Determining the Dark Matter distribution in galaxies, using AI

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in collaboration with: M. de los Ríos, S. di Gioia, R. Trotta

Based on: arXiV:2510.18964, and arXiV: 2111.08725

2nd SMASH-ing workshop

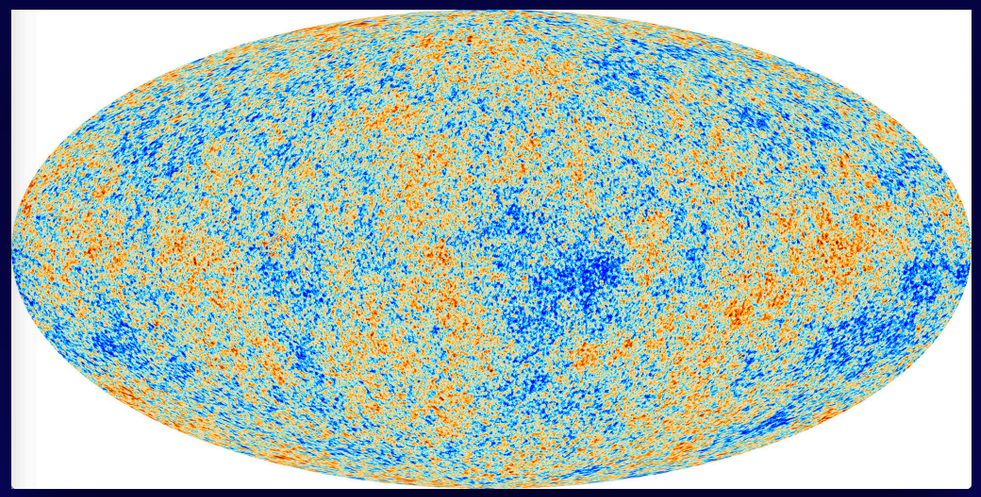
Vipava, October 21st, 2026



DIPARTIMENTO DI FISICA ETTORE PANCINI

Dark Matter

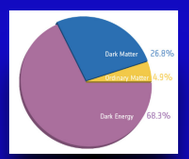
Evidence over large range of scales







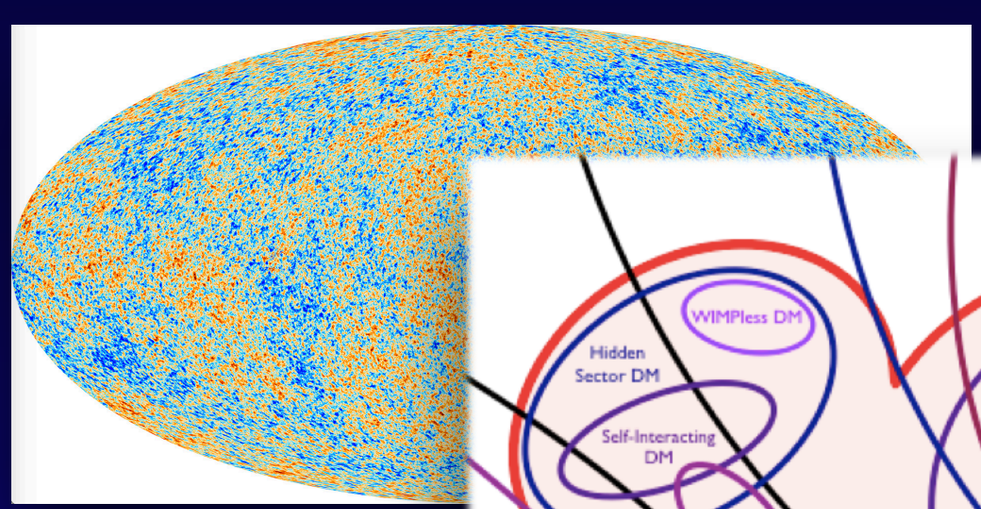




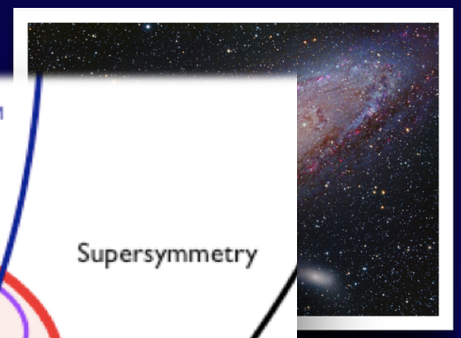
NATURE STILL UNKNOWN

Dark Matter

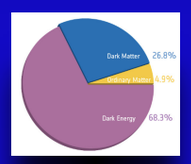
Evidence over large range of scales







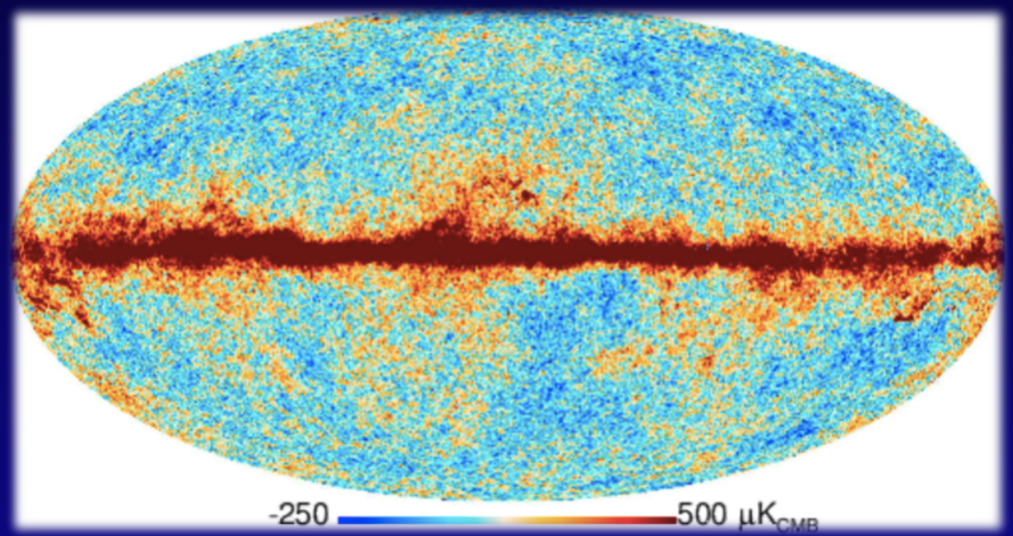


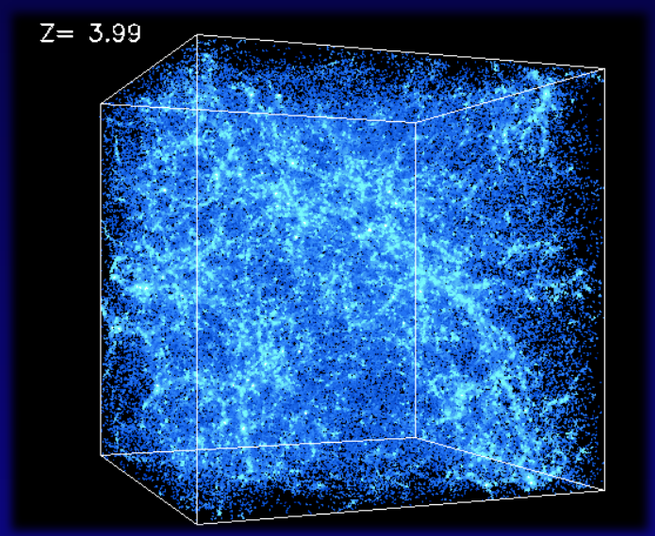


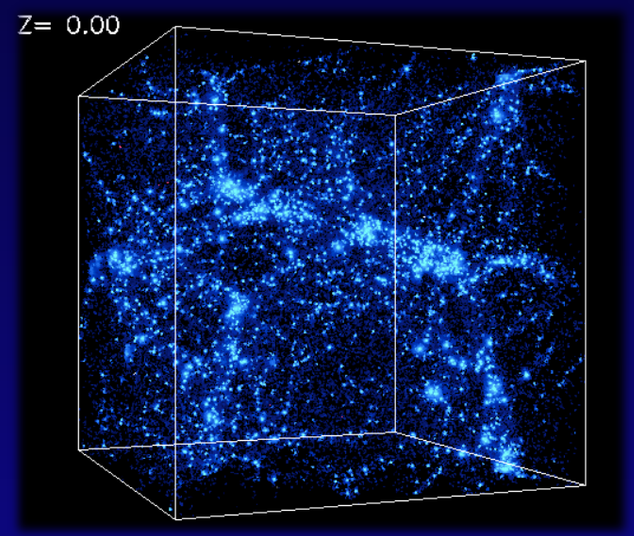
NATURE STILL UNKNOWN

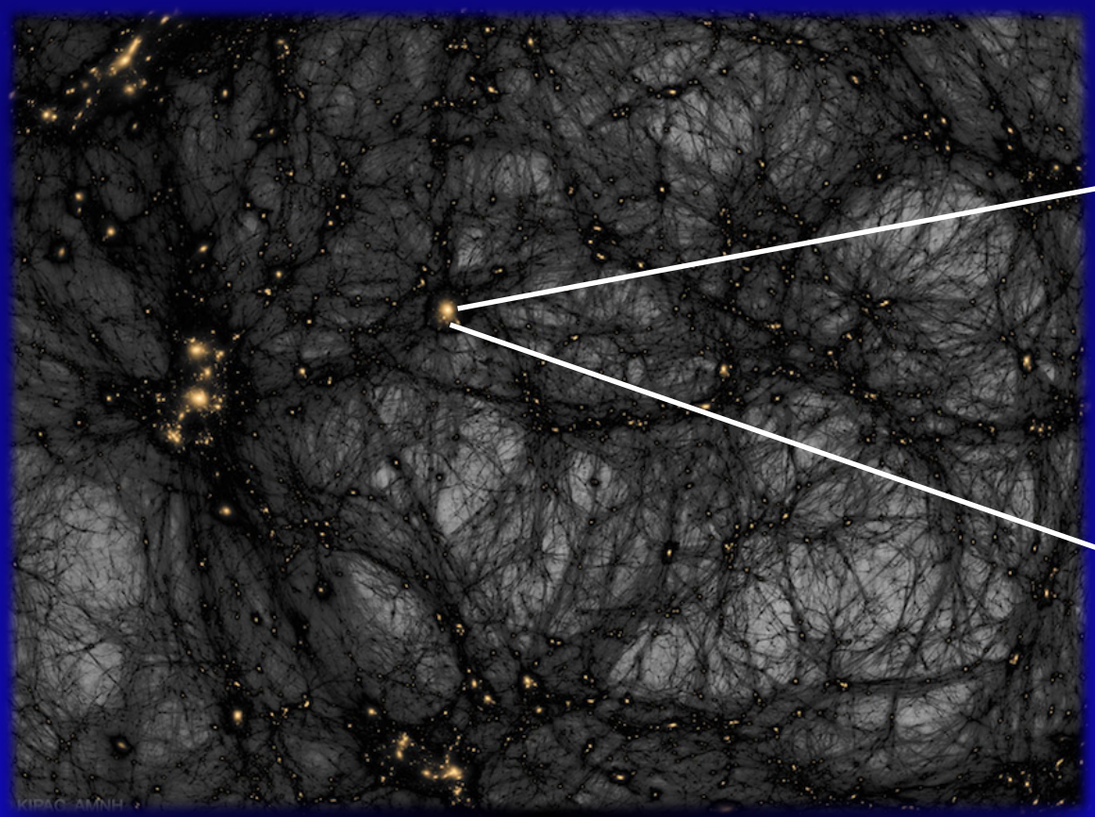
A story of LCDM
I: structure formation

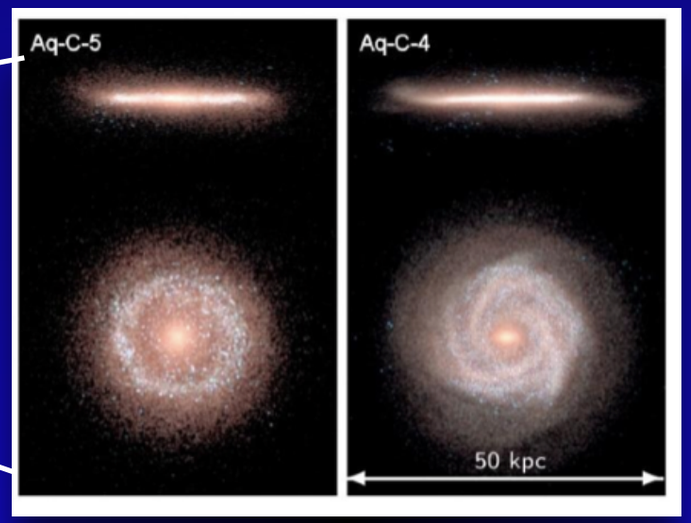
age of Universe







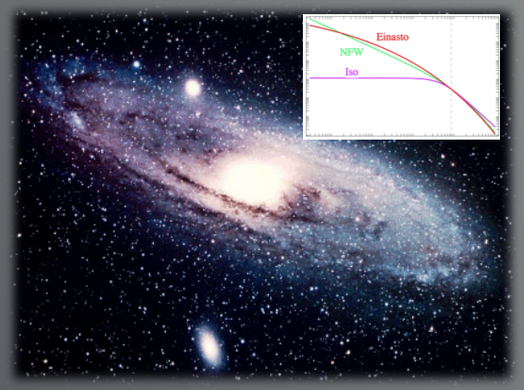




physical size

A story of LCDM
