Detecting and characterizing dark matter sub-halos with the Cherenkov Telescope Array

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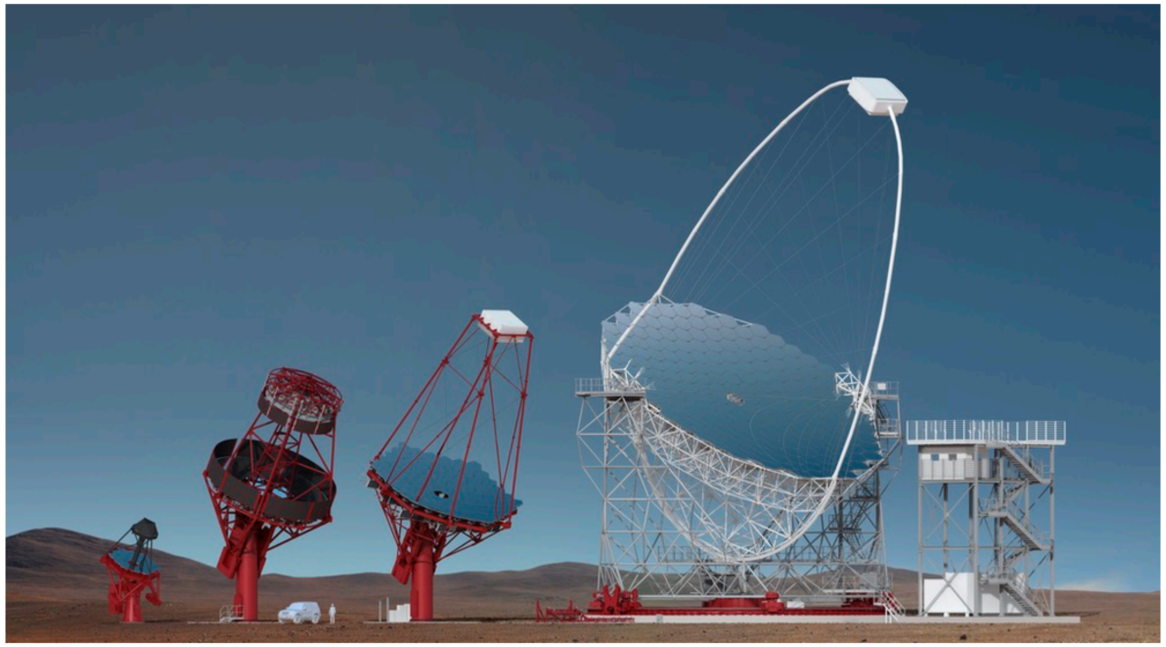
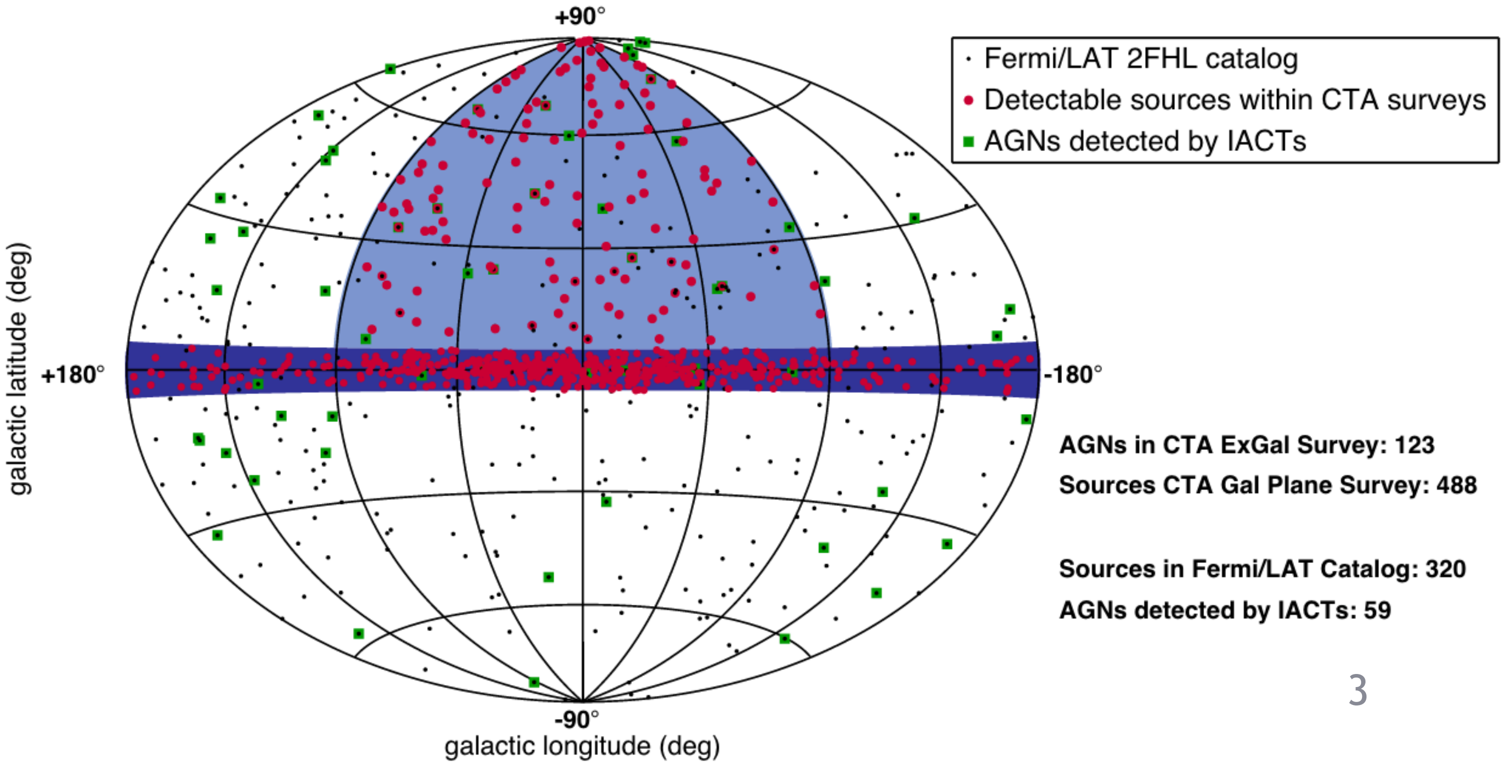
About Cherenkov Telescope Array

- CTA is an Imaging Atmospheric Cherenkov Telescope, detecting gamma rays in the energy range 20 GeV — 300 TeV
- CTA will
  - Cover the entire sky (IACT arrays in Northern and Southern Hemispheres)
  - Improve the sensitivity of current IACTs and boost detection area
  - Improve angular resolution and field of view —> better capability to image extended sources
  - Enhance surveying and monitoring capabilities
  - Large surveys of the sky are part of the Key Science Projects of CTA, e.g.:
    - Extragalactic survey (1/4 of the sky)
    - Galactic Plane Survey (GPS)





Dark matter (DM) sub-halos

- DM sub-halo is a gravitationally bound clump of dark matter that exists within a larger dark matter halo
- 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

