

Statistics of the subhalo population in the Milky Way for the detection of dark matter point sources

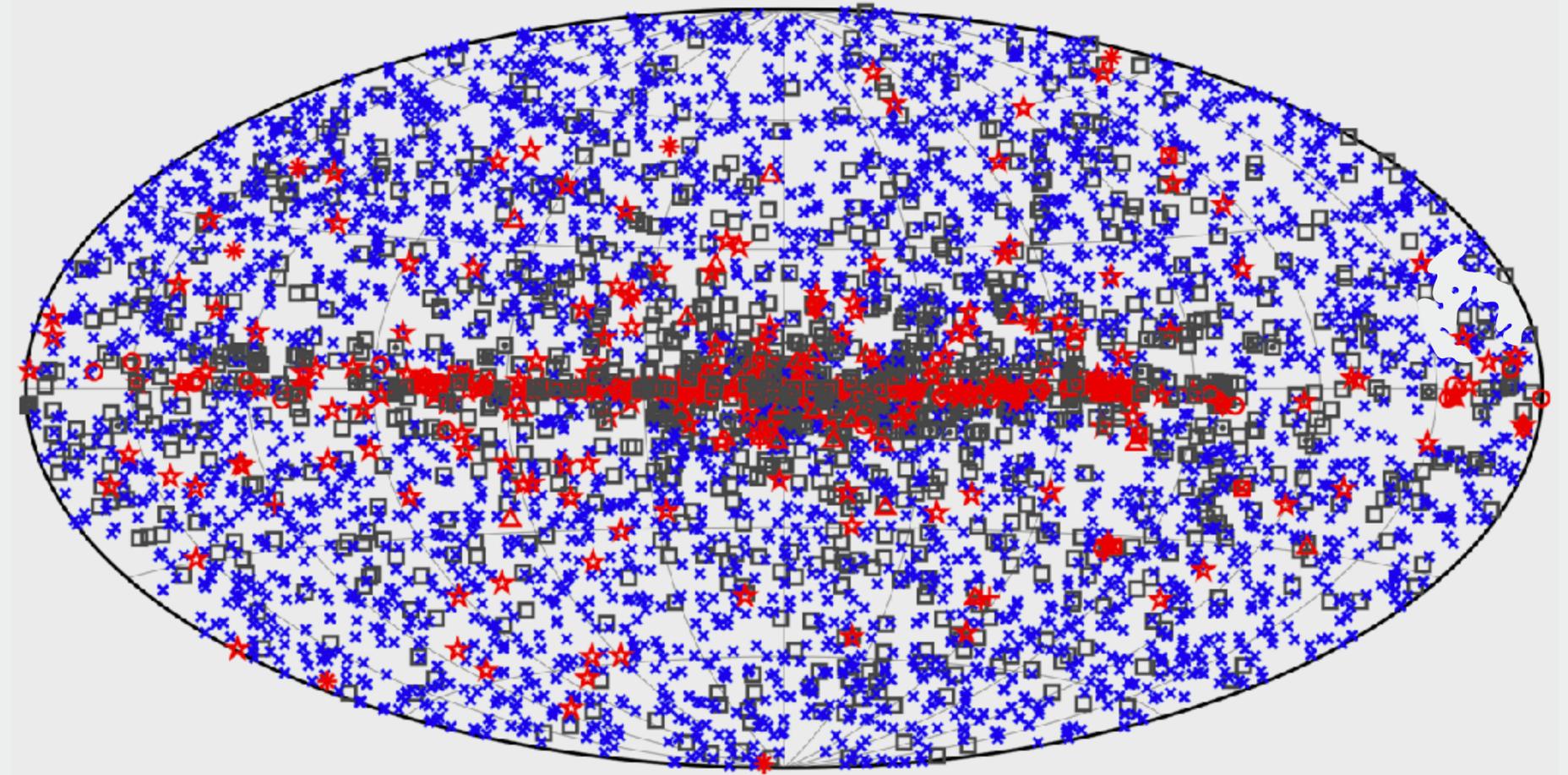


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Gaétan Facchinetti & Julien Laval



The search of
point-like subhalos
in the Milky Way



[Fermi-LAT collaboration 19]

Smooth contribution
(From the host halo)

N_{sub} subhalos
(CDM paradigm)

$$\rho_{\chi} = \rho_{\text{smooth}} + \sum_{i=1}^{N_{\text{sub}}} \rho_i$$

The DM distribution in the Milky Way (MW) is made of two components ₃

1525

**unassociated point sources
in Fermi-LAT 4th catalog (4FGL)**

[Fermi-LAT collaboration 19]

992

**unassociated point sources
in Fermi-LAT 3rd catalog (3FGL)**

[Acero +15]

Most expected to be from extragalactic origin (AGNi, SBGs, etc.)

**This raises a question
in the context of **Dark Matter** searches**

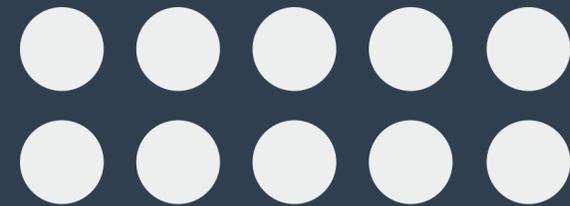
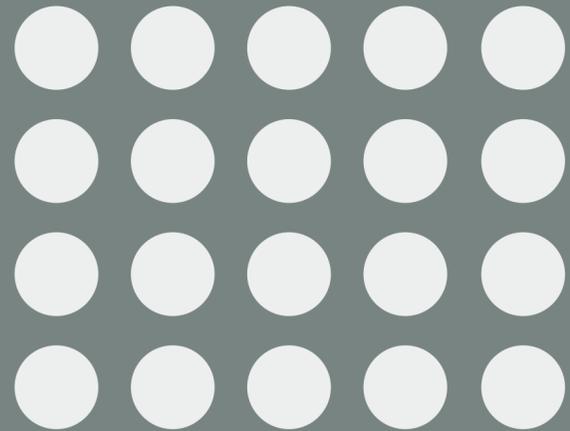
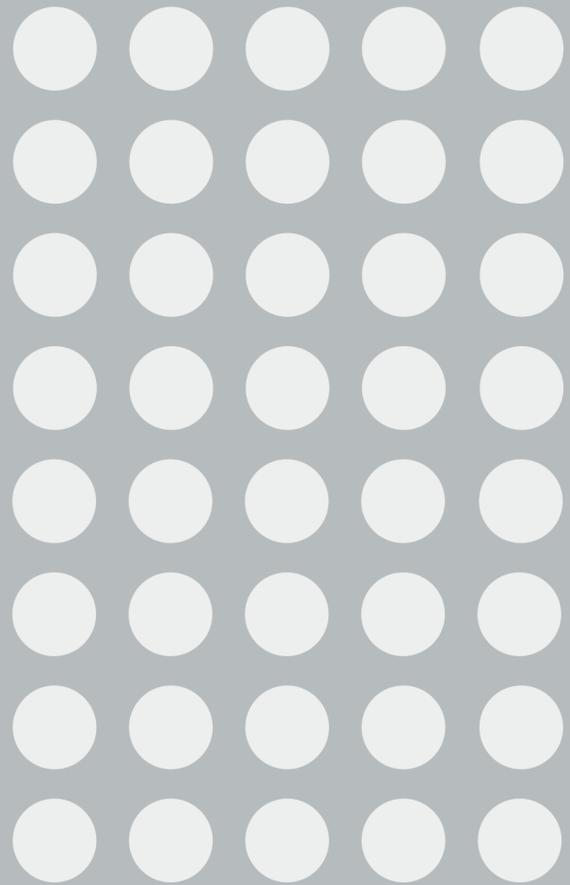
**Can some of these sources
be DM subhalos?**

(assuming DM can self-annihilate)

**Can some of these sources
be DM subhalos?**

(assuming DM can self-annihilate)

The question has already been addressed...



Buckley+10

~ 20-60 candidates

Bertoni+15

~ 20 candidates

Pieri+09

~ 1-10 subhalos

Calore+17

~ 1 subhalo

Different analysis techniques have given different results

So far



[Illustris collaboration]

The usual methods involve data analysis
and/or blind extrapolations from cosmological simulations

**The total galactic halo (smooth + subhalo)
is constrained by theory and observations**

**Assuming a dynamically consistent model
for the subhalo properties (including baryonic tides, etc.)
and a realistic gamma-ray foreground,**

**do we expect to detect
point-like subhalos?**

The **subhalo population** and **photon background**



[The Via Lactea project - Diemand et al. 2008]

4 questions ...

1

**How do we describe
the **subhalo population** in the Milky Way?**

A semi-analytical model for the subhalo population

[Stref & Lavallo 2017]

Start from a cosmological distribution of subhalos

(Press-Schechter mass function)

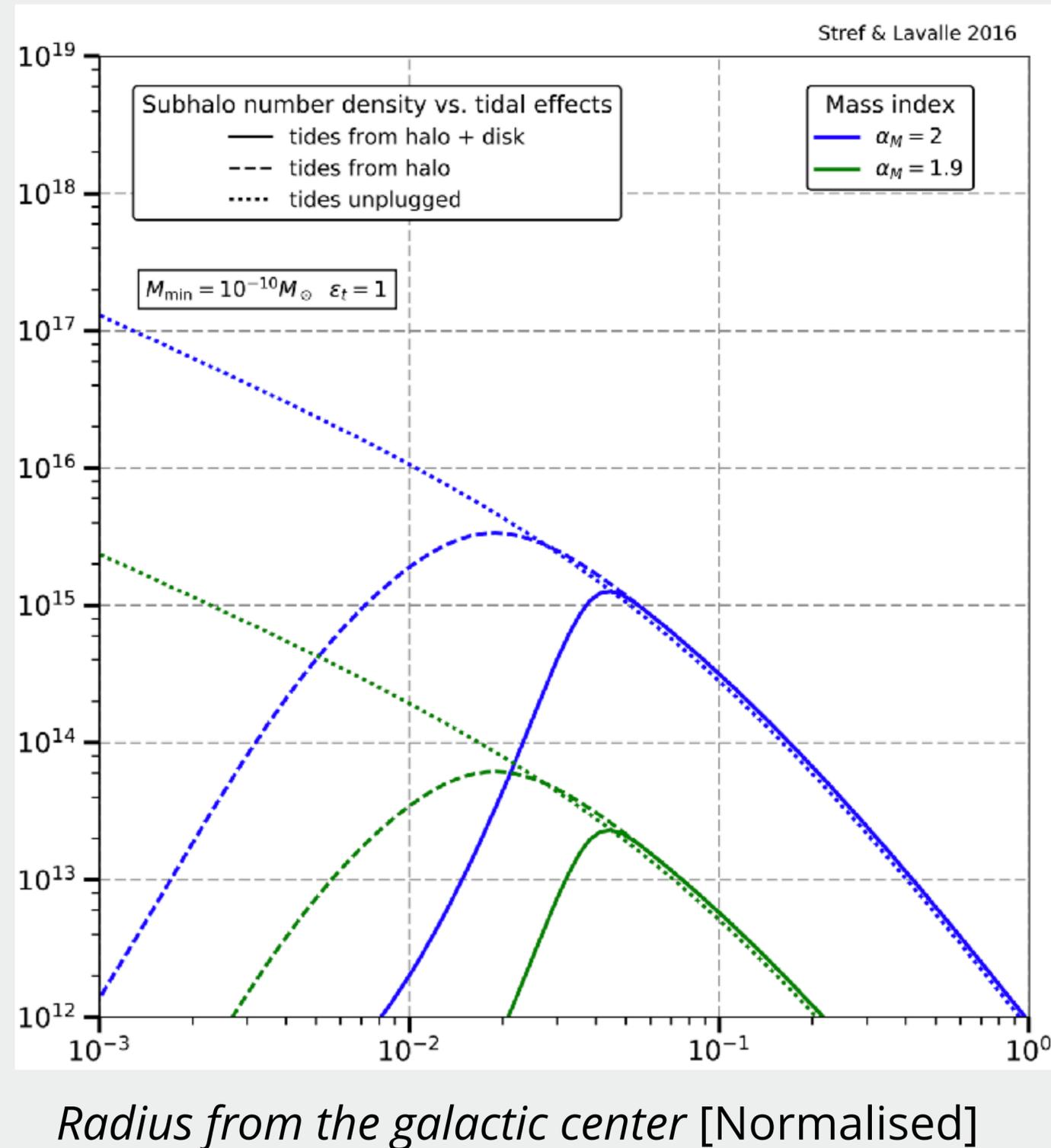
(Mass-Concentration relation)

(Cosmological concentration probability density)

(Spatial distribution in the host halo)

Then, constrain it from dynamical effects in the MW

*Subhalo
number density
[kpc⁻³]*



1.

Position from the center of the galaxy

R

2.

Virial mass

$$m \equiv m_{200}$$

\neq Physical mass

3.

Concentration

$$c \equiv c_{200}$$

$$\left(c = \frac{r_{200}}{r_s} \right)$$

Parameter of the subhalo population

[Stref+17]

All subhalos are characterized by three parameters

1.

Position from the center of the galaxy

R

In 1 to 1 relationship with scale radius and scale density of the subhalo profile e.g.

