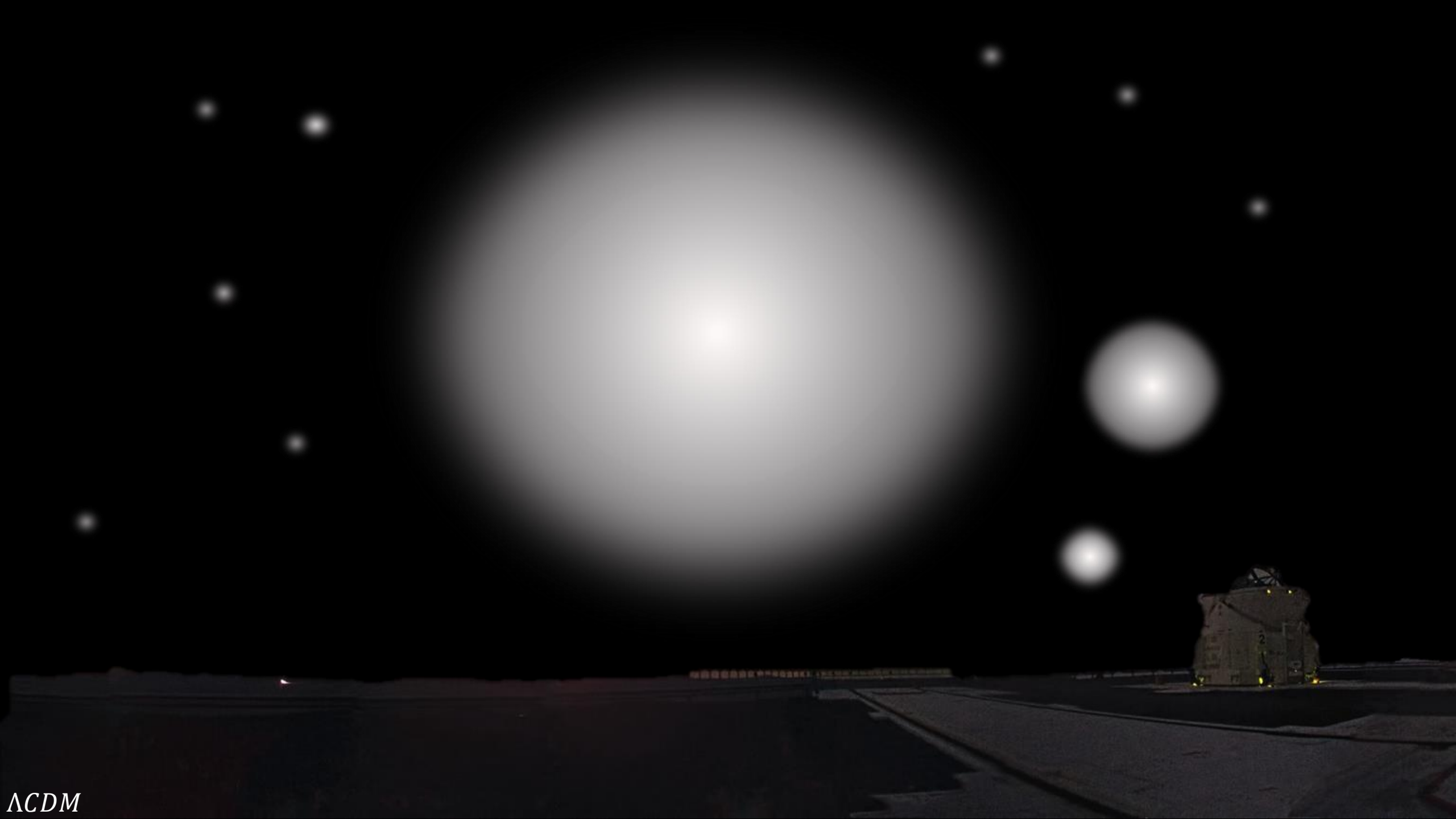
MAPPING OUT THE DARK MATTER IN THE MILKY WAY

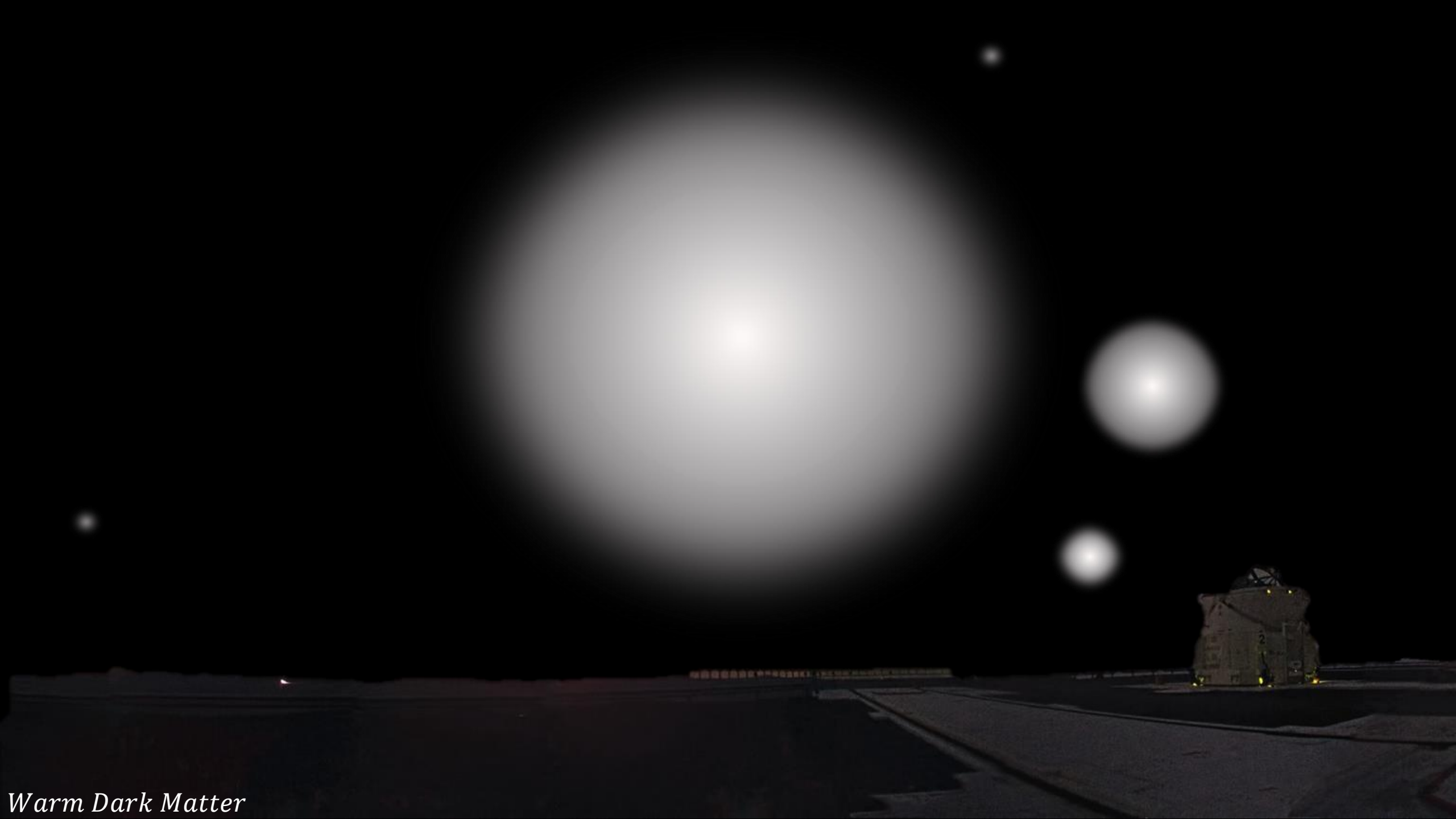
Lina Necib

Massachusetts Institute of Technology

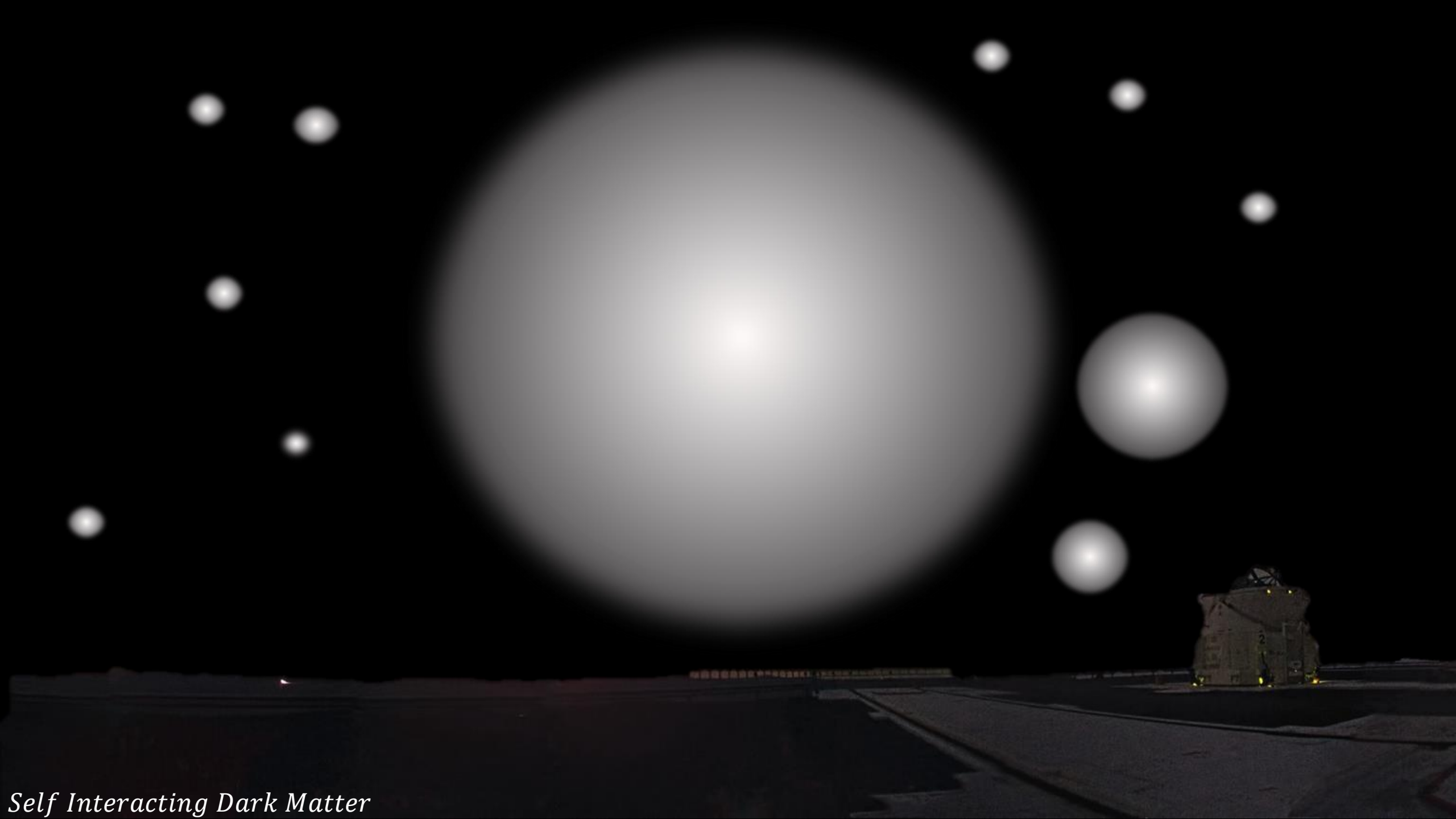
MIT KAVLI INSTITUTE

Credit: ESO/Y. Beletsky

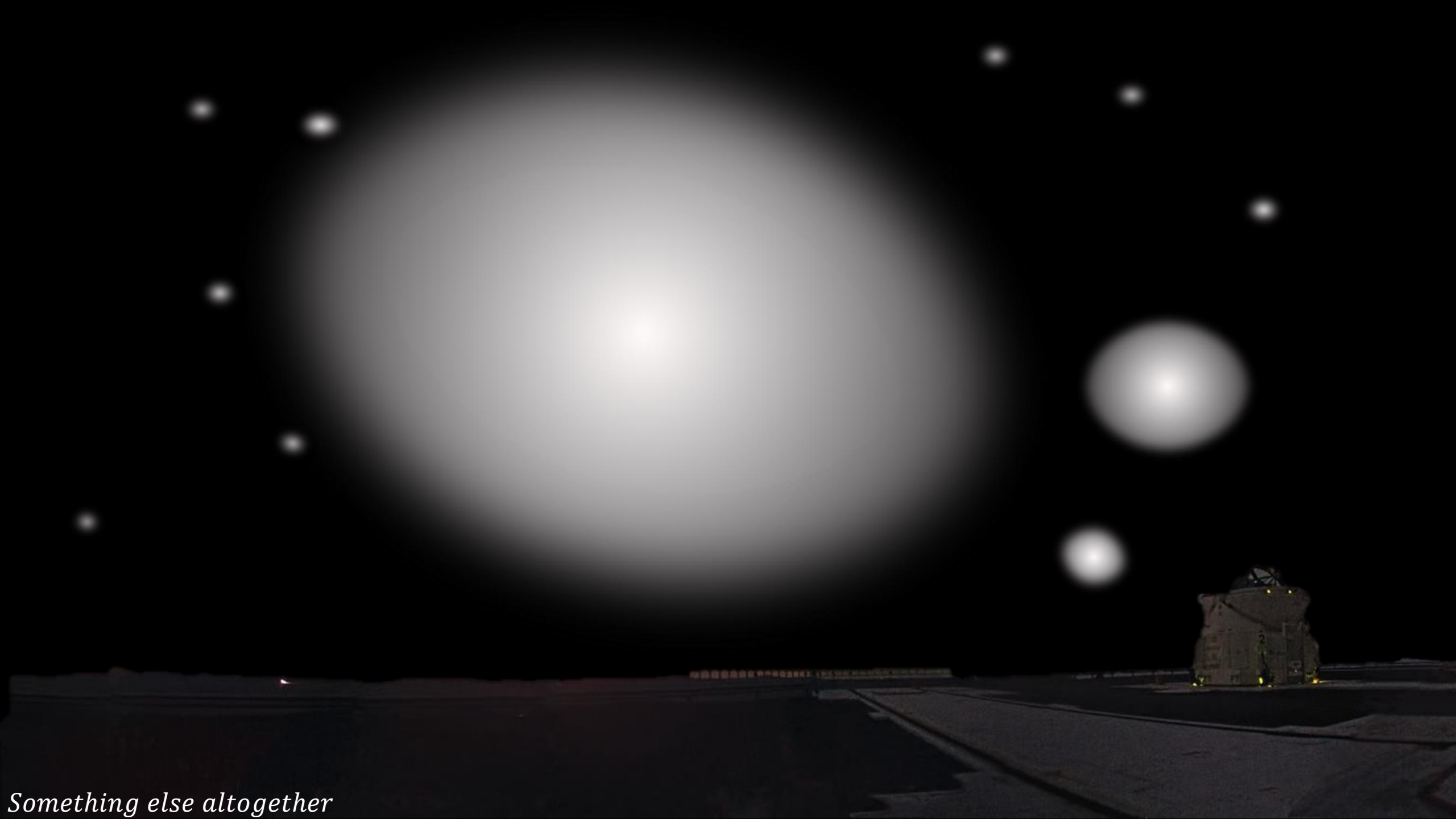

ΛCDM



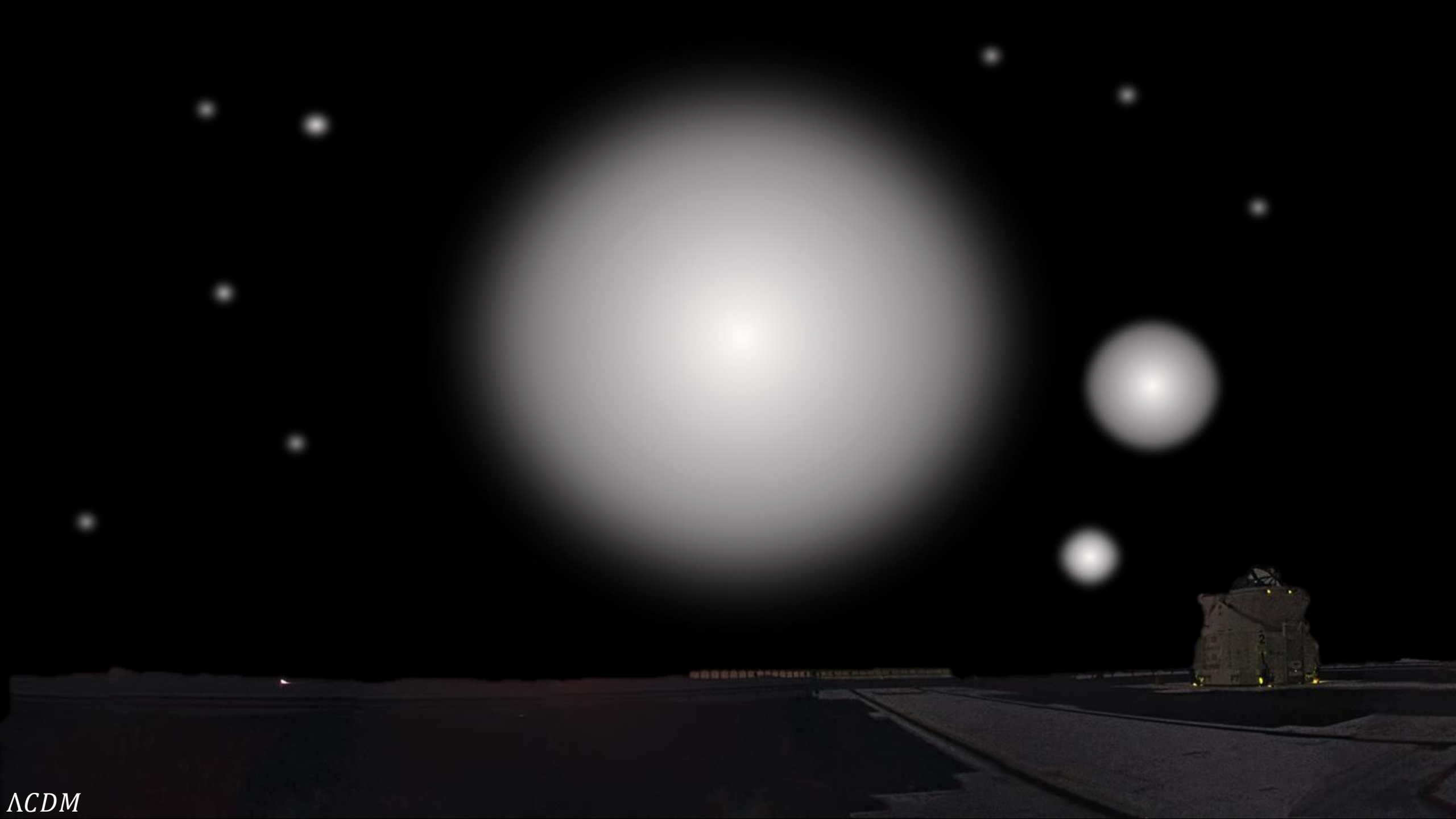
Warm Dark Matter



Self Interacting Dark Matter



Something else altogether


ΛCDM

GOAL:
MAPPING FROM THE STARS TO THE DARK MATTER

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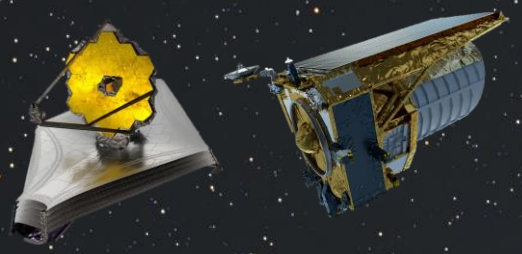
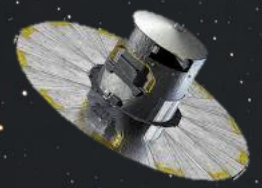
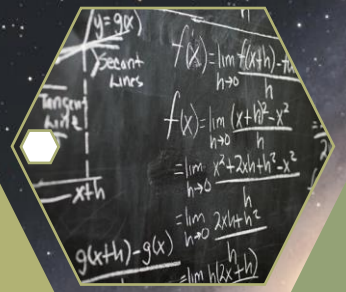




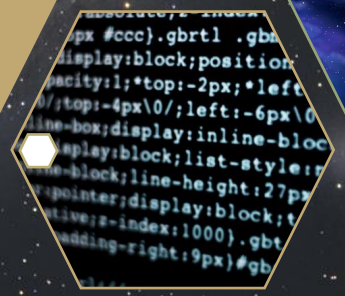
Telescopes

Astroparticle Theory



Machine Learning

Galactic Dynamics



Simulations

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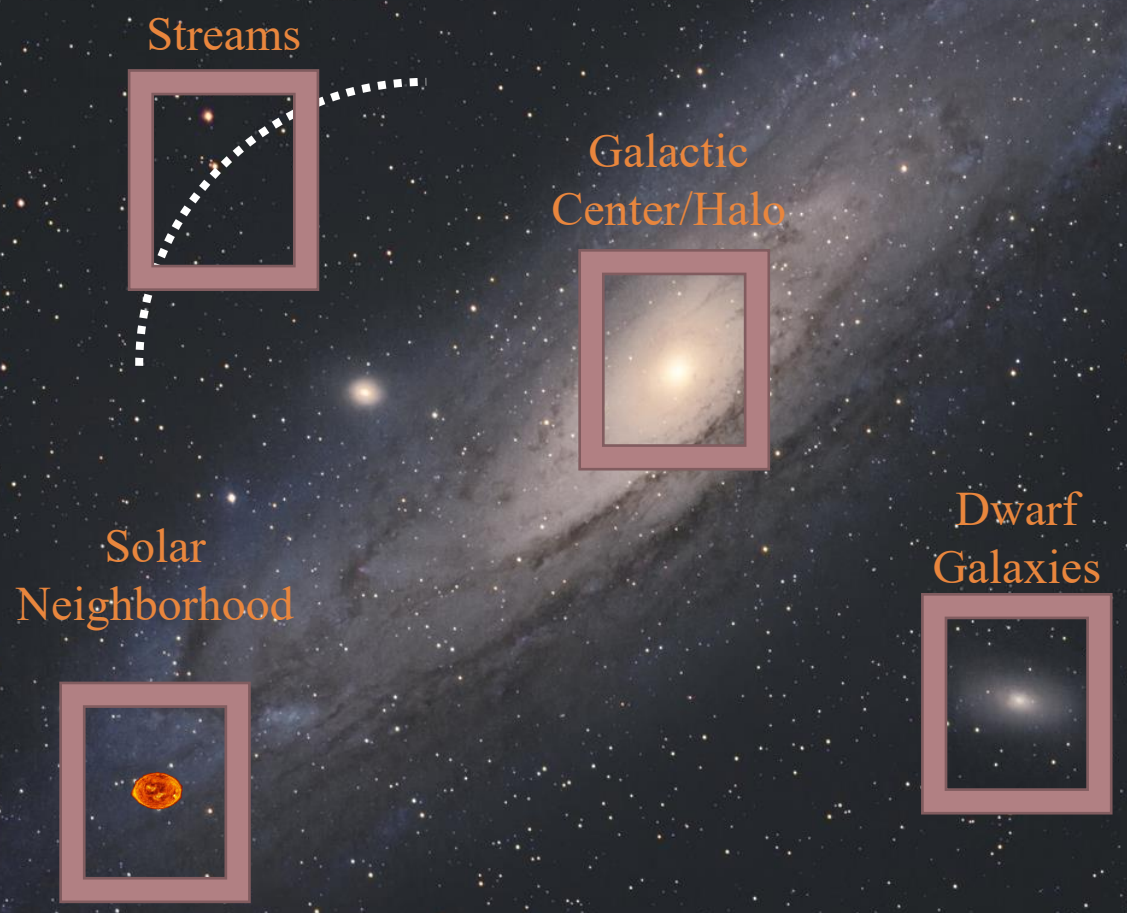
https://www.ge.com/reports/5-coolest-things-earth-week-29-6/andromeda-galaxy/

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

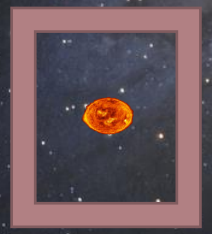
Xiaowei Ou
PhD' 25

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

GOAL:
MAPPING FROM TH TO THE DARK MATTER

Check out Nathaniel's talk Thursday morning

Check out Abdelaziz' talk this afternoon at 18:30

Check out Xiuyuan's talk Friday morning

Streams

Nora Shipp

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Brinson Fellow

Galactic Center/Halo

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Dwarf Galaxies

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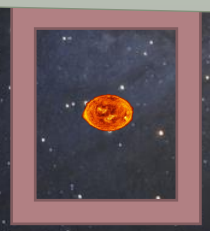
PhD' 24

After MIT: CIERA Fellow, Northwestern

Solar Neighborhood



Zeineb Mezghanni

Xiuyuan Zhang

Lina Necib, MIT

GOAL:
MAPPING FROM THE STARS TO THE DARK MATTER

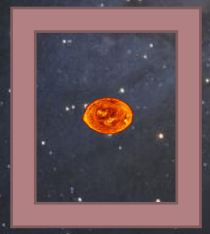
Streams

Dropulic, Ship,…, Necib, et al (2024)
Shih, Buckley, Necib (2024)
Shipp, Panithanpaisal, Necib, et al. (2024)
Shipp, Riley,…, Necib, et al. (2024)

Galactic Center/Halo

Ou, Necib, et al. (2025)
Hussein, Necib, et al. 2025)
Ou, Eilers, Necib, Frebel (2024)
Nguyen, Ou,…, Necib, et al. (2024)
Roche, Necib, Lin (2024)
Necib, Lin (2022a,b)

Solar Neighborhood



Zhang, Necib, Erkal (2025)
Ou, Necib, Frebel (2023)
Wang, Necib, et al. (2023)
Necib, Ostdiek, Lisanti, et al. (2020a,b)
Ostdiek, Necib, et al. (2020)
Necib, Lisanti, et al. (2019)
Necib, Lisanti, Belokurov (2019)

Dwarf Galaxies

Nguyen, Read, Necib, et al. (2025)
Ou, Chiti,…, Necib, et al. (2024)
Sands, Hopkins,…, Necib, et al. (2024)
Shen, Hopkins, Necib, et al. (2024)
Rose, Torrey,…, Necib et al (2024)
Folsom, Lisanti, Necib, et al (2024)
Nguyen, Villaescusa-Navarro, …, Necib, et al. (2024)
Nguyen, Mishra-Sharma, Williams, Necib (2023)
Chang, Necib (2021)

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

Galactic Center/Halo

Ou, Necib, et al. (2025)
Hussein, Necib, et al. 2025)
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Roche, Necib, Lin (2024)
Necib, Lin (2022a,b)

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Chang, Necib (2021)

Lina Necib, MIT

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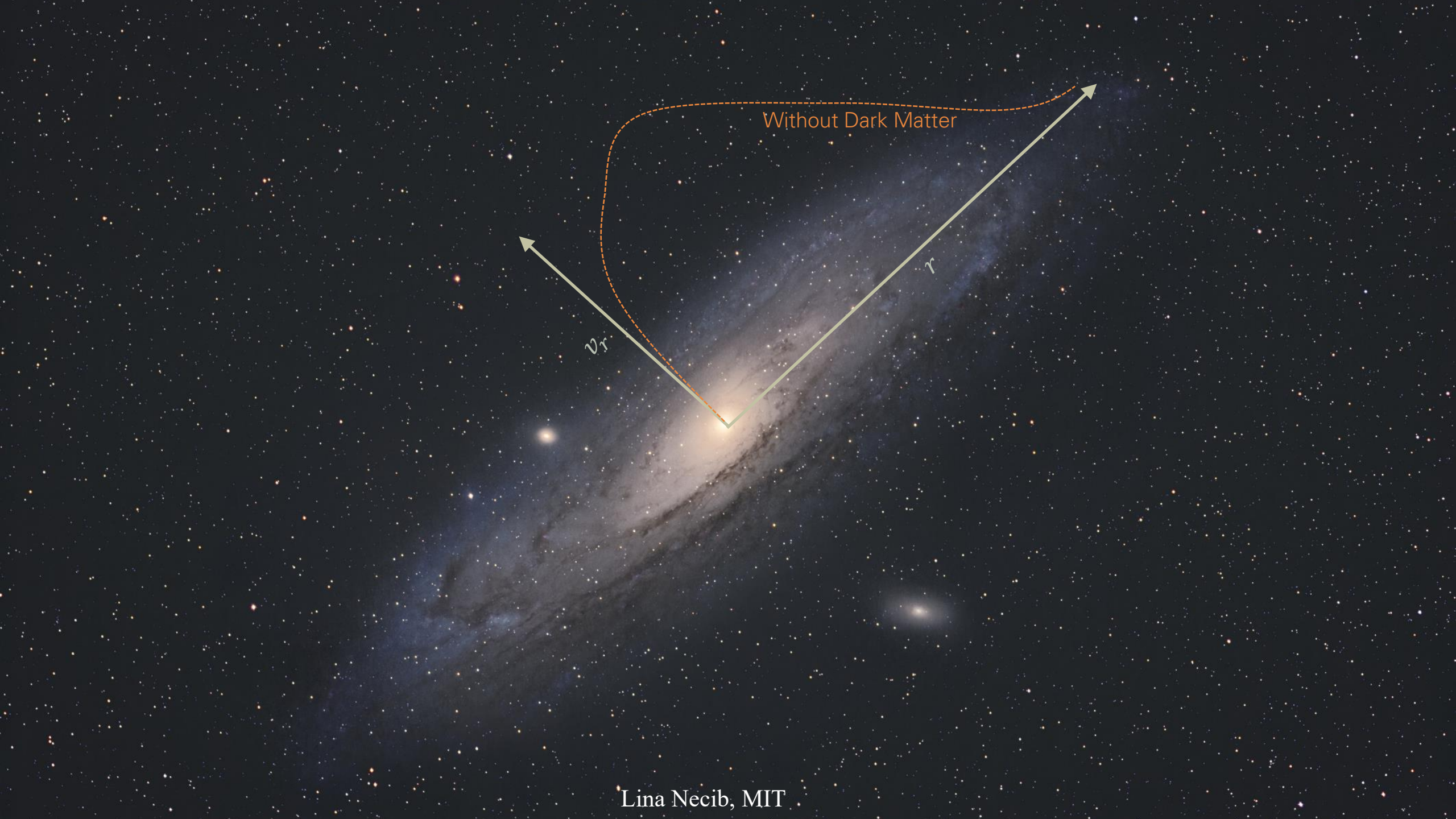
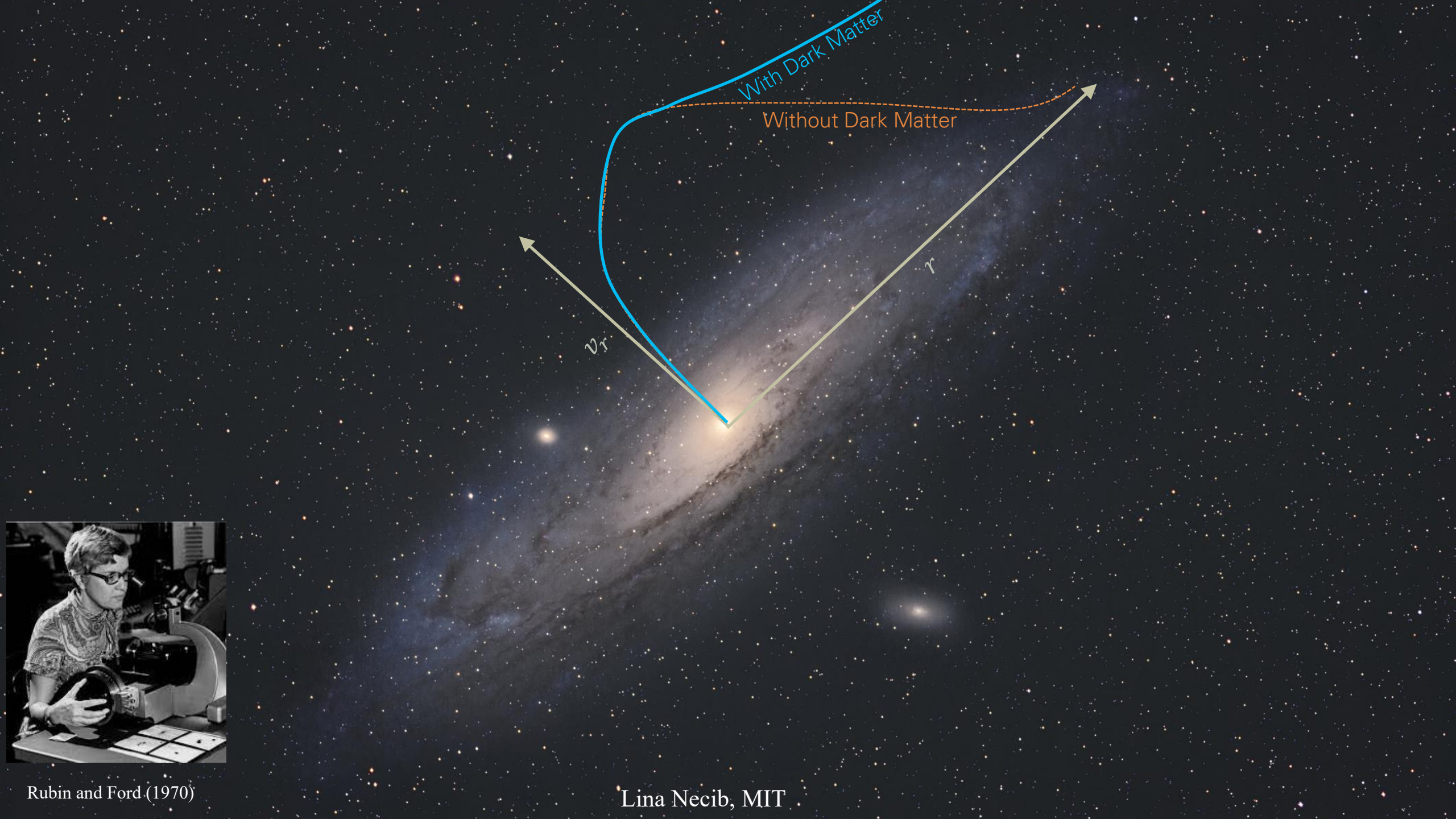
Roche, Necib, Lin (2024)
Necib, Lin (2022a,b)

Lina Necib, MIT

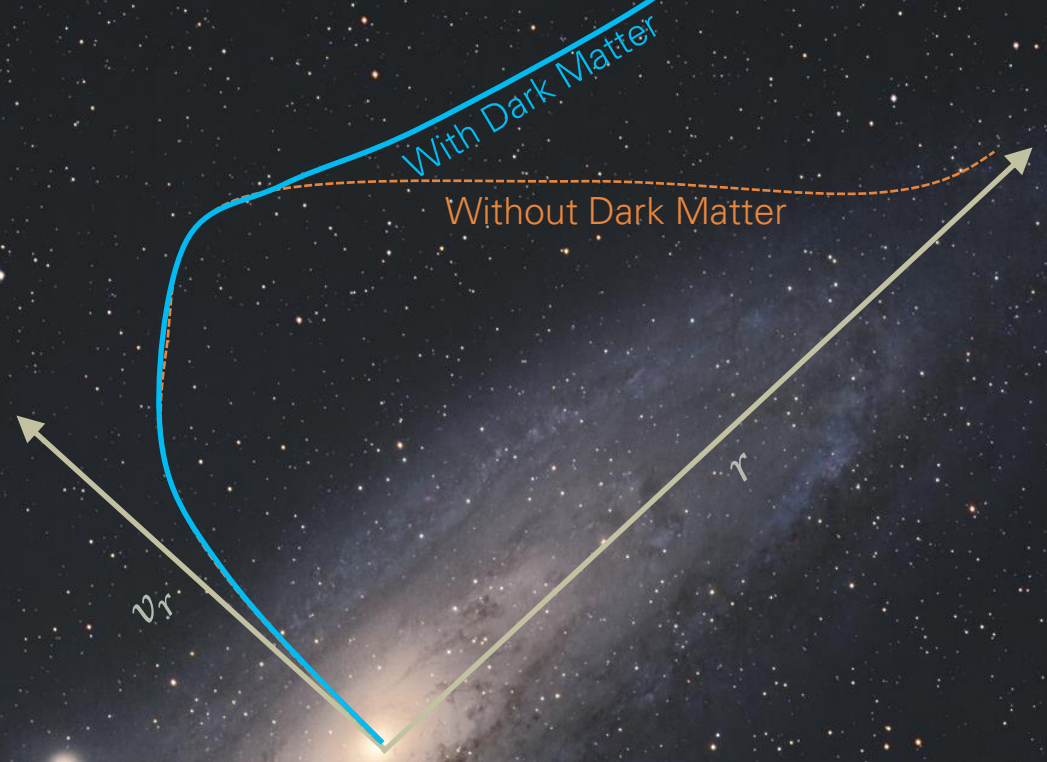


Lina Necib, MIT

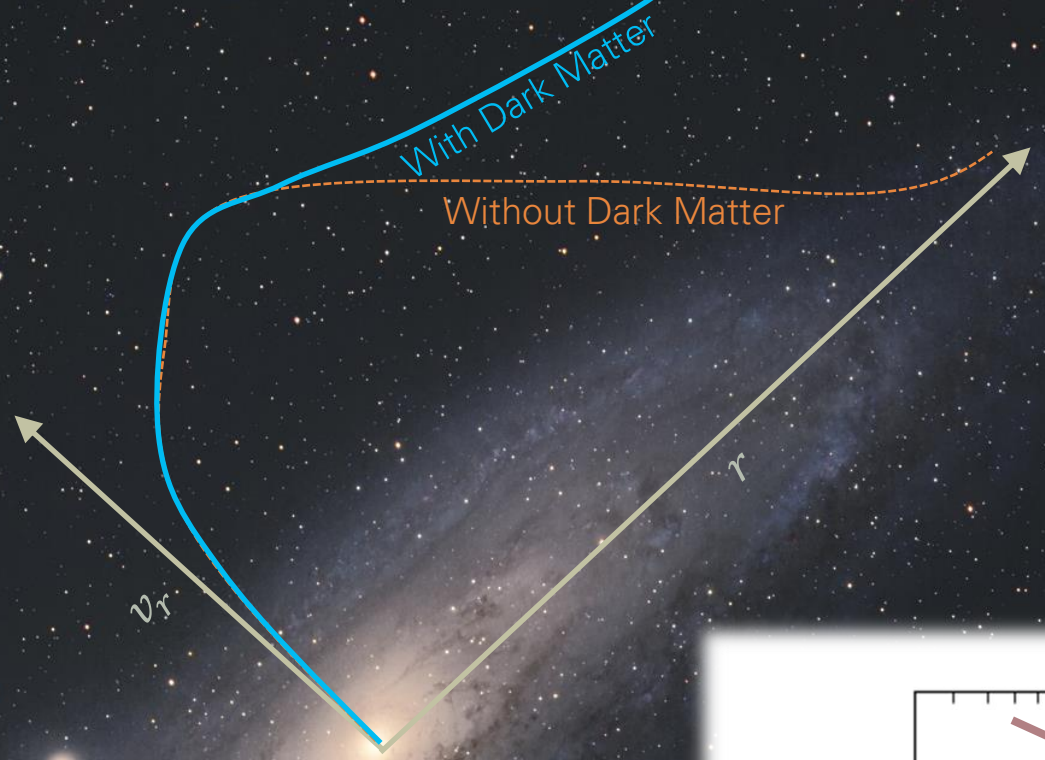


Rubin and Ford (1970)

Lina Necib, MIT



Circular Velocity → Gravitational Potential → Dark Matter Density



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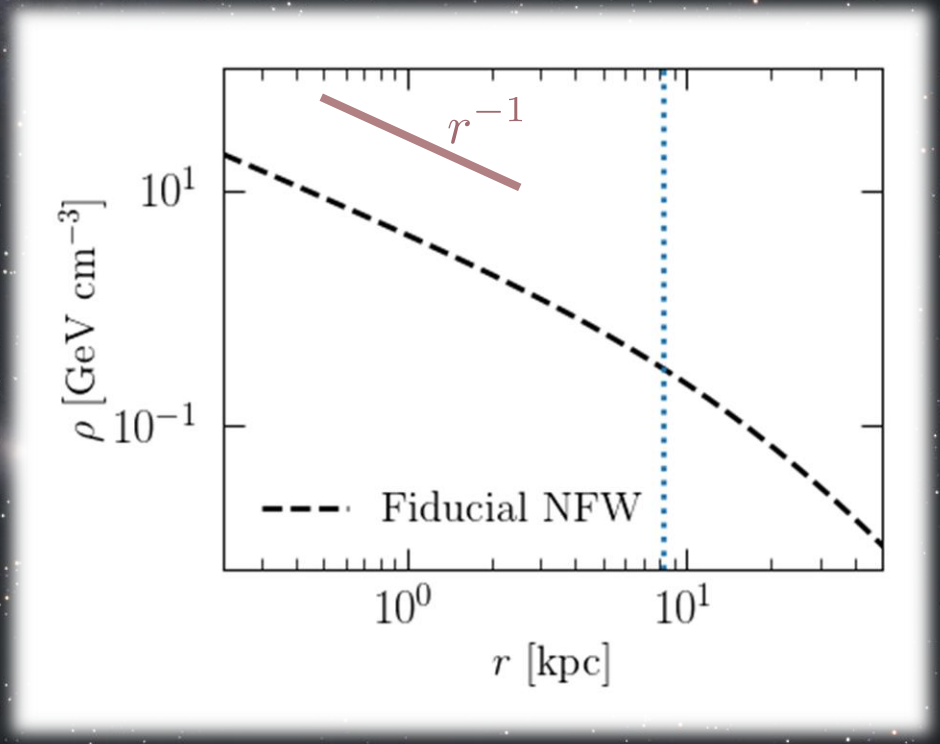

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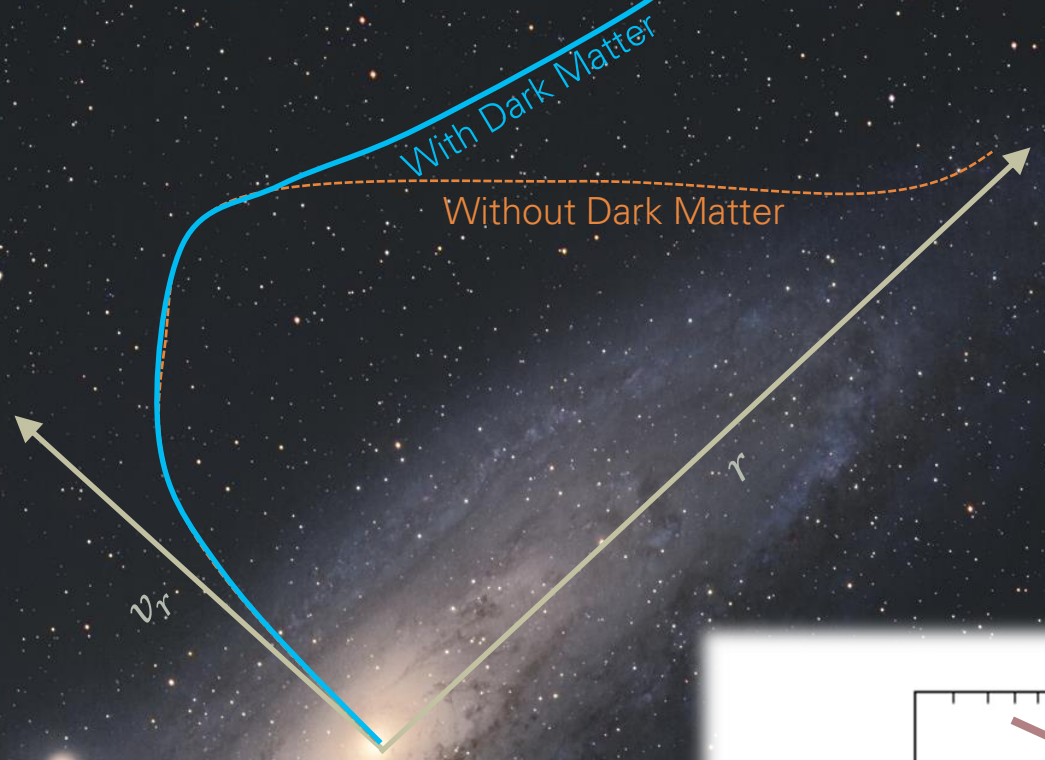
Navarro et al. (1997)



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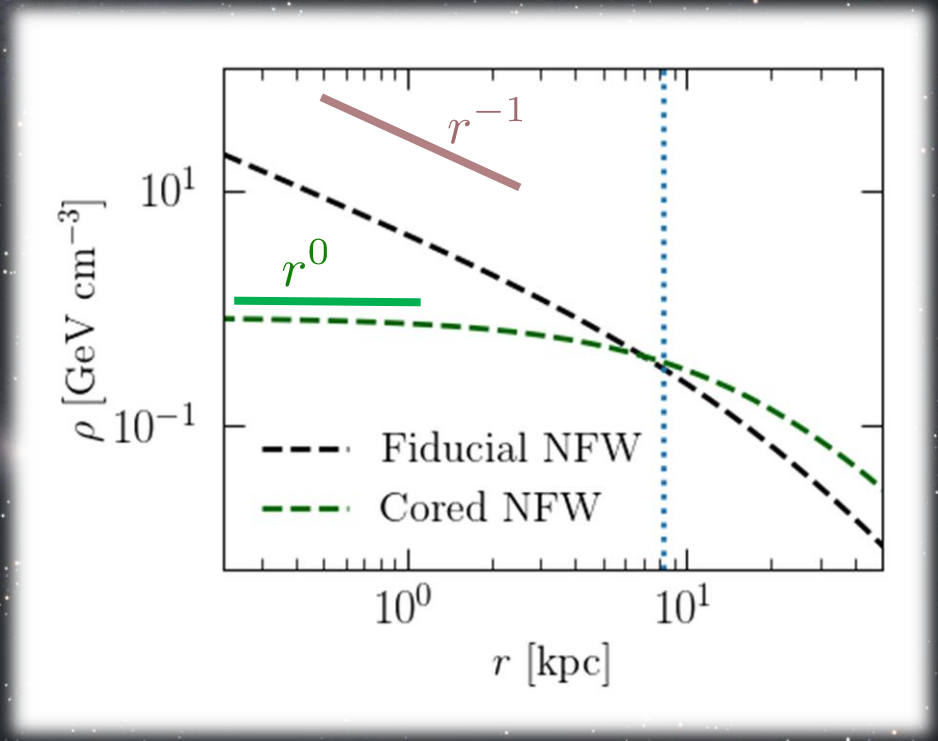

