constraints *from the* satellite dwarf galaxies *of the* Milky Way

Stacy Kim

University of Surrey

SIDM Pollica Workshop 2023

Caia DR1 sky map

constraints *from the* satellite dwarf galaxies *of the* Milky Way

AND BEYOND!

Stacy Kim

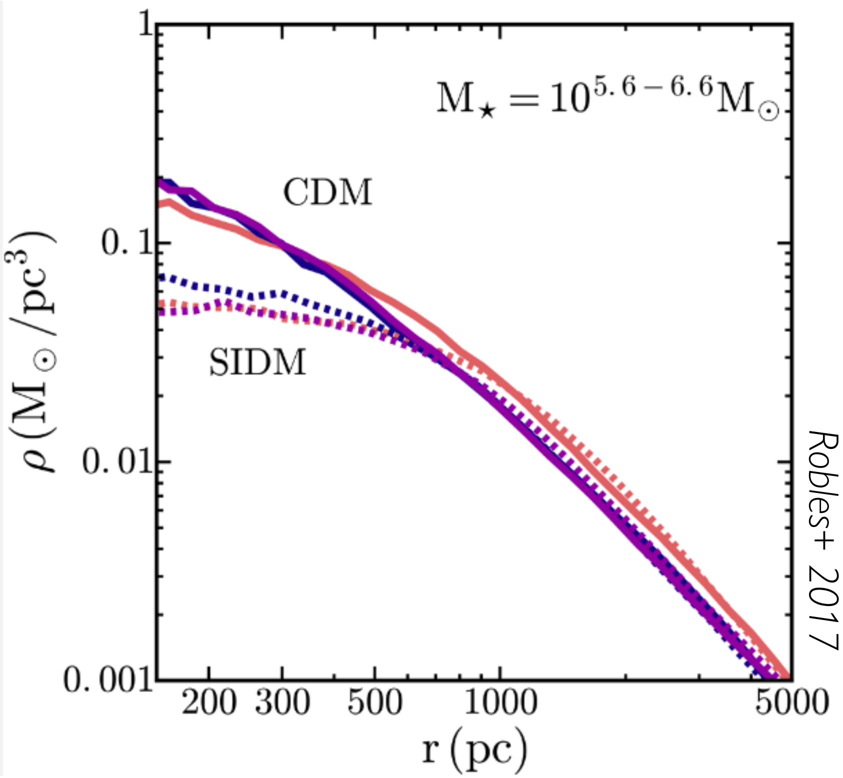
University of Surrey

SIDM Pollica Workshop 2023

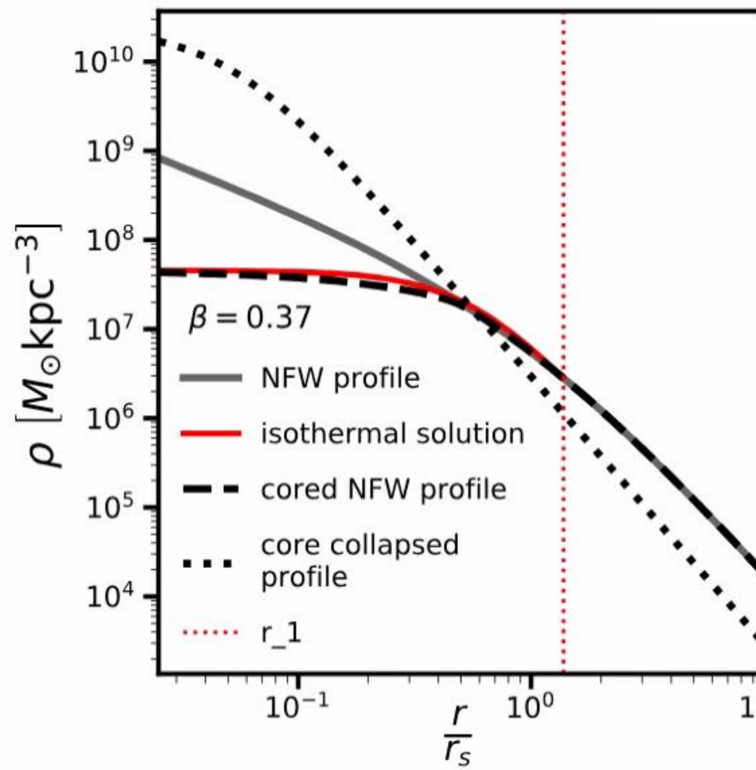
Gaia DR1 sky map

Key classical SIDM prediction: low density central cores

Stars live where densities can differ significantly from CDM:



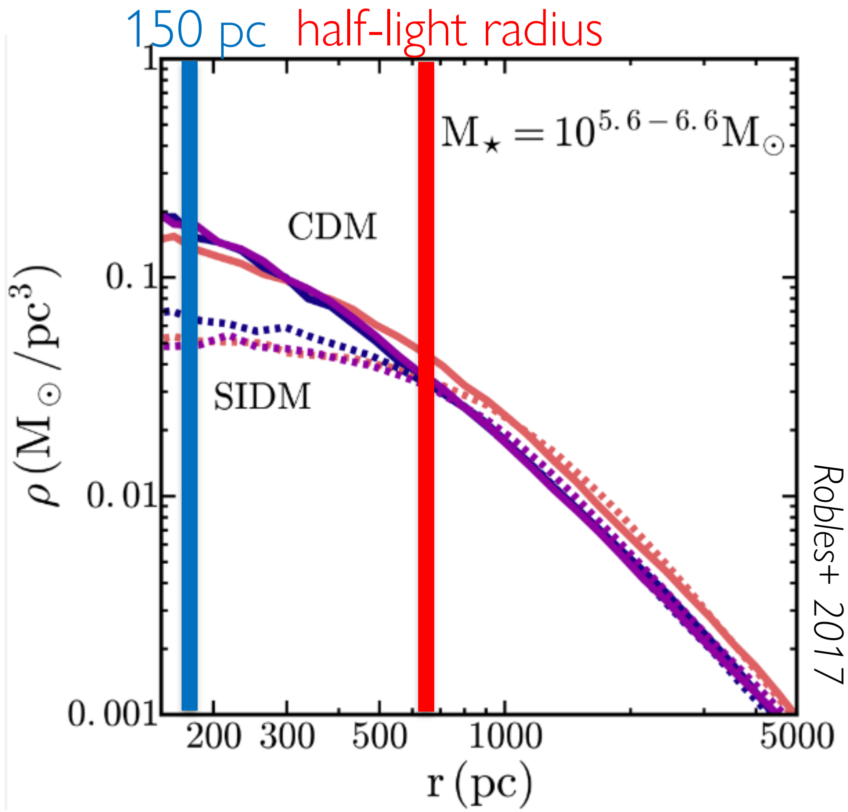
Robles+ 2017

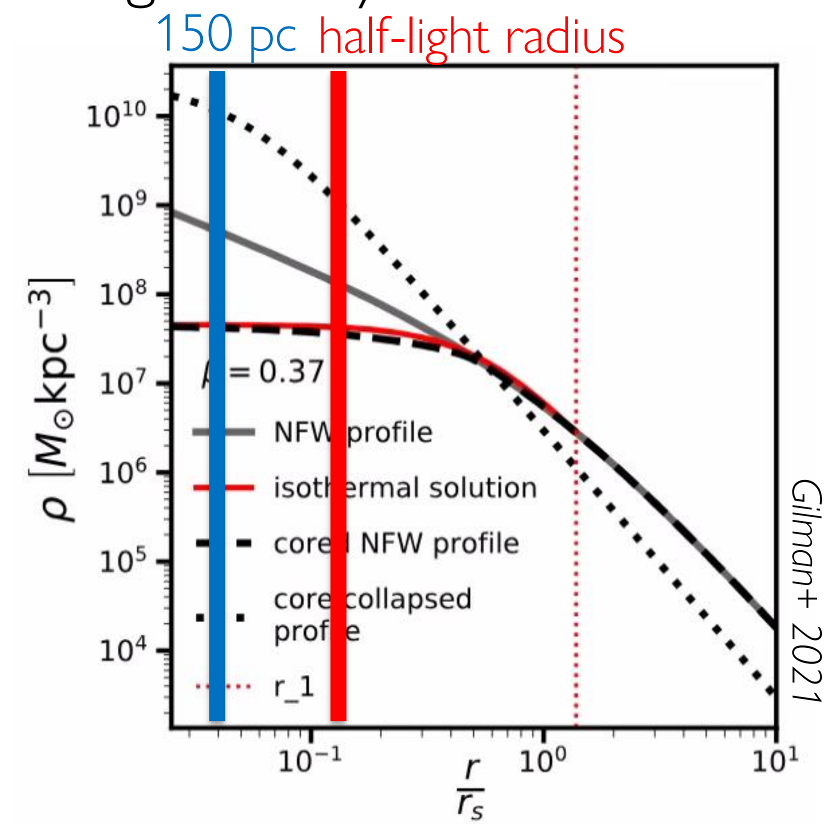


Gilman+ 2021

Key classical SIDM prediction: low density central cores

Stars live where densities can differ significantly from CDM:

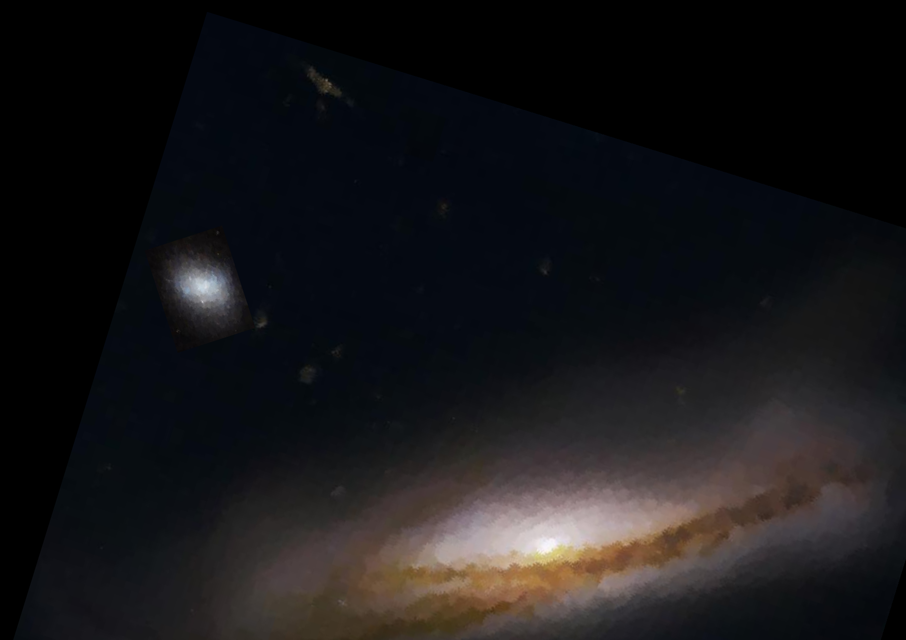




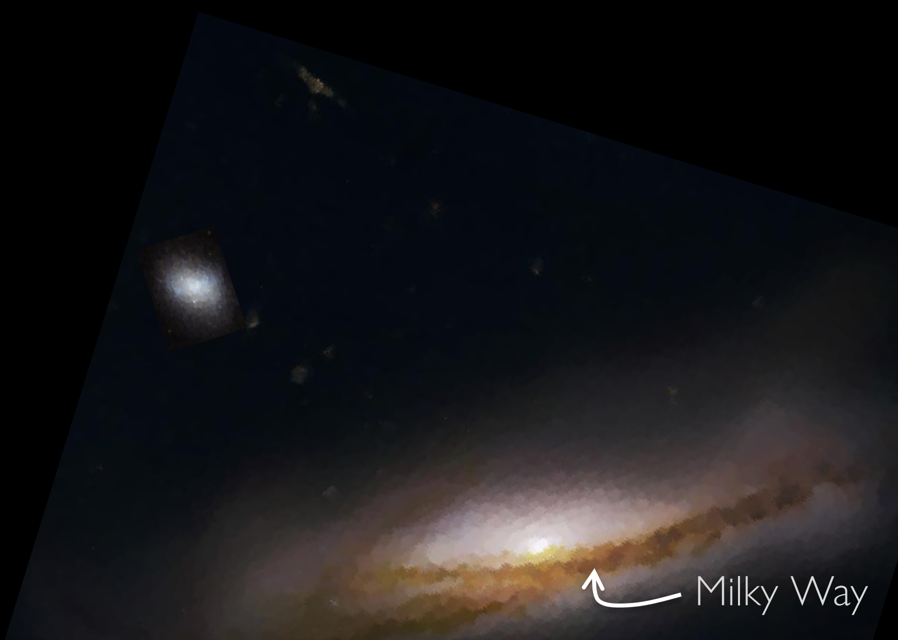
Thus stellar kinematics can be highly sensitive to SIDM!

as well as other processes/models with differing central densities

constraining SIDM via satellite kinematics



constraining SIDM via satellite kinematics



constraining SIDM via satellite kinematics

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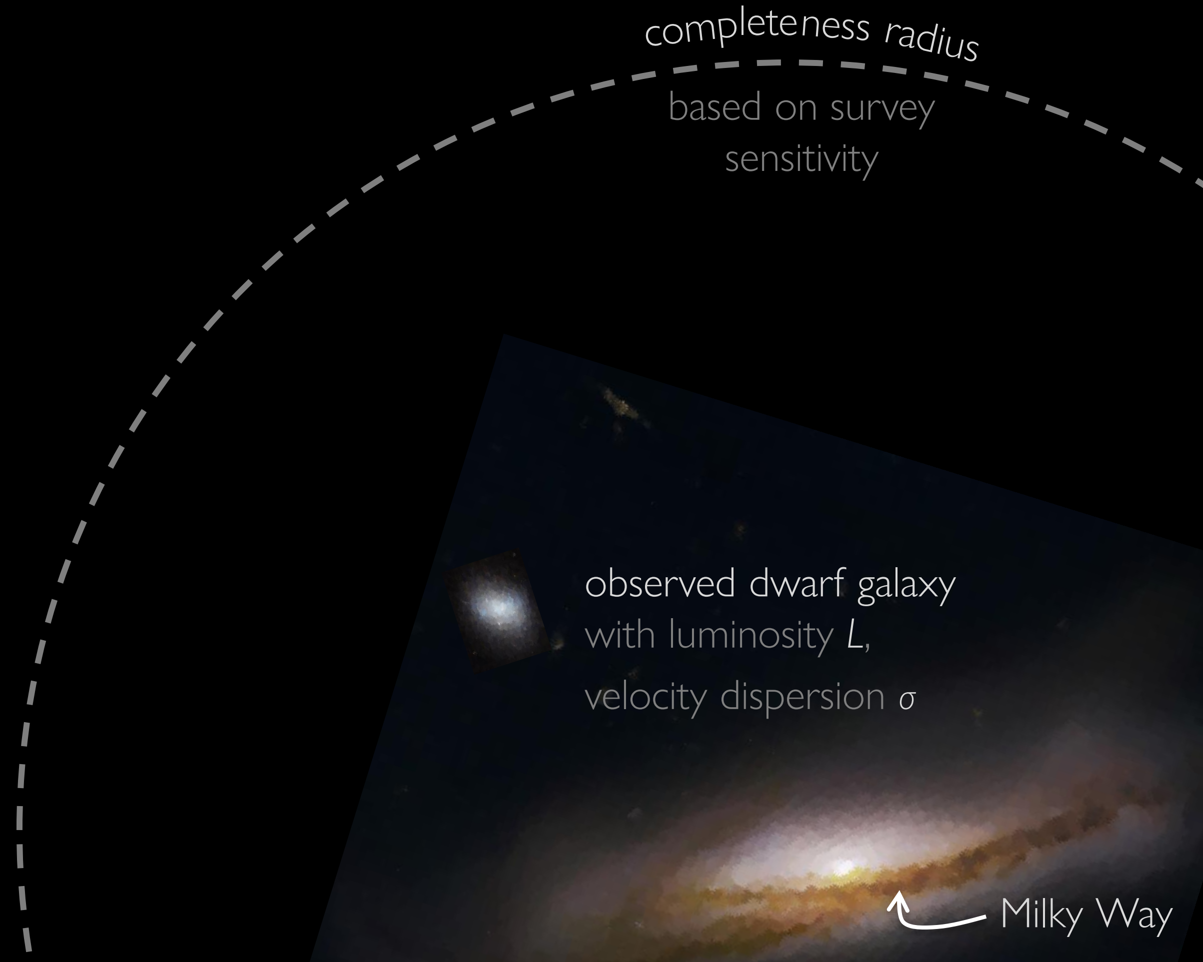
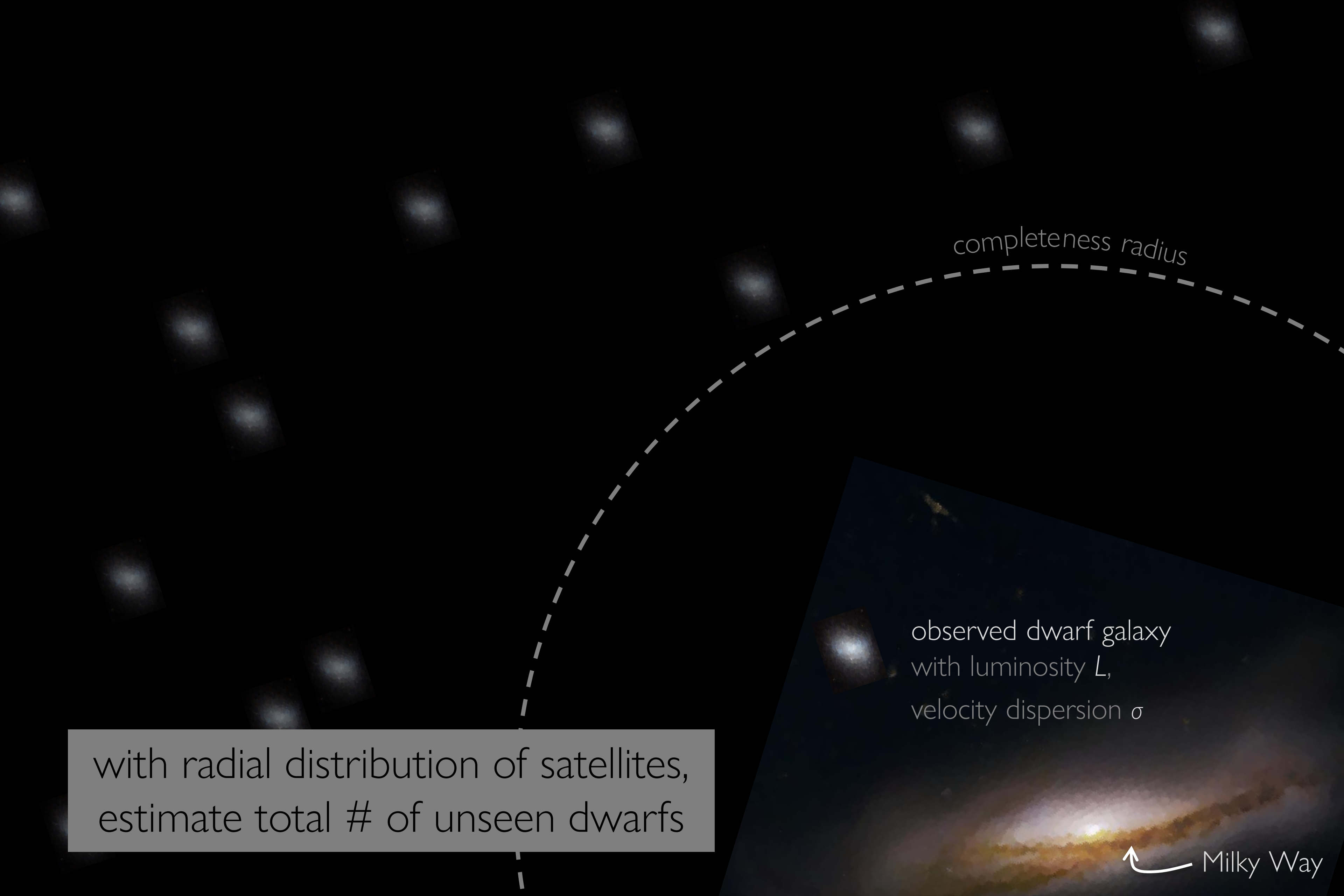
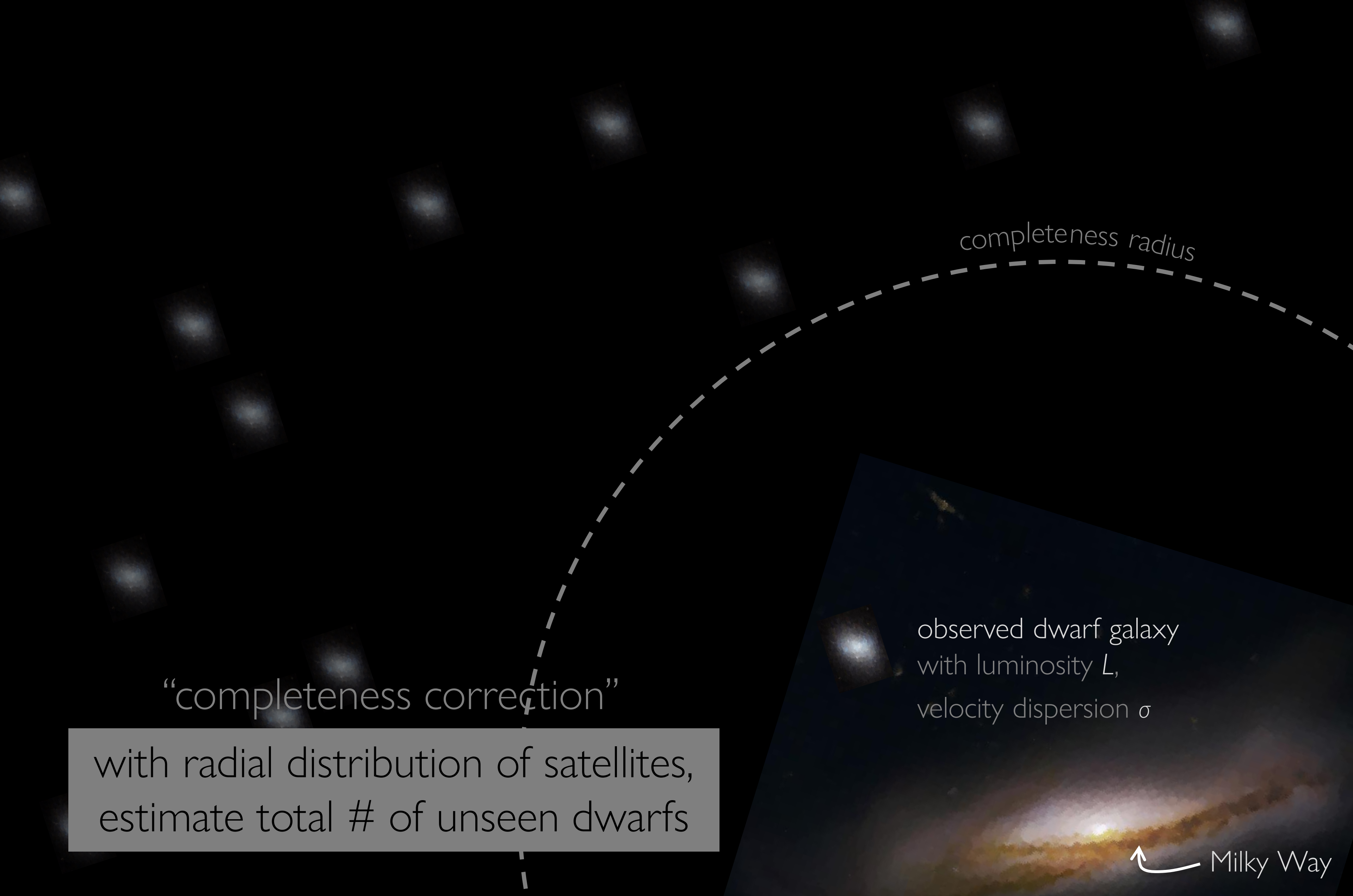


constraining SIDM via satellite kinematics



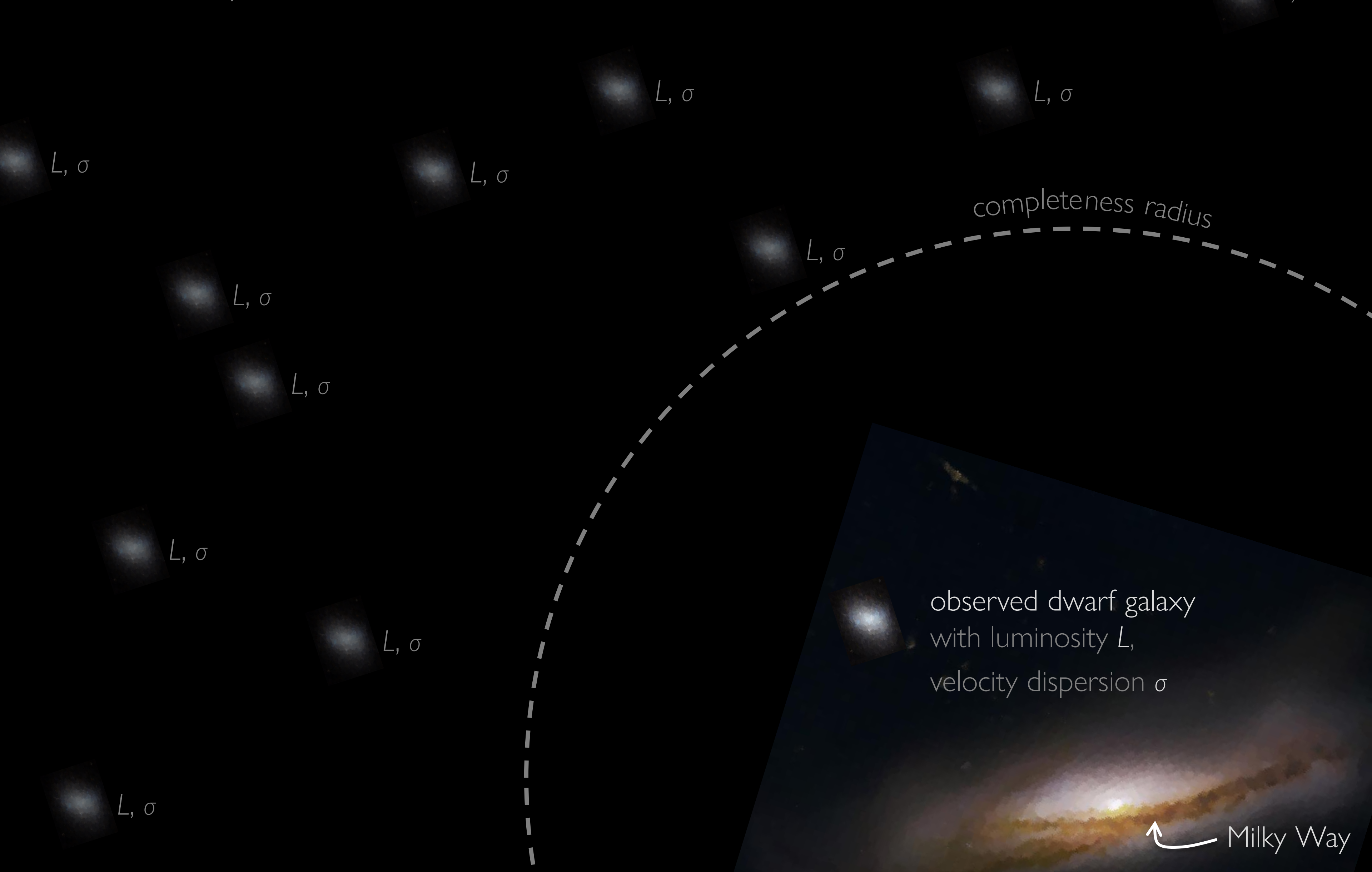
with radial distribution of satellites,
estimate total # of unseen dwarfs

constraining SIDM via satellite kinematics



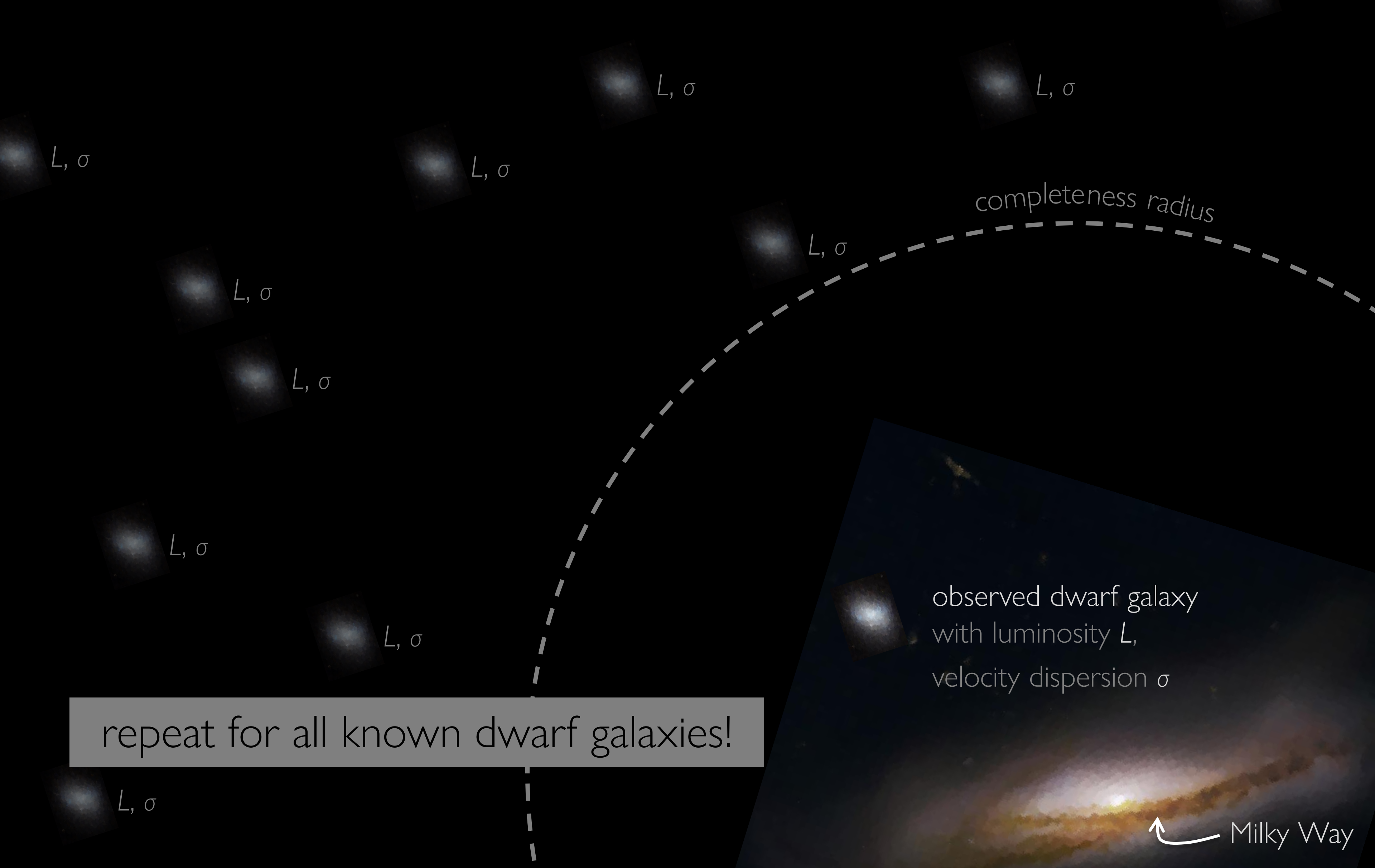
constraining SIDM via satellite kinematics

with completeness corrections



constraining SIDM via satellite kinematics

with completeness corrections



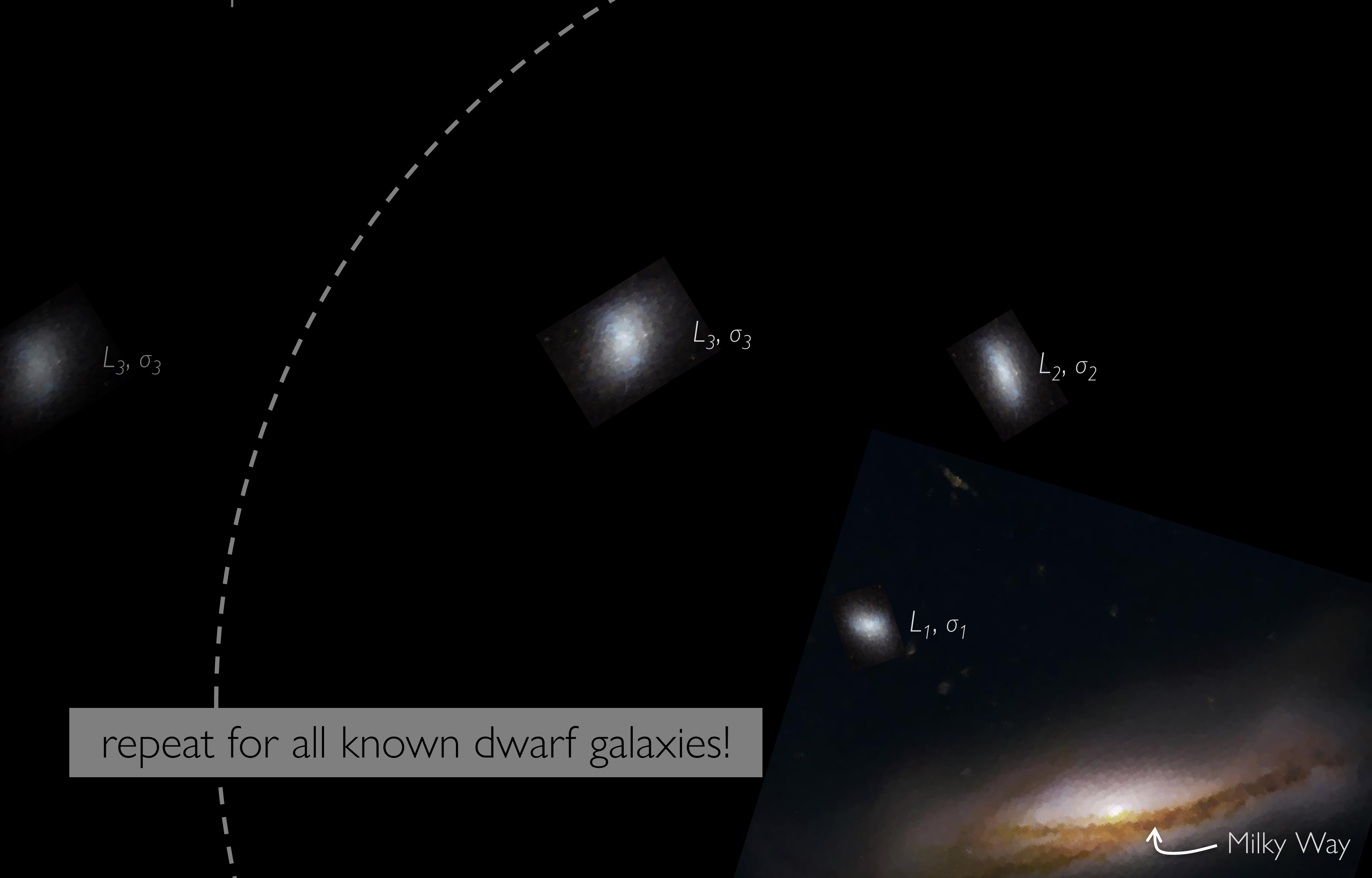
constraining SIDM via satellite kinematics

with completeness corrections

repeat for all known dwarf galaxies!