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

Parameter of the subhalo population

[Stref+17]

All subhalos are characterized by three parameters

Element of integration in parameter space

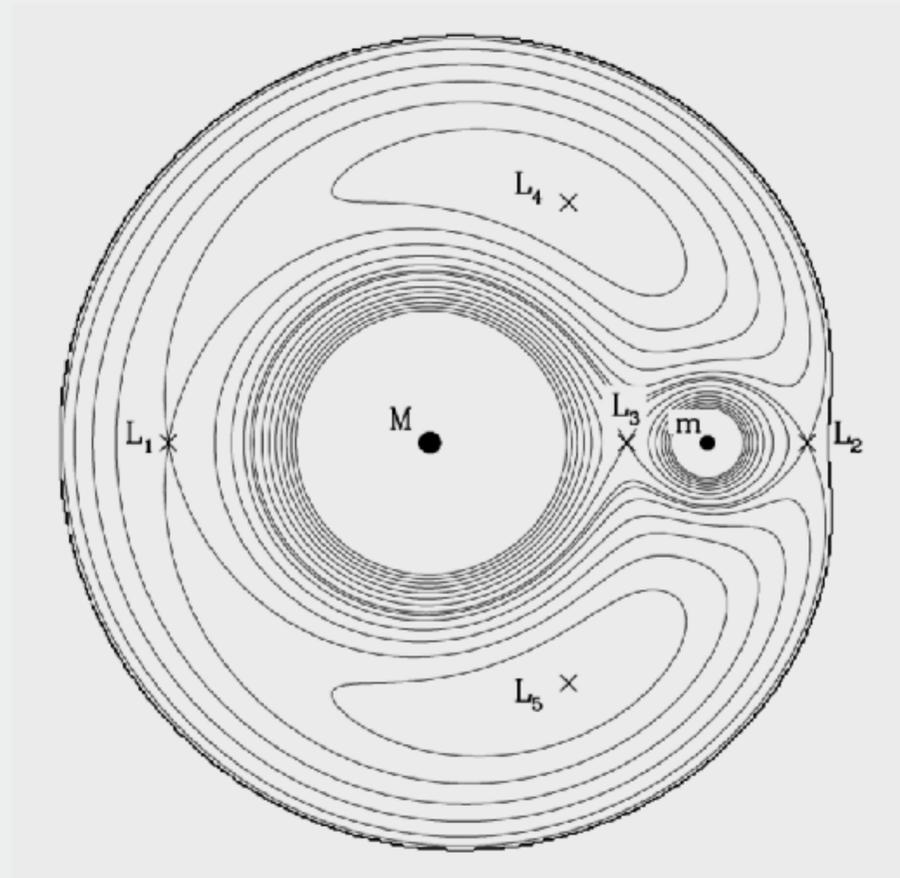
$$d\Gamma = \prod_{i=1}^{N_{\text{sub}}} 4\pi R_i^2 dR_i dm_i dc_i$$

Associated probability density

$$p(\{m_i\}_i, \{c_i\}_i, \{R_i\}_i)$$

Our subhalos are defined by a probability density p

$$r_t = R \left\{ \frac{M_{\text{int}}(R)}{3M(R)f[M(R)]} \right\}^{1/3}$$



Global tides

$$\left\langle \frac{\delta E}{m_\chi} \right\rangle = \frac{2}{3} \frac{g_d^2}{V_z^2} A(\eta) r^2$$



Disk shocking

Two sources of tidal stripping are considered and impact on the probability distribution

Probability density

$$p(\{m_i\}_i, \{c_i\}_i, \{R_i\}_i) \neq \prod_{i=1}^{N_{\text{sub}}} p_m(m_i) p_c(c_i, m_i) p_R(R_i)$$

Parameter space depends on 3 variables

1.

Mass index

$$\left(\frac{dn}{dm} \propto m^{\alpha_m} \right)$$

2.

Disruption parameter

$$\epsilon_t = \min \left(\frac{r_t}{r_s} \right)$$

(Fragile vs resilient subhalos)

3.

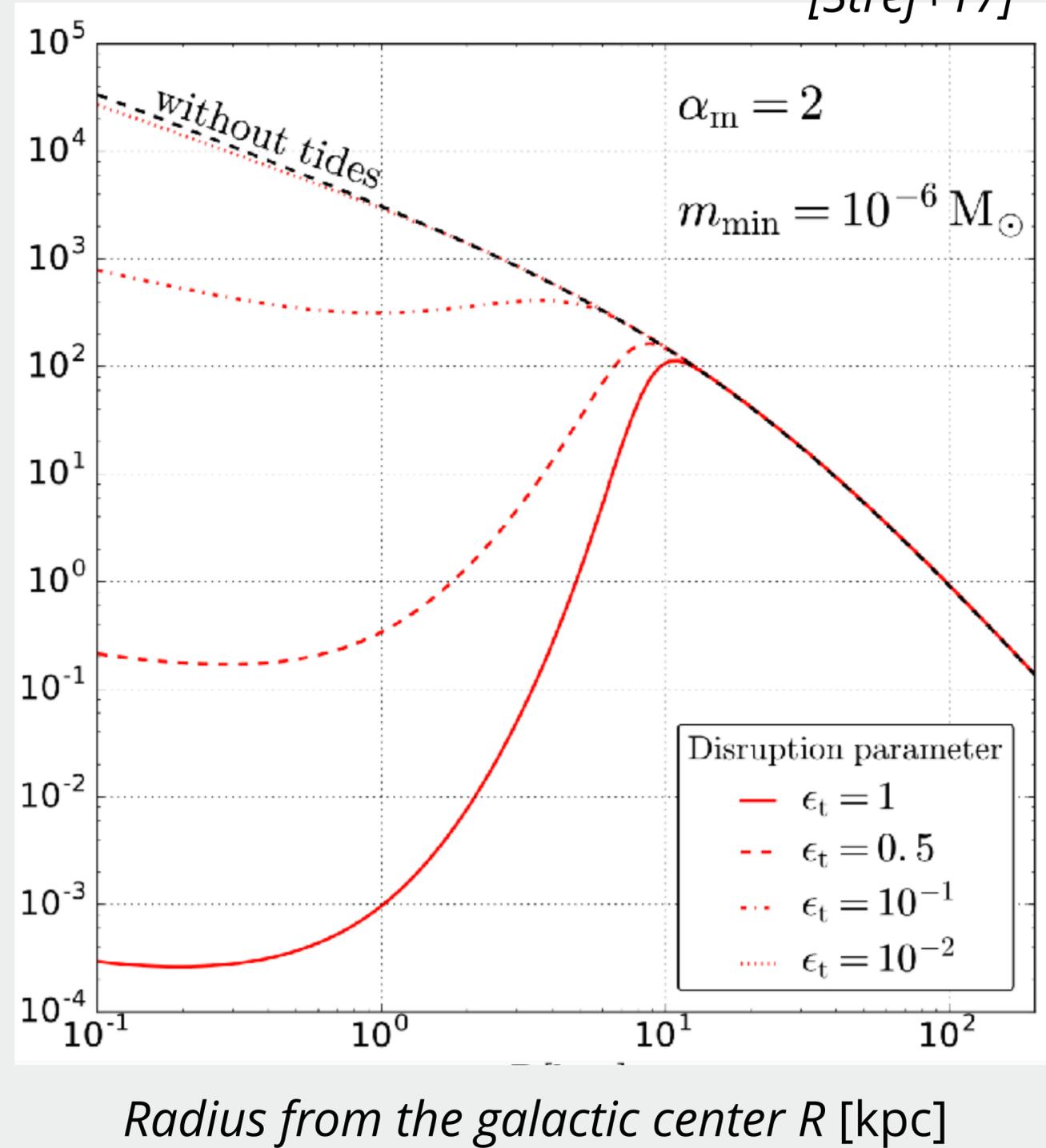
Minimal halo mass

$$m_{\text{min}}$$

The probability density depends on 3 variables

[Stref+17]

Subhalo number density
[pc⁻³]



An example of what is possible using this model

Subhalo population
semi-analytical
probabilistic model

Key parameters

mass index

disruption parameter

subhalos minimal mass

2

Photon flux from DM annihilation?

Differential photon flux:

$$\frac{d\phi_\gamma}{dE_\gamma}(l_0, b_0, \Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \frac{1}{4\pi} \int_{\Delta\Omega_0} d\Omega \int_{\text{l.o.s.}} ds \rho_\chi^2(s, l, b)$$

Particle physics part

Astrophysics part

Photon flux due to Dark Matter annihilation

Differential photon flux:

$$\frac{d\phi_\gamma}{dE_\gamma}(l_0, b_0, \Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \frac{1}{4\pi} \int_{\Delta\Omega_0} d\Omega \int_{\text{l.o.s.}} ds \rho_\chi^2(s, l, b)$$

$$J(l_0, b_0, \Delta\Omega) \equiv \frac{1}{4\pi} \int_{\Delta\Omega_0} d\Omega \int_{\text{l.o.s.}} ds \rho_\chi^2(s, l, b)$$

J-factor

3

Photon flux from standard astrophysical sources?

For $1 \text{ GeV} < E_\gamma < 100 \text{ GeV}$
(Fermi case)

Isotropic component
(mostly from extragalactic origin)

Fermi data *[Ackermann+12]*

Pi-meson decay component
(diffuse Galactic emission)

Fermi data *[Ackermann+12]*

Model of HI and H₂ distribution *[McMillan 16]*
+ simple model of cosmic ray flux

For $1 \text{ TeV} < E_\gamma < 100 \text{ TeV}$
(CTA case)



Work in progress

For $1 \text{ GeV} < E_\gamma < 100 \text{ GeV}$
(Fermi case)

Isotropic component
(mostly from extragalactic origin)

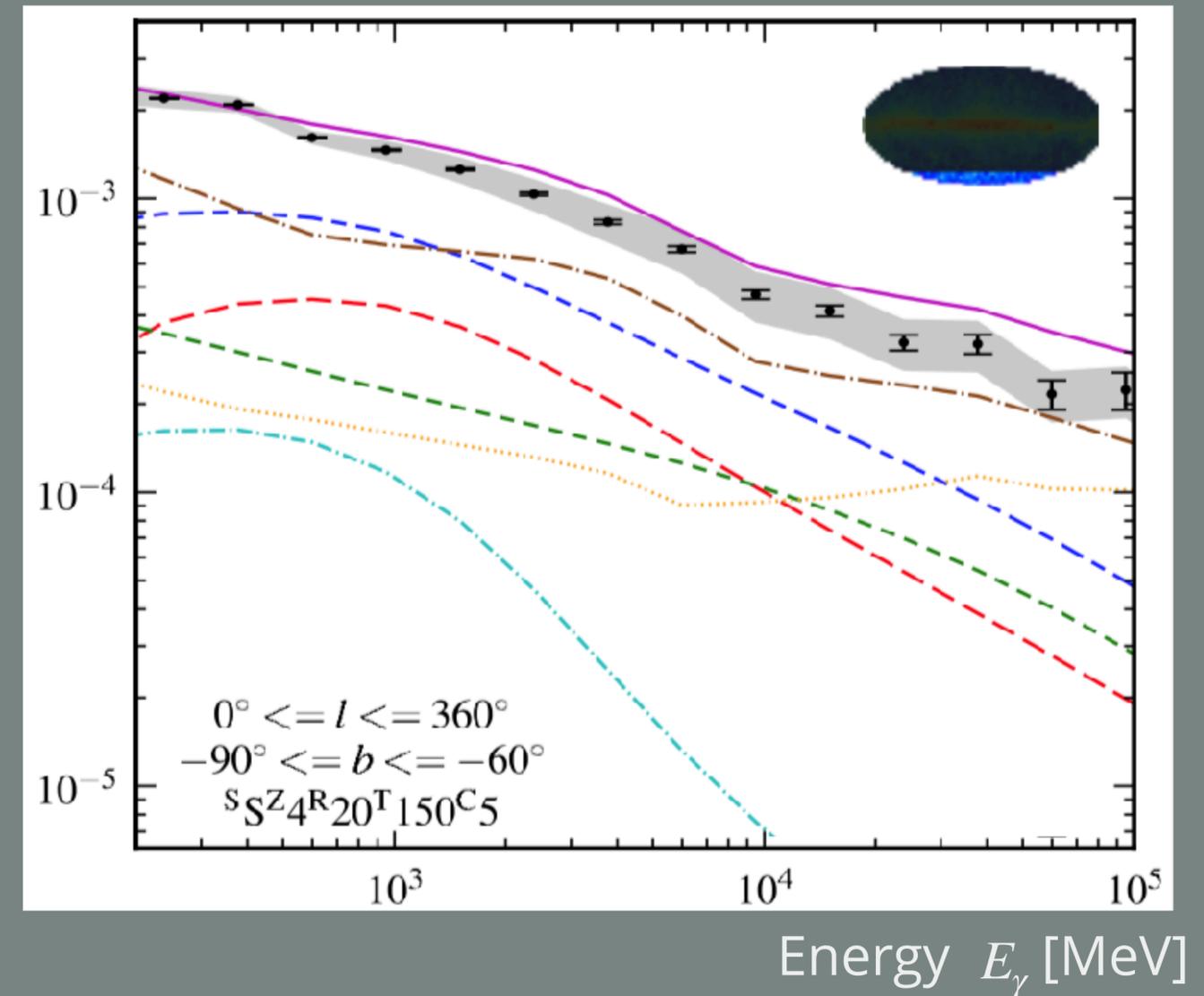
Fermi data [Ackermann+12]

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$E_\gamma^2 \times \text{differential flux}$
[MeV⁻¹ cm⁻² s⁻¹ sr⁻¹]