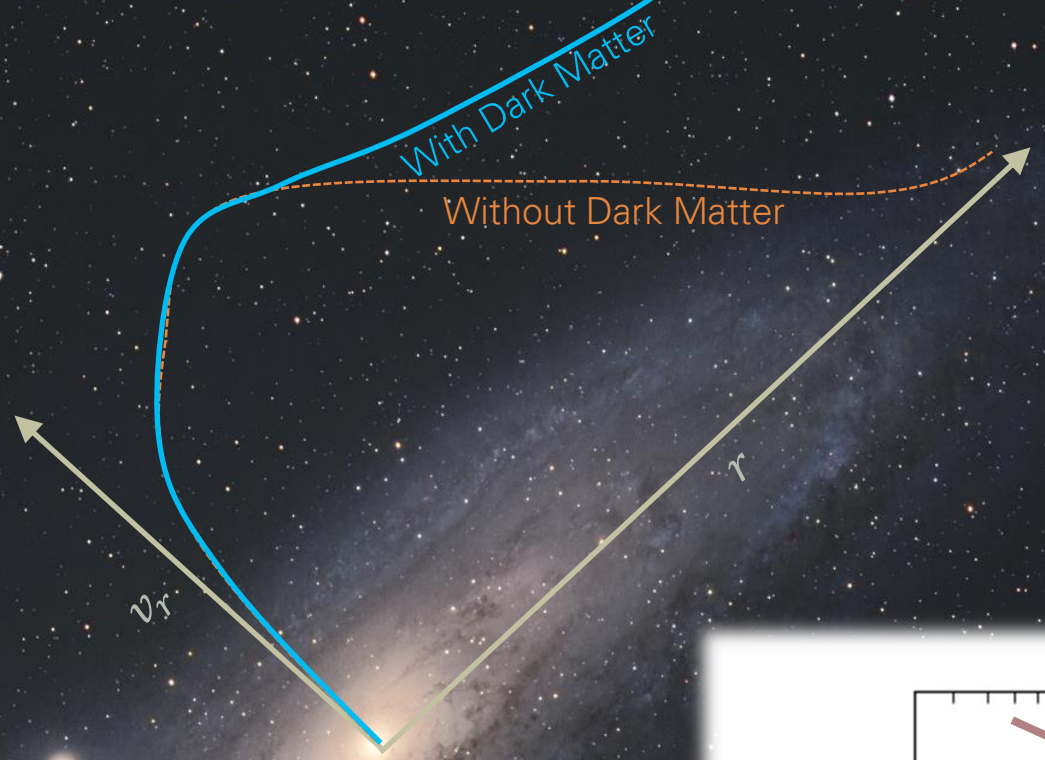

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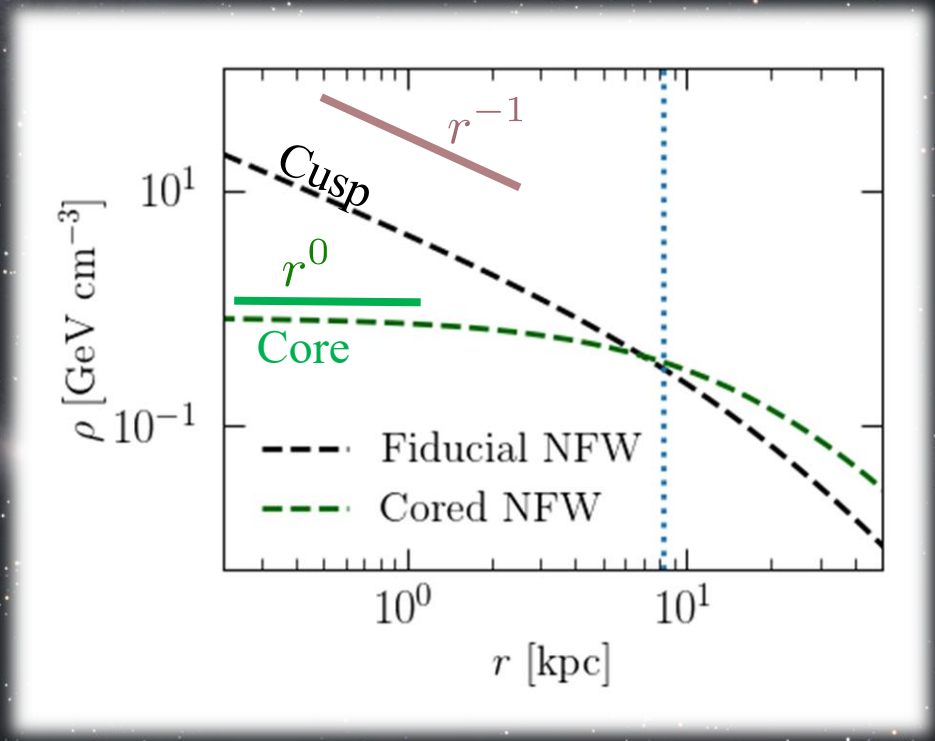
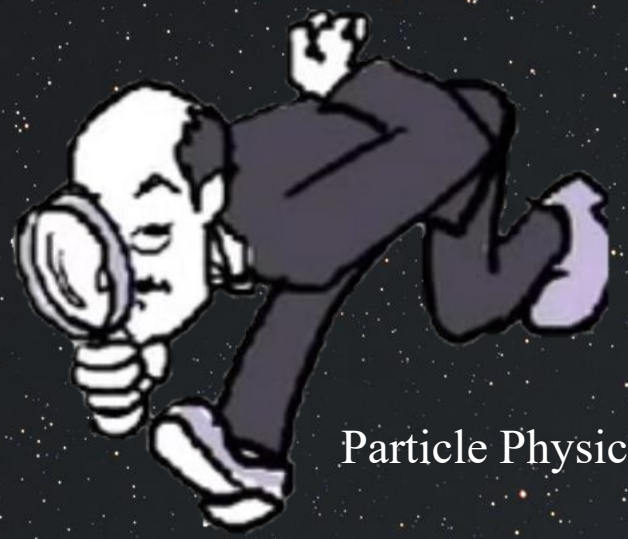
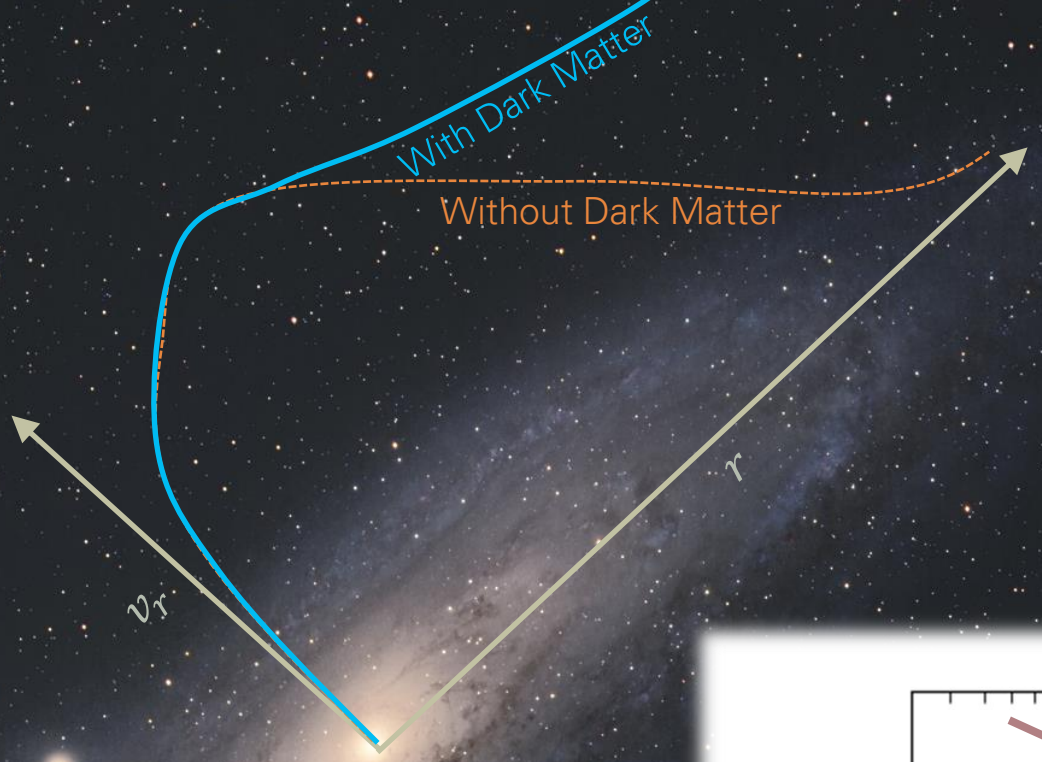
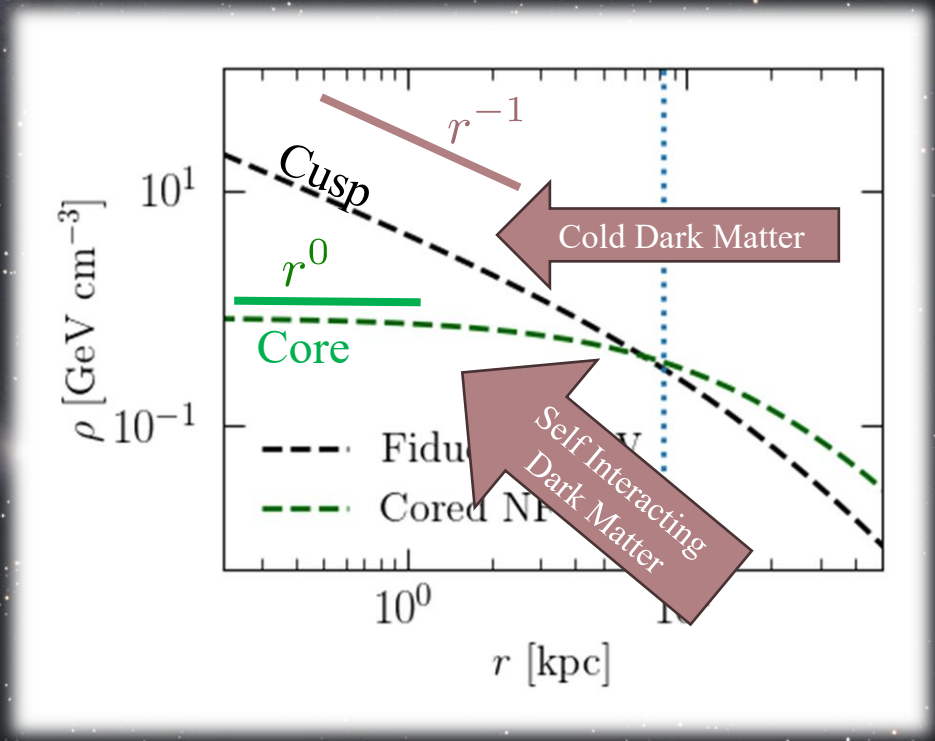




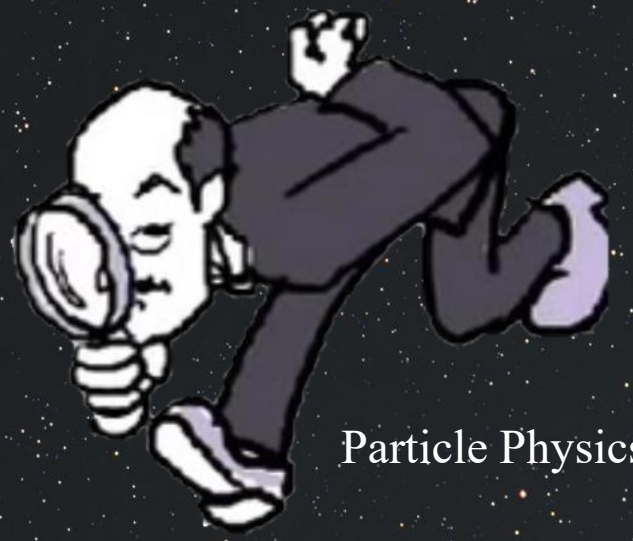
Particle Physics



Circular Velocity → Gravitational Potential → Dark Matter Density

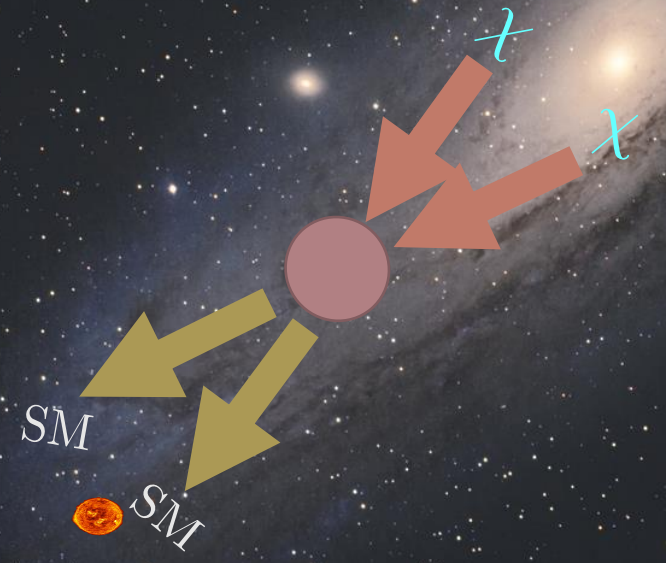


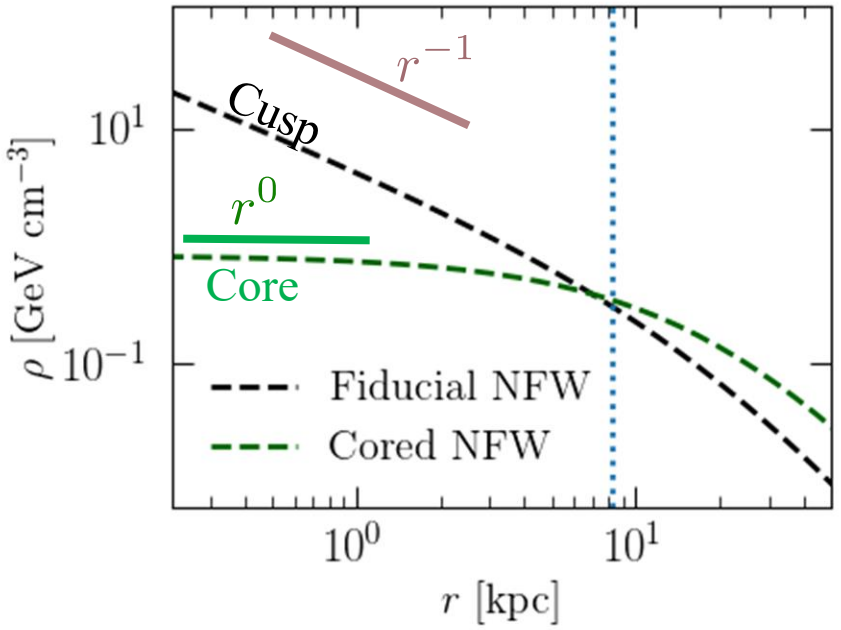
Lina Necib, MIT



Particle Physics

Dark Matter
Annihilation Signal





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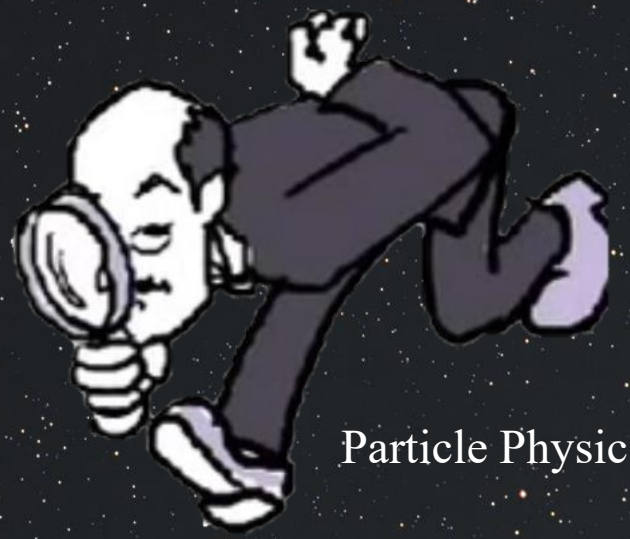
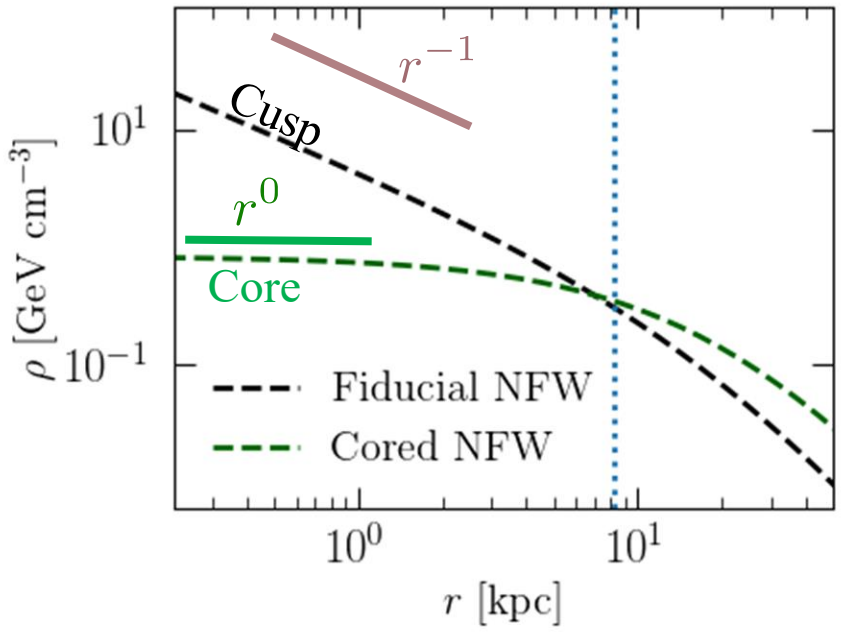


Particle Physics

Dark Matter
Annihilation Signal

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



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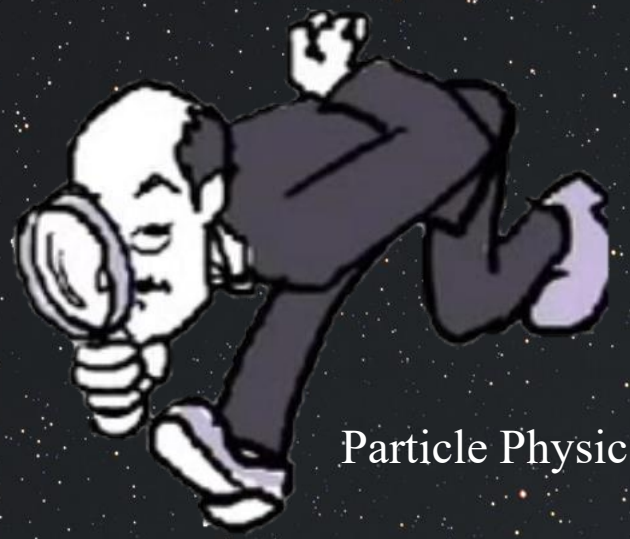

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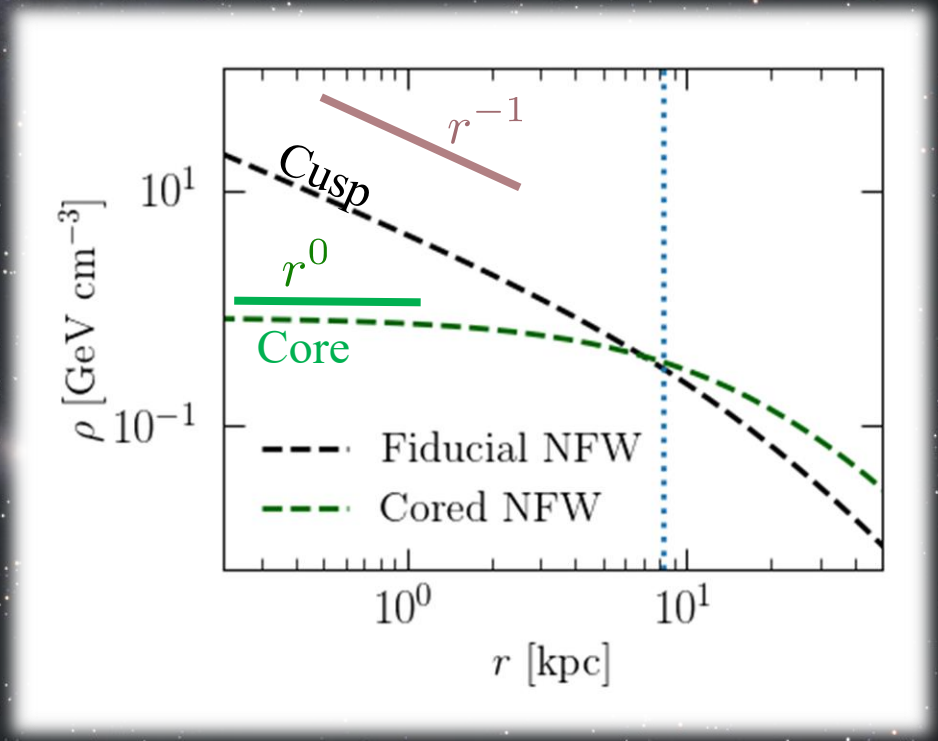
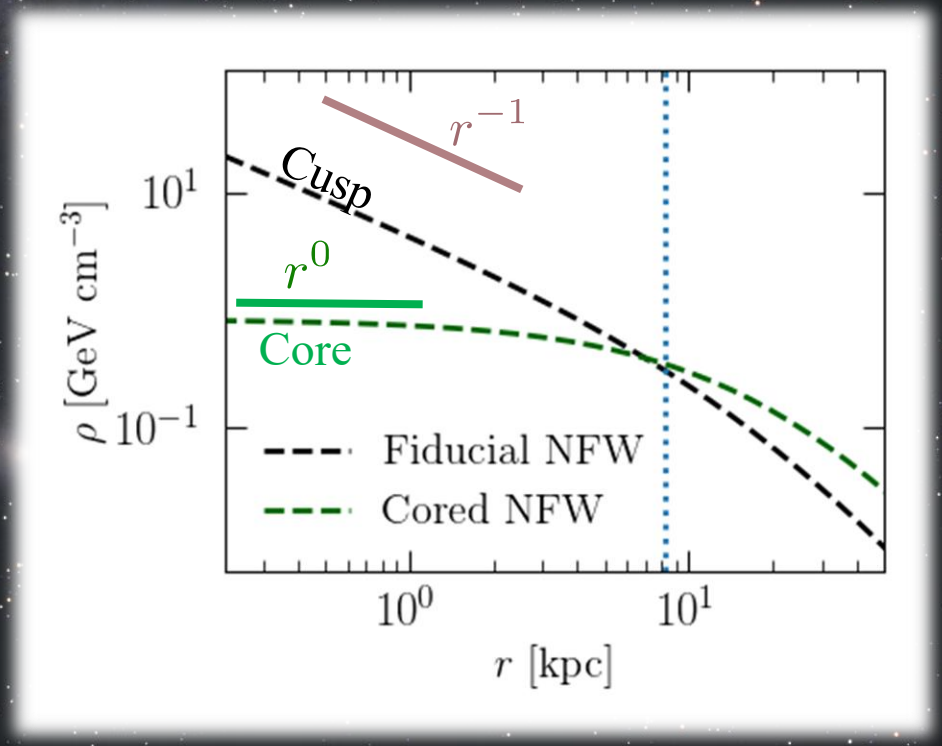


The effect can be orders of magnitude in signal expectation.

Astrophysics



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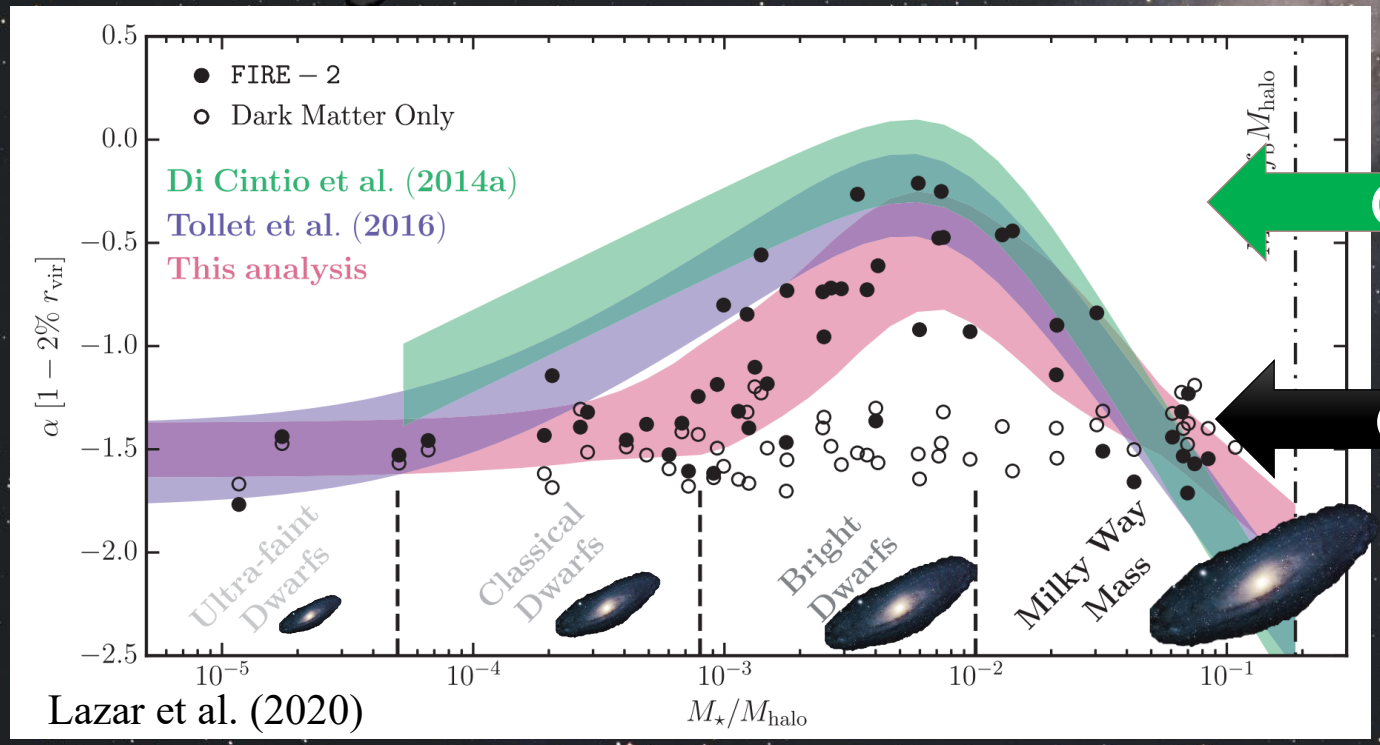
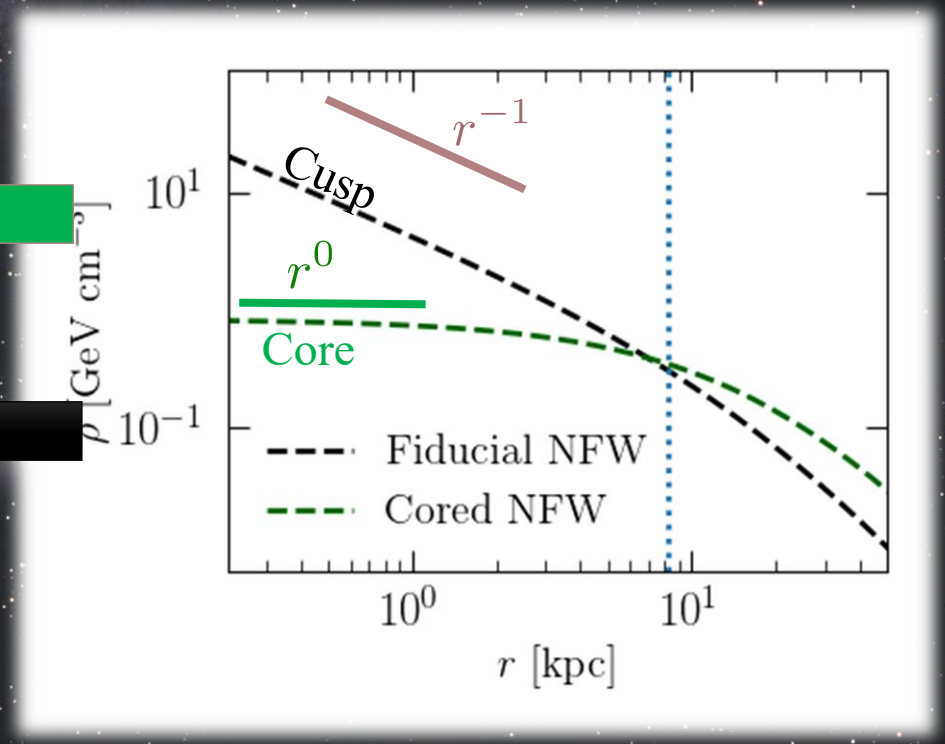
Astrophysics



Lazar et al. (2020)

Core

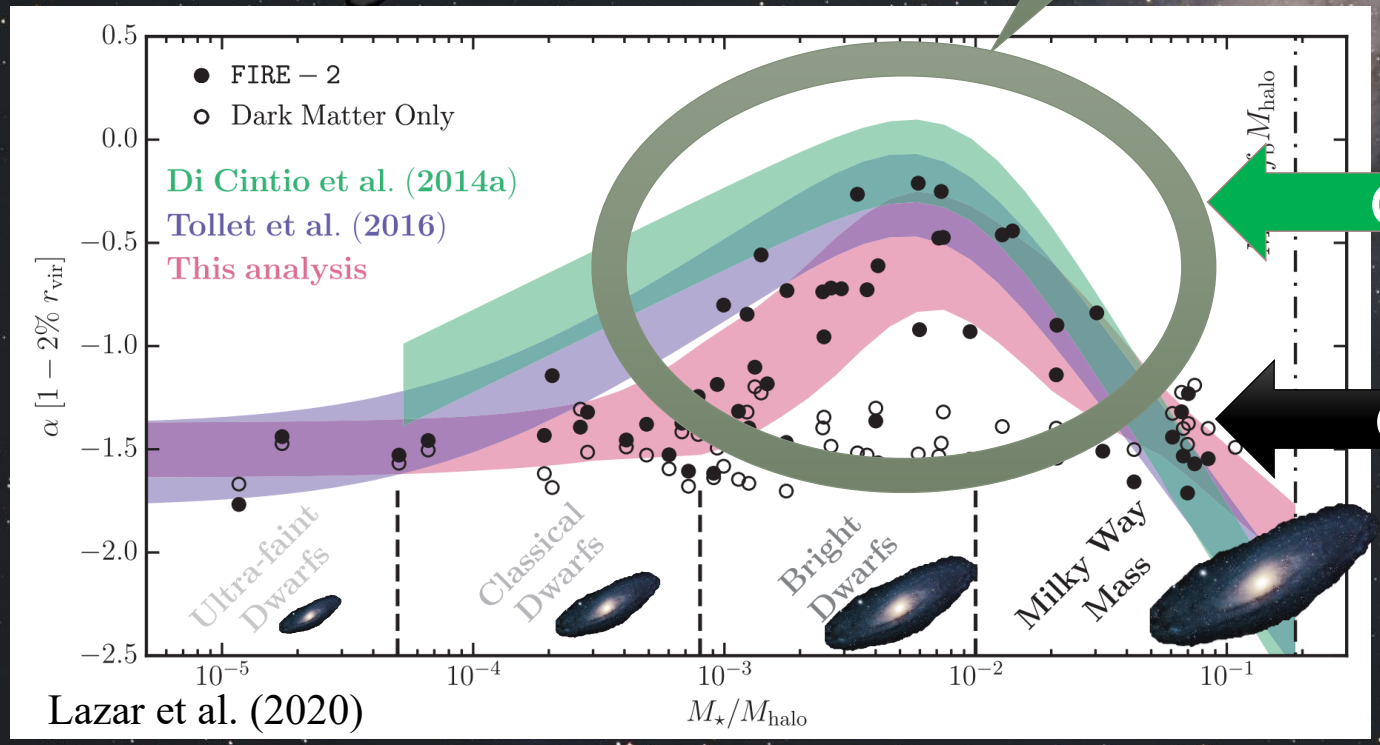
Cusp



Lina Necib, MIT

Astrophysics

Baryonic Feedback



Lazar et al. (2020)

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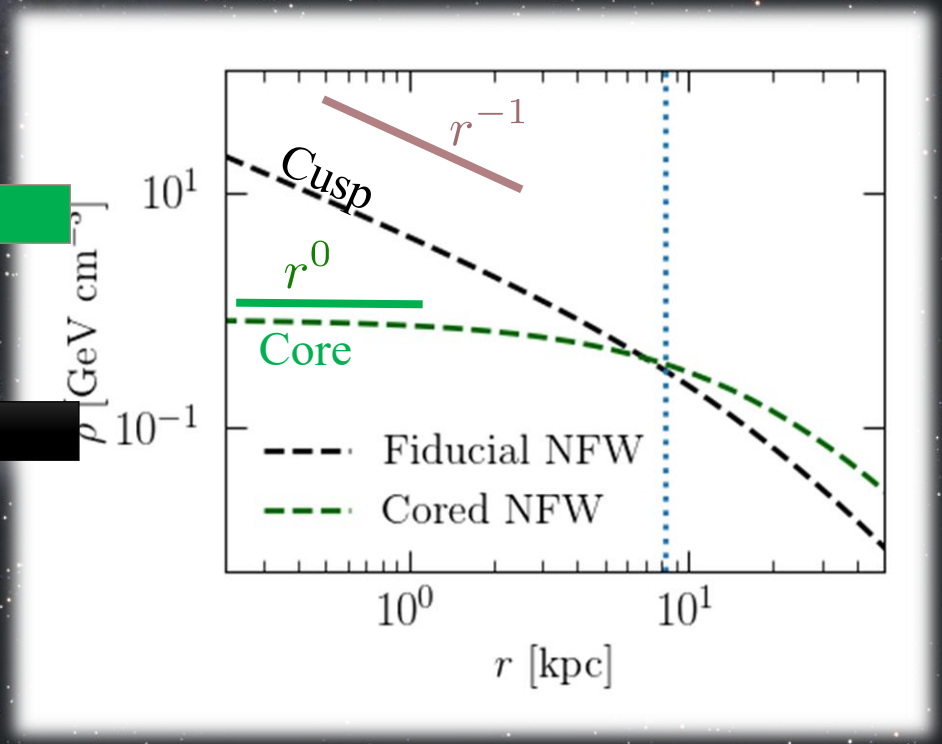

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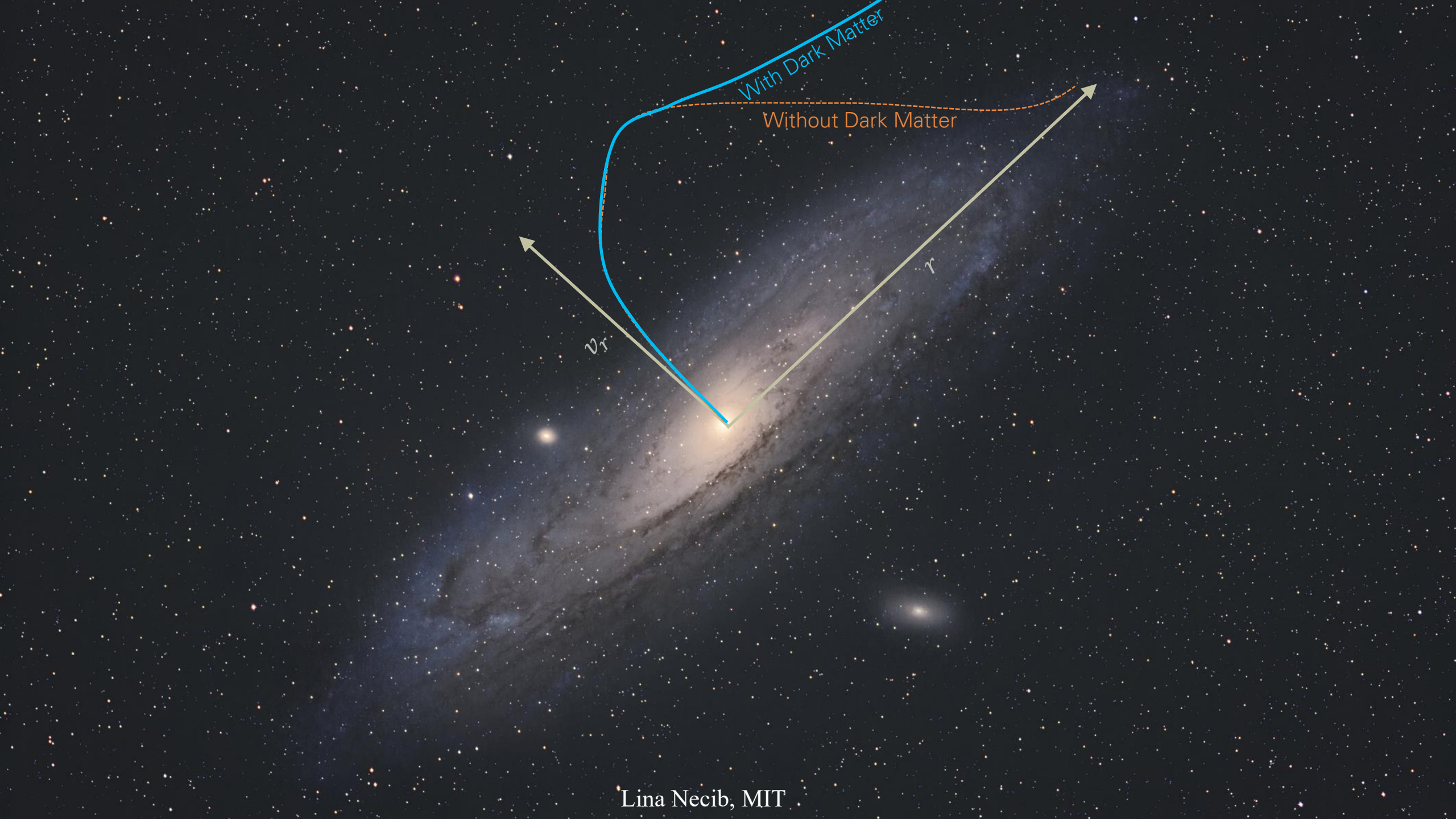

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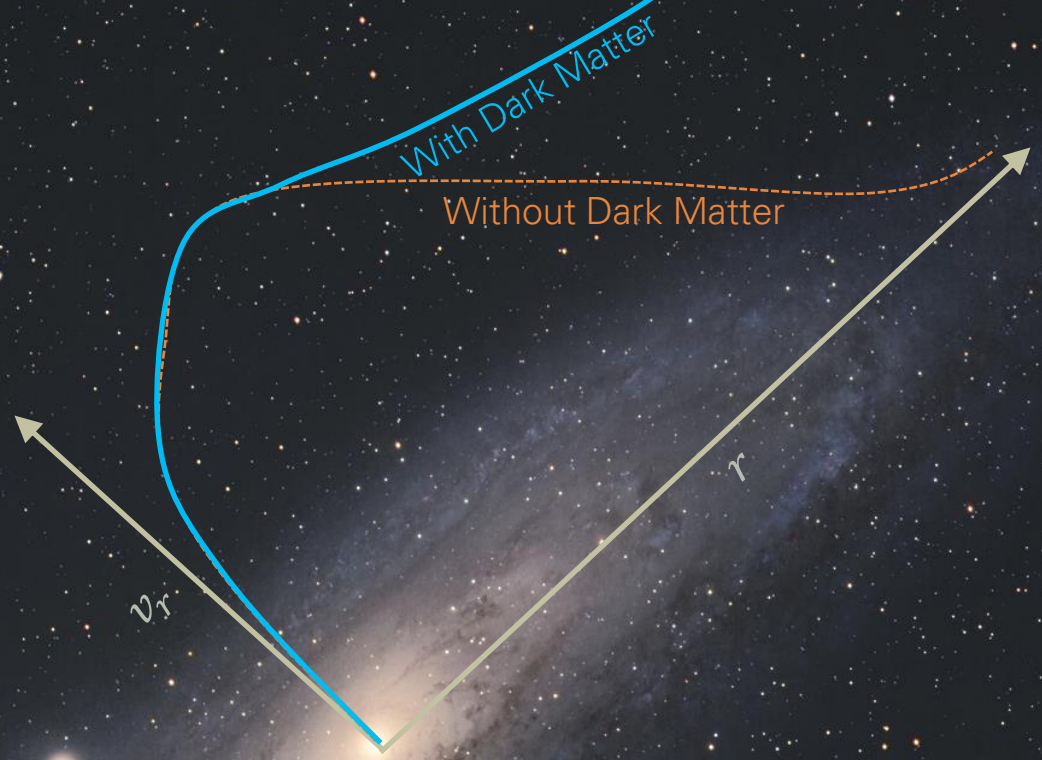
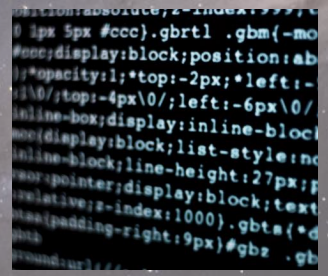


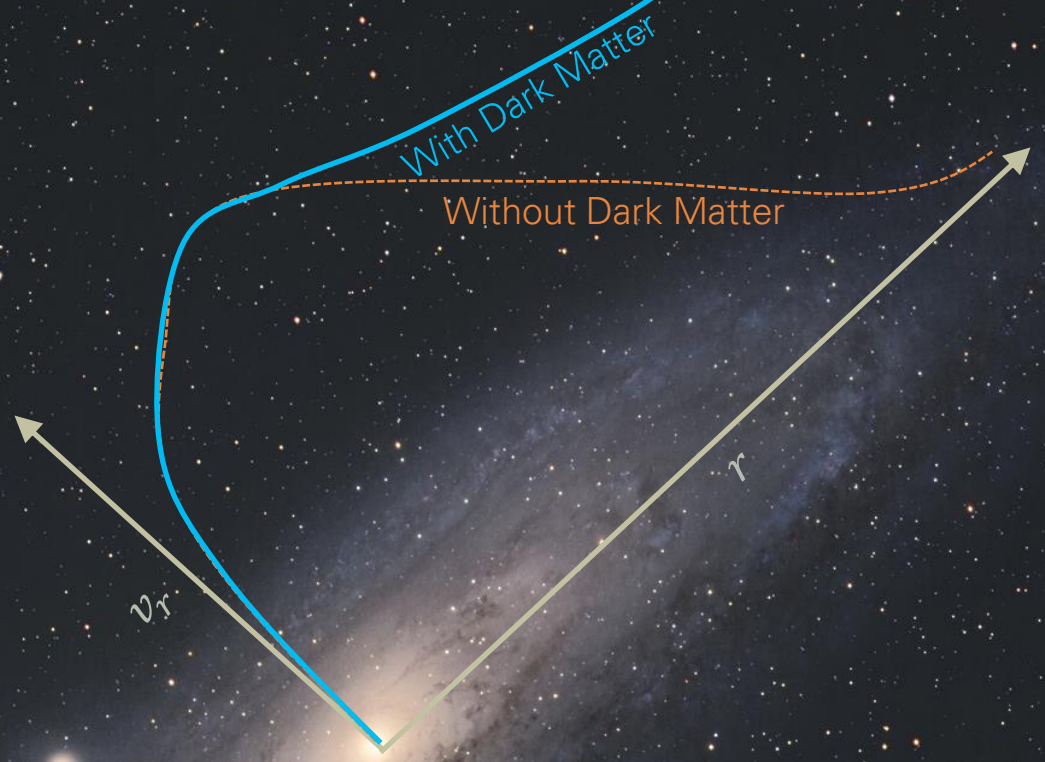
To build the Milky Way's circular velocity, we need

Velocities

Distances



Modeling



To build the Milky Way's circular velocity, we need

Velocities

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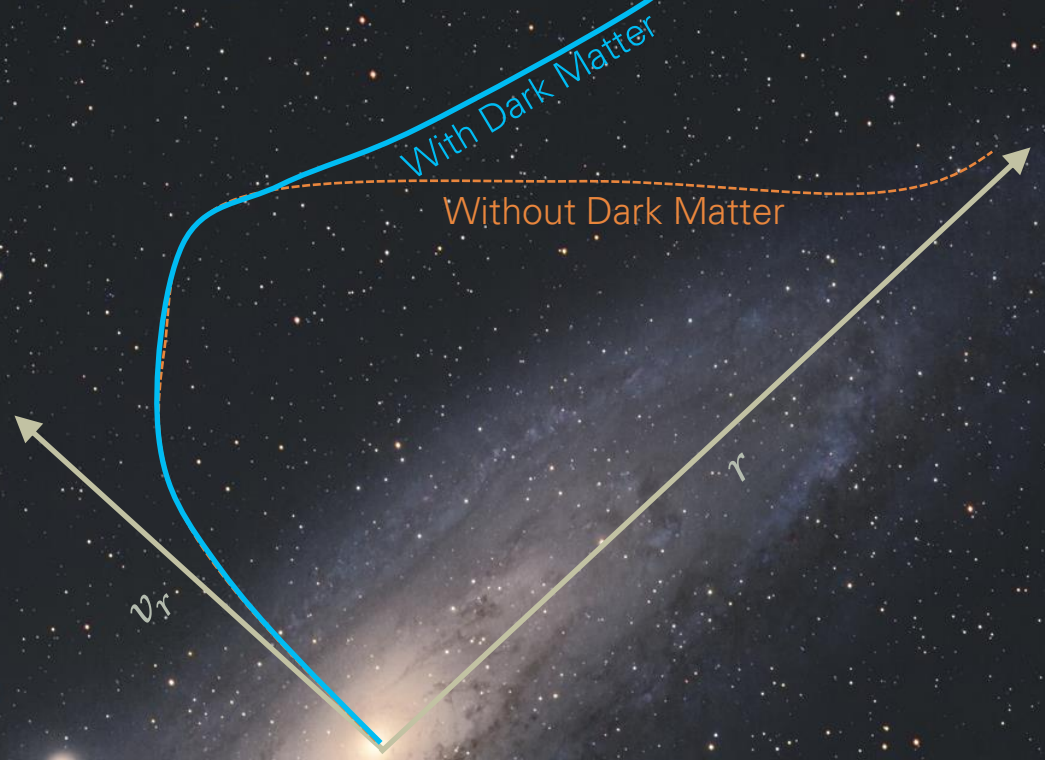
Modeling

Gaia DR3: Positions and proper motions (5D) of 1.5 billion stars, with a subset of 33 million stars with radial velocities (6D)



