

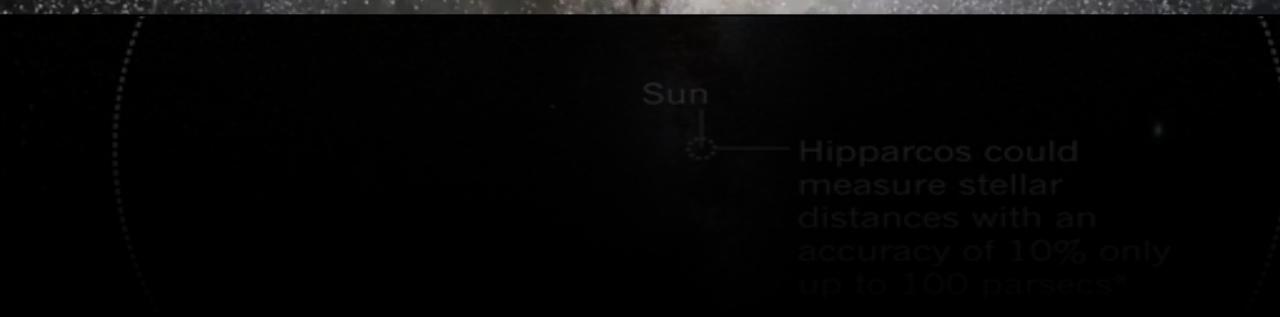
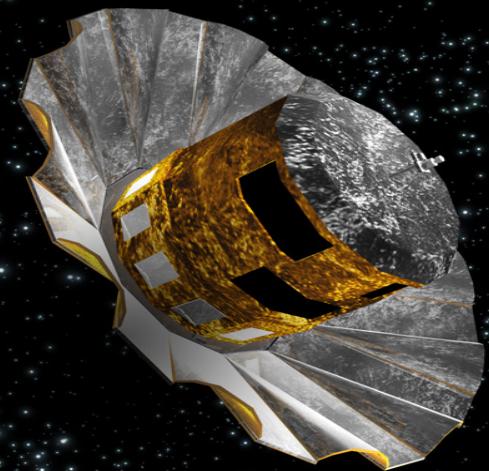
Unraveling Dark Matter with Gaia

Lina Necib

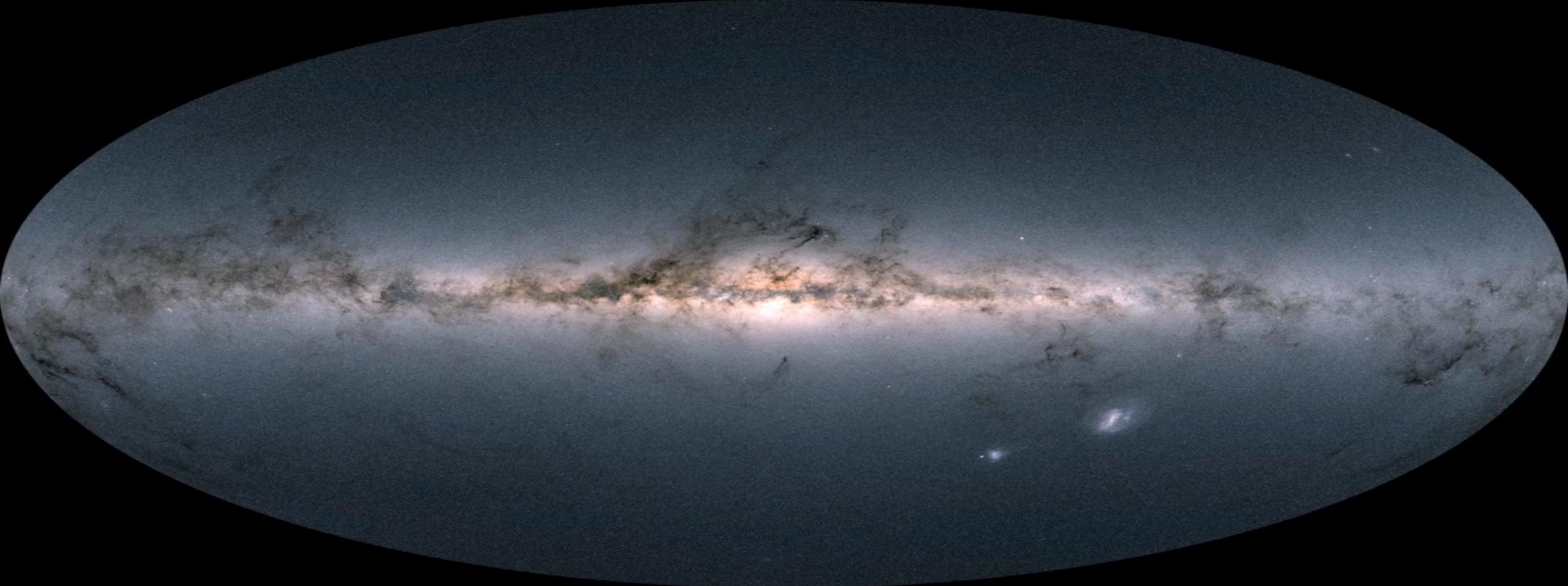
MIT

Gaia

- Launched December 2013
- Goal: Positional and kinematic measurement (3 positions + 2 velocities) of 1.5 billion stars (1% of the Milky Way)
- DR2: 7 million radial velocities (April 2018)
- DR3: 33 million radial velocities (June 2022)



Gaia

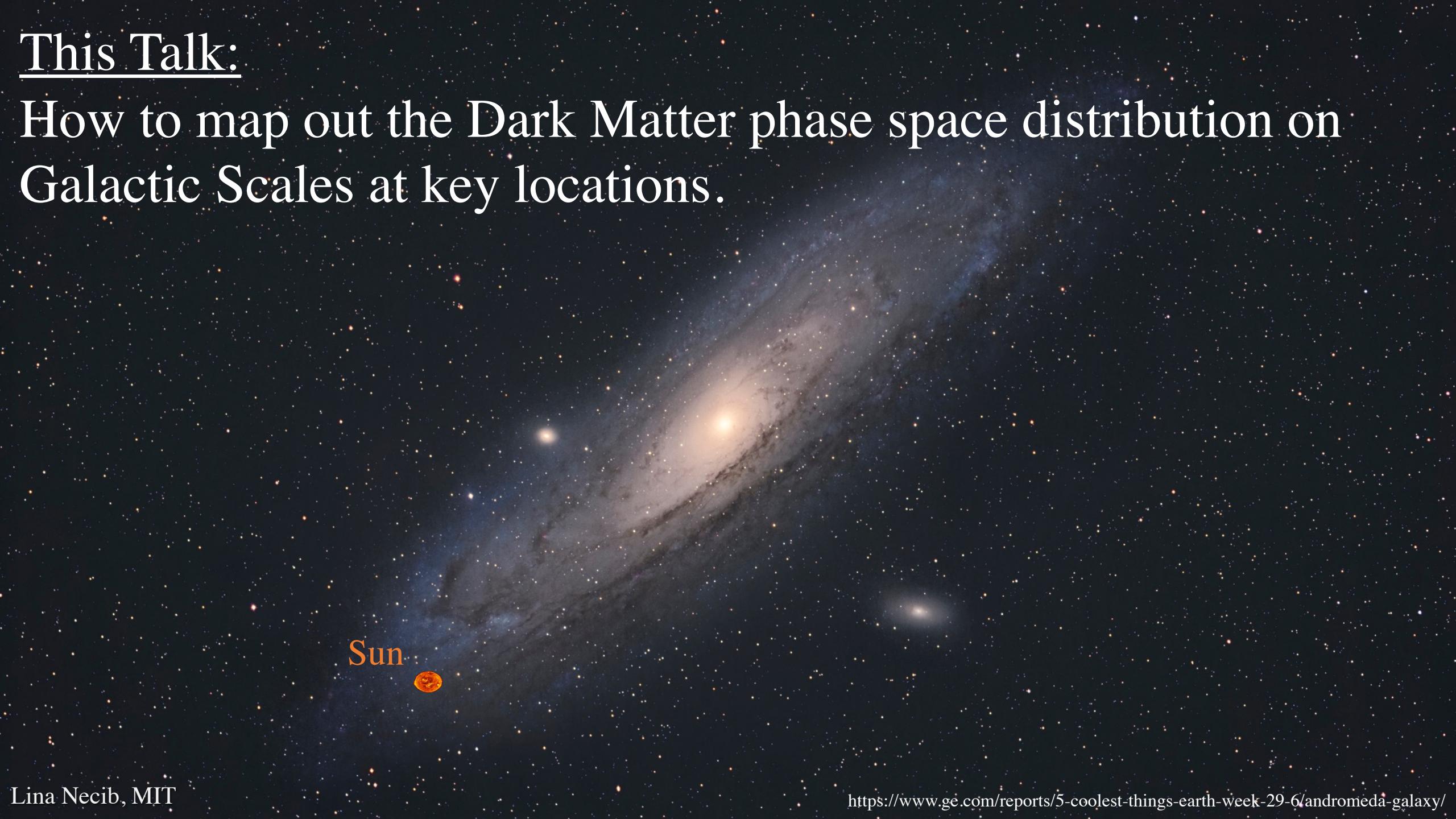


Lina Necib, MIT

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

This Talk:

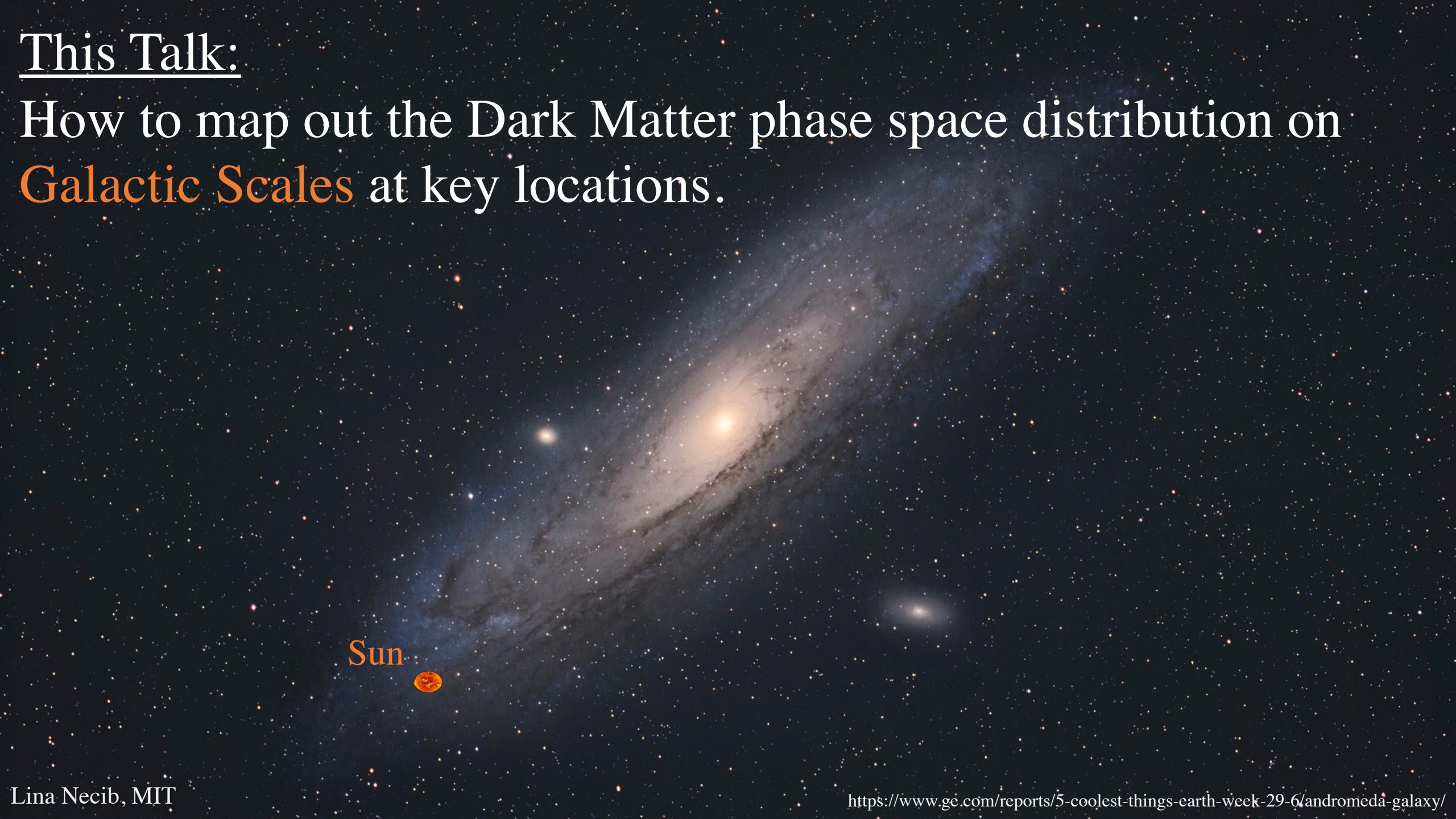
How to map out the Dark Matter phase space distribution on
Galactic Scales at key locations.



Sun

This Talk:

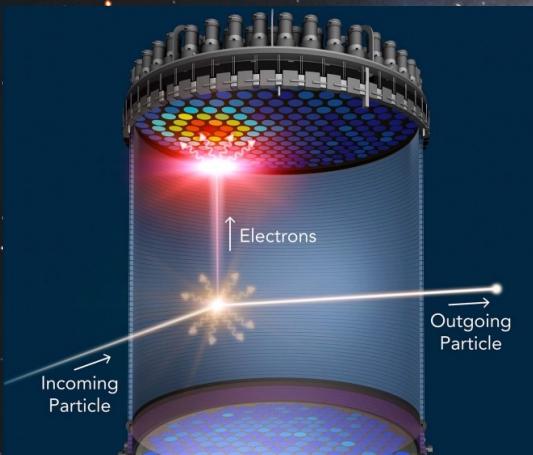
How to map out the Dark Matter phase space distribution on
Galactic Scales at key locations.



Sun

This Talk:

How to map out the Dark Matter phase space distribution on
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1. Terrestrial Experiments

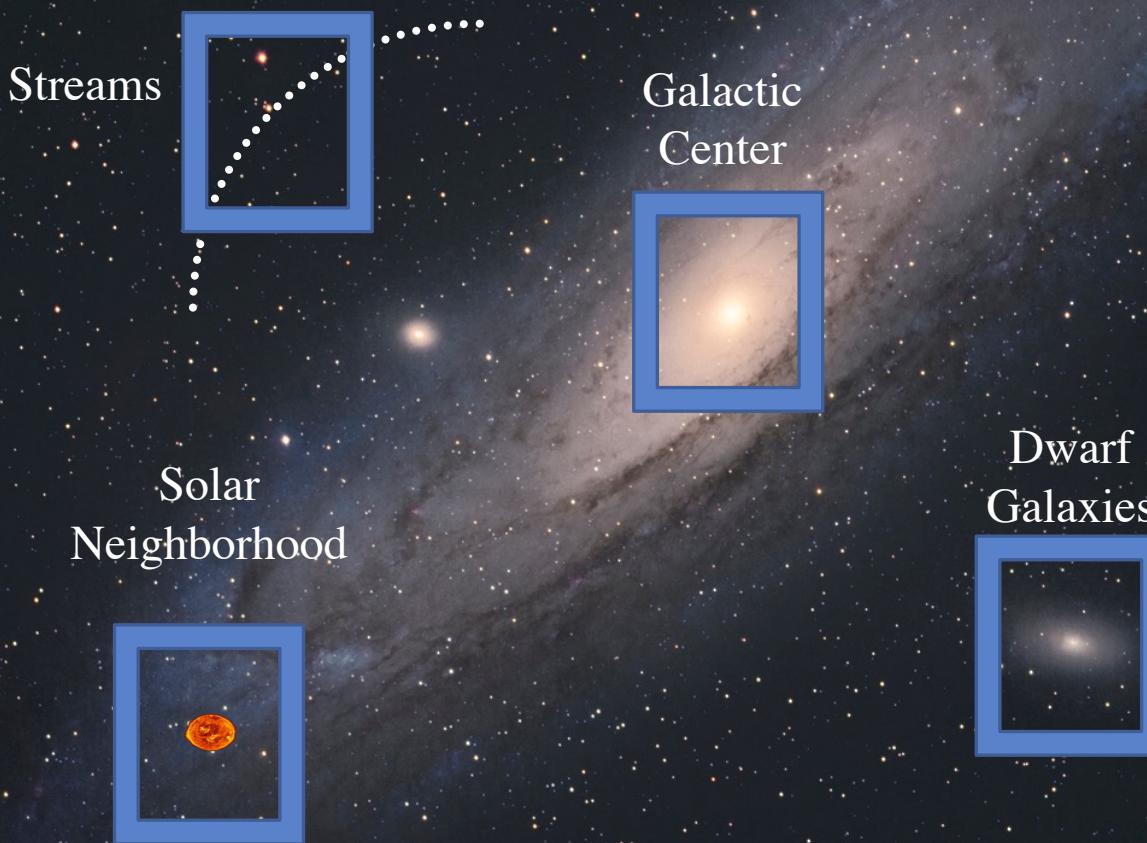
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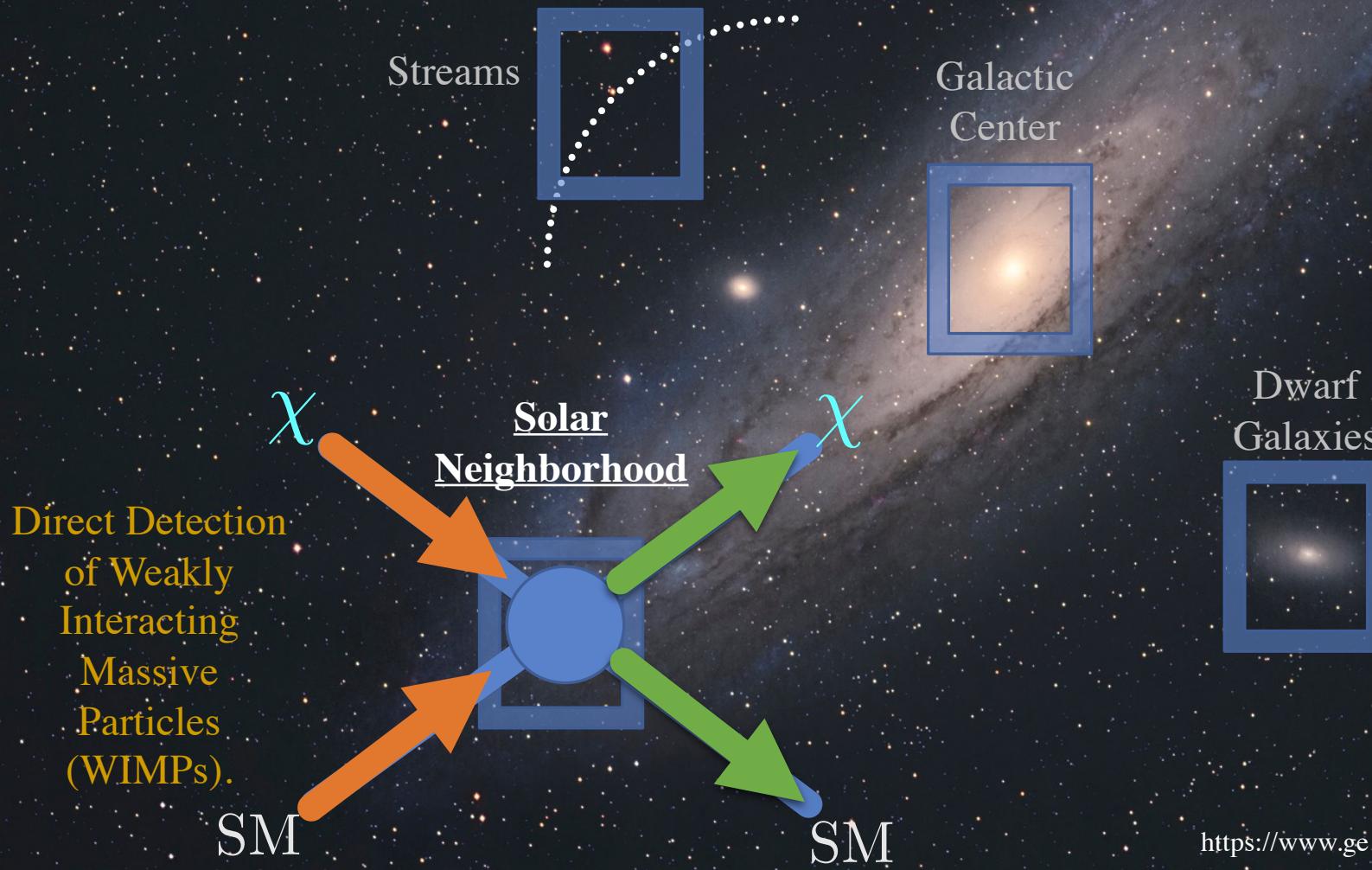
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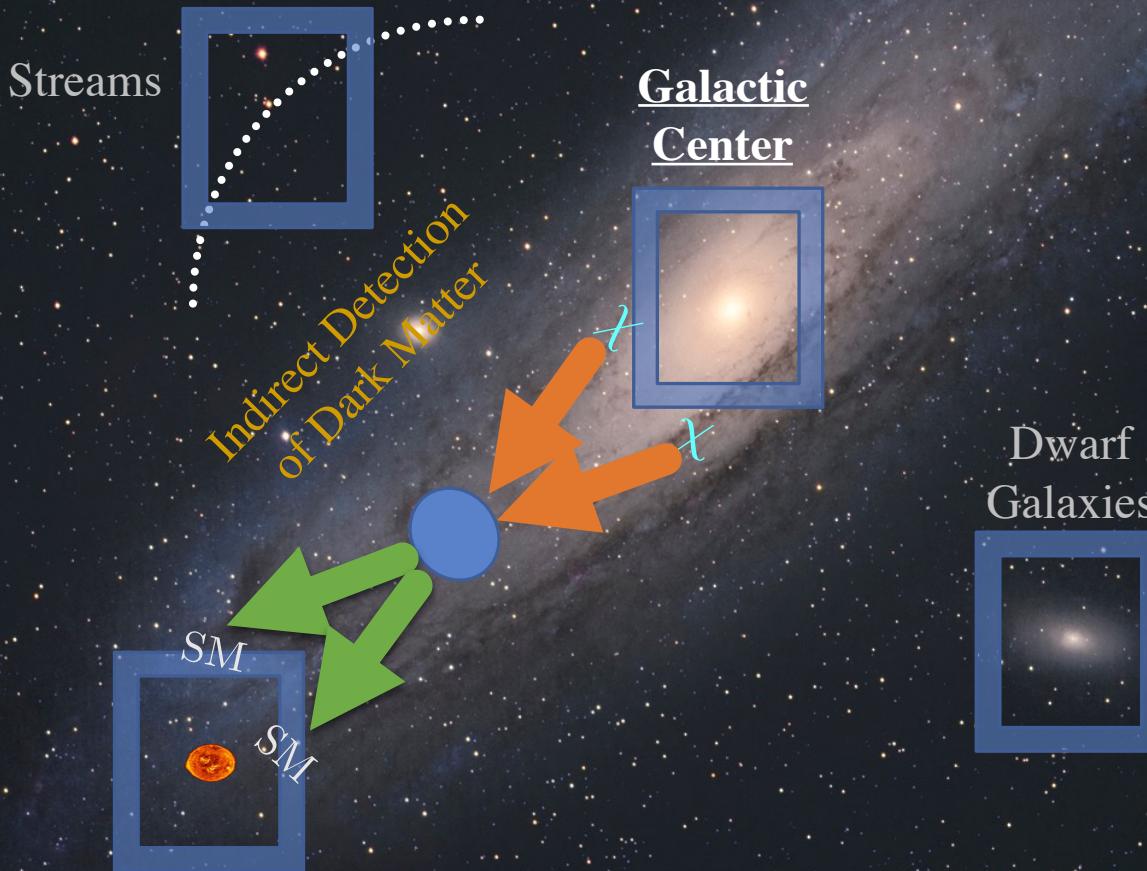
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This Talk:

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



This Talk:

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

Streams

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



Solar Neighborhood



Galactic Center

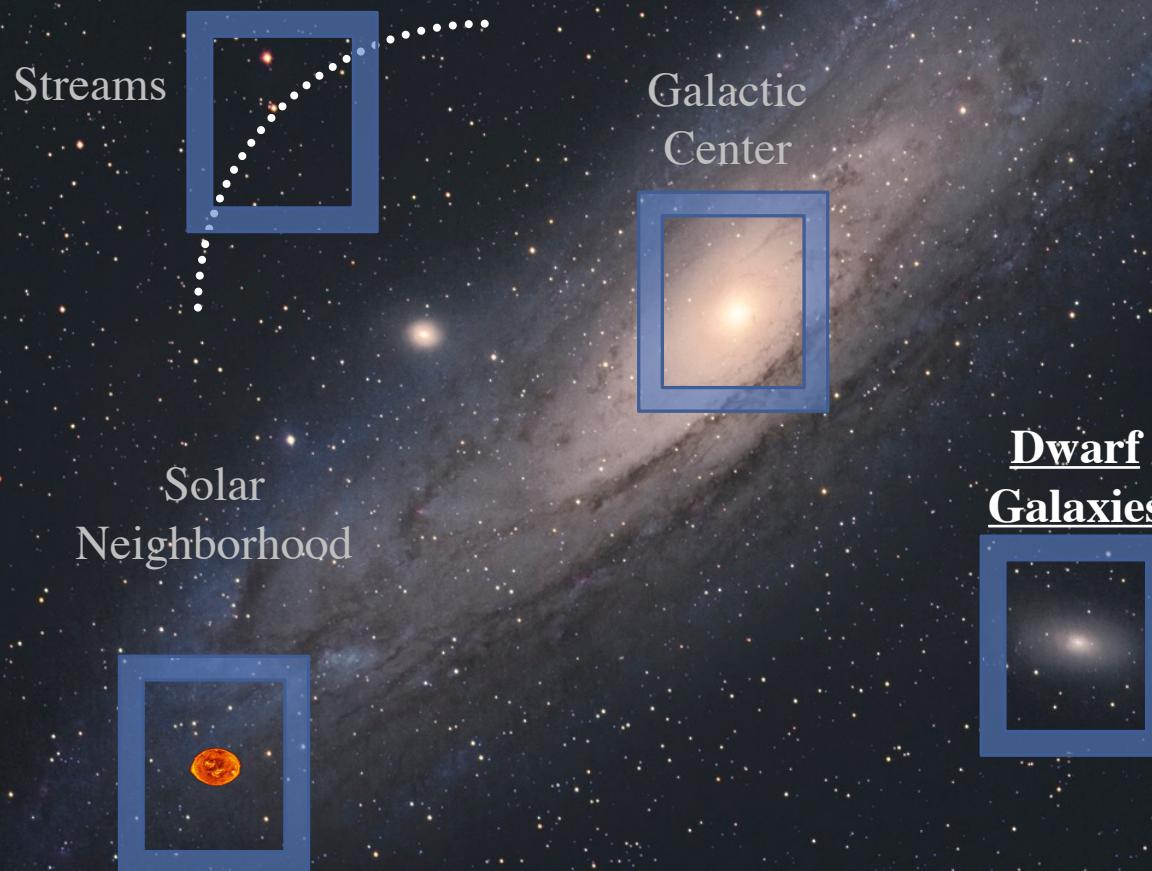


Dwarf Galaxies



This Talk:

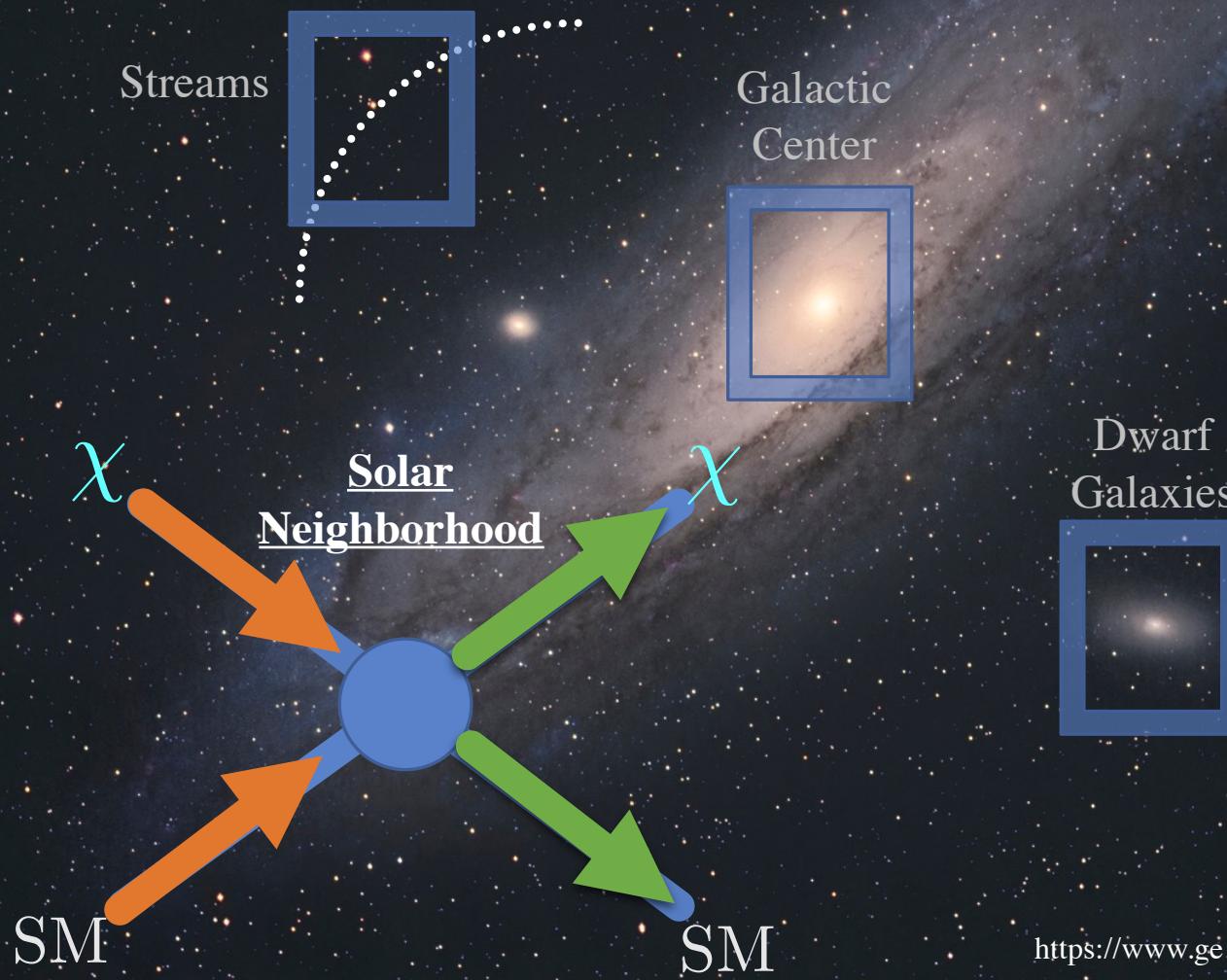
How to map out the Dark Matter phase space distribution on Galactic Scales at key locations.