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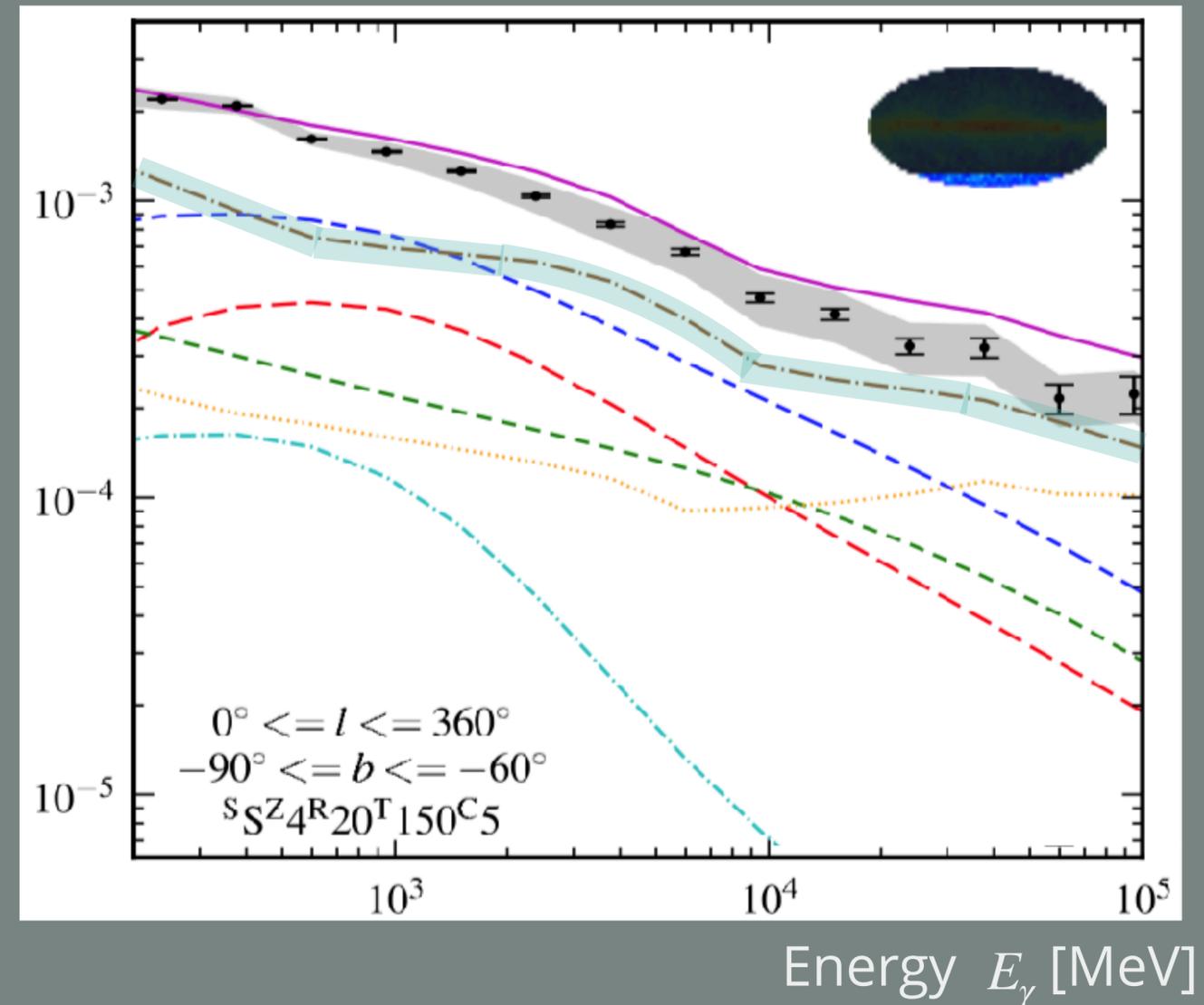
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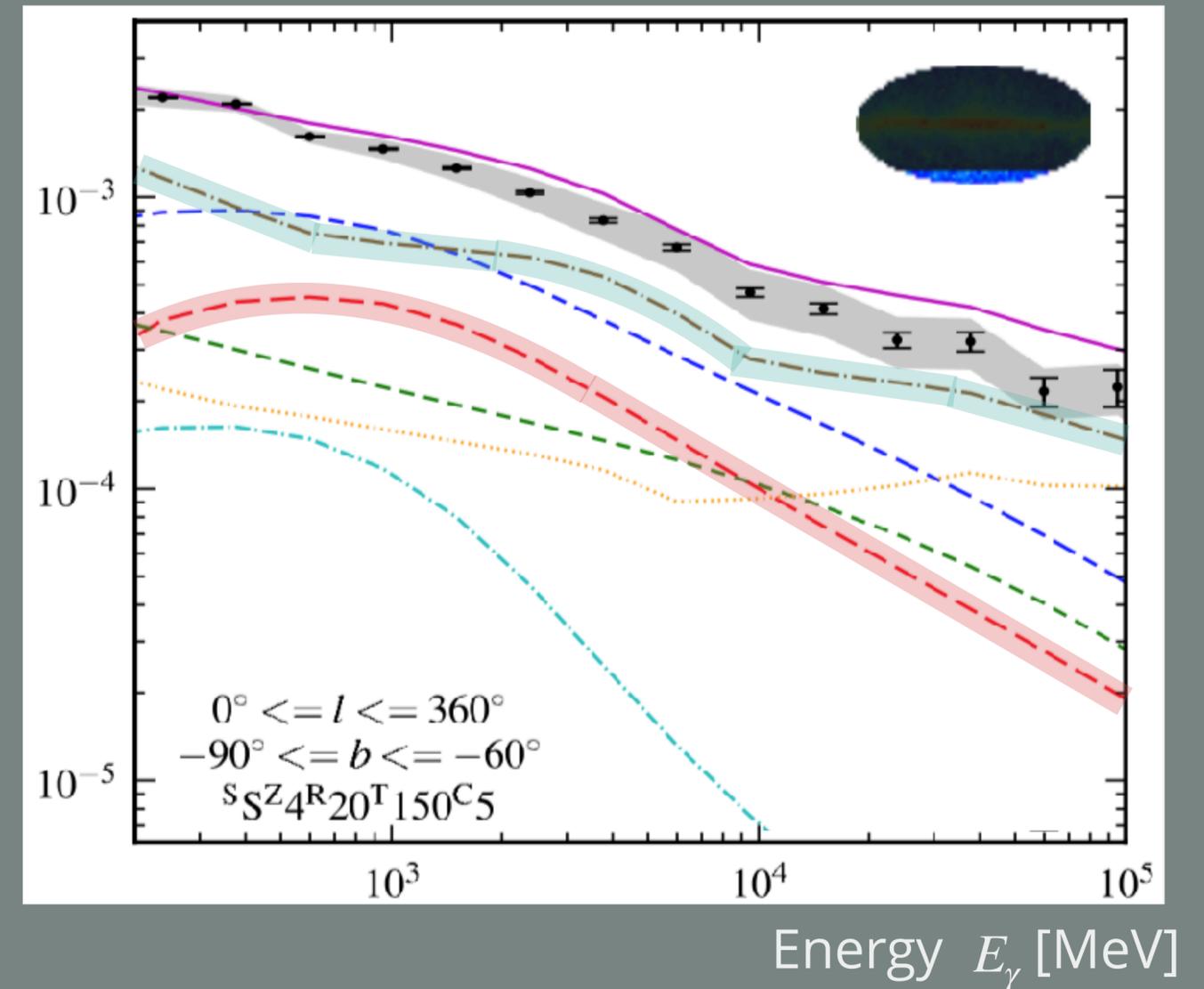
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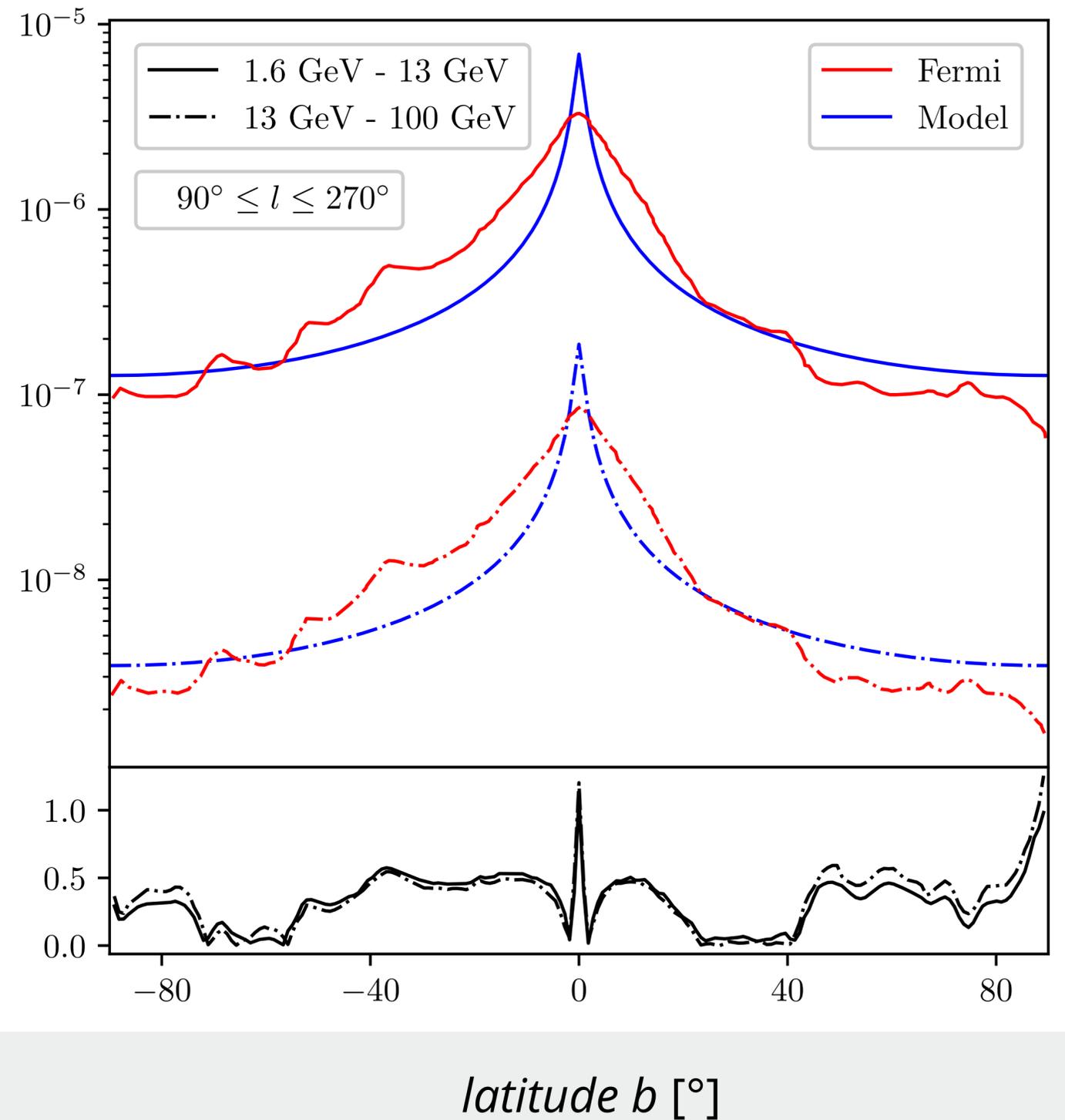
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$E_\gamma^2 \times \text{differential flux}$
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Flux
from π^0 decay
[$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

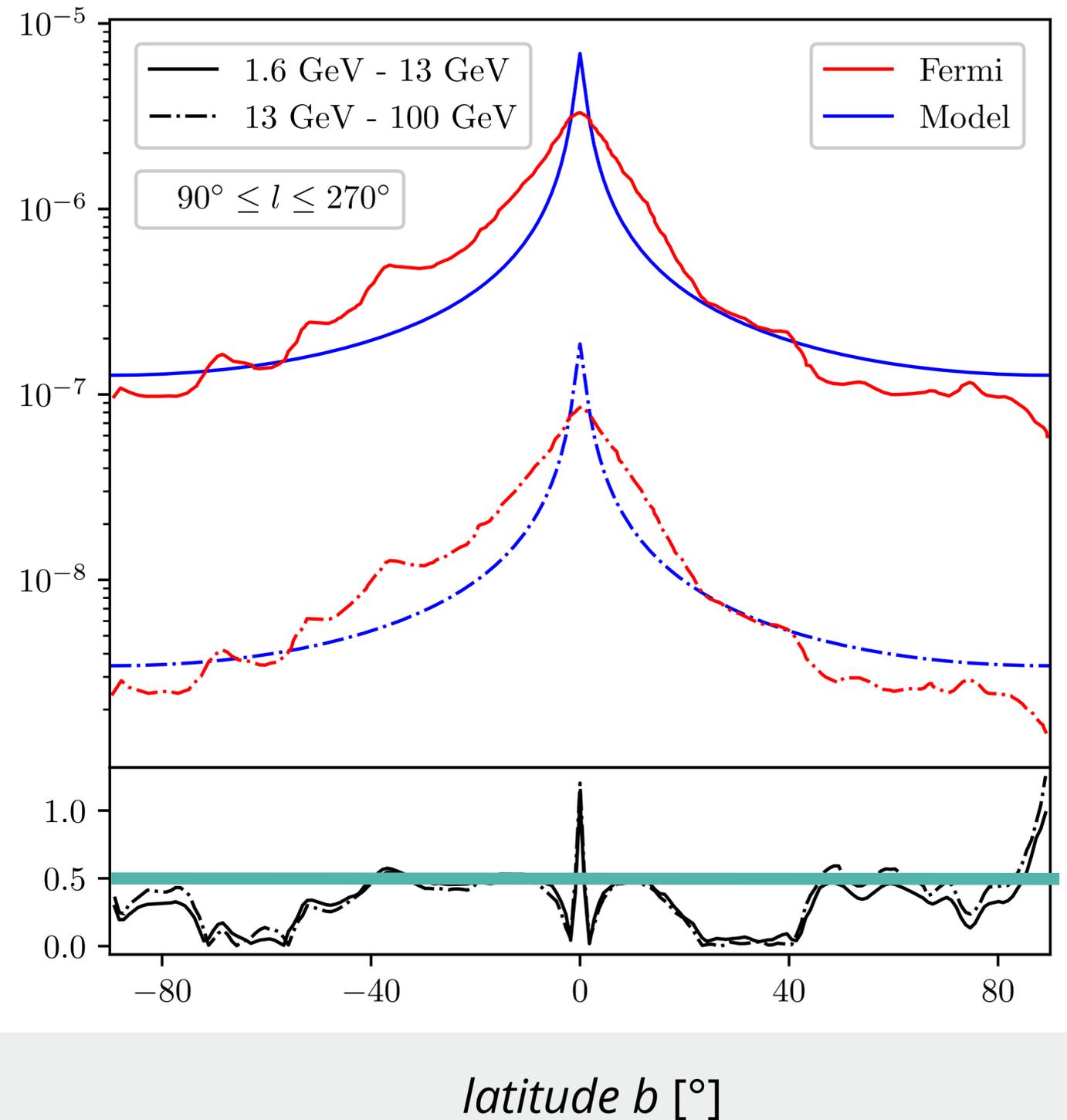


Relative
difference

[Ackermann+12]

The standard foreground spectrum is calibrated on Fermi data

Flux
from π^0 decay
[cm⁻² s⁻¹ sr⁻¹]



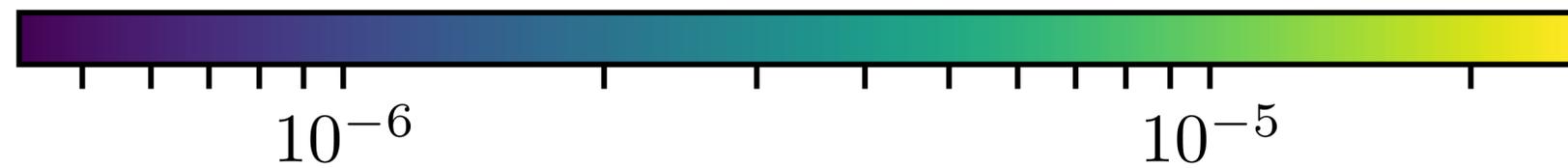
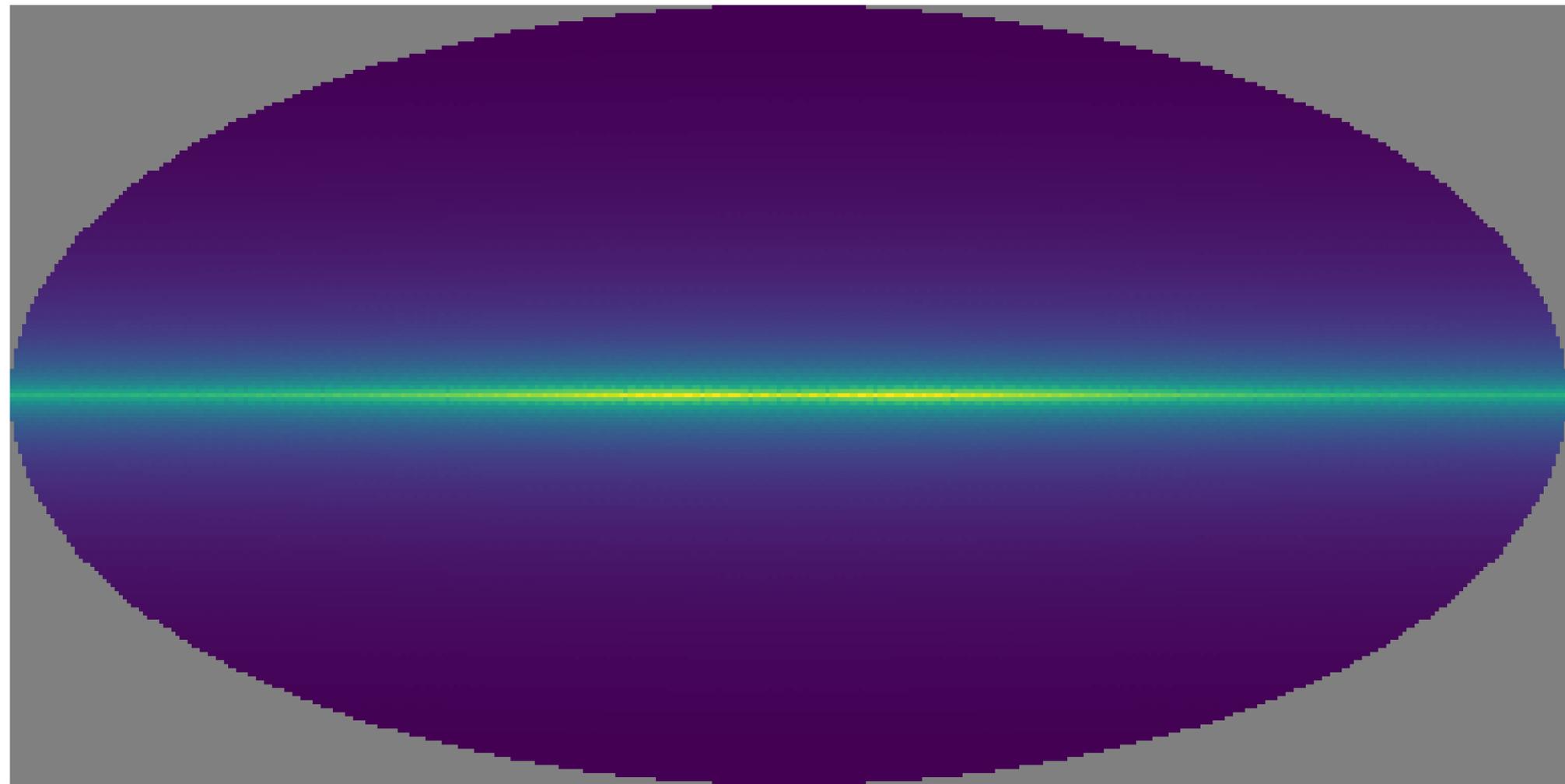
**Relative difference
after calibration**