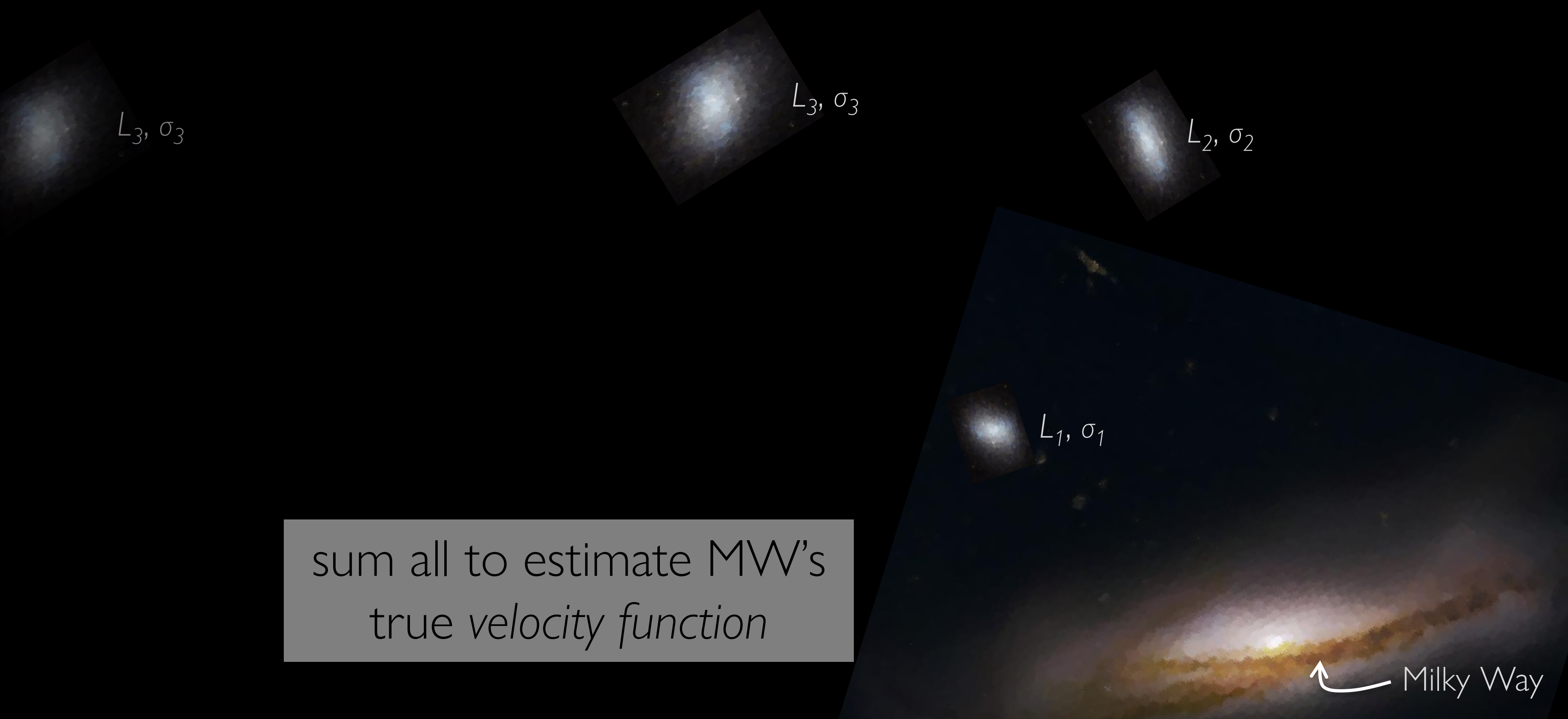
constraining SIDM via satellite kinematics

with completeness corrections



constraining SIDM via satellite kinematics

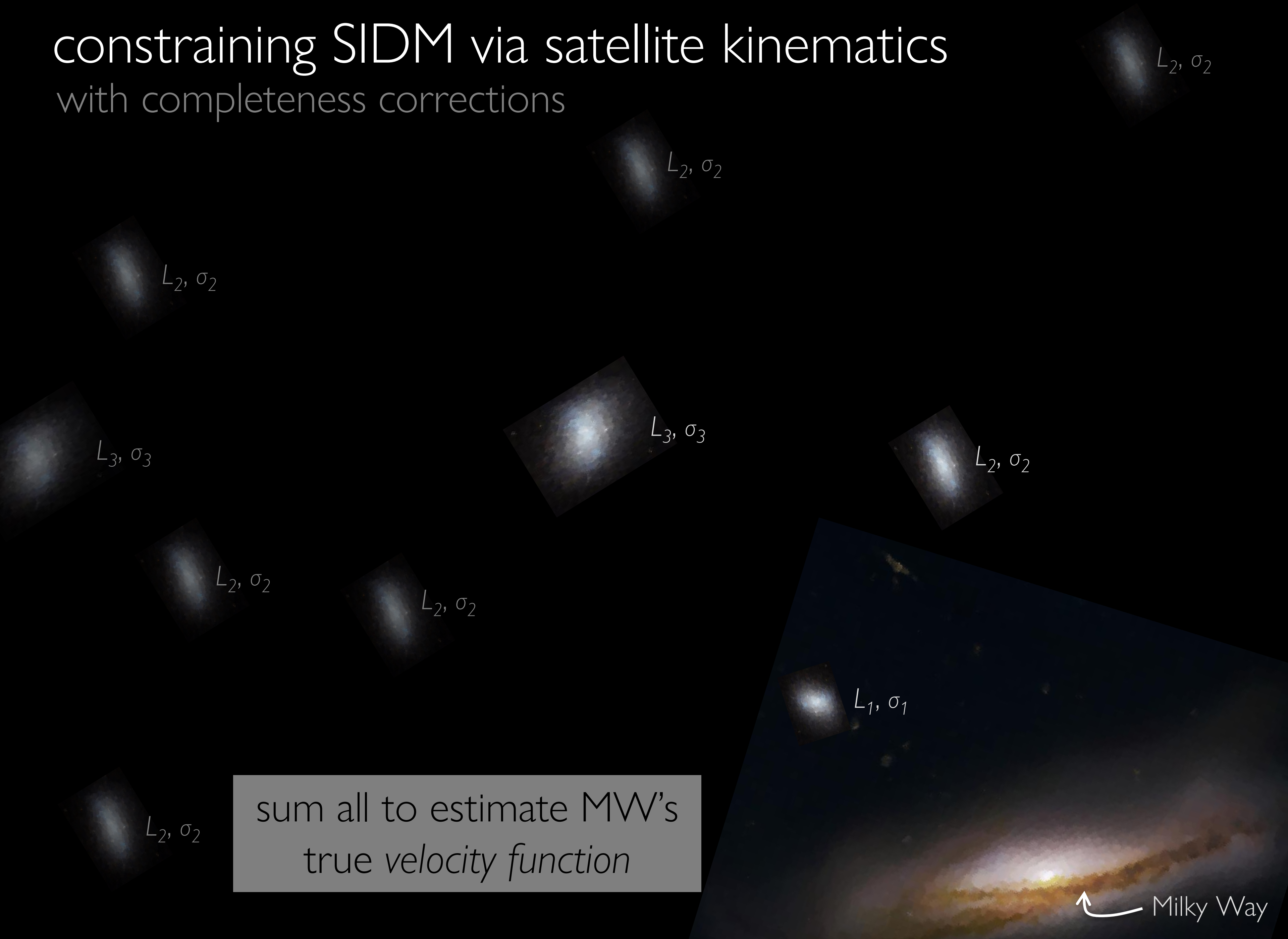
with completeness corrections



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

constraining SIDM via satellite kinematics

with completeness corrections



constraining SIDM via satellite kinematics

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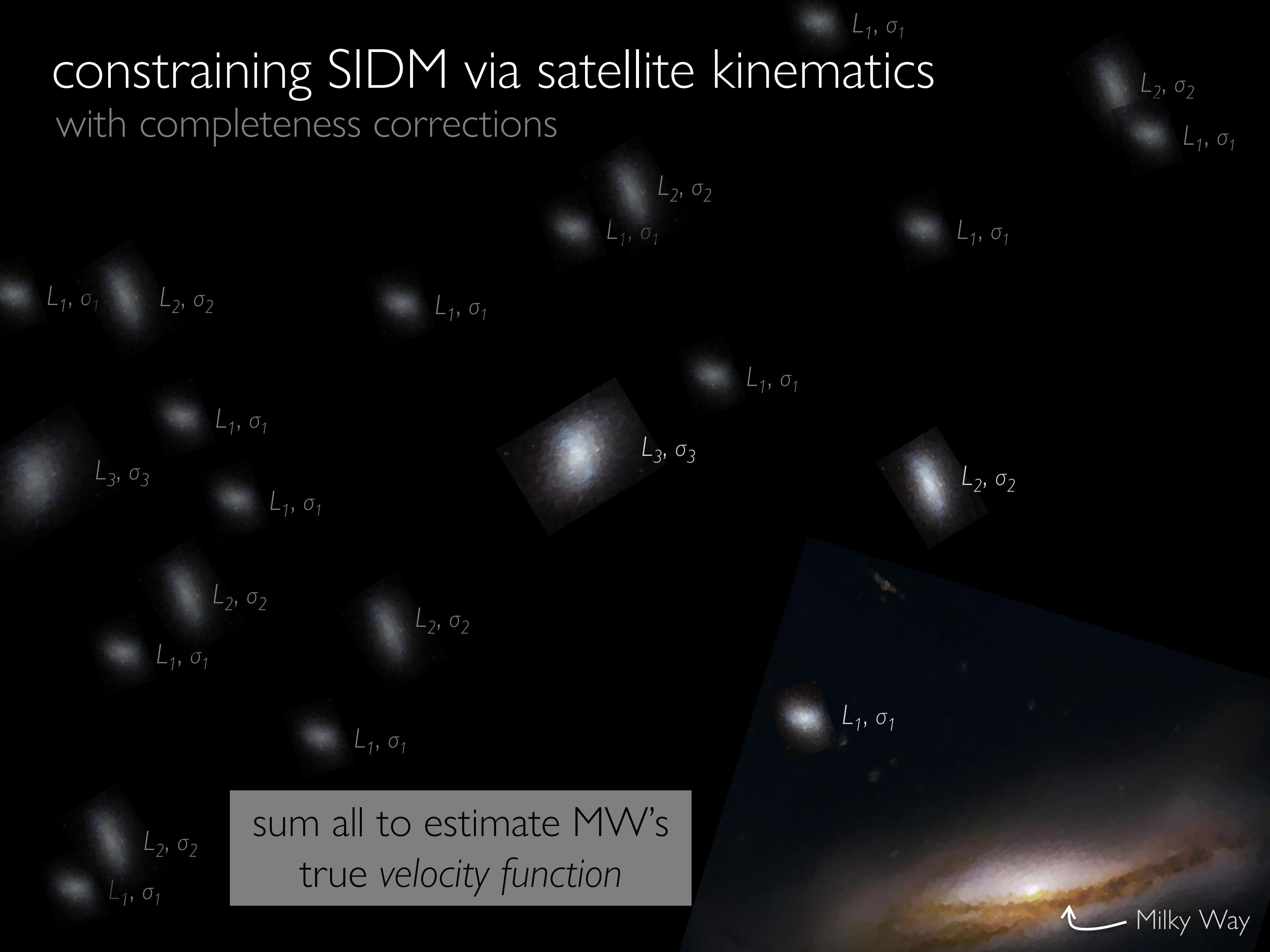
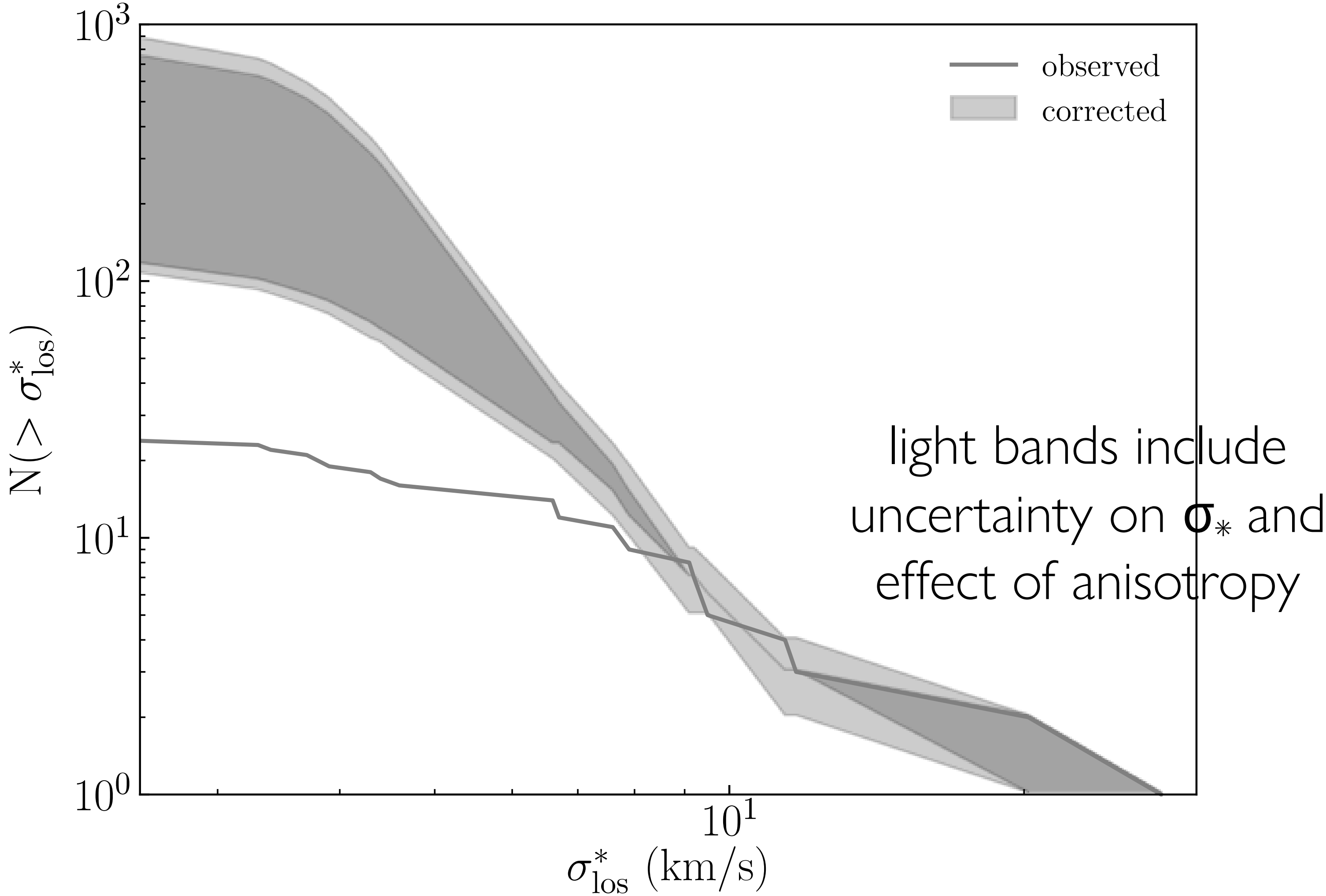


sum all to estimate MW's true *velocity function*

corrected velocity function

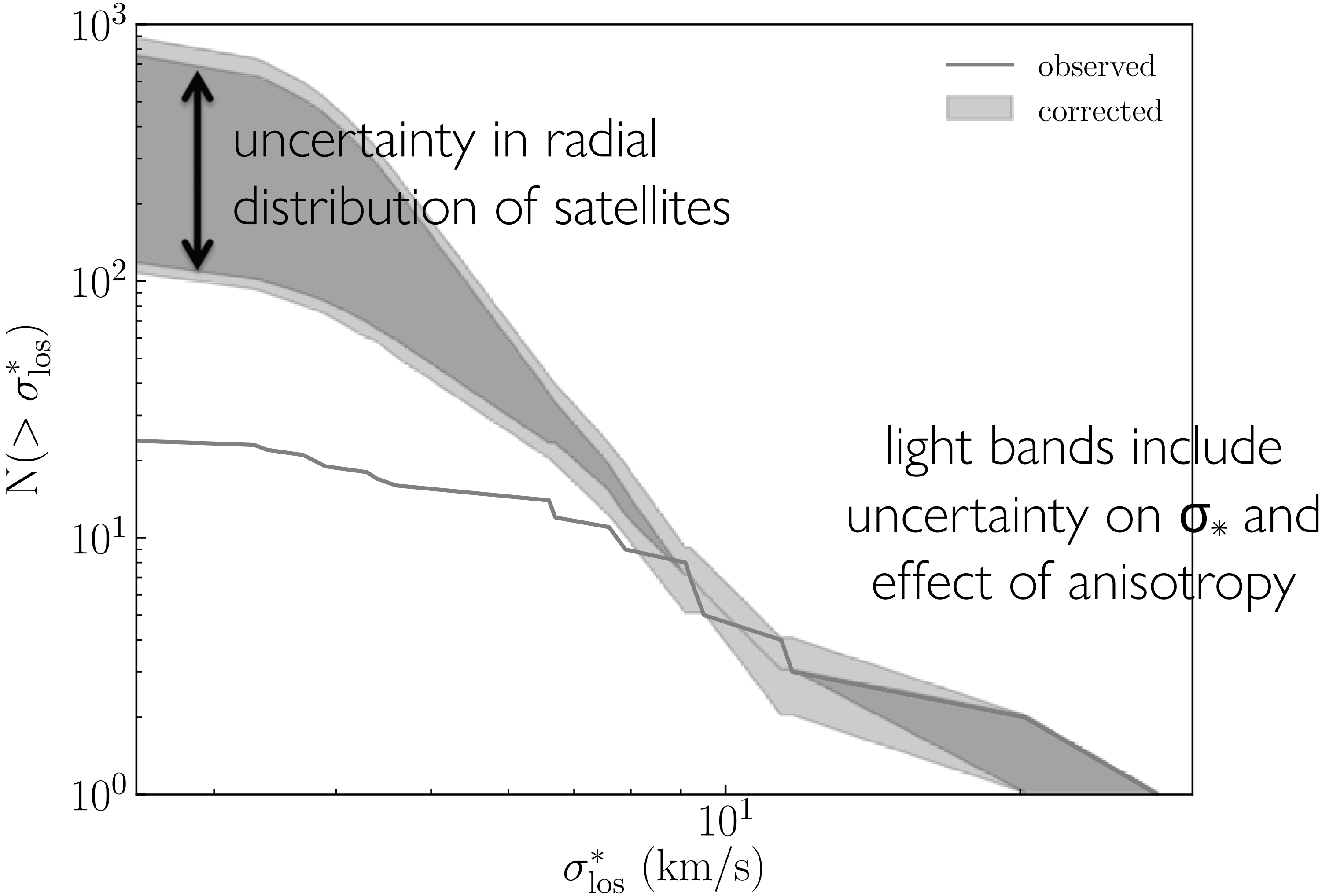
for satellites discovered by SDSS



SYK+ 2022 (arXiv:2106.09050)

corrected velocity function

for satellites discovered by SDSS



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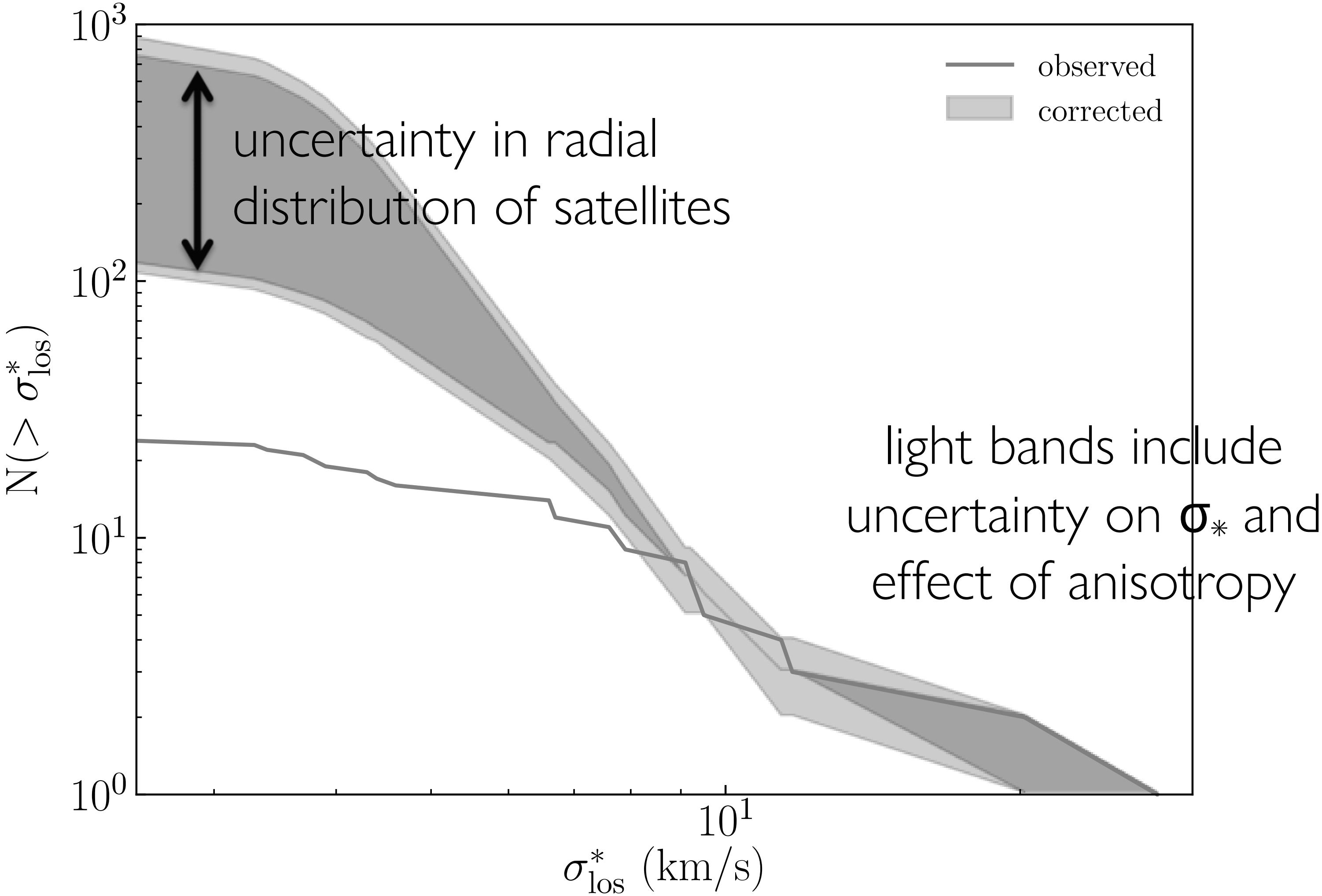

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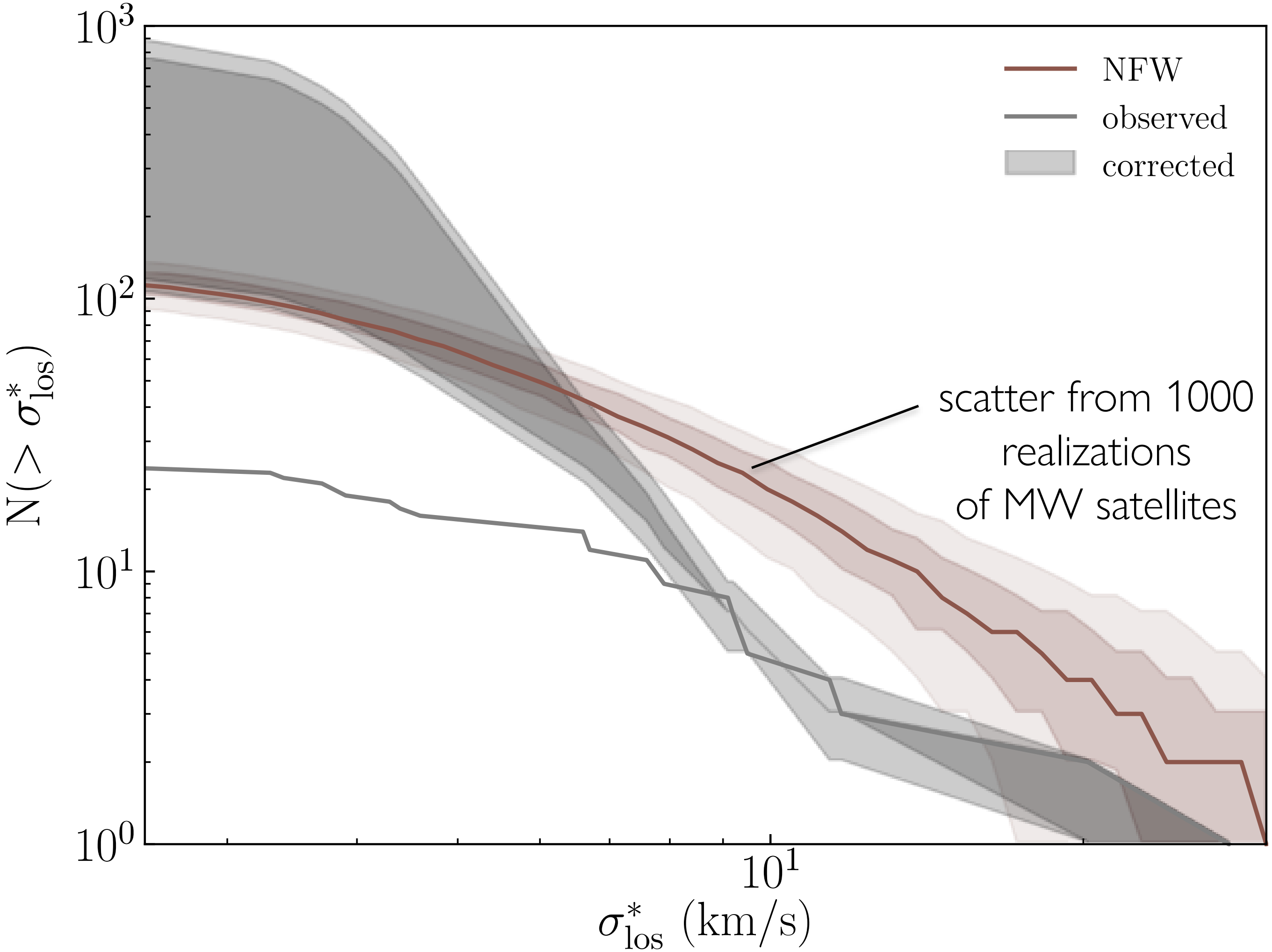

SYK+ 2022 (arXiv:2106.09050)

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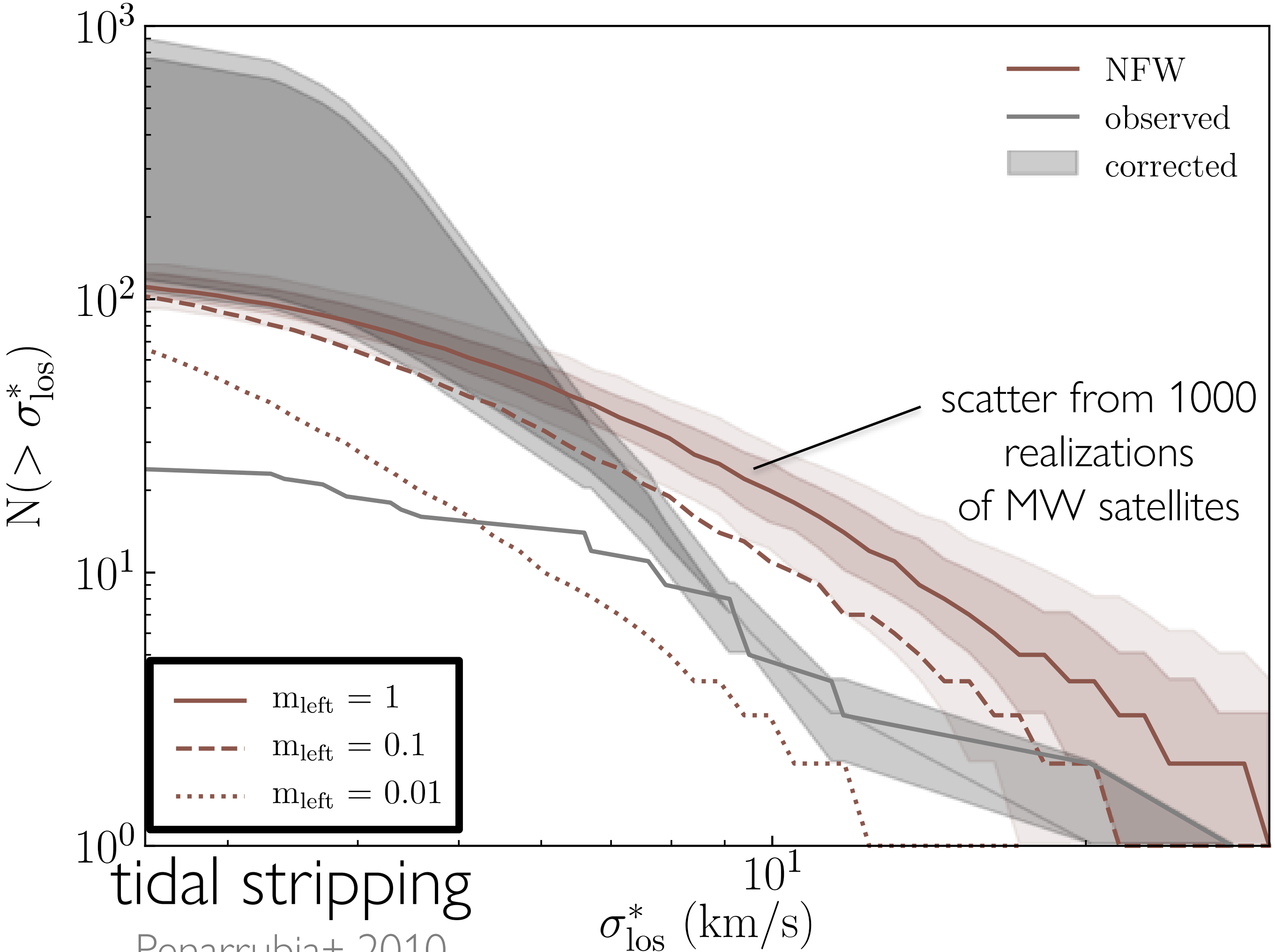
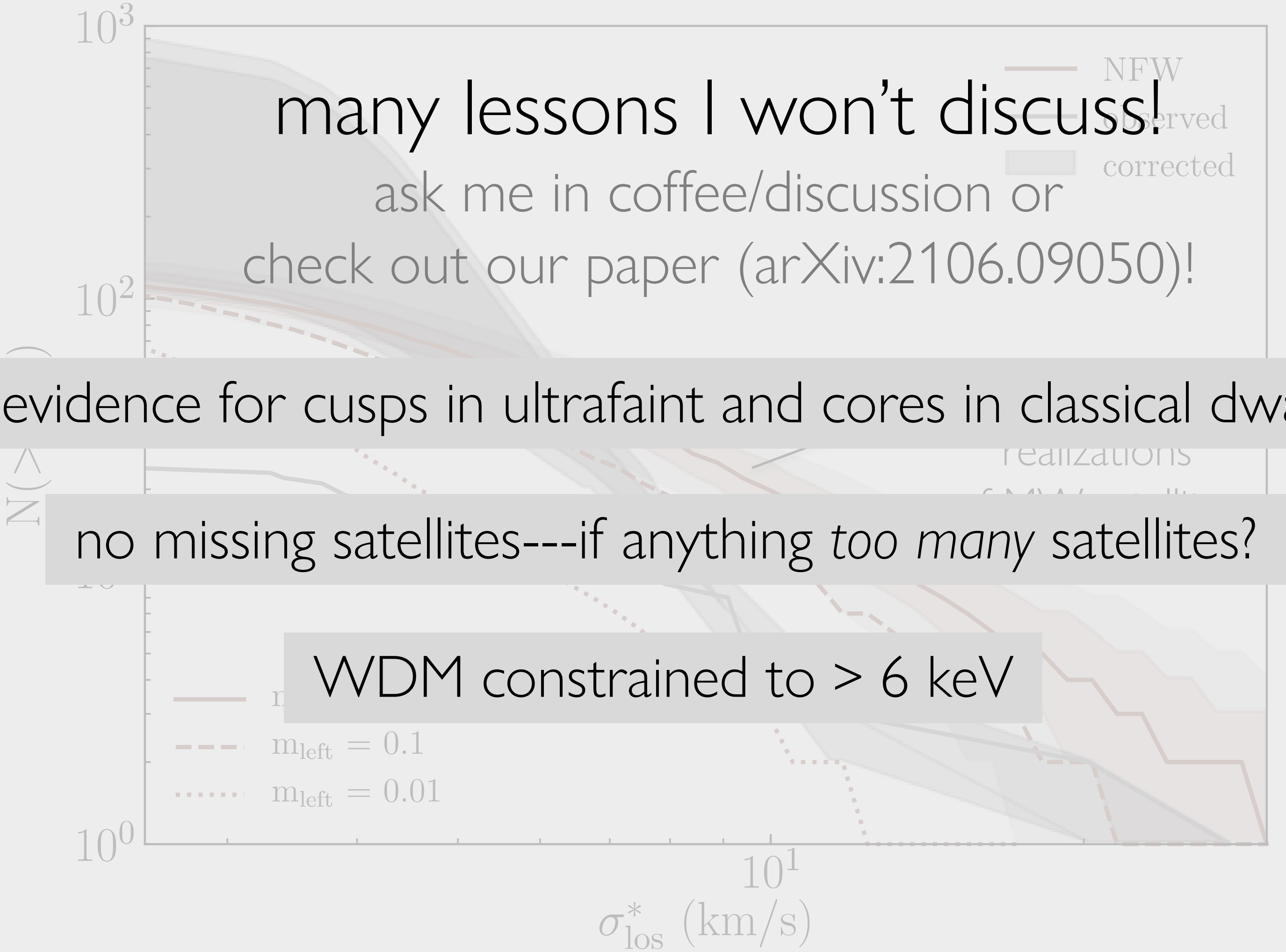


tidal stripping

Penarrubia+ 2010

SYK+ 2022 (arXiv:2106.09050)

theory vs. observations



many lessons I won't discuss!

