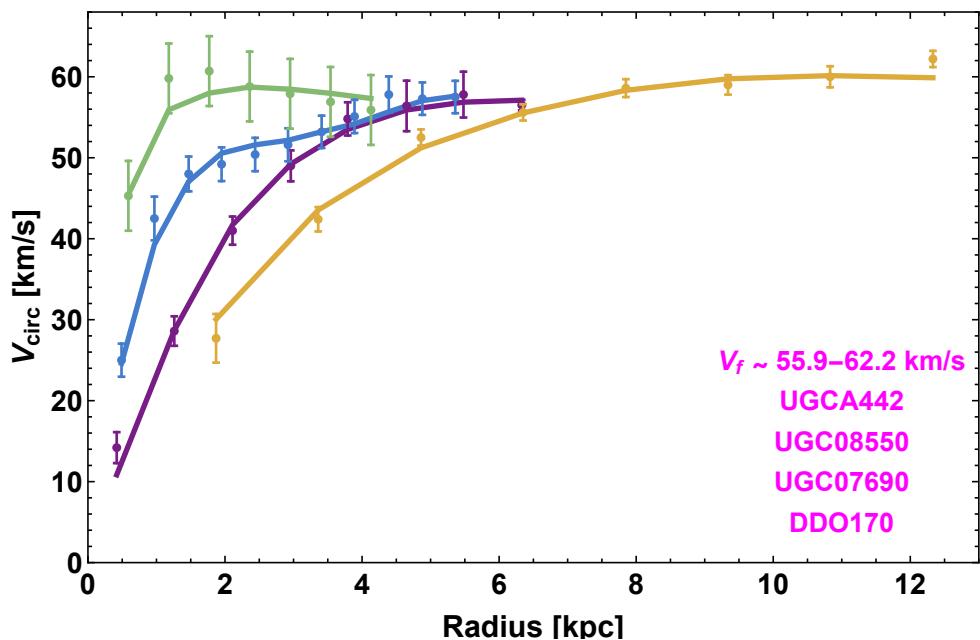
DM

MS: MCMC sampling  
CS: Controlled sampling

with  $\sigma/m = 3 \text{ cm}^2/\text{g}$ .

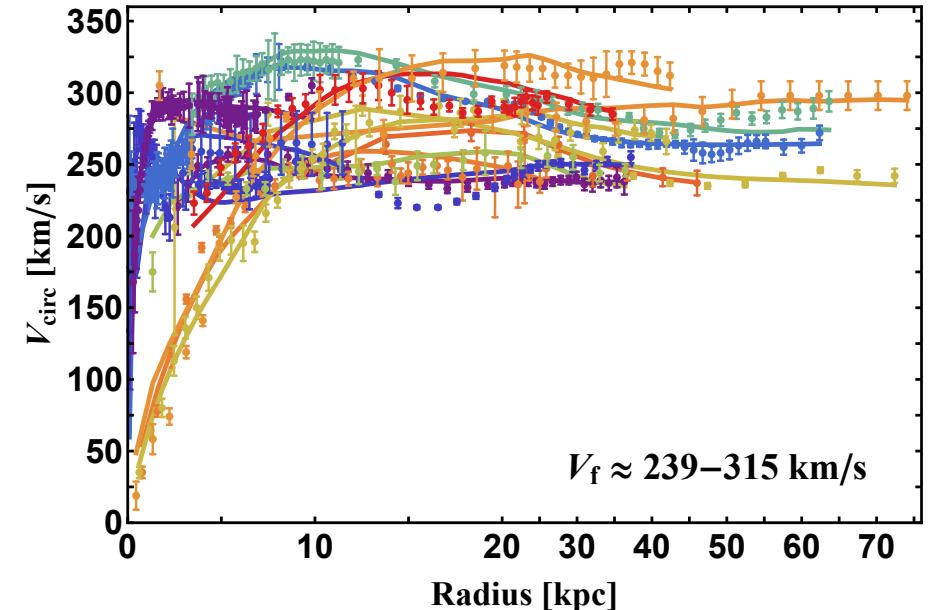
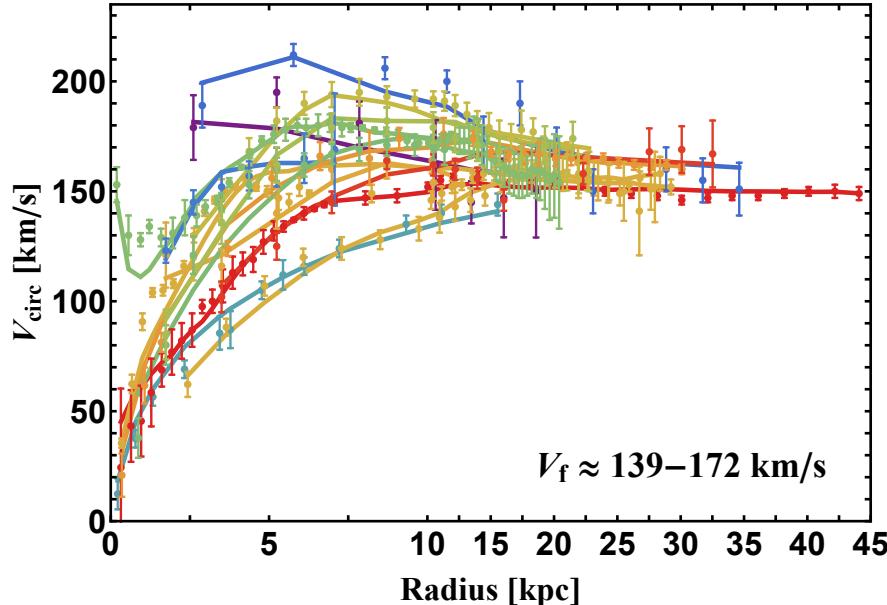
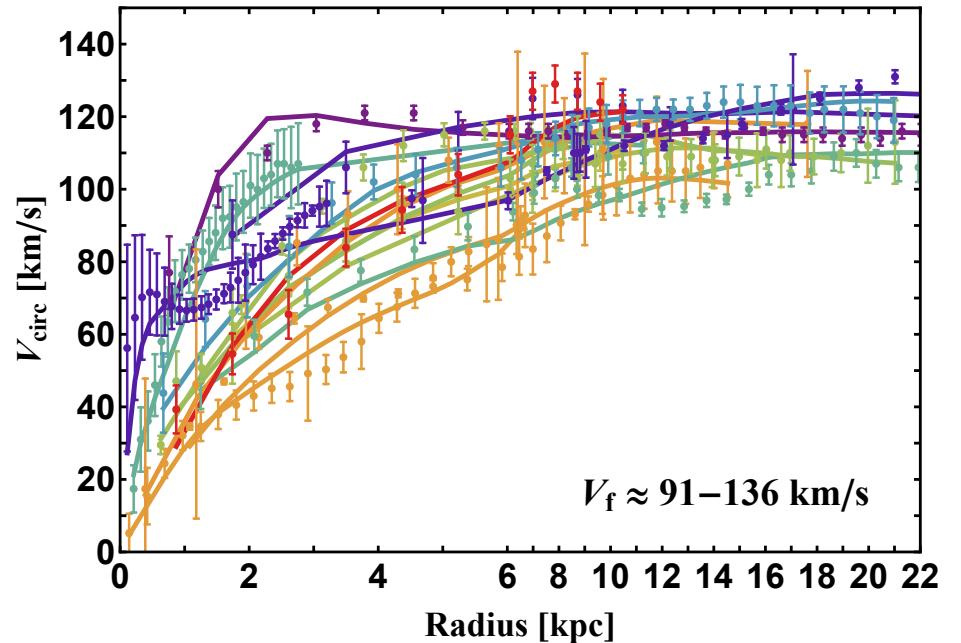
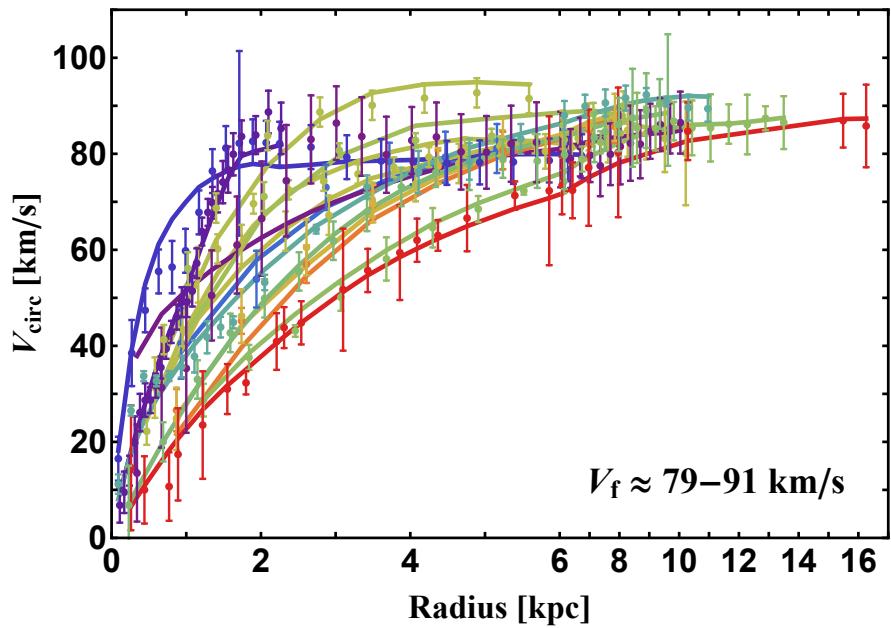


# SIDM Fitting Examples

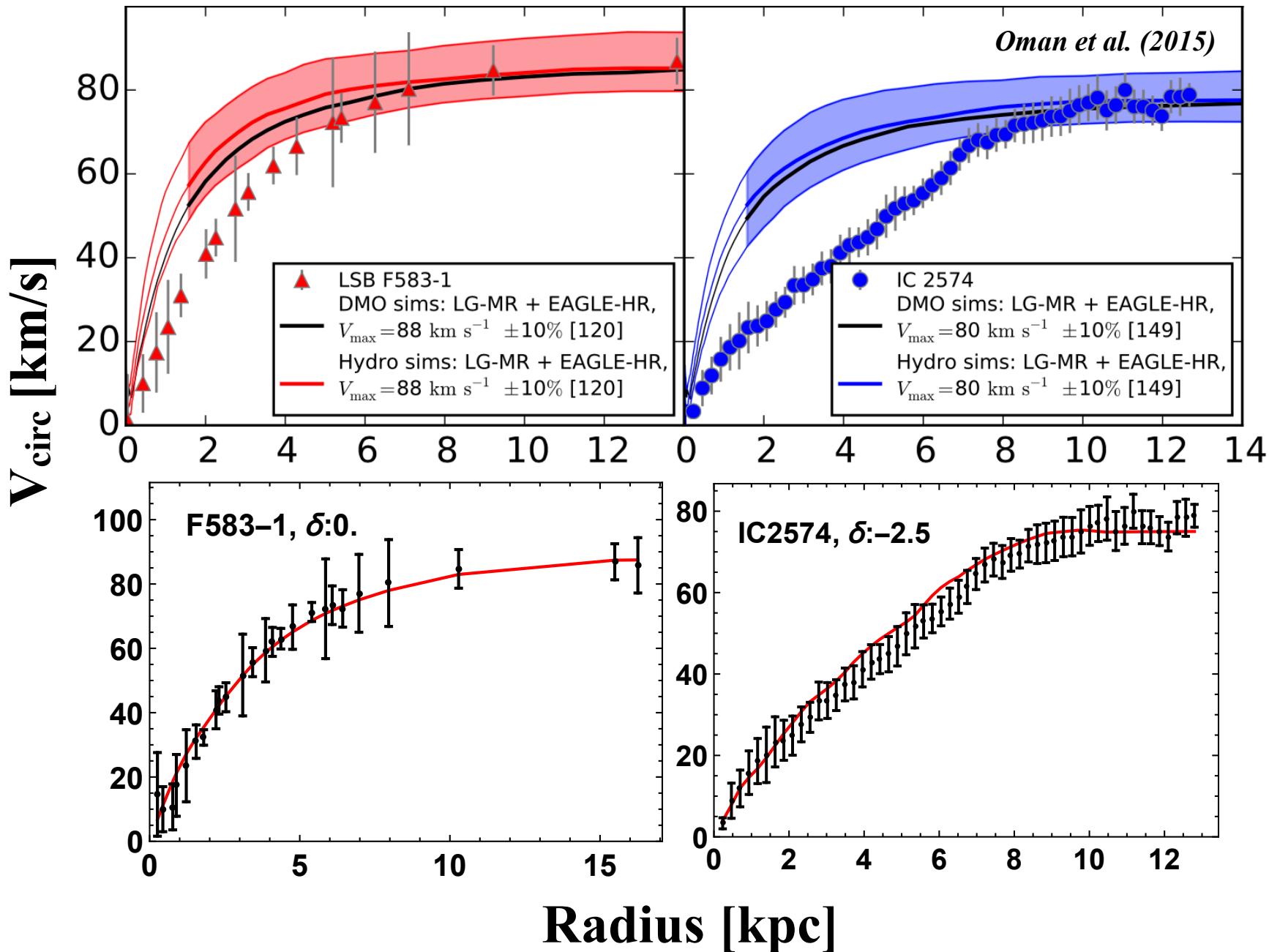


# More Examples

Ren, Kwa, Kaplinghat, Yu, (PRX, under review)



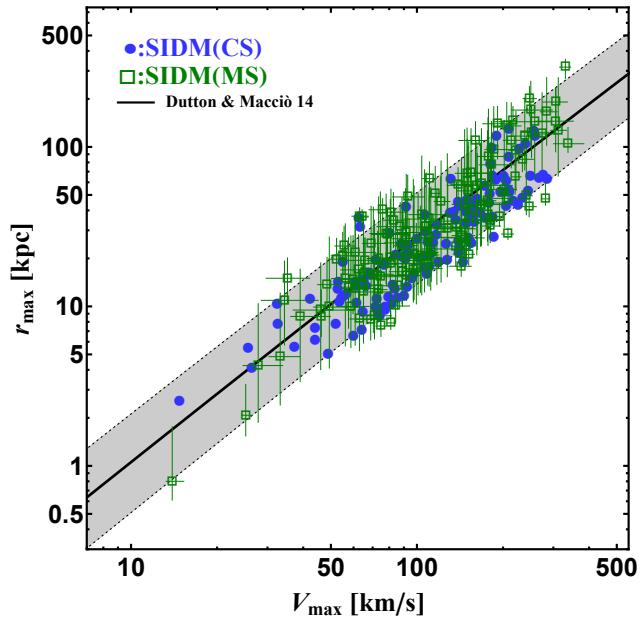
# SIDM Fits to the Outliers



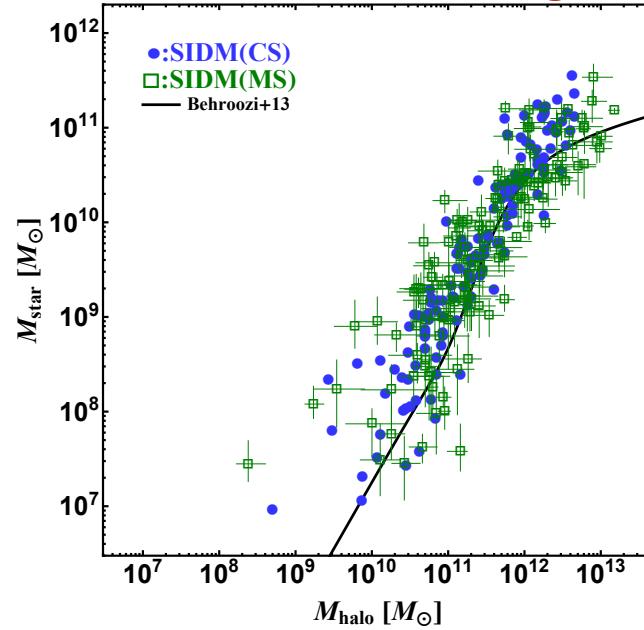
# Other Constraints

*Ren, Kwa, Kaplinghat, Yu, (PRX, under review)*

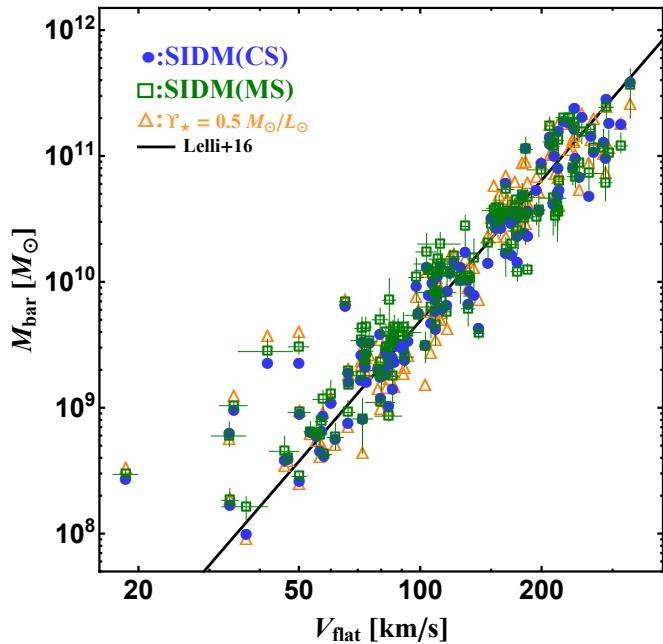
## Concentration-Mass Relation



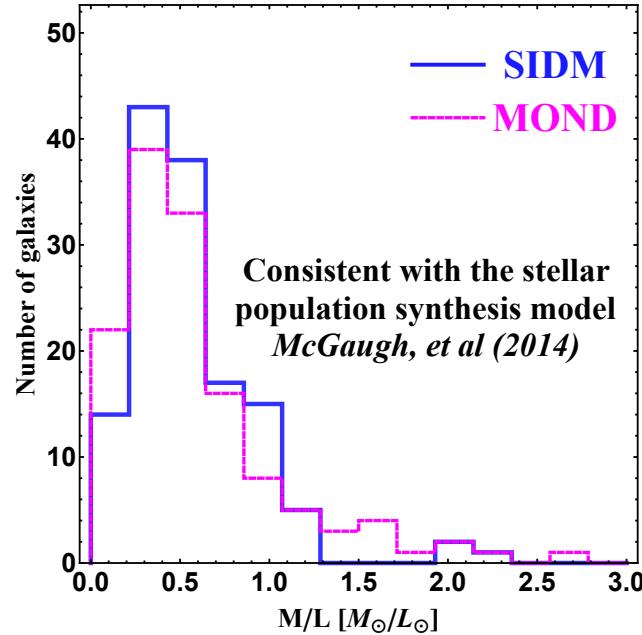
## Abundance Matching



## Tully-Fisher Relation



## Mass-to-Light Ratio



# Content

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- Research Background
- { Diversity  
Uniformity    of Galactic Rotation Curves
- Comparison with Cold Dark Matter Simulations
- Applications in Early-Type Galaxies
- Summary & Outlook

# Modified Newtonian Dynamics (MOND)

## A brief review of MOND

Milgrom, (1983)

**Force: Newtonian Gravity**

$$F = \frac{GMm}{R^2}$$

**Kinematics: Acceleration**

$$g_{\text{obs}} = \frac{V^2}{R}$$

**Newton's 2nd Law**

$$F = m \cdot g_{\text{obs}}$$

**Rotation Curves**

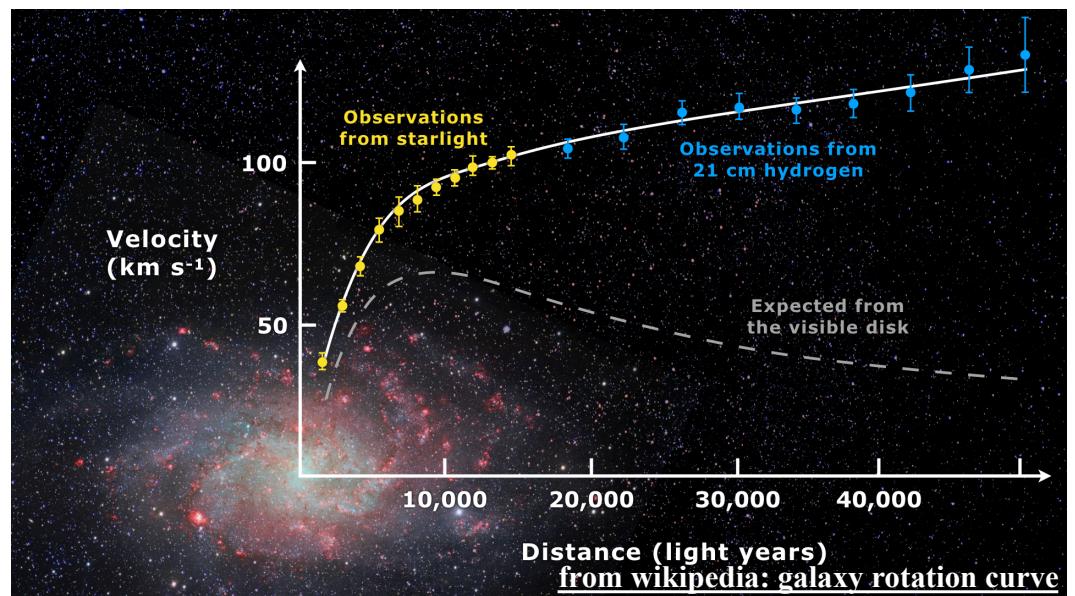
$$F \neq m \cdot g_{\text{obs}}$$

**New relation ?**  $F = \frac{GMm}{R^2} \quad m \cdot g_{\text{obs}} = \frac{V^2}{R}$

**In the outer region of a galaxy:**

$$F \propto \frac{1}{R^2}, \quad g_{\text{obs}} \propto \frac{1}{R} \quad \xrightarrow{\text{blue arrow}} \quad F = m \cdot \frac{g_{\text{obs}}^2}{g_{\dagger}}$$

$$g_{\text{obs}} = g_{\dagger} \cdot f\left(\frac{g_{\text{bar}}}{g_{\dagger}}\right) = \begin{cases} g_{\text{bar}}, & g_{\text{bar}} \gg g_{\dagger} \\ \sqrt{g_{\dagger} \cdot g_{\text{bar}}}, & g_{\text{bar}} \ll g_{\dagger} \end{cases}$$



