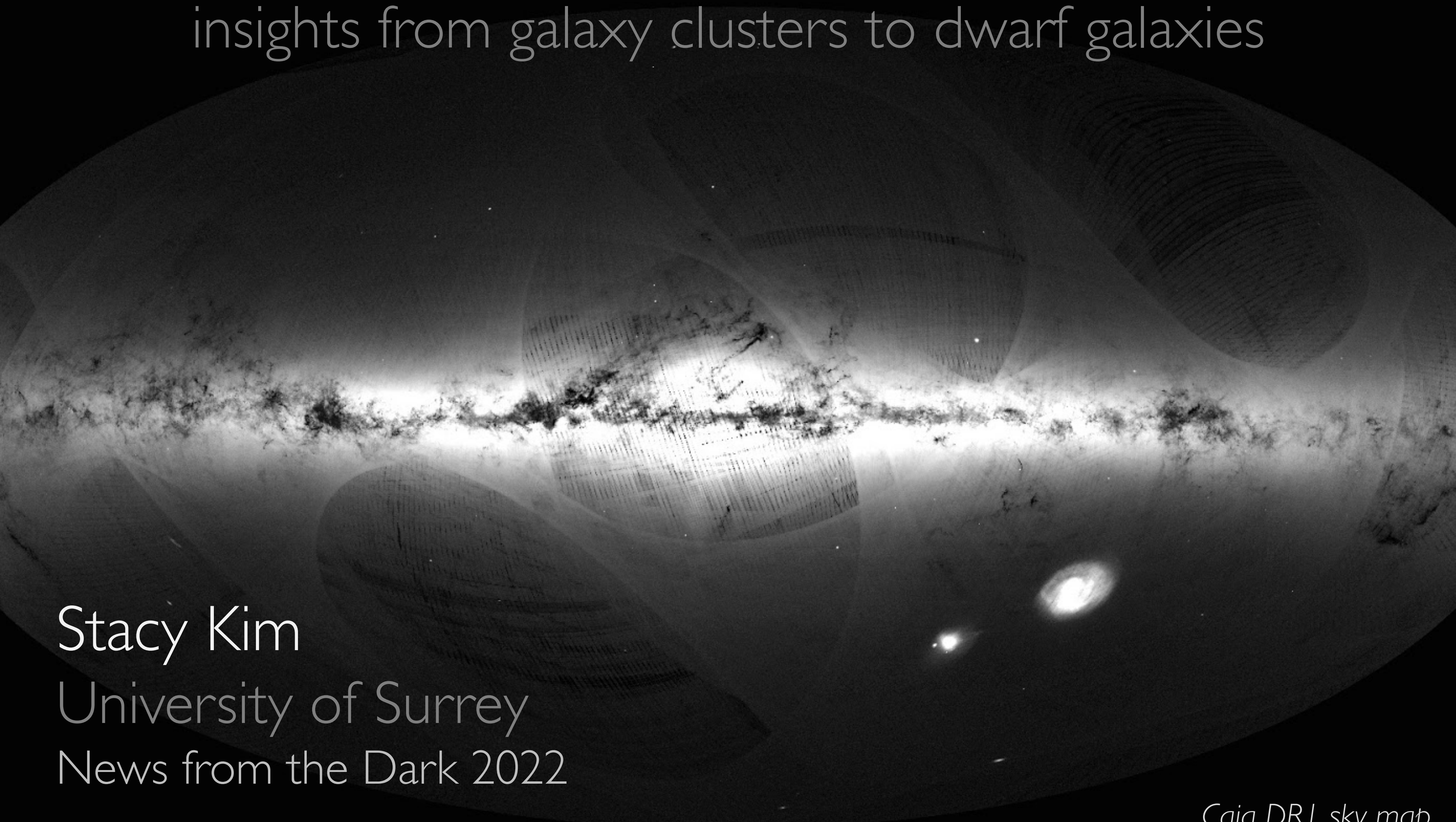
SIDM Subhalos

insights from galaxy clusters to dwarf galaxies



Stacy Kim
University of Surrey
News from the Dark 2022

Caia DR1 sky map

What is self-interacting dark matter? (SIDM)

Typically assumes dark matter is cold and collisionless.

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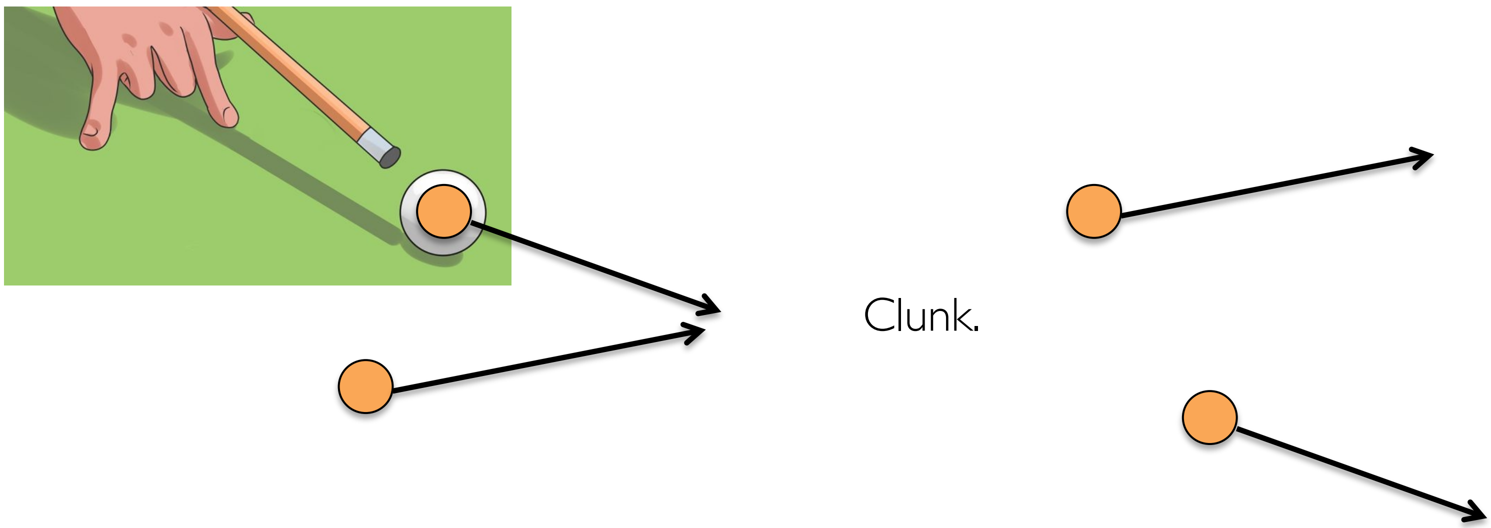

The simplest model possible: billard ball-type interactions

(elastic, isotropic, no dependence on interaction velocity, angle, etc.)

slide adapted from A. H. G. Peter

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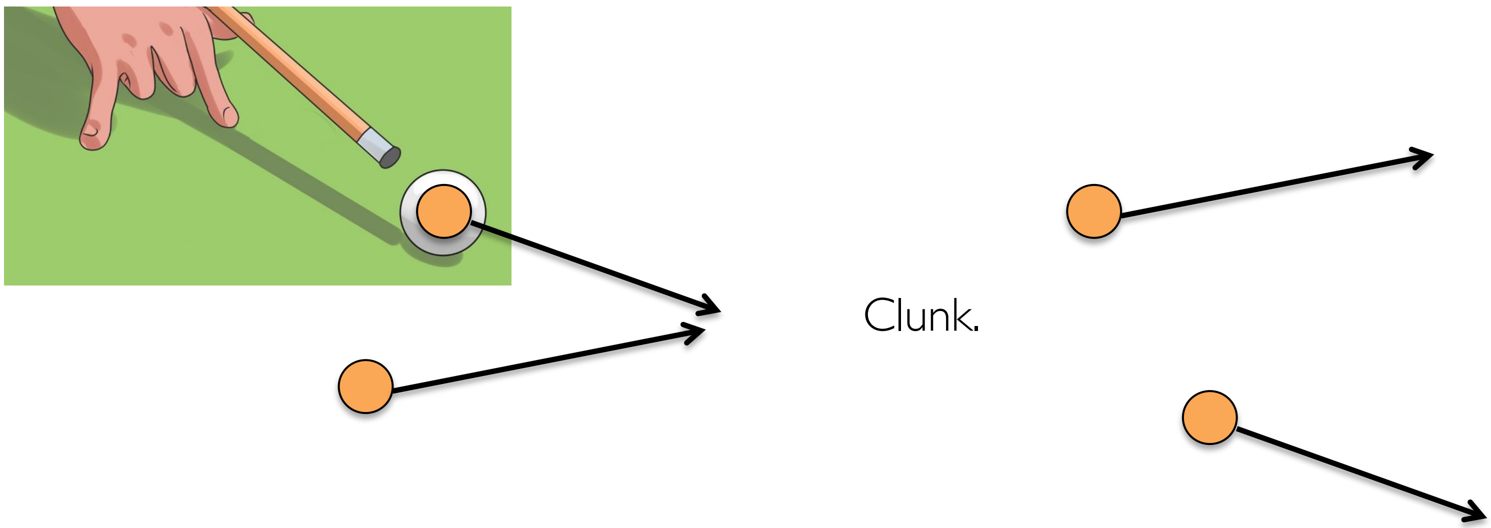

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Frequency of "self-interactions" parameterized by $\frac{\sigma_{\mathrm{SI}}}{m_\chi}$.

slide adapted from A. H. G. Peter

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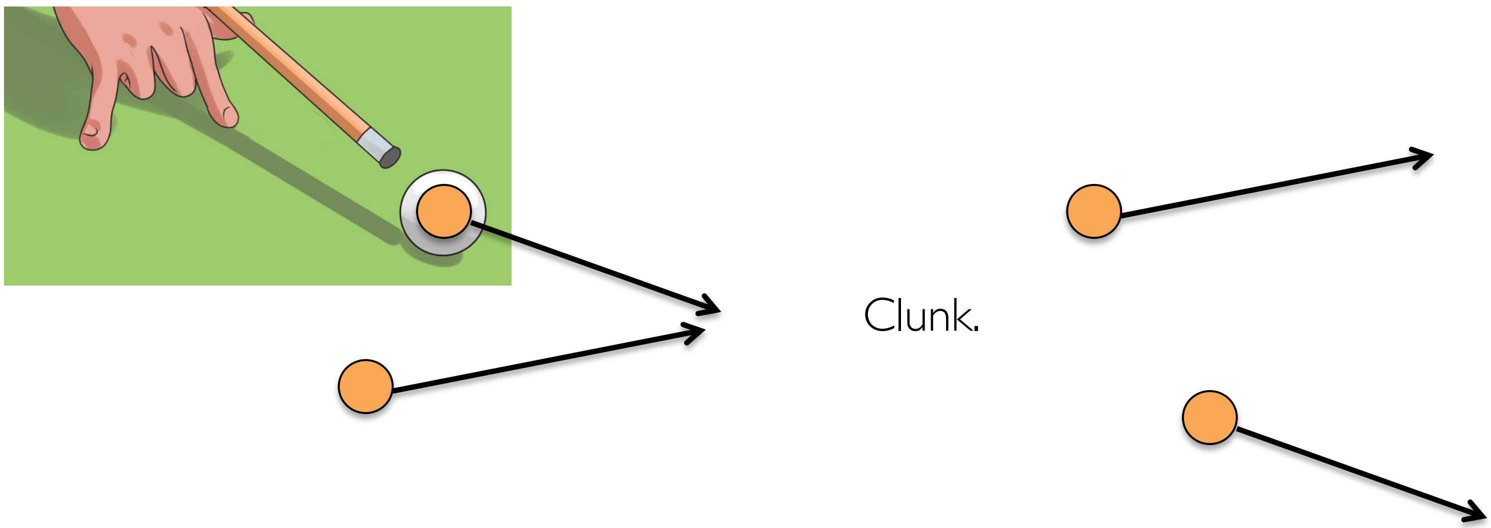

The simplest model possible: billard ball-type interactions
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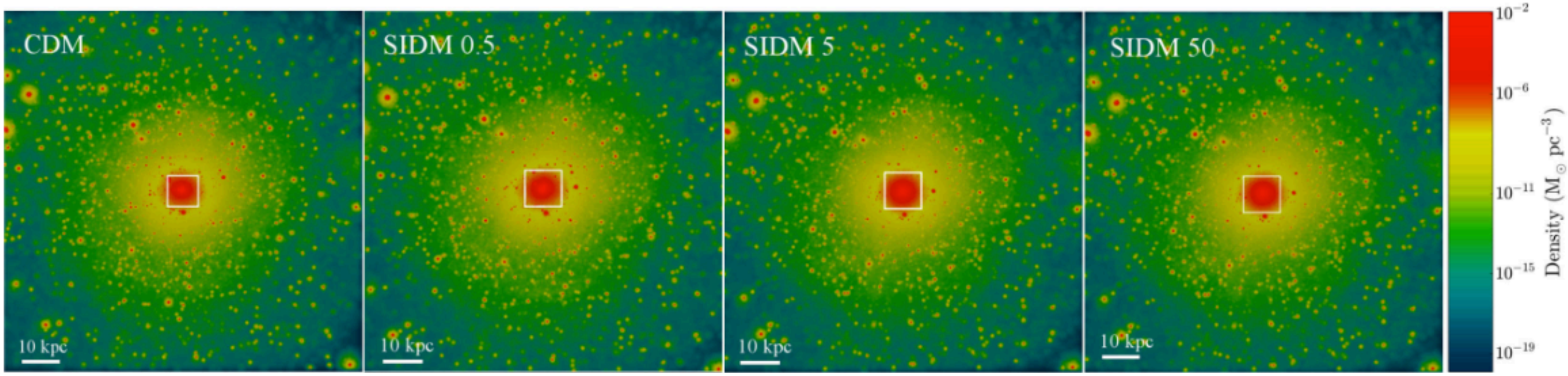
"constant cross section"

Frequency of "self-interactions" parameterized by $\frac{\sigma_{\rm SI}}{m_\chi}$.

slide adapted from A. H. G. Peter

What is self-interacting dark matter? (SIDM)

number and positions of subhalos don't change…



$M_{vir}=10^{10}\ M_\odot$; *Elbert+ 2015*

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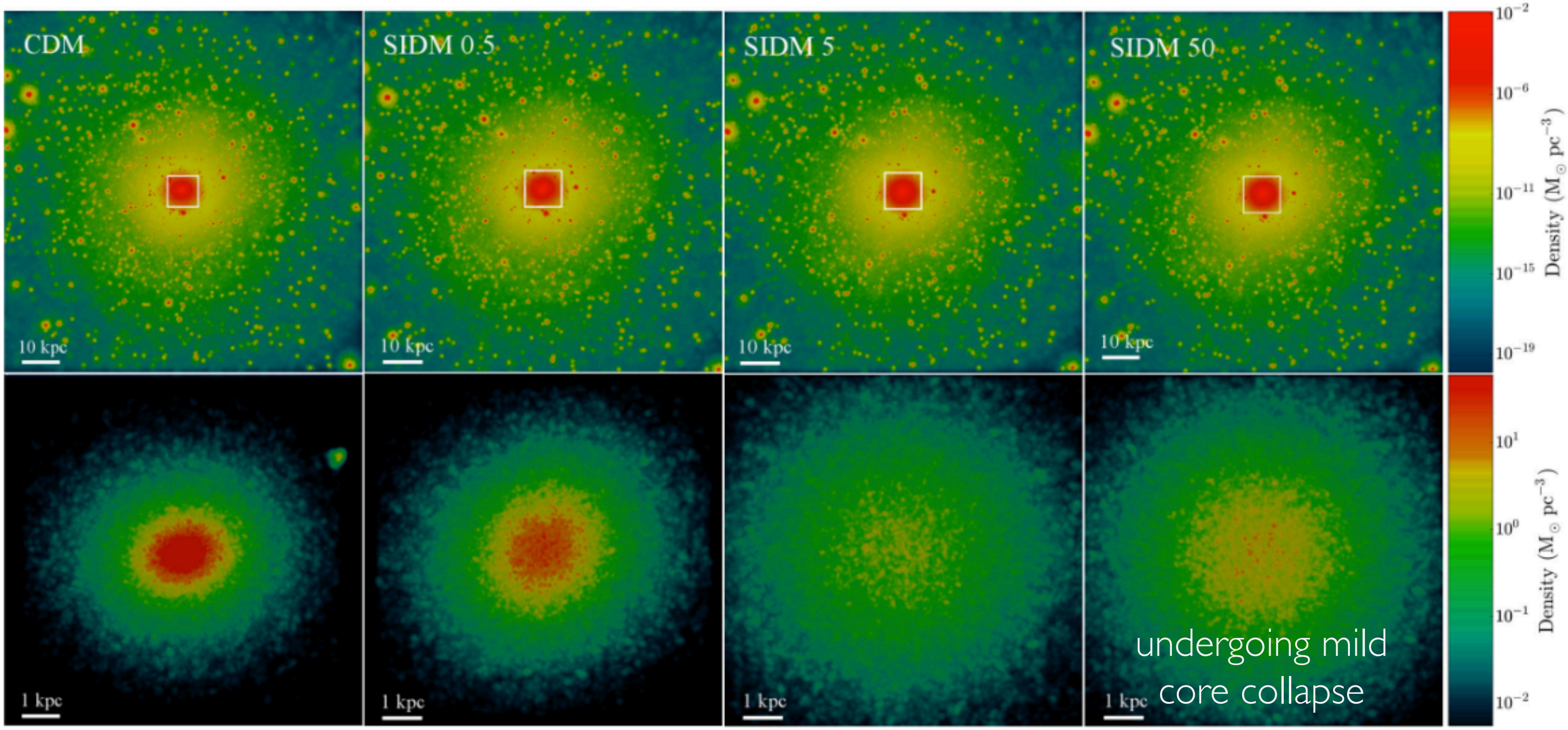

but forms low-density central cores!

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Key SIDM prediction: low density central cores

Robles+ 2017

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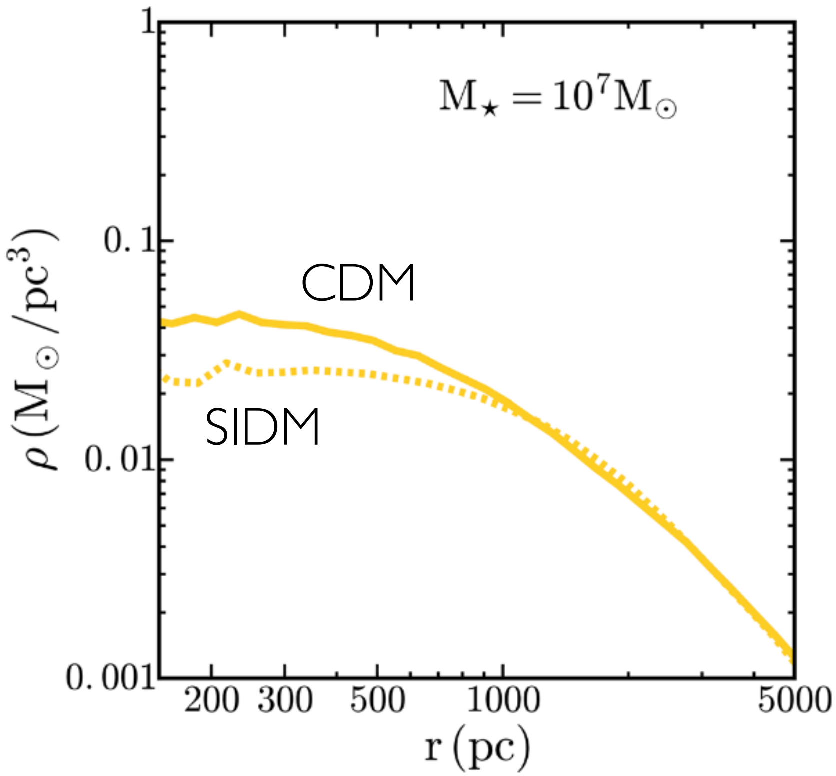
BUT SIDM is not the only method to create cores…



Hydro sims show cores form via baryonic feedback in CDM

Robles+ 2017

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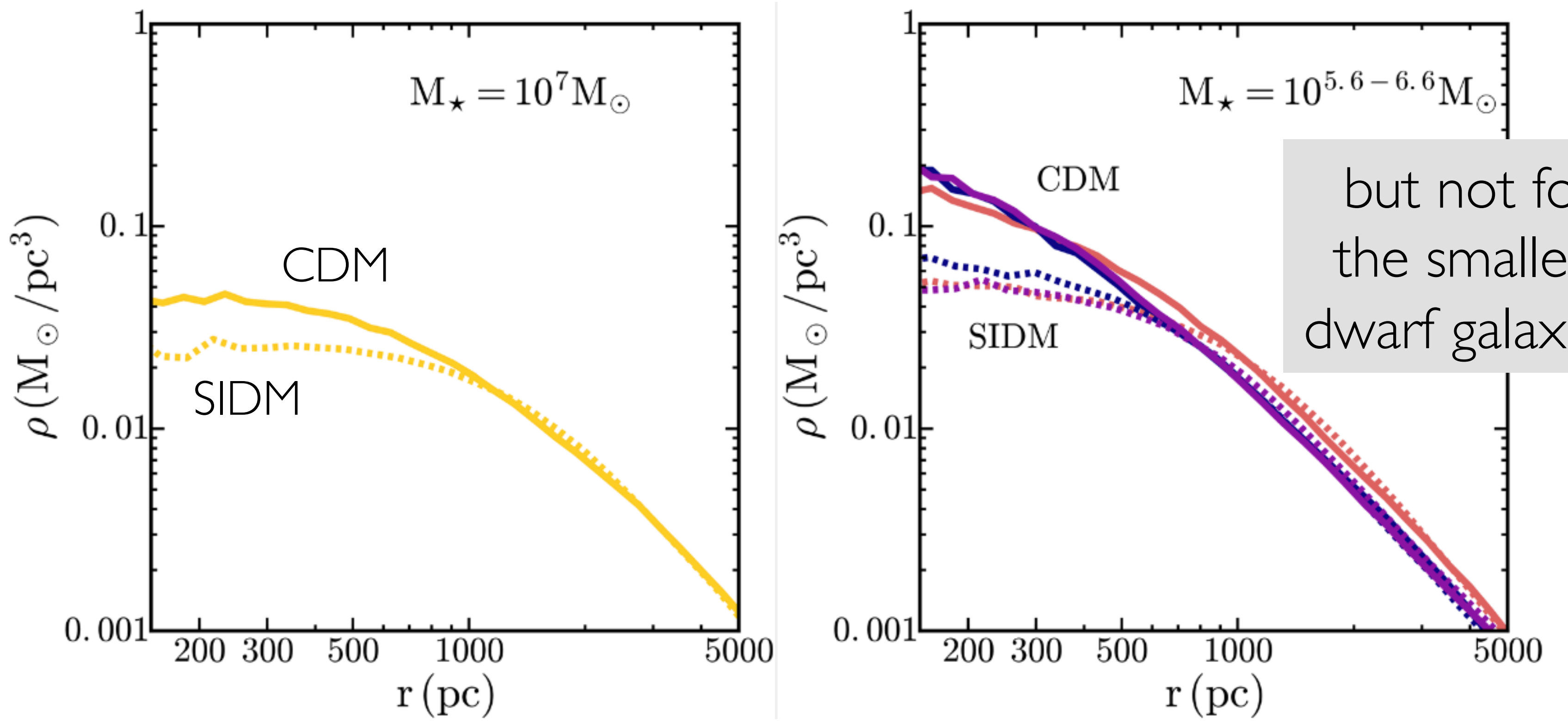
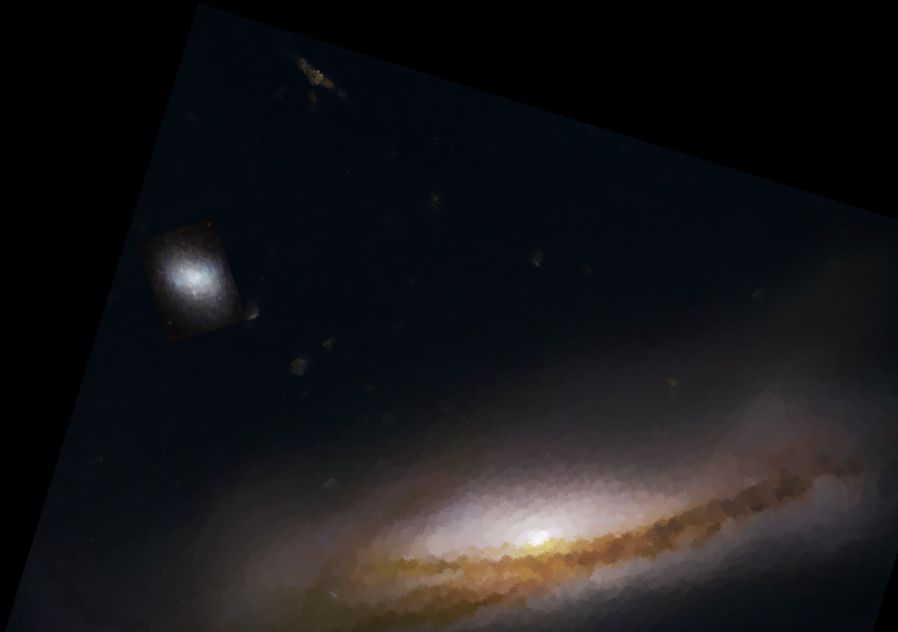


but not for the smallest dwarf galaxies!

Hydro sims show cores form via baryonic feedback in CDM

Robles+ 2017

constraining SIDM via satellite kinematics



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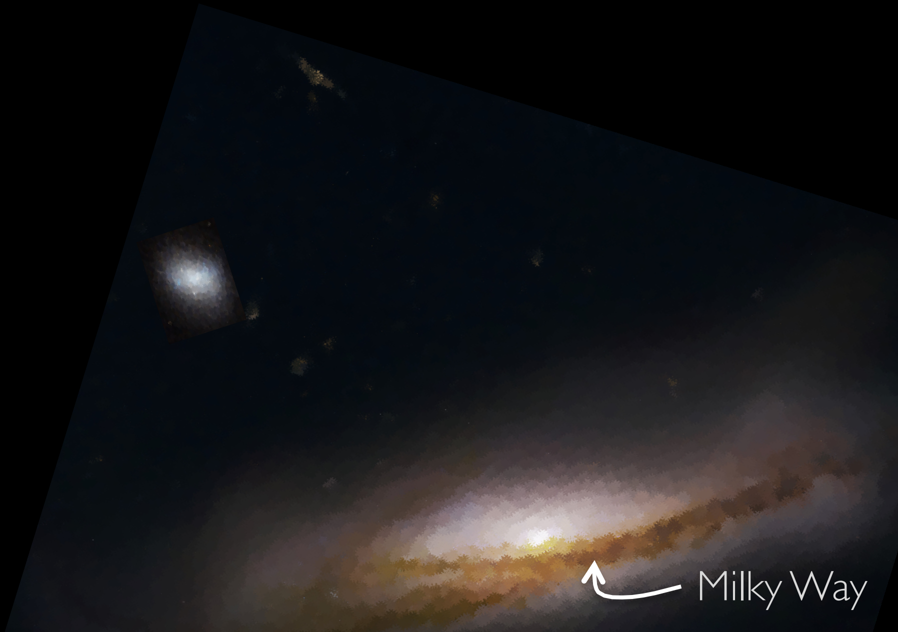

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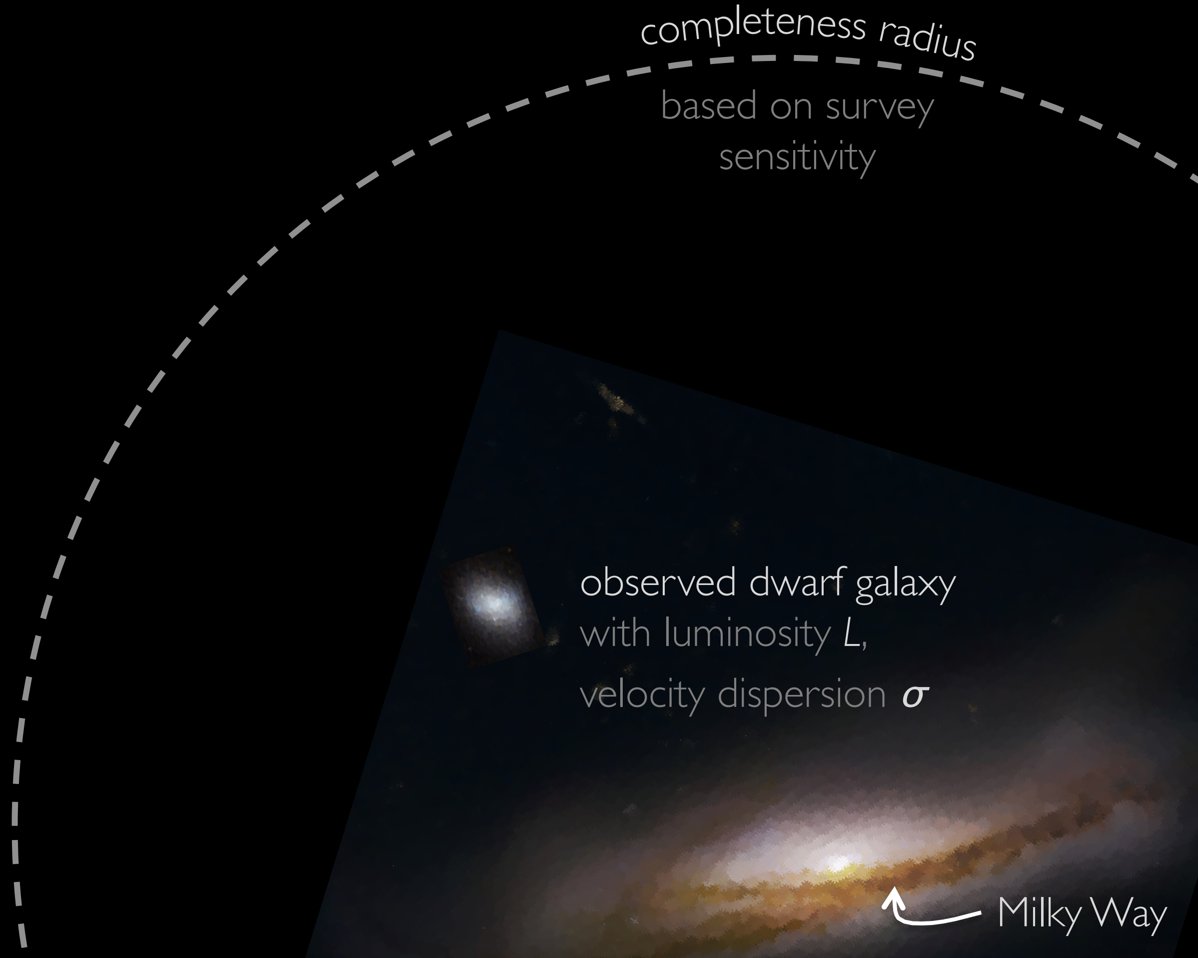

