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

UCR
Particle Theory

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

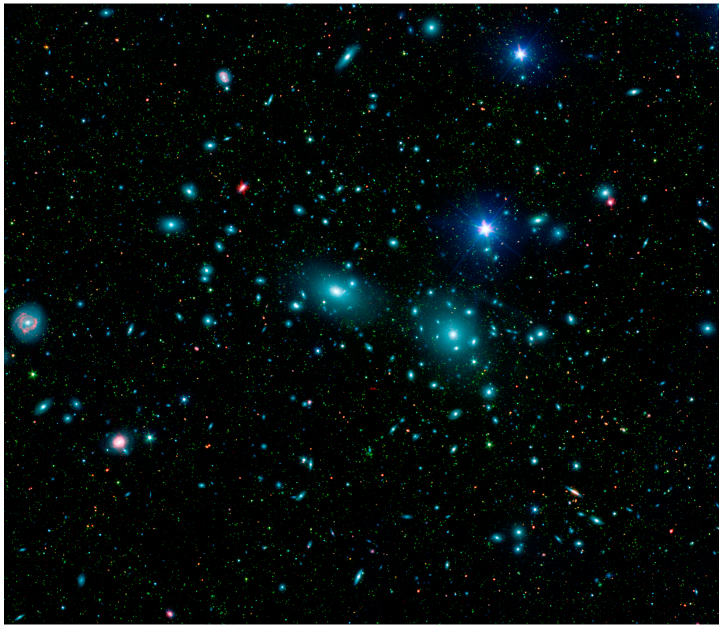
- Research Background
- {Diversity / Uniformity} of Galactic Rotation Curves
- Comparison with Cold Dark Matter Simulations
- Applications in Early-Type Galaxies
- Summary & Outlook

Content

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

Why Dark Matter?

Coma Cluster



Credit: NASA/JPL-Caltech/SDSS

$\Longleftarrow$ 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*".

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

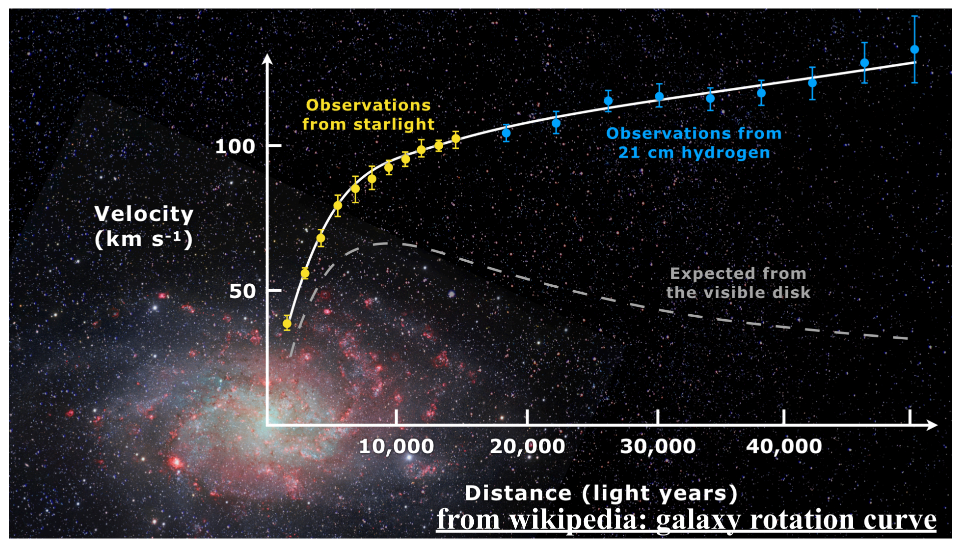
Galaxy

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

- Keplerian decline VS Flat rotation curve

$$\frac{GM_{obs}}{R^2} \overset{?}{\Longleftrightarrow} \frac{V^2_{flat}}{R} \qquad (F = ma)$$

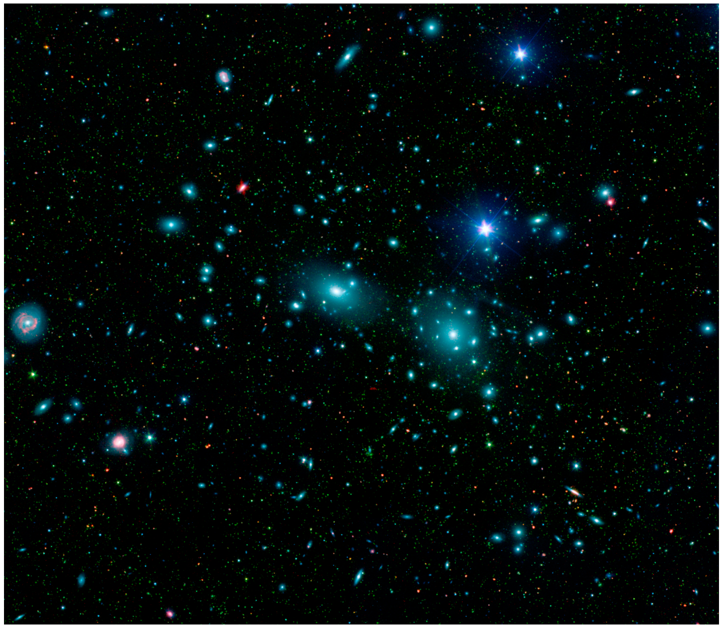
- Ostriker, Peebles, and others (1970s) showed the instability of stellar-only disk and embedding the disk in a dark halo would help.



Rotation curve of Messier 33

Why Dark Matter?

Coma Cluster



Credit: NASA/JPL-Caltech/SDSS

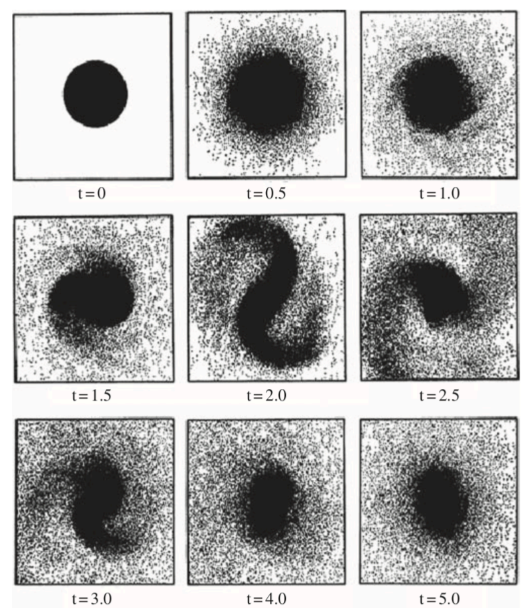
$\Longleftarrow$ **long-wavelength infrared (red), short-wavelength infrared (green), and visible light.**

- **In 1933, Fritz Zwicky found the galaxies were moving too fast (line-of-sight velocity) to be bound by observed mass.** $L \times (M/L)$

- **Virial theorem implied huge dynamical mass. Zwicky commented "*dunkle Materie*".**

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

Galaxy



A cold disk of stars.

(Frank Hohl, 1971)

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

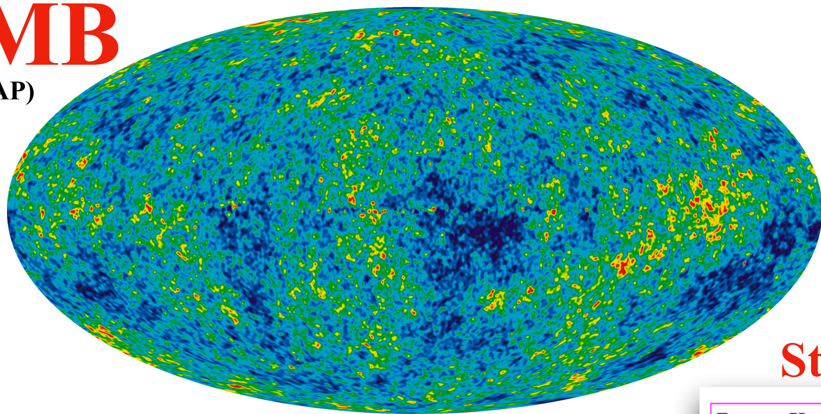
- **Keplerian decline VS Flat rotation curve**

$$\frac{GM_{obs}}{R^2} \overset{?}{\Longleftrightarrow} \frac{V_{flat}^2}{R} \qquad (F = ma)$$

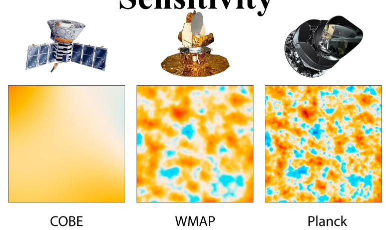
- **Ostriker, Peebles, and others (1970s) showed the instability of stellar-only disk and embedding the disk in a dark halo would help.**

Why Dark Matter?

CMB
(WMAP)



Sensitivity

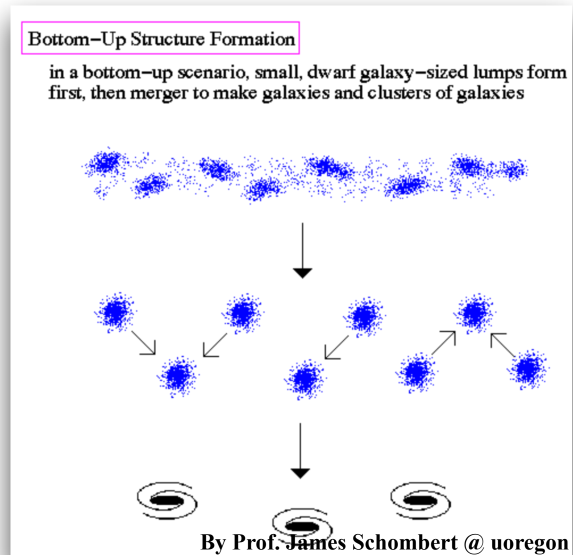


- **CMB indicates structure formation in a *baryonic universe* began after z=1000.**
- **Density fluctuations were *too small* to develop the observed large-scale structure.**

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

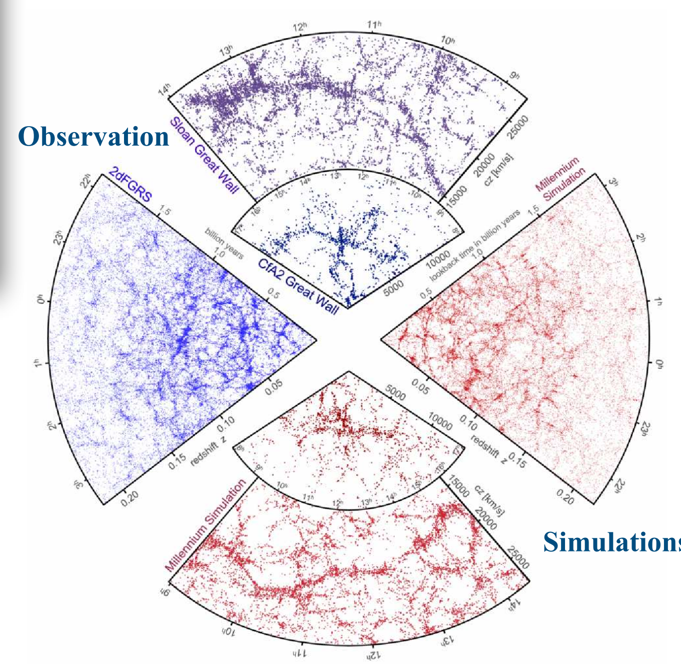
CMB : $\delta T/T \approx 10^{-5}$

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.**

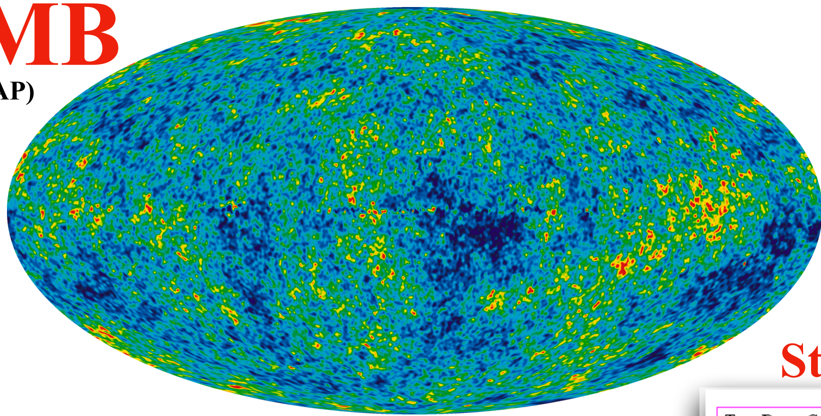
Large-Scale Structure



2dF Galaxy Redshift Survey

Why Dark Matter?

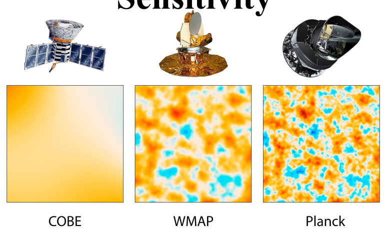
CMB
(WMAP)



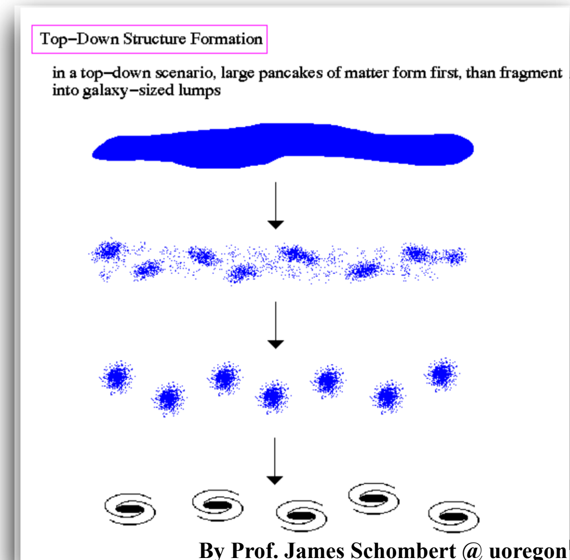
- **CMB indicates structure formation in a *baryonic universe* began after z=1000.**
- **Density fluctuations were *too small* to develop the observed large-scale structure.**

$$\text{Required} : \delta\rho/\rho \approx 10^{-4}$$
$$\text{CMB} : \delta T/T \approx 10^{-5}$$

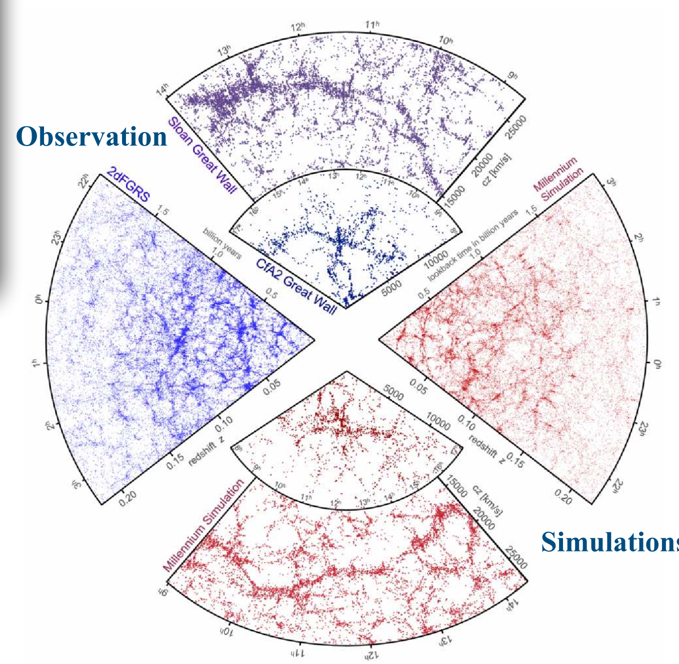
Sensitivity



Structure Formation



Large-Scale Structure

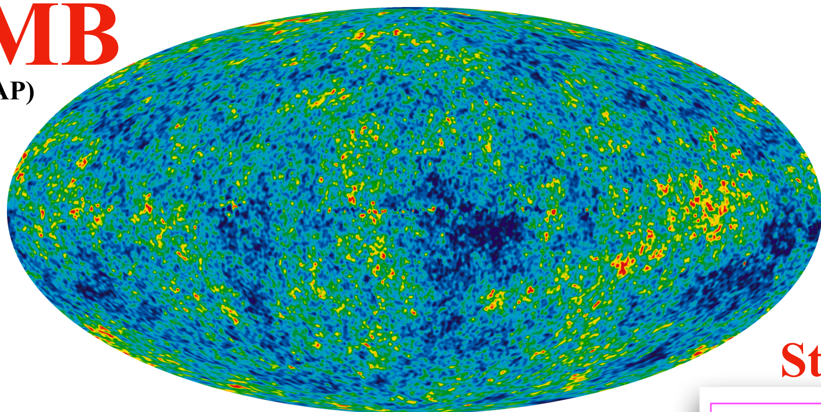


2dF Galaxy Redshift Survey

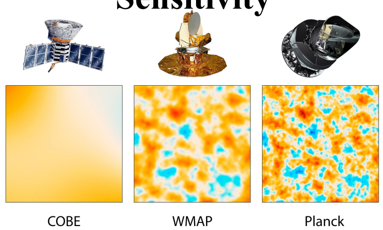
- **Dark matter come to rescue. Freeze out and start structure formation earlier.**
- **Cold Dark Matter VS Hot Dark Matter (e.g. neutrinos)**
- **Cold Dark Matter paradigm successfully explained large-scale structure of the Universe.**

Why Dark Matter?

CMB
(WMAP)



Sensitivity

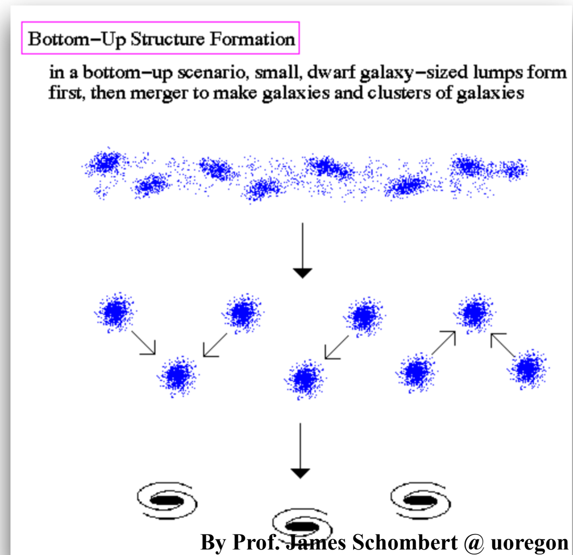


- **CMB indicates structure formation in a *baryonic universe* began after z=1000.**
- **Density fluctuations were *too small* to develop the observed large-scale structure.**

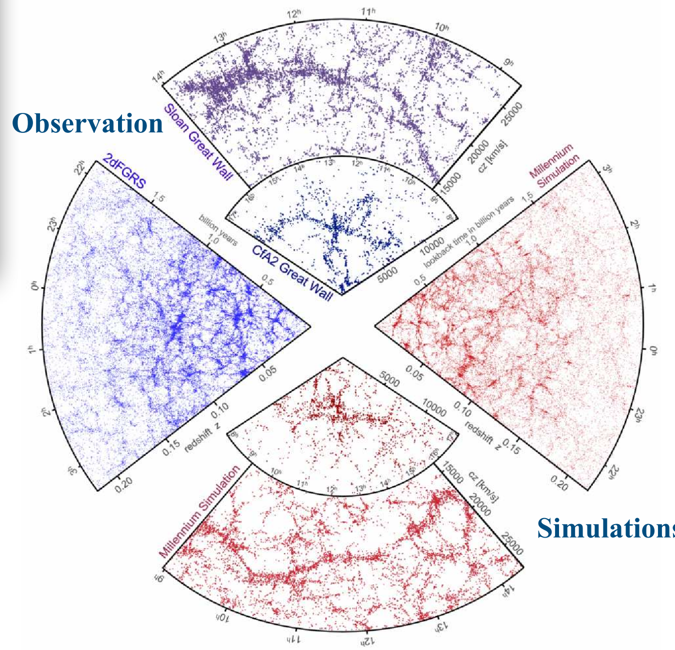
Required : $\delta\rho/\rho \approx 10^{-4}$

CMB : $\delta T/T \approx 10^{-5}$

Structure Formation



Large-Scale Structure

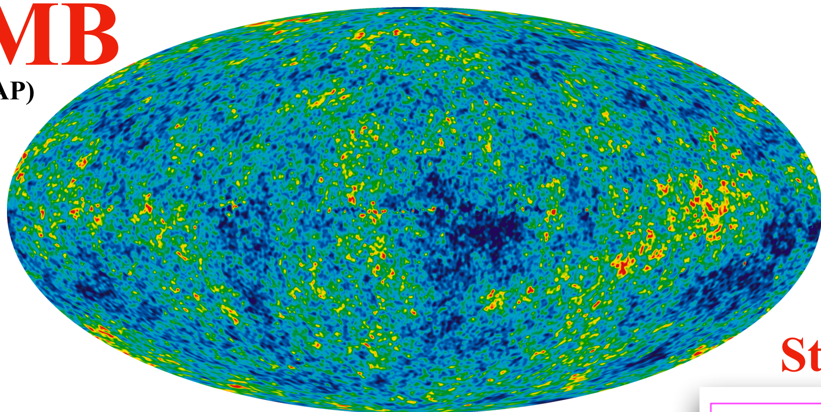


2dF Galaxy Redshift Survey

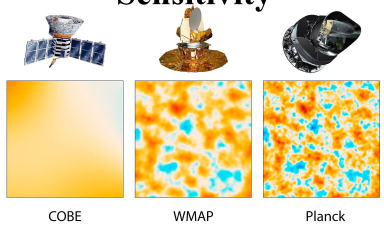
- **Dark matter come to rescue. Freeze out and start structure formation earlier.**
- **Cold Dark Matter VS Hot Dark Matter (e.g. neutrinos)**
- **Cold Dark Matter paradigm successfully explained large-scale structure of the Universe.**

Why Dark Matter?

CMB
(WMAP)



Sensitivity

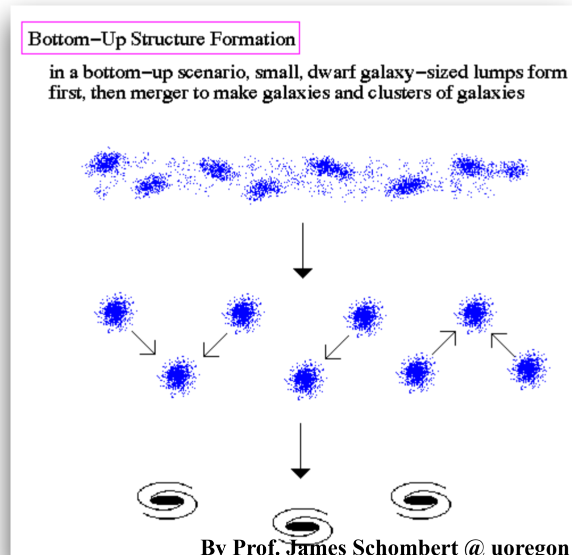


- **CMB indicates structure formation in a *baryonic universe* began after z=1000.**
- **Density fluctuations were *too small* to develop the observed large-scale structure.**

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

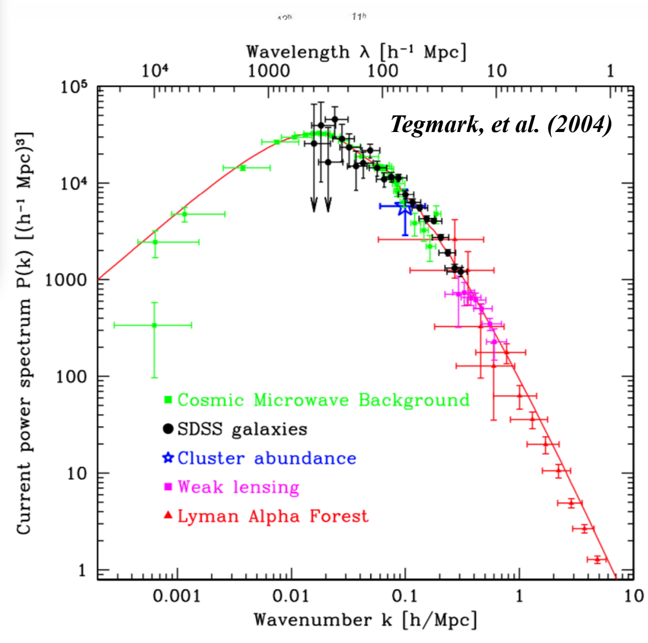
CMB : $\delta T/T \approx 10^{-5}$

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.**

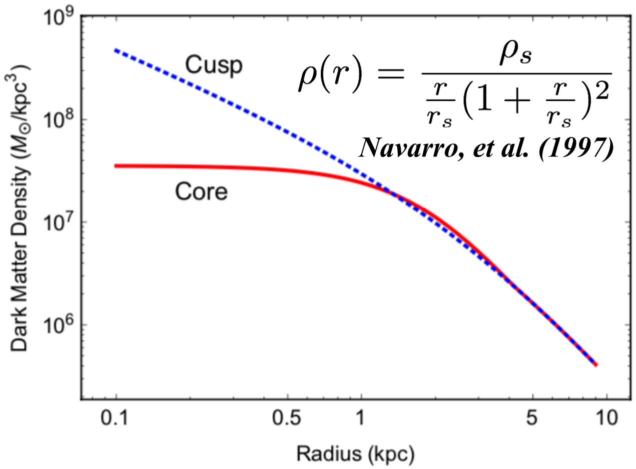
Large-Scale Structure



2dF Galaxy Redshift Survey

CDM Paradigm on Galactic Scales

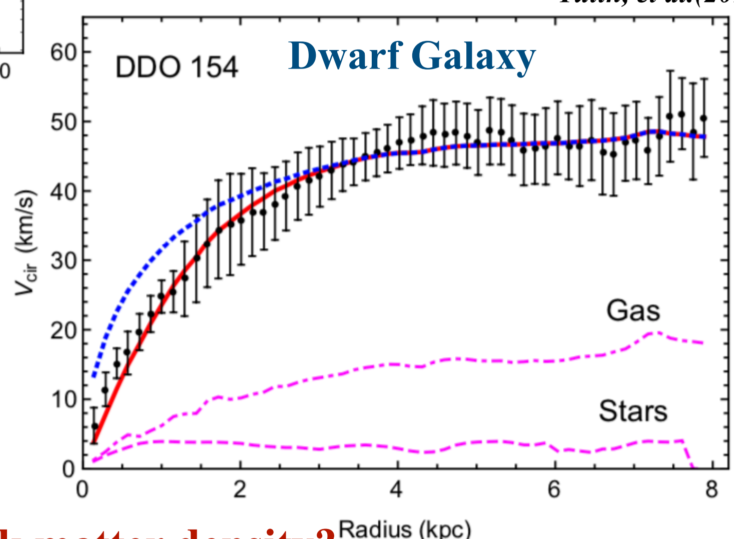
NFW Profile



- **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.**

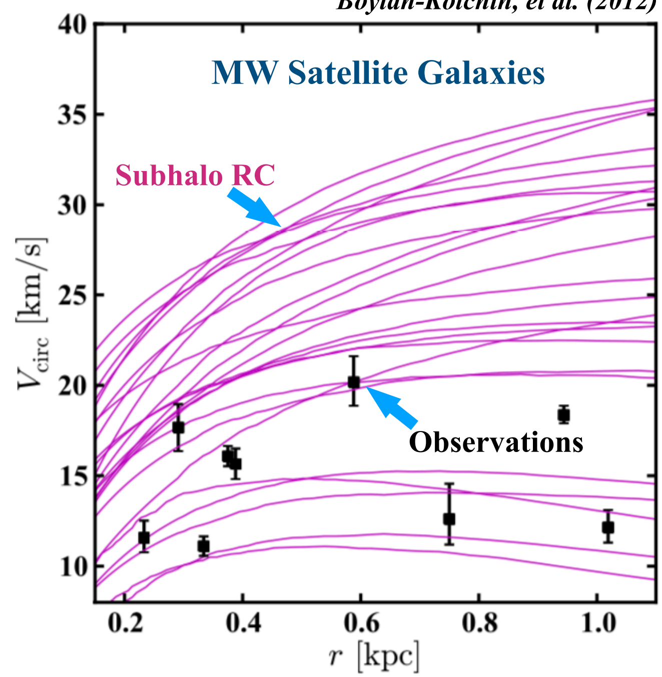
Core vs Cusp Problem

Tulin, et al.(2018)