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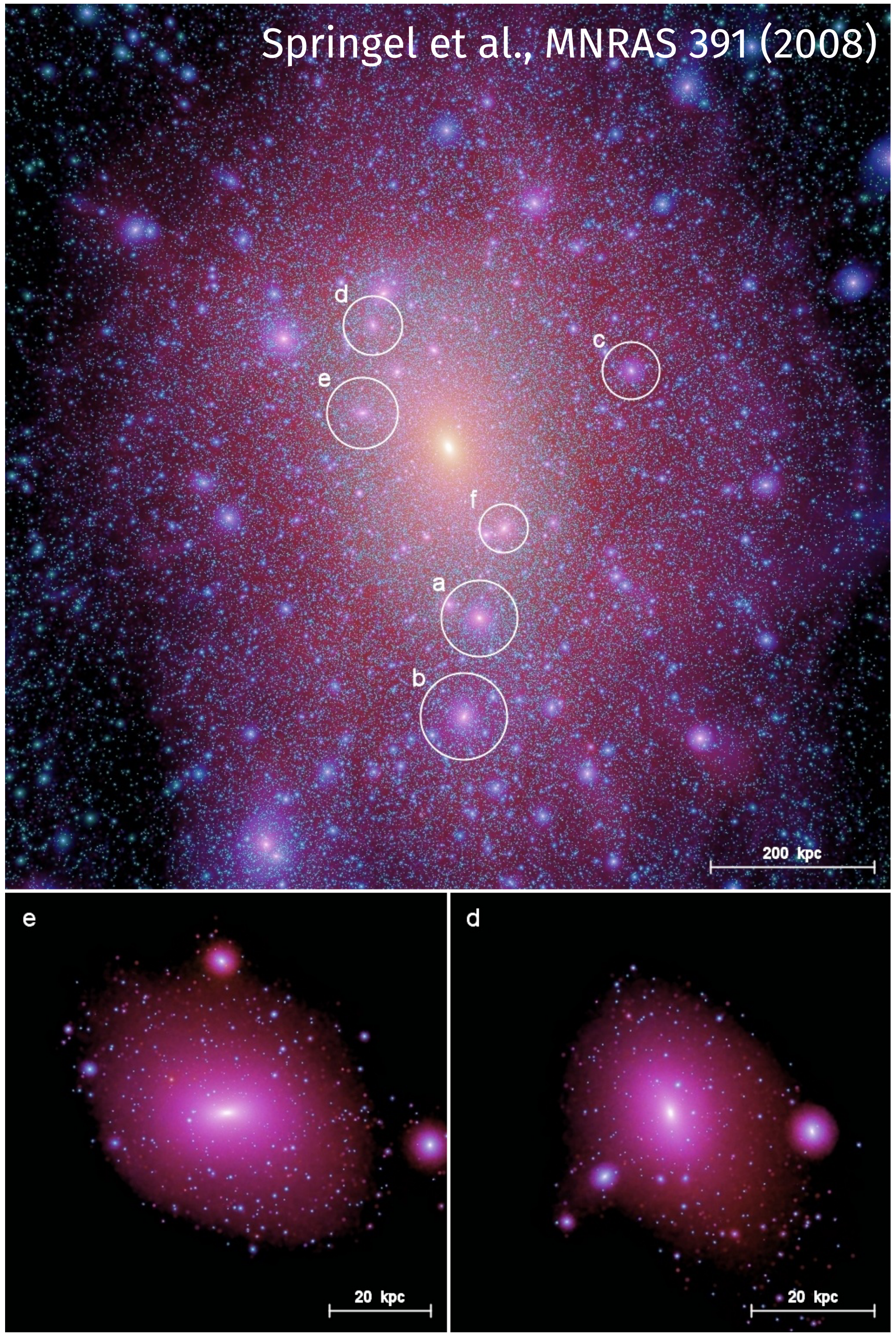
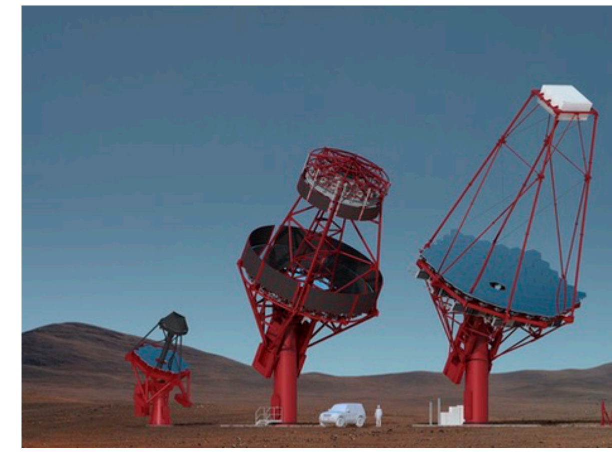
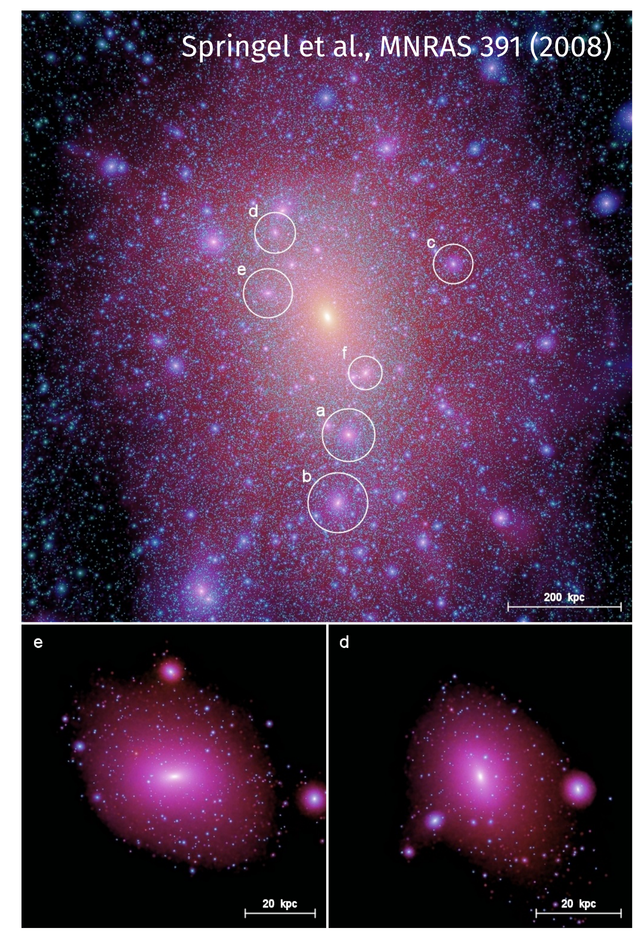
Minimal gravitationally bound dark matter halo



Motivation for our study

- Sub-halos of masses below ~ 10^8 $M_\odot$ do not accumulate a sizeable amount of baryons to initiate star formation
- Dim sources of conventional electromagnetic emission, better indirect DM detection prospects
- Previous works on CTA sensitivity to DM subhalos
  - Javier Coronado-Blázquez et al. 2021
    - Detectability of dark subhalos considering different observational scenarios for serendipitous detection
- This work
  - Adopting a similar approach as in Christopher Eckner et al. 2023
    - Assessing the sensitivity of CTA's Galactic Plane Survey to extended sources, in particular to pulsar halos
  - Assessing the sensitivity to DM subhalos considering the planned Galactic Plane Survey observations
  - Assessing the discrimination power from known astro sources





Sub-halo modelling and data simulations

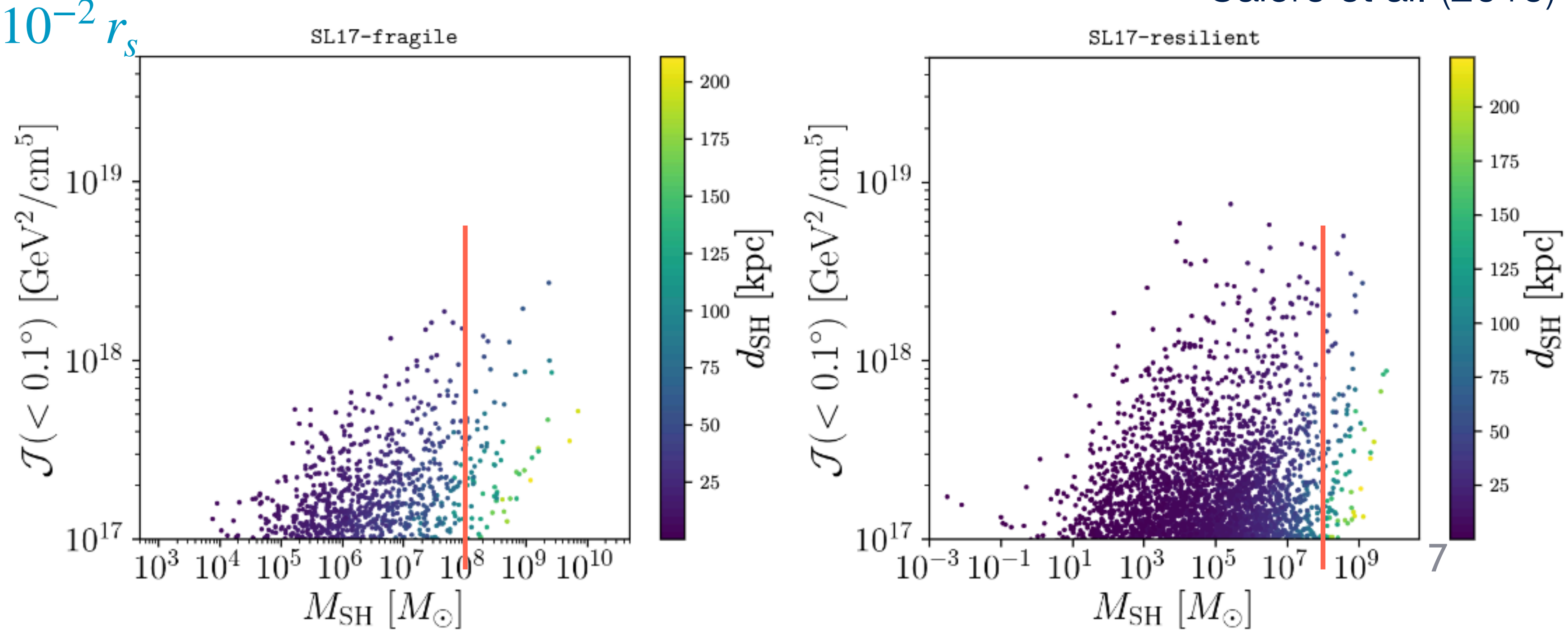
Single sub-halo and population model

- Spectral and spatial model
  - We assume the thermal WIMP DM, with mass 1 TeV annihilating into b-quarks
  - We employ the spectral model from M. Cirelli et al. (2011)
  - Navarro-Frenk-White DM profile with different parameterisations
- Modelling the Galactic sub-halo population
  - Modeling based on work by F. Calore et al. (2019) and M. Hütten et al. (2019)
  - M. Stref & J. Lavalle (2017)
    - Two variants of a sub-halo population model (based on uncertainties caused by the tidal effects, i.e. tidal vs. scale radius):
      - SL17 fragile: $r_t < r_s$
      - SL17 resilient: $r_t < 10^{-2}\, r_s$

