Detecting and characterizing dark matter subhalos with the Cherenkov Telescope Array

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on behalf of Veronika Vodeb, Tejas Satheesh, Francesca Calore, Gabrijela Zaharijas, Moritz Hütten, Pierrick Martin and the CTA Consortium

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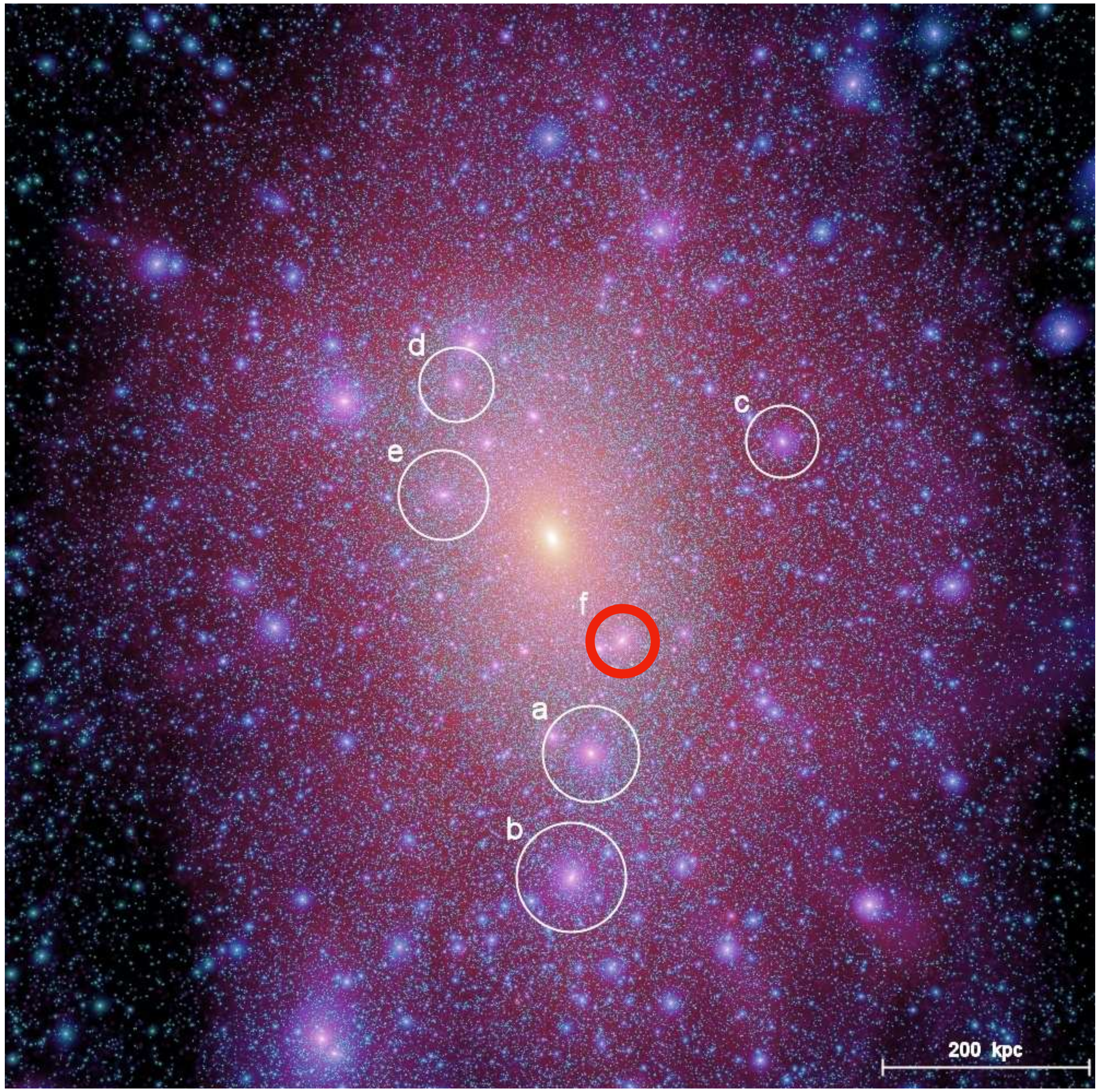
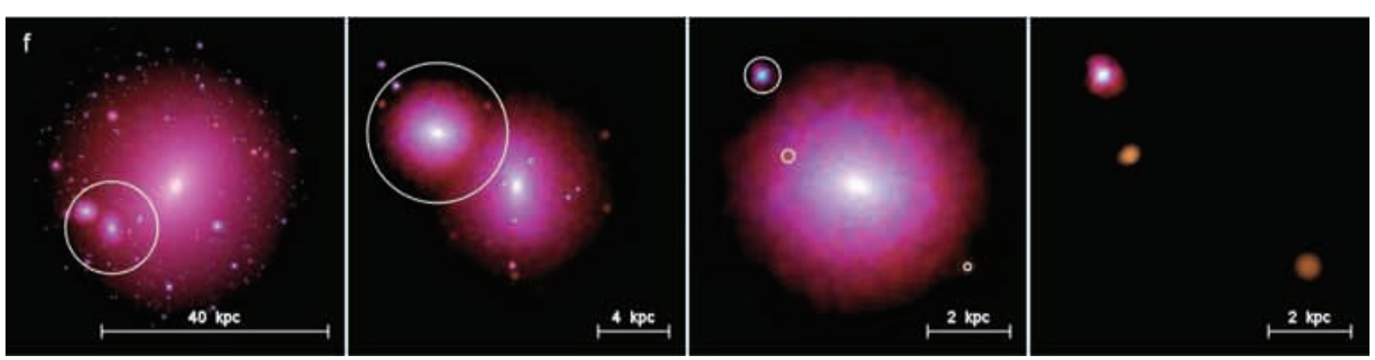
Find out more about the activities of LAPTh's AstroCosmo group at: https://astrocosmolapth.wordpress.com/

We gratefully acknowledge financial support from the agencies and organizations listed here:
http://www.cta-observatory.org/consortium_acknowledgments

Brief introduction of Galactic dark matter subhalos

[V. Springel et al., MNRAS 391 (2008)]





The concordance model of cosmology ΛCDM predicts bottom-up structure formation in the universe.

↓

Massive objects like galaxies are the results of mergers of less massive, virialised objects.

