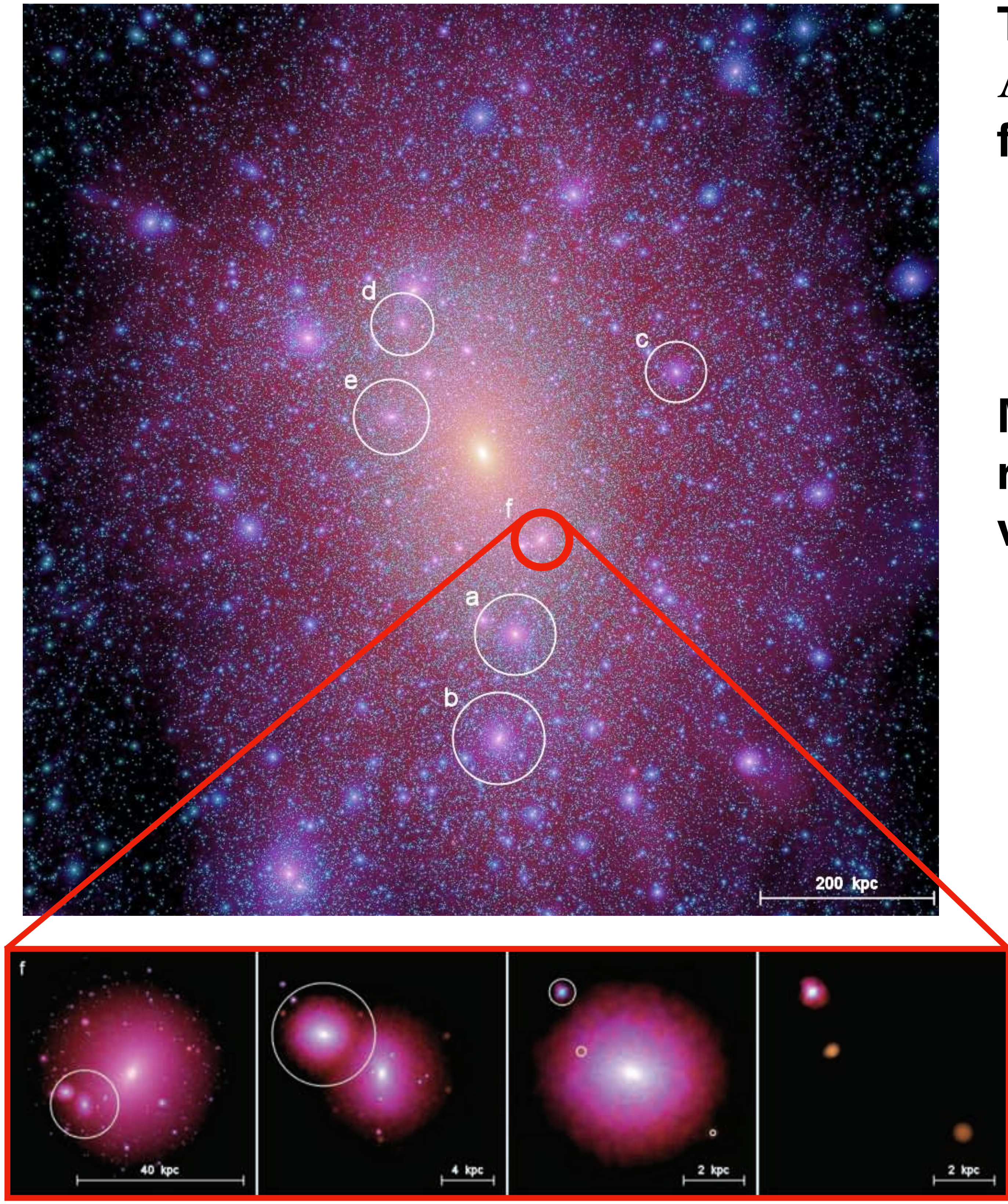
Unveiling dark sub-haloes in the Galactic plane with the Cherenkov Telescope Array Observatory

Christopher Eckner (christopher.eckner@ung.si)
SMASH post-doctoral fellow
University of Nova Gorica, Center for Astrophysics and Cosmology, Slovenia

Identification of Dark Matter (IDM) 2024
11th of July 2024 | L'Aquila, Italy

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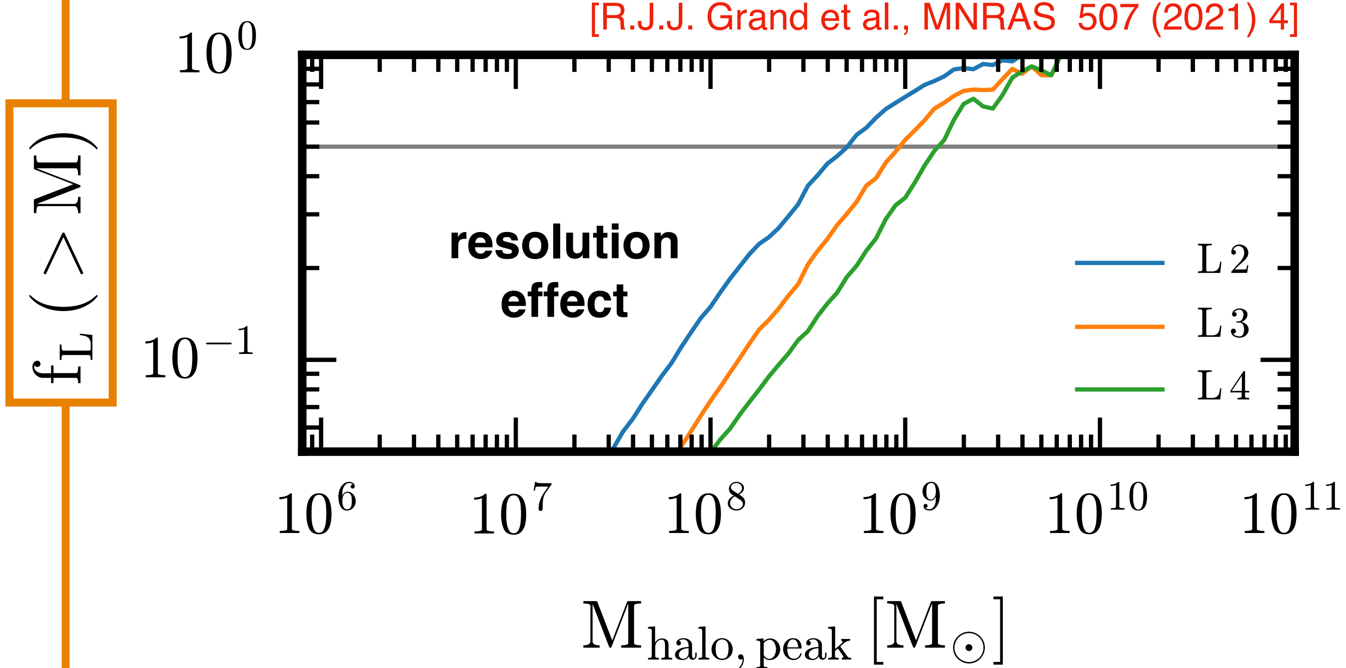
minimal gravitationally bound dark matter halo

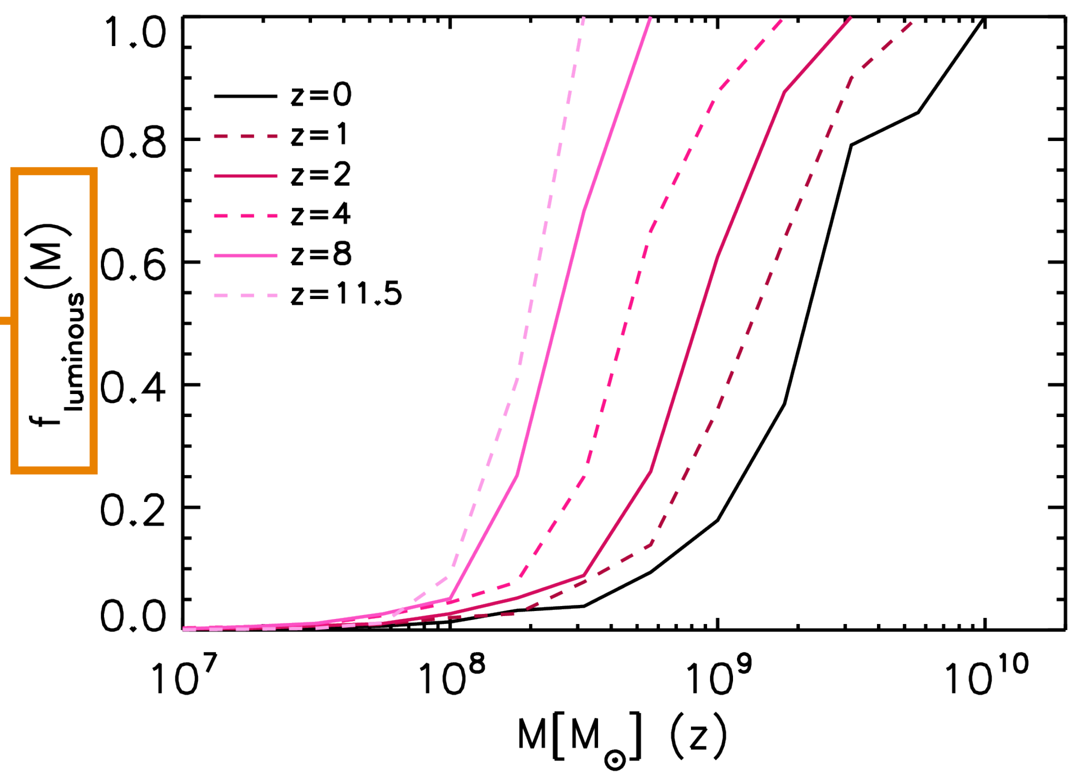
Brief introduction of Galactic dark matter subhalos