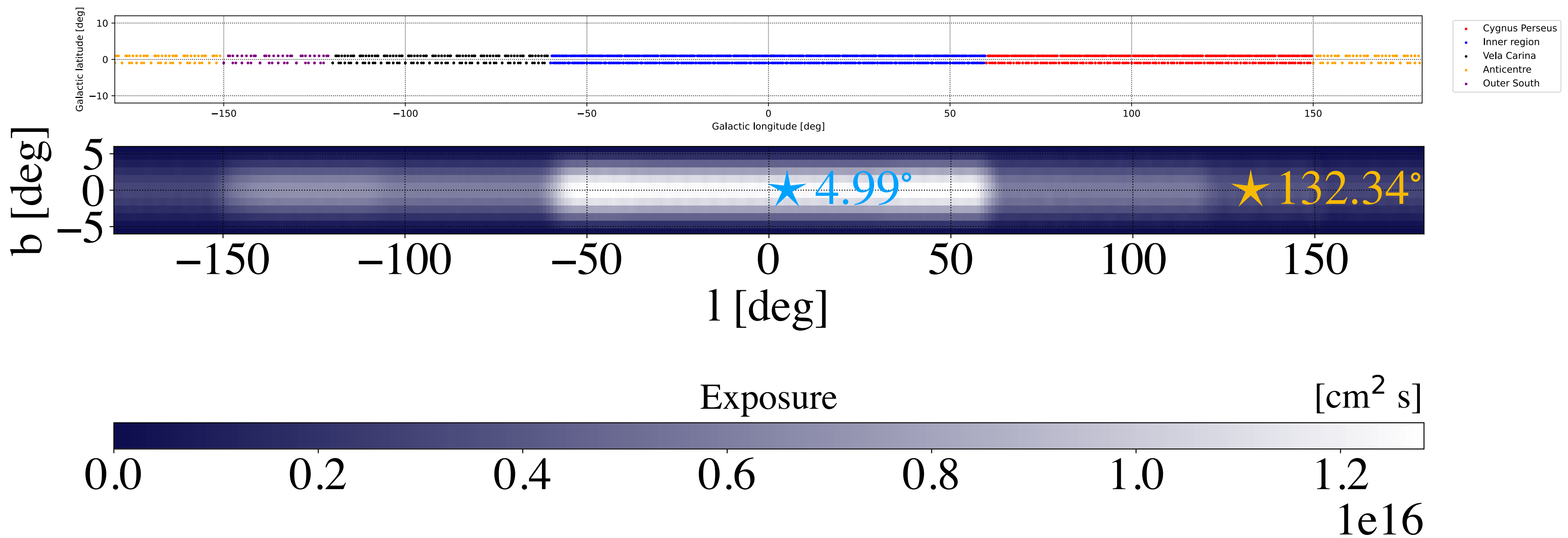
$$\mathcal{F}(E_{\rm min}, E_{\rm max}) = \frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2}\, \mathcal{J} \int_{E_{\rm min}}^{E_{\rm max}} \frac{dN^i_{\rm DM}}{dE}\, dE$$

$$\mathcal{J} = \int_0^{\Delta\Omega} \int_{\rm l.o.s.} d\ell\, d\Omega\, \rho_{\rm DM}^2(\ell)$$

Calore et al. (2019)



Simulating Galactic Plane Survey observations



- Pointing strategy
  - Two-row observation strategy
  - ~0.5 hours per pointing
  - Varying density of pointings resulting in varying exposure for different regions
  - A realistic pointing schedule adopted from L. Tibaldo (https://github.com/cta-observatory/cta-gps-simulation-paper)
- Tools
  - gammapy (0.18.2) and CTA provided IRFs (prod5-v0.1)
- Template fitting analysis: Source (sub-halo) + Instrumental background (CR) + IE model (De la Torre Luque, 2022)

cherenkov
telescope
array

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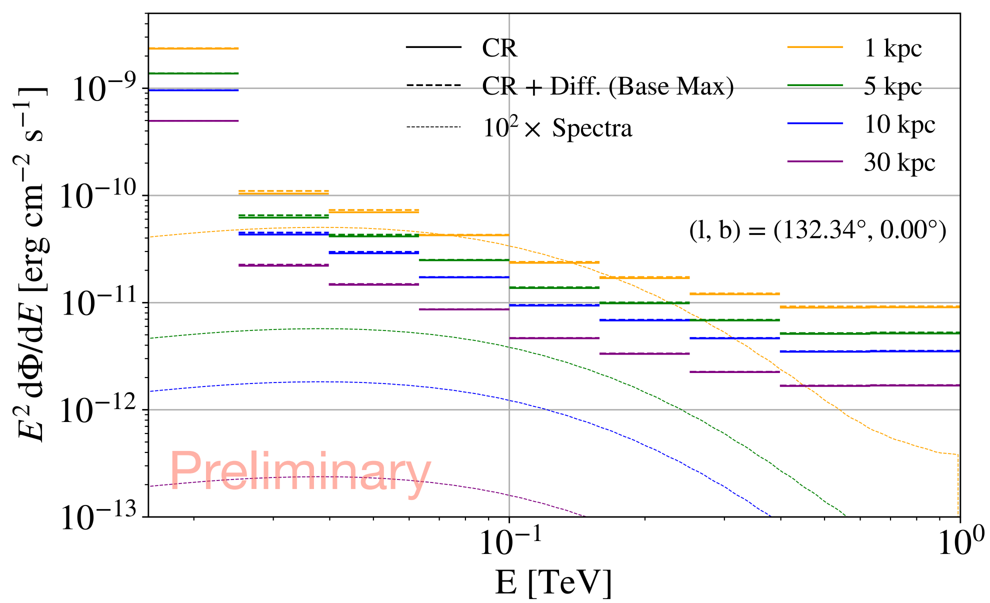
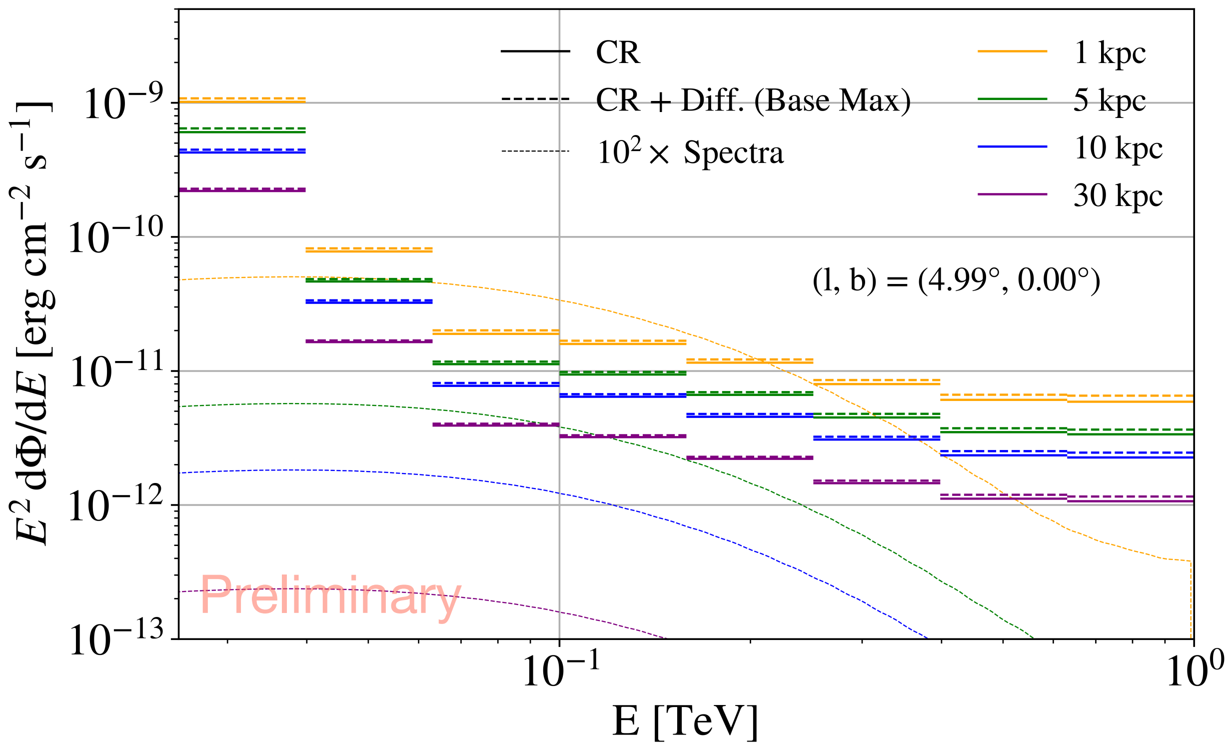
CTA's GPS sensitivity to DM sub-halos