↓

Galactic dark matter halo
dark matter sub-halo
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dark matter sub-sub-sub-sub-halo
dark matter sub-sub-sub-sub-sub-halo
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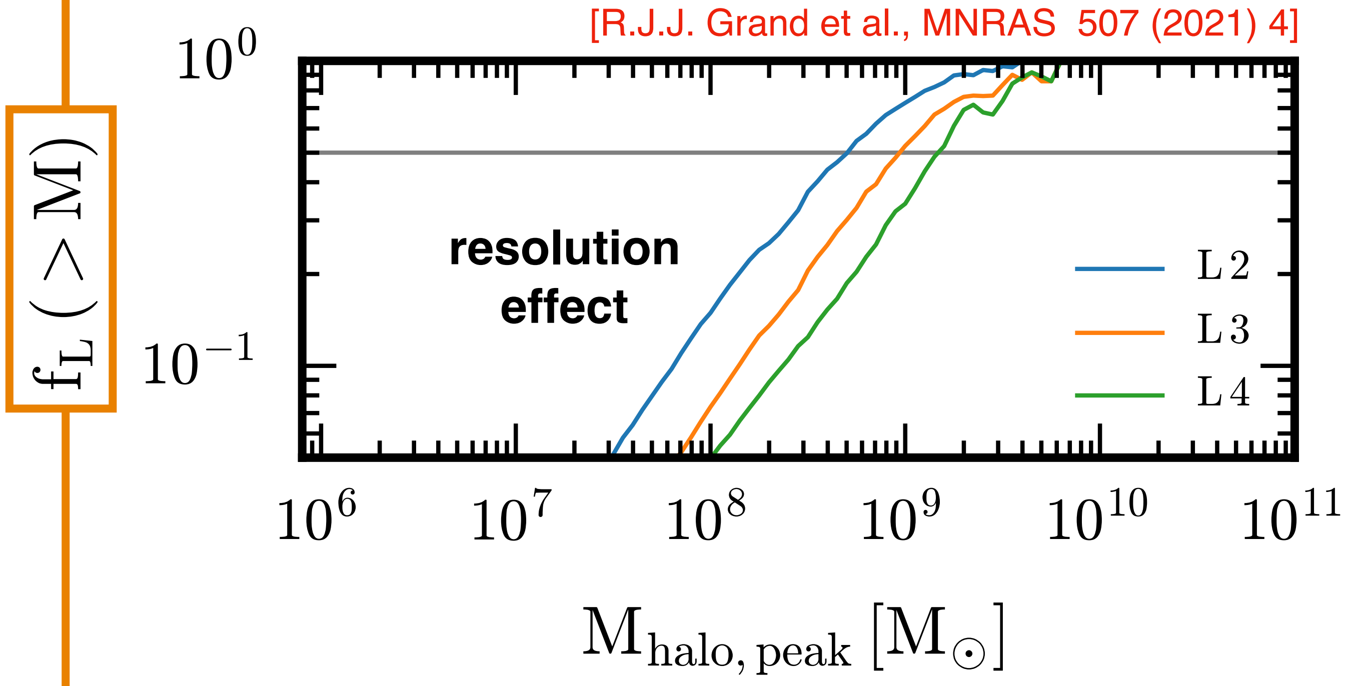
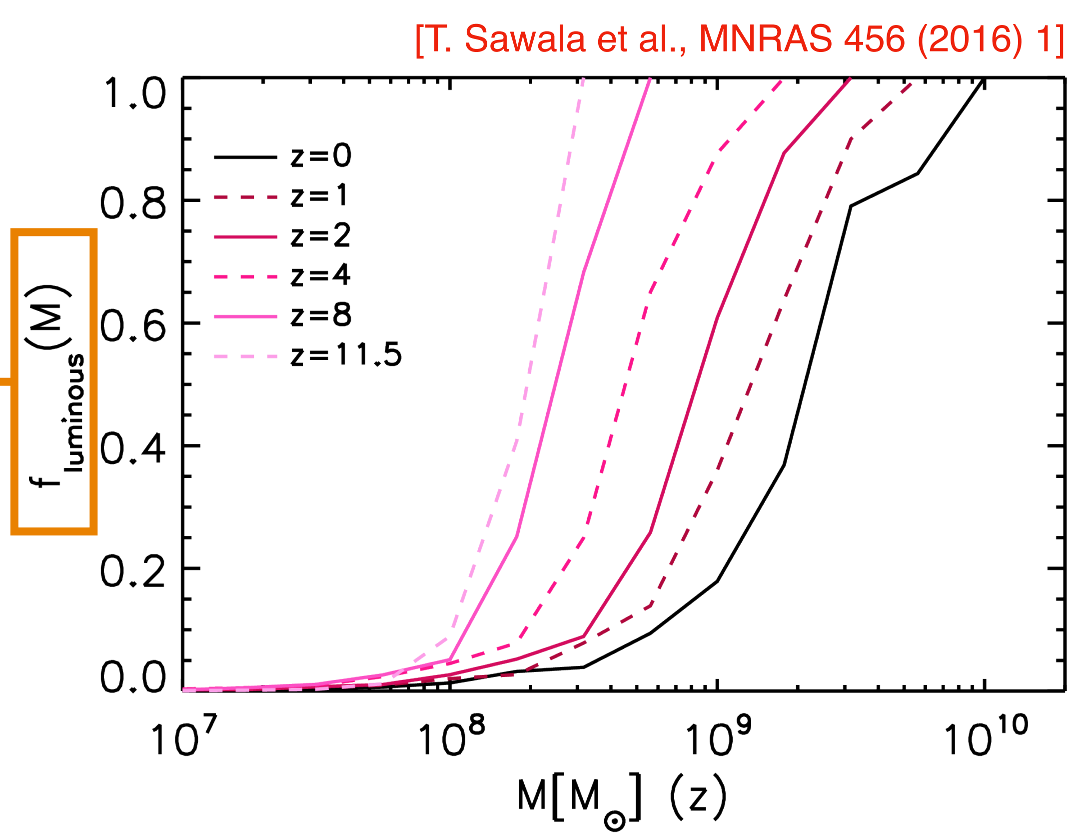
minimal gravitationally bound dark matter halo

Brief introduction of Galactic dark matter subhalos

Fraction of dark matter halos hosting luminous matter





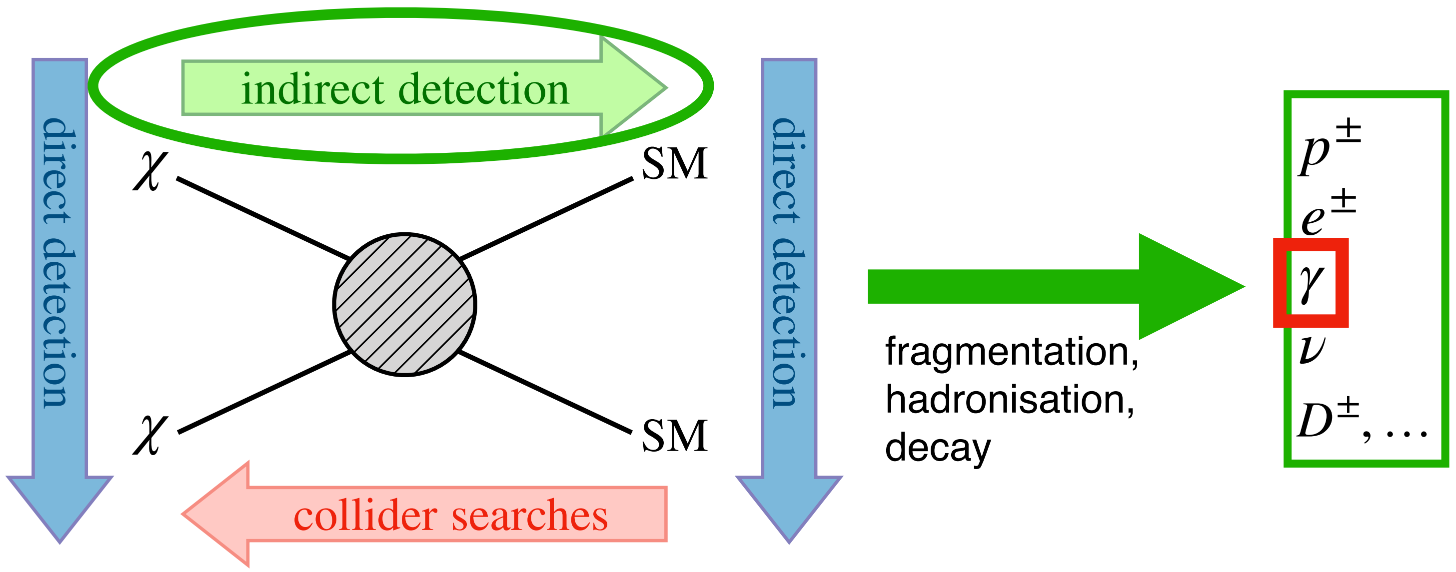
Subhalos of masses below $\sim 10^8\,M_\odot$ do not accumulate a sizeable amount of baryons to initiate star formation.

↓

Dim sources of conventional electromagnetic emission, in particular, gamma rays.

Rendering dark matter subhalos luminous

Darling candidate for particle dark matter: Weakly Interacting Massive Particles (WIMPs).
Even feeble couplings of dark matter to the Standard Model can produce observable signatures!



The expected gamma-ray signal:

$$\frac{d\Phi_\gamma}{d\Omega\, dE_\gamma}(E_\gamma, \psi) = \frac{1}{4\pi} \int_{\mathrm{l.o.s}} d\ell(\psi)\rho_\chi^2(\mathbf{r}) \left(\frac{\langle \sigma v \rangle_{\mathrm{ann}}}{2 S_\chi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \right)$$

cosmology/astrophysics "*J*-factor" — particle physics

Although not as massive as the Milky Way halo, the density of subhalos boosts their gamma-ray emission.

ρ_χ — dark matter density profile Navarro-Frenk-White (NFW)

$\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ — gamma-ray spectrum per annihilation event per energy (for us: $\chi\chi \to b\bar{b}$ from [M. Cirelli et al., JCAP 03 (2011) 051])

The study

Motivation:

— Current gamma-ray source catalogues (*Fermi*-LAT, IACTs) contain up to 1/3 unidentified sources

—> dark matter sub halos may be part of them, so for CTA

— Understand the potential to discriminate exotic extended gamma-ray sources from known classes