II. the single halo

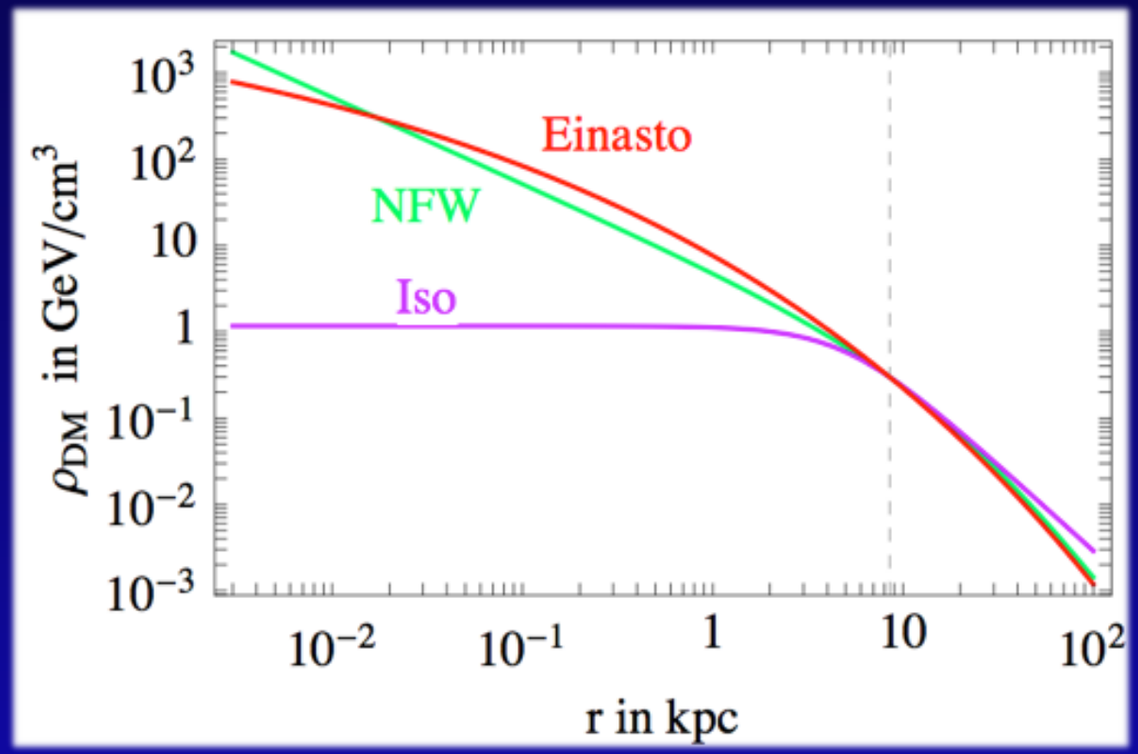
big halo around



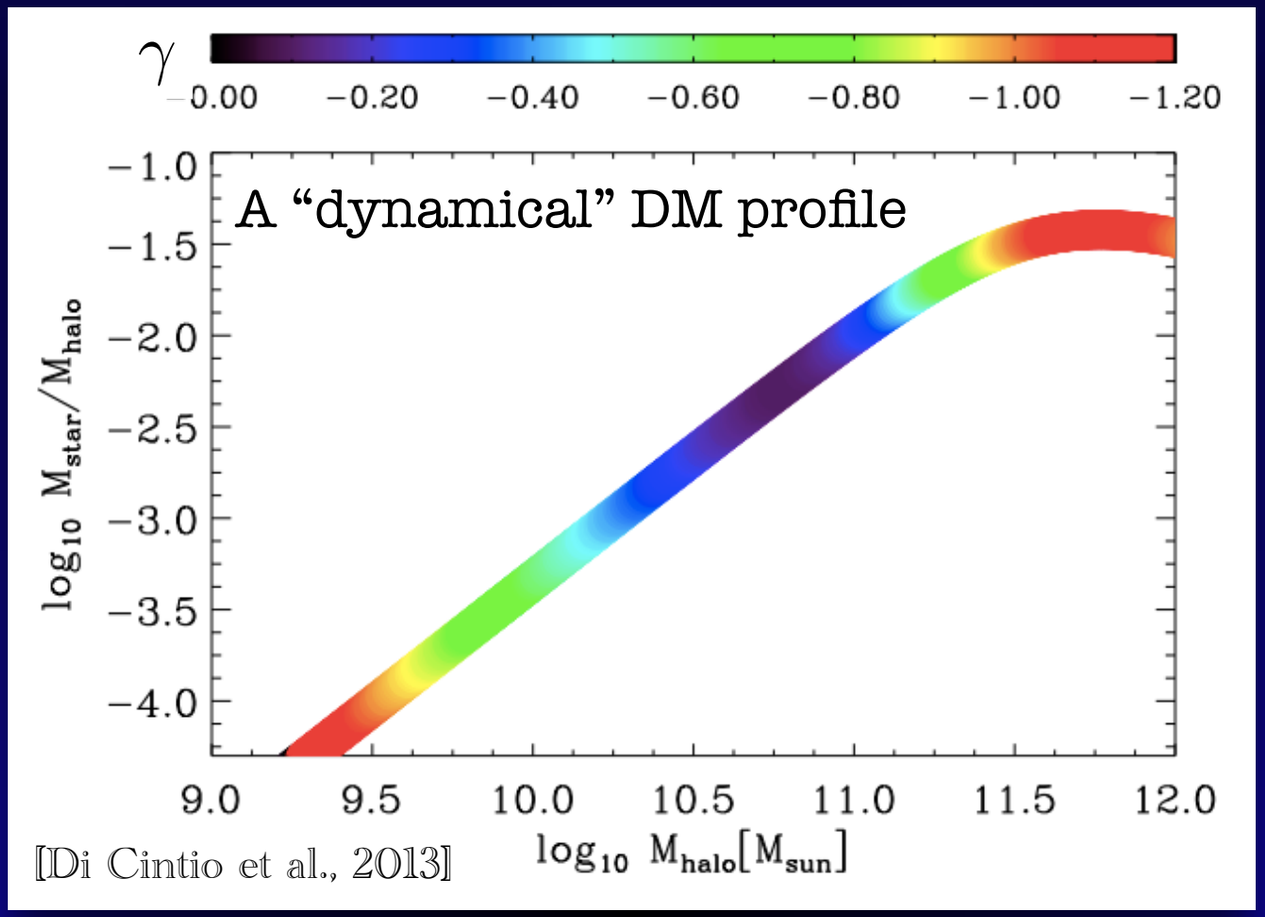
a small galaxy

(not in scale!)

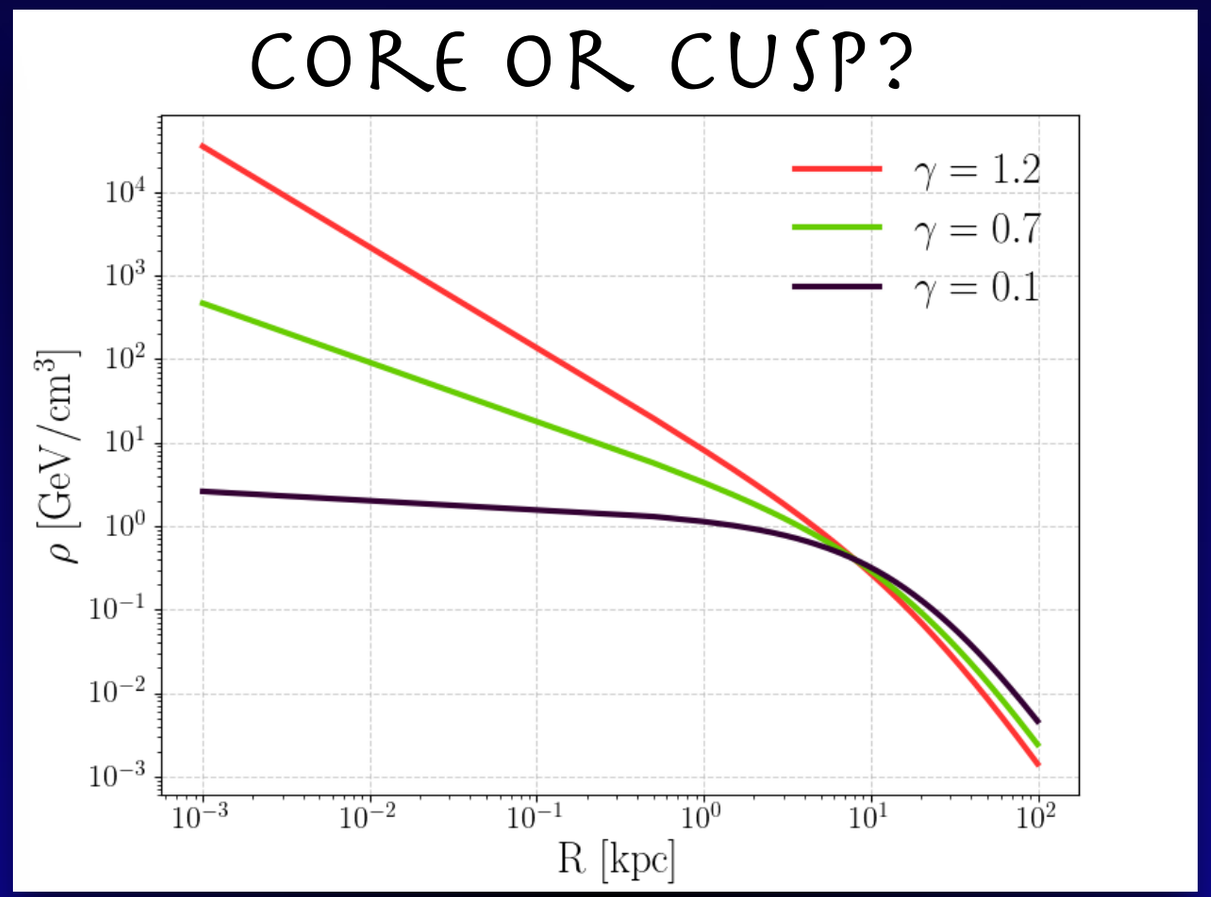
A “universal” DM profile?



A story of LCDM
III: halo matters



[Di Cintio et al., 2013]



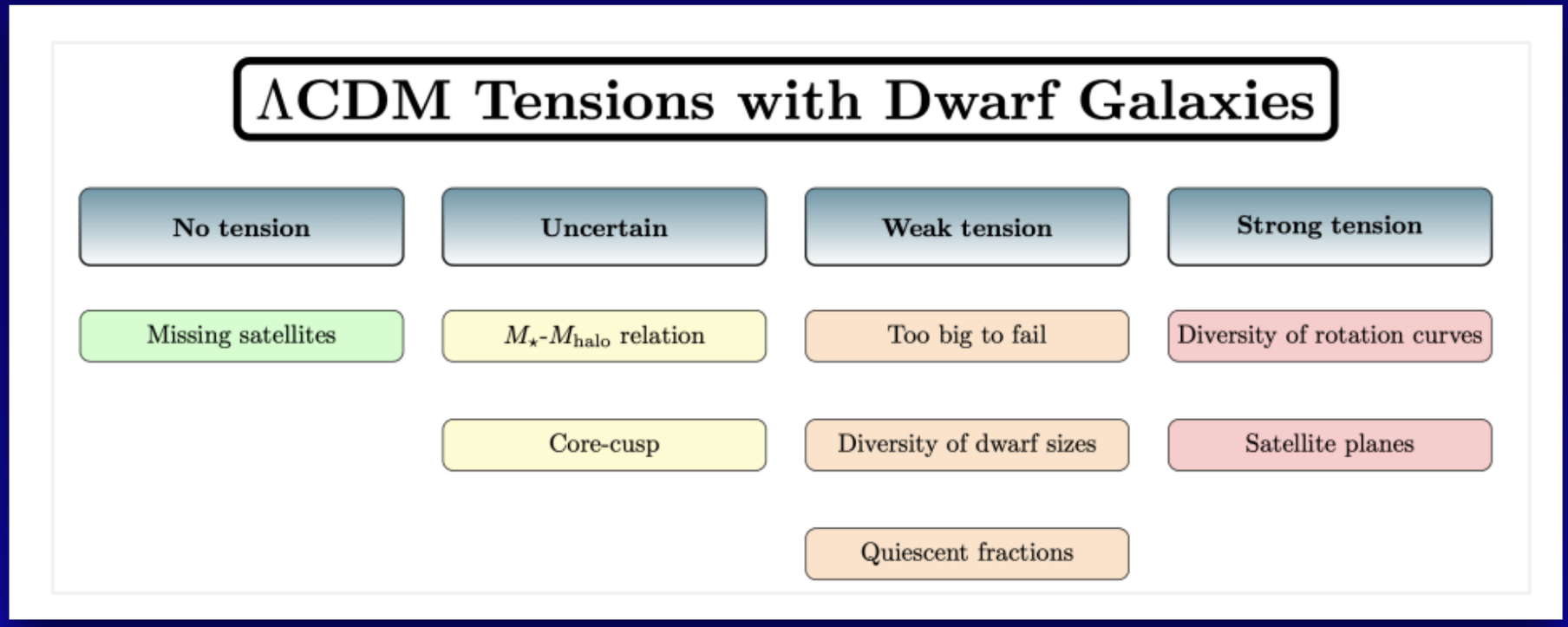
DM distribution in halo is part of cosmology puzzle

$$\rho_{DM}(R) \propto \rho_0 \left(\frac{R}{R_s}\right)^{-\gamma} \left(1+\frac{R}{R_s}\right)^{-3+\gamma}$$

A story of ΛCDM
IV: small scale "tensions"

Baryonic solutions and challenges for cosmological models of dwarf galaxies

Laura V. Sales[1,*], Andrew Wetzel[2], and Azadeh Fattahi[3]



[Sales, Wetzel, Fattahi, Nature Astronomy 2022, arXiV:2206.05295]

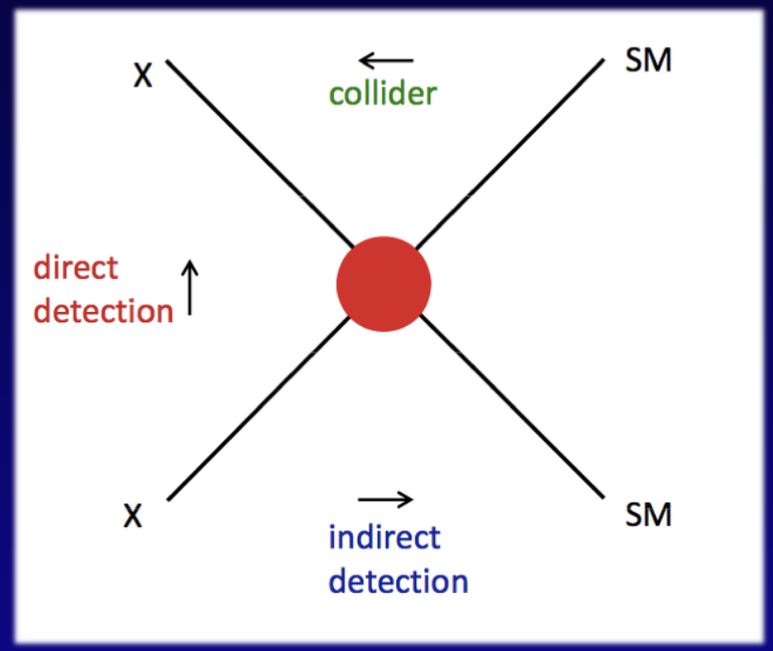
Direct and indirect searches of WIMP DM

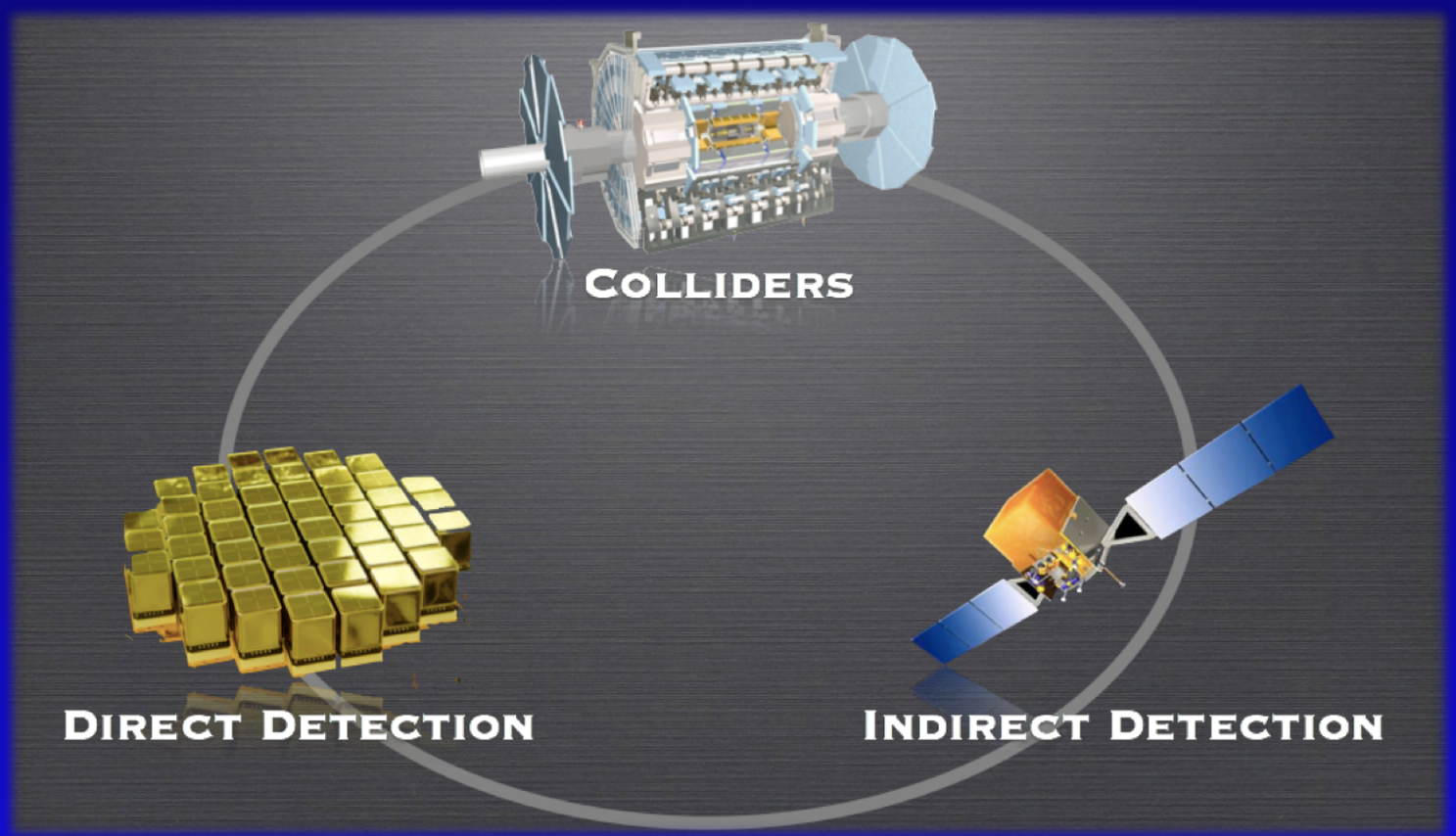
complementary to colliders

Direct detection:
DM scattering against nuclei, recoil

Indirect detection:
Annihilation in astrophysical envir.
Observation of SM products of annih.