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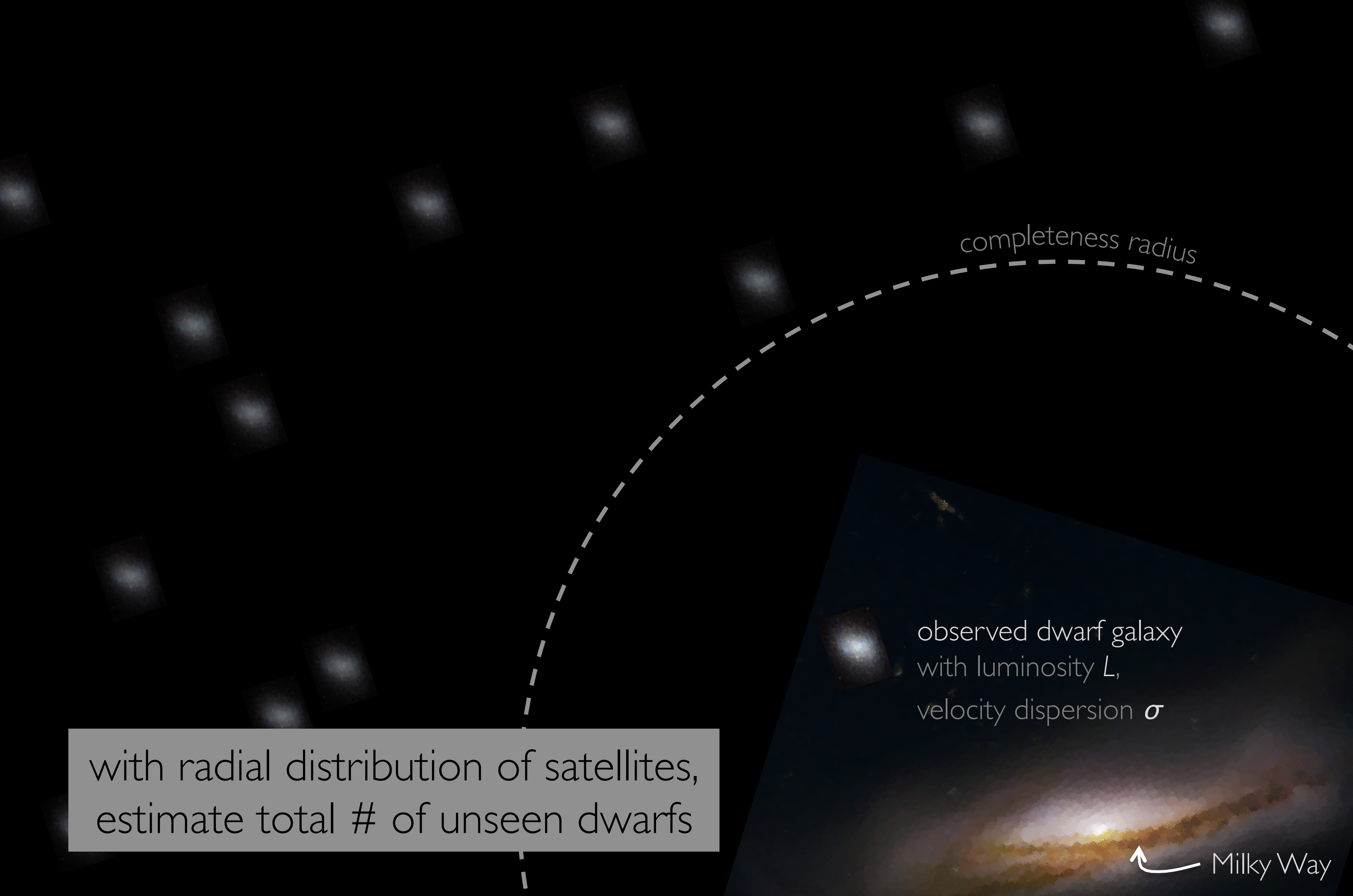
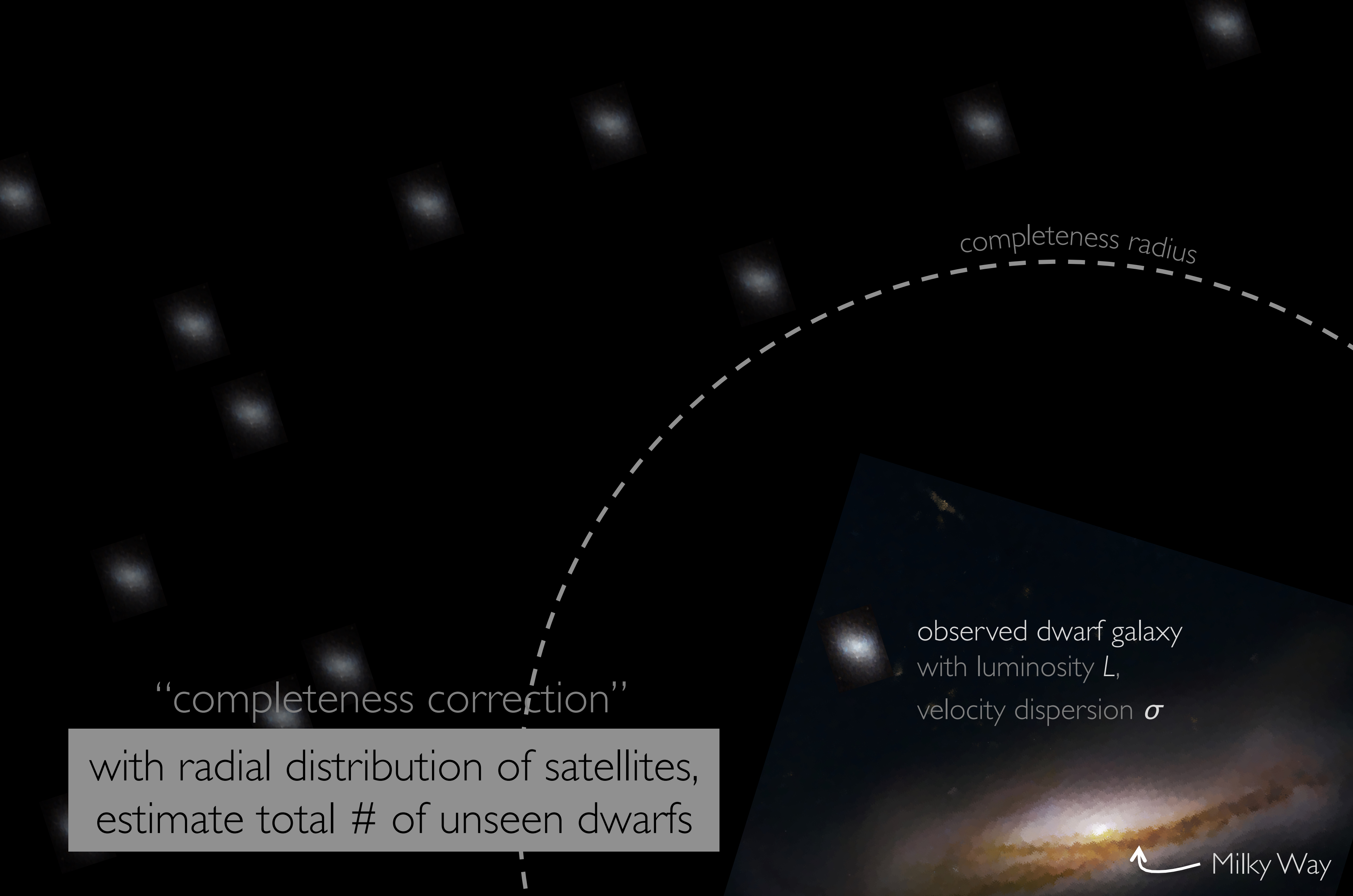


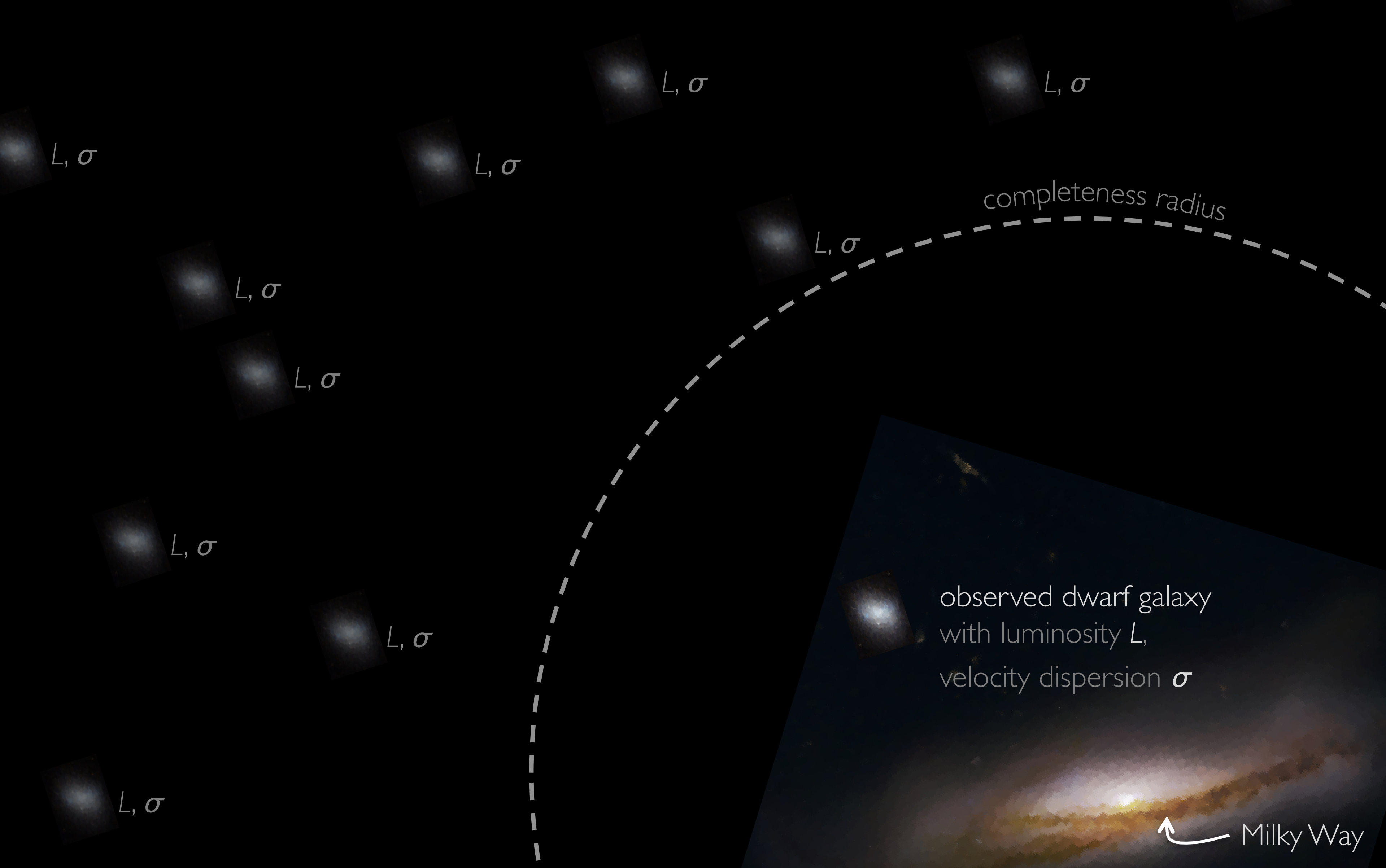
with radial distribution of satellites,
estimate total # of unseen dwarfs

constraining SIDM via satellite kinematics



constraining SIDM via satellite kinematics

with completeness corrections



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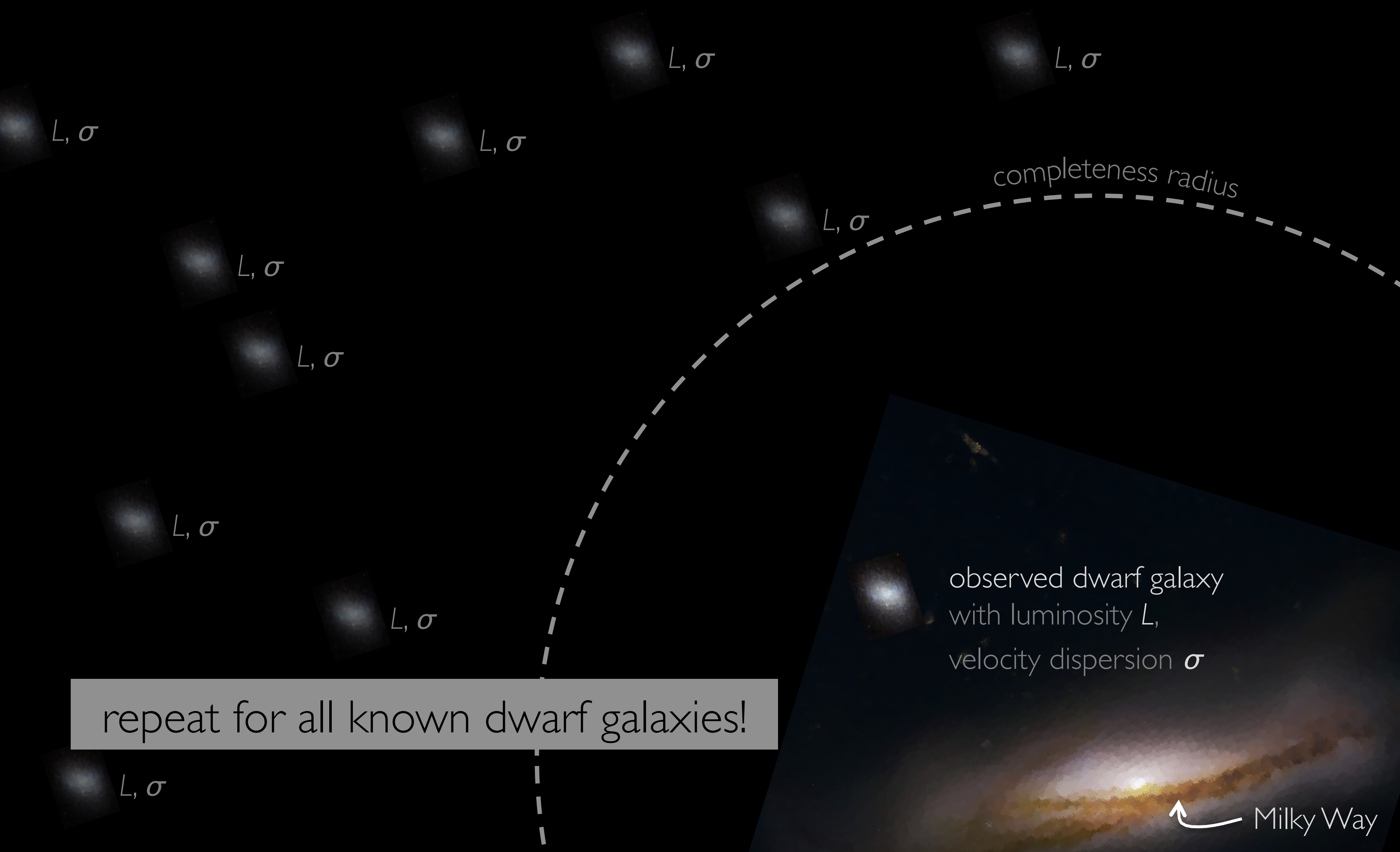

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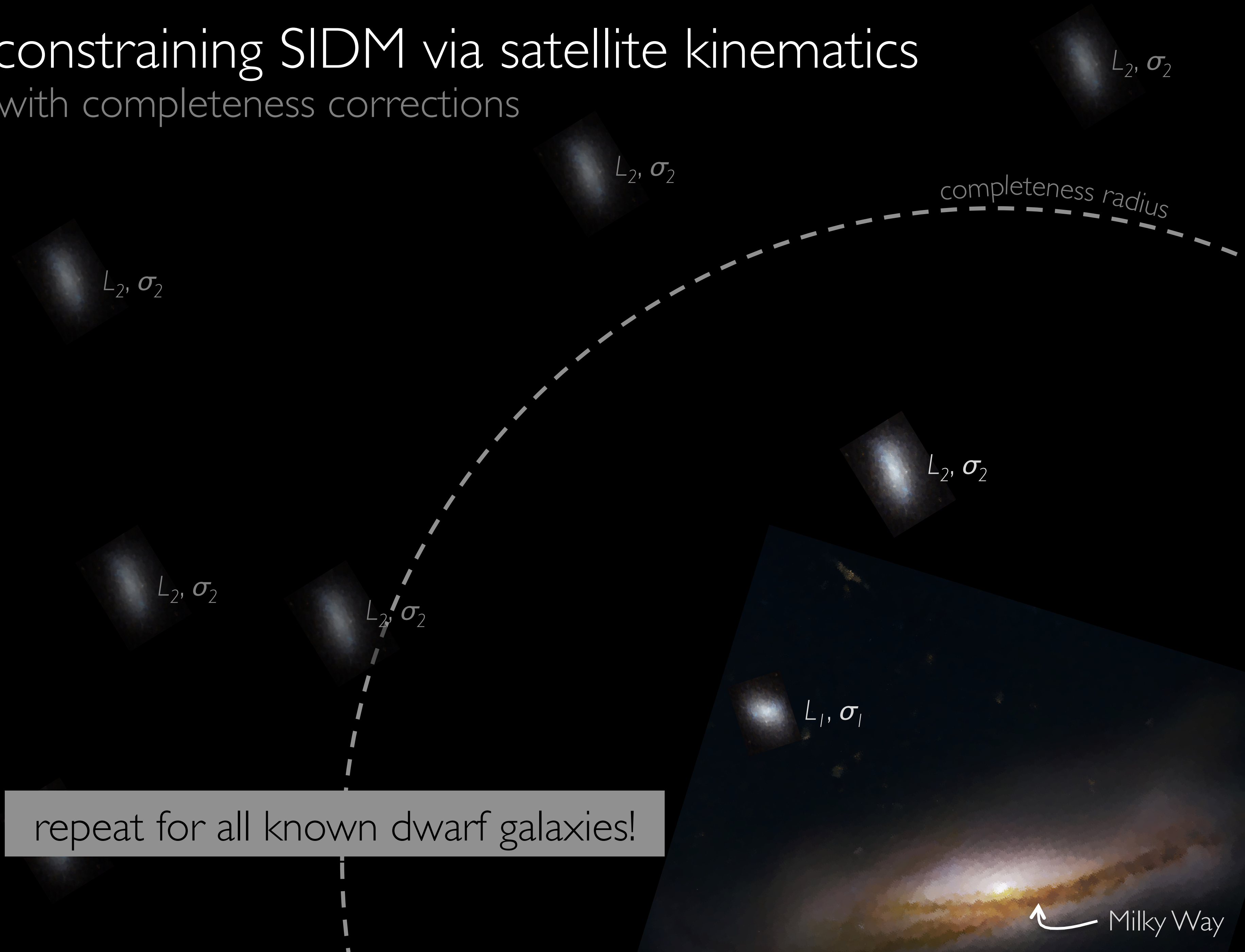


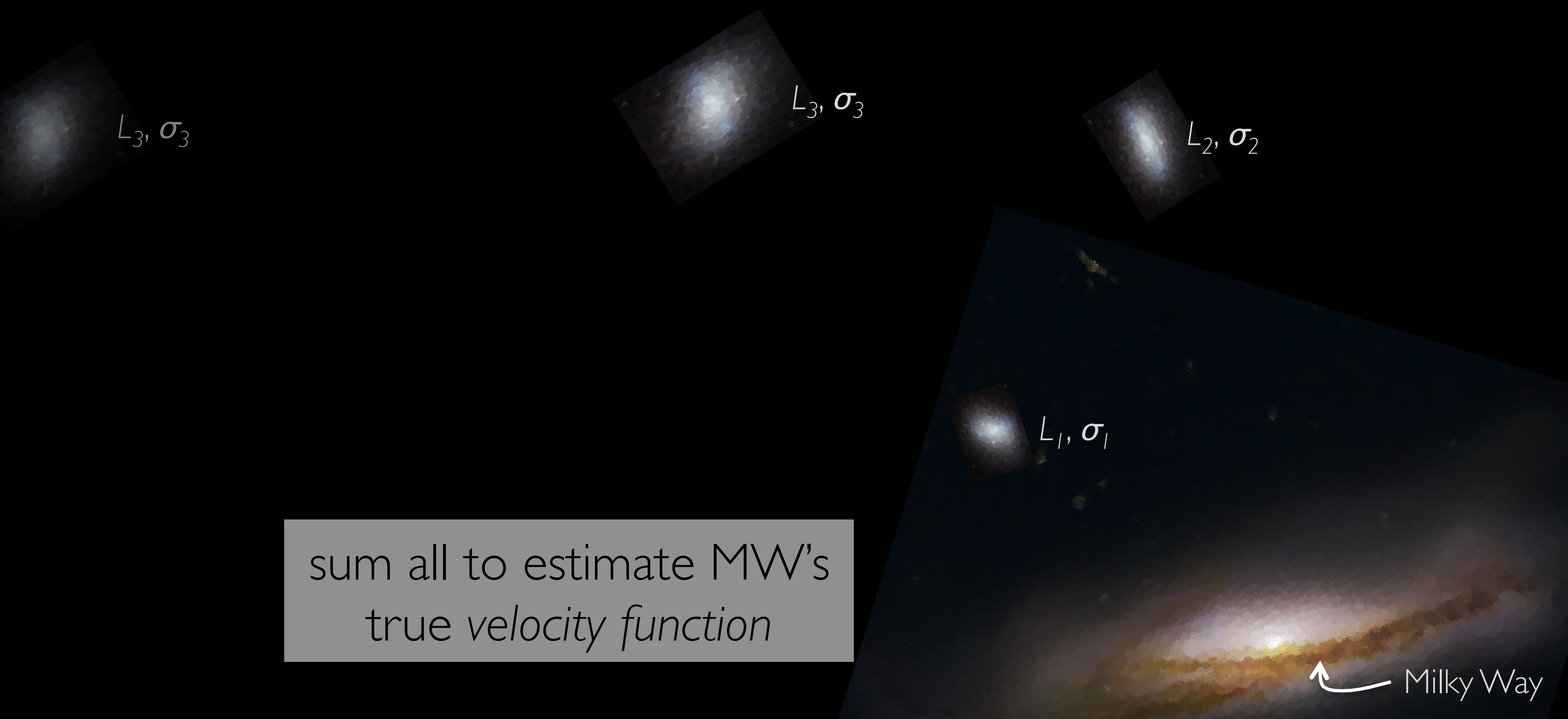
constraining SIDM via satellite kinematics

with completeness corrections

repeat for all known dwarf galaxies!

constraining SIDM via satellite kinematics

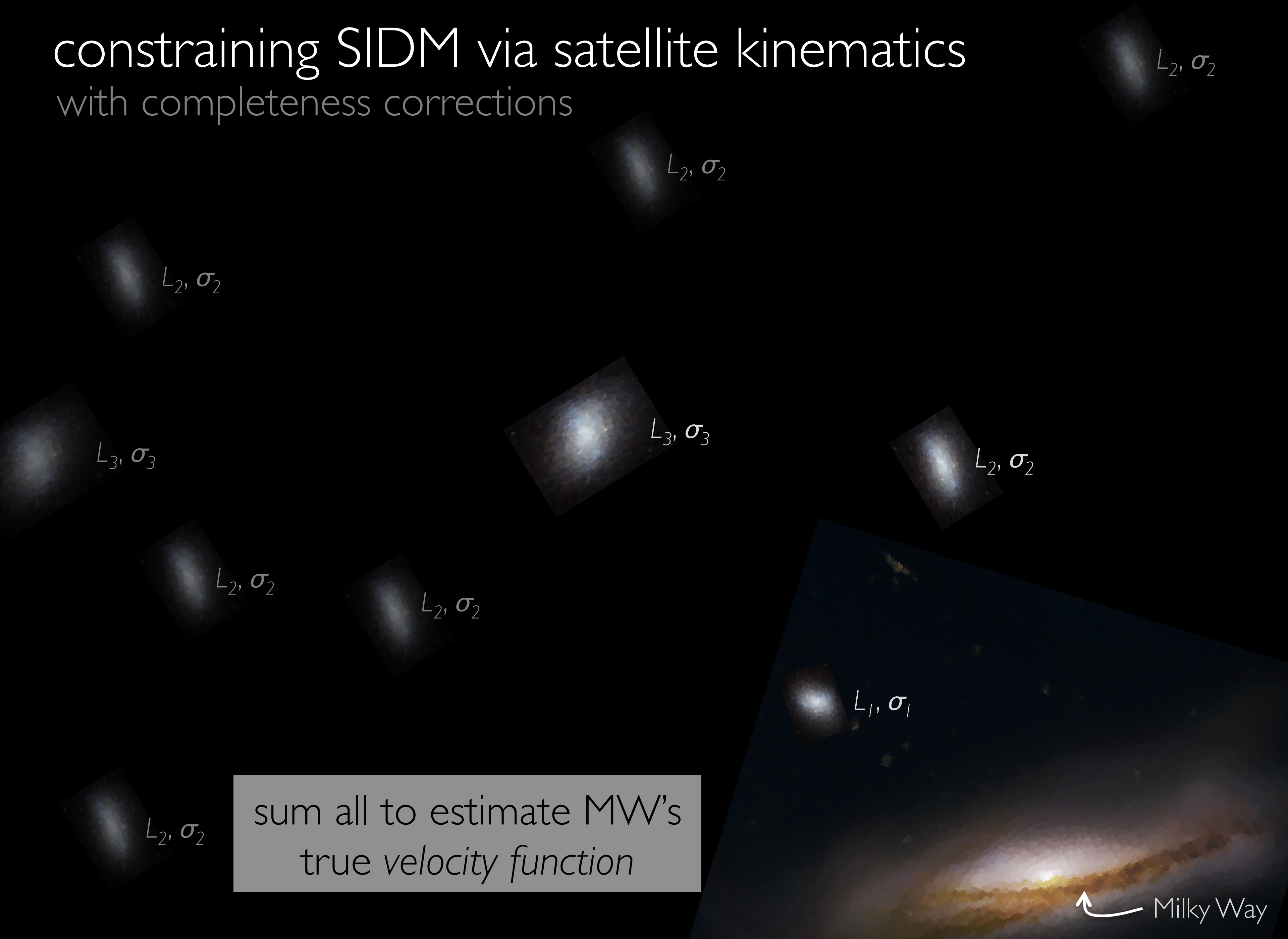
with completeness corrections



sum all to estimate MW's true *velocity function*

constraining SIDM via satellite kinematics

with completeness corrections



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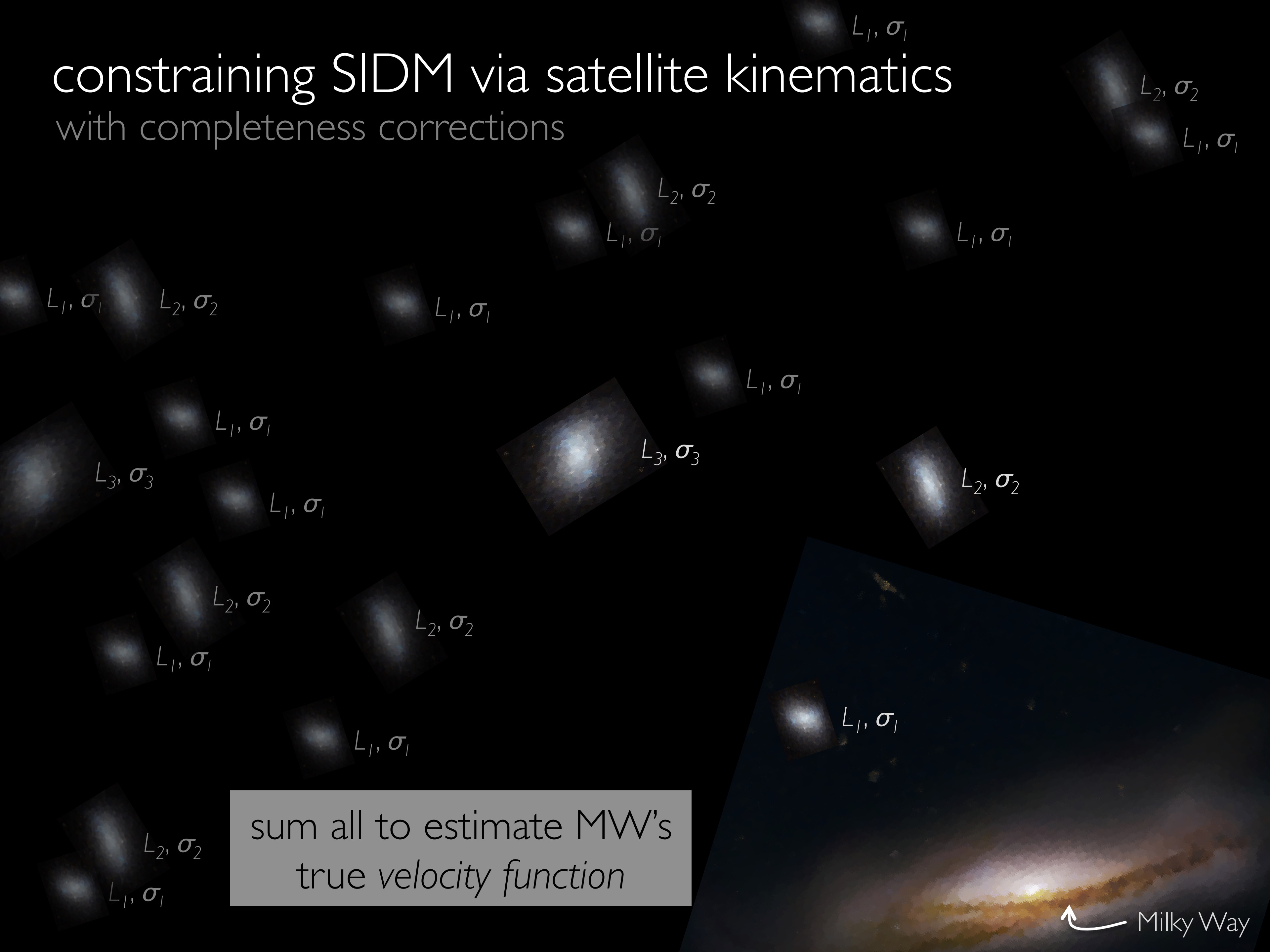
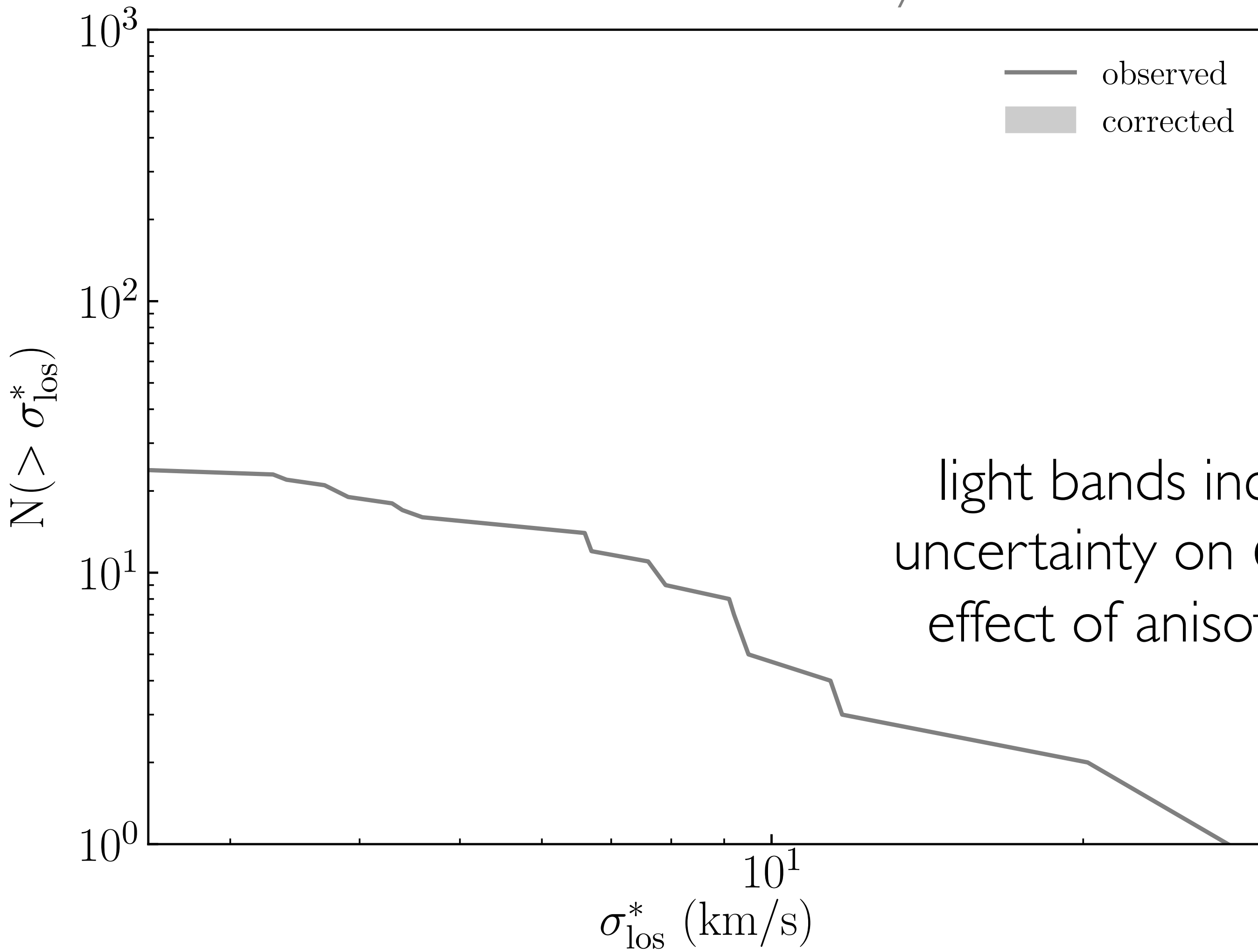


sum all to estimate MW's true *velocity function*

corrected velocity function

for satellites discovered by SDSS



light bands include uncertainty on σ_* and effect of anisotropy

Kim et al. 2022 (arXiv:2106.09050)

corrected velocity function

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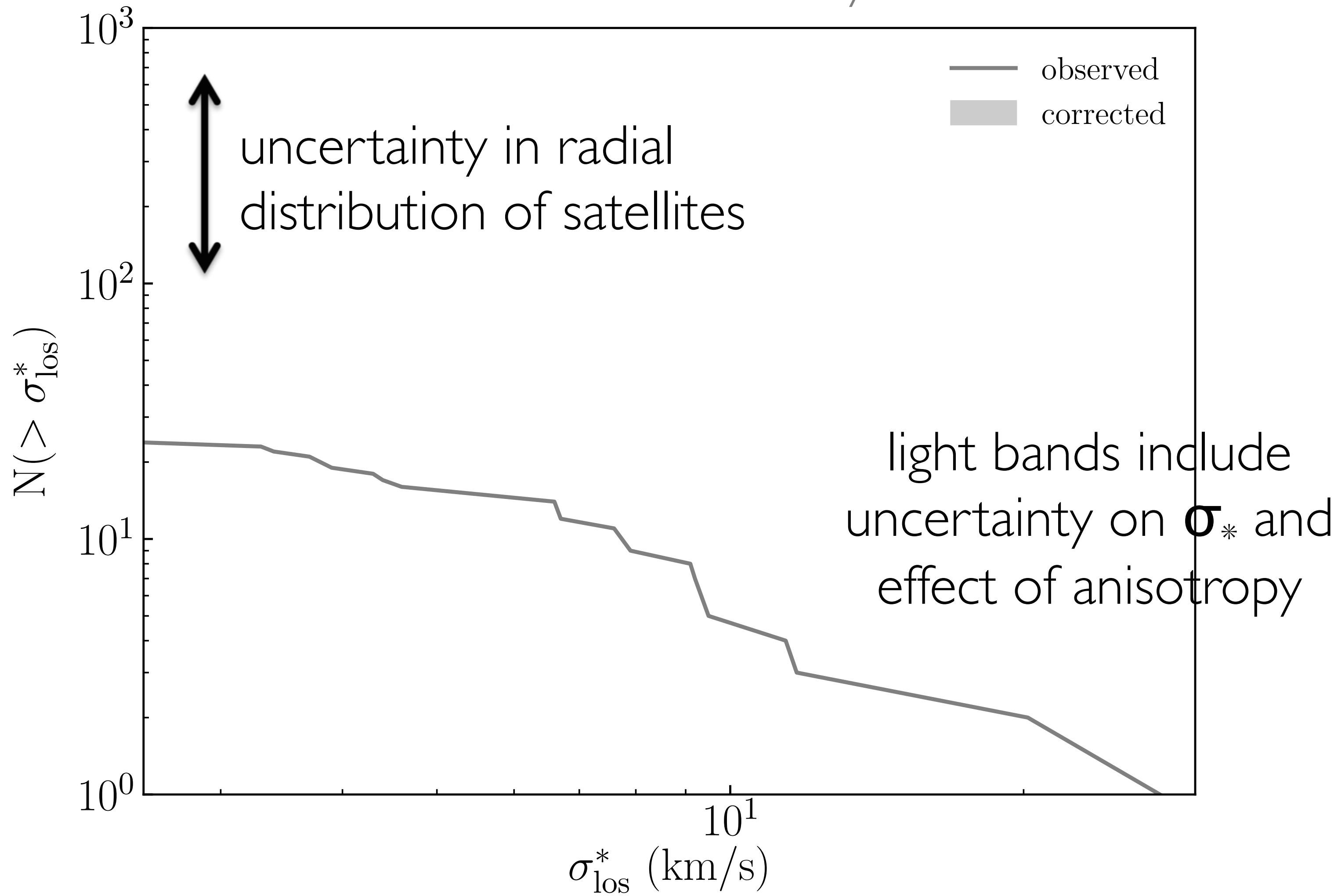

