Tracing Dark Matter with Stars

Lina Necib

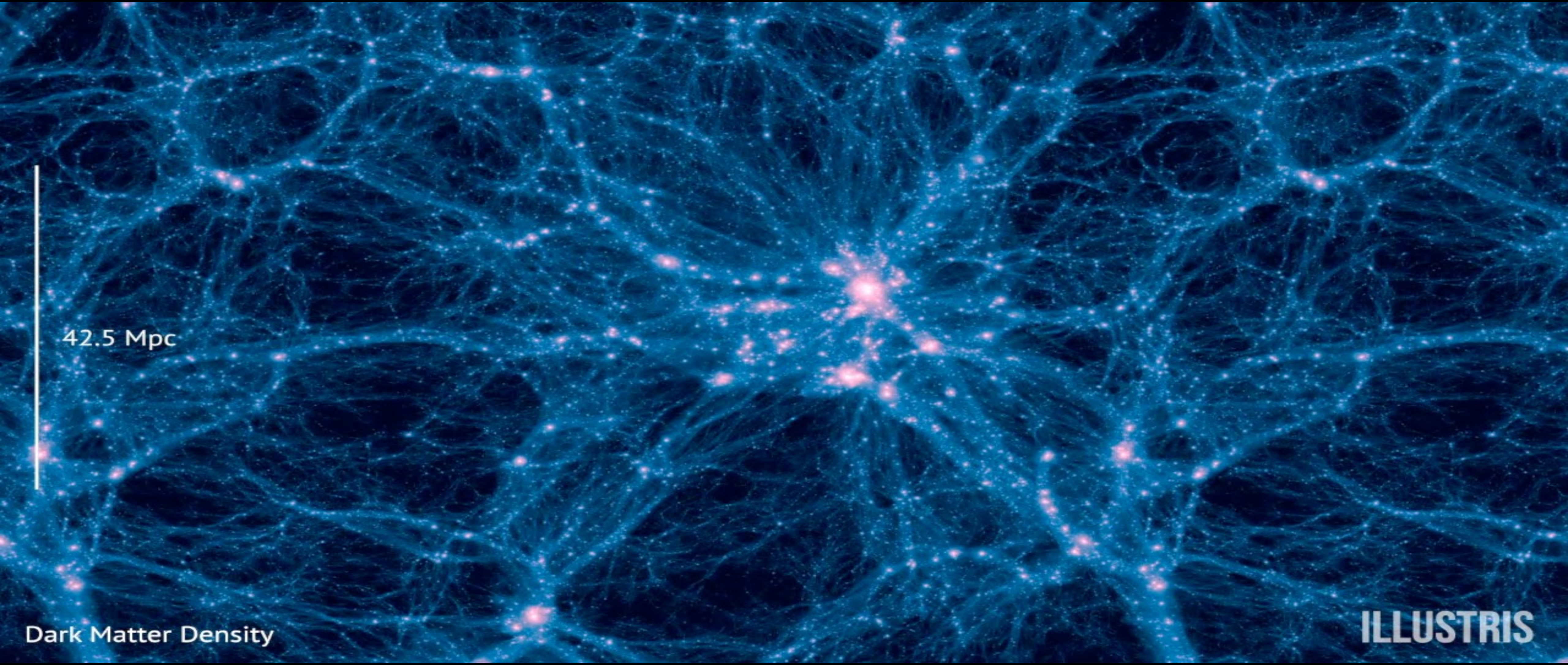
MIT

https://www.cbc.ca/news/technology/faintest-satellite-dwarf-galaxy-milky-way-discovered-virgo-1.3862377

Goal

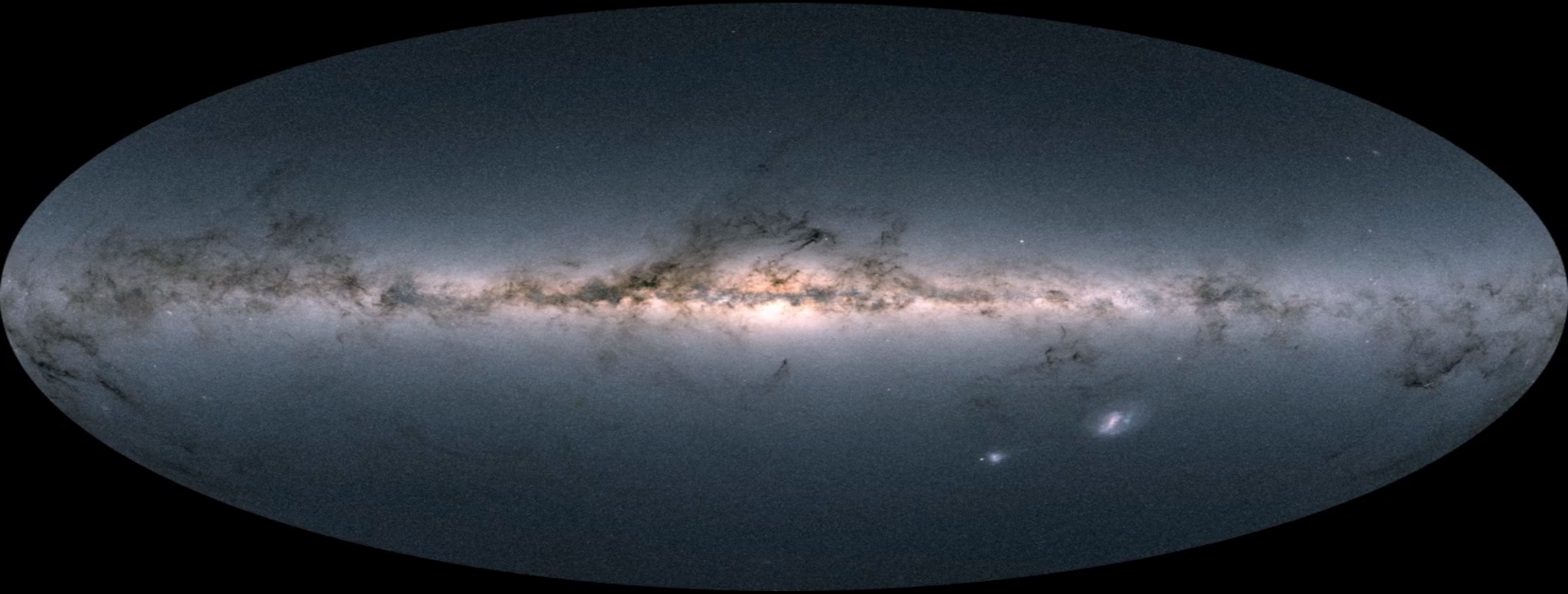
A Local Map of Dark Matter

Simulations



http://www.illustris-project.org

Gaia



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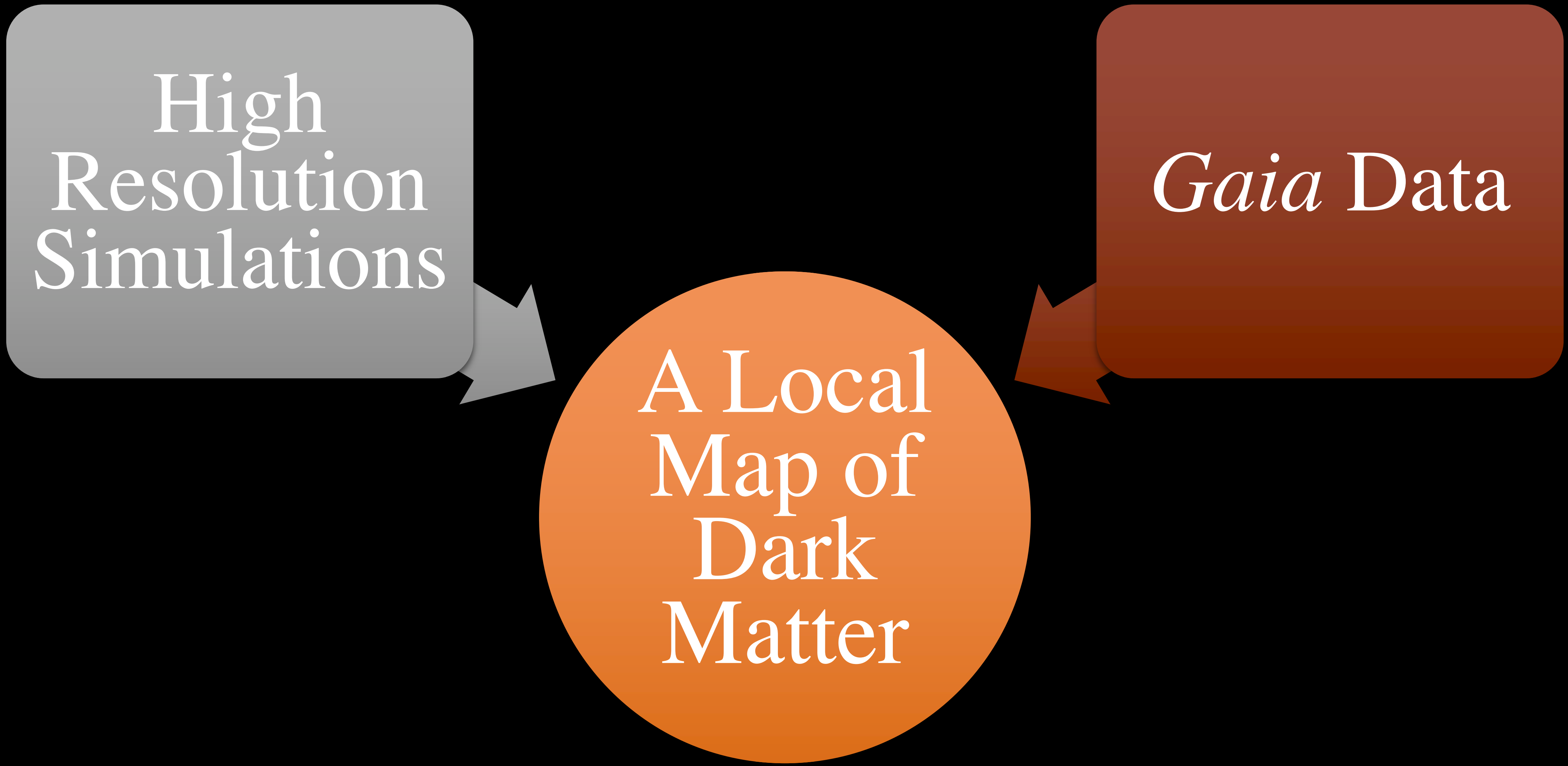
Credit: Gaia Sky; S. Jordan / T. Sagristà


High Resolution Simulations
Gaia Data
A Local Map of Dark Matter

This Talk:

How to map out the Dark Matter phase space distribution on Galactic Scales at key locations.

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

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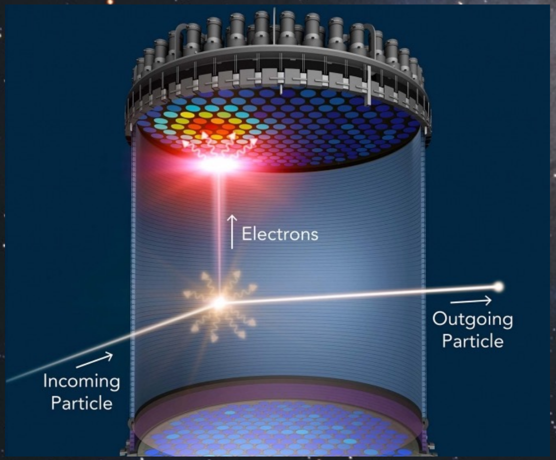

1. Terrestrial Experiments

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

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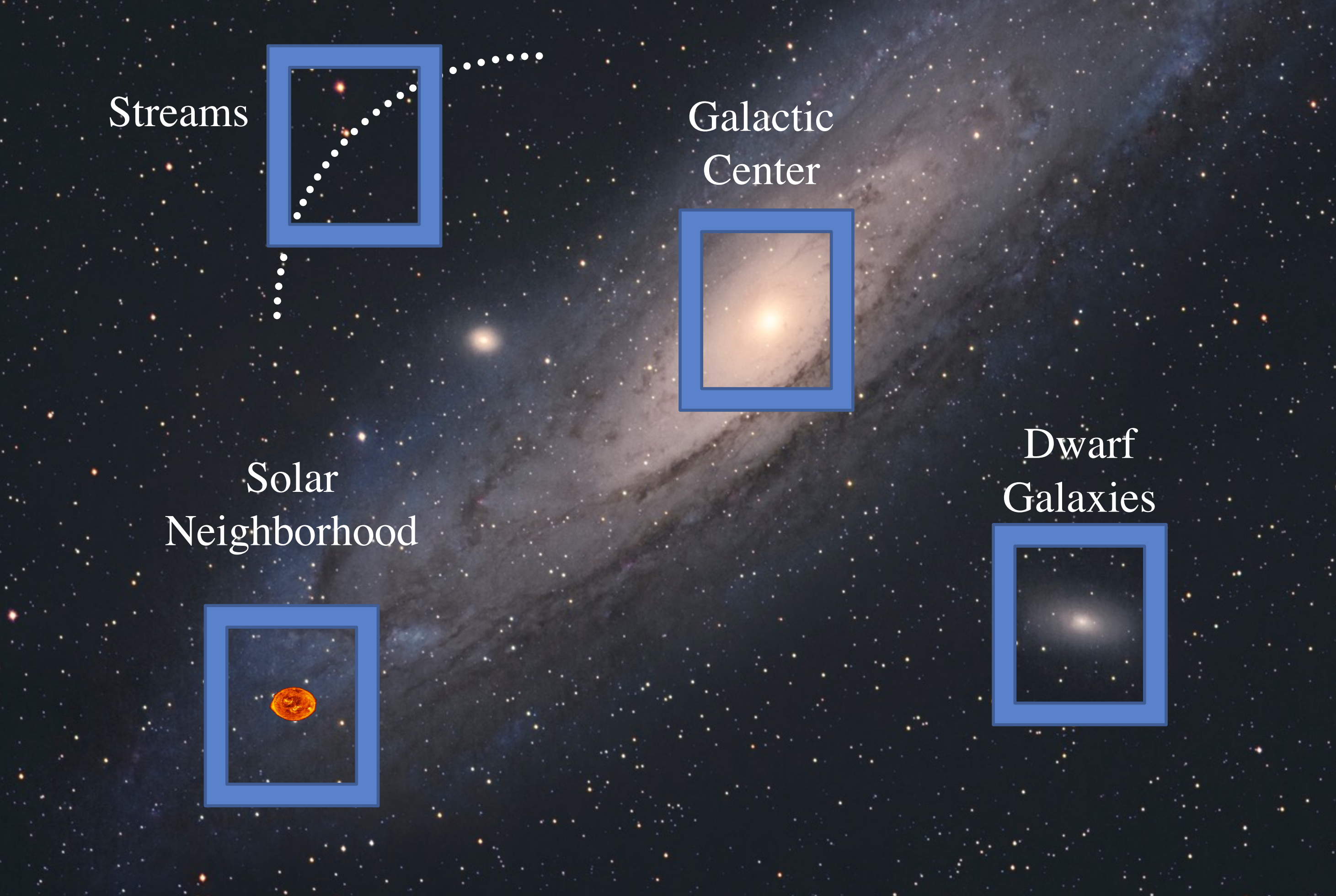

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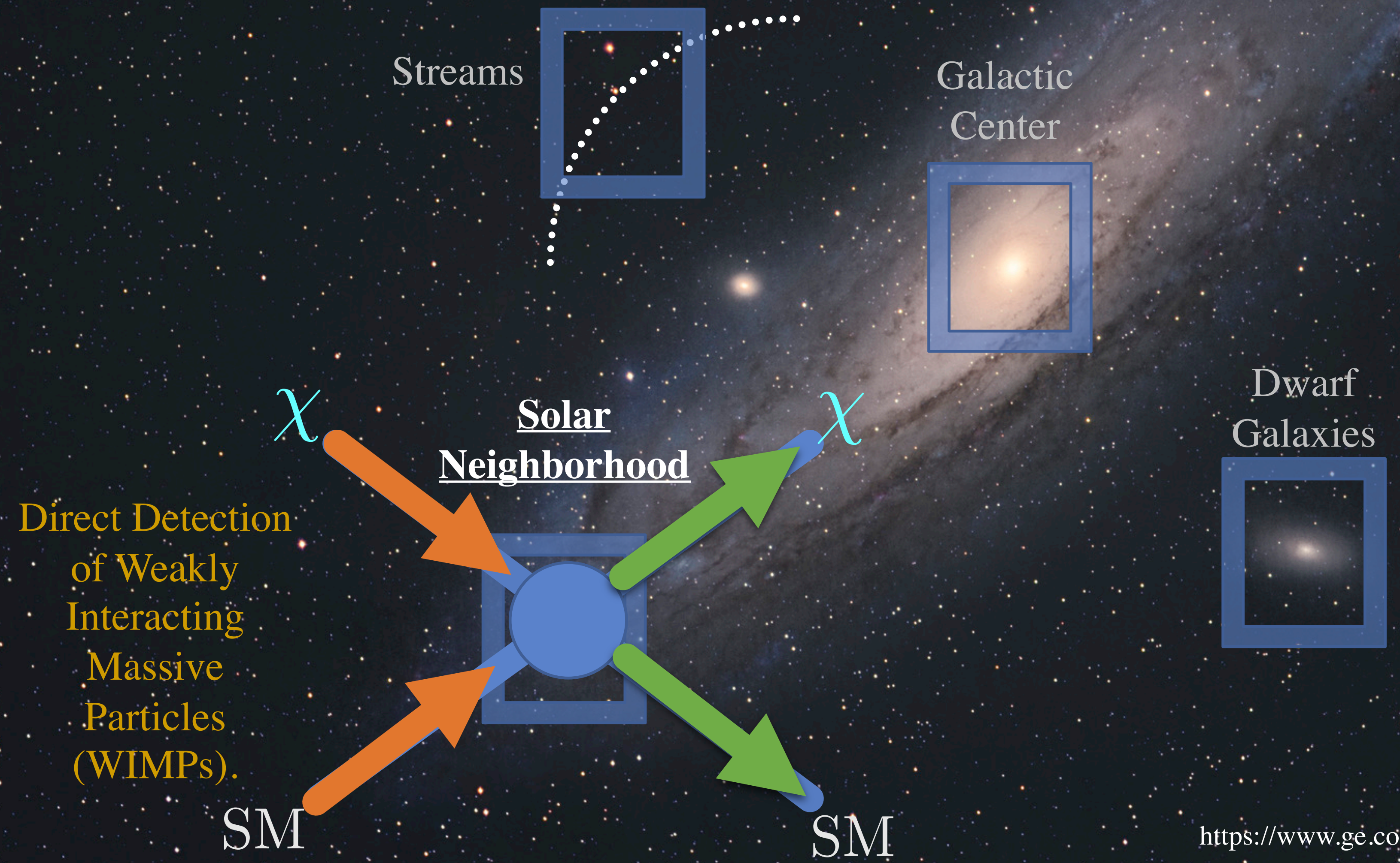

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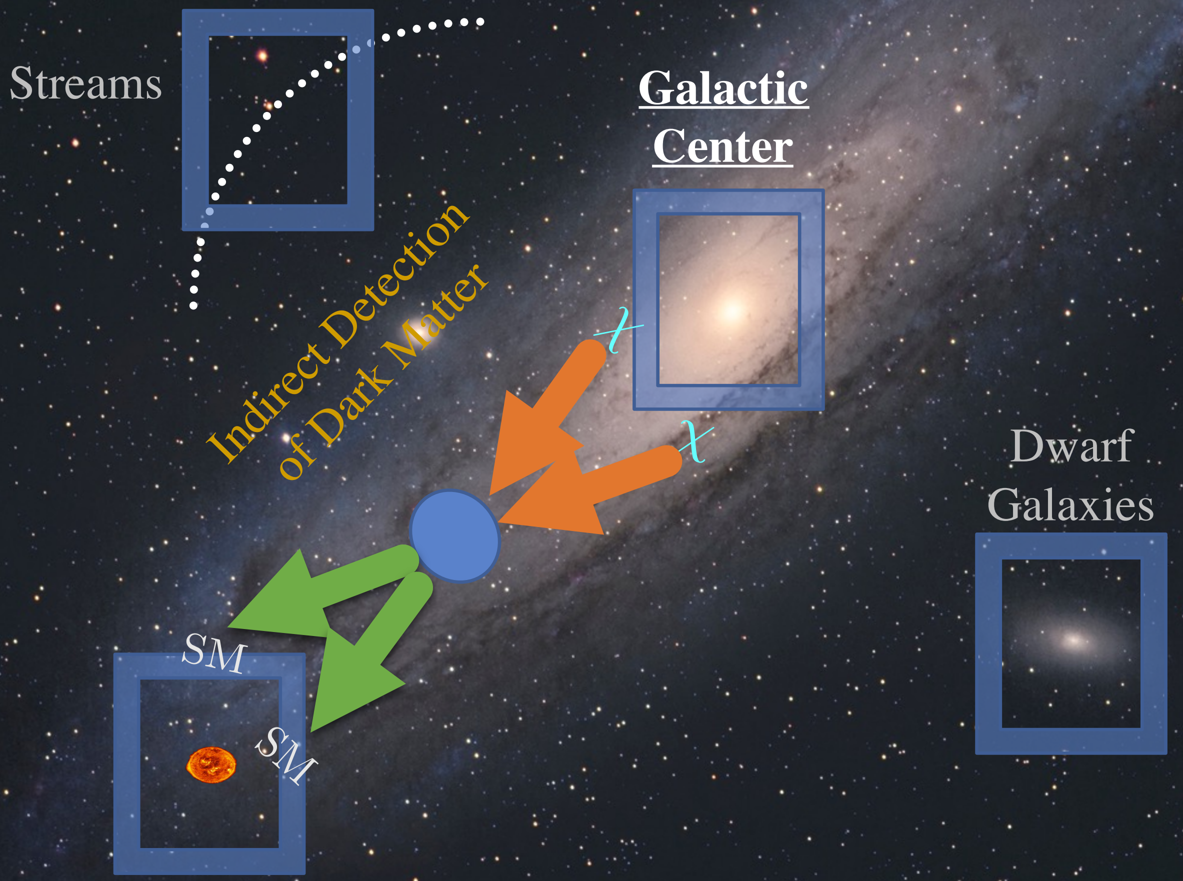

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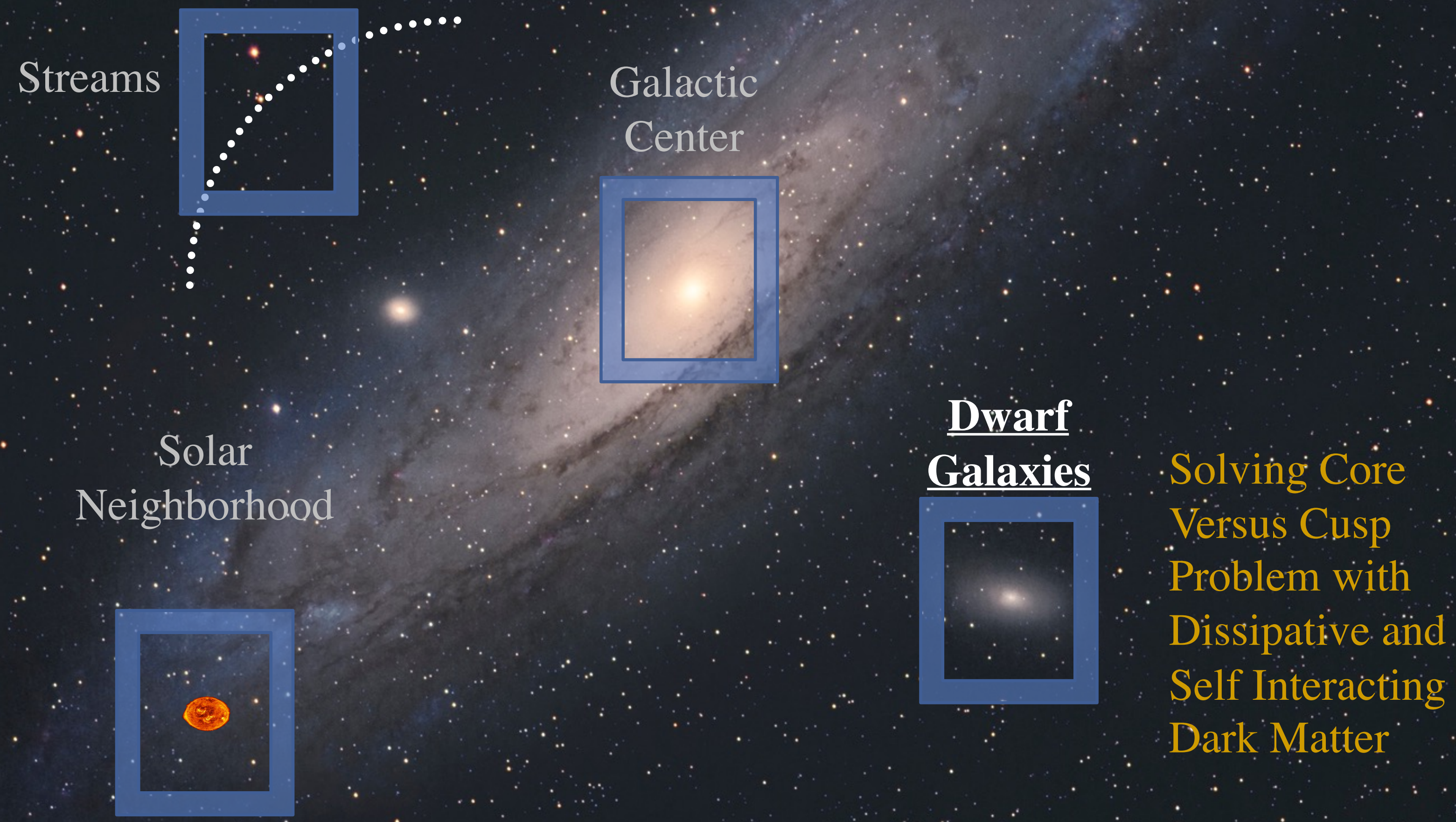

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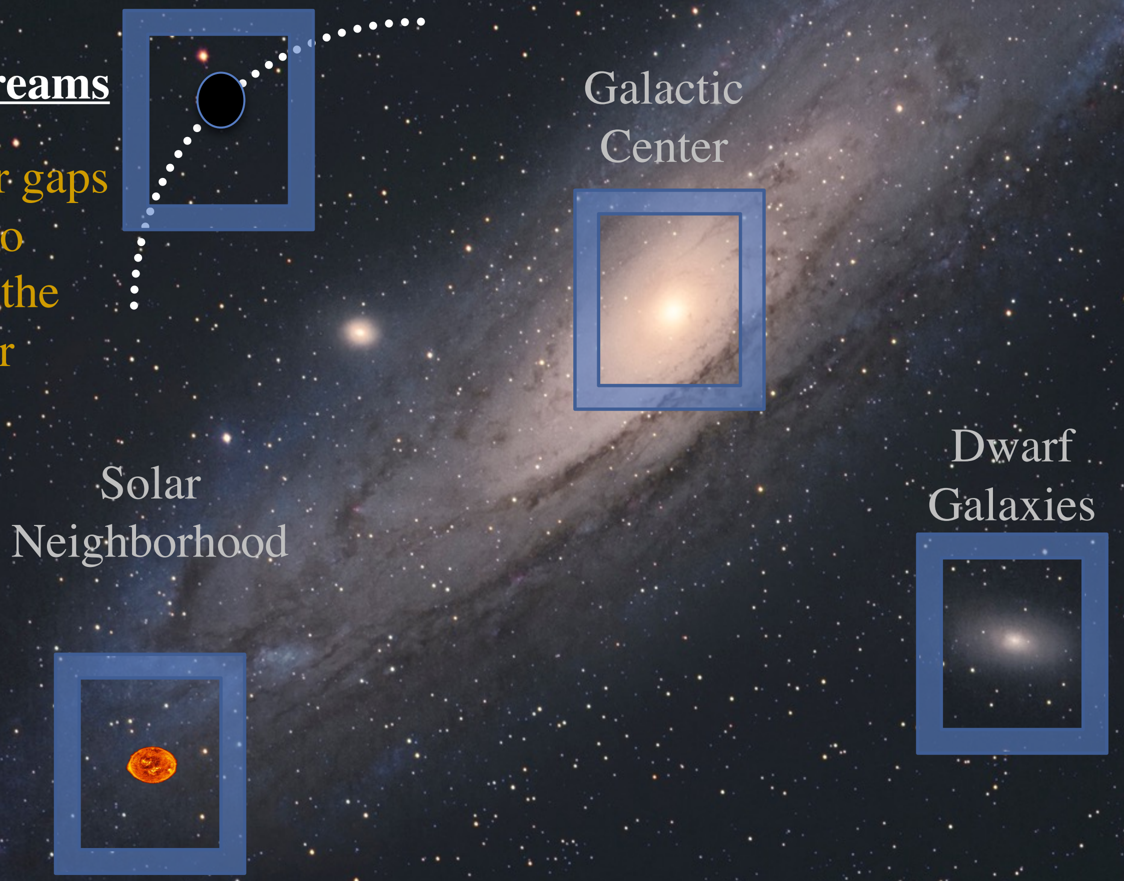
Streams

Looking for gaps in streams to understand the Dark Matter subhalo population



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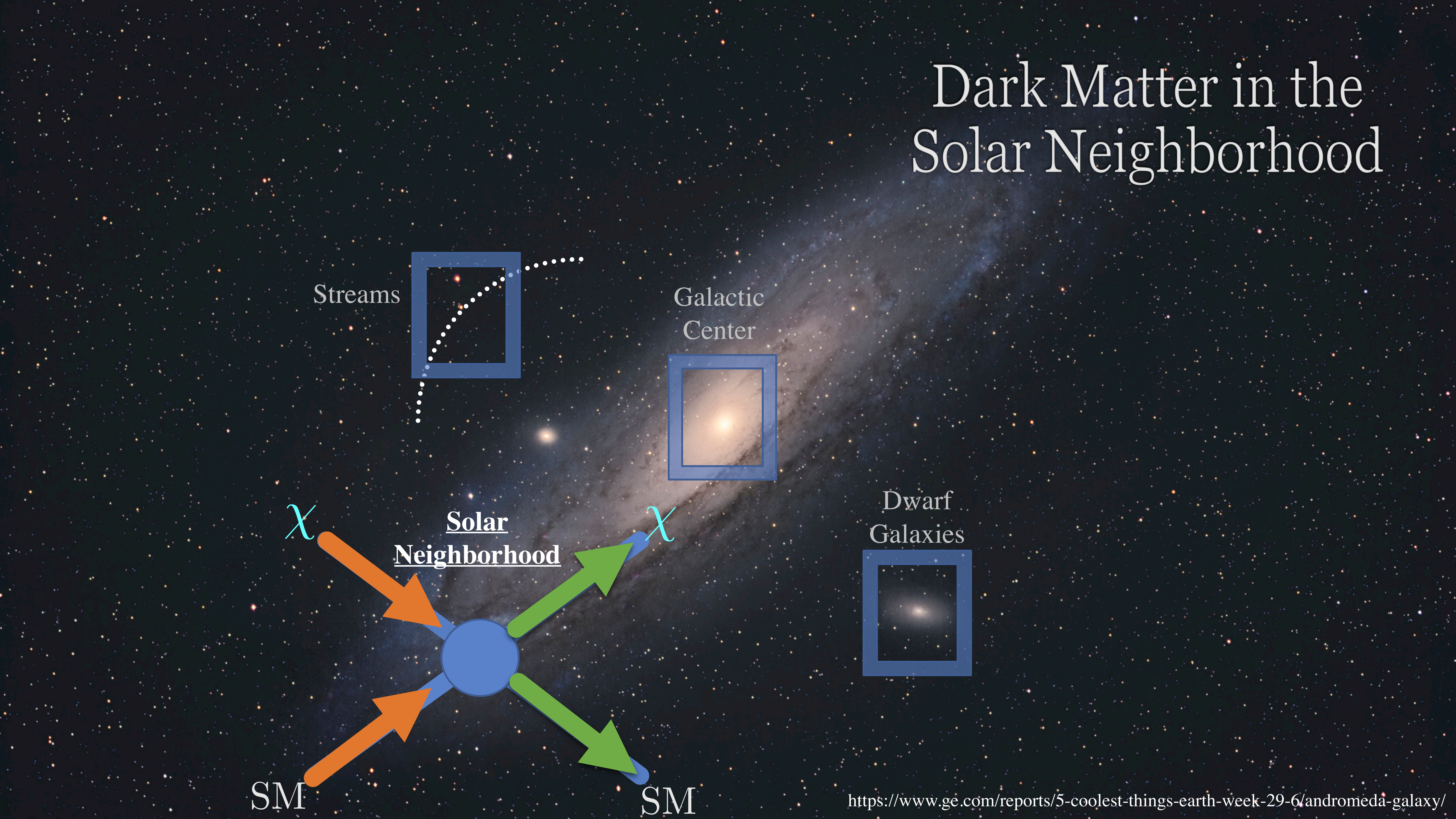
Dark Matter in the Solar Neighborhood



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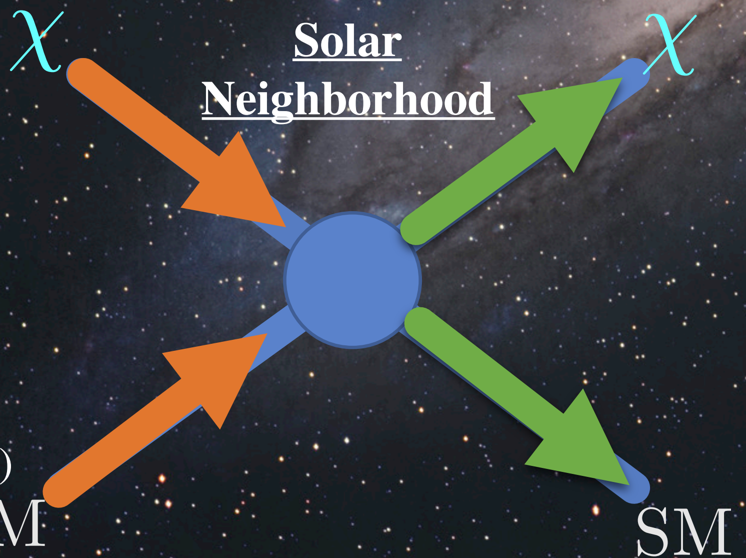
Credit: Science Friday, LUX Experiment

Dark Matter in the Solar Neighborhood

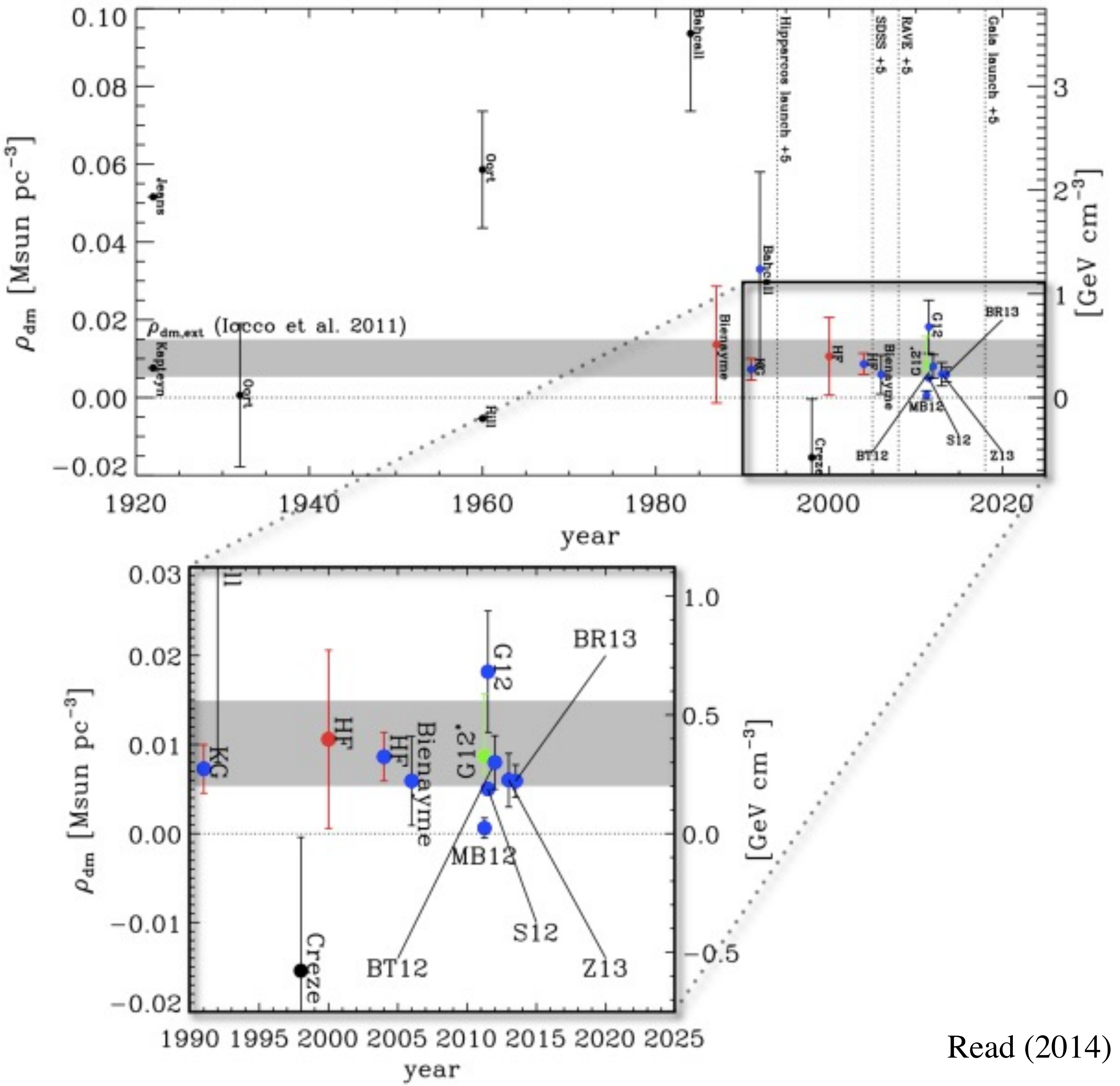


$$\text{Rate} \propto \rho_{\odot} \int \frac{f(v)}{v} dv$$

$\rho_{\odot}$: Local Dark Matter Density

$f(v)$: Local Dark Matter Velocity Distribution

Goodman & Witten (1985)
Freese et al. (1986)



Read (2014)

Dark Matter in the Solar Neighborhood

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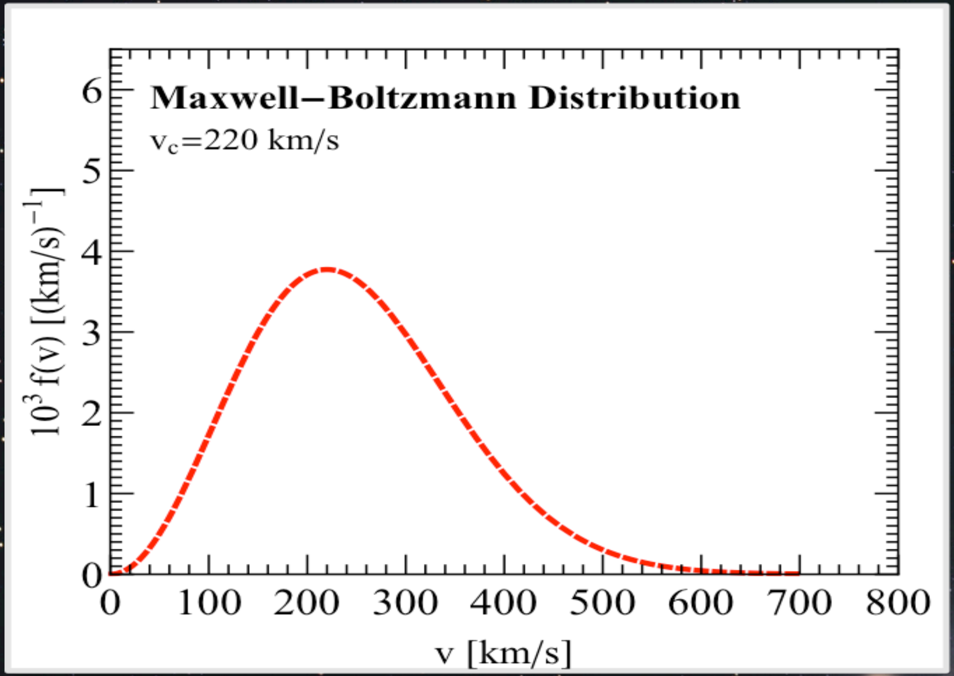

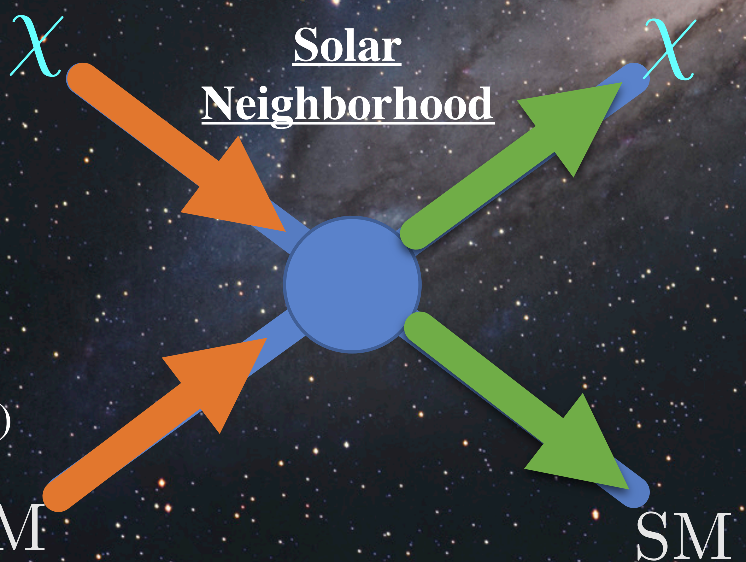

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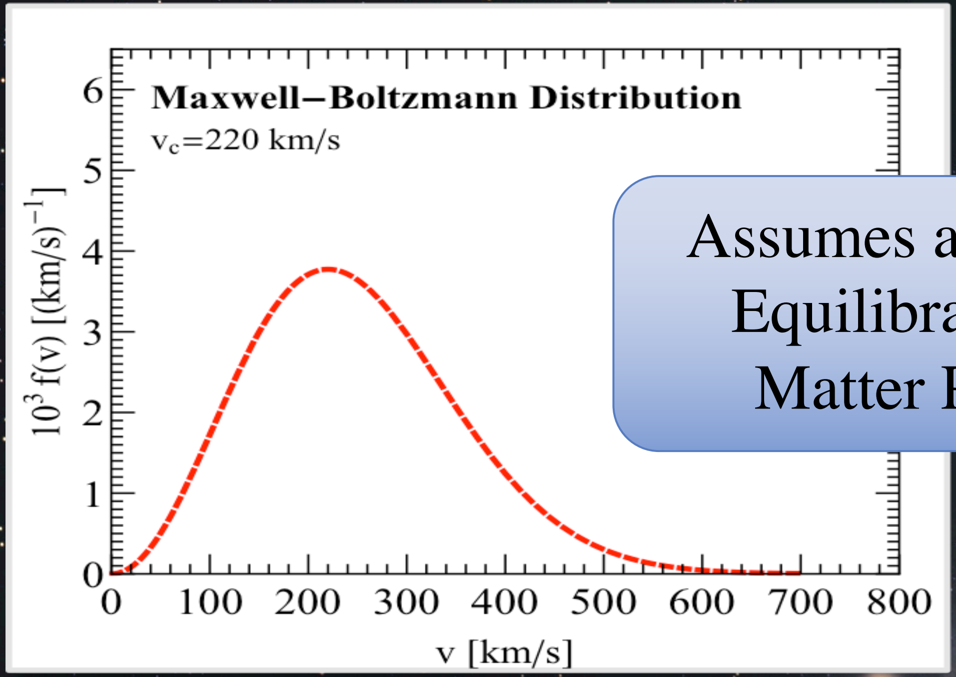
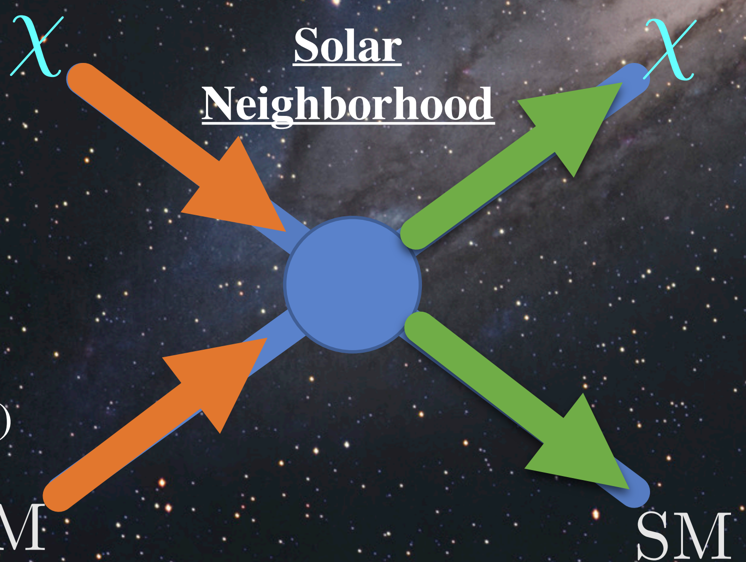


Assumes an Isotropic Equilibrated Dark Matter Potential



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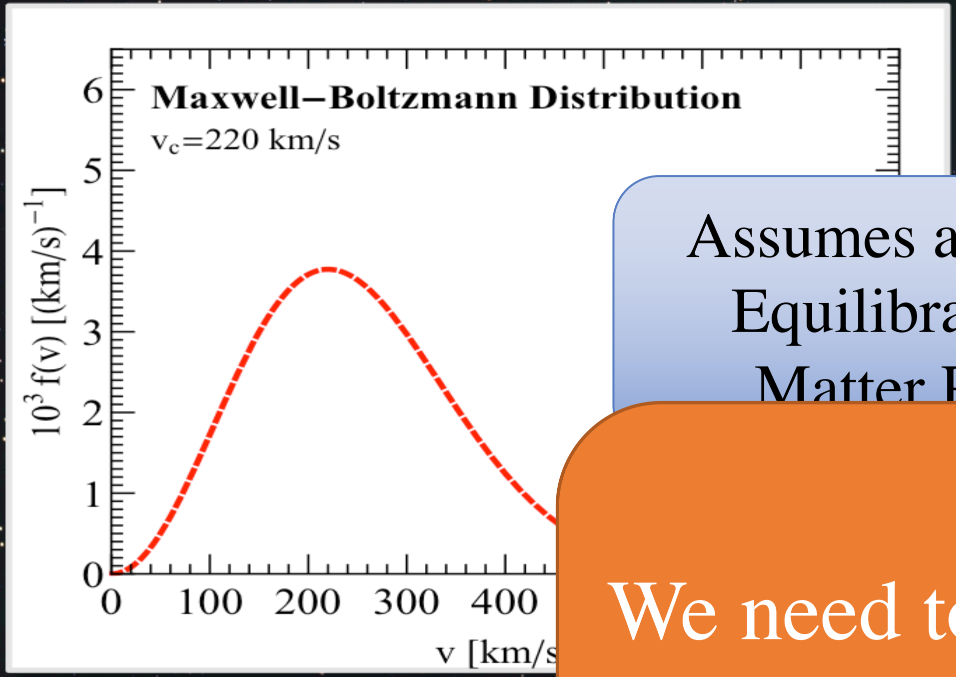

Assumes an Isotropic Equilibrated Dark Matter Potential

We need to build an empirical velocity distribution of Dark Matter.