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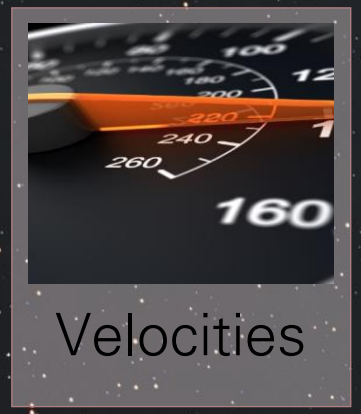
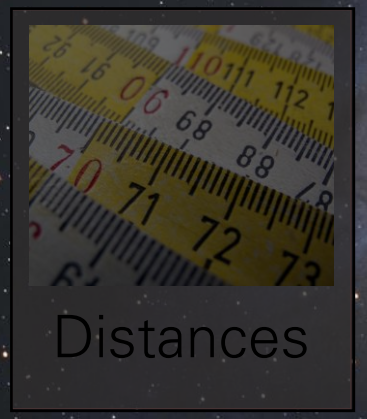
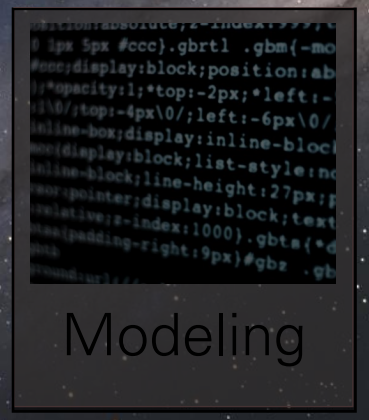
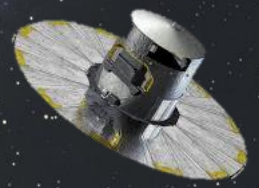




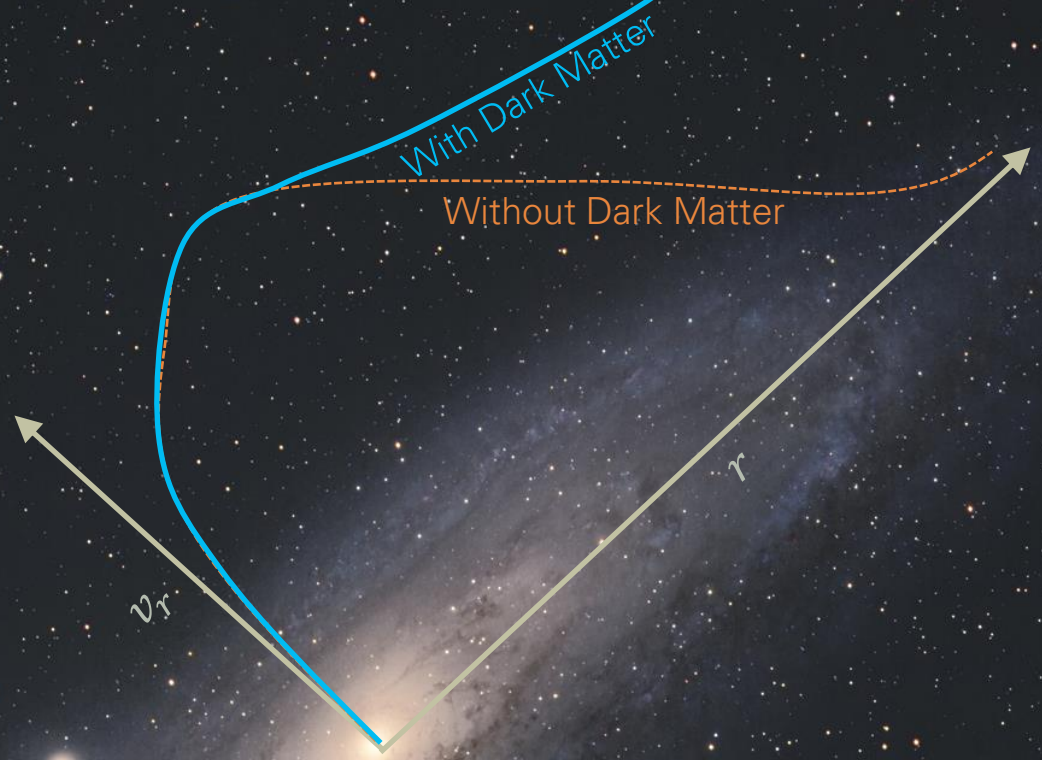




Gaia Products (DR3):

- 1.5 billion proper motions.
- 1.5 billion parallaxes.
- 33 million line of sight velocities

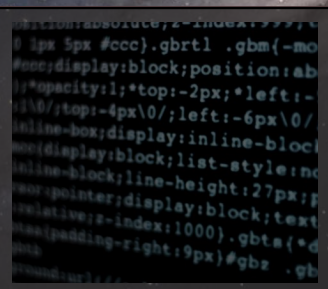
Gaia collaboration et al. (2016, 2018, 2021, 2023)



To build the Milky Way's circular velocity, we need

Velocities

Distances



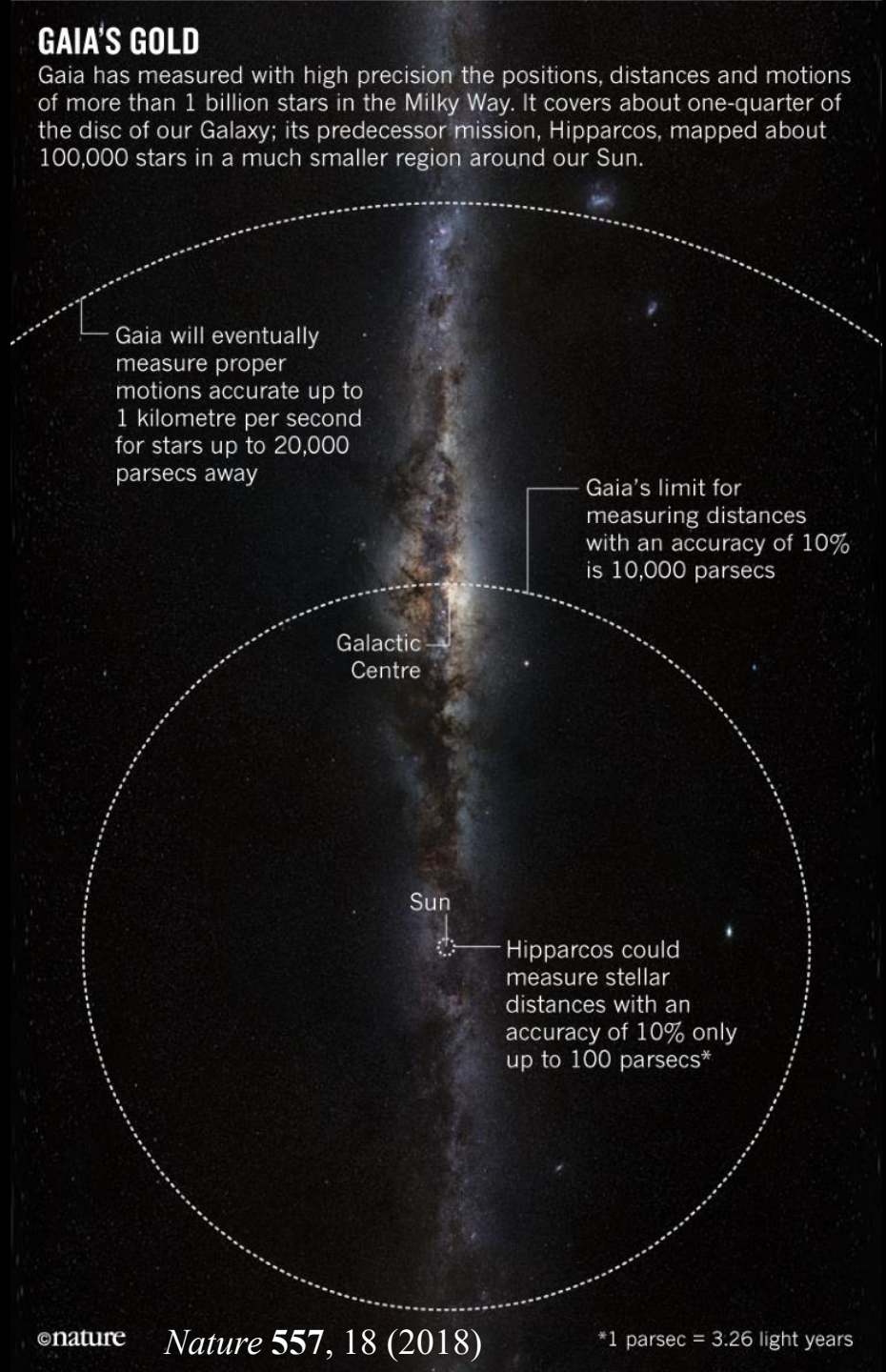
Modeling

Lina Necib, MIT

https://www.ge.com/reports/5-coolest-things-earth-week-29-6/andromeda-galaxy/

Issue:

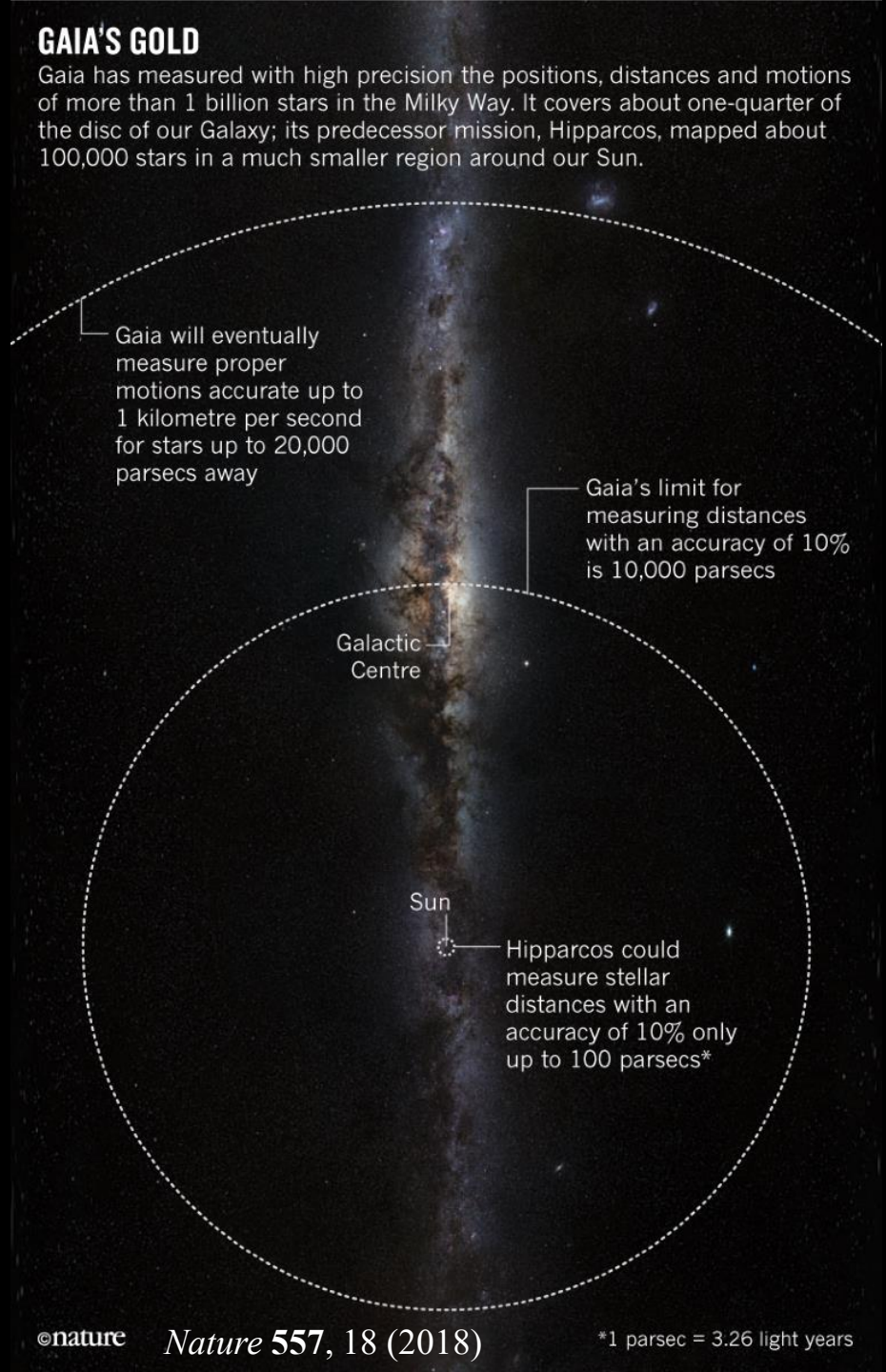
Although Gaia is extremely powerful, calculating distances via parallax is still challenging, especially at large distances.



Nature **557**, 18 (2018)

Issue: Although Gaia is extremely powerful, calculating distances via parallax is still challenging, especially at large distances.

Solution: Use a data driven model to compute distances.



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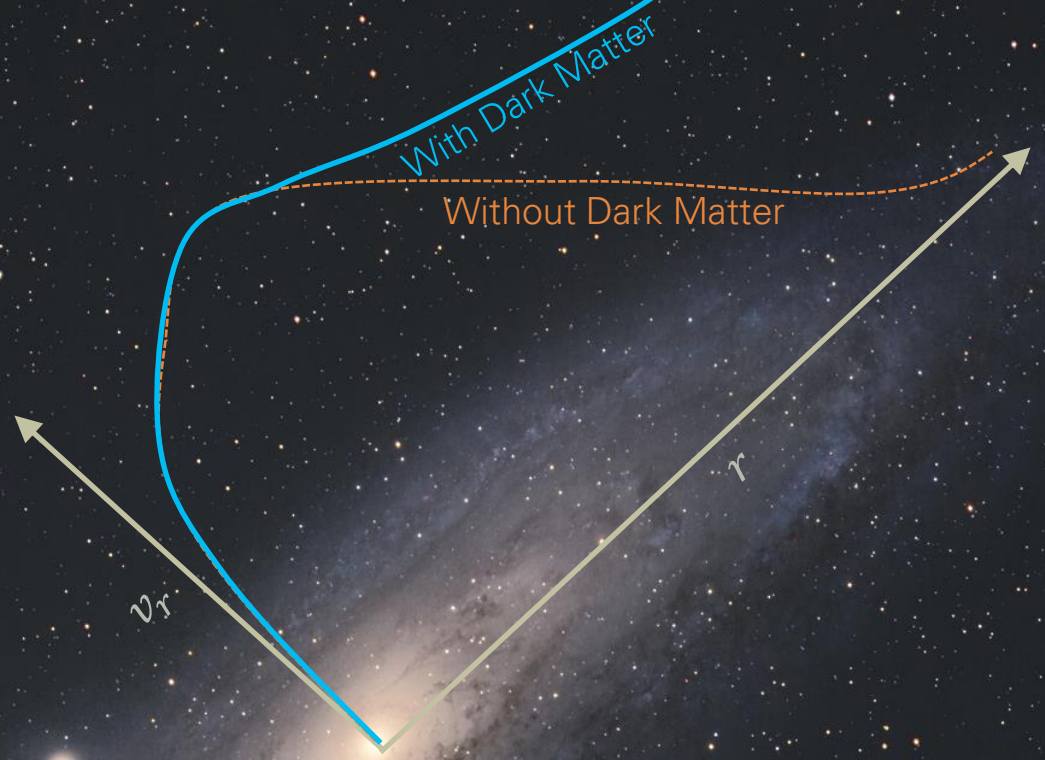
Credit: S.R. Majewski

Lina Necib, MIT



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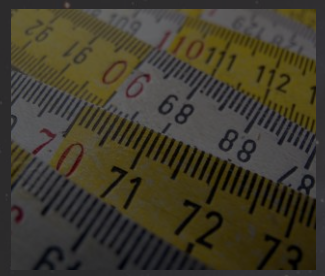
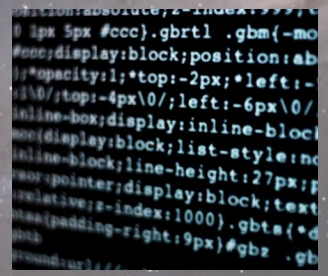


Distances



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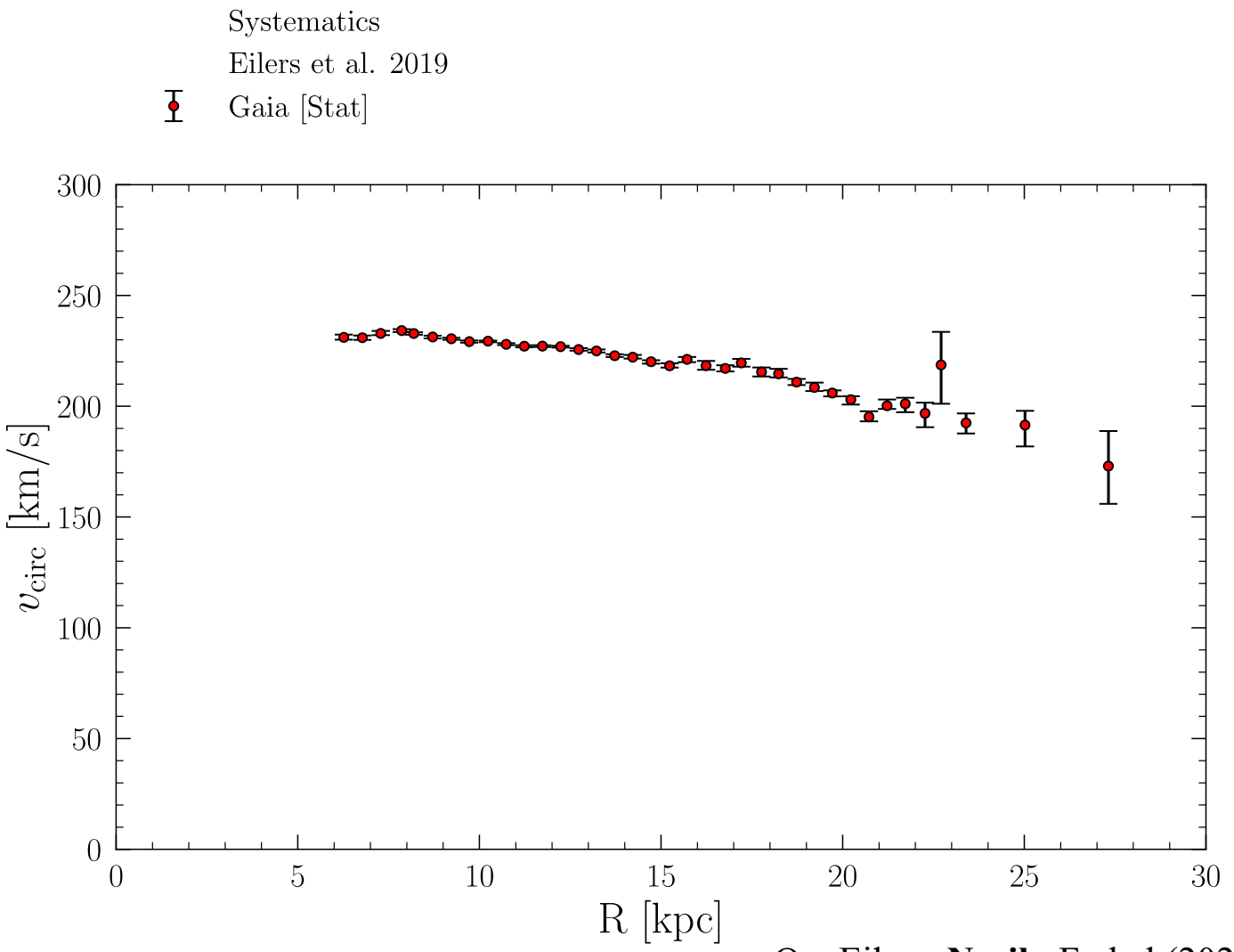
LET'S CONSTRUCT THE MILKY WAY'S CIRCULAR VELOCITY



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

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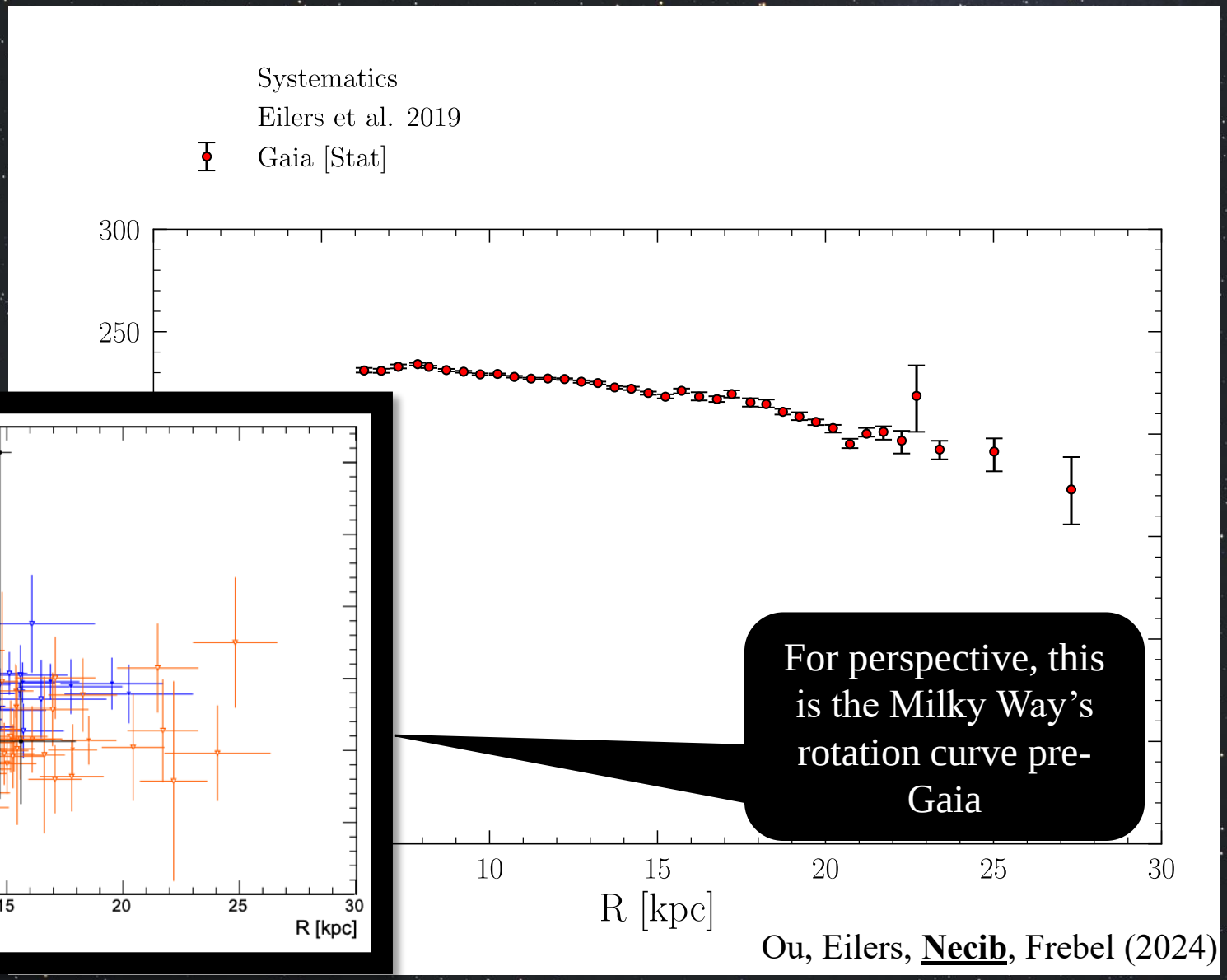
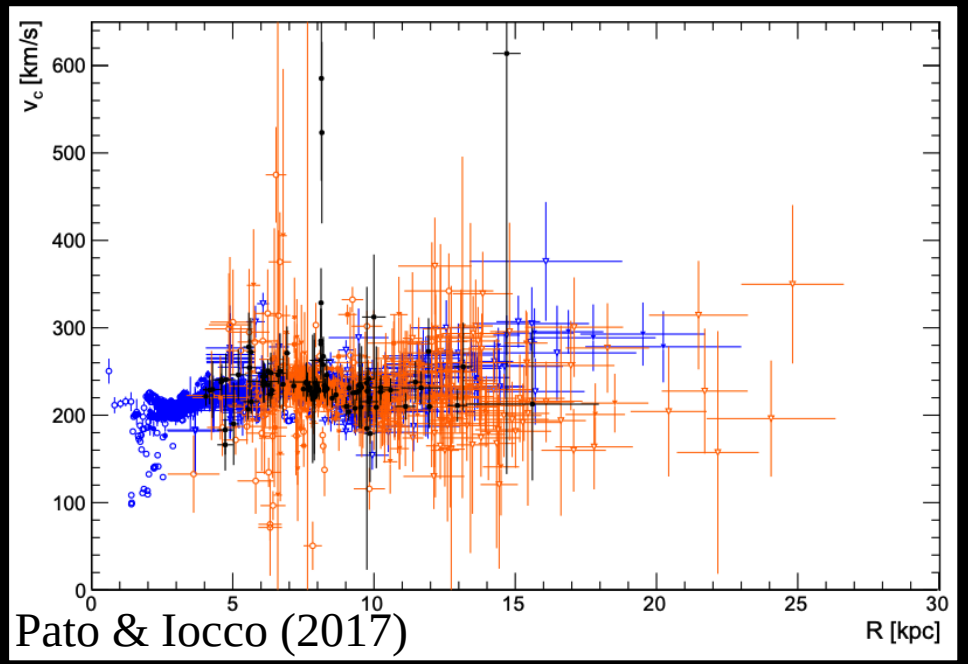


For perspective, this is the Milky Way's rotation curve pre-Gaia

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



Pato & Iocco (2017)

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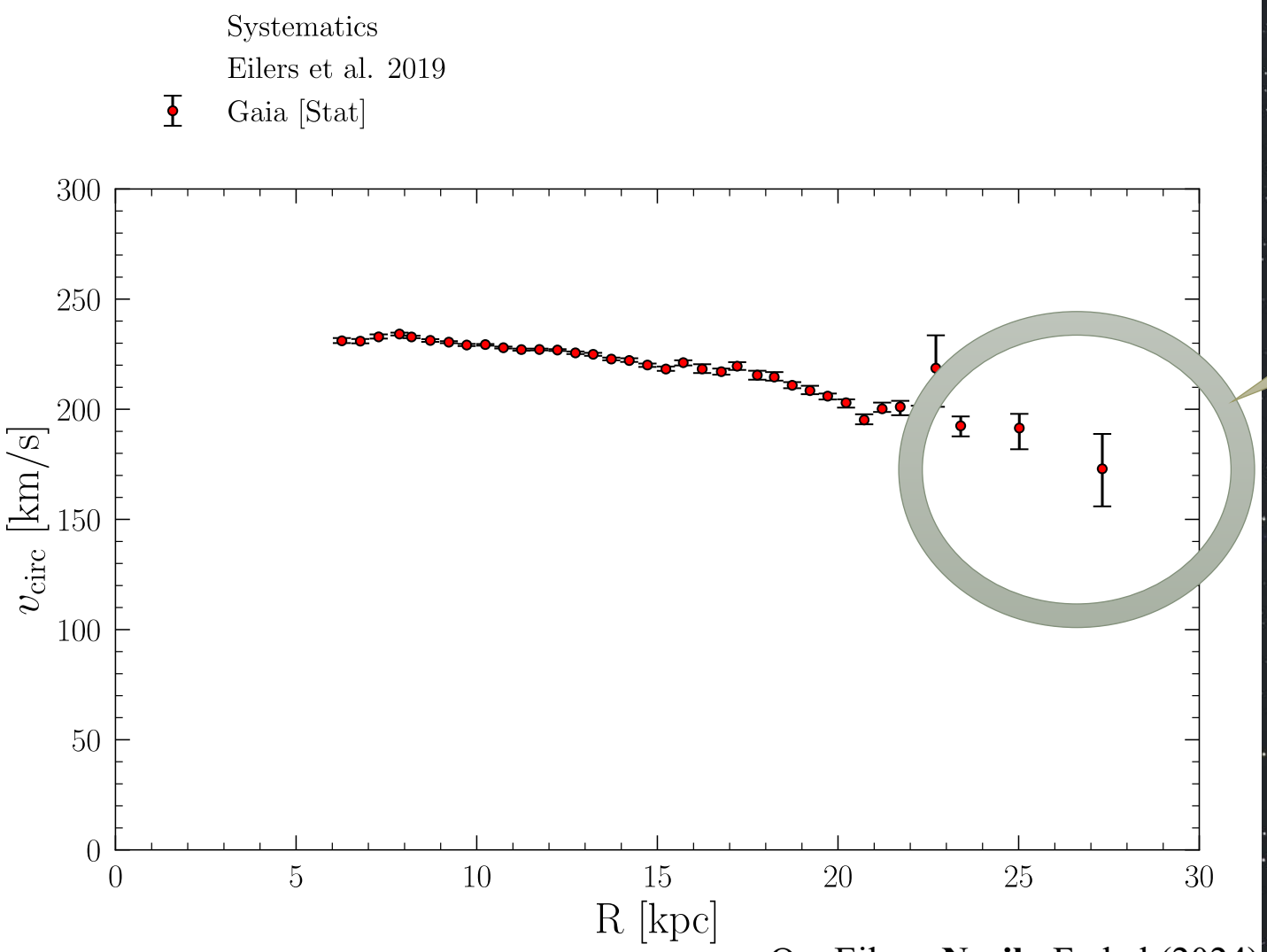

Data is declining here!

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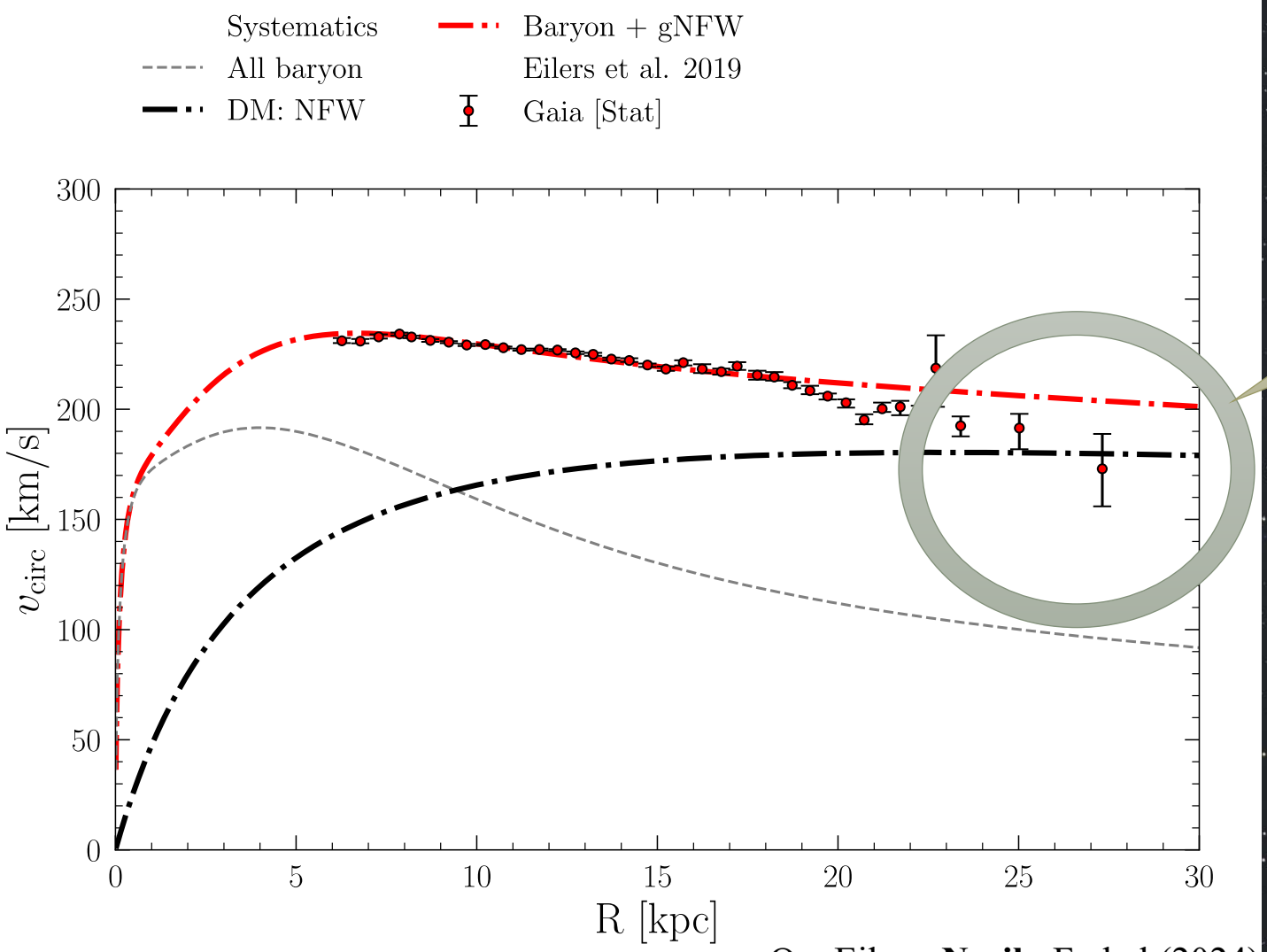

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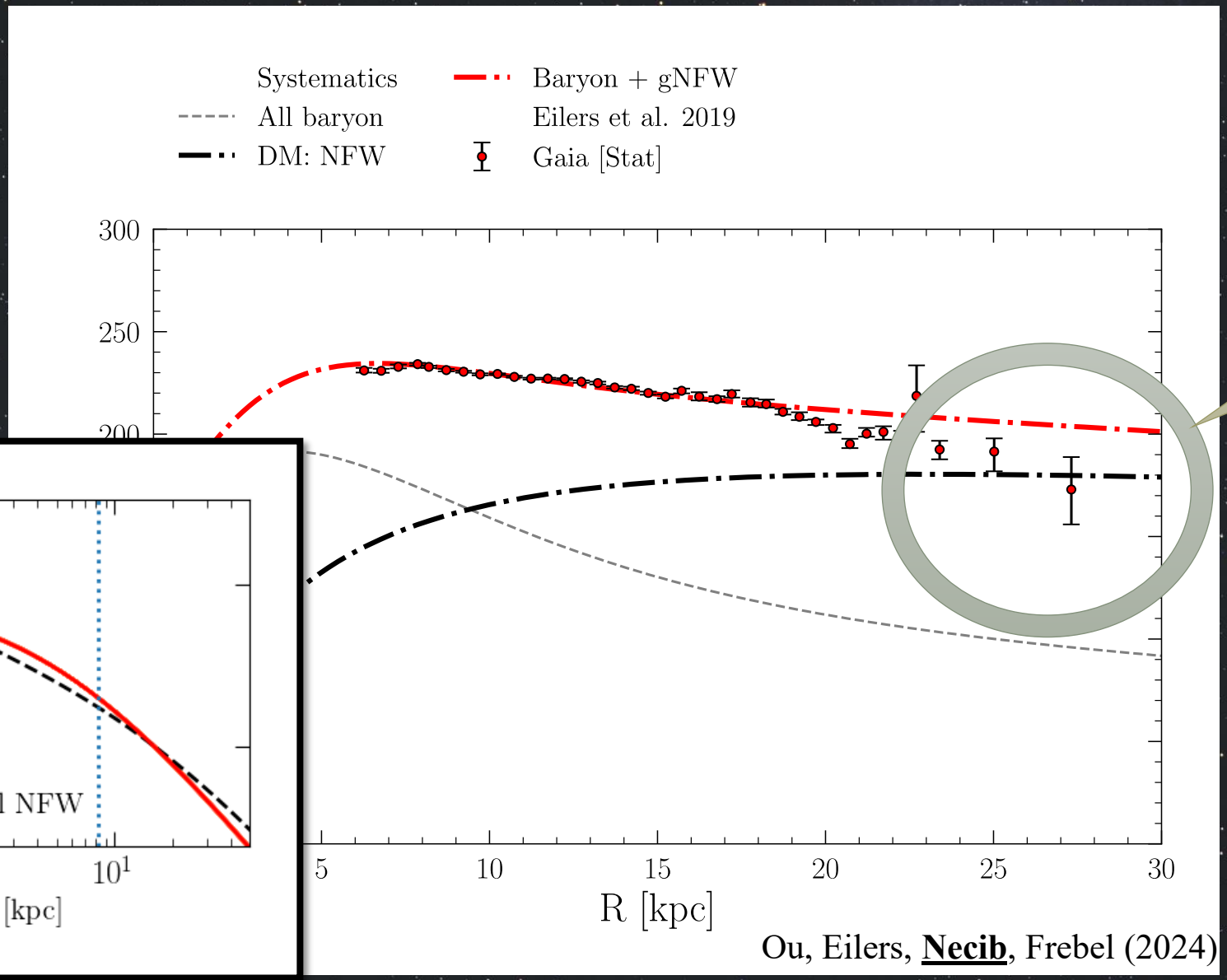

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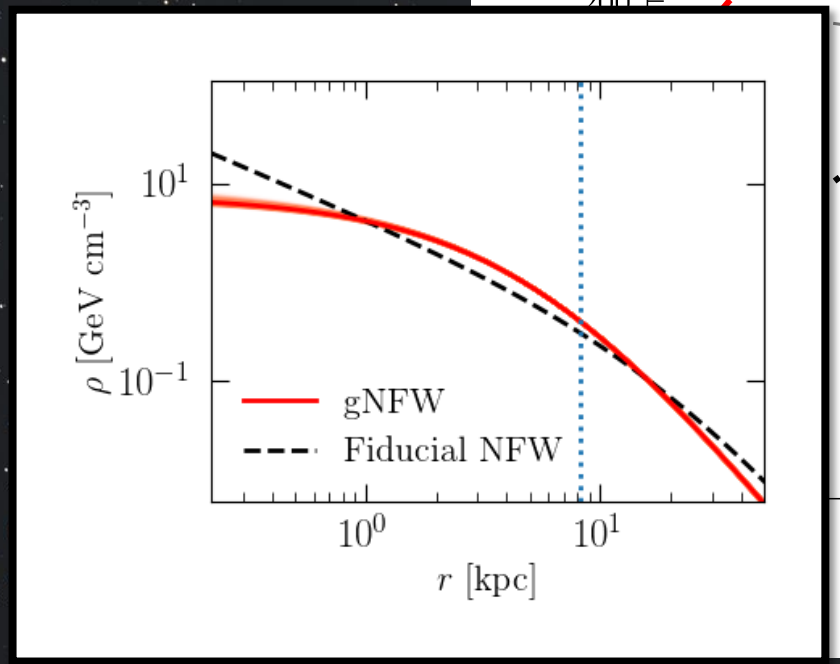
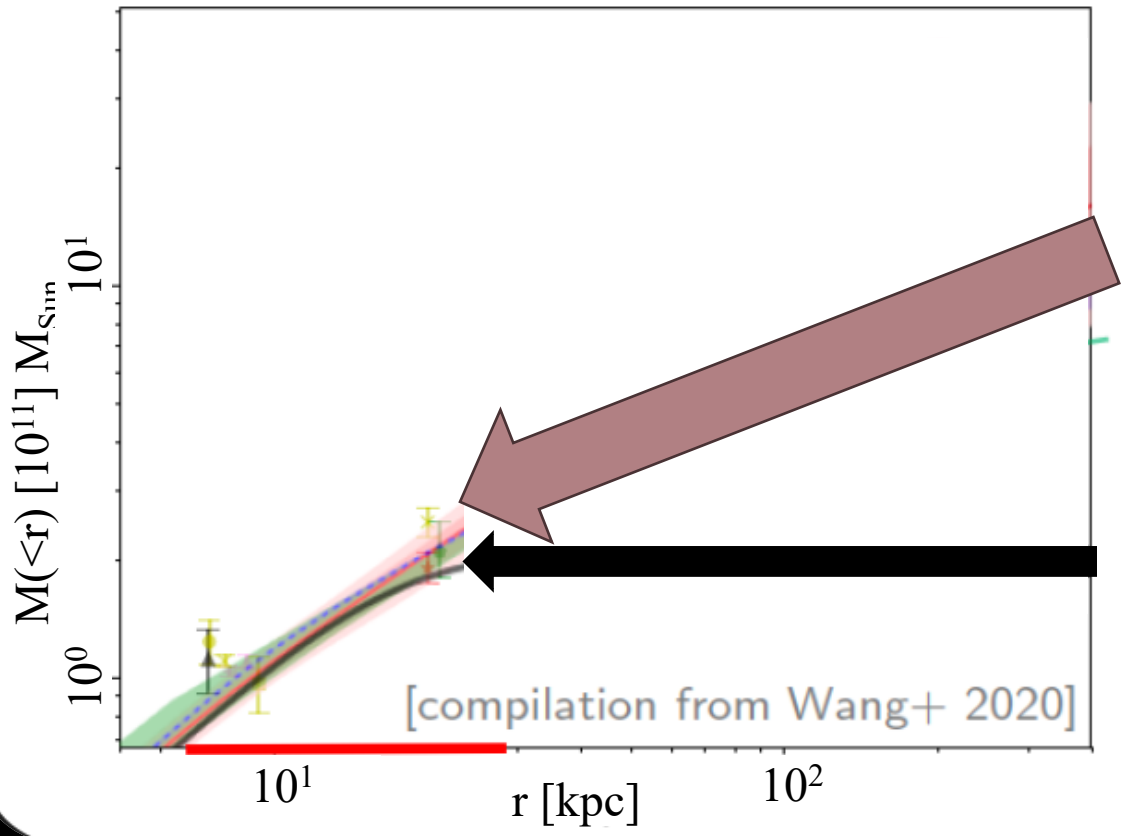


Ou, Eilers, **Necib**, Frebel (2024)

LETS PUT THAT CORED PROFILE IN CONTEXT.



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

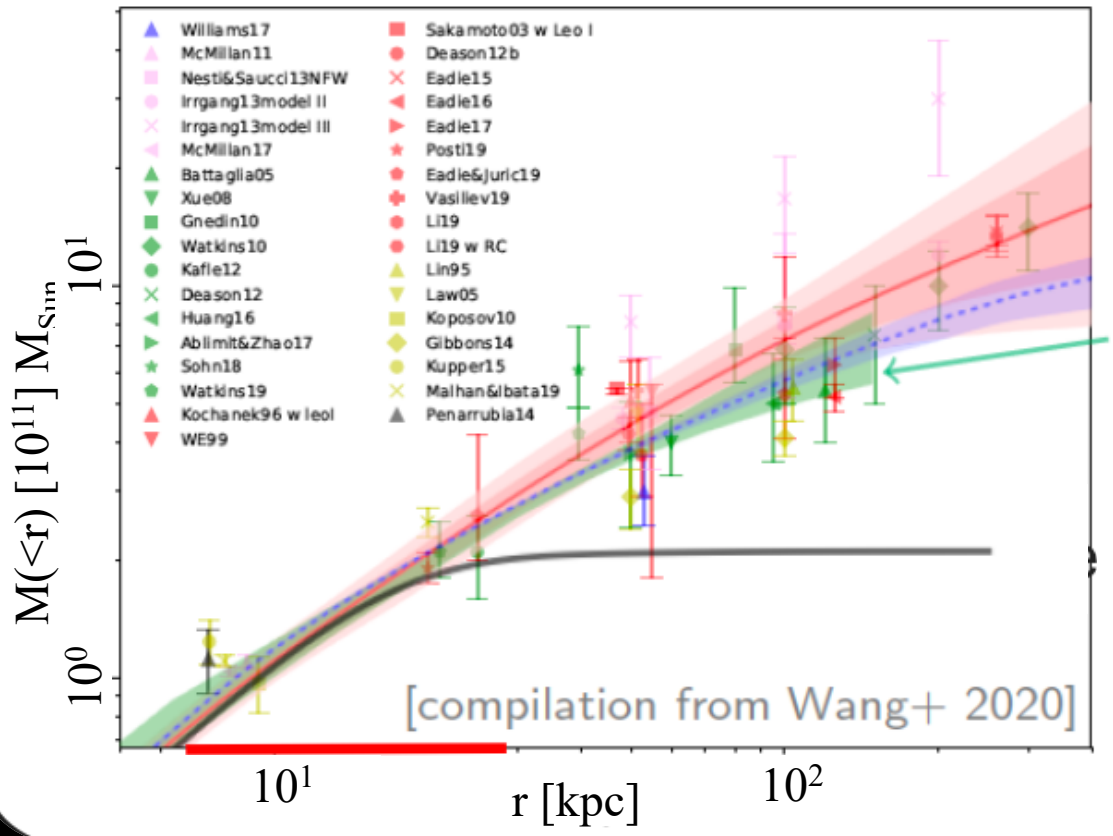
Sgr stream (incl. LMC) [Vasiliev+ 2021]

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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LET'S REVIEW THE ASSUMPTION WE MADE

Observational Selection Function

Axisymmetry

Dynamical Equilibrium

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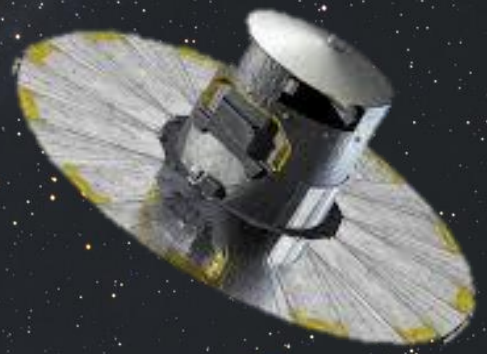
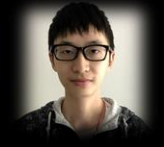


Is Gaia picking some stars over others?
Is that biasing the results of our circular velocity measurements?