Fraction of dark matter halos hosting luminous matter

[R.J.J. Grand et al., MNRAS 507 (2021) 4]



[T. Sawala et al., MNRAS 456 (2016) 1]

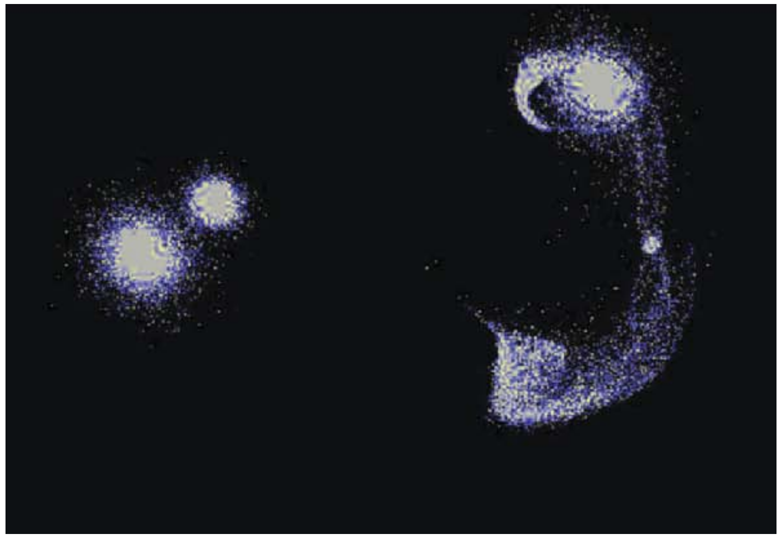


Subhalos of masses below $\sim 10^8\,M_\odot$ do not accumulate a sizeable amount of baryons to initiate star formation.

↓

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

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

Evolution in Galactic potential from prescription in [M. Stref and J. Lavalle, PRD 95, 063003]**:**

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

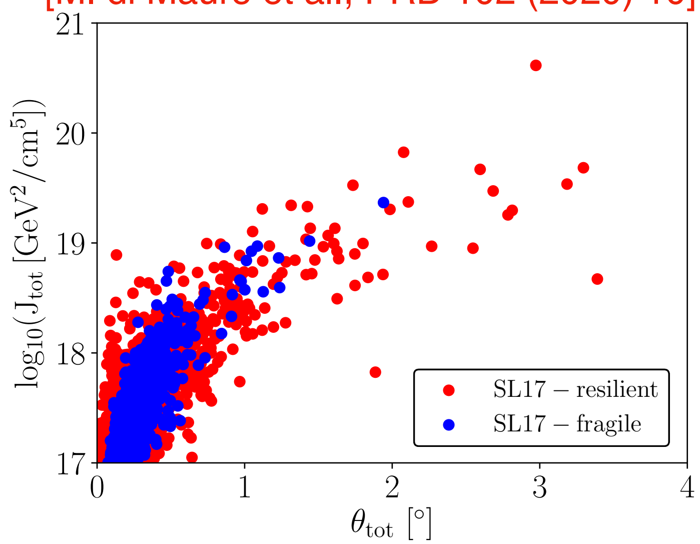
— Full disruption of subhalo may occur or not (within the uncertainty of simulations), hence two bracketing cases (**"SL17 fragile"** and **"SL17 resilient" sub halos**)

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

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

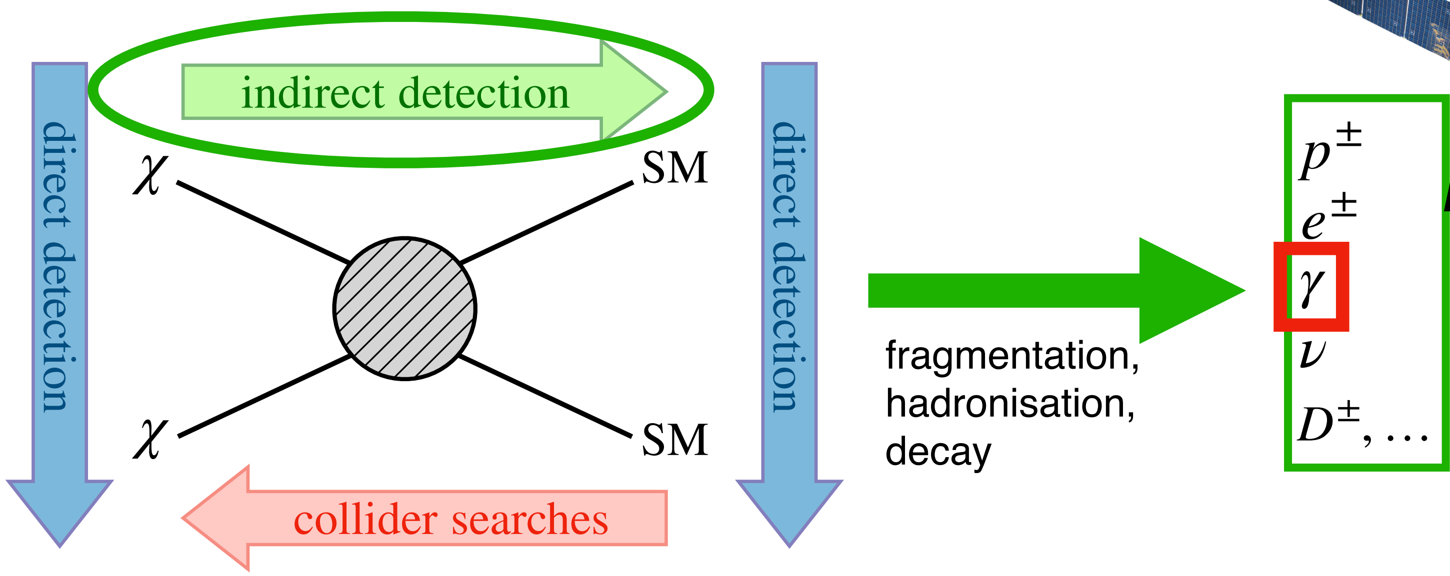
Total angular size and mass of the subhalo population in the sky.

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



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:

$$\frac{d\Phi_\gamma}{d\Omega\, dE_\gamma}(E_\gamma, \psi) = \frac{1}{4\pi} \underbrace{\boxed{\int_{\rm l.o.s} d\ell(\psi)\rho_\chi^2(\mathbf{r})}}_{\text{cosmology/astrophysics ``}J\text{-factor''}} \underbrace{\boxed{\left(\frac{\langle\sigma v\rangle_{\rm ann}}{2S_\chi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}\right)}}_{\text{particle physics}}$$

Although not as massive as the Milky Way halo, the density of subhalos generates potentially measurable gamma-ray emission.

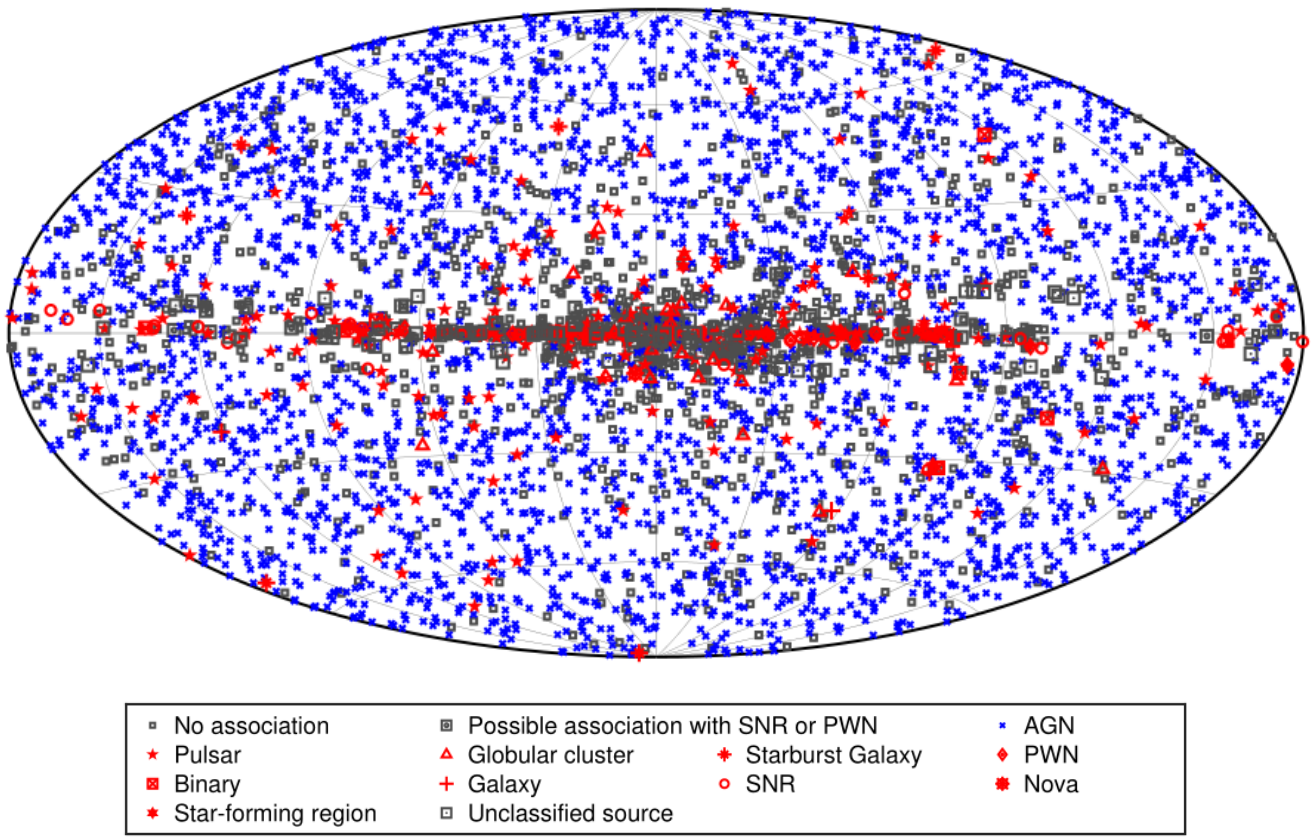
ρ_χ — dark matter density profile Navarro-Frenk-White (NFW)