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Goodman & Witten (1985)
Freese et al. (1986)
Drukier et al. (1987)

From simulations:

Correlate the dark matter to the stars

From *Gaia*:

Measure the phase space map of the stars

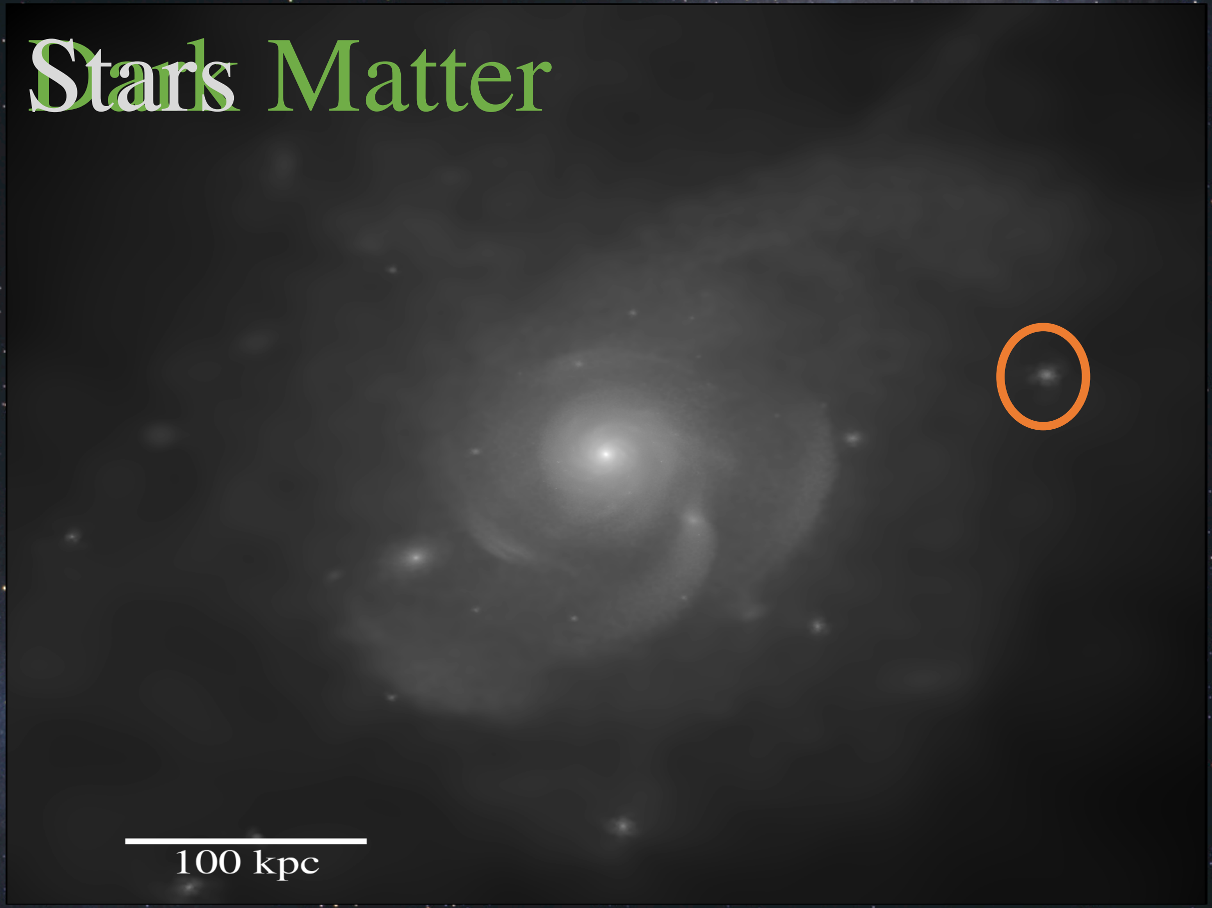
Therefore:

Empirically obtain the local phase-space distribution of dark matter

Herzog-Arbeitman, Lisanti, Madau, **Necib** (2018)
Herzog-Arbeitman, Lisanti, **Necib** (2018)
Necib, Lisanti, Belokurov (2019)
Necib, Lisanti, Garrison-Kimmel, et al. (2018)

Building the Dark Matter Map

Strategy: Reconstruct the Dark Matter from the distributions of the stars.



Hopkins et al. (2014)
Wetzel et al. (2016)
Hopkins et al. (2017)

Necib, Lisanti, Garrison-Kimmel et al. (2018)

Feedback in Realistic Environments (FIRE)

Hopkins et al. (2014)
Wetzel et al. (2016)
Hopkins et al. (2017)

Video by Shea Garisson-Kimmel, http://www.tapir.caltech.edu/~sheagk/firemovies.html

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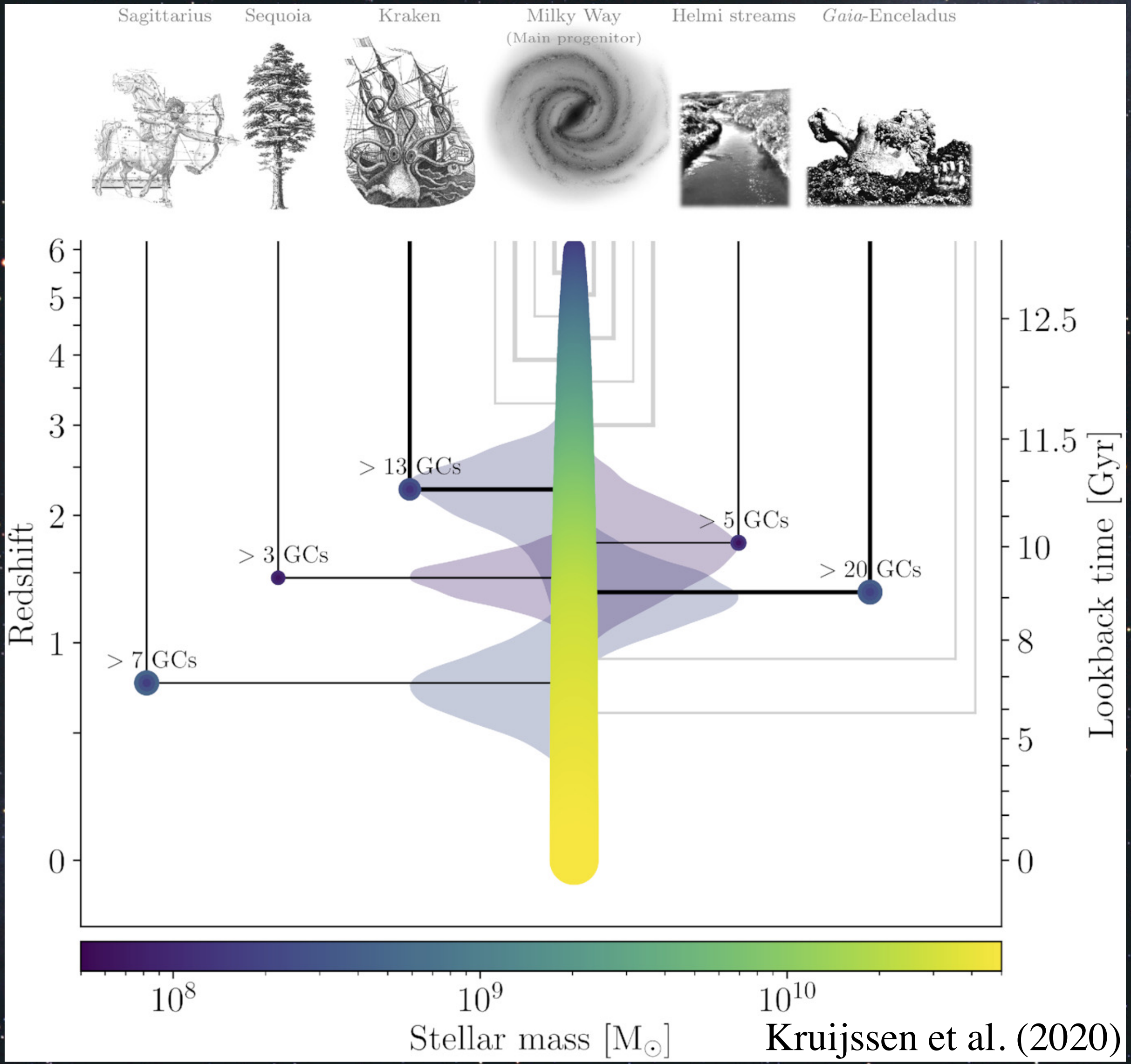

Kruijssen et al. (2020)

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Belukorov et al. (2018)
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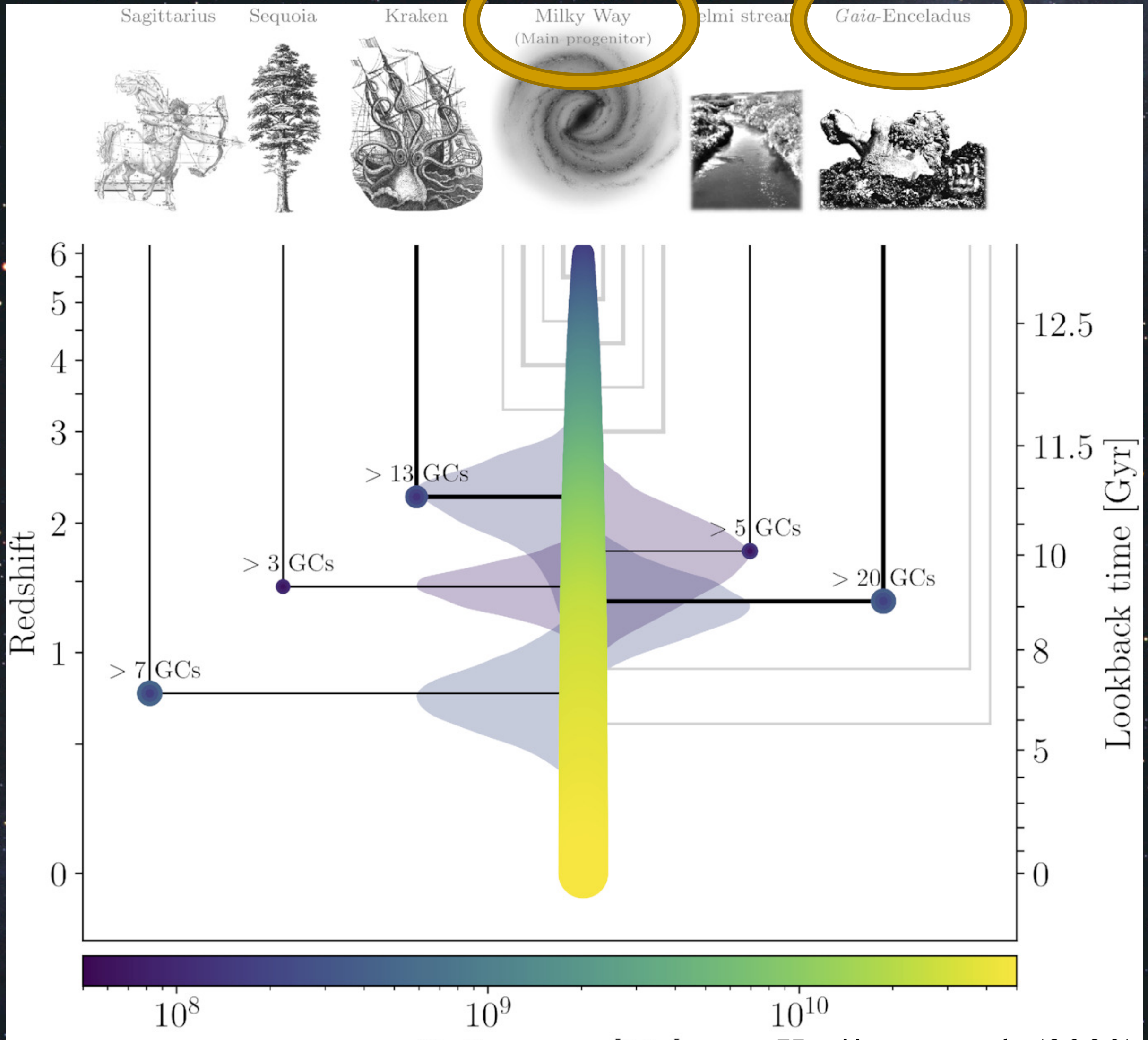

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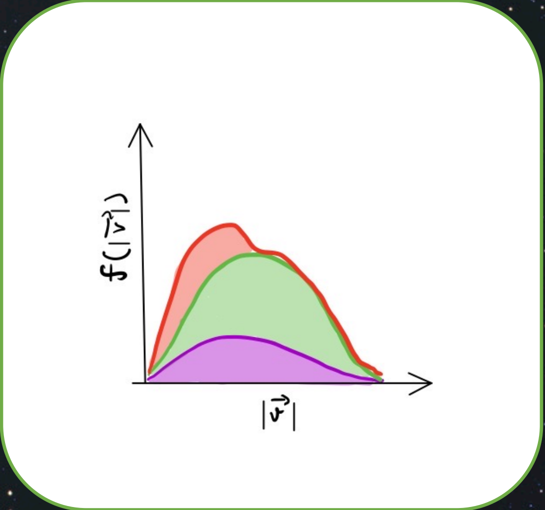
Strategy: Reconstruct the Dark Matter from the distributions of the stars.

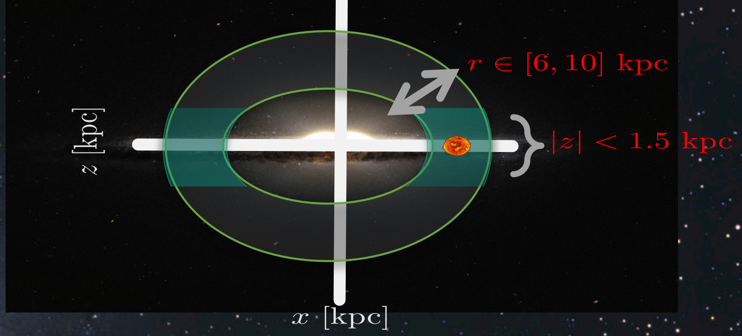
Different Components:

1. Old Halo
2. Sausage/ Gaia Enceladus
3. Nyx



Necib, Lisanti, Garrison-Kimmel et al. (2018)

Building the Dark Matter Map



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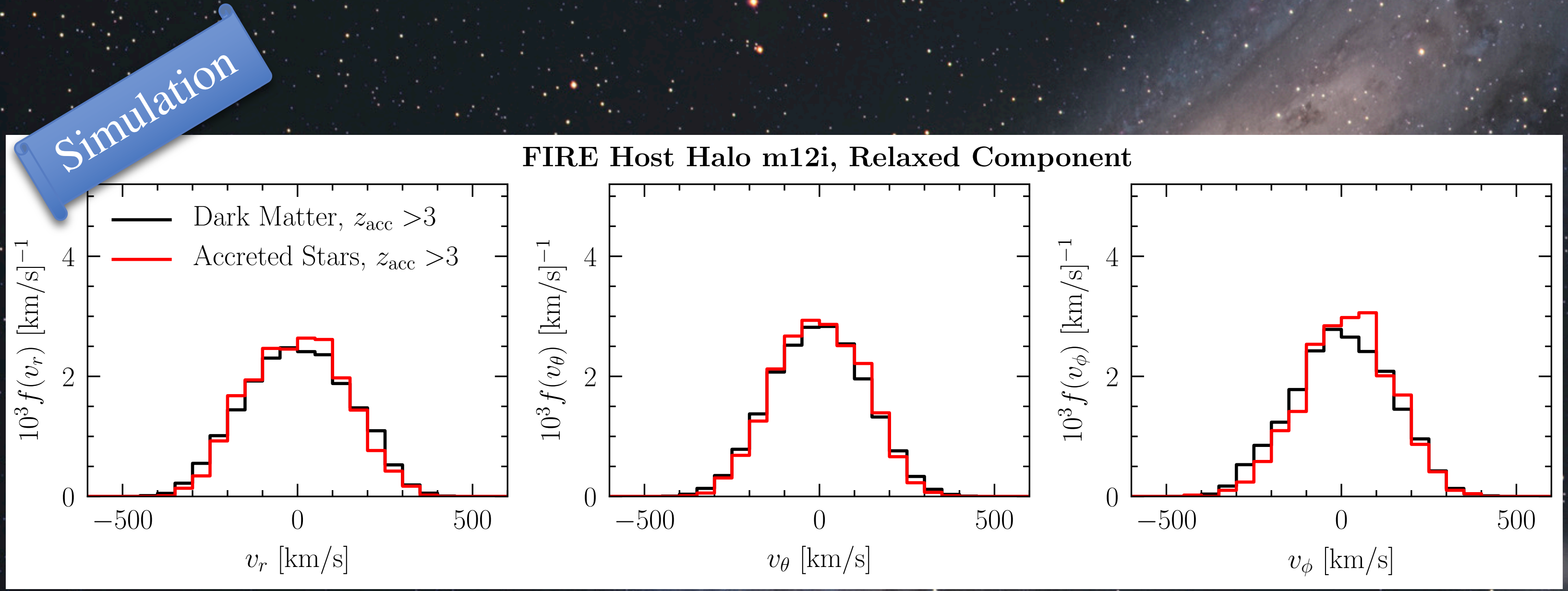

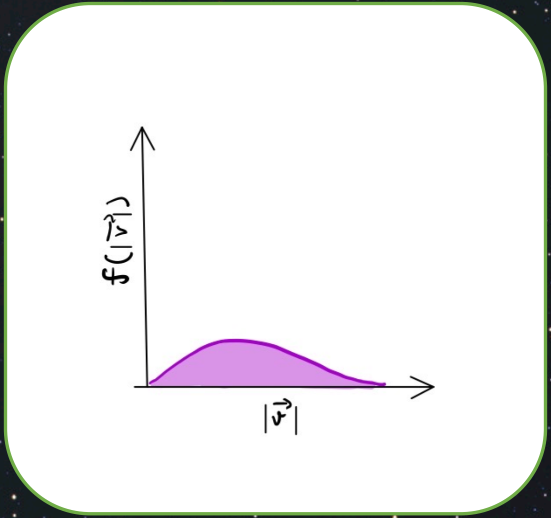

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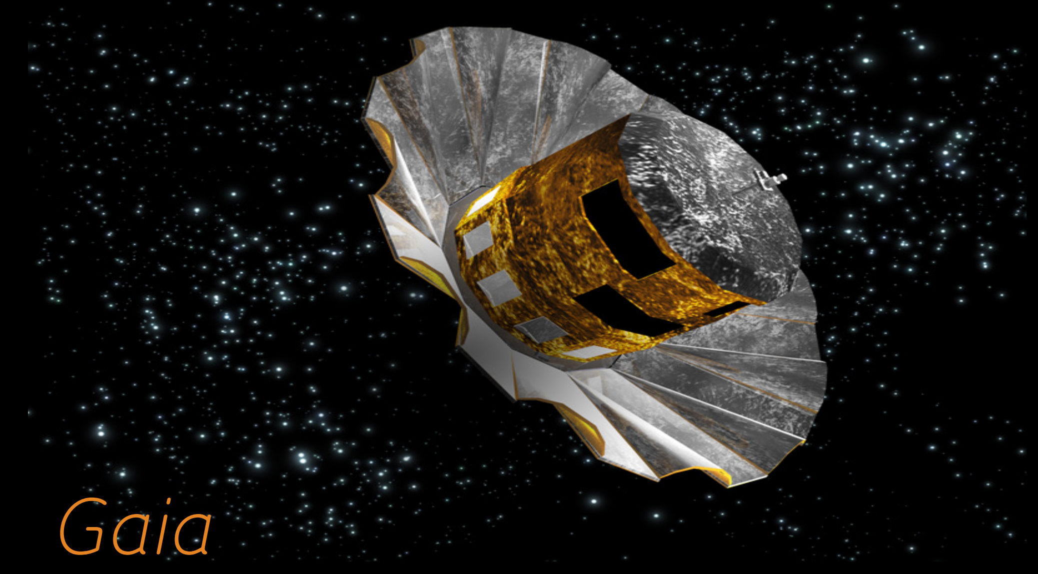
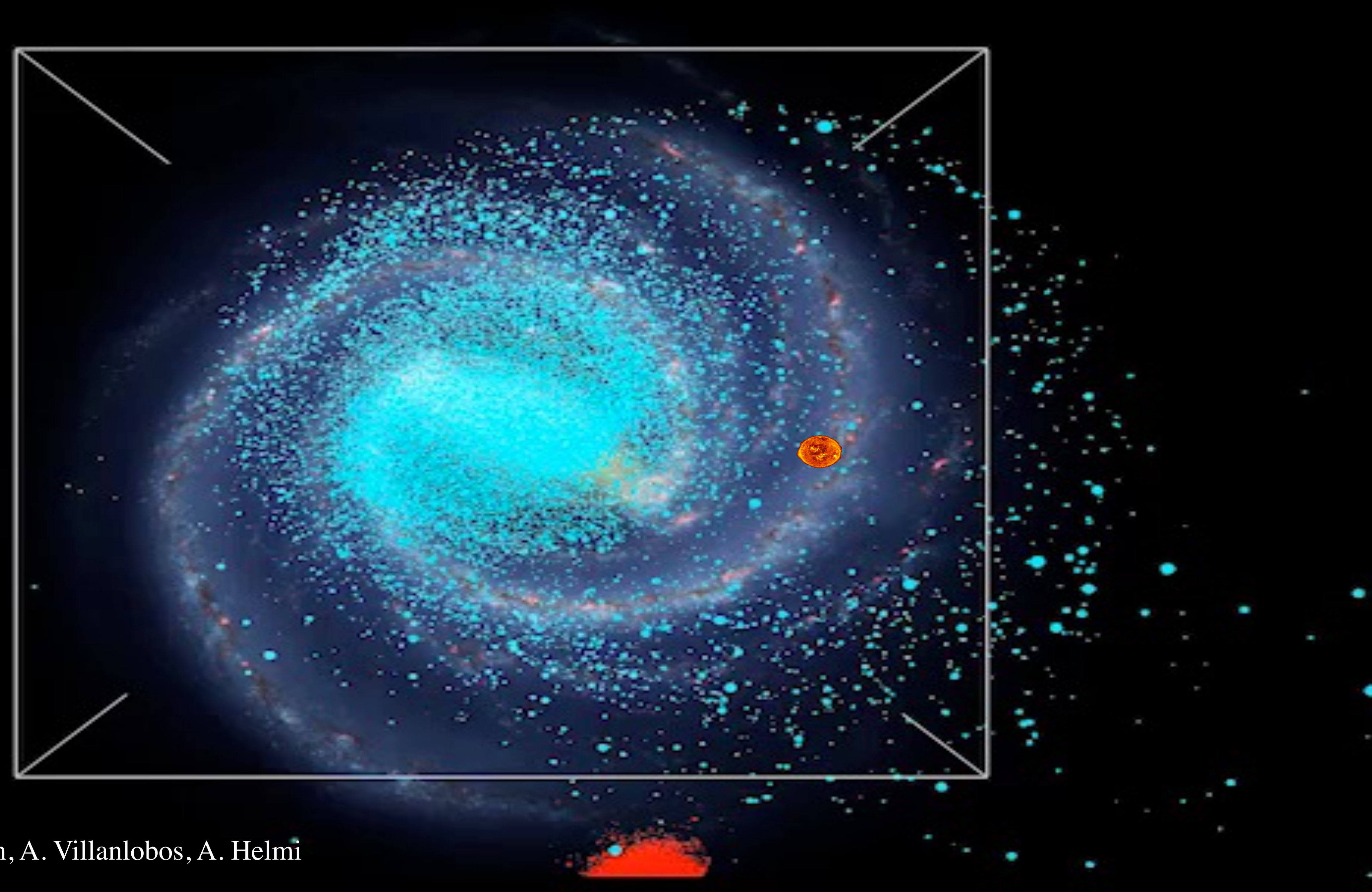
Necib, Lisanti, Garrison-Kimmel et al. (2018)



- Launched December 2013
- Goal: Positional and kinematic measurement of 1 billion stars (1% of the Milky Way)
- DR2: 7 million radial velocities

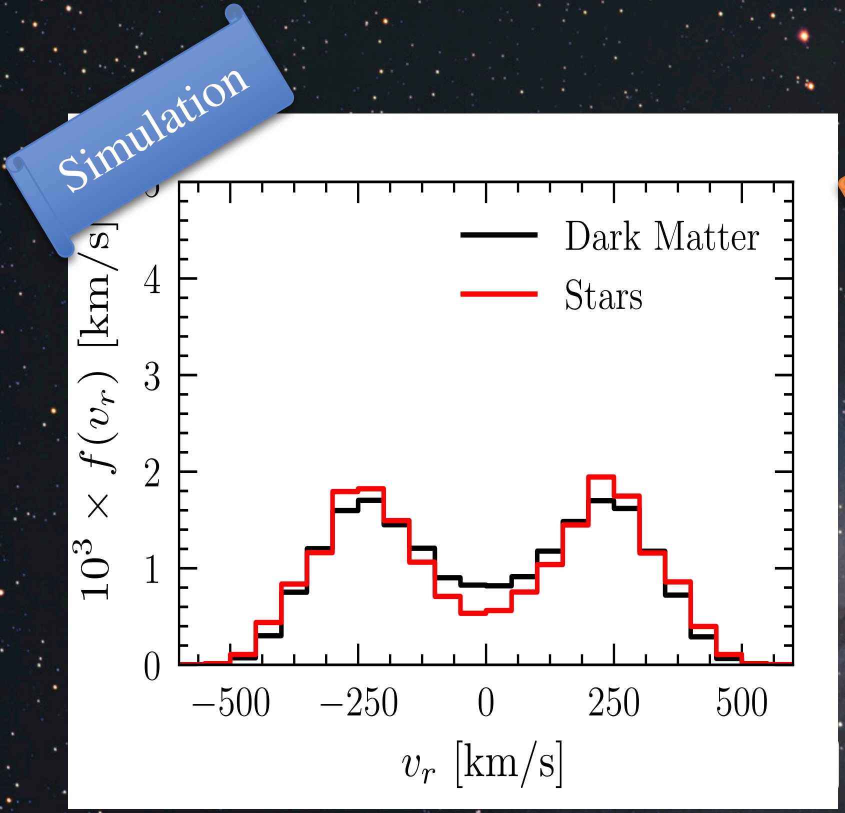


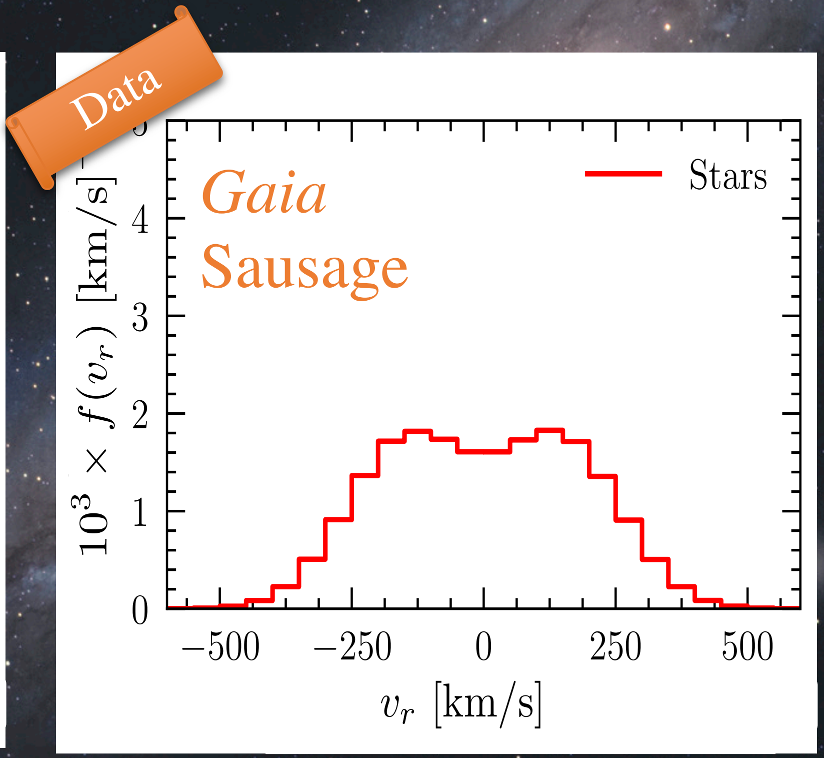
Credit: H.H. Koppelman, A. Villanlobos, A. Helmi

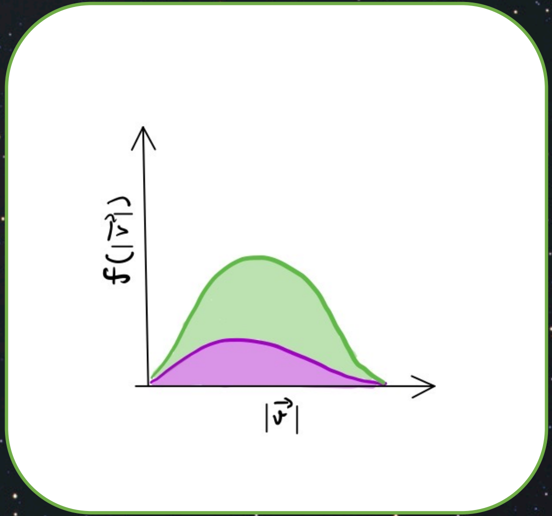
Building the Dark Matter Map

Strategy: Reconstruct the Dark Matter component by component from the distributions of the stars.

Different Components:
1. Old Halo
2. Sausage/ Gaia Enceladus
3. Nyx







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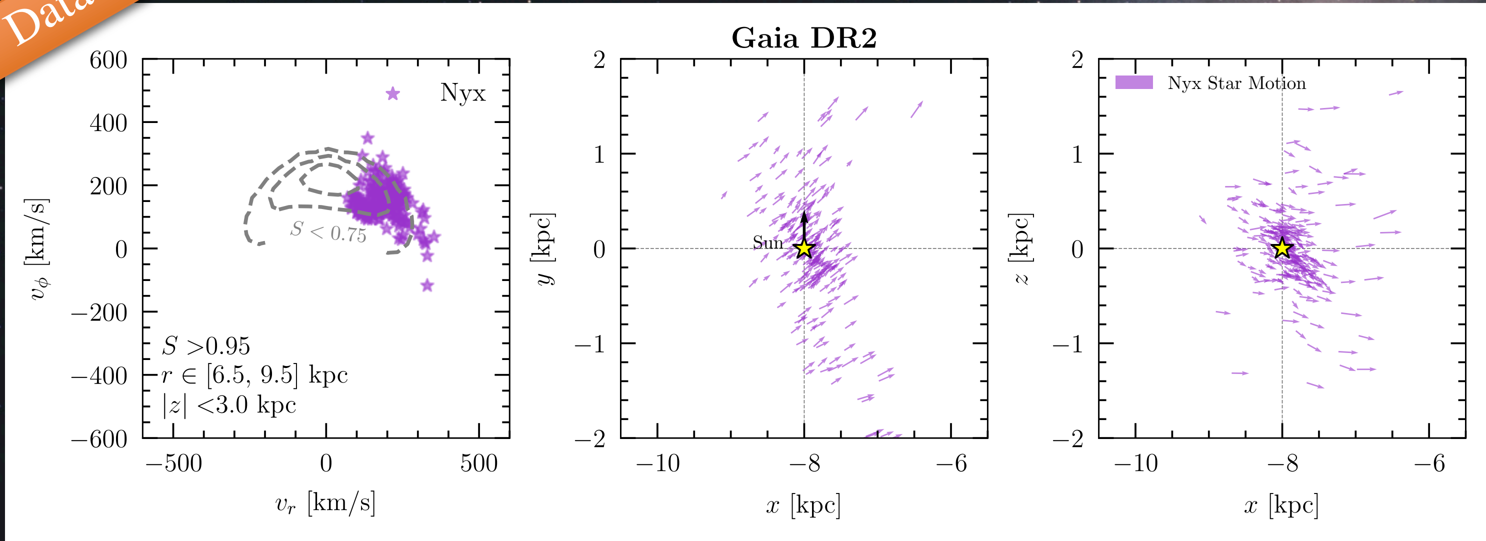
Necib, Lisanti, Garrison-Kimmel et al. (2018)

Building the Dark Matter Map

Strategy: Reconstruct the Dark Matter from the distributions of the stars.

Data



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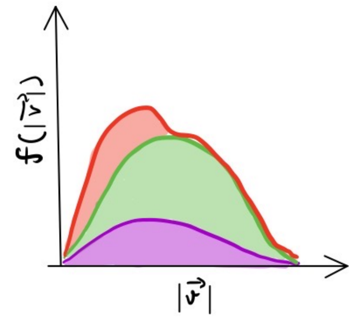

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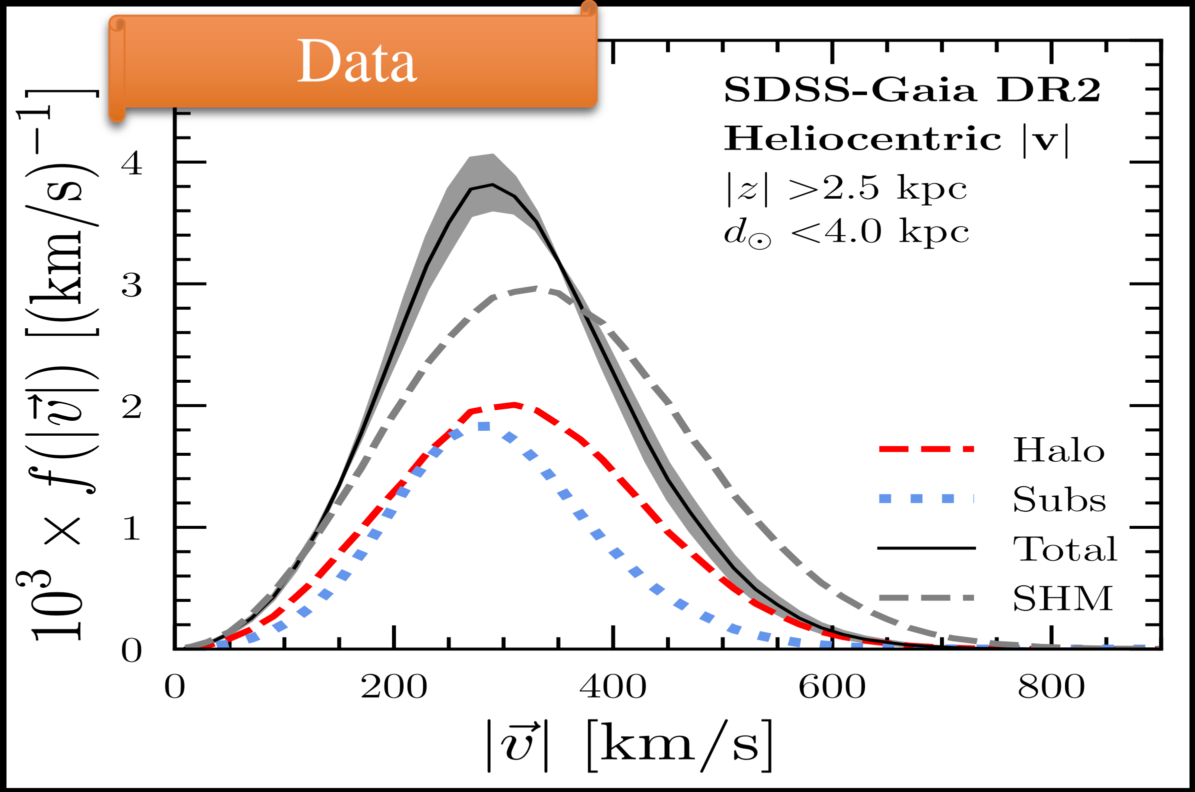
Necib, Lisanti, Garrison-Kimmel et al. (2018)

First Empirical Dark Matter Distribution



Sausage

$$f_{\text{total}}(v) = c_{\text{halo}} f_{\text{halo}}(v) + c_{\text{subs}} f_{\text{subs}}(v)$$

Kirby et al. (2013)
Garrison-Kimmel et al. (2015)
Necib, Lisanti, Belokurov (2018)
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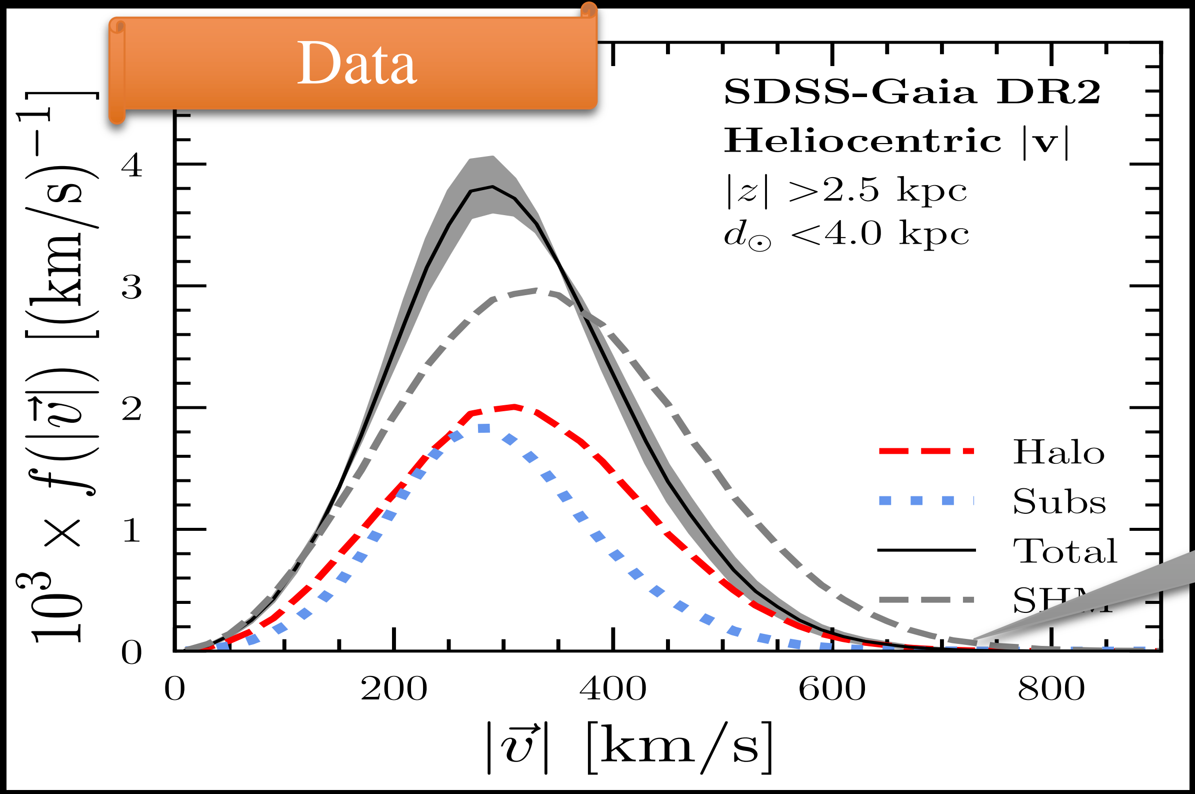

$$f_{\rm total}(v) = c_{\rm halo} f_{\rm halo}(v) + c_{\rm subs} f_{\rm subs}(v)$$

$$c_{\rm subs} = 0.42^{+0.26}_{-0.22}$$

Final distribution different from the assumed Maxwell Boltzmann distribution

Kirby et al. (2013)
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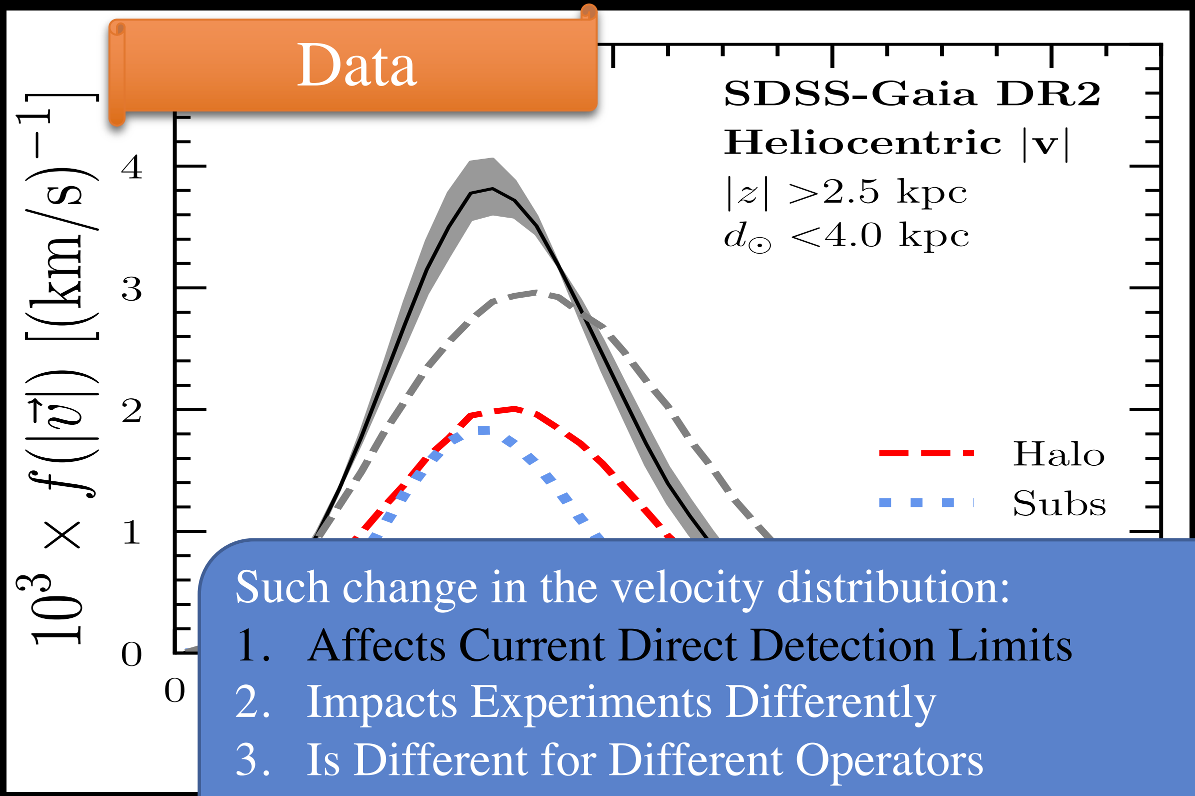

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Final distribution different from the assumed Maxwell Boltzmann distribution

Such change in the velocity distribution:

1. Affects Current Direct Detection Limits
2. Impacts Experiments Differently
3. Is Different for Different Operators
4. Affects Yearly Modulations

Kirby et al. (2013)
Garrison-Kimmel et al. (2015)
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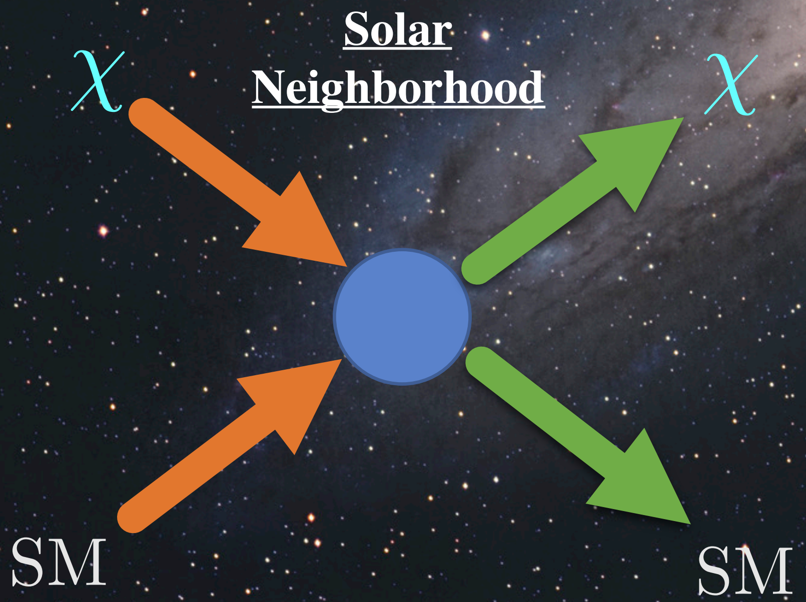
Direct Detection

Direct detection depends on astrophysical parameters:

- Dark matter density
- Dark Matter velocity



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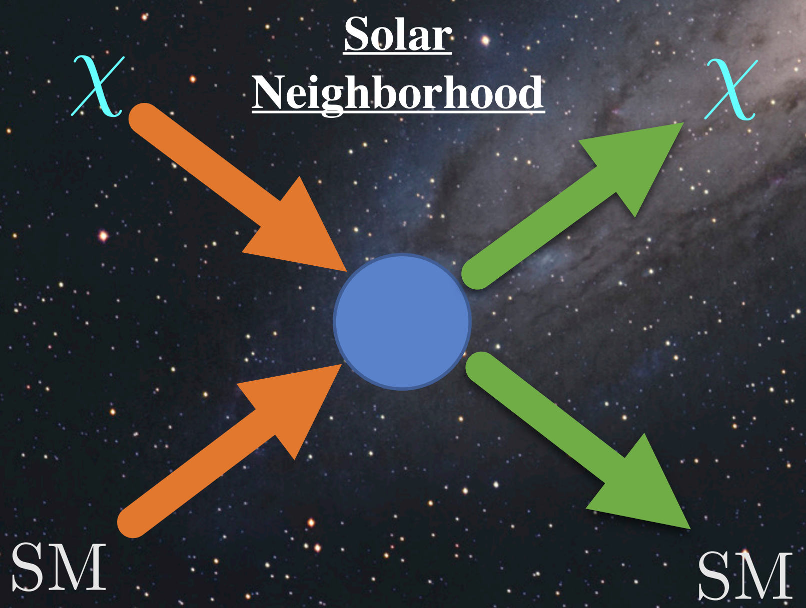

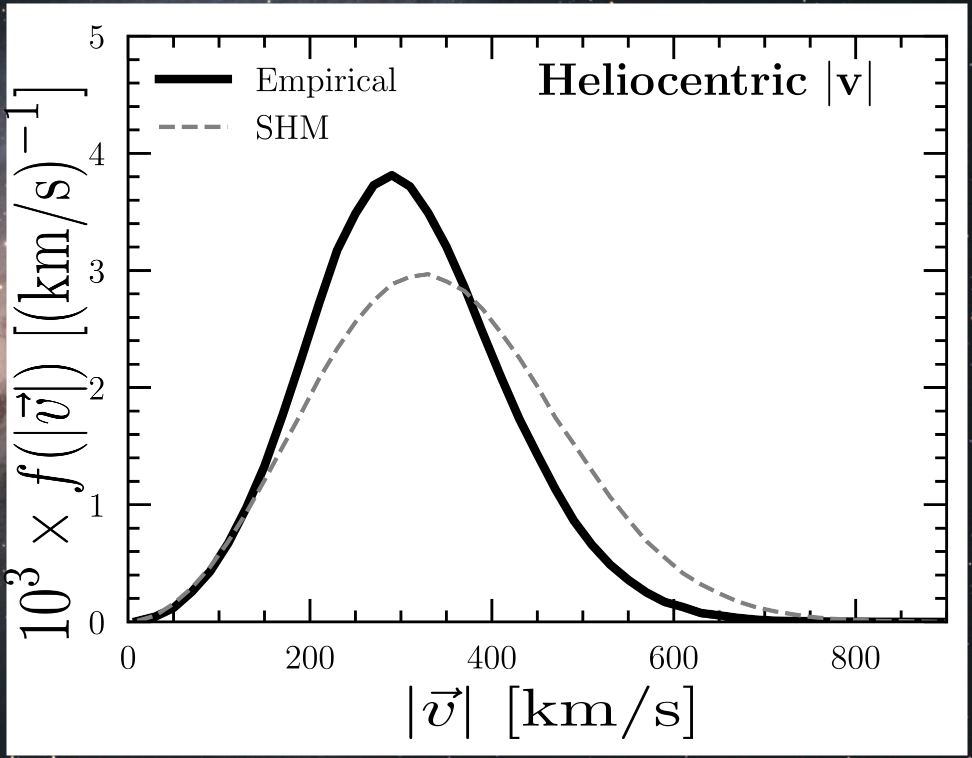

$$\text{Rate} \propto \rho_{DM} \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\, dv$$

$$v_{\min} = v_{\min}(E_{\text{thresh}}, m_\chi)$$

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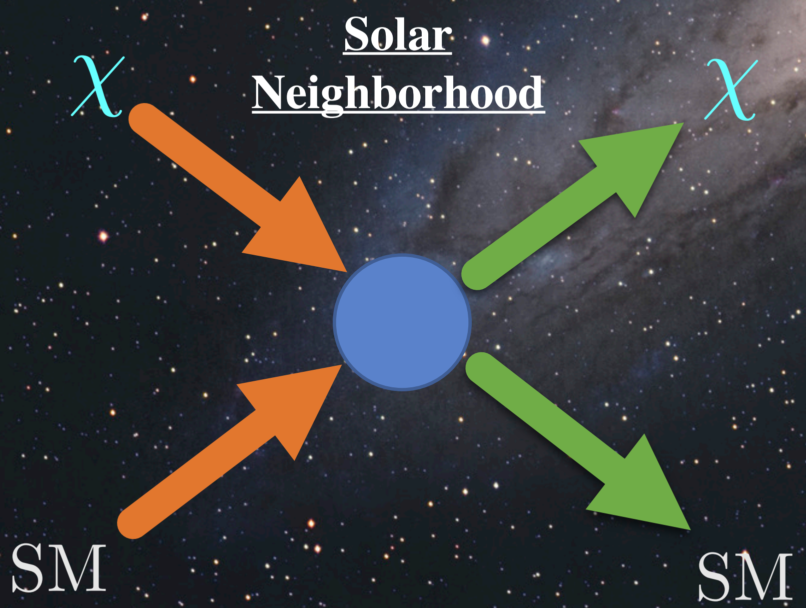