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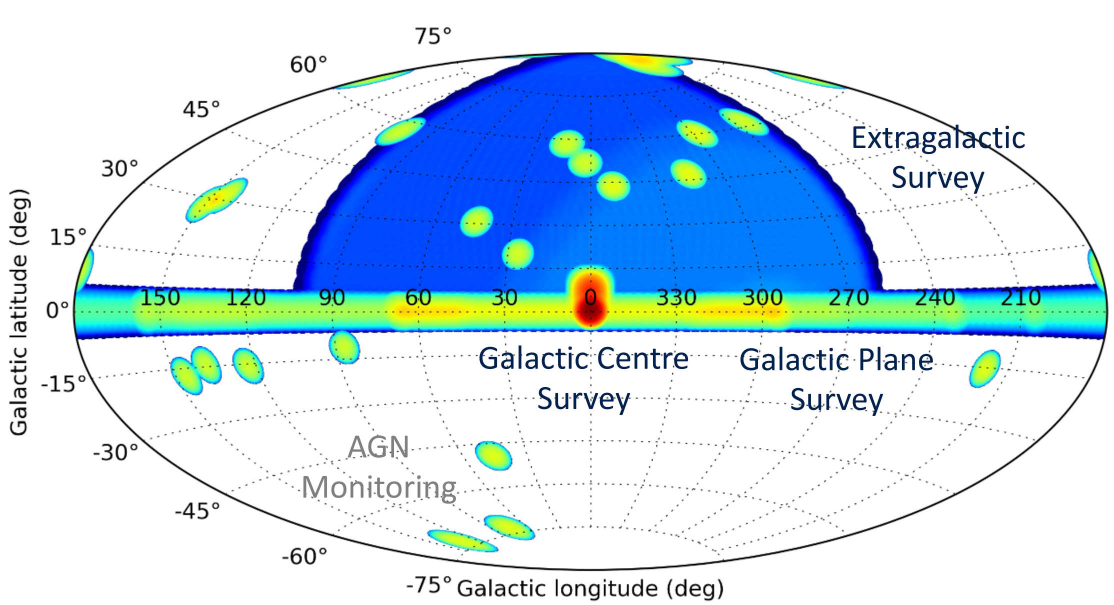
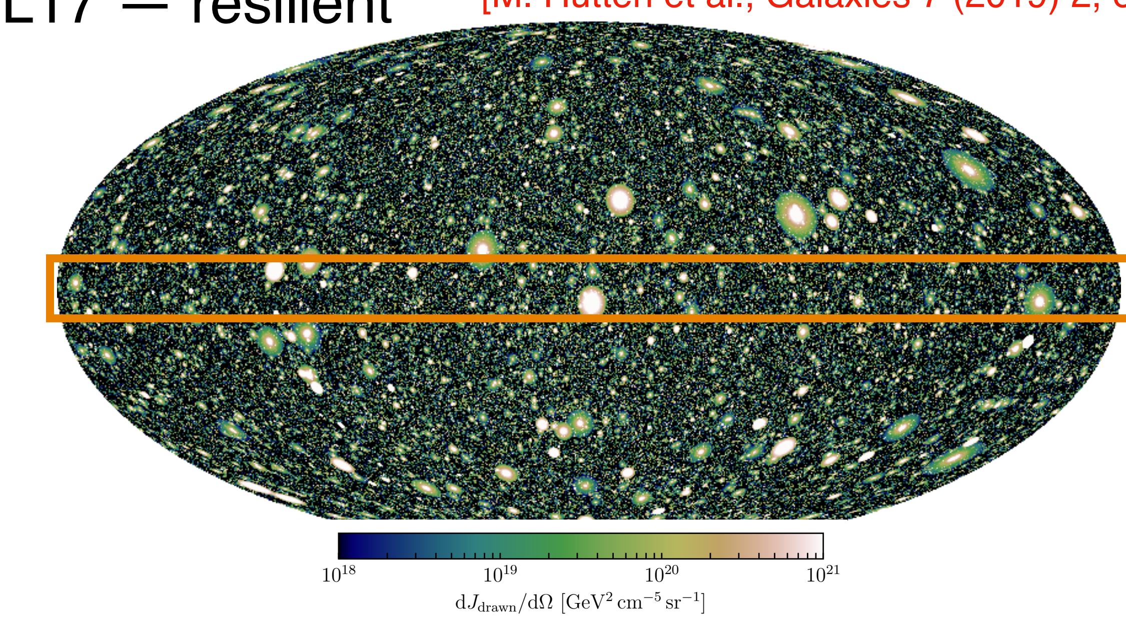
— Anticipate the potential of CTA's Galactic Plane Survey (GPS) for their study: Higher exposure than large-scale extragalactic survey + reasonably high abundance of subhalos (model-dependent)



[The CTA Consortium; Science with the CTA]

SL17 — resilient

[M. Hütten et al., Galaxies 7 (2019) 2, 60]



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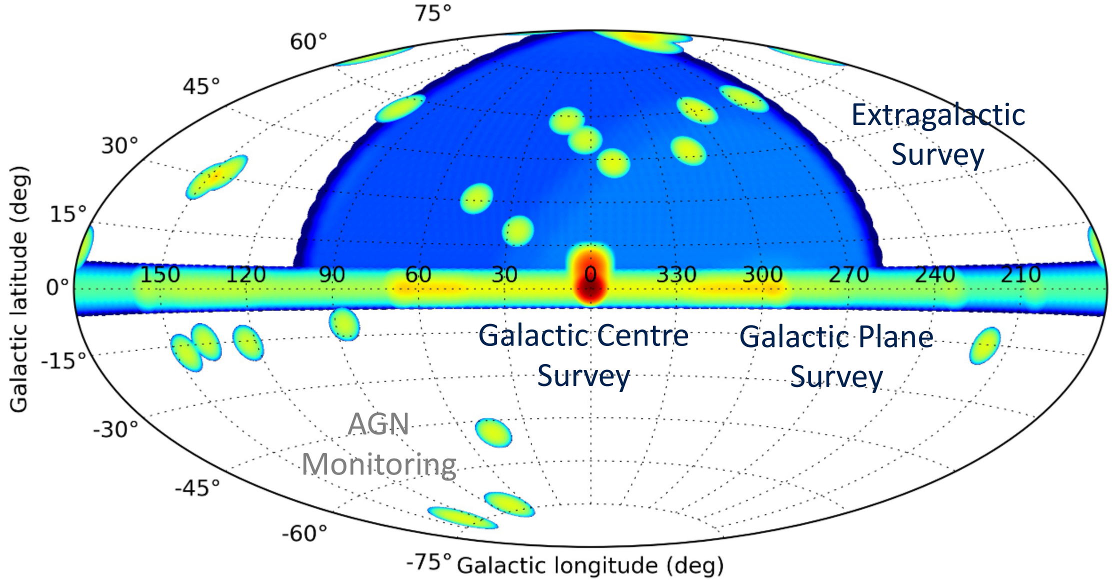
Methodology:

— Subhalo models incorporating tidal effects (baryonic physics) to bracket uncertainties

— Simulation of CTA observations and instrument response function with gammapy/ctools
 > three-dimensional template-based analysis
 > specifications of CTA's GPS following consortium publication
 > similar to our study of pulsar halos in the GPS: [C. Eckner et al., MNRAS 521 (2023) 3]

