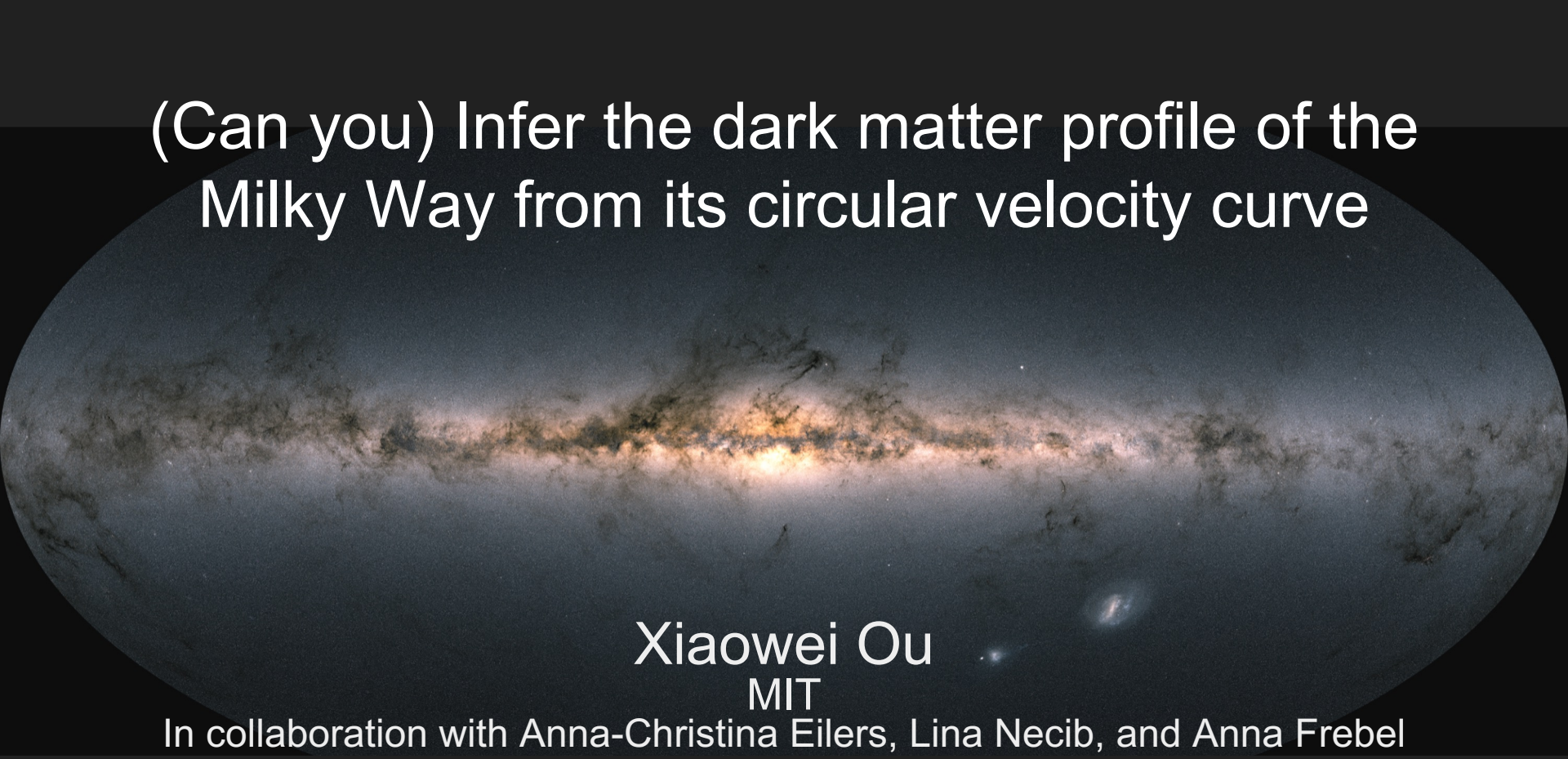
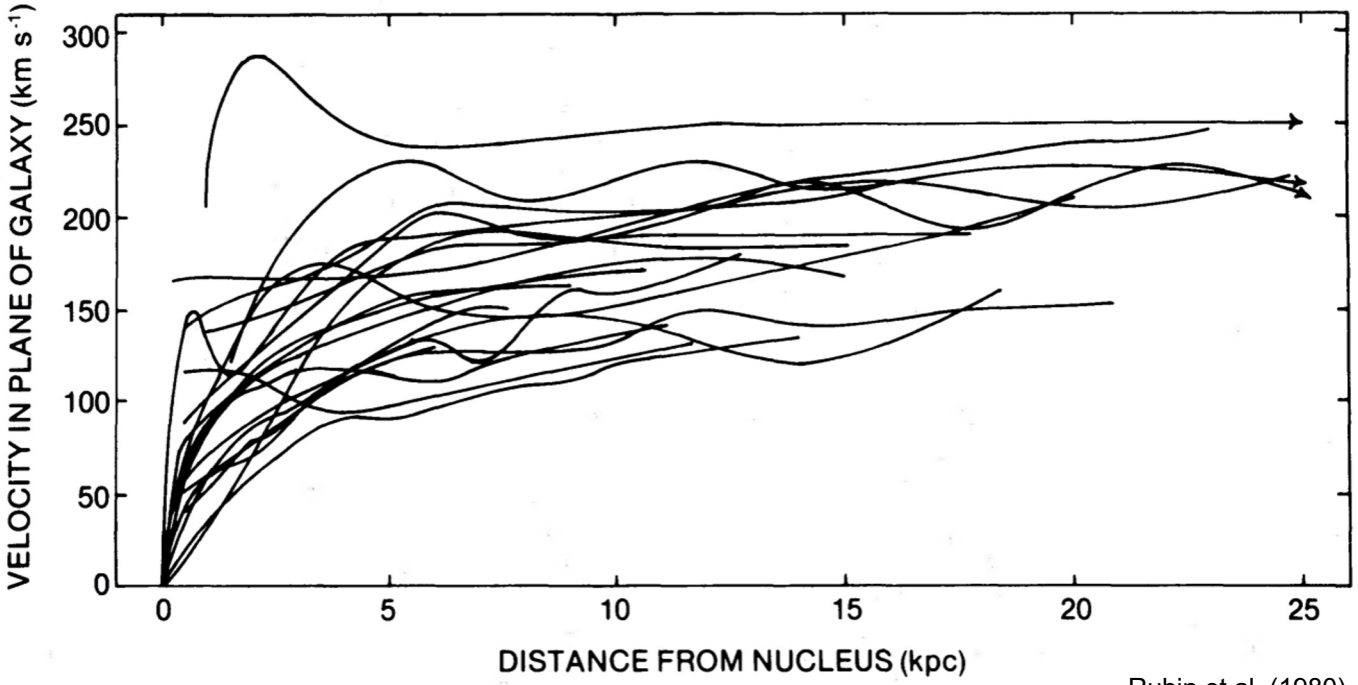
(Can you) Infer the dark matter profile of the Milky Way from its circular velocity curve



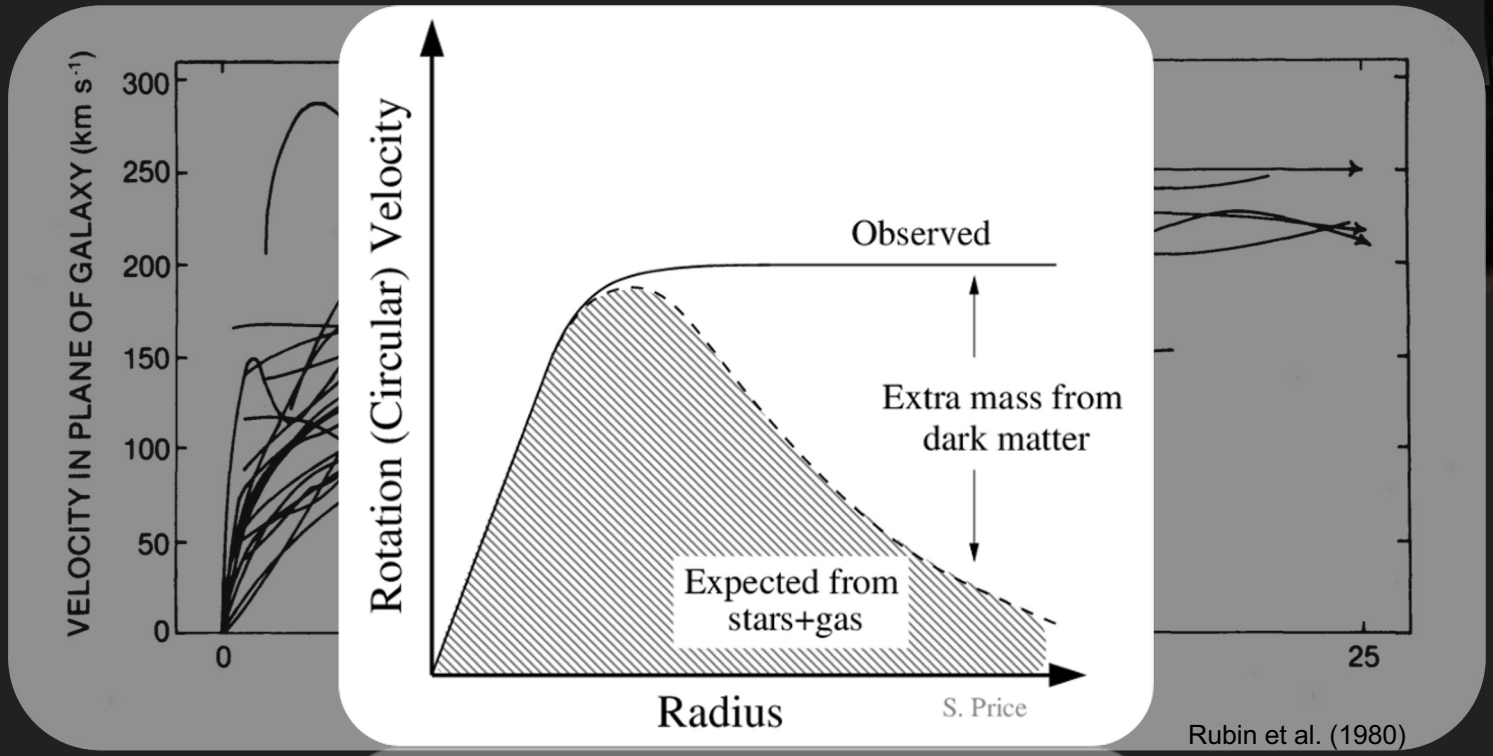
Xiaowei Ou
MIT
In collaboration with Anna-Christina Eilers, Lina Necib, and Anna Frebel

Credit: ESA/Gaia/DPAC



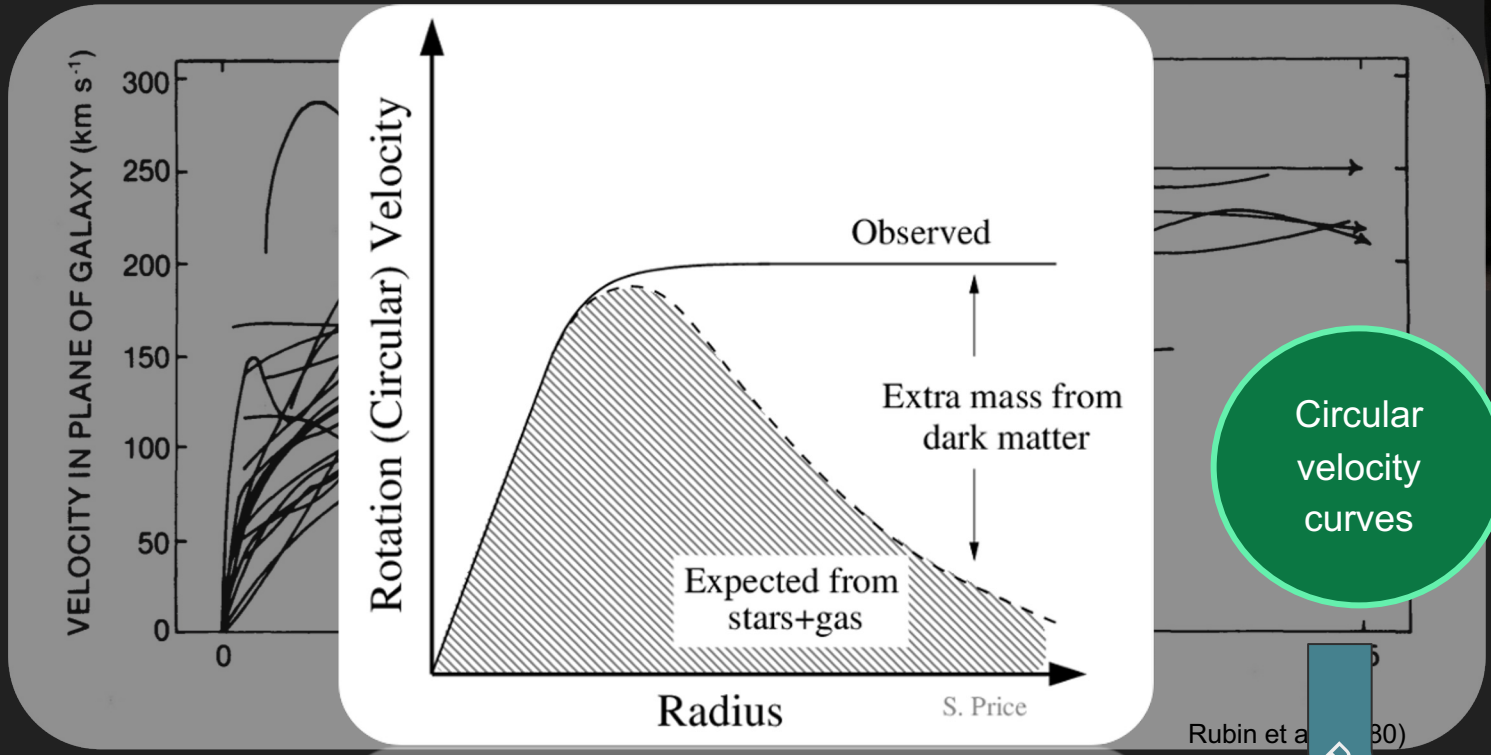
Rubin et al. (1980)

Vera Rubin Credit: NASA/NOIRLab



Vera Rubin Credit: NASA/NOIRLab

Rubin et al. (1980)



Vera Rubin Credit: NASA/NOIRLab

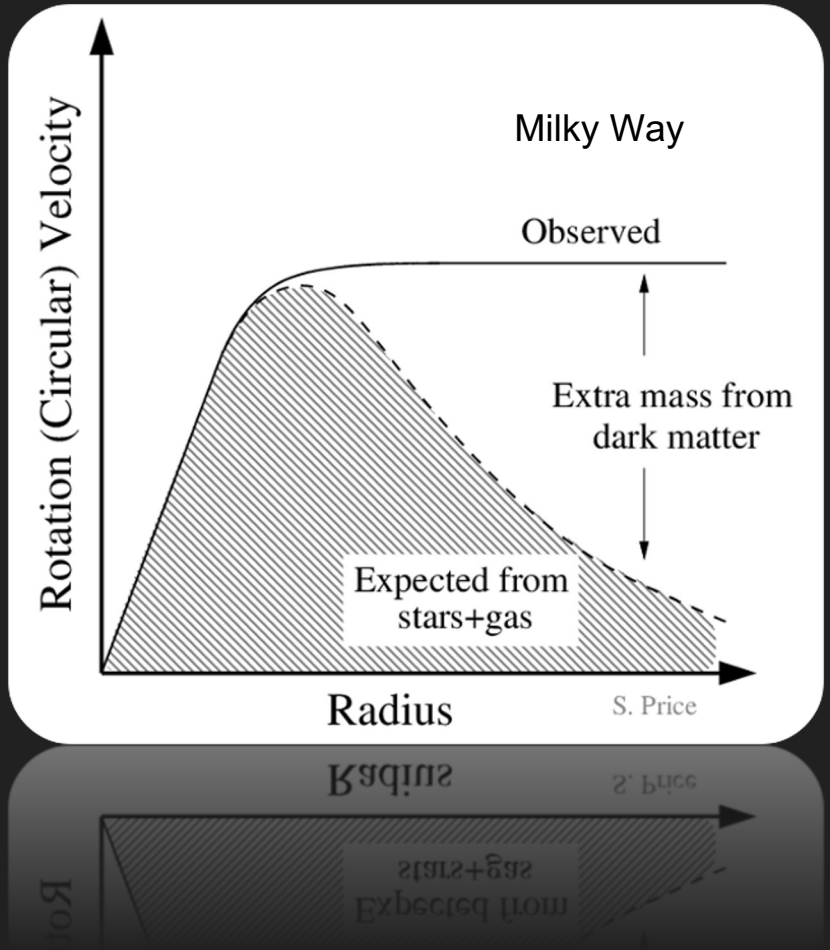
Rubin et a 80)

