Dark matter modeling of astrophysical targets

From dark clumps to galaxy clusters and the extragalactic signal

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After this lecture, you will (hopefully)

1. know the basics of dark matter halo modeling
2. know what are the targets for DM indirect detection and how to model their DM content, based on 1. but also on their specific properties
3. become aware of the limitations and uncertainties linked to the DM modeling of these targets
4. feel like exploring how things can be improved!
5. have all you need for the CLUMPY tutorial/hands on this afternoon

Outline

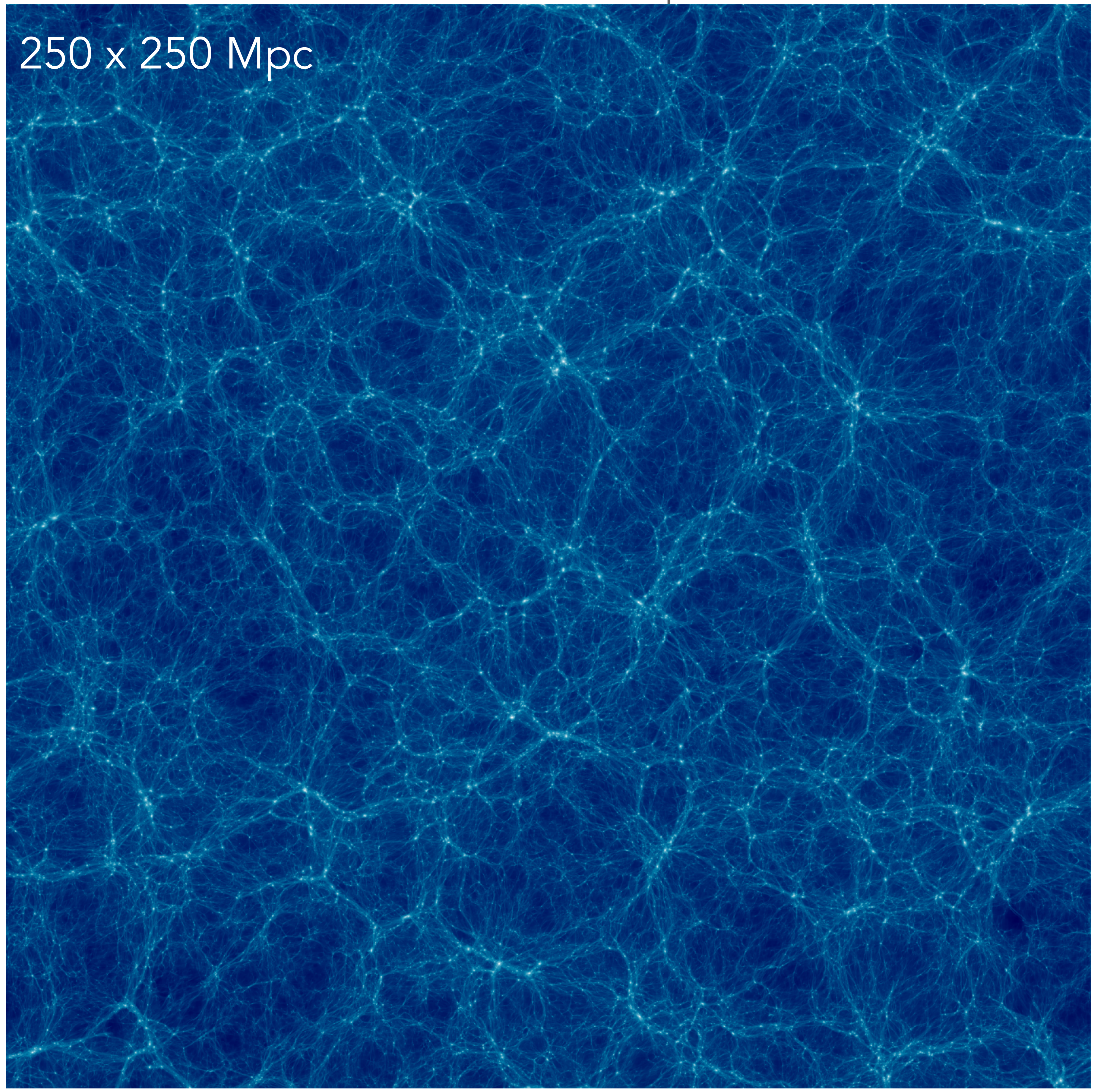
1. Reminder: structure formation
2. Dark matter halos: basic modeling
3. The gamma-ray signal from DM annihilation/decay
   - Derivation of the exotic signal
   - General considerations to compute the "astrophysical" factor
4. DM modeling and J-factor estimation of astrophysical targets
   - Galactic targets
   - Extragalactic scale

Reminder: structure formation

Structure formation in ΛCDM

- structures in the universe form from fluctuations in the primordial density field
- structure growth depends on the underlying cosmology (expansion vs gravity)
- haloes form after the collapse of "high density" regions
- today, the universe is highly structured (voids, filaments and haloes)

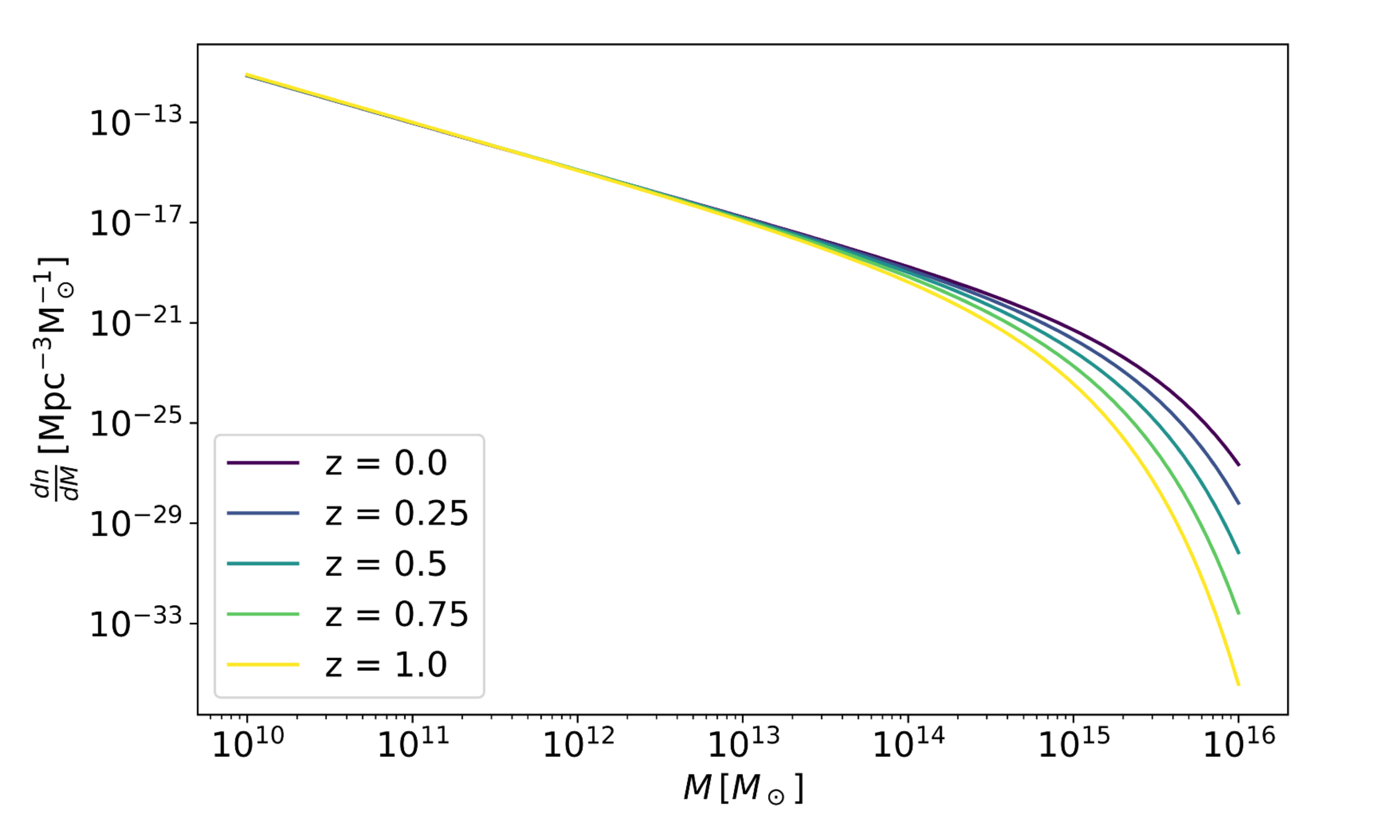
http://www.benediktdiemer.com



Structure formation in ΛCDM

The halo mass function

- Number density of halos as a function of mass and redshift; depends on the underlying cosmology
- General properties
  - The lower the mass, the more numerous the haloes
  - Forming high mass haloes takes time. Less massive haloes at high redshift than at low redshift
- First described by Press & Schechter (1974), later (semi-)analytical refinements (Sheth & Tormen 1999). Now generally fitted using numerical simulations (DM-only or hydro)

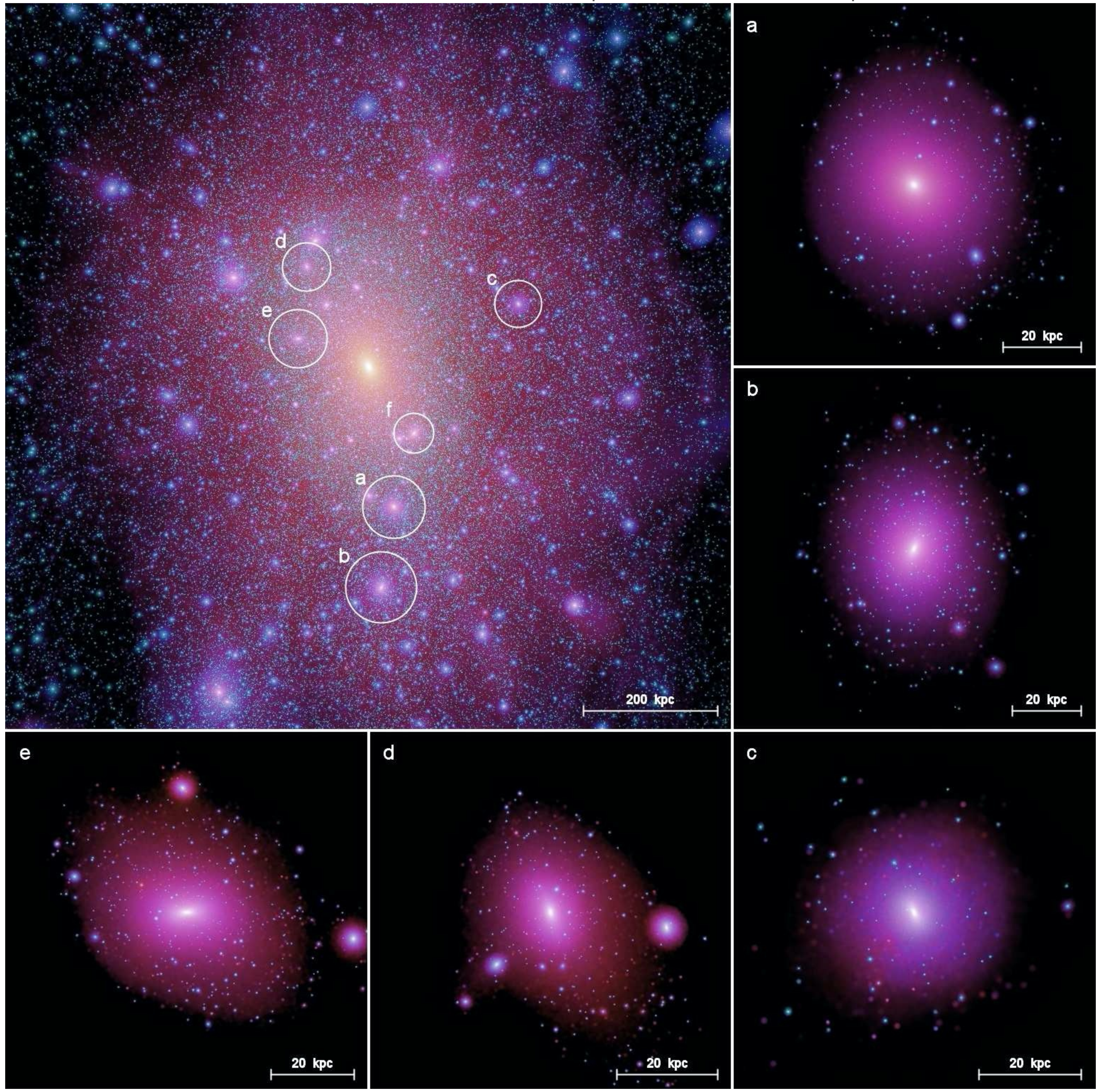


Structure formation in ΛCDM

Substructures, halo mass range

- bottom-up structure formation: smallest haloes from first and merge into larger structures
- substructures: haloes in haloes in haloes…
- halo mass range:
  - ✳ Theoretical M_{min} ~ 10^{-12} - 10^{-6} $M_{sun.}$ Depends on the free-streaming scale
  - ✳ [Simulated M_{min} depends on simulation resolution > theoretical M_{min}]
  - ✳ M_{max} ~ 10^{15} M_{sun} (galaxy clusters)

Galactic halo from the Aquarius Simulation, Springel et al (2008)



Structure formation in ΛCDM

Locations of DM haloes?

- Gas accumulates in massive haloes. If dense enough, trigger star formation.
- Locations of DM haloes we know about: galaxy clusters, galaxies…
- Plenty of low mass DM haloes that we don't "see"!
- DM haloes extend much beyond the visible part

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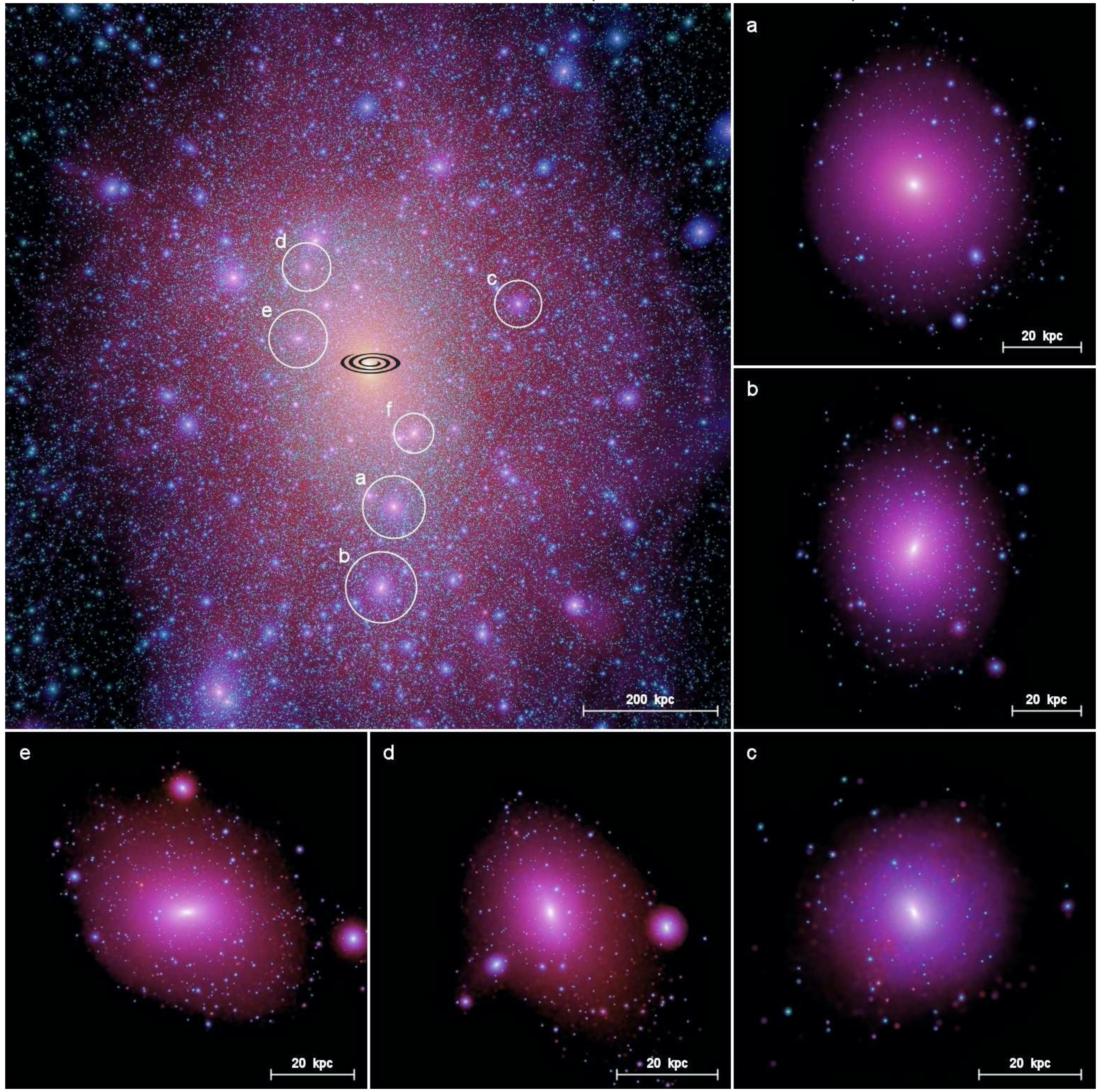


Dark matter halo: basic modeling

DM halo properties

General properties from DM-only simulations

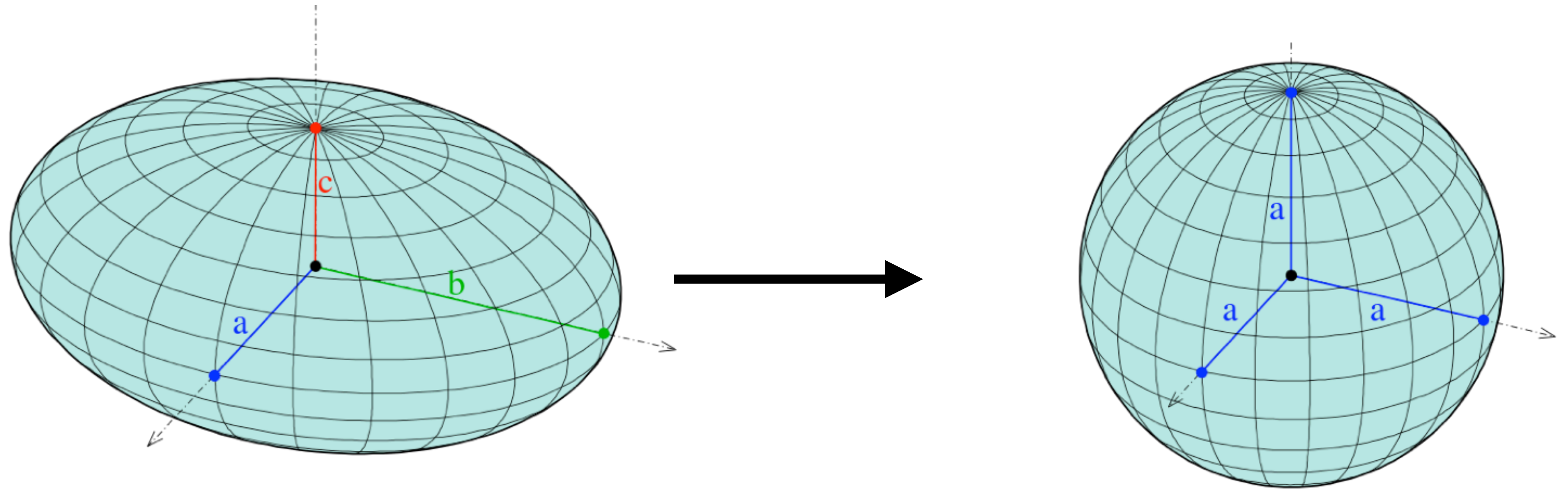
- Haloes are triaxial, preferentially prolate
- In practice, generally measure spherical density profile
- Two main parametrisations are used to described to radial density profile

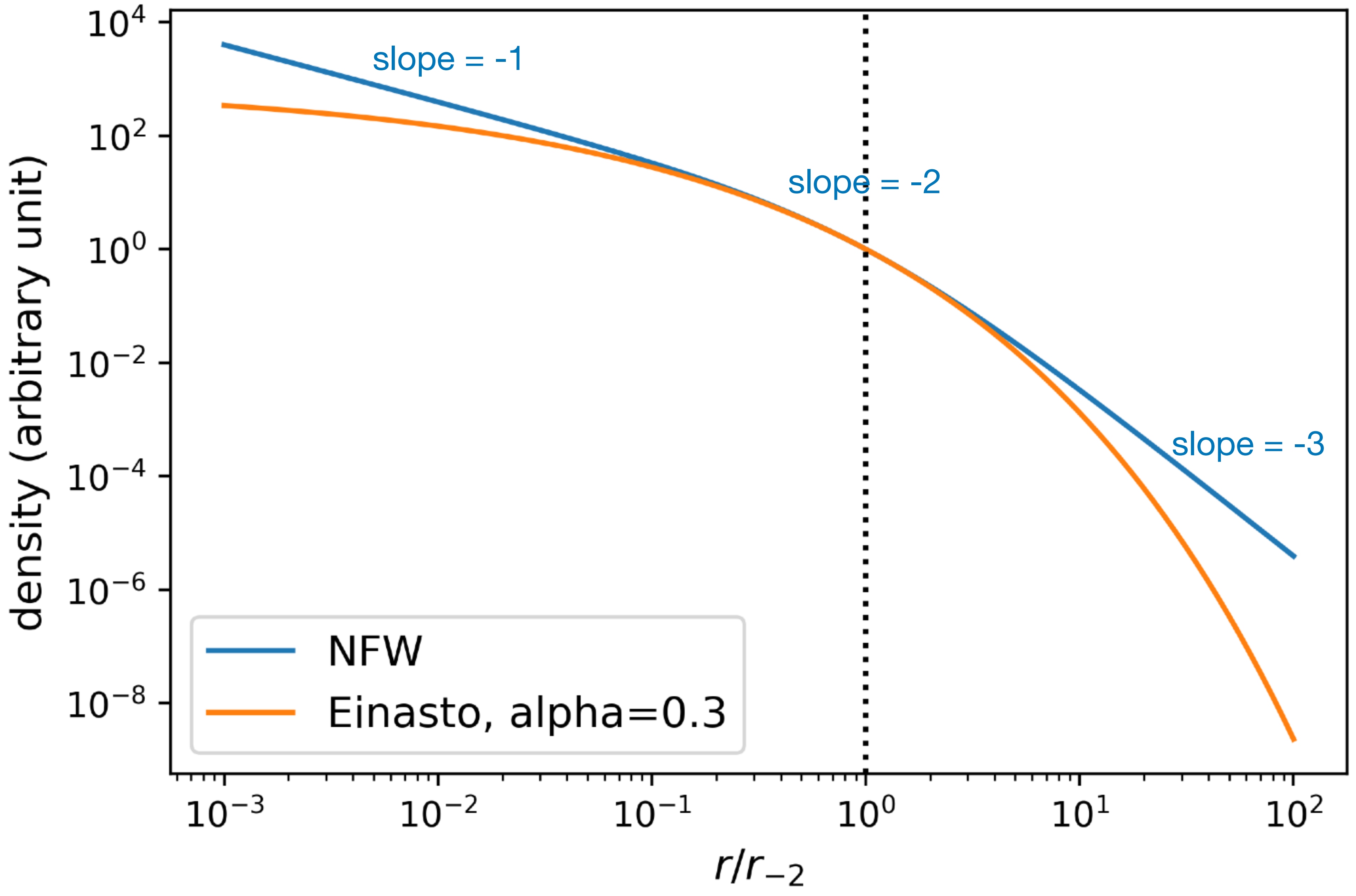
$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$$

NFW (Navarro, Frenk & White (1997))

$$\rho(r) = \rho_{-2} \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]\right\}$$

Einasto (1965, stellar systems)





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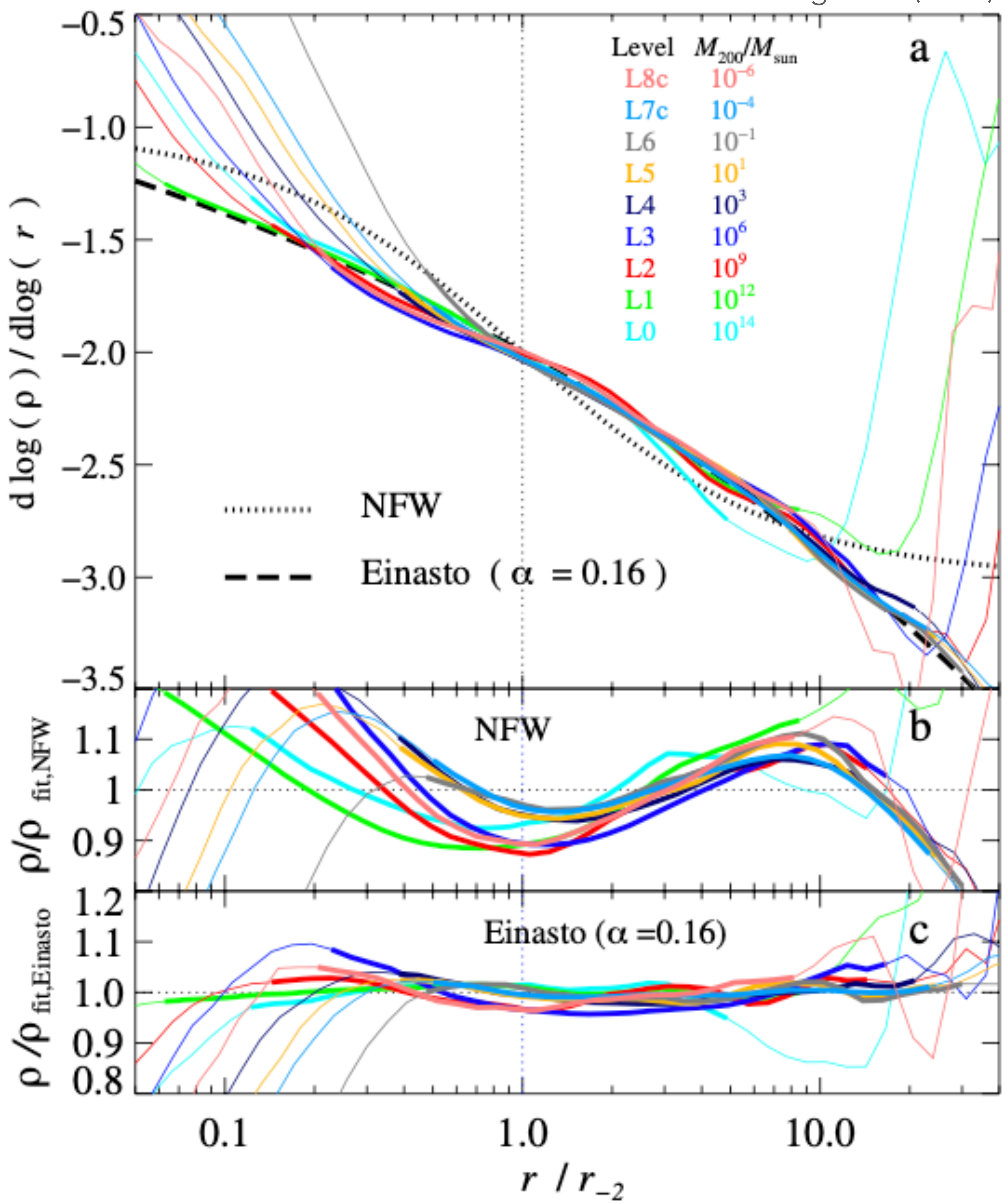
From DM-only simulations, NFW and Einasto (with α=0.16) are good representations of the DM halo profiles between 10^{-6} and $10^{14\text{-}15}$ M_{sun}

Wang et al. (2020)



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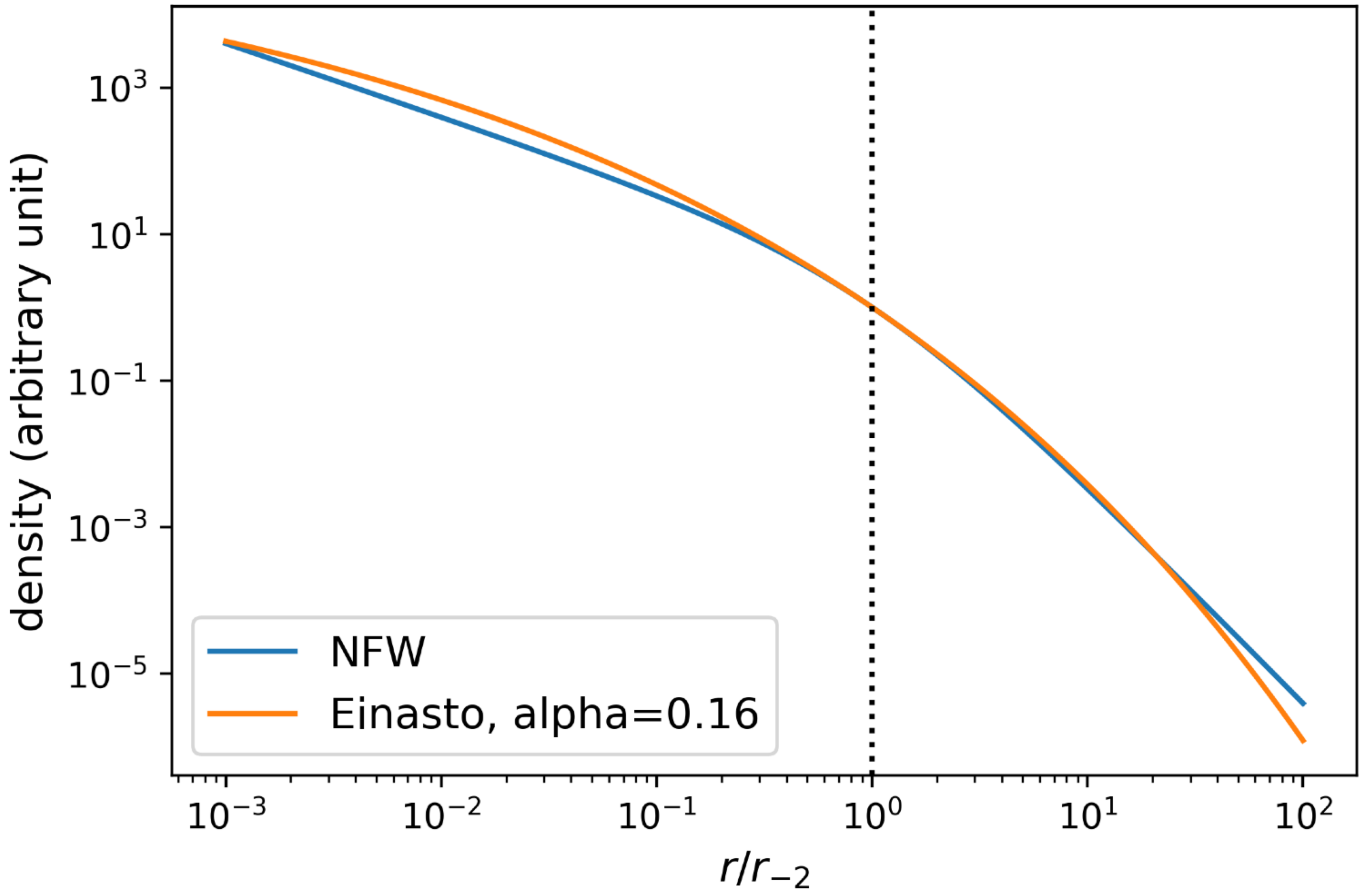

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DM halo properties

Mass, radius and concentration

- The spherical overdensity mass/radius definition

$$M_{\Delta,\mathrm{bkg}} \equiv \frac{4}{3}\pi R_\Delta^3 \times \Delta \times \rho_{\mathrm{bkg}}(z) \qquad \rho_{\mathrm{bkg}}(z) = \begin{cases} \rho_{\mathrm{crit}}(z) = \frac{3H(z)^2}{8\pi G} \\ \rho_{\mathrm{m}}(z) = \Omega_m(z)\rho_{\mathrm{crit}}(z) \end{cases}$$

$M_{200,c}$, $M_{200,m}$, $M_{500,c}$, etc.

Δ = 200 often used as "halo size"

$M_{200,c}$ = 10^{-6} M_{sun} ~1 M_{earth}, $R_{200,c}$ ~ 65000 AU

$M_{200,c}$ = 10^{15} M_{sun}, $R_{200,c}$ ~ 2 Mpc

- Which is the largest: $R_{200,c}$ or $R_{500,c}$?

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- The concentration parameter

$$c_\Delta = \frac{R_\Delta}{r_{-2}}$$

(for NFW, $r_{-2} = r_s$)

- Which is the largest: $R_{200,c}$ or $R_{500,c}$?
- Profile has 2 free parameters (ρ_{-2}, r_{-2}). Show that it can be equivalently determined for (M_Δ, c_Δ)

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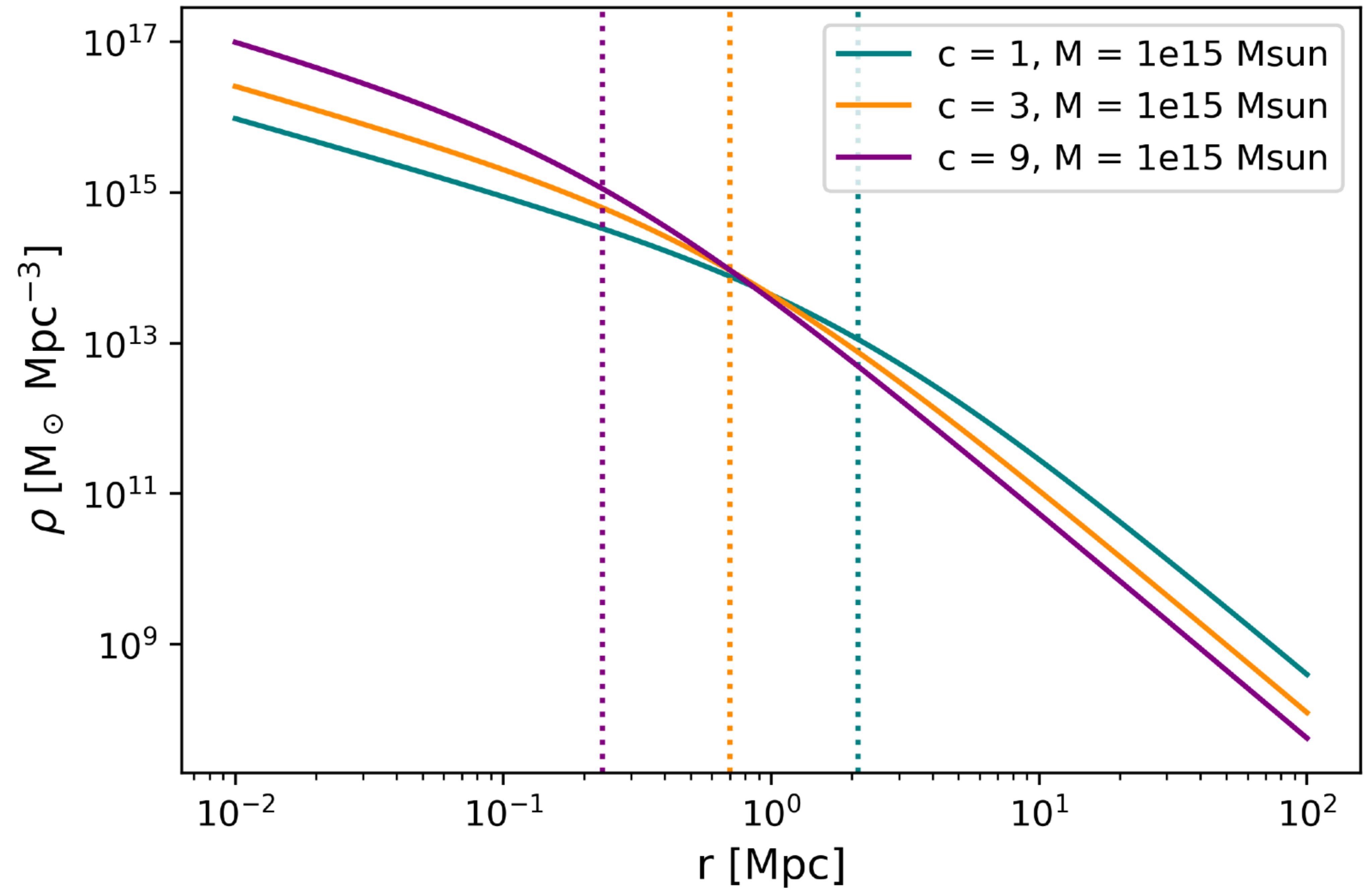
At a given mass, the higher the concentration the denser the inner regions of the halo

- Which is the largest: $R_{200,c}$ or $R_{500,c}$?
- Profile has 2 free parameters (ρ_{-2}, r_{-2}). Show that it can be equivalently determined for (M_Δ, c_Δ)

1. $M_\Delta \rightarrow R_\Delta \rightarrow r_{-2} = \dfrac{R_\Delta}{c_\Delta}$
2. $M_\Delta = \displaystyle\int_0^{R_\Delta} 4\pi r^2 \rho(r) dr \rightarrow \rho_{-2}$



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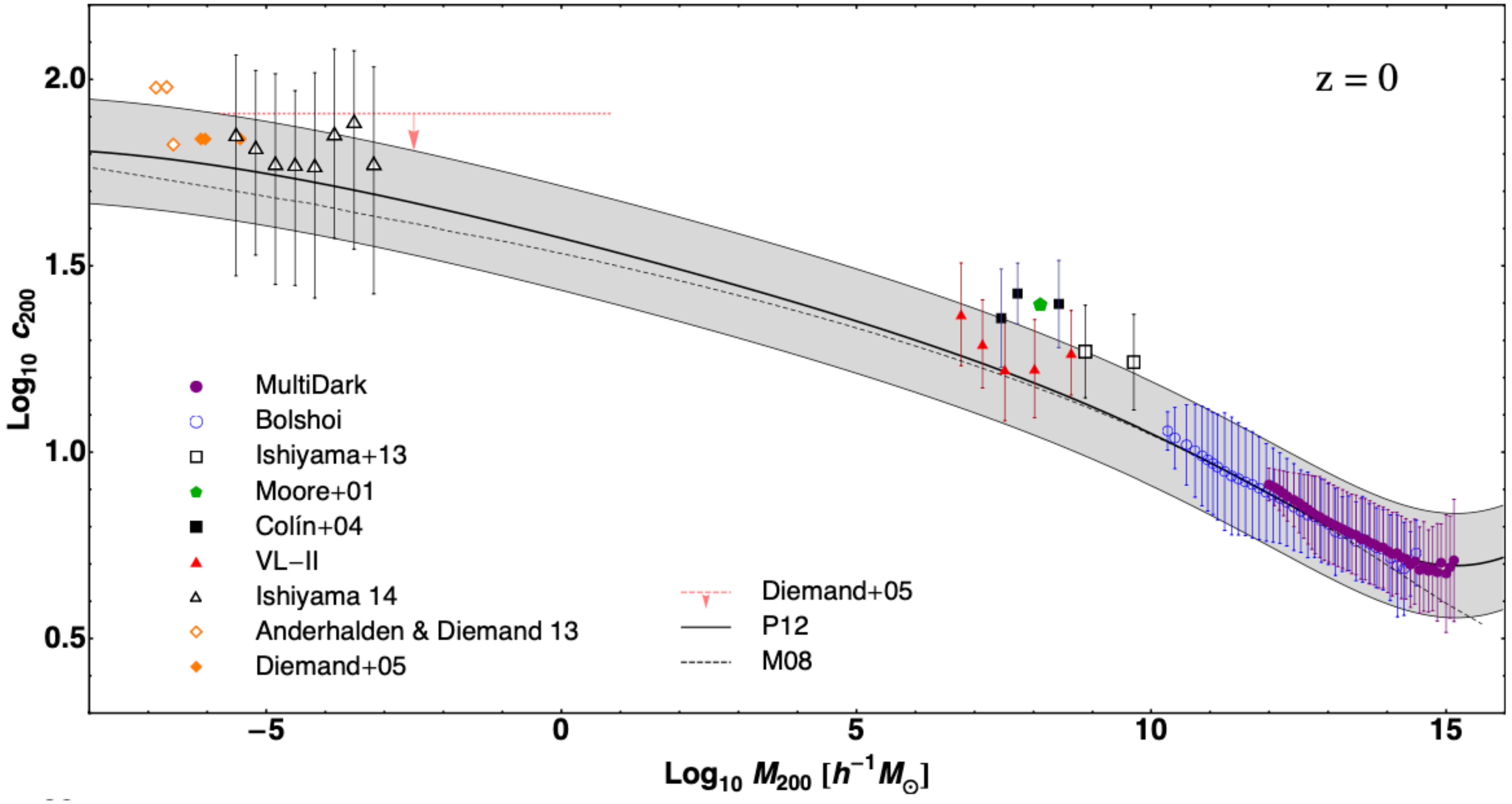
Concentration depends on mass and redshift:

- Low mass haloes are more concentrated than high mass counterparts
- Concentration decreases with increasing redshift as ~$(1+z)^{-1}$

Sanchez-Conde et al. (2014)



DM halo properties

Cusps vs. cores

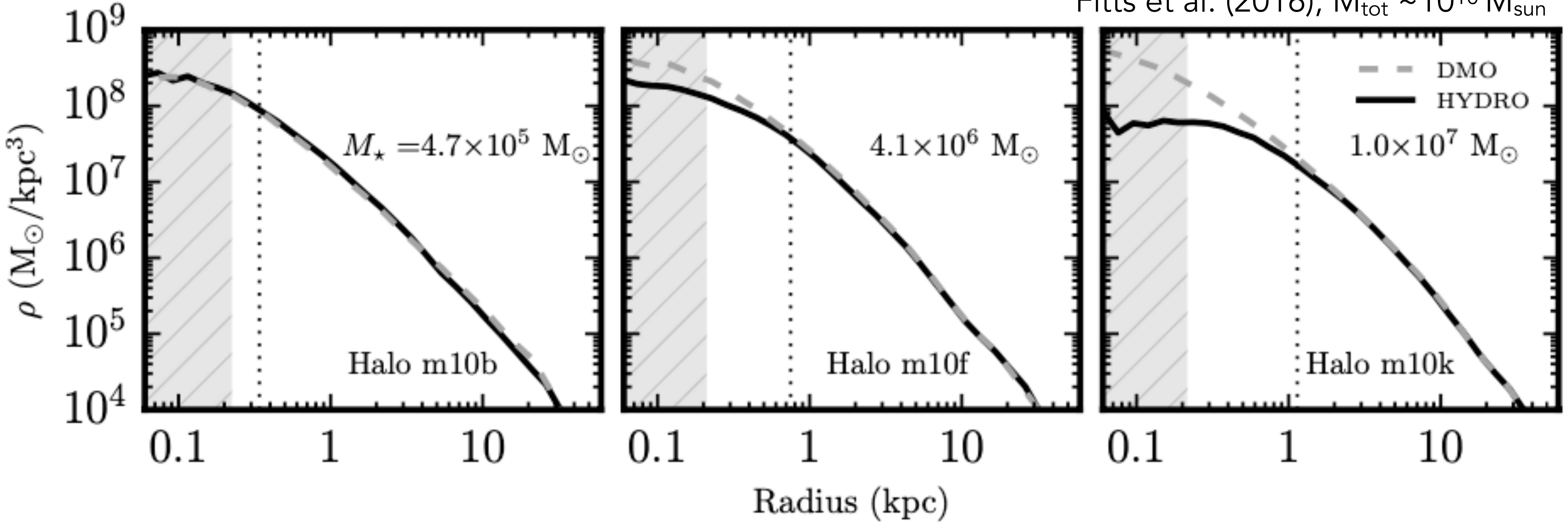
- DM-only simulations → DM halos are cuspy (steep inner slope, e.g $\gamma = 1$ for NFW)
- Adiabatic contraction in the presence of baryon condensation/central BH can make the halo cuspier
- Observations of galaxies and dwarf galaxies suggests that the density can be 'cored' ($\gamma \to 0$). ***Cusp vs. Core problem***
  - Baryonic feedback may produce core denstiy profiles
  - Self-Interacting DM

Allow for more general parametrisation

- free α in the Einasto profile (not fixed to 0.17-0.16)
- Zhao parametrisation($=$ NFW for $(\alpha, \beta, \gamma) = (1,3,1)$)

$$\rho(r) = \frac{\rho_s}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Fitts et al. (2016), $M_{tot} \sim 10^{10}\, M_{sun}$



The γ-ray signal from DM annihilation (or decay)

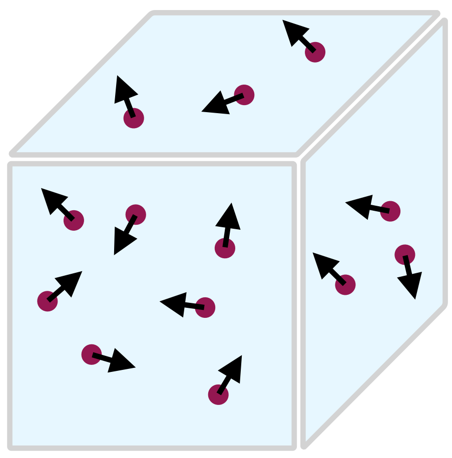
1. Derivation, definition of the J-factor
2. General considerations on estimating the J-factor

The exotic DM signal

The source emission

Consider a volume V containing N dark matter particles

- If Majorana DM, $\chi = \bar{\chi}$
- If not, N/2 χ and N/2 $\bar{\chi}$



1. For a pair of DM particles, express the annihilation probability in a time *dt*, given the annihilation cross section $\sigma_{\text{ann}}(v)$ and their relative velocity v

$$\mathrm{d}p_{1\text{pair}} = \frac{\mathrm{d}V}{V} = \frac{\sigma_{\text{ann}} v \mathrm{d}t}{V}$$

2. Express the total annihilation rate (#/s), in the volume V, considering the N particles

3. Transform the above per unit volume, as a function of the mass of the particle m_χ and mass density ρ

4. Given the differential photon spectrum dN/dE, find the source photon emission rate, per unit of volume

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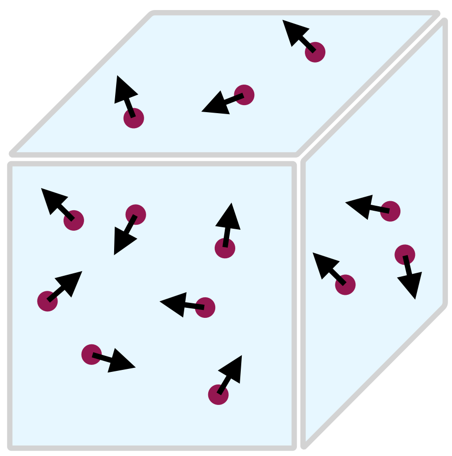

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$$\Gamma_{\rm tot} = \sum_{\rm pairs} \frac{dp_{\rm 1pair}}{dt} = \frac{\langle \sigma_{\rm ann} v \rangle}{V} \times N_{\rm pairs} = \dots$$

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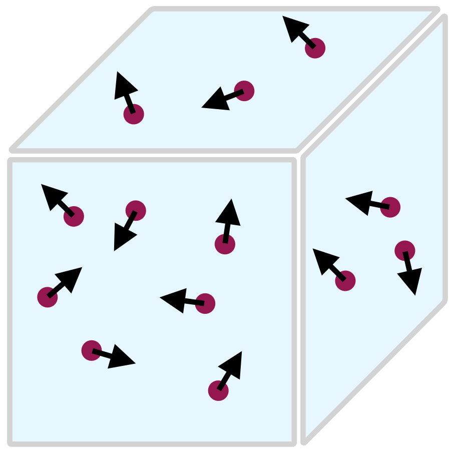

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Adapted fom T. Lohse

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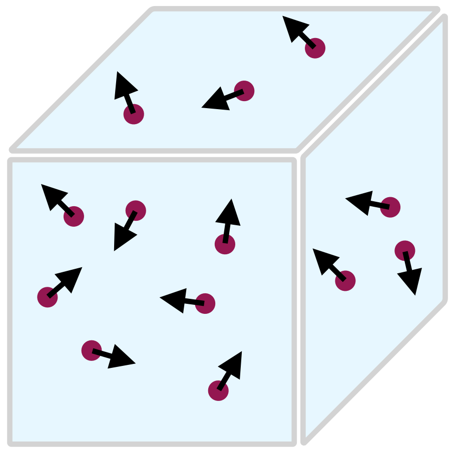

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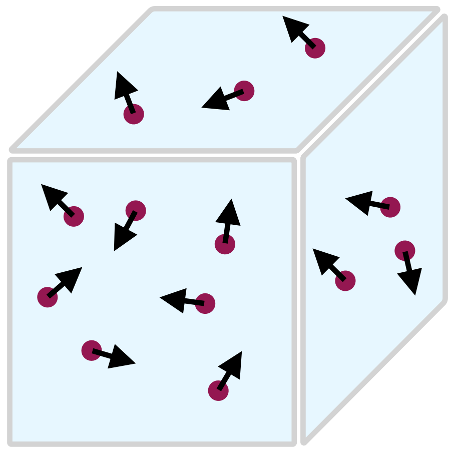

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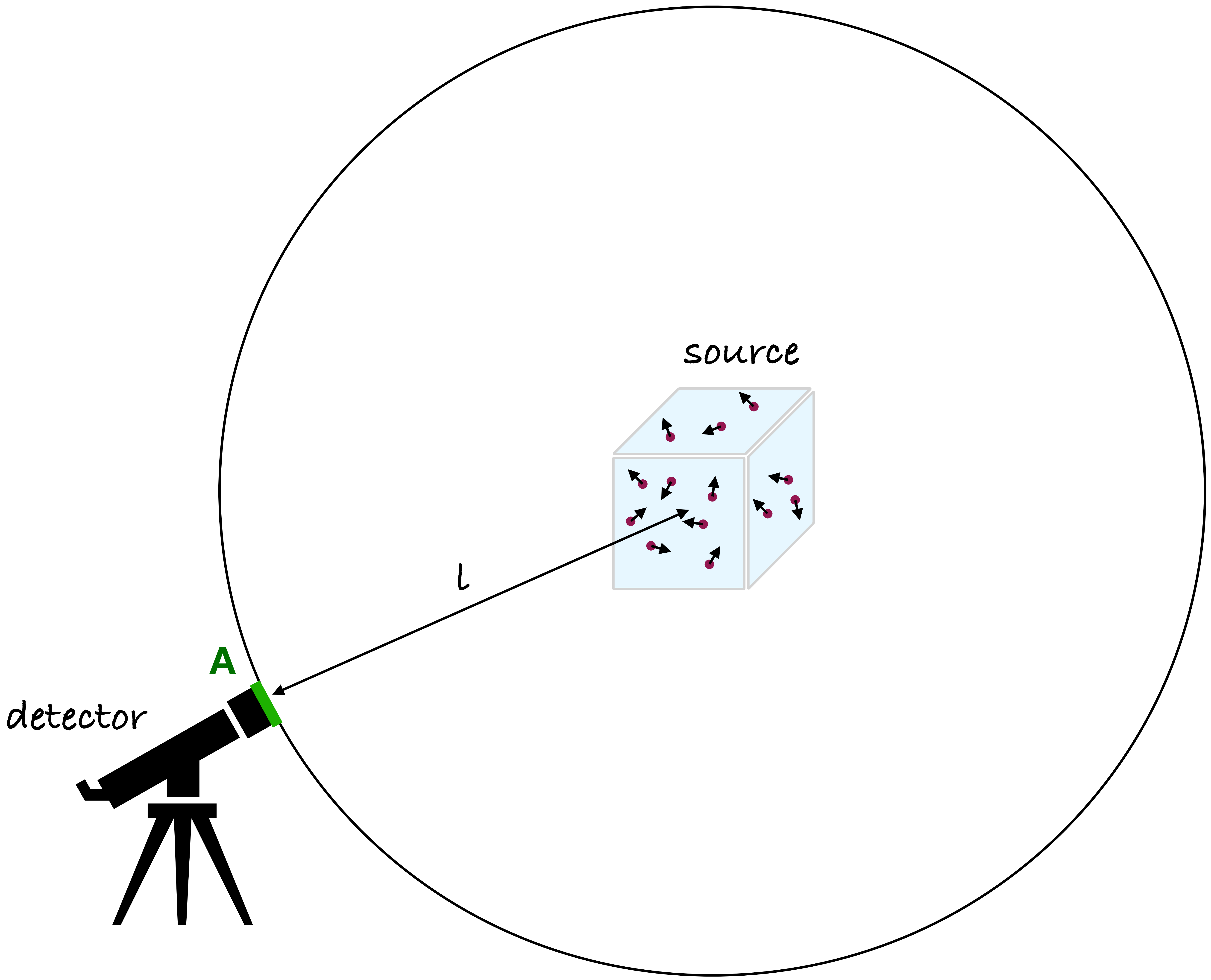
$$\frac{\mathrm{d}\Gamma_{\mathrm{src}}}{\mathrm{d}V\mathrm{d}E} = \frac{\mathrm{d}\Gamma_{\mathrm{tot}}}{\mathrm{d}V} \times \frac{\mathrm{d}N_\gamma}{\mathrm{d}E}$$

Adapted fom T. Lohse

The exotic DM signal

The received flux



1. Differential photon rate received in the detector?

$$\frac{d\Gamma_{det}}{dV dE} =$$

Adapted fom T. Lohse

The exotic DM signal

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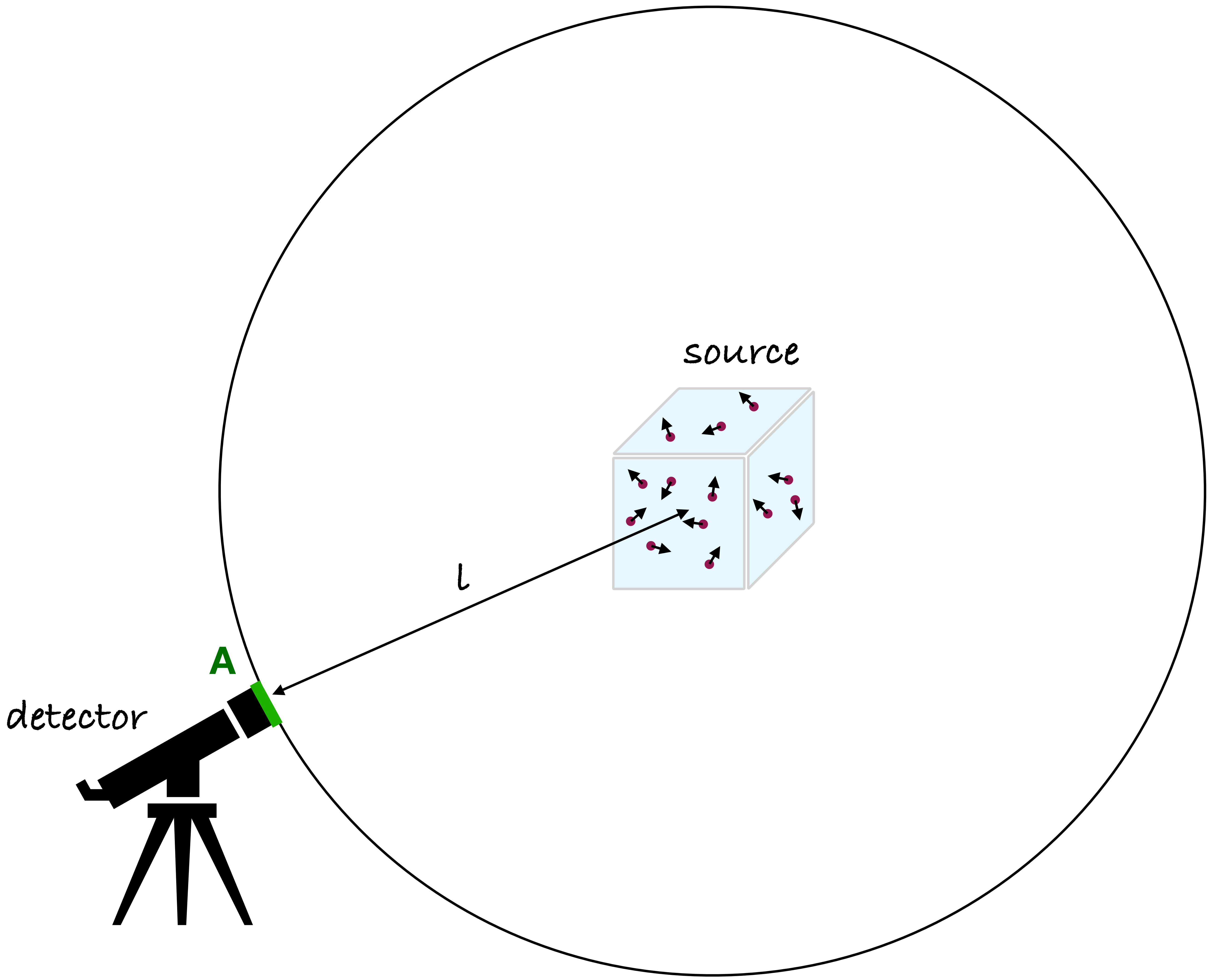

