cherenkov telescope array

Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre

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on behalf of the CTA Consortium

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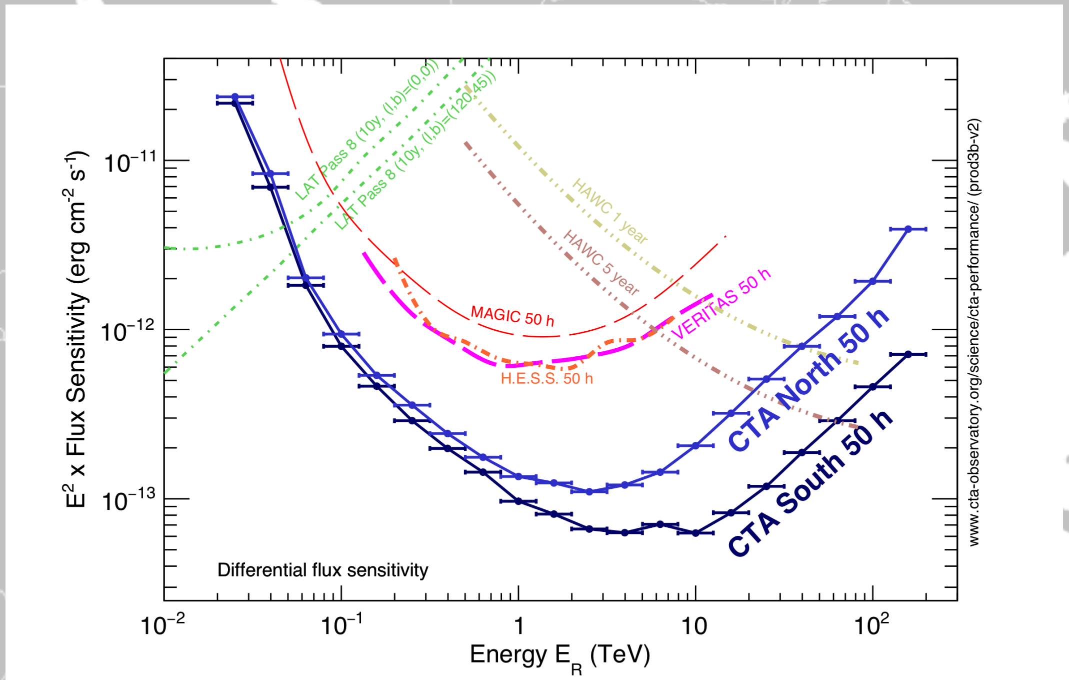