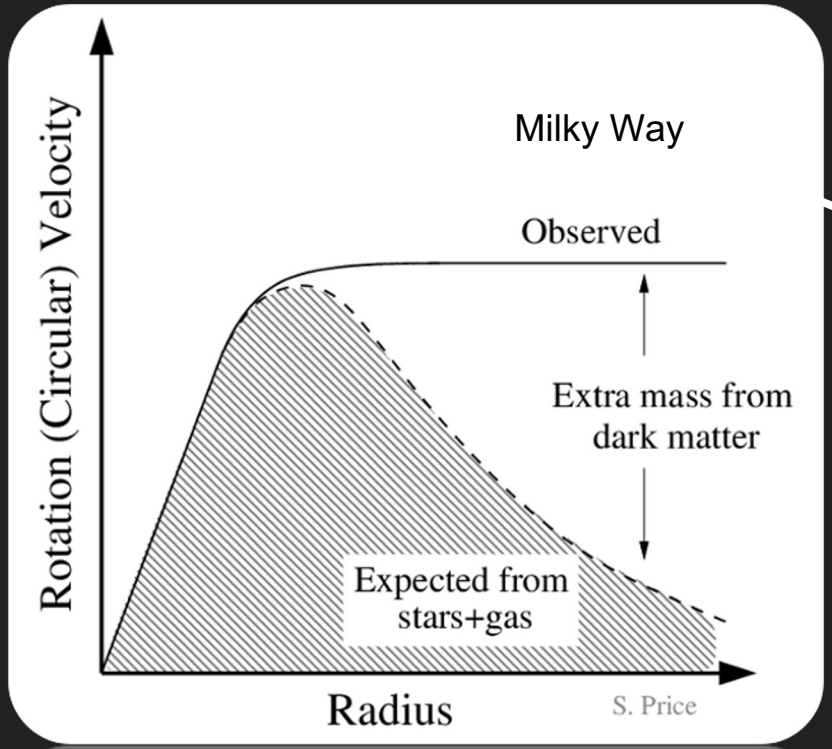
Circular velocity curves

Evidence

Probe

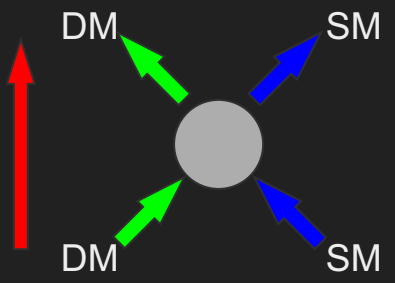
Dark matter

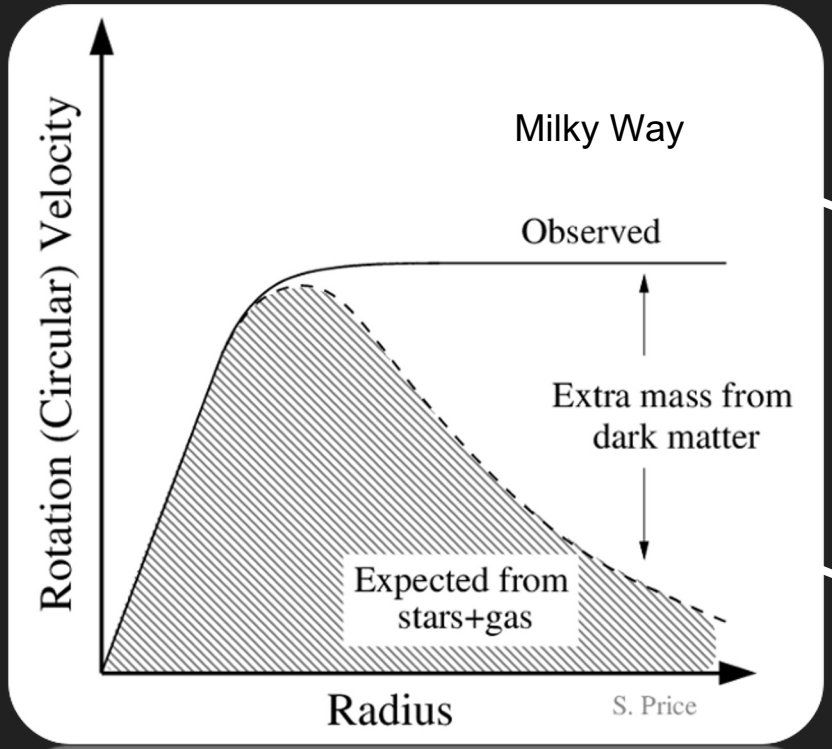

Milky Way
Observed
Extra mass from
dark matter
Expected from
stars+gas
Rotation (Circular) Velocity
Radius
S. Price



Direct detection

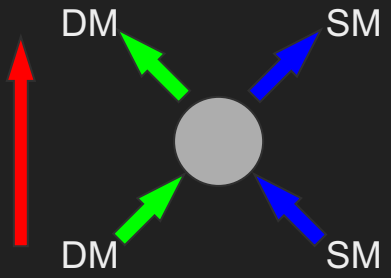
Local dark matter density





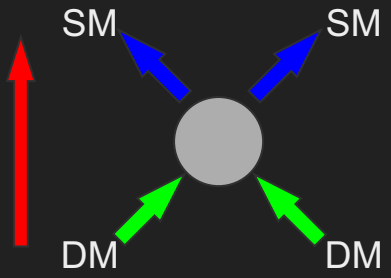
Direct detection

Local dark matter density



Indirect detection

Galactic center *J*-factor
Core vs. Cusp

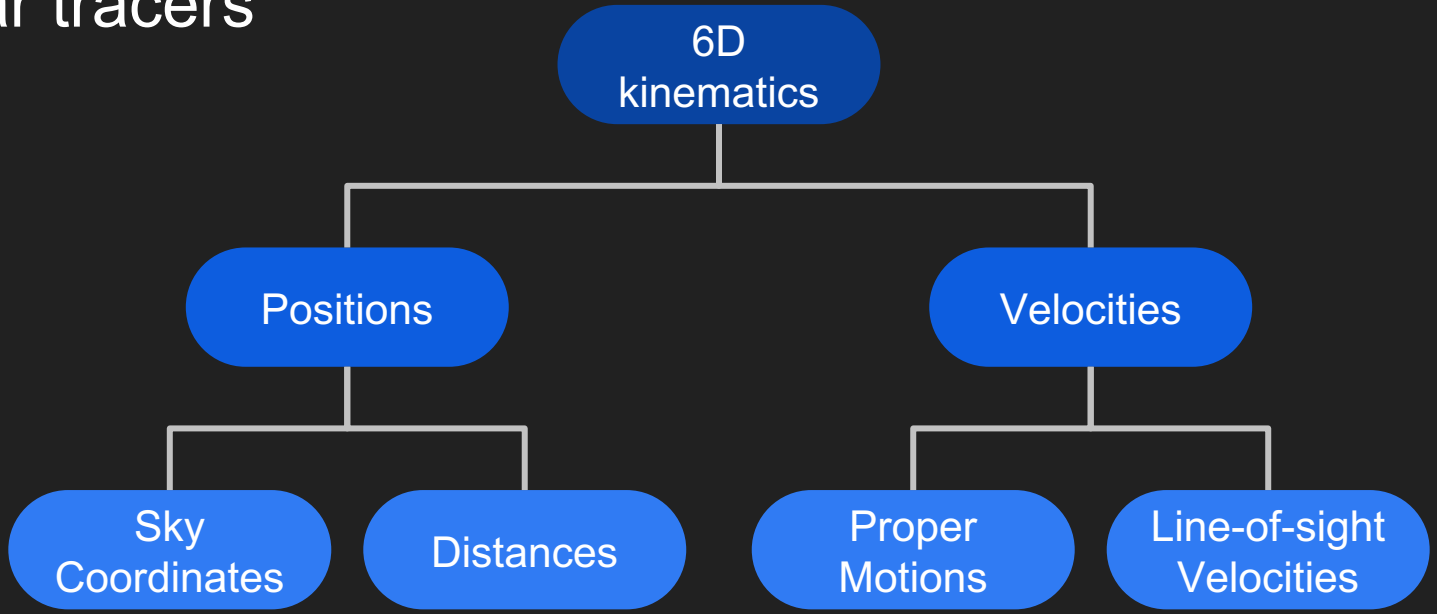


Goal:

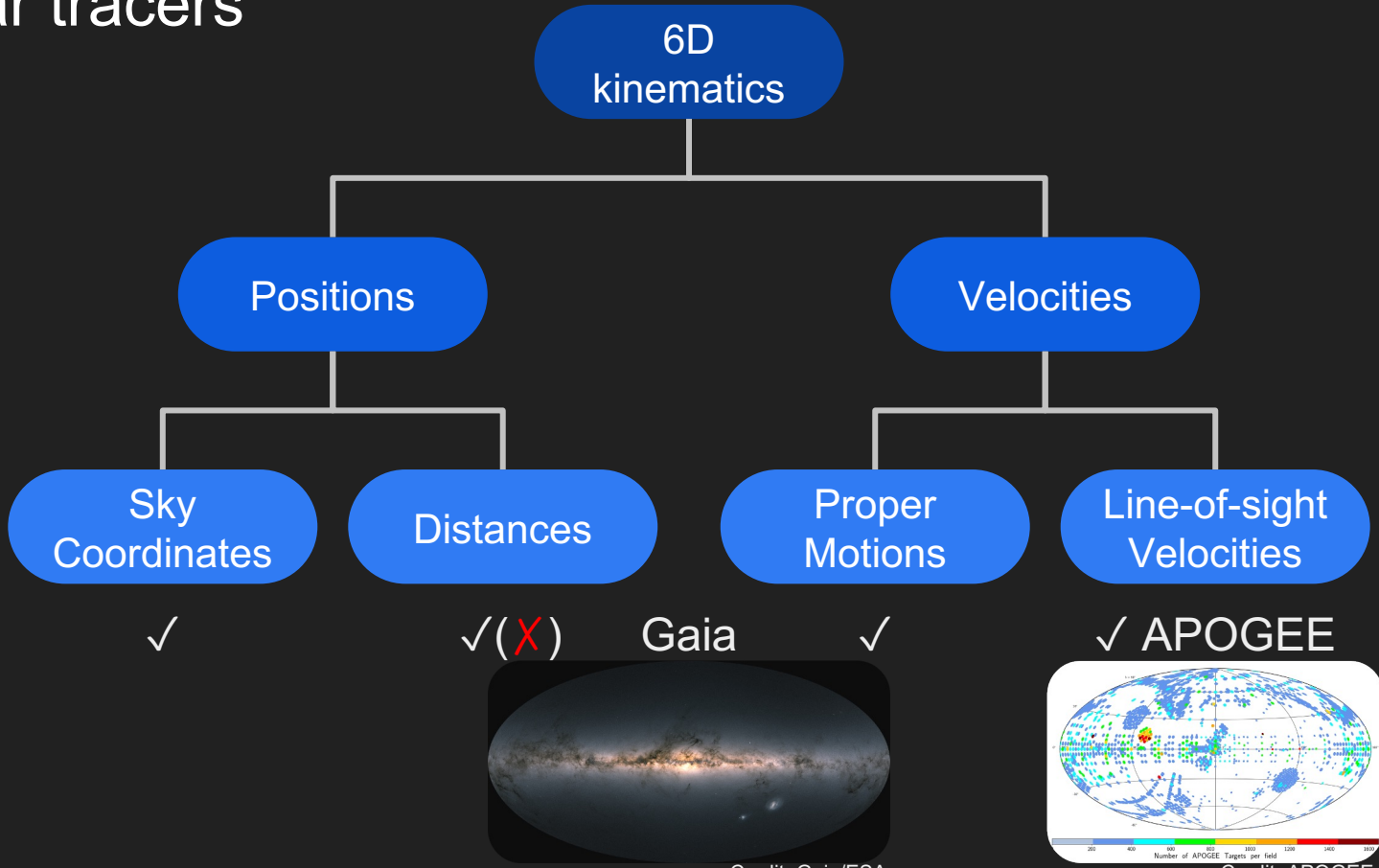
Measure the circular velocity curve for the Milky Way