≈ 50%

[Ackermann+12]

The standard foreground spectrum is calibrated on Fermi data

Total foreground flux [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

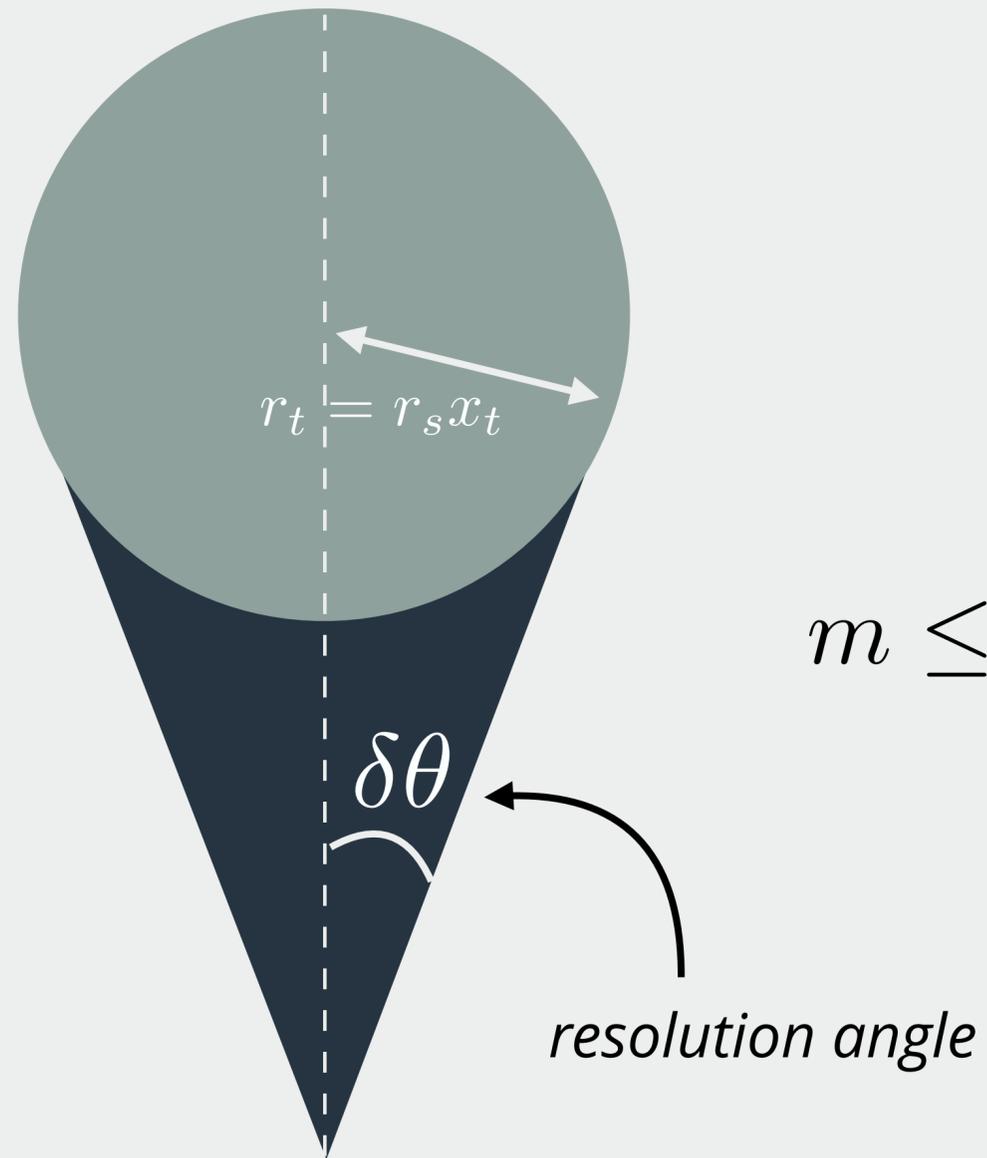


Adding the isotropic component we get a full background flux

**We use a simplified model for
the gamma-ray foreground
calibrated on Fermi**

4

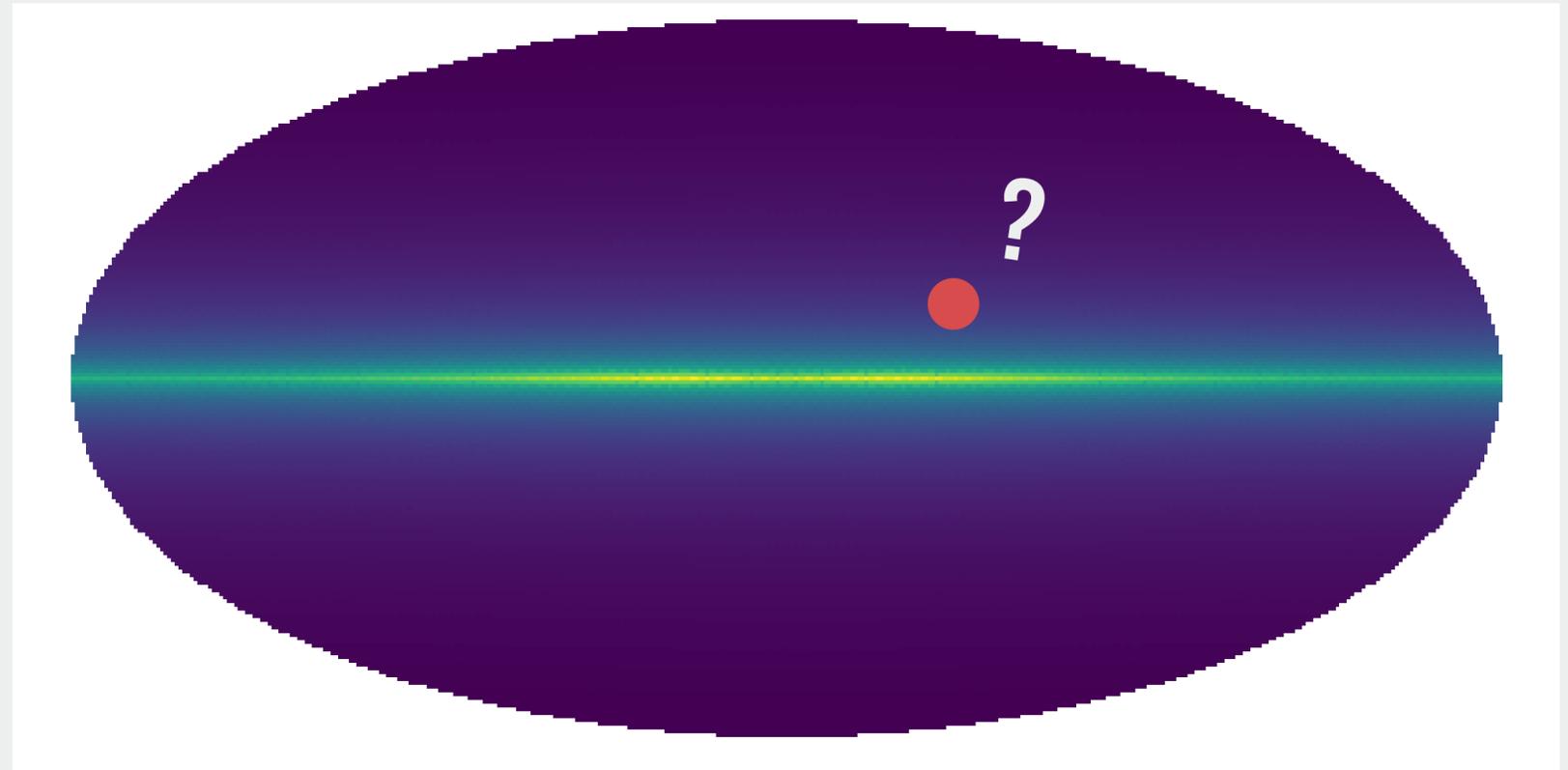
What is a point-like subhalo?



$$m \leq \frac{4\pi 200\rho_c}{3} \left(\frac{c}{\min(x_t(c, s, \psi), 2)} s\eta \sin \delta\theta \right)^3$$

Condition on the size translates on a **maximal bound on the mass**

Detectability of
point-like subhalos



Point-like subhalo detection

$$\frac{N_{\gamma}^i(l, b)}{\sqrt{N_{\gamma}^{\text{tot}}(l, b)}} > n_{\sigma}$$

Number a photons received from a point-like subhalo

$$N_{\gamma}^i(l, b) = \frac{\langle \sigma v \rangle}{2m_{\chi}^2} \int dE_{\gamma} \mathcal{E} \frac{dN_{\gamma}}{dE_{\gamma}} J_i^{\text{pt}}(\psi)$$

Number a photons received from all DM

$$N_{\gamma}^{\text{x}}(l, b) = \frac{\langle \sigma v \rangle}{2m_{\chi}^2} \int dE_{\gamma} \mathcal{E} \frac{dN_{\gamma}}{dE_{\gamma}} \langle J(\delta\Omega, \psi) \rangle$$

Total number of photon received

$$N_{\gamma}^{\text{tot}}(l, b) = N_{\gamma}^{\text{st.}}(l, b) + N_{\gamma}^{\text{x}}(l, b)$$

$N_{\gamma}^{\text{st.}}(l, b)$: number of photons
from standard sources

\mathcal{E} : Exposure

Two conditions must be satisfied

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Constraint on the smooth halo + unresolved subhalos

$$\frac{N_{\gamma}^{\chi}(l, b)}{\sqrt{N_{\gamma}^{\text{st.}}(l, b)}} < \tilde{n}_{\sigma}$$

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$N_{\gamma}^{\text{st.}}(l, b)$: number of photons
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\mathcal{E} : Exposure

Two conditions must be satisfied

Point-like subhalo detection

$$\frac{N_{\gamma}^i(l, b)}{\sqrt{N_{\gamma}^{\text{tot}}(l, b)}} > n_{\sigma} \quad \Rightarrow \quad J_{\text{min}}$$

Constraint on the smooth halo + unresolved subhalos

$$\frac{N_{\gamma}^{\chi}(l, b)}{\sqrt{N_{\gamma}^{\text{st.}}(l, b)}} < \tilde{n}_{\sigma} \quad \Rightarrow \quad \langle \sigma v \rangle_{\text{max}}$$

Number a photons received from a point-like subhalo

$$N_{\gamma}^i(l, b) = \frac{\langle \sigma v \rangle}{2m_{\chi}^2} \int dE_{\gamma} \mathcal{E} \frac{dN_{\gamma}}{dE_{\gamma}} J_i^{\text{pt}}(\psi)$$

Number a photons received from all DM

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Total number of photon received

