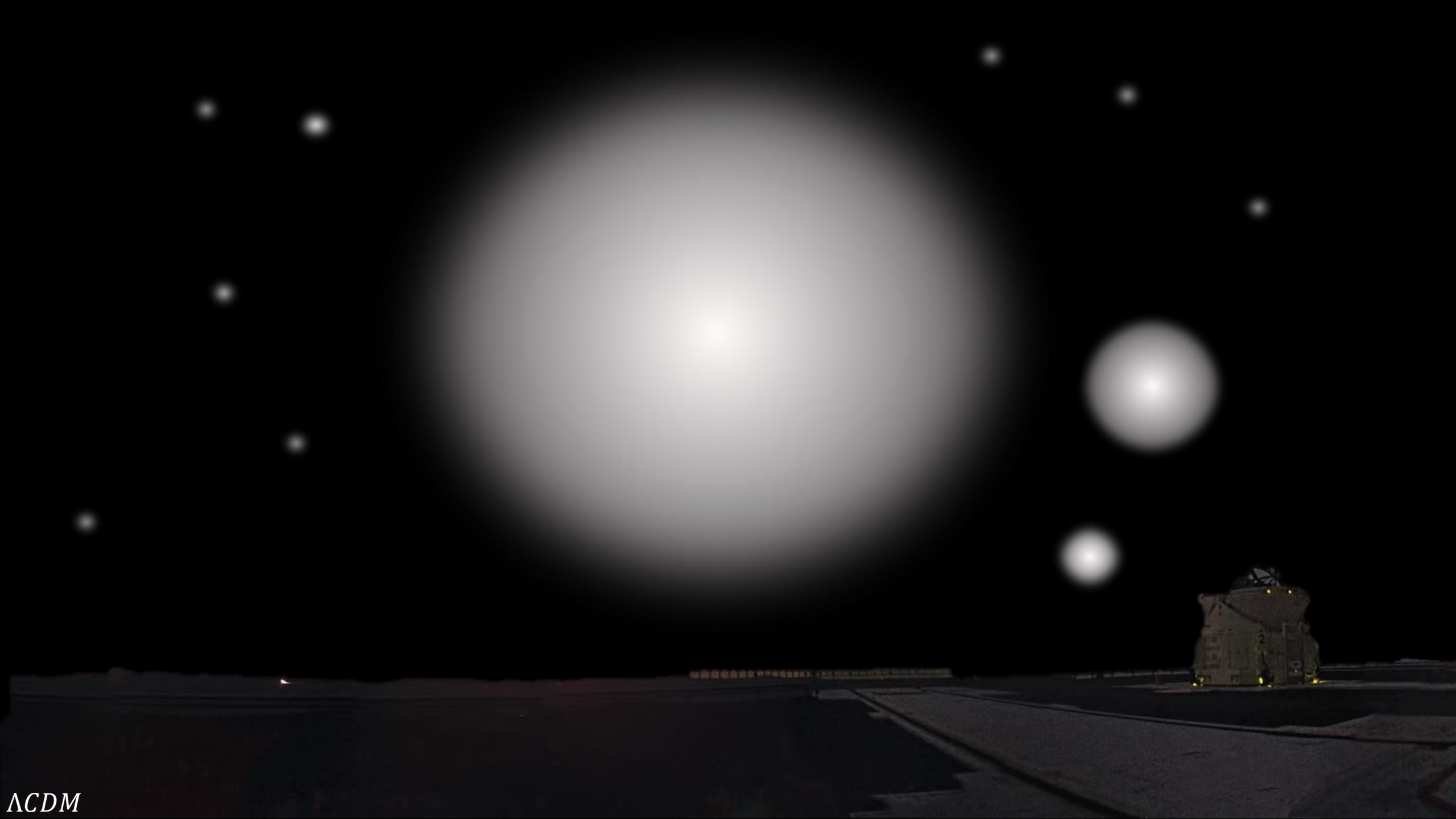
MAPPING OUT THE DARK MATTER IN THE MILKY WAY

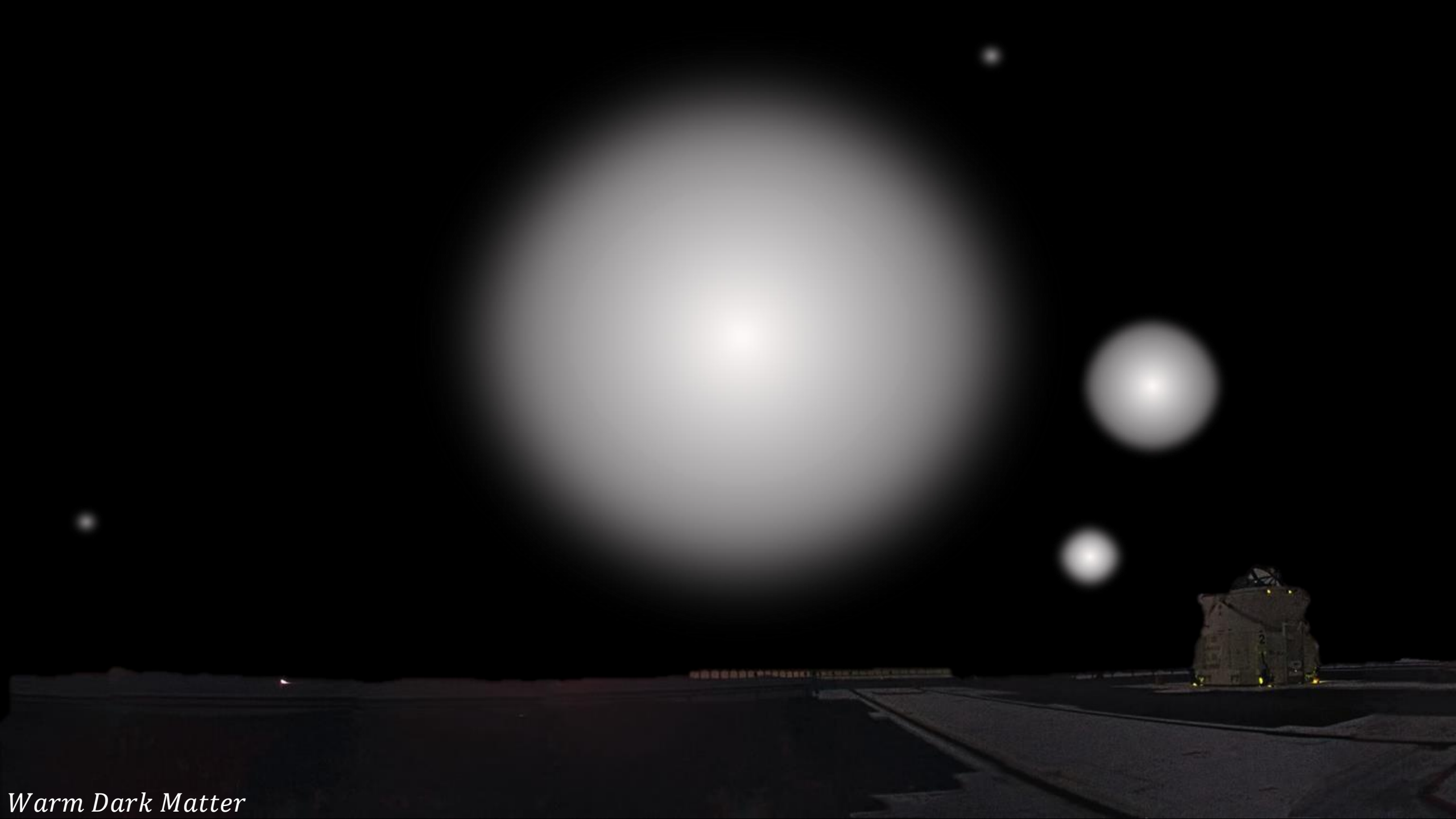
Lina Necib

Massachusetts Institute of Technology

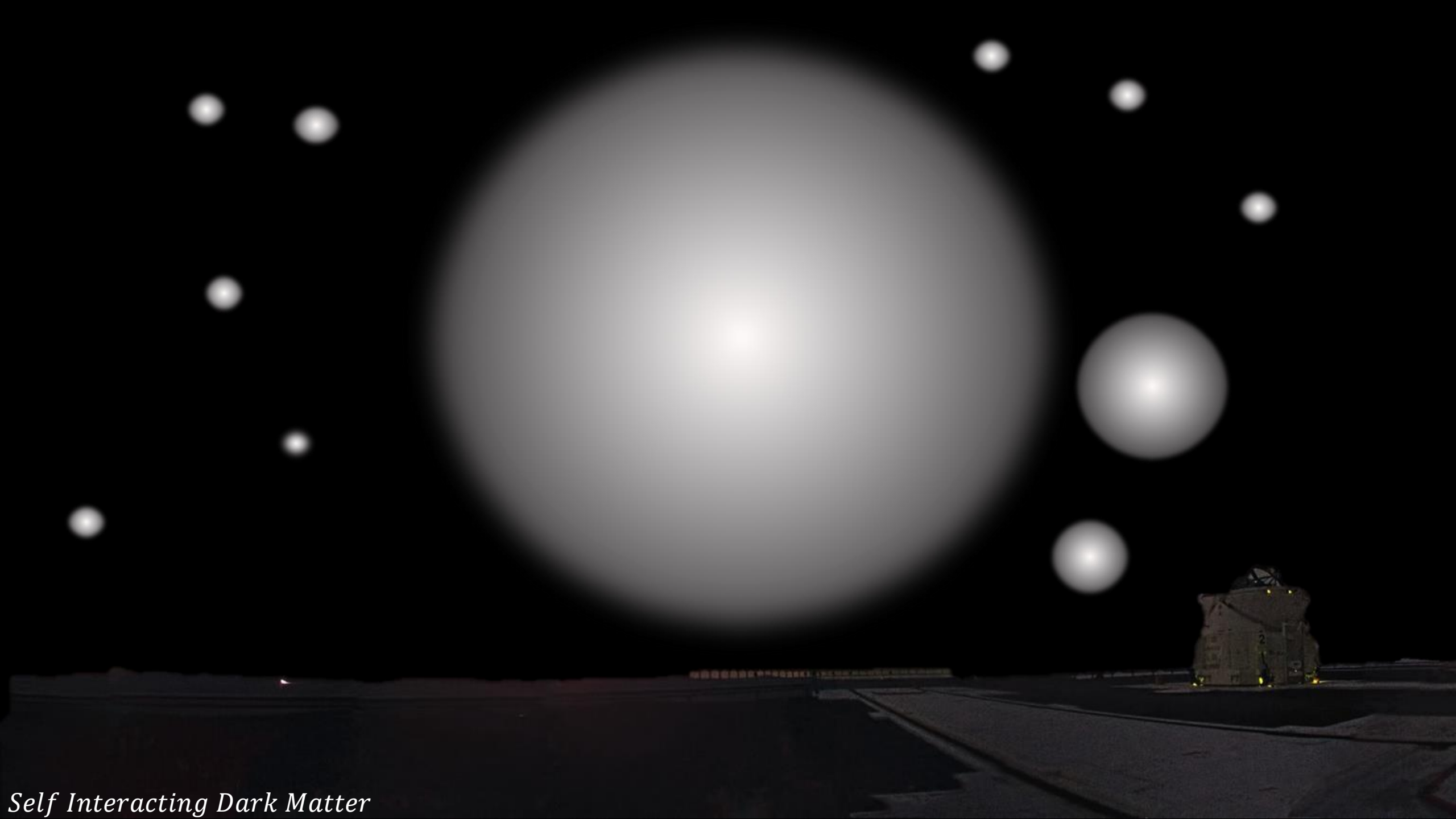
MIT KAVLI INSTITUTE

Credit: ESO/Y. Beletsky

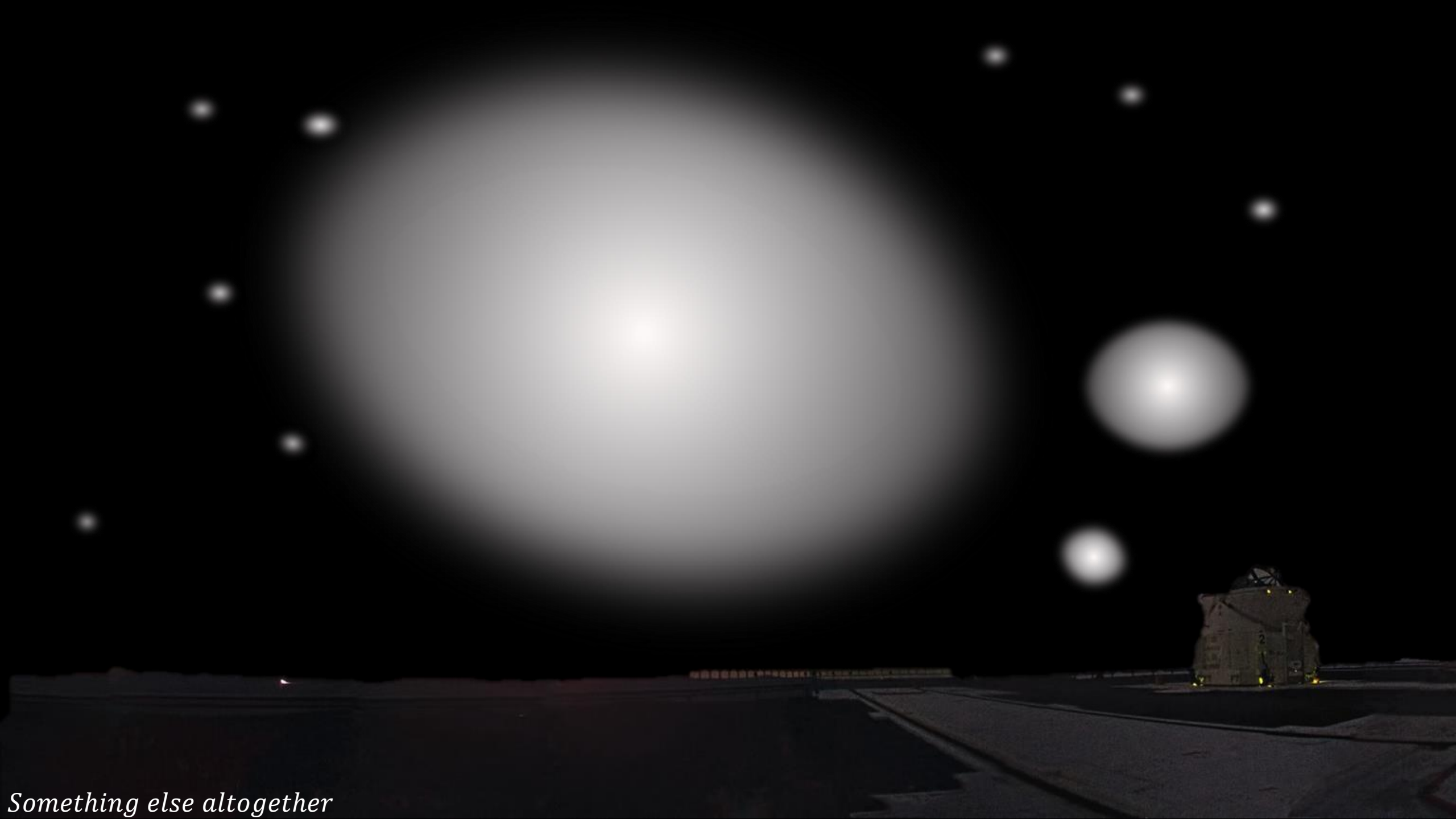

ΛCDM



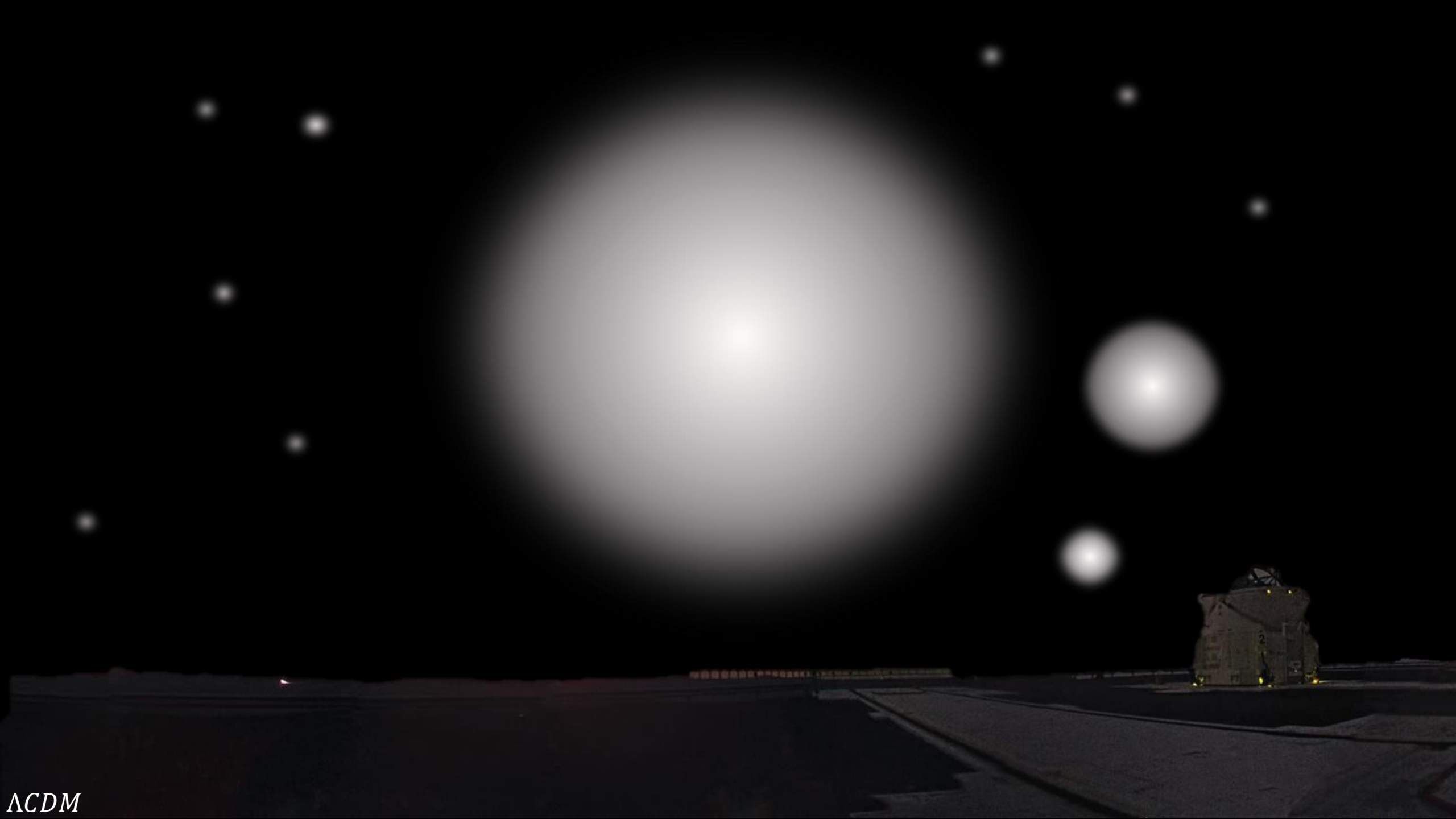
Warm Dark Matter



Self Interacting Dark Matter



Something else altogether


ΛCDM

GOAL:
MAPPING FROM THE STARS TO THE DARK MATTER

GOAL:
MAPPING FROM THE STARS TO THE DARK MATTER

Streams

Nora Shipp

After MIT: Faculty at University of Washington

Nathaniel Starkman

Brinson Fellow

Galactic Center/Halo

Abdelaziz Hussein

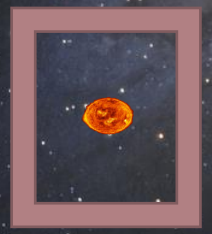
Xiaowei Ou
PhD' 25

After MIT:
GECO/CosmicAI Fellow
University of Virginia

Solar Neighborhood

Zeineb Mezghanni

Xiuyuan Zhang



Dwarf Galaxies

Tri Nguyen,
PhD' 24

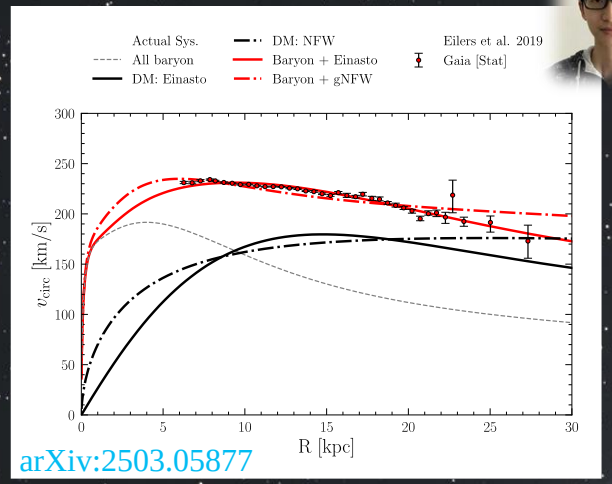
After MIT:
CIERA Fellow,
Northwestern

Lina Necib, MIT

TODAY'S TALK: MAPPING THE DARK MATTER DENSITY PROFILE IN THE MILKY WAY AND DWARF GALAXIES

Ask me about this

Xiaowei Ou

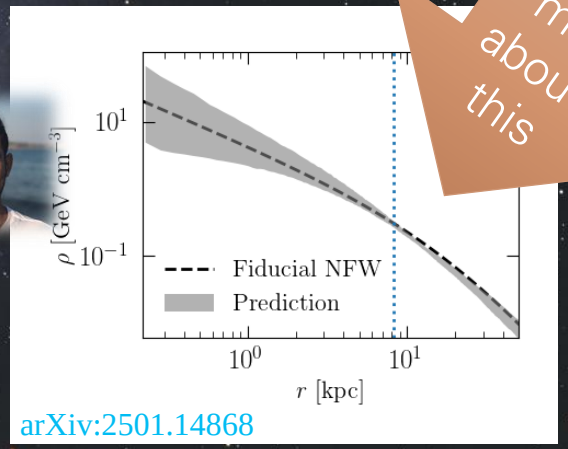


arXiv:2503.05877

Used synthetic surveys to build the true systematic uncertainties of the circular velocity measurements of the Milky Way, and obtained a new Dark Matter density profile.

Galactic Center/Halo

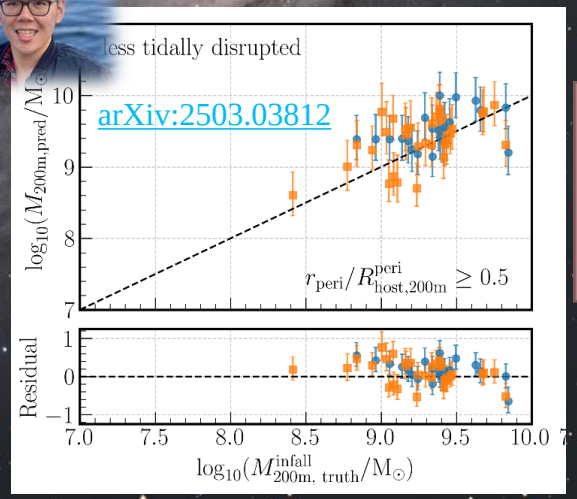
Abdelaziz Hussein



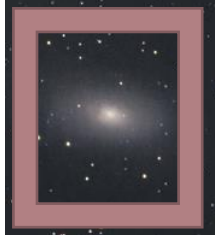
arXiv:2501.14868

Built a theoretical range for the density profile of Dark Matter at the center of the Milky Way, based on adiabatic contraction and baryonic feedback.

Tri Nguyen

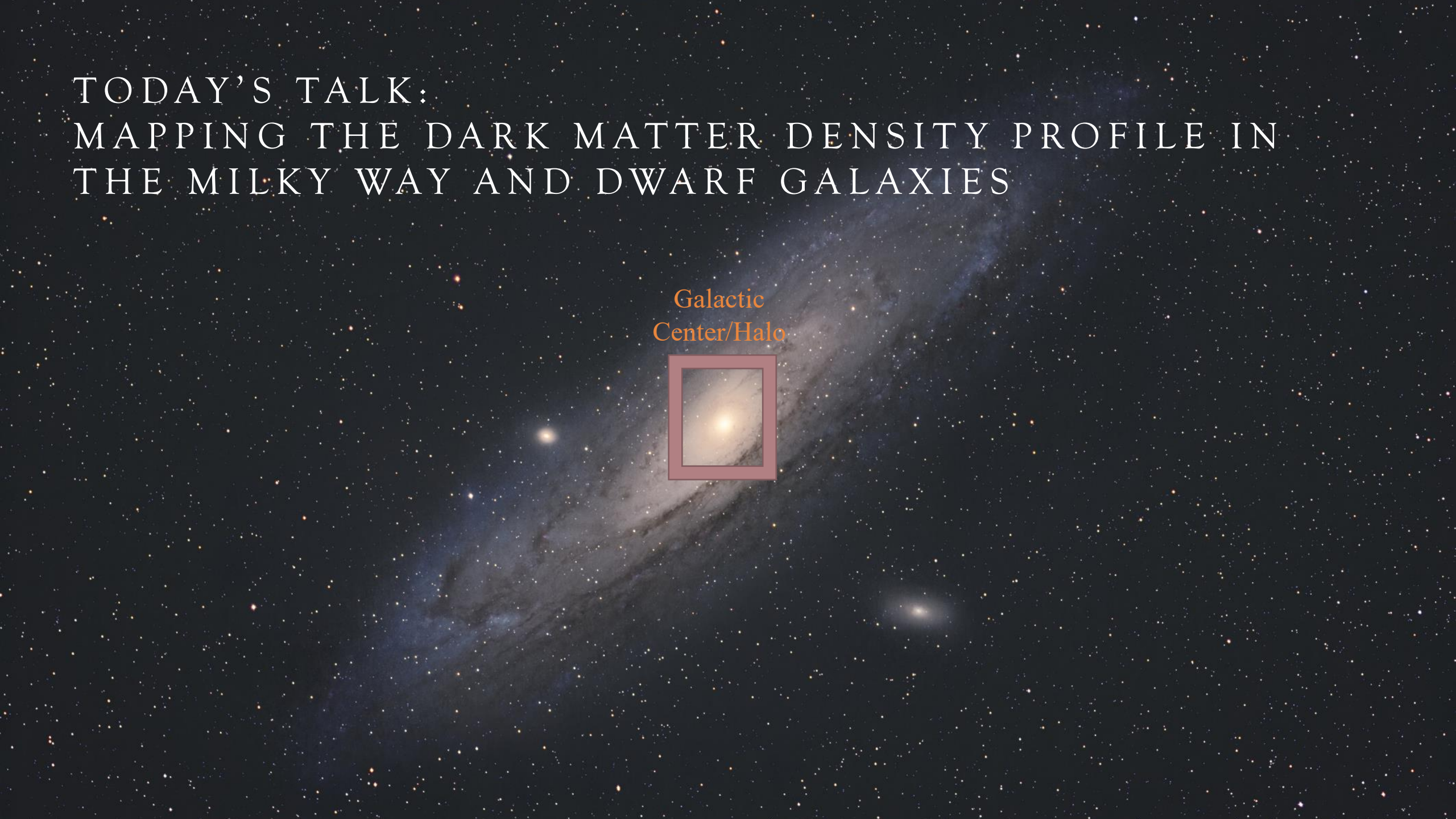


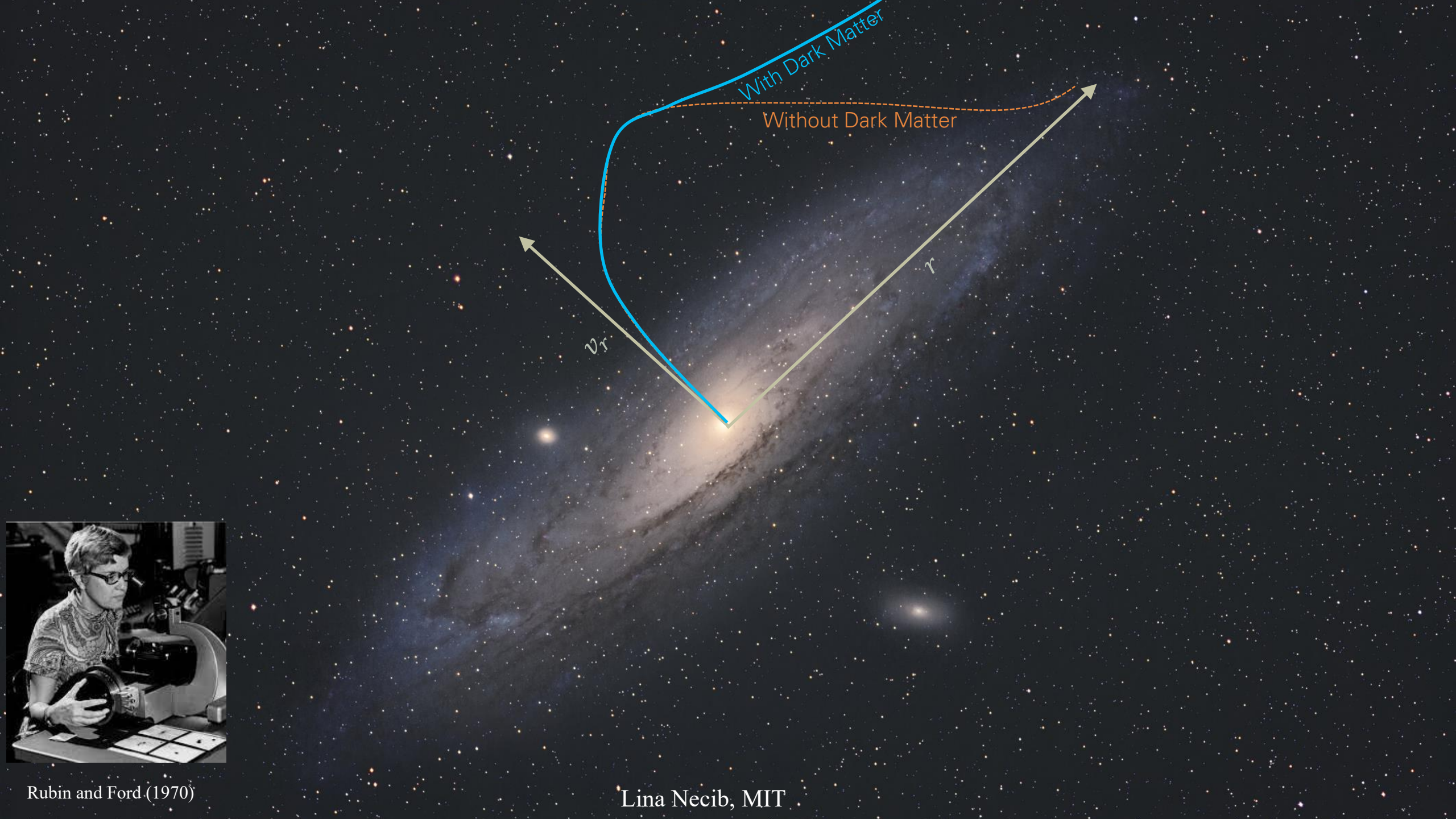
Dwarf Galaxies



Used Graph Neural Networks to construct the density profiles of Dark Matter in dwarf galaxies, based on line-of-sight velocities.
Tested this new method on FIRE simulations to show robustness. Next we will apply this to data.

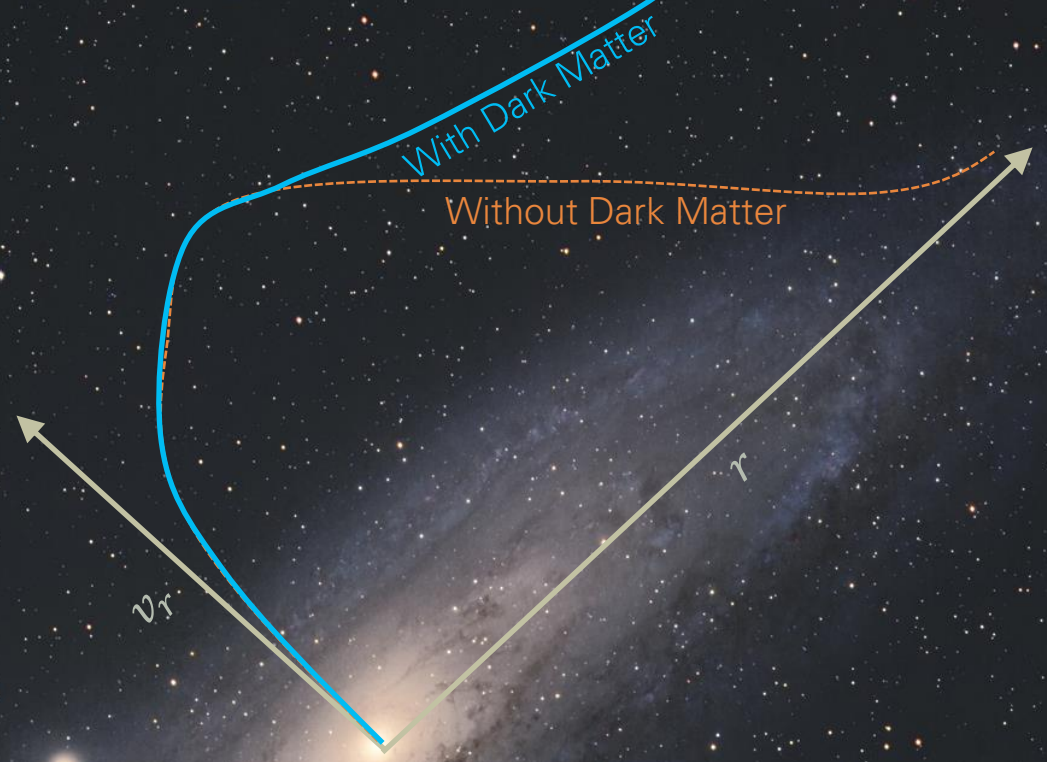
TODAY'S TALK:
MAPPING THE DARK MATTER DENSITY PROFILE IN THE MILKY WAY AND DWARF GALAXIES



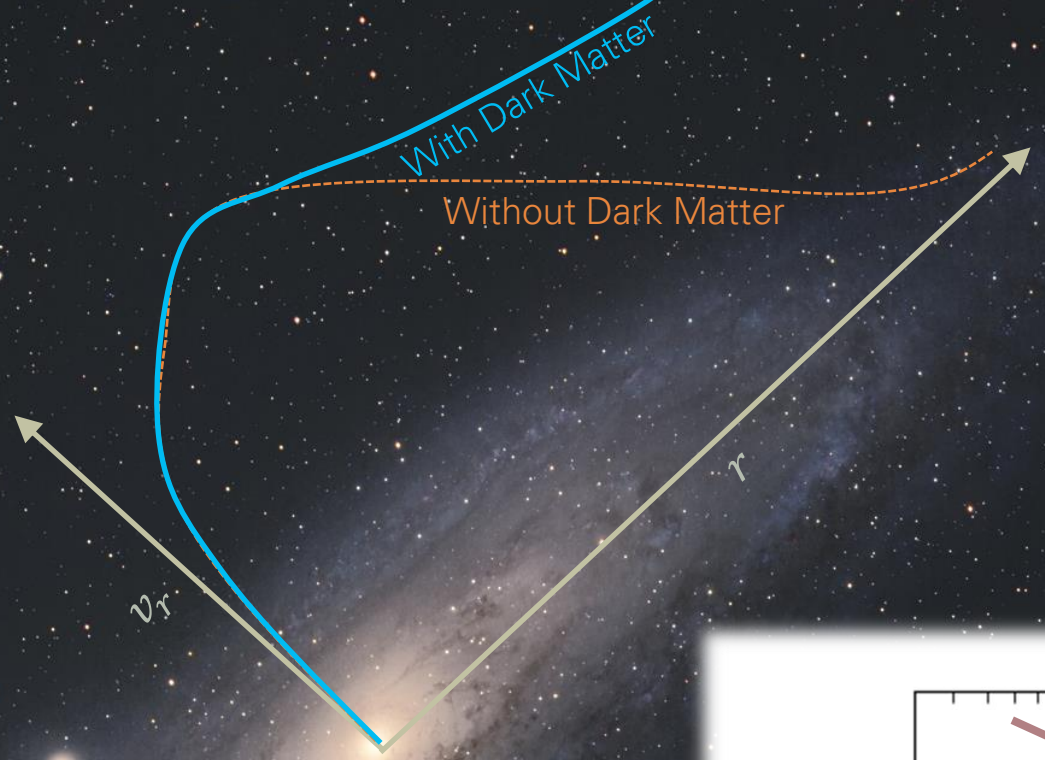


Rubin and Ford (1970)

Lina Necib, MIT



Circular Velocity → Gravitational Potential → Dark Matter Density



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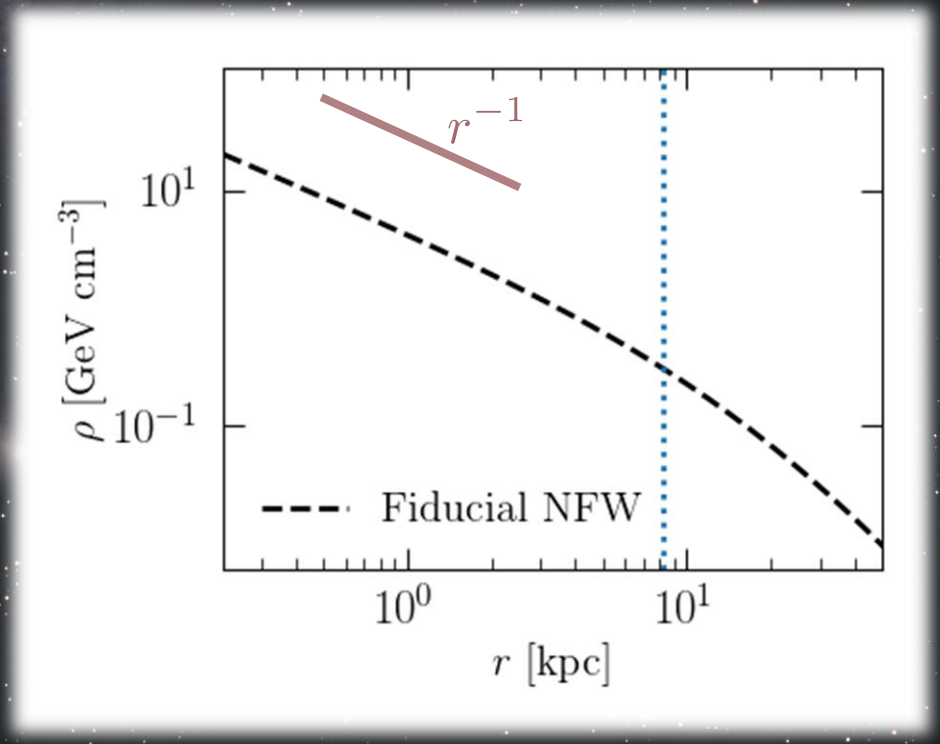
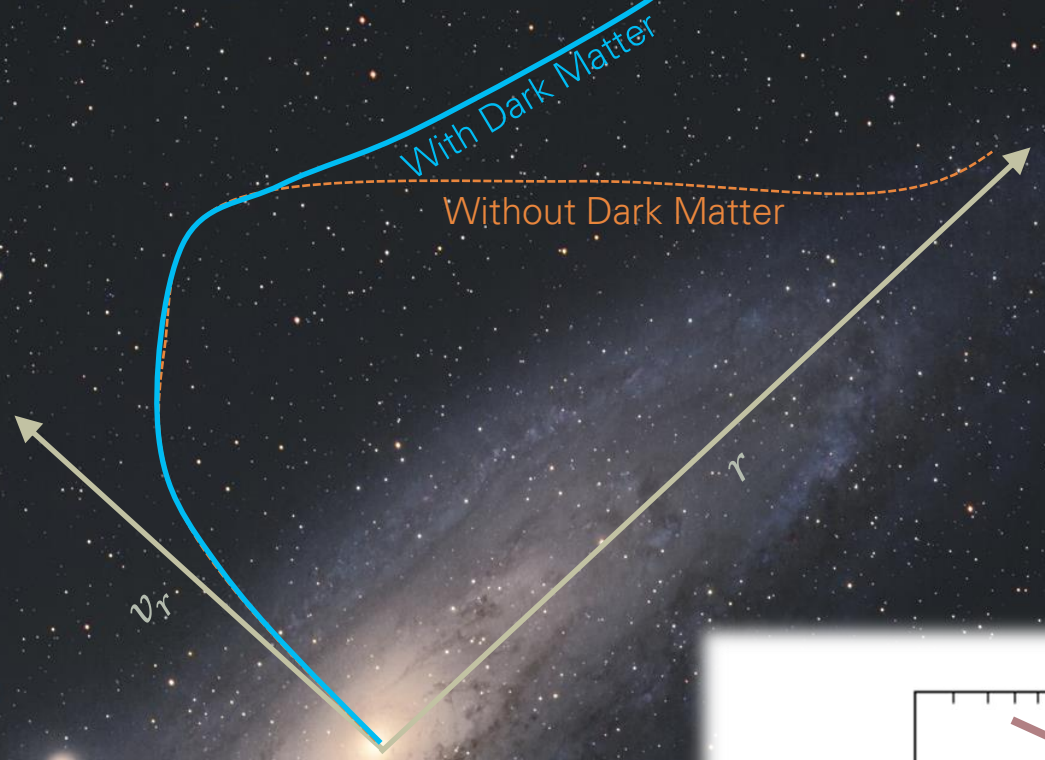


Lina Necib, MIT

Navarro et al. (1997)