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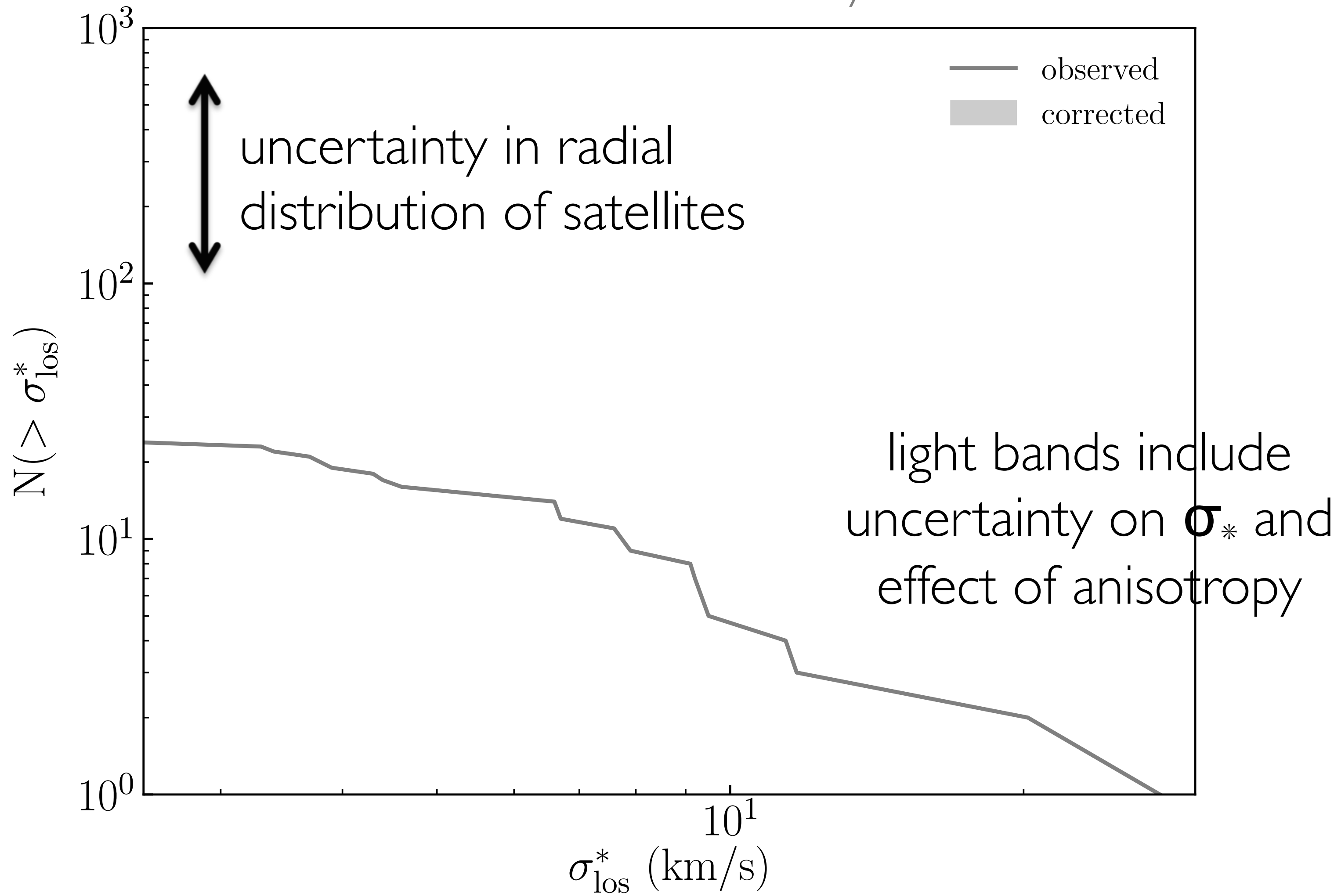

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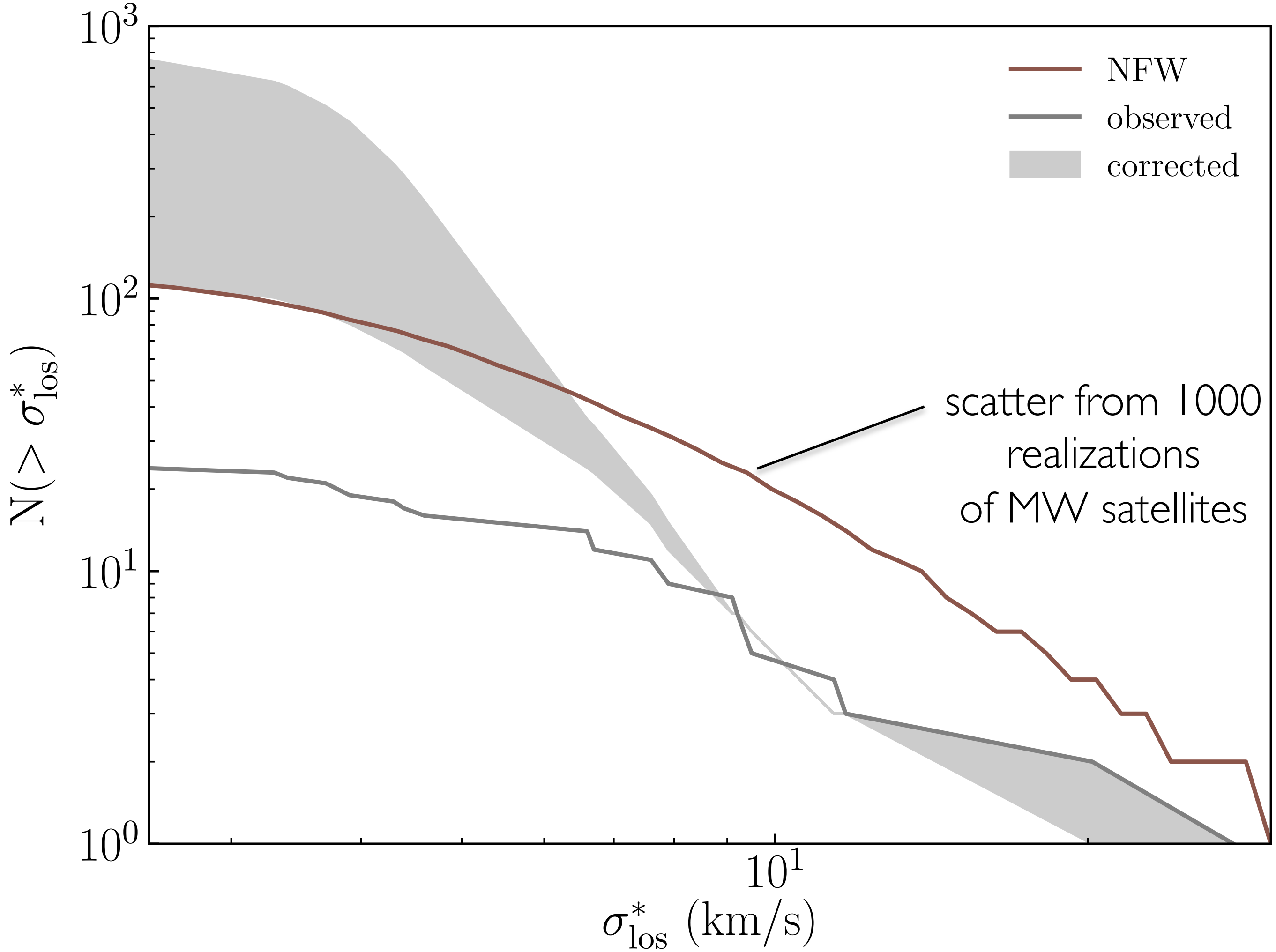
theory vs. observations



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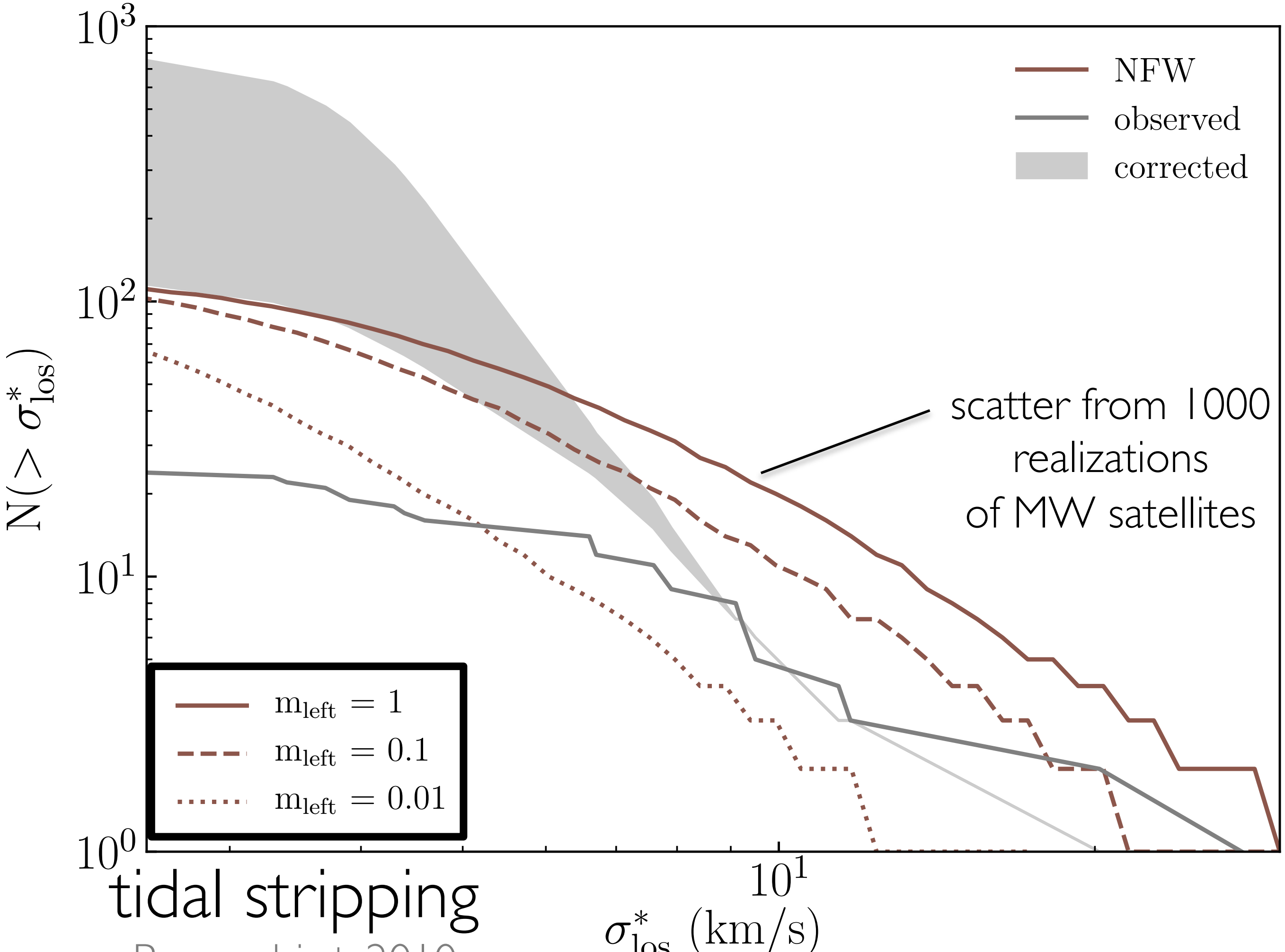
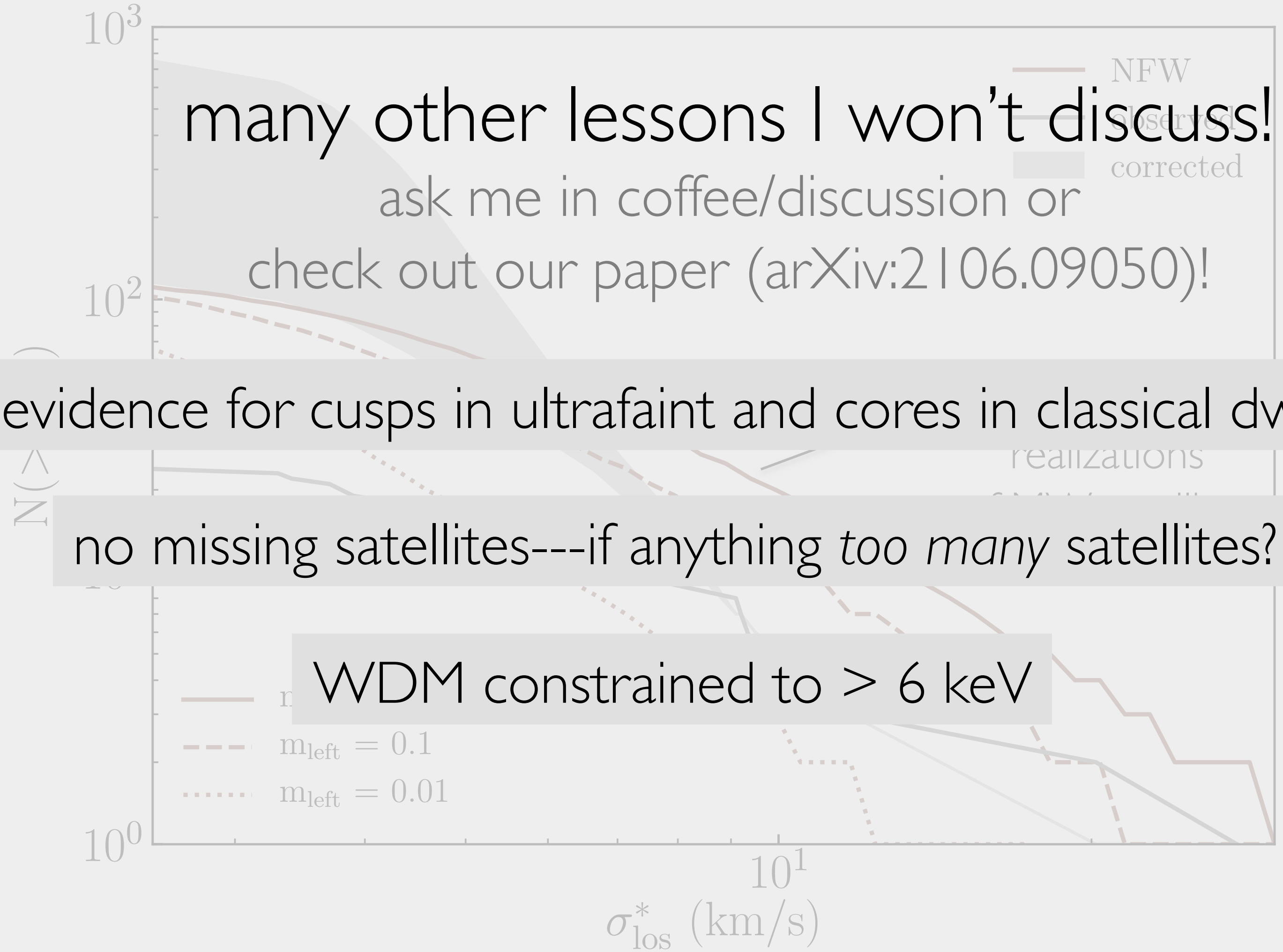


tidal stripping

Penarrubia+ 2010

Kim et al. 2022 (arXiv:2106.09050)

theory vs. observations



many other lessons I won't discuss!

ask me in coffee/discussion or
check out our paper (arXiv:2106.09050)!

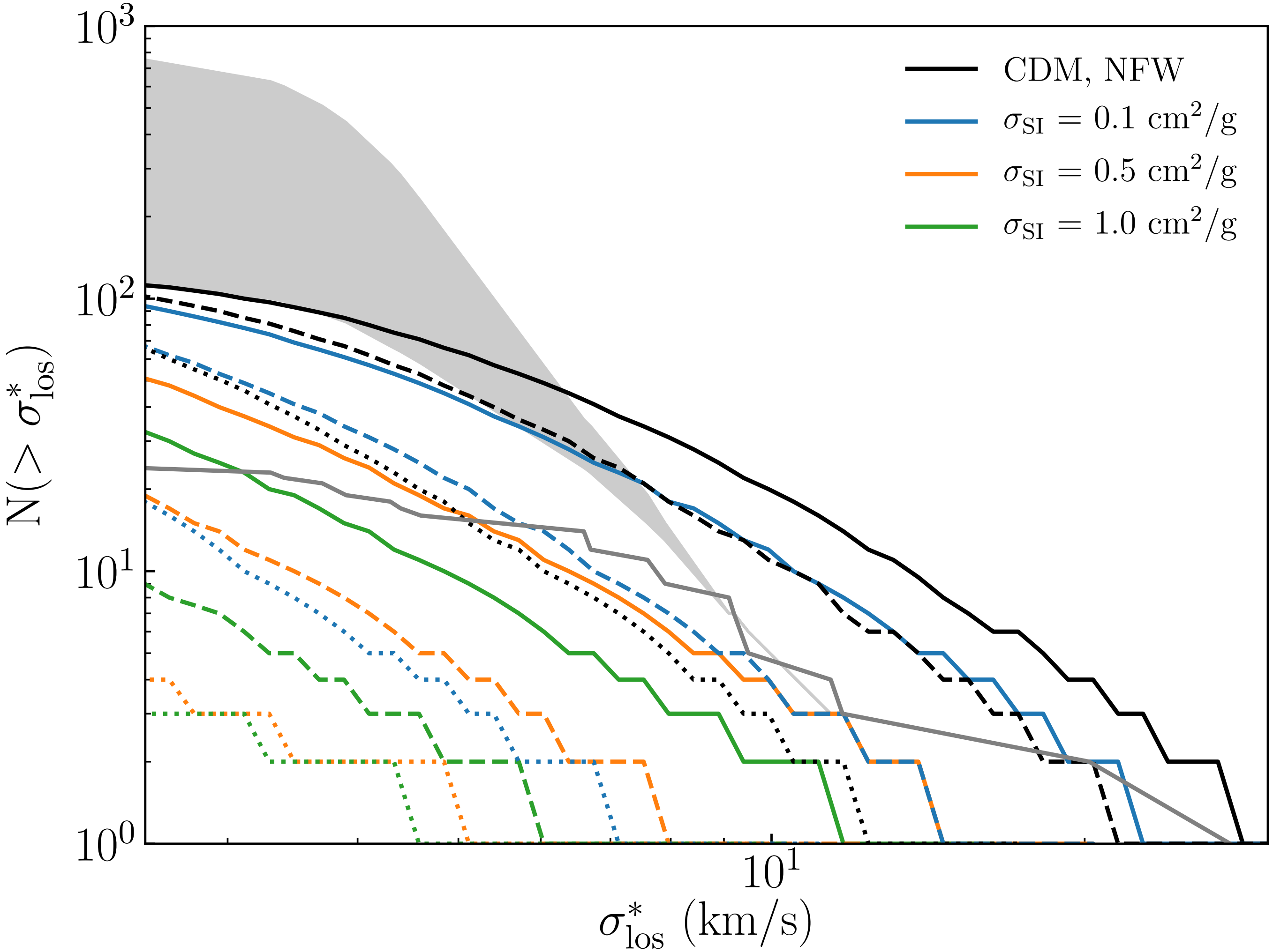
evidence for cusps in ultrafaint and cores in classical dwarfs

no missing satellites---if anything *too many* satellites?

WDM constrained to > 6 keV

Kim et al. 2022 (arXiv:2106.09050)

implications for self-interactions



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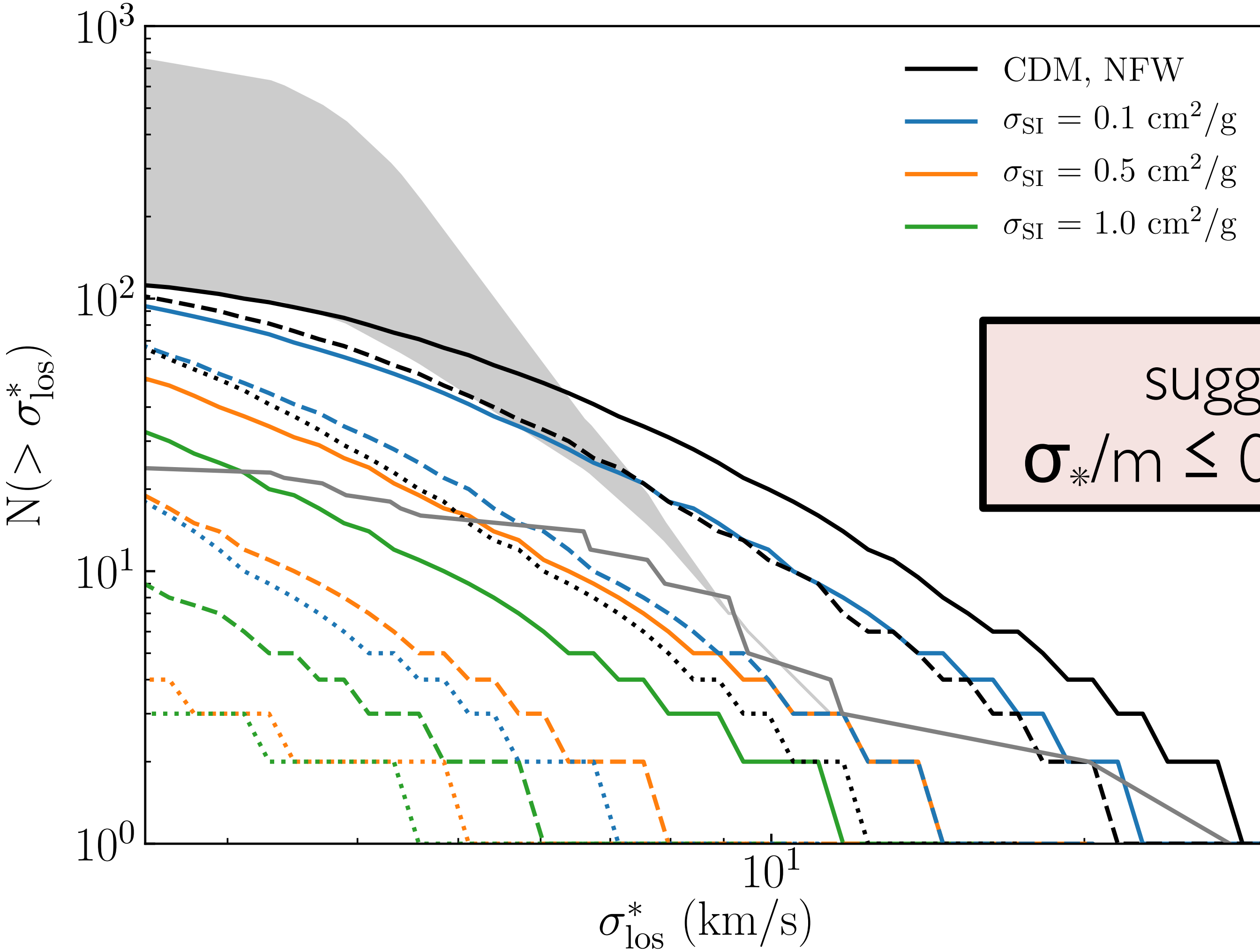


suggests
$\sigma_*/m \lesssim 0.3\ cm^2/g$!

Kim et al. 2022 (arXiv:2106.09050)

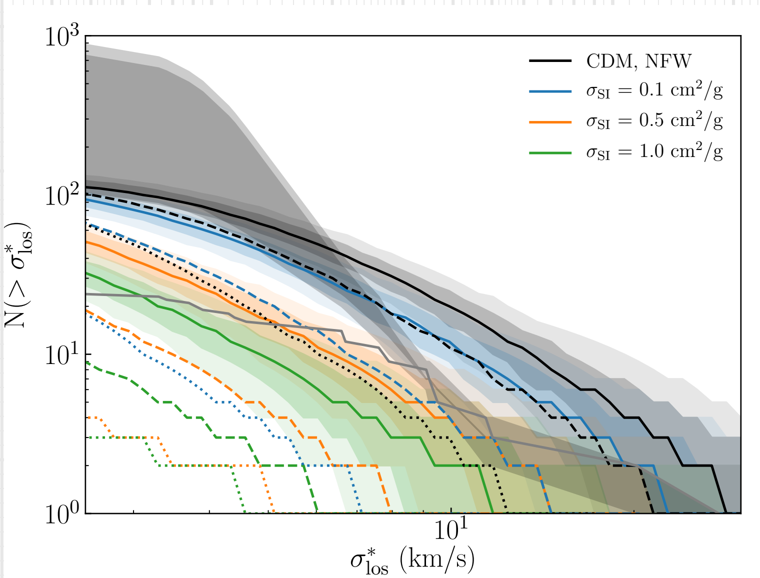
the picture for constant cross sections

dwarfs

halo mass ($M_\odot$)

≤ 0.3 cm²/g

10^{11} 10^{12} 10^{13} 10^{14}



MW velocity function

Kim & Peter 2022

the picture for constant cross sections

dwarfs — *halo mass ($M_\odot$)*

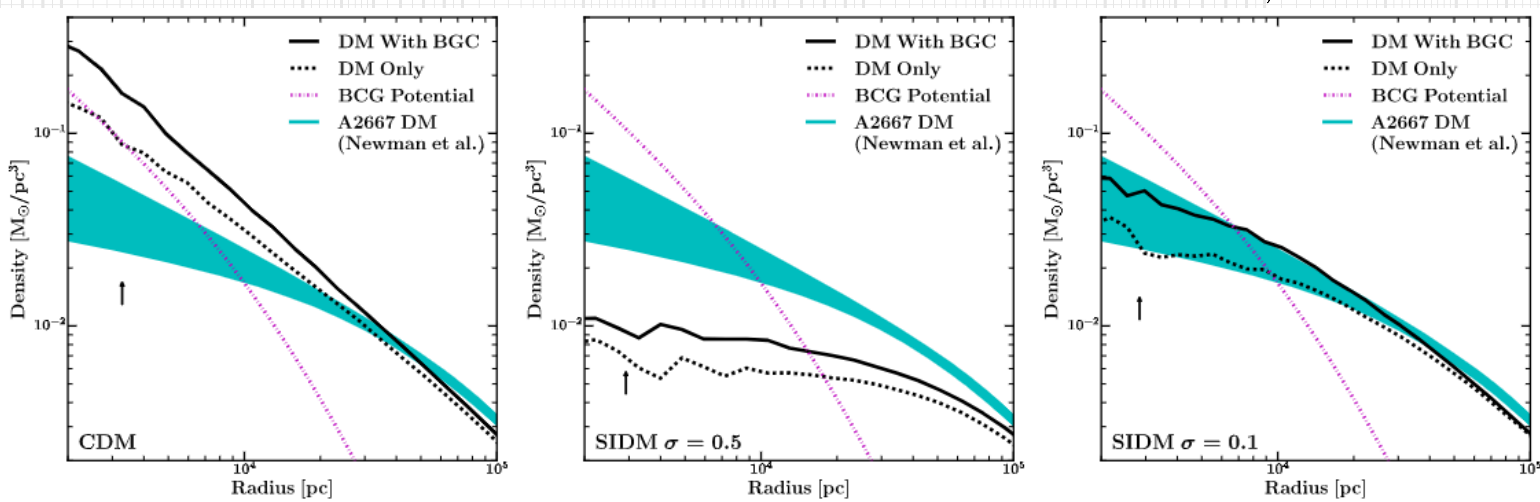
$\lesssim 0.3$ cm²/g — 10^{11} — 10^{12} — 10^{13} — 10^{14}

BCG offsets

Kim+ 2017, Harvey+ 2019, Fischer+ 2022

galaxy clusters:
O(0.1) cm²/g

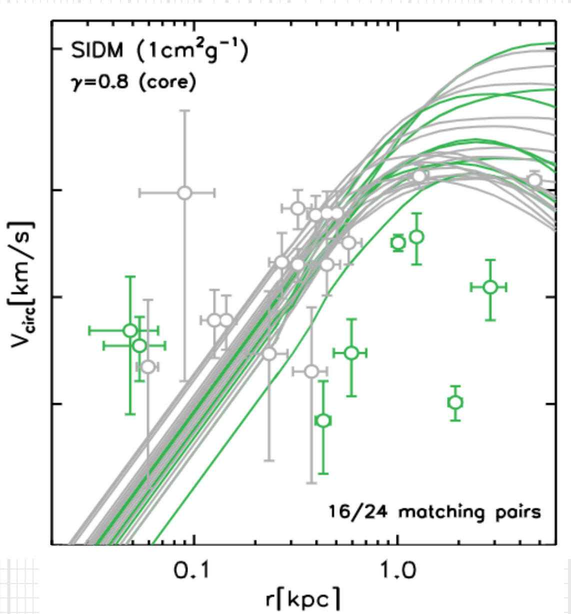
central densities *Elbert+ 2018, Rocha+ 2019*



the picture for constant cross sections

dwarfs — *halo mass ($M_\odot$)*

$\leq 0.3\ cm^2/g$ | 10^{11} | 10^{12} | 10^{13} | 10^{14} | $O(0.1)\ cm^2/g$



diversity problem

Zavala+ 2019

However, constant cross sections struggle to explain the diversity of observed rotation curves.