Dwarf
Galaxies

Solving Core
Versus Cusp
Problem with
Dissipative and
Self Interacting
Dark Matter

Dark Matter in the Solar Neighborhood

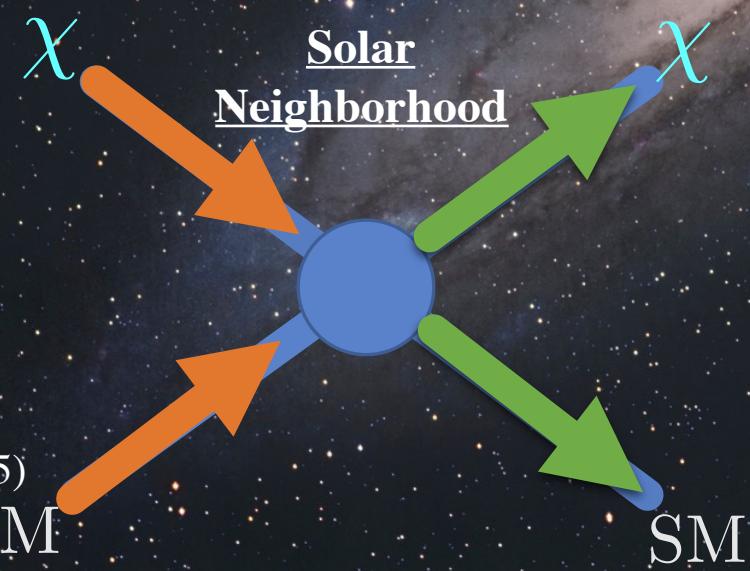




Lina Necib, MIT

Credit: Science Friday, LUX Experiment

Dark Matter in the Solar Neighborhood



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

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

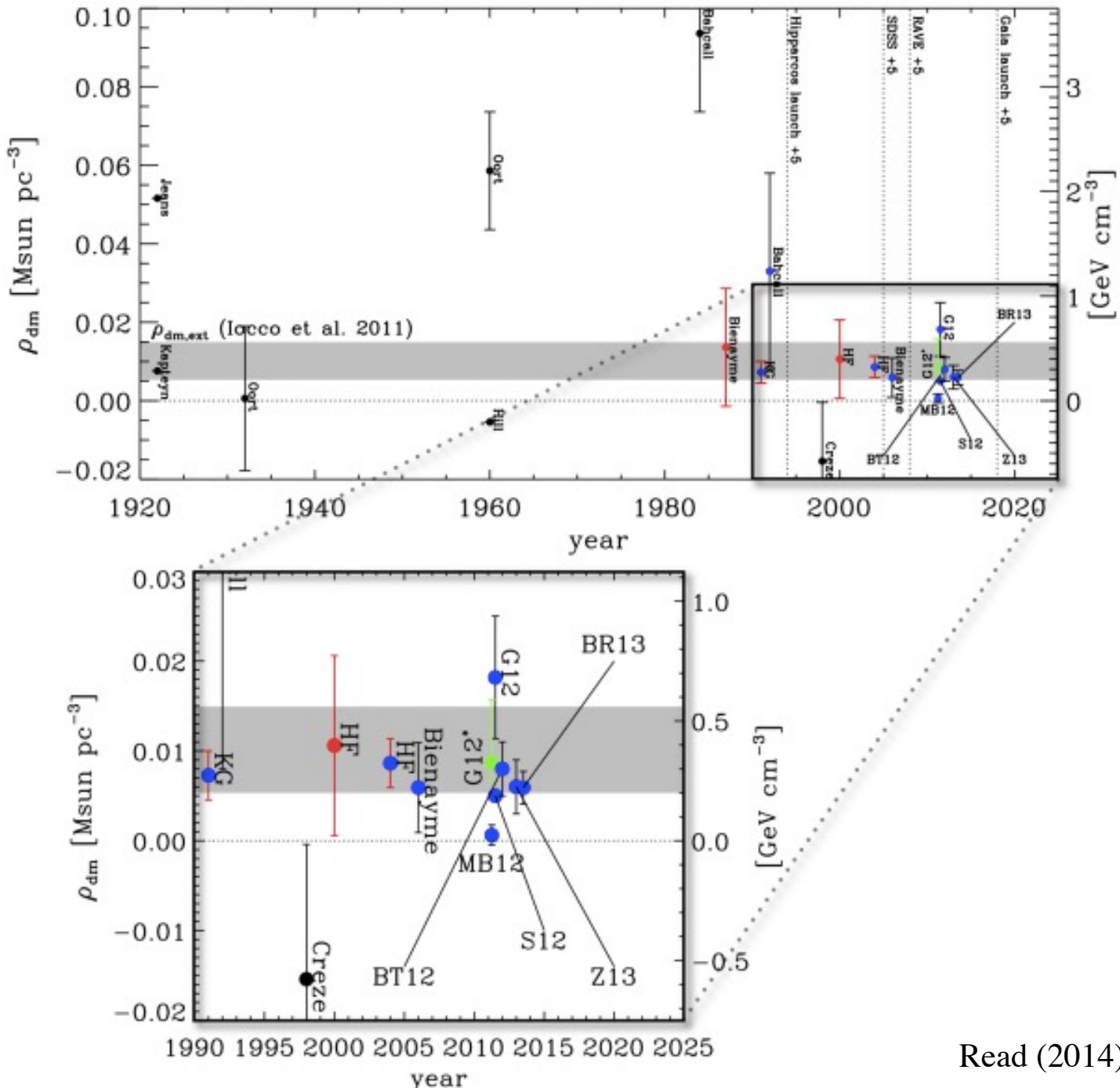
ρ_{\odot} : Local Dark Matter Density

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

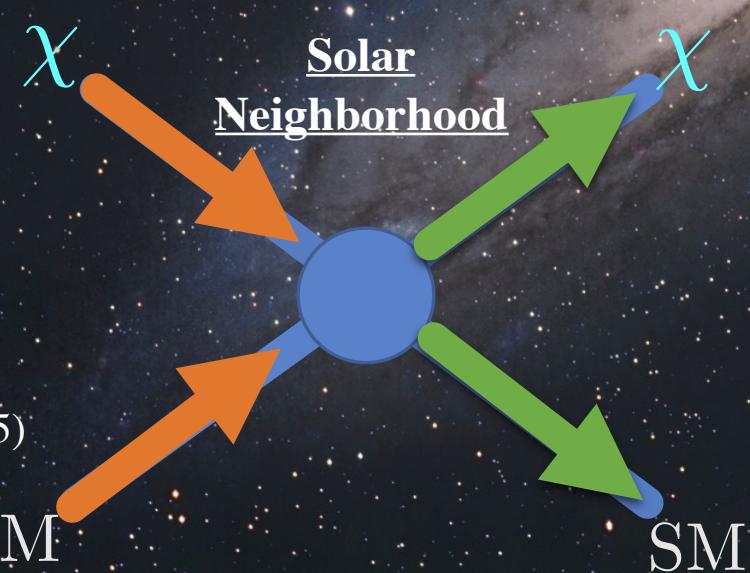
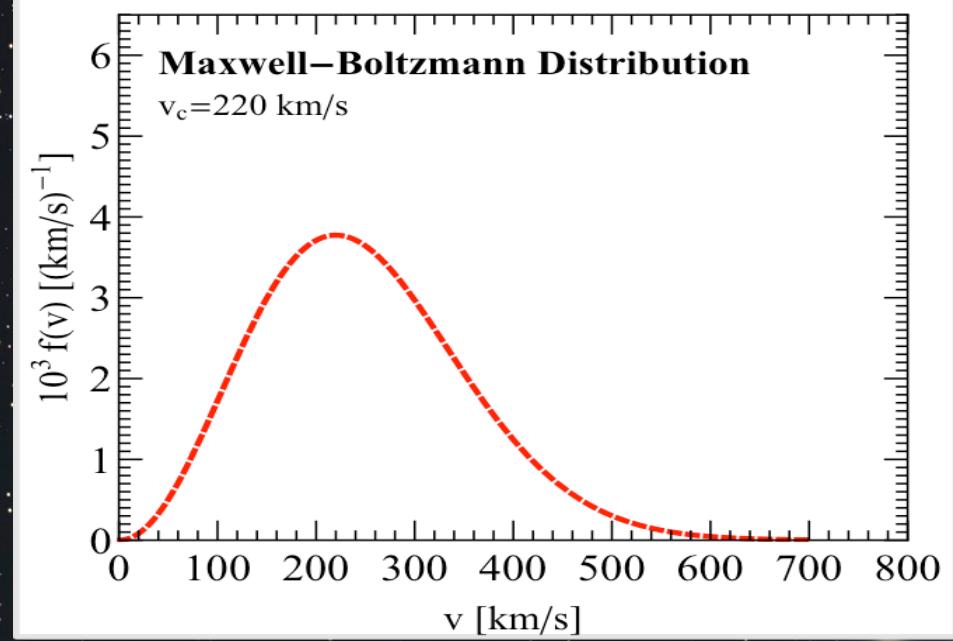
Dark Matter in the Solar Neighborhood

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ρ_{\odot} : Local Dark Matter Density
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Dark Matter in the Solar Neighborhood



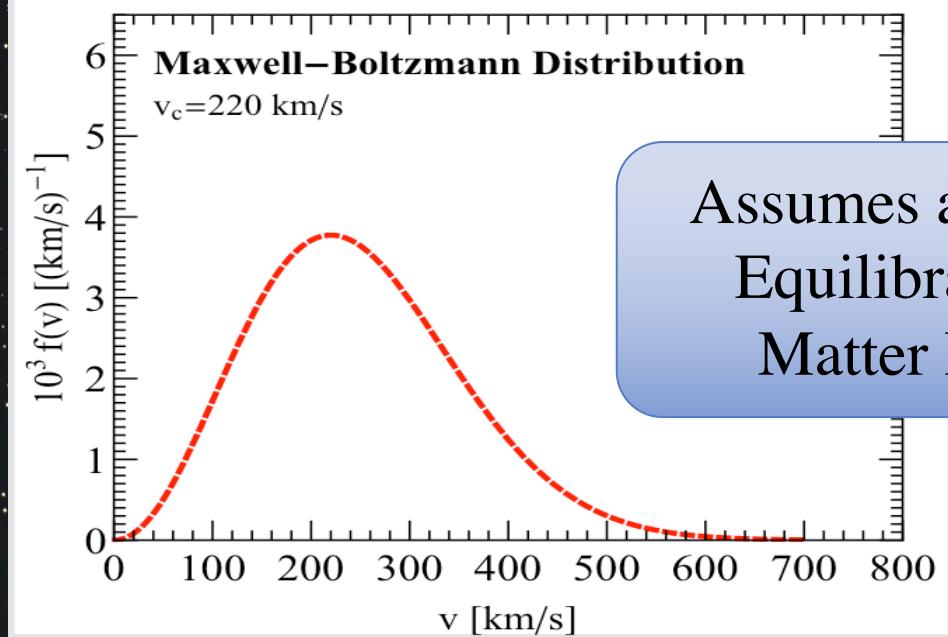
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Freese et al. (1986)
Drukier et al. (1987)

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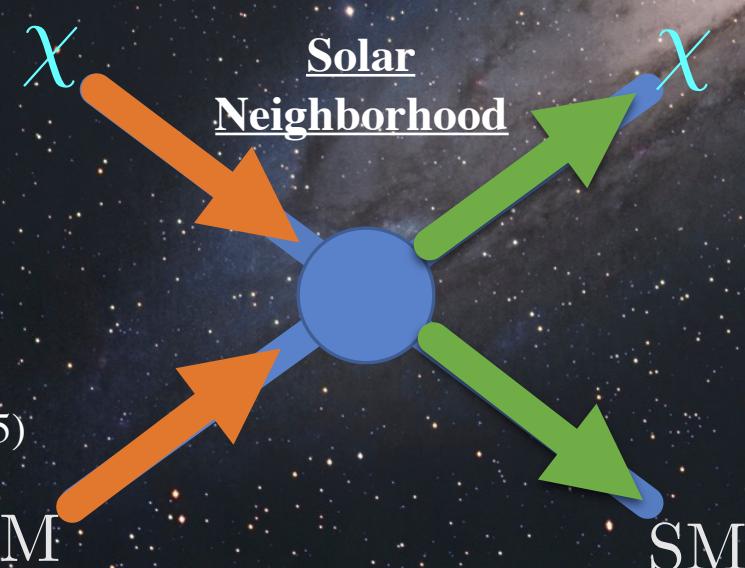
ρ_\odot : Local Dark Matter Density

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

Dark Matter in the Solar Neighborhood



Assumes an Isotropic
Equilibrated Dark
Matter Potential



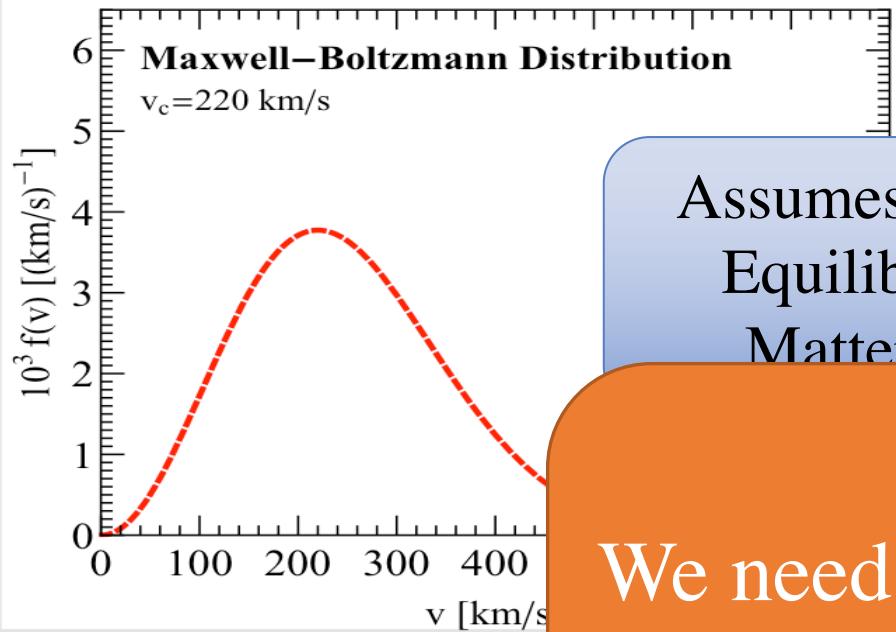
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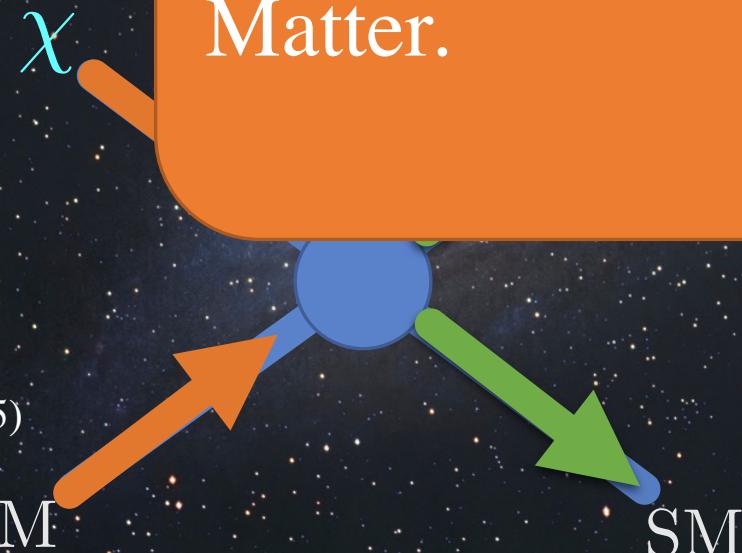
$f(v)$: Local Dark Matter Velocity
Distribution

Dark Matter in the Solar Neighborhood



Assumes an Isotropic
Equilibrated Dark
Matter Potential

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



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

ρ_{\odot} : Local Dark Matter Density

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

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)

Feedback in Realistic Environments (FIRE)

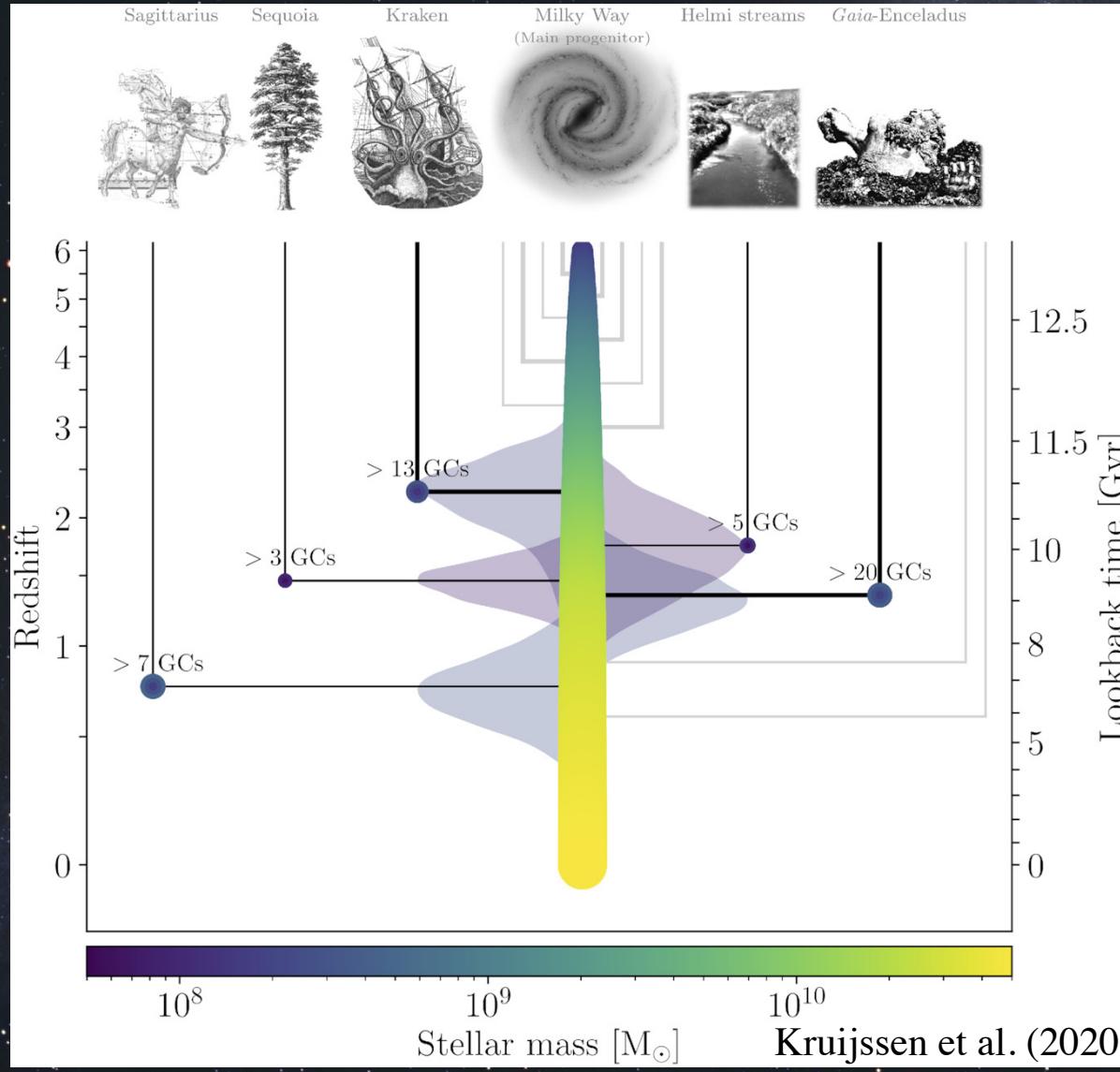
z=9.9



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

Building the Dark Matter Map

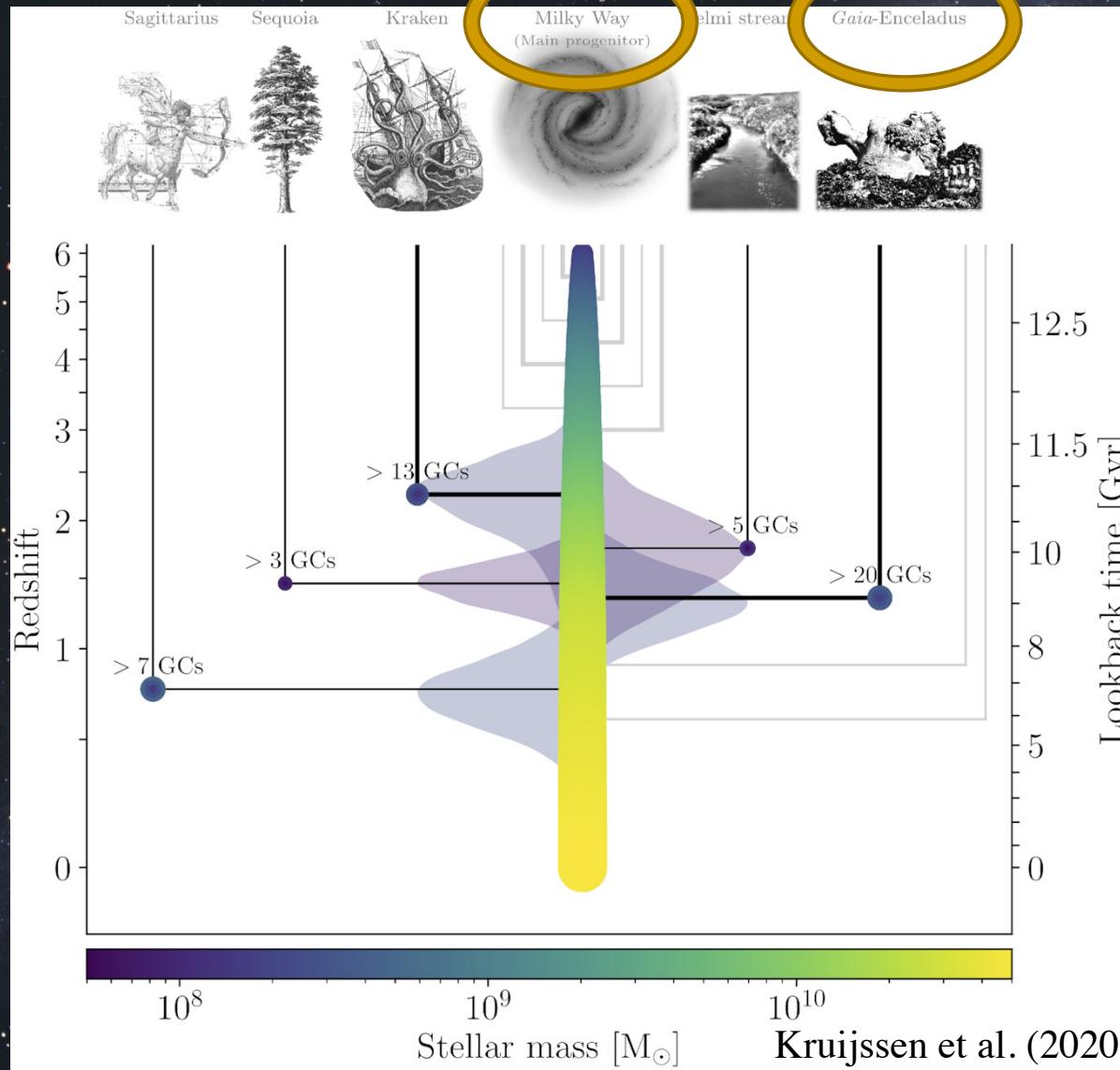
Strategy: Reconstruct the Dark Matter from the distributions of the stars.



Belukorov et al. (2018)
Helmi et al. (2018)
Kruijssen et al. (2020)

Building the Dark Matter Map

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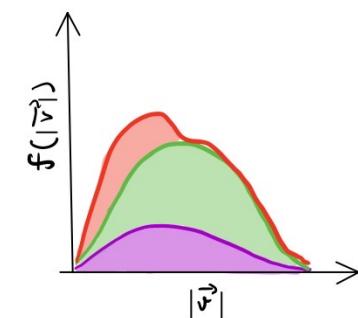
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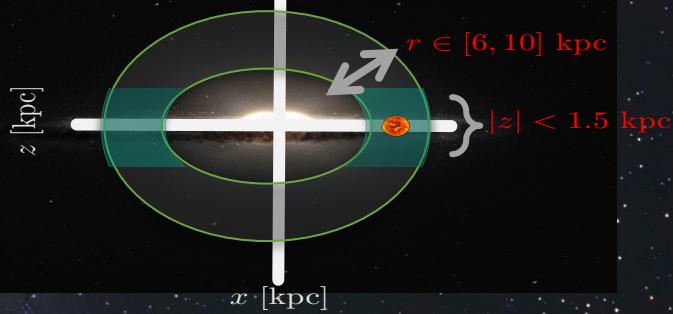
Different Components:

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

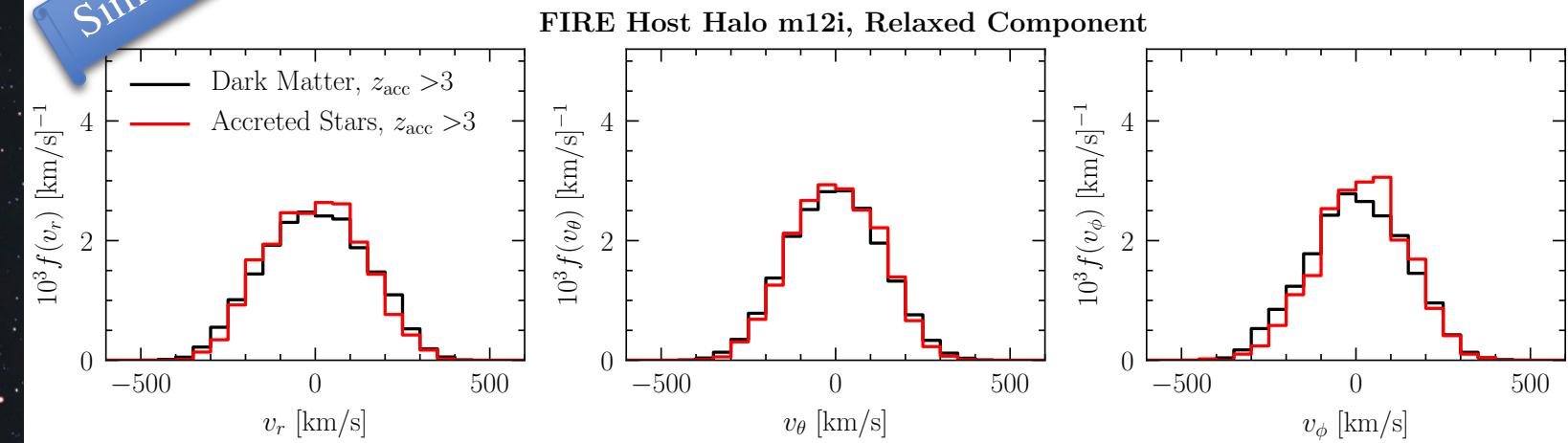


Building the Dark Matter Map

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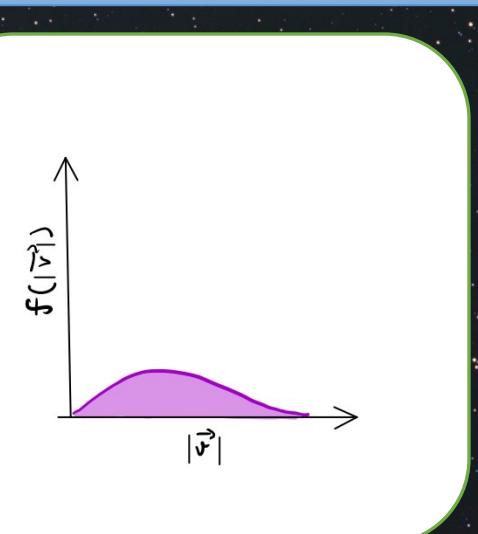


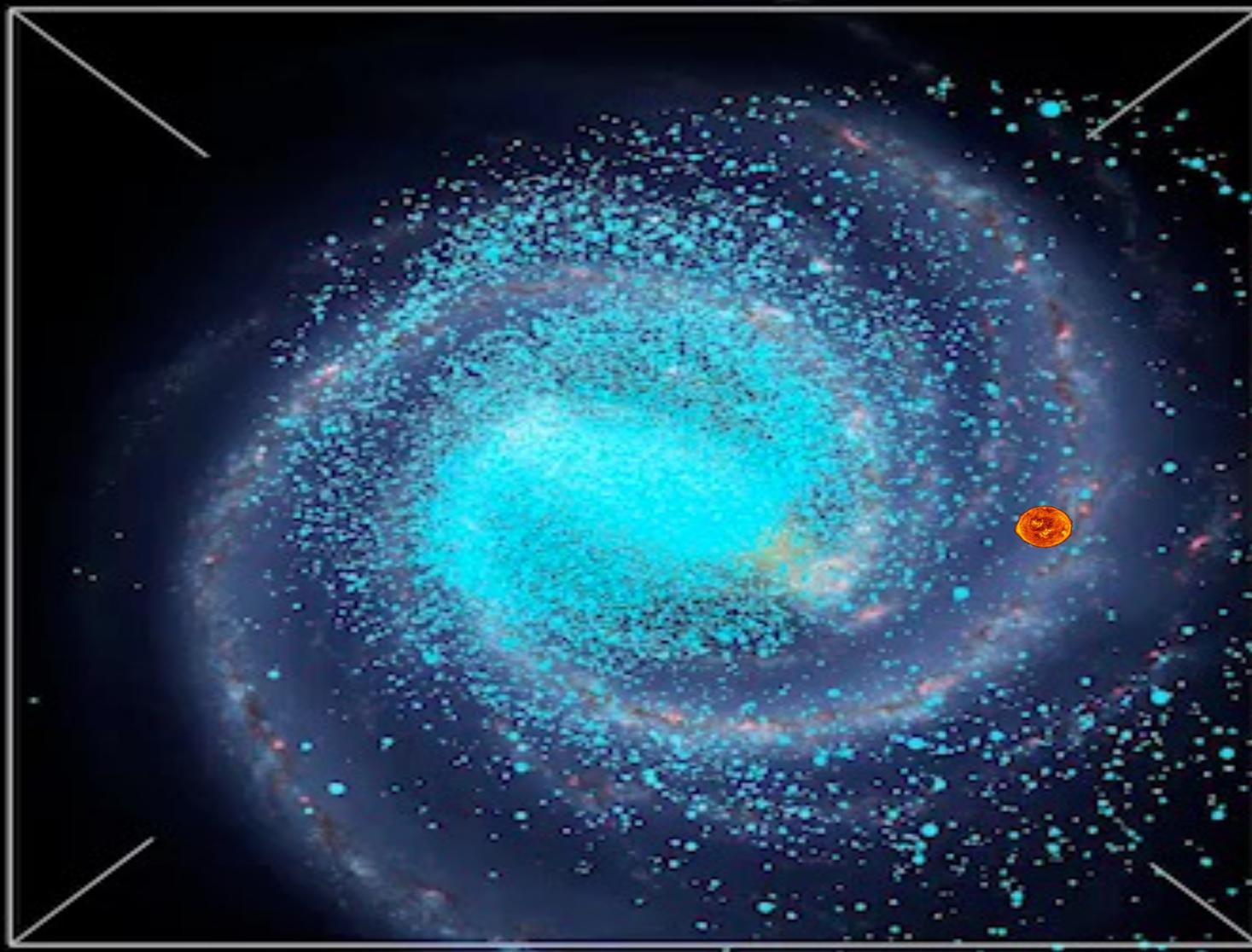
Simulation



Different Components:

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



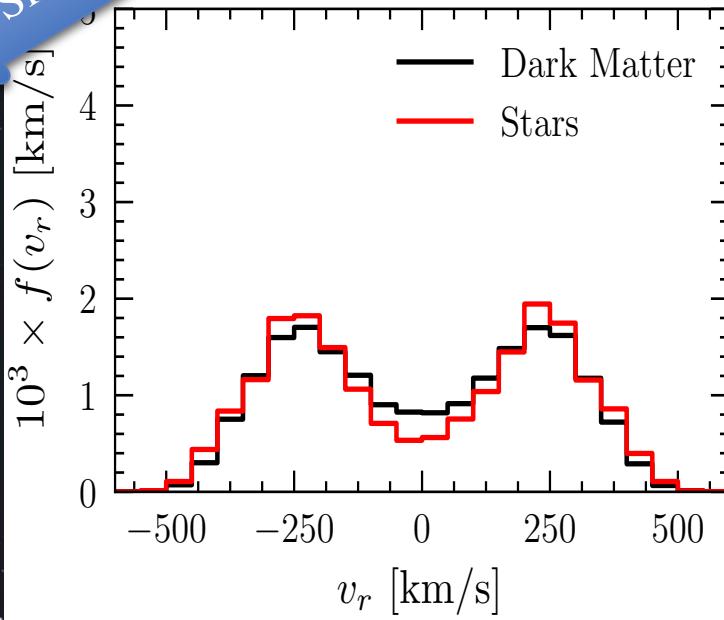


Credit: H.H. Koppelman, A. Villanlobos, A. Helmi

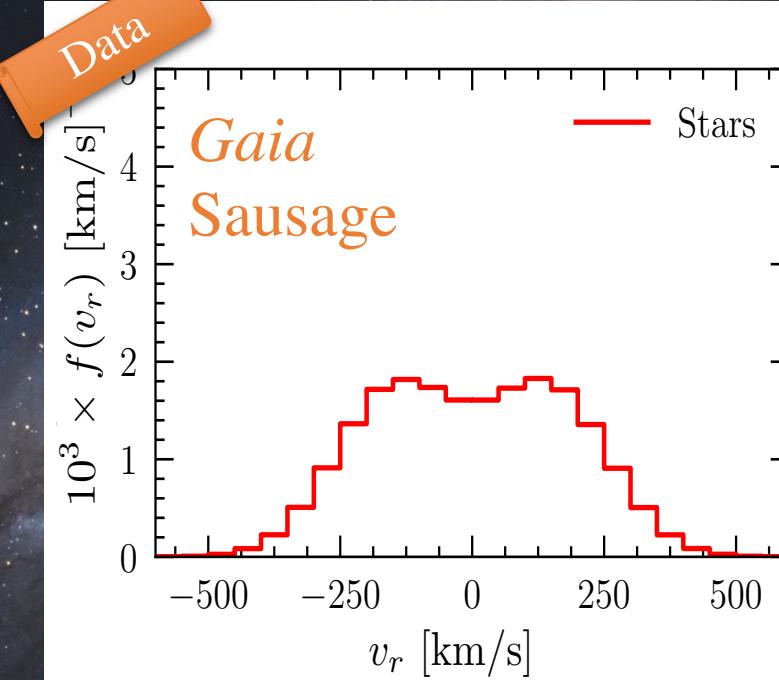
Building the Dark Matter Map

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

Simulation

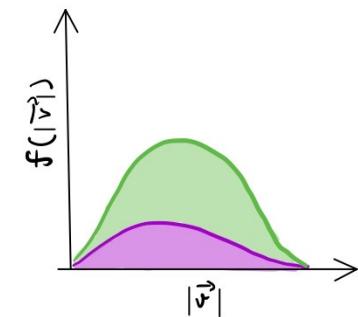


Data



Different Components:

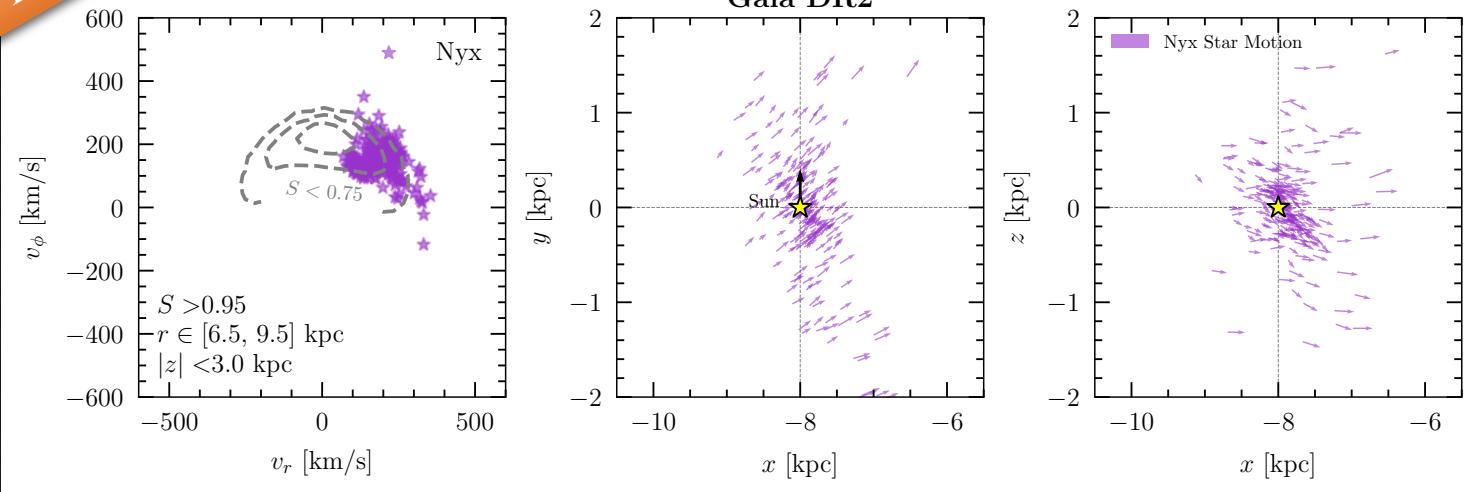
1. Old Halo
2. Sausage/ Gaia Enceladus
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Building the Dark Matter Map

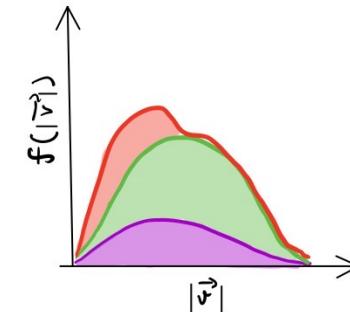
Strategy: Reconstruct the Dark Matter from the distributions of the stars.

