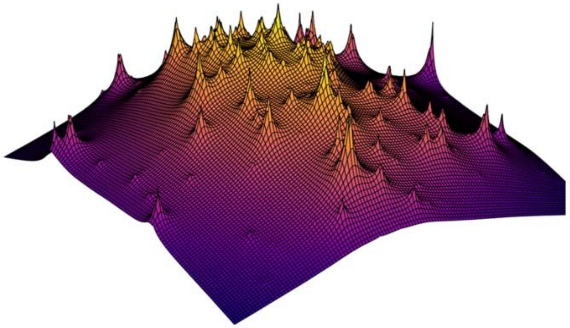
A Monte-Carlo code for simulating subhalos signals for indirect dark matter searches: CLUMPY

(on behalf of the CLUMPY team)

1) γ-rays from DM: brief reminder
2) What is CLUMPY?
3) A few results: focus on subhalos
4) Conclusions



CLUMPY past and present developers
V. Bonnivard, A. Charbonnier, C. Combet,
M. Hütten & E. Nezri

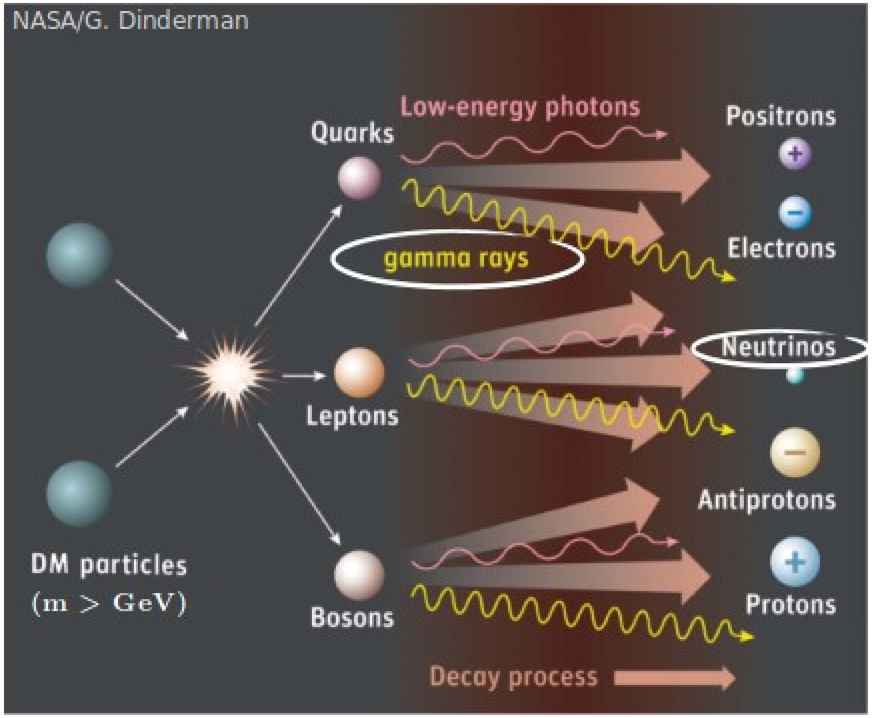
N.B.: Many slides borrowed from M. Hütten and C. Combet!

David Maurin
(LPSC)
`dmaurin@lpsc.in2p3.fr`

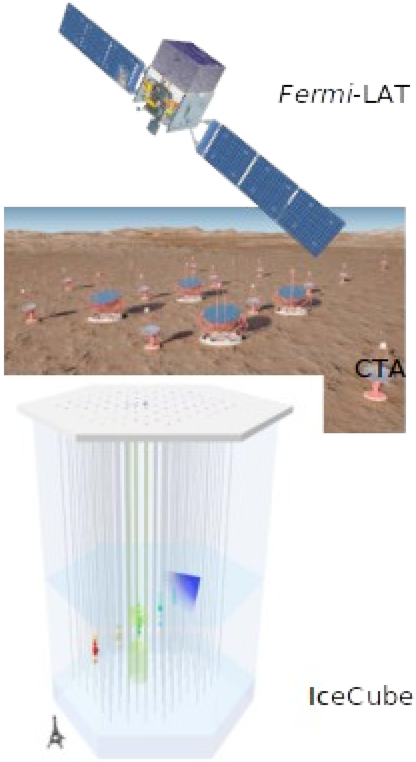
News from the Dark 6
Annecy, 23 Nov. 2021

1) Intro: from DM to γ-rays

Dense & massive astrophysical DM budget → Annihilation or decay of the DM → Detectors for astrophysical γ-rays and neutrinos

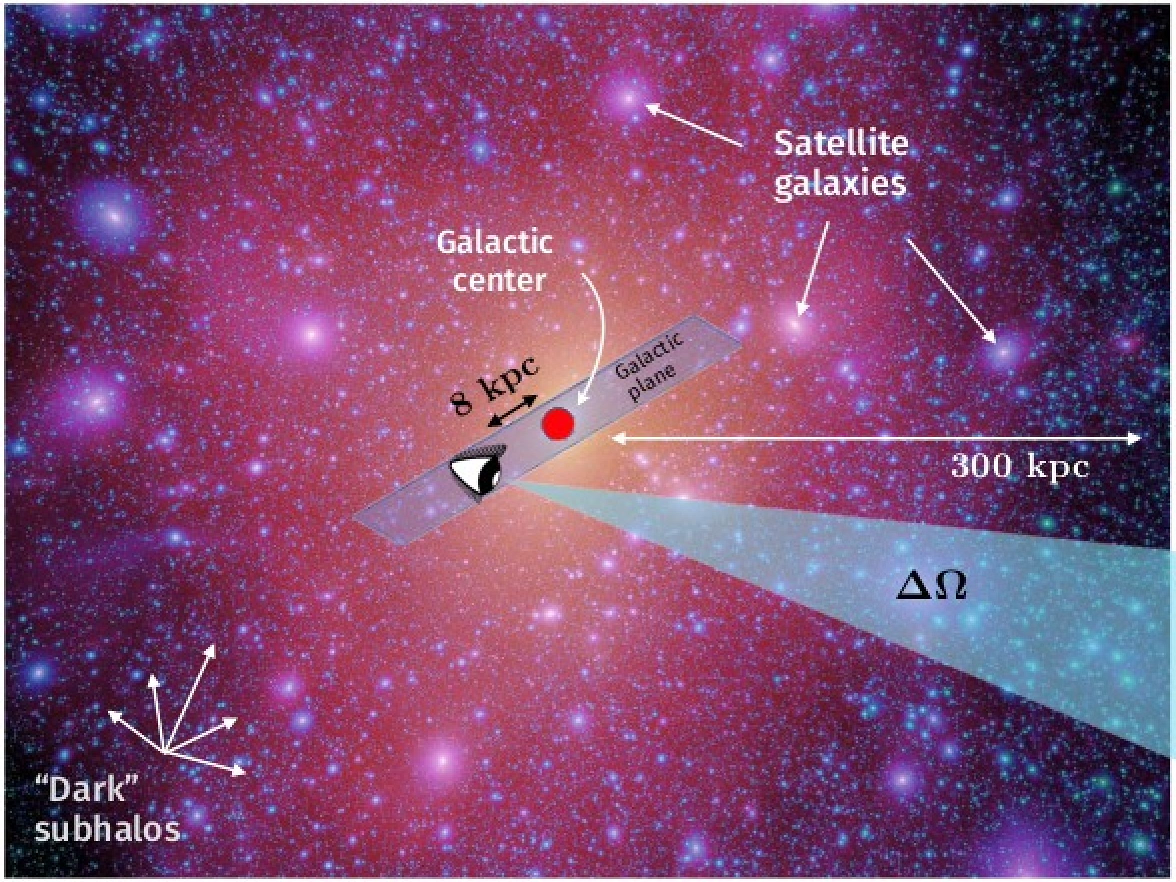


NASA/G. Dinderman



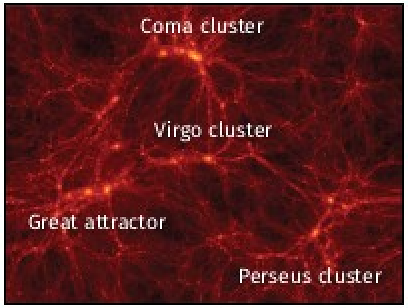
1) Intro: best targets?

Massive & dense (M^2/V) vs. close $(1/d^2)$ vs. little astrophysical background



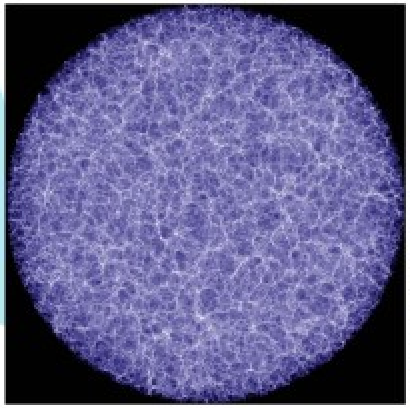
Aquarius simulation – Springel et al. (Nature, 2008)

- single galaxy clusters $(d > \mathrm{Mpc})$



Gottlöber et. al. (2010)

- ensemble average of extra-galactic DM $(d > \mathrm{Gpc})$



Angulo et al. (2008)

CLUMPY calculates J-factors/fluxes for all the various targets

1) Intro: γ-ray flux from local source

N.B.: velocity-dependant annihilations not discussed here, not (yet?) in CLUMPY

Prompt γ-ray/ν flux for single source & DM **annihilation:**

$$\frac{d\Phi^{\rm ann}}{dE_{\rm obs}} = \boxed{\frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{\delta\, m_\chi^2} \times \frac{dN}{dE}(E)} \times \boxed{\int_{\Delta\Omega}\int_{l.o.s.} \rho_{\rm DM}^2 \; dl \, d\Omega}$$

Flux $=$ Particle physics $\times$ J : Astrophysical factor $\overset{\propto}{\sim} \frac{1}{d^2}\frac{M^2}{V}$

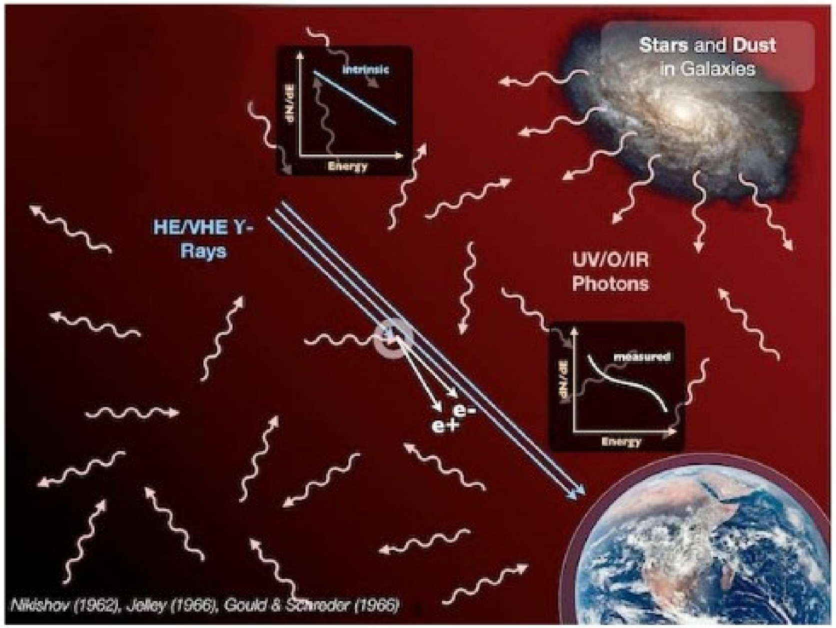
(CLUMPY can also do all calculations for DM **decay**)

J-factor main uncertainty in indirect DM searches

1) Intro: γ-ray flux from source at redshift z

→ Redshifting of the γ-rays/ neutrino energy loss

→ absorption by pair-production with extragalactic background light (EBL)



LEXI, University of Hamburg

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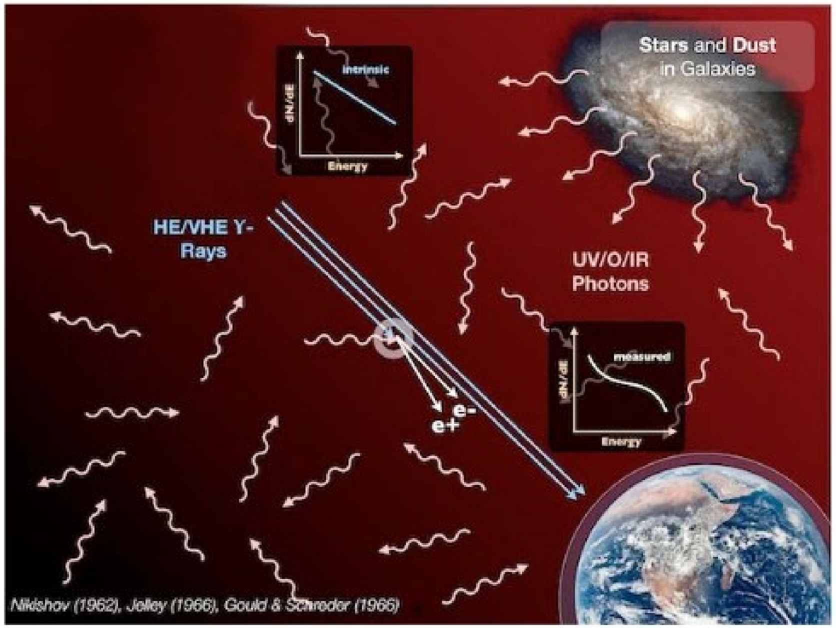

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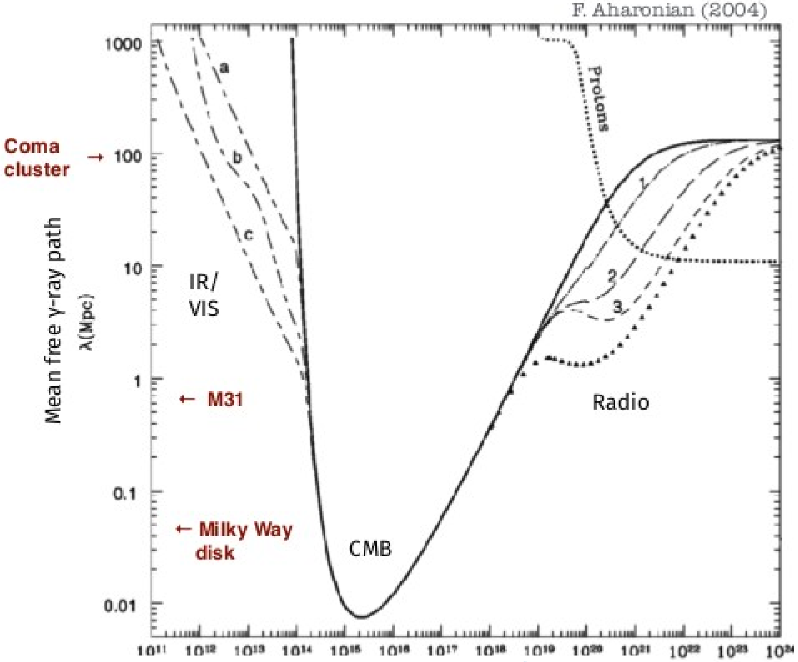

EBL absorption

$$\frac{d\Phi_\gamma^{\text{ann.}}}{dE_\gamma^{\text{obs}}} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2} \times \frac{dN_\gamma}{dE_\gamma^{\text{source}}}\left(\left[1+z\right]E_\gamma^{\text{obs}}\right) \times e^{-\tau(z,E_\gamma)}$$

redshift

$$\times\,(1+z)^3 \int_{\Delta\Omega}\int_{l_c} \rho_{\text{DM}}^2 \, dl_c \, d\Omega$$

annihilation boost in smaller proper volume

description in comoving coordinates

→ Separation in particle physics/astrophysics term
breaks down for sources in z range

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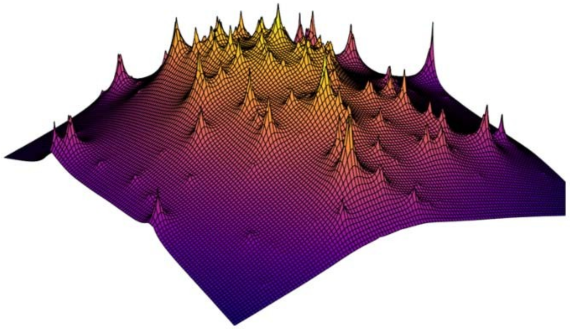
2) What is CLUMPY?