Tri Nguyen Xiaowei Ou

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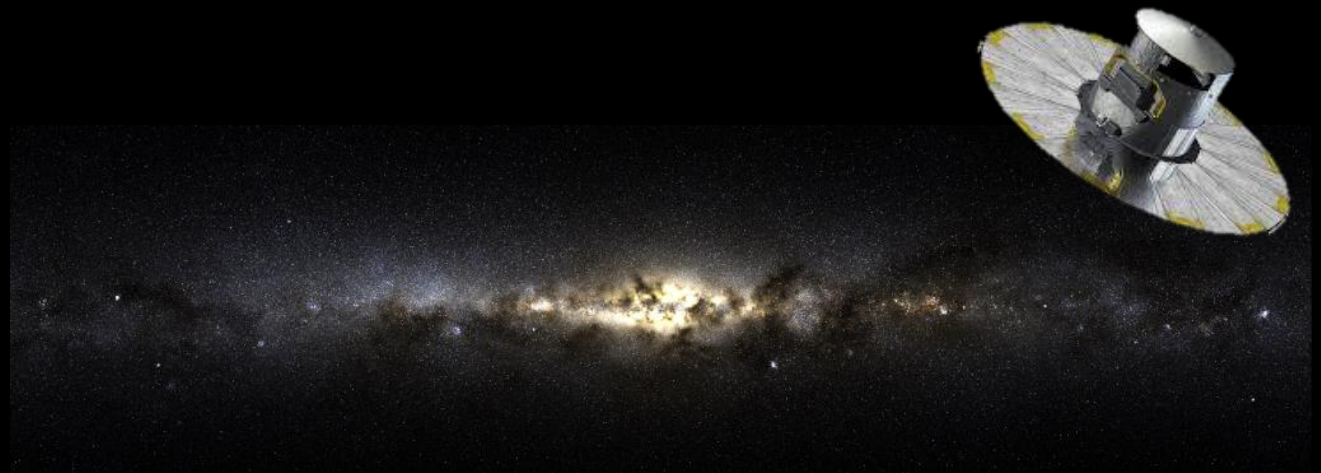

Synthetic Gaia Survey (DR3) of a Simulated FIRE Galaxy

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?

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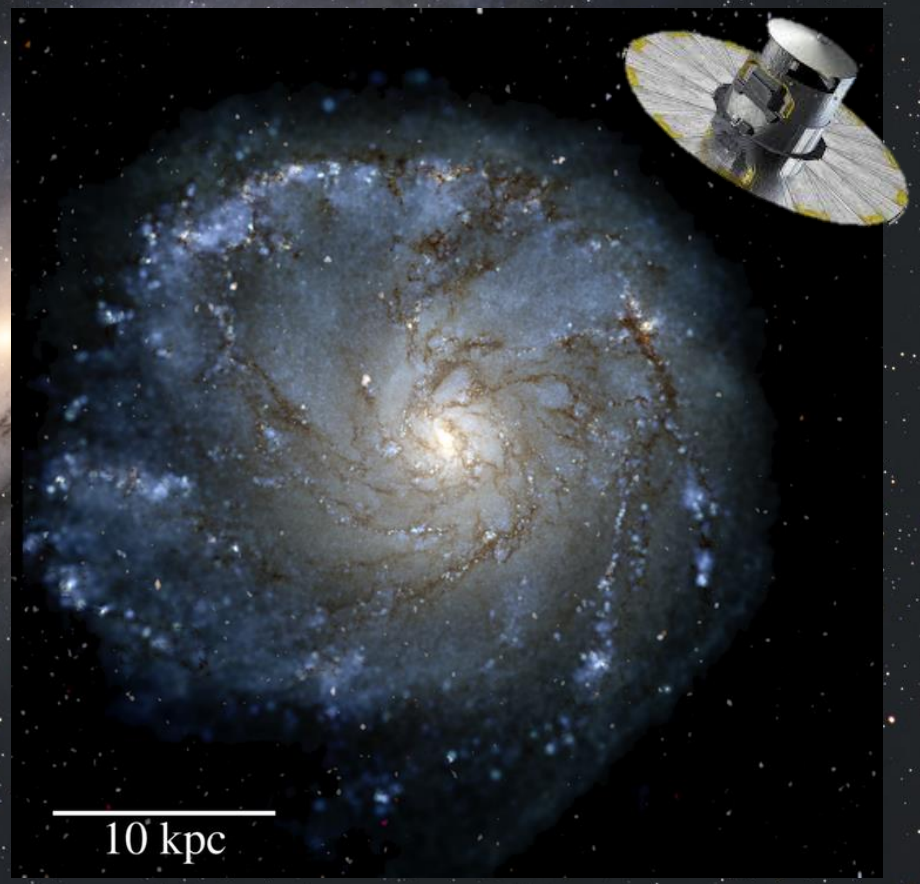

Produced synthetic surveys and found no effect of the observational selection function

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

Lina Necib, MIT

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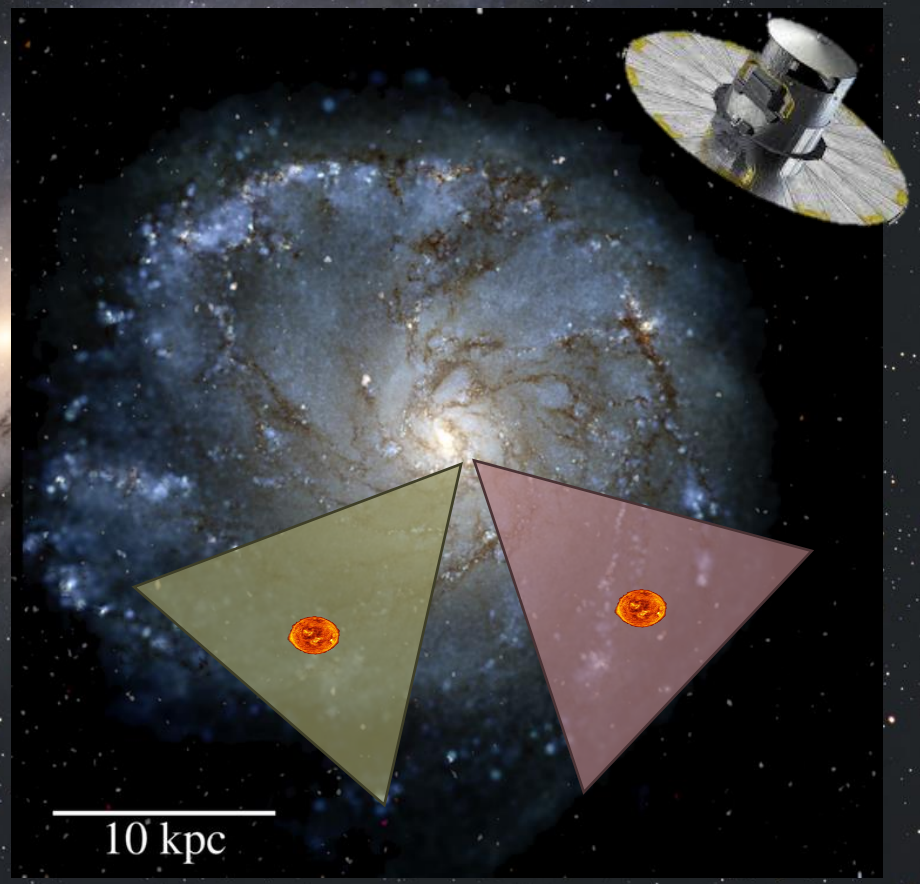

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Redid the analysis on different slices, and indeed there is a large effect

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✓

Observational Selection Function

✗

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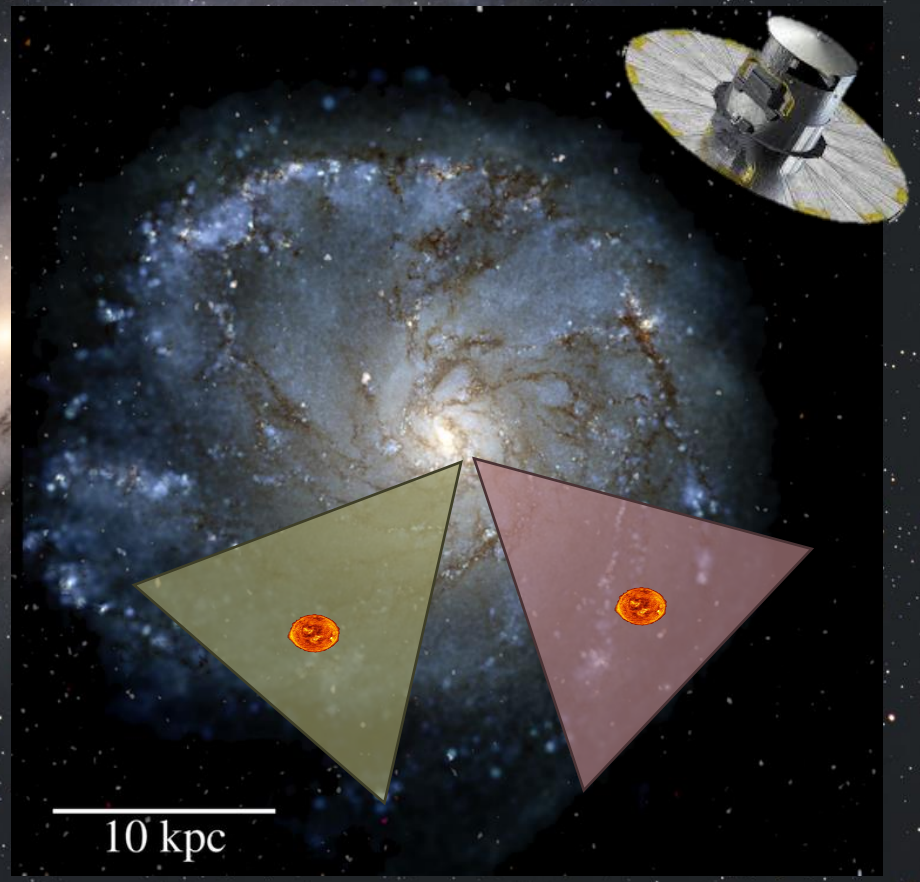
Dynamical Equilibrium



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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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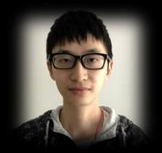

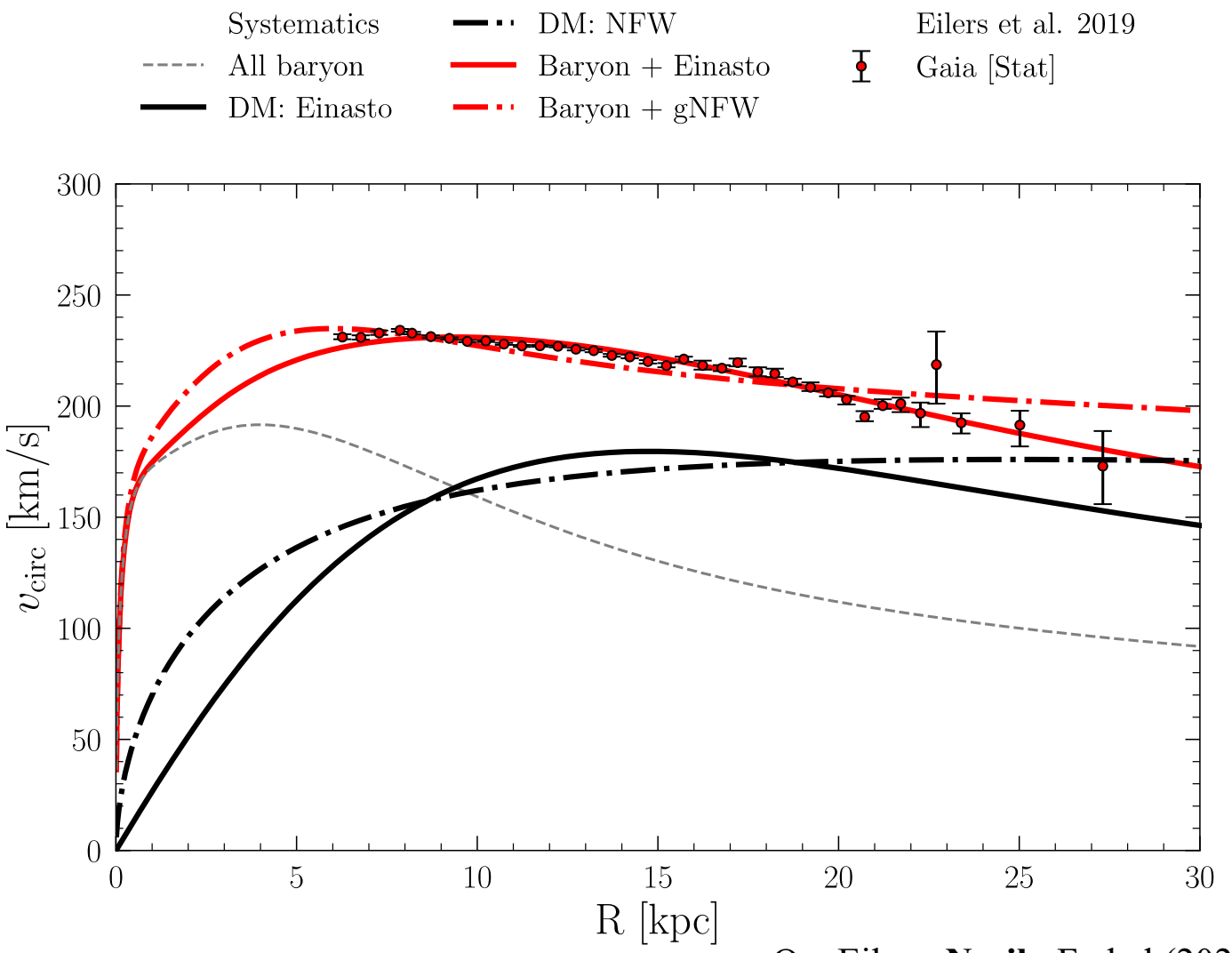

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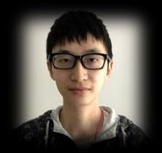

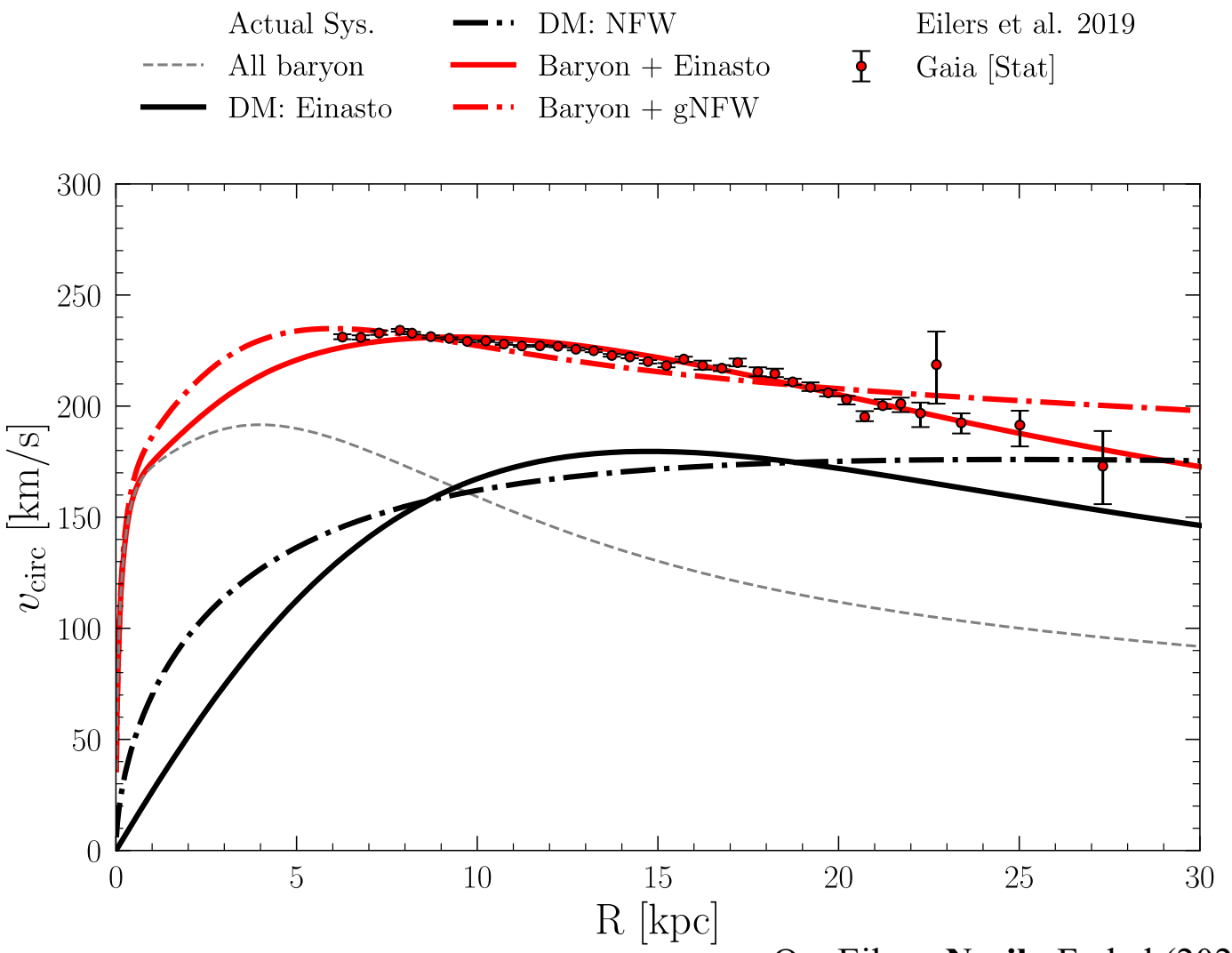

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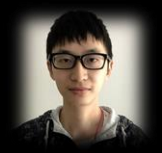
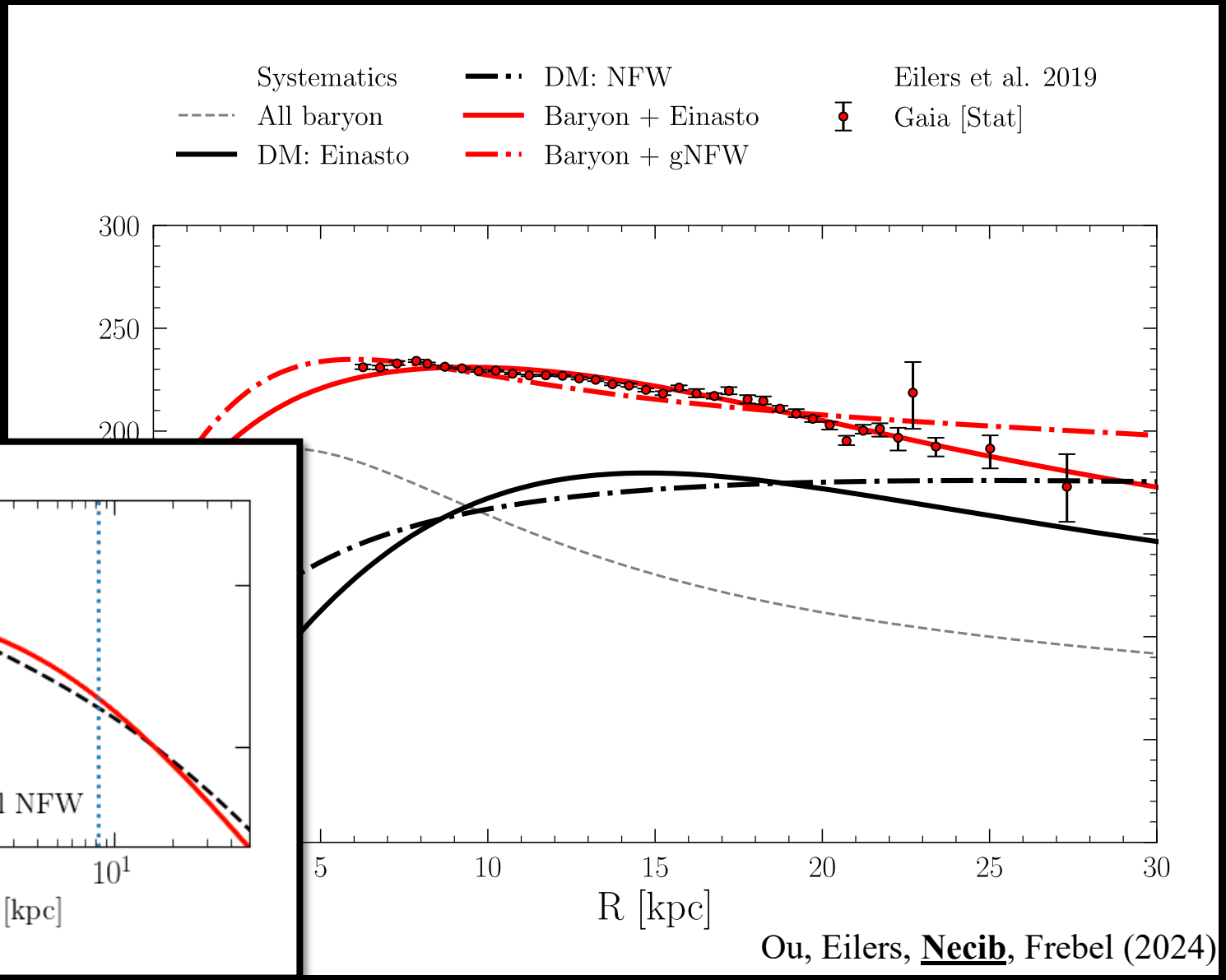
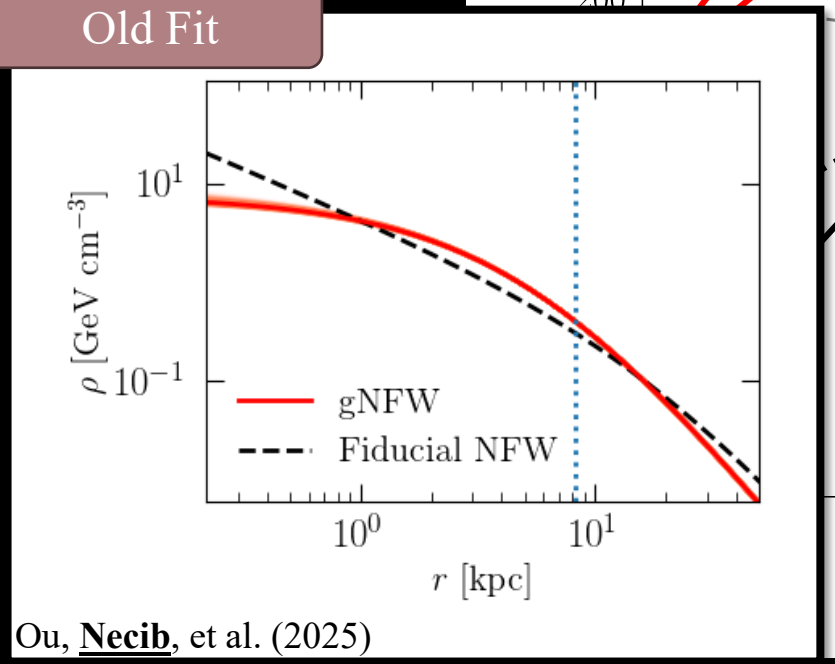




Ou, Eilers, **Necib**, Frebel (2024)

Old Fit



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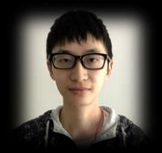

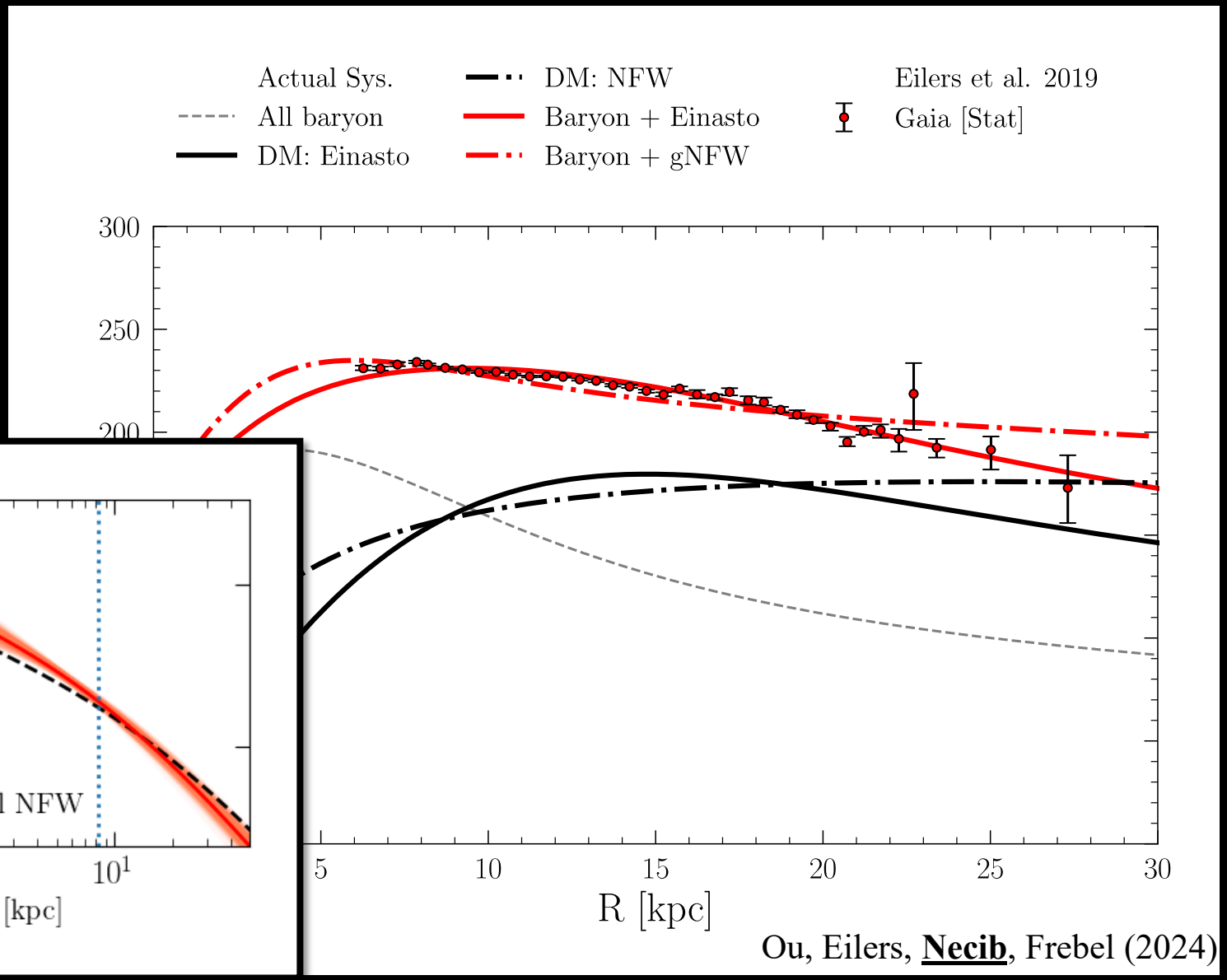

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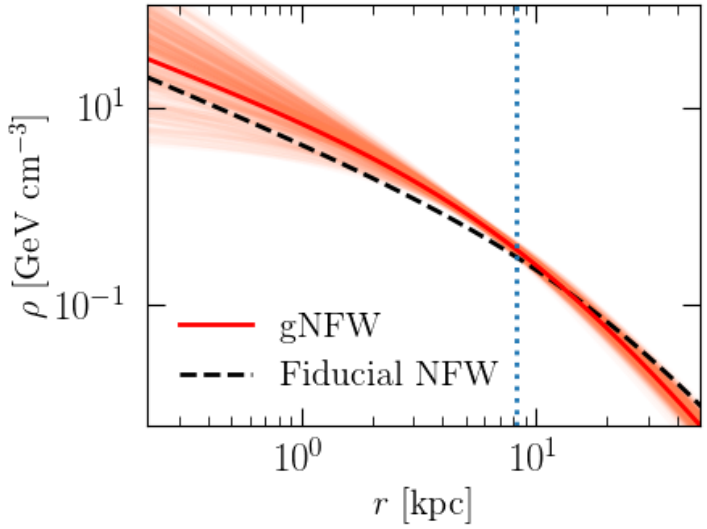

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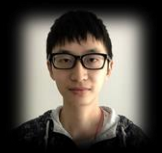

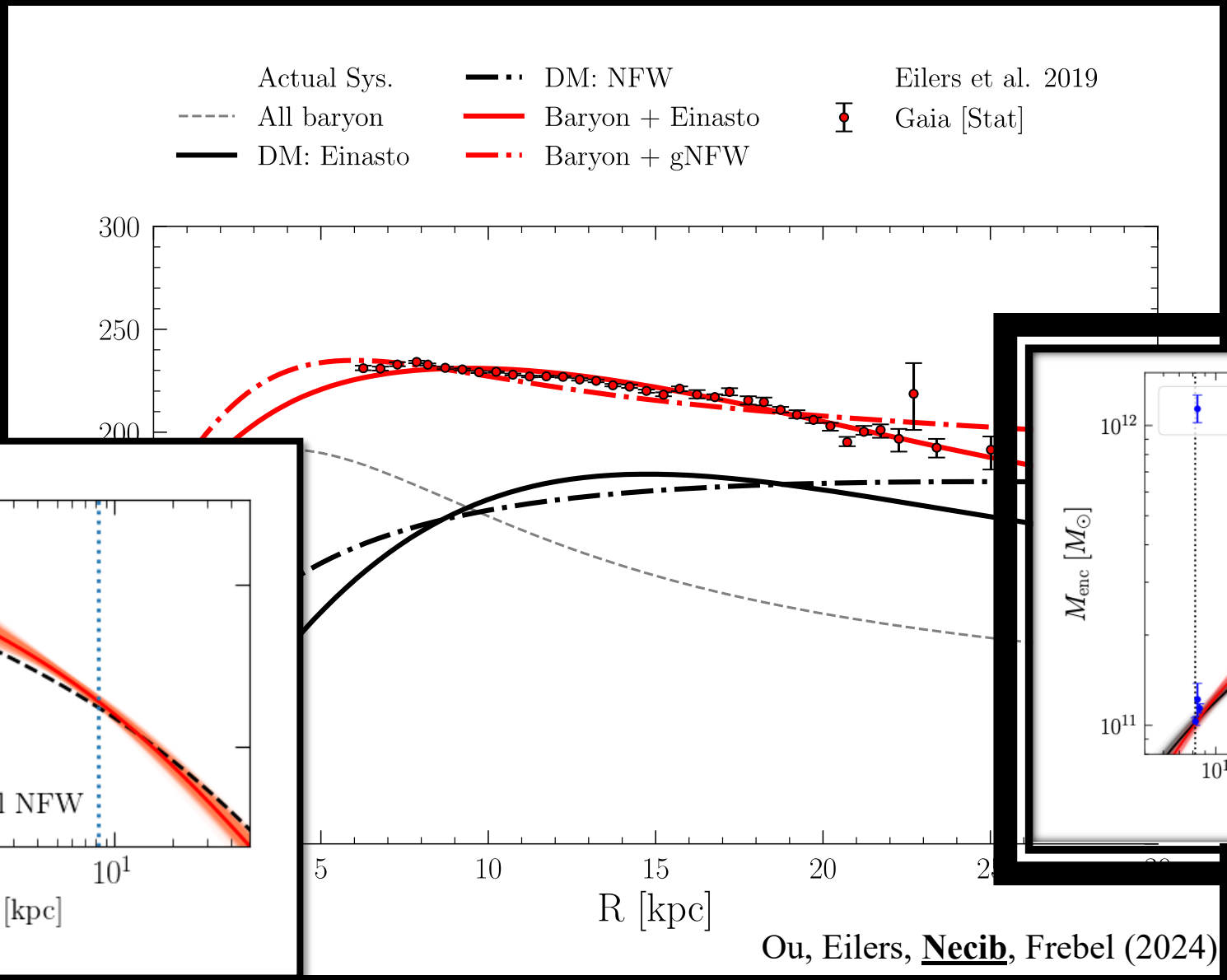

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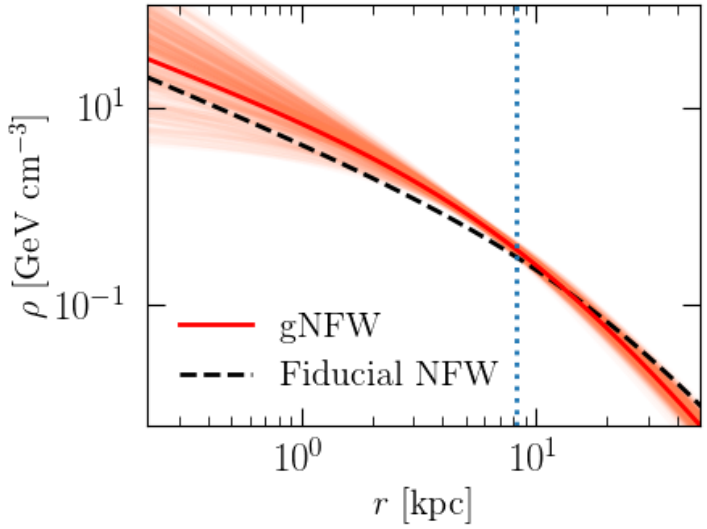

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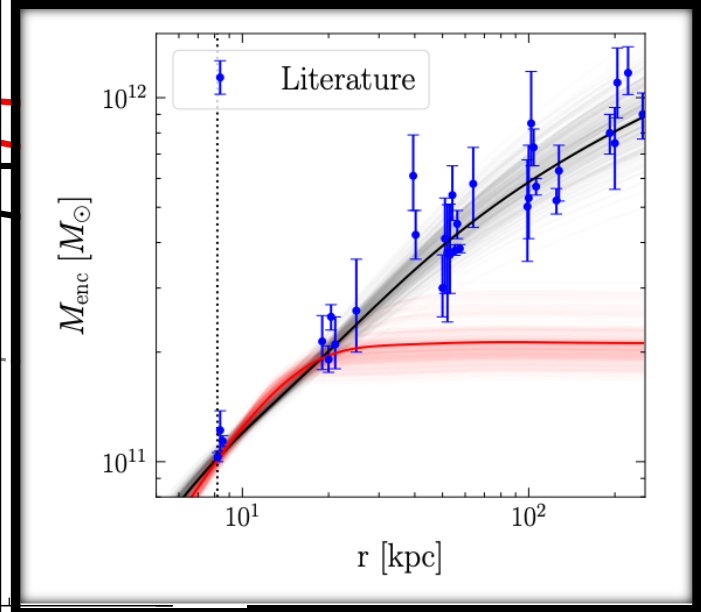

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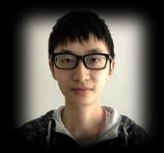

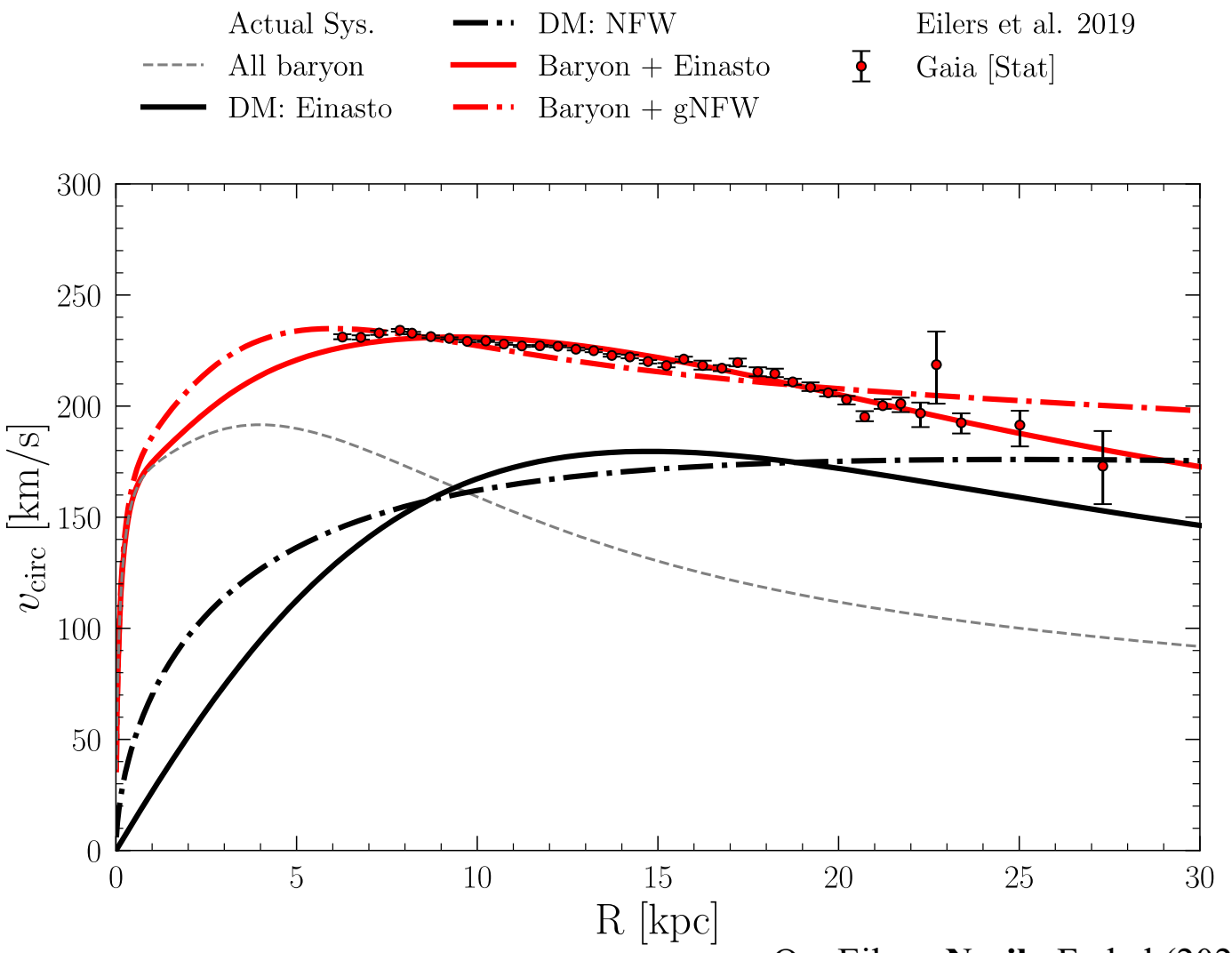

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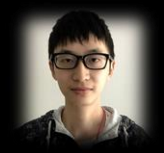

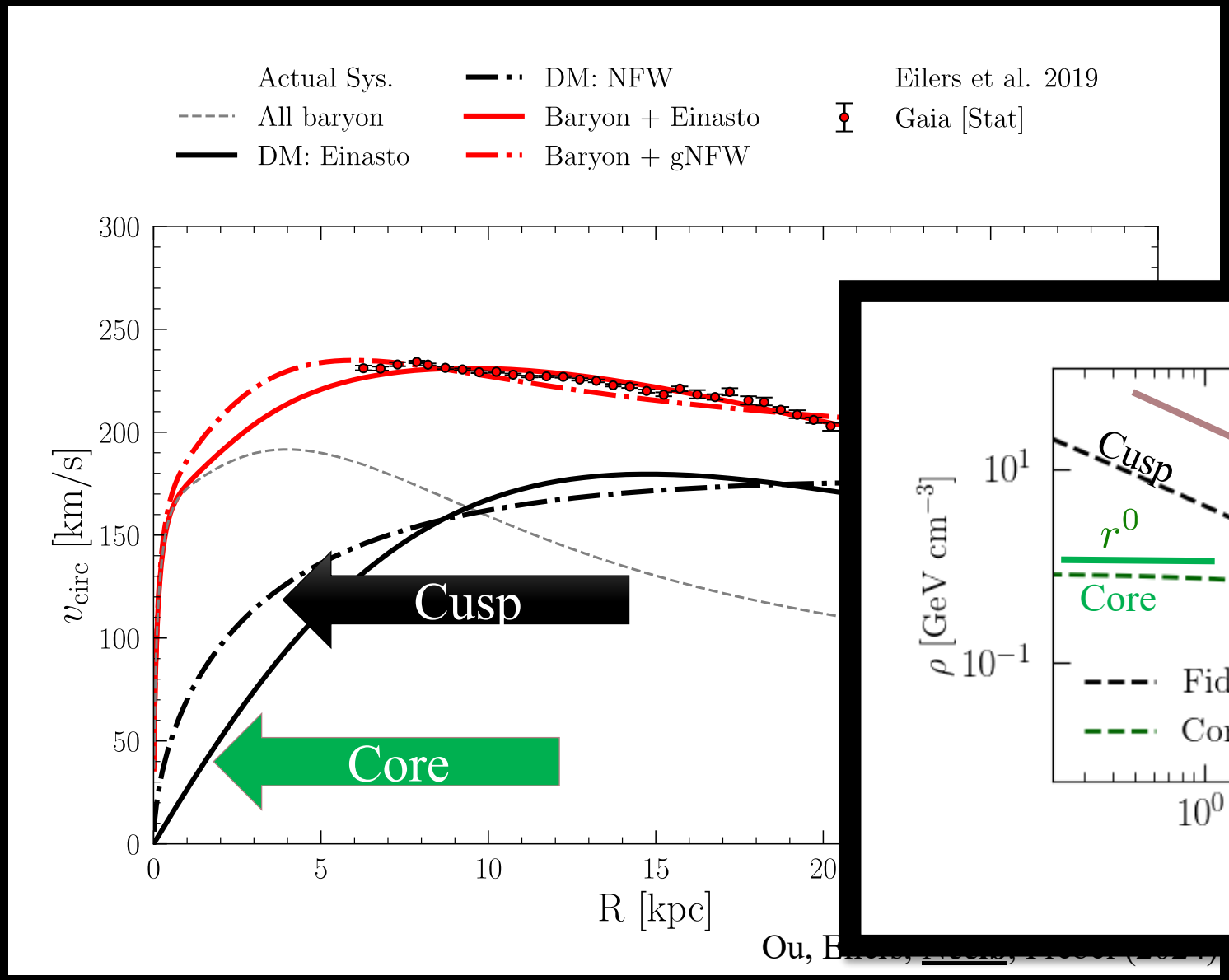

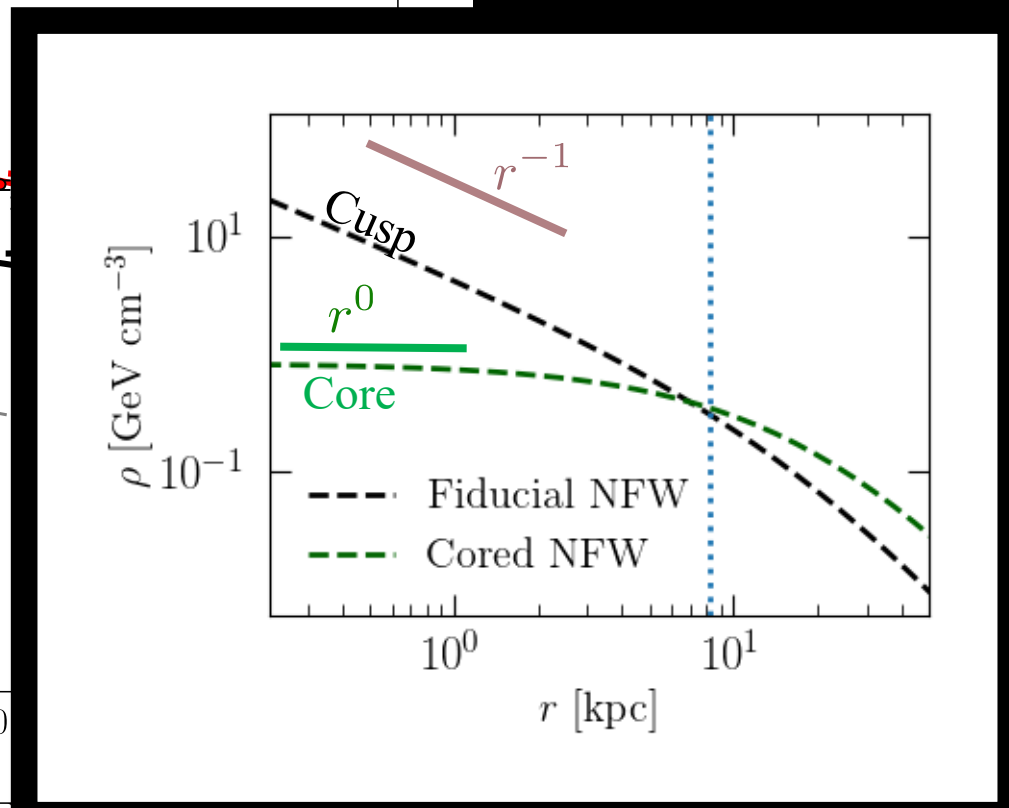

Ou, **Necib**, et al. (2025)

Ou, E

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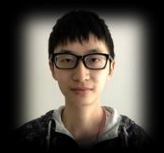
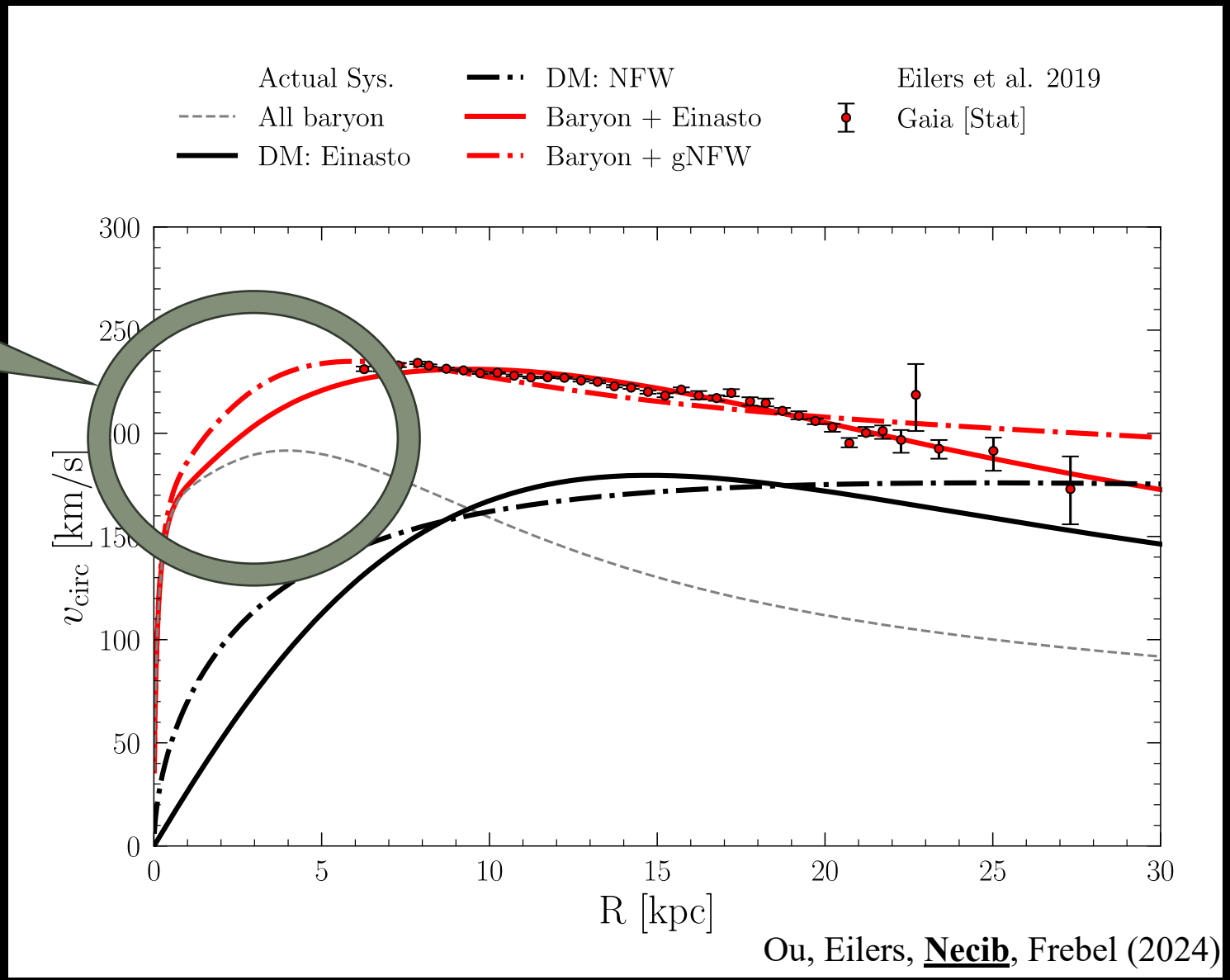


What I really want, is data here!