Data



Different Components:

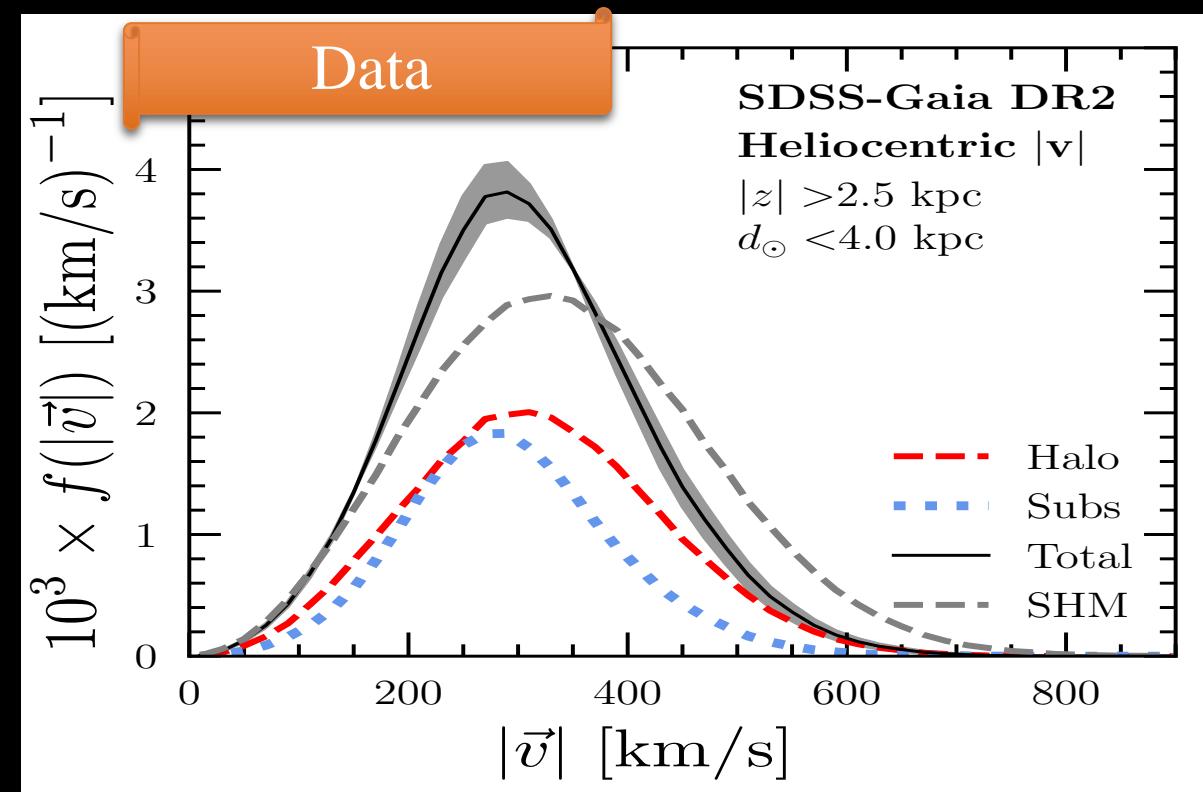
1. Old Halo
2. Sausage/ Gaia Enceladus
3. Nyx



Incomplete

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)

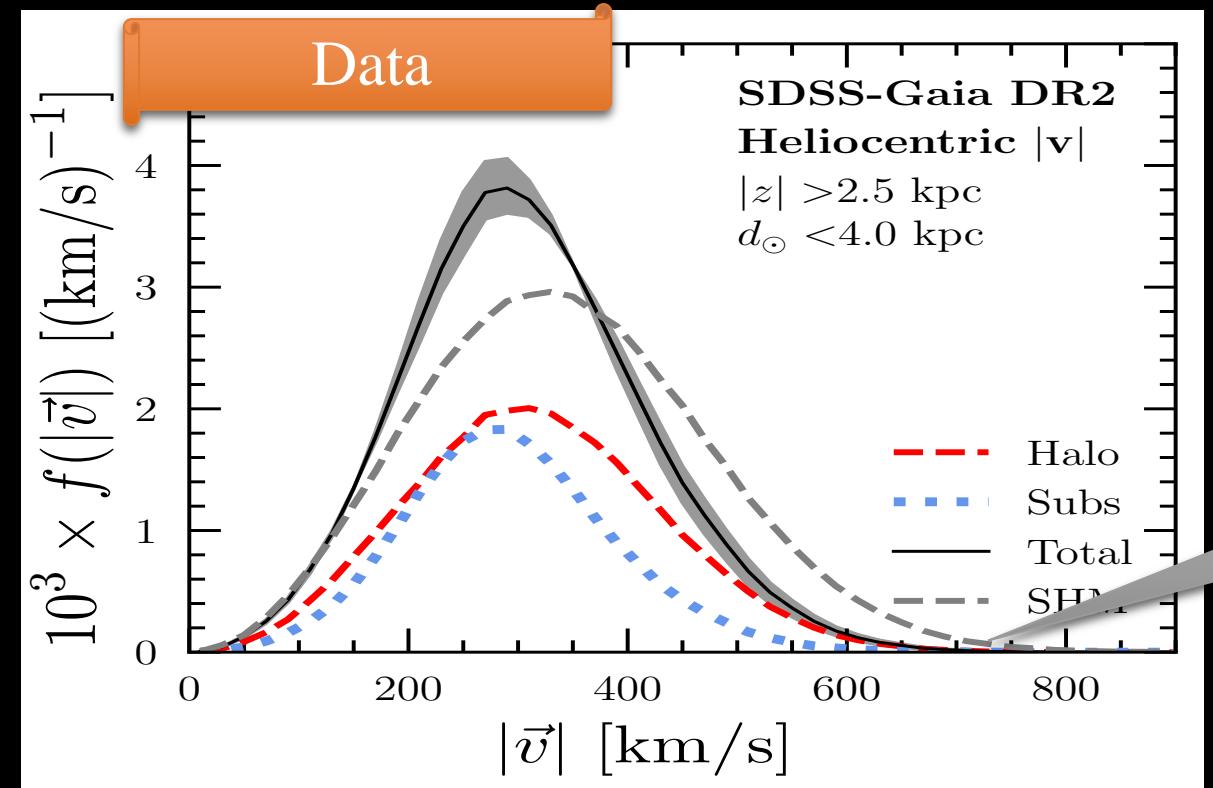
Garrison-Kimmel et al. (2015)

Necib, Lisanti, Belokurov (2018)

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

Incomplete

First Empirical Dark Matter Distribution



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

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

Final distribution different from
the assumed Maxwell
Boltzmann distribution

Kirby et al. (2013)

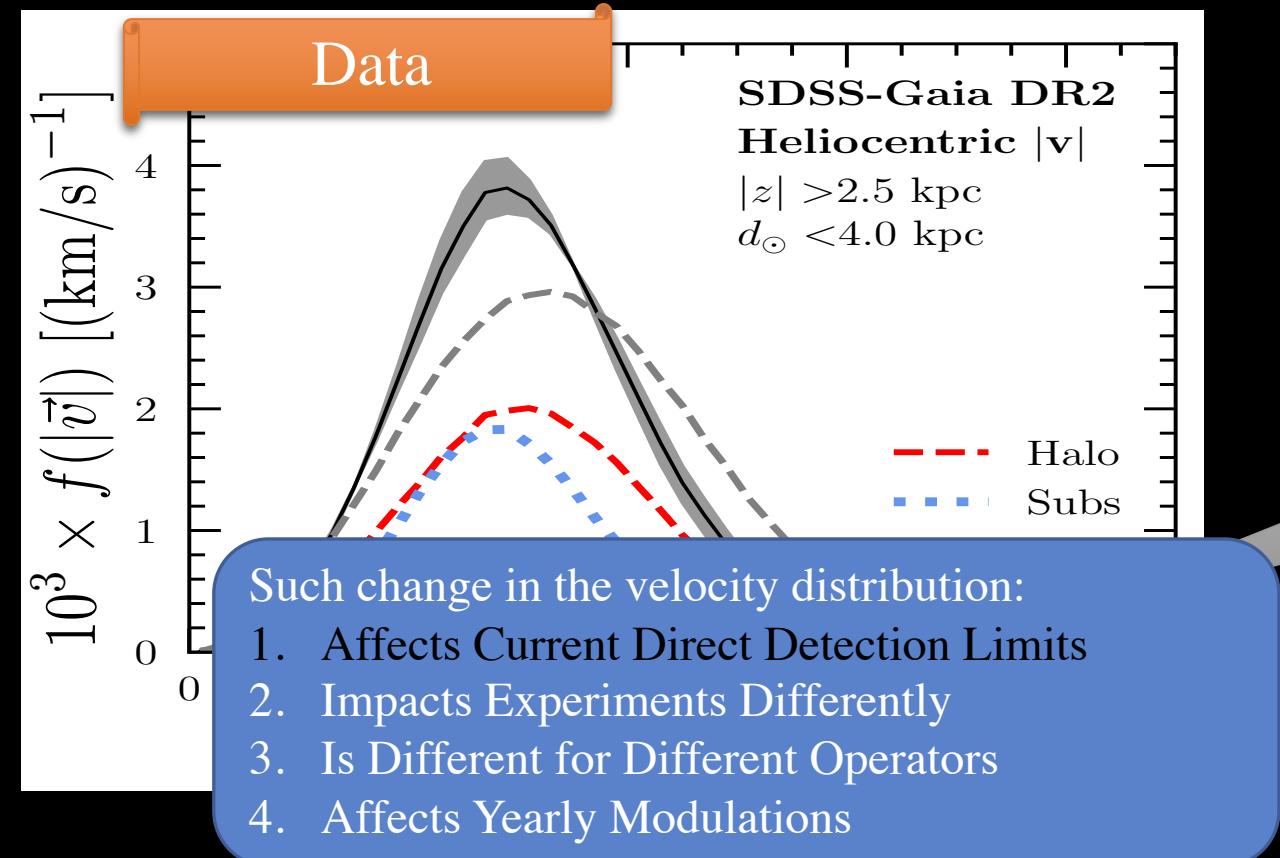
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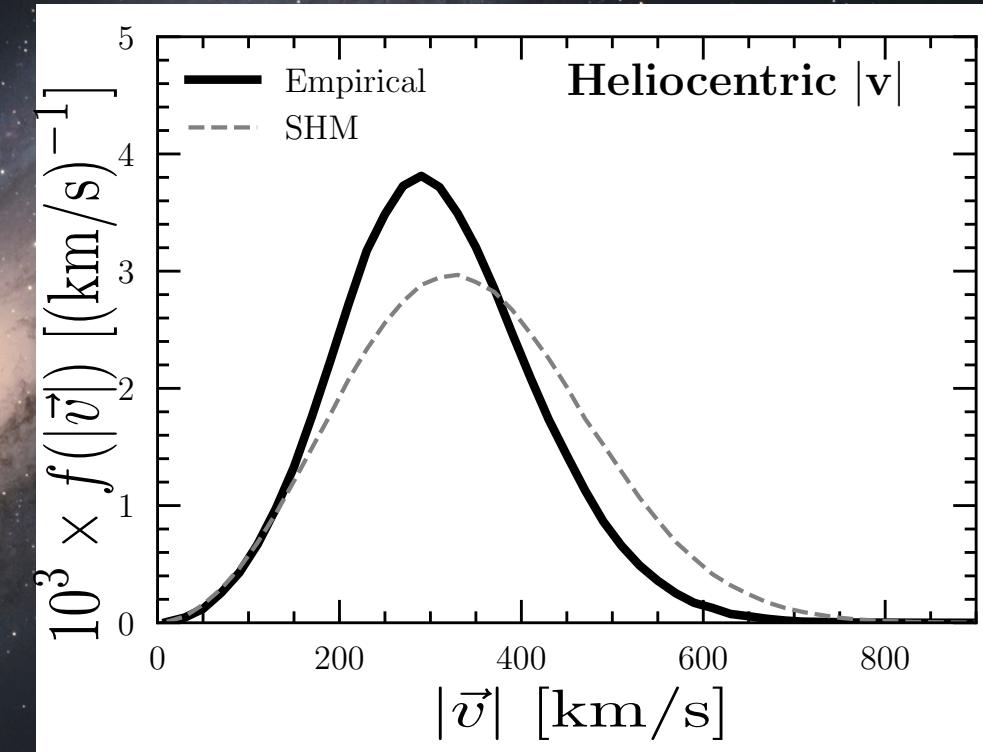
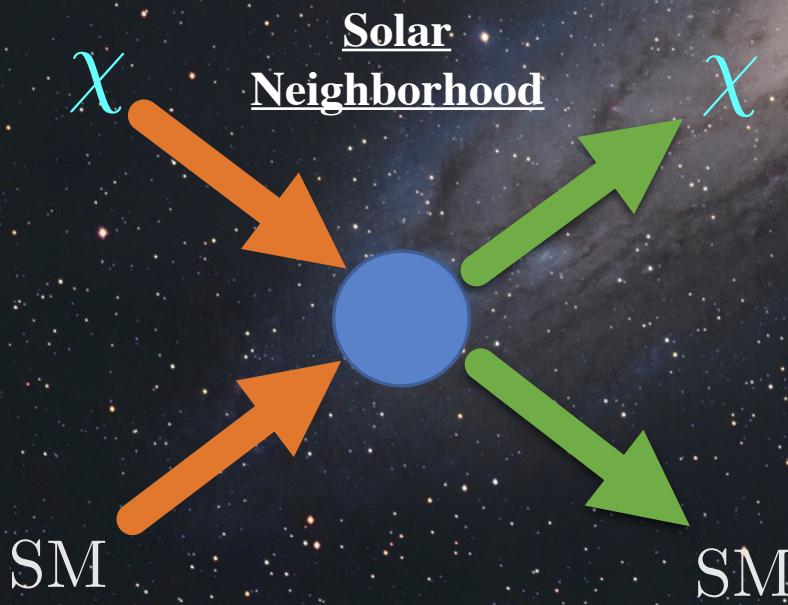
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Direct Detection

Direct detection depends on astrophysical parameters:

- Dark matter density
- Dark Matter velocity



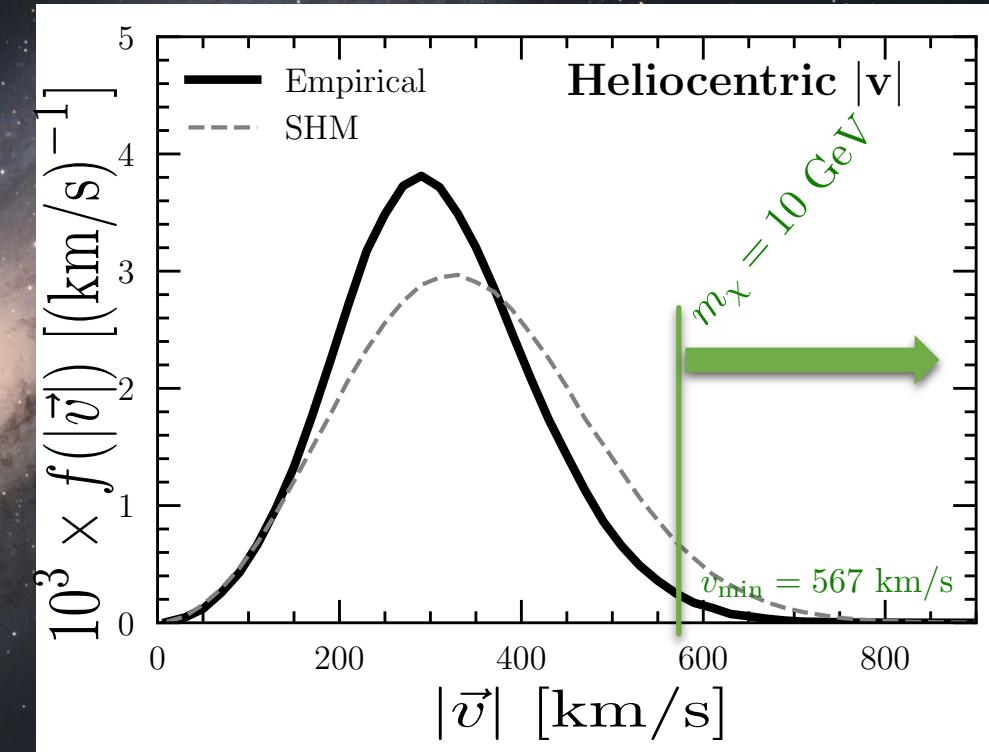
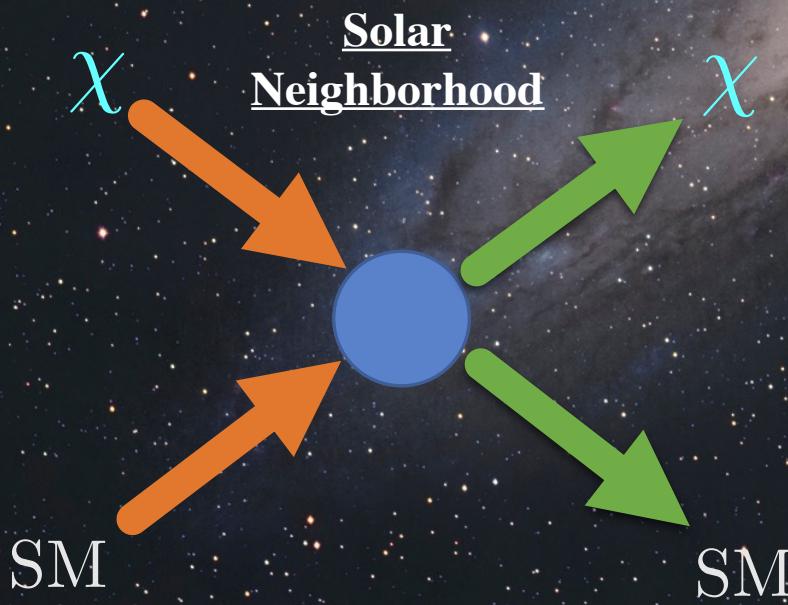
$$\text{Rate} \propto \rho_{DM} \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$

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

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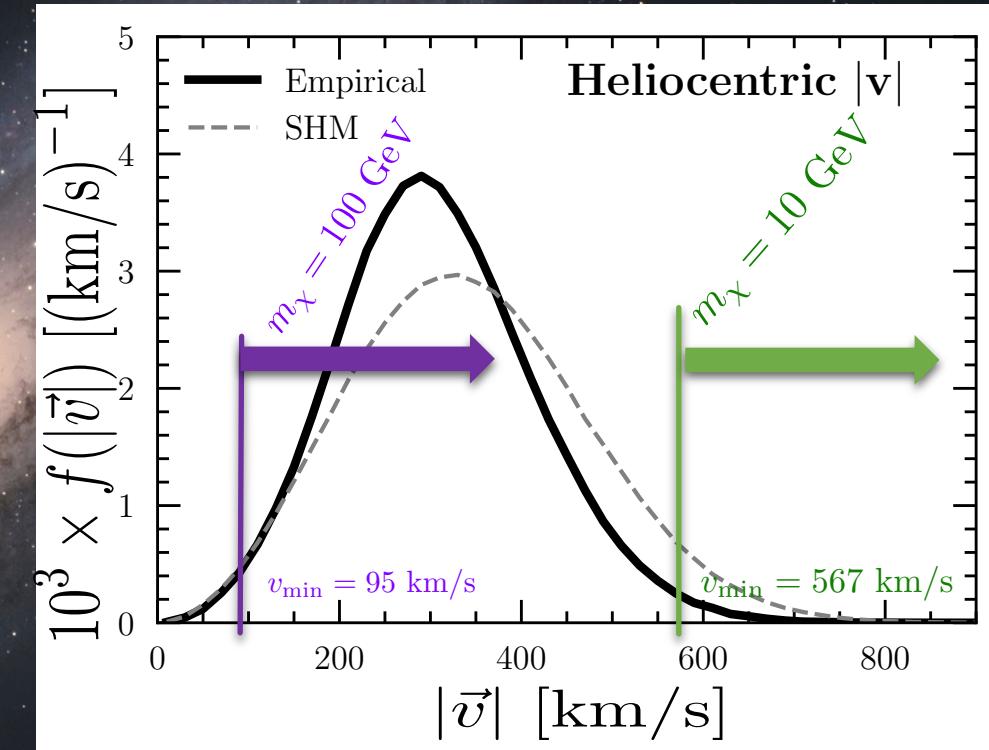
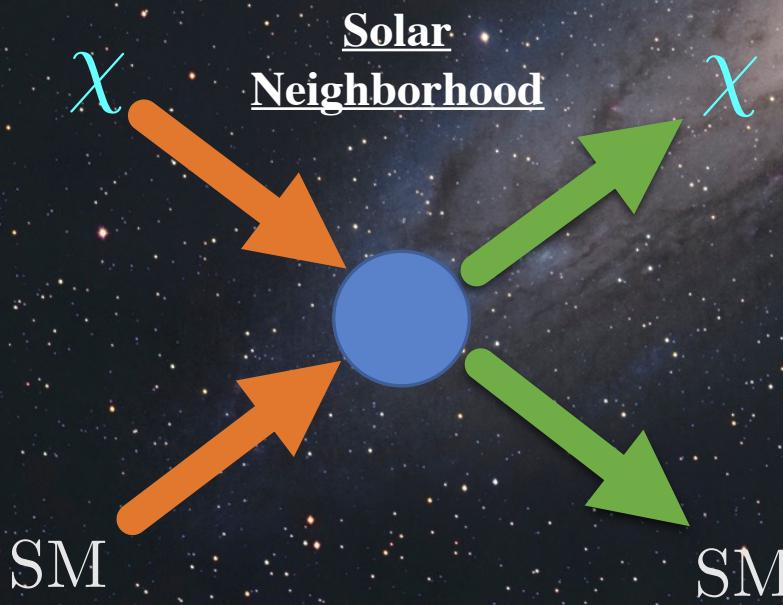
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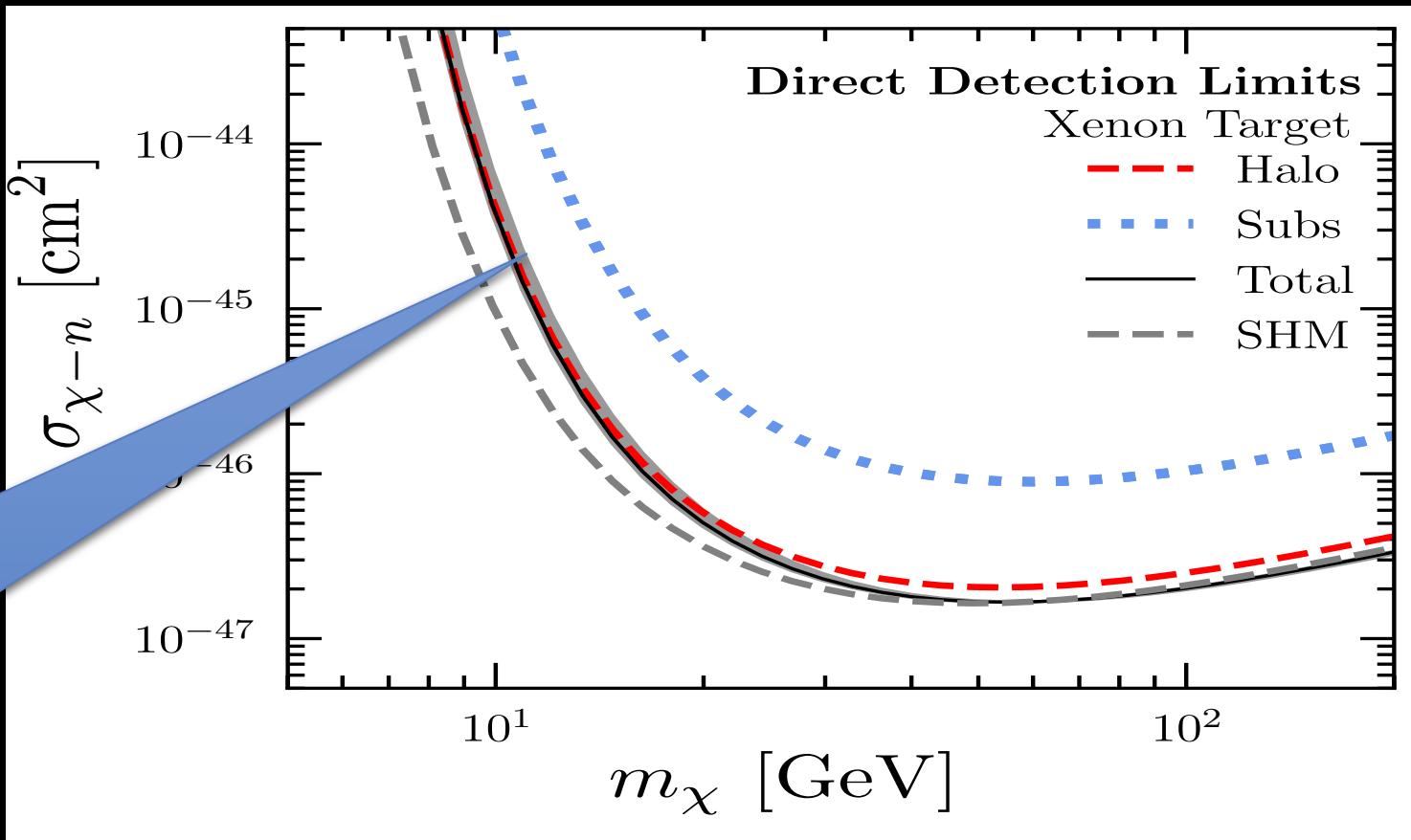
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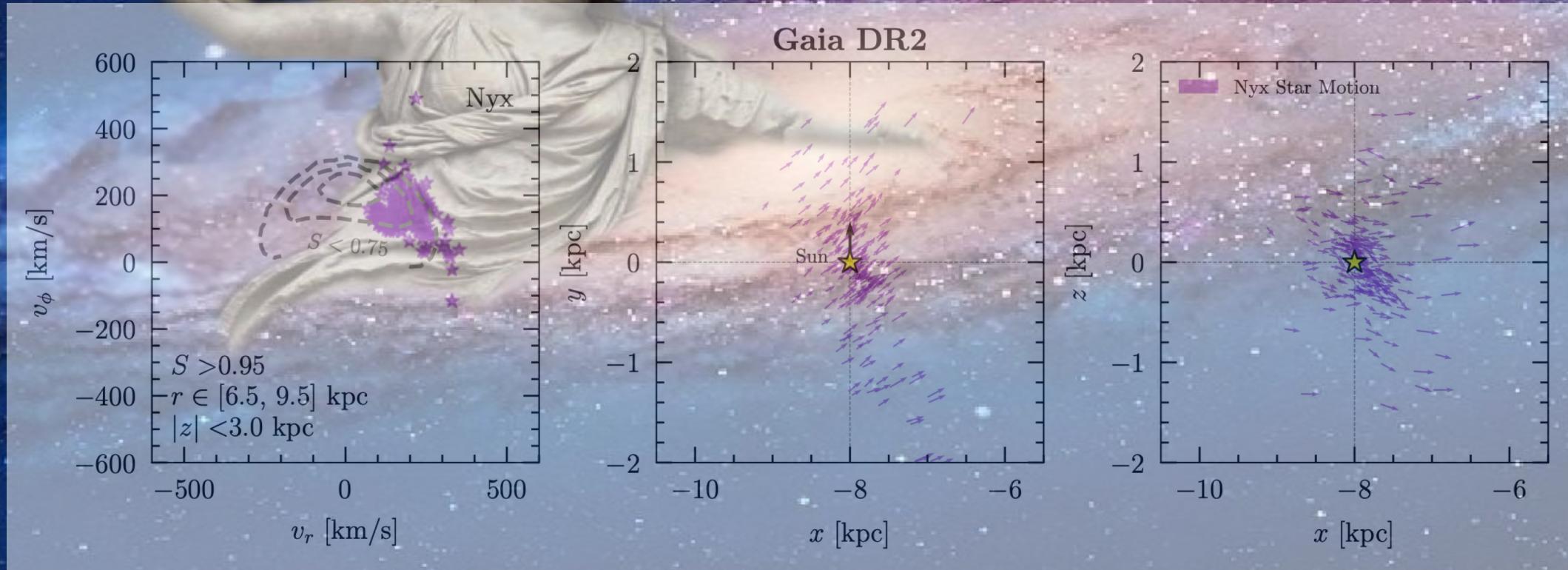
Implications for Direct Detection



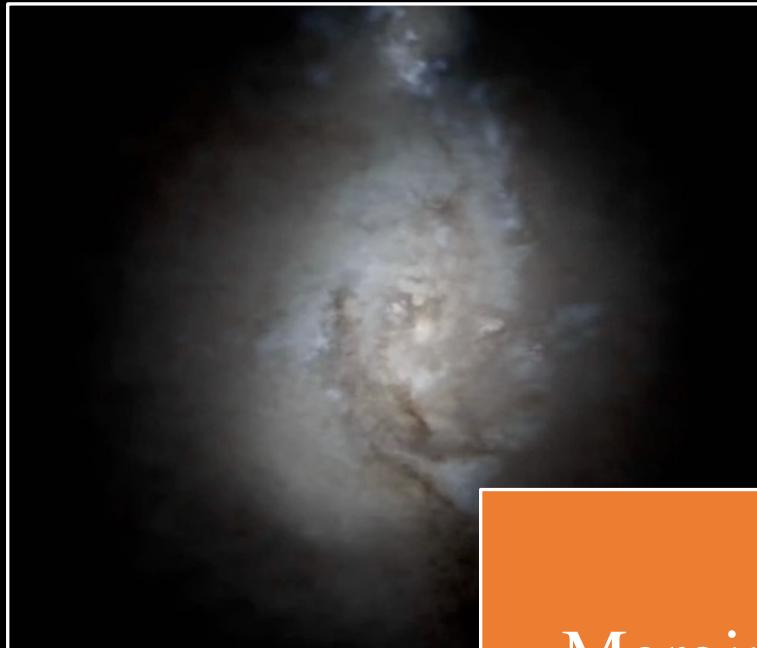
Largest changes are at low dark matter masses

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

Nyx: Greek Goddess of the Night

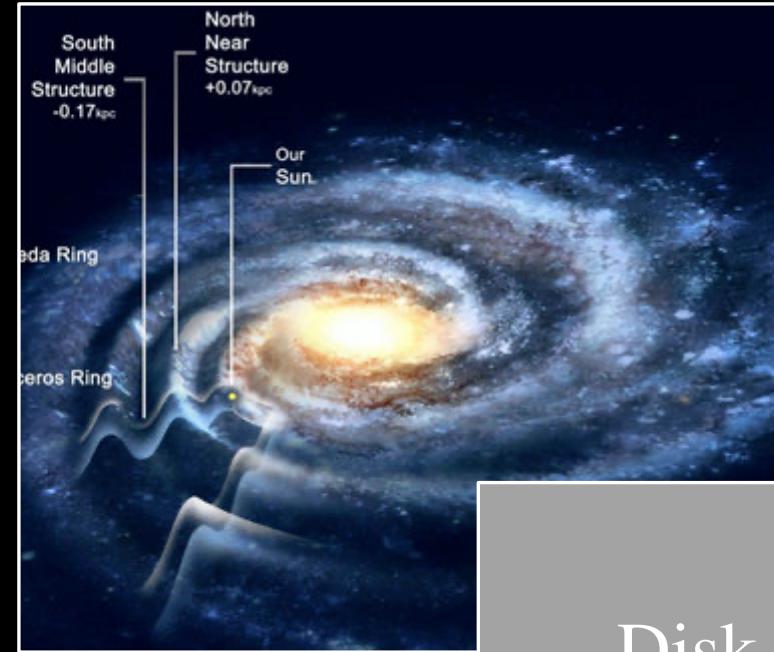


Nyx



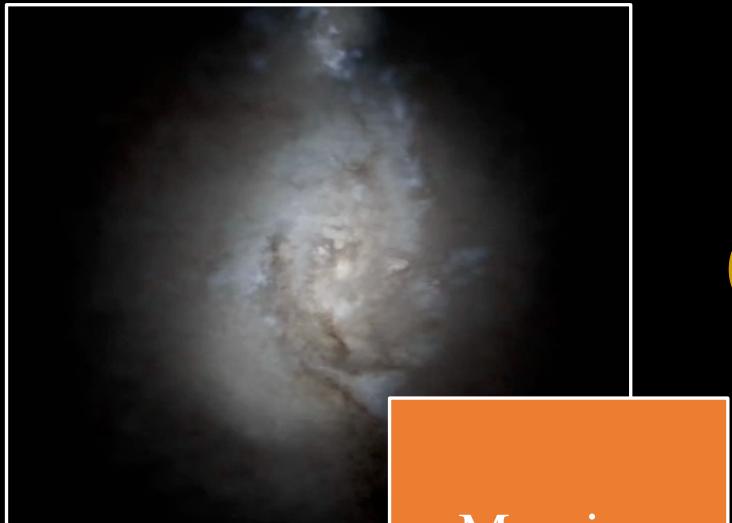
Merging
Galaxy

Or



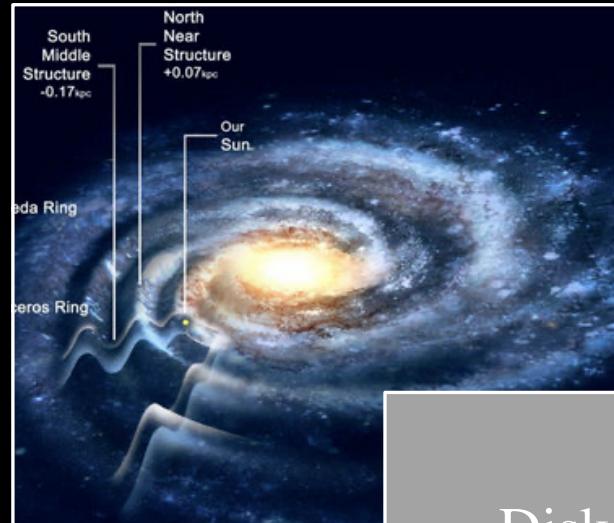
Disk
Perturbation

Nyx



Merging
Galaxy

Or



Disk
Perturbation

Observe Nyx stars at Magellan
and Keck II to obtain high
resolution chemical abundances.