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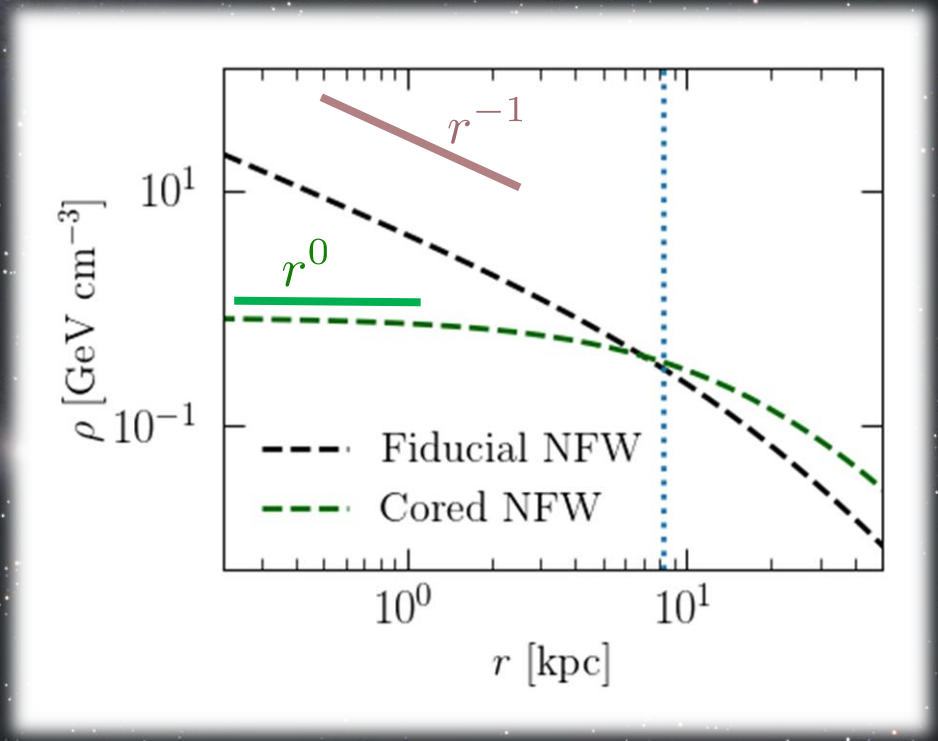

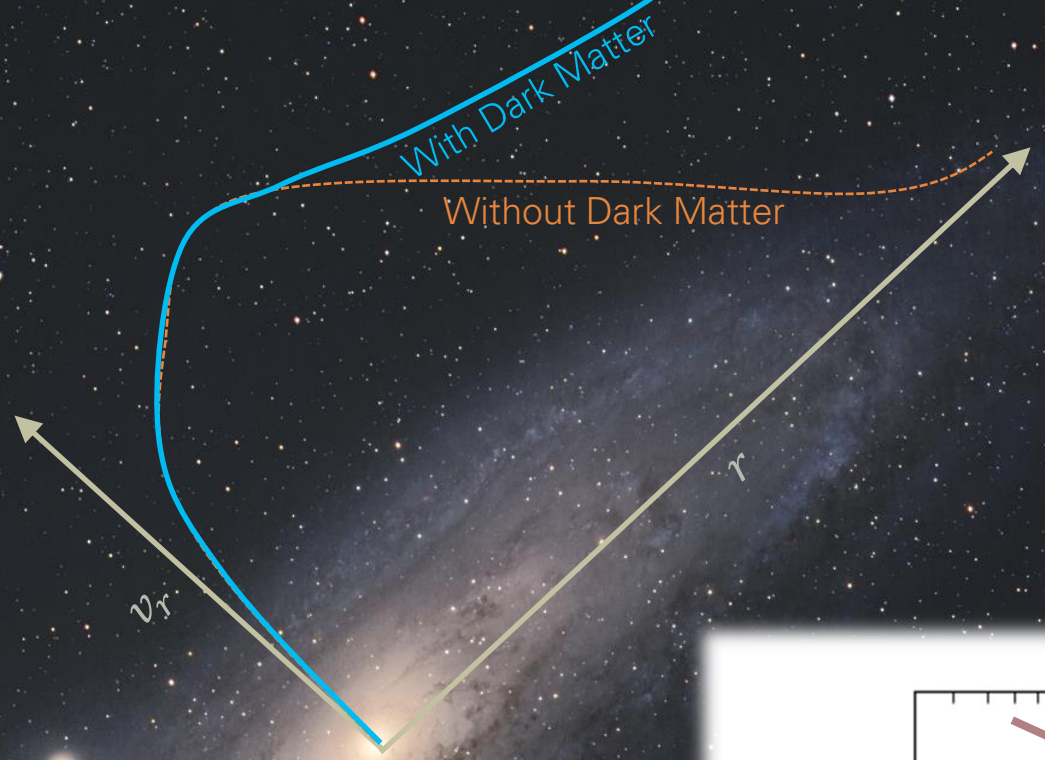

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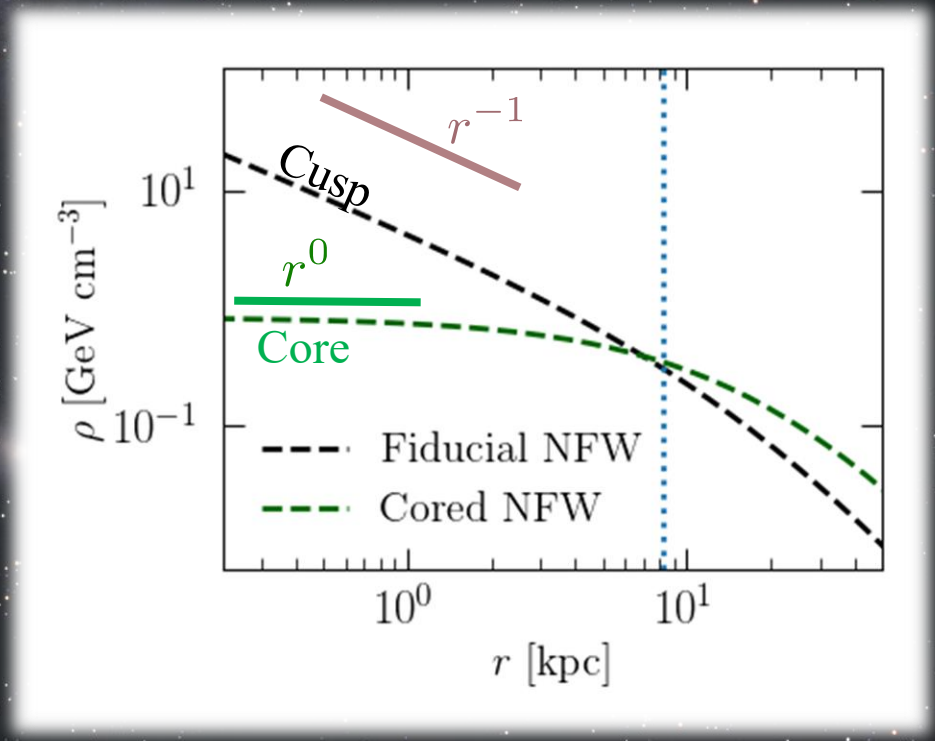
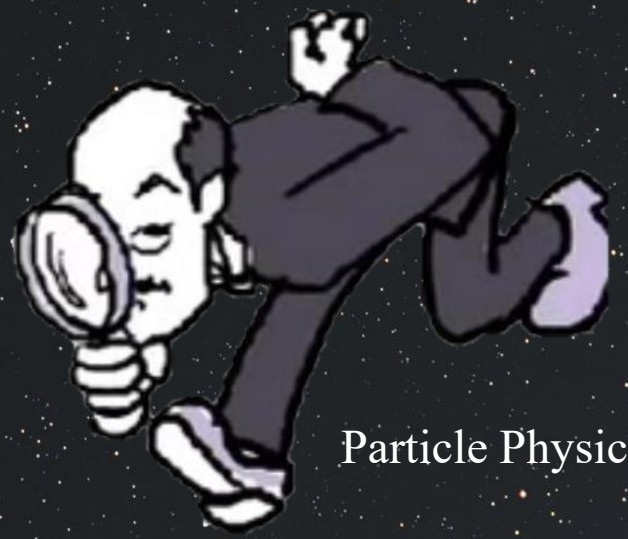
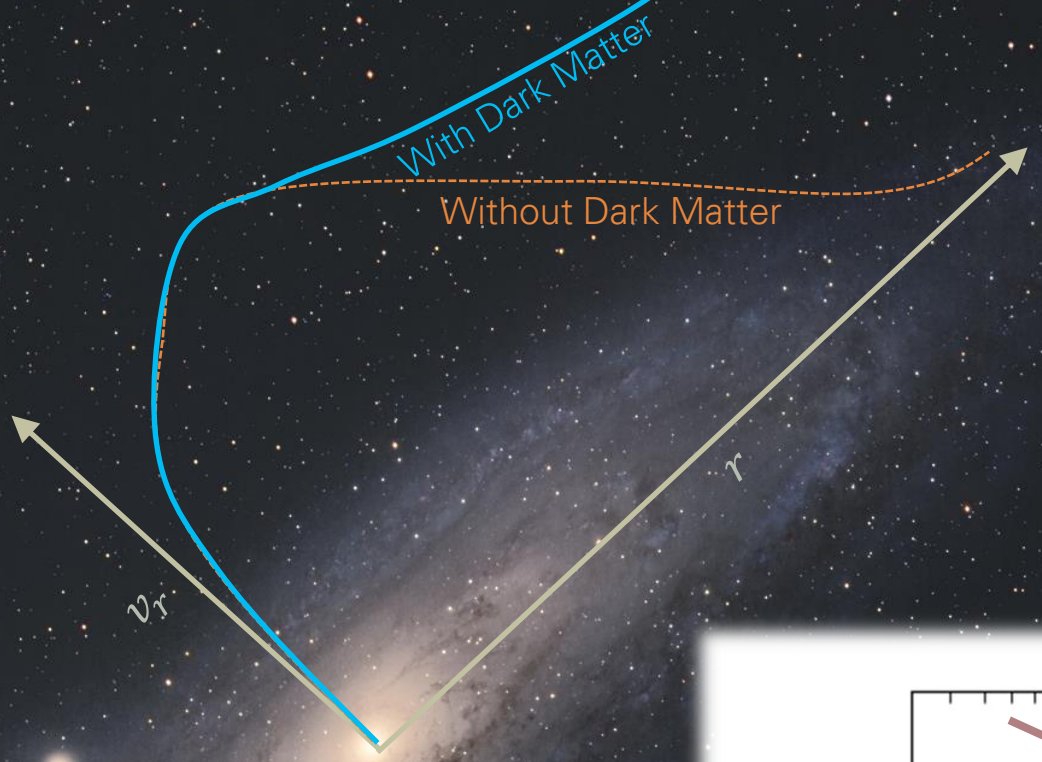
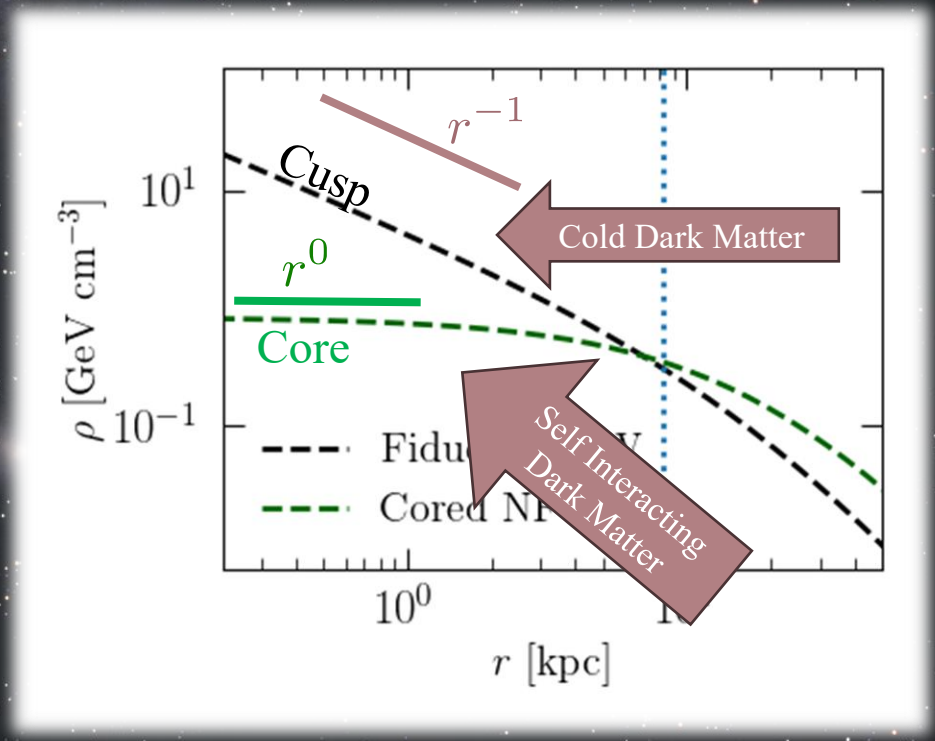




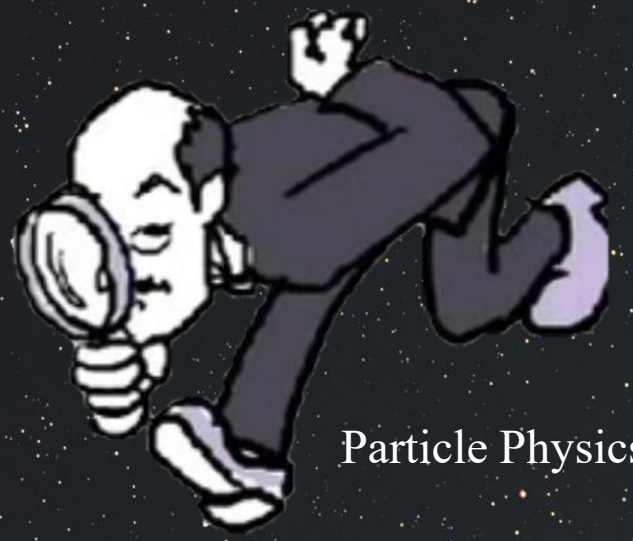
Particle Physics



Circular Velocity → Gravitational Potential → Dark Matter Density

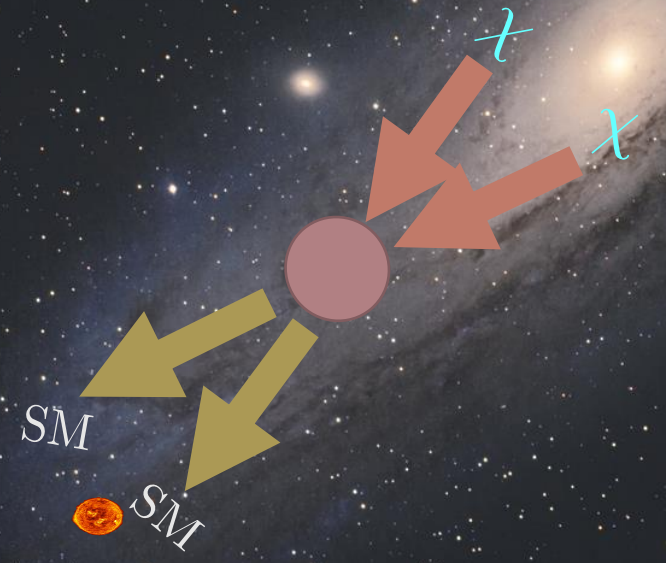


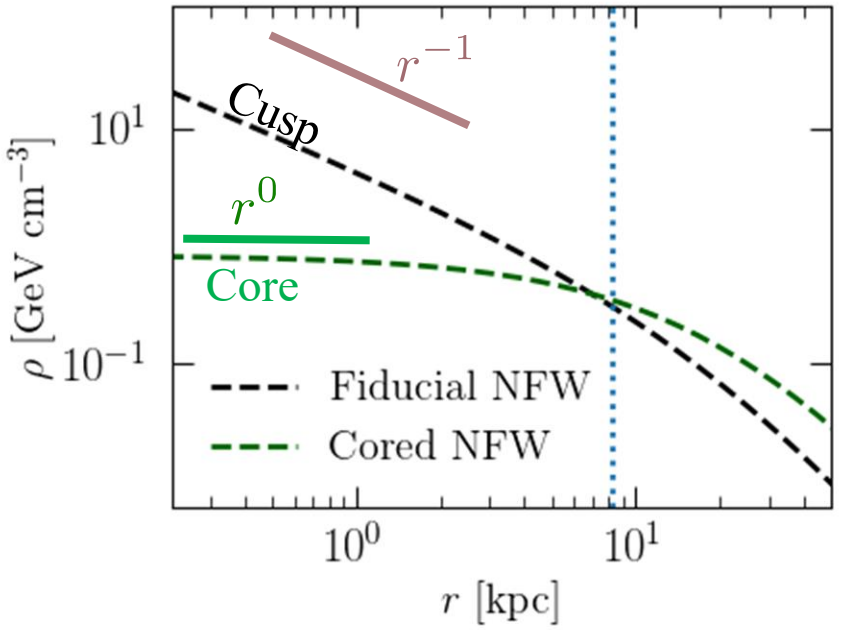
Lina Necib, MIT



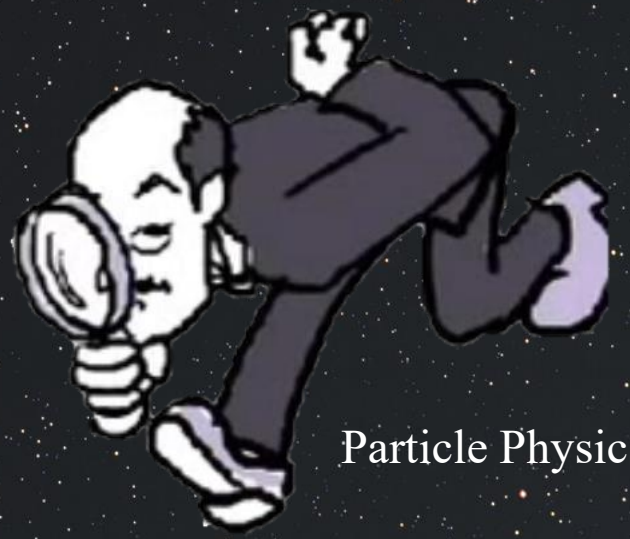
Particle Physics

Dark Matter
Annihilation Signal





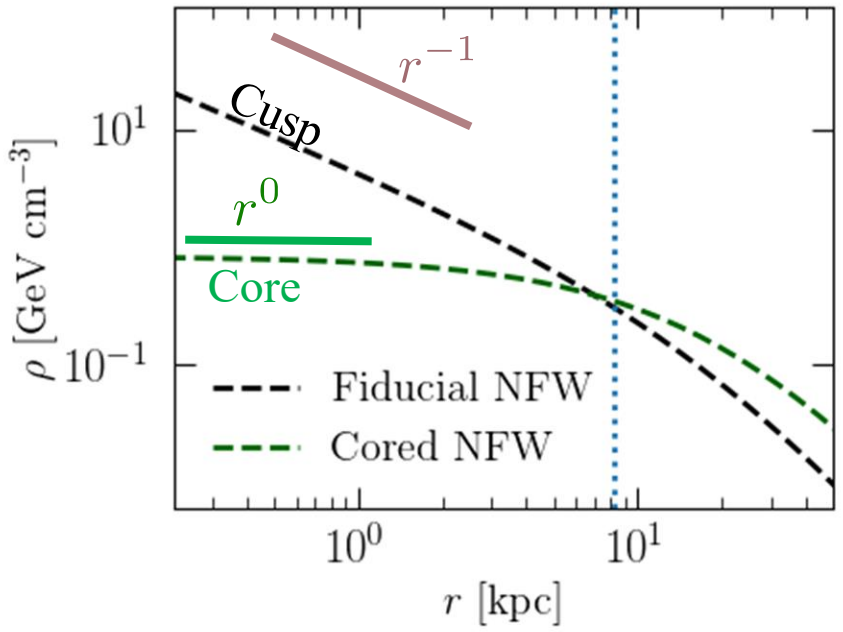
Lina Necib, MIT



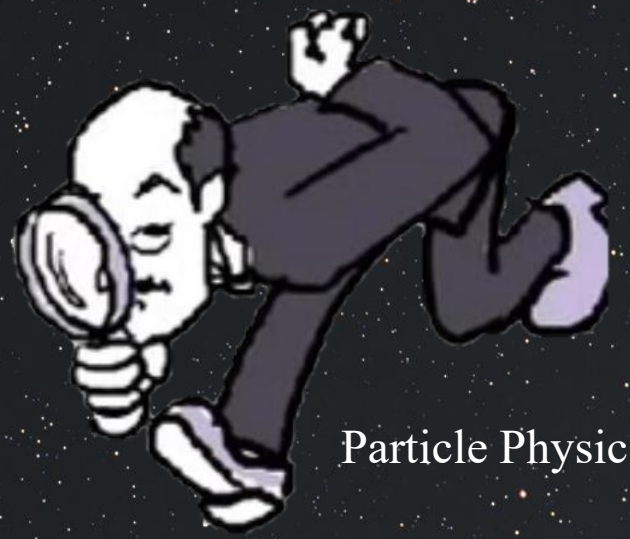
Particle Physics

Dark Matter
Annihilation Signal

$$\text{Signal} \propto \int \rho^2 \mathrm{ds}$$



Lina Necib, MIT



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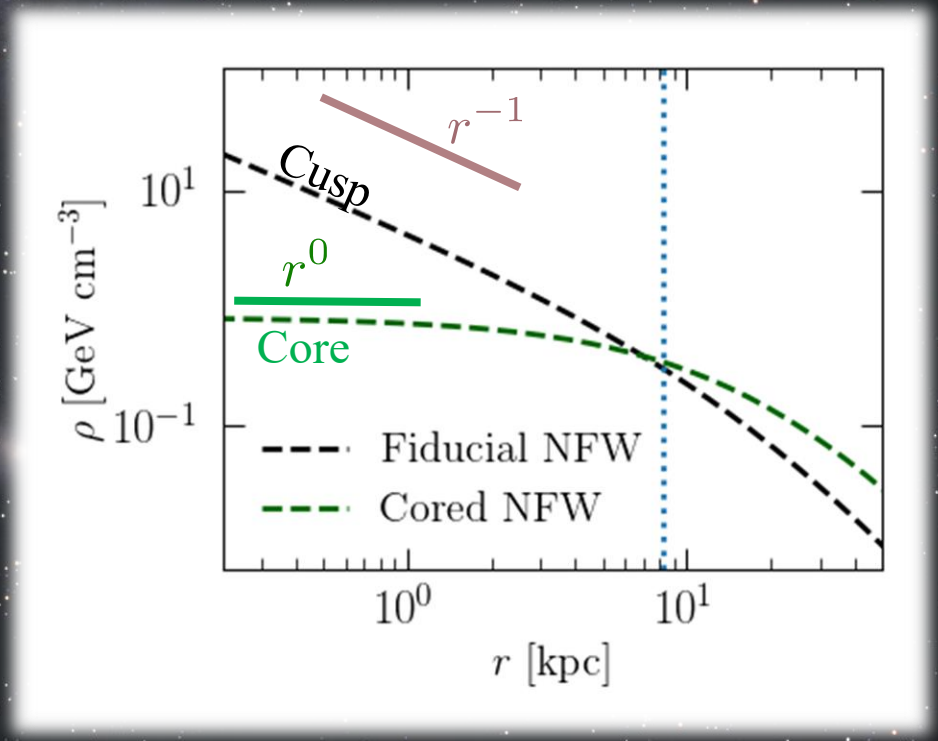
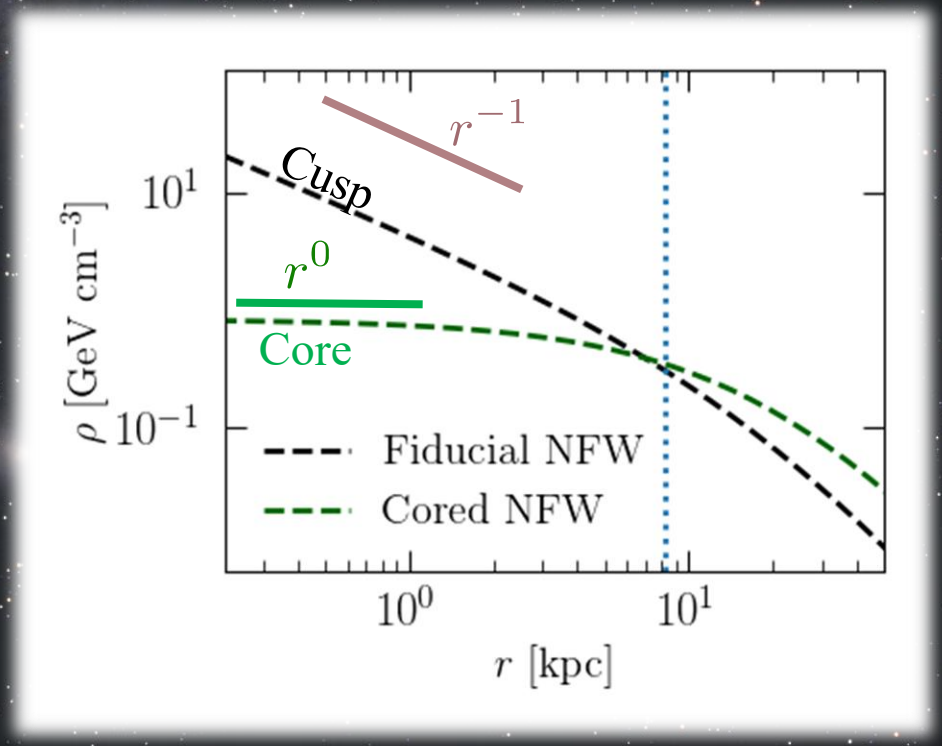


The effect can be orders of magnitude in signal expectation.

Astrophysics



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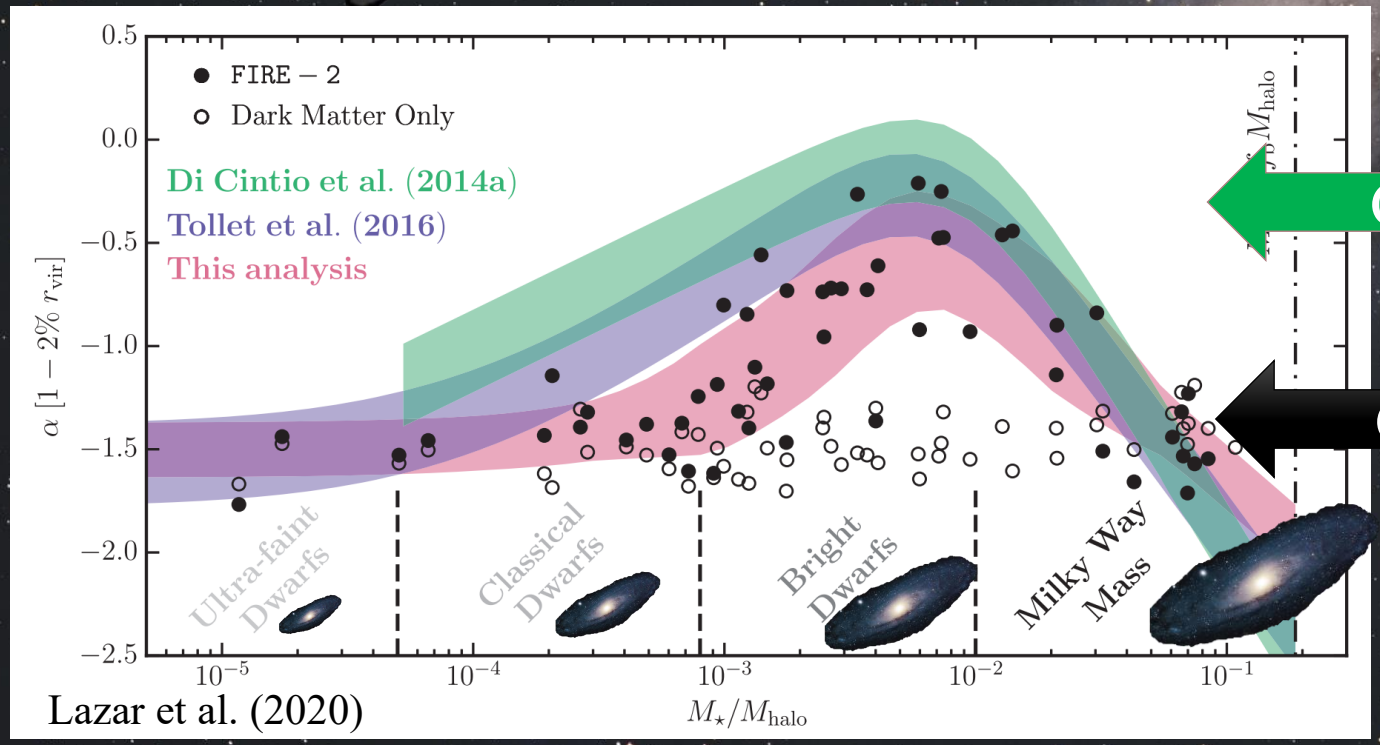
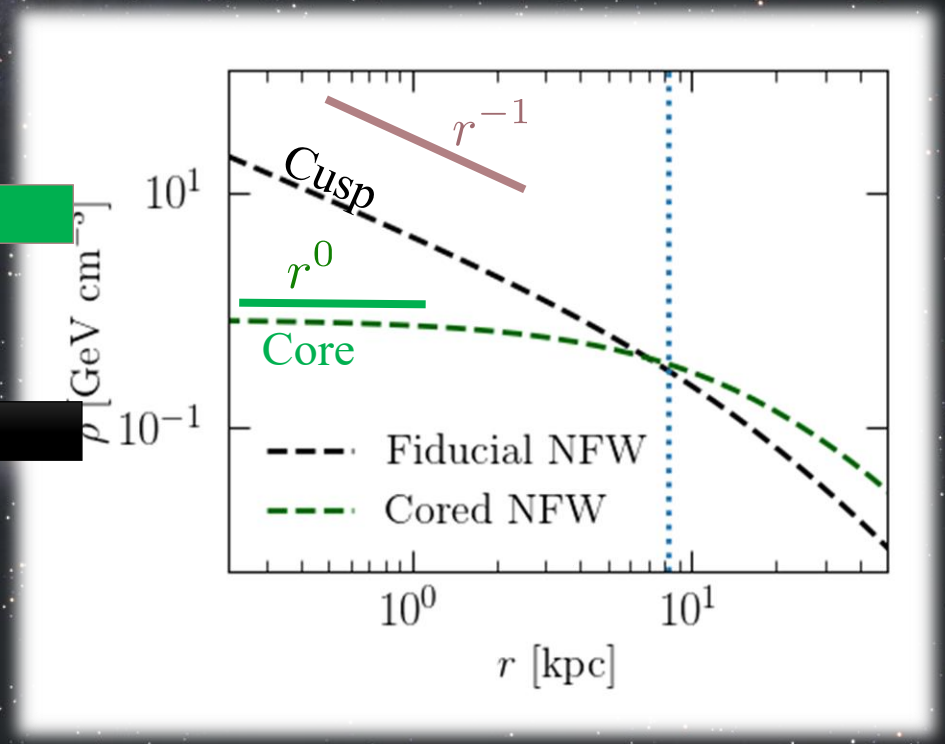
Astrophysics



Lazar et al. (2020)

Core

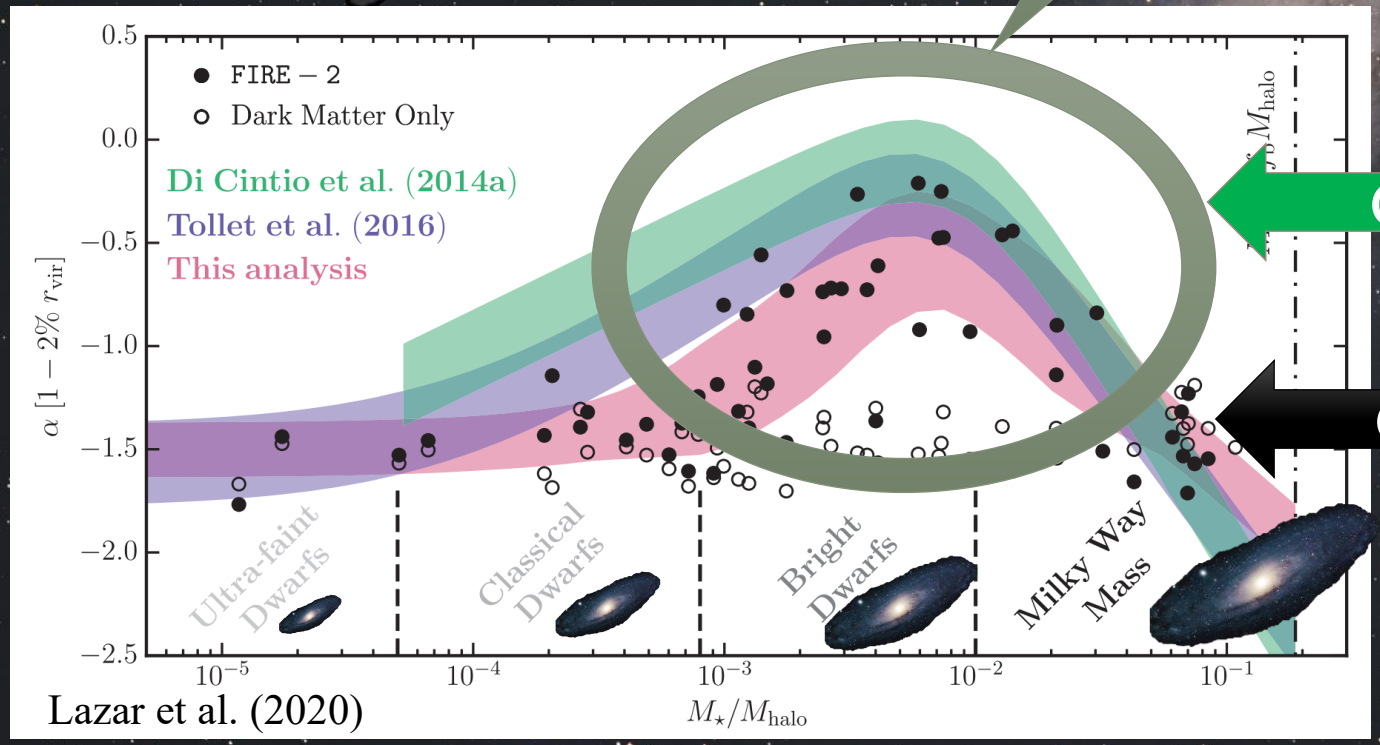
Cusp



Lina Necib, MIT

Astrophysics

Baryonic Feedback



Lazar et al. (2020)

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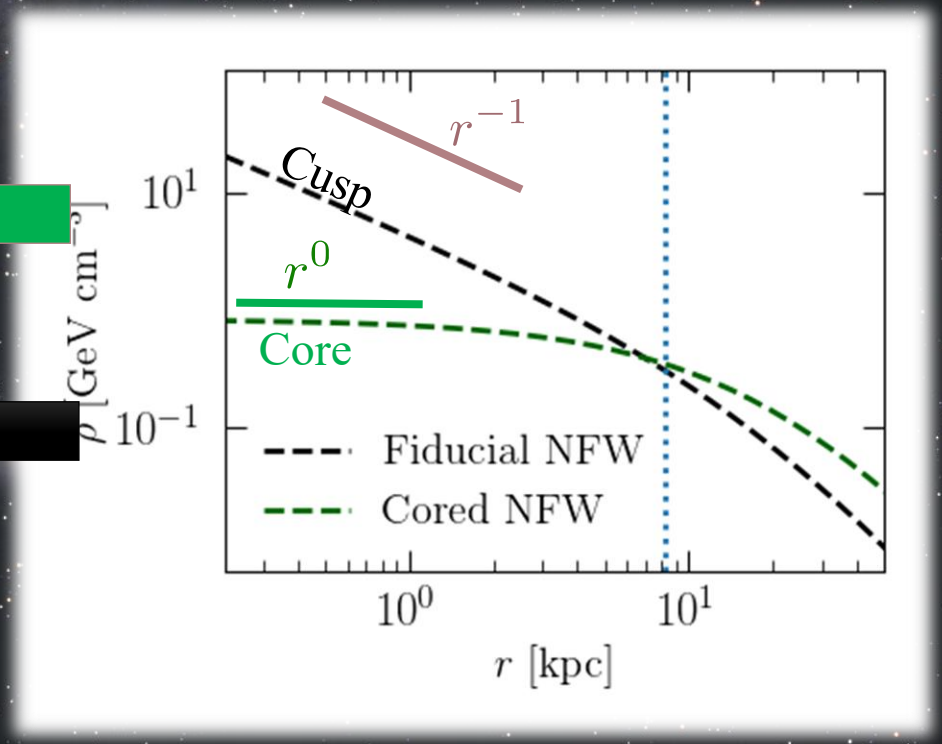
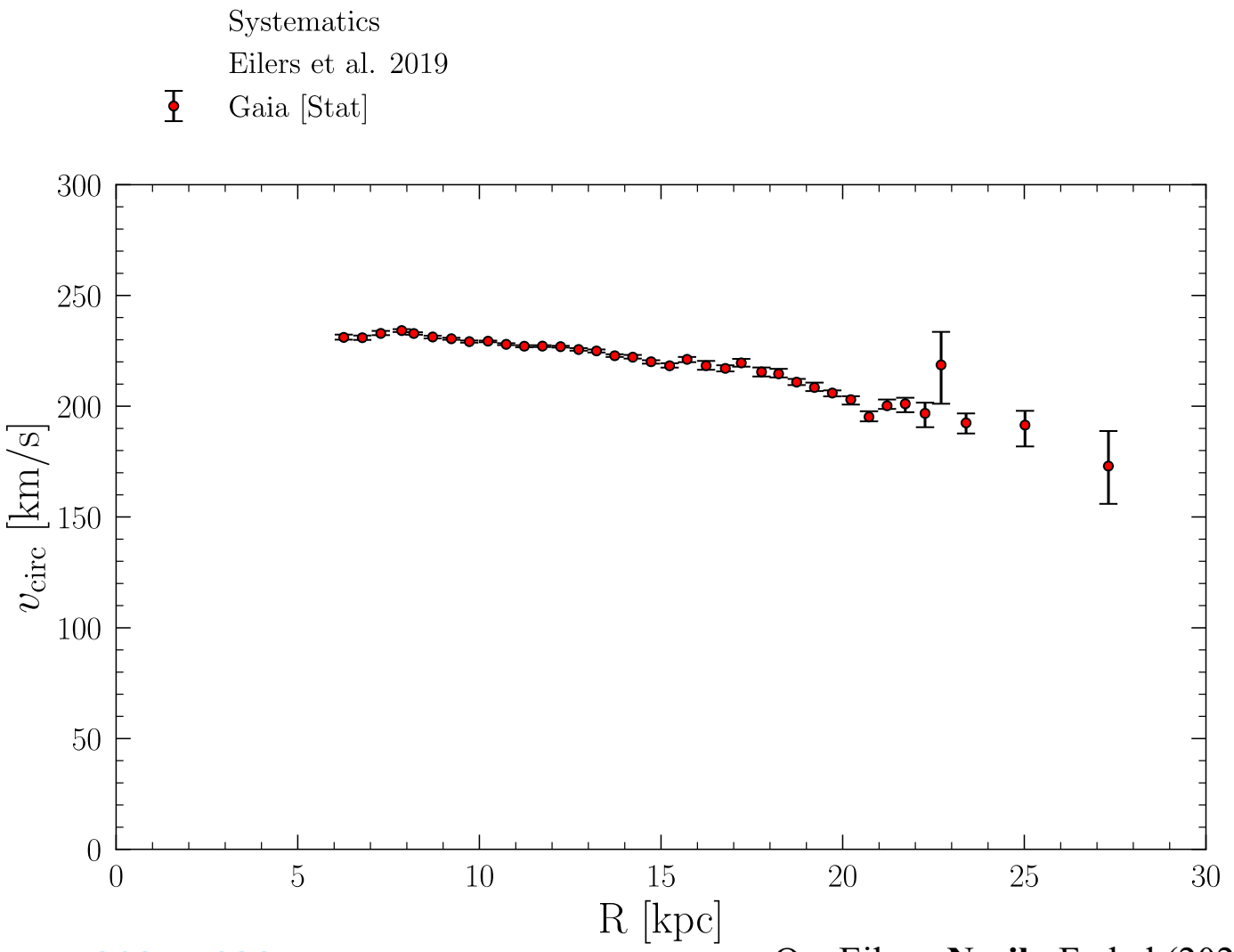


Lina Necib, MIT

LET'S CONSTRUCT THE MILKY WAY'S CIRCULAR VELOCITY



arXiv.2303.12838

Ou, Eilers, **Necib**, Frebel (2024)

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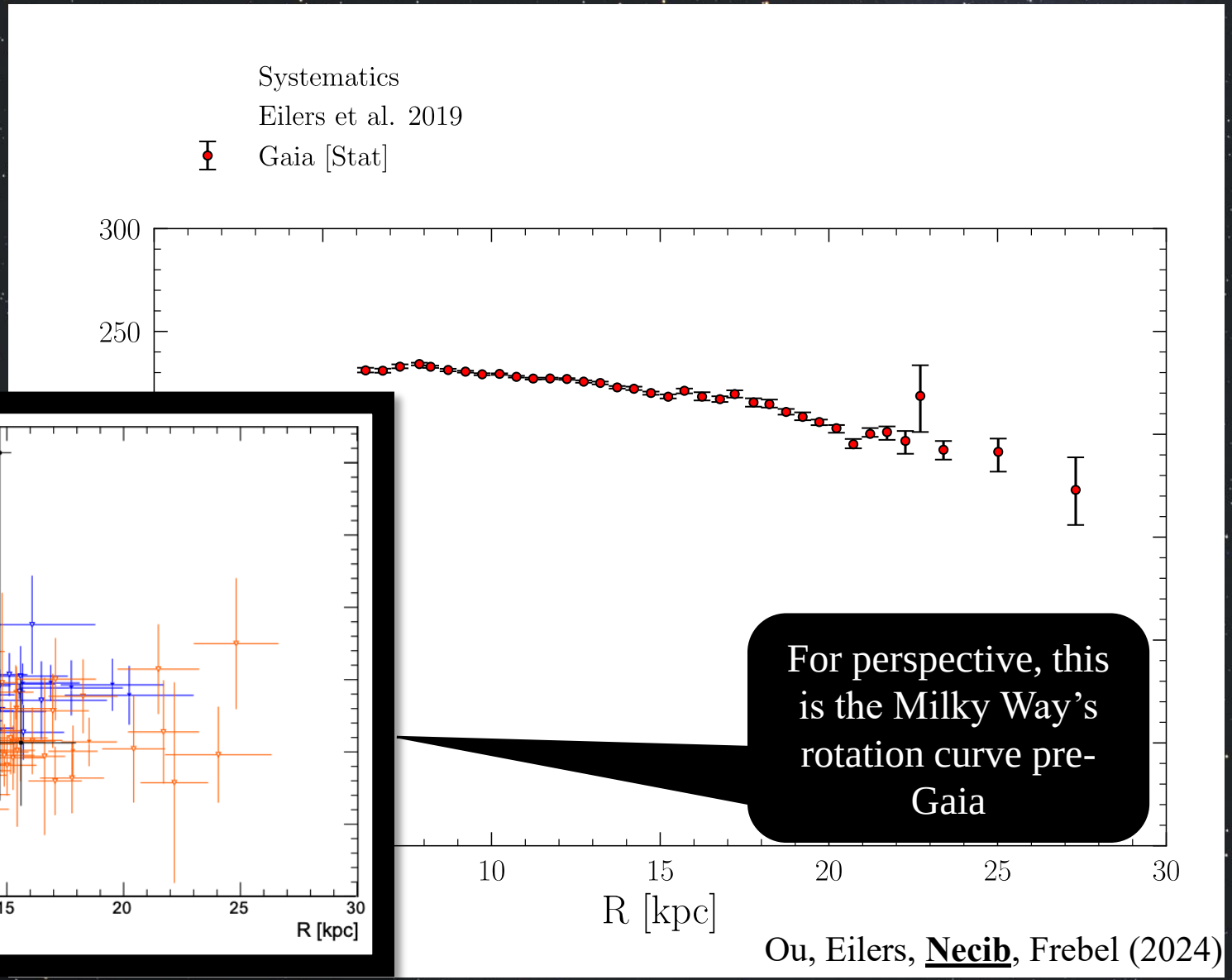