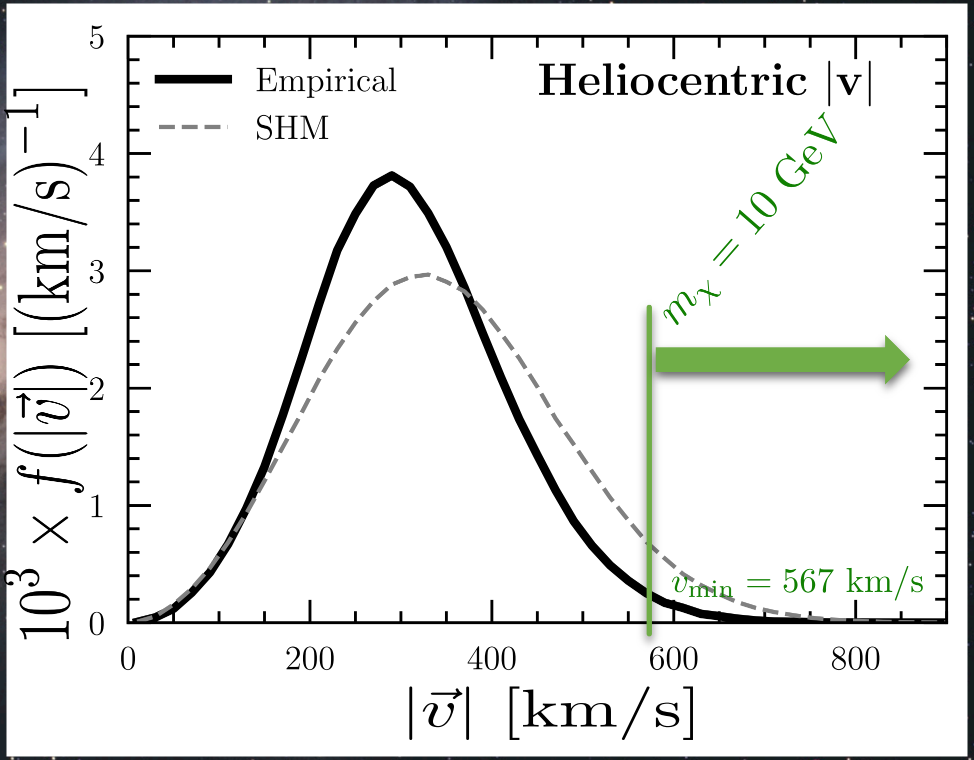

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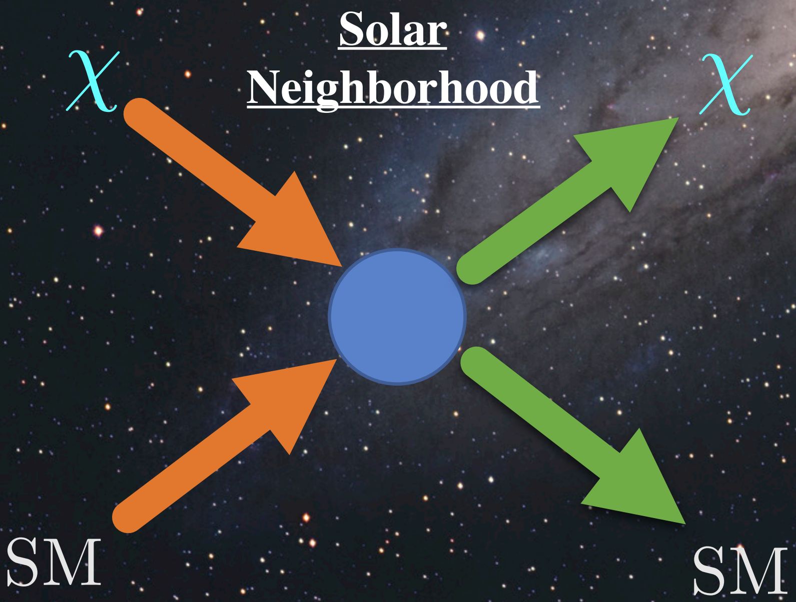

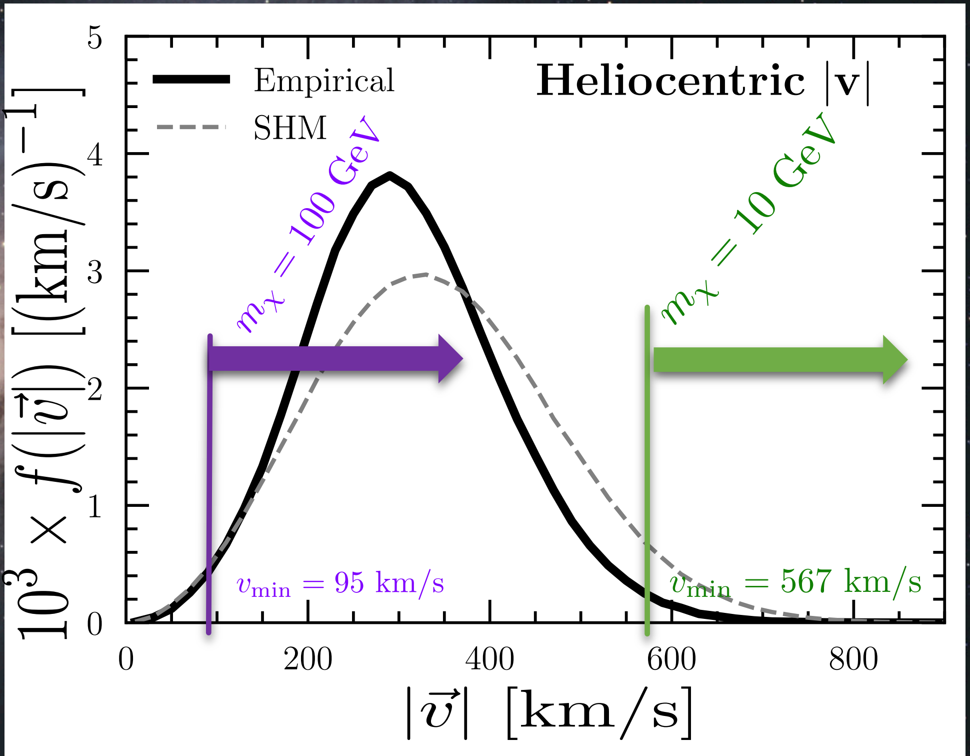

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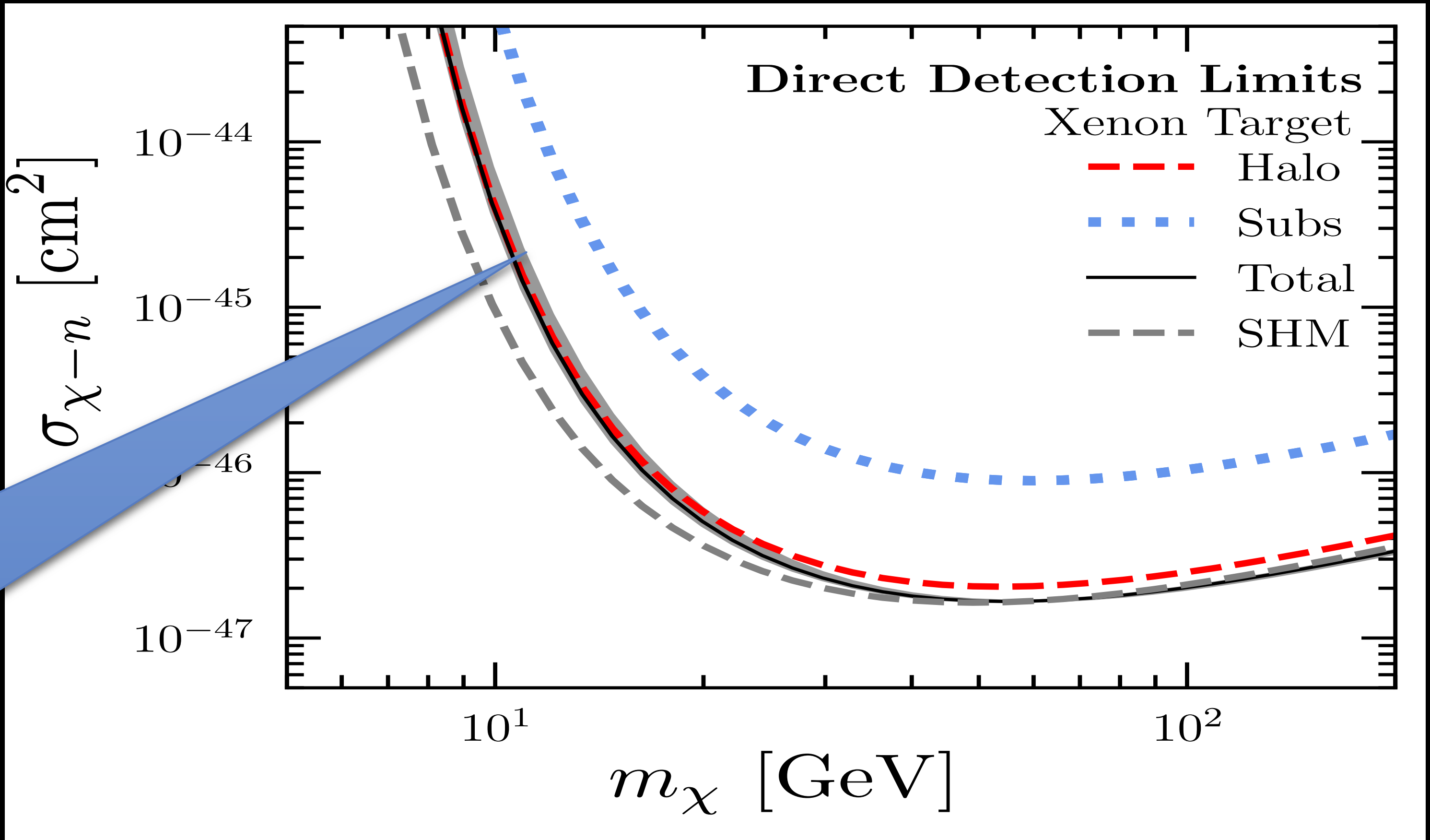
Implications for Direct Detection



Largest changes are at low dark matter masses

Other theory models might have stronger effects.
See for example Buch et al. 2019

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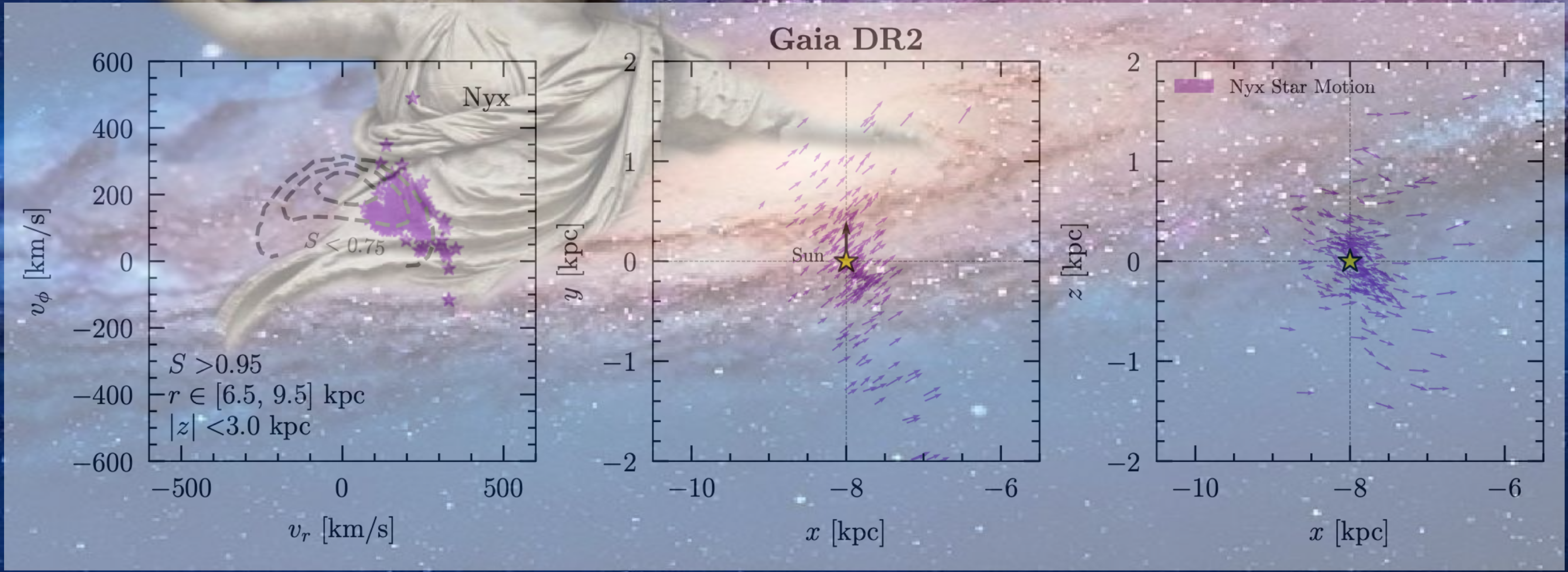
Nyx: Greek Goddess of the Night



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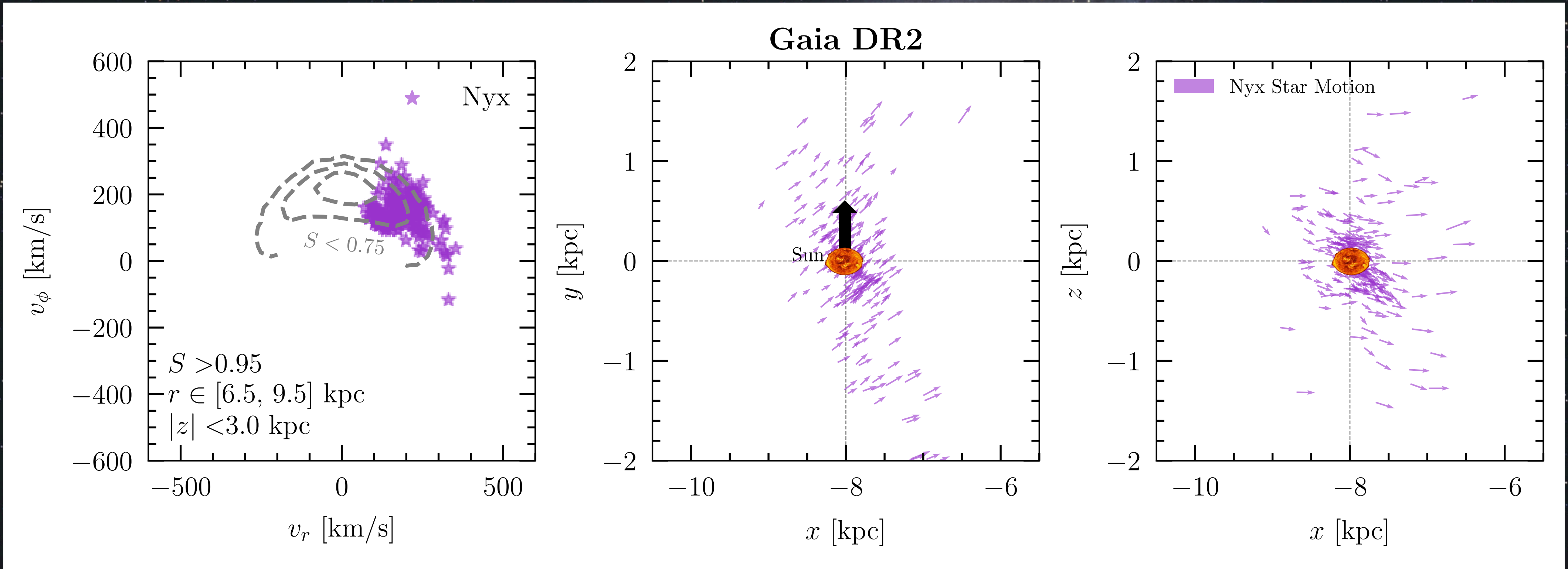
Dark Matter in the Solar Neighborhood



Necib, Ostdiek, et al. (2019a)

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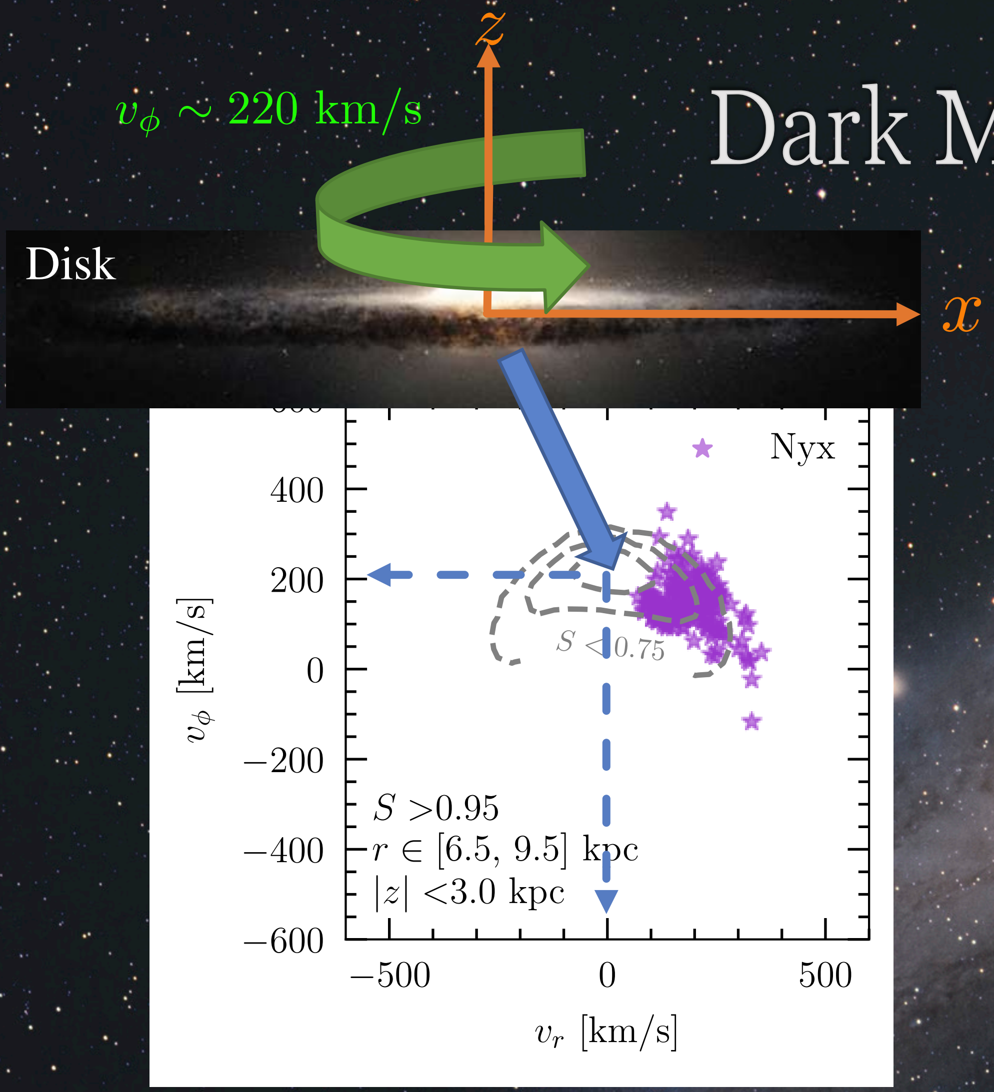

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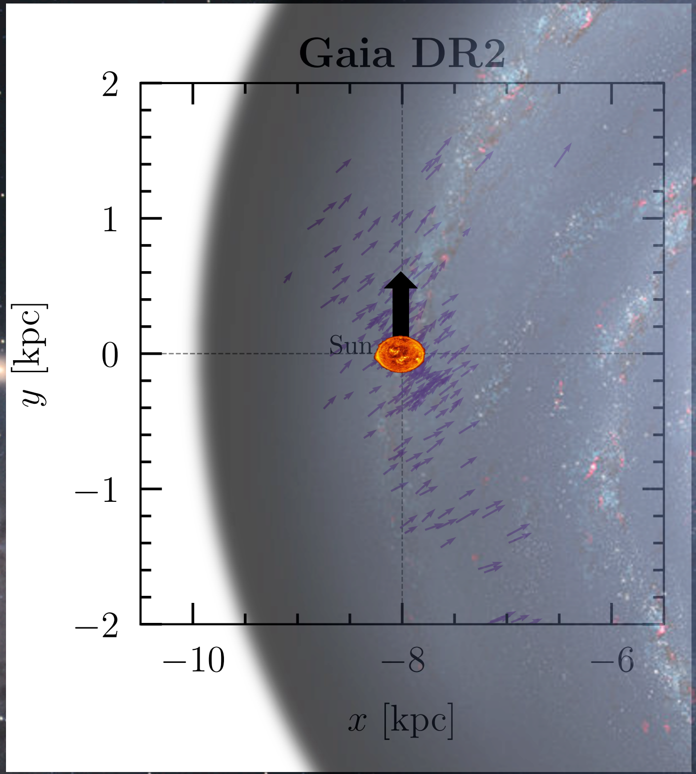

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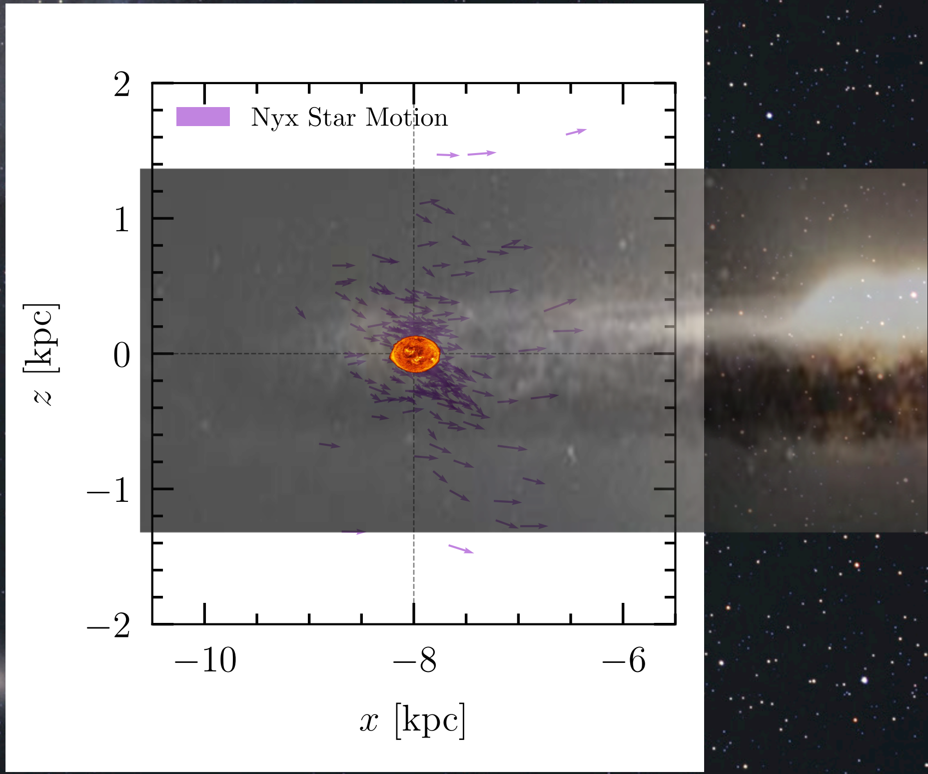

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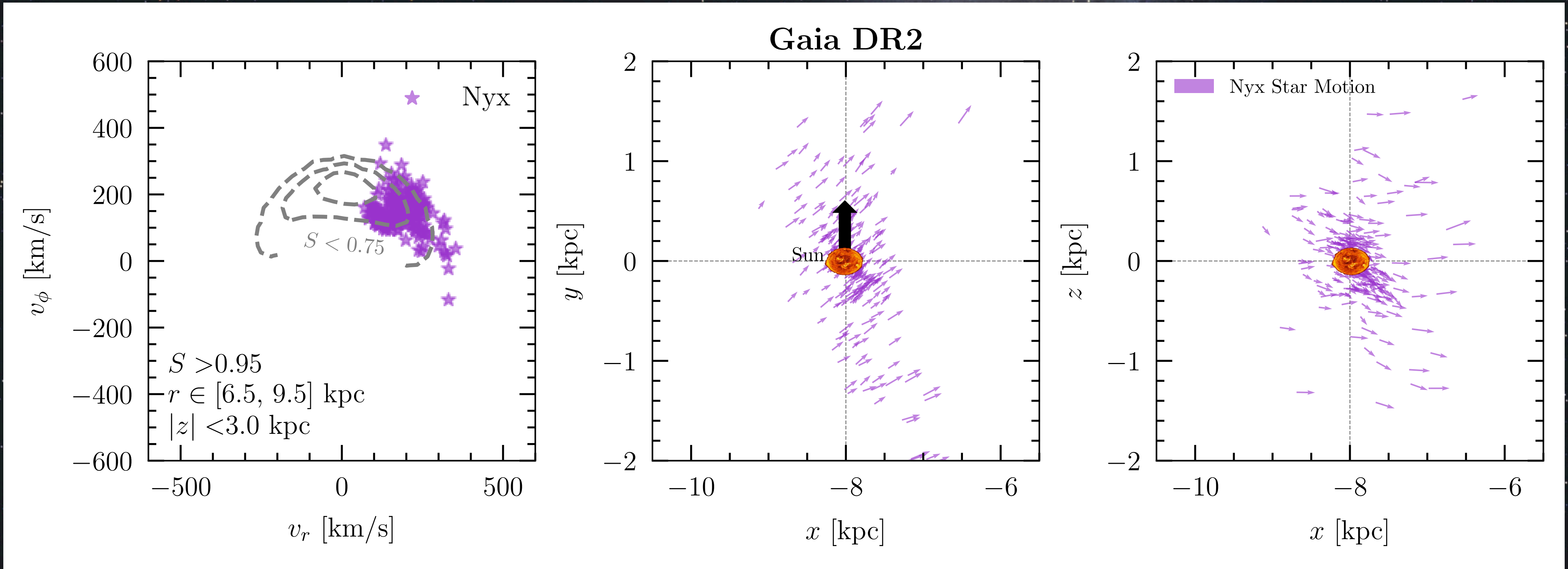

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Simulation Analog

Hopkins et al. (2014)
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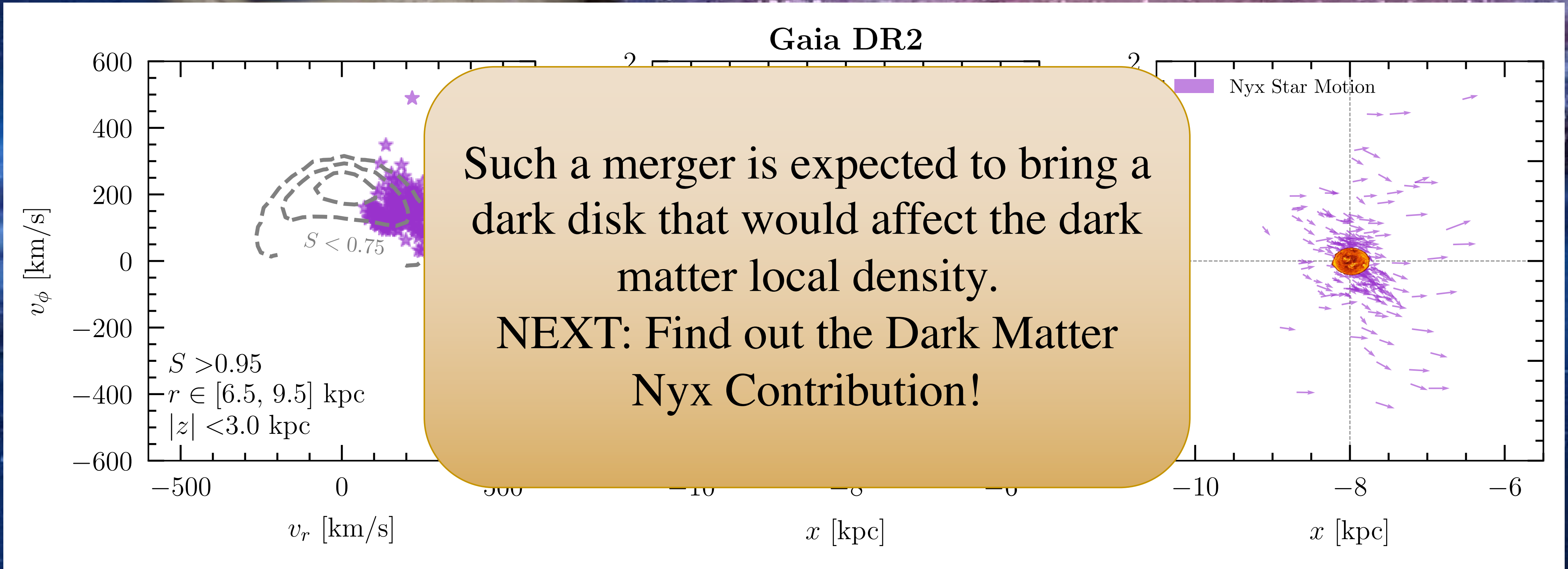
Video by Shea Garisson-Kimmel,
http://www.tapir.caltech.edu/~sheagk/firemovies.html

Nyx: Greek Goddess of the Night



Such a merger is expected to bring a dark disk that would affect the dark matter local density.

NEXT: Find out the Dark Matter Nyx Contribution!

Necib, Ostdiek, et al. (2019a)

Dark Disk

As satellites are torn apart by tidal forces, they deposit both their stars *and their dark matter* into a thick disc (Lake 1989). The latter point is the key new idea presented in this work: a dark matter disc must form in a ΛCDM cosmology

Read et al. (2008)

Lake (1989)
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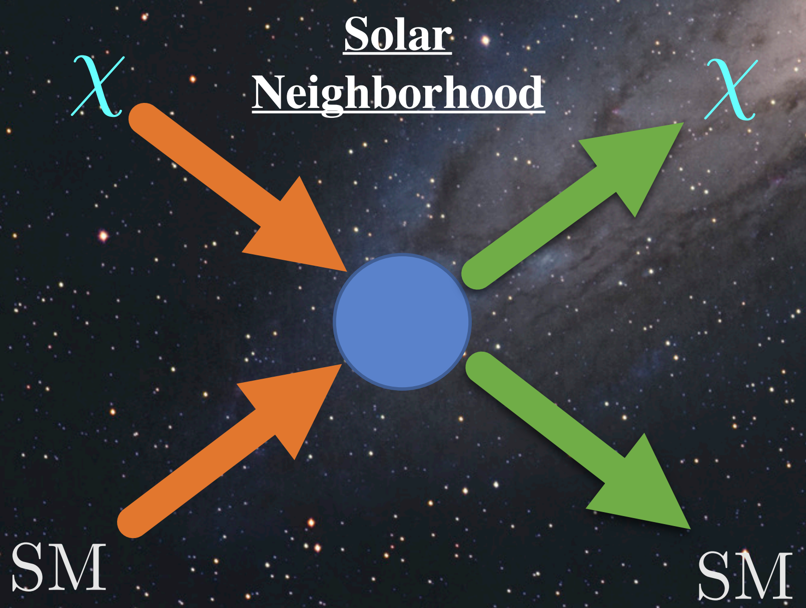
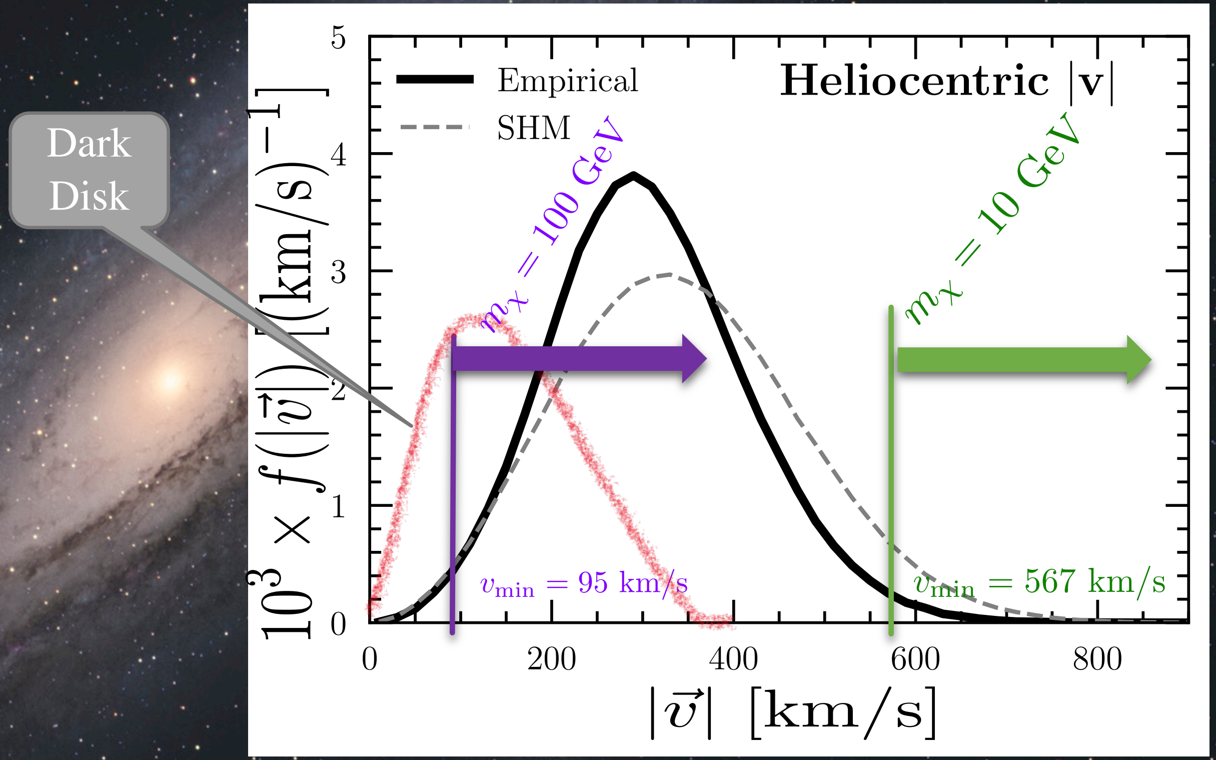
Direct Detection

Direct detection depends on astrophysical parameters:

- Dark matter density
- Dark Matter velocity

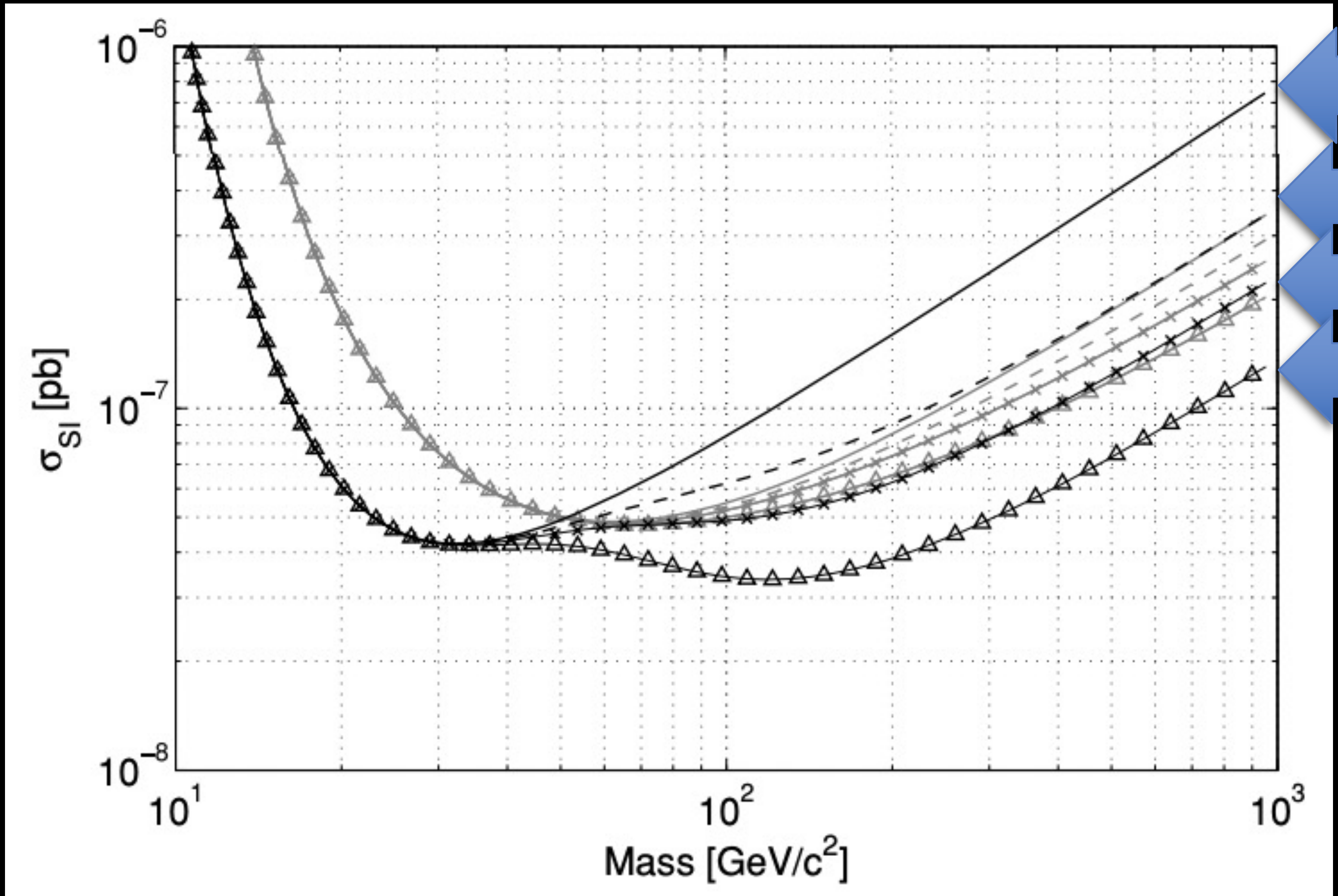




$$\text{Rate} \propto \rho_{DM} \int_{v_{\rm min}}^{\infty} \frac{f(v)}{v}\, dv$$

$$v_{\rm min} = v_{\rm min}(E_{\rm thresh}, m_\chi)$$

Effect of Dark Disk on Direct Detection



No Dark Disk

$\rho_d/\rho_h = 0.5$

$\rho_d/\rho_h = 1$

$\rho_d/\rho_h = 2$

ρ_d : Dark Disk Density

ρ_h : Dark Halo Density

Bruch et al. (2008)

Simulation Analog

NEXT:

- Observational study of Nyx
- Correlating dark matter and stars in streams
- Estimating relative contribution of dark matter in Nyx
- Estimating relative contribution of Dark Subhalos to the local Dark Matter

Simulation Analog

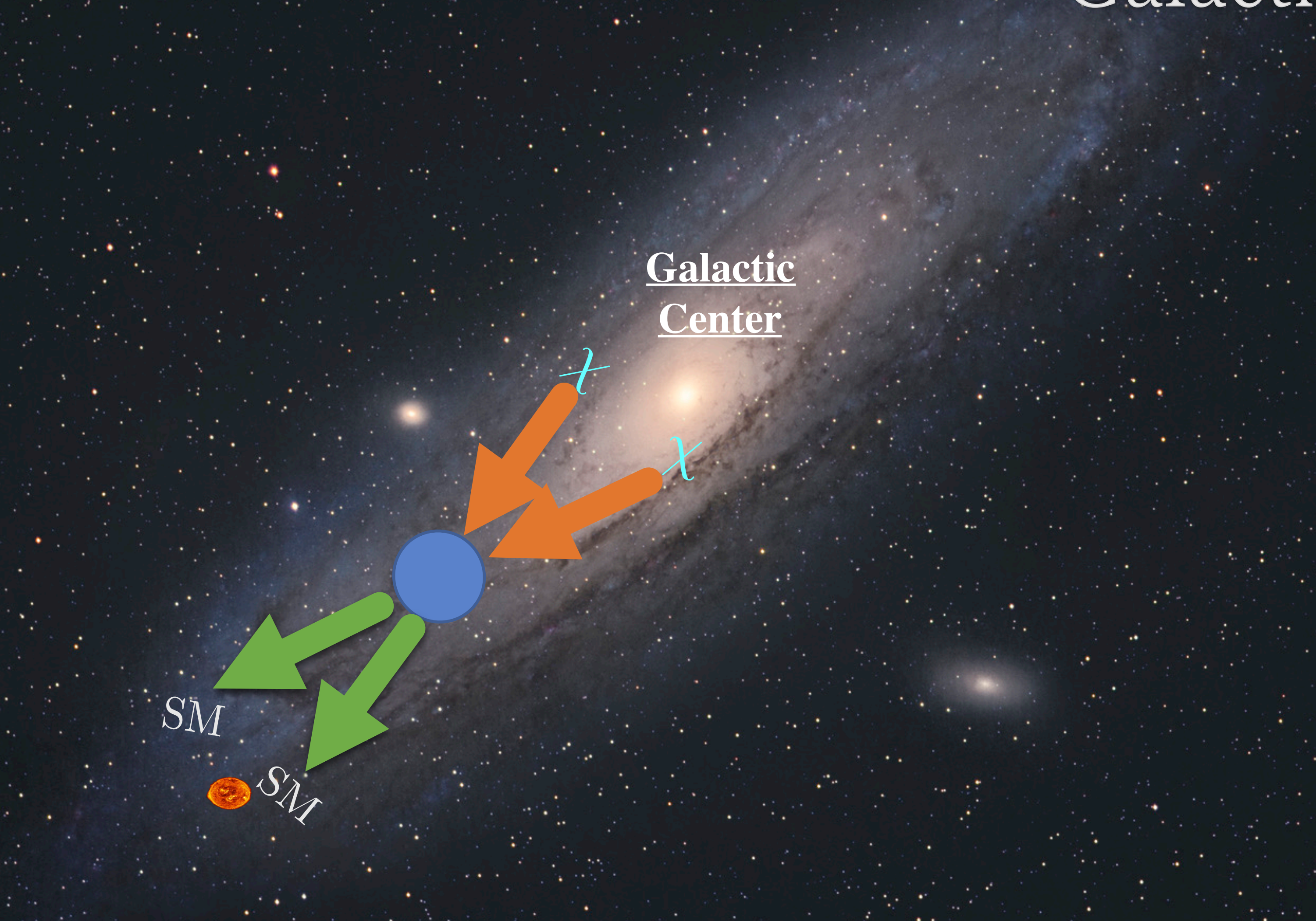
NEXT:

- Observational study of Nyx
- Correlating dark matter and stars in streams
- Estimating relative contribution of da… matter in Nyx
- Estimating relative contribution of Da… Subhalos to the local Dark Matter

Using Keck and Magellan, with Alex Ji, Mimi Truong, Allison Strom, and Mia de los Reyes, we observed a selection of Nyx stars.
So far, the majority is consistent with the thick disk. However, we have an interesting low metallicity tail to investigate.

Credit: Anna Frebel

Dark Matter in the Galactic Center



Lina Necib, MIT

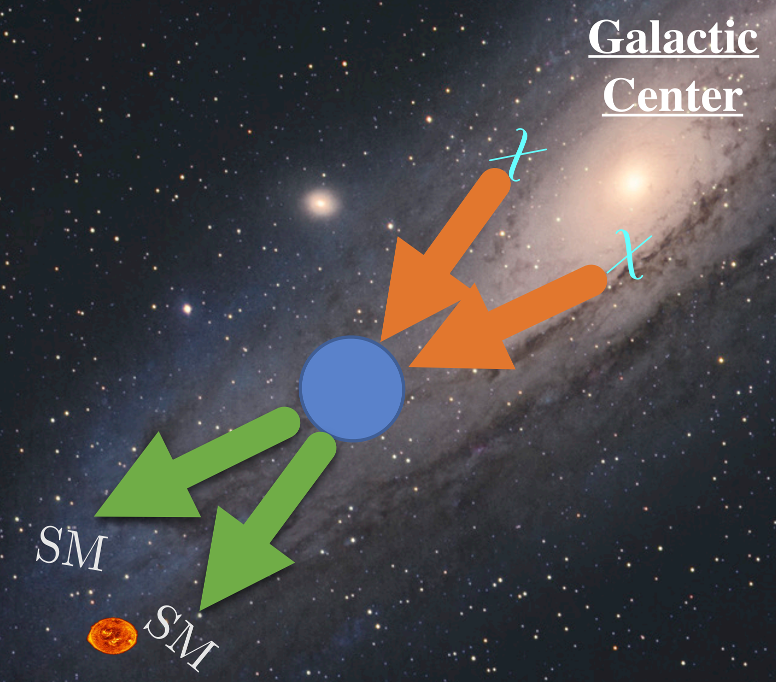
https://www.ge.com/reports/5-coolest-things-earth-week-29-6/andromeda-galaxy/

Dark Matter in the Galactic Center

J factor:

Integrated density squared of Dark Matter along the line of sight.

$$J = \int ds \int d\Omega \; \rho^2$$



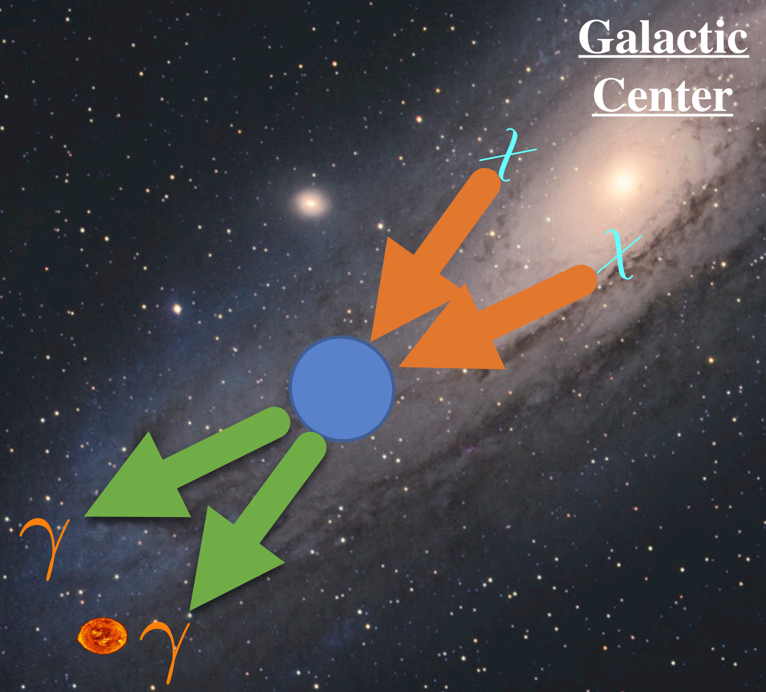
Pros	Cons
• Largest Density of Dark Matter	• Largest Astrophysical Backgrounds

Lina Necib, MIT

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

Dark Matter in the Galactic Center

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}(i\not{D} + M)\chi$$



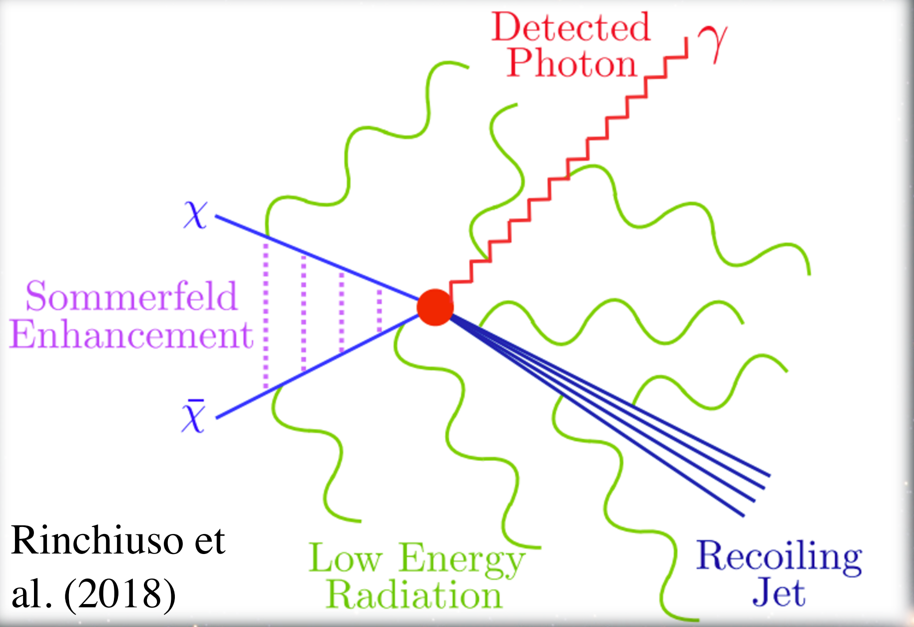
χ A simple extension of the Standard Model.
Single New Electroweak Triplet Fermion.
Expected in TeV mass scale, hard to probe in colliders.