Rotation curve of Messier 33

from wikipedia: galaxy rotation curve

# Modified Newtonian Dynamics

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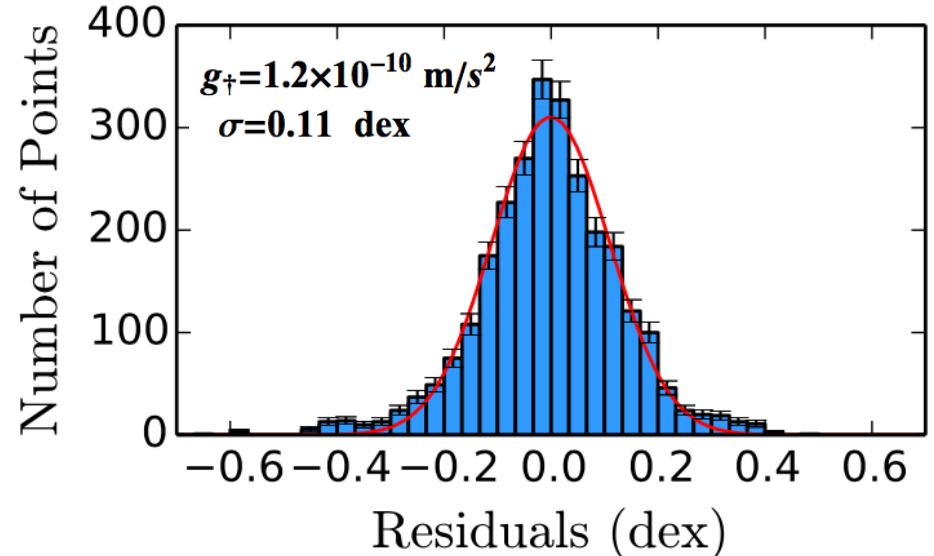
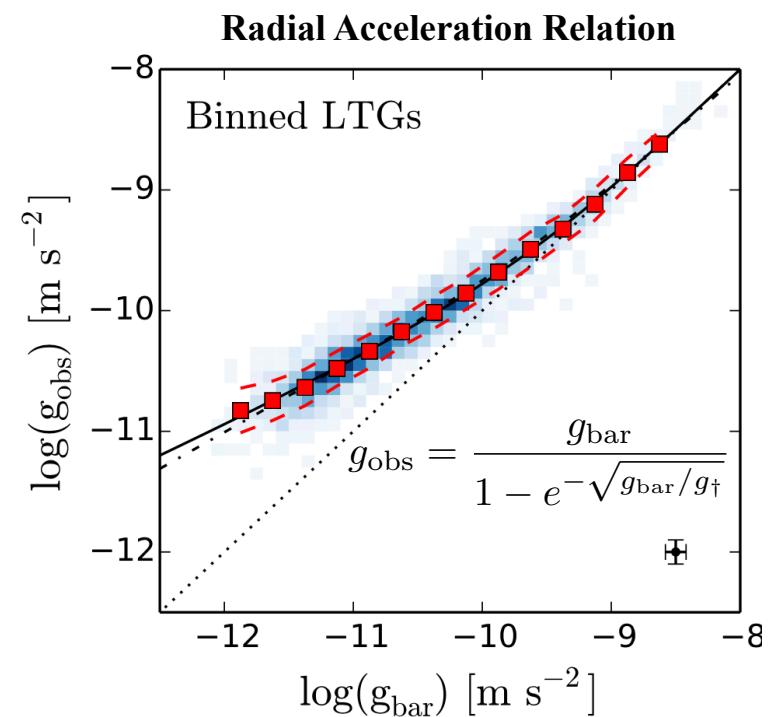
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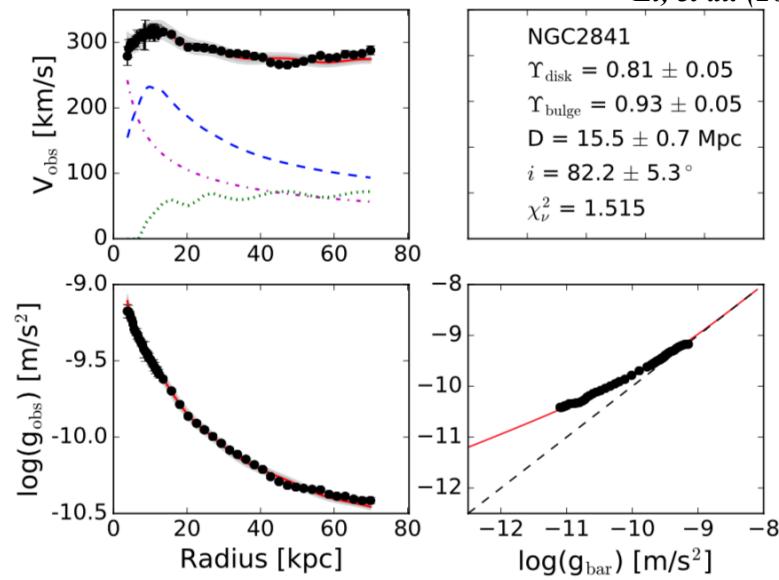


McGaugh, Lelli, Schombert, Pawlowski (2017)

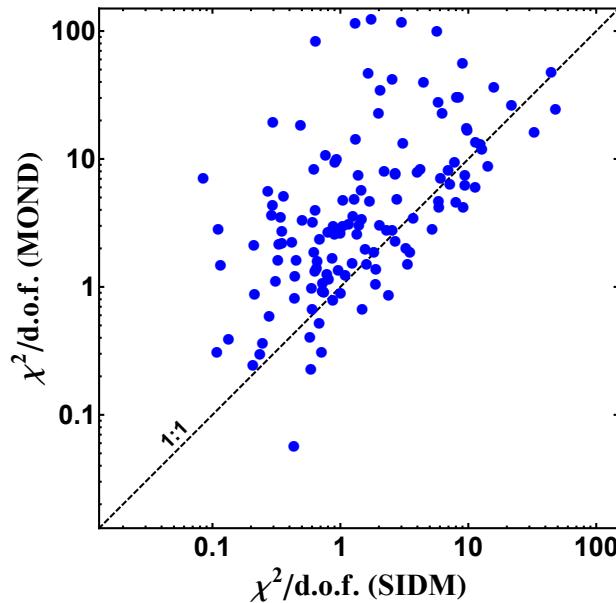
# Fits from SIDM & MOND

## MOND Fit Example

*Li, et al. (2018)*



## Fitting Quality

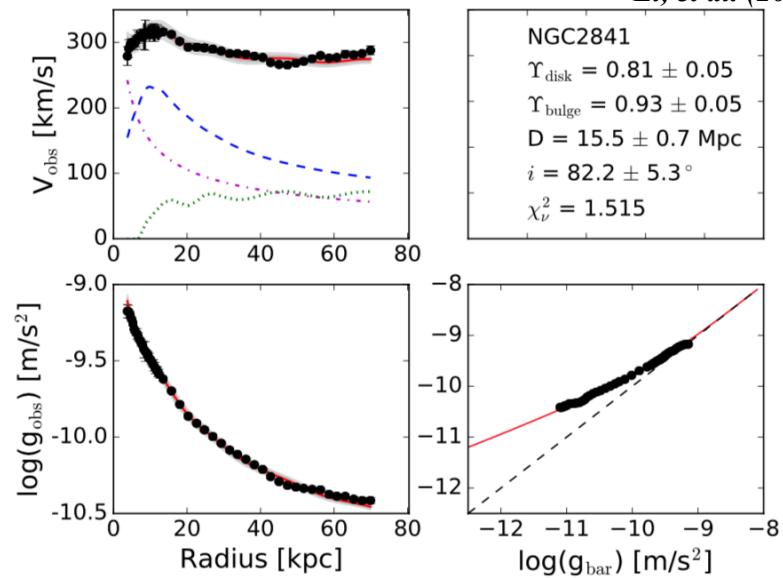


- MOND can fit to rotation curves well.
- SIDM does a better job.

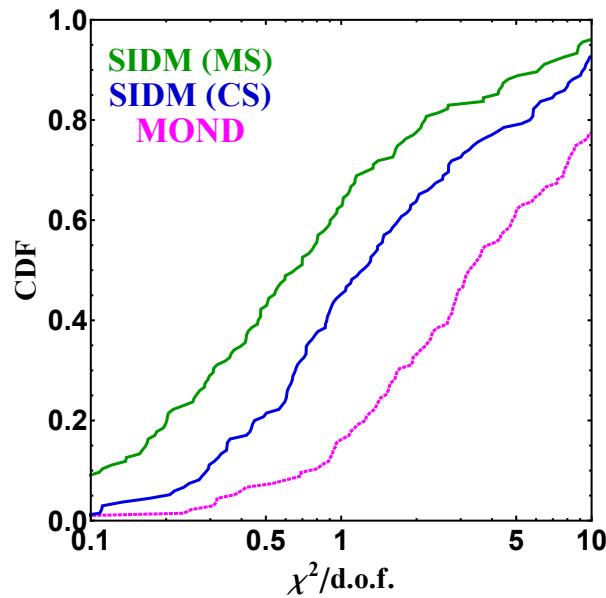
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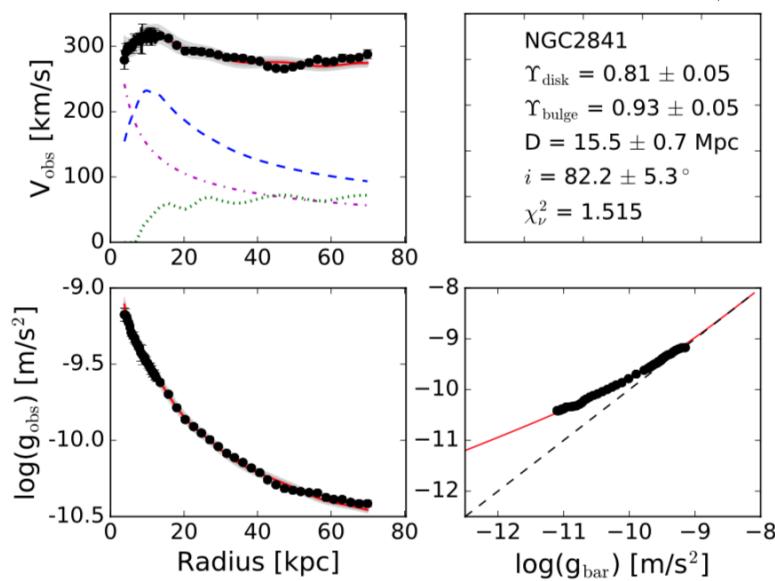


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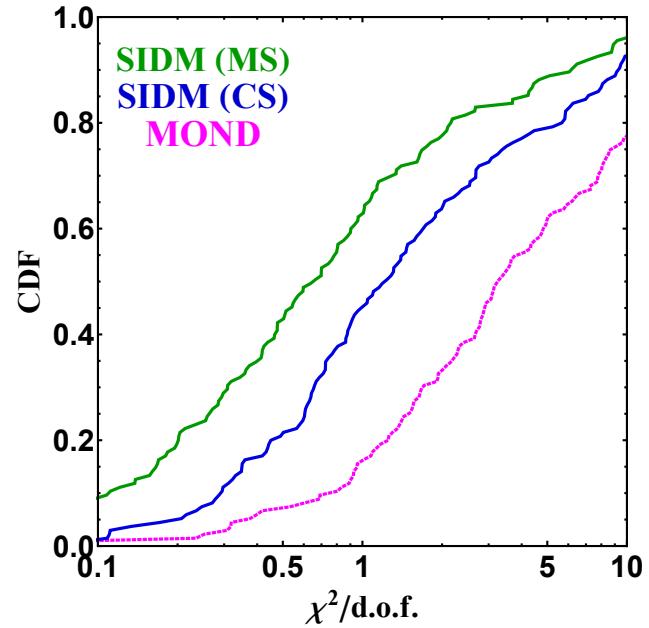
# Fits from SIDM & MOND

## MOND Fit Example

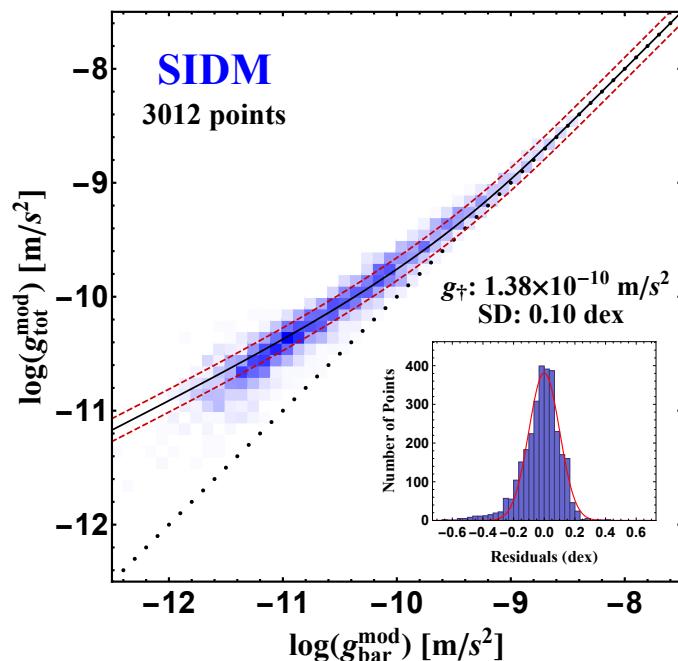
*Li, et al. (2018)*



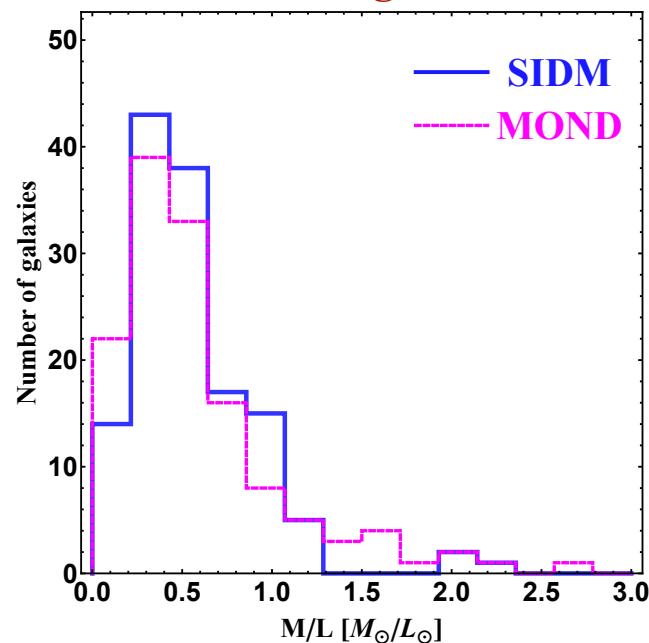
## Fitting Quality



## Radial Acceleration Relation from SIDM



## Mass-to-Light Ratio



# What does MOND tell us in “SIDMish”?

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# What does MOND tell us in “SIDMish”?

---

**SIDM**

**MOND**

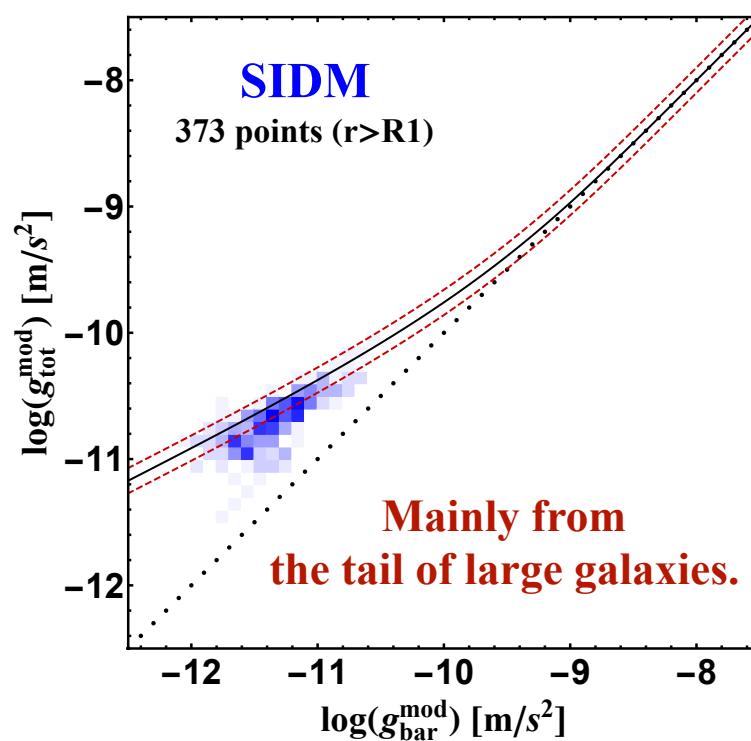
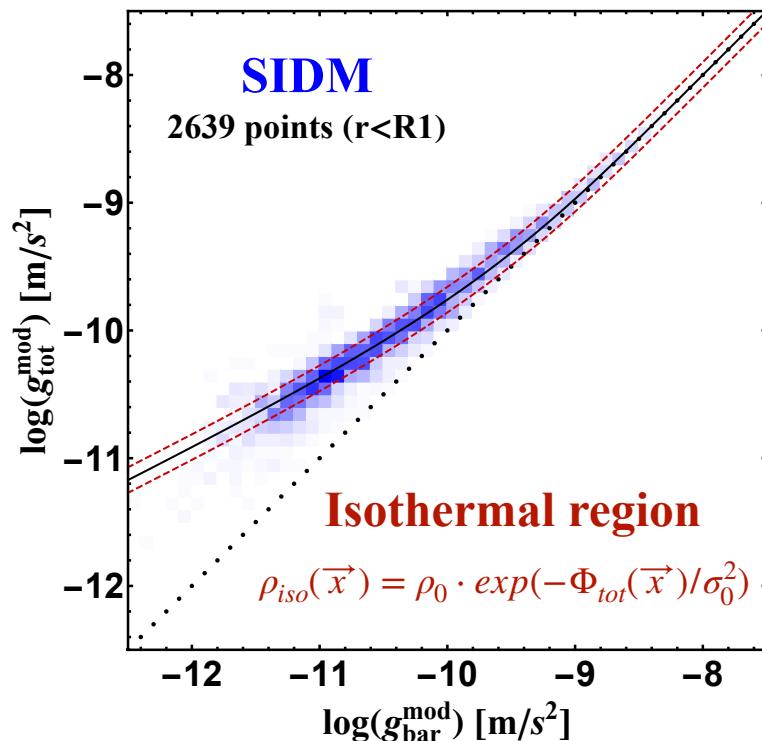


# What does MOND tell us in “SIDMish”?



## First Evidence

- ~88% data points are within isothermal region.
- The radial acceleration relation is largely determined by data in the isothermal region.