Too-big-to-fail Problem

Boylan-Kolchin, et al. (2012)



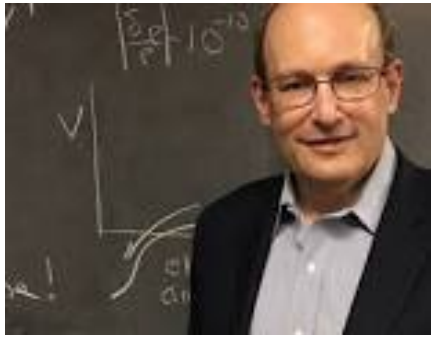
- **Some dwarf galaxies prefer cored profiles.**
- **How to lower the central dark matter density?**
  Baryon physics may help.
  (e.g. feedback effect like the explosion of supernovae.)
- **Alternative dark matter model beyond the collisionless scenario, e.g. Self-Interating Dark Matter.**

The Rise of Self-Interacting Dark Matter

D. N. Spergel

Princeton

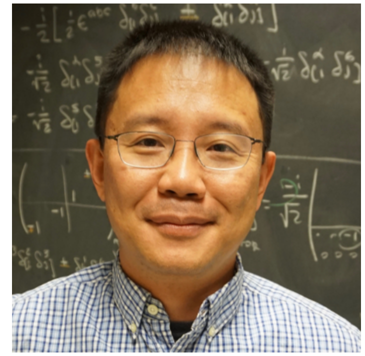
P. J. Steinhardt



Princeton

2000 → **Present**

Hai-Bo Yu



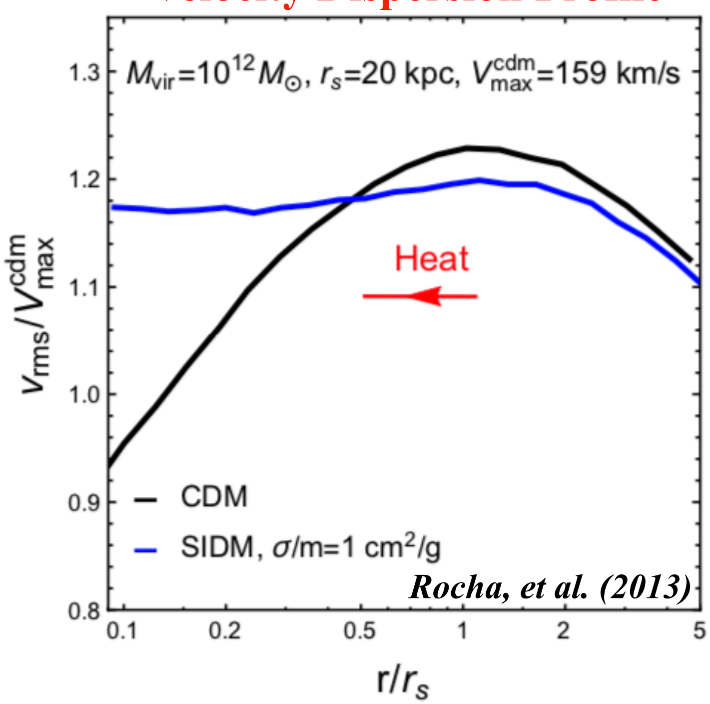
UC Riverside

Manoj Kaplinghat

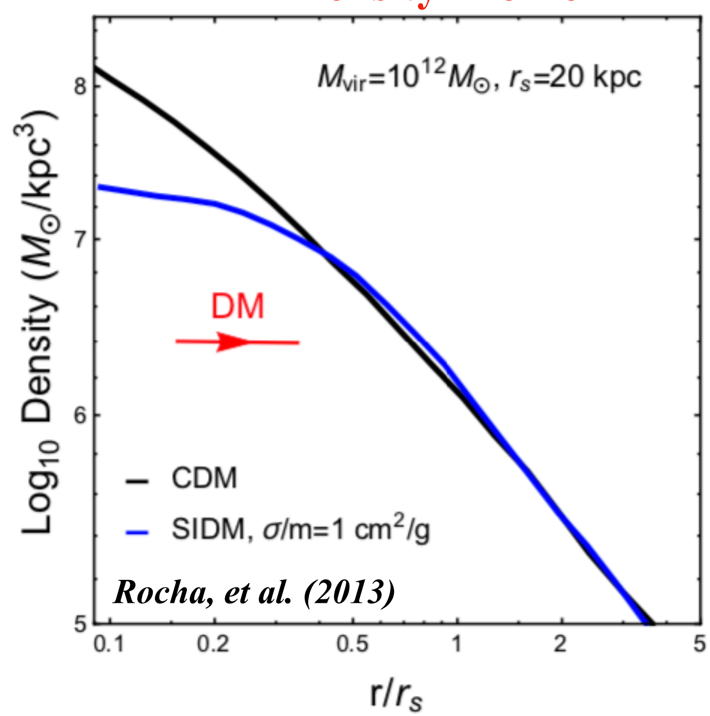
UC Irvine

Mechanism of SIDM

Velocity Dispersion Profile



DM Density Profile

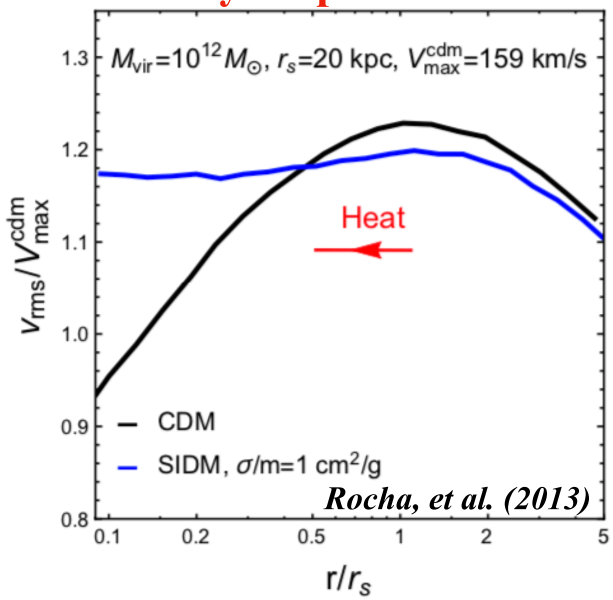


- **Heat is transferred from outer region to inner region through DM self-interactions.**
- **DM particles get higher energy and escape the bound of gravity from original cusp.**

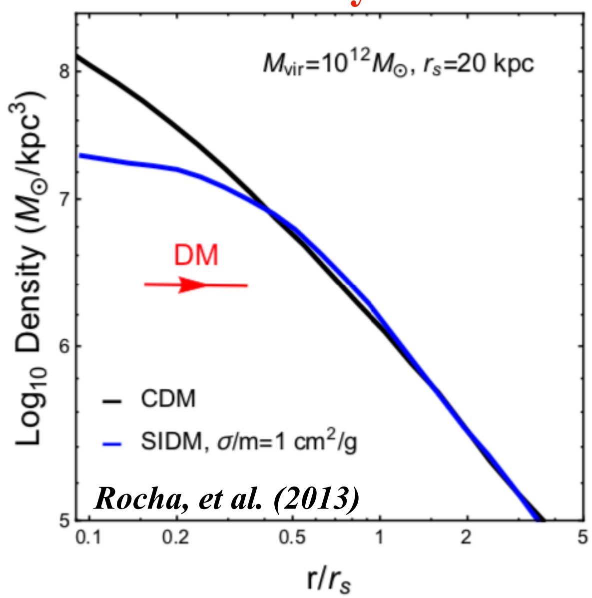
SIDM Modeling

Mechanism of SIDM

Velocity Dispersion Profile



DM Density Profile



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.**

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

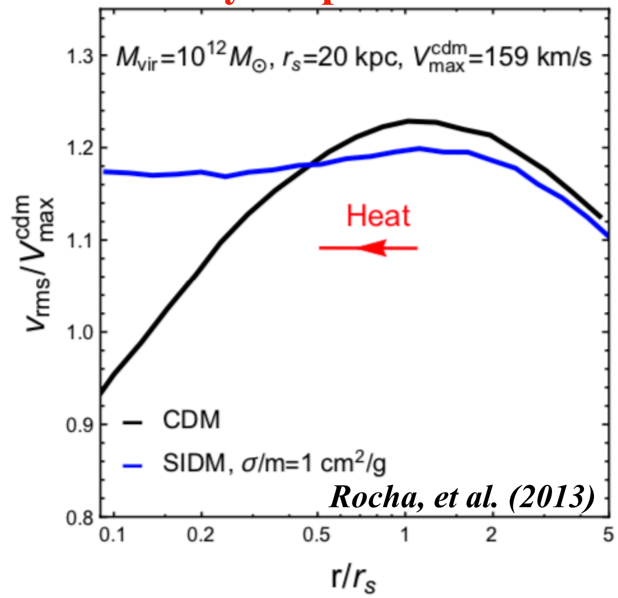
$$\rho_{\text{SIDM}}(r) = \begin{cases} \rho_{\text{iso}}(r), & r < r_1 \\ \rho_{\text{NFW}}(r), & r > r_1 \end{cases}$$

(Mass & density continuity at r_1)

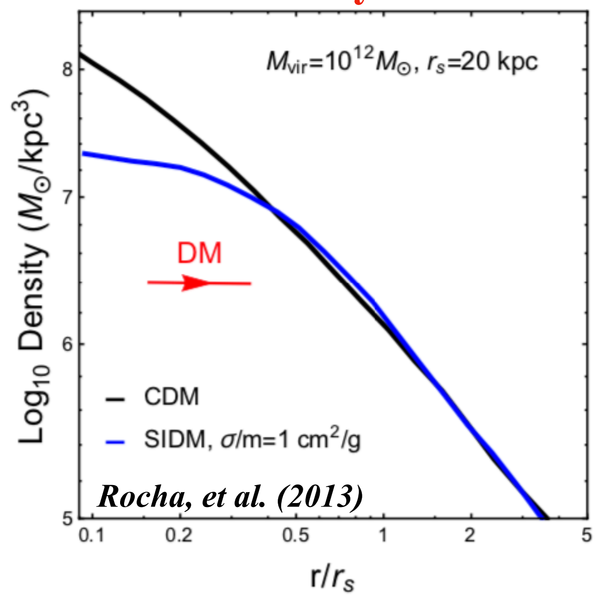
SIDM Modeling

Mechanism of SIDM

Velocity Dispersion Profile



DM Density Profile



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.**

Particle physics input.
Focus on macroscopic effects.

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

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

(Mass & density continuity at r_1)

Content

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

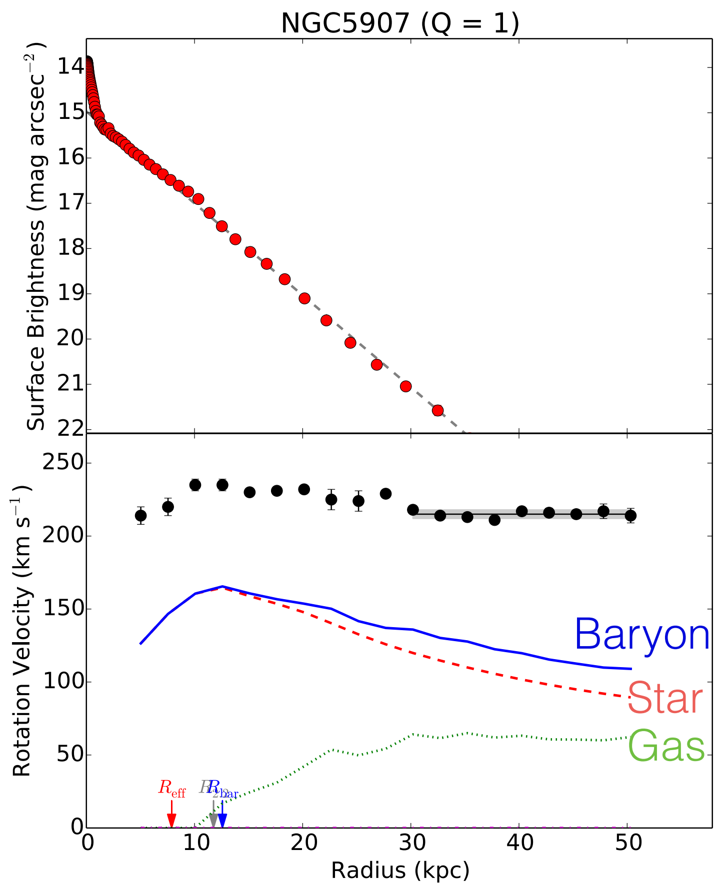
Spitzer Photometry & Accurate RCs (SPARC) Dataset

Lelli, et al. (2016)

- **SPARC contains a sample of 175 nearby spiral galaxies with homogeneous photometry at 3.6 μm and high-quality RC data from previous HI/Hα 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.**

Edge-on view

NGC5907



Abs. magnitude & Luminosity

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

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

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

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

Data Selection

Goal: High quality + Large size

Criterion: measured flat velocity

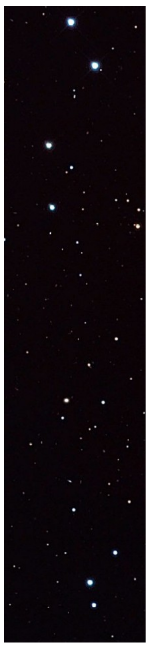
135 galaxies

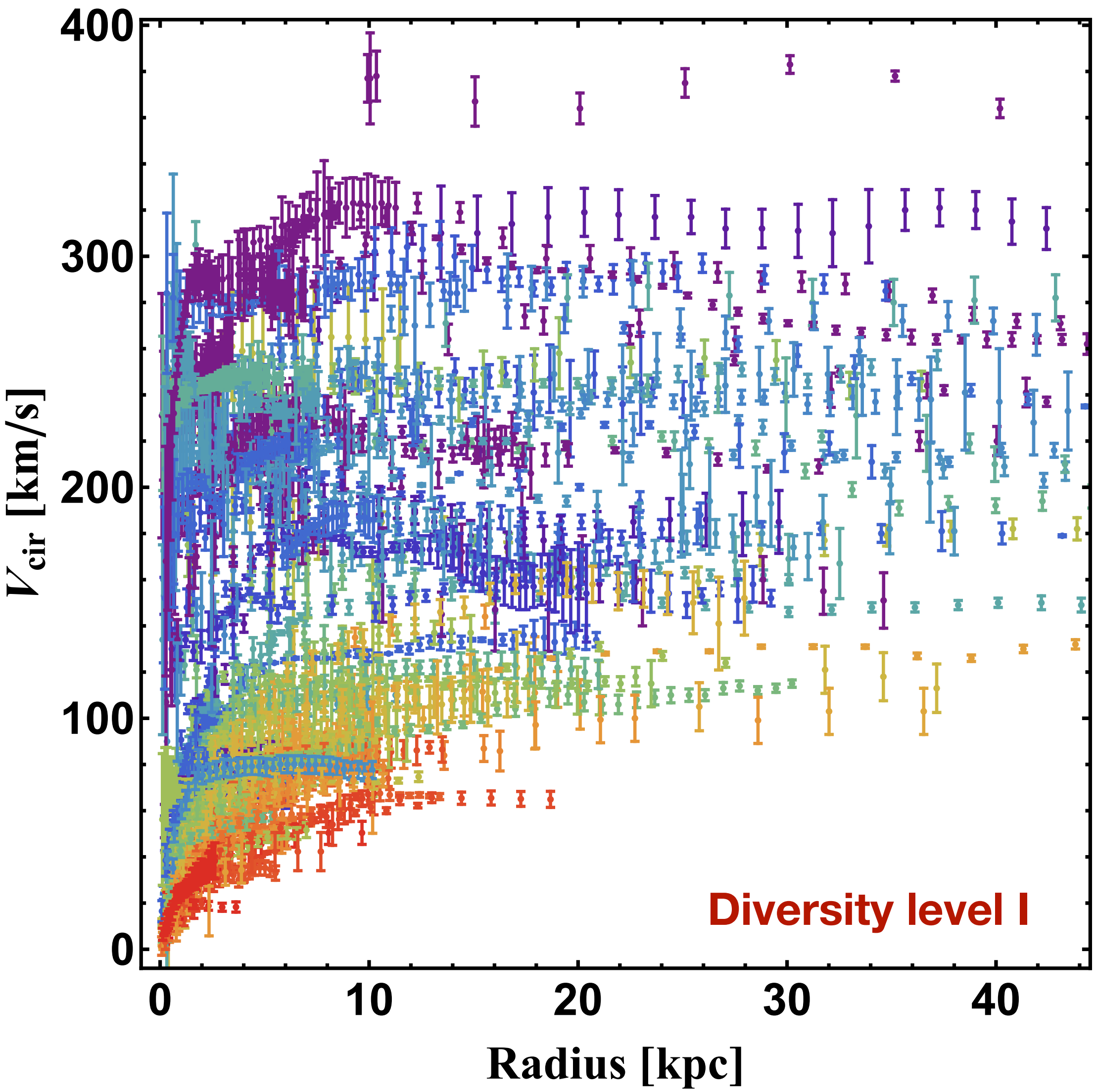
Spitzer Photometry & Accurate RCs (SPARC) Dataset

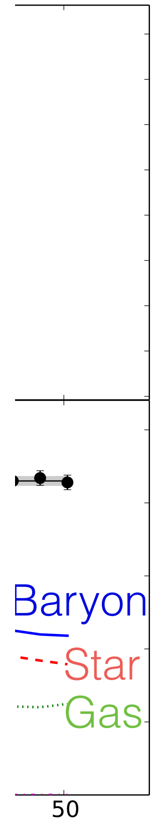
Lelli, et al. (2016)

- **SPARC contains a sample of 175 nearby spiral galaxies with homogeneous photometry at 3.6 μm and high-quality RC data from previous HI/Hα studies.**

- **SPARC spans very broad ranges in luminosity, surface brightness, rotation velo sample of spiral galaxies in the**