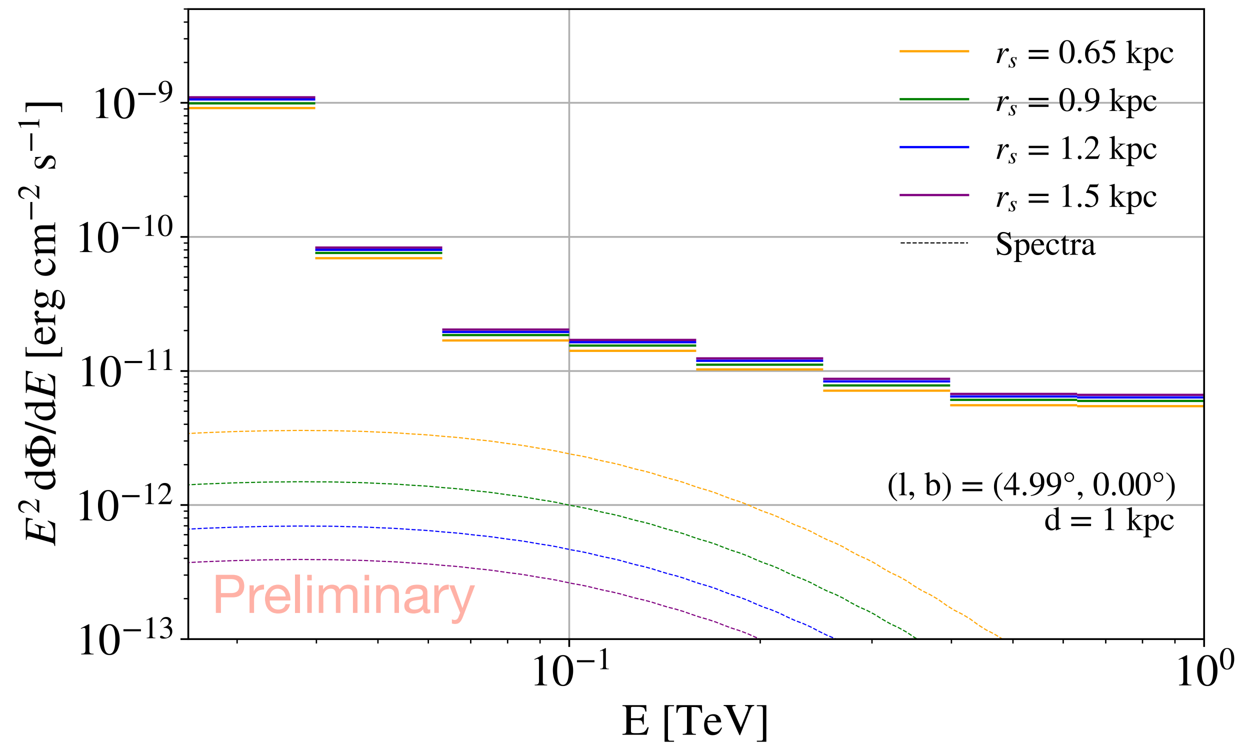
Flux sensitivity to brightest subhalo



$\sigma v = 3 \cdot 10^{-26}\,\mathrm{cm^3\,s^{-1}}$

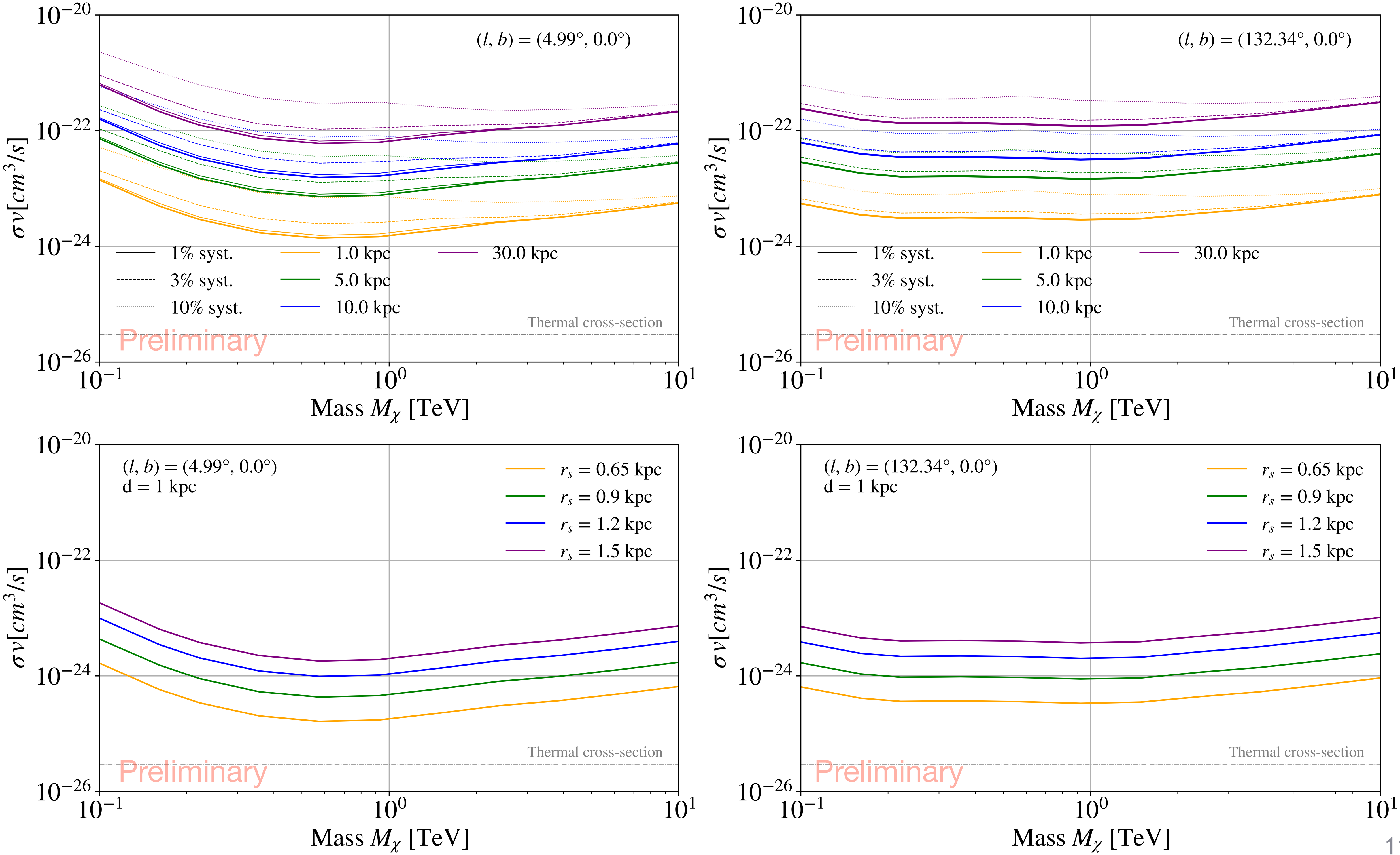
Sub-halo mass	Distance	r_s	J-factor	r_s/distance	Extension
$10^8 M_\odot$	1.0 kpc	1.36 kpc	$1.5508 \cdot 10^{21}$ GeV^2 cm^{-5}	1.360	53.7°
$10^8 M_\odot$	5.0 kpc	1.36 kpc	$1.7582 \cdot 10^{20}$ GeV^2 cm^{-5}	0.272	15.2°
$10^8 M_\odot$	10.0 kpc	1.36 kpc	$5.6194 \cdot 10^{19}$ GeV^2 cm^{-5}	0.136	7.7°
$10^8 M_\odot$	30.0 kpc	1.36 kpc	$7.3086 \cdot 10^{18}$ GeV^2 cm^{-5}	0.045	2.6°
$10^8 M_\odot$	1.0 kpc	1.50 kpc	$9.7468 \cdot 10^{18}$ GeV^2 cm^{-5}	1.50	56.3°
$10^8 M_\odot$	1.0 kpc	1.20 kpc	$5.0527 \cdot 10^{18}$ GeV^2 cm^{-5}	1.20	50.2°
$10^8 M_\odot$	1.0 kpc	0.90 kpc	$2.1534 \cdot 10^{18}$ GeV^2 cm^{-5}	0.90	42.0°
$10^8 M_\odot$	1.0 kpc	0.65 kpc	$8.1656 \cdot 10^{17}$ GeV^2 cm^{-5}	0.65	33.0°