— Application of results to single objects and entire subhalo population



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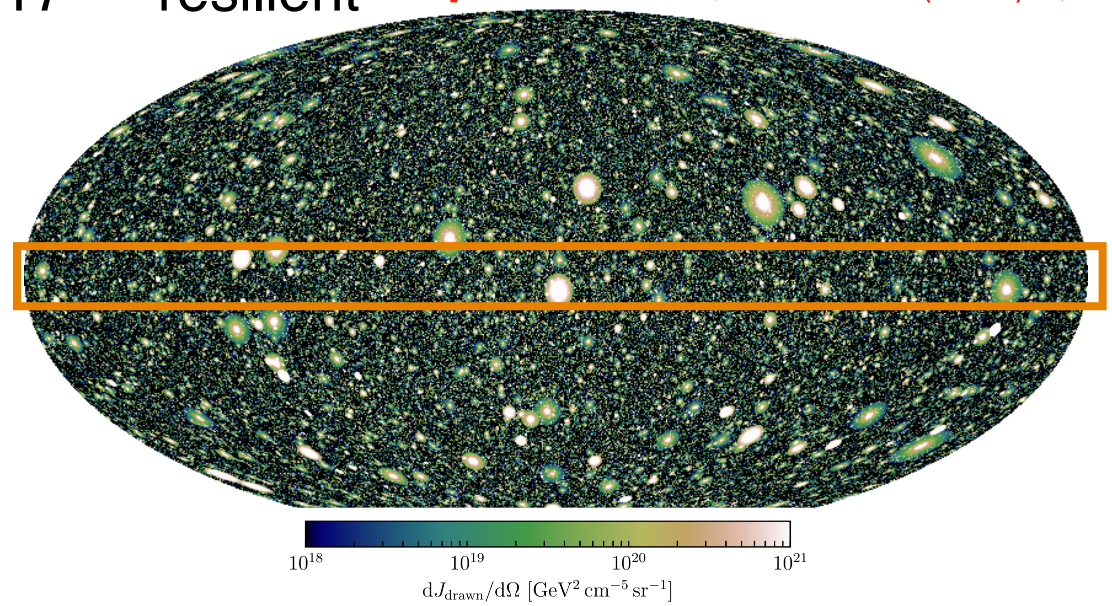
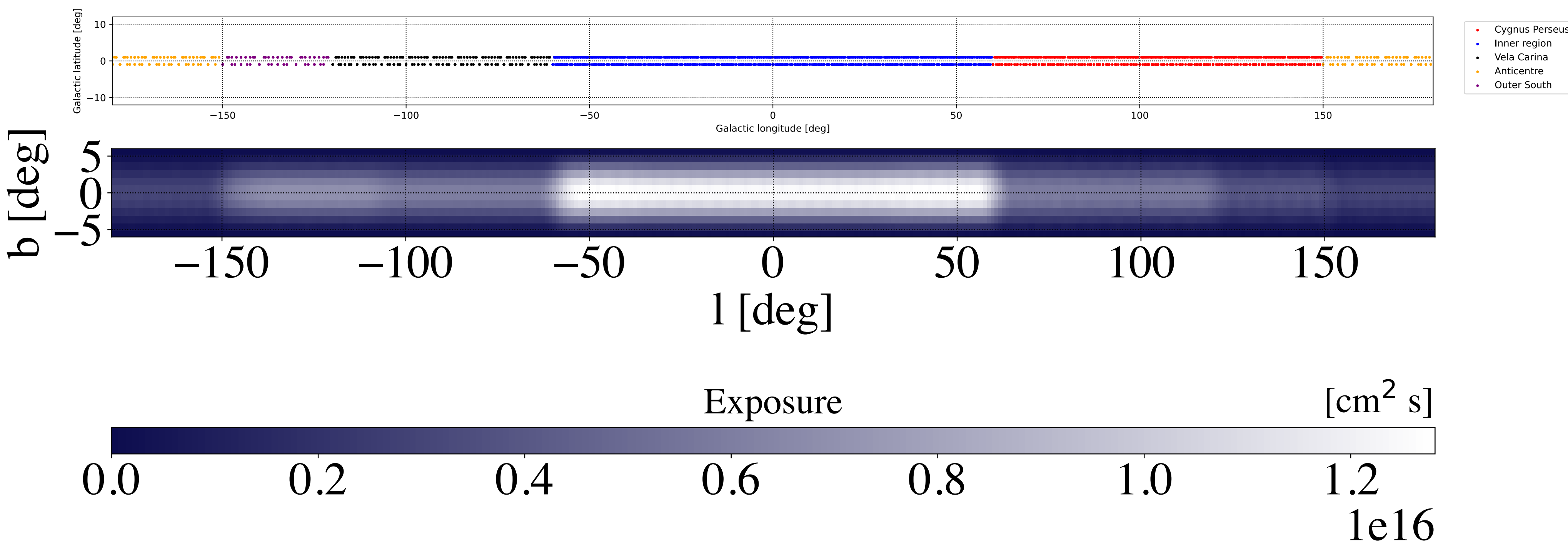


The CTA Galactic plane survey

The Galactic plane survey assigns different exposure times to different sky regions.

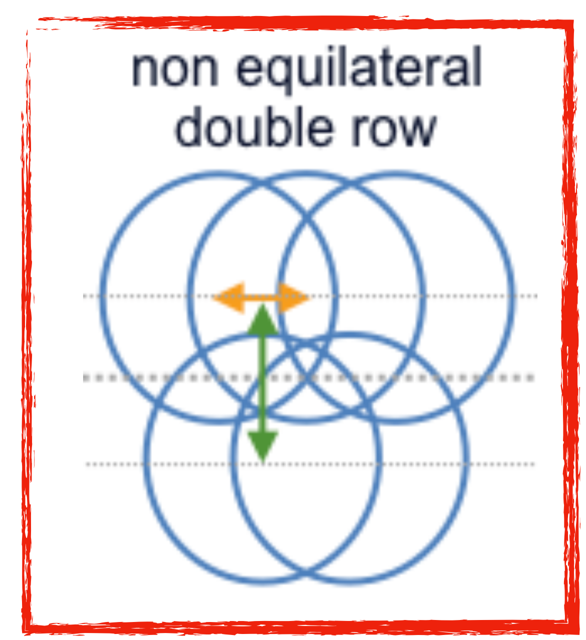


Observation pointing strategy:

— double row, non equilateral tiling of the plane

— ~30 min per position

— Pointing position schedule adopted from CTA GPS consortium paper (at https://github.com/cta-observatory/cta-gps-simulation-paper plus the full synthetic population model)



[Remy et al., ICRC 2021 PoS 395 (2021) 886]

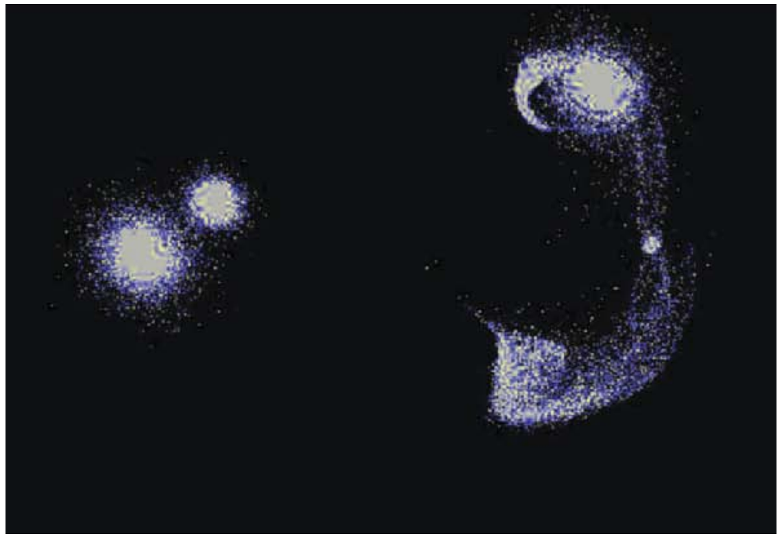
Simulations:

— based on the Alpha-layout of CTA and its IRFs (prod5-v0.1)
—> includes instrumental background

— astrophysical background component: interstellar emission according to [De la Torre Luque et al., A&A 672, A58 (2023)] (Base-Max)

— gammapy (0.18.2) + ctools (1.6.3)

Interplay of baryonic physics and DM subhalos



[E. D'Onghia et al., Nature 460, 605–607 (2009)]

Subhalos are subject to the gravitational potential of the Milky Way's stellar disc and bulge.

↓

Tidal effects: mass loss (stripping), disruption

We follow the model derived from prescription in [M. Stref and J. Lavalle, PRD 95, 063003]**:**

— Stripping effects from Galactic potential and shocking effects from the disc are included.

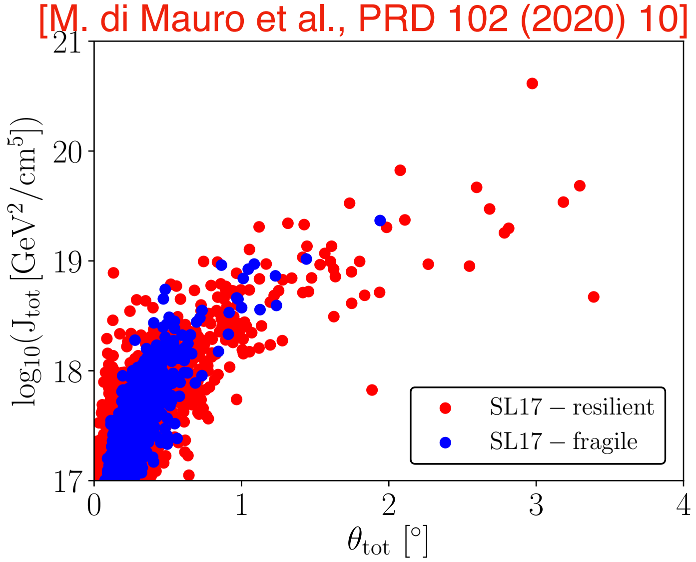
— Full disruption of subhalo may occur or not (within the uncertainty of simulations), hence two bracketing cases (**fragile and resilient sub halos**)