Abs. magnitude & Luminosity

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

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

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

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

Data Selection

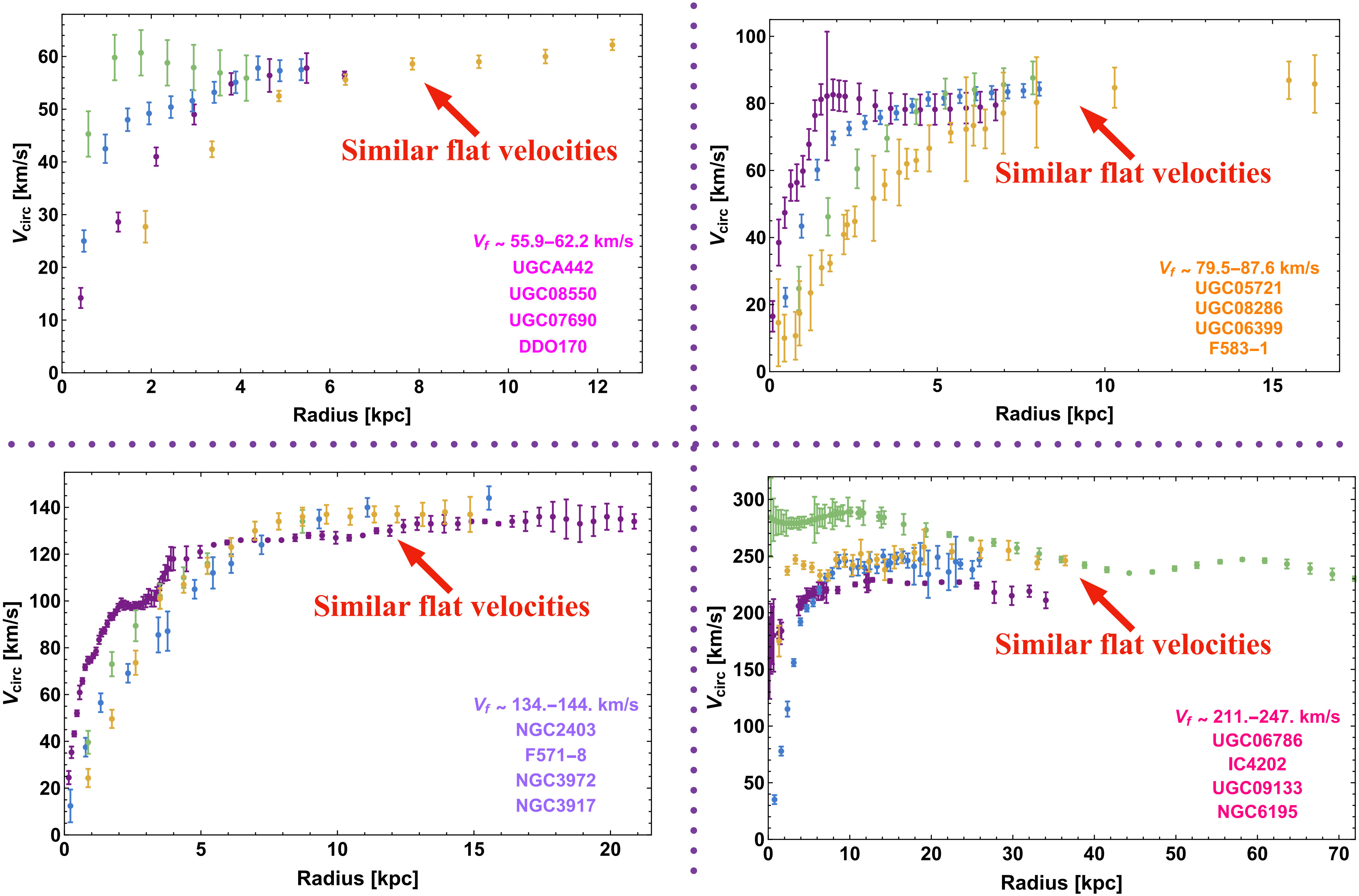
Goal: High quality + Large size

Criterion: measured flat velocity

$\Rightarrow$ **135 galaxies**

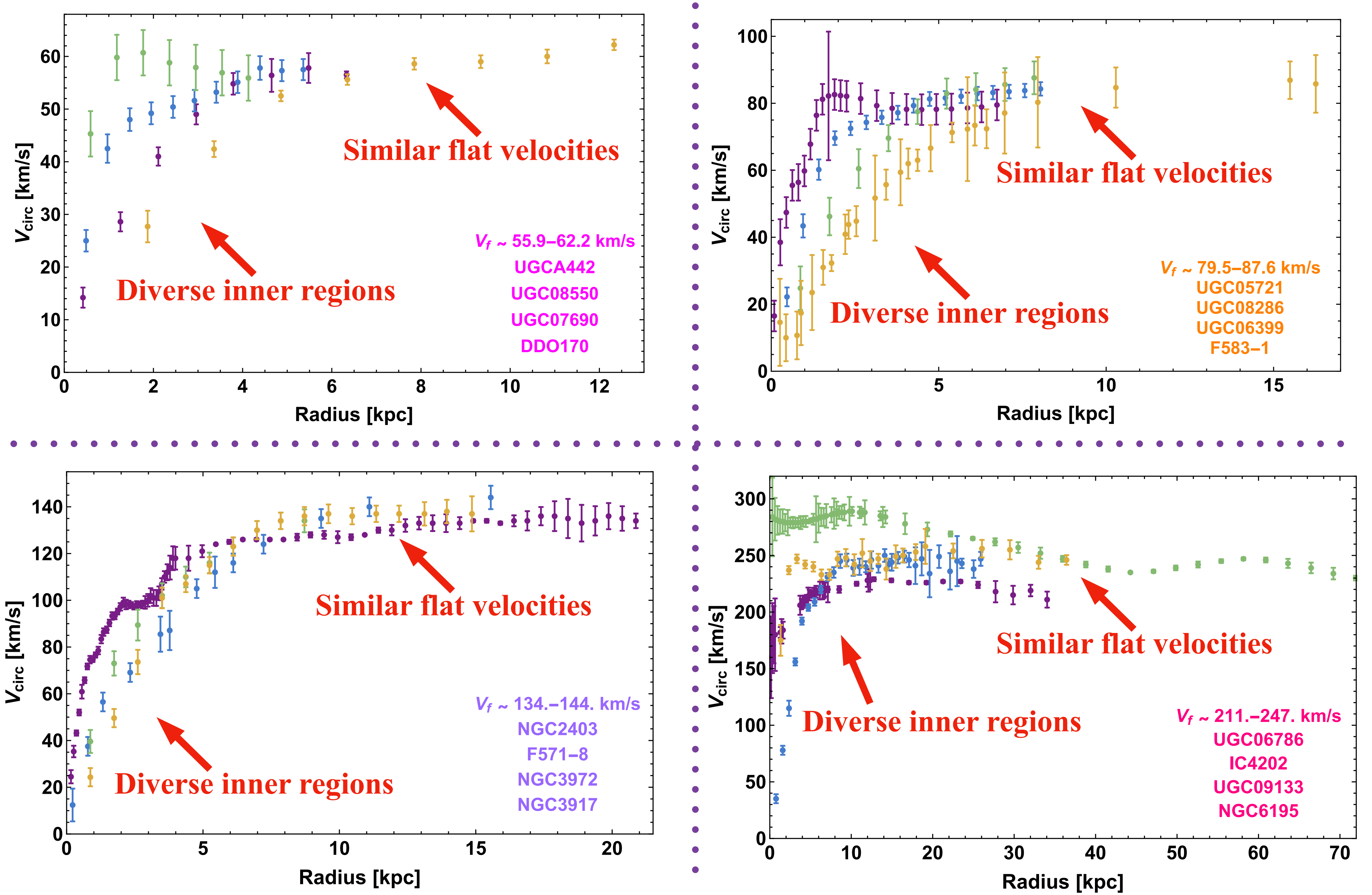
Diversity in Rotation Curves

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



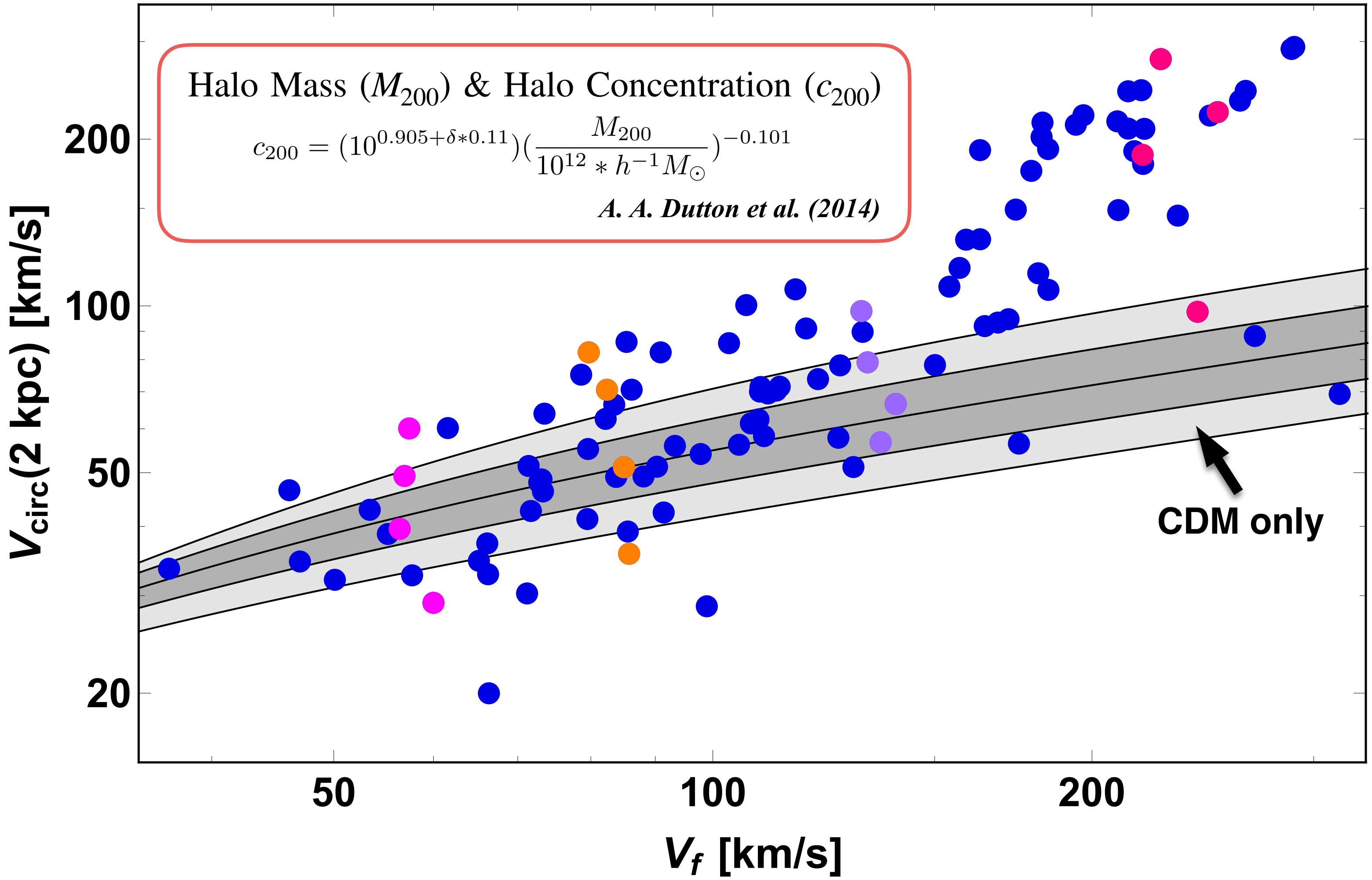
Diversity in Rotation Curves

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



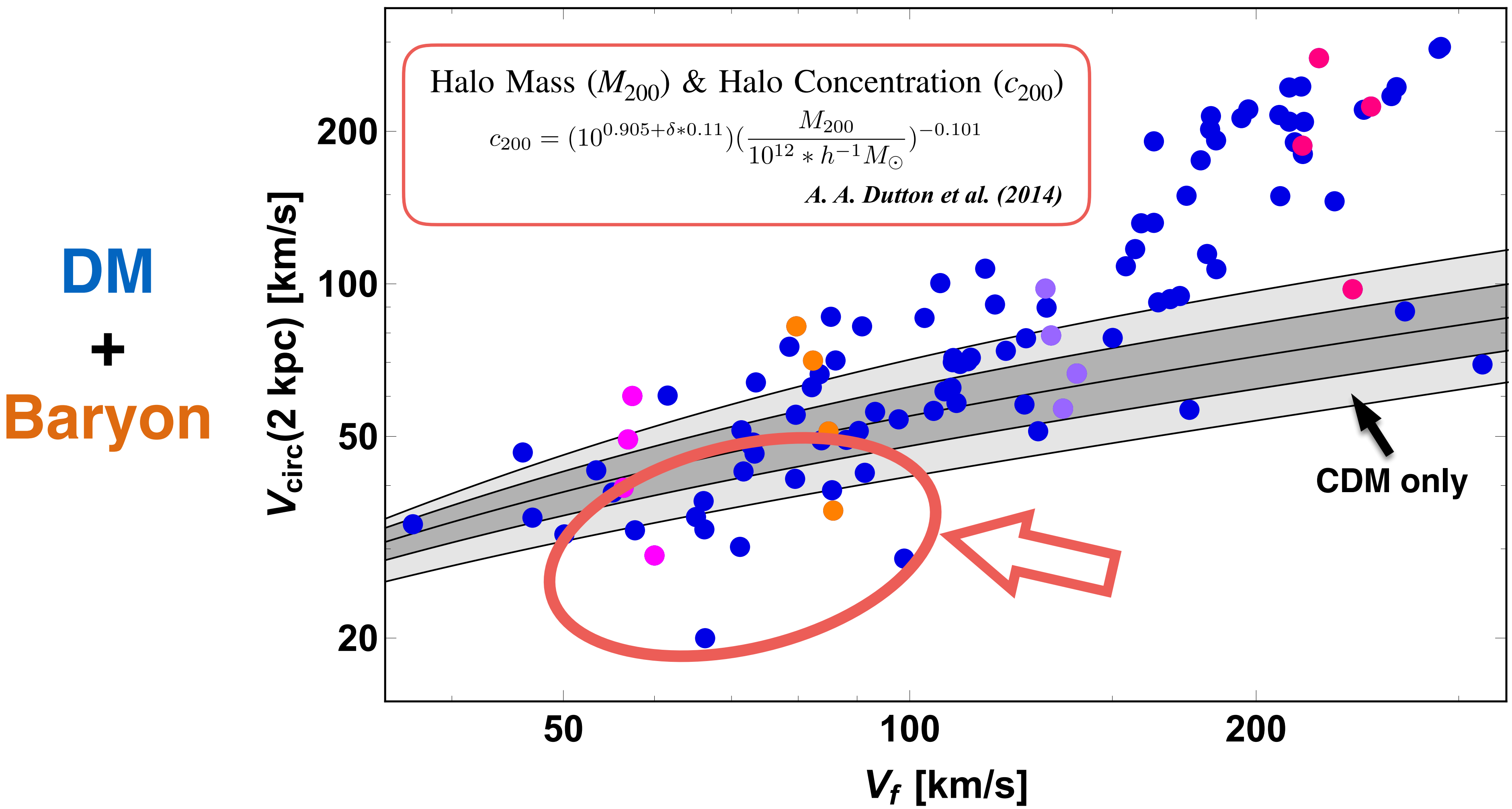
Challenges for Cold Dark Matter (CDM)

DM
+
Baryon



- Diversity is the scatter of the data points at a fixed V_f value.
-

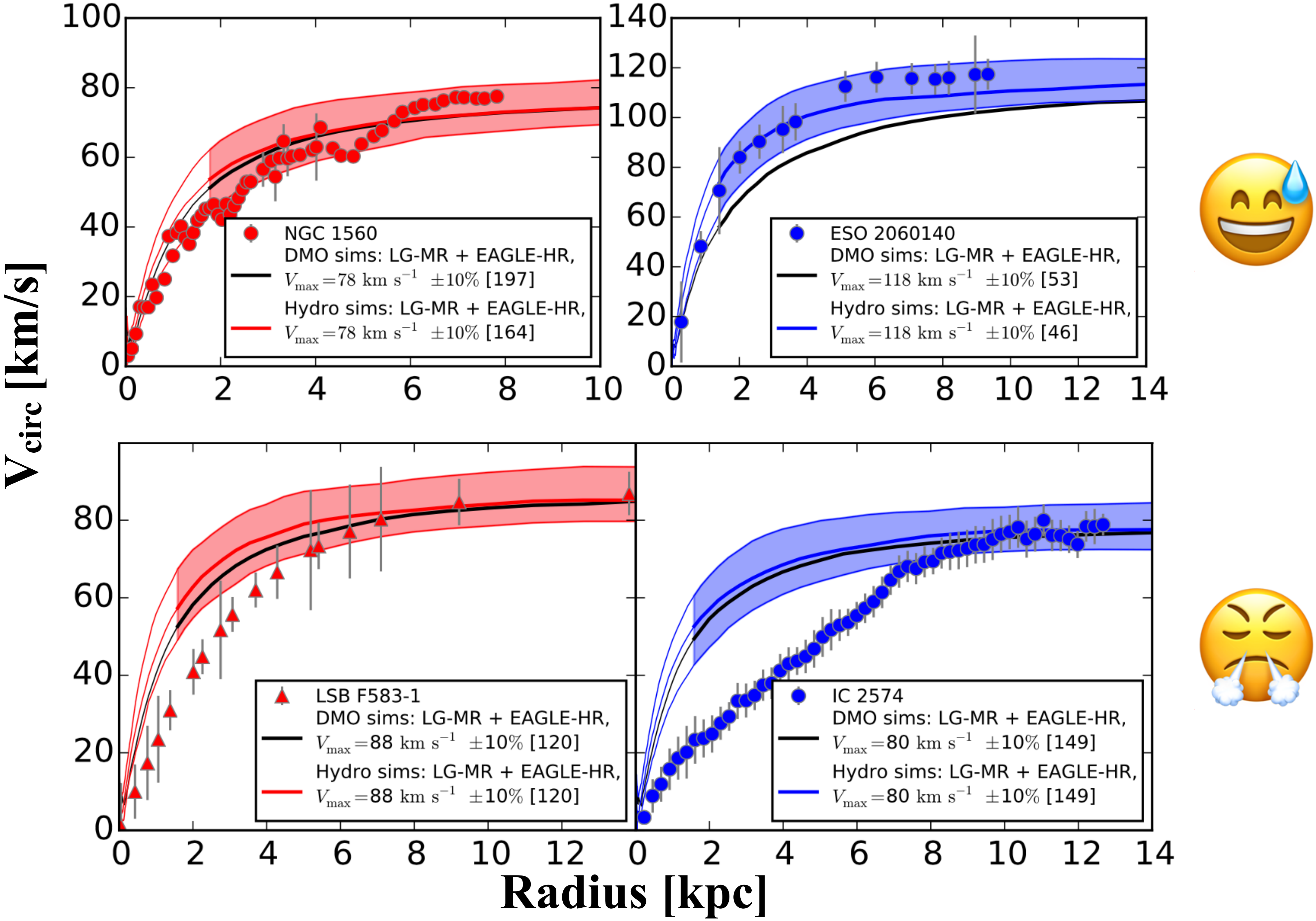
Challenges for Cold Dark Matter (CDM)



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

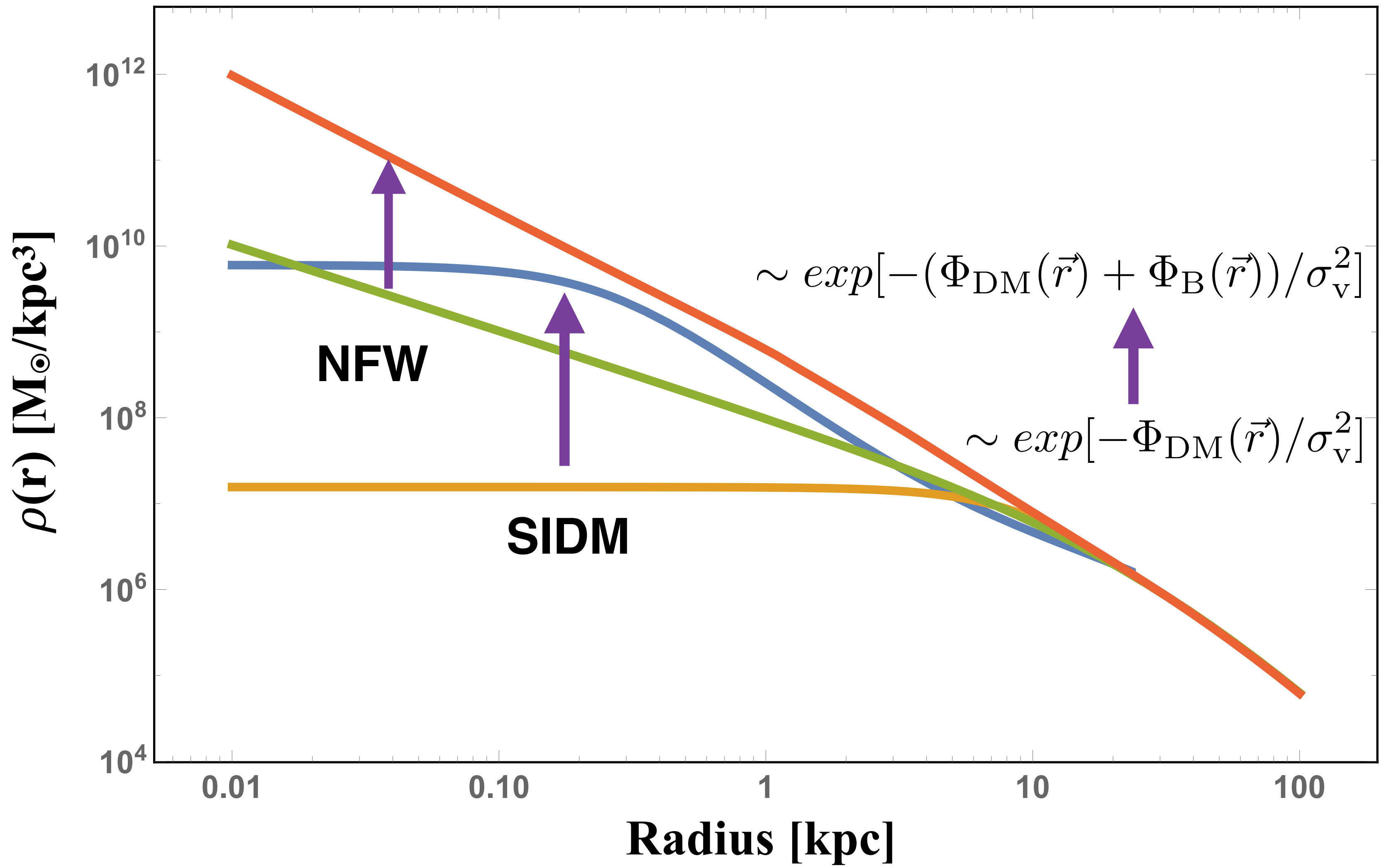
Examples

Oman et al. (2015)



SIDM & CDM Density Profiles w/ Baryons

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

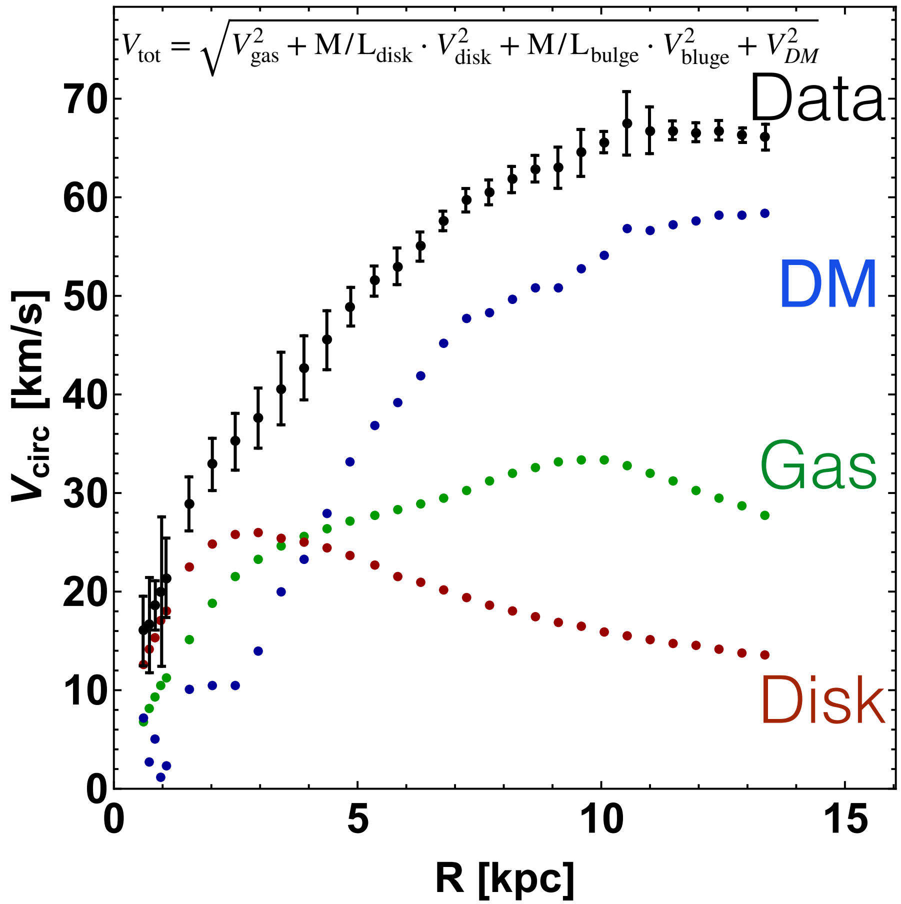


How SIDM works:

Self-Interaction + Baryon Effect + M_{200}-c_{200} Relation

CDM : *Gnedin, et al. (2004) Chan, et al. (2015)*

SIDM: Fit to the Rotation Curves

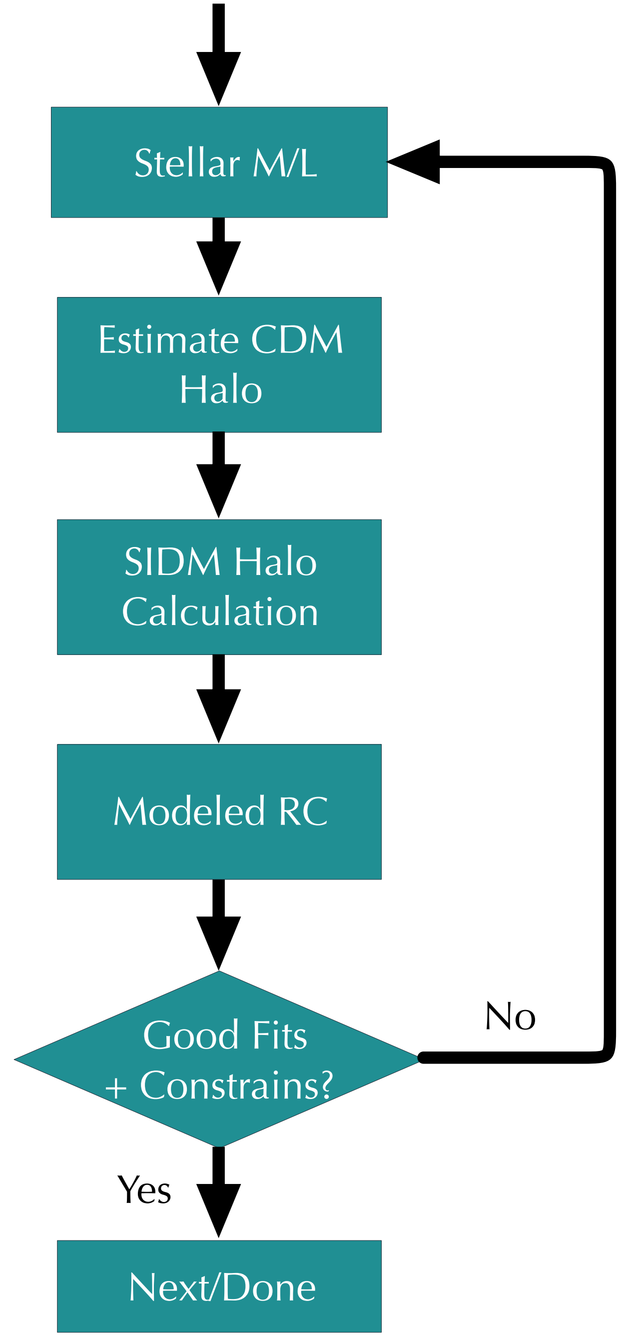


Parameters in SIDM model

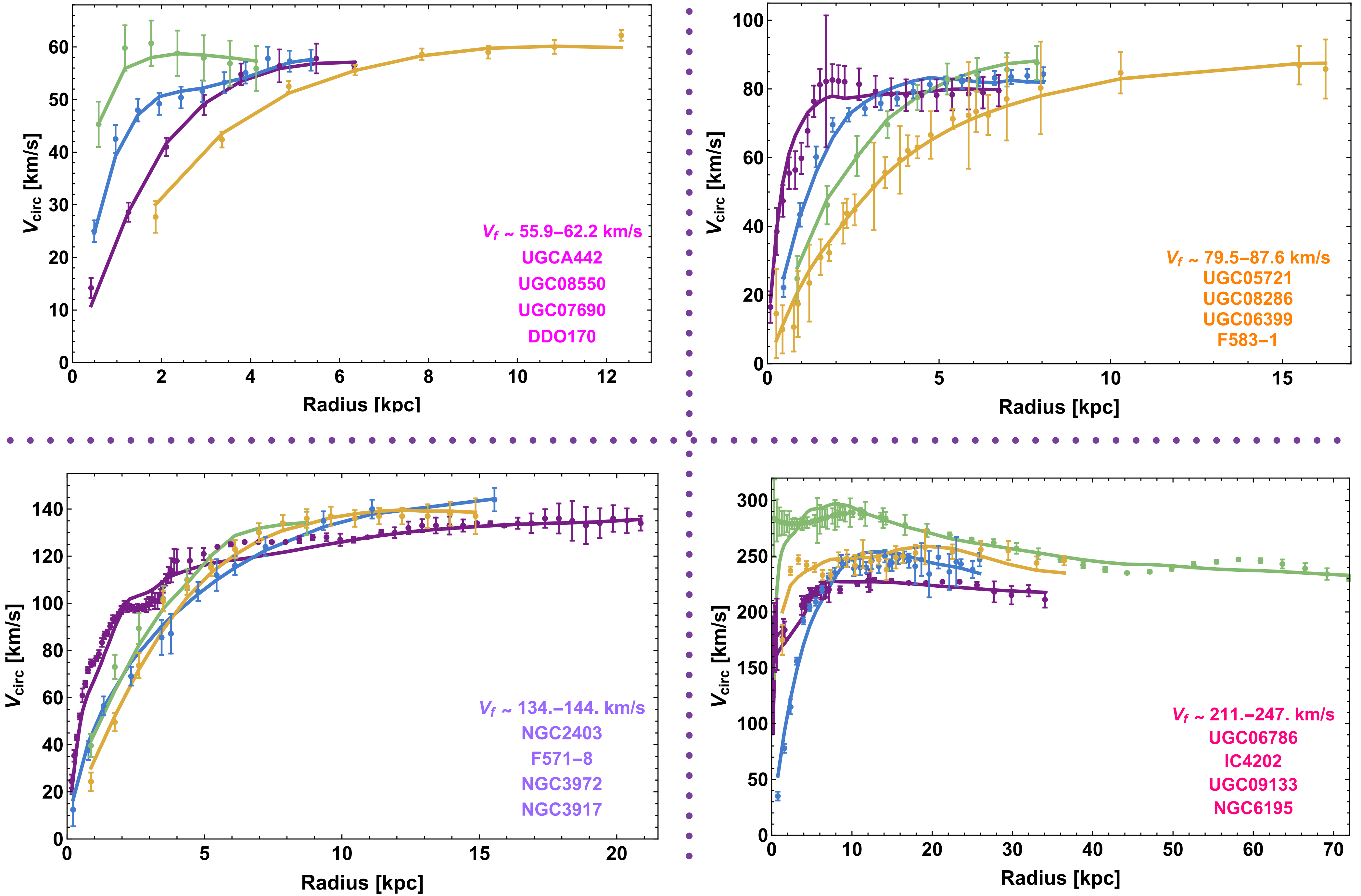
$$\underbrace{(\mathrm{M/L_{Disk}},\ \mathrm{M/L_{Bulge}},}_{\textbf{Baryon}}\ \underbrace{\mathrm{M_{200}},\ \mathrm{c_{200}}\ (V_{\rm max},\ R_{\rm max}))}_{\textbf{DM}}$$