DM mass vs. σv for brightest subhalo

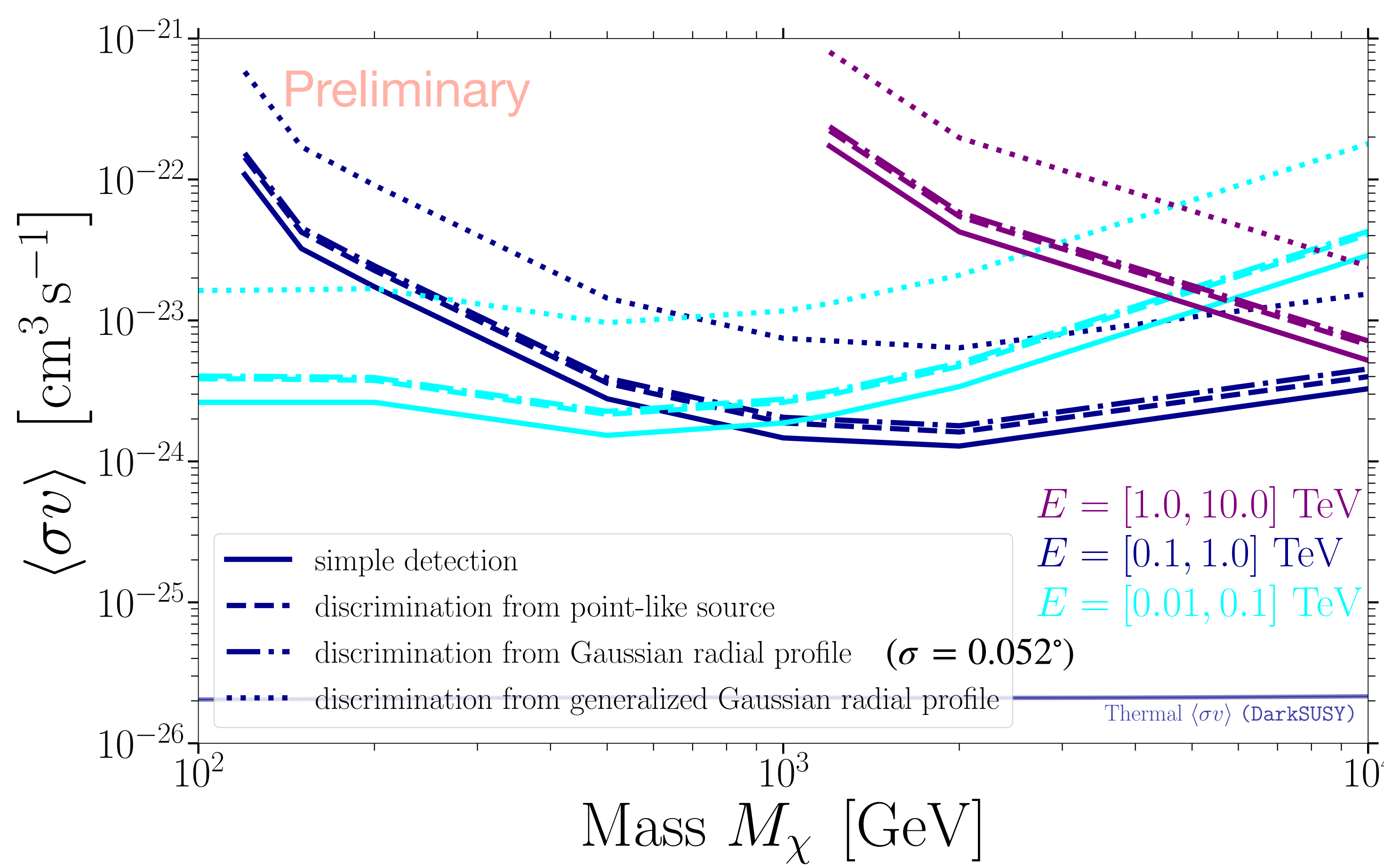
Ann. channel: $b\bar{b}$



Discrimination between DM sub-halos and known astrophysical sources

Source discrimination

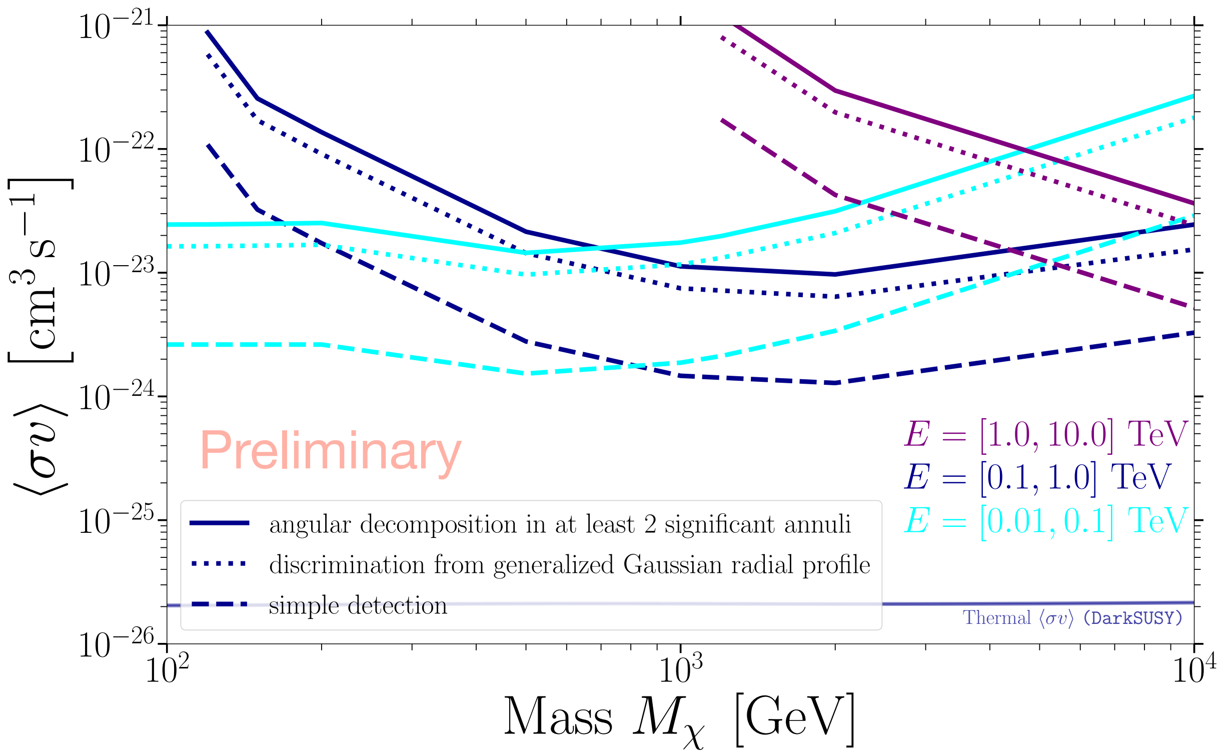
- How well can potentially detected DM sub-halos be distinguished from point-like sources or other extended sources?
- The analysis:
  - Inject DM signal at fixed cross-section value into mock data
  - Fit a nested model of DM sub-halo + alternative spatial model
  - What is the cross-section at which the DM sub-halo is significantly preferred?



Sub-halo:

$(l, b) = (5.0°, 0.0°)$
$d = 1$ kpc
NFW profile
$r_s = 1.36$ kpc

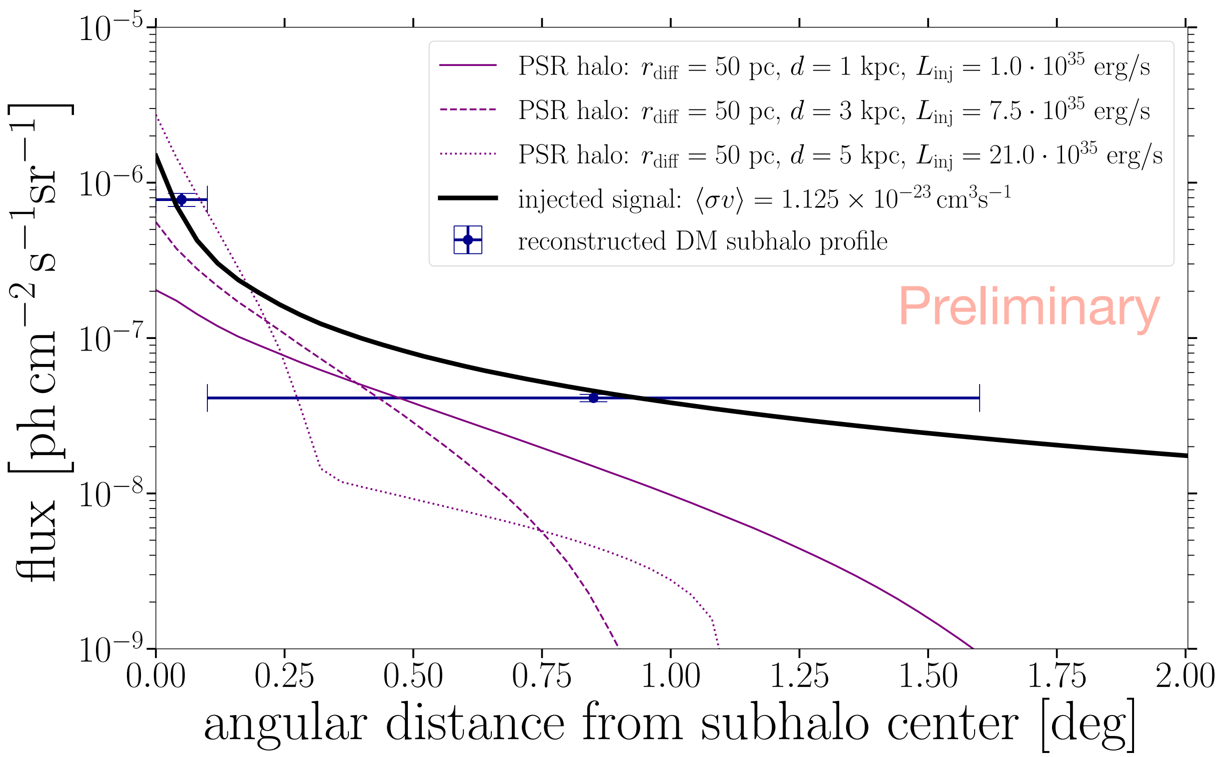
Angular decomposition of the SH profile



- σv necessary to guarantee a decomposition of the detected DM subhalo signal into at least two significant annuli up to 30 pc from the subhalo's center