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

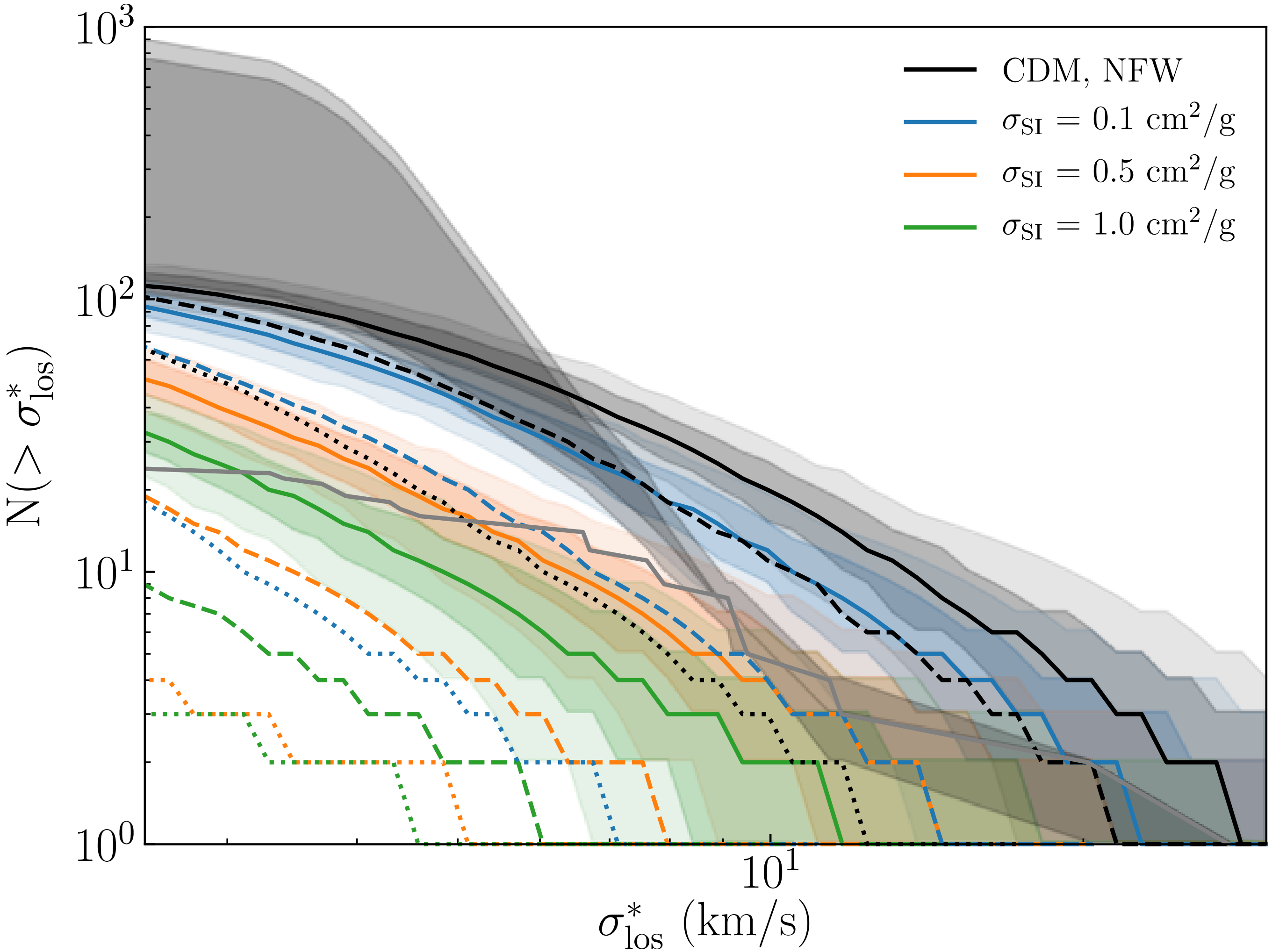
evidence for cusps in ultrafaint and cores in classical dwarfs

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

WDM constrained to > 6 keV

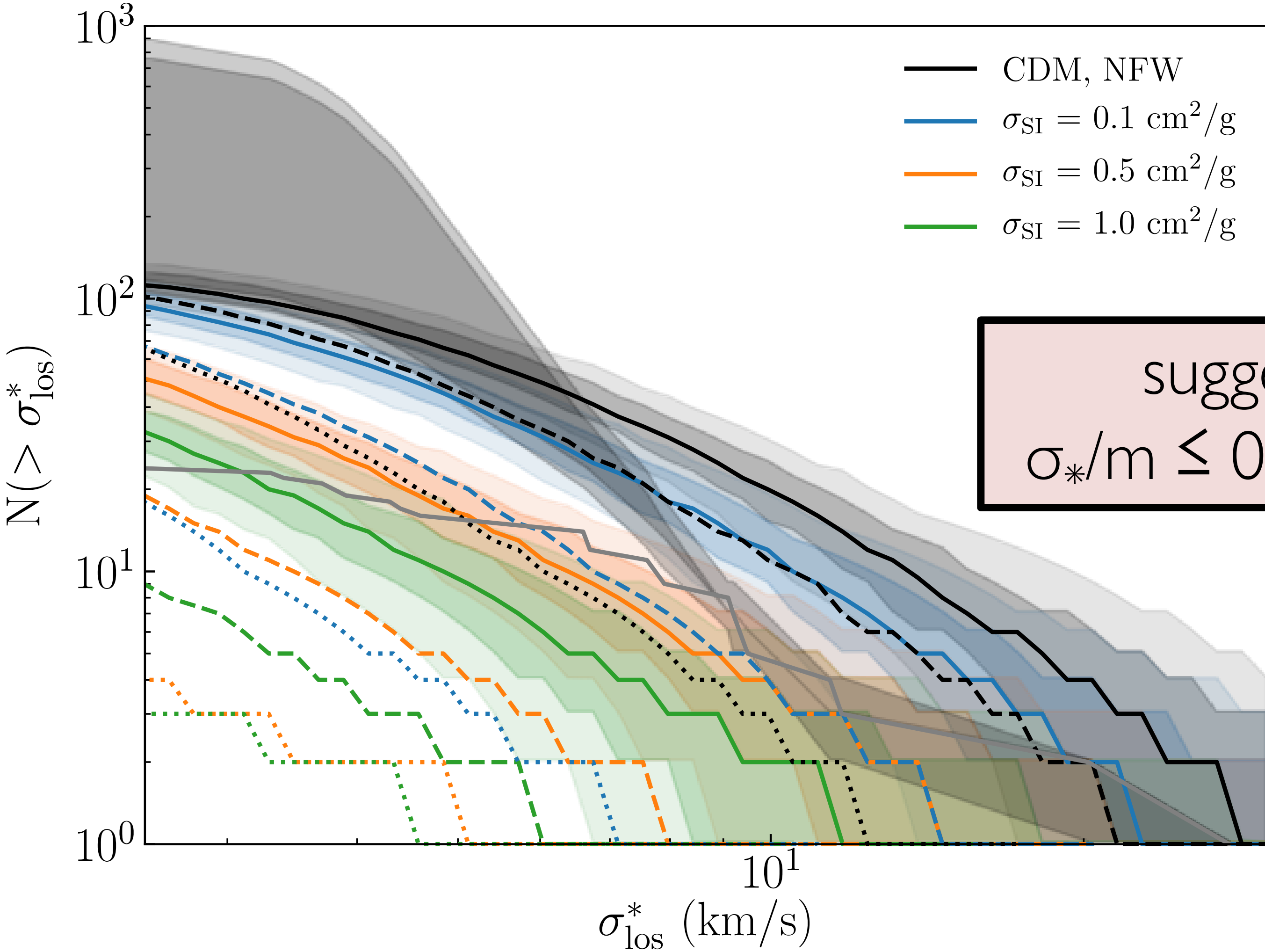
SYK+ 2022 (arXiv:2106.09050)

implications for self-interactions



SYK+ 2022 (arXiv:2106.09050)

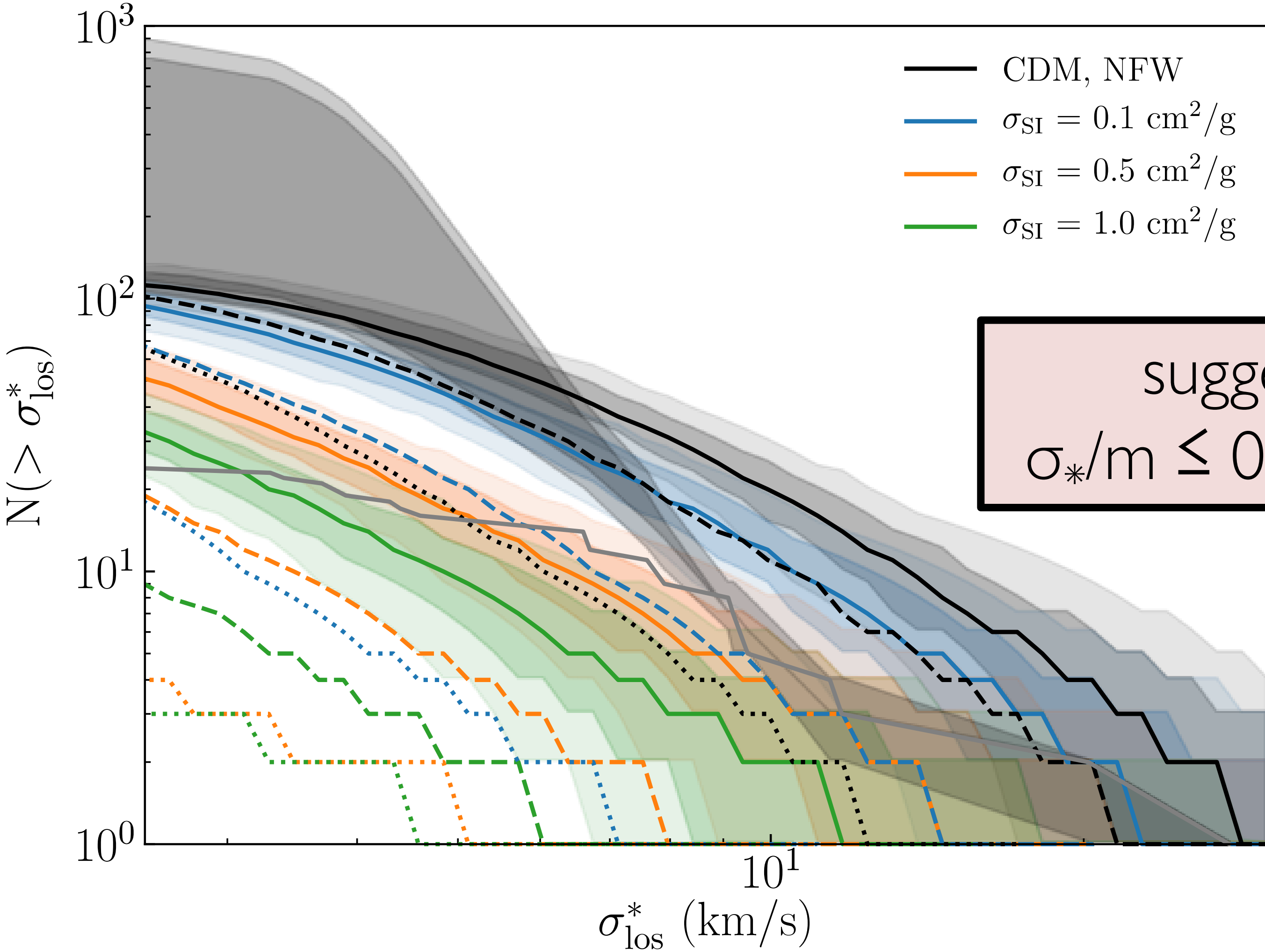
implications for self-interactions



suggests
$\sigma_*/m \lesssim 0.5\ {\rm cm^2/g}$!

SYK+ 2022 (arXiv:2106.09050)

implications for self-interactions



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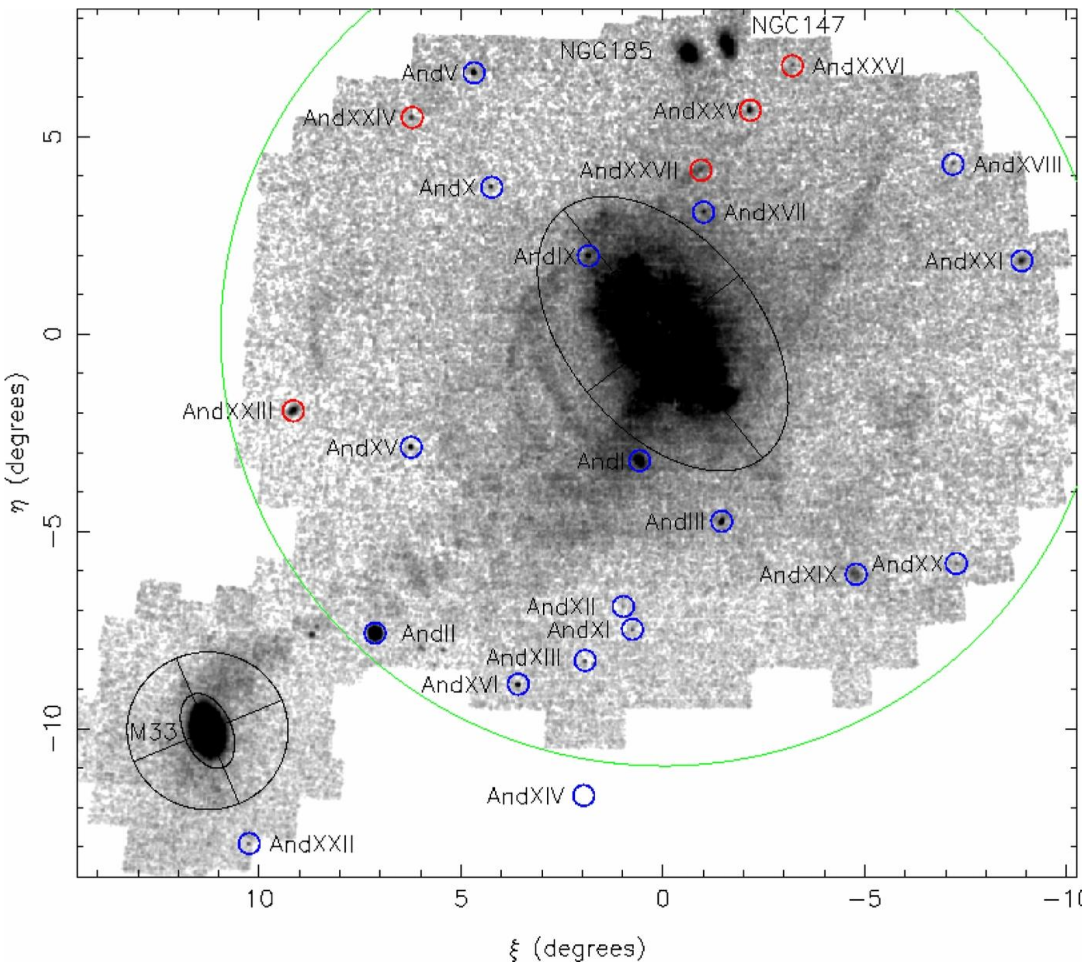
SYK+ 2022 (arXiv:2106.09050)

What about M31's satellites?



Richardson+ 2011, PAndAS

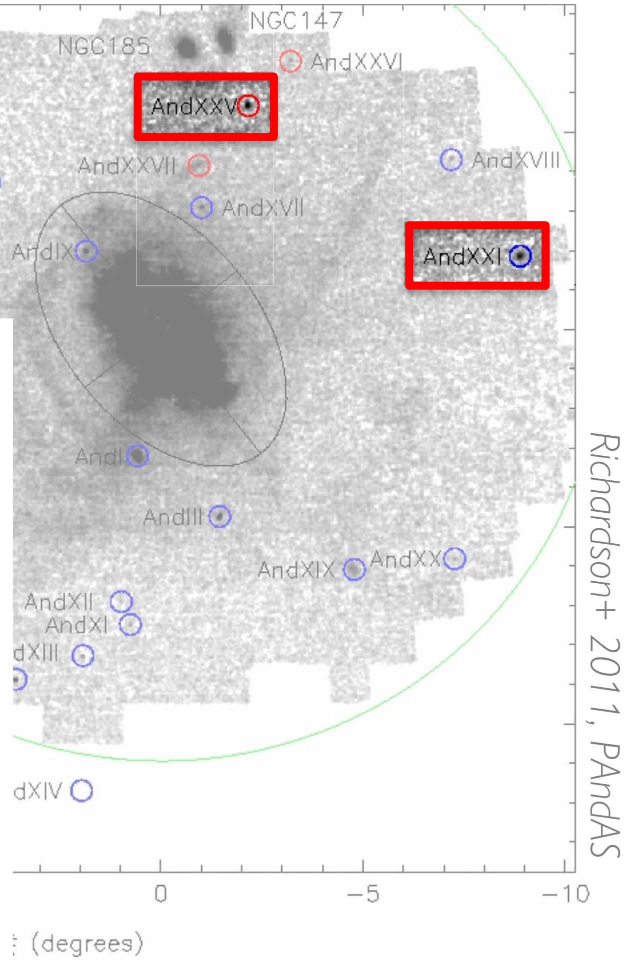
Kinematics harder to measure!

sample incomplete for velocity function analysis (but stay tuned…)

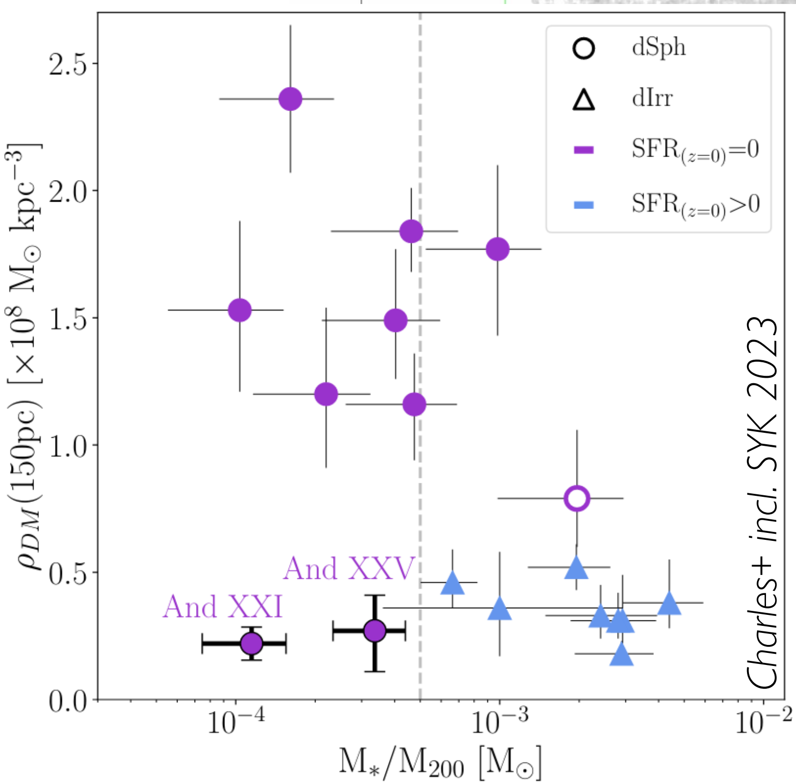
What about M31's satellites?

Emily Charles

start with And XXI and And XXV, two unusually low-density dwarfs



Richardson+ 2011, PAndAS



Charles+ incl. SYK 2023

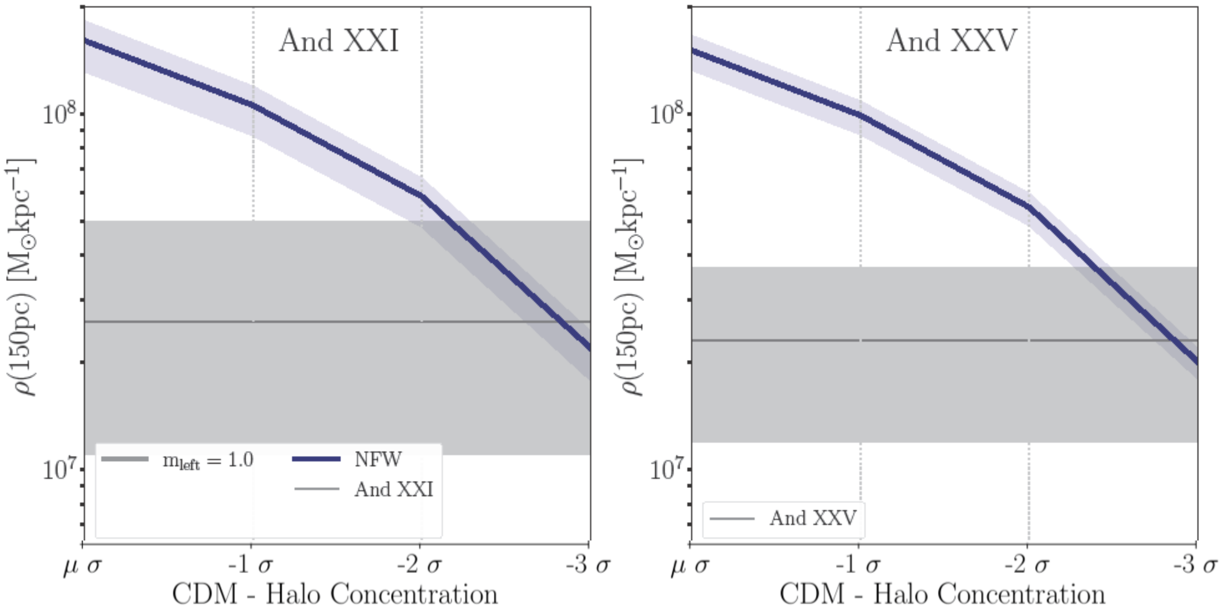
arder to measure!

function analysis (but stay tuned…)

constraints from M31 satellites

Emily Charles

density at 150 pc



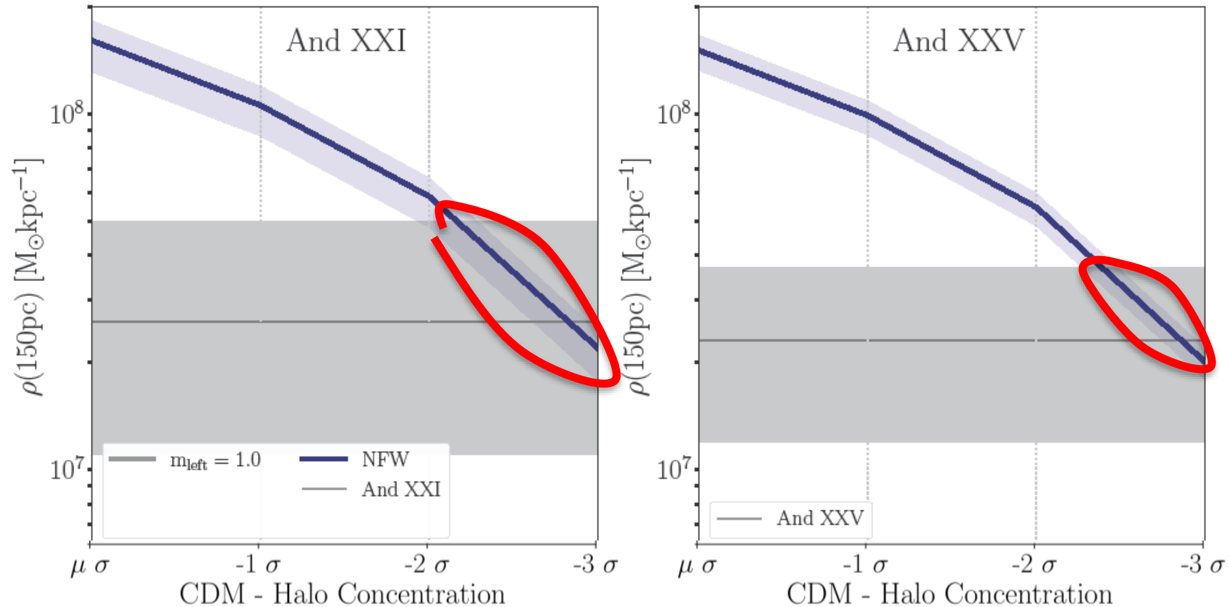
Charles, SYK+, in prep.

constraints from M31 satellites

Emily Charles

NFW

density at
150 pc



Requires concentrations
that are 2-3 sigma outliers(!)

Charles, SYK+, in prep.

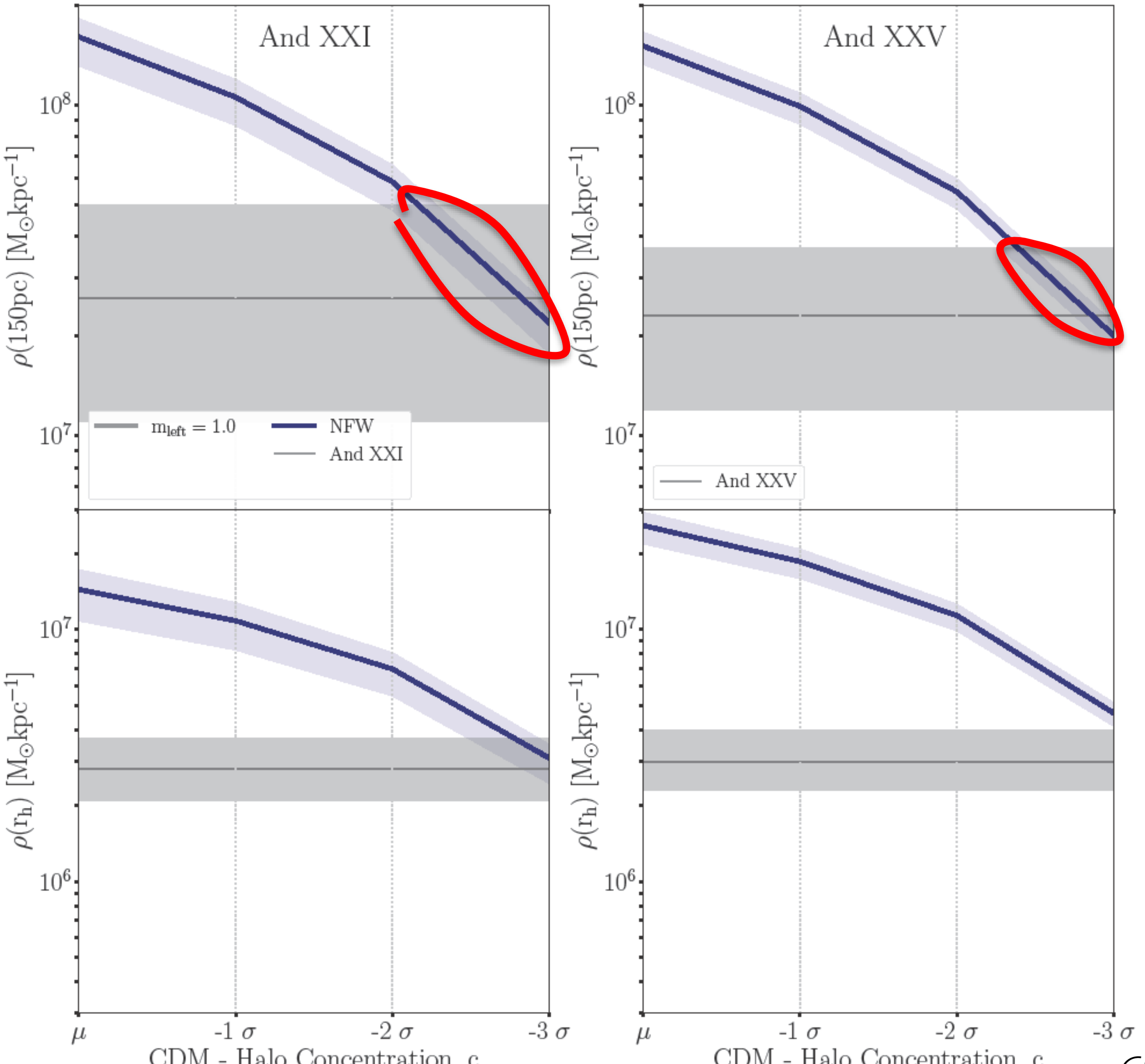
constraints from M31 satellites

Emily Charles

NFW

density at 150 pc

density at half-light radius



Charles, SYK+, in prep.

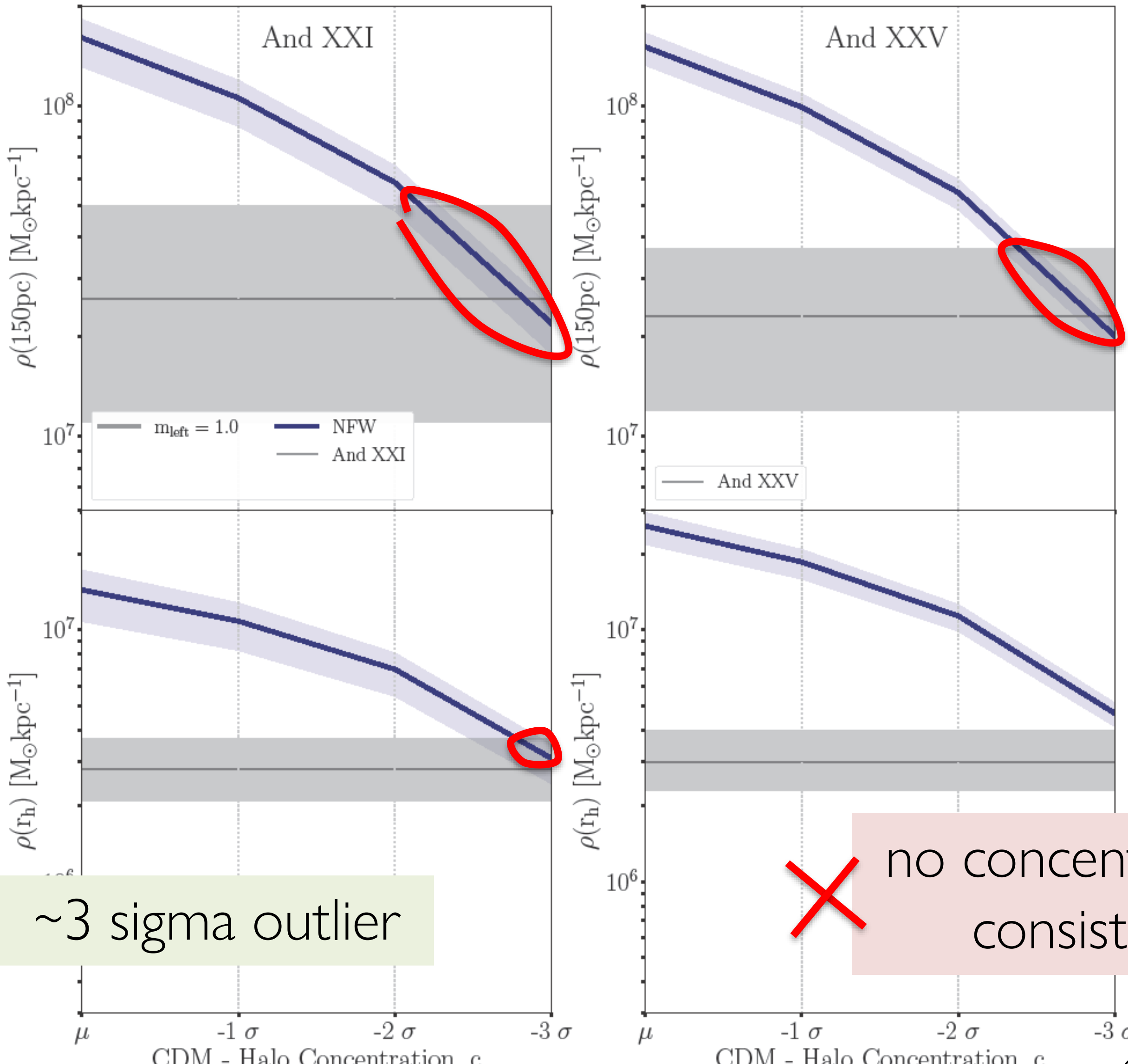
constraints from M31 satellites

Emily Charles

NFW

density at 150 pc

density at half-light radius



~3 sigma outlier

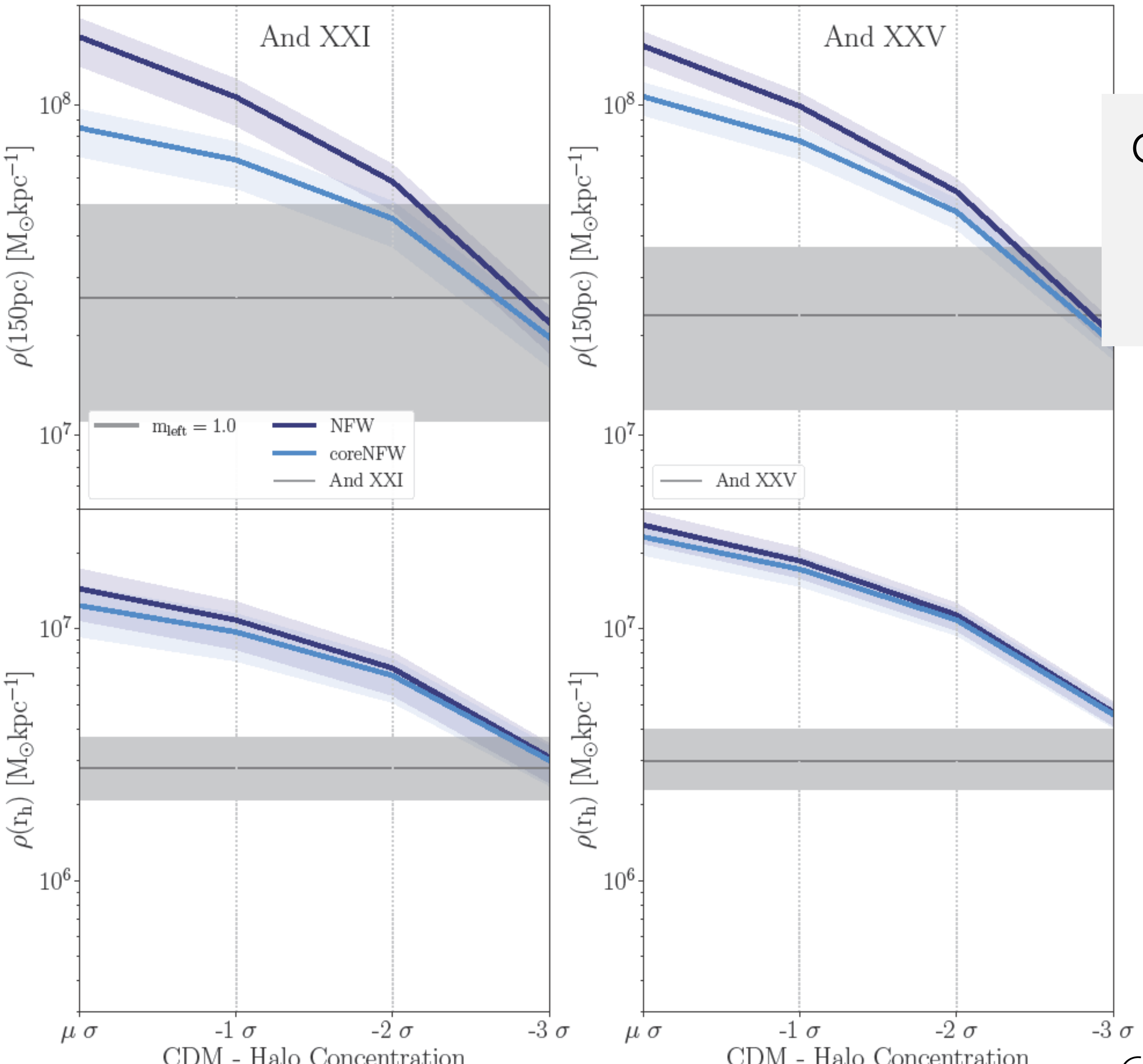
no concentrations consistent!

Charles, SYK+, in prep.

constraints from M31 satellites


Emily Charles

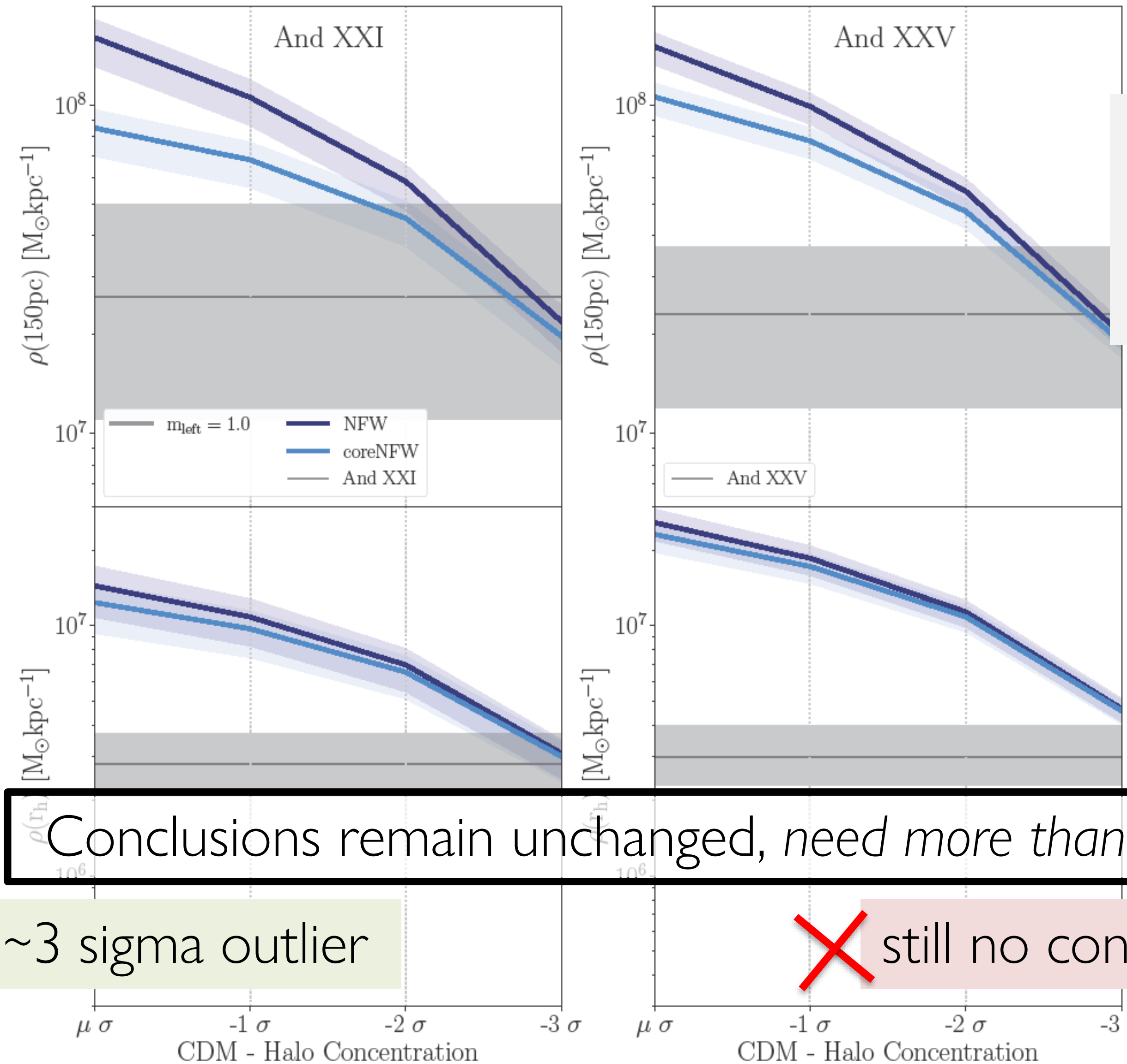
cores from baryonic feedback?