MS: MCMC sampling
CS: Controlled sampling

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

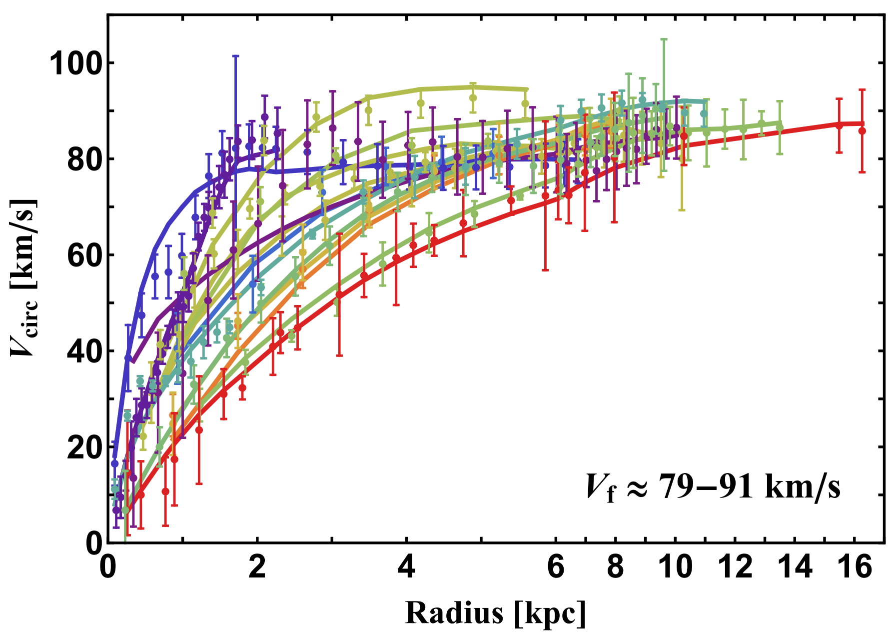


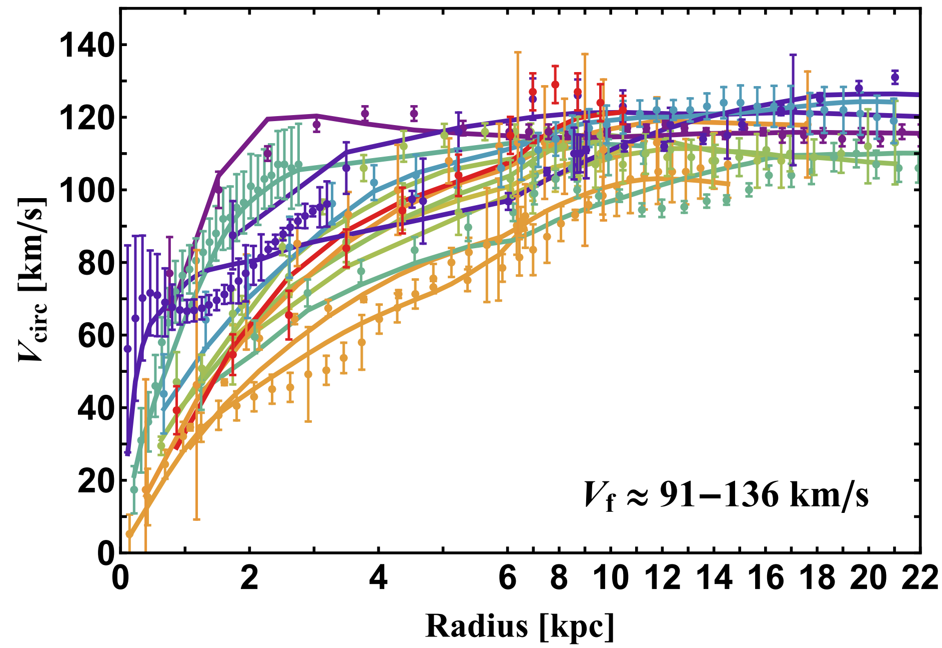
SIDM Fitting Examples

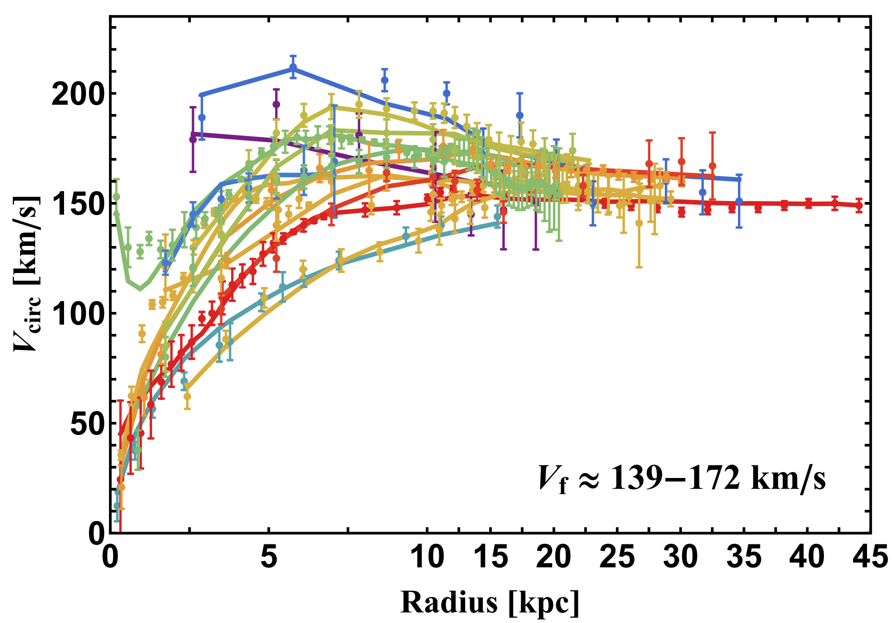


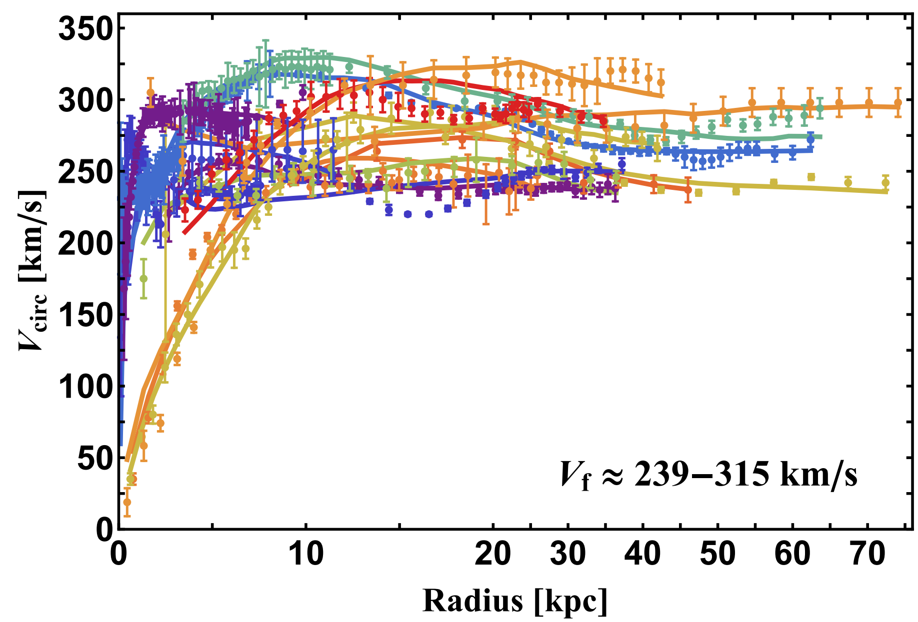
More Examples

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

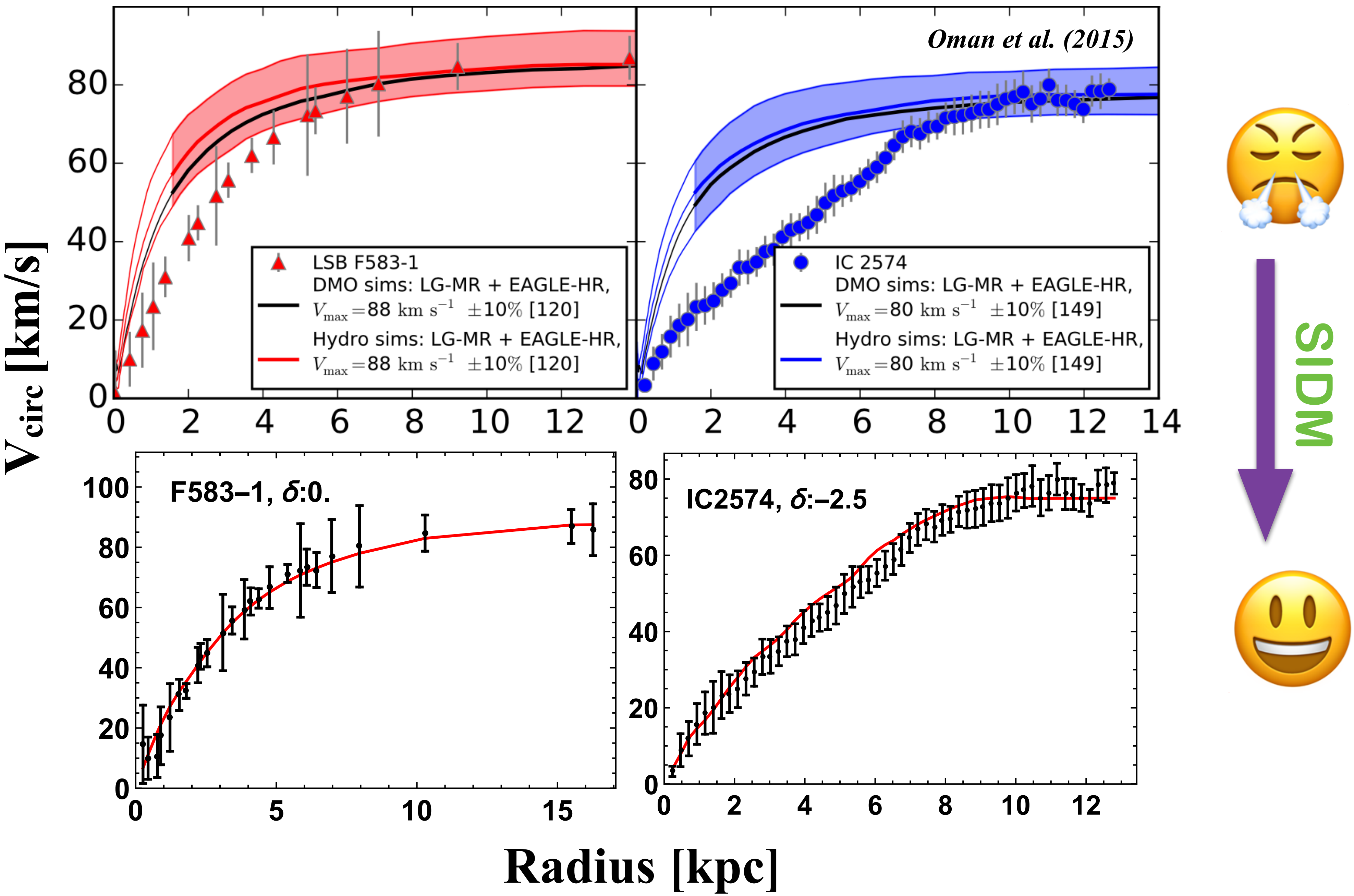








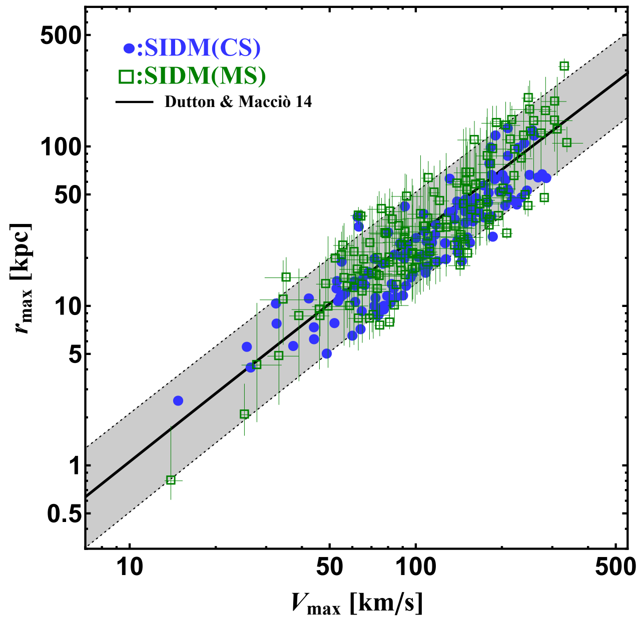
SIDM Fits to the Outliers



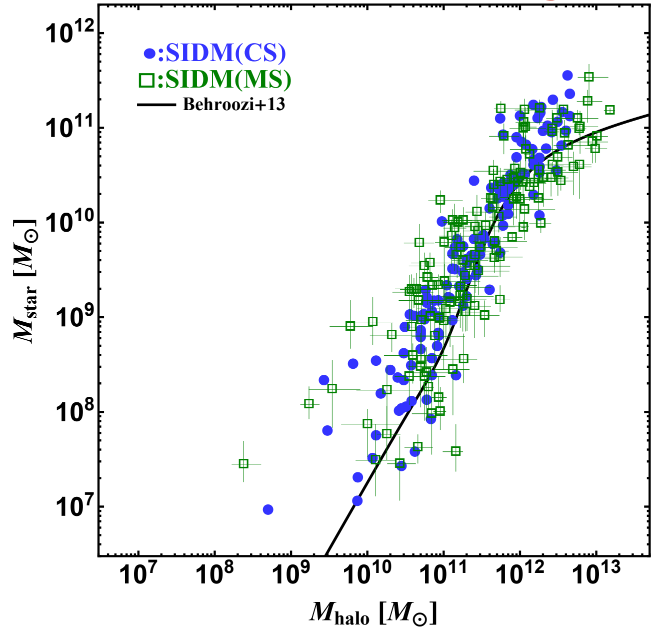
Other Constrains

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

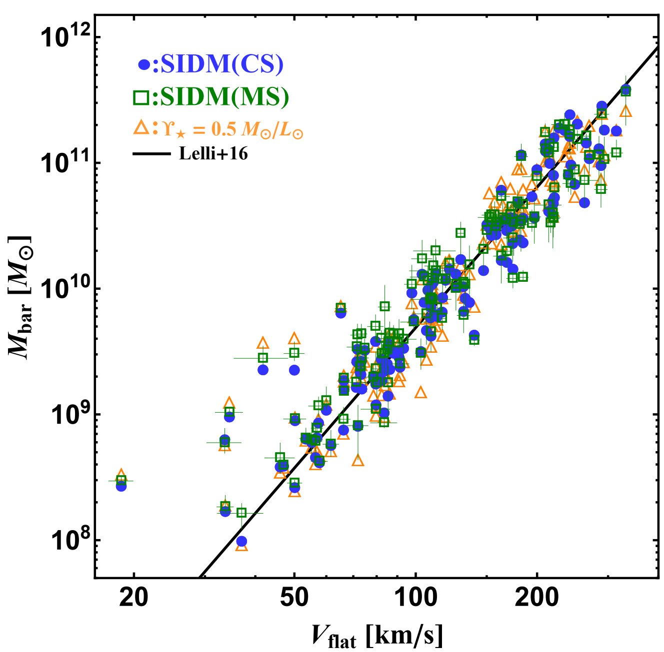
Concentration-Mass Relation



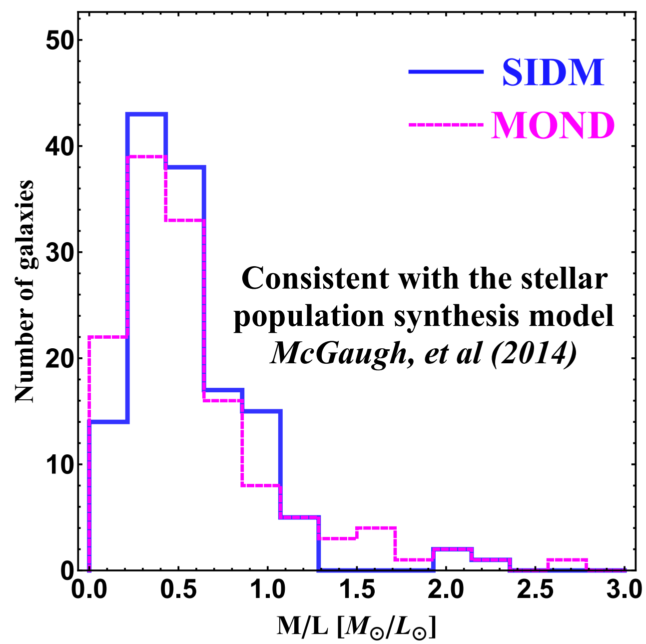
Abundance Matching



Tully-Fisher Relation



Mass-to-Light Ratio



Content

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

Modification of Newtonian Dynamics (MOND)

A brief review of MOND

Milgrom, (1983)

Force: Newtonian Gravity $F = \dfrac{GMm}{R^2}$

Kinematics: Acceleration $g_{\text{obs}} = \dfrac{V^2}{R}$

Newton's 2nd Law $F = m \cdot g_{\text{obs}}$

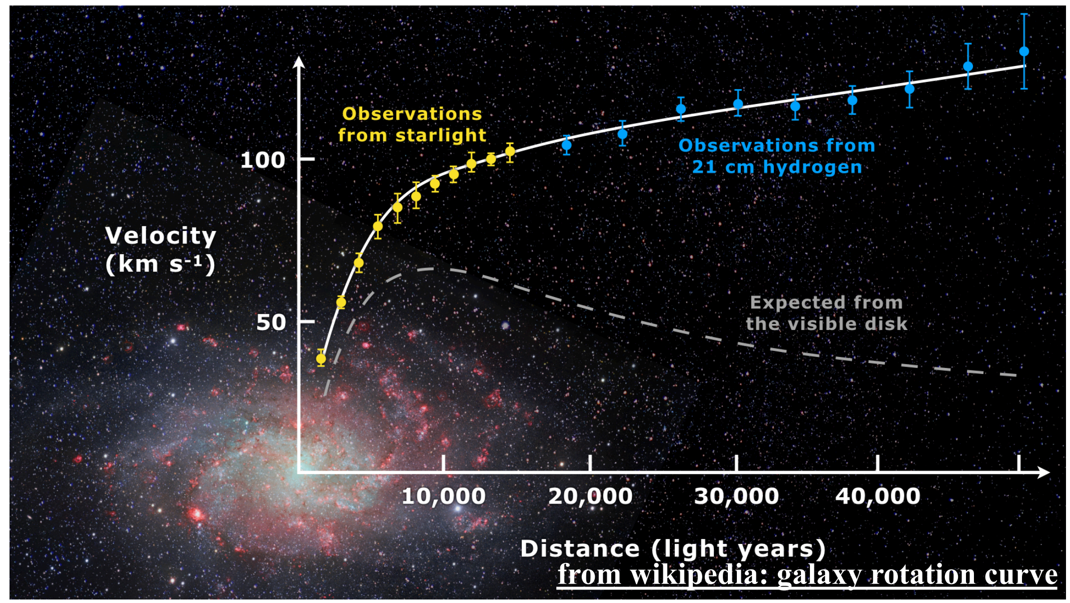
Rotation Curves $F \neq m \cdot g_{\text{obs}}$

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

In the outer region of a galaxy:

$$F \propto \frac{1}{R^2},\ g_{obs} \propto \frac{1}{R} \ \Rightarrow\ F = m \cdot \frac{g_{\text{obs}}^2}{g_\dagger}$$

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



Rotation curve of Messier 33

Modification of Newtonian Dynamics

A brief review of MOND

Milgrom, (1983)

Force: Newtonian Gravity $F = \dfrac{GMm}{R^2}$

Kinematics: Acceleration $g_{\rm obs} = \dfrac{V^2}{R}$

Newton's 2nd Law $F = m \cdot g_{\rm obs}$

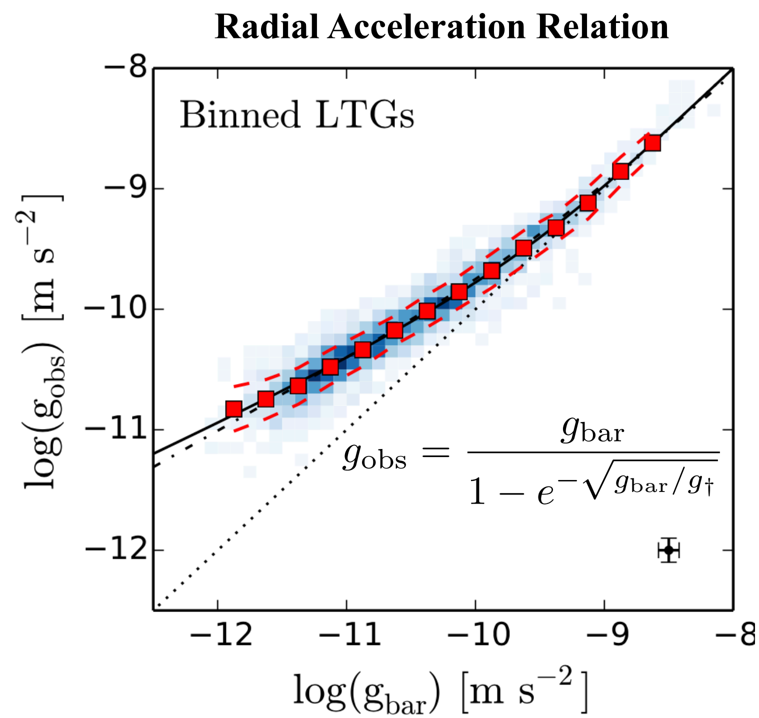
Rotation Curves $F \neq m \cdot g_{\rm obs}$

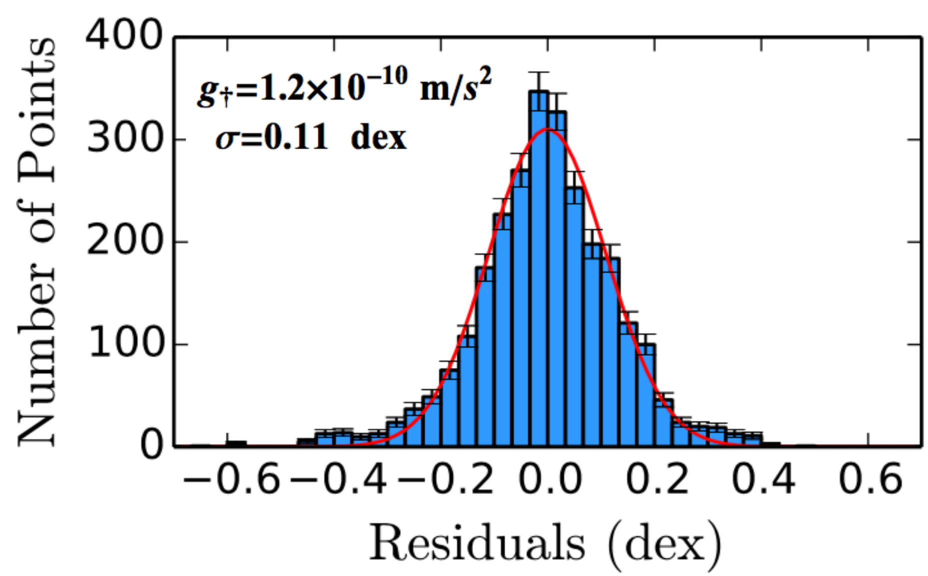
New relation ? $F = \dfrac{GMm}{R^2} \quad m \quad g_{\rm obs} = \dfrac{V^2}{R}$

In the outer region of a galaxy:

$F \propto \dfrac{1}{R^2},\ g_{obs} \propto \dfrac{1}{R} \Rightarrow F = m \cdot \dfrac{g_{\rm obs}^2}{g_\dagger}$

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



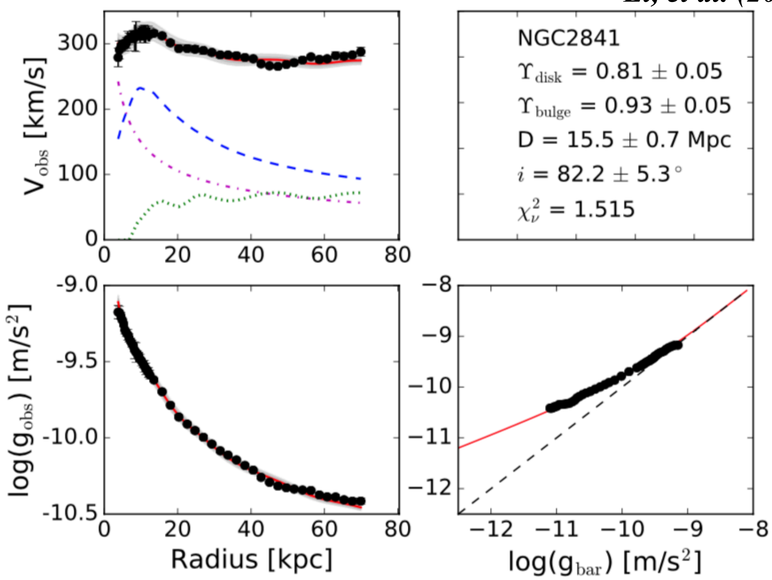


McGaugh, Lelli, Schombert, Pawlowski (2017)

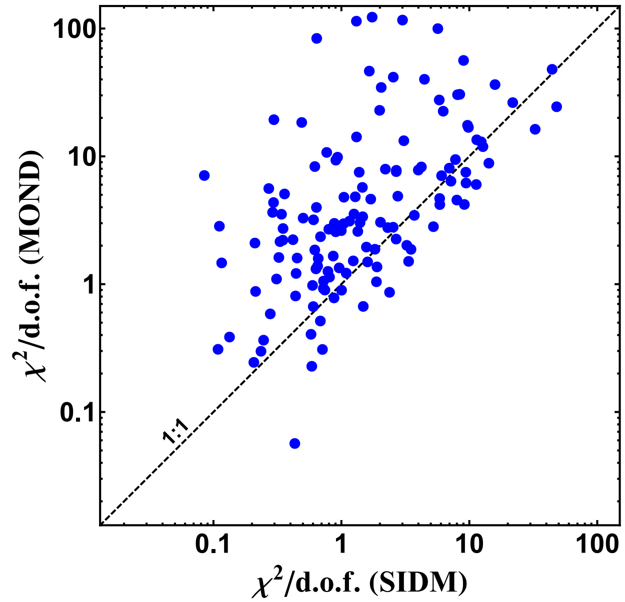
Fits from SIDM & MOND

MOND Fit Example

Li, et al. (2018)



Fitting Quality

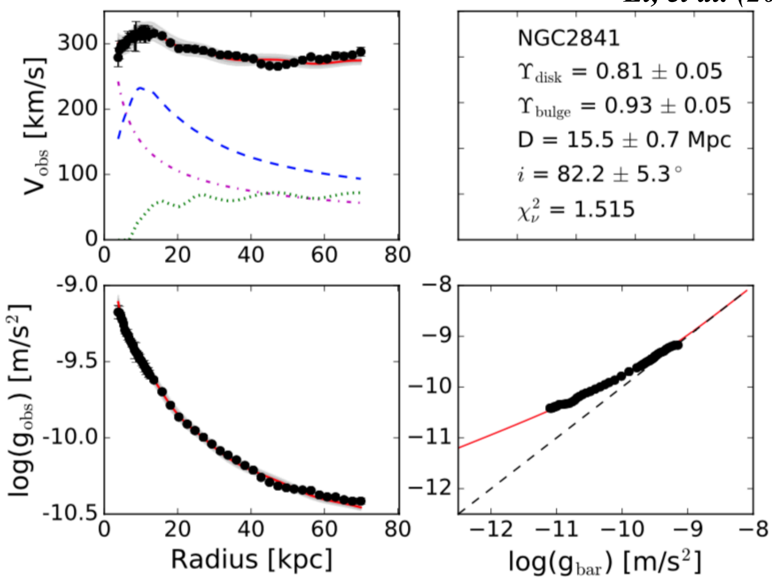


- **MOND can fit to rotation curves well.**
- **SIDM does a better job.**

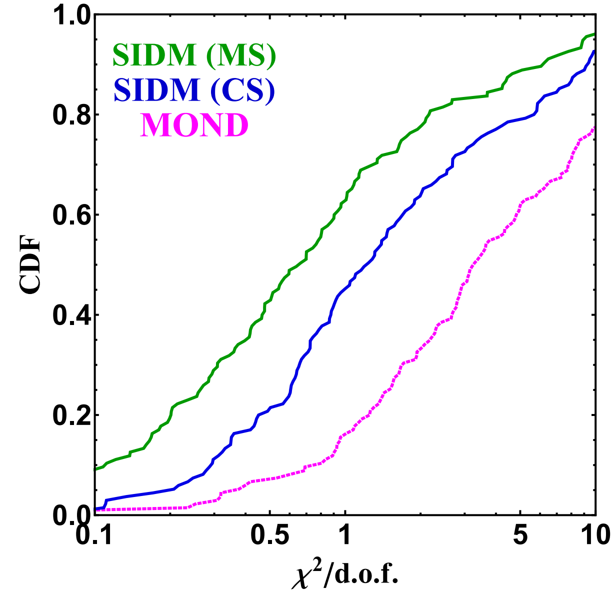
Fits from SIDM & MOND

MOND Fit Example

Li, et al. (2018)



Fitting Quality



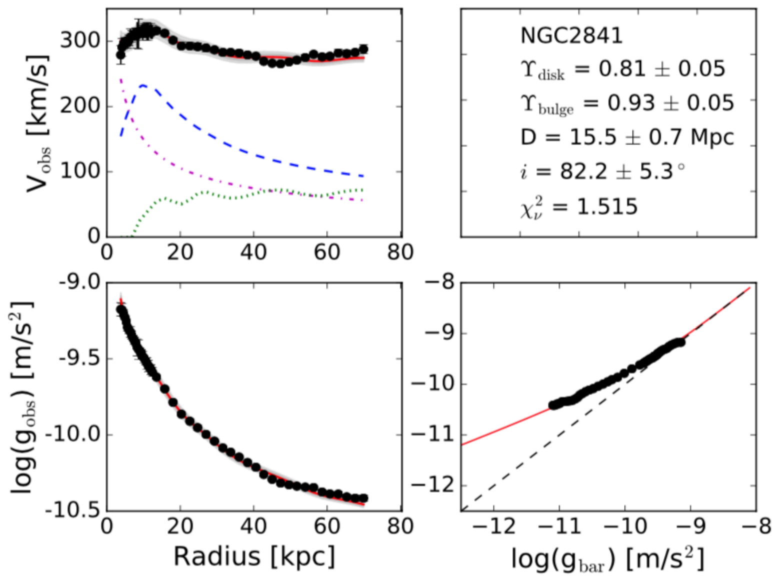
- **MOND can fit to rotation curves well.**

- **SIDM does a better job.**

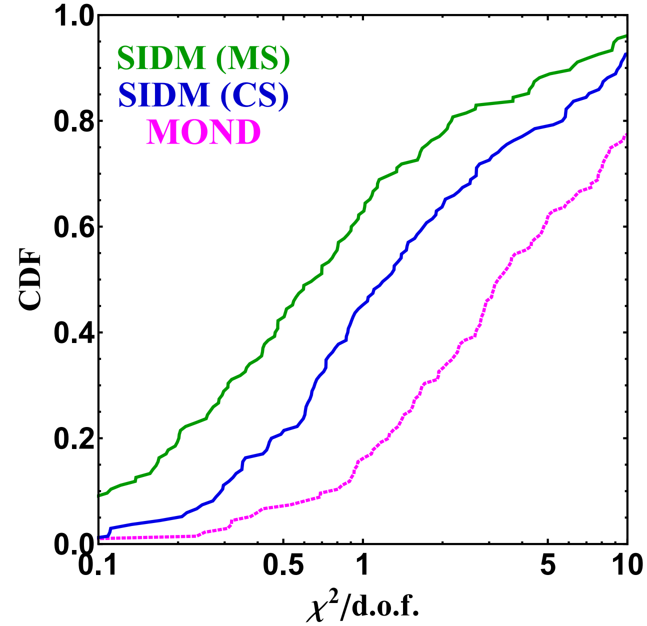
Fits from SIDM & MOND

MOND Fit Example

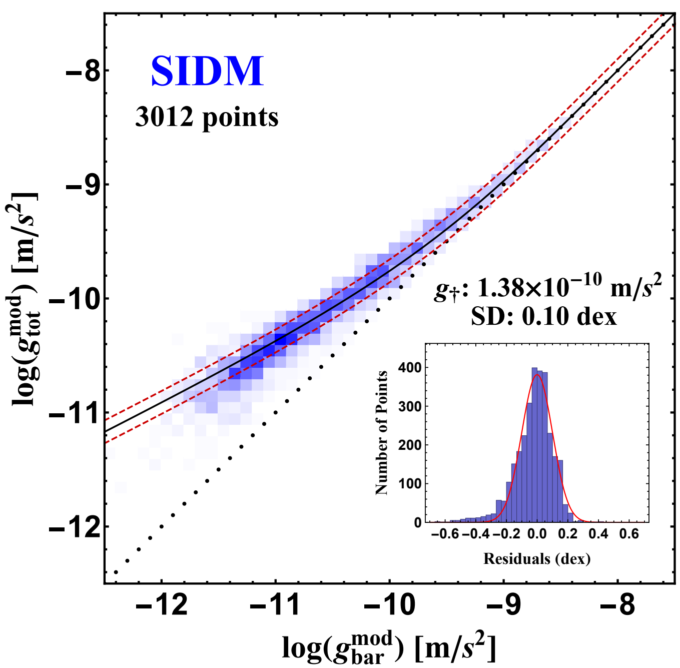
Li, et al. (2018)



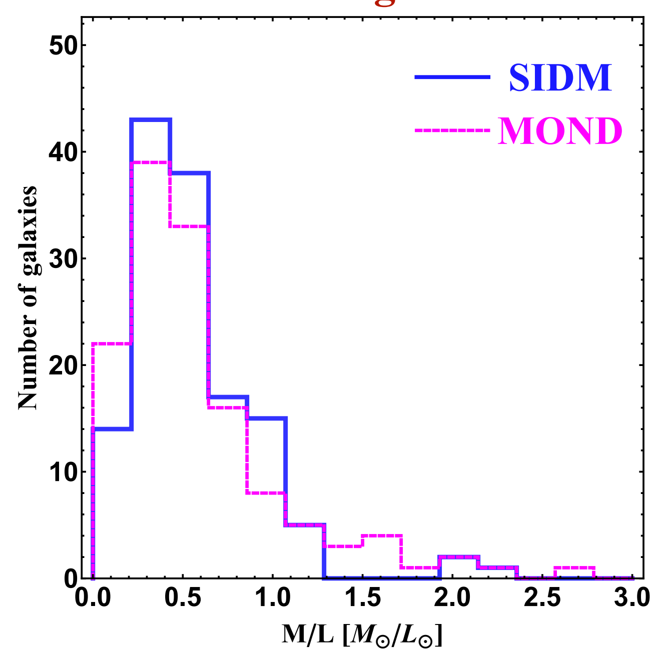
Fitting Quality



Radial Acceleration Relation from SIDM



Mass-to-Light Ratio



What does MOND tell us in “SIDMish”?