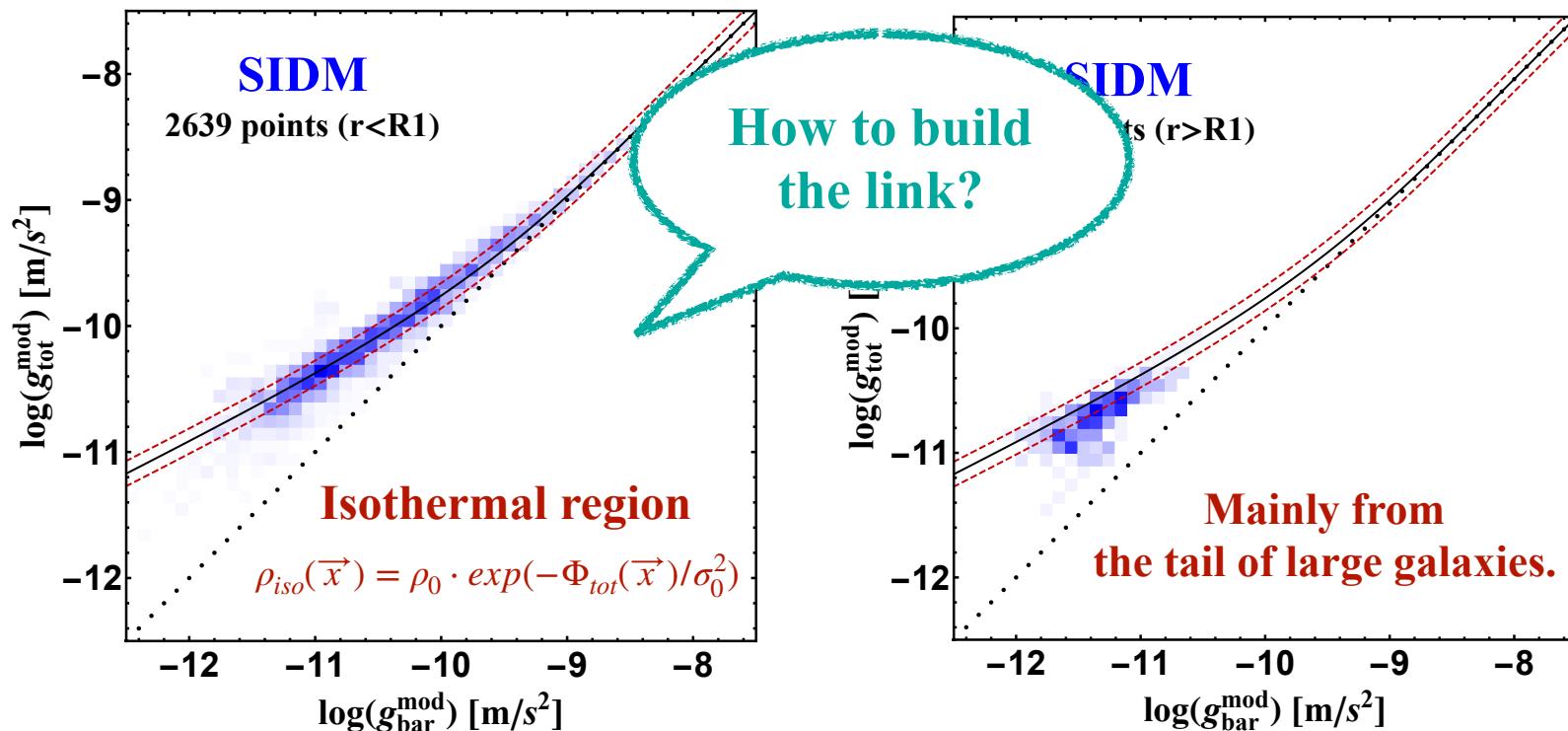


# What does MOND tell us in “SIDMish”?



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# What does MOND tell us in “SIDMish”?

---

**SIDM**



**MOND**

$g_{\text{bar}}$

# What does MOND tell us in “SIDMish”?

**SIDM**

**MOND**



$$g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/g_{\dagger}}}}$$

A mathematical equation for the MOND acceleration  $g_{\text{obs}}$  in terms of the bar acceleration  $g_{\text{bar}}$ . The equation is 
$$g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/g_{\dagger}}}}$$
. To the right of the equation is another blue double-headed arrow pointing to the right, labeled  $g_{\text{bar}}$ .

# What does MOND tell us in “SIDMish”?

**SIDM**

**MOND**



$$g_{\text{tot}} = - \nabla \Phi_{\text{tot}}$$

$$g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/g_{\dagger}}}}$$

$$g_{\text{bar}}$$

# What does MOND tell us in “SIDMish”?

**SIDM**

**MOND**

Observations:  
Rotation Curves

$$\rho_{\text{iso}} = \rho_0 \cdot e^{-\frac{\Phi_{\text{tot}}}{\sigma_0^2}} \quad g_{\text{tot}} = -\nabla \Phi_{\text{tot}} \quad g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/g_{\dagger}}}} \quad g_{\text{bar}}$$

# What does MOND tell us in “SIDMish”?

**SIDM**



**MOND**

$$\rho_{\text{iso}} = \rho_0 \cdot e^{-\frac{\Phi_{\text{tot}}}{\sigma_0^2}}$$

$$g_{\text{tot}} = -\nabla \Phi_{\text{tot}}$$

$$g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/g_{\dagger}}}}$$

$$g_{\text{tot}} = g_0 \cdot f(r_n)$$

$$\left\{ \begin{array}{l} g_0 = \frac{\sigma_0^2}{r_d}, \quad r_n = r/r_d \\ f(r_n) = \left| \frac{\log \text{Slope}(r_n)}{r_n} \right| \\ \log \text{Slope}(r_n) = \frac{d \ln(\rho_{\text{iso}})}{d \ln(r)} \end{array} \right.$$

$g_{\text{bar}}$  dependence through  $g_{\text{bar}}(r_n)$

$$g_{\text{obs}} = g_{\dagger} \cdot f(x)$$

$$\left\{ \begin{array}{l} x = g_{\text{bar}}/g_{\dagger} \\ f(x) = \frac{x}{1 - \exp(-\sqrt{x})} \end{array} \right.$$

- **(a characteristic acceleration)  $\times$  (a dimensionless function)**
- The characteristic acceleration and dimensionless function in SIDM is different for each galaxy.
- The connection at this level has been shown in RAR.

# What does MOND tell us in “SIDMish”?

**SIDM**



**MOND**

$$\rho_{\text{iso}} = \rho_0 \cdot e^{-\frac{\Phi_{\text{tot}}}{\sigma_0^2}}$$

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g<sub>bar</sub> dependence through g<sub>bar</sub>(r<sub>n</sub>)

$$g_{\text{obs}} = g_{\dagger} \cdot f(x)$$

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# What does MOND tell us in “SIDMish”?

**SIDM**



**MOND**

$$\rho_{\text{iso}} = \rho_0 \cdot e^{-\frac{\Phi_{\text{tot}}}{\sigma_0^2}}$$

$$g_{\text{tot}} = -\nabla \Phi_{\text{tot}}$$

$$g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/g_{\dagger}}}}$$

$$g_{\text{bar}}$$

$$g_{\text{tot}} = g_0 \cdot f(r_n)$$

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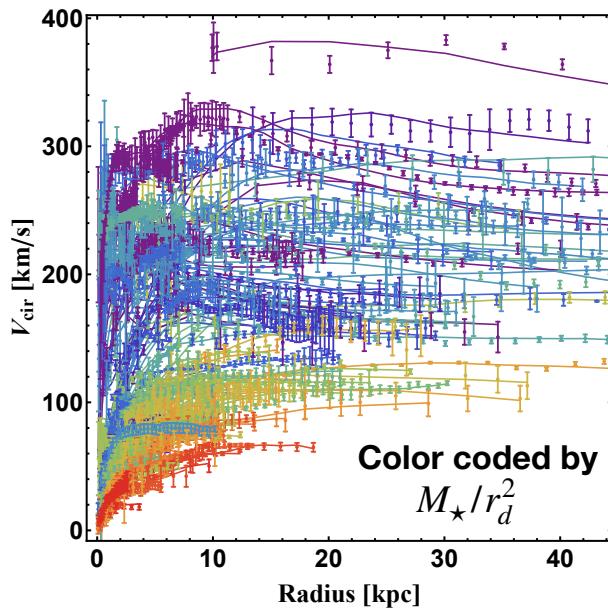
$$\left\{ \begin{array}{l} x = g_{\text{bar}}/g_{\dagger} \\ y = g_{\text{obs}}/g_{\dagger} \\ f(x) = \frac{x}{1 - \exp(-\sqrt{x})} \end{array} \right. \implies y = \frac{x}{1 - \exp(-\sqrt{x})}$$

- SIDM & MOND connection  $\implies g_{\text{tot}}/g_0$  &  $g_{\text{bar}}/g_0$  correlation
- Correlation similar to the MOND function

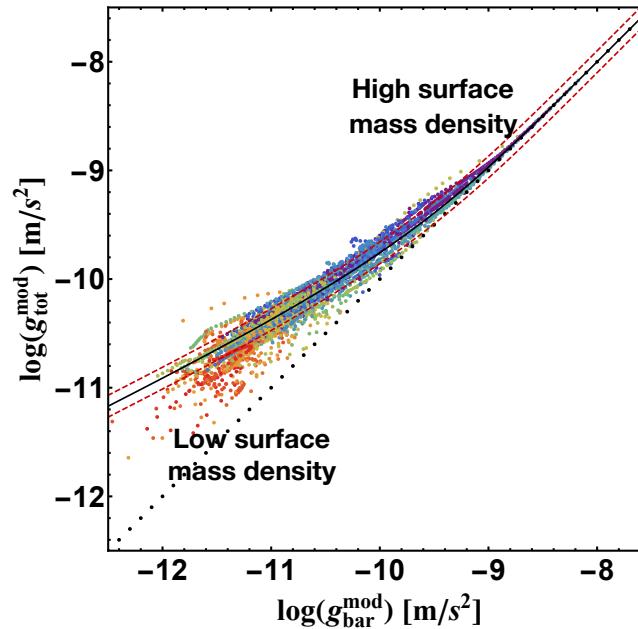


# What does MOND tell us in “SIDMish”?

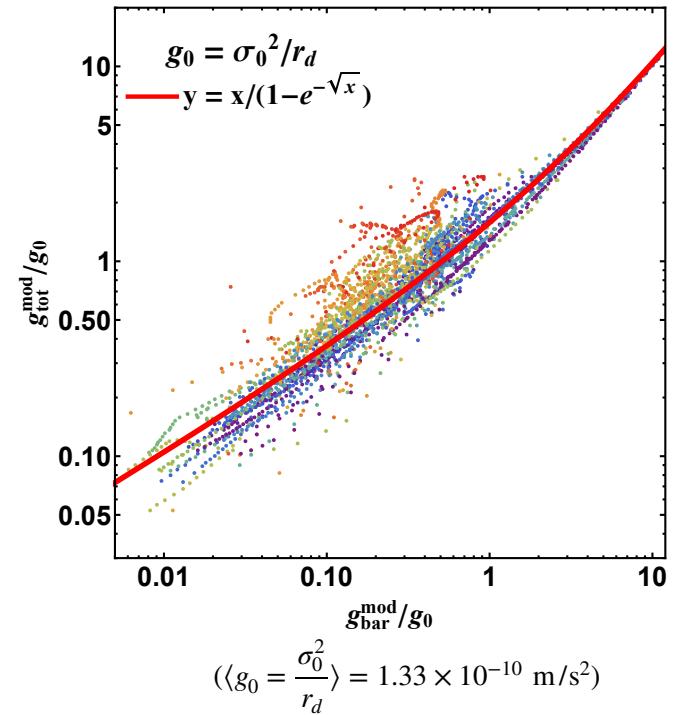
Rotation Curves w/ SIDM Fits



Radial Acceleration Relation



New Correlation



## In SIDM Framework:

- The RAR is a reflection of the coupling between dark matter and baryon through thermalization.
- The tight correlation captured by MOND formalism is actually telling us how the baryon will effect the dark matter profile (e.g. slope).

# Content

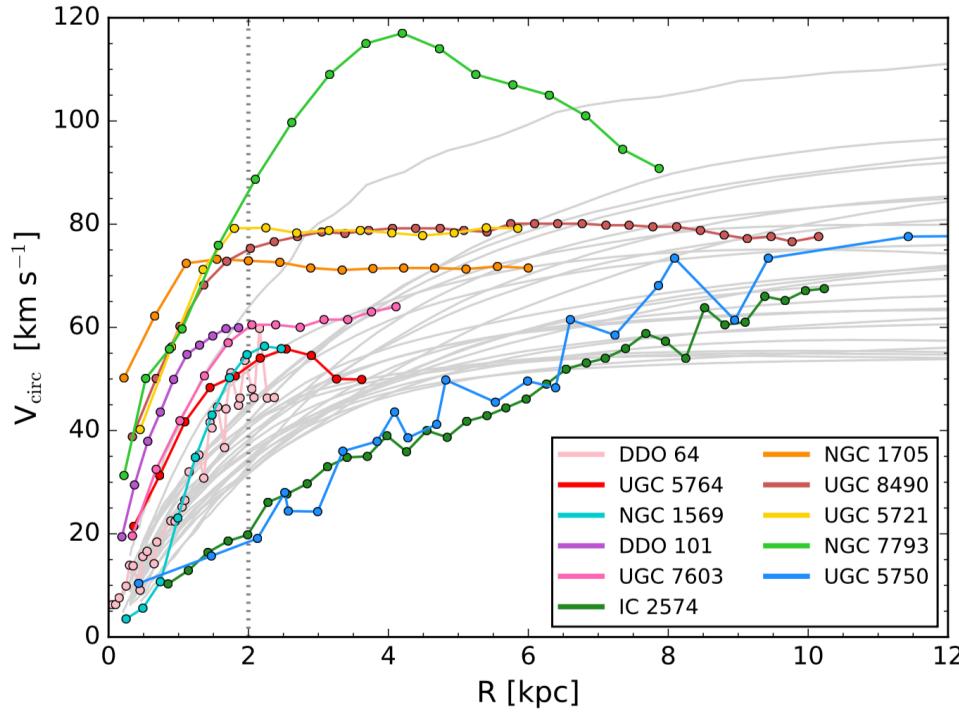
---

- Research Background
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Uniformity } of Galactic Rotation Curves
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# Outliers from Simulations

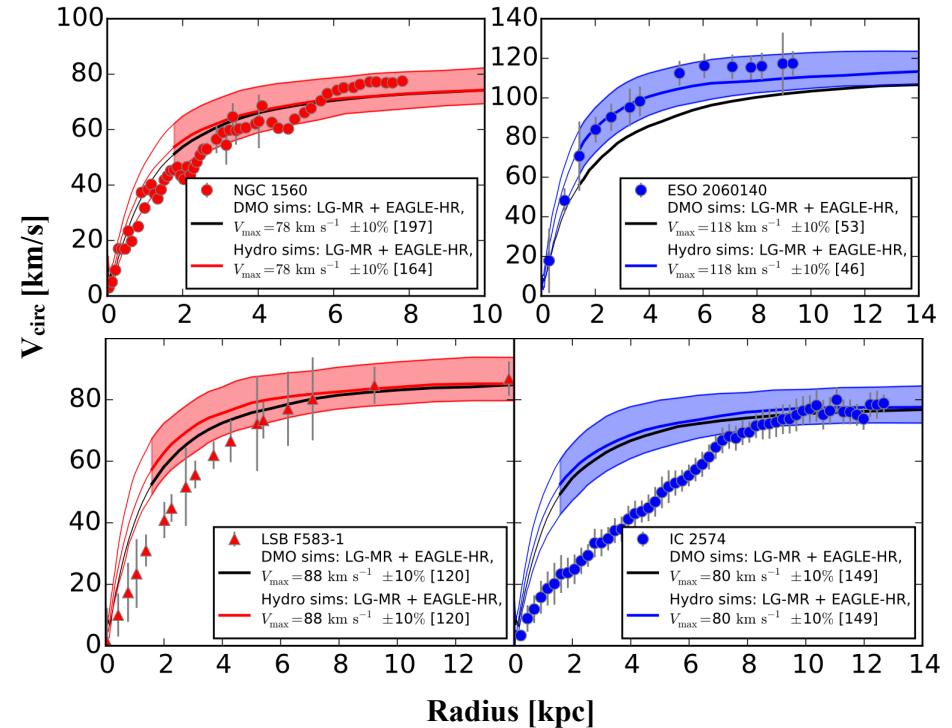
## NIHAO Simulations

Santos-Santos, et al. (2017)



## EAGLE Simulations

Oman, et al. (2015)



Two opposite cases for baryon feedback effect

### • NIHAO:

- Barely cover the shallow ones
- Hard to reach the steep ones
- Feedback is too strong

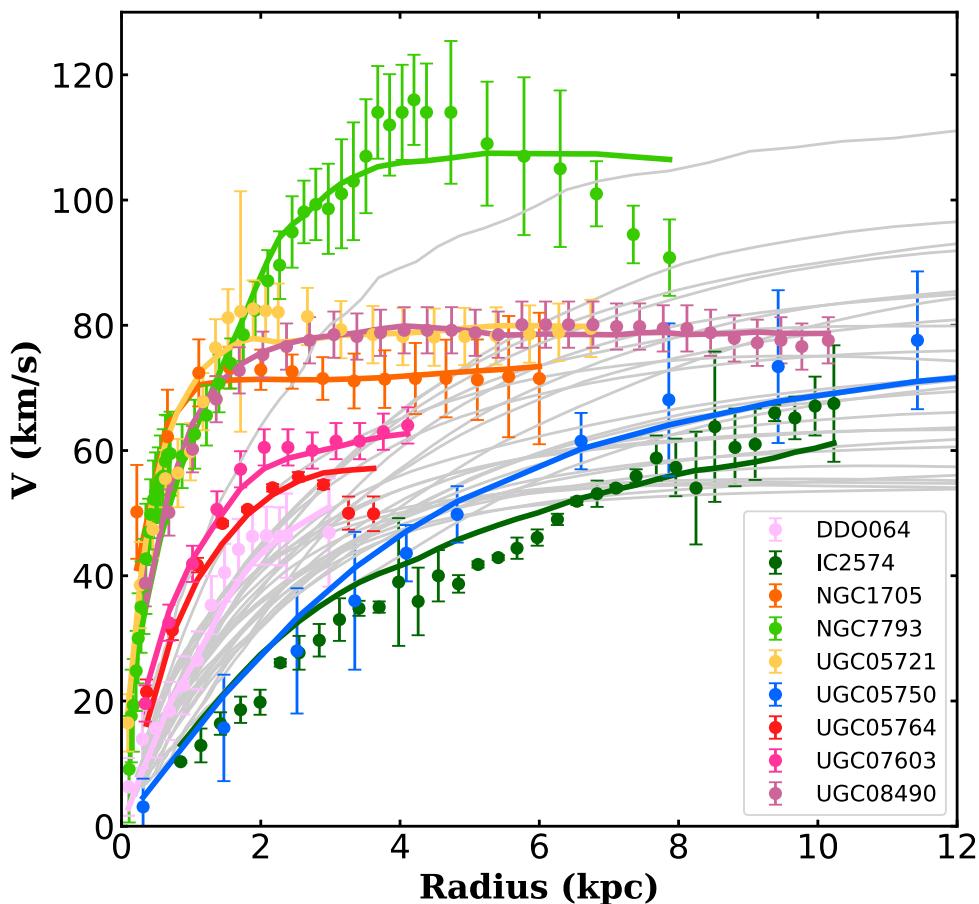
### • EAGLE:

- Cover the steep ones
- Hard to reach the shallow ones
- Too much mass in the central region

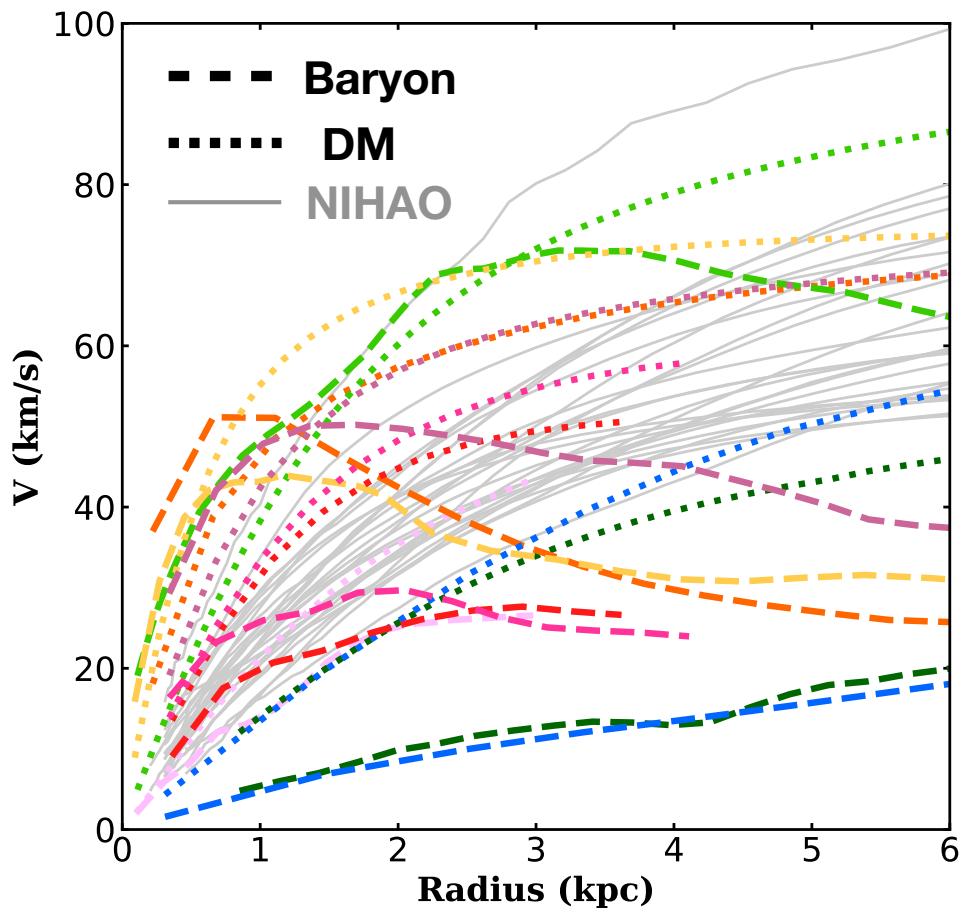
# SIDM vs NIHAO (CDM) Simulations

Ren, Kaplinghat, Yu, (2019, in preparation)