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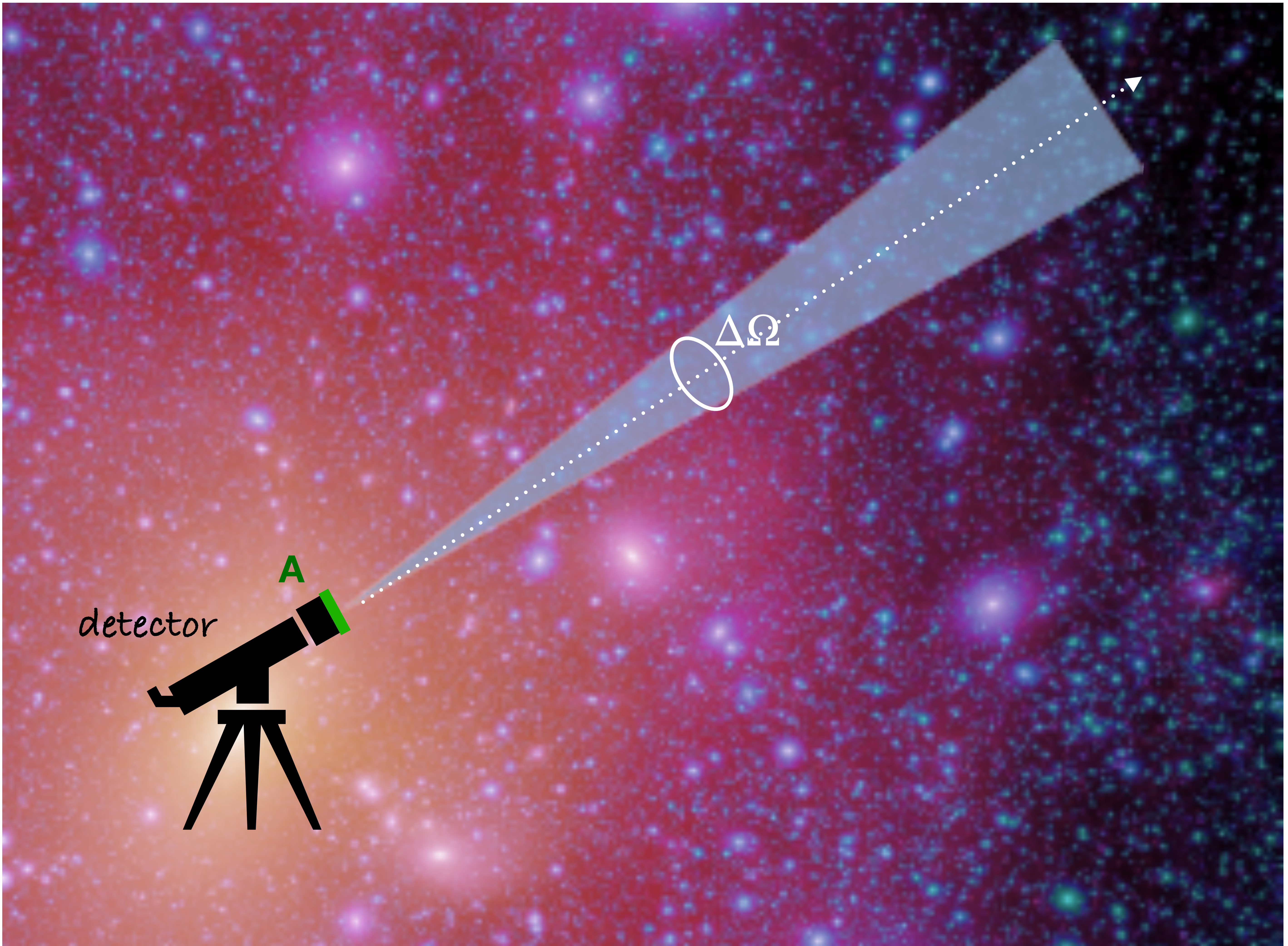

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2. What is the differential flux received, integrating over the entire observed volume (with $\sigma v = \mathrm{cst}$)?

$$\frac{\mathrm{d}\phi_{\rm det}}{\mathrm{d}E} = \int_V \frac{1}{A}\frac{\mathrm{d}\Gamma_{\rm det}}{\mathrm{d}V\mathrm{d}E}\,\mathrm{d}V = \ldots$$

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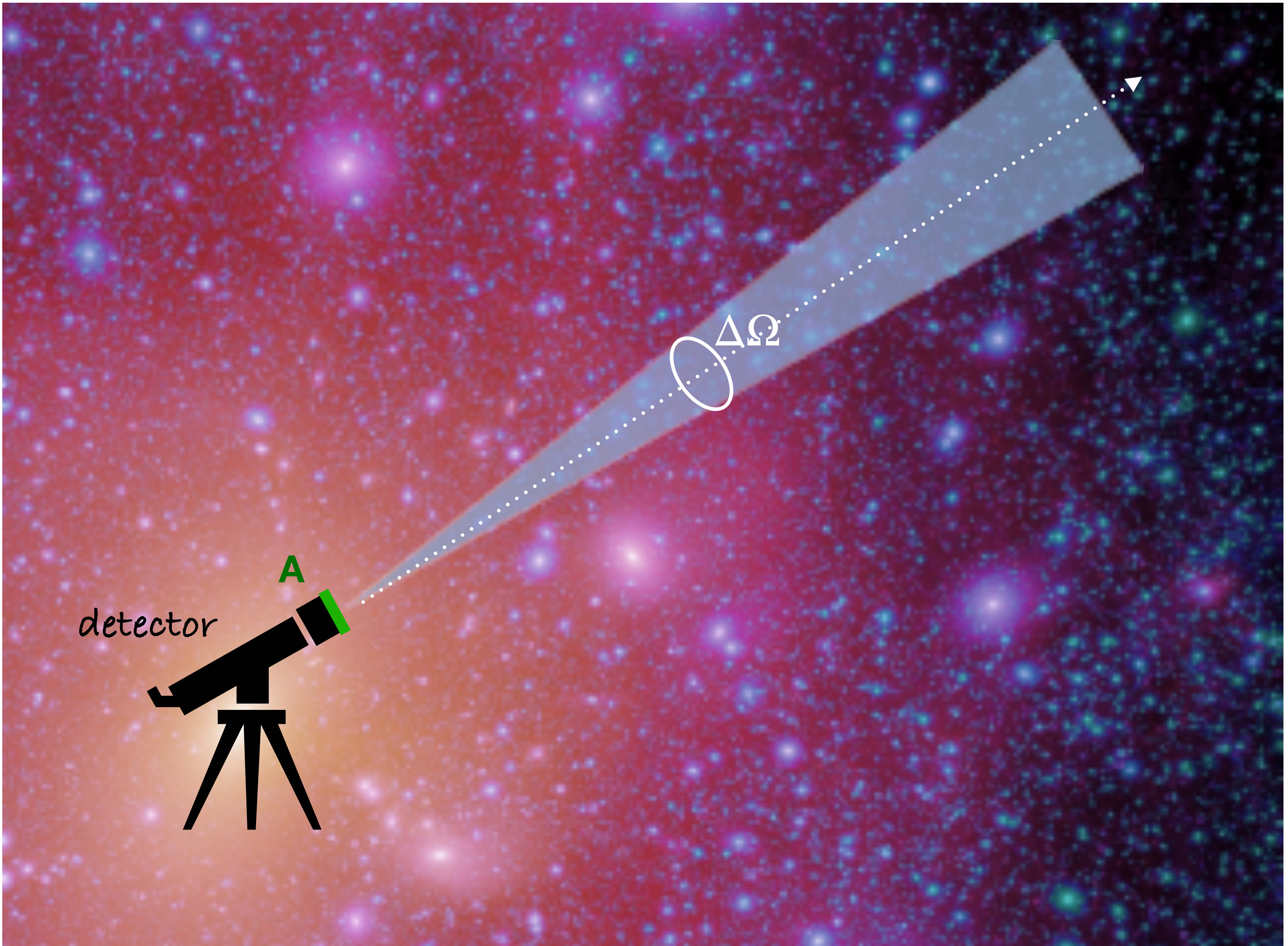

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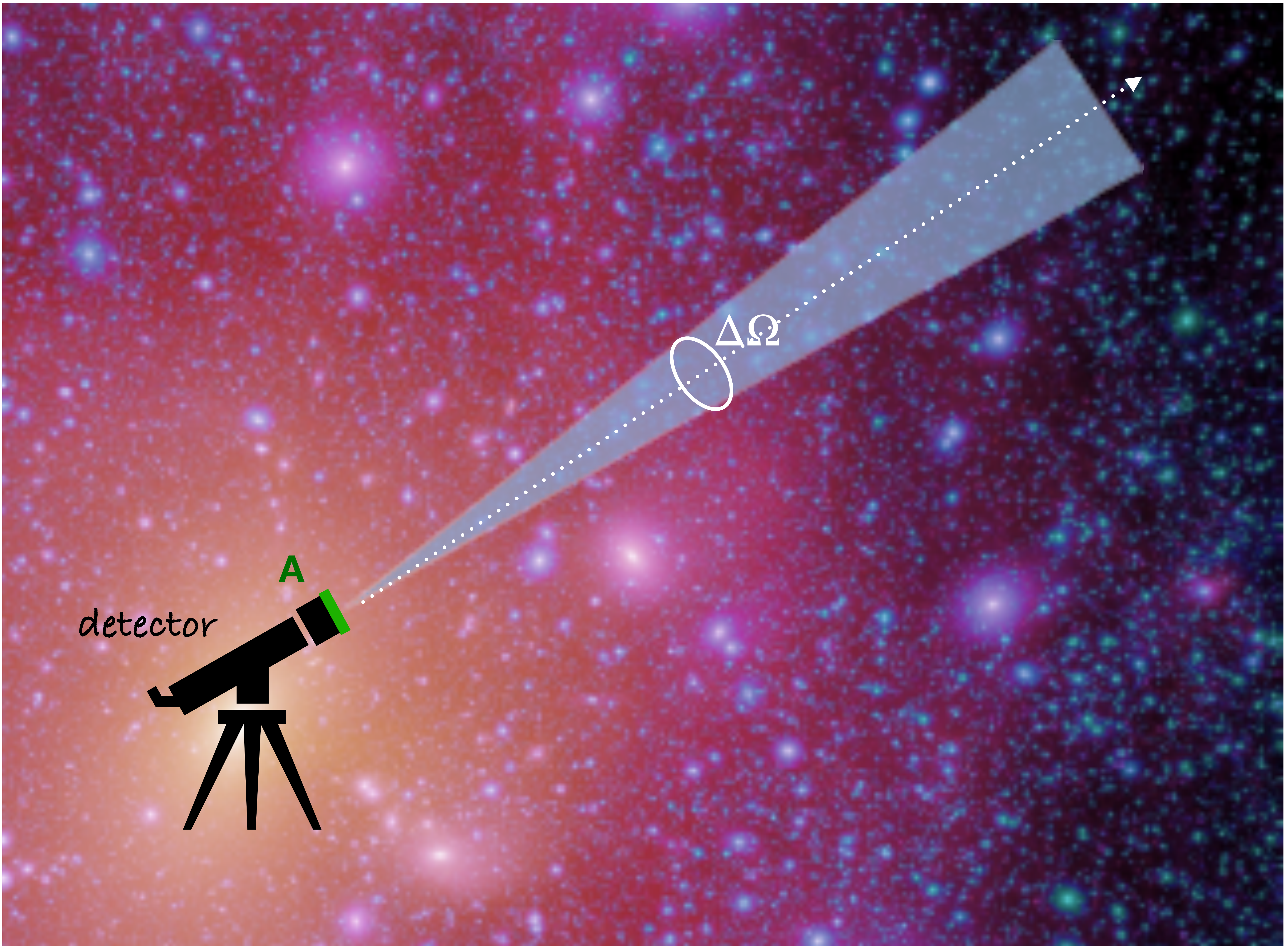
$$\frac{\mathrm{d}\phi_{\mathrm{det}}}{\mathrm{d}E} = \int_V \frac{1}{A} \frac{\mathrm{d}\Gamma_{\mathrm{det}}}{\mathrm{d}V\mathrm{d}E} \mathrm{d}V = \frac{\langle \sigma_{\mathrm{ann}} v \rangle}{4\pi\delta m_\chi^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E} \times \int_{\Delta\Omega} \int_l \rho^2(l,\Omega)\, \mathrm{d}l\, \mathrm{d}\Omega$$

using $dV = l^2 \sin\alpha\, \mathrm{d}l\, \mathrm{d}\alpha\, \mathrm{d}\beta = l^2\, \mathrm{d}l\, \mathrm{d}\Omega$

NB: if $\sigma v \neq \mathrm{cst}$, cannot factor it out (e.g. Boddy et al. 2020)

The exotic DM signal

The received flux



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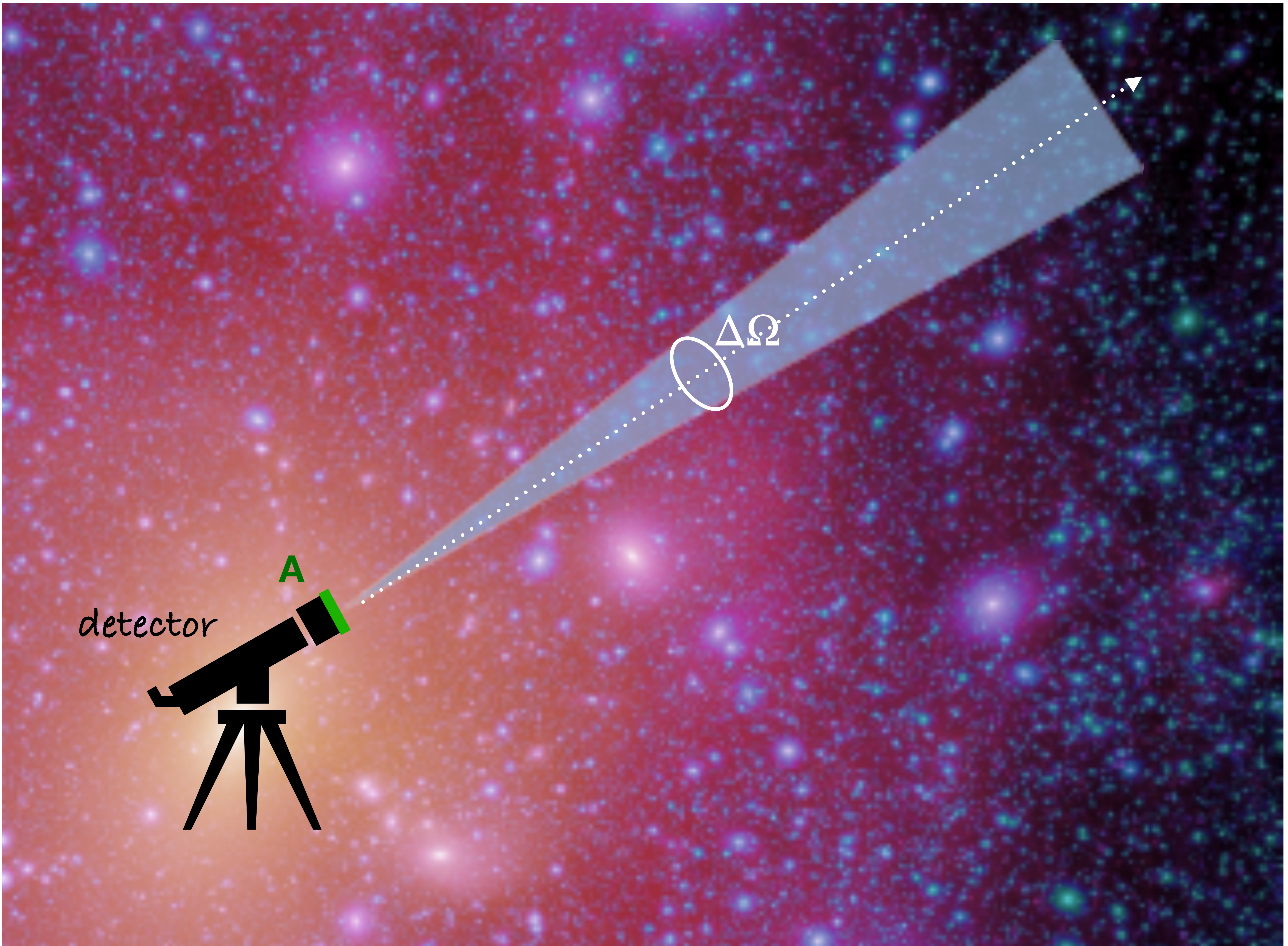
using $dV = l^2 \sin\alpha\,\mathrm{d}l\,\mathrm{d}\alpha\,\mathrm{d}\beta = l^2\,\mathrm{d}l\,\mathrm{d}\Omega$

What does this become for decaying DM (single particle process) ?

The exotic DM signal

The received flux



1. Differential photon rate received in the detector?

$$\frac{\mathrm{d}\Gamma_{\mathrm{det}}}{\mathrm{d}V\mathrm{d}E} = \frac{A}{4\pi l^2} \frac{\mathrm{d}\Gamma_{\mathrm{src}}}{\mathrm{d}V\mathrm{d}E}$$

2. What is the differential flux received, integrating over the entire observed volume (with $\sigma v = \mathrm{cst}$)?

$$\frac{\mathrm{d}\phi_{\mathrm{det}}}{\mathrm{d}E} = \int_V \frac{1}{A} \frac{\mathrm{d}\Gamma_{\mathrm{det}}}{\mathrm{d}V\mathrm{d}E} \mathrm{d}V = \frac{\langle \sigma_{\mathrm{ann}} v \rangle}{4\pi\delta m_\chi^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E} \times \int_{\Delta\Omega} \int_l \rho^2(l, \Omega)\, \mathrm{d}l\, \mathrm{d}\Omega$$

using $dV = l^2 \sin\alpha\, \mathrm{d}l\, \mathrm{d}\alpha\, \mathrm{d}\beta = l^2\, \mathrm{d}l\, \mathrm{d}\Omega$

Decaying DM = single particle process

- $\delta = 1$
- $\langle \sigma_{\mathrm{ann}} v \rangle \to 1/\tau_\chi$, τ_χ = lifetime
- $\rho^2, m_\chi^2 \to \rho, m_\chi$

The exotic annihilation DM signal

Recap

particle physics

Astrophysical “J-factor”: $[M_\odot^2 \text{ kpc}^{-5}]$ or $[\text{GeV}^2\text{cm}^{-5}]$

$$\frac{d\Phi}{dE}(E, \vec{k}, \Delta\Omega(\alpha_{\text{int}})) = \frac{\langle \sigma v \rangle}{4\pi\ \delta\ m_{\text{DM}}^2} \sum_f \frac{dN^f}{dE} B_f \times \int_0^{2\pi} d\beta \int_0^{\alpha_{\text{int}}} \sin\alpha d\alpha \int_0^{l_{\max}} \rho^2(\vec{k}\ l, \alpha, \beta)\ dl$$

- Predicted flux depends on the DM mass, annihilation cross section, instrument resolution, and DM distribution
- An accurate estimation of the J-factor (i.e. of ρ) is required to place robust limit son the DM candidate properties.
- "Model uncertainties" should always be considered

The exotic annihilation DM signal

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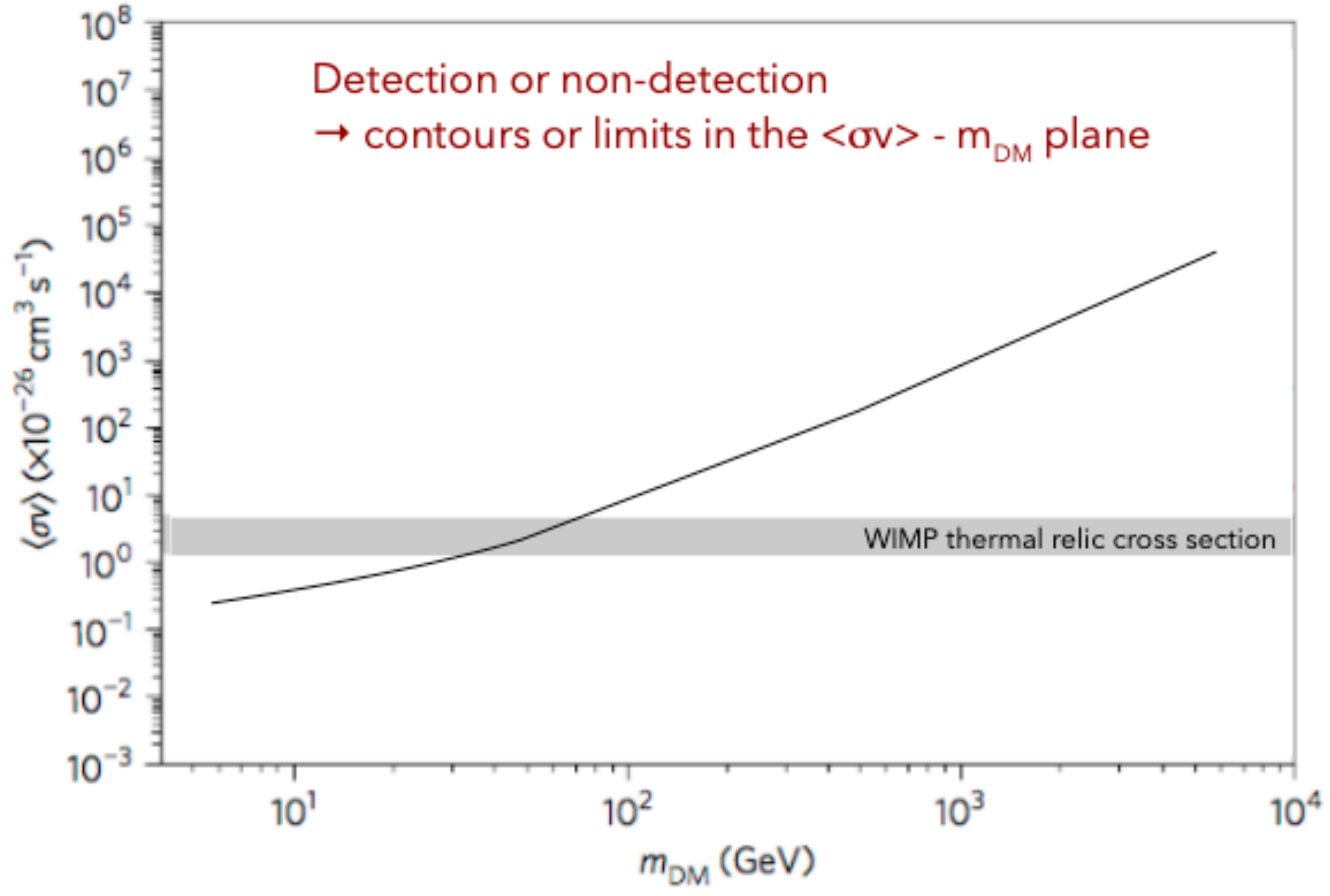

The exotic annihilation DM signal

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Source of confusion: some authors have the 4pi in the J-factor

- Predicted flux depends on the DM mass, annihilation cross section, instrument resolution, and DM distribution
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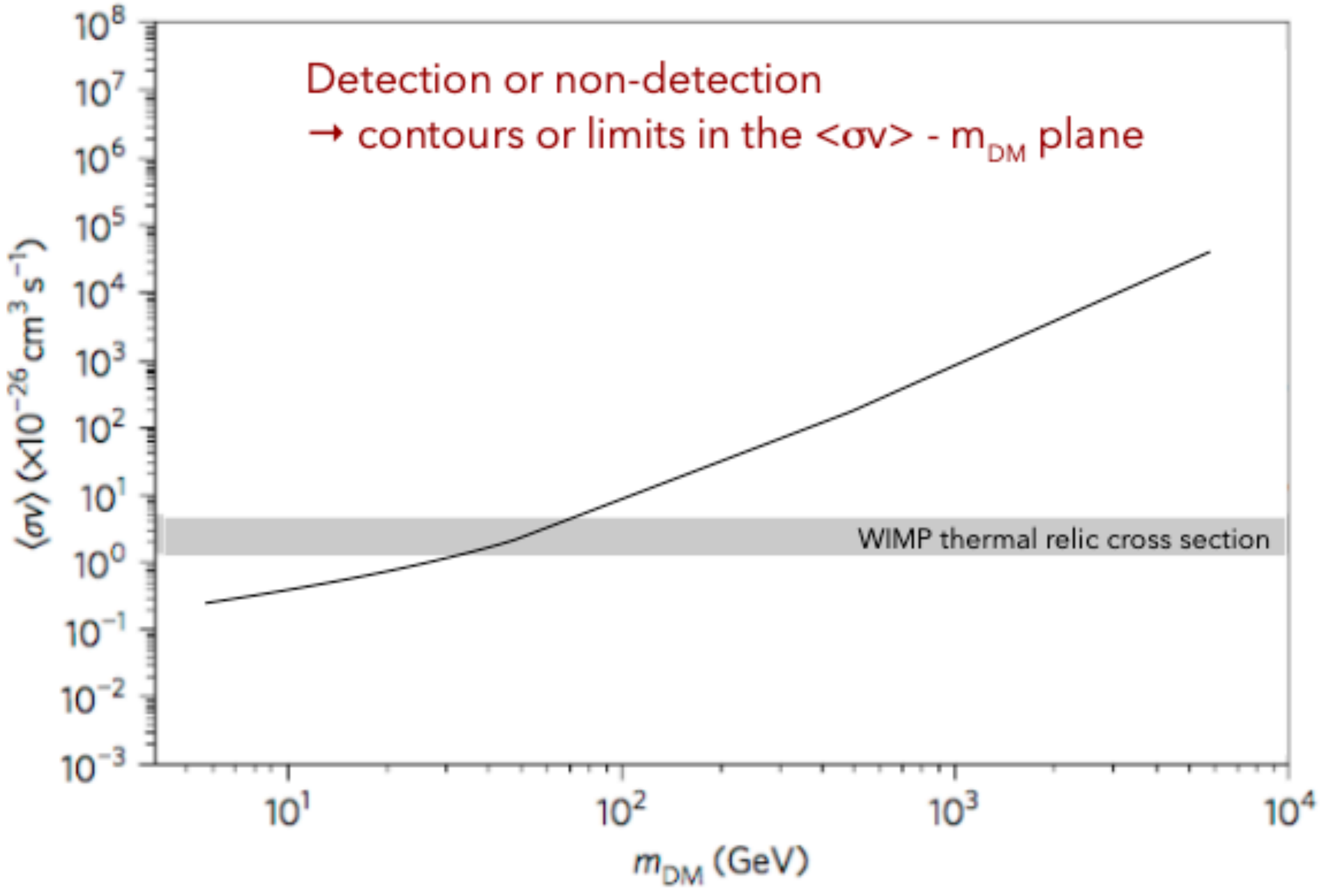
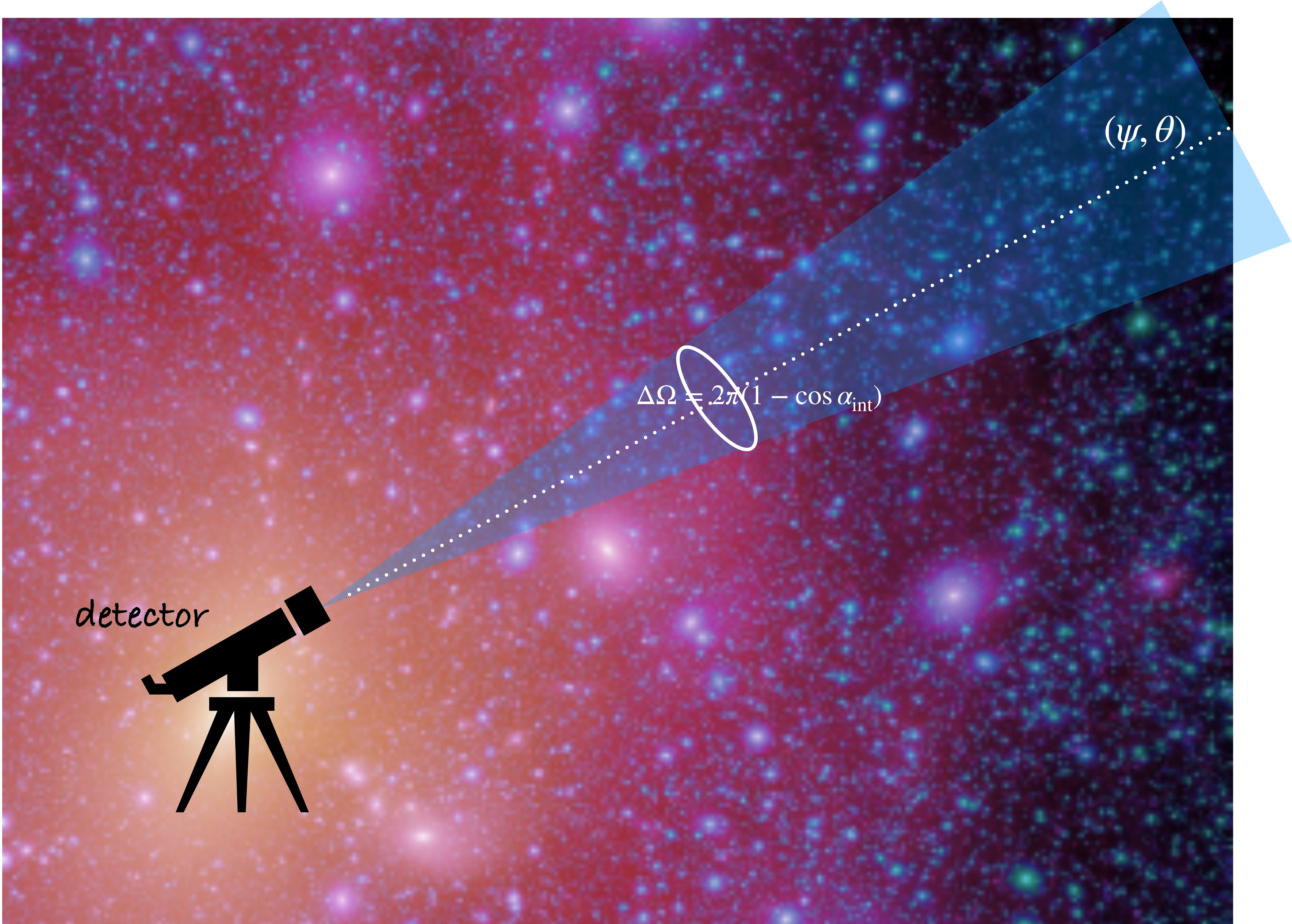


The γ-ray signal from DM annihilation (or decay)

1. Derivation, definition of the J-factor
2. General considerations regarding the J-factor

The J-factor

Global picture



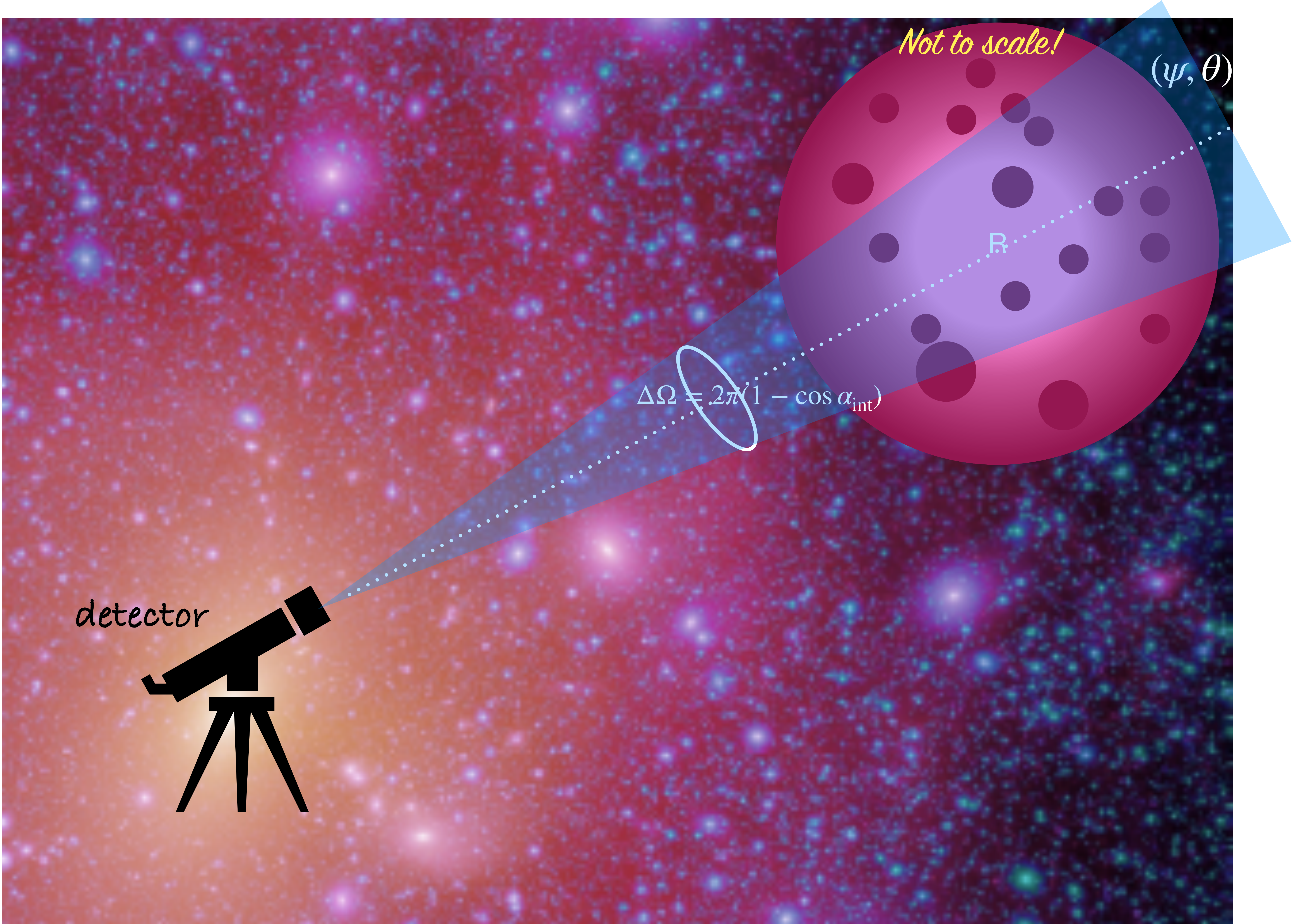
$$J(\psi, \theta, \alpha_{\text{int}}) = \int_0^{2\pi} d\beta \int_0^{\alpha_{\text{int}}} \sin\alpha d\alpha \int_{\text{los}} \rho^2(l, \alpha, \beta; \psi, \theta) dl$$

Without assumption, ρ is a complicated function

1. Wherever we look, we are looking through the MW halo
   - smooth component
   - substructure component, low mass dark haloes

The J-factor

Global picture



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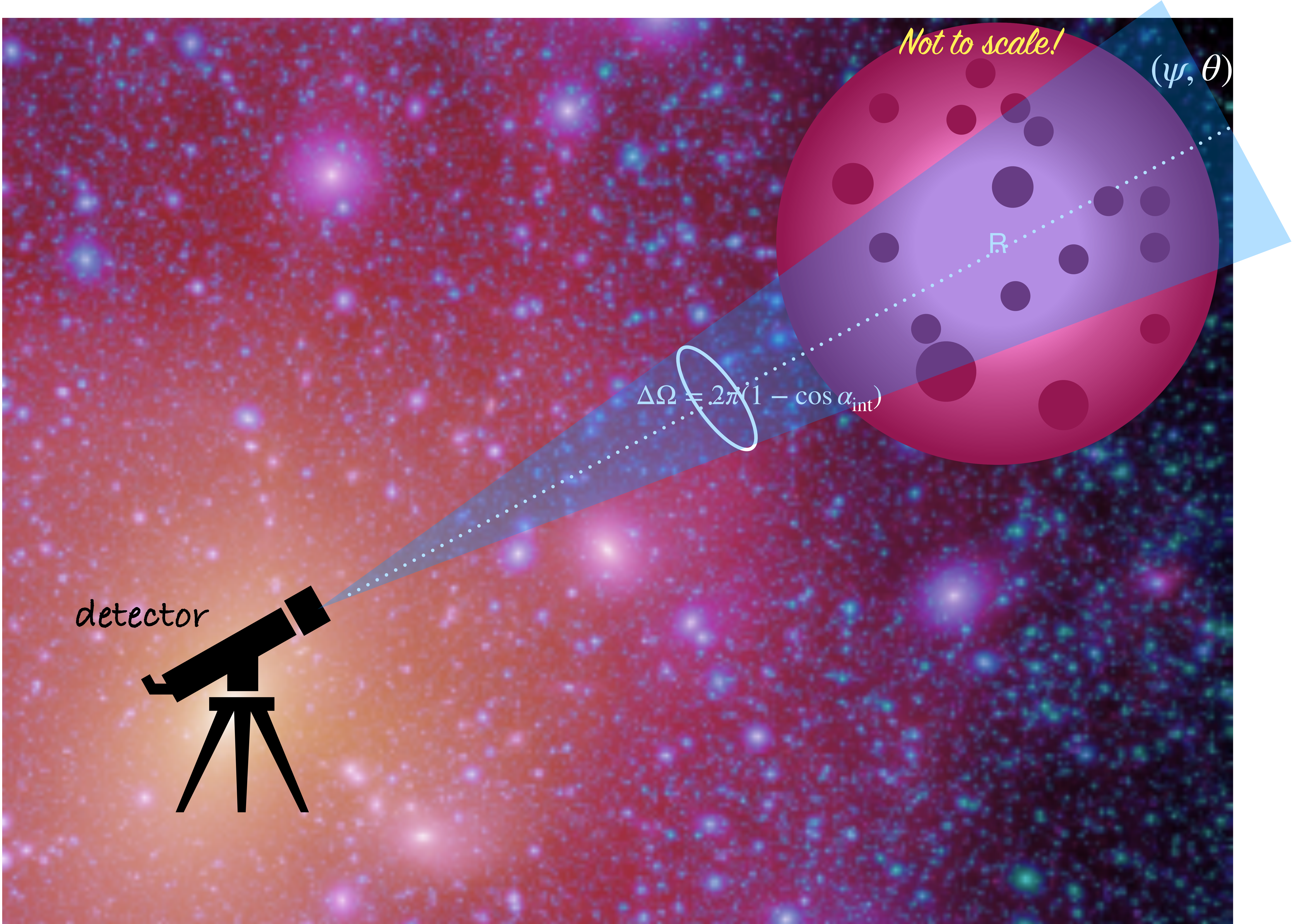
Without assumption, ρ is a complicated function

1. Wherever we look, we are looking through the MW halo
   - smooth component
   - substructure component, low mass dark haloes

2. If looking in the direction of a specific target, the target will have
   - a smooth component
   - a population of subhaloes

The J-factor

Global picture



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What ingredients are needed to predict the J-factor?

Effect of substructures on the J-factor?

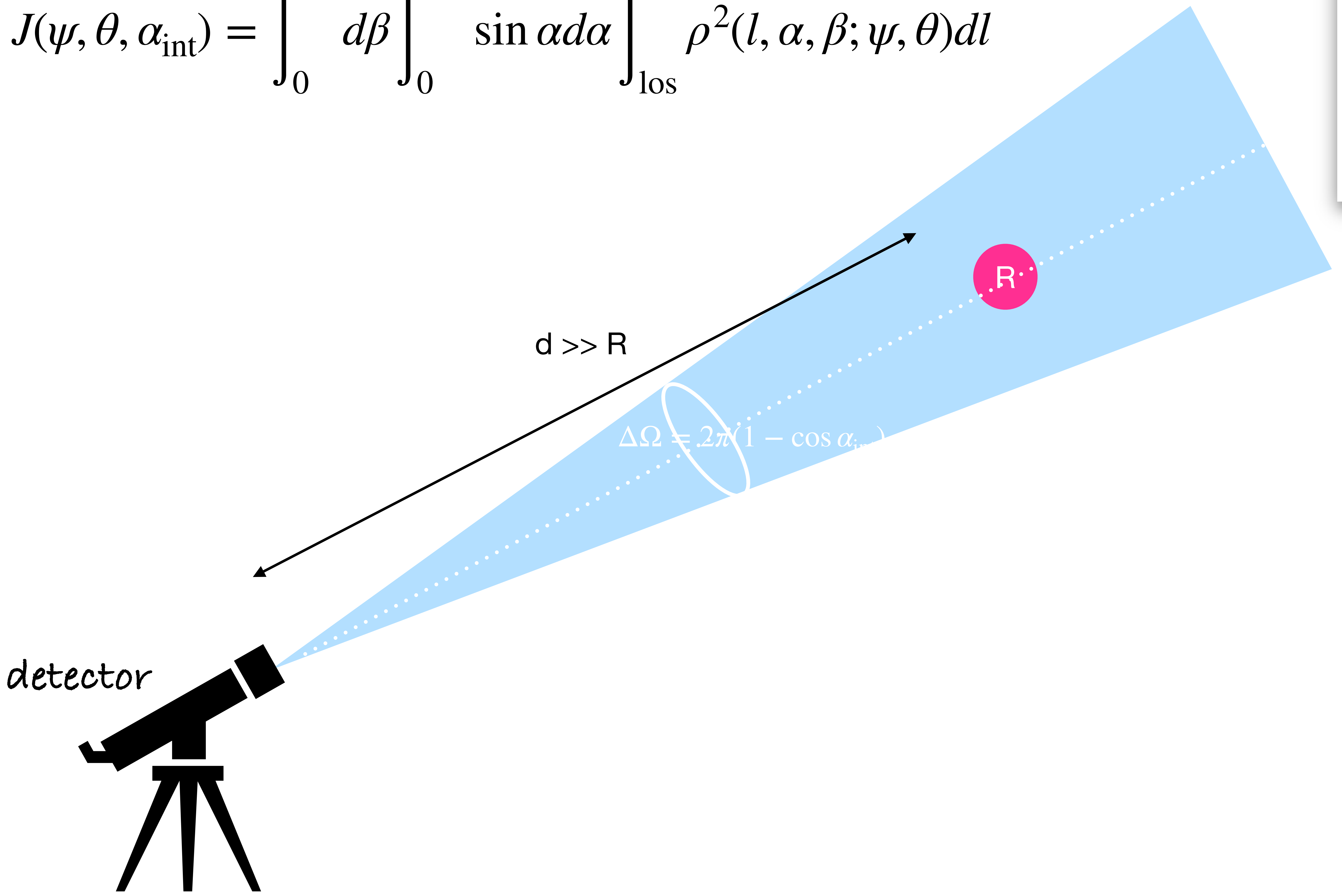
The J-factor

Point-like approximation

$$J(\psi, \theta, \alpha_{\rm int}) = \int_0^{2\pi} d\beta \int_0^{\alpha_{\rm int}} \sin\alpha d\alpha \int_{\rm los} \rho^2(l, \alpha, \beta; \psi, \theta) dl$$

Consider a DM halo
1. fully contained in the integration volume
2. with size << distance to the observer
3. ignore the contribution from the smooth MW

How is the J-factor expressed ?



The J-factor

Point-like approximation

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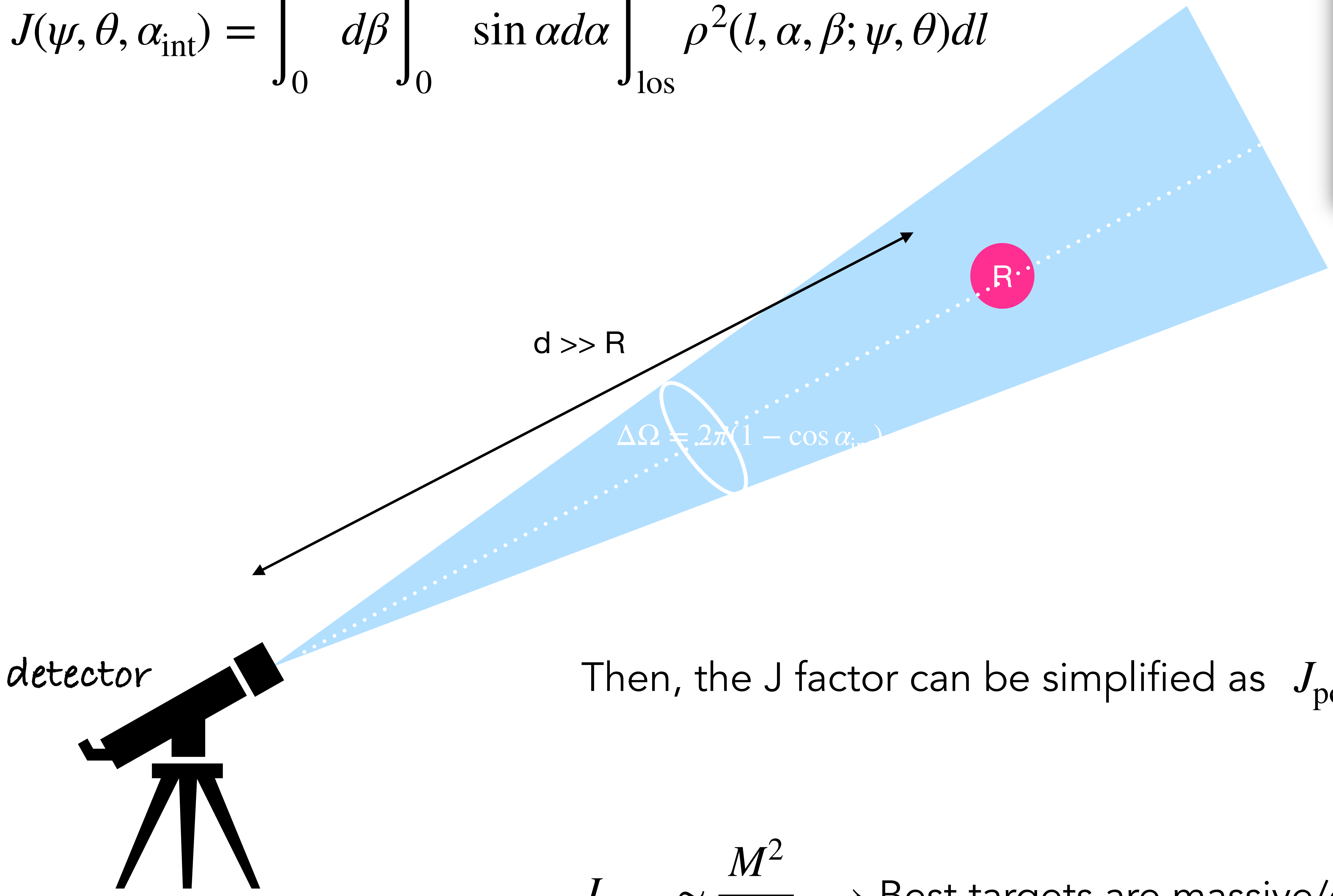


Then, the J factor can be simplified as $J_{\text{point}} = \frac{\mathscr{L}}{d^2}$ with $\mathscr{L} = \mathscr{L}(M,c) = \int_{V_{\text{halo}}} \rho^2(M,c)\, dV$

halo "luminosity"

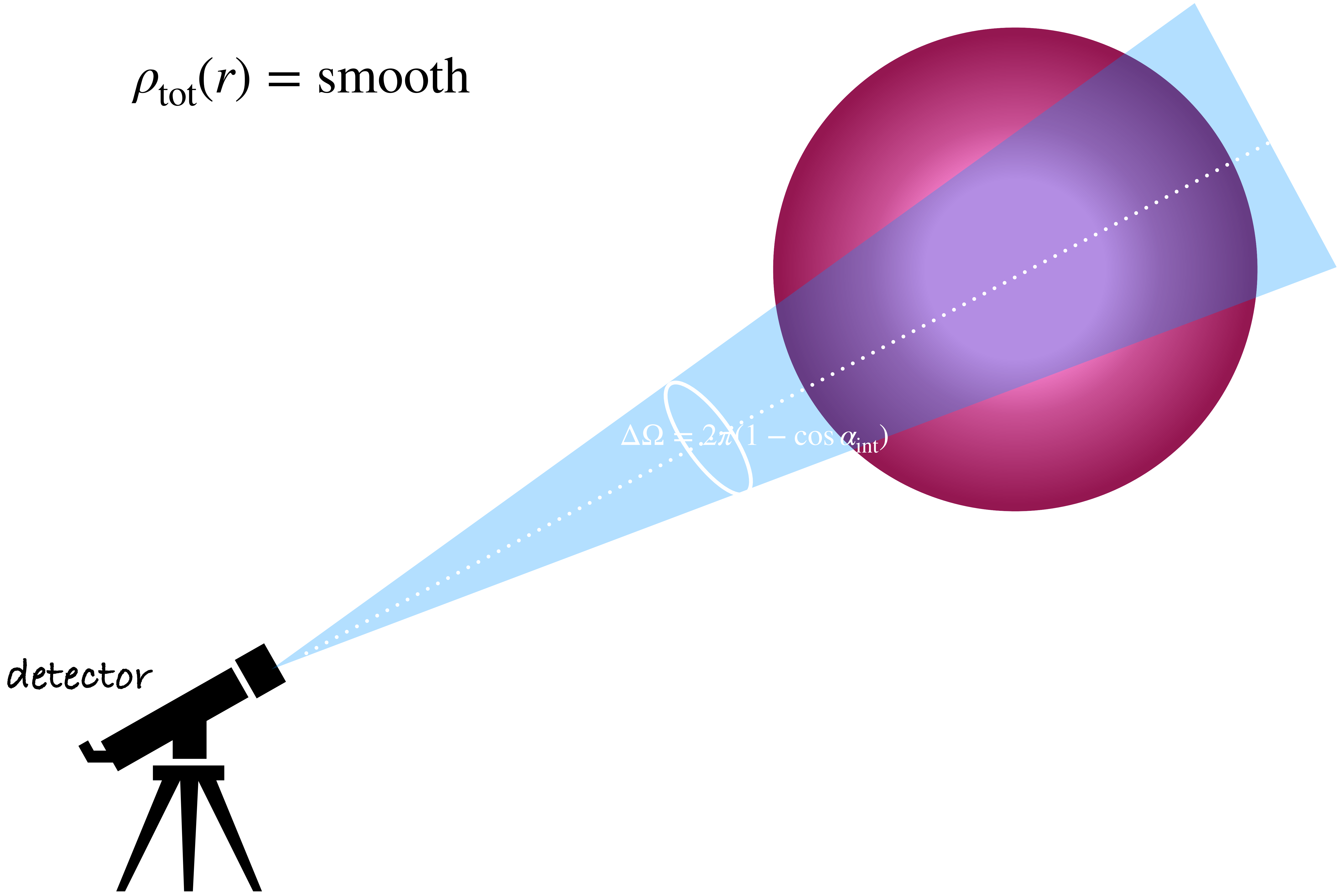
$J_{\text{point}} \sim \frac{M^2}{d^2 V}$ → Best targets are massive/dense and close

The J-factor

Extended halo

$\rho_{\rm tot}(r) = \text{smooth}$

$$J = \int_0^{\Delta\Omega} \int_{\rm los} \rho_{\rm tot}^2 \, dl \, d\Omega$$



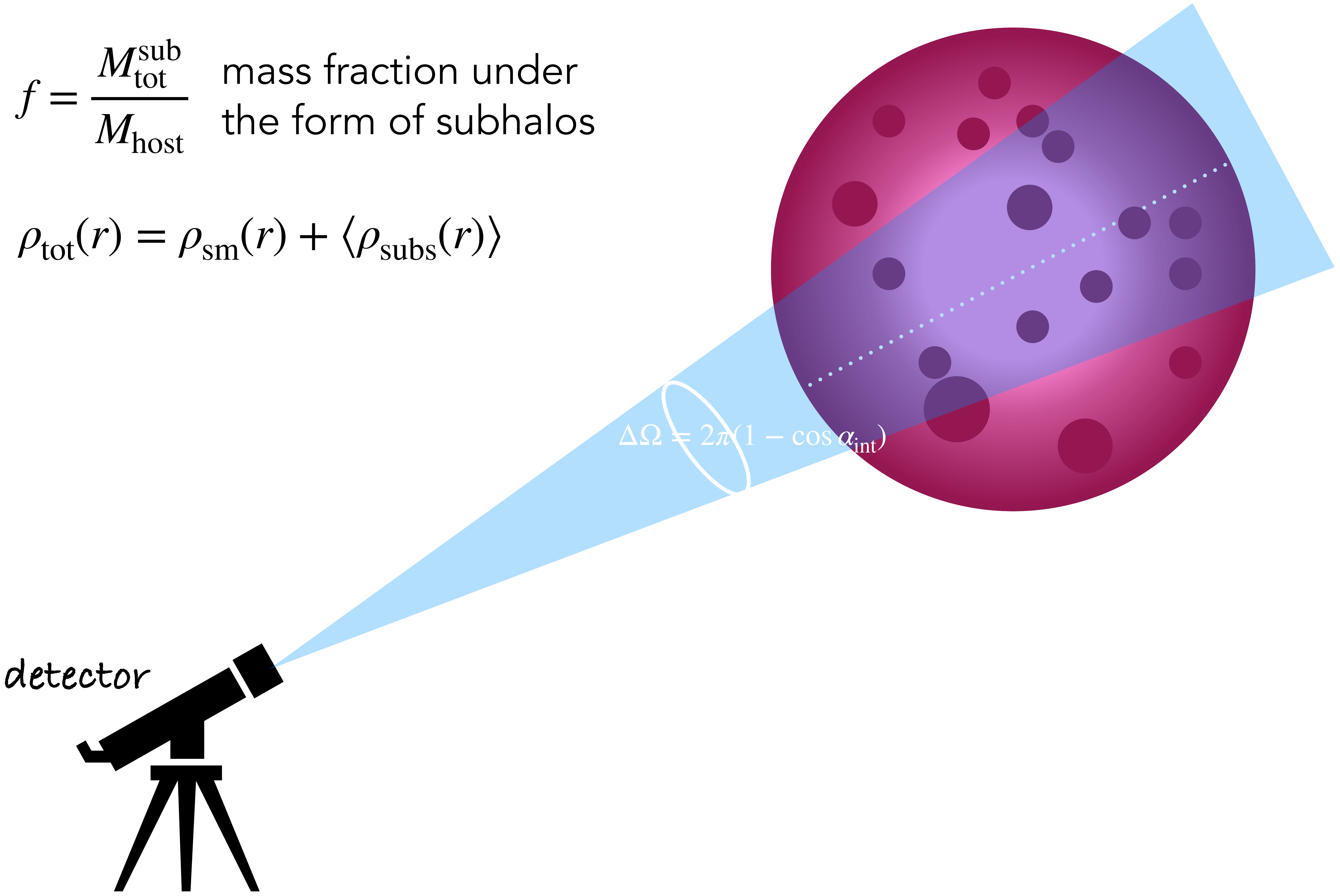
The J-factor

Extended halo with substructures

$f = \frac{M_{tot}^{sub}}{M_{host}}$ mass fraction under the form of subhalos

$\rho_{tot}(r) = \rho_{sm}(r) + \langle \rho_{subs}(r) \rangle$

$$J = \int_0^{\Delta\Omega} \int_{los} \left(\rho_{sm} + \sum_i \rho_{cl}^i \right)^2 dl d\Omega$$