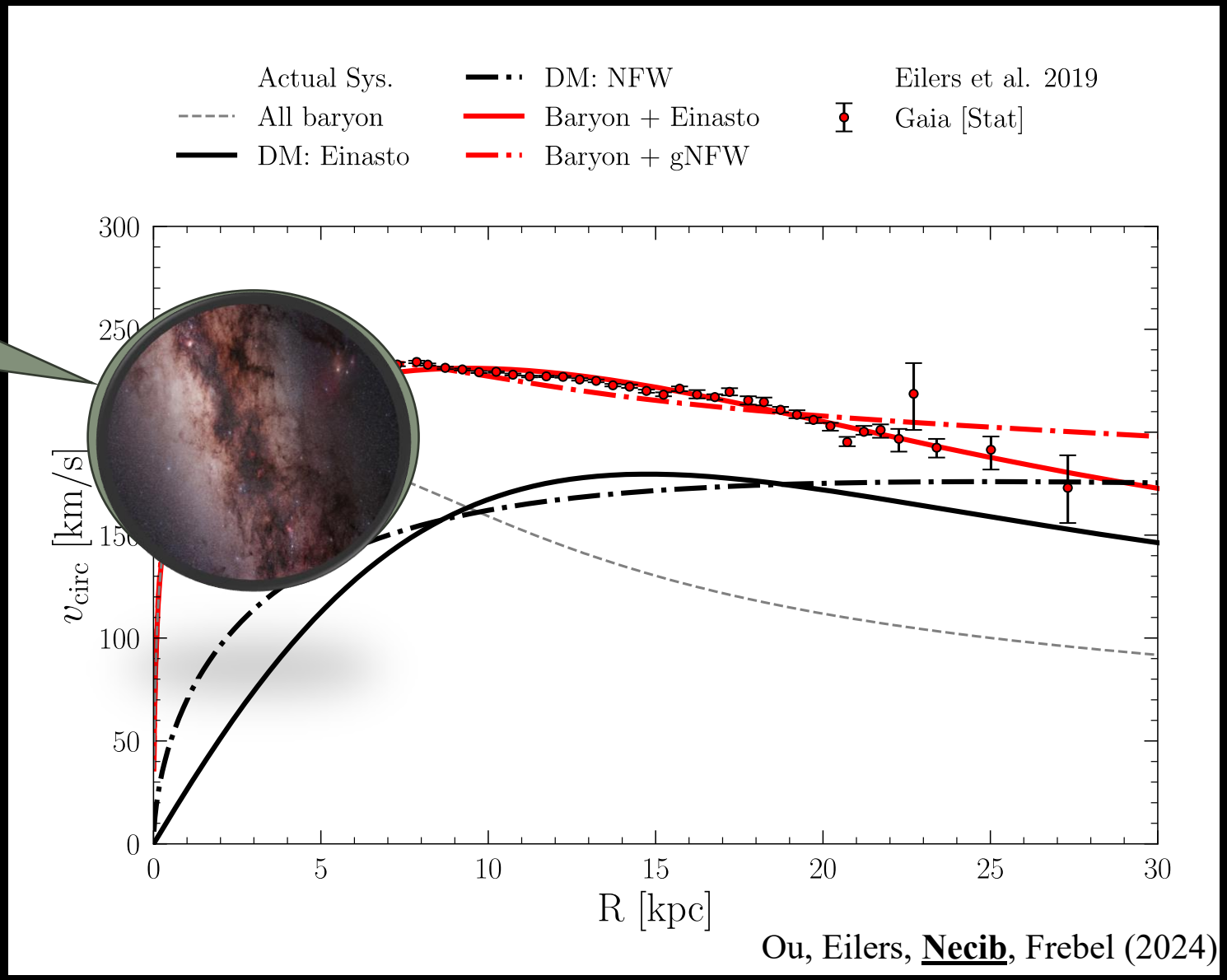


Ou, Eilers, **Necib**, Frebel (2024)

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

BUT DUST...

What I really want, is data here!

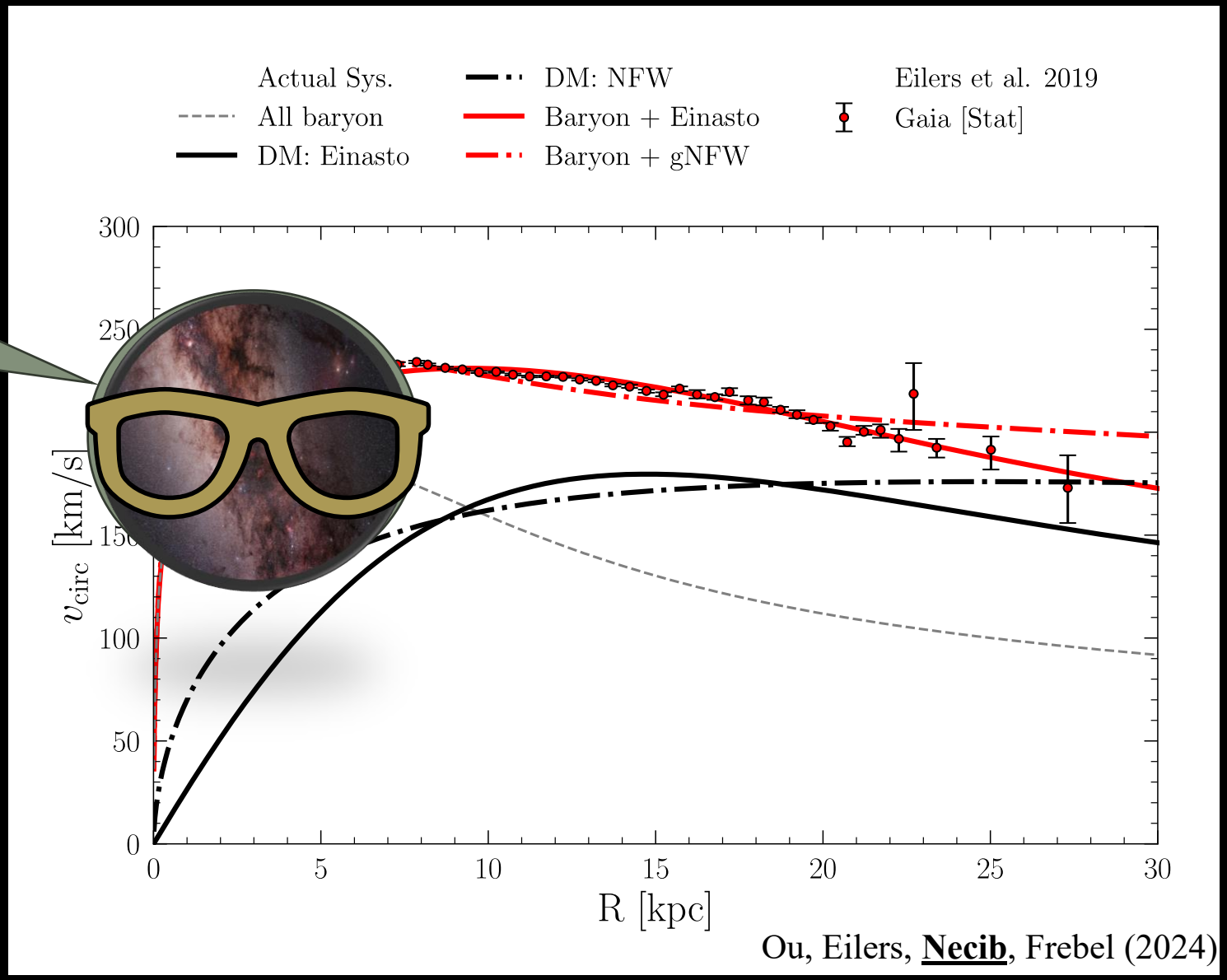


Ou, Eilers, **Necib**, Frebel (2024)

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

WHAT I NEED THEN IS SEE-THROUGH-DUST GLASSES

What I really want, is data here!



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

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

WE ACTUALLY HAVE SEE-THROUGH-DUST GLASSES…

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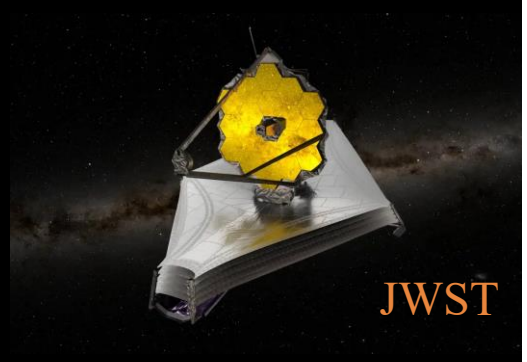
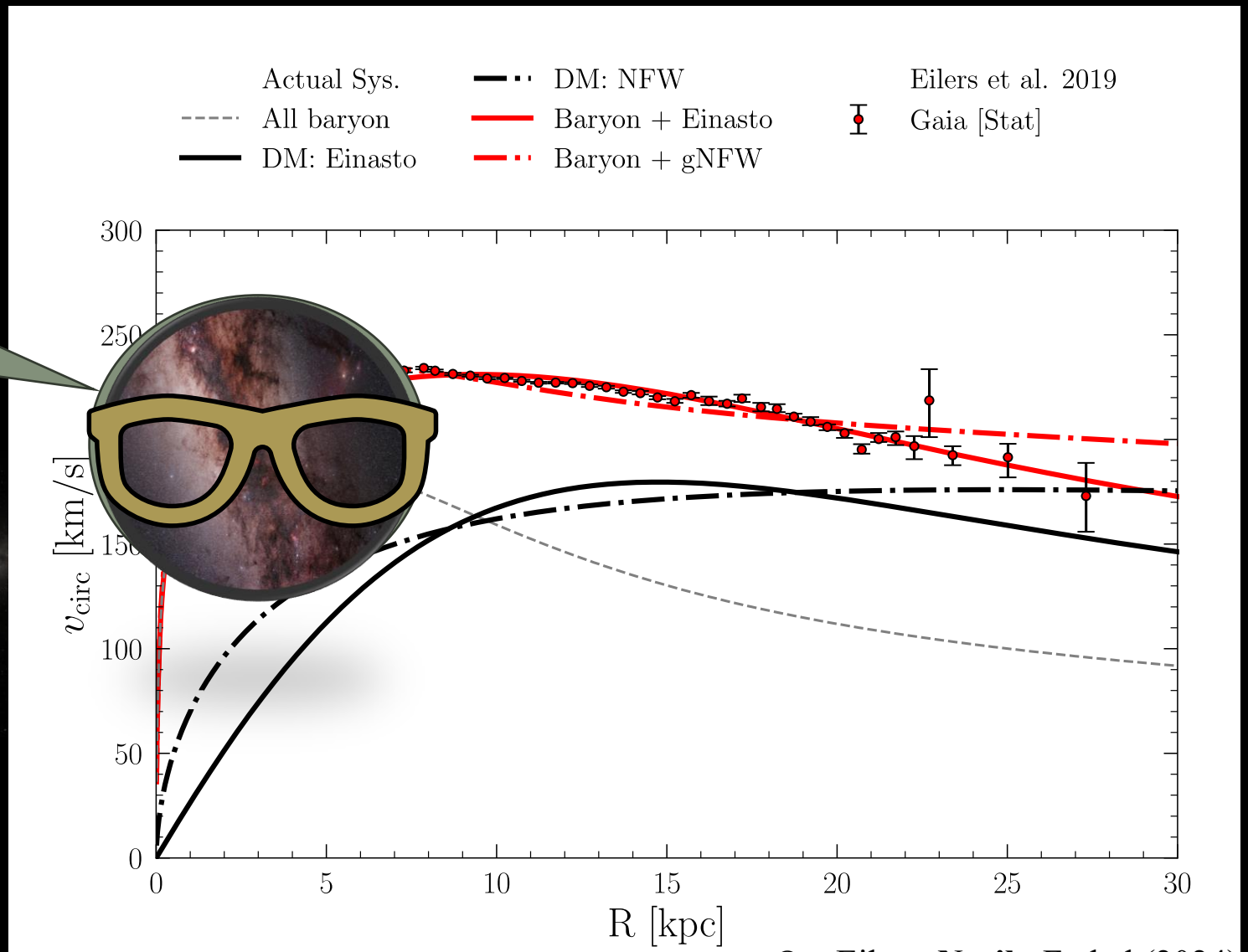


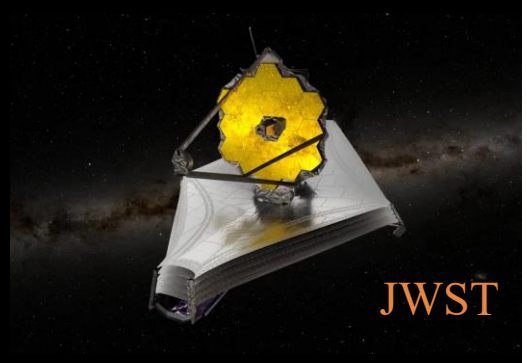


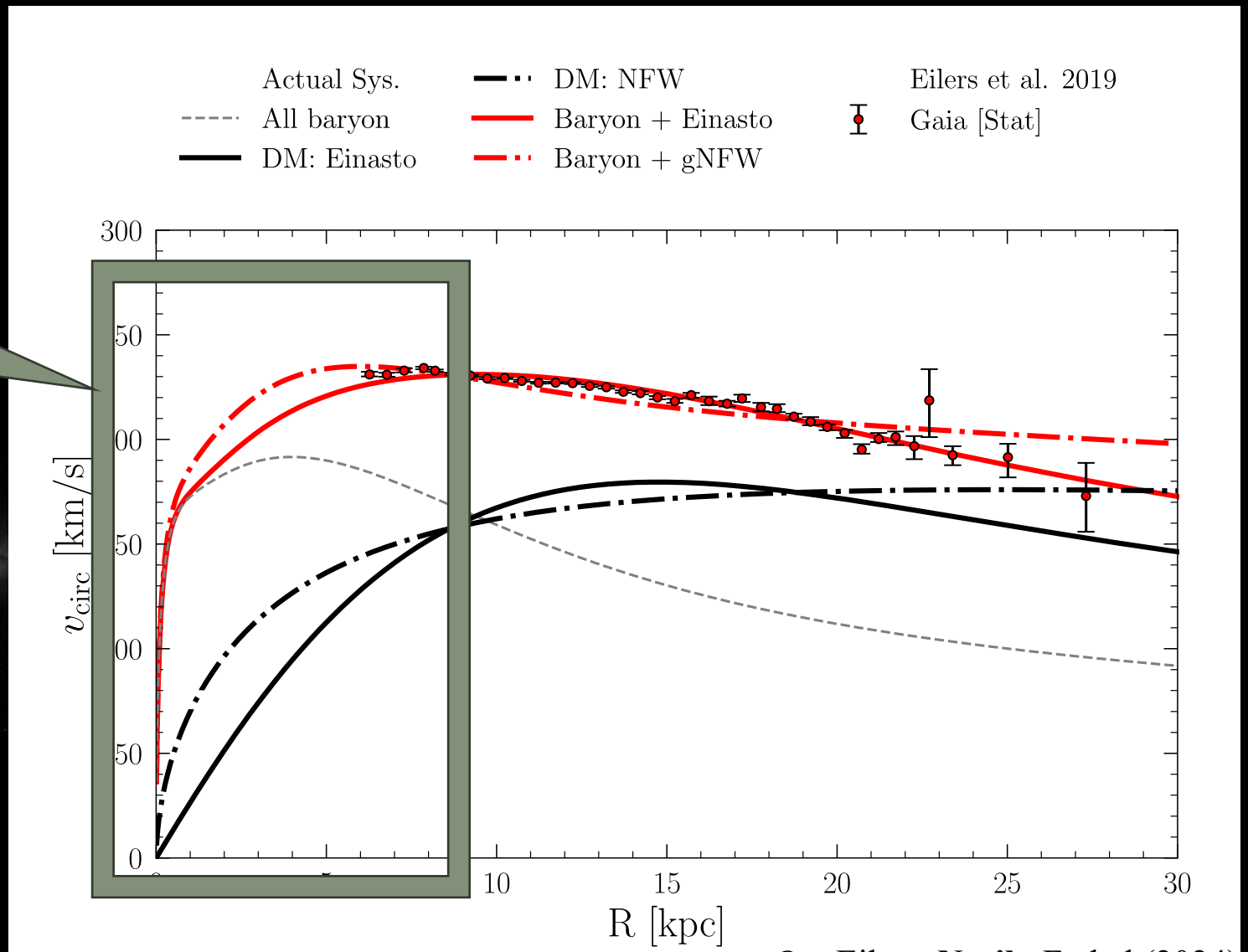
Ou, Eilers, **Necib**, Frebel (2024)

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

CAN WE SOLVE THIS IN FINITE TIME?

Let's Zoom in





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

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NEED THE SAME INGREDIENTS, EACH WITH A DIFFERENT SET OF CHALLENGES

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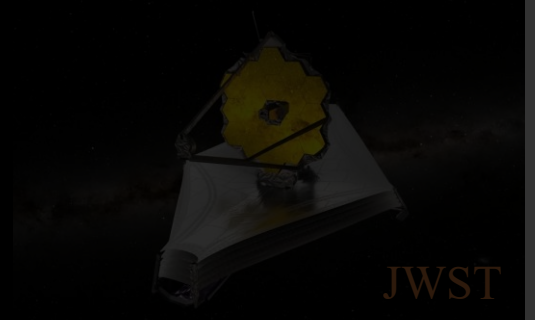

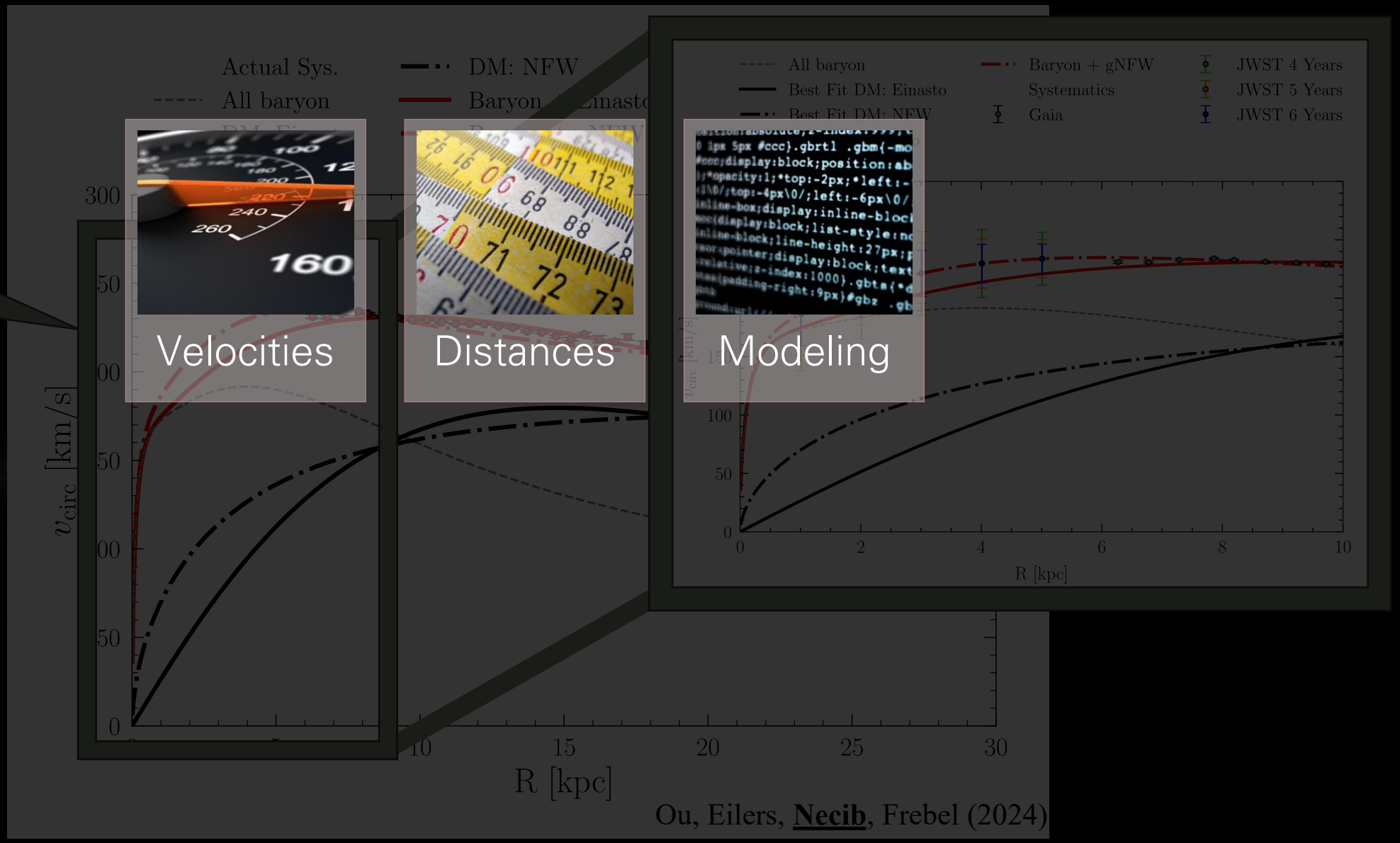

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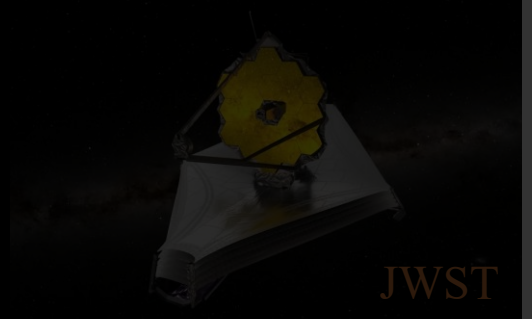

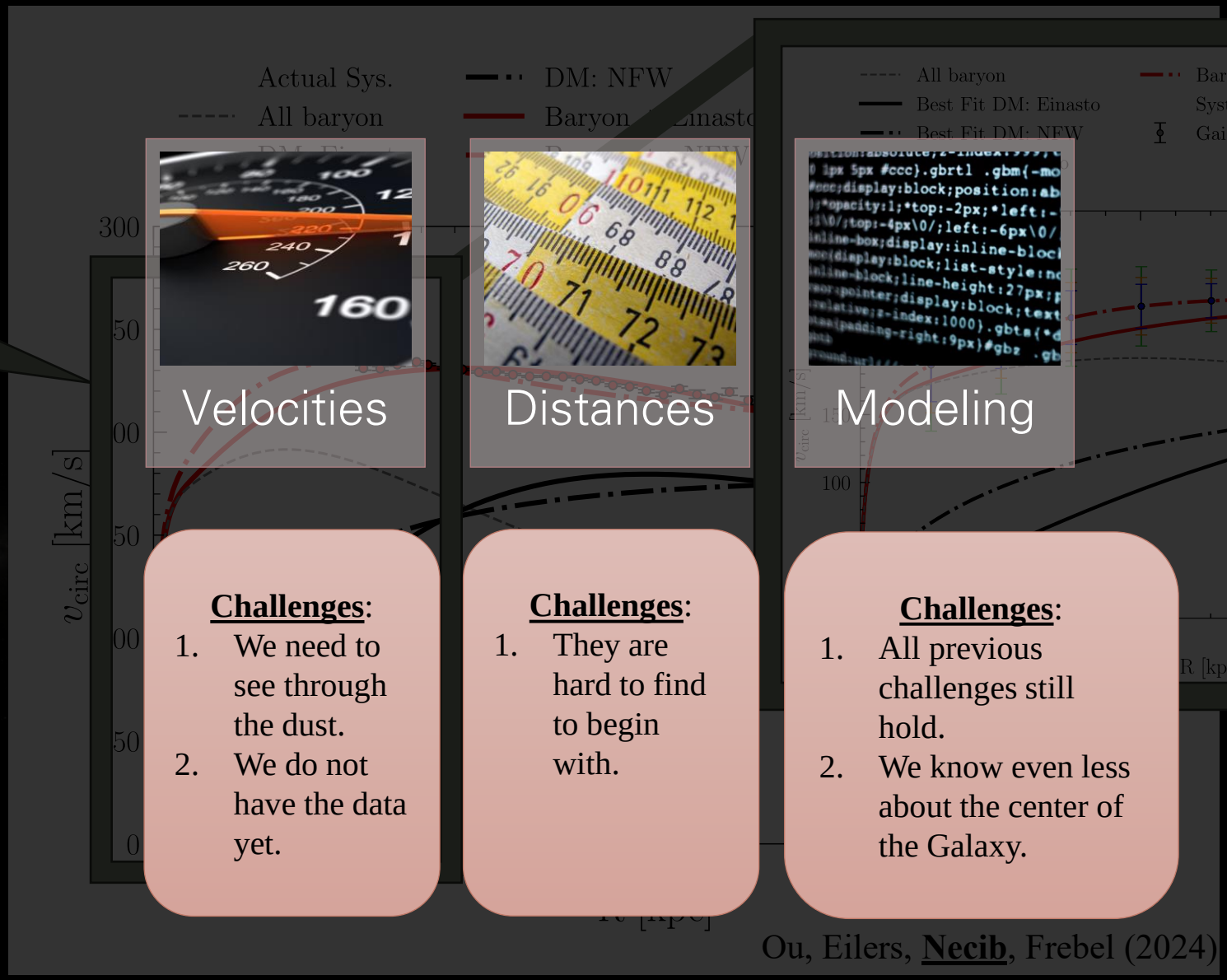

Velocities

Distances

Modeling

Challenges:
1. We need to see through the dust.
2. We do not have the data yet.

Challenges:
1. They are hard to find to begin with.

Challenges:
1. All previous challenges still hold.
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Ou, Eilers, **Necib**, Frebel (2024)

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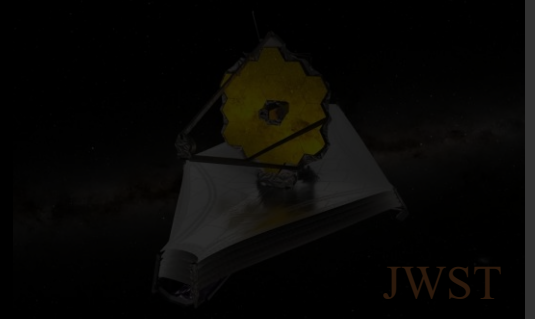

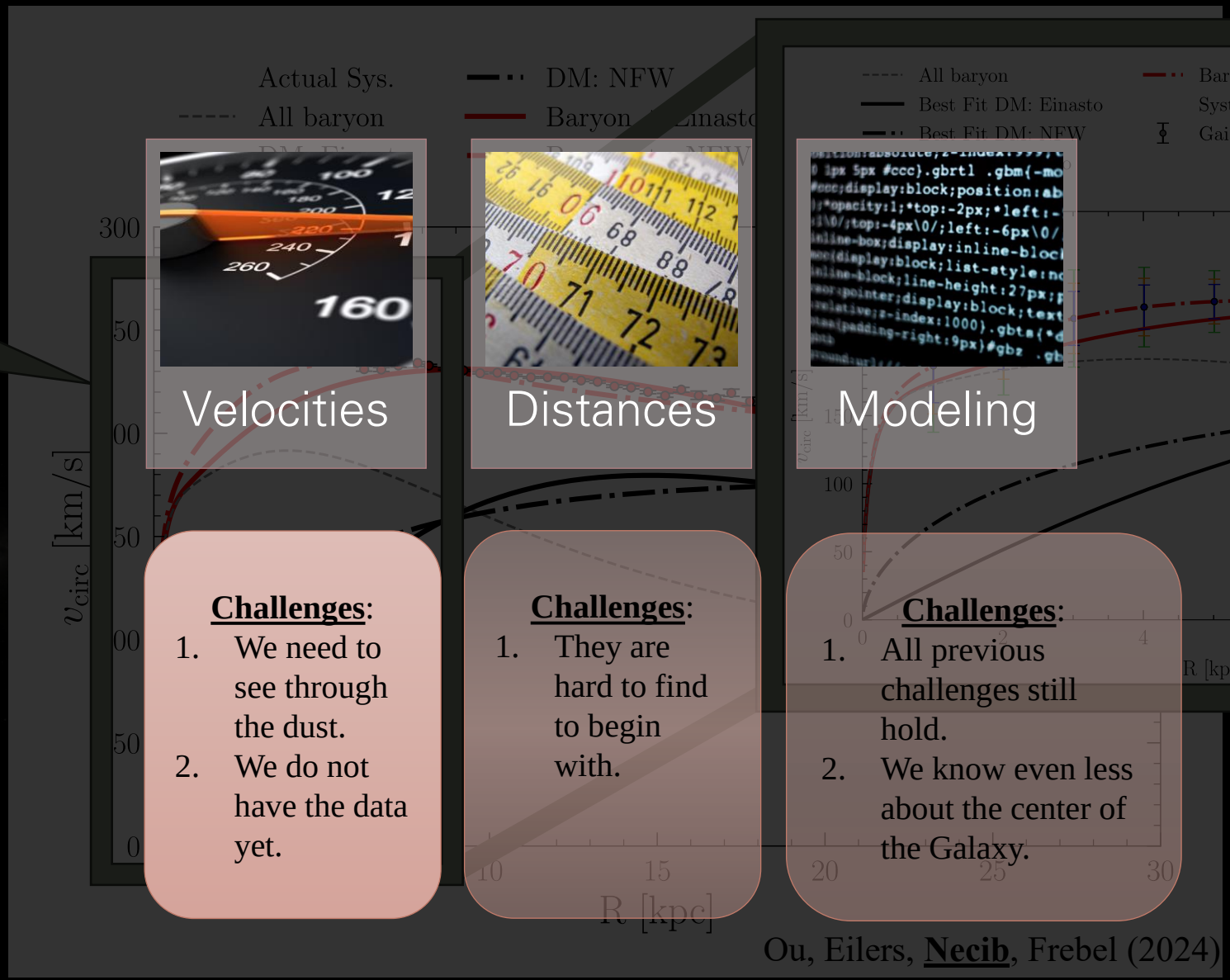

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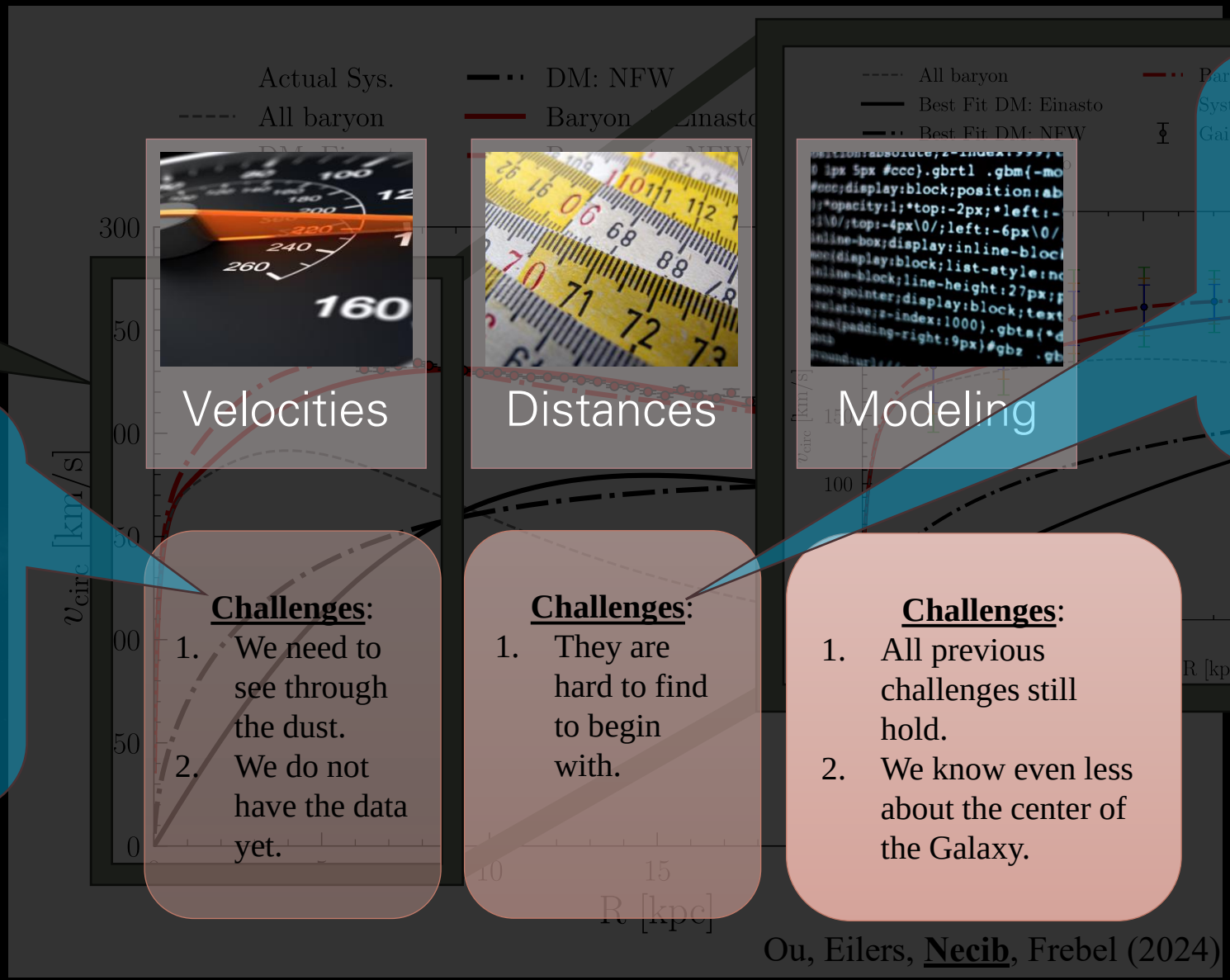

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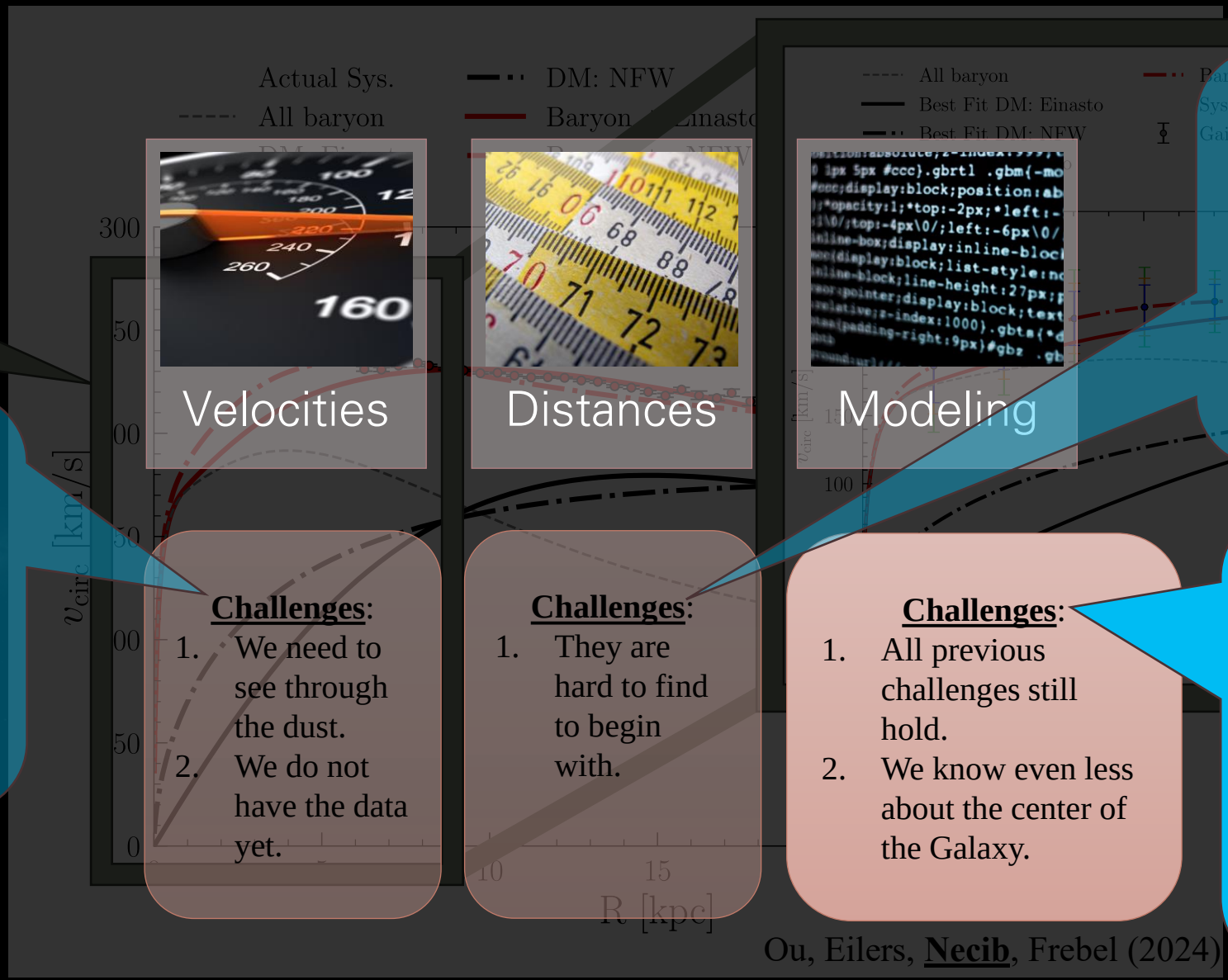

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1. Searching for RR Lyrae stars with well defined distances in published catalogs.

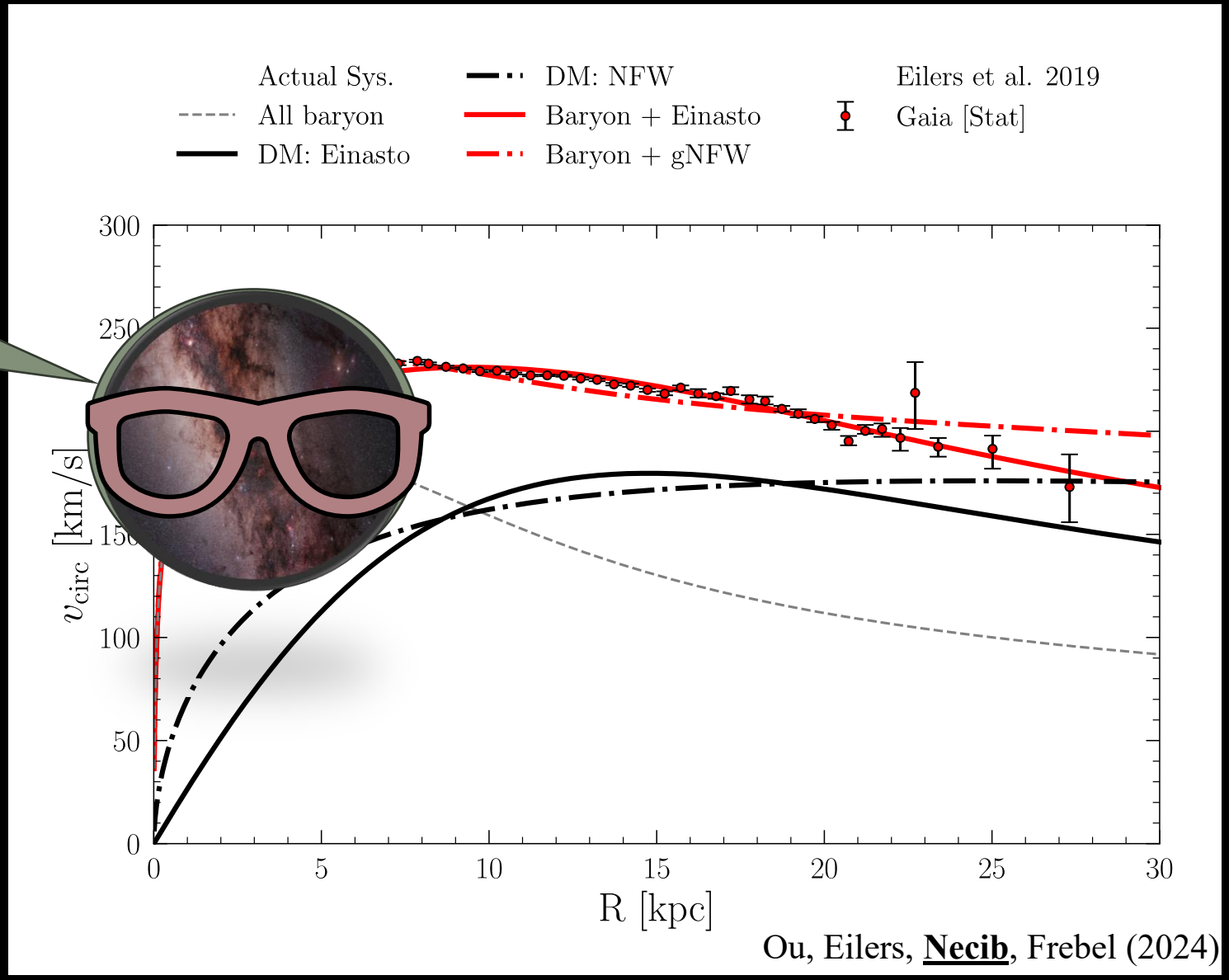
1. Using large scale structure methods to map out the gravitational potential based on the stellar map (from Gaia).
2. Going through the literature of the bar (mainly to figure out how to avoid it)

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

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

IN THE MEANTIME, LET'S HAVE THEORY GLASSES

What I really want, is data here!