Infer the dark matter profile

Stellar tracers

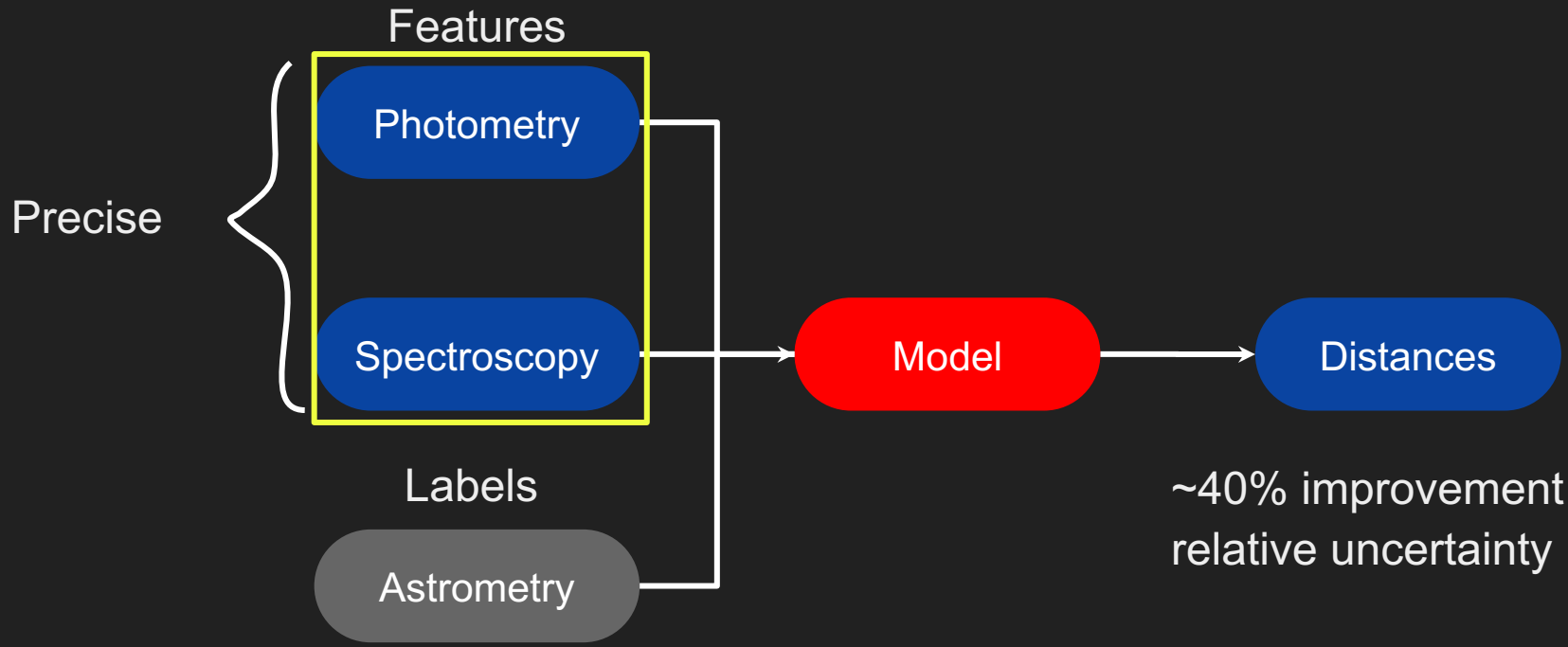


Stellar tracers

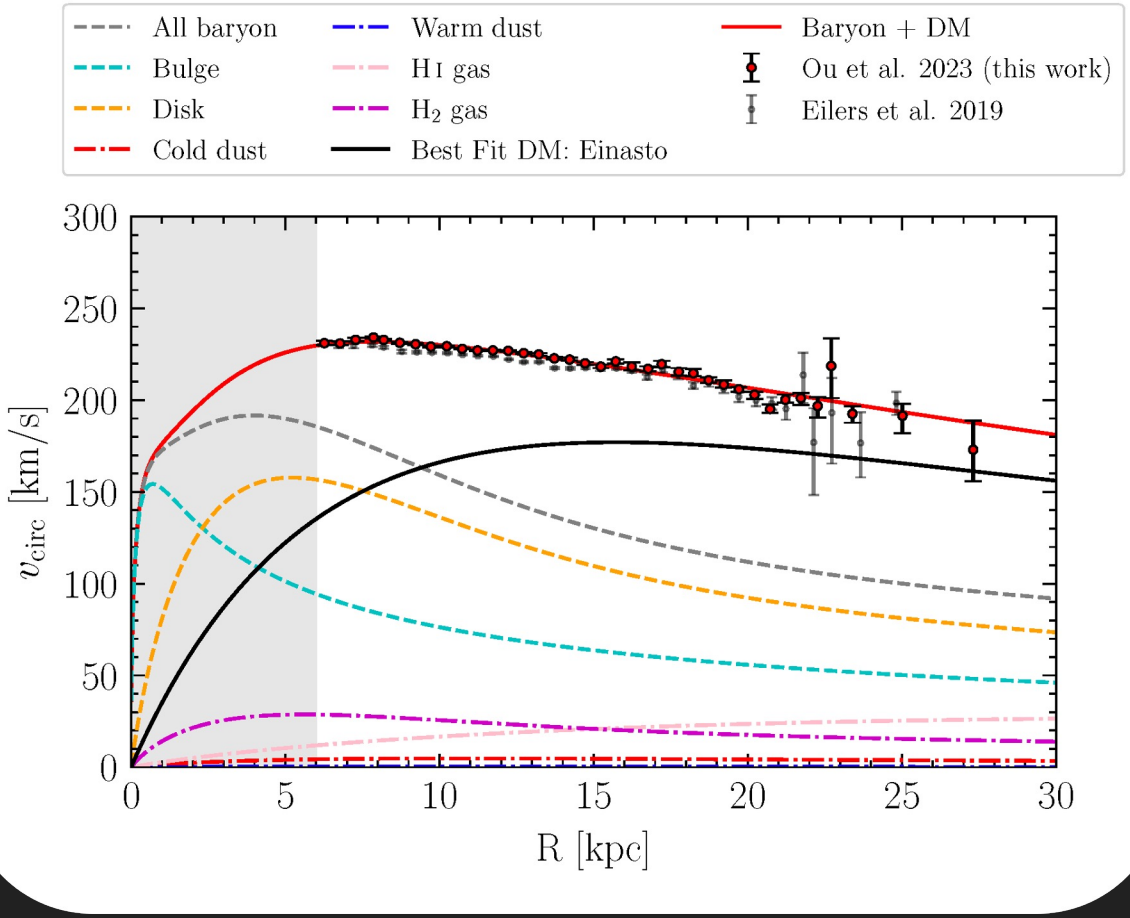


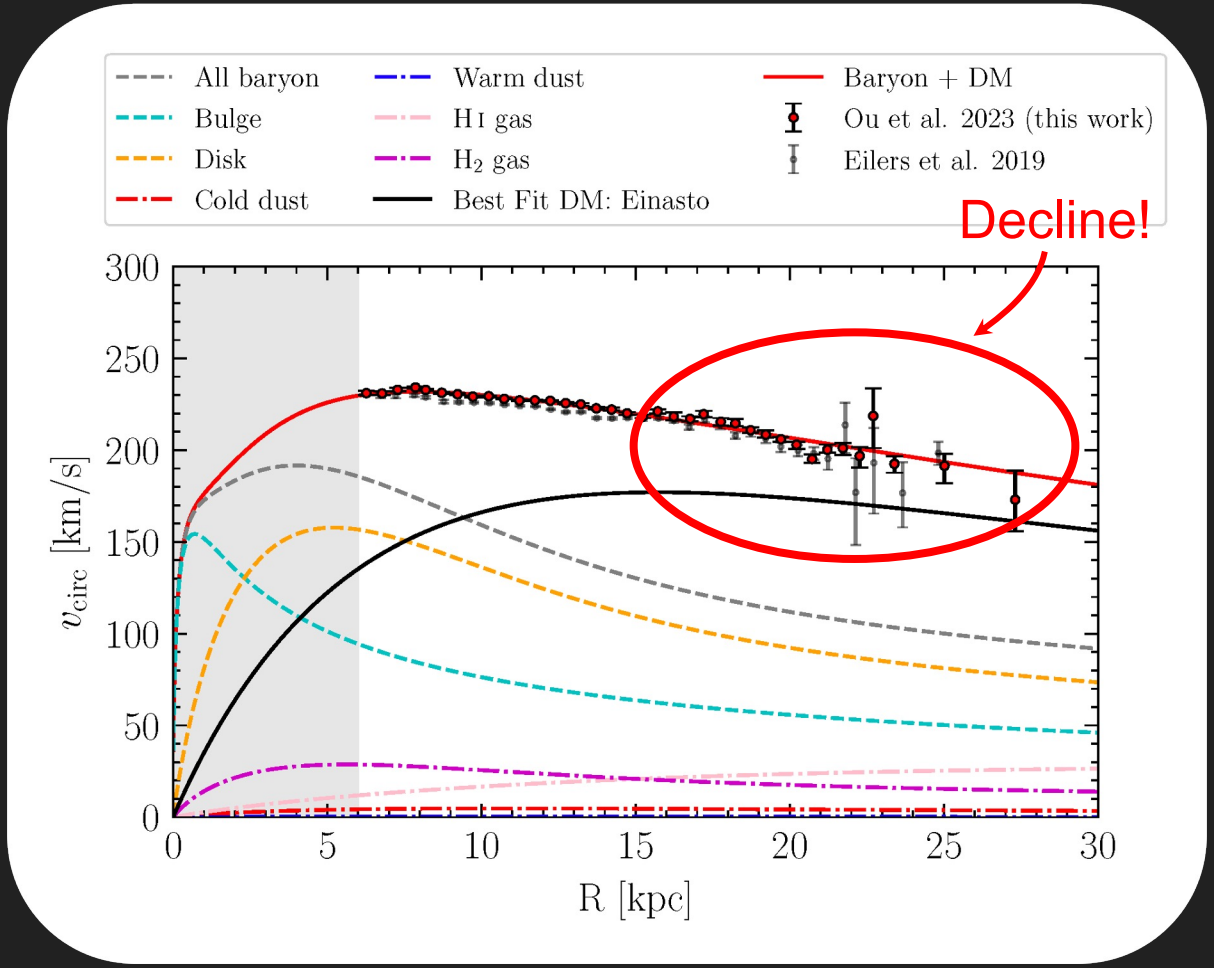
Ou et al. (2024a); arXiv:2303.12838

A data-driven model for more precise distances*



*: parallax


All baryon
Bulge
Disk
Cold dust
Warm dust
H I gas
H_2 gas
Best Fit DM: Einasto
Baryon + DM
Ou et al. 2023 (this work)
Eilers et al. 2019
300
250
200
150
100
50
0
$v_{\rm circ}$ [km/s]
0
5
10
15
20
25
30
R [kpc]


All baryon
Bulge
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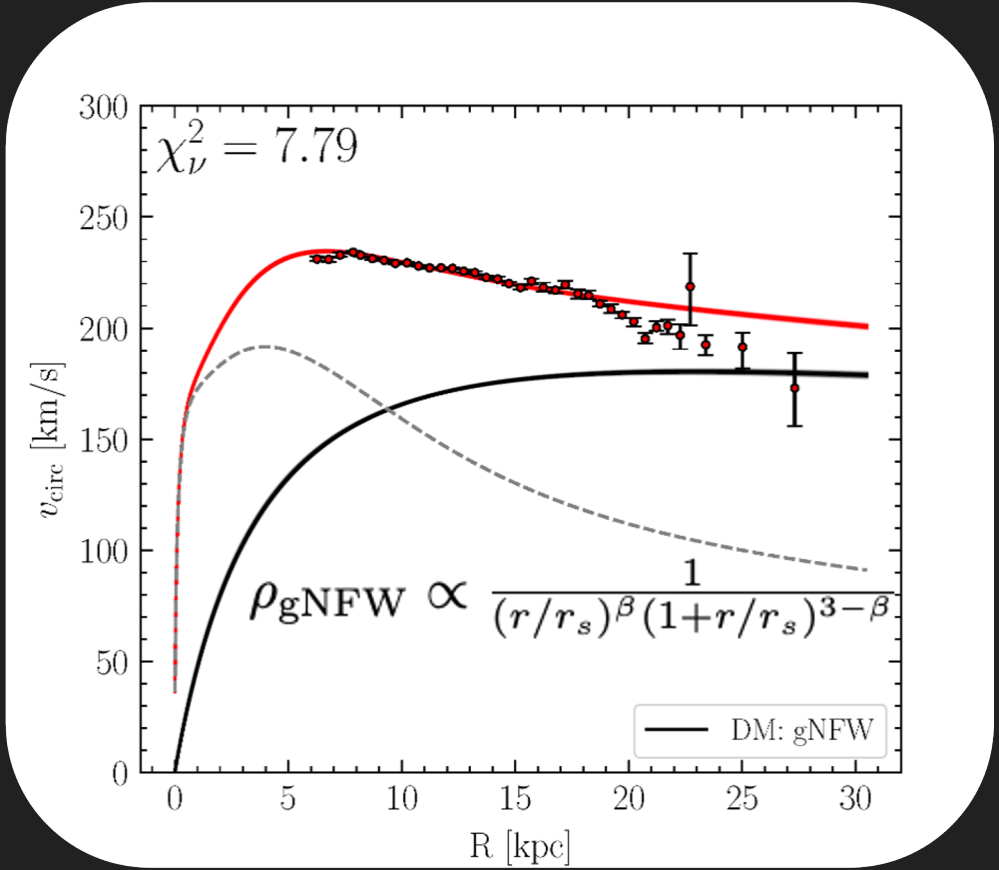
H I gas
H_2 gas
Best Fit DM: Einasto
Baryon + DM
Ou et al. 2023 (this work)
Eilers et al. 2019
Decline!
$v_{\rm circ}$ [km/s]
R [kpc]
0
50
100
150
200
250
300
0
5
10
15
20
25
30

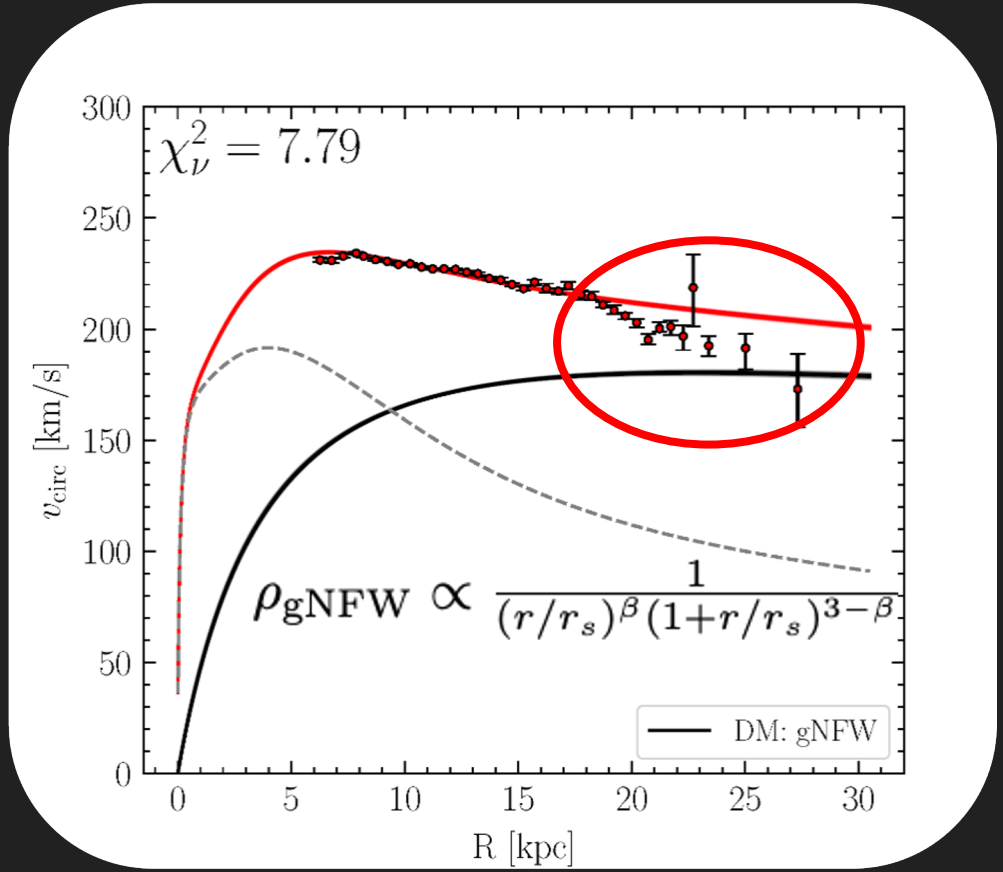
Modeling the curve: generalized NFW vs. Einasto profiles



Ou et al. (2024a); arXiv:2303.12838

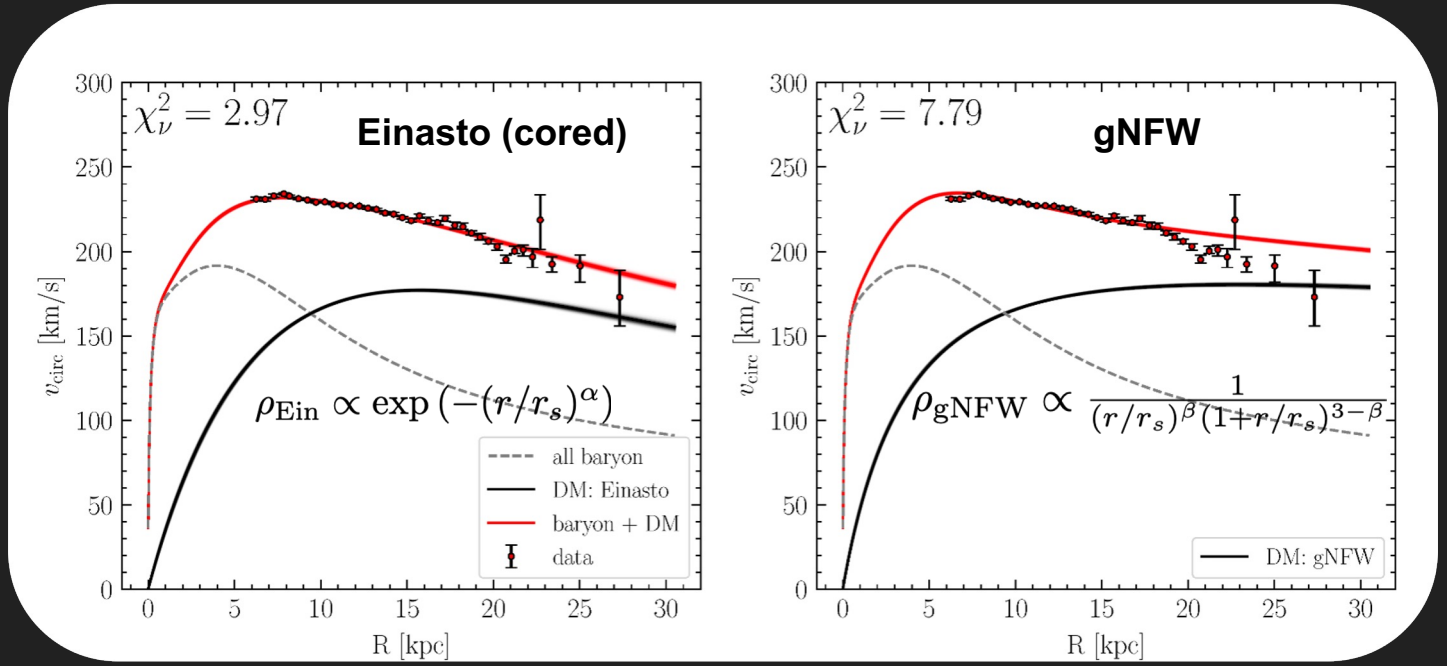
Modeling the curve: generalized NFW vs. Einasto profiles

gNFW profile cannot model the decline



Ou et al. (2024a); arXiv:2303.12838

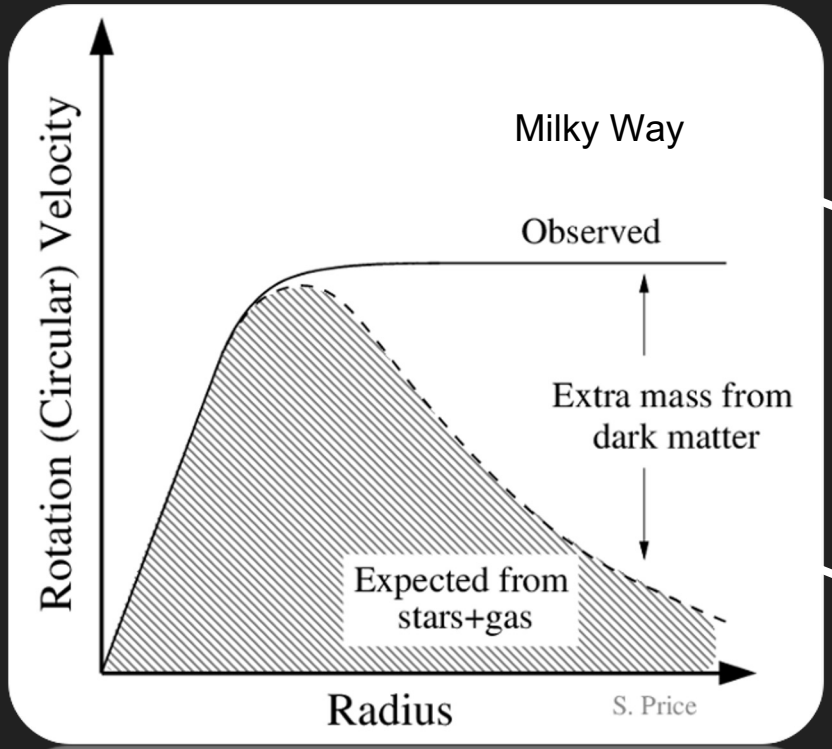
Modeling the curve: Einasto vs. generalized NFW profiles