## SIDM Fits to the Outliers



## Components in SIDM Fits

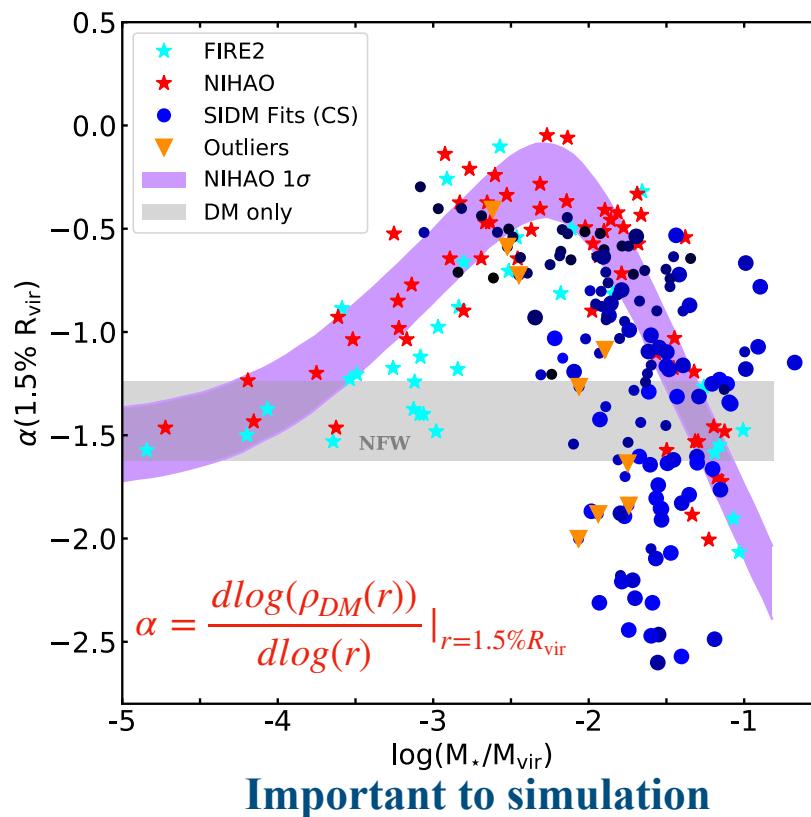


- SIDM gives excellent fits to the outliers from NIHAO
- Some baryon profiles are steeper than total ones from NIHAO
- Correlation between baryon profiles and dark matter profiles

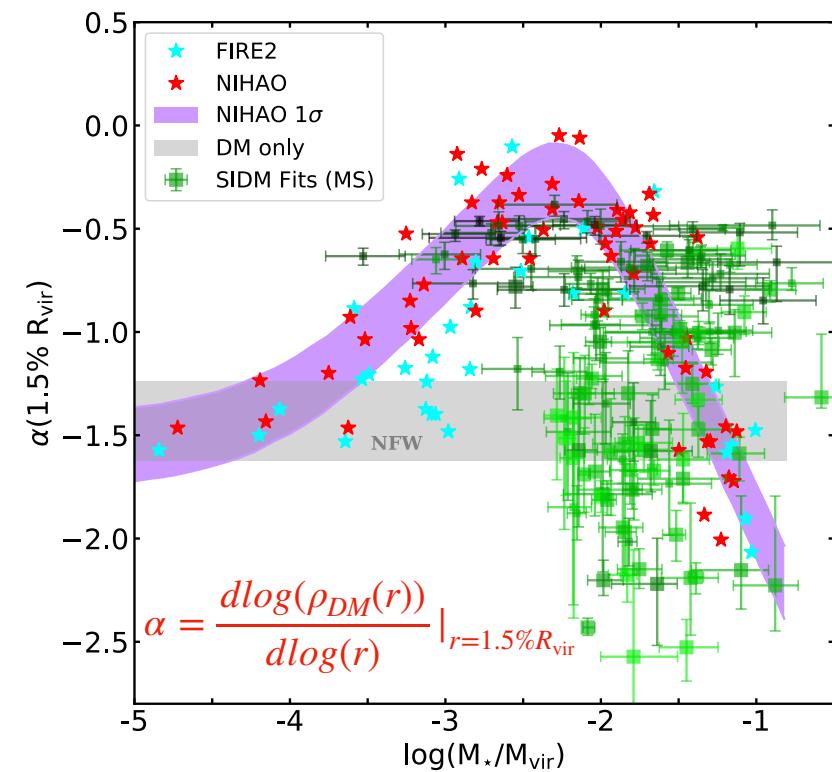
# Inner Dark Matter Density Profiles

*Ren, Kaplinghat, Yu, (2019, in preparation)*

Reflect baron effect



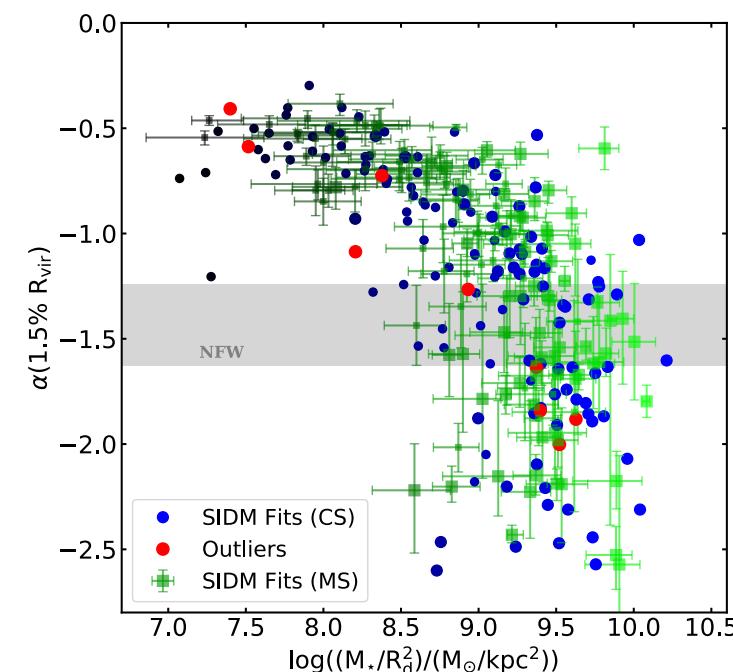
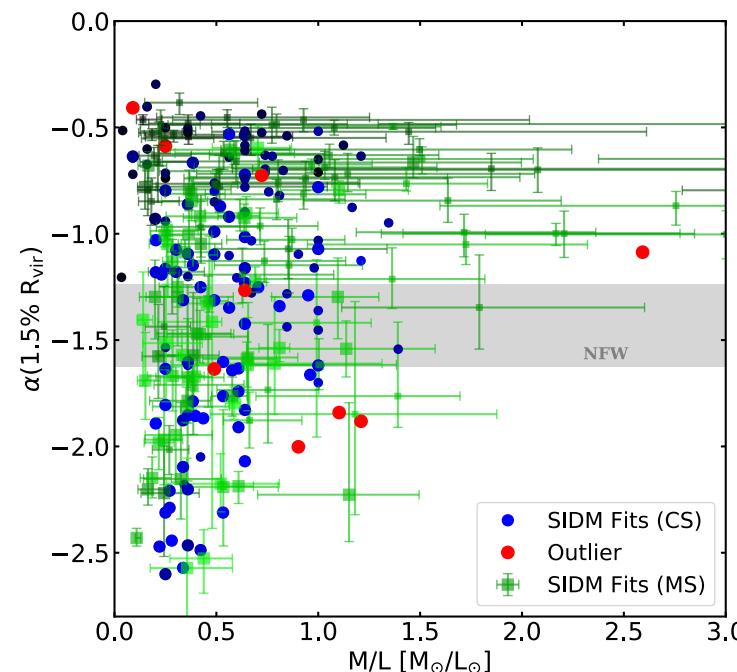
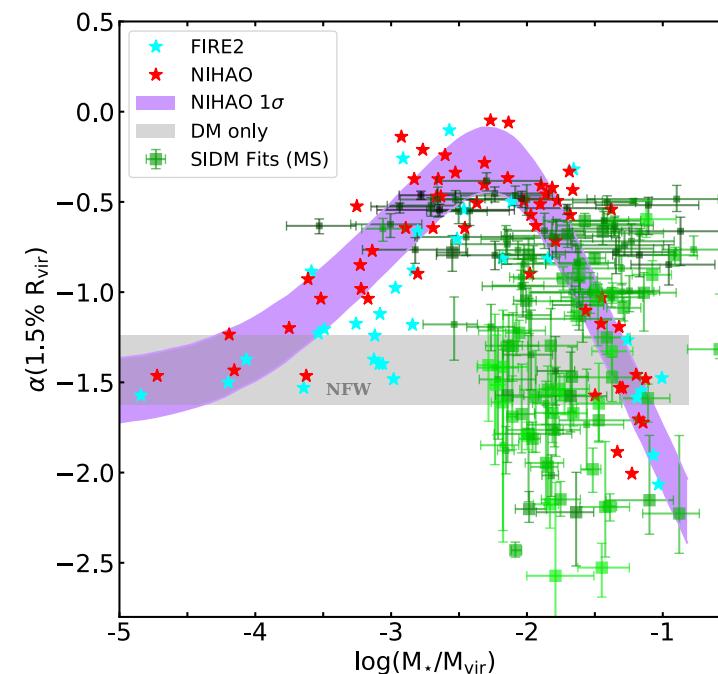
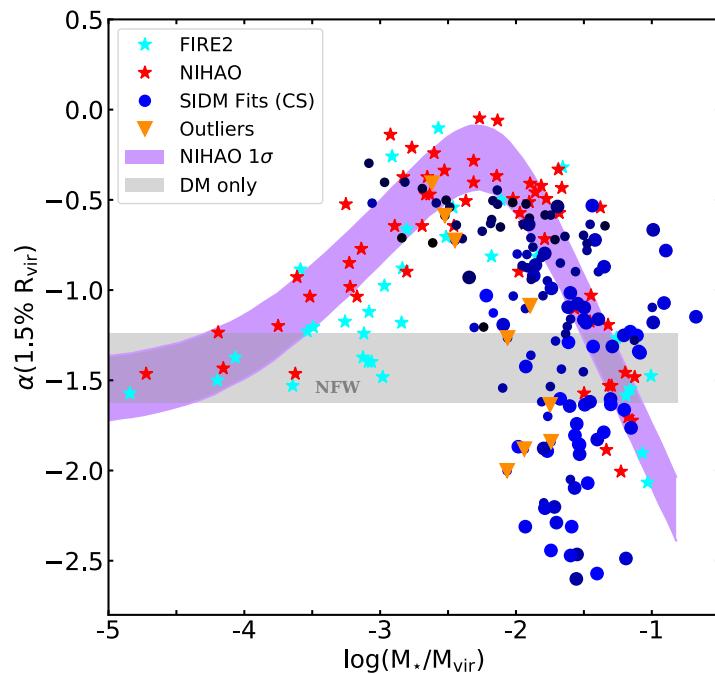
Important to simulation



- The purple band is a result of two competing effect: feedback & contraction in CDM framework
- By fitting to rotation curves, SIDM data shows wide spread in log-slope value

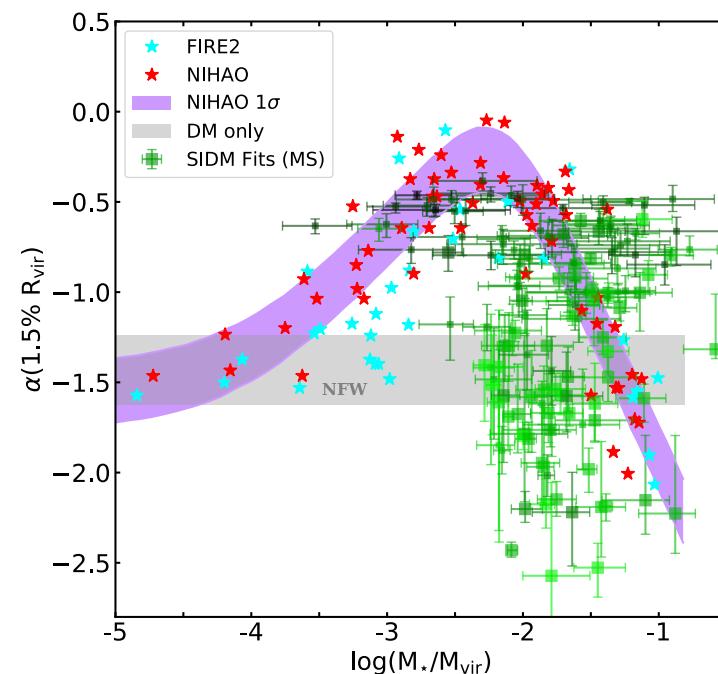
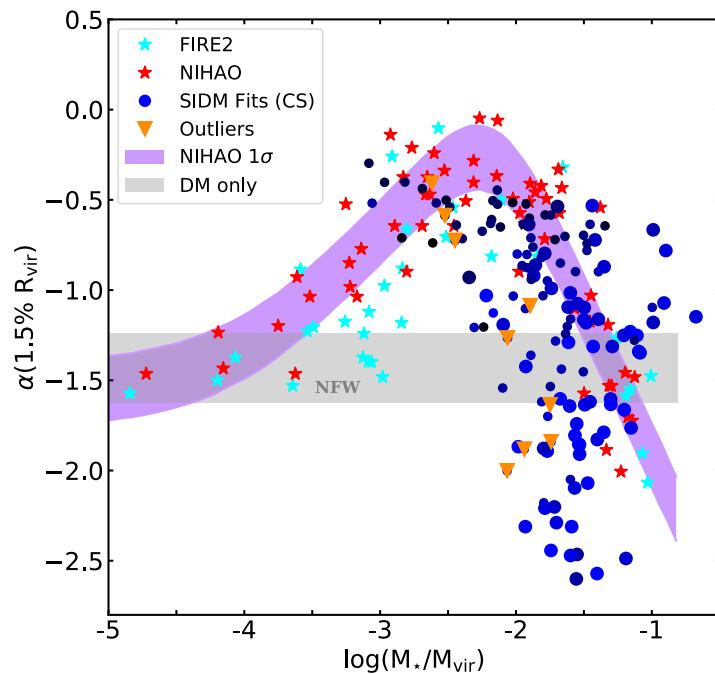
# Correlations

*Ren, Kaplinghat, Yu, (2019, in preparation)*

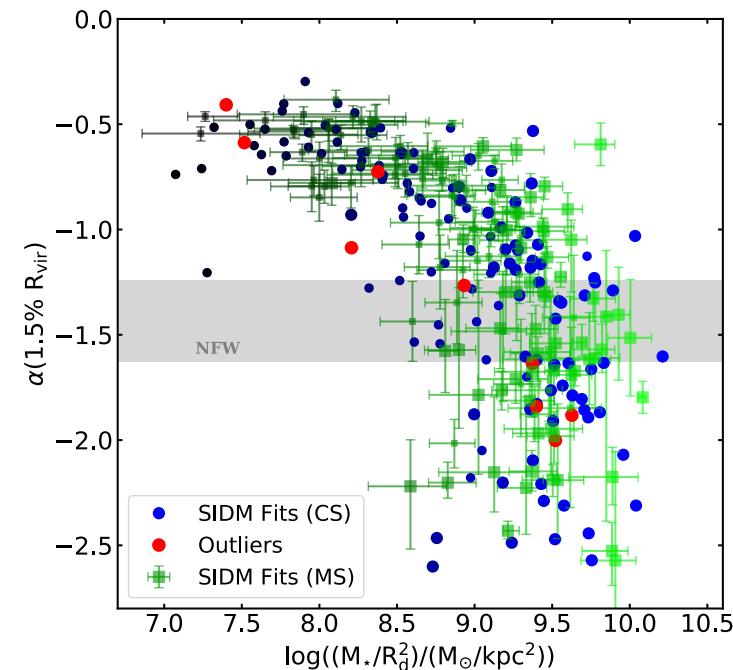


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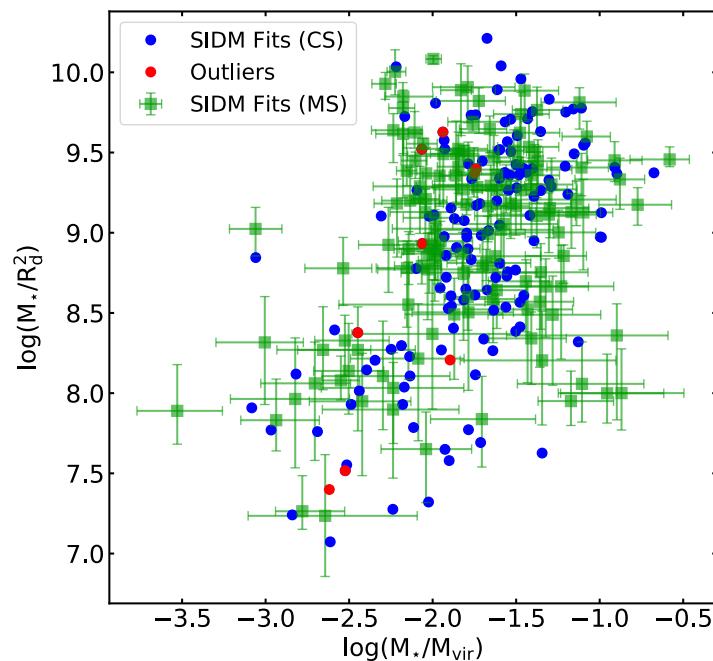
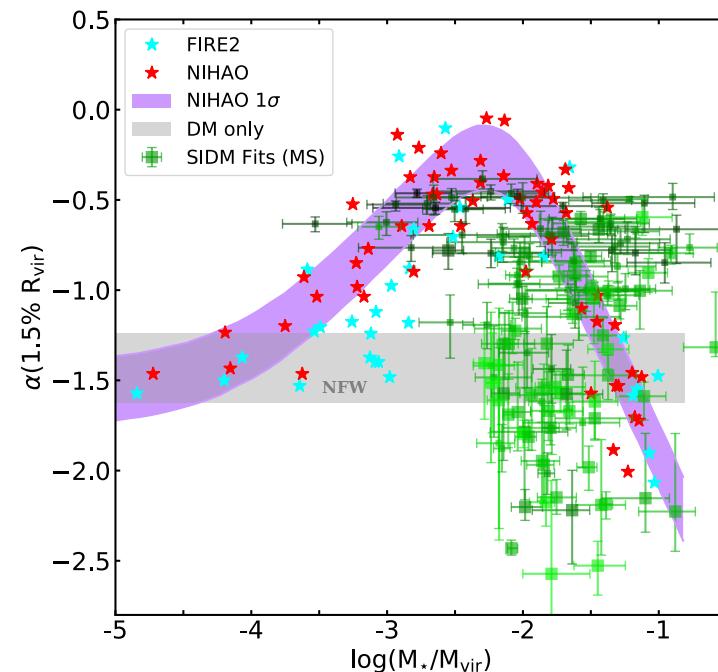
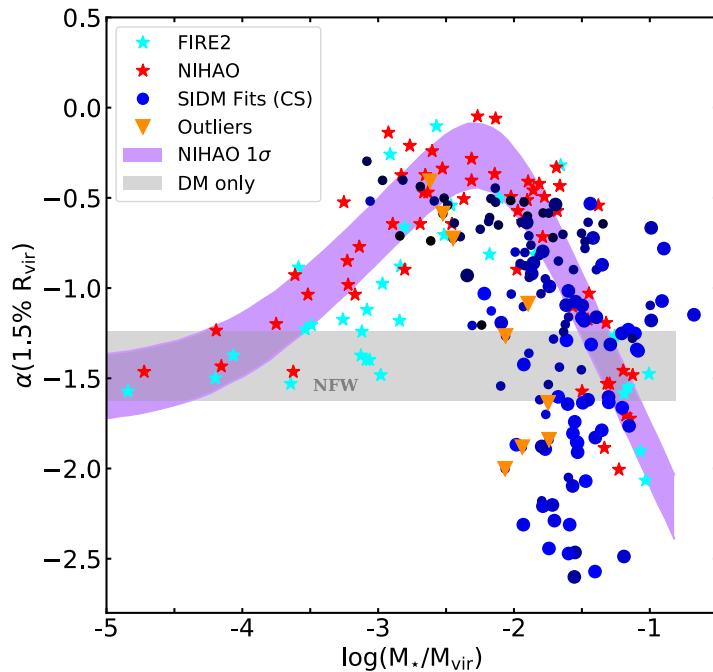