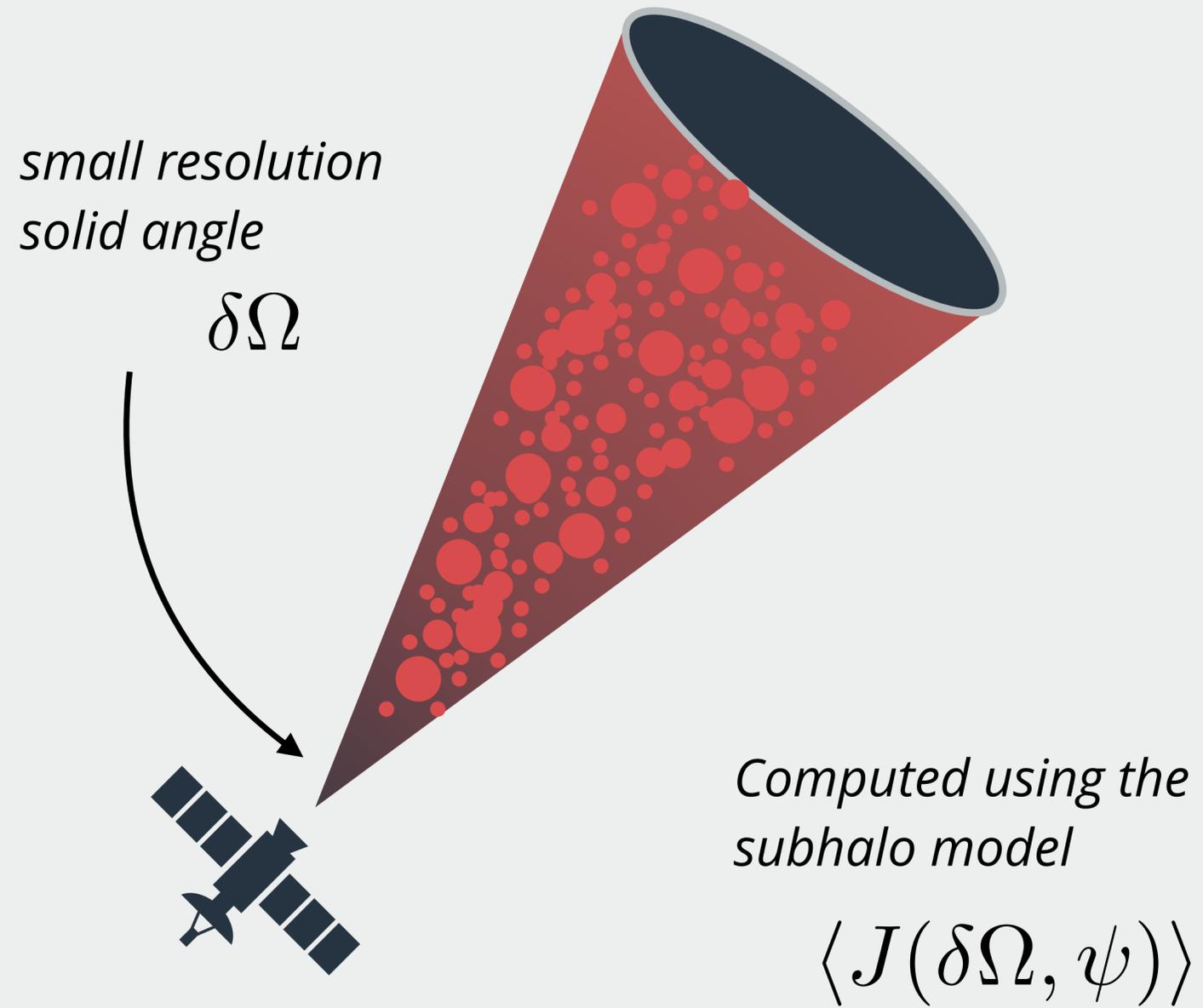
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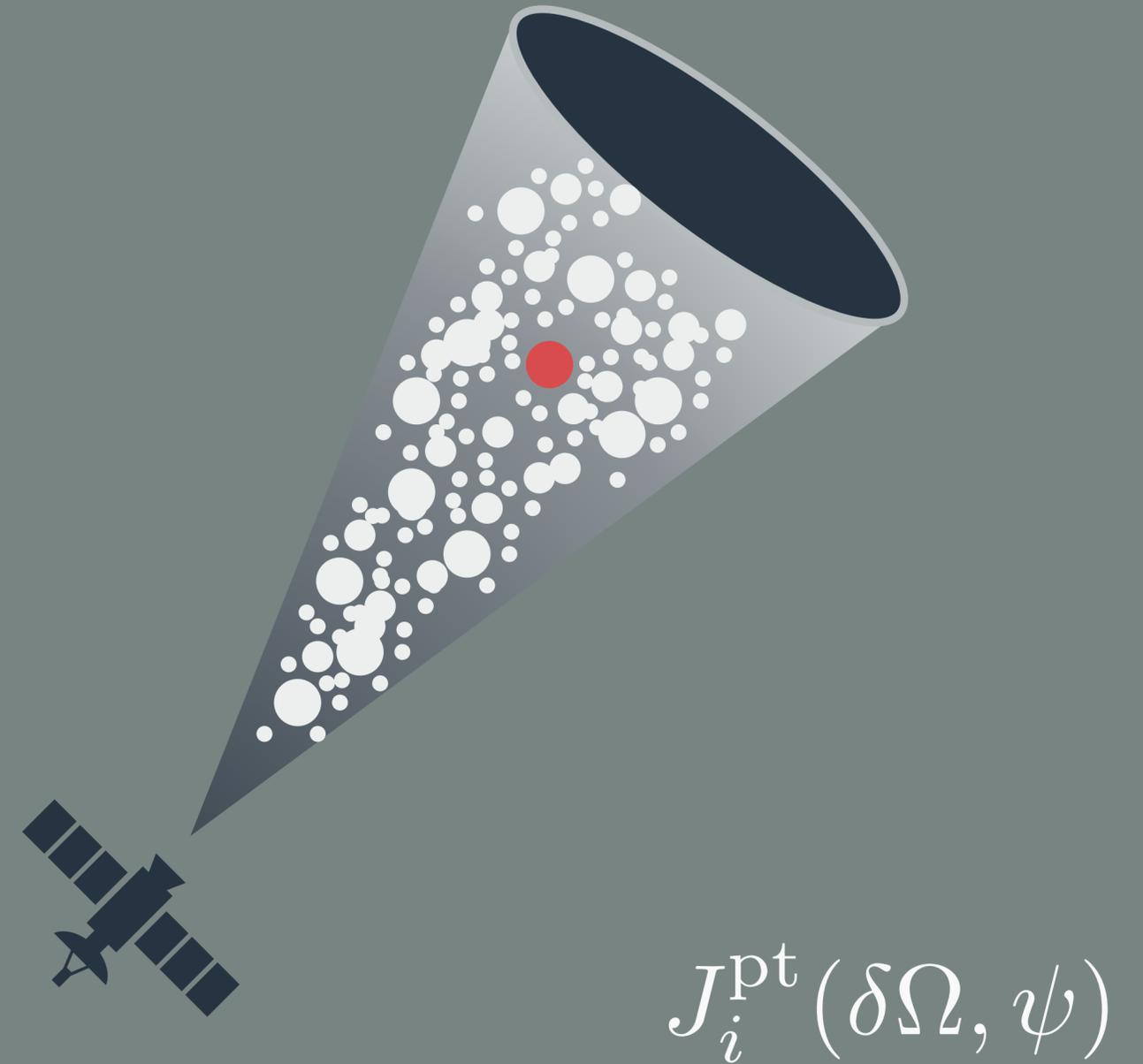
\mathcal{E} : Exposure

Two conditions must be satisfied

The averaged J-factor



The J-factor of a single point-like subhalo (i)



Two quantities are important

Most favorable case:

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{\max}$$

Infinite exposure time in every direction

$$J_{\min} \equiv J_{\infty} = \frac{n_{\sigma}}{\tilde{n}_{\sigma}} \sqrt{N_{\gamma}^{\text{st.}}(l, b)} \max_{(l, b)} \left\{ \frac{\langle J(\delta\Omega, \psi) \rangle}{\sqrt{N_{\gamma}^{\text{st.}}(l, b)}} \right\}$$

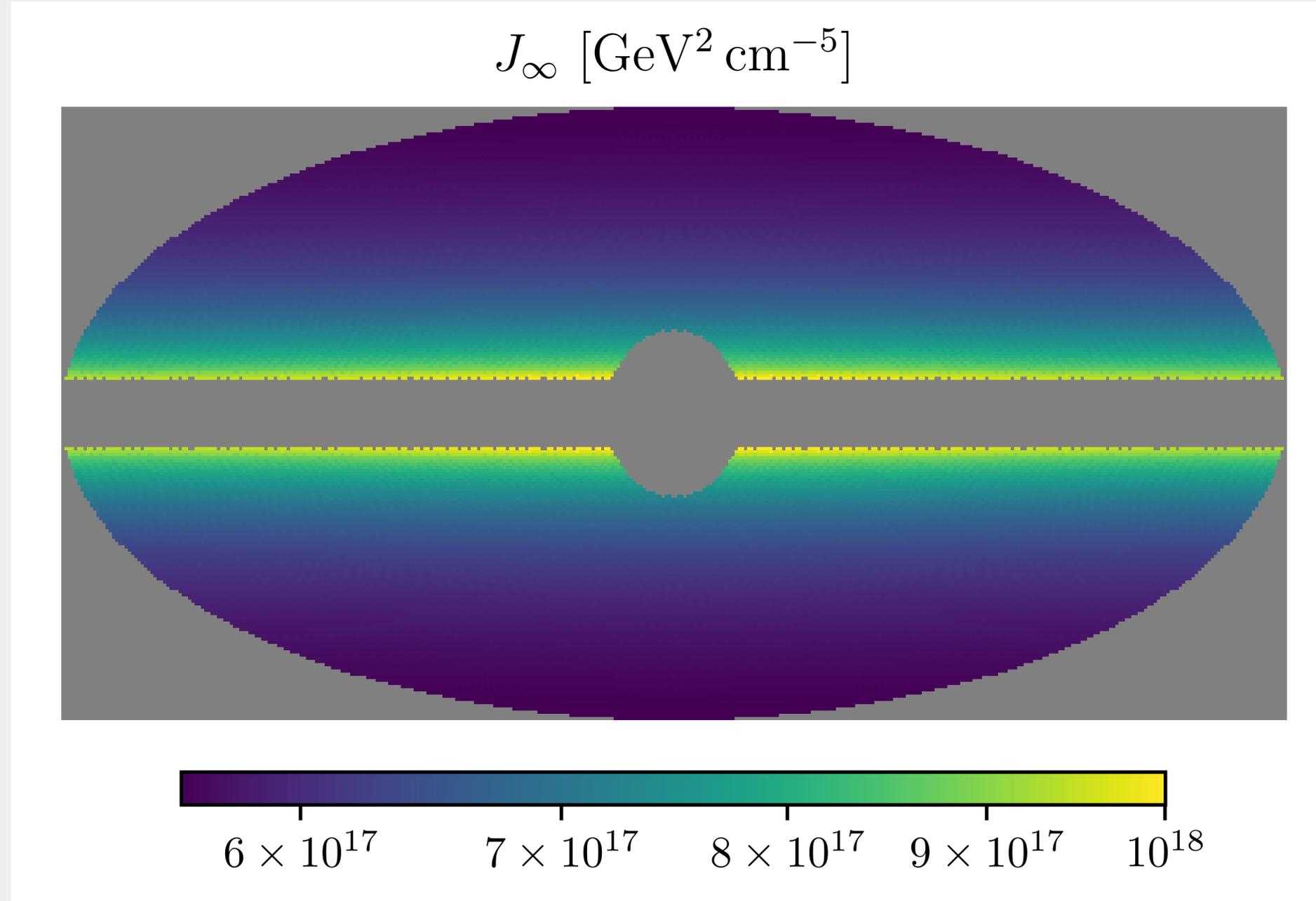
Let us assume the most favorable case:

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{\max}$$

Infinite exposure time in every direction

$$J_{\min} \equiv J_{\infty} = \frac{n_{\sigma}}{\tilde{n}_{\sigma}} \sqrt{N_{\gamma}^{\text{st.}}(l, b)} \max_{(l, b)} \left\{ \frac{\langle J(\delta\Omega, \psi) \rangle}{\sqrt{N_{\gamma}^{\text{st.}}(l, b)}} \right\}$$

Parameterizes some freedom in the background level
and on the statistical criterion

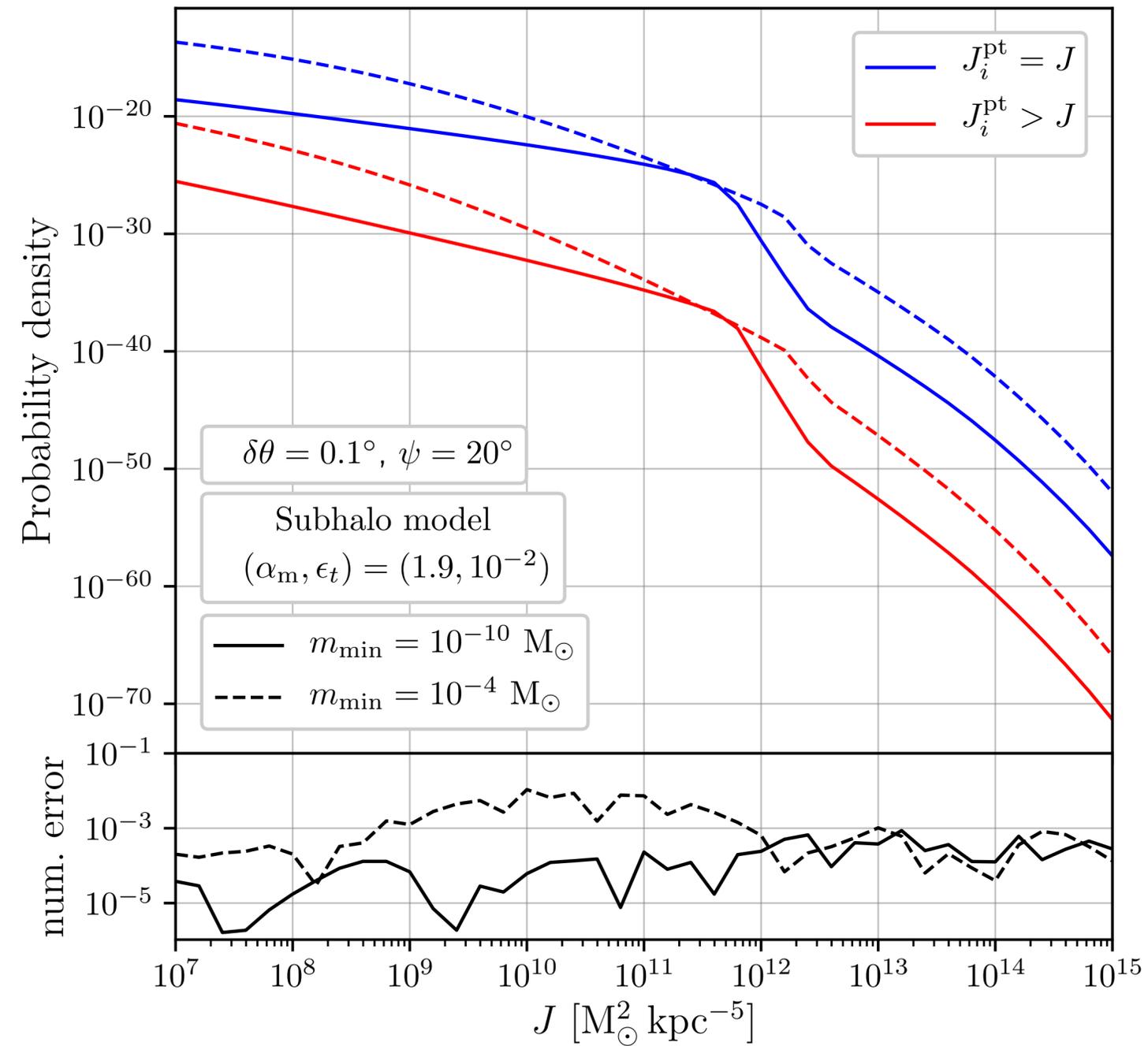


The minimal J-factor to be detectable J_∞ is then independent of the particle physics nature of DM

Probability to find a **point-like** subhalo with a J factor J_i greater than J :

$$\mathbb{P}_{\delta\Omega}(J_i > J; \psi) = \delta\Omega \int_{\mathcal{P}(\psi)} d\sigma p_t(\sigma, \psi) \Theta(J_i - J)$$

Integration on parameter space of
Point subhalos in direction ψ



Probability densities

Mean number of detectable point-like subhalos:

$$\langle K \rangle = N_{\text{sub}} \mathbb{P}_{\delta\Omega}(J_i > J_{\text{min}}; \psi)$$