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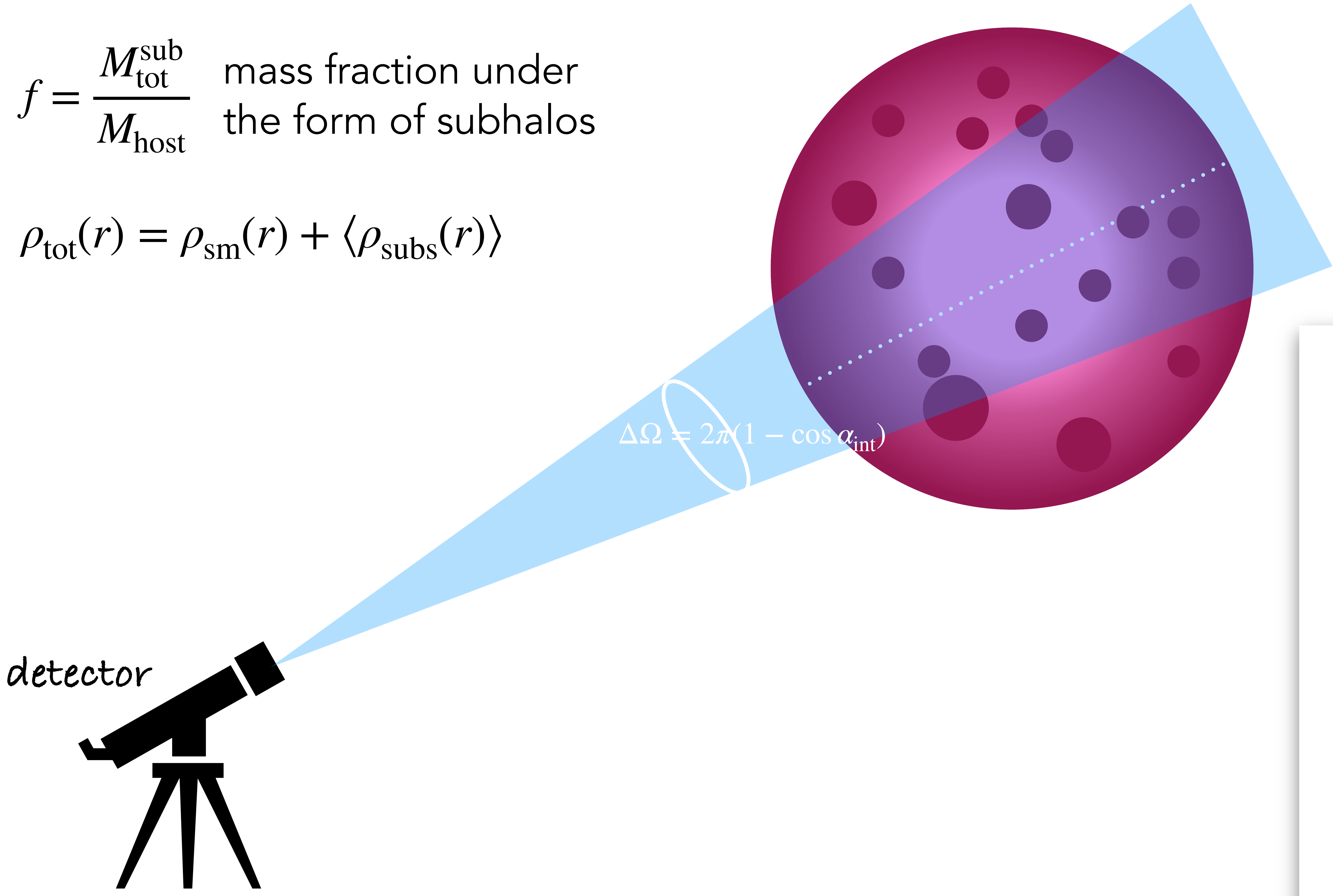

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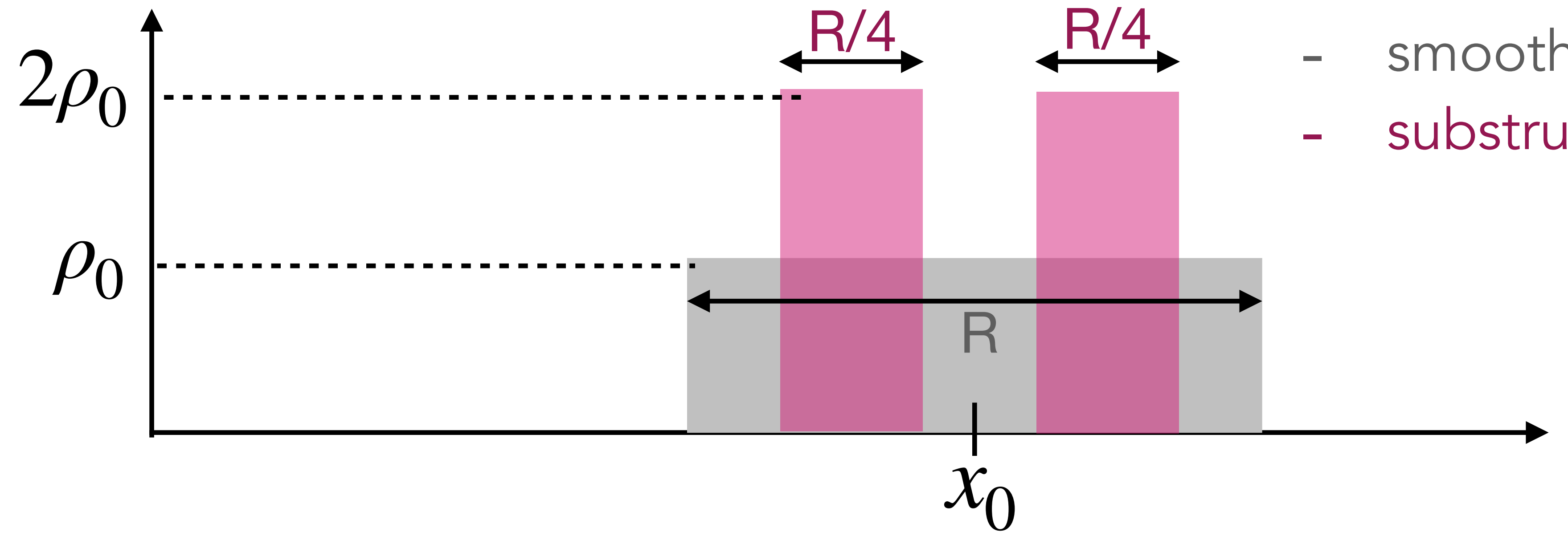
1D toy model

Same total mass distributed (f=1)

- smoothly
- substructures



$$J_{no-subs} = ?$$

$$J_{subs} = ?$$

The J-factor

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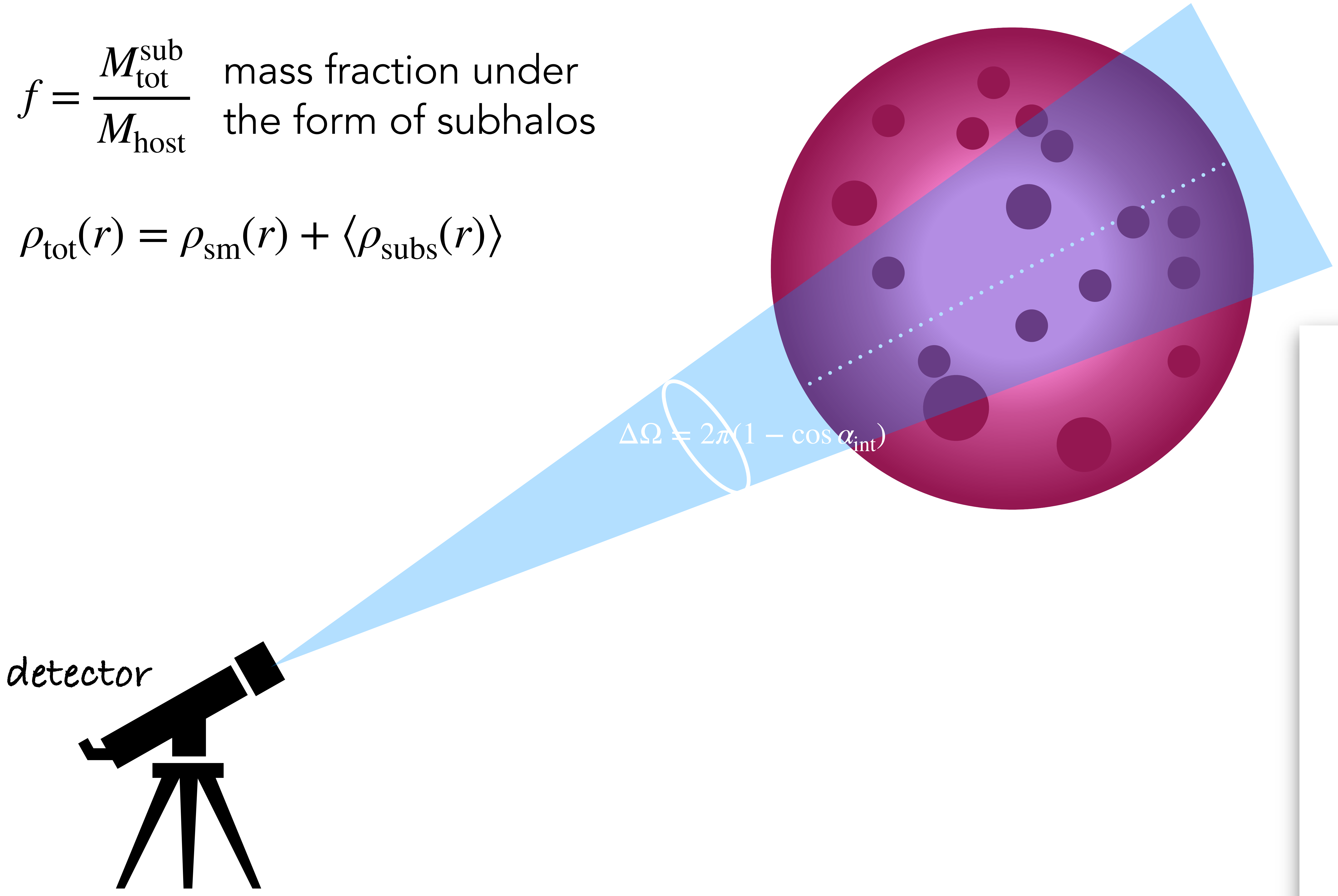

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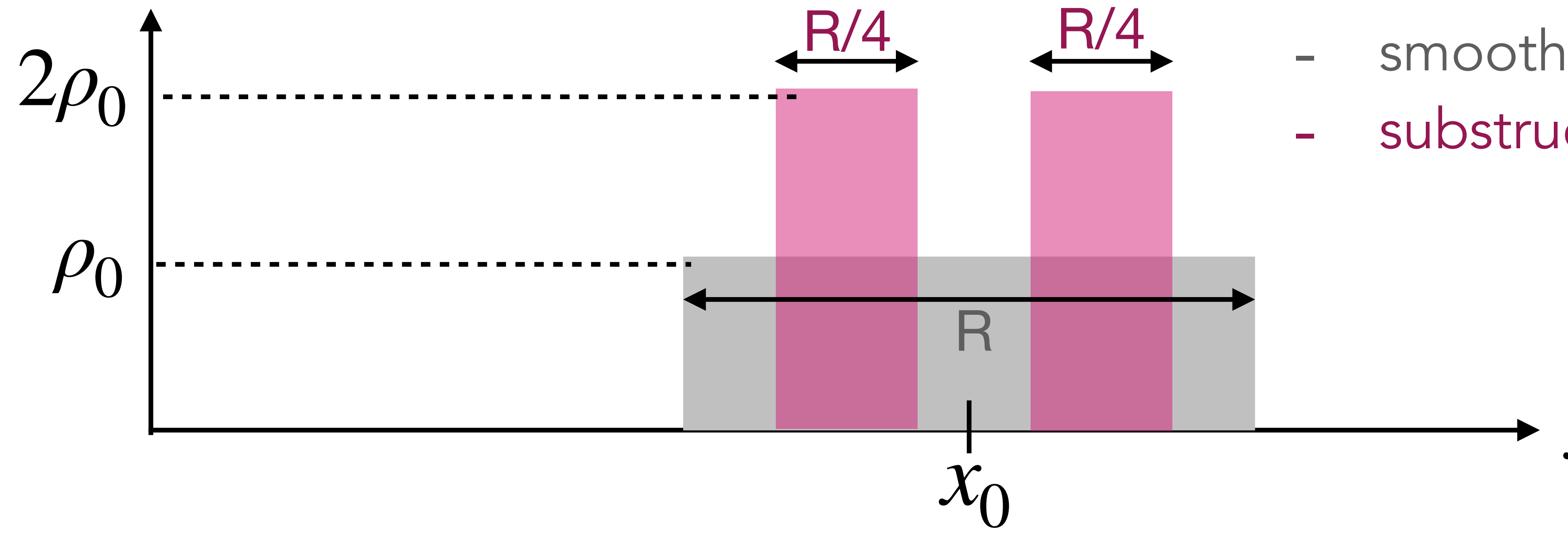

Same total mass distributed (f=1)

- smoothly
- substructures

$$J_{no-subs} \propto \int_{x_0-R/2}^{x_0+R/2} \rho_0^2 \, dx = \rho_0^2 R$$

$$J_{subs} \propto \sum_i \int_{x_i-R/8}^{x_i+R/8} (2\rho_0)^2 \, dx = 2\rho_0^2 R$$

Substructures will boost the annihilation signal

(what about decay?)

The J-factor

Extended halo with substructures

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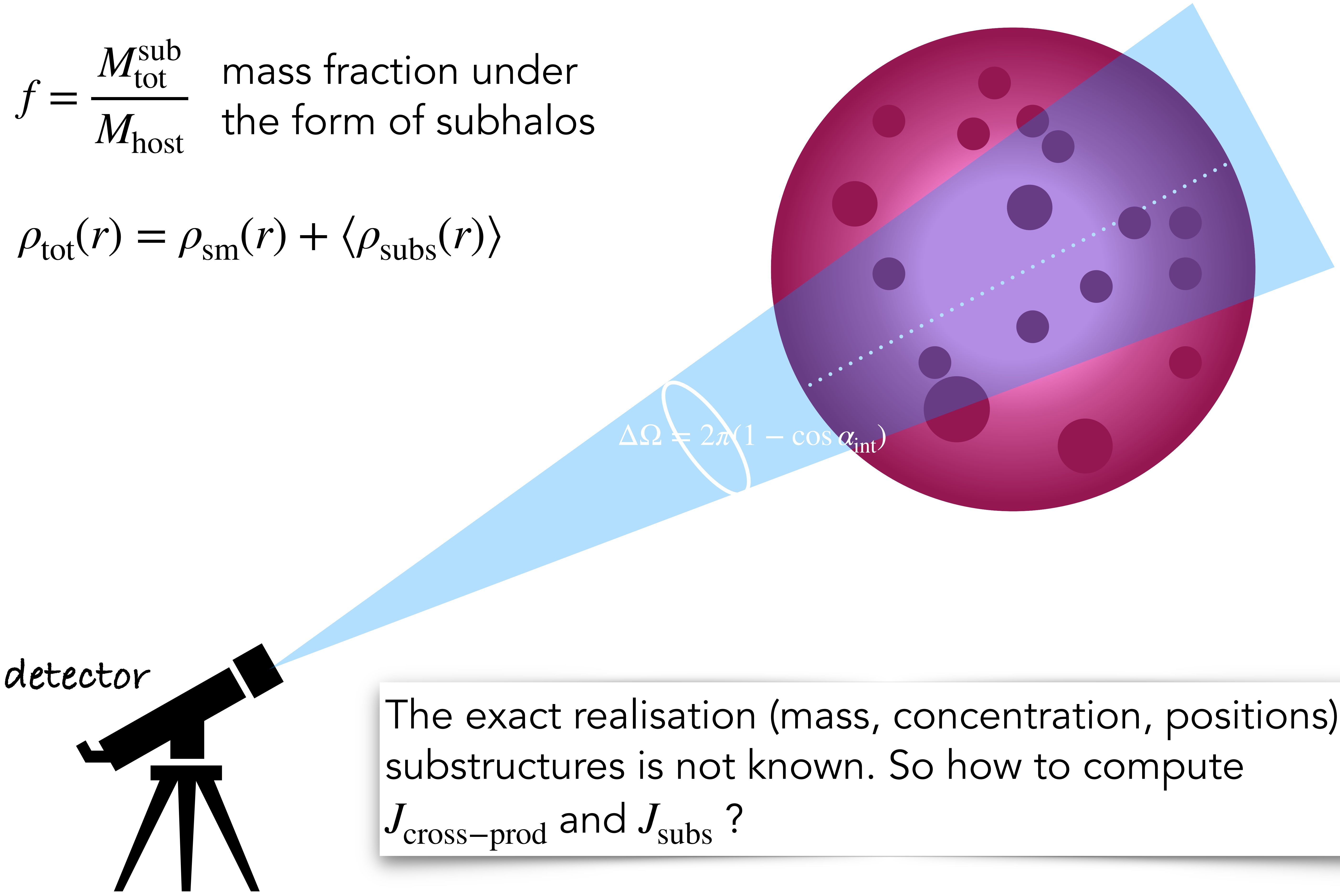

$$J = \int_0^{\Delta\Omega} \int_{los} \left(\rho_{sm} + \sum_i \rho_{cl}^i \right)^2 dl d\Omega$$

expands into 3 terms

$$J_{sm} \equiv \int_0^{\Delta\Omega} \int_{los} \rho_{sm}^2 dl d\Omega$$

$$J_{cross-prod} \equiv 2 \int_0^{\Delta\Omega} \int_{los} \rho_{sm} \sum_i \rho_{cl}^i \, dl d\Omega$$

$$J_{subs} = \int_0^{\Delta\Omega} \int_{los} \left(\sum_i \rho_{cl}^i \right)^2 dl d\Omega$$

The exact realisation (mass, concentration, positions) of substructures is not known. So how to compute $J_{cross-prod}$ and J_{subs} ?

The J-factor

Extended halo with substructures

Solution: go to the continuous limit, assuming substructure spatial, mass and concentration distributions.

$$\frac{\mathrm{d}^3 N}{\mathrm{d}V \mathrm{d}M \mathrm{d}c} = N_{\mathrm{tot}} \frac{\mathrm{d}\mathscr{P}_V}{\mathrm{d}V}(r) \cdot \frac{\mathrm{d}\mathscr{P}_M}{\mathrm{d}M}(M) \cdot \frac{\mathrm{d}\mathscr{P}_c}{\mathrm{d}c}(M, c)$$

This assumes that spatial and mass/concentration distributions are NOT correlated. Does not hold when baryonic effects are considered (see later)

The J-factor

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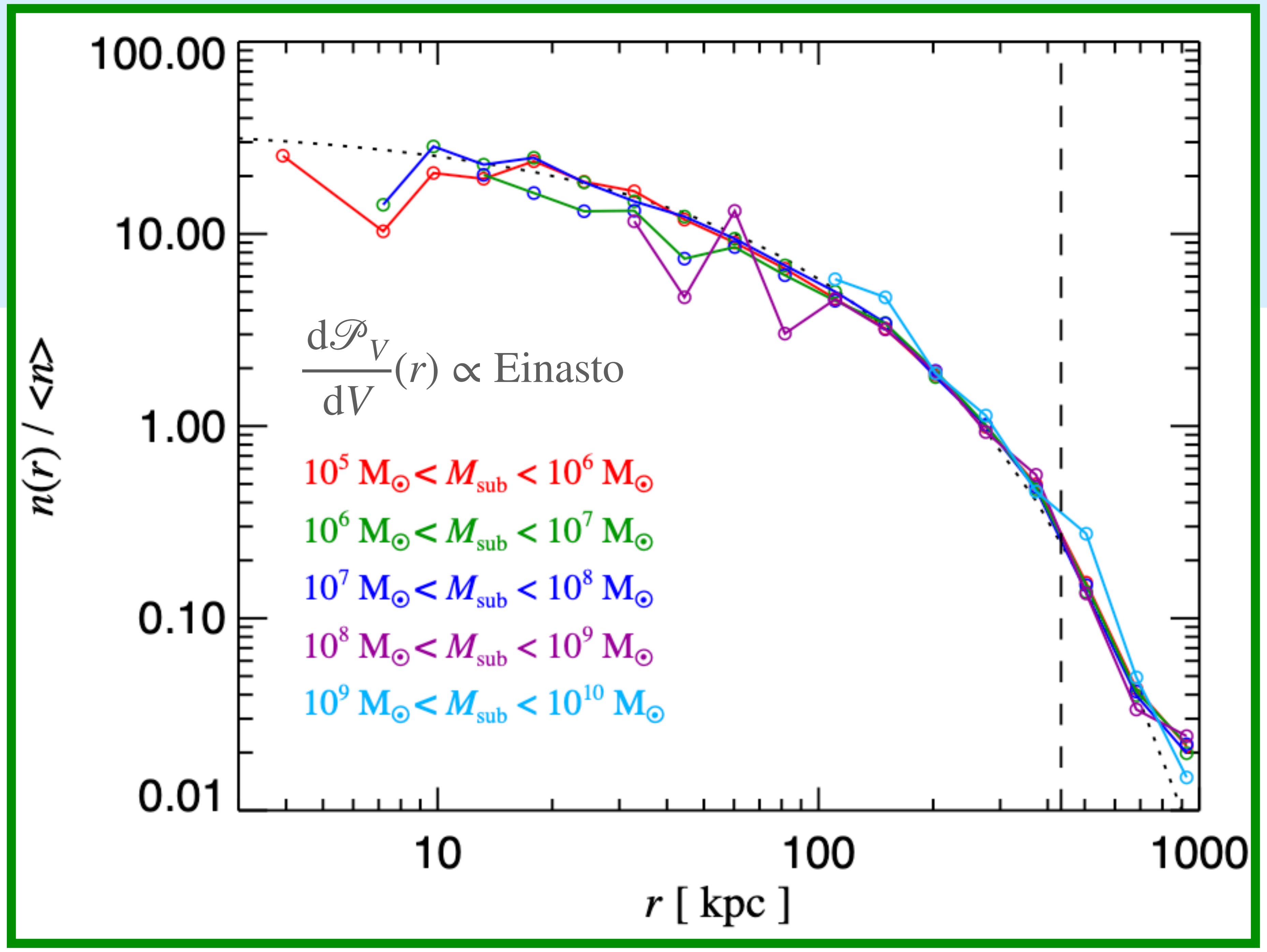

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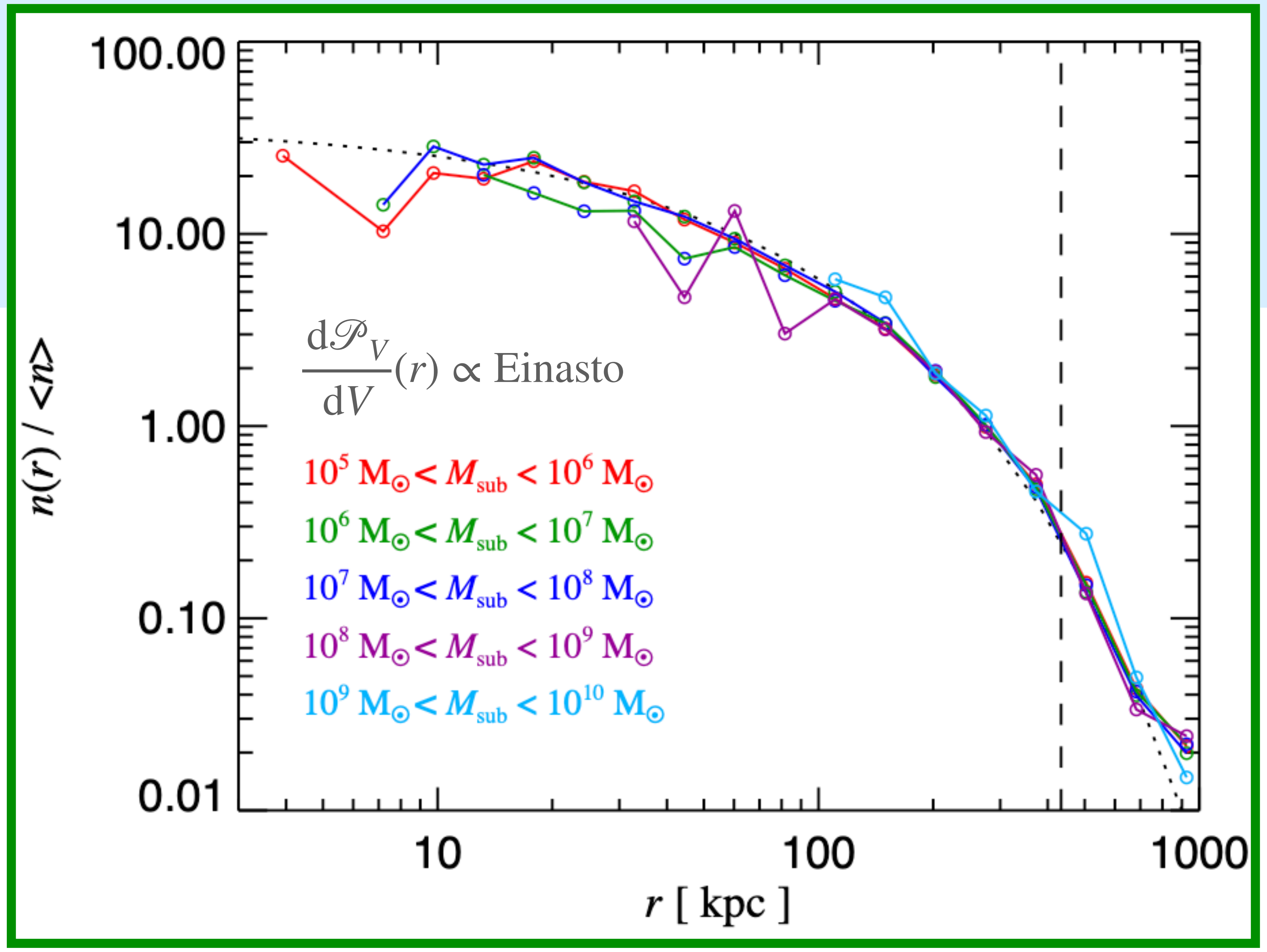
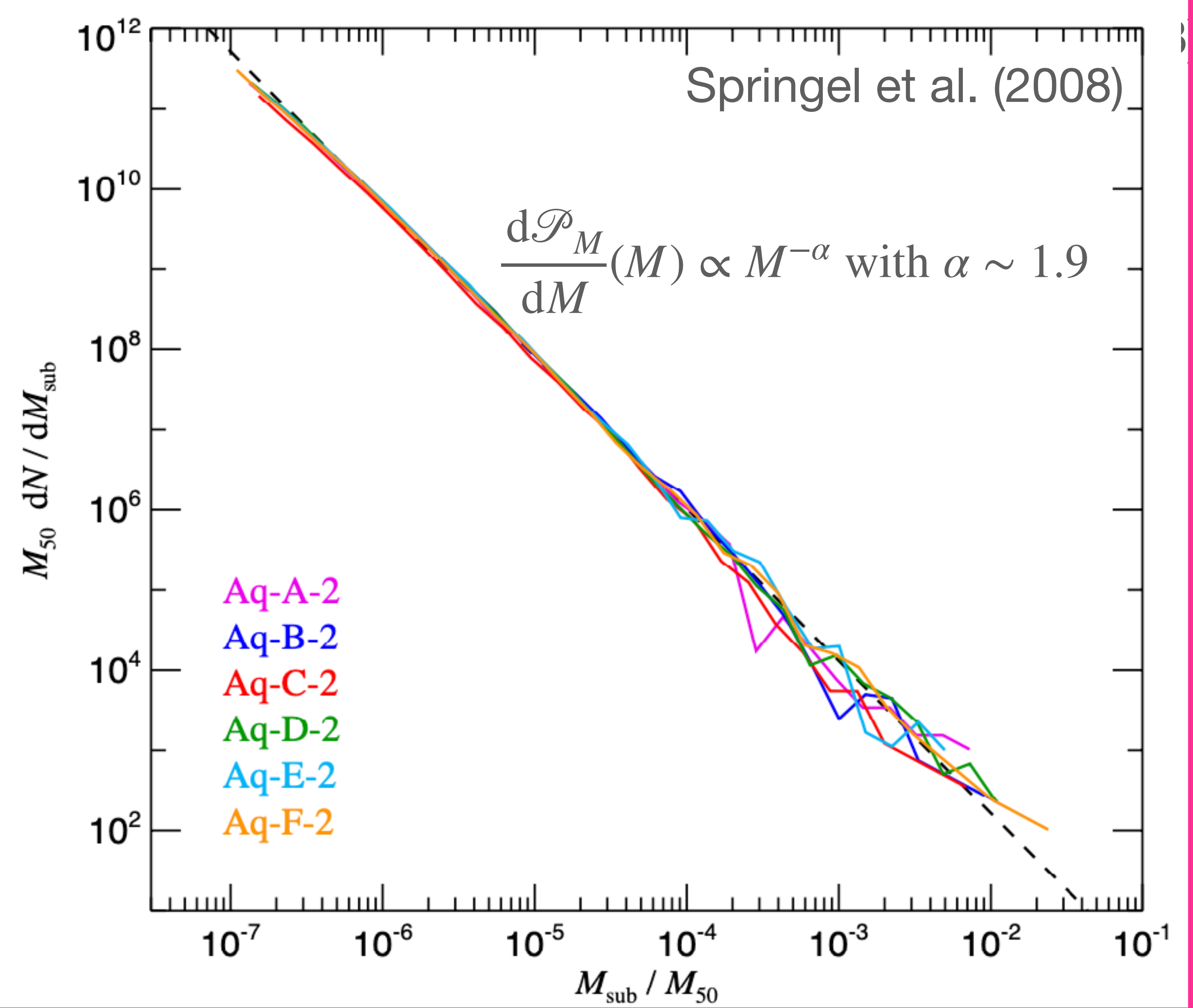


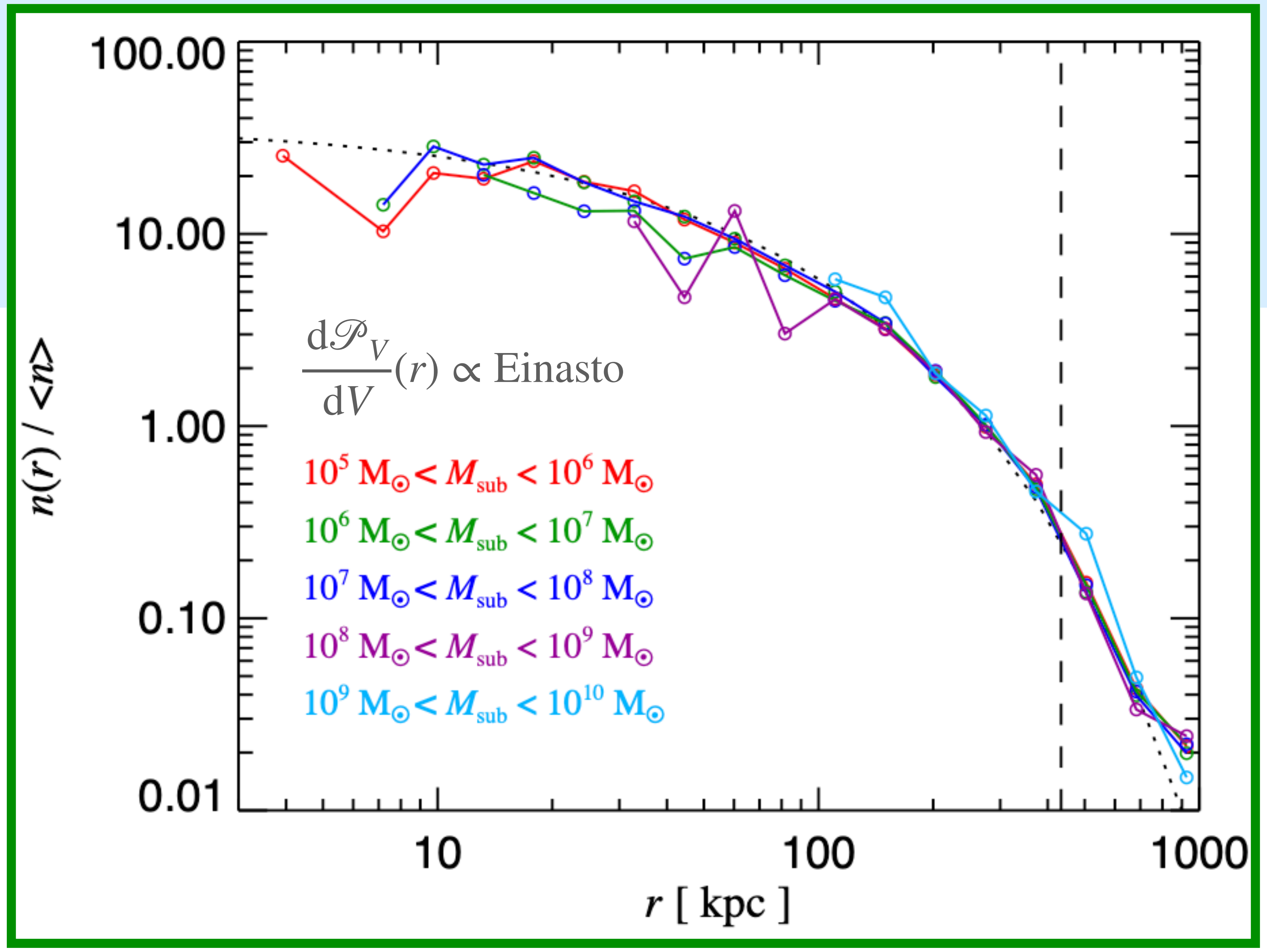


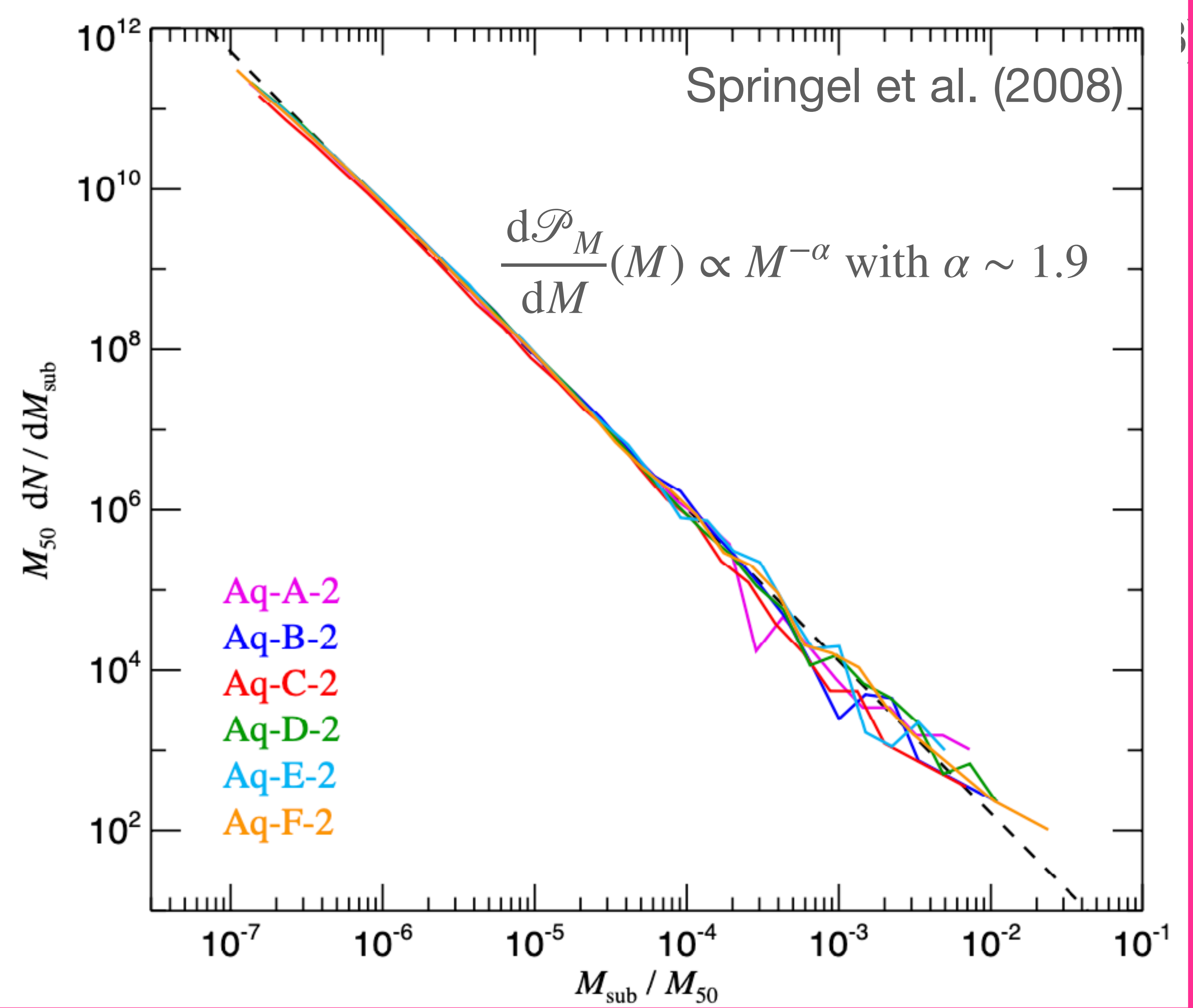
The J-factor

Extended halo with substructures

Solution: go to the continuous limit, assuming substruction spatial, mass and concentration distributions.

$$\frac{d^3N}{dVdMdc} = N_{tot} \frac{d\mathscr{P}_V}{dV}(r) \cdot \frac{d\mathscr{P}_M}{dM}(M) \cdot \frac{d\mathscr{P}_c}{dc}(M,c)$$





DM-only simulations give ~100 clumps between 10^8-10^{10} M_{sun}. How many subhalos pertain a MW-like halo if Mmin = 10^{-6} M_{sun} ?

The J-factor

Extended halo with substructures

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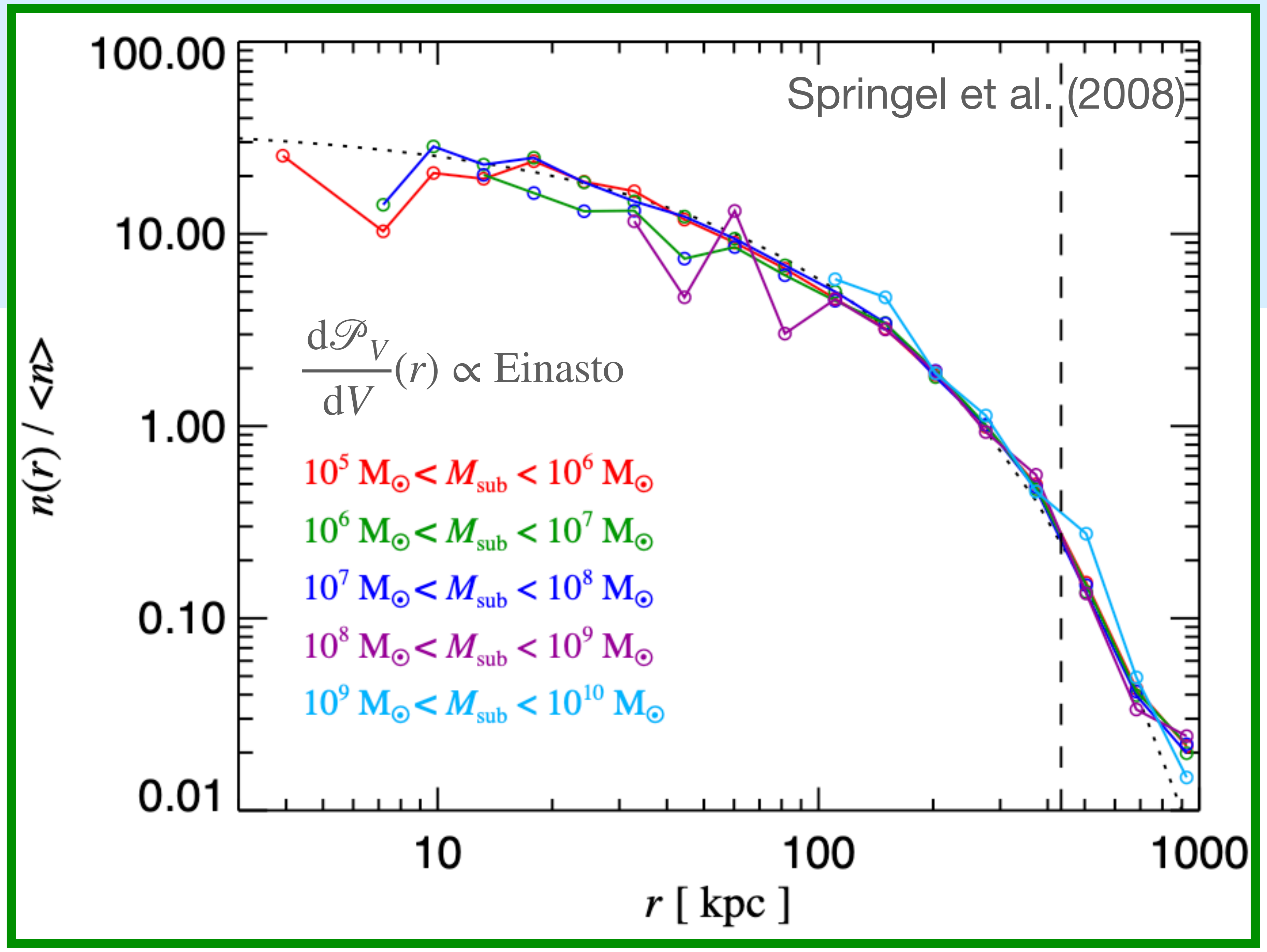

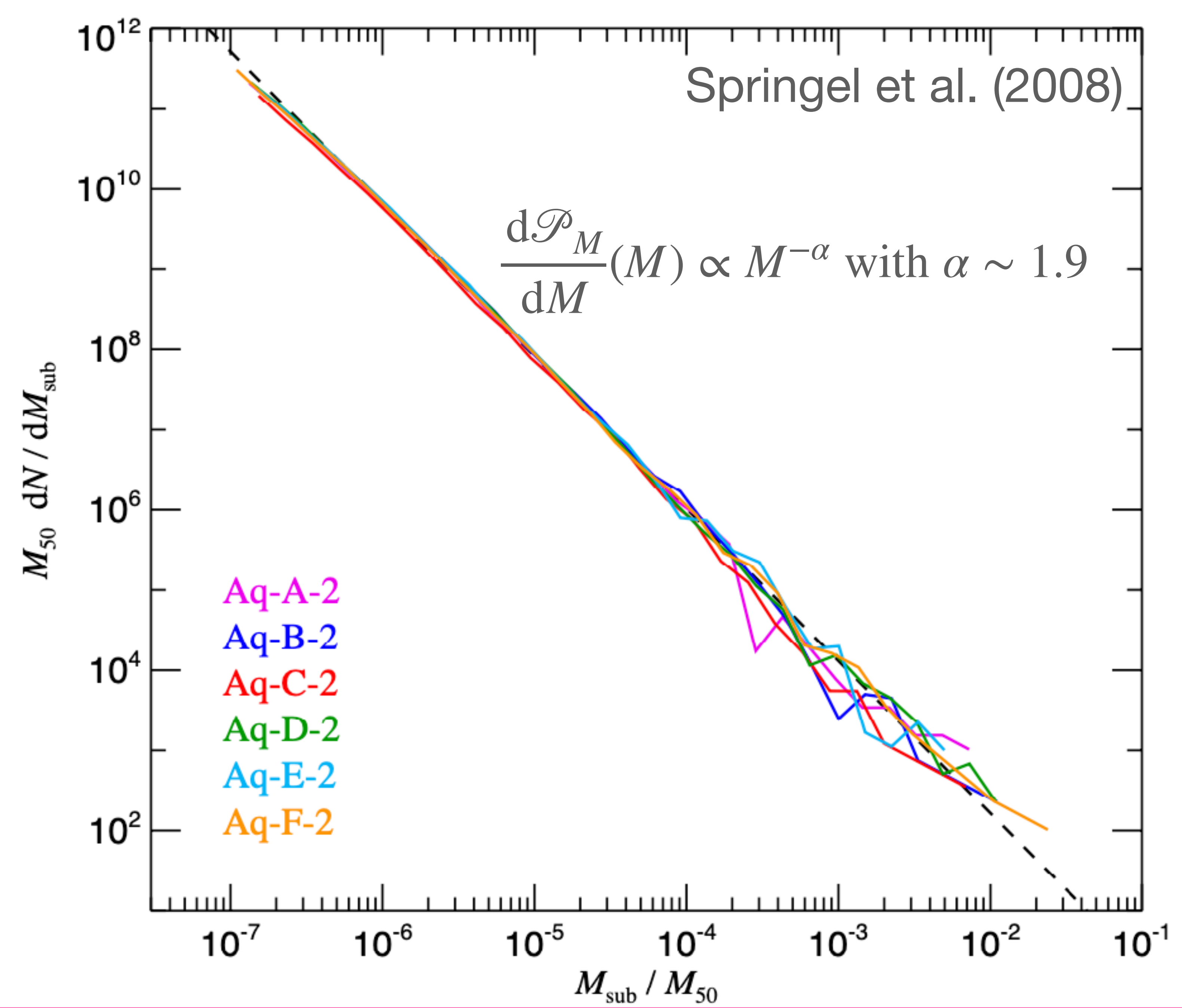

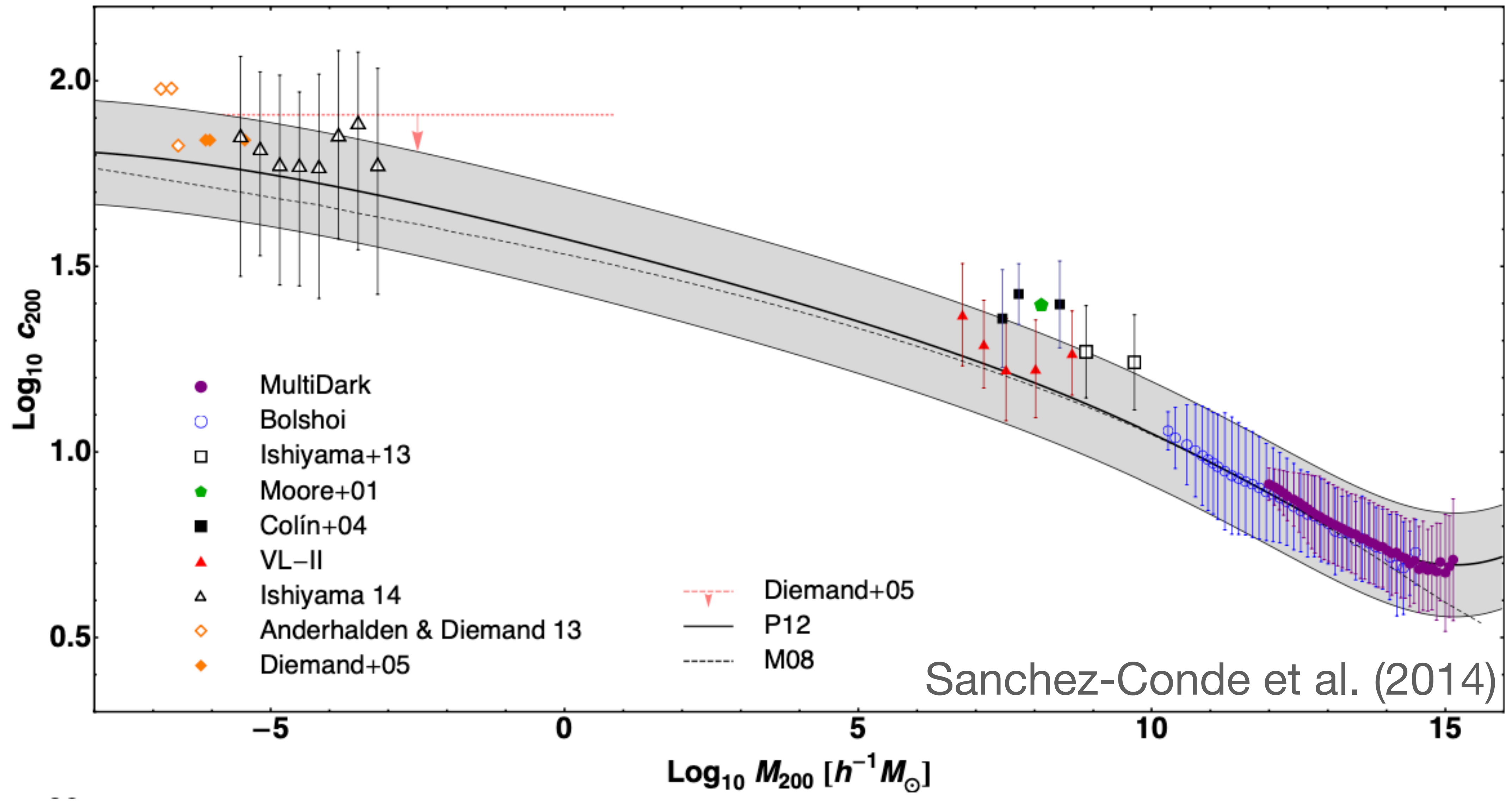

The J-factor

Extended halo with substructures

Solution: go to the continuous limit, assuming substruction spatial, mass and concentration distributions.