- $\rho_{\text{iso}}(\vec{r}) = \rho_0 \times \exp[-(\Phi_{\text{DM}}(\vec{r}) + \Phi_{\text{Bar}}(\vec{r}))/\sigma_{v0}^2]$
- $M_*/R_d^2 \leftrightarrow \text{Surface mass density} \leftrightarrow \Phi_{\text{bar}}$
- Different systems, different weights for  $\Phi_{\text{DM}}$  &  $\Phi_{\text{bar}}$

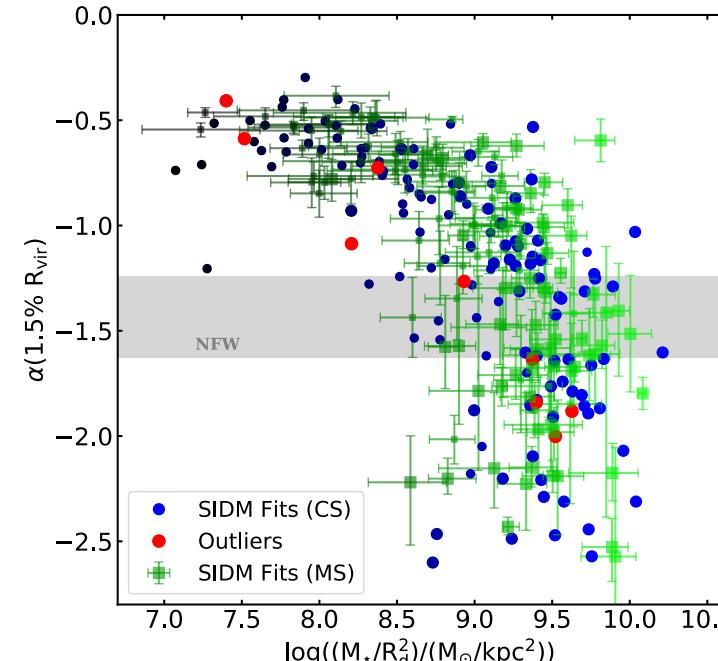


# Correlations

*Ren, Kaplinghat, Yu, (2019, in preparation)*



SIDM  $\implies$  CDM

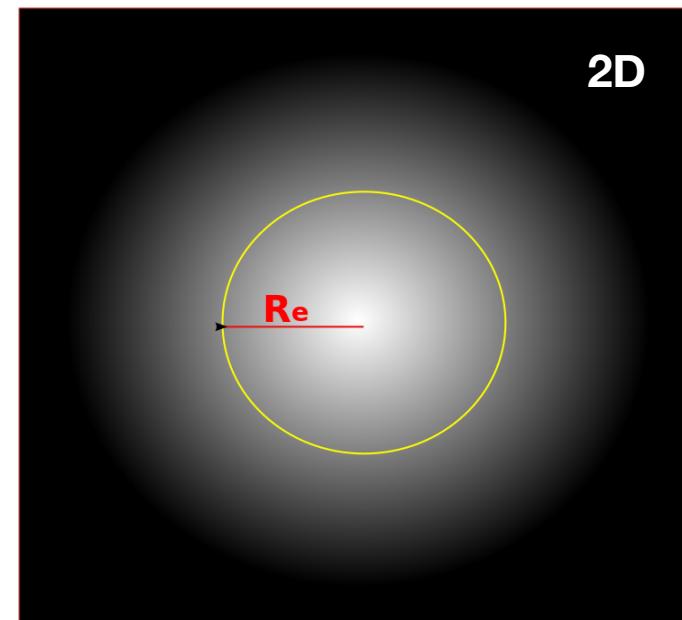
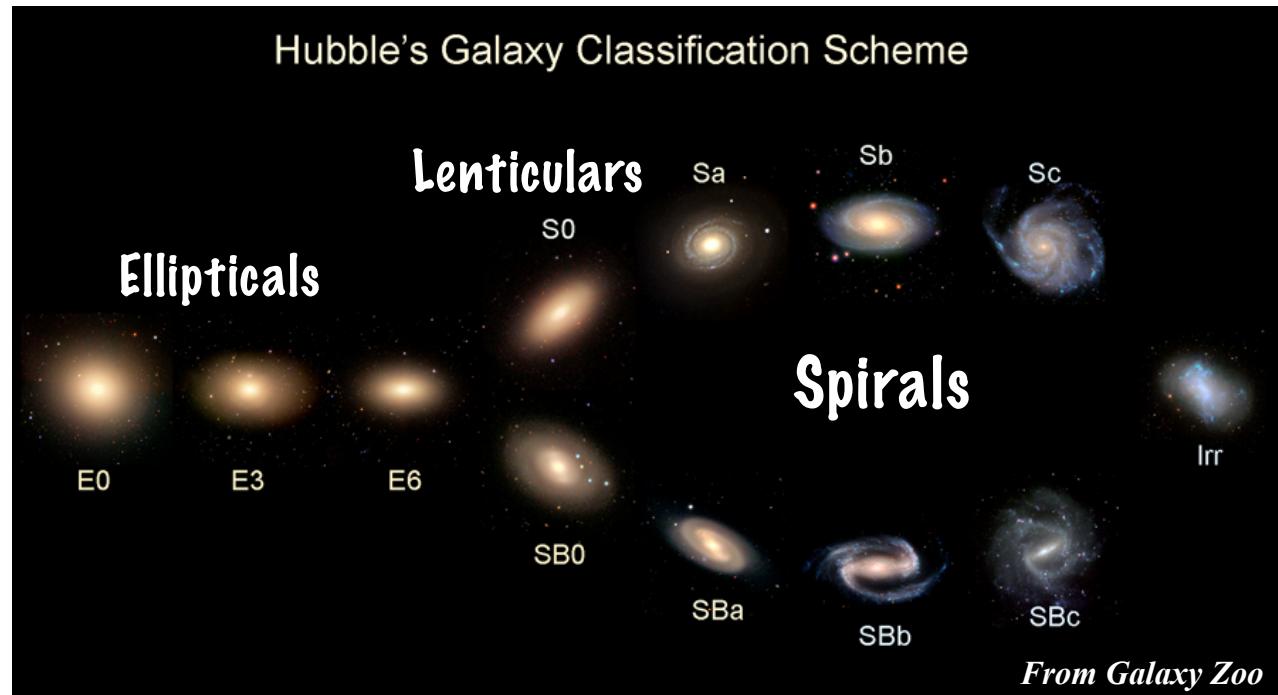


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# Introduction to Early-Type Galaxy (ETG)



- Early-Type Galaxies = Ellipticals + Lenticulars
- ETGs are much rounder, more smooth, featureless and pressure supported
- ETGs have very little gas left for star formation and lack HI gas for dynamical study
- ETGs are good places to study baryon contraction effect

Effective radius  $R_e$  (2D):  
enclose  
half of the total light

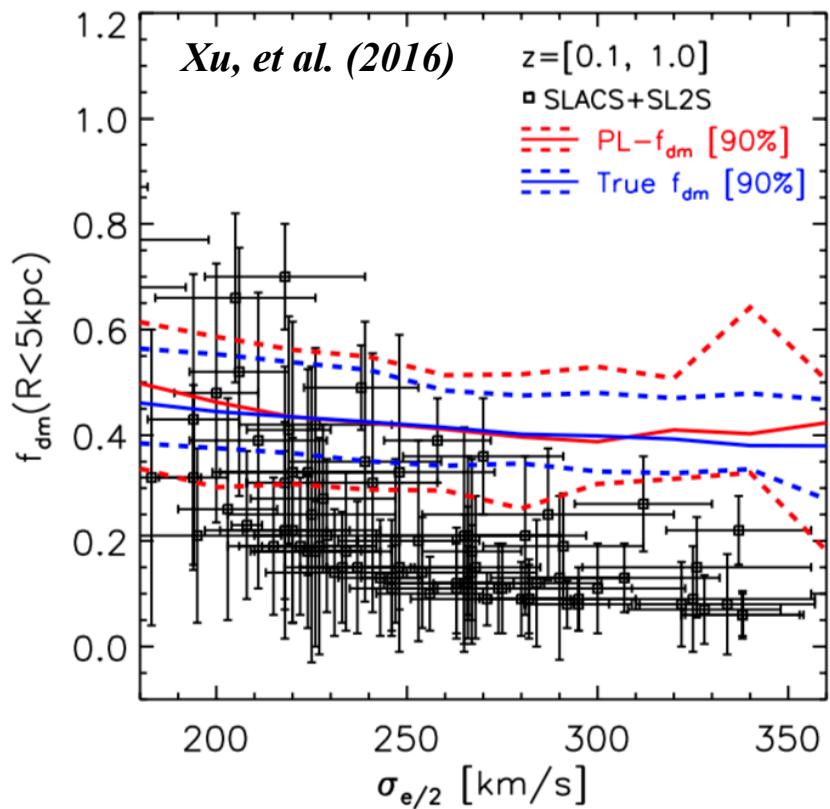
**Sersic profile:** **Surface mass density**

$$\Sigma(R) = \Sigma_0 \times \exp\left(-b_n\left(\frac{R}{R_e}\right)^{1/n}\right)$$
$$b_n = 2n - 1/3 + 0.009876/n$$
$$\rho_{\text{bar}}(r) = -\frac{1}{\pi} \int_r^{\infty} \frac{dR}{\sqrt{R^2 - r^2}} \frac{d\Sigma}{dR}$$

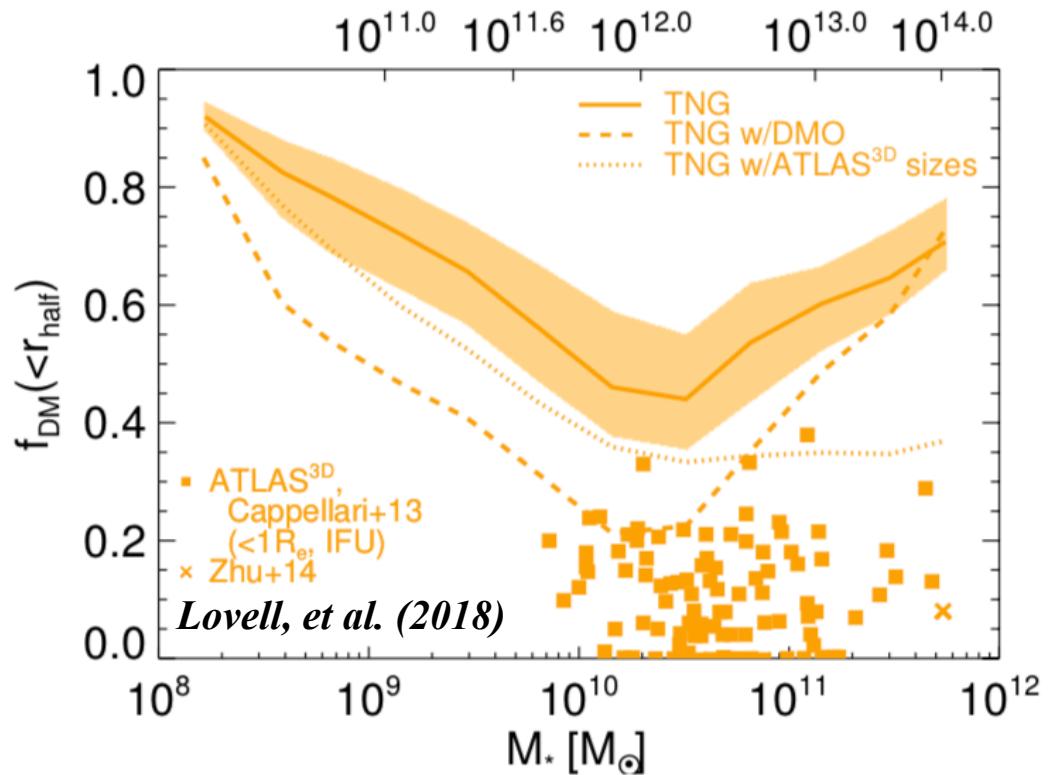
**Inverse Abel transformation**

# Dark Matter Fraction in ETGs

## Illustris Simulations



## IllustrisTNG Simulations



- Dark matter fractions from observations (strong lensing and stellar kinematics) are systematically lower than simulation results.

## SIDM w/ Spherical Symmetry

$$\sigma/m = 0.8 \text{ cm}^2/\text{g}$$

$$\rho_{iso}(\vec{x}) = \rho_0 \cdot \exp(-\Phi_{tot}(\vec{x})/\sigma_0^2)$$

$$\nabla^2 \Phi_{tot} = 4\pi G(\rho_{iso} + \rho_b)$$

$$\rho_{\text{SIDM}}(r) = \begin{cases} \rho_{\text{iso}}(r), & r < r_1 \\ \rho_{\text{NFW}}(r), & r > r_1 \end{cases}$$

## Adiabatic Contraction for CDM Halo

$$M(\bar{r})r = \text{const.} \quad \bar{r} = Ar^w$$

$$(M_{DM}(\bar{r}_f) + M_B(\bar{r}_f)) \cdot r_f = (M'_{DM}(\bar{r}_i) + M'_B(\bar{r}_i)) \cdot r_i$$

with  $A \approx 0.85 \pm 0.05$   $w = 0.8 \pm 0.02$

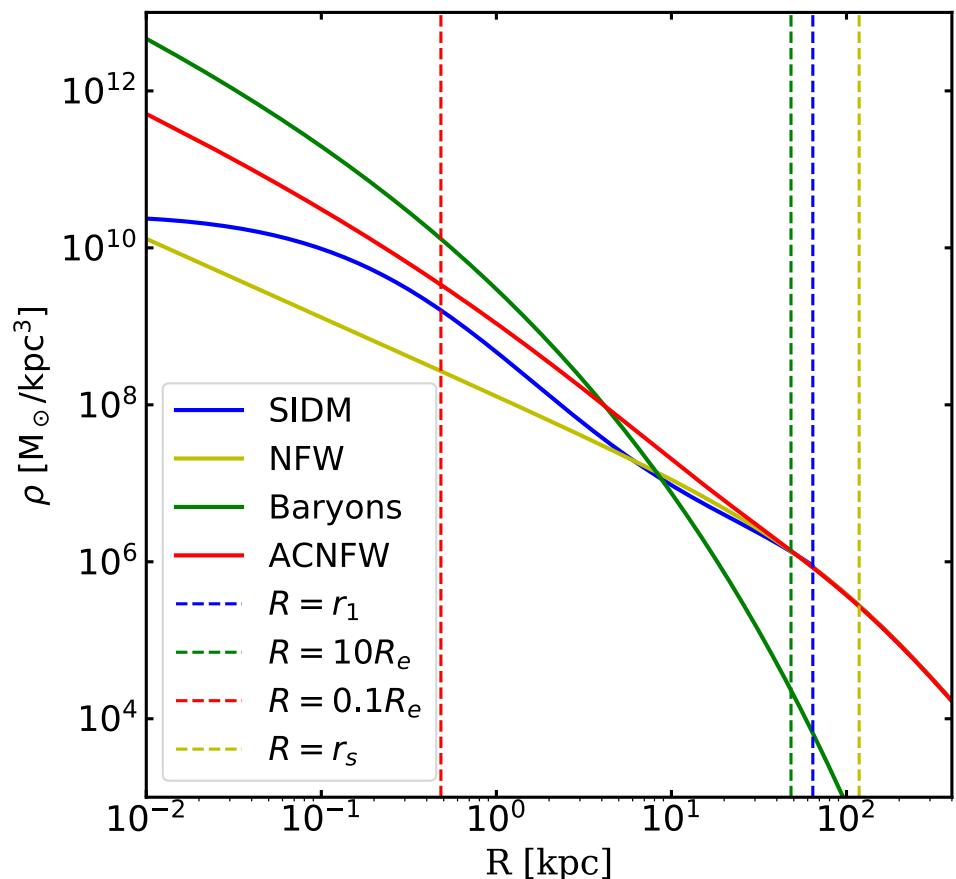
*Gnedin, et al. (2004)*

## Data Source: SL2S

Parameters of 29 ETGs based on Strong Lensing and Stellar Kinematics Analysis.

*Sonnenfeld, et al. (2015)*

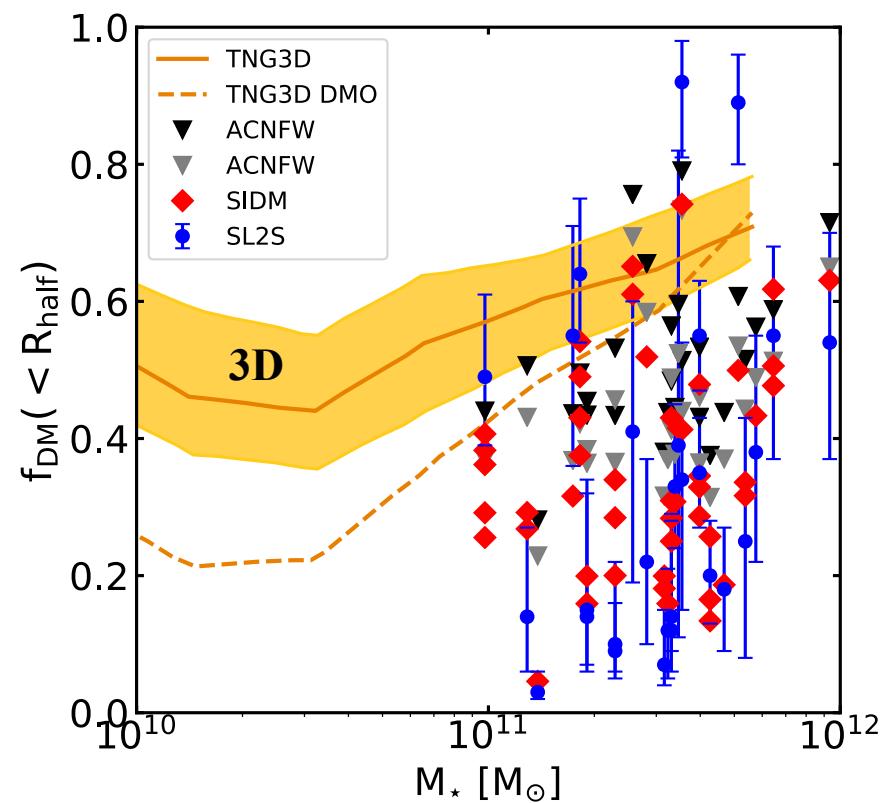
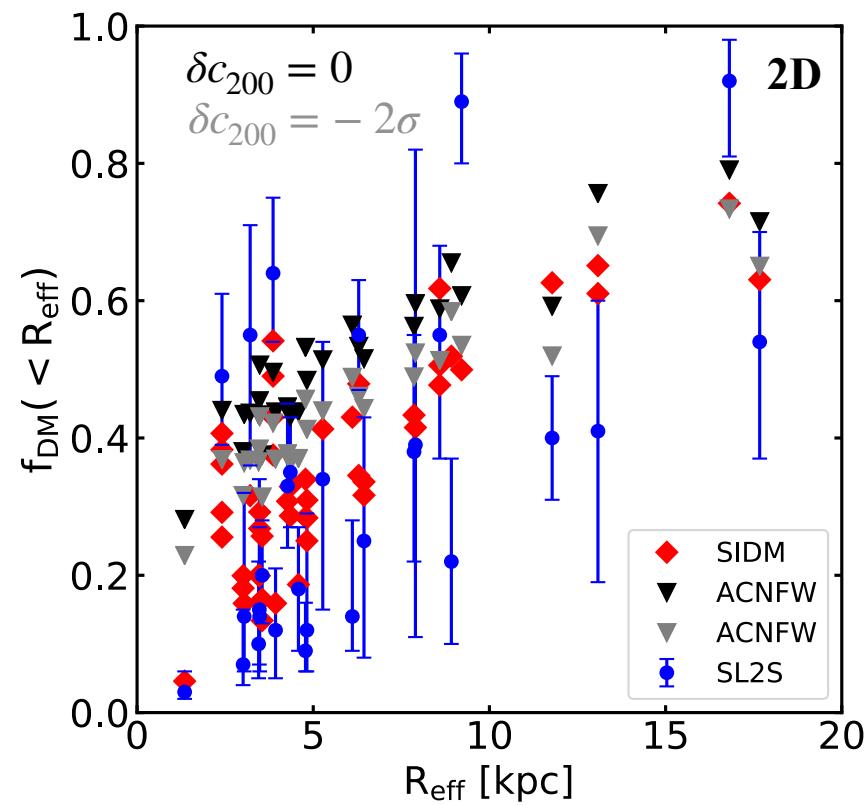
## Different Density Profiles



- Stellar density drops much faster
- SIDM and ACNFW profile match onto NFW
- ACNFW is contracted more than SIDM