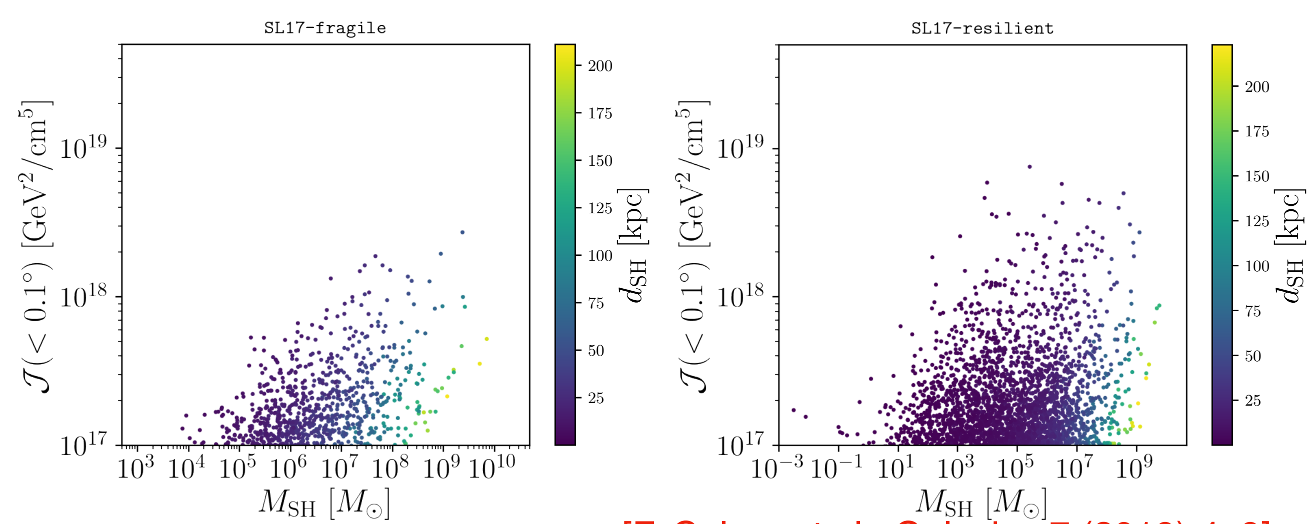
disruption: tidal radius $r_t \leq r_s$ scale radius

disruption: tidal radius $r_t \leq 10^{-2} r_s$ scale radius

Total angular size and mass of the subhalo population in the sky.

[M. di Mauro et al., PRD 102 (2020) 10]





[F. Calore et al., Galaxies 7 (2019) 4, 9]

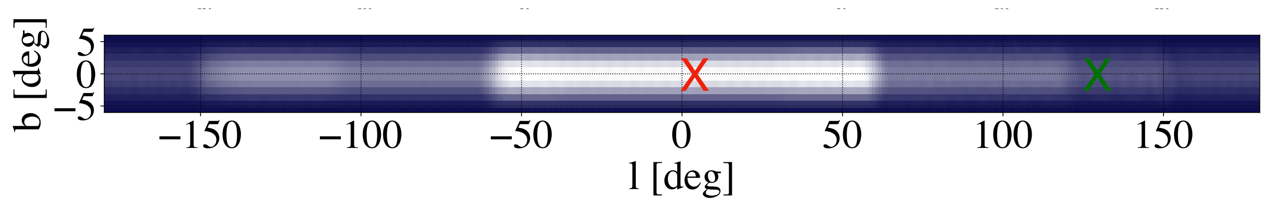
Spectral sensitivity to single subhalos

Our population representative is the brightest subhalo in the simulation.

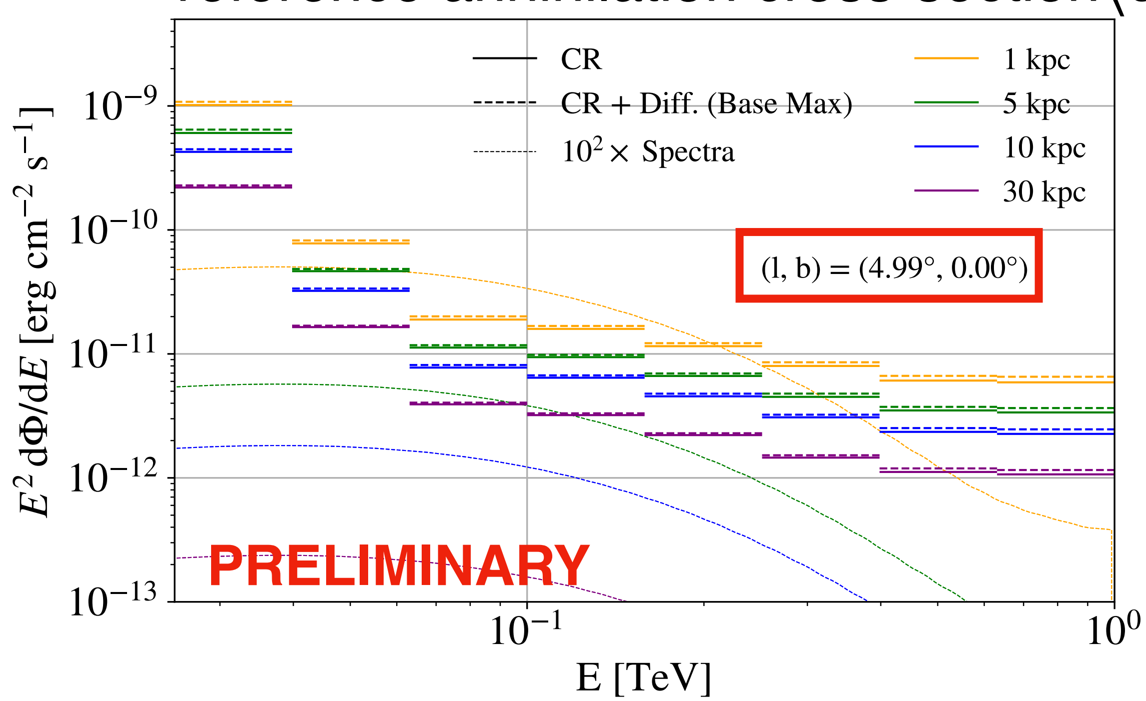
Located at various distances from Earth and within …

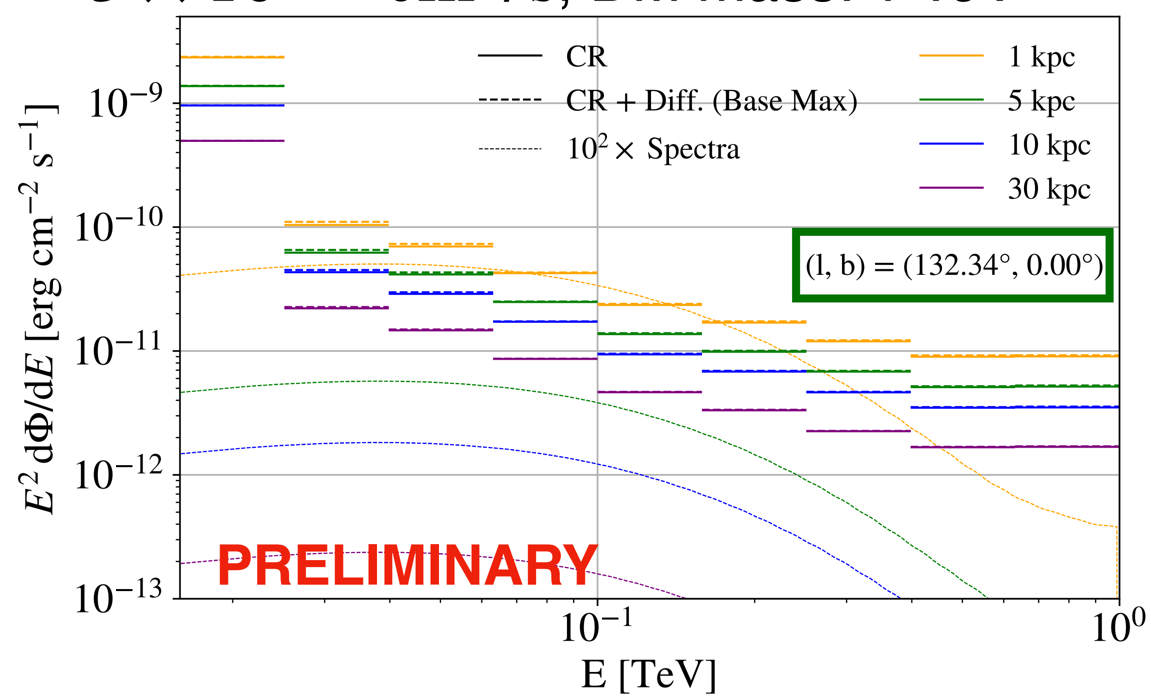
Sub-halo mass	Distance	J-factor	r_s/distance
$10^8 M_\odot$	1.0 kpc	$1.5508 \cdot 10^{21}$ GeV^2 cm^{-5}	1.36
$10^8 M_\odot$	5.0 kpc	$1.7582 \cdot 10^{20}$ GeV^2 cm^{-5}	0.272
$10^8 M_\odot$	10.0 kpc	$5.6194 \cdot 10^{19}$ GeV^2 cm^{-5}	0.136
$10^8 M_\odot$	30.0 kpc	$7.3086 \cdot 10^{18}$ GeV^2 cm^{-5}	0.045

GPS exposure band:



reference annihilation cross-section $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3/s, DM mass: 1 TeV