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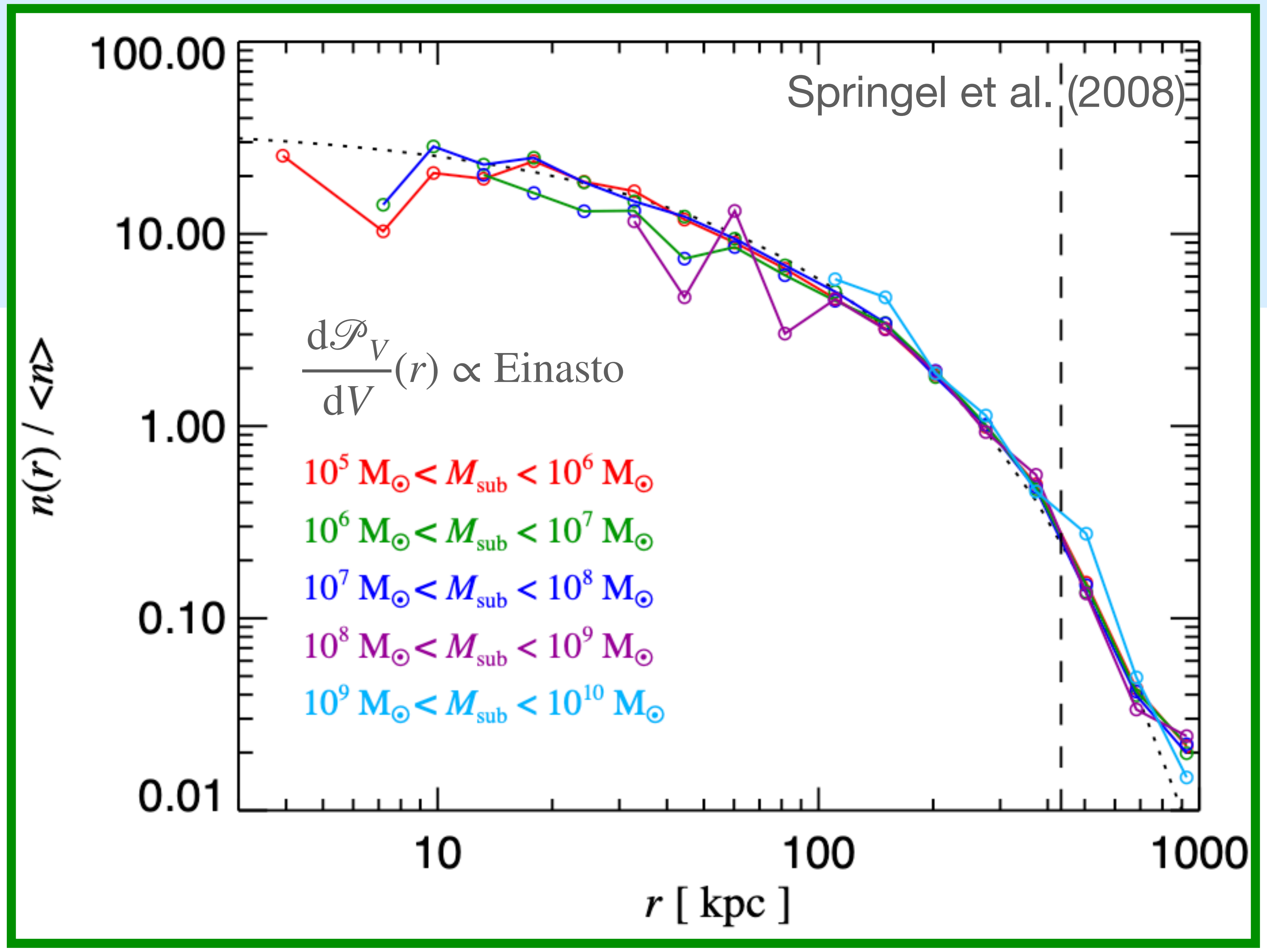

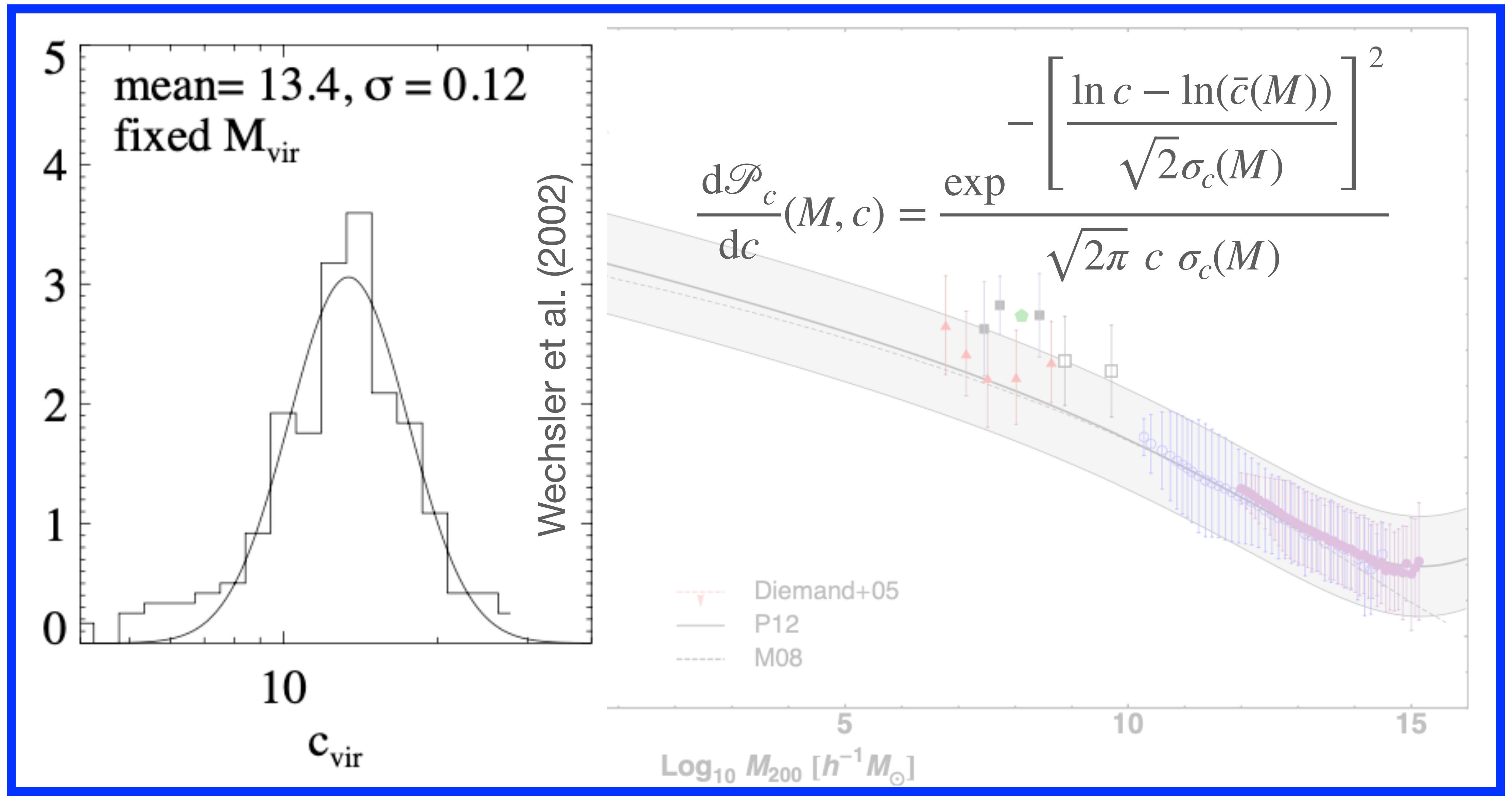

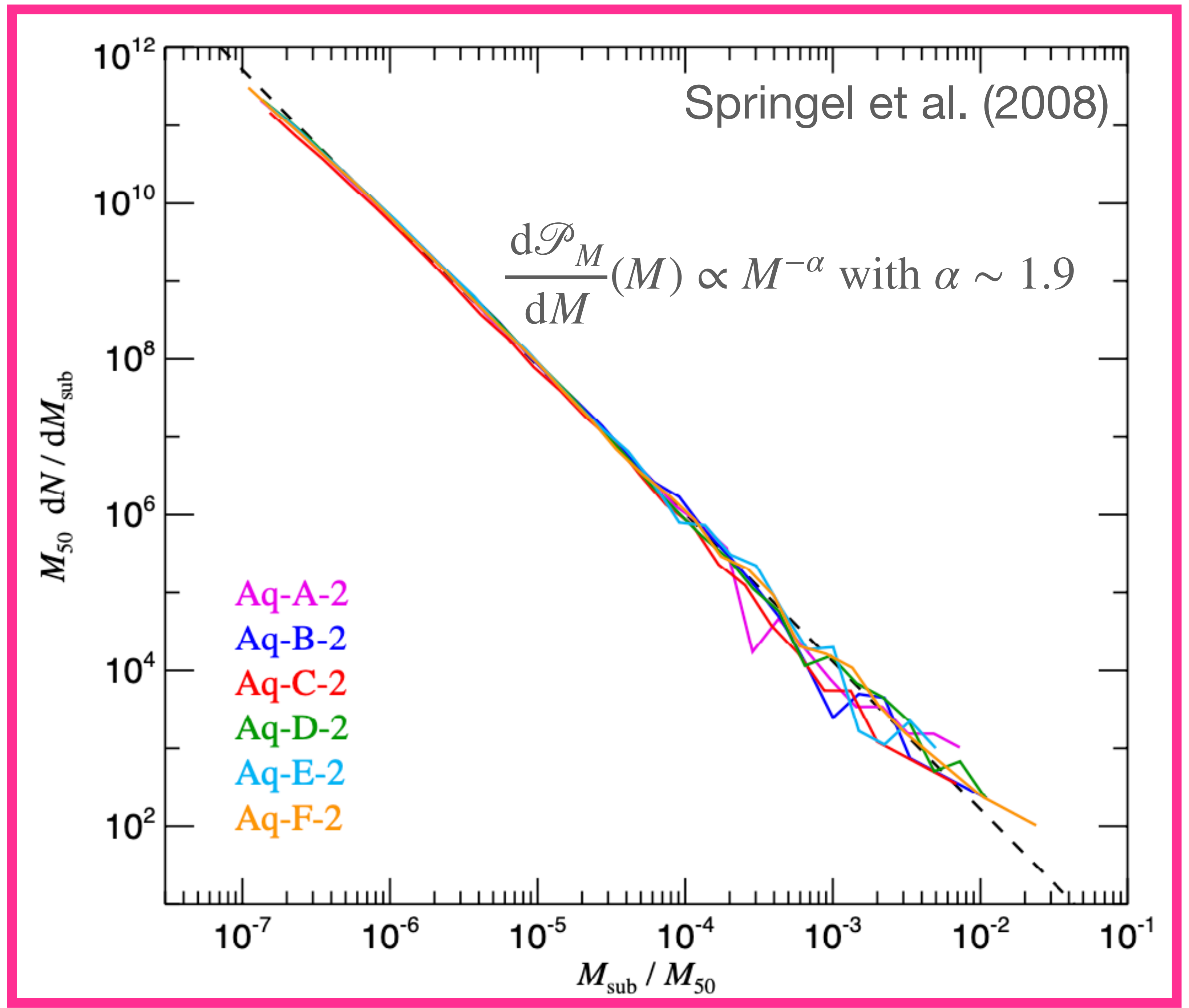

The J-factor

Extended halo with substructures

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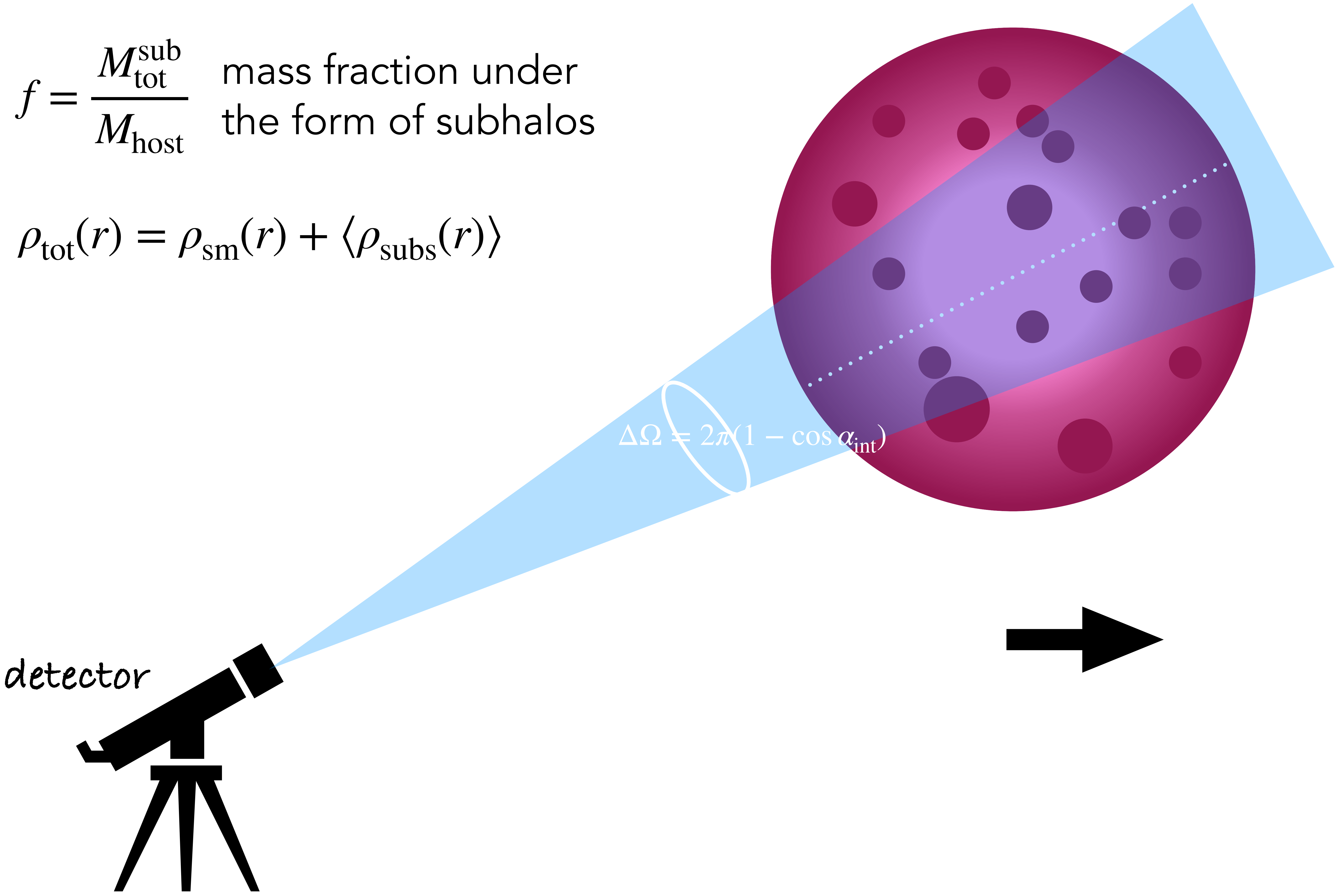
$$\rho_{tot}(r) = \rho_{sm}(r) + \langle \rho_{subs}(r) \rangle$$



$$J = \int_0^{\Delta\Omega} \int_{los} \left(\rho_{sm} + \sum_i \rho_{cl}^i \right)^2 dl d\Omega$$

expands into 3 terms

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$$J_{cross-prod} \equiv 2 \int_0^{\Delta\Omega} \int_{los} \rho_{sm} \sum_i \rho_{cl}^i \, dl d\Omega$$

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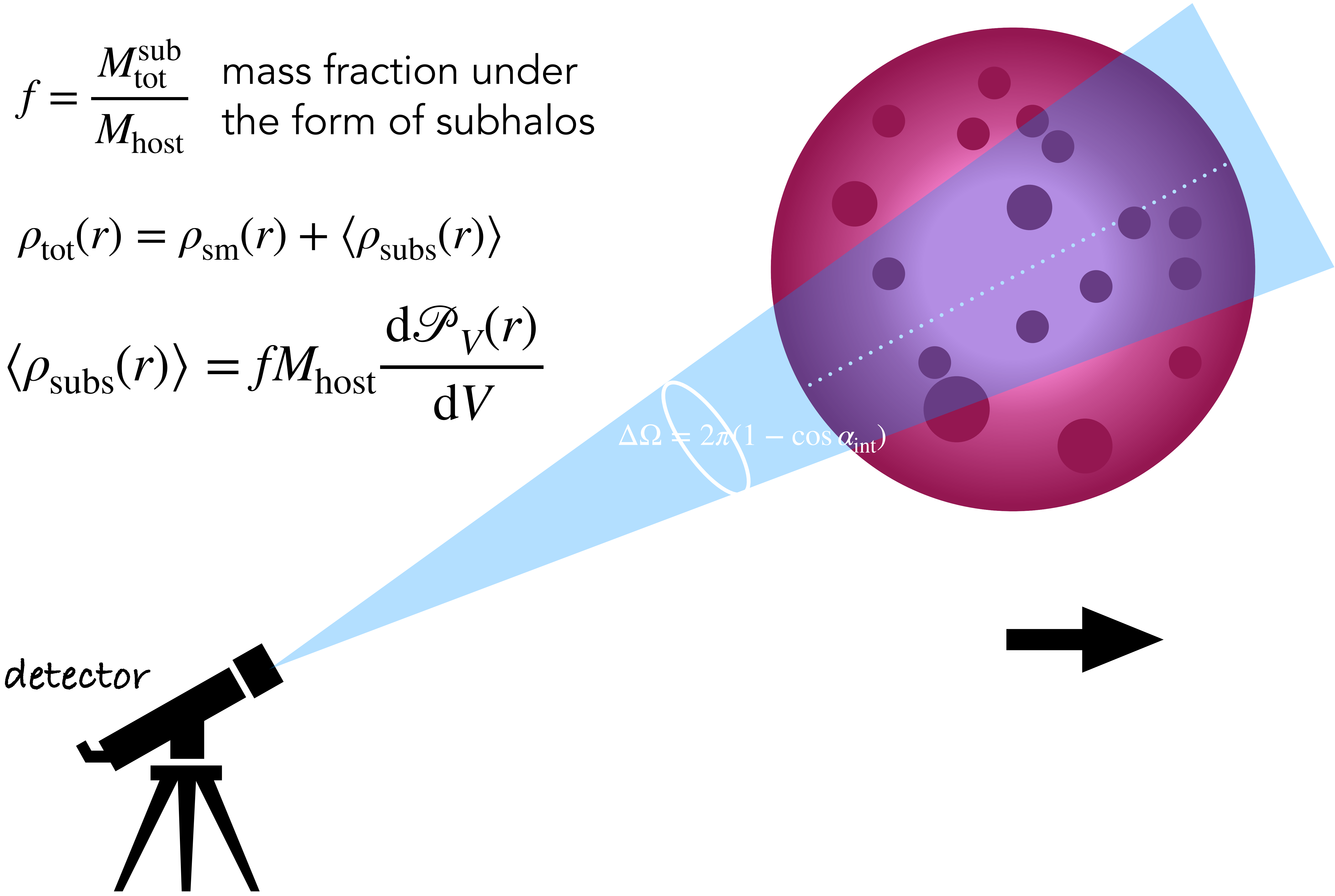

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The J-factor

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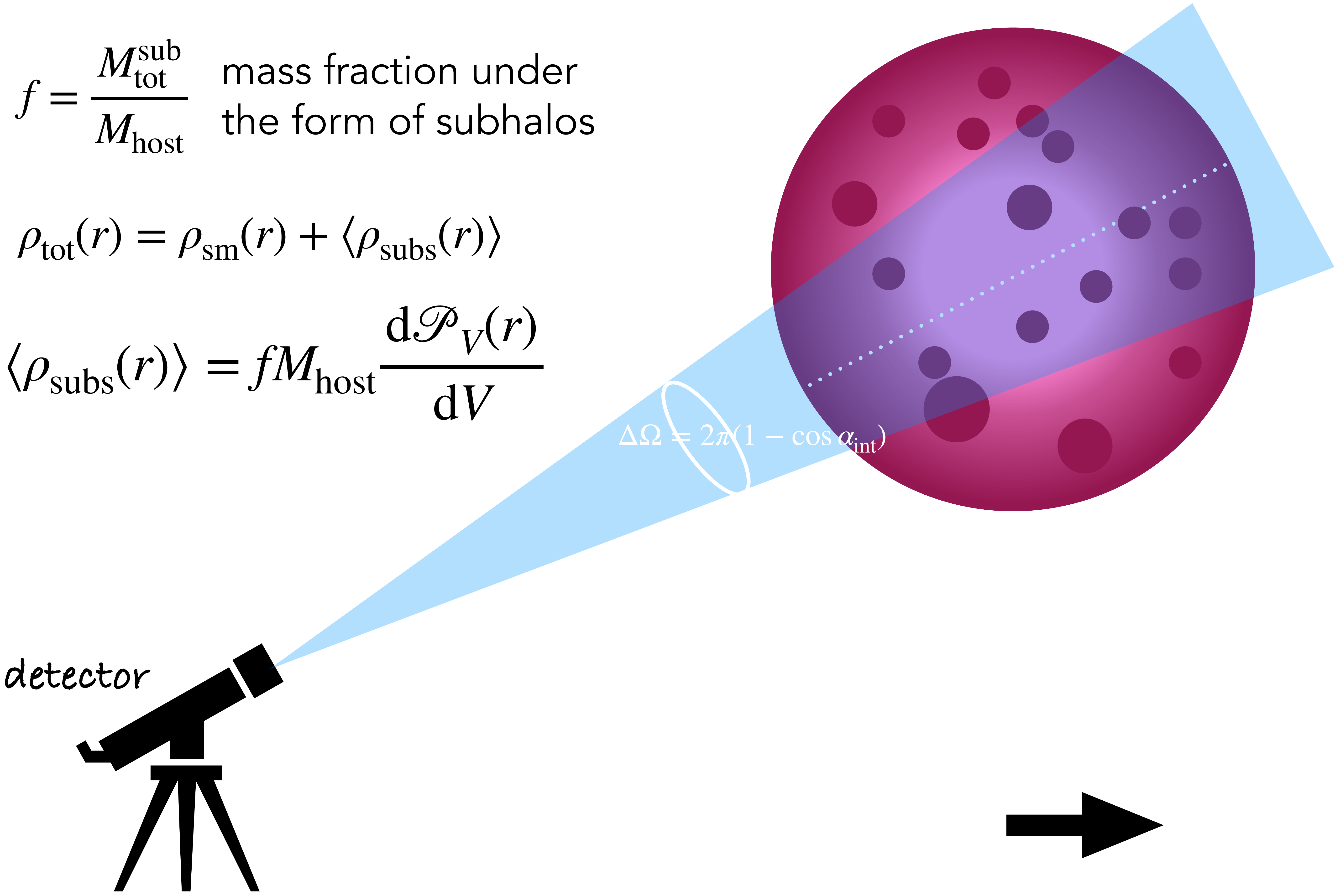

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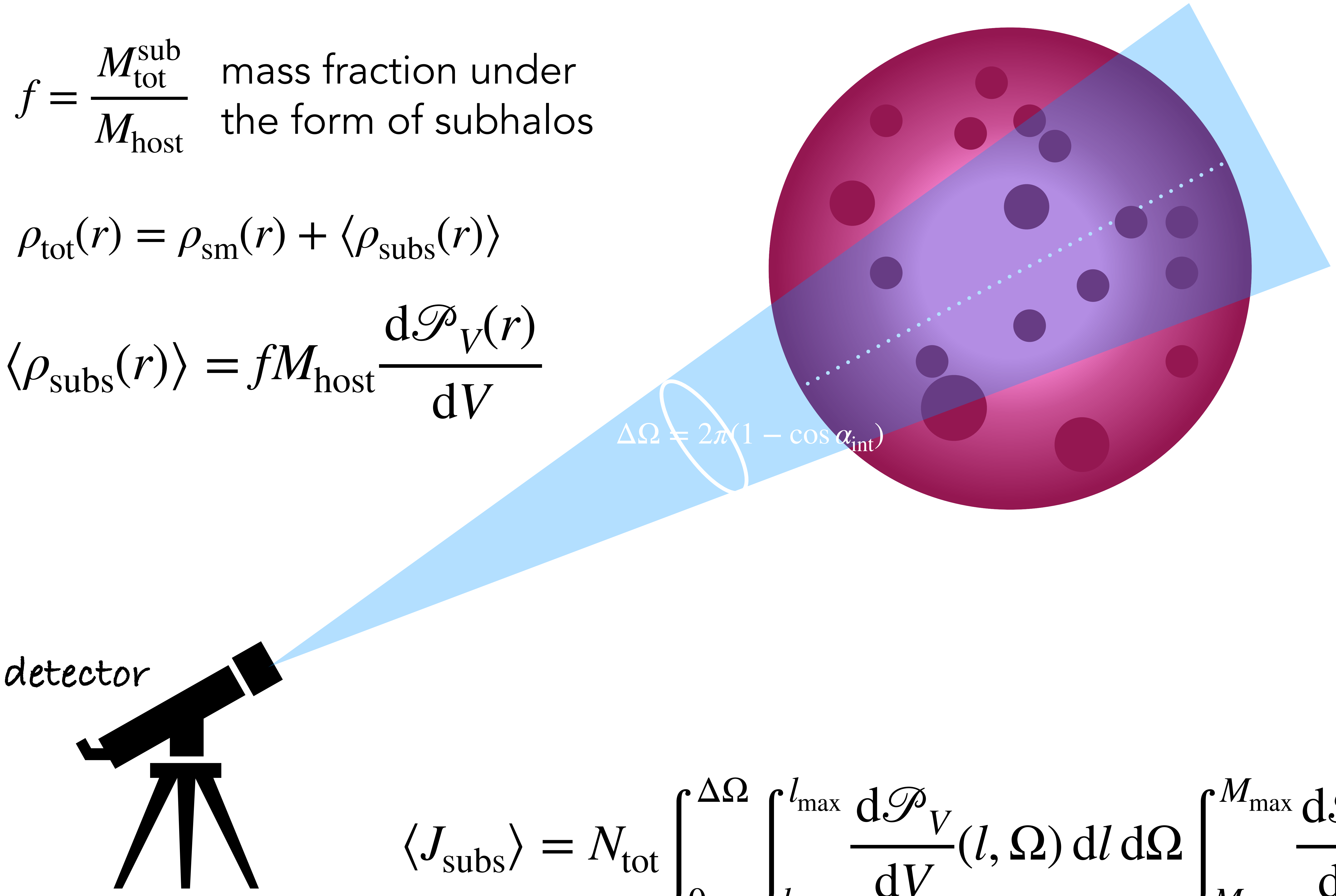

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$$\langle J_{subs} \rangle = N_{tot} \int_0^{\Delta\Omega} \int_{l_{min}}^{l_{max}} \frac{\mathrm{d}\mathscr{P}_V}{\mathrm{d}V}(l, \Omega)\, \mathrm{d}l\, \mathrm{d}\Omega \int_{M_{min}}^{M_{max}} \frac{\mathrm{d}\mathscr{P}_M}{\mathrm{d}M}(M) \times \int_{c_{min}(M)}^{c_{max}(M)} \frac{\mathrm{d}\mathscr{P}_c}{\mathrm{d}c}(c, M)\, \boxed{\mathscr{L}(M, c)}\, \mathrm{d}c\, \mathrm{d}M$$

single halo luminosity

The J-factor

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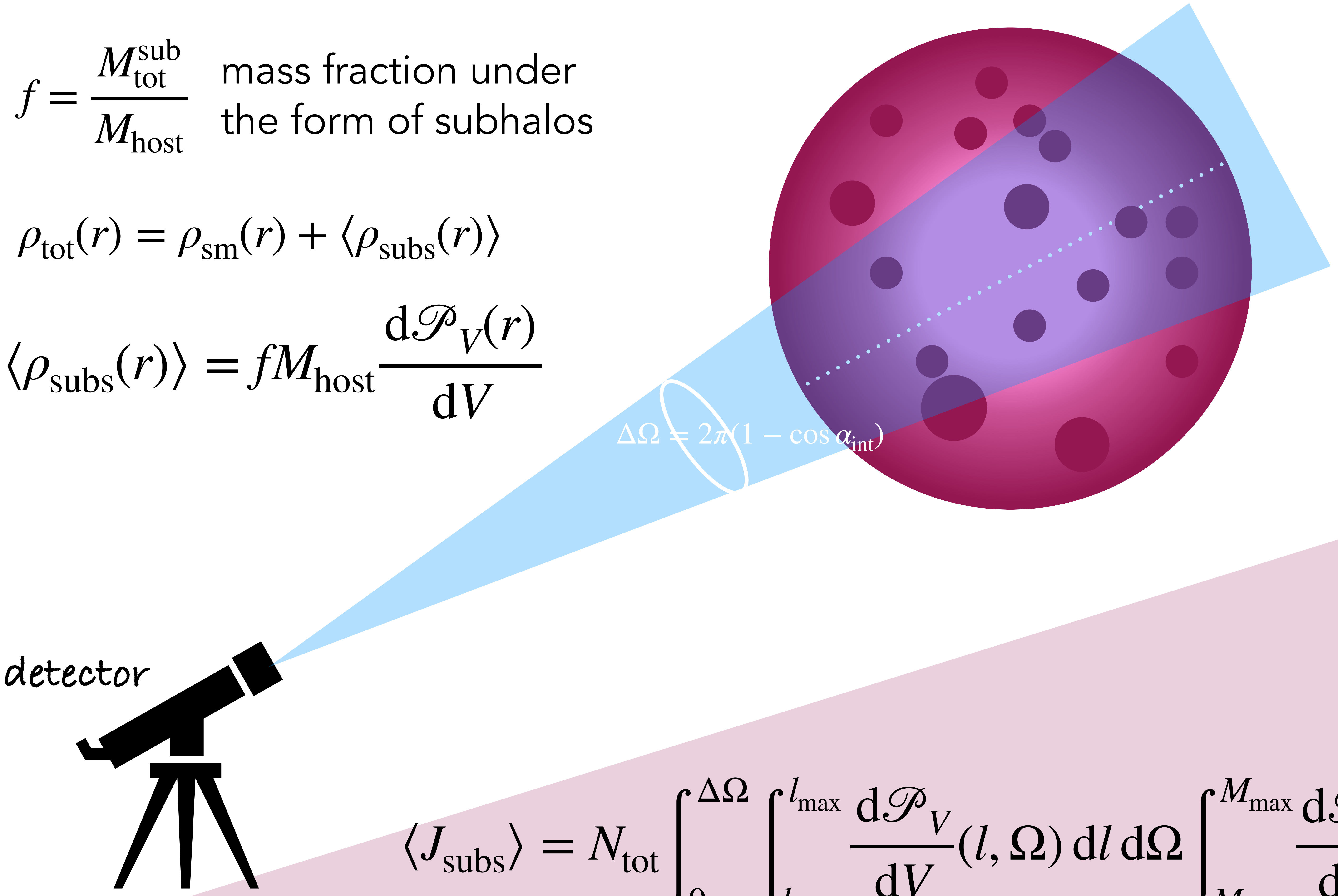


$$J = \int_0^{\Delta\Omega} \int_{\rm los} \left(\rho_{\rm sm} + \sum_i \rho_{\rm cl}^i \right)^2 dl d\Omega$$

expands into 3 terms

$$J_{\rm sm} \equiv \int_0^{\Delta\Omega} \int_{\rm los} \rho_{\rm sm}^2 dl d\Omega$$

$$\langle J_{\rm cross-prod} \rangle = 2 \int_0^{\Delta\Omega} \int_{\rm los} \rho_{\rm sm} \langle \rho_{\rm subs} \rangle dl d\Omega$$

$$\langle J_{\rm subs} \rangle = N_{\rm tot} \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \frac{\mathrm{d}\mathscr{P}_V}{\mathrm{d}V}(l, \Omega)\, \mathrm{d}l\, \mathrm{d}\Omega \int_{M_{\rm min}}^{M_{\rm max}} \frac{\mathrm{d}\mathscr{P}_M}{\mathrm{d}M}(M) \times \int_{c_{\rm min}(M)}^{c_{\rm max}(M)} \frac{\mathrm{d}\mathscr{P}_c}{\mathrm{d}c}(c, M)\, \boxed{\mathscr{L}(M, c)}\, \mathrm{d}c\, \mathrm{d}M$$

single halo luminosity

The J-factor

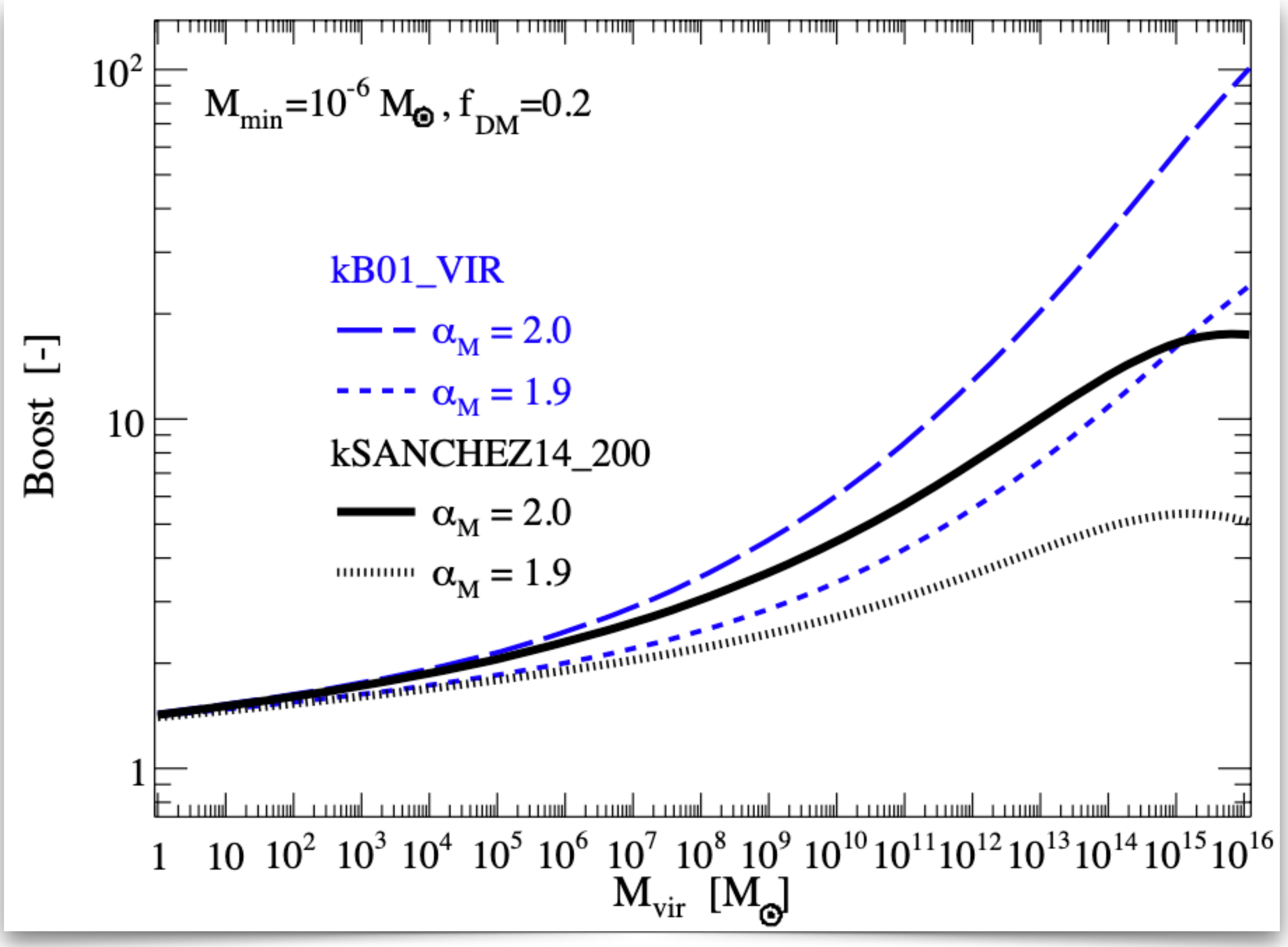
Substructure boost

$$\text{Boost} = \frac{J_{\text{sm}} + J_{\text{subs}} + J_{\text{crossprod}}}{J_{\text{no-subs}}}$$

Boost sensitive to subhalo

- spatial distribution
- mass distribution
- mass-concentration relation + distribution
- inner density profile
- mass range
- distance from halo centre, integration angle

Bonnivard et al. (2016)



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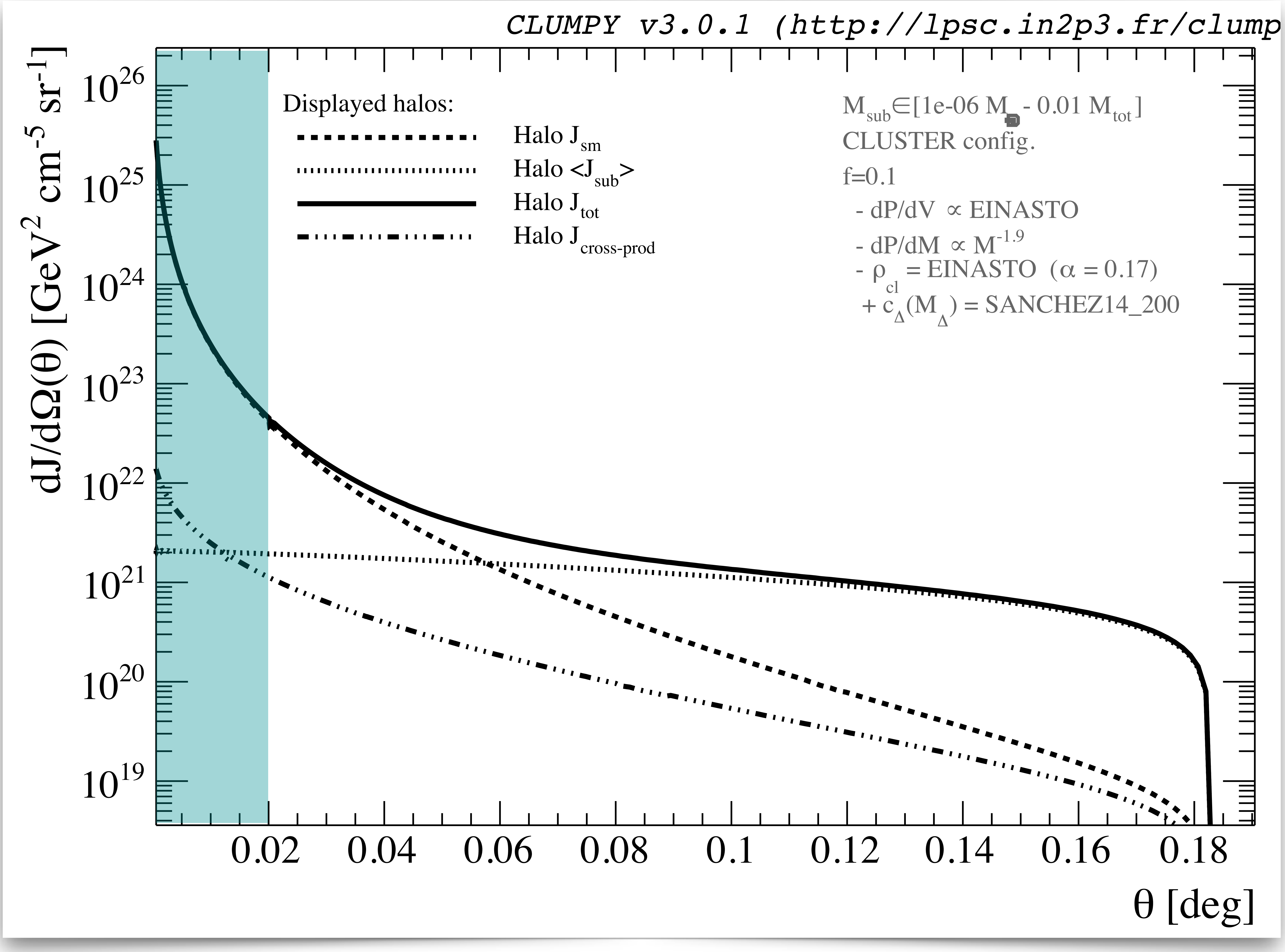

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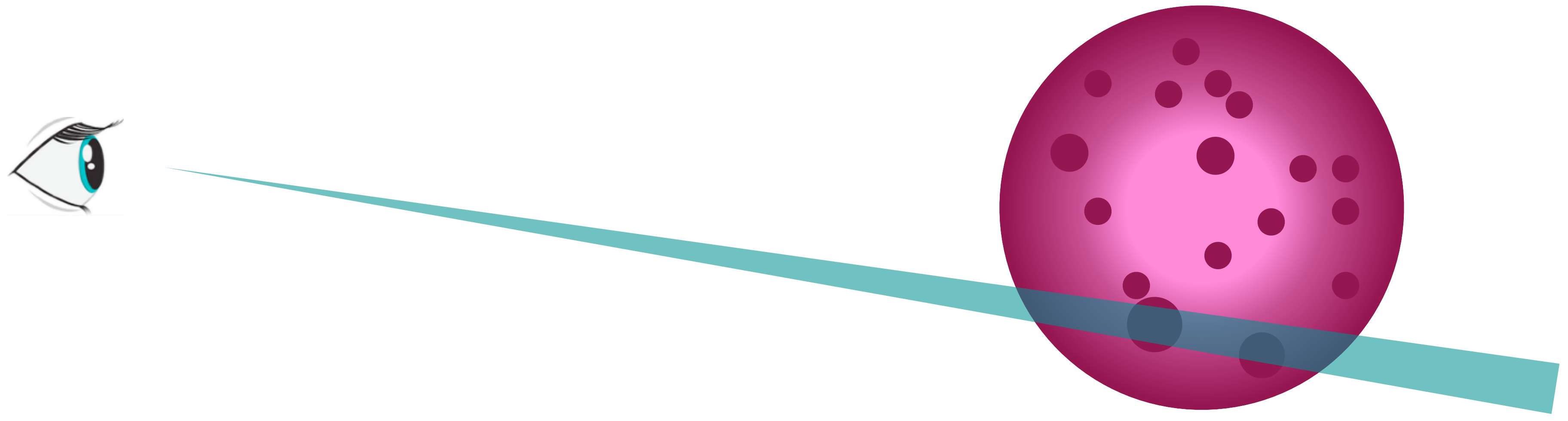

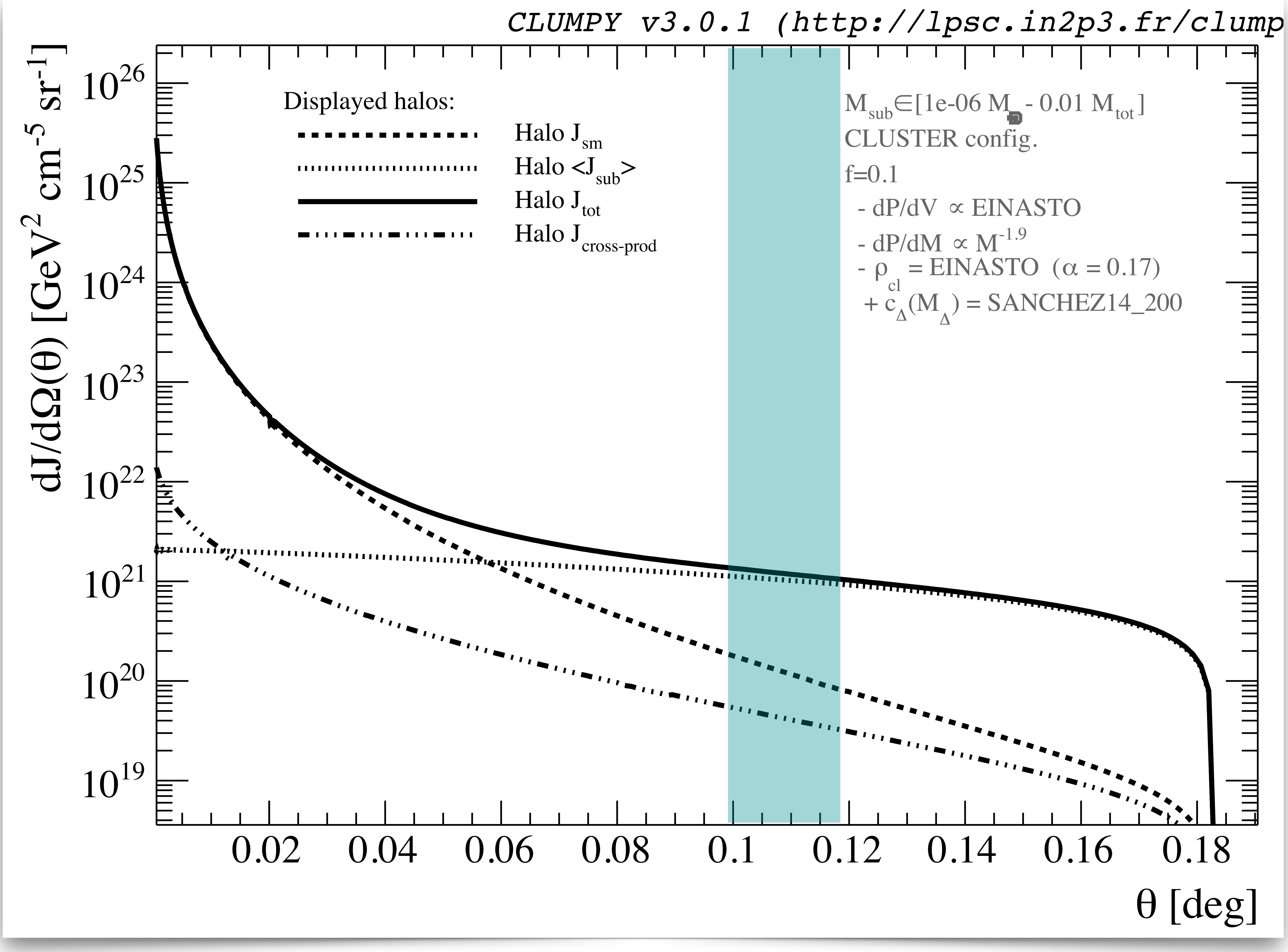

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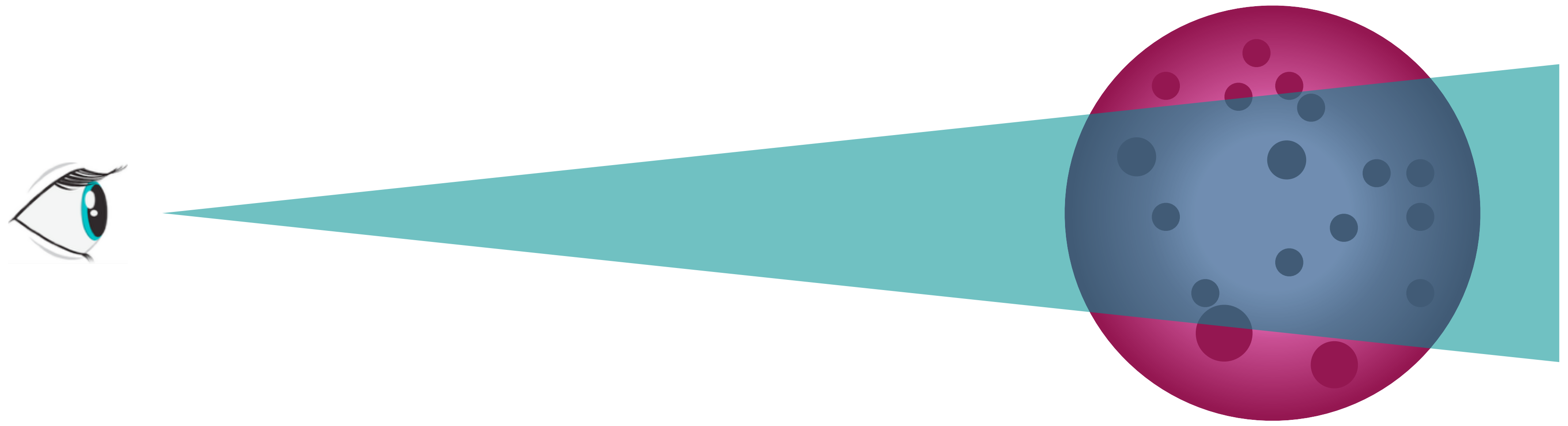
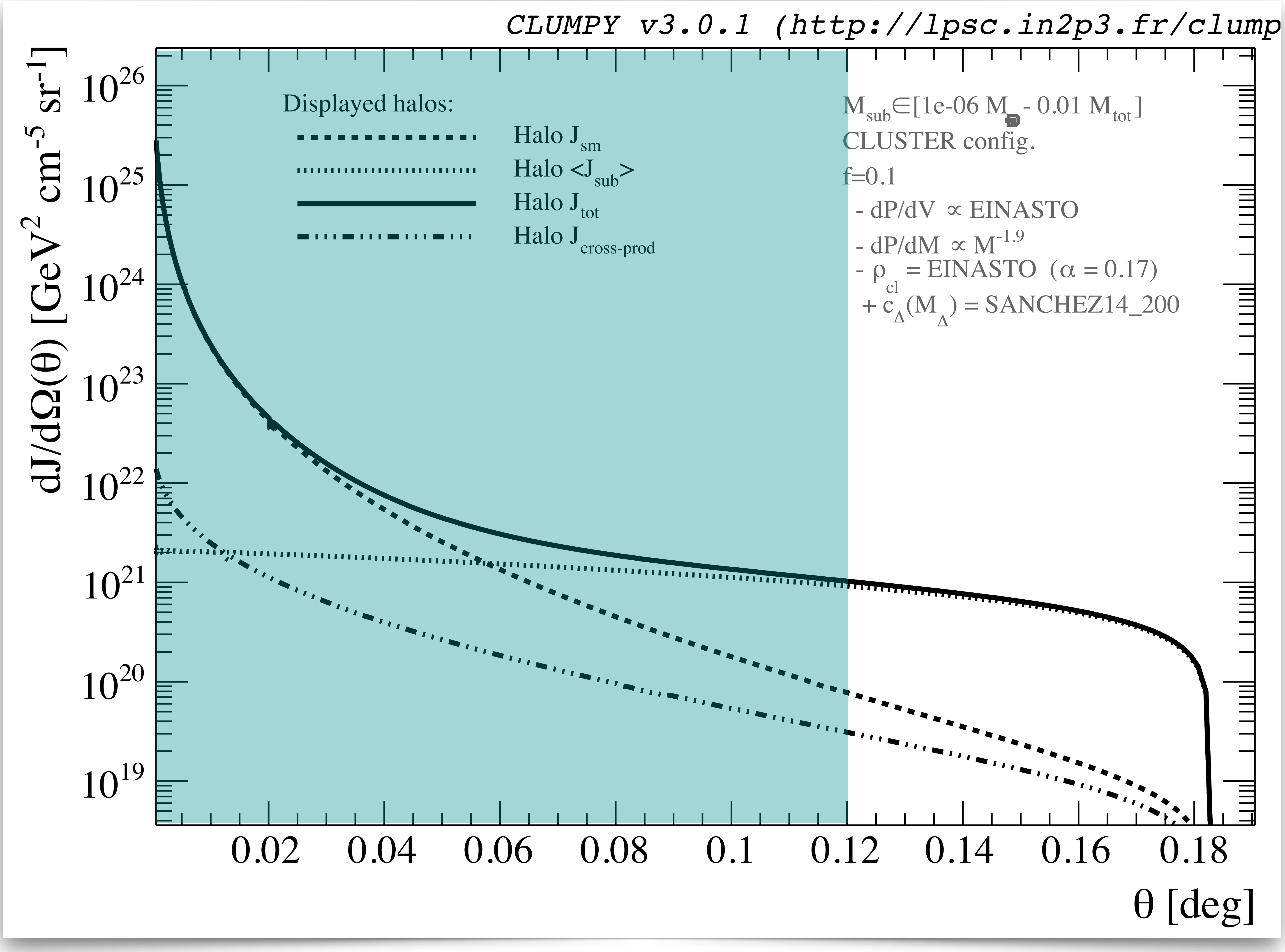




The J-factor

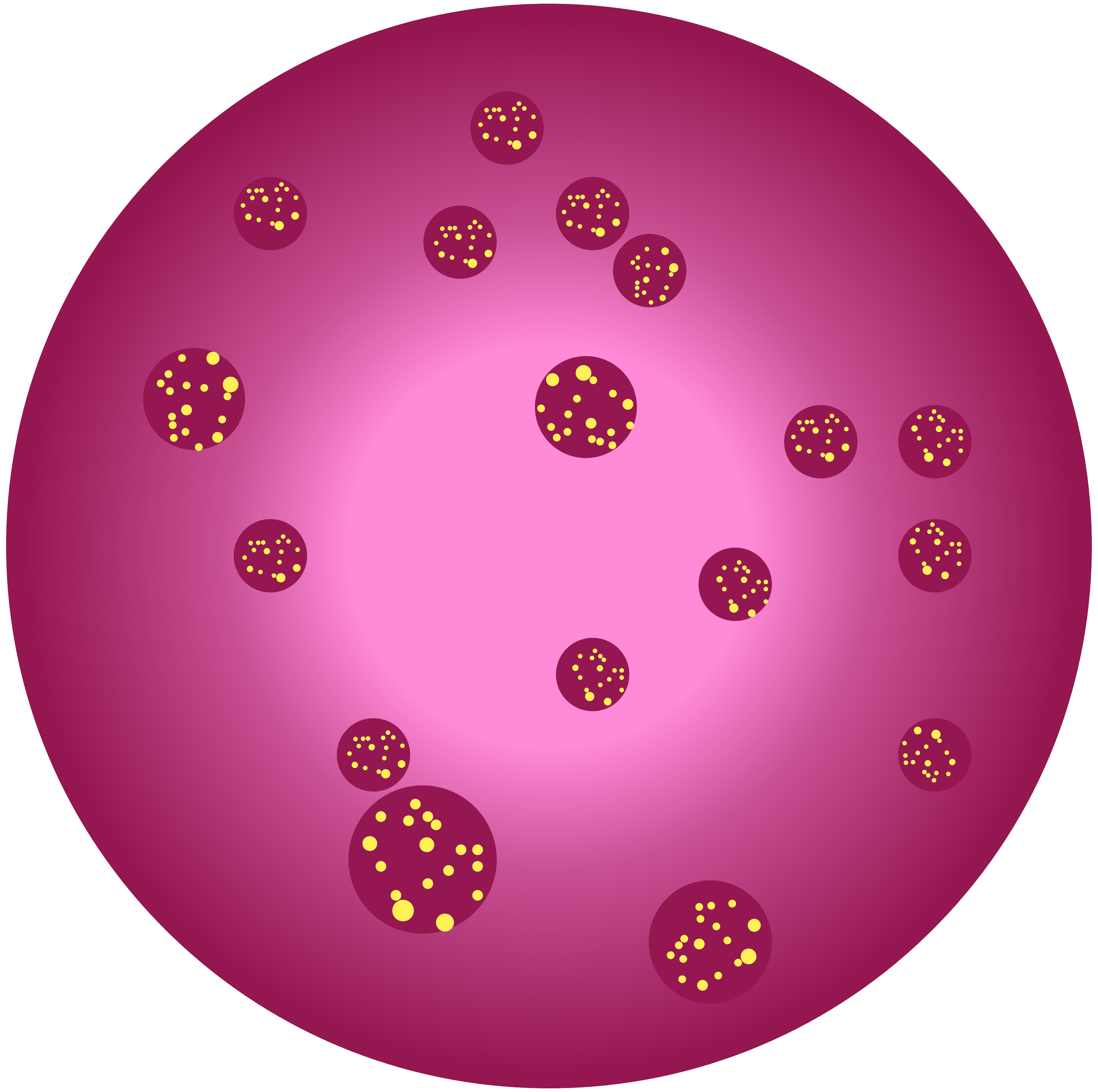
Multi-level boost factor?

So far, we considered one level of substructure within the parent halo. But hierarchical formation: haloes in haloes in haloes, etc…

Considering "point-like" subhalos, show that the 'boosted' luminosity for n levels of substructures can be recursively computed as

$$\mathscr{L}_n(M) = \mathscr{L}_{\rm sm}(M) + \mathscr{L}_{\rm crossprod}(M)$$
$$+N_{\rm tot}(M)\int_{M_{\rm min}}^{M_{\rm max}(M)} \mathscr{L}_{n-1}(M')\frac{d\mathscr{P}_M}{dM'}(M')\, dM'$$

with $\mathscr{L}_0(M,c) \equiv \int_{V_{\rm cl}} \left[\rho_{\rm cl}^{\rm tot}(M,c)\right]^2 dV$



The J-factor

Multi-level boost factor?

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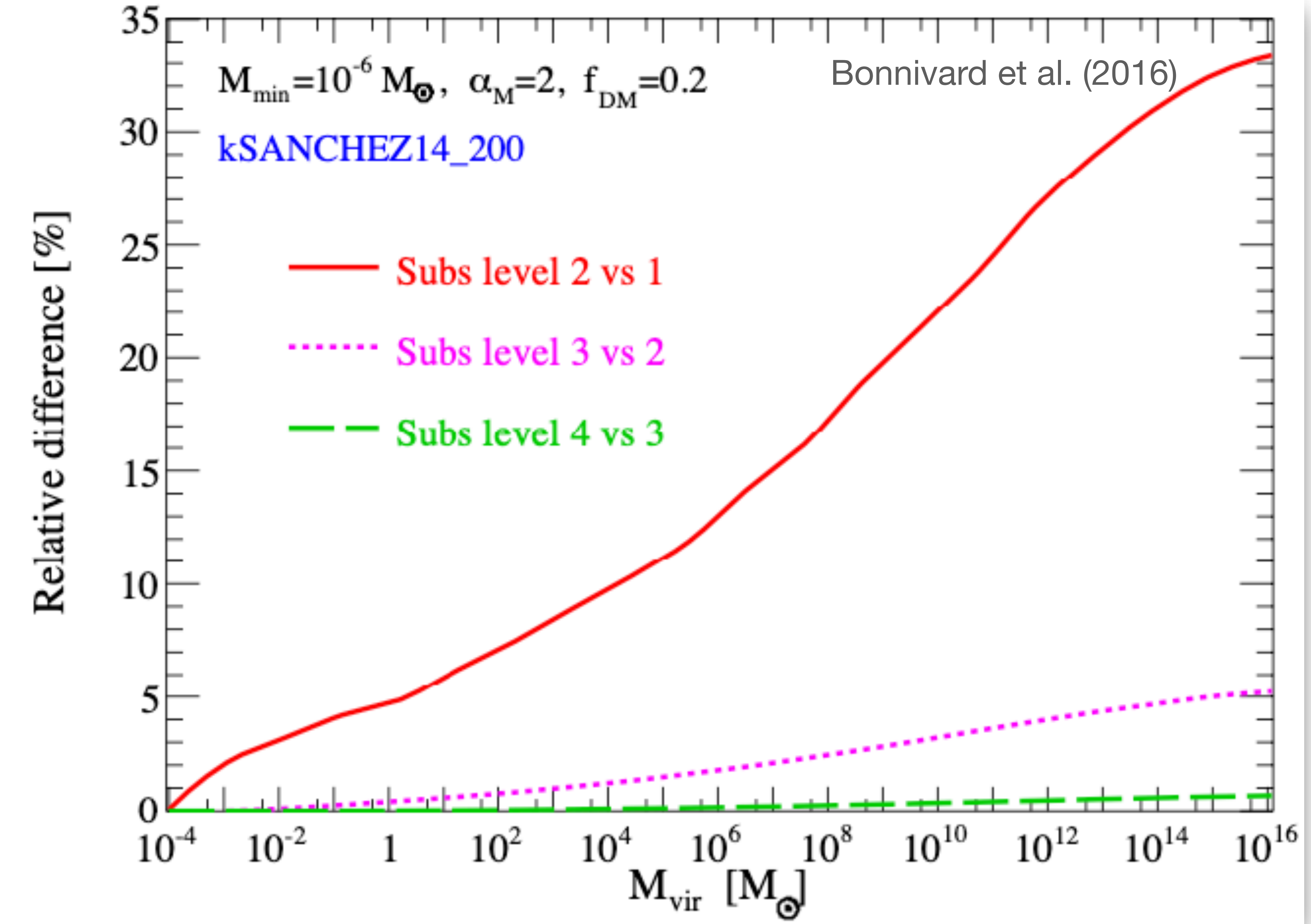

No much gain to go beyond n=1 or 2 and computationally expensive…

The J and D factors

Recap

$$J(\psi, \theta, \alpha_{\text{int}}) = \int_0^{2\pi} d\beta \int_0^{\alpha_{\text{int}}} \sin\alpha d\alpha \int_{\text{los}} \rho^2(l, \alpha, \beta; \psi, \theta) dl$$

- Need a robust estimation of the J-factor (or D-factor) to constrain the dark matter properties
  - ✳ DM mass - $\langle \sigma v \rangle$ for annihilation
  - ✳ DM mass - lifetime for decay
- Modeling of the DM distribution generally assumes spherical symmetry and
  - ✳ a smooth DM component
  - ✳ a subhalo population that may boost the annihilation signal
- Determination of the smooth and substructure component generally relies on
  - ✳ results from numerical simulations (DM-only or hydro)
  - ✳ and/or observational properties of the systems under scrutiny

} Second half of the lecture 😅

The J and D factors

Recap

$$D(\psi, \theta, \alpha_{\rm int}) = \int_0^{2\pi} d\beta \int_0^{\alpha_{\rm int}} \sin \alpha d\alpha \int_{\rm los} \rho(l, \alpha, \beta; \psi, \theta) dl$$

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Targets for indirect detection in gamma-rays?