# Dark Matter Fraction in ETGs

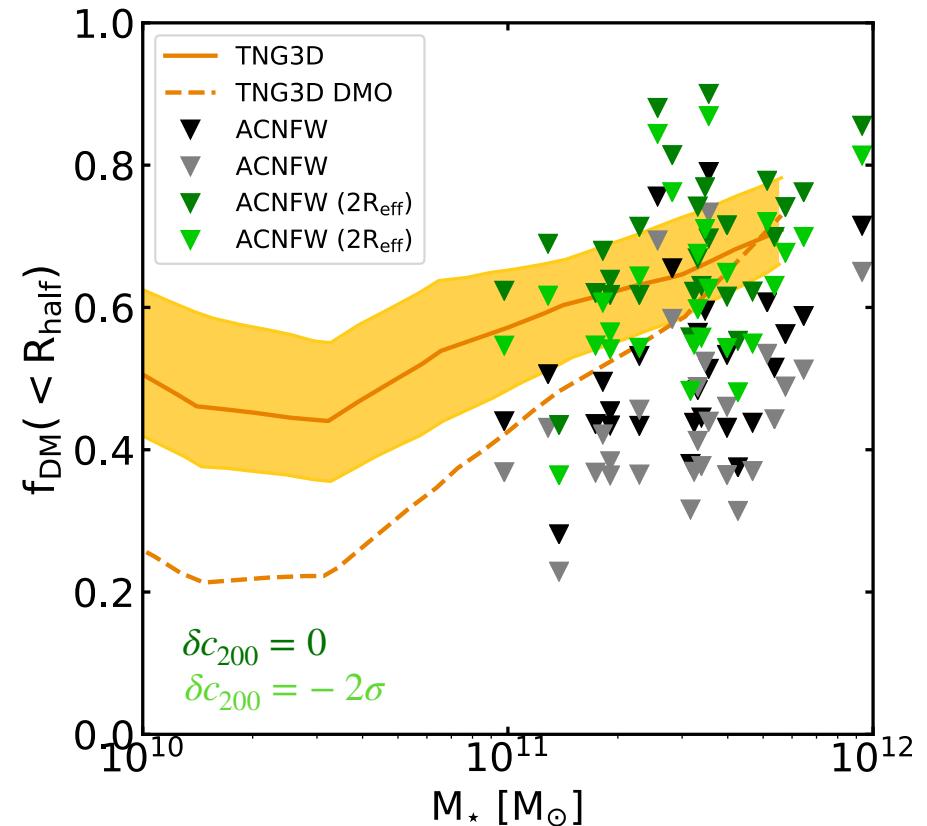
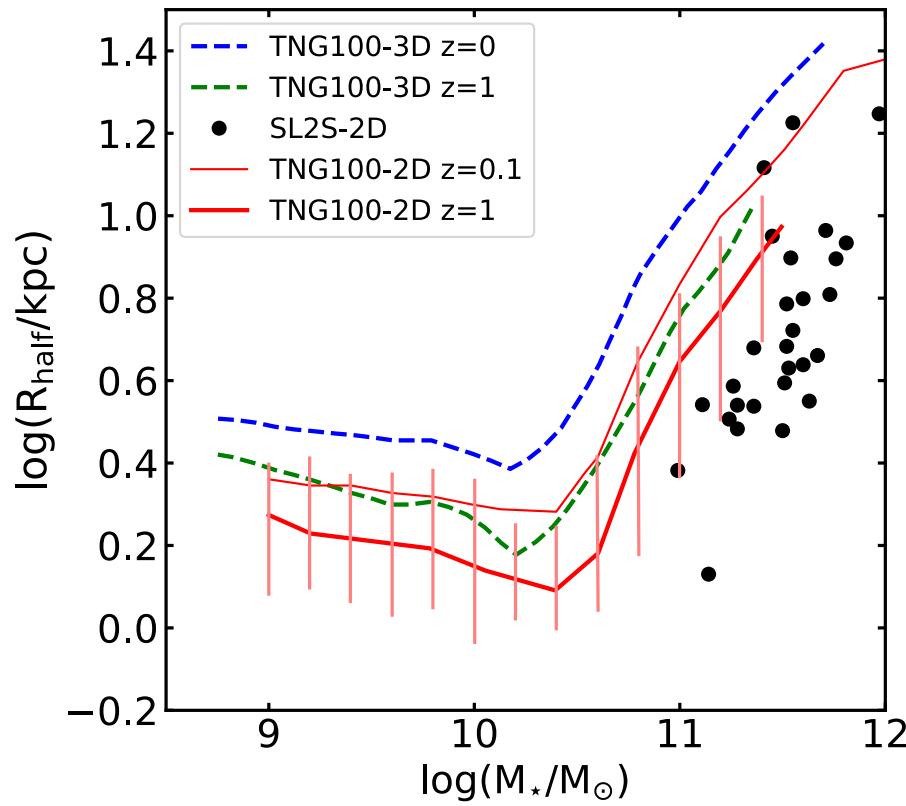
*Ren, Kaplinghat, Yu, (in progress)*



- Dark matter fractions increase with  $R_{\text{eff}}$
- SIDM results are much diverse and agree better with data, not perfect
- TNG results are systematically higher than those from data, SIDM and ACNFW

# Different Baryon Profiles

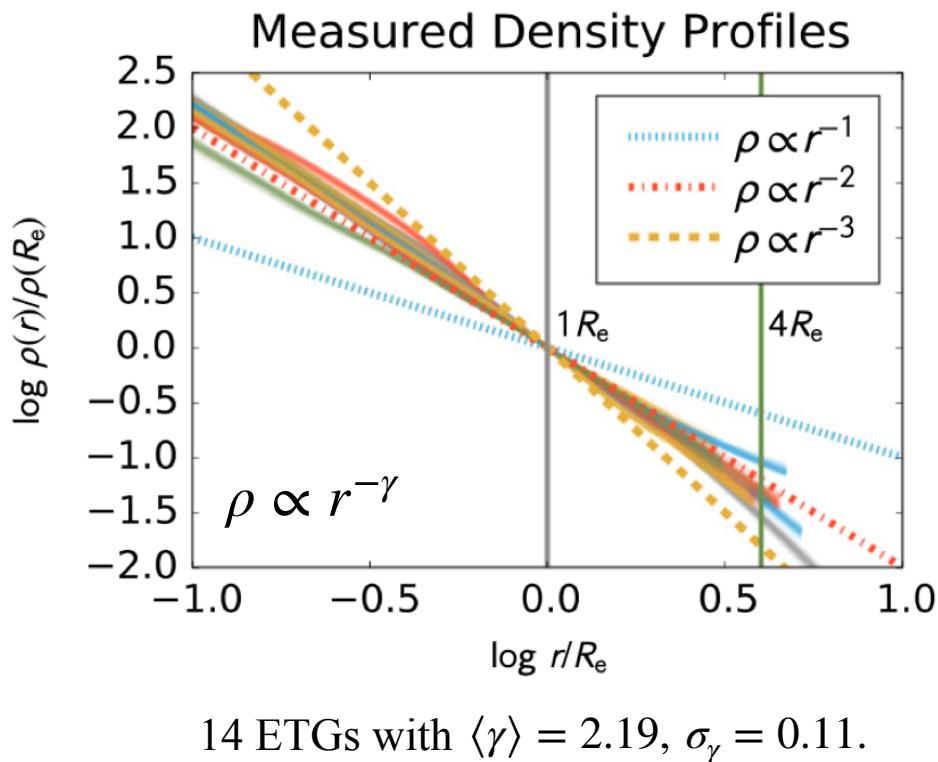
Ren, Kaplinghat, Yu, (in progress)



- **3D half mass radius is larger than 2D ones**
- **Half mass radii from the simulation are systematically larger than those from observation**
- **The ETGs in simulations are more extended than those from observation**
- **Similar problems of baryon distributions as in spirals**

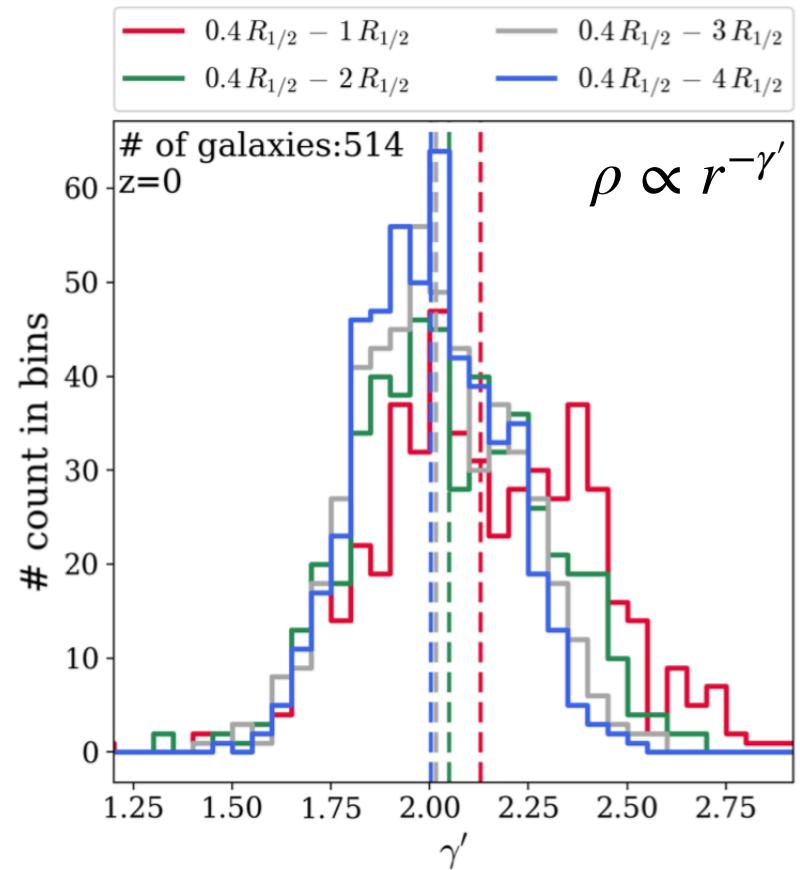
# Isothermal Density Profile in ETGs

Cappellari, et al. (2015)



Stellar Kinematics

Wang, et al. (2018) IllustrisTNG Simulations



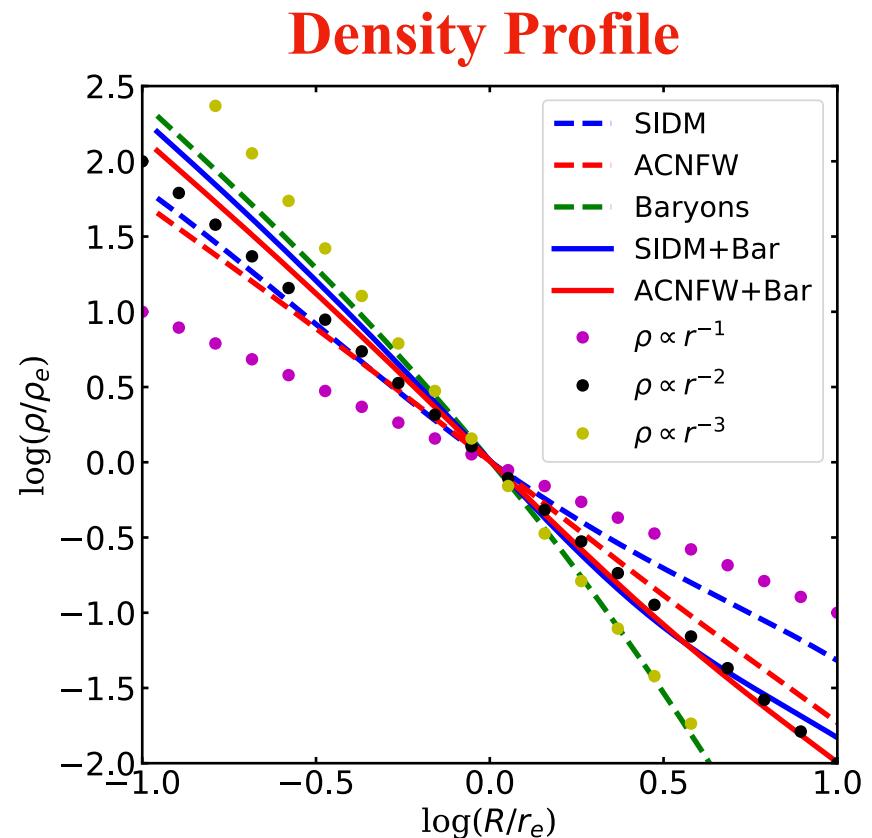
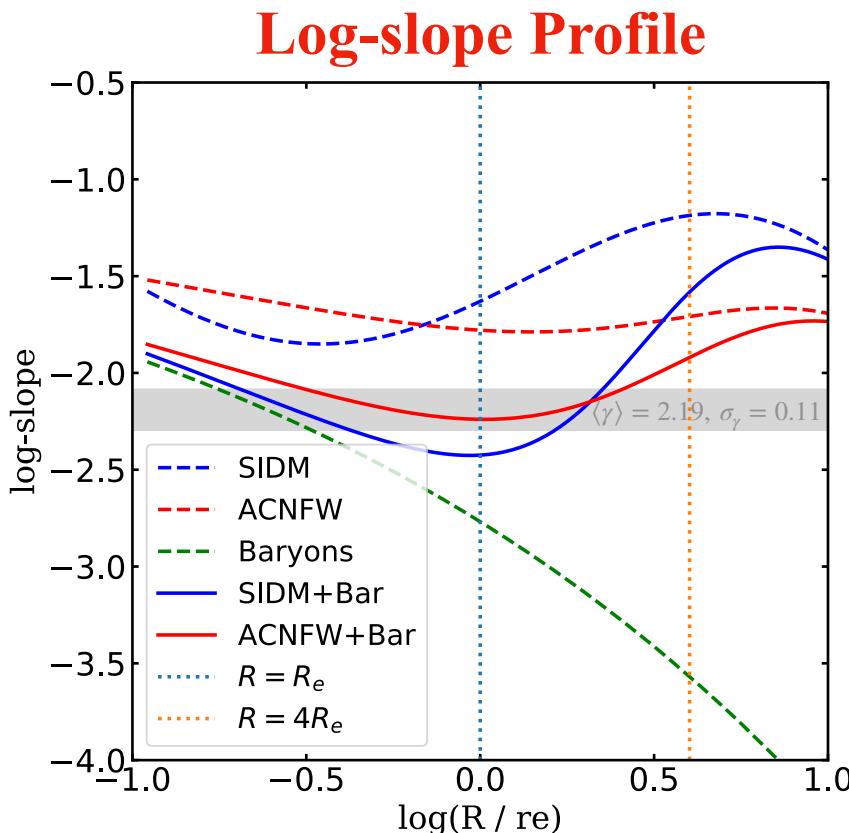
- Total density profiles are nearly isothermal
- Scatter is relatively small
- Dark matter - baryon conspiracy

Radial range	$\langle \gamma' \rangle$	$\sigma_{\gamma'}$
$0.4 R_{1/2} - 1 R_{1/2}$	$2.130 \pm 0.012$	0.282
$0.4 R_{1/2} - 2 R_{1/2}$	$2.050 \pm 0.010$	0.234
$0.4 R_{1/2} - 3 R_{1/2}$	$2.016 \pm 0.009$	0.199
$0.4 R_{1/2} - 4 R_{1/2}$	$2.003 \pm 0.008$	0.175

# Isothermal Density Profile in ETGs

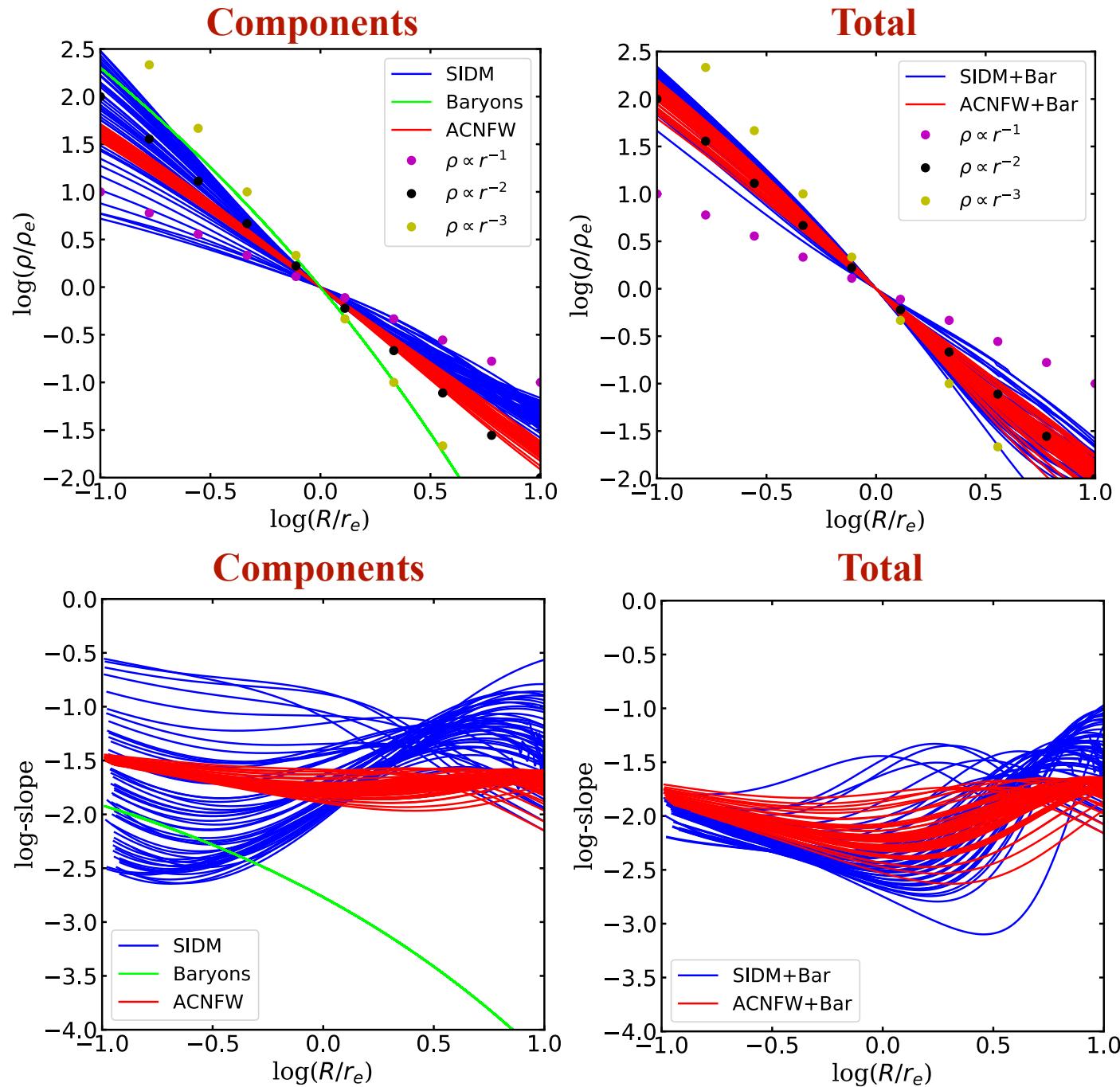
$$\left\{ \begin{array}{l} d(\log_{10}(\frac{\rho_{DM}}{\rho_{eDM}})) = \alpha * d(\log_{10}(\frac{r}{R_e})) \\ d(\log_{10}(\frac{\rho_{bar}}{\rho_{estar}})) = \beta * d(\log_{10}(\frac{r}{R_e})) \\ d(\log_{10}(\frac{\rho_{tot}}{\rho_{etot}})) = \gamma * d(\log_{10}(\frac{r}{R_e})) \end{array} \right. \implies \gamma = \frac{\alpha * 1 + \beta * f(r)}{1 + f(r)} \quad \text{with } f(r) = \rho_{bar}/\rho_{DM}$$

The total log-slope is the density weighted average value of DM & Star component.