Chardonnet, Salati, Fayet (1993)
Hisano et al. (2003, 2004, 2005, 2006, 2007)
Cirelli et al. (2006, 2007)

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

Example: Dark Matter Search at H.E.S.S.

Dark Matter in the Galactic Center



Rinchiuso et al. (2018)

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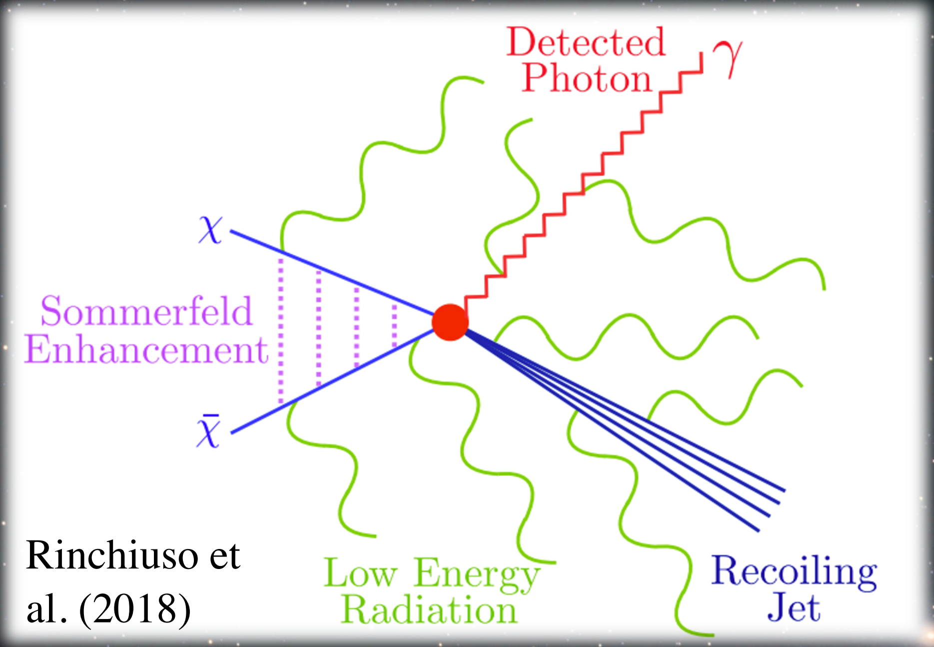

Rinchiuso et al. (2018)

$$N_{\text{signal}} = \text{Flux}_\gamma \times \text{Experimental Efficiency} \times \text{Exposure}$$

$$\propto \langle \sigma v \rangle \int_{\text{line of sight}} \int_{\text{angles}} \rho_\chi^2 \, d\Omega \, ds \times A_{\text{eff}}^\gamma$$

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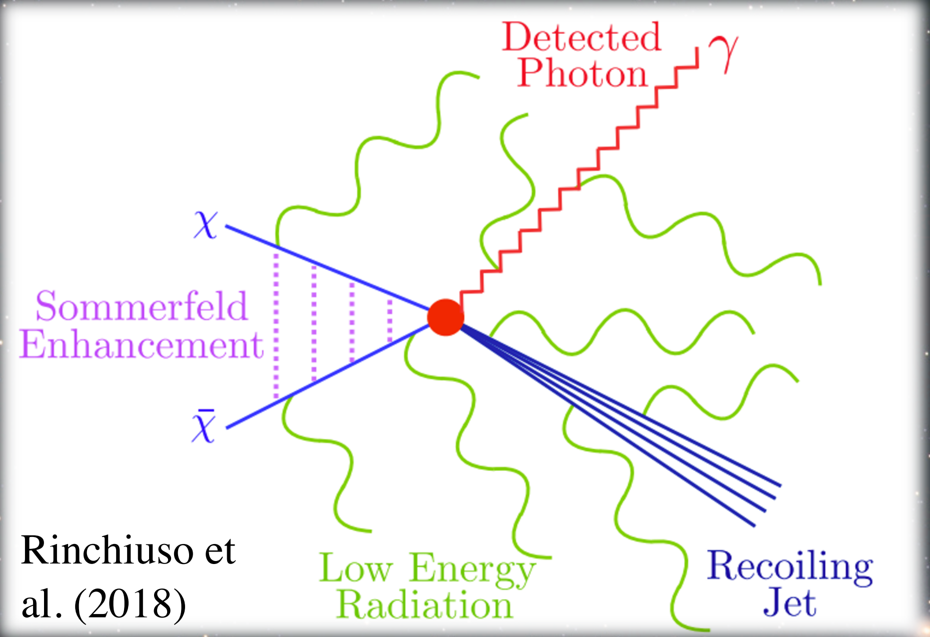

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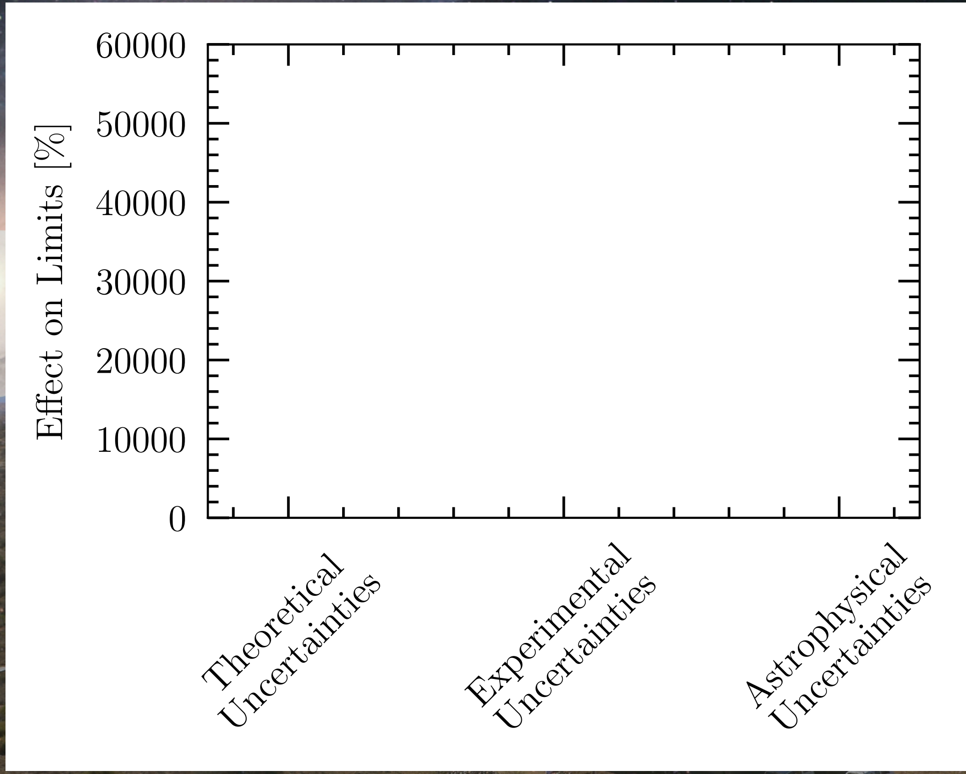

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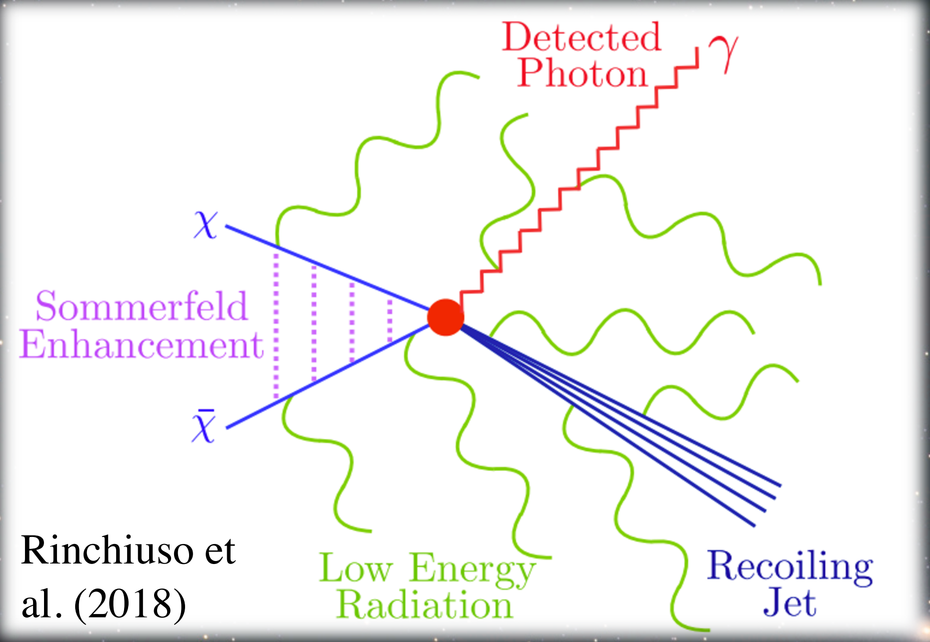

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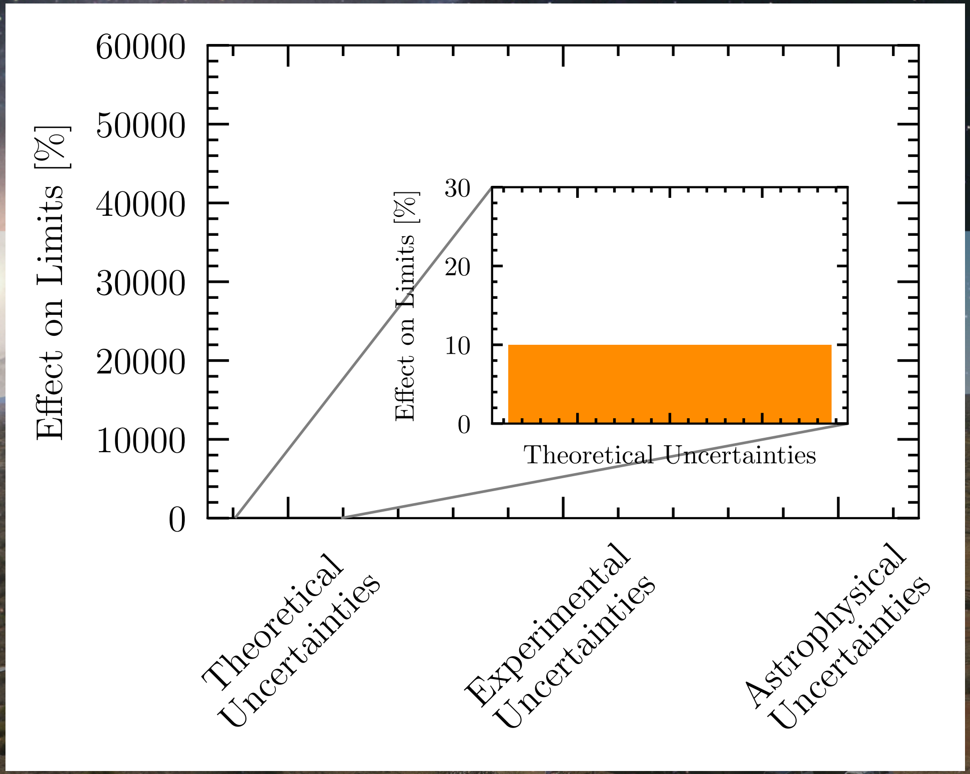
Bauer et al. (2015),
Ovanesyan et al. (2015),
Ovanesyan et al. (2017),
Baumgart et al. (2017),
Baumgart et al. (2018)



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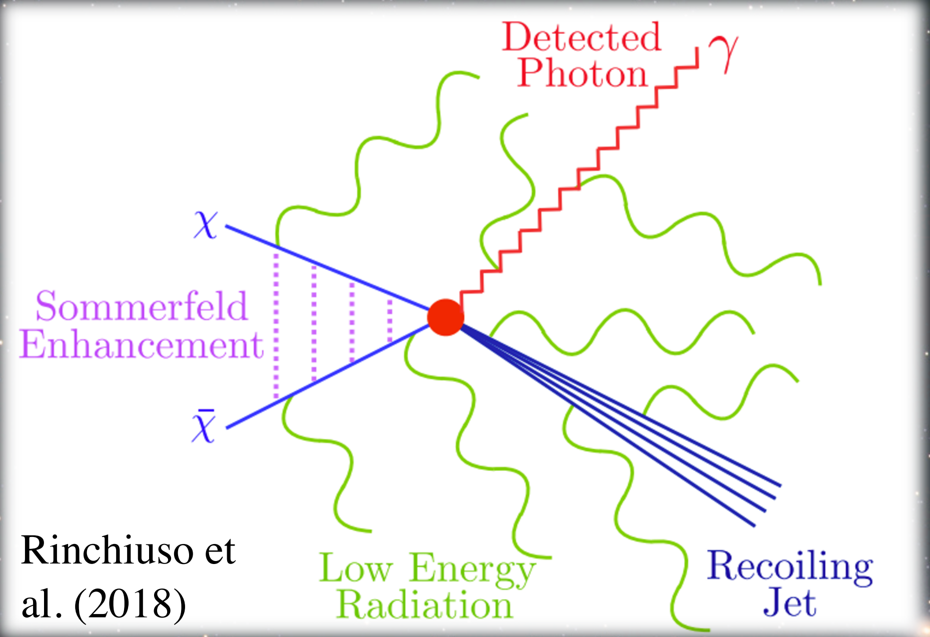
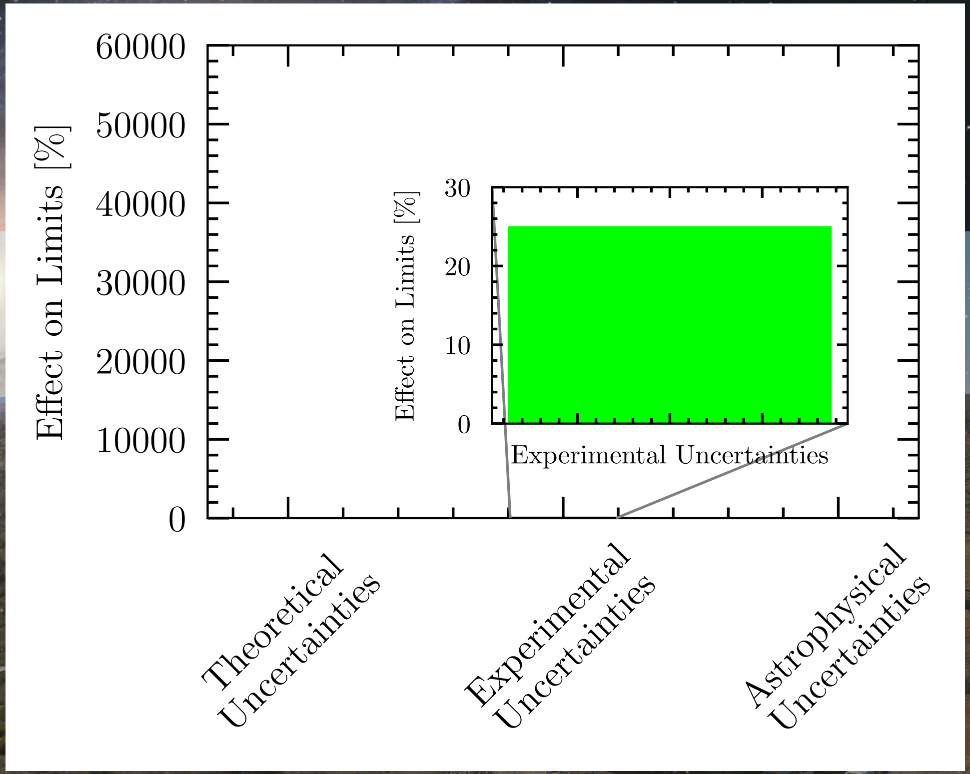
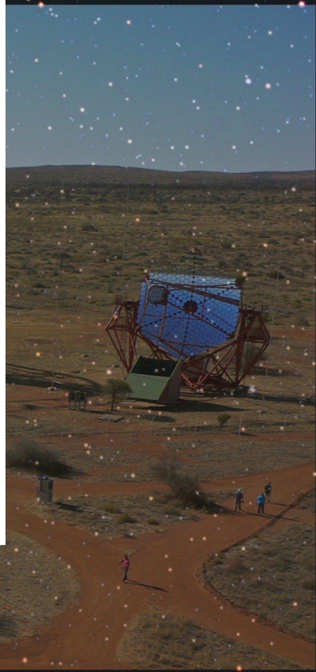


Rinchiuso et al. (2018)

Dark Matter in the Galactic Center





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H.E.S.S Collaboration (2006)
Holler et al. (2017)
H.E.S.S. Collaboration (2018)

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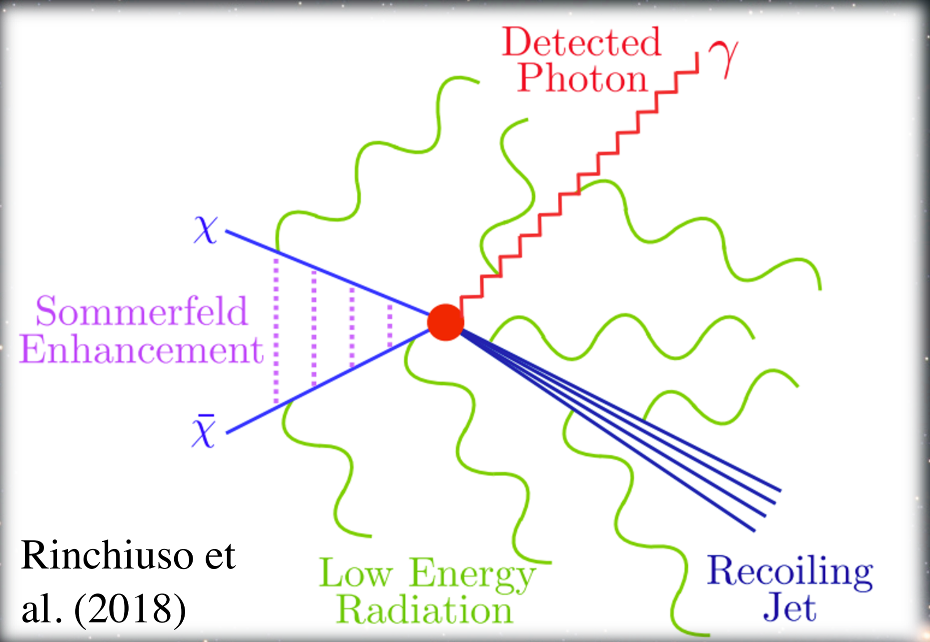

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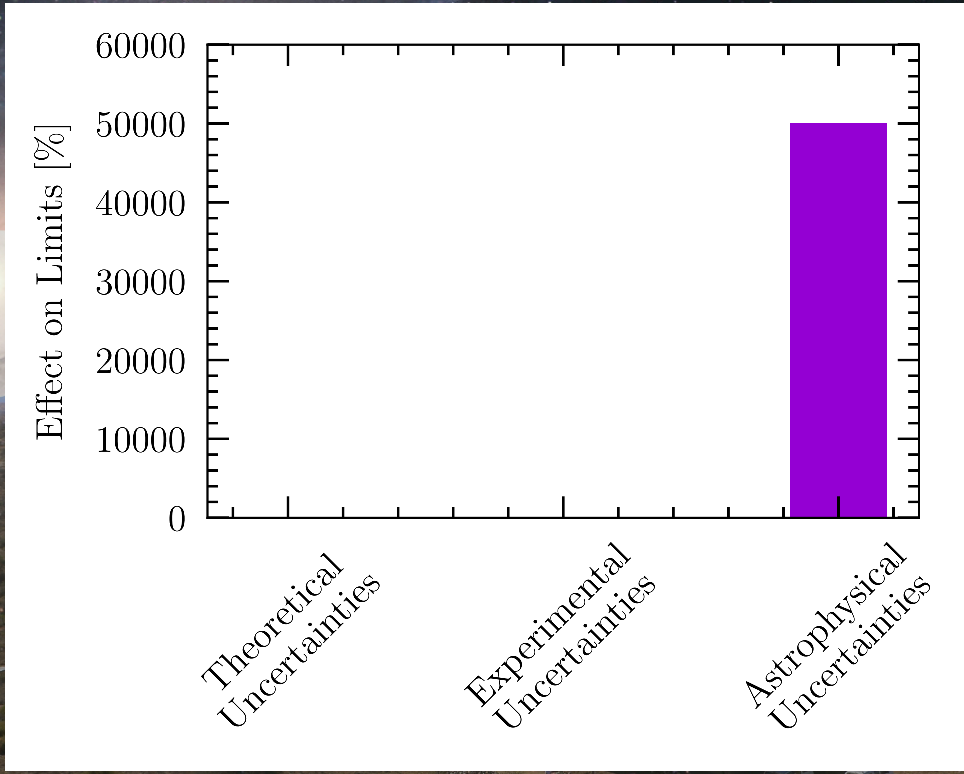
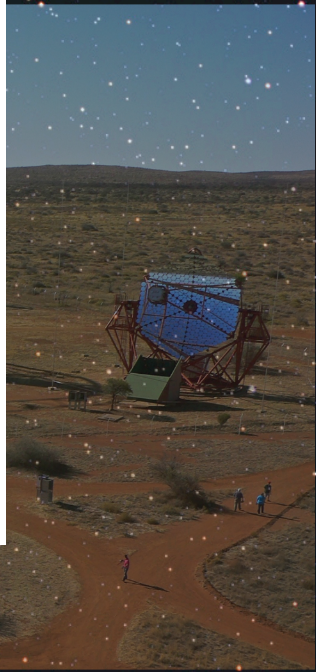
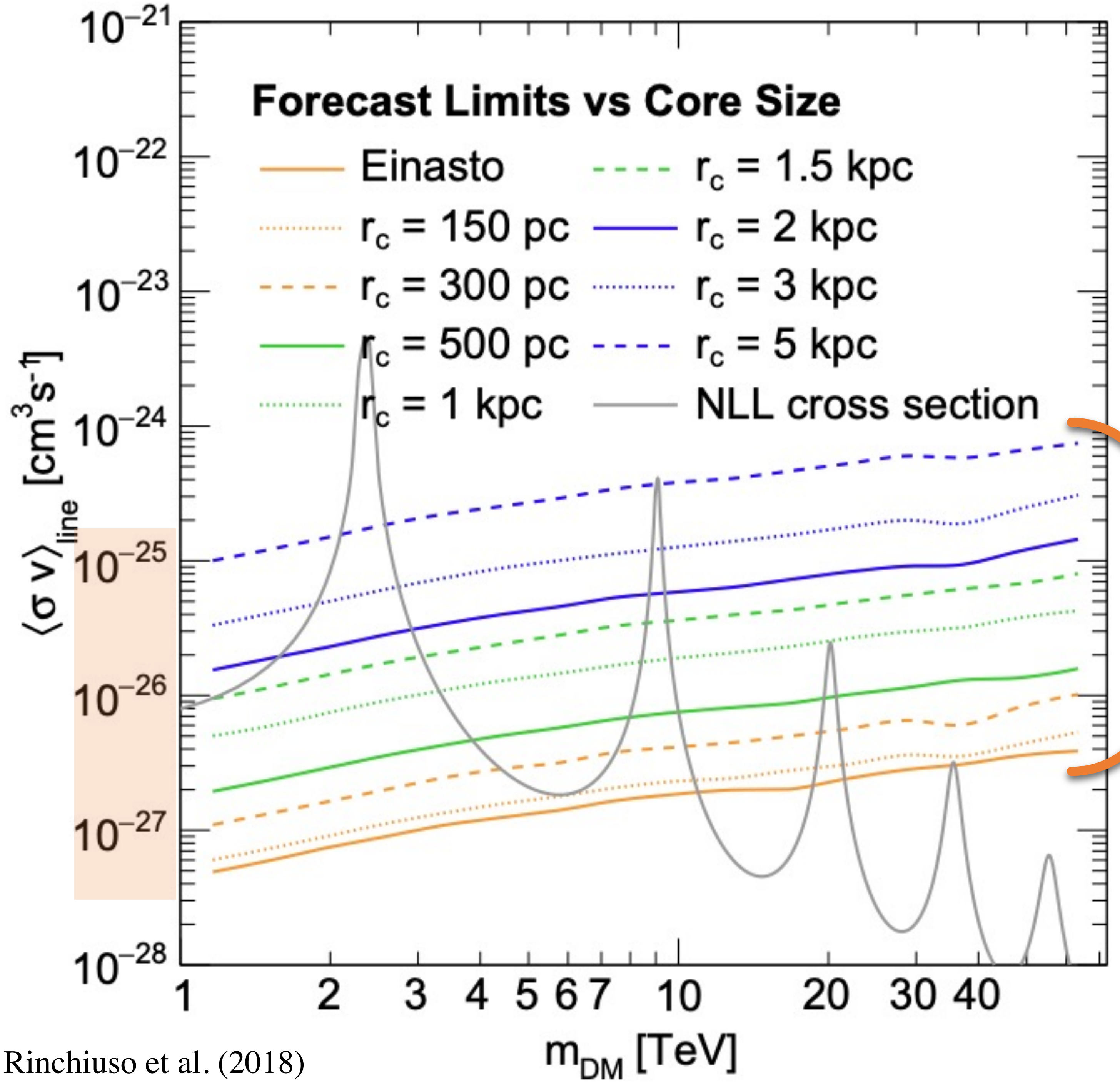




Einasto (1965)

By Klepser at English Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=61288242



Rinchiuso et al. (2018)

Dark Matter in the Galactic Center

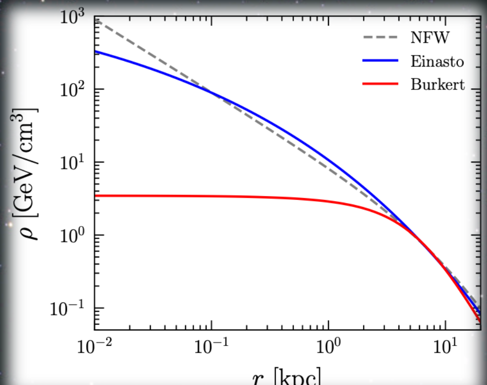
Different Profiles

$$J \propto \int \int_{\mathrm{l.o.s}} \rho^2 \; ds \; d\Omega$$

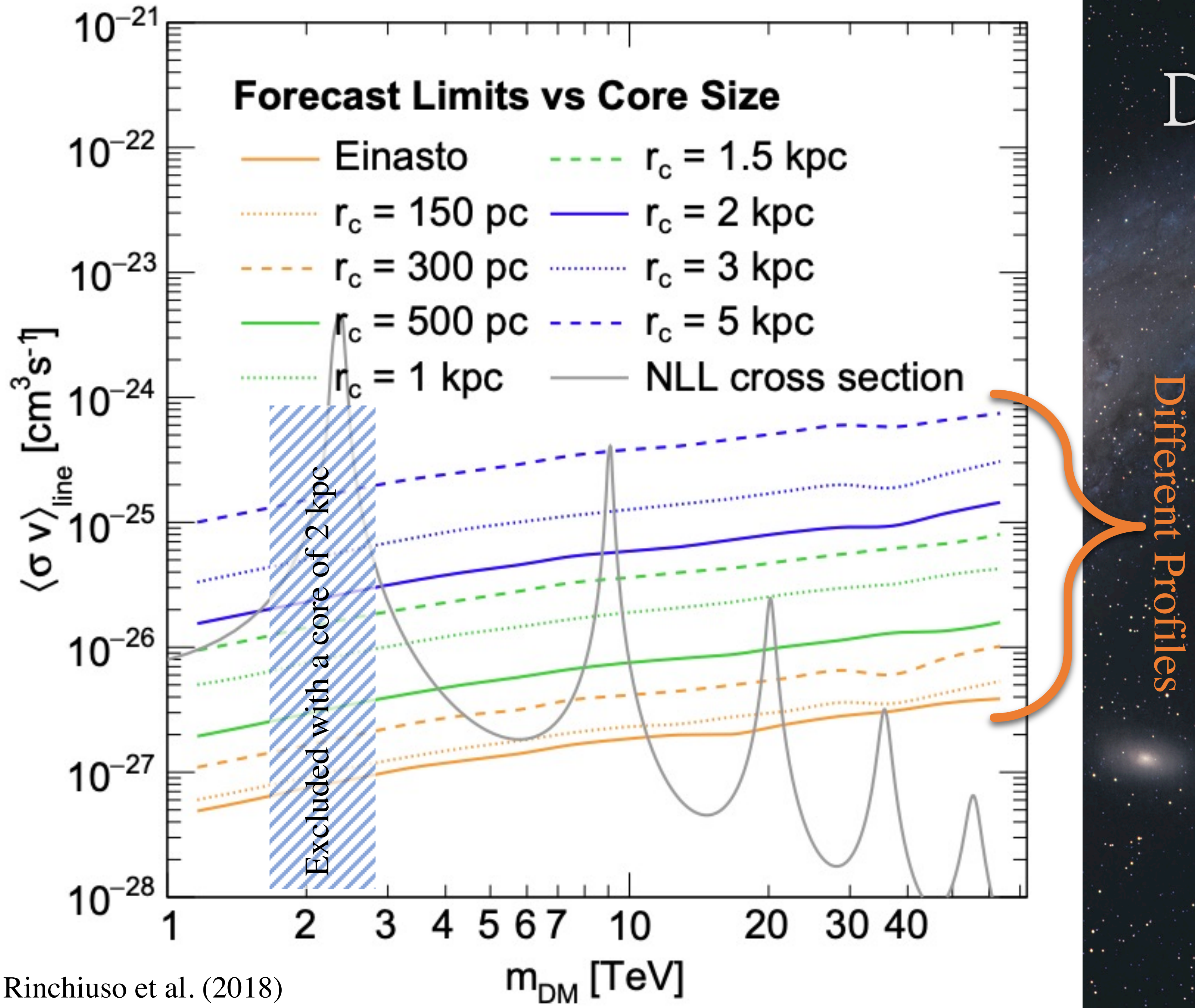
ρ : Dark Matter Density

ds : Line of Sight Integral

$d\Omega$: Solid Angle Integral



Dark Matter in the Galactic Center



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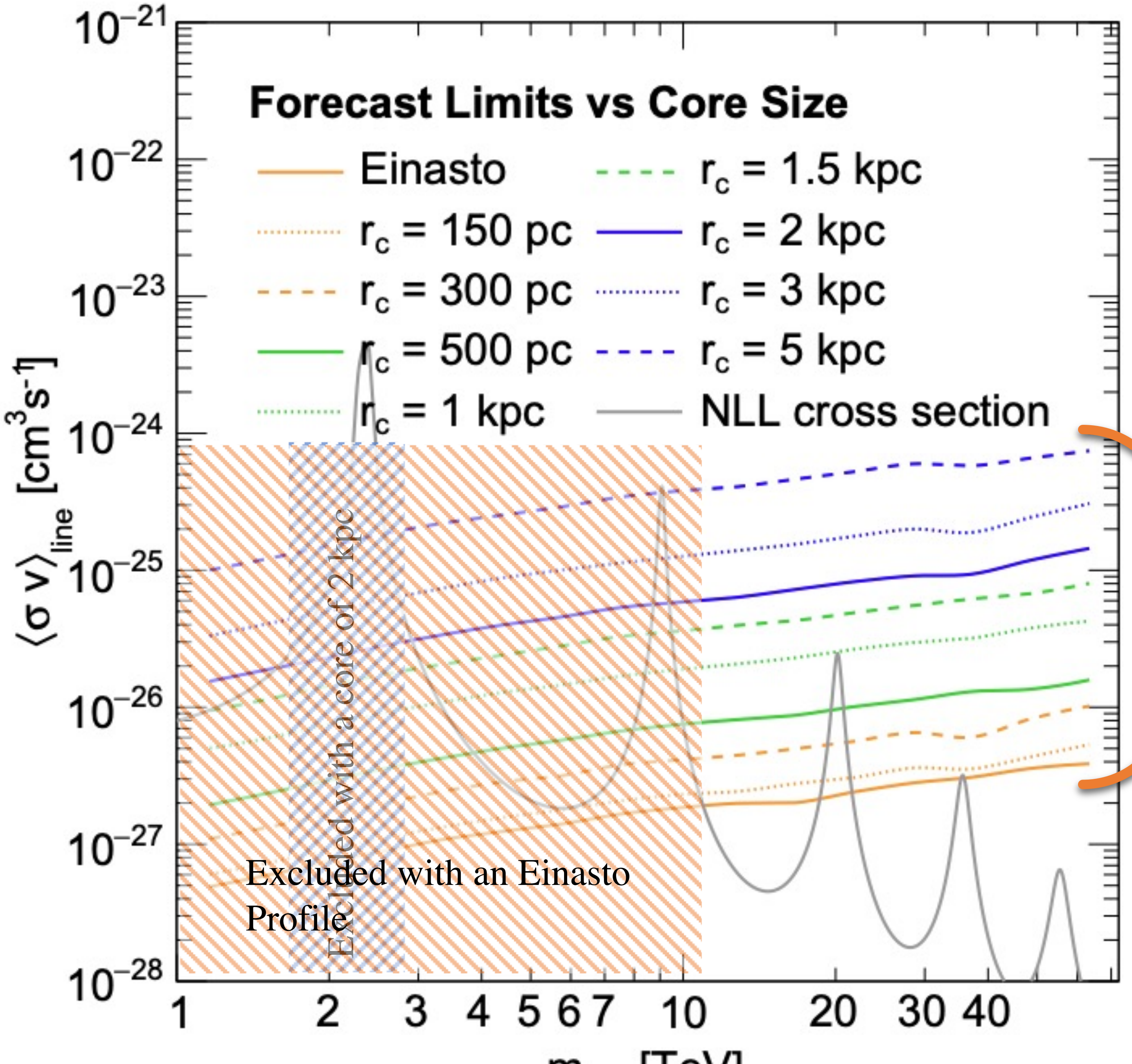

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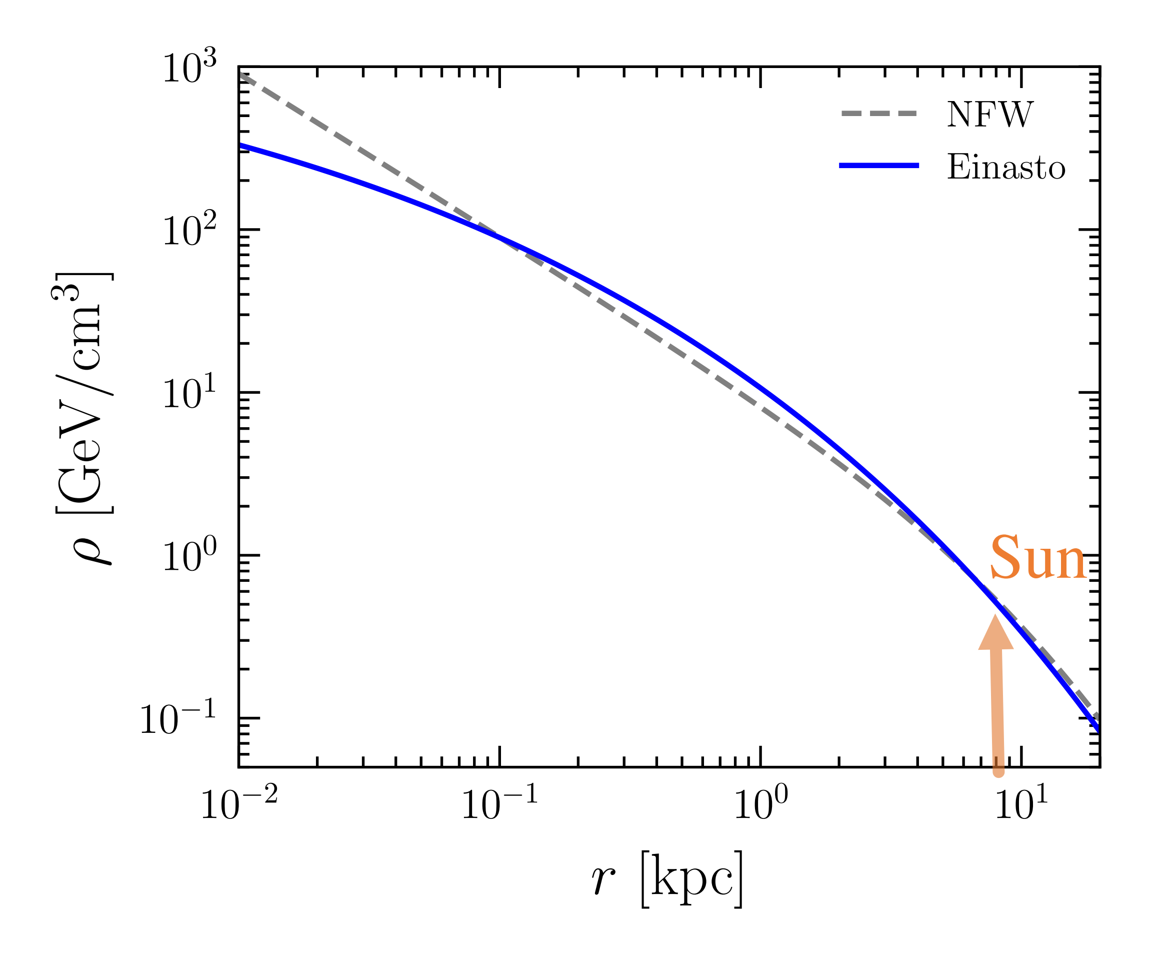
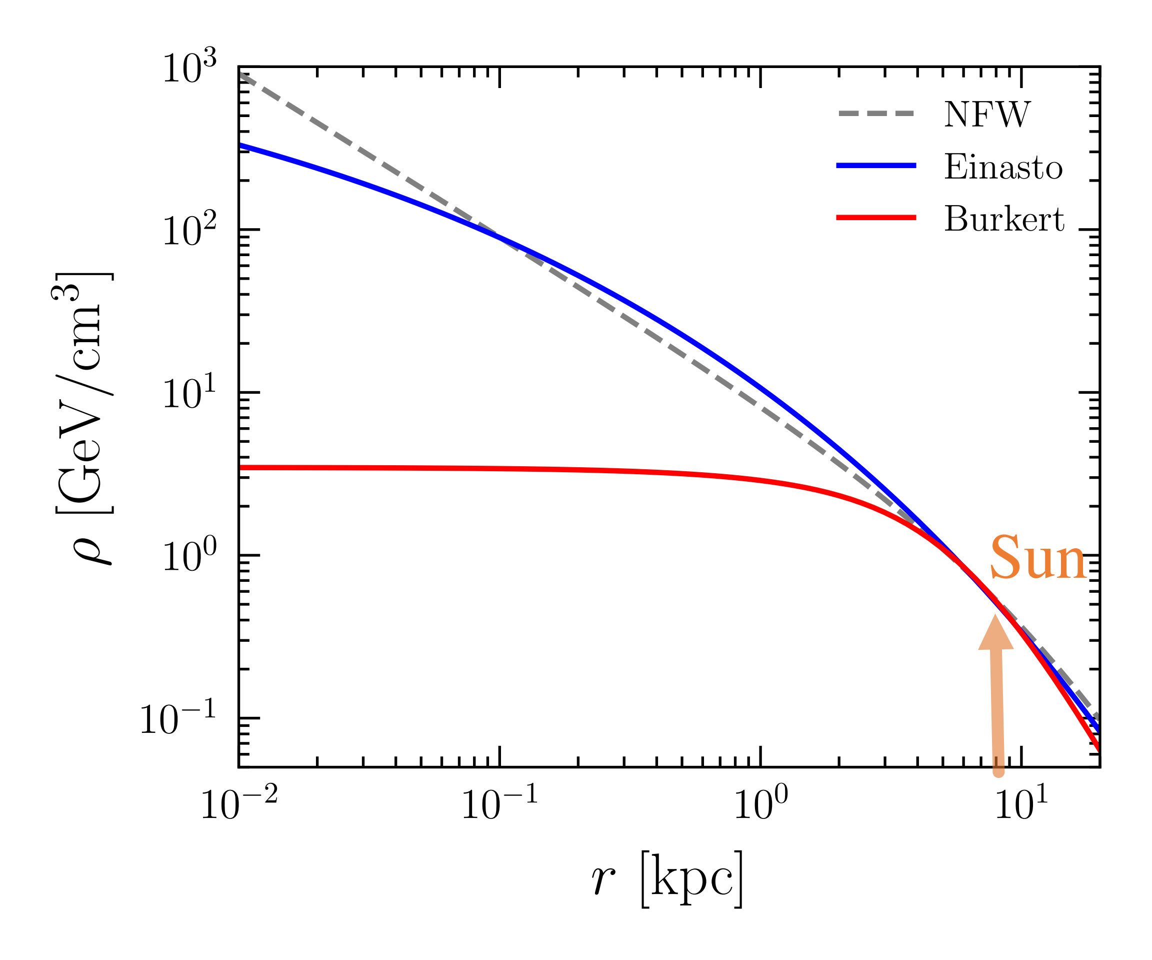
Dark Matter Density Distribution



Einasto (1965)
Navarro, Frenk, White (1996)
Fornasa & Green (2013)
Gaskins (2016)

Dark Matter Density Distribution

Density profiles can vary by orders of magnitude.