3) A few results: focus on subhalos

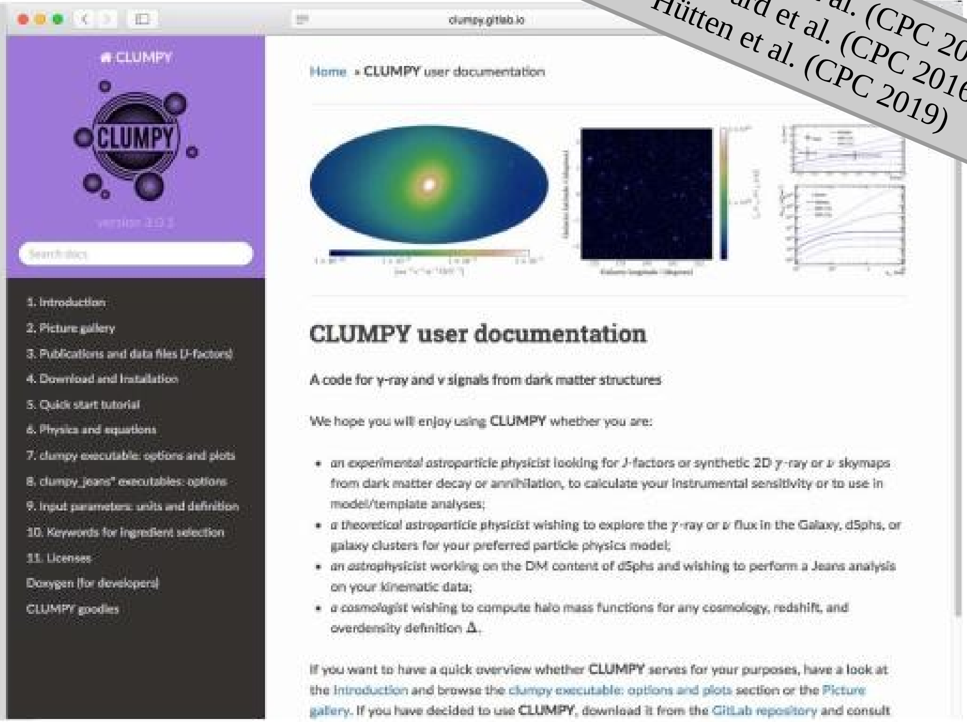
4) Conclusions



2) CLUMPY: public code (https://lpsc.in2p3.fr/clumpy)

Charbonnier et al. (CPC 2012)
Bonnivard et al. (CPC 2016)
Hütten et al. (CPC 2019)

- Open-source code, written in C/C++
- Public development on GitLab
- Depends on:
  - gsl
  - Heasarc's cfitsio
  - ~~HEALPix~~ (shipped with the code)
  - CERN's ROOT (optional)
  - GreAT (lpsc.in2p3.fr/great, optional)
  - CLASS (optional)
- Runs on Linux and MacOS X
- Extensive web documentation



1. Introduction
2. Picture gallery
3. Publications and data files (J-factors)
4. Download and Installation
5. Quick start tutorial
6. Physics and equations
7. clumpy executable: options and plots
8. clumpy_jeans* executables: options
9. Input parameters: units and definition
10. Keywords for ingredient selection
11. Licenses

Doxygen (for developers)

CLUMPY goodies

Home » CLUMPY user documentation

CLUMPY user documentation

A code for γ-ray and ν signals from dark matter structures

We hope you will enjoy using **CLUMPY** whether you are:

- *an experimental astroparticle physicist* looking for J-factors or synthetic 2D γ-ray or ν skymaps from dark matter decay or annihilation, to calculate your instrumental sensitivity or to use in model/template analyses;
- *a theoretical astroparticle physicist* wishing to explore the γ-ray or ν flux in the Galaxy, dSphs, or galaxy clusters for your preferred particle physics model;
- *an astrophysicist* working on the DM content of dSphs and wishing to perform a Jeans analysis on your kinematic data;
- *a cosmologist* wishing to compute halo mass functions for any cosmology, redshift, and overdensity definition Δ.

If you want to have a quick overview whether **CLUMPY** serves for your purposes, have a look at the Introduction and browse the clumpy executable: options and plots section or the Picture gallery. If you have decided to use **CLUMPY**, download it from the GitLab repository and consult

Provide the community reproducible models for J-factors and prompt γ-ray/ν fluxes

Bridge between heavy numerical simulations and experiments:

- Fast emulator to calculate J-factors/fluxes from simulation end-products down to smallest mass scales
- Explore varying simulation results in a parametric way: fast, flexible, user-friendly
- Jeans-analysis module to reconstruct dSph DM density profiles from kinematic data

2) CLUMPY: principle

$$J = \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \frac{1}{l^2} \left(\rho_{\rm sm} + \sum_i \rho_{\rm cl}^i \right)^2 l^2 dl d\Omega$$

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

$$J_{\rm cross-prod} \equiv 2 \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \rho_{\rm sm} \sum_i \rho_{\rm cl}^i dl d\Omega$$

$$J_{\rm subs} \equiv \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \left(\sum_i \rho_{\rm cl}^i \right)^2 dl d\Omega$$

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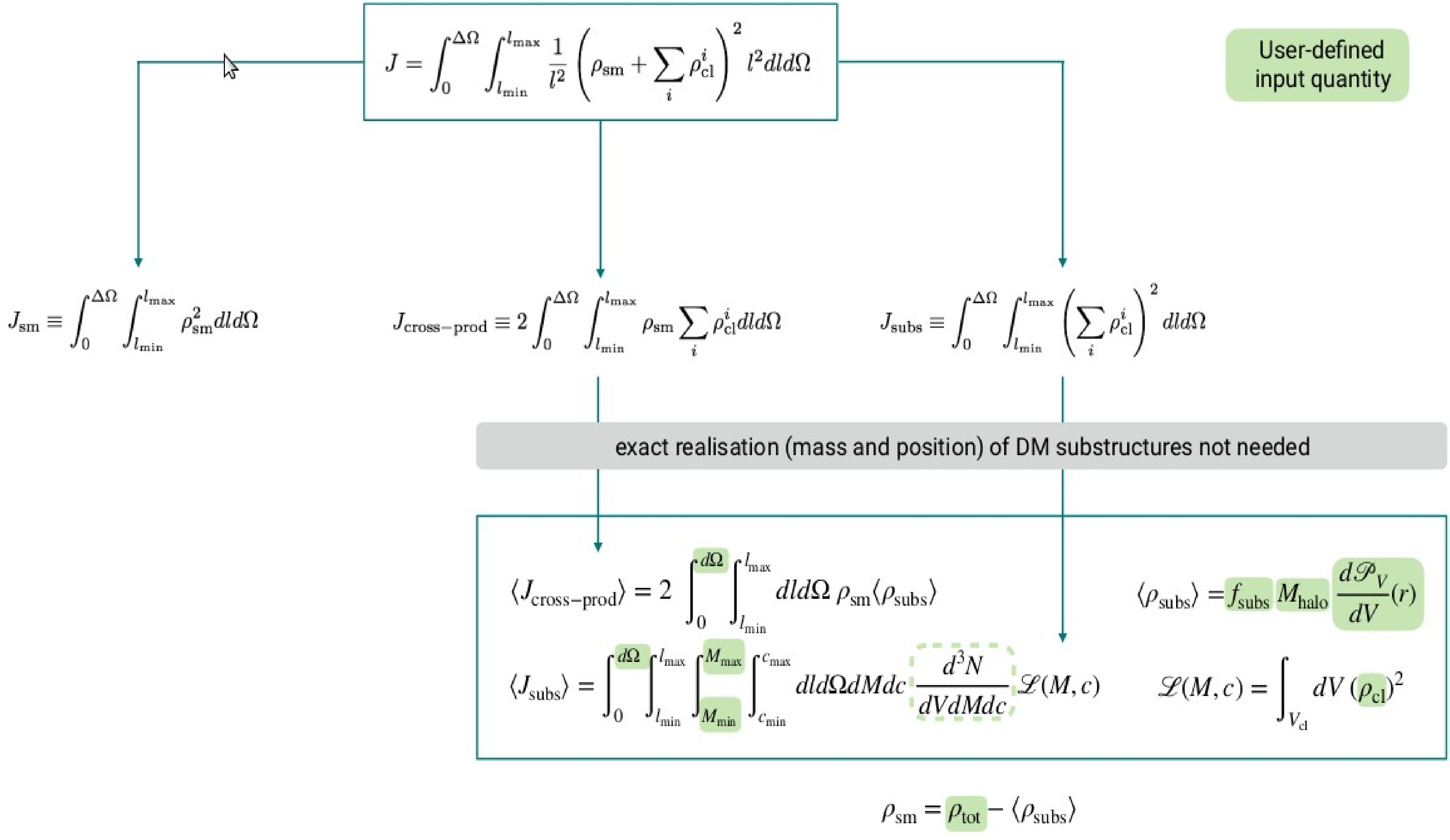

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User-defined input quantity

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

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$$J_{\rm subs} \equiv \int_0^{\Delta\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \left(\sum_i \rho_{\rm cl}^i \right)^2 dl d\Omega$$

exact realisation (mass and position) of DM substructures not needed

$$\langle J_{\rm cross-prod} \rangle = 2 \int_0^{d\Omega} \int_{l_{\rm min}}^{l_{\rm max}} dl d\Omega \, \rho_{\rm sm} \langle \rho_{\rm subs} \rangle$$

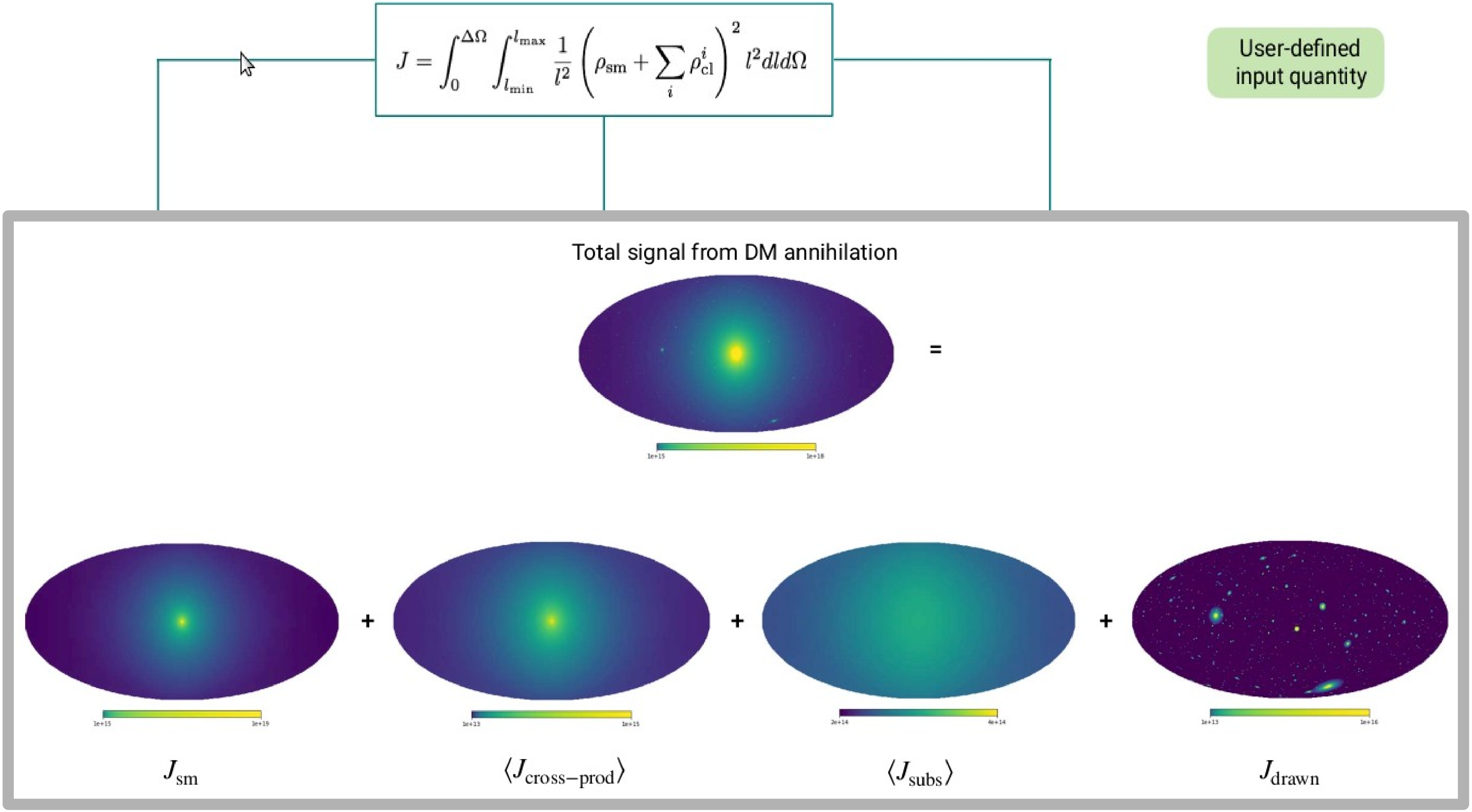
$$\langle \rho_{\rm subs} \rangle = f_{\rm subs} \, M_{\rm halo} \, \frac{d\mathscr{P}_V}{dV}(r)$$

$$\langle J_{\rm subs} \rangle = \int_0^{d\Omega} \int_{l_{\rm min}}^{l_{\rm max}} \int_{M_{\rm min}}^{M_{\rm max}} \int_{c_{\rm min}}^{c_{\rm max}} dl d\Omega dM dc \, \frac{d^3N}{dV dM dc} \mathscr{L}(M,c)$$