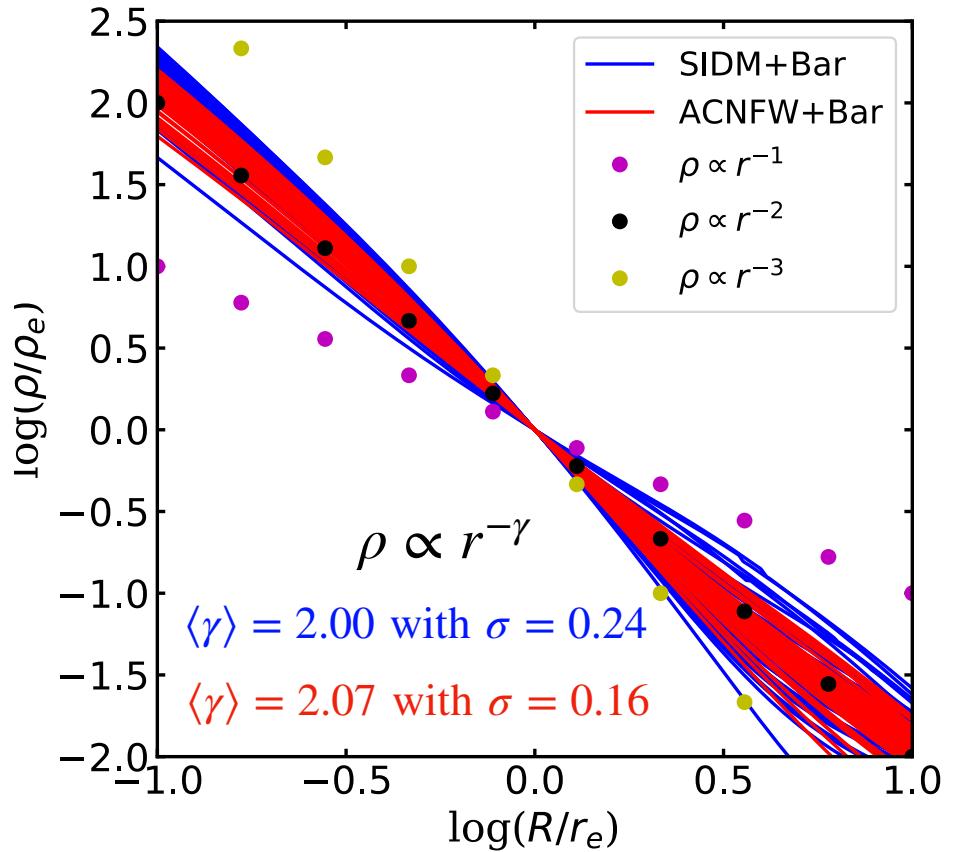
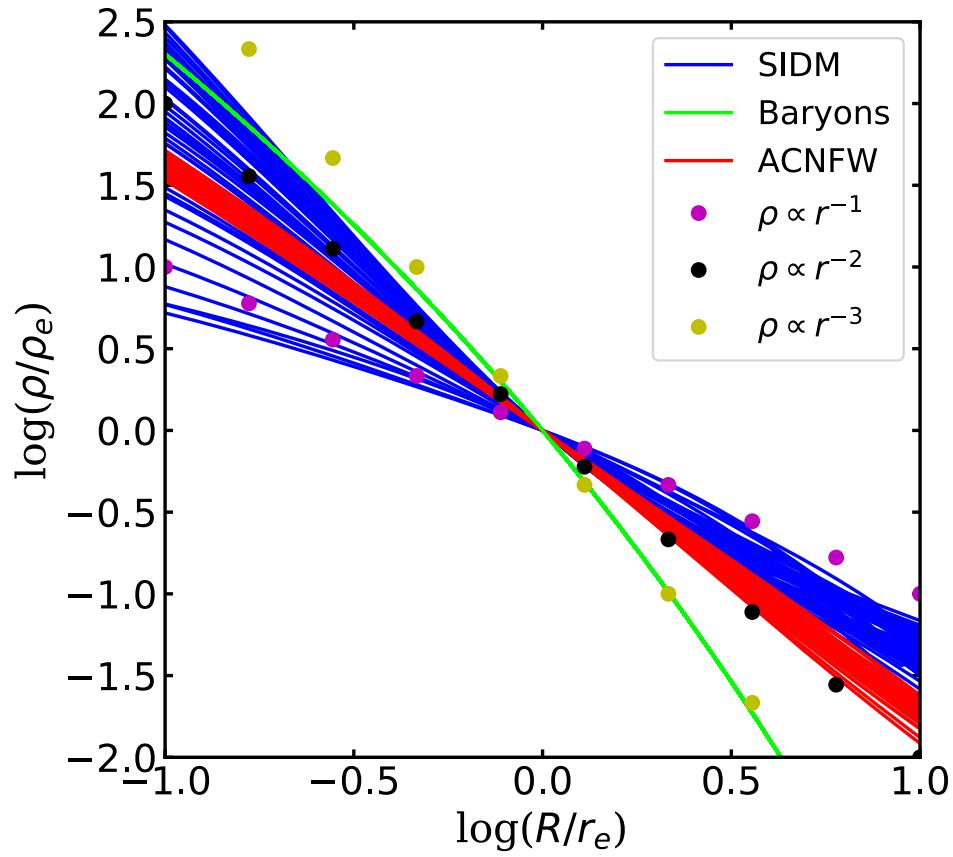


# Isothermal Density Profiles in ETGs

Ren, Kaplinghat, Yu, (in progress)



# Isothermal Density Profiles in ETGs



- SIDM halos are more responsive to different baryon distributions
- Both DM models reproduce isothermal total density profiles
- The ACNFW model predicts smaller scatter
- Inner: baryon + Outer: dark matter

# Content

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- Research Background
- { Diversity  
Uniformity } of Galactic Rotation Curves
- Comparison with Cold Dark Matter Simulations
- Applications in Early-Type Galaxies
- Summary & Outlook

# Summary & Outlook

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We have demonstrated:

- SIDM has strong potential to solve small scale problems
- The thermalization of inner galaxy regions is highly possible

## Results

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Spiral Galaxy

{ Diversity  
Uniformity in RCs

Interpretation for MOND

Comparison  
w/ Simulations

Baryons are the key!

## Outlook

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Equilibrium → Non-equilibrium

Analytical method → Simulations

Early-Type  
Galaxy

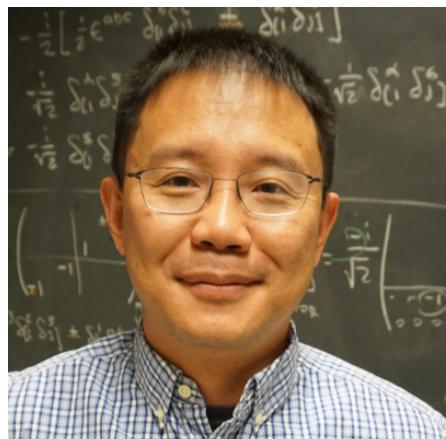
Small DM fractions  
Isothermal density profiles

Combine w/ lensing & kinematics  
Baryon distributions

# Acknowledgement

## Collaborators

**Hai-Bo Yu**



UC Riverside

**Anna Kwa**



UC Irvine

**Manoj Kaplinghat**



UC Irvine

## Committee

**Yanou Cui**



UC Riverside

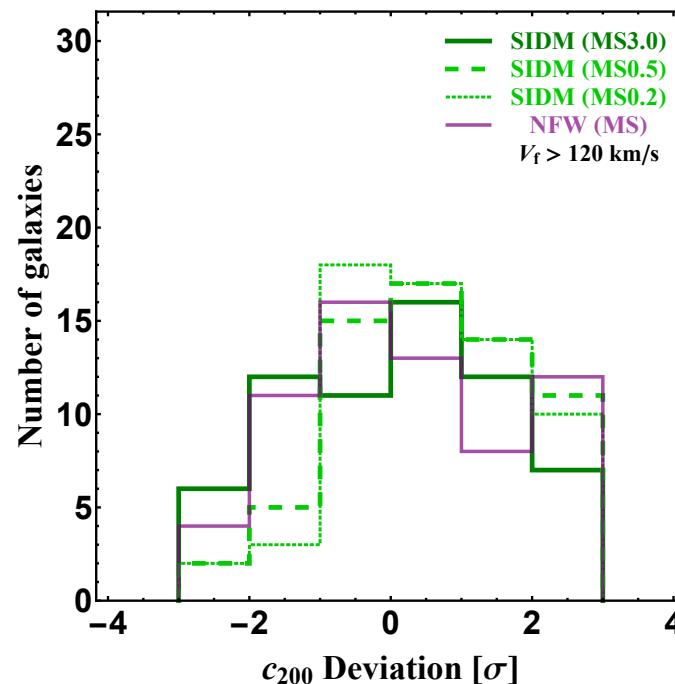
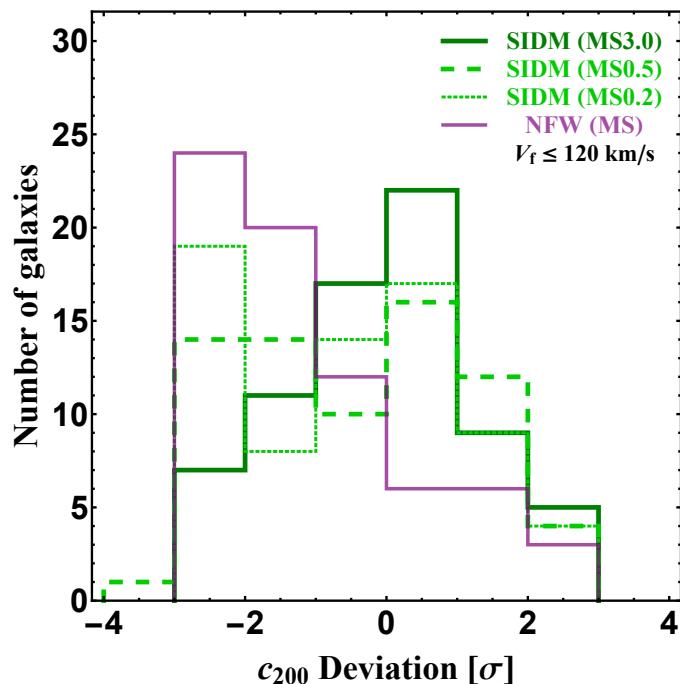
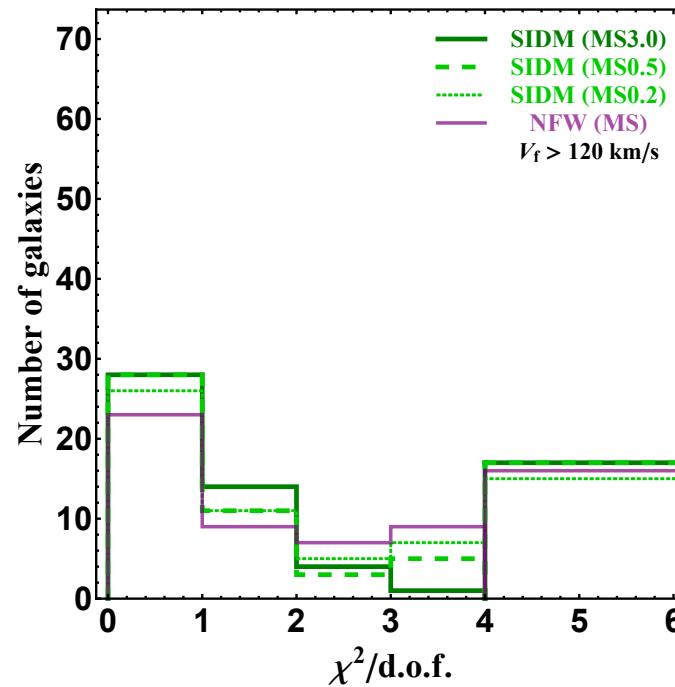
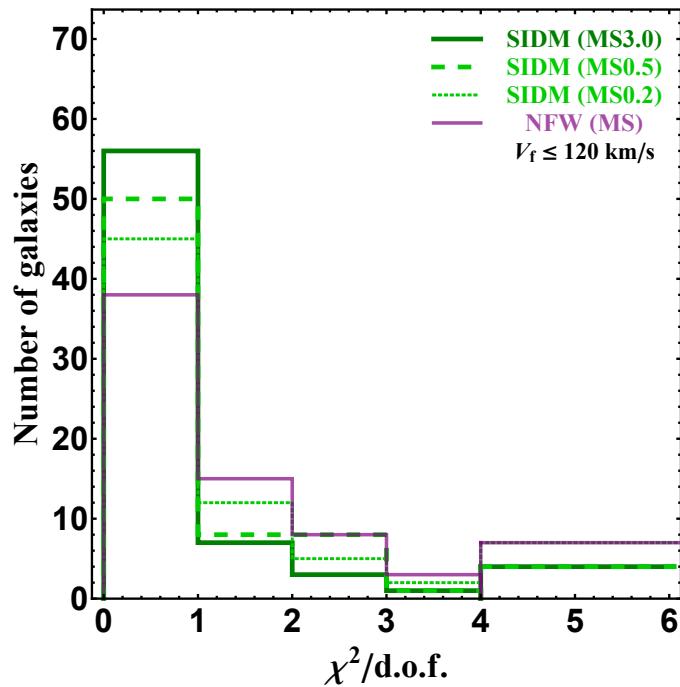
**Flip Tanedo**



UC Riverside

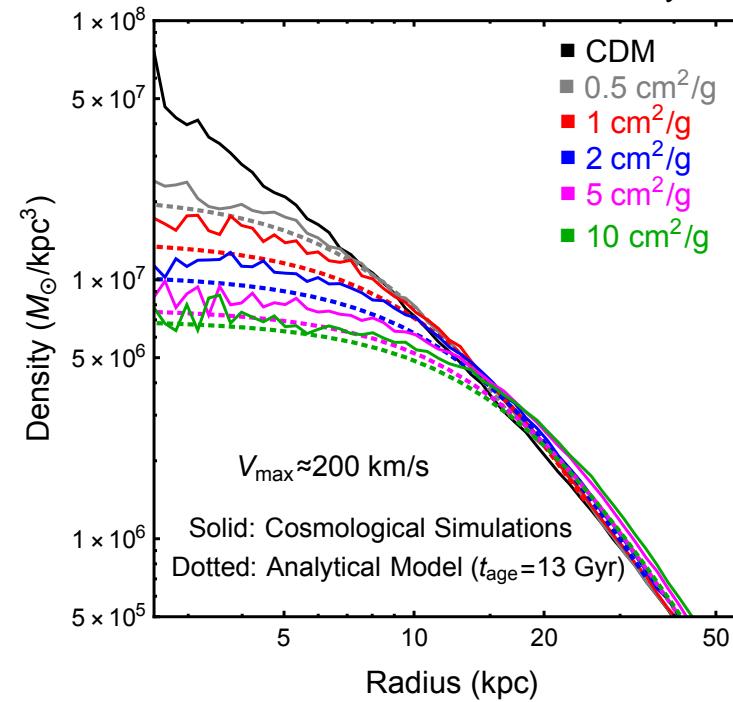
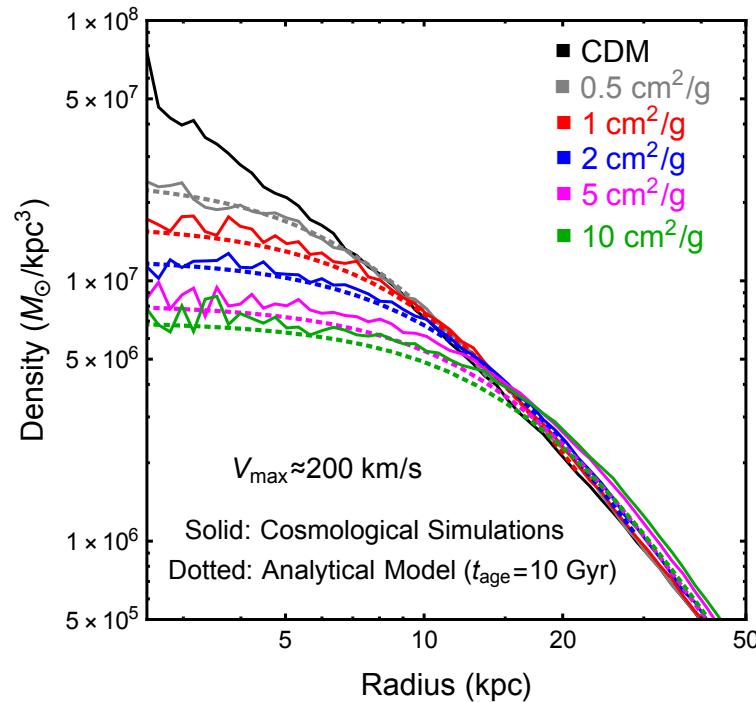
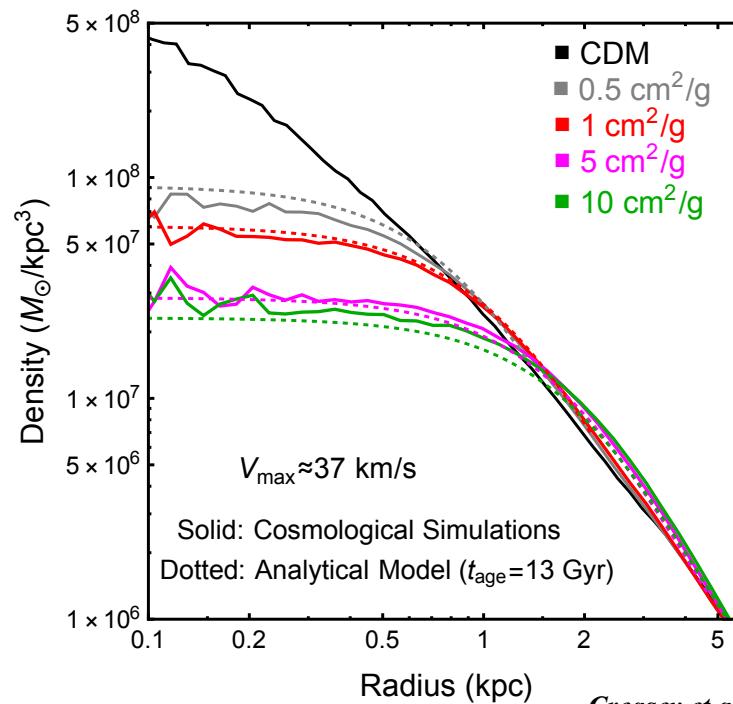
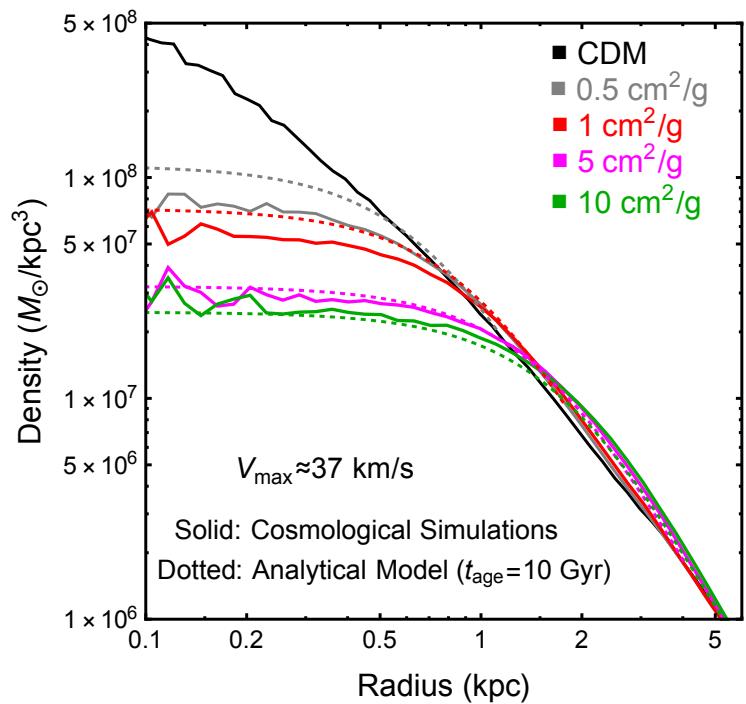
**Back Up Slides  
&  
Supporting Information**