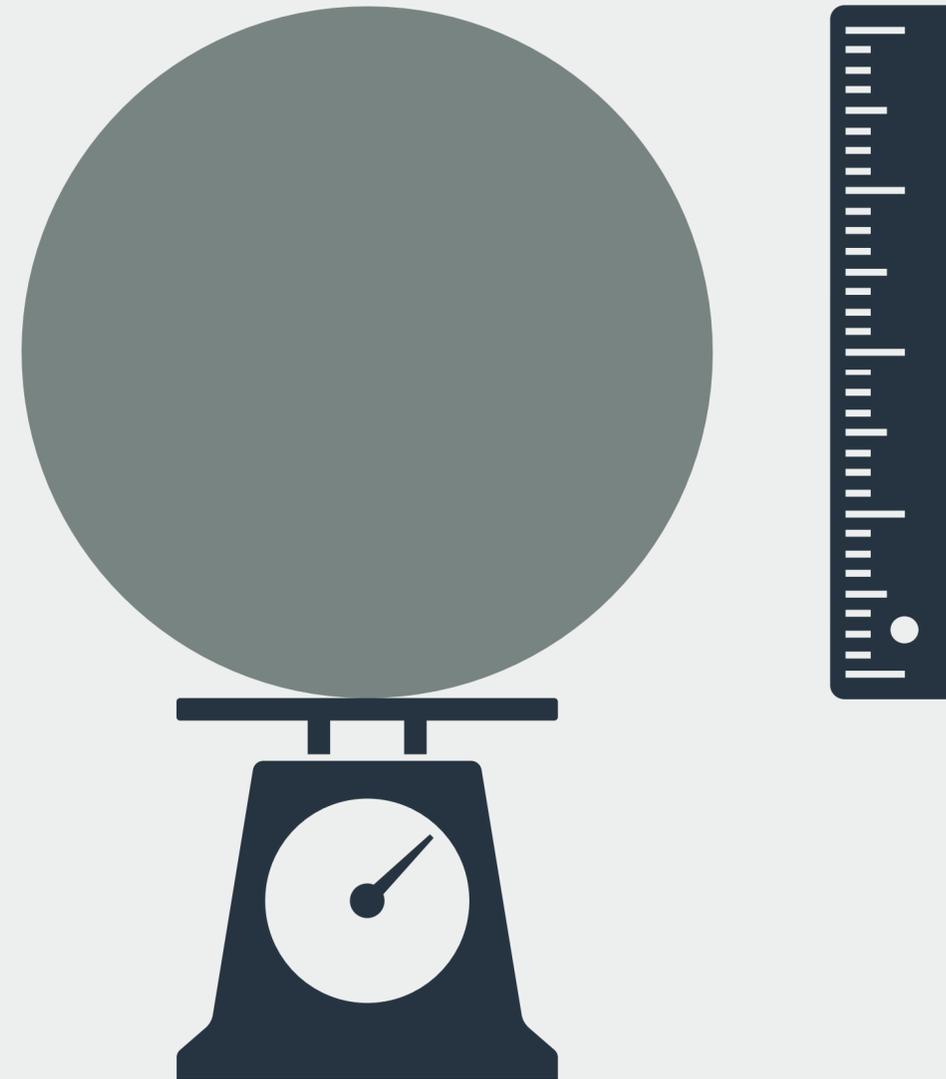


Probability density for the number of detectable point-like subhalos:

$$\mathbb{P}(K = k) = \frac{\langle K \rangle^k}{k!} e^{-\langle K \rangle}$$

In the end it is possible to derive
a probability density for the number of visible sources

Properties of detectable point-like subhalos



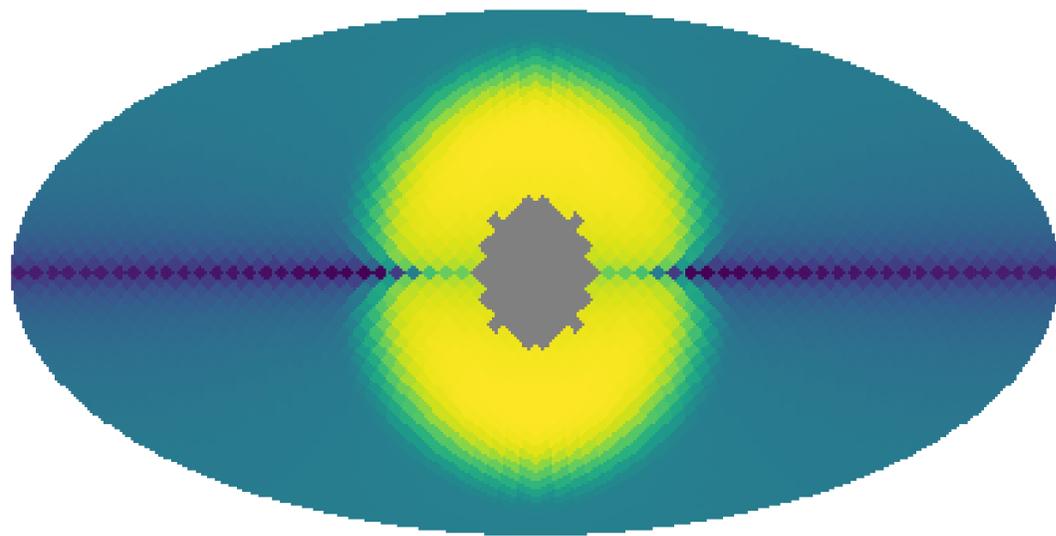
Consider a given configuration (as an example)

Cosmological parameters: $(\alpha_m, m_{\min}) = (1.9, 10^{-10} M_{\odot})$

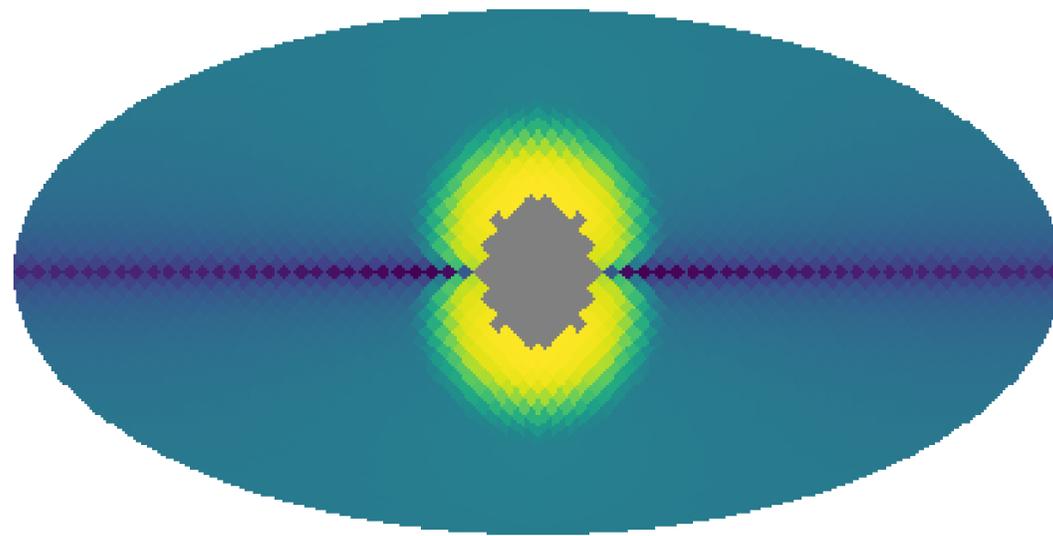
Resilient subhalos: $\epsilon_t = 10^{-2}$

Energy range: $1 \text{ GeV} < E_{\gamma} < 100 \text{ GeV}$

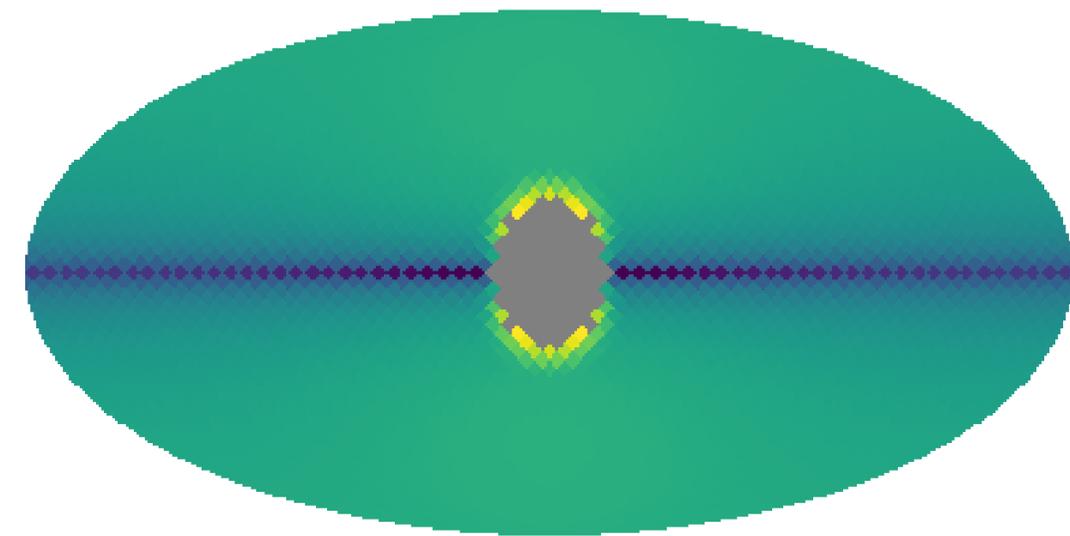
$\text{Log}_{10}(\text{Number of detectable subhalos by units of solid angle}) \text{ [sr}^{-1}\text{]}$



Angular resolution $\delta\theta = 1^\circ$



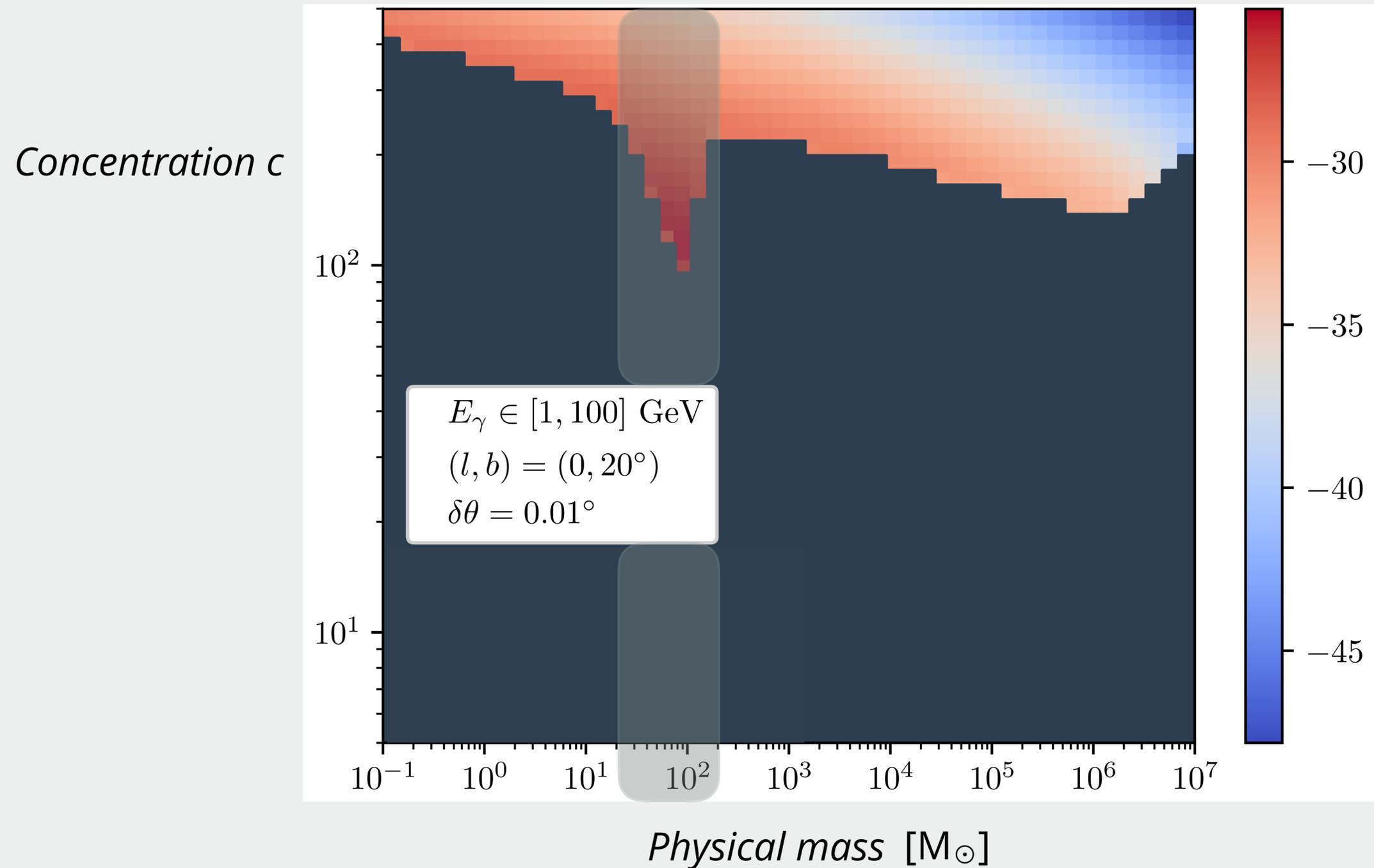
Angular resolution $\delta\theta = 0.1^\circ$