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

$$\rho_{\rm sm} = \rho_{\rm tot} - \langle \rho_{\rm subs} \rangle$$

2) CLUMPY: principle



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User-defined input quantity

Do not resolve trillions of subhalos

→ Calculate average signal for most masses

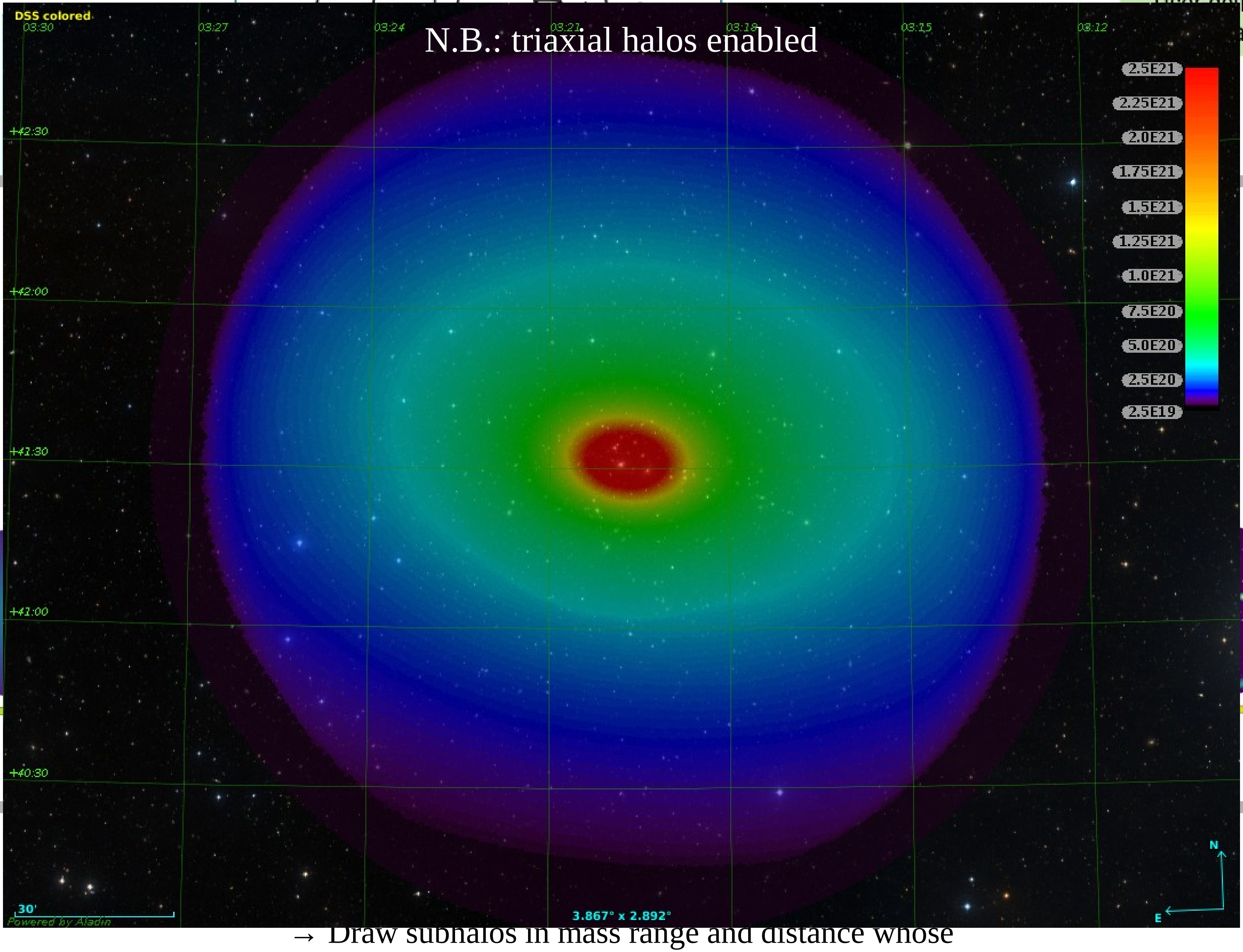
→ Draw subhalos in mass range and distance whose contribution fluctuates above user-defined selection

2) CLUMPY: principle

$$\int^{\Delta\Omega}\int^{l_{\max}} 1 \left(\quad \right)^2$$

User defined

antity



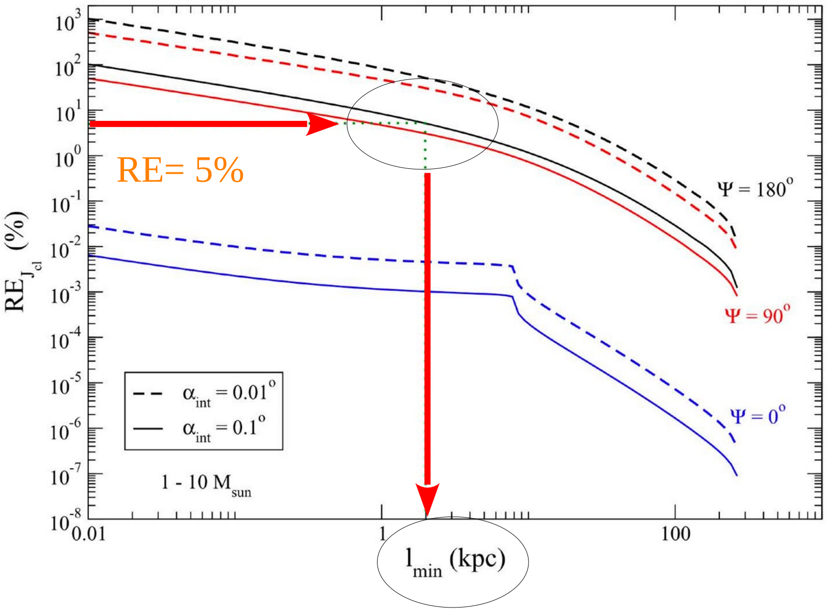
N.B.: triaxial halos enabled

→ Draw subhalos in mass range and distance whose contribution fluctuates above user-defined selection

2) CLUMPY: principle

→ In each mass decade, draw subhalos whose fluctuations (above average) > RE

$$RE_{J_{\rm clumps}} = \frac{\sqrt{N_{\rm cl}}\ \sigma_{1\,\rm cl}}{N_{\rm cl}\langle J_{1\,\rm cl}\rangle + J_{\rm smooth}}$$



→ Draw subhalos in [0, l_crit] only

Do not resolve trillions of subhalos
→ Calculate average signal for most masses
→ Draw subhalos in mass range and distance whose contribution fluctuates above user-defined selection

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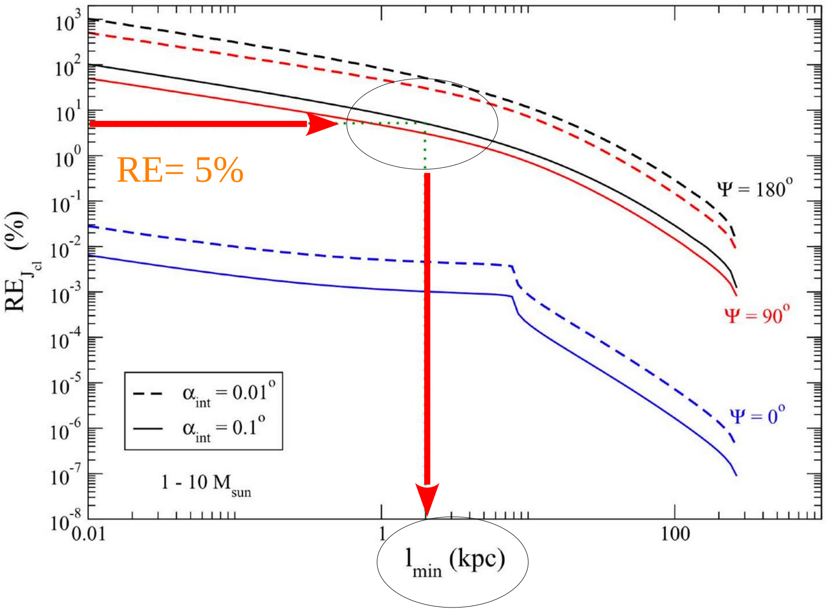

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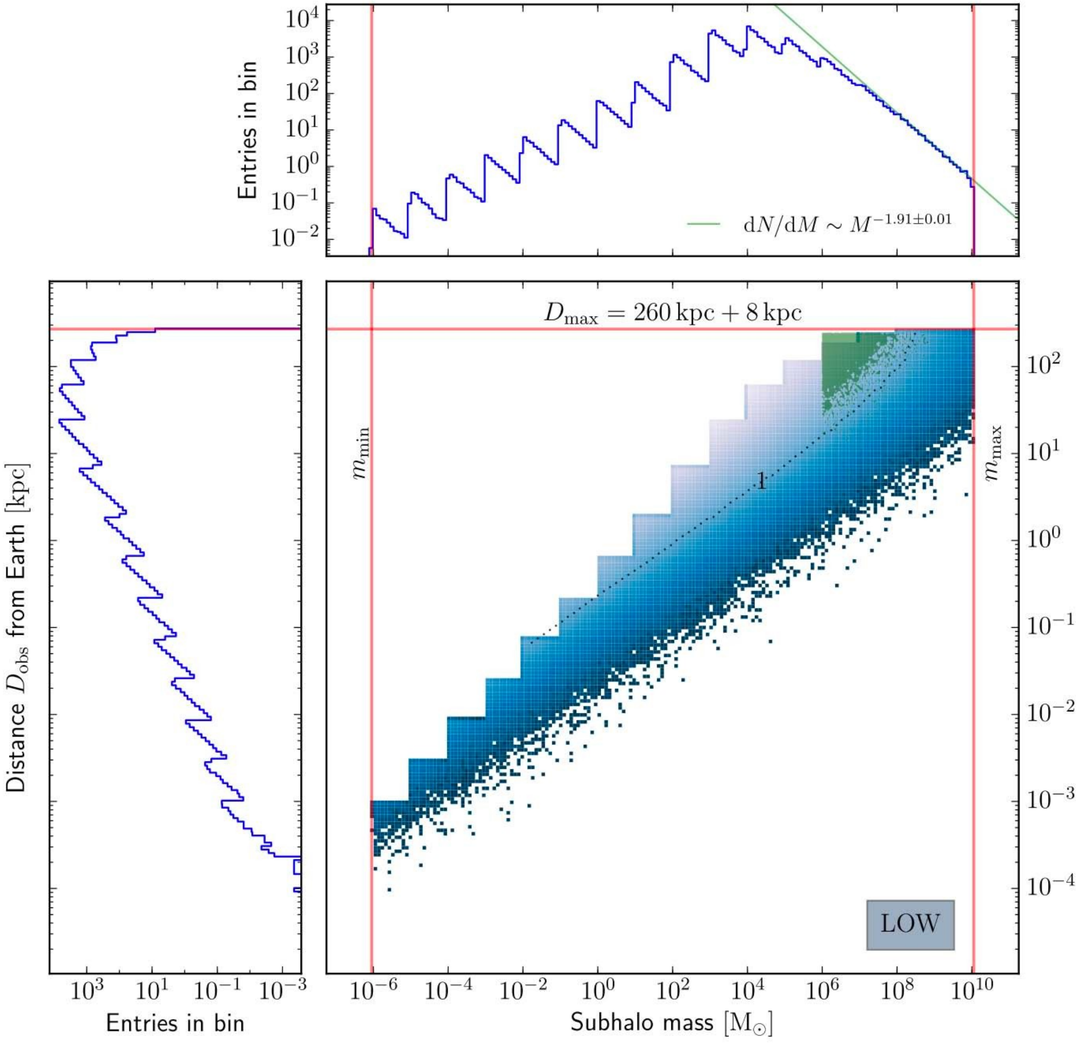
Runs from M. Hütten



Do not resolve trillions of subhalos

→ Calculate average signal for most masses

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2) CLUMPY: more on average of subhalos

$$\langle J_{\rm subs}\rangle = \int_0^{d\Omega}\int_{l_{\rm min}}^{l_{\rm max}}\int_{M_{\rm min}}^{M_{\rm max}}\int_{c_{\rm min}}^{c_{\rm max}} dl\,d\Omega\,dM\,dc\;\frac{d^3N}{dV\,dM\,dc}\;\mathscr{L}(M,c)$$

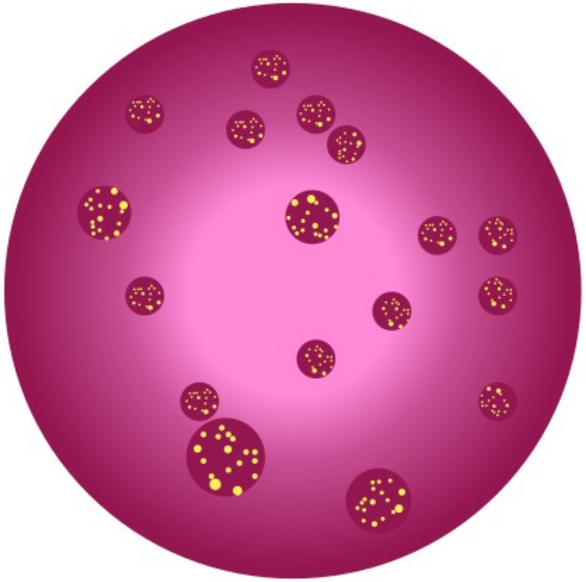
$$\frac{d^3N}{dV\,dM\,dc} = N_{\rm subs}\,\frac{d\mathscr{P}_V}{dV}(r)\times\frac{d\mathscr{P}_M}{dM}(M)\times\frac{d\mathscr{P}_c}{dc}(M,r,c)$$

User-defined input quantity

- $d\mathscr{P}_V/\,dV$: Probability to fin clump at some radial position in the host halo: usually flatter than total DM density
- $d\mathscr{P}_M/\,dM \sim M^{-\alpha_M}$: probability density of substructure mass: independent of position in halo
- $N_{\rm subs} = f_{\rm subs}\,M_{\rm halo}\Big/\int_{M_{\rm min}}^{M_{\rm max}} dM\,M\,\dfrac{d\mathscr{P}_M}{dM}$: total number of substructures in halo
- $d\mathscr{P}_c/\,dc$: Log-normal distribution around mean $\bar{c}(M,r)$

In worst/naive case, $5^{\rm N\,sub-levels}$ dimensional integral to calculate (slow…)

2) CLUMPY: boost from sub-subhalos



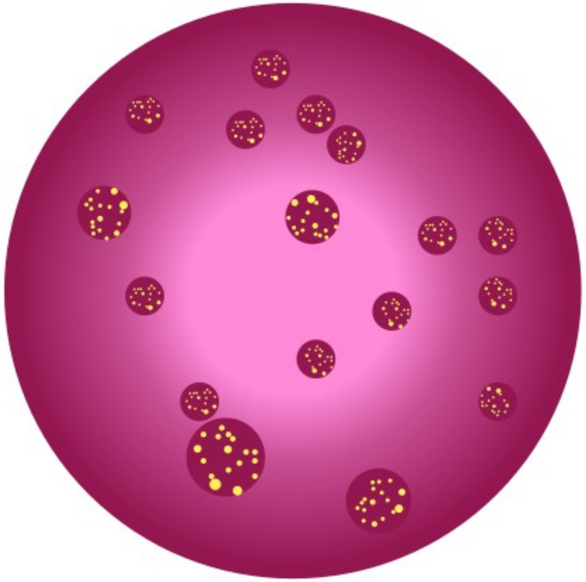
So far, we considered one level of substructure within the parent halo. But hierarchical formation: haloes in haloes in haloes, etc…

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

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

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

2) CLUMPY: boost from sub-subhalos



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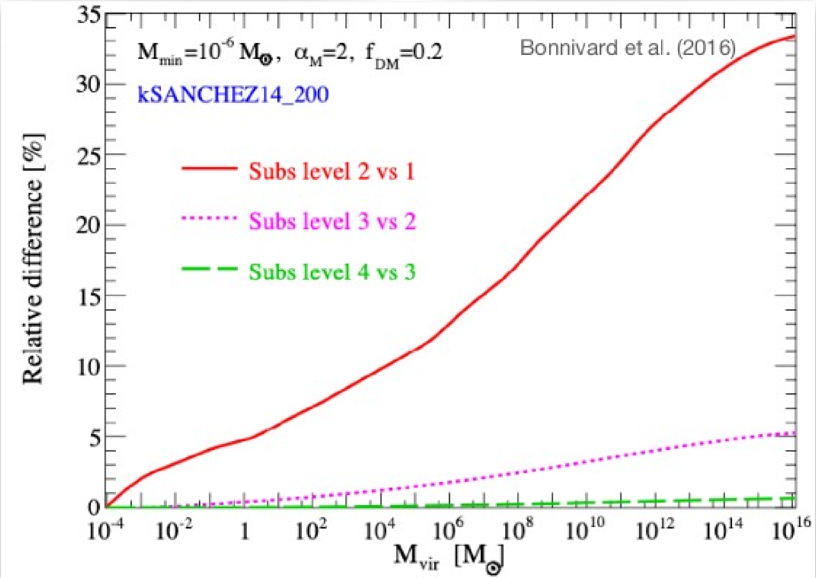

No much gain to go beyond n=1 or 2 and computationally expensive…

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2) What is CLUMPY?