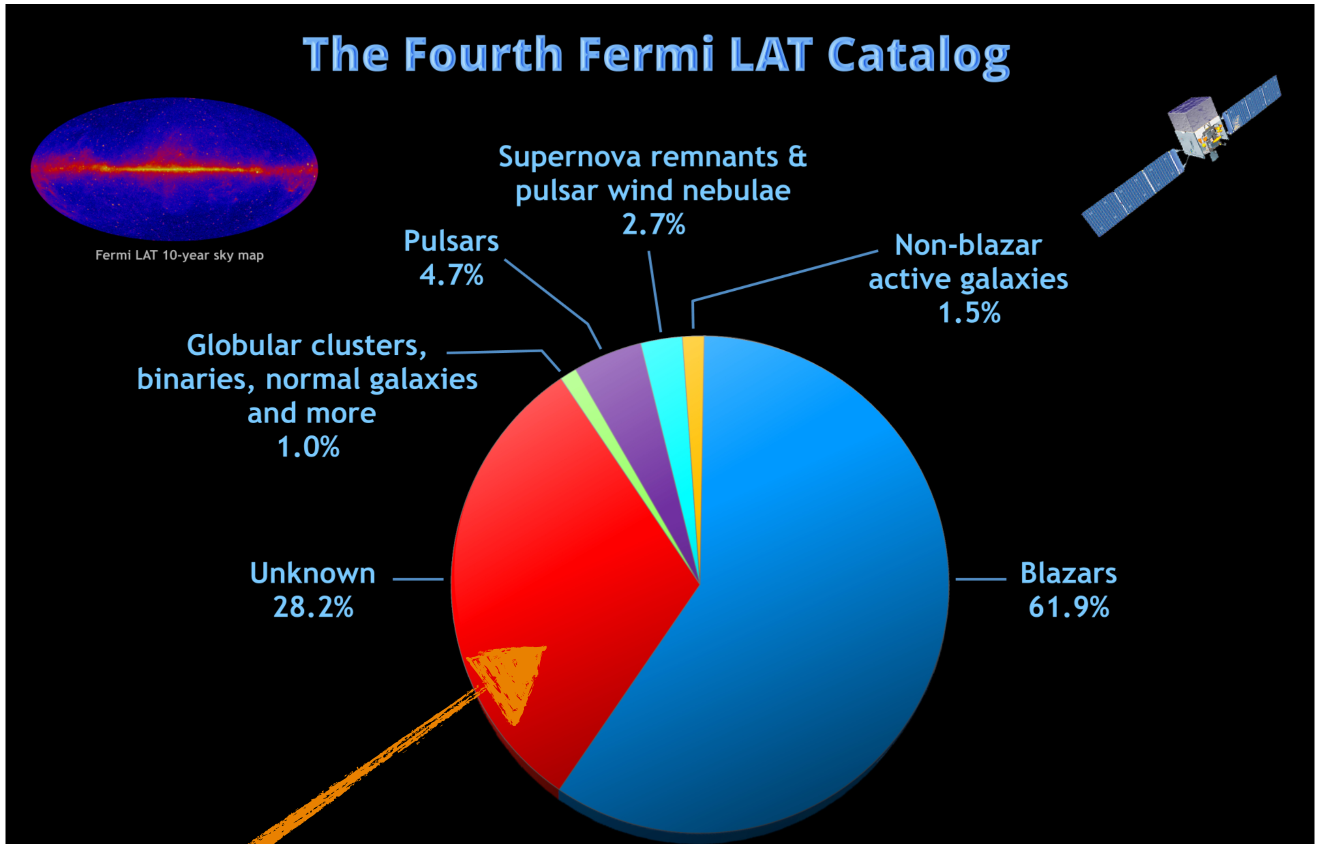
$\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ — gamma-ray spectrum per annihilation event per energy (for us: $\chi\chi \rightarrow b\bar{b}$ from [M. Cirelli et al., JCAP 03 (2011) 051])

The study — Motivation

The current gamma-ray source catalogue of the *Fermi*-LAT collaboration contains up to 1/3 unidentified sources.

[The Fermi-LAT collab., ApJS 247 (2020) 1]





credit: Jean Ballet, Isabelle Grenier

Dark matter sub halos may be part of the un-associated sources.
→ The same will apply to CTAO.

What is the potential to discriminate exotic extended gamma-ray sources from known classes?

The study — Objective

Exploration of the potential of the planned CTAO Galactic Plane Survey (GPS) for the study of dark subhalos as extended objects.

Benefits:

— higher exposure than, e.g., extragalactic survey (see [J. Coronado-Blazques et al., Phys.Dark Univ. 32 (2021)] for an assessment)

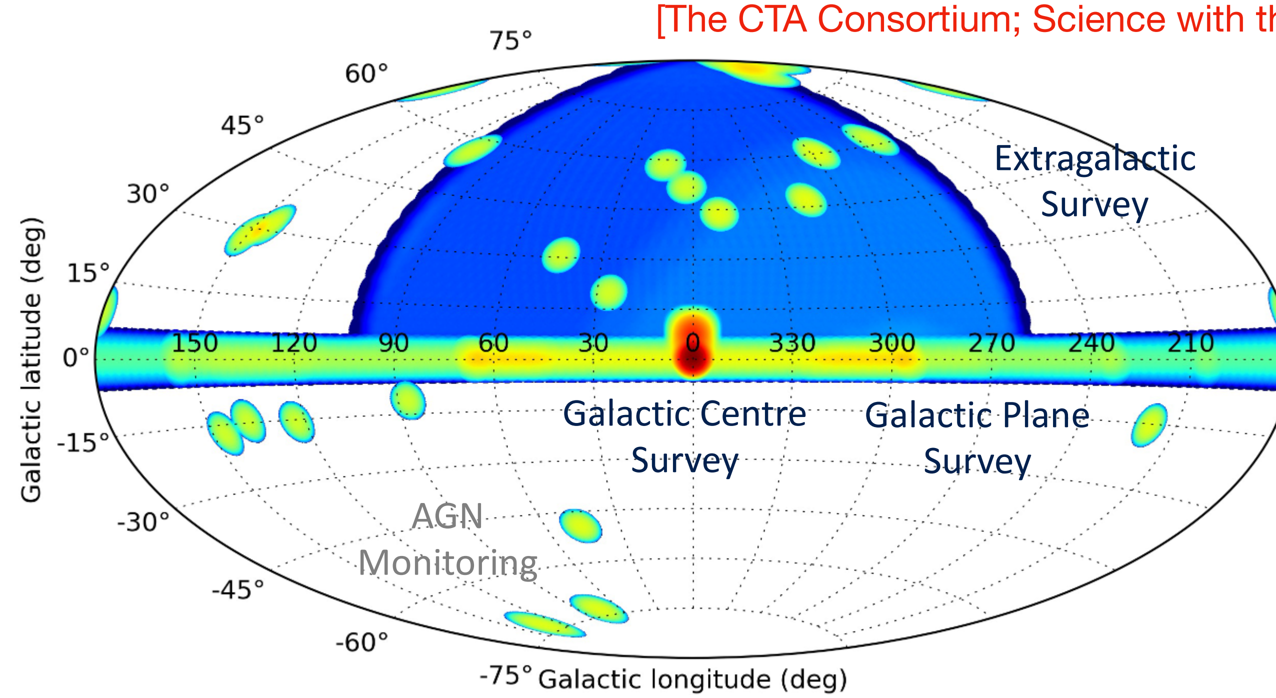
— reasonably high abundance of subhalos (model-dependent: fragile/resilient)

Downsides:

— source confusion due to crowdedness

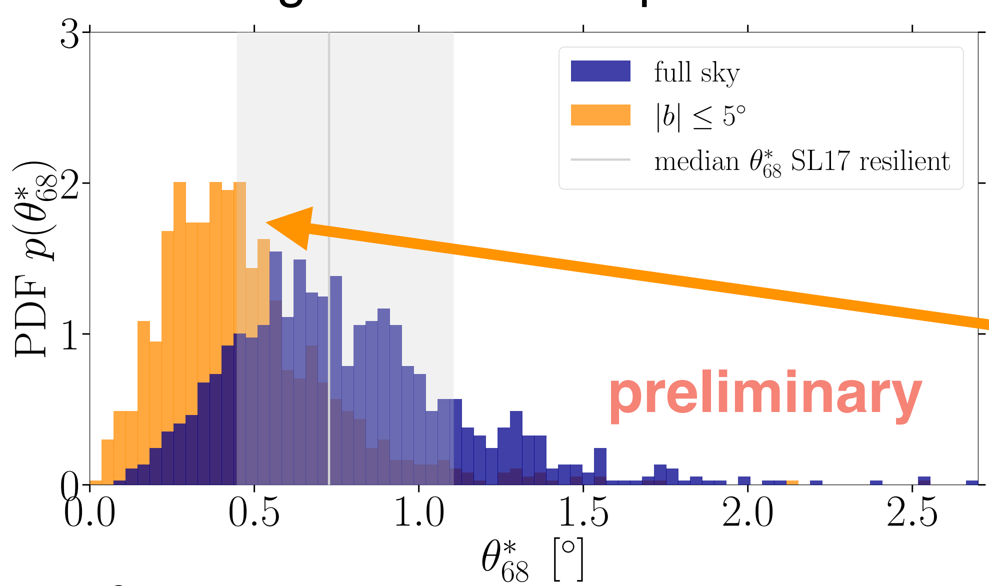
— small fraction of full sky

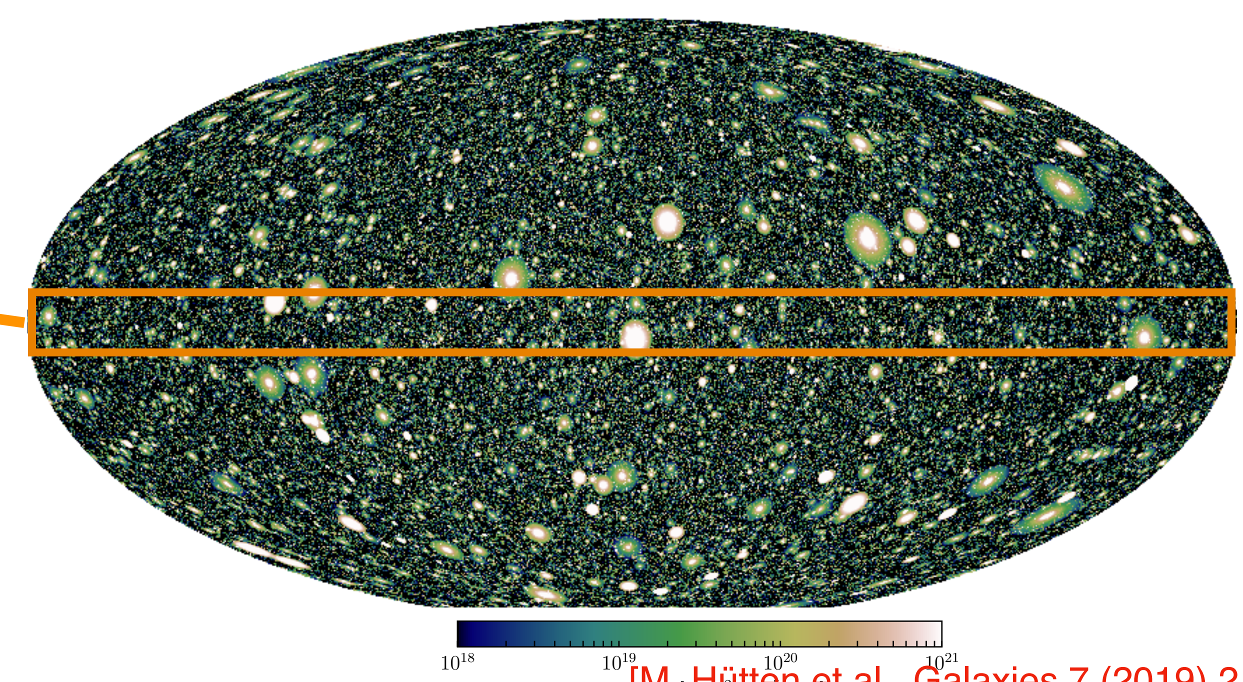
[The CTA Consortium; Science with the CTA]



SL17 resilient

Extension of brightest subhalo per realisation





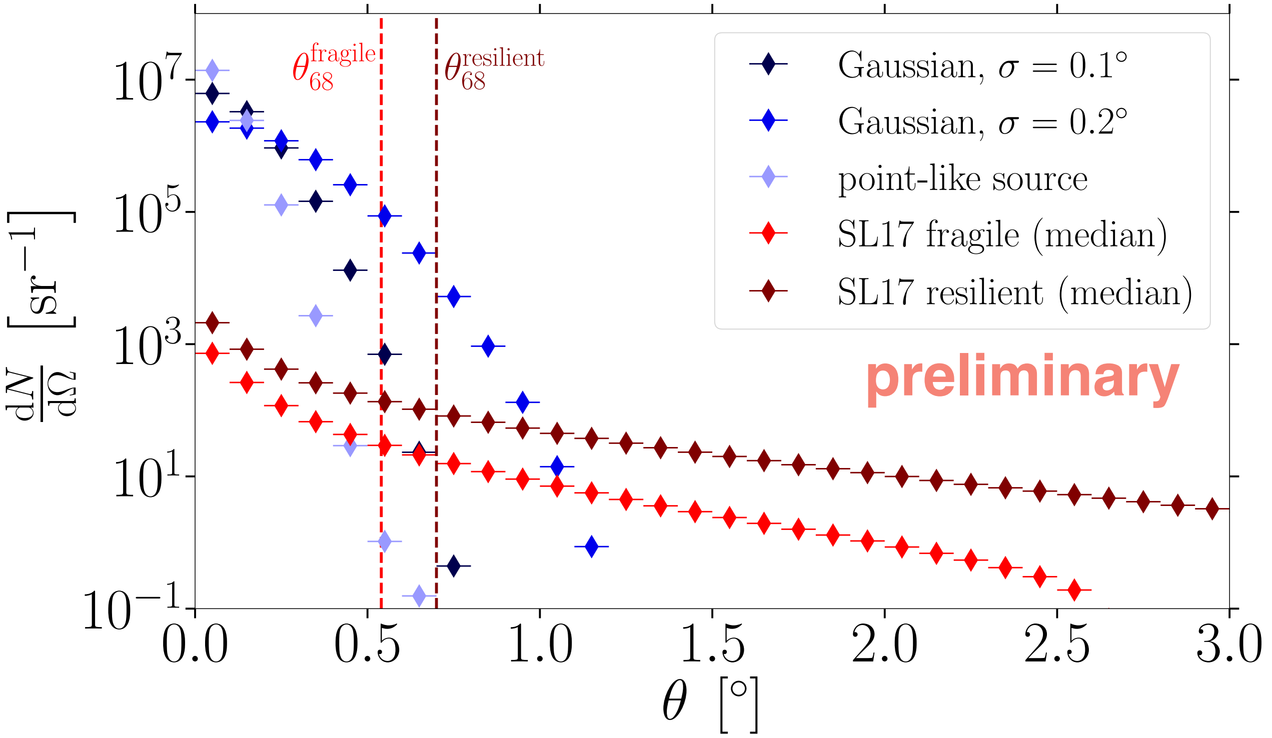
θ_{68}: angular extension comprising 68% of the total J-factor

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

The study — Methodology

Our study adheres to the following principles:

— **Subhalo models incorporating tidal effects** (baryonic physics) to bracket uncertainties (SL17 resilient and fragile).
— Statistics from 1000 realisations per population model.
— Simulation of sub halo models with CLUMPYv3 [M Hütten et al., Computer Physics Communications 235] as 2D maps to **capture spatial extension**.

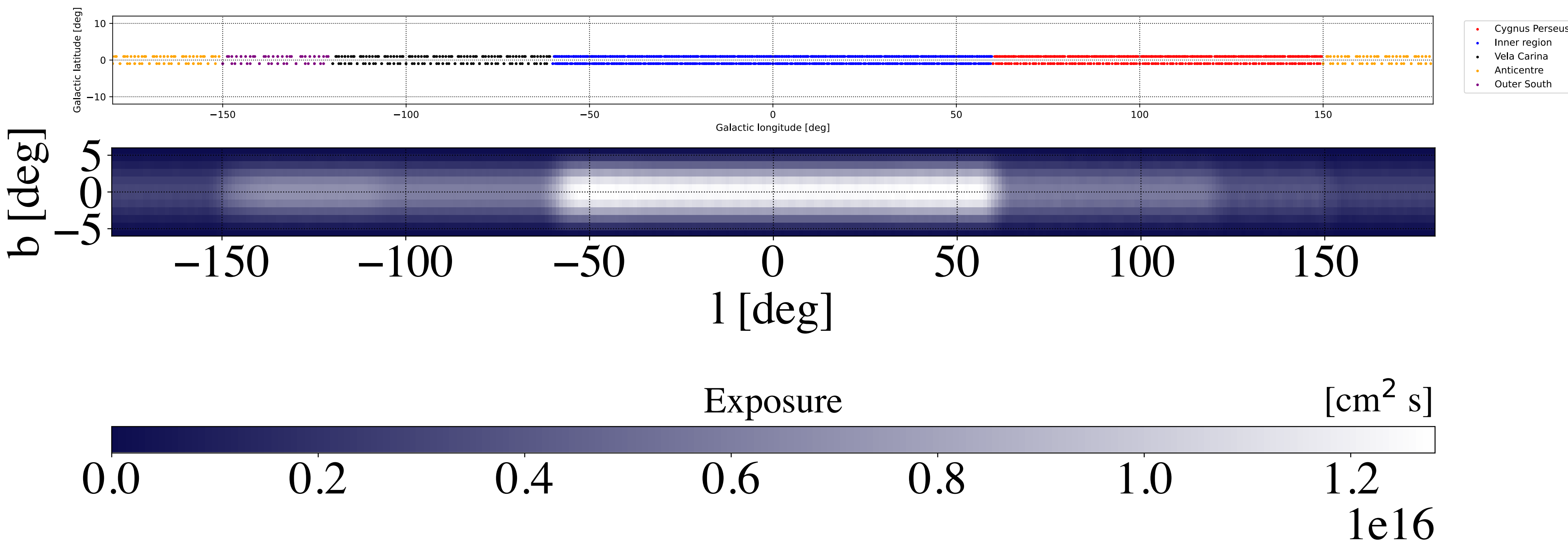


— Simulation of CTA observations and instrument response function with gammapy/ctools
→ **three-dimensional template-based analysis**
→ specifications of CTA's GPS following consortium publication
→ similar to our study of pulsar halos in the GPS [C. Eckner et al., MNRAS 521 (2023) 3]

— Application of results to a **single object representing a most optimistic scenario for CTAO** and **entire subhalo population**.