Angular resolution $\delta\theta = 0.01^\circ$

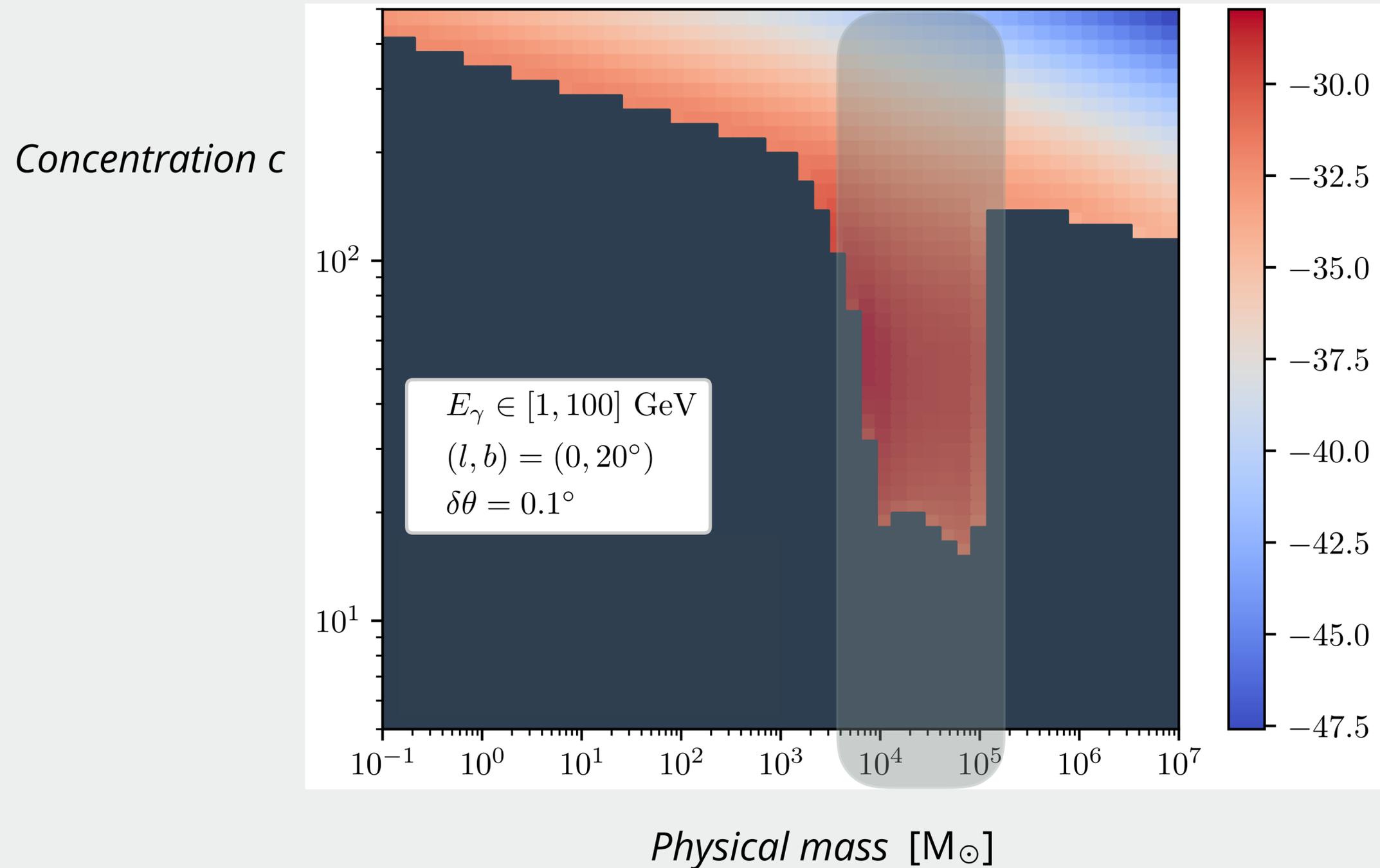
Subhalos are more visible toward the center of the galaxy

$\log_{10}(\text{Probability density of point-like detectable subhalos}) \text{ [M}_{\odot}^{-1} \text{ sr}^{-1}]$



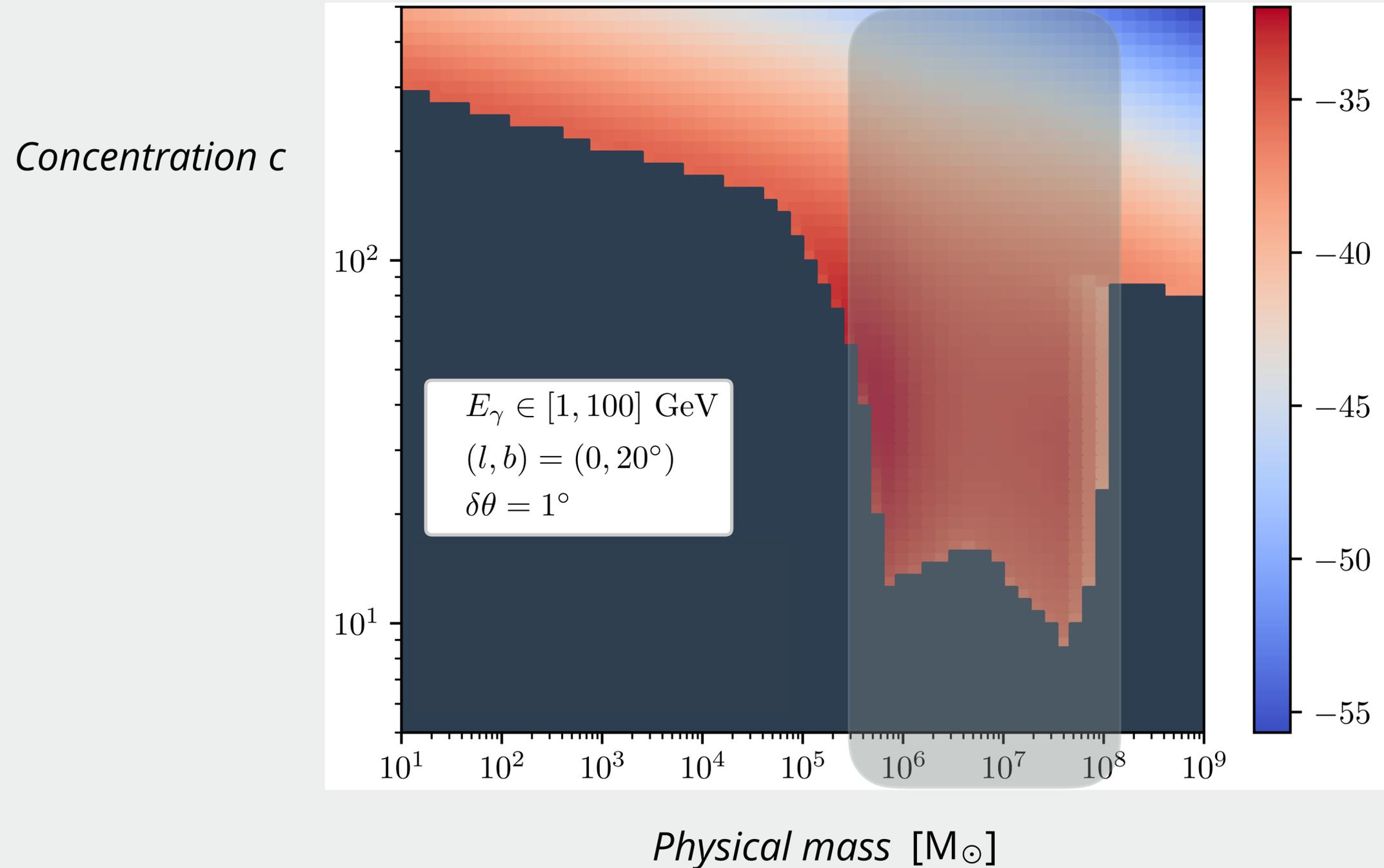
The density of visible subhalo in parameter space gives us the expected characteristics

$\log_{10}(\text{Probability density of point-like detectable subhalos}) \text{ [M}_{\odot}^{-1} \text{ sr}^{-1}]$



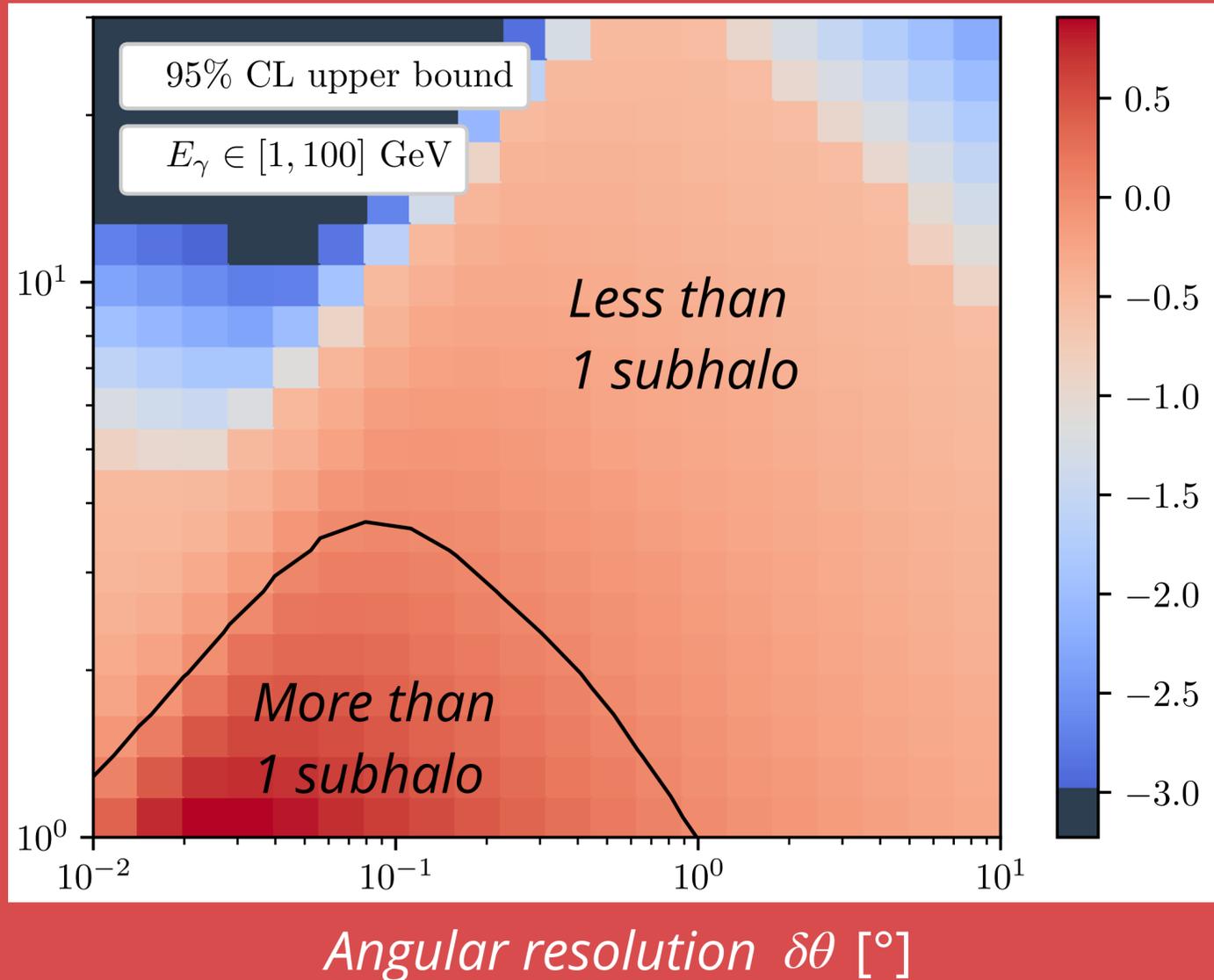
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The density of visible subhalo in parameter space gives us the expected characteristics

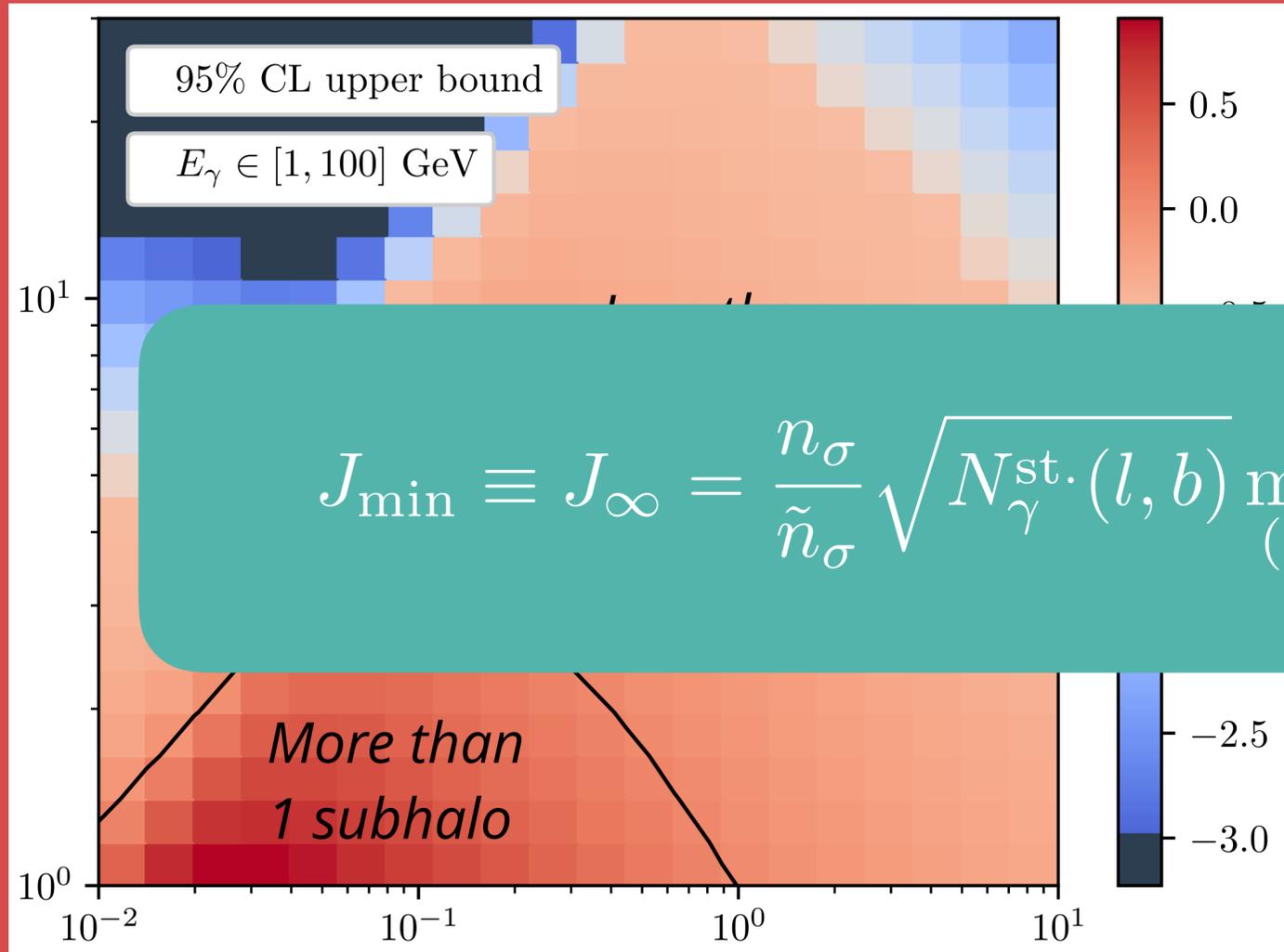
$\text{Log}_{10}(\text{Number of detectable subhalos})$



In the most favorable case we do not expect more than **~10** subhalos at 95% CL (8 in this plot)

(For Fermi, on this energy range)