Production at LHC





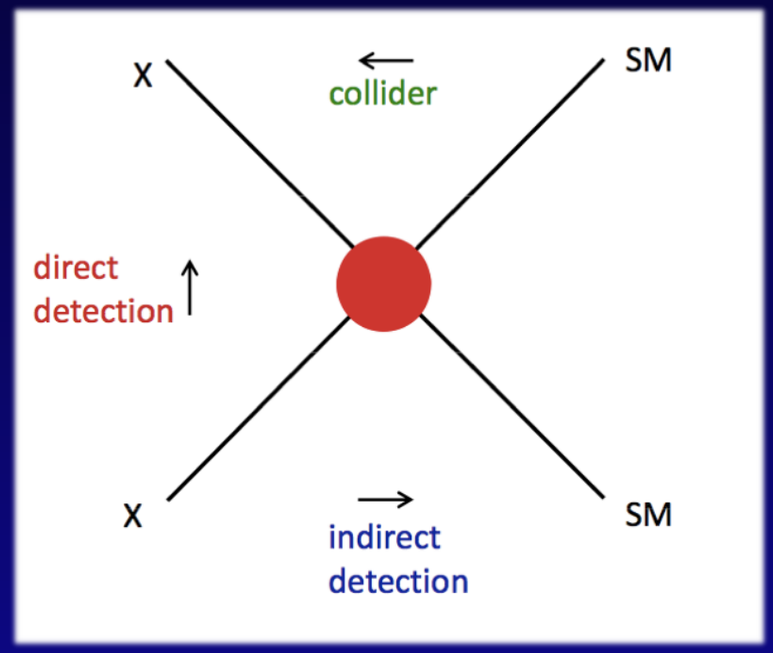
Direct and indirect searches of WIMP DM

complementary to colliders

Direct detection:
DM scattering against nuclei, recoil

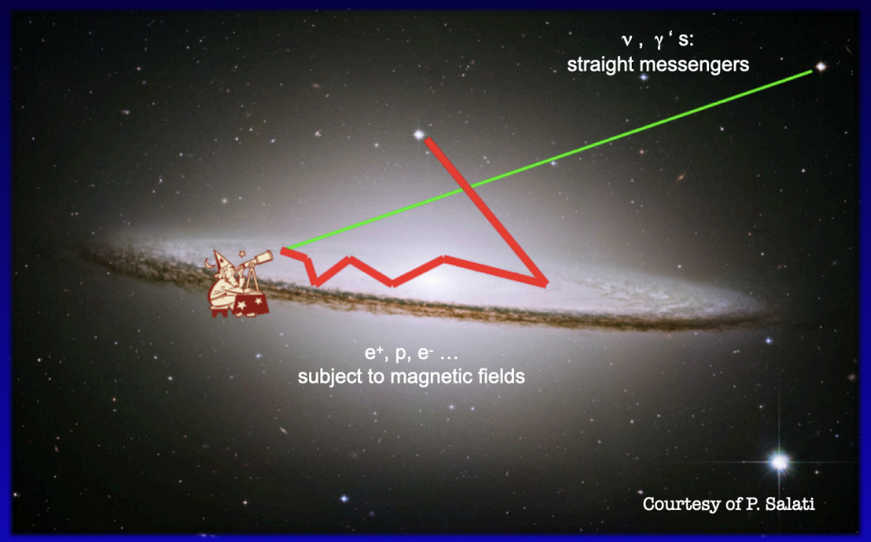
Indirect detection:
Annihilation in astrophysical envir.
Observation of SM products of annih.

Production at LHC



Indirect Detection: principles and dependencies

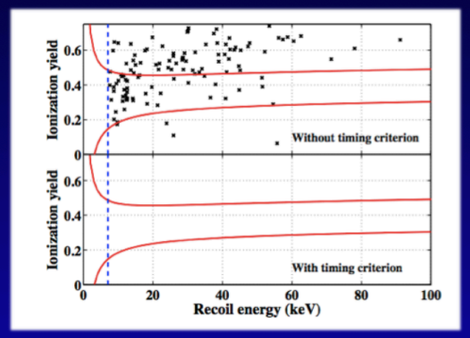
$$\chi + \chi \to q\bar{q}, W^+W^-, \ldots \to \gamma, \bar{p}, \ \bar{D}, \ e^+ \ \& \ \nu's$$

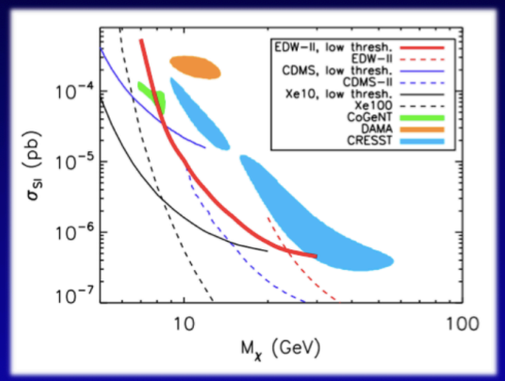


$$F_i \propto \frac{1}{4\pi d^2} B_i \frac{\langle \sigma v \rangle}{m_\chi} \int \rho^2(r) dV$$

Direct Detection: principles and dependencies (to go…)

from this → to this

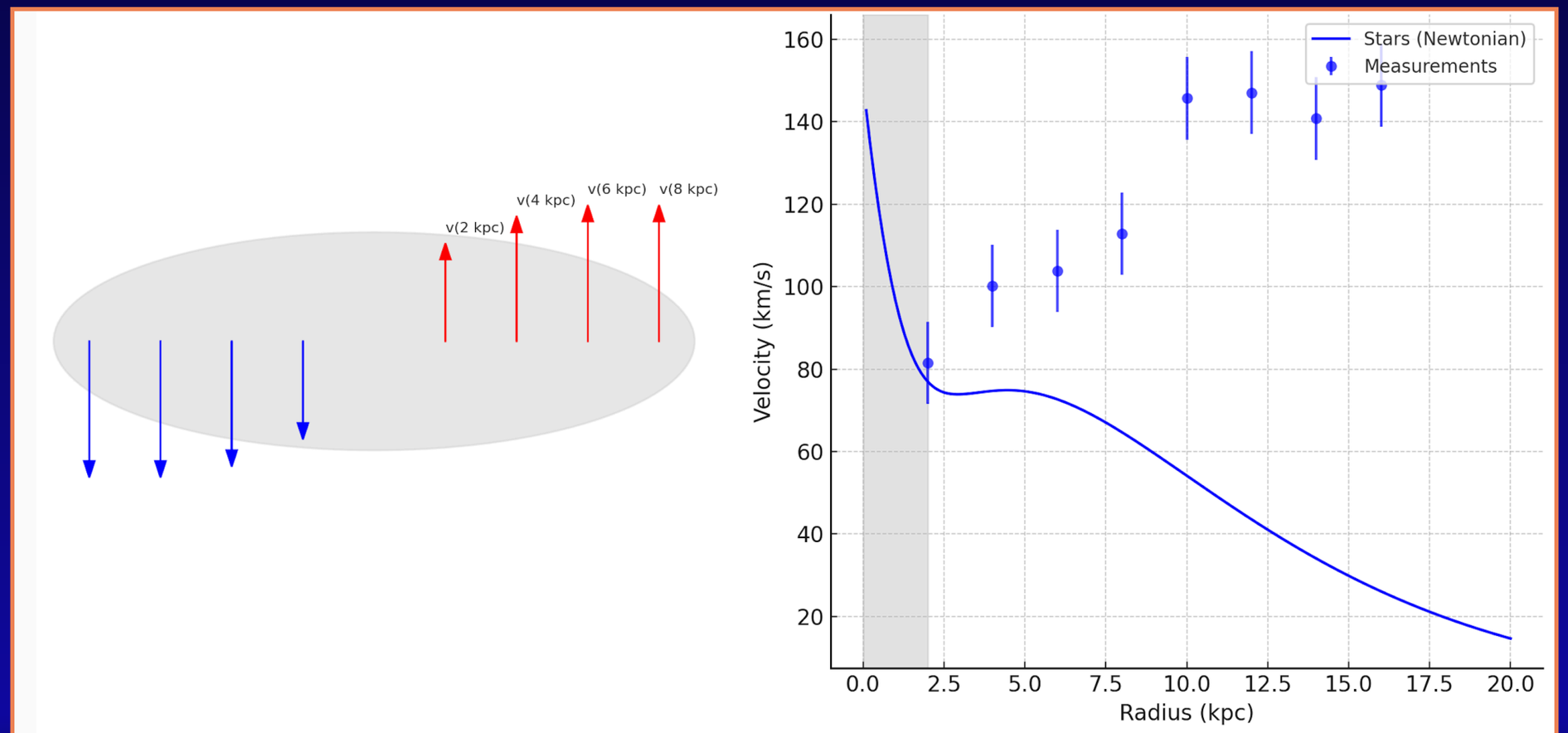




you need this

$$\frac{dR}{dE} \propto \frac{1}{\mu^2} \frac{\sigma_\chi}{m_\chi} \rho_0 \eta(v,t)$$

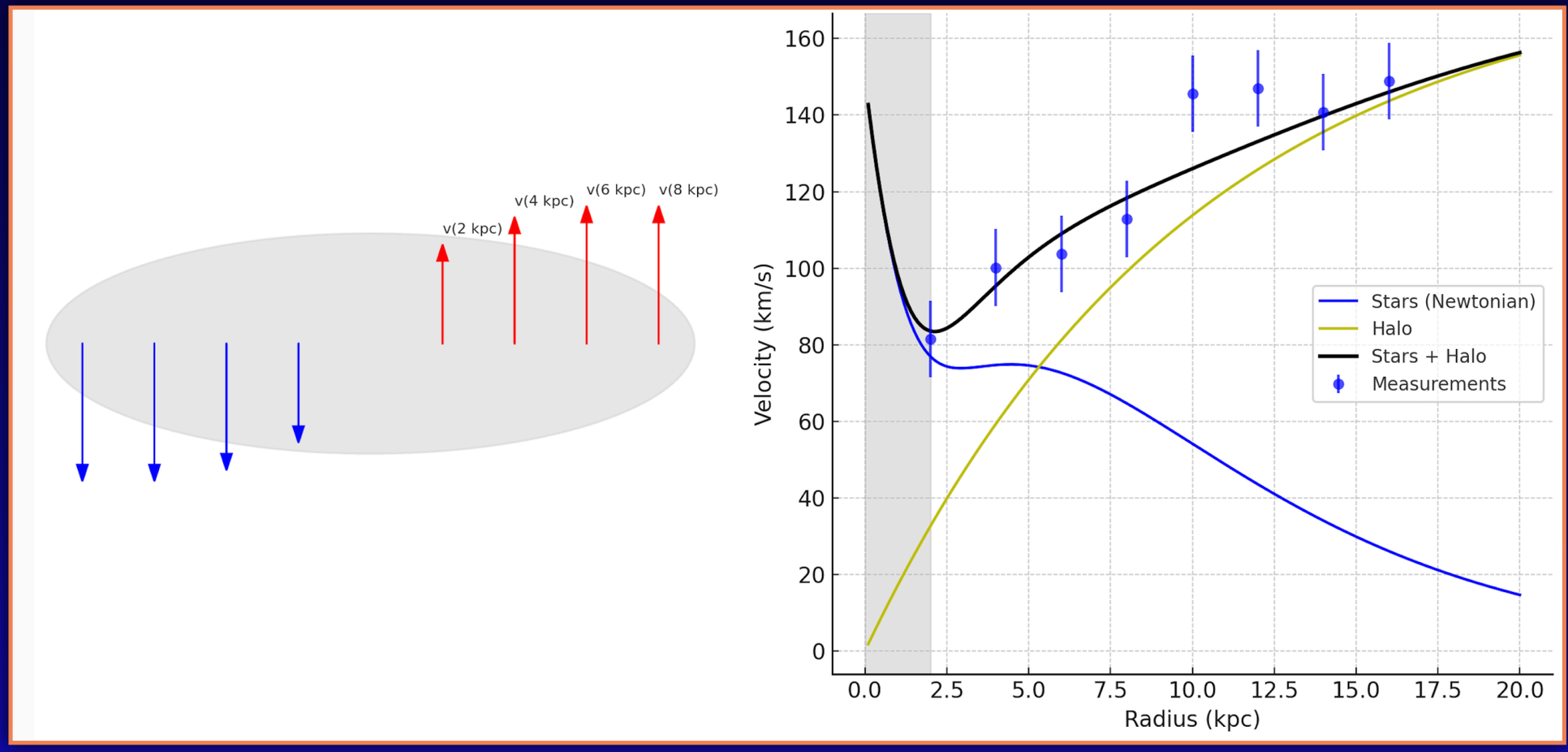
How do we know about DM?
One example: the Rotation Curve method



$$v(R) \propto \sqrt{\frac{M_{grav}(R)}{R}}$$

Rotational velocities tells us the total (gravitational mass)

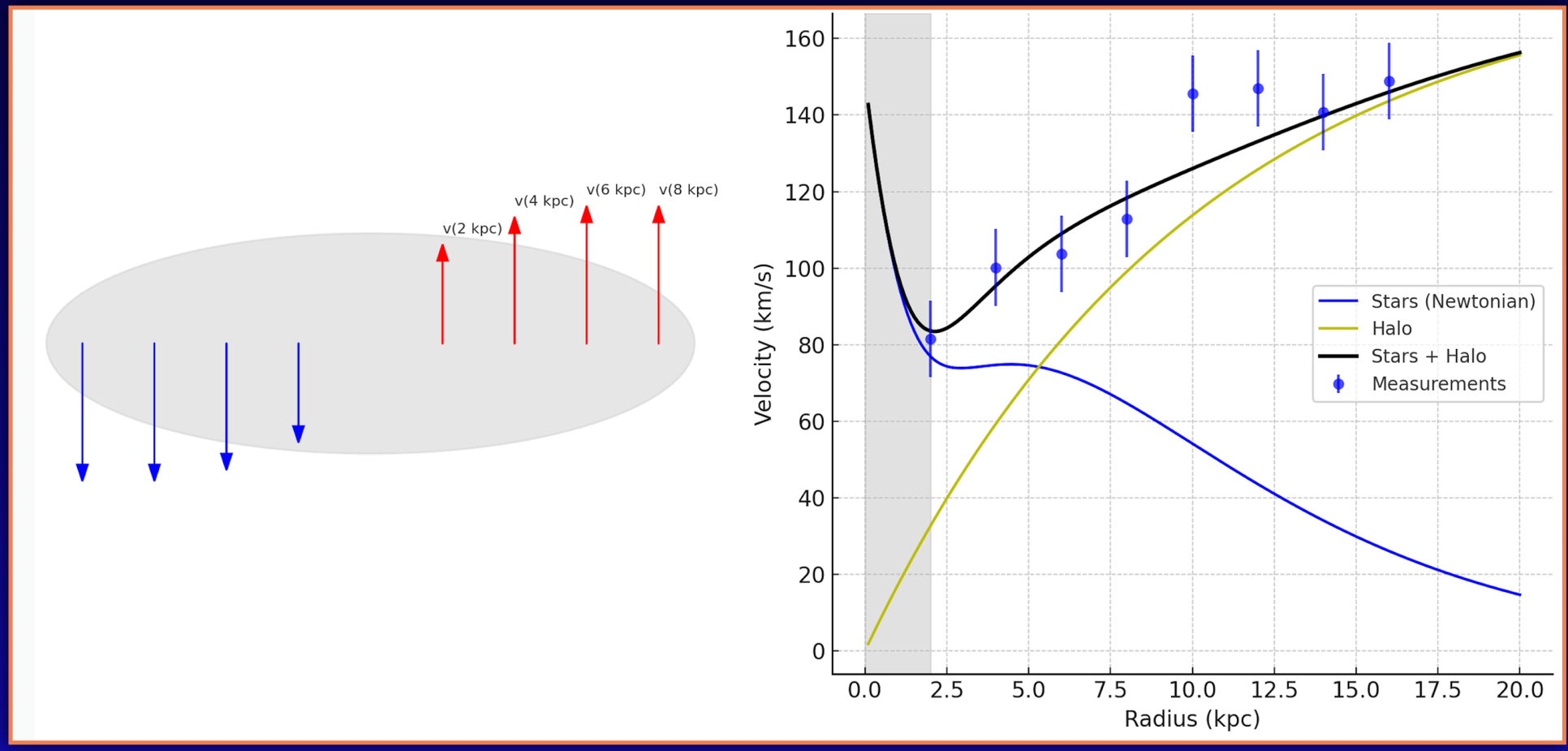
How do we know about DM?
One example: the Rotation Curve method