The outlook for constant cross sections is not promising!

new wrinkles in the fold

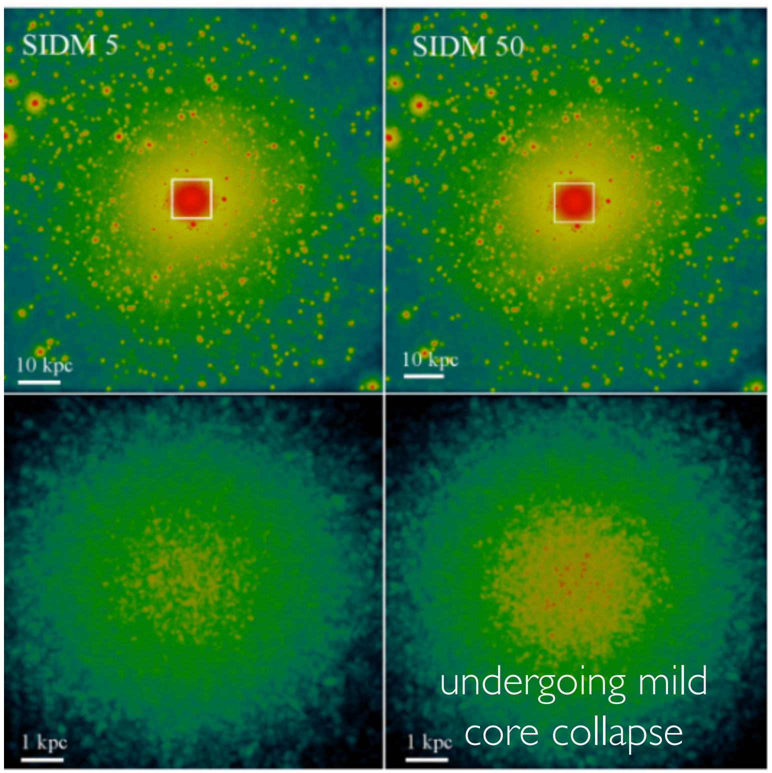
The outlook for constant cross sections is not promising!

undergoing mild
core collapse

new wrinkles in the fold

The outlook for constant cross sections is not promising!

BUT there have been a couple recent developments…



Elbert+ 2015

new wrinkles in the fold

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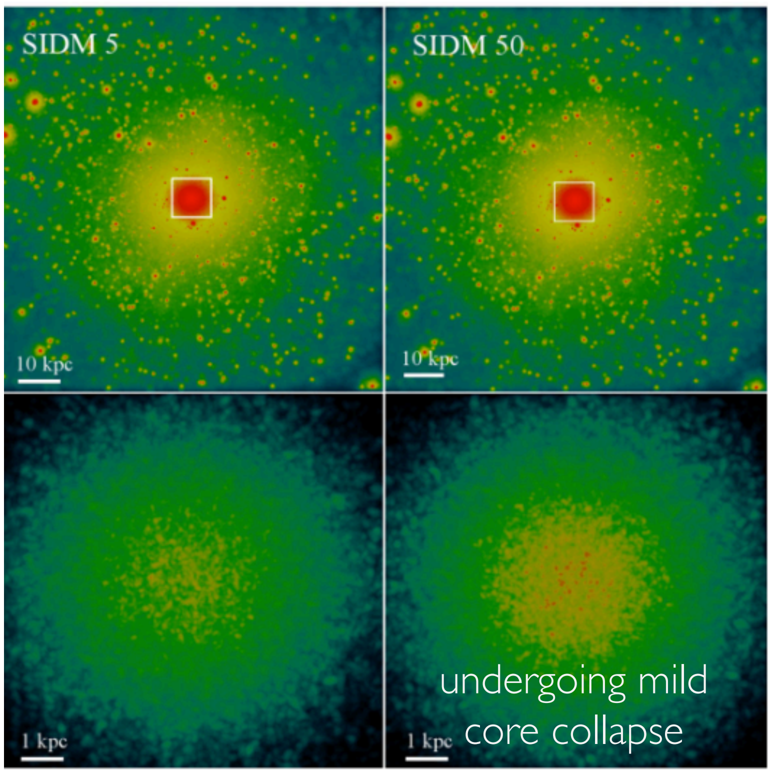
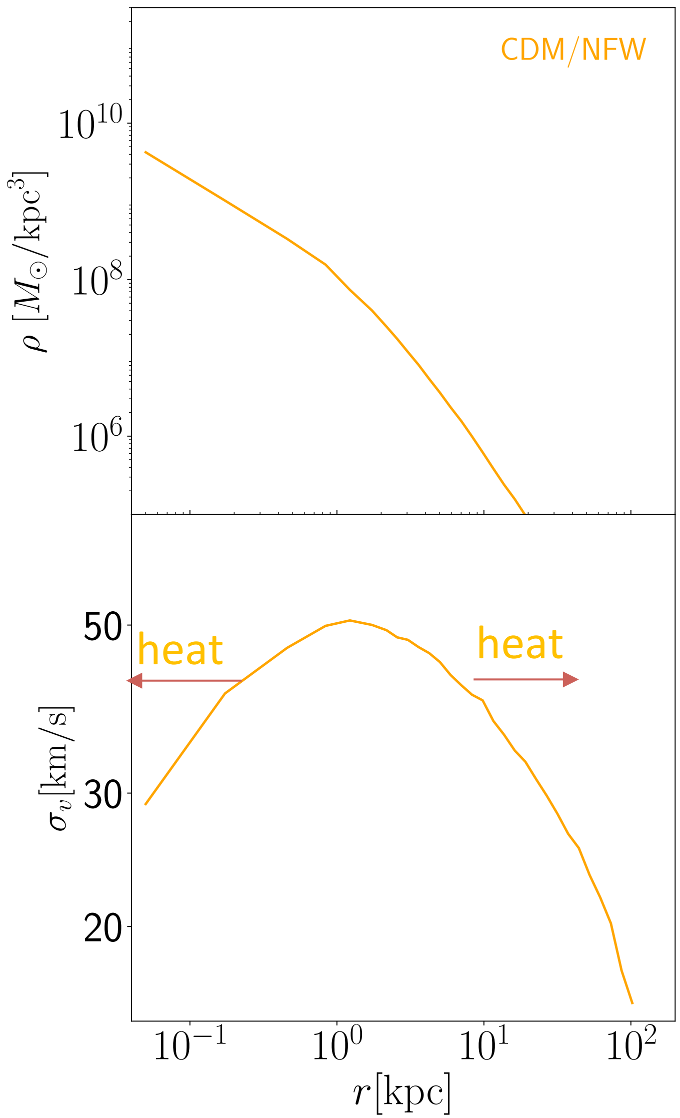


Core collapse can reintroduce dense cores, and even reestablish cusps.

Accelerated by tidal stripping?

Elbert+ 2015, Essig+ 2019, Nishikawa+ 2020

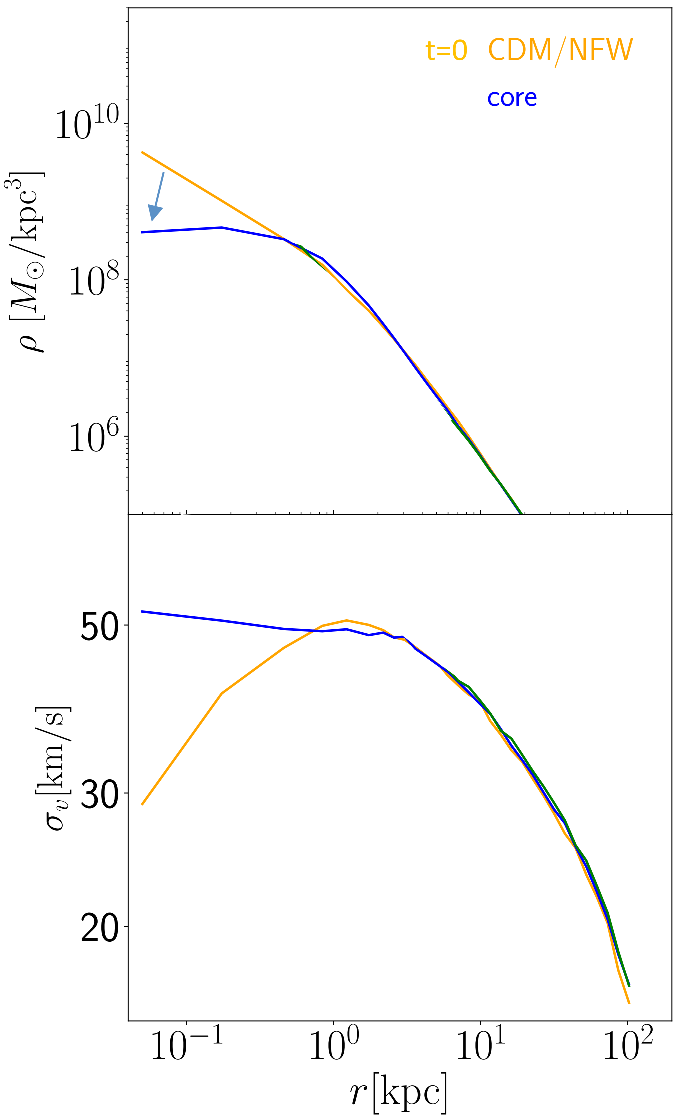
SIDM core collapse



Energy exchange via self-interactions leads to 'heat' flow.

Zeng+ incl. Kim 2022

SIDM core collapse



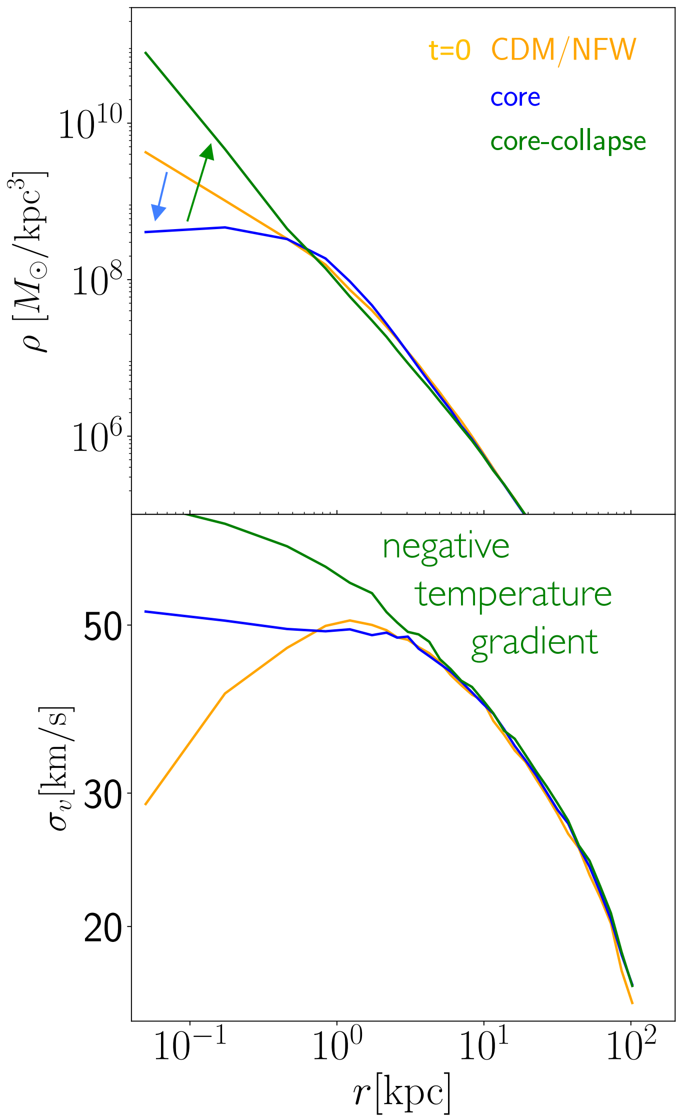
Energy exchange via self-interactions leads to 'heat' flow.

Phase I

isothermal core forms

Zeng+ incl. Kim 2022

SIDM core collapse



Energy exchange via self-interactions leads to ‘heat’ flow.

Phase 1

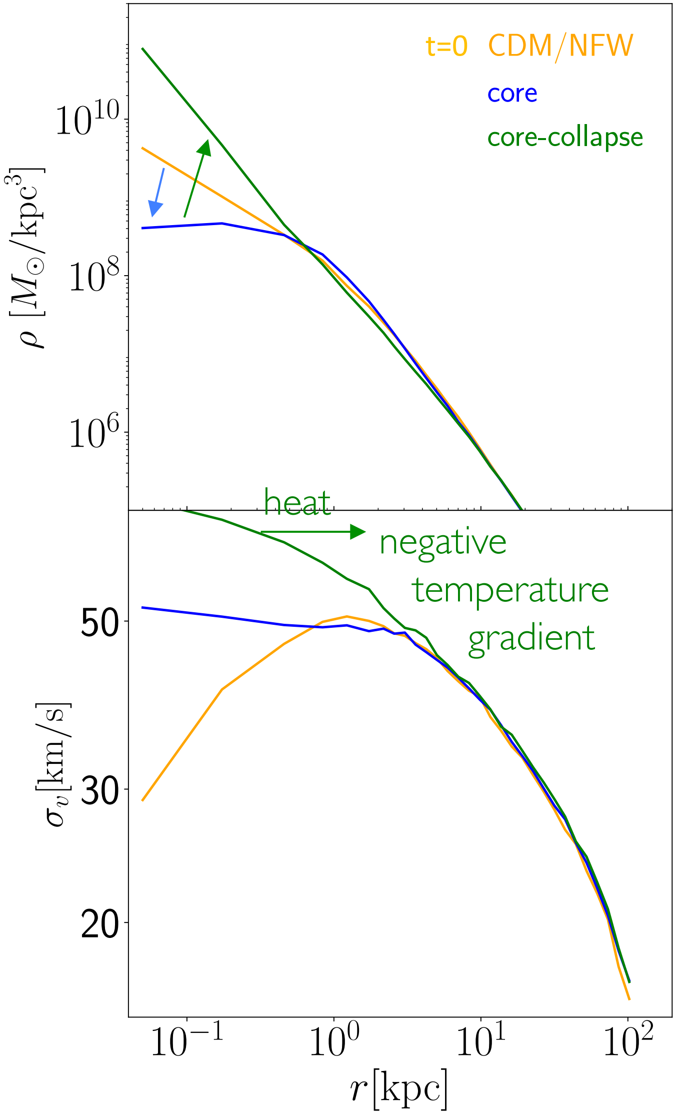
isothermal core forms

Phase 2

core slowly loses heat to outskirts, dark matter infall to more bound orbits that are hotter than before

Zeng+ incl. Kim 2022

SIDM core collapse



Energy exchange via self-interactions leads to ‘heat’ flow.

Phase 1

isothermal core forms

Phase 2

core slowly loses heat to outskirts, dark matter infall to more bound orbits that are hotter than before

more heat flow, more infall, runaway core collapse!

Zeng+ incl. Kim 2022

SIDM core collapse

Simulating subhalos under core collapse is expensive.

scattering probability $\propto \frac{\sigma_{\mathrm{SI}}}{m_\chi} \Delta v \; \rho \; \Delta t$

Zeng+ incl. Kim 2022

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increases by orders of magnitude

Zeng+ incl. Kim 2022

SIDM core collapse

Simulating subhalos under core collapse is expensive.

$$\underline{\text{scattering probability}} \propto \frac{\sigma_{\rm SI}}{m_\chi} \Delta v \, \rho \, \Delta t < 1$$

increases by orders of magnitude

keeping $P < 1$ requires *tiny* timesteps!

Zeng+ incl. Kim 2022

SIDM core collapse

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scattering probability $\propto \frac{\sigma_{SI}}{m_\chi} \Delta v \, \rho \, \Delta t < 1$

↑ increases by orders of magnitude

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high dynamic range: e.g. in substructure lenses, 10^{13} $M_\odot$ host (main lens) + as low as 10^6 $M_\odot$ sub

Zeng+ incl. Kim 2022

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high dynamic range: e.g. in substructure lenses, 10^{13} $M_\odot$ host (main lens) + as low as 10^6 $M_\odot$ sub

We adopt a hybrid approach

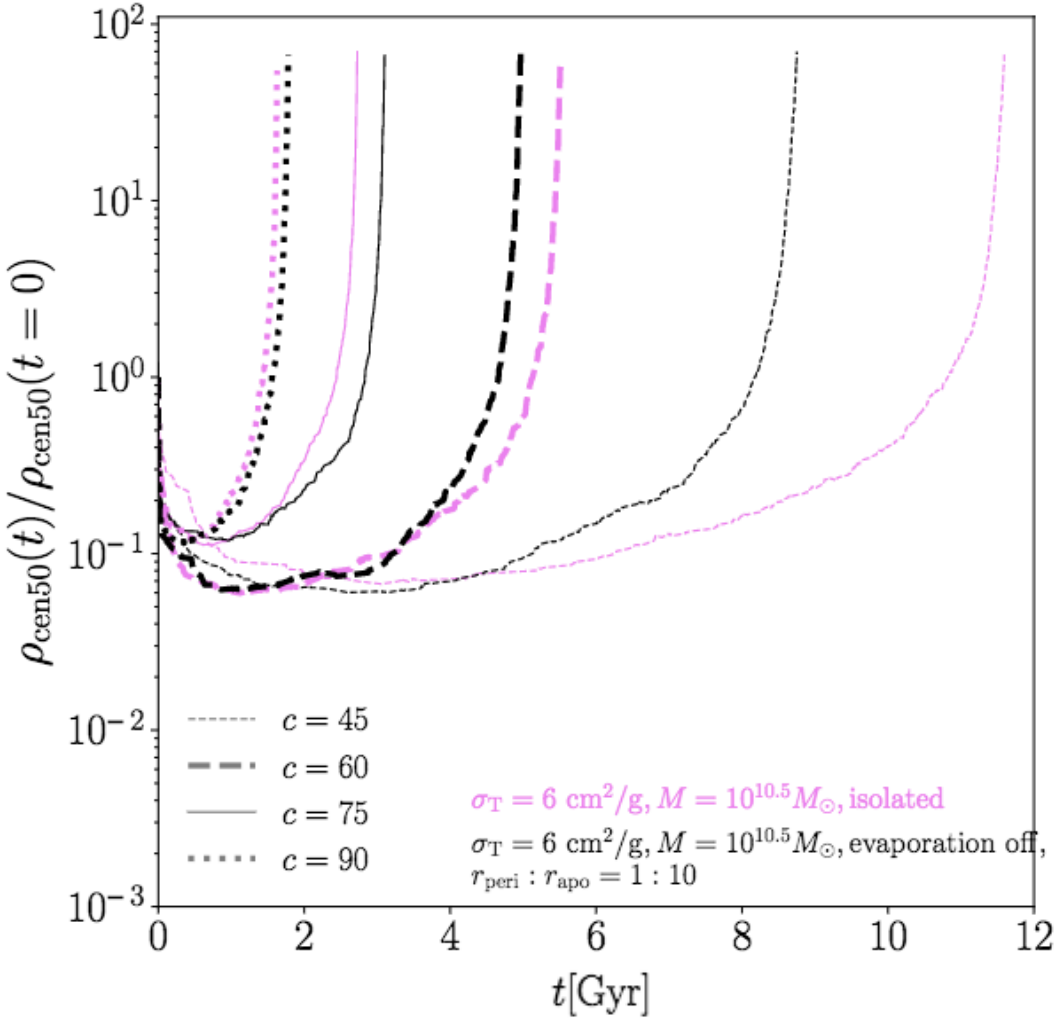
analytic host + 'live' (N-body) subhalo + evaporation

host-sub interactions

that reduces computational time by orders of magnitude!

Zeng+ incl. Kim 2022

SIDM core collapse



Zeng+ incl. Kim 2022

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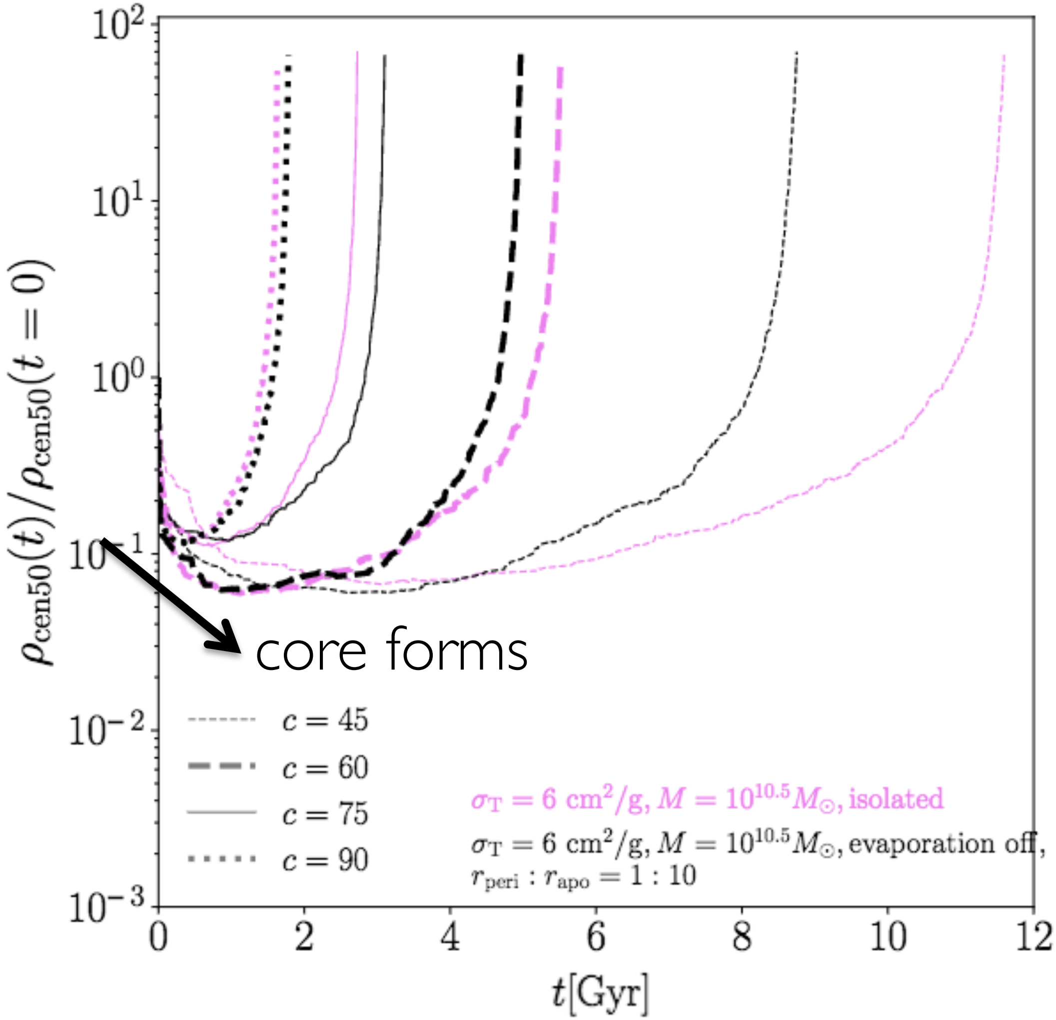

Zeng+ incl. Kim 2022

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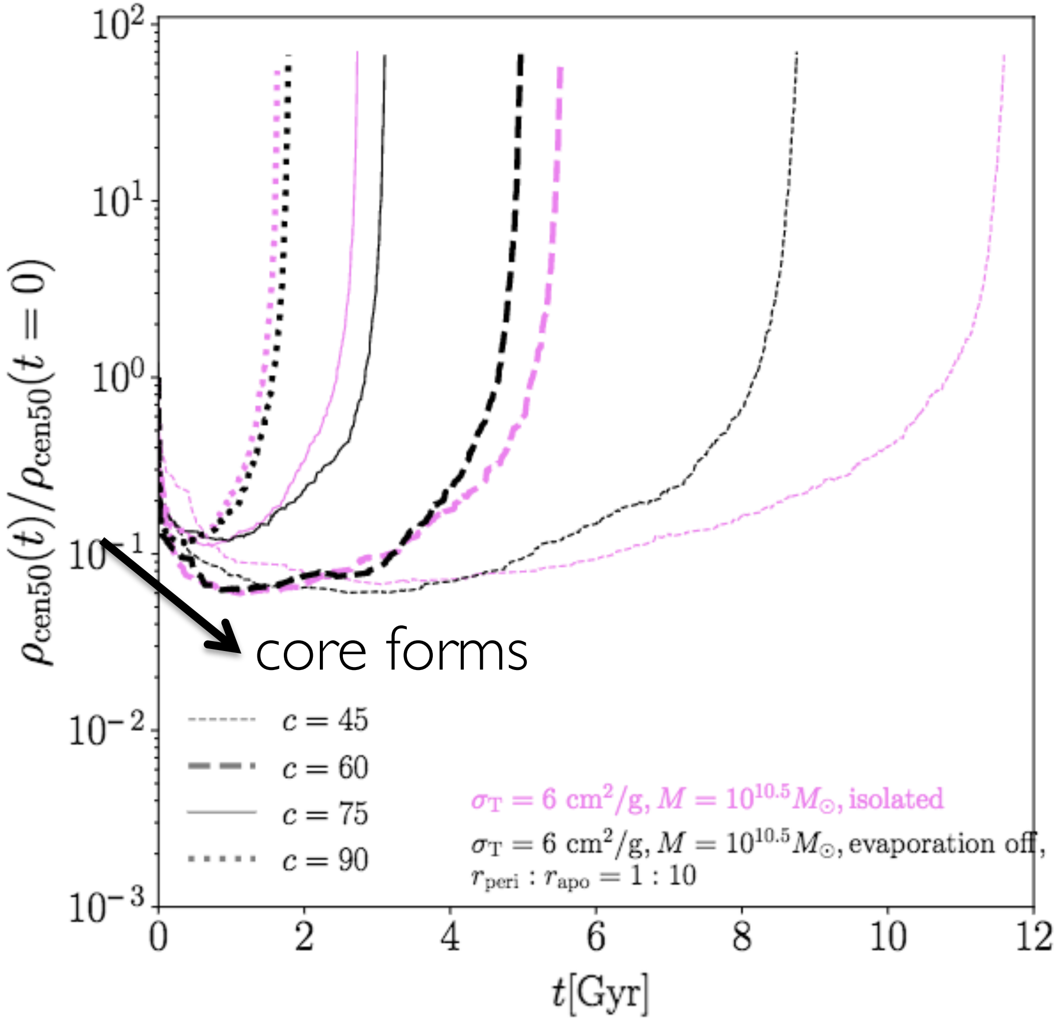
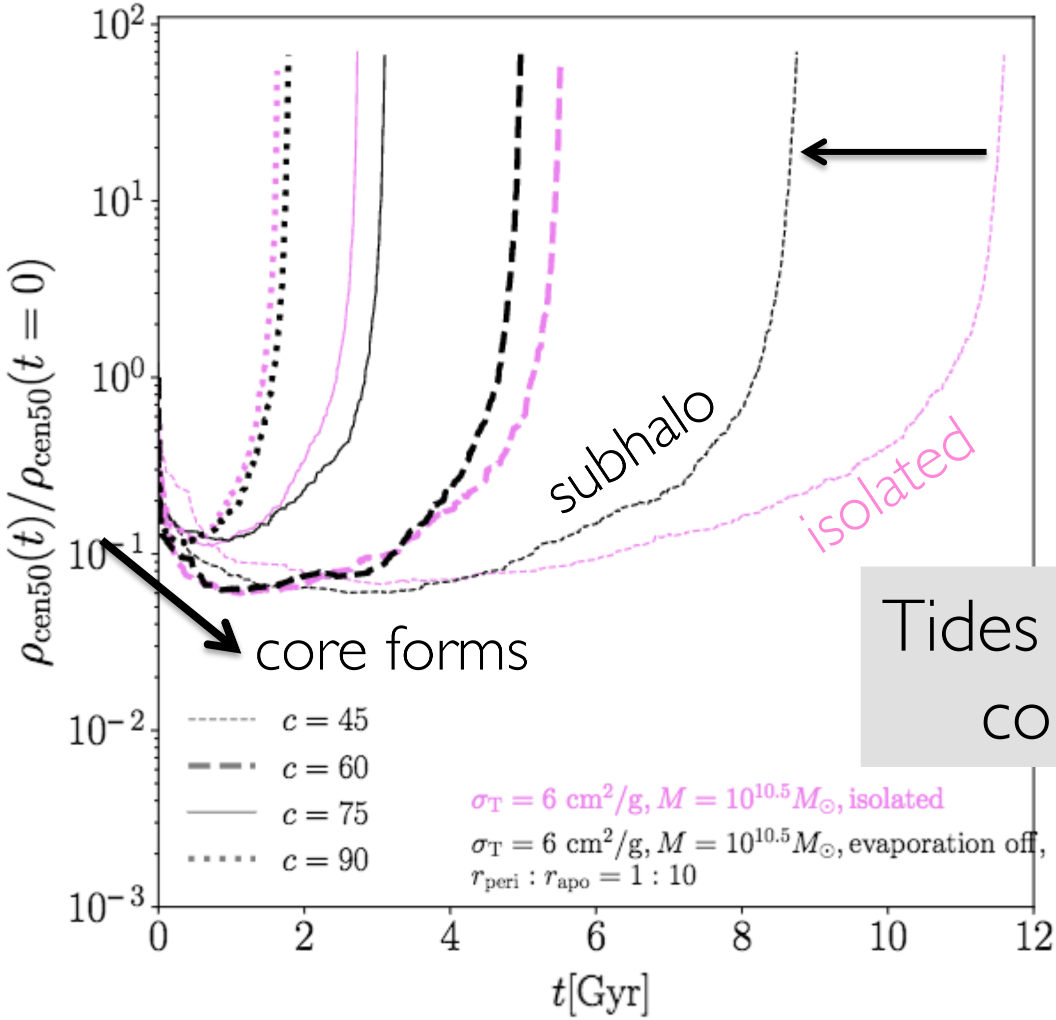


core collapse!

stop simulation when central density grows by 100

Zeng+ incl. Kim 2022

SIDM core collapse

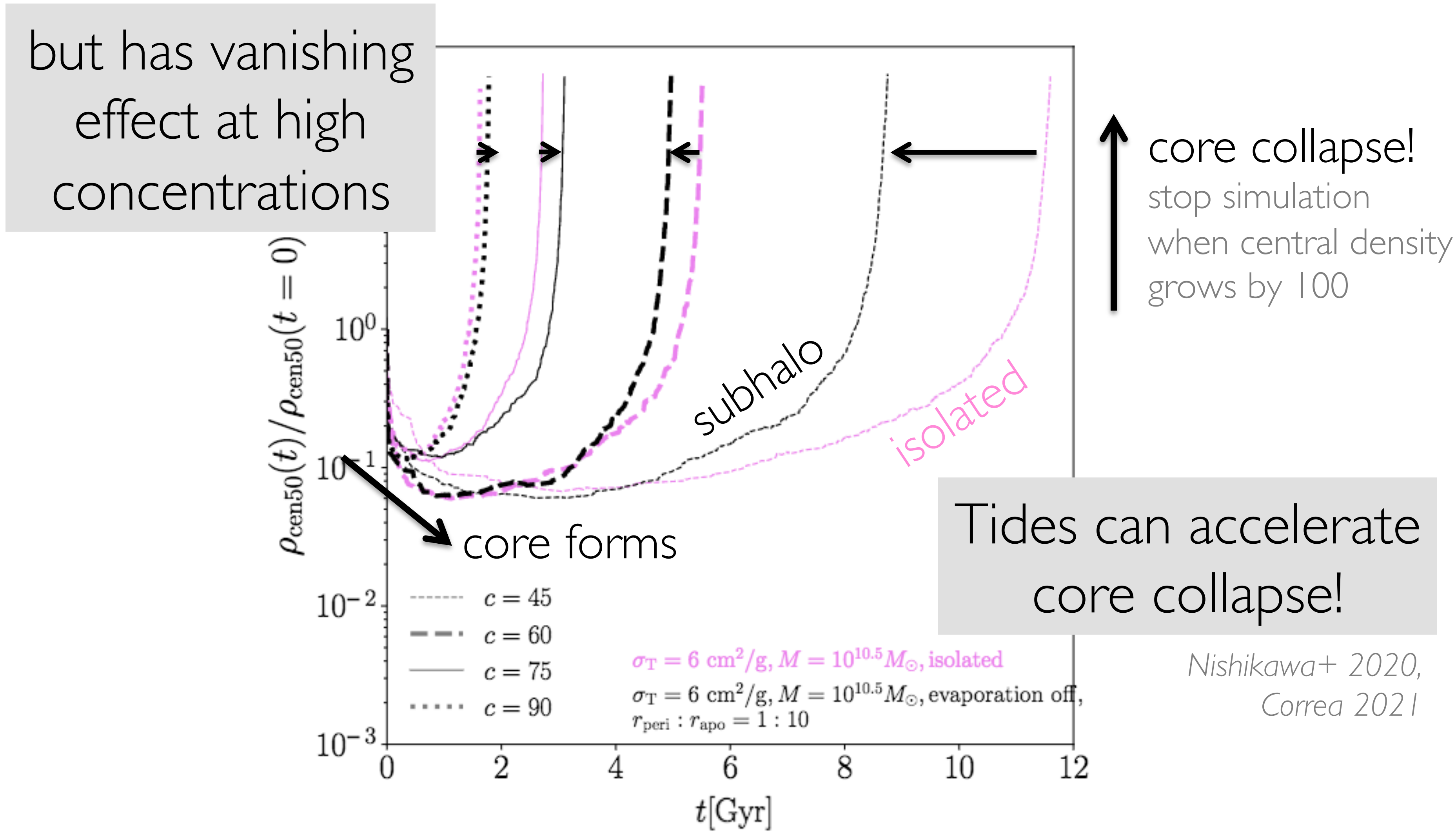


Tides can accelerate core collapse!