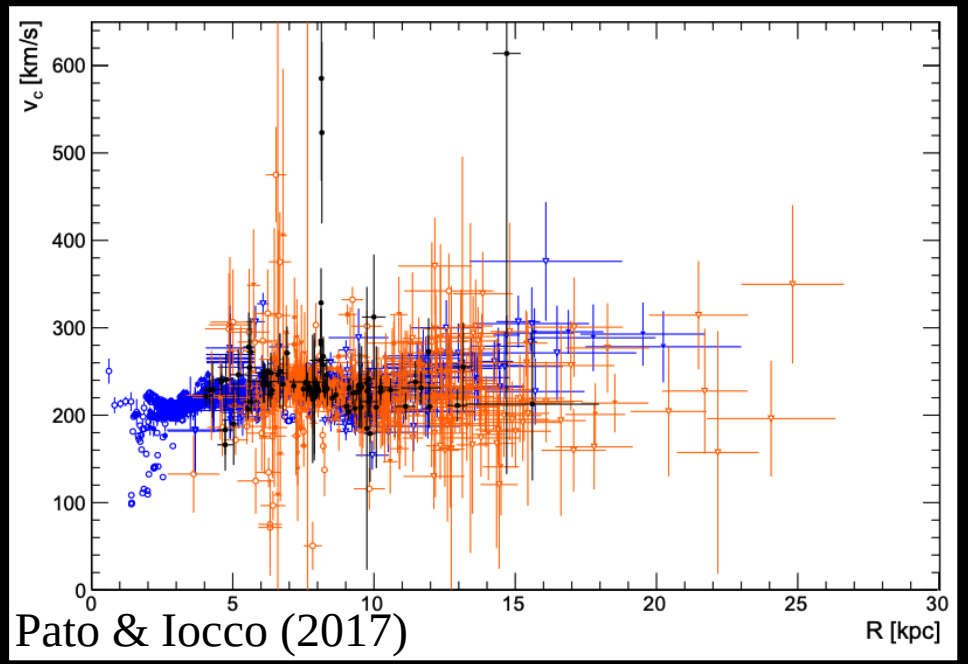

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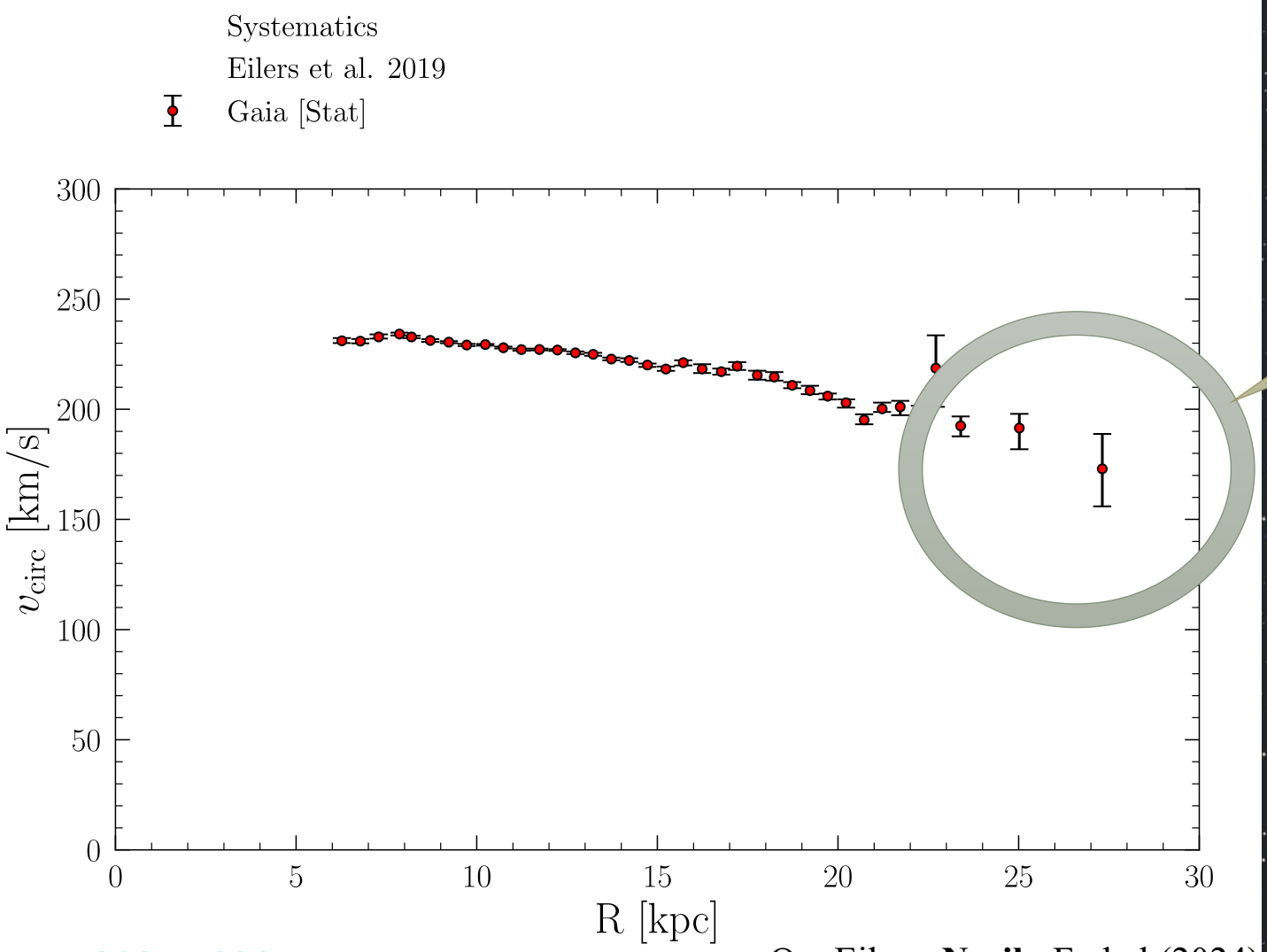

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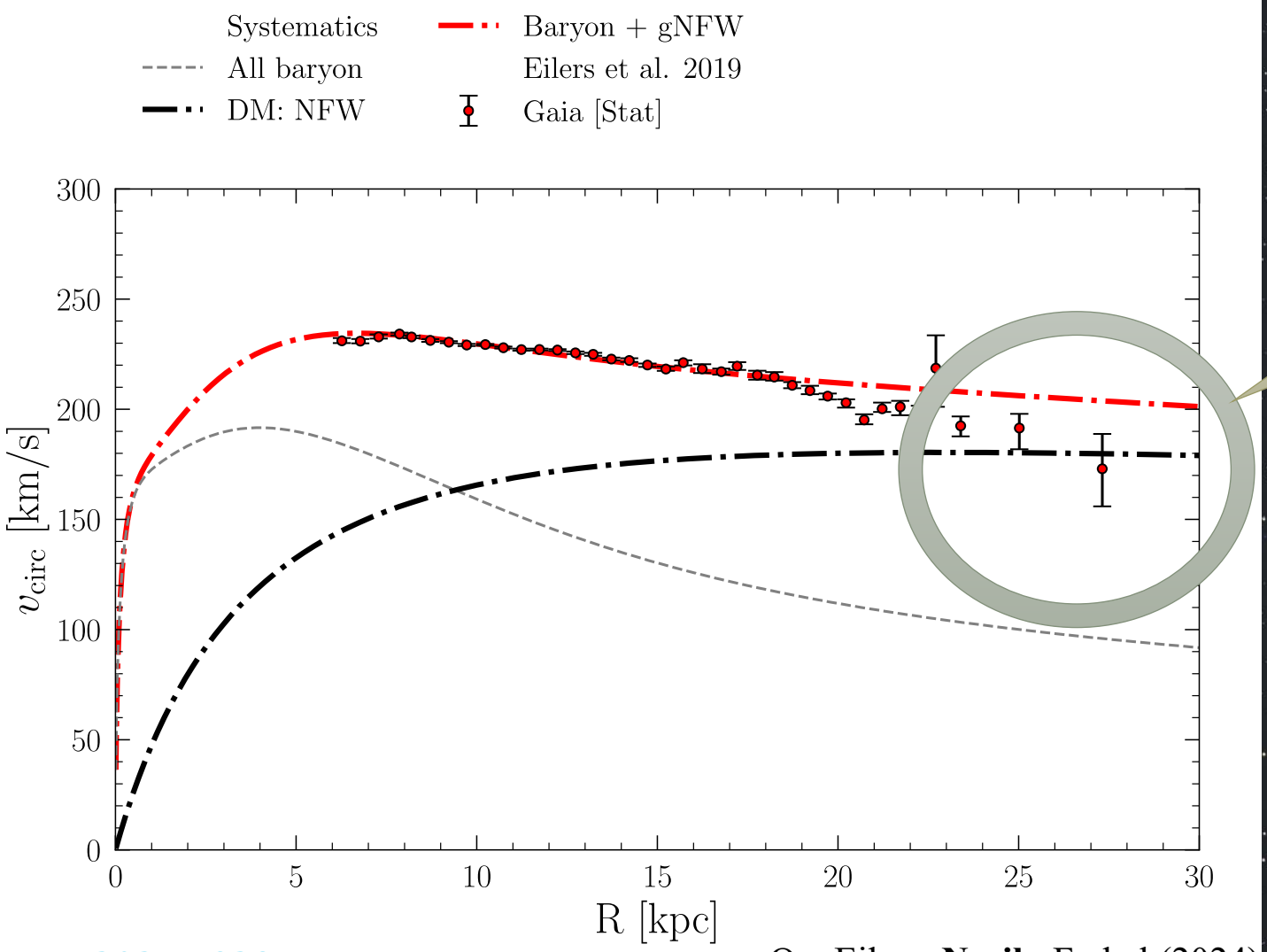
arXiv.2303.12838

Ou, Eilers, **Necib**, Frebel (2024)

LET'S CONSTRUCT THE MILKY WAY'S CIRCULAR VELOCITY



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Ou, Eilers, **Necib**, Frebel (2024)

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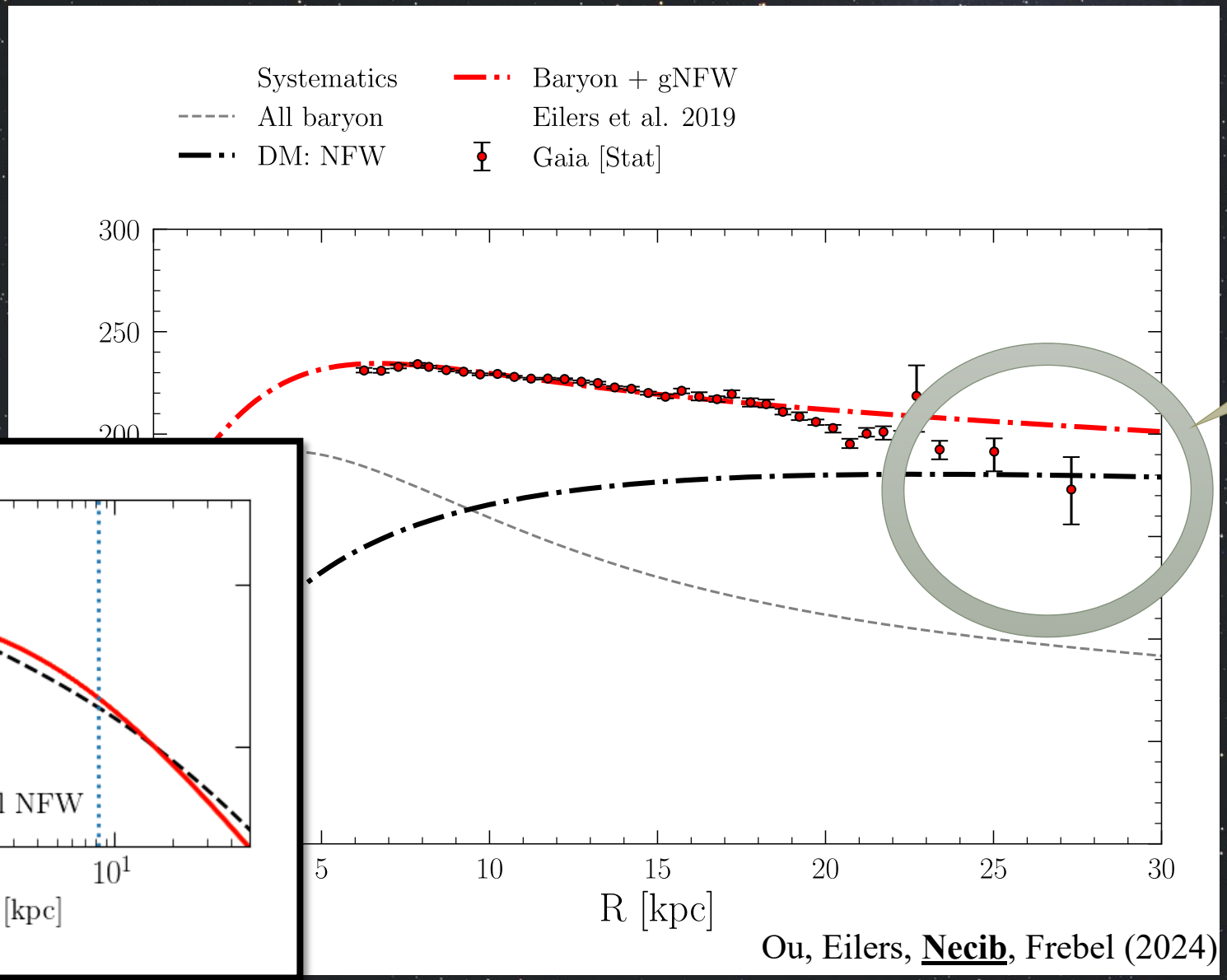

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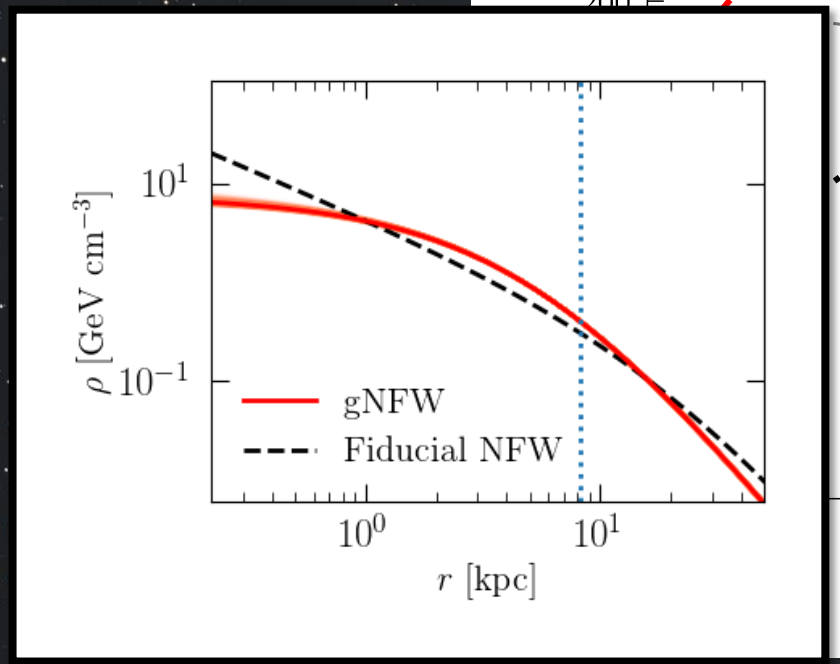
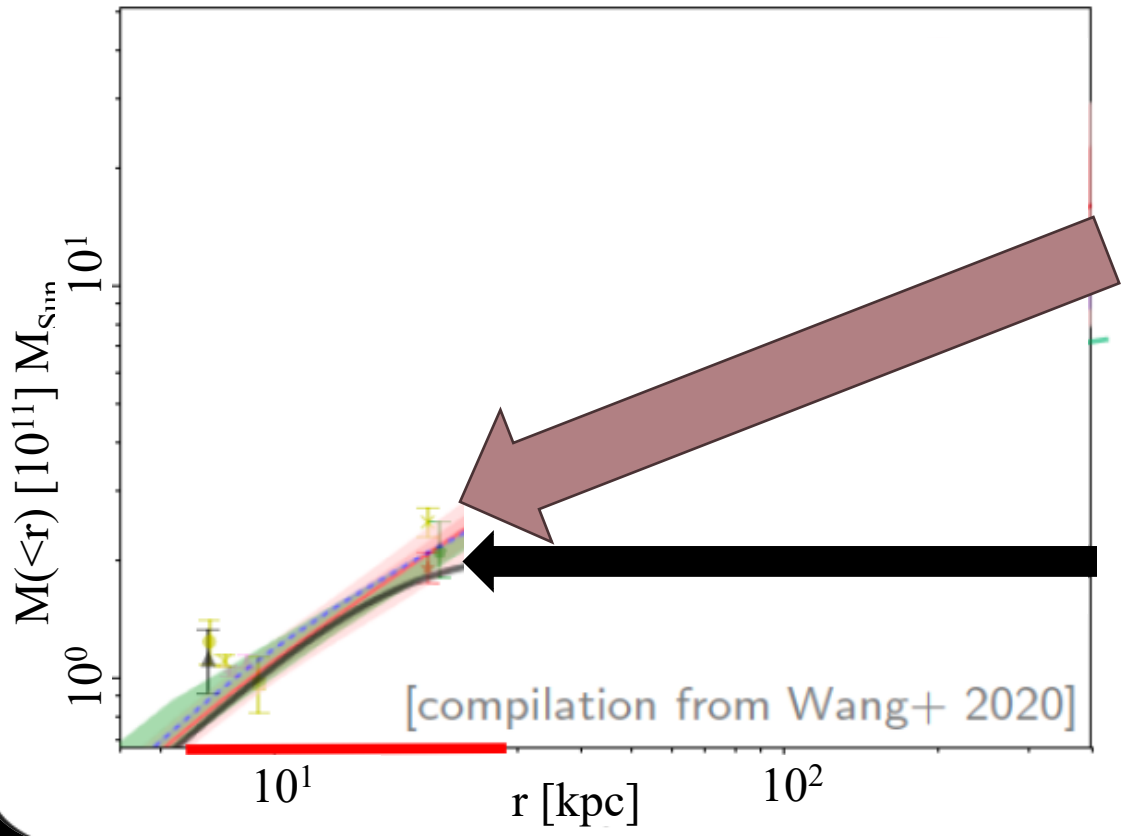


Ou, Eilers, **Necib**, Frebel (2024)

LETS PUT THAT CORED PROFILE IN CONTEXT.



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

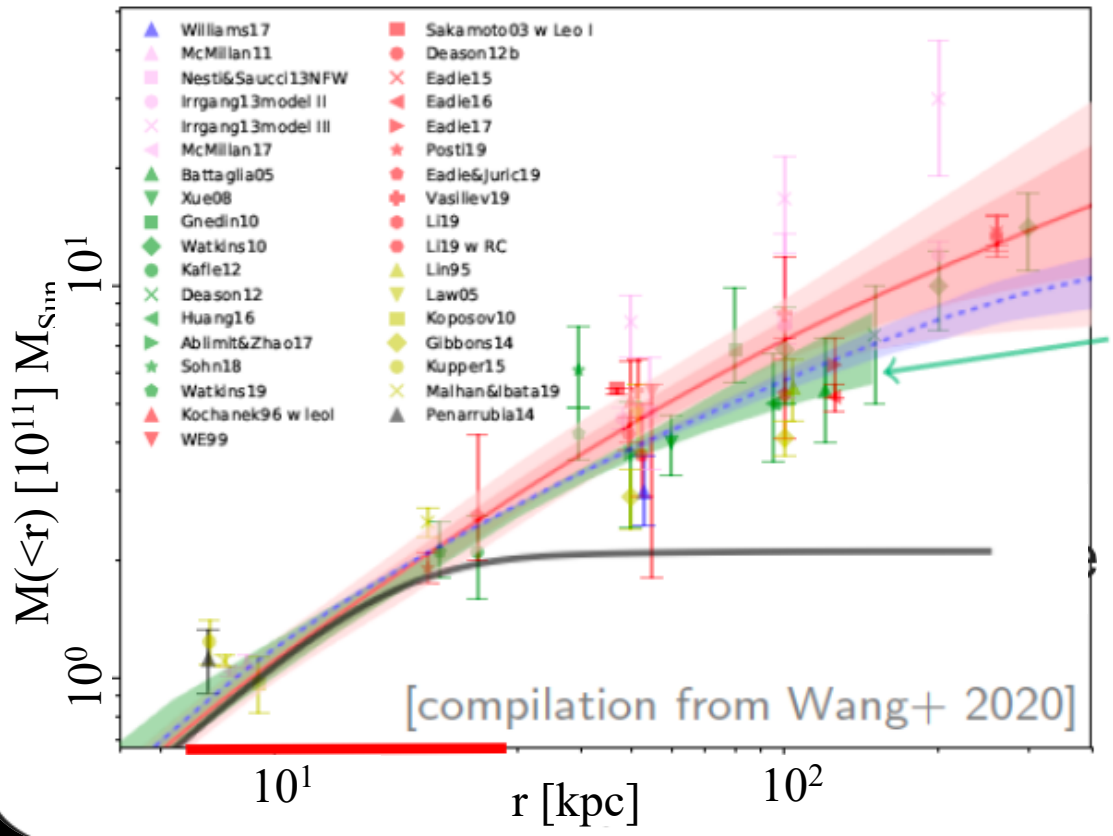
Sgr stream (incl. LMC) [Vasiliev+ 2021]

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

Best Fit from Ou, Eilers, Necib, Frebel (2024)

(Courtesy of Eugene Vasiliev)

SUCH CORED PROFILE IS IN TENSION WITH OTHER PROBES OF DARK MATTER IN THE MILKY WAY.



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Best Fit from Ou, Eilers, Necib, Frebel (2024)

(Courtesy of Eugene Vasiliev)

LET'S REVIEW THE ASSUMPTION WE MADE

Observational Selection Function

Axisymmetry

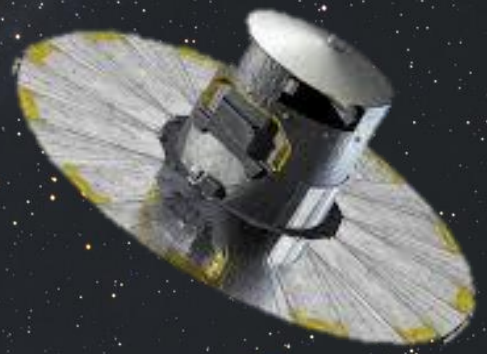
Dynamical Equilibrium

LET'S REVIEW THE ASSUMPTION WE MADE

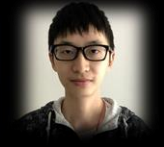
Observational Selection Function

Axisymmetry

Dynamical Equilibrium



Is Gaia picking some stars over others?
Is that biasing the results of our circular velocity measurements?



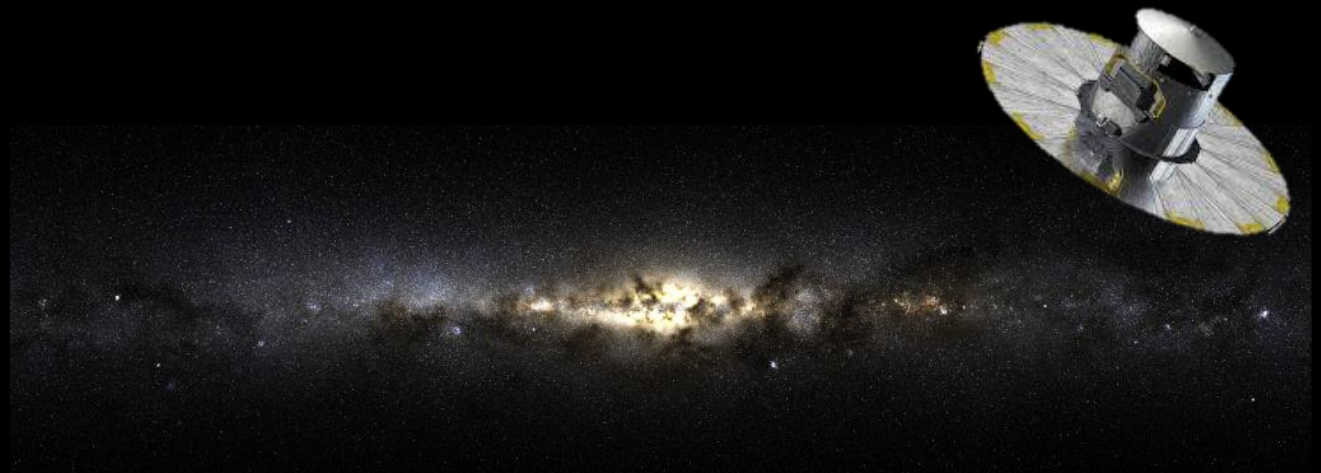
Tri Nguyen Xiaowei Ou

LET'S REVIEW THE ASSUMPTION WE MADE

Observational Selection Function

Axisymmetry

Dynamical Equilibrium



Synthetic Gaia Survey (DR3) of a Simulated FIRE Galaxy

Is Gaia picking some stars over others?
Is that biasing the results of our circular velocity measurements?

Sanderson et al. (2020)
Nguyen, Ou, Panithanpaisal, Shipp, **Necib**, Sanderson, Wetzel (2024)

Publicly available at https://fire.northwestern.edu/ananke/

Tri Nguyen

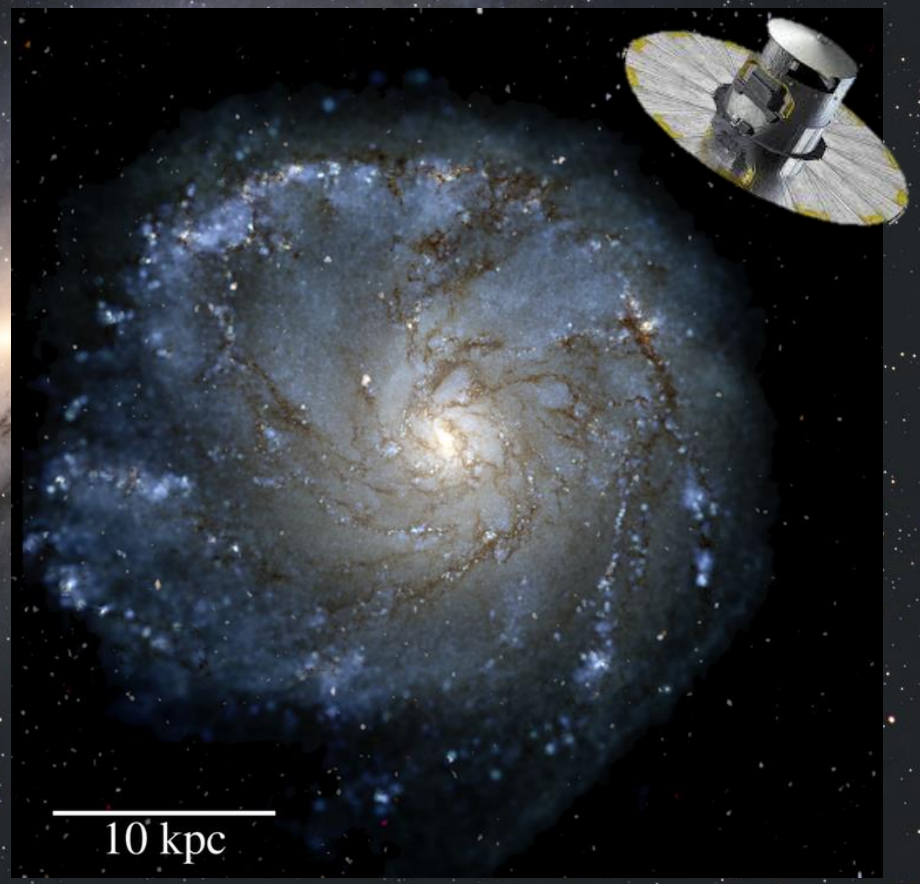
Xiaowei Ou

ARE THESE REASONABLE ASSUMPTIONS?

Observational Selection Function

Axisymmetry

Dynamical Equilibrium



Produced synthetic surveys and found no effect of the observational selection function

Nguyen, Ou,…, **Necib**, et al. (2024)
Ou, **Necib**, et al. (2025)

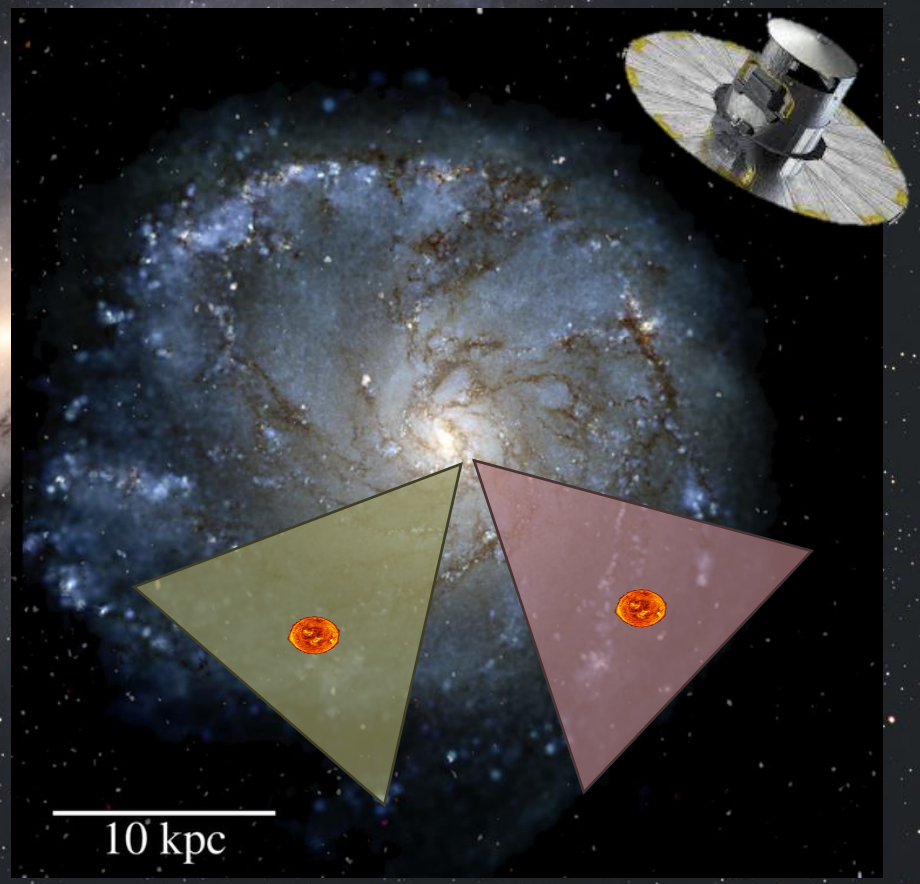
Lina Necib, MIT

ARE THESE REASONABLE ASSUMPTIONS?

Observational Selection Function

Axisymmetry

Dynamical Equilibrium



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Redid the analysis on different slices, and indeed there is a large effect

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Observational Selection Function

✗

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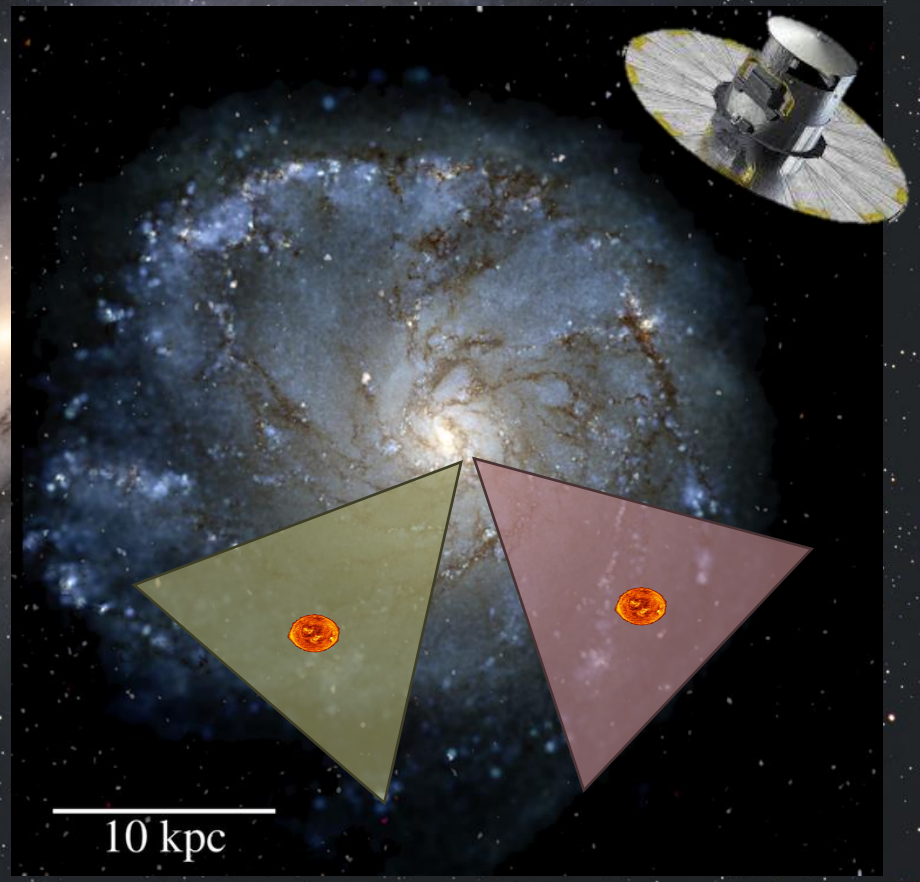

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We know that the Galaxy is not in equilibrium as evidenced by the different structures we found.

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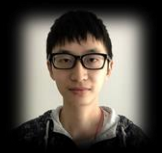
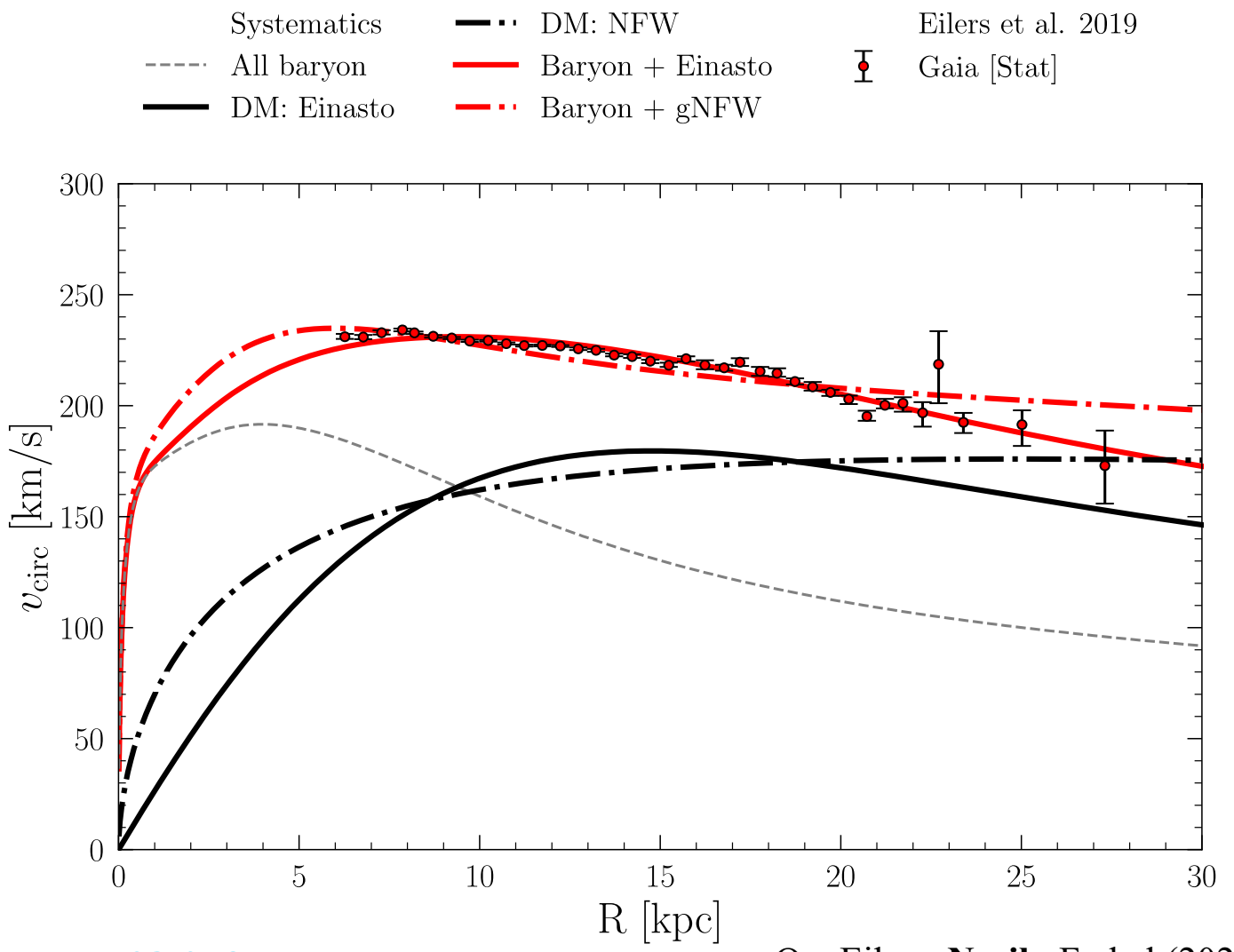
LET'S GO BACK TO THIS, WHAT ARE OUR REAL SYSTEMATICS?





arXiv:2503.05877

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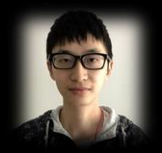