$$M_{grav}(R) = M_{\star}(R) + M_{DM}(R)$$

Allows us to infer mass of “missing” (dark) matter

How do we know about DM?
One example: the Rotation Curve method



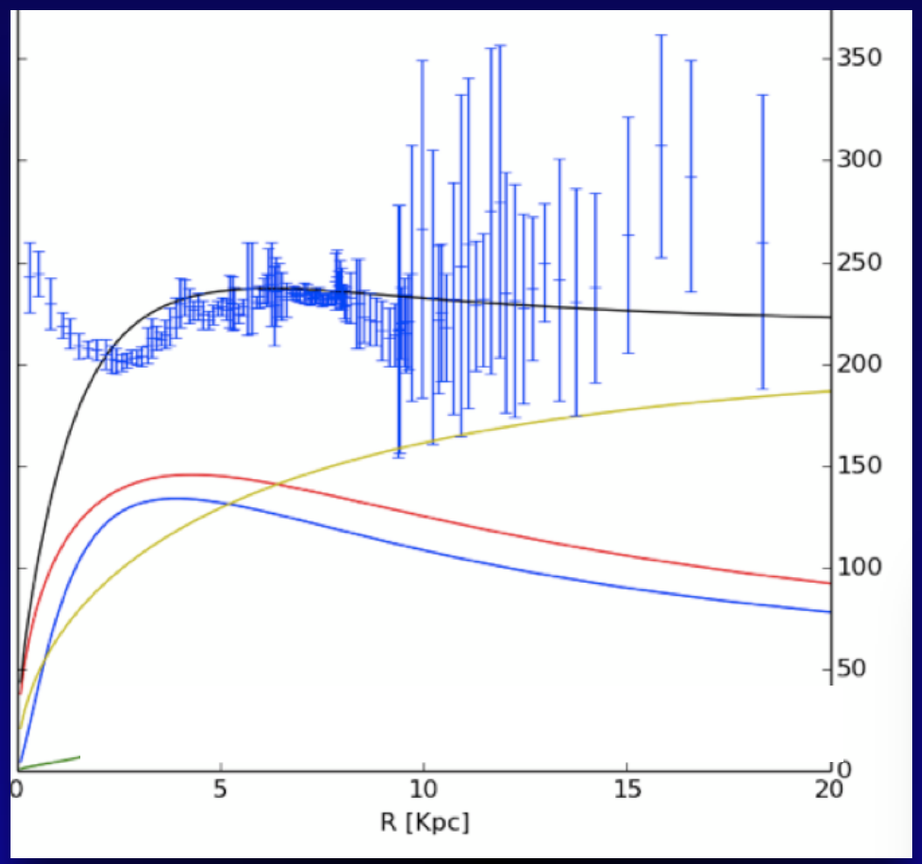


"Anna Karenina principle":
to be happy,
everything has to go right

galaxies where RC method applicable
are a specific subsample
rotating, symmetric, ….

Rotation Curves: inferring the DM distribution

Fitting a pre-assigned shape on top of luminous

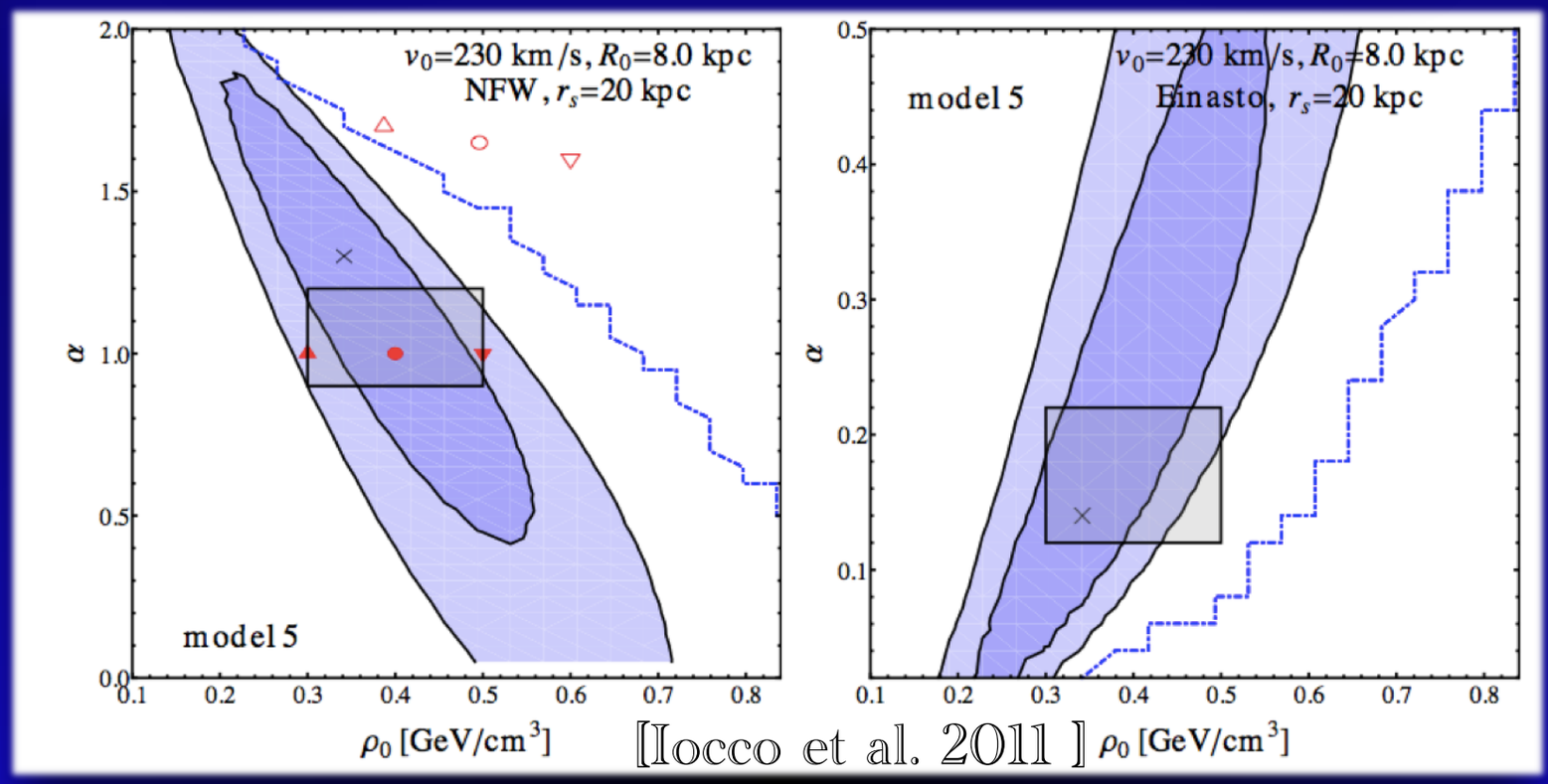


gNFW

$$\rho_{DM}(R) \propto \rho_0 \left(\frac{R}{R_s}\right)^{-\gamma} \left(1+\frac{R}{R_s}\right)^{-3+\gamma}$$

$$\rho_{DM}(R) \propto \rho_0 \exp\left[-\frac{2}{\gamma}\left(\left(\frac{R}{R_s}\right)^{\gamma}-1\right)\right]$$

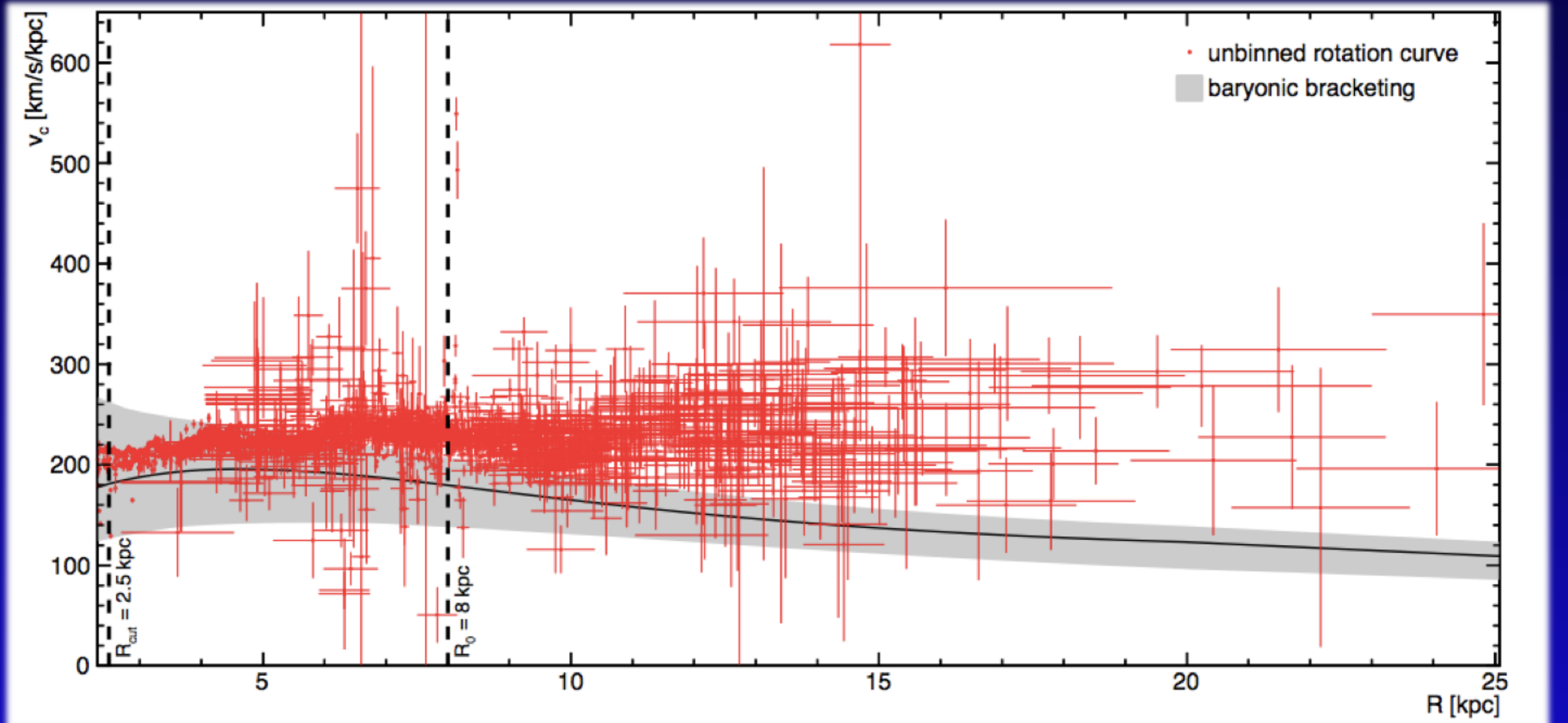
Einasto



[Iocco et al. 2011]

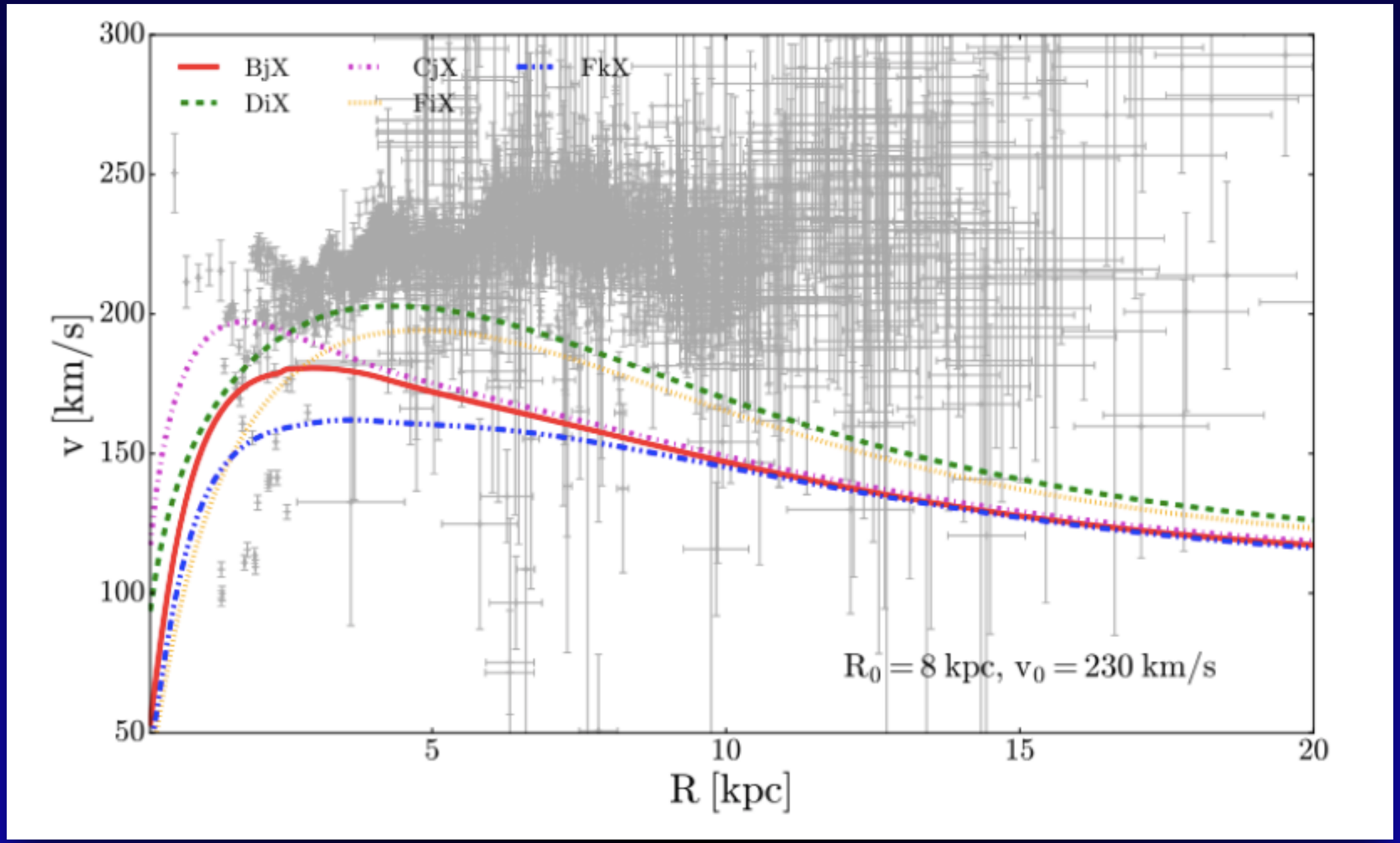
[many autors, e.g. Iocco et al. 2011, 2015, 2020…]