The CTAO Galactic plane survey

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

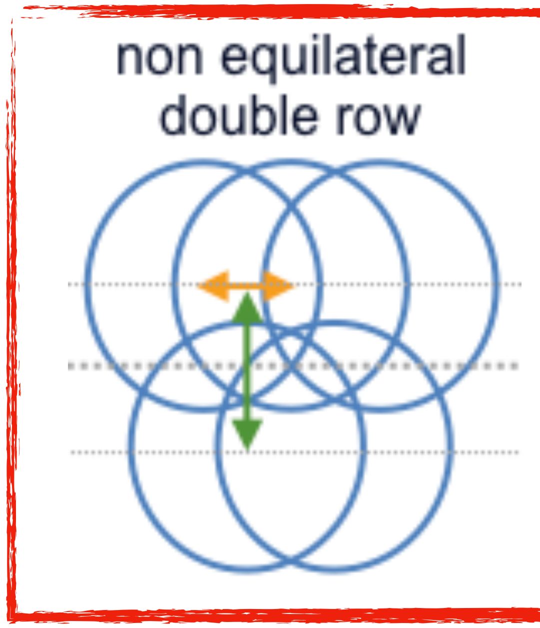


Observation pointing strategy:

— 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)



[CTA Consortium, arXiv:2310.02828]

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)

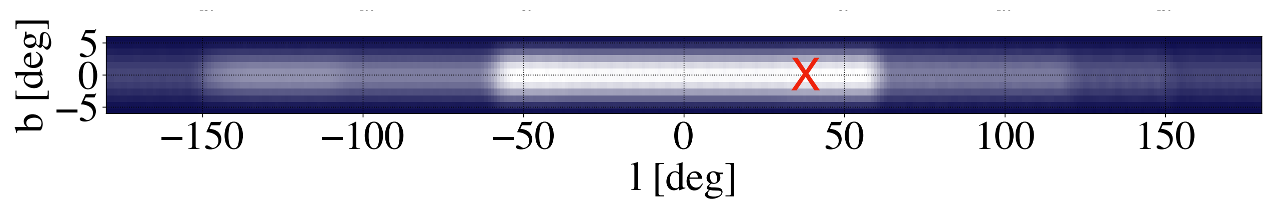
Spectral sensitivity to brightest subhalo (optimistic)

We analyse for the most optimistic case the brightest subhalo found among all realisations (in fact, an SL17 resilient object).

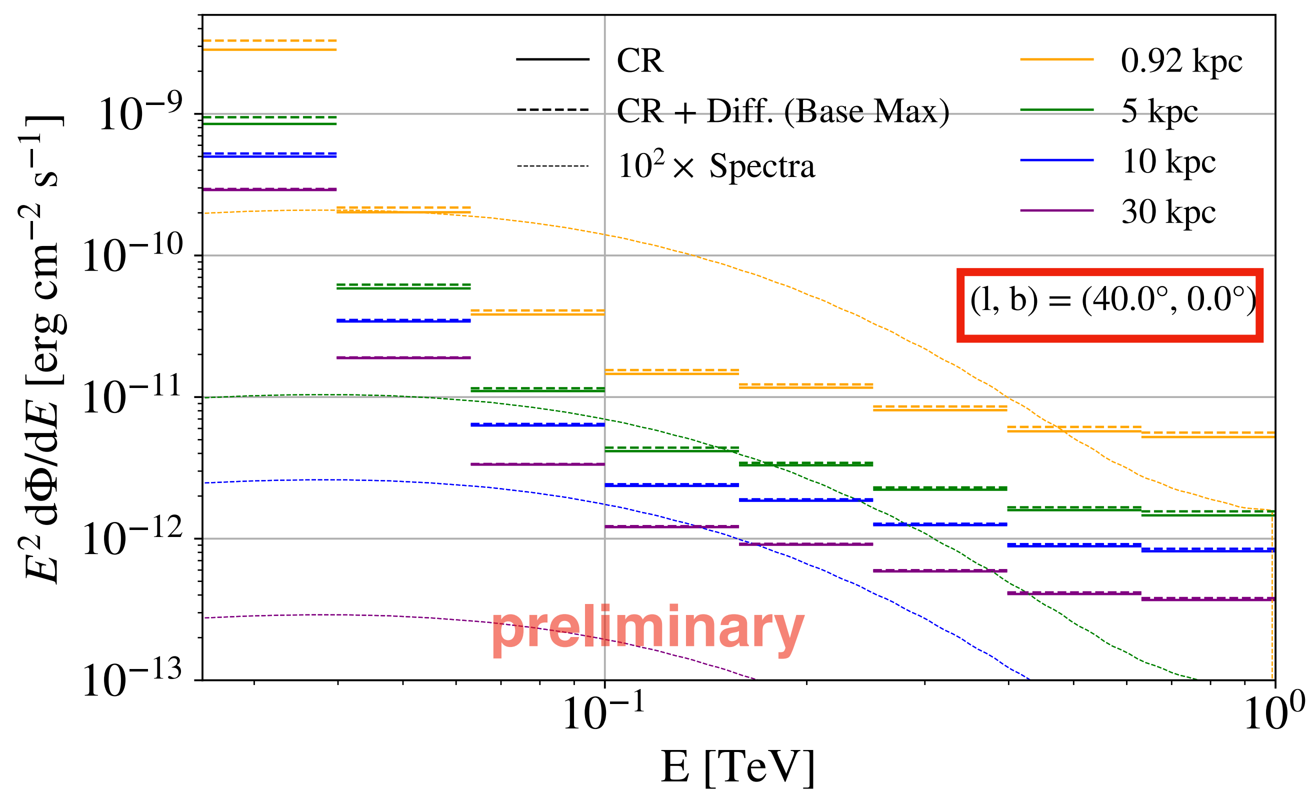
Sub-halo mass M_Δ	Distance	r_s	$\mathcal{J}_{\rm tot}$ [GeV^2 cm^{-5}]	$\mathcal{J}_{\rm FoV}$ [GeV^2 cm^{-5}]	r_Δ	θ_{68}
$4.8 \cdot 10^6 M_\odot$	0.92 kpc	2.36 kpc	$9.56 \cdot 10^{21}$	$6.44 \cdot 10^{21}$	0.162 kpc	1.54°
$4.8 \cdot 10^6 M_\odot$	5.0 kpc	2.36 kpc	$3.21 \cdot 10^{20}$	$3.21 \cdot 10^{20}$	0.162 kpc	0.46°
$4.8 \cdot 10^6 M_\odot$	10.0 kpc	2.36 kpc	$8.02 \cdot 10^{19}$	$8.02 \cdot 10^{19}$	0.162 kpc	0.23°
$4.8 \cdot 10^6 M_\odot$	30.0 kpc	2.36 kpc	$8.94 \cdot 10^{18}$	$8.94 \cdot 10^{18}$	0.162 kpc	0.08°

We located it at various distances from Earth essentially decreasing the J-factor but shrinking the angular extension.

GPS exposure band:



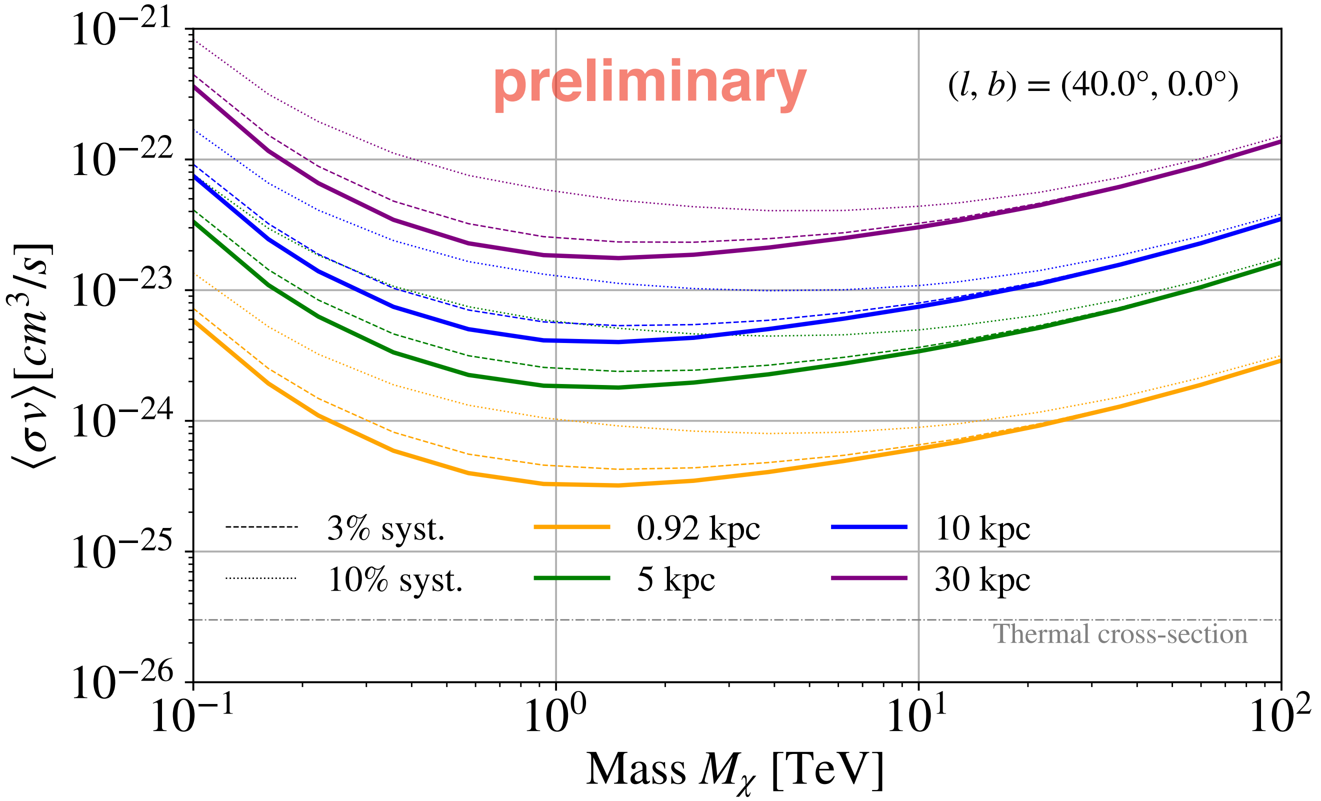
Solid lines x 10^2:
$\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3/s,
DM mass: 1 TeV
annihilation channel: $b\bar{b}$