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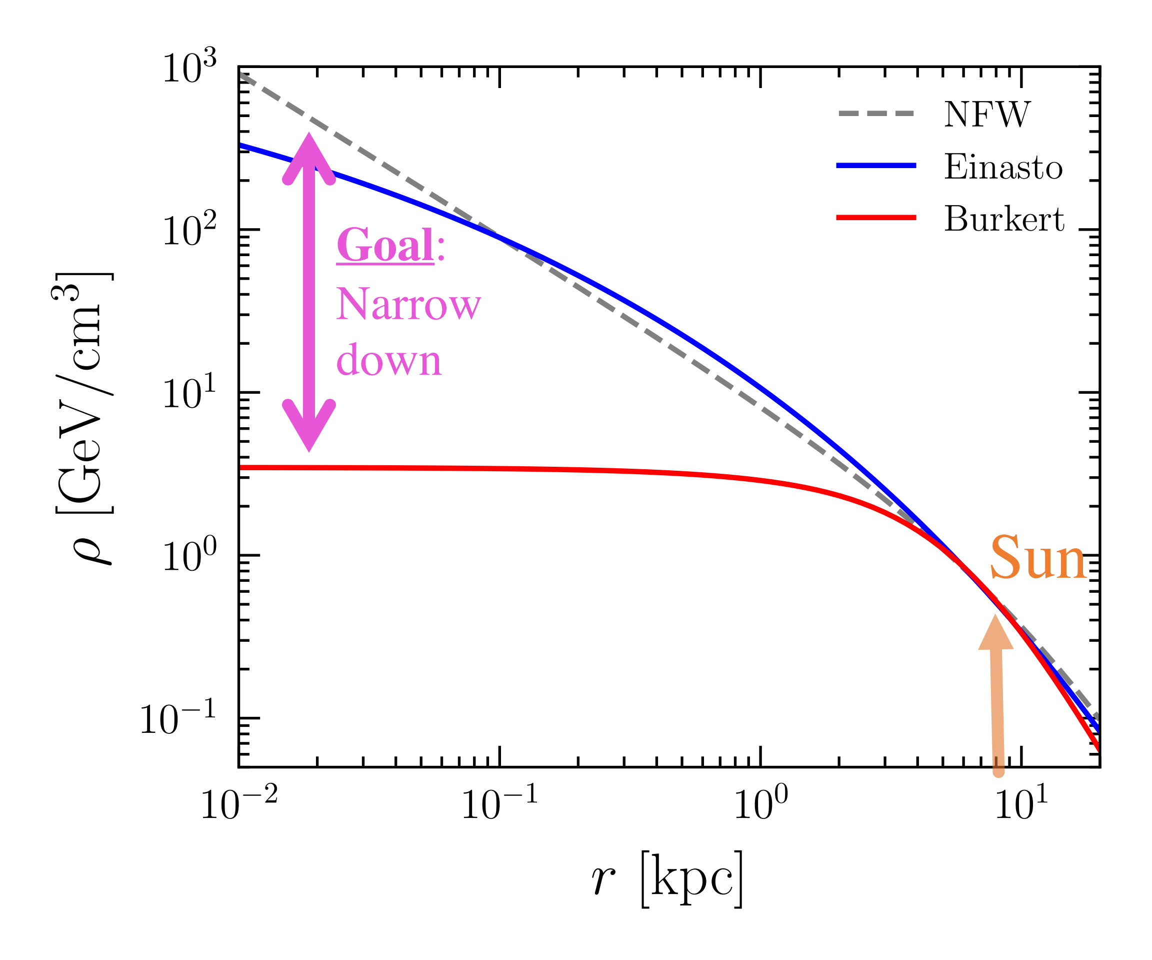

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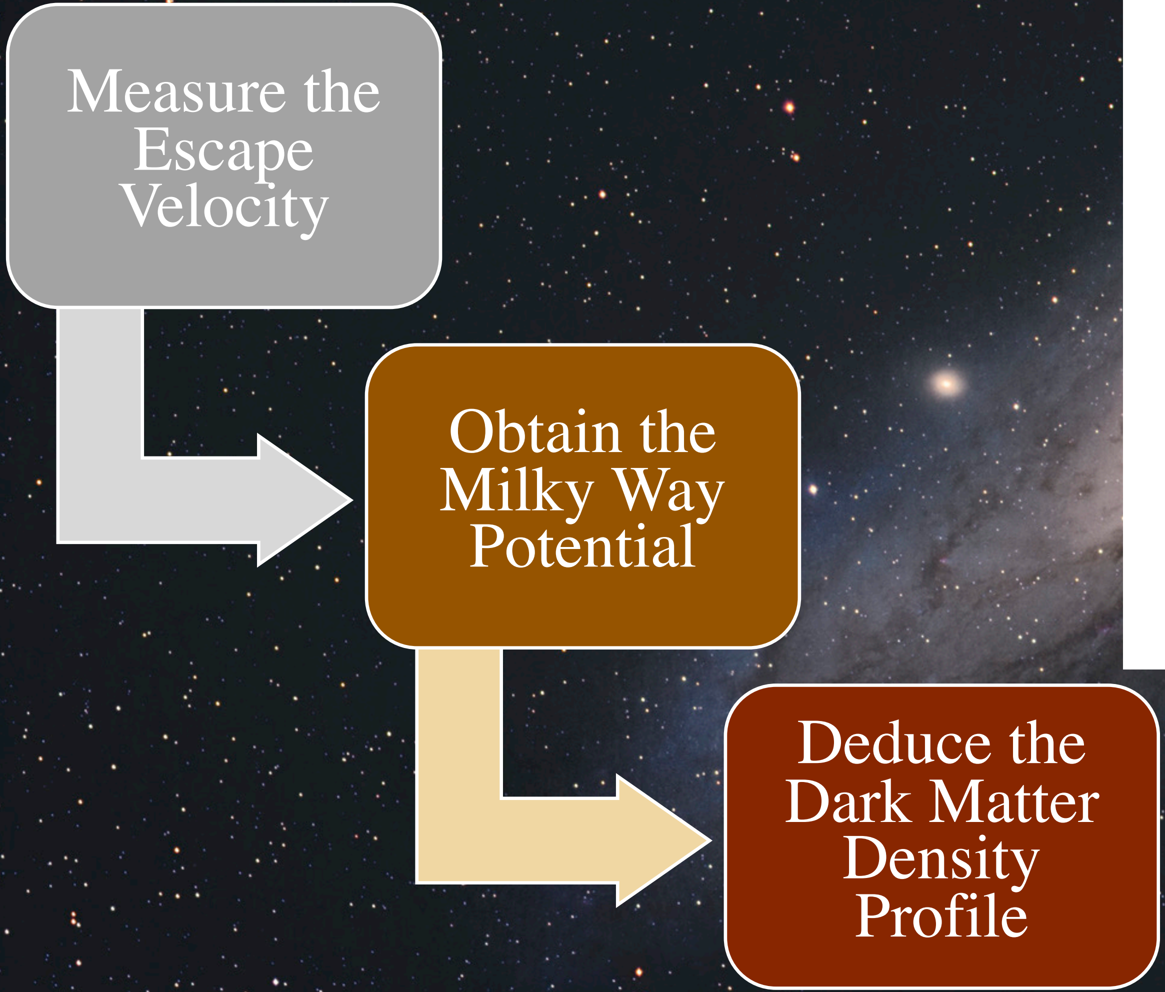

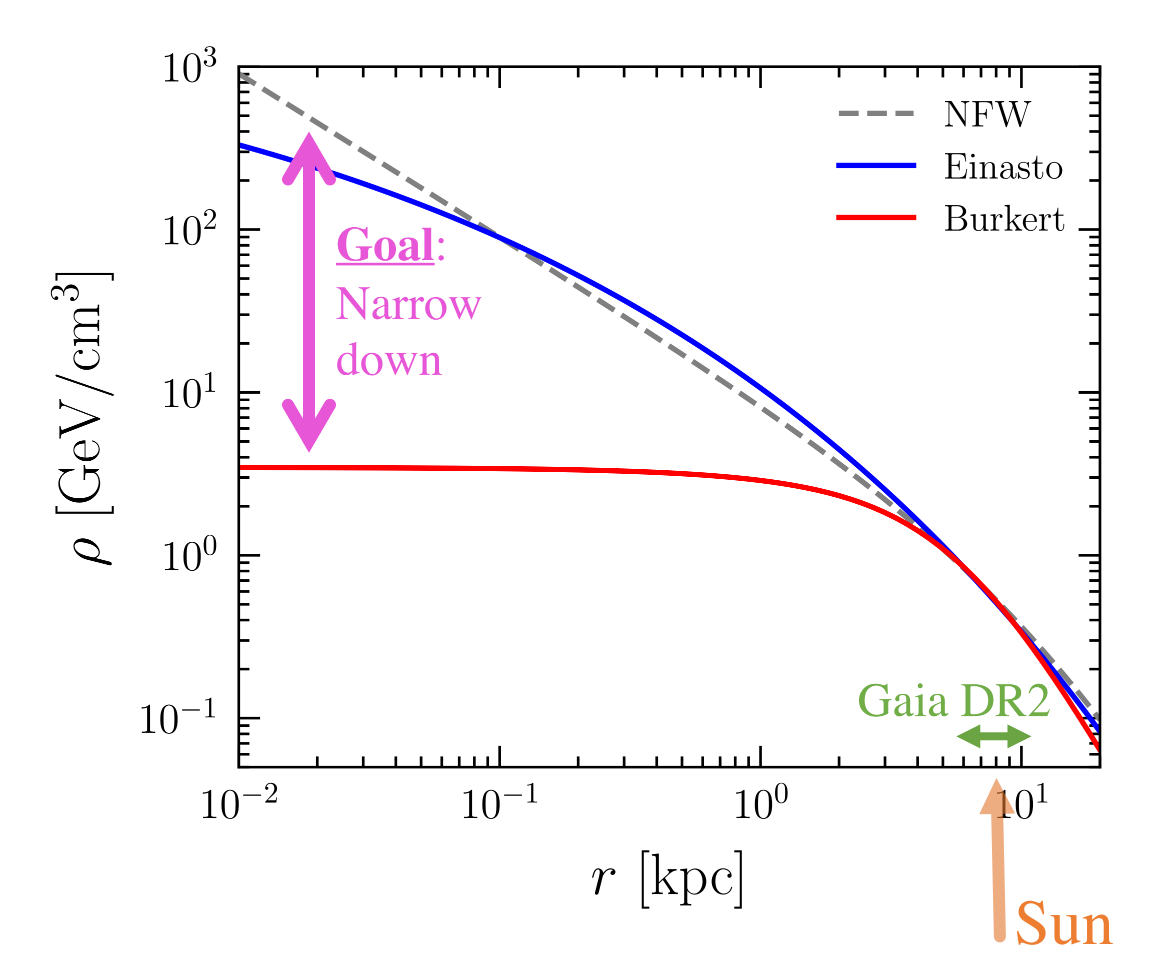

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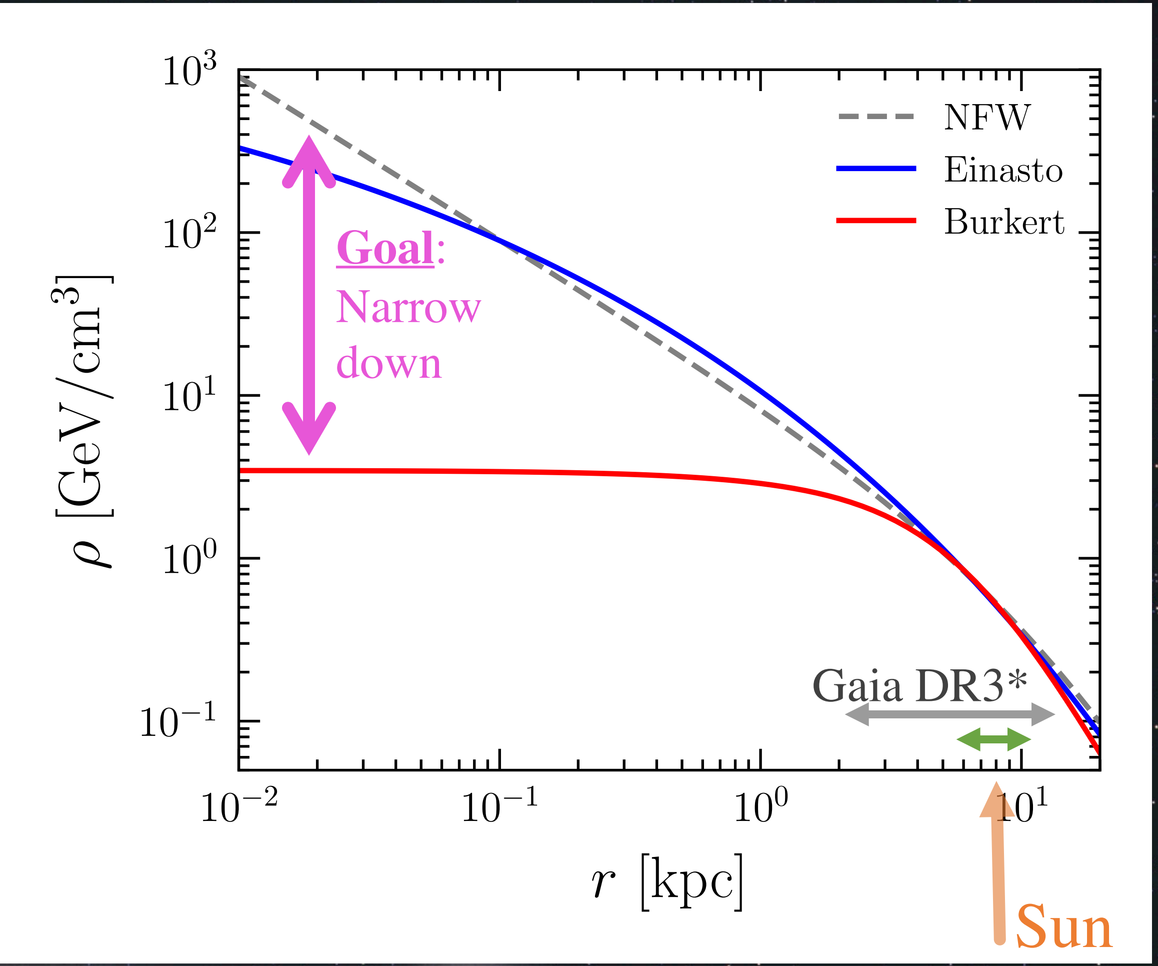
Lina Necib, MIT

Dark Matter Density Distribution

Measure the Escape Velocity

Obtain the Milky Way Potential

Deduce the Dark Matter Density Profile



(*Estimate)

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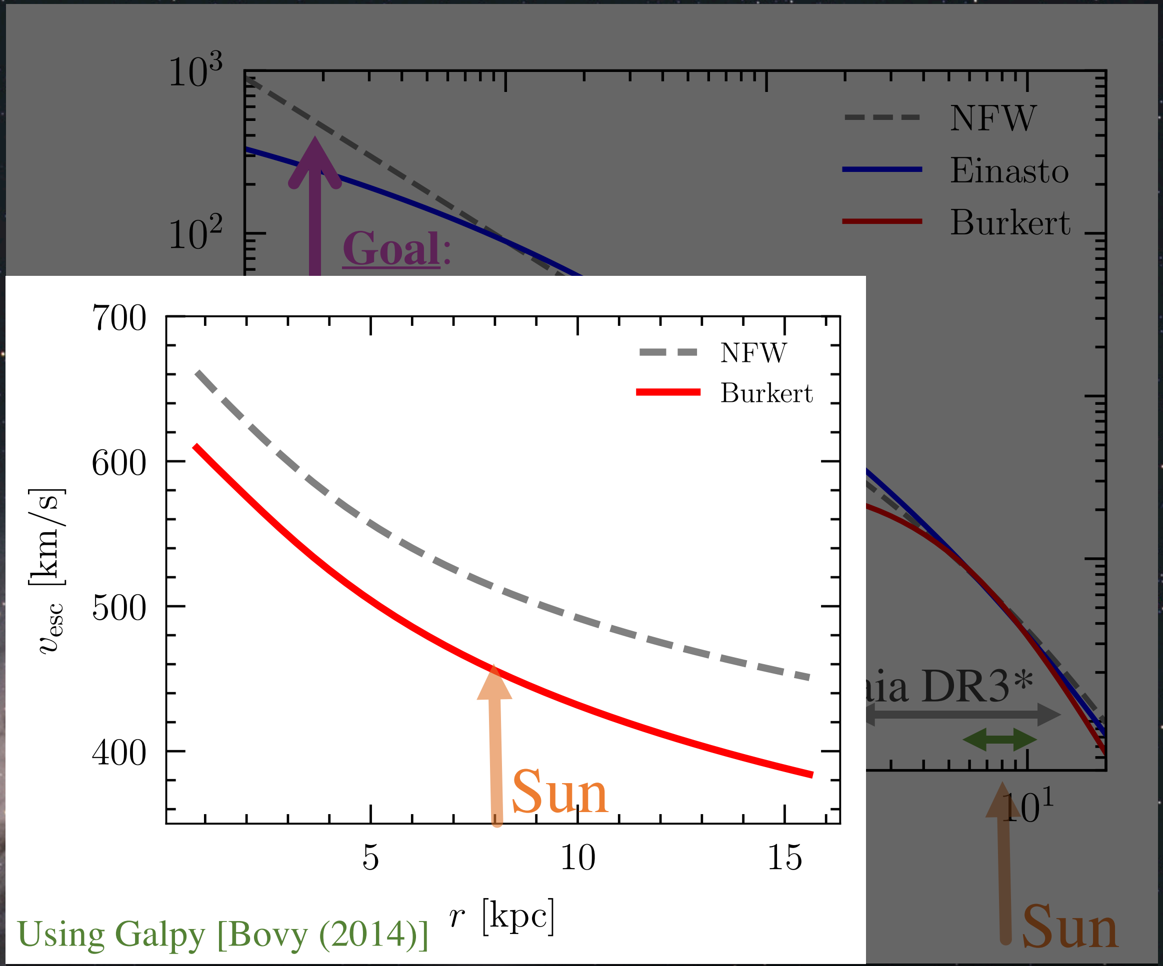

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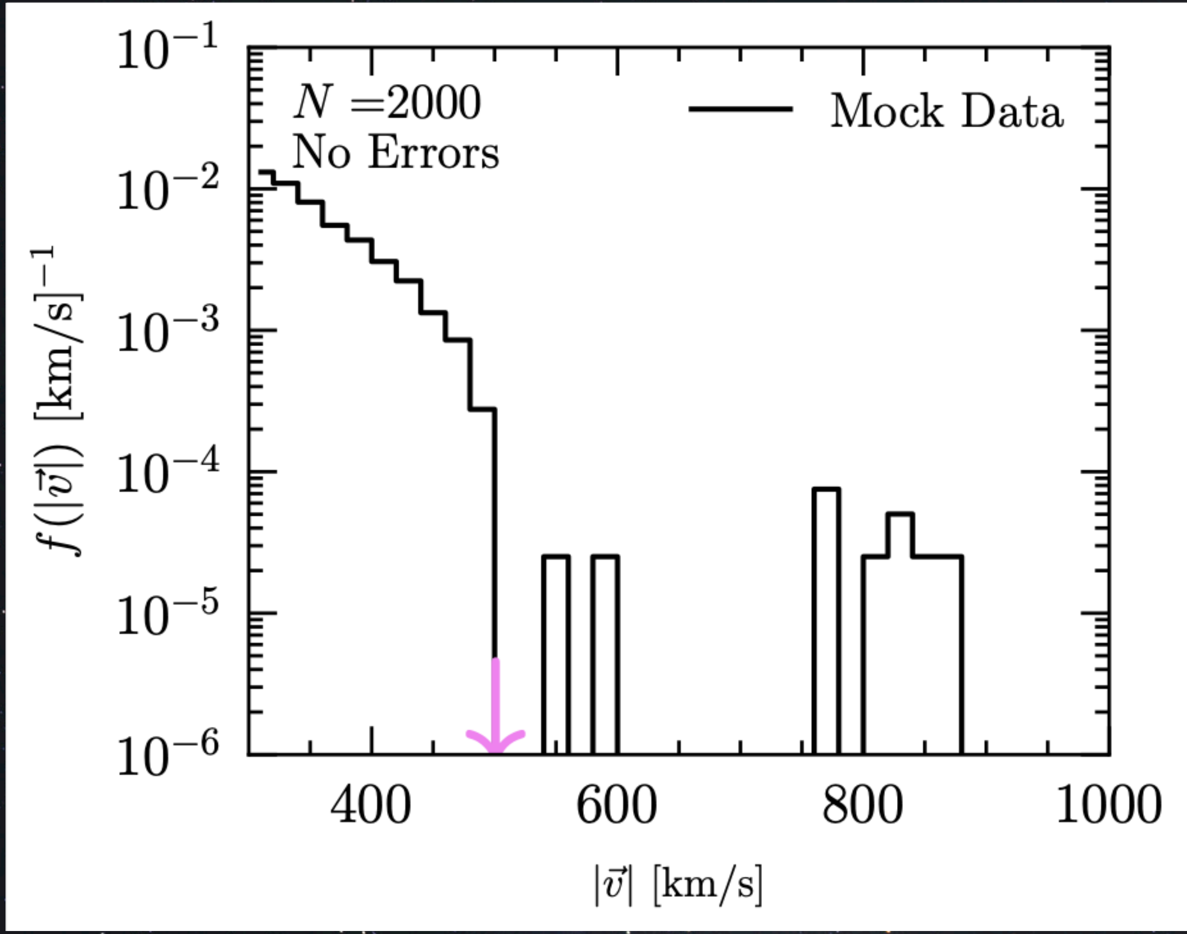
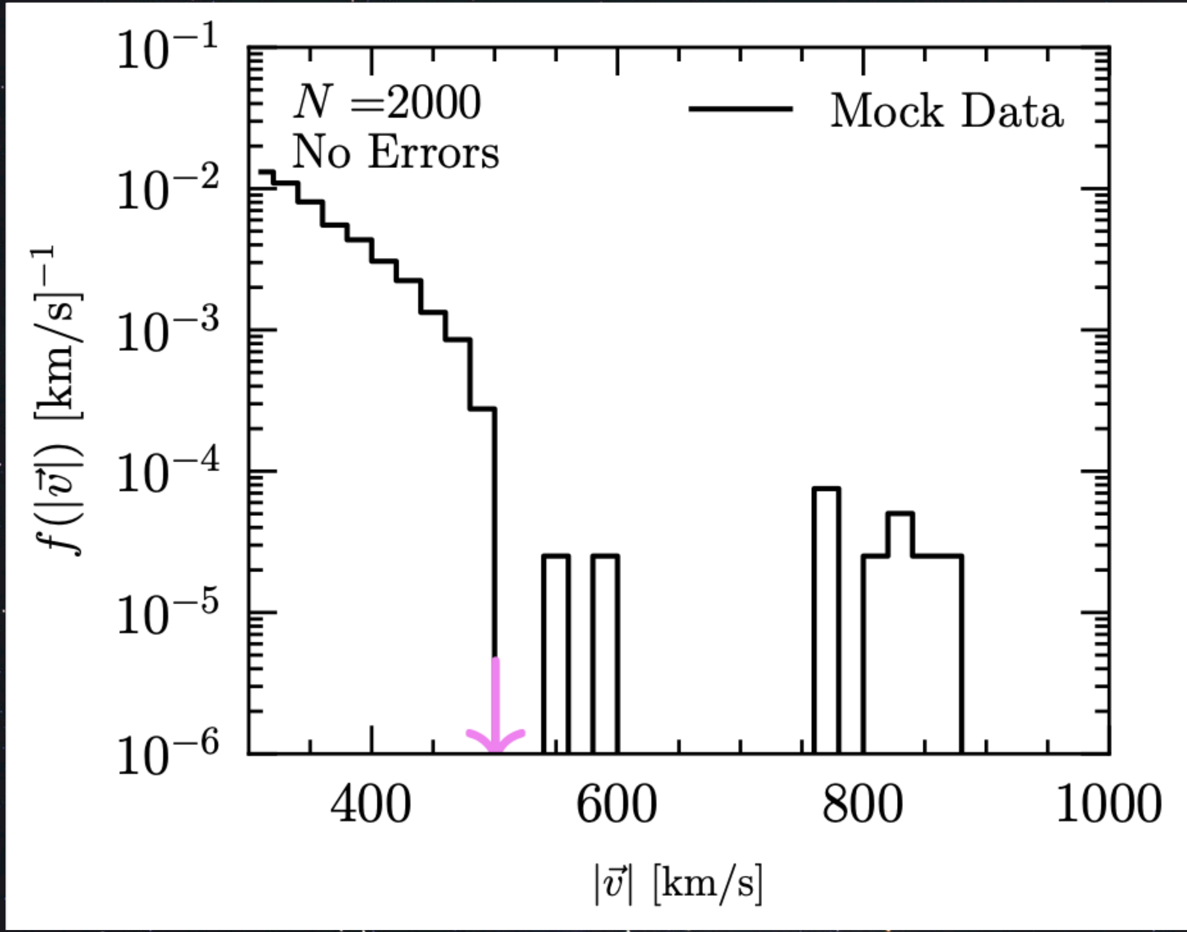
Determining the Escape Velocity



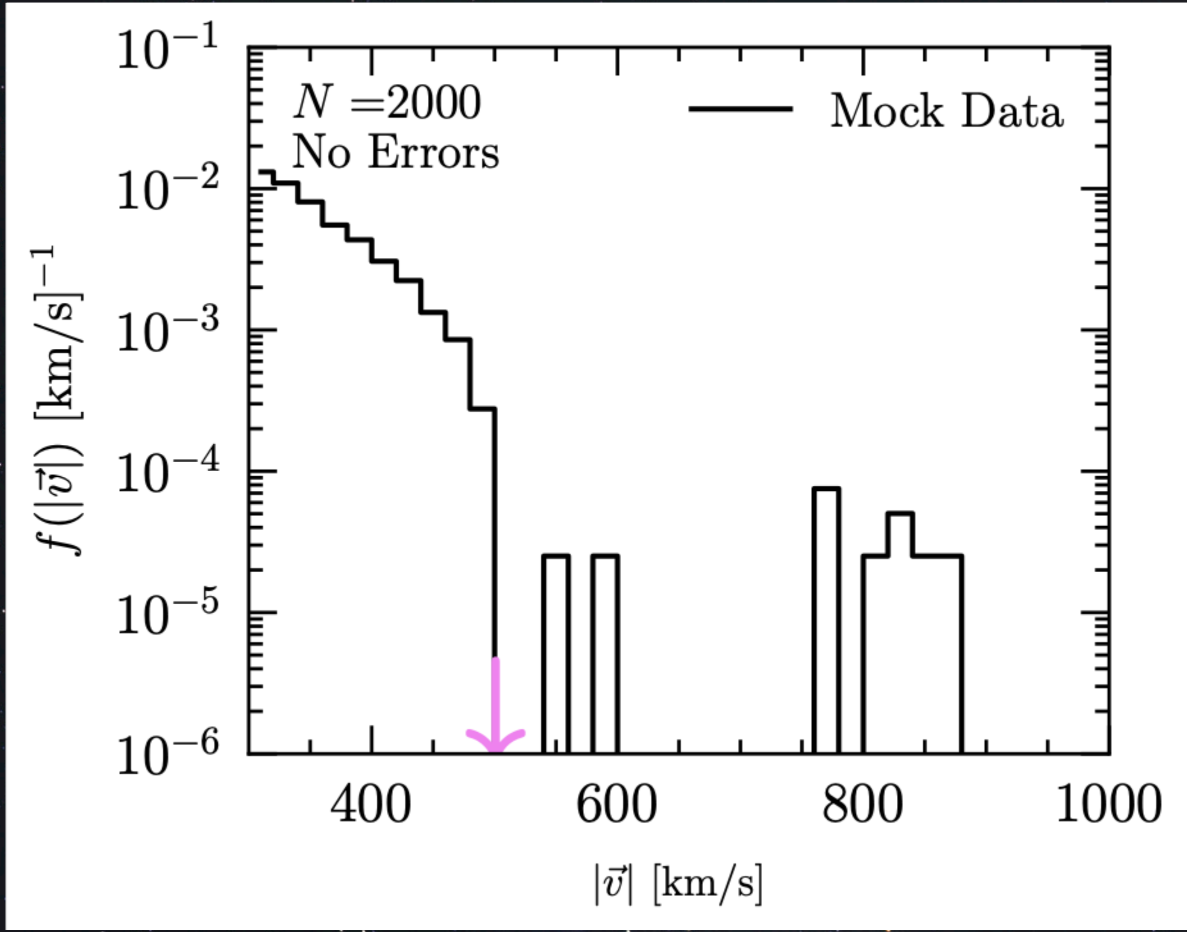
Necib & Lin,(2021a,b)

Determining the Escape Velocity



Goal:
Fit for the escape velocity

Determining the Escape Velocity



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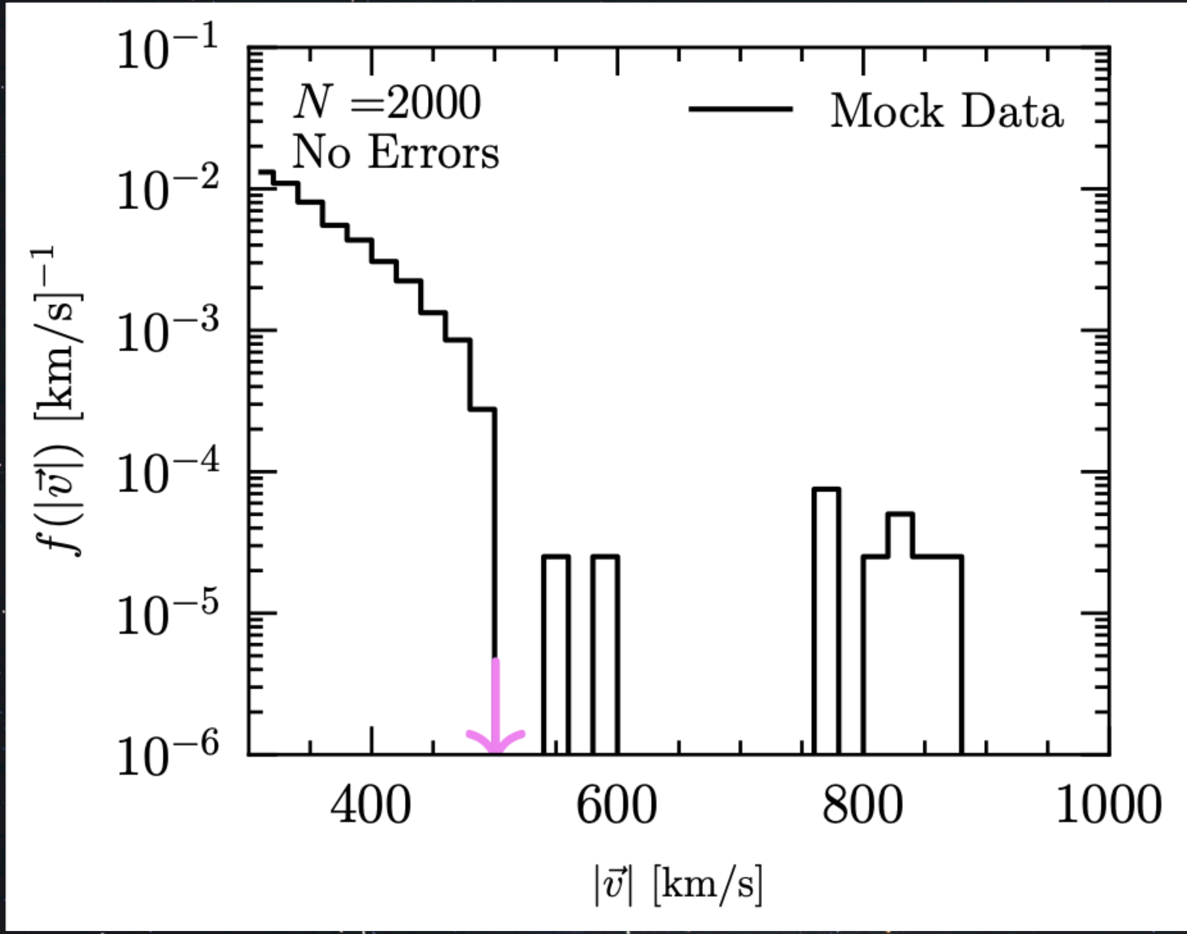
$$f(v) \propto (v_{\rm esc} - v)^k$$

$$v > v_{\rm min}$$

Leonard & Tremaine (1990)
Necib & Lin,(2021a,b)

Determining the Escape Velocity



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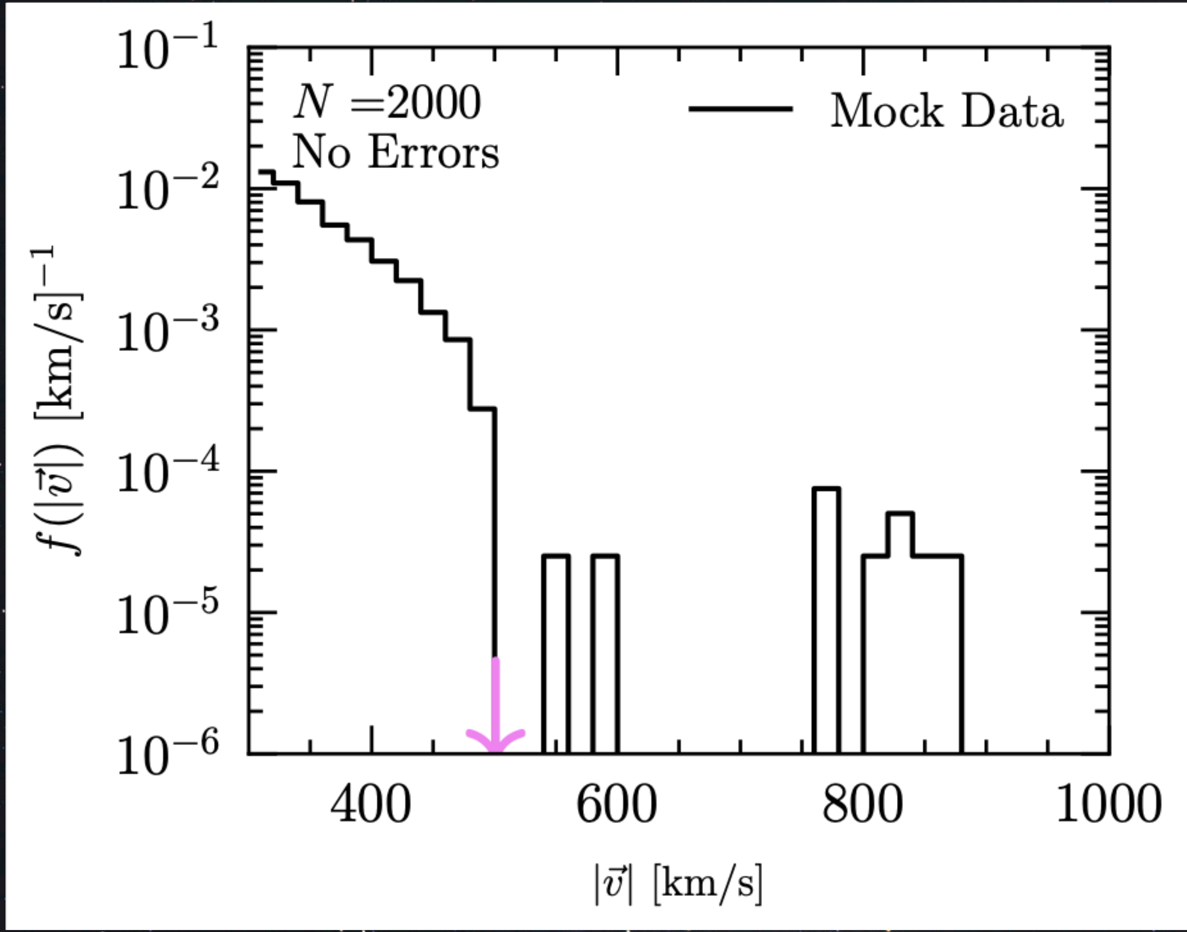
1. Take into account errors.
2. Presence of outliers.
3. Presence of multiple components.

Lina Necib, MIT

Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

Determining the Escape Velocity



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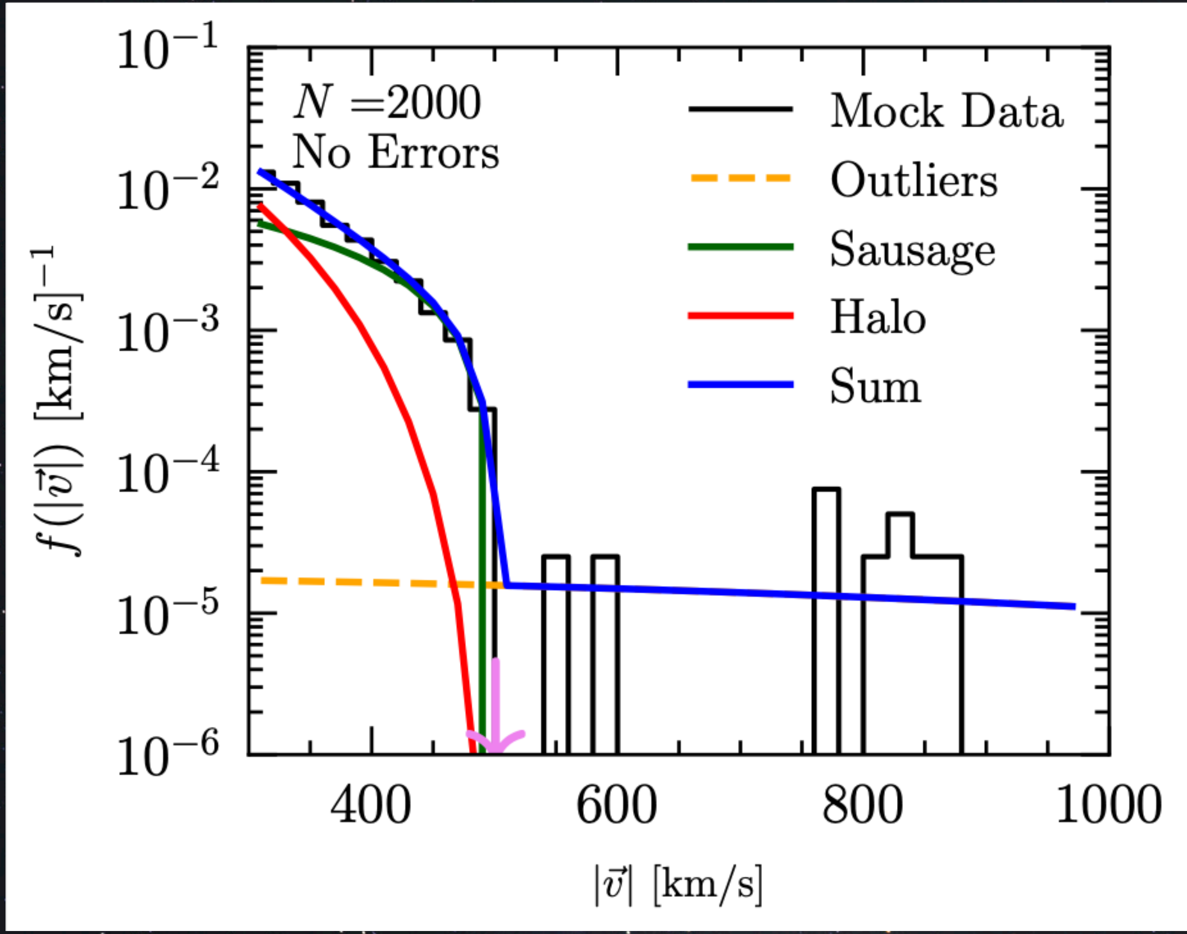

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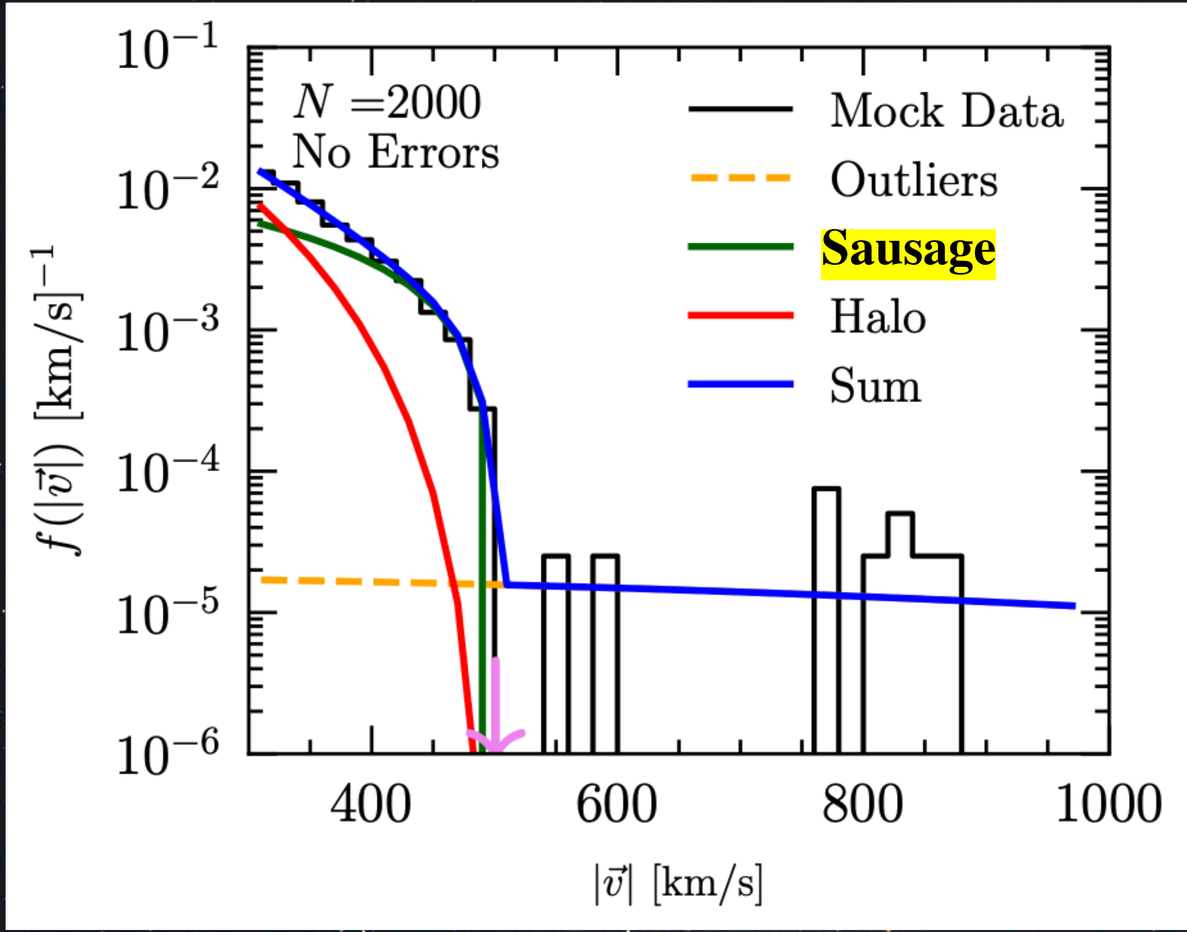

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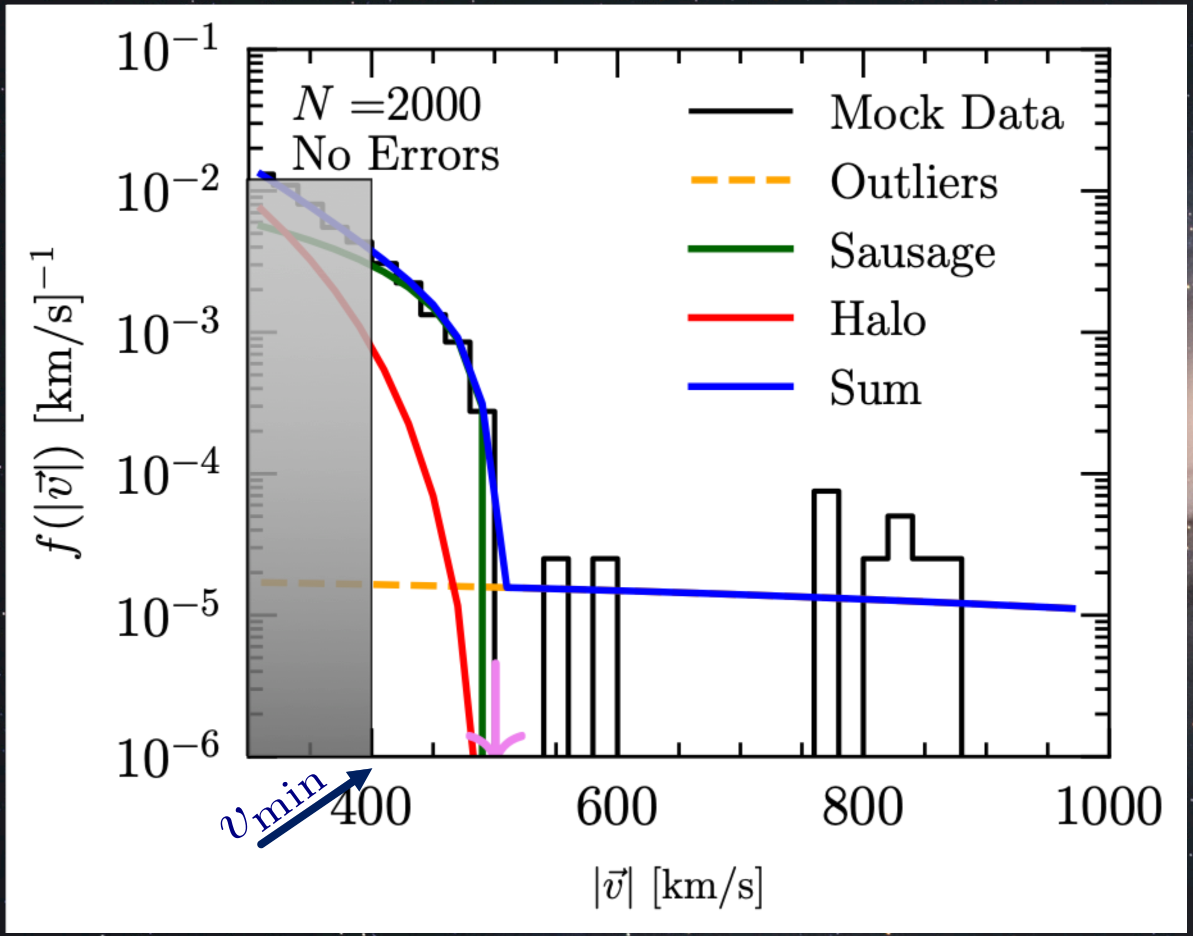

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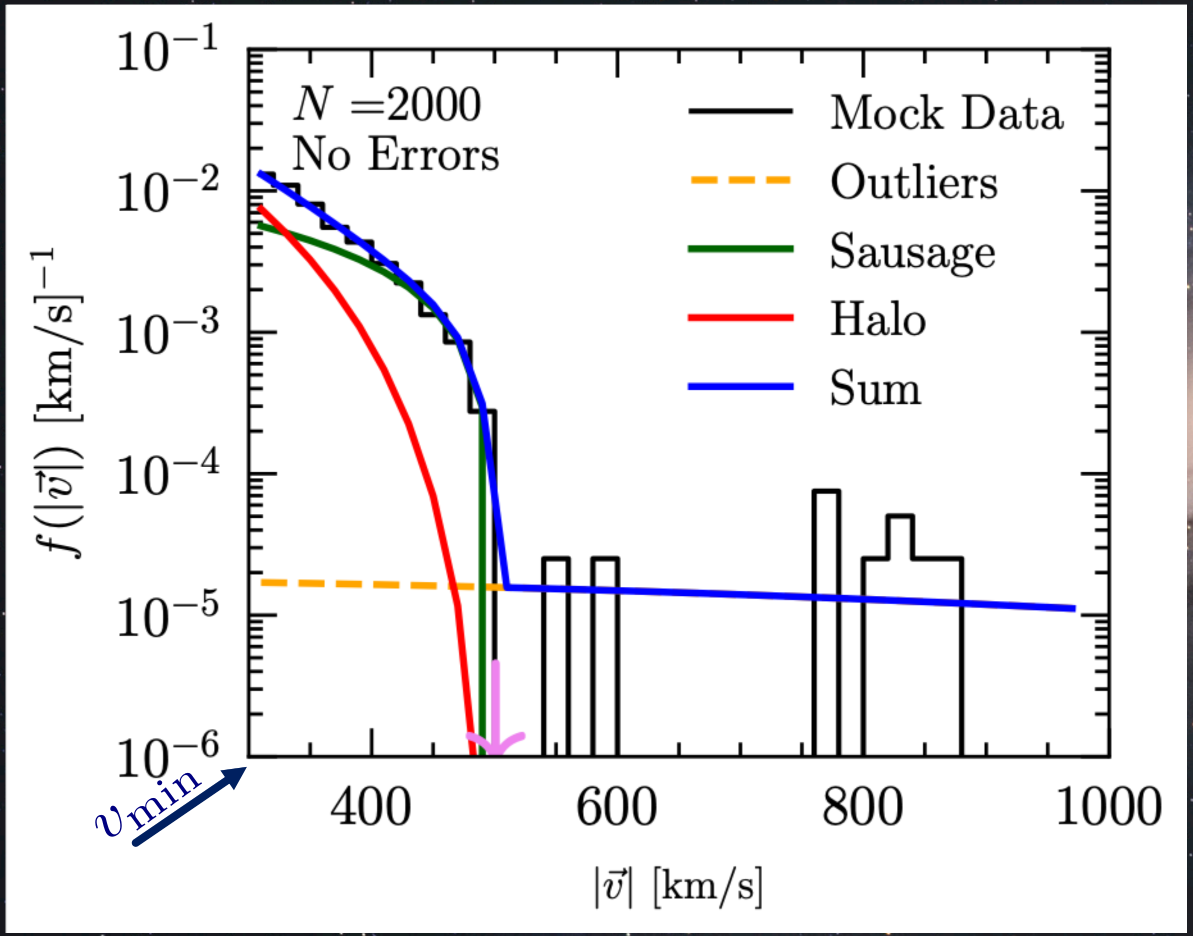

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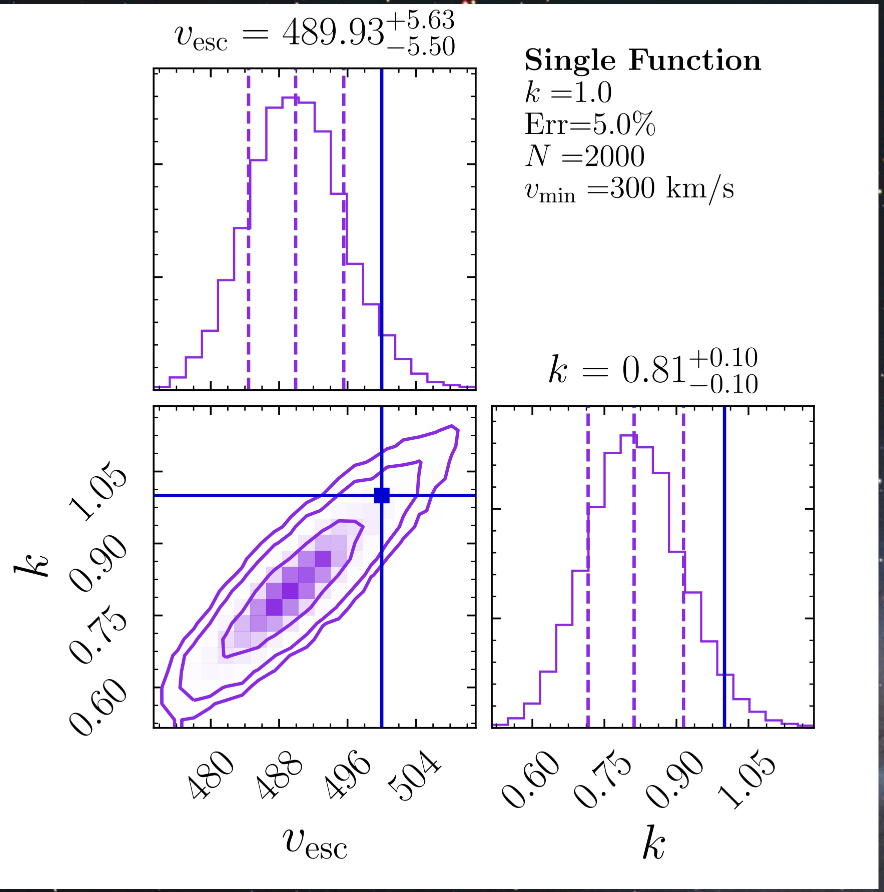


If the real function is dominated by a single distribution, the fit works.