Charles, SYK+, in prep.

constraints from M31 satellites

Emily Charles



cores from baryonic feedback?

Conclusions remain unchanged, *need more than cores*!

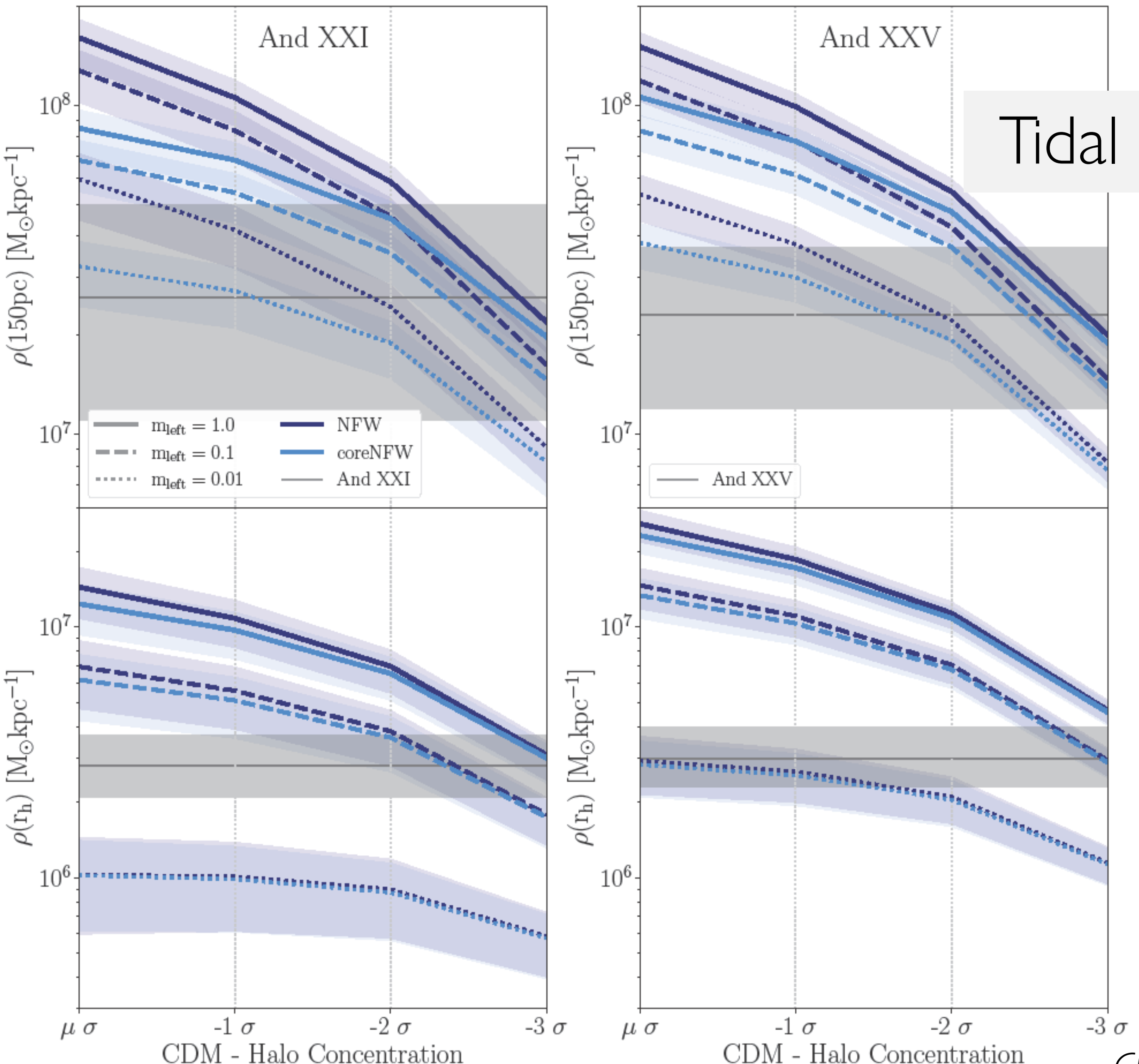
~3 sigma outlier

still no consistency!

Charles, SYK+, in prep.

constraints from M31 satellites

Emily Charles



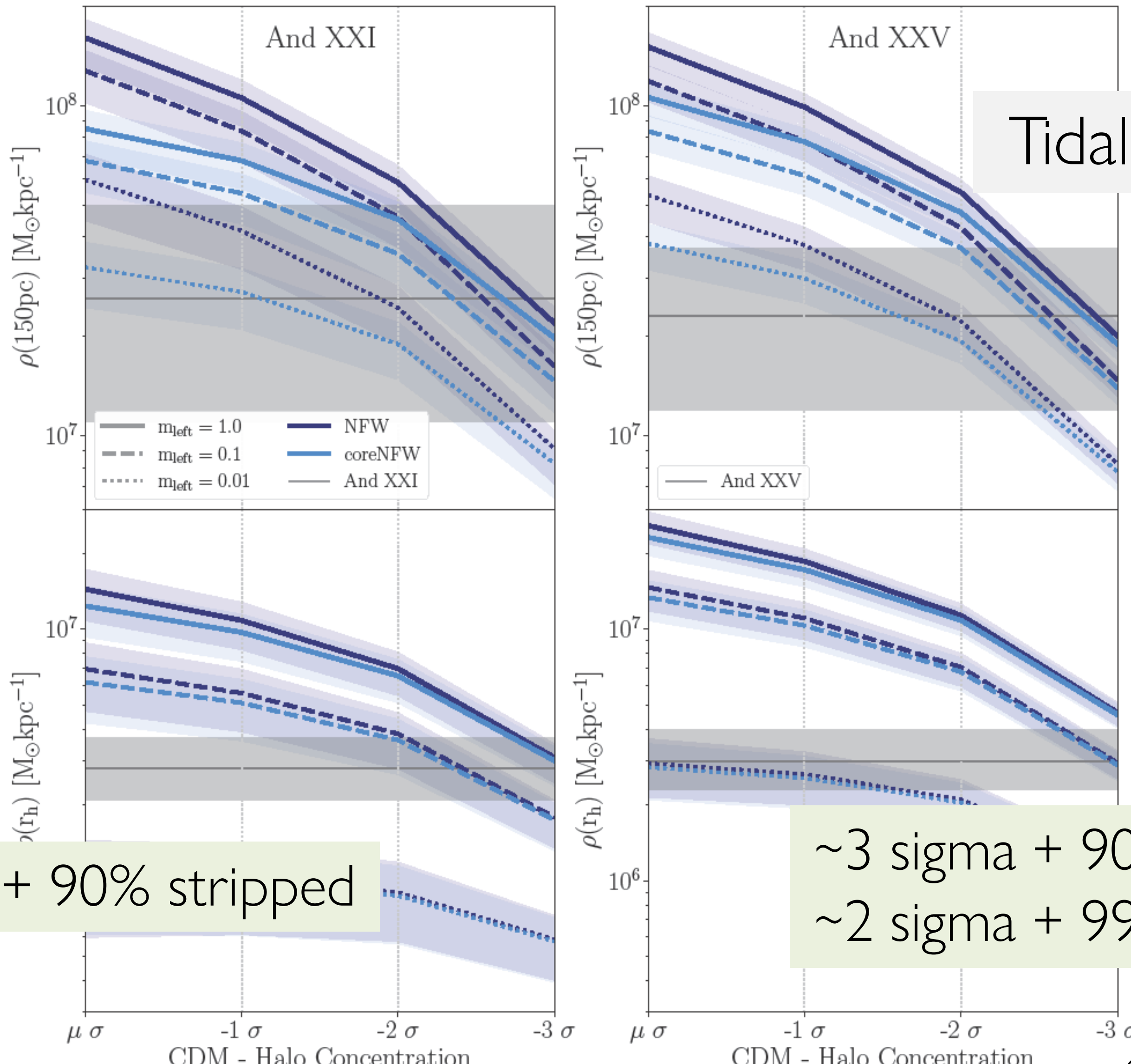
Tidal stripping?

no orbits!
but kinematic flaring, large size for mass

Charles, SYK+, in prep.

constraints from M31 satellites

Emily Charles



Tidal stripping?

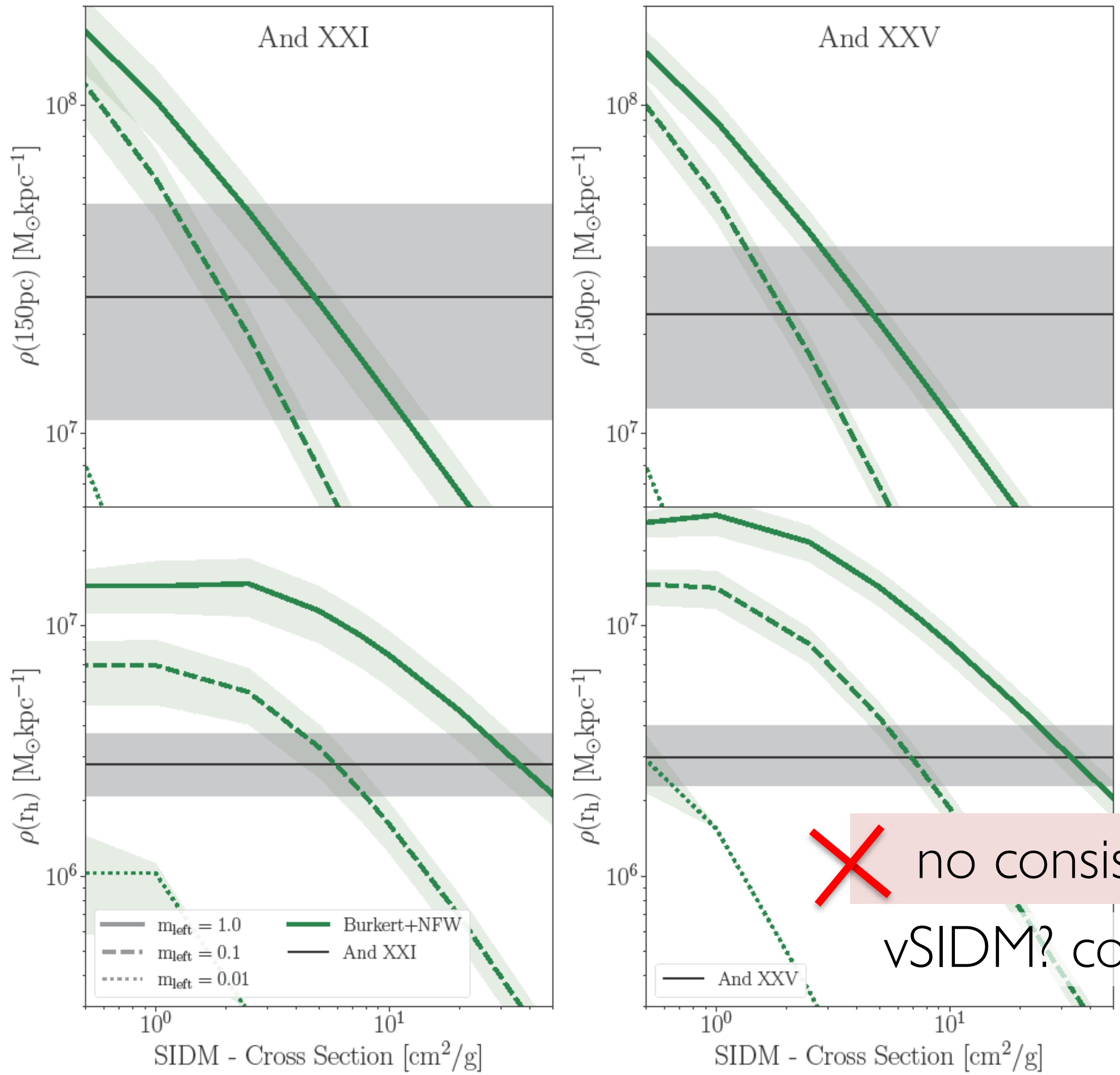
no orbits!
but kinematic flaring, large size for mass

~2 sigma + 90% stripped

~3 sigma + 90% stripped
~2 sigma + 99% stripped

Charles, SYK+, in prep.

constraints from M31 satellites



Emily Charles

SIDM

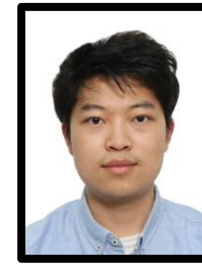
constant cross-section

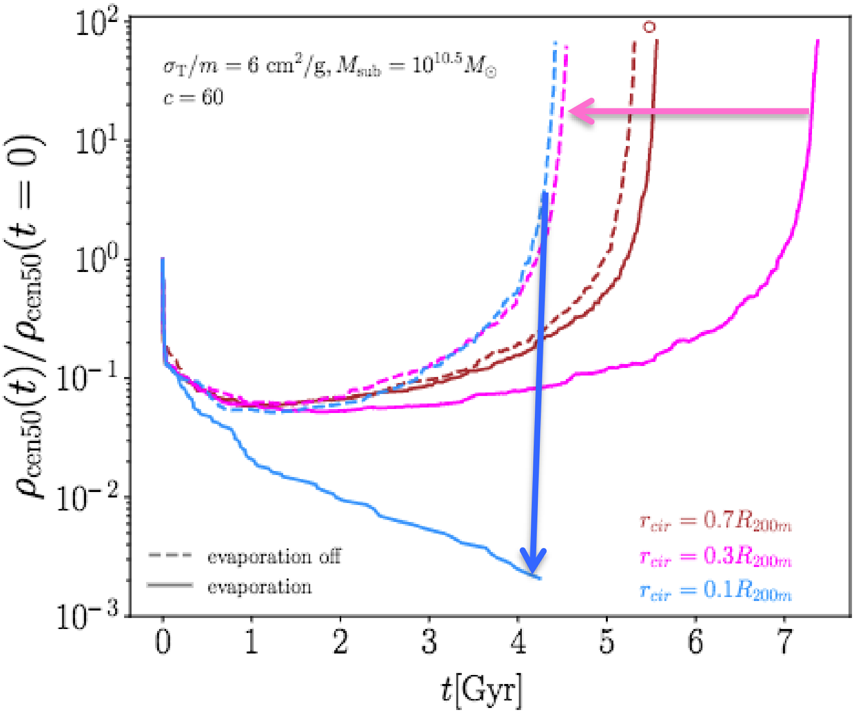
no consistency!

vSIDM? core collapse?

Charles, SYK+, in prep.

Core collapse in satellites of lenses



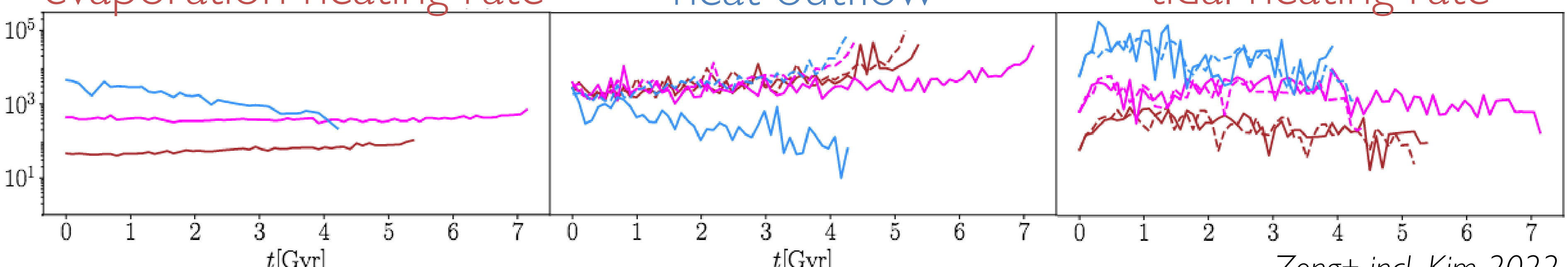


lessons from circular orbits

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

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

evaporation heating rate | heat outflow | tidal heating rate



Zeng+ incl. Kim 2022

Core collapse in satellites of lenses

Carton Zeng

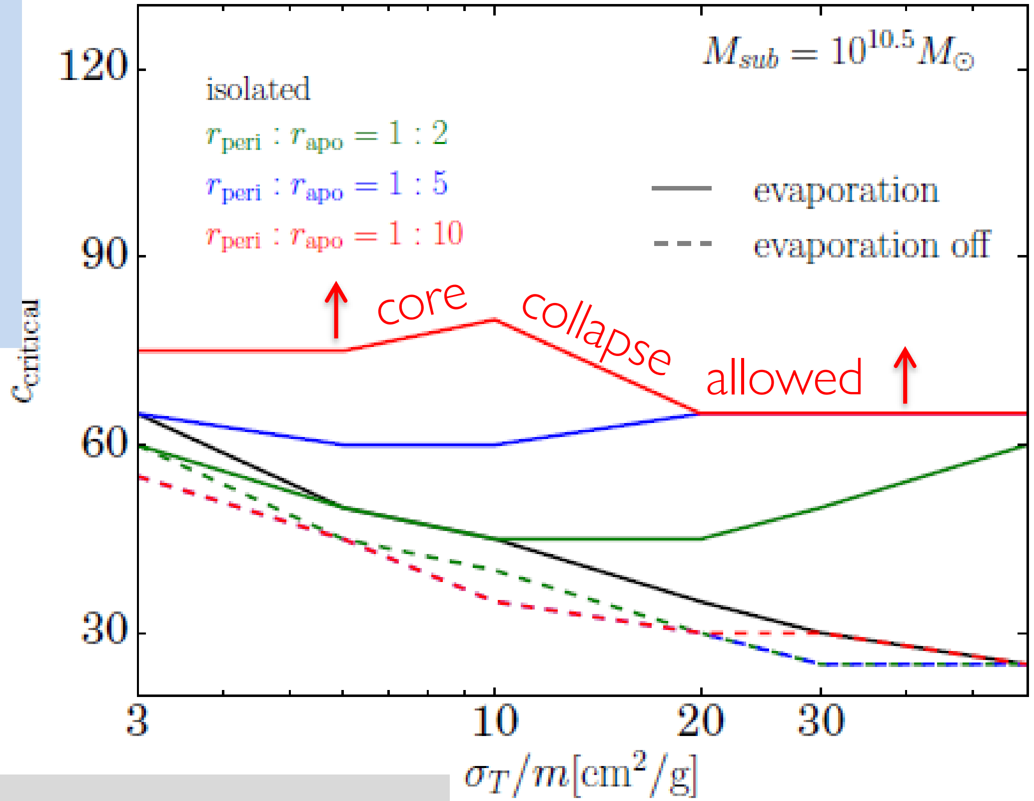
Parameter space for subhalo core collapse

core collapse not feasible with constant σ/m

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

smaller c needed for isolated subhalos or no evaporation

mimics vSIDM!



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

Zeng+ incl. SYK 2022

SIDM constraints from satellites

Milky Way satellite kinematics imply $\sigma/m \lesssim 0.5\ \mathrm{cm}^2/\mathrm{g}$

Kinematics of M31 satellites And XXI and And XXV cannot be explained with constant cross sections

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

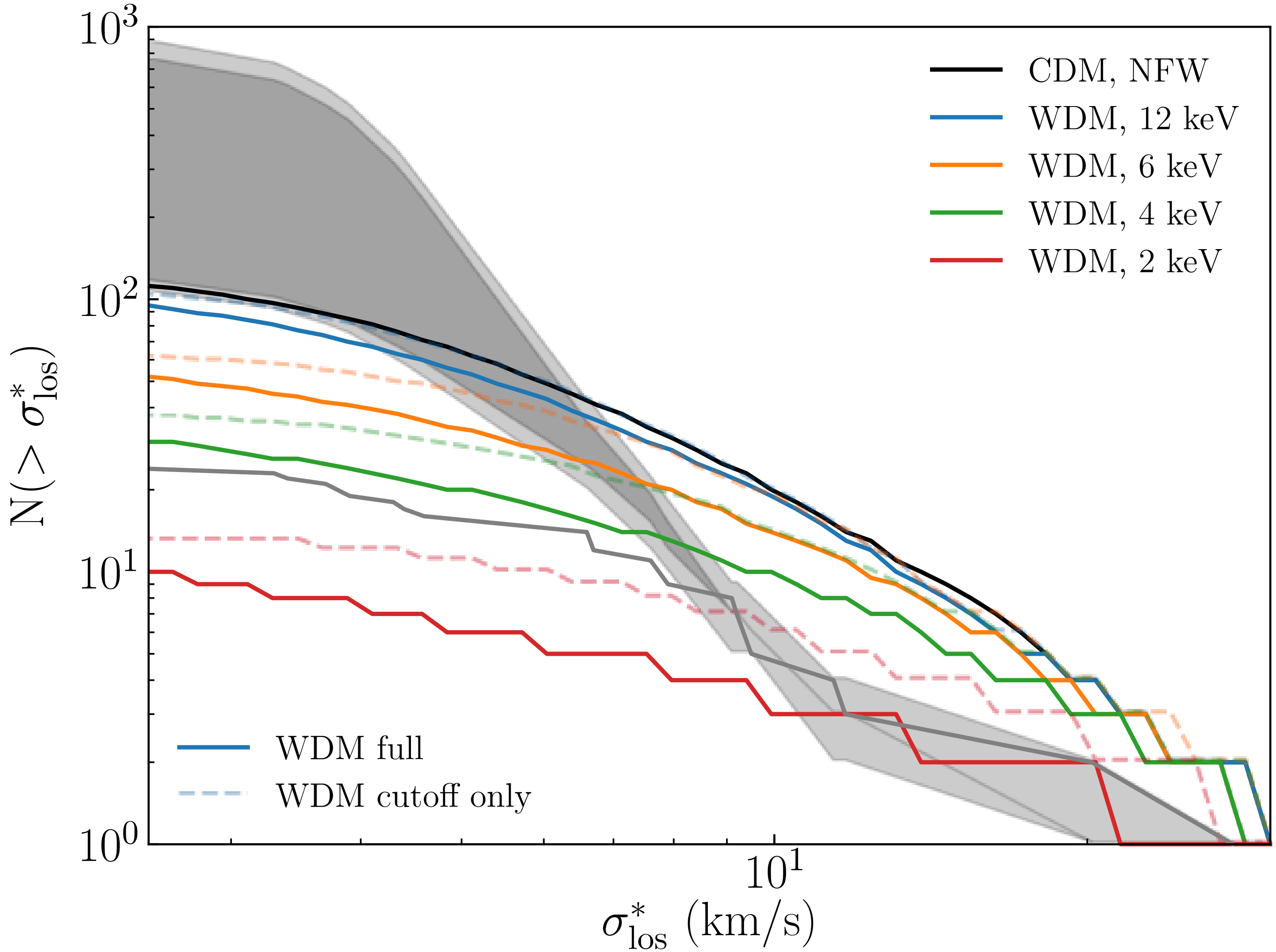
Important to include evaporation, which can suppress core-collapse

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

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

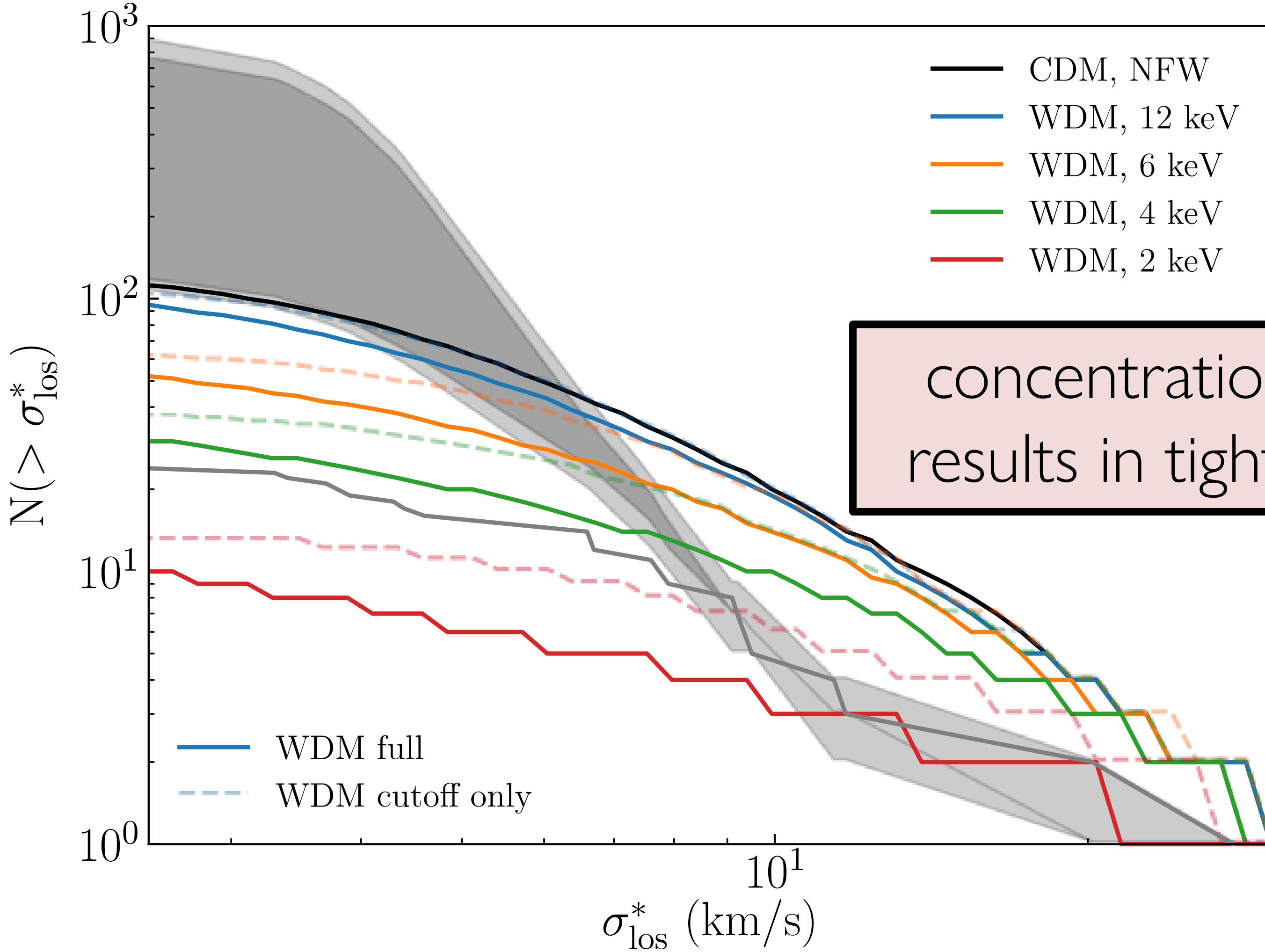
EXTRAS: MW VF

theory vs. observations



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

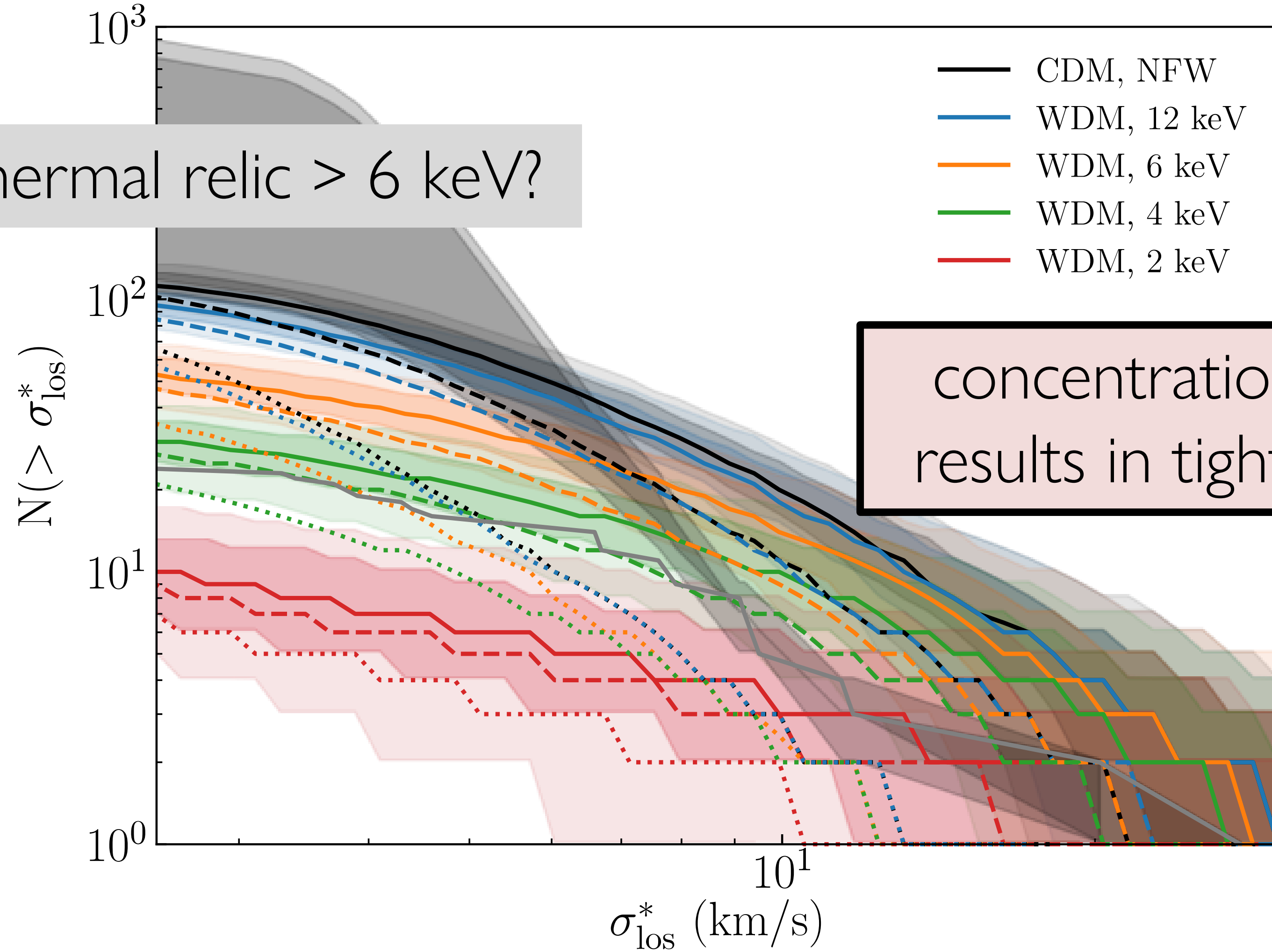
theory vs. observations



concentration is key!
results in tighter limits

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

theory vs. observations

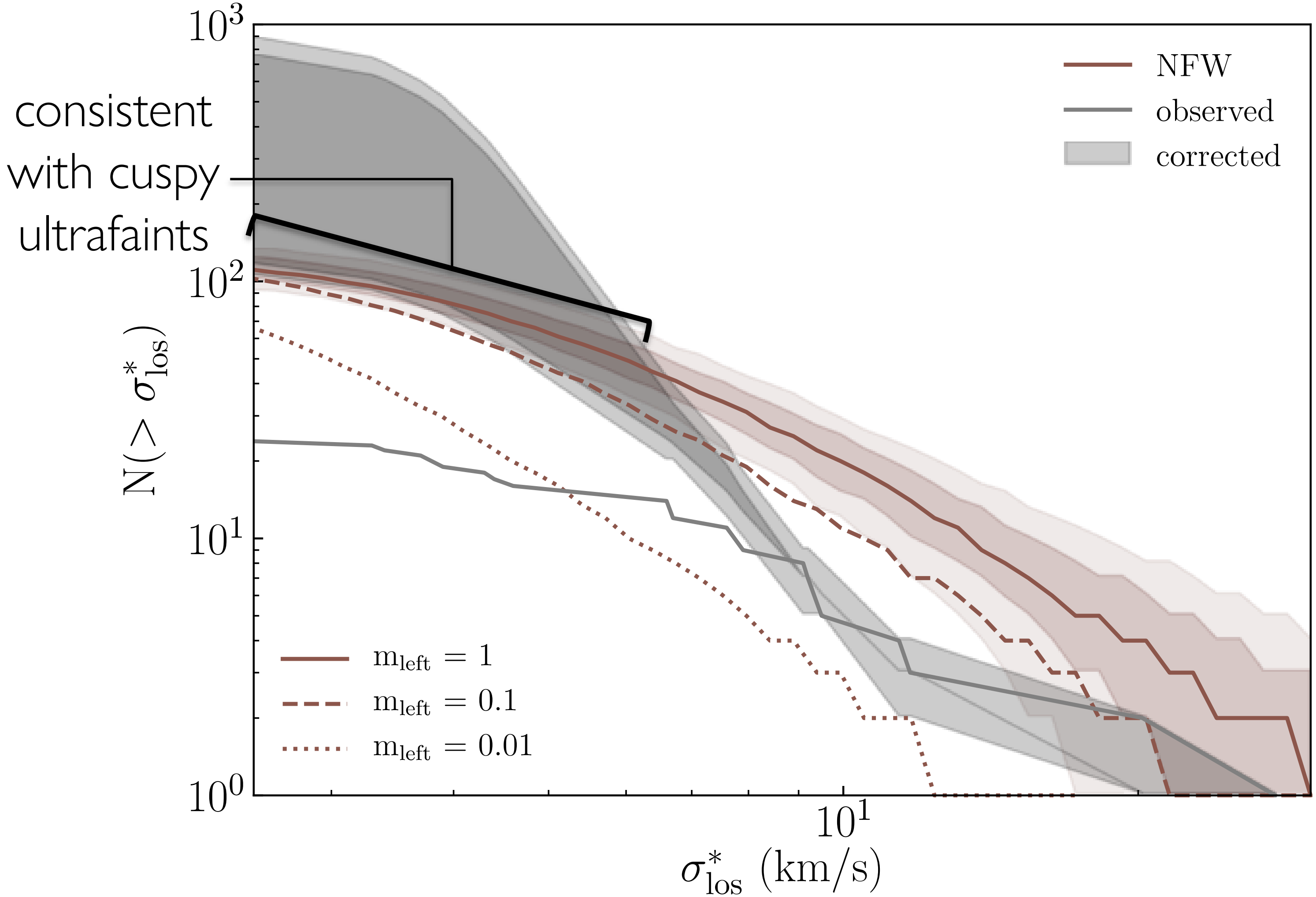


thermal relic > 6 keV?