Sub-halo:

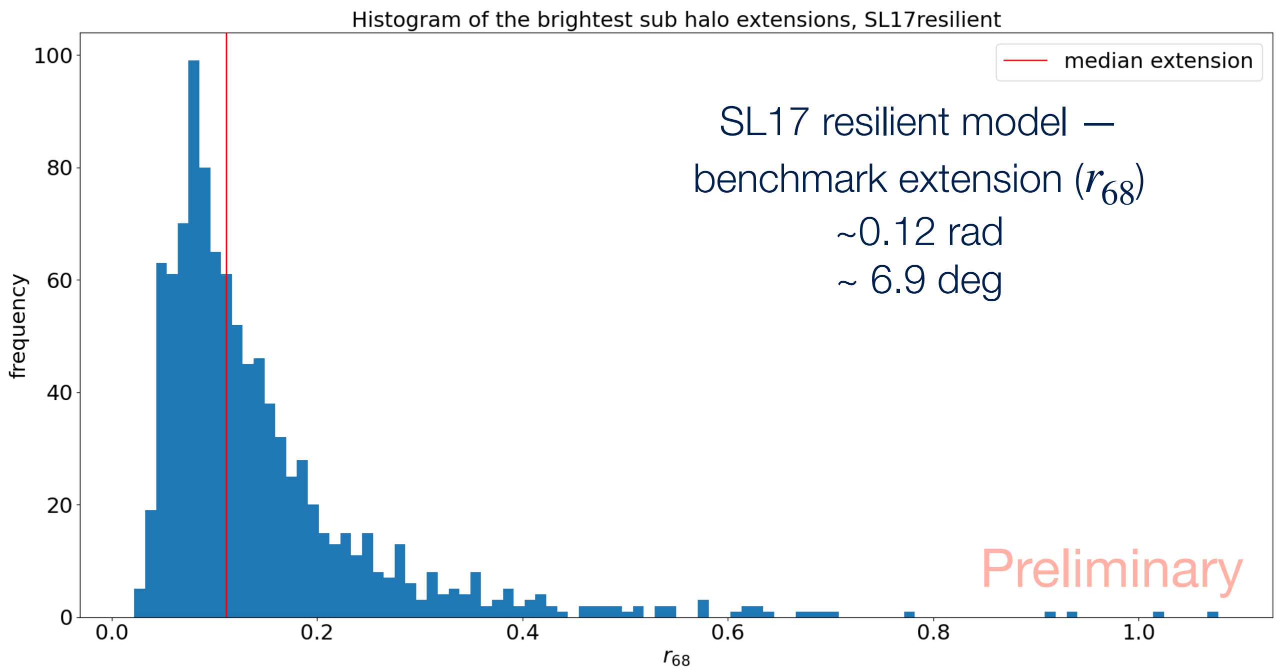
$(l, b) = (5.0^\circ, 0.0^\circ)$
$d = 1$ kpc
NFW profile
$r_s = 1.36$ kpc

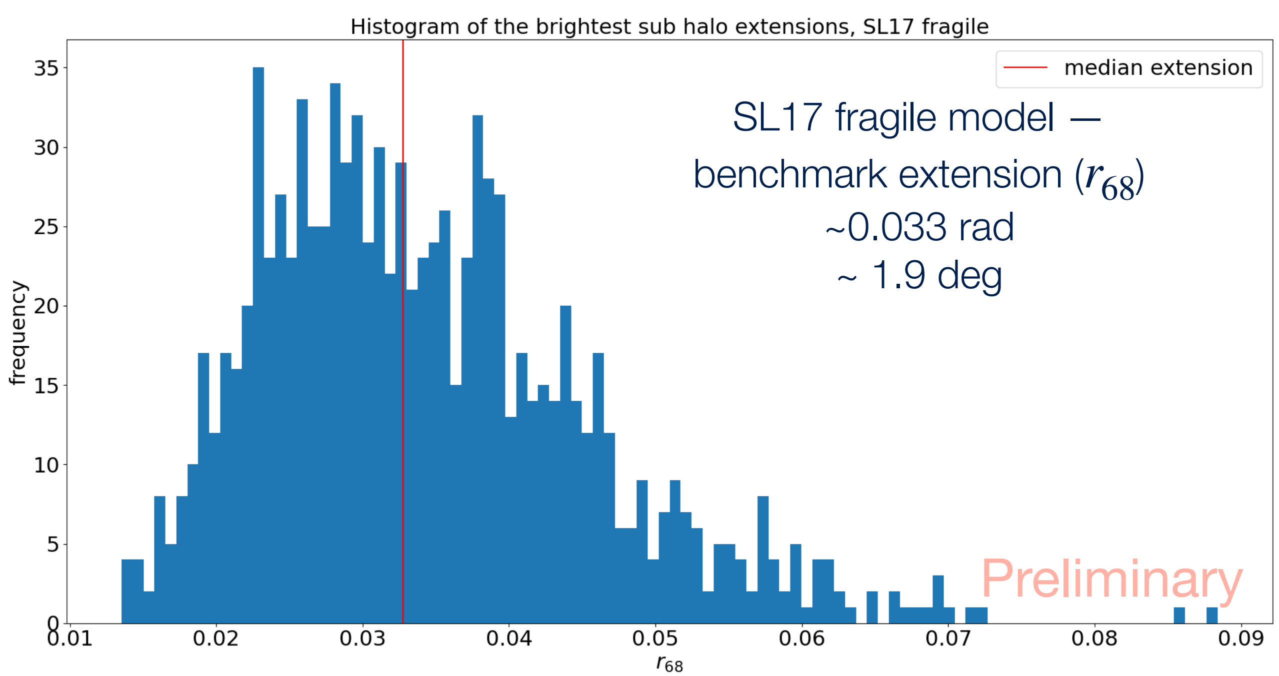


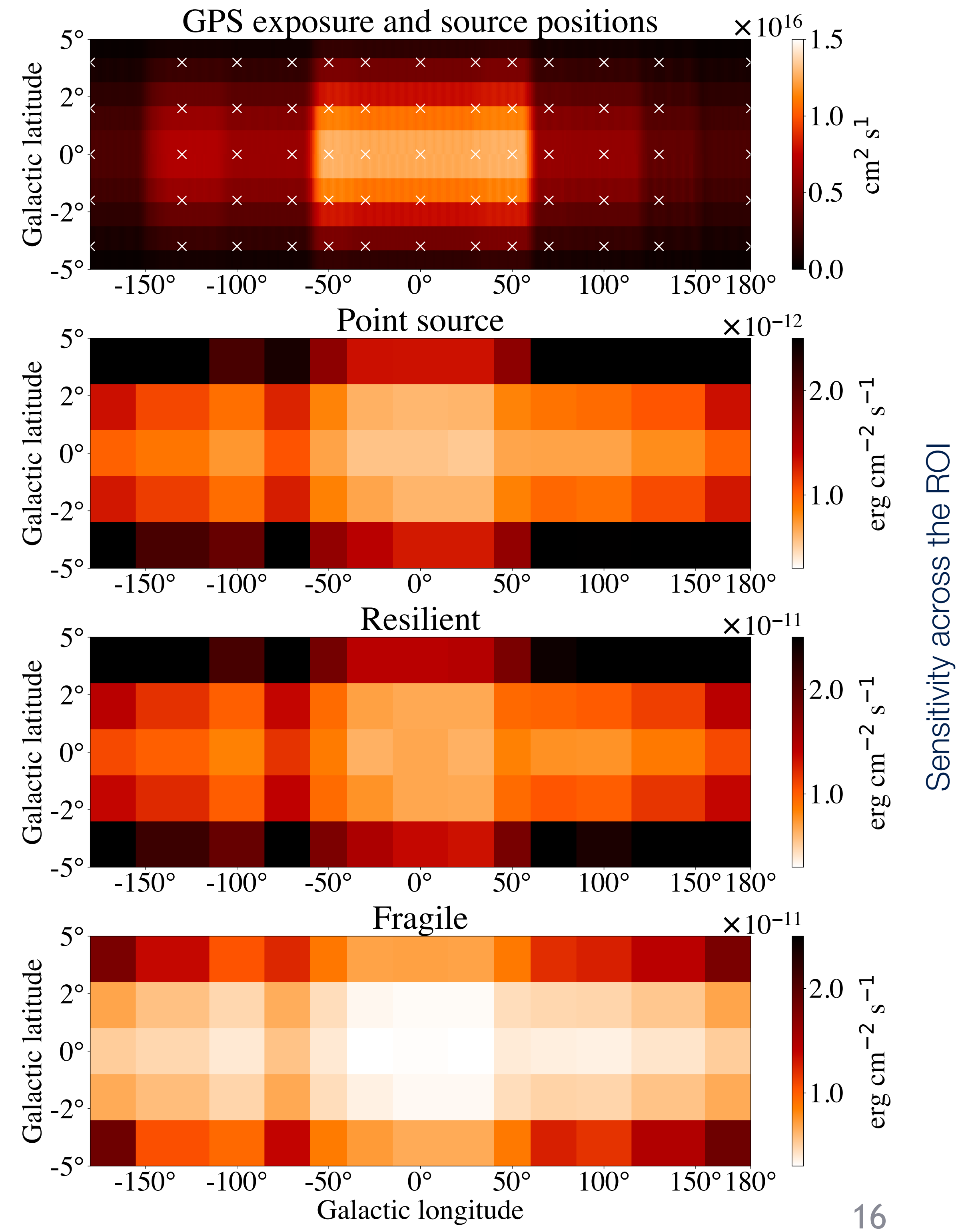
- Discrimination from other novel source classes like pulsar halos (model from C. Eckner et al., MNRAS 521, 2023)