Nishikawa+ 2020, Correa 2021

Zeng+ incl. Kim 2022

SIDM core collapse



Nishikawa+ 2020, Correa 2021

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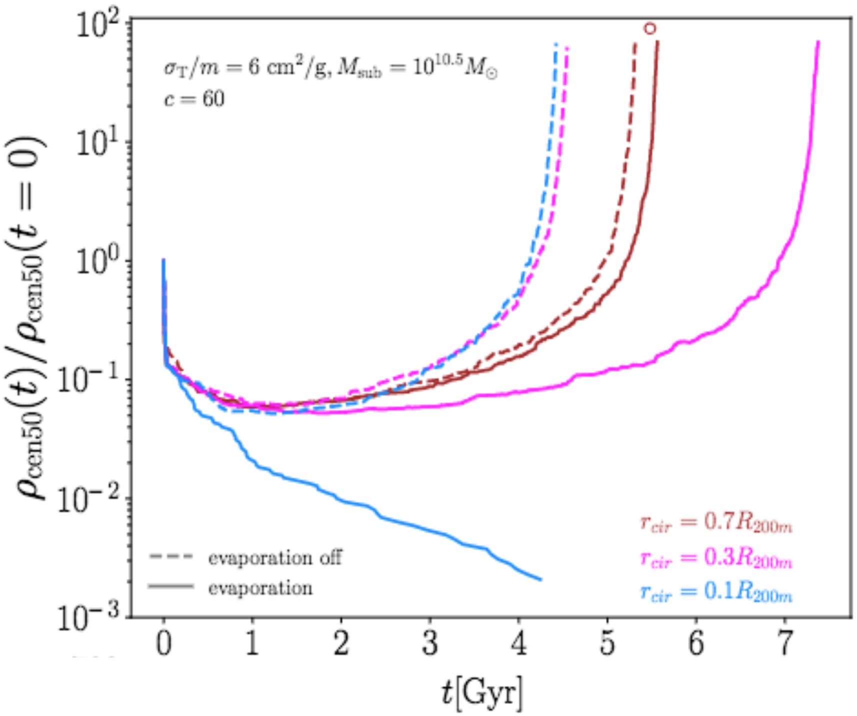
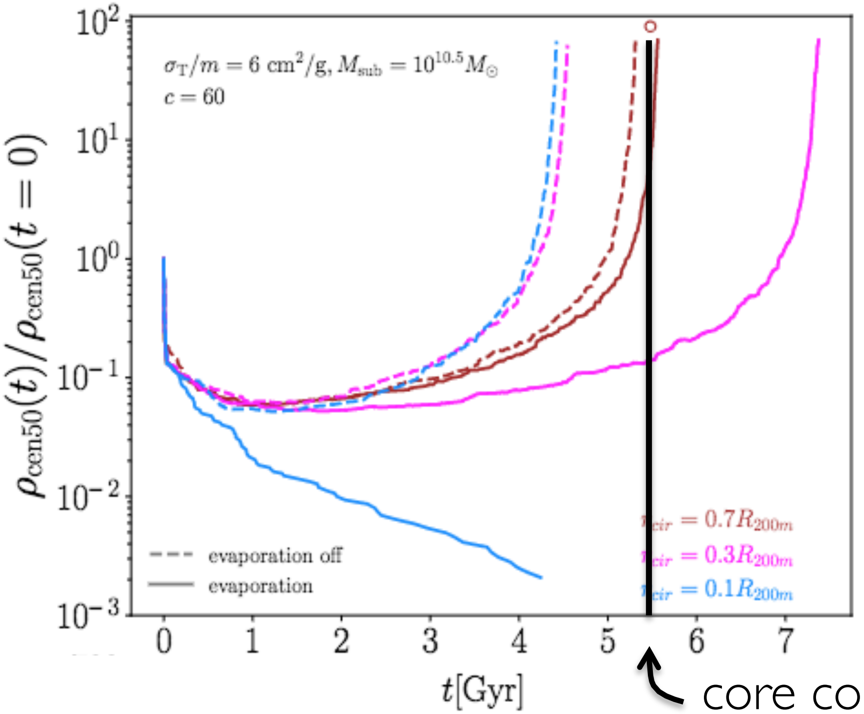
SIDM core collapse



Lessons from circular orbits

Zeng+ incl. Kim 2022

SIDM core collapse

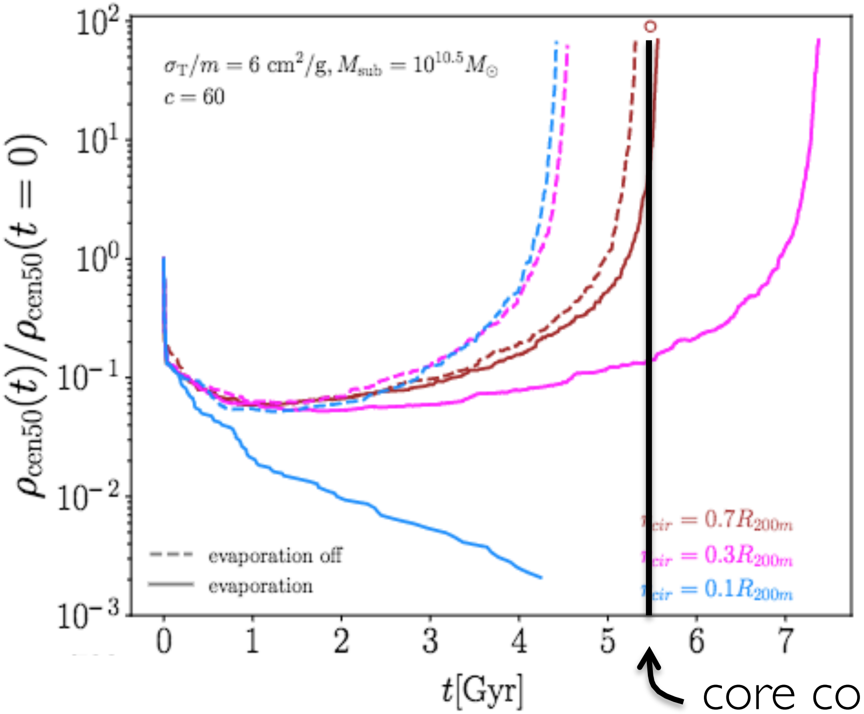


Lessons from circular orbits

core collapse time if (sub)halo were isolated

Zeng+ incl. Kim 2022

SIDM core collapse

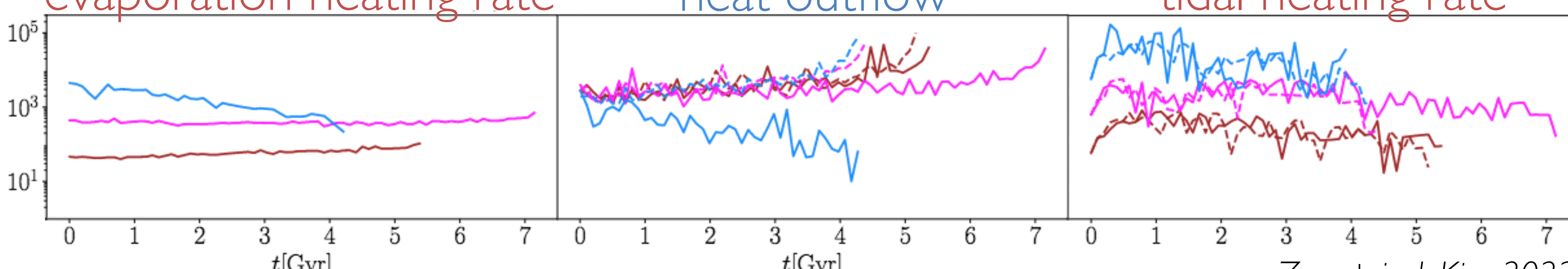


core collapse time if (sub)halo were isolated

Lessons from circular orbits

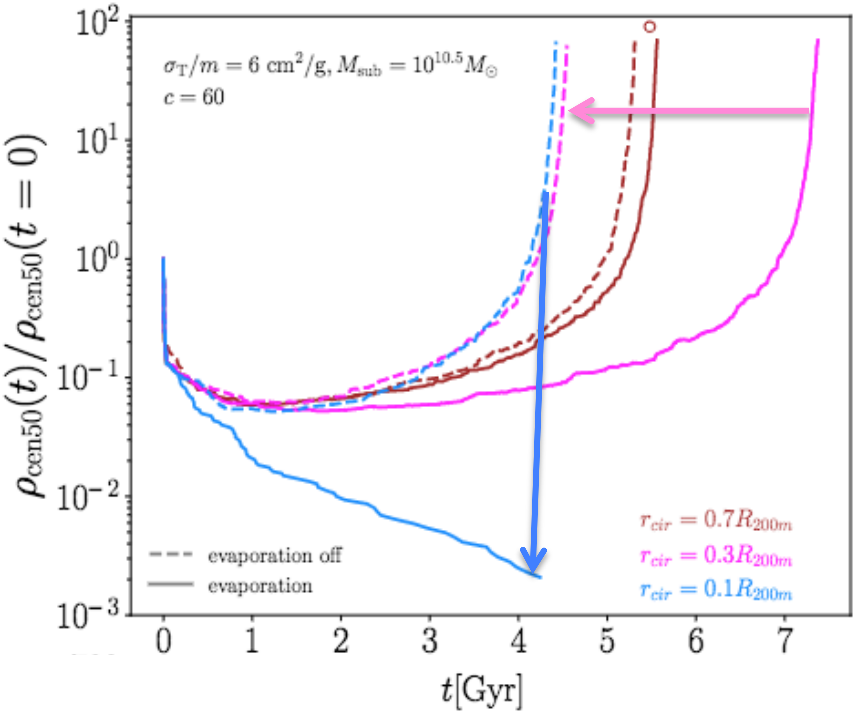
subhalo central density grows if
cooling > heating
(recall: negative heat capacity)

evaporation heating rate | heat outflow | tidal heating rate



Zeng+ incl. Kim 2022

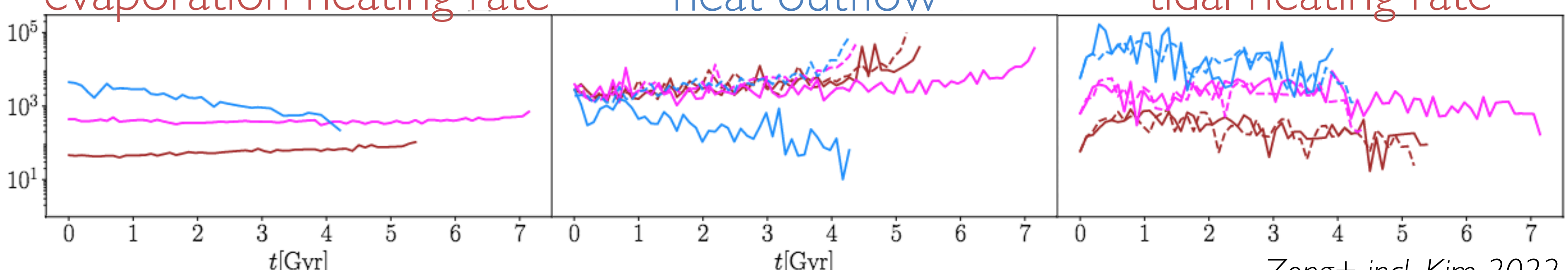
SIDM core collapse



Lessons from circular orbits

subhalo central density grows if
cooling > heating
(recall: negative heat capacity)

evaporation is significant!
can be strong enough to
disrupt core-collapse



Zeng+ incl. Kim 2022

SIDM core collapse

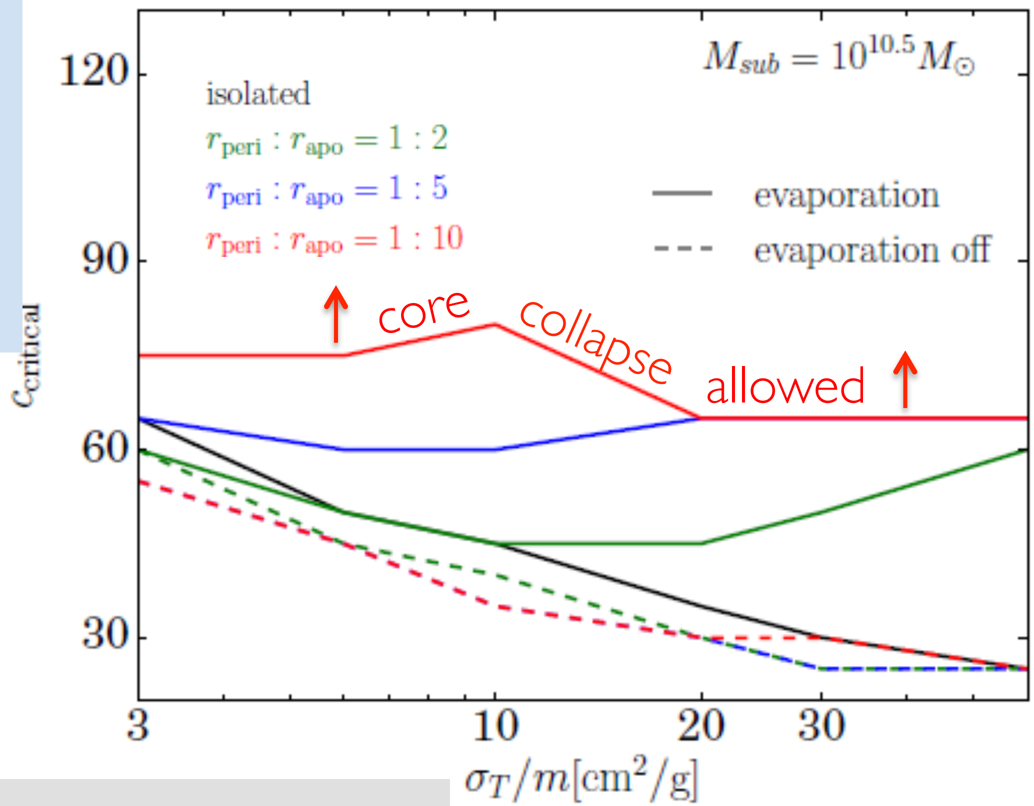
Parameter space for subhalo core collapse

core collapse not feasible with constant **σ**/m

need *very high* concentrations (median c = 10-20)

smaller c needed for isolated subhalos or <u>no evaporation</u>

mimics vSIDM!



if ultra-compact substructure found, strongly favors vSIDM, inelastic SIDM, etc

Zeng+ incl. Kim 2022

SIDM subhalos: a summary

The outlook is not looking so promising for constant cross section models!

Milky Way satellite kinematics imply $\sigma/m \lesssim O(0.1)$ cm^2/g

Core collapse could reestablish steeper densities, but requires unphysically high concentrations

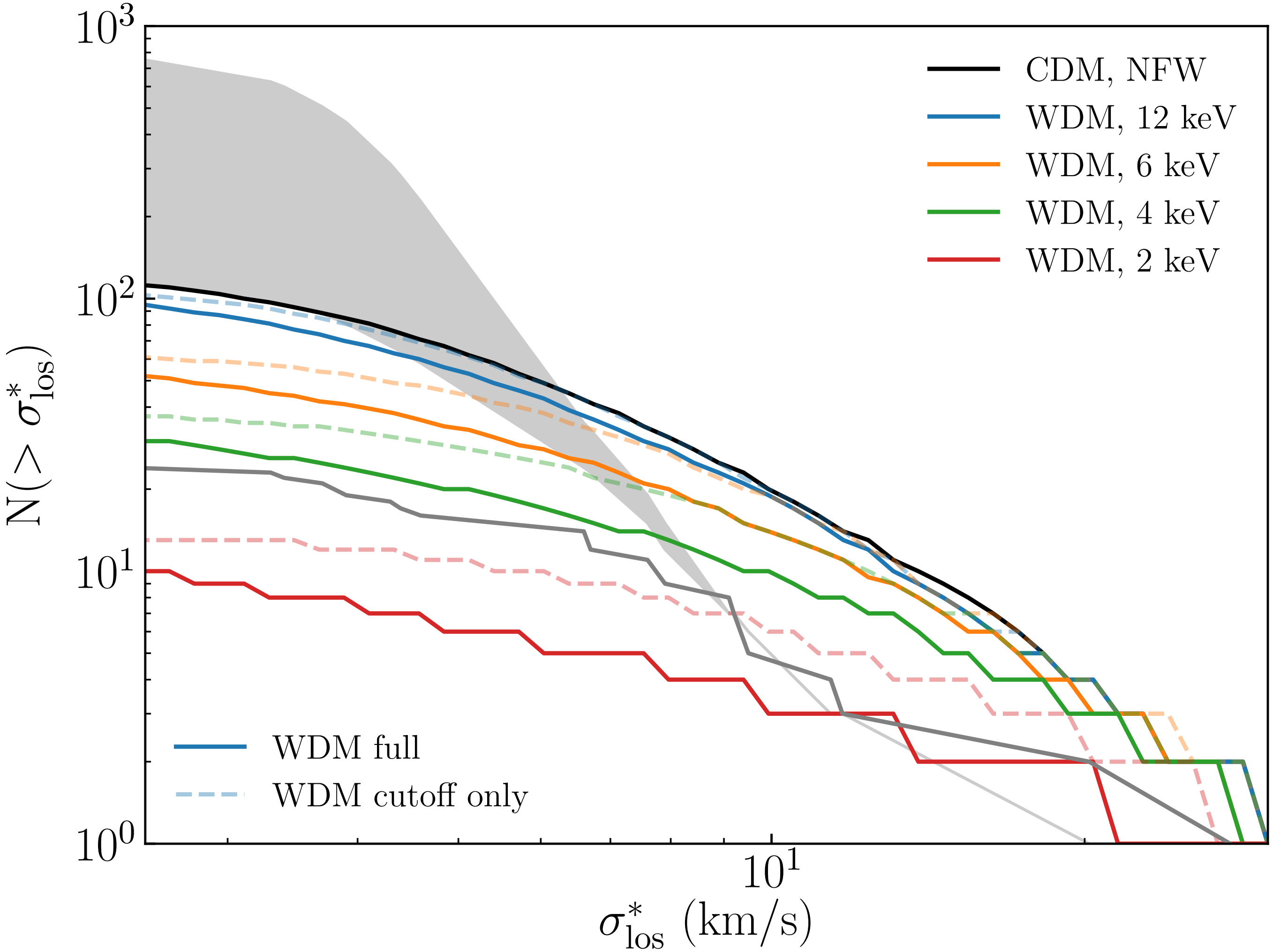
Important to include evaporation, which suppresses core-collapse

The door is still open for other SIDM models with additional degrees of freedom!

(velocity-dependent SIDM, inelastic scattering, etc.)

EXTRAS: MWVF

theory vs. observations



Lovell+ 2020 Kim et al. 2022 (arXiv:2106.09050)

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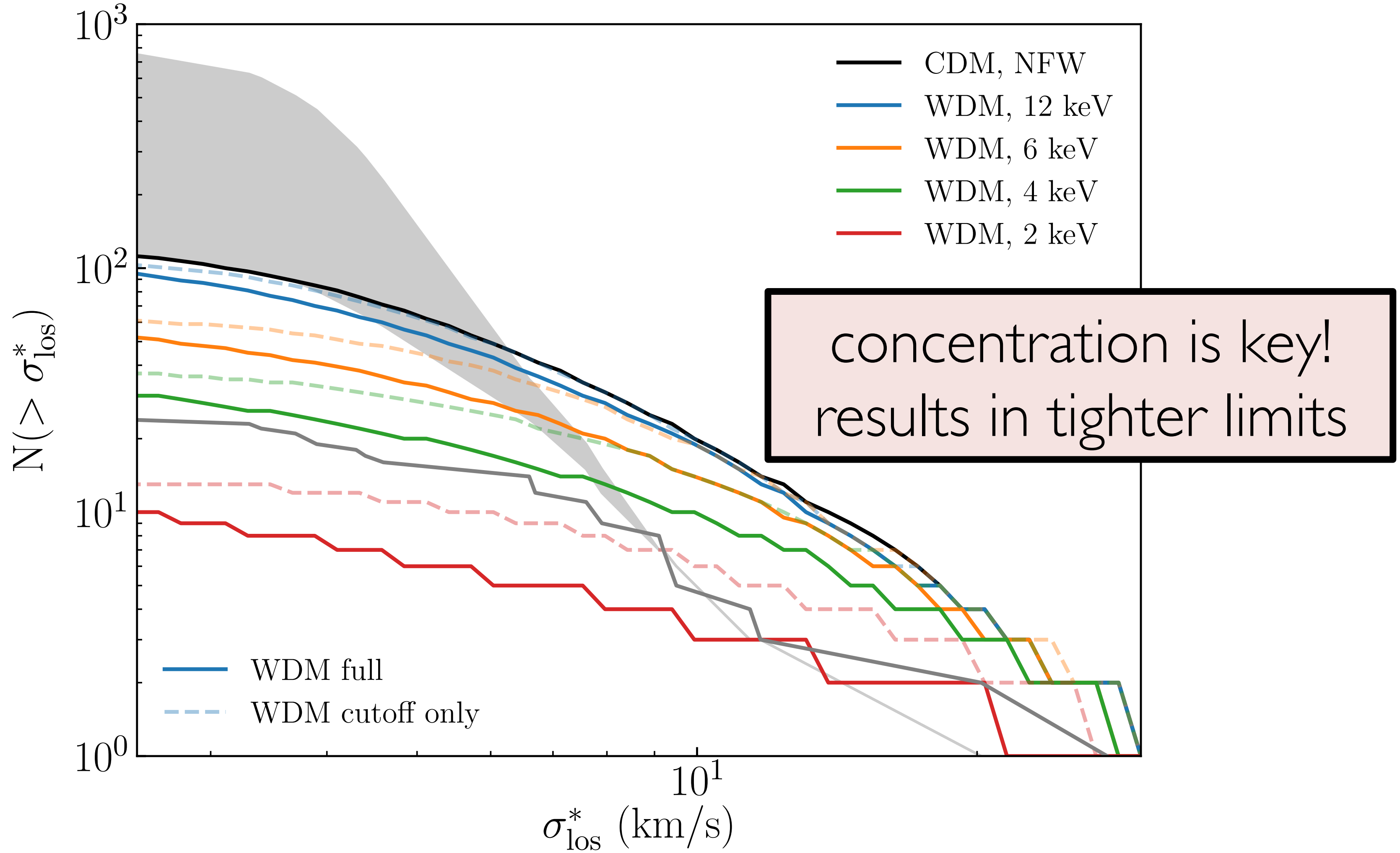
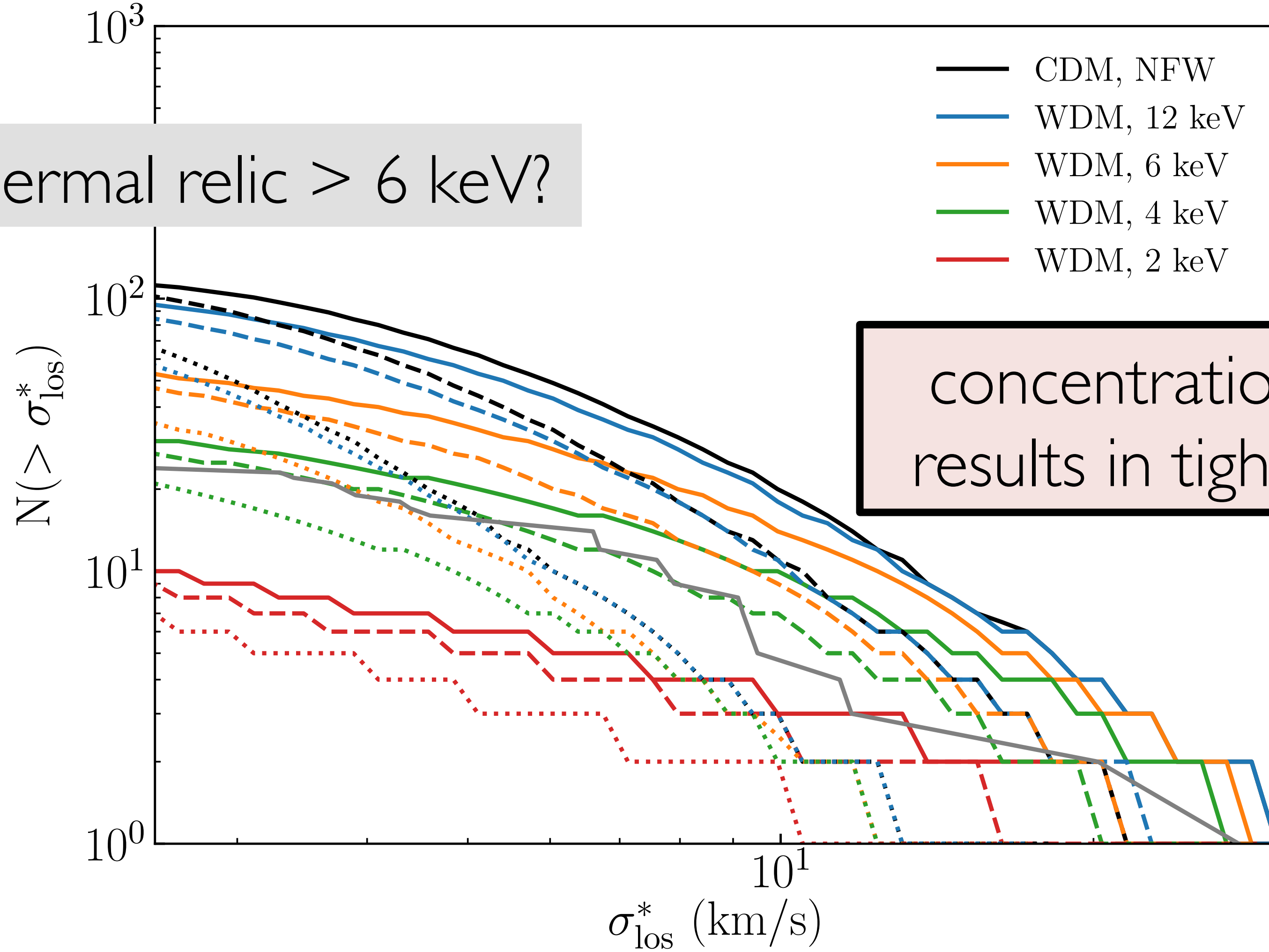


Lovell+ 2020 Kim et al. 2022 (arXiv:2106.09050)

theory vs. observations

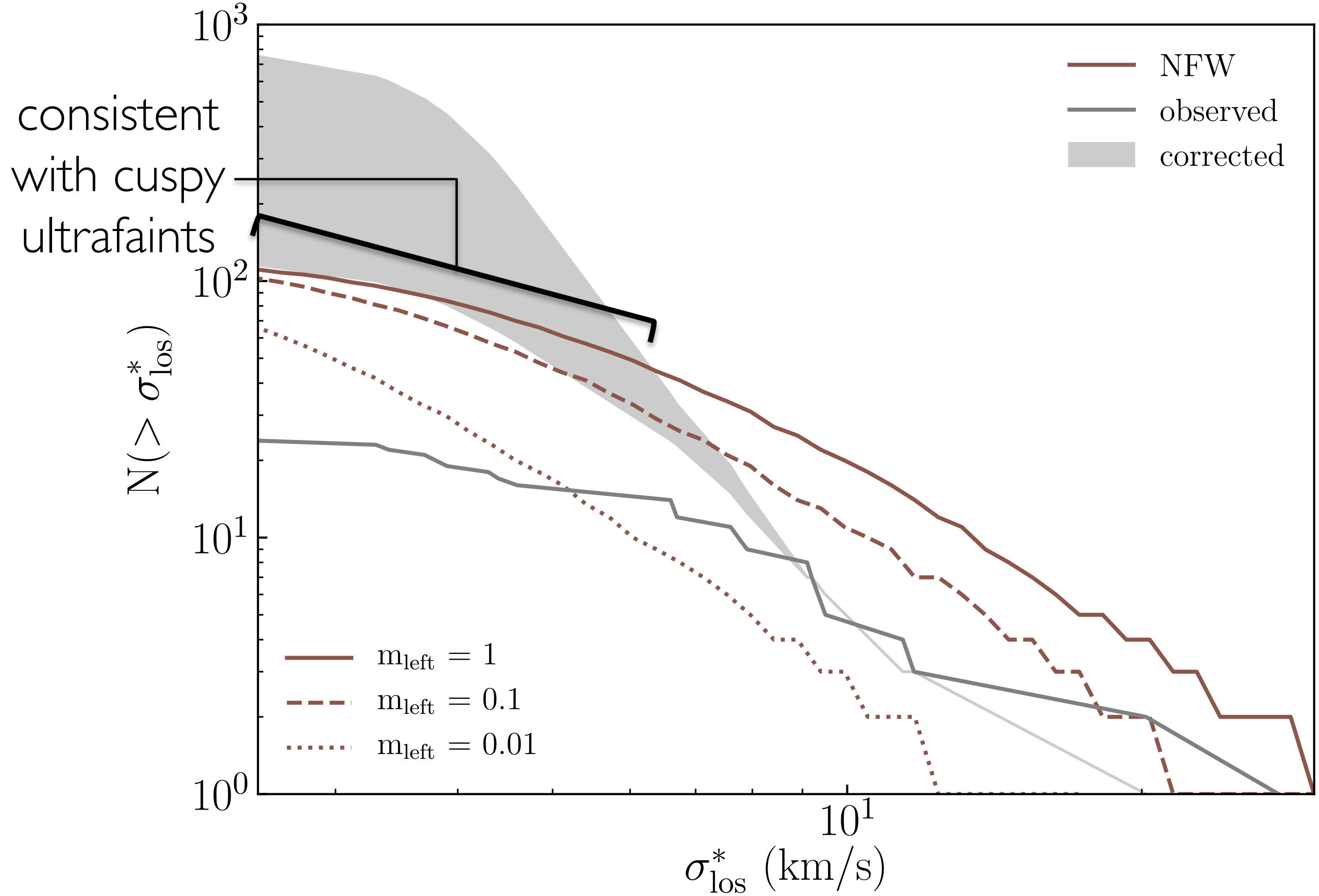


thermal relic > 6 keV?