If Nyx is a Merger

$z=0.12$

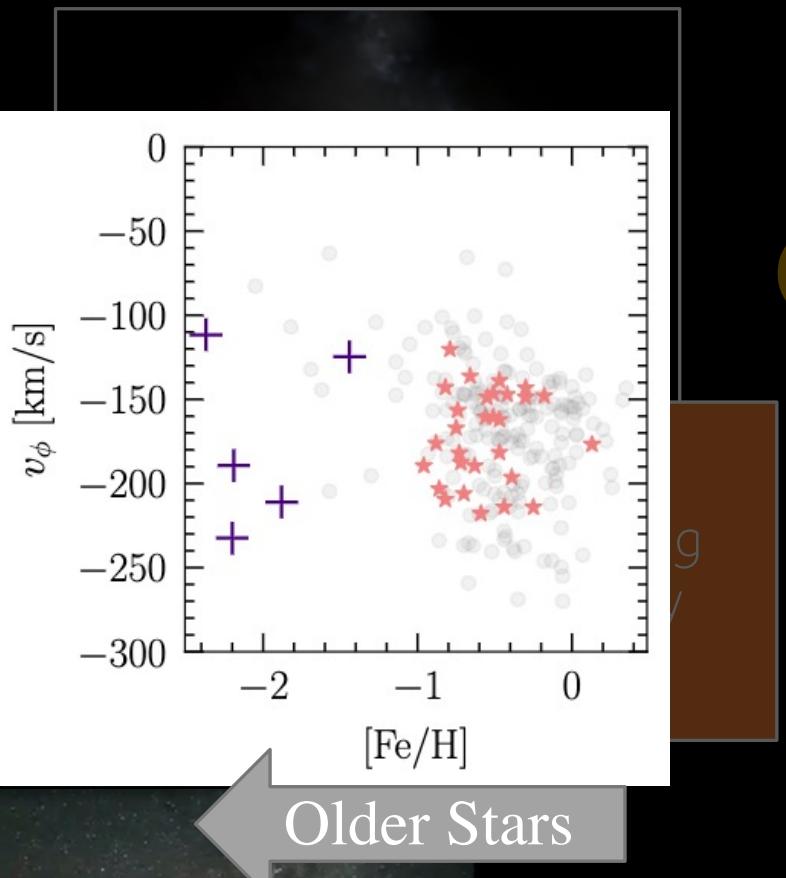


10 kpc

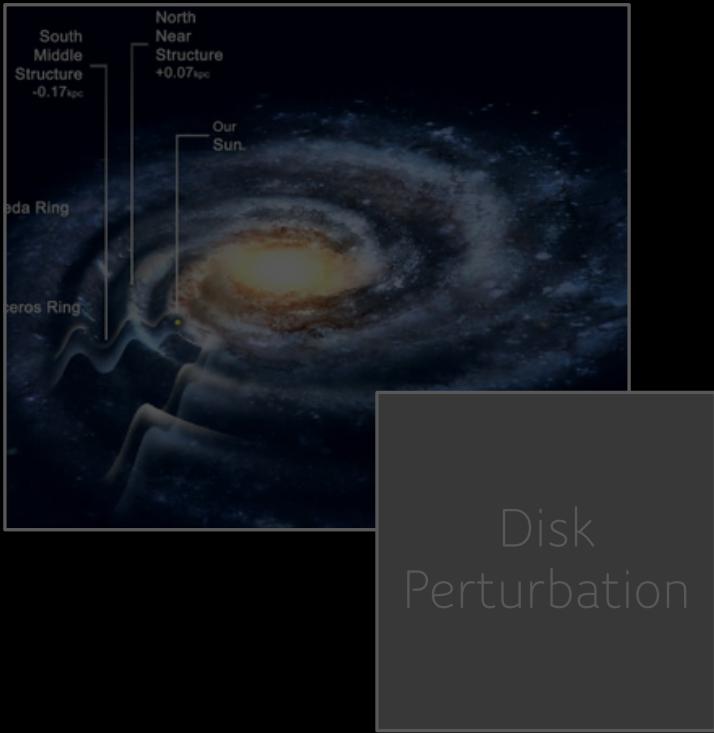
Hopkins et al. (2014)
Wetzel et al. (2016)
Hopkins et al. (2017)

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

Nyx



Or



Observe Nyx stars at Magellan
and Keck II to obtain high
resolution chemical abundances.

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 Λ CDM cosmology

Read et al. (2008)

Lake (1989)

Read et al. (2008)

Bruch et al. (2008)

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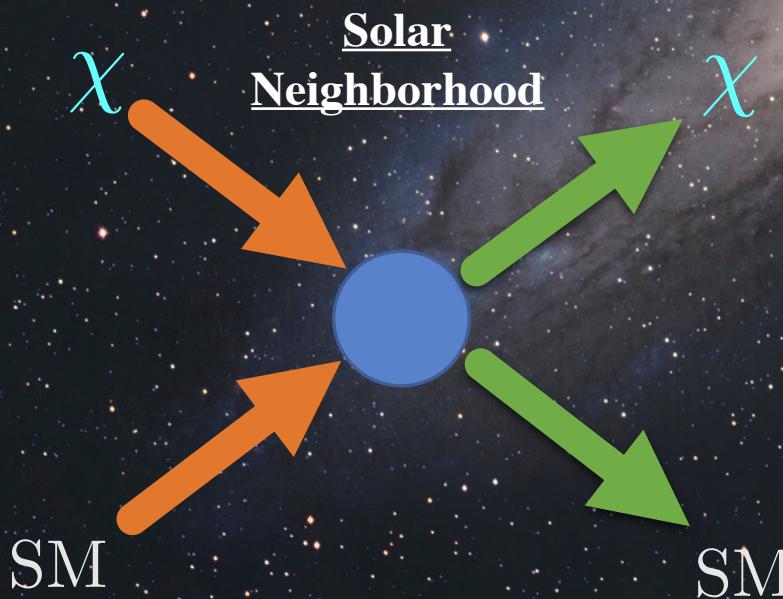
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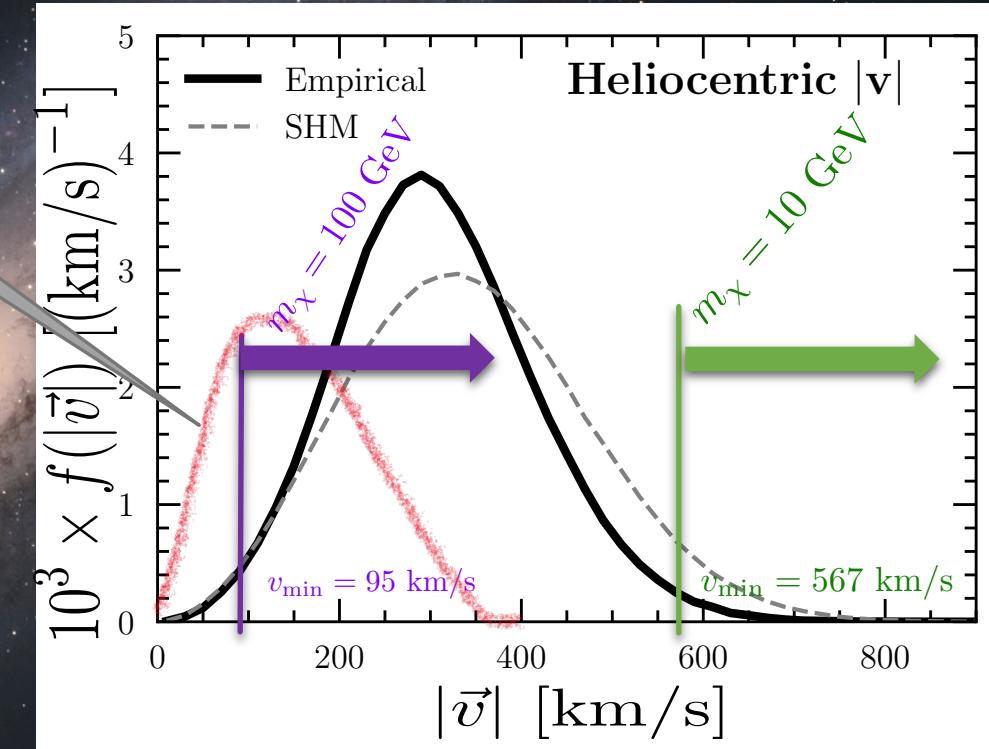
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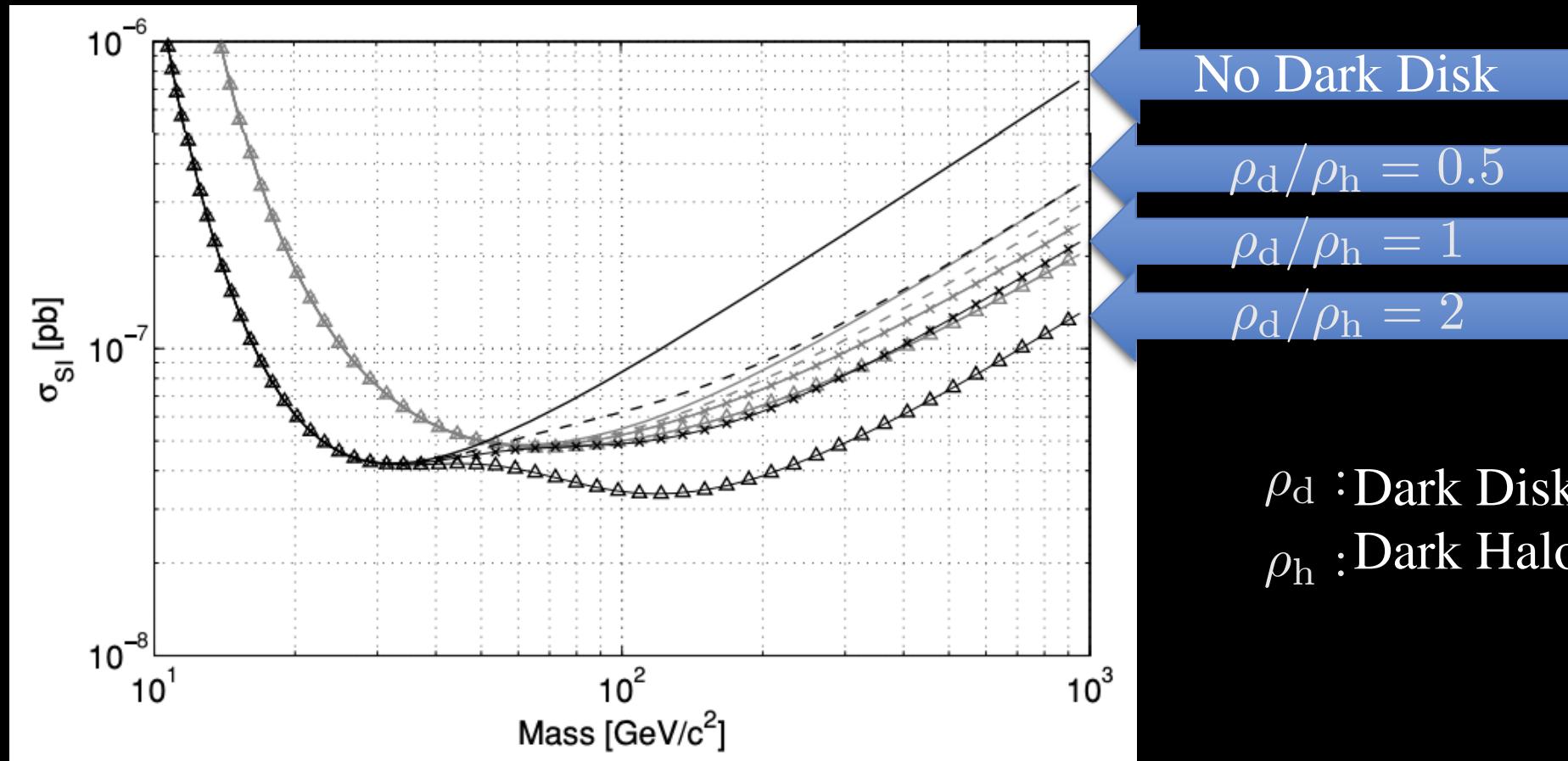


Dark Disk



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

Effect of Dark Disk on Direct Detection

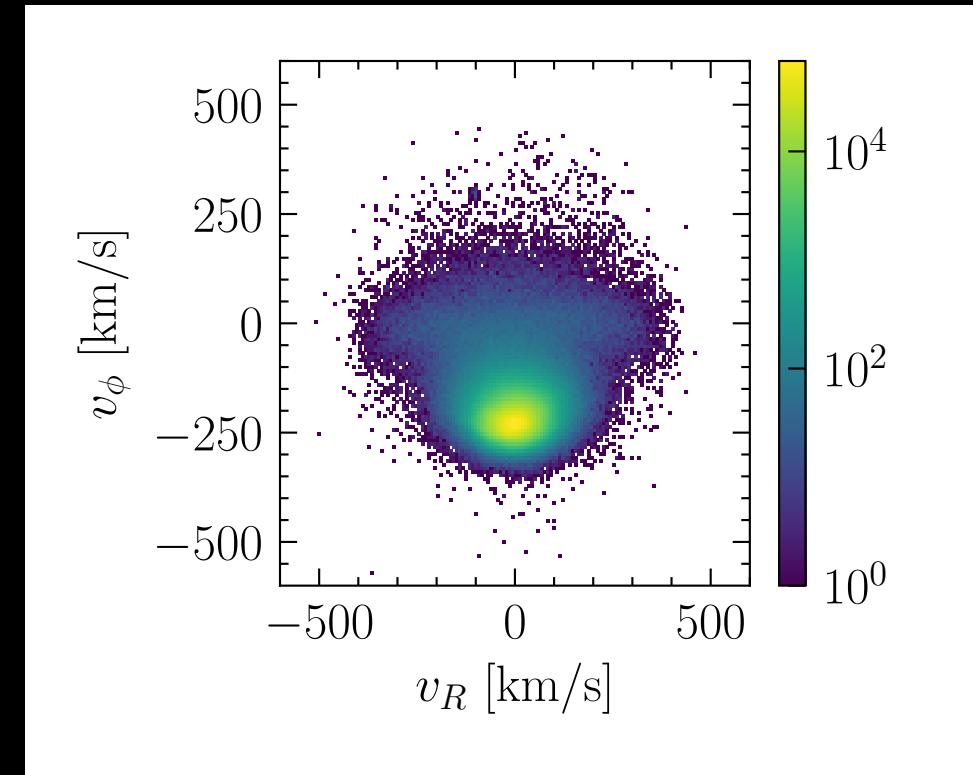
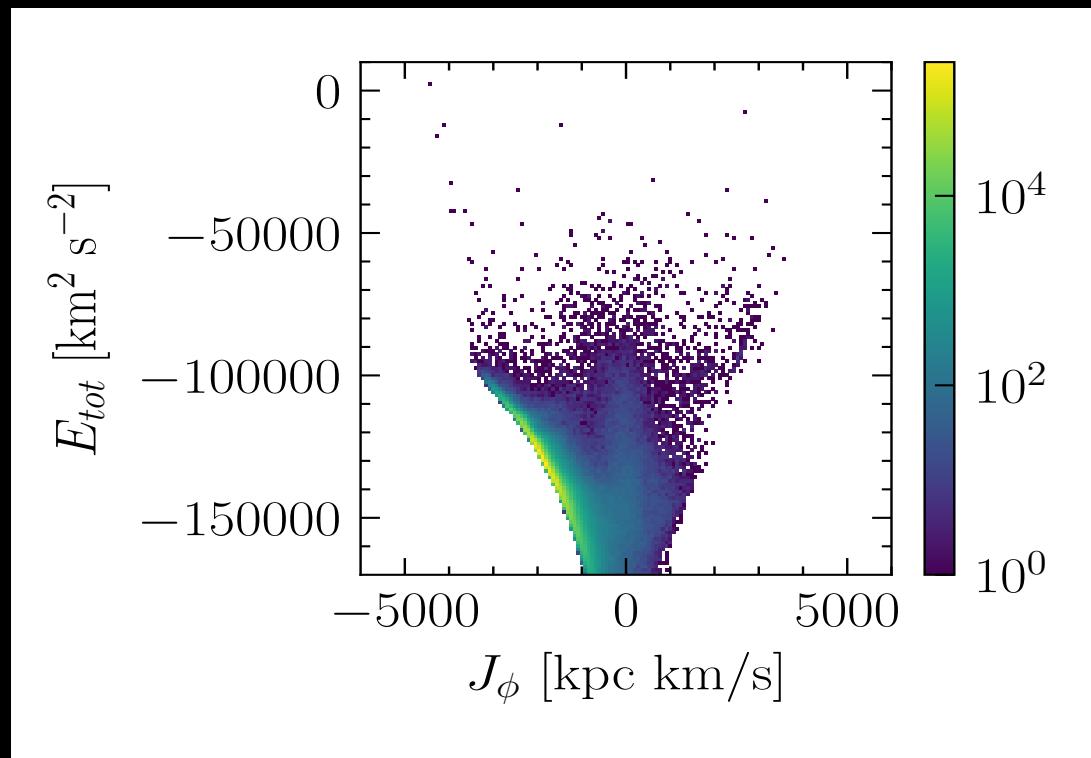


Bruch et al. (2008)

Beyond the largest structures, The use of Clustering



Xiaowei Ou

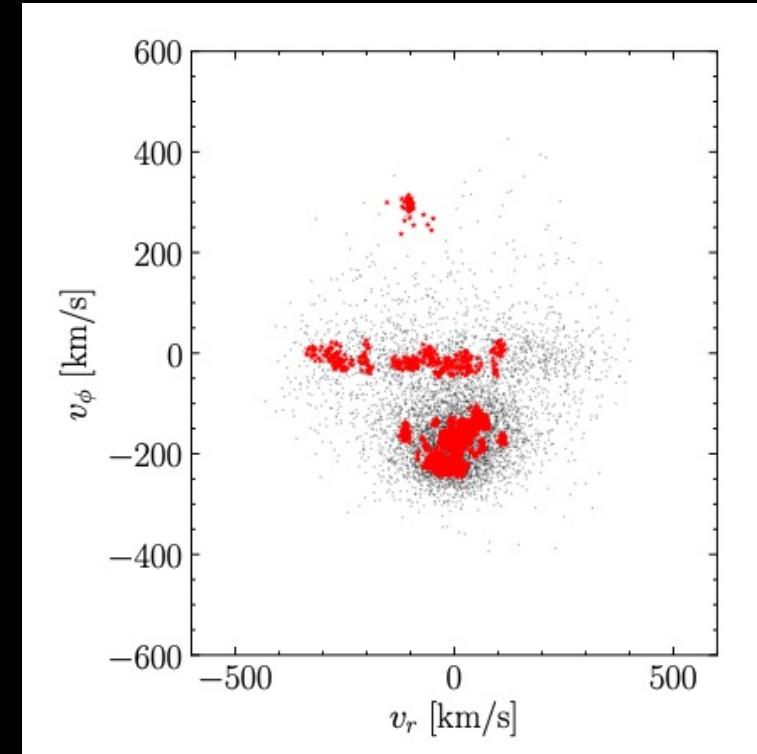
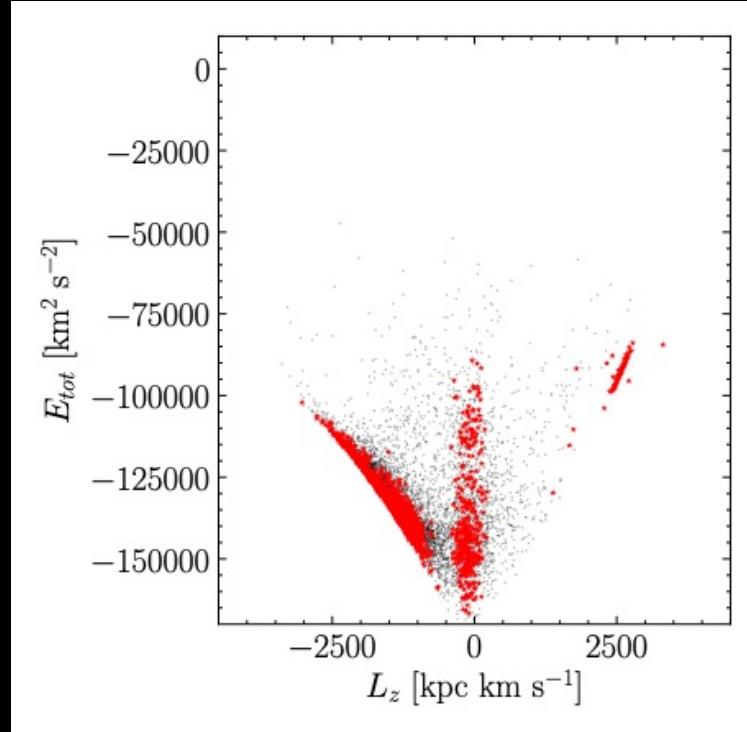


- Gaia eDR3 proper motions
- Gaia DR2 radial velocities
- Quality cuts

Beyond the largest structures, The use of Clustering



Xiaowei Ou

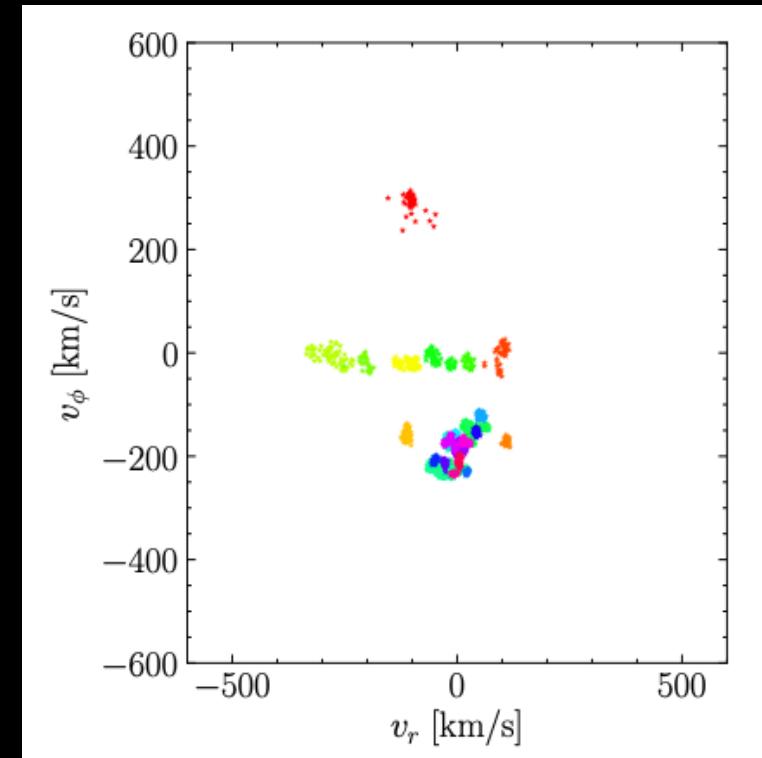
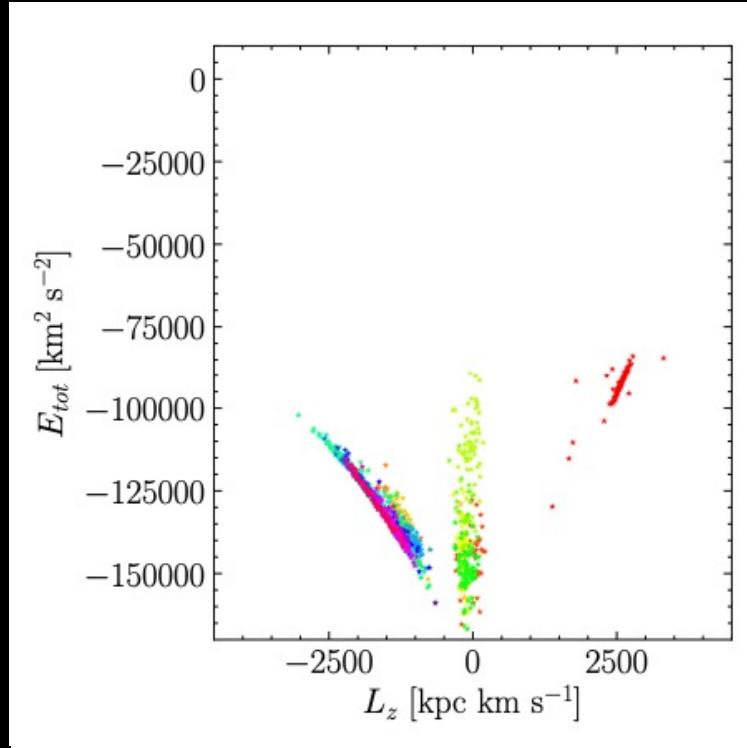


- ❖ Prioritized stable clusters.
- ❖ Looked at the stars that got clustered at least 40 times through 100 realizations. Dropped the stars always associated as noise.
- ❖ These structures are stable, although possibly incomplete.

Beyond the largest structures, The use of Clustering



Xiaowei Ou



- ❖ Prioritized stable clusters.
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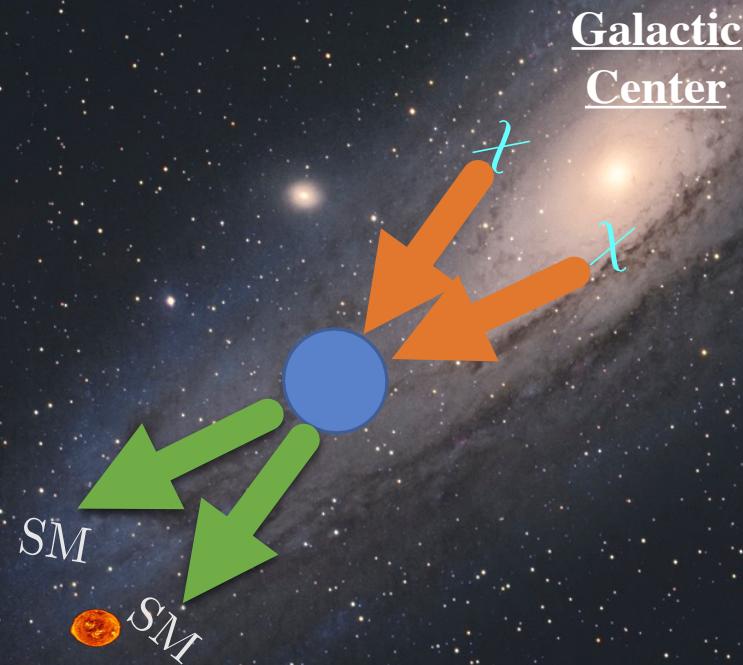
Building the empirical velocity distribution of Dark Matter

NEXT:

- 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



Dark Matter in the Galactic Center

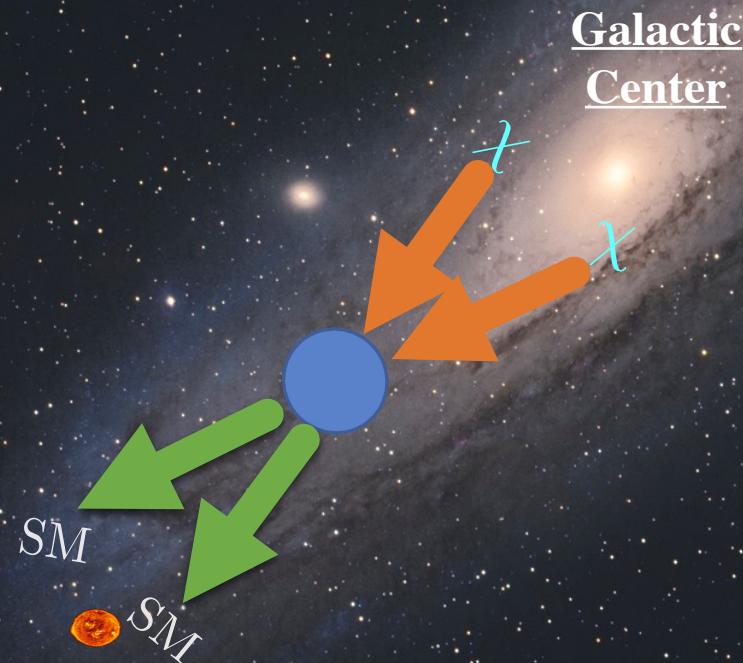


Dark Matter in the Galactic Center

J factor:

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

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



Pros

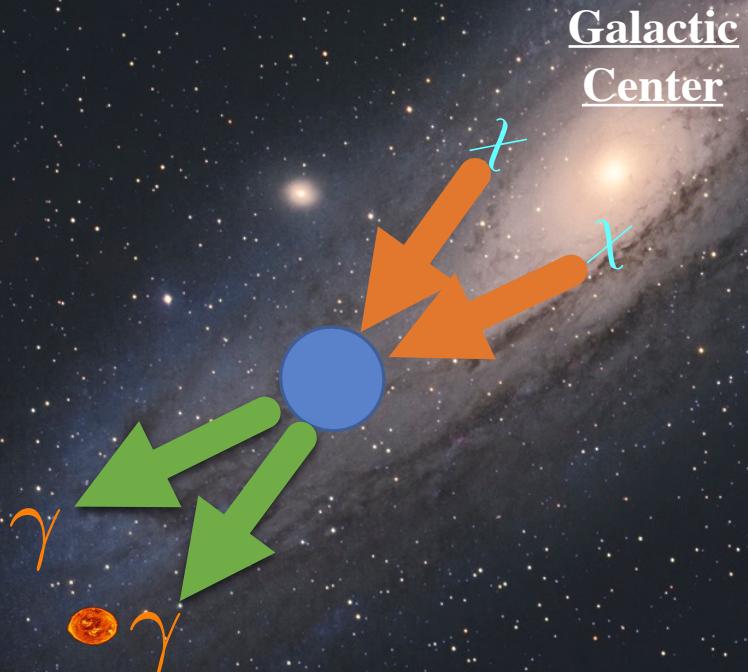
- Largest Density of Dark Matter

Cons

- Largest Astrophysical Backgrounds

Dark Matter in the Galactic Center

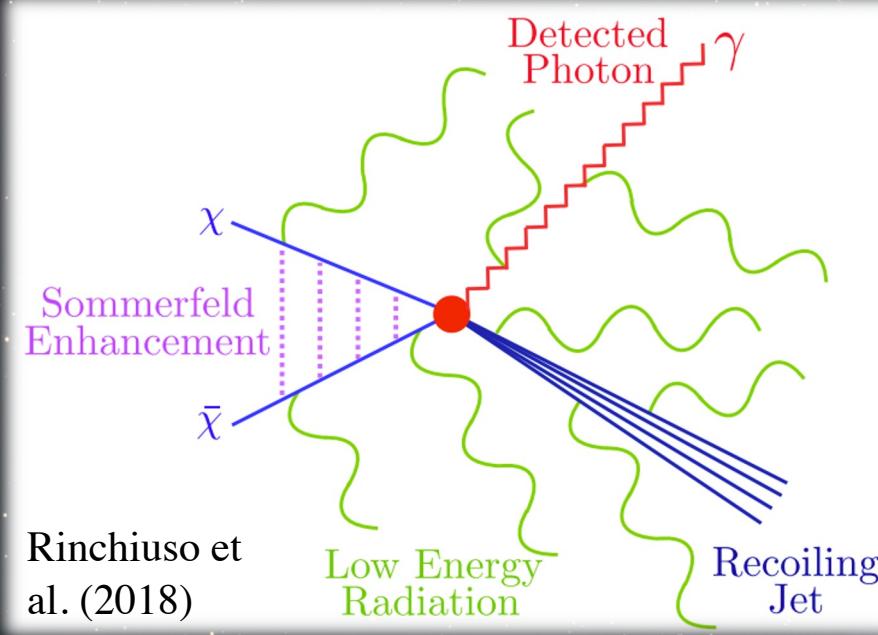
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{\chi}(iD + M)\chi$$



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)

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

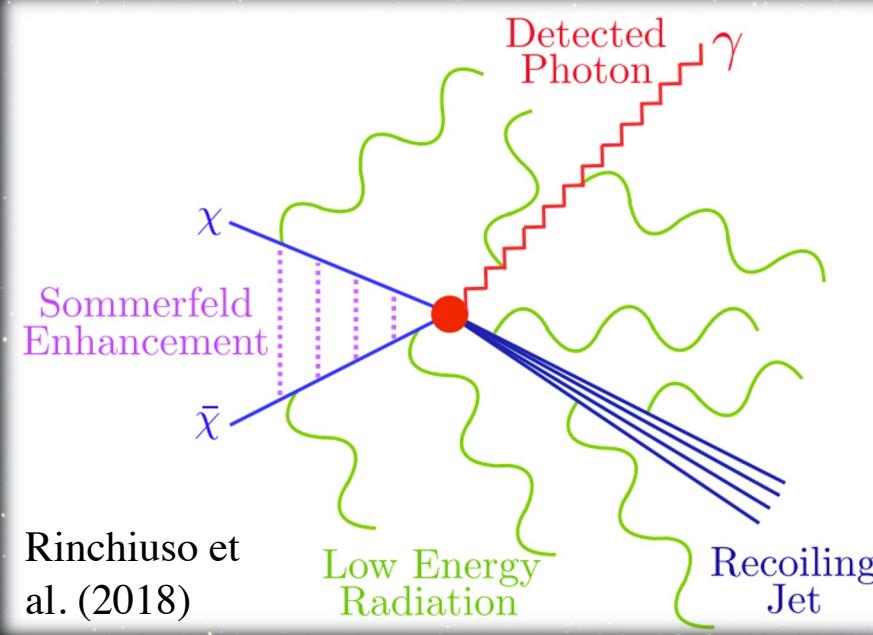


Dark Matter in the Galactic Center



H.E.S.S.