A real Universe case: the Milky Way



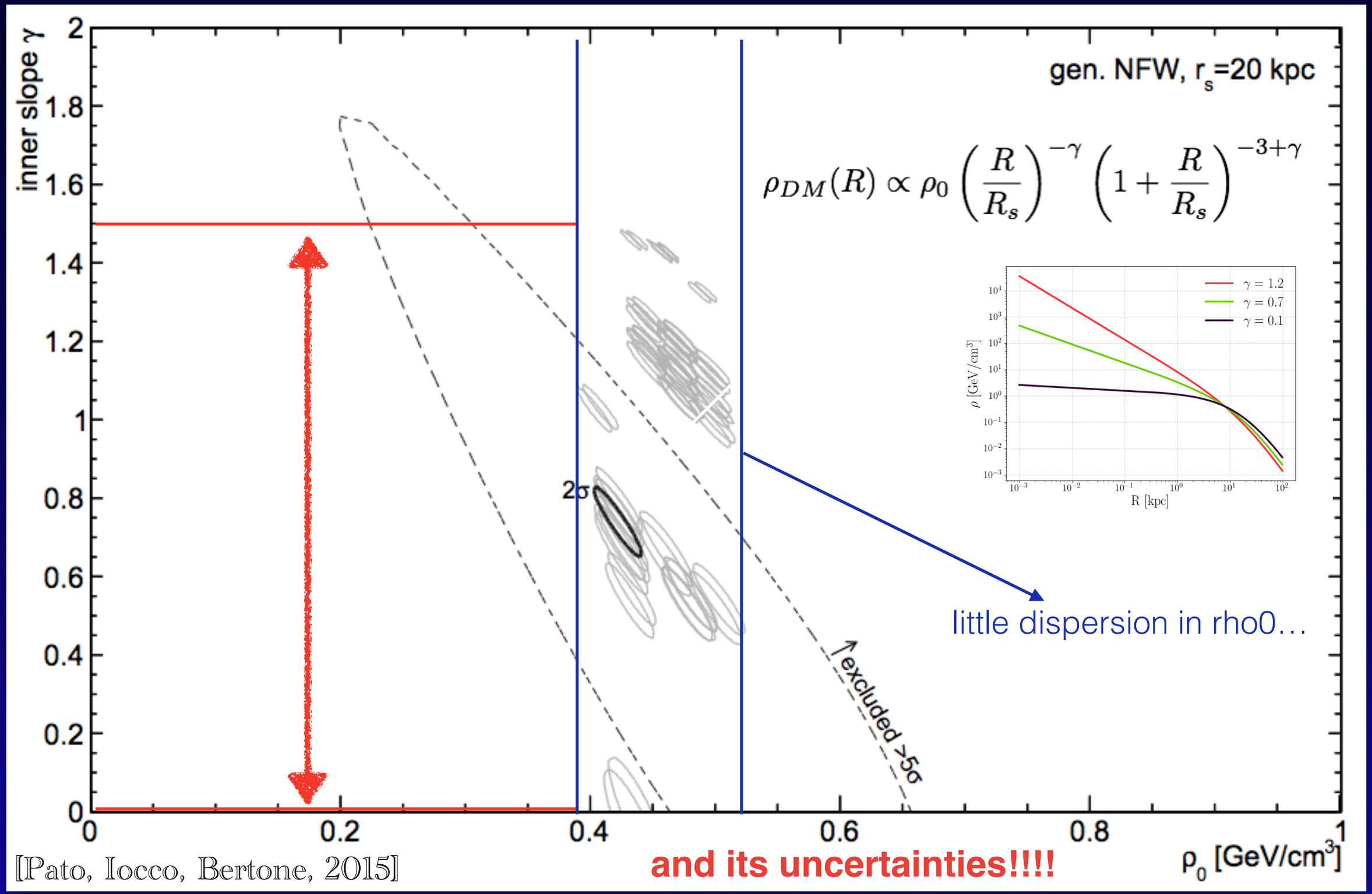
[Iocco, Pato, Bertone, Nature Physics 2015]

The Milky Way
(its unavoidable uncertainties)



[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017] [Iocco, Pato, Bertone, Nature Physics 2015]

MW: the DM distribution



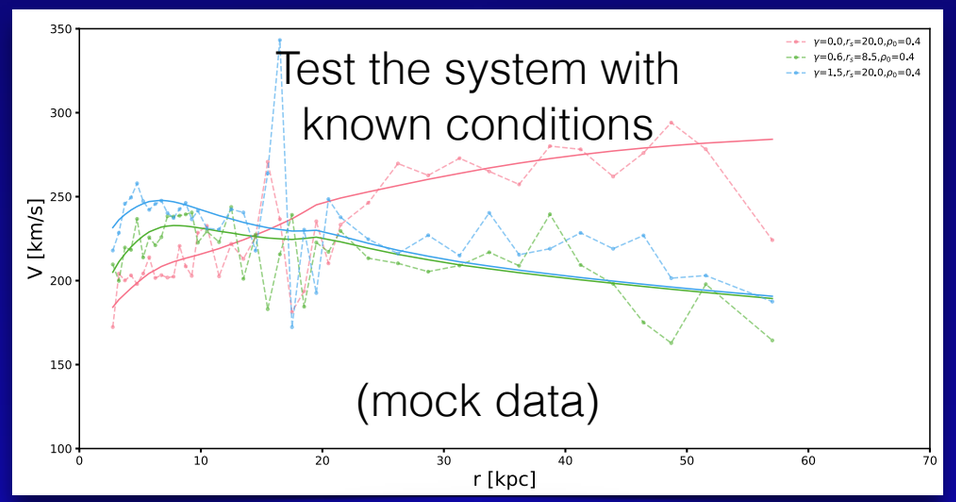
[Pato, Iocco, Bertone, 2015]

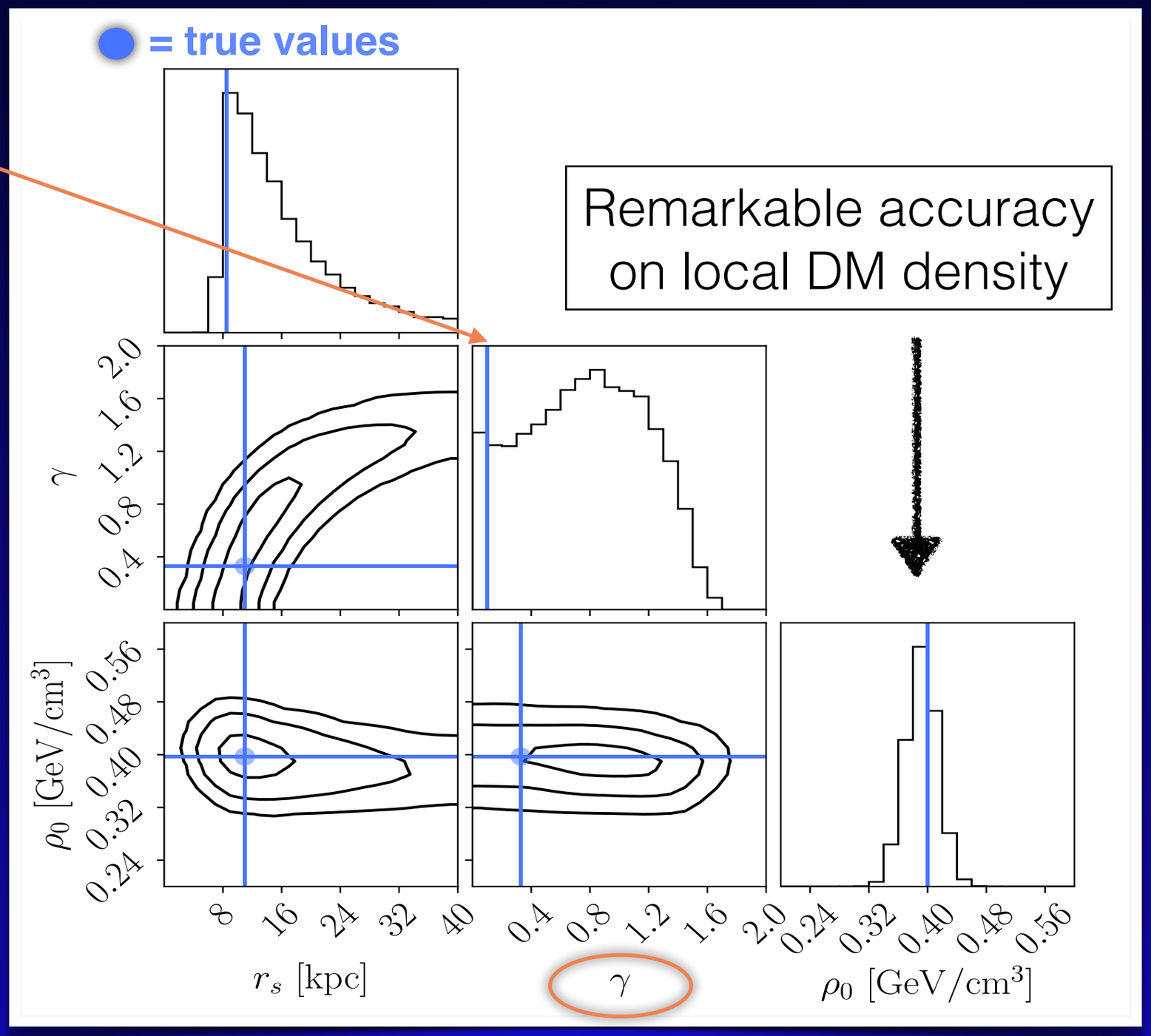
What to do of our measurement?

(Our instrument is very precise. Is it accurate?)



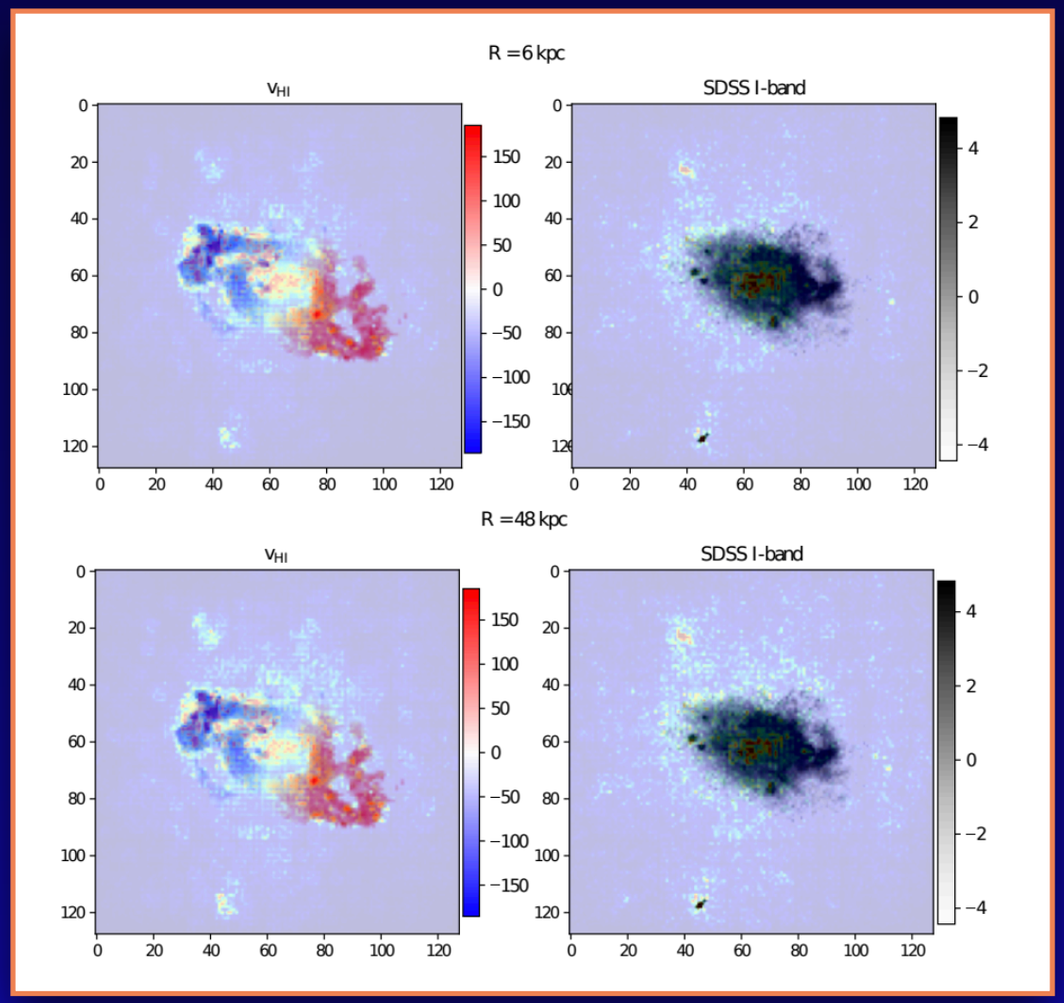






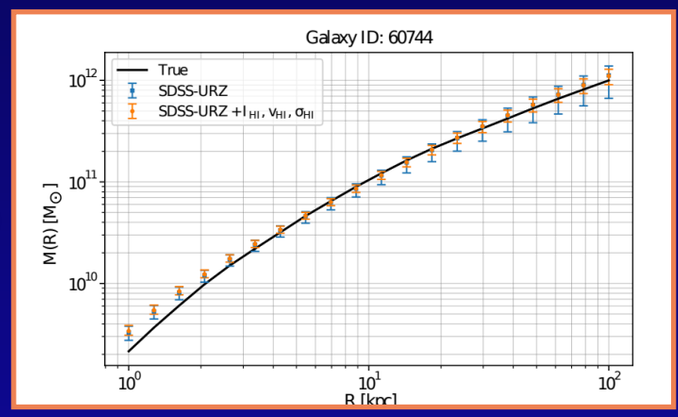
[Karukes, Benito, F.I., Geringer-Sameth, Trotta] arXiv:1901.02463

Where to calibrate our instrument?