Targets

What makes a good target for indirect detection in γ-rays?

- it is massive/dense (and we have means to evaluate its density) [Remember $J_{\text{point}} \sim \frac{M^2}{d^2 V}$]
- it is located close to us
- it has little astrophysical gamma-ray background
- optional: it is visible at other wavelengths [so we know where to look]

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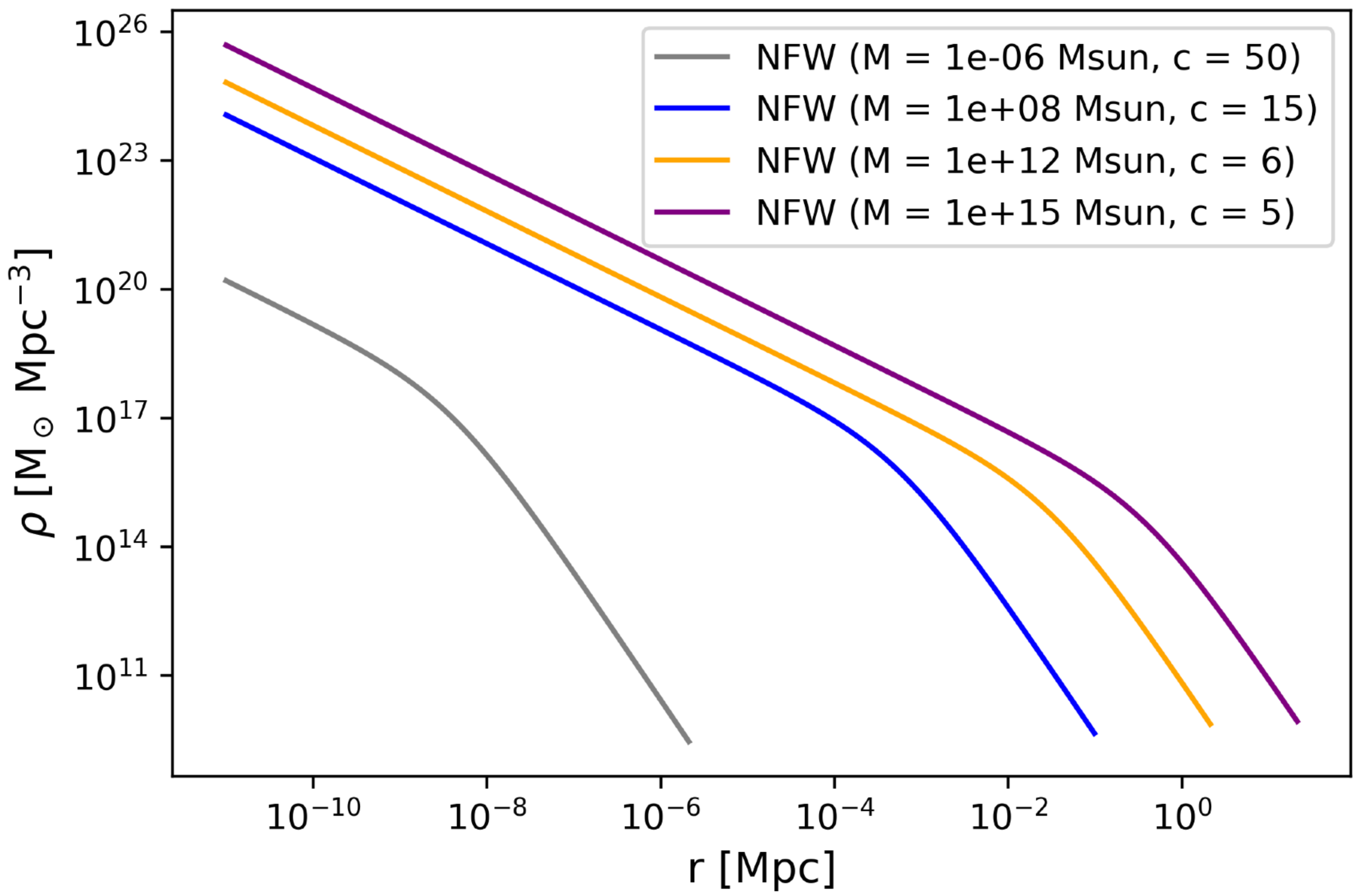

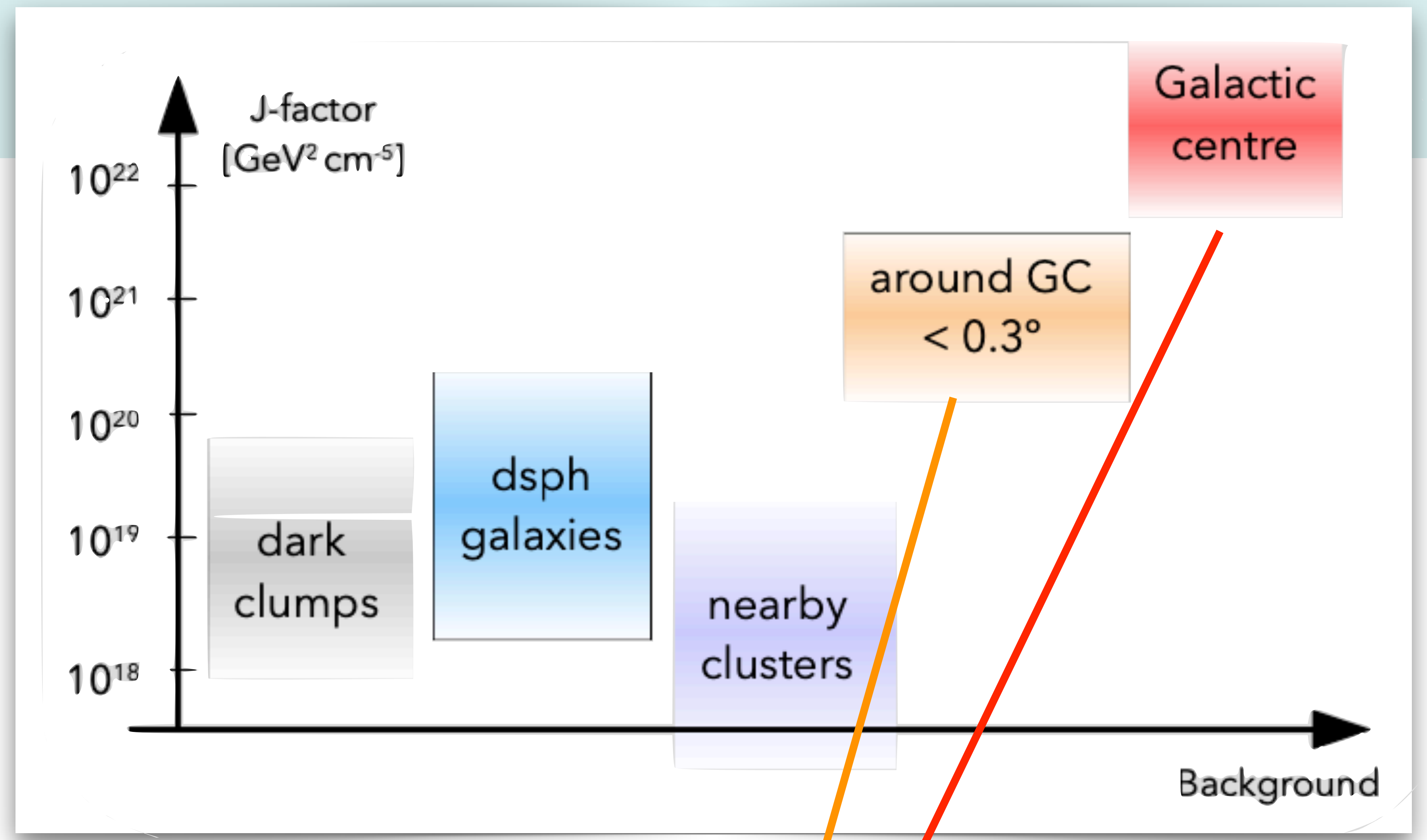

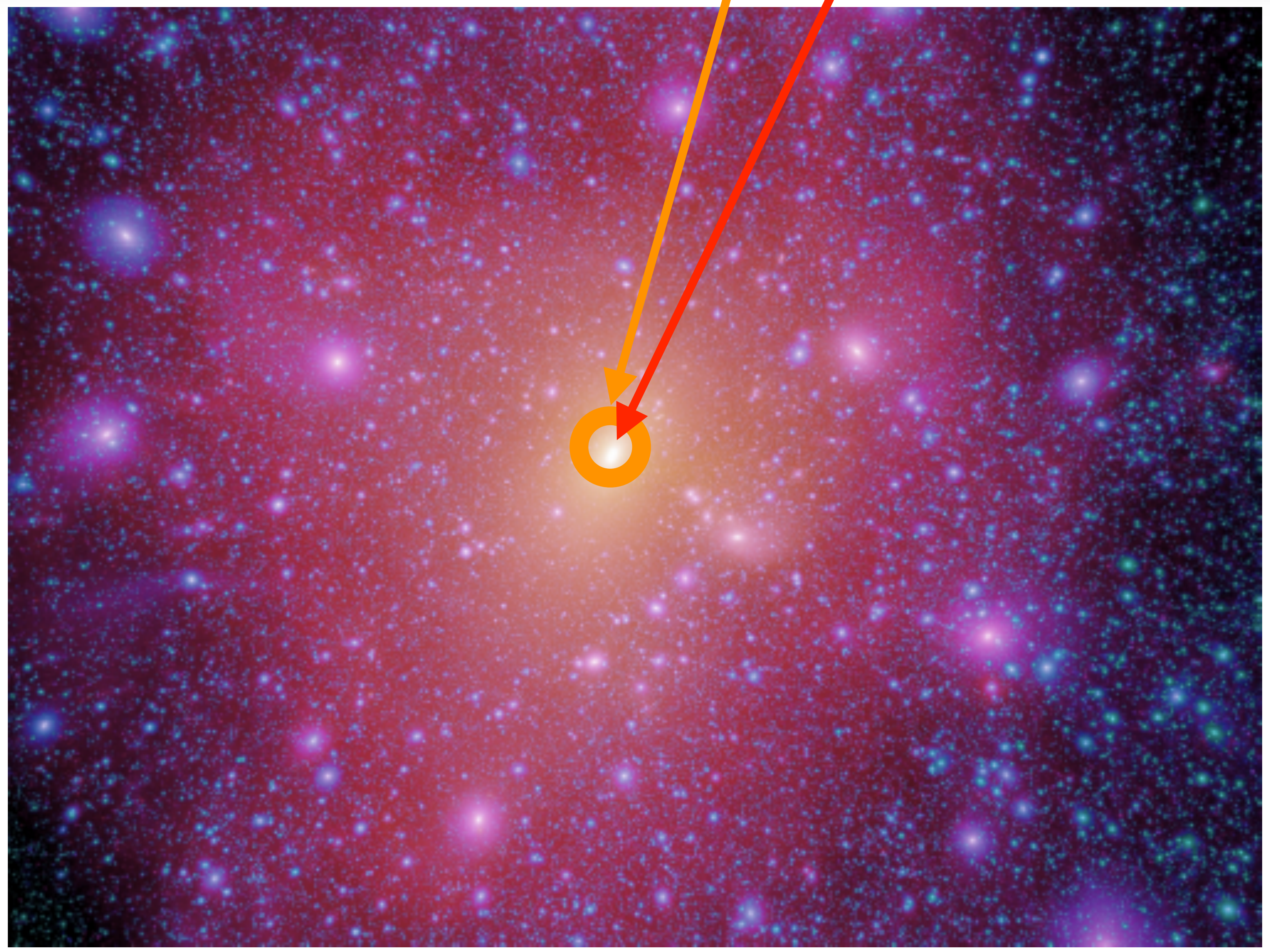

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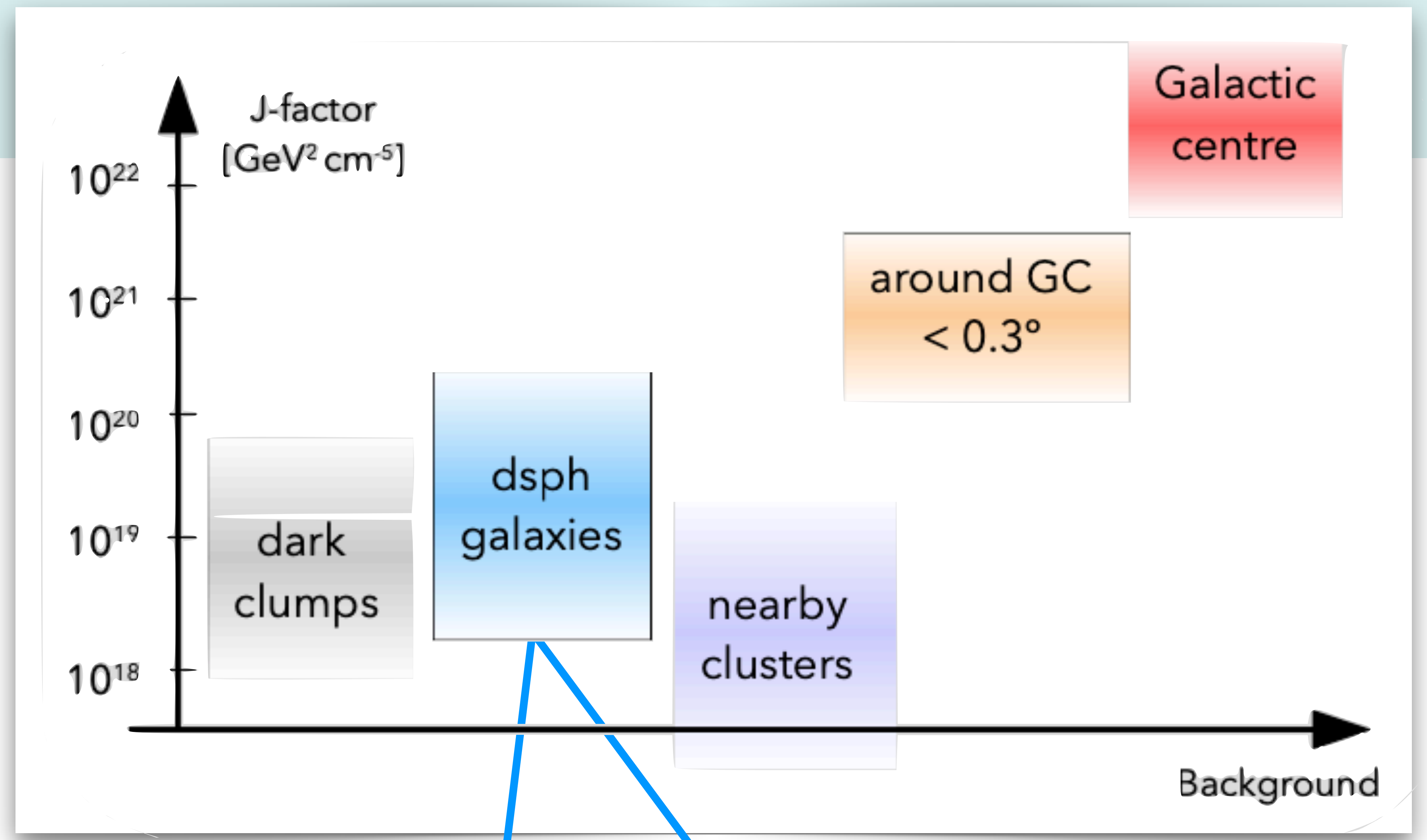

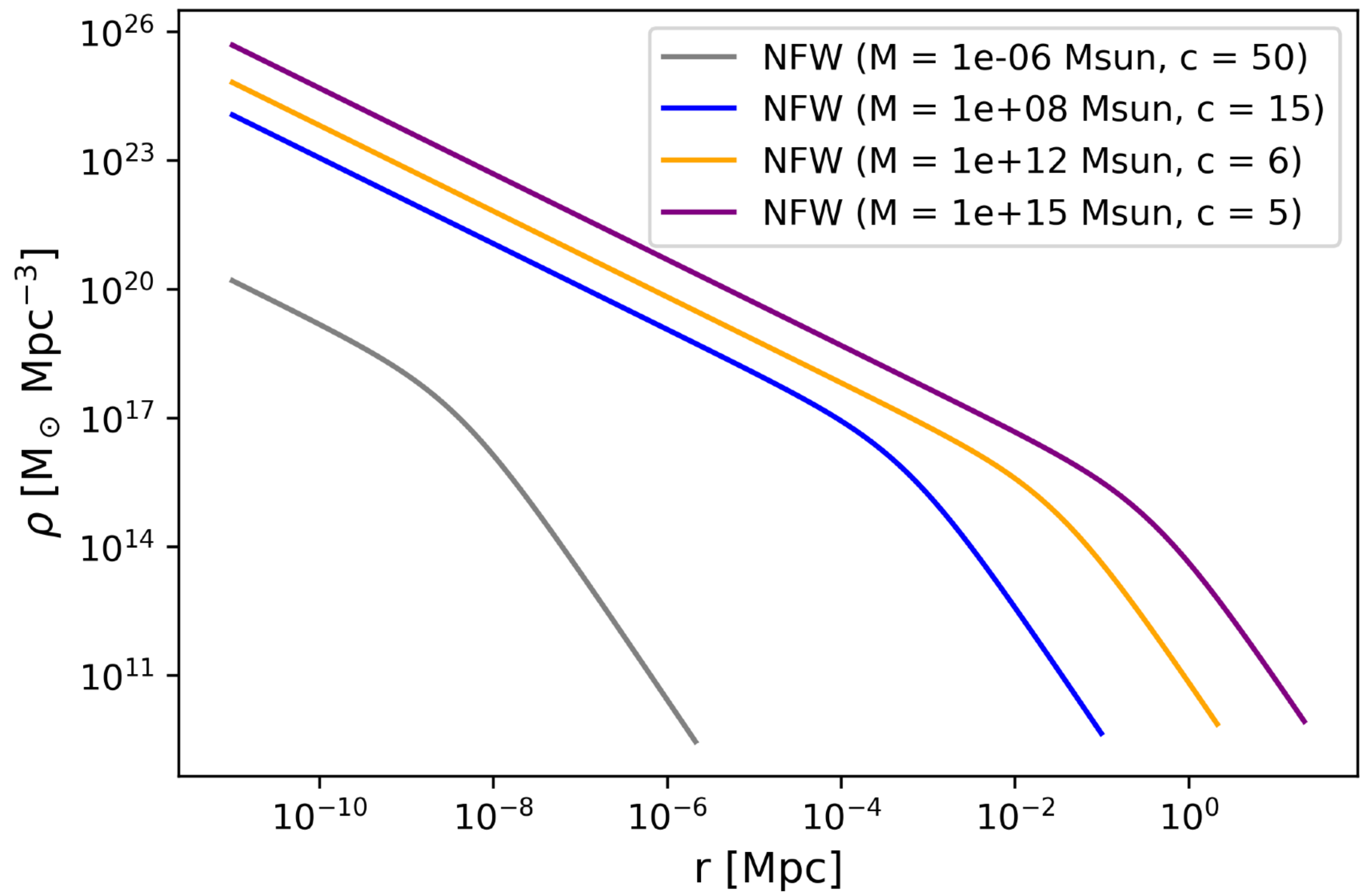

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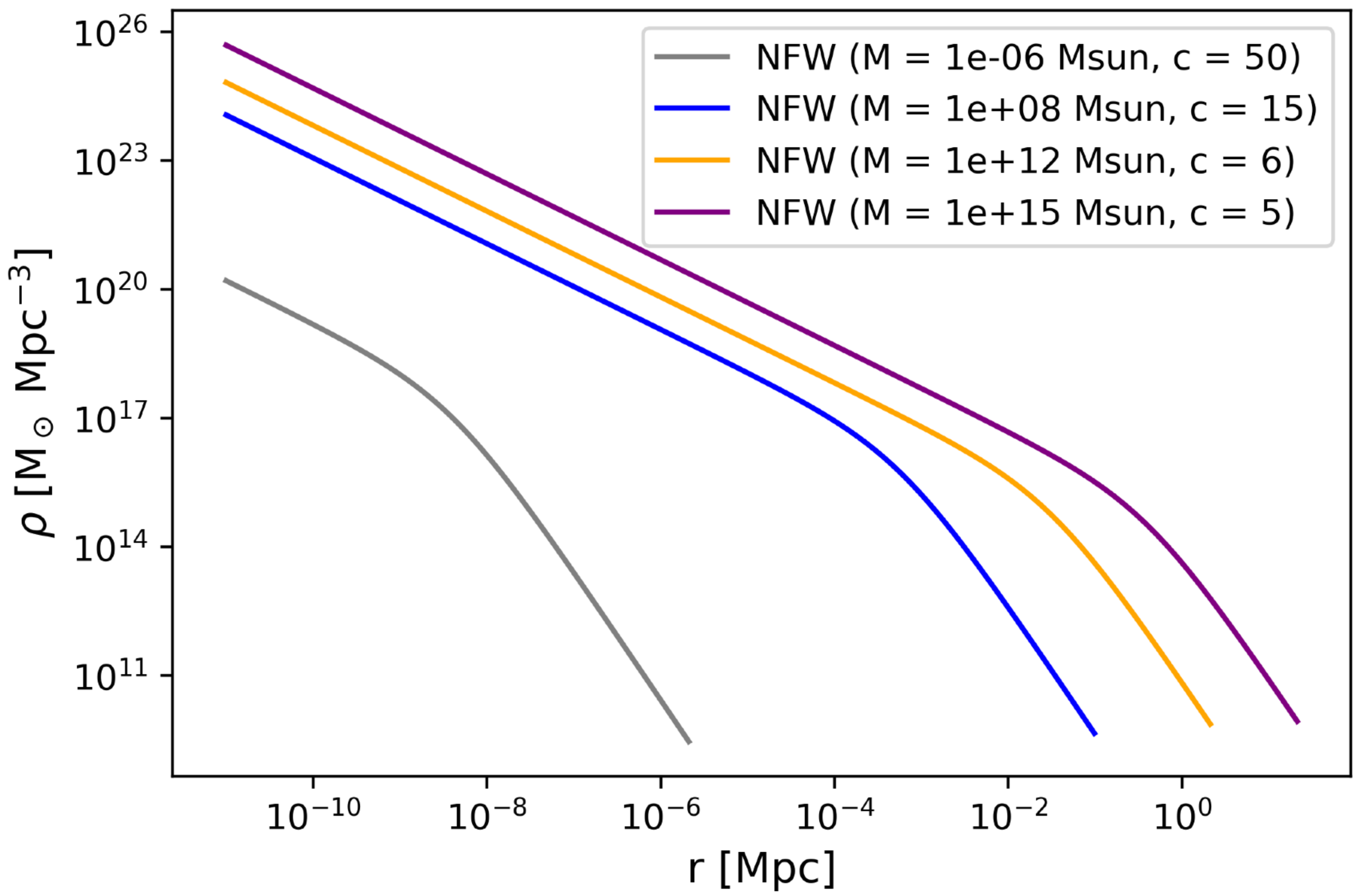

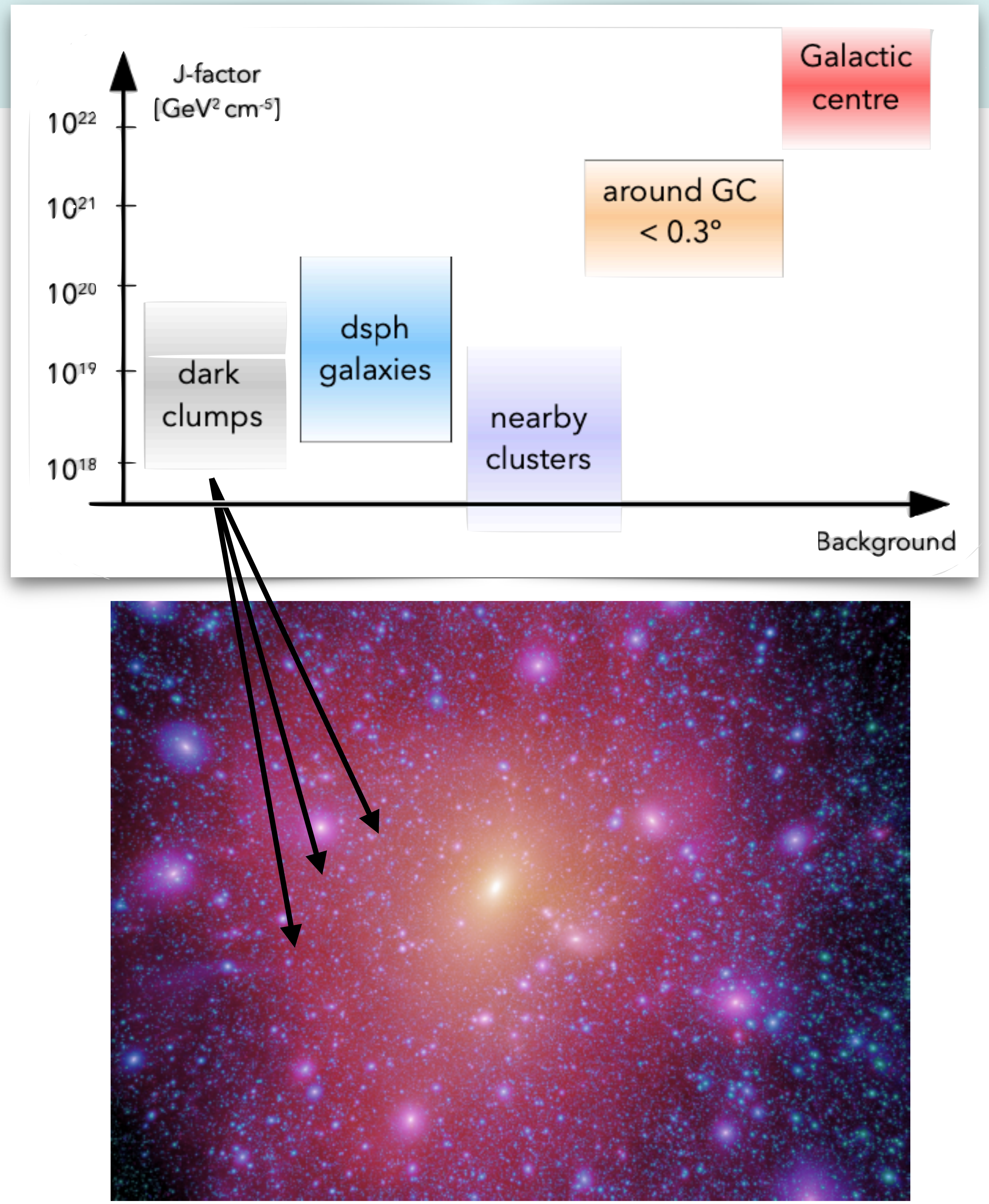

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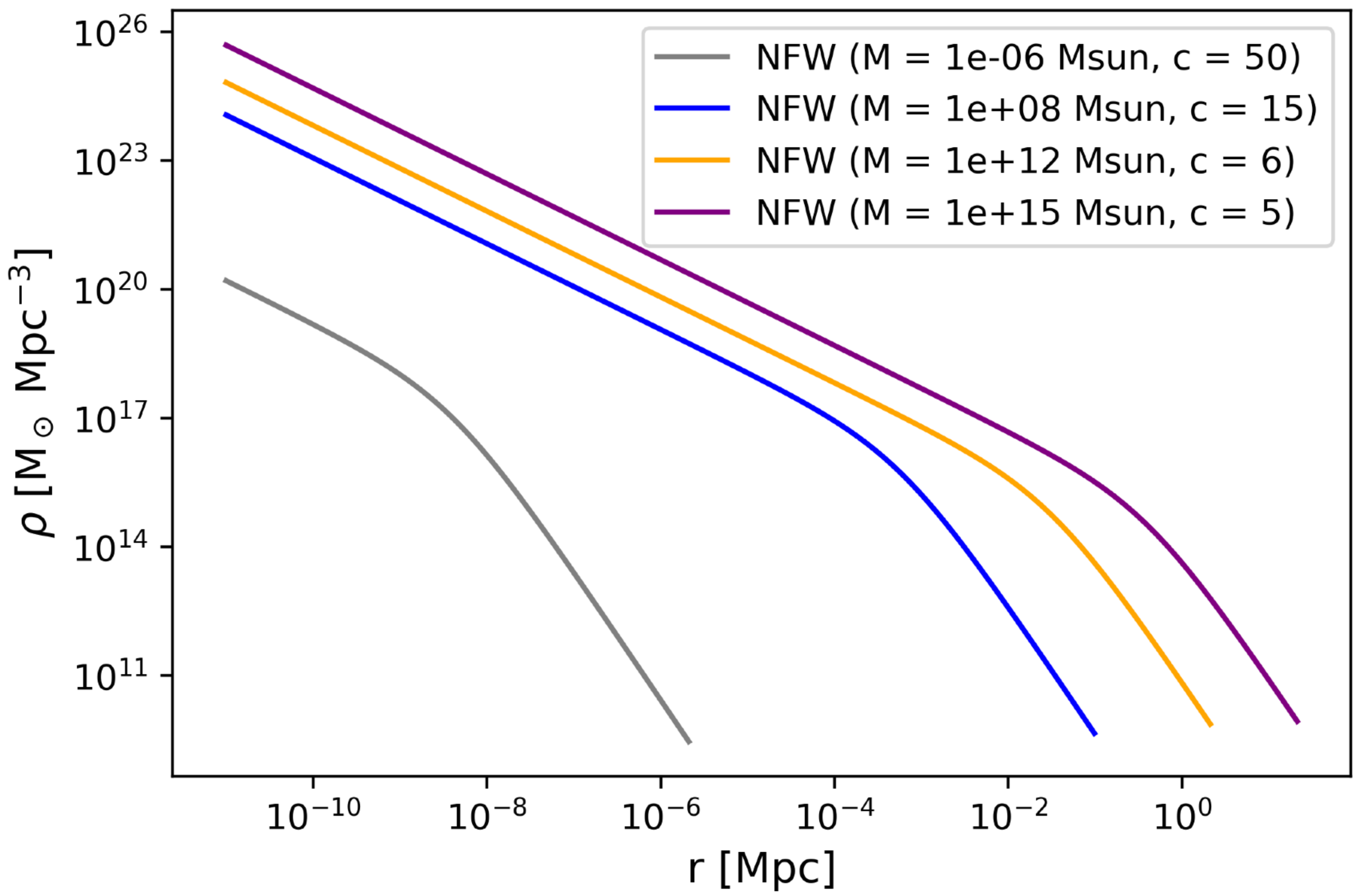

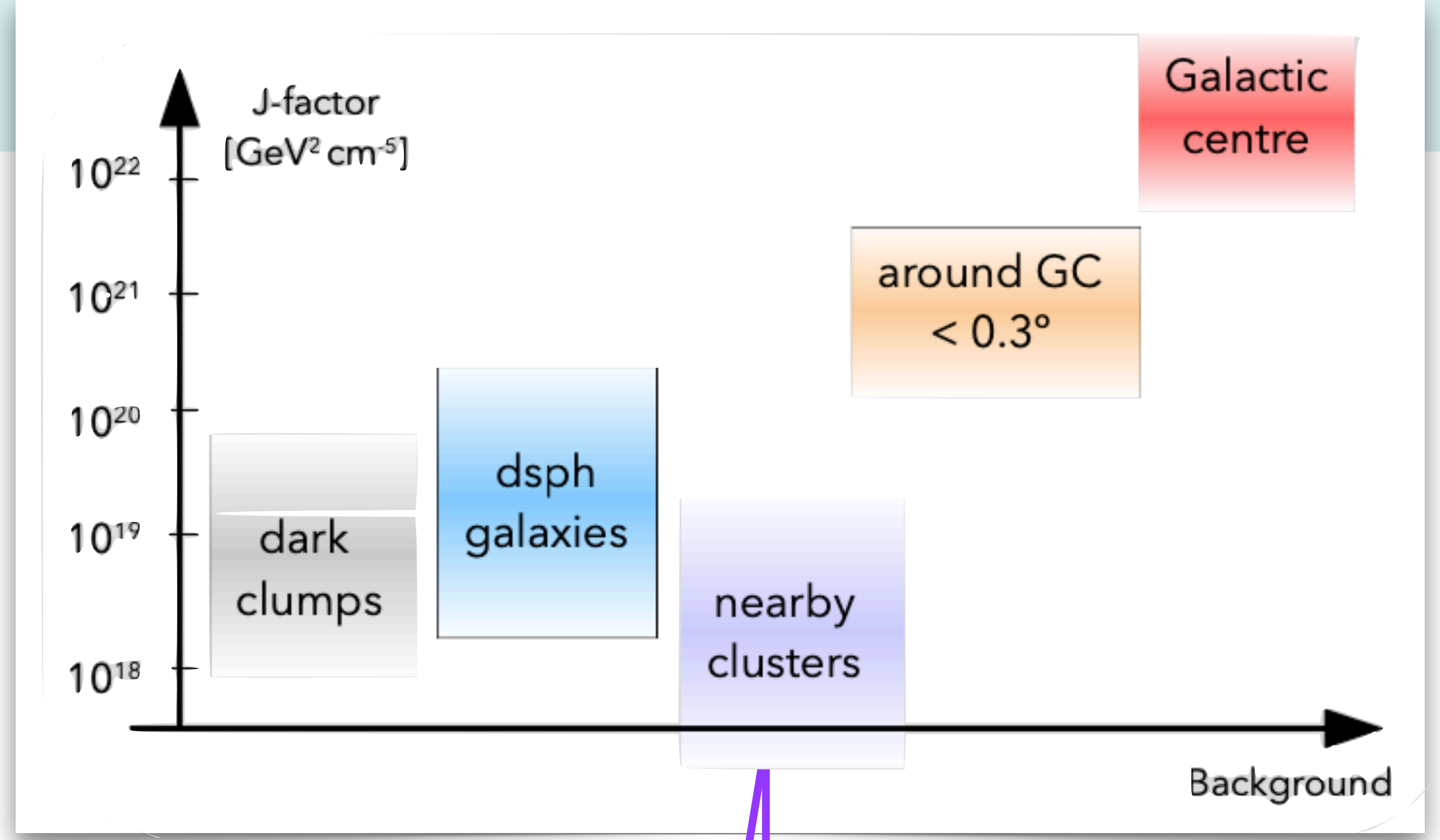

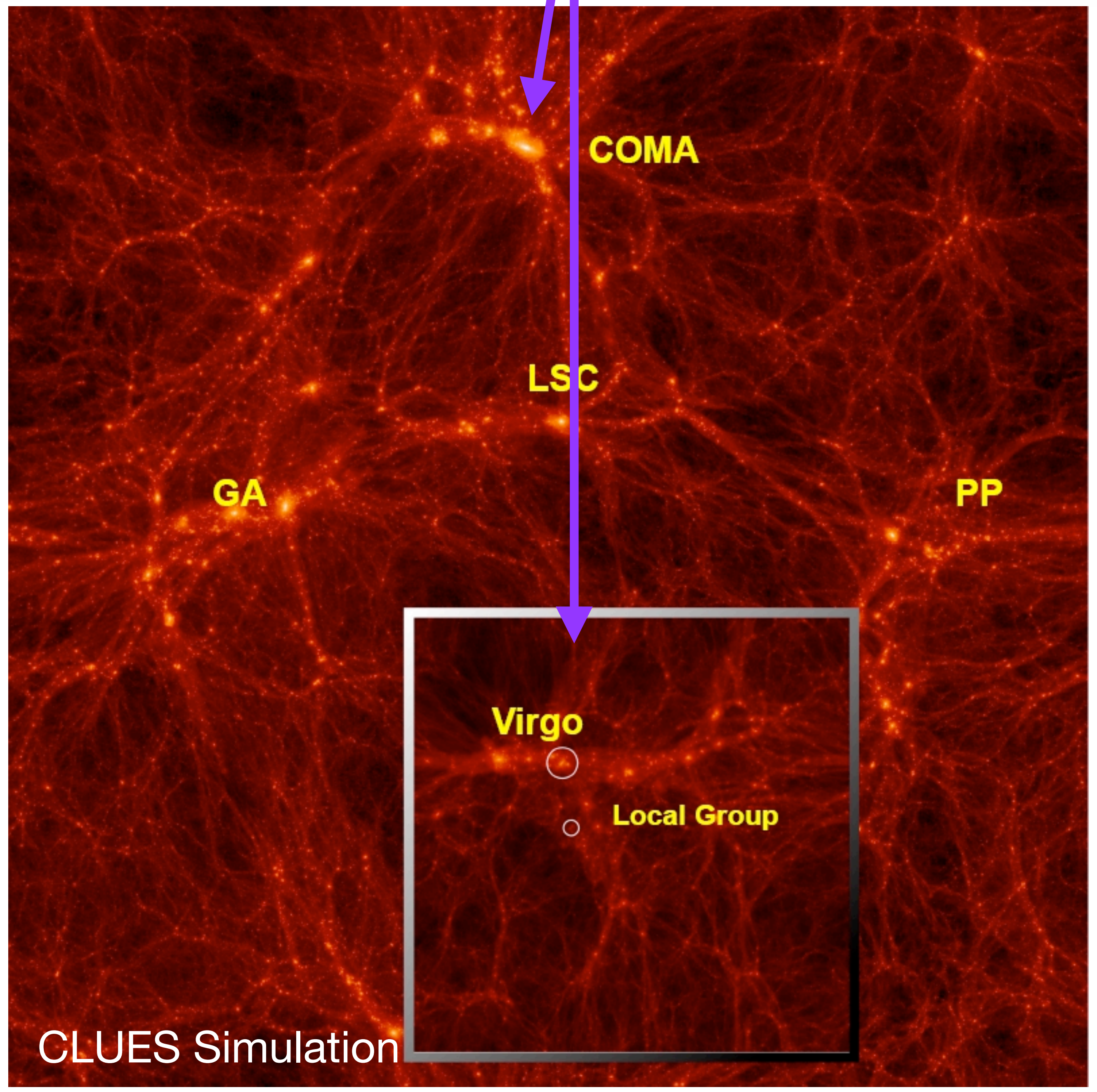

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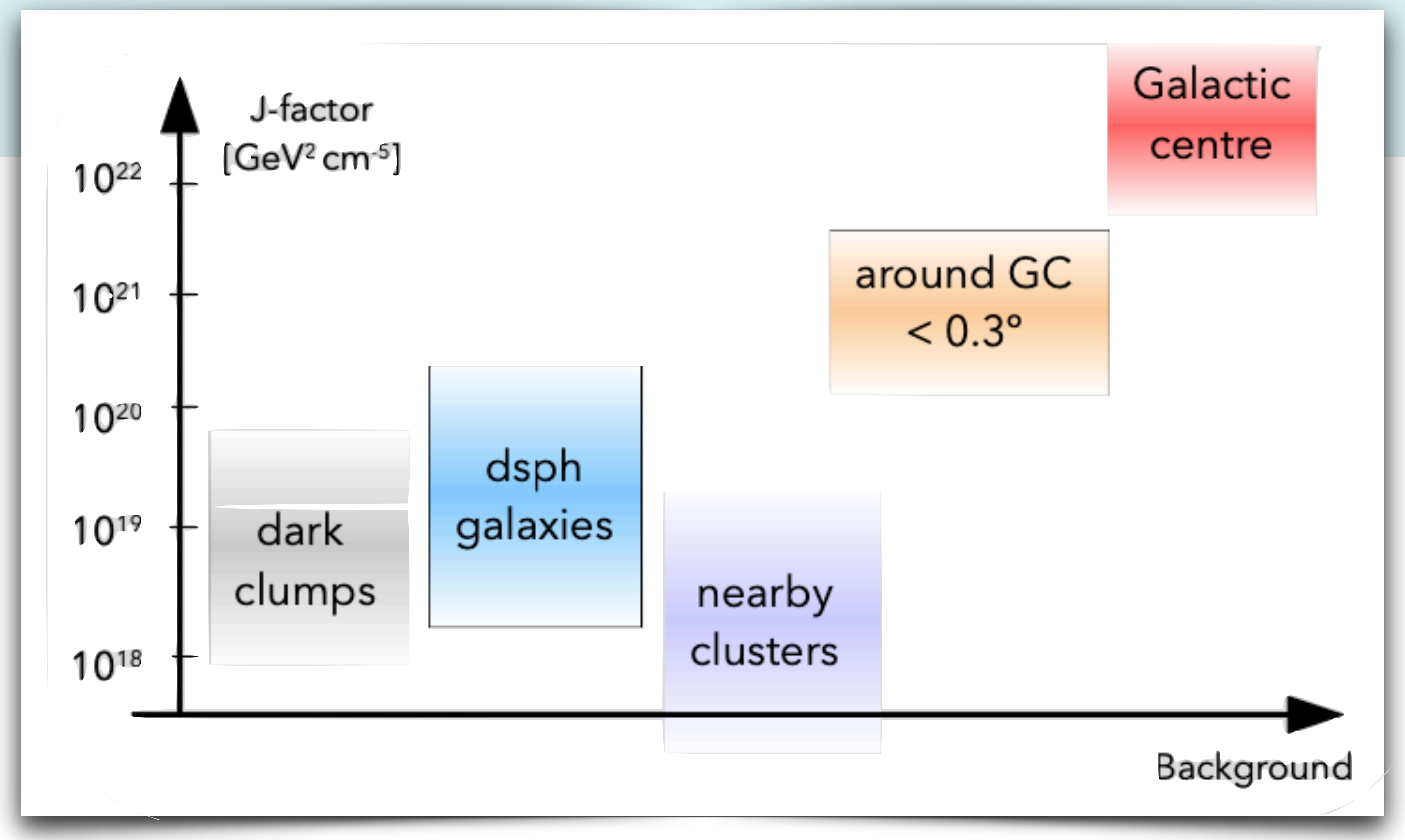
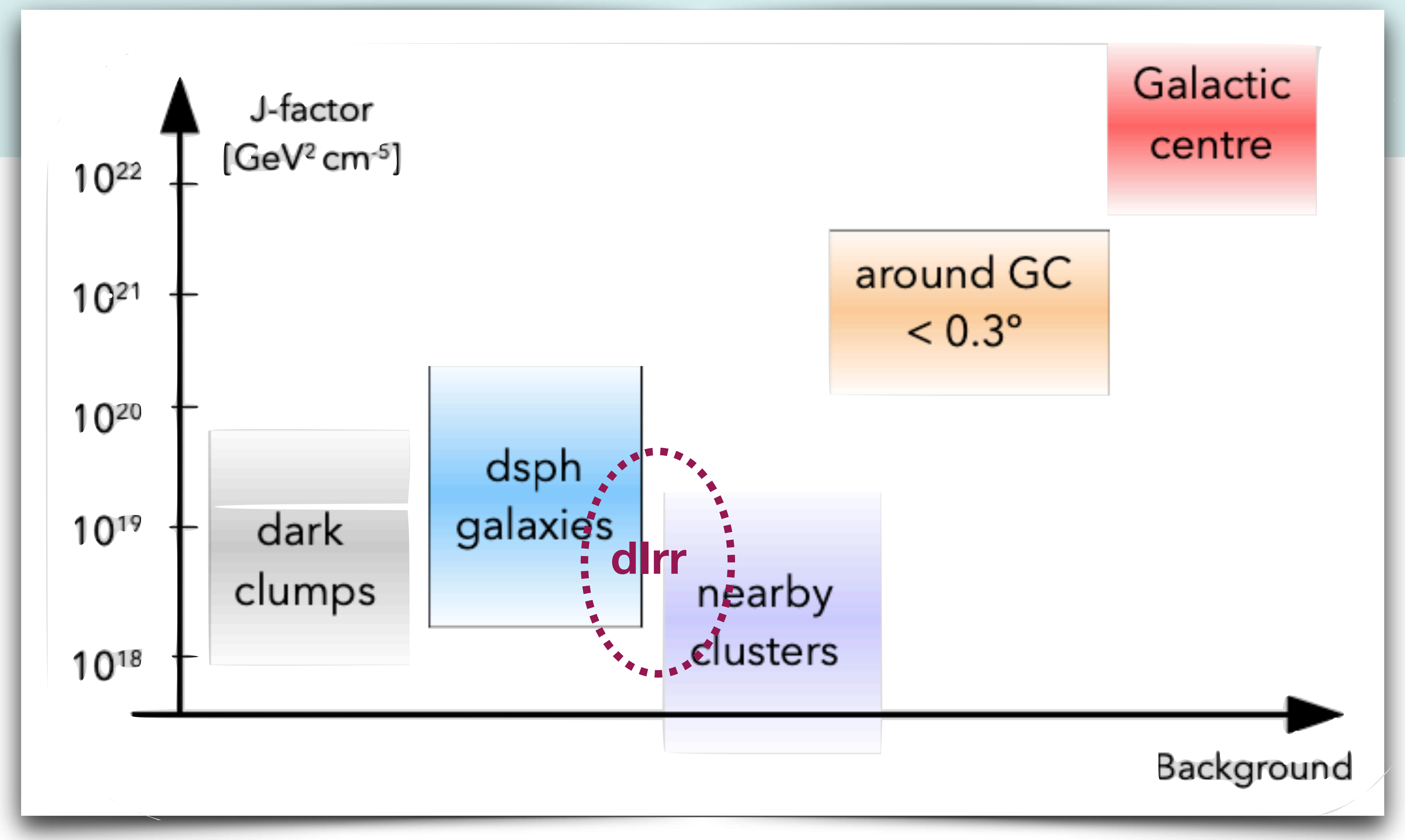


Now: go through the specifics of the DM modeling of each type of targets!

Targets



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Now: go through the specifics of the DM modeling of each type of targets!