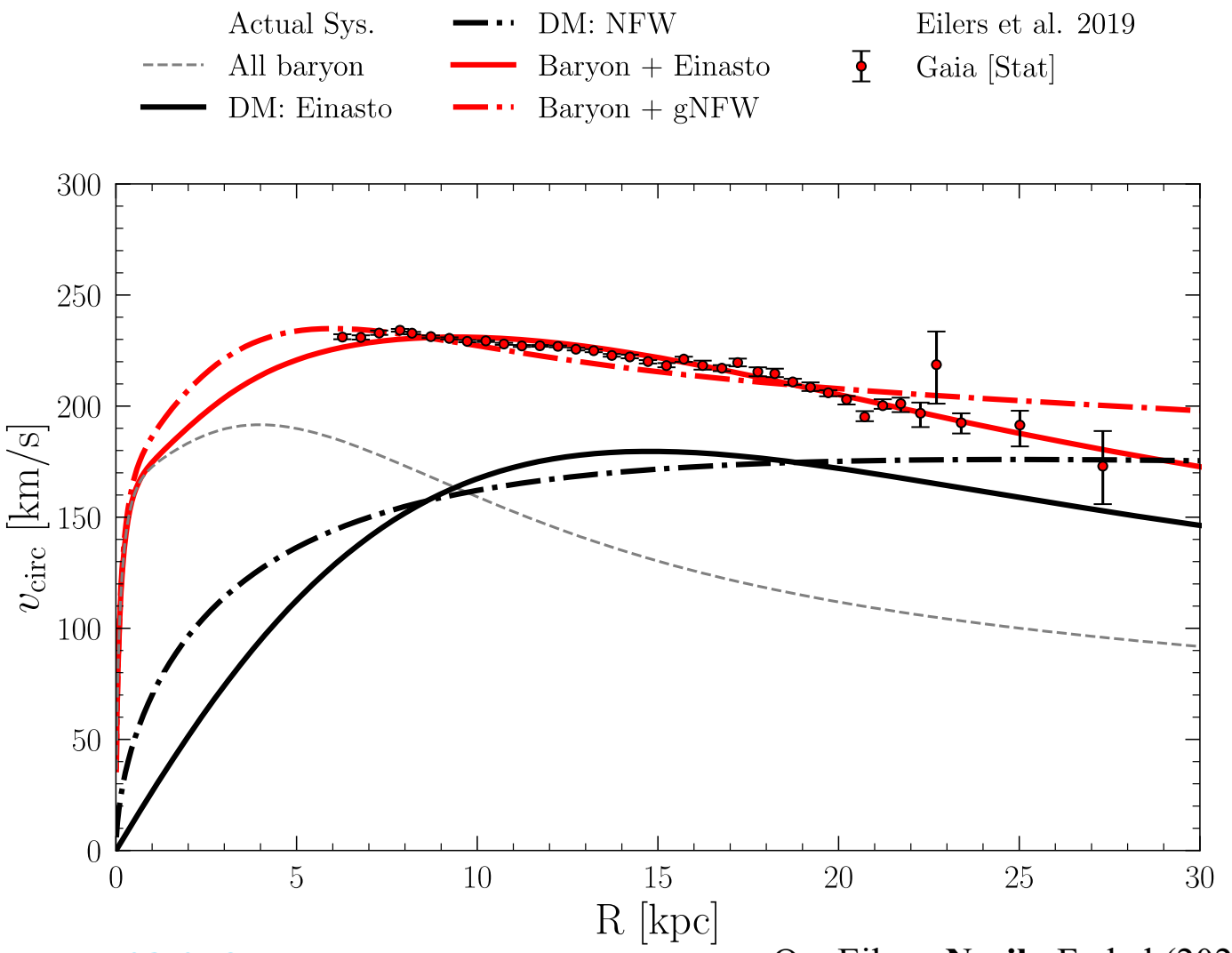

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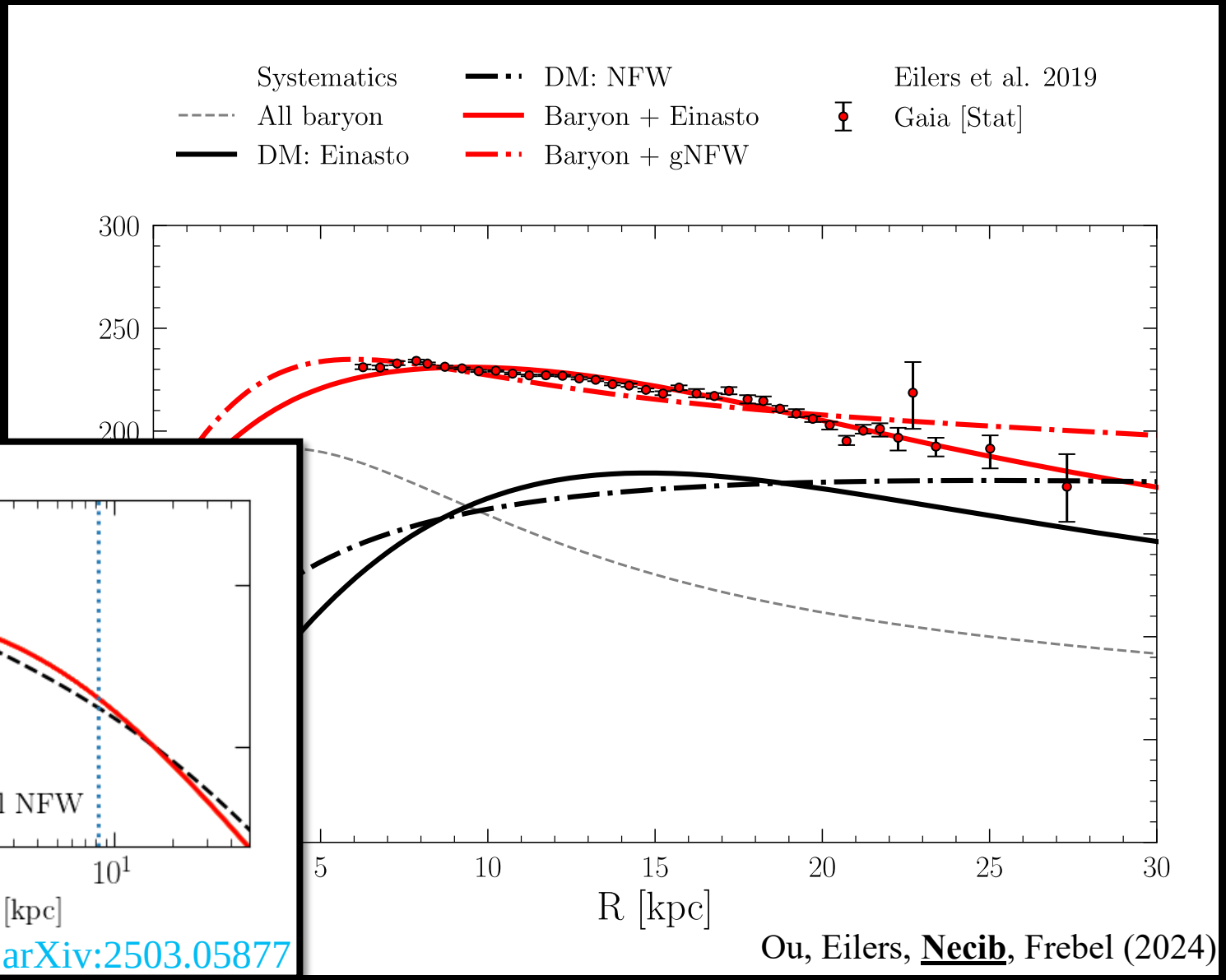

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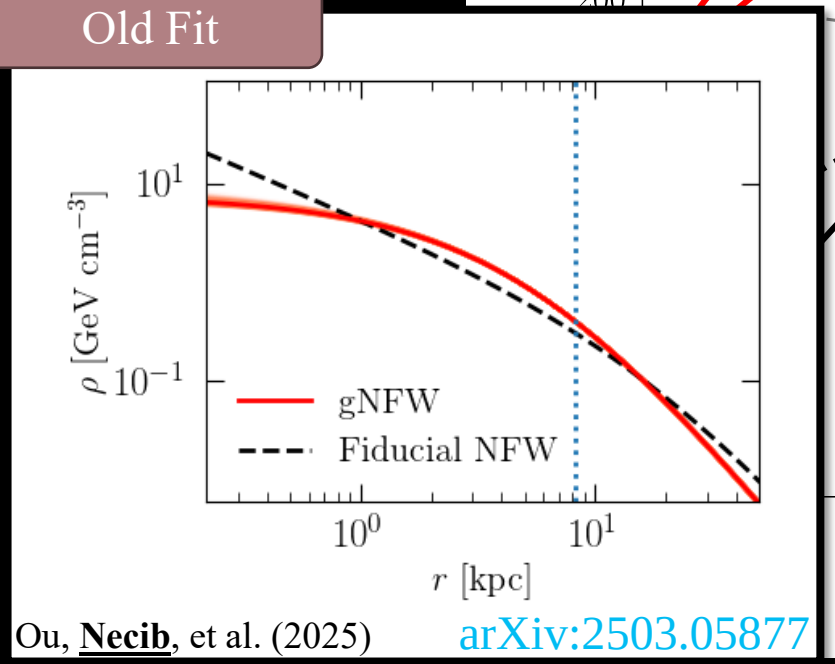
Old Fit



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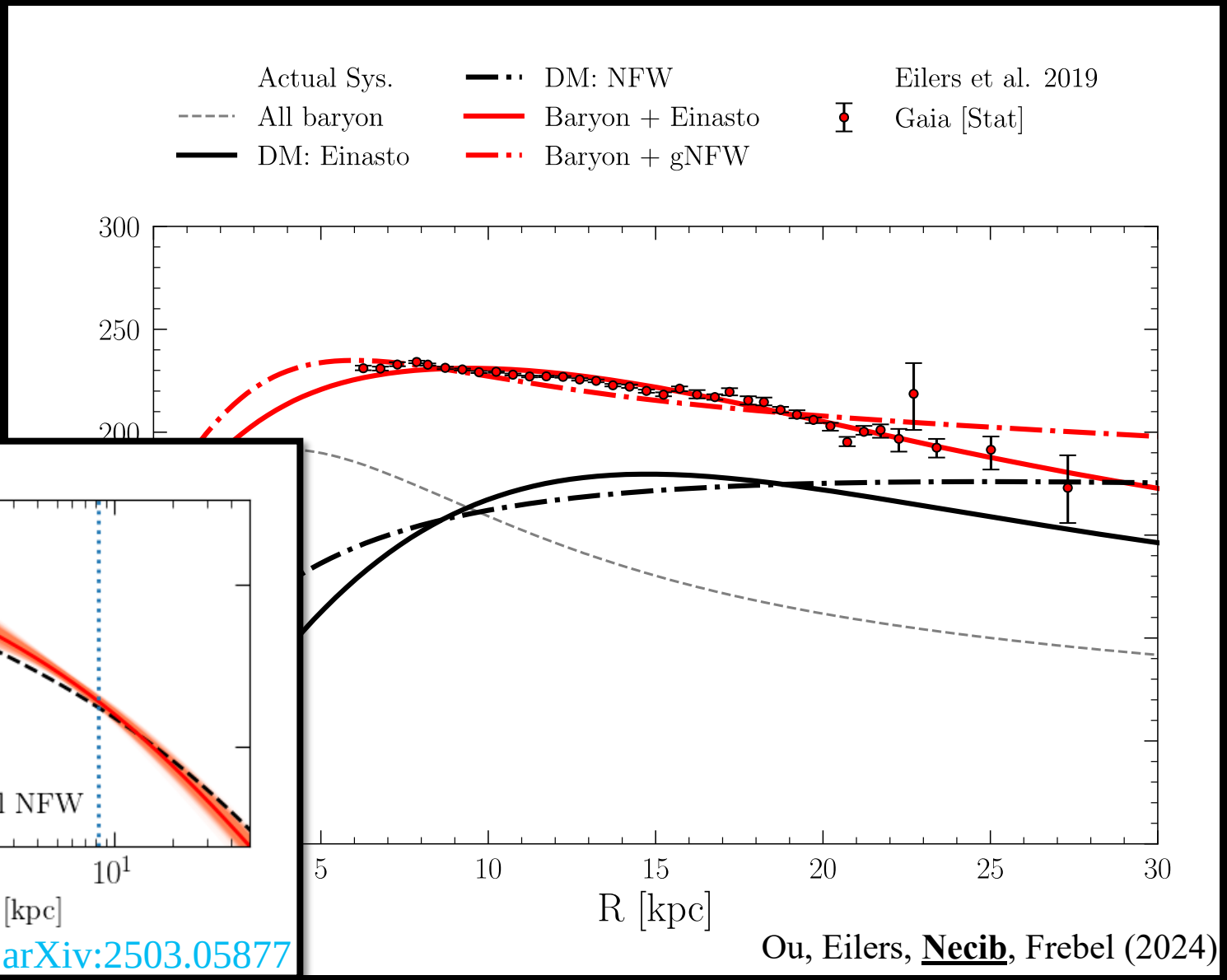

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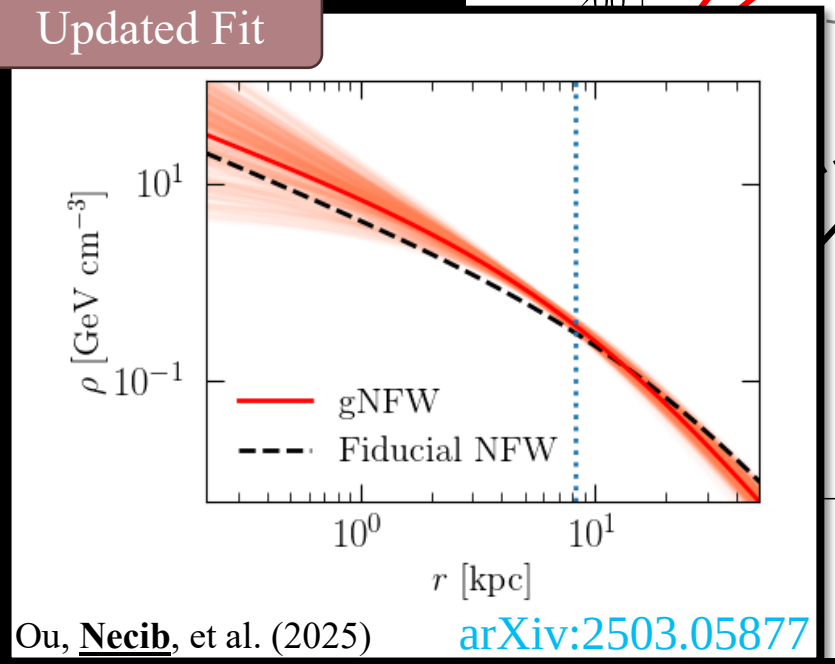
Updated Fit



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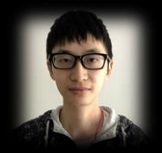

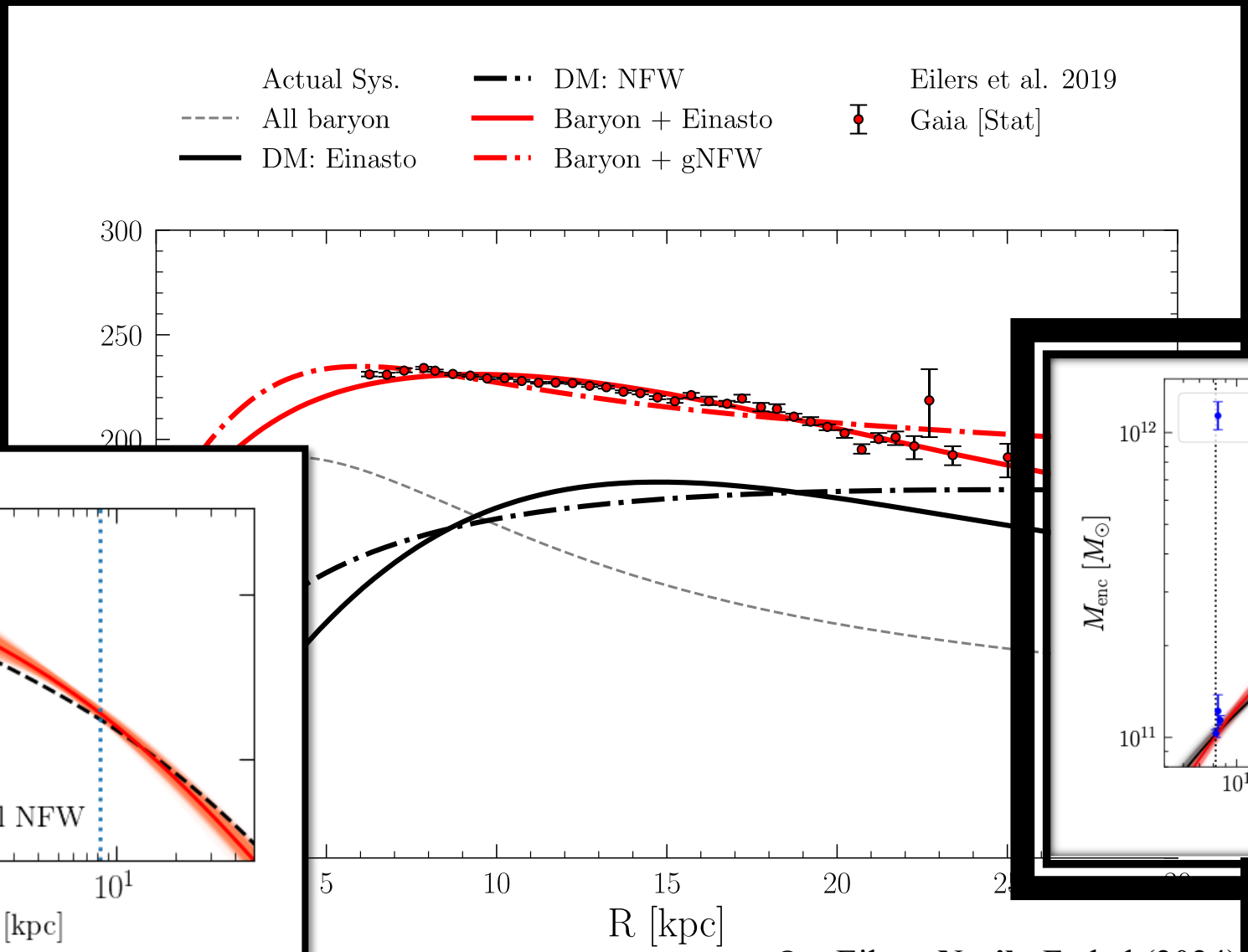

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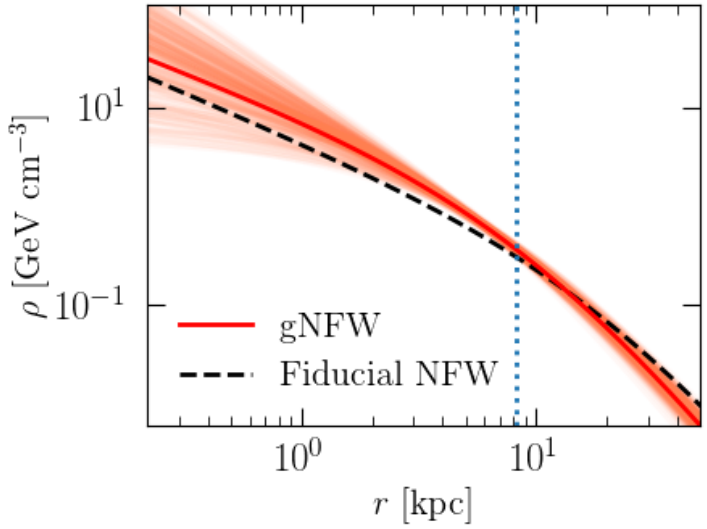

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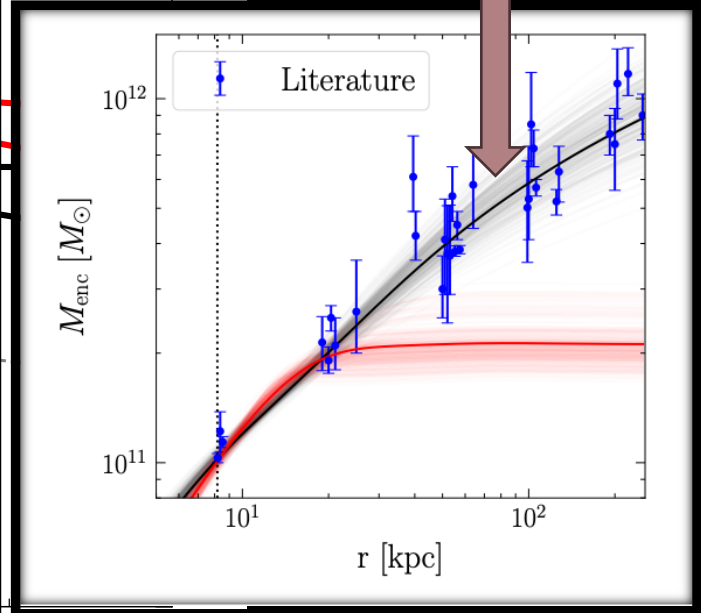
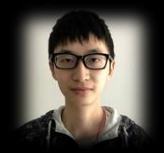
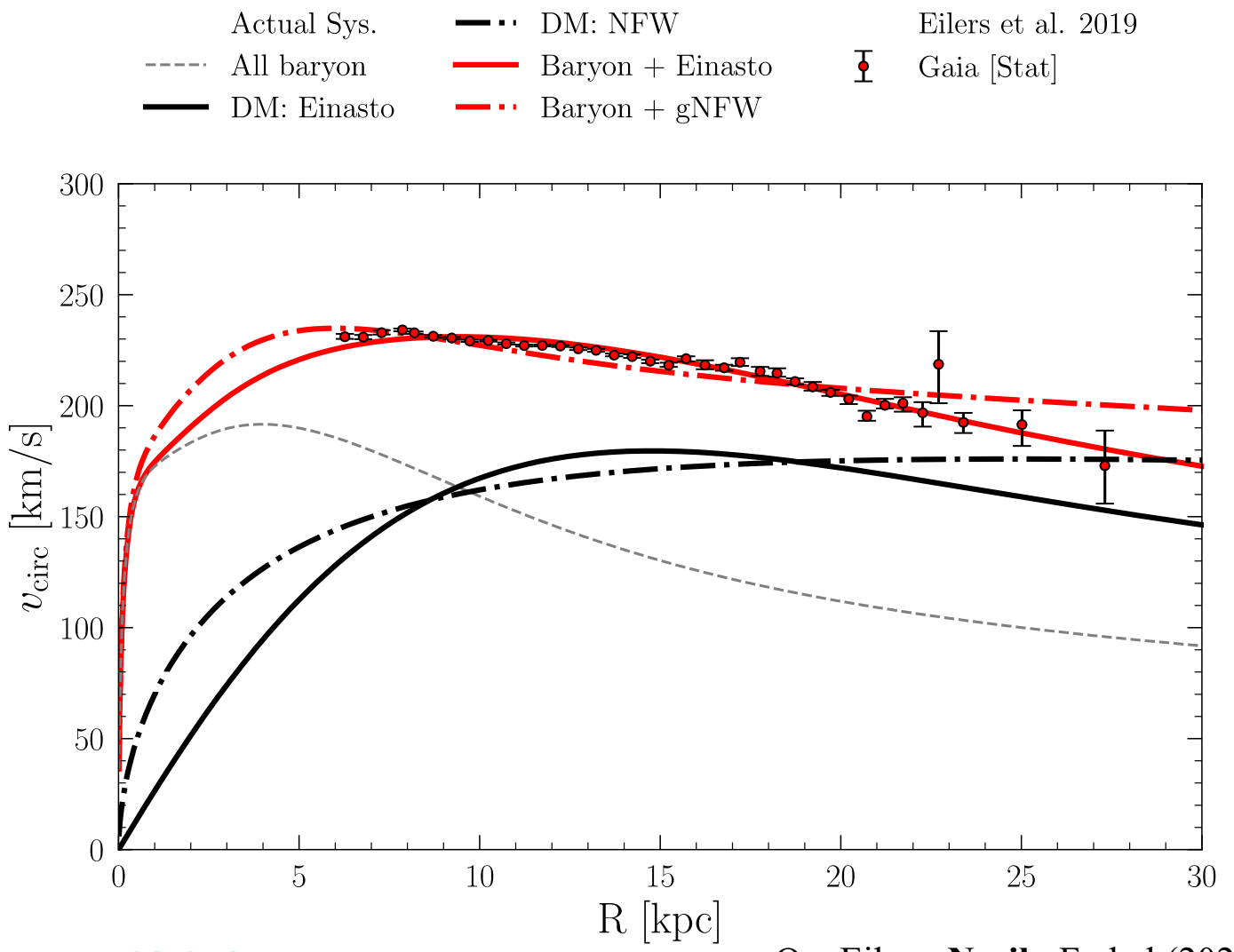


WE HAVE A BETTER FIT, THAT IS NOT IN TENSION, BUT WE STILL NEED TO SOLVE DARK MATTER...





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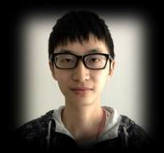

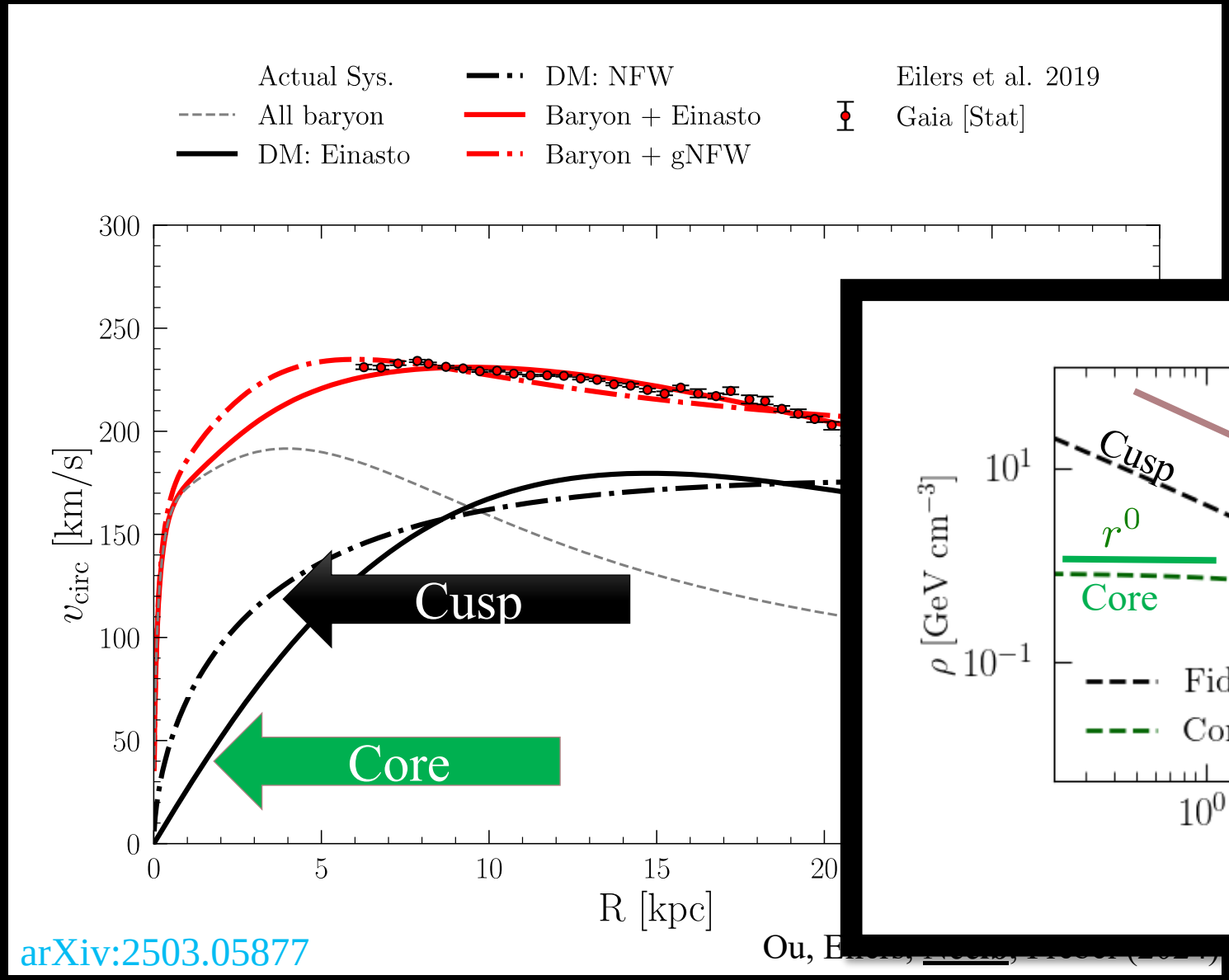

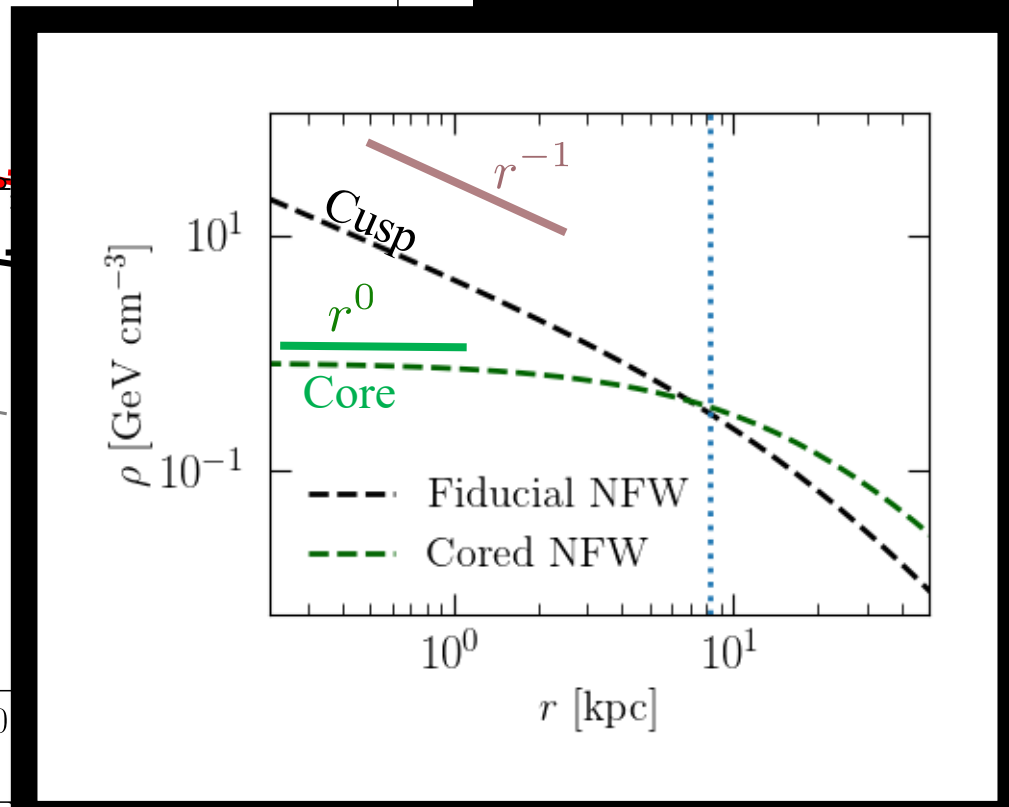

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Ou, **Necib**, et al. (2025)

Ou, E

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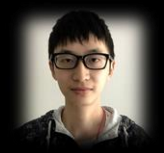
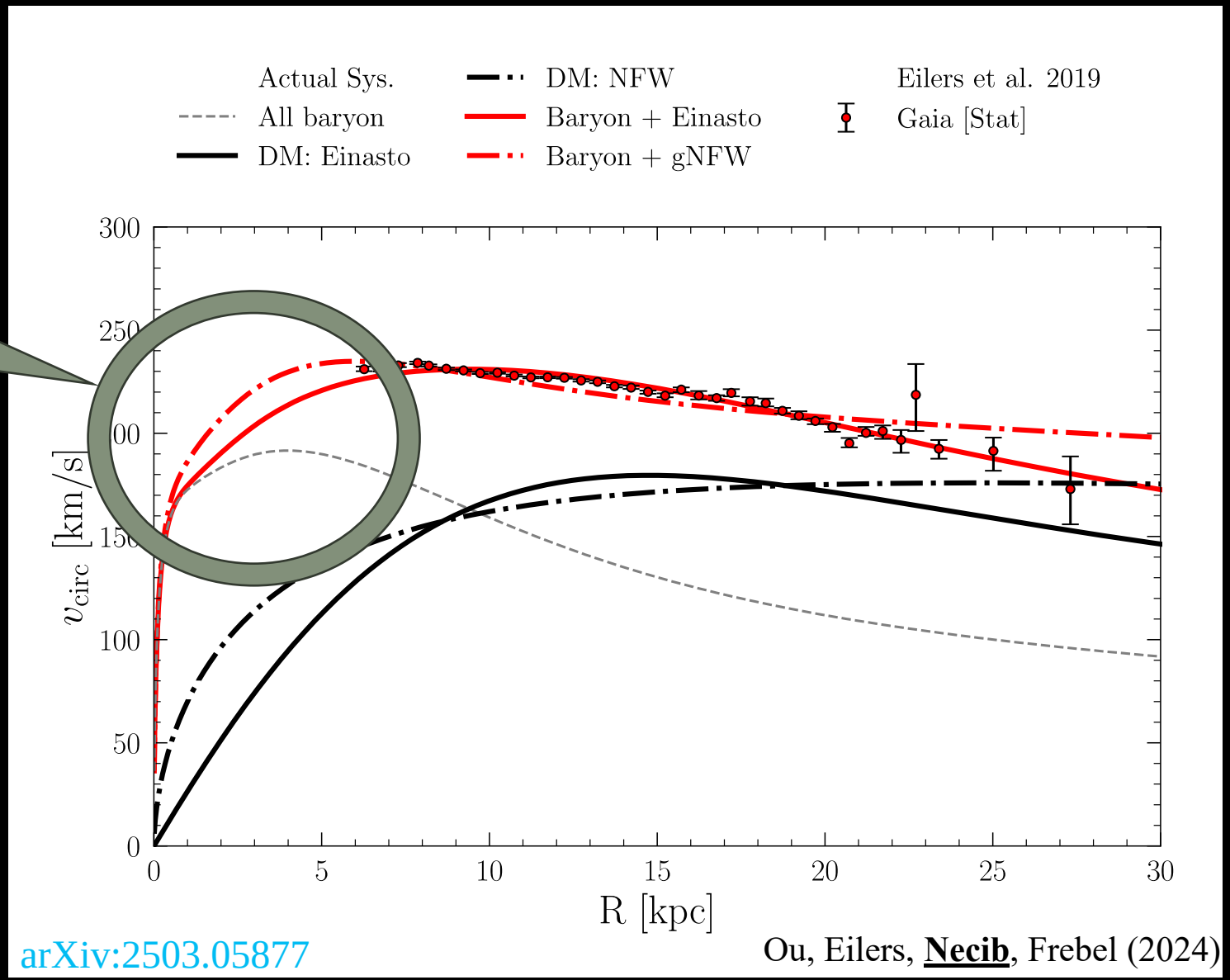


What I really want, is data here!



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BUT DUST...

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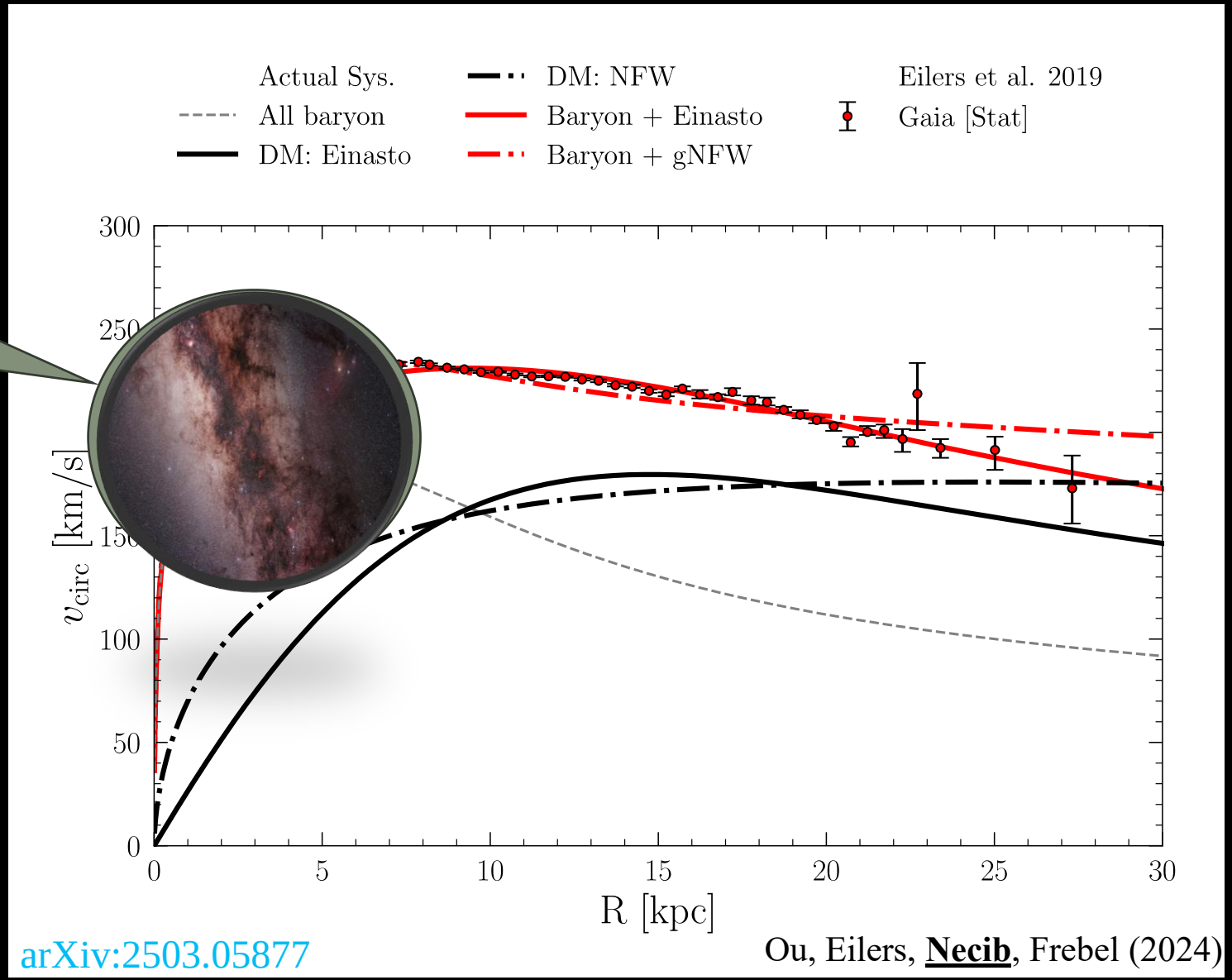

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Ou, Eilers, **Necib**, Frebel (2024)

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WHAT I NEED THEN IS SEE-THROUGH-DUST GLASSES

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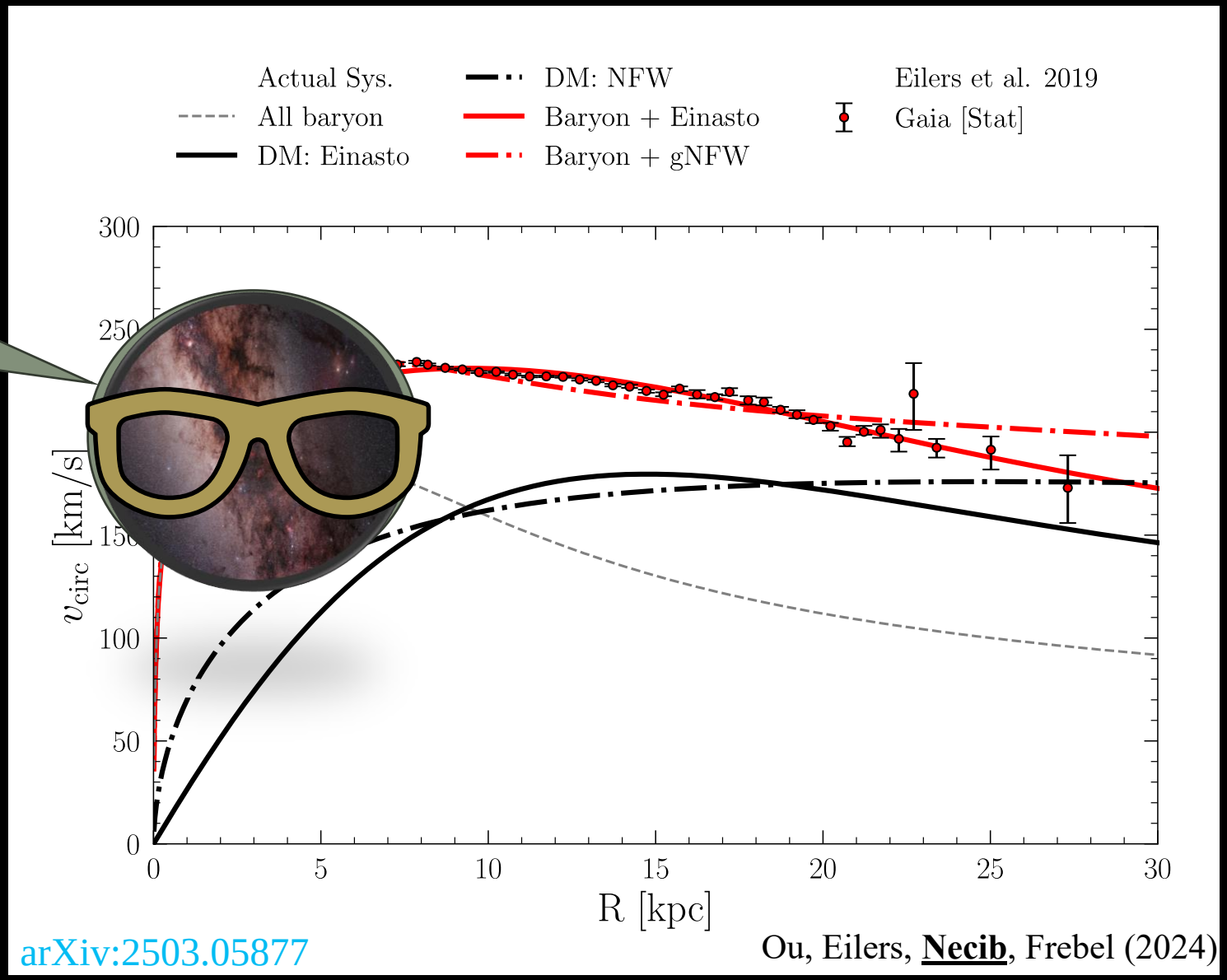

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WE ACTUALLY HAVE SEE-THROUGH-DUST GLASSES…

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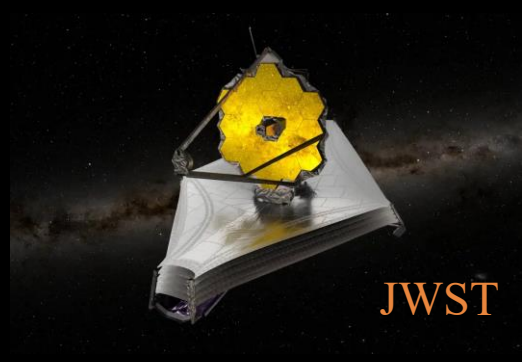