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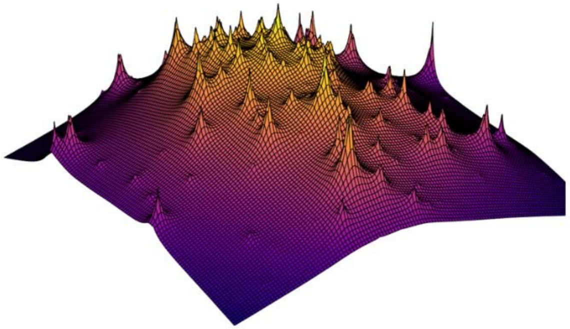
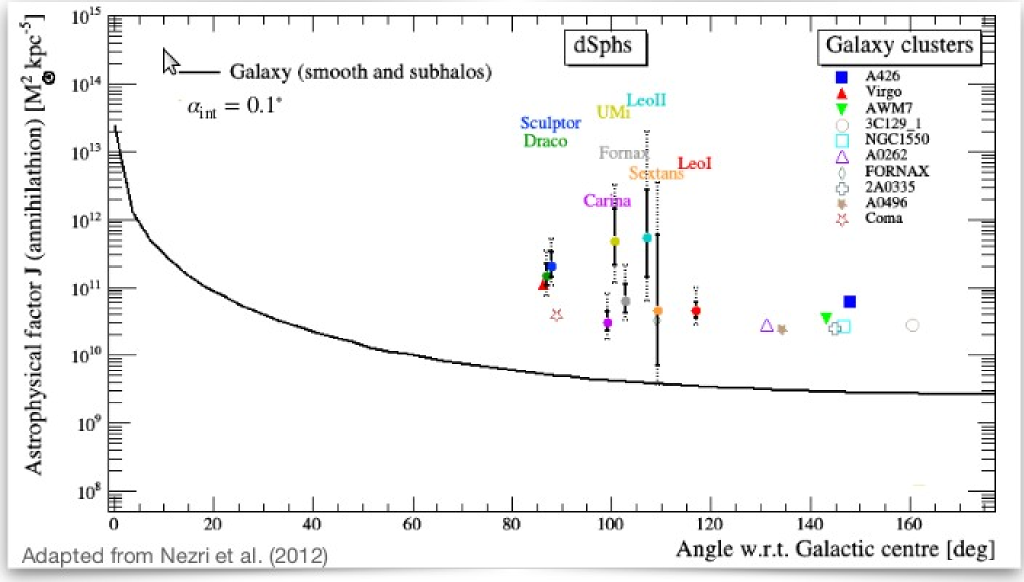
4) Conclusions



3) Results: dSph and galaxy clusters

Charbonnier et al. (2011), Nezri et al. (2012), Bonnivard et al. (2015a,b,c)

→ dSphs or galaxy clusters?



Adapted from Nezri et al. (2012)

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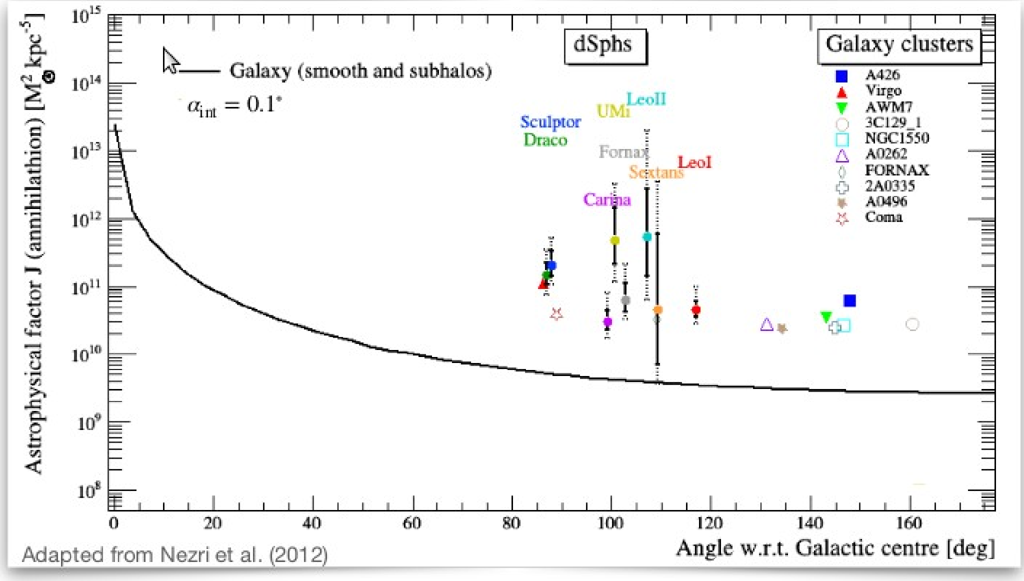
→ dSphs better targets than galaxy clusters



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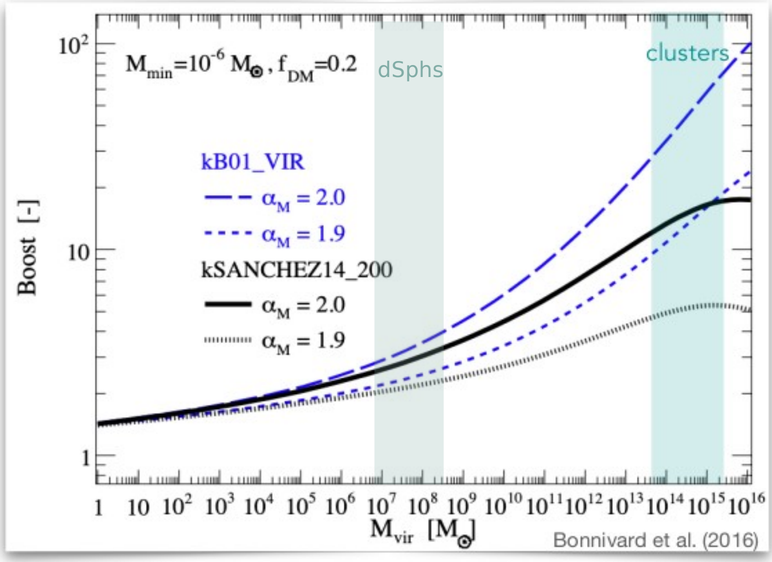
… and beware of boost!



Bonnivard et al. (2016)

What is the best observation strategy?

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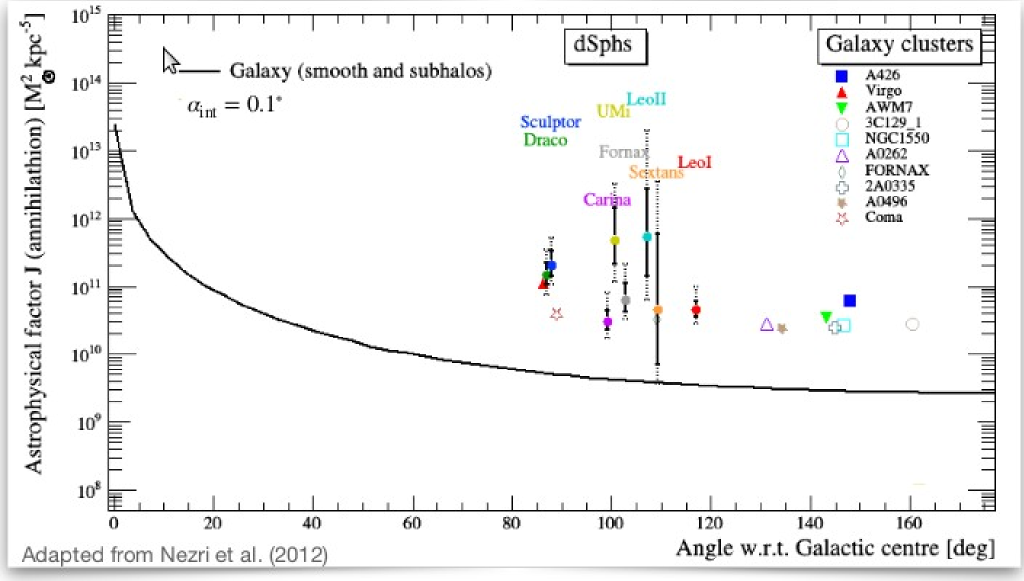

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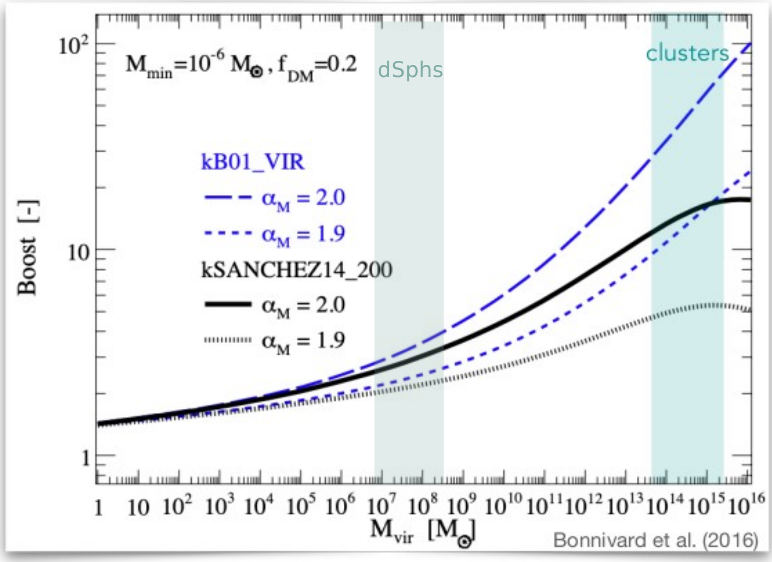

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What is the best observation strategy?

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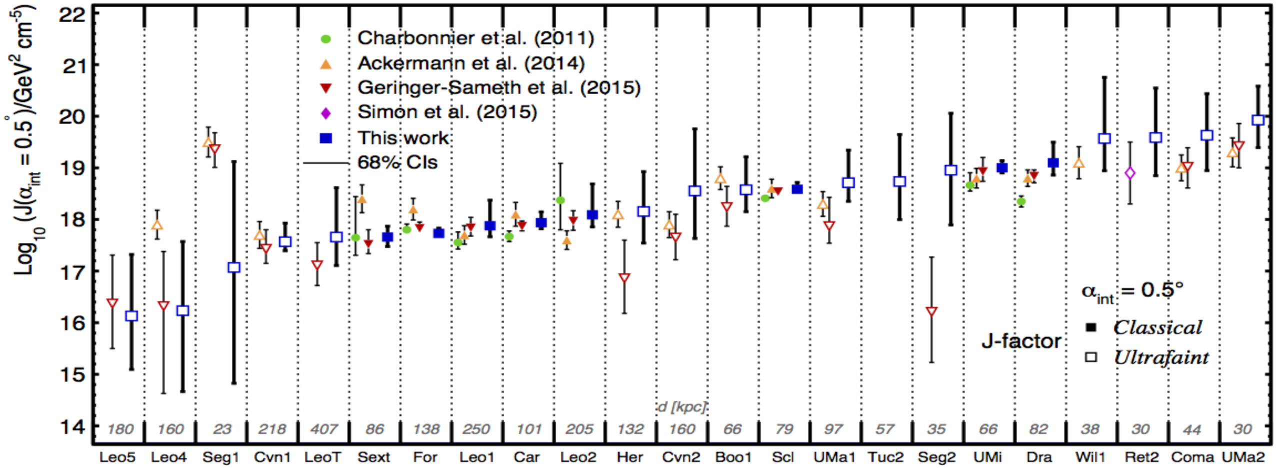

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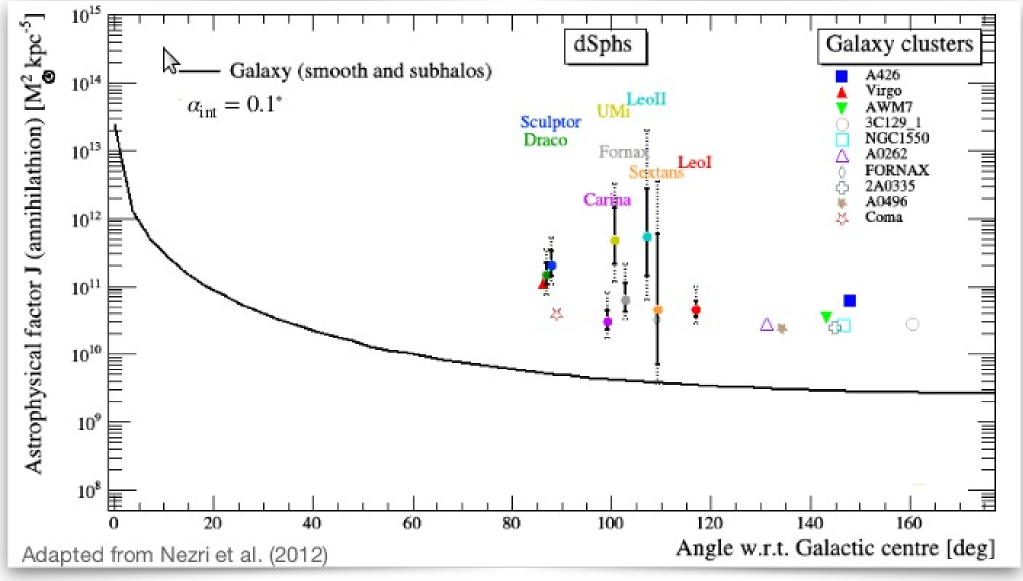