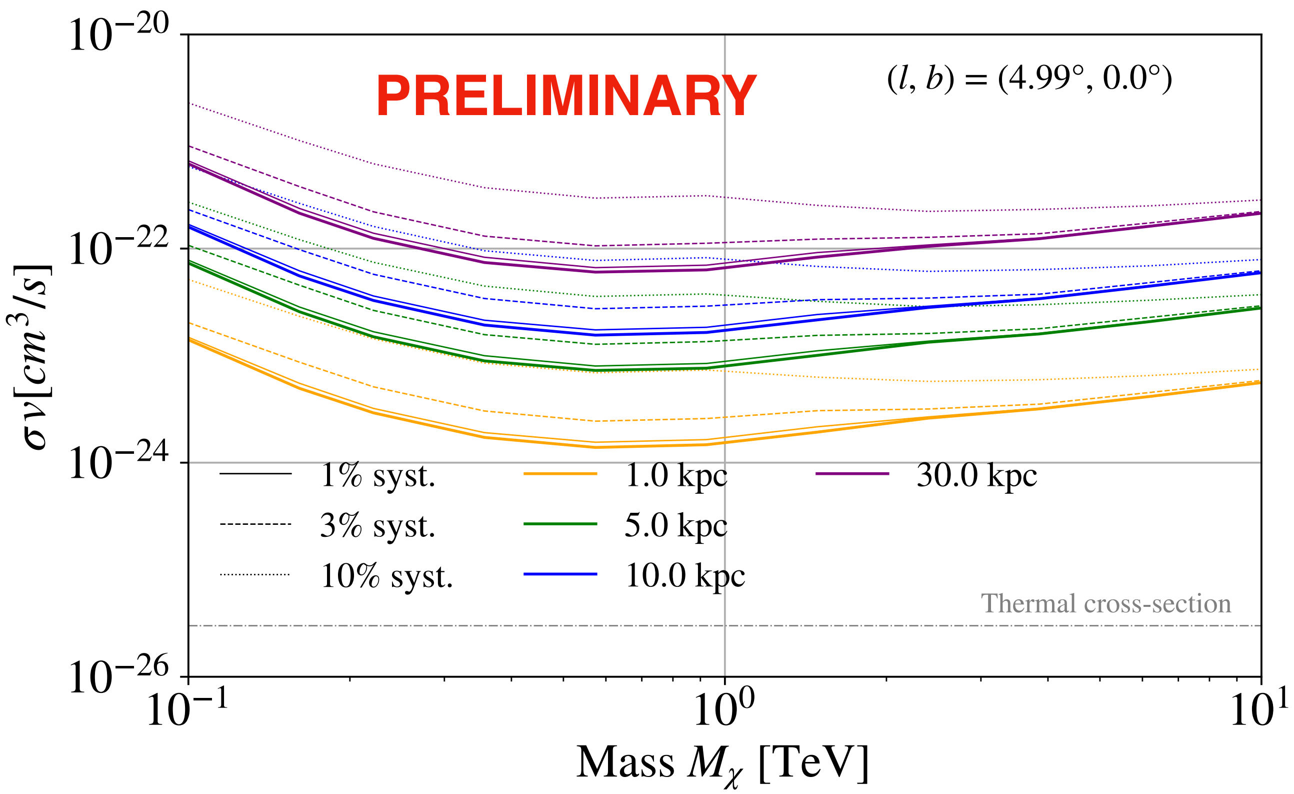


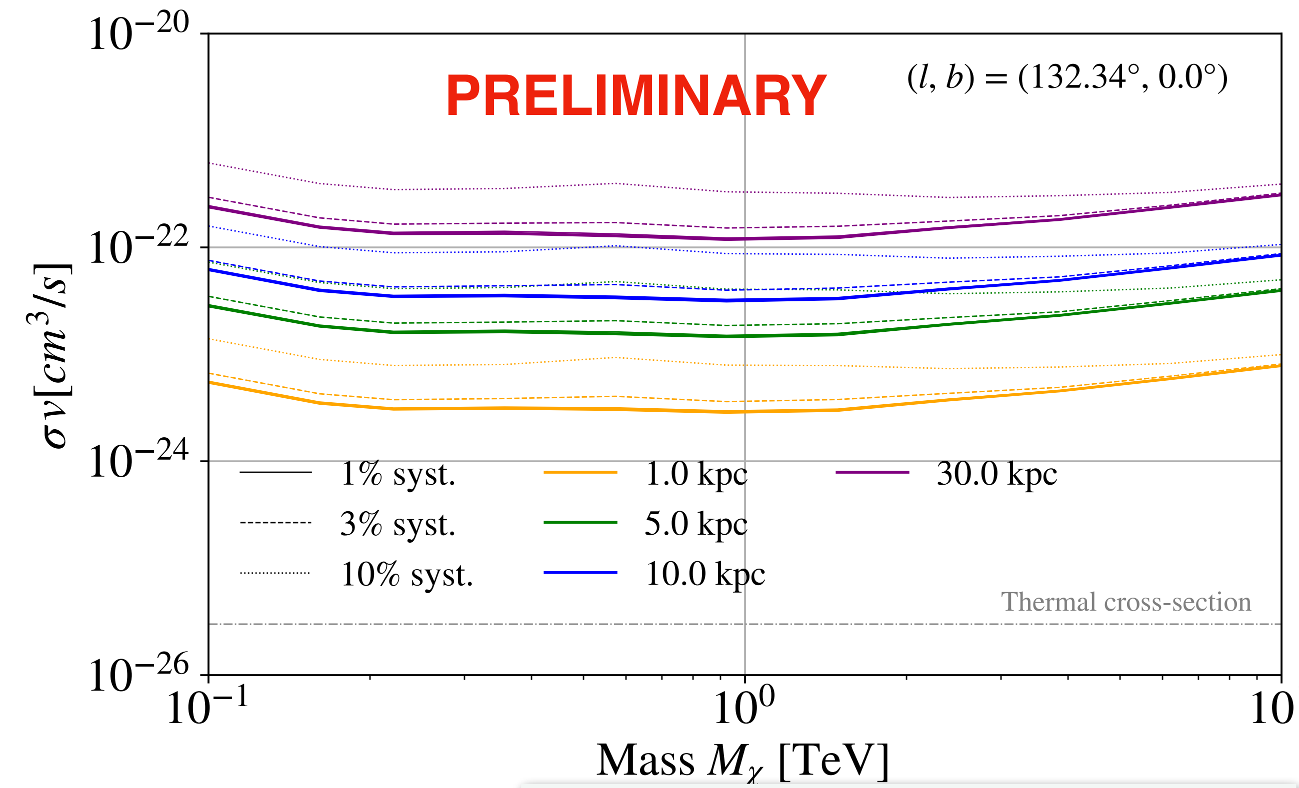


Flux per energy bin required for a 5σ detection: Possible for cross-section $\sim 10^{-24}$ cm^3/s for close subhalos up to 1 kpc and TeV-scale dark matter.

Spectral sensitivity to single subhalos (cont'd)

We can explore the full dark matter mass range in this setting!
… Detection when the spectrum is above the sensitivity threshold in at least one energy bin.

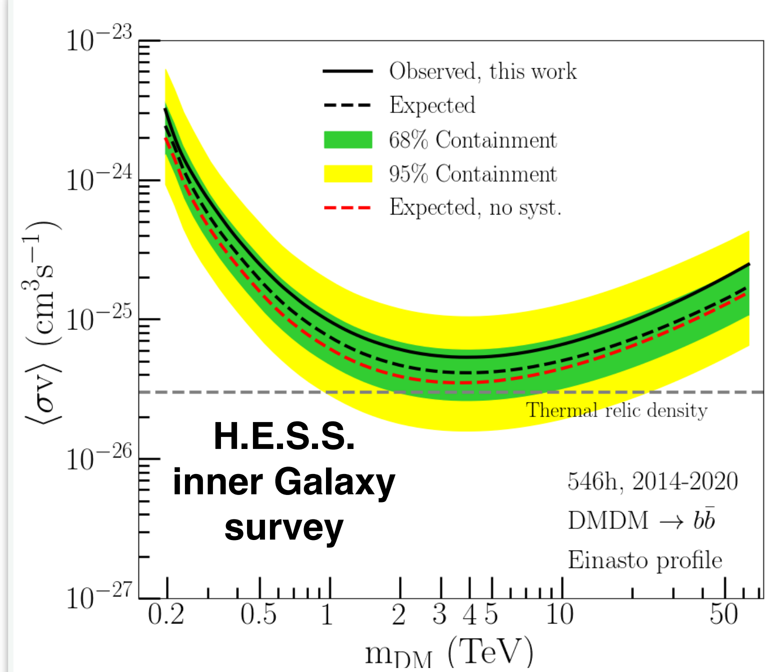




1. **Impact of interstellar emission rather weak.**

2. **Instrumental systematic uncertainties up to ~3% can be tolerated (implementation follows** [The CTA Consortium, JCAP 01 (2021) 057]**; bin-by-bin fluctuations)**