concentration is key! results in tighter limits

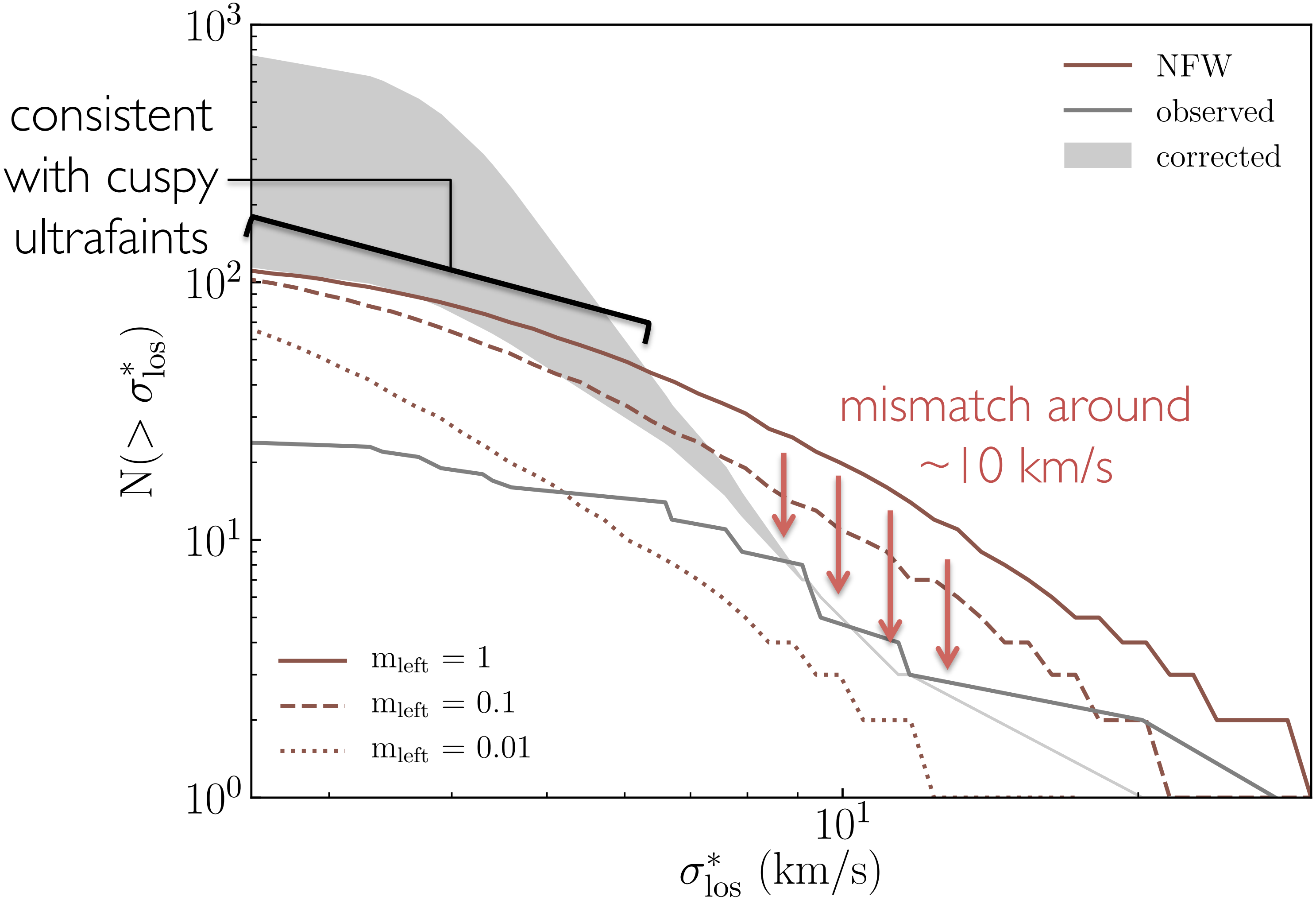
Lovell+ 2020 *Kim et al. 2022 (arXiv:2106.09050)*

theory vs. observations



Kim et al. 2022 (arXiv:2106.09050)

theory vs. observations



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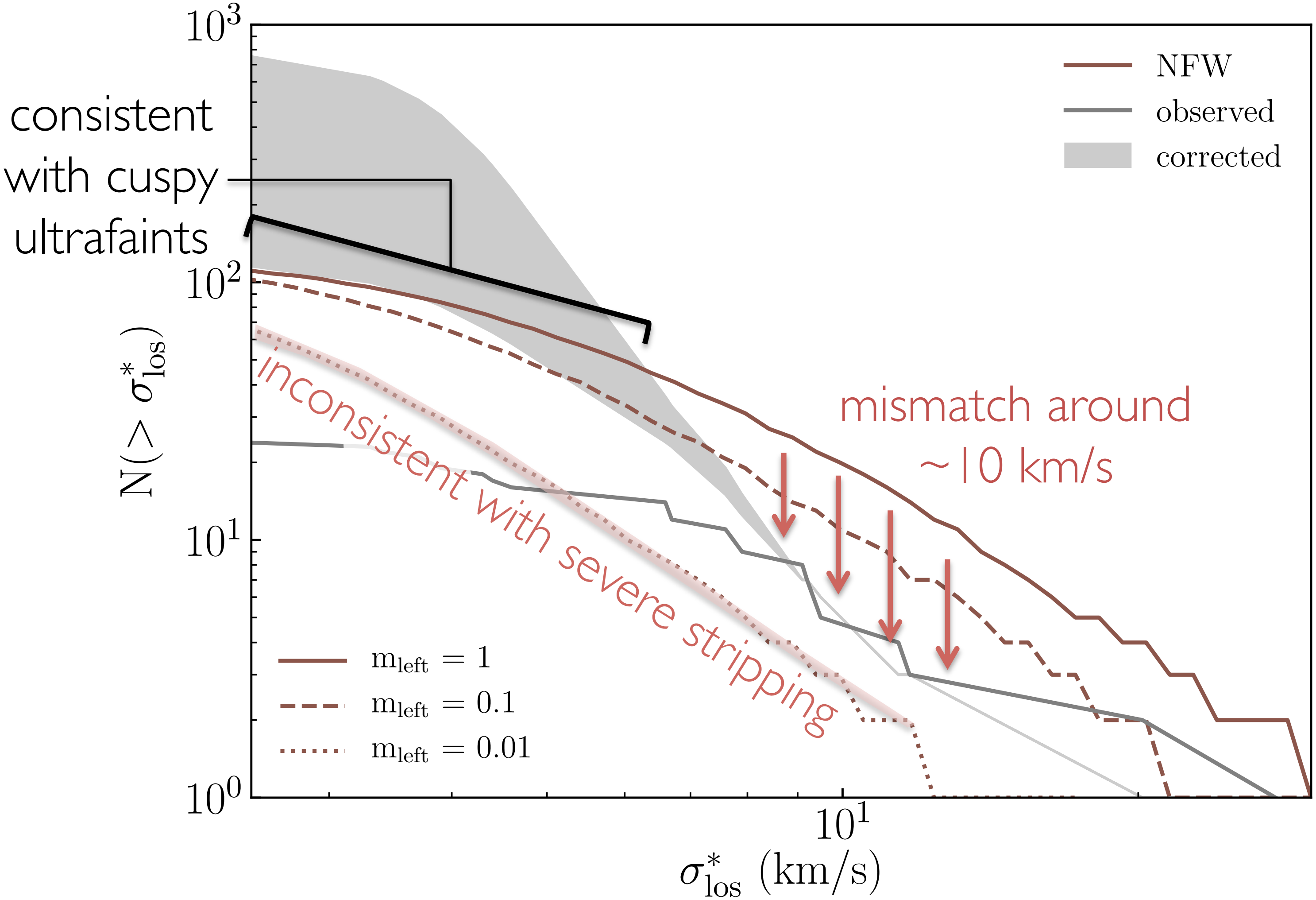
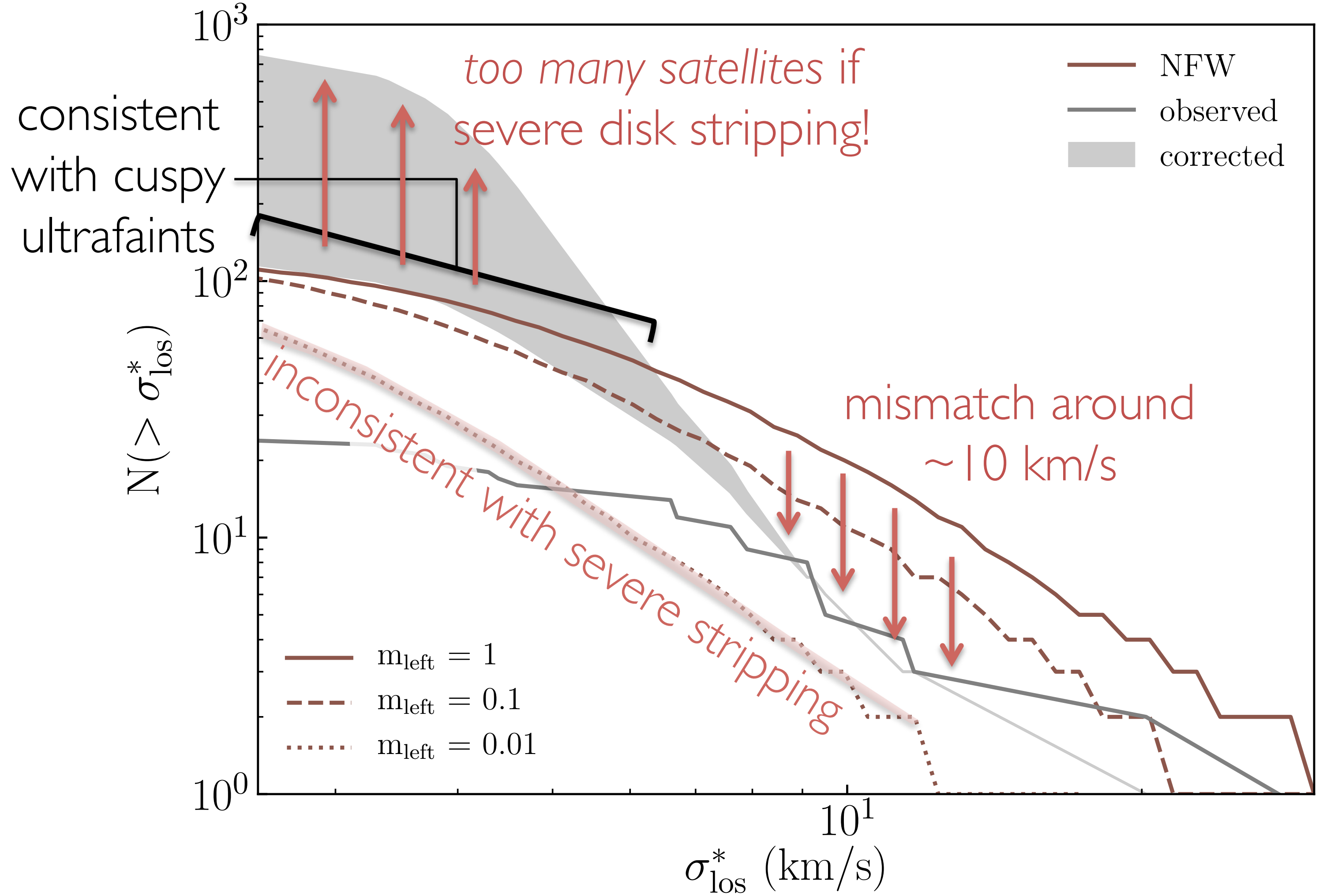


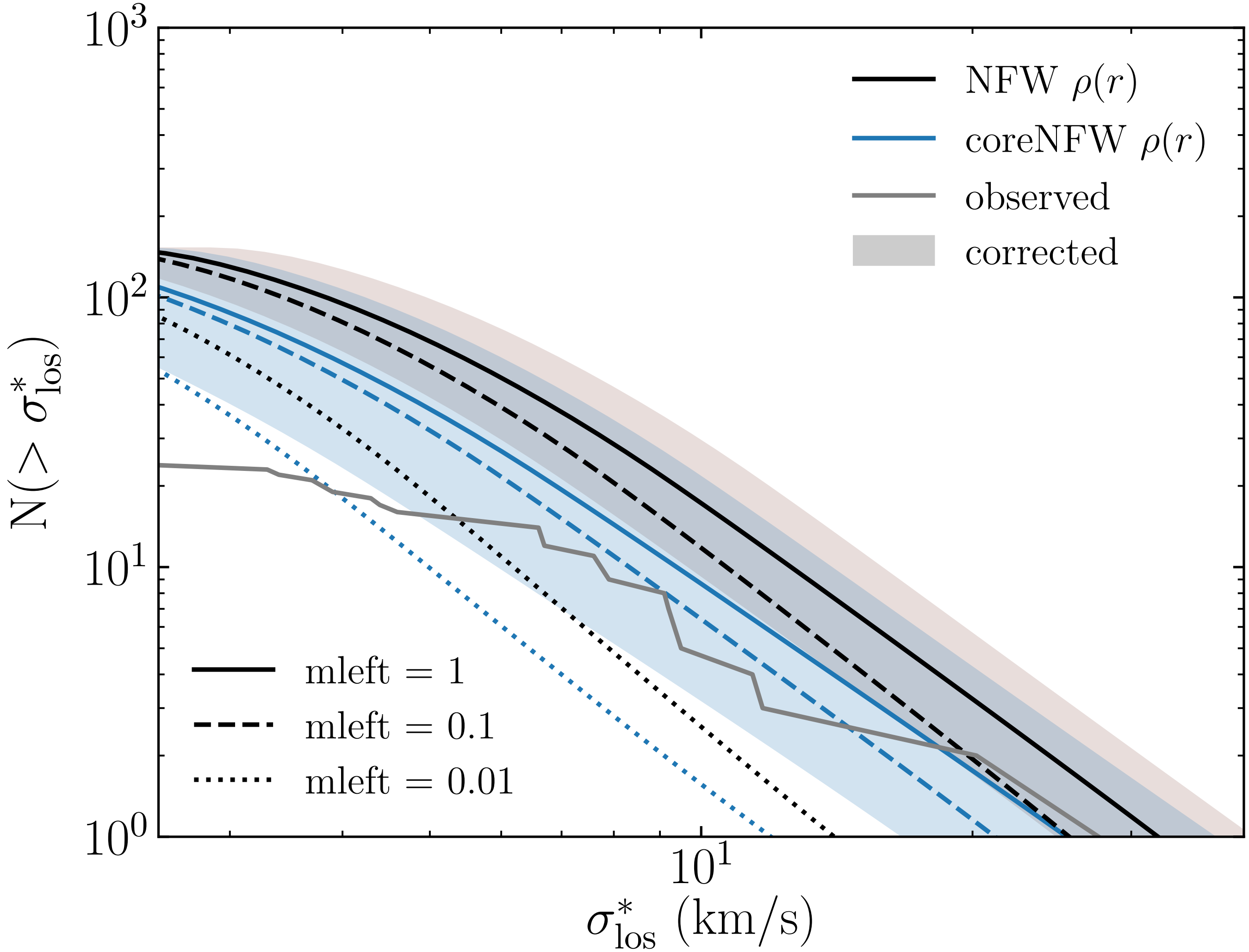
Kim et al. 2022 (arXiv:2106.09050)

theory vs. observations



Kim et al. 2022 (arXiv:2106.09050)

theory vs. observations



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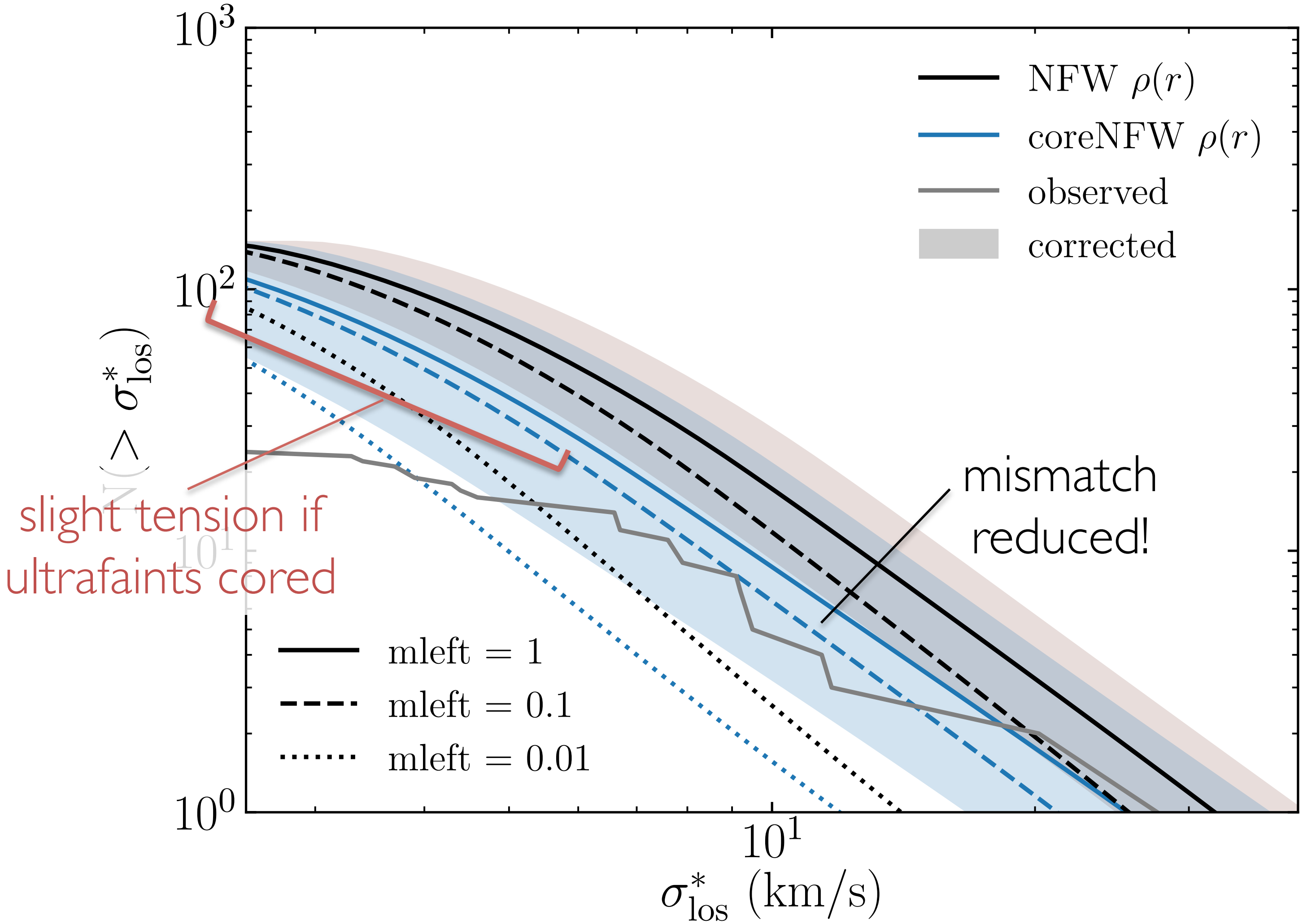
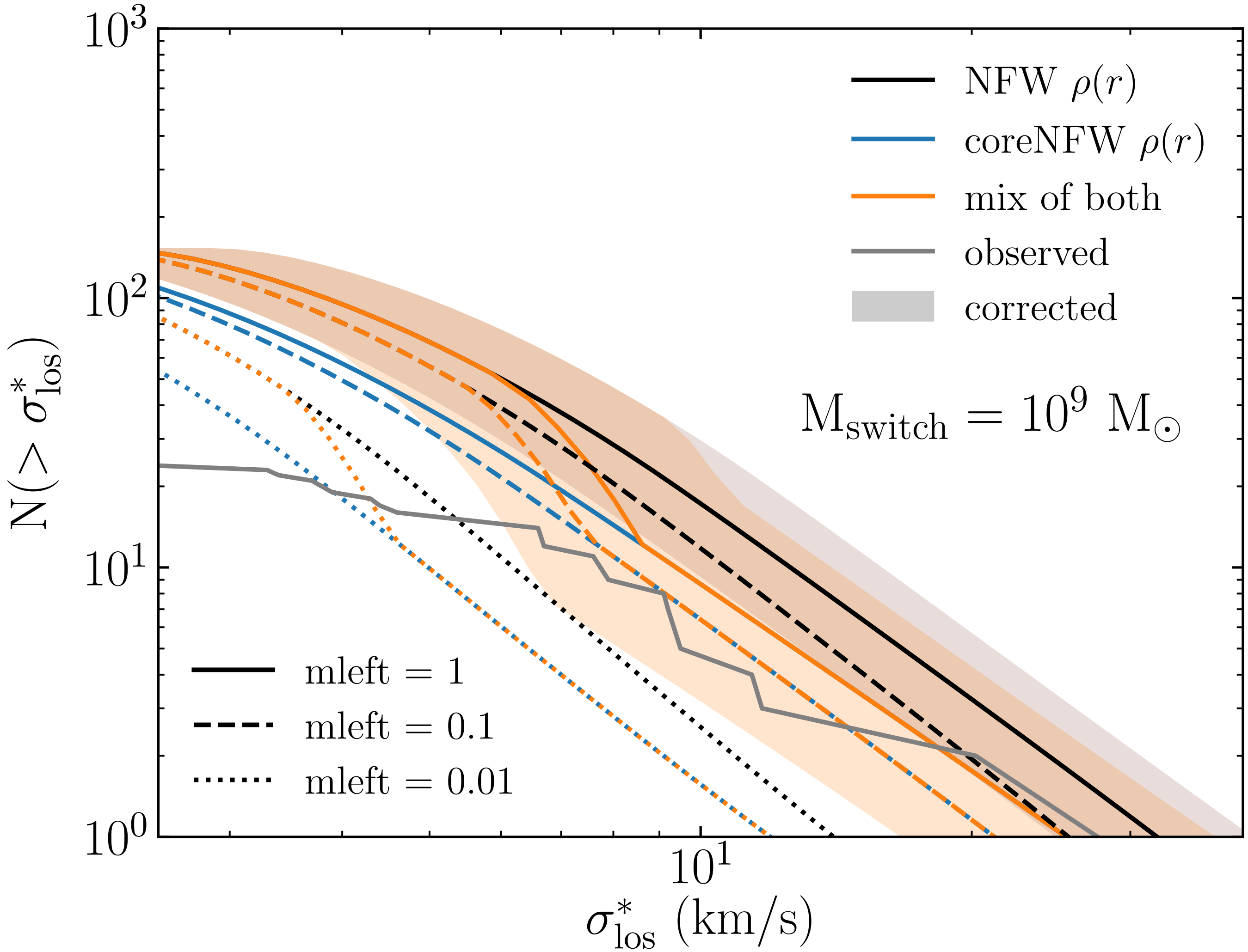
theory vs. observations



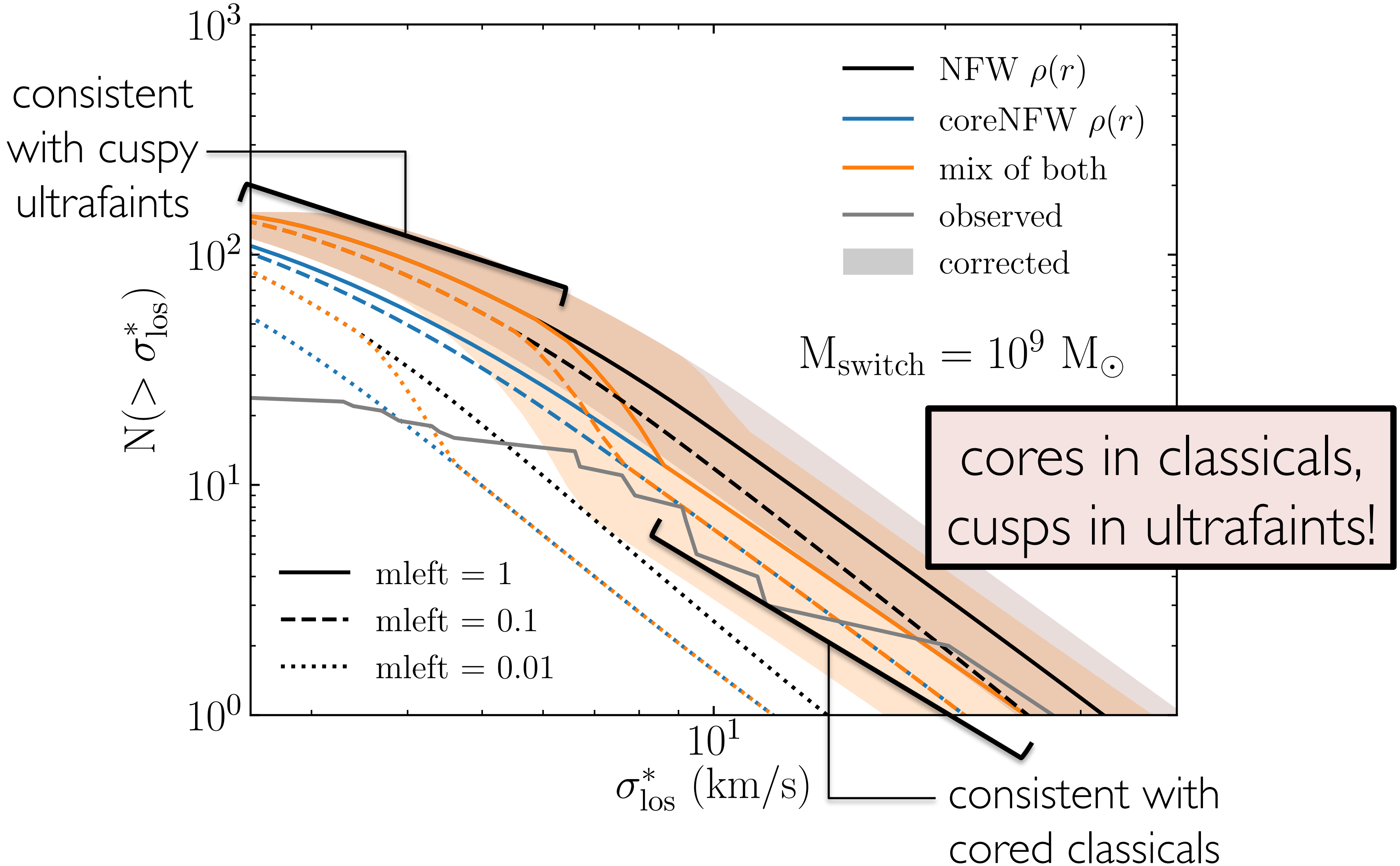
Kim et al. 2022 (arXiv:2106.09050)

theory vs. observations



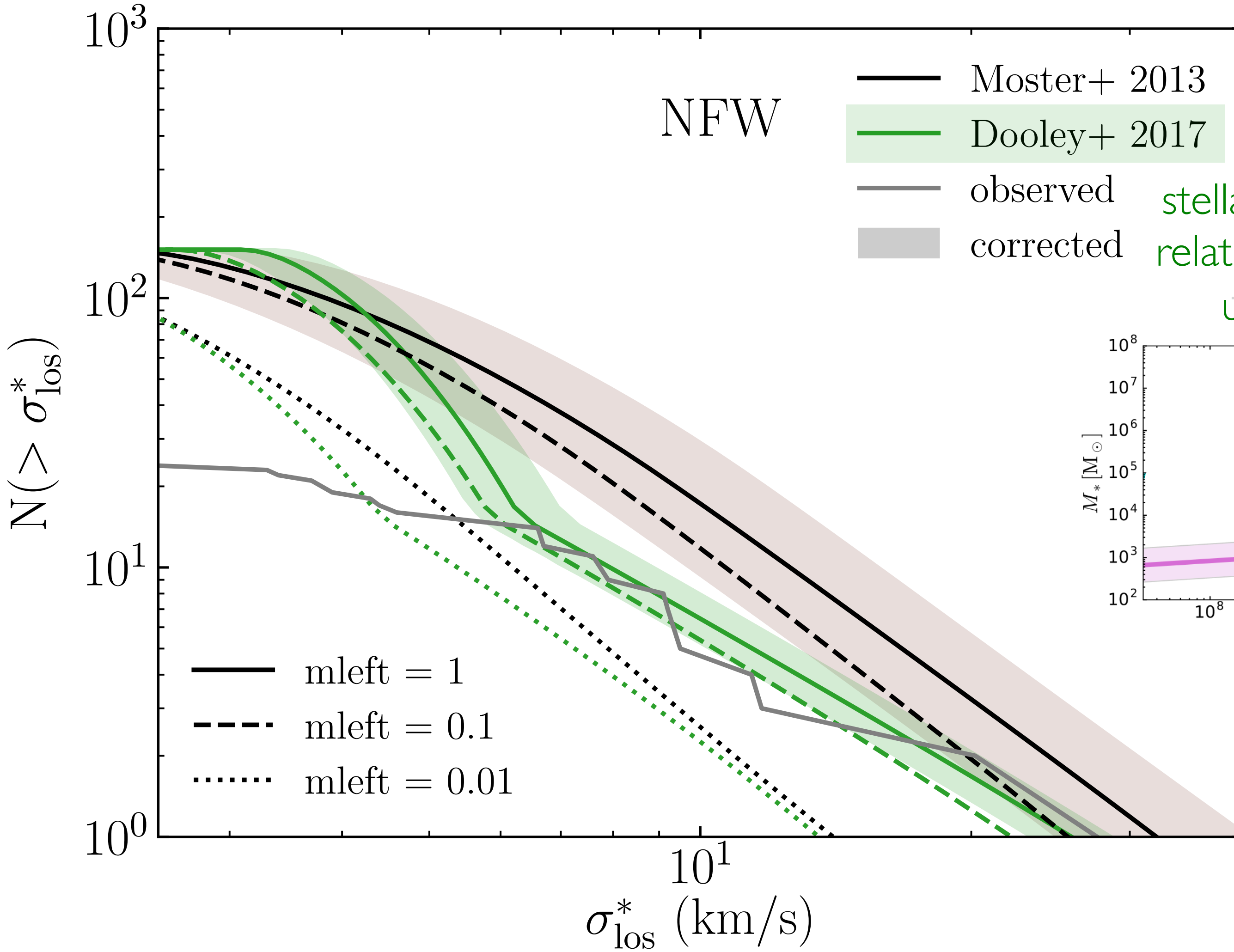
Kim et al. 2022 (arXiv:2106.09050)