NB - Not covered in this lecture: dwarf irregular galaxies have recently joined the list of possible targets

- dSph < M_{irr} < MW-like galaxies
- relevant when part of the local group (d~Mpc)
- star forming regions, so may have gamma-ray background

DM modeling of galactic targets

1. Galactic center region
2. Dwarf spheroidal galaxies
3. Dark galactic clumps

The Galactic halo - central regions

- The Milky Way sits in a ~10^{12} M_{sun} DM halo and the Earth is located at 8.5 kpc from the center
  → suggests large J-factor, hence prime target for indirect detection

- However, large gamma-ray emission from astrophysical processes (see M. Doro's lecture)
  → Not ideal, and complex data analysis

- Need an estimation of the DM profile of the MW

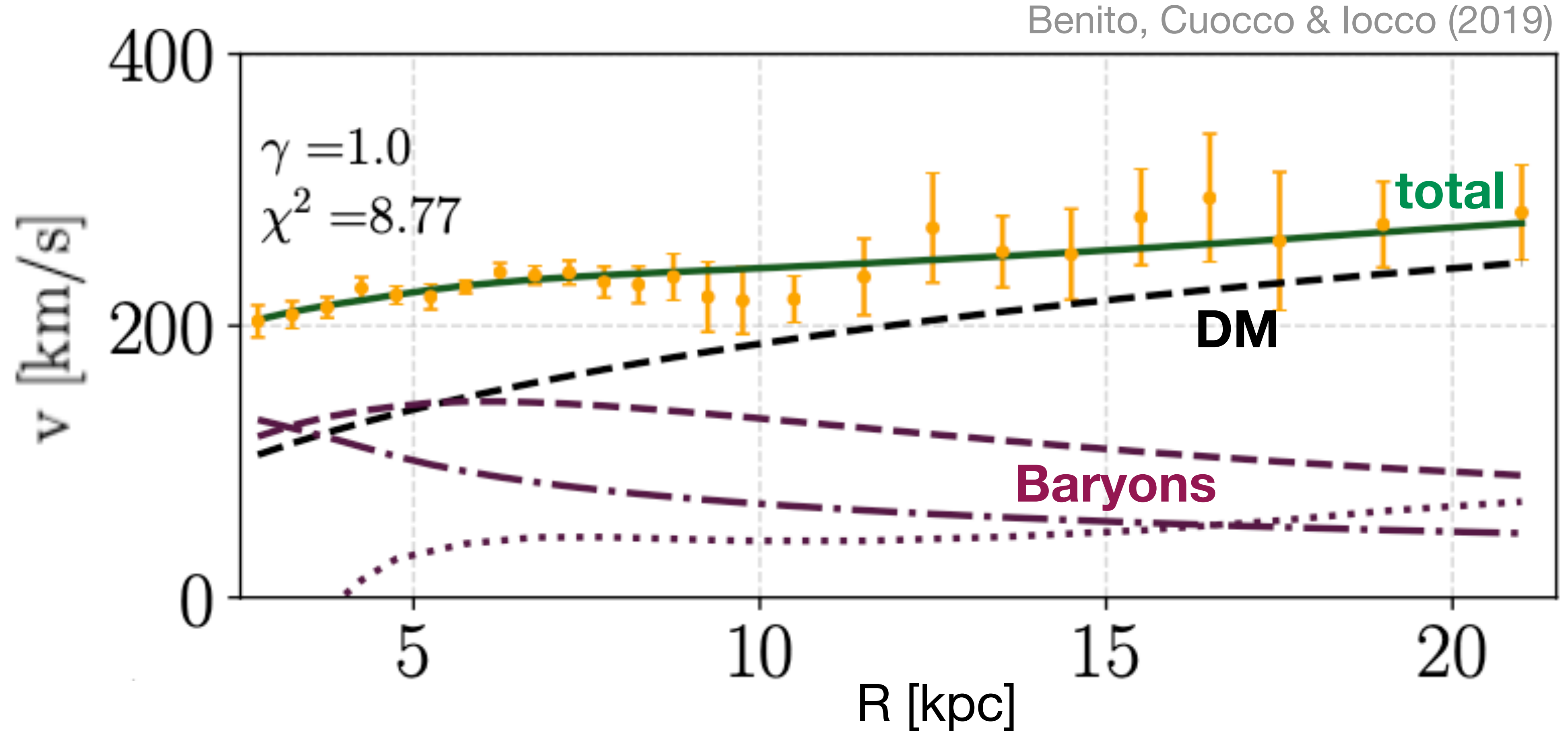
Modeling of the Galactic halo

Adjust multi-component MW mass modeling on Galactic rotation curves

- dark matter halo component (NFW or free inner slope)
- stellar disk
- gas
- stellar bulge/bar

to a compilation of kinematic data (stars, masers, gas, K-stars)

Benito, Cuocco & Iocco (2019)



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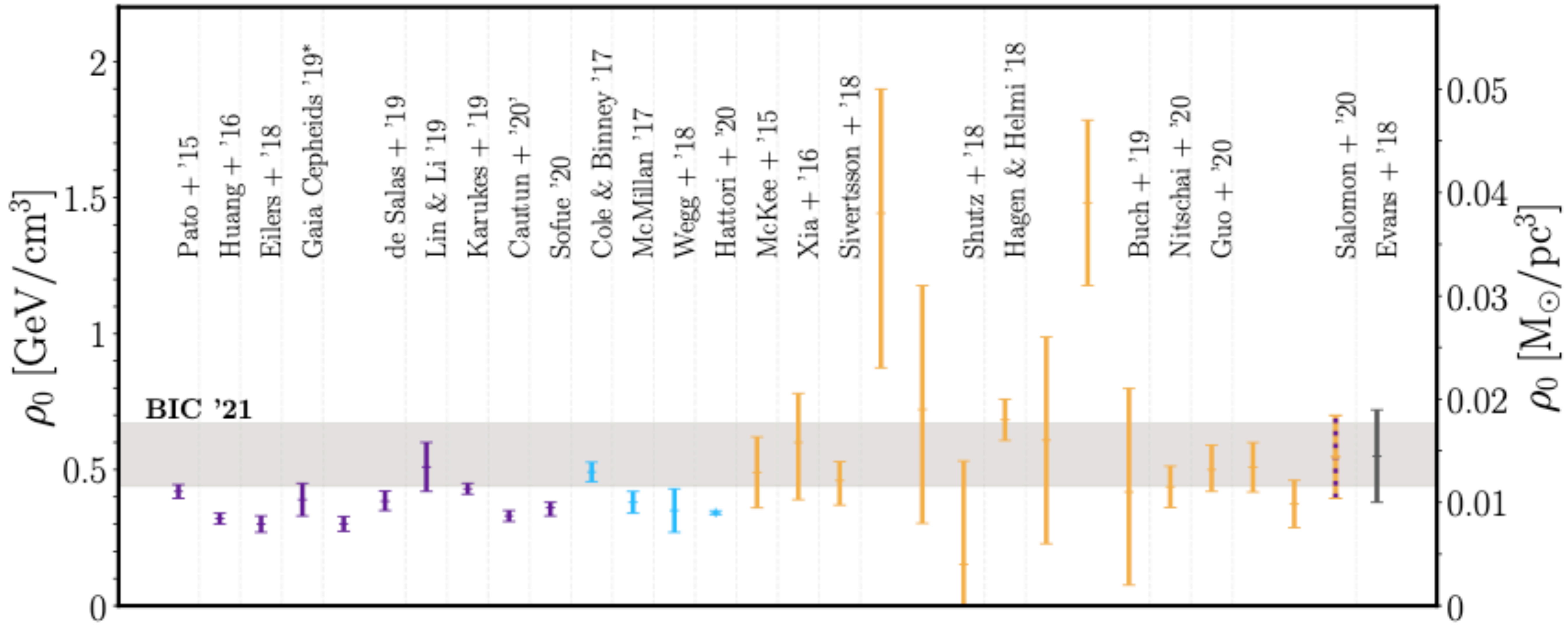


Depending on analyses, determination of the **local DM density** but also parameters of the DM profile

Inner slope of the profile is not well constrained

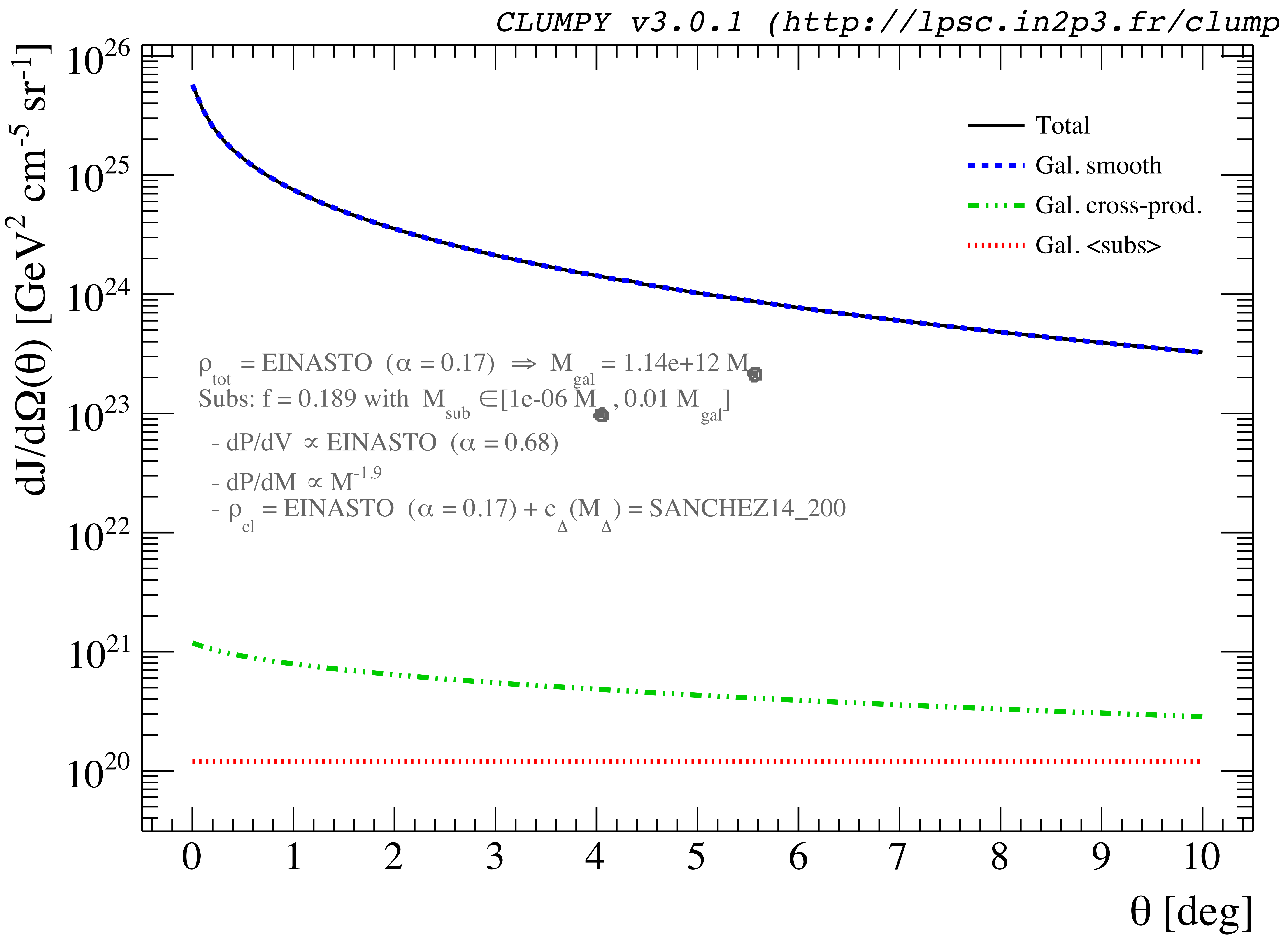
Modeling of the Galactic halo

Recipe

1. Find MW halo parametrisations/normalisation from the literature, either simulations and/or global MW modeling typically
    - NFW profile, with $r_s \sim 20$ kpc
    - Einasto, with $r_{-2} \sim 20$ kpc and $\alpha \sim 0.17$
    - $\rho_\odot = \rho(R_\odot) = 0.4$ GeV cm$^{-3} \rightarrow \rho_s$
    - Alternatively, provide $\rho_\odot$ and $M(<R)$

2. Indirect detection towards the Galactic centre (or close to the GC)
    - Explore various inner slopes as not well constrained (e.g. H.E.S.S or Fermi-LAT galactic centre analyses)

The Galactic halo - central regions



Towards the Galactic centre, substructures may be neglected and only need to model the smooth component

DM modeling of galactic targets

1. Galactic center region
2. Dwarf spheroidal galaxies
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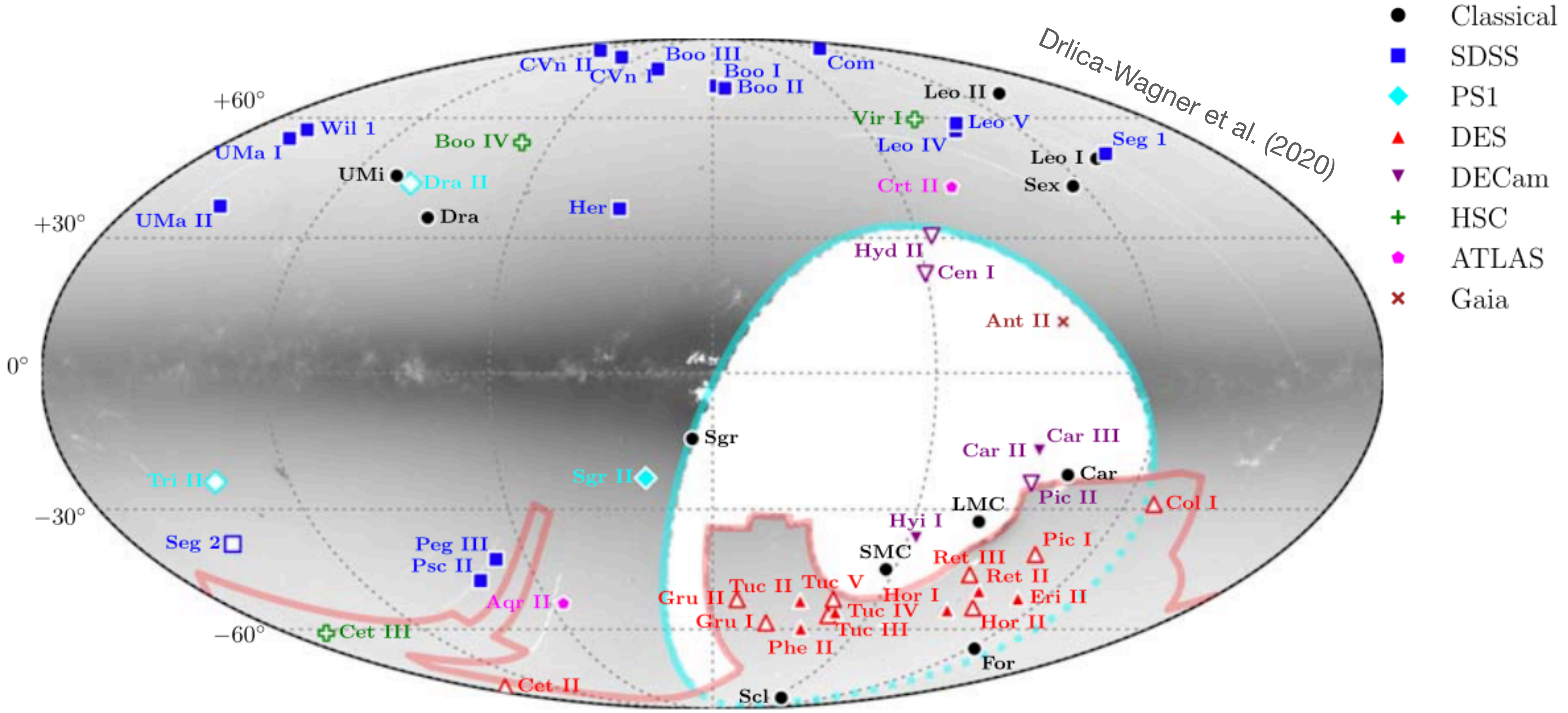
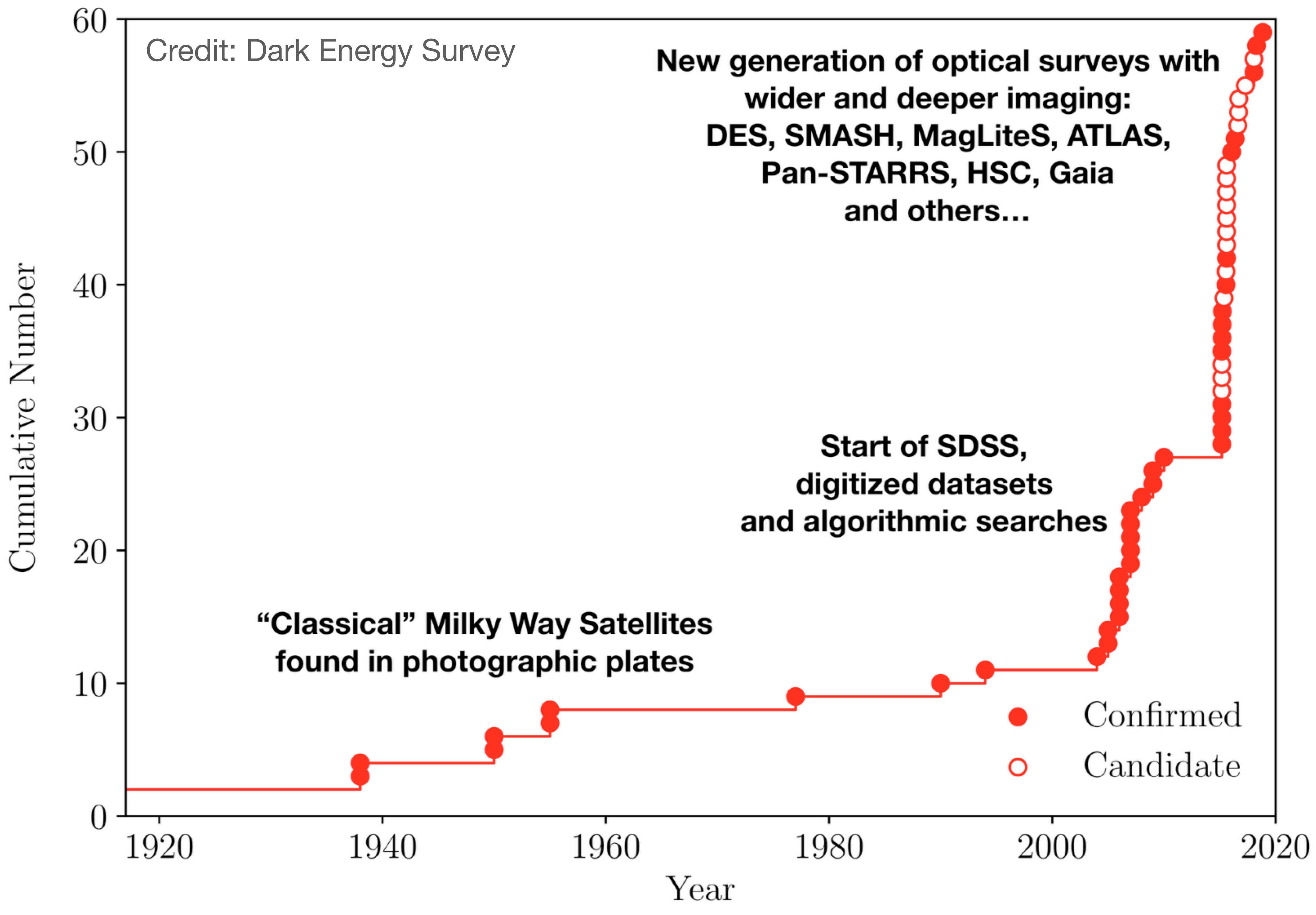
Satellite galaxies of the MW

Overview

- Population of faint galaxies orbiting the MW
- No gamma-ray background
- Distance: ~20 - 300 kpc
- Size ~ 10^{-2} size of spiral galaxies





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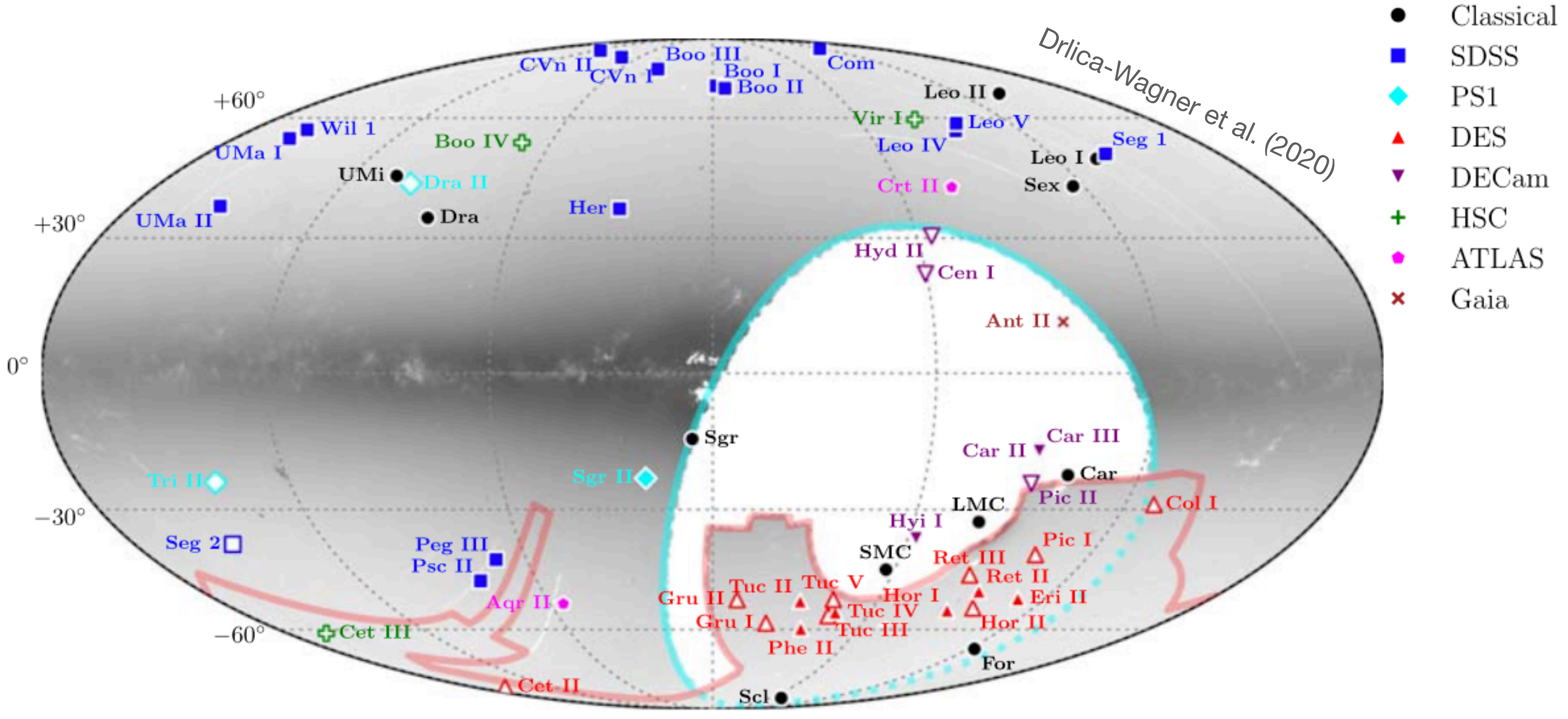

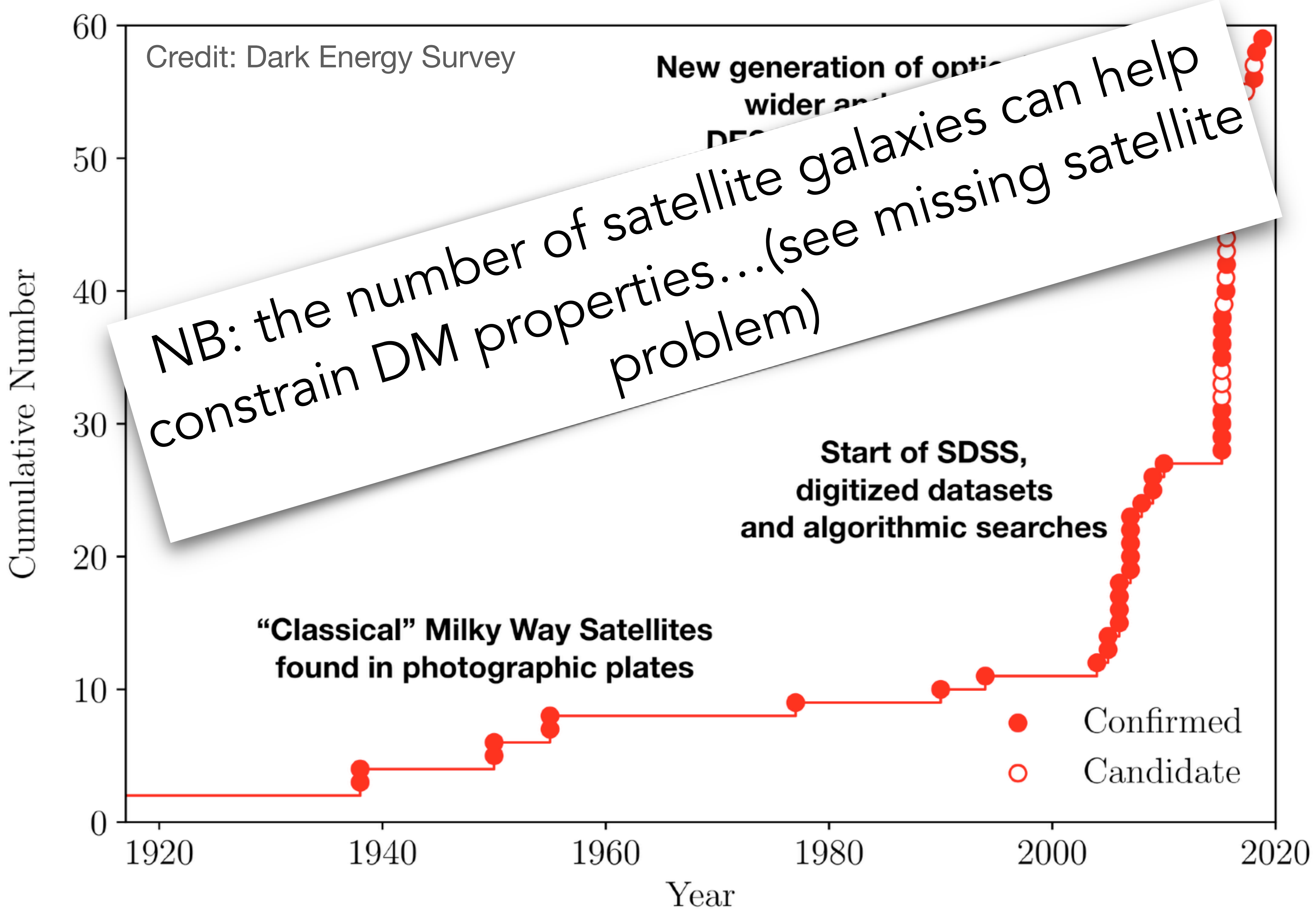

NB: the number of satellite galaxies can help constrain DM properties…(see missing satellite problem)

Satellite galaxies of the MW

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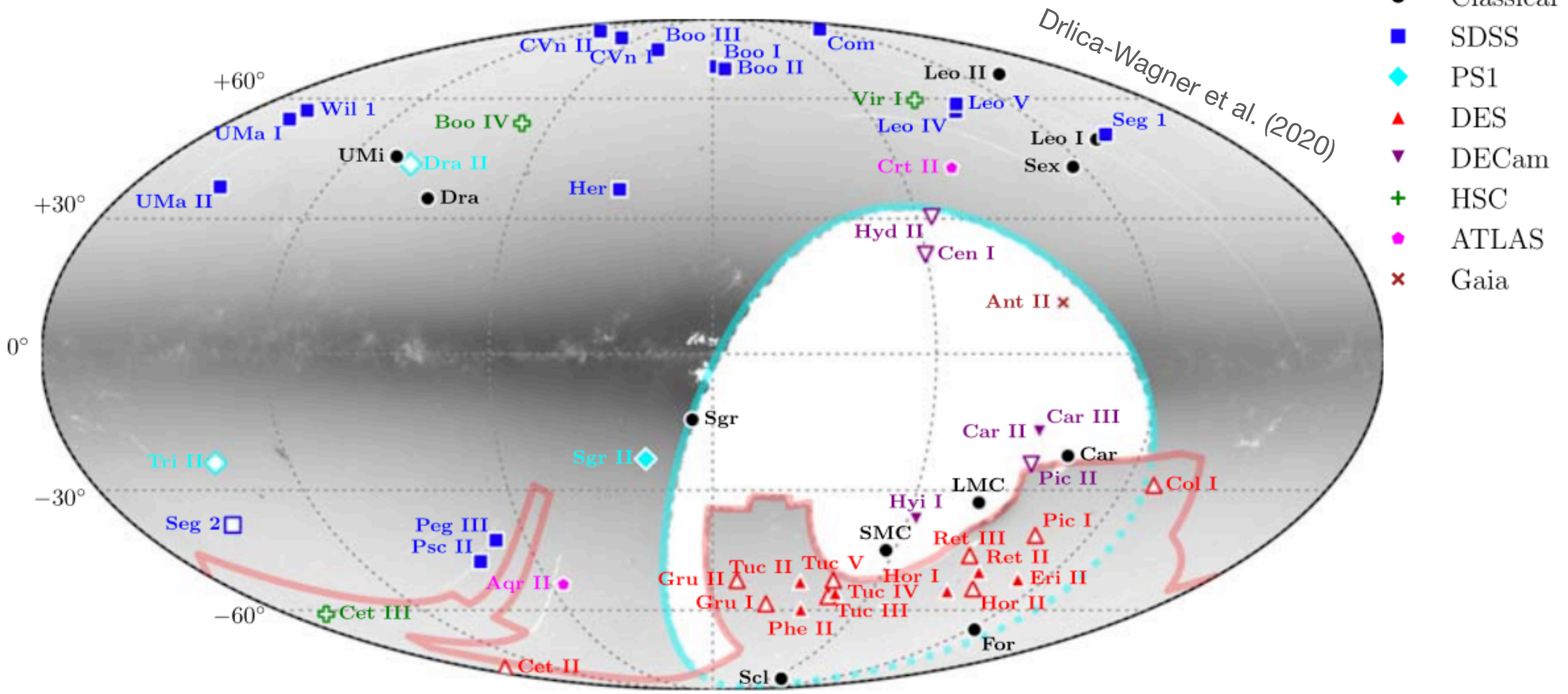
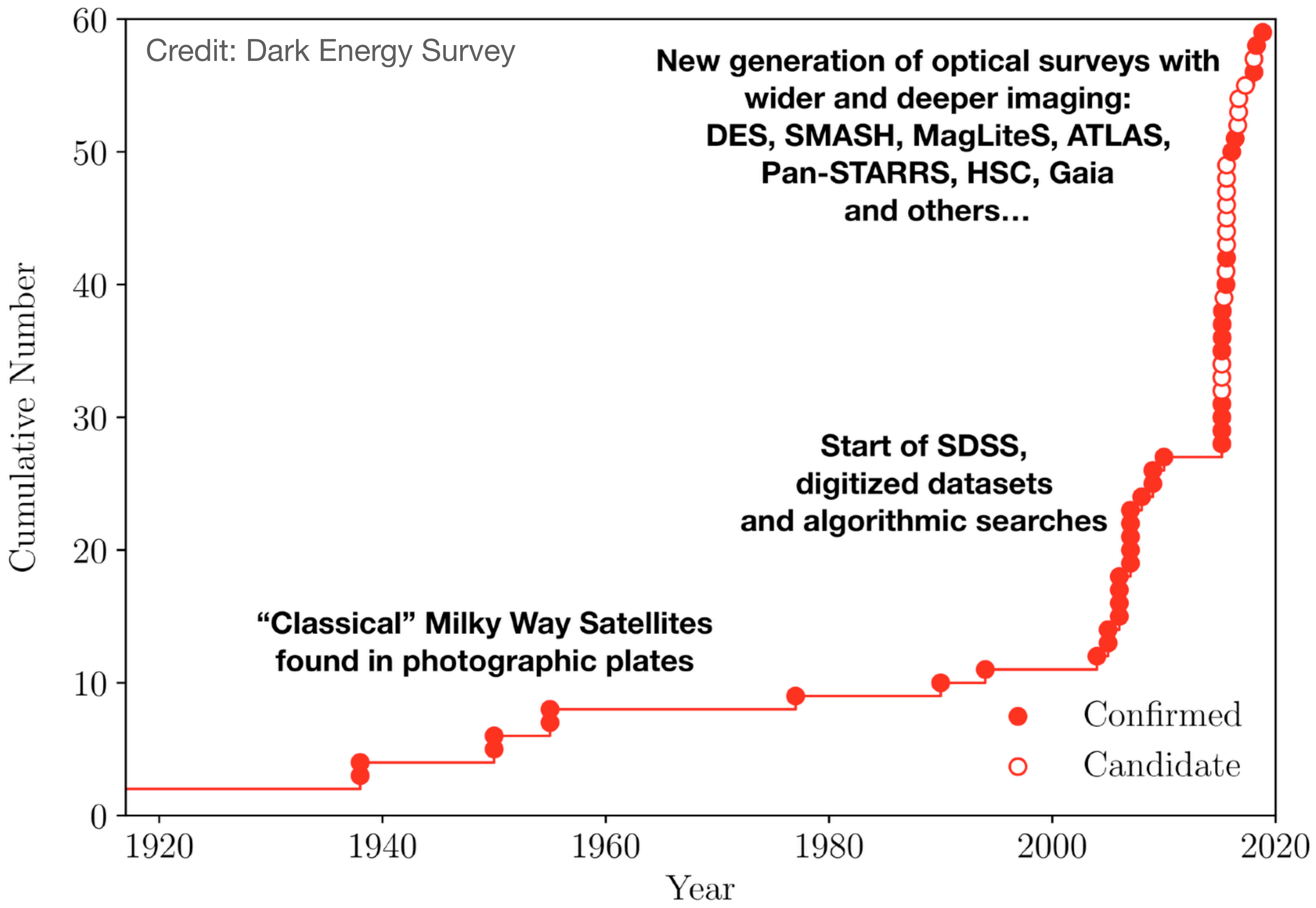
Strongly DM-dominated systems!
Great targets for indirect detection

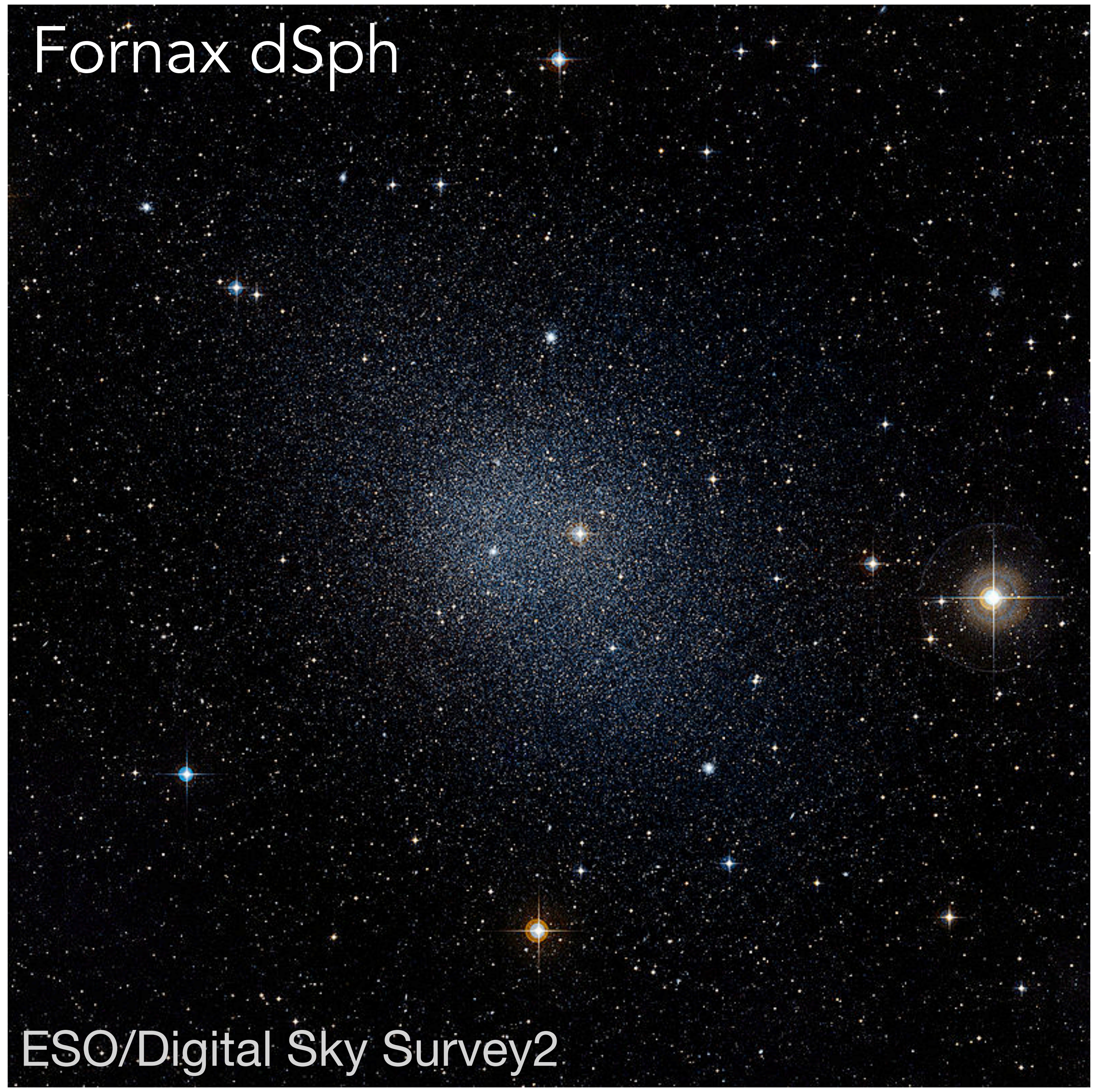




Dwarf spheroidal galaxies

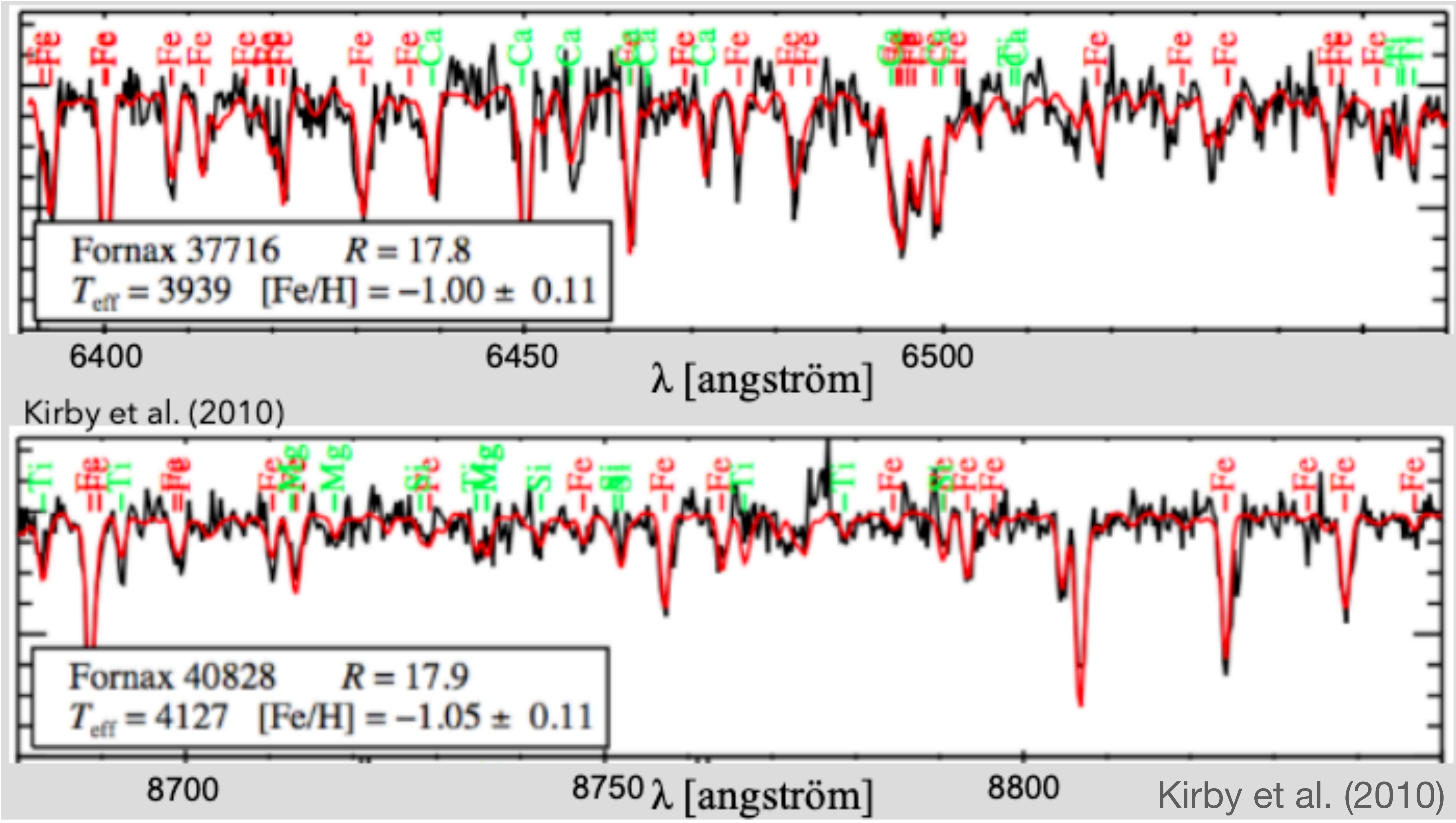
Observables

Photometry



"Light profile"→ dSph candidate

Spectroscopy of individual stars in the object



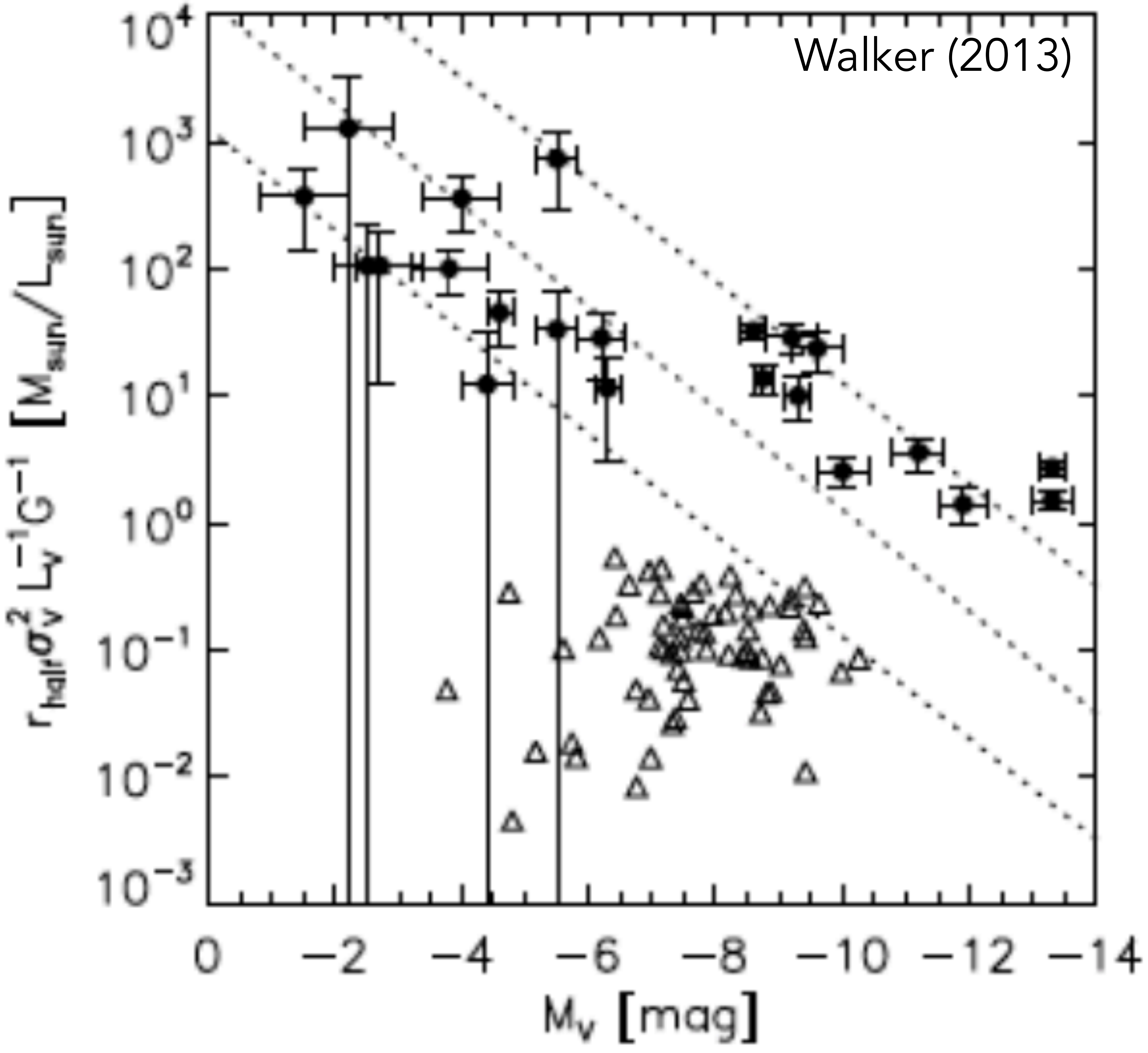
Dynamics - velocity dispersion σ^2 → dSph status confirmation

Dwarf spheroidal galaxies

DM-dominated systems

Virial theorem $$\sigma^2 \sim \frac{GM}{R}$$

Mass-to-light ratio $$\frac{M}{L} \sim \frac{R\sigma^2}{L_V G}$$



Dwarf spheroidal galaxies

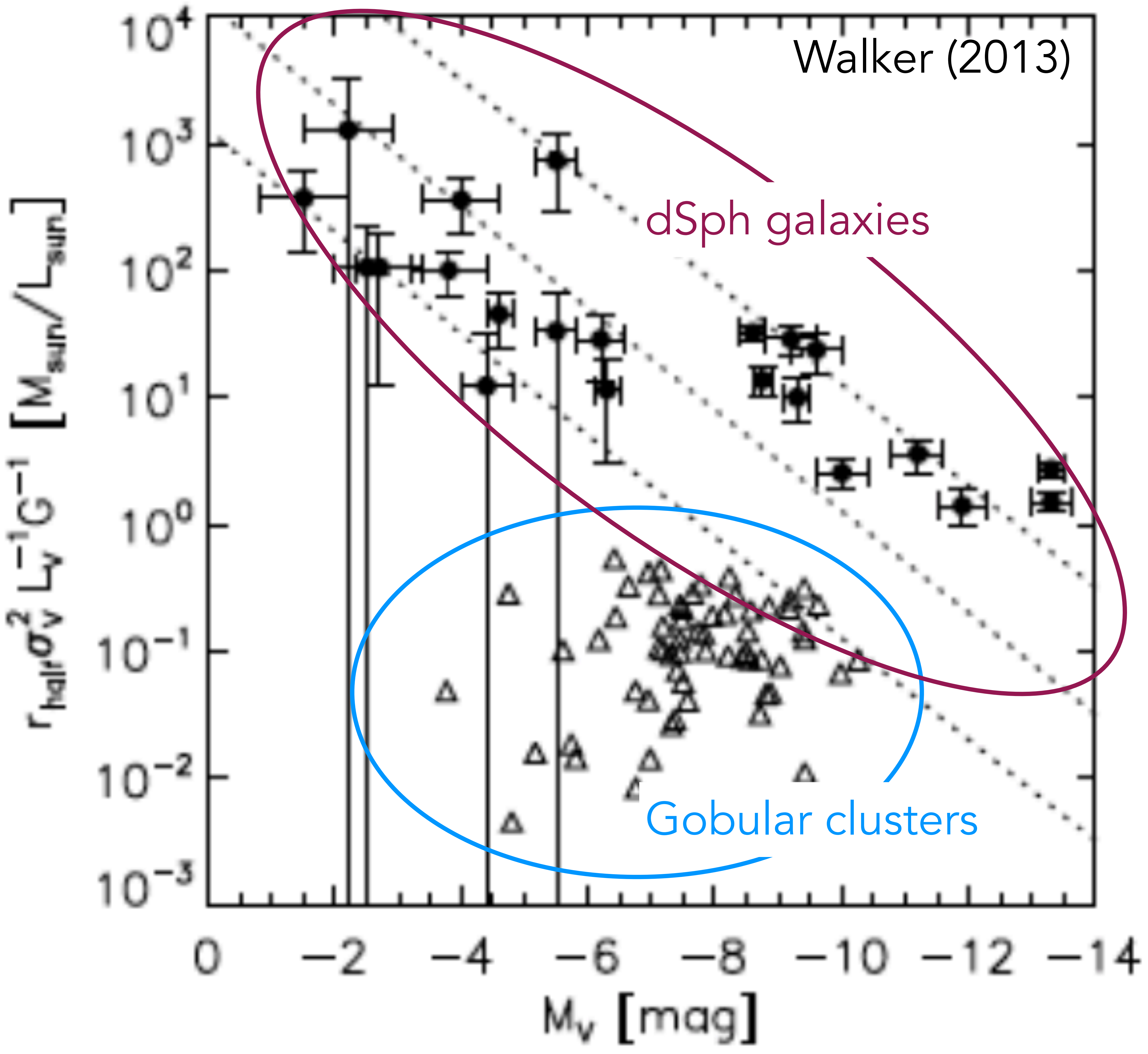
DM-dominated systems

Virial theorem $\sigma^2 \sim \frac{GM}{R}$

Mass-to-light ratio $\frac{M}{L} \sim \frac{R\sigma^2}{L_V G}$

Dsph galaxies have large M/L ratios indicating DM-dominated systems

How can we constrain the DM profile in those object for robust estimation of the J-factor?



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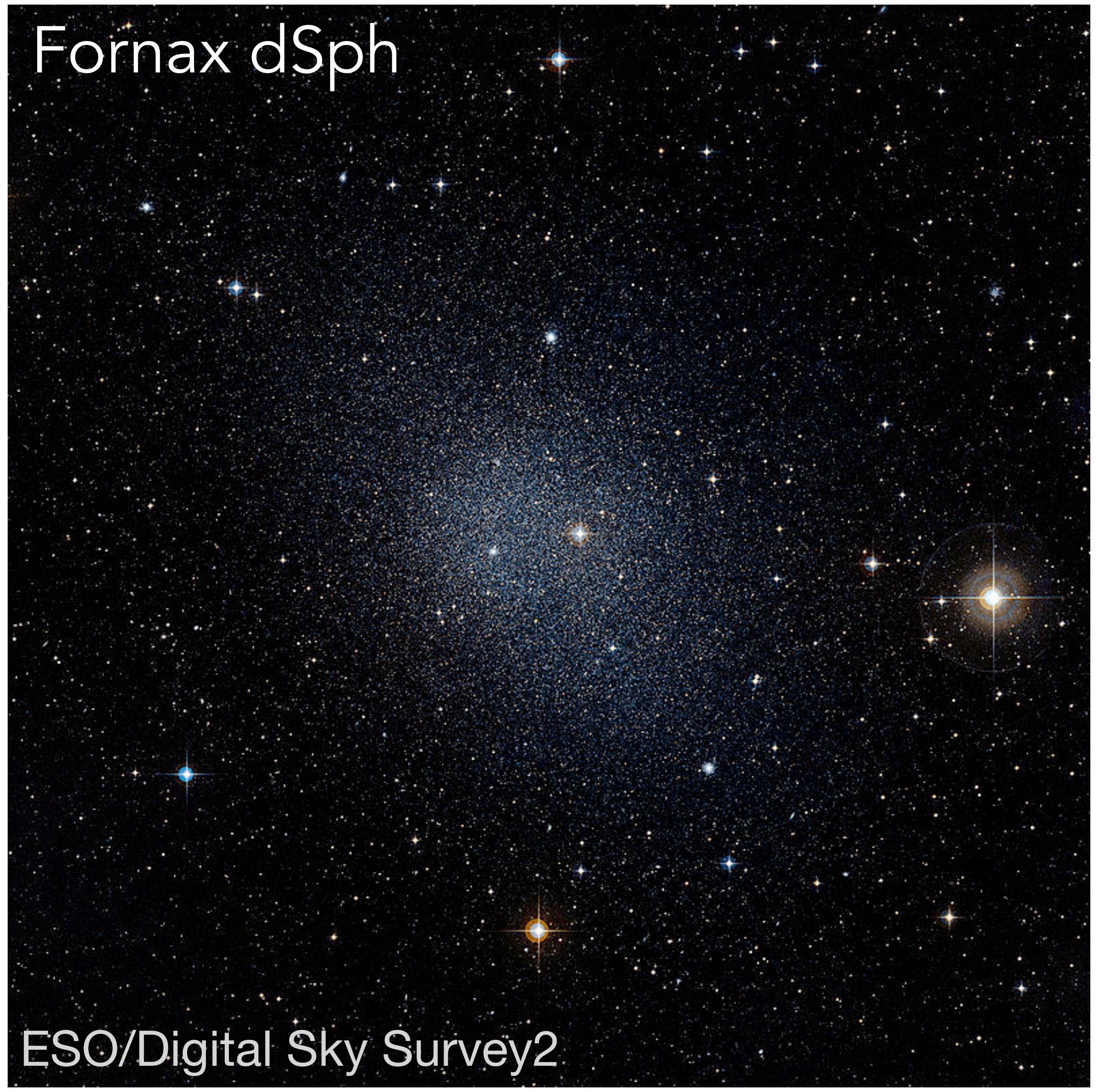

"Light profile"→ $I(R)$

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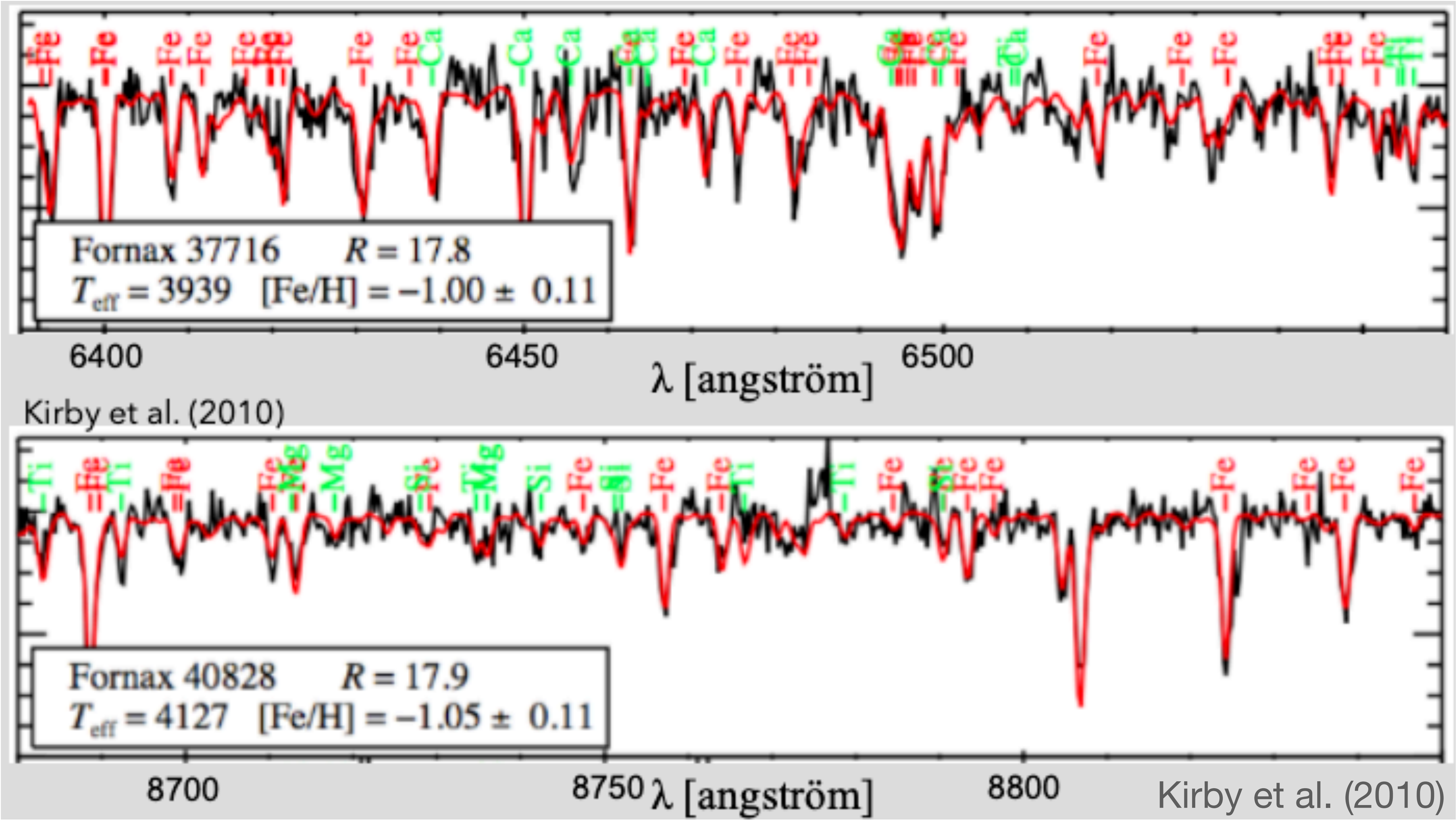

Dynamics - velocity dispersion $\sigma_p^2(R)$

Dwarf spheroidal galaxies

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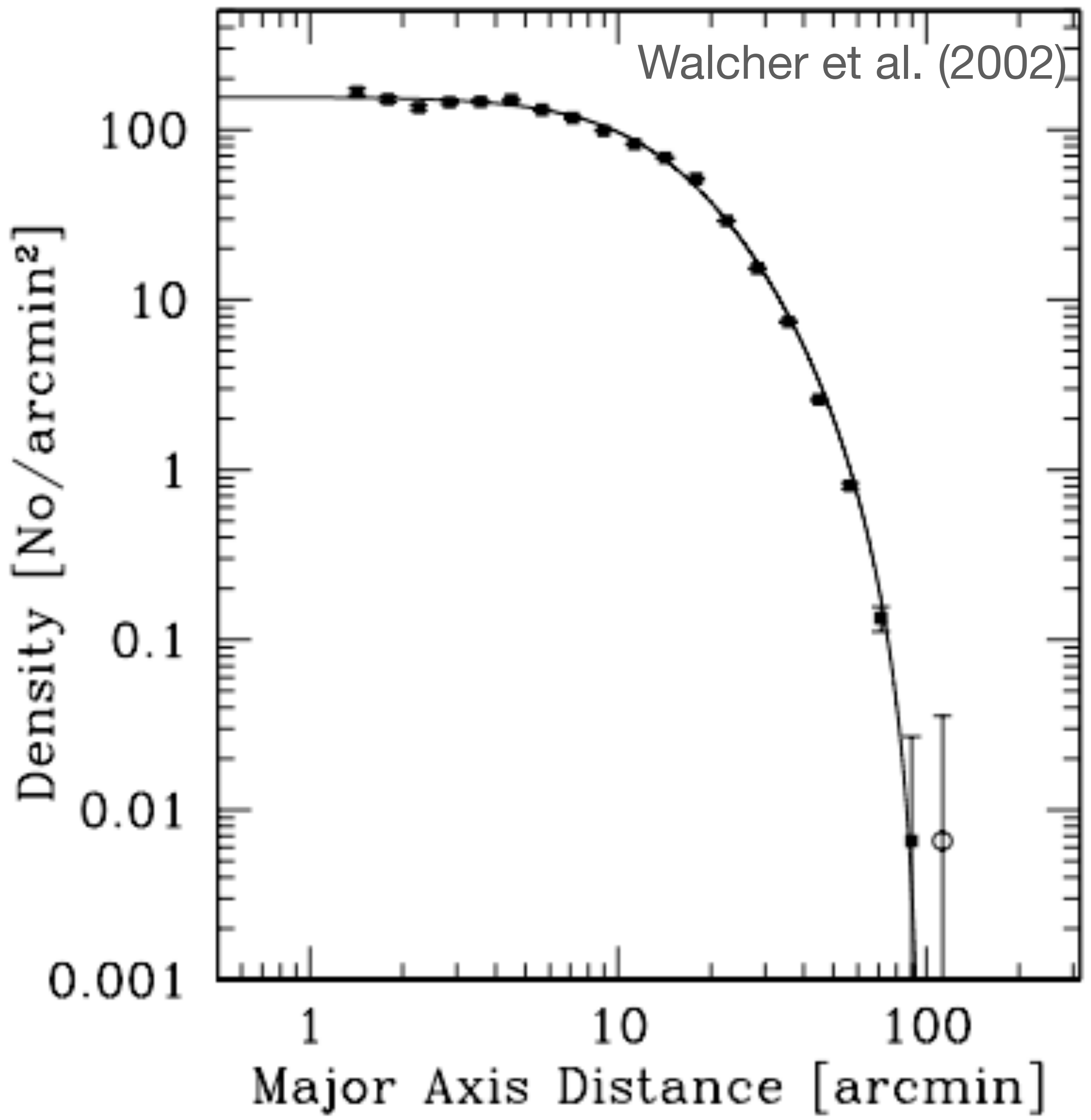