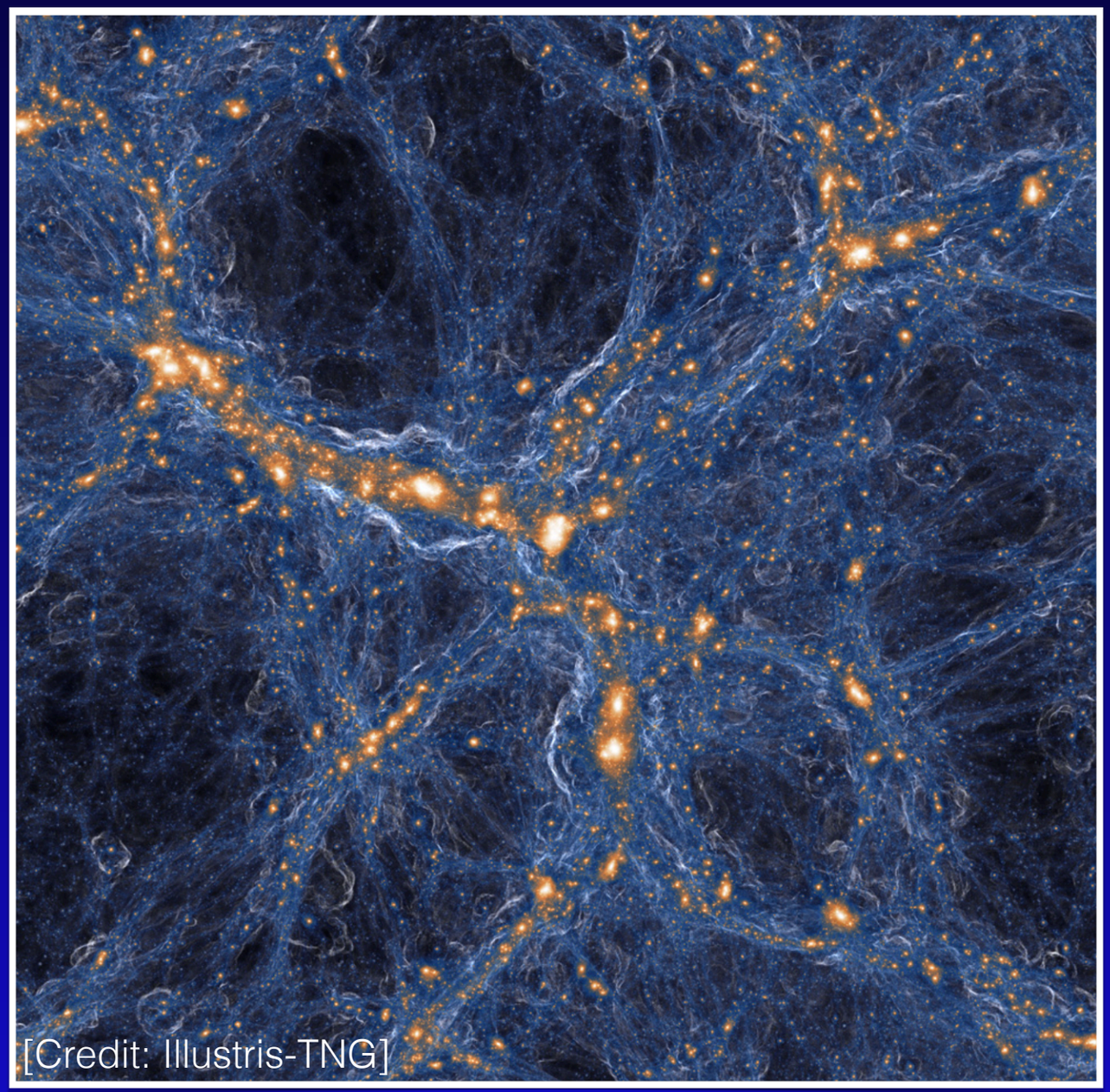
spectroscopy + photometry

something happens

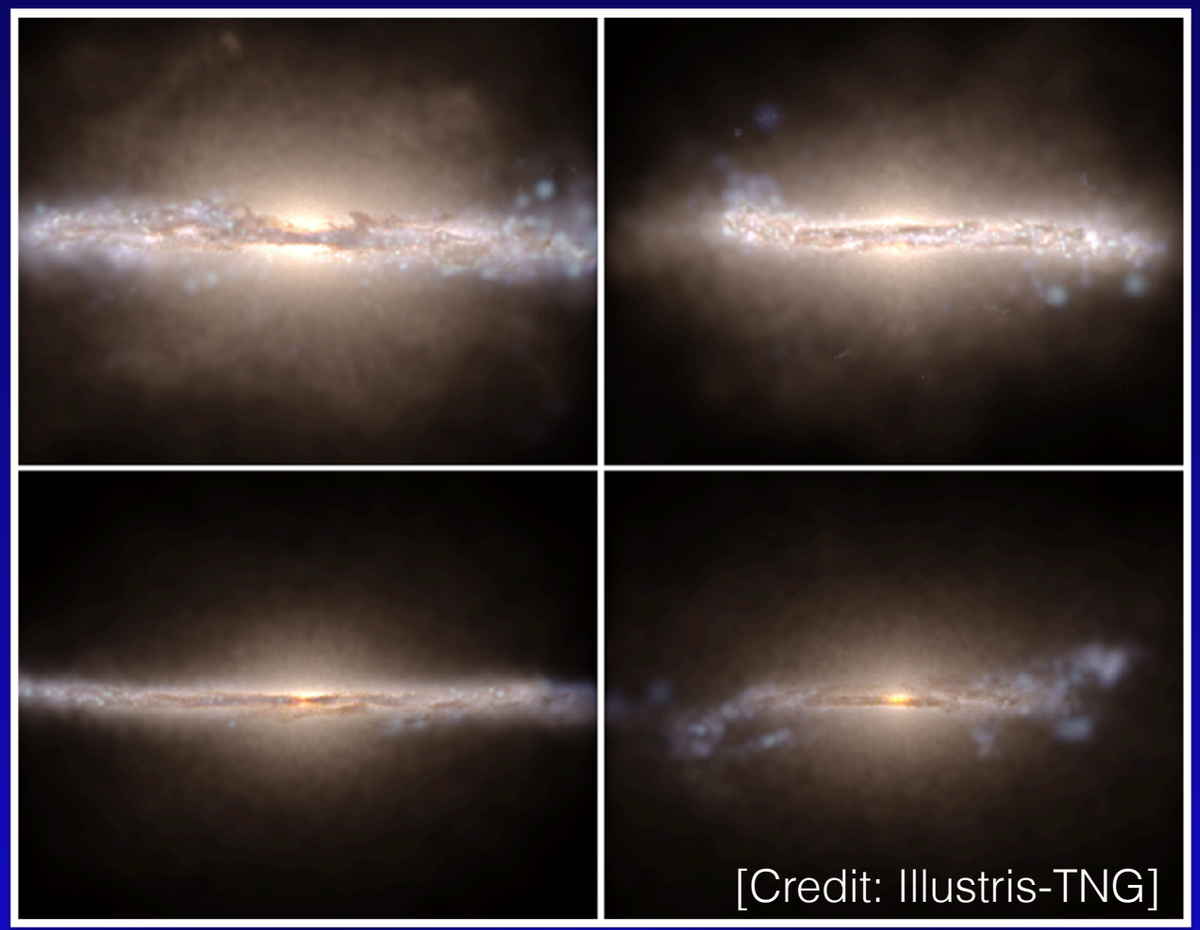


(dark) matter distribution

Where to calibrate our instrument?


[Credit: Illustris-TNG]

A Universe where we know everything.
Including the invisibile secrets.
In silico cosmologies including
astrophysics down to *small* scales
(devil in details, more later)

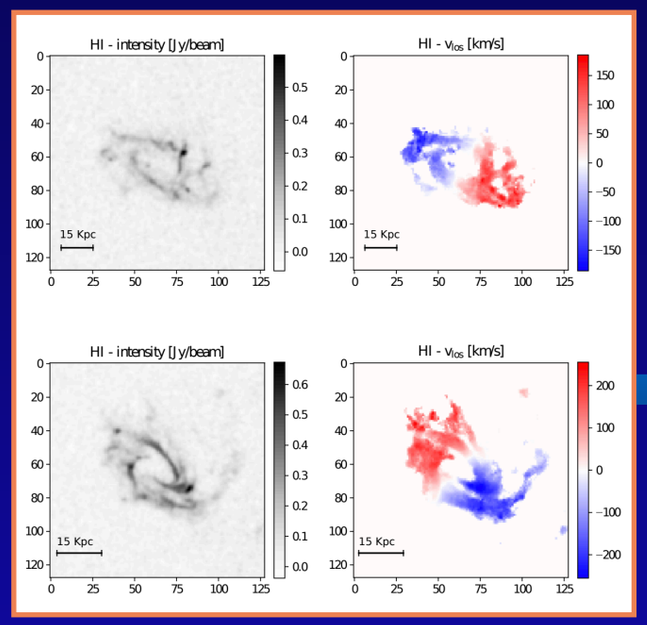

[Credit: Illustris-TNG]

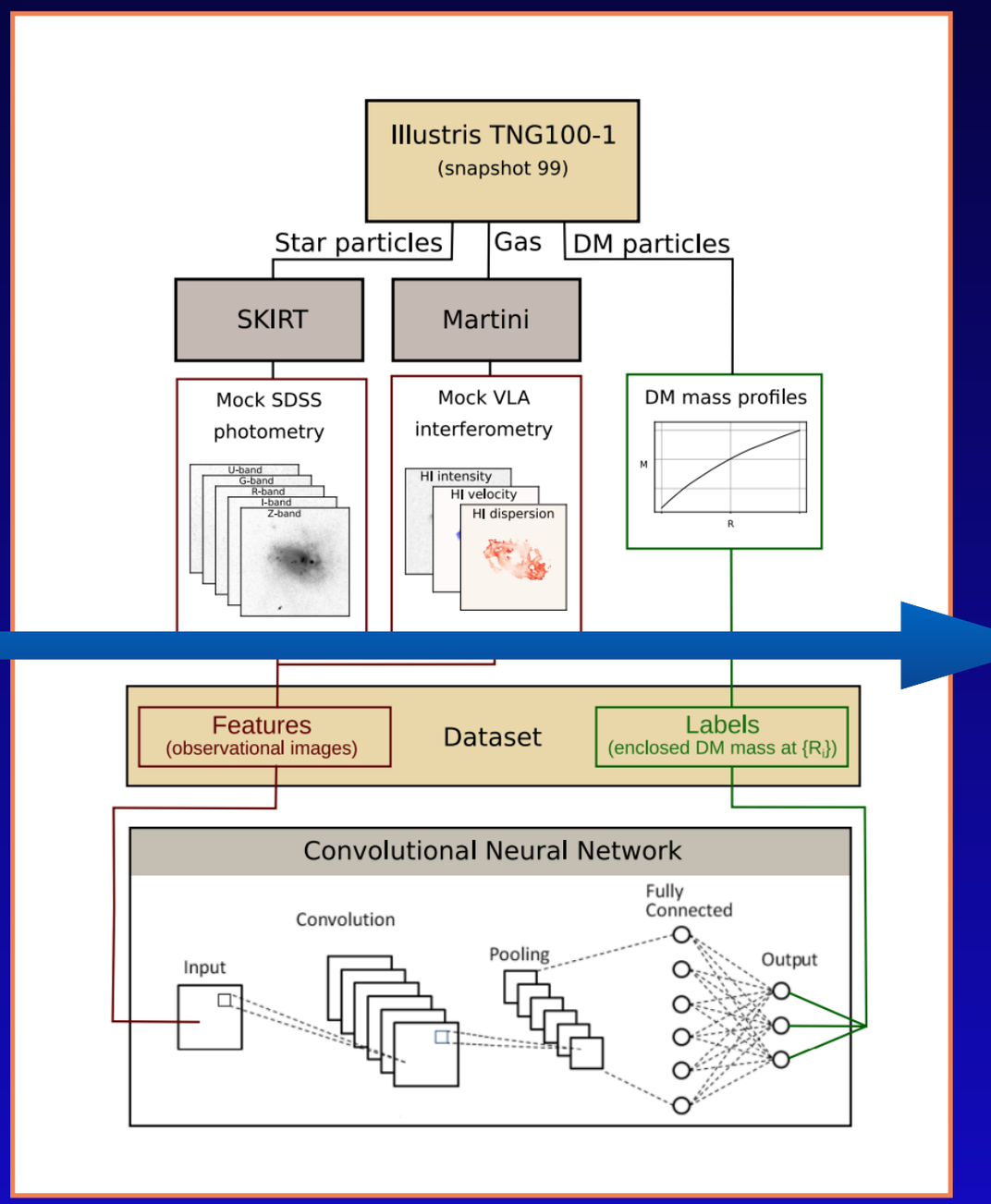
Cosmological numerical simulations provide such environment

(dark matter distribution, density & velocity field of components… all known)

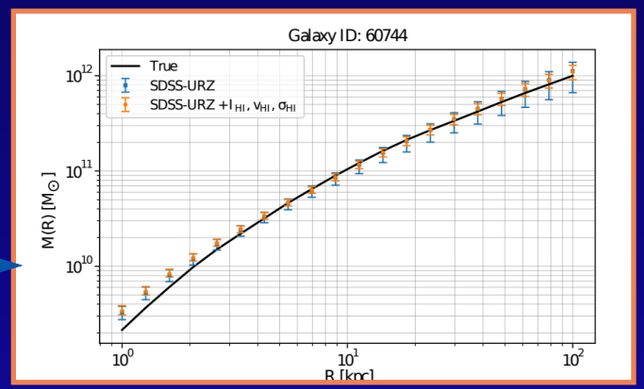
How we calibrate our instrument

mock data
(generated in sim)





DM density
(known in silico)



[deLosRios, Petac, Zaldivar, Bonaventura, Calore, Iocco, MNRAS; arXiv:2111.08725]

How we set our instrument up

picking the sample

Property	Criterium
Simulation snapshot	99 ($z = 0$)
Stellar mass	$10^{10}\ M_\odot \leq M_\star \leq 10^{12}\ M_\odot$
Star formation rate	$sSFR \geq 0.1\ M_\odot/yr$
Central galaxy	SubhaloParent $= 0$
Cosmological origin	SubhaloFlag $= 1$

Illustris-TNG100-1

2972 galaxies
(70% tr, 25% val, 5% test)

77% spiral, 33% elliptical

10-20Mpc from "observer"

the machine: steerable E(2)-CNN

The (mock) input data

Photometry:
5 SDSS bands (SKIRT)

Spectroscopy:
21-cm VLA Interferometry (Martini)

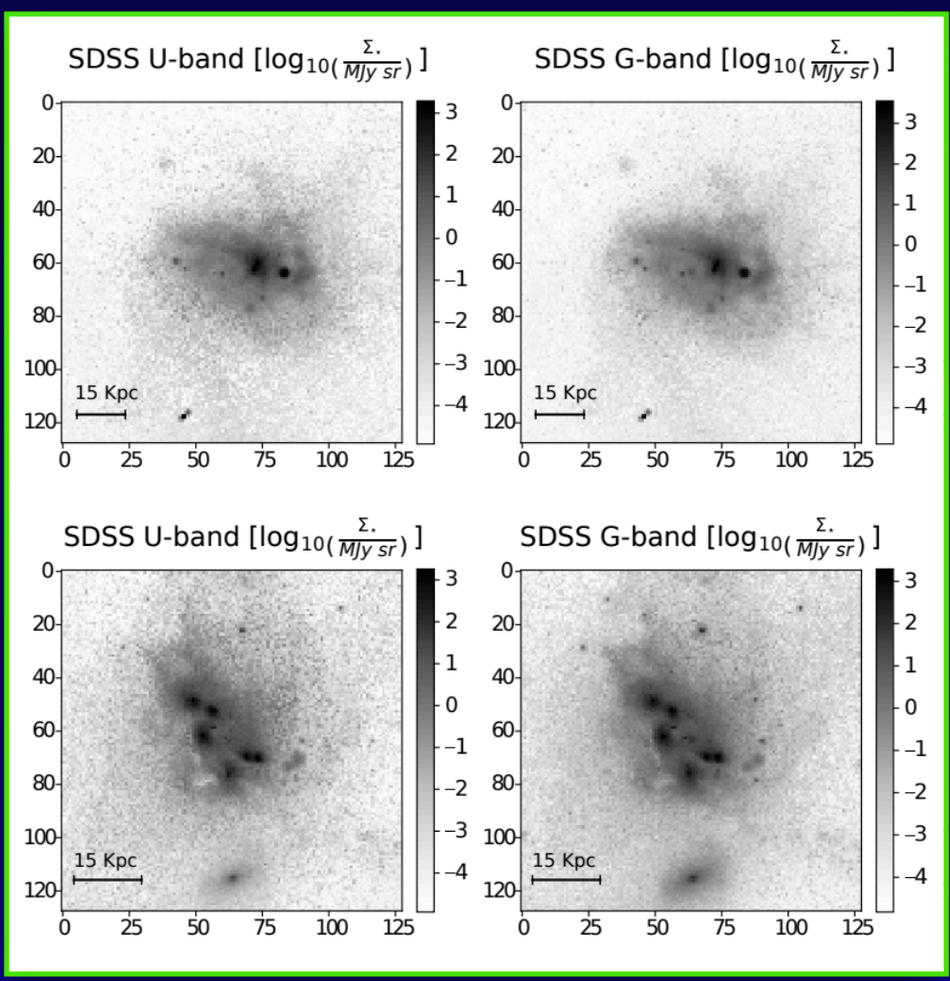
The output

20 bin radial DM profile

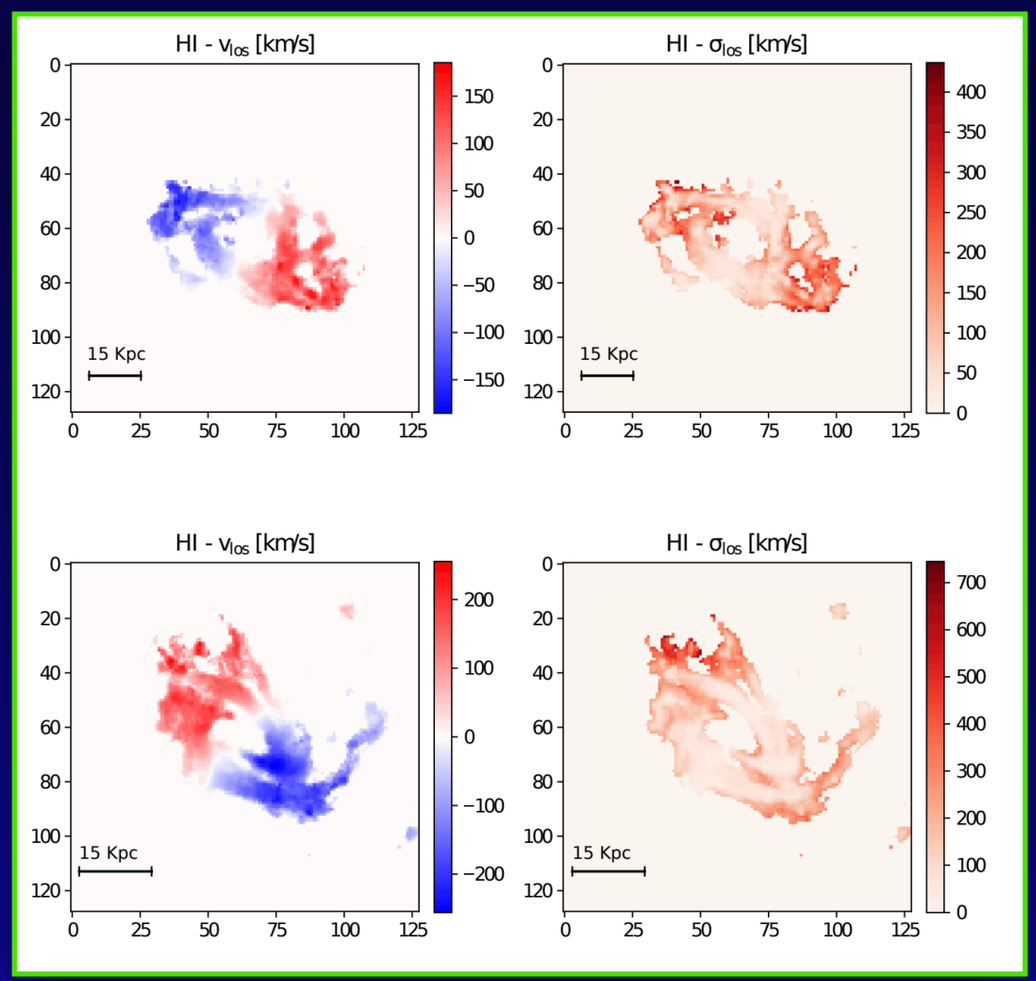
[deLosRios, di Gioia, FI, Trotta, arXiV:2510.18964]