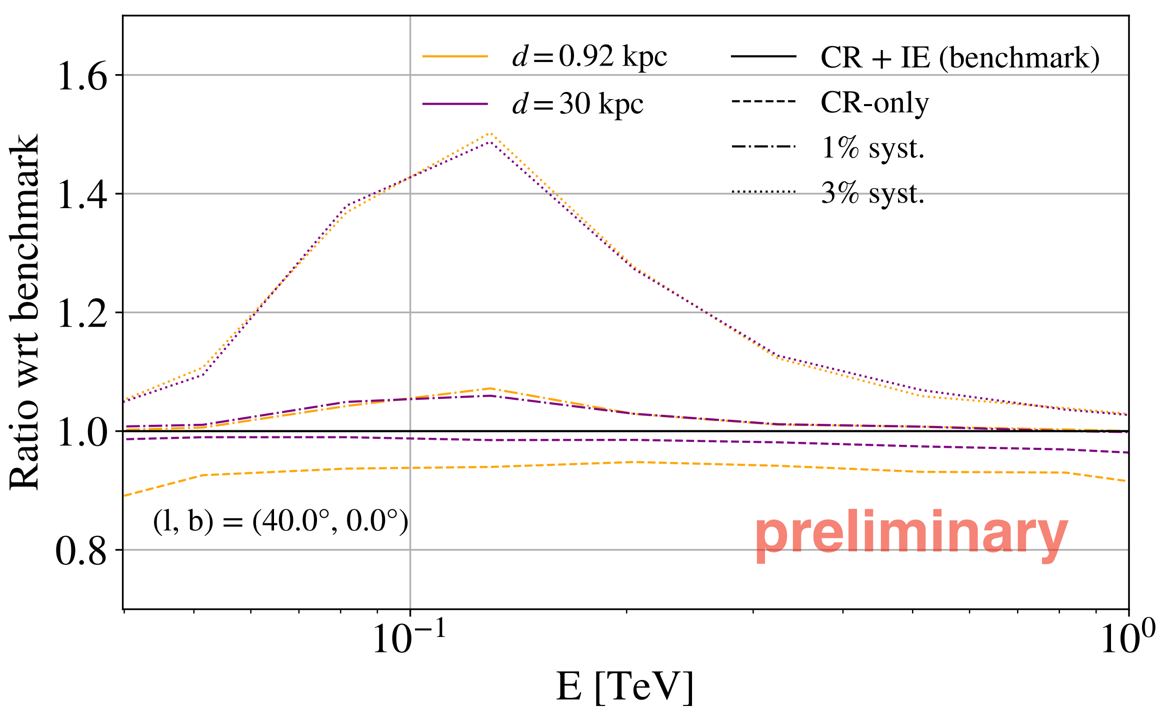


Flux per energy bin required for a 5σ detection: Possible for cross-section $\sim 3 \times 10^{-25}$ cm^3/s **for close subhalos up to 1 kpc and TeV-scale dark matter.**

Spectral sensitivity to brightest subhalo (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.

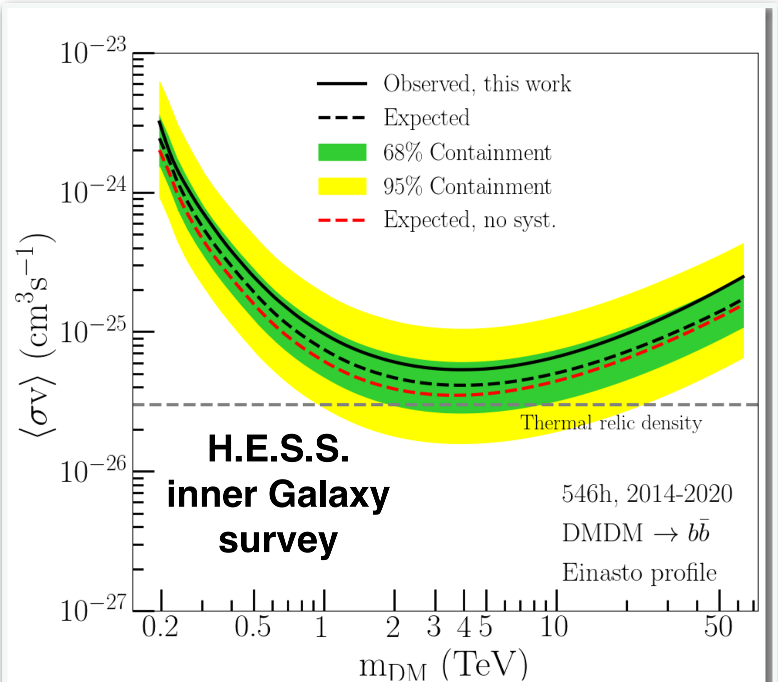




1. **Impact of interstellar emission rather weak.**

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-gen. IACTs like H.E.S.S.: DM profile in Galactic centre rather uncertain, flat densities strongly weaken the constraints!**

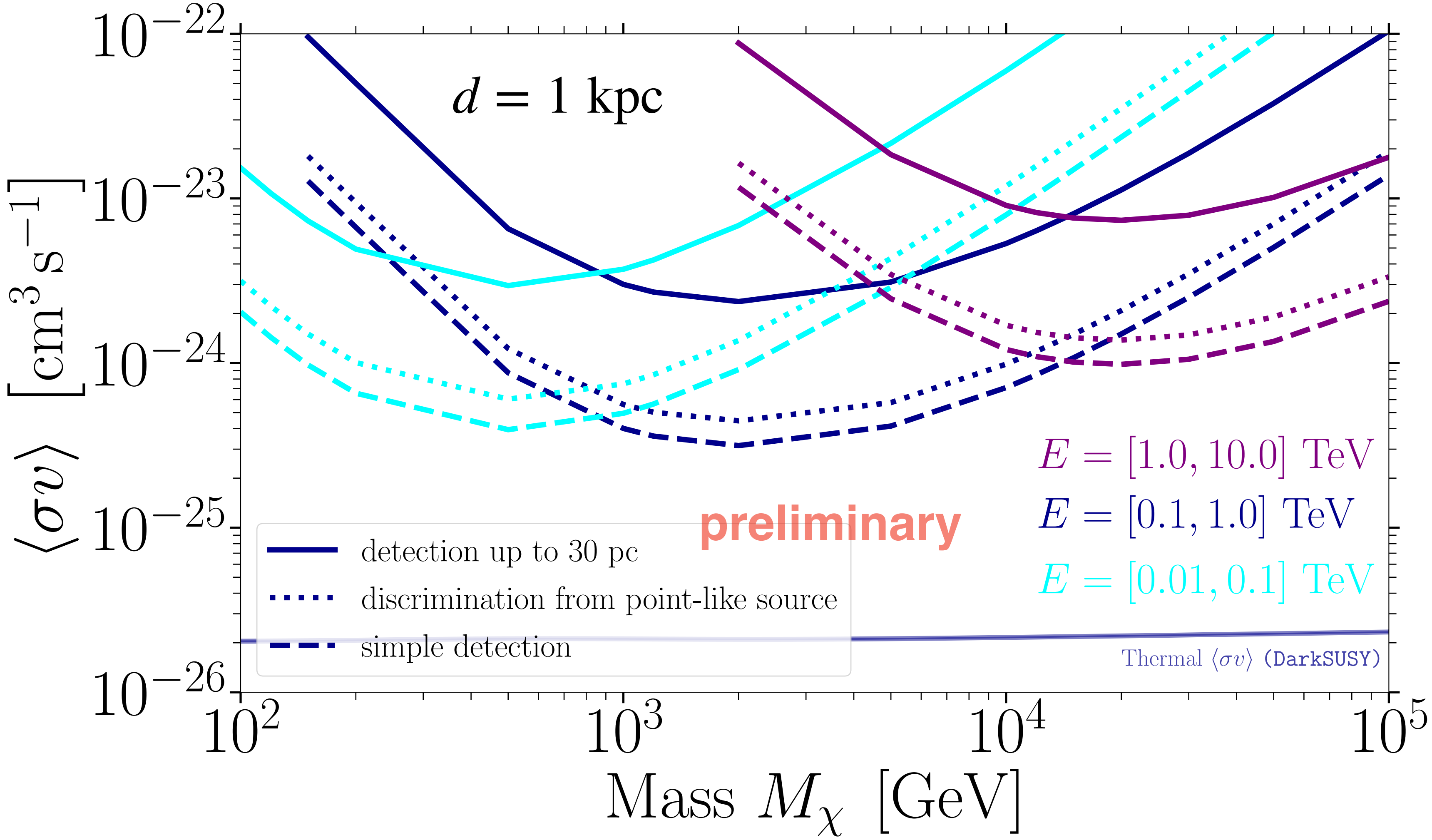


[H.E.S.S. collab., PRL 129, 111101 (2022)]

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.