Lina Necib, MIT

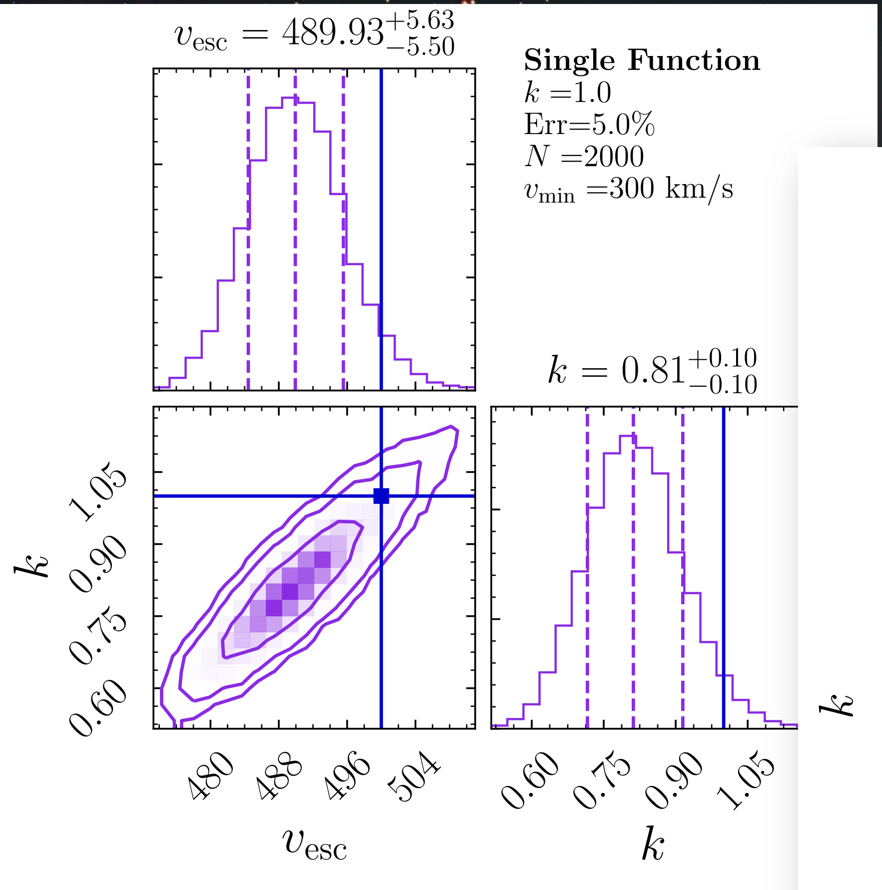
Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

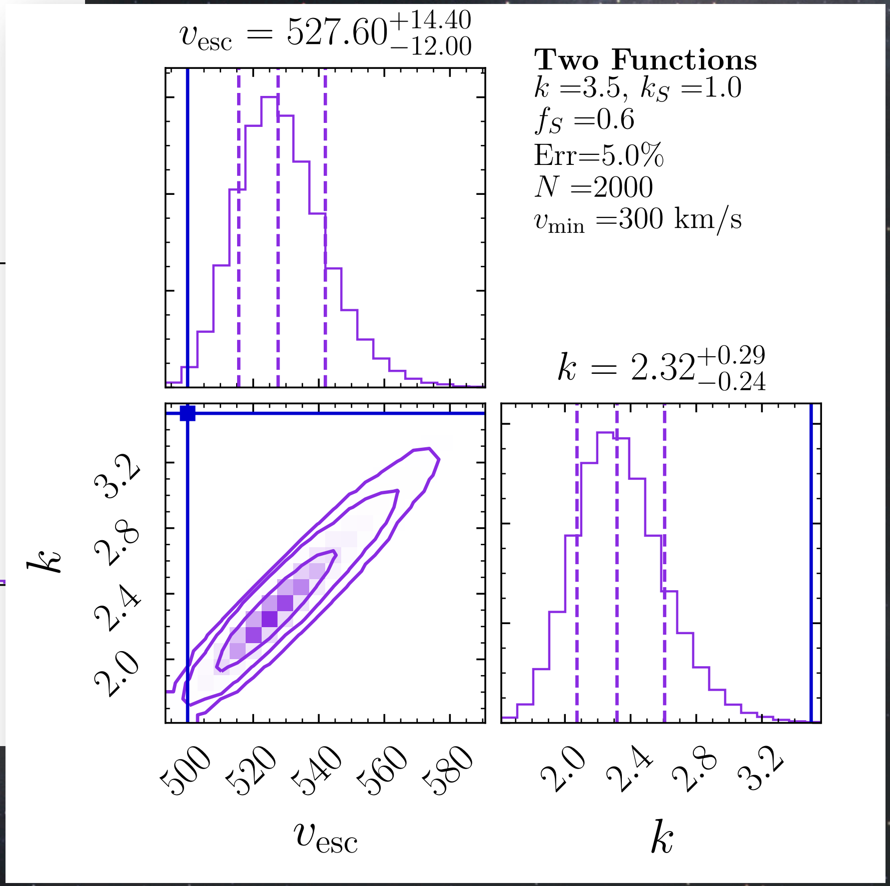
Determining the Escape Velocity

$$f(v) \propto (v_{\rm esc} - v)^k$$

$$v > v_{\rm min}$$

If the real function is the sum of two functions, we do not get the right answer.





Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

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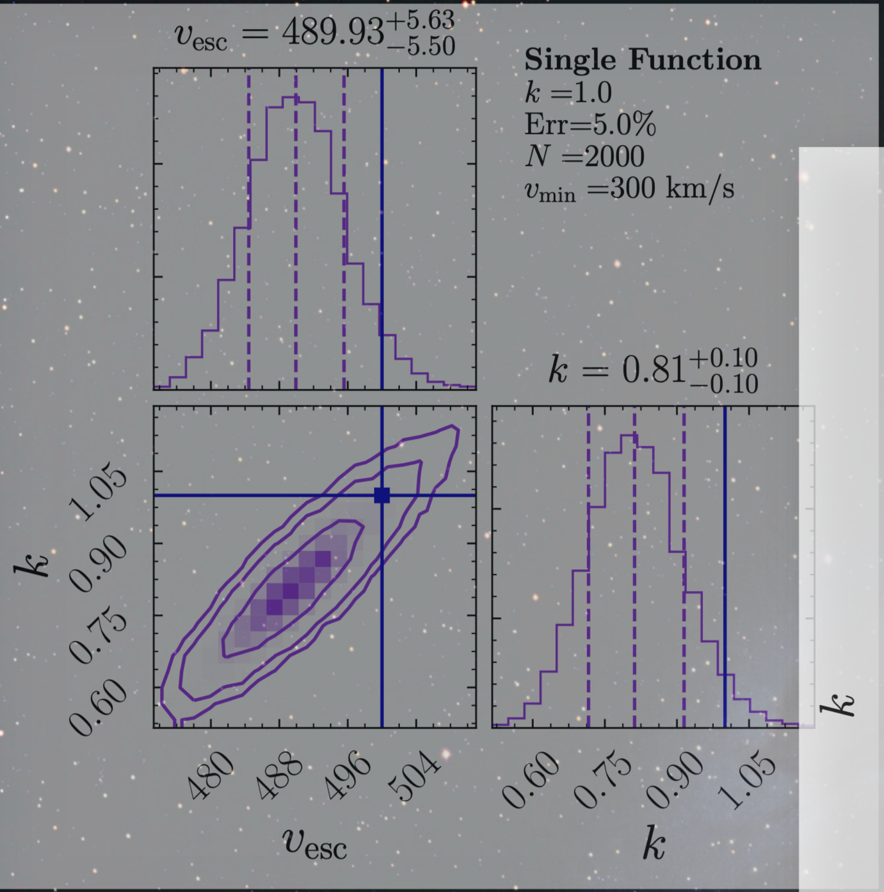

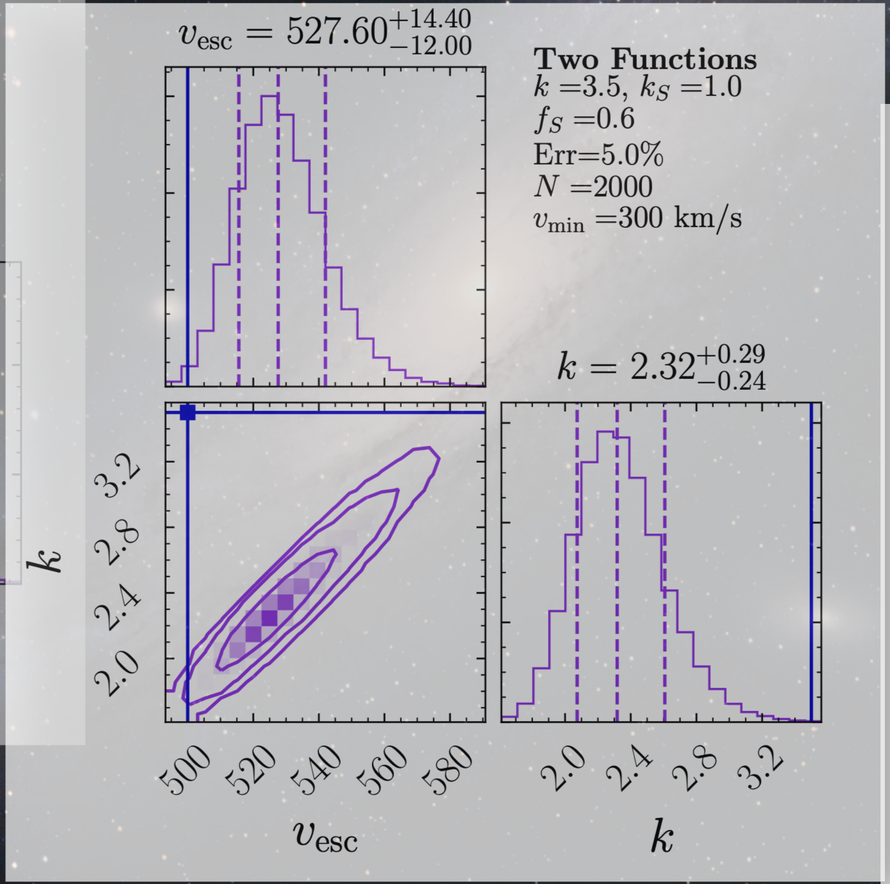

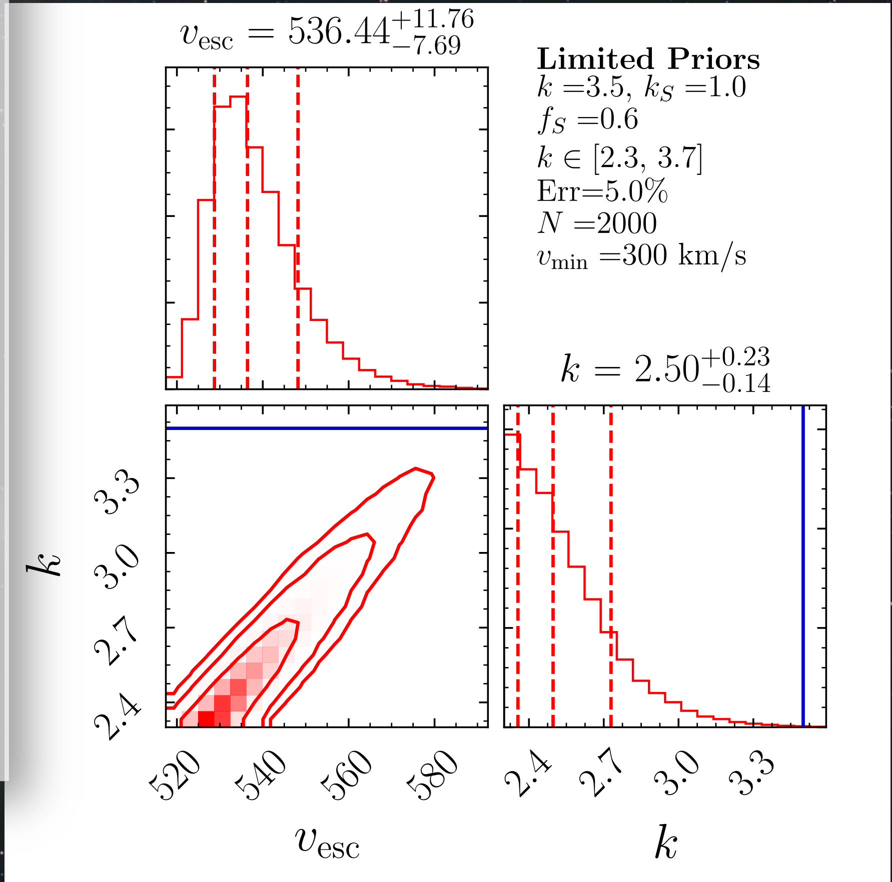

Lina Necib, MIT

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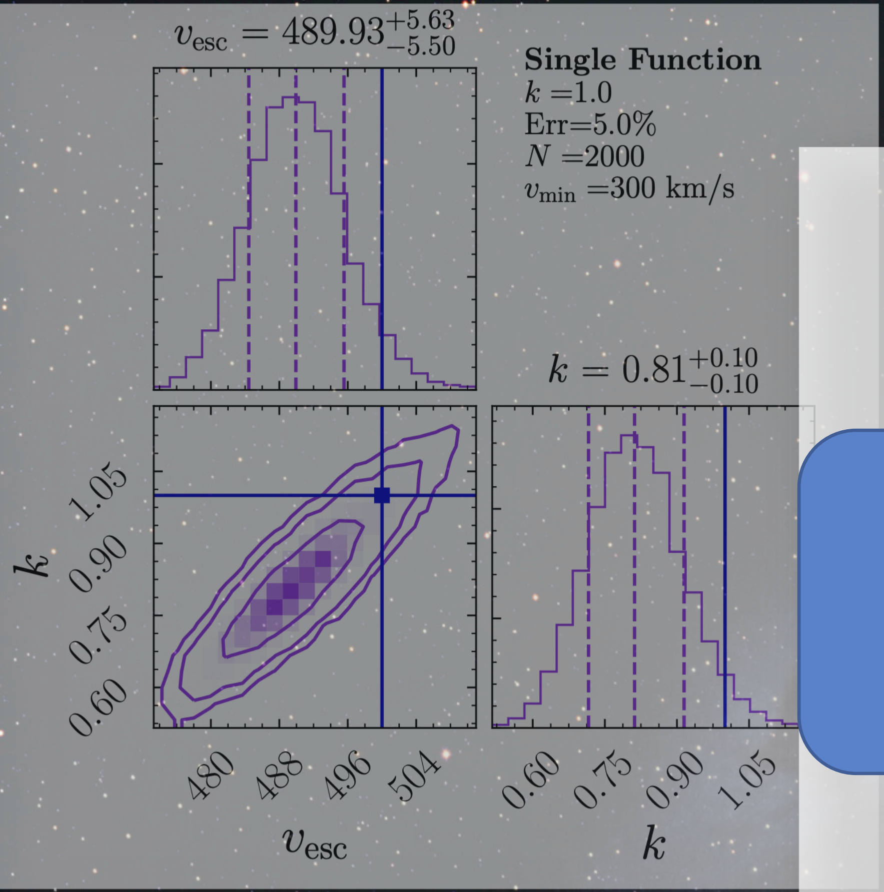
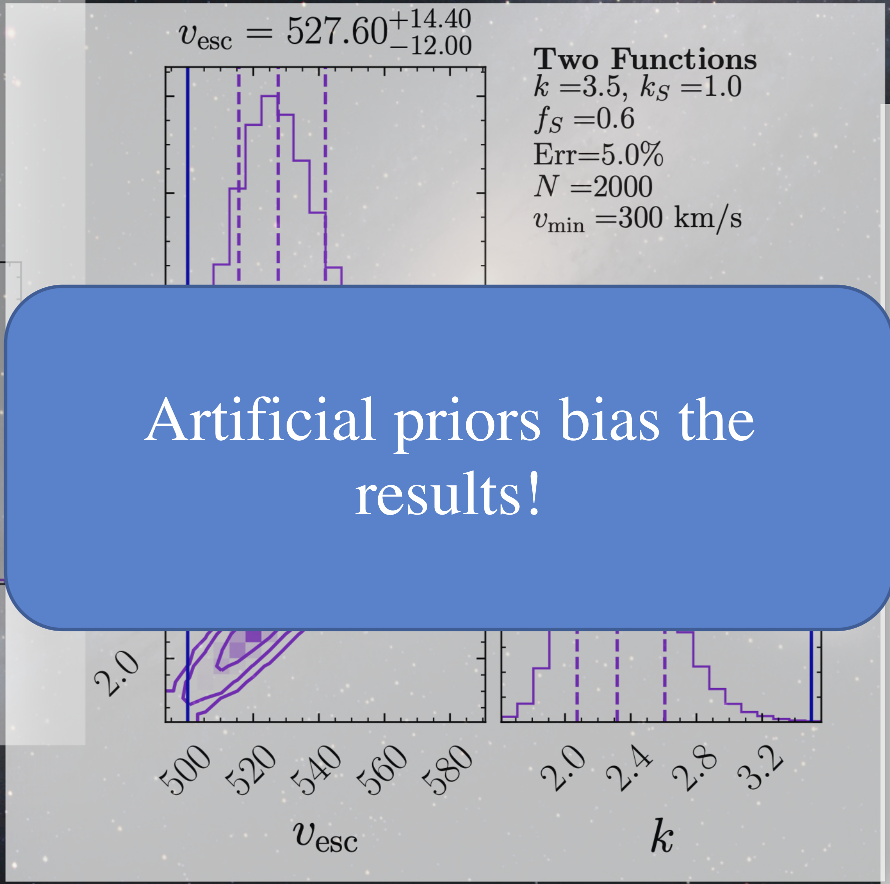
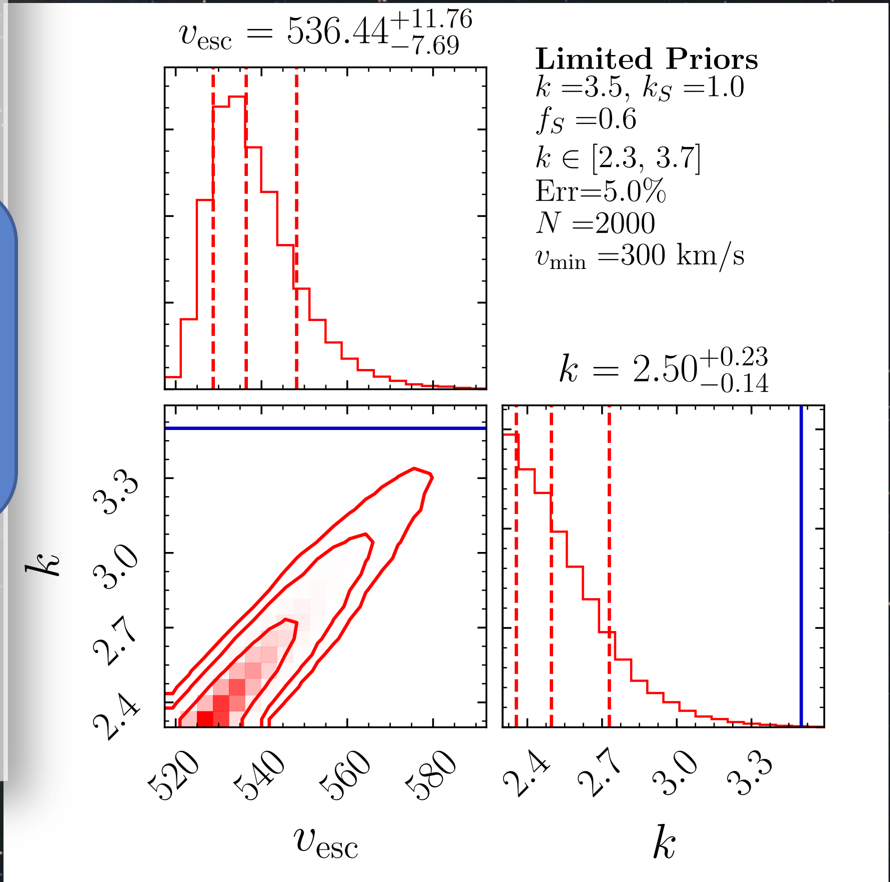
$$f(v) \propto (v_{\rm esc} - v)^k$$

$$v > v_{\rm min}$$

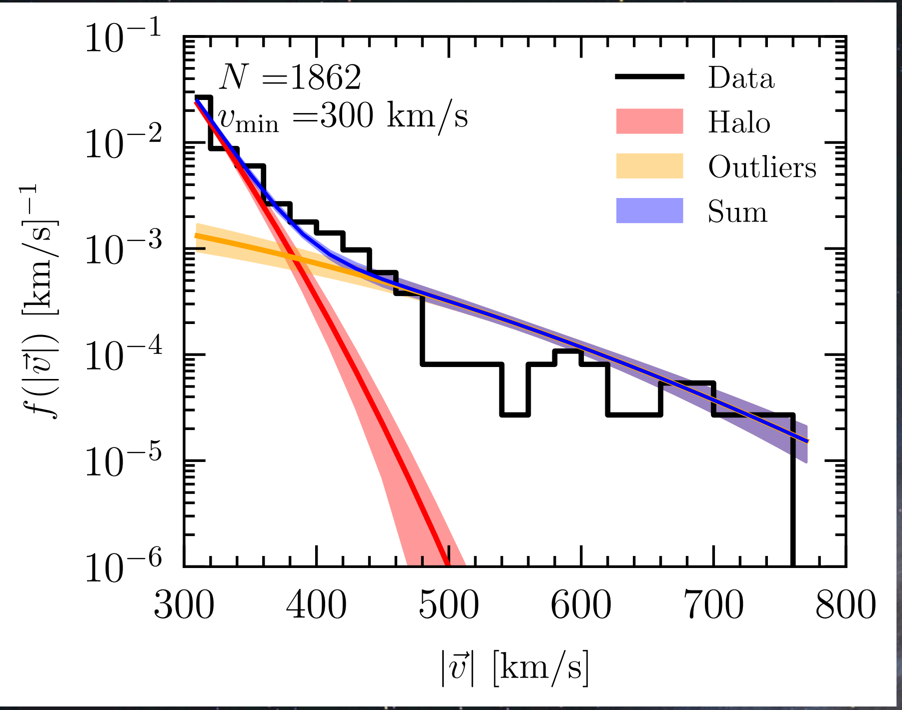






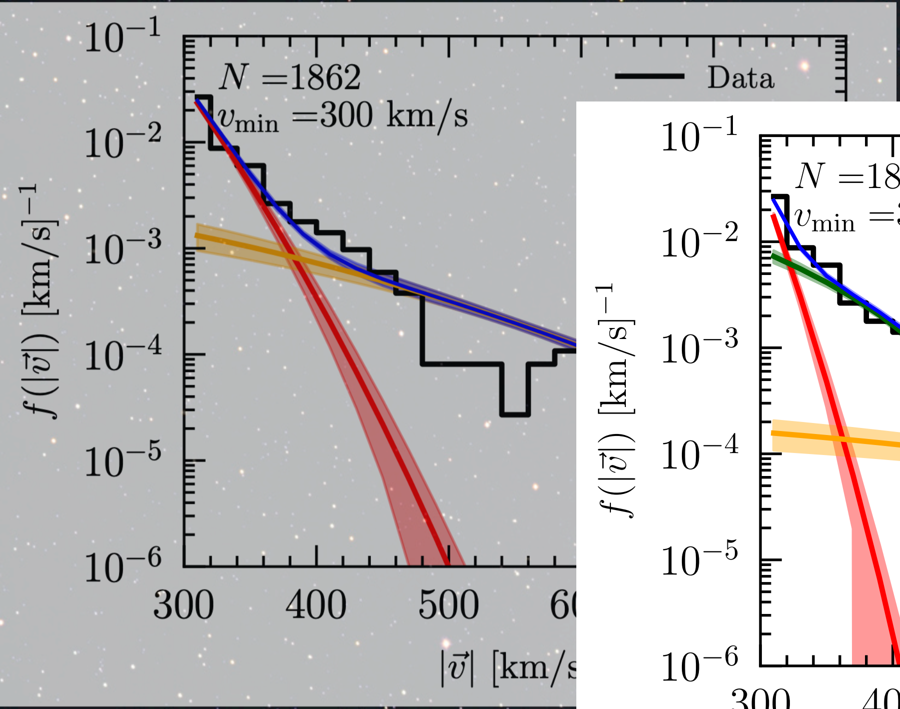
Artificial priors bias the results!

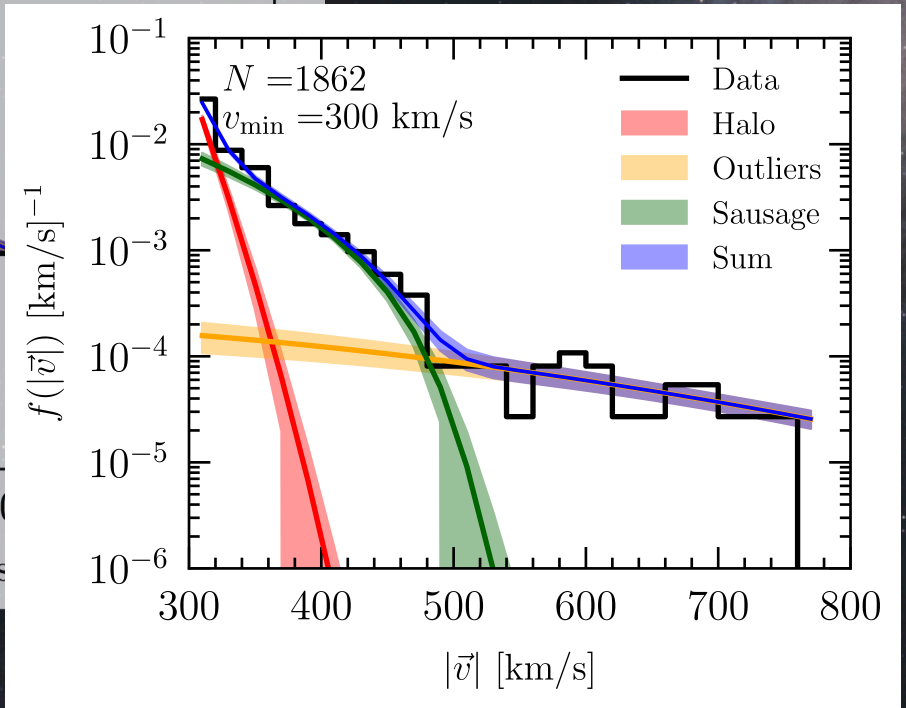
Determining the Escape Velocity



Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

Determining the Escape Velocity





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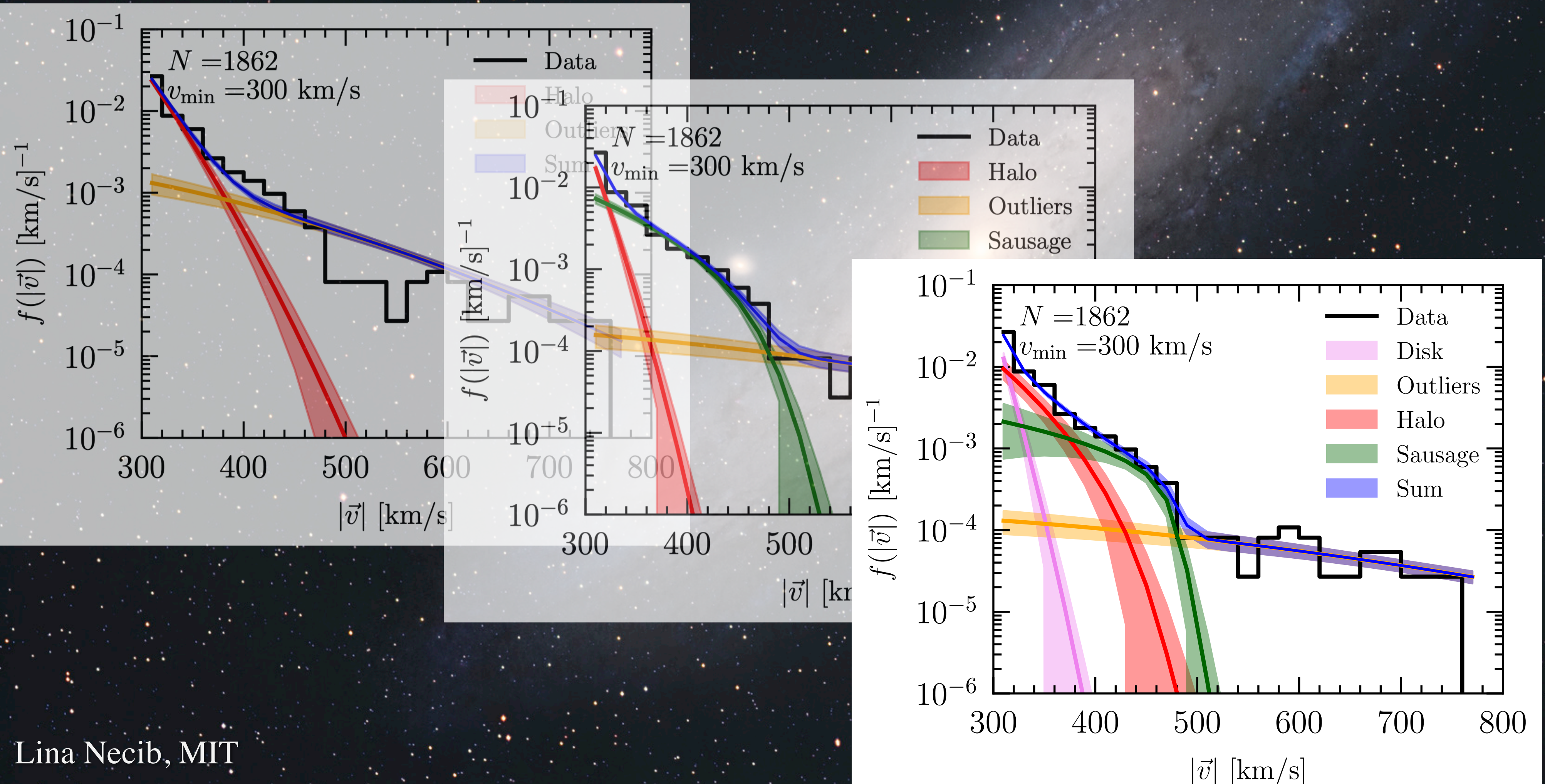
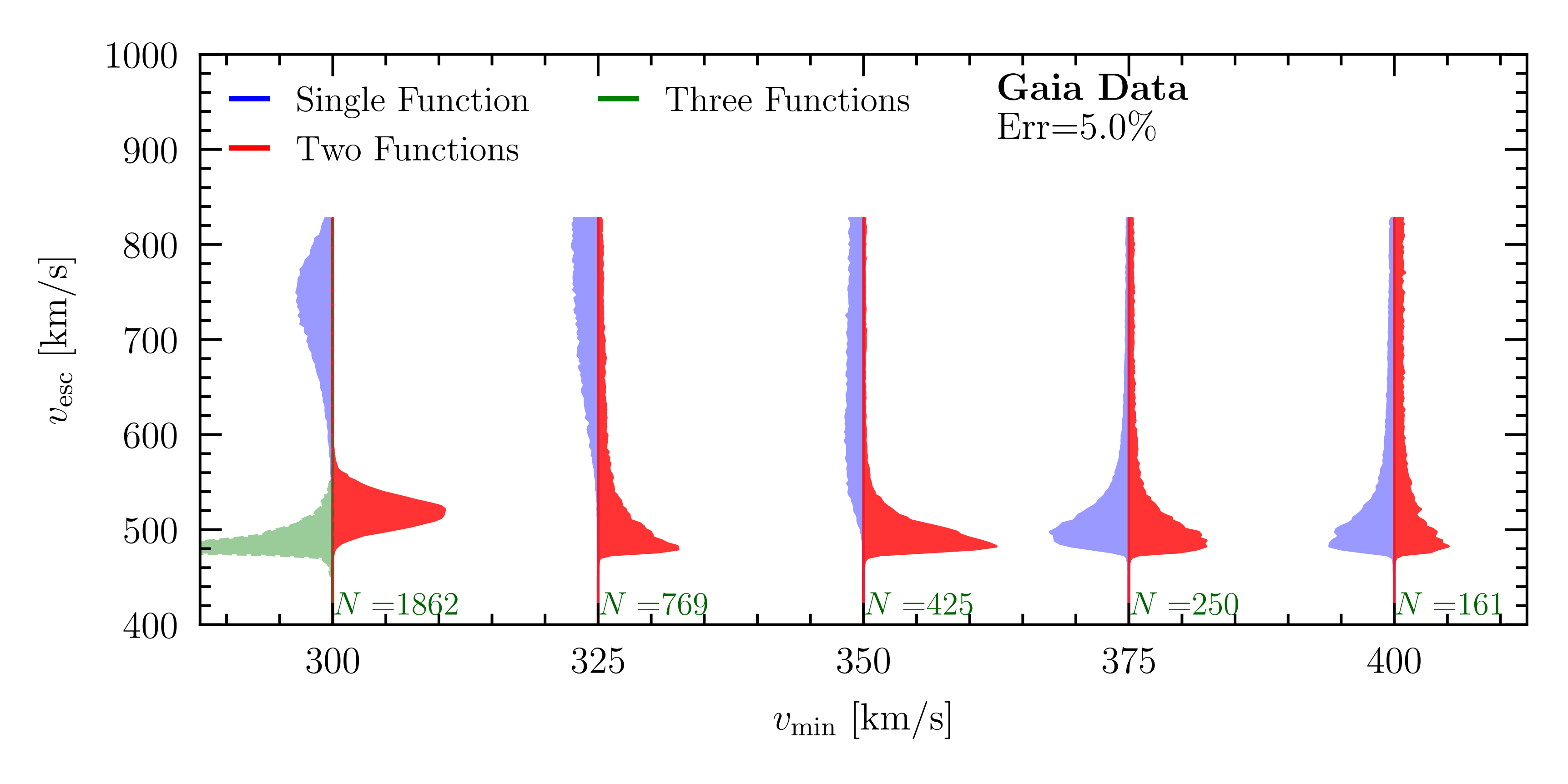
Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

Determining the Escape Velocity



Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

Determining the Escape Velocity



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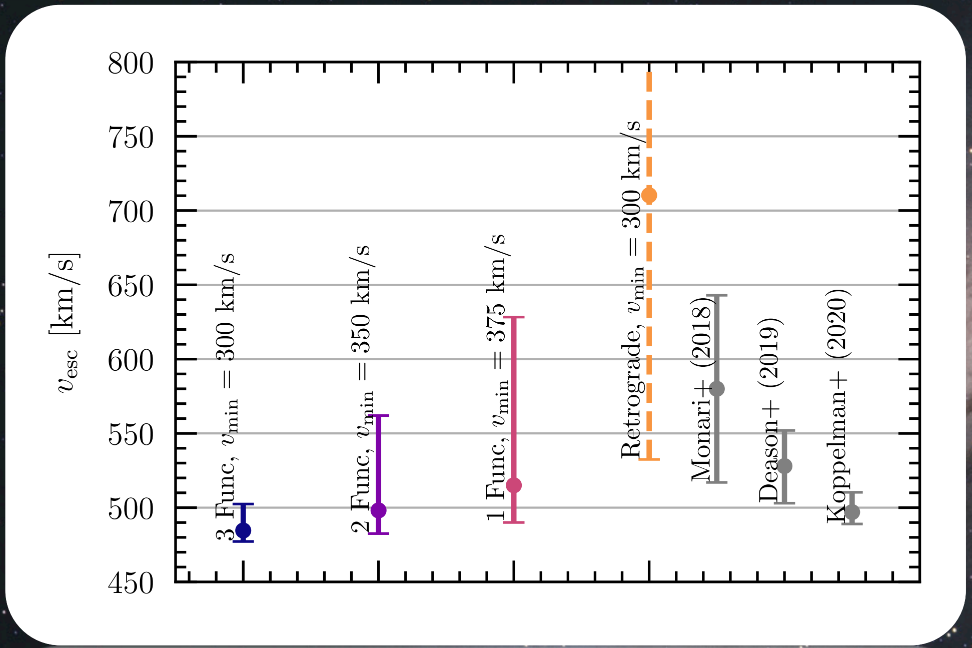
Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

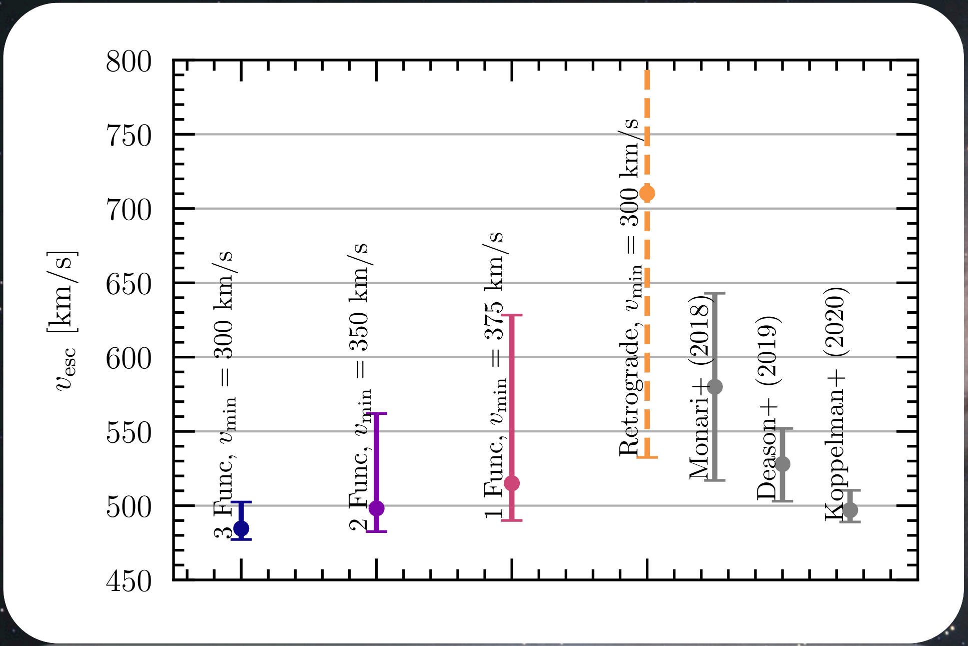
Determining the Escape Velocity



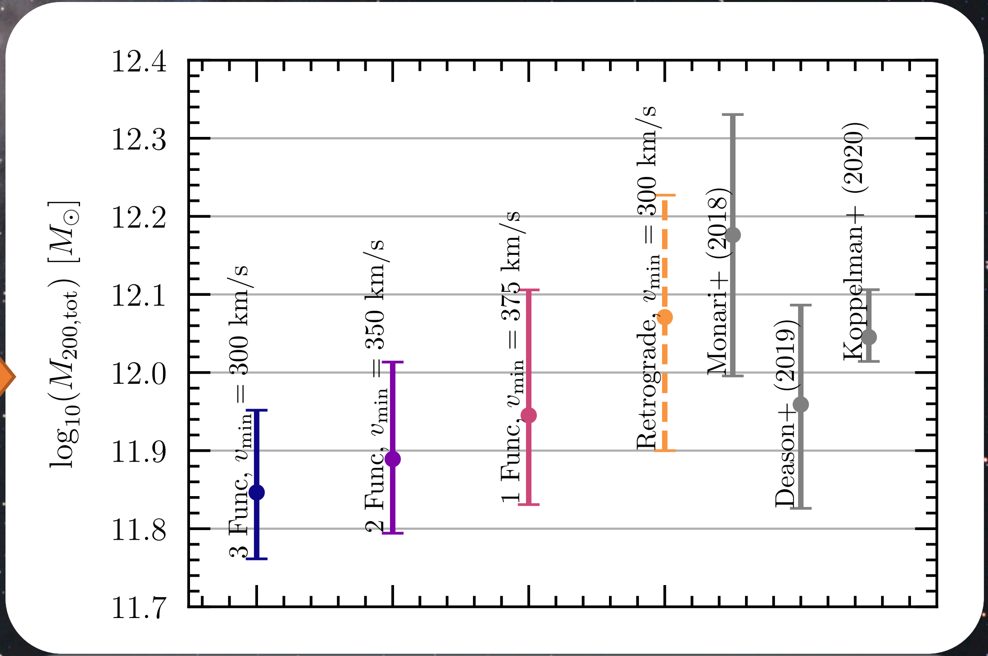
Lina Necib, MIT

Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

Determining the Escape Velocity



Assume Milky Way Potential



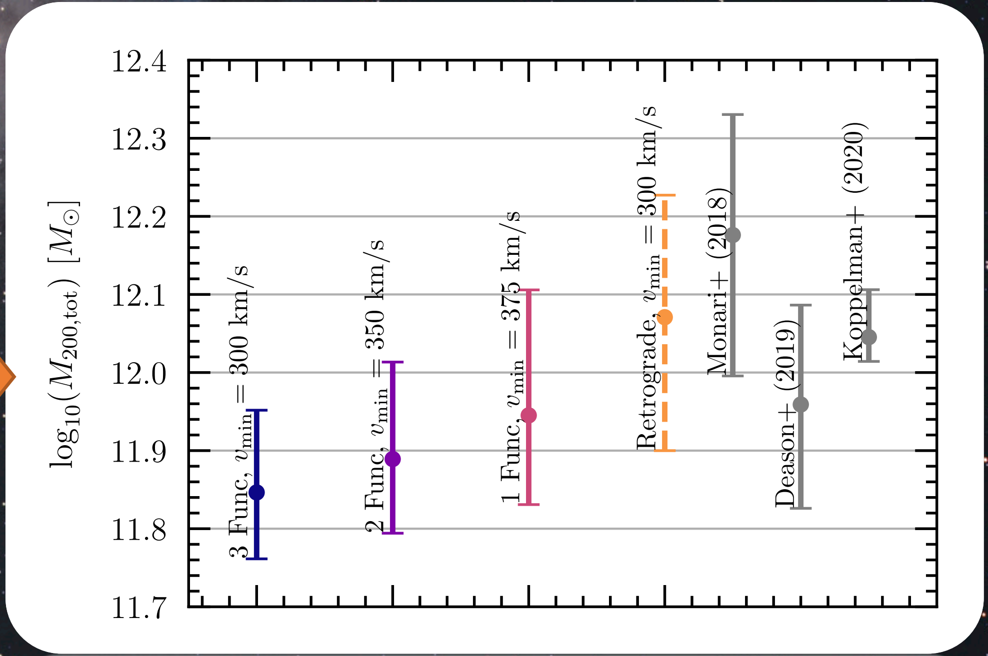
$$M_{200} = 7.0^{+1.9}_{-1.2} \times 10^{11} M_\odot$$

Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

Determining the Escape Velocity

Stay Tuned for Full Density Profile Results and Updates with Gaia DR3 in 2022!