Exponential drop-off in dark matter density outside of R~10 kpc

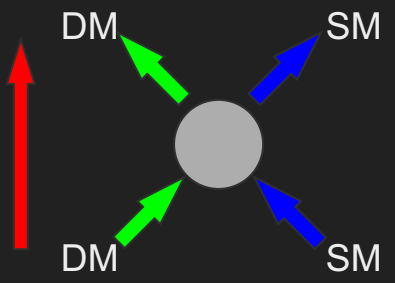
needed to explain the decline*

Ou et al. (2024a); arXiv:2303.12838



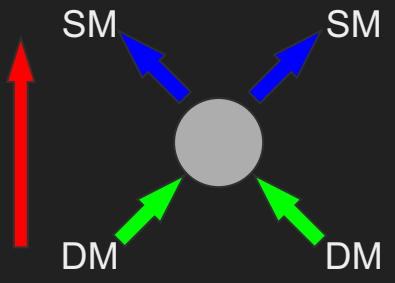
Direct detection

Local dark matter density

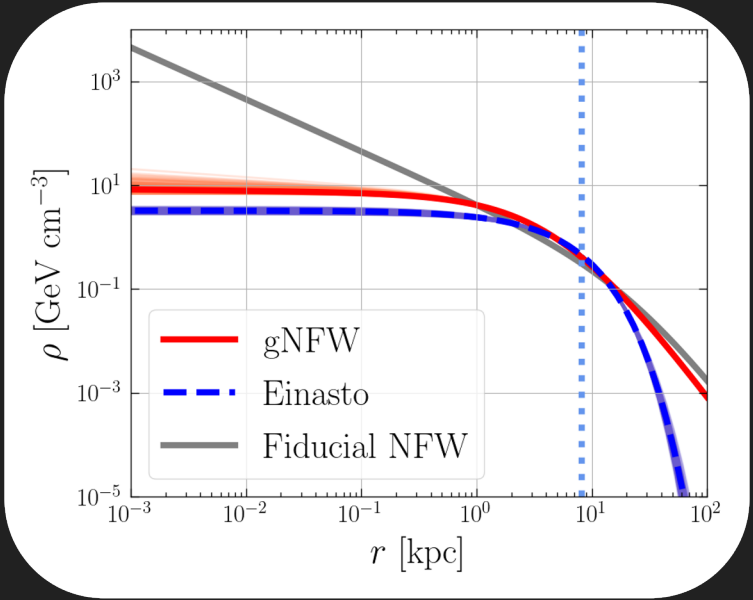


Indirect detection

Galactic center *J*-factor
Core vs. Cusp

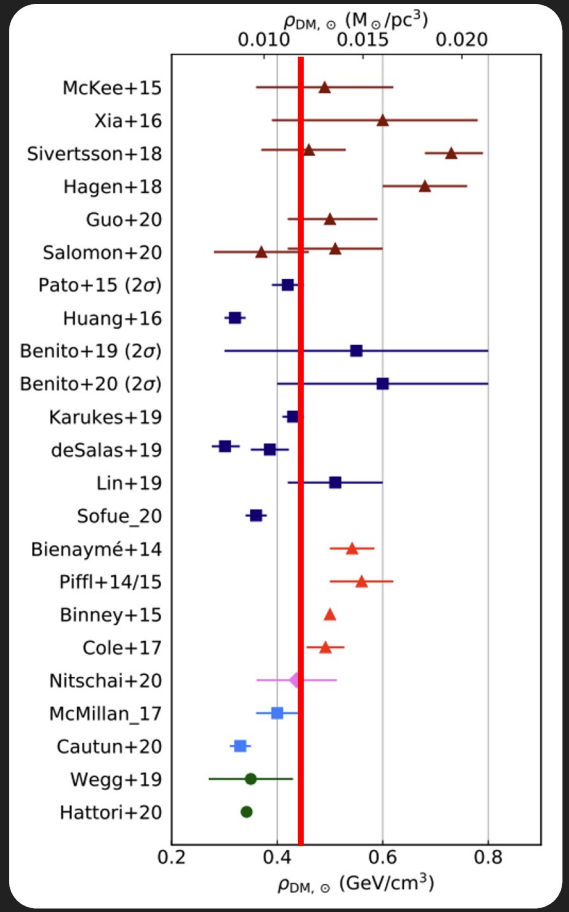


Local dark matter density



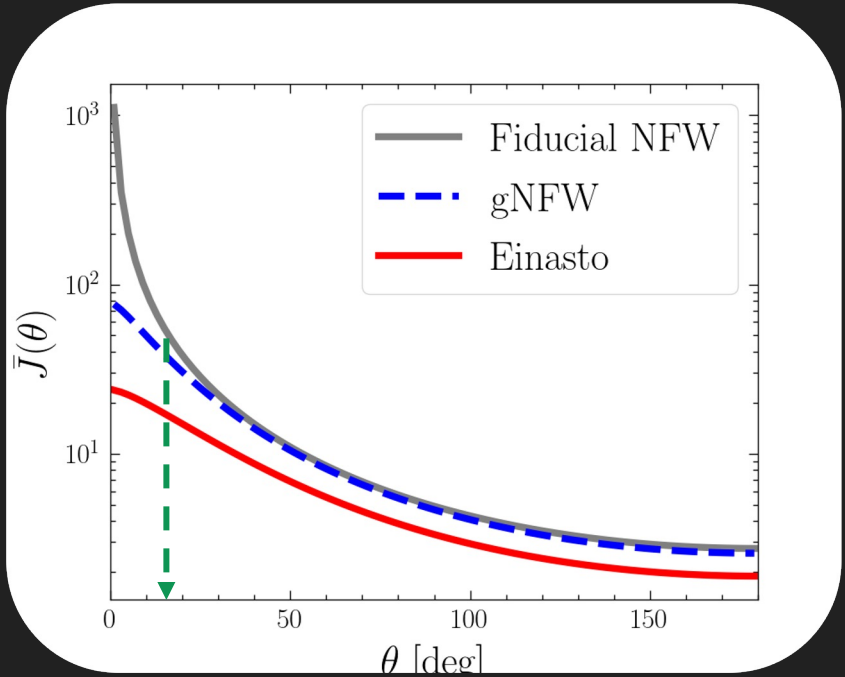
DM density at 8kpc in the MW: 0.45 GeV/cm^3

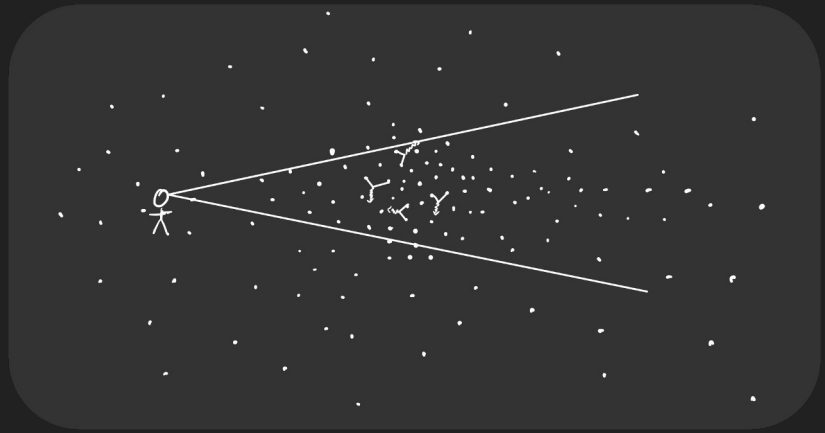
Both gNFW and Einasto results are consistent and also agreeable with literature results



Credit: de Salas & Widmark (2021)

Galactic center *J*-factor



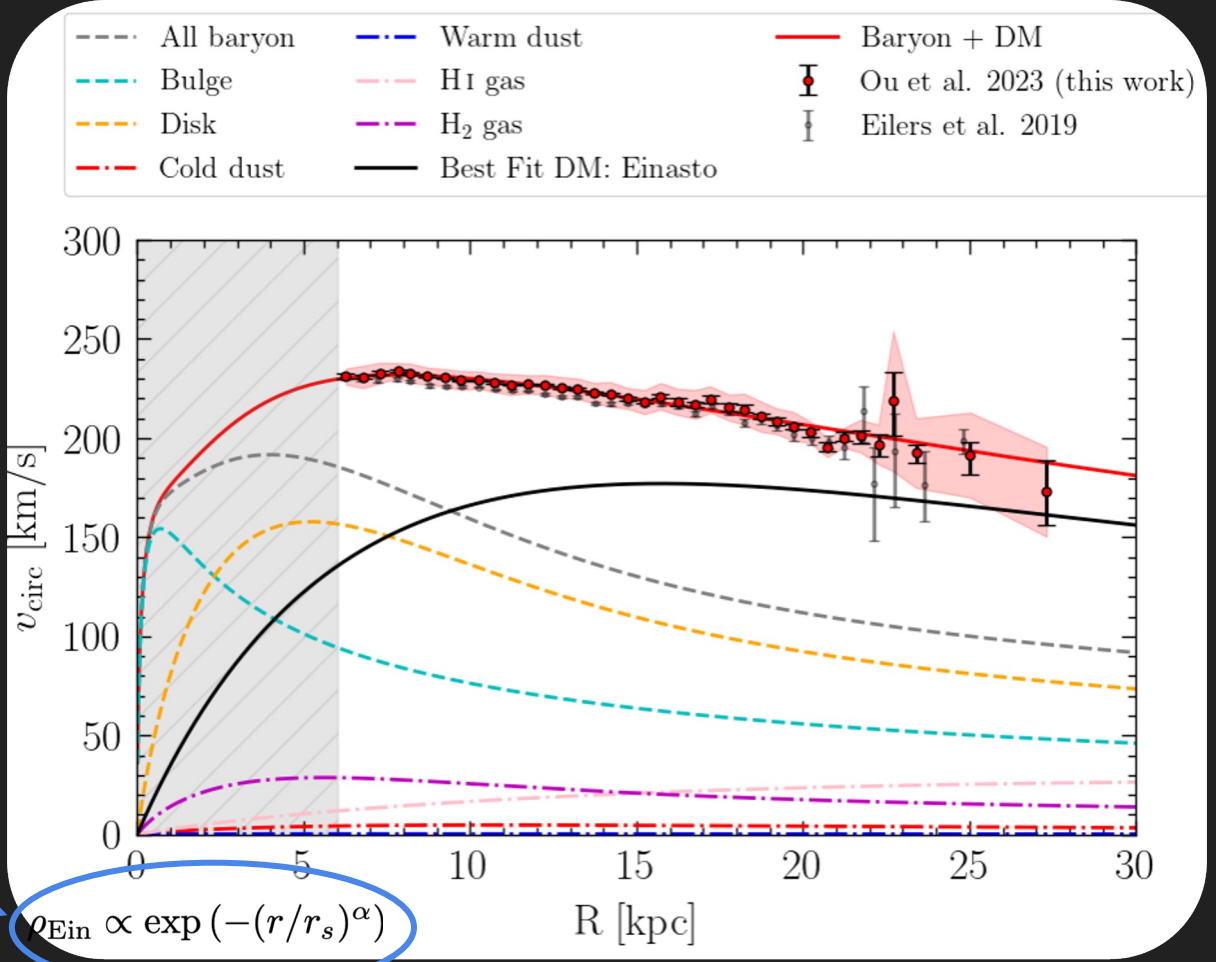


Consistently lower normalized average *J*-factor

$$J = \int \rho^2 ds$$

Integrated *J*-factor at 15° from the Einasto an order of magnitude lower than from the fiducial NFW profile

Caveats

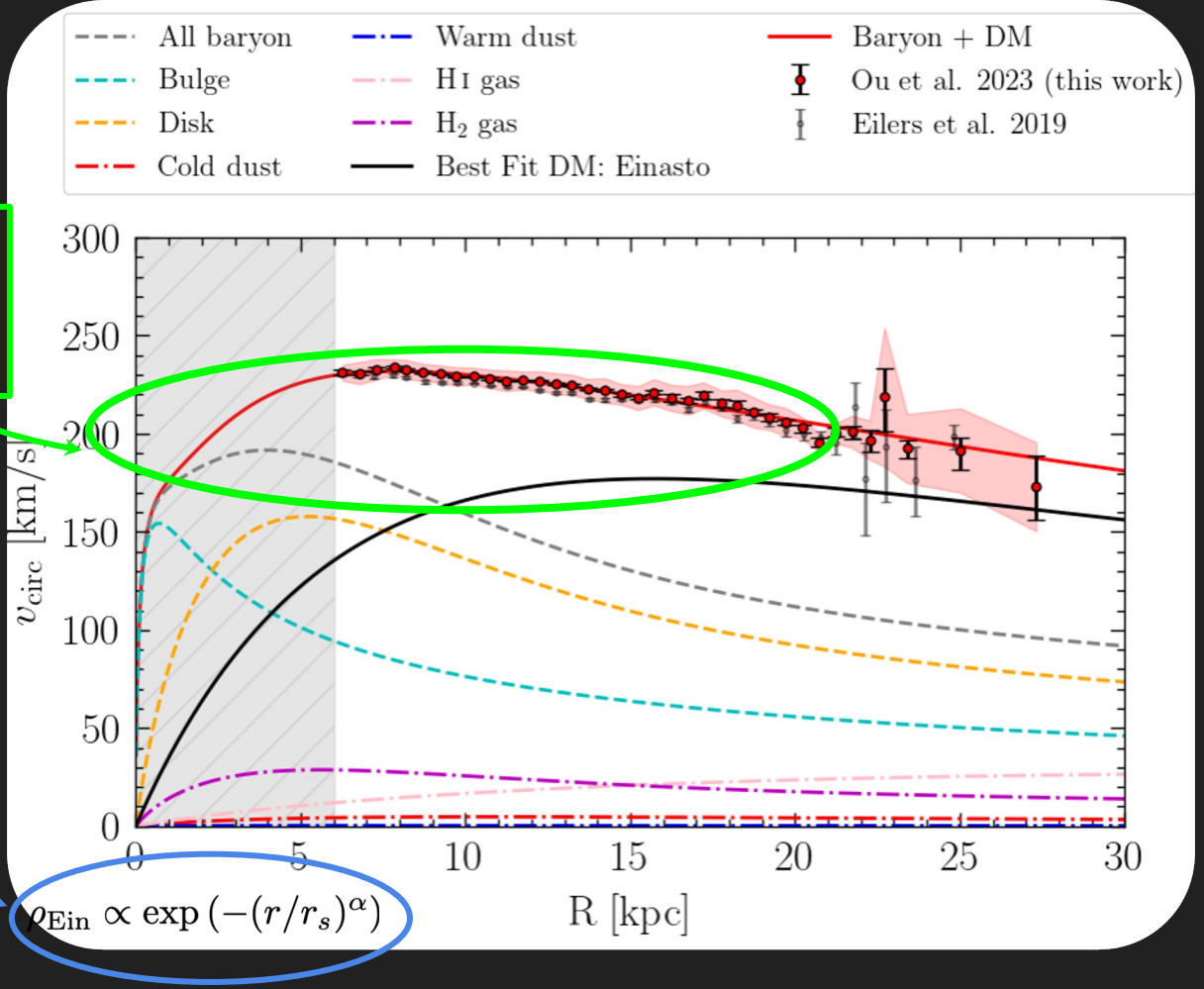


Parametric model

Caveats

Axisymmetry
+
Dynamical
Equilibrium

Parametric
model

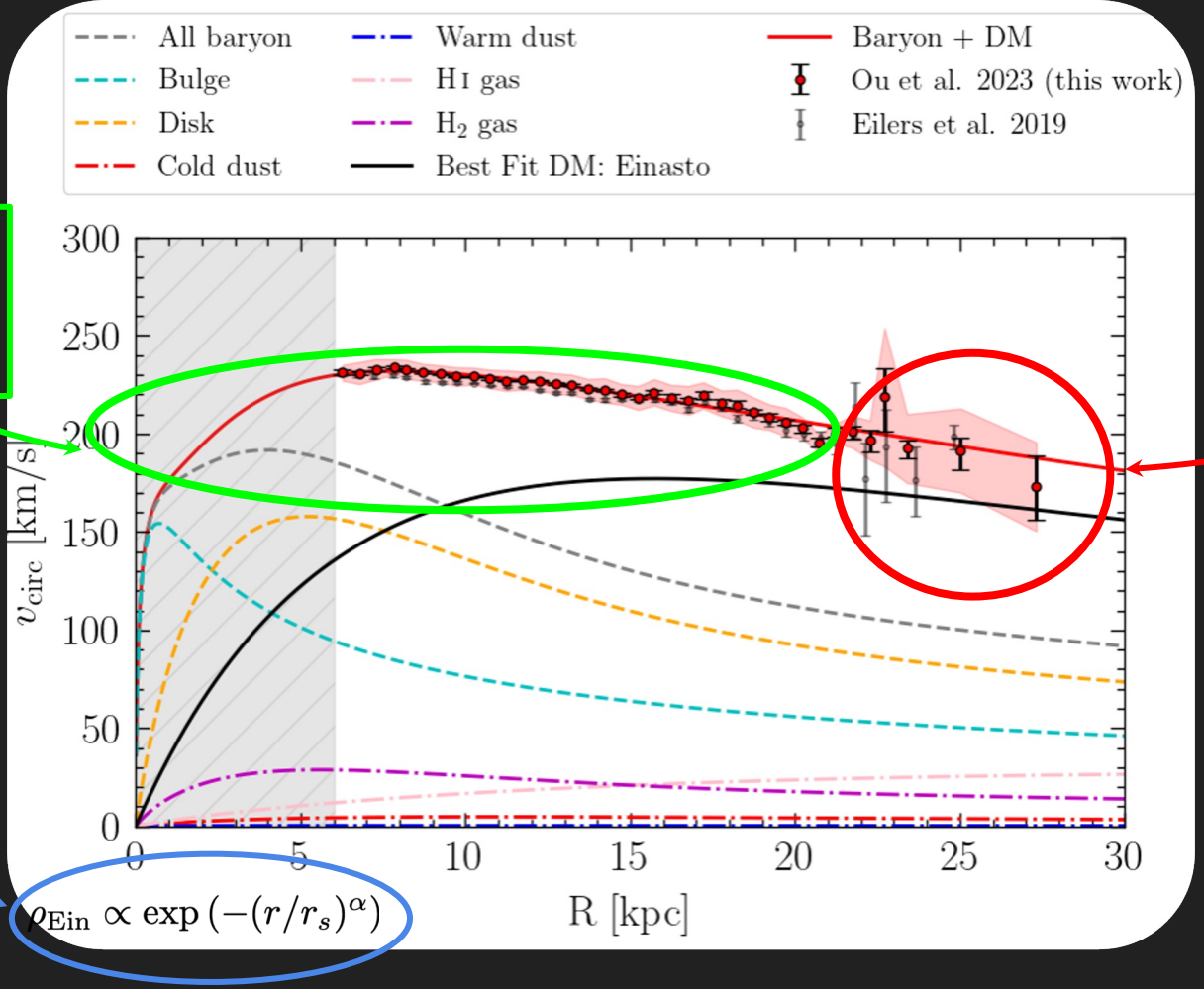


Ou et al. (2024a); arXiv:2303.12838

Caveats

Axisymmetry
+
Dynamical Equilibrium

Parametric model



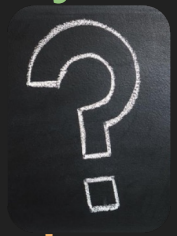
Negligible higher order correction
+
Unbiased stellar population

Ou et al. (2024a); arXiv:2303.12838

Goal:

Measure the circular velocity curve for the Milky Way

(Can you)



Infer the dark matter profile

How can we understand this measurement?