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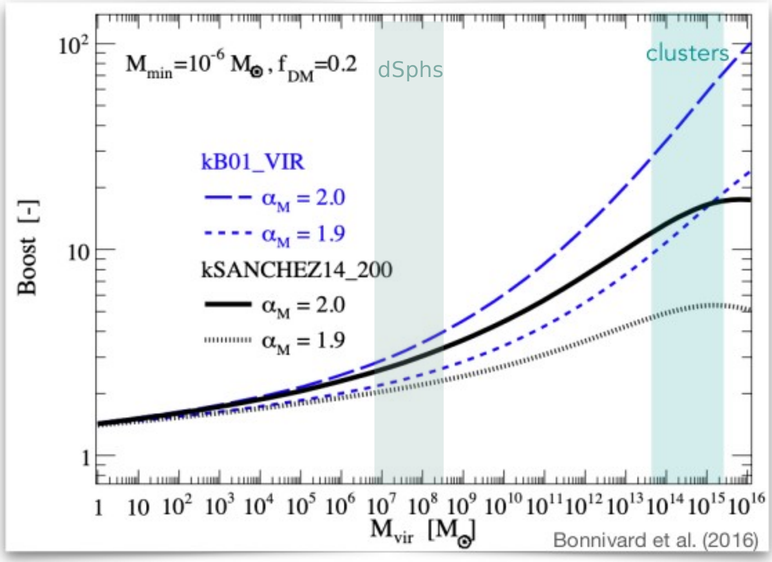

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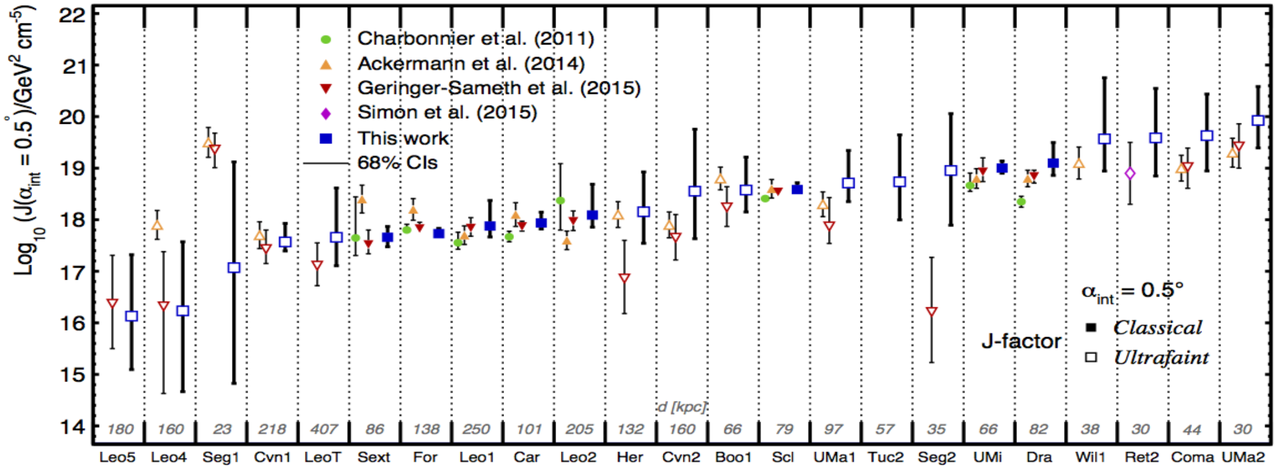
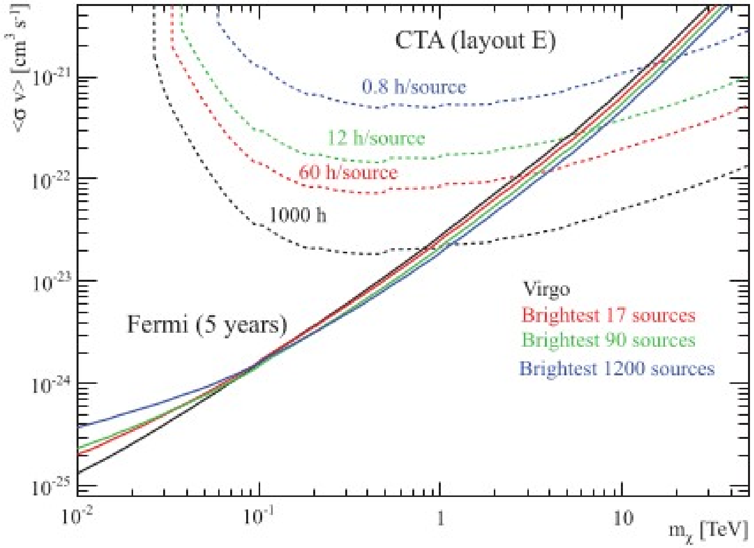


→ Benefit of stacking strategy (clusters)



3) Results: extragalactic

Hütten et al. (2018)

$$I(E_\gamma) = \left\langle \frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma\,\mathrm{d}\Omega} \right\rangle_{\mathrm{sky}} = \frac{\overline{\varrho}^2_{\mathrm{DM},0}\,\langle\sigma v\rangle}{8\pi\, m_\chi^2} \int\limits_0^{z_{\max}} c\,\mathrm{d}z\, \frac{(1+z)^3}{H(z)}\, \langle\delta^2(z)\rangle\, \left.\frac{\mathrm{d}N^\gamma_{\mathrm{source}}}{\mathrm{d}E_\mathrm{e}}\right|_{E_\mathrm{e}=(1+z)E_\gamma} \times e^{-\tau(z,\,E_\gamma)}$$

Intensity multiplier

Single halo

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

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→ Thorough analysis of main uncertainties (varying critical ingredients)

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Single halo

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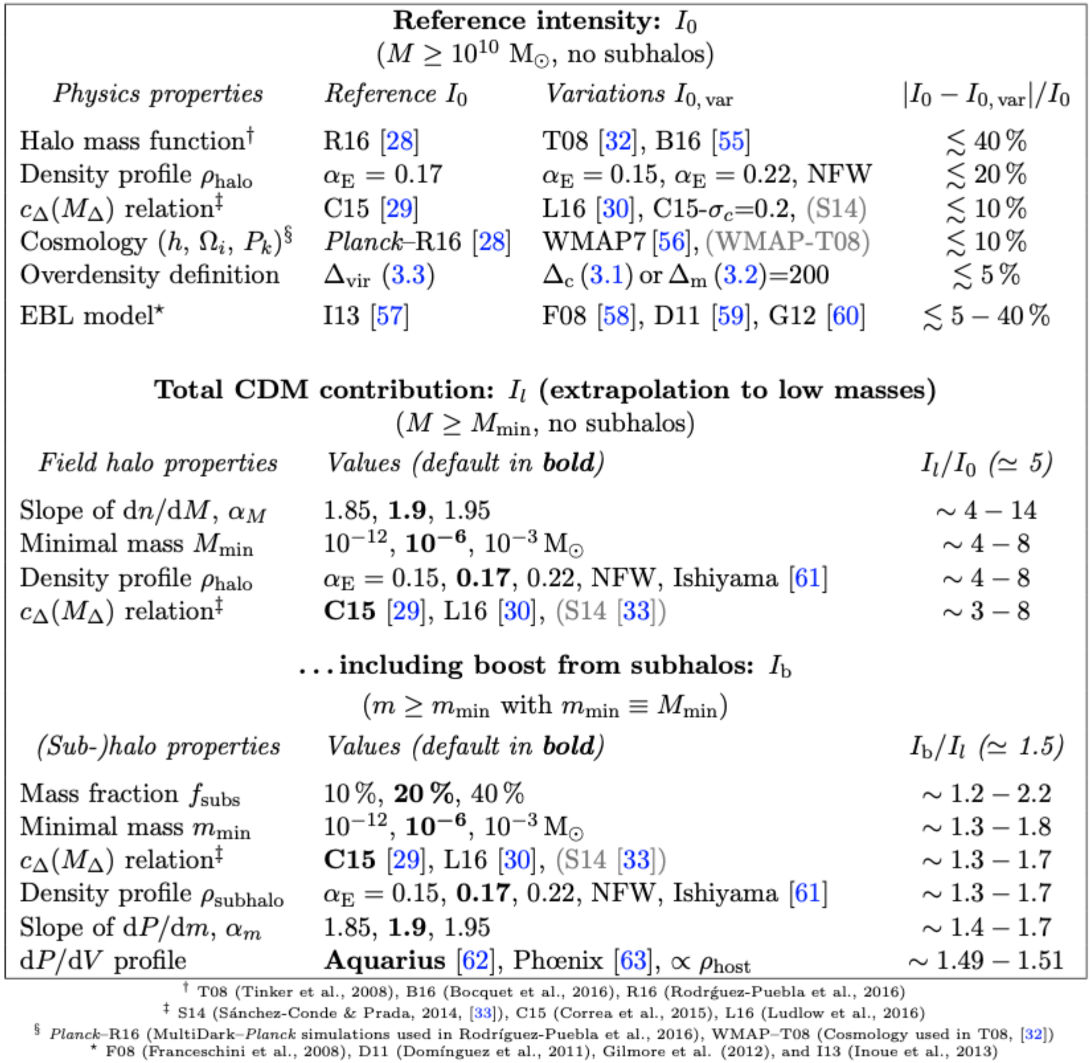


Reference intensity: I_0
($M \geq 10^{10}$ $\mathrm{M}_\odot$, no subhalos)

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}	$\alpha_{\mathrm{E}} = 0.17$	$\alpha_{\mathrm{E}} = 0.15$, $\alpha_{\mathrm{E}} = 0.22$, 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} $\mathrm{M}_\odot$	$\sim 4 - 8$
Density profile ρ_{halo}	$\alpha_{\mathrm{E}} = 0.15$, **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} $\mathrm{M}_\odot$	$\sim 1.3 - 1.8$
$c_\Delta(M_\Delta)$ relation[‡]	**C15** [29], L16 [30], (S14 [33])	$\sim 1.3 - 1.7$
Density profile ρ_{subhalo}	$\alpha_{\mathrm{E}} = 0.15$, **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 (Rodrǵuez-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)

3) Results: extragalactic

Hütten et al. (2018)

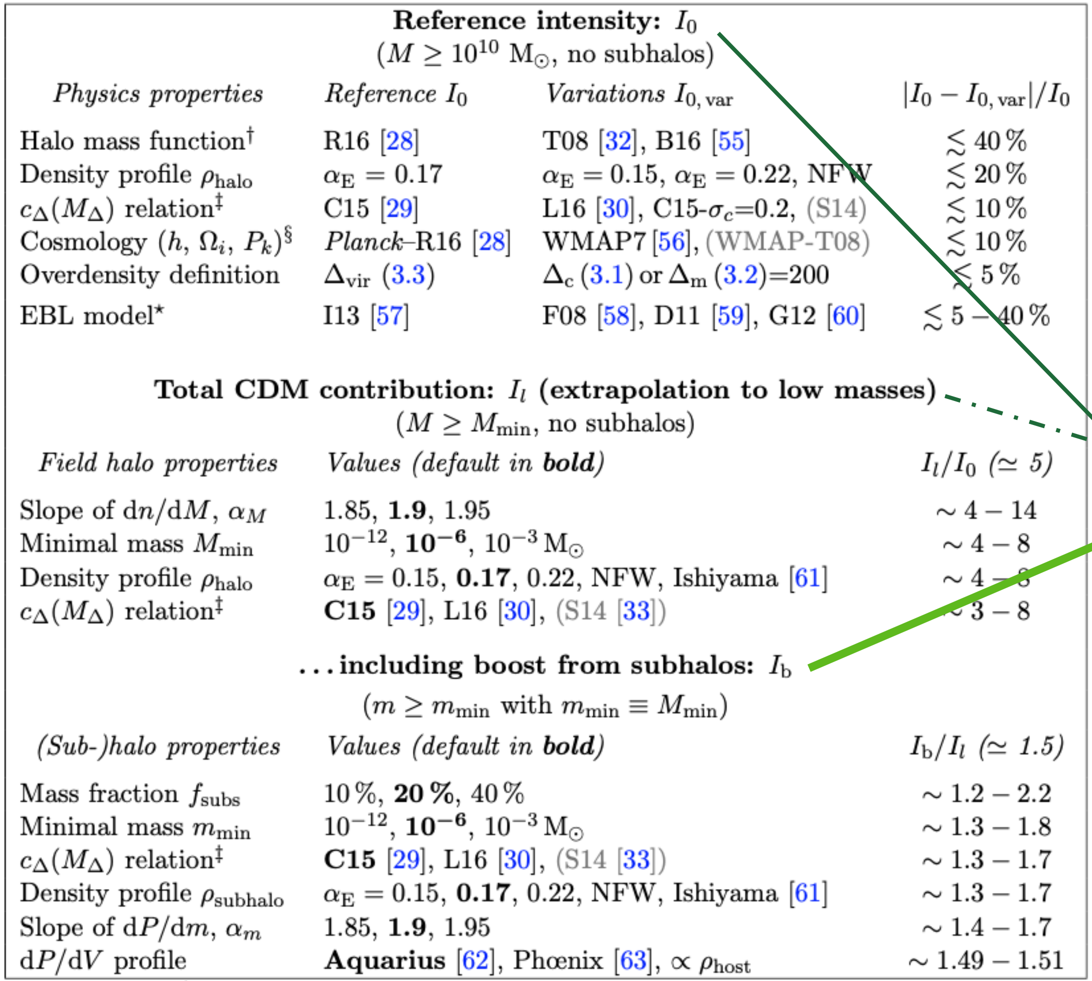
$$I(E_\gamma) = \left\langle \frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma\,\mathrm{d}\Omega}\right\rangle_{\mathrm{sky}} = \frac{\overline{\varrho}^2_{\mathrm{DM},0}\,\langle\sigma v\rangle}{8\pi\, m_\chi^2}\int_0^{z_{\max}} c\,\mathrm{d}z\,\frac{(1+z)^3}{H(z)}\,\langle\delta^2(z)\rangle\,\left.\frac{\mathrm{d}N^\gamma_{\mathrm{source}}}{\mathrm{d}E_{\mathrm{e}}}\ri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

→ Thorough analysis of main uncertainties
(varying critical ingredients)