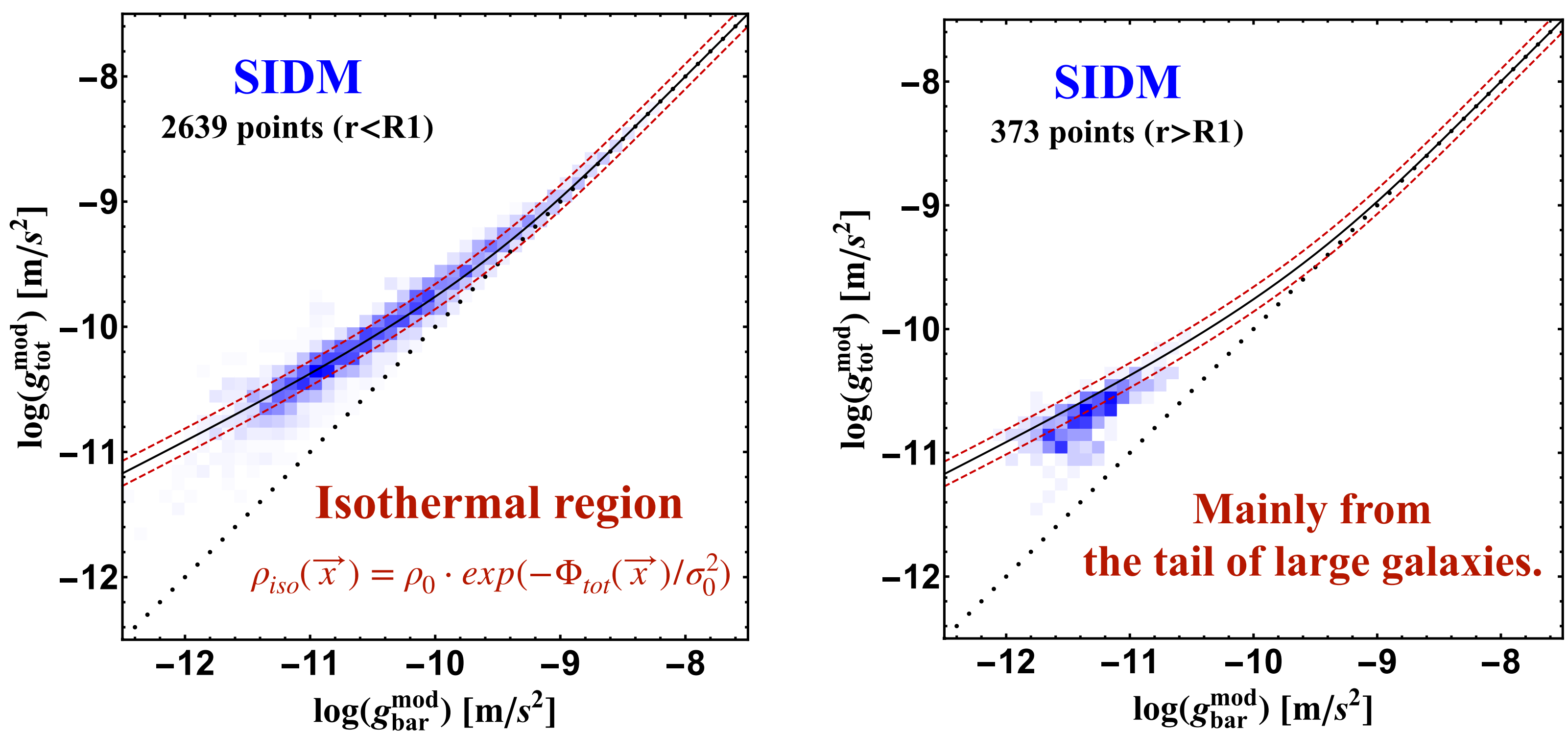
SIDM $\rightleftarrows$ **Observations: Rotation Curves** $\rightleftarrows$ **MOND**

What does MOND tell us in “SIDMish”?

What does MOND tell us in "SIDMish"?

First Evidence

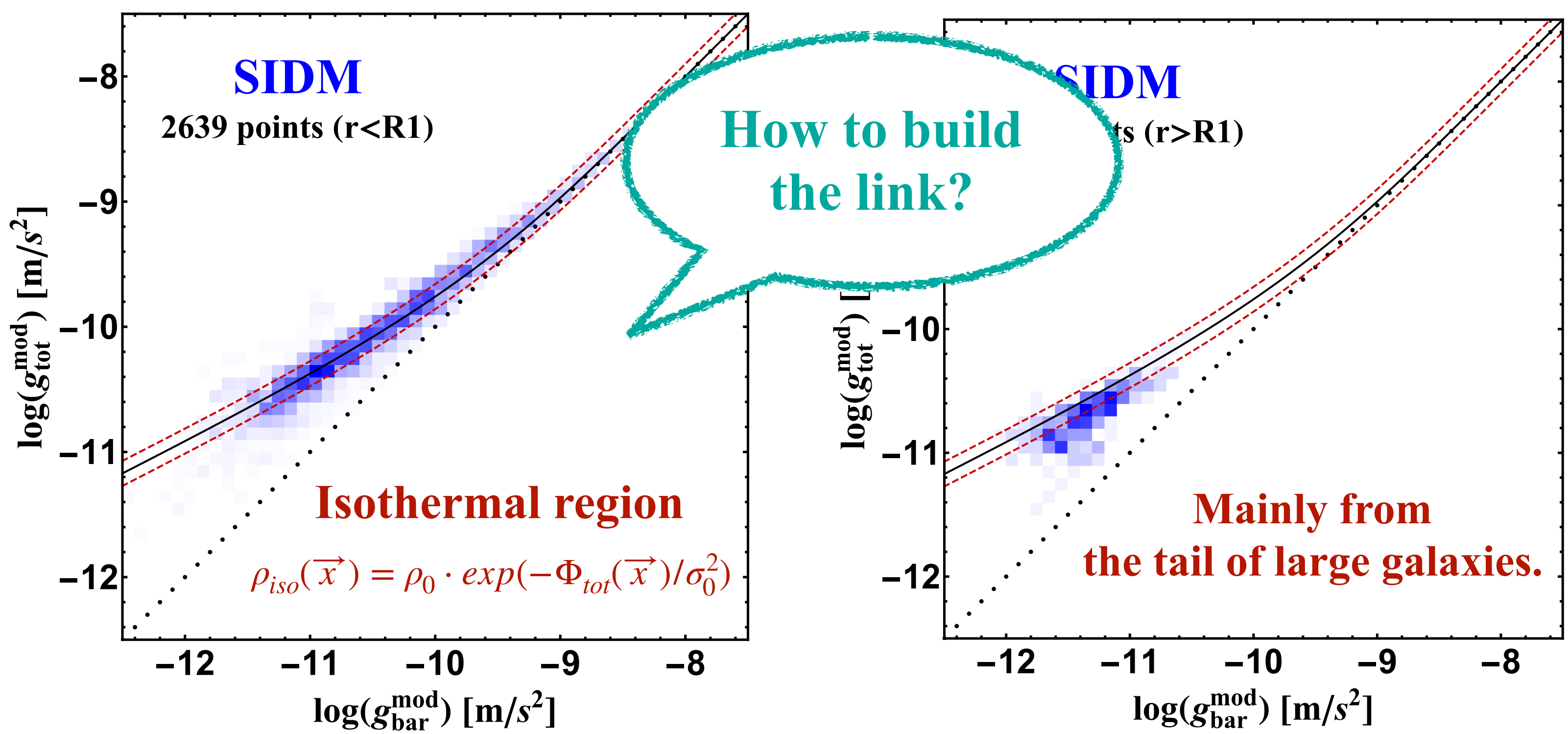
- ~88% data points are within isothermal region.
- The radial acceleration relation is largely determined by data in the isothermal region.



What does MOND tell us in “SIDMish”?

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”?

SIDM

Observations: Rotation Curves

MOND

g_{bar}

What does MOND tell us in “SIDMish”?

SIDM

Observations: Rotation Curves

MOND

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

What does MOND tell us in “SIDMish”?

SIDM **Observations: Rotation Curves** **MOND**

$$g_{\rm tot} = -\nabla\Phi_{\rm tot} \longleftrightarrow \boxed{g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_\dagger}}} \longleftrightarrow g_{\rm bar}}$$

What does MOND tell us in “SIDMish”?

SIDM

Observations: Rotation Curves

MOND

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

What does MOND tell us in “SIDMish”?

SIDM ⇄ **Observations: Rotation Curves** ⇄ **MOND**

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

$$g_{\rm tot} = g_0 \cdot f(r_{\rm n})$$

$$\begin{cases} g_0 = \dfrac{\sigma_0^2}{r_{\rm d}},\ r_{\rm n} = r/r_{\rm d} \\ f(r_{\rm n}) = \left|\dfrac{logSlope(r_{\rm n})}{r_{\rm n}}\right| \\ logSlope(r_{\rm n}) = \dfrac{dln(\rho_{\rm iso})}{dln(r)} \end{cases}$$

$g_{\rm bar}$ dependance through $g_{\rm bar}(r_{\rm n})$

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

$$\begin{cases} x = g_{\rm bar}/g_\dagger \\ f(x) = \dfrac{x}{1-exp(-\sqrt{x})} \end{cases}$$

- **(a characteristic acceleration) × (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

Observations: Rotation Curves

MOND

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

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

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

$$\begin{cases} g_0 = \frac{\sigma_0^2}{r_d},\ r_n = r/r_d \\ f(r_n) = \left|\frac{logSlope(r_n)}{r_n}\right| \\ logSlope(r_n) = \frac{dln(\rho_{iso})}{dln(r)} \end{cases} \Longrightarrow \frac{g_{tot}}{g_0} = \left|\frac{logSlope(r_n)}{r_n}\right|$$

g_{bar} dependance through $g_{bar}(r_n)$

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

$$\begin{cases} x = g_{bar}/g_\dagger \\ y = g_{obs}/g_\dagger \\ f(x) = \frac{x}{1 - exp(-\sqrt{x})} \end{cases} \Longrightarrow y = \frac{x}{1 - exp(-\sqrt{x})}$$

What does MOND tell us in "SIDMish"?

SIDM ⇄ **Observations: Rotation Curves** ⇄ **MOND**

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

$$g_{\rm tot} = g_0 \cdot f(r_{\rm n})$$

$$\left\{ \begin{array}{l} g_0 = \frac{\sigma_0^2}{r_{\rm d}},\ r_{\rm n} = r/r_{\rm d} \\ f(r_{\rm n}) = \left|\frac{logSlope(r_{\rm n})}{r_{\rm n}}\right| \\ logSlope(r_{\rm n}) = \frac{dln(\rho_{\rm iso})}{dln(r)} \end{array} \right. \Longrightarrow \frac{g_{\rm tot}}{g_0} = \left|\frac{logSlope(r_{\rm n})}{r_{\rm n}}\right|$$

$g_{\rm bar}$ dependance through $g_{\rm bar}(r_{\rm n})$

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

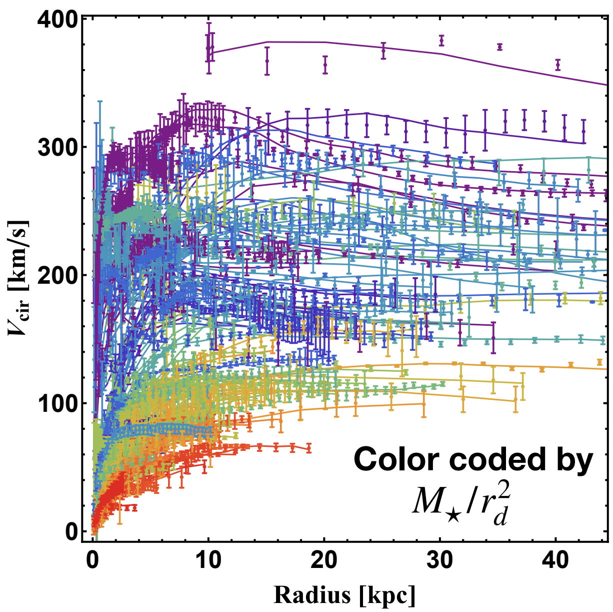
$$\left\{ \begin{array}{l} x = g_{\rm bar}/g_\dagger \\ y = g_{\rm obs}/g_\dagger \\ f(x) = \frac{x}{1 - exp(-\sqrt{x})} \end{array} \right. \Longrightarrow y = \frac{x}{1 - exp(-\sqrt{x})}$$

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

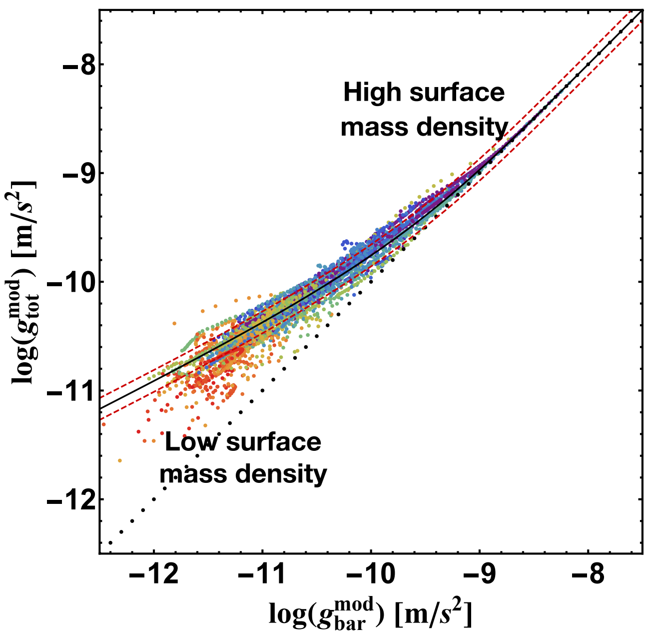
🤔 ?

What does MOND tell us in “SIDMish”?

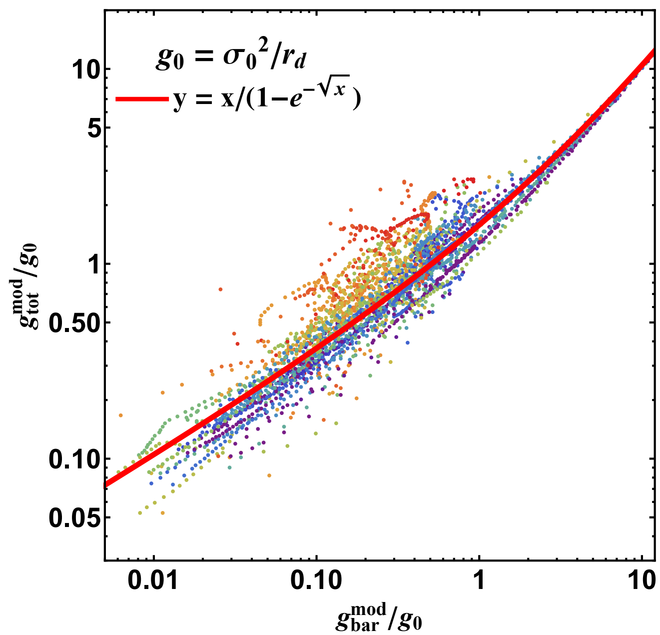
Rotation Curves w/ SIDM Fits



Radial Acceleration Relation



New Correlation



$(\langle g_0 = \frac{\sigma_0^2}{r_d} \rangle = 1.33 \times 10^{-10}\ \mathrm{m/s^2})$

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).**

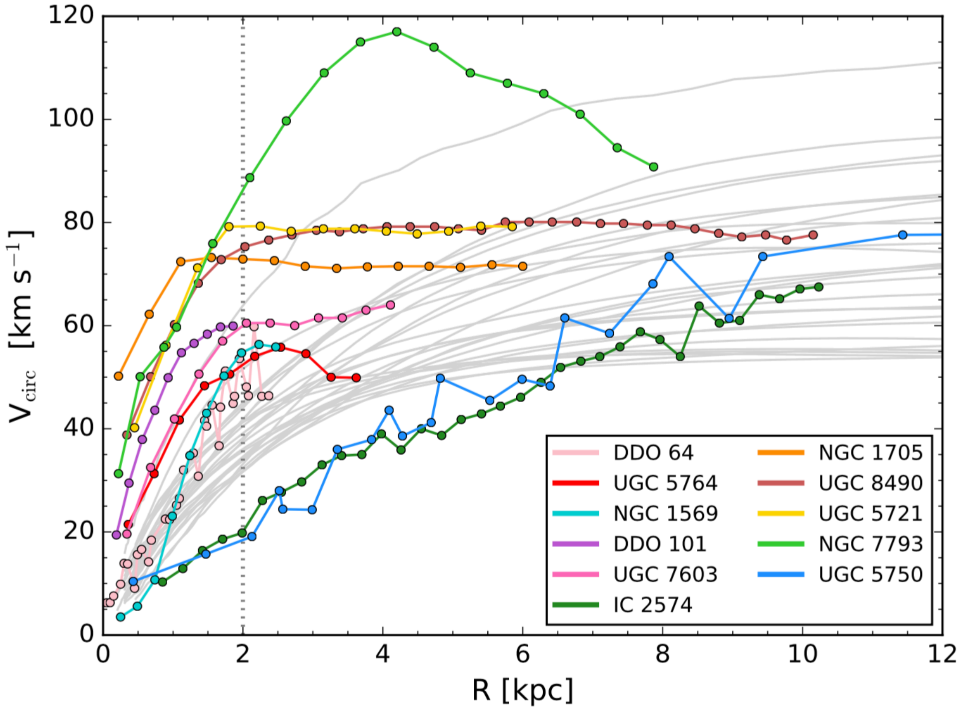
Content

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

Outliers from Simulations

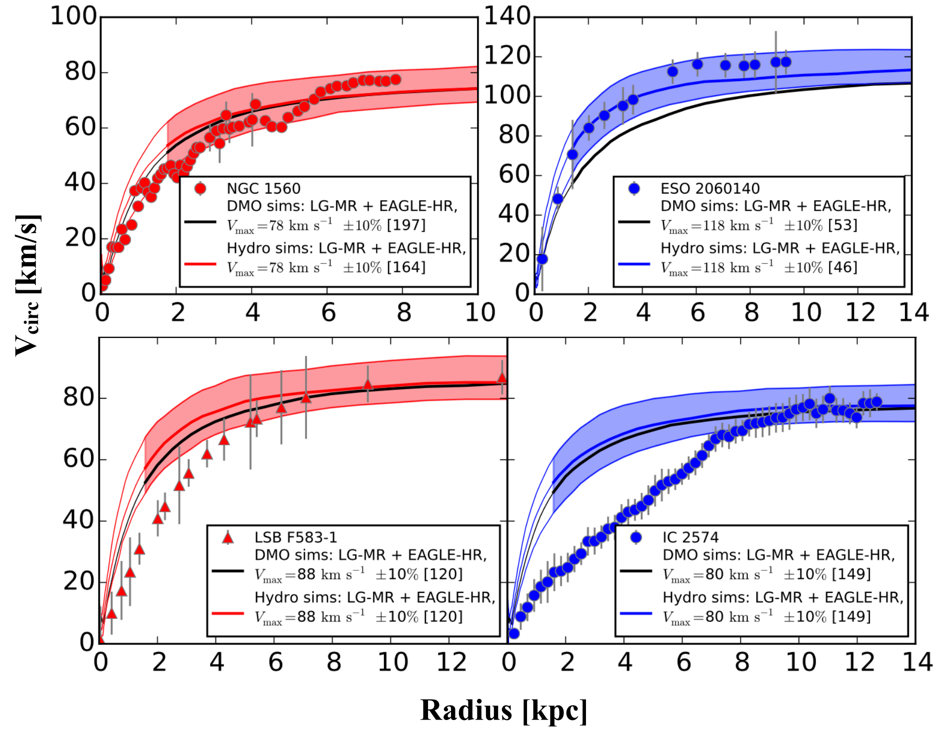
NIHAO Simulations

Santos-Santos, et al. (2017)



EAGLE Simulations

Oman, et al. (2015)

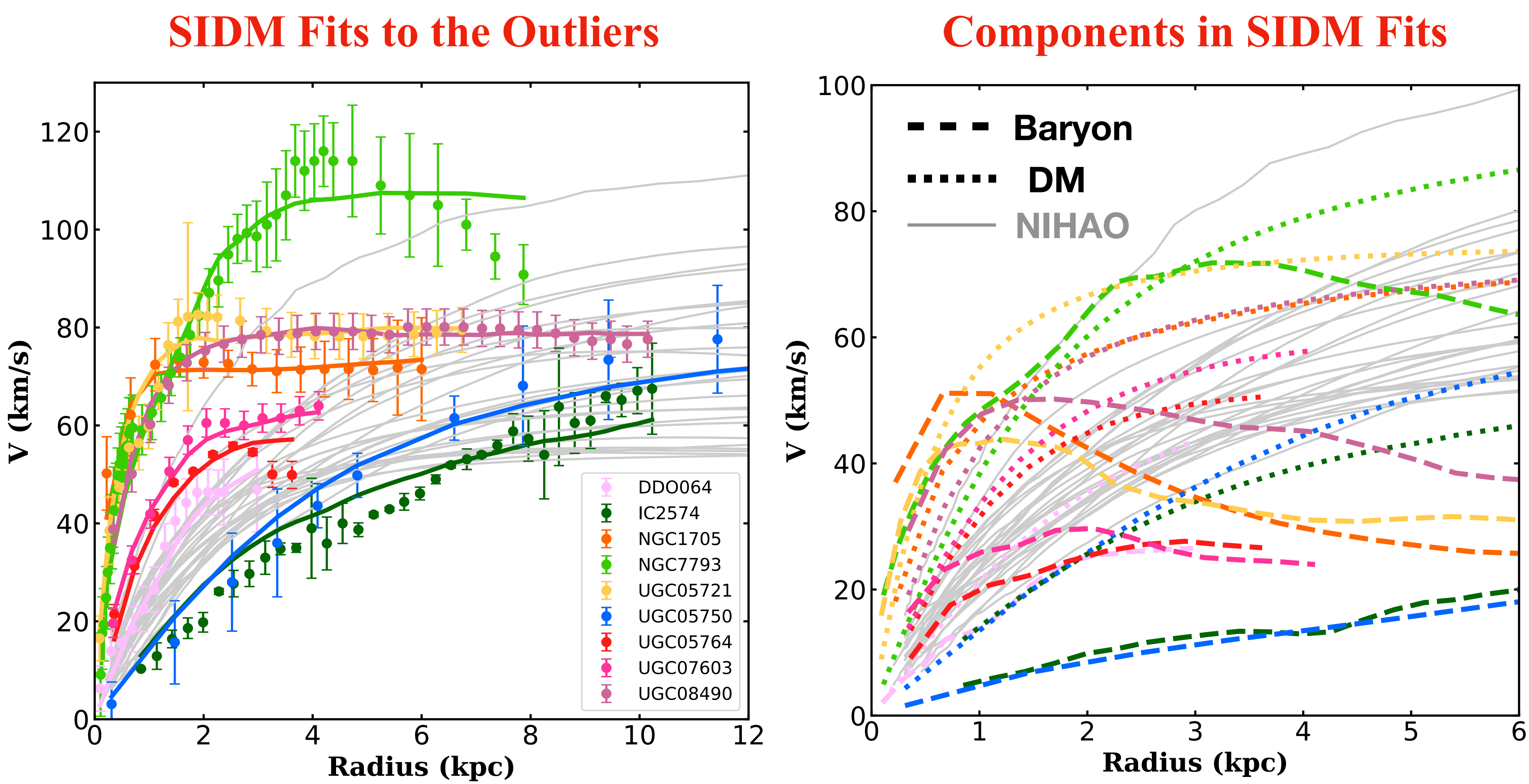


Two opposite cases for baryon feedback effect

- **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)

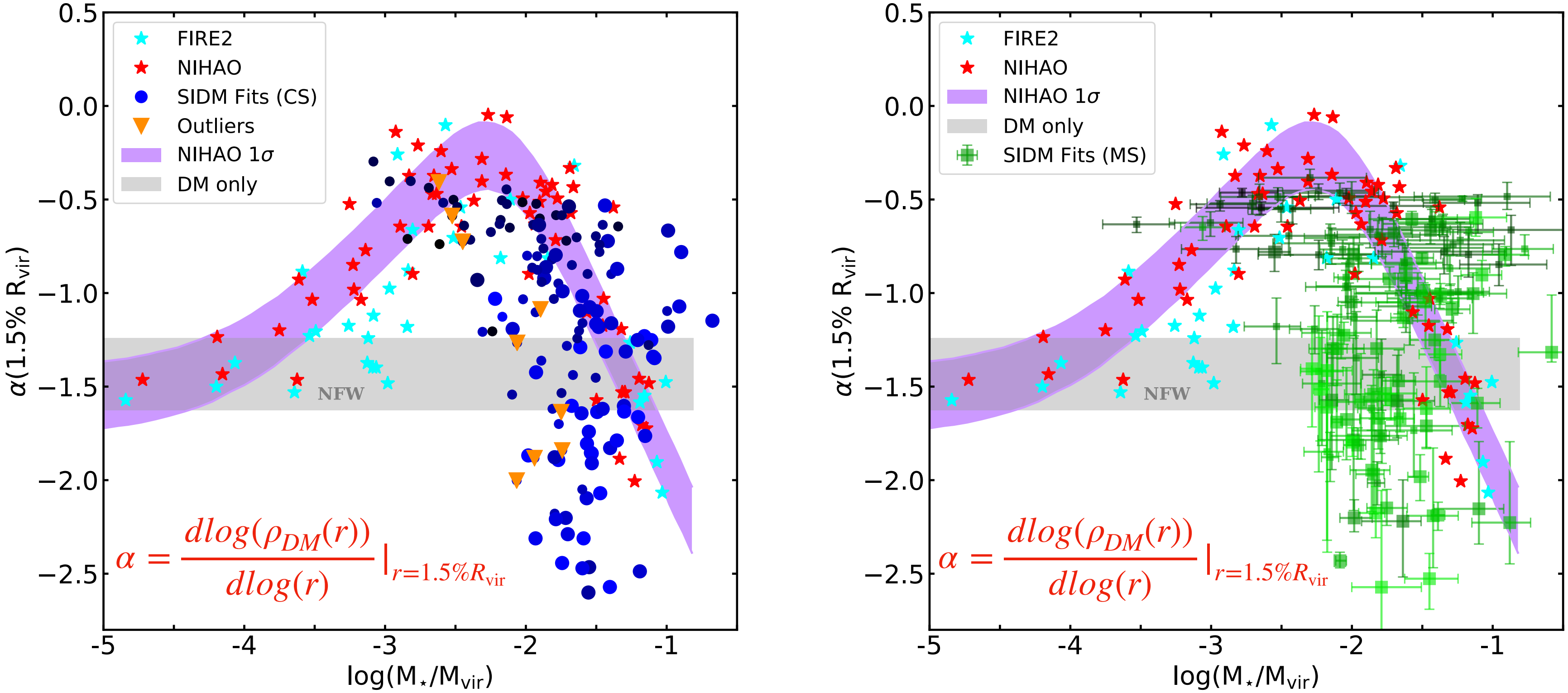


- **SIDM gives excellent fits to the outliers from NIHAO**
- **Some baryon profiles are steeper than total ones from NIHAO**
- **Correlation between baryon profiles and dark matter profiles**