theory vs. observations

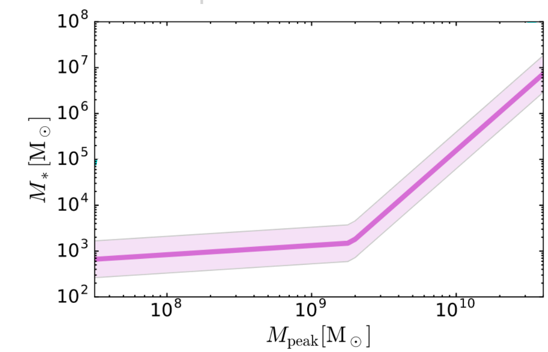


theoretical uncertainties

an alternative method to reduce the mismatch at 10 km/s

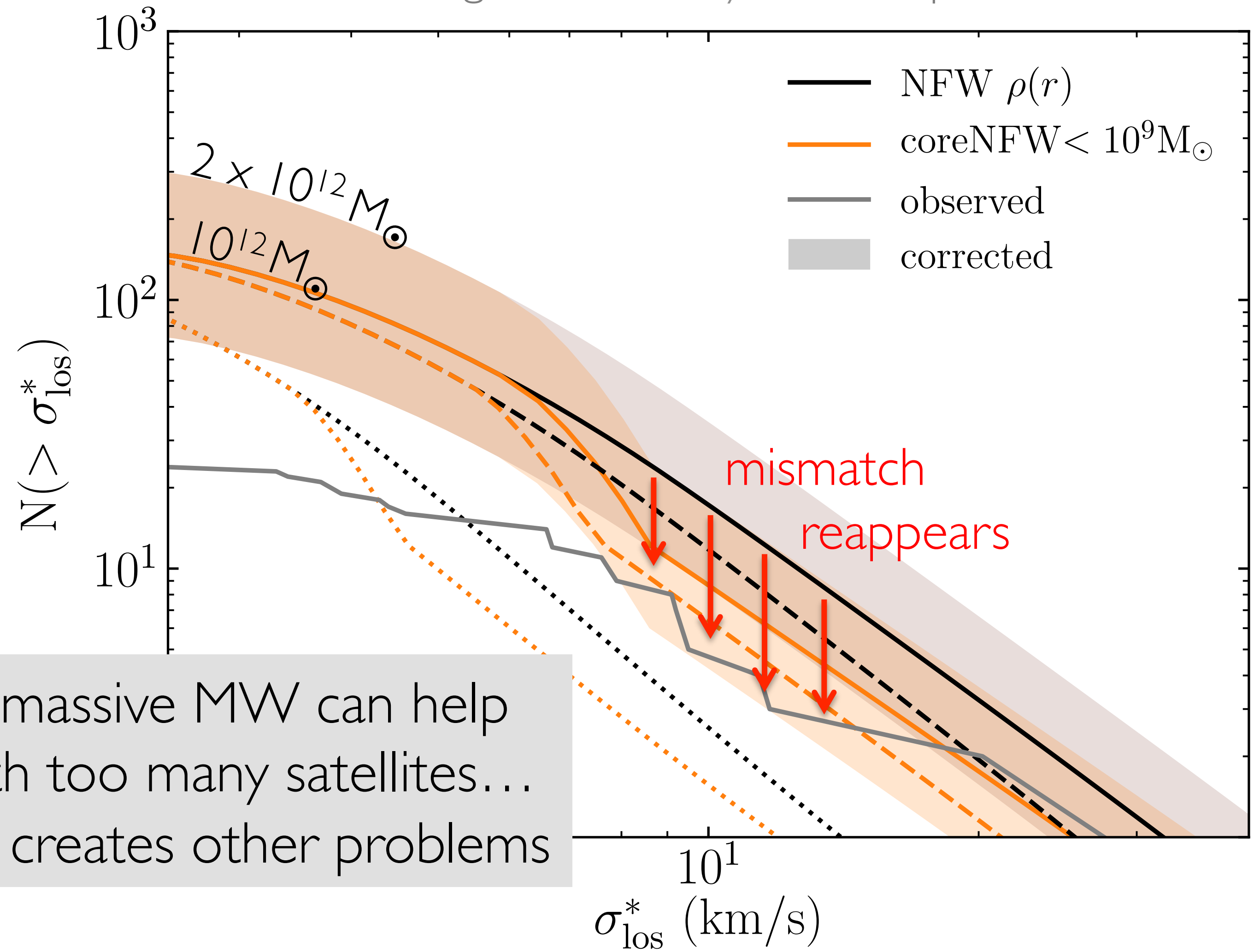


stellar mass-halo mass relation that flattens at ultrafaint scales



theoretical uncertainties

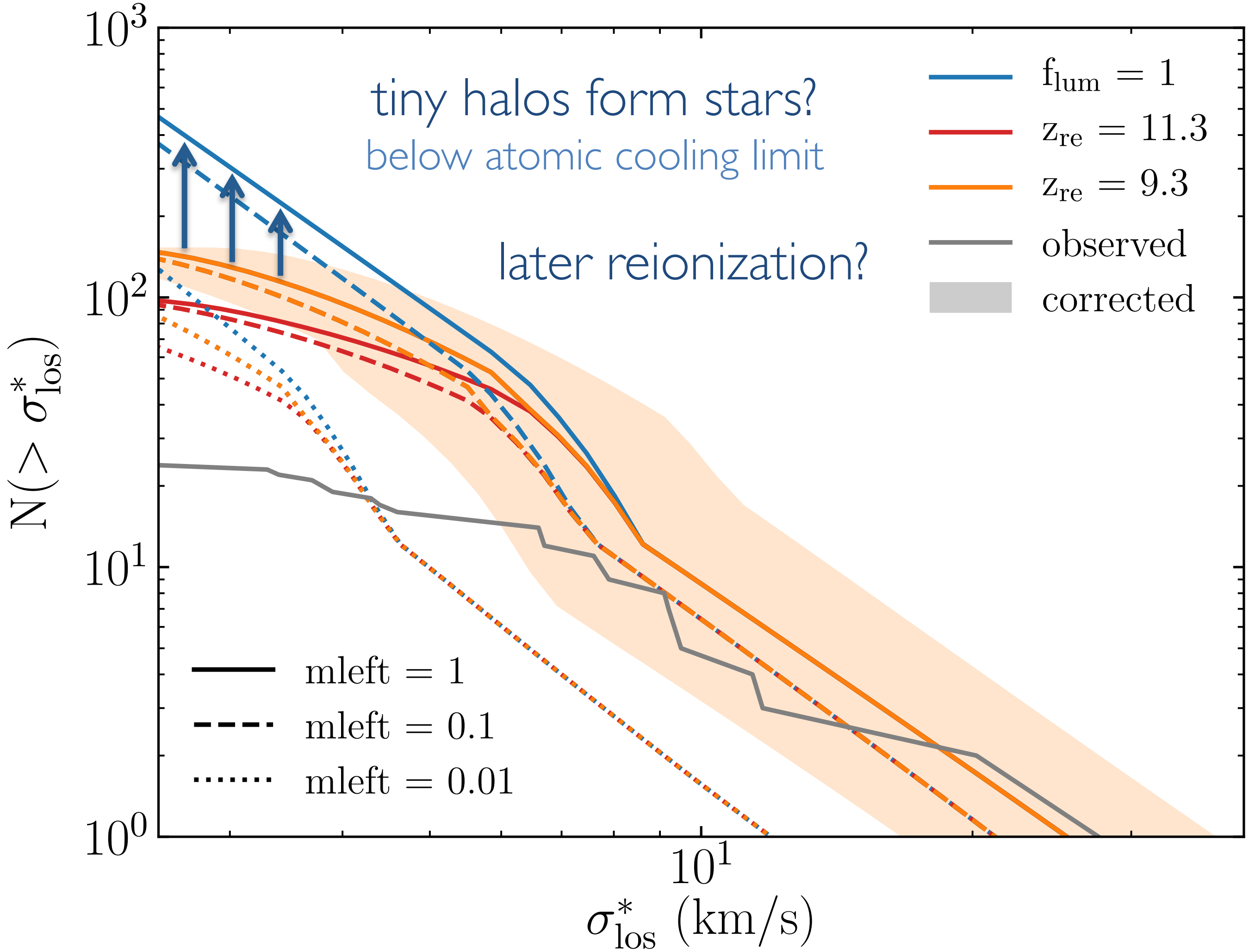
addressing the *too many satellites* problem



a massive MW can help with too many satellites… but creates other problems

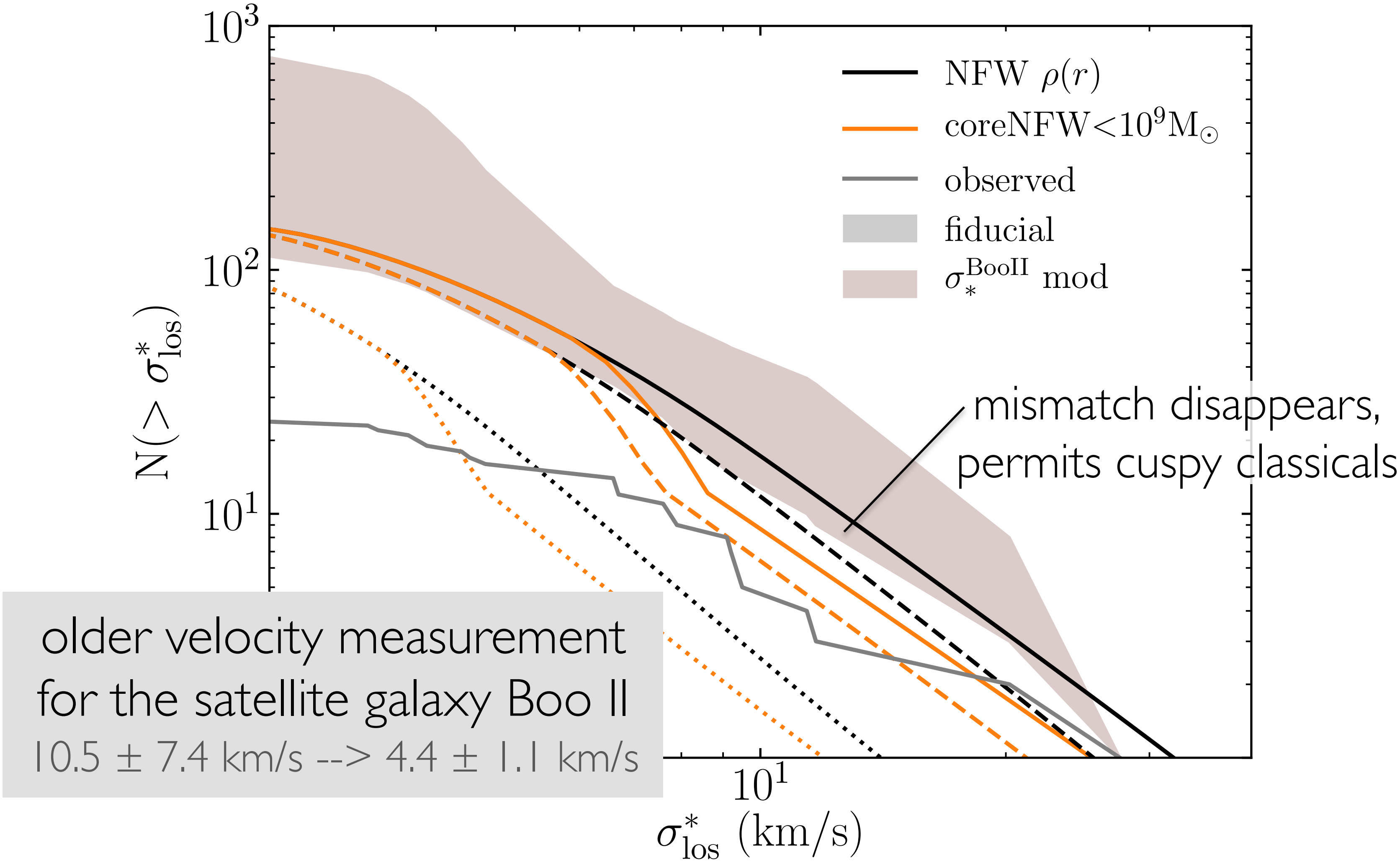
theoretical uncertainties

addressing the *too many satellites* problem



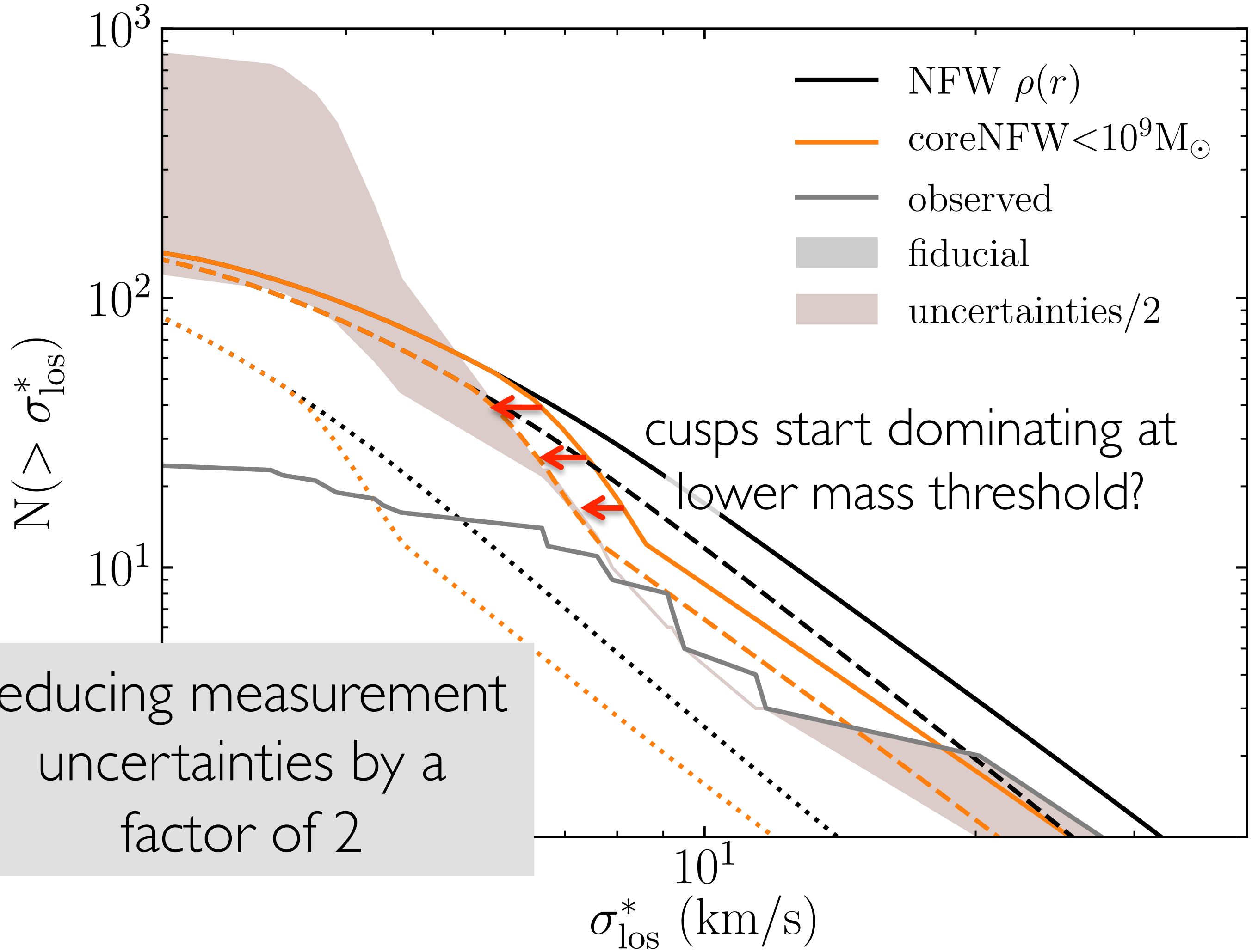
see Graus+ 2019

observational uncertainties



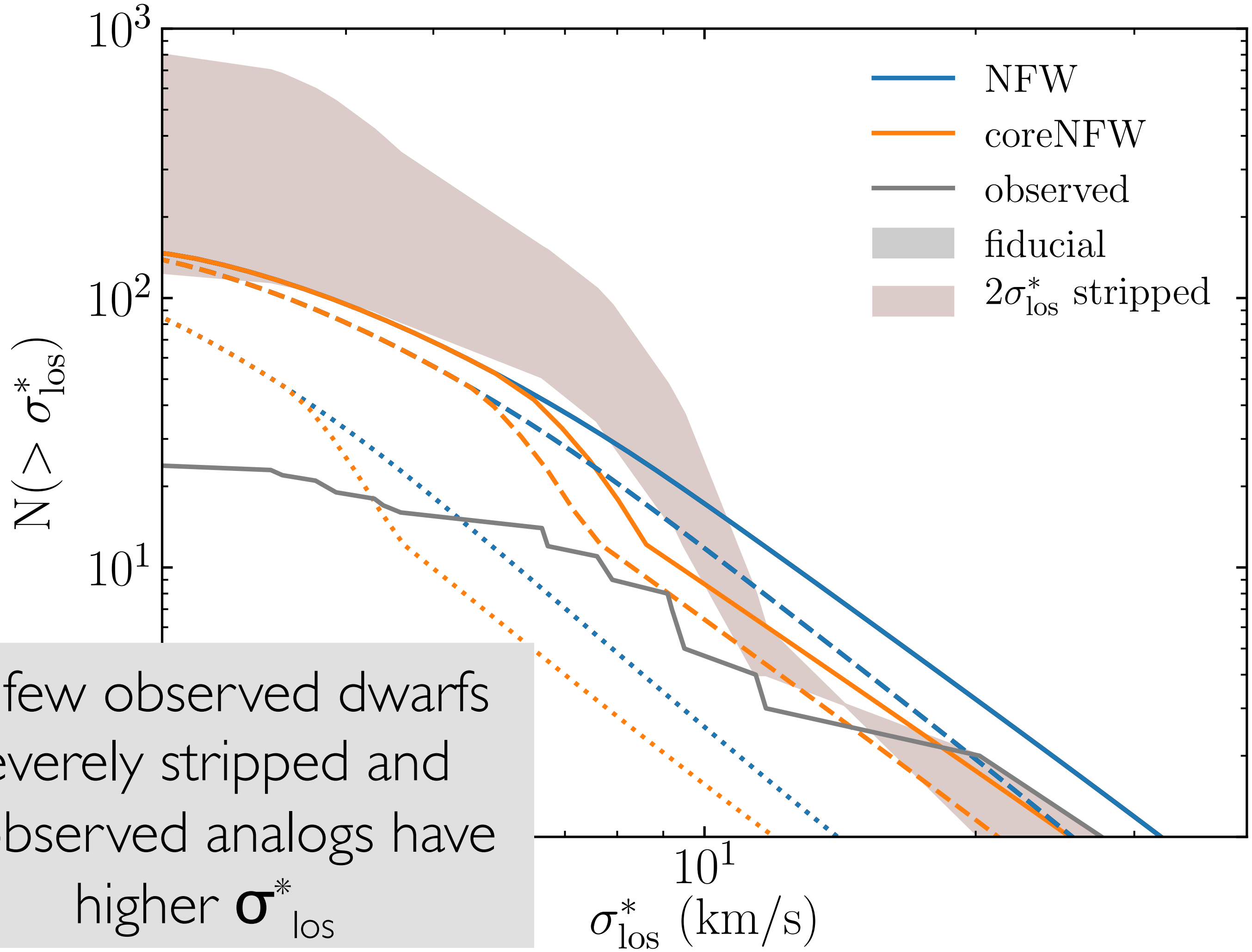
Geha+, private communication

observational uncertainties



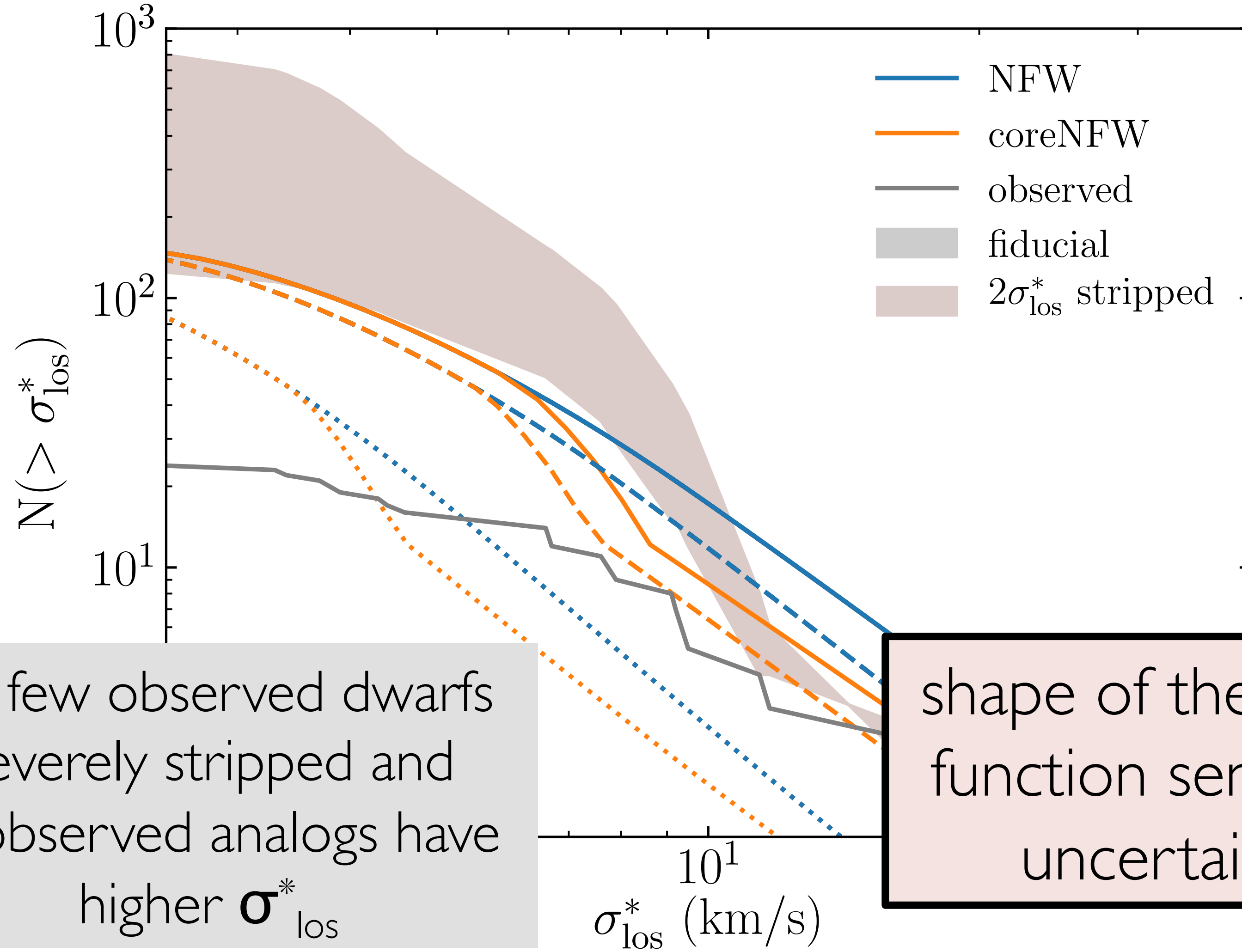
reducing measurement uncertainties by a factor of 2

observational uncertainties



if a few observed dwarfs severely stripped and unobserved analogs have higher $\boldsymbol{\sigma}^*_{los}$

observational uncertainties

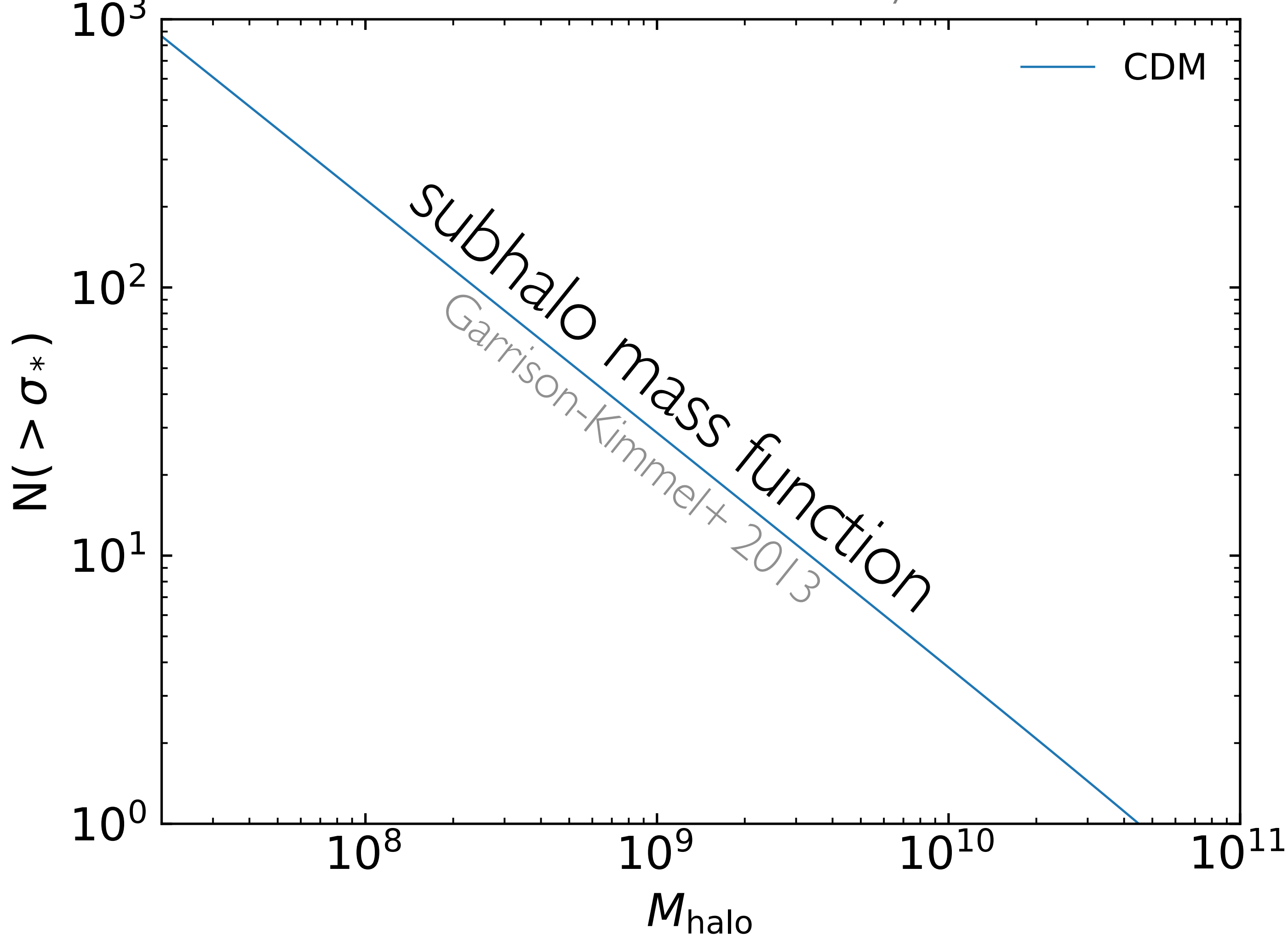


if a few observed dwarfs severely stripped and unobserved analogs have higher $\boldsymbol{\sigma}^*_{los}$

shape of the velocity function sensitive to uncertainties!

theoretical predictions

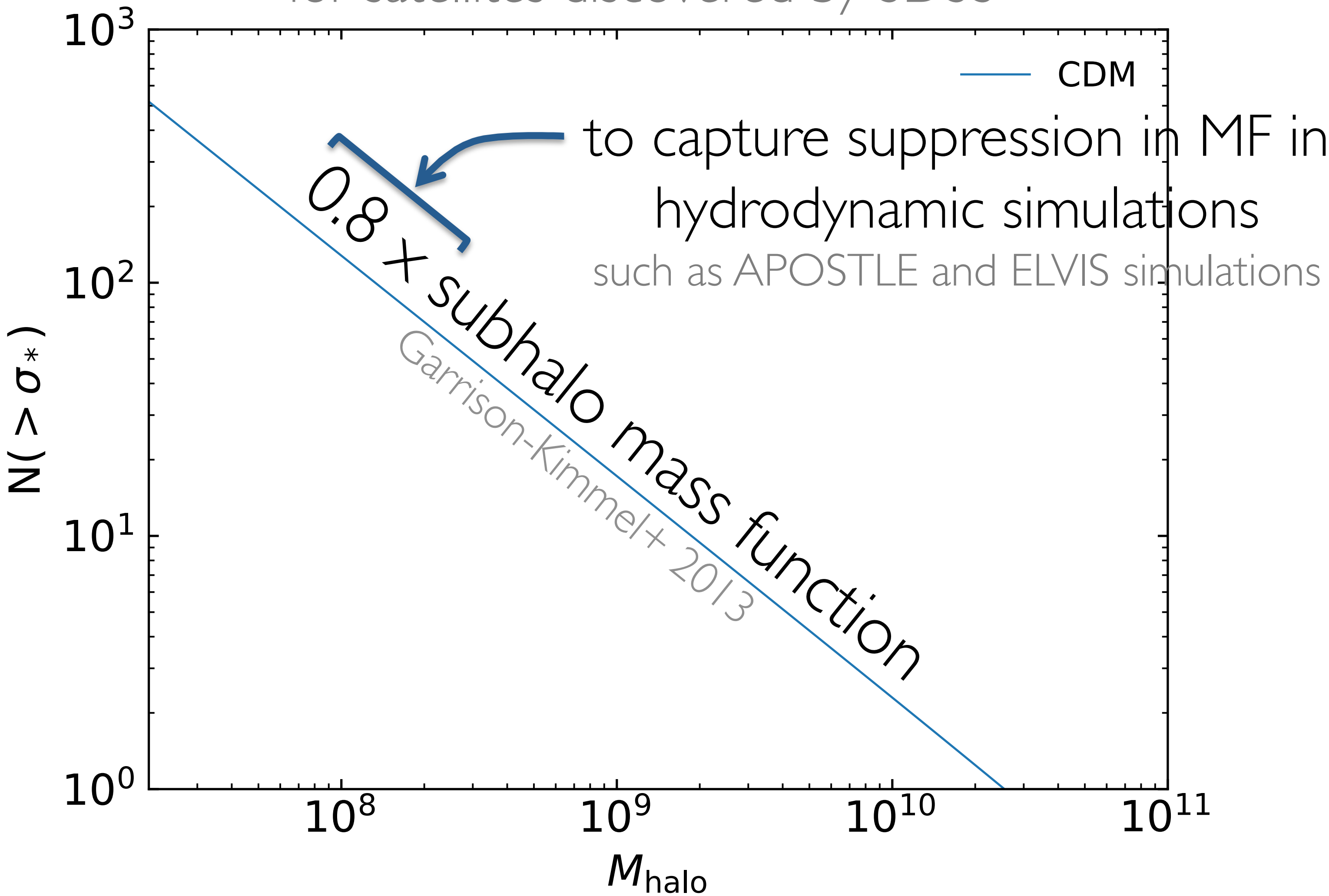
for satellites discovered by SDSS



Kim et al. 2021 (arXiv:2106.09050)

theoretical predictions

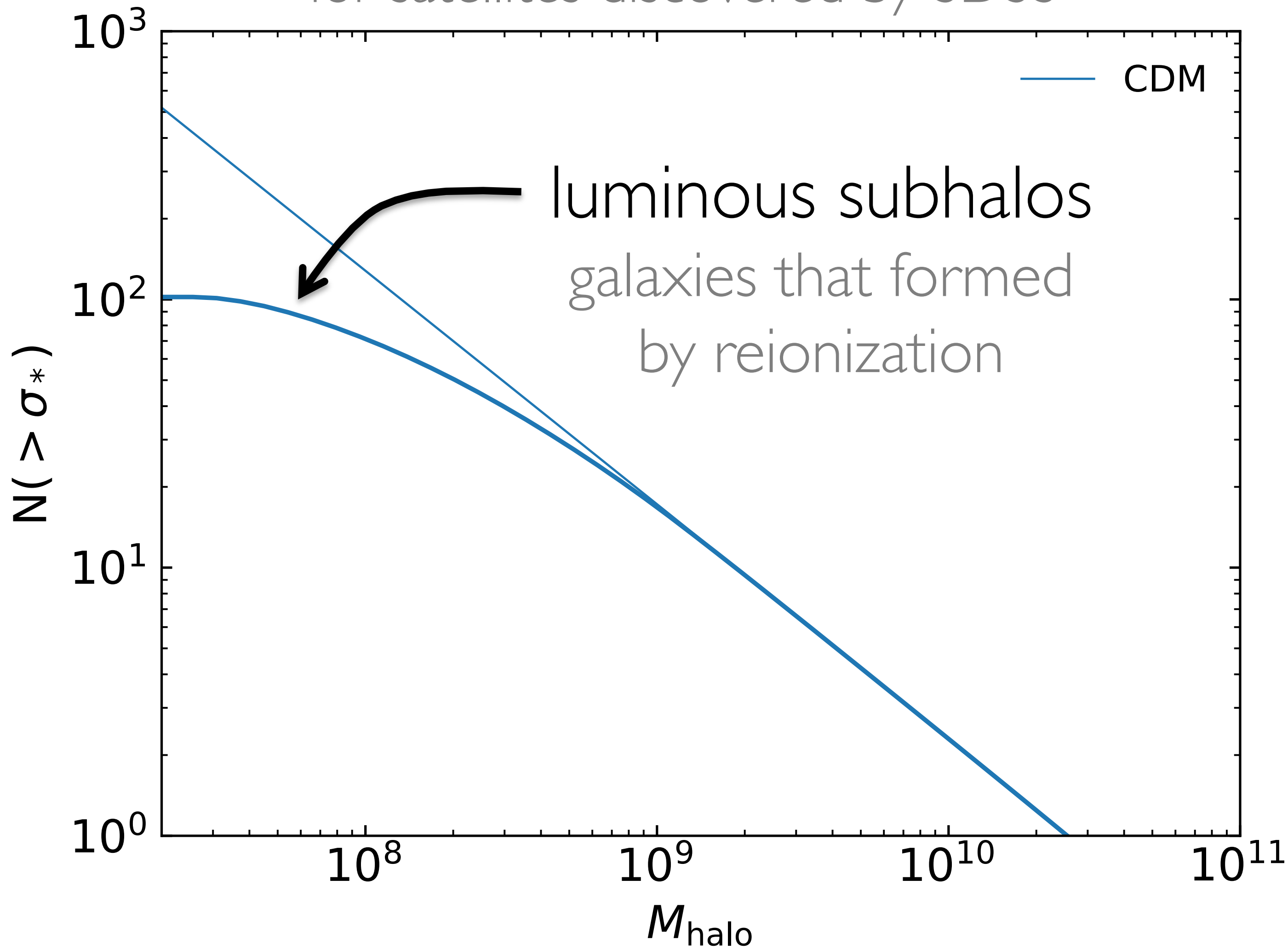
for satellites discovered by SDSS



Kim et al. 2021 (arXiv:2106.09050)