Intensity multiplier

Single halo

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



Reference intensity: I_0
($M \geq 10^{10}\ \mathrm{M}_\odot$, 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}	$\alpha_{\mathrm{E}} = 0.17$	$\alpha_{\mathrm{E}} = 0.15$, $\alpha_{\mathrm{E}} = 0.22$, NFW	$\lesssim 20\,\%$
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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	$\lesssim 5\,\%$
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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}, $\mathbf{10^{-6}}$, $10^{-3}\ \mathrm{M}_\odot$	$\sim 4 - 8$
Density profile ρ_{halo}	$\alpha_{\mathrm{E}} = 0.15$, **0.17**, 0.22, NFW, Ishiyama [61]	$\sim 4 - 8$
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. . . 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}, $\mathbf{10^{-6}}$, $10^{-3}\ \mathrm{M}_\odot$	$\sim 1.3 - 1.8$
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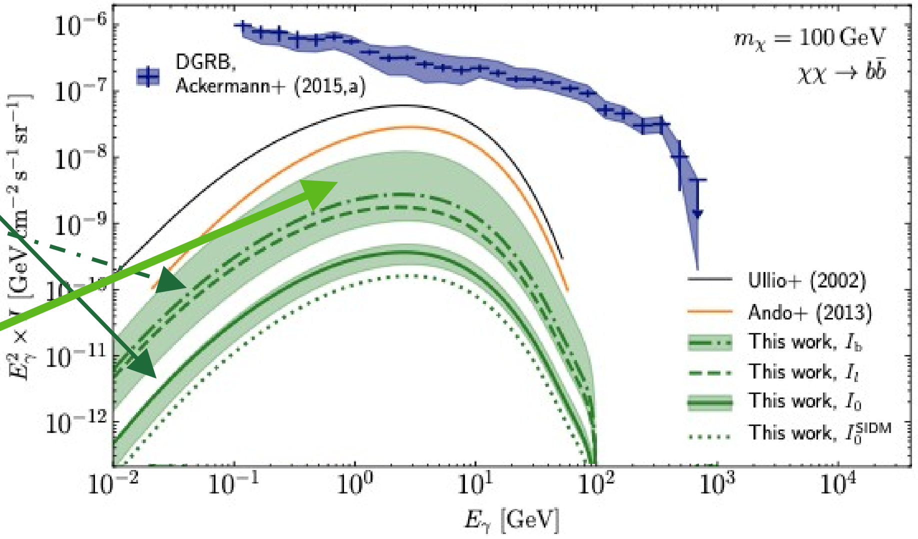
→ Large uncertainties from boost

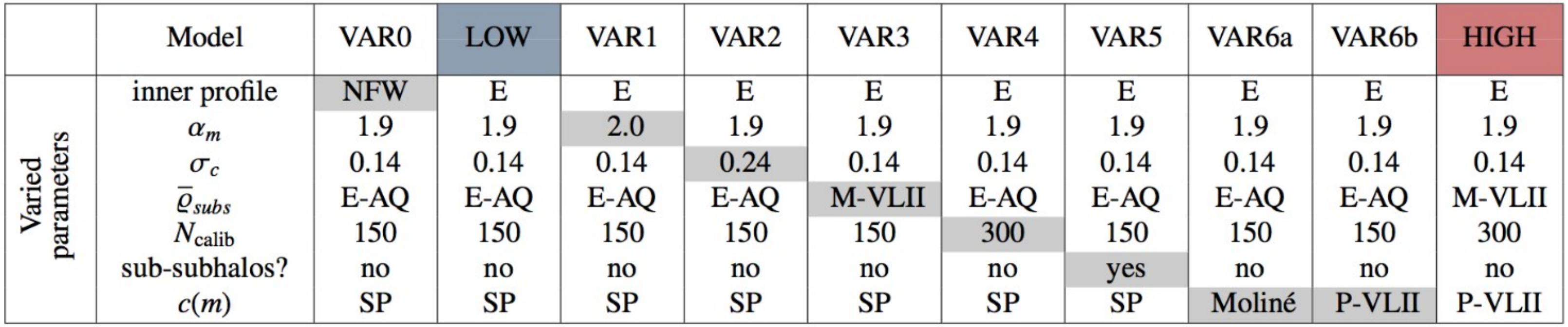


3) Results: dark halos (1000 realisations)

$$\frac{\mathrm{d}^3\mathcal{P}}{\mathrm{d}V\,\mathrm{d}m\,\mathrm{d}c} = \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}V}(\vec{r}) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}m}(m) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}c}(c, m).$$

Hütten et al. (2016)

→ Varying parameter in allowed range



	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
	$\overline{\varrho}_{subs}$	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

3) Results: dark halos (1000 realisations)

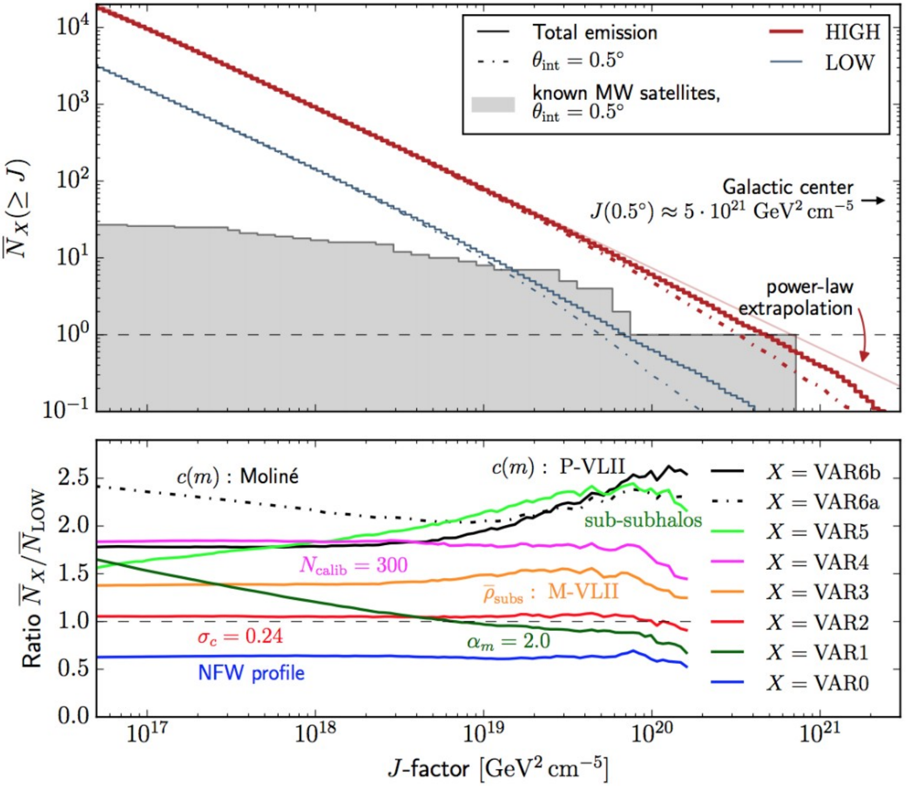
$$\frac{\mathrm{d}^3\mathcal{P}}{\mathrm{d}V\mathrm{d}m\,\mathrm{d}c} = \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}V}(\vec{r}) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}m}(m) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}c}(c, m).$$

Hütten et al. (2016)

→ Varying parameter in allowed range

	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
	$N_{\rm calib}$	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

→ Largest differences: c-M relation



3) Results: dark halos (1000 realisations)

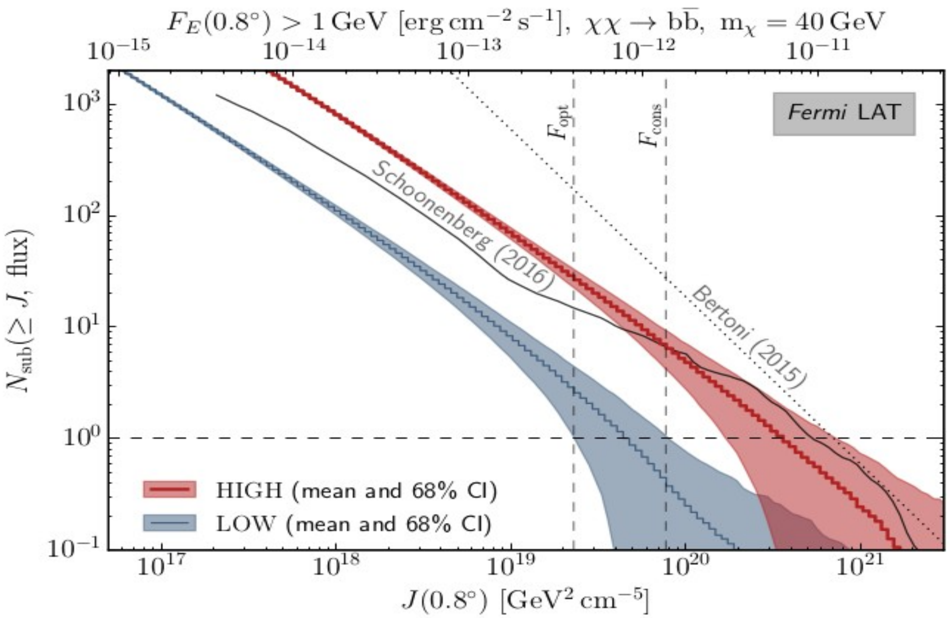
$$\frac{\mathrm{d}^3\mathcal{P}}{\mathrm{d}V\mathrm{d}m\,\mathrm{d}c} = \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}V}(\vec{r}) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}m}(m) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}c}(c, m).$$

Hütten et al. (2016)

→ Varying parameter in allowed range

	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
	$N_{\rm calib}$	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

→ Comparison to other results



→ Probability to observe a “flux” (non-gaussian tail) determines sensitivity

→ In practice, search (e.g., in Fermi-LAT catalog) for unassociated sources

3) Results: dark halos (1000 realisations)

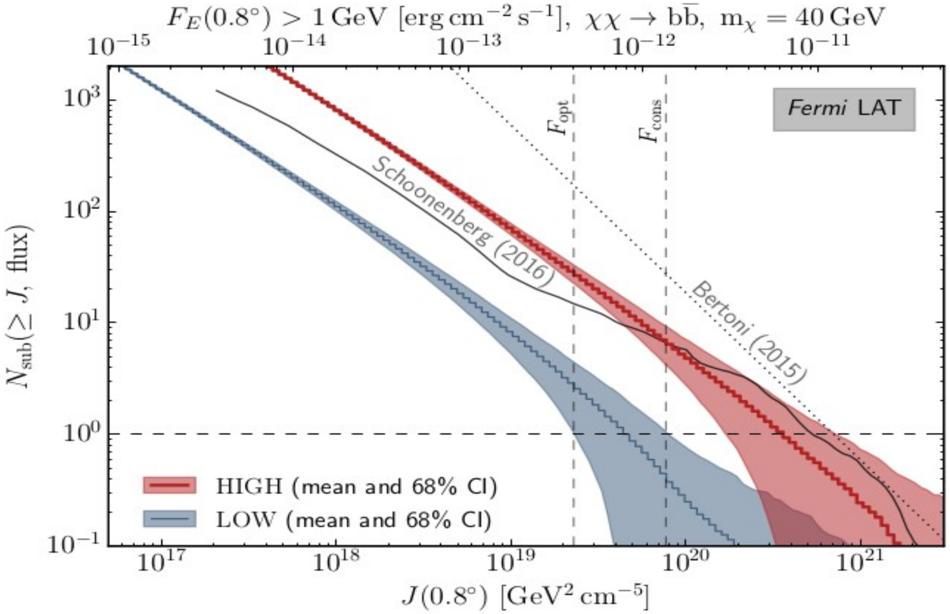
$$\frac{d^3\mathcal{P}}{dV\,dm\,dc} = \frac{d\mathcal{P}}{dV}(\vec{r}) \times \frac{d\mathcal{P}}{dm}(m) \times \frac{d\mathcal{P}}{dc}(c,m).$$

Hütten et al. (2016)

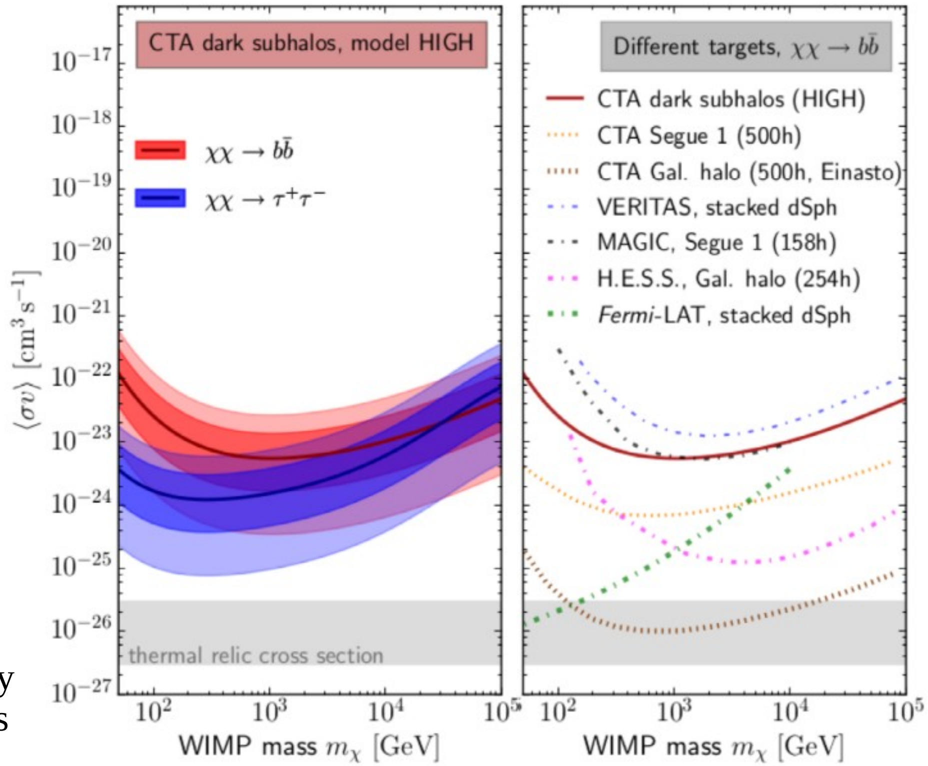
→ Varying parameter in allowed range

	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
	$N_{\rm calib}$	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

→ Comparison to other results



→ Prospects for CTA + complementary limits to dSphs



→ Probability to observe a “flux” (non-gaussian tail) determines sensitivity
→ In practice, search (e.g., in Fermi-LAT catalog) for unassociated sources

3) Results: dark halos (1000 realisations)