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



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

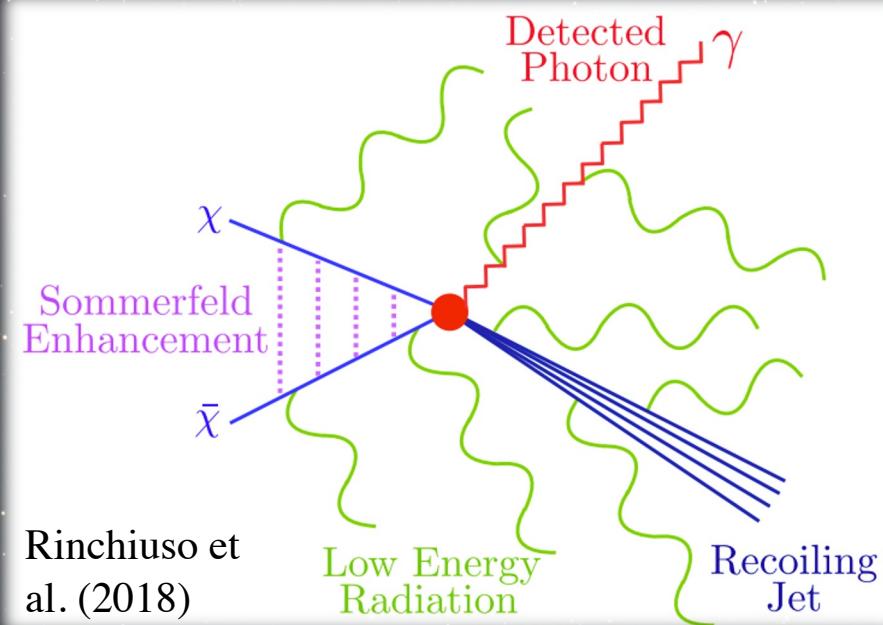
$$\propto \langle \sigma v \rangle \int_{\text{line of sight}} \int_{\text{angles}} \rho_\chi^2 d\Omega ds \times A_{\text{eff}}^\gamma$$

Dark Matter in the Galactic Center



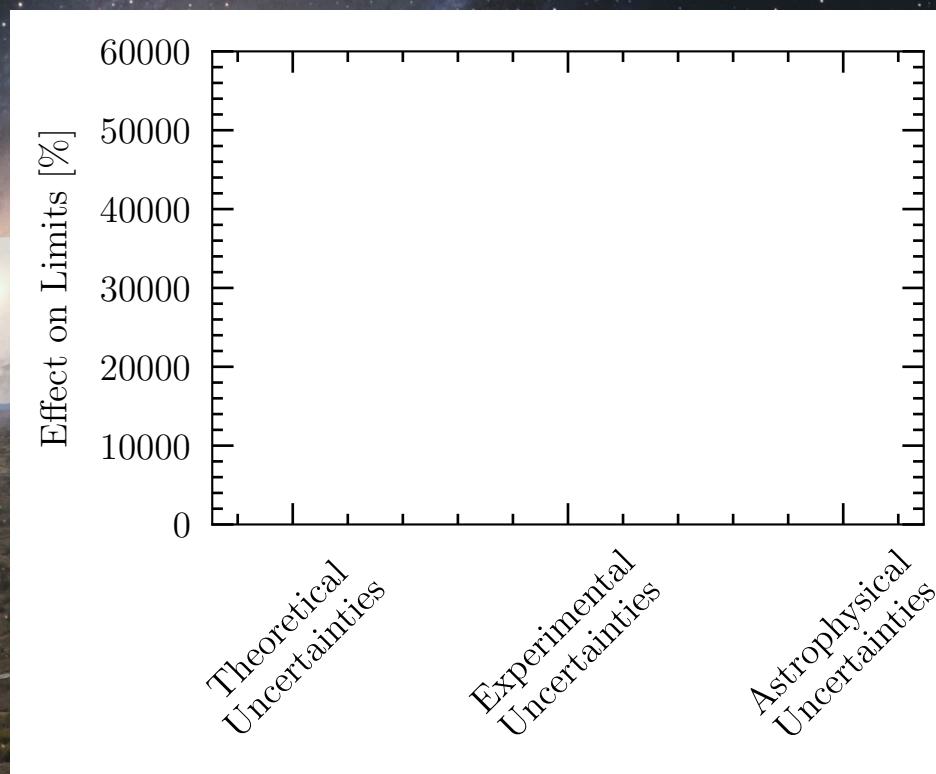
By Klepser at English Wikipedia, CC BY-SA 3.0,
<https://commons.wikimedia.org/w/index.php?curid=61288242>

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



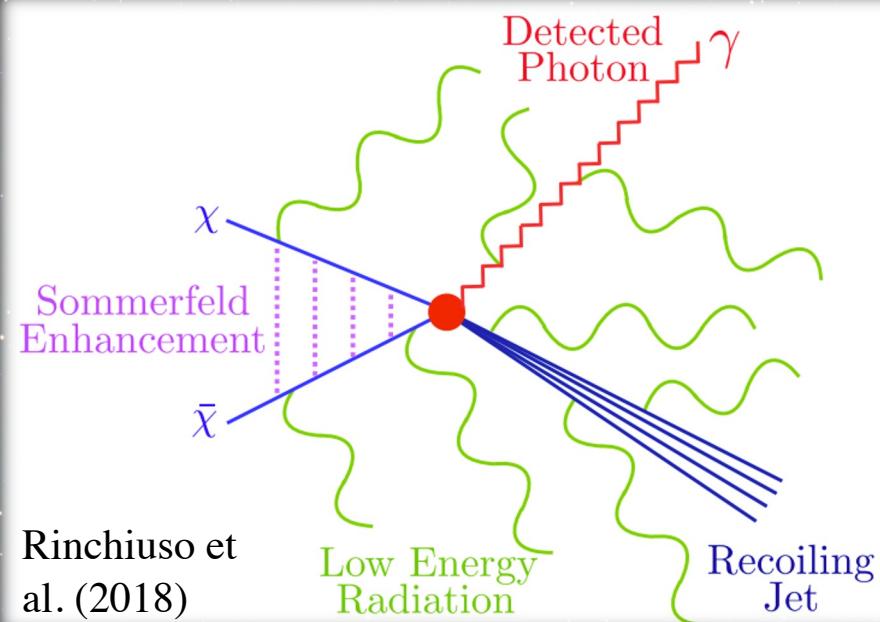
$$N_{\text{signal}} = \text{Flux}_\gamma \times \text{Experimental Efficiency} \times \text{Exposure}$$
$$\propto \langle \sigma v \rangle \int_{\text{line of sight}} \int_{\text{angles}} \rho_\chi^2 d\Omega ds \times A_{\text{eff}}^\gamma$$

Dark Matter in the Galactic Center



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

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

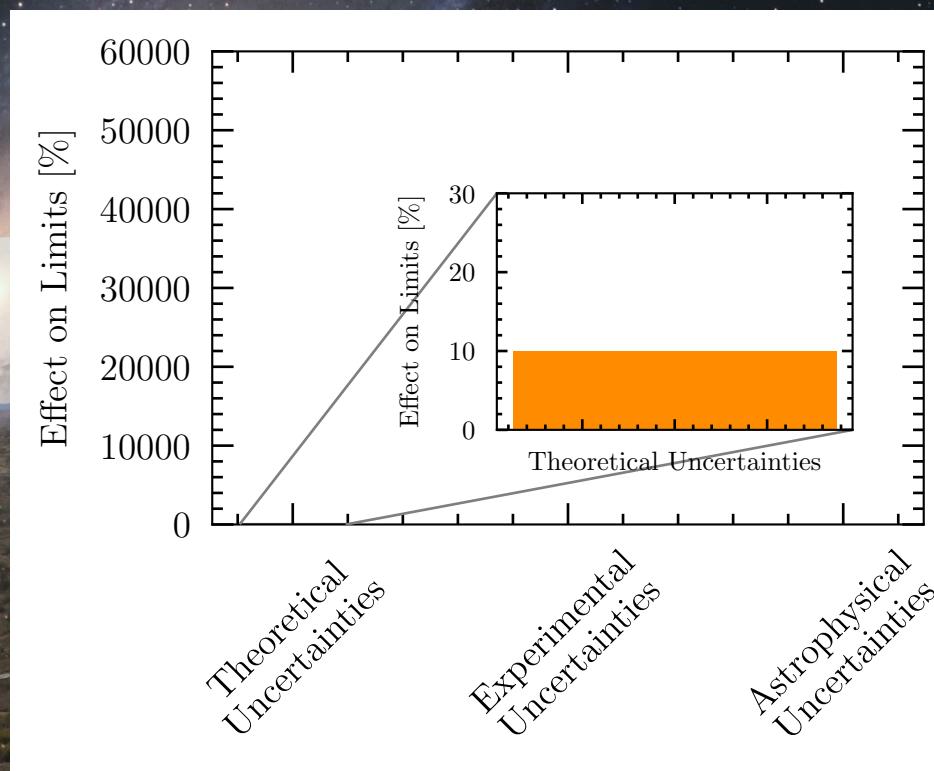


$$N_{\text{signal}} = \text{Flux}_\gamma \times \text{Experimental Efficiency} \times \text{Exposure}$$

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

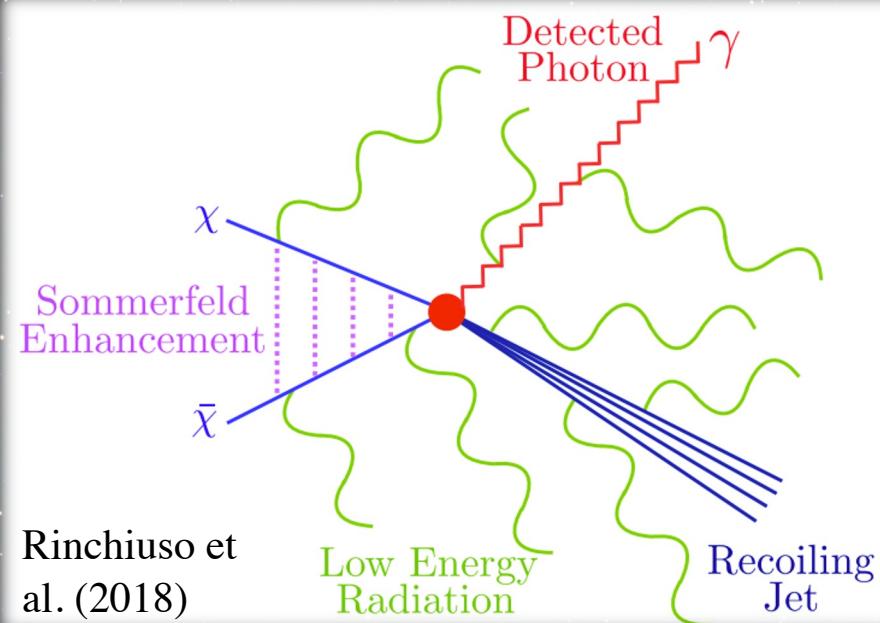
Bauer et al. (2015),
 Ovanesyan et al. (2015),
 Ovanesyan et al. (2017),
 Baumgart et al. (2017),
 Baumgart et al. (2018)

Dark Matter in the Galactic Center



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

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



Rinchiuso et
al. (2018)

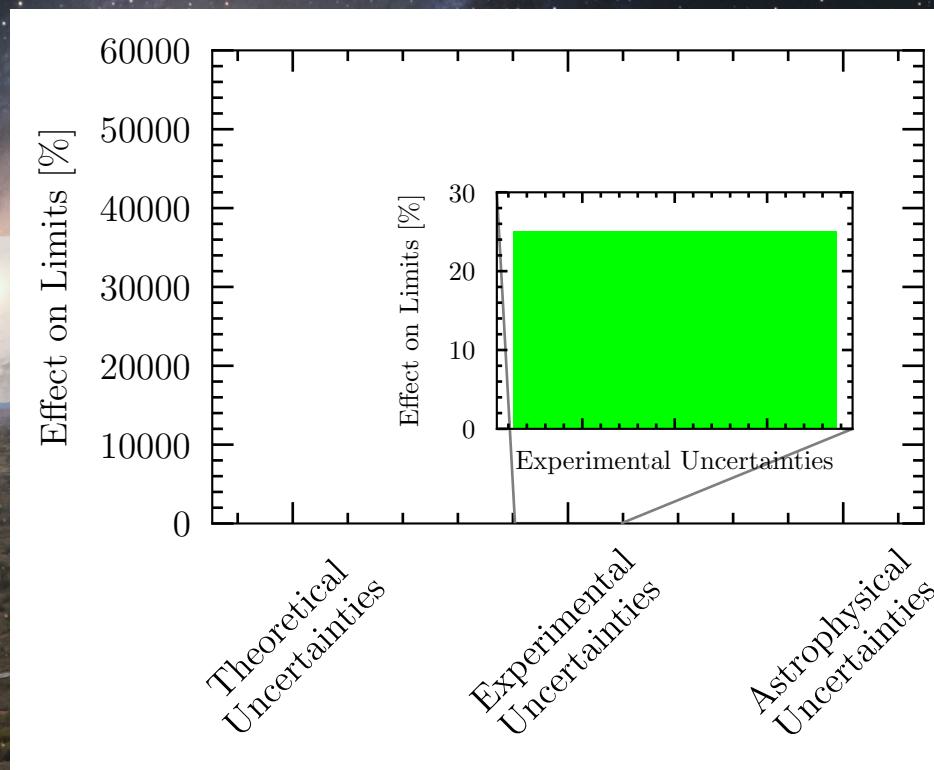
$$N_{\text{signal}} = \text{Flux}_{\gamma} \times \text{Experimental Efficiency} \times \text{Exposure}$$
$$\propto \langle \sigma v \rangle \int_{\text{line of sight}} \int_{\text{angles}} \rho_{\chi}^2 d\Omega ds \times A_{\text{eff}}^{\gamma}$$

H.E.S.S Collaboration (2006)

Holler et al. (2017)

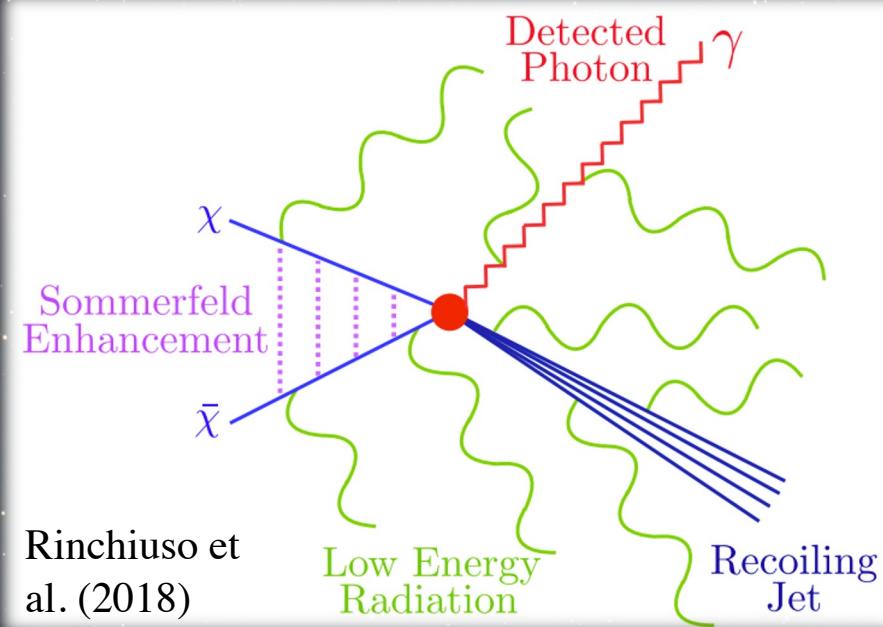
H.E.S.S. Collaboration (2018)

Dark Matter in the Galactic Center



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

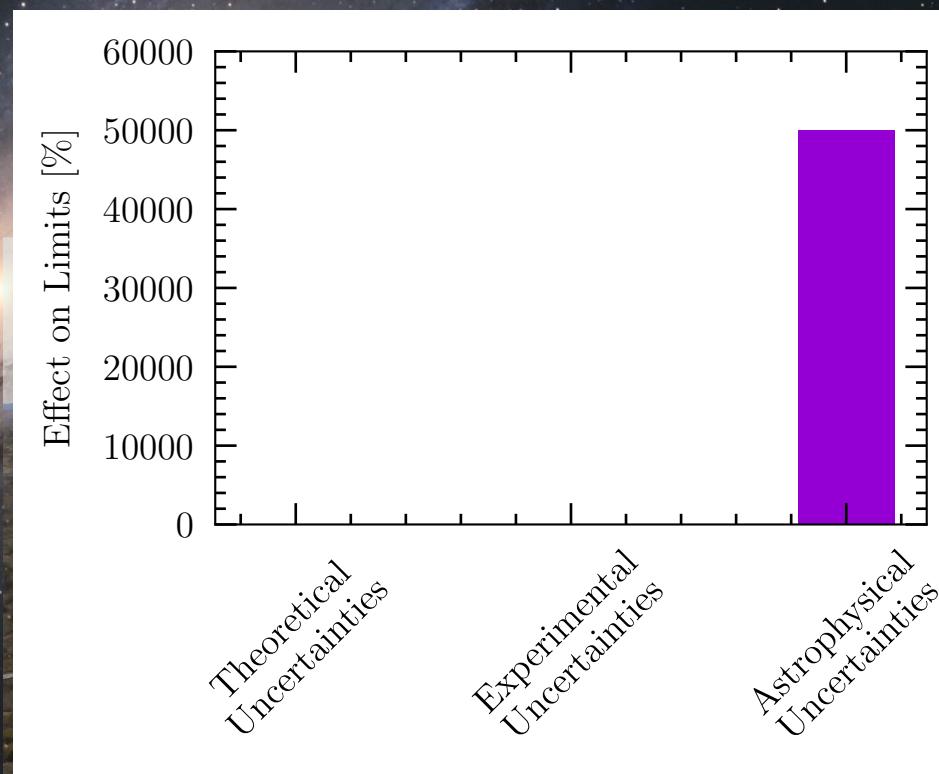
Example: Dark Matter Search at H.E.S.S.



$$N_{\text{signal}} = \text{Flux}_\gamma \times \text{Experimental Efficiency} \times \text{Exposure}$$
$$\propto \langle \sigma v \rangle \int_{\text{line of sight}} \int_{\text{angles}} \rho_\chi^2 d\Omega ds \times A_{\text{eff}}^\gamma$$

Einasto (1965)

Dark Matter in the Galactic Center



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

Dark Matter in the Galactic Center

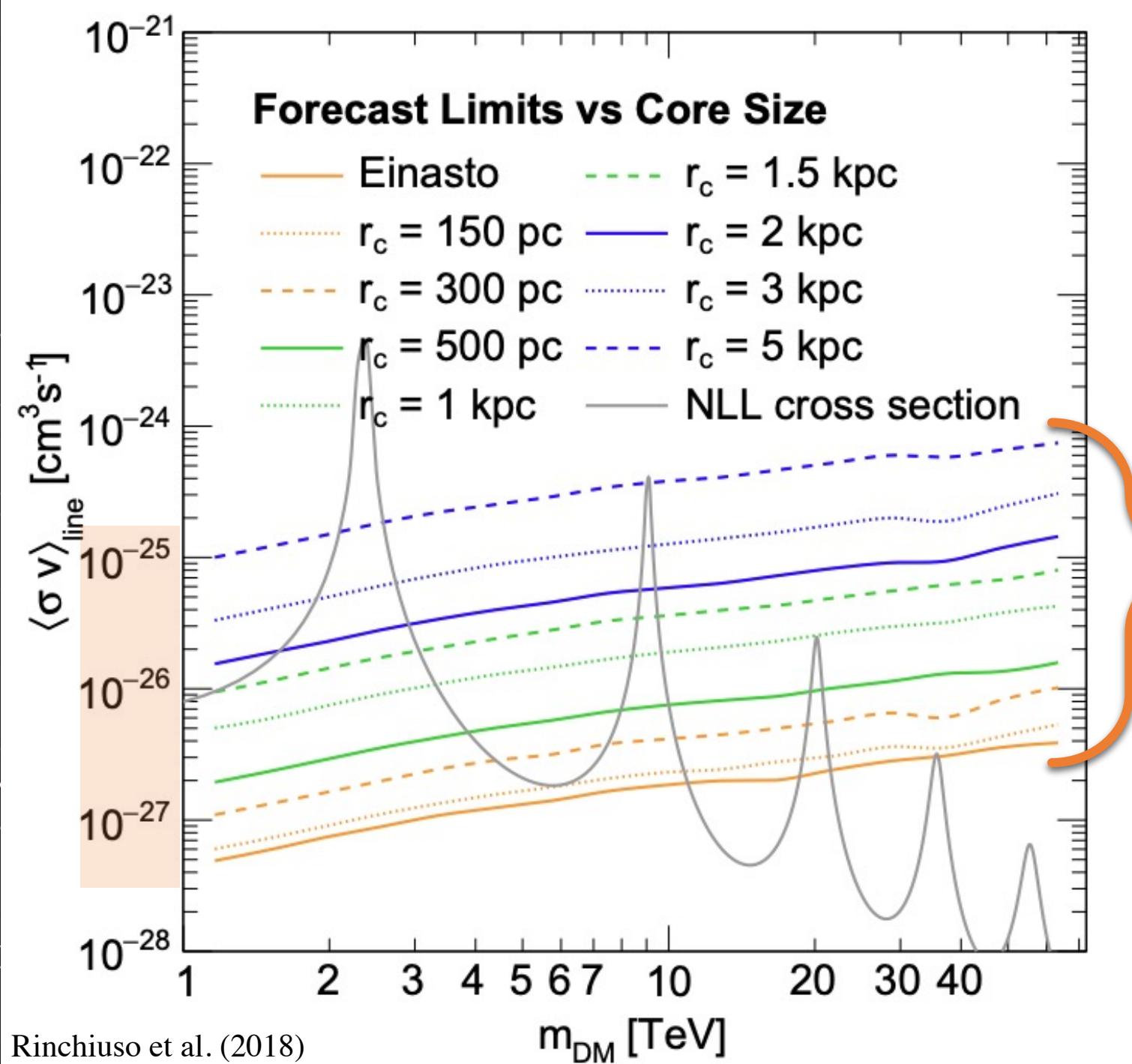
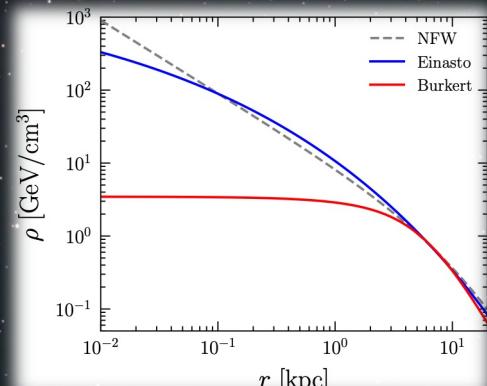
Different Profiles

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

ρ : Dark Matter Density

ds : Line of Sight Integral

$d\Omega$: Solid Angle Integral



Dark Matter in the Galactic Center

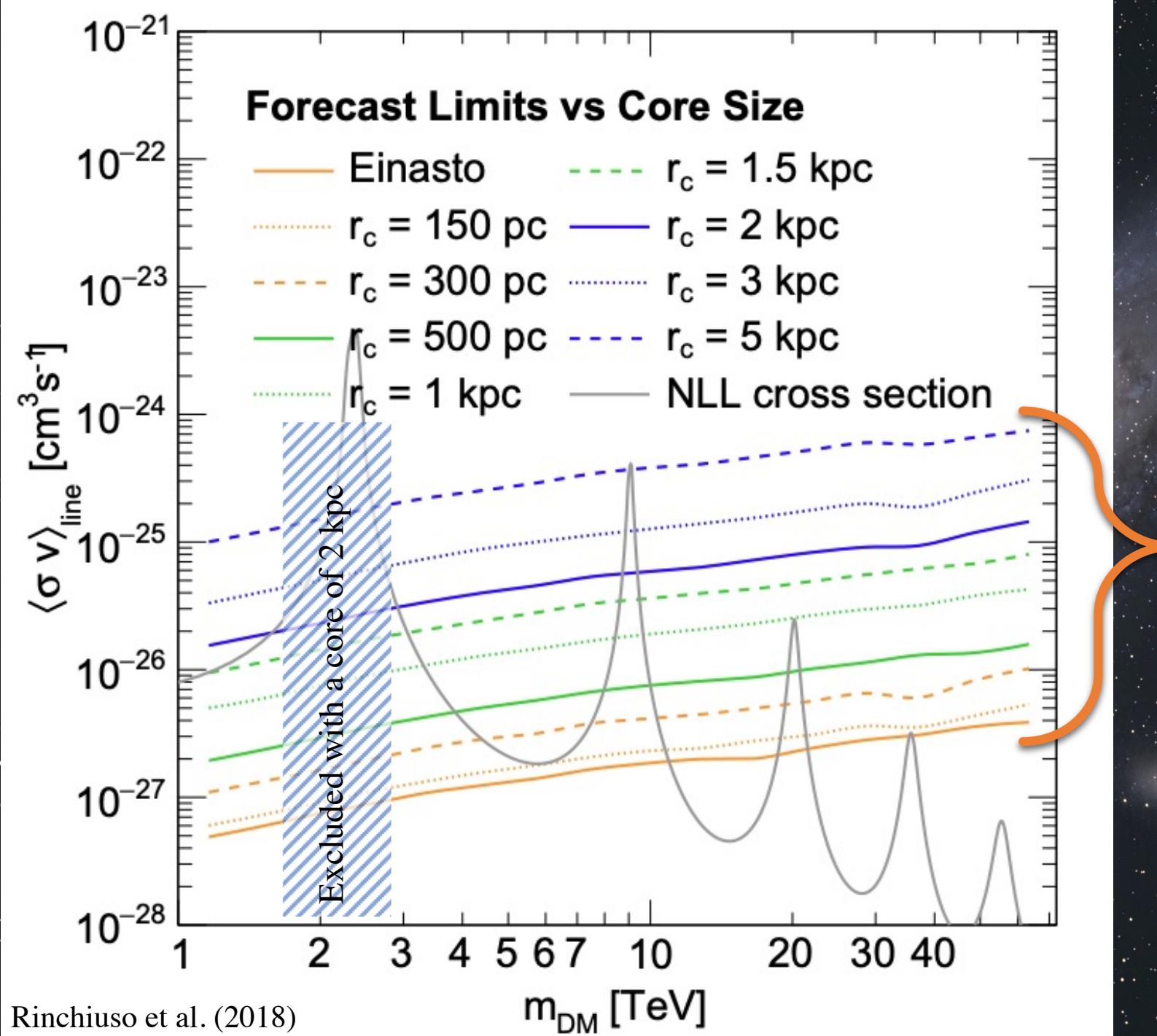
Different Profiles

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

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Dark Matter in the Galactic Center

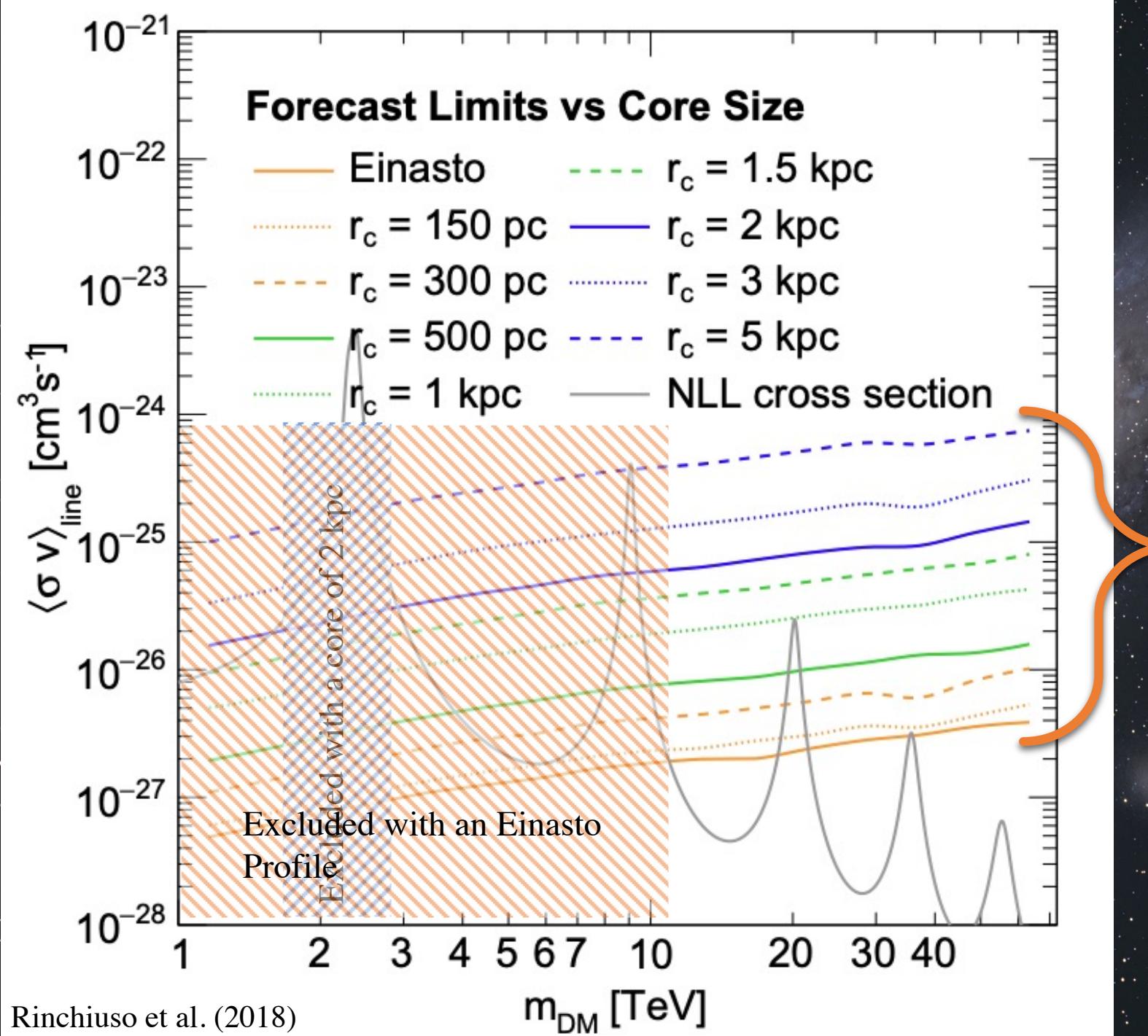
$$J \propto \int \int_{\text{l.o.s}} \rho^2 \, ds \, d\Omega$$