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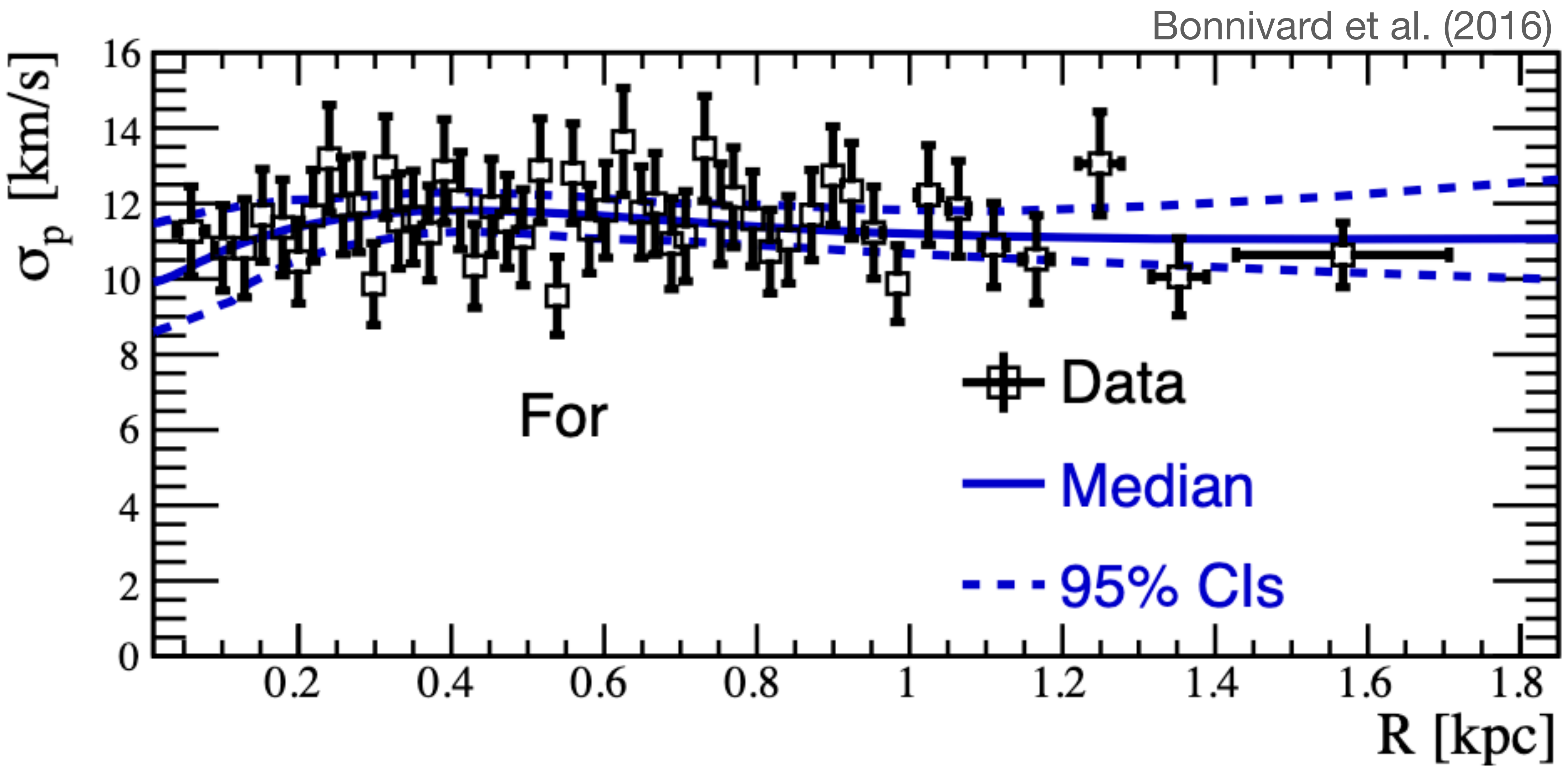

Dynamics - velocity dispersion $\sigma_p^2(R)$

Dwarf spheroidal galaxies

Jeans modeling

Light and velocity dispersion profiles

$I(R)$ $\quad$ $\sigma_p^2(R)$

de-project $\downarrow$ $\quad$ project $\uparrow$

$\nu(r)$ $\quad$ $\overline{v_r^2}(r)$

Jeans equation: solve for $\nu\overline{v_r^2}$

$$\frac{1}{\nu(r)}\frac{d}{dr}(\nu(r)\overline{v_r^2}(r)) + 2\frac{\beta_{\rm ani}(r)v_r^2(r)}{r} = -\frac{GM(r)}{r^2}$$

$$\beta_{\rm ani} = 1 - \overline{v_\theta^2}/\overline{v_r^2} \qquad M(r) = \int_0^r 4\pi s^2 \rho(s)\, ds$$

given a DM profile parameterisation
(NFW, Einasto, or more general form)

$$\rho(r) = f(\rho_s, r_s, \alpha_i)$$

Dwarf spheroidal galaxies

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1. start from collisionless Boltzmann equation
2. integrate moments 0 and 1 over velocities
3. combine them to get the Jeans equation

See Binney and Tremaine (2008)

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$\overline{v_r^2}(r)$ → project → $\sigma_p^2(R)$

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given a DM profile parameterisation (NFW, Einasto, or more general form)

$$\rho(r) = f(\rho_s, r_s, \alpha_i)$$

Given the observables $I(R)$ and $\sigma_p^2(R)$, fit for the DM profile parameters (ρ_s, r_s, α_i)

Jeans equation assumes
- Spherical symmetry
- Dynamical equilibrium
- No rotation

} Not necessarily true

Parametric approach
- Light profile (Plummer, King,...)
- Anisotropy (zero, constant, β(r))
- DM profile (NFW, core, Einasto)

Bayesian inference needs
- Likelihood (binned or unbinned)
- Priors ("informative" or not)

} different choices = different results

Dwarf spheroidal galaxies

Jeans modeling

Light and velocity dispersion profiles

$I(R)$ — de-project ↓ — $\nu(r)$

$\sigma_p^2(R)$ — project ↑ — $\overline{v_r^2}(r)$

Jeans equation: solve for $\nu \overline{v_r^2}$

$$\frac{1}{\nu(r)}\frac{d}{dr}(\nu(r)\overline{v_r^2}(r)) + 2\frac{\beta_{\rm ani}(r)\overline{v_r^2}(r)}{r} = -\frac{GM(r)}{r^2}$$

$$\beta_{\rm ani} = 1 - \overline{v_\theta^2}/\overline{v_r^2} \qquad M(r) = \int_0^r 4\pi s^2 \rho(s)\, ds$$

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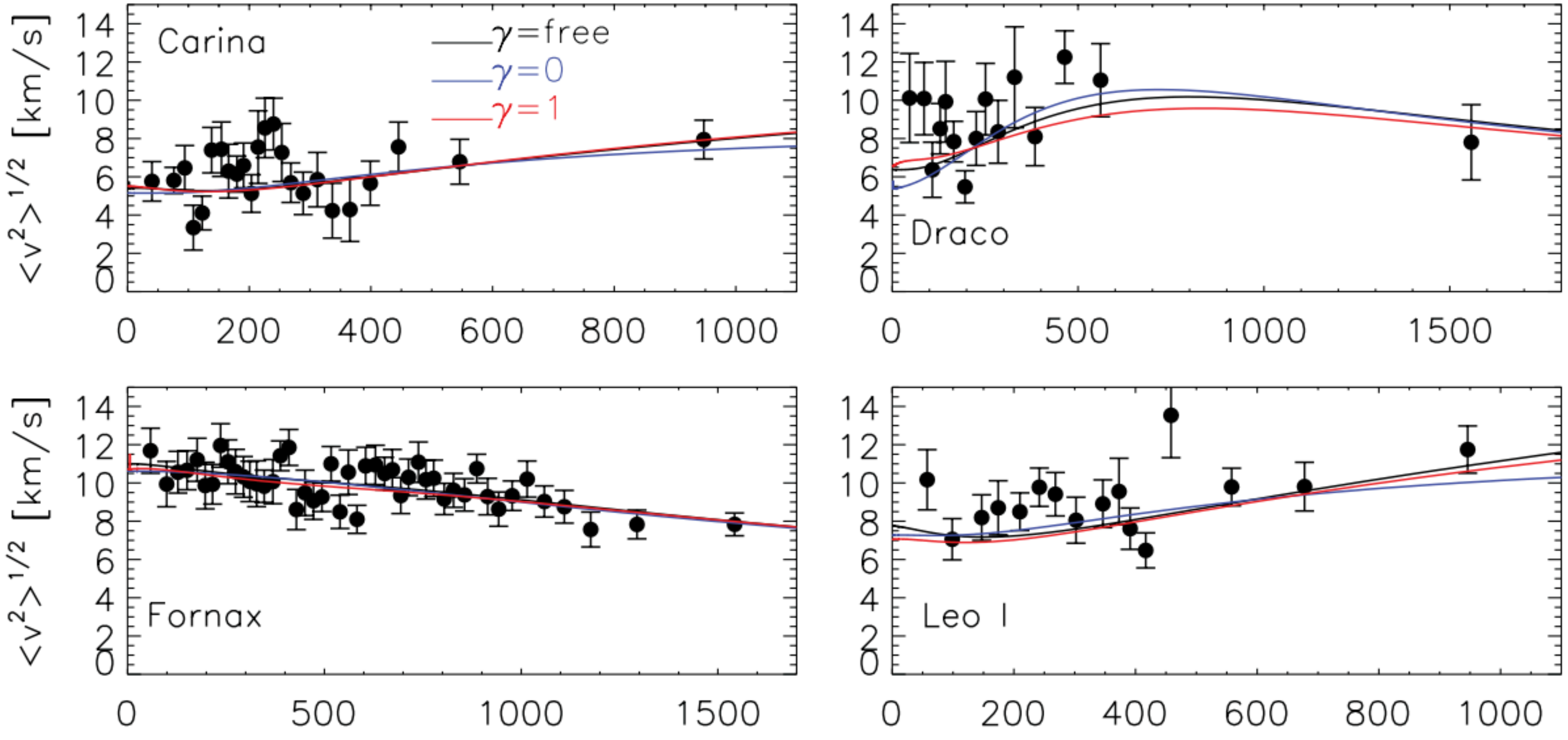
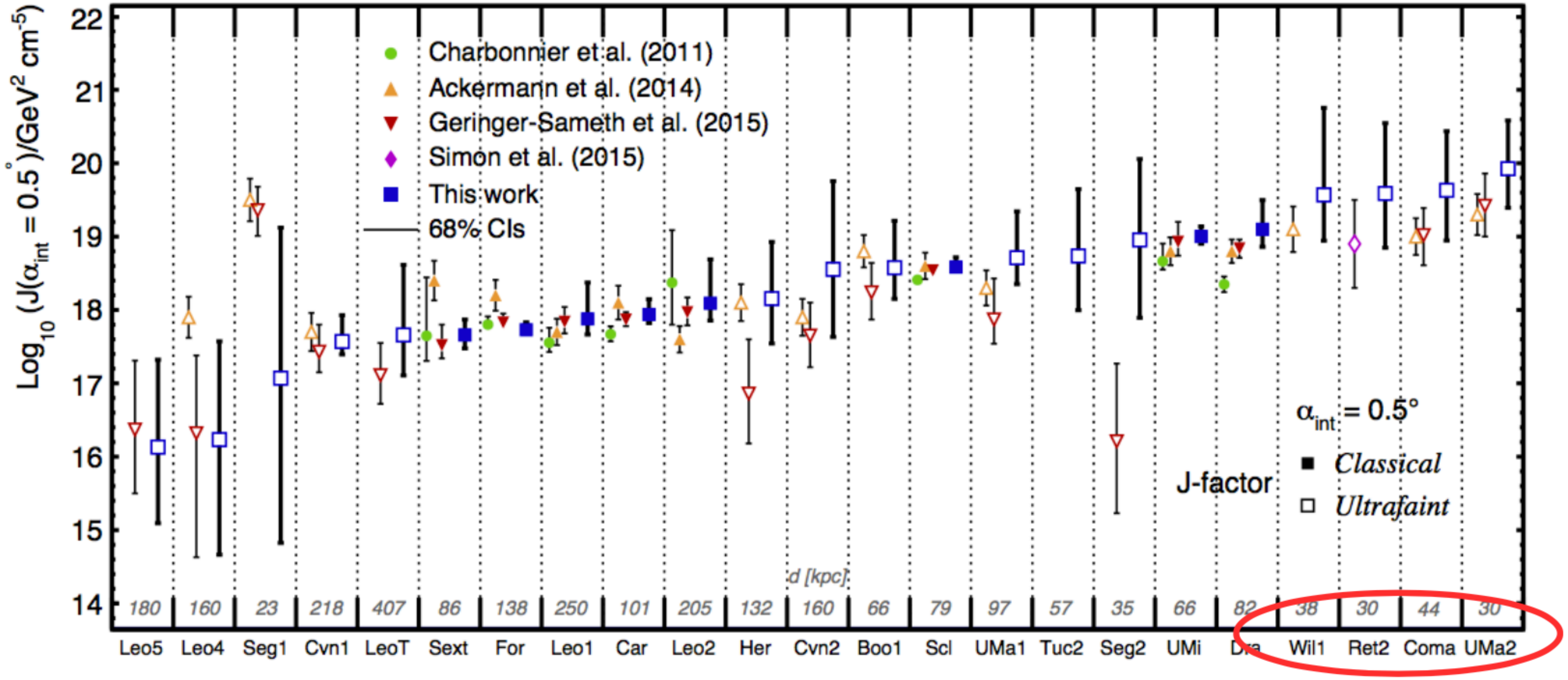


NB: The inner slope is not well constrained

Dwarf spheroidal galaxies

Ranking fo best targets?

Bonnivard et al. (2015b,c), Walker et al. (2016)

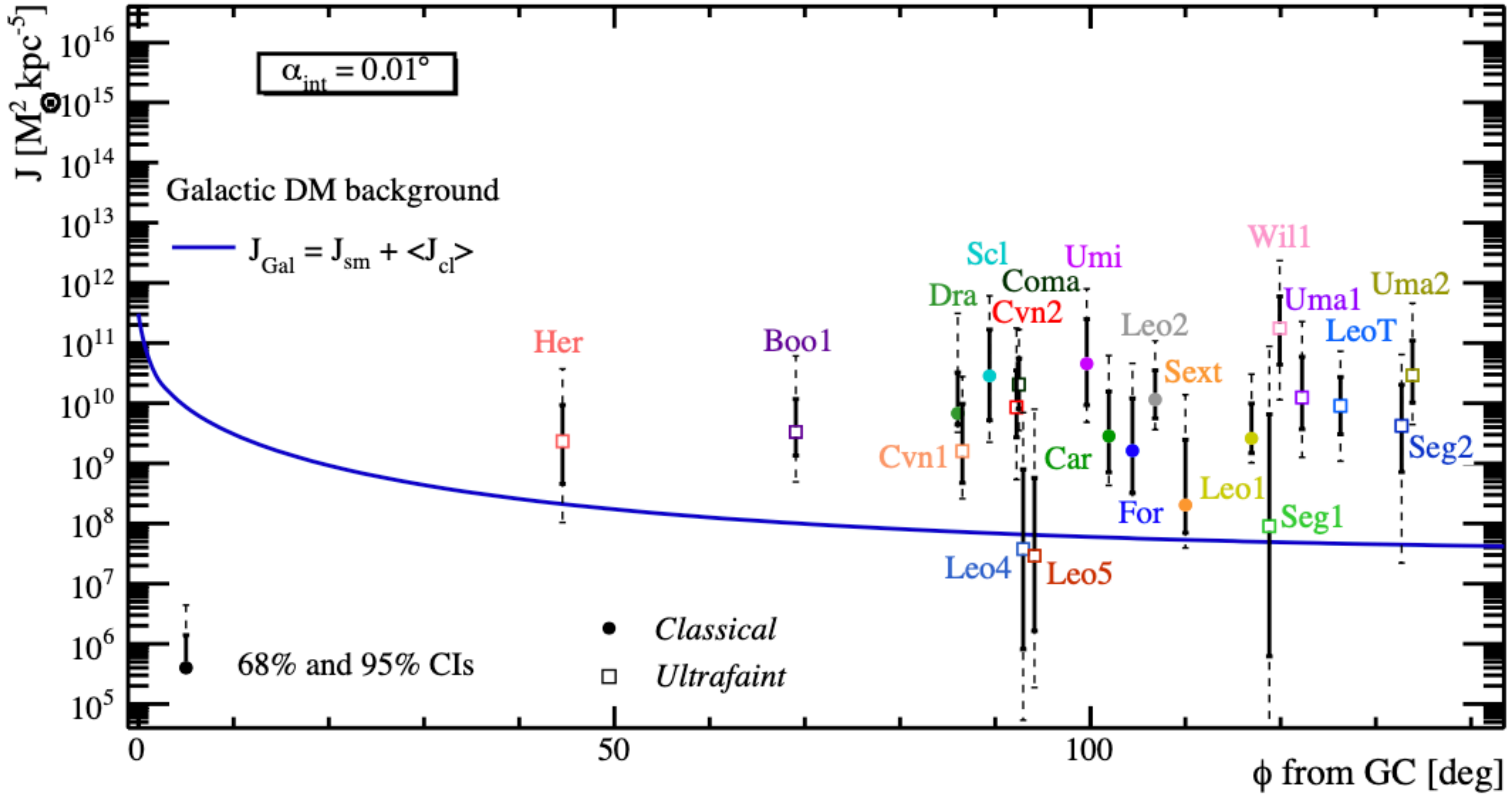


Distance is the main driver for the J-factor

Error bars depends on the size of the data sample and on the modeling choices (number of free parameters, priors, etc.)

Dwarf spheroidal galaxies

Contribution of the MW halo ?

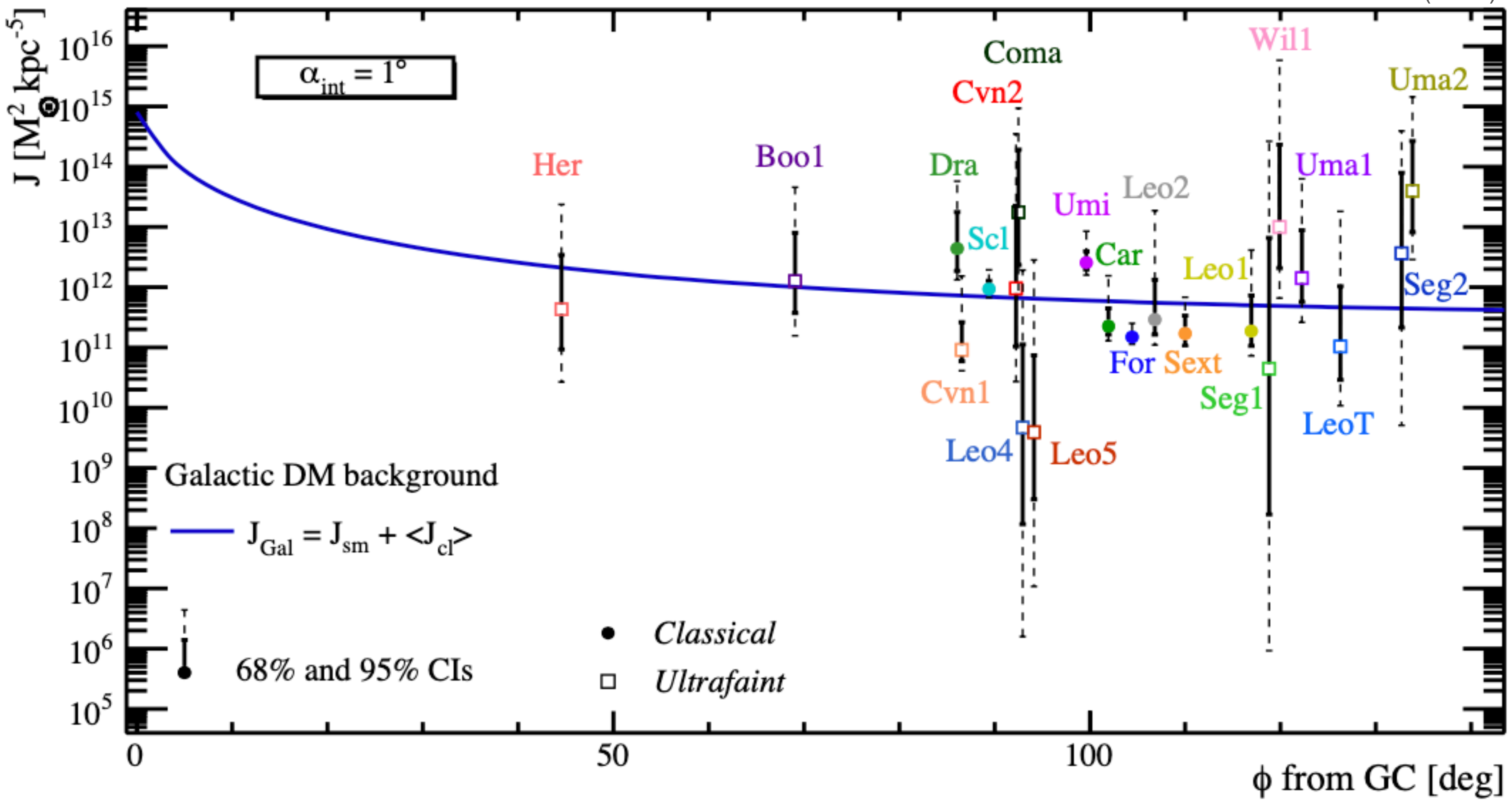


For small integration angles the MW halo contribution may be neglected

Dwarf spheroidal galaxies

Contribution of the MW halo ?

Bonnivard et al. (2016)

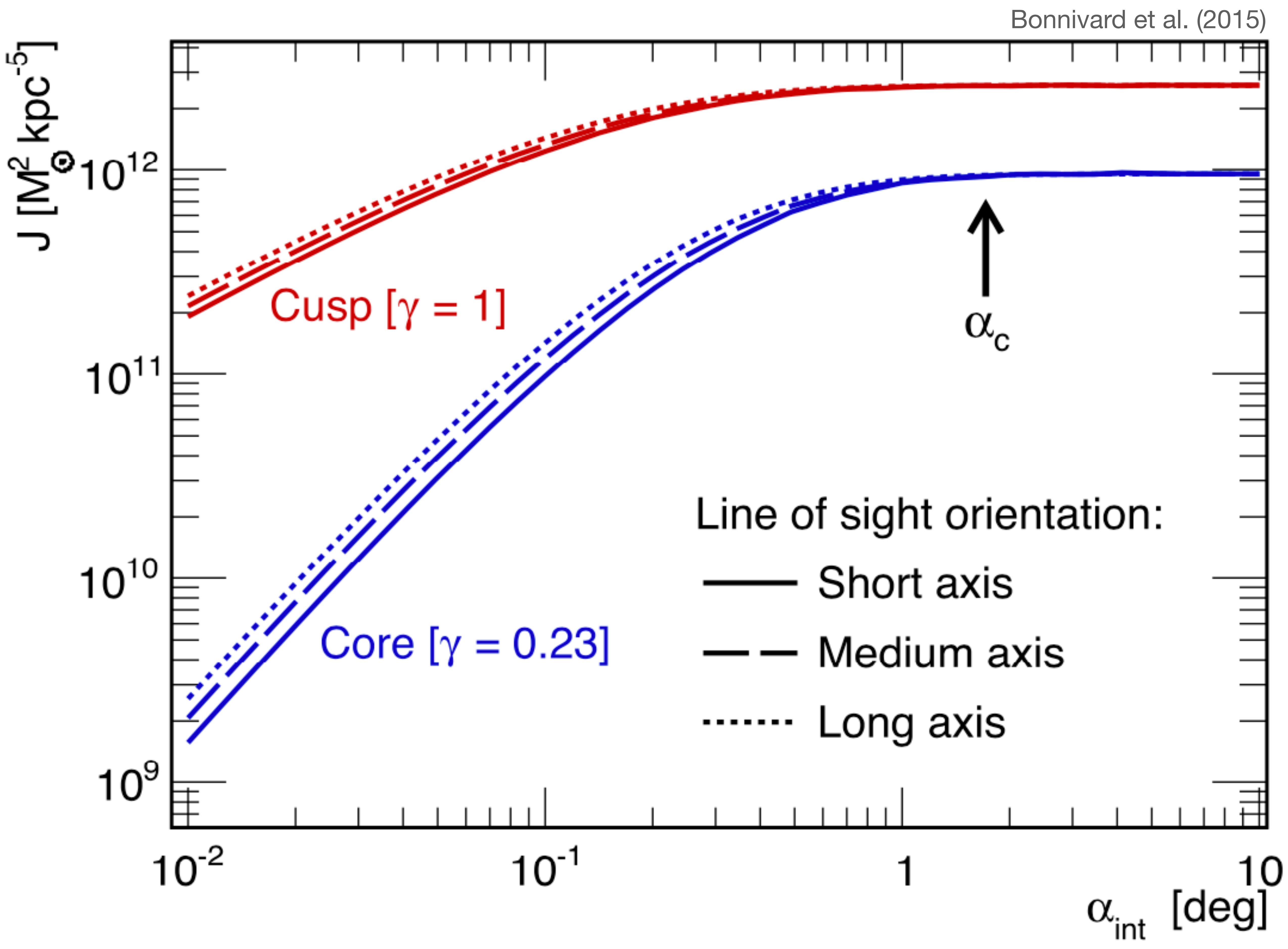


For small integration angles the MW halo contribution may be neglected

The larger the integration angle, the smaller the contrast with the MW halo exotic contribution

Dwarf spheroidal galaxies

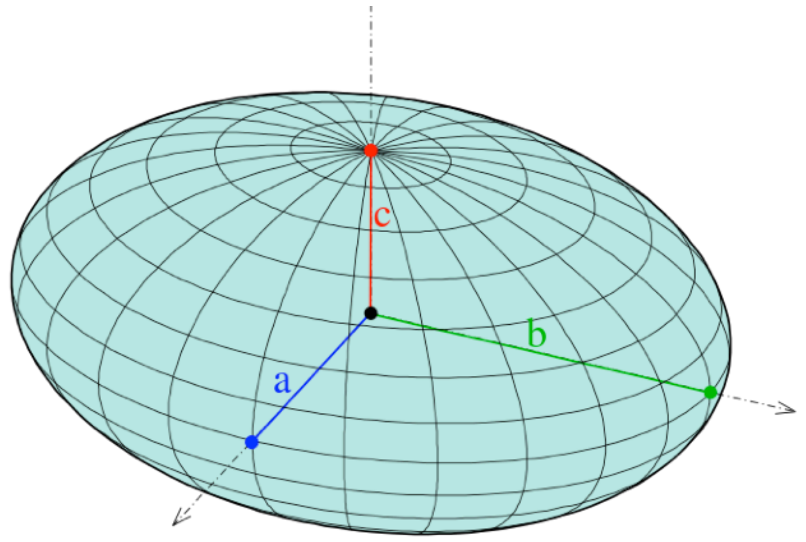
Triaxiality and projection effects (mock data)



Triaxial Zhao profile

$$\rho(r) = \frac{\rho_s}{(r_e/r_s)^\gamma[1 + (r_e/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

$$r_e = \sqrt{\frac{X^2}{a^2} + \frac{Y^2}{b^2} + \frac{Z^2}{c^2}}$$

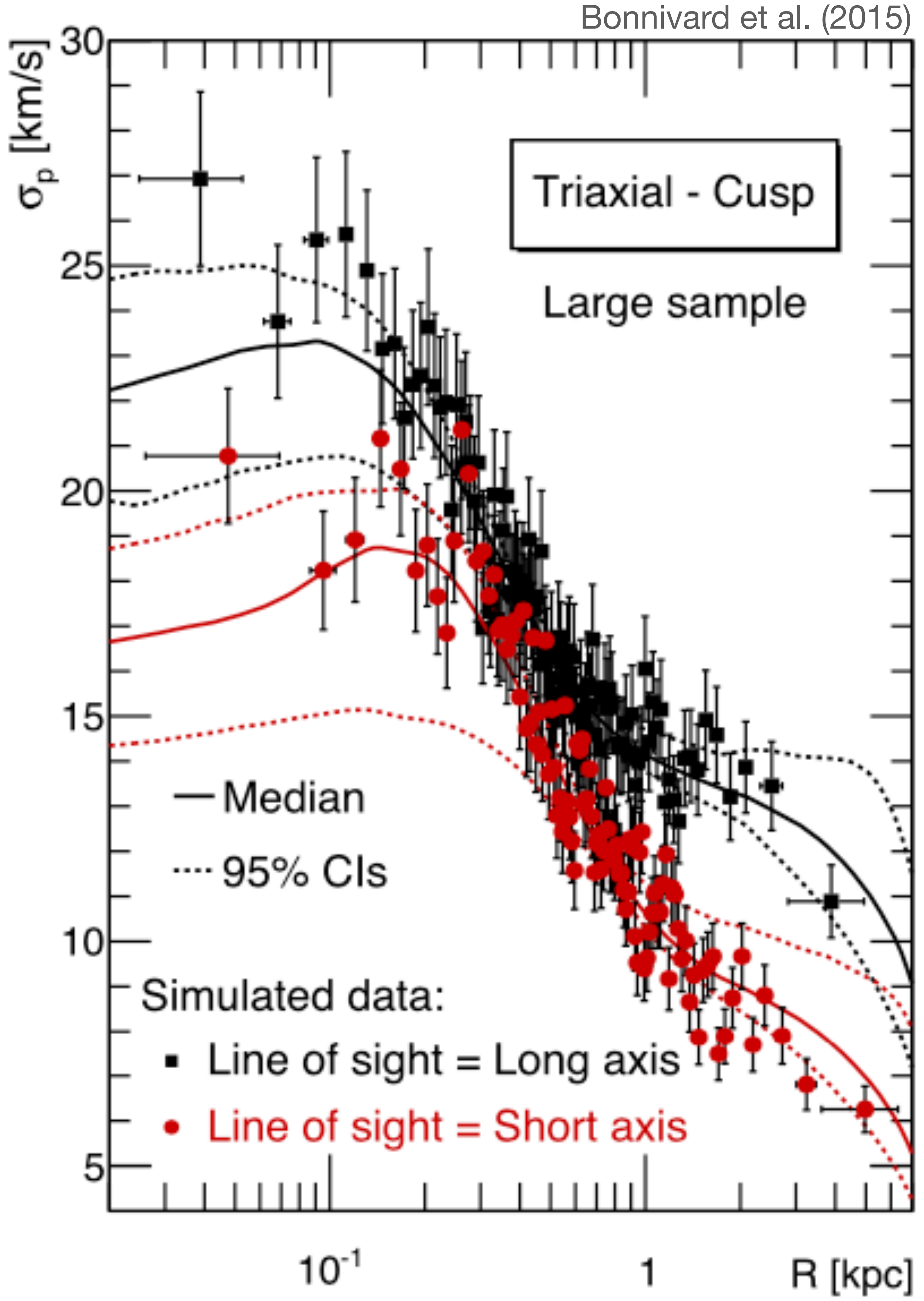


Typically, dSph-like halos in simulations have a/b~0.8, a/c~0.6

Compute the J-factor for the 3 l.o.s
→ little impact on the value of the J-factor
→ good news, but…

Dwarf spheroidal galaxies

Triaxiality and projection effects (mock data)

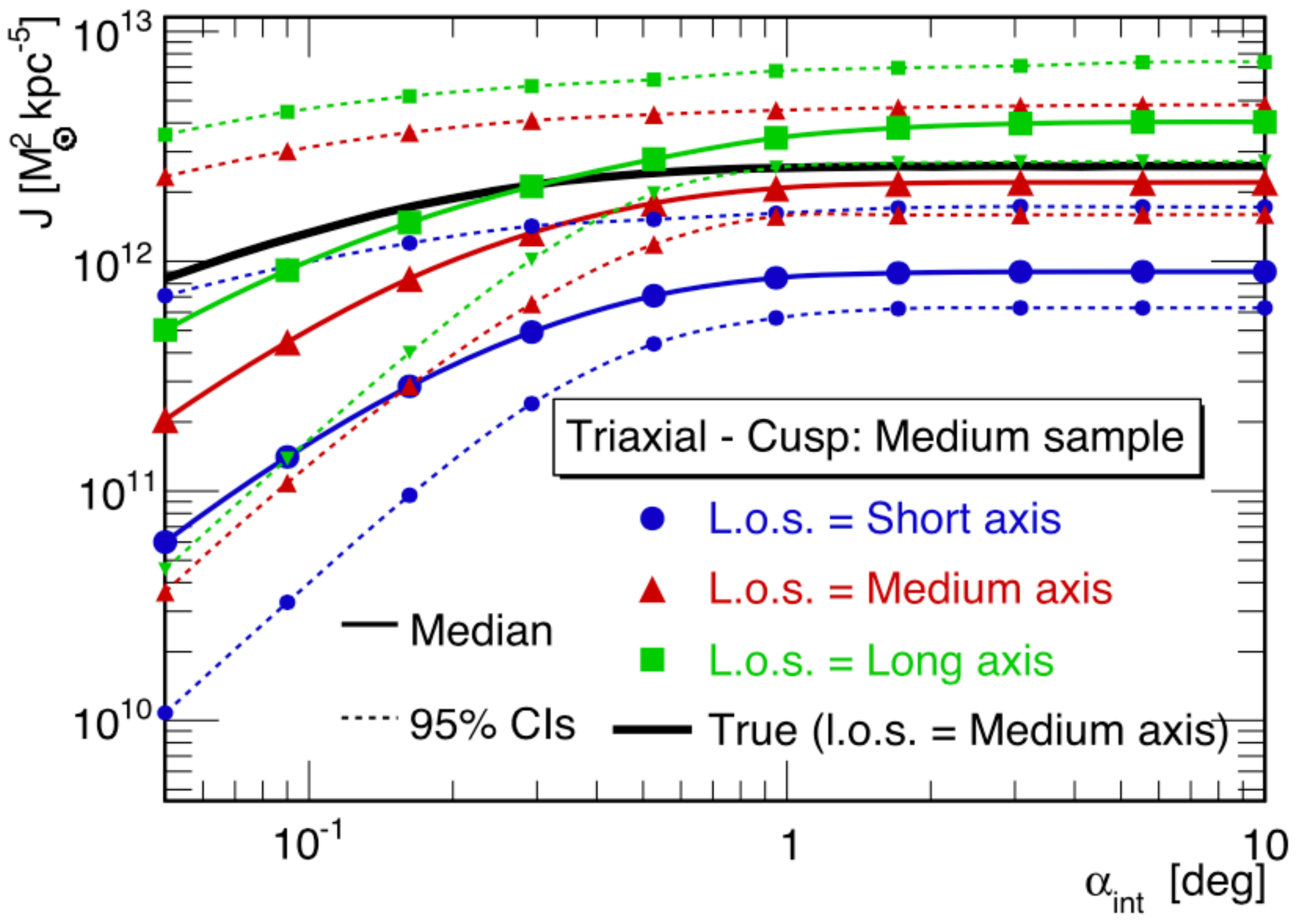


Triaxiality strongly impacts the projected velocity dispersion profile

Spherical Jeans anlaysis to constrain

$\rho(r) \rightarrow J$

will yield bias values



Solutions exist (but more expensive computationnally)

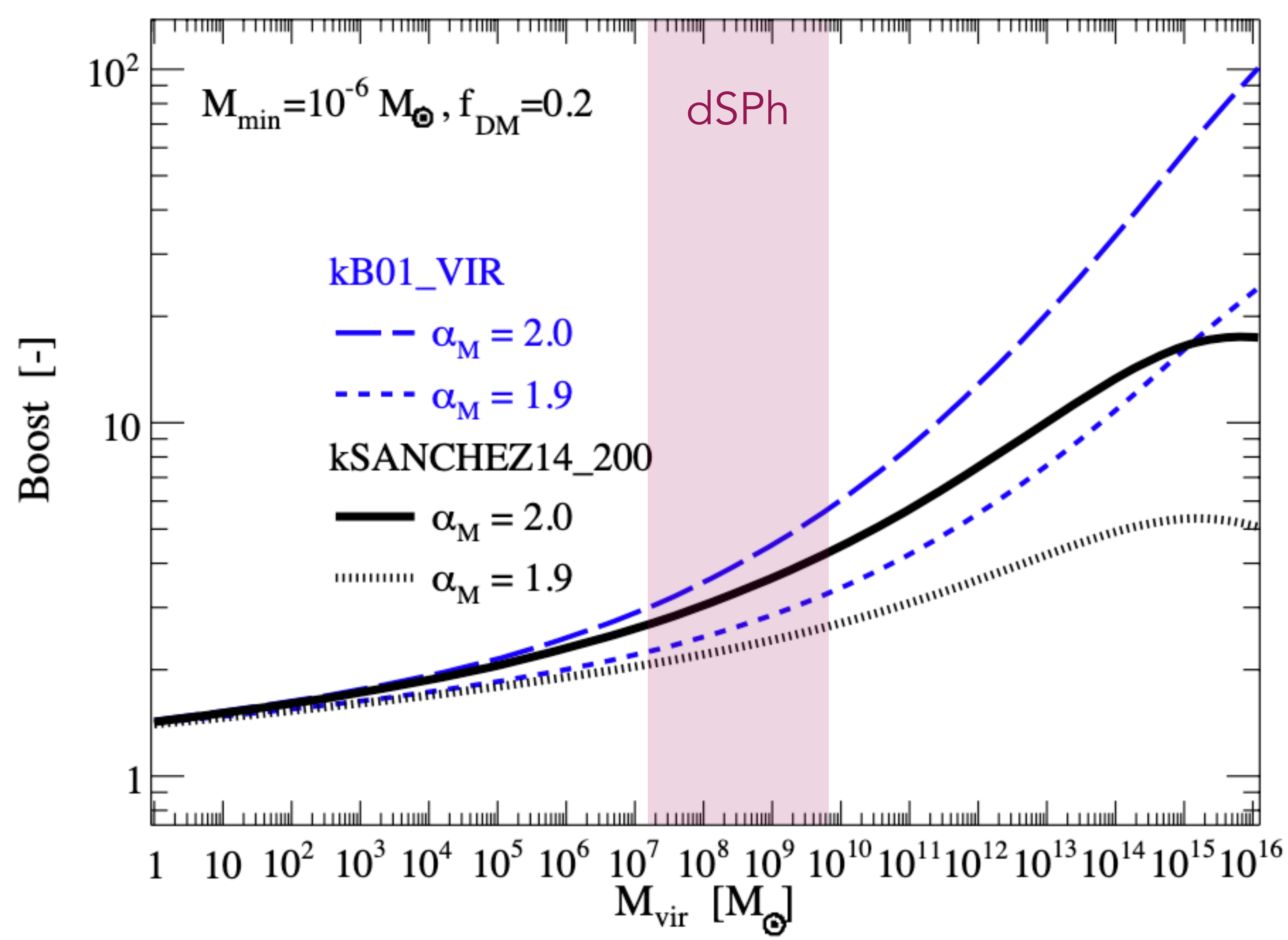
- axisymmetric Jeans analysis (e.g. Hayashi et al. 2016)
- made-to-measure models

Dwarf spheroidal galaxies

And what about substructure boost?

Negligible boost from substructures, so generally not considered at the scale of dSph galaxies

Bonnivard et al. (2016)



Dwarf spheroidal galaxies

Summary

- dSph are arguably the best targets to place stringent constraints on DM: High J-factors thanks to a favorable combination of distance and density
- Stellar kinematics trace the underlying gravitational potential
  - Standard approach: spherical Jeans analysis in Bayesian framework to constrain the DM density
  - Need to be careful of possibles biases introduced by modeling choices: extensive checking on mock data!
  - Continuous development:
    - axisymmetric Jeans analysis (e.g. Hayashi et al. 2016)
    - informative priors (e.g. Ando et al. (2020))
    - non-parametric approach + higher orders of the velocity distribution (e.g. Read & Steger 2017)

DM modeling of galactic targets

1. Galactic center region
2. Dwarf spheroidal galaxies
3. Dark galactic clumps

Dark galactic haloes

- Low mass dark haloes pertain the Galactic DM halo
- Some may be quite close to us
- DM annihilation in a dark clump would be seen as a point-like emission in γ-rays, with no counterpart
- If no-detection, place limits *provided a model of* ***the subhalo population***
- Conversely to Galactic halo or dSph galaxies, all we can rely on are results from numerical simulations or semi-analytical modeling to use as ingredients

Dark galactic haloes

The ingredients

From Part 1, recall the 7 ingredients to described the average contribution of substructures to J-factor

$$\langle J_{\rm subs}\rangle = N_{\rm tot}\int_0^{\Delta\Omega}\int_{l_{\rm min}}^{l_{\rm max}}\frac{\mathrm{d}\mathscr{P}_V}{\mathrm{d}V}(r(l,\Omega))\,\mathrm{d}l\,\mathrm{d}\Omega\int_{M_{\rm min}}^{M_{\rm max}}\frac{\mathrm{d}\mathscr{P}_M}{\mathrm{d}M}(M)\times\int_{c_{\rm min}(M)}^{c_{\rm max}(M)}\frac{\mathrm{d}\mathscr{P}_c}{\mathrm{d}c}(c,M)\,\mathscr{L}(M,c)\,\mathrm{d}c\,\mathrm{d}M$$

$$\mathscr{L}(M,c) = \int_{V_{\rm halo}}\rho^2(M,c)\,dV$$

Those distributions give a full statistical description of the subhalo population
- → can generate realisations
- → early studies: stick to one configuration
- → to bracket modeling uncertainties, need to explore various options for each of these

Dark galactic haloes

The ingredients

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→ to bracket modeling uncertainties, need to explore various options for each of these

Hütten et al (2016)

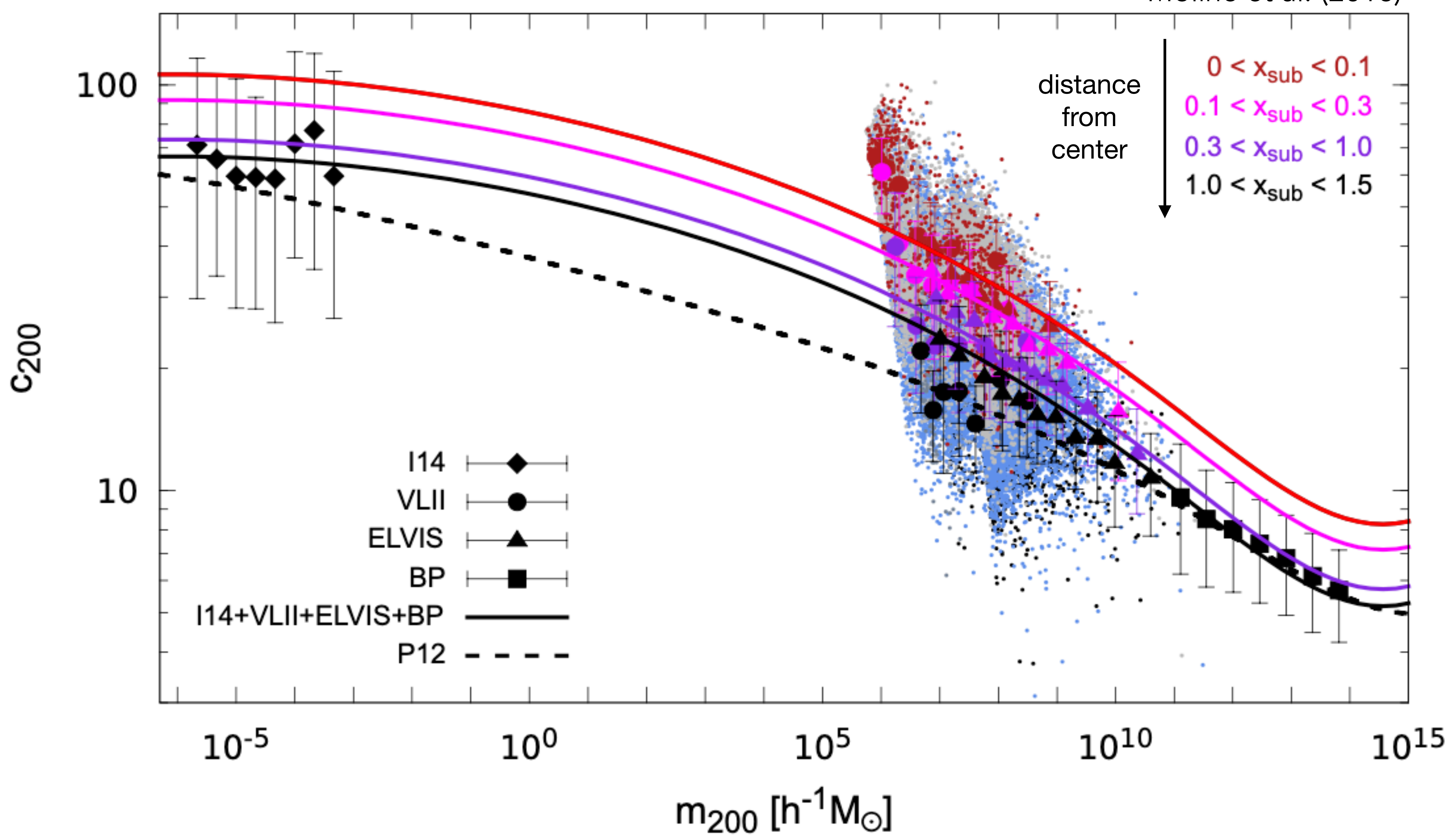
	Model	VAR0	LOW	VAR1	VAR2	VAR3	VAR4	VAR5	VAR6a	VAR6b	HIGH
Varied parameters	inner profile	NFW	E	E	E	E	E	E	E	E	E
	α_m	1.9	1.9	2.0	1.9	1.9	1.9	1.9	1.9	1.9	1.9
	σ_c	0.14	0.14	0.14	0.24	0.14	0.14	0.14	0.14	0.14	0.14
	$\bar{\varrho}_{subs}$	E-AQ	E-AQ	E-AQ	E-AQ	M-VLII	E-AQ	E-AQ	E-AQ	E-AQ	M-VLII
	N_{calib}	150	150	150	150	150	300	150	150	150	300
	sub-subhalos?	no	no	no	no	no	no	yes	no	no	no
	$c(m)$	SP	SP	SP	SP	SP	SP	SP	Moliné	P-VLII	P-VLII

Dark galactic haloes

Subhalo specificities: radial-dependent concentration

$$\langle J_{\rm subs}\rangle = N_{\rm tot}\int_0^{\Delta\Omega}\int_{l_{\rm min}}^{l_{\rm max}} \frac{\mathrm{d}\mathscr{P}_V}{\mathrm{d}V}(r(l,\Omega))\,\mathrm{d}l\,\mathrm{d}\Omega \int_{M_{\rm min}}^{M_{\rm max}} \frac{\mathrm{d}\mathscr{P}_M}{\mathrm{d}M}(M) \times \int_{c_{\rm min}(M)}^{c_{\rm max}(M)} \frac{\mathrm{d}\mathscr{P}_c}{\mathrm{d}c}(c,M)\,\mathscr{L}(M,c)\,\mathrm{d}c\,\mathrm{d}M$$

Moliné et al. (2016)



Compared to field haloes, subhaloes d are subject to tidal stripping, making them more compact.

The closer to the center of the host halo, the more concentrated the subhalos.

$$c(M) \rightarrow c(M,r)$$

Dark galactic haloes

Subhalo specificities: radial-dependent concentration

$$\langle J_{\rm subs}\rangle = N_{\rm tot}\int_0^{\Delta\Omega}\int_{l_{\min}}^{l_{\max}}\frac{\mathrm{d}\mathscr{P}_V}{\mathrm{d}V}(r(l,\Omega))\,\mathrm{d}l\,\mathrm{d}\Omega\int_{M_{\min}}^{M_{\max}}\frac{\mathrm{d}\mathscr{P}_M}{\mathrm{d}M}(M)\times\int_{c_{\min}(M)}^{c_{\max}(M)}\frac{\mathrm{d}\mathscr{P}_c}{\mathrm{d}c}(c,M,r(l,\Omega))\,\mathscr{L}(M,c,r(l,\Omega))\,\mathrm{d}c\,\mathrm{d}M$$

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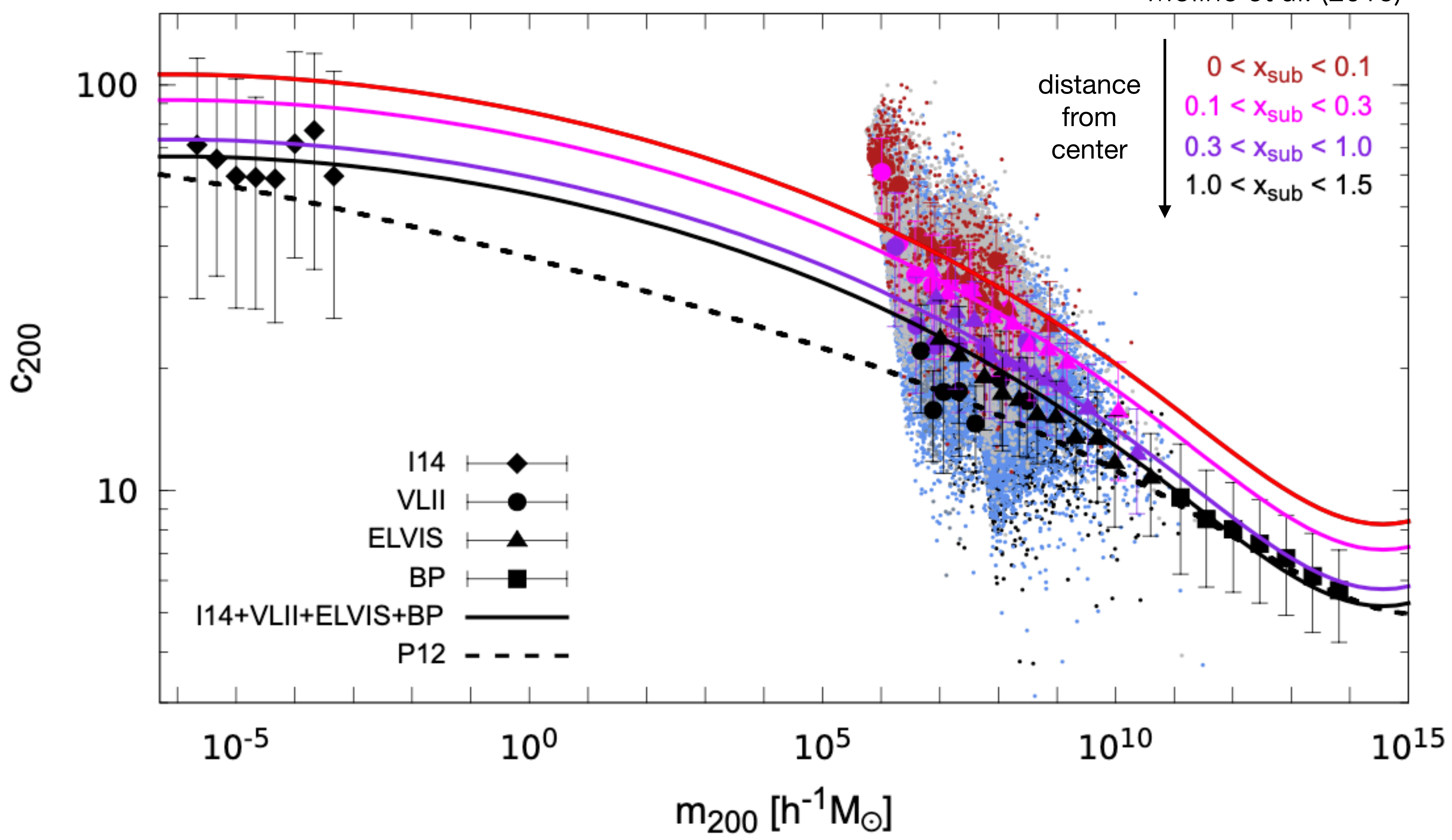

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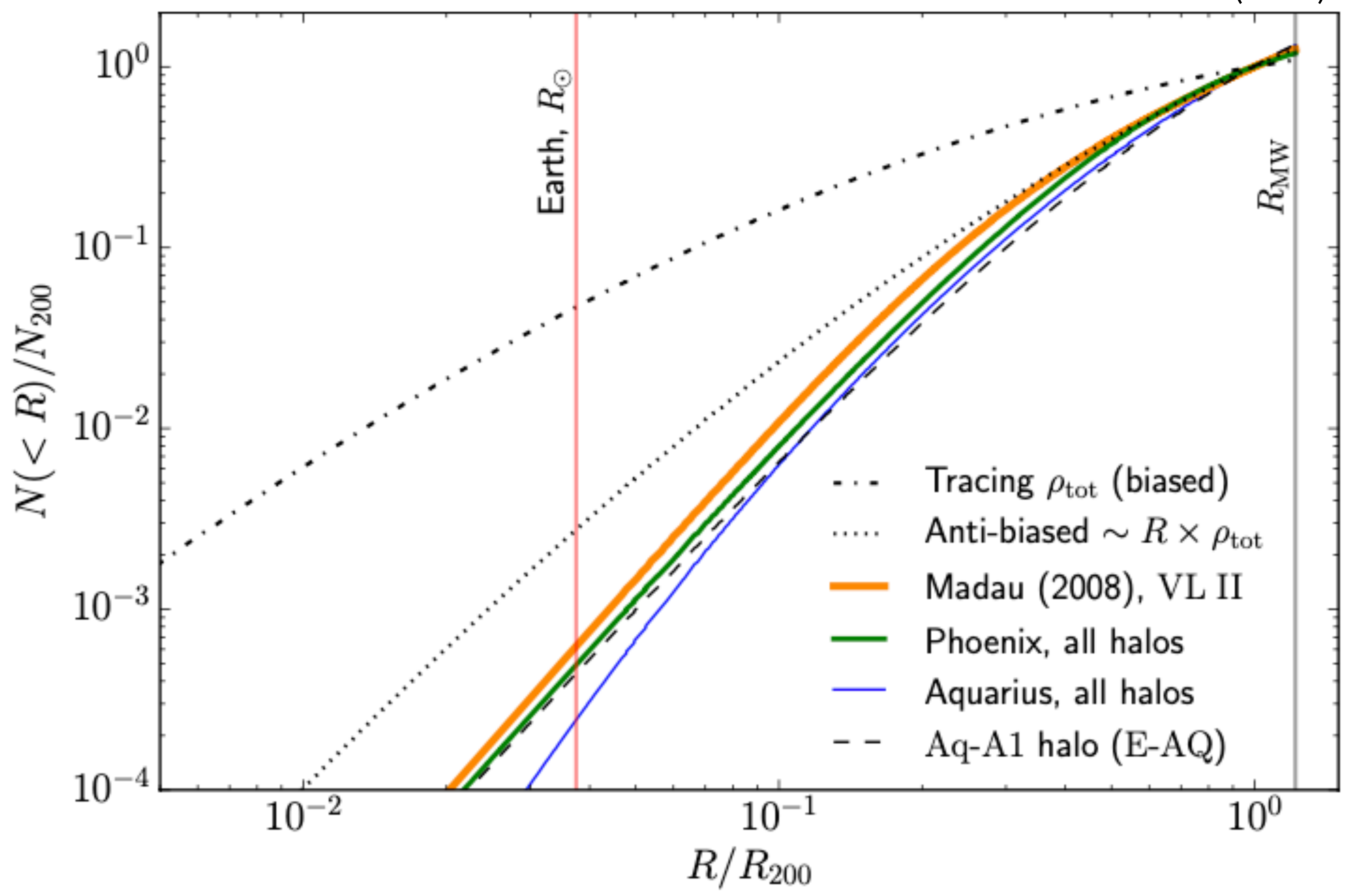
The closer to the center of the host halo, the more concentrated the subhalos.

$$c(M) \to c(M, r)$$

Dark galactic haloes

Subhalo specificities: tidal disruption from the host DM halo

Hütten et al (2016)