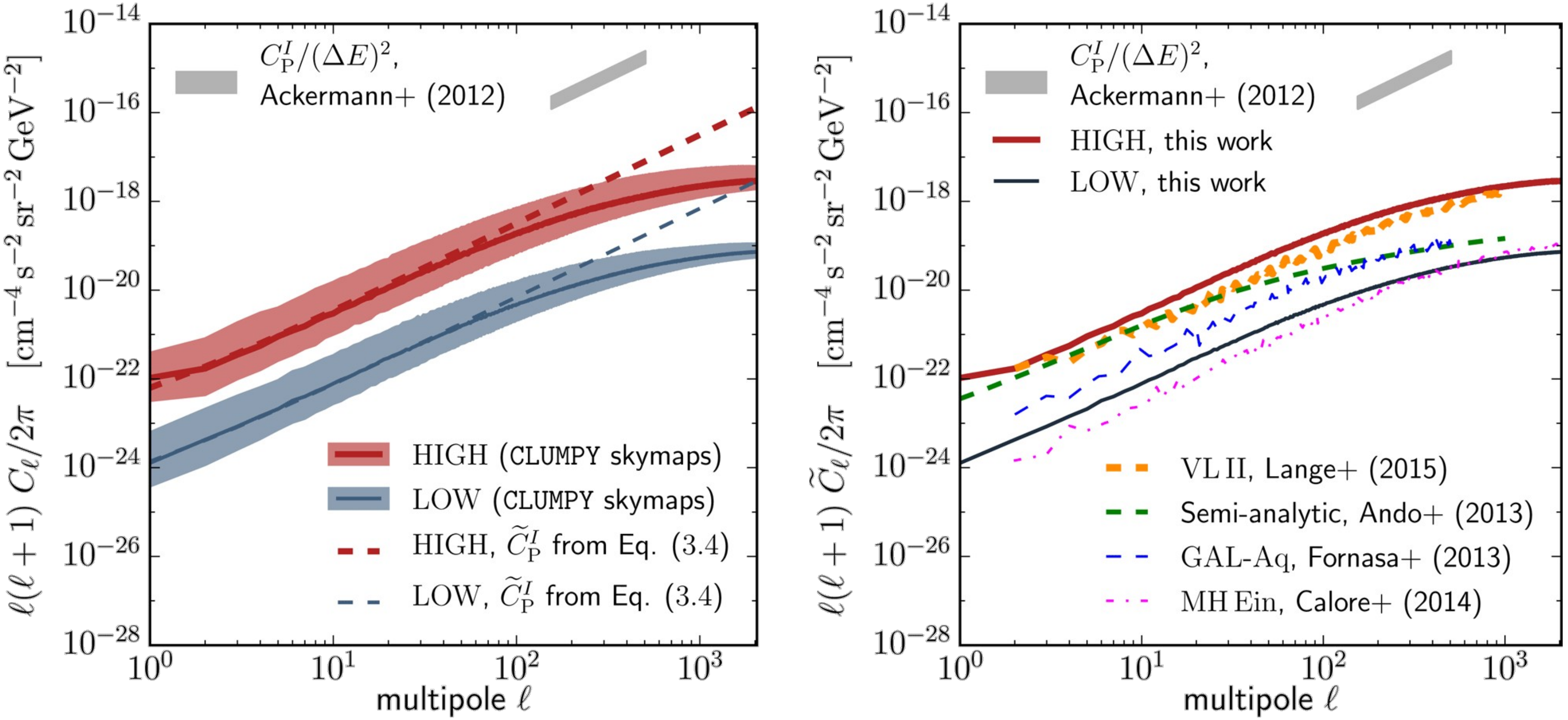
$$\frac{d^3\mathcal{P}}{dV\,dm\,dc} = \frac{d\mathcal{P}}{dV}(\vec{r}) \times \frac{d\mathcal{P}}{dm}(m) \times \frac{d\mathcal{P}}{dc}(c, m).$$

Hütten et al. (2016)

→ Varying parameter in allowed range

	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
	$\overline{\varrho}_{subs}$	E-AQ	E-AQ	E-AQ	E-AQ	M-VLII	E-AQ	E-AQ	E-AQ	E-AQ	M-VLII
	$N_{\rm calib}$	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

→ Angular power spectrum (APS)



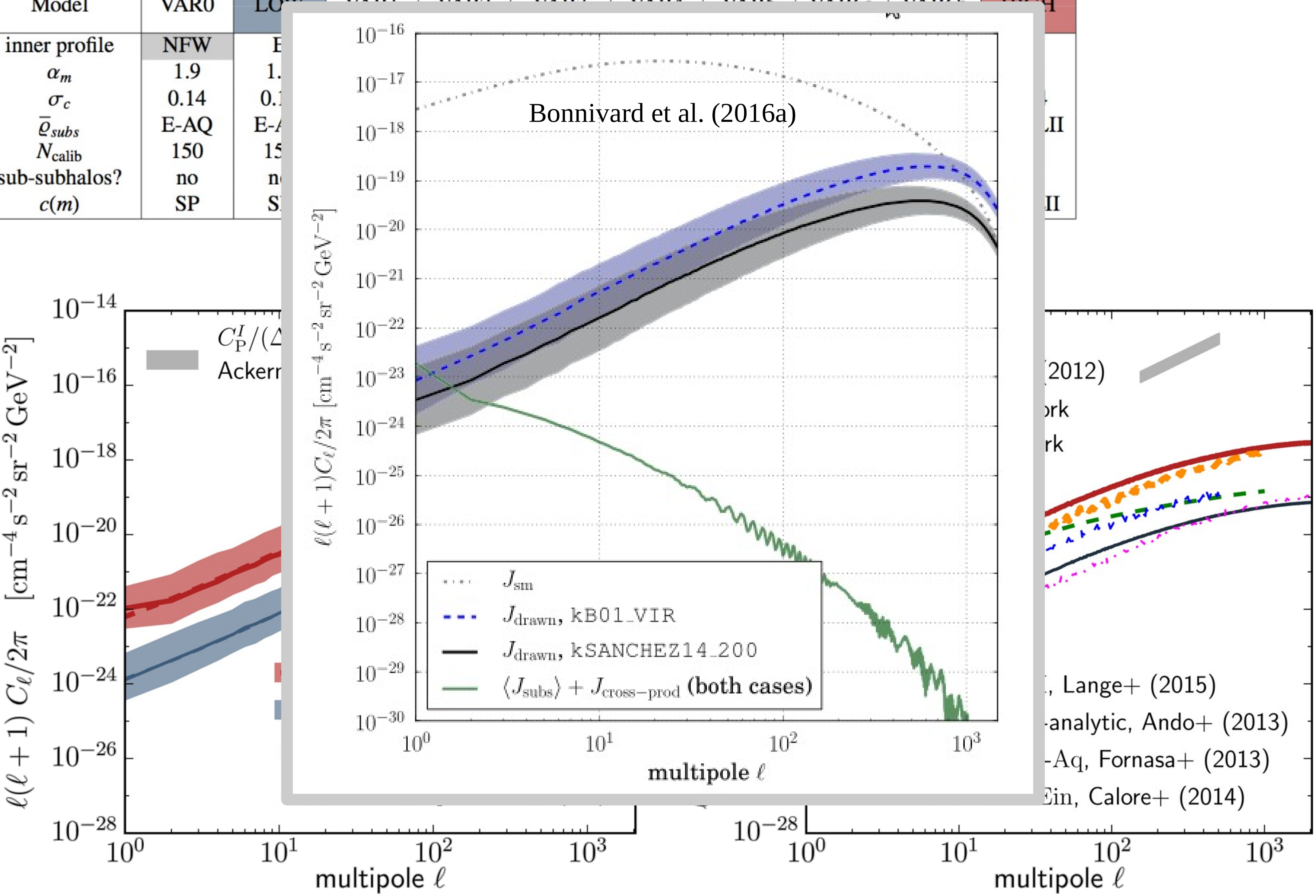
3) Results: dark halos (1000 realisations)

$$\frac{\mathrm{d}^3\mathcal{P}}{\mathrm{d}V\mathrm{d}m\,\mathrm{d}c} = \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}V}(\vec{r}) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}m}(m) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}c}(c,m).$$

Hütten et al. (2016)

→ Varying parameter in allowed range

	Model	VAR0	LOW	VAR1	VAR2	VAR3	VAR4	VAR5	VAR6a	VAR6b	HIGH
Varied parameters	inner profile	NFW	E								
	α_m	1.9	1.								
	σ_c	0.14	0.1								
	$\overline{\varrho}_{subs}$	E-AQ	E-A								II
	$N_{\rm calib}$	150	15								
	sub-subhalos?	no	n								
	$c(m)$	SP	S								II



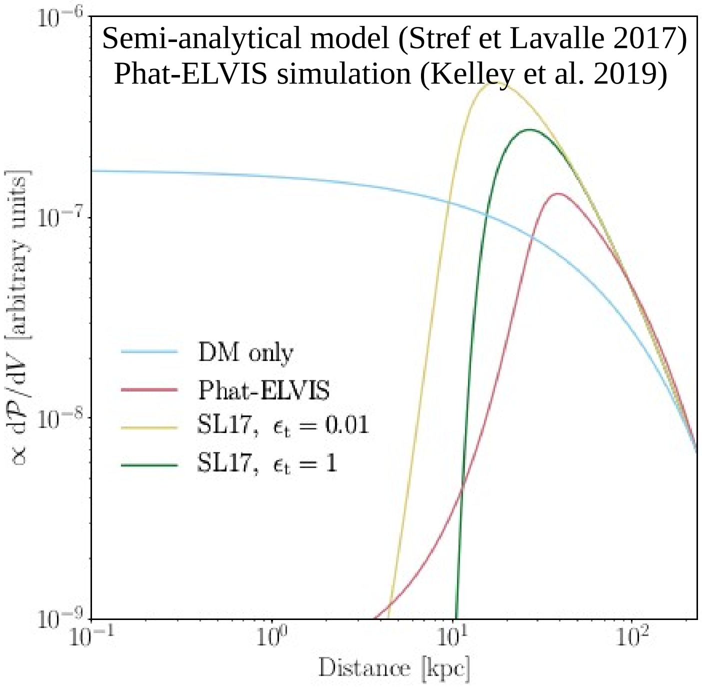
Bonnivard et al. (2016a)

3) Results: dark halos (1000 realisations)

$$\frac{\mathrm{d}^3\mathcal{P}}{\mathrm{d}V\mathrm{d}m\,\mathrm{d}c} = \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}V}(\vec{r}) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}m}(m) \times \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}c}(c, m).$$

Hütten et al. (2019)

Subhalos disrupted by Milky Way baryonic potential


Semi-analytical model (Stref et Lavalle 2017)
Phat-ELVIS simulation (Kelley et al. 2019)

3) Results: dark halos (1000 realisations)

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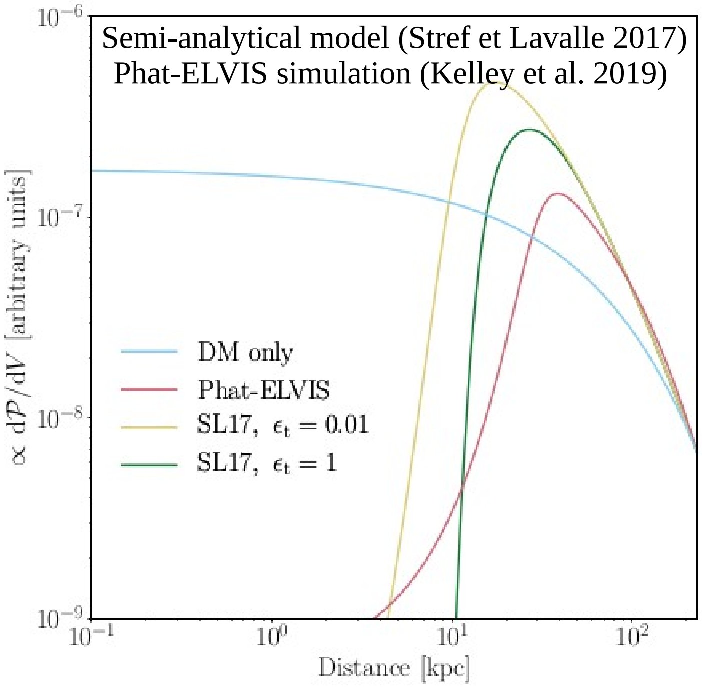
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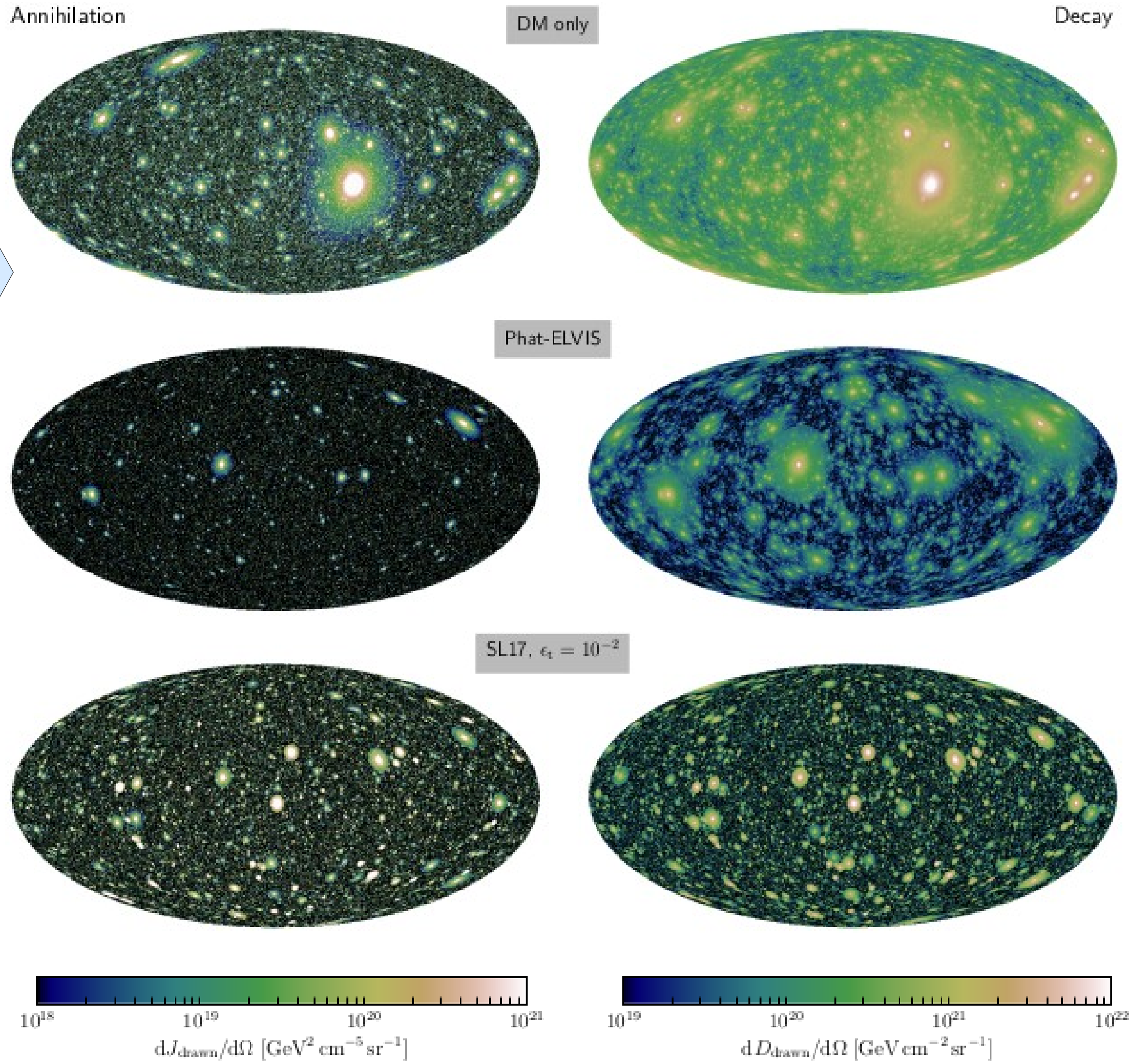
→ Strong impact on flux/detectability (and DM constraints)