ρ : Dark Matter Density

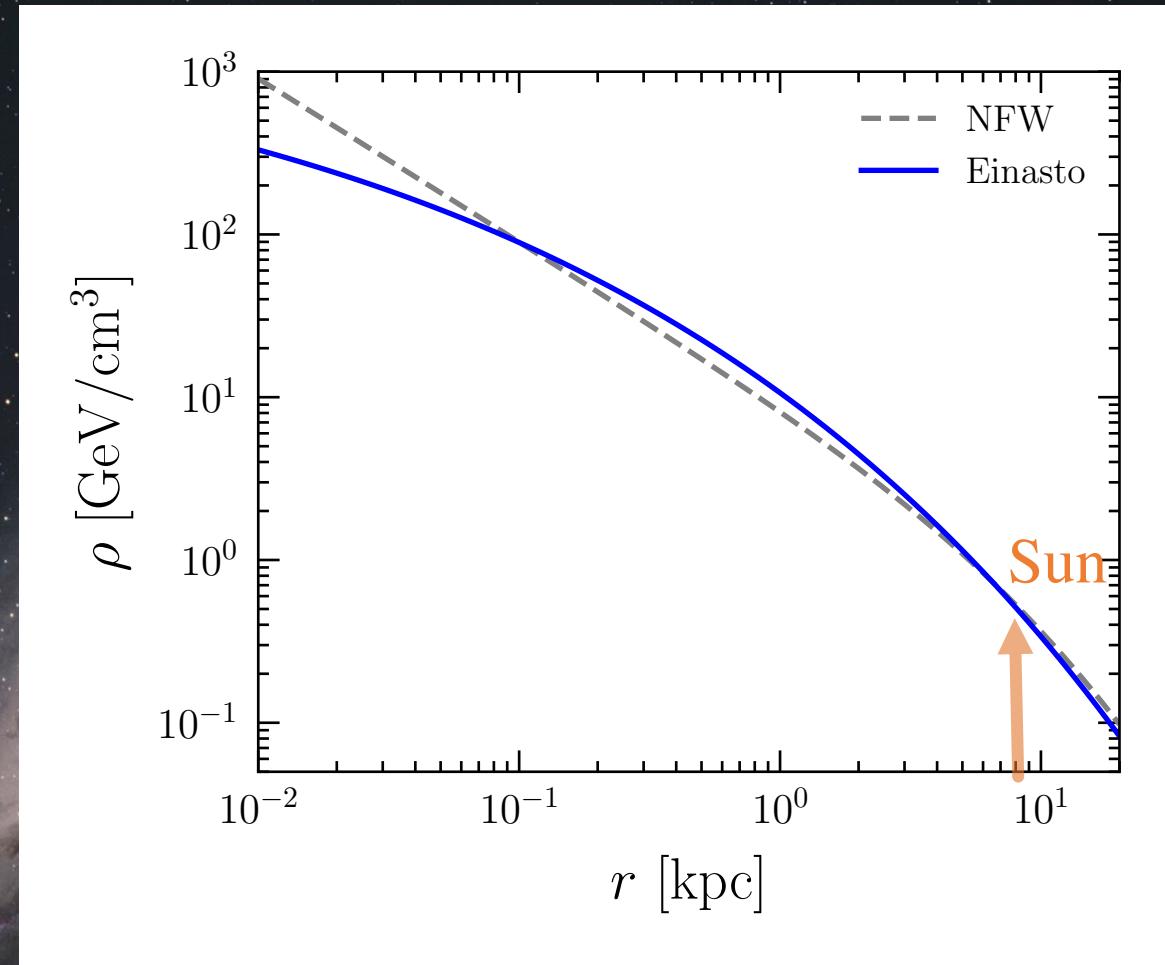
ds : Line of Sight Integral

$d\Omega$: Solid Angle Integral

Different Profiles



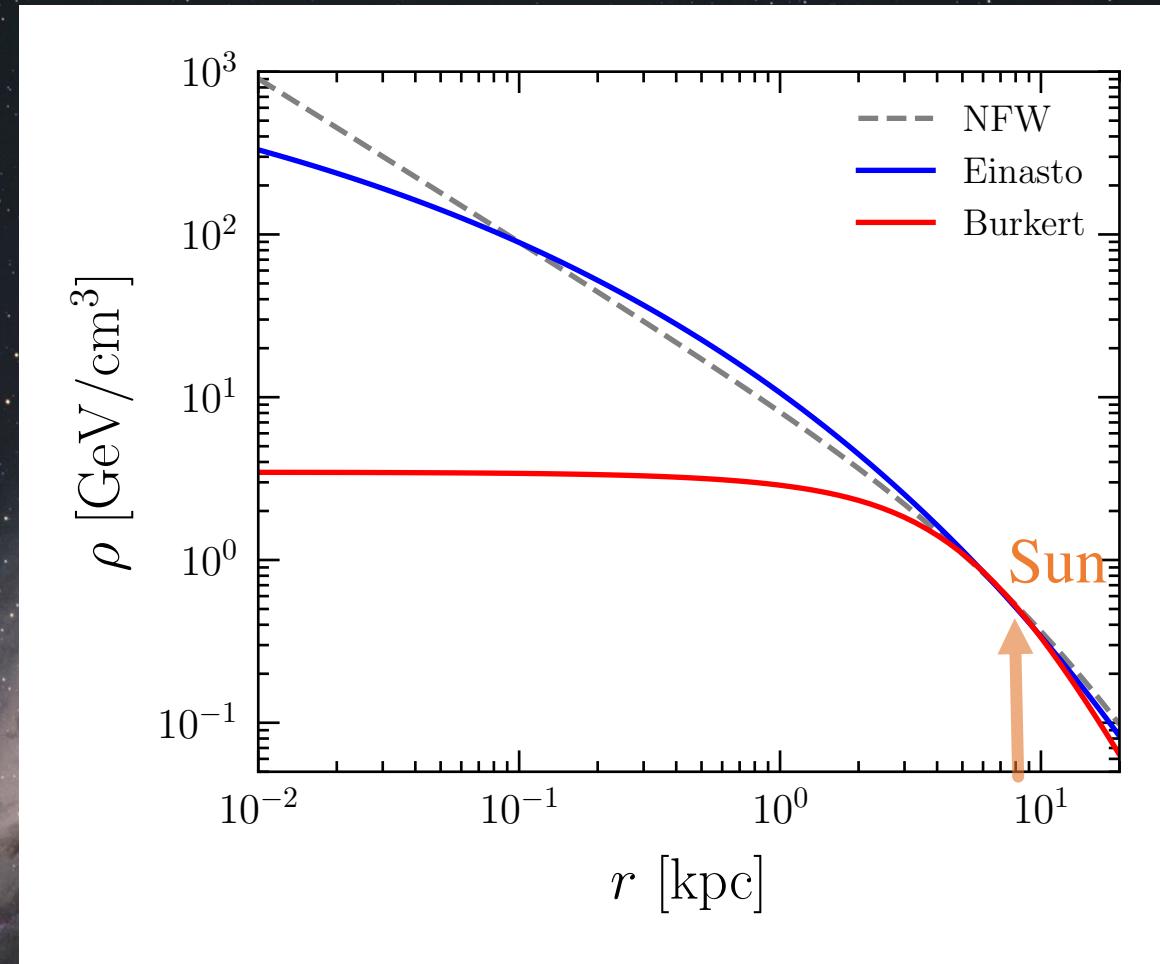
Dark Matter Density Distribution



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

Dark Matter Density Distribution

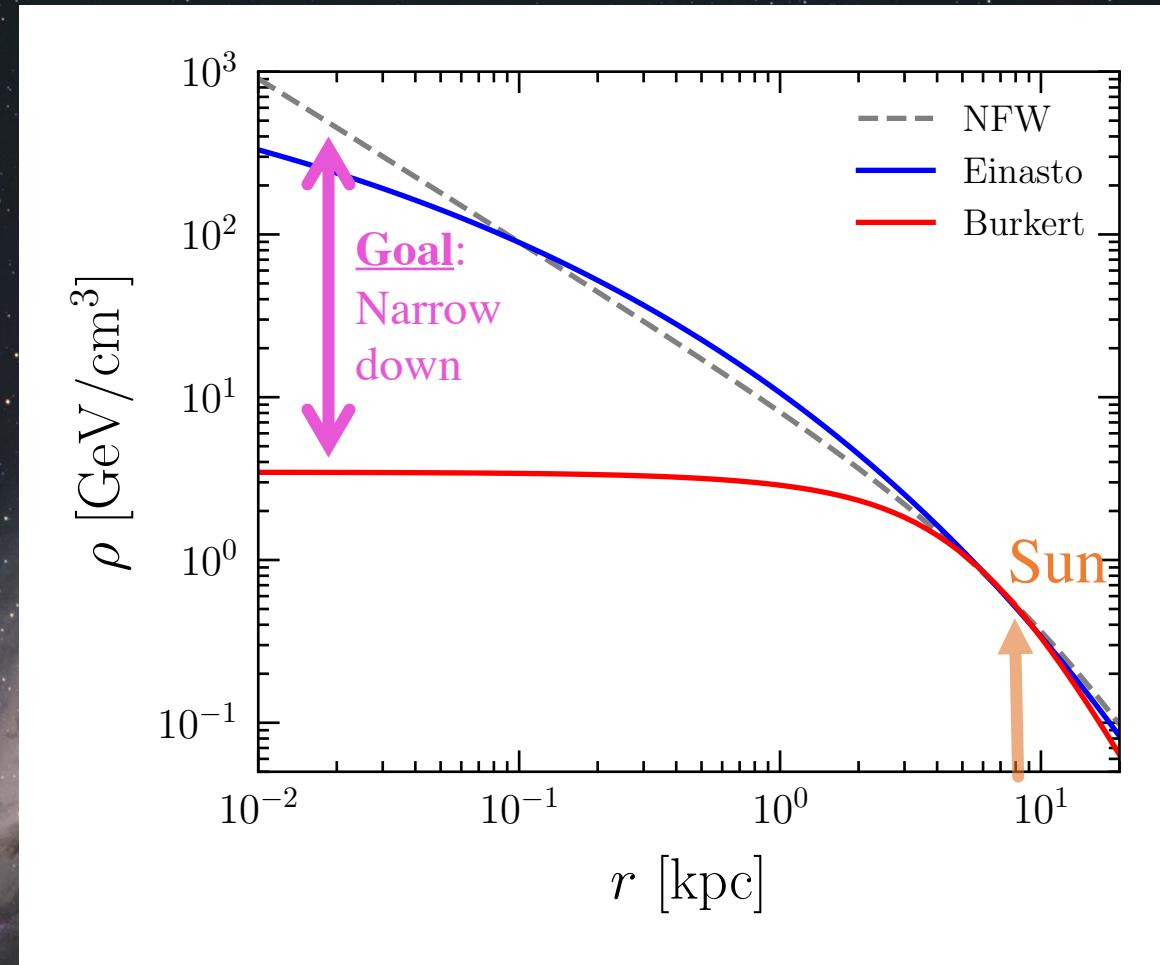
Density profiles can vary by orders of magnitude.



- Einasto (1965)
- Burkert (1995)
- Navarro, Frenk, White (1996)
- Fornasa & Green (2013)
- Gaskins (2016)

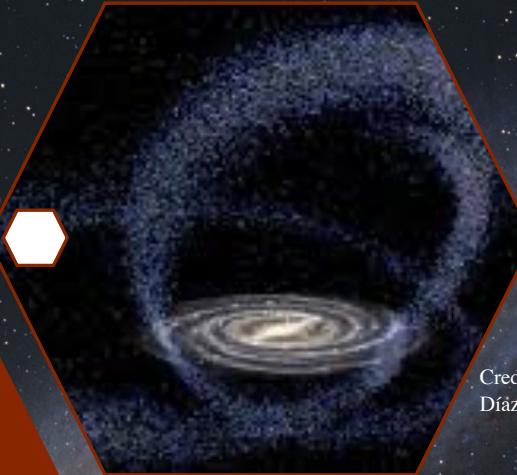
Dark Matter Density Distribution

Density profiles can vary by orders of magnitude.

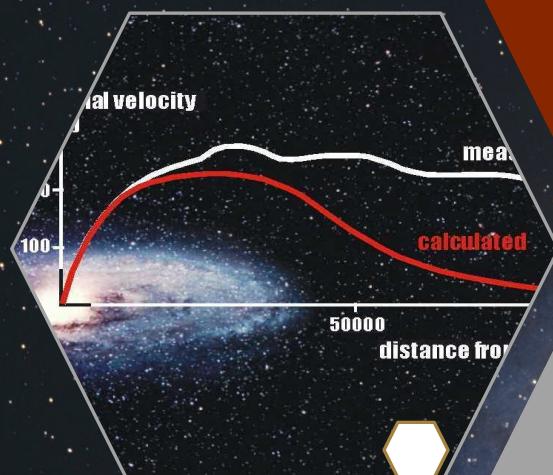


- Einasto (1965)
- Burkert (1995)
- Navarro, Frenk, White (1996)
- Fornasa & Green (2013)
- Gaskins (2016)

Dark Matter Density Distribution



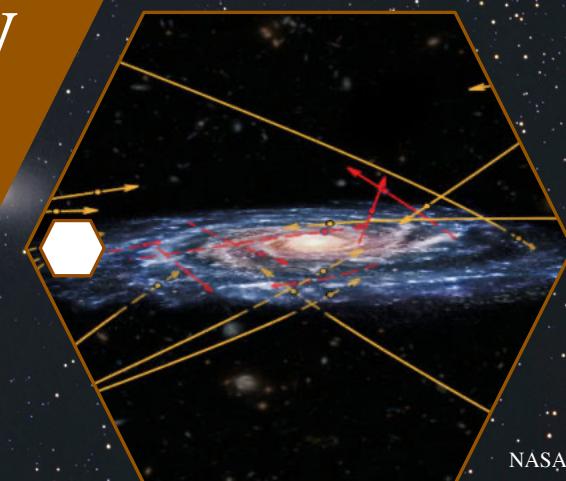
Credit: Gabriel Pérez
Díaz, SMM (IAC).



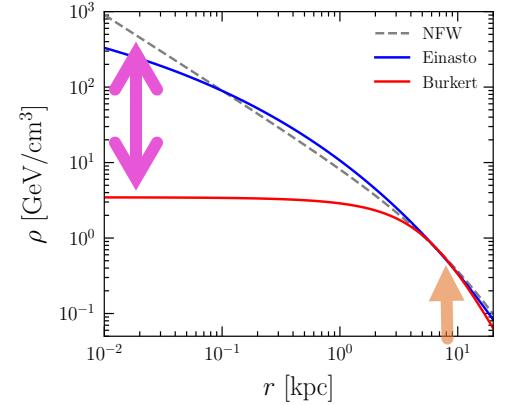
<https://www.universetoday.com/91520/astronomy-without-a-telescope-could-dark-matter-not-matter/>

Circular Velocity

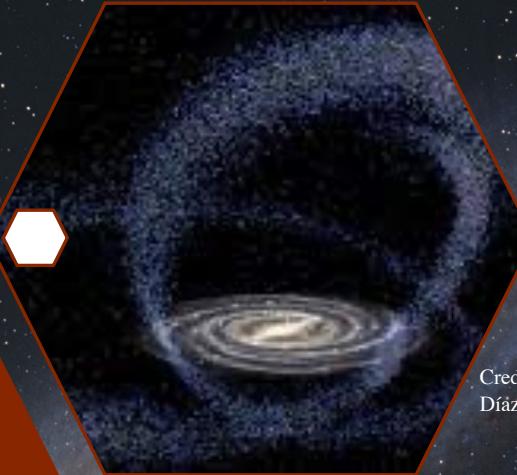
Escape Velocity



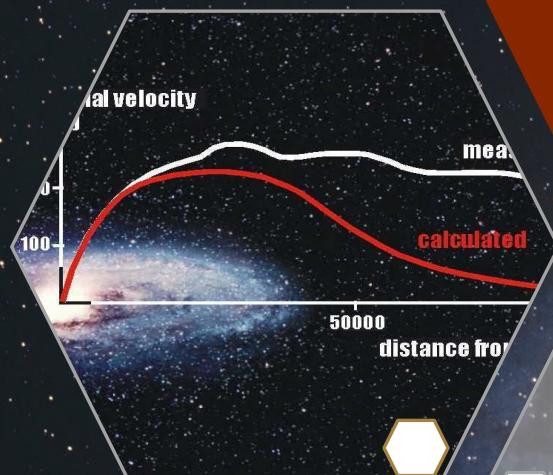
NASA / ESA / Hubble / Marchetti et al. 2018



Dark Matter Density Distribution



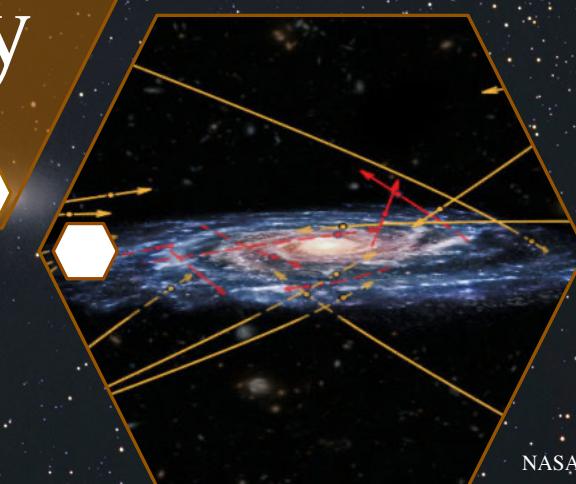
Credit: Gabriel Pérez
Díaz, SMM (IAC).



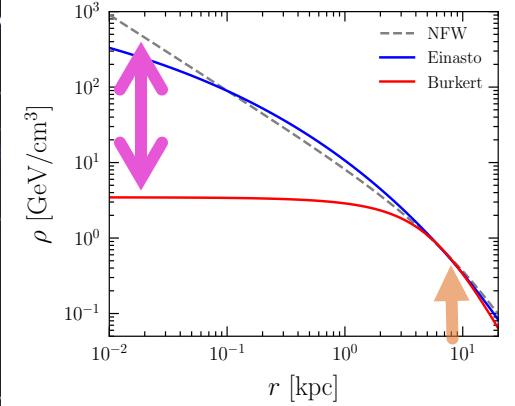
<https://www.universetoday.com/91520/astronomy-without-a-telescope-could-dark-matter-not-matter/>

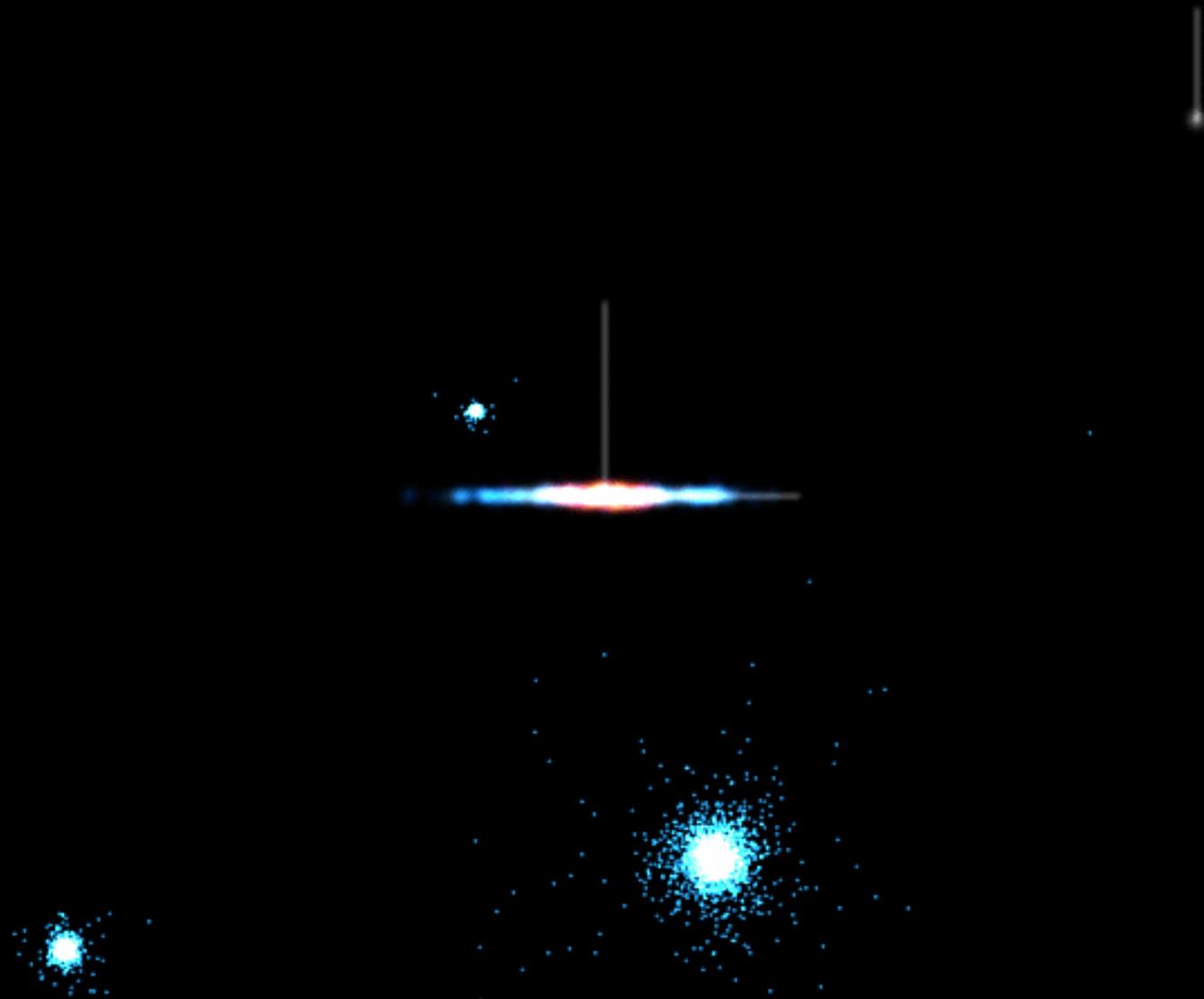
Circular Velocity

Escape Velocity

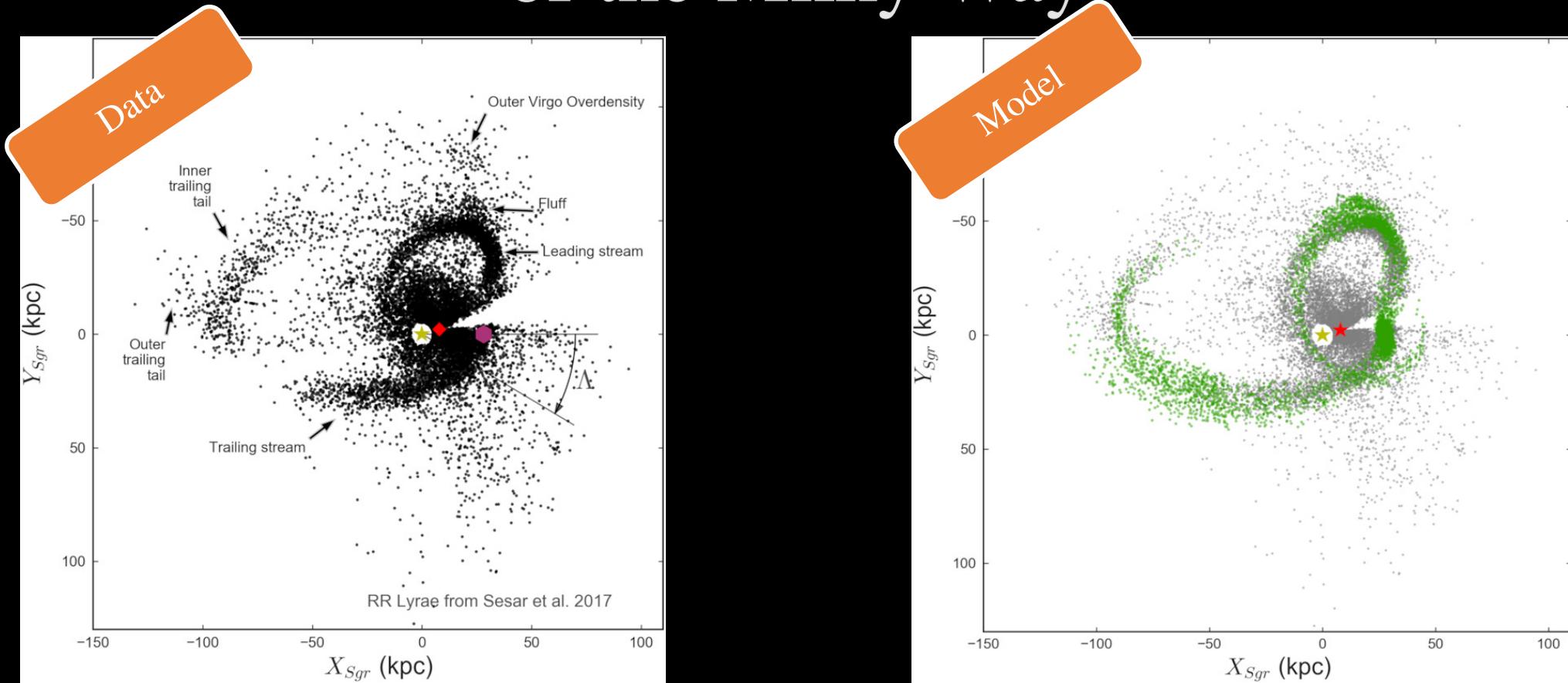


NASA / ESA / Hubble / Marchetti et al. 2018

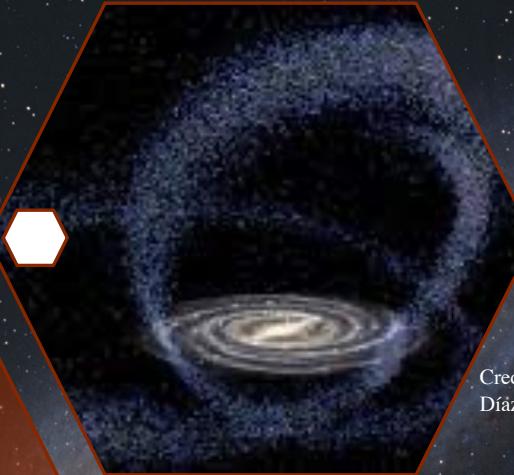




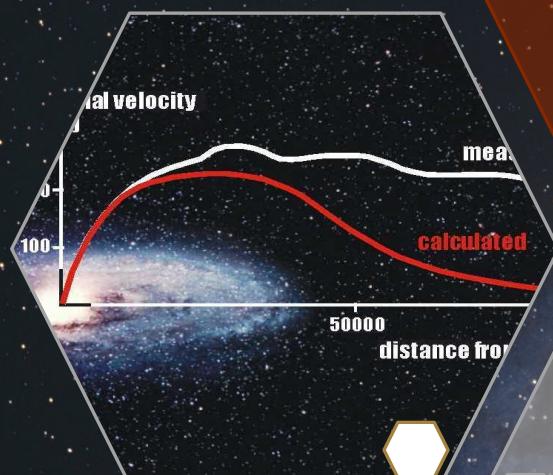
Using Sagittarius Stream to Model the Potential of the Milky Way



Dark Matter Density Distribution



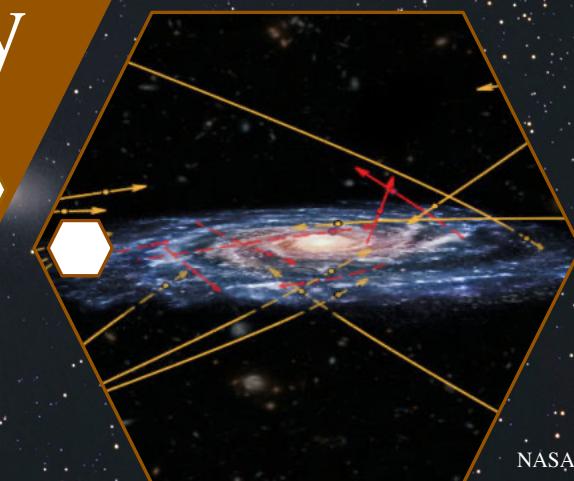
Credit: Gabriel Pérez
Díaz, SMM (IAC).



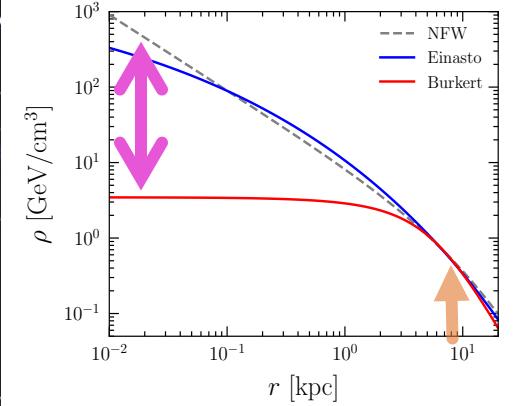
<https://www.universetoday.com/91520/astronomy-without-a-telescope-could-dark-matter-not-matter/>

Circular Velocity

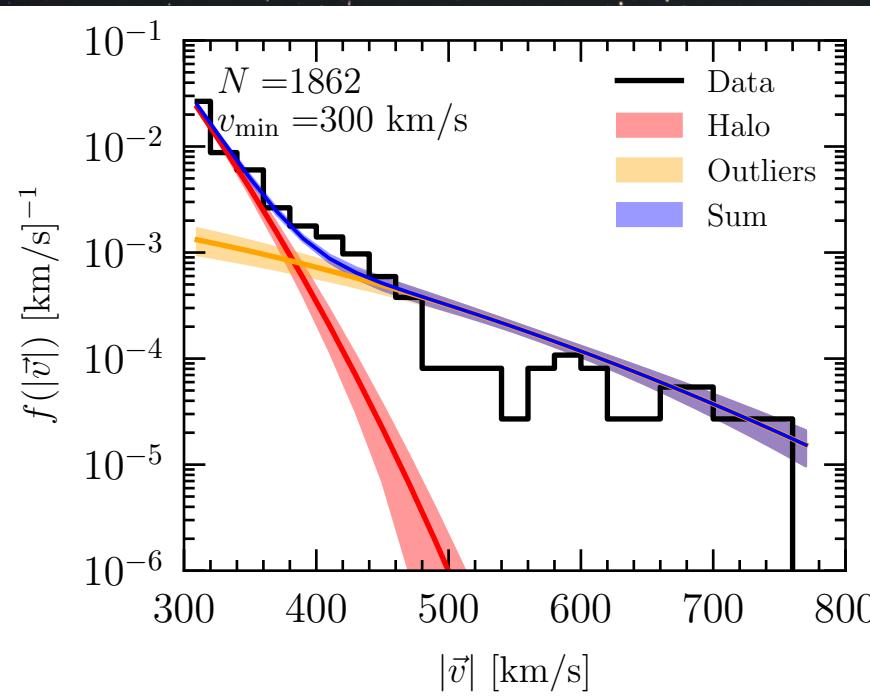
Escape Velocity



NASA / ESA / Hubble / Marchetti et al. 2018

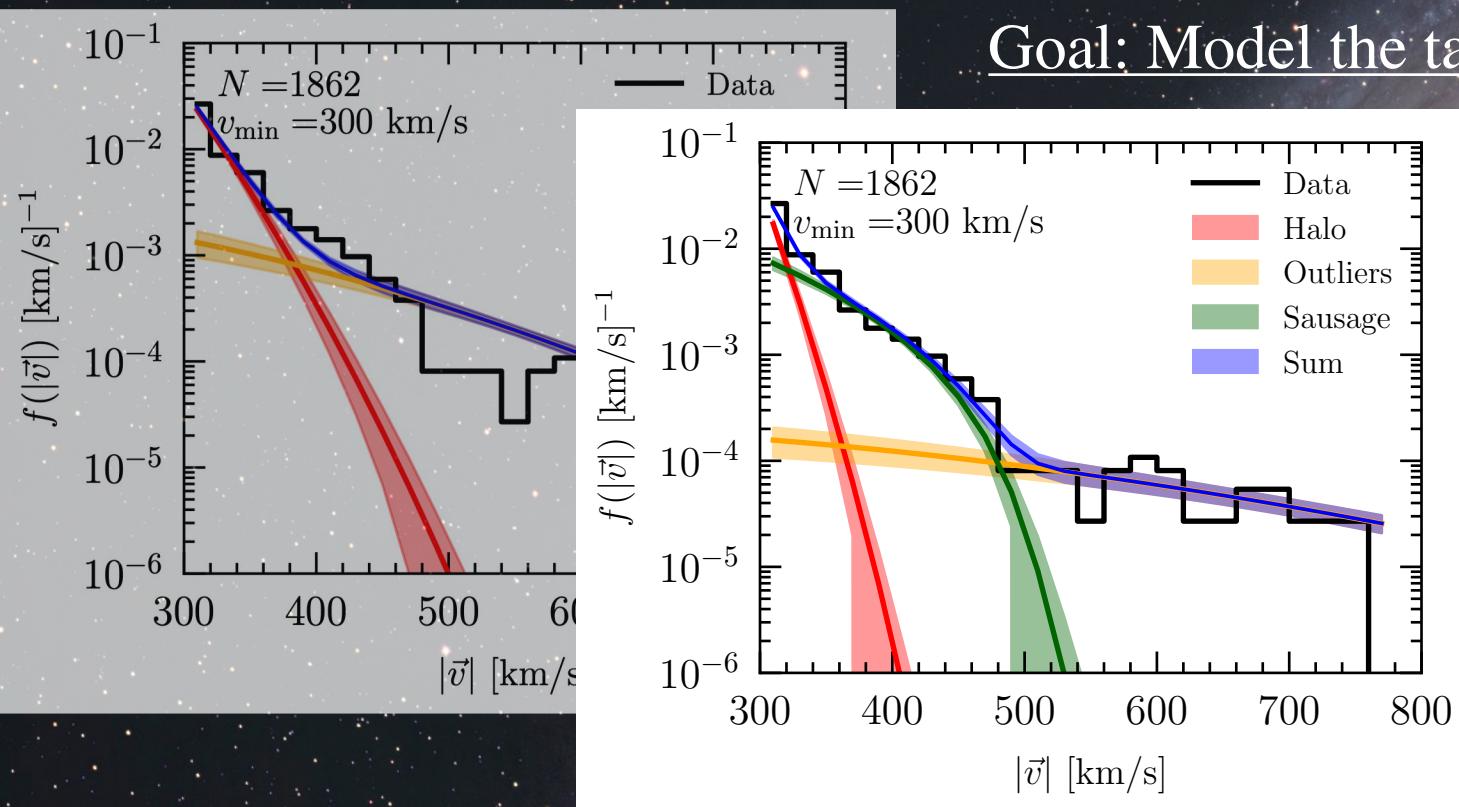


Determining the Escape Velocity



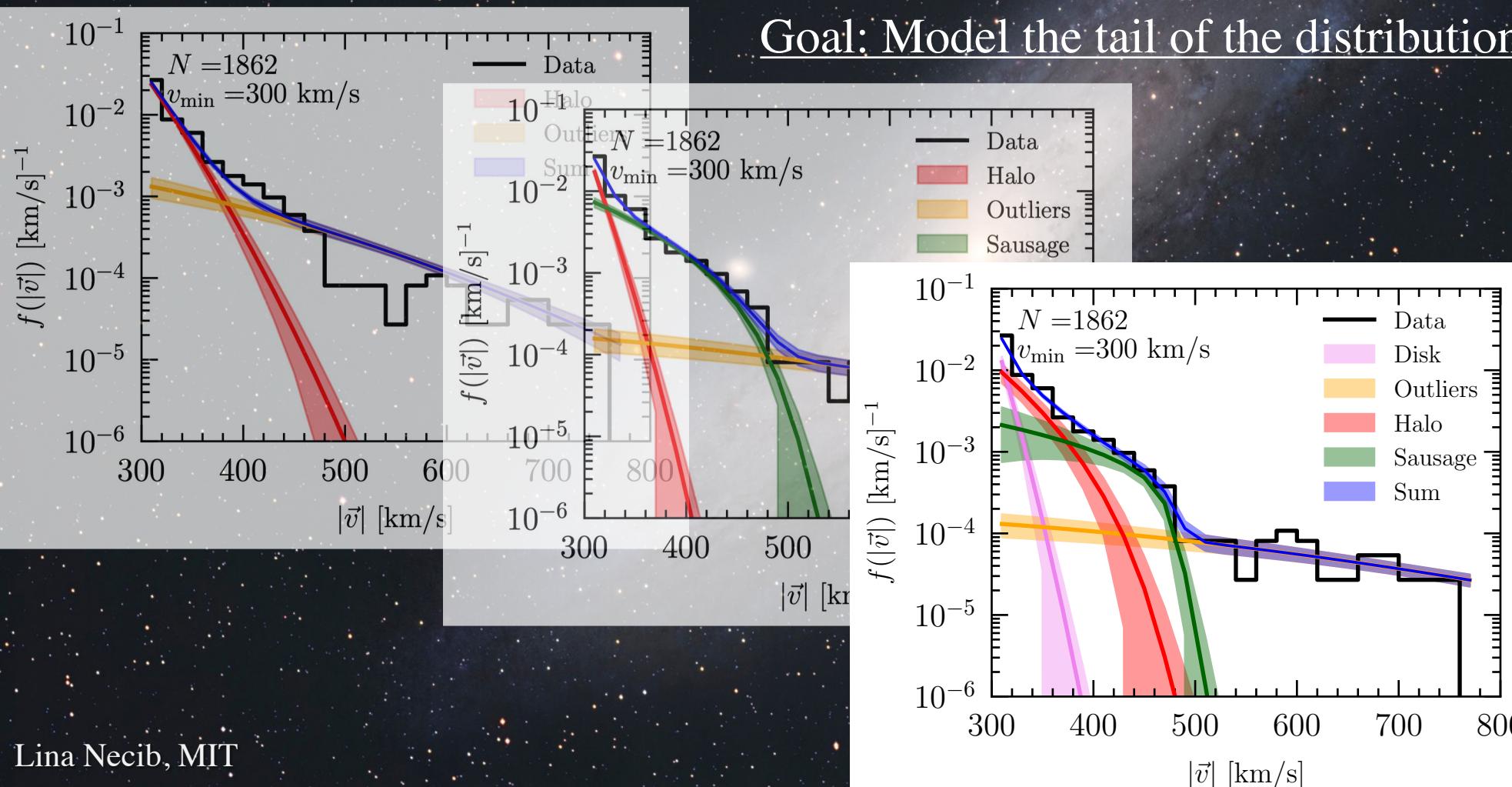
Goal: Model the tail of the distribution