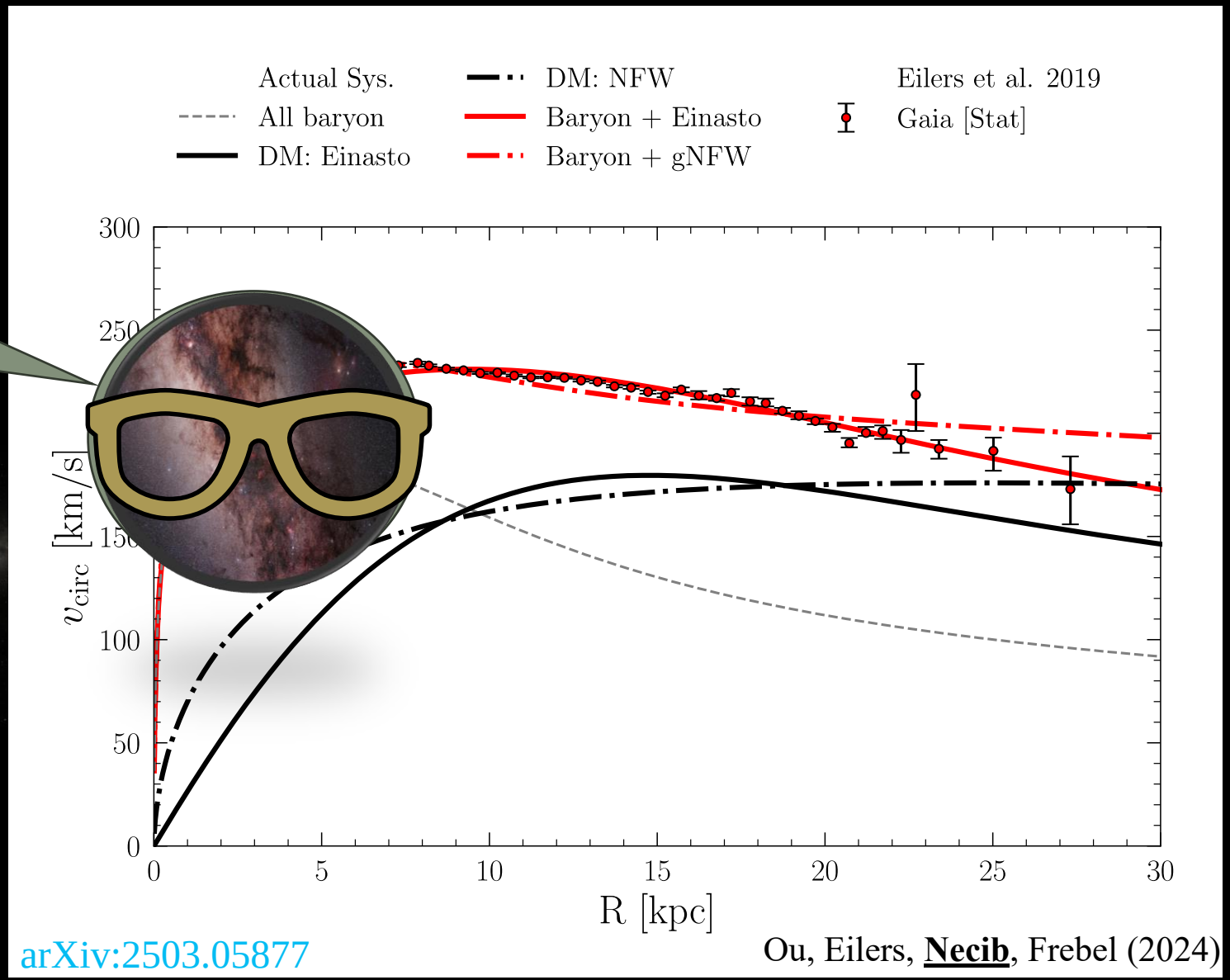

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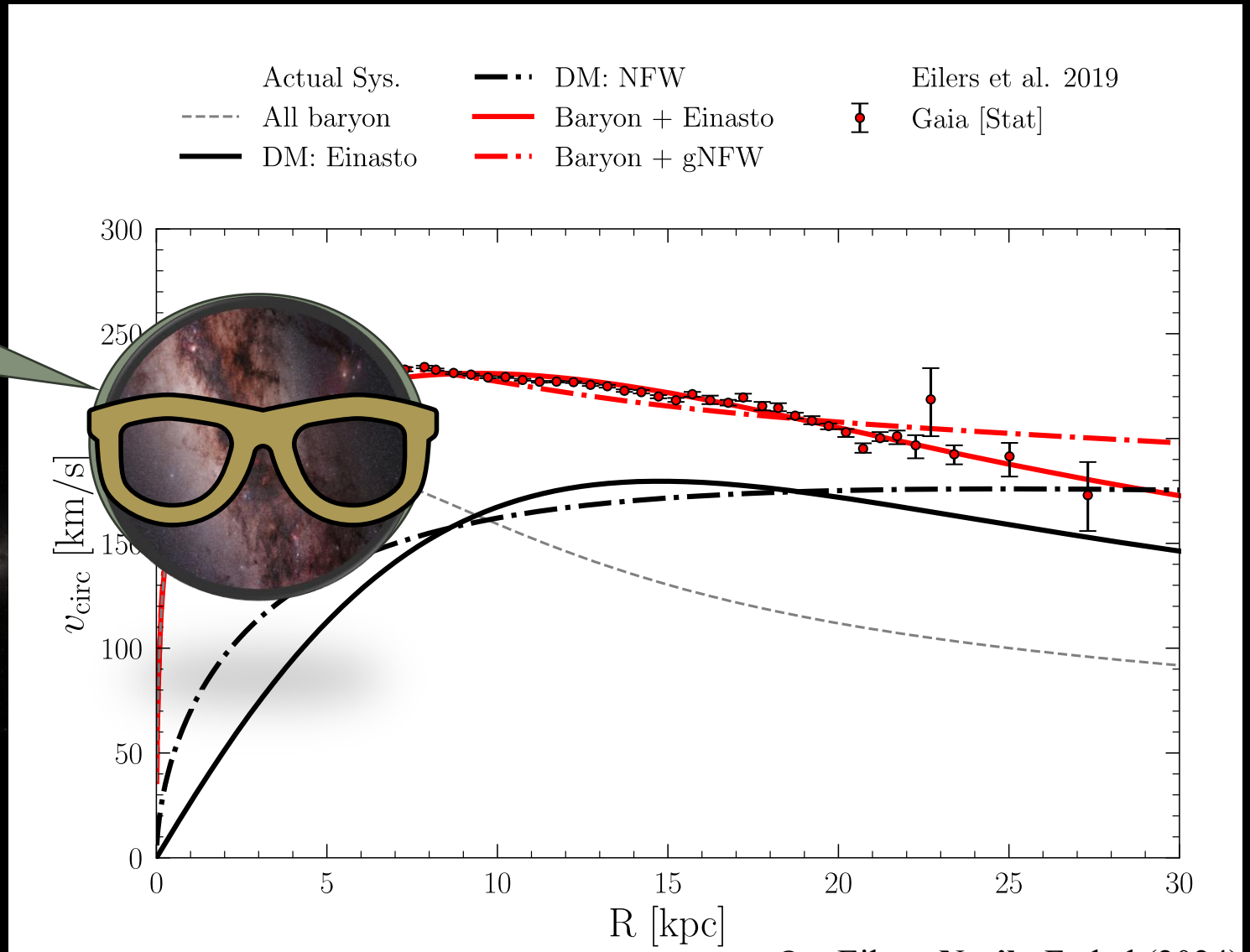

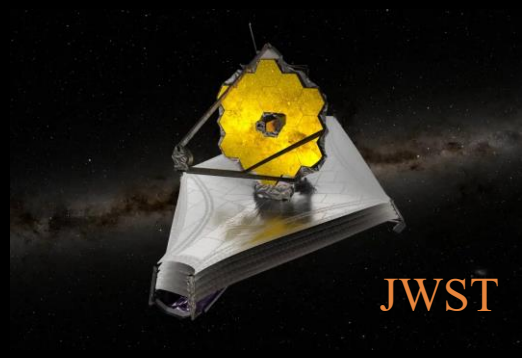

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IN THE MEANTIME, LET'S HAVE THEORY GLASSES

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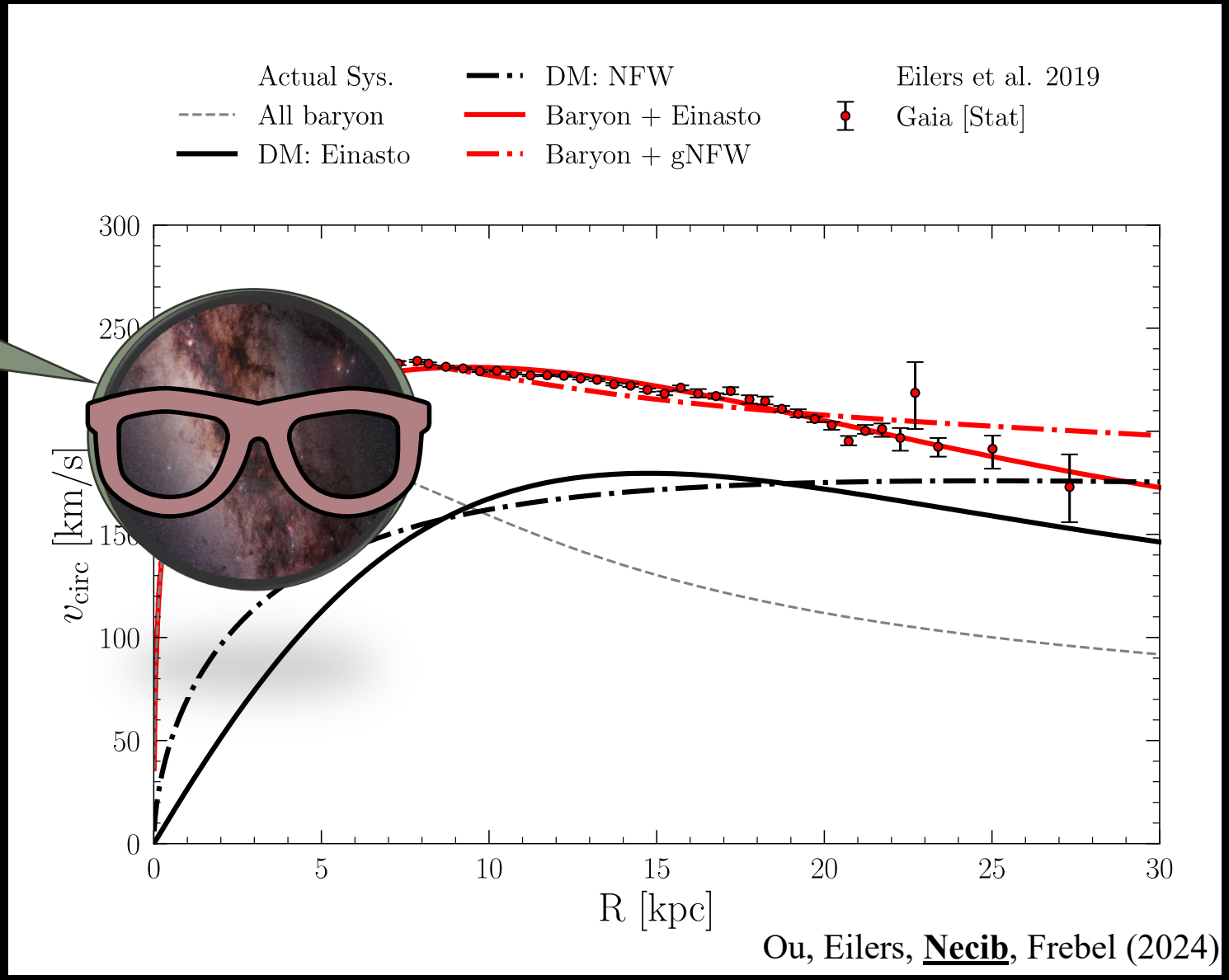

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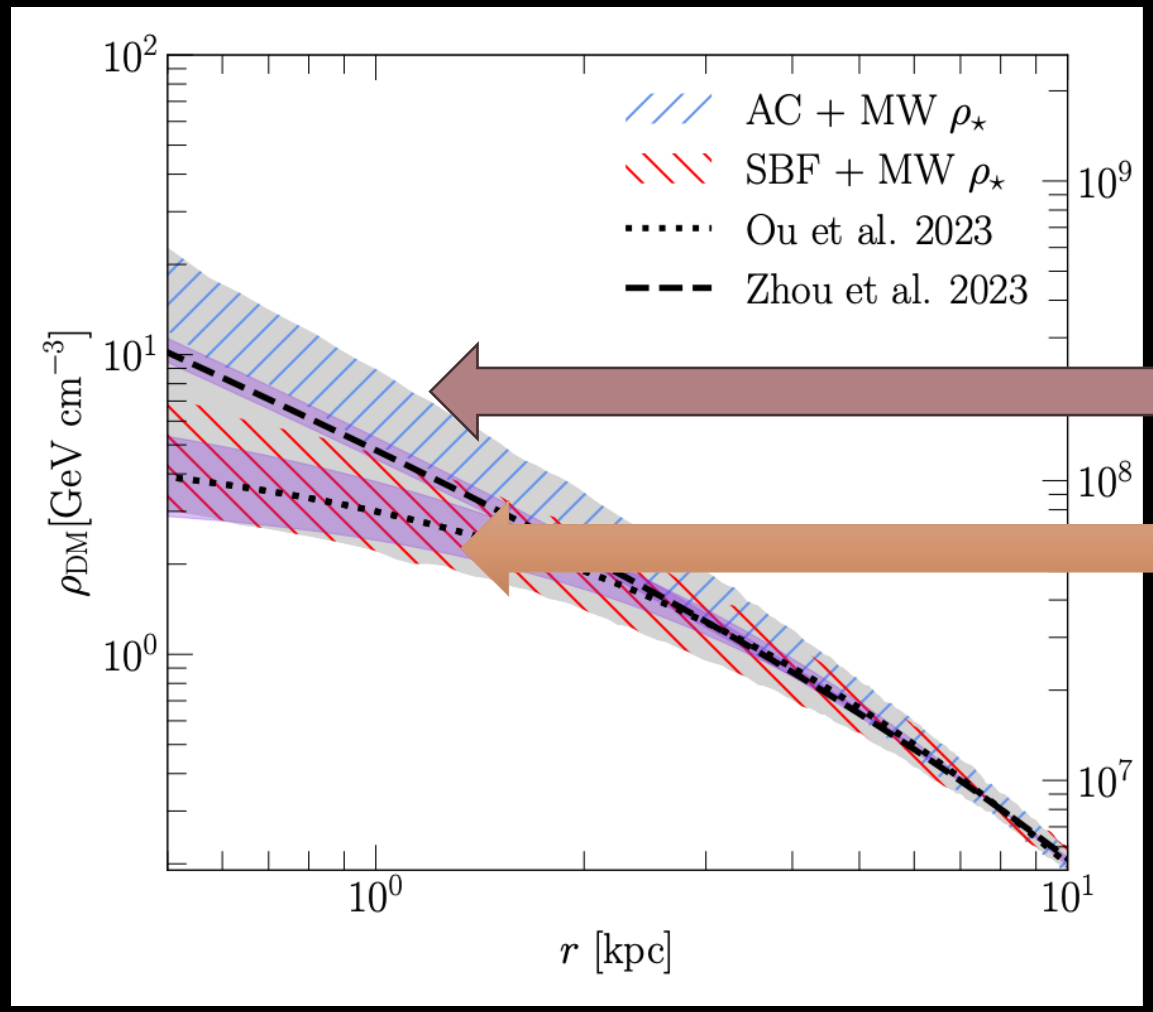
LET'S QUANTIFY OUR IGNORANCE BY SETTING A SYSTEMATIC BAND FOR THE MILKY WAY

Abdelaziz Hussein



Adiabatic Contraction density profile based on the Milky Way observed stellar distribution

Strong Baryonic Feedback model from FIRE-2, assuming the Milky Way observed stellar distribution

Hussein, **Necib**, Kaplinghat et al. (2025) arXiv:2501.14868

Lina Necib, MIT

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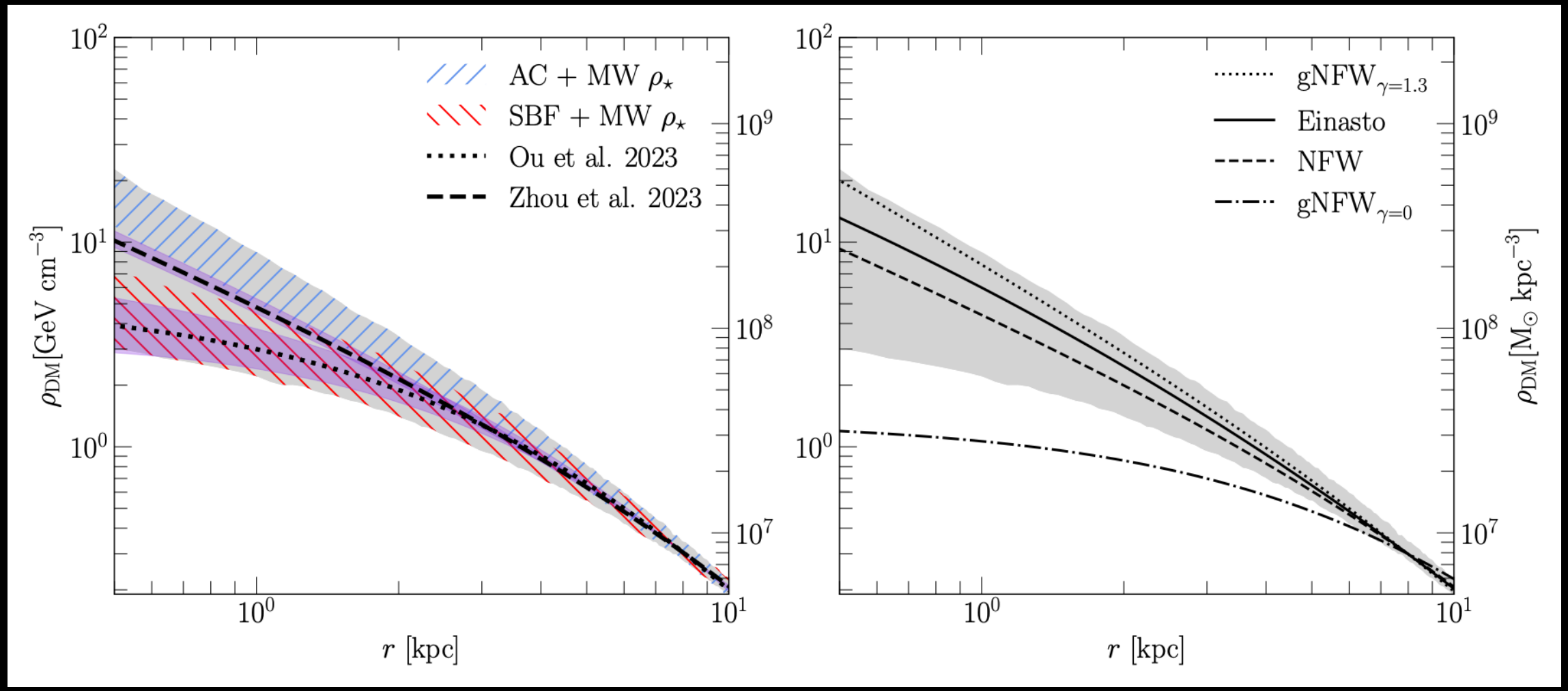

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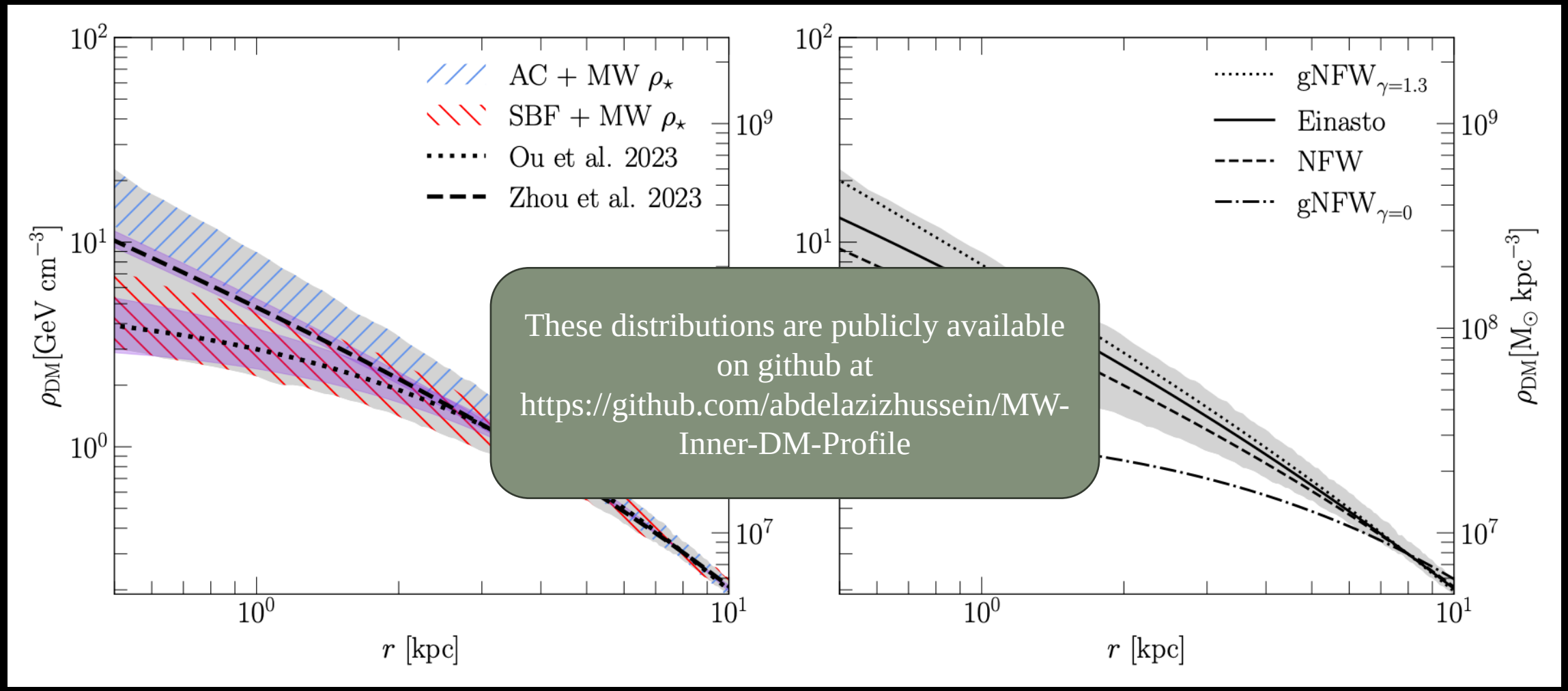


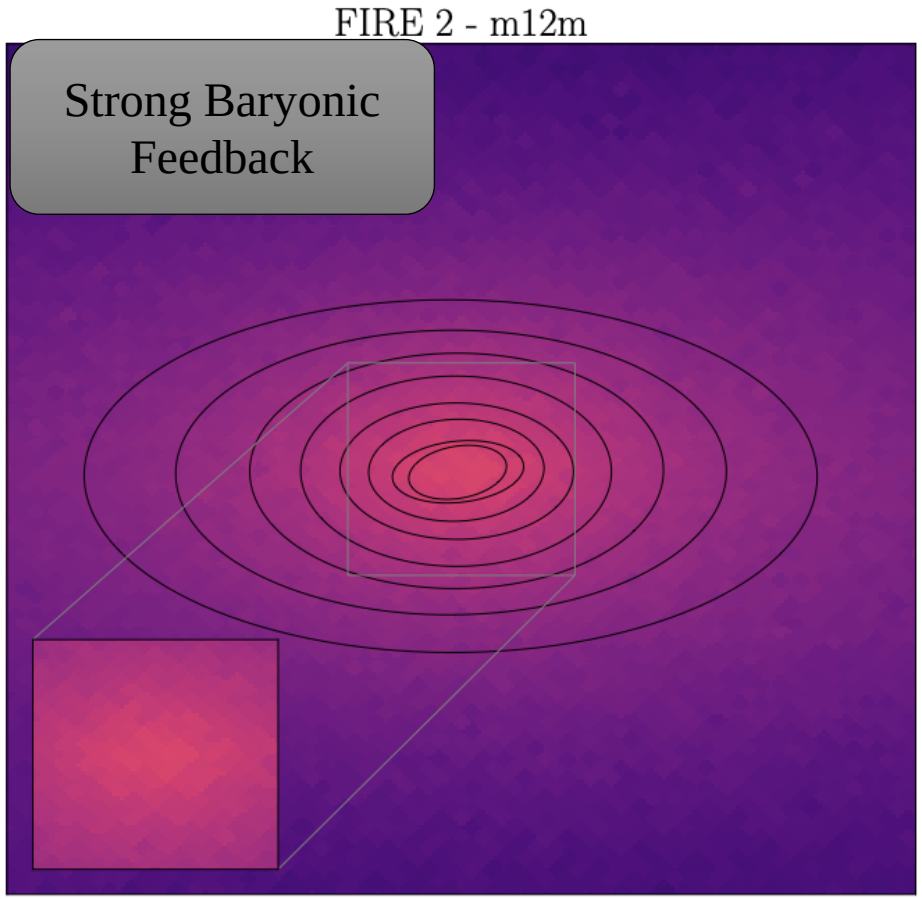
These distributions are publicly available on github at https://github.com/abdelazizhussein/MW-Inner-DM-Profile

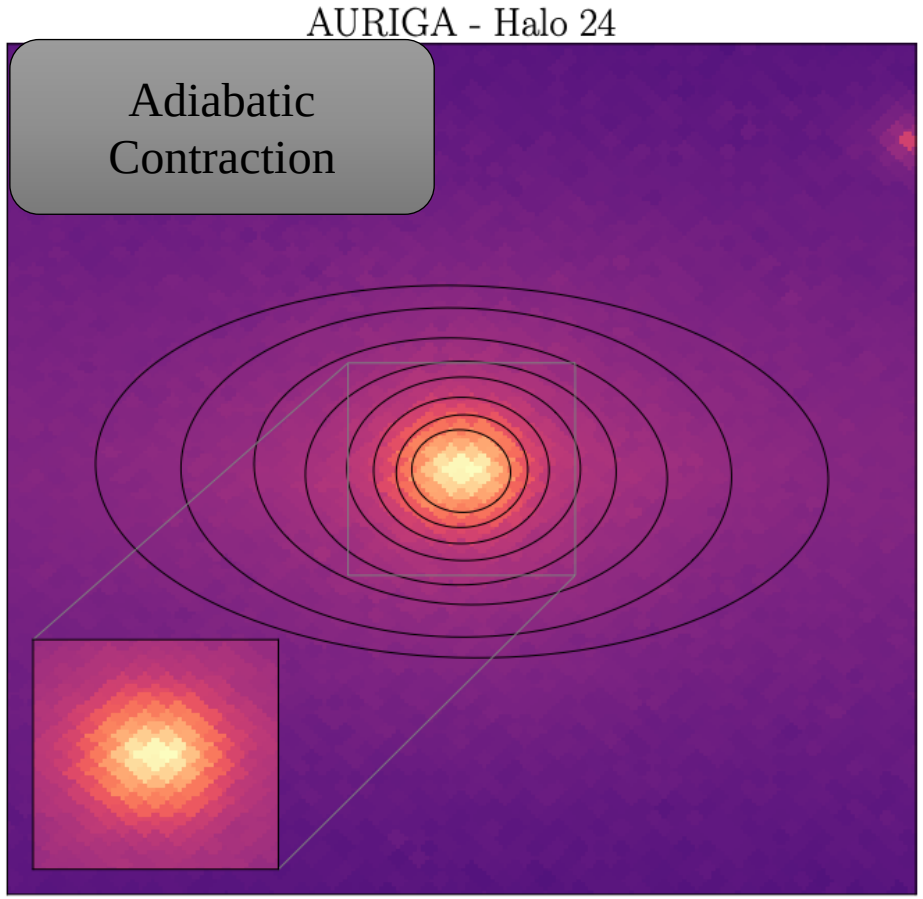
Hussein, **Necib**, Kaplinghat et al. (2025) arXiv:2501.14868

Lina Necib, MIT

THE DIFFERENT MECHANISMS ALSO AFFECT THE DARK MATTER SPATIAL DISTRIBUTION

Abdelaziz Hussein





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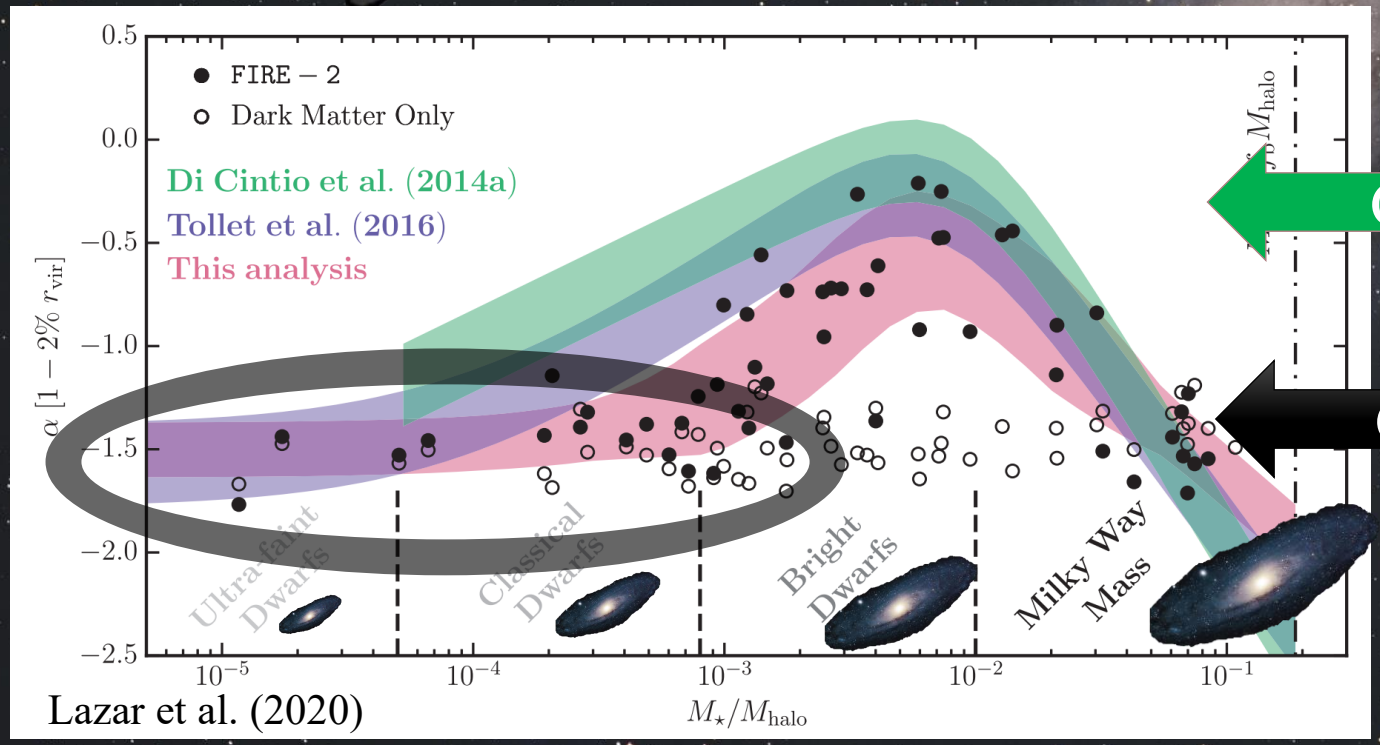
TODAY'S TALK:
MAPPING THE DARK MATTER DENSITY PROFILE IN THE MILKY WAY AND DWARF GALAXIES

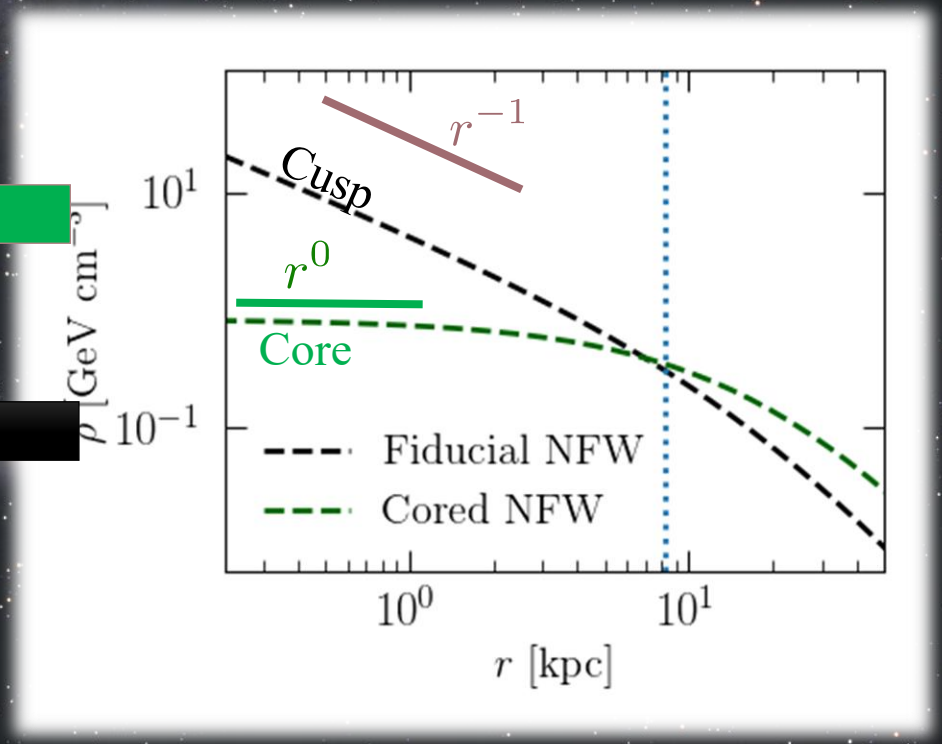
Astrophysics



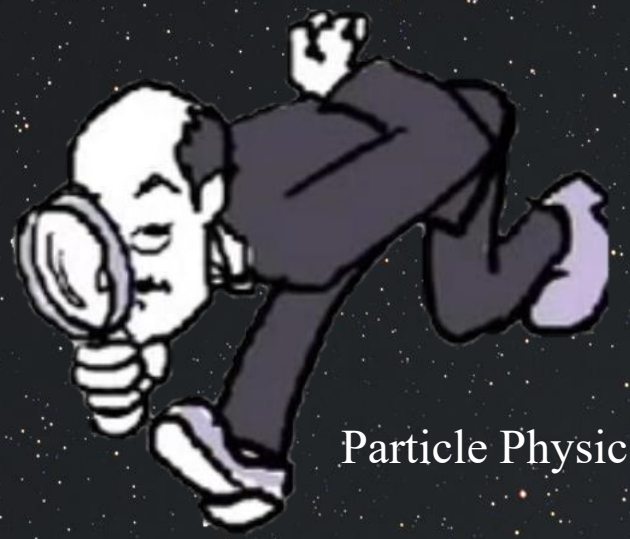
Lazar et al. (2020)

Core

Cusp

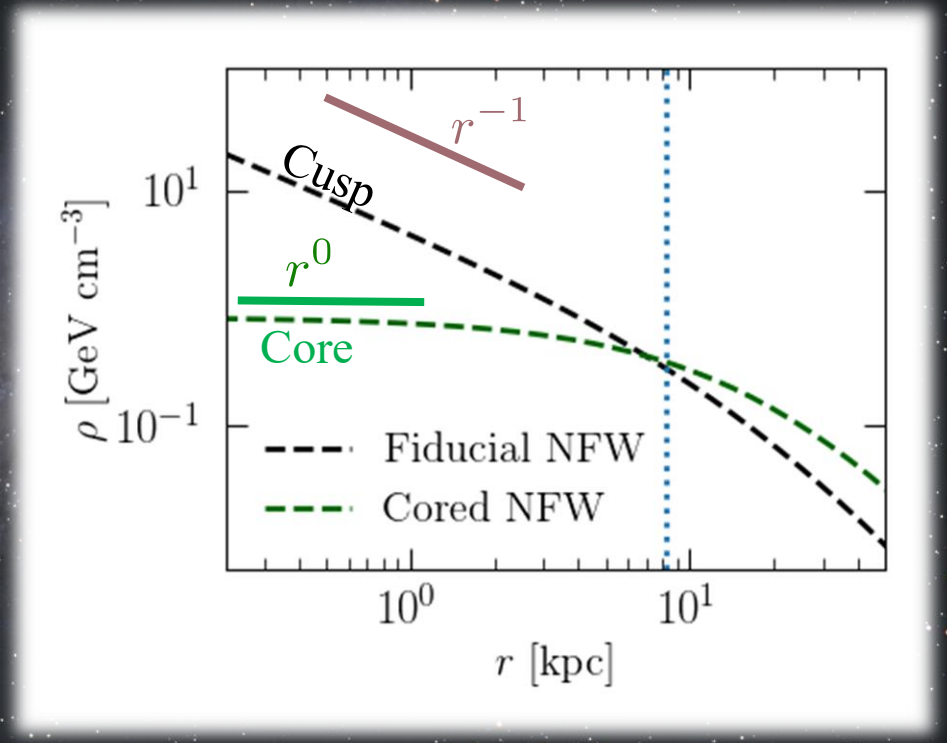


Lina Necib, MIT



Particle Physics

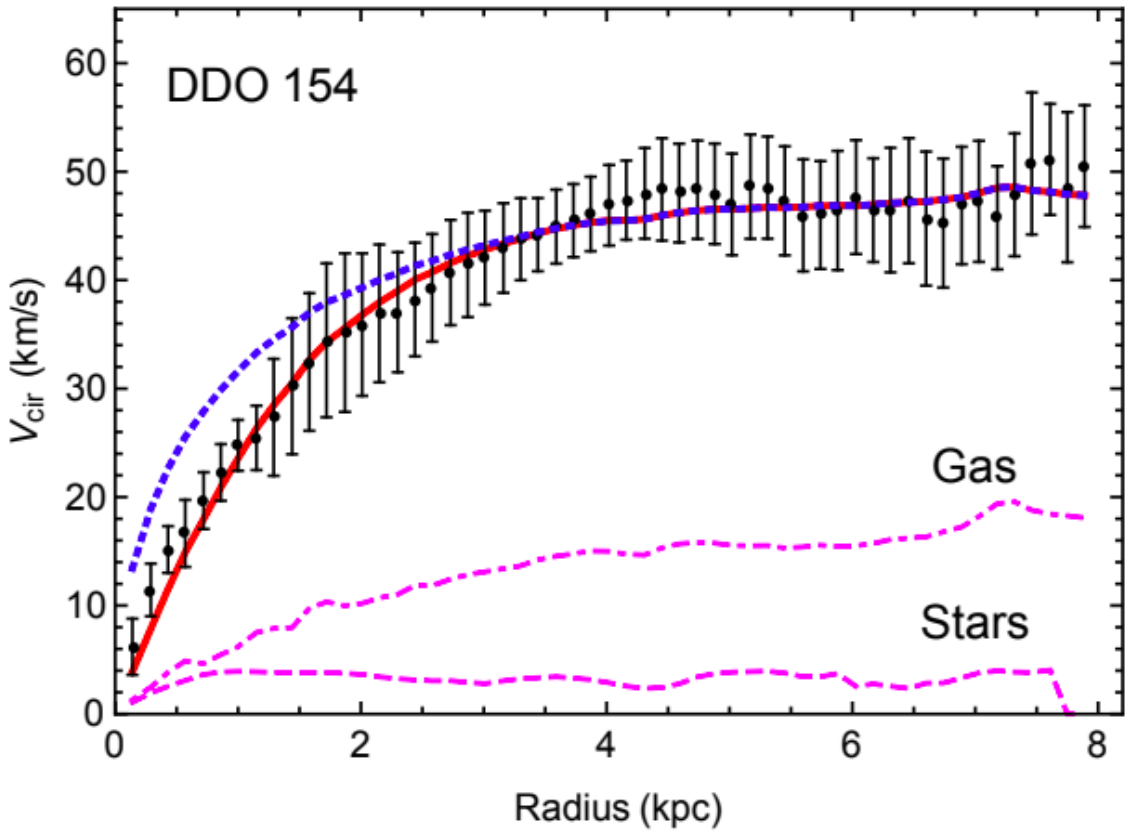
Dark Matter Annihilation Signal

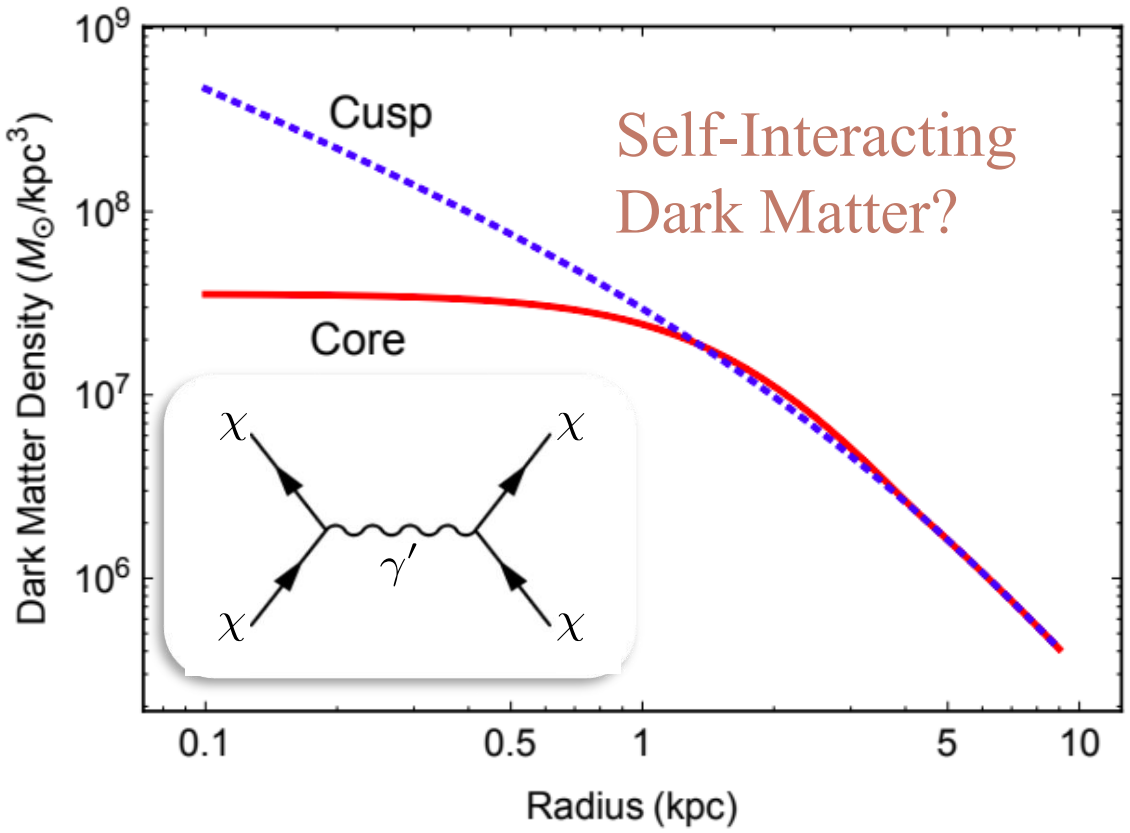


$$\text{Signal} \propto \int \rho^2 \mathrm{ds}$$

The effect can be orders of magnitude in signal expectation.