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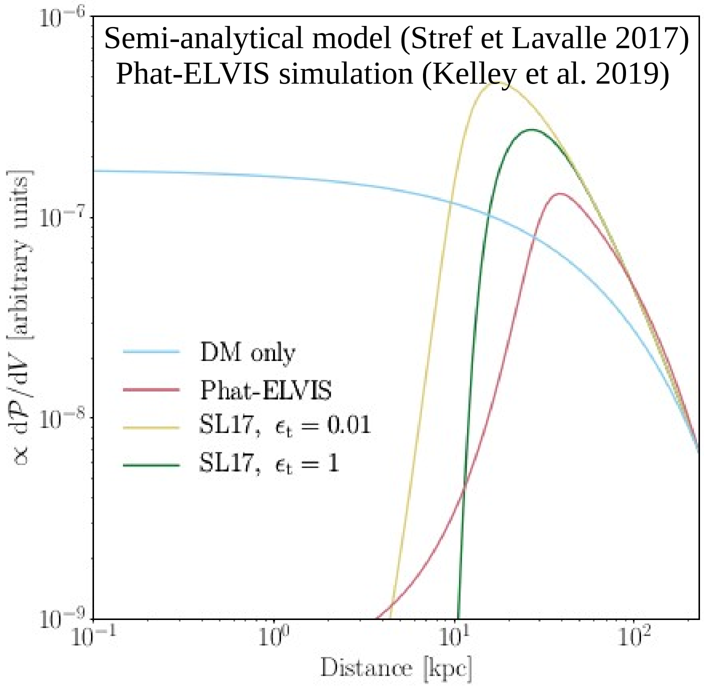
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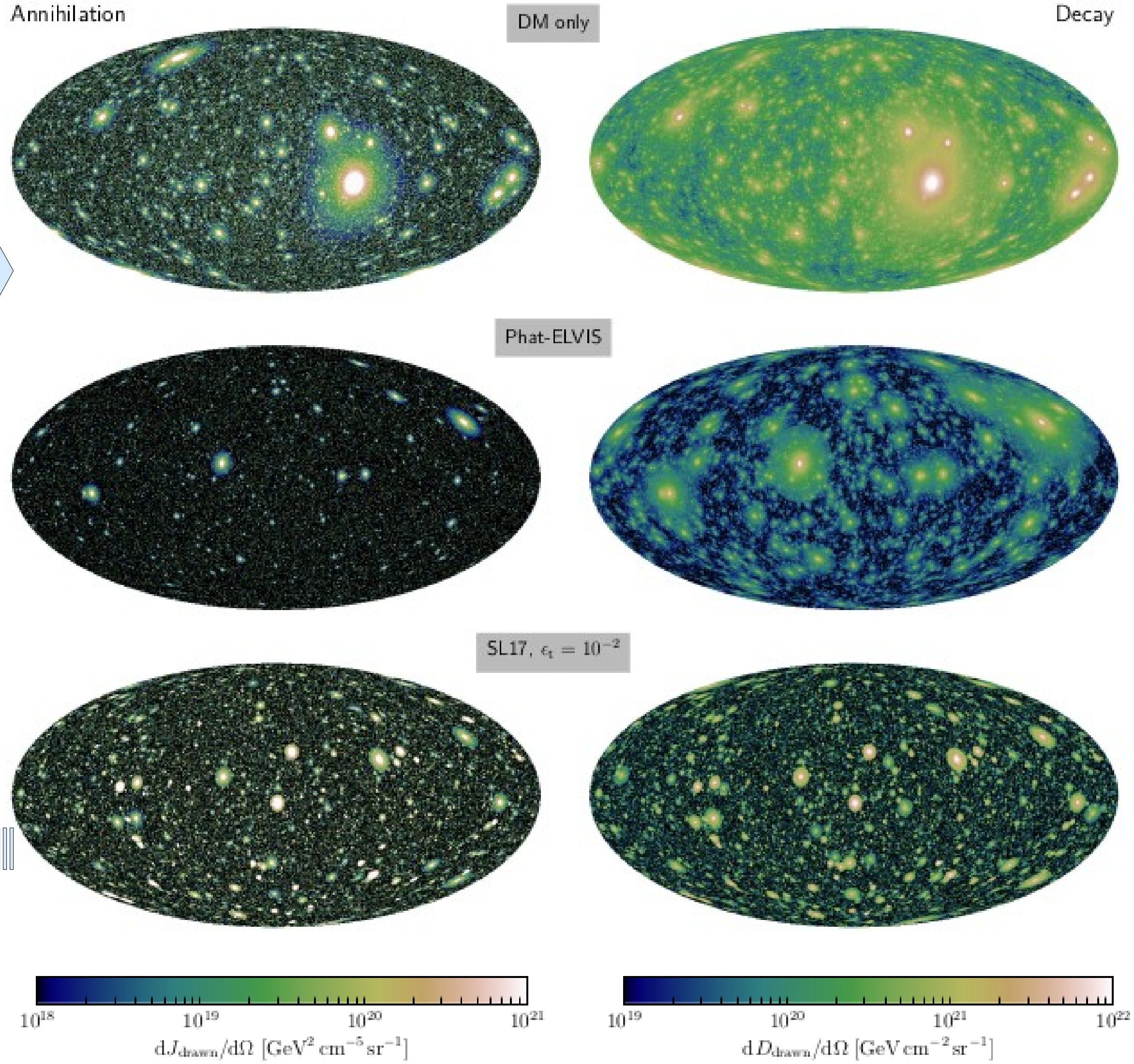

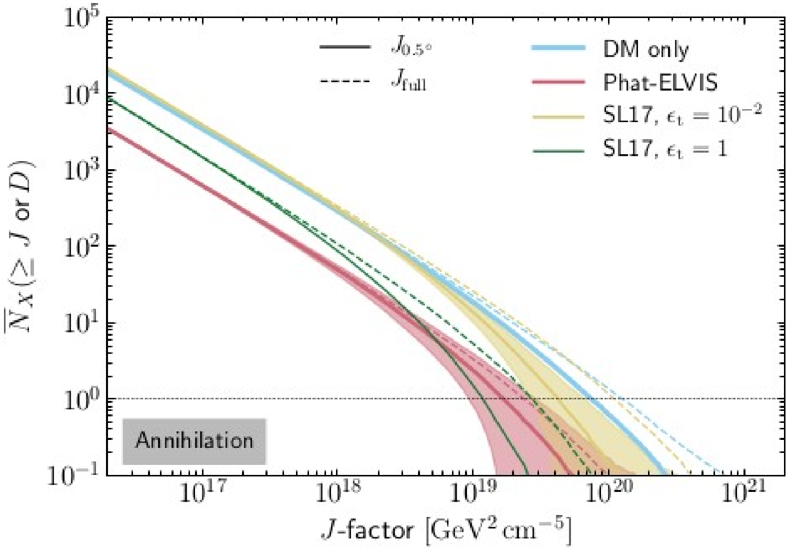

3) Results: dark halos (1000 realisations)

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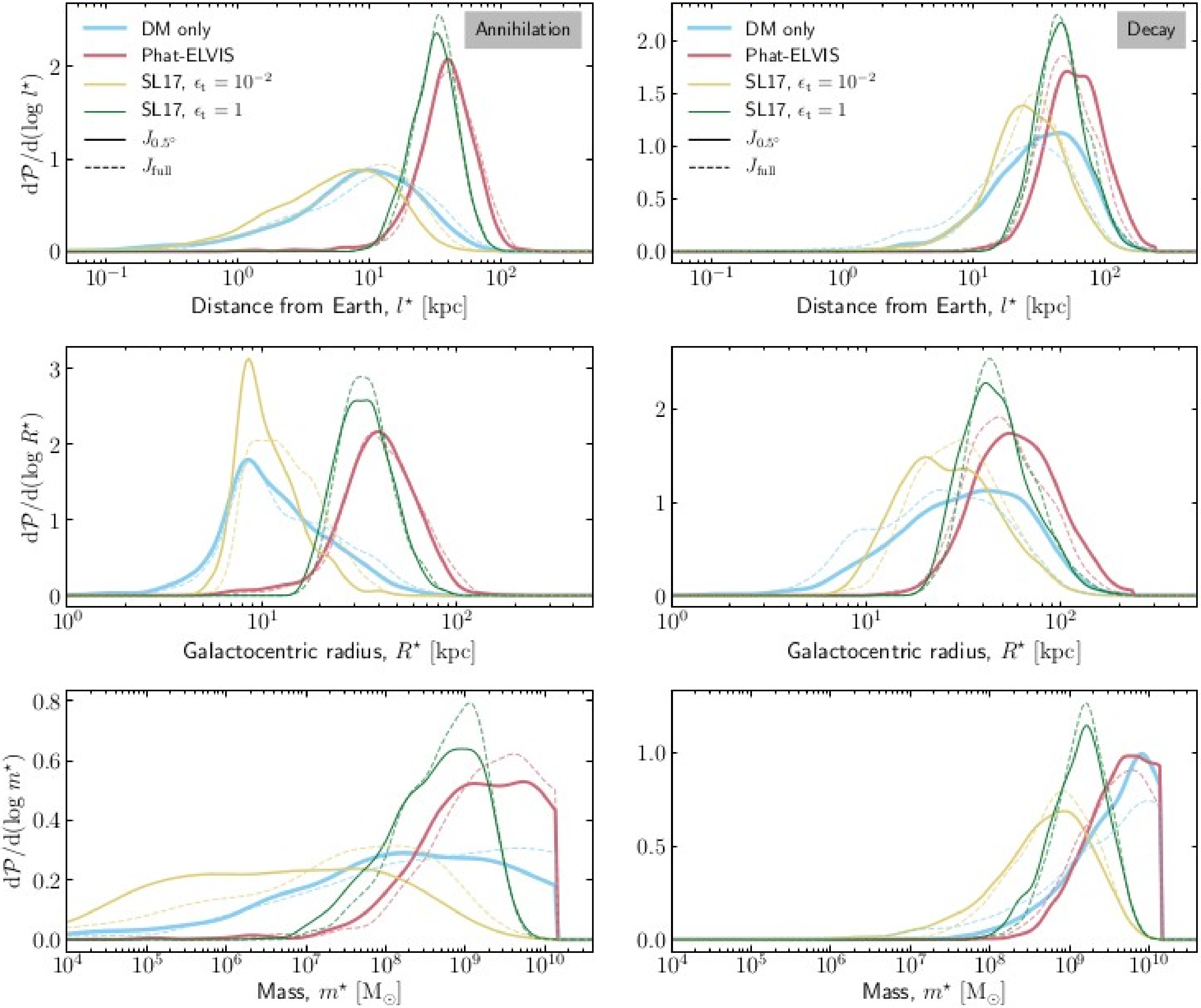
→ Allows to study statistical properties (here of brightest sub-halos)



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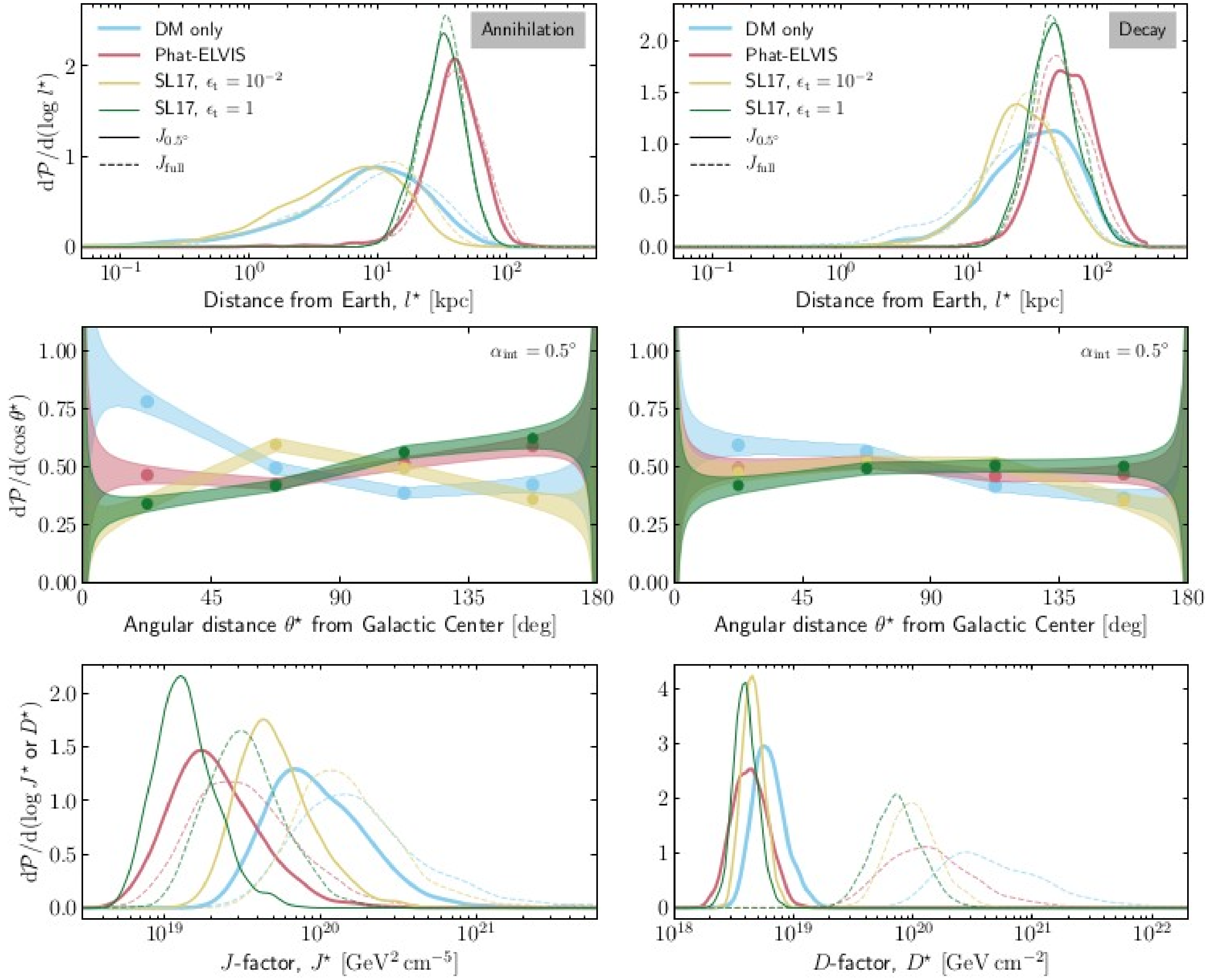


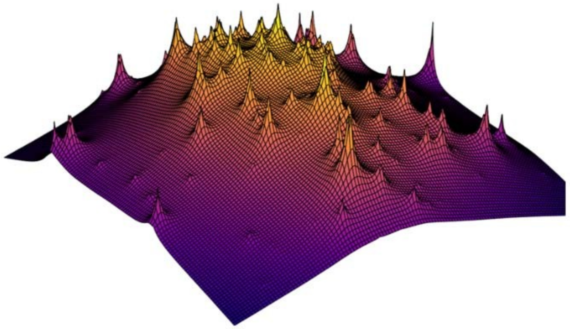
→ Useful to test detectability by Fermi-LAT (e.g., Di Mauro, Stref & Calore 2020)

1) γ-rays from DM: brief reminder

2) What is CLUMPY?

3) A few results: focus on subhalos

4) Conclusions



Conclusions

Status of CLUMPY

- 3 public releases (on git, full documentation)
- From dark clumps to extragalactic
  → Impact of tidal disruption implemented for dark halos in v3.1 (released last year)
- Growing use in community
  → Used in DM analyses by Antares, Fermi-LAT, CTA, HAWC

Desired developments

1) Synthetic skymaps for extragalactic: average + nearby known/relevant (as for dark clumps)
   → 1-point statistics, direct calculation of higher-order statistics, full skymap simulation
2) Include calculation of generalised J-factors (velocity-dependent cross-sections)
   → Stay tune for Lacroix et al. (see M. Stref's talk)... that would be nice to implement in CLUMPY
3) More exotic or more technical issues
   → Python interface, simple parallelisation, etc.

Unfortunately, workforce of the CLUMPY team asymptotically goes to N < 1 with time!
(contact us if you are interested: clumpy@lpsc.in2p3.fr)