Determining the Escape Velocity



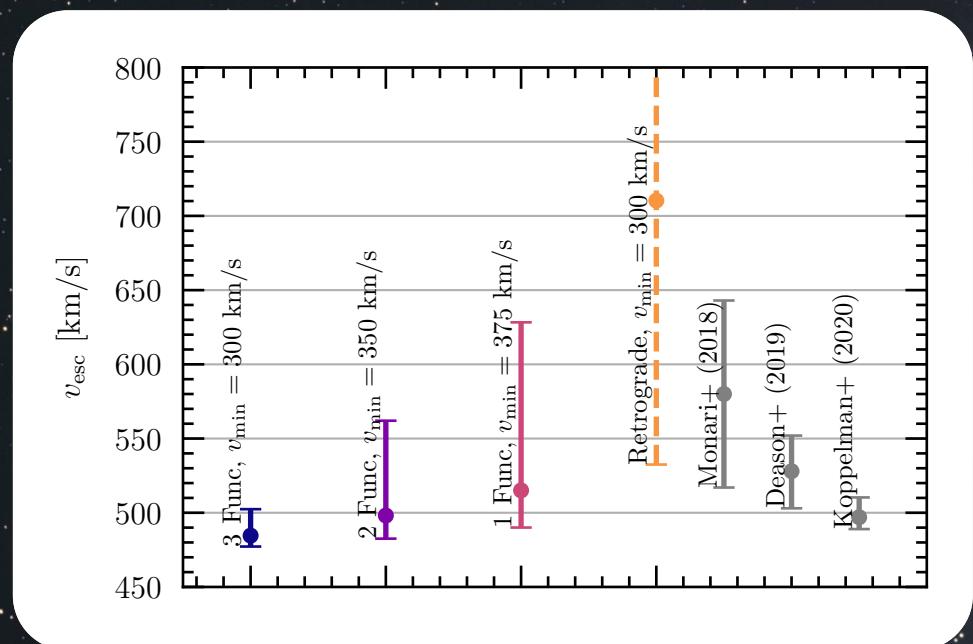
Goal: Model the tail of the distribution

Determining the Escape Velocity

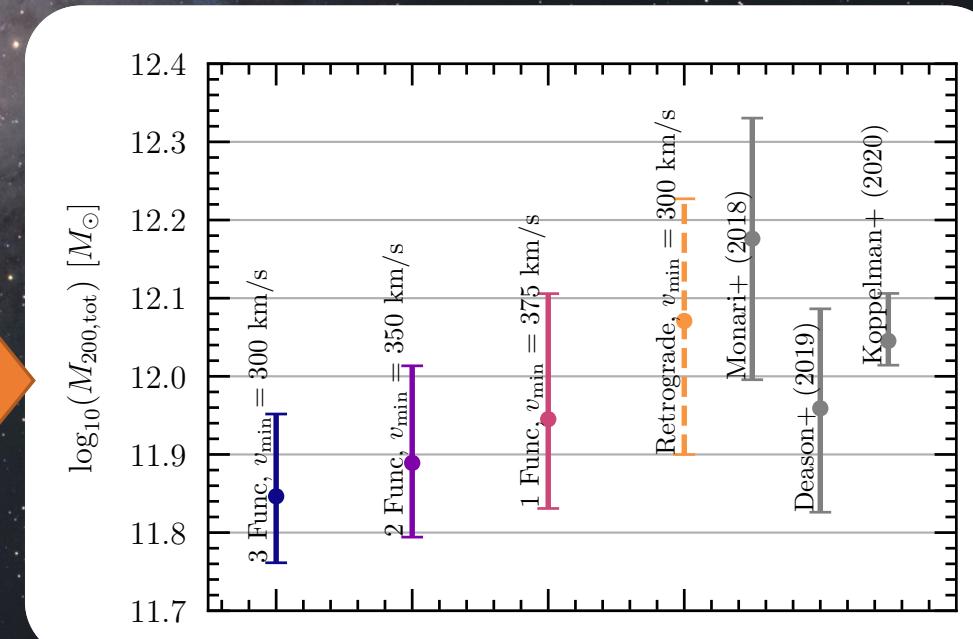


Leonard & Tremaine (1990)
Necib & Lin (2021a,b)

Determining the Escape Velocity



Assume
Milky Way
Potential

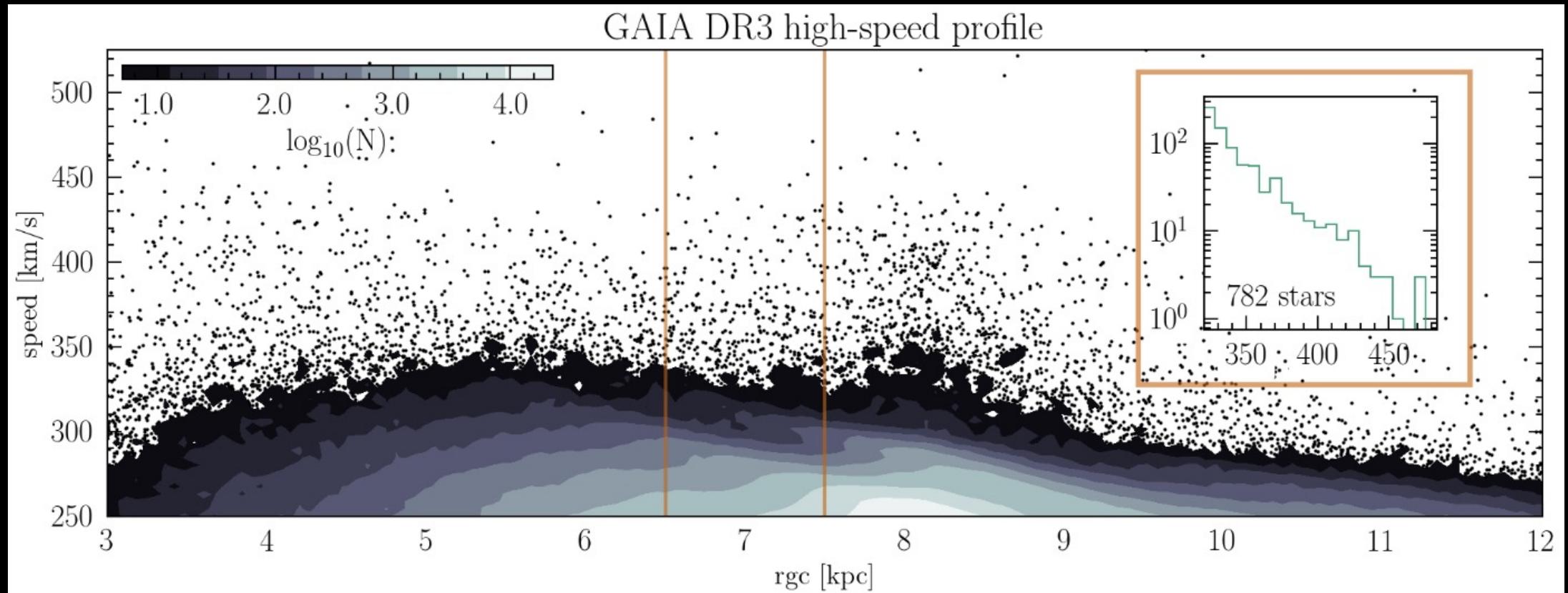


Gaia DR2 $M_{200} = 7.0^{+1.9}_{-1.2} \times 10^{11} M_{\odot}$

Gaia eDR3 $M_{200} = 4.6^{+1.5}_{-0.8} \times 10^{11} M_{\odot}$

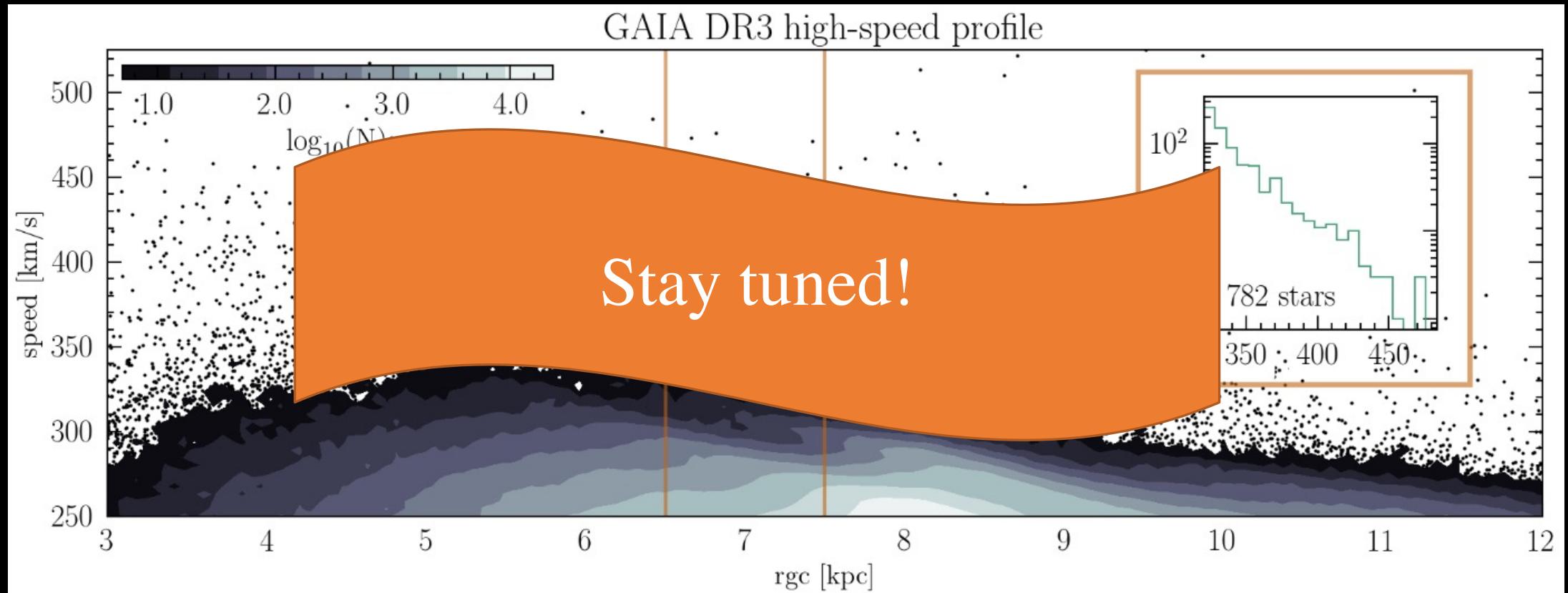
Leonard & Tremaine (1990)
Necib & Lin, (2021a,b)

Now onto *Gaia* DR3



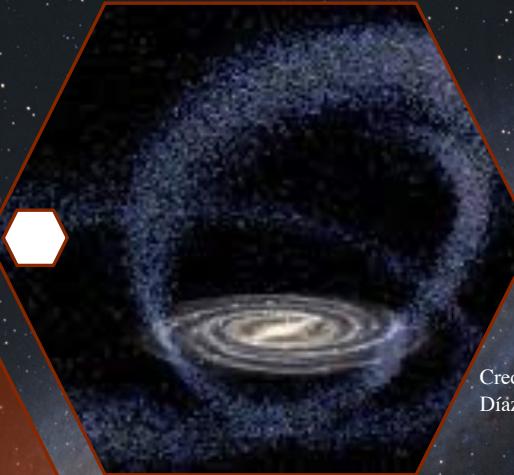
Roche, **Necib** & Lin (in prep)

Now onto *Gaia* DR3

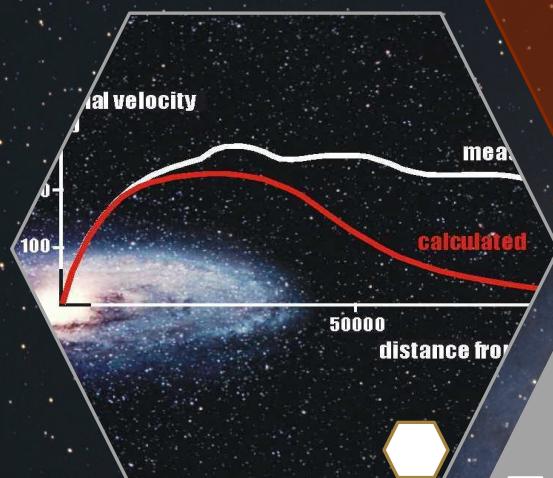


Roche, **Necib** & Lin (in prep)

Dark Matter Density Distribution



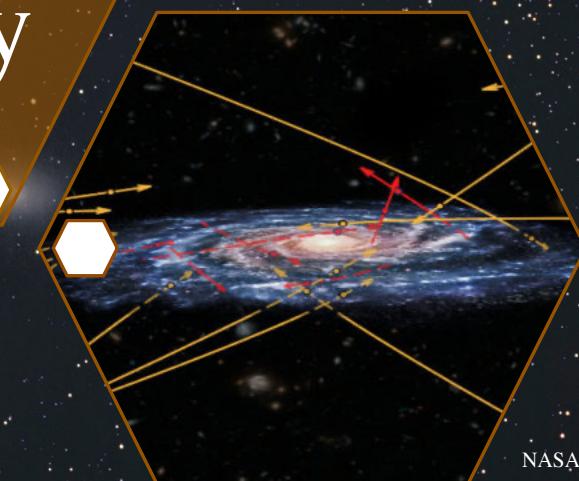
Credit: Gabriel Pérez
Díaz, SMM (IAC).



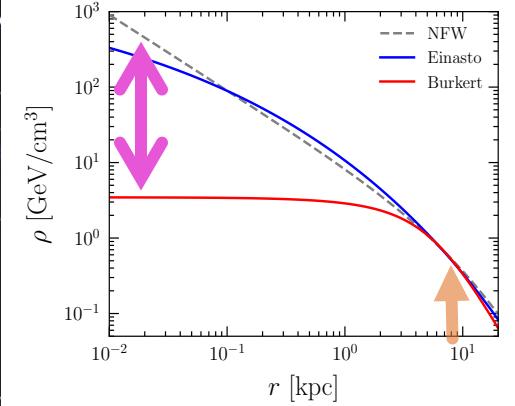
<https://www.universetoday.com/91520/astronomy-without-a-telescope-could-dark-matter-not-matter/>

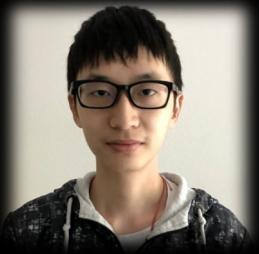
Circular Velocity

Escape Velocity

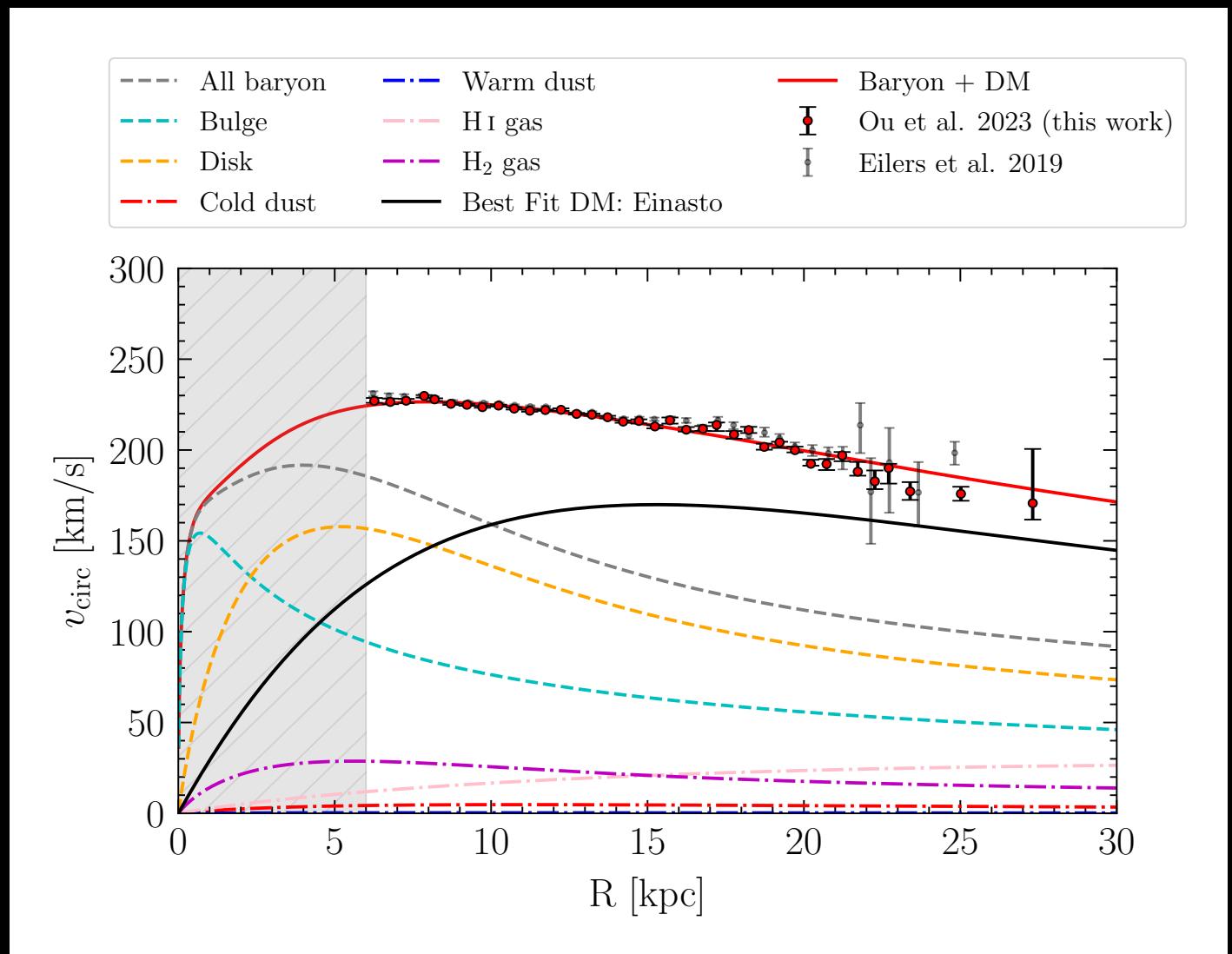


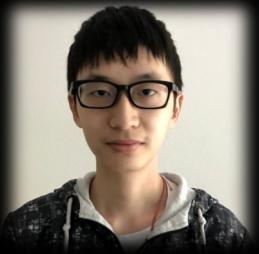
NASA / ESA / Hubble / Marchetti et al. 2018