theoretical predictions

for satellites discovered by SDSS



Dooley+ 2017, Barber+ 2014

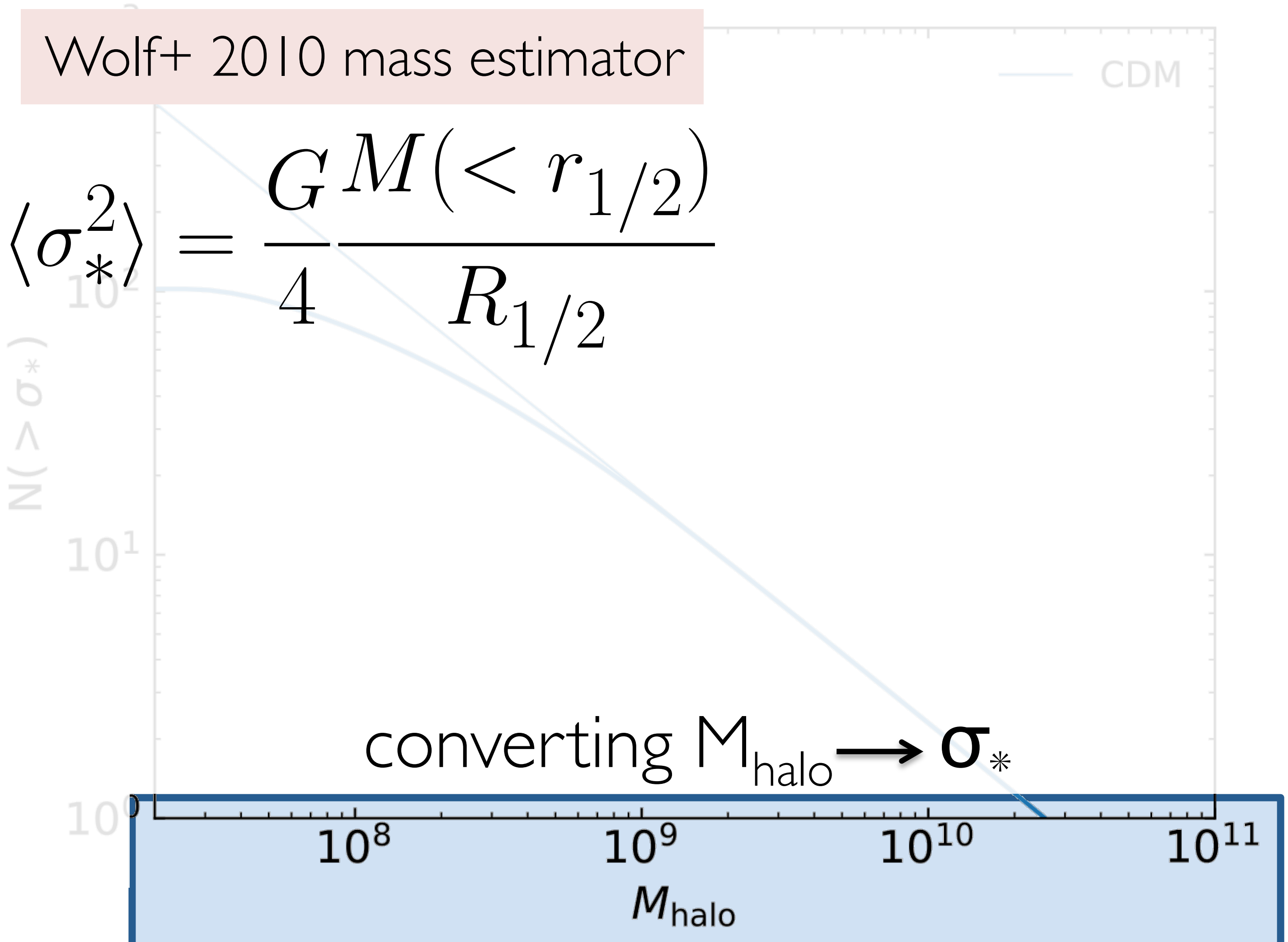
Kim et al. 2021 (arXiv:2106.09050)

theoretical predictions

Wolf+ 2010 mass estimator

$$\langle \sigma_*^2 \rangle = \frac{G}{4} \frac{M(< r_{1/2})}{R_{1/2}}$$

converting $M_{halo} \longrightarrow \boldsymbol{\sigma}_*$



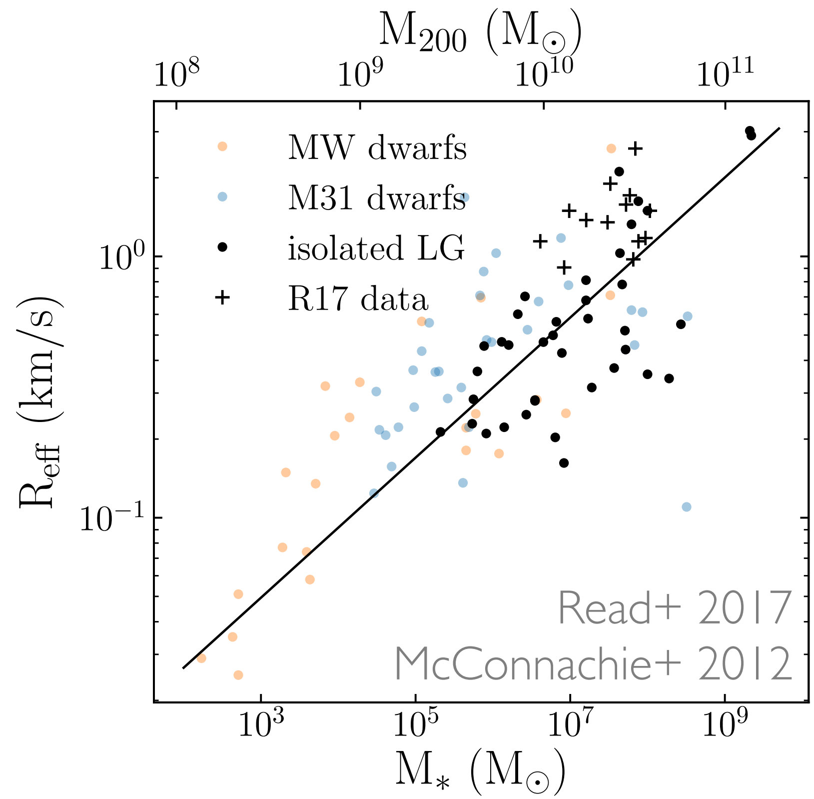
Kim et al. 2021 (arXiv:2106.09050)

theoretical predictions

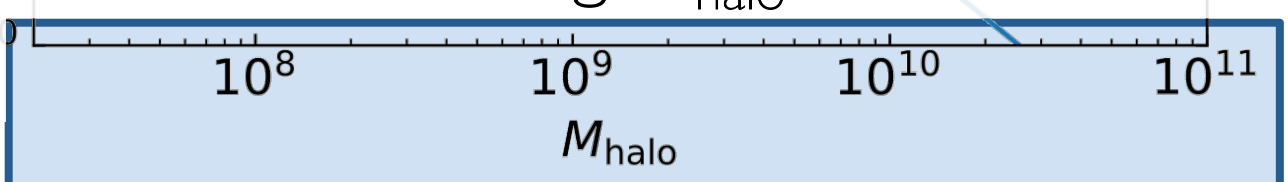
Wolf+ 2010 mass estimator

$$\langle \sigma_*^2 \rangle = \frac{G}{4} \frac{M(< r_{1/2})}{R_{1/2}}$$

from fit to observed isolated dwarfs



converting $M_{halo} \longrightarrow \sigma_*$



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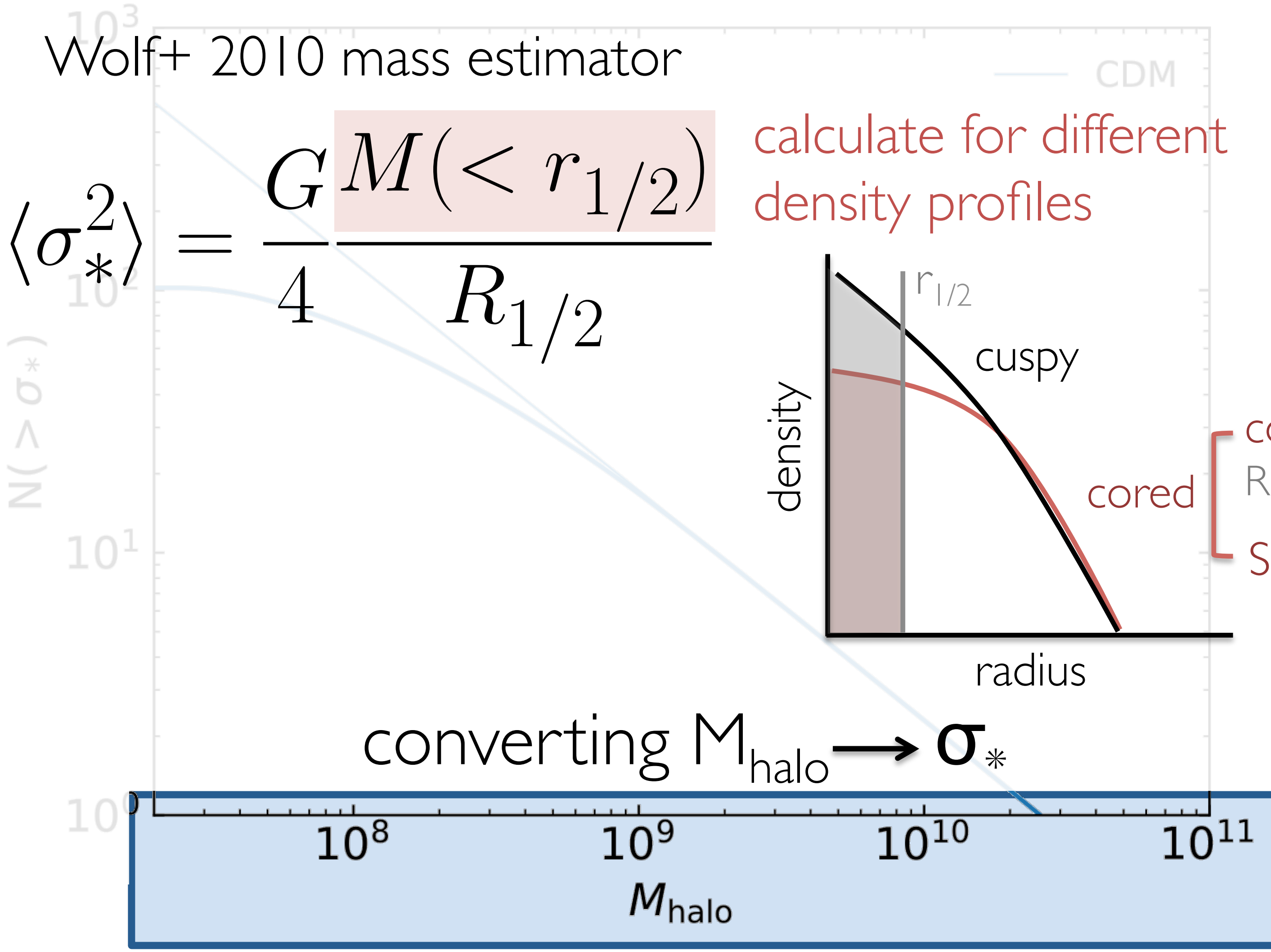
calculate for different density profiles



coreNFW
Read+ 2017
SIDM

converting $M_{halo} \longrightarrow \sigma_*$

Kim et al. 2021 (arXiv:2106.09050)

theoretical predictions

Wolf+ 2010 mass estimator

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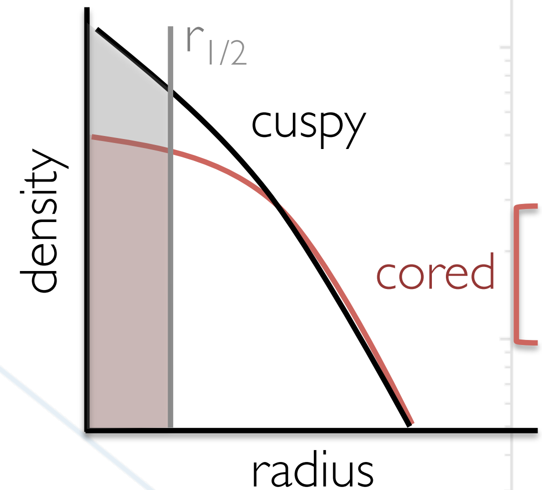


coreNFW
Read+ 2017

SIDM

and a few others choices, e.g.

c-M relation	Diemer & Joyce 2019
infall redshift	z = 1

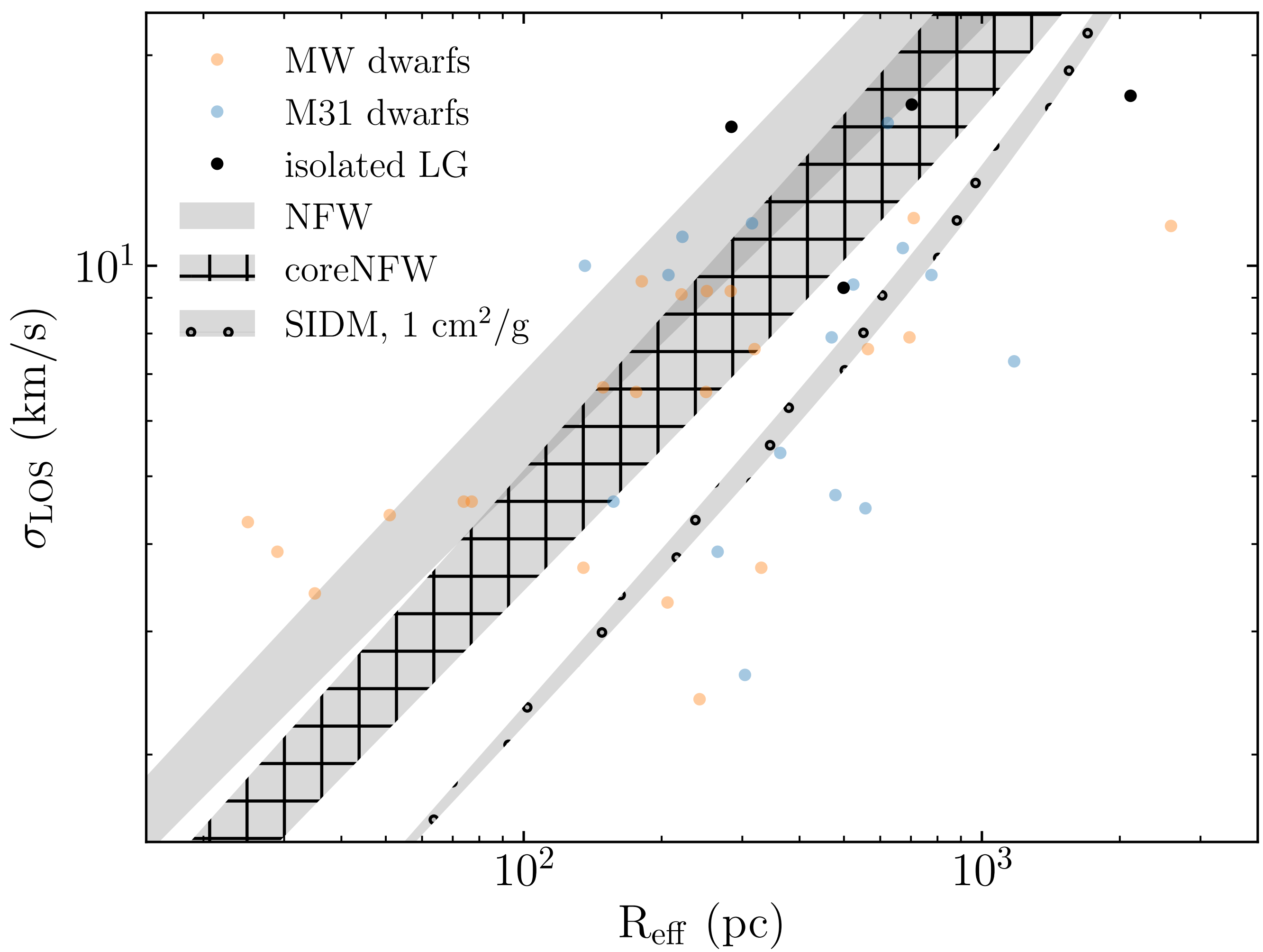
converting $M_{halo} \longrightarrow \sigma_*$

10^8 10^9 10^{10} 10^{11}

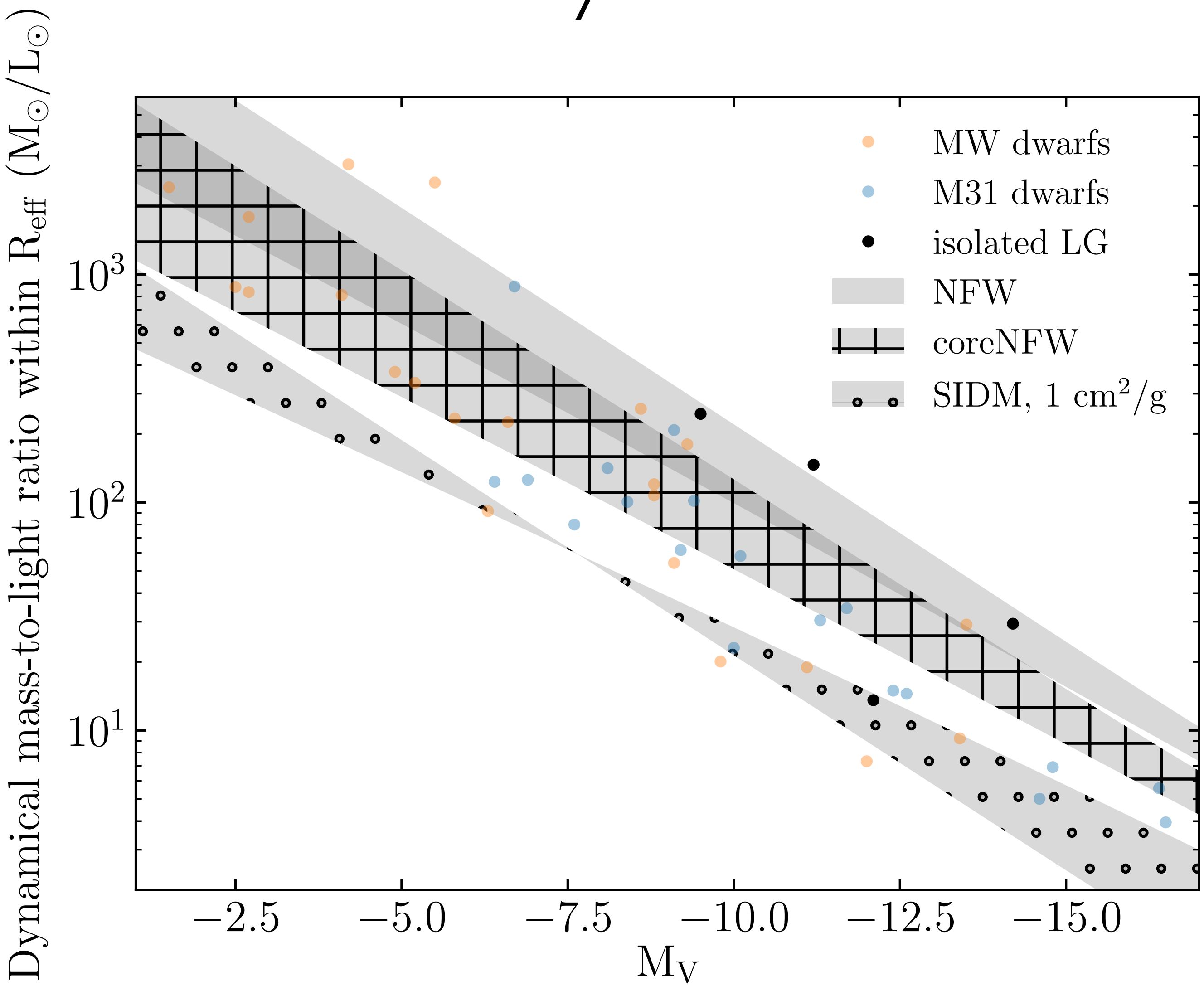
M_{halo}

Kim et al. 2021 (arXiv:2106.09050)

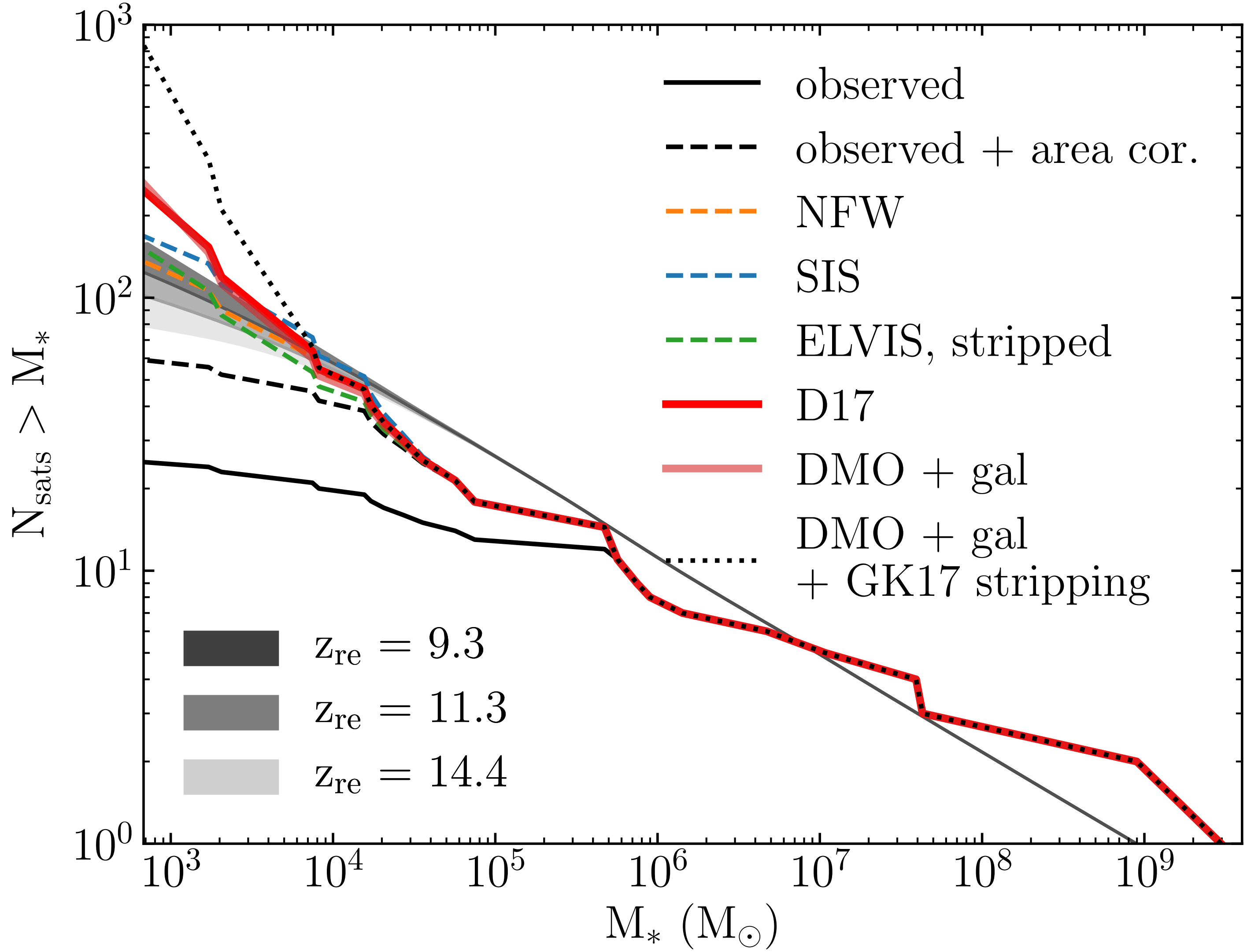
sanity checks



sanity checks



corrected luminosity function

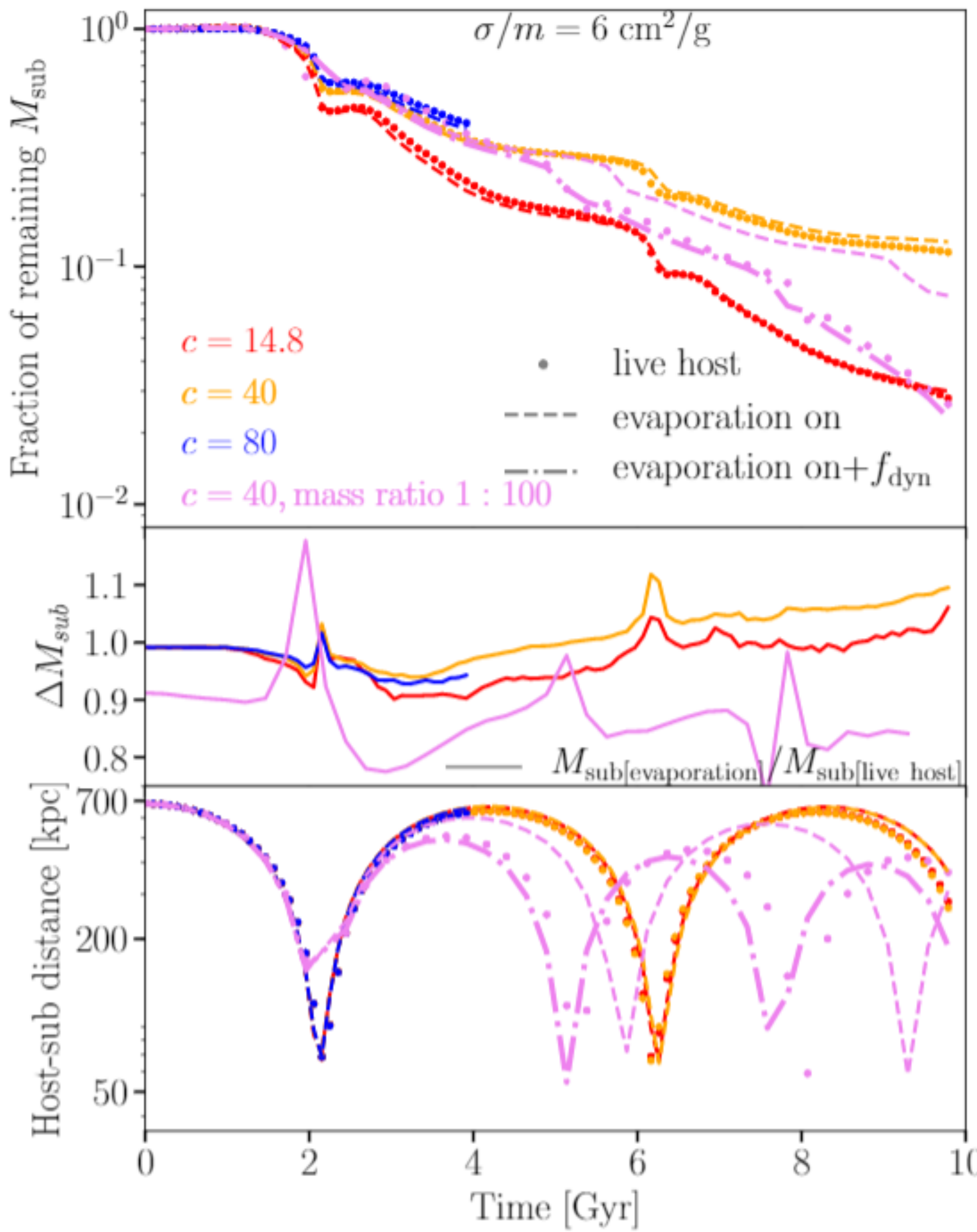


EXTRAS: CORE COLLAPSE

Hybrid ccSIDM validation: mass loss

- Discrepancy < 10% for subs 1/1000 of the host
- Mostly due to missing dynamical friction
- But for smaller subhalos less significant

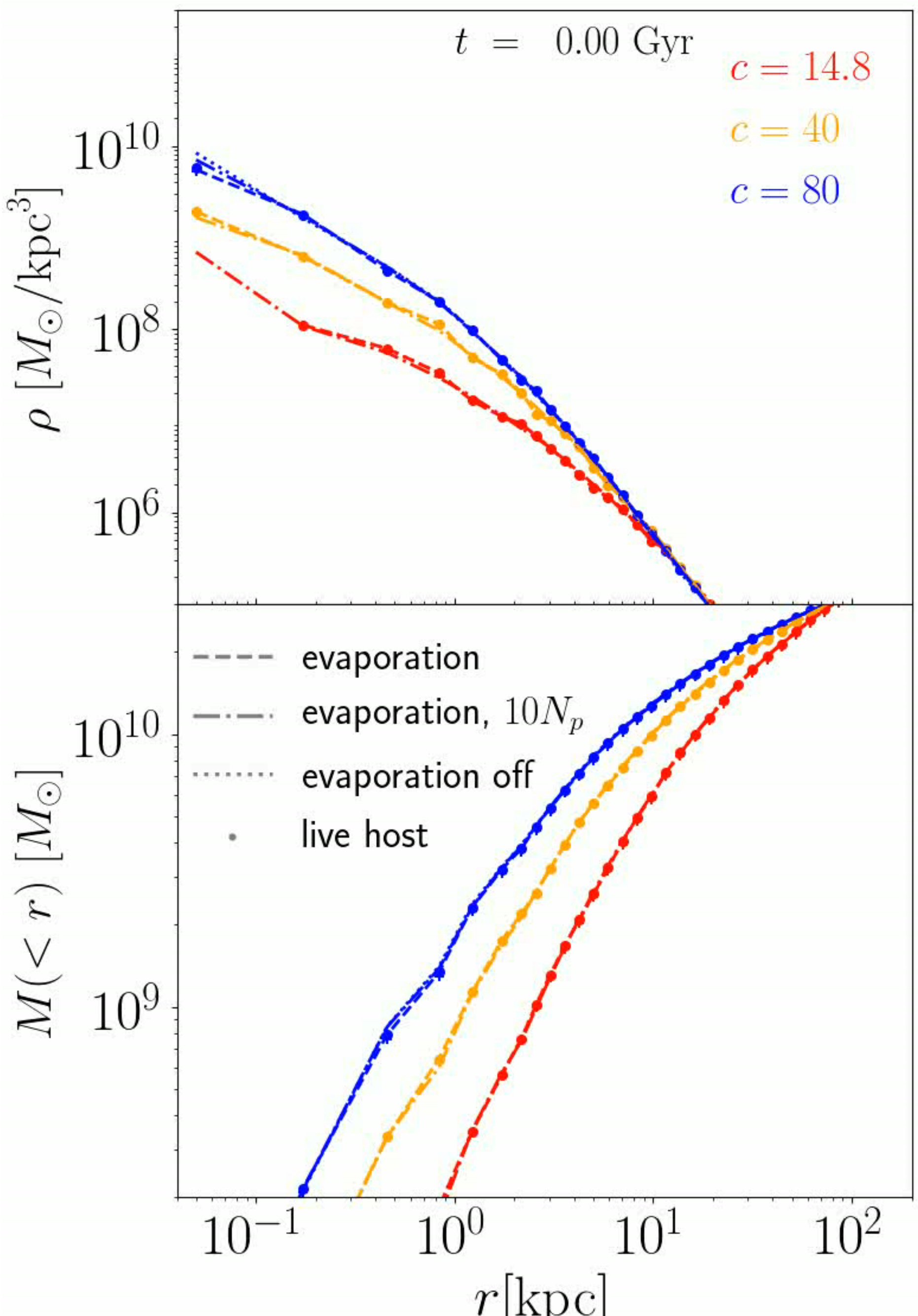
Can study *arbitrarily* small subhalos



Adapted from slides by Carton Zeng

Hybrid ccSIDM validation: density profiles

- Good agreement w/live host simulation for both cored and core-collapsing
- Robust for the particle resolution
- Evaporation is significant



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