EARLY WORKS HAVE SHOWN THAT DWARF GALAXIES MIGHT HAVE CORES





Lina Necib, MIT

Spergel & Steinhardt (2000)

Oh et al. (2015)
Tulin & Yu (2017)

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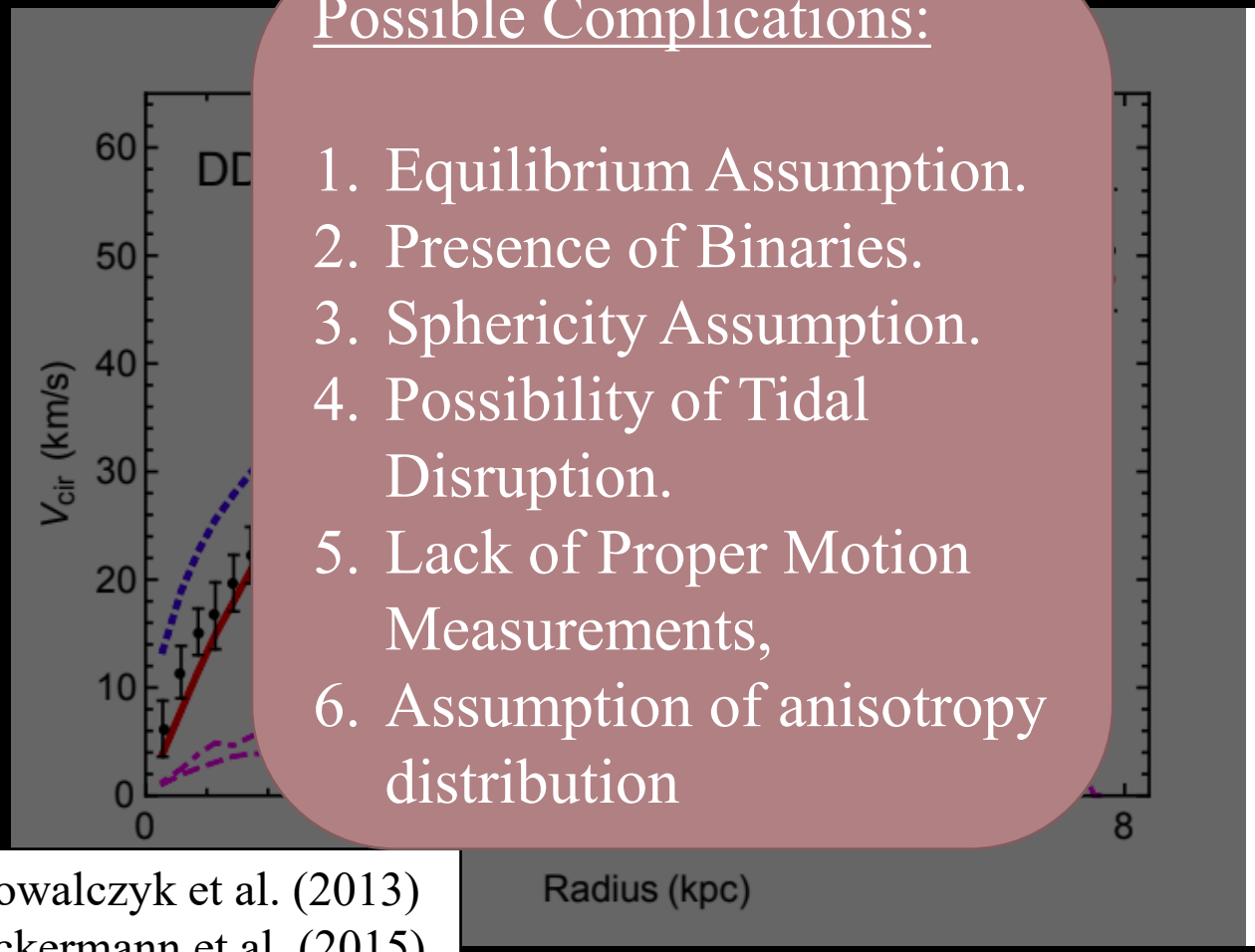
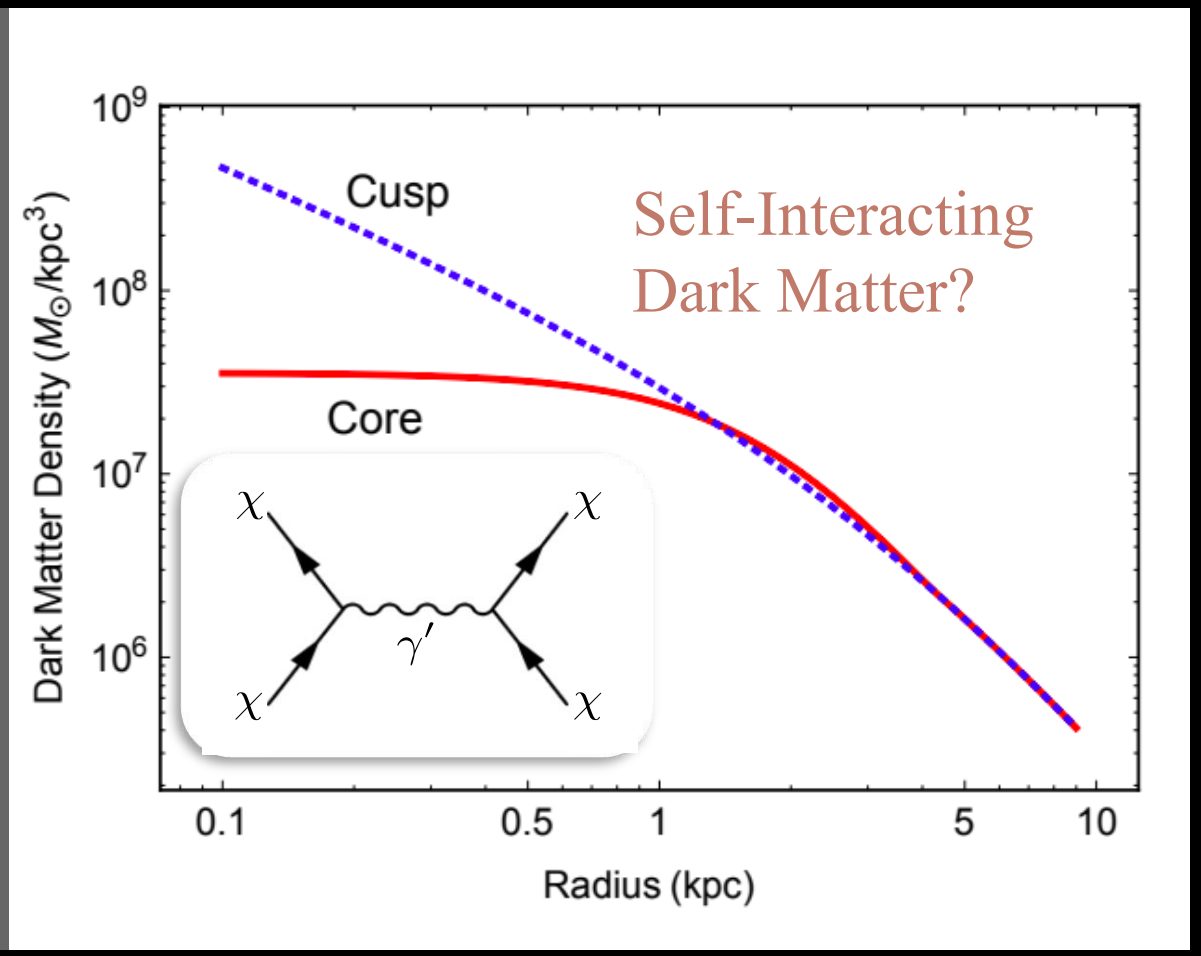


Possible Complications:

1. Equilibrium Assumption.
2. Presence of Binaries.
3. Sphericity Assumption.
4. Possibility of Tidal Disruption.
5. Lack of Proper Motion Measurements,
6. Assumption of anisotropy distribution



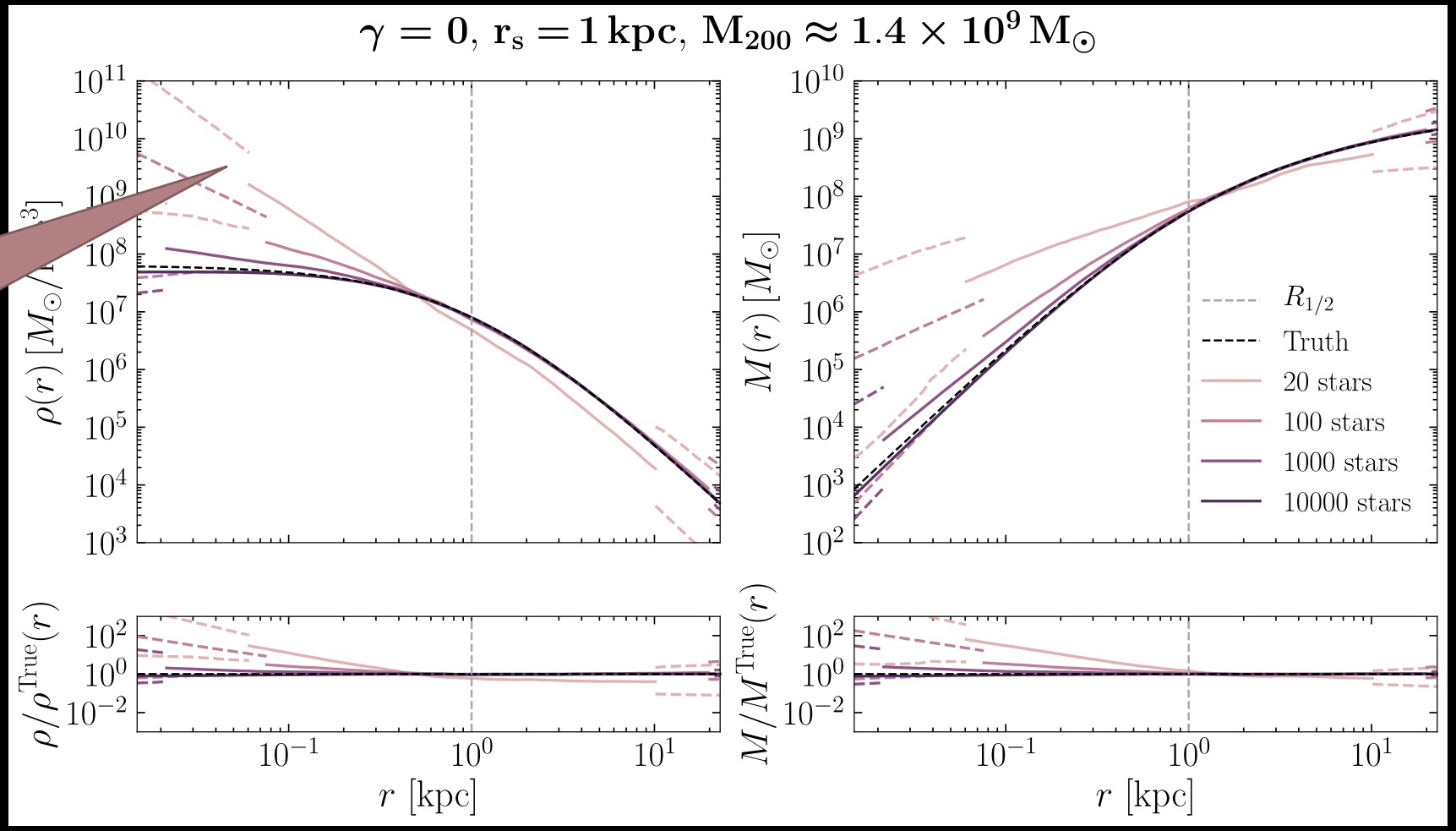
Kowalczyk et al. (2013)
Ackermann et al. (2015)
Bonnivard et al. (2015)
El-Badry et al. (2017)

Spergel & Steinhardt (2000)

Oh et al. (2015)
Tulin & Yu (2017)

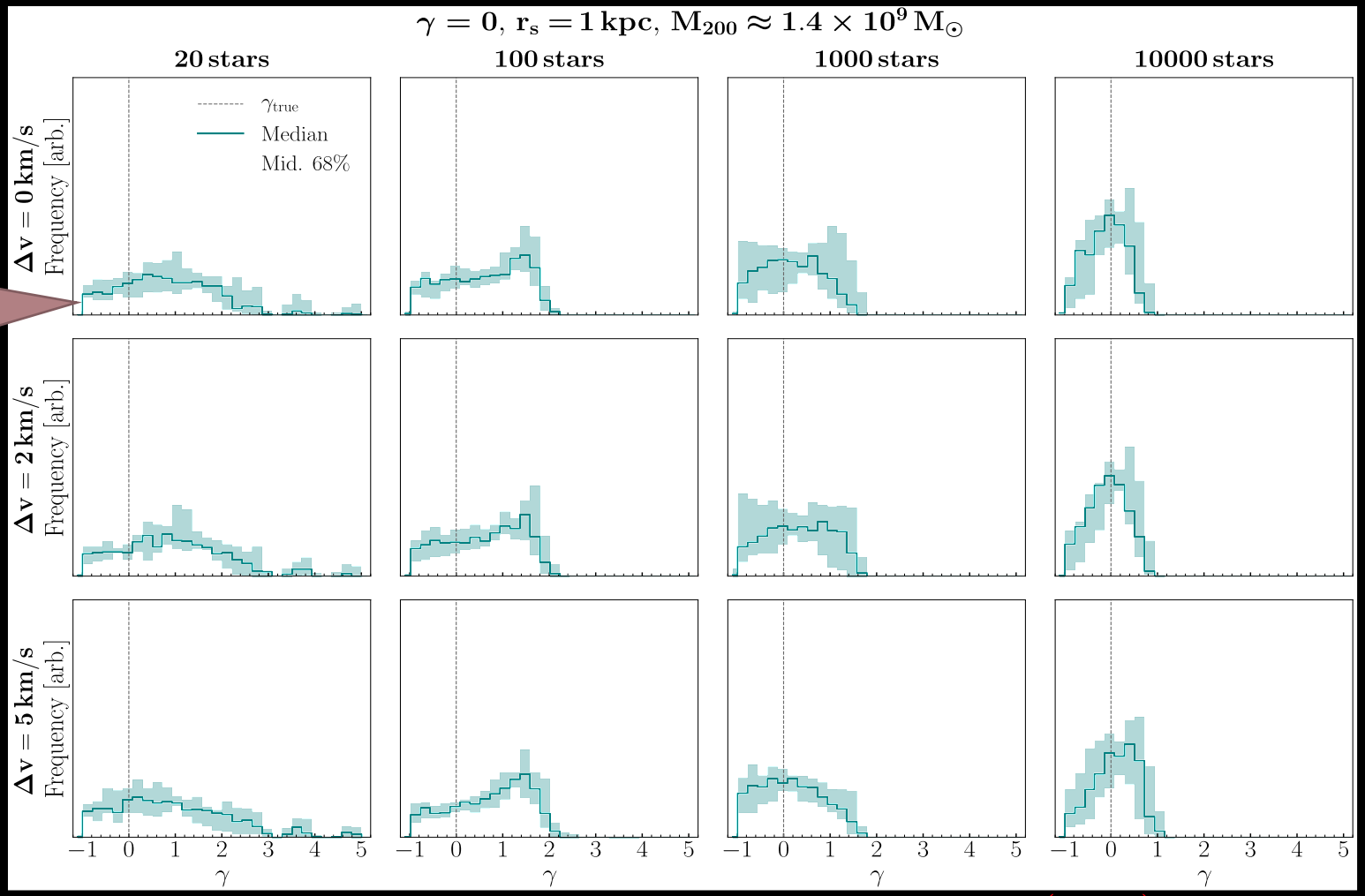
ONE NEEDS ABOUT 10,000 STARS TO GET THE PROFILE CORRECTLY IN THE STANDARD JEANS ANALYSIS

Cores are harder to resolve with fewer statistics



Chang & **Necib** (2020)

ONE NEEDS ABOUT 10,000 STARS TO GET THE PROFILE CORRECTLY IN THE STANDARD JEANS ANALYSIS



Cores are harder to resolve with fewer statistics

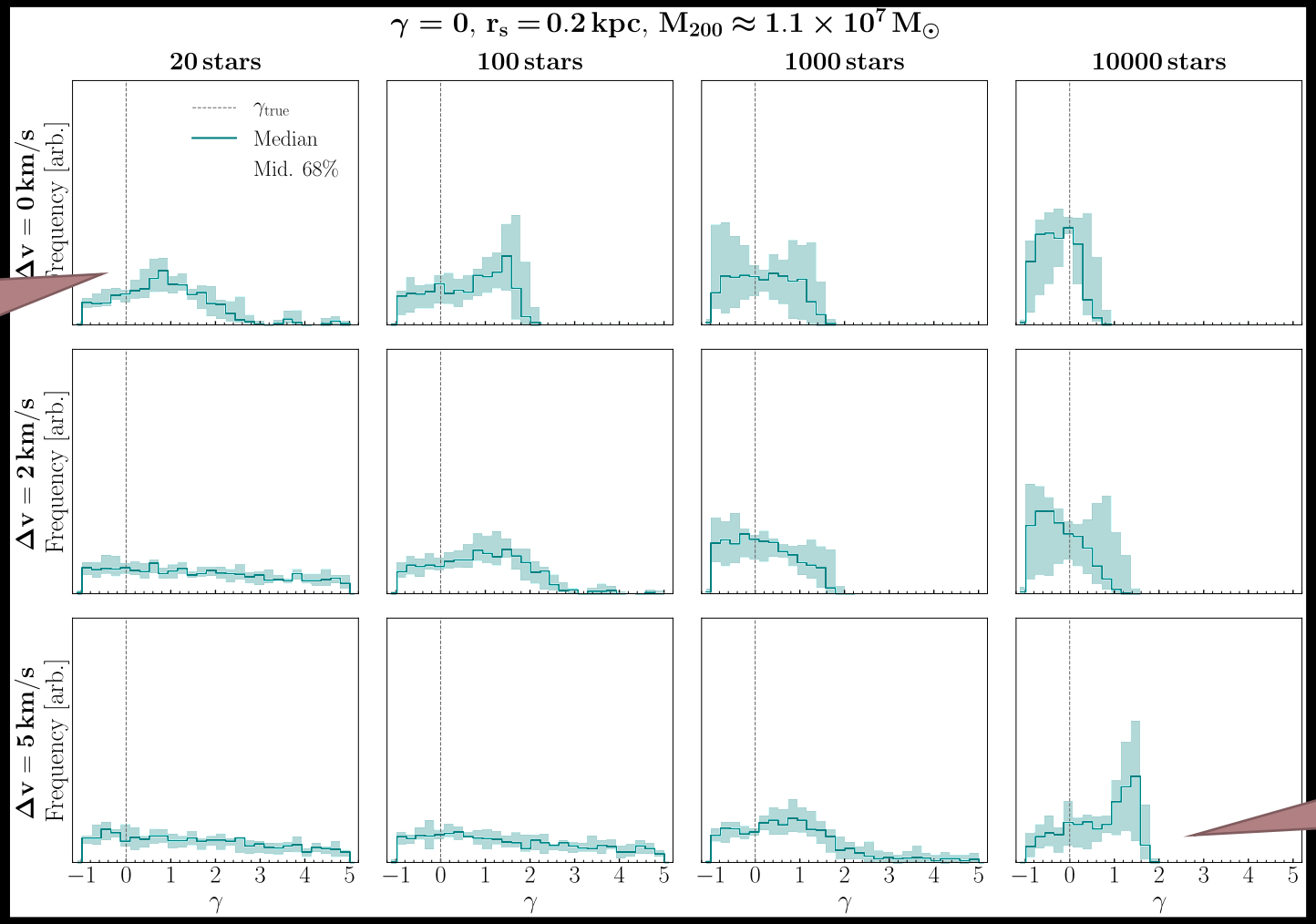
Cusp: $\gamma = 1$
Core: $\gamma = 0$

$$M_{200} \approx 10^9 M_\odot$$

$$\rho = \rho_0 \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-(3-\gamma)}$$

Chang & **Necib** (2020)

ONE NEEDS ABOUT 10,000 STARS TO GET THE PROFILE CORRECTLY IN THE STANDARD JEANS ANALYSIS



Cores are harder to resolve with fewer statistics

Cusp: $\gamma = 1$
Core: $\gamma = 0$

The errors are worse for the ultrafaints

$$M_{200} \approx 10^7 M_\odot$$

$$\rho = \rho_0 \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-(3-\gamma)}$$

Chang & **Necib** (2020)

Goal:

Build a method where we can get the correct inner density profile of Dark Matter.

Issue:

Solution:

Goal: Build a method where we can get the correct inner density profile of Dark Matter.

Issue: Jeans analysis, the standard method, makes a lot of assumptions to deal with this problem, and requires a LOT of statistics to get the answer right.

Solution:

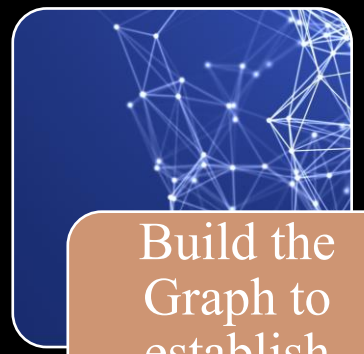
Goal: Build a method where we can get the correct inner density profile of Dark Matter.

Issue: Jeans analysis, the standard method, makes a lot of assumptions to deal with this problem, and requires a LOT of statistics to get the answer right.

Solution: Use simulation based inference + Graph Neural Networks to train a model that obtains the density profiles of dwarfs.

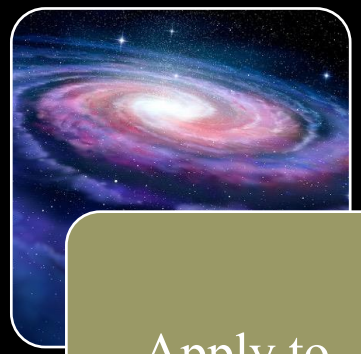
WE USE SIMULATION-BASED INFERENCE TO OBTAIN THE INNER PROFILE OF THE DARK MATTER FROM THE KINEMATICS OF THE STARS

Generate Idealized Simulations



Build the Graph to establish relationships between the stars

Train the Network



Apply to data

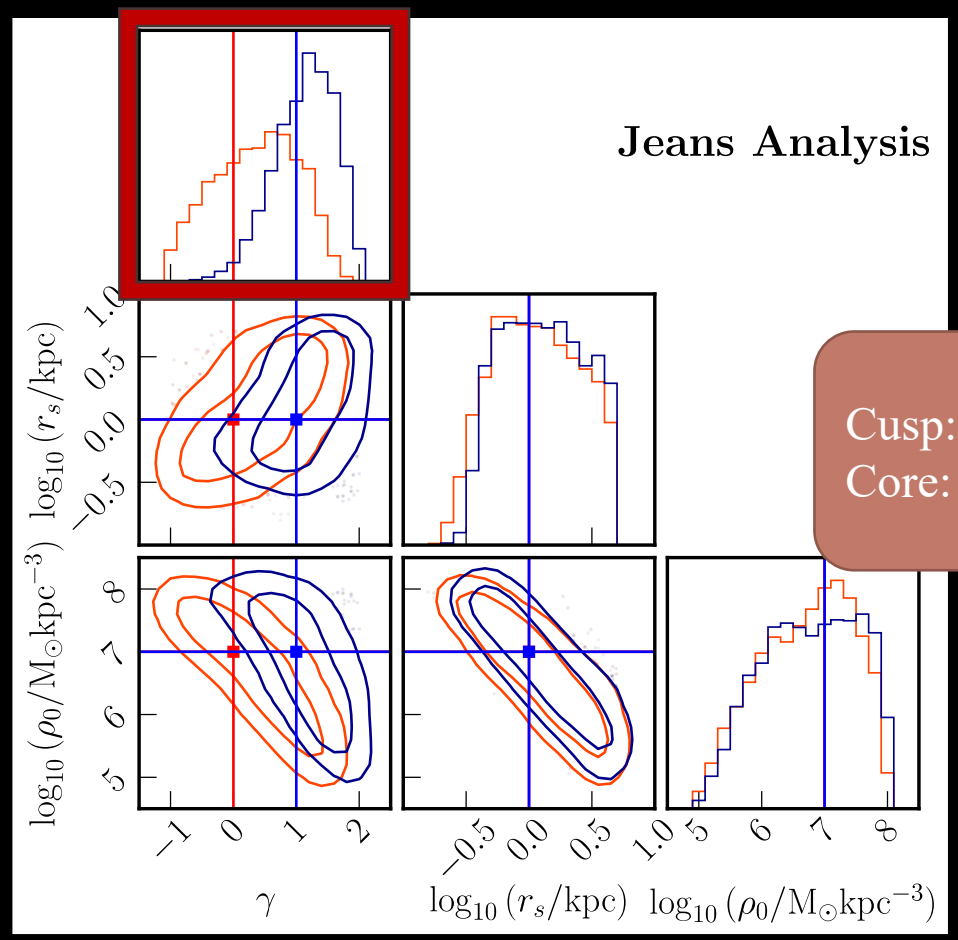
Use Normalizing Flow to obtain a posterior distribution

Nguyen, Mishra-Sharma, Williams, & **Necib** (2022)

GNN + NORMALIZING FLOWS OUTPERFORMS JEANS ANALYSIS

Tri Nguyen

$$\rho = \rho_0 \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-(3-\gamma)}$$



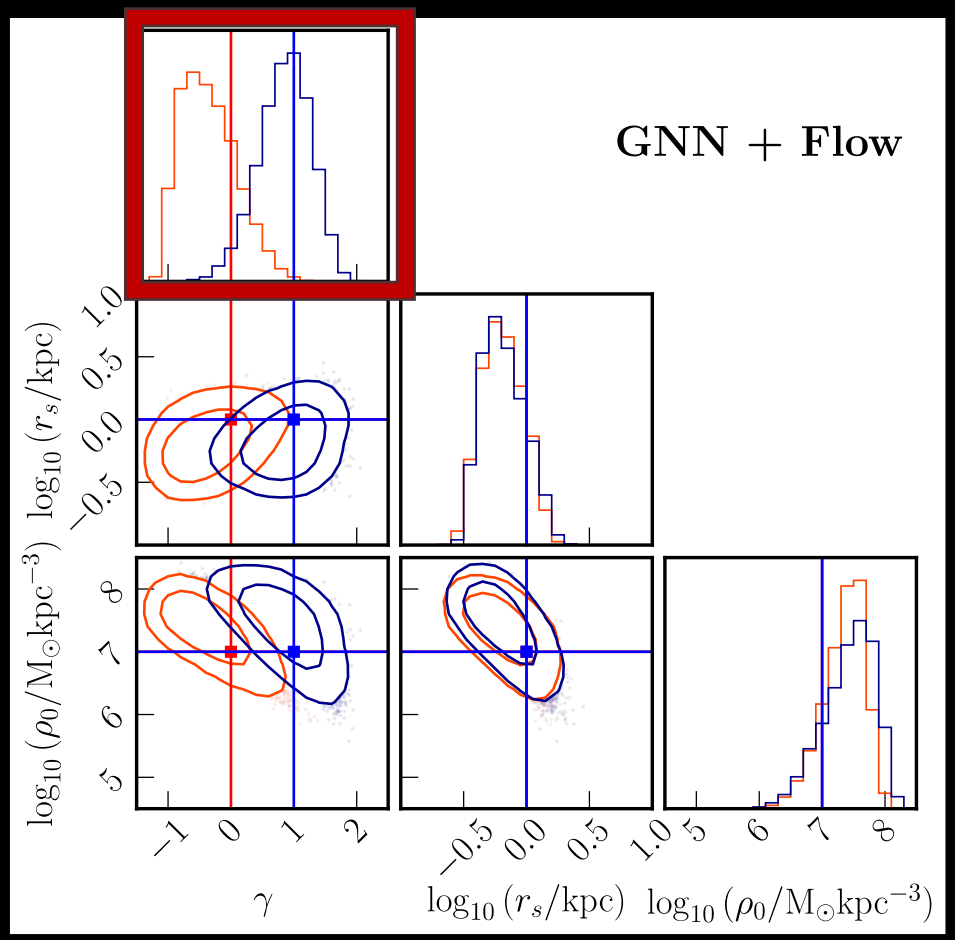
Cusp: $\gamma = 1$
Core: $\gamma = 0$

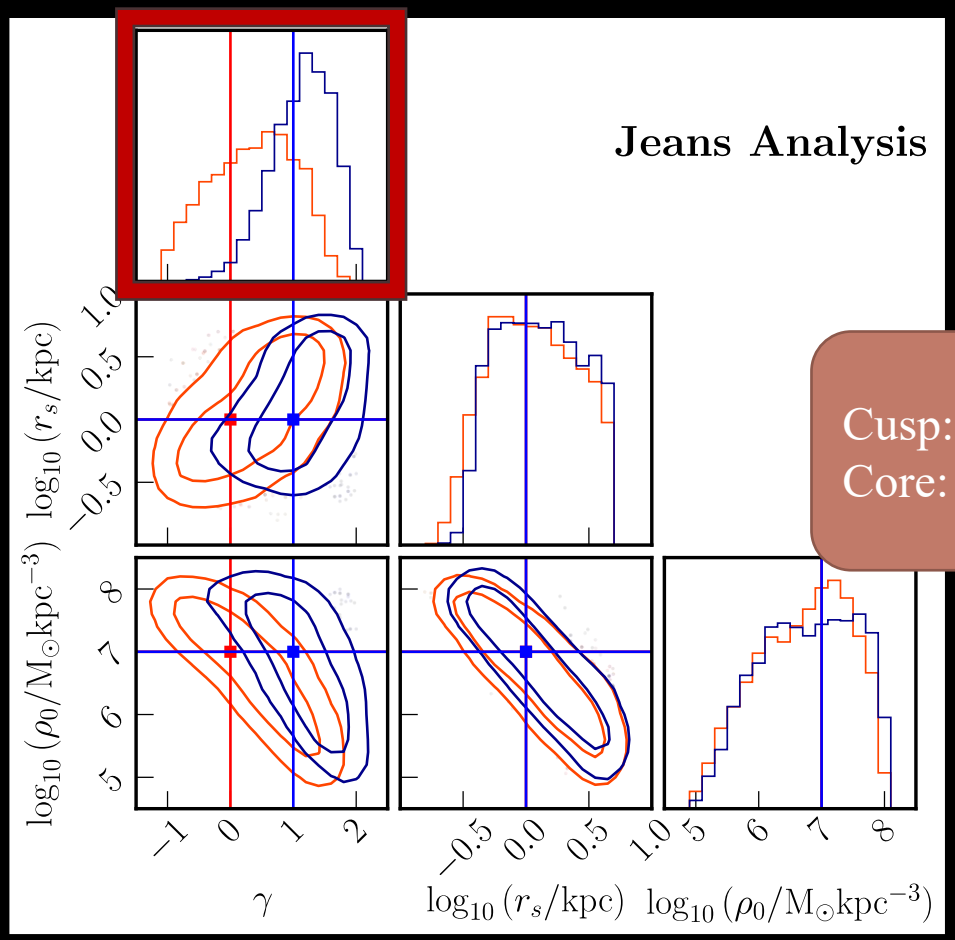
Lina Necib, MIT

Nguyen, Mishra-Sharma, Williams, & **Necib** (2022)

GNN + NORMALIZING FLOWS OUTPERFORMS JEANS ANALYSIS

Tri Nguyen





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Lina Necib, MIT

Nguyen, Mishra-Sharma, Williams, & **Necib** (2022)

GNN + NORMALIZING FLOWS OUTPERFORMS JEANS ANALYSIS

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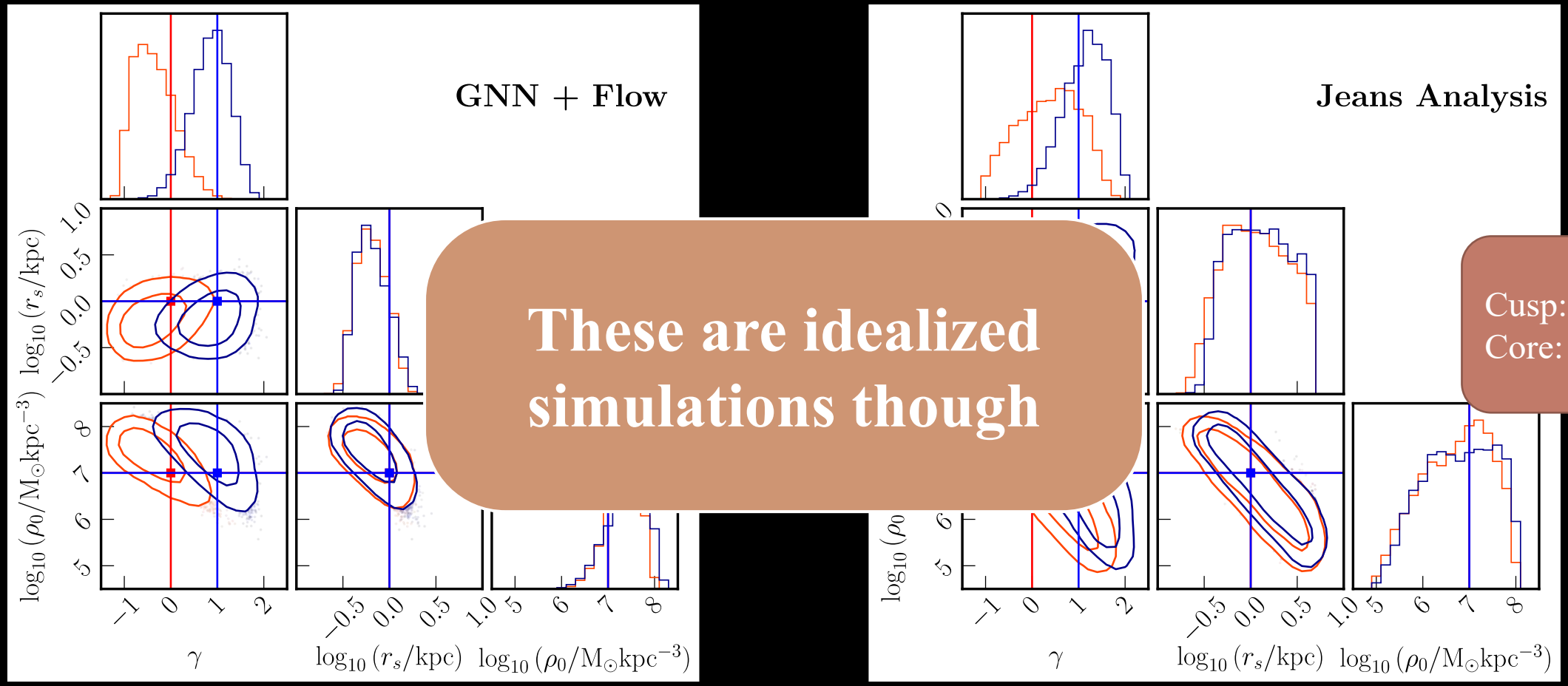


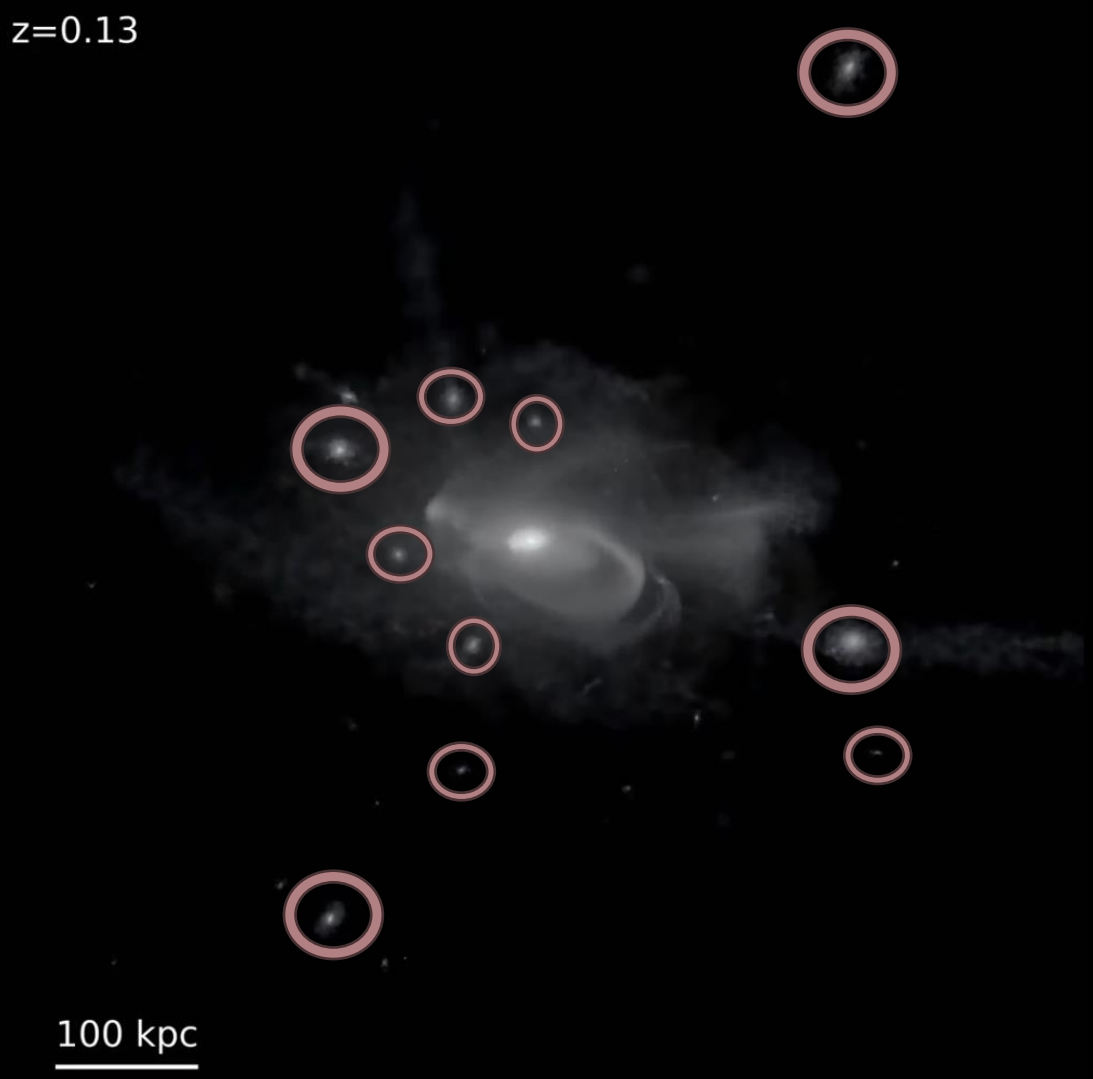
These are idealized simulations though

Cusp: $\gamma = 1$
Core: $\gamma = 0$

Lina Necib, MIT

Nguyen, Mishra-Sharma, Williams, & **Necib** (2022)

Tri Nguyen



Wetzel et al. (2016)
Hopkins et al. (2018)
Wetzel et al. (2023)

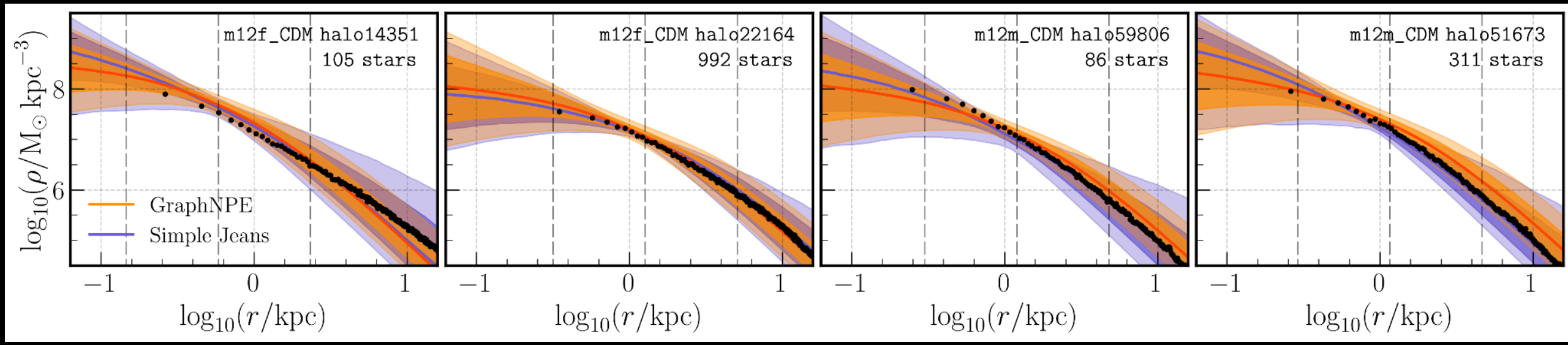
Lina Necib, MIT

Nguyen, Read, **Necib**, et al. (2025)

APPLYING THIS TO FIRE-2 CDM SATELLITES YIELDS GOOD FITS

Tri Nguyen

GraphNPE Jeans



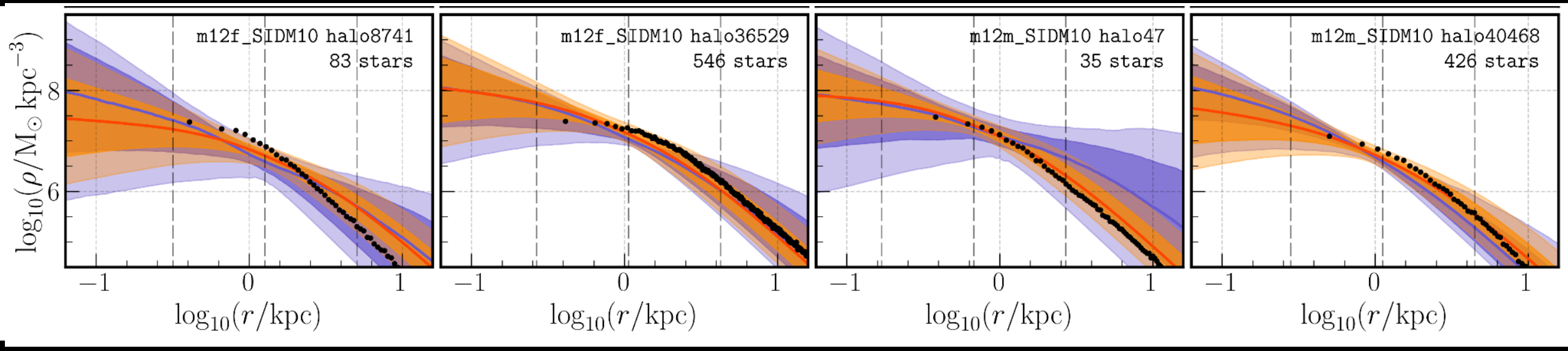
Lina Necib, MIT

Strigari et al. (2008)
Nguyen, Read, **Necib**, et al. (2025)