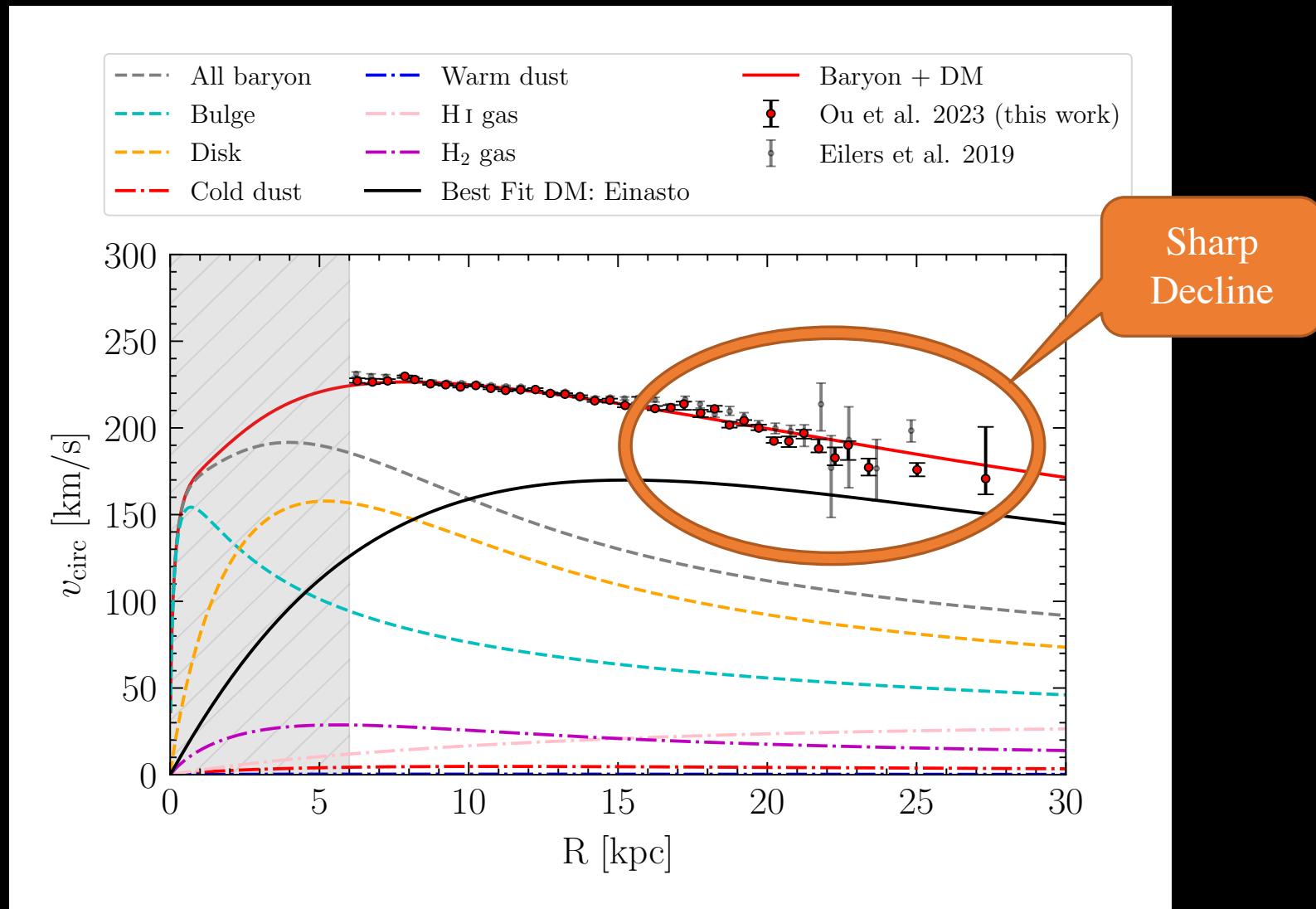


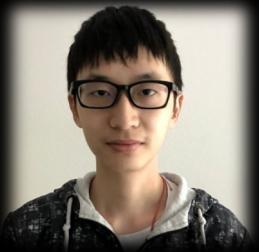
Xiaowei Ou



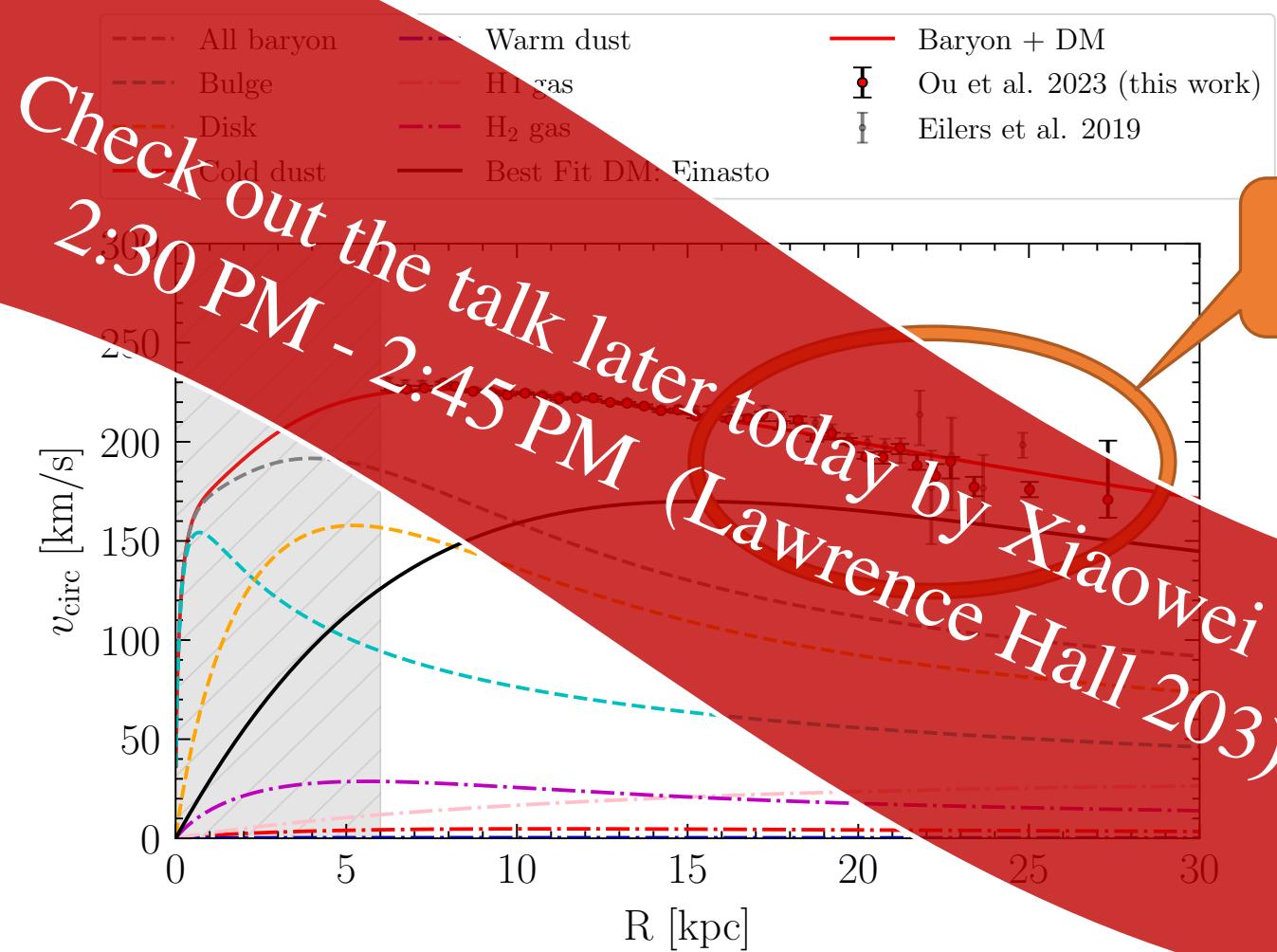


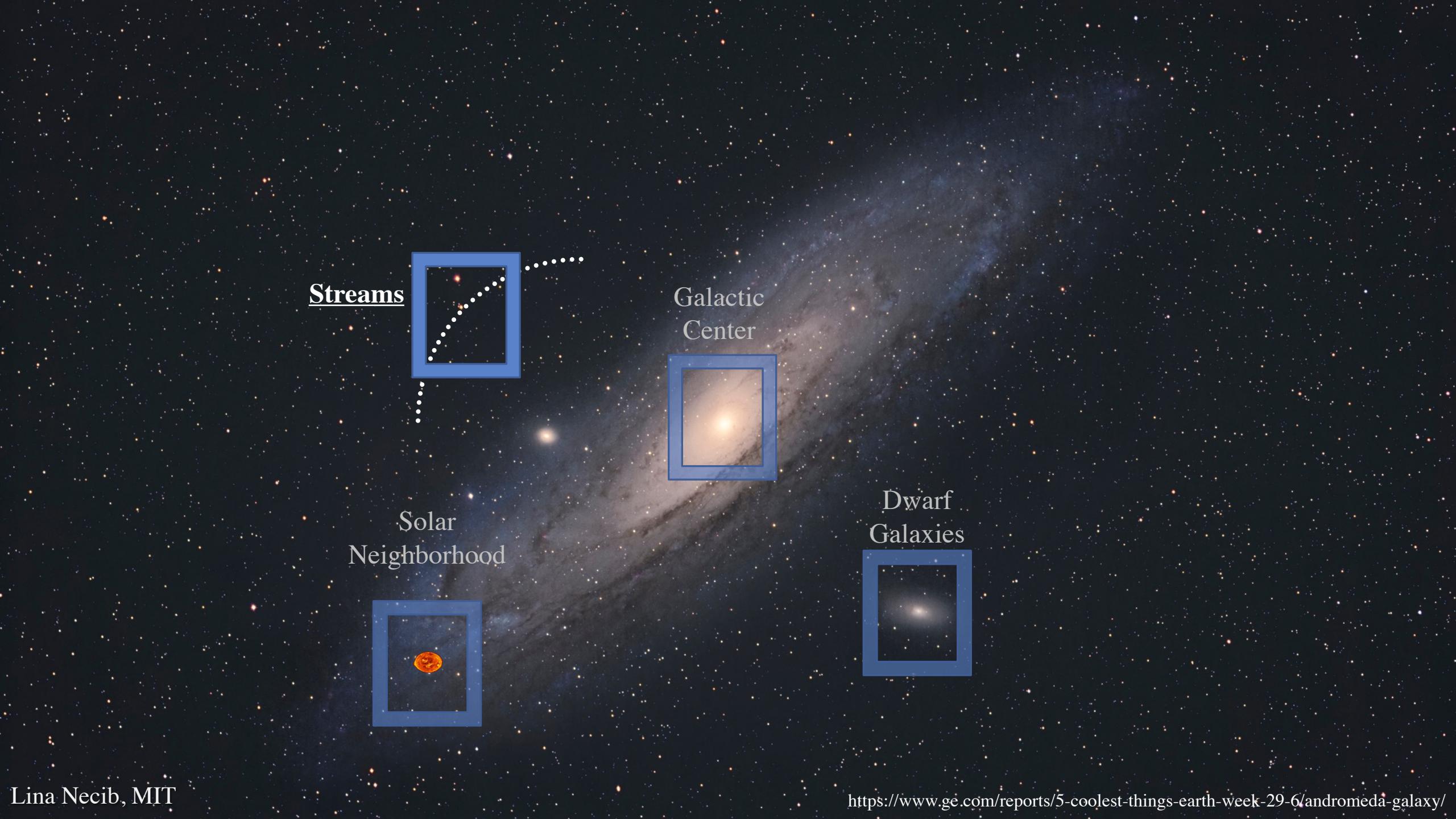
Xiaowei Ou



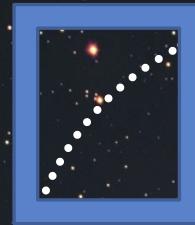


Xiaowei Ou





Streams



Galactic
Center



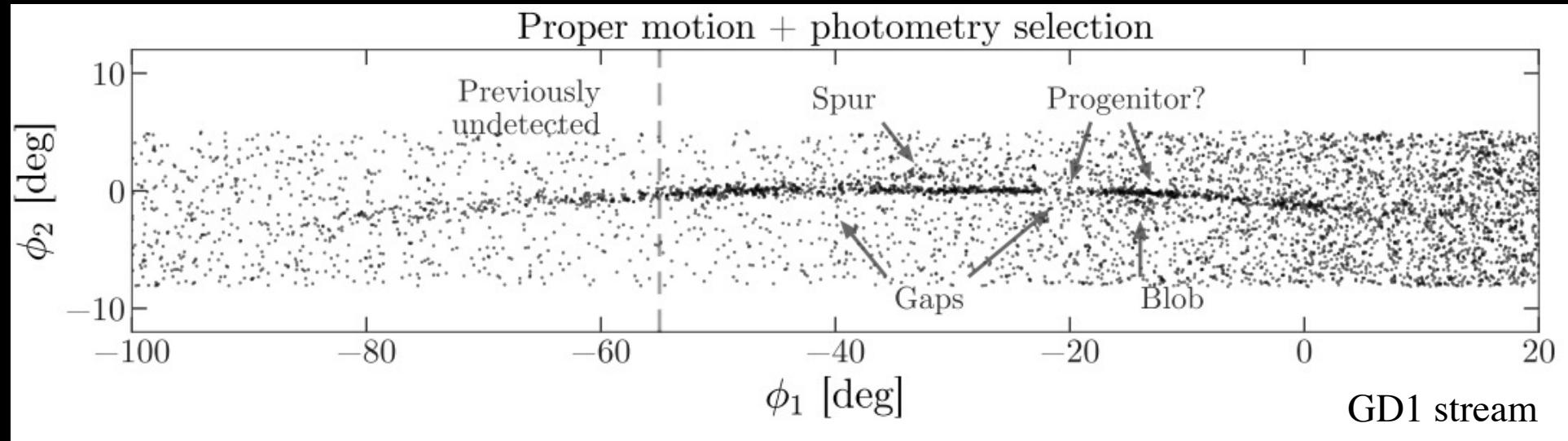
Solar
Neighborhood



Dwarf
Galaxies



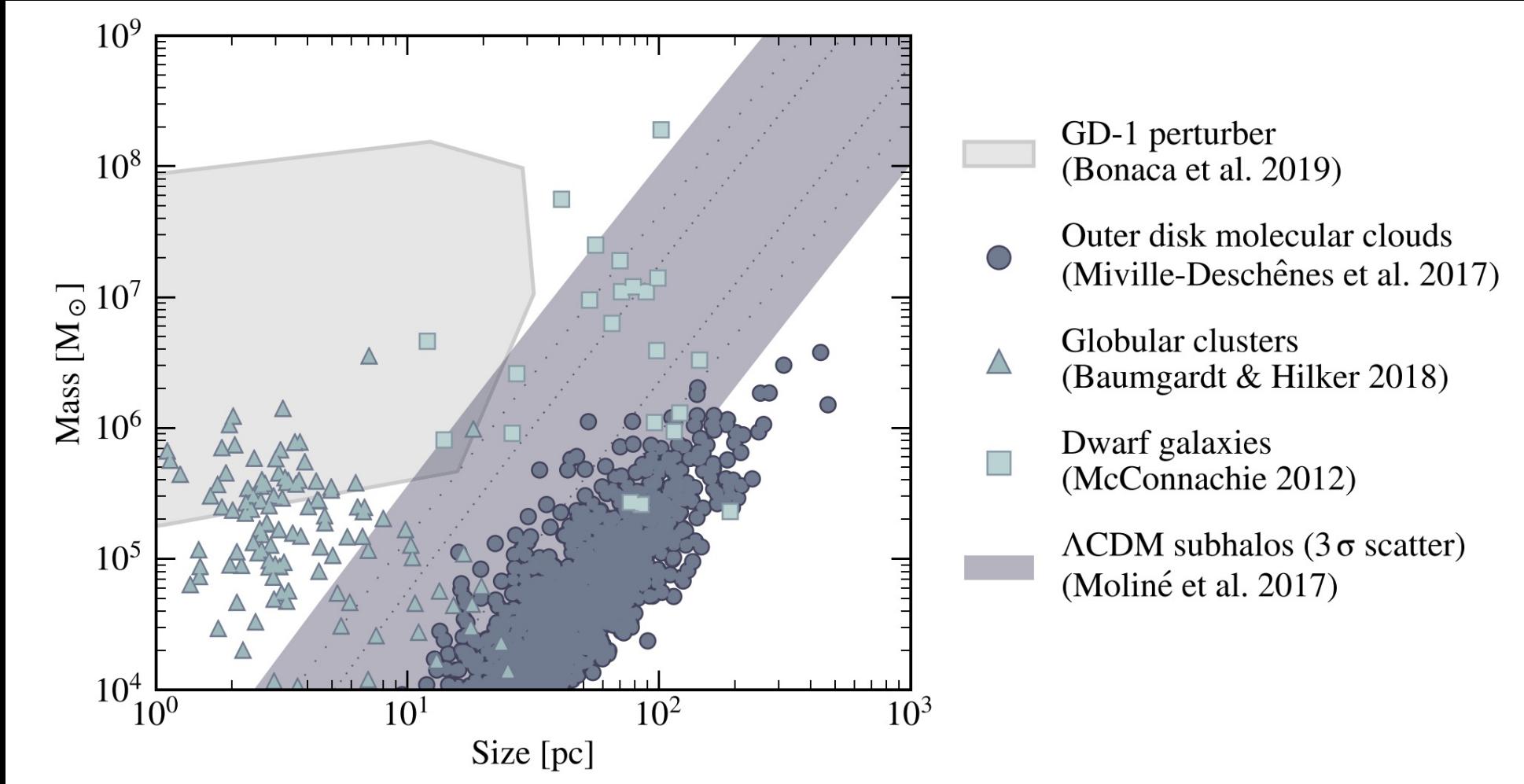
Streams: An insight into Dark Matter



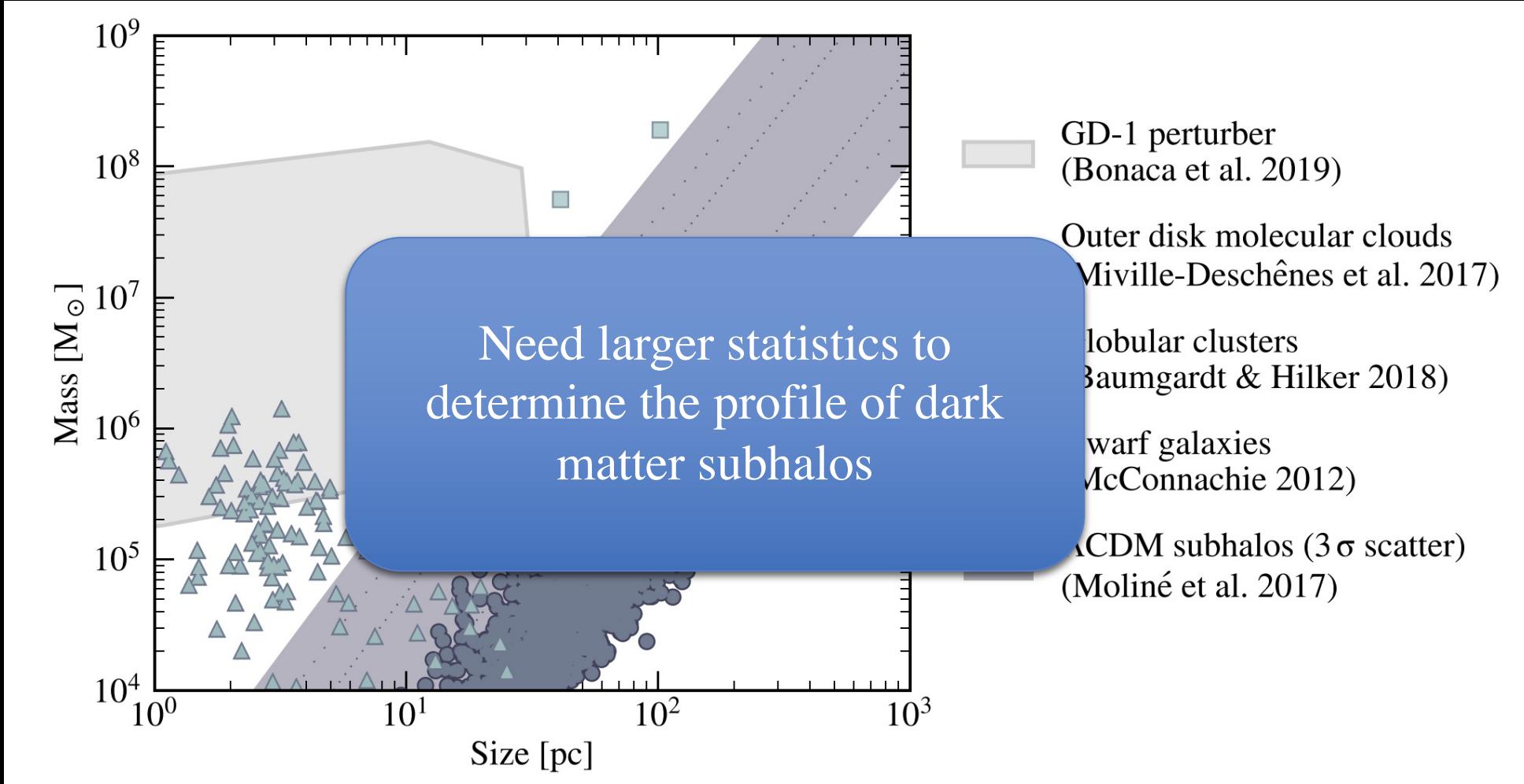
- Gaps in streams can constrain dark matter subhalo masses, and therefore models of warm dark matter!
- Streams are also used to constrain the potential of the Milky Way.

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

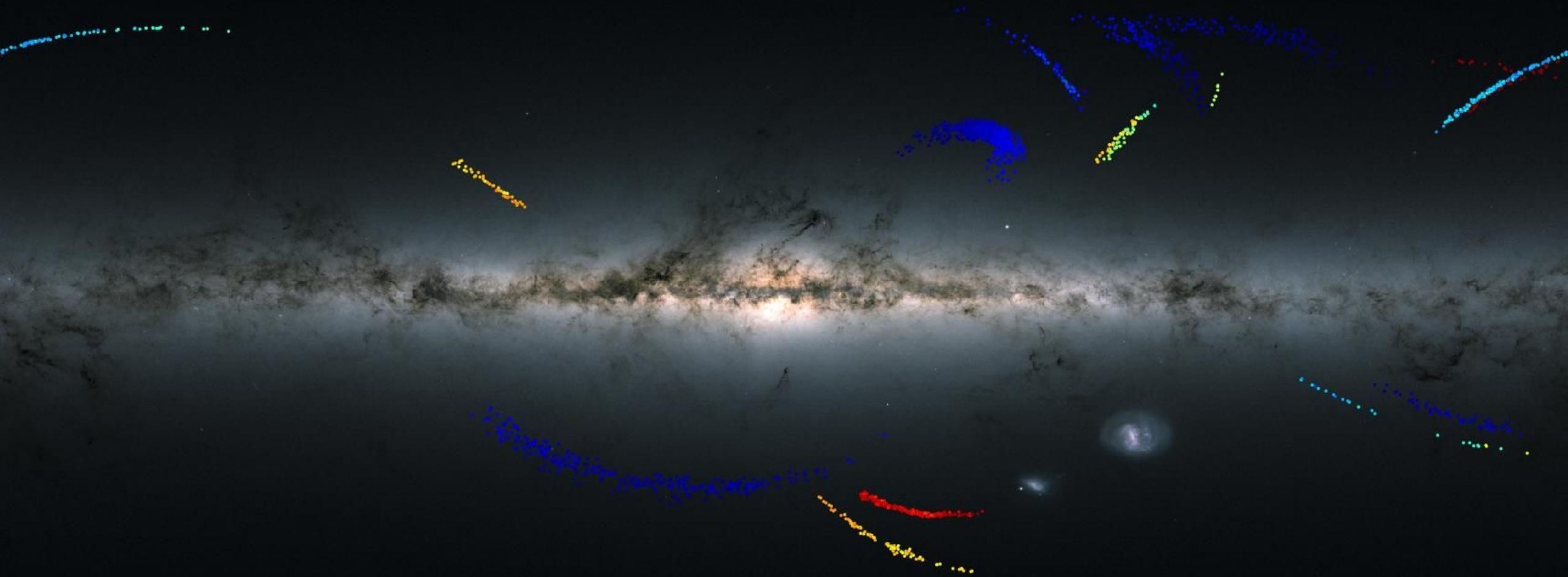
GD-1 Perturber?



GD-1 Perturber?



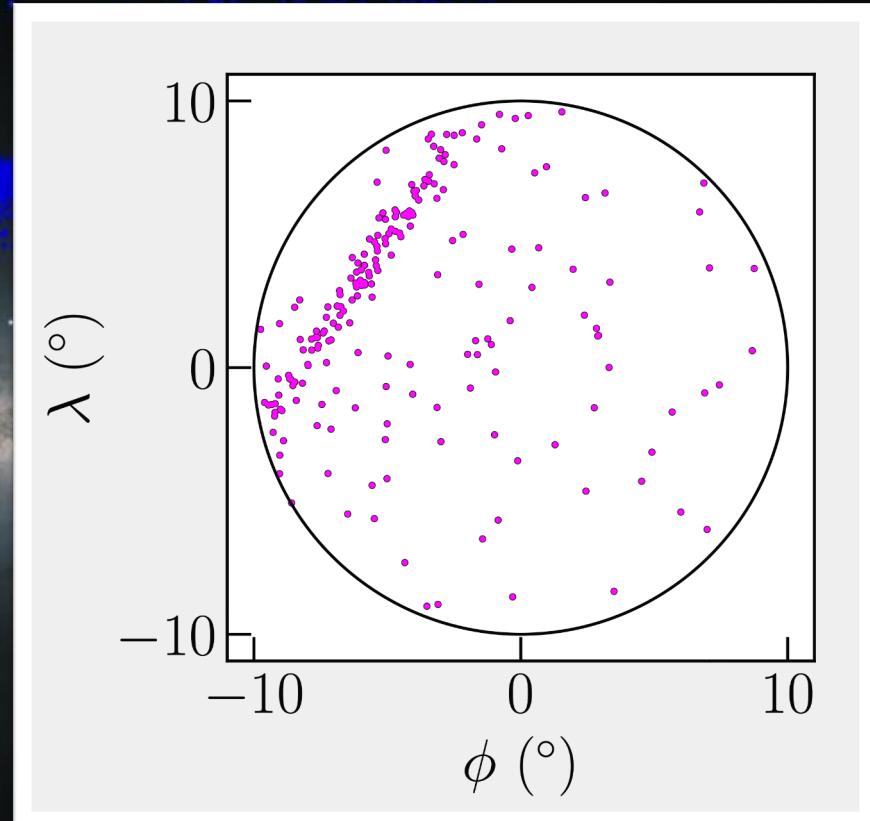
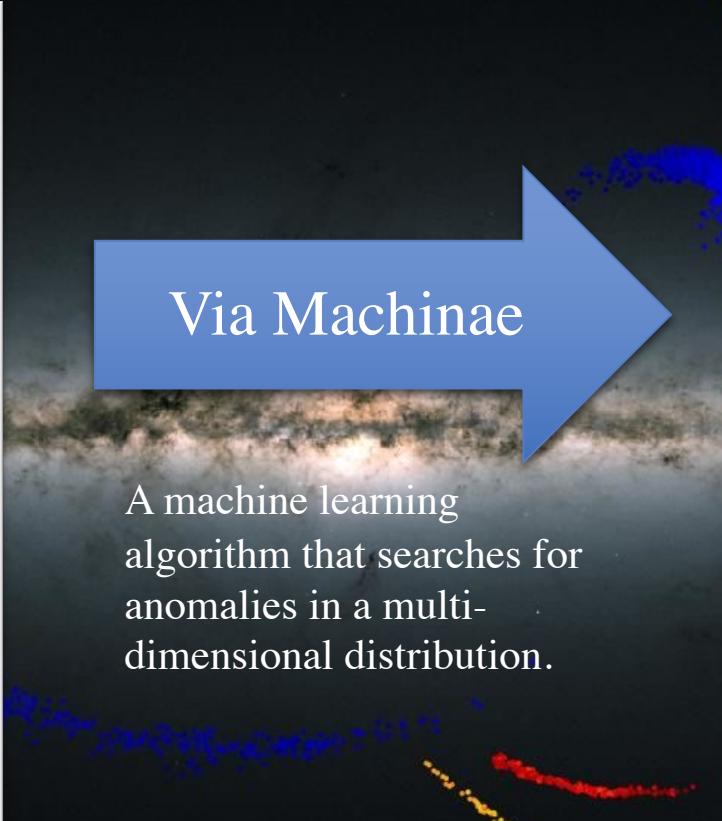
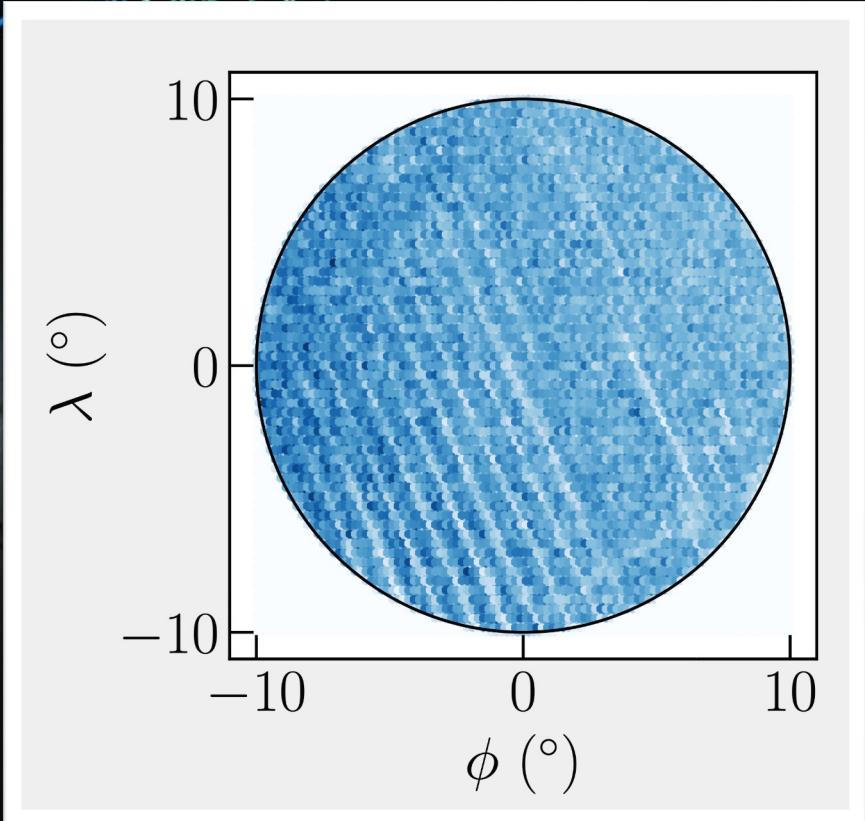
Need to increase statistics of streams



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

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

Build a Stream Finder Algorithm

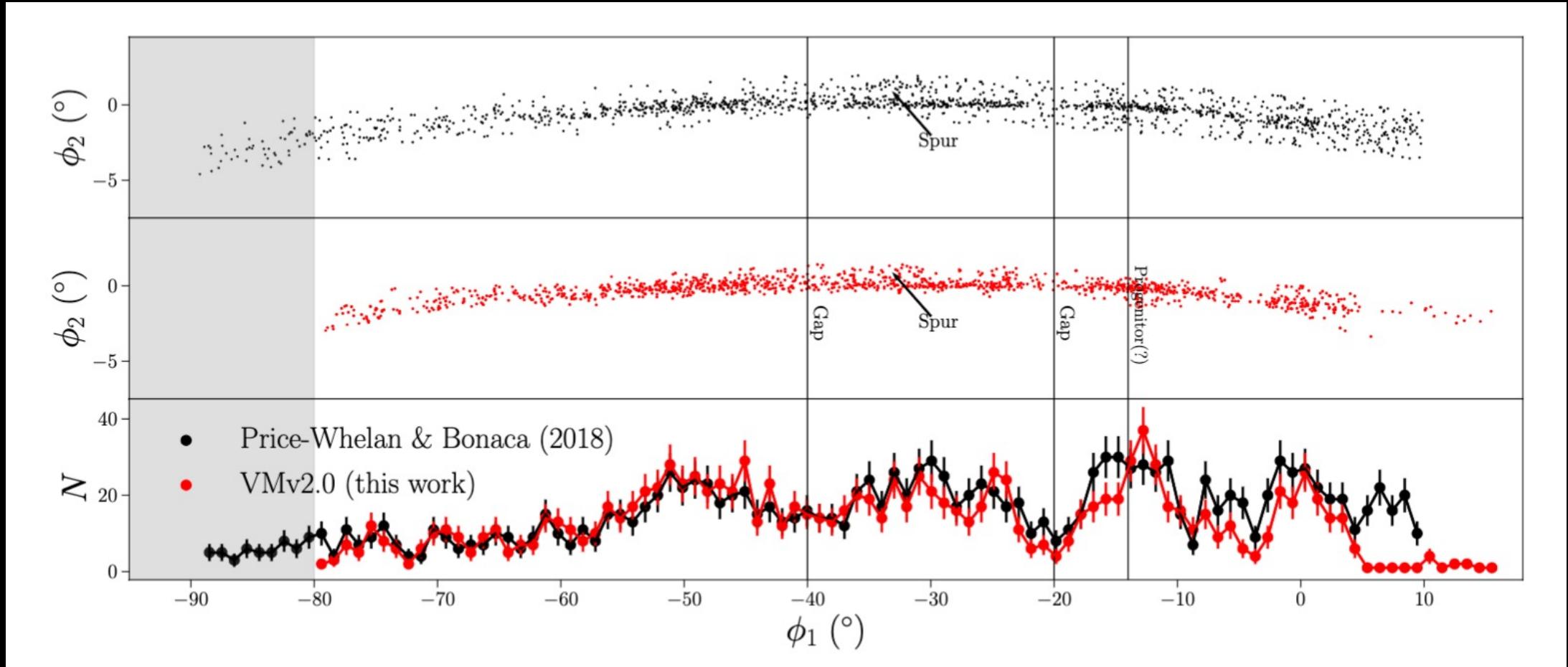


Galaxy Picture
Credit : ESA/Gaia/DPAC
Stellar Streams

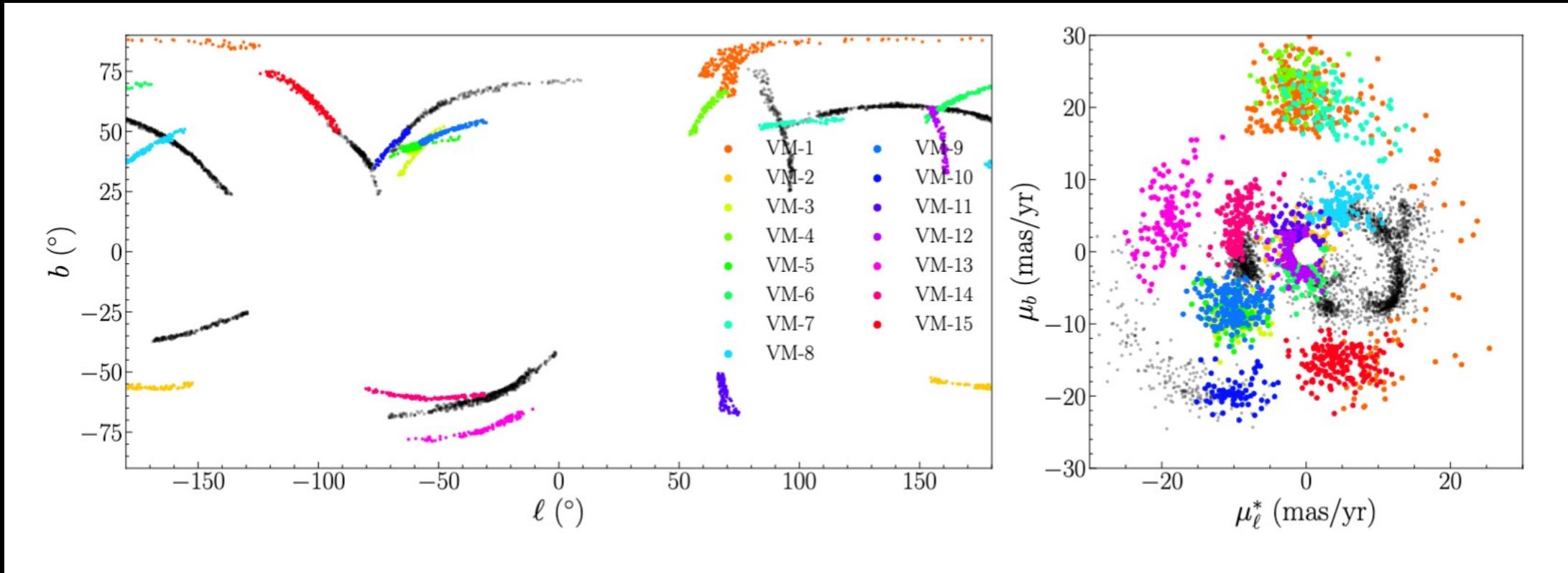
Malhan et al. (2018), Ibata et al. (2019)

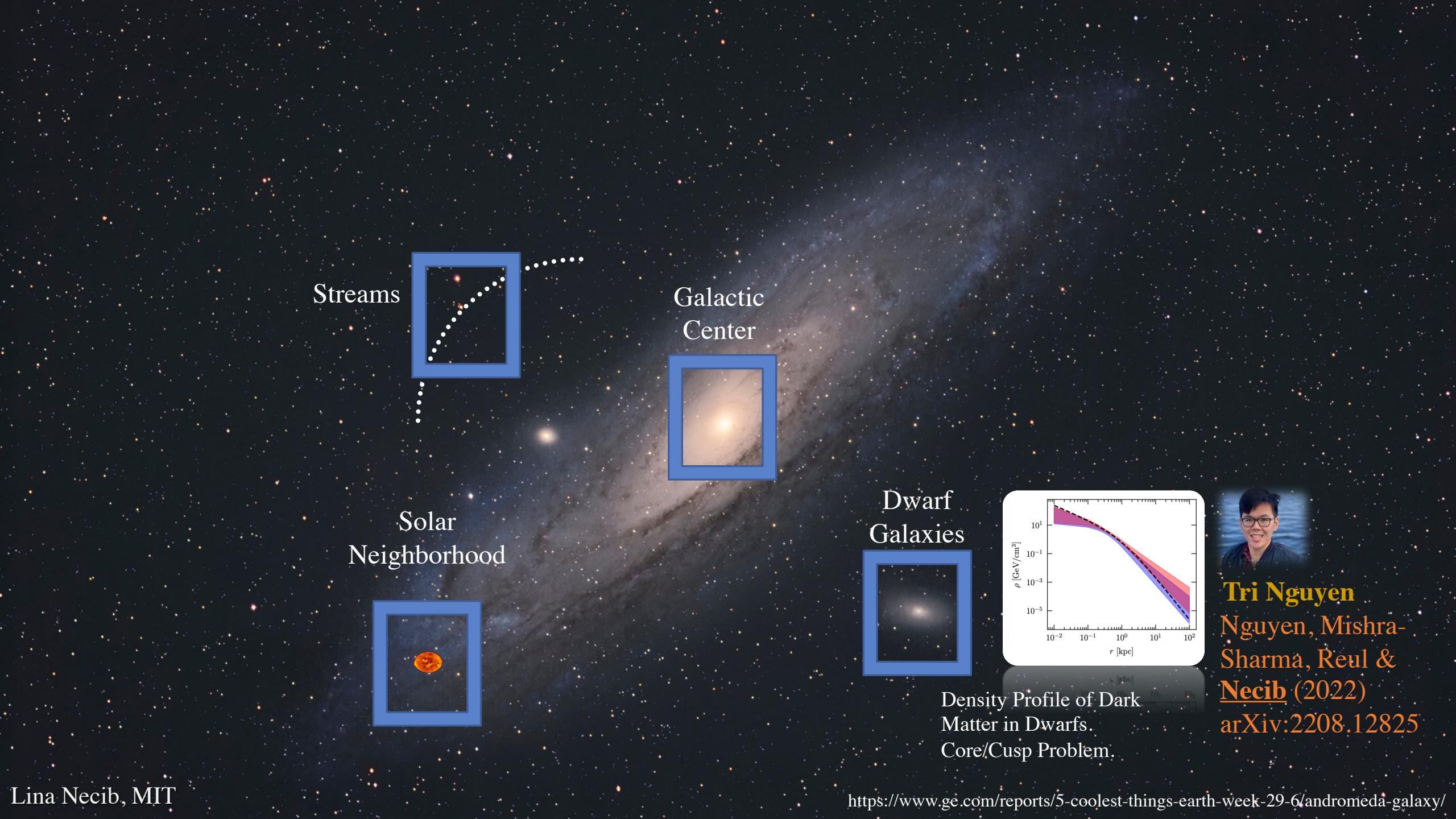
Shih, Buckley, **Necib**, Tamanas (2021)

Apply Via Machinae on GD-1



102 New Stream Candidates, 90 of which are expected to match stellar structures





Streams



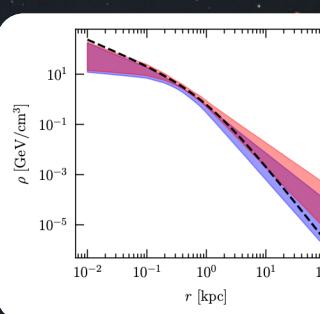
Galactic
Center



Solar
Neighborhood



Dwarf
Galaxies

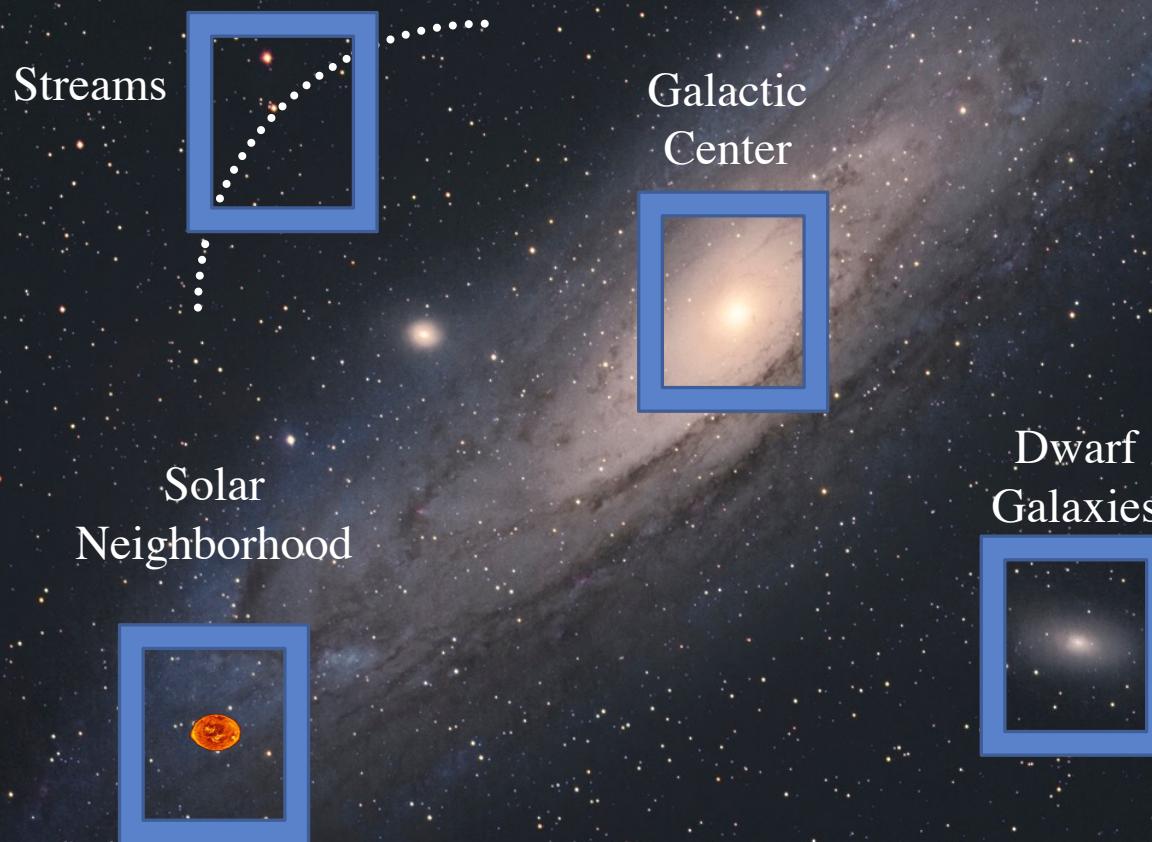


Density Profile of Dark
Matter in Dwarfs.
Core/Cusp Problem.

Tri Nguyen
Nguyen, Mishra-
Sharma, Reul &
Necib (2022)
arXiv:2208.12825

This Talk:

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





Survey for your thoughts
on the postdoc deadline
of January 7

Thank you!