$\text{Log}_{10}(\text{Number of detectable subhalos})$



Background normalisation
 $n_\sigma / \tilde{n}_\sigma$

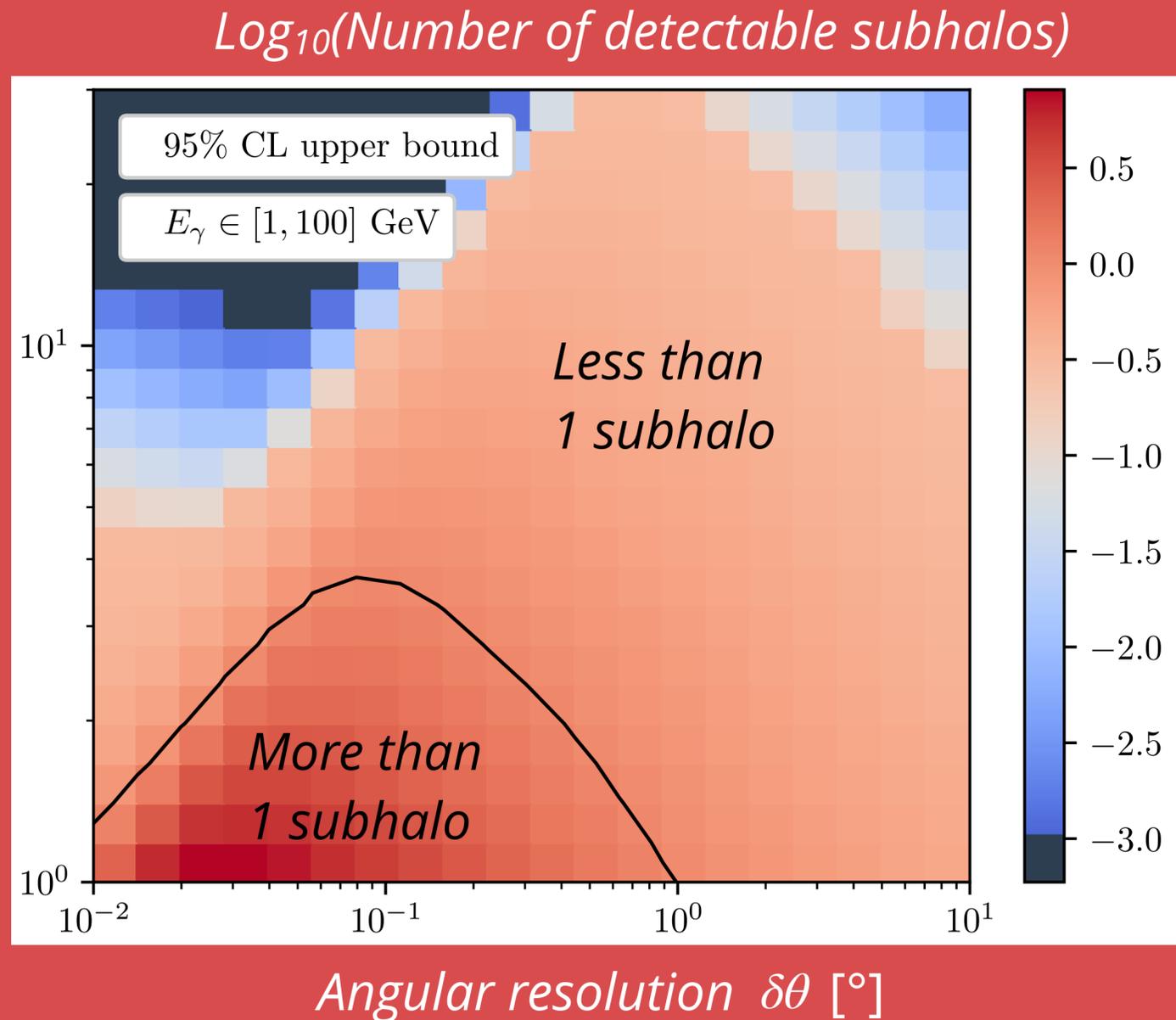
$$J_{\min} \equiv J_\infty = \frac{n_\sigma}{\tilde{n}_\sigma} \sqrt{N_\gamma^{\text{st.}}(l, b)} \max_{(l, b)} \left\{ \frac{\langle J(\delta\Omega, \psi) \rangle}{\sqrt{N_\gamma^{\text{st.}}(l, b)}} \right\}$$

Angular resolution $\delta\theta$ [°]

In the most favorable case we do not expect more than 8 subhalos at 95% CL (8 in this plot)

(For Fermi, on this energy range)

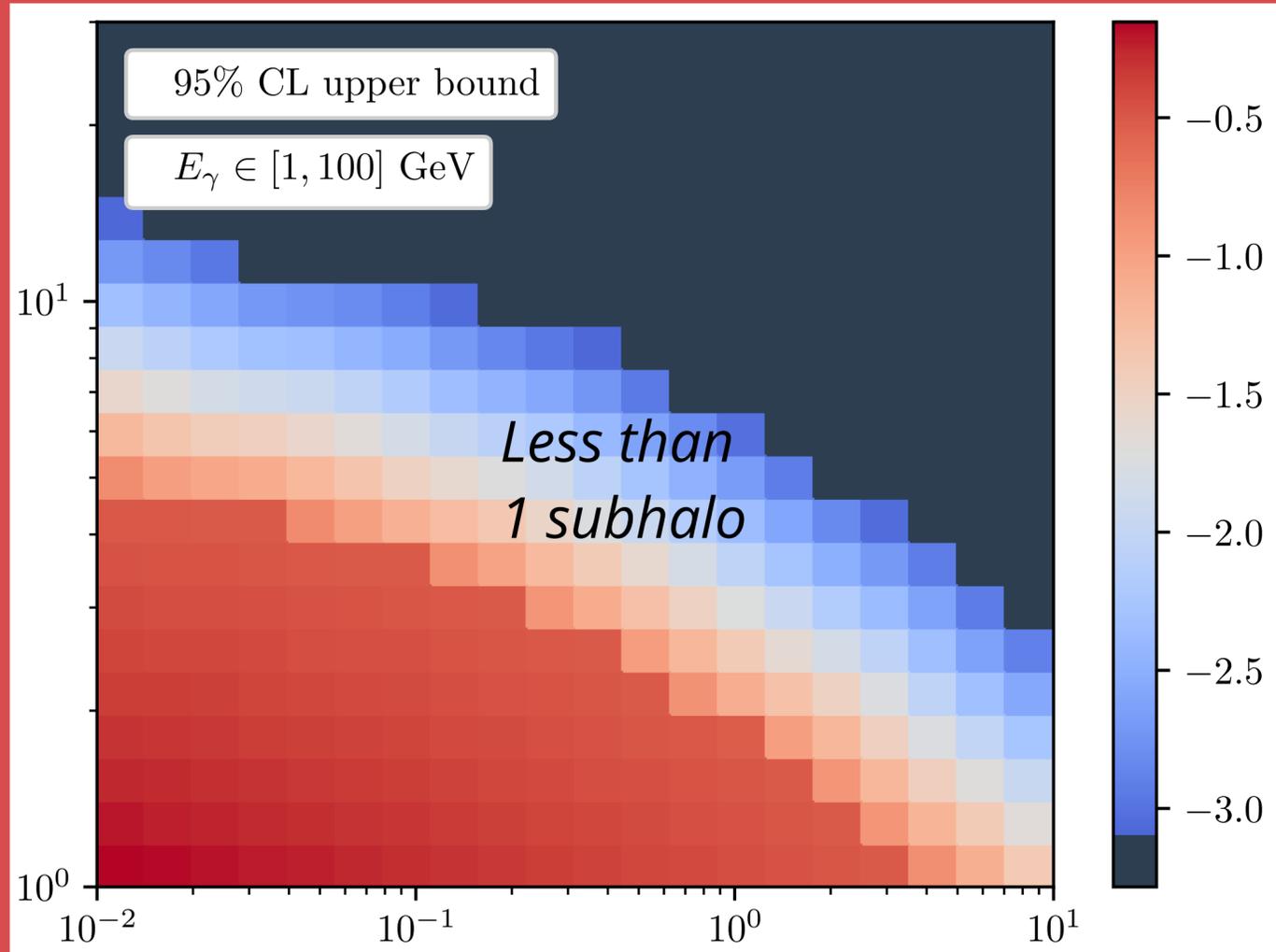
Background
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 $n_\sigma/\tilde{n}_\sigma$



In the most
favorable case we
do not expect more
than **~10** subhalos
at 95% CL
(8 in this plot)

(For Fermi, on this energy range)

$\text{Log}_{10}(\text{Number of detectable subhalos})$



Background
normalisation
 $n_\sigma/\tilde{n}_\sigma$

Angular resolution $\delta\theta$ [°]

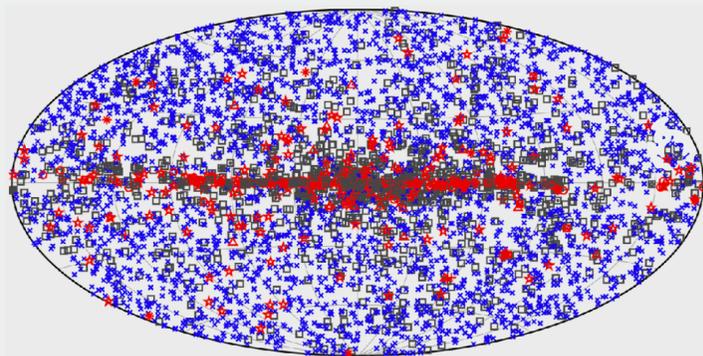
In the most
favorable case we
do not expect more
than **~1** subhalos
at 95% CL for
fragile subhalos

(For Fermi, on this energy range)



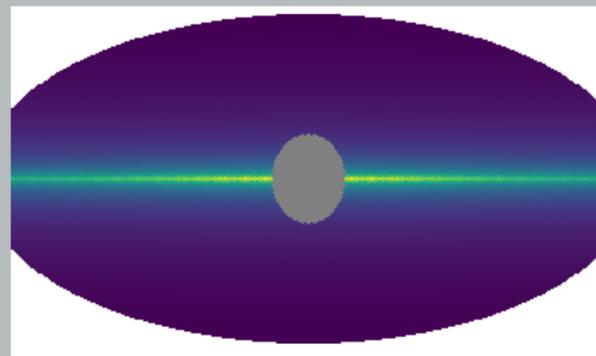
Gaétan Facchinetti — gaetan.facchinetti@umontpellier.fr

1.



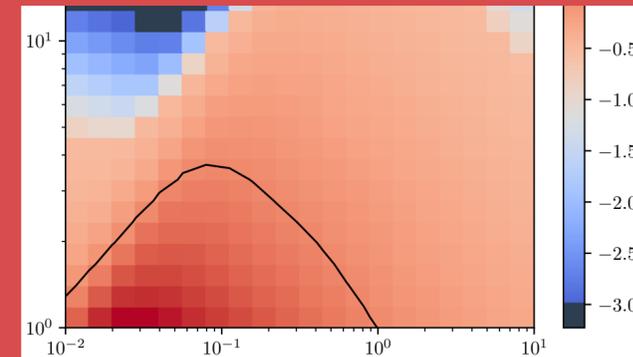
1525 unassociated point sources are in the fermi 4-th catalog. We propose a new analytical method to say if any of them could be DM halos.

2.



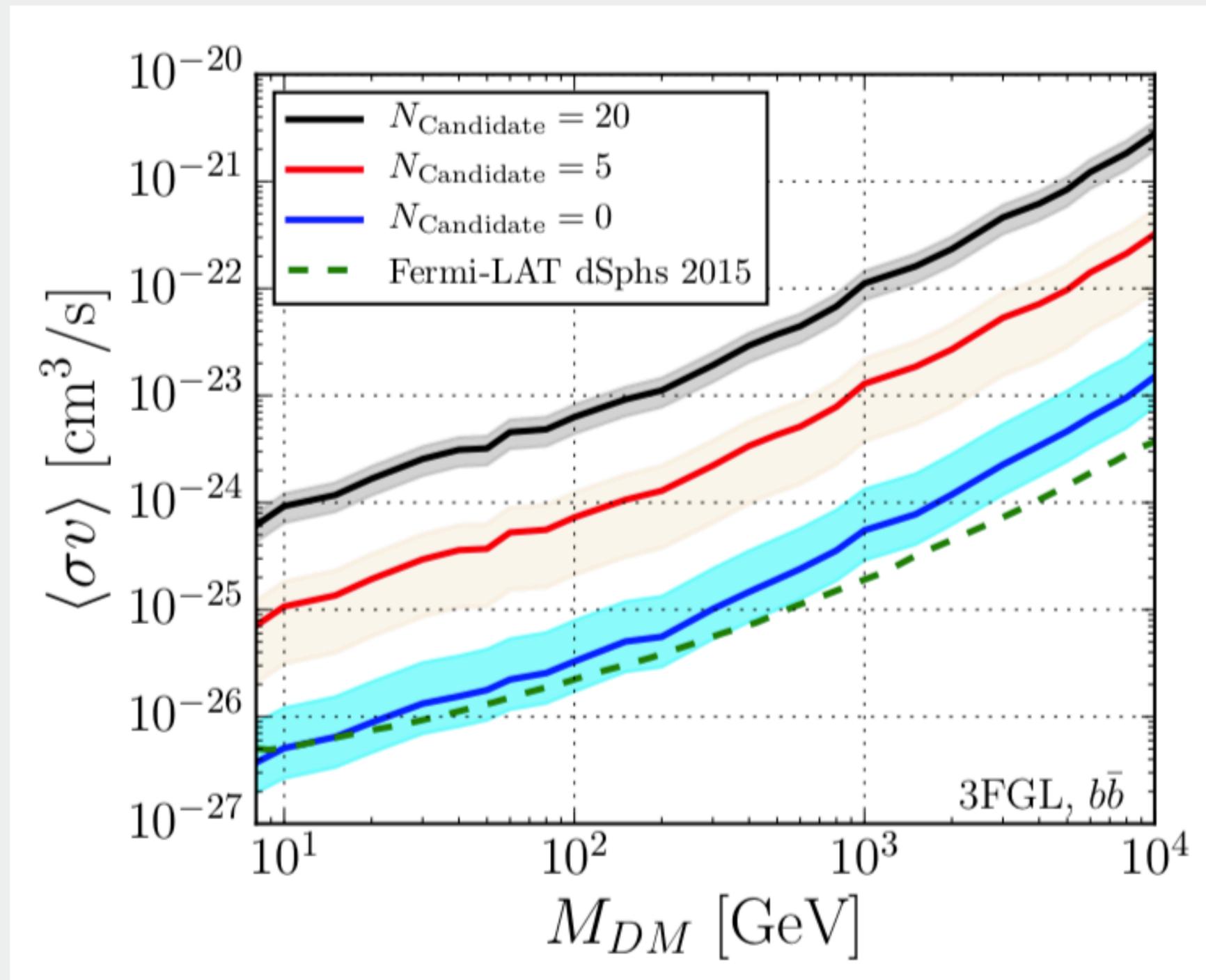
With a simplified model for the standard astrophysical emission we can consistently derive the conditions for a given point-like subhalo to be detectable

3.



Detectable subhalos are around the center of the galaxy with properties depending on the angular resolution. Their number is expected to be close or less than 1 ~ 10.

Back-up slides



[Calore+17]

Also interesting if no point subhalo detected:
 can set constraint on DM properties