APPLYING THIS TO FIRE-2 SIDM SATELLITES YIELDS GOOD FITS

Tri Nguyen

GraphNPE Jeans



Lina Necib, MIT

Strigari et al. (2008)
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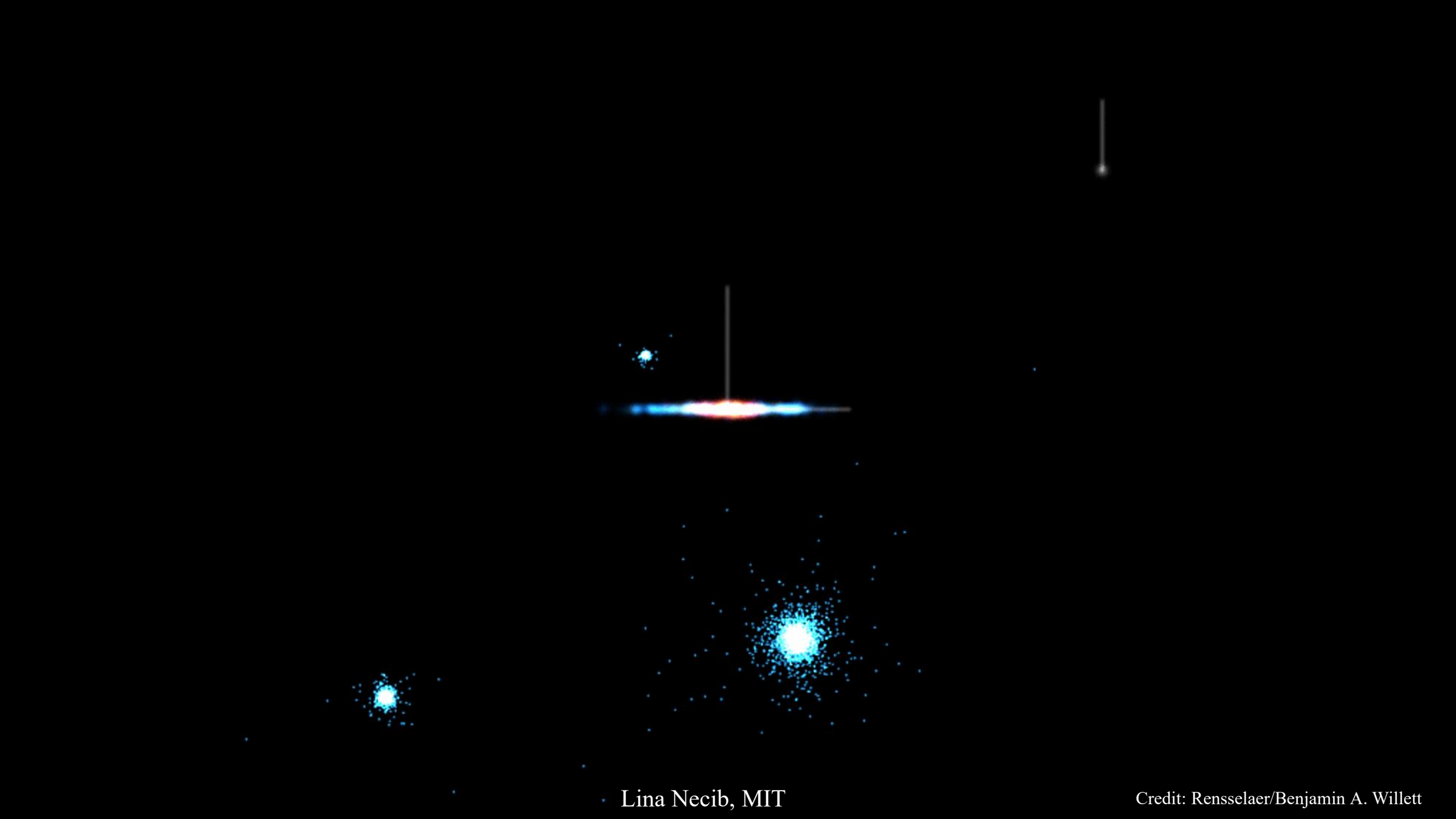
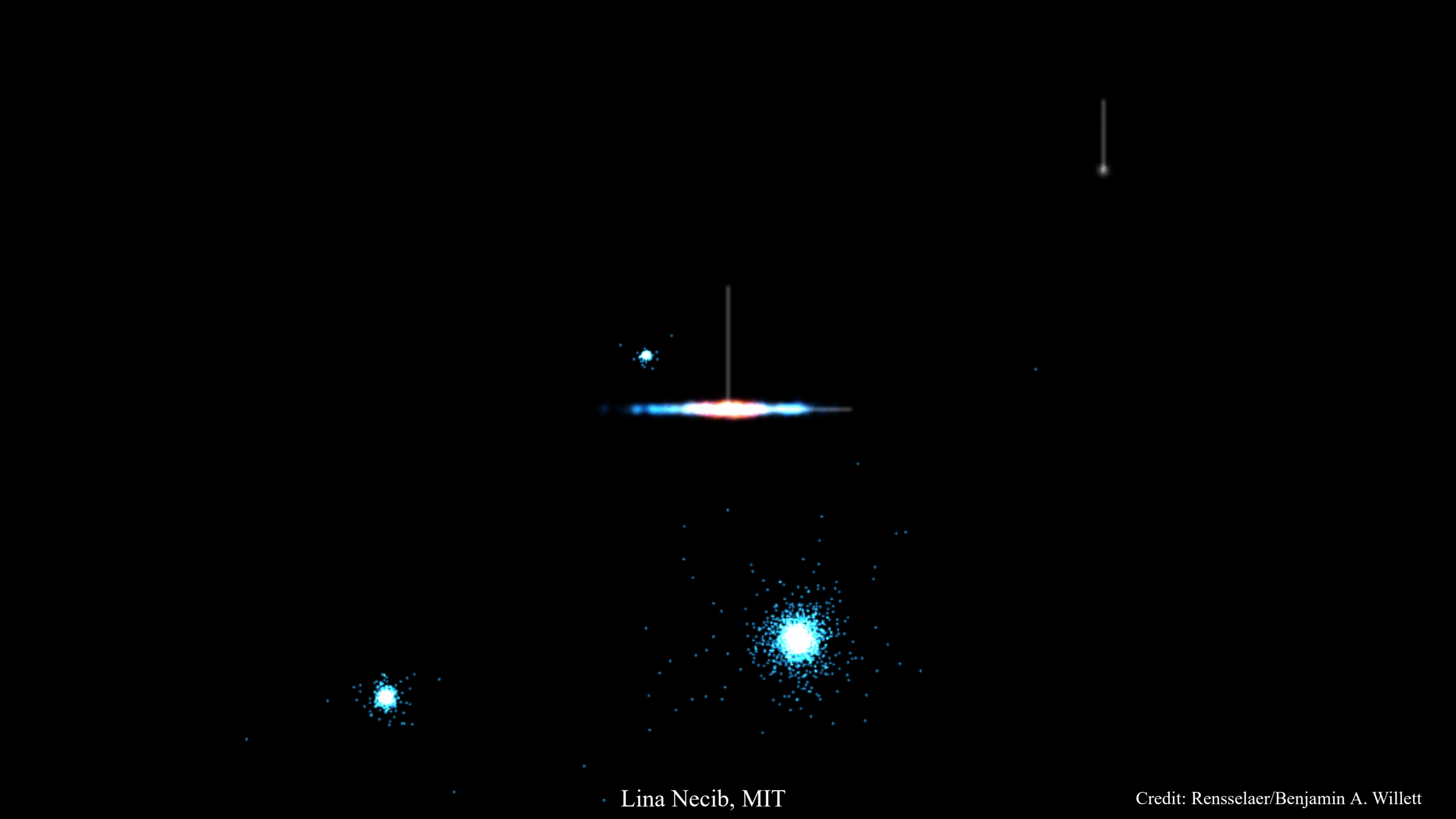


Lina Necib, MIT

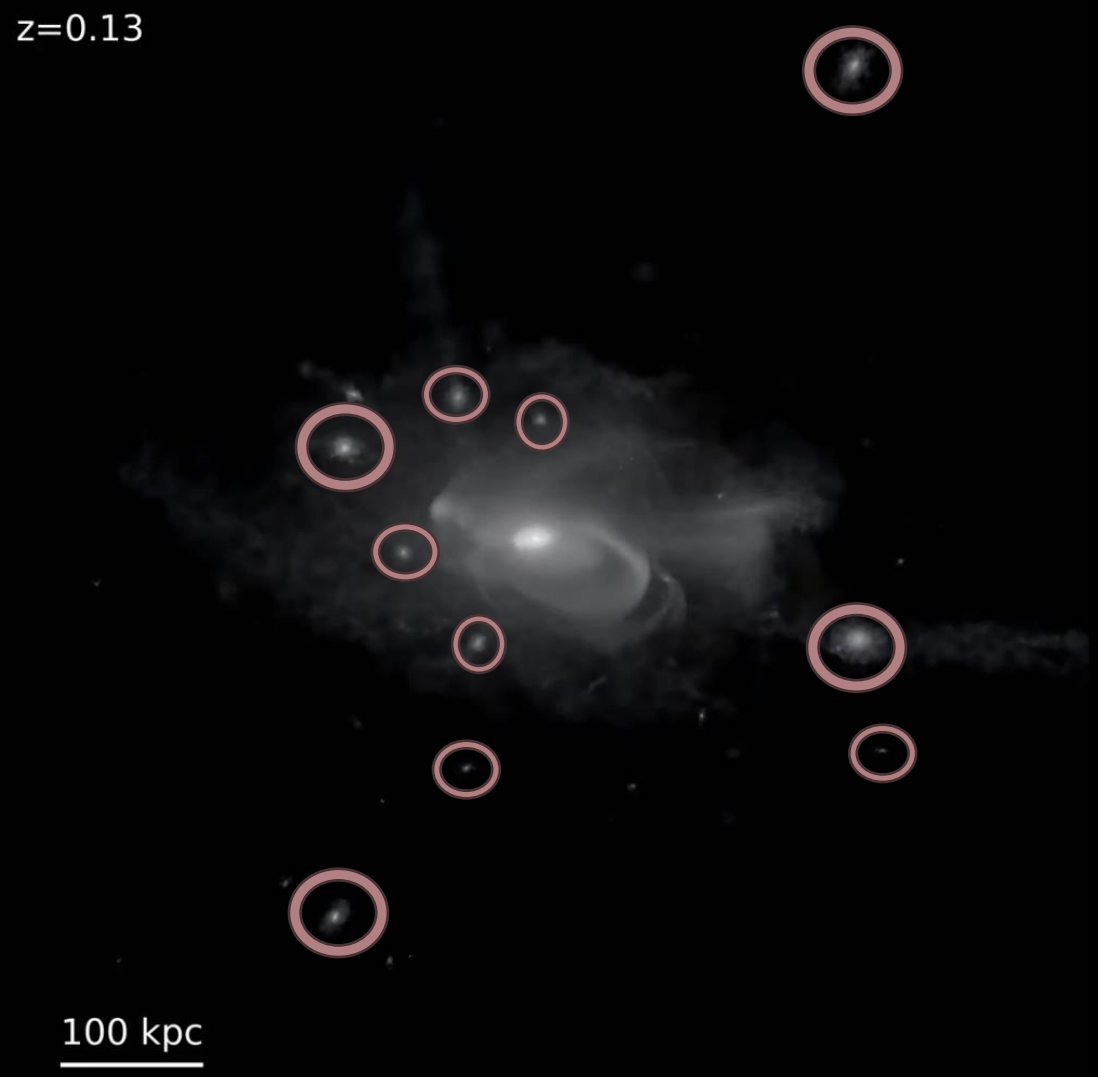
Credit: Rensselaer/Benjamin A. Willett



Lina Necib, MIT

Credit: Rensselaer/Benjamin A. Willett

Nora Shipp

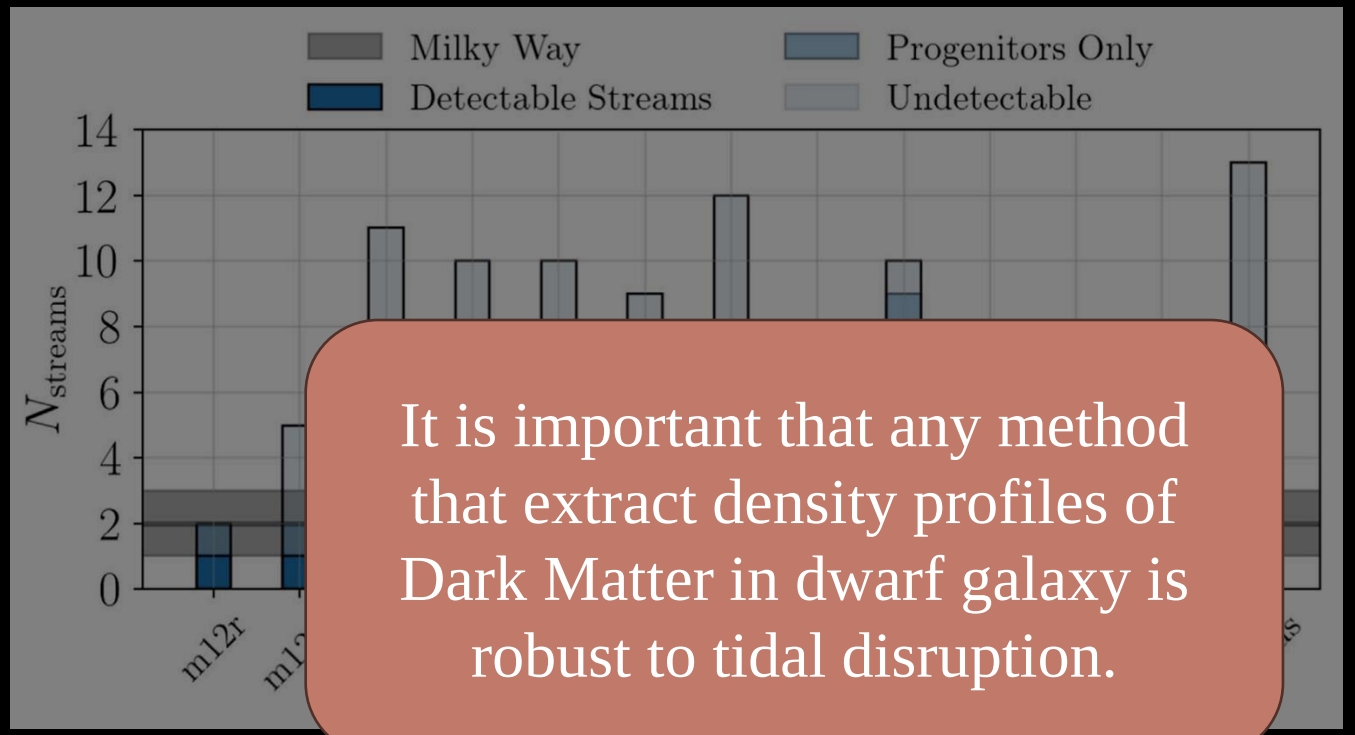


Shipp, Panithanpaisal, **Necib**, et al. (2023)
Shipp, Riley, …, **Necib**, et al. (2024)

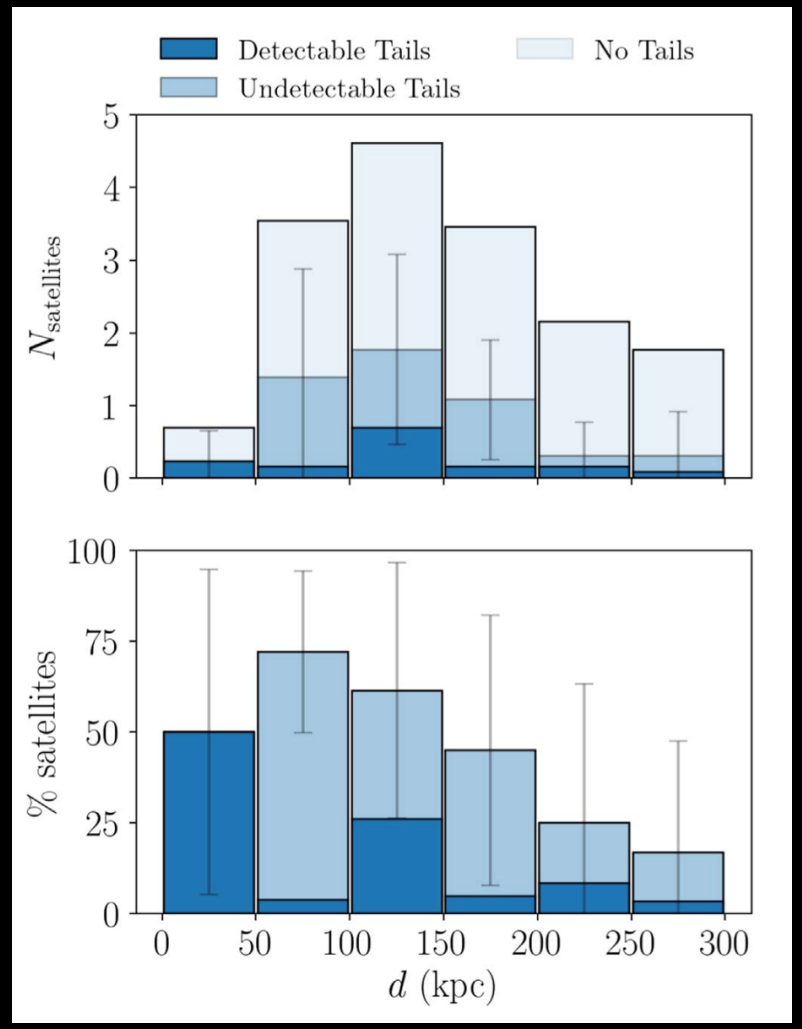
Lina Necib, MIT

WE EXPECT THAT MANY OF THE CURRENT SATELLITES OF THE MILKY WAY ARE BEING TIDALLY DISRUPTED.

Nora Shipp

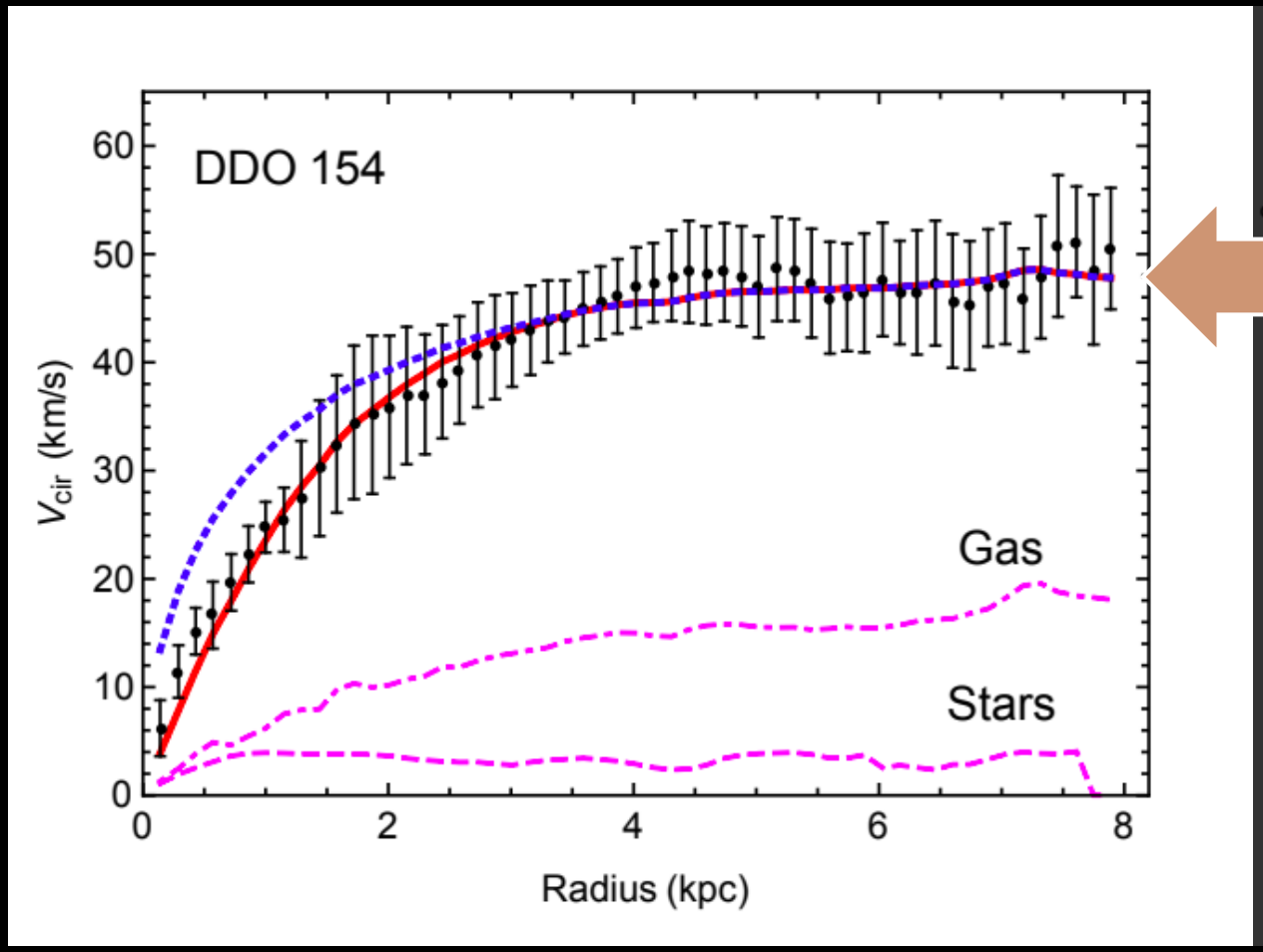


It is important that any method that extract density profiles of Dark Matter in dwarf galaxy is robust to tidal disruption.

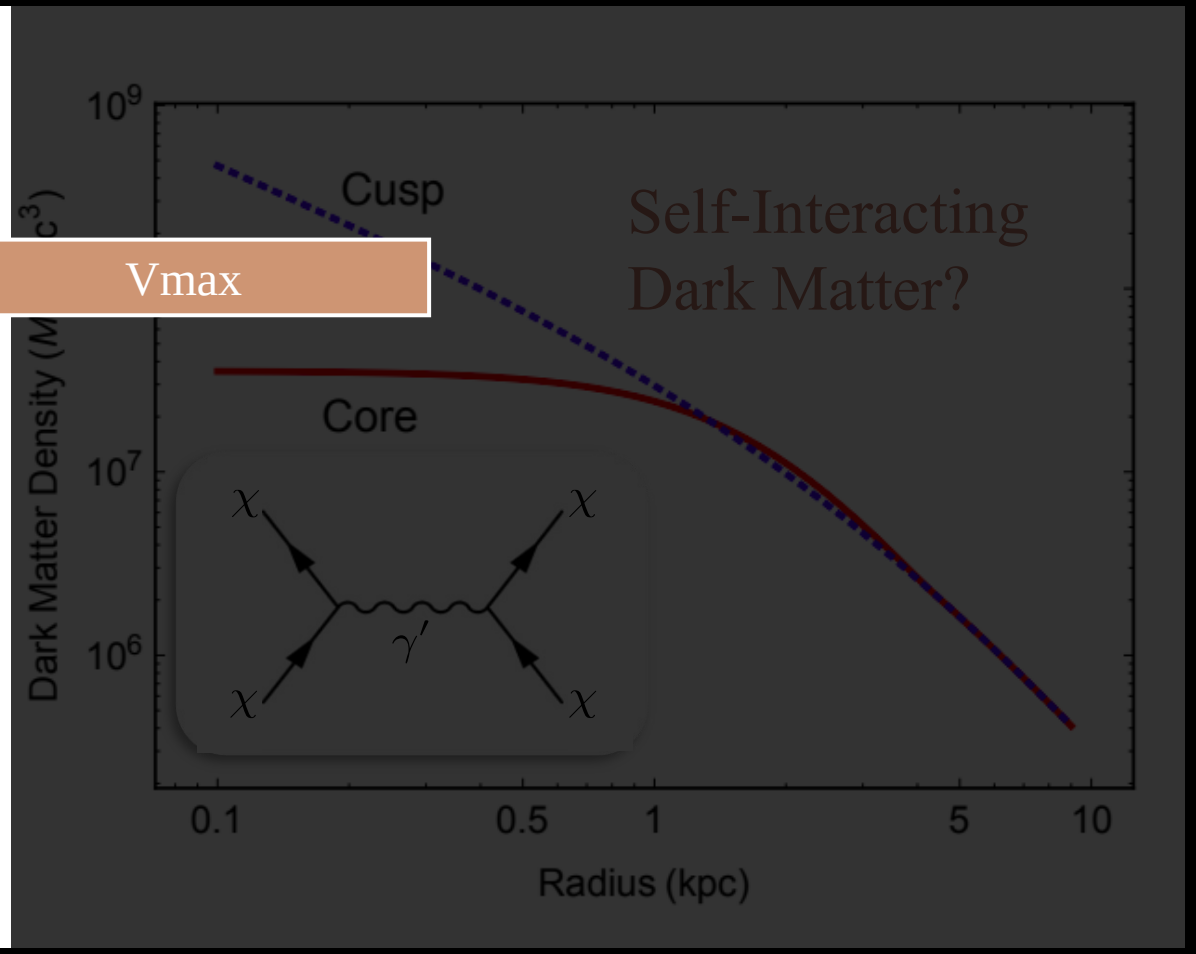


Shipp, Panithanpaisal, **Necib**, et al. (2023)
Shipp, Riley, …, **Necib**, et al. (2024)

EARLY WORKS HAVE SHOWN THAT DWARF GALAXIES MIGHT HAVE CORES



Vmax



Lina Necib, MIT

Spergel & Steinhardt (2000)

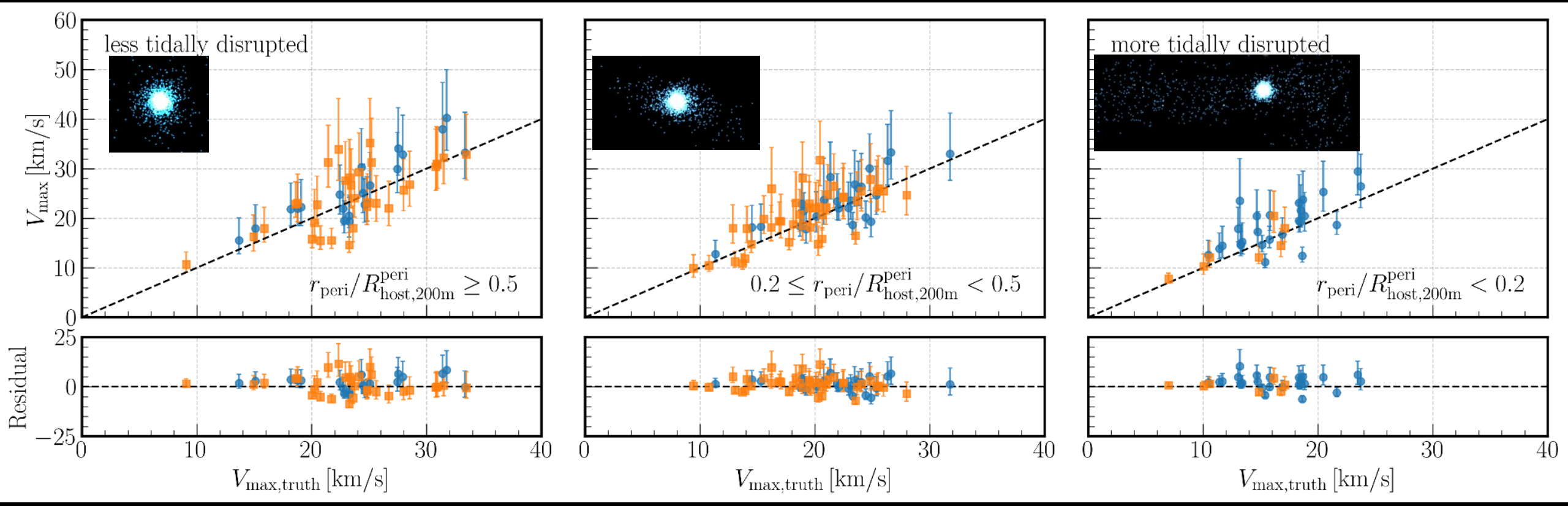
Oh et al. (2015)
Tulin & Yu (2017)

WE OBTAIN A GOOD FIT FOR PROPERTIES OF GALAXIES EVEN IN THE CASES OF TIDAL DISRUPTION: VMAX

Tri Nguyen

SIDM

CDM



Lina Necib, MIT

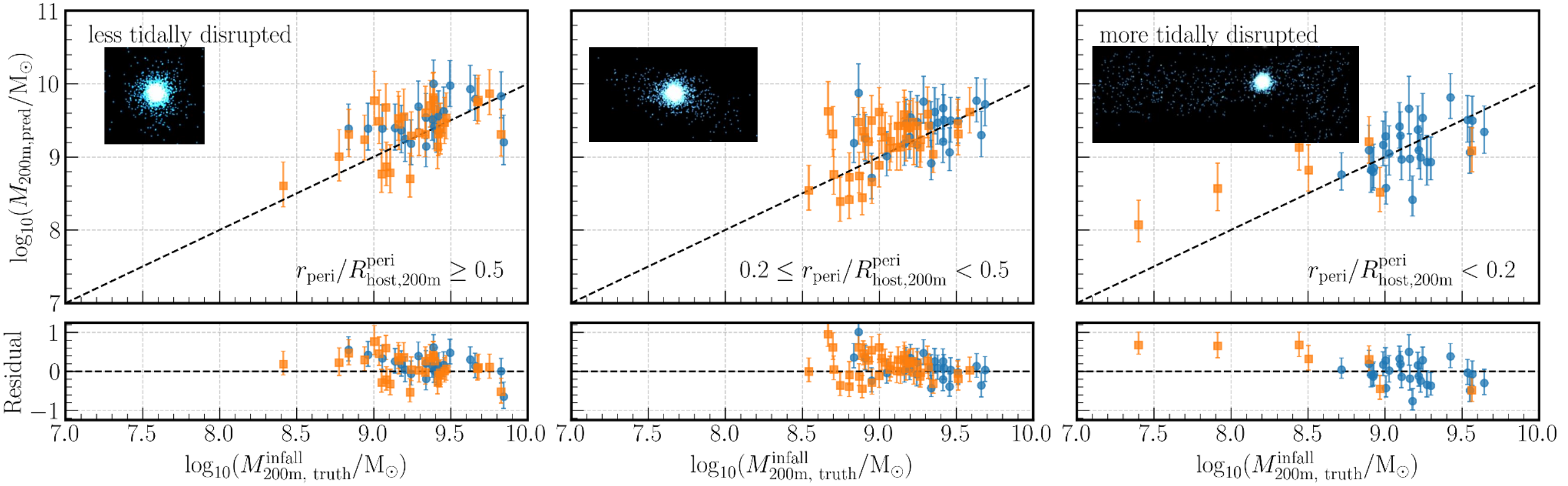
Nguyen, Read, **Necib**, et al. (2025)

WE OBTAIN A GOOD FIT FOR PROPERTIES OF GALAXIES EVEN IN THE CASES OF TIDAL DISRUPTION: M200

Tri Nguyen

SIDM

CDM



Lina Necib, MIT

Nguyen, Read, **Necib**, et al. (2025)

WE OBTAIN A GOOD FIT FOR PROPERTIES OF GALAXIES EVEN IN THE CASES OF TIDAL DISRUPTION: M200

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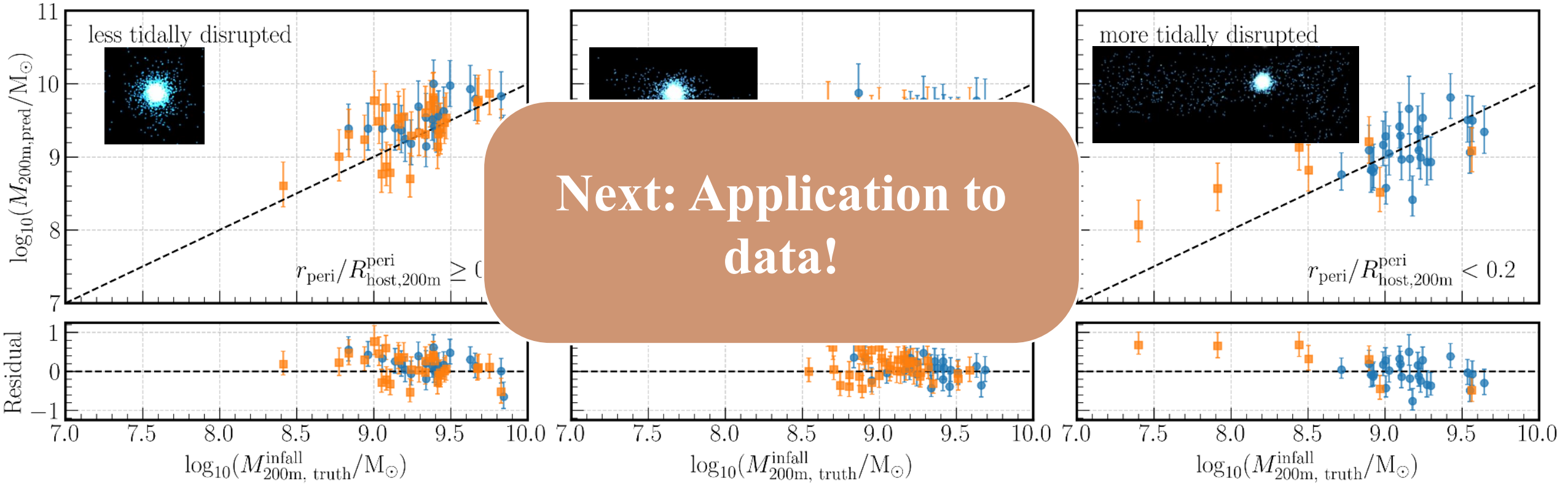
SIDM CDM

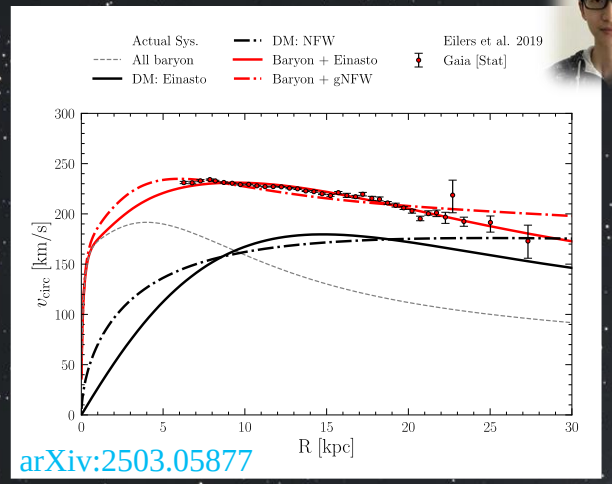


Next: Application to data!

Lina Necib, MIT

Nguyen, Read, **Necib**, et al. (2025)

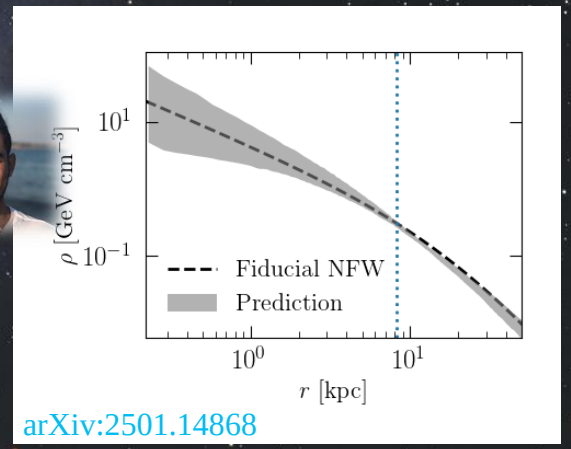
TODAY'S TALK: MAPPING THE DARK MATTER DENSITY PROFILE IN THE MILKY WAY AND DWARF GALAXIES



Xiaowei Ou

Used synthetic surveys to build the true systematic uncertainties of the circular velocity measurements of the Milky Way, and obtained a new Dark Matter density profile.

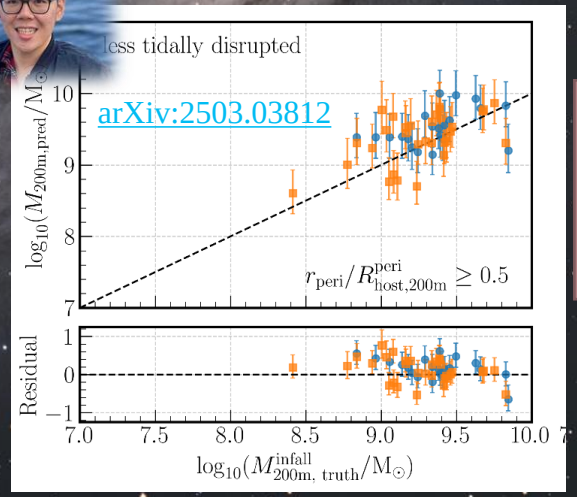
Galactic Center/Halo



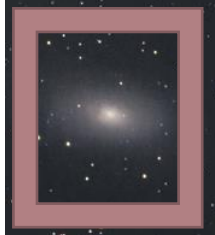
Abdelaziz Hussein

Built a theoretical range for the density profile of Dark Matter at the center of the Milky Way, based on adiabatic contraction and baryonic feedback.

Tri Nguyen



Dwarf Galaxies



Used Graph Neural Networks to construct the density profiles of Dark Matter in dwarf galaxies, based on line-of-sight velocities.
Tested this new method on FIRE simulations to show robustness. Next we will apply this to data.

GOAL:
MAPPING FROM THE STARS TO THE DARK MATTER

Thank you!