concentration is key!
results in tighter limits

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

theory vs. observations



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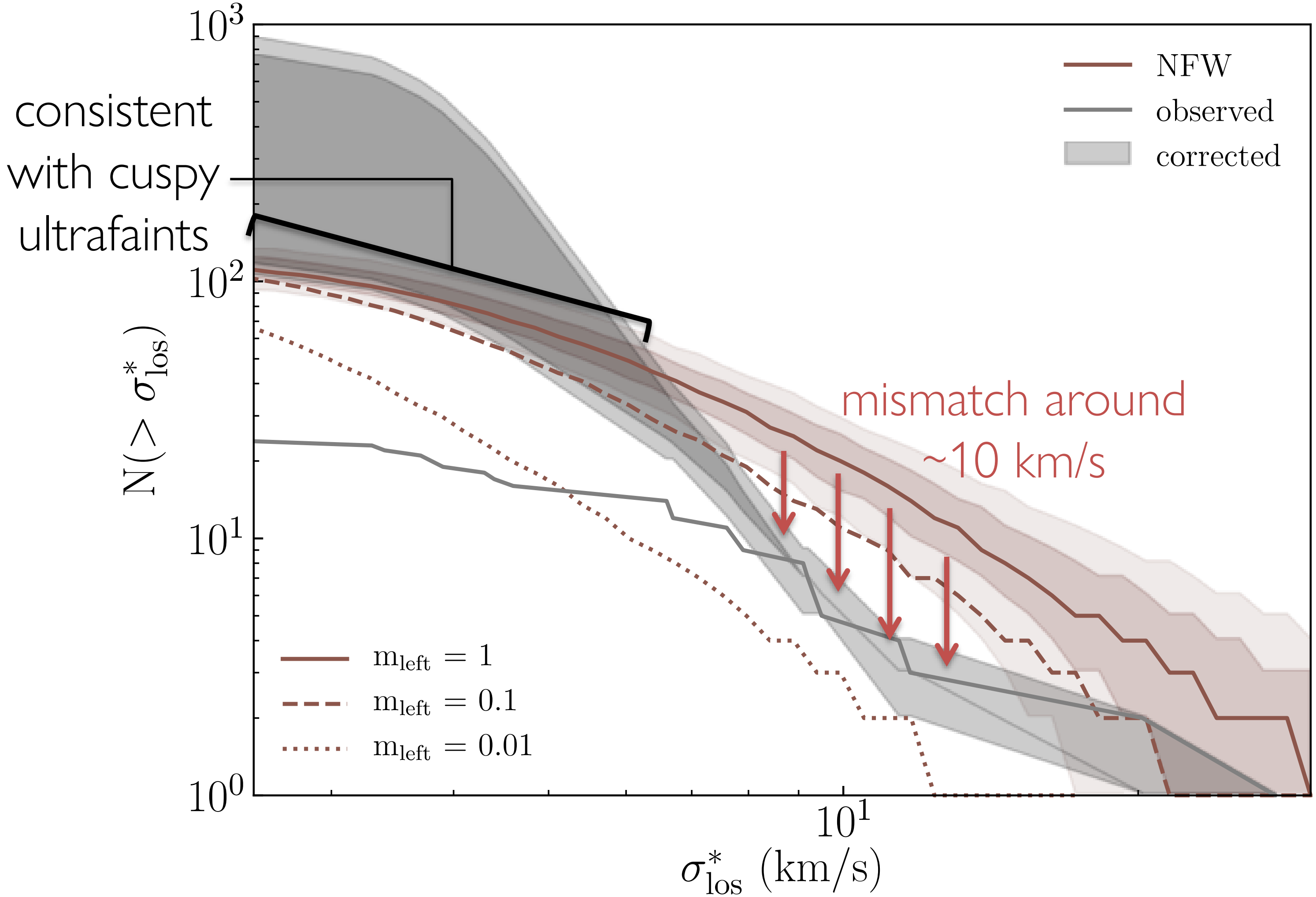

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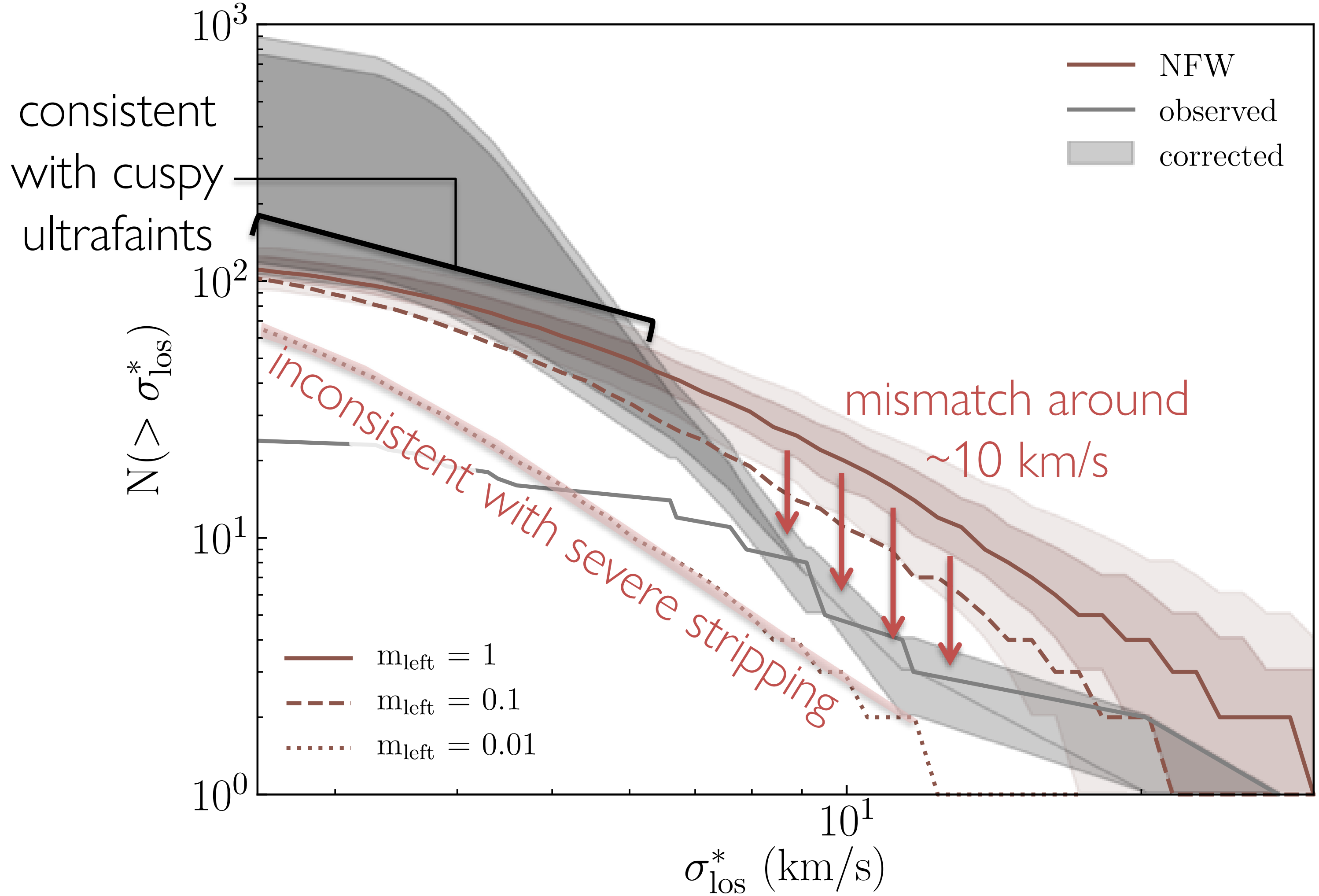

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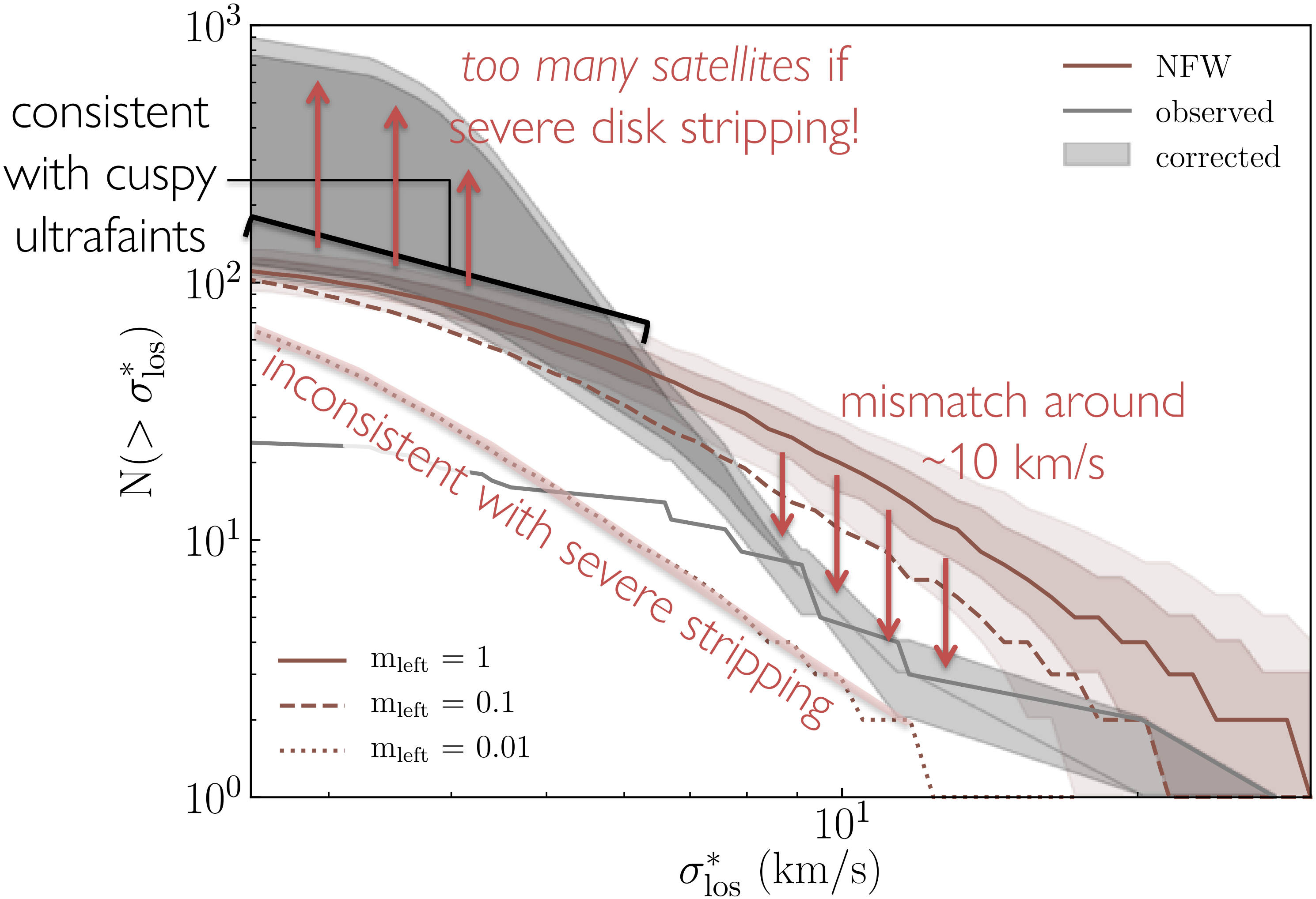

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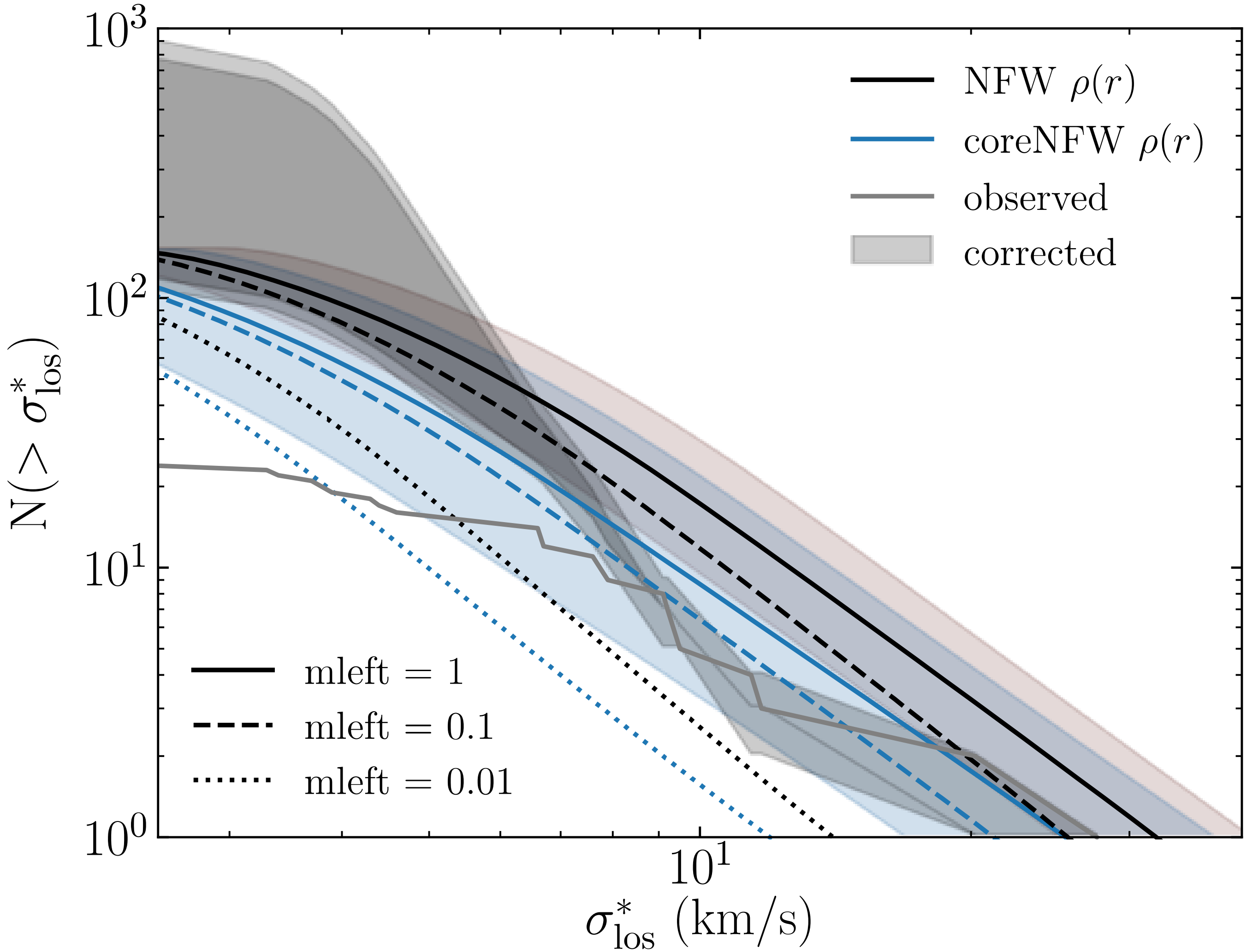

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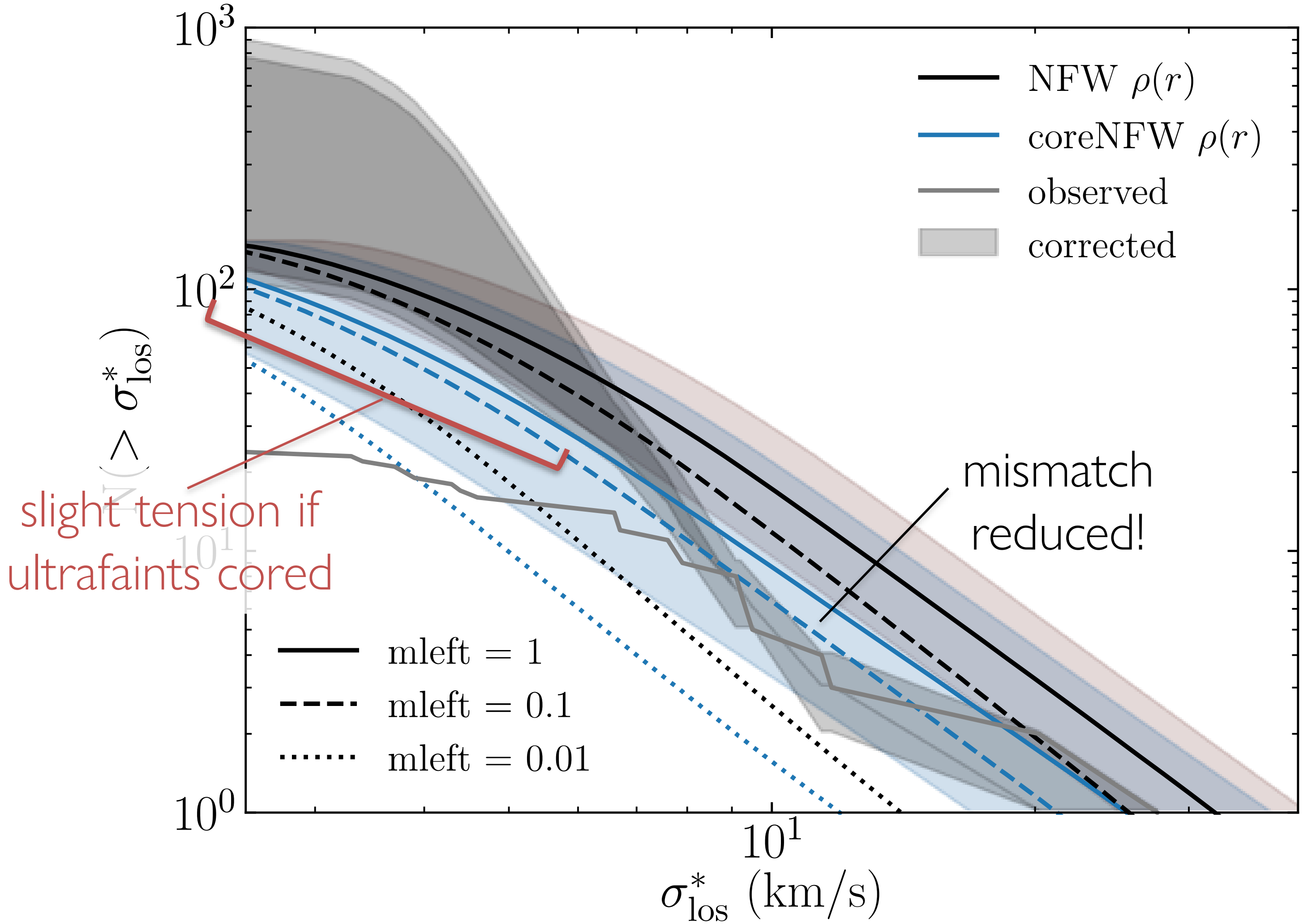

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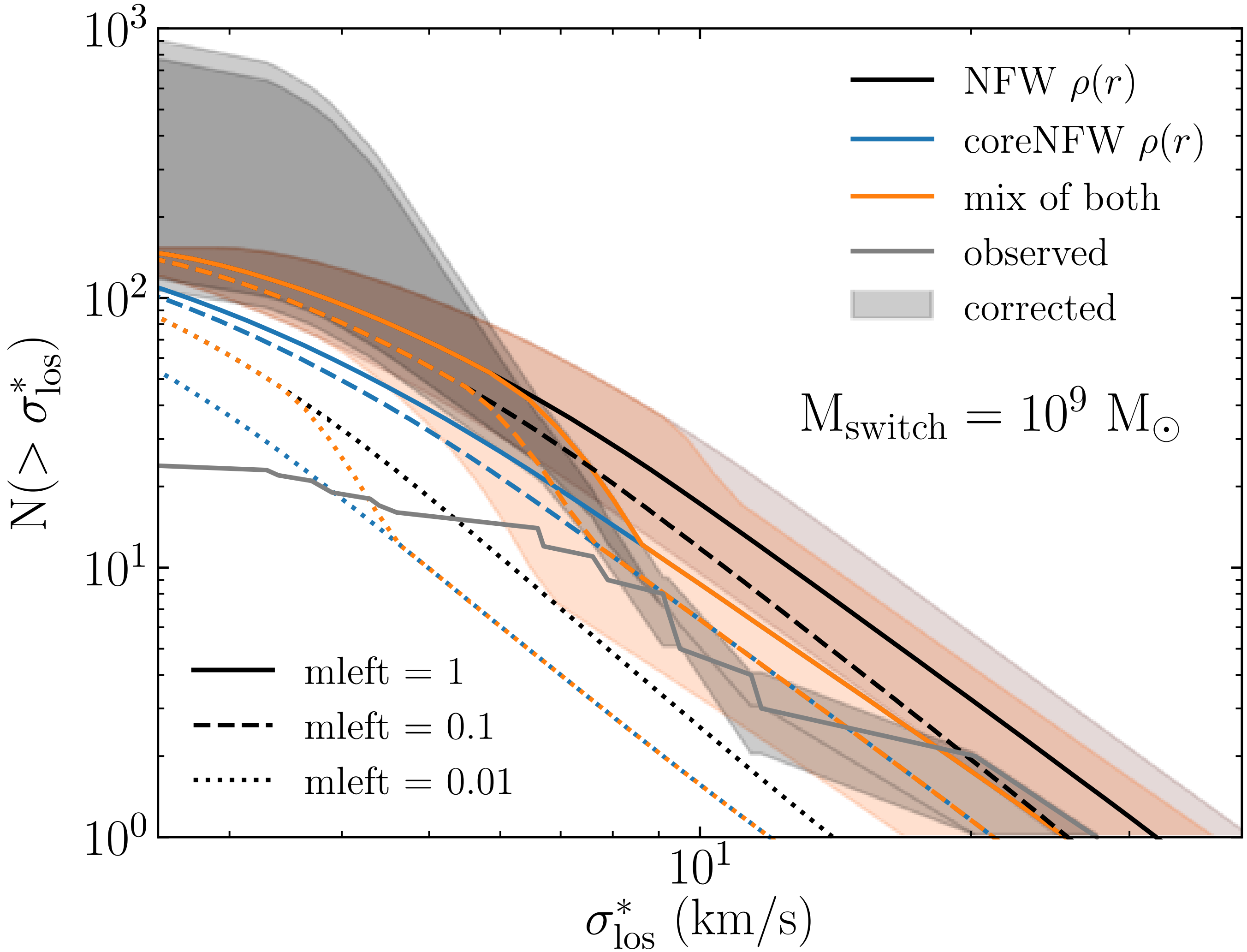

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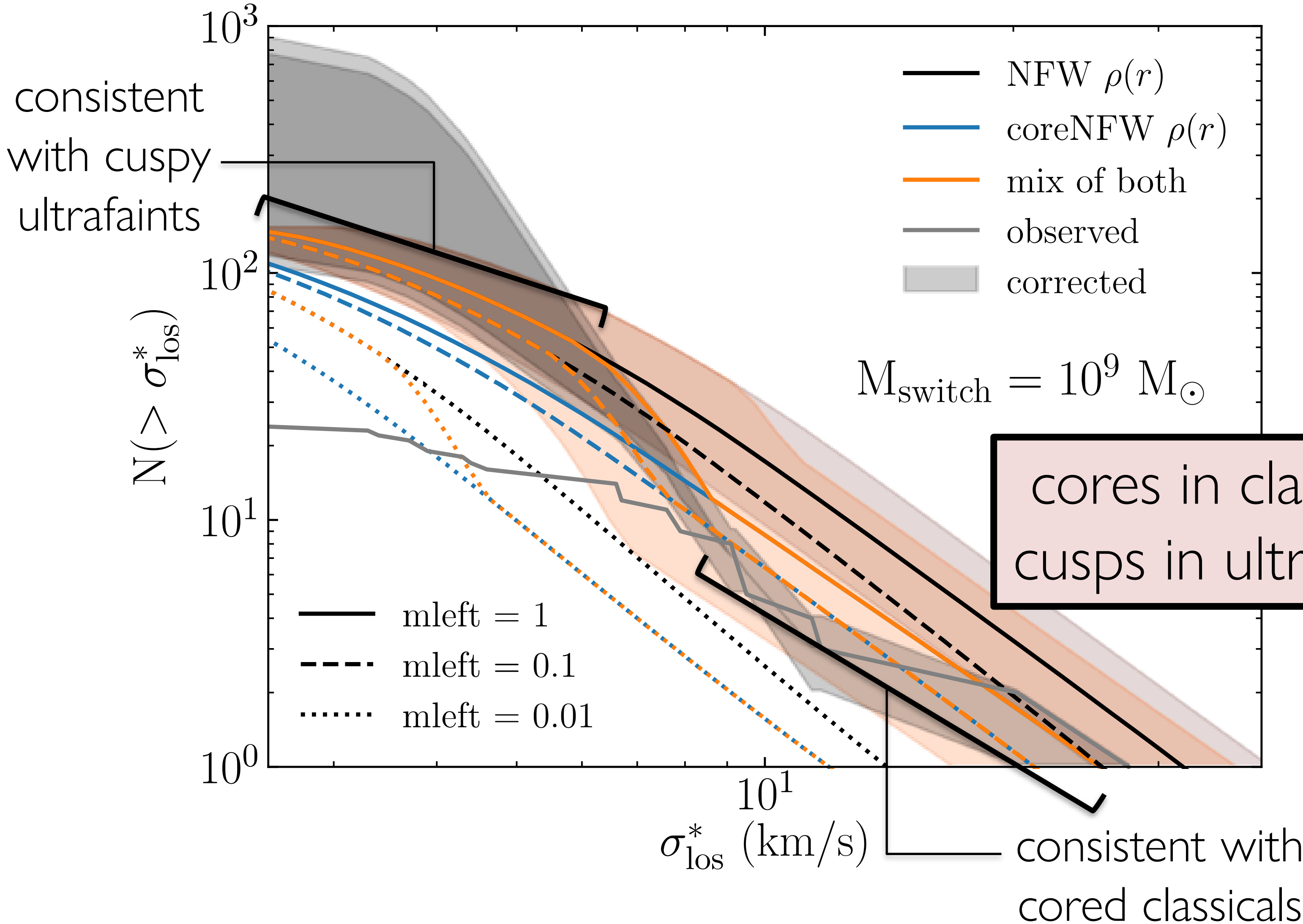
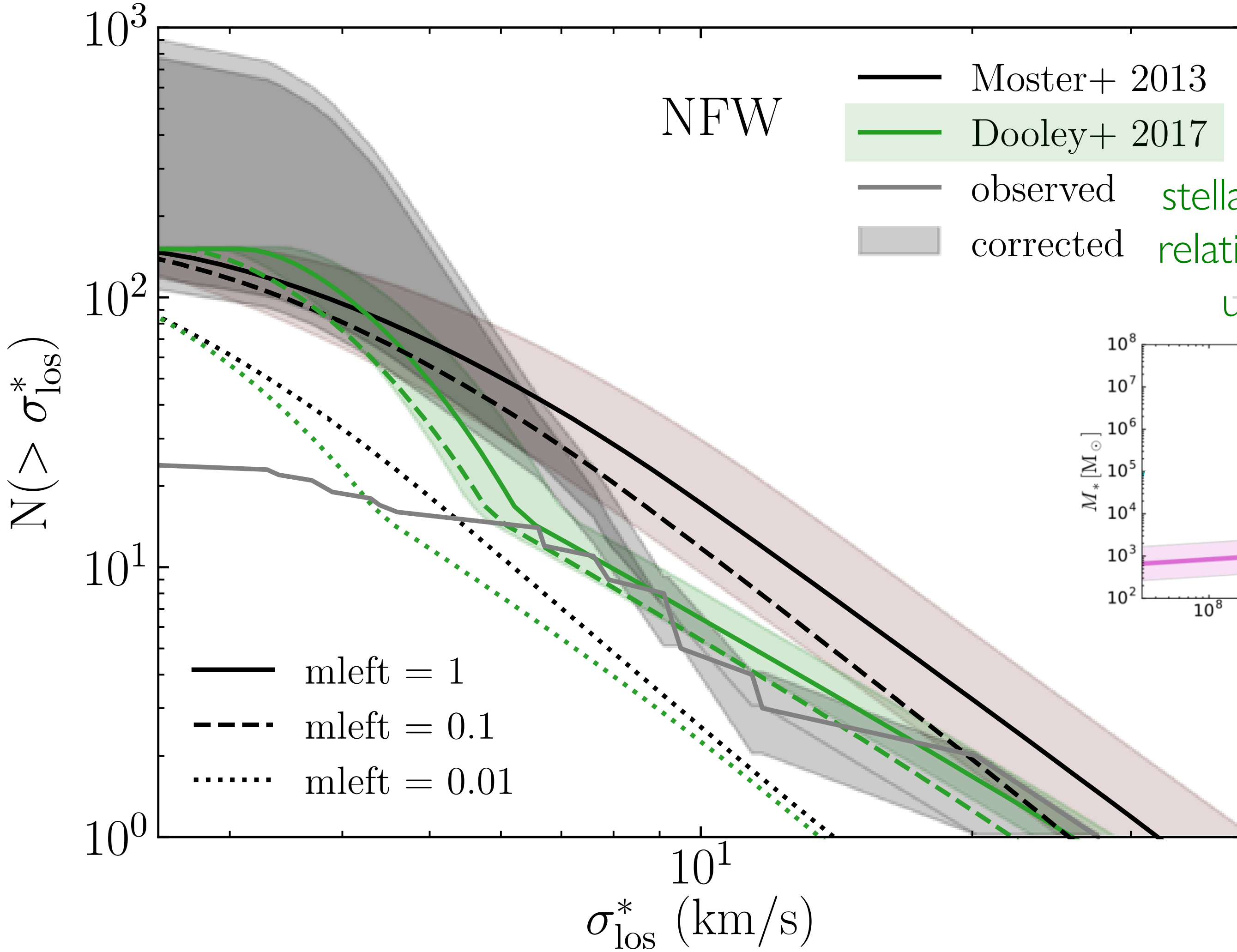
theory vs. observations



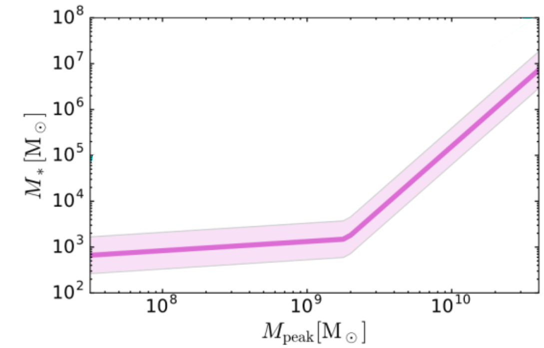
cores in classicals, cusps in ultrafaints!

theoretical uncertainties

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

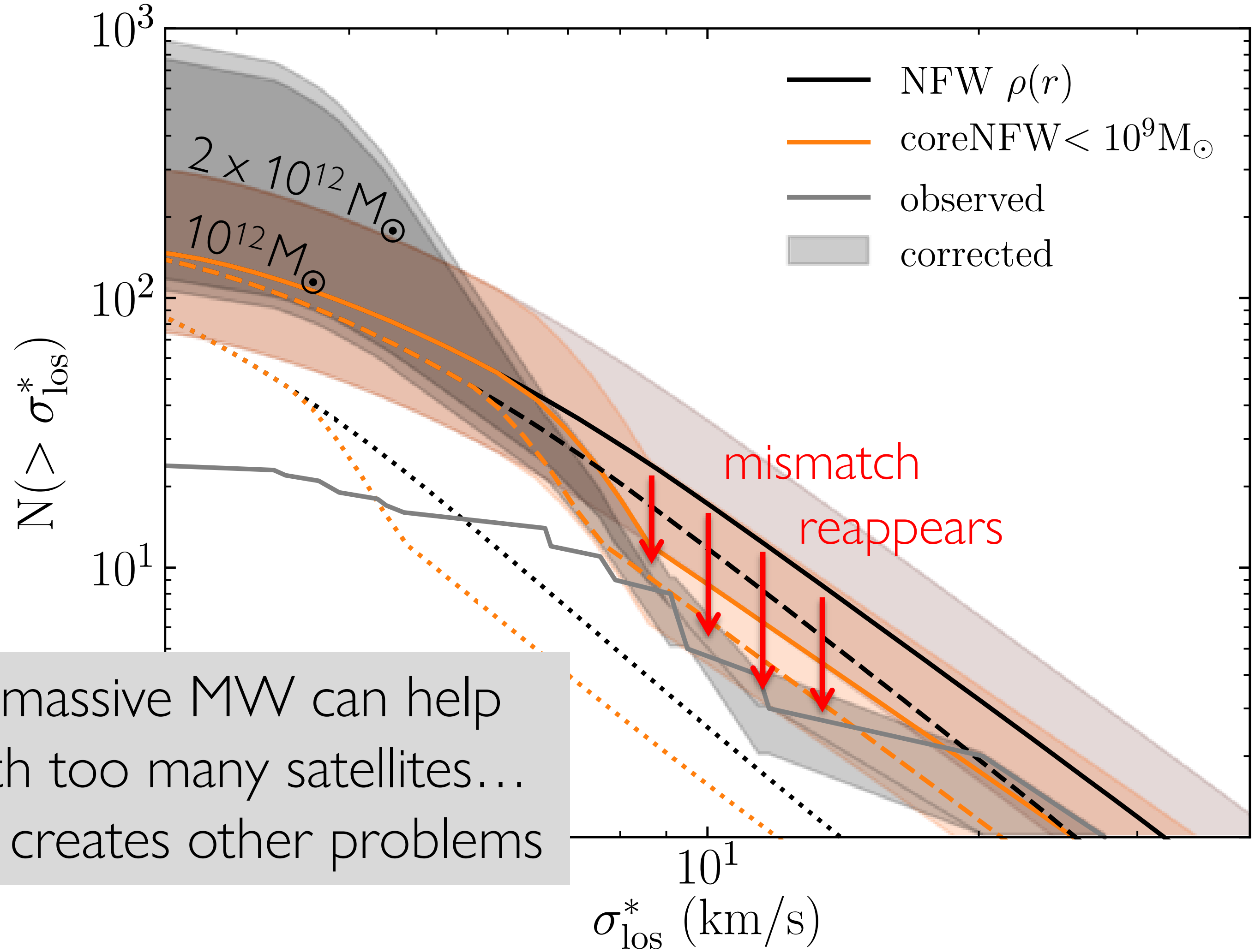


stellar mass-halo mass relation that flattens at ultrafaint scales



theoretical uncertainties

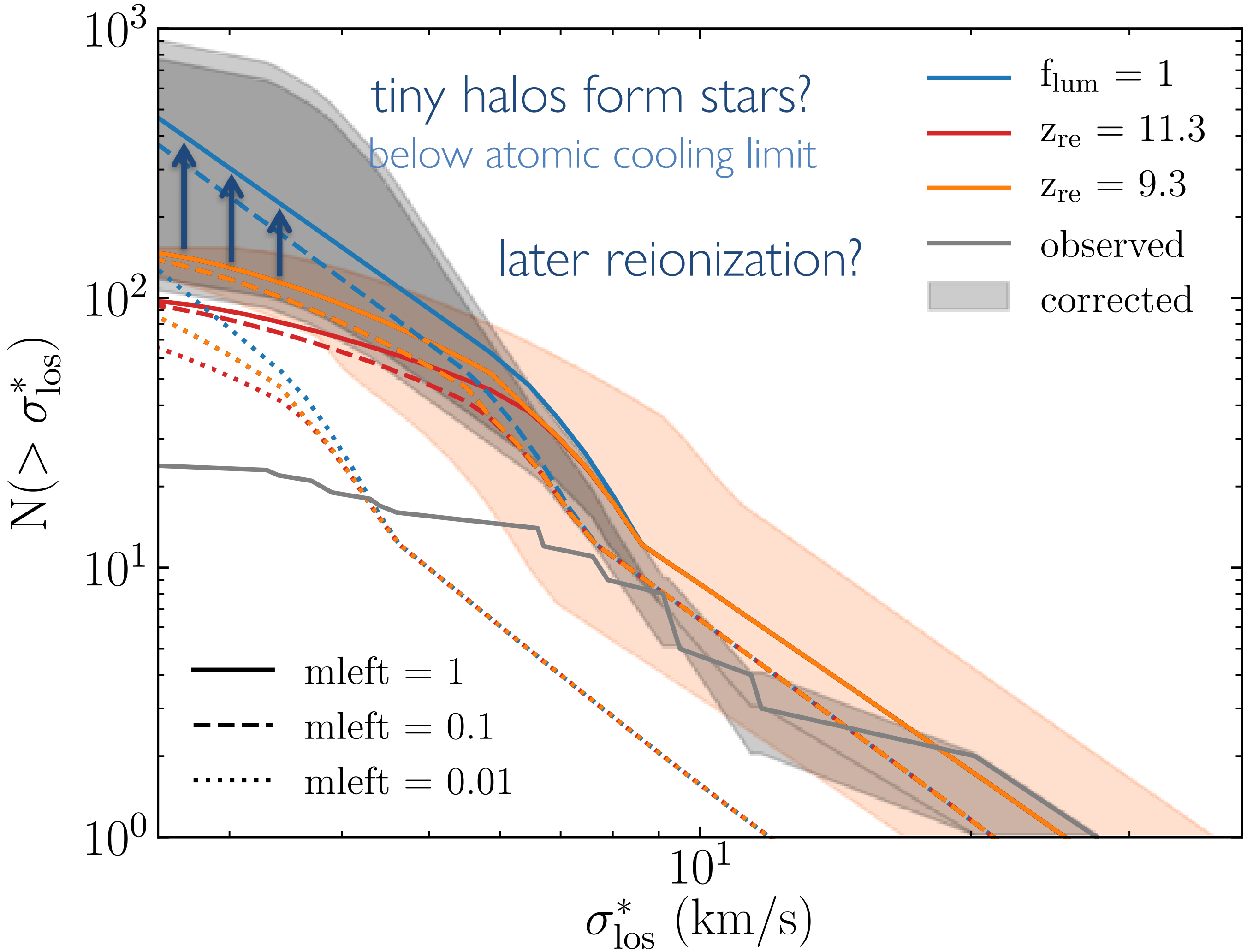
addressing the *too many satellites* problem