Inner Dark Matter Density Profiles

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

Reflect baron effect



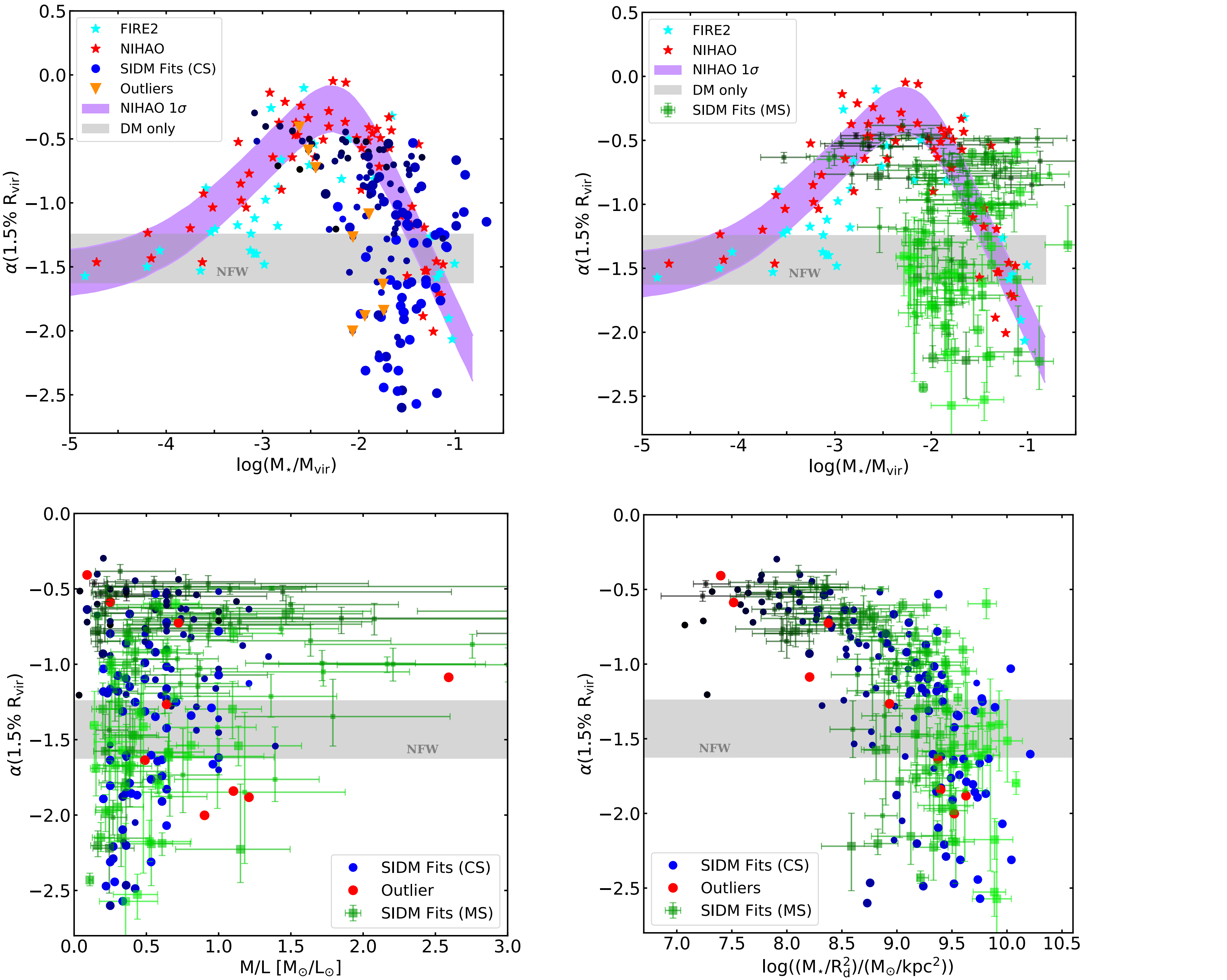
Important to simulation

- **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**

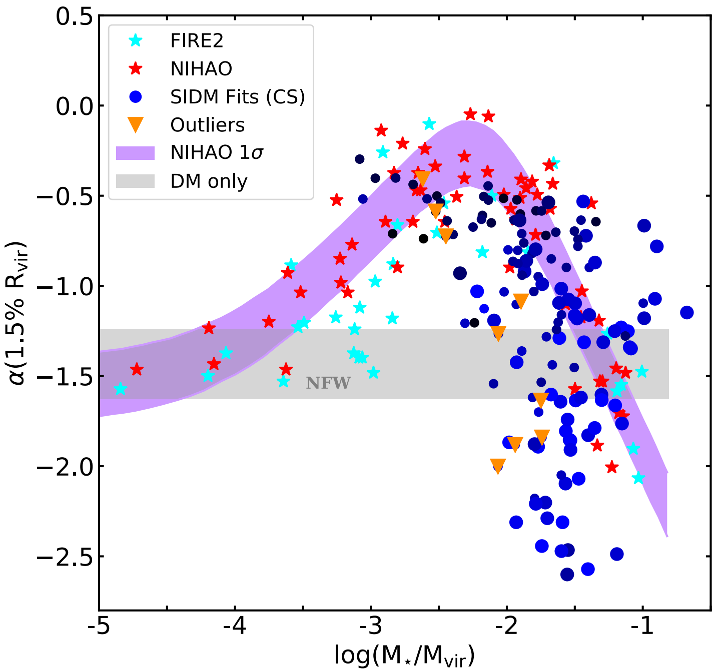
Correlations

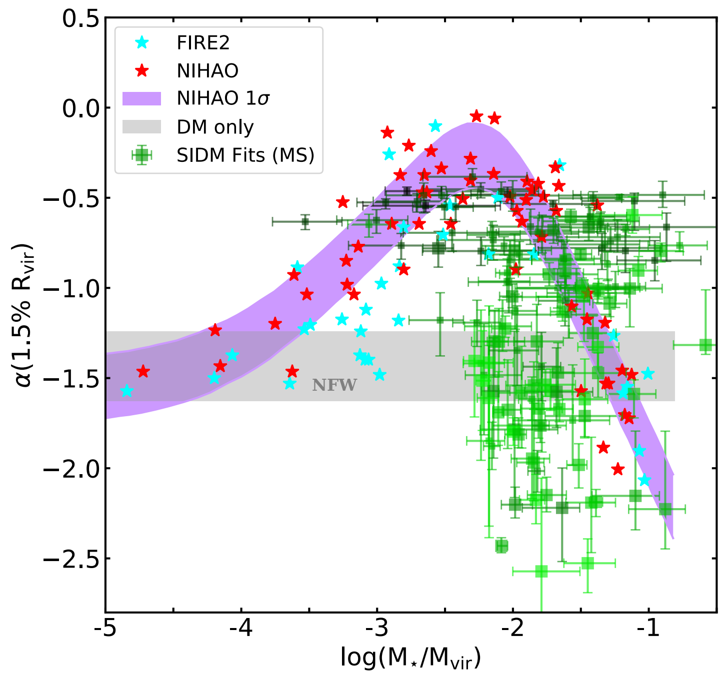
Ren, Kaplinghat, Yu, (2019, in preparation)

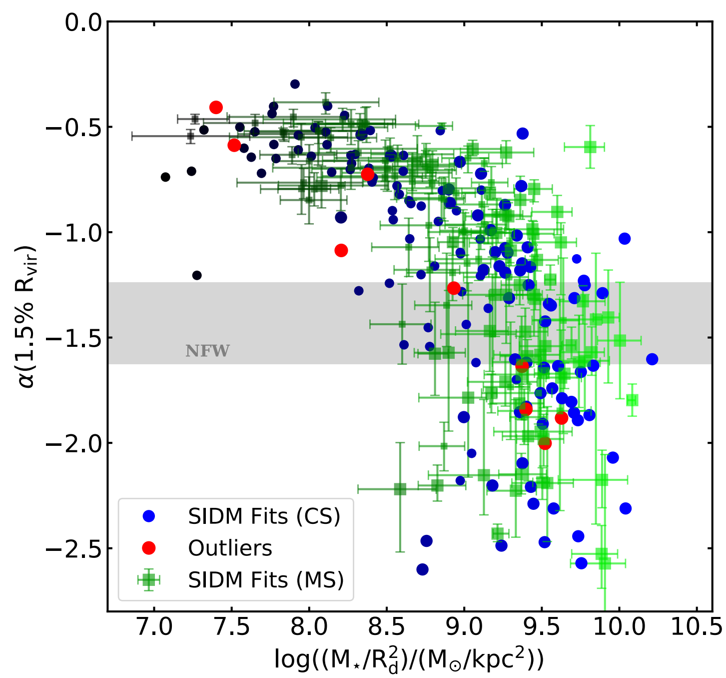


Correlations

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



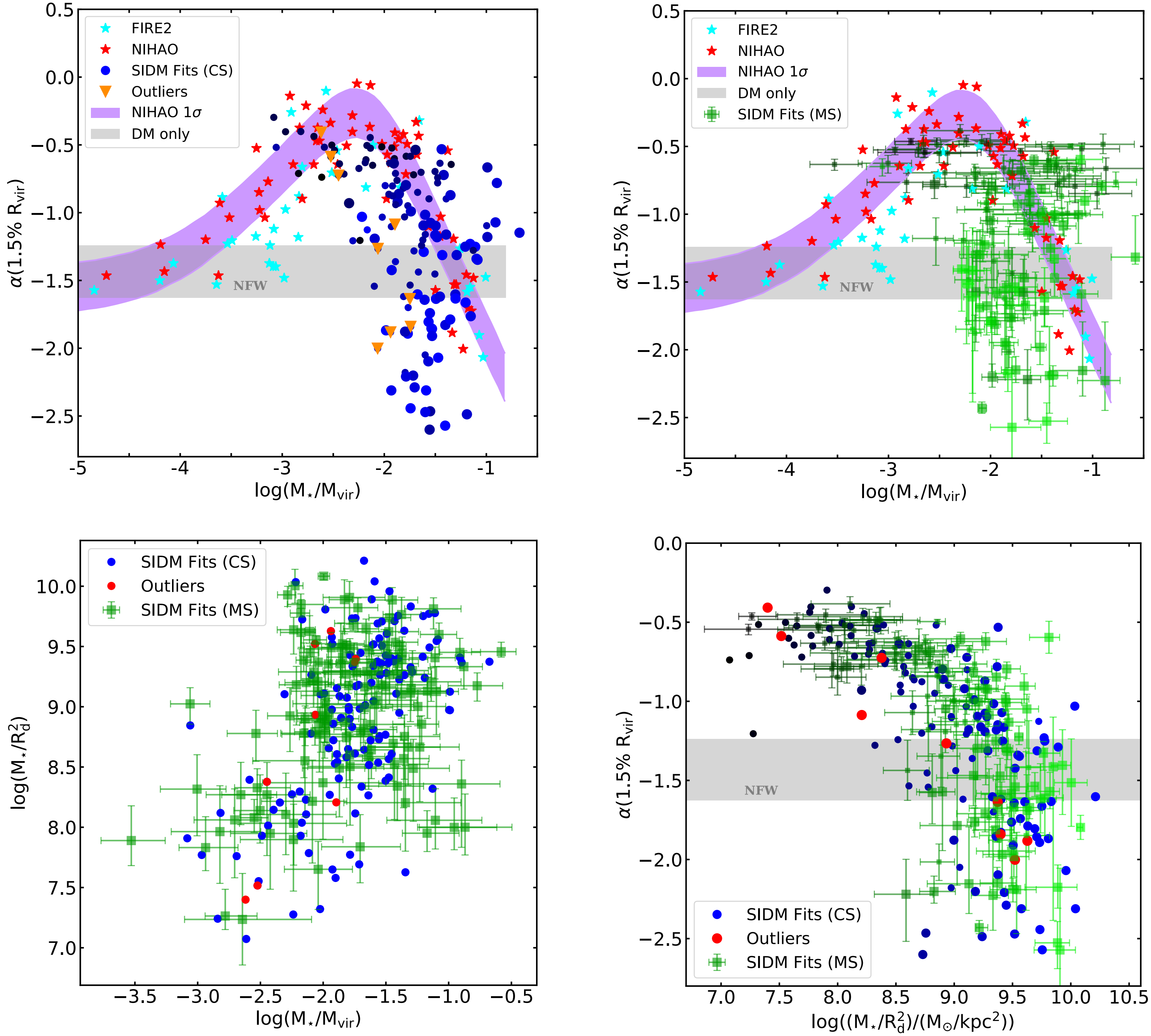




- $\rho_{\rm iso}(\vec{r}) = \rho_0 \times exp[-(\Phi_{\rm DM}(\vec{r}) + \Phi_{\rm Bar}(\vec{r}))/\sigma_{v0}^2]$
- $M_\star/R_d^2 \longleftrightarrow$ Surface mass density $\longleftrightarrow$ $\Phi_{\rm bar}$
- Different systems, different weights for $\Phi_{\rm DM}$ & $\Phi_{\rm bar}$

Correlations

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



SIDM

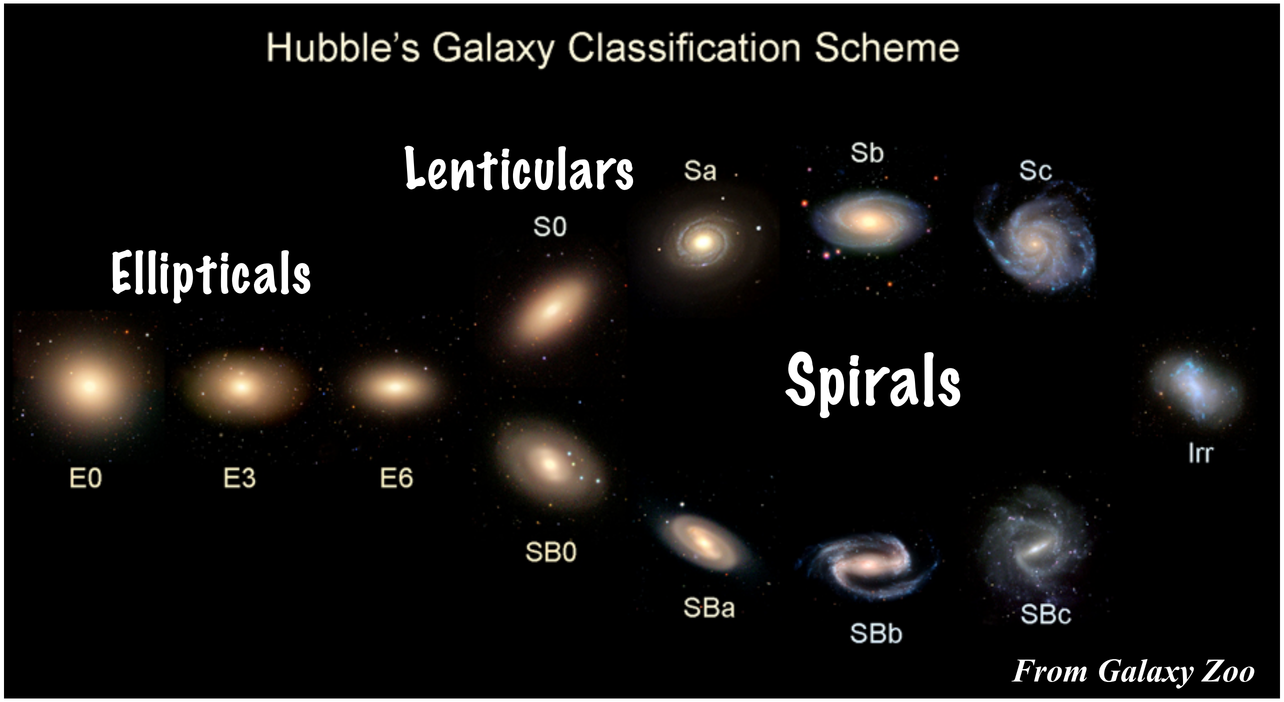
⟹

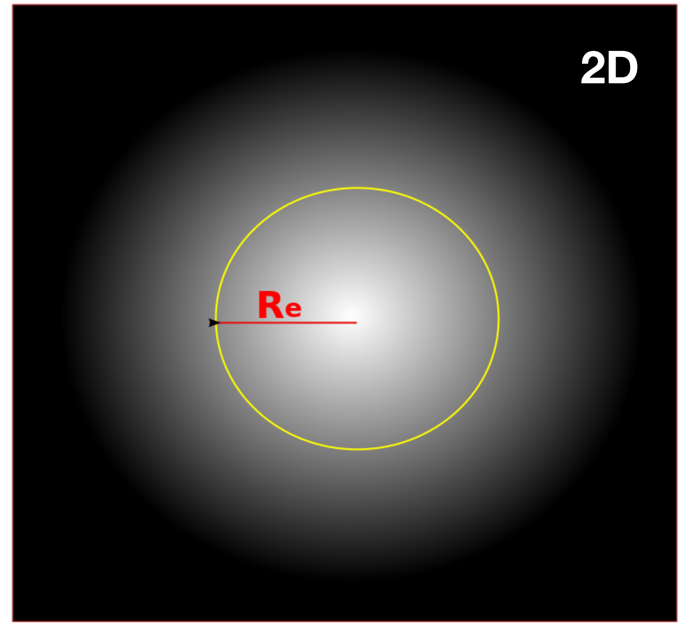
CDM

Content

- Research Background
- $\left\{\begin{array}{l}\text{Diversity}\\\text{Uniformity}\end{array}\right.$ of Galactic Rotation Curves
- Comparison with Cold Dark Matter Simulations
- **Applications in Early-Type Galaxies**
- Summary & Outlook

Introduction to Early-Type Galaxy (ETG)





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

- **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**

Sersic profile: Surface mass density

$$\Sigma(R) = \Sigma_0 \times exp(-b_n(\frac{R}{R_e})^{1/n})$$

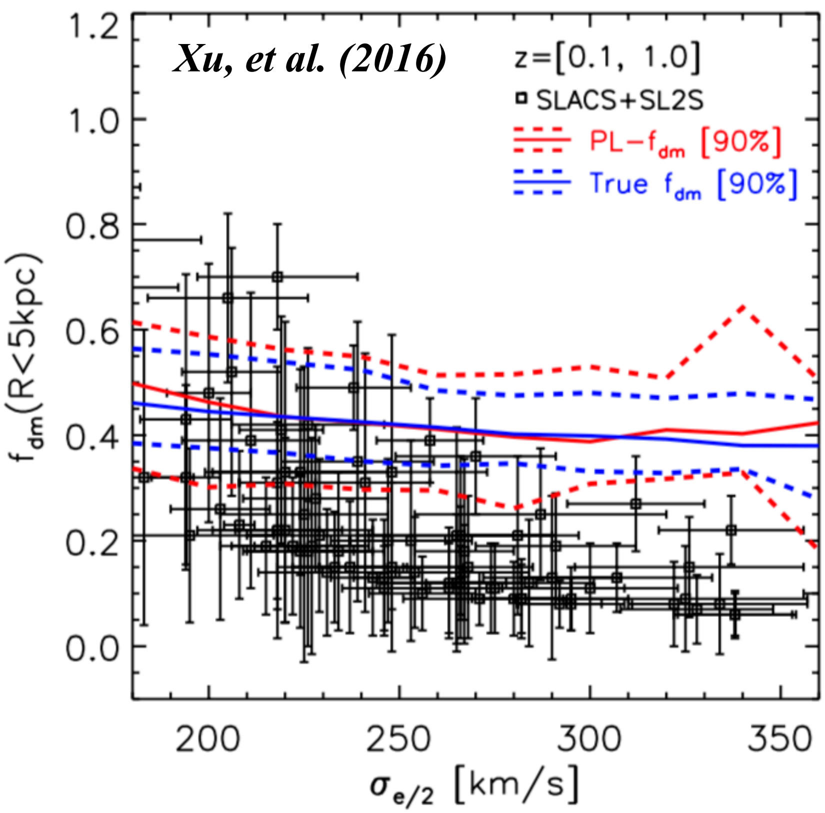
$$b_n = 2n - 1/3 + 0.009876/n$$

$$\rho_{\rm bar}(r) = -\frac{1}{\pi}\int_r^\infty \frac{dR}{\sqrt{R^2 - r^2}}\frac{d\Sigma}{dR}$$

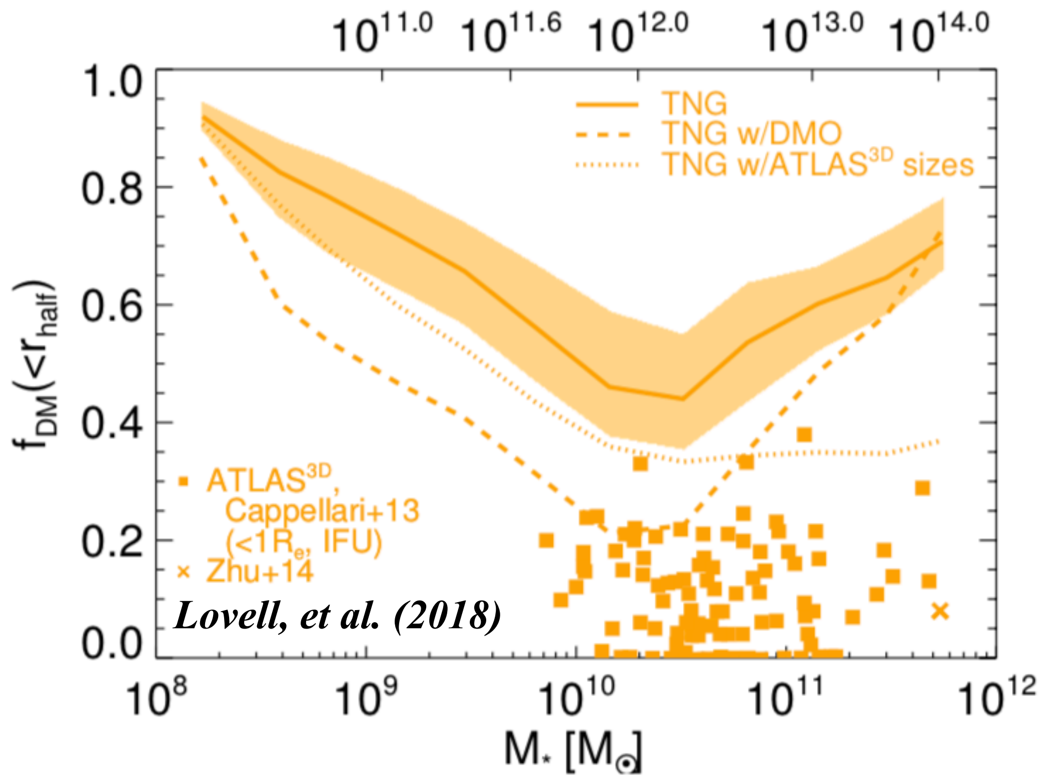
Inverse Abel transformation

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 & Baryon Model

Ren, Kaplinghat, Yu, (in progress)

SIDM w/ Spherical Symmetry

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

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

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

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

Adiabatic Contraction for CDM Halo

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

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

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

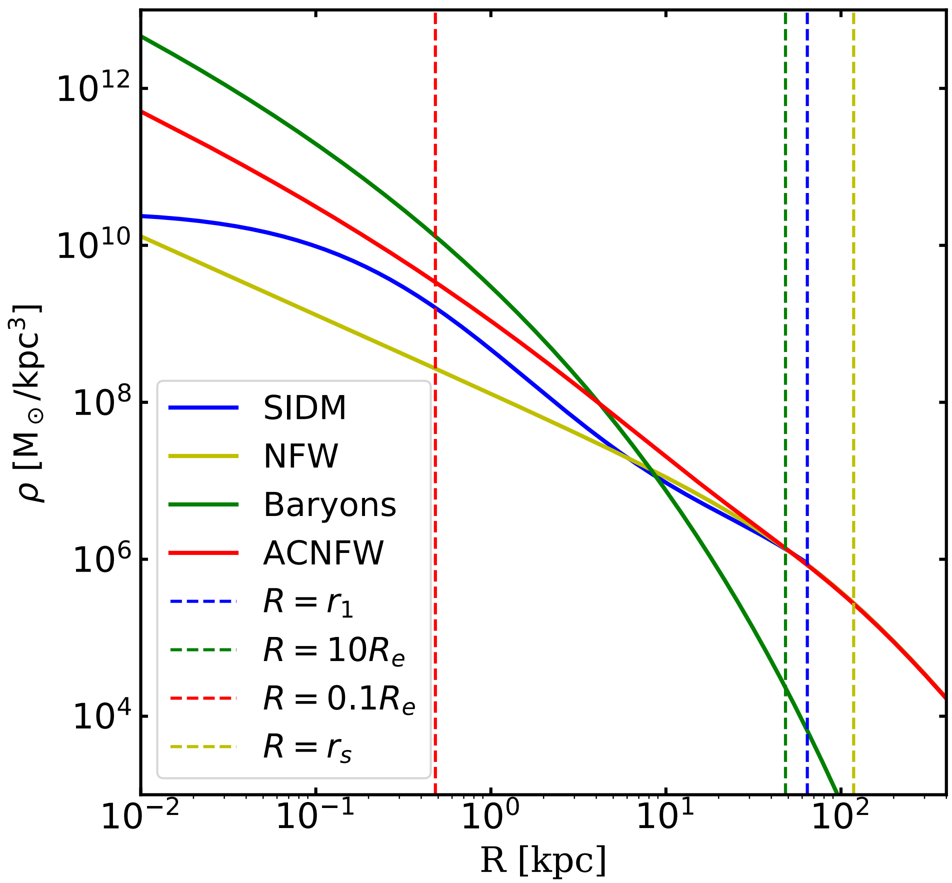
Gnedin, et al. (2004)

Data Source: SL2S

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

Sonnenfeld, et al. (2015)