IN THE MEANTIME, LET'S HAVE THEORY GLASSES

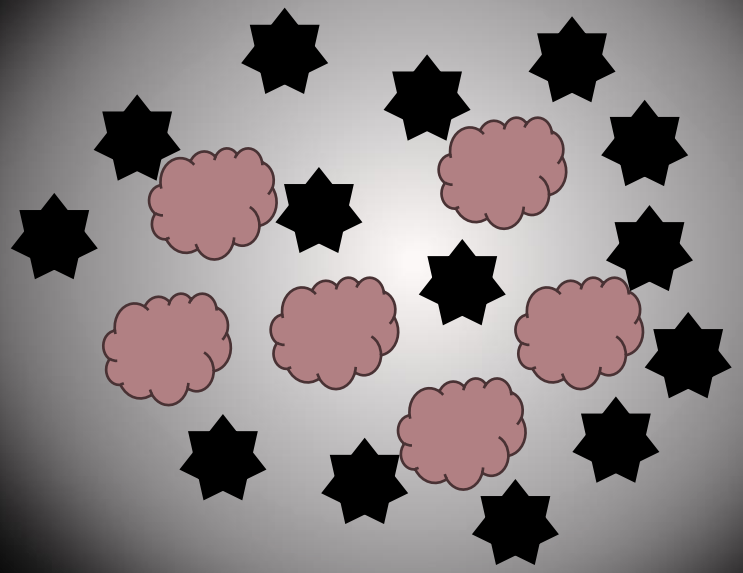
Abdelaziz Hussein

ΛCDM

Lina Necib, MIT

IN THE MEANTIME, LET'S HAVE THEORY GLASSES

Abdelaziz Hussein



Adiabatic Contraction

Lina Necib, MIT

Blumenthal et al. 1986
Gnedin et al. 2004

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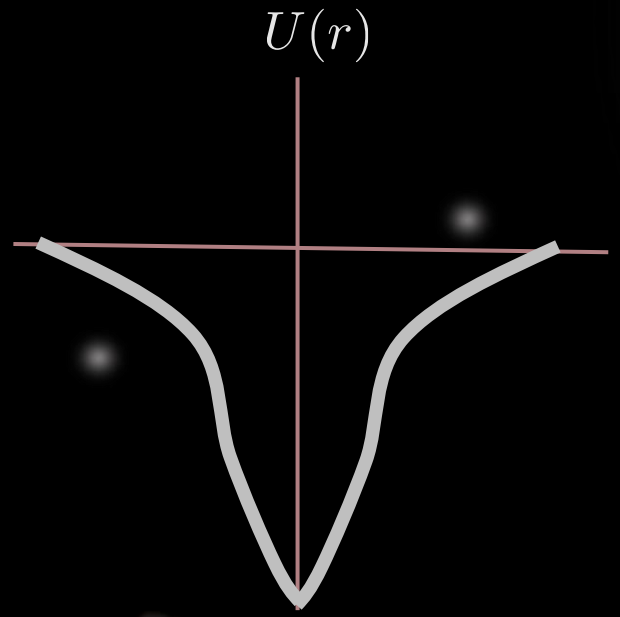
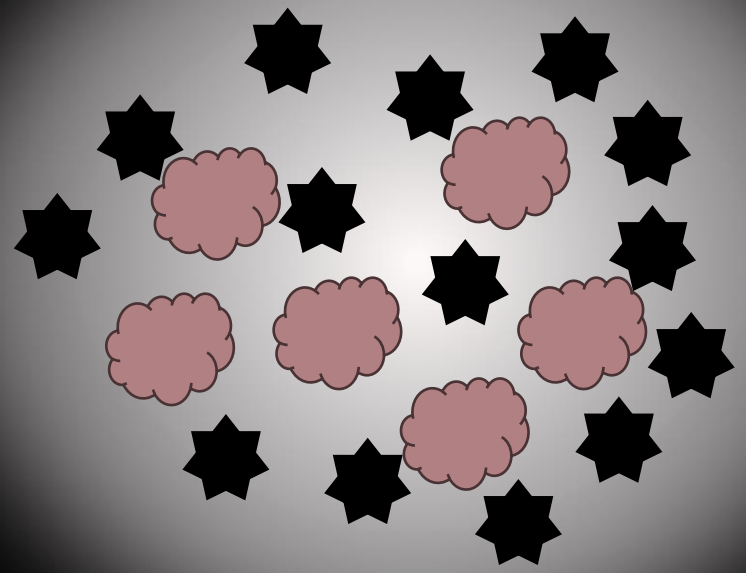
Abdelaziz Hussein





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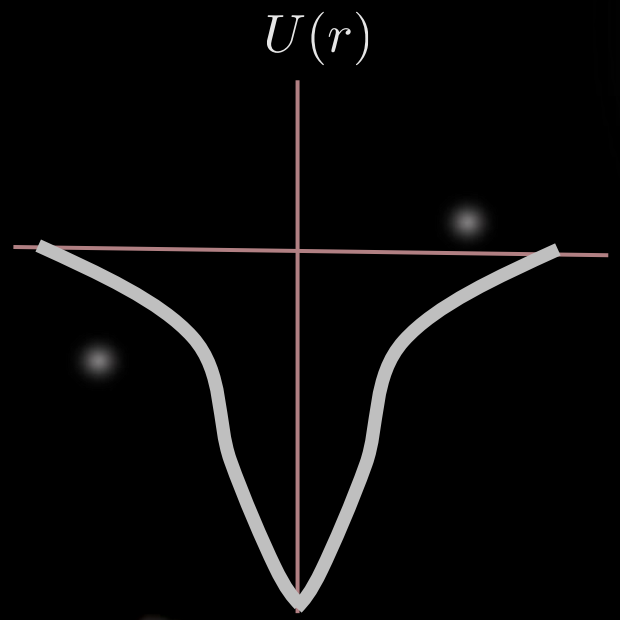
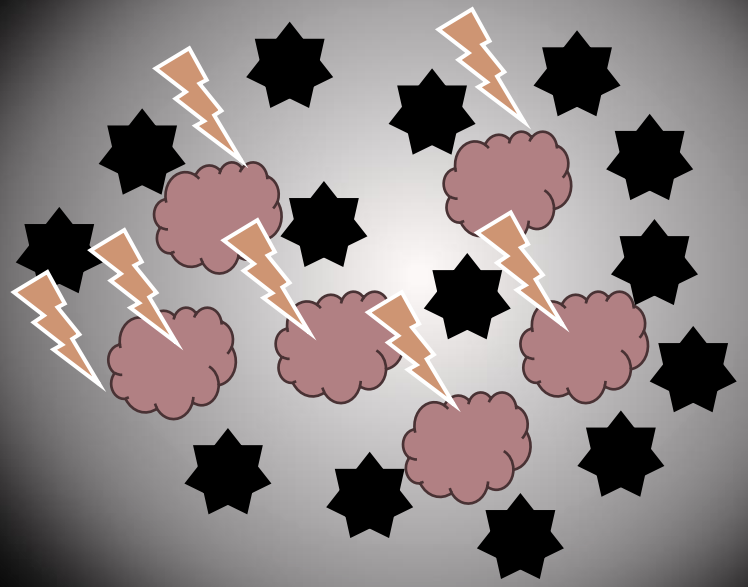
Abdelaziz Hussein





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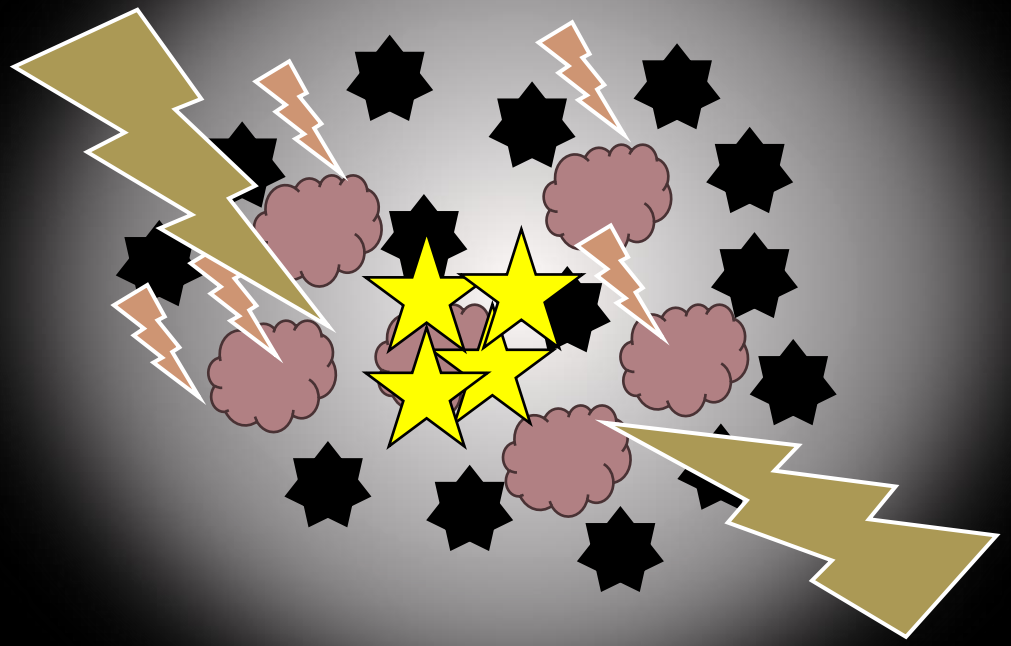
Abdelaziz Hussein



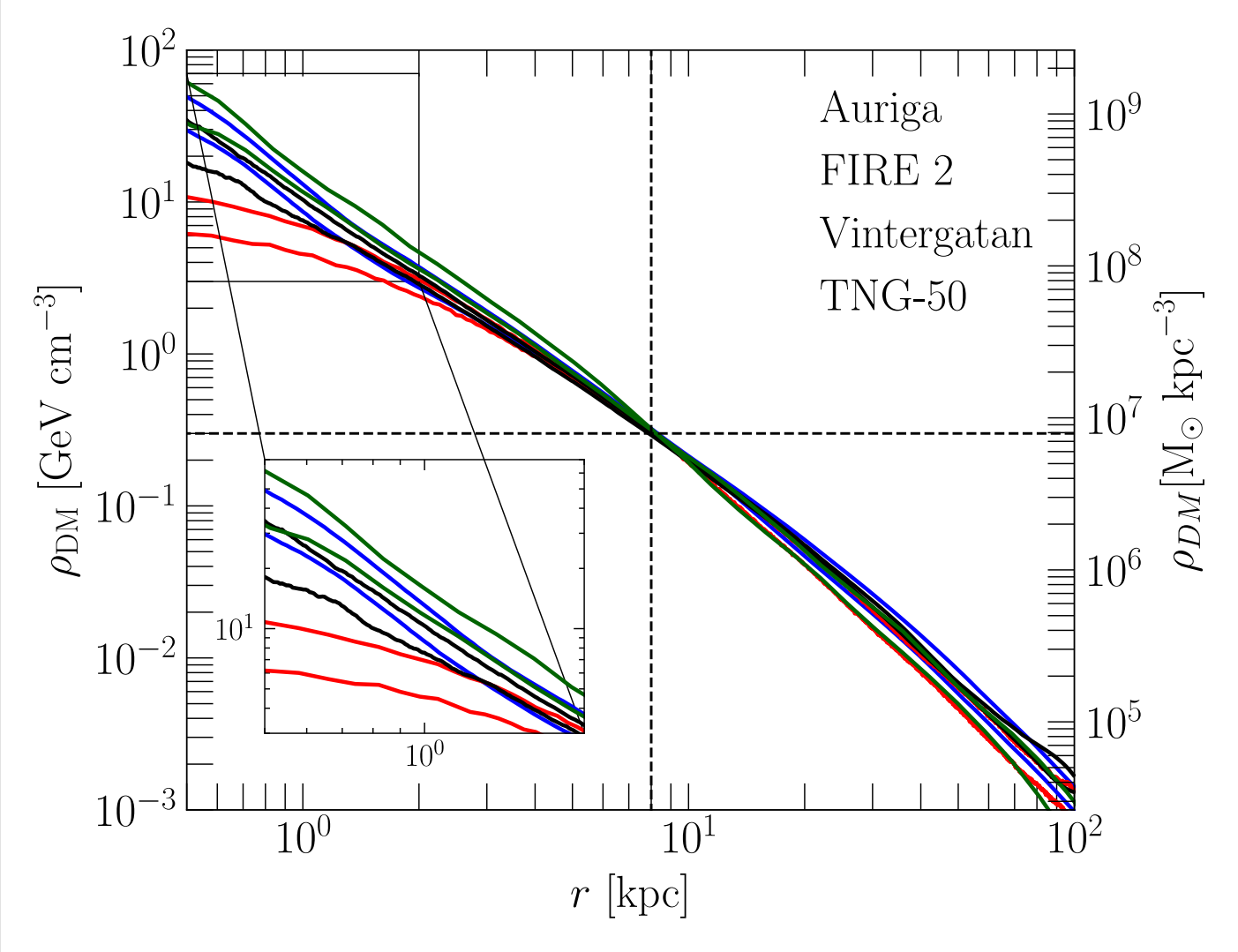
Adiabatic Contraction

Lina Necib, MIT

Blumenthal et al. 1986
Gnedin et al. 2004

DIFFERENT SIMULATIONS IMPLEMENT PROCESSES AFFECTING THE DENSITY PROFILE DIFFERENTLY

Abdelaziz Hussein



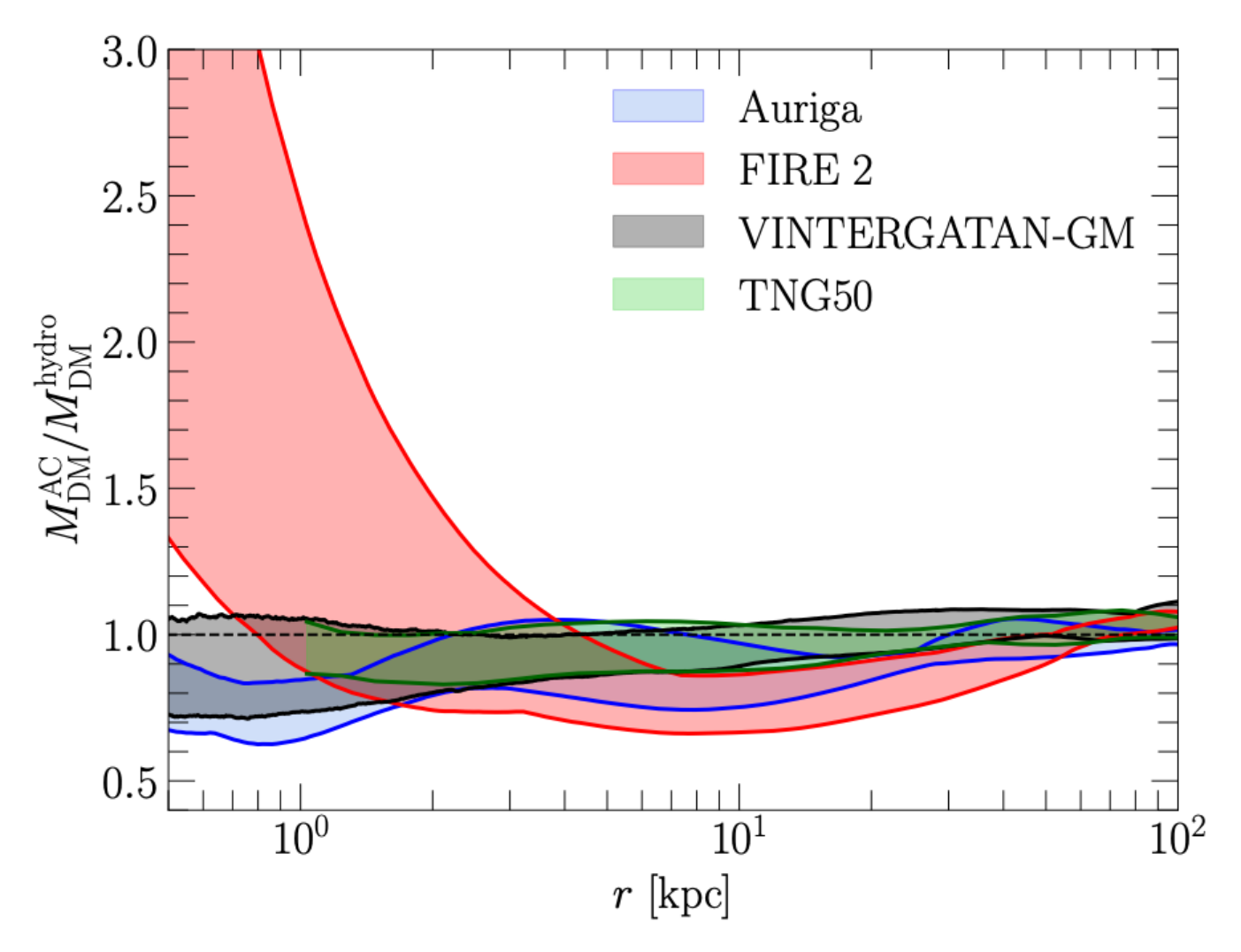
Wetzel et al. (2016)
Hopkins et al. (2018)
Wetzel et al. (2023)
Grand et al. (2024)
Agertz et al. (2021)
Rey et al. (2023)
Pillepich et al. (2023)

Hussein, **Necib**, Kaplinghat et al. (2025) arXiv:2501.14868

Lina Necib, MIT

COMPARING THESE RESULTS TO THE THEORY PREDICTION LEADS TO

Abdelaziz Hussein



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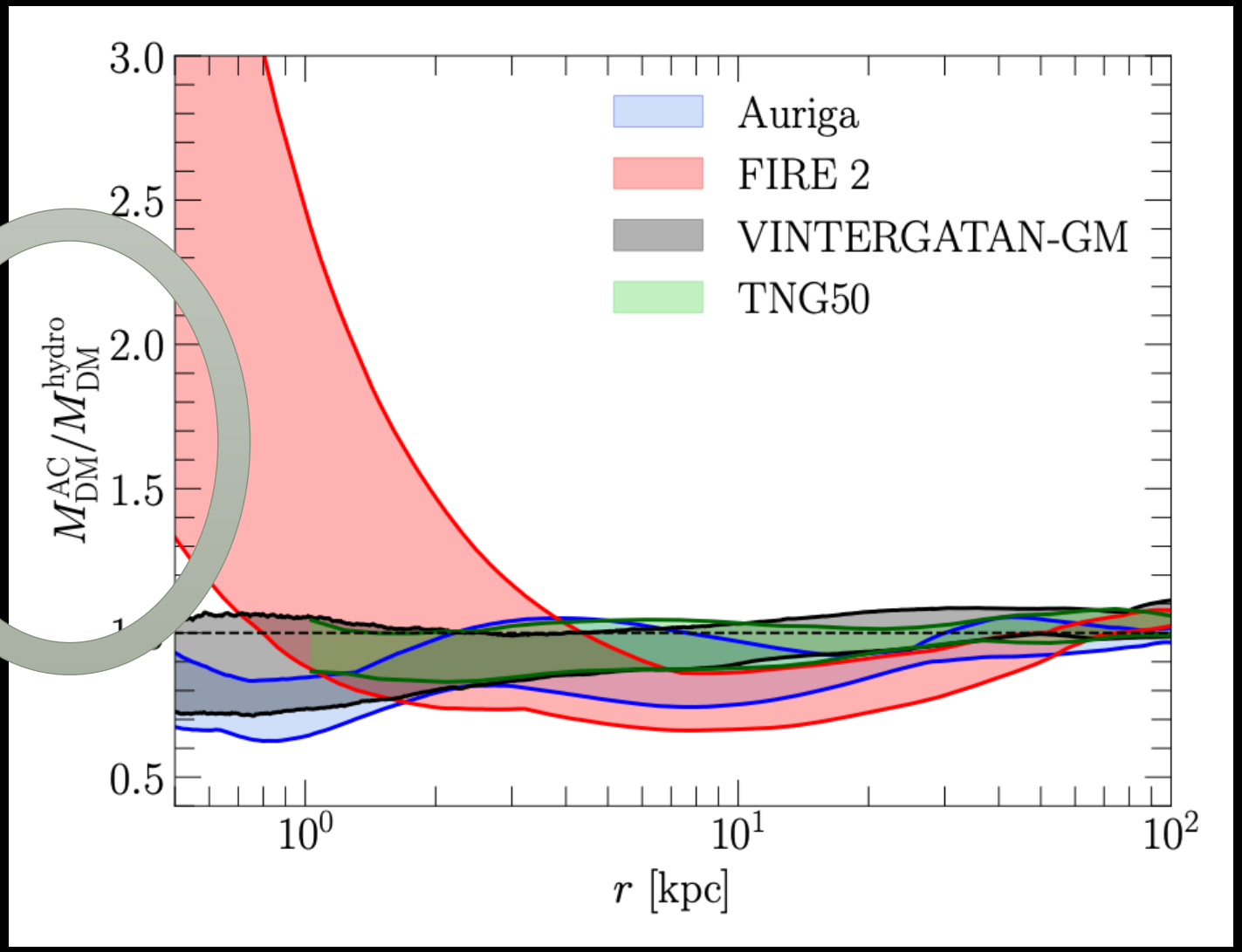
Ratio of theory expectation to simulation results



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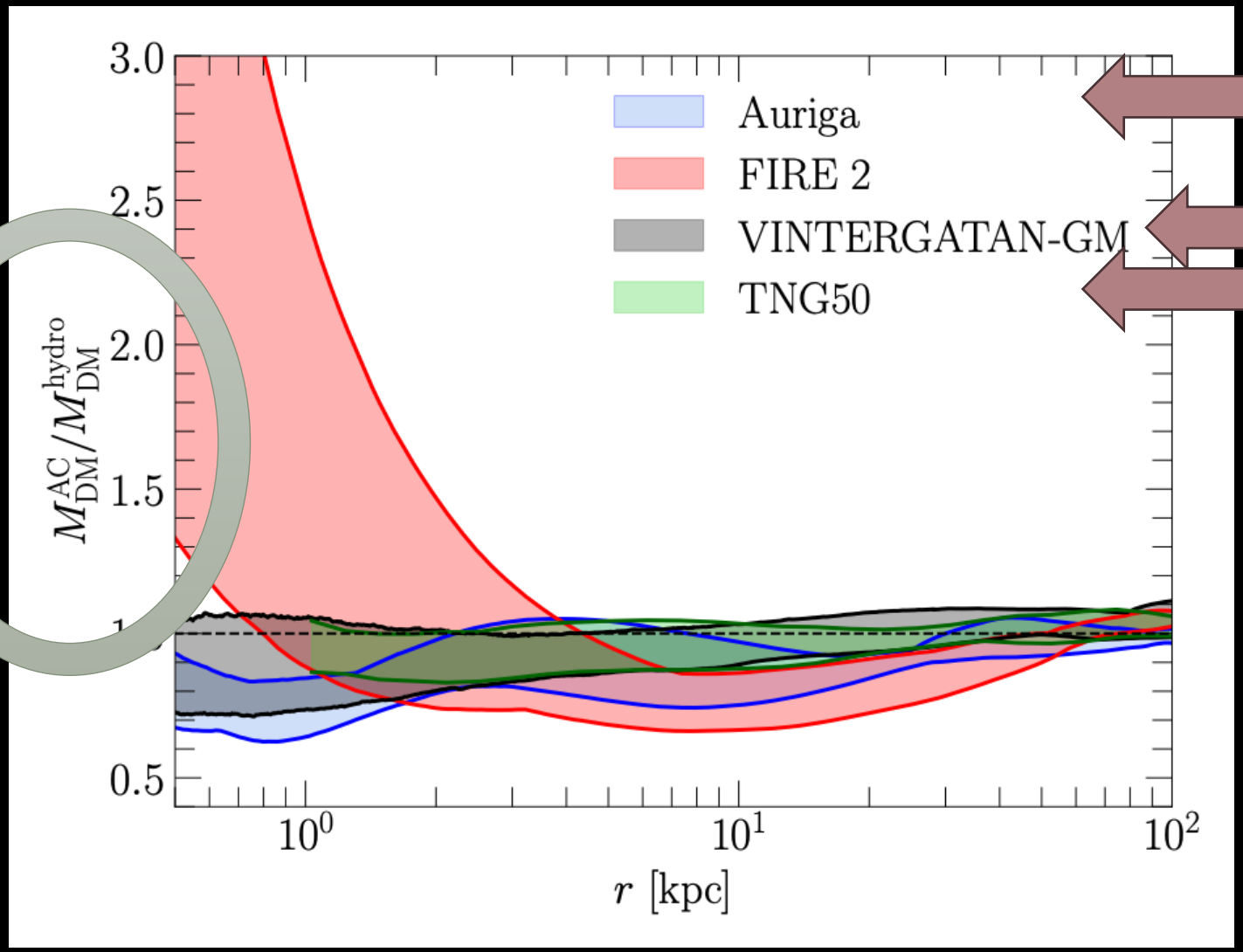

Adiabatic Contraction is a good description of the model

Wetzel et al. (2016)
Hopkins et al. (2018)
Wetzel et al. (2023)
Grand et al. (2024)
Agertz et al. (2021)
Rey et al. (2023)
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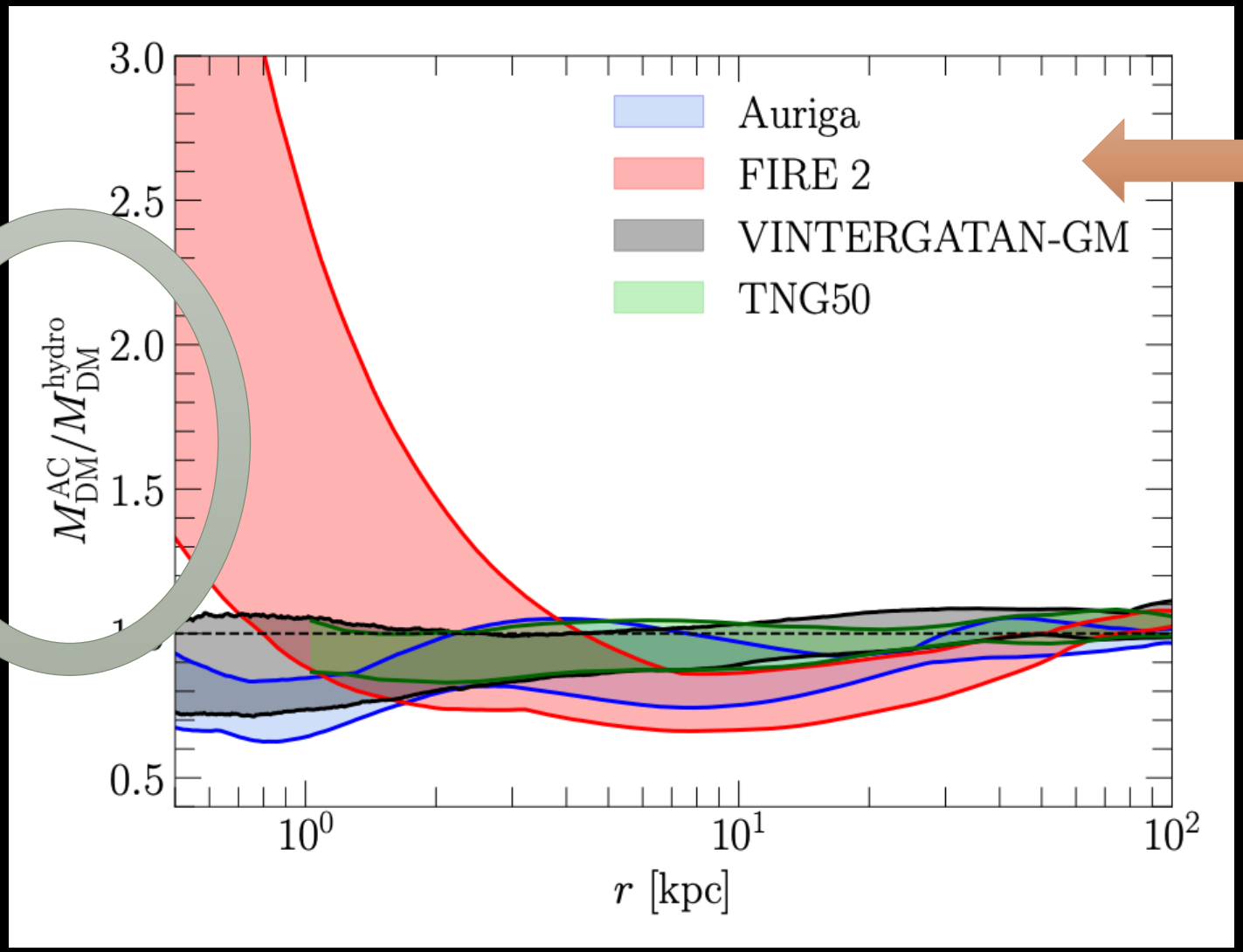


Strong Feedback is breaking the adiabatic contraction model

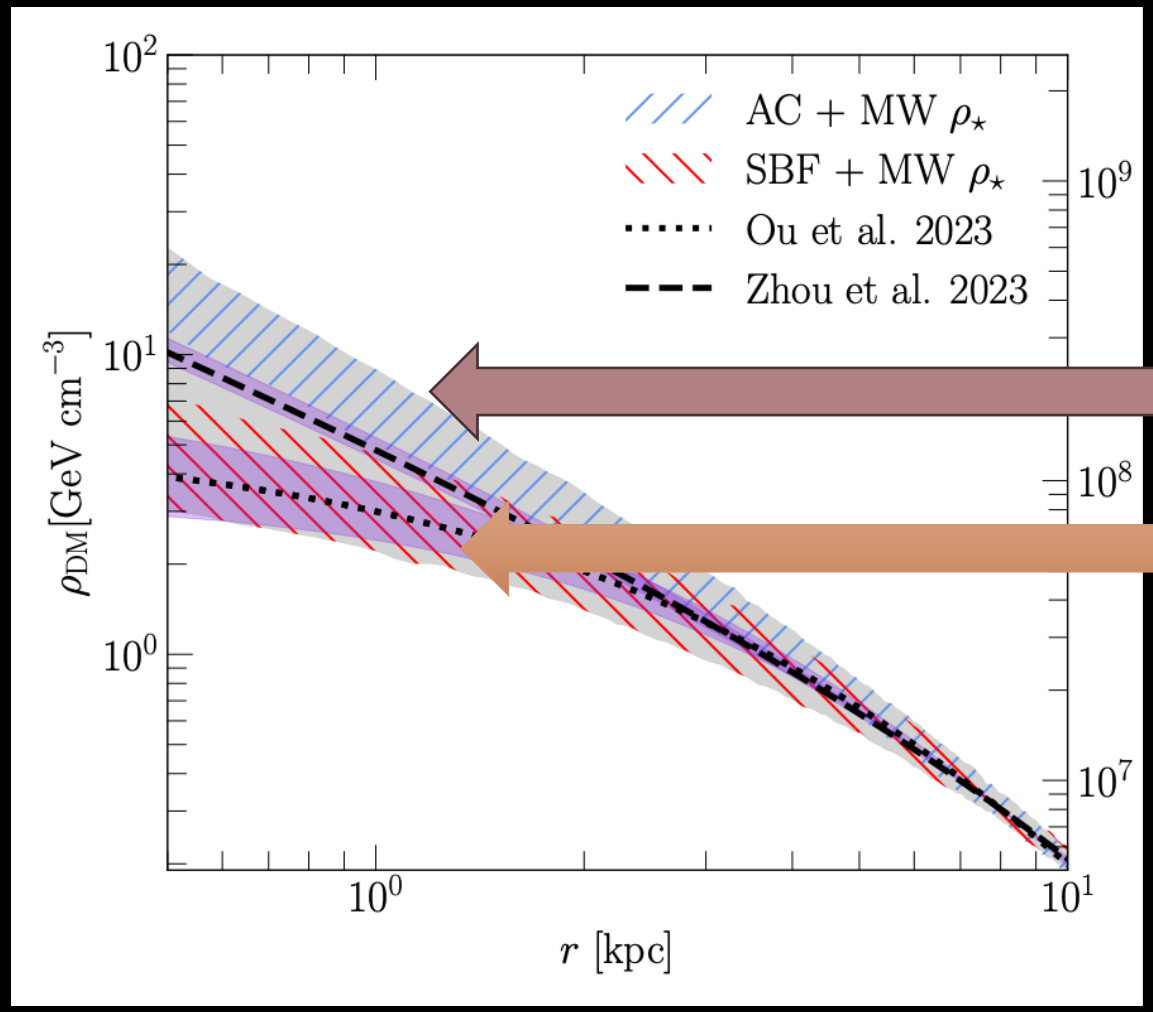
Wetzel et al. (2016)
Hopkins et al. (2018)
Wetzel et al. (2023)
Grand et al. (2024)
Agertz et al. (2021)
Rey et al. (2023)
Pillepich et al. (2023)

Hussein, **Necib**, Kaplinghat et al. (2025) arXiv:2501.14868

Lina Necib, MIT

LET'S QUANTIFY OUR IGNORANCE BY SETTING A SYSTEMATIC BAND FOR THE MILKY WAY

Abdelaziz Hussein



Adiabatic Contraction density profile based on the Milky Way observed stellar distribution

Strong Baryonic Feedback model from FIRE-2, assuming the Milky Way observed stellar distribution

Hussein, **Necib**, Kaplinghat et al. (2025) arXiv:2501.14868

Lina Necib, MIT

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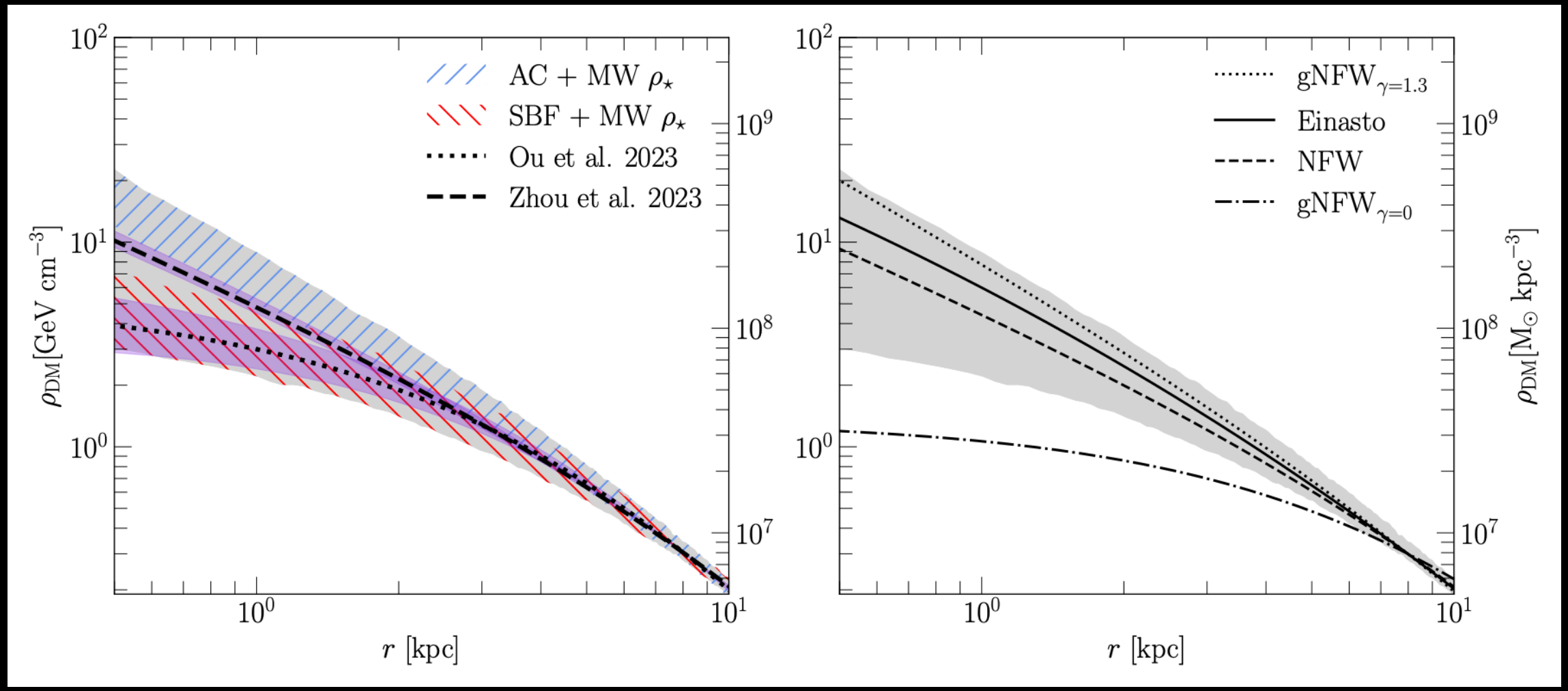

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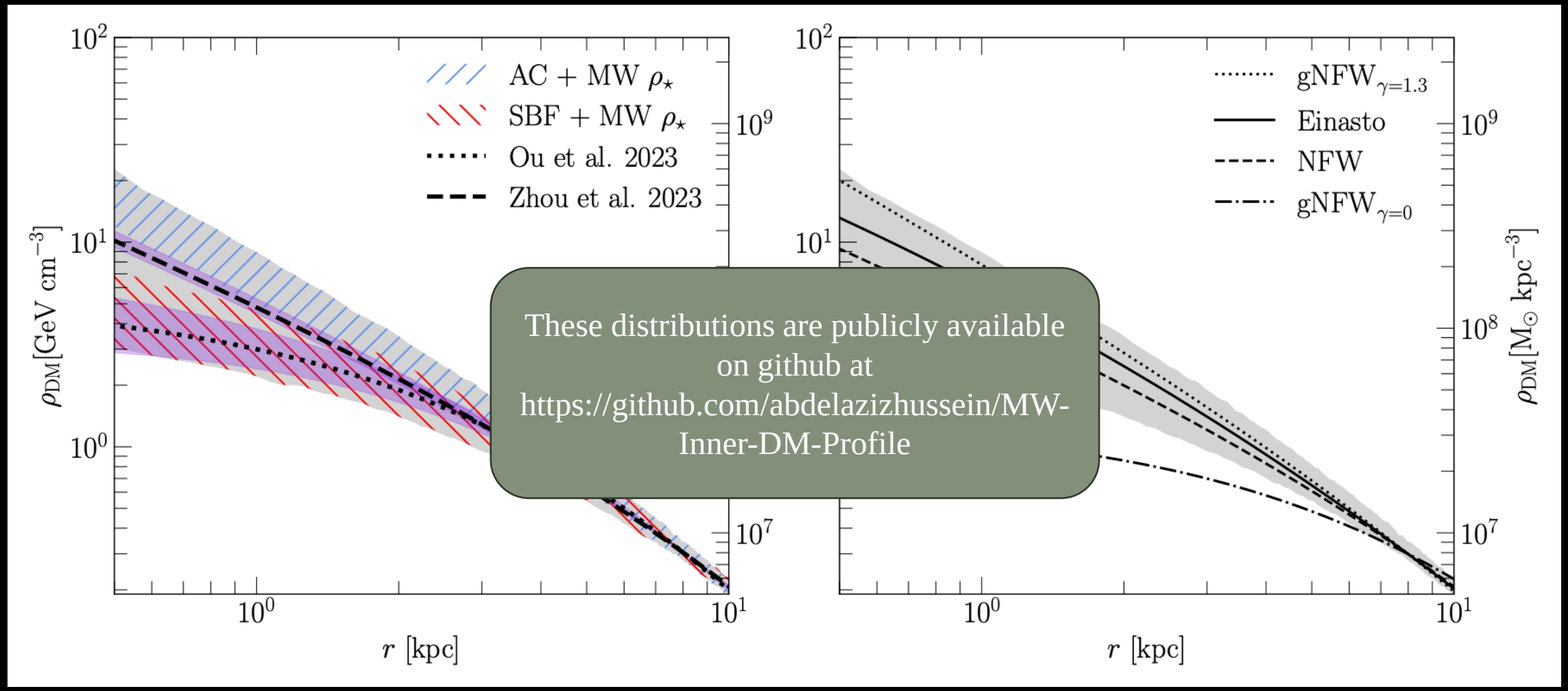


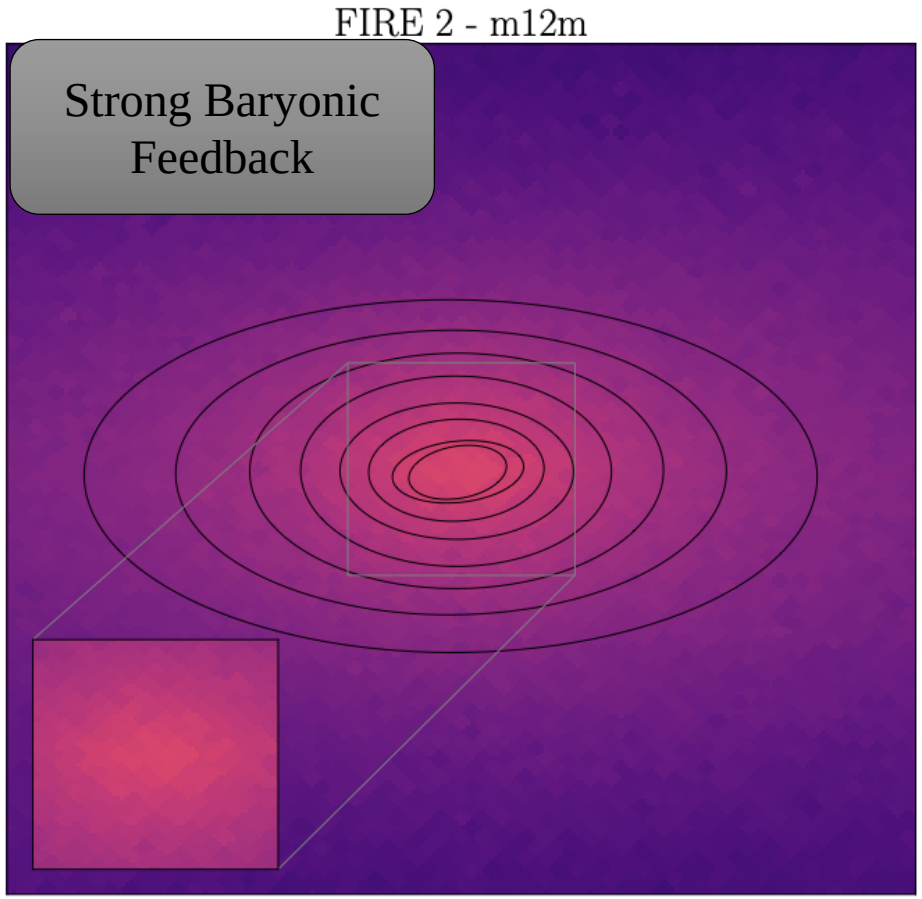
These distributions are publicly available on github at https://github.com/abdelazizhussein/MW-Inner-DM-Profile

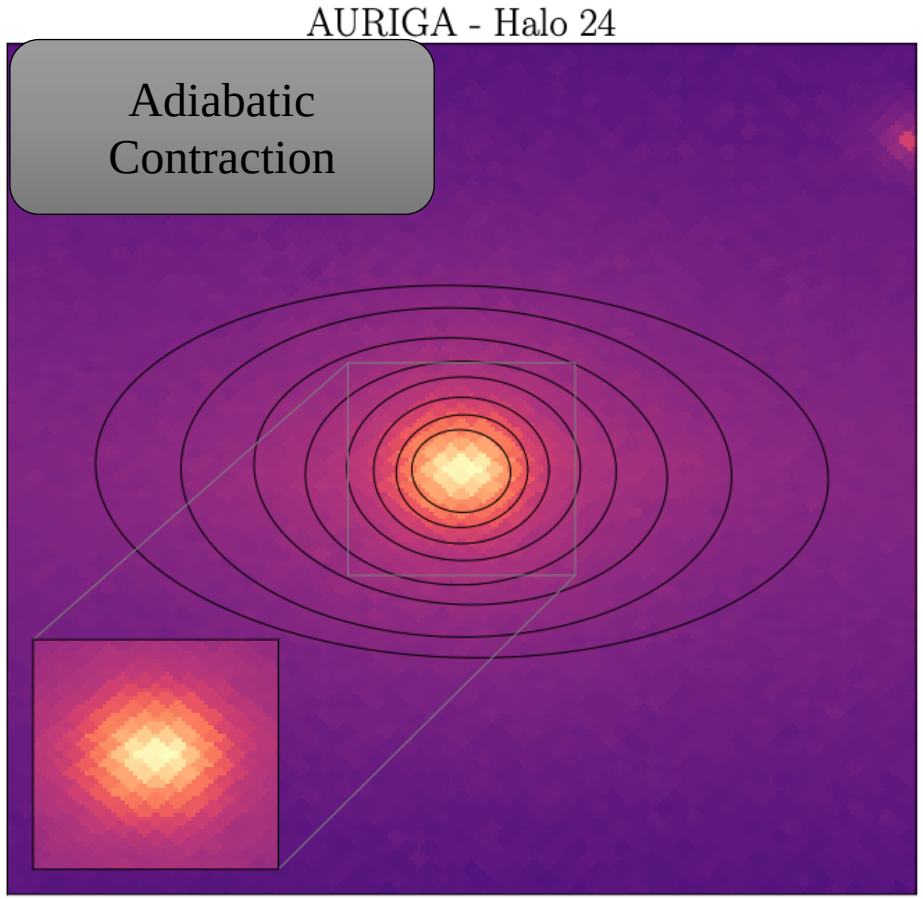
Hussein, **Necib**, Kaplinghat et al. (2025) arXiv:2501.14868

Lina Necib, MIT

THE DIFFERENT MECHANISMS ALSO AFFECT THE DARK MATTER SPATIAL DISTRIBUTION

Abdelaziz Hussein





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