Galactic sub-halo population study

Integrated sensitivity across the GPS



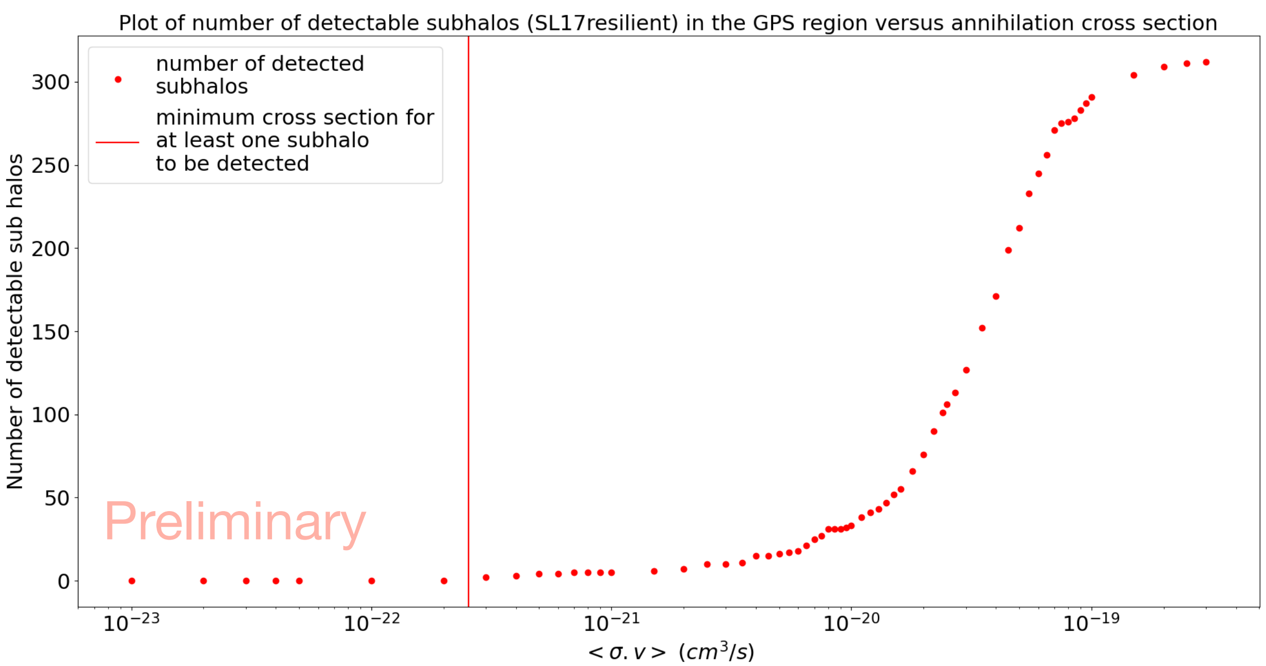




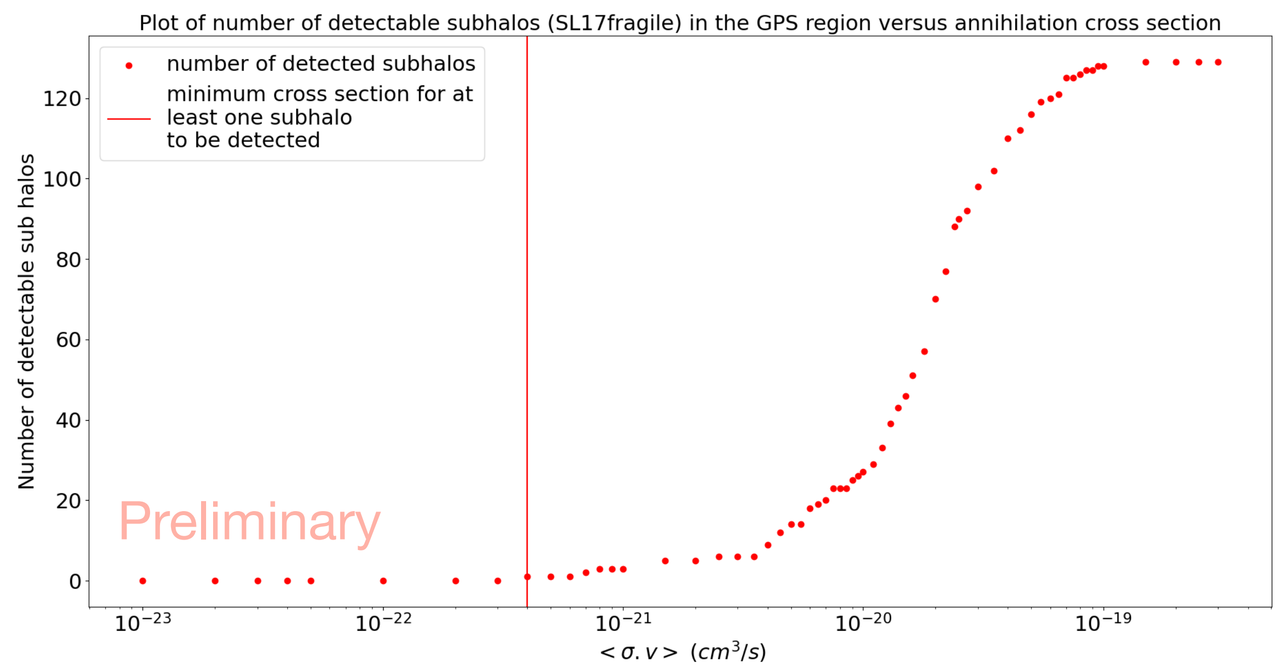
Number of detected sub-halos vs. σv

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

Resilient model



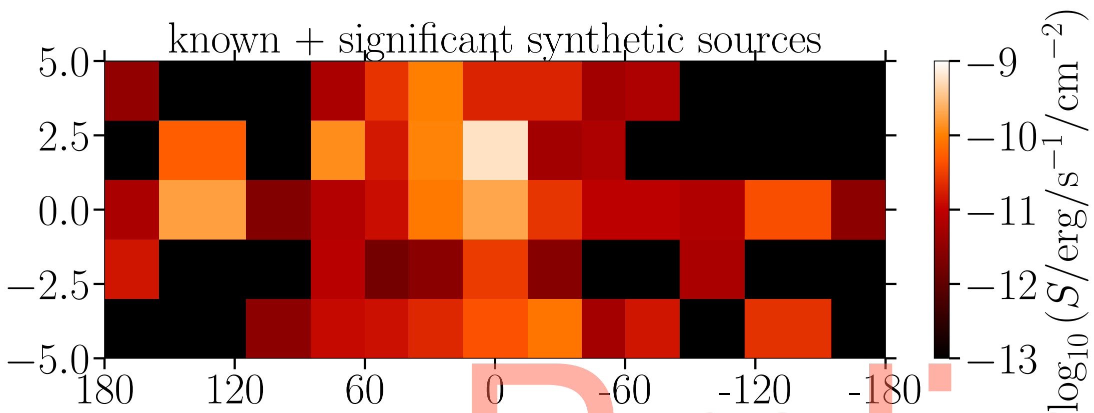
Fragile model

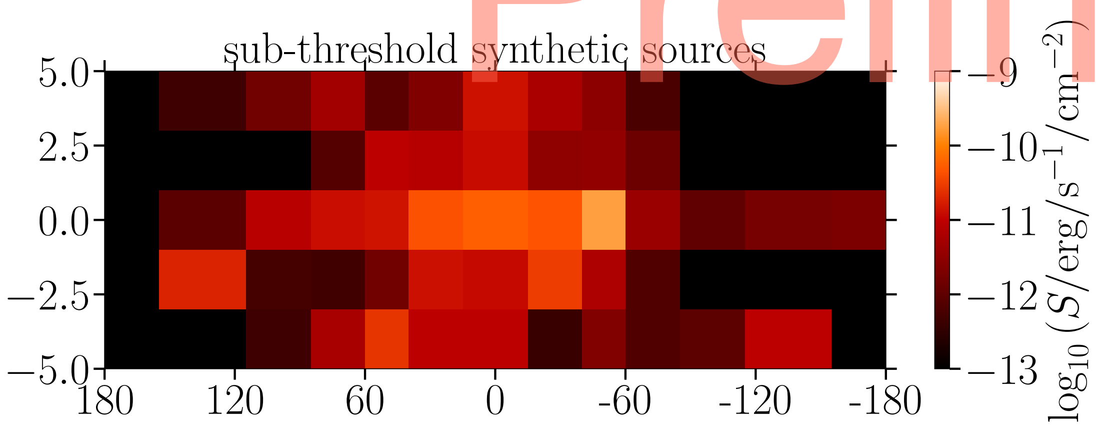


Detection of least one sub-halo for either fragile or resilient scenario:

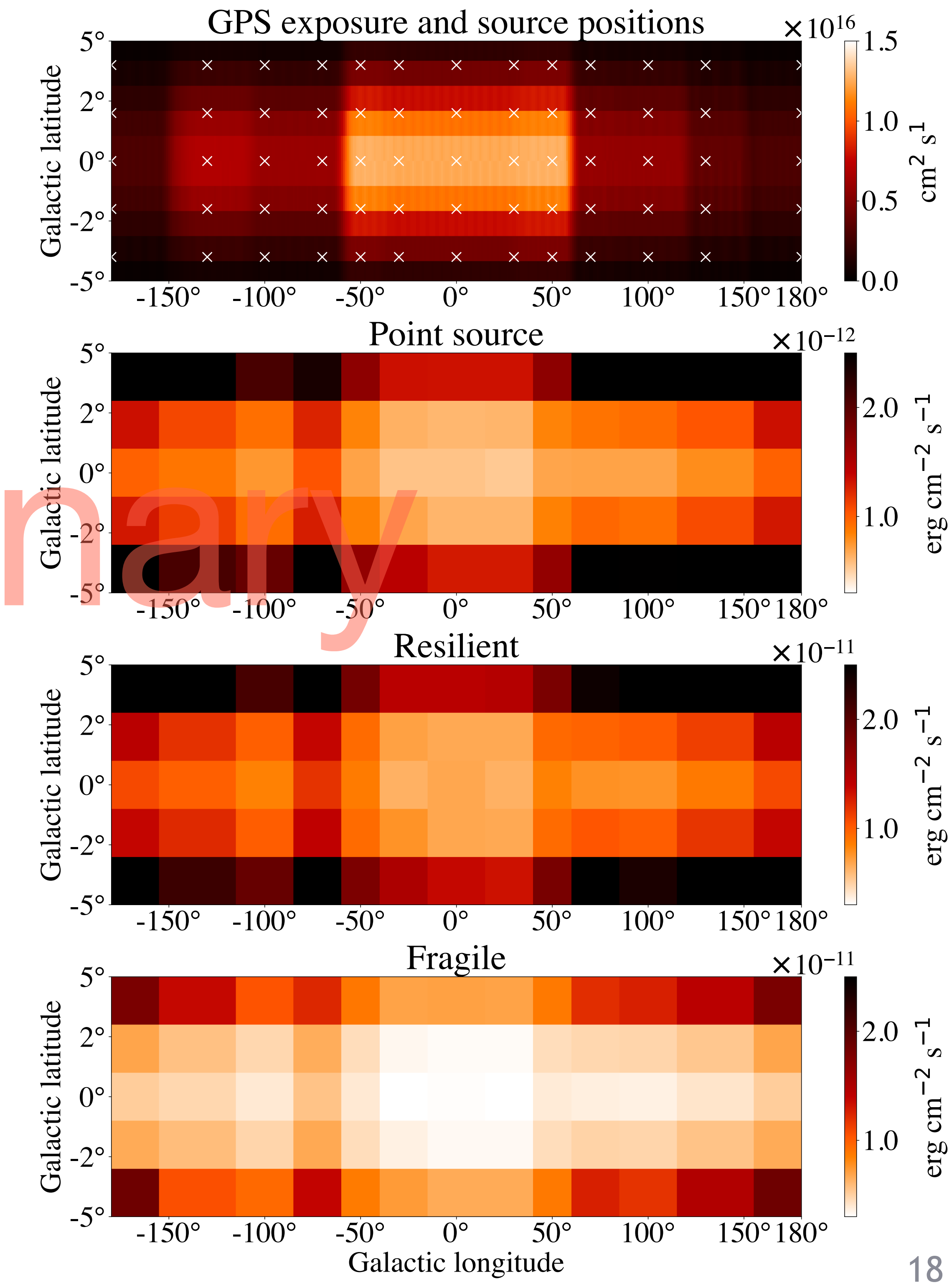
$$(\sigma v)_1 \sim 3 \cdot 10^{-22}\,\mathbf{cm}^3\,\mathbf{s}^{-1}$$

Astro vs. DM (preliminary)





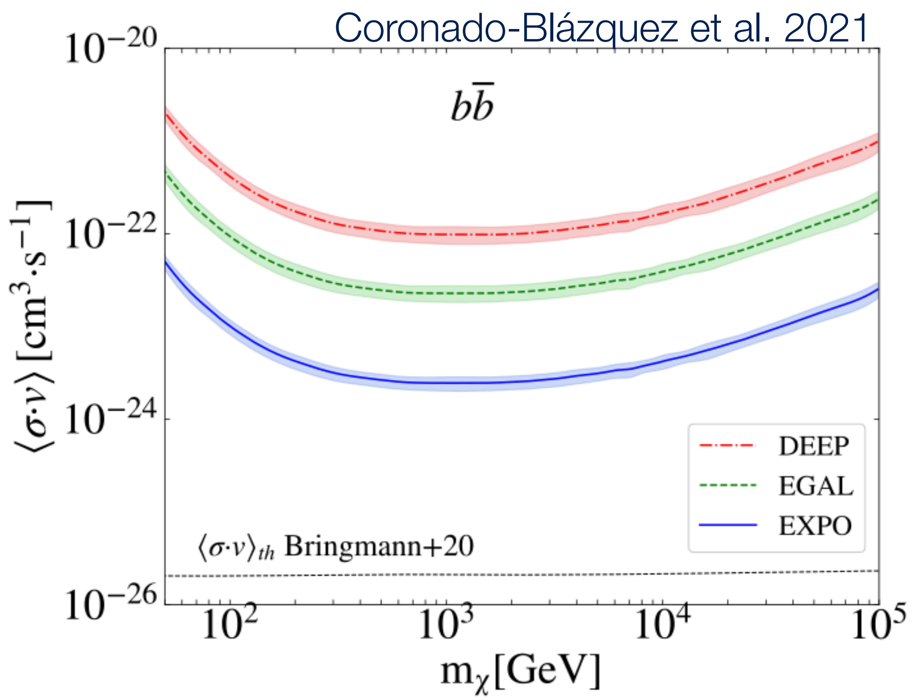
Preliminary

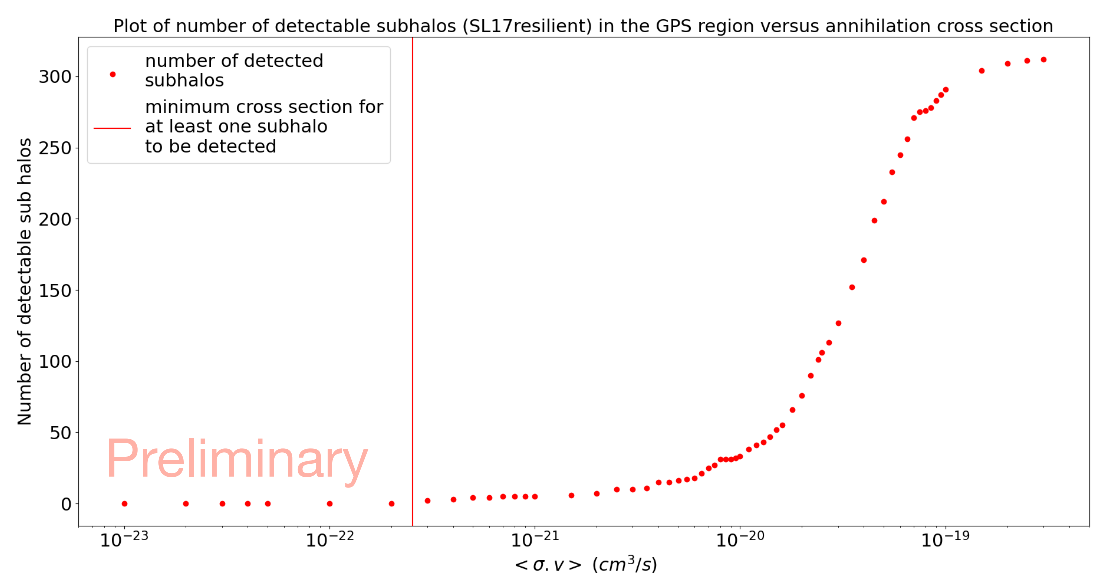


Sensitivity across the ROI

Comments and conclusions

- CTA's Galactic plane survey will uncover many extended gamma-ray sources along the Galactic plane, some of which will remain unidentified.
  - The cold dark matter scenario predicts the presence of dark matter subhalos in that ROI.
  - Among unassociated/unidentified point sources there may be SH.
- We quantify how many and under which conditions
  - We show the importance of using realistic SH profiles for the reconstruction of the emissivity profile.
  - A genuine subhalo, once detected, is easily distinguishable from a point-like source or Gaussian profile.
  - σv values in the same ballpark of what other strategies can probe: $\sigma v \sim 10^{-22}$ cm^{-3} s^{-1} for detection of one, brightest sub-halo.





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We made use of ctools (http://cta.irap.omp.eu/ctools/).