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

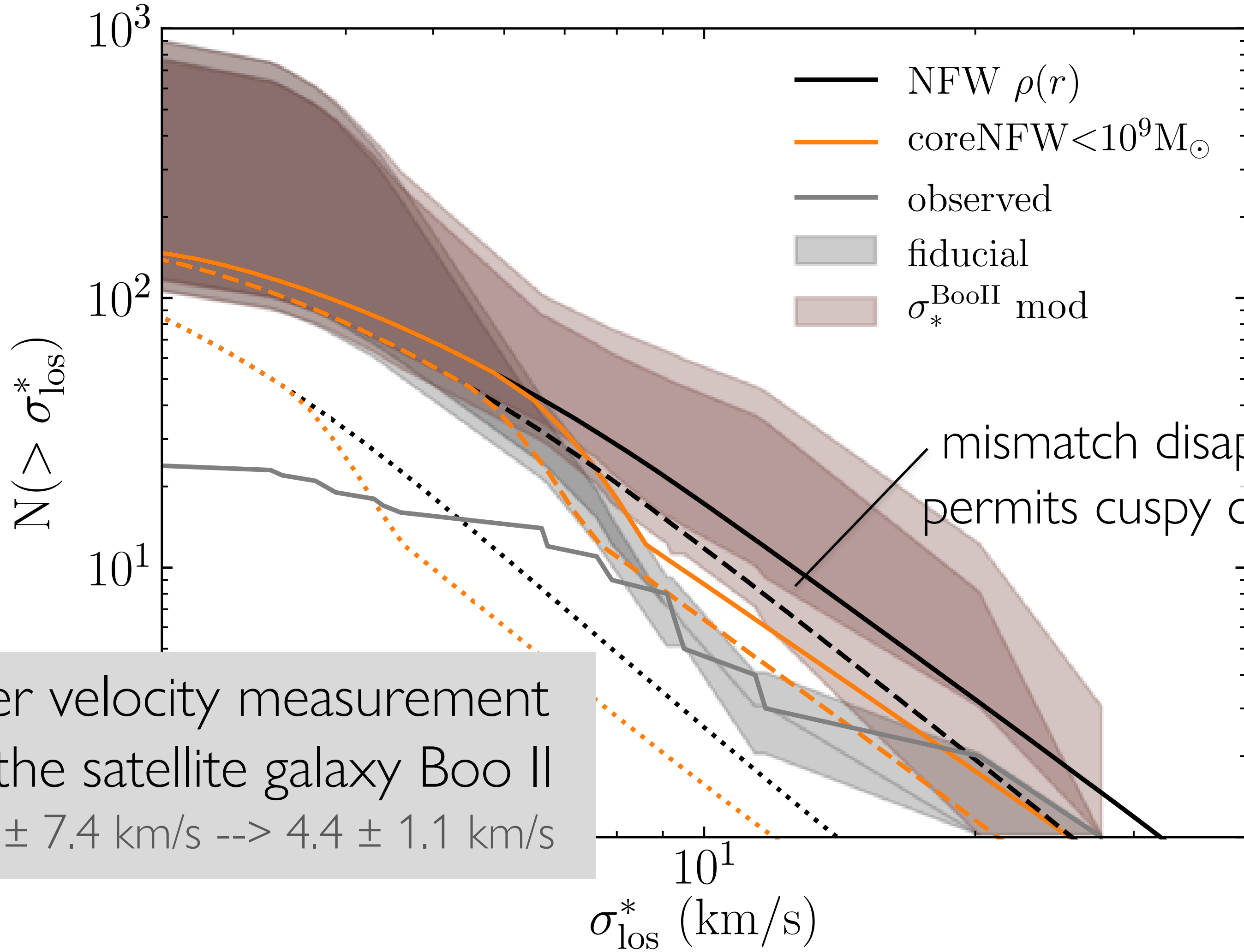
theoretical uncertainties

addressing the *too many satellites* problem



see Graus+ 2019

observational uncertainties

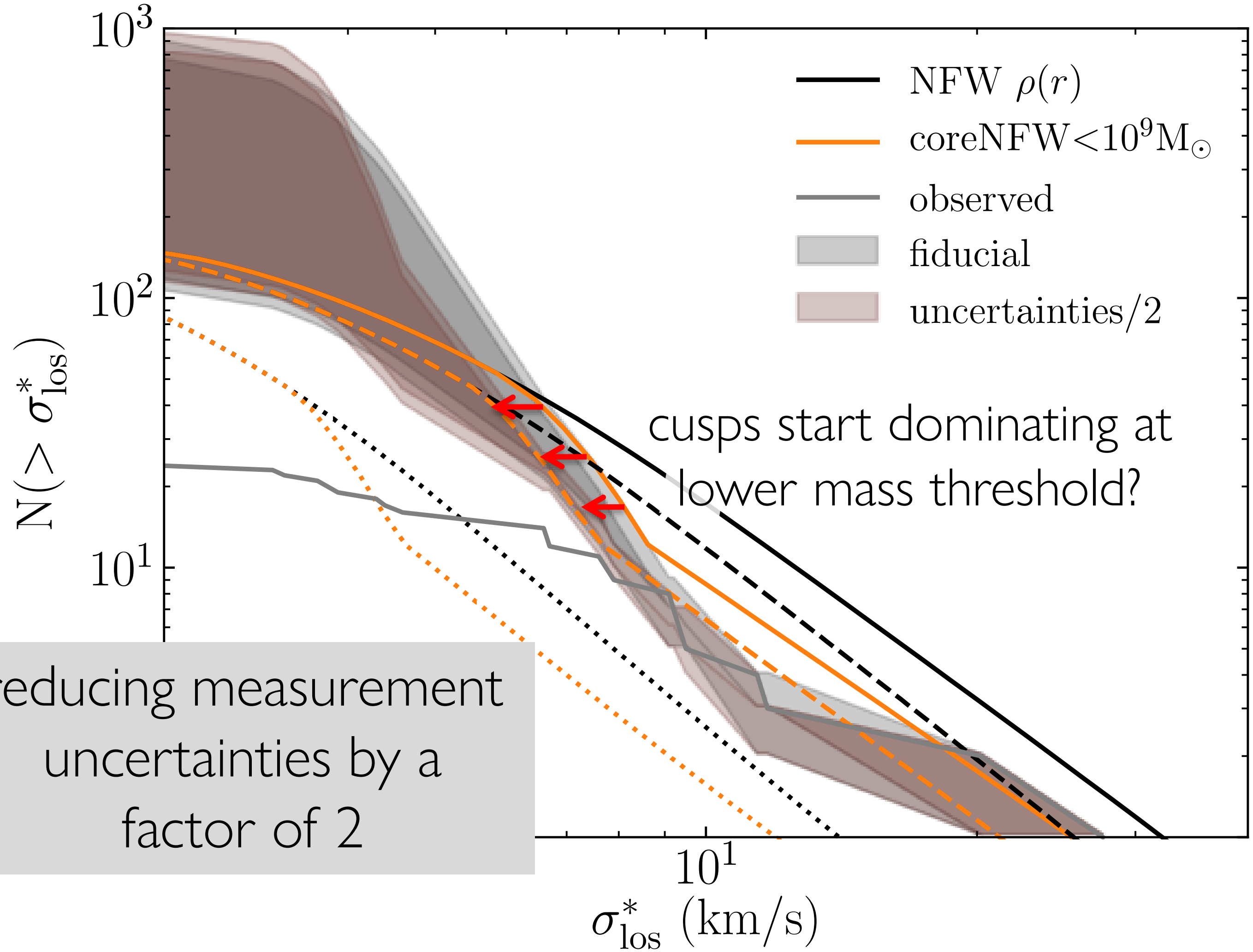


older velocity measurement for the satellite galaxy Boo II

10.5 ± 7.4 km/s --> 4.4 ± 1.1 km/s

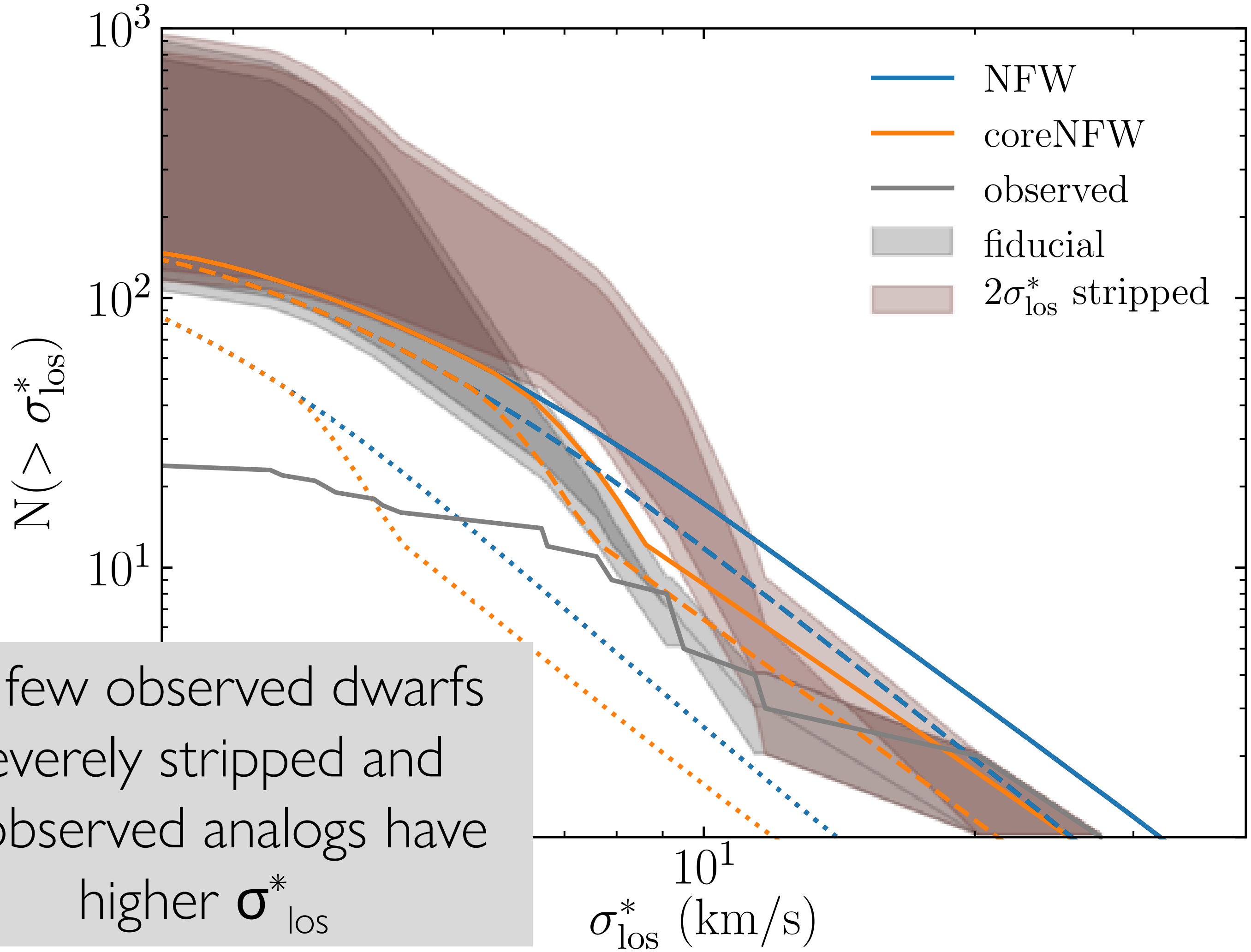
Geha+, private communication

observational uncertainties



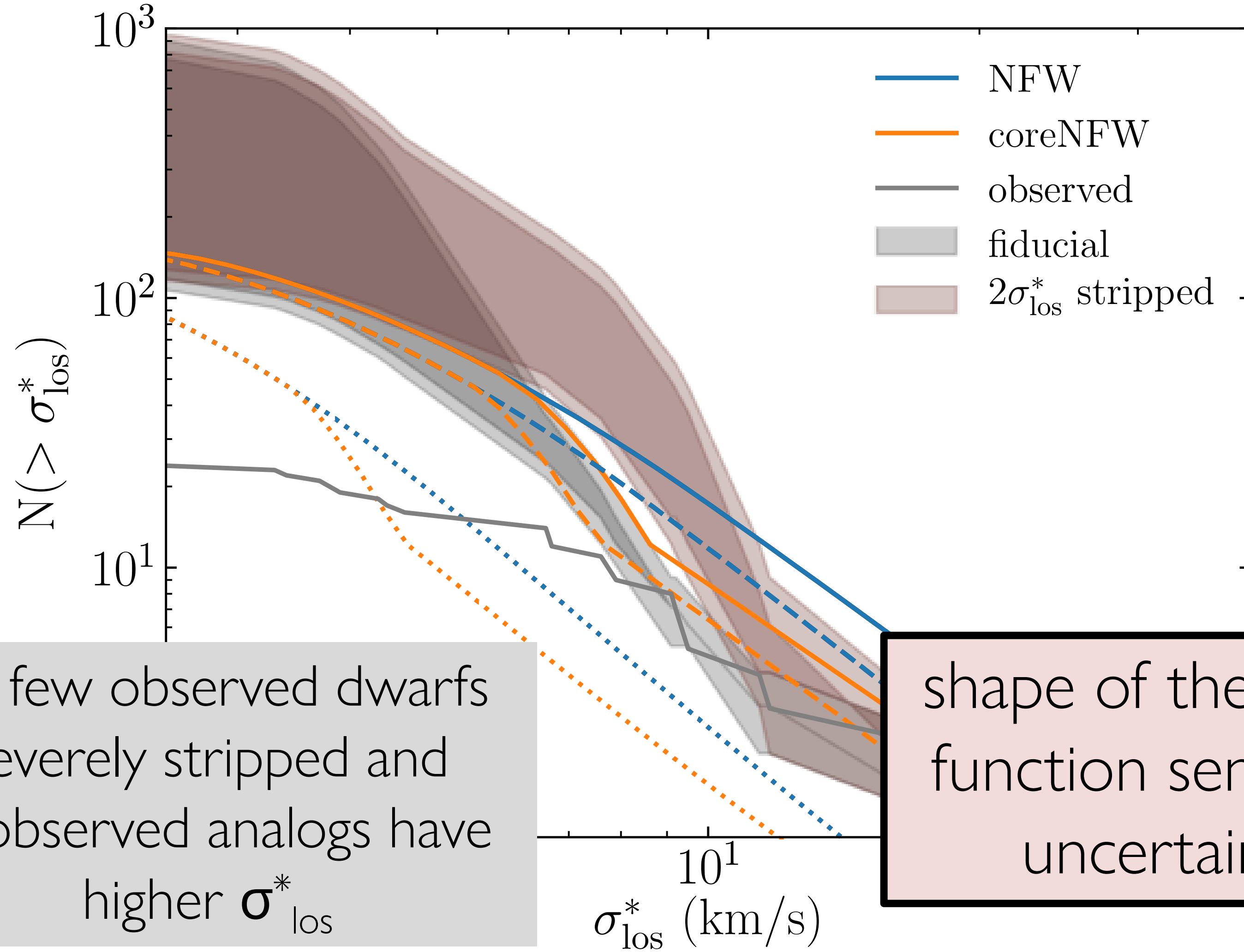
reducing measurement uncertainties by a factor of 2

observational uncertainties



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

observational uncertainties

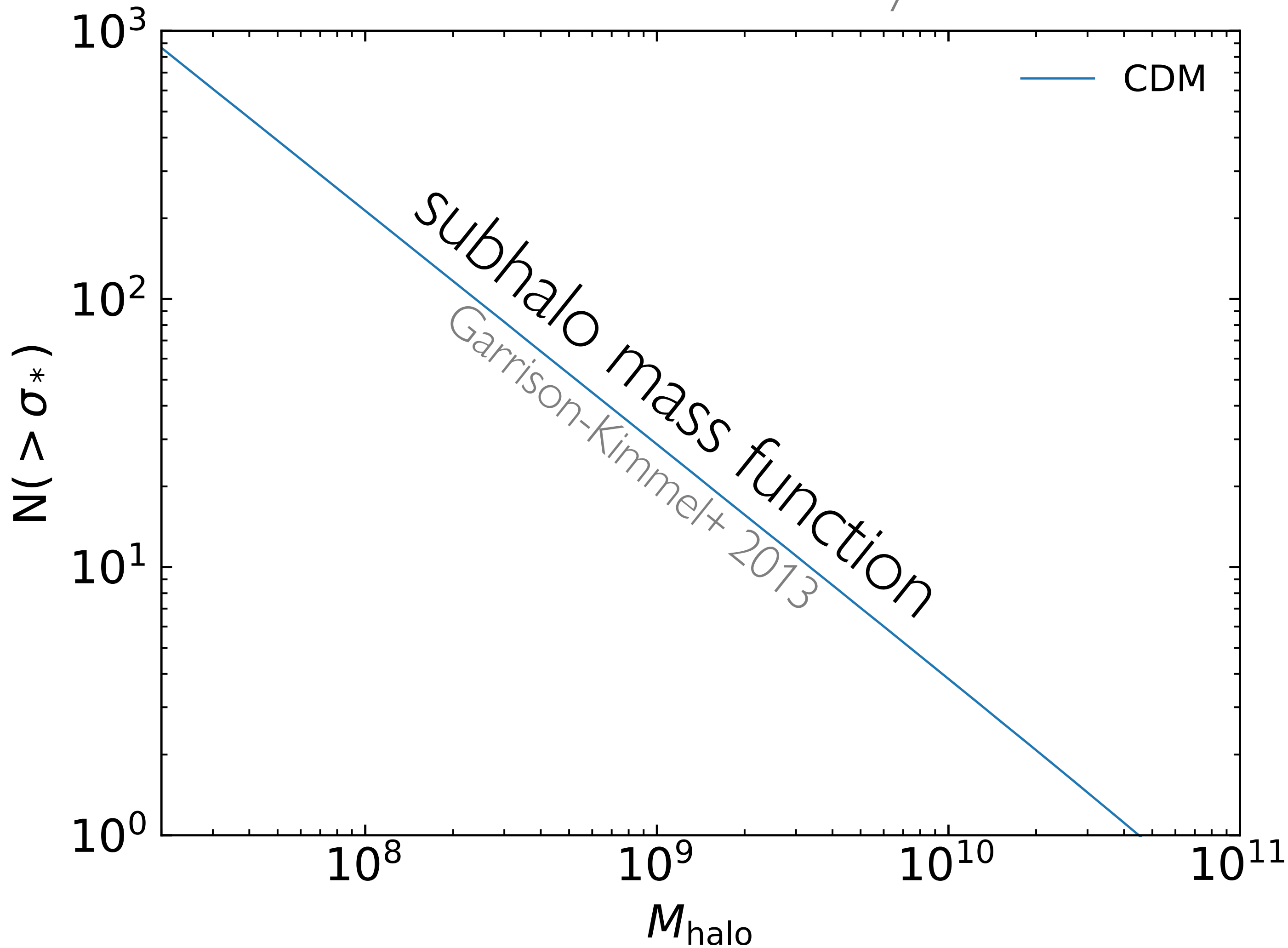


if a few observed dwarfs severely stripped and unobserved analogs have higher $\boldsymbol{\sigma}^*_{\rm los}$

shape of the velocity function sensitive to uncertainties!

theoretical predictions

for satellites discovered by SDSS



Kim et al. 2021 (arXiv:2106.09050)

theoretical predictions

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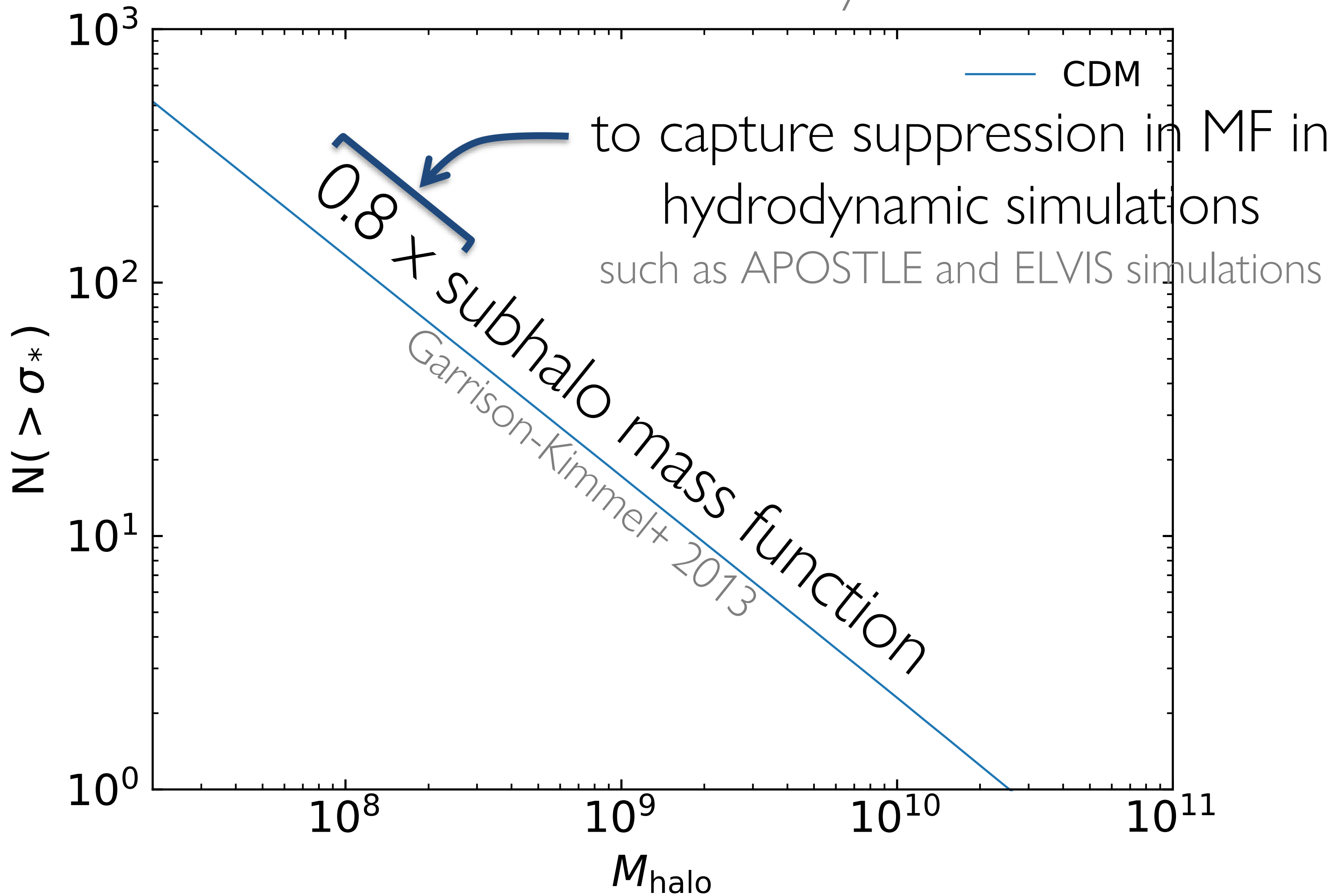

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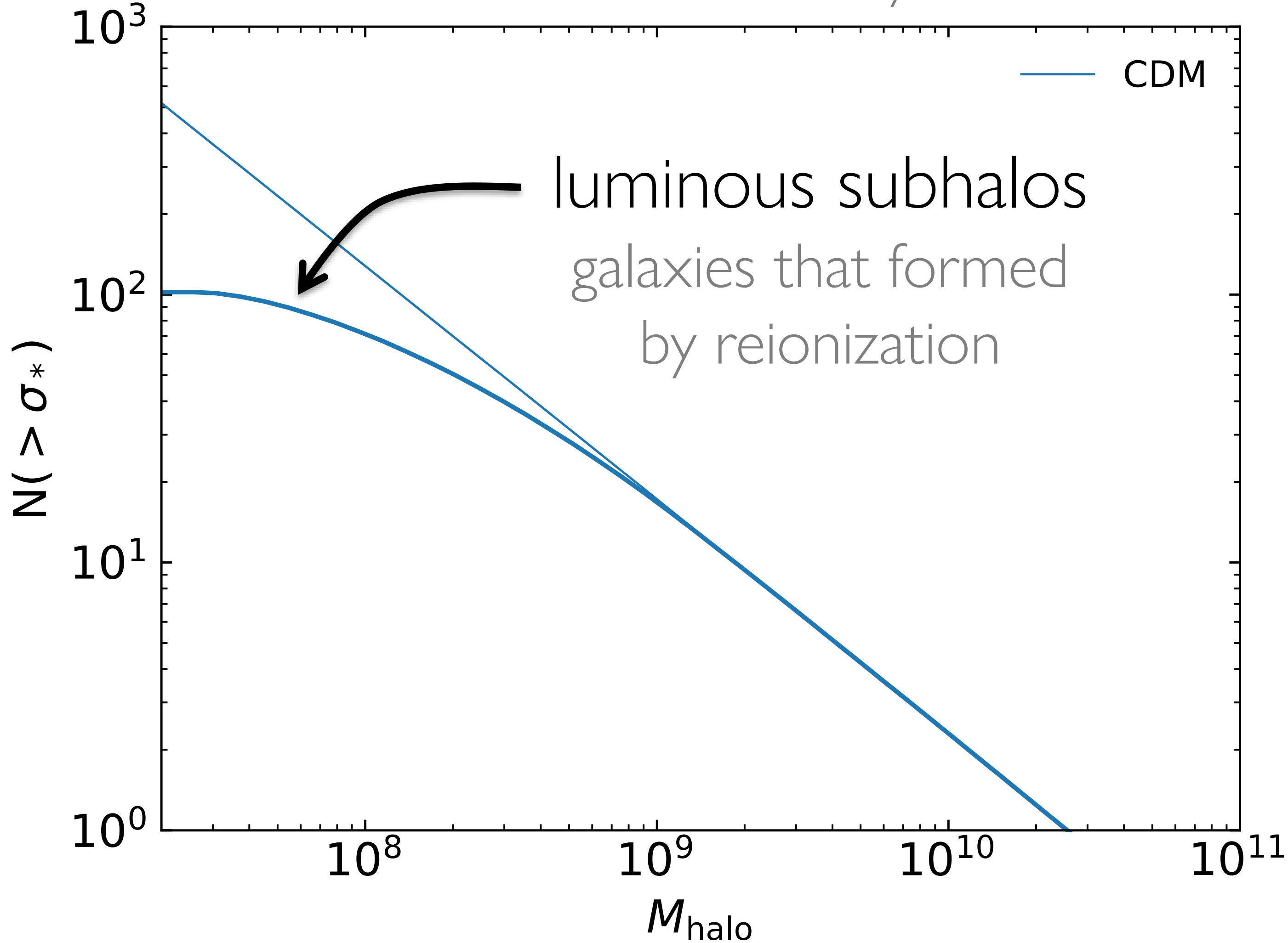


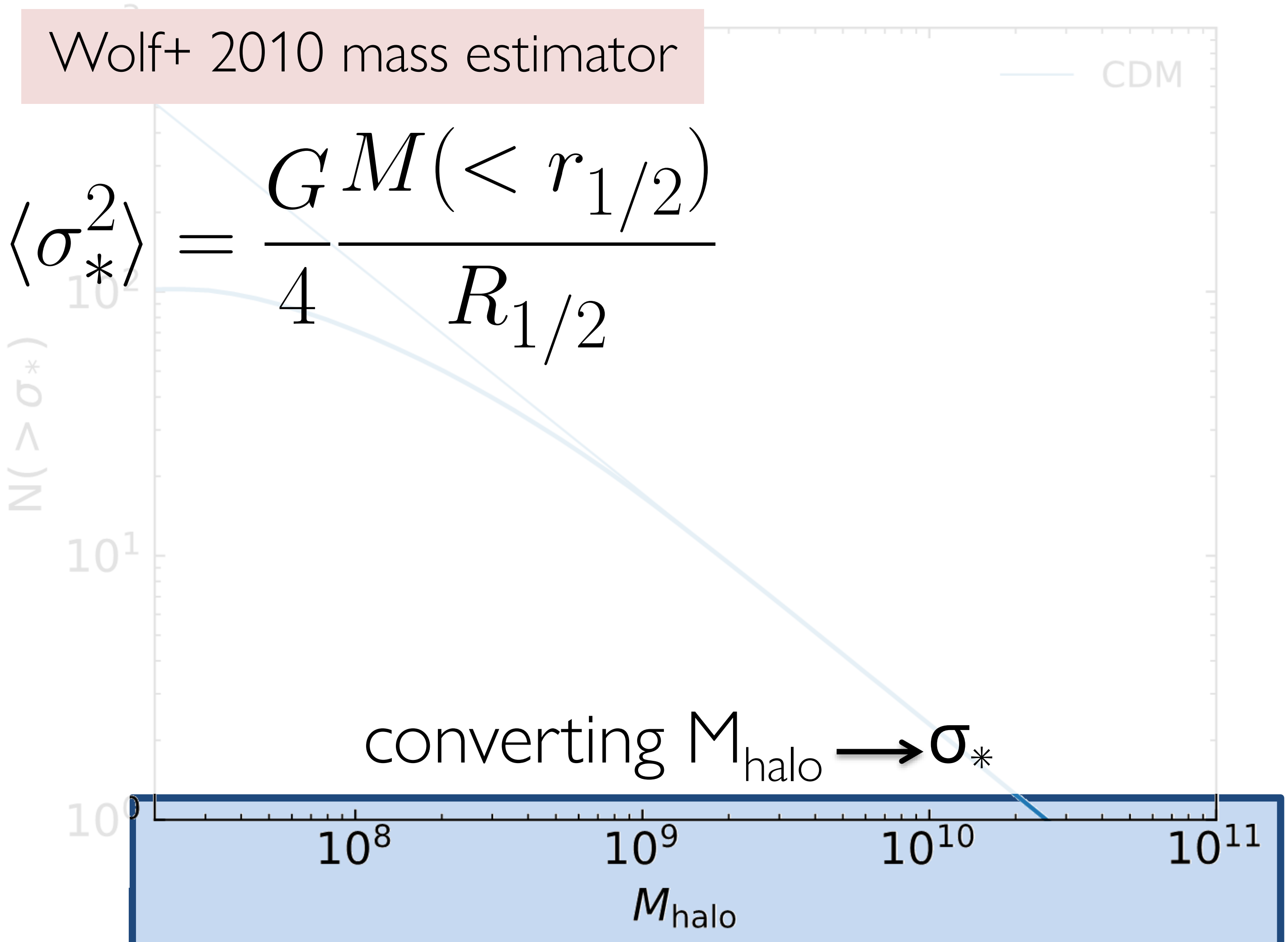
Dooley+ 2017, Barber+ 2014

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 $M_{halo} \longrightarrow \sigma_*$