Poses questions on these topics:

Non-axisymmetric potential

Dynamical disequilibrium from recent mergers

Uncertainty in tracer population profile

Underestimated asymmetric drift correction

Observational selection function

Milky Way mass profile

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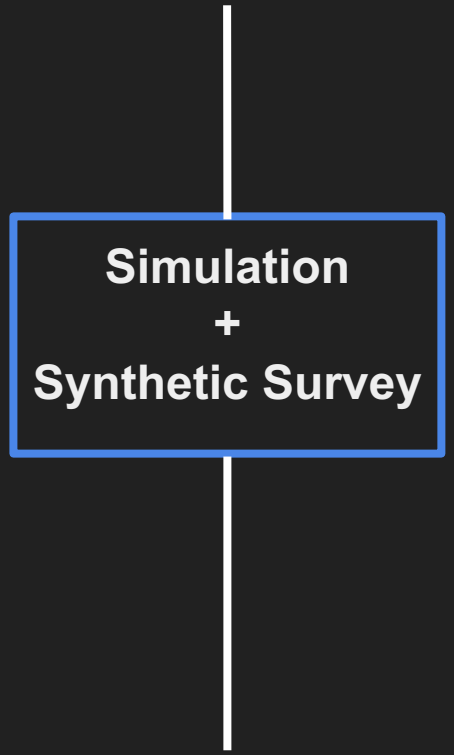
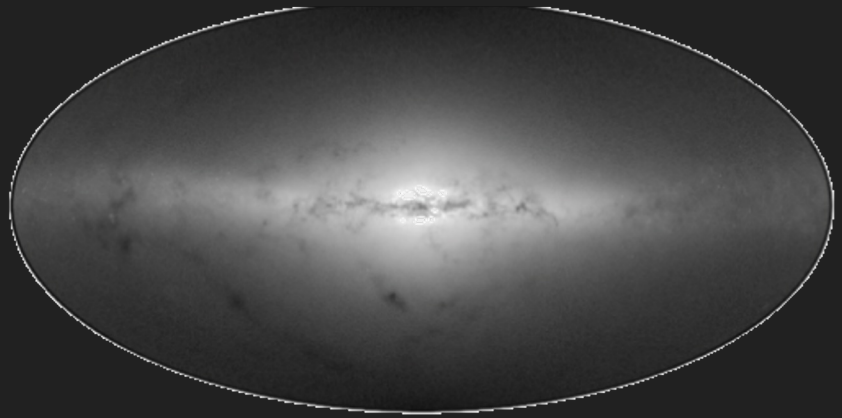


Milky Way mass profile

Test with simulation and synthetic surveys

(Nguyen & Ou et al. 2024)



Test the robustness of the same method

From stellar sample selection to Jean's equation calculation

Compare with underlying truth from the simulation

arXiv:2306.16475; http://ananke.hub.yt/; https://github.com/trivnguyen/ananke_dr3; https://github.com/athob/py-ananke;

Test with simulation and synthetic surveys

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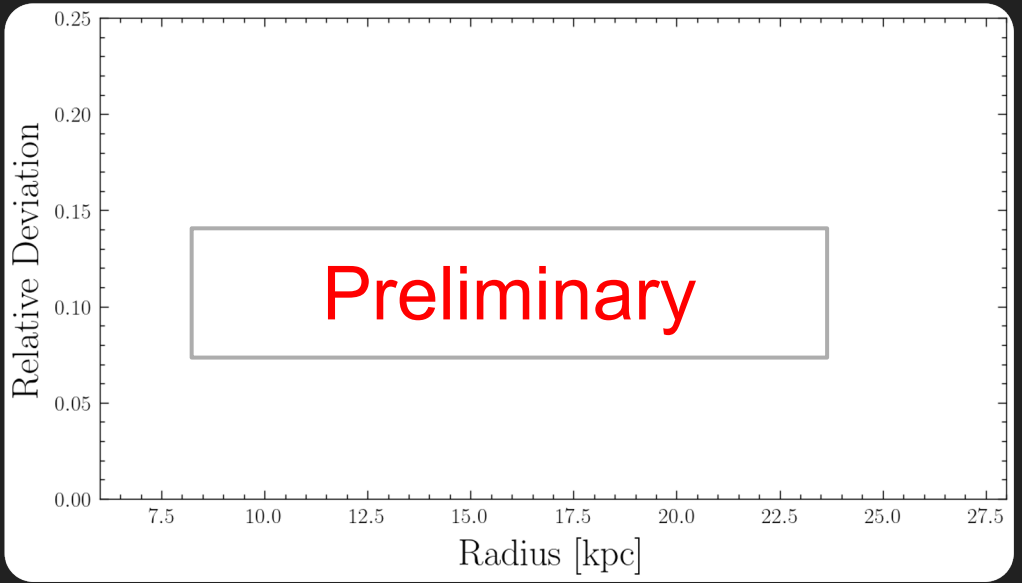
Uncertainty in tracer population profile

Underestimated asymmetric drift correction

Observational selection function



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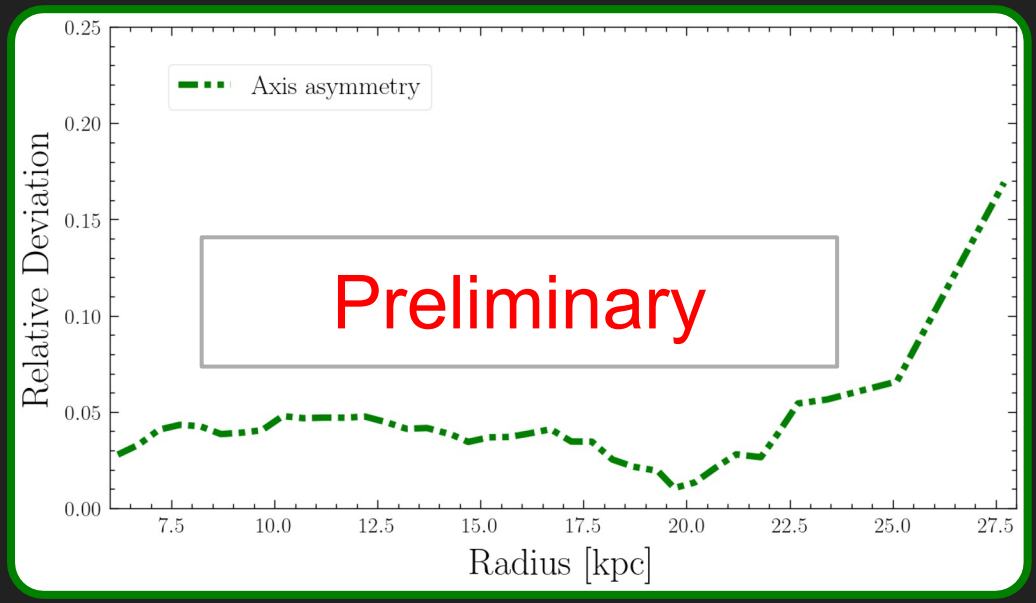

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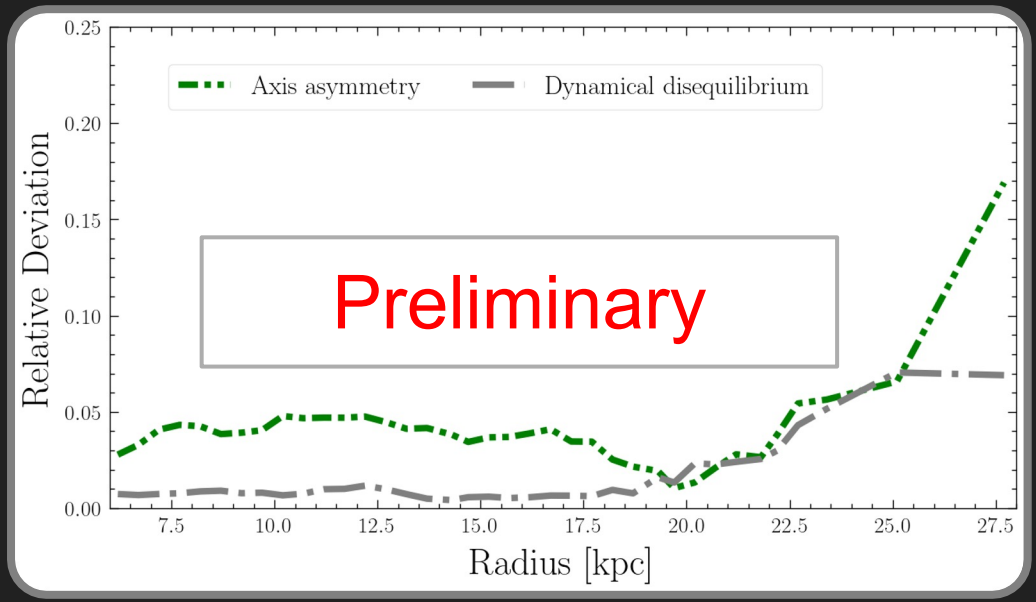

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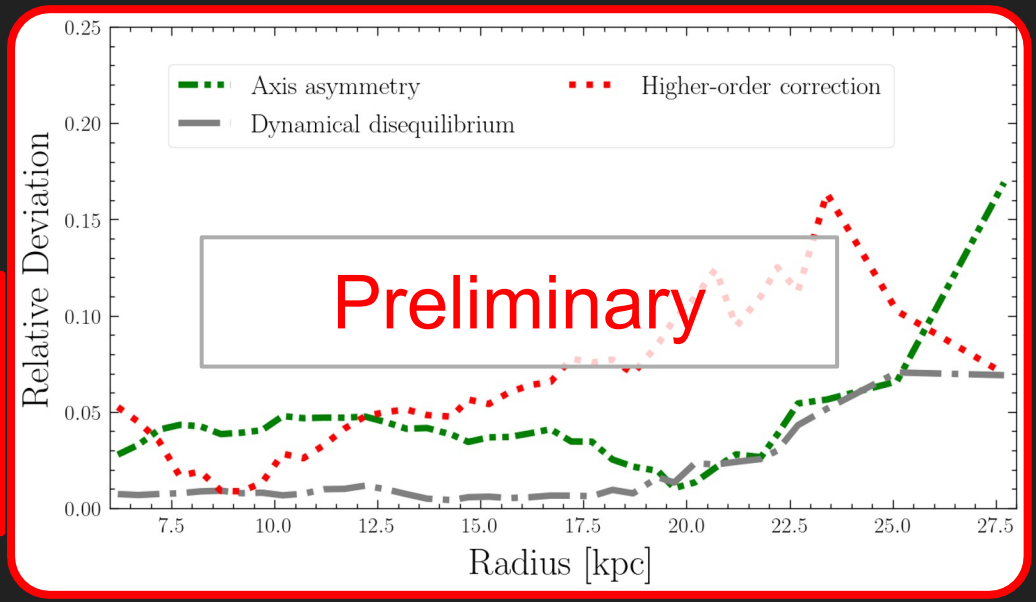

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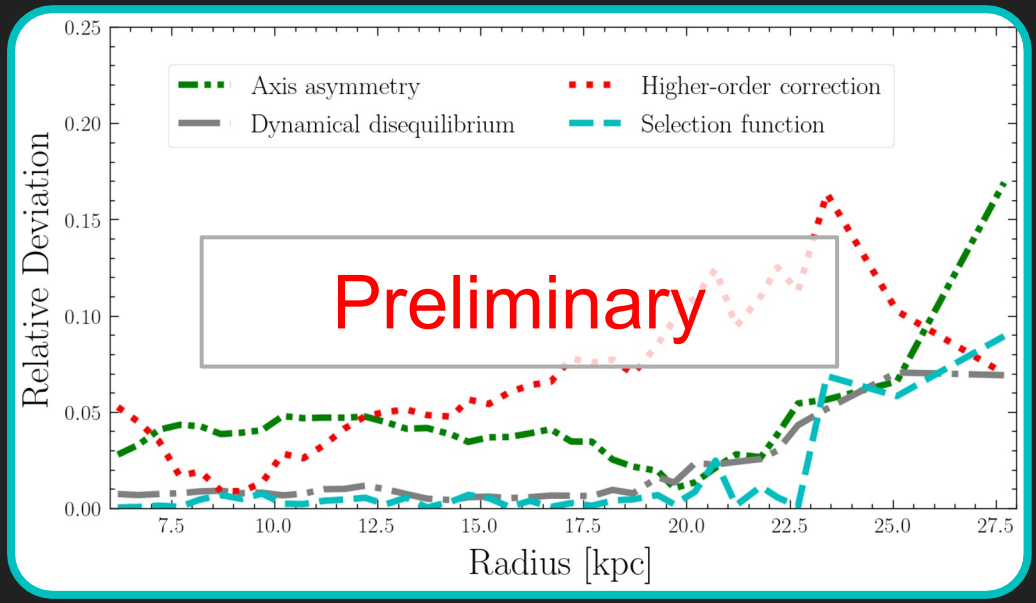