3. **Not necessarily excluded by current-men IACTs like H.E.S.S.: DM profile in Galactic centre rather uncertain, flat densities strongly weaken the constraints!**



[H.E.S.S. collab., PRL 129, 111101 (2022)]

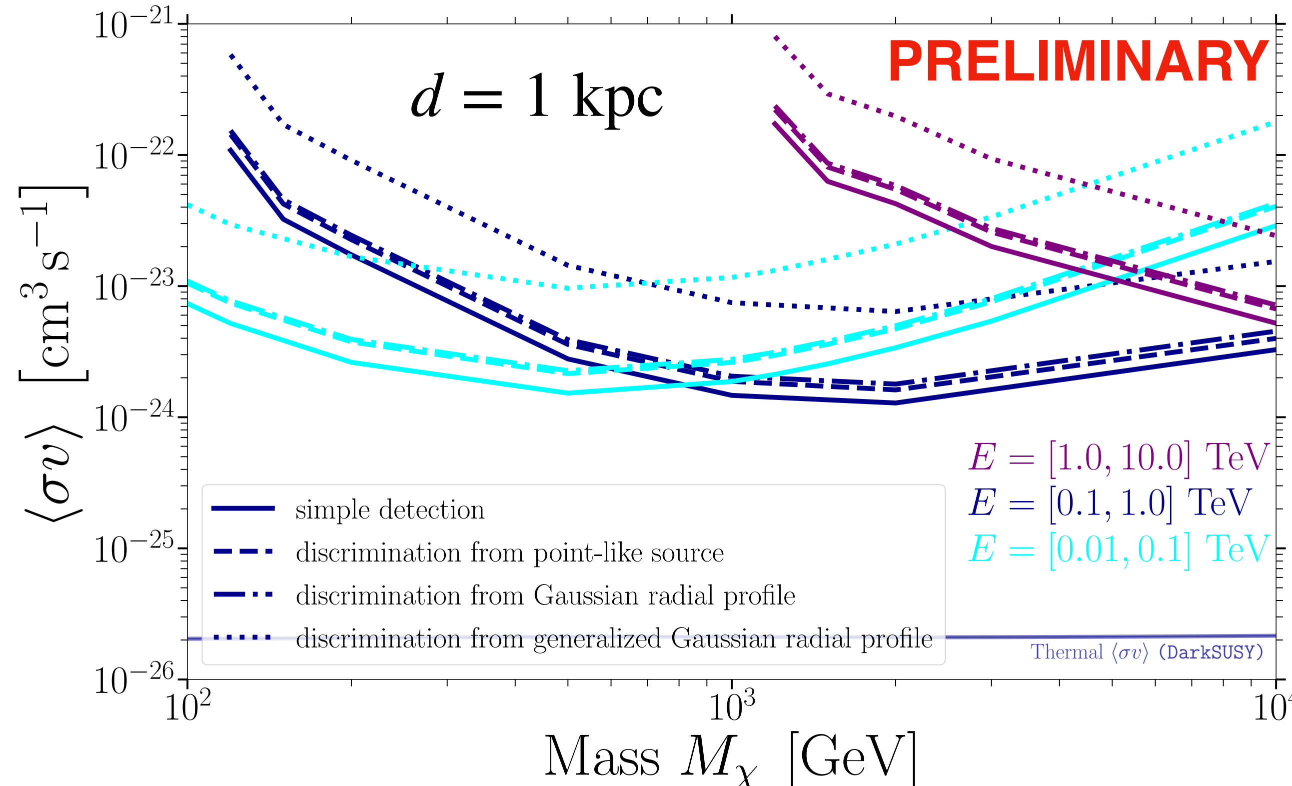
Discrimination from other TeV-bright objects

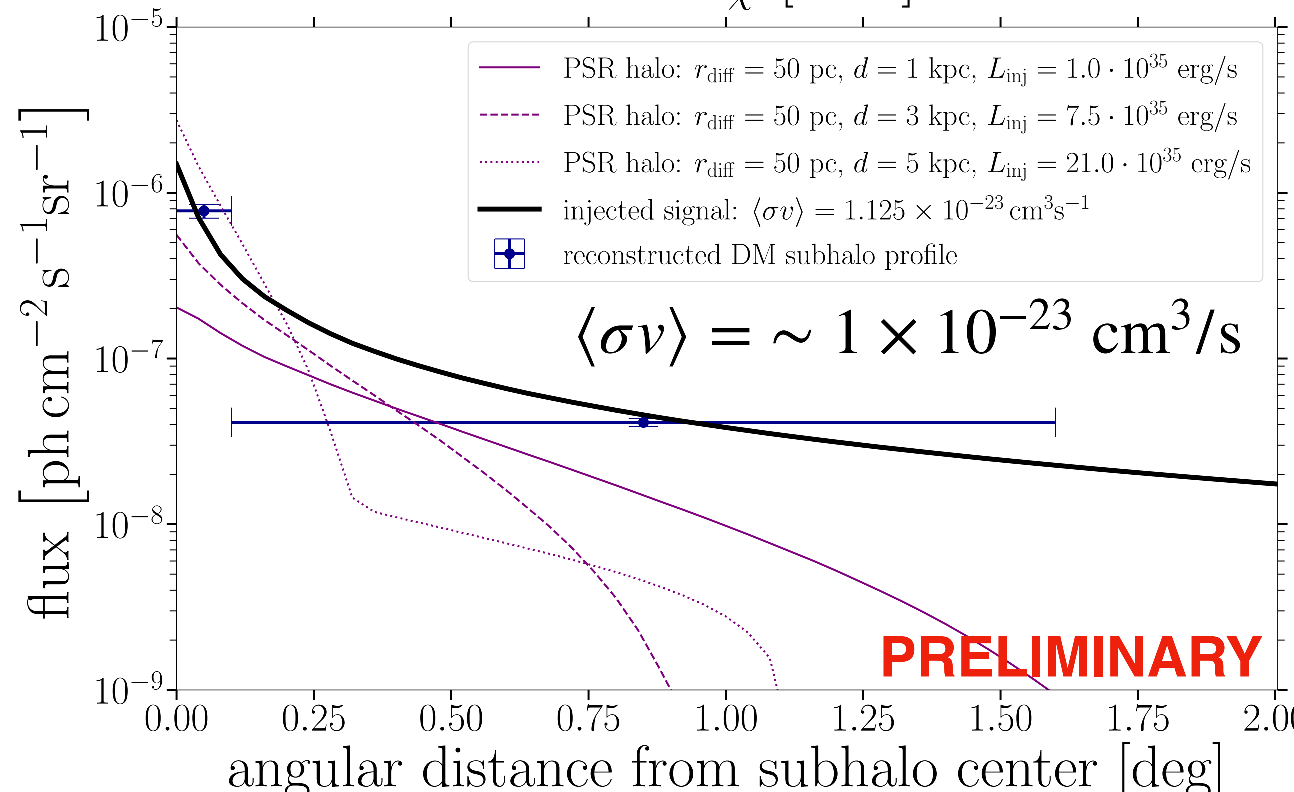
Suppose we detect a new source, which cannot be associated. When can we exclude known astrophysical source classes, like pulsar wind nebulae, binaries or supernova remnants?

Recipe:
— Inject DM signal at fixed cross-section value into mock data
— Fit a nested model of (DM subhalo + alternative spatial model).
— Retrieve cross-section at which DM is significantly preferred.

Cross-section for detection times less than a factor of 2 sufficient to exclude point-like source or Gaussian profile!

Angular decomposition to study extended profile becomes feasible for fluxes where even other novel source classes like pulsar halos (model from [C. Eckner et al., MNRAS 521 (2023) 3]) can be discriminated.