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

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

IN THE MEANTIME, LET'S HAVE THEORY GLASSES

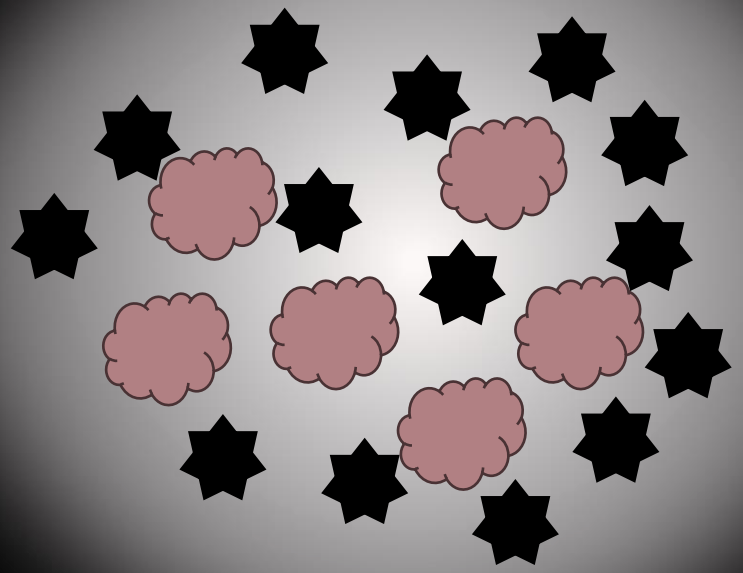
Abdelaziz Hussein

ΛCDM

Lina Necib, MIT

IN THE MEANTIME, LET'S HAVE THEORY GLASSES

Abdelaziz Hussein



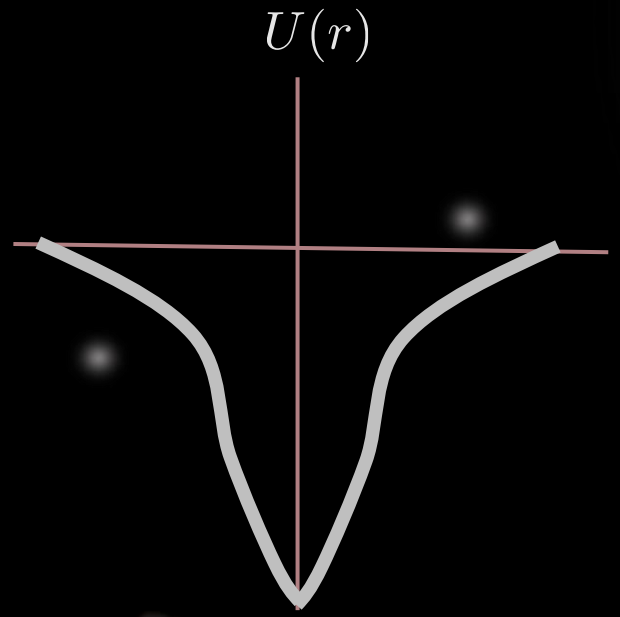
Adiabatic Contraction

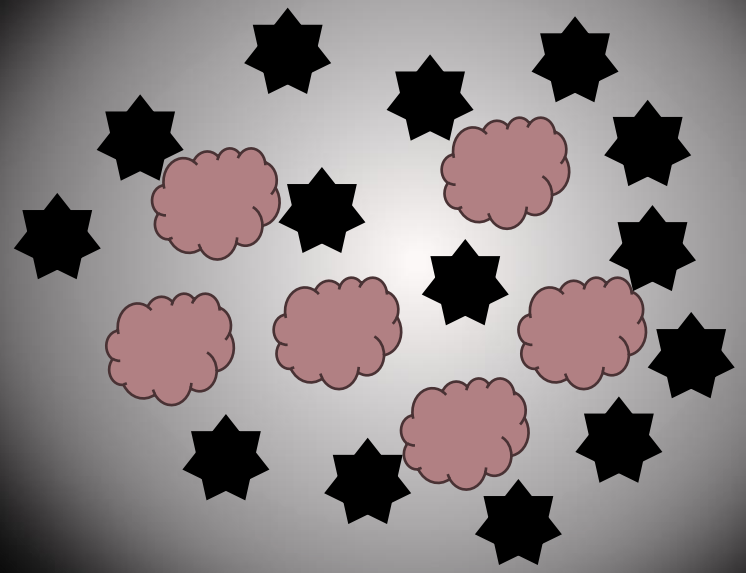
Lina Necib, MIT

Blumenthal et al. 1986
Gnedin et al. 2004

IN THE MEANTIME, LET'S HAVE THEORY GLASSES

Abdelaziz Hussein





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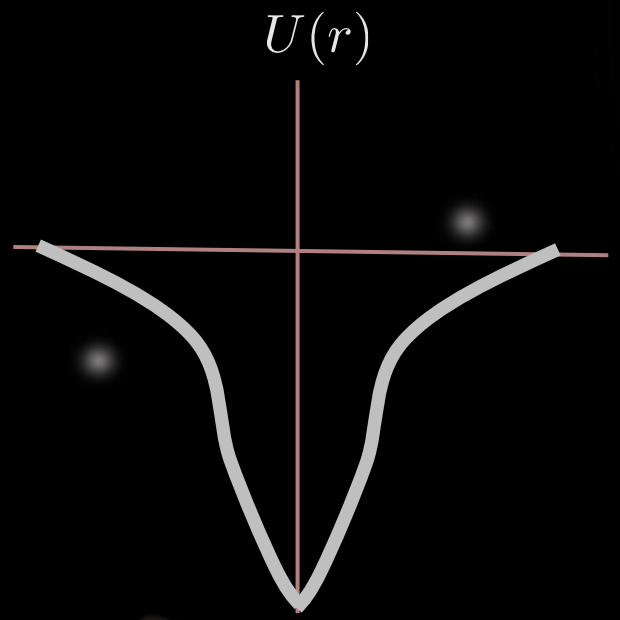
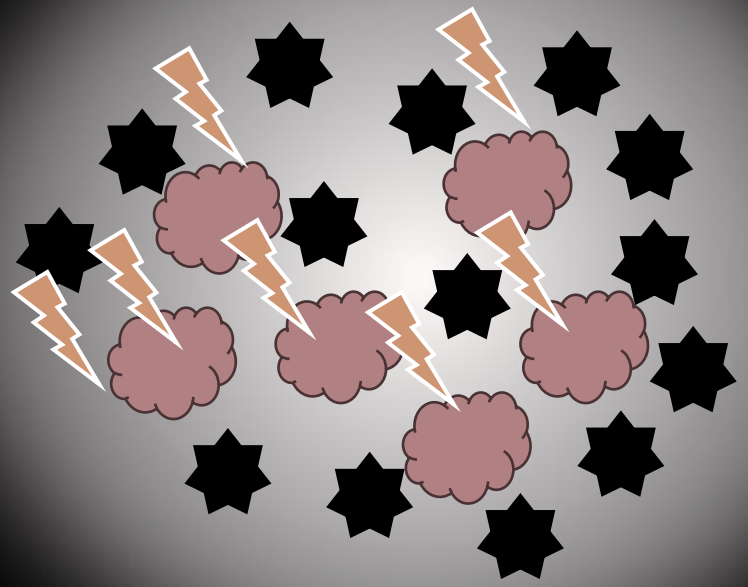
Abdelaziz Hussein





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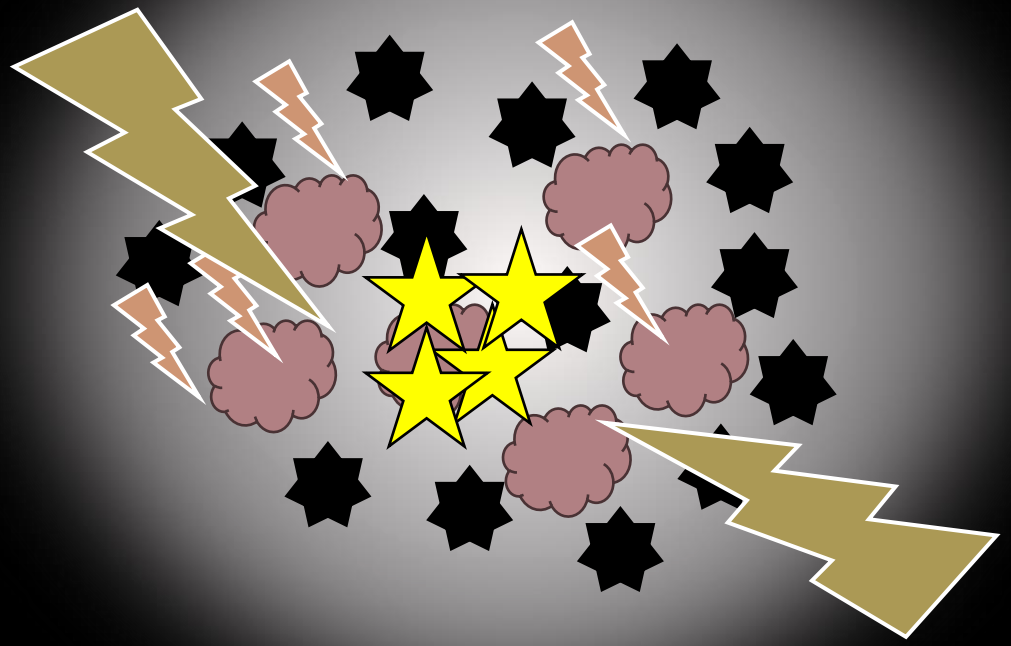

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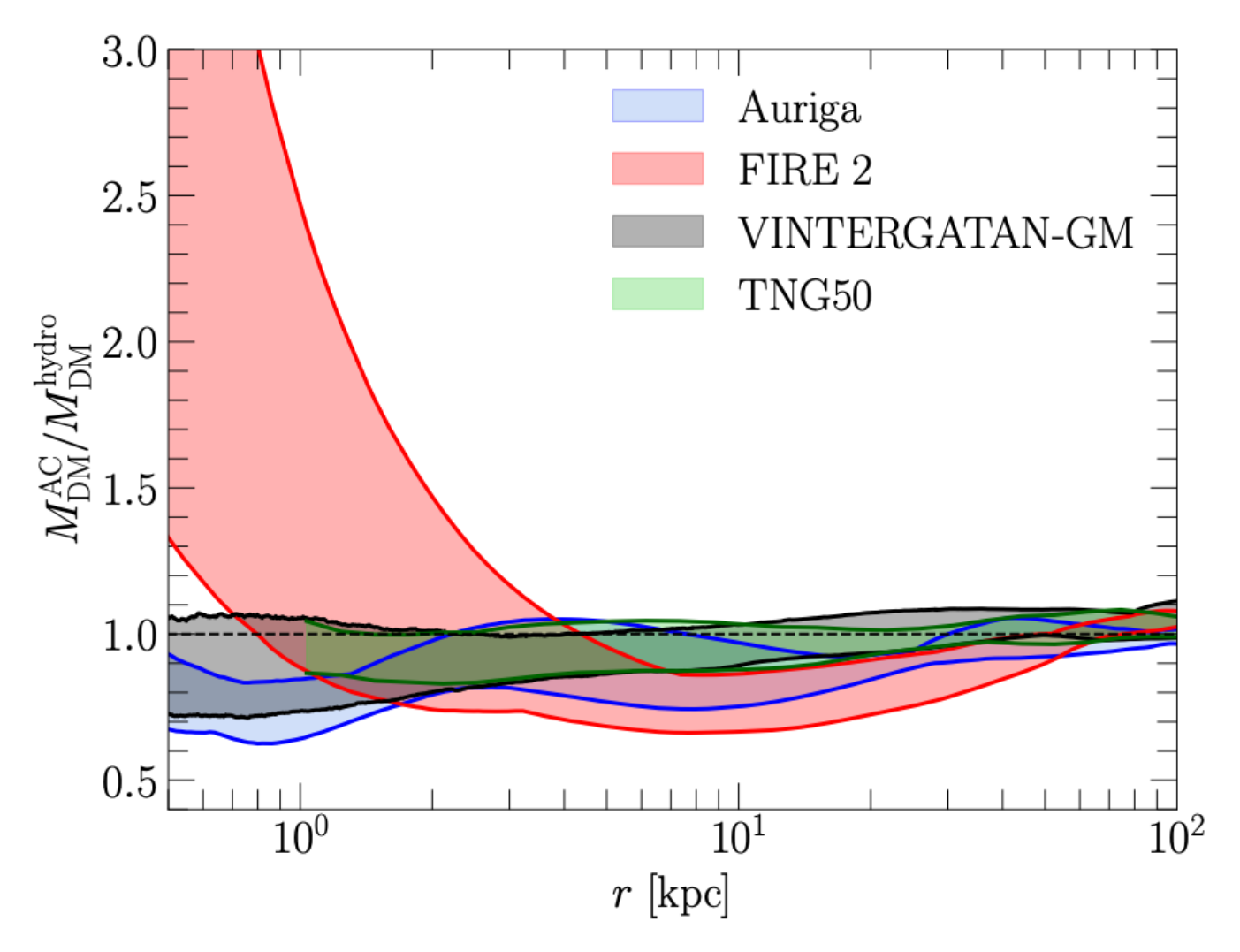
COMPARING THESE RESULTS TO THE THEORY PREDICTION LEADS TO

Abdelaziz Hussein



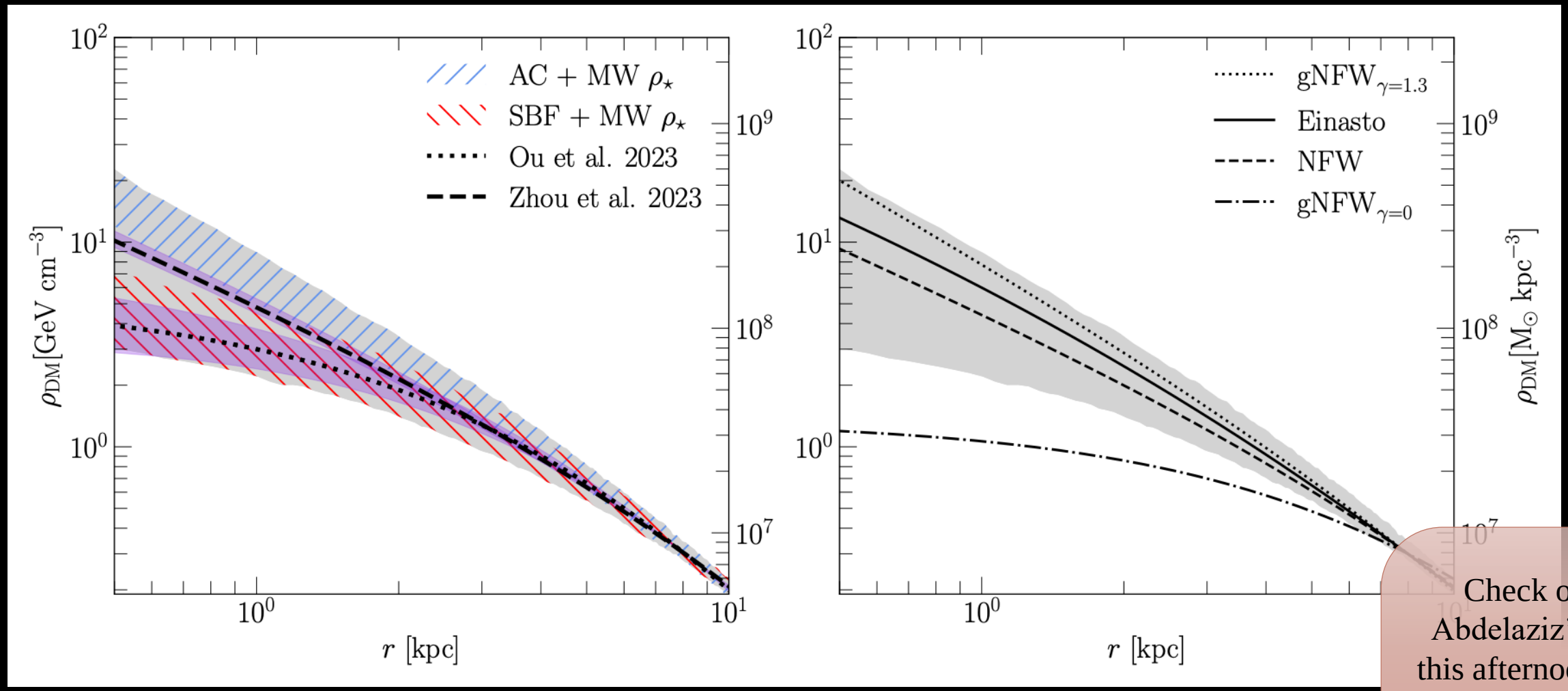
Wetzel et al. (2016)
Hopkins et al. (2018)
Wetzel et al. (2023)
Grand et al. (2024)
Agertz et al. (2021)
Rey et al. (2023)
Pillepich et al. (2023)

Hussein, **Necib**, 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



Check out Abdelaziz' talk this afternoon for more details

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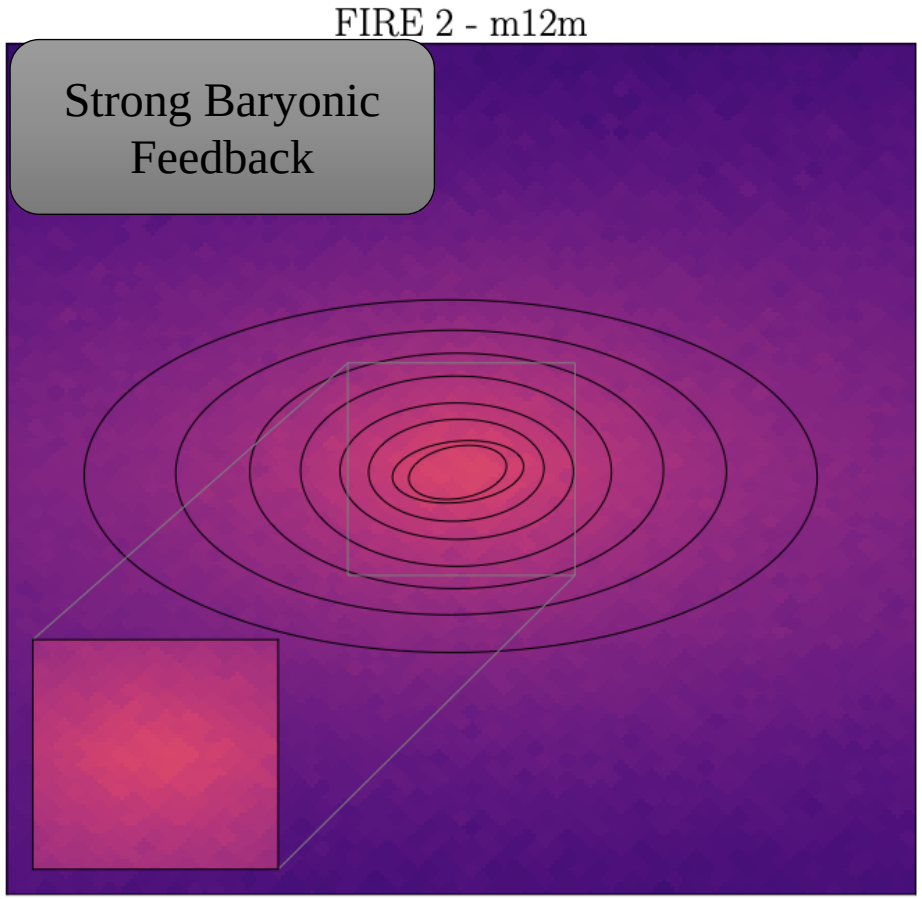
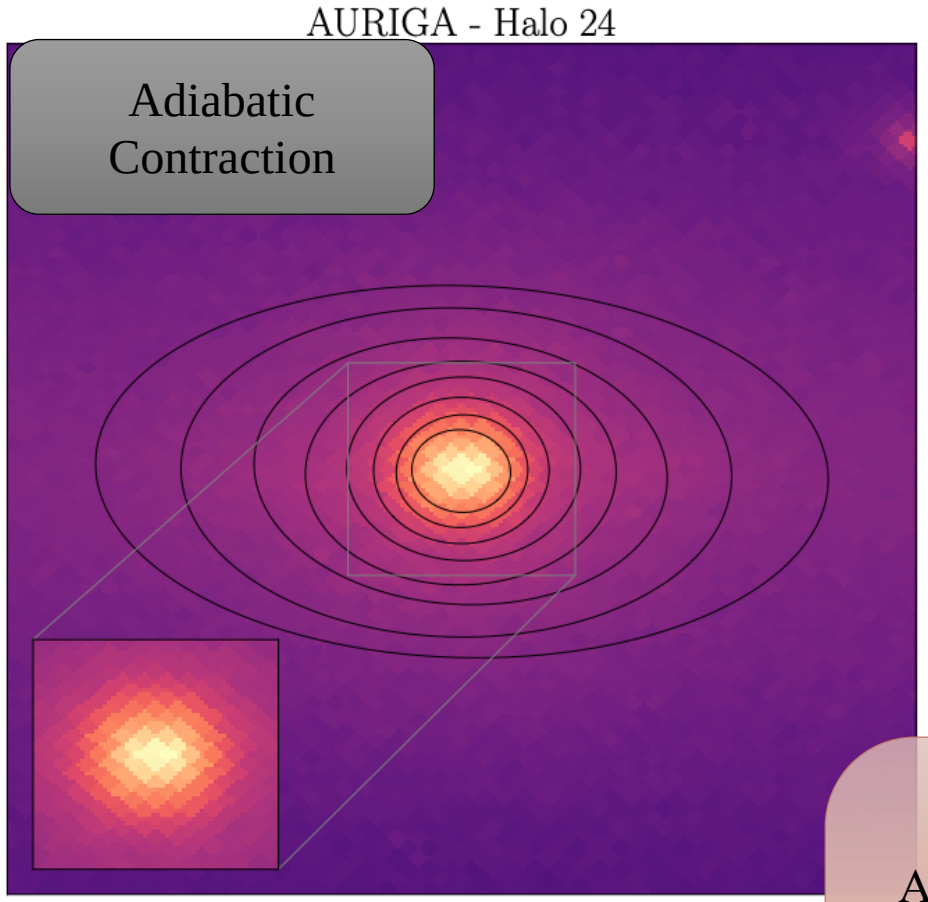
THE DIFFERENT MECHANISMS ALSO AFFECT THE DARK MATTER SPATIAL DISTRIBUTION

Abdelaziz Hussein





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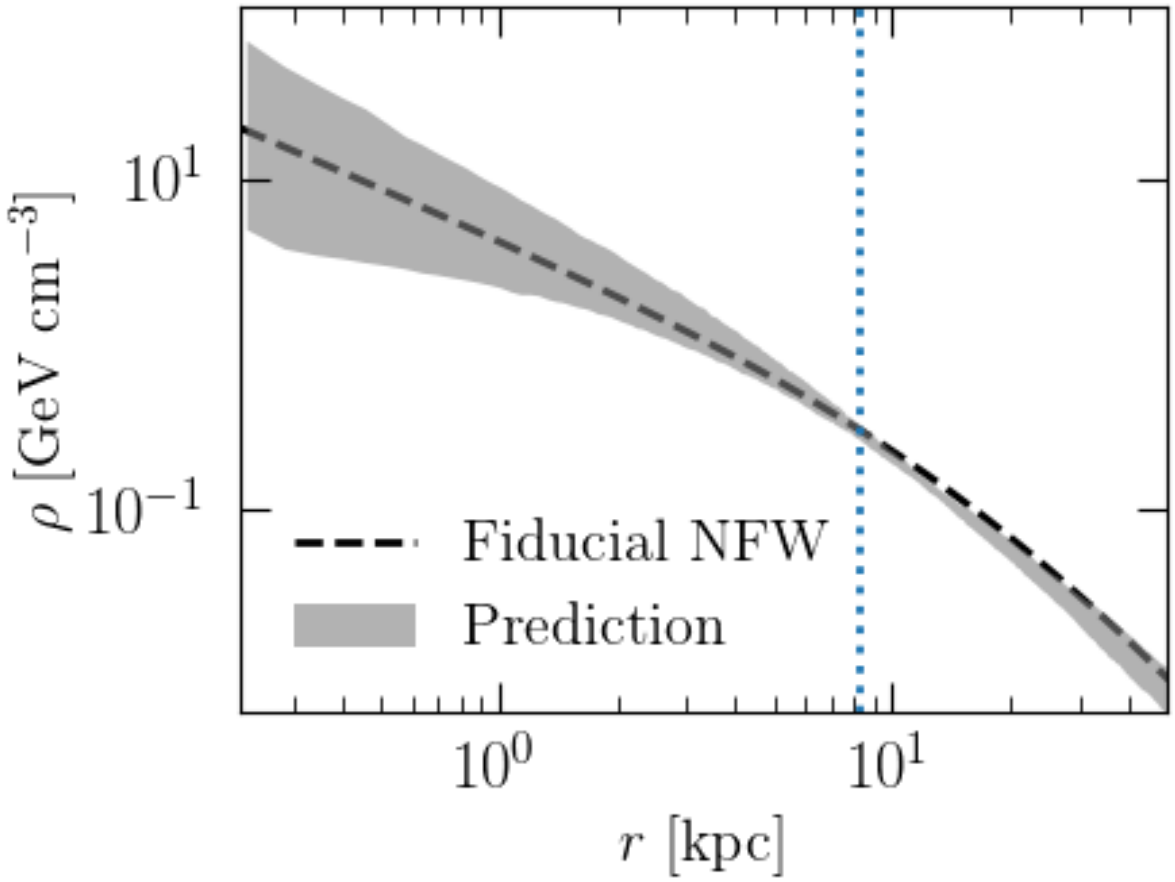
PUTTING EVERYTHING INTO PERSPECTIVE. THEORY, OBSERVATIONS, EVERYTHING...

Abdelaziz Hussein



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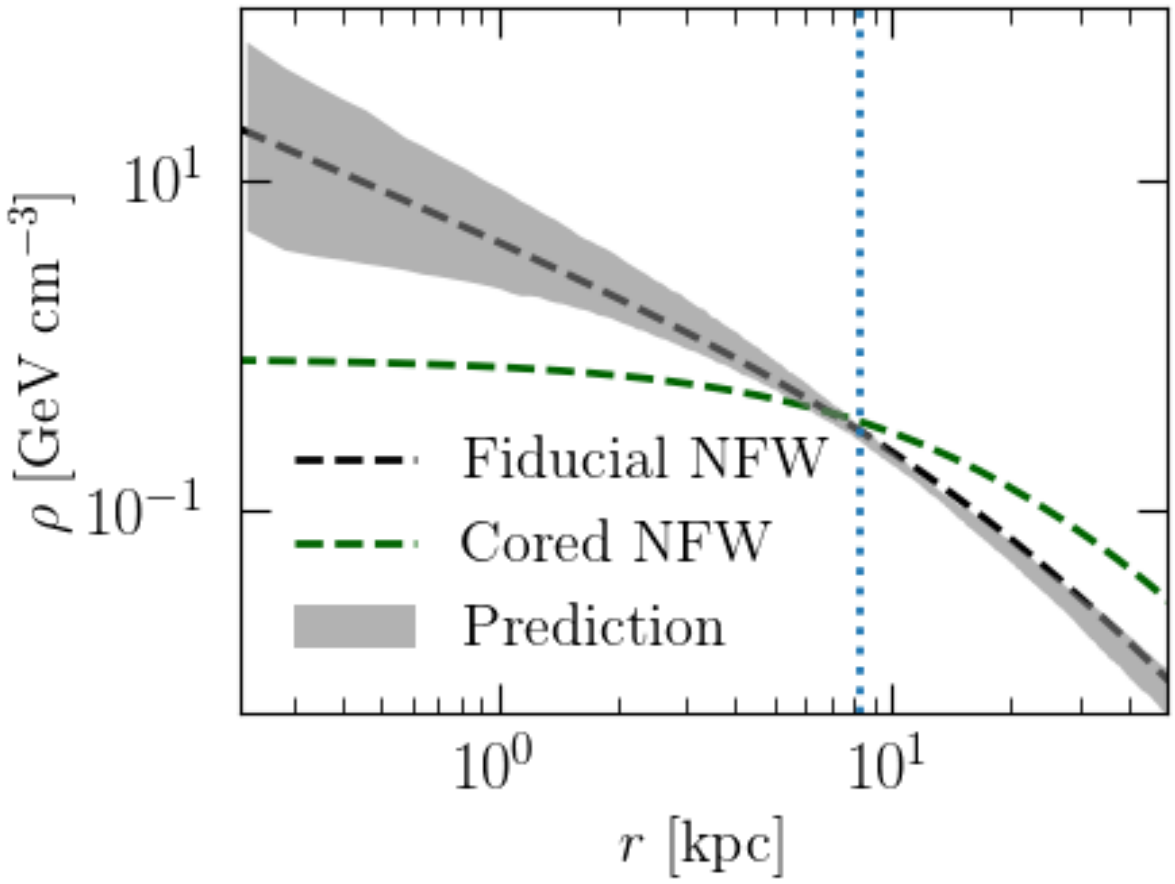

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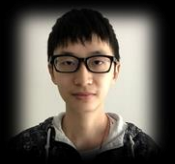
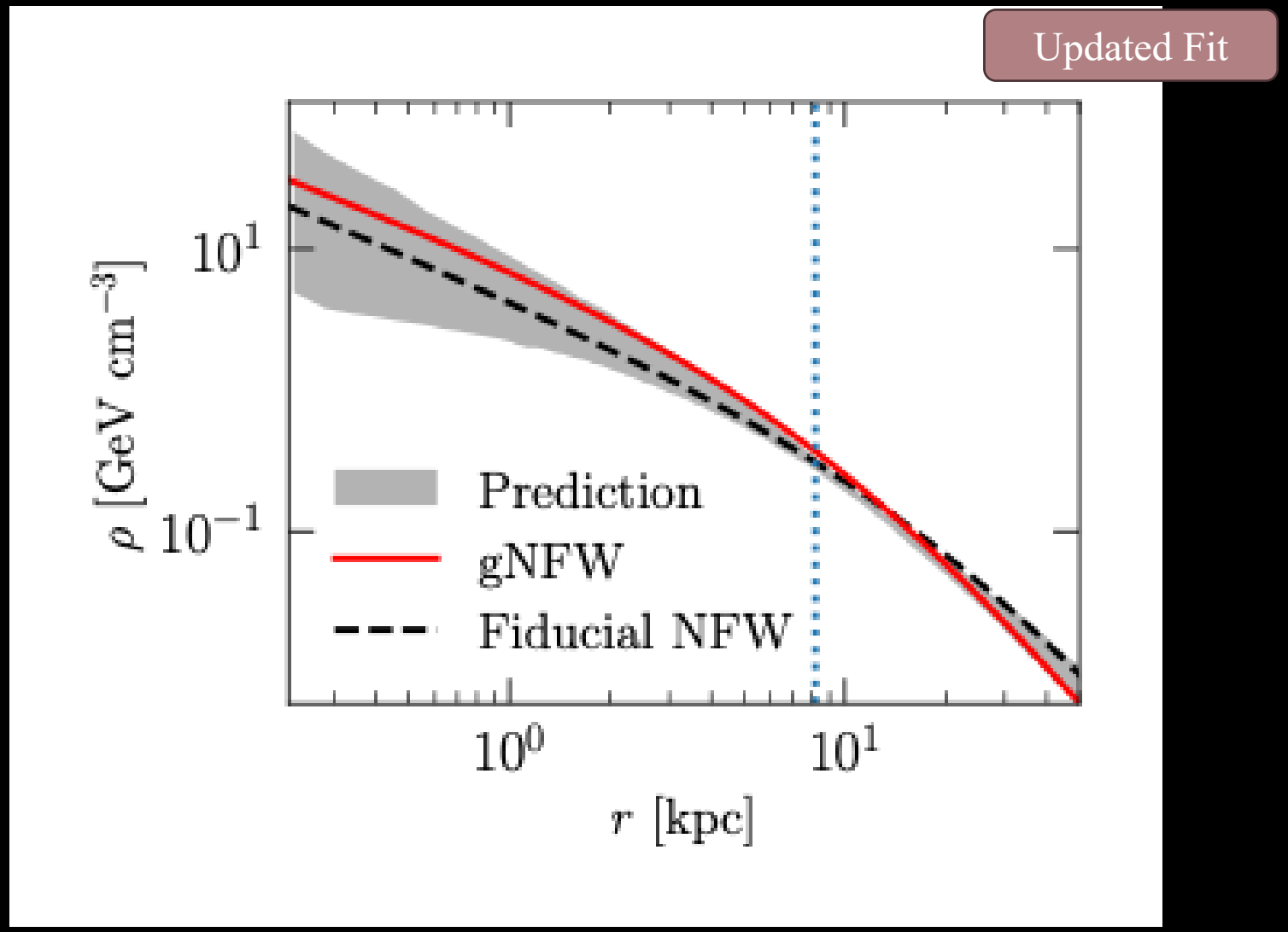


Xiaowei Ou



Ou, **Necib**, et al. (2025)
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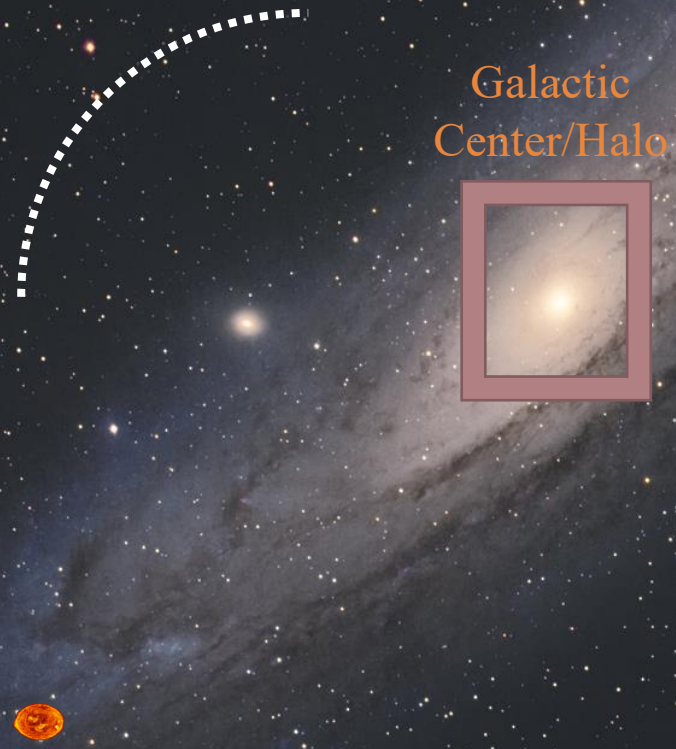
TODAY'S TALK: MAPPING THE DARK MATTER DENSITY PROFILE IN THE MILKY WAY



Ou, Necib, Wetzel et al. (2025)
Hussein, Necib, et al. (2025)
Ou, Eilers, Necib, Frebel (2024)
Nguyen, Ou,…, Necib, et al. (2024)
Roche, Necib, Lin (2024)
Necib, Lin (2022a,b)

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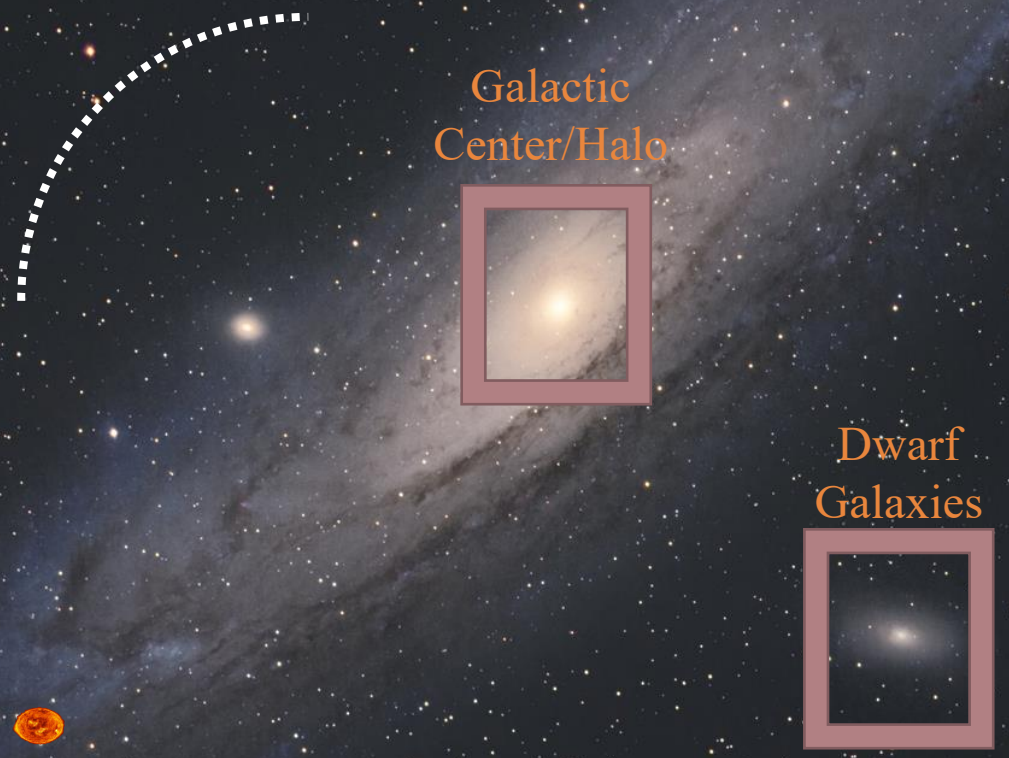

Lina Necib, MIT

TODAY'S TALK:
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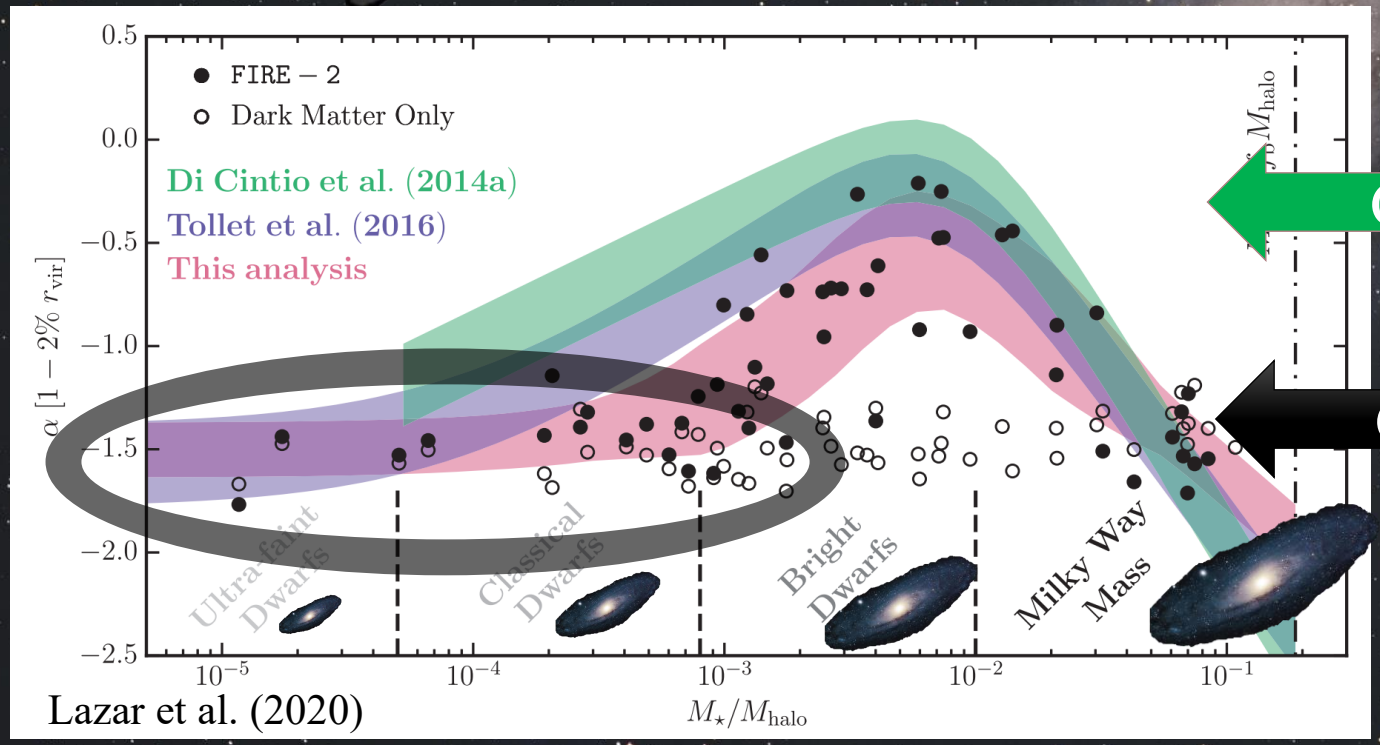
Lina Necib, MIT

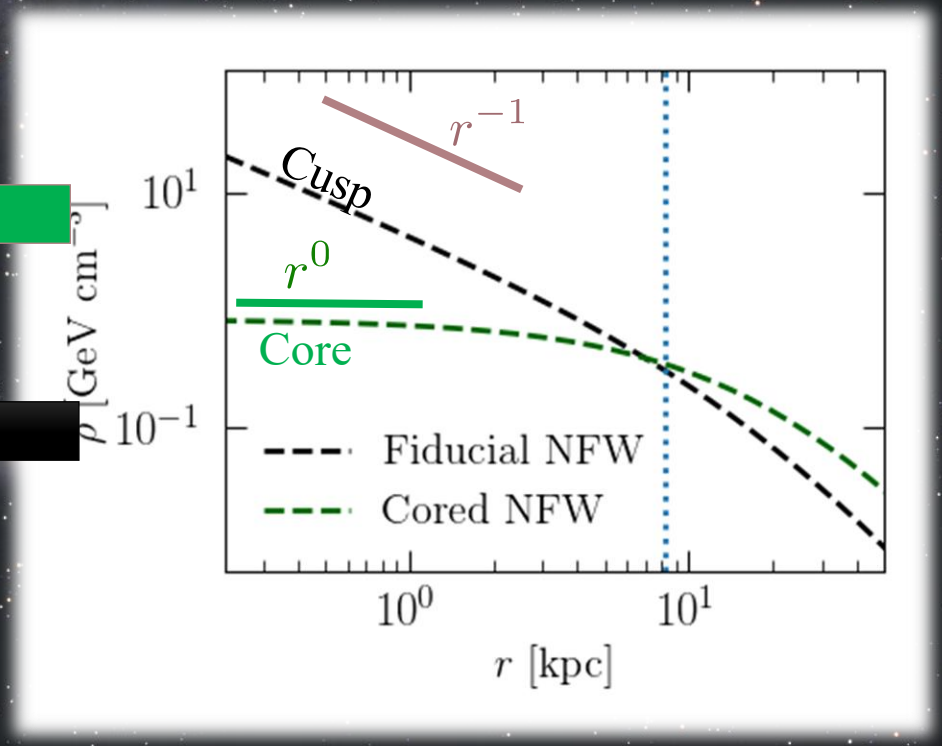
Astrophysics



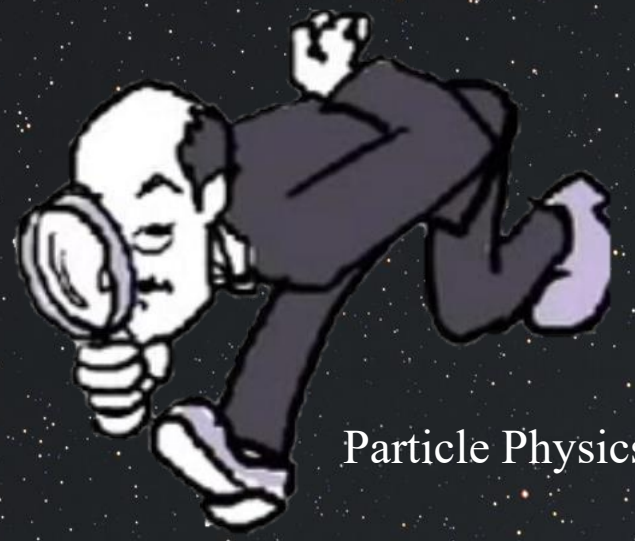
Lazar et al. (2020)