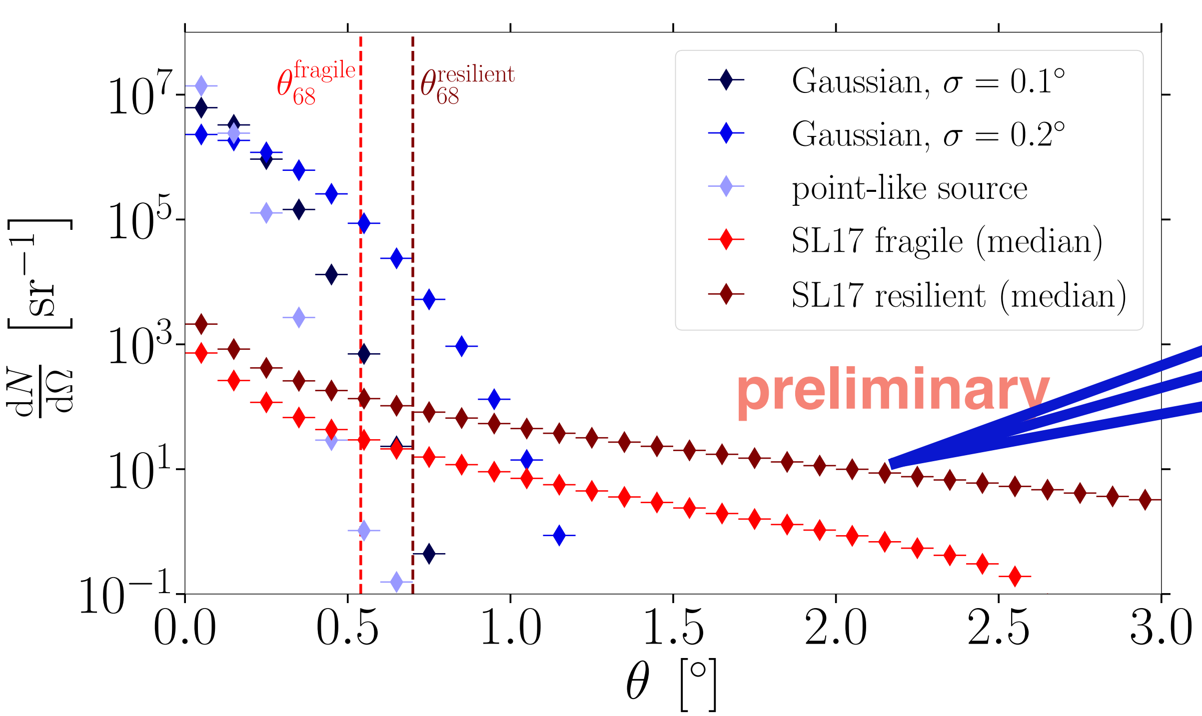
Less than a factor of 2 difference between cross-section required for detection and exclusion of point-like character! Detection up to 30 pc ensures discrimination power from astrophysical sources.

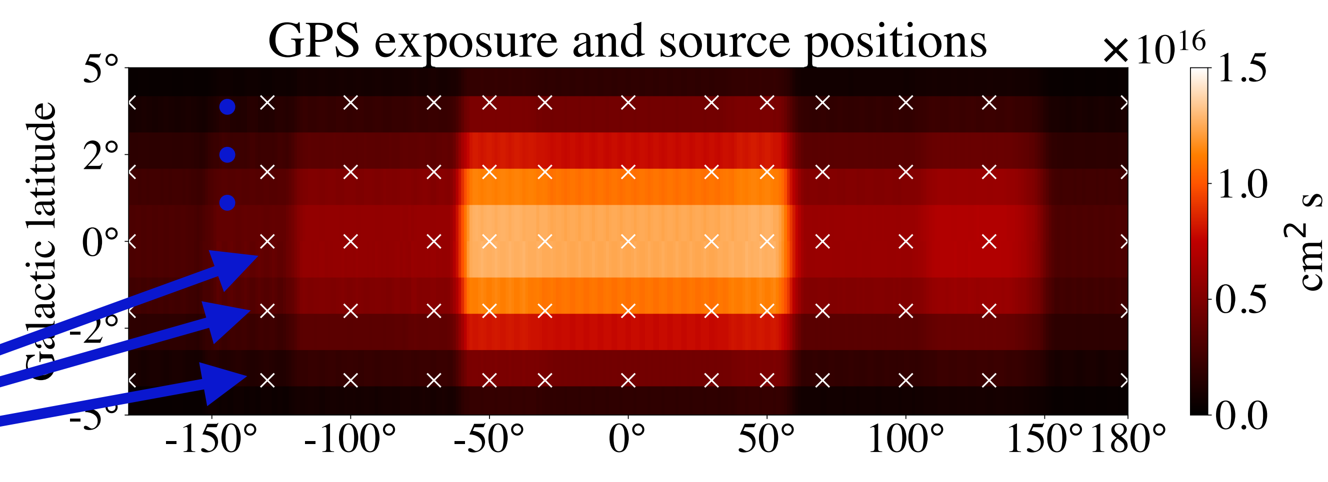
Addressing the full subhalo population

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

→ **Problem**: Analysing each sub halo individually in a template-based approach is way too time-consuming.

→ **Solution**: Apply a re-scaling of the detection sensitivity based on the angular extension of the respective object gauged via representative cases
(1) point-like
(2) median fragile extension (of brightest subhalo per realisation)
(3) median resilient extension (of brightest subhalo per realisation)

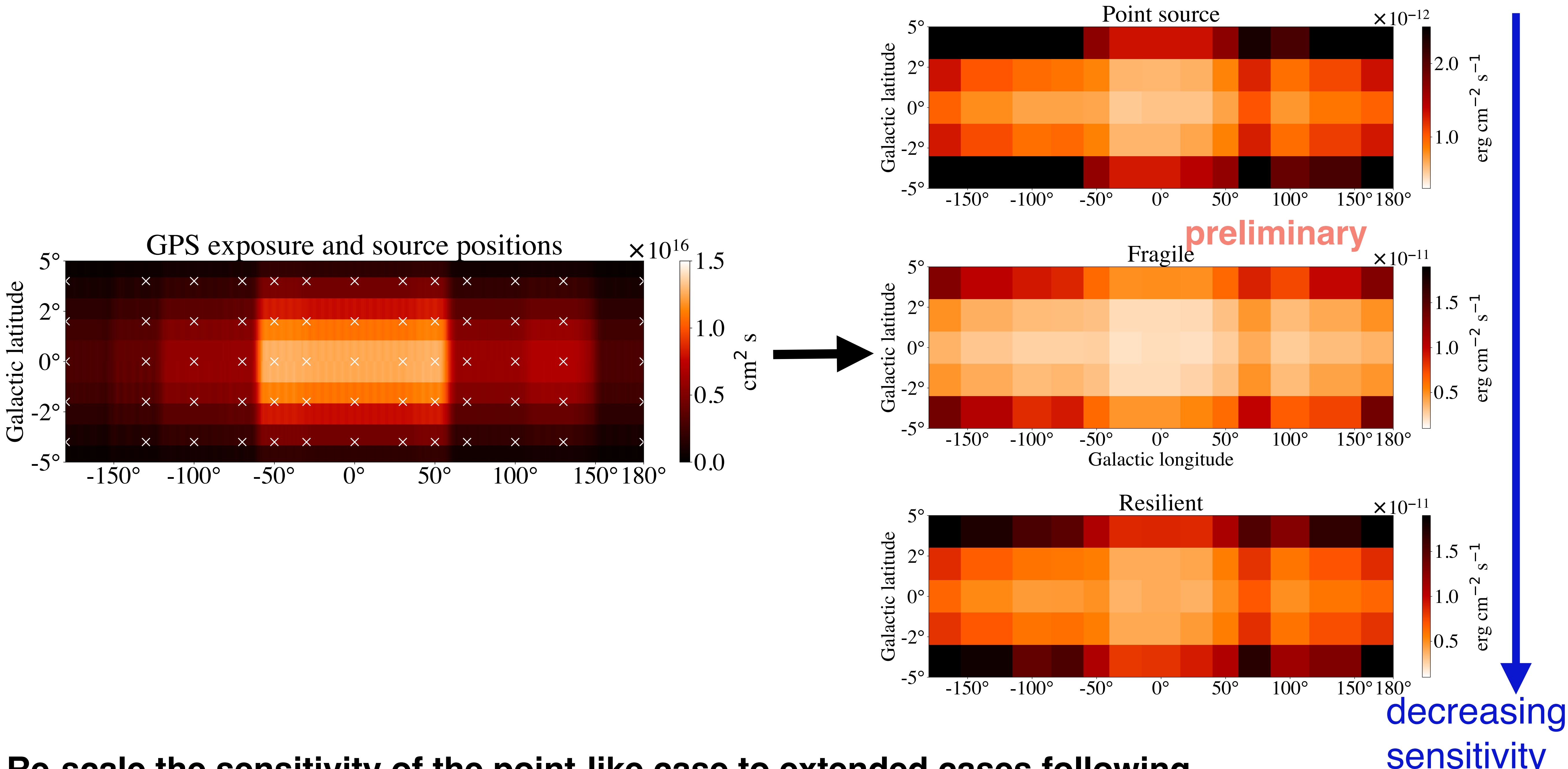




Perform template-based analysis at each representative position for each source class!

Addressing the full subhalo population

Each grid states the required integrated flux for a 5σ detection depending on the source class.