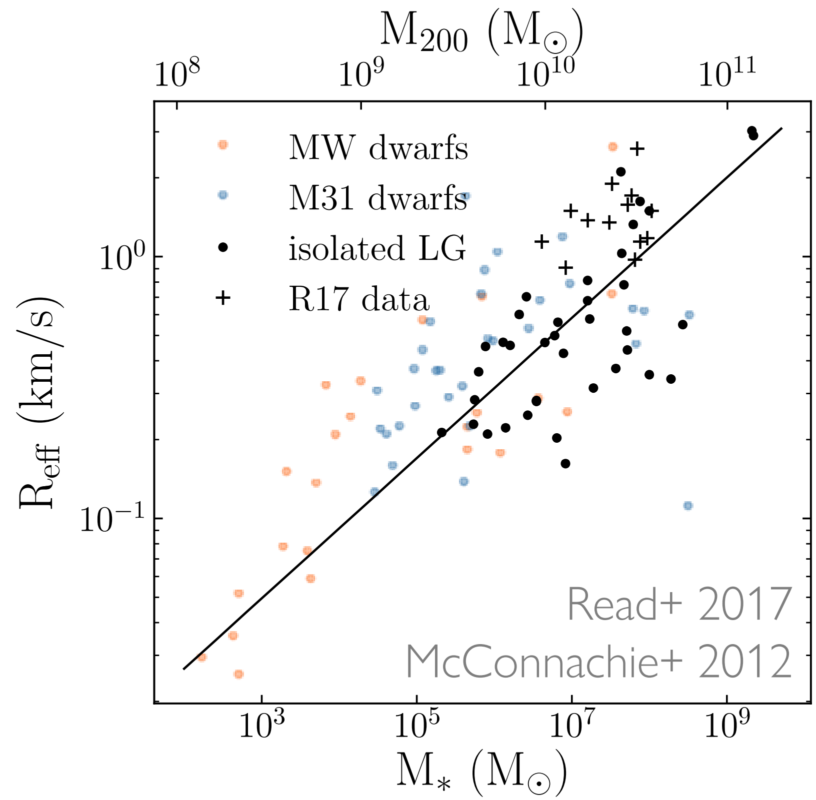
Kim et al. 2021 (arXiv:2106.09050)

theoretical predictions

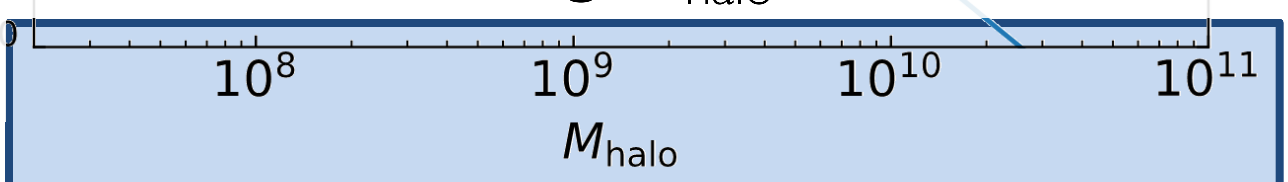
Wolf+ 2010 mass estimator

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

from fit to observed isolated dwarfs



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



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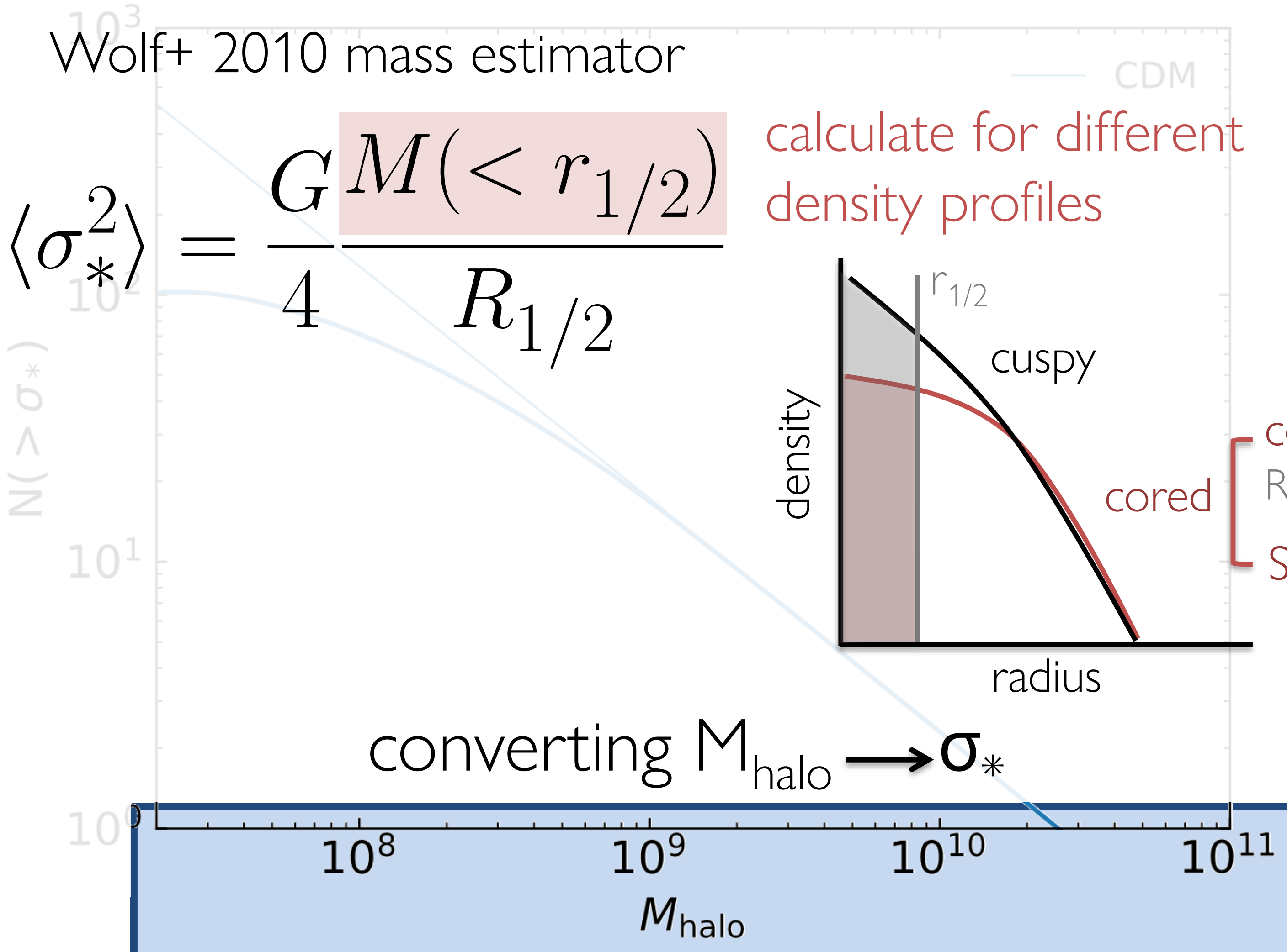
calculate for different density profiles

coreNFW

Read+ 2017

SIDM

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



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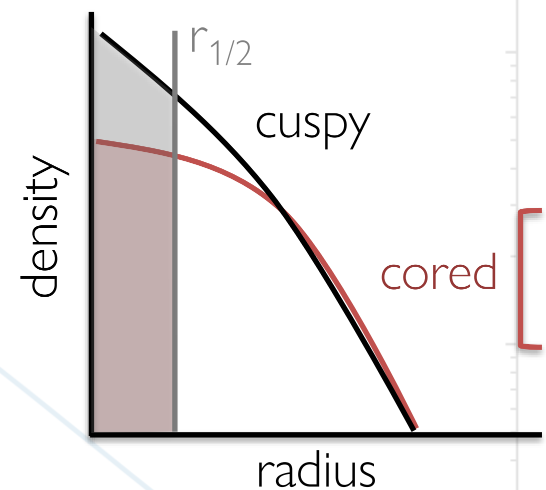


coreNFW
Read+ 2017
SIDM

and a few others choices, e.g.

c-M relation Diemer & Joyce 2019

infall redshift $z = 1$

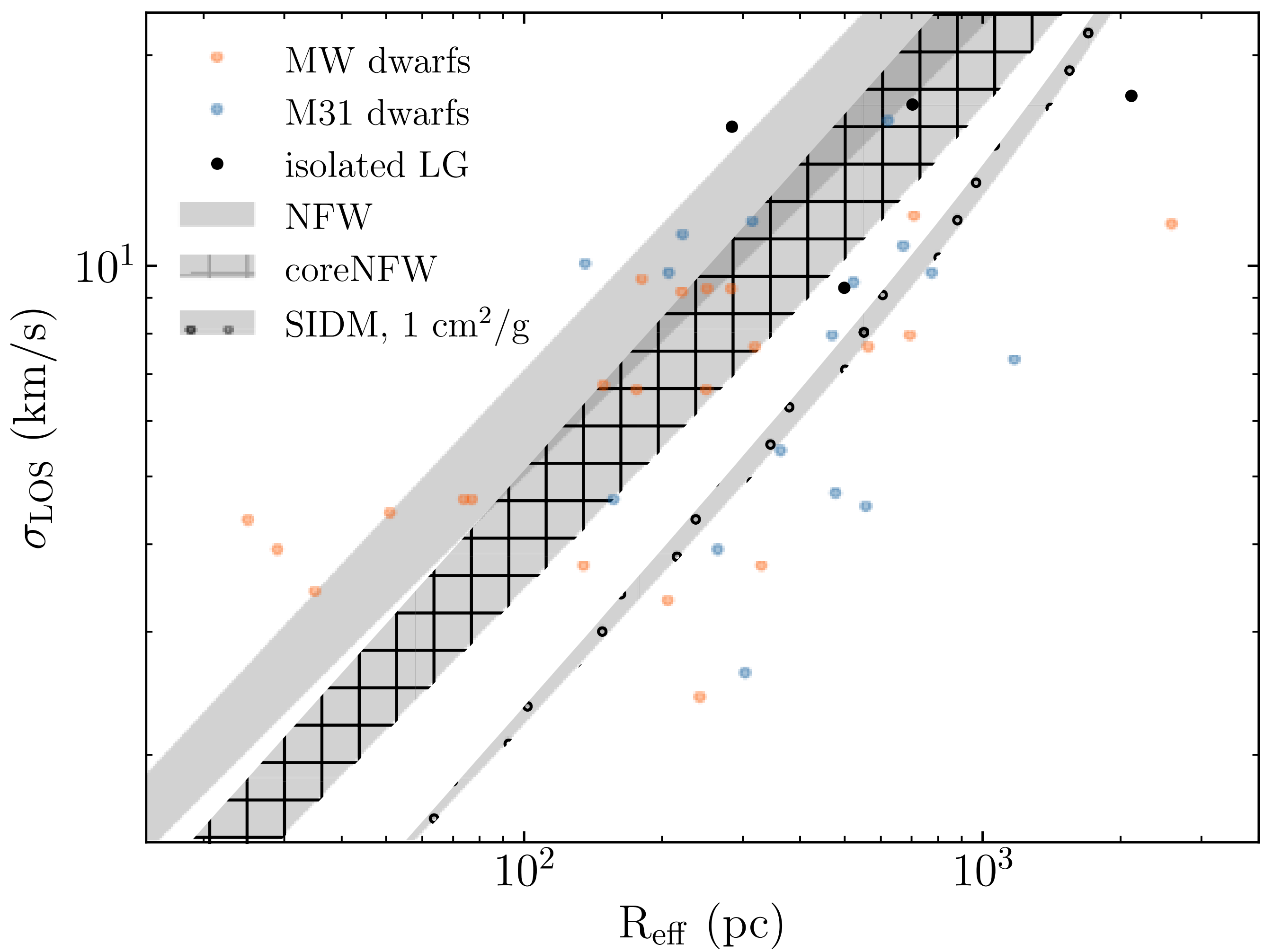
converting $M_{halo} \longrightarrow \sigma_*$

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

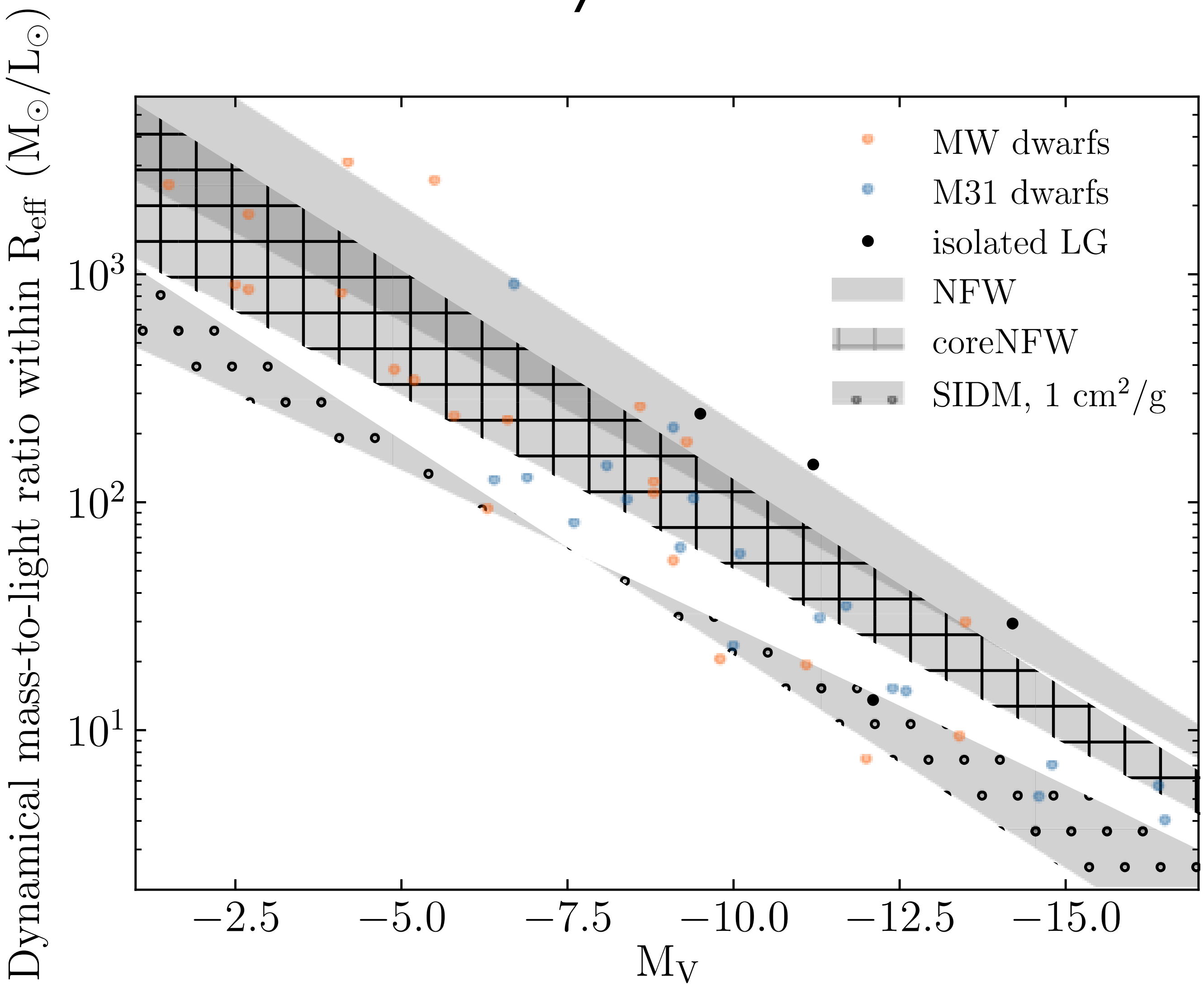
M_{halo}

Kim et al. 2021 (arXiv:2106.09050)

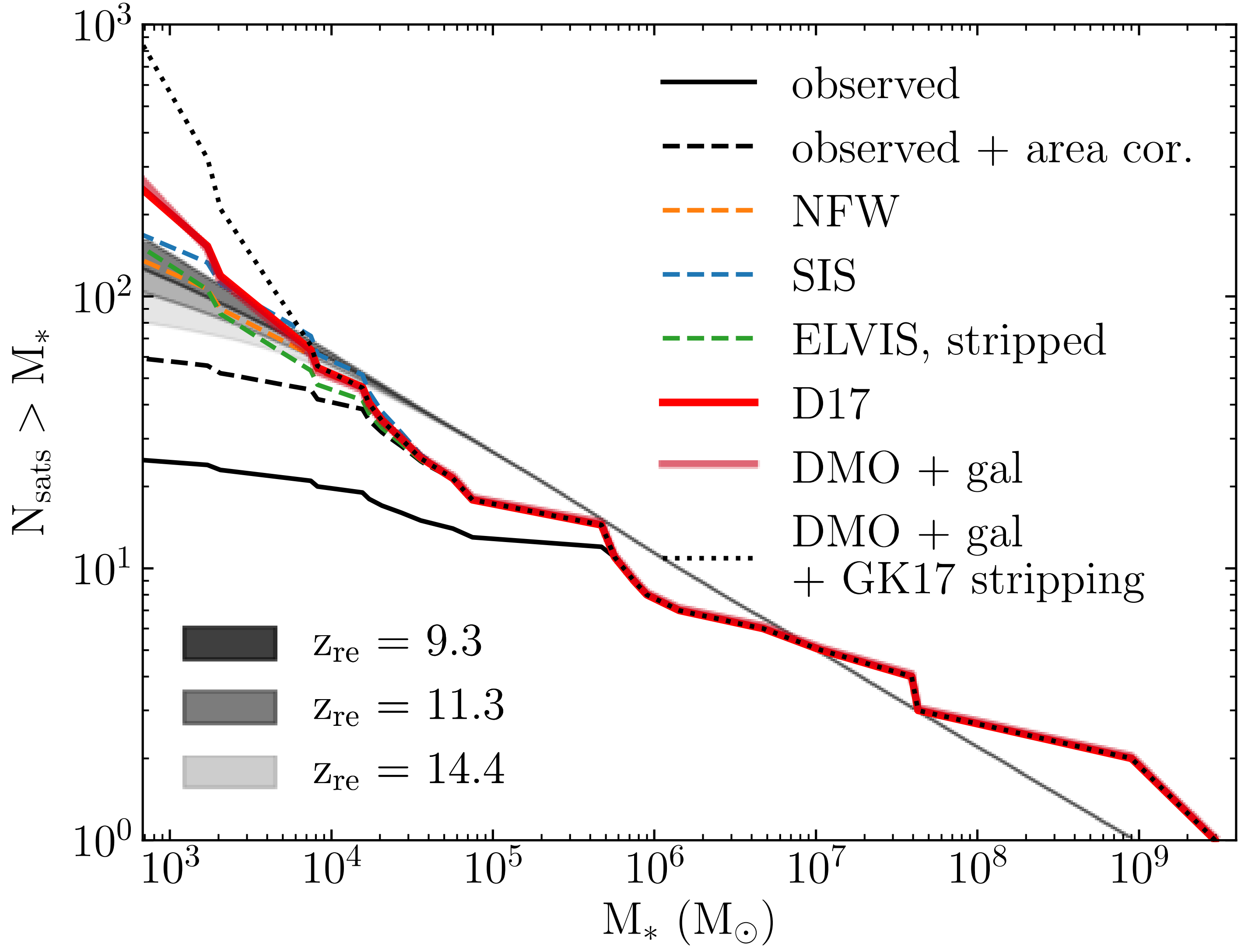
sanity checks



sanity checks



corrected luminosity function

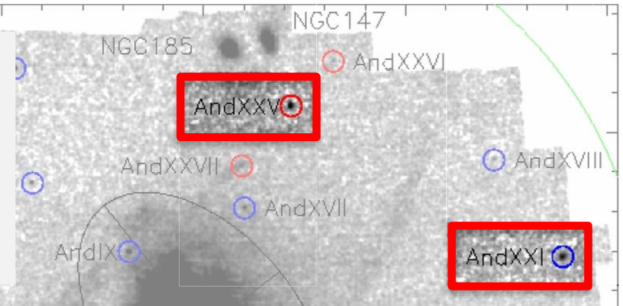


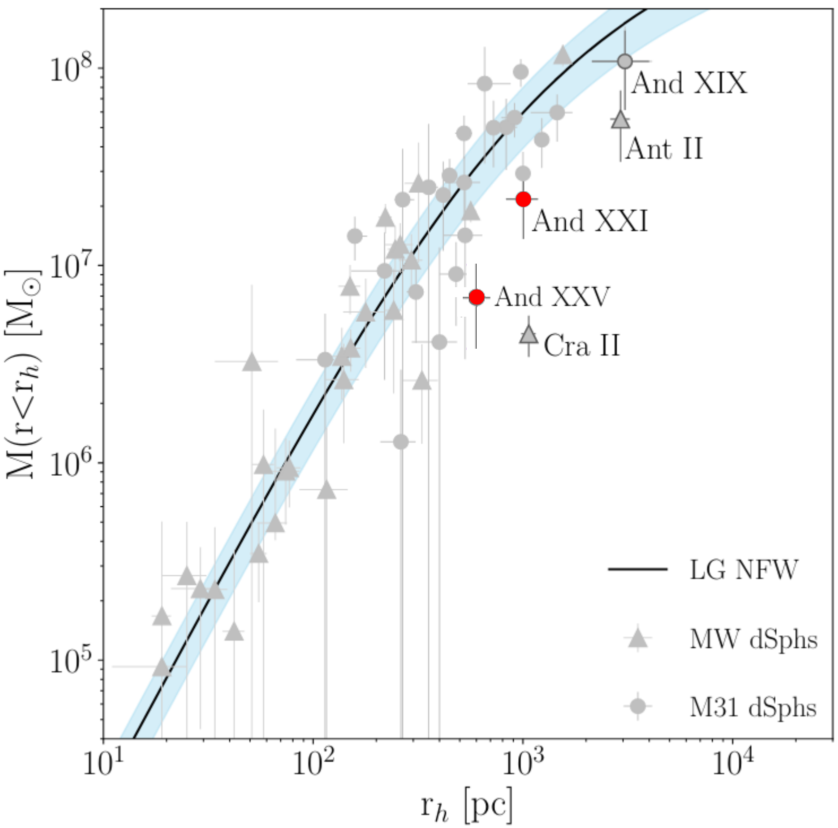
EXTRAS: M31

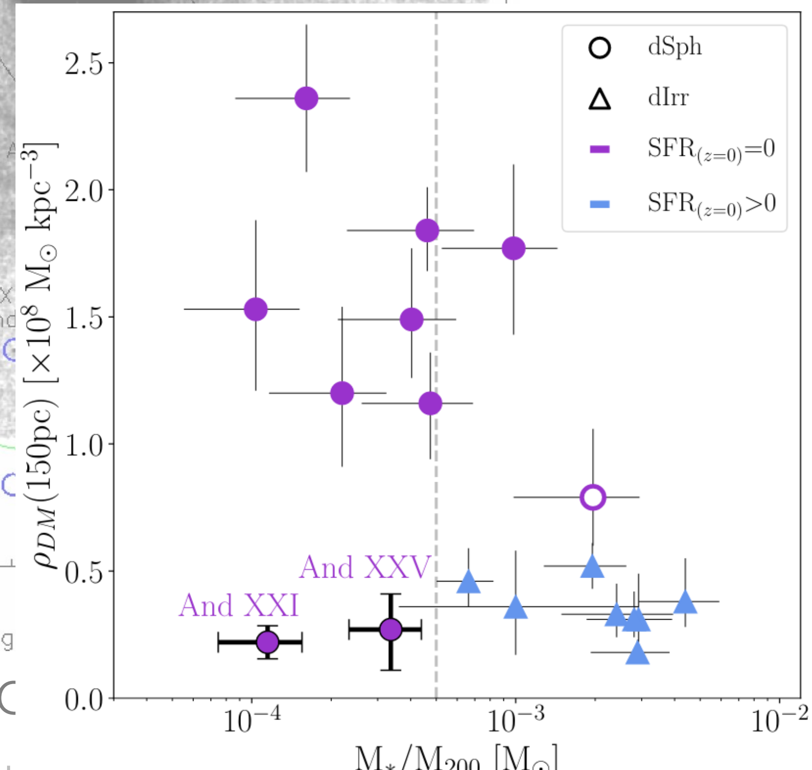
What about M31's satellites?

Emily Charles

start with And XXI and And XXV, two unusually low-density dwarfs







Charles+ incl. SYK 2023

EXTRAS: CORE COLLAPSE

new wrinkles in the fold

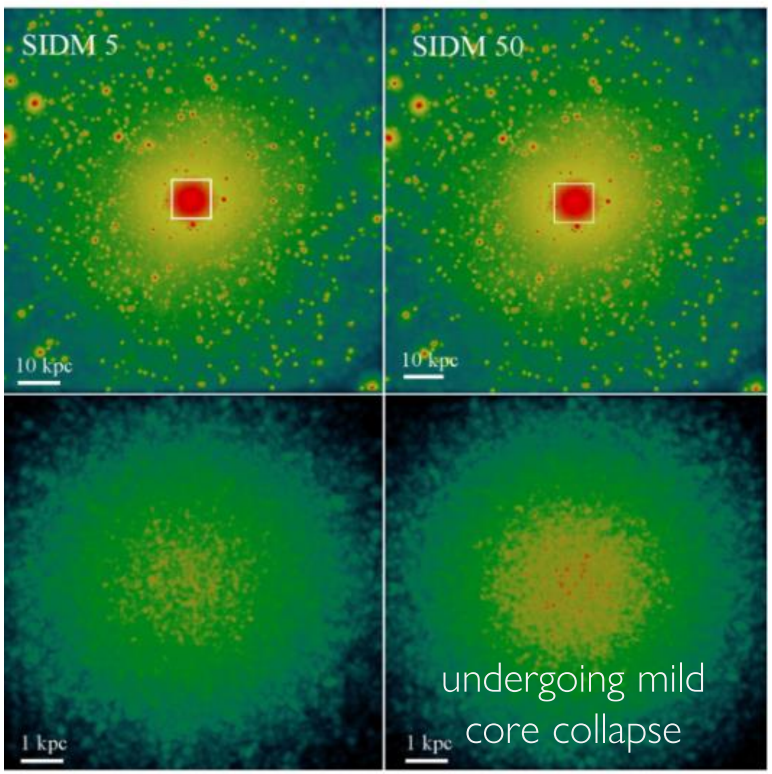
The outlook for constant cross sections is not promising!

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…

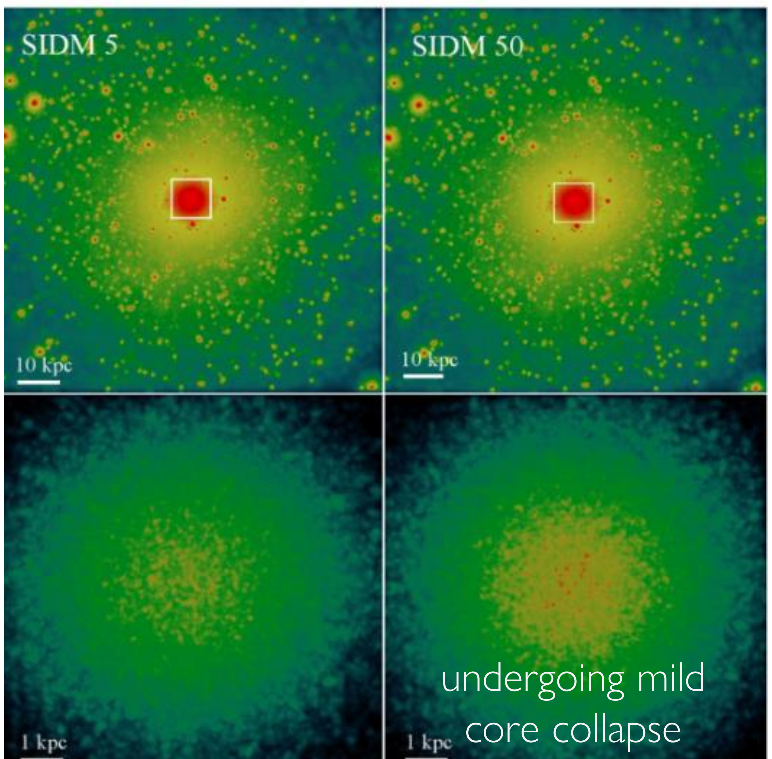


Elbert+ 2015

new wrinkles in the fold

The outlook for constant cross sections is not promising!

BUT there have been a couple recent developments…

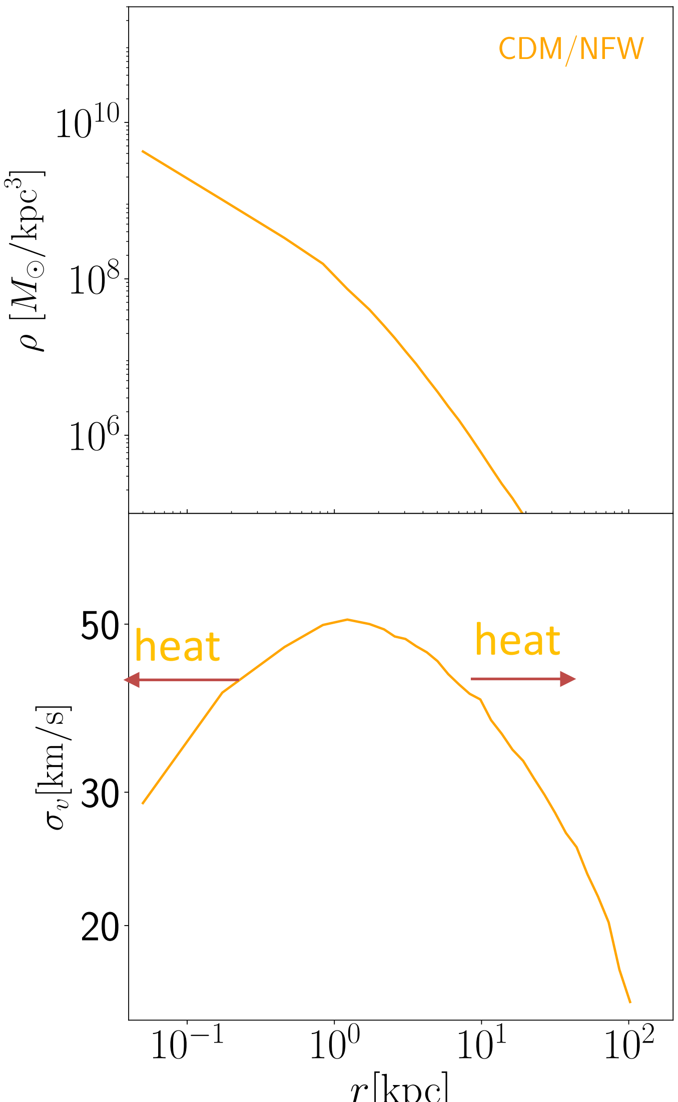


Core collapse can reintroduce dense cores, and even reestablish cusps.

Accelerated by tidal stripping?

Elbert+ 2015, Essig+ 2019, Nishikawa+ 2020

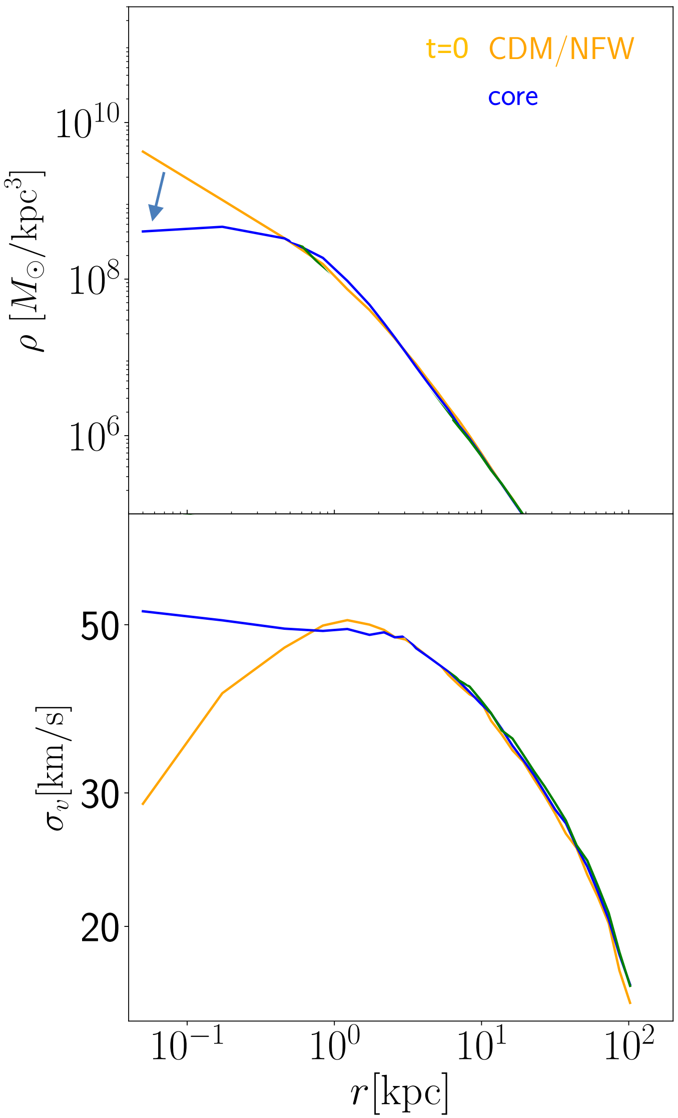
SIDM core collapse



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

Zeng+ incl. SYK 2022

SIDM core collapse



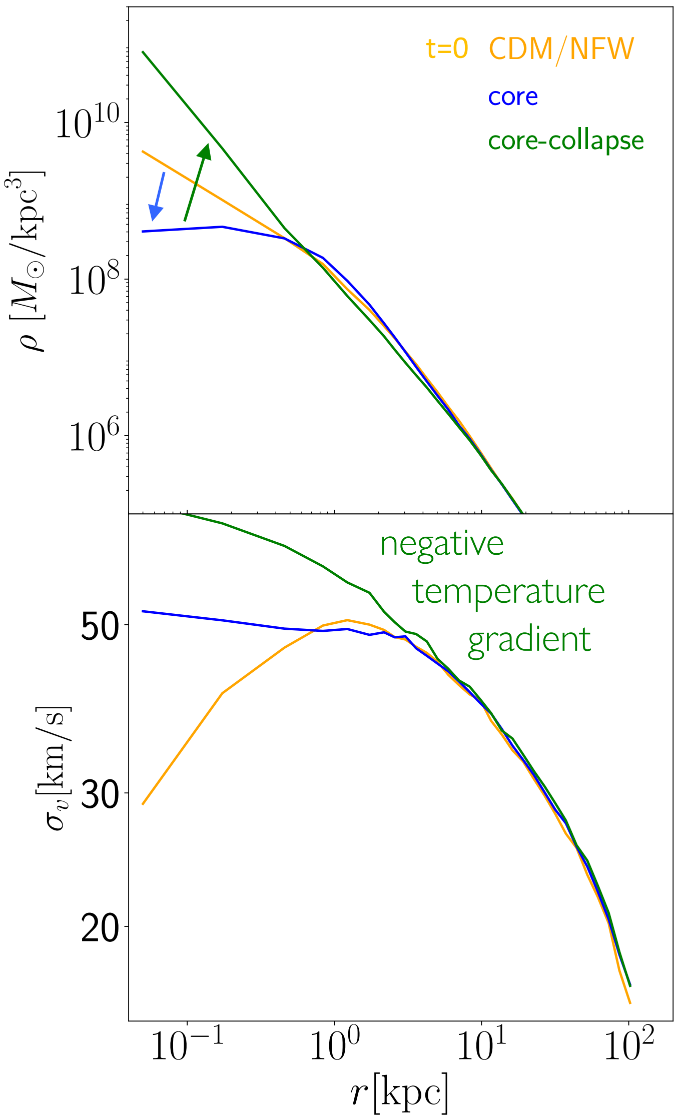
Energy exchange via self-interactions leads to 'heat' flow.

Phase 1

isothermal core forms

Zeng+ incl. SYK 2022

SIDM core collapse



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

Phase 1

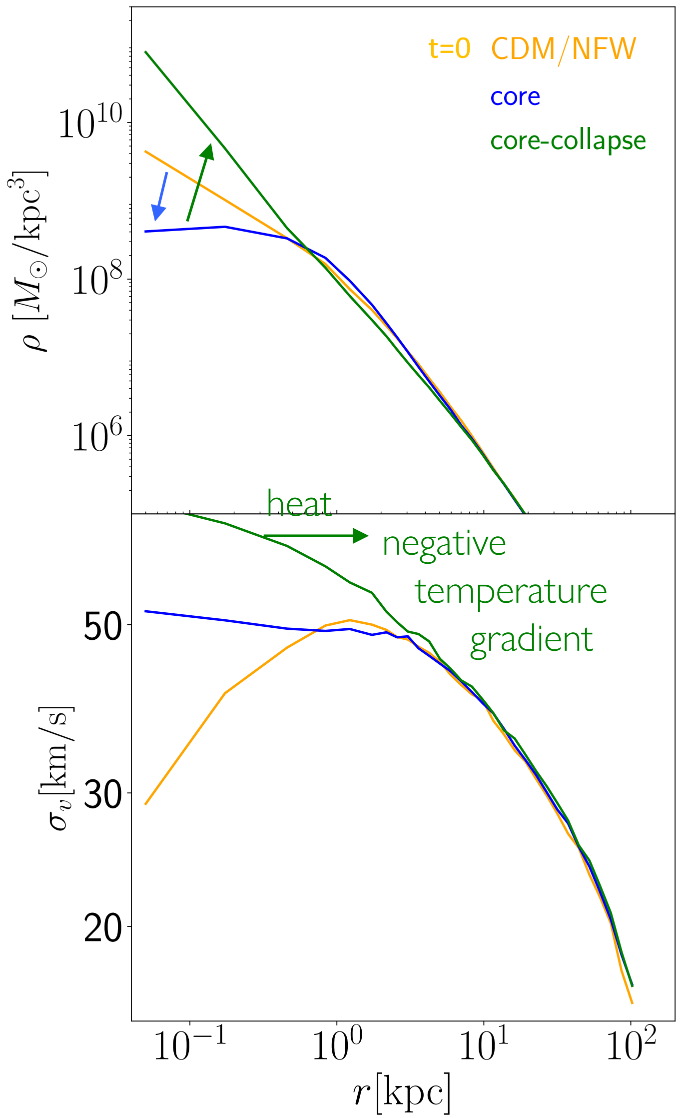
isothermal core forms

Phase 2

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

Zeng+ incl. SYK 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. SYK 2022

SIDM core collapse

Simulating subhalos under core collapse is expensive.

<u>scattering probability</u> $\propto \dfrac{\sigma_{\rm SI}}{m_\chi} \Delta v \; \rho \; \Delta t$

Zeng+ incl. SYK 2022

SIDM core collapse

Simulating subhalos under core collapse is expensive.

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

increases by orders of magnitude

Zeng+ incl. SYK 2022

SIDM core collapse

Simulating subhalos under core collapse is expensive.

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

increases by orders of magnitude

keeping P < 1 requires *tiny* timesteps!