Core

Cusp

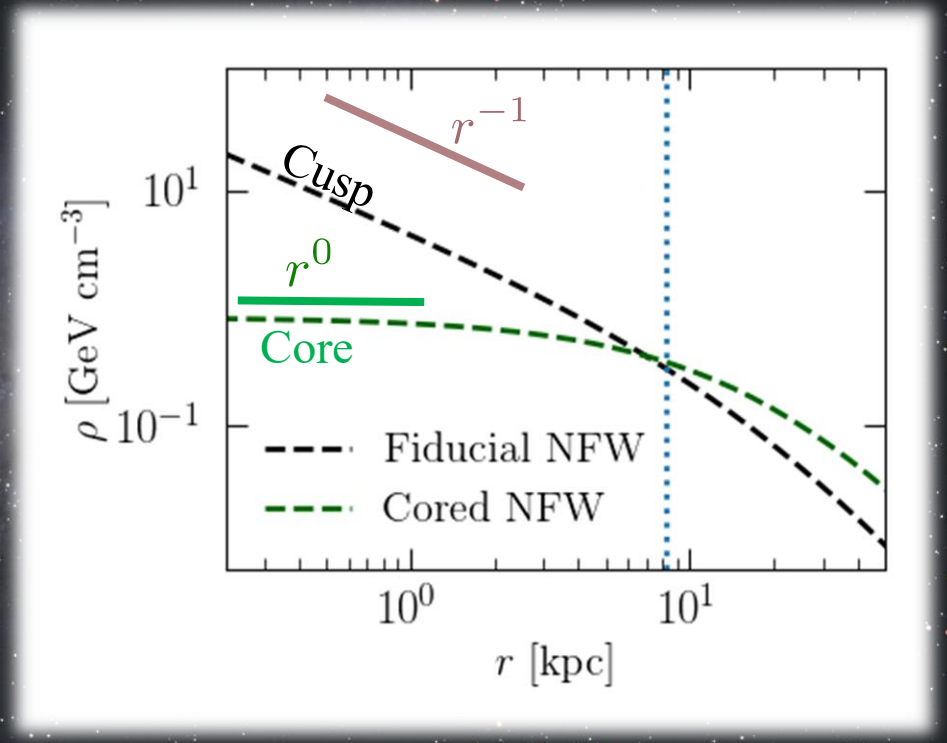


Lina Necib, MIT



Particle Physics

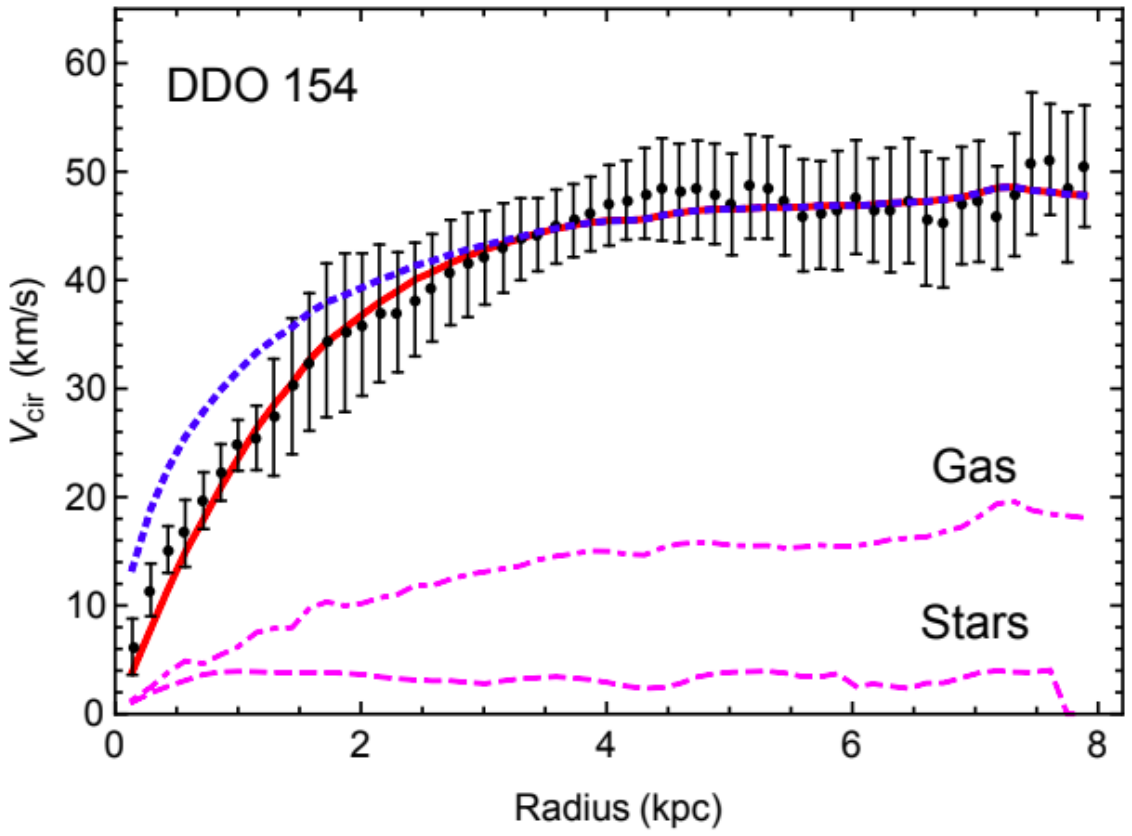
Dark Matter Annihilation Signal

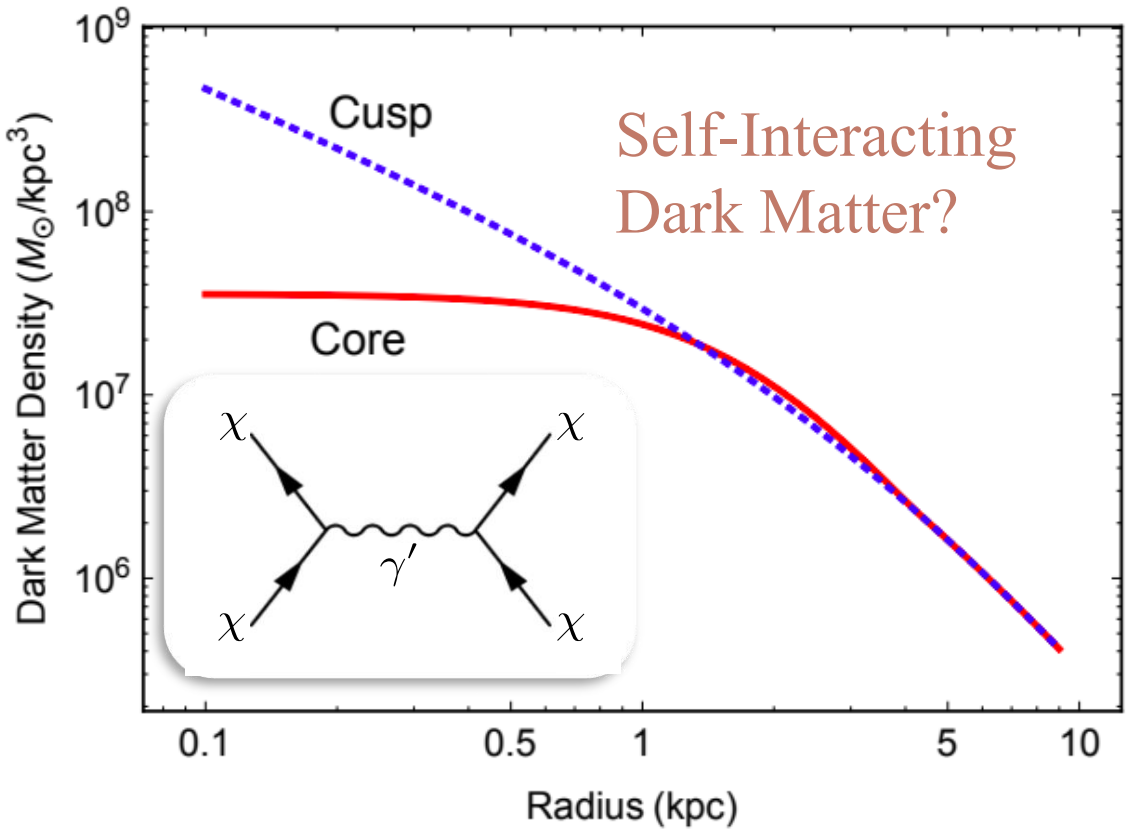


$$\text{Signal} \propto \int \rho^2 \mathrm{ds}$$

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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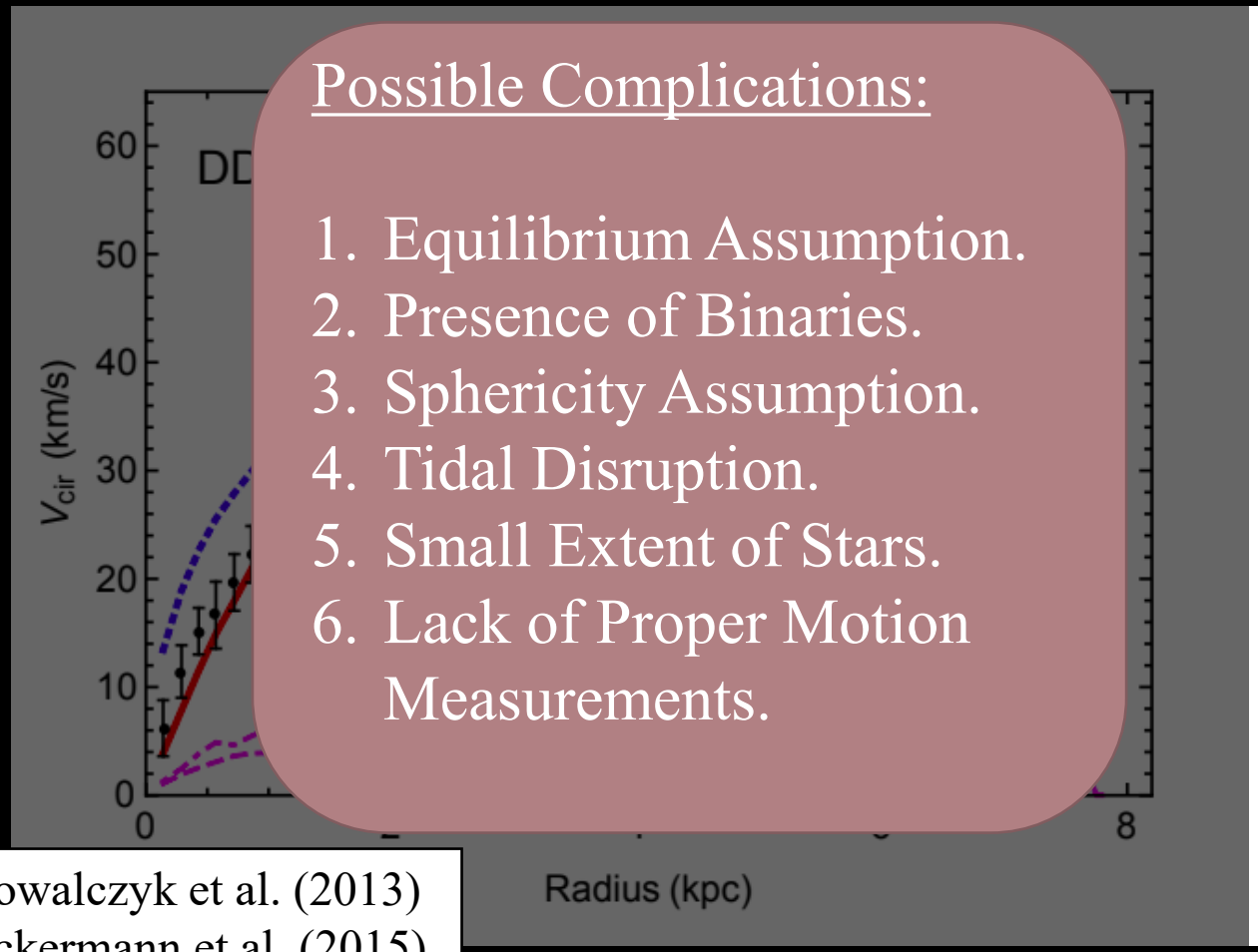
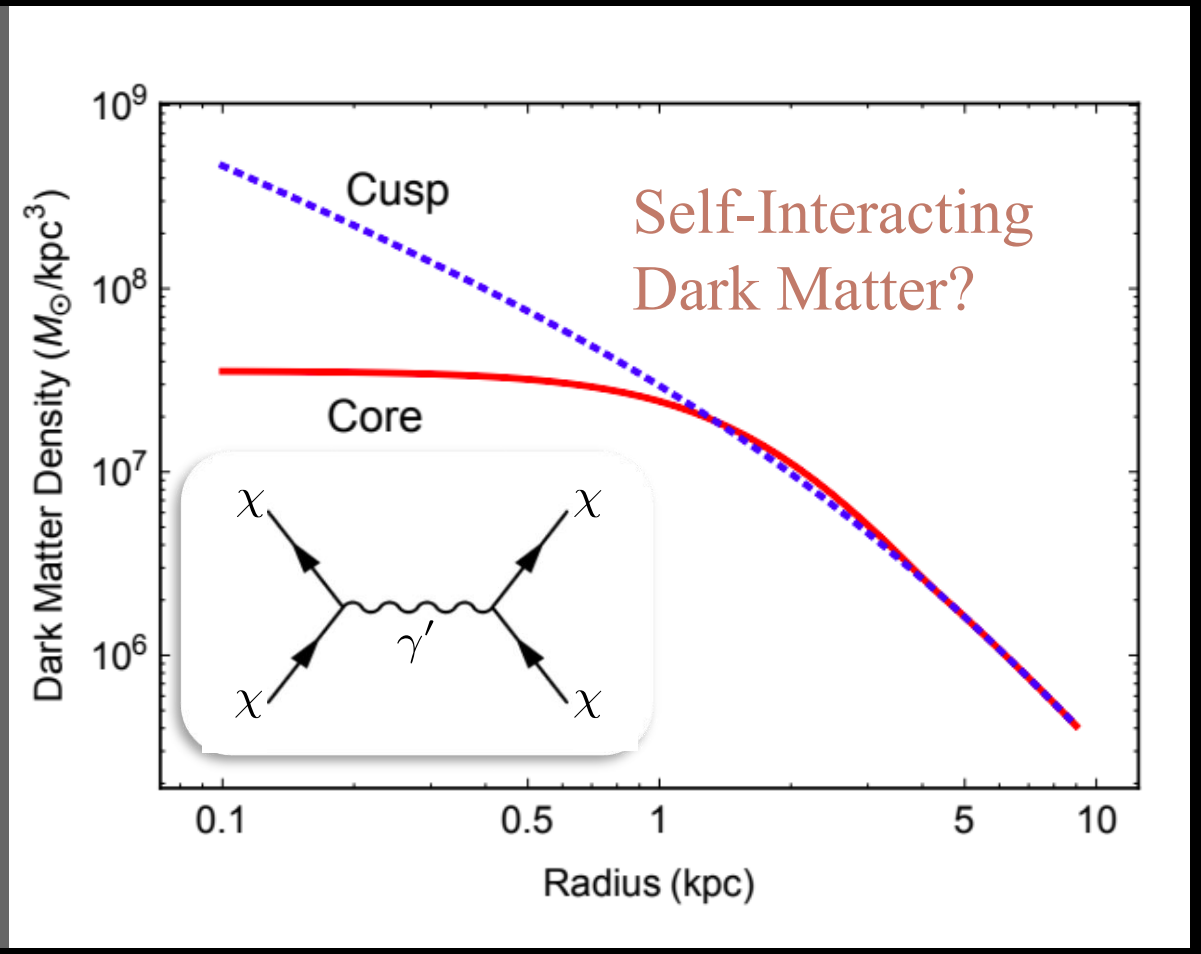


Possible Complications:

1. Equilibrium Assumption.
2. Presence of Binaries.
3. Sphericity Assumption.
4. Tidal Disruption.
5. Small Extent of Stars.
6. Lack of Proper Motion Measurements.



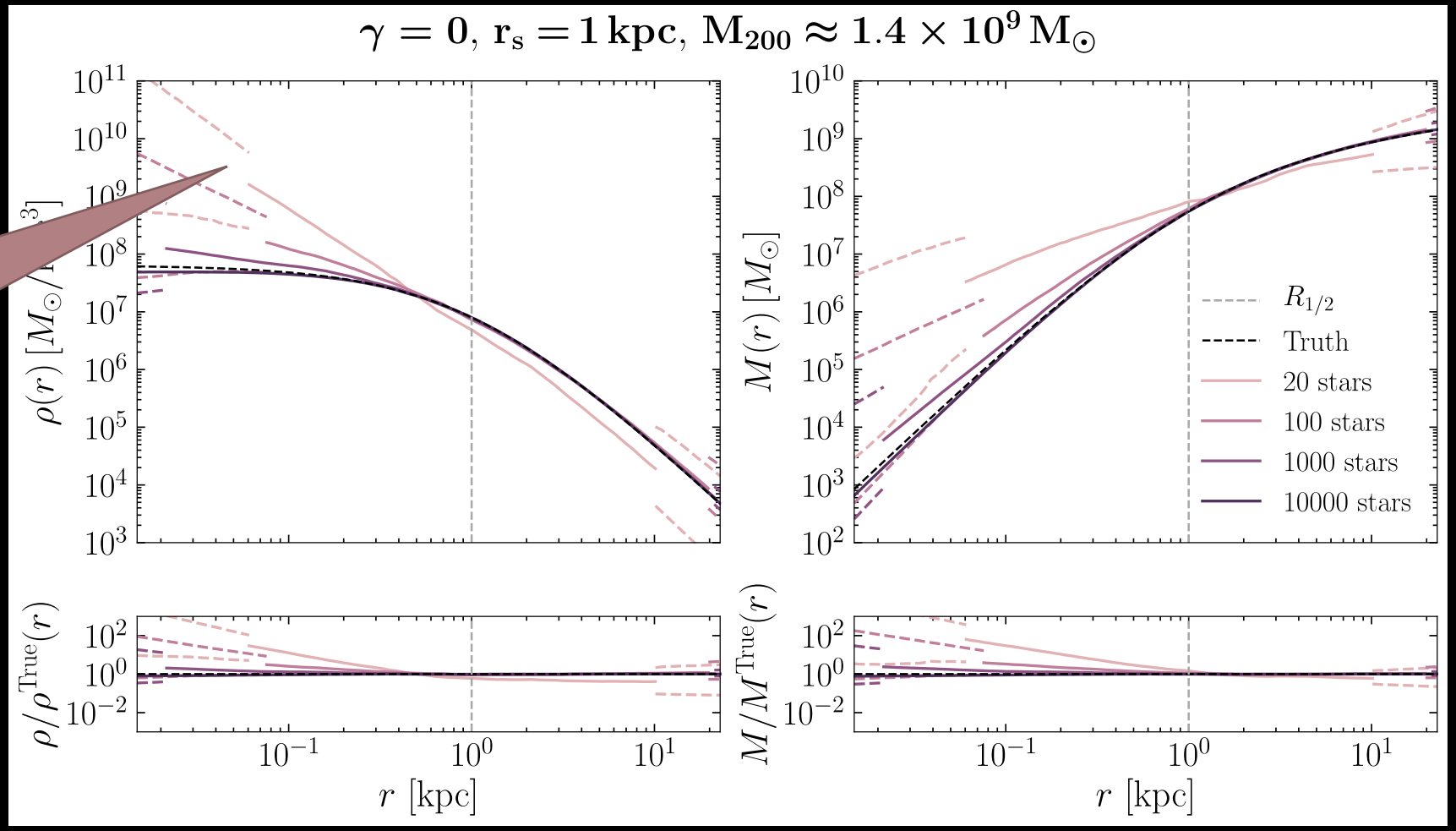
Kowalczyk et al. (2013)
Ackermann et al. (2015)
Bonnivard et al. (2015)
El-Badry et al. (2017)

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)

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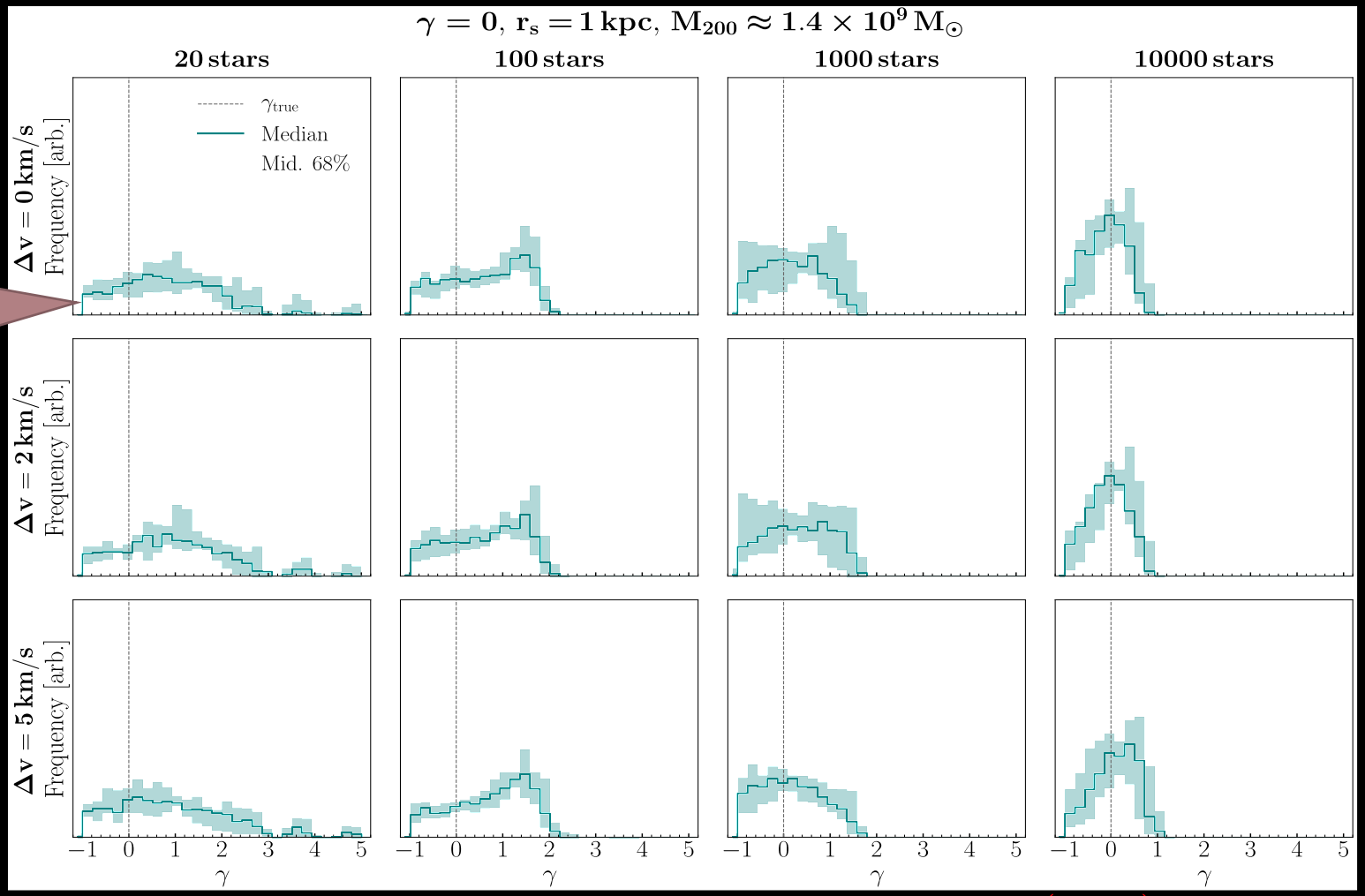


Cores are harder to resolve with fewer statistics

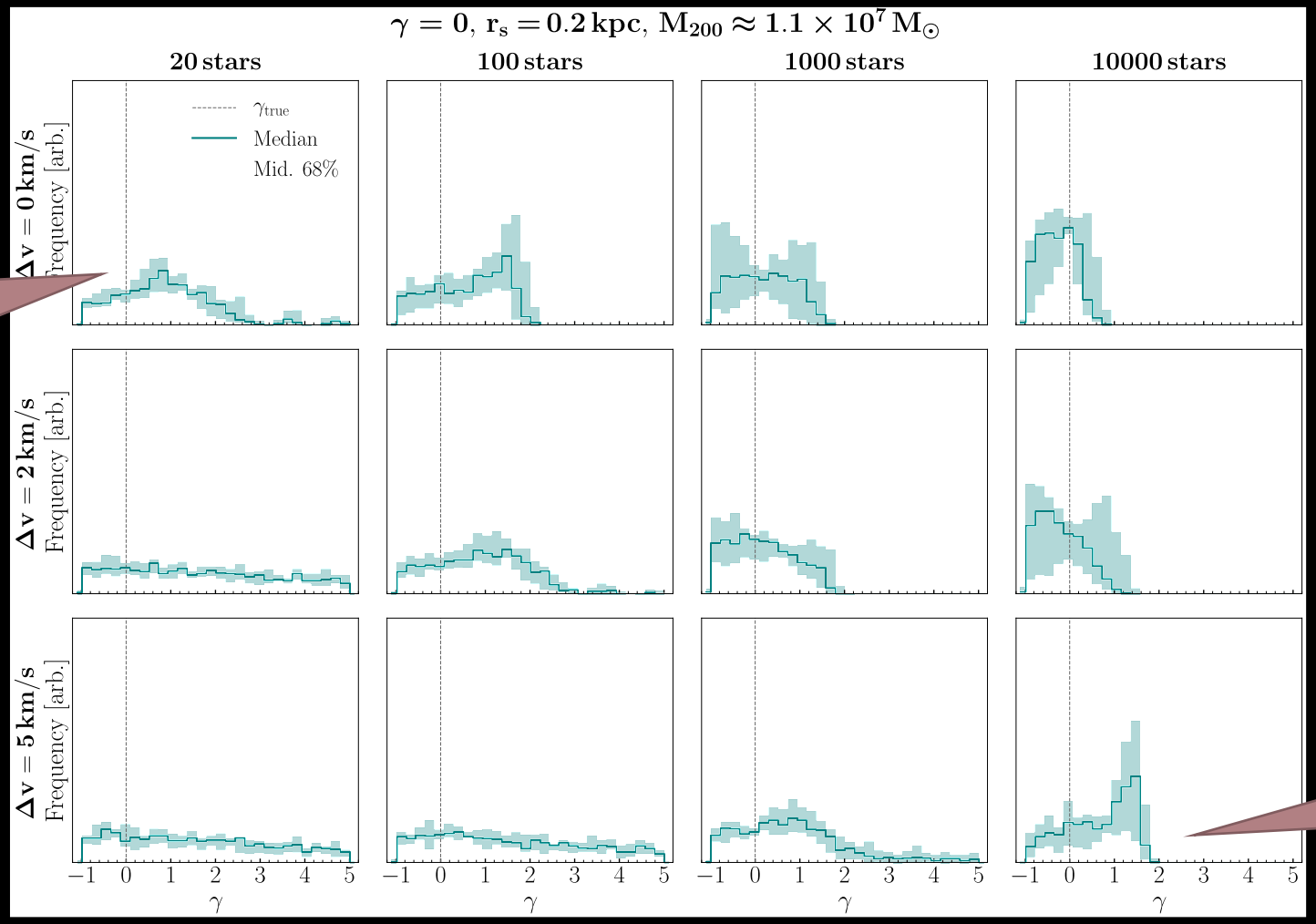
Cusp: $\gamma = 1$
Core: $\gamma = 0$

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

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

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:

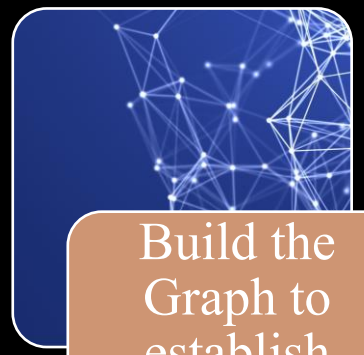
Goal: Build a method where we can get the correct inner density profile of Dark Matter.

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.

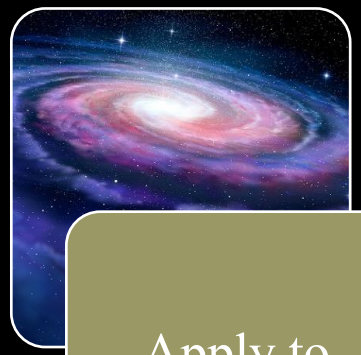
WE USE SIMULATION-BASED INFERENCE TO OBTAIN THE INNER PROFILE OF THE DARK MATTER FROM THE KINEMATICS OF THE STARS

Generate Idealized Simulations



Build the Graph to establish relationships between the stars

Train the Network



Apply to data

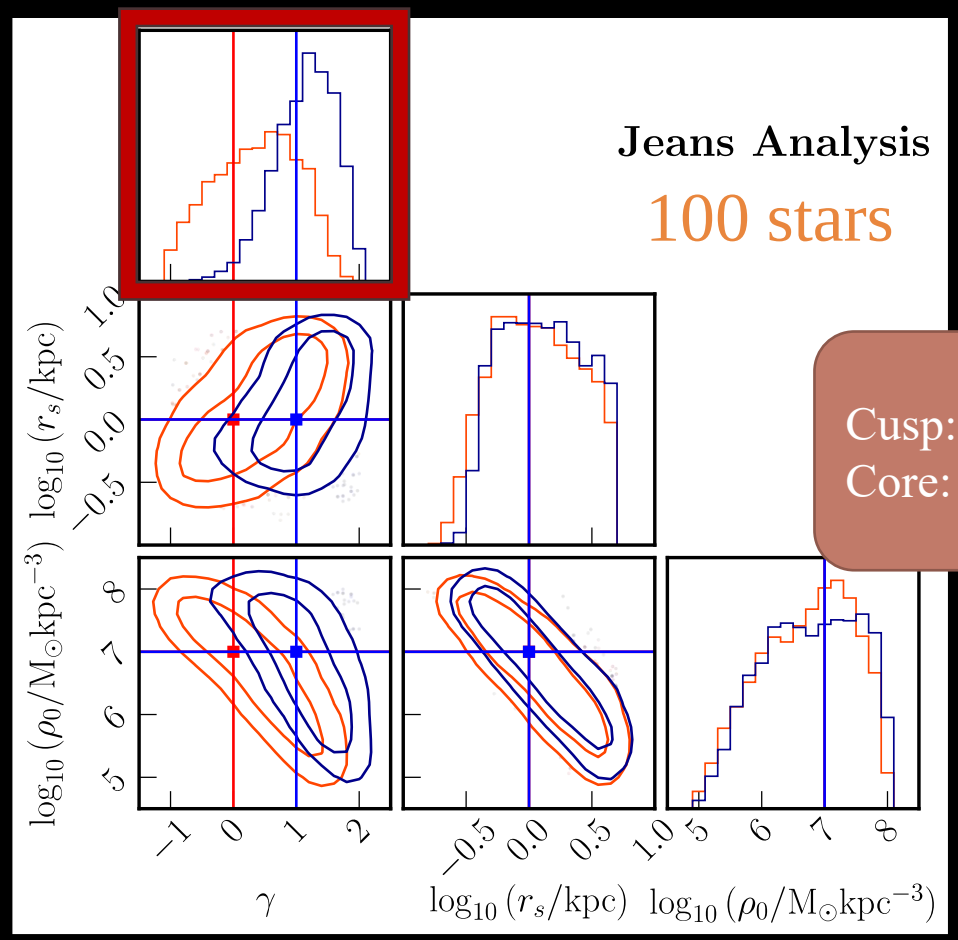
Use Normalizing Flow to obtain a posterior distribution

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

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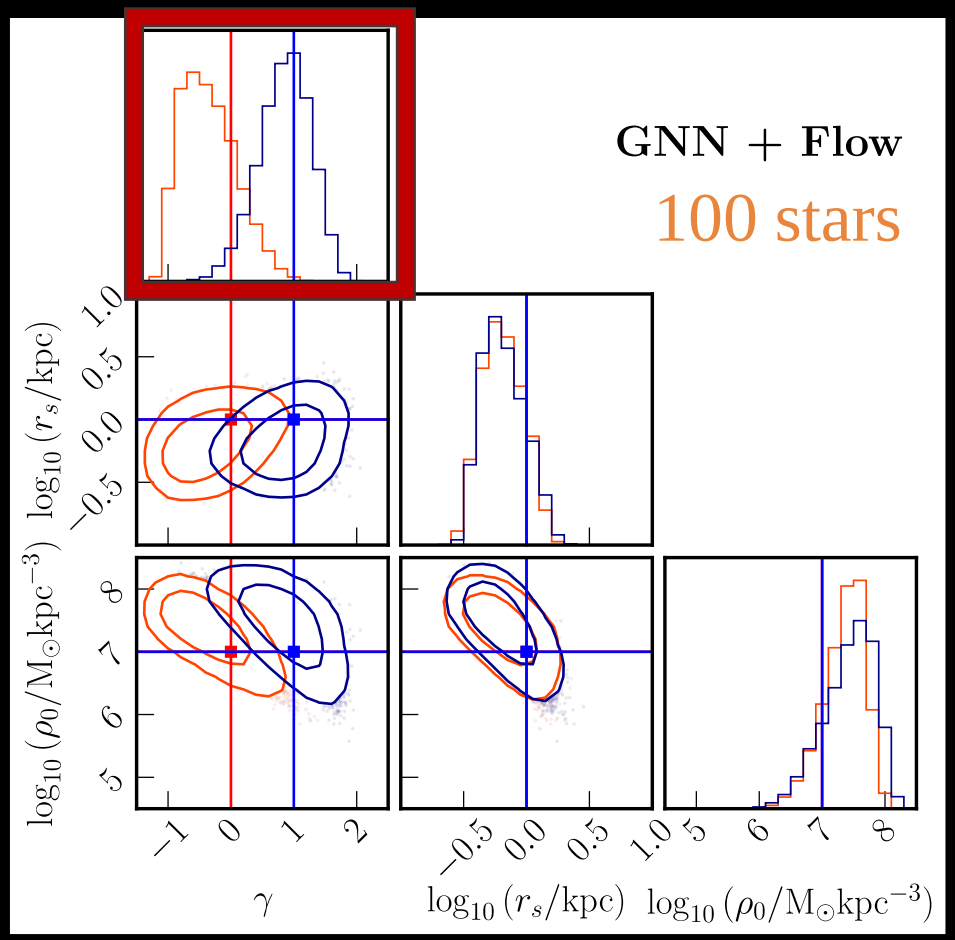

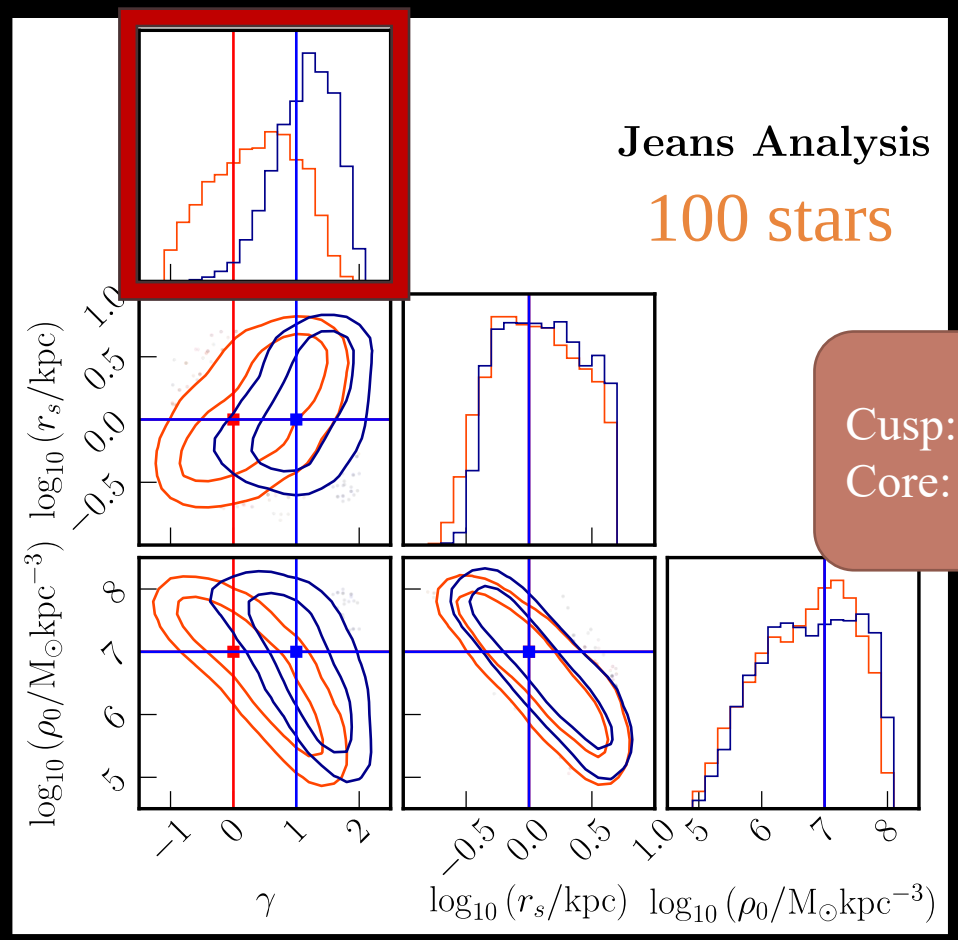

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GNN + NORMALIZING FLOWS OUTPERFORMS JEANS ANALYSIS

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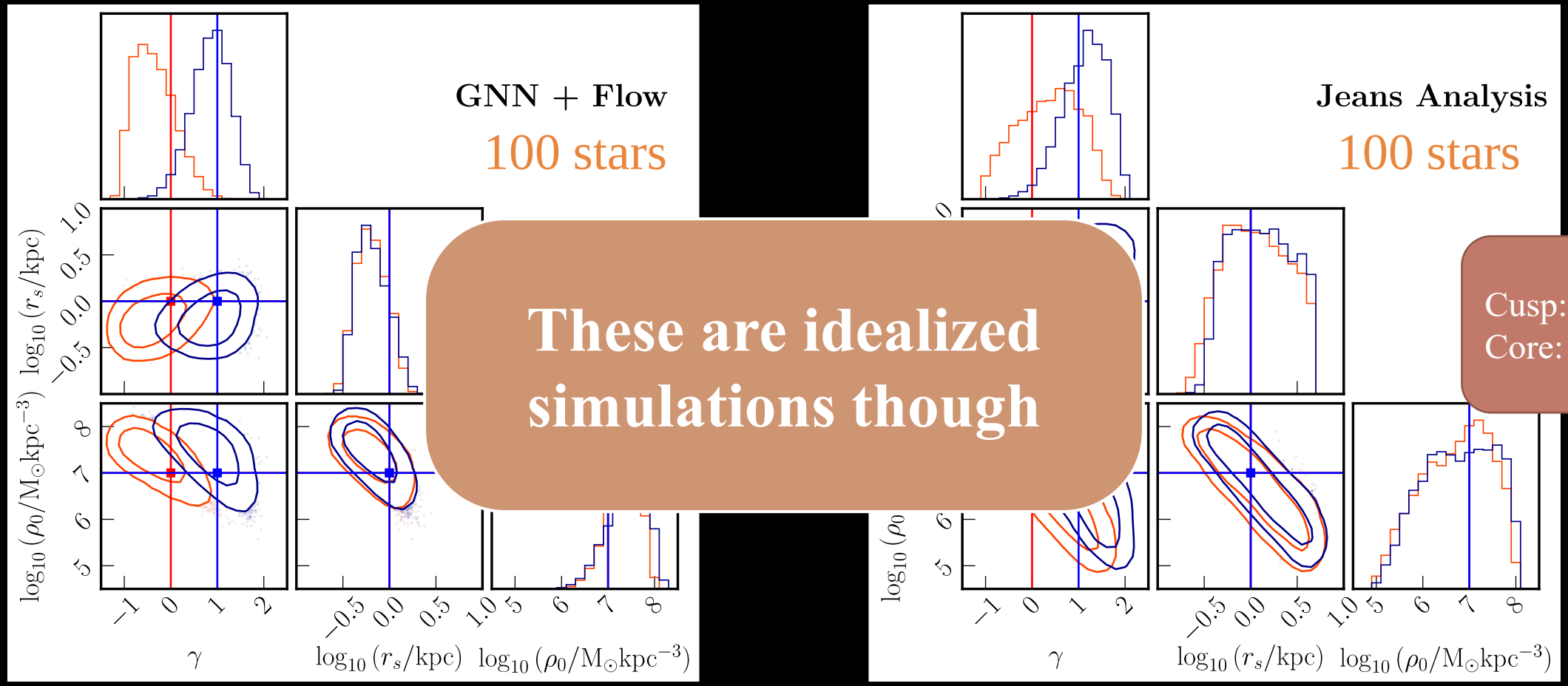

These are idealized simulations though

Cusp: $\gamma = 1$
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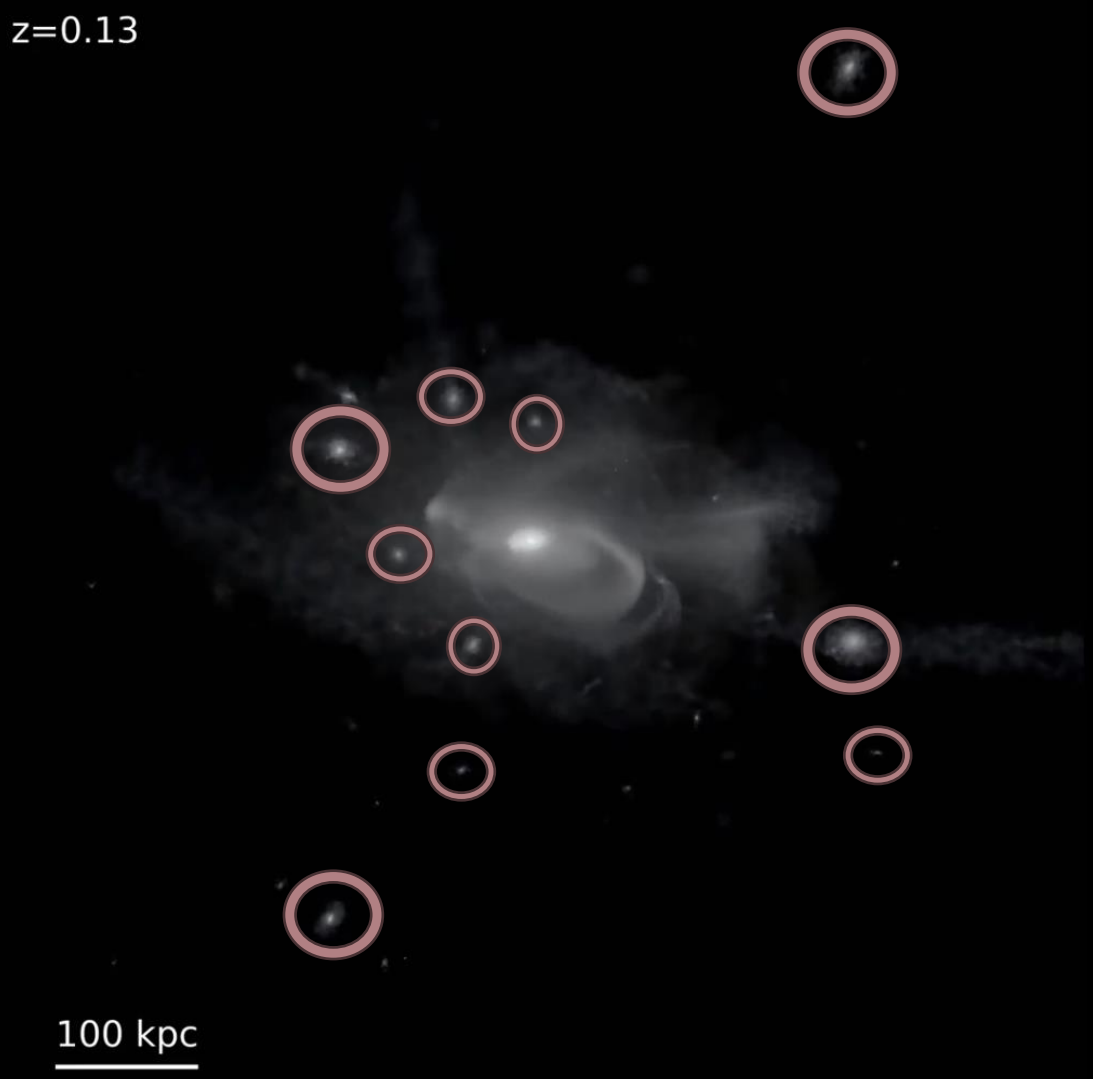
Lina Necib, MIT

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

Tri Nguyen



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

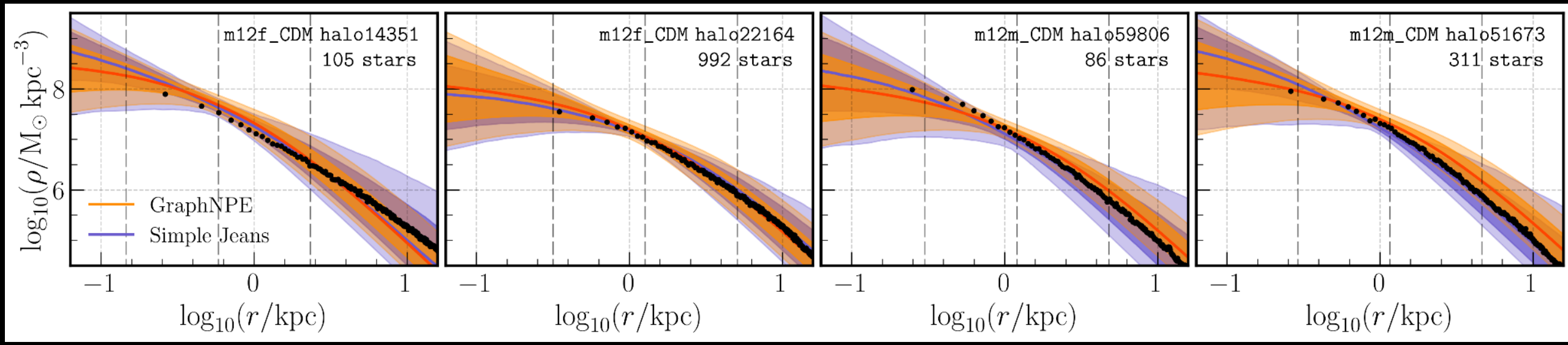
Lina Necib, MIT

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)
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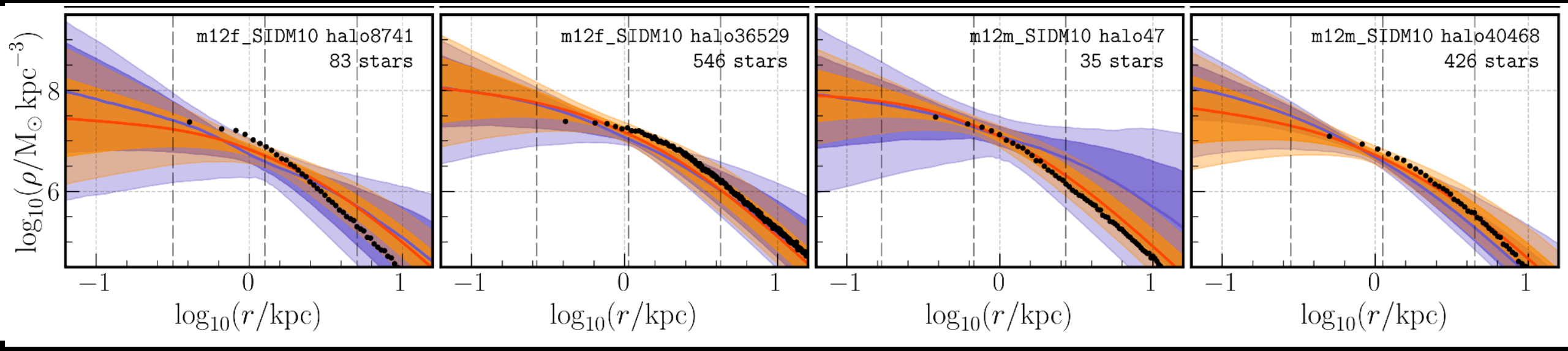

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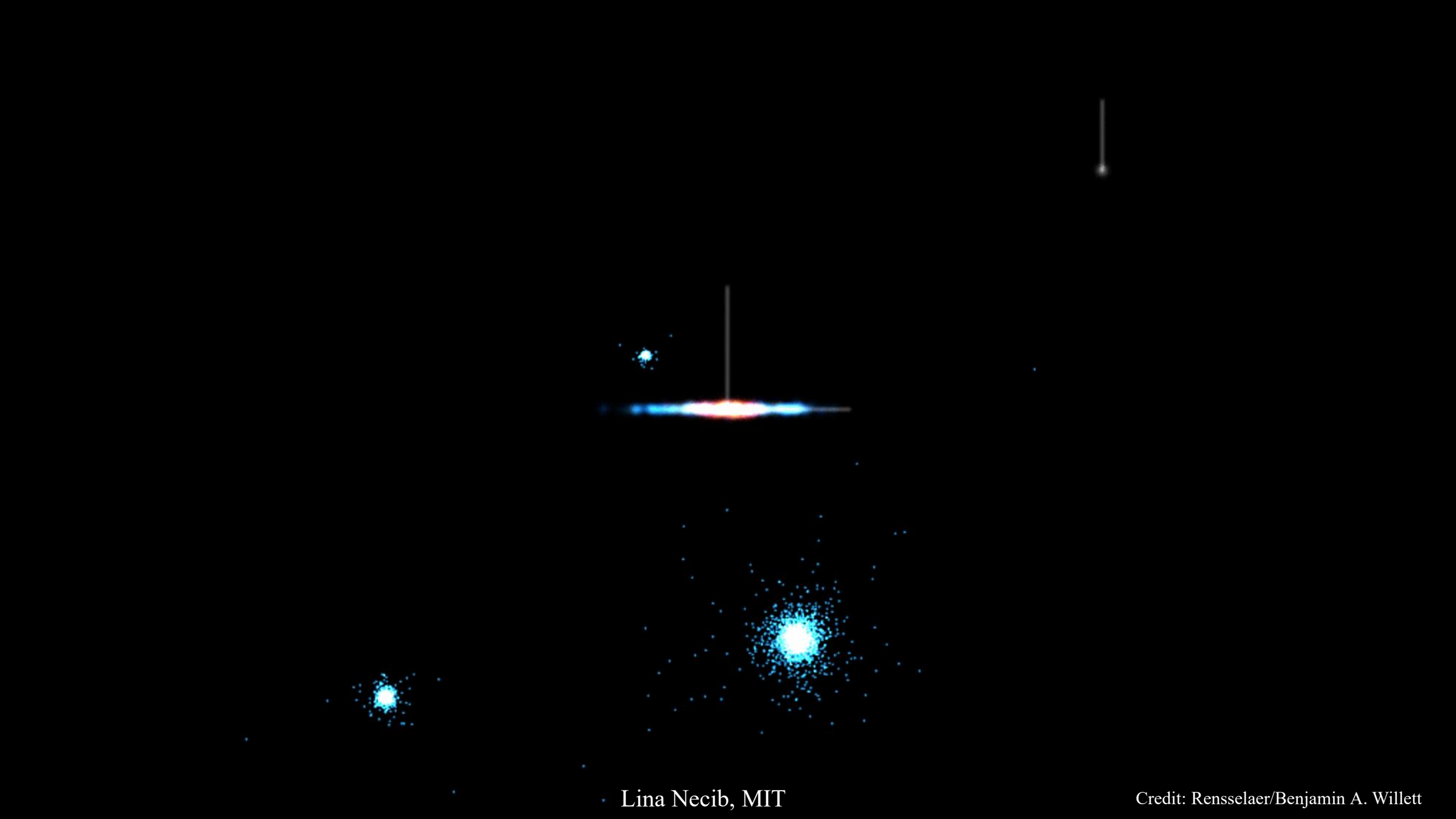
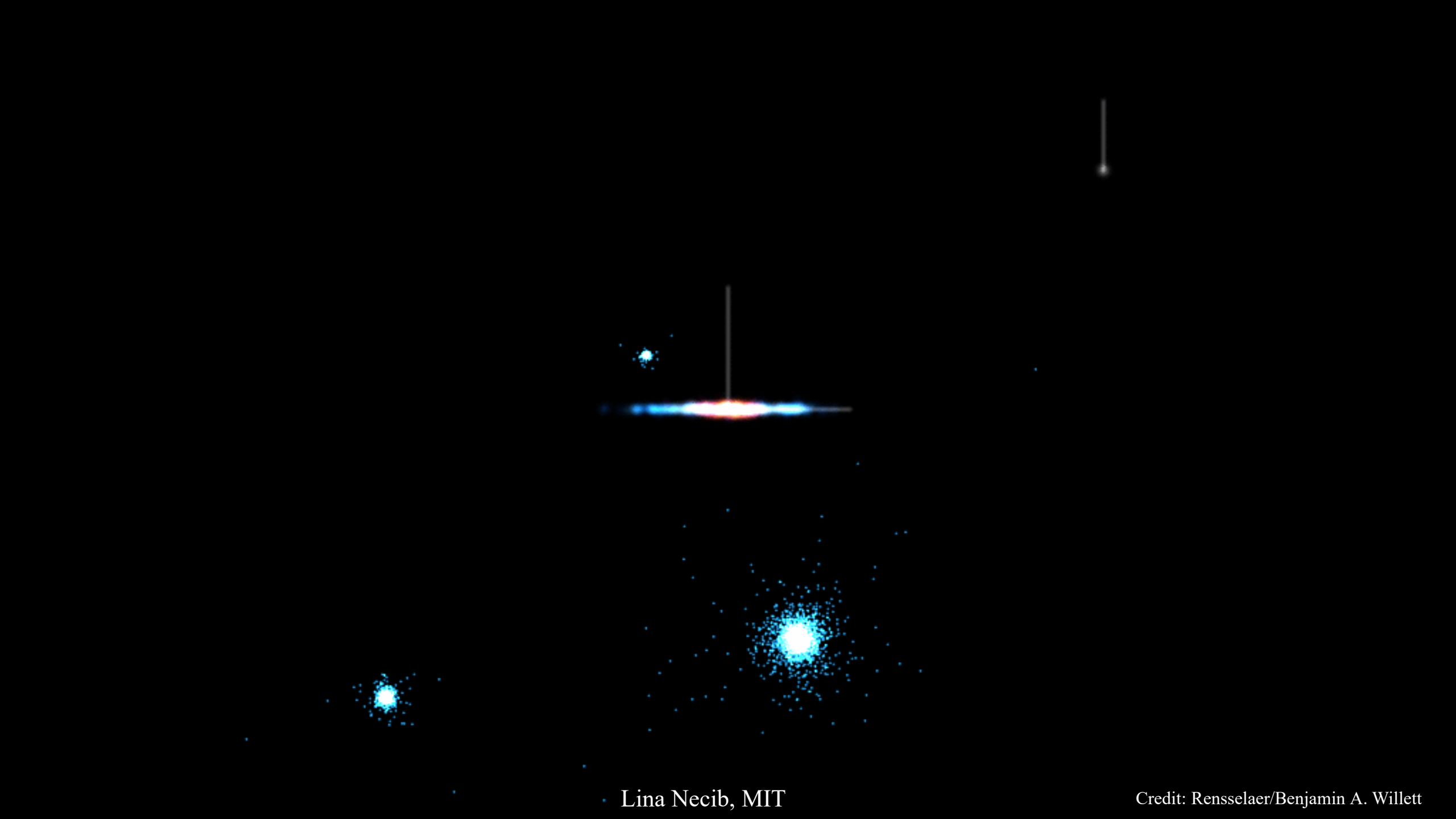