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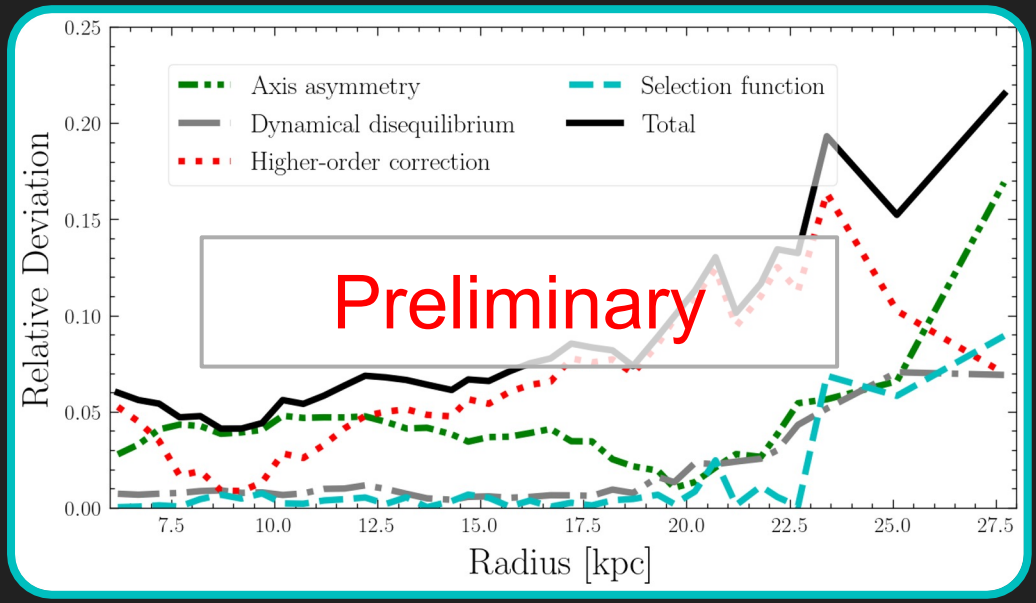
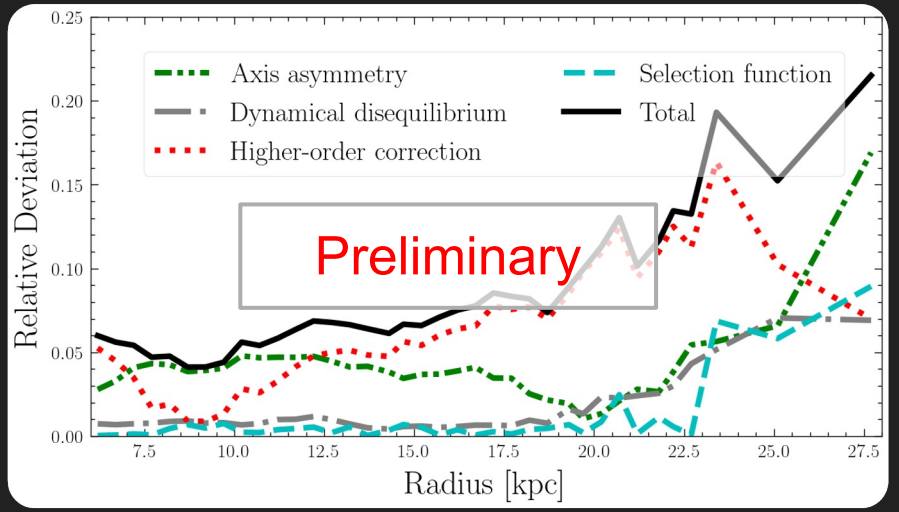
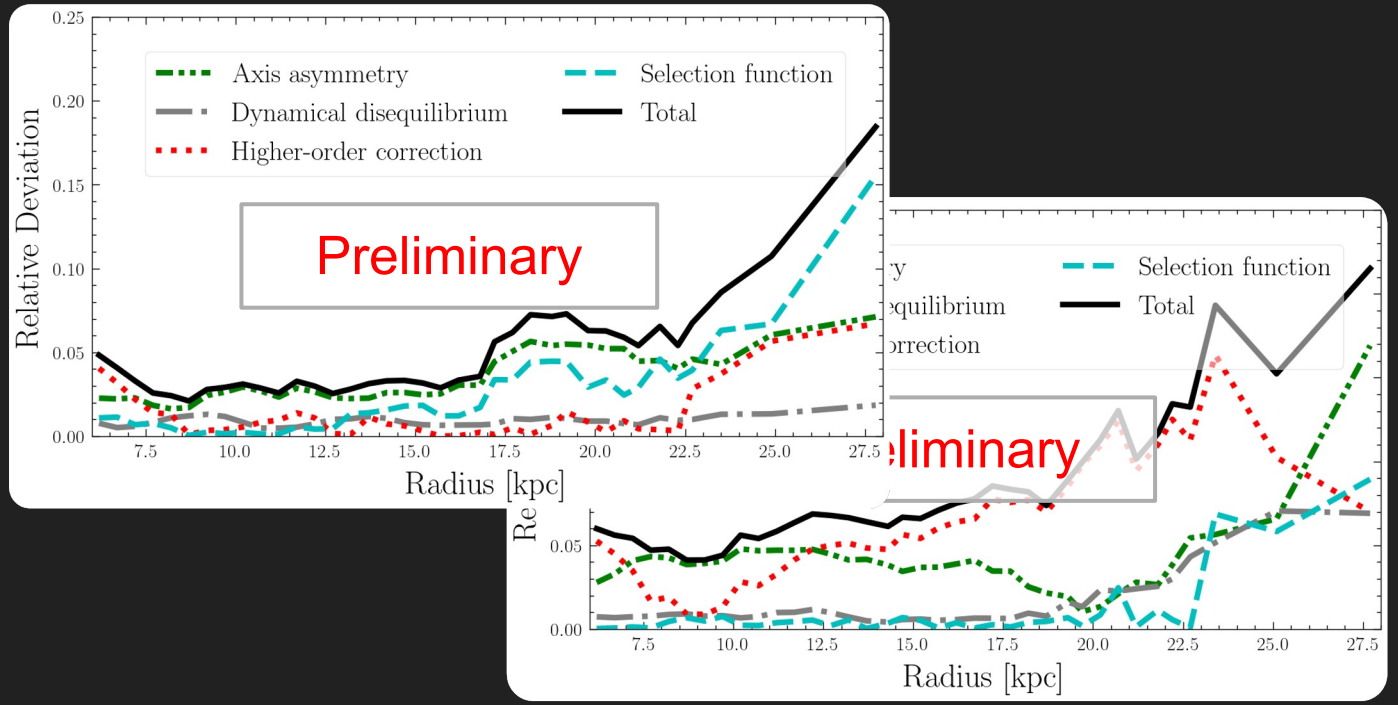


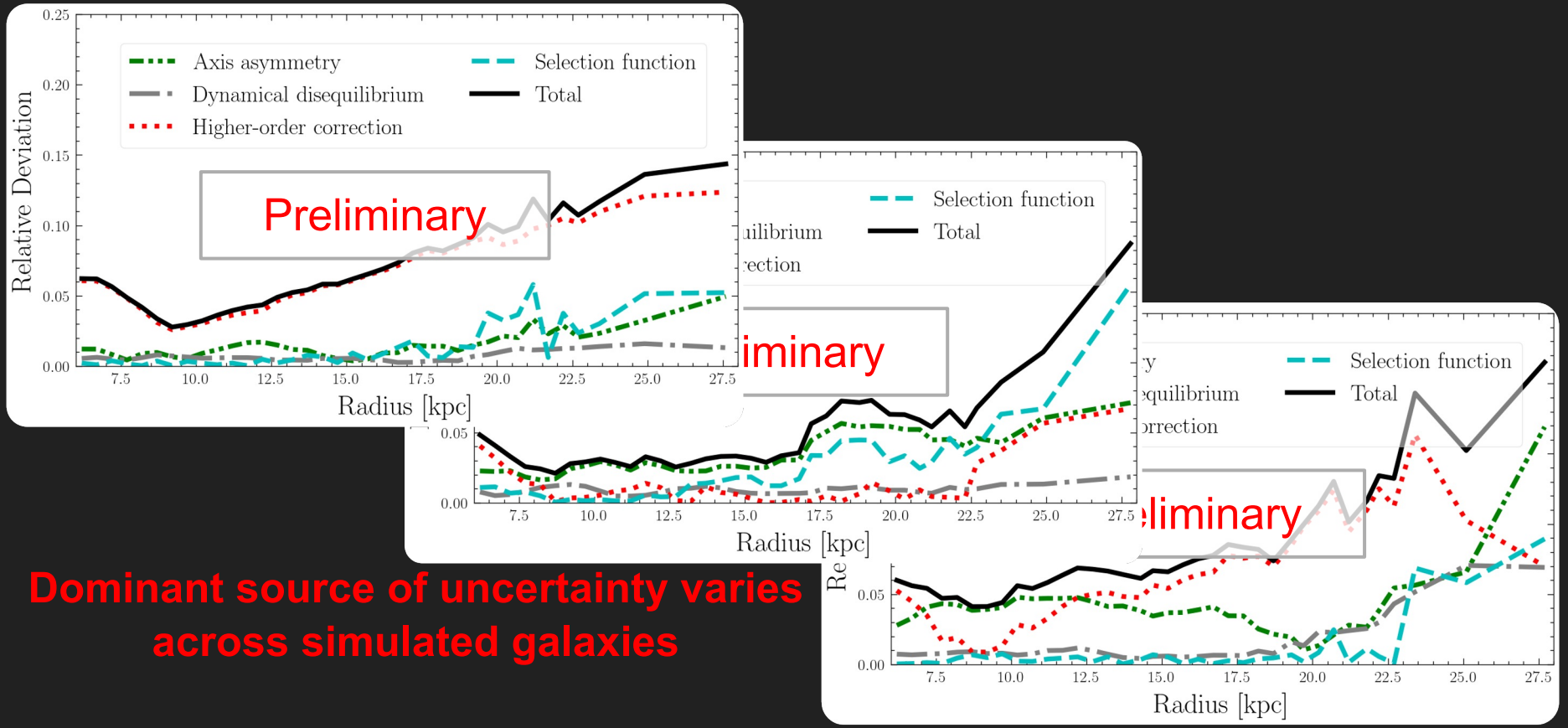
Test with simulation and synthetic surveys: summary



Test with simulation and synthetic surveys: summary

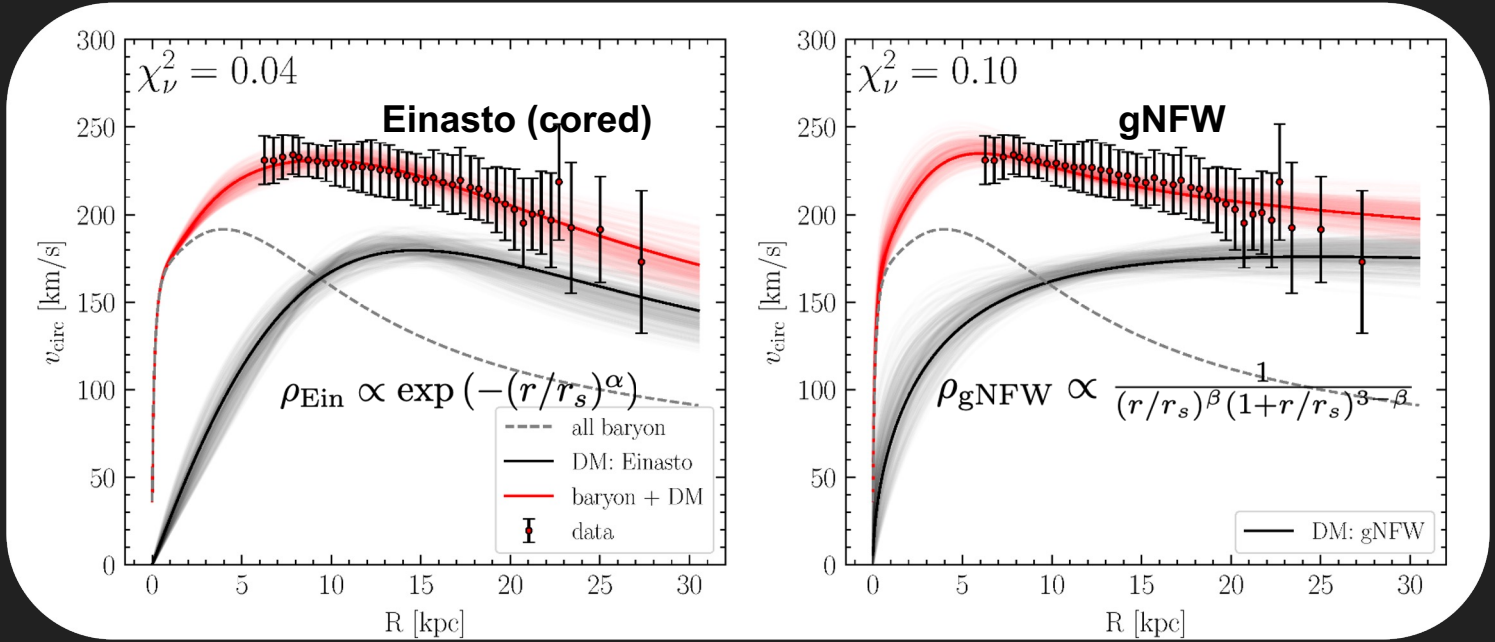


Test with simulation and synthetic surveys: summary



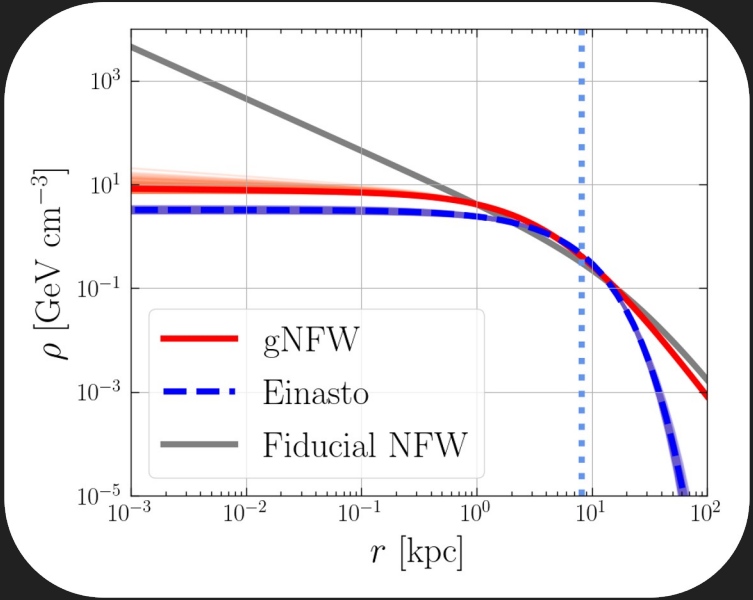
Dominant source of uncertainty varies across simulated galaxies

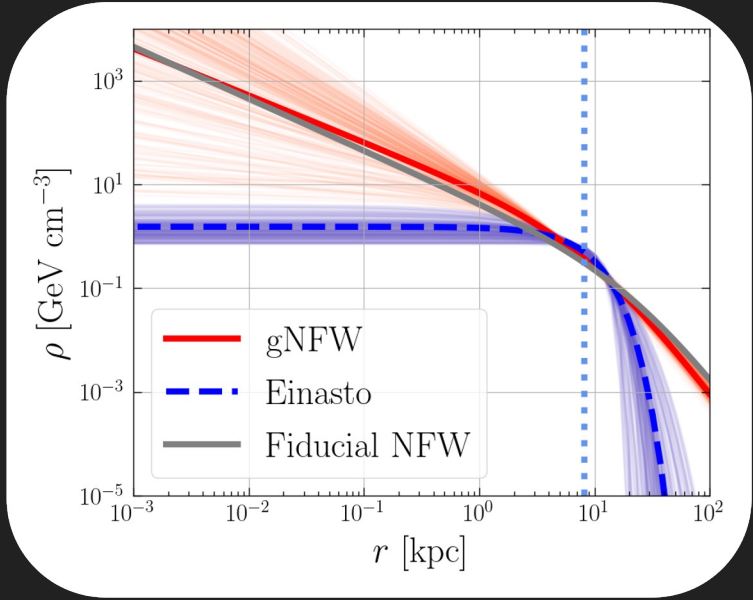
Conservatively increase the uncertainties:



Both Einasto and gNFW fits are plausible.

Dark matter density: before and after





DM density at 8kpc in the MW: 0.37 vs. 0.49 GeV/cm^3

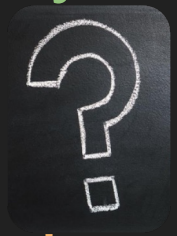
gNFW fit is consistent with the fiducial NFW profile.

Cusp or Cored?

Goal:

Measure the circular velocity curve for the Milky Way

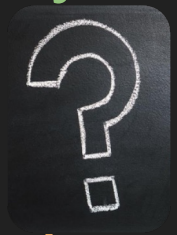
(Can you)



Infer the dark matter profile

Goal:

Measure the circular velocity curve for the Milky Way



Simulation
+
Synthetic Survey

Infer the dark matter profile

Goal:

Measure the circular velocity curve for the Milky Way

Simulation
+
Synthetic Survey

Infer the dark matter profile

Non-parametric
Profiles

Goal:

Measure the circular velocity curve for the Milky Way

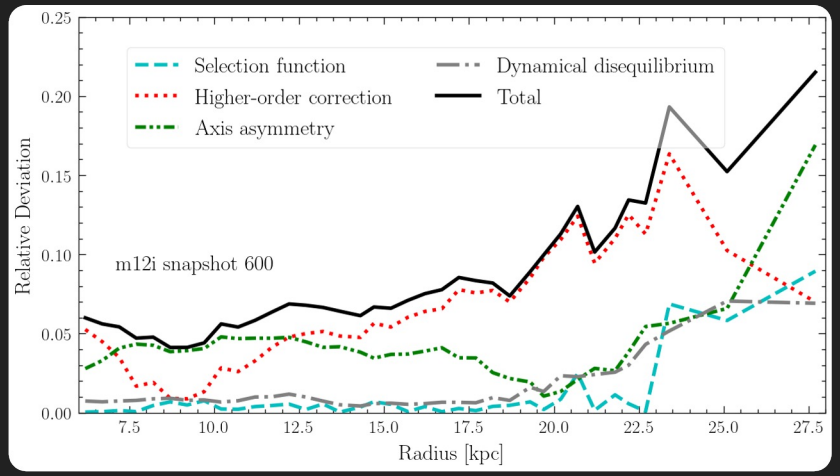
Additional Probes

Simulation + Synthetic Survey

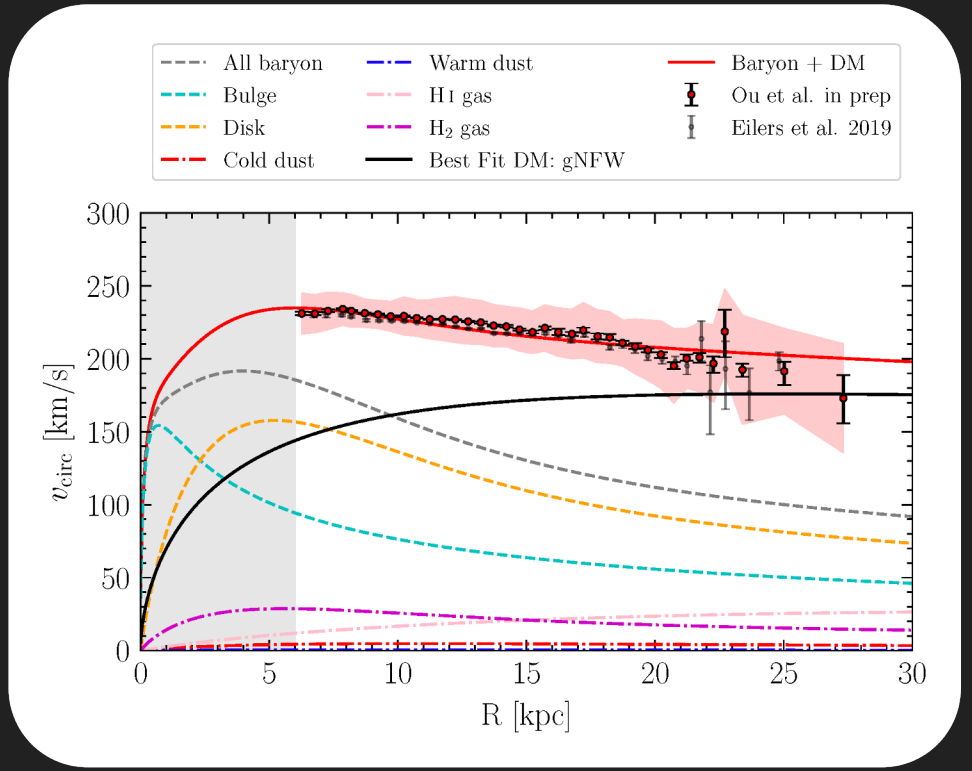
Infer the dark matter profile

Non-parametric Profiles

Summary:

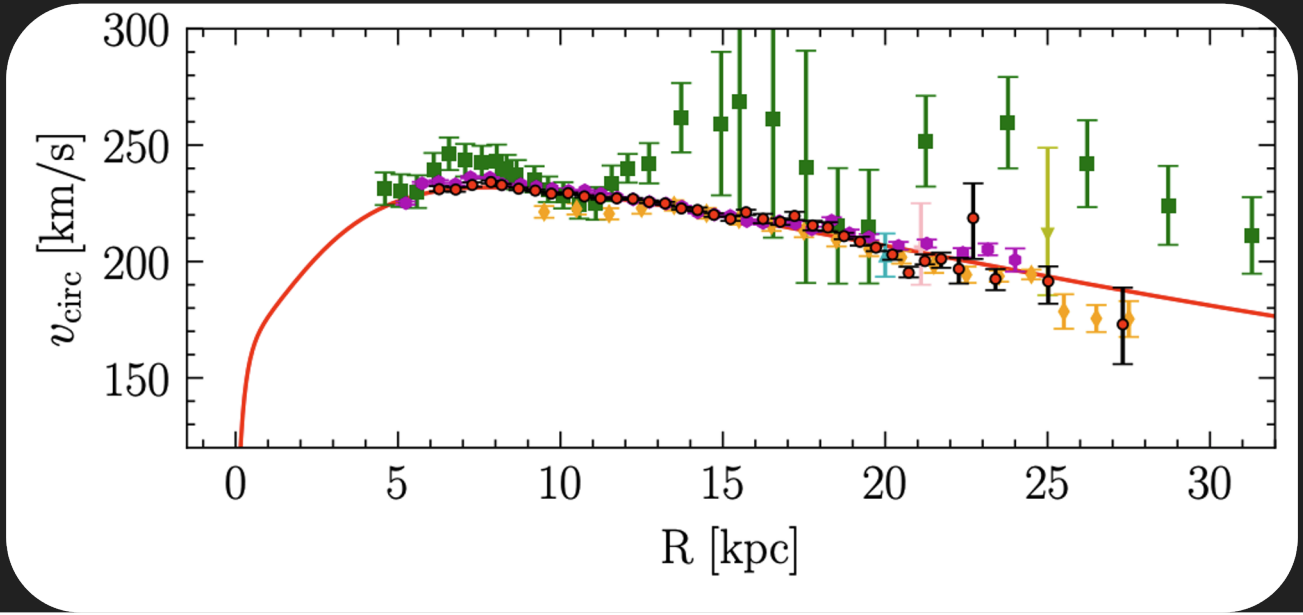


Measuring circular velocity curve alone is not sufficient to understand the nature of dark matter in the Milky Way.

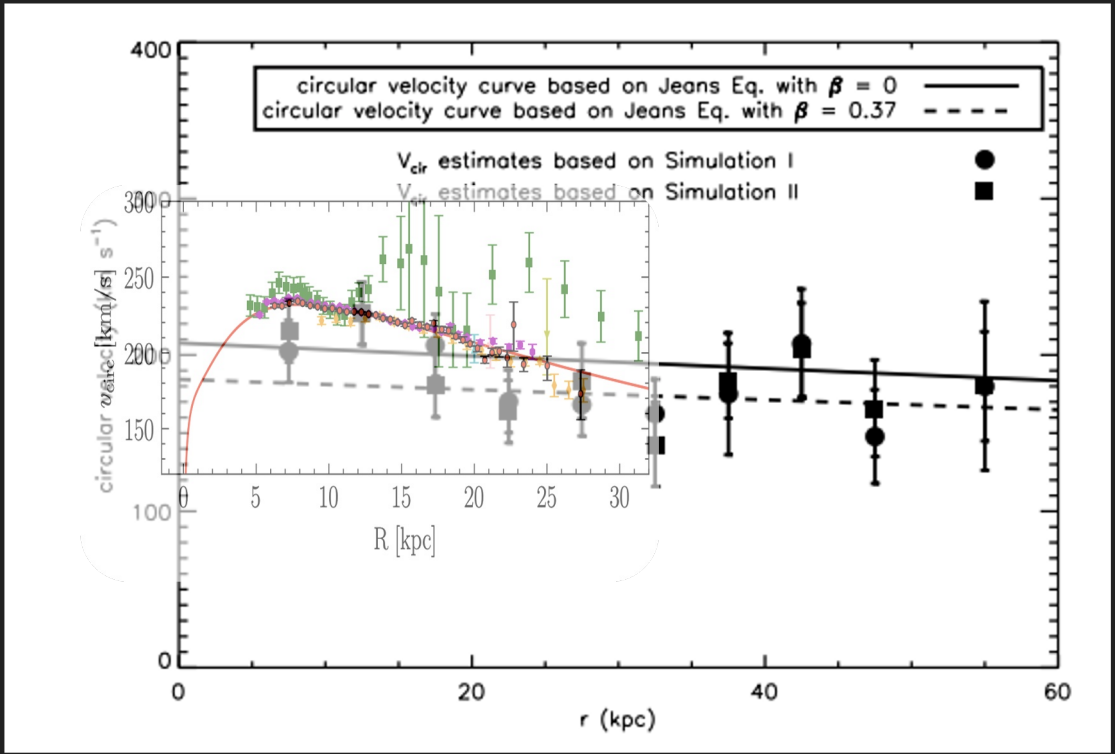


Backup slides

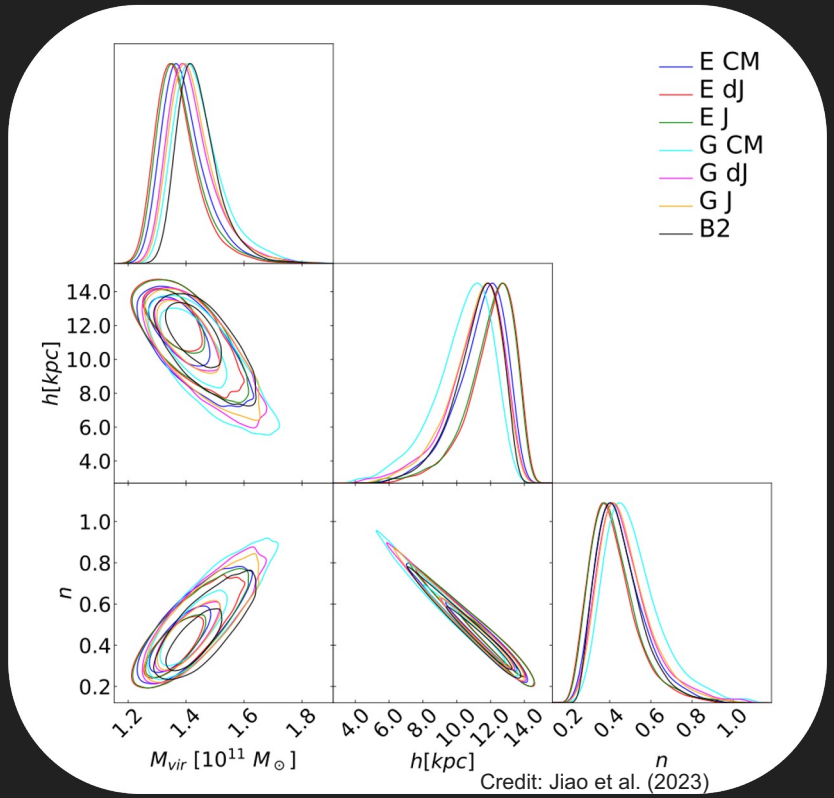
Comparison with the current literature



Comparison


circular velocity curve based on Jeans Eq. with β = 0
circular velocity curve based on Jeans Eq. with β = 0.37
V_cir estimates based on Simulation I
V_cir estimates based on Simulation II
circular velocity [km/s] s⁻¹
r (kpc)
R [kpc]
0
20
40
60
100
150
200
250
300
400
5
10
15
20
25
30

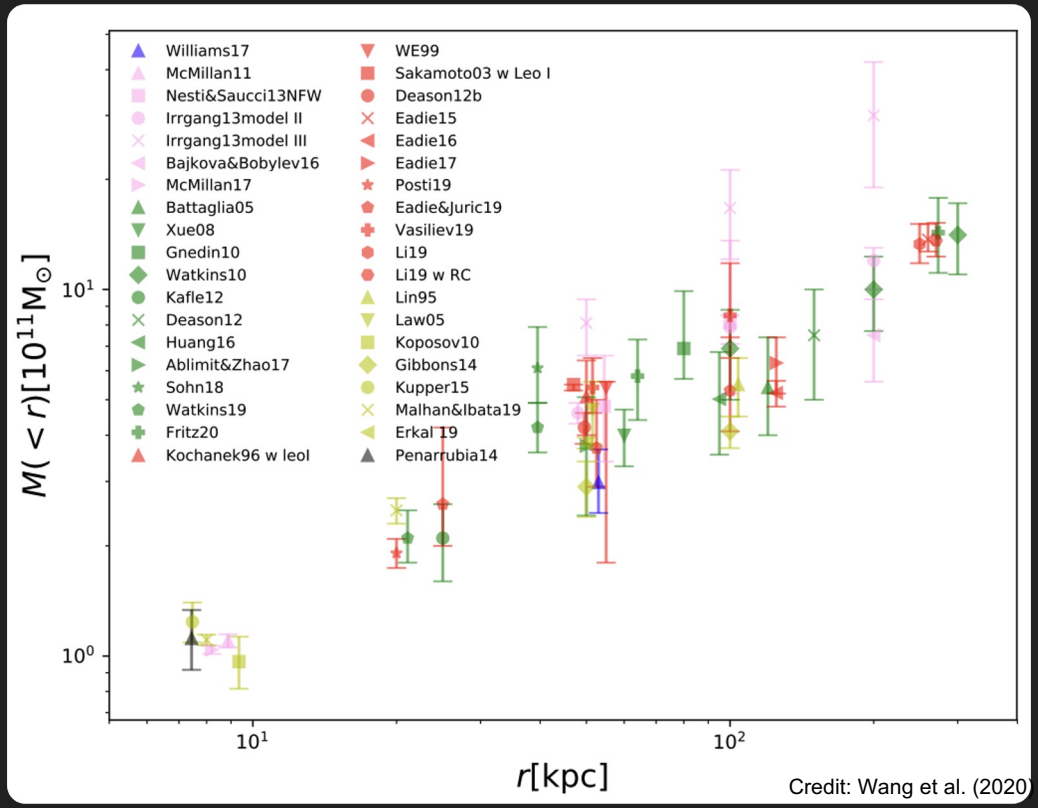
More tests on the robustness of the curve and the fit



Credit: Jiao et al. (2023)

Varying baryonic models yields consistent dark matter halo fitting results

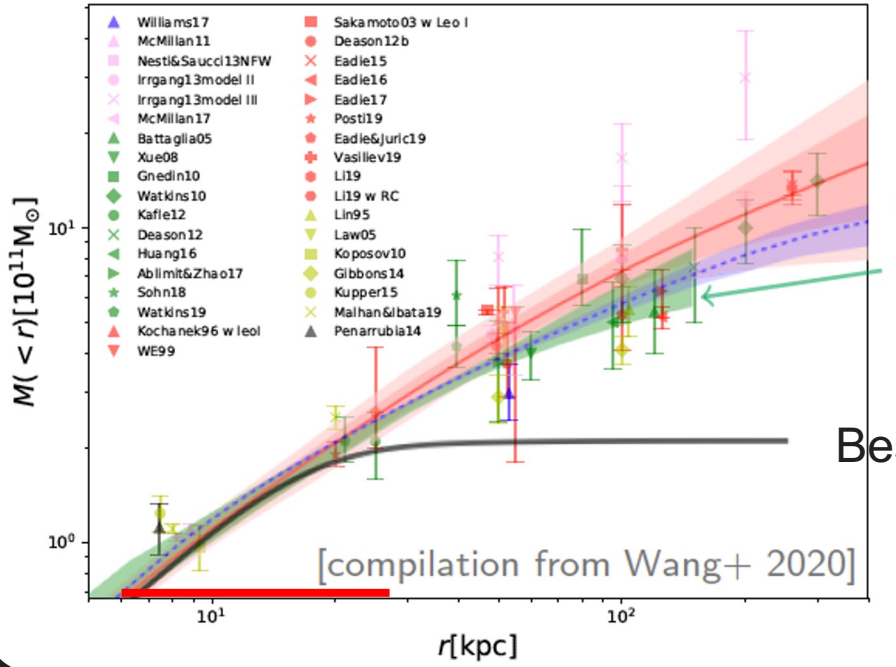
Dynamical mass of the Milky Way from different tracers



Credit: Wang et al. (2020)

Ou et al. (2024a); arXiv:2303.12838

Dynamical mass of the Milky Way from different tracers



GC+dSph (+LMC rewinding) [Correa Magnus & Vasiliev 2022]

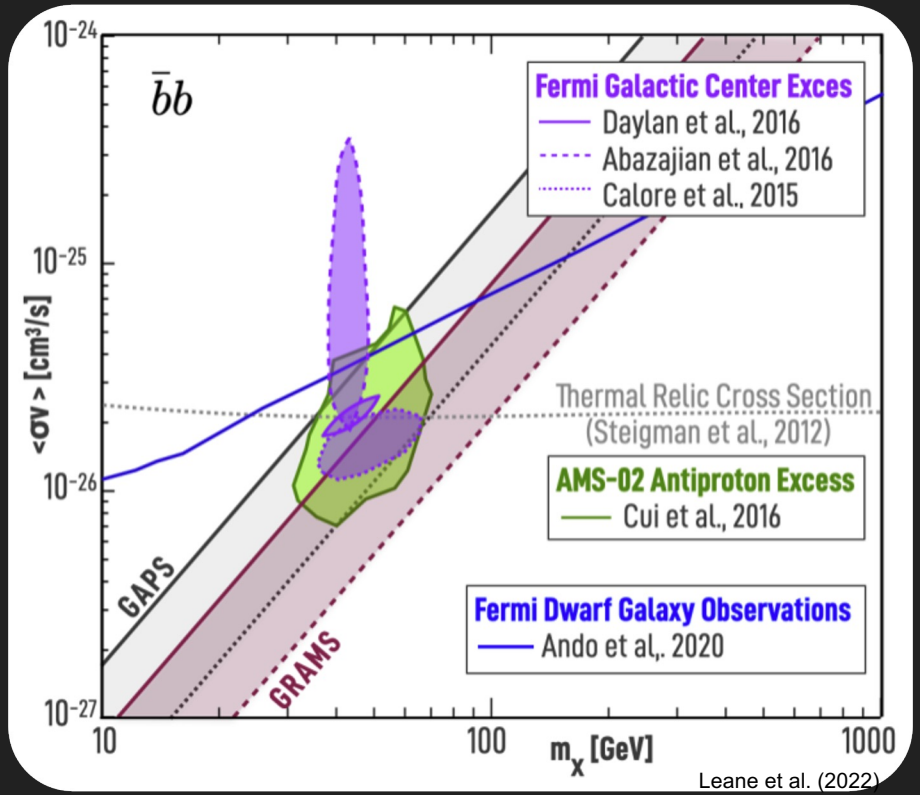
Sgr stream (incl. LMC) [Vasiliev+ 2021]

Orphan stream (incl. LMC) [Koposov+ 2022]

Best-fit model from Ou et al. (2024a)

(Courtesy of Eugene Vasiliev)

Annihilation cross section



Leane et al. (2022)

$$J = \int \rho^2 ds$$

Lower *J*-factor ***increases*** the inferred annihilation cross section

Tension with dwarf galaxy constraint!