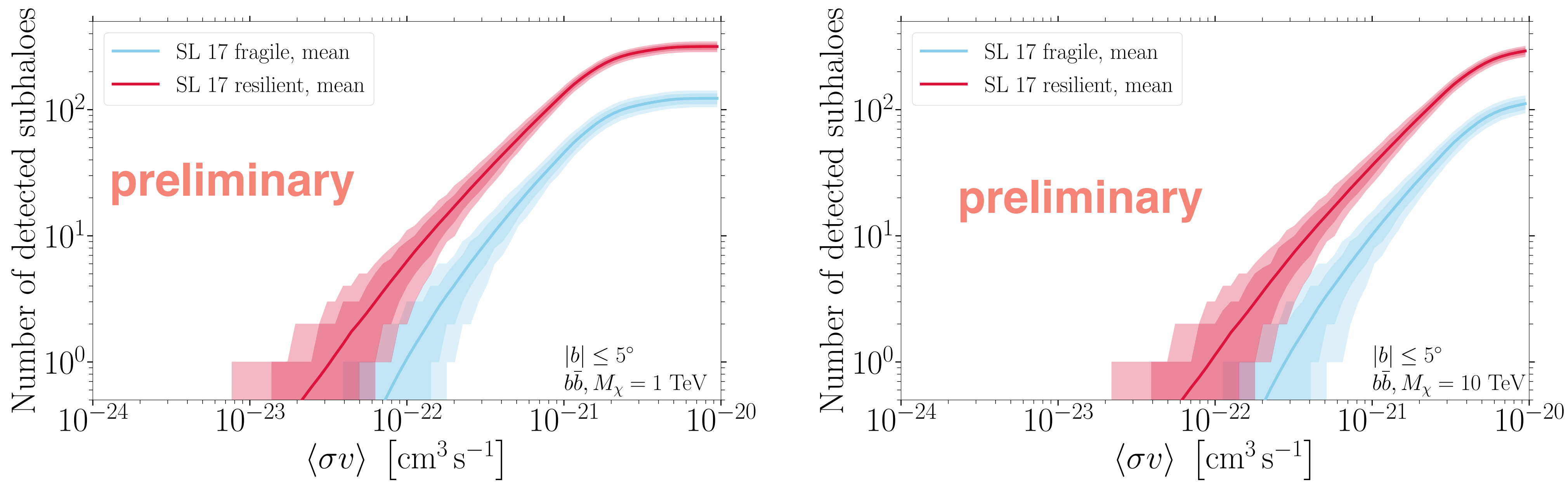
Re-scale the sensitivity of the point-like case to extended cases following the parametric formula (inspired by H.E.S.S. Galactic Plane survey [H.E.S.S. collab., A&A 612 (2018) A1]**).**

$$F(\theta_{68}) = A(\boldsymbol{x})\sqrt{\alpha\theta_{68}^2 + \sigma_{\mathrm{PSF}}^2}$$

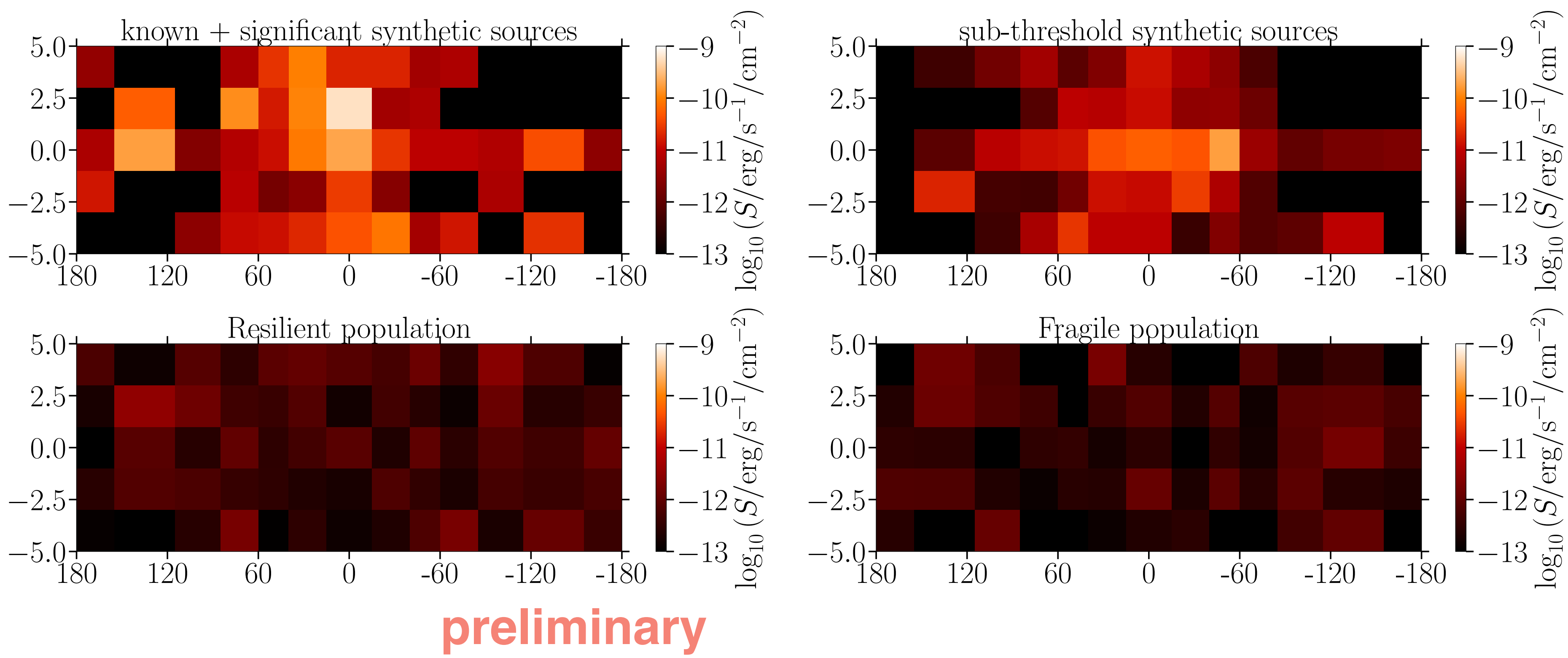
→ $A(x)$ fixed with point-like case.
→ α optimised to reproduce extended sensitivities

Addressing the full subhalo population

Expected number of subhalos with statistics of our 1000 realisations per scenario.



Subhalos will also contribute to the diffuse gamma-ray flux along the Galactic plane.



— synthetic sources: pulsar wind nebulae used for the CTAO Galactic plane survey study

[CTA Consortium, arXiv:2310.02828]

— Off-plane subhalos can contribute sizeably!

Summary

- **CTAO'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.

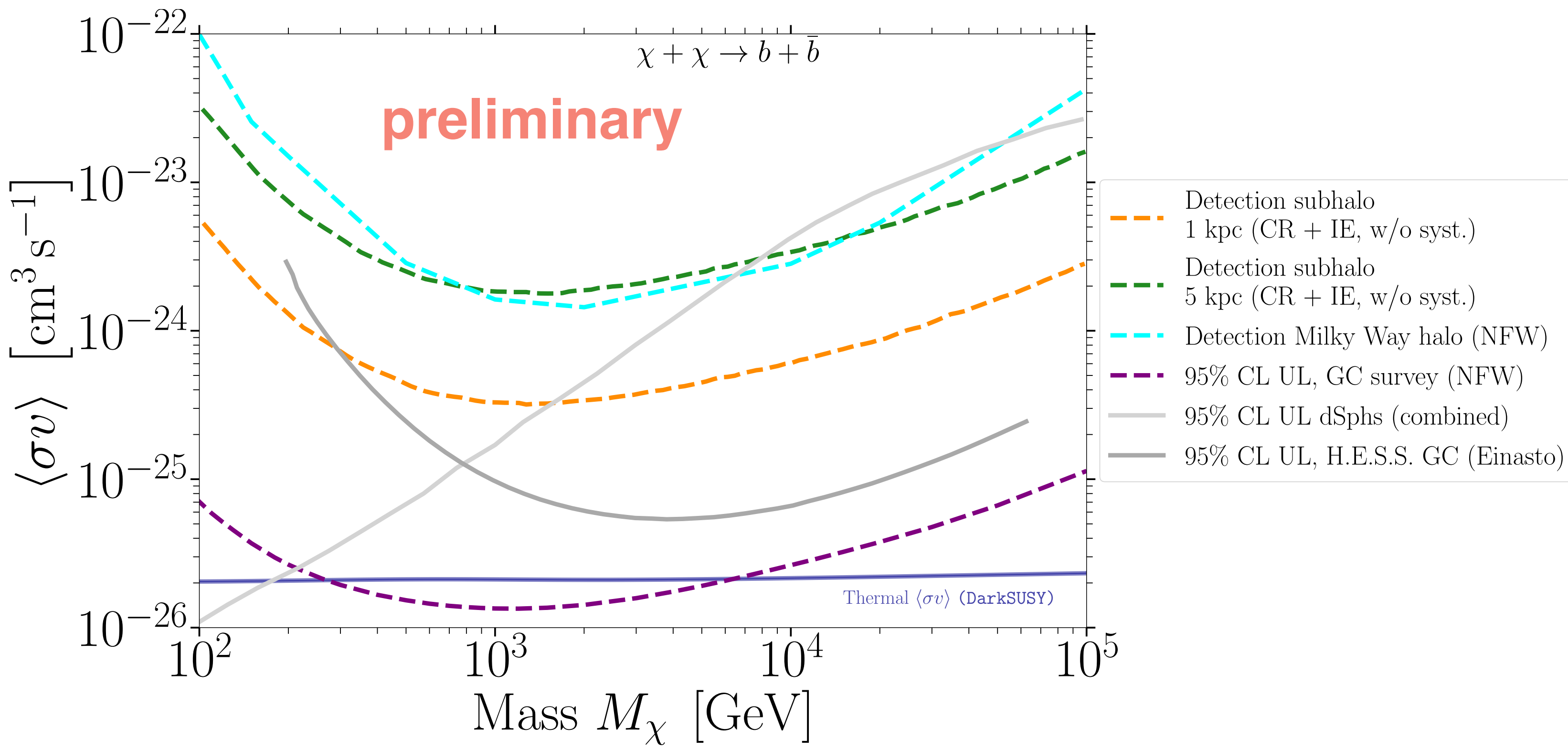
- **We provide a missing study of the potential of CTAO's GPS to detect DM subhalos.**

- **We demonstrated that the GPS' sensitivity is promising to detect the bright parts of the subhalo population for $\langle \sigma v \rangle \geq 3 \times 10^{-25}$ cm^3 s^{-1}.**

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

- Detection potential of the bright part of the population larger than prospects to detect Milky Way parent halo.

- Viable targets for dark matter particles $M_\chi > 10$ TeV, especially if the MW-halo exhibits a core.



Back-up slides

Comparison with previous CTAO prospects

CTAO prospects were derived for the extragalactic survey (25% of the sky) and the collection of all data taken by CTAO (not only limited to consortium surveys).
→ extension not taken into account

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