Zeng+ incl. SYK 2022

SIDM core collapse

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

Zeng+ incl. SYK 2022

SIDM core collapse

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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

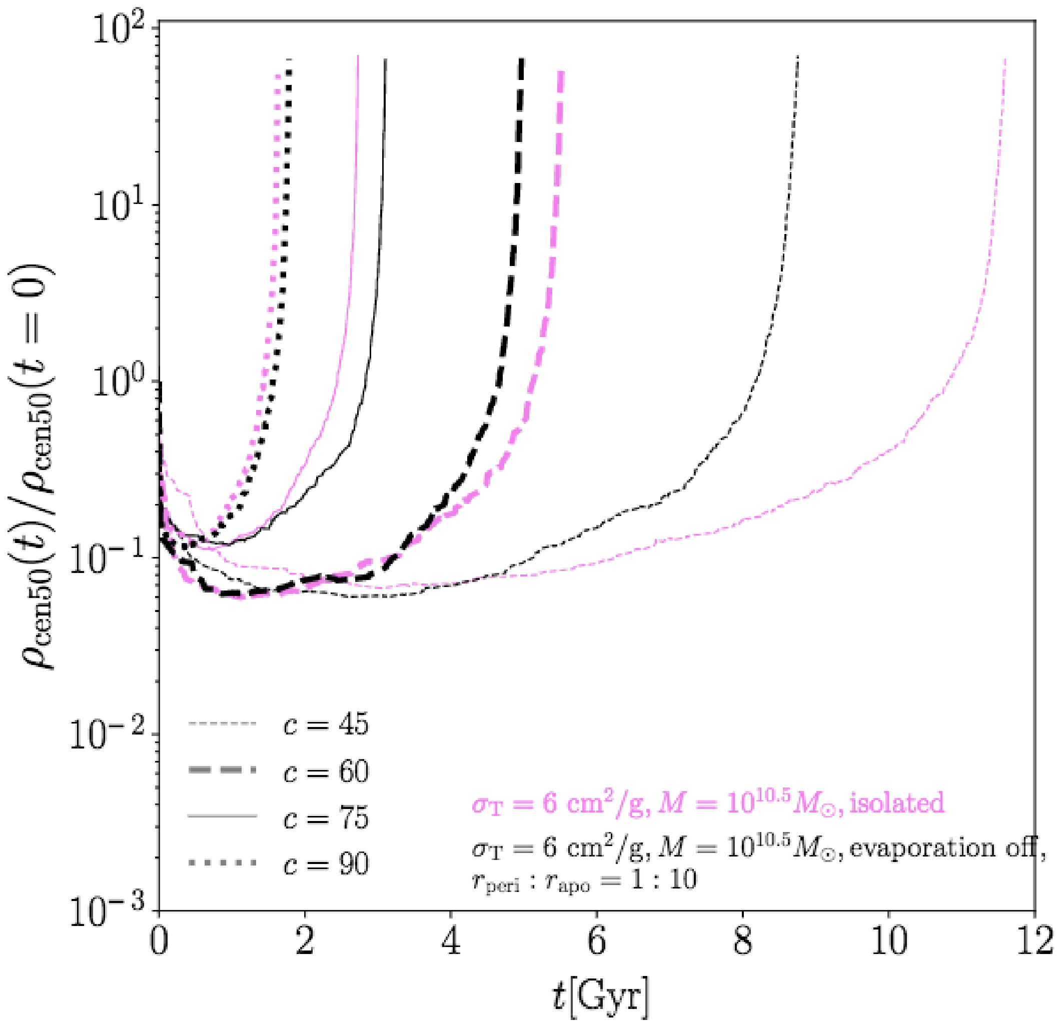
analytic host + 'live' (N-body) subhalo + evaporation

host-sub interactions

that reduces computational time by orders of magnitude!

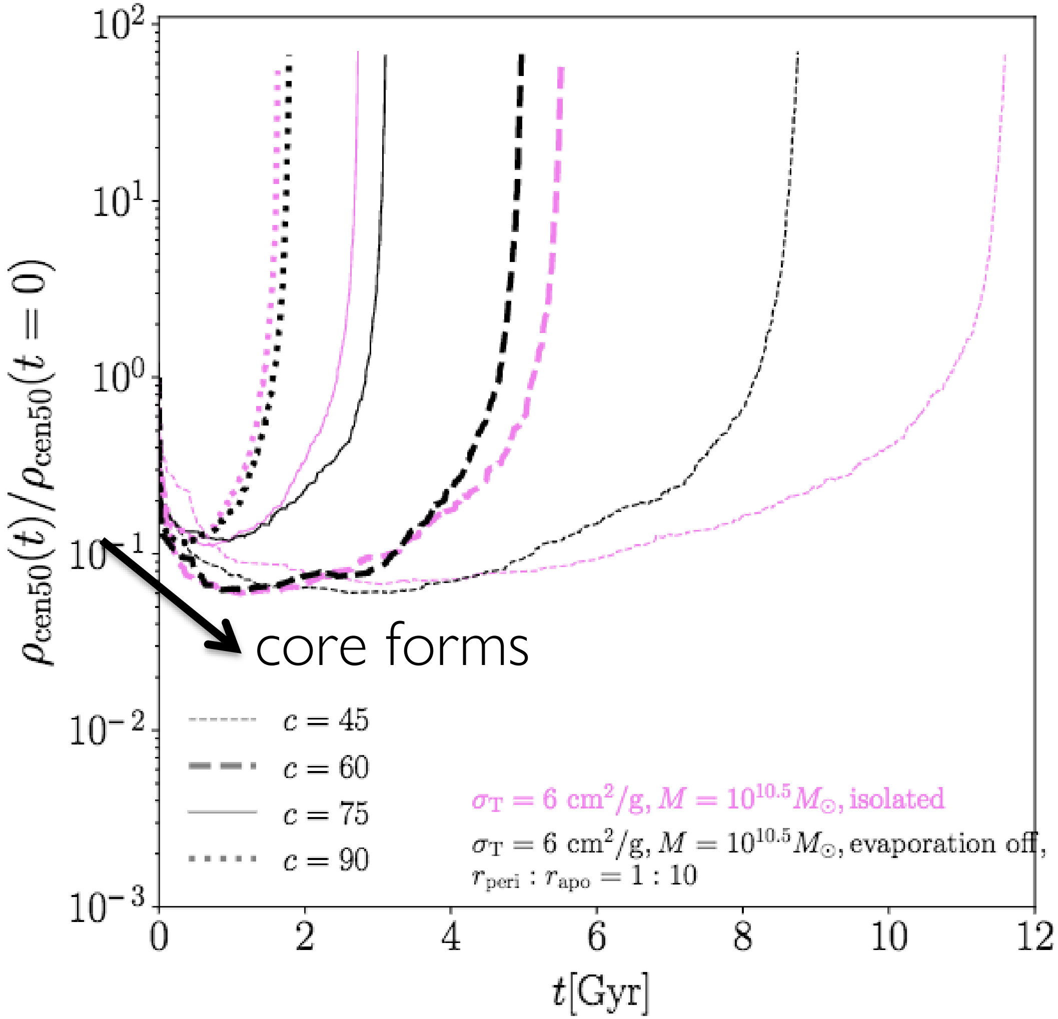
Zeng+ incl. SYK 2022

SIDM core collapse



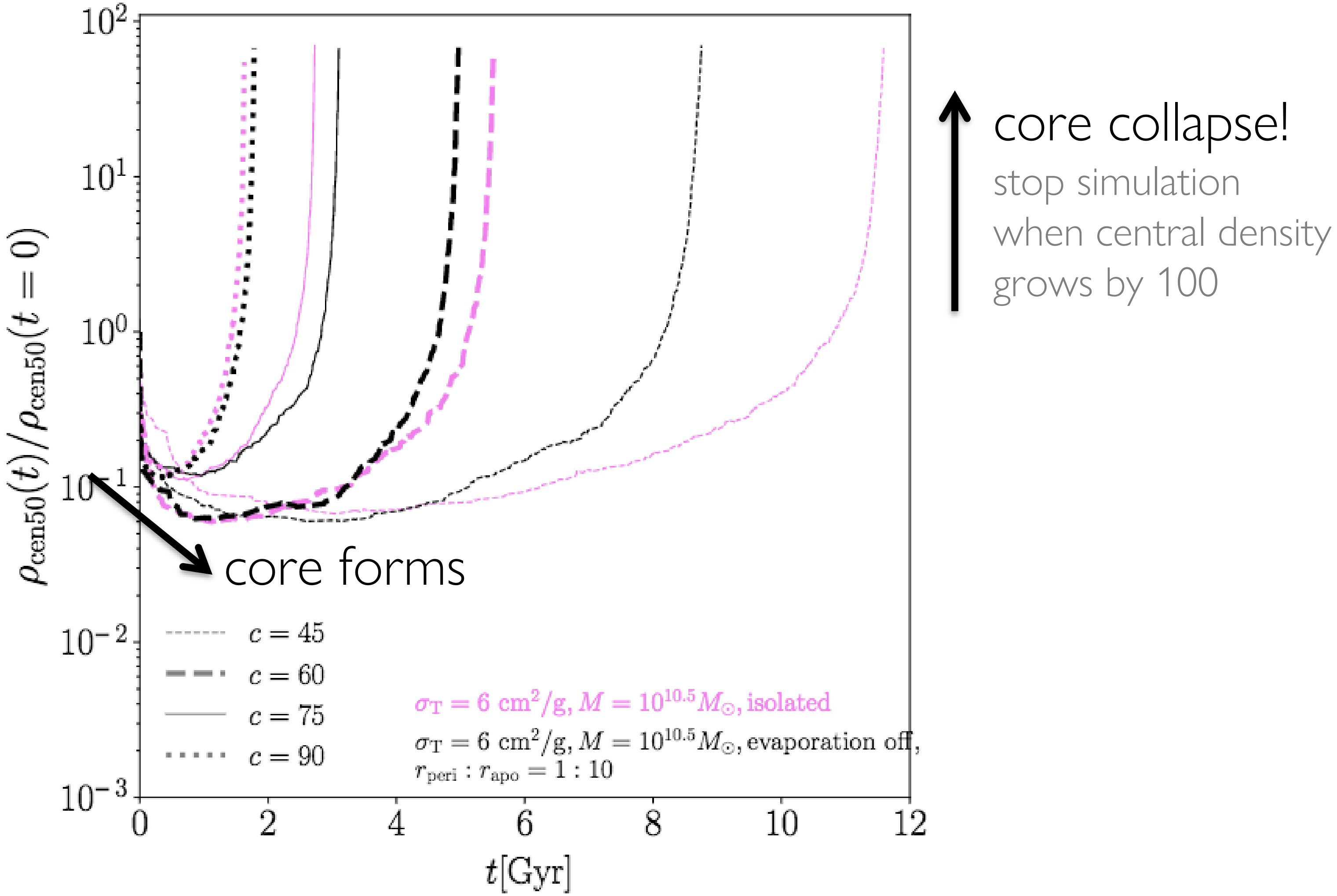
Zeng+ incl. Kim 2022

SIDM core collapse



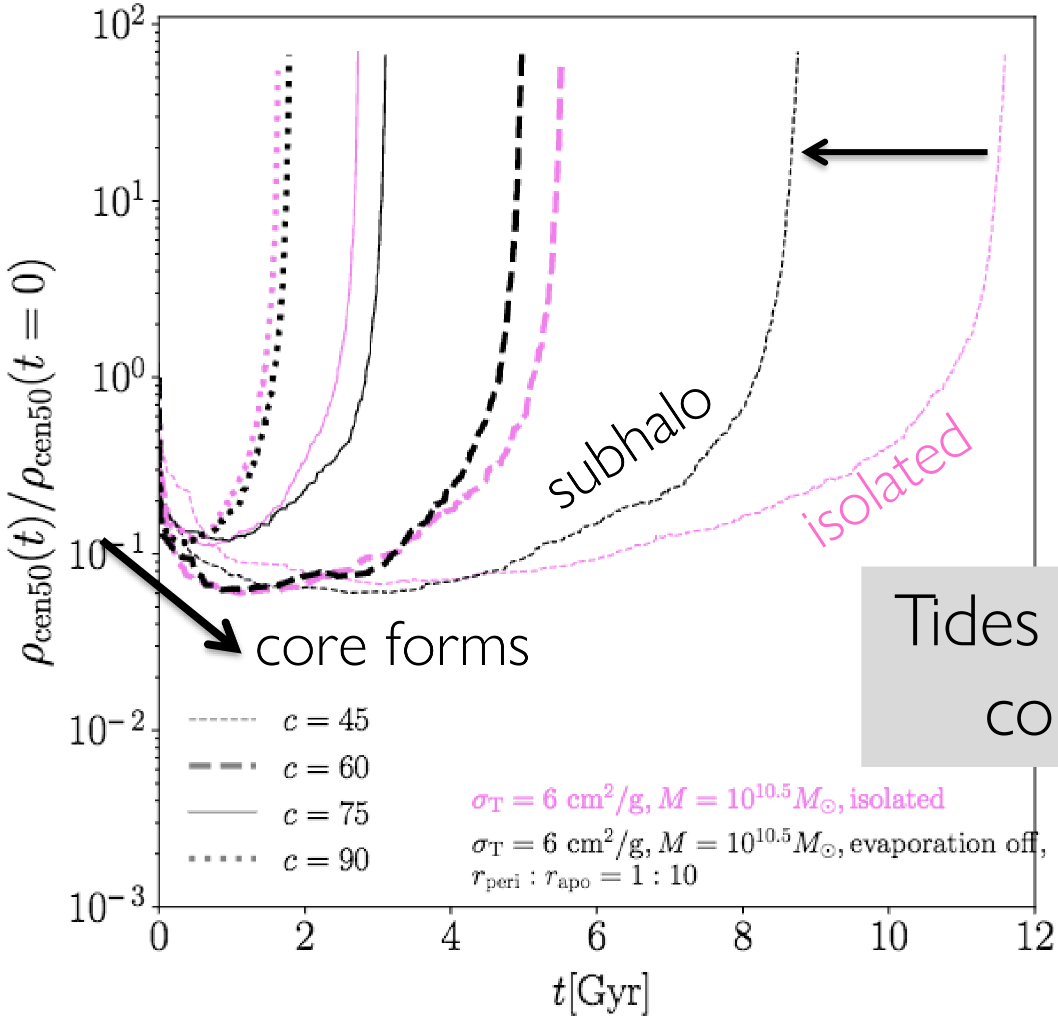
Zeng+ incl. Kim 2022

SIDM core collapse



Zeng+ incl. Kim 2022

SIDM core collapse



core collapse!

stop simulation when central density grows by 100

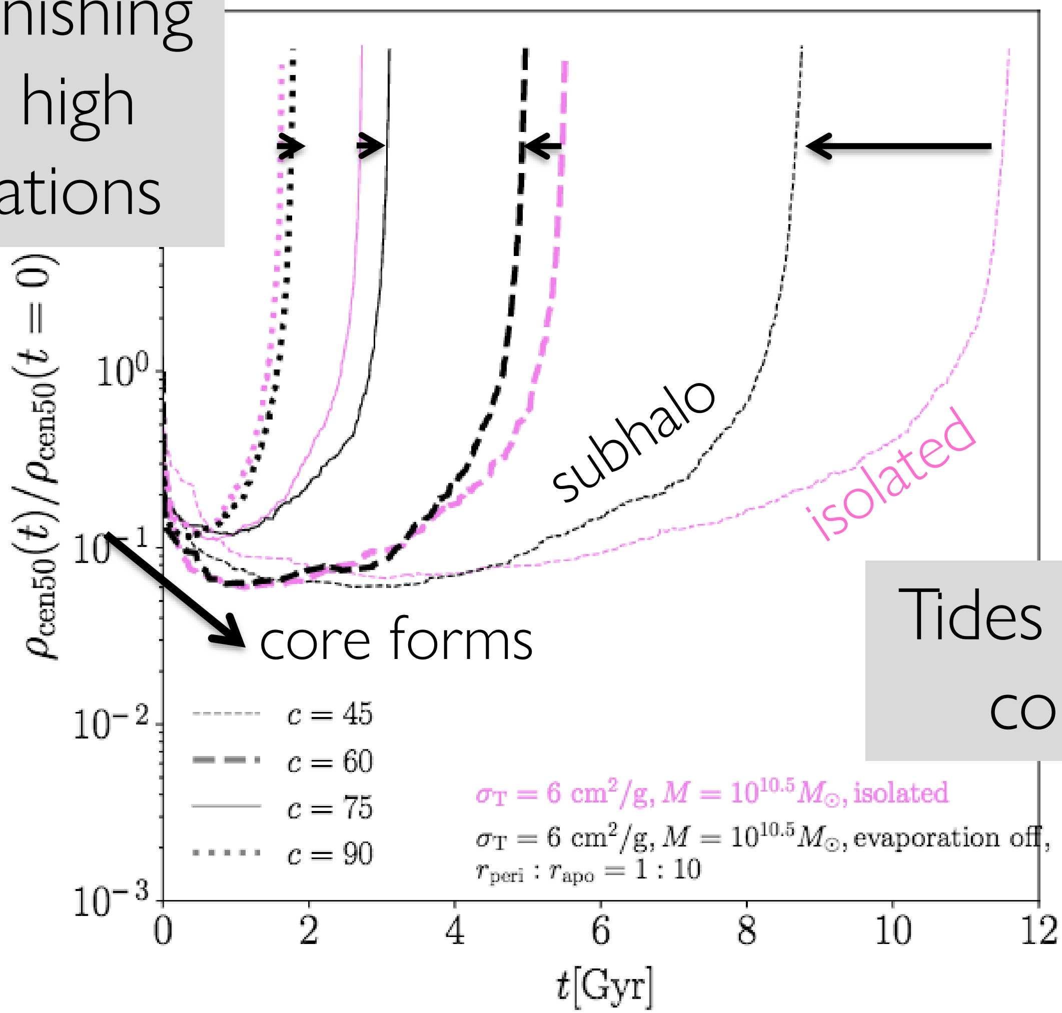
Tides can accelerate core collapse!

Nishikawa+ 2020, Correa 2021

Zeng+ incl. Kim 2022

SIDM core collapse

but has vanishing effect at high concentrations



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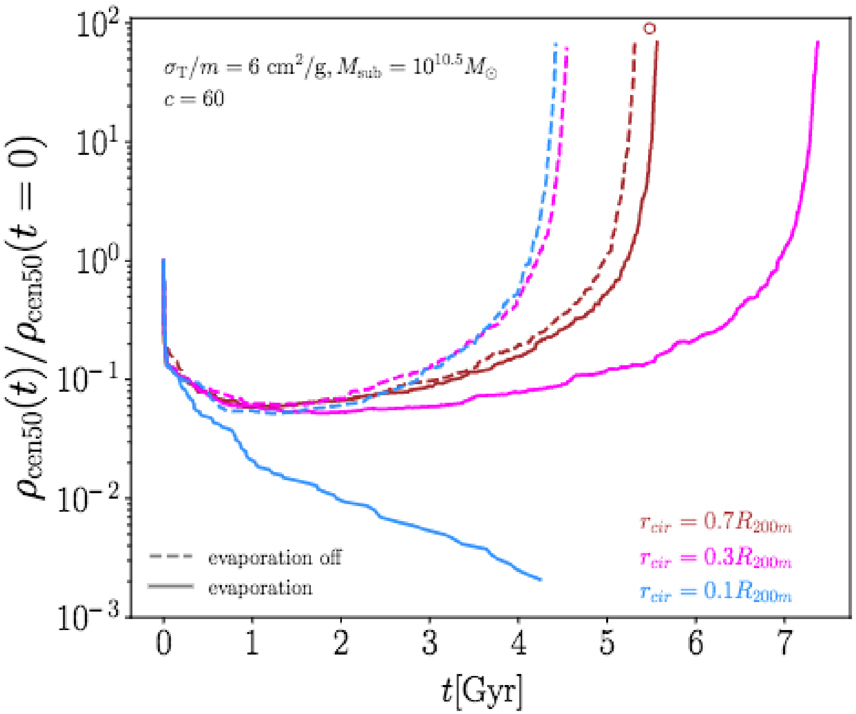
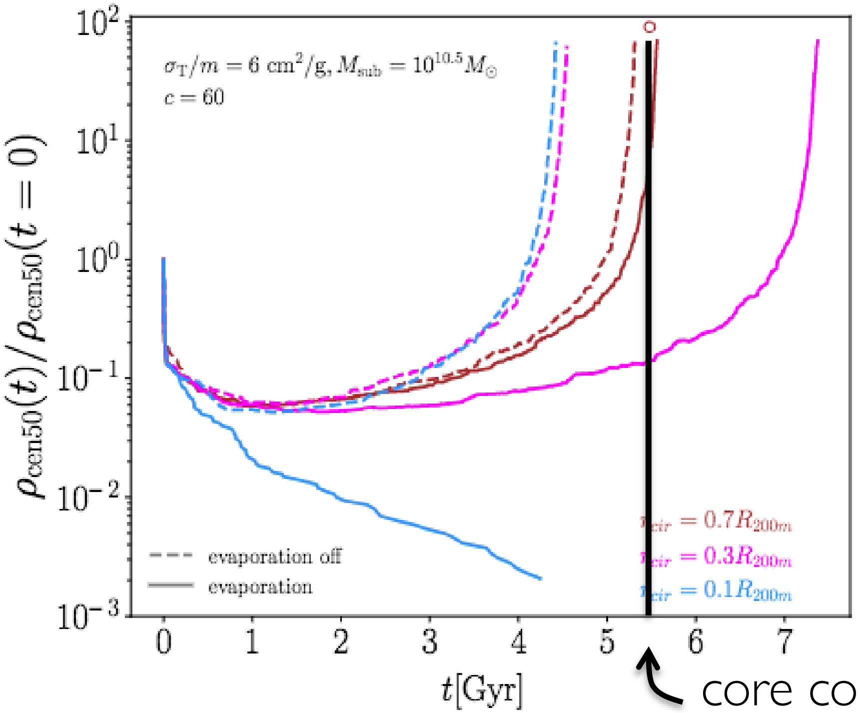


Lessons from circular orbits

Zeng+ incl. Kim 2022

SIDM core collapse

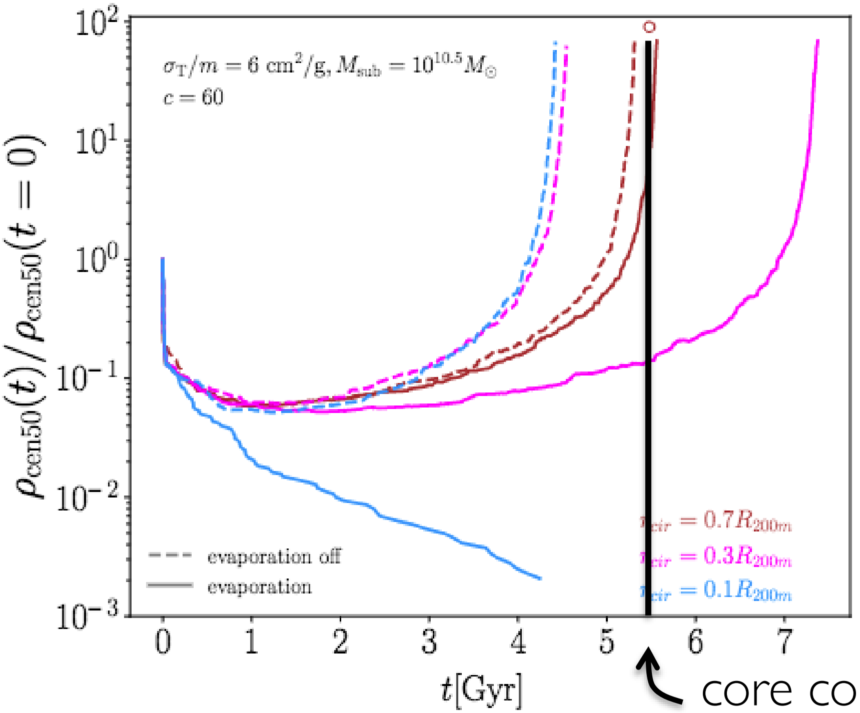


Lessons from circular orbits

core collapse time if (sub)halo were isolated

Zeng+ incl. Kim 2022

SIDM core collapse



core collapse time if (sub)halo were isolated

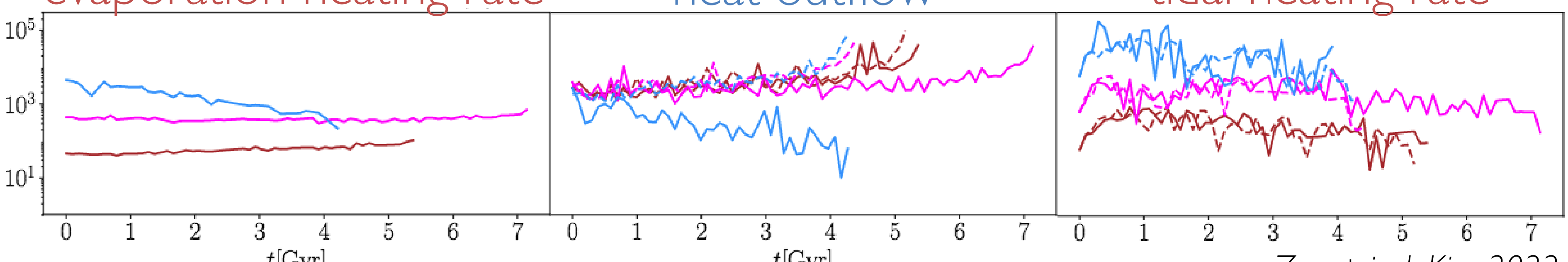
Lessons from circular orbits

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

evaporation heating rate

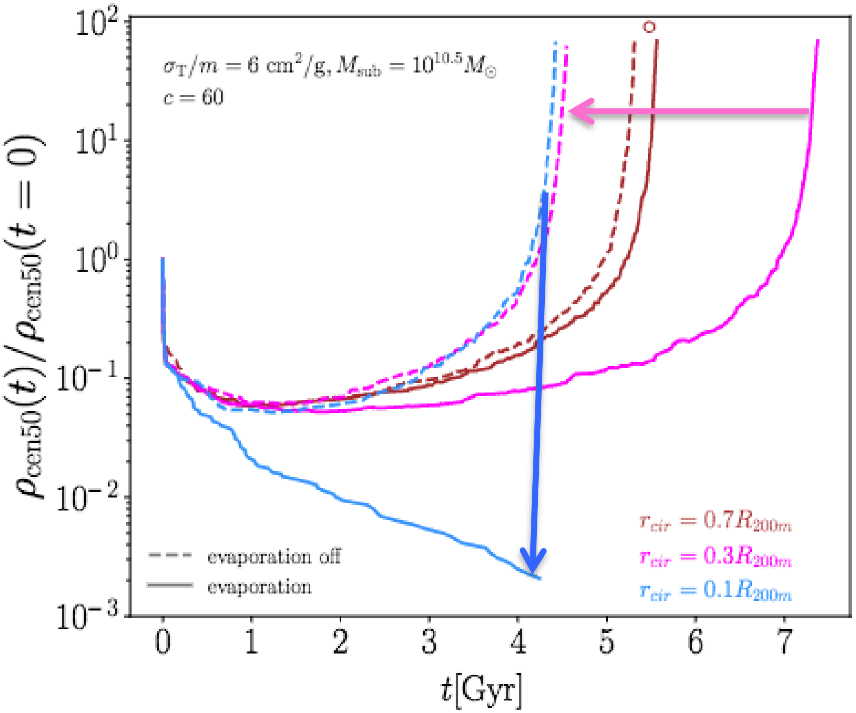
heat outflow

tidal heating rate



Zeng+ incl. Kim 2022

Core collapse in satellites of lenses

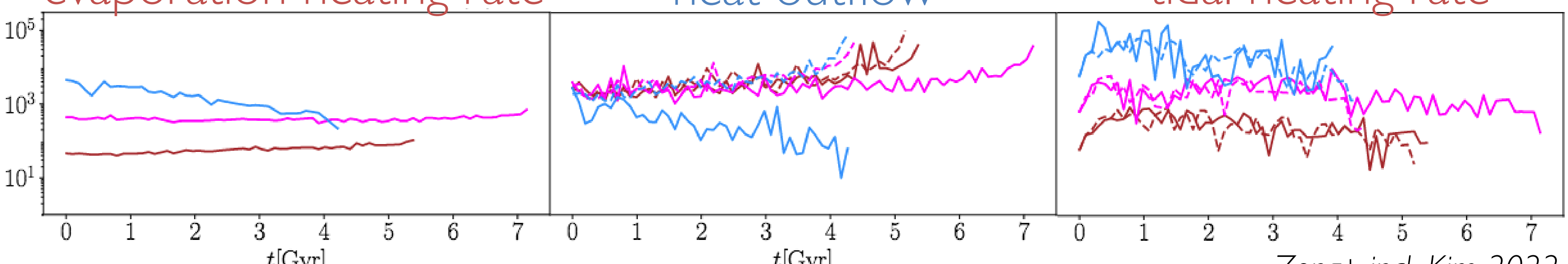


Lessons from circular orbits

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

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

evaporation heating rate | heat outflow | tidal heating rate

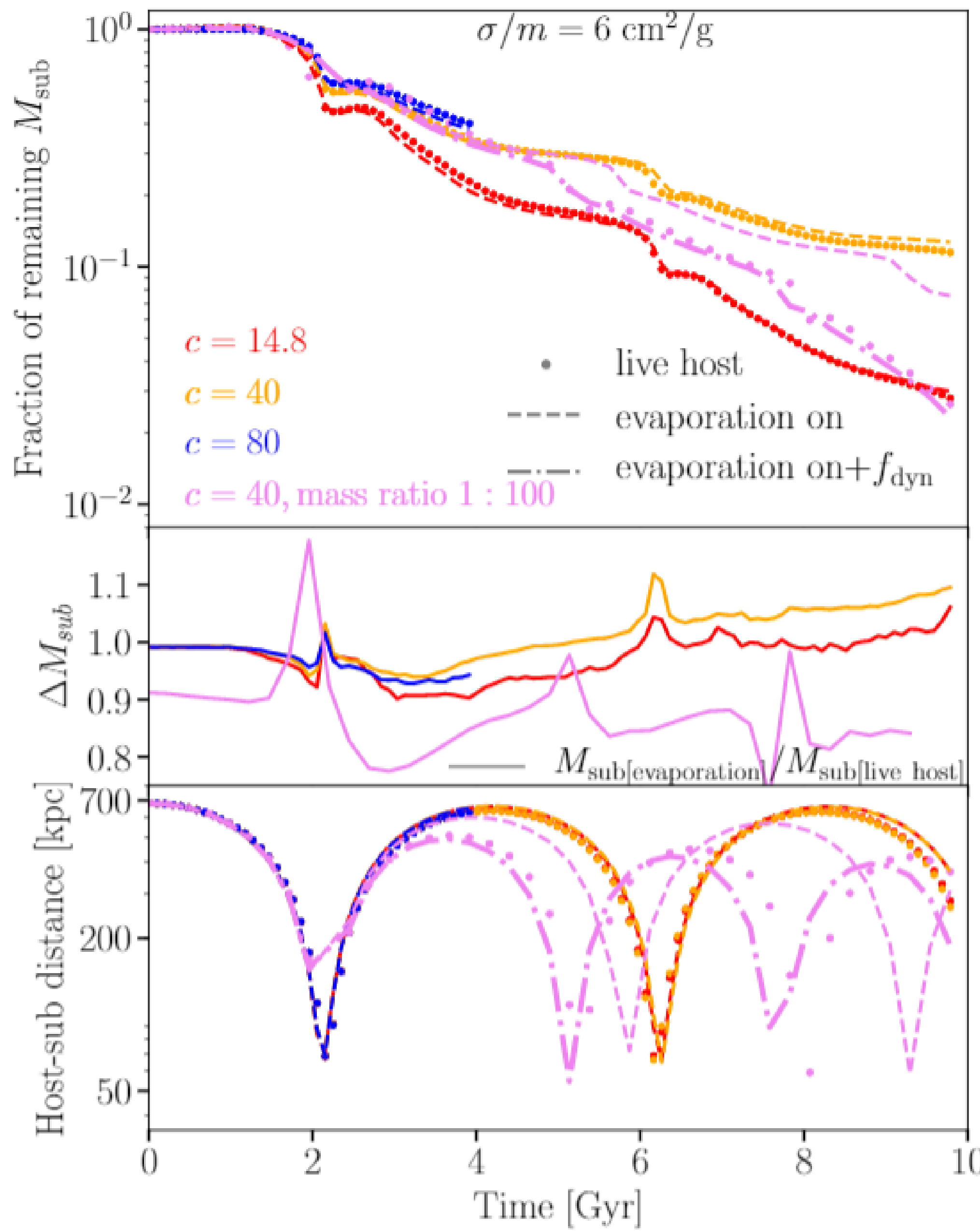


Zeng+ incl. Kim 2022

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

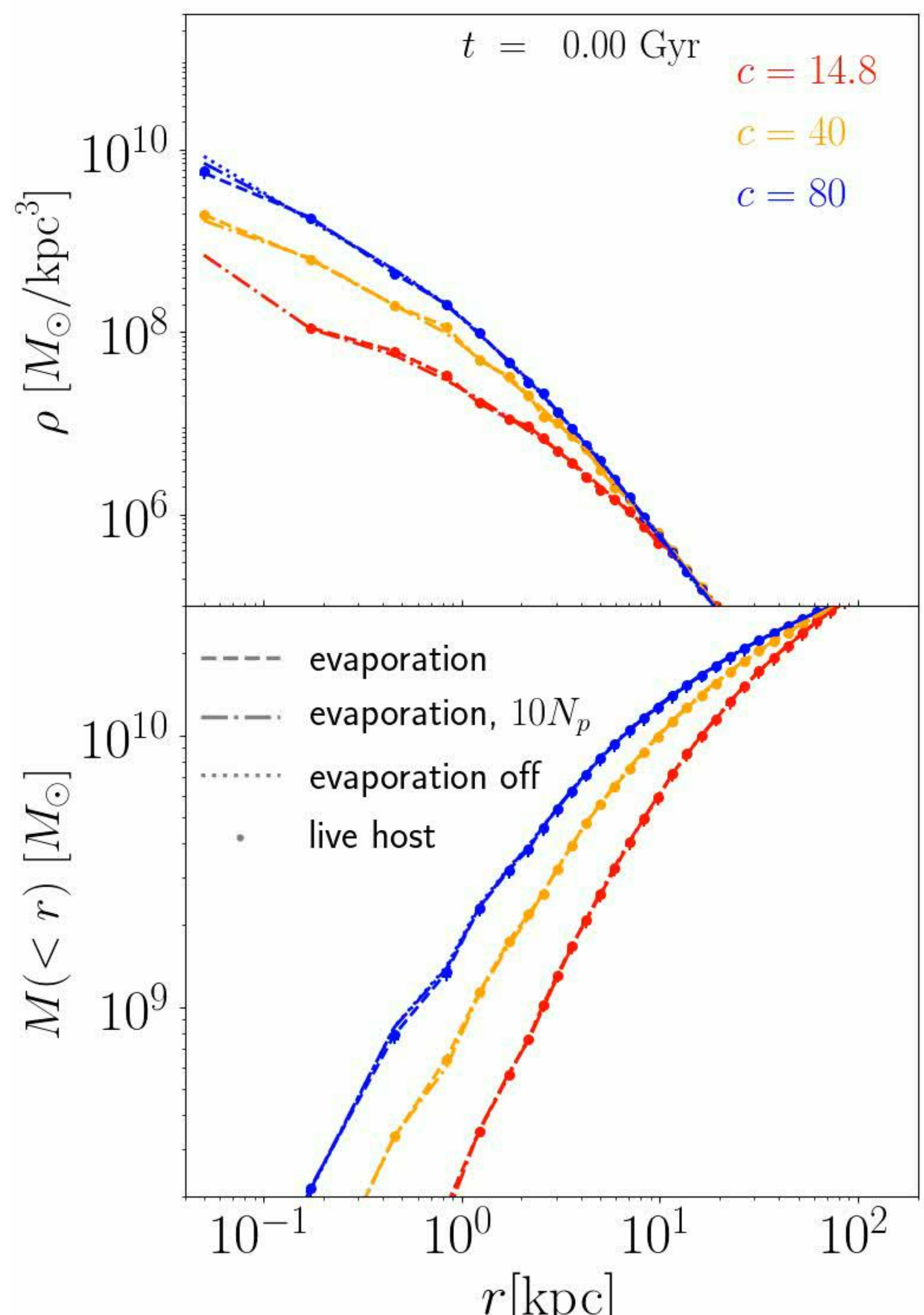
Can study *arbitrarily* small subhalos



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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