Lina Necib, MIT

Credit: Rensselaer/Benjamin A. Willett



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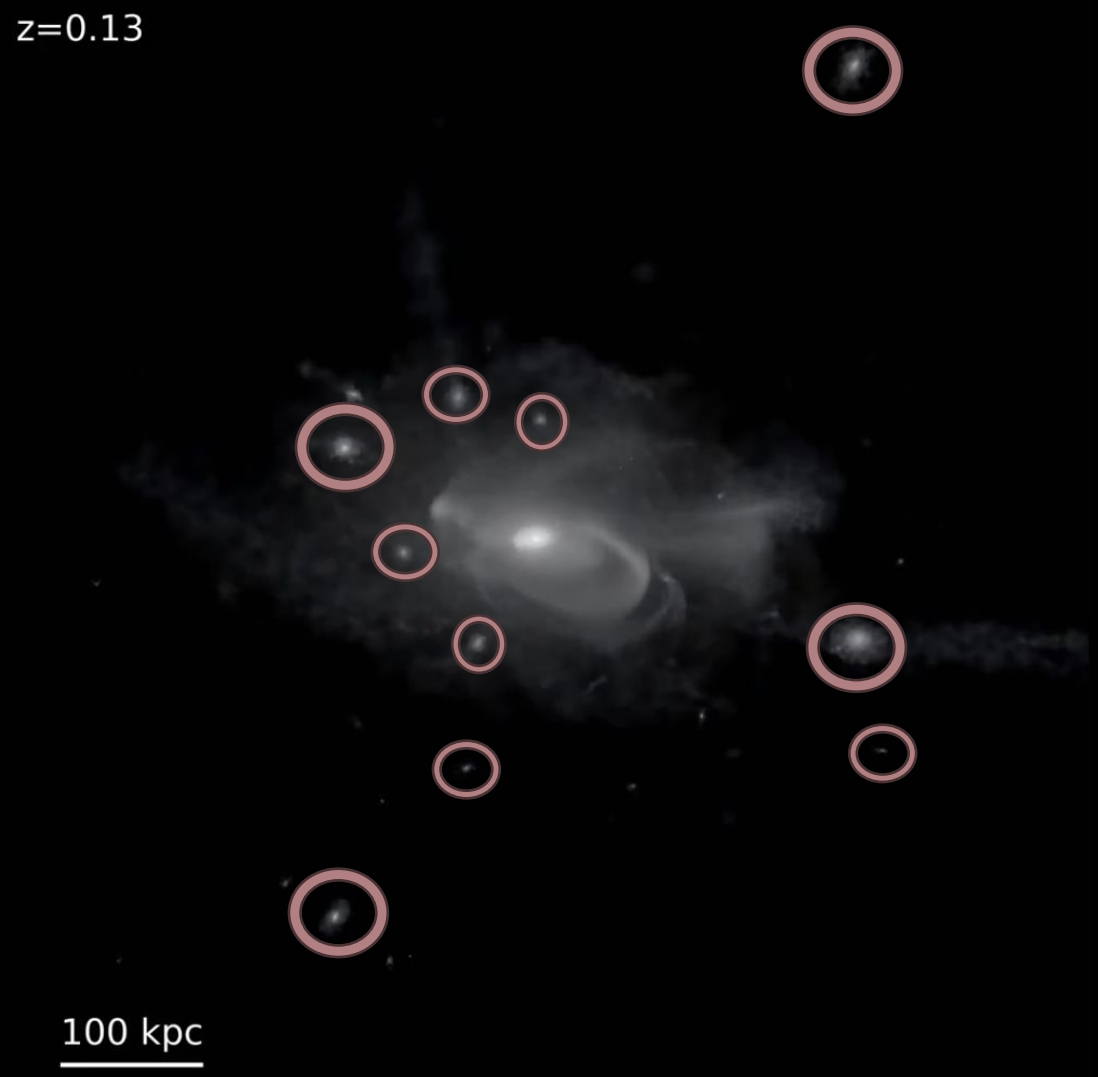
Nora Shipp



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

Lina Necib, MIT

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Credit: Hernan Stockebrand

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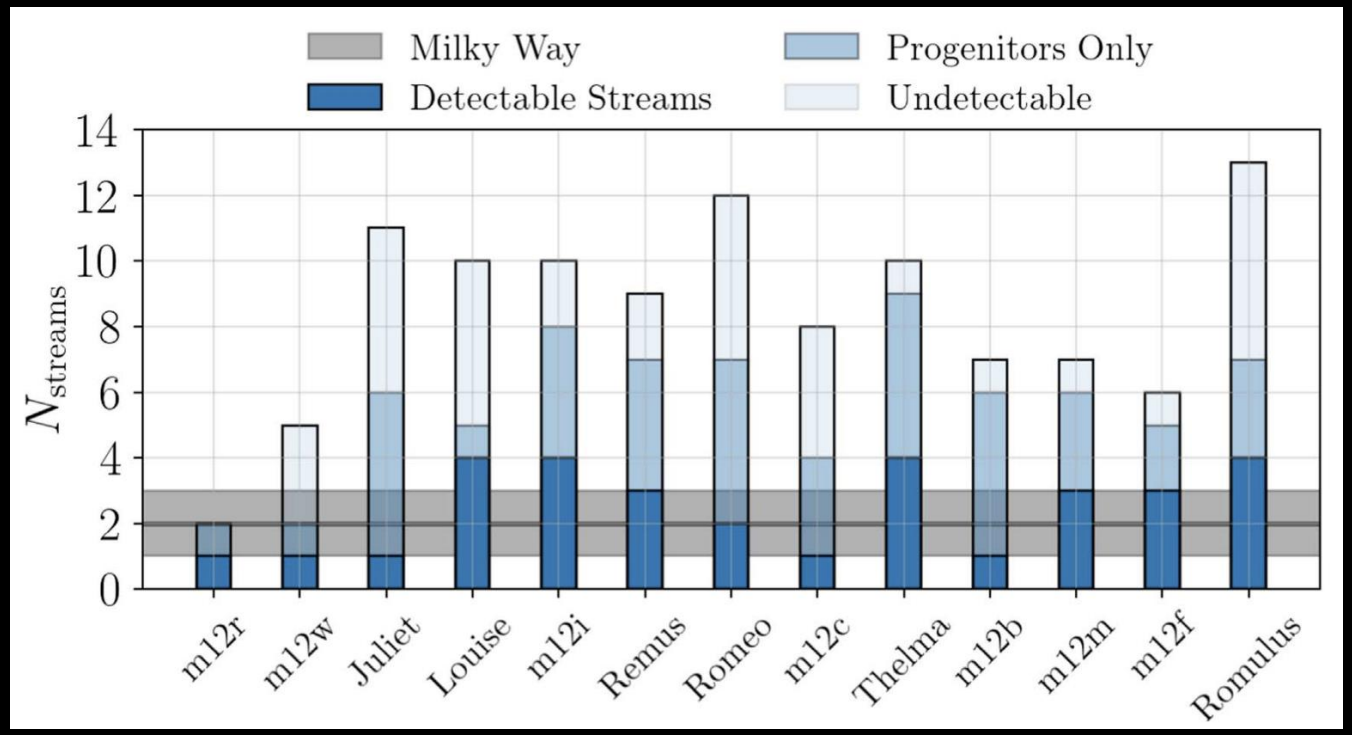
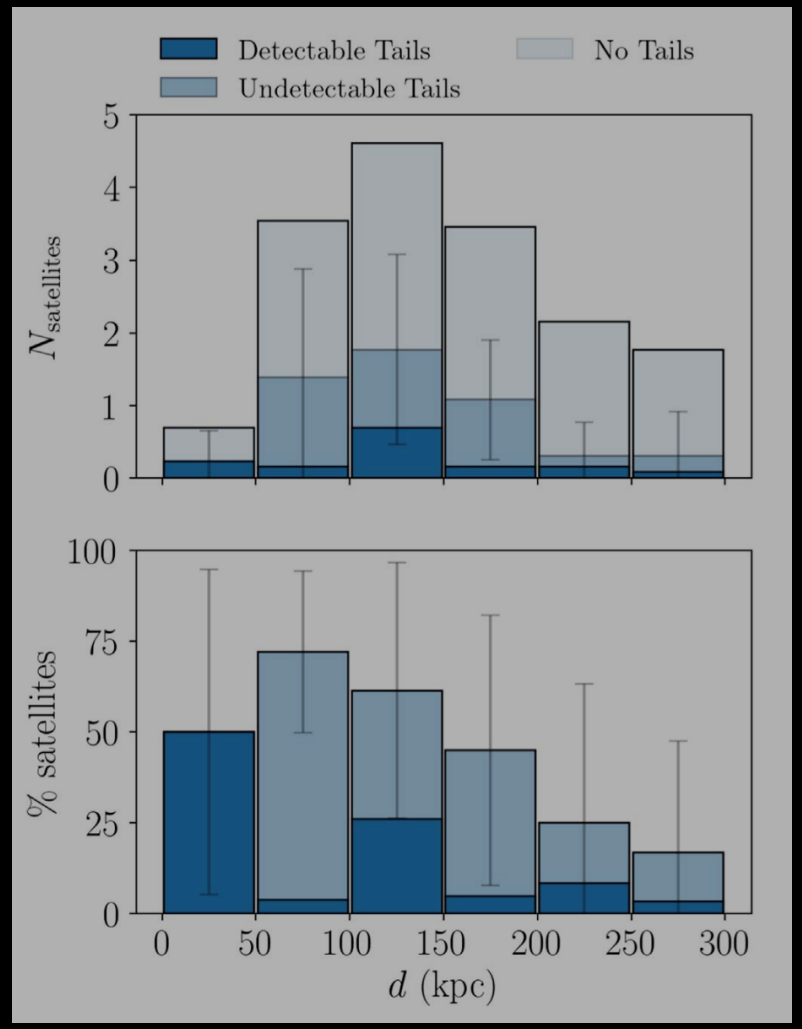
Credit: Hernan Stockebrand

Lina Necib, MIT

MOST SIMULATED MILKY WAYS CONTAIN STELLAR STREAMS WHERE WE WOULD ONLY DETECT THE PROGENITOR

Nora Shipp

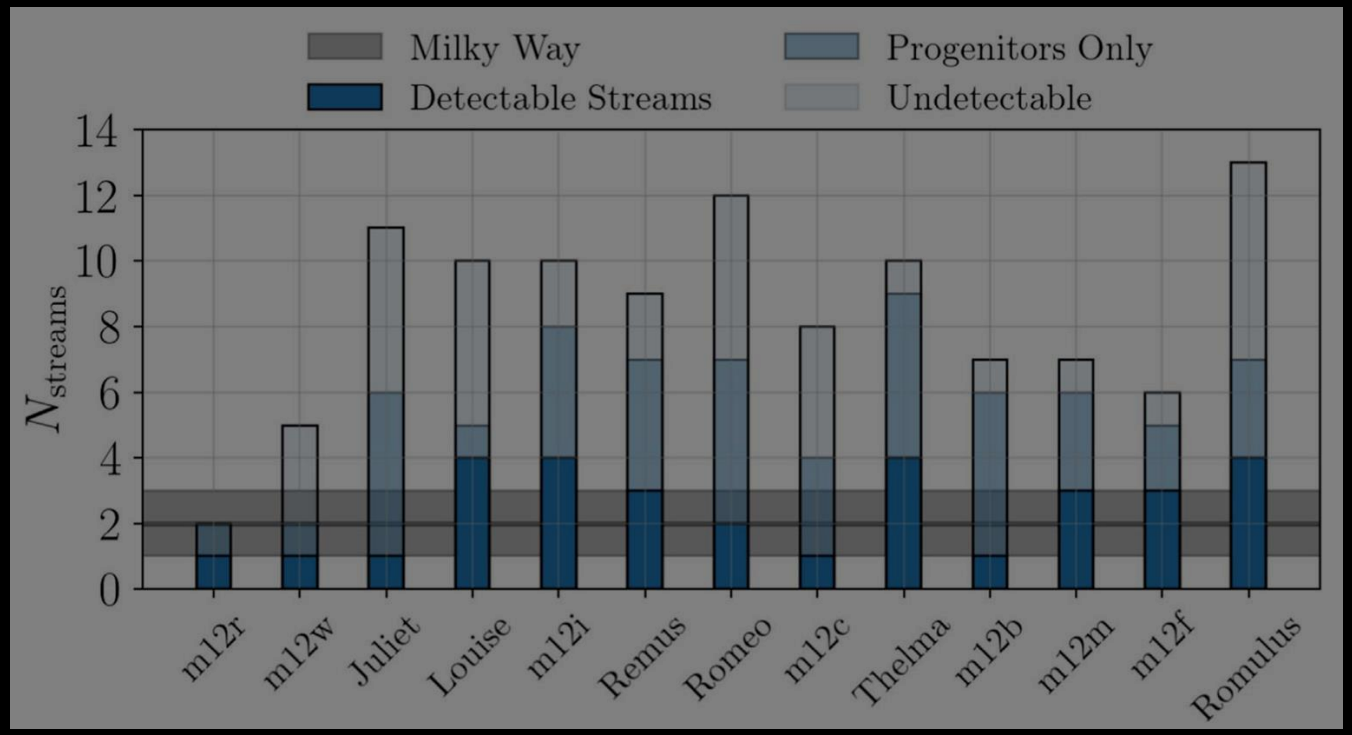


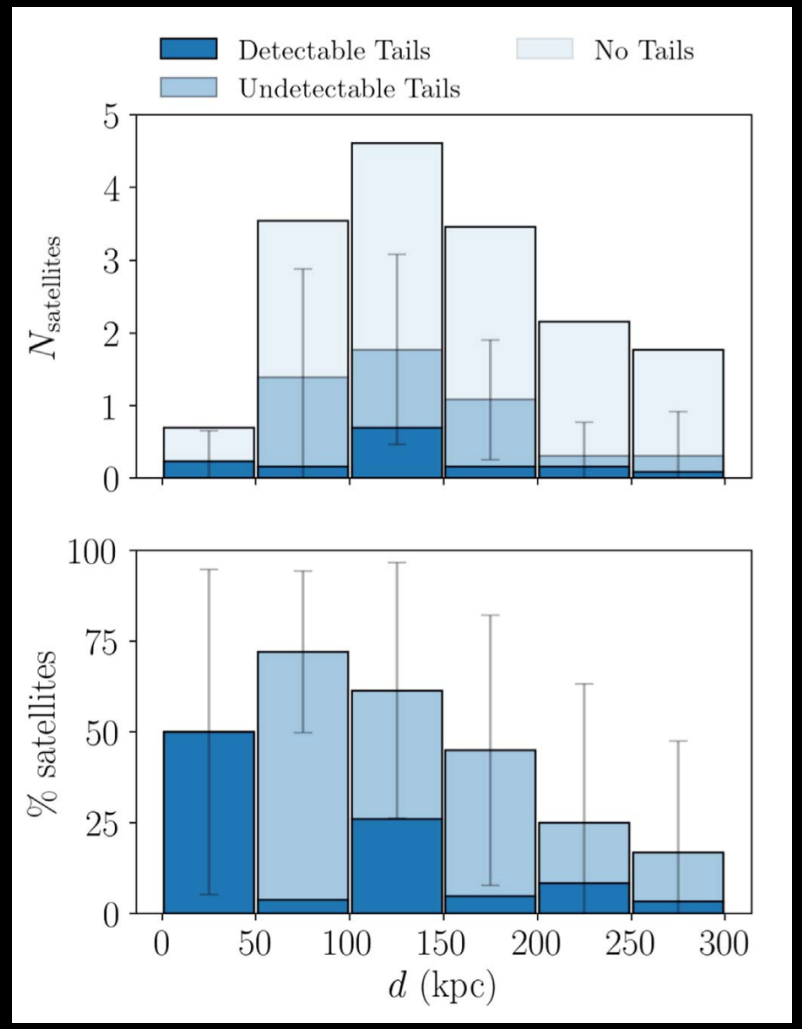


Shipp, Panithanpaisal, **Necib**, et al. (2023)
Shipp, Riley, …, **Necib**, et al. (2024)

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

Nora Shipp





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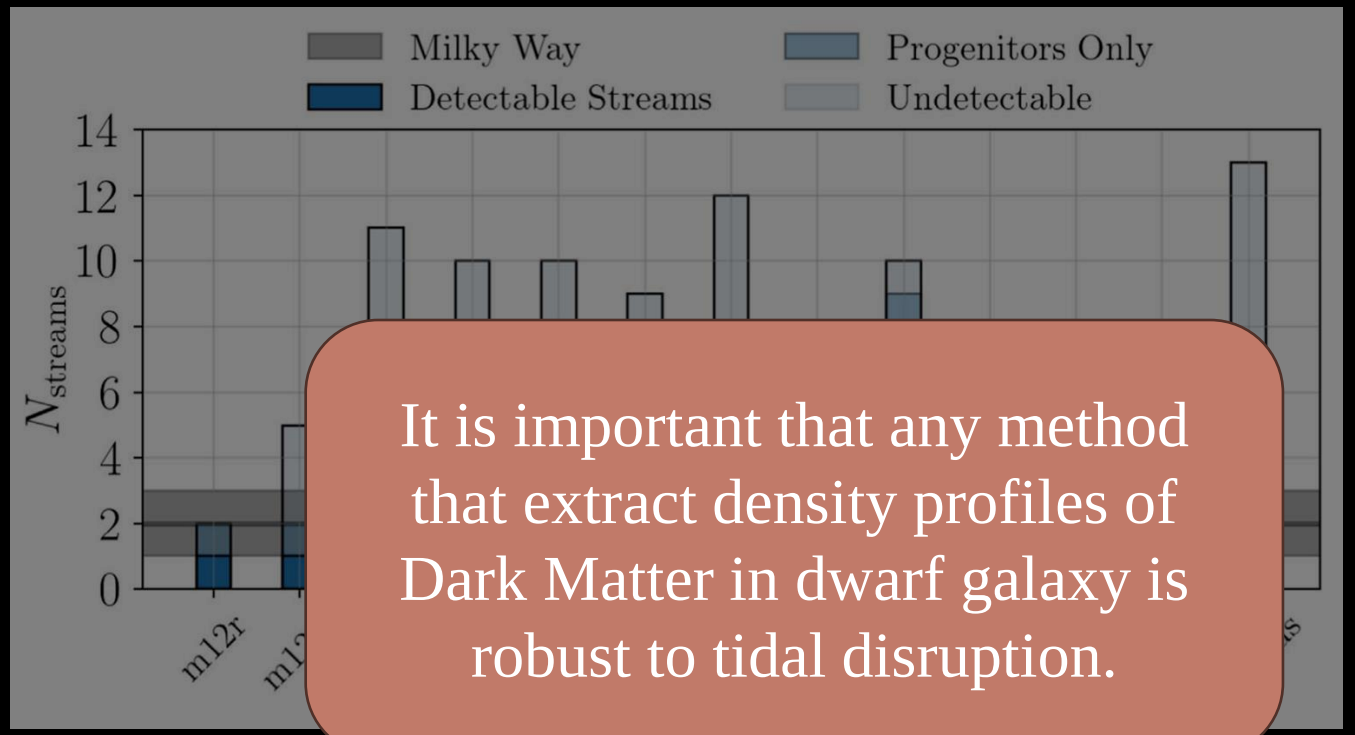
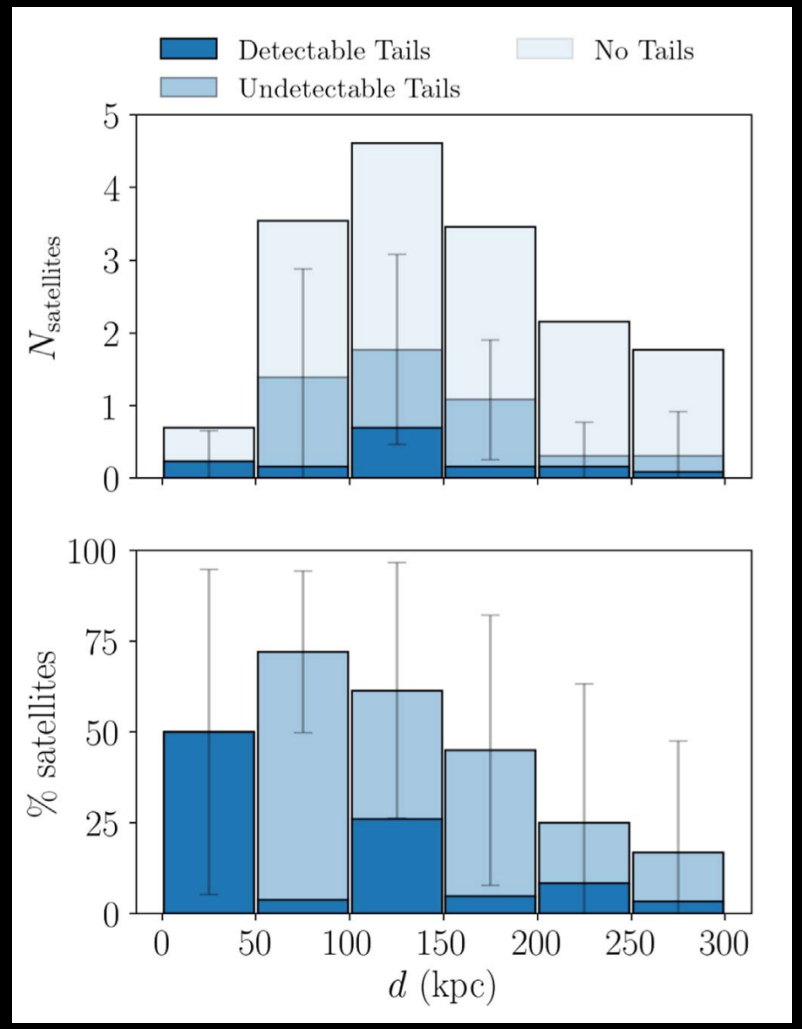


It is important that any method that extract density profiles of Dark Matter in dwarf galaxy is robust to tidal disruption.



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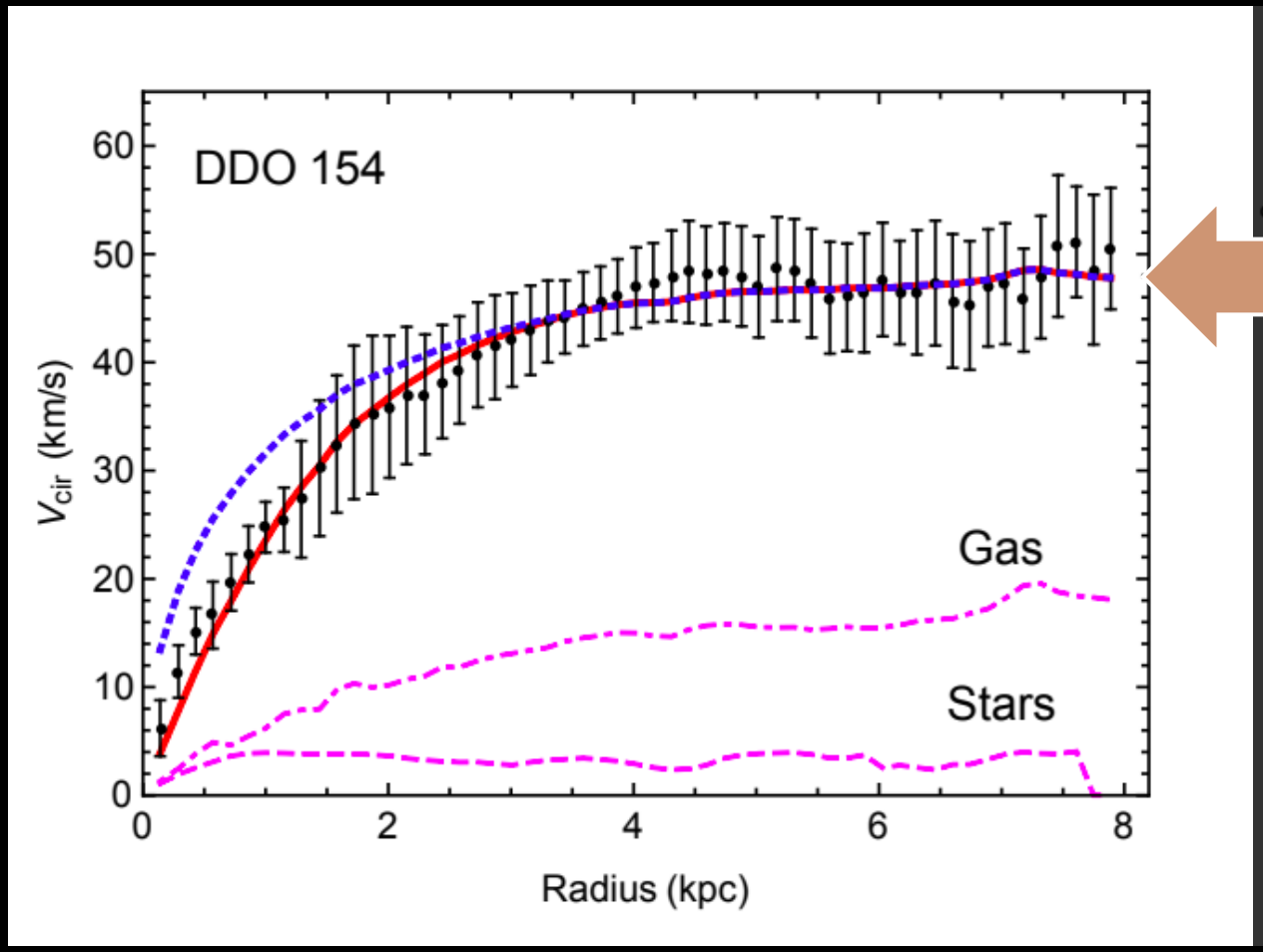
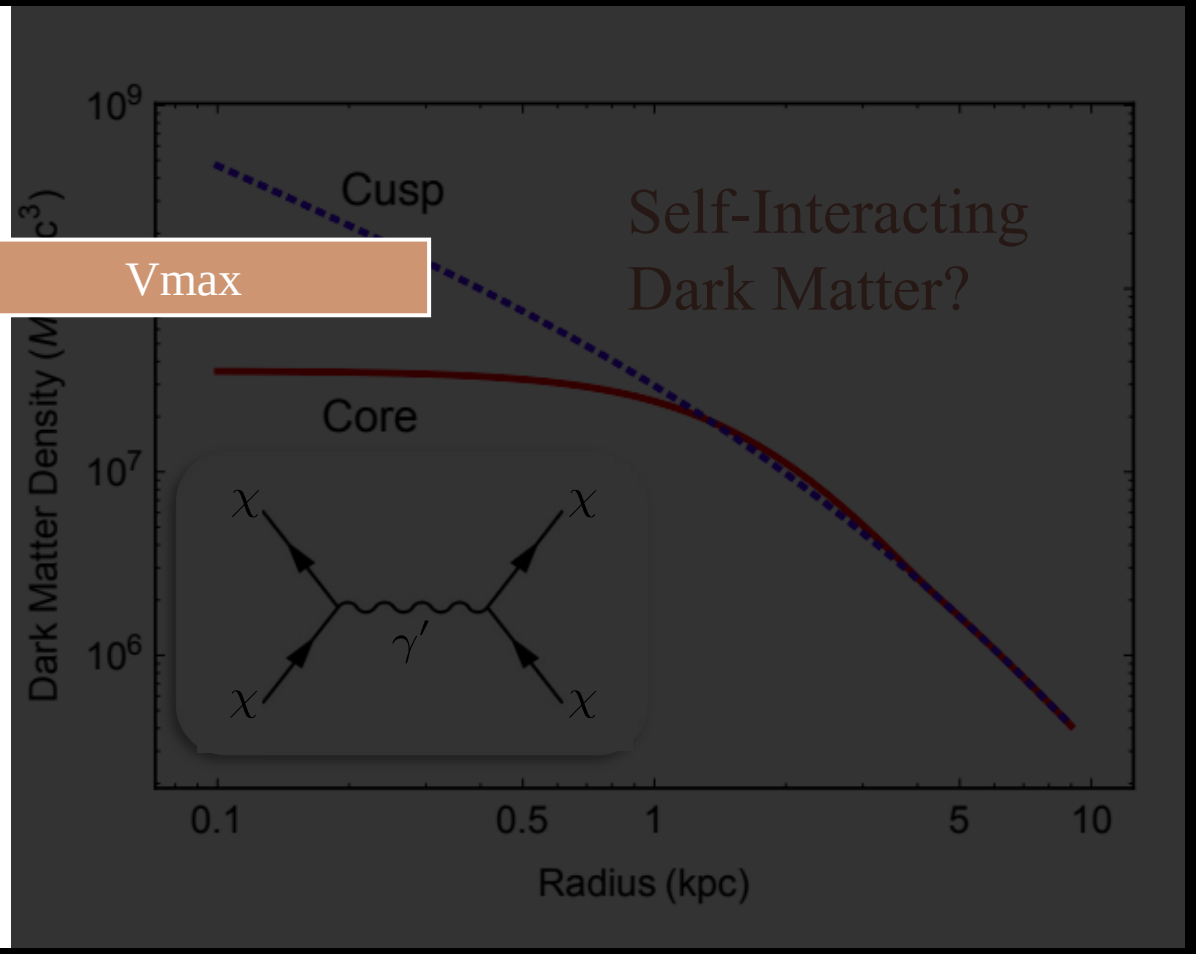


Vmax



Lina Necib, MIT

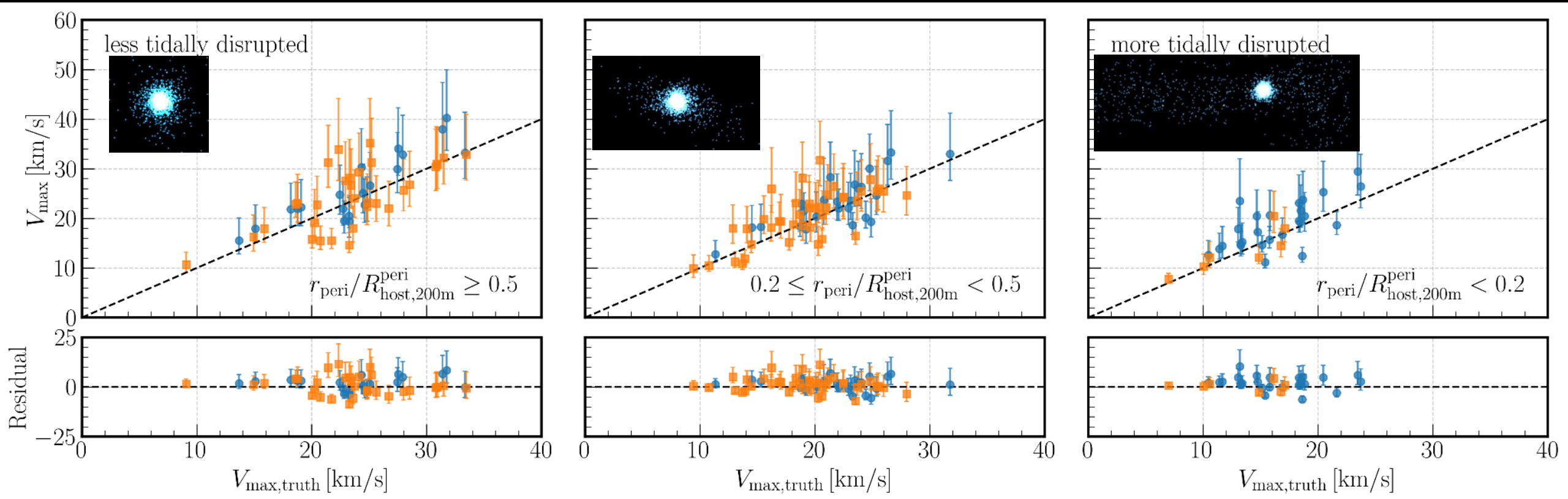
Spergel & Steinhardt (2000)

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

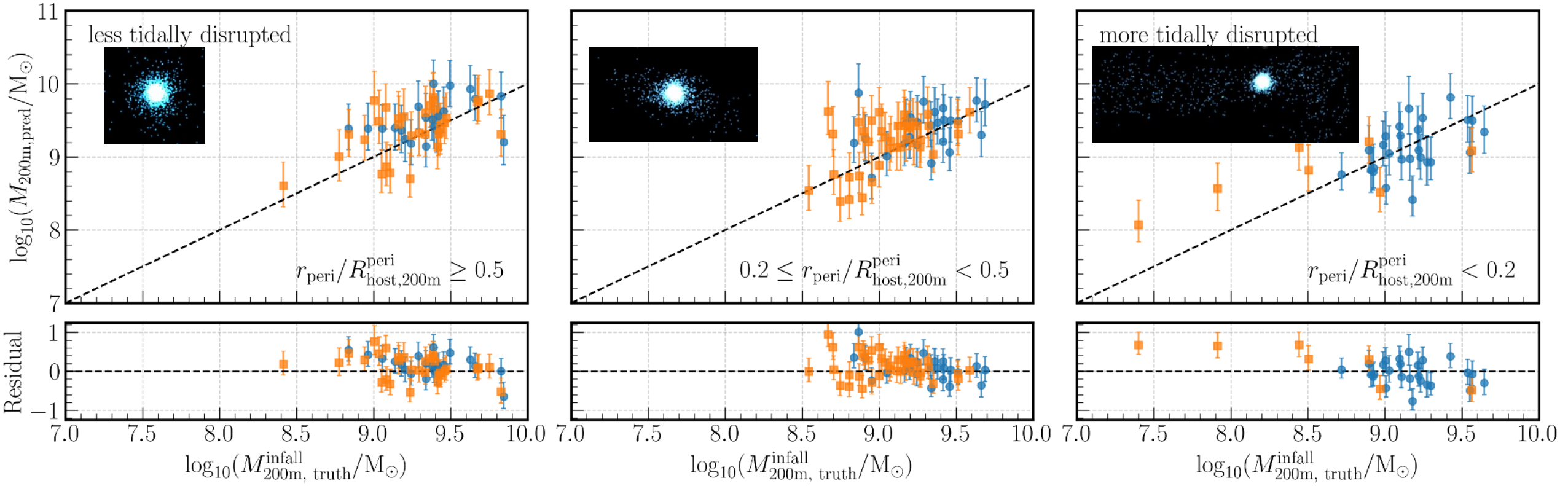
Nguyen, Read, **Necib**, et al. (2025)

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

Tri Nguyen

SIDM

CDM



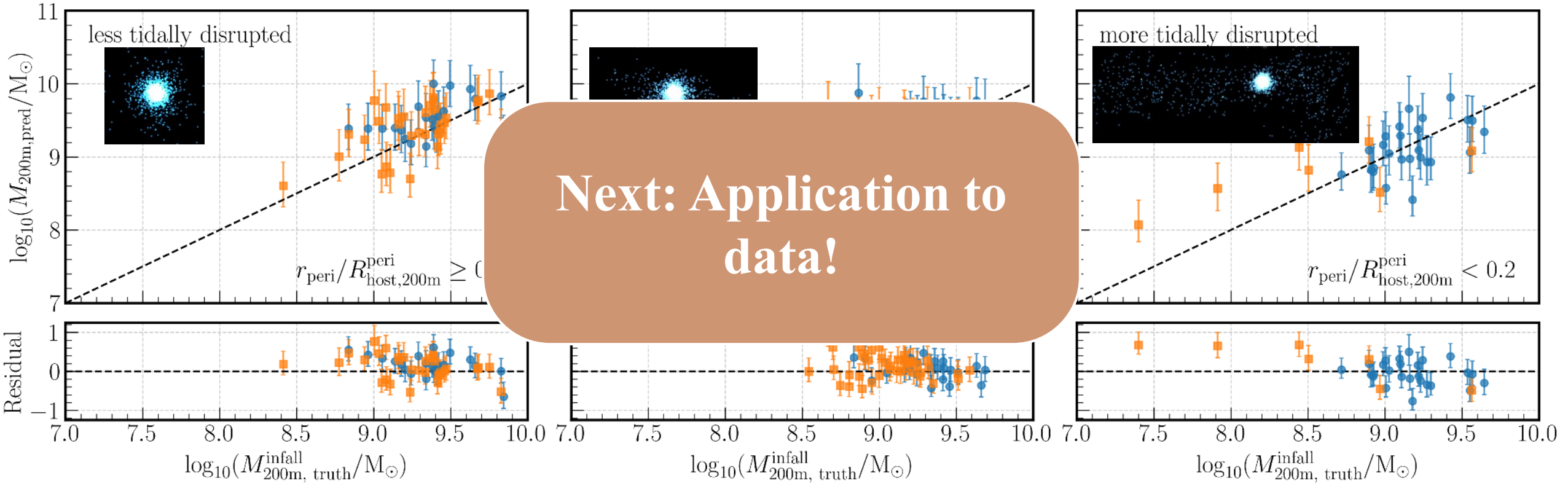
Lina Necib, MIT

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

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

Tri Nguyen

SIDM CDM

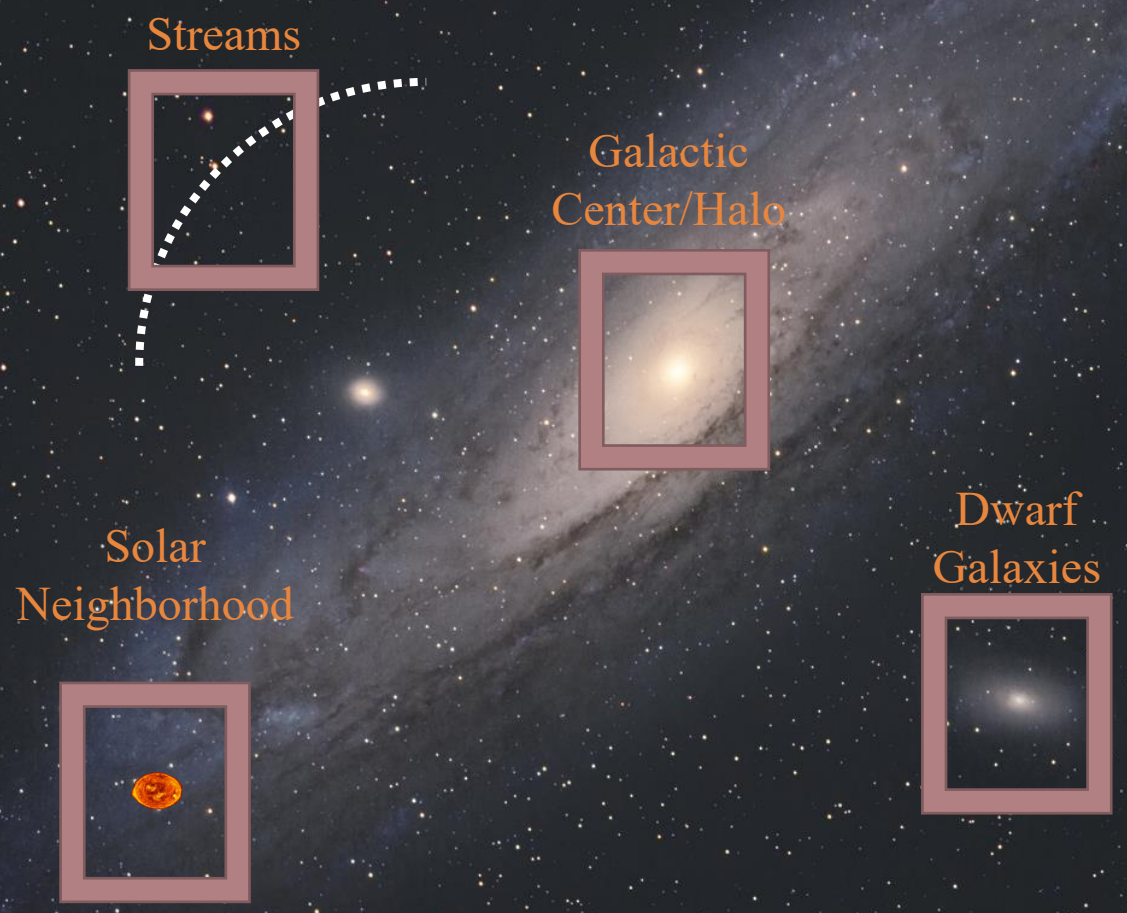


Next: Application to data!

Lina Necib, MIT

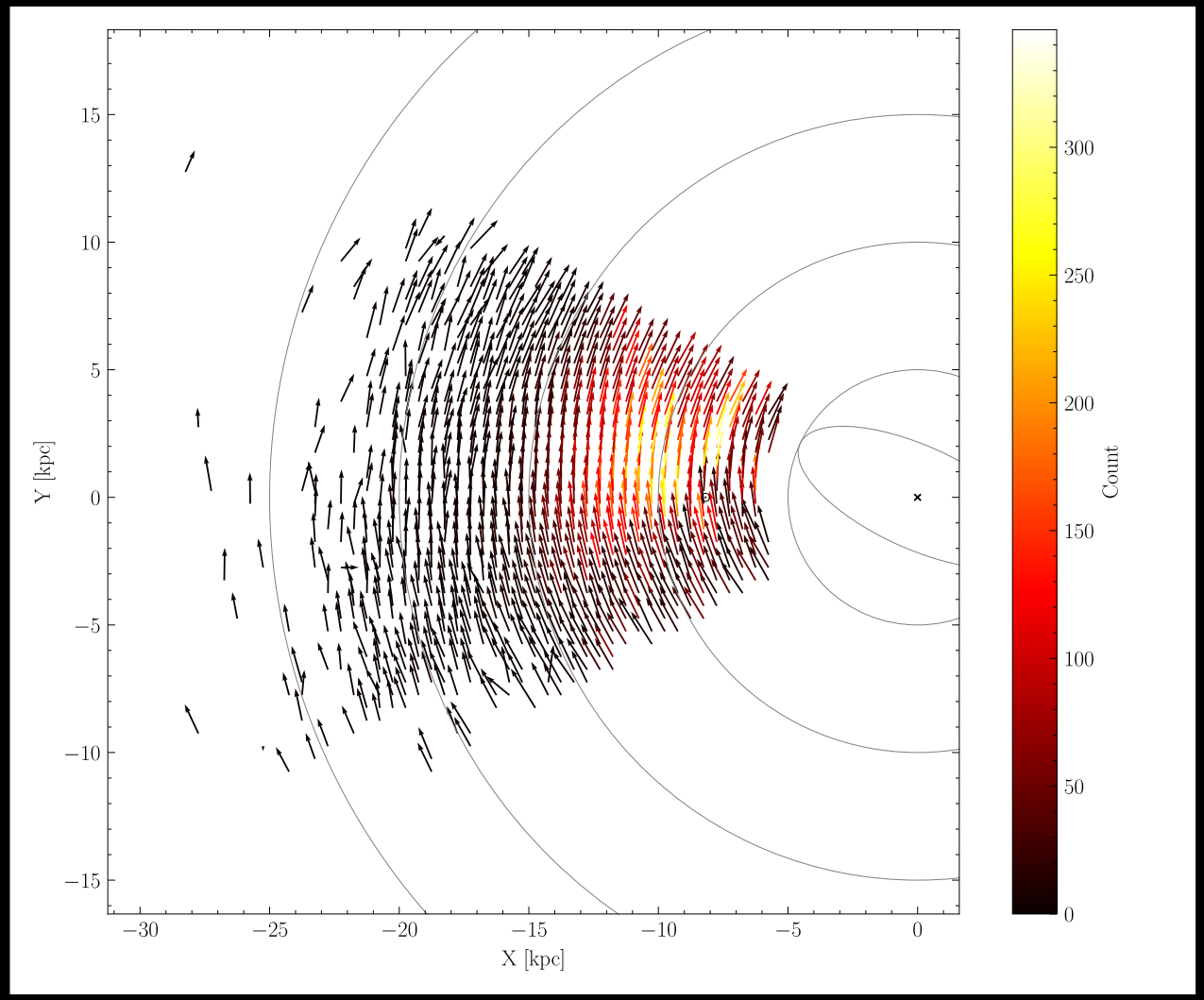
Nguyen, Read, **Necib**, et al. (2025)

GOAL:
MAPPING FROM THE STARS TO THE DARK MATTER



GOAL:
MAPPING FROM THE STARS TO THE DARK MATTER

Thank you!



NEED MORE ACCURATE DISTANCES THAN THOSE PROVIDED BY GAIA.

Build a completely data-driven model, that assumes that the parallax can be described as a linear combination of spectroscopic and photometric information.

$$\varpi_n^{(a)} = \exp\left(\vec{\theta} \cdot \vec{x}_n\right) + \text{noise}.$$

Astrometric Parallax

Coefficients

Photometry + Spectra

Hogg et al. (2019)
Eilers et al. (2019)