Assume Milky Way Potential



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Leonard & Tremaine (1990)
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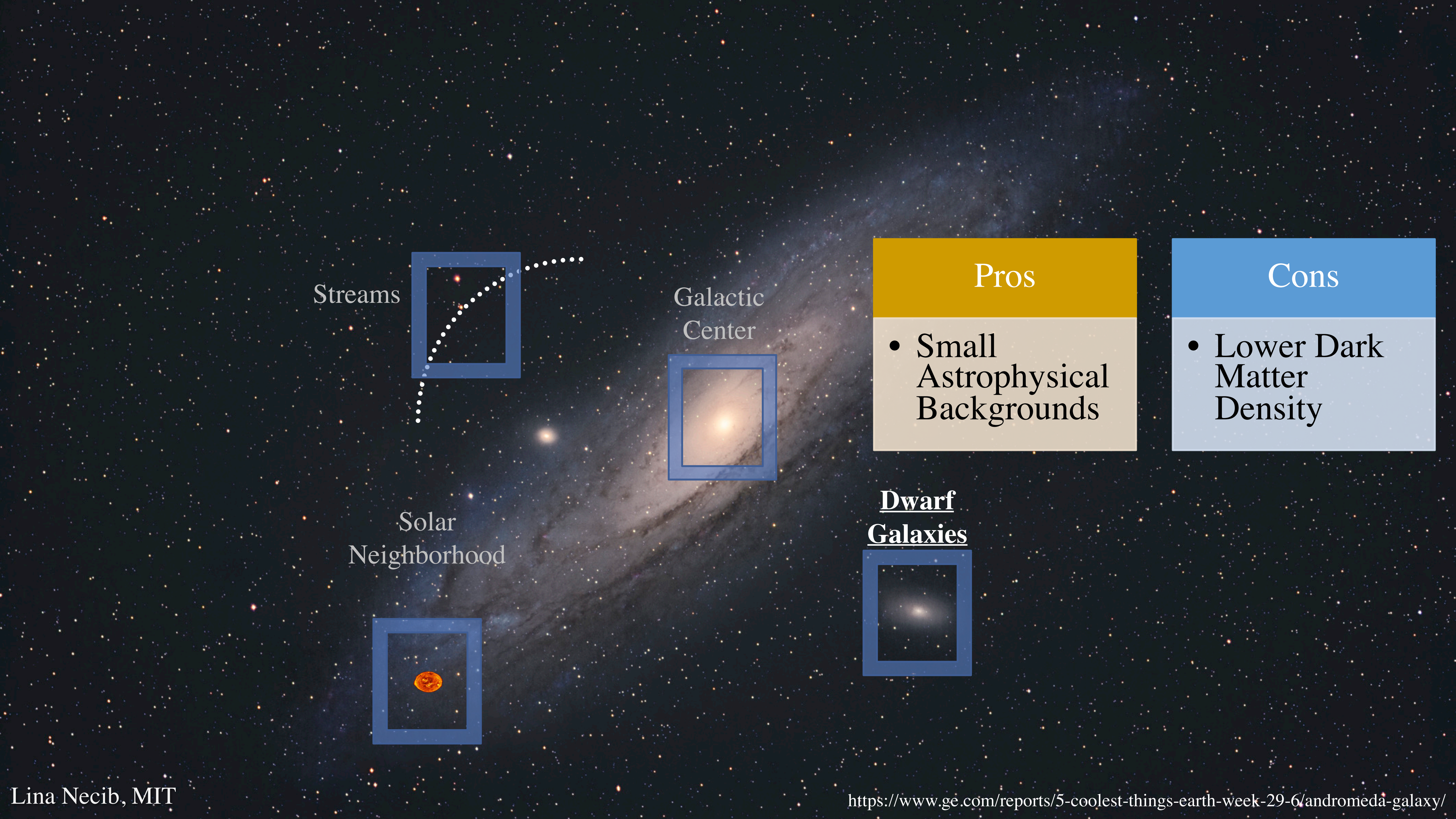
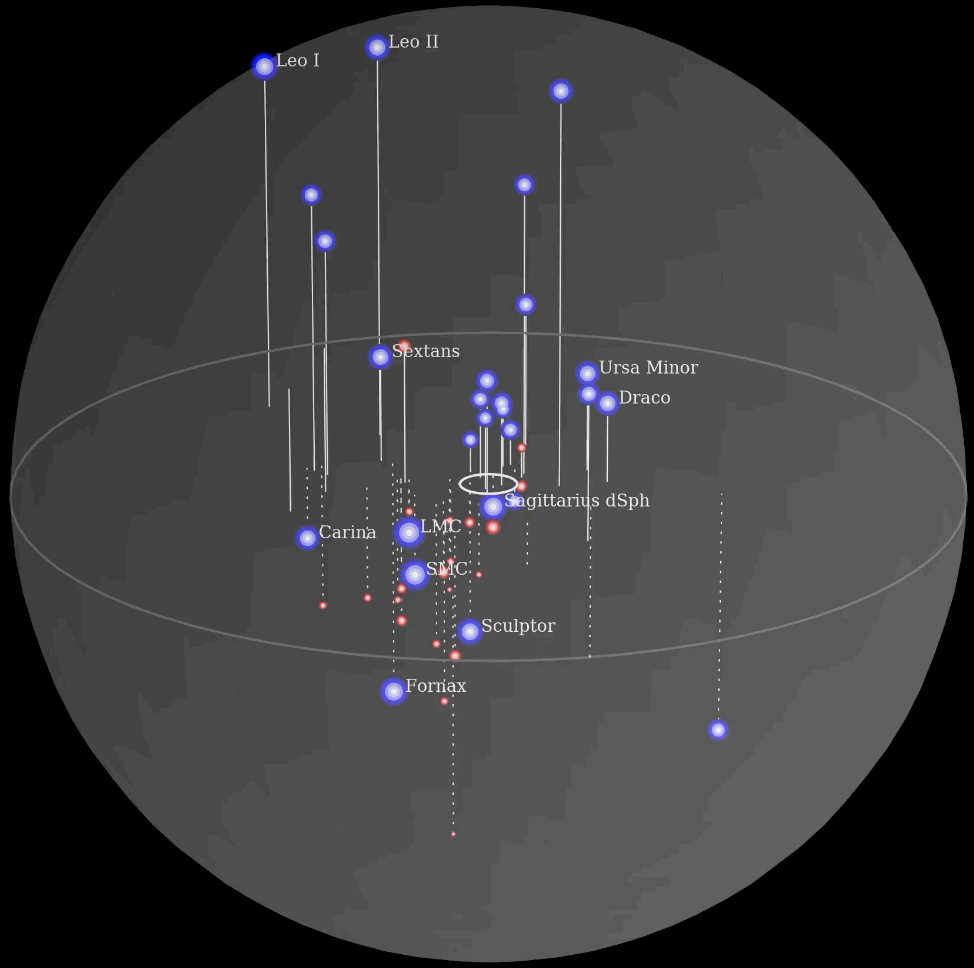


Pros	Cons
• Small Astrophysical Backgrounds	• Lower Dark Matter Density

Lina Necib, MIT

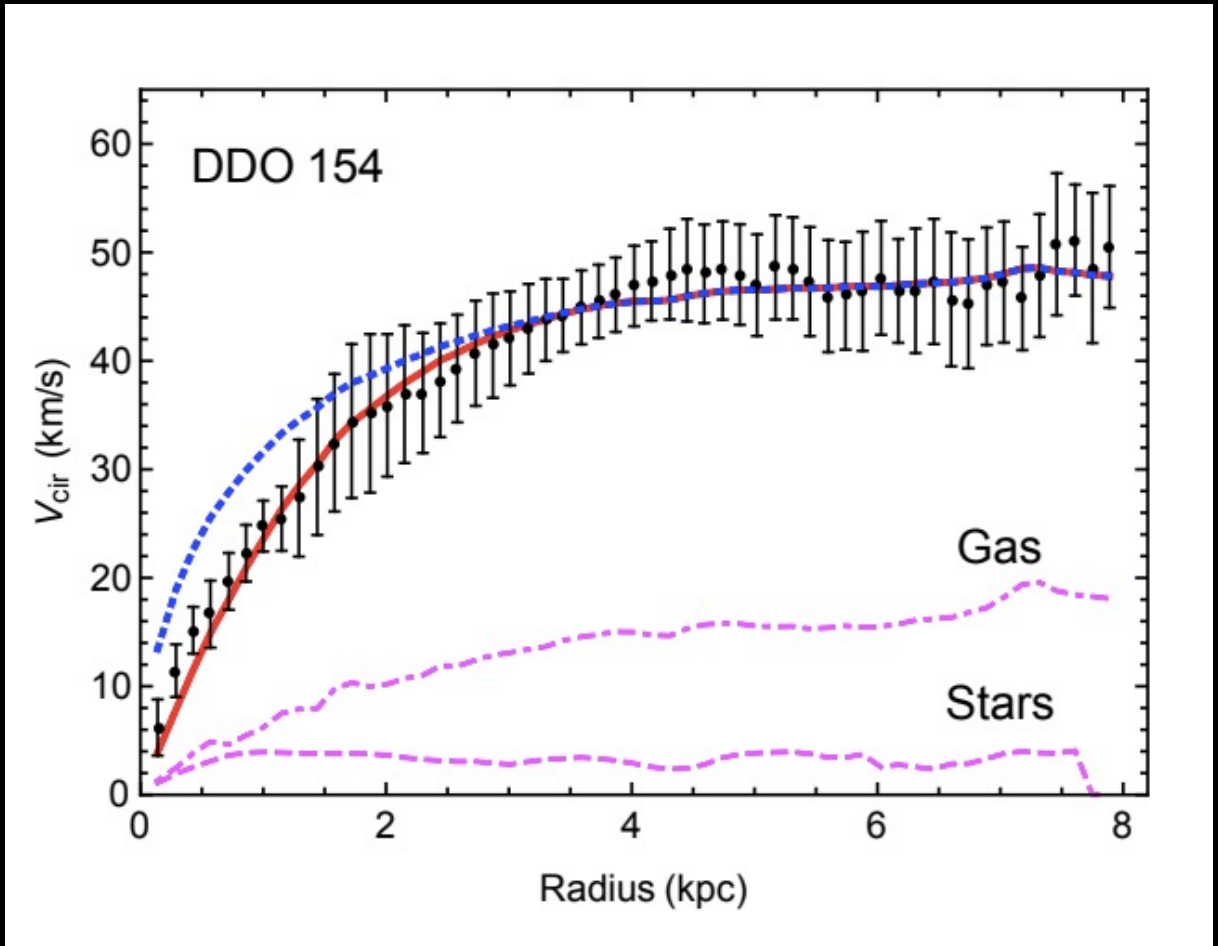
https://www.ge.com/reports/5-coolest-things-earth-week-29-6/andromeda-galaxy/

Dwarf Galaxies



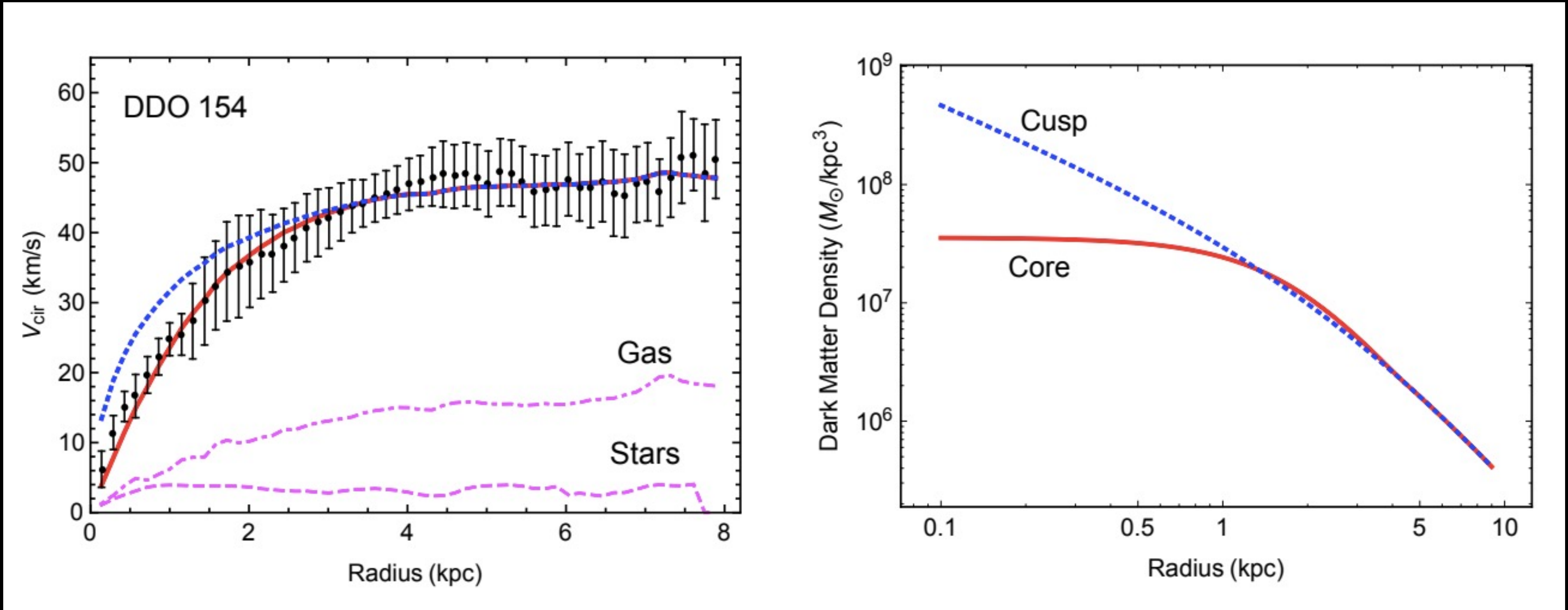
Pawlowski/Bullock/Boylan-Kolchin

Density Profiles of Dwarf Galaxies



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

Density Profiles of Dwarf Galaxies



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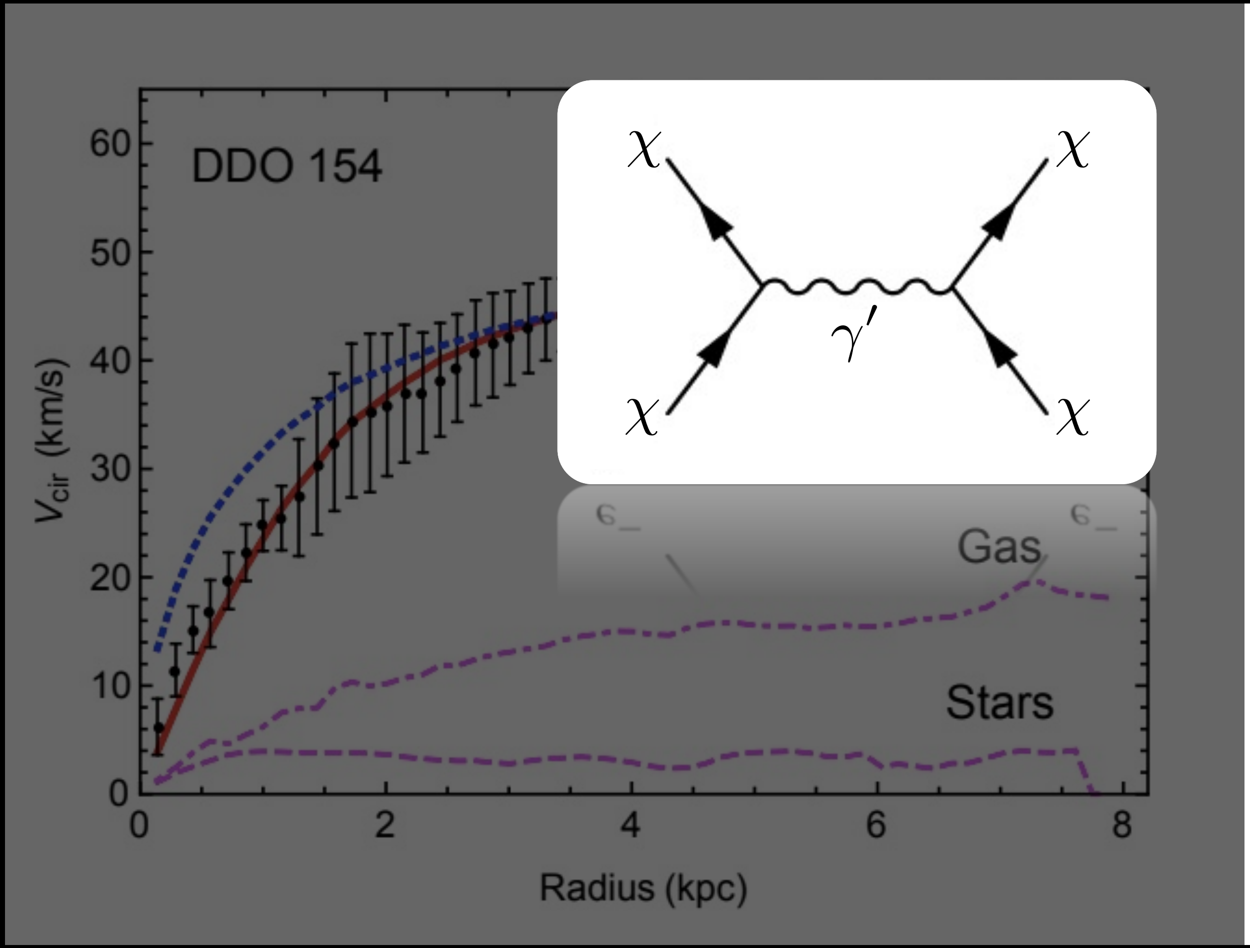
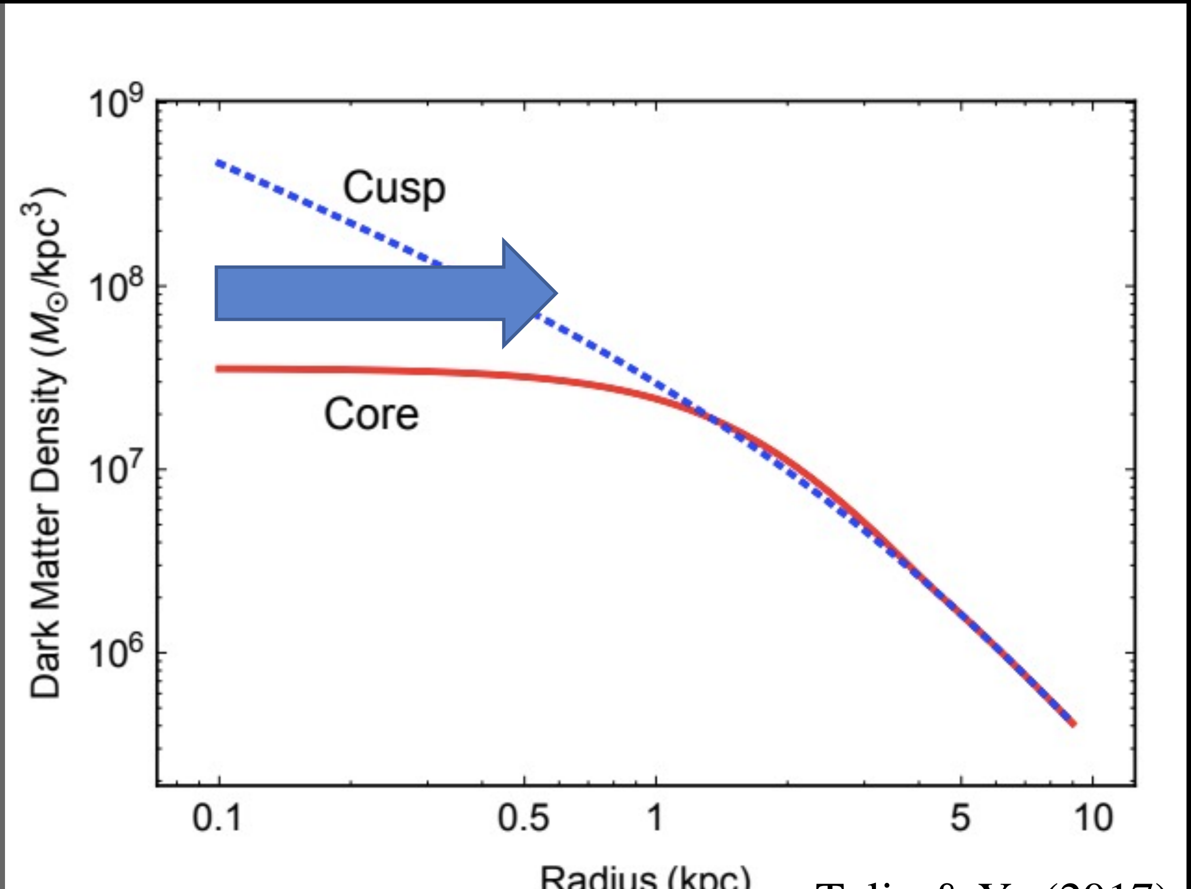
Density Profiles of Dwarf Galaxies



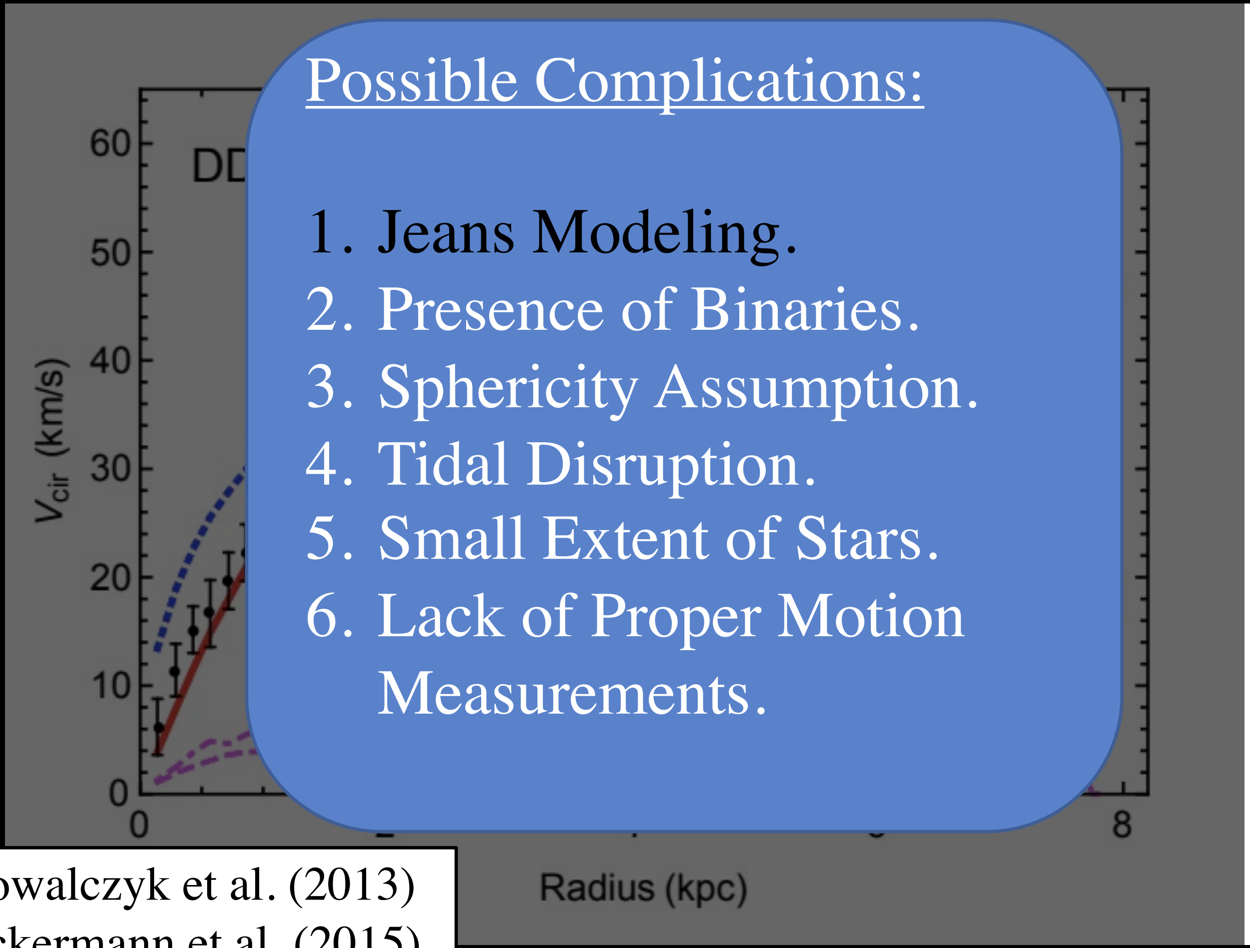


Tulin & Yu (2017)

Spergel & Steinhardt (2000)
Oh et al. (2015)

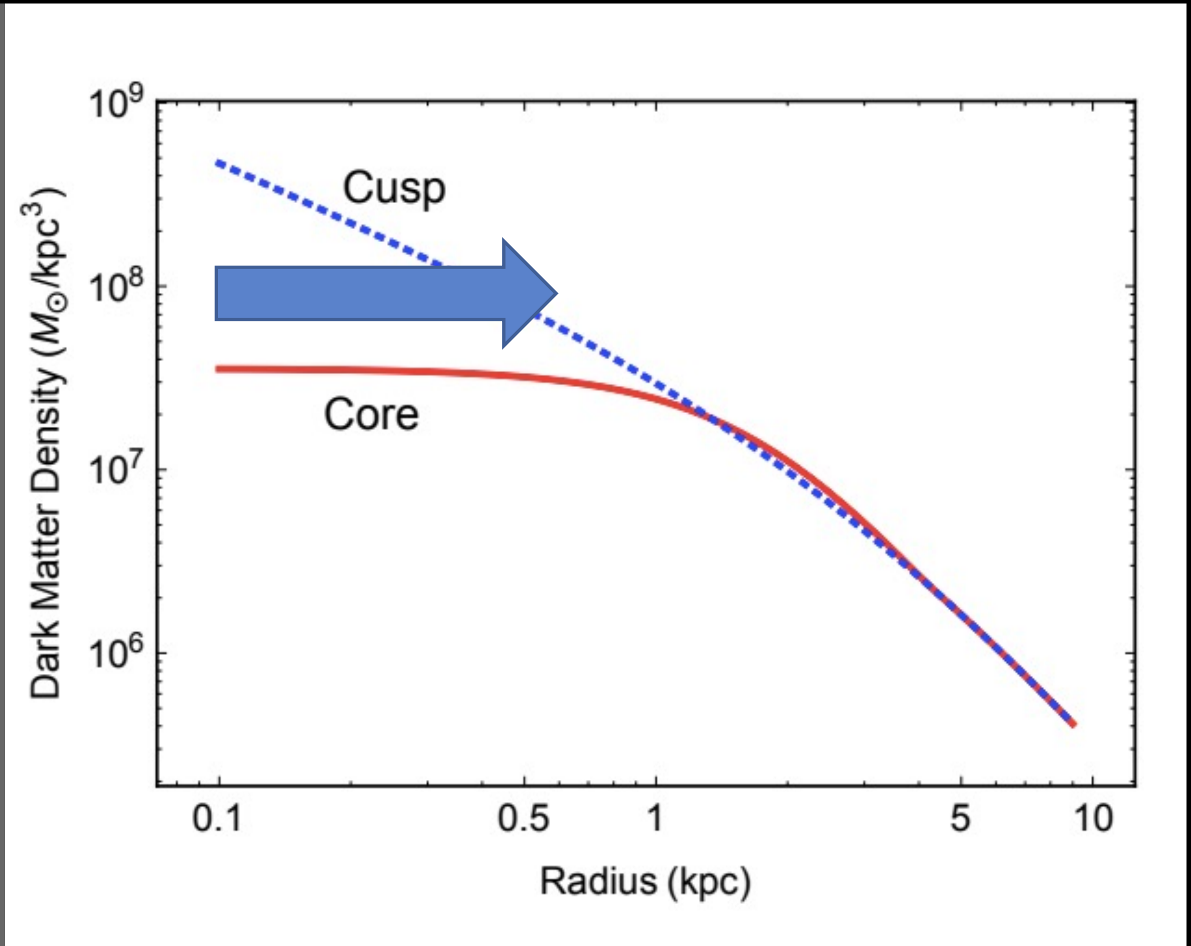
Lina Necib, MIT

Density Profiles of Dwarf Galaxies



Possible Complications:

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

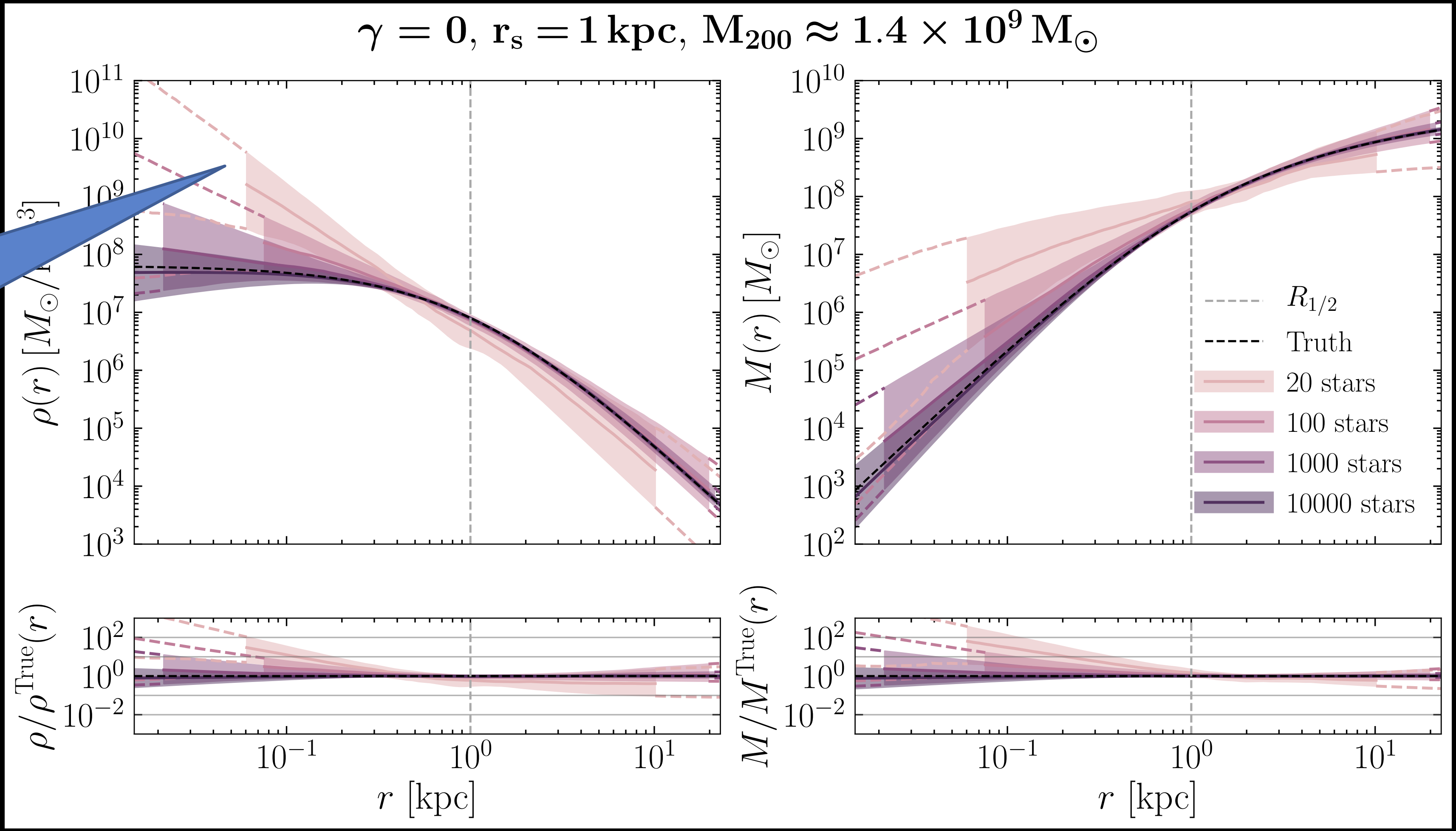


Kowalczyk et al. (2013)
Ackermann et al. (2015)
Bonnivard et al. (2015)
El-Badry et al. (2017)

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

Density Profiles of Dwarf Galaxies

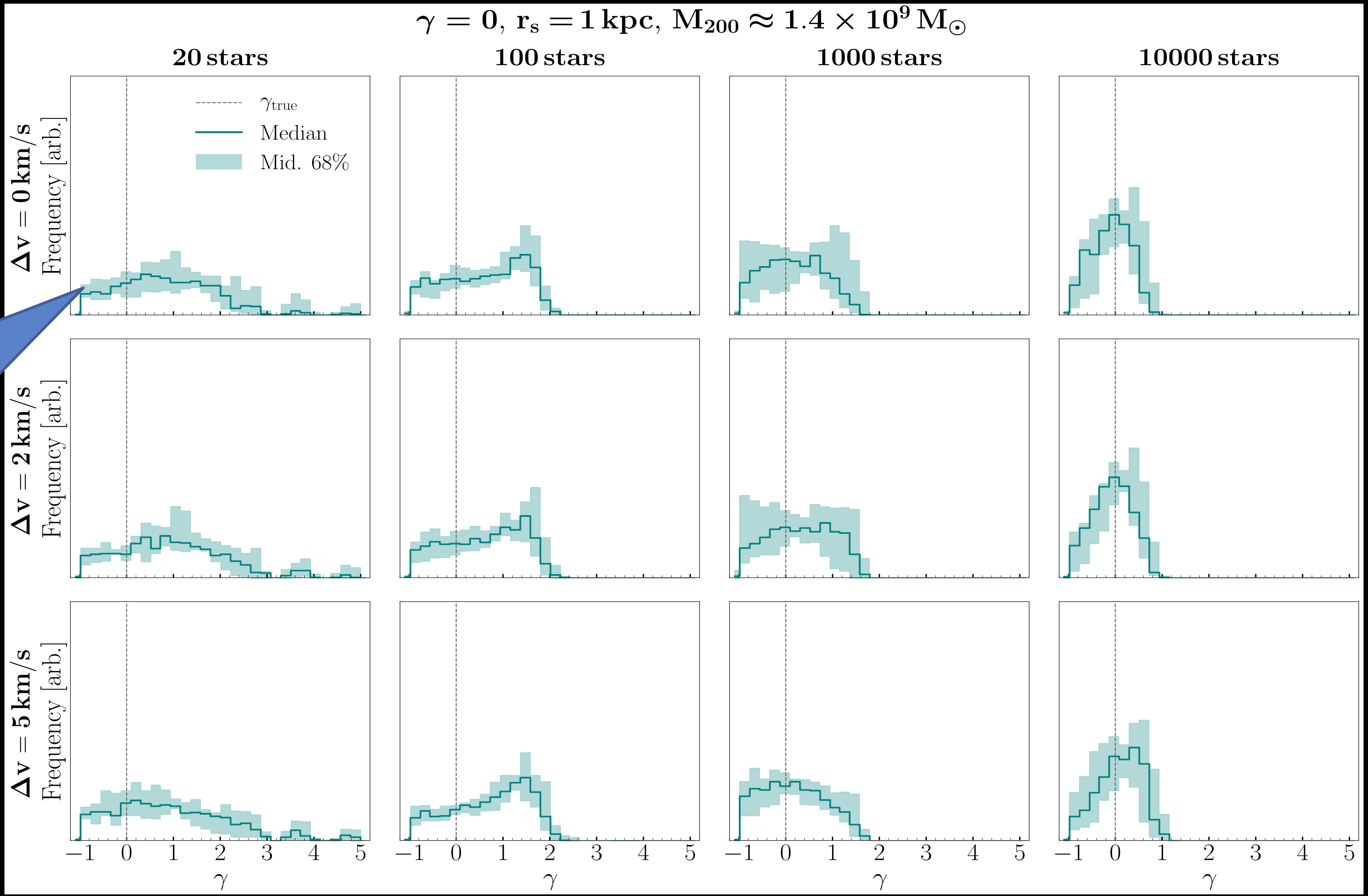
Cores are harder to resolve with fewer statistics



Chang & **Necib** (2020)

Lina Necib, MIT

Density Profiles of Dwarf Galaxies



Cores are harder to resolve with fewer statistics

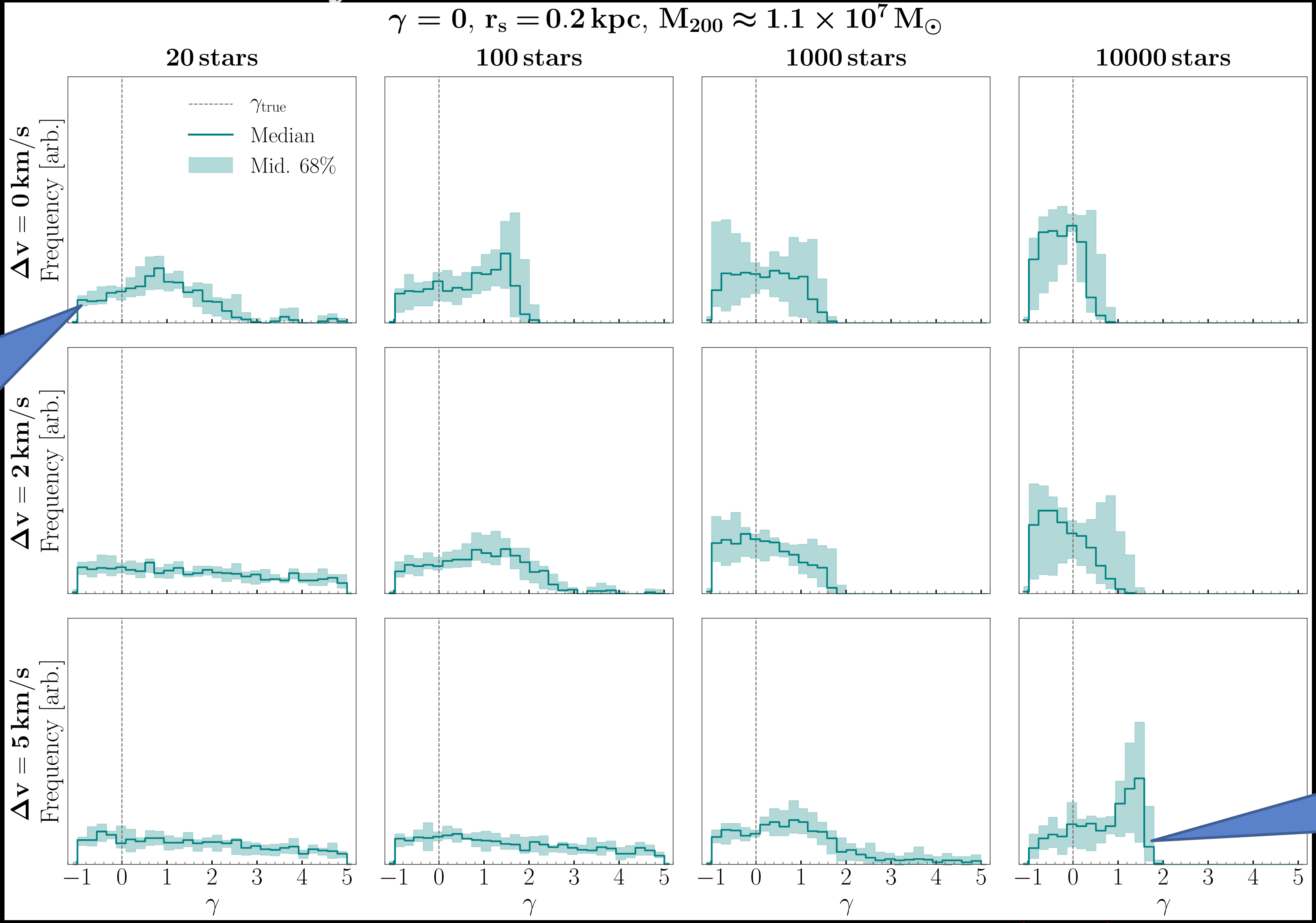
Cusp: $\gamma = 1$
Core: $\gamma = 0$

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

Chang & **Necib** (2020)

Lina Necib, MIT

Density Profiles of Dwarf Galaxies



Cores are harder to resolve with fewer statistics

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

The errors are worse for the ultrafaints

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

Chang & **Necib** (2020)

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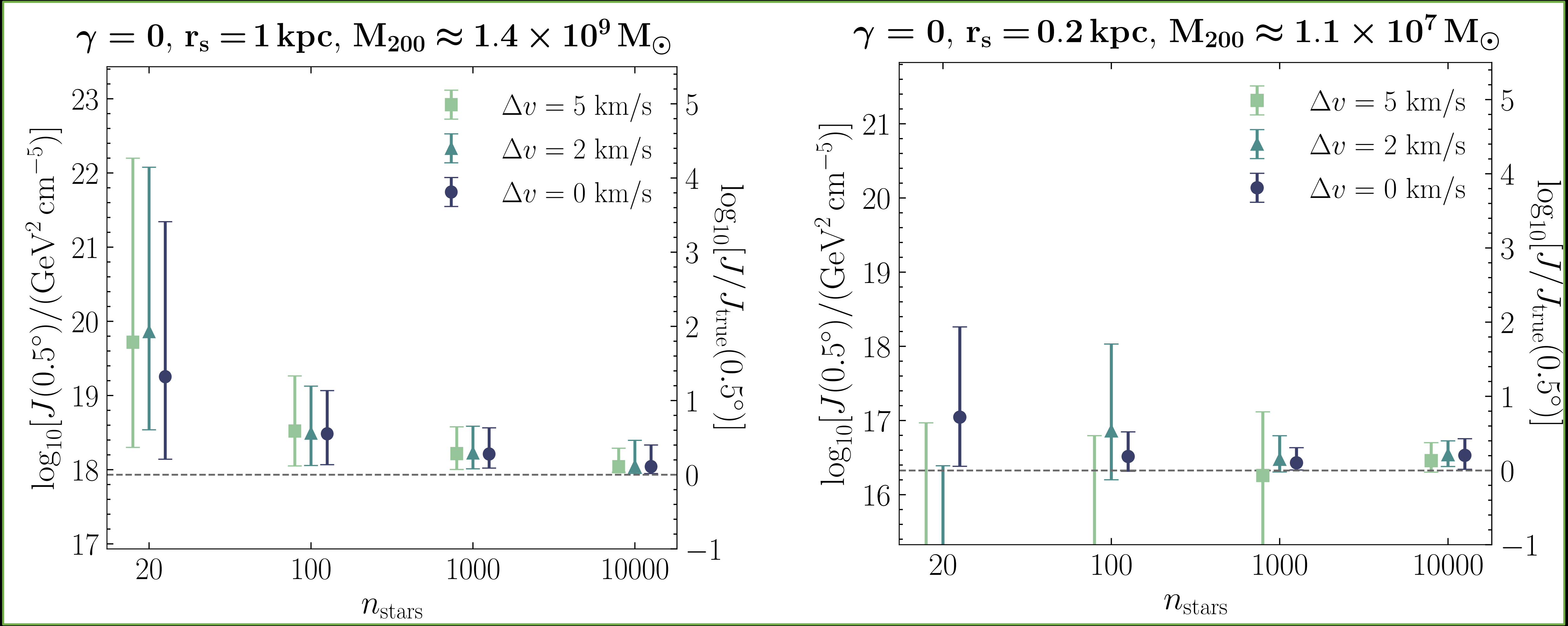
J factors of Dwarf Galaxies



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

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Chang & **Necib** (2020)

Dwarf	N Stars	$\log_{10} J(0.5°)$ [$\mathrm{GeV}^2\ \mathrm{cm}^{-5}$]	Dispersion [km/s]	References
Ursa Major II	20	$19.42^{+0.44}_{-0.42}$	$5.6^{+1.4}_{-1.4}$	Simon (2019)
Segue 1	70	$19.36^{+0.32}_{-0.35}$	$3.7^{+1.4}_{-1.1}$	Simon & Geha (2007)
Coma Berenices	59	$19.02^{+0.37}_{-0.41}$	$4.6^{+0.8}_{-0.8}$	Simon & Geha (2007)
Ursa Minor	313	$18.93^{+0.27}_{-0.19}$	$9.5^{+1.2}_{1.2}$	Walker et al. (2009b)
Draco	292	$18.84^{+0.12}_{-0.13}$	$9.1^{+1.2}_{-1.2}$	Walker et al. (2009b)
Sculptor	1365	$18.54^{+0.06}_{-0.05}$	$9.2^{+1.1}_{-1.1}$	Walker et al. (2009a)
Bootes I	37	$18.24^{+0.40}_{-0.37}$	$4.6^{+0.8}_{-0.6}$	Koposov et al. (2011)
Leo II	126	$17.97^{+0.20}_{-0.18}$	$7.4^{+0.4}_{-0.4}$	Spencer et al. (2017)
Carina	774	$17.87^{+0.10}_{-0.09}$	$6.6^{+1.2}_{-1.2}$	Walker et al. (2009a)
Ursa Major I	39	$17.87^{+0.56}_{-0.33}$	$7.0^{+1.0}_{-1.0}$	Simon (2019)
Leo I	267	$17.84^{+0.20}_{-0.16}$	$9.2^{+0.4}_{-0.4}$	Mateo et al. (2008)
Fornax	2483	$17.83^{+0.12}_{-0.06}$	$11.7^{+0.9}_{-0.9}$	Walker et al. (2009a)
Canes Venatici II	25	$17.65^{+0.45}_{-0.43}$	$4.6^{+1.0}_{-1.0}$	Simon & Geha (2007)
Sextans	441	$17.52^{+0.28}_{-0.18}$	$7.9^{+1.3}_{-1.3}$	Walker et al. (2009a)
Canes Venatici I	214	$17.43^{+0.37}_{-0.28}$	$7.6^{+0.4}_{-0.4}$	Simon & Geha (2007)
Leo T	19	$17.11^{+0.44}_{-0.39}$	$7.5^{+1.6}_{-1.6}$	Simon & Geha (2007)
Hercules	30	$16.86^{+0.74}_{-0.68}$	$5.1^{+0.2}_{-0.2}$	Simon & Geha (2007)
Leo V	5	$16.37^{+0.94}_{-0.87}$	$2.3^{+3.2}_{-1.6}$	Collins et al. (2017)
Leo IV	18	$16.32^{+1.06}_{-1.69}$	$3.3^{+1.7}_{-1.7}$	Simon & Geha (2007)
Segue 2	25	$16.21^{+1.06}_{-0.98}$	< 2.2	Kirby et al. (2013)

Chang & **Necib** (2020)

Dwarf	N Stars	$\log_{10} J(0.5^\circ)$ [$\mathrm{GeV}^2\ \mathrm{cm}^{-5}$]	Dispersion [km/s]	References
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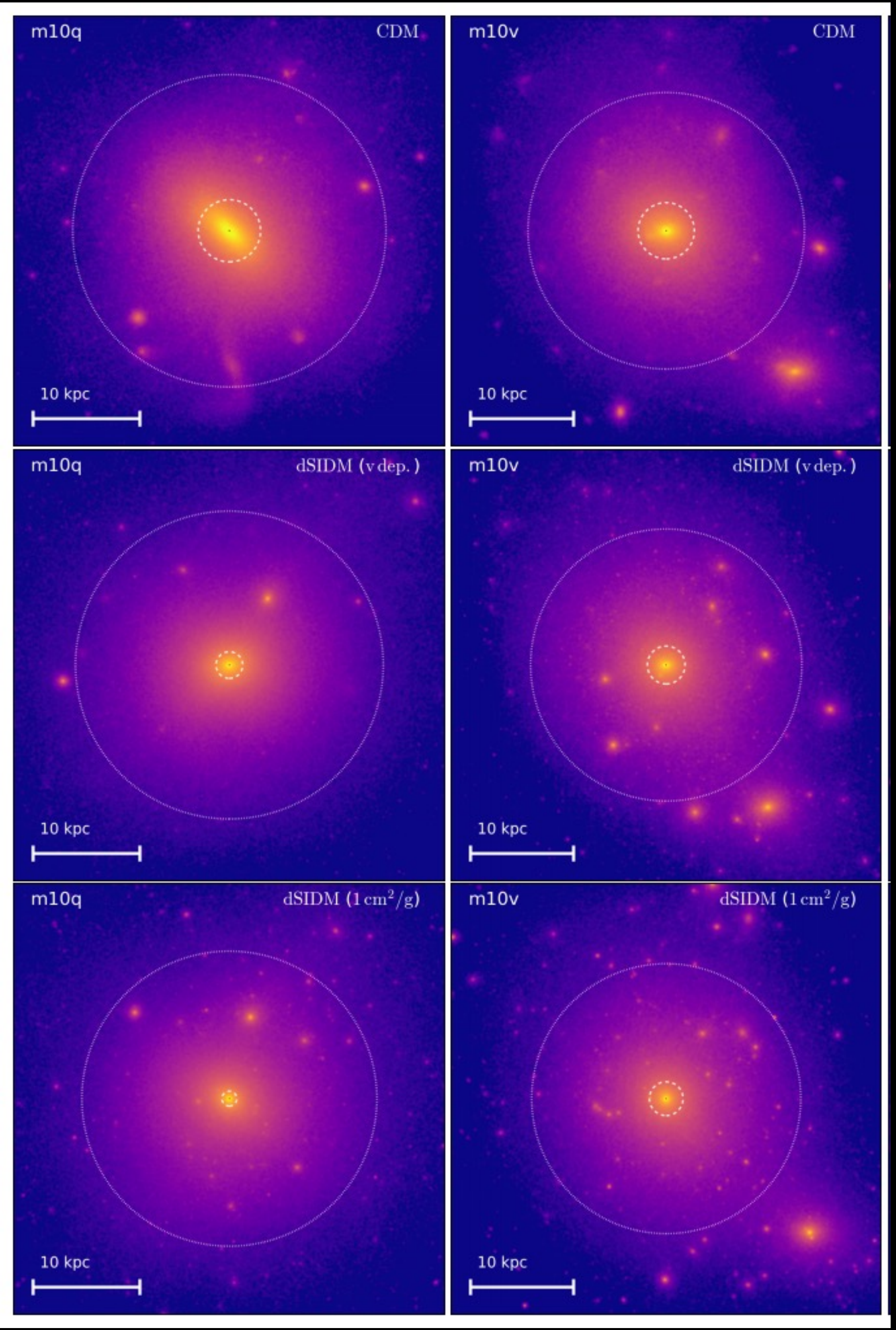
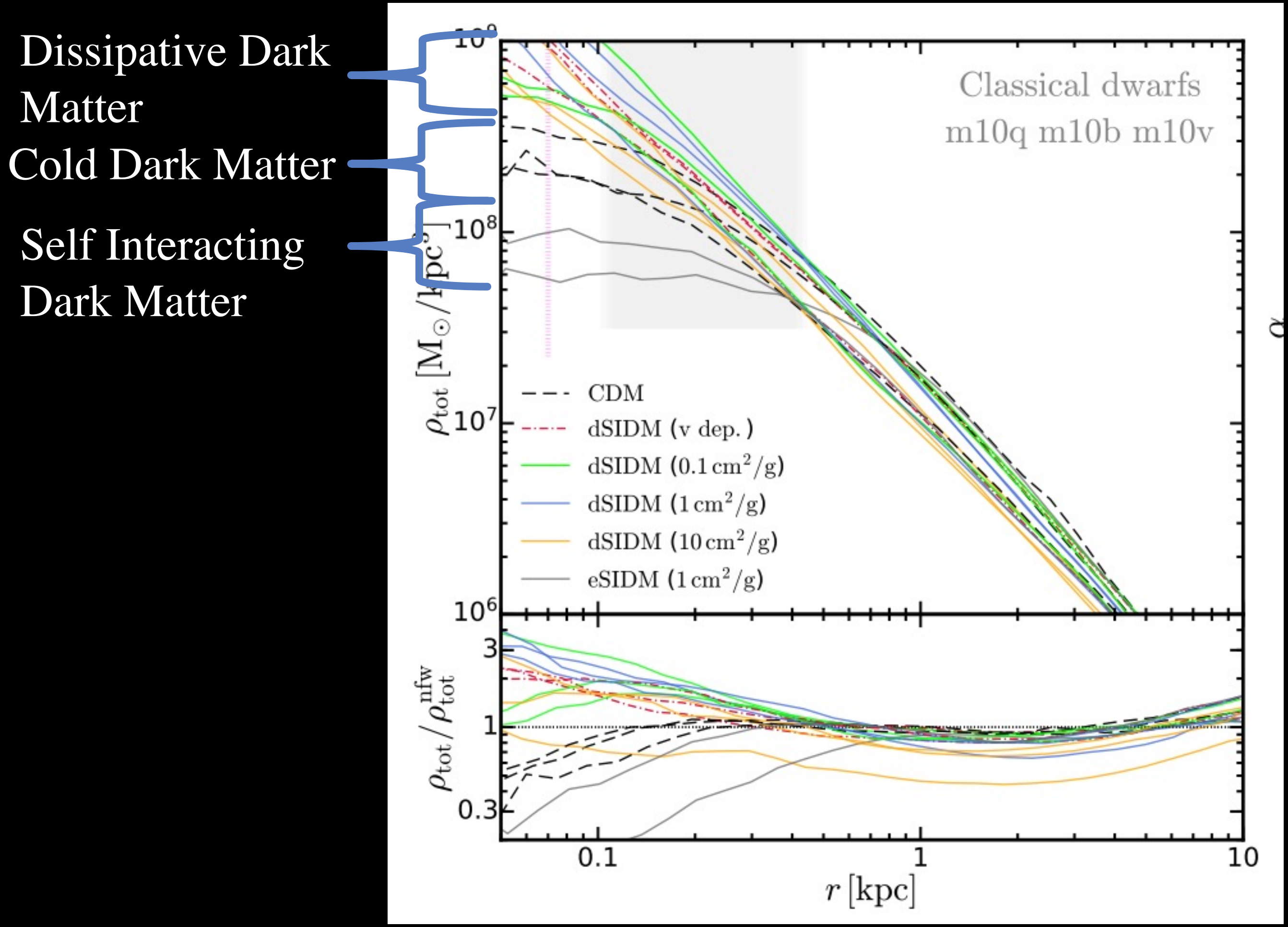
Chang & **Necib** (2020)