Dark matter models in general

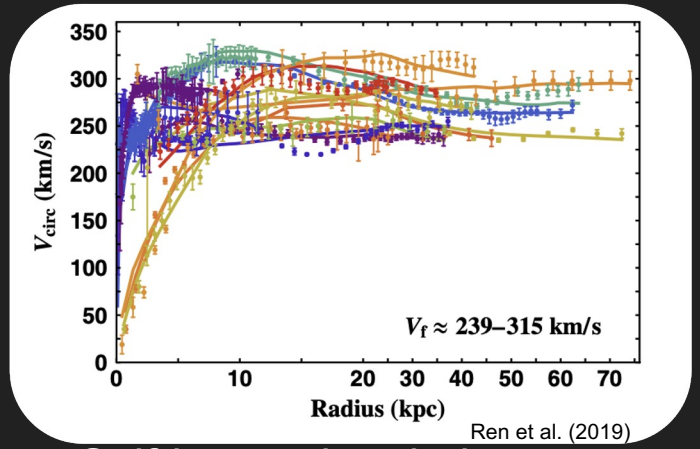
Baryonic feedback

- intense star formation episodes with decreased rate of dark matter accretion rate at the center

Non-equilibrium stellar kinematics

- non-axisymmetric potential;
- recent mergers;
- tracer population profile;
- underestimated asymmetric drift correction from vertical motion

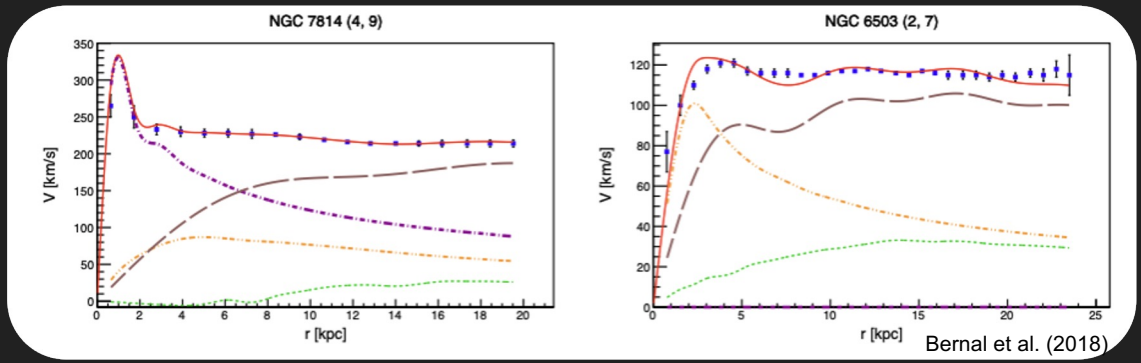
Astrophysics



Ren et al. (2019)

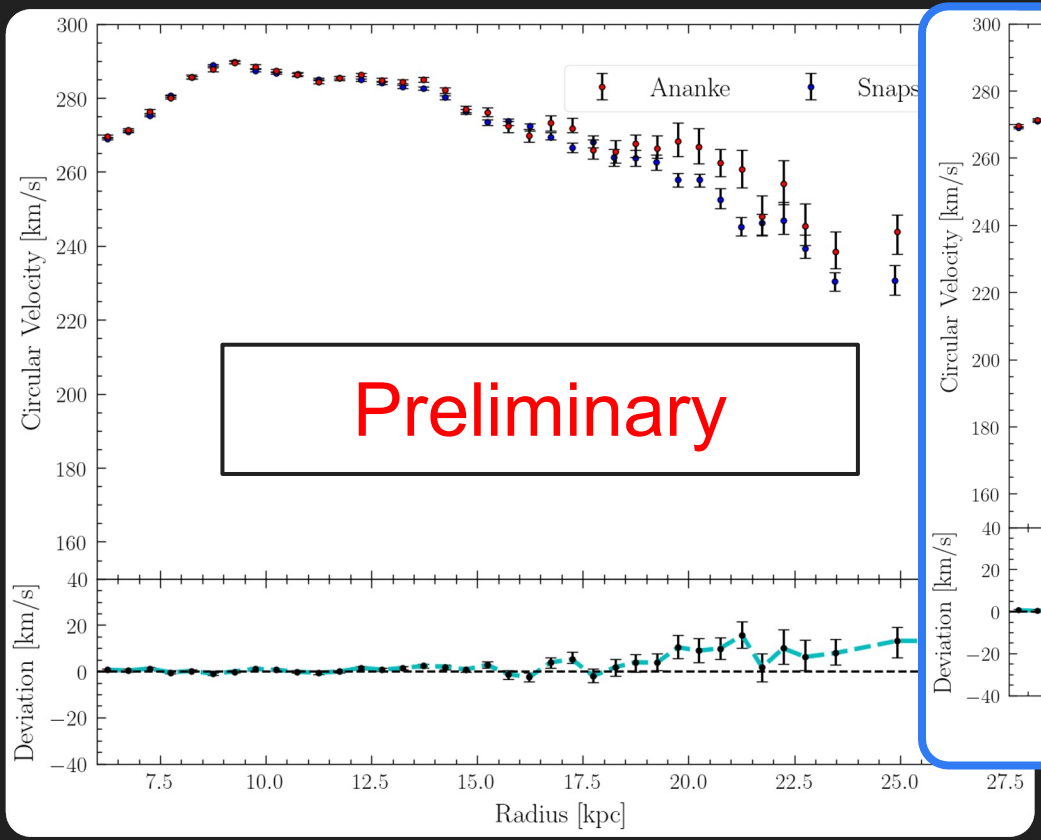
Self-interacting dark matter

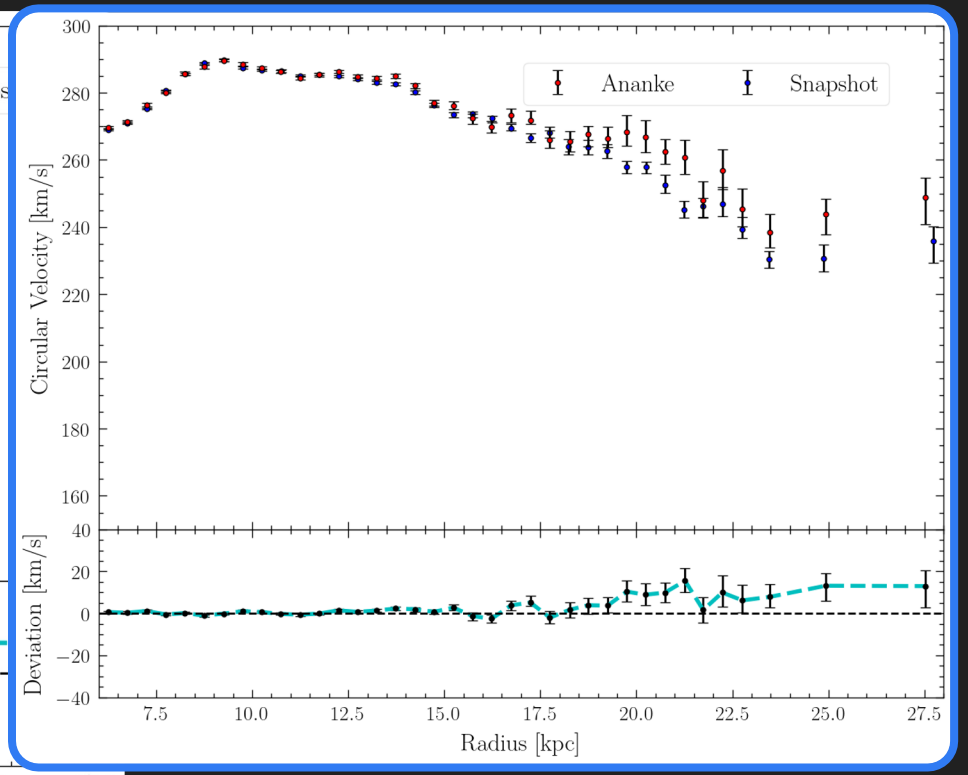
Fuzzy dark matter



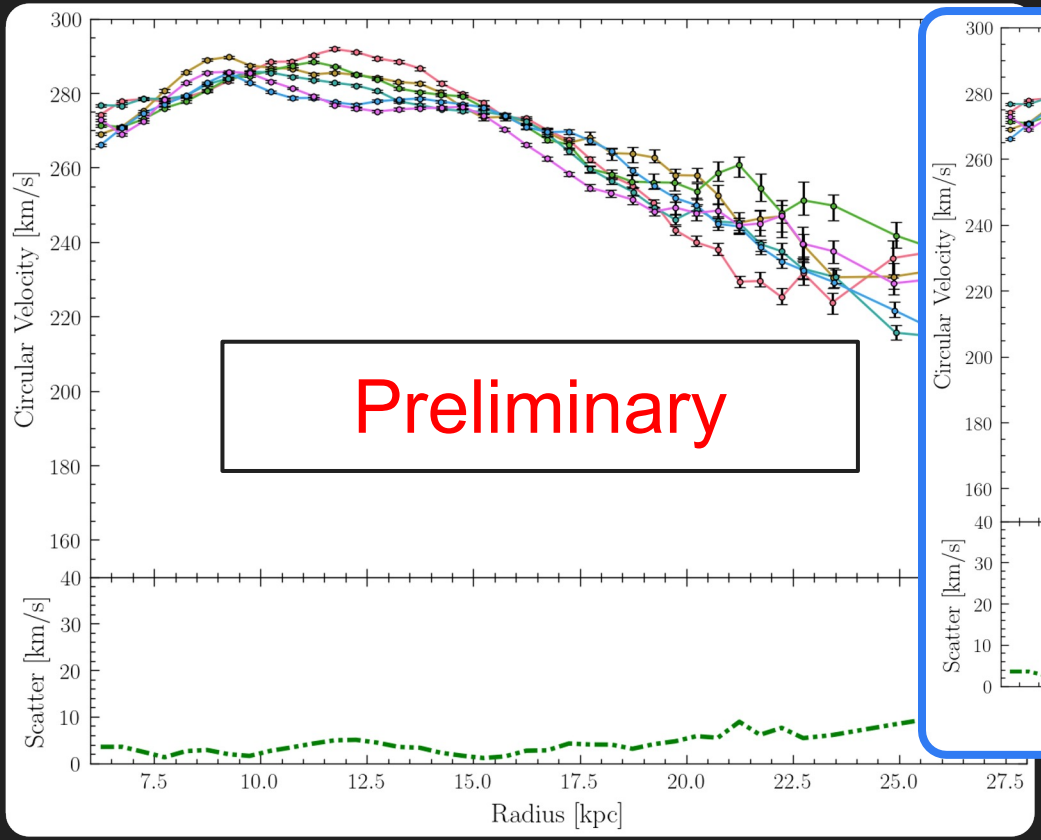
Bernal et al. (2018)

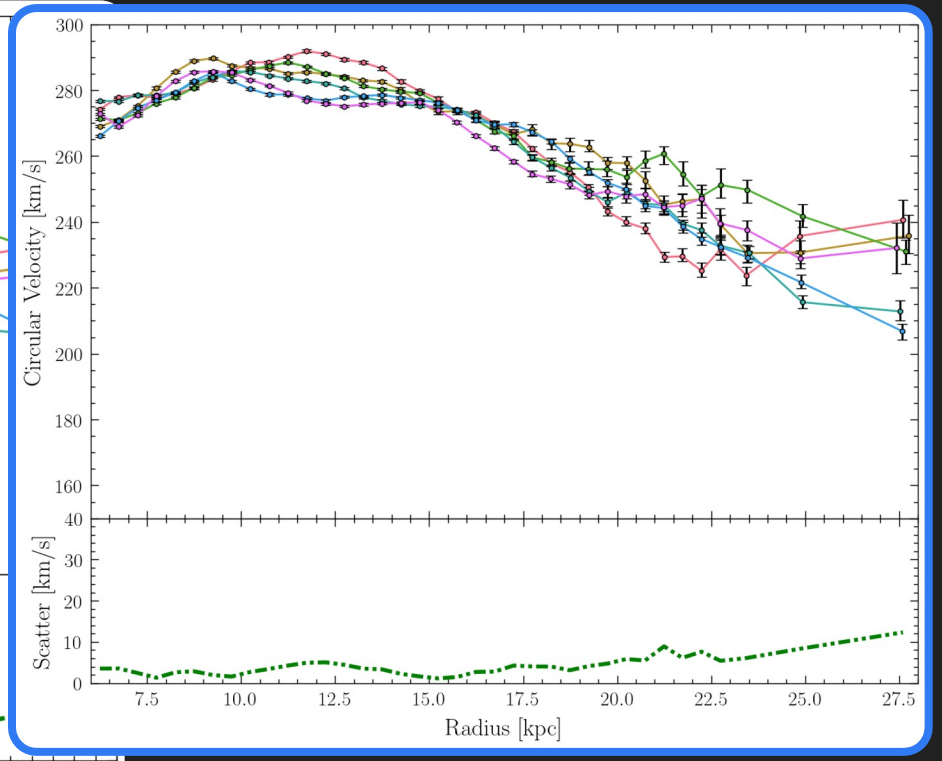
Test with simulation and synthetic surveys



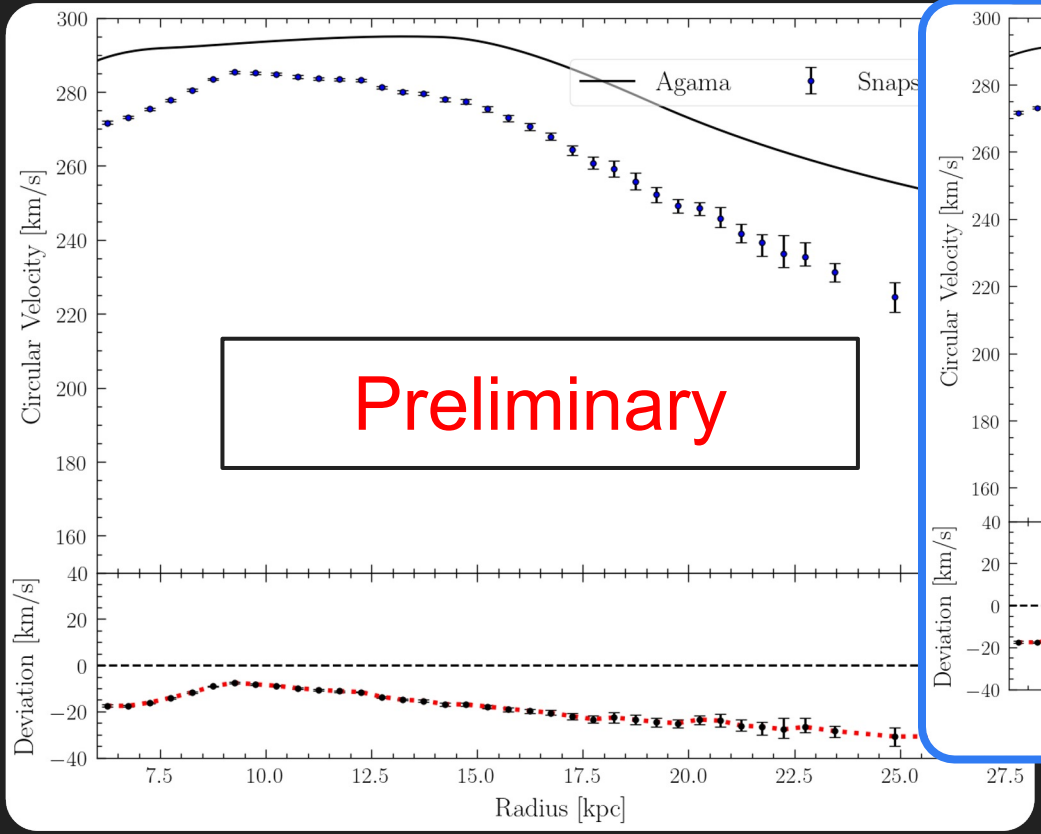


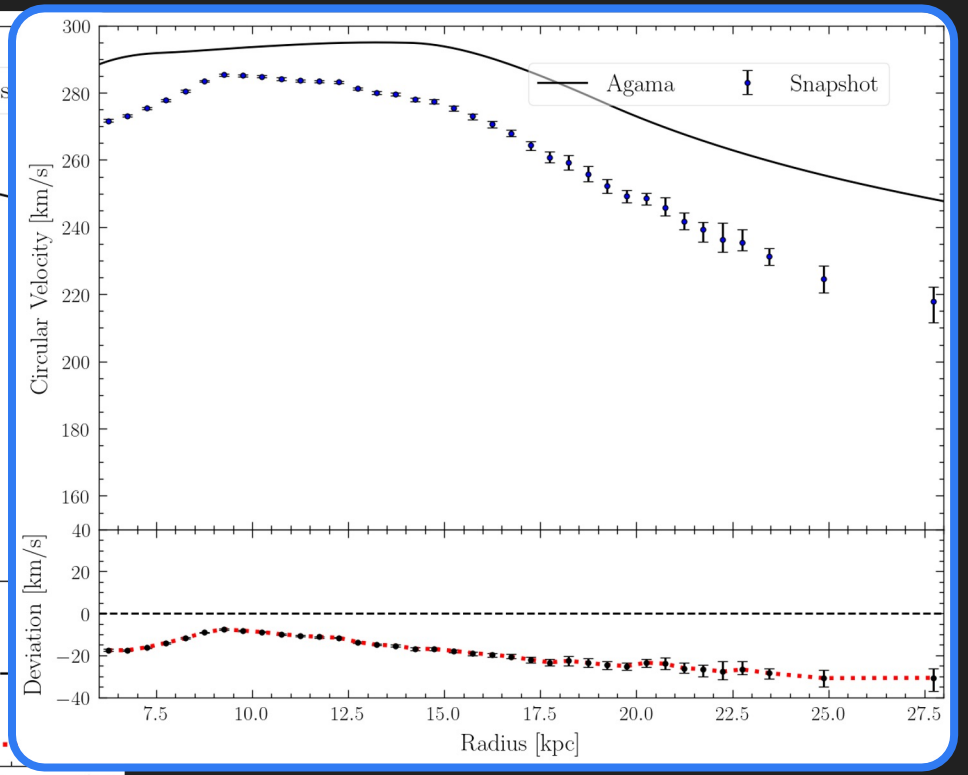
Test with simulation and synthetic surveys





Test with simulation and synthetic surveys





Test with simulation and synthetic surveys