Seeing our setup: input

SDSS mock



VLA mock



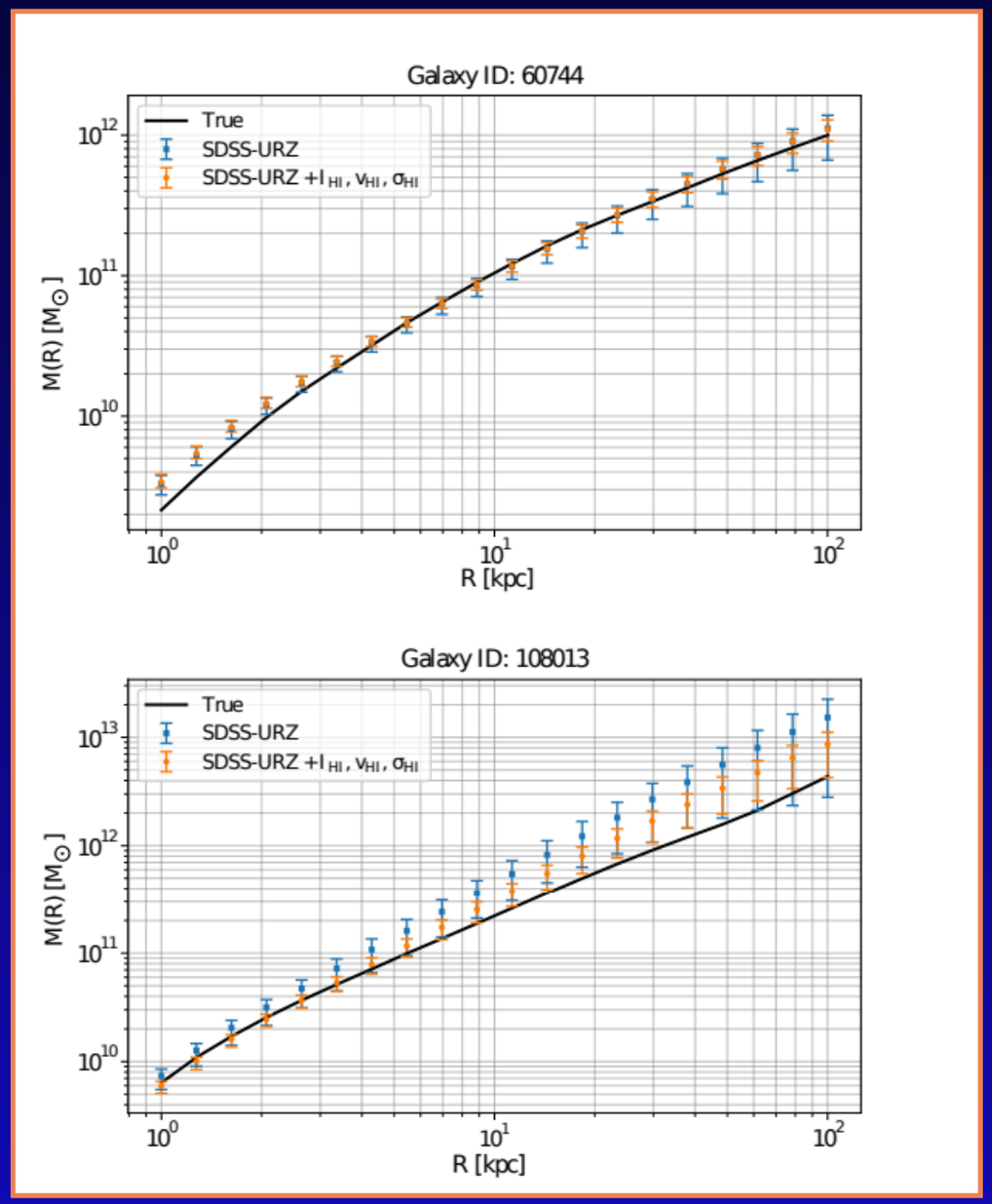
Photometry

Spectroscopy

[deLosRios, di Gioia, FI, Trotta, arXiV:2510.18964]

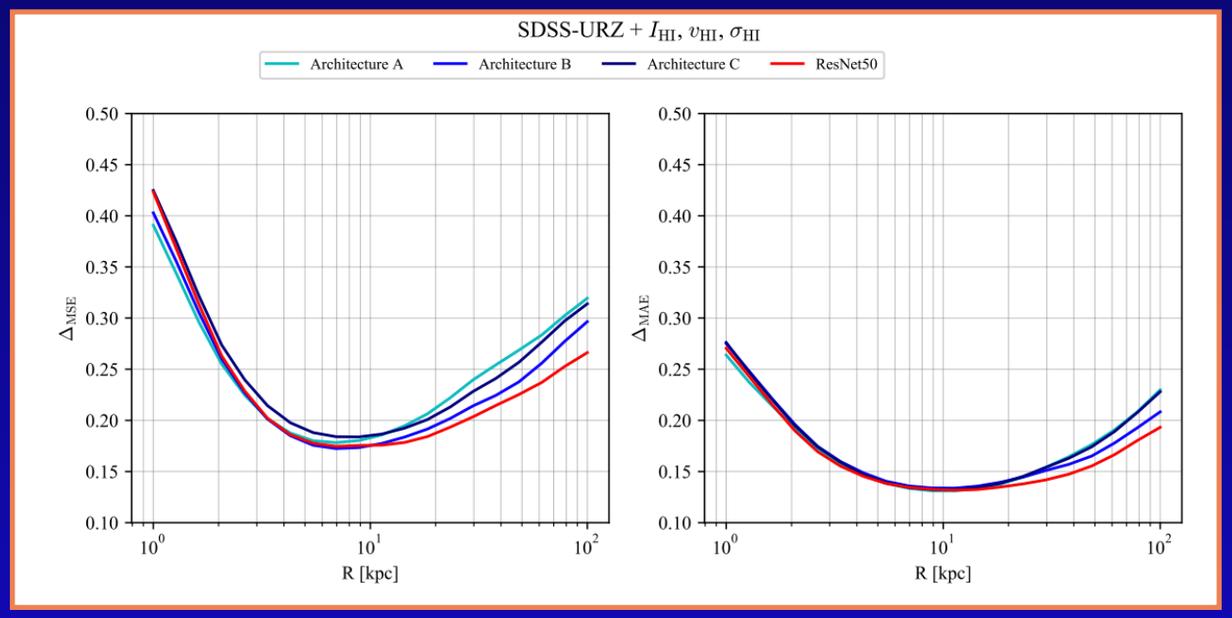
[deLosRios, Petac, Zaldivar, Bonaventura, Calore, Iocco, MNRAS; arXiv:2111.08725]

Seeing our setup: output



ECNN trained within sims

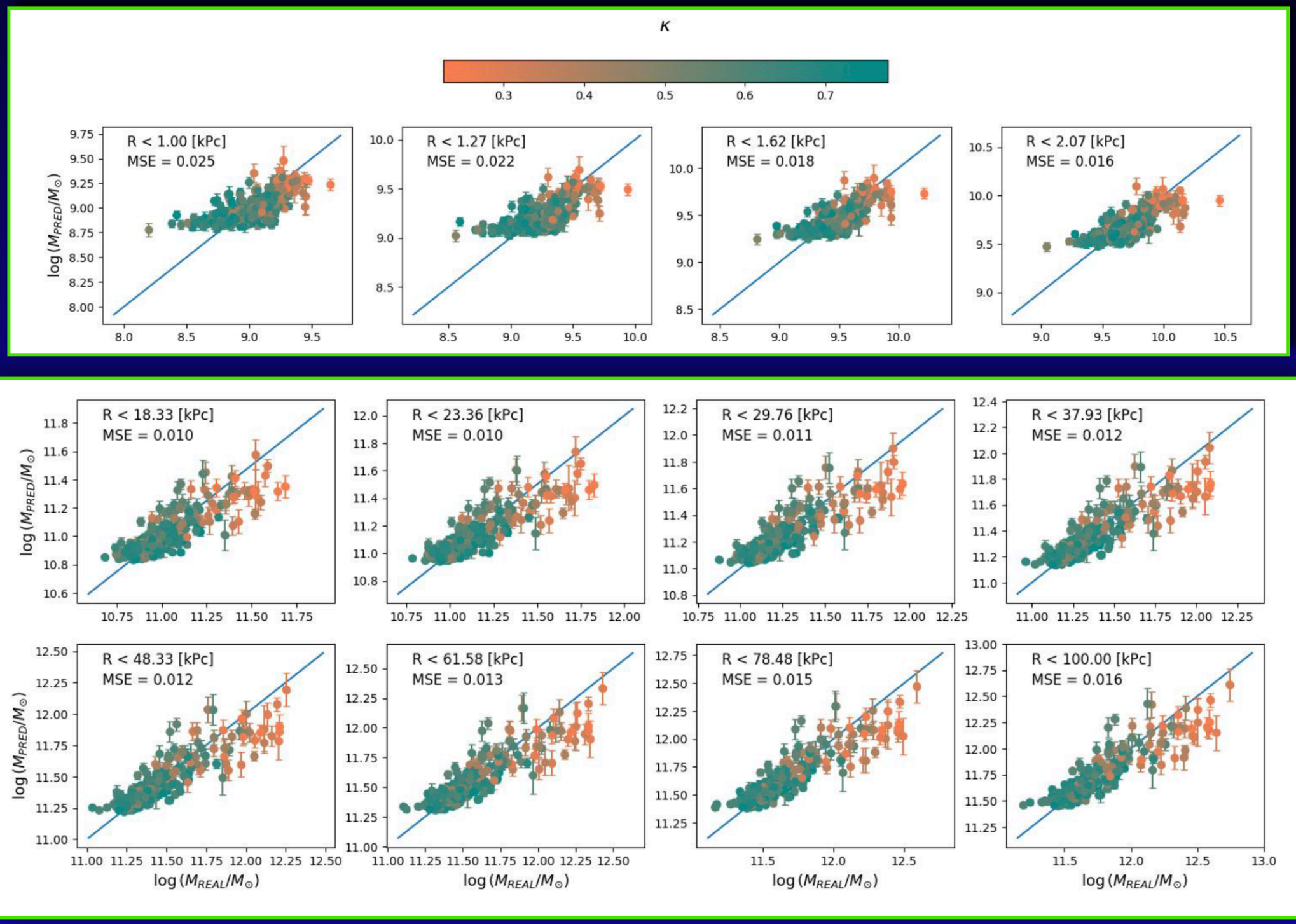
<u>can</u> infer encloses DM mass
with high accuracy
& precision



$$MSE = \frac{1}{N_{obs} N_{bins}} \sum_{i}^{N_{obs}} \sum_{j}^{N_{bins}} \left[\log M^{i}_{RE,j} - \log M^{i}_{PR,j} \right]^2$$

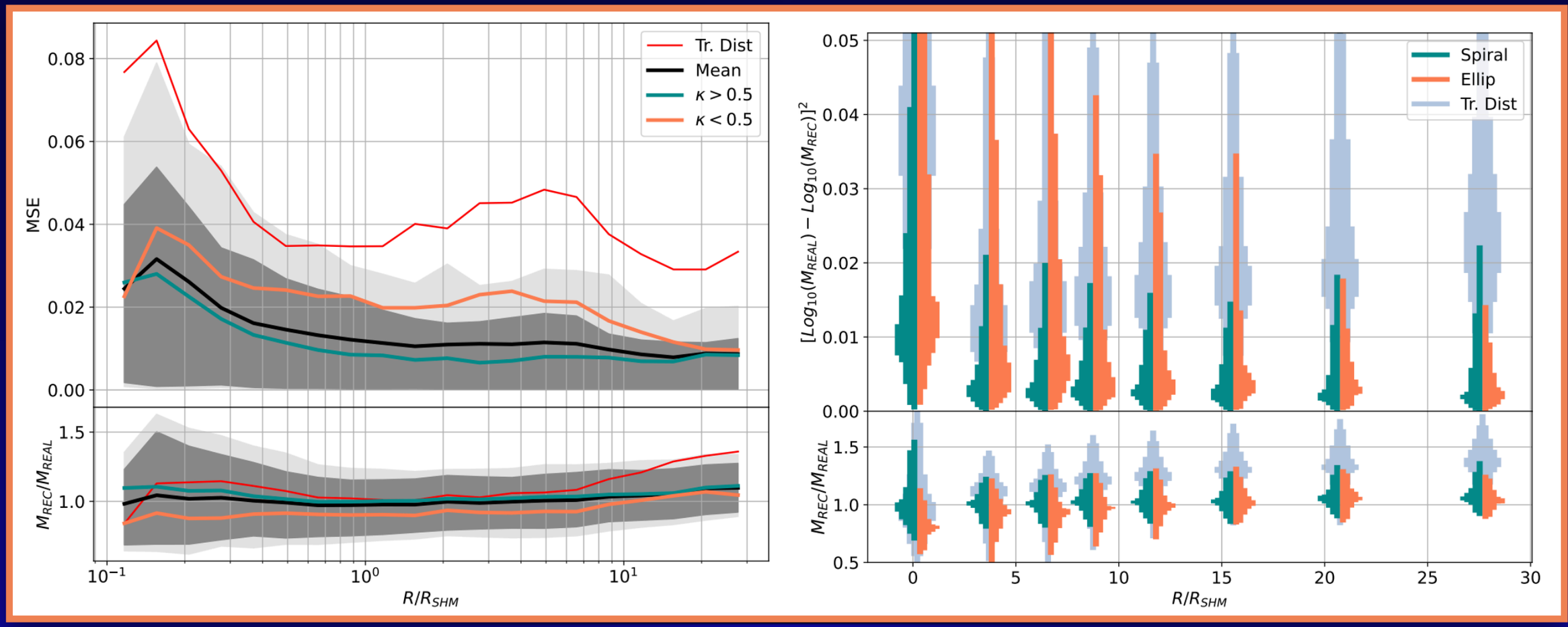
[deLosRios, Petac, Zaldivar, Bonaventura, Calore, Iocco, MNRAS; arXiv:2111.08725]

Into the analysis: inner vs outer



[deLosRios, di Gioia, FI, Trotta, arXiV:2510.18964]

Into the analysis: general behavior

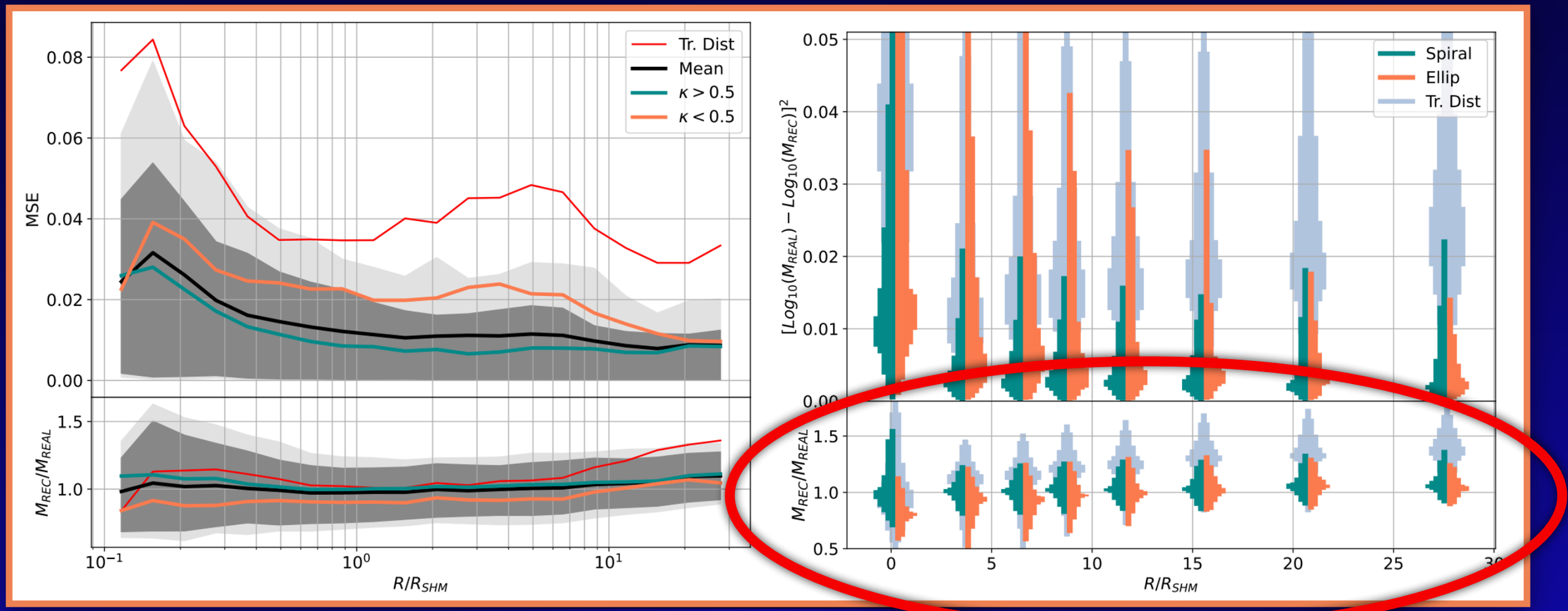


Excellent reconstruction of mass profile (MSE < 0.01)