# Results w/ Various Cross-Section



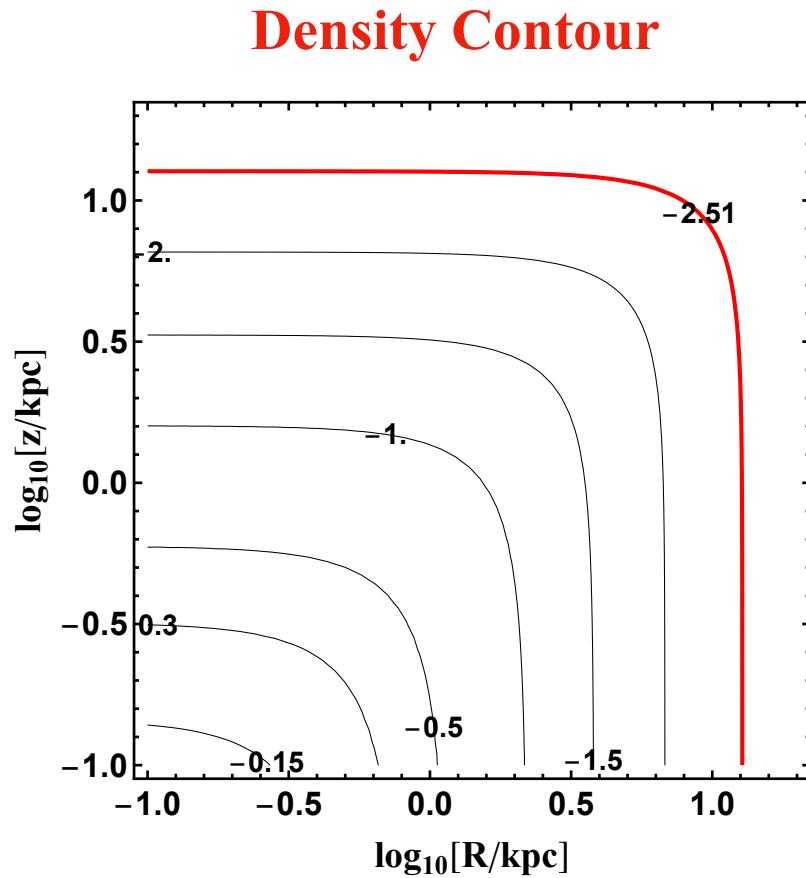
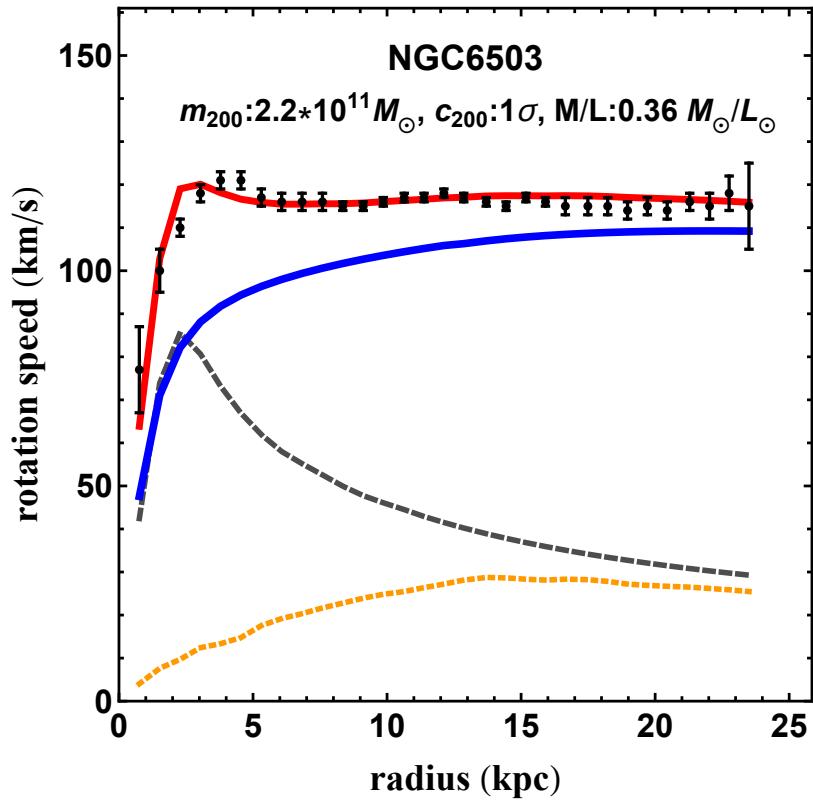
# Validity of SIDM model

Elbert et al., MNRAS 453 (2015)



Creasey et al., MNRAS 468 (2017)

# Stellar Disk's Effect on SIDM Halo



# Stellar Population Synthesis Model

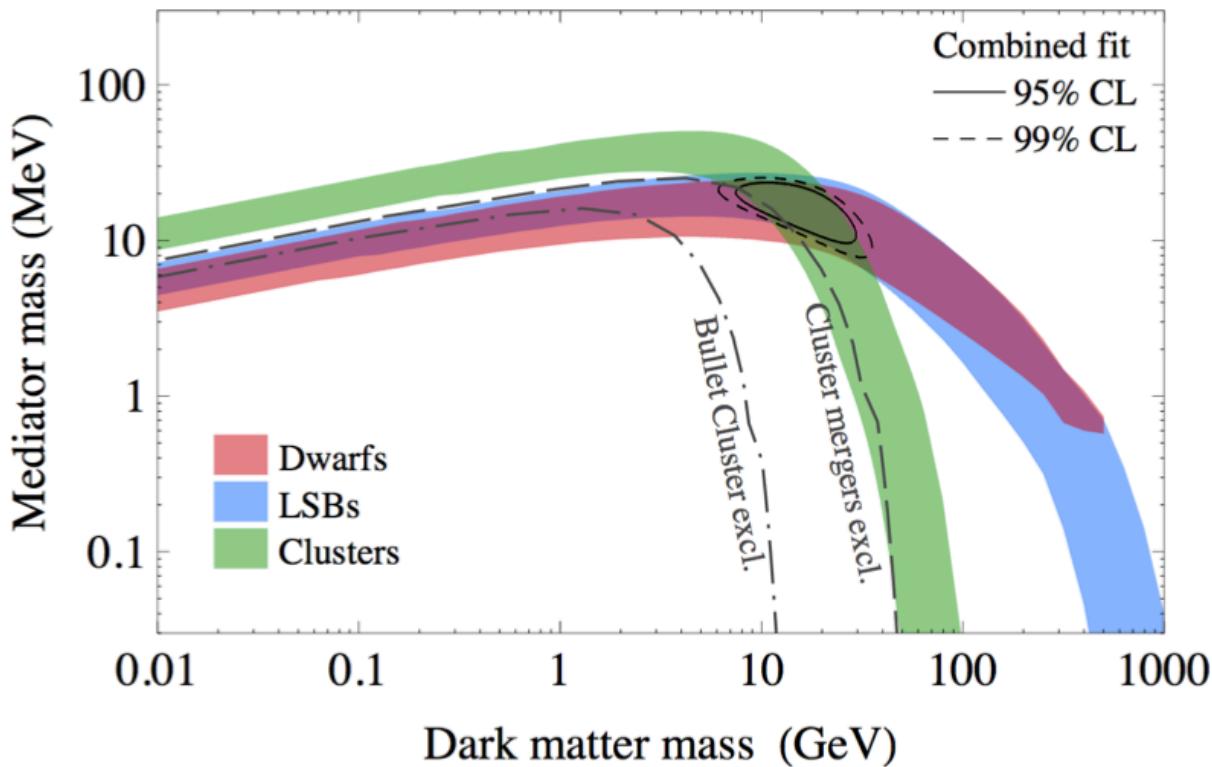
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- Study stellar population as a function of their mass, age, and metallicity
- SPS provides the fundamental link between theory/models and observations
- e.g.
  - The star formation histories
  - Metallicities of galaxies
  - Galaxy colours and spectra
- Tools:
  - The stellar initial mass function (IMF)
  - The star formation rate (SFR)
  - The rate of chemical enrichment



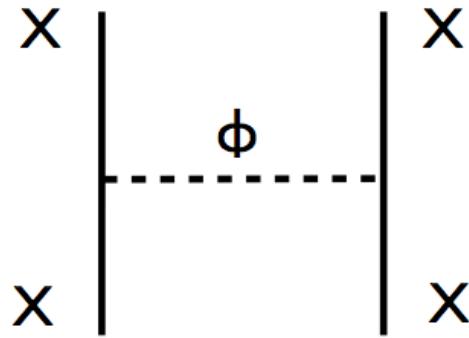
# SIDM Model Example & Parameter Measurement

Kaplinghat, et al. (PRL, 2015)

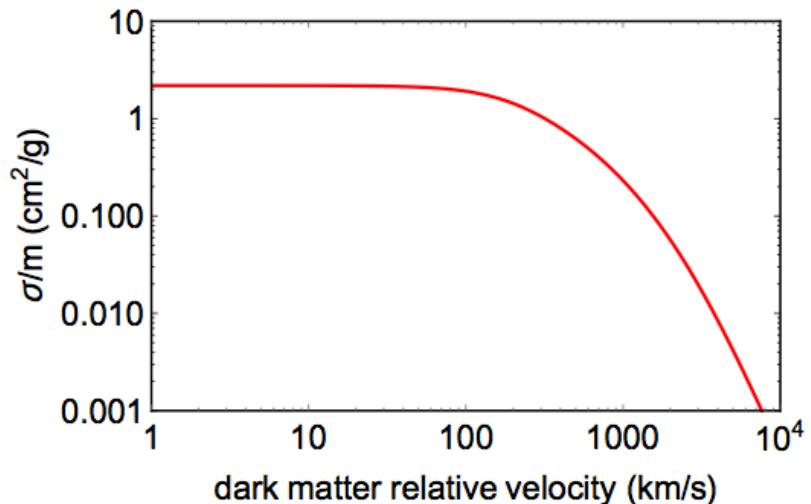


$$\alpha_X = 1/137$$

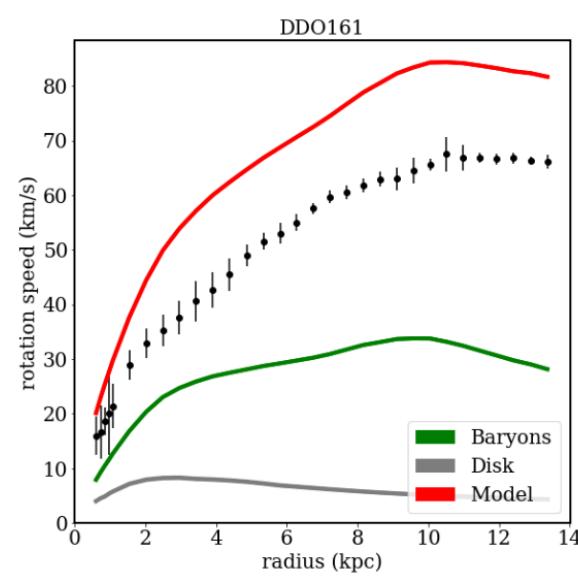
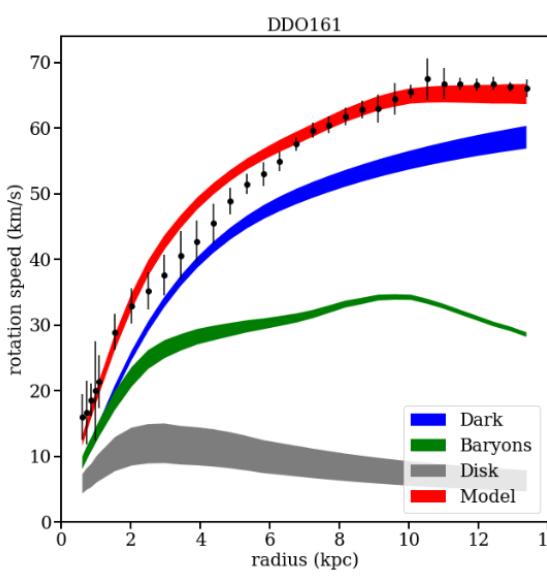
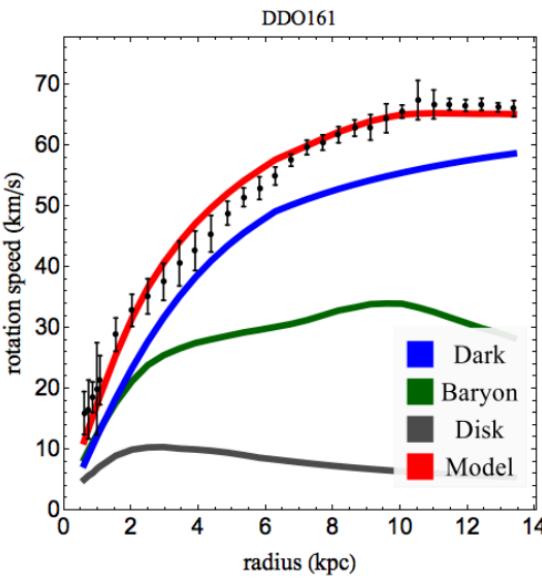
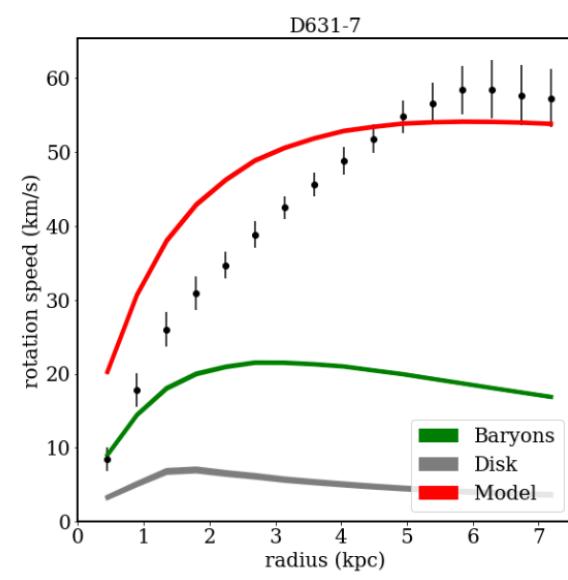
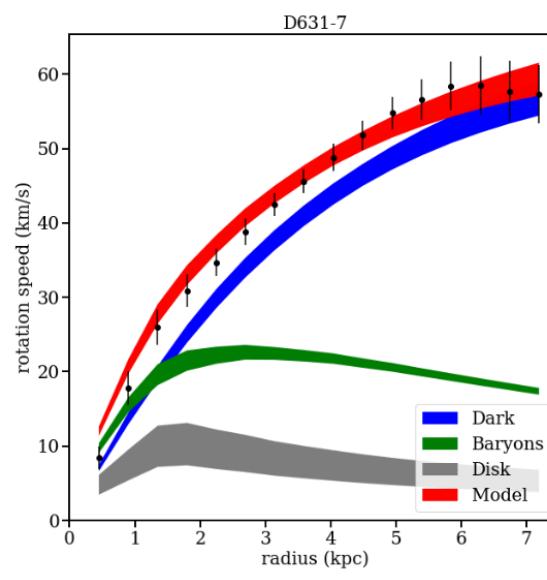
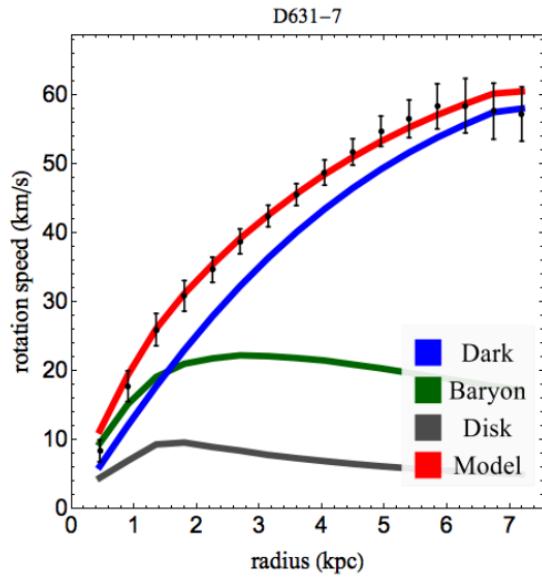
$$m_X \approx 15 \text{ GeV}, m_\phi \approx 17 \text{ MeV}$$



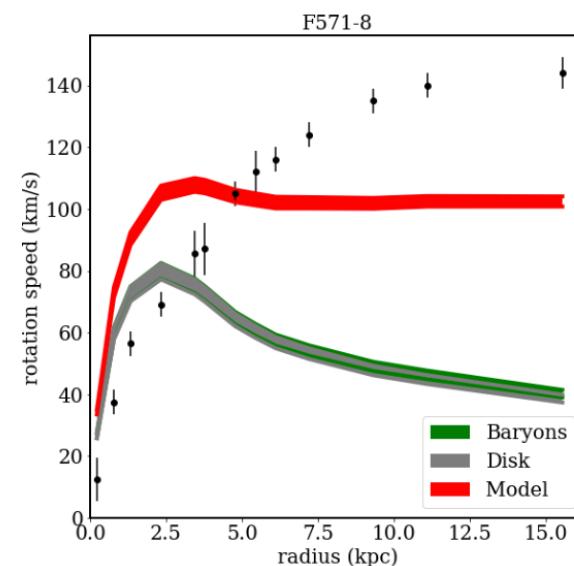
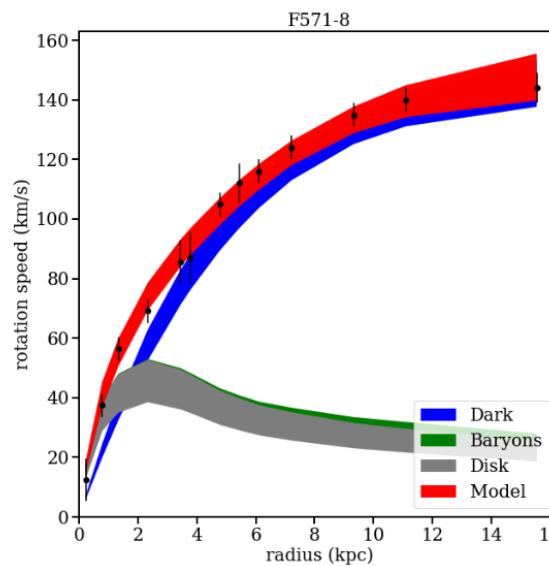
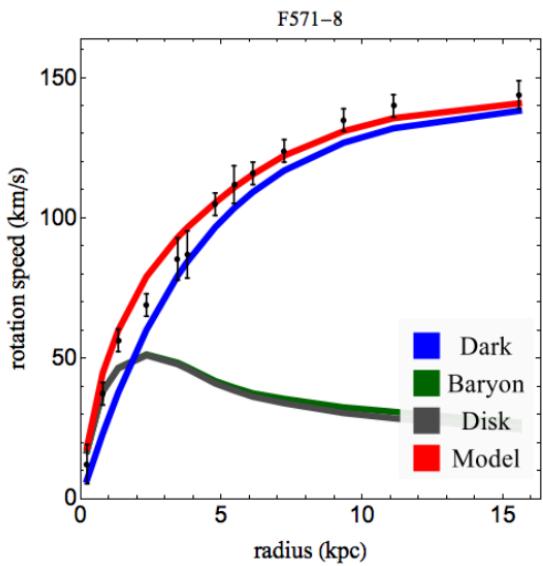
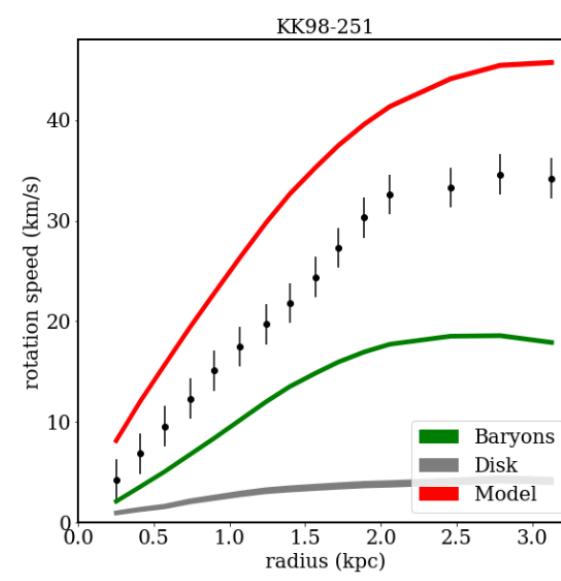
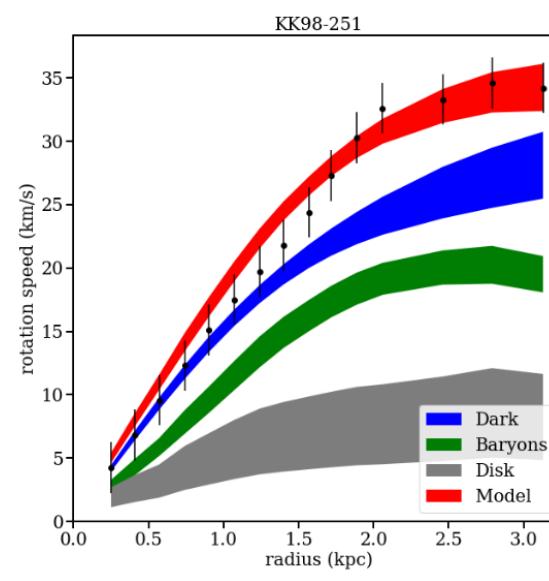
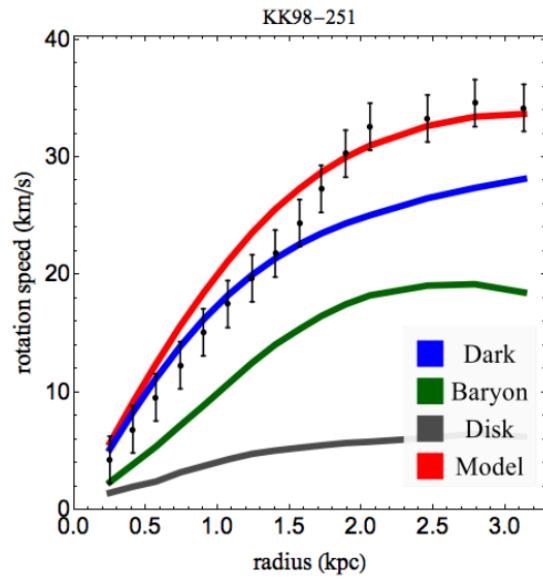
$$V(r) = \frac{\alpha_X}{r} e^{-m_\phi r}$$



# SIDM vs MOND



# SIDM vs MOND



# Two Extreme cases in Outliers