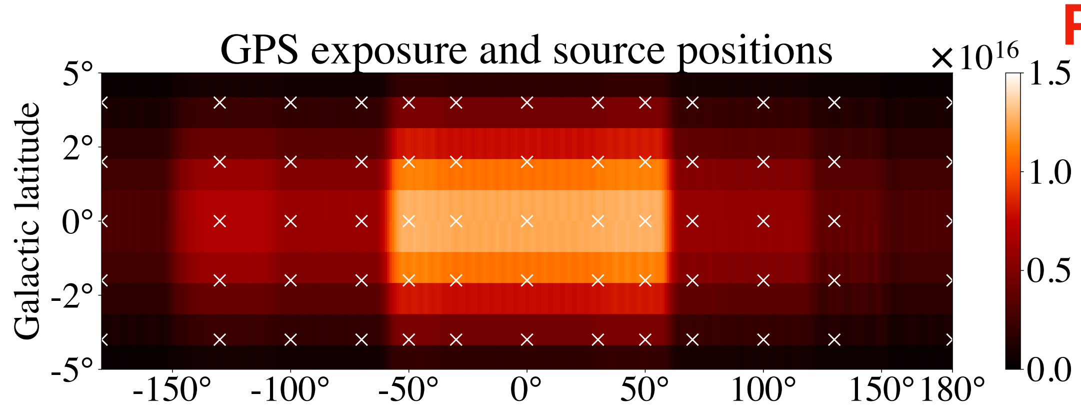




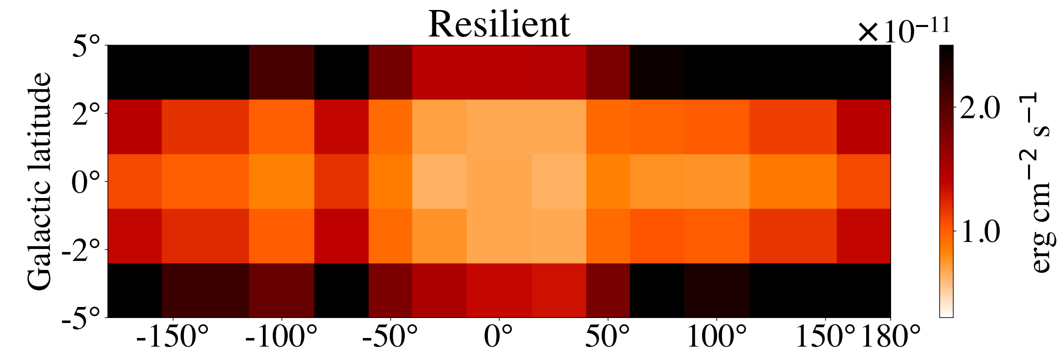
Accessibility of the sub halo population

There will be more than one subhalo within the GPS band. What can we say about the entire population?

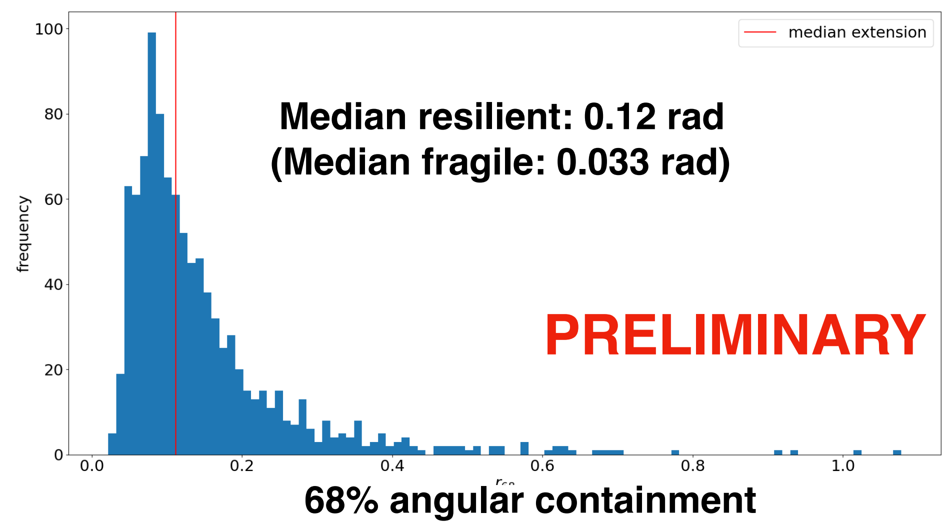
Divide GPS region into tiles and define representative positions.



PRELIMINARY

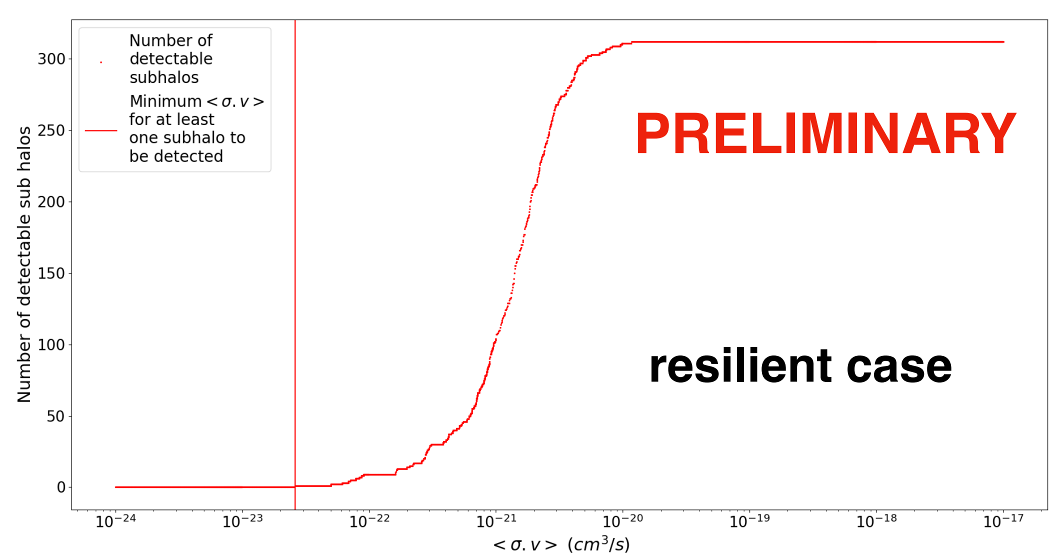


Test spatial model of point-like source and representatives of the median extension of fragile and resilient halos



Find 5σ flux detection threshold for representative positions and sources.

Average over all available realisations of subhalo population simulations to infer the number of detections in the GPS for a certain cross-section.



A cross-section around $3 \times 10^{-23}\ \mathrm{cm}^3/\mathrm{s}$ guarantees a detection of least one subhalo for either, fragile or resilient, scenarios.

Summary

- **CTA's Galactic plane survey will uncover many extended gamma-ray sources** along the Galactic plane; **some of them will remain unidentified**.

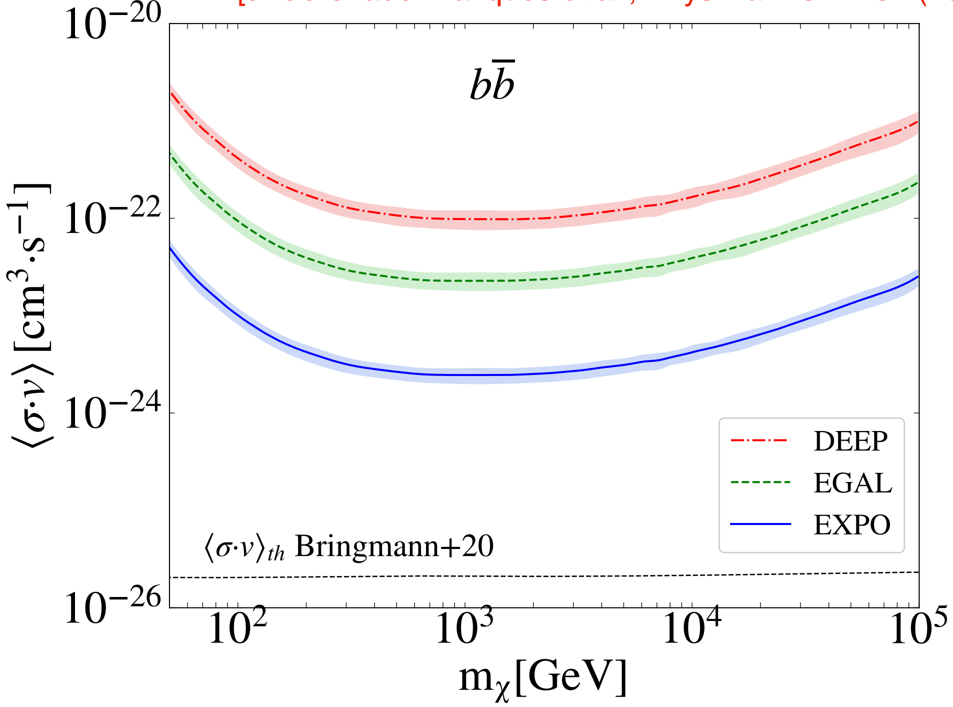
- The **cold dark matter scenario predicts the presence of dark matter subhalos along the Galactic plane** that may produce TeV emission due to DM pair annihilation.

- **We provide a missing study of the potential of CTA's GPS to detect DM subhalos.**

- **We demonstrated that the GPS' sensitivity is promising to detect the bright parts of the subhalo population for $\langle \sigma v \rangle \geq 10^{-24}$ cm³ s⁻¹.**

- Our results reveal prospects that are comparable to those of other CTA survey campaigns.

[J. Coronado-Blazques et al., Phys.Dark Univ. 32 (2021)]



- An average representative of the subhalo population becomes detectable for $\langle \sigma v \rangle \geq 3 \cdot 10^{-23}$ cm³ s⁻¹.

- **A genuine subhalo, once detected, is easily distinguishable from a point-like source or Gaussian profile reducing the impact of source confusing along the plane.**