Rotating galaxis perform better in innermost regions

[deLosRios, di Gioia, FI, Trotta, arXiV:2510.18964]

Into the analysis: general behavior

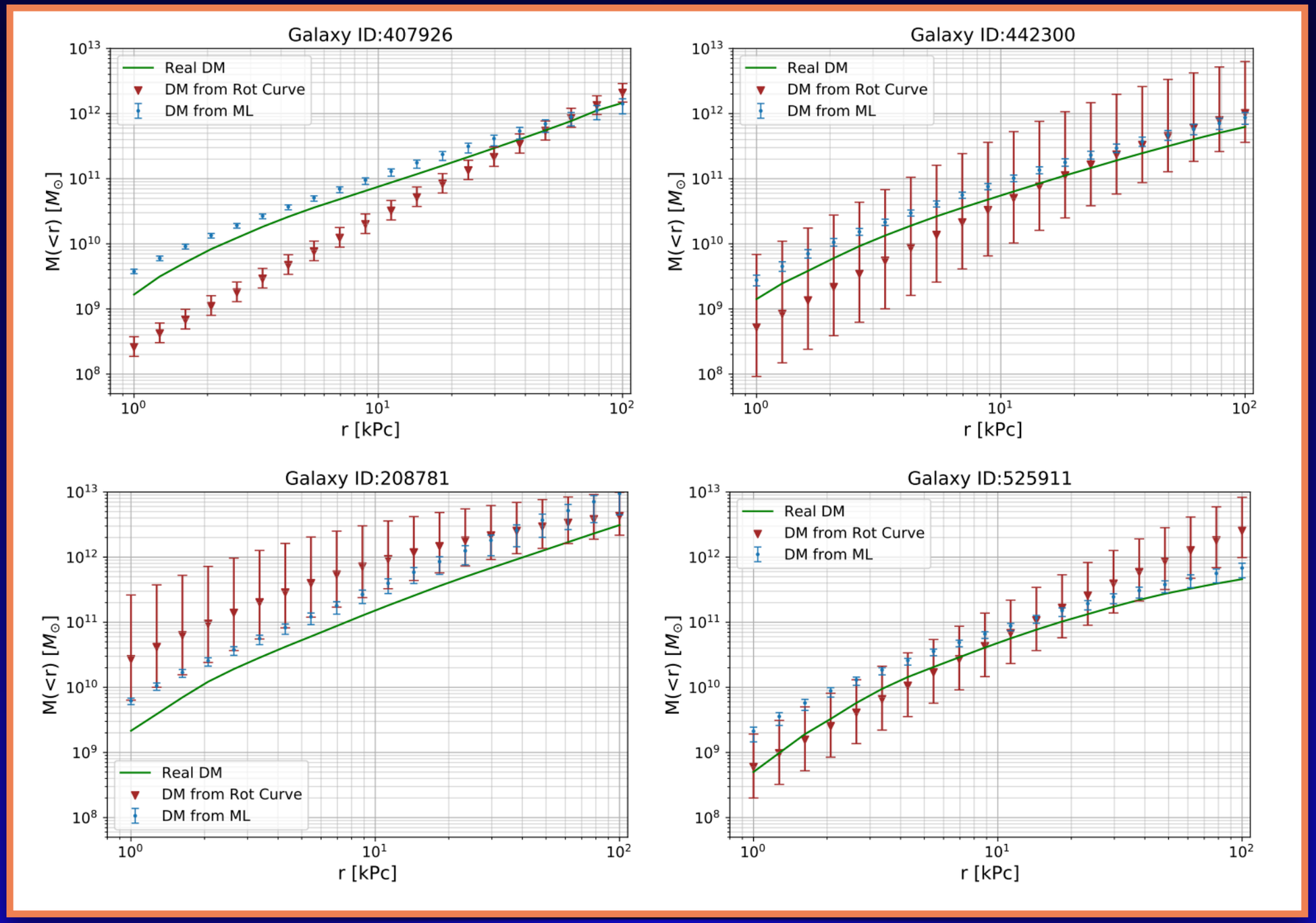


Excellent reconstruction of mass profile (MSE < 0.01)

Rotating galaxies perform better than ellipticals in innermost regions

[deLosRios, di Gioia, FI, Trotta, arXiV:2510.18964]

Comparing with RC method



[deLosRios, Petac, Zaldivar, Bonaventura, Calore, Iocco, MNRAS; arXiv:2111.08725]

Cuncta stricte

- In silico, it works: machines reliably reconstruct DM profile

- Very exciting features: non-parametric, features explainable, processing on different masses / types galaxies

- Extending to different types of (mock) data, and expanding into different redshifts.

- Expanding to different types of features (asphericity, ... ?)

- Works better than Rotation Curve method (to be stat. confirm.)

Discussurus

- Possible to use for in vivo applications?

- Portability / testing across simulation suites?

- Other uses than DM (if you're interested in the actual visible stuff, for instance. A Di Cintio's plenary tomorrow?)

- Can we actually learn anything about cosmology / astrophysics of DM / structure formation ?

Similar analysis, recent literature

Inferring halo masses with Graph Neural Networks, Villanueva-Domingo et al. arXiV:2111.08683

Total and dark mass from observations of galaxy centers with Machine Learning, Wu et al. arXiV:2310.02816

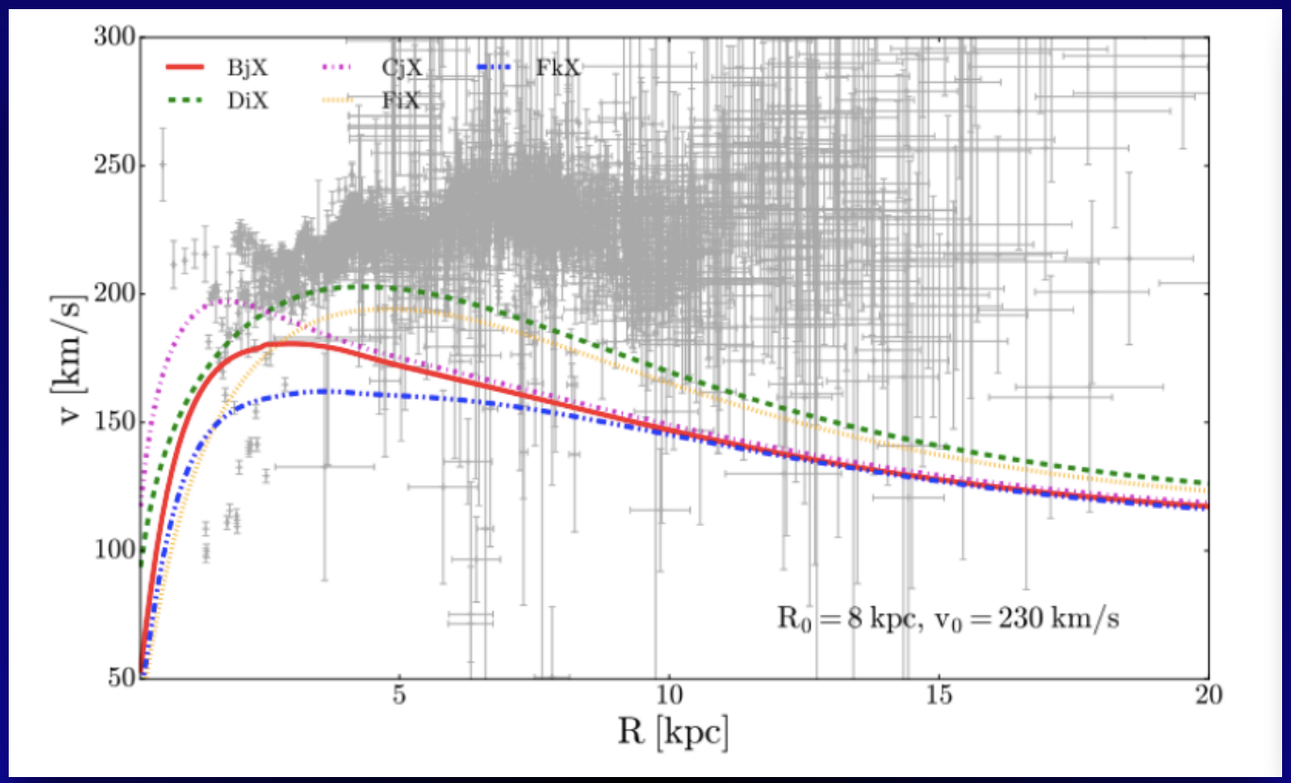
Dispersion-supported galaxy mass profiles with convolutional neural networks, Sarrato-Alós et al. arXiV:2503.07717

Reconstruction of Dark Matter and Baryon Density From Galaxies: A Comparison of Linear, Halo Model and Machine Learning-Based Methods, Krywonos et al. arXiV:2507.12530

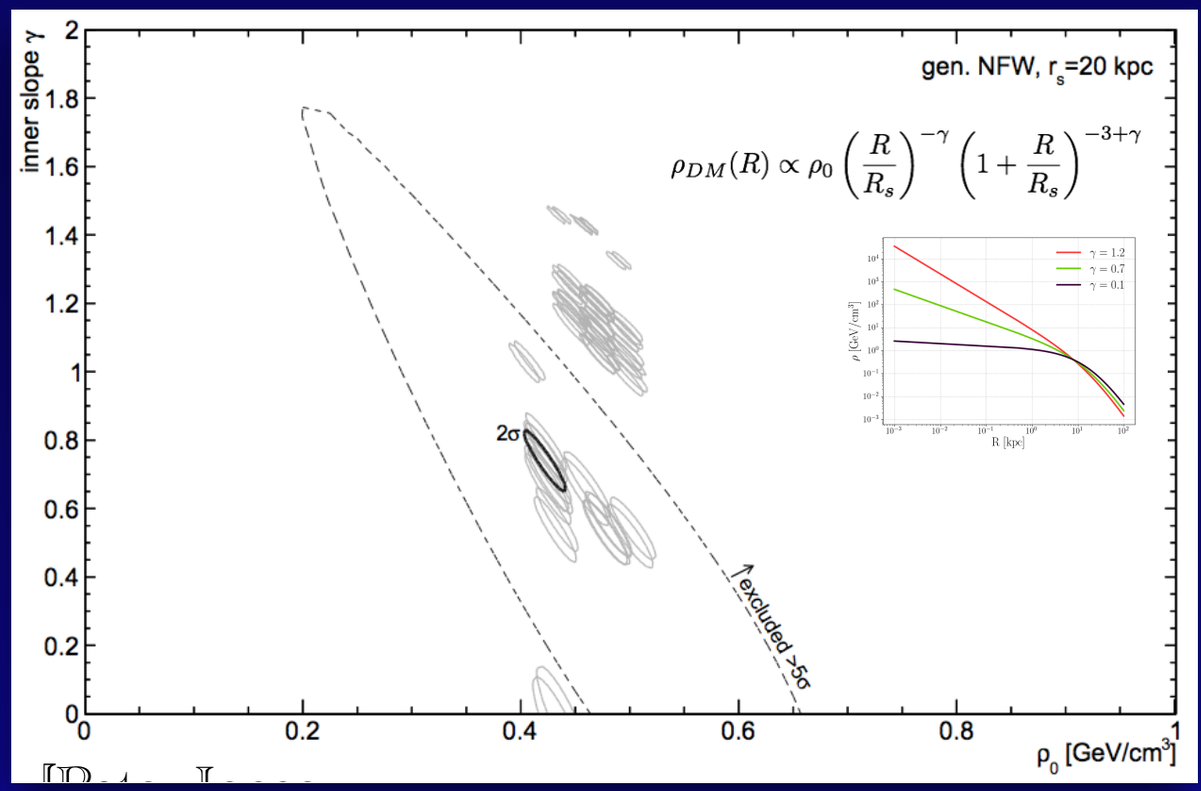
[Incomplete list, apologies already!]

Rotation Curves: inferring the DM distribution

(with systematic uncertainties)

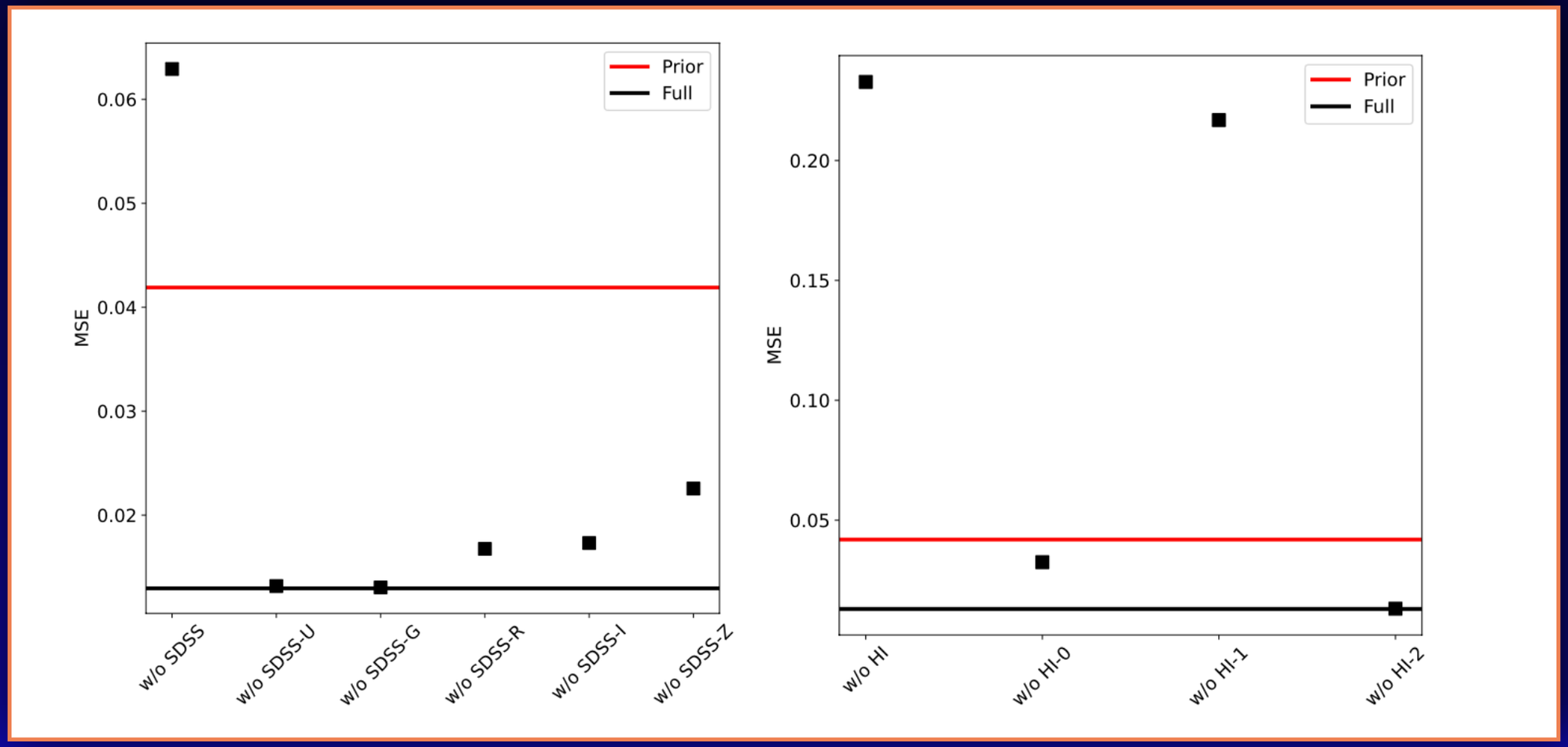


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017]



[Iocco, Pato, Bertone, Nature Physics 2015]

Some (more) astro details



Testing interpretability of results

[deLosRios, di Gioia, FI, Trotta, arXiV:2509.XXXX]