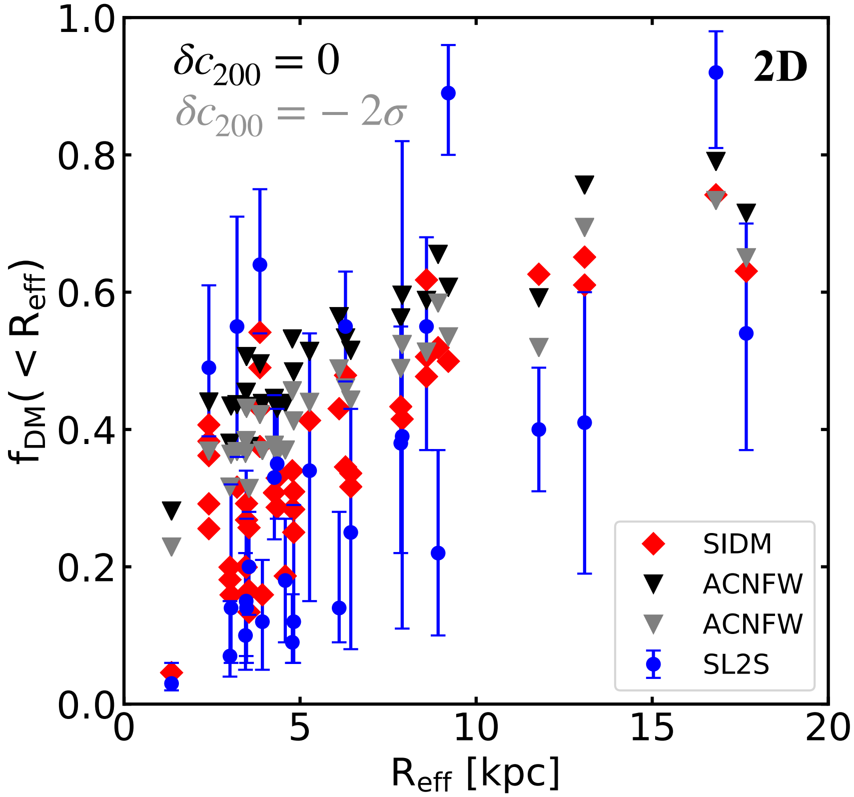
Different Density Profiles

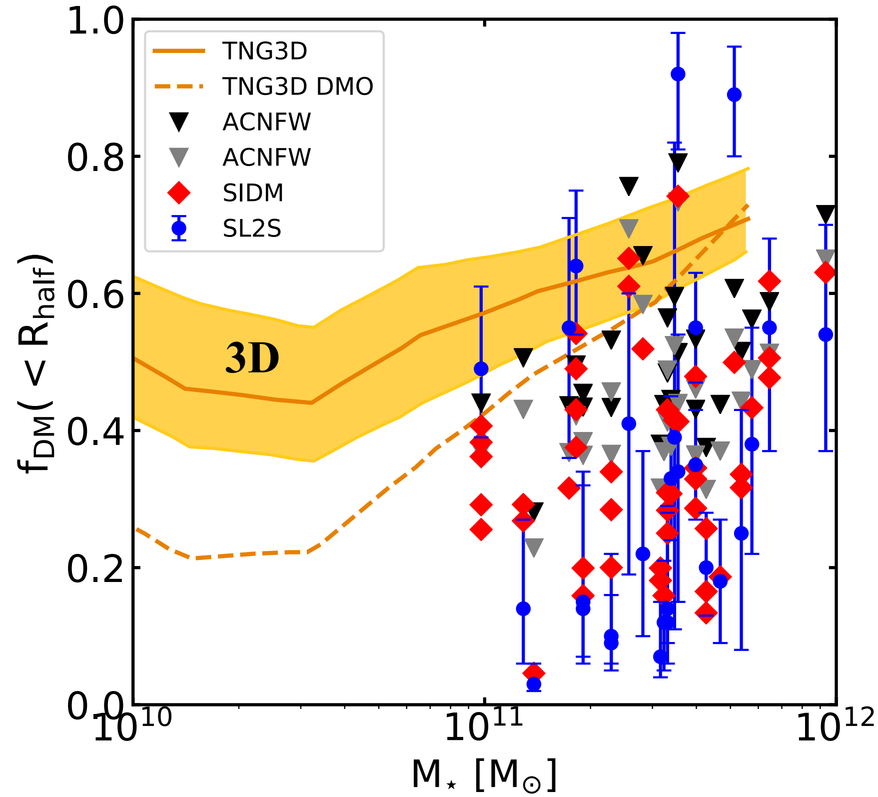


- **Stellar density drops much faster**
- **SIDM and ACNFW profile match onto NFW**
- **ACNFW is contracted more than SIDM**

Dark Matter Fraction in ETGs

Ren, Kaplinghat, Yu, (in progress)

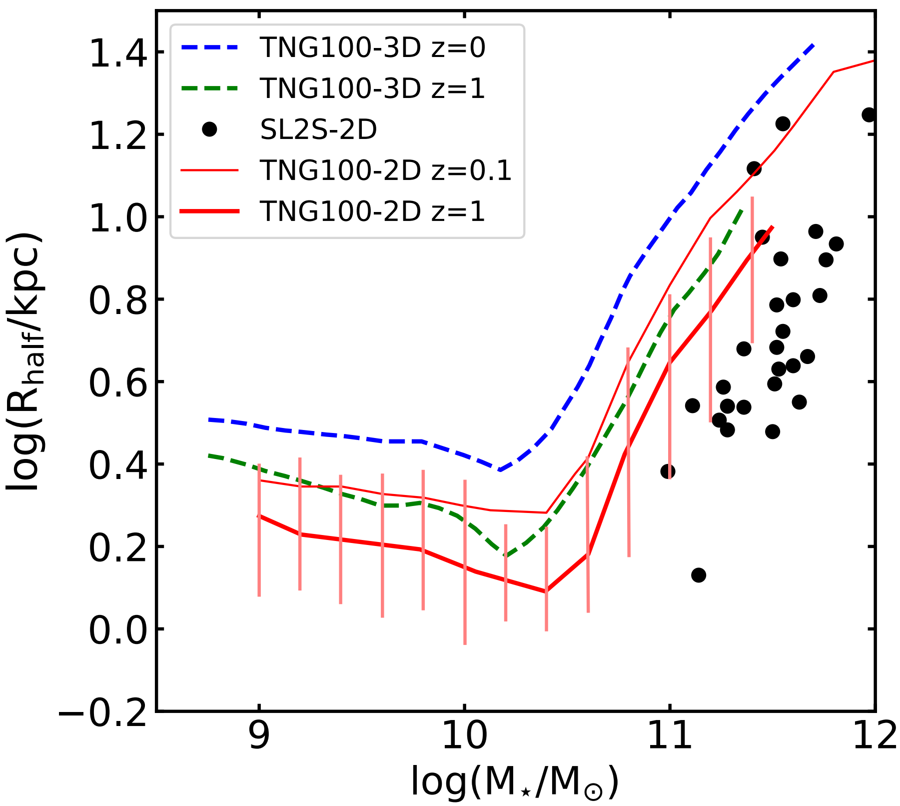


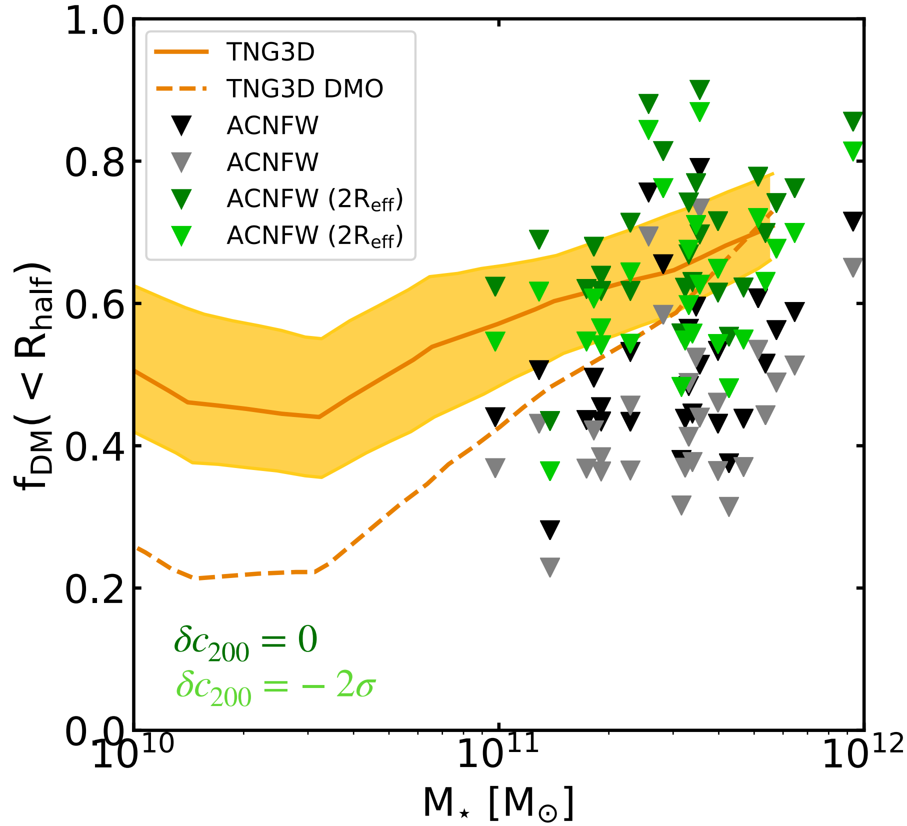


- **Dark matter fractions increase with R_{eff}**
- **SIDM results are much diverse and agree better with data, not perfect**
- **TNG results are systematically higher than those from data, SIDM and ACNFW**

Different Baryon Profiles

Ren, Kaplinghat, Yu, (in progress)

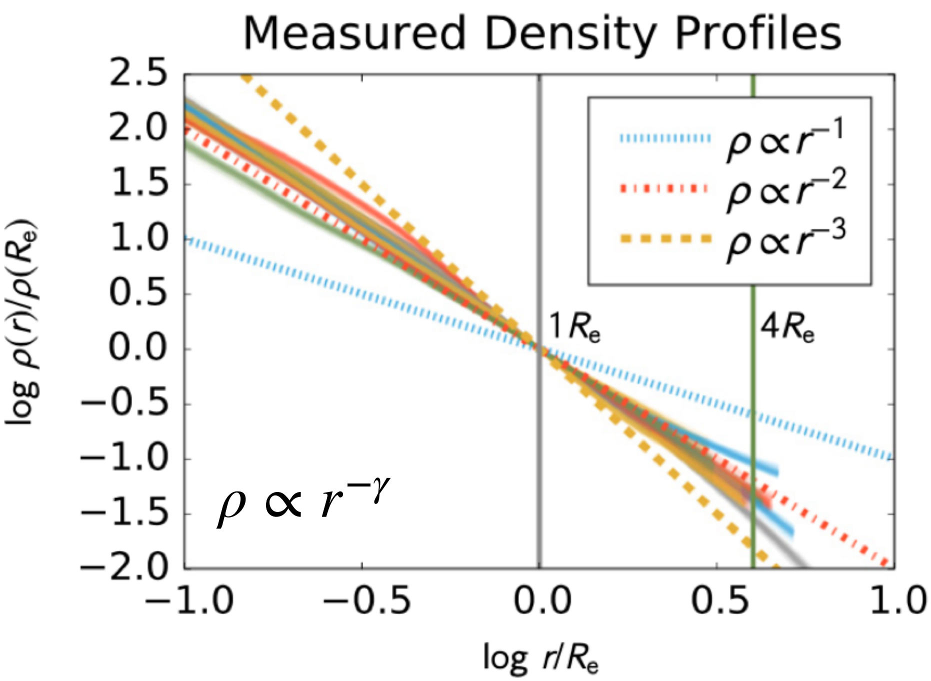




- **3D half mass radius is larger than 2D ones**
- **Half mass radiuses from the simulation are systematically larger than those from observation**
- **The ETGs in simulations are more extended than those from observation**
- **Similar problems of baryon distributions as in spirals**

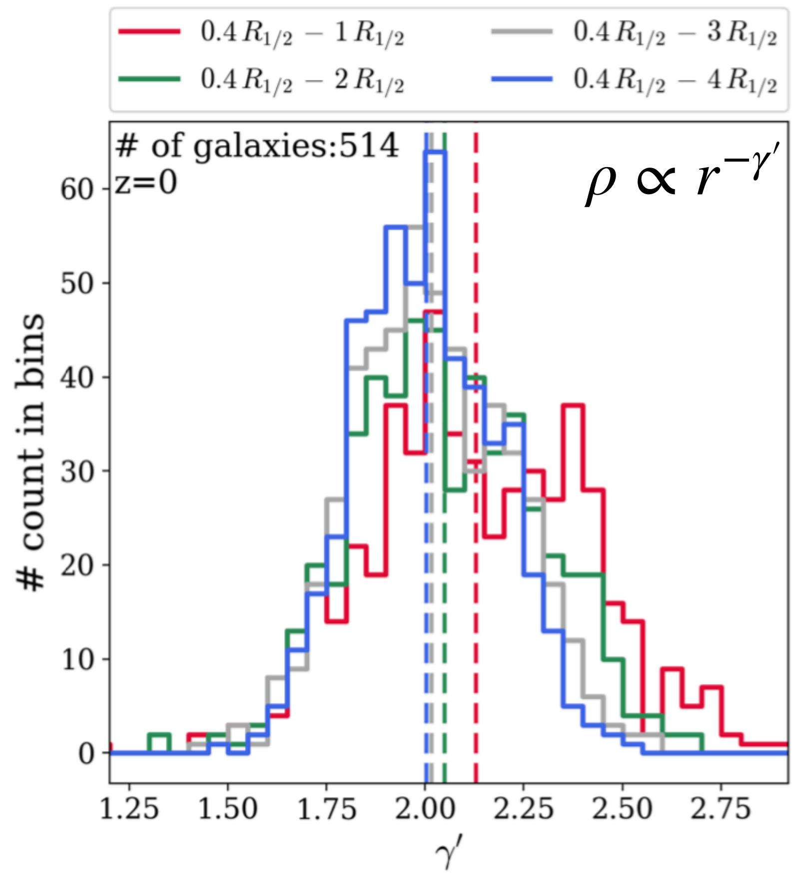
Isothermal Density Profile in ETGs

Cappellari, et al. (2015) **Stellar Kinematics**



14 ETGs with $\langle\gamma\rangle = 2.19$, $\sigma_\gamma = 0.11$.

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 ± 0.012	0.282
$0.4\,R_{1/2} - 2\,R_{1/2}$	2.050 ± 0.010	0.234
$0.4\,R_{1/2} - 3\,R_{1/2}$	2.016 ± 0.009	0.199
$0.4\,R_{1/2} - 4\,R_{1/2}$	2.003 ± 0.008	0.175

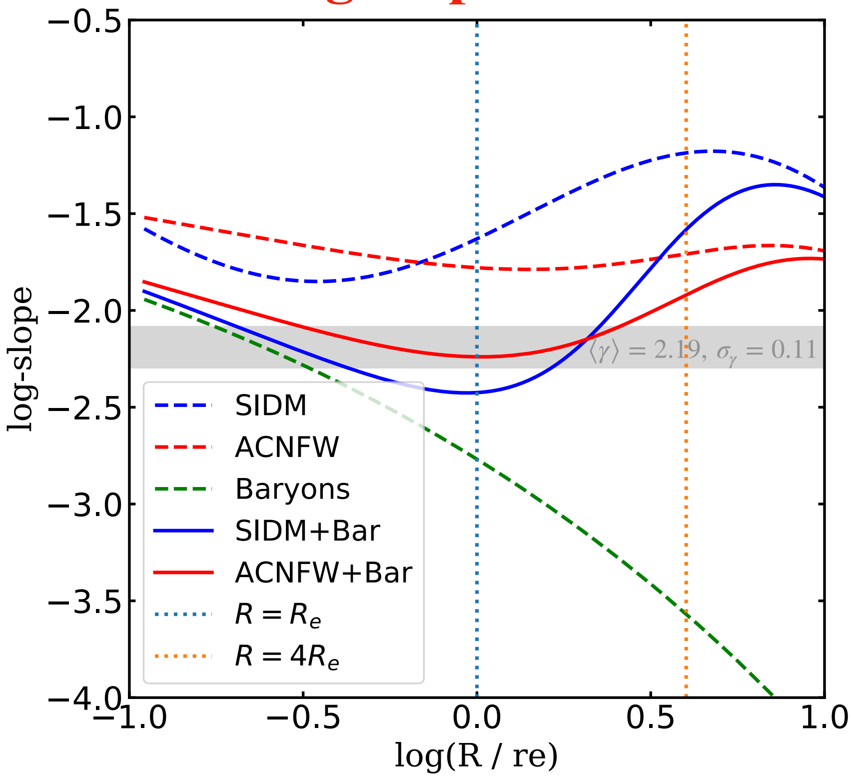
Isothermal Density Profile in ETGs

Ren, Kaplinghat, Yu, (in progress)

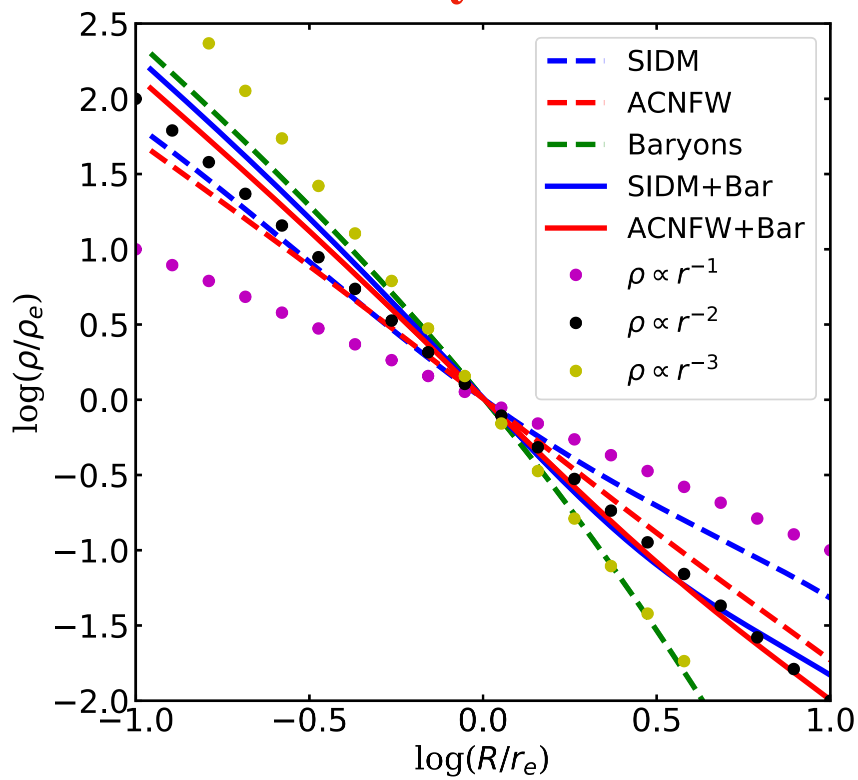
$$\begin{cases} d(log_{10}(\frac{\rho_{DM}}{\rho_{eDM}})) = \alpha * d(log_{10}(\frac{r}{R_e})) \\ d(log_{10}(\frac{\rho_{bar}}{\rho_{estar}})) = \beta * d(log_{10}(\frac{r}{R_e})) \\ d(log_{10}(\frac{\rho_{tot}}{\rho_{etot}})) = \gamma * d(log_{10}(\frac{r}{R_e})) \end{cases} \Longrightarrow \gamma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

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

Log-slope Profile

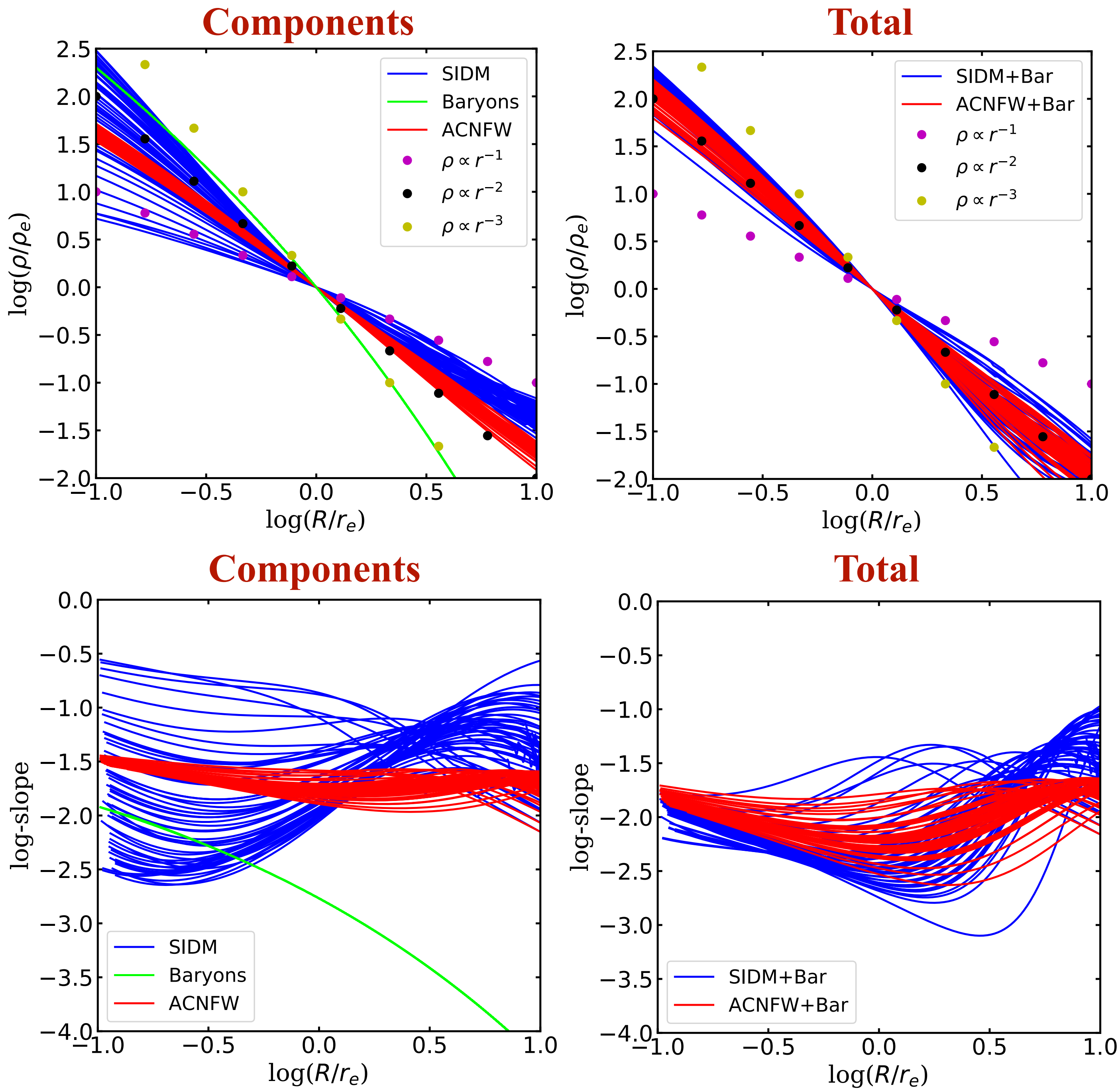


Density Profile

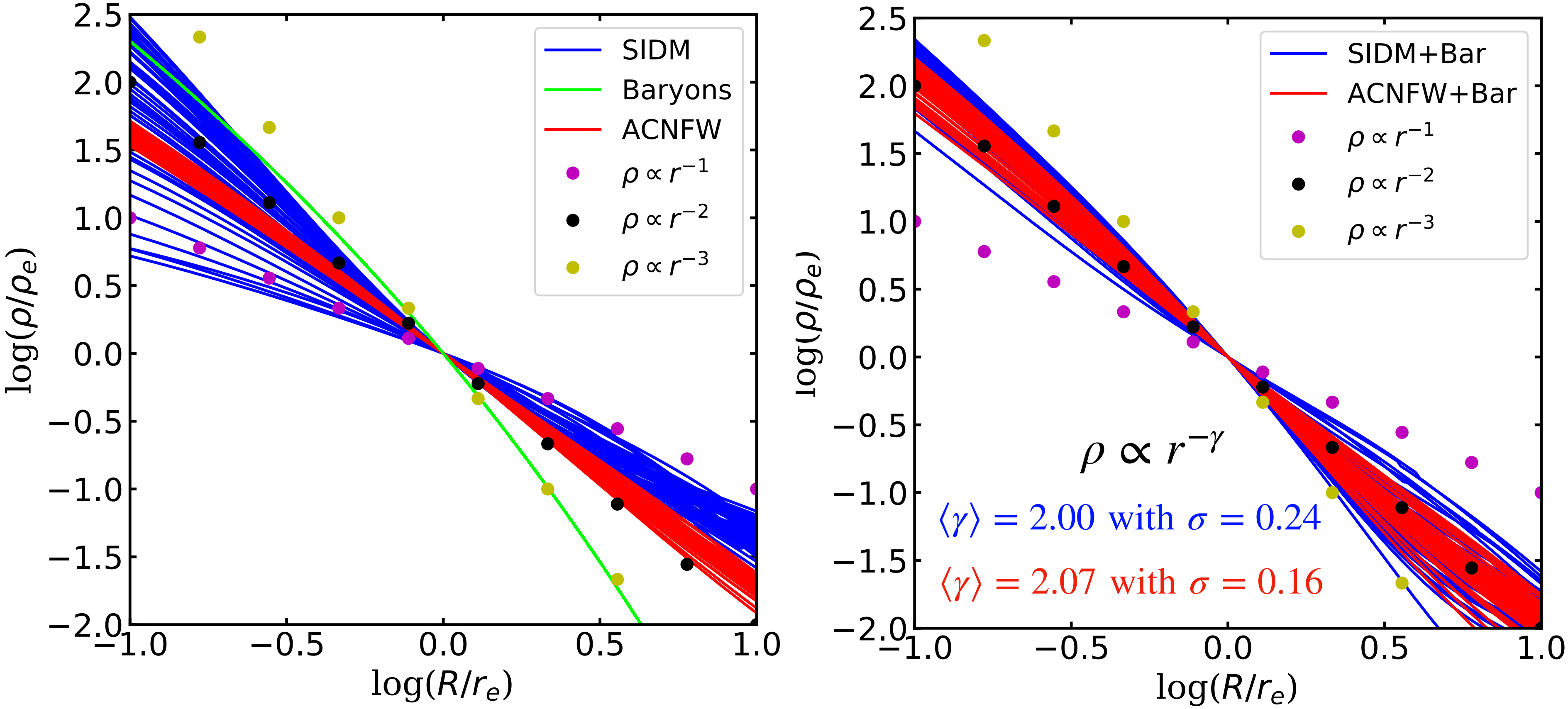


Isothermal Density Profiles in ETGs

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

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

Summary & Outlook

We have demonstrated:

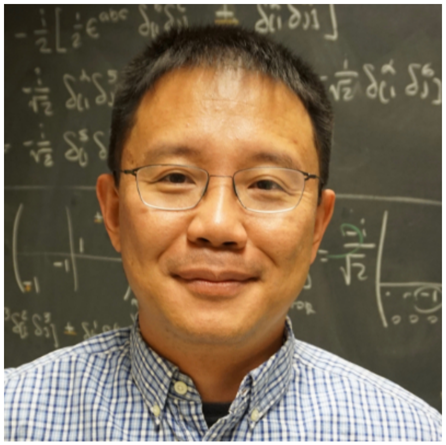
- **SIDM has strong potential to solve small scale problems**
- **The thermalization of inner galaxy regions is highly possible**

	Results	Outlook
Spiral Galaxy	{Diversity, Uniformity} in RCs Interpretation for MOND	Equilibrium → Non-equilibrium
Comparison w/ Simulations	Baryons are the key!	Analytical method → Simulations
Early-Type Galaxy	Small DM fractions Isothermal density profiles	Combine w/ lensing & kinematics Baryon distributions