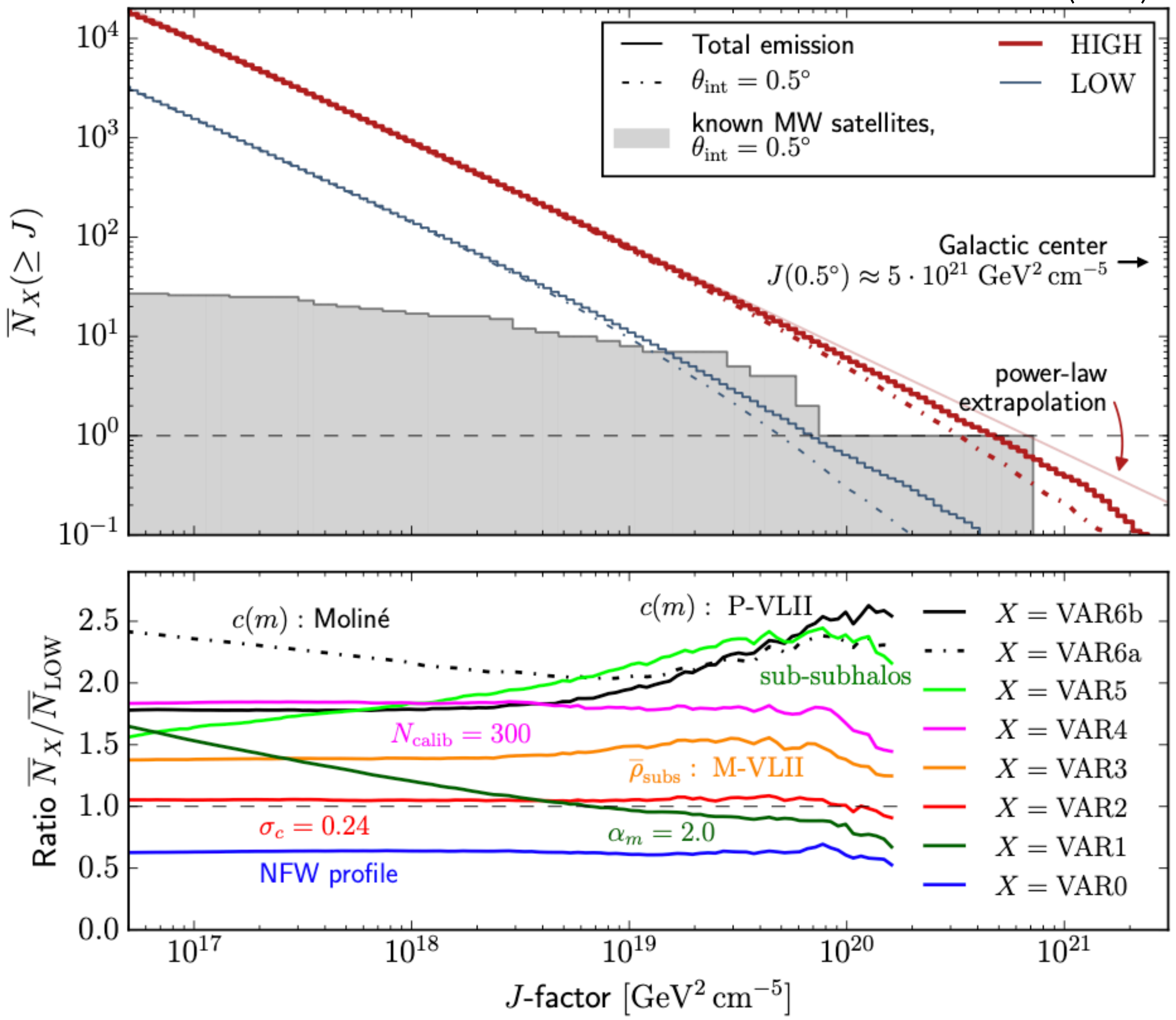


- unevolved population: spatial distribution follows the total/smooth distribution
- tidal stripping/disruption due to the strong gravitational gradient in the inner region
  → reduces the number of haloes in the inner region of the host halo
- effect captured naturally captured by simulations, but can also be model from (semi-)analytical considerations (Han et al. 2016)

Dark galactic haloes

Cumulative source count distribution

Hütten et al (2016)



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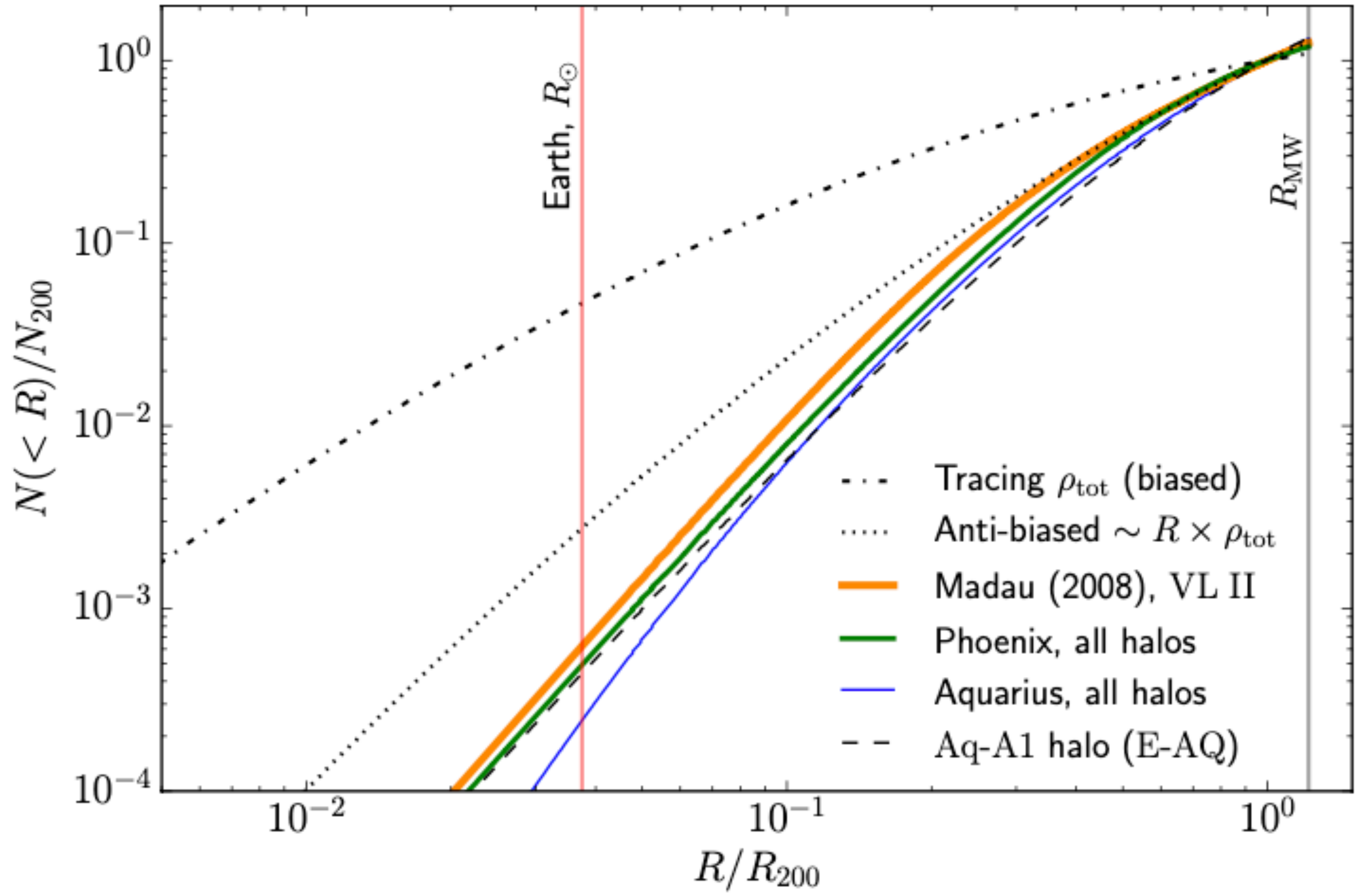
	$N_{\rm calib}$	150	150	150	150	150	300	150	150	150	300
	sub-subhalos?	no	no	no	no	no	no	yes	no	no	no
	$c(m)$	SP	SP	SP	SP	SP	SP	SP	Moliné	P-VLII	P-VLII

Modeling choices matter and the cumulative source count distribution can vary by ~ 1 order of magnitude

Dark galactic haloes

Subhalo specificities: tidal disruption from the host DM halo

Hütten et al (2016)



- unevolved population: spatial distribution follows the total/smooth distribution
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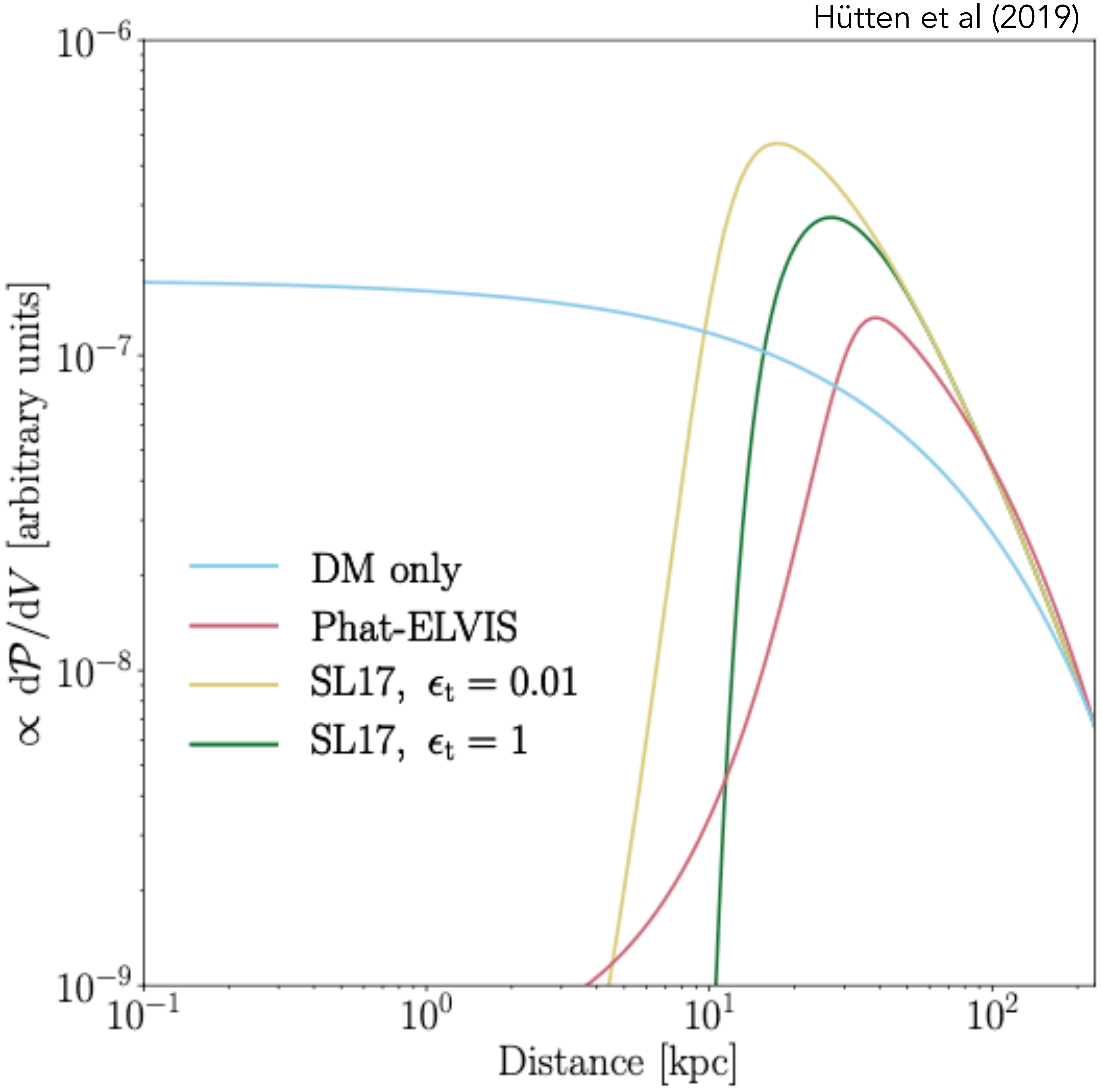
Dark galactic haloes

Subhalo specificities: tidal disruption from the host DM halo + baryonic disk

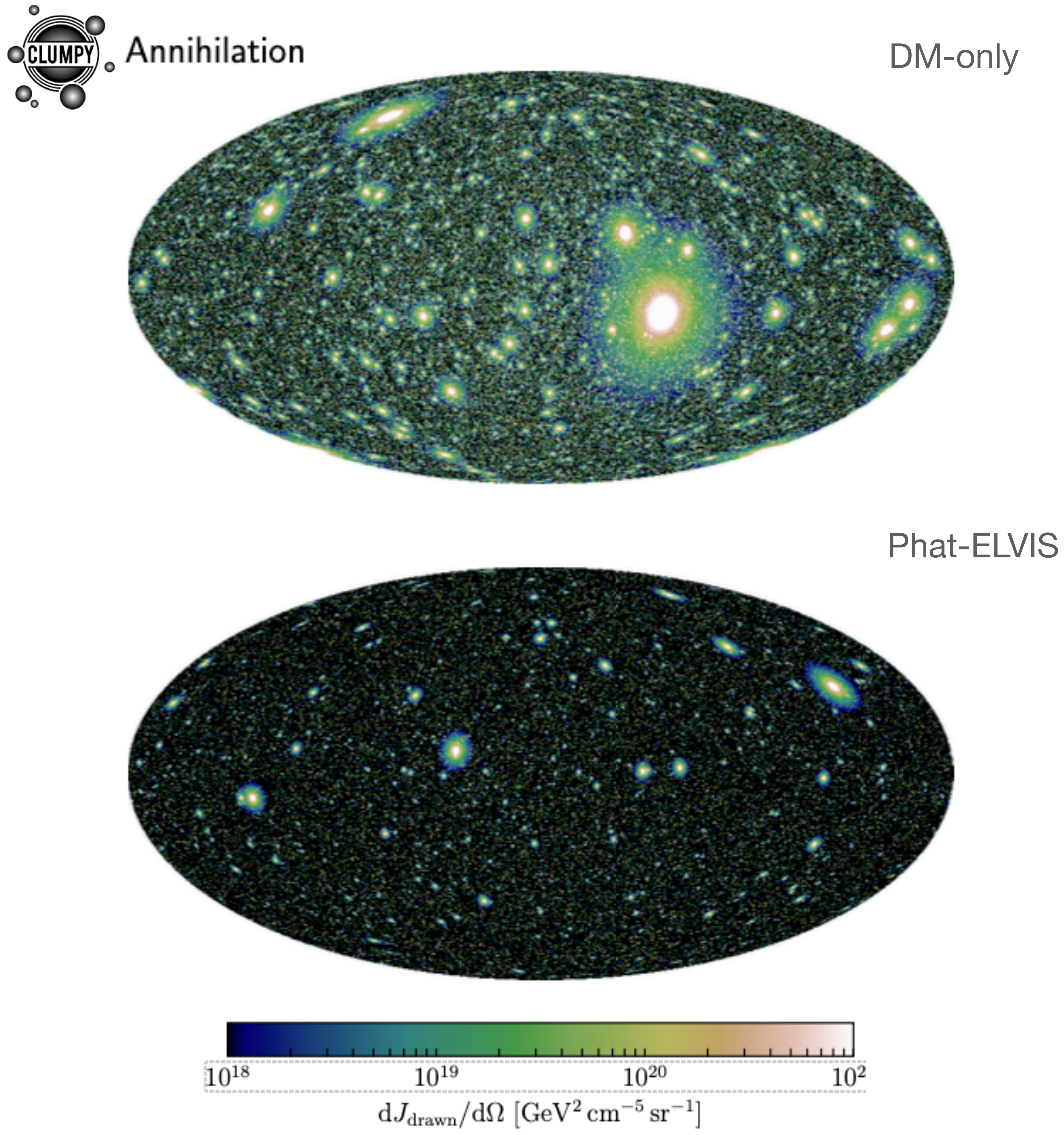
Hütten et al (2019)



- adding potential from a baryonic disk has an even stronger impact, with total depletion of subhaloes in the innermost regions
- effect captured captured by simulations with added disk potential (Kelley et al. 2019), but can also be modeled from (semi-)analytical considerations (Stref & Lavalle 2017)

Dark galactic haloes

Subhalo specificities: tidal disruption from the host DM halo + baryonic disk



- Drastic consequences on the properties of the brightest subhalo in annihilation, with decrease of the flux of the brightest subhalo by a factor of 2 to 7 when adding disk potential

- Caution: semi-analytical model use simplifying assumptions and simulations may suffer from numerical disruption of subhaloes

Dark galactic haloes

Summary

- Dark subhaloes in the MW Galactic halo can be constraining “targets”
  → Fermi-LAT all sky survey, CTA planned extragalatic survey

- Modeling of the subhalo population requires 7 ingredients. Constraints may only come from numerical simulations or semi-analytical modeling

- Need to better pin down the effect of tidal stripping in the full MW potential to get a better picture

DM modeling of extragalactic targets

1. Galaxy clusters

2. The extragalactic diffuse exotic signal

Galaxy clusters

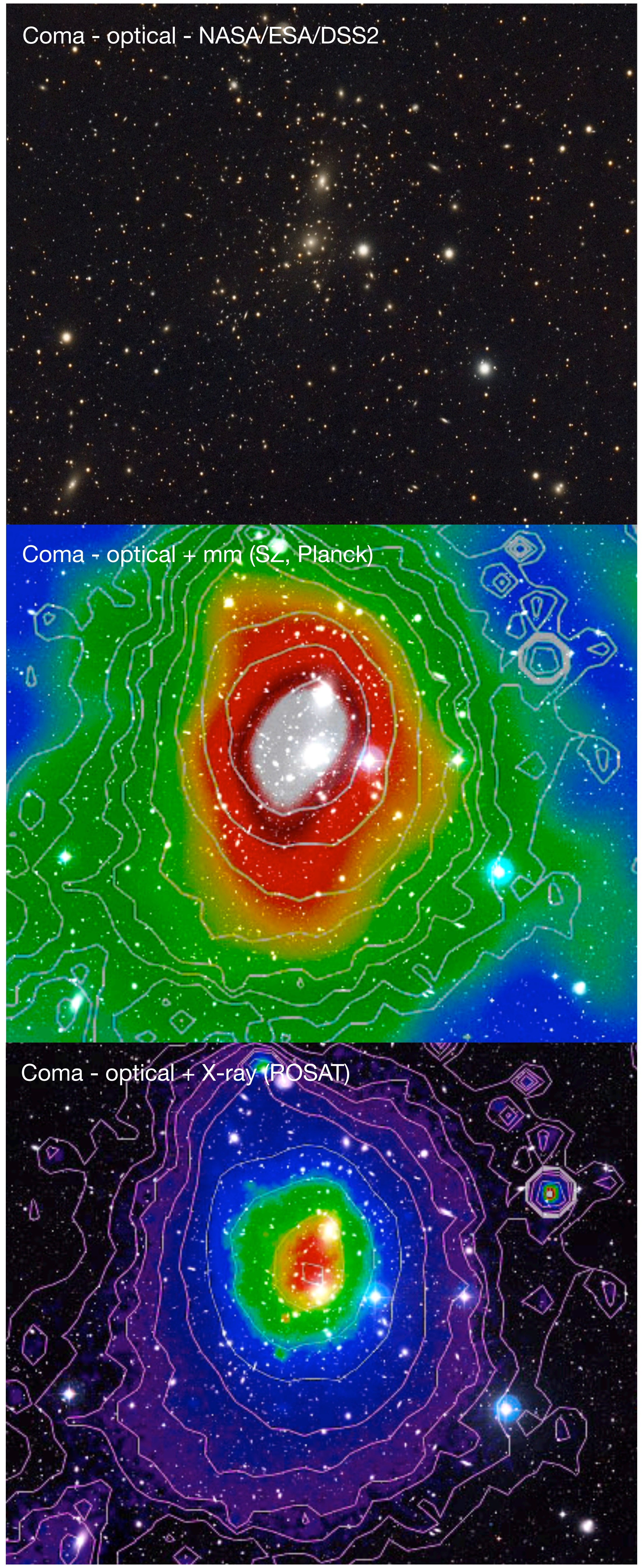
Overview

- Last stage of structure formation; largest gravitationnally-bound objects in the universe

- ~10^{14} - 10^{15} M_{sun}, densest regions in the universe
  - ~80% dark matter
  - ~15% hot gas
  - ~a few% galaxies

- "Close by" clusters: Virgo (~16 Mpc), Coma (~102 Mpc)
  - large $1/d^2$ dilution the exotic signal

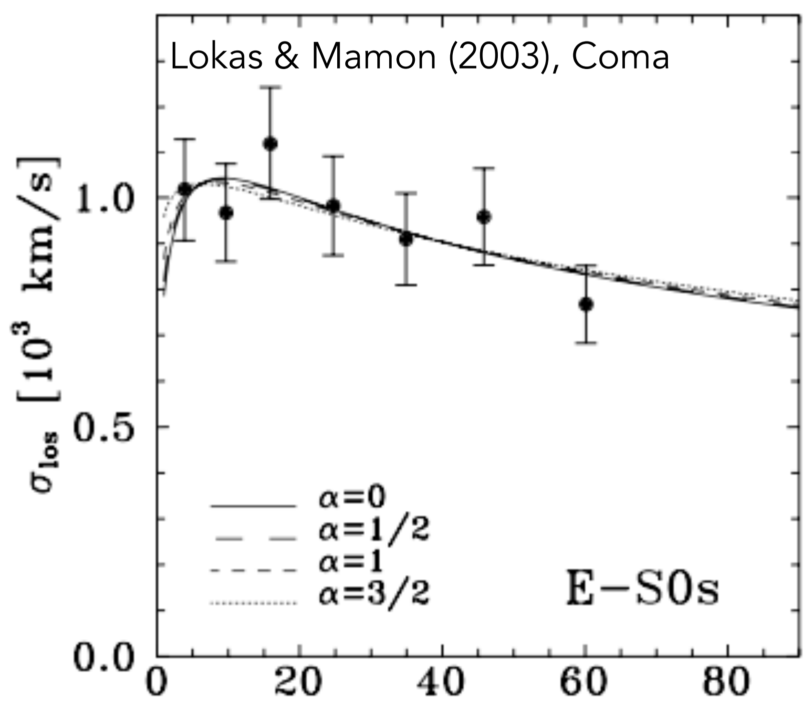
- Observationnally
  - X-rays: hot gas emission (free-free from ICM e^-)
  - mm-wavelength: hot gas - CMB interaction (SZ effect)
  - Visible, infrared: galaxies
  - γ-rays? expected emission from interaction between gas and cosmic rays (background for DM indirect detection)



Galaxy clusters

Mass, DM profile determination

Dynamical estimation (visible, spectroscopy)

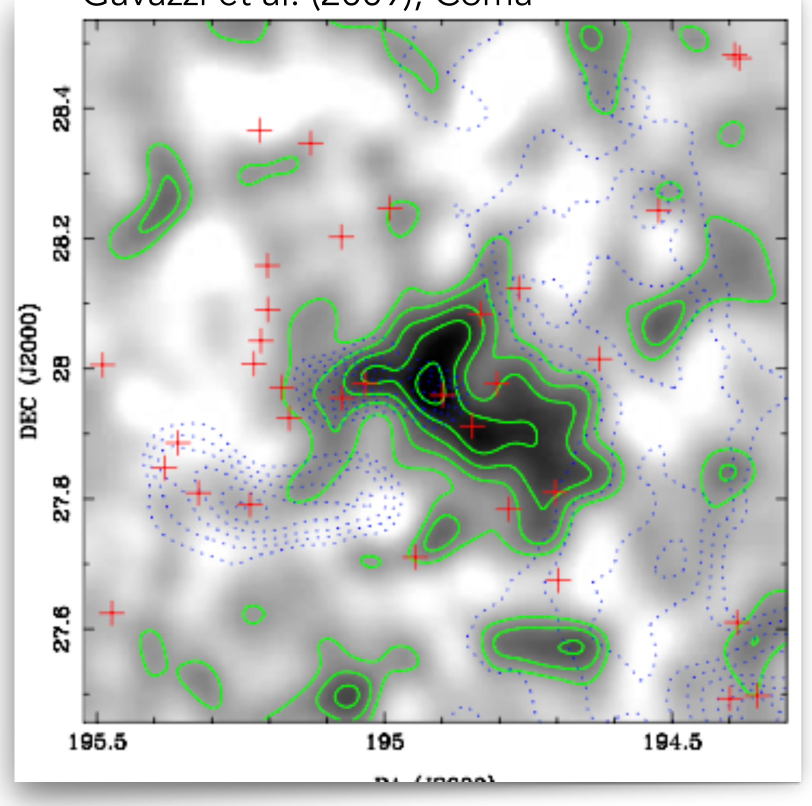


Measure velocity dispersion of galaxies in the cluster
→ use virial theorem to get the mass
→ perform Jeans analysis and fit for the density profile

In the Jeans equation (≠ dSph)
$M_{tot}(r) = M_{DM}(r) + M_{gas}(r) + M_{stars}(r)$

Weak lensing mass estimate (visible)

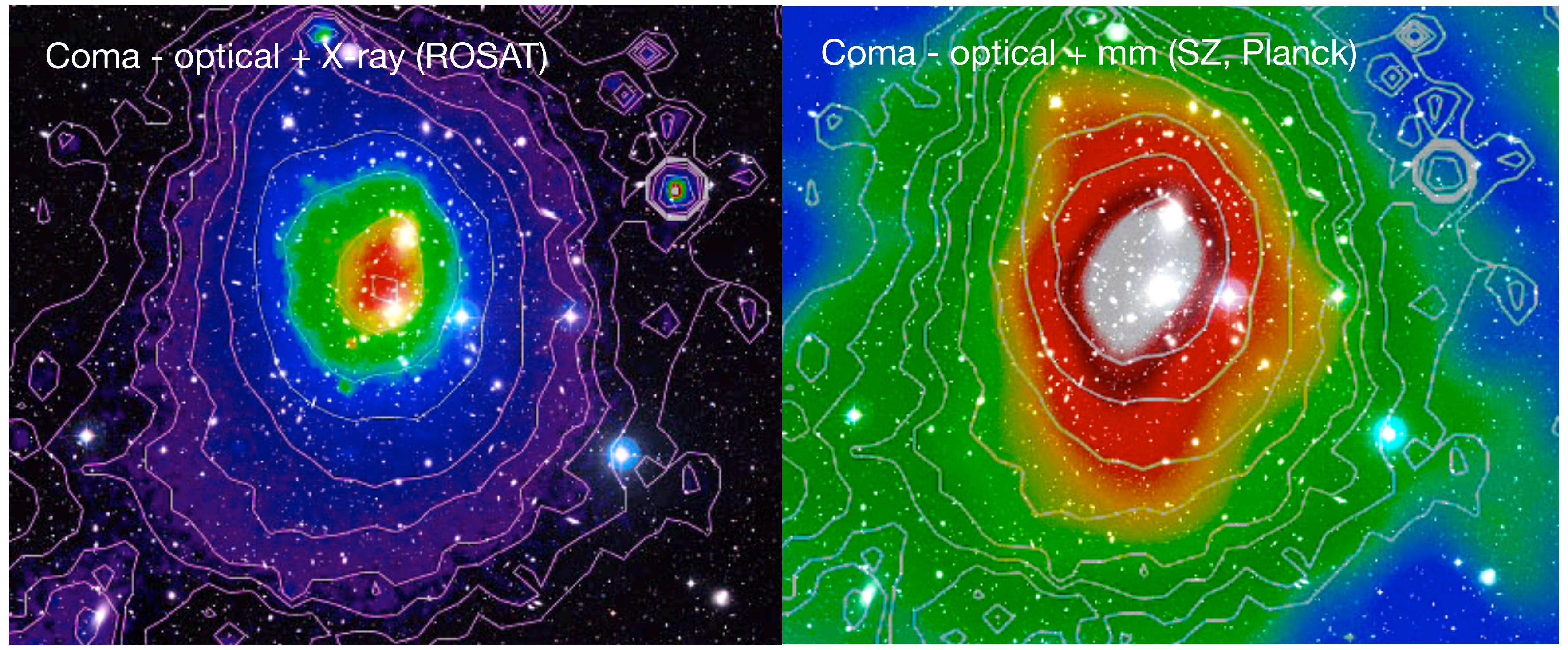
Gavazzi et al. (2009), Coma



Weak gravitational lensing:
- the shape of background galaxies are coherently distorted in the presence of a foreground cluster (lens).
- the amount of distorsion depends on the project mass density of the lens

No assumption on dynamical state of the system

Mass estimation from baryonic proxies (X-rays, SZ)



$n_e(r), T_e(r)$

$P(r) = n_e(r) k T_e(r)$

Assume hydrostatic equilibrium

$$\frac{dP}{dr} = -\rho g = -\rho \frac{G M_{HSE}(r)}{r^2}$$

$$M_{HSE}(r) = -\frac{r^2}{G \mu m_p n_e(r)} \times \frac{dP(r)}{dr}$$

- If HSE is wrong, reconstructed mass may be biased
- Large catalogs

Galaxy clusters

Mass, DM profile determination

Dynamical estimation (visible, spectroscopy)

Measure velocity dispersion of galaxies in the cluster
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→ perform Jeans analysis and fit for the density profile

In the Jeans equation (≠ dSph)

$M_{tot}(r) = M_{DM}(r) + M_{gas}(r) + M_{stars}(r)$

At the cluster scale, NFW profiles are generally a good fit the data

Weak lensing mass estimate (visible)

Weak gravitational lensing:

- the shape of background galaxies are coherently distorted in the presence of a foreground cluster (lens).
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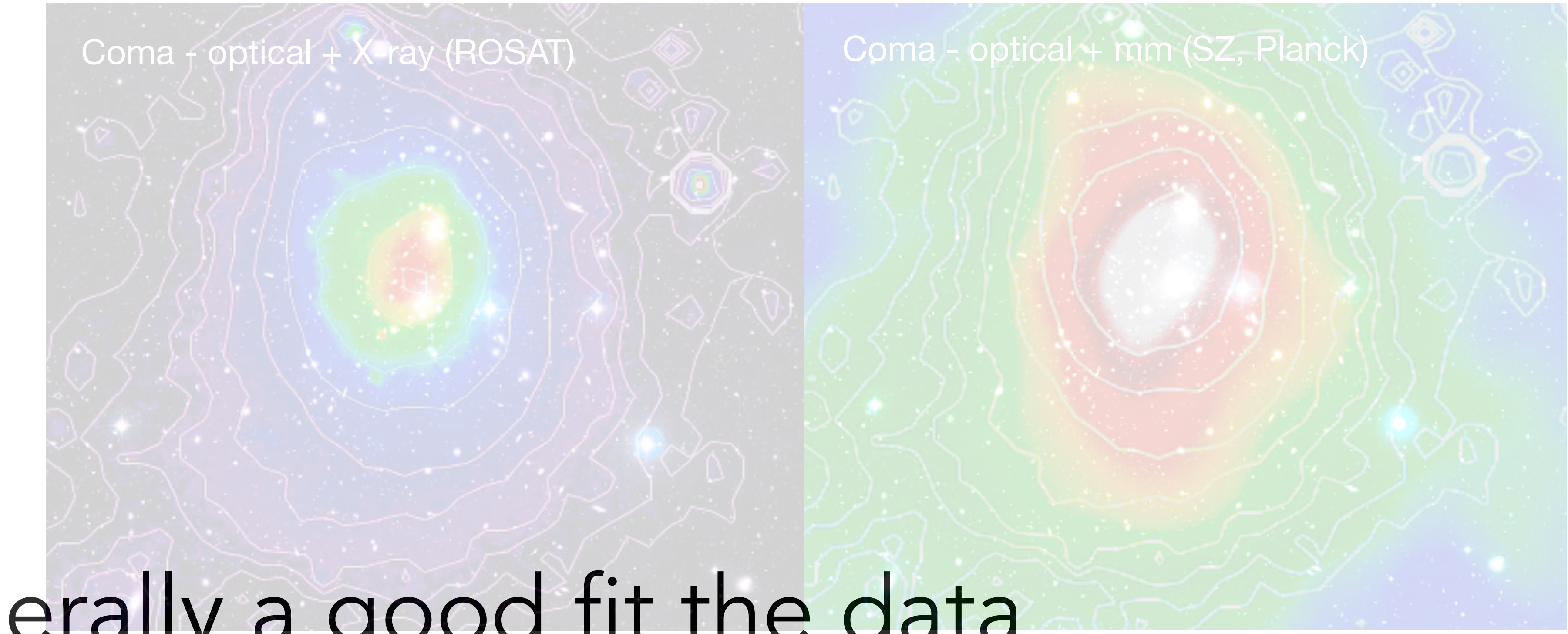

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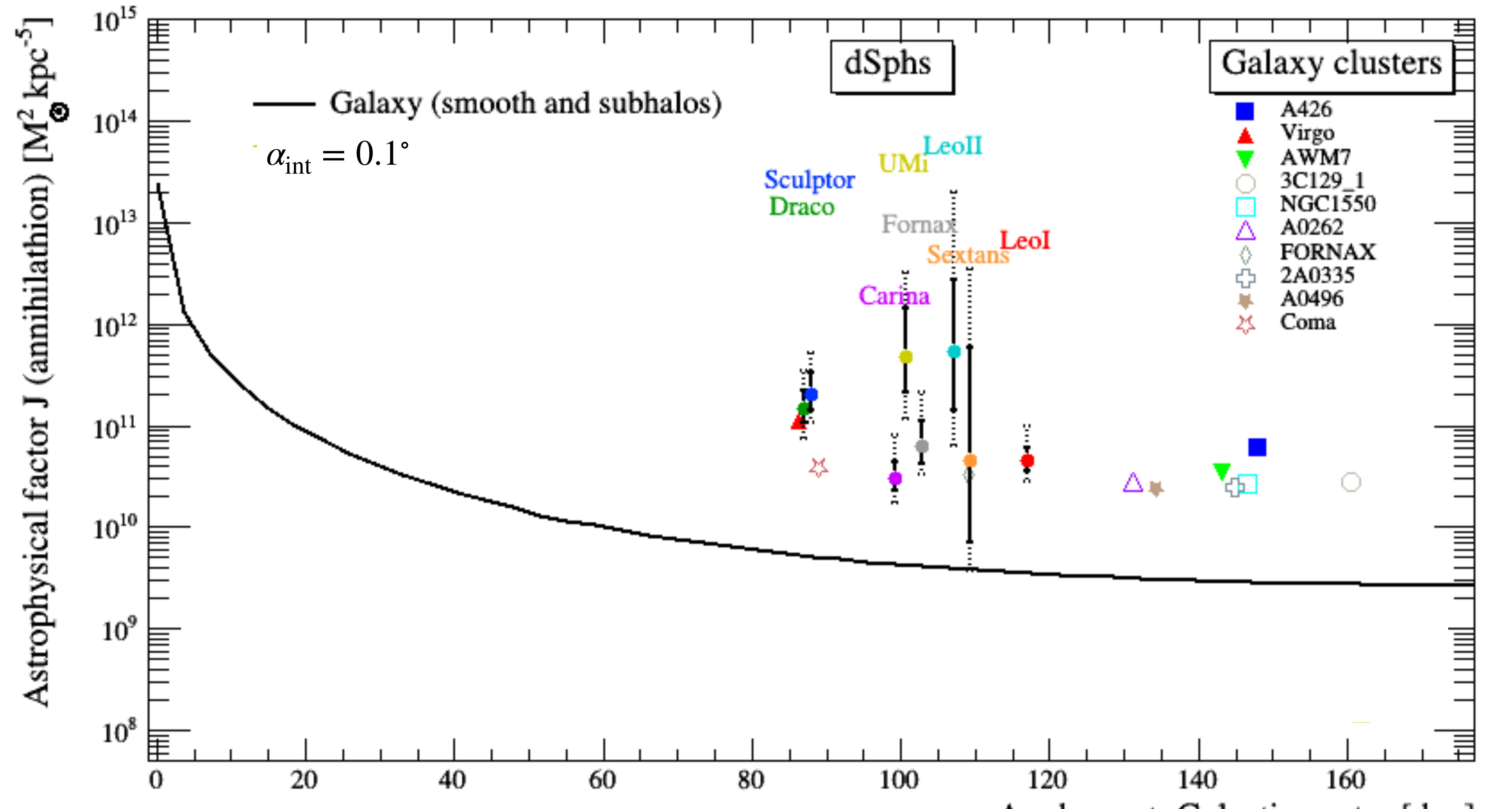
Galaxy clusters

J-factors, boost from substructures?

Varied type of information available from the literature

- directly get ρ_s, r_s
- get the mass with a given radius, e.g. $M_{500,c}$
  - in that case, need to use a M-c relation
  - be careful with the mass definition!



Adapted from Nezri et al. (2012)

Best cluster J-factors $\lesssim$ than that of dSphs

Galaxy clusters

J-factors, boost from substructures?

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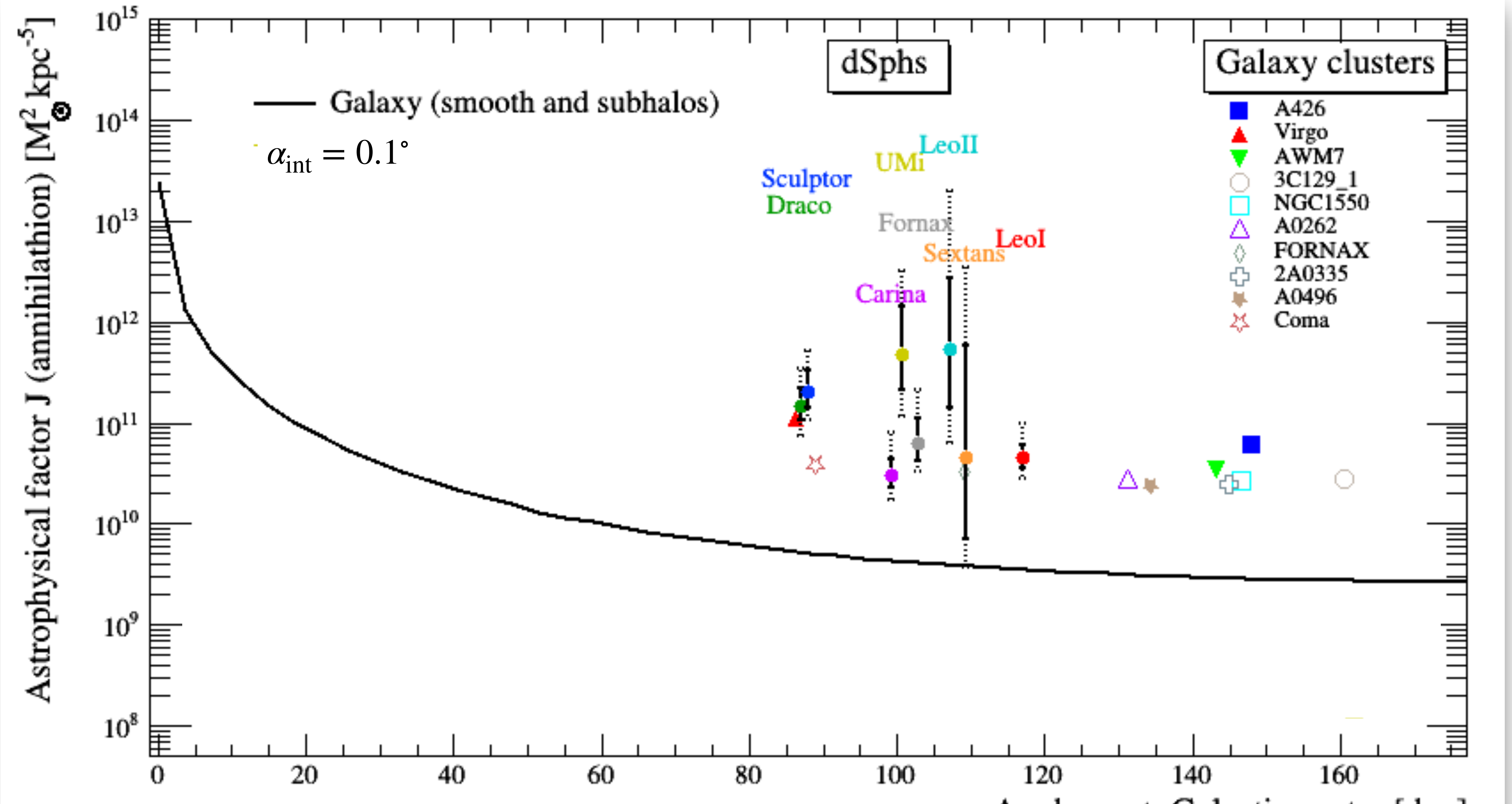
Boost in galaxy clusters?

- early 2010s, boost ~1000! Power-law extrapolation down to 10^{-6} M_{sun} of M-c relations obtained from simulations ($M>10^{10}$ M_{sun})
- Now, using flattened M-c relation, boost~10-50



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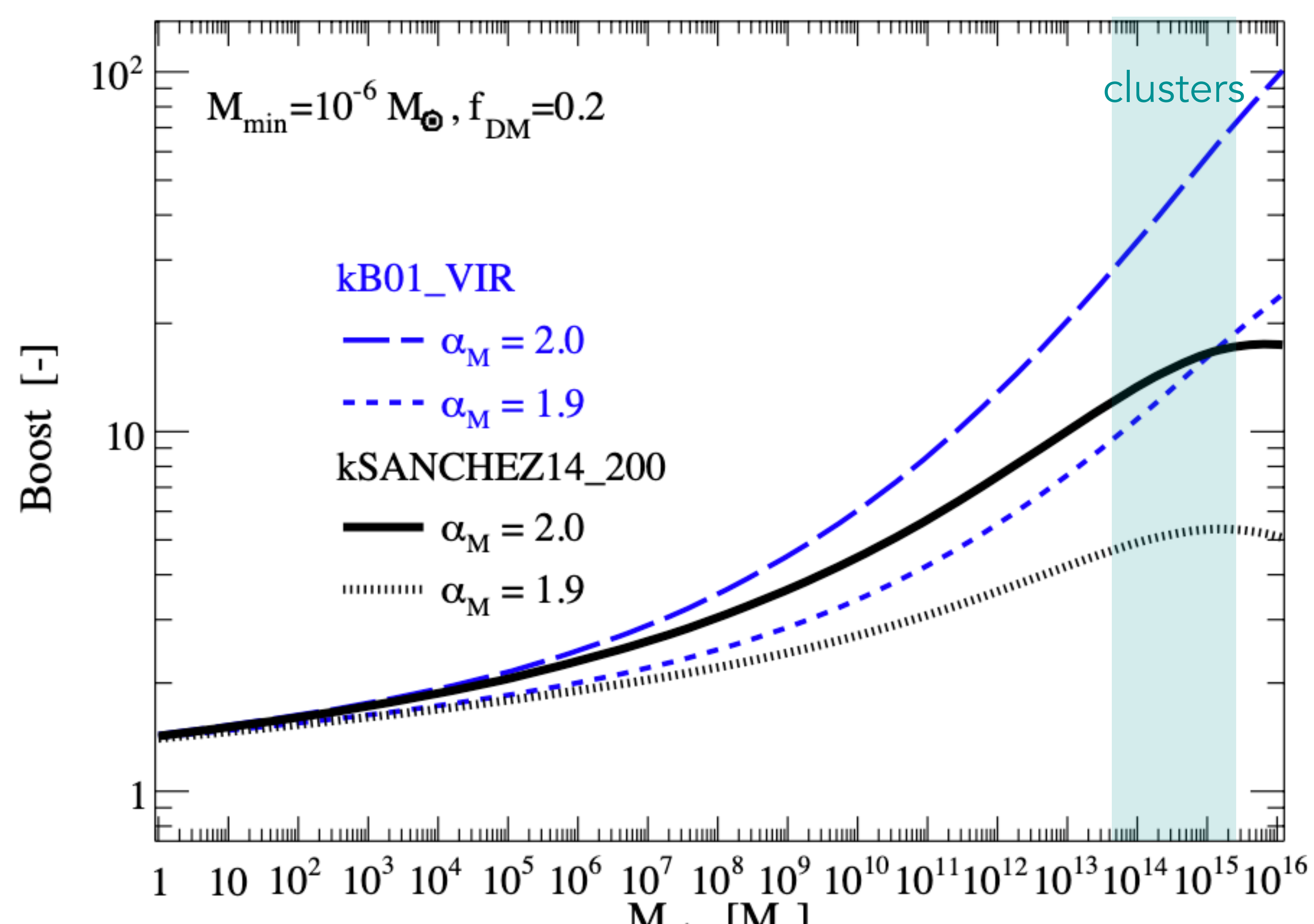

Bonnivard et al. (2016)

Galaxy clusters

Summary

- Galaxy clusters are the densest part of the universe
- Large X-ray catalogs of “close-by” clusters. Option to stack the signal in survey data
- Their masses/profiles can be determined in multiple wavelength
  → allow to cross-check results
  → cuspy profiles, NFW
- Substructures may boost the annihilation signal by ~10-50
- J-factors $\lesssim$ than that of dSphs

DM modeling of extragalactic targets

1. Galaxy clusters
2. The extragalactic diffuse exotic signal

The diffuse extragalactic signal

Getting started

- Dark matter in the entire universe annihilates

  → gives raise to an isotropic exotic gamma-ray signal

- Recall: at the Galactic scale, we had

particle physics

Astrophysical "J-factor": $[M_\odot^2\ \mathrm{kpc}^{-5}]$ or $[\mathrm{GeV}^2\mathrm{cm}^{-5}]$

$$\frac{d\Phi}{dE}(E,\vec{k},\Delta\Omega(\alpha_{\rm int})) = \frac{\langle\sigma v\rangle}{4\pi\ \delta\ m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f \times \int_0^{2\pi} d\beta \int_0^{\alpha_{\rm int}} \sin\alpha d\alpha \int_0^{l_{\rm max}} \rho^2(\vec{k}\ l,\alpha,\beta)\ dl$$

The diffuse extragalactic signal

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Can we separate the spectral and astrophysical part when considering the extragalactic emission? Why?

What new ingredients do we need?

The diffuse extragalactic signal

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Can we separate the spectral and astrophysical part when considering the extragalactic emission? Why?

No. Integration along los = integration over redshift range and spectrum depends on redshift

What new ingredients do we need?

- Cosmology
- Halo mass function
- EBL absorption model

The diffuse extragalactic signal

$$I(E_\gamma) = \left\langle \frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma\,\mathrm{d}\Omega} \right\rangle_{\mathrm{sky}} = \frac{\overline{\varrho}^2_{\mathrm{DM},0}\,\langle\sigma v\rangle}{8\pi\, m_\chi^2} \int_0^{z_{\max}} c\,\mathrm{d}z\, \frac{(1+z)^3}{H(z)} \langle \delta^2(z) \rangle \left. \frac{\mathrm{d}N^\gamma_{\mathrm{source}}}{\mathrm{d}E_\mathrm{e}} \right|_{E_\mathrm{e}=(1+z)E_\gamma} \times e^{-\tau(z,\,E_\gamma)}$$

Structure formation

Source Spectrum and EBL absoprtion

"Intensity multiplier"

$$\langle \delta^2(z) \rangle = \frac{1}{\overline{\varrho}^2_{\mathrm{m},0}} \int \mathrm{d}M\, \frac{\mathrm{d}n}{\mathrm{d}M}(M,z) \times \mathcal{L}(M,z)$$

single halo luminosity

Halo mass function

$$\frac{\mathrm{d}n}{\mathrm{d}M}(M,\,z) = f(\sigma,z)\,\frac{\overline{\varrho}_{\mathrm{m},0}}{M}\,\frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}M}$$

Variance of the density field on scale defined by R(M)

$$\sigma^2(M,\,z) = \frac{D(z)^2}{2\pi^2}\int P_{\mathrm{lin}}(k, z=0)\, \widehat{W}^2(kR)\, k^2\,\mathrm{d}k$$

Linear matter power spectrum = f(cosmo)

The diffuse extragalactic signal

Capturing the modeling uncertainties

Hütten et al (2018)

Reference intensity: I_0
($M \geq 10^{10}$ $M_\odot$, no subhalos)

Physics properties	*Reference I_0*	*Variations $I_{0,\,\mathrm{var}}$*	$\lvert I_0 - I_{0,\,\mathrm{var}} \rvert / I_0$
Halo mass function†	R16 [28]	T08 [32], B16 [55]	$\lesssim 40\,\%$
Density profile ρ_{halo}	$\alpha_E = 0.17$	$\alpha_E = 0.15$, $\alpha_E = 0.22$, NFW	$\lesssim 20\,\%$
$c_\Delta(M_\Delta)$ relation‡	C15 [29]	L16 [30], C15-σ_c=0.2, (S14)	$\lesssim 10\,\%$
Cosmology (h, Ω_i, P_k)§	*Planck*–R16 [28]	WMAP7 [56], (WMAP-T08)	$\lesssim 10\,\%$
Overdensity definition	Δ_{vir} (3.3)	Δ_c (3.1) or Δ_m (3.2)=200	$\lesssim 5\,\%$
EBL model⋆	I13 [57]	F08 [58], D11 [59], G12 [60]	$\lesssim 5 - 40\,\%$

Total CDM contribution: I_l (extrapolation to low masses)
($M \geq M_{\mathrm{min}}$, no subhalos)

Field halo properties	*Values (default in **bold**)*	*I_l/I_0 ($\simeq$ 5)*
Slope of $\mathrm{d}n/\mathrm{d}M$, α_M	1.85, **1.9**, 1.95	$\sim 4 - 14$
Minimal mass M_{min}	10^{-12}, $\mathbf{10^{-6}}$, 10^{-3} $M_\odot$	$\sim 4 - 8$
Density profile ρ_{halo}	$\alpha_E = 0.15$, **0.17**, 0.22, NFW, Ishiyama [61]	$\sim 4 - 8$
$c_\Delta(M_\Delta)$ relation‡	**C15** [29], L16 [30], (S14 [33])	$\sim 3 - 8$

. . . including boost from subhalos: I_b
($m \geq m_{\mathrm{min}}$ with $m_{\mathrm{min}} \equiv M_{\mathrm{min}}$)

(Sub-)halo properties	*Values (default in **bold**)*	*I_b/I_l ($\simeq$ 1.5)*
Mass fraction f_{subs}	10 %, **20 %**, 40 %	$\sim 1.2 - 2.2$
Minimal mass m_{min}	10^{-12}, $\mathbf{10^{-6}}$, 10^{-3} $M_\odot$	$\sim 1.3 - 1.8$
$c_\Delta(M_\Delta)$ relation‡	**C15** [29], L16 [30], (S14 [33])	$\sim 1.3 - 1.7$
Density profile ρ_{subhalo}	$\alpha_E = 0.15$, **0.17**, 0.22, NFW, Ishiyama [61]	$\sim 1.3 - 1.7$
Slope of $\mathrm{d}P/\mathrm{d}m$, α_m	1.85, **1.9**, 1.95	$\sim 1.4 - 1.7$
$\mathrm{d}P/\mathrm{d}V$ profile	**Aquarius** [62], Phœnix [63], $\propto \rho_{\mathrm{host}}$	$\sim 1.49 - 1.51$

† T08 (Tinker et al., 2008), B16 (Bocquet et al., 2016), R16 (Rodríguez-Puebla et al., 2016)
‡ S14 (Sánchez-Conde & Prada, 2014, [33]), C15 (Correa et al., 2015), L16 (Ludlow et al., 2016)
§ *Planck*–R16 (MultiDark–*Planck* simulations used in Rodríguez-Puebla et al., 2016), WMAP–T08 (Cosmology used in T08, [32])
⋆ F08 (Franceschini et al., 2008), D11 (Domínguez et al., 2011), Gilmore et al. (2012), and I13 (Inoue et al., 2013)

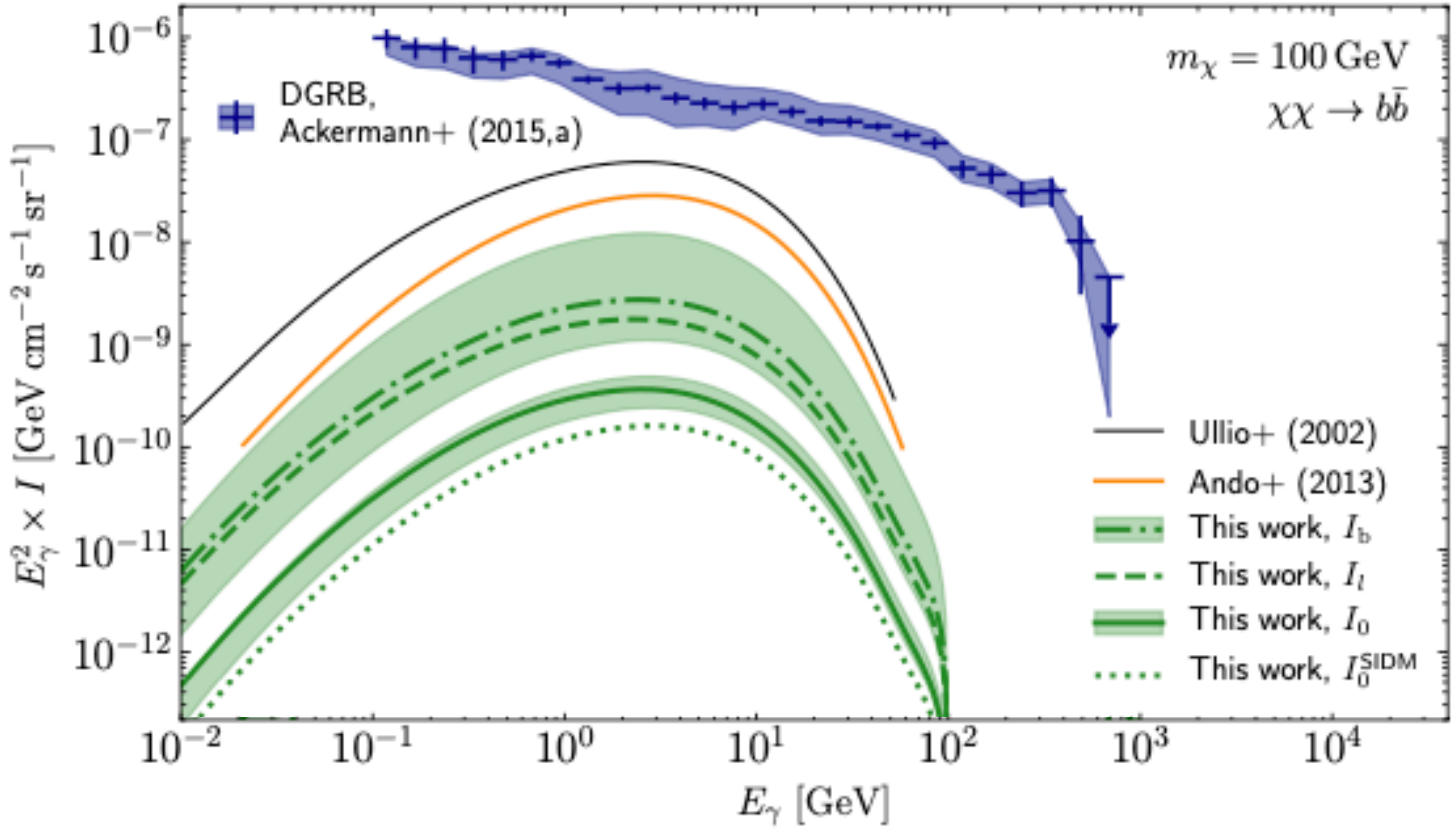
A lot of possible options, all available in

CLUMPY

The diffuse extragalactic signal

Estimation of the signal

Hütten et al (2018)



Modeling uncertainties: ~1 order of magnitude

So, to conclude

- Robust contraints on DM properties require robust J- (or D-) factors determination
- Numerical simulations provide a lot of insight into modeling of DM distribution
- Apart for dark clumps, observational information (dynamics, etc.) specific to the targets under scrutiny can help up infer the DM profile
- Doing so, there are a lot of user-defined choices that may impact the results so remember to check the dependence of the results with respect to a range of these choices.
- CLUMPY v3.1 is out! Update for this afternoon's hands on if you wish/can.