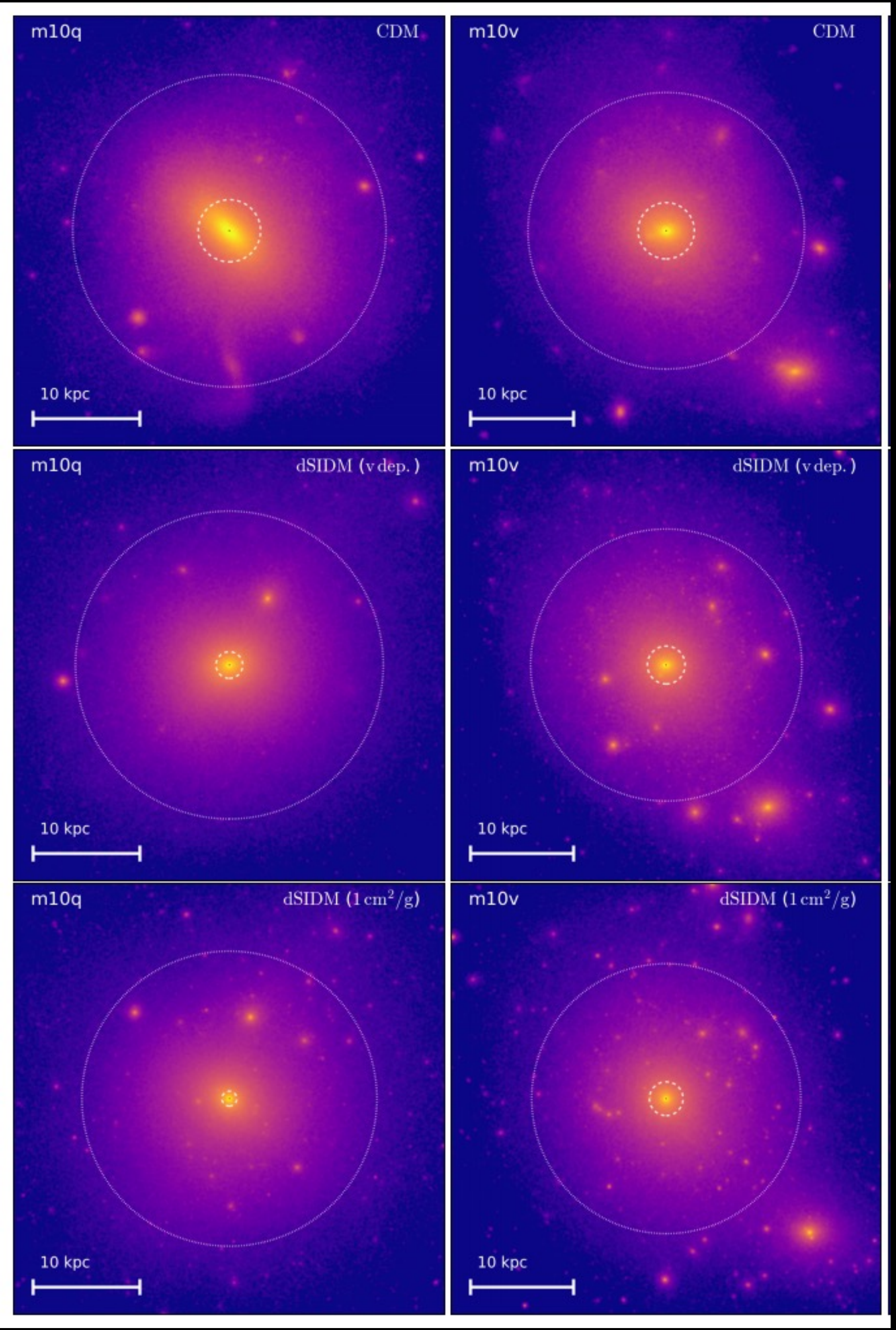
Once we have the Density Profiles of Galaxies under Control

Beyond Cold Dark Matter





Shen, Hopkins, **Necib**, et al. (2021)

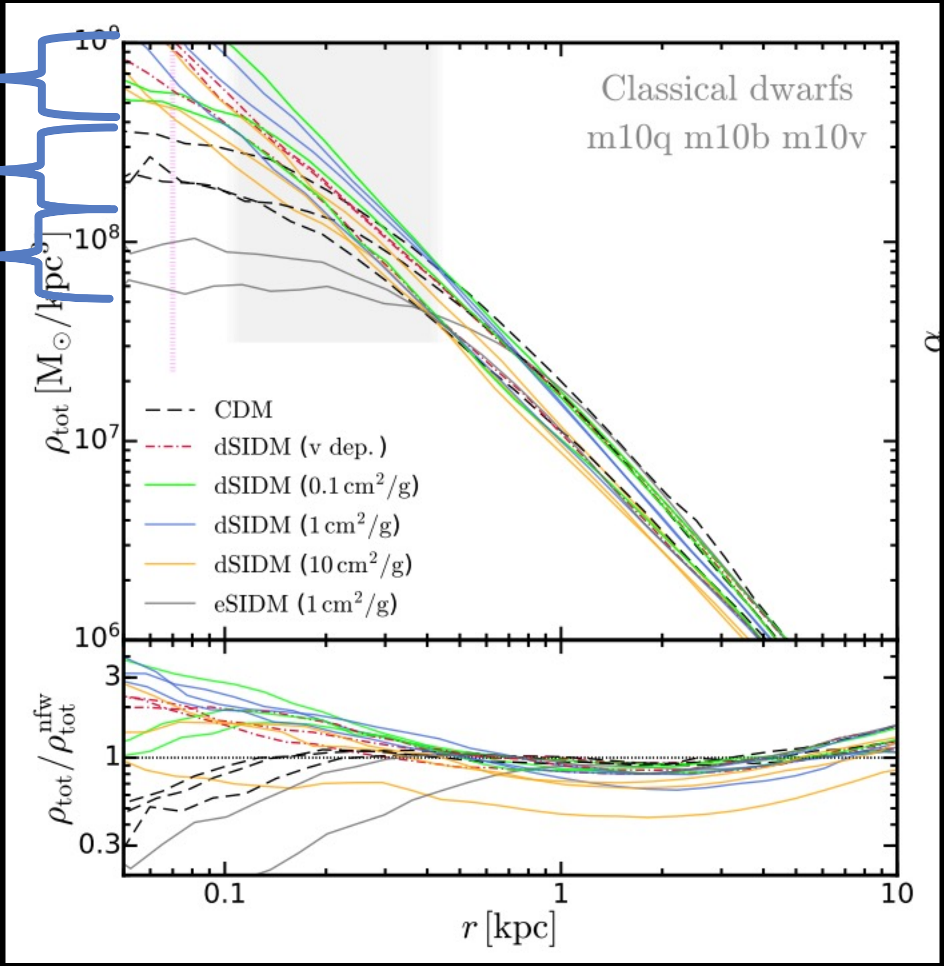


Beyond Cold Dark Matter

Dissipative Dark Matter

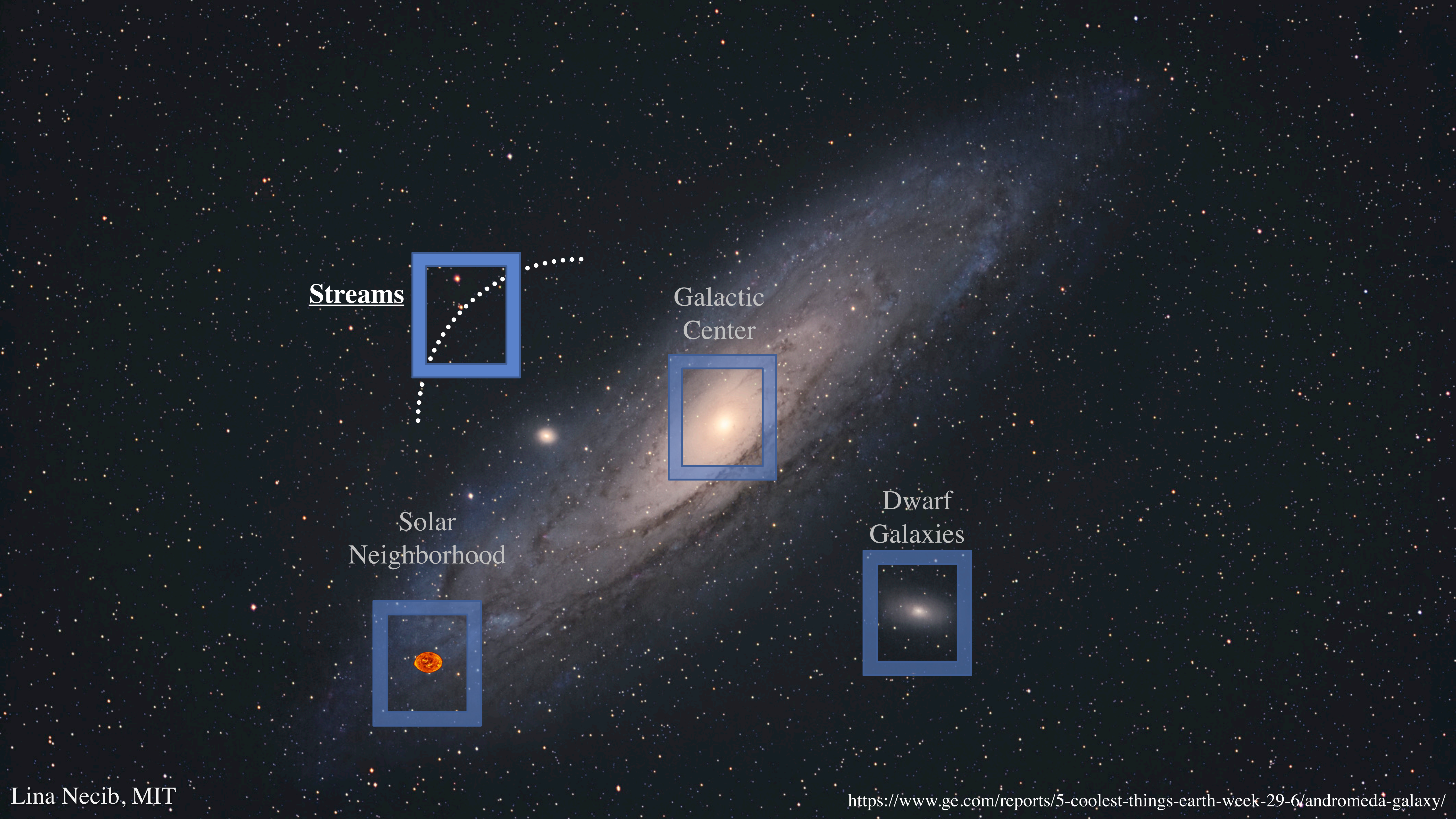
Cold Dark Matter

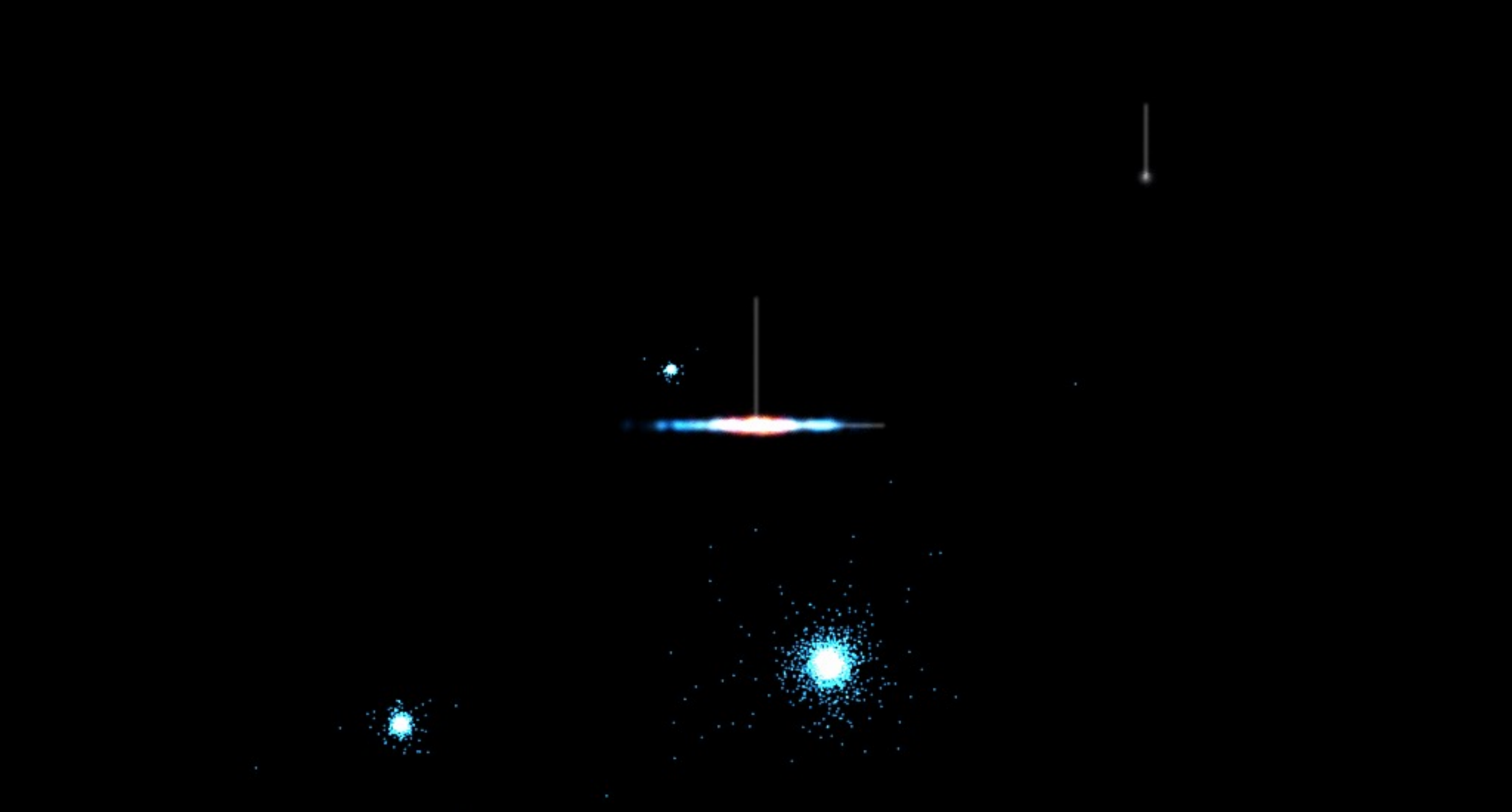
Self Interacting Dark Matter



We need to explore transferring Particle Physics Dark Matter Models into Hydrodynamics large scale simulations

Shen, Hopkins, **Necib**, et al. (2021)

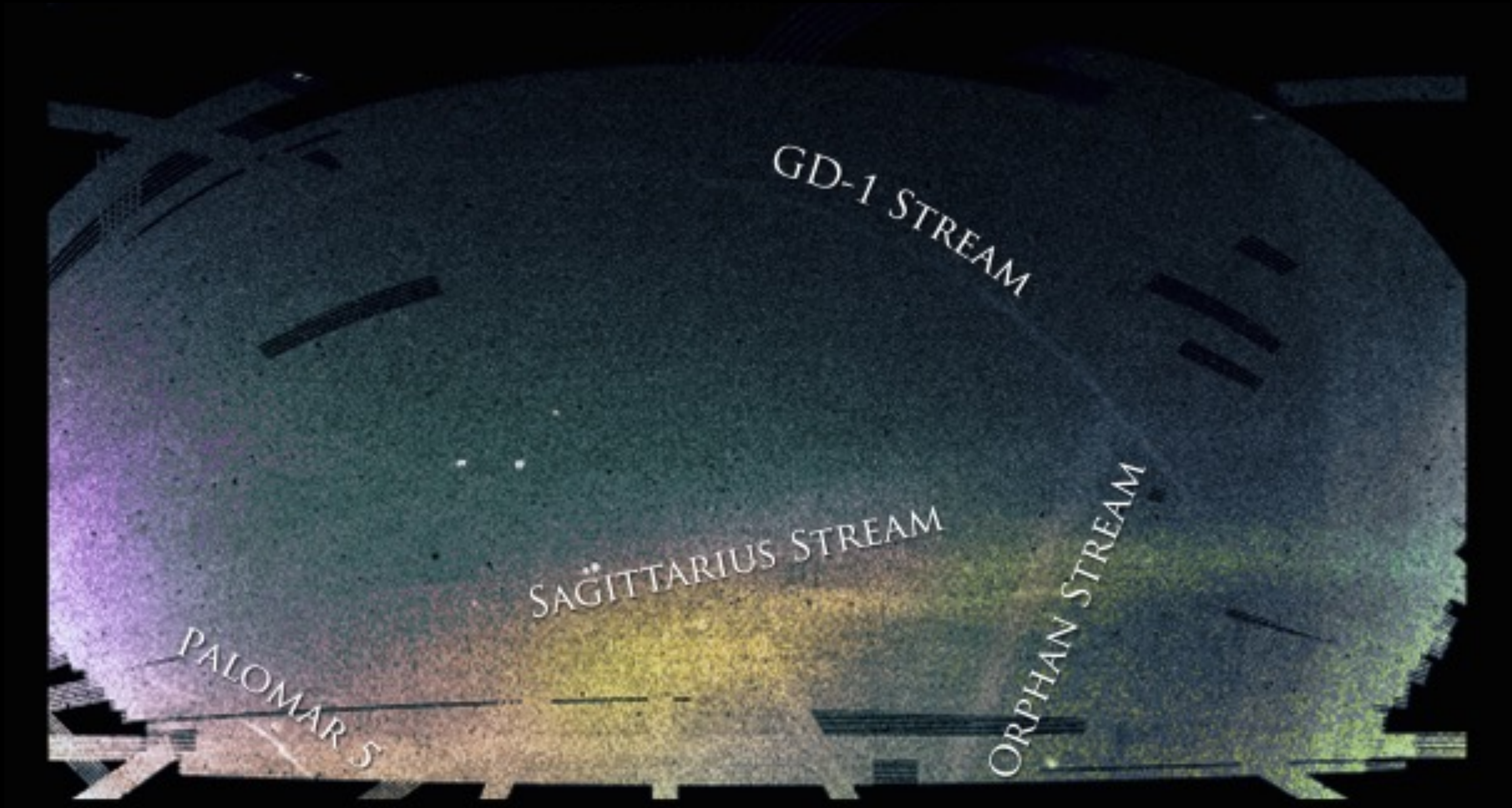

Streams
Galactic Center
Solar Neighborhood
Dwarf Galaxies
Lina Necib, MIT
https://www.ge.com/reports/5-coolest-things-earth-week-29-6/andromeda-galaxy/



Lina Necib, MIT

Credit: Rensselaer/Benjamin A. Willett

Field of Streams

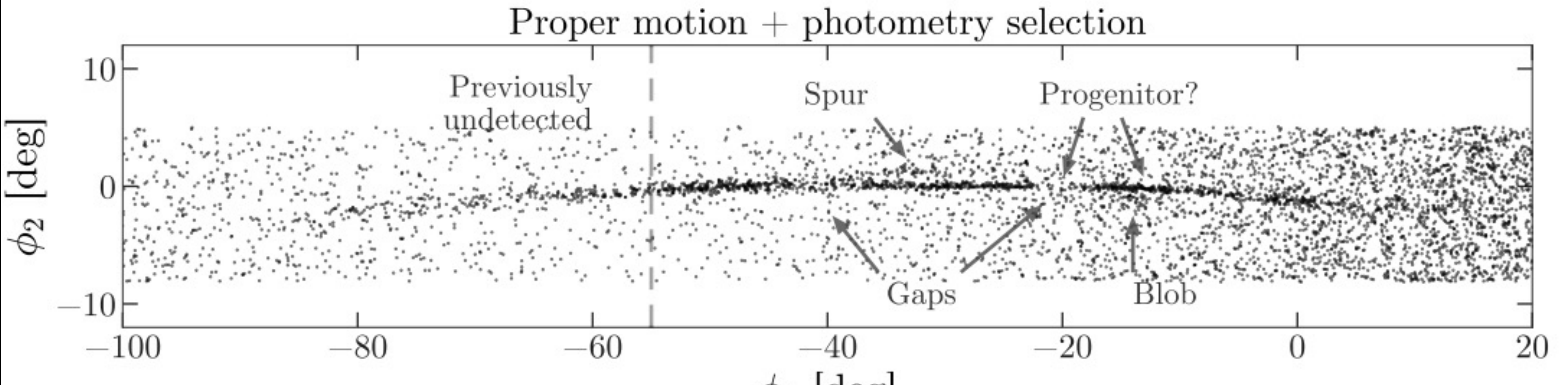


Credit: Bonaca, Geha, Kallivayalil

Data: Sloan Digital Sky Survey

Belokurov, Zucker, Evans, et al. (2007)

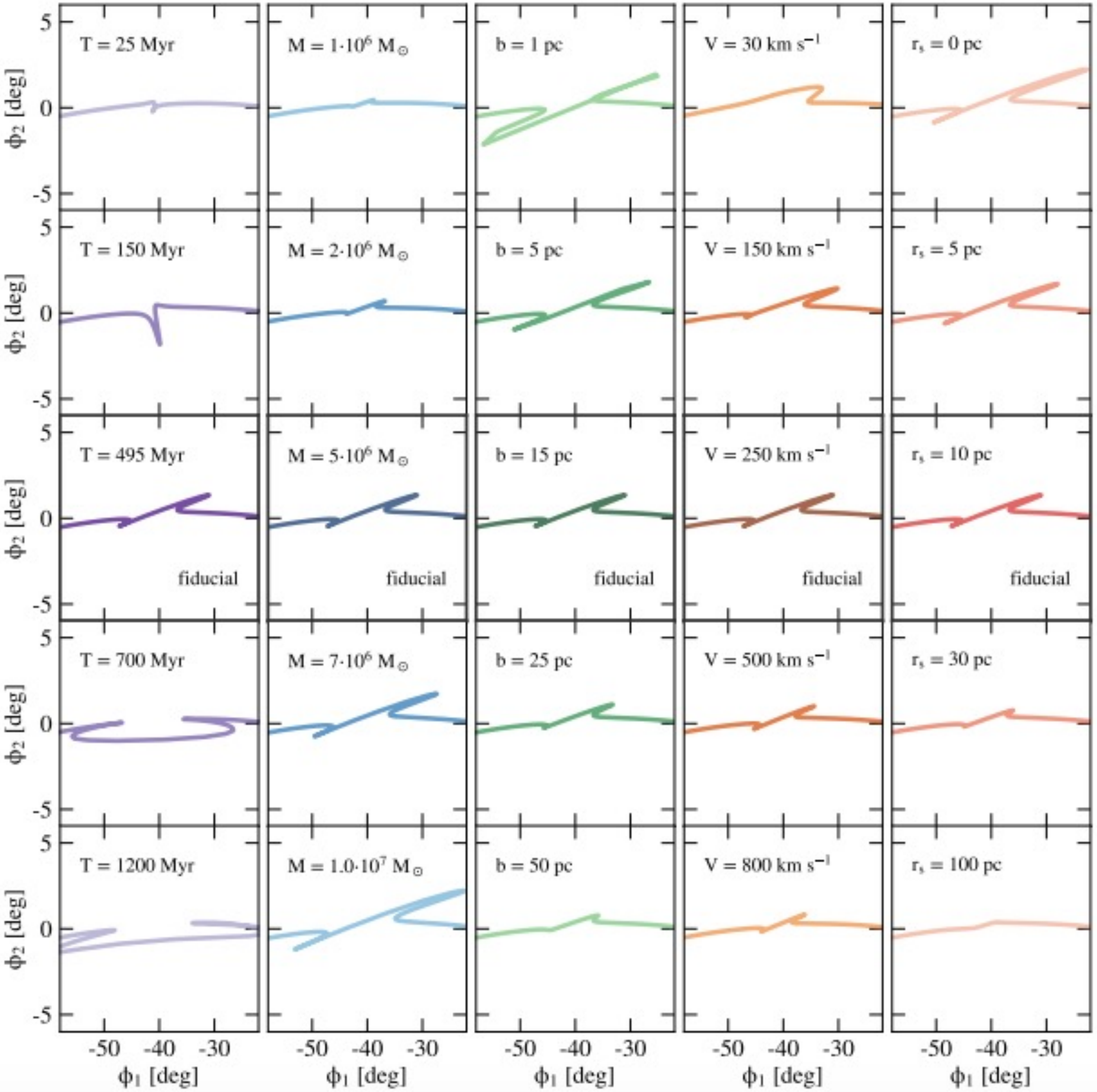
Streams: An insight into Dark Matter



GD1 stream

- Gaps in streams can constrain dark matter subhalo masses, and therefore models of warm dark matter!
- Streams are also used to constrain the potential of the Milky Way.

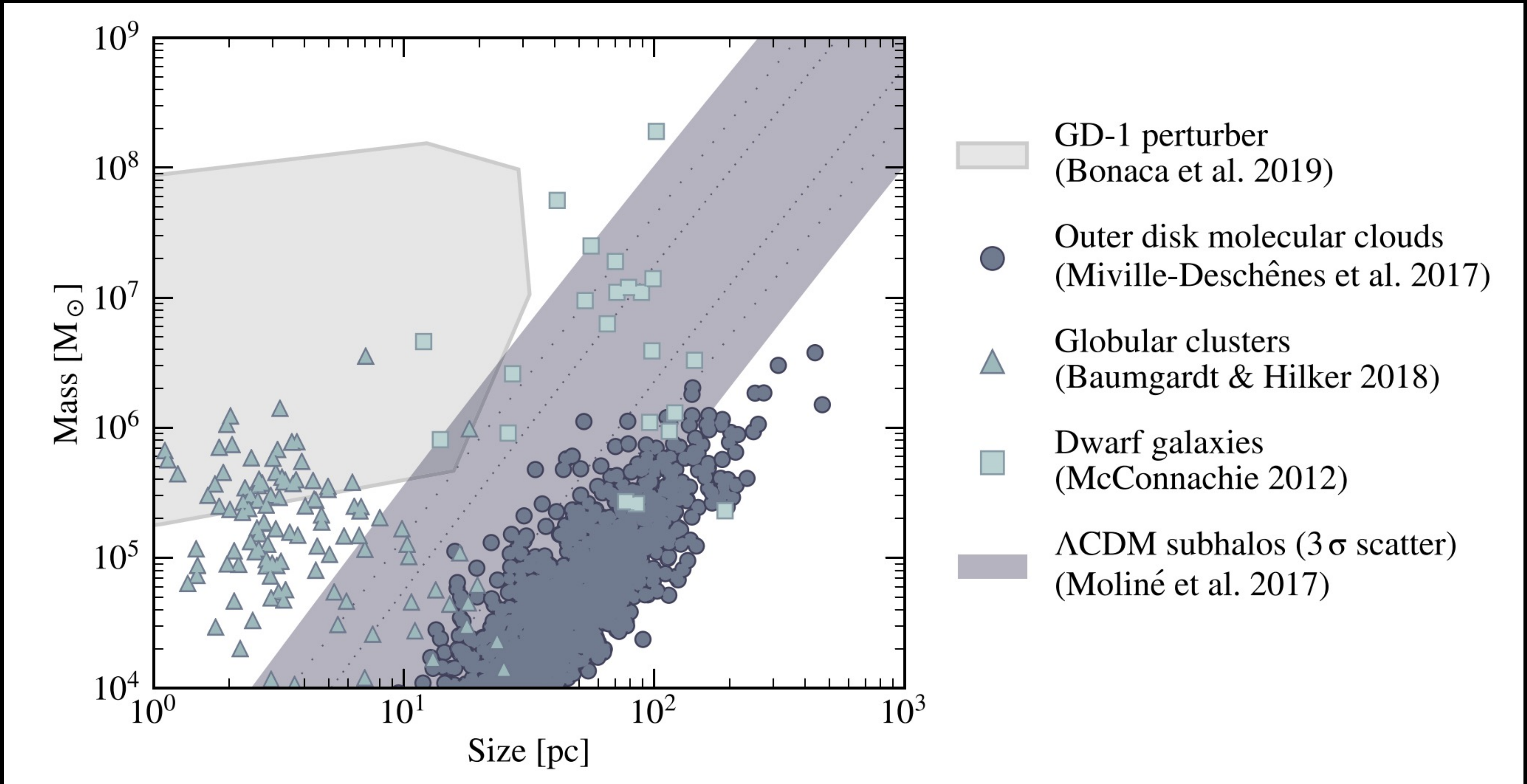
Grillmair & Dionatos (2006b)
Koposov et al. (2010)
Price-Whelan & Bonaca (2018)
Bonaca et al. (2019)



Lina Necib, MIT

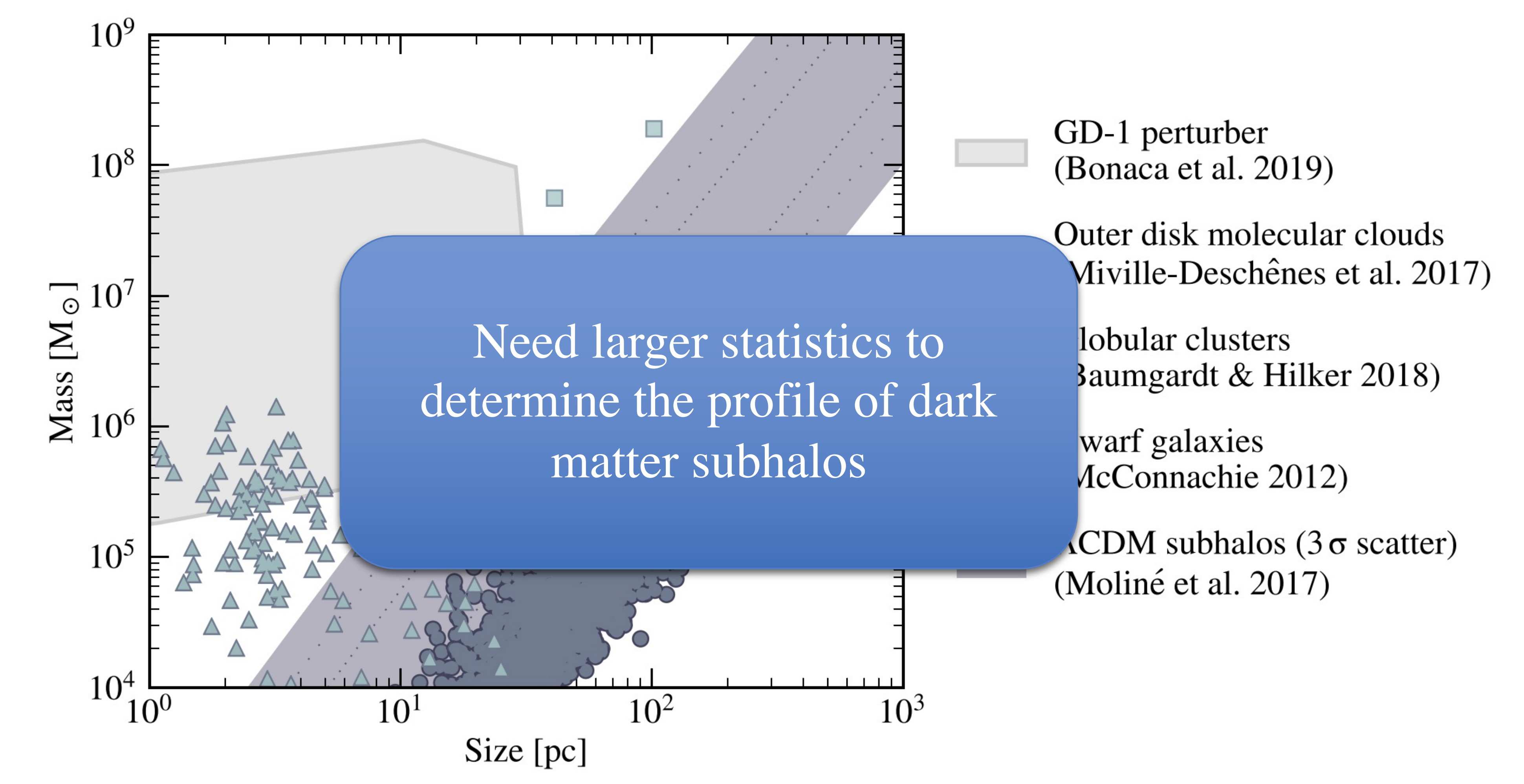
Bonaca et al. (2019)

GD-1 Perturber?



Bonaca et al. (2019)

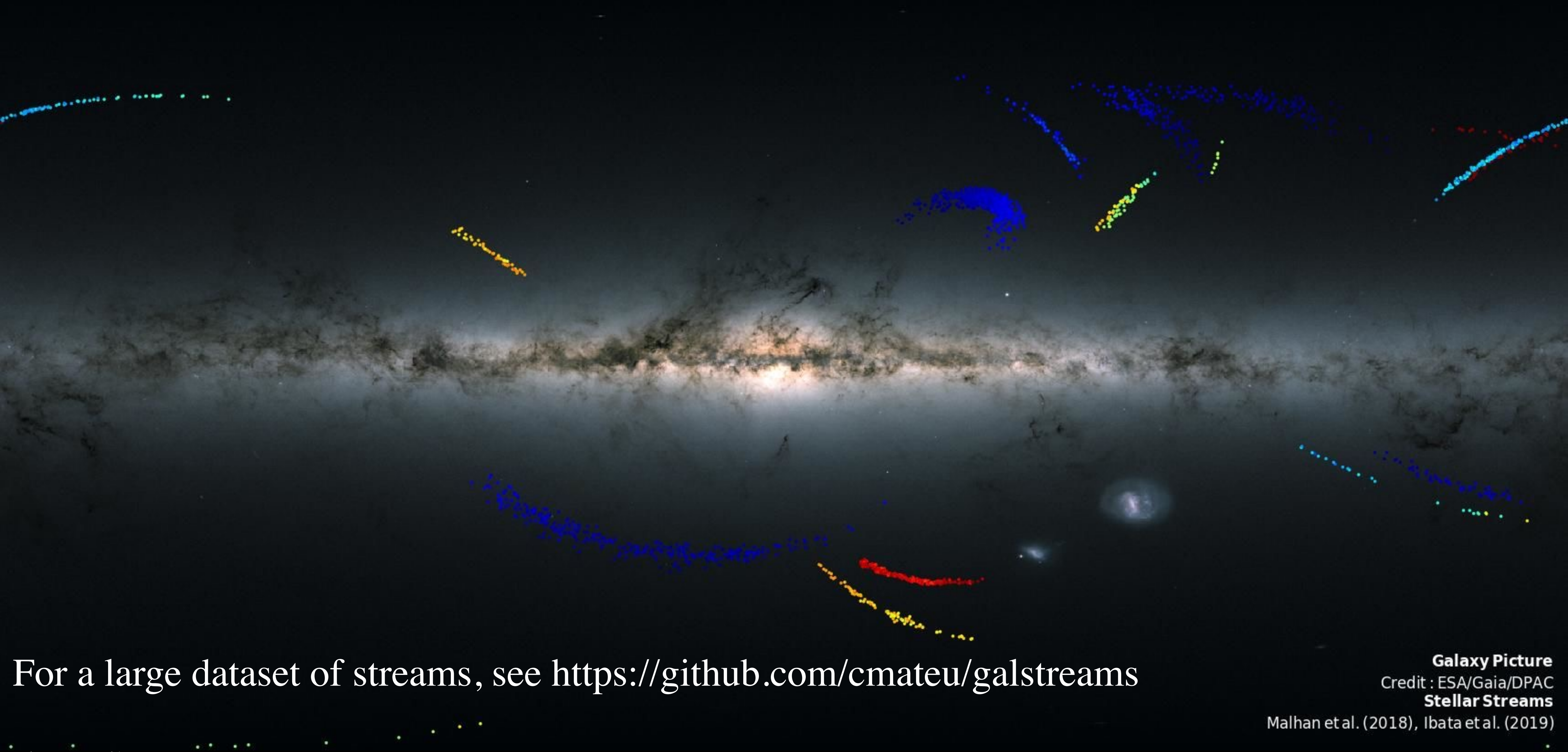
GD-1 Perturber?



Need larger statistics to determine the profile of dark matter subhalos

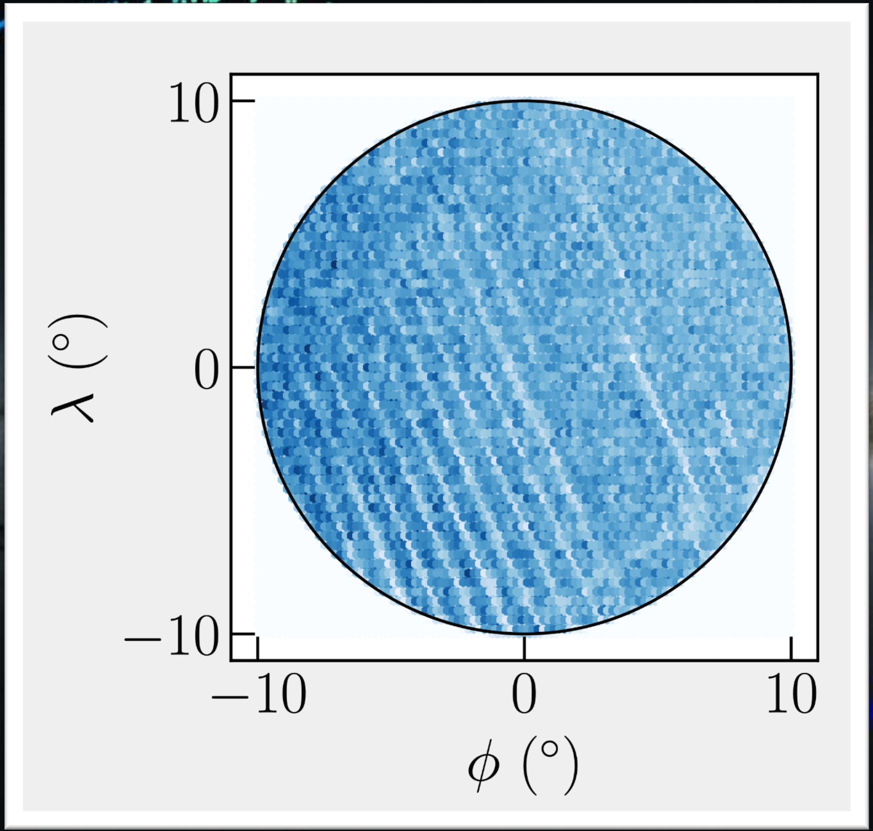
Bonaca et al. (2019)

Need to increase statistics of streams



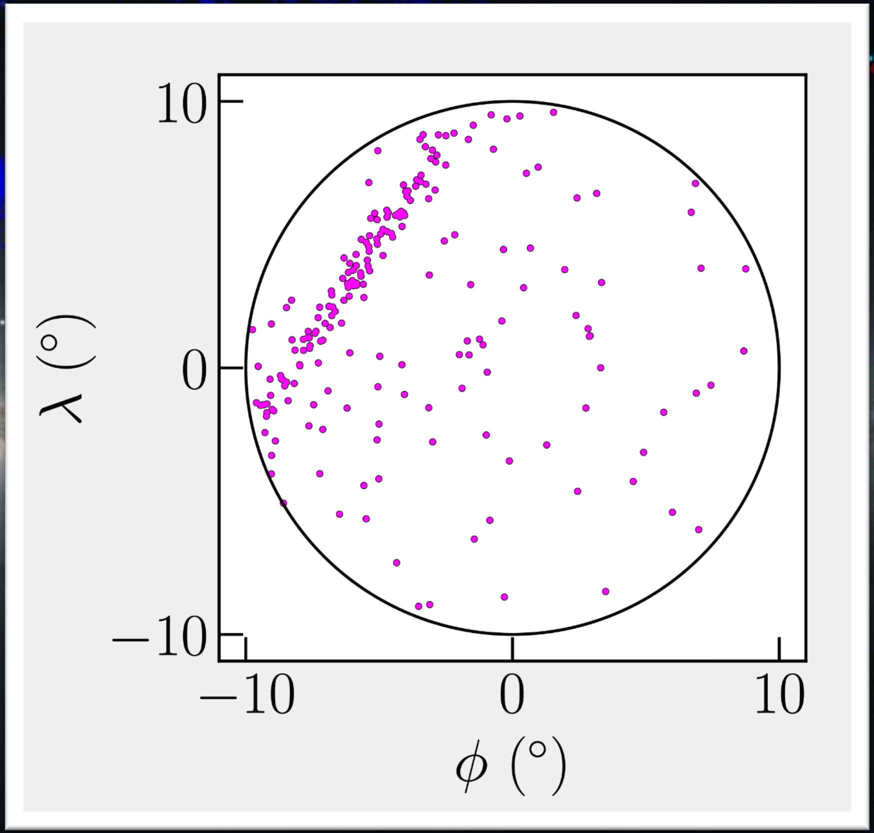
For a large dataset of streams, see https://github.com/cmateu/galstreams

Need to increase statistics of streams



Via Machinae

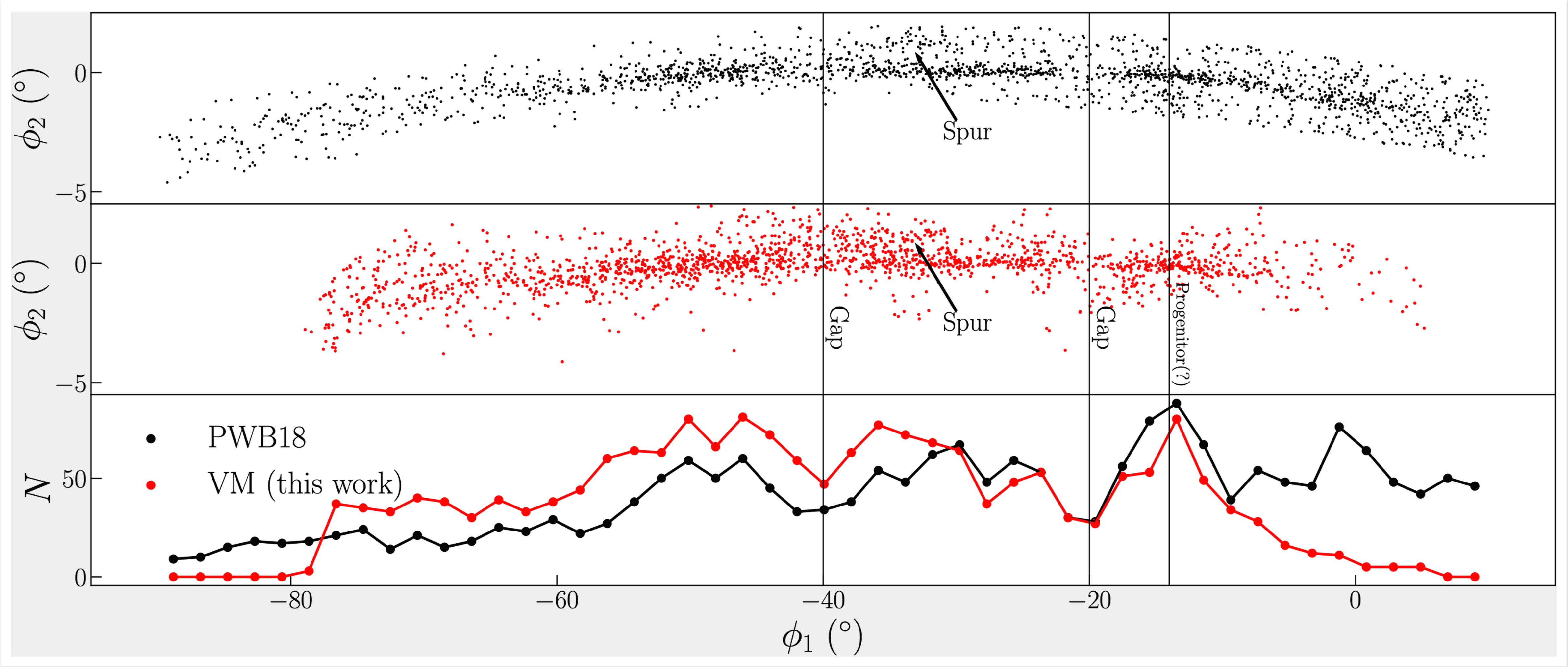
A machine learning algorithm that searches for anomalies in a multi-dimensional distribution.



Galaxy Picture
Credit : ESA/Gaia/DPAC
Stellar Streams
Malhan et al. (2018), Ibata et al. (2019)

Shih, Buckley, **Necib**, Tamanas (2021)

Apply Via Machinae on GD-1

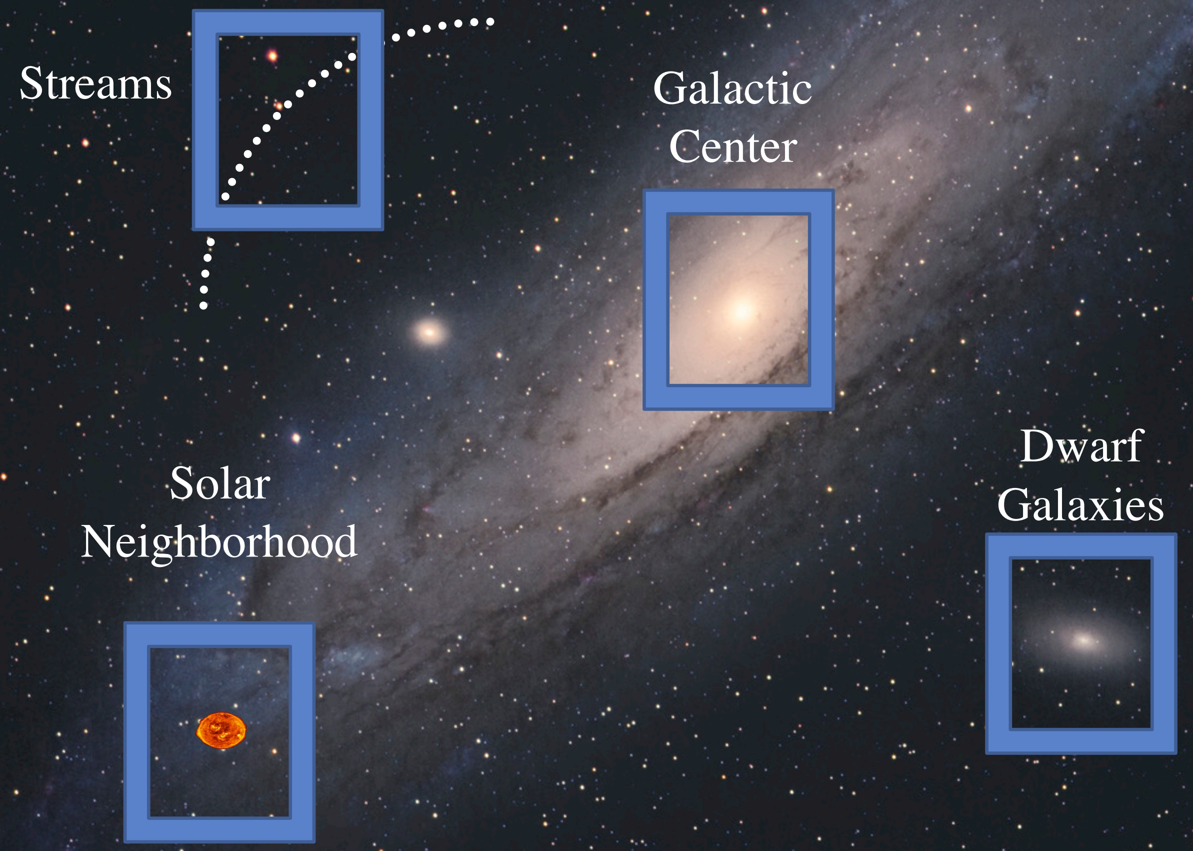


Lina Necib, MIT

Shih, Buckley, **Necib**, Tamanas (2021)

This Talk:

How to map out the Dark Matter phase space distribution on Galactic Scales at key locations.



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


Thank you!