Acknowledgement

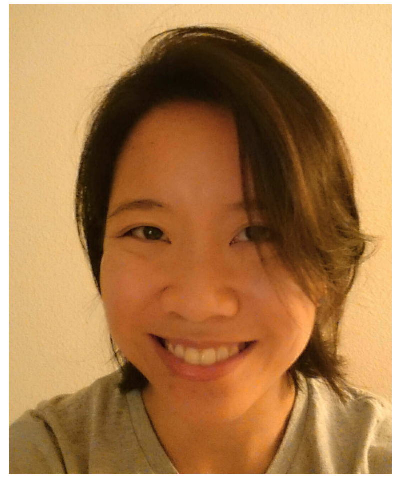
Collaborators

Hai-Bo Yu



UC Riverside

Anna Kwa



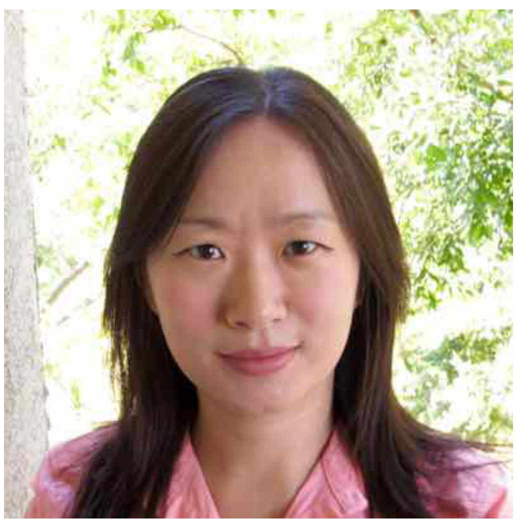
UC Irvine

Manoj Kaplinghat

UC Irvine

Committee

Yanou Cui



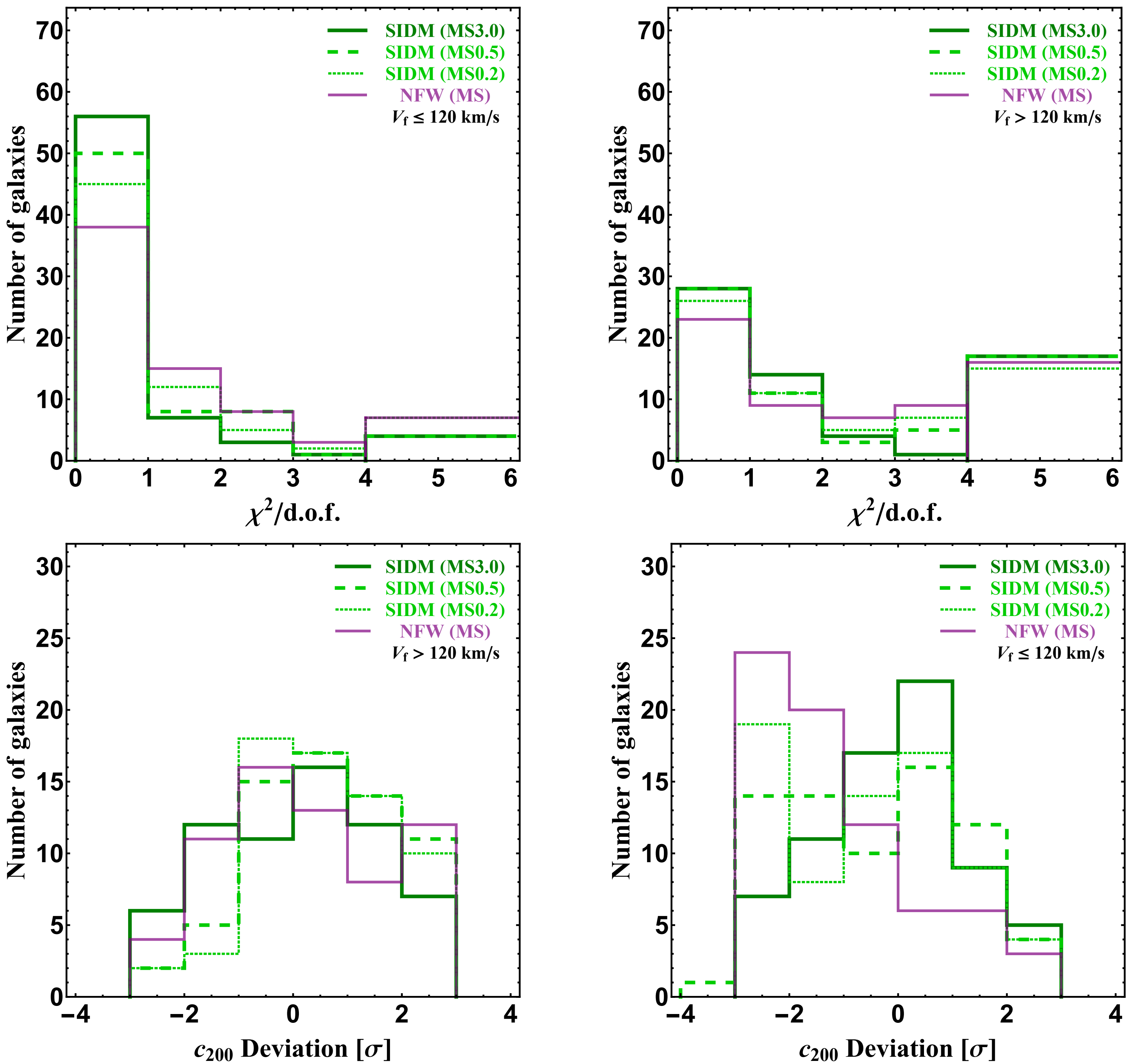
UC Riverside

Flip Tanedo

UC Riverside

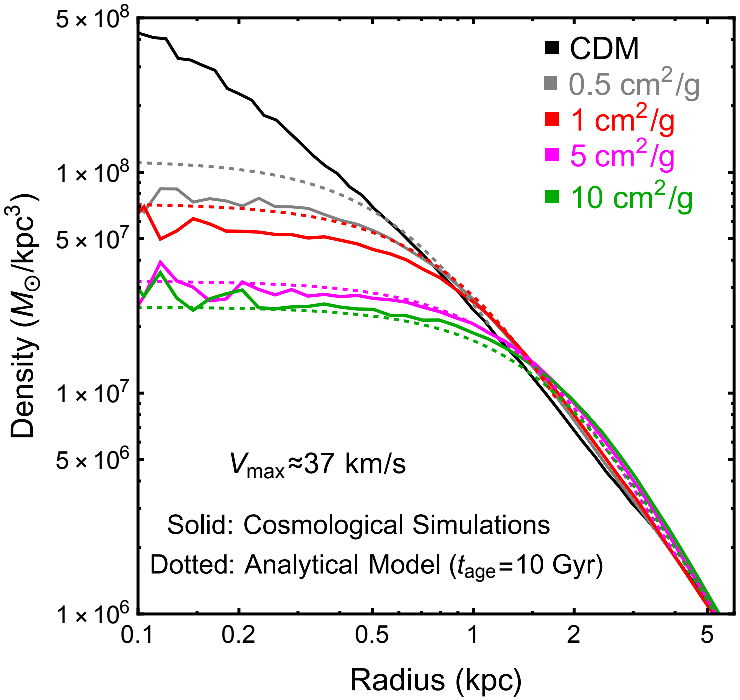
Back Up Slides
&
Supporting Information

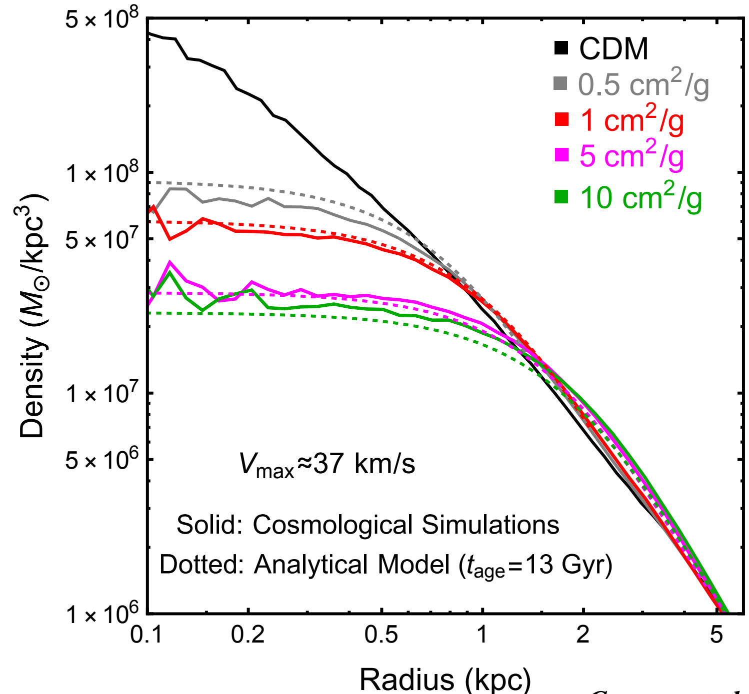
Results w/ Various Cross-Section



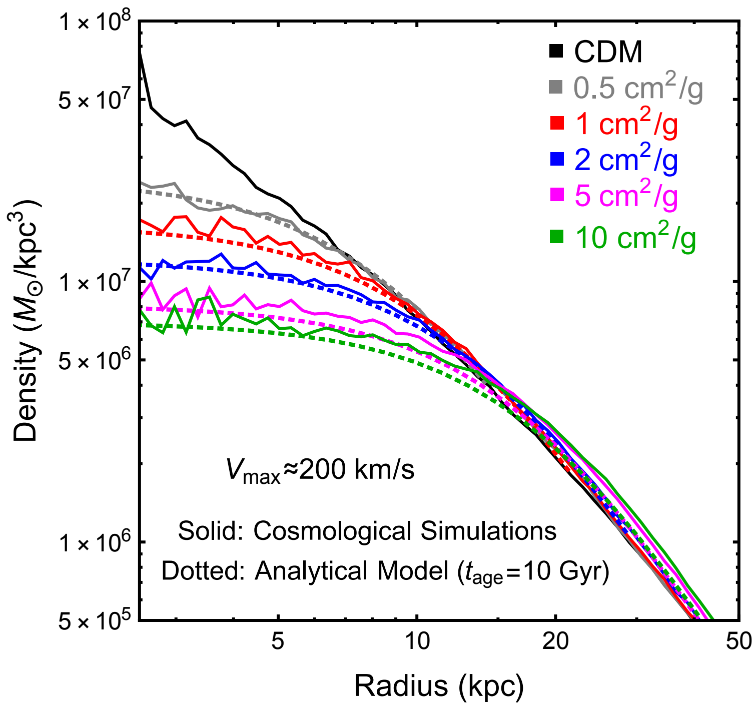
Validity of SIDM model

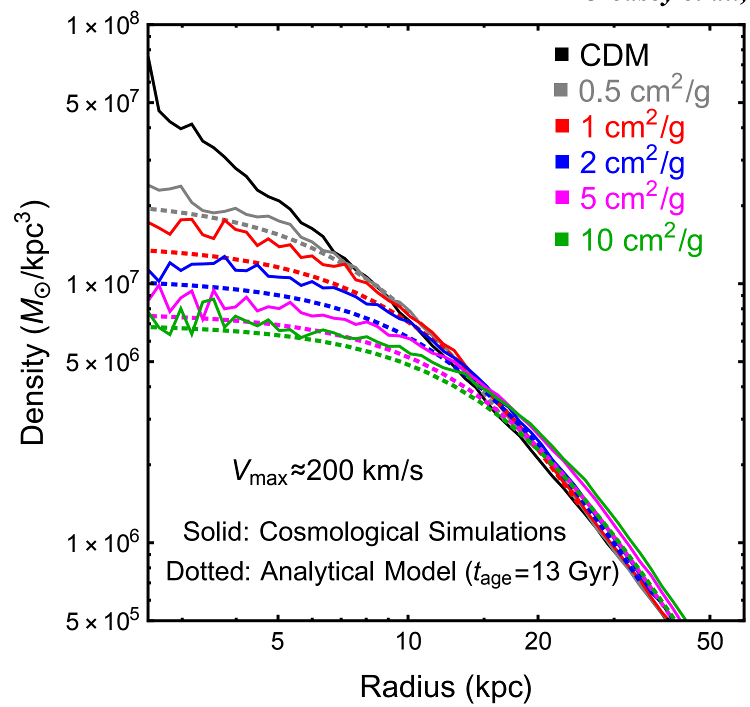
Elbert et al., MNRAS 453 (2015)



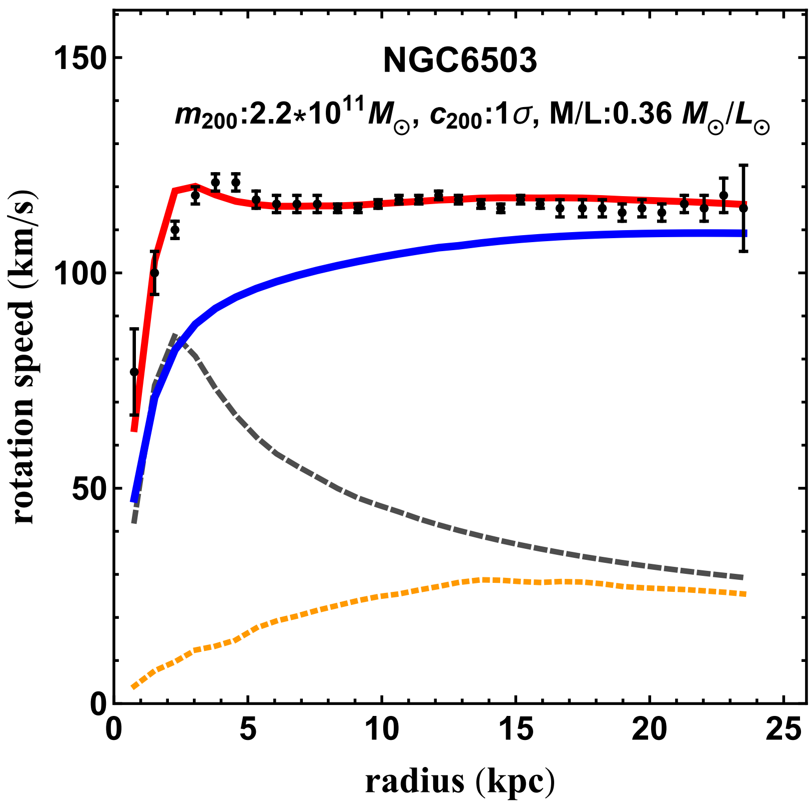


Creasey et al., MNRAS 468 (2017)

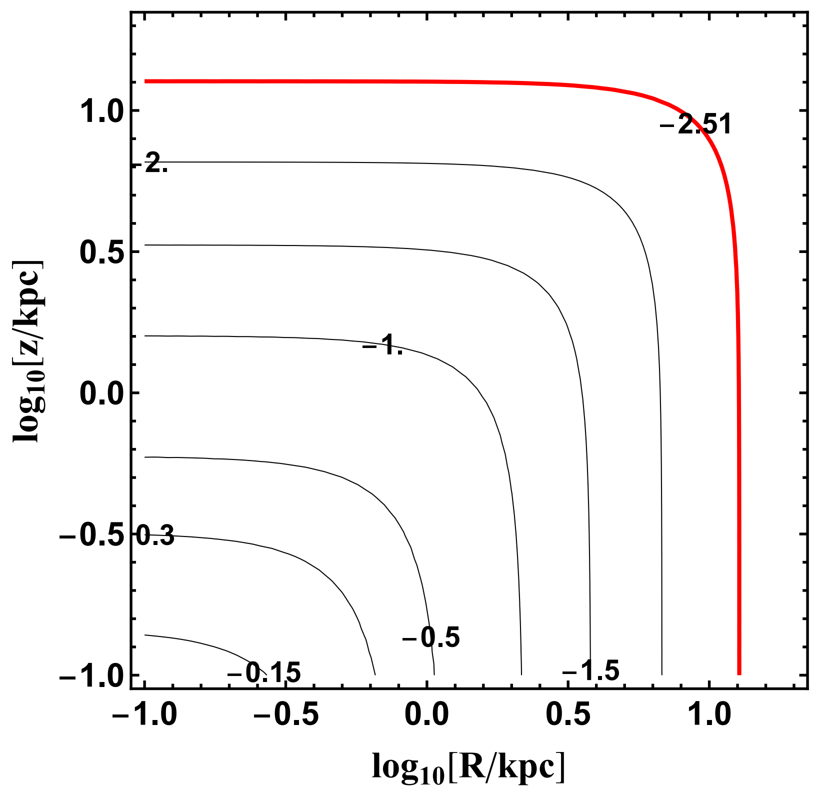




Stellar Disk's Effect on SIDM Halo



Density Contour



Stellar Population Synthesis Model

- **Study stellar population as a function of their mass, age, and metallicity**

- **SPS provides the fundamental link between theory/ models and observations**

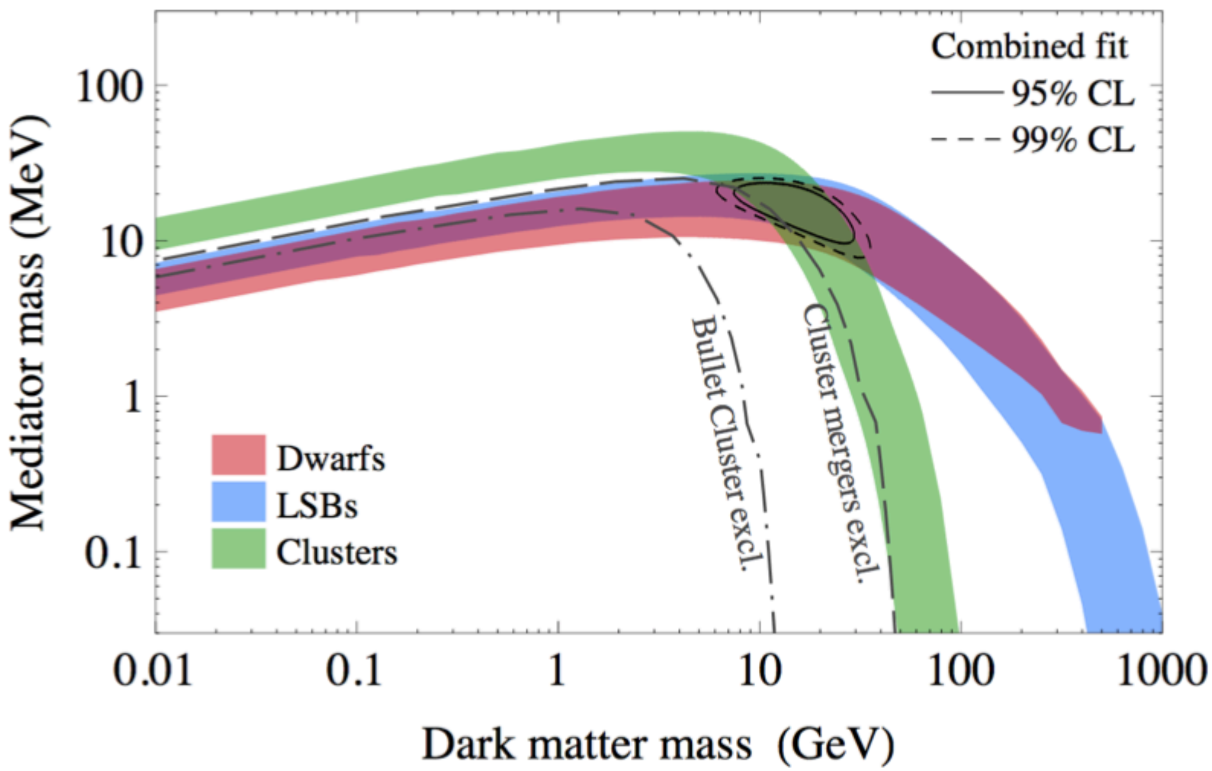
- **e.g.**
  The star formation histories
  Metallicities of galaxies
  Galaxy colours and spectra

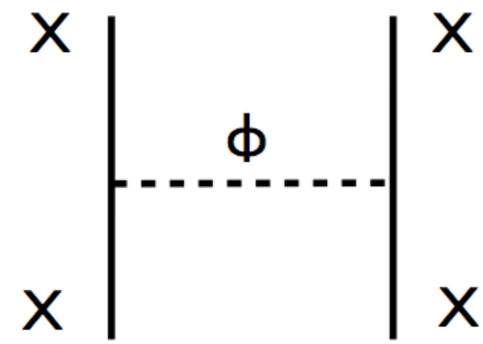
Mass
Age
Metallicity $\Longleftrightarrow$ **Spectrum**
Photometry

- **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)

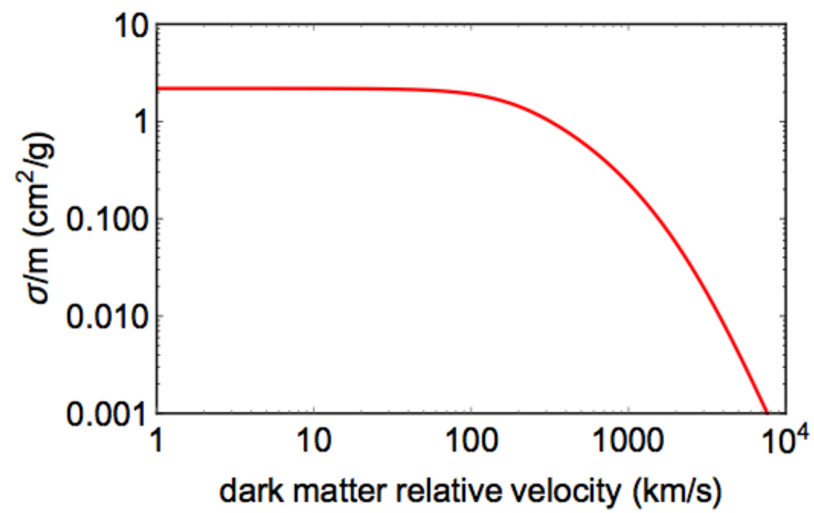




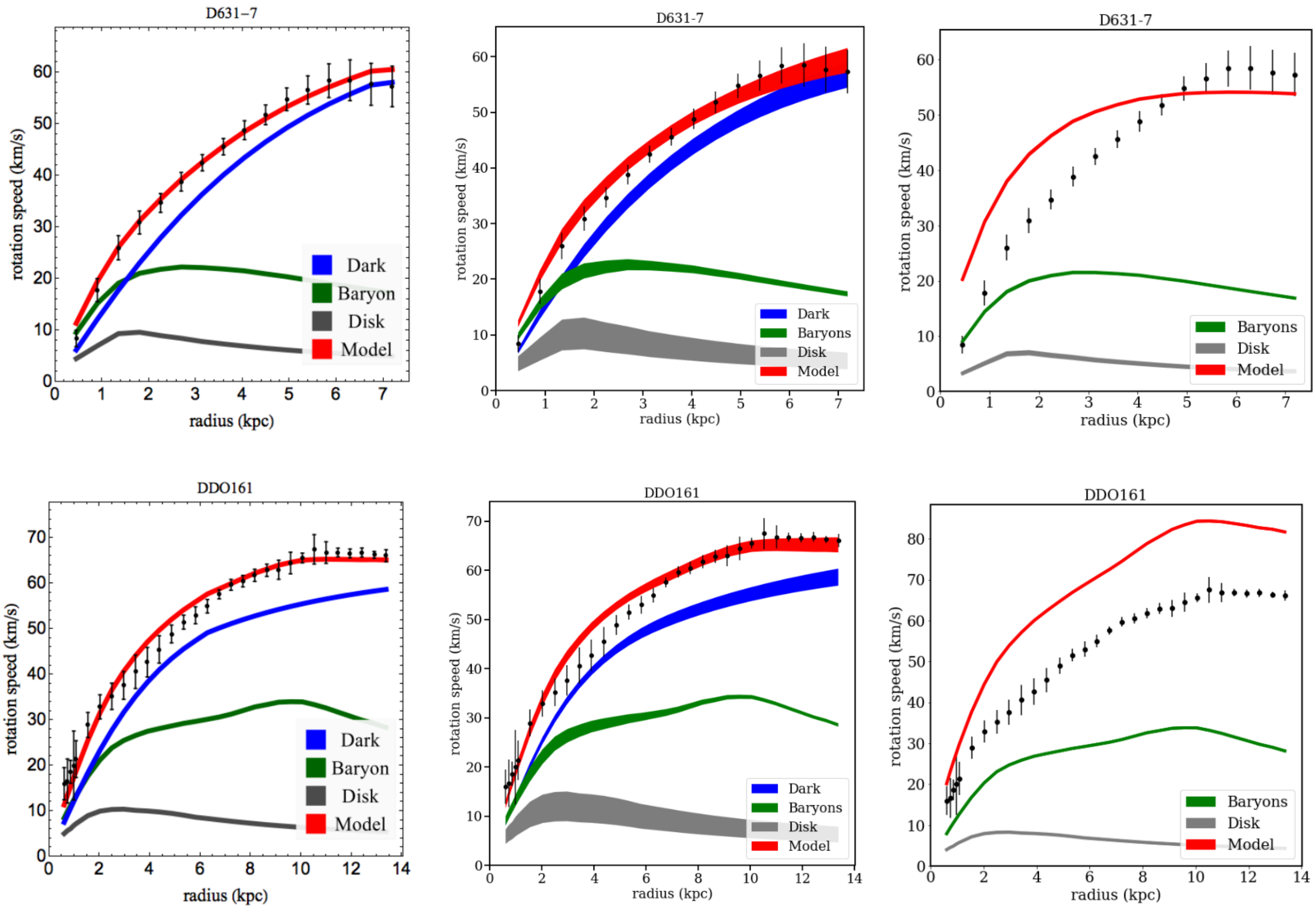
$$V(r) = \frac{\alpha_X}{r} e^{-m_\phi r}$$

$\alpha_X = 1/137$

m_X: ~15 GeV, m_ϕ: ~17 MeV

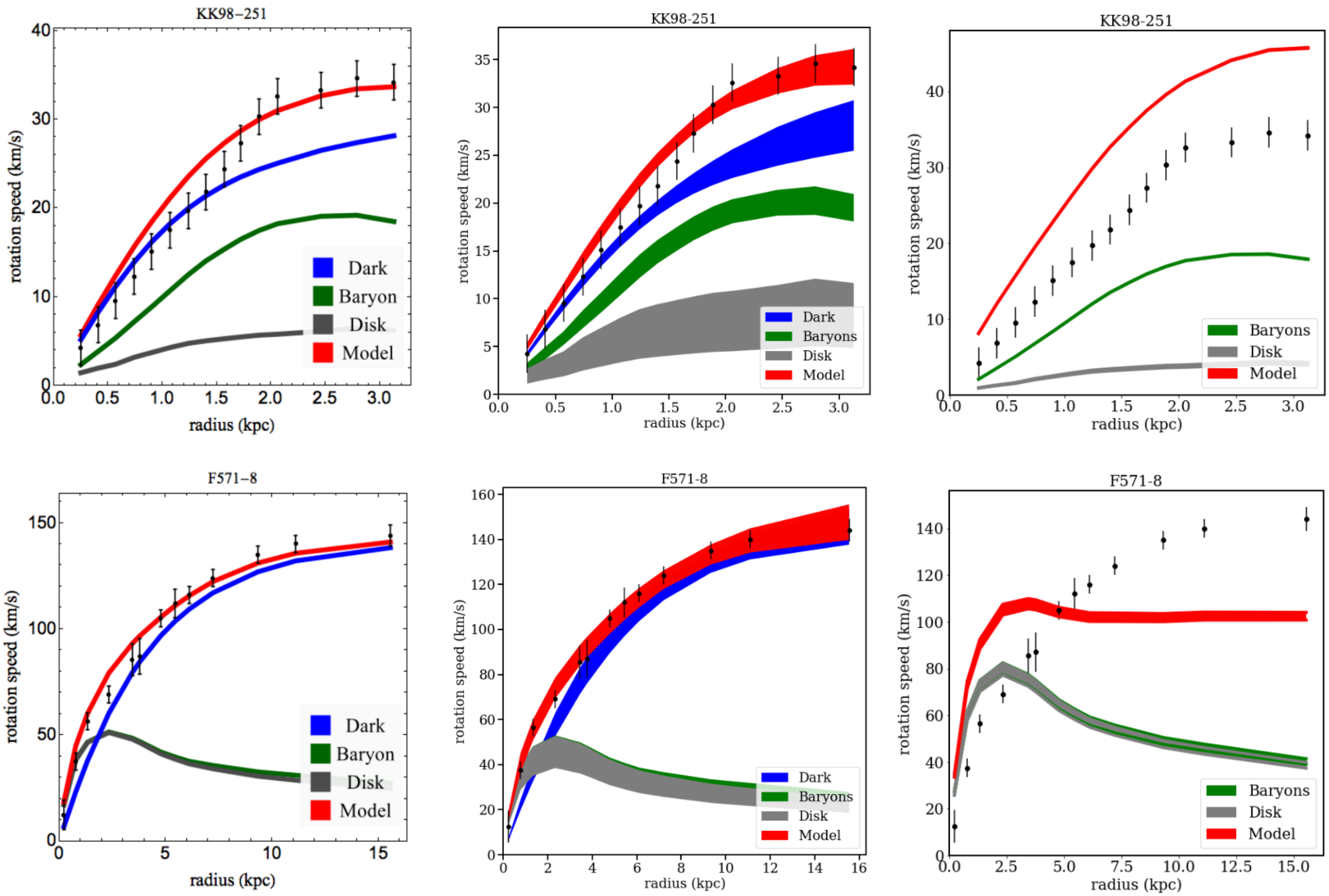


SIDM vs MOND



D631−7
D631-7
D631-7
DDO161
DDO161
DDO161
rotation speed (km/s)
radius (kpc)
Dark
Baryon
Baryons
Disk
Model

SIDM vs MOND



KK98-251
rotation speed (km/s)
radius (kpc)
Dark
Baryon
Disk
Model
KK98-251
Dark
Baryons
Disk
Model
KK98-251
Baryons
Disk
Model
F571-8
Dark
Baryon
Disk
Model
F571-8
Dark
Baryons
Disk
Model
F571-8
Baryons
Disk
Model

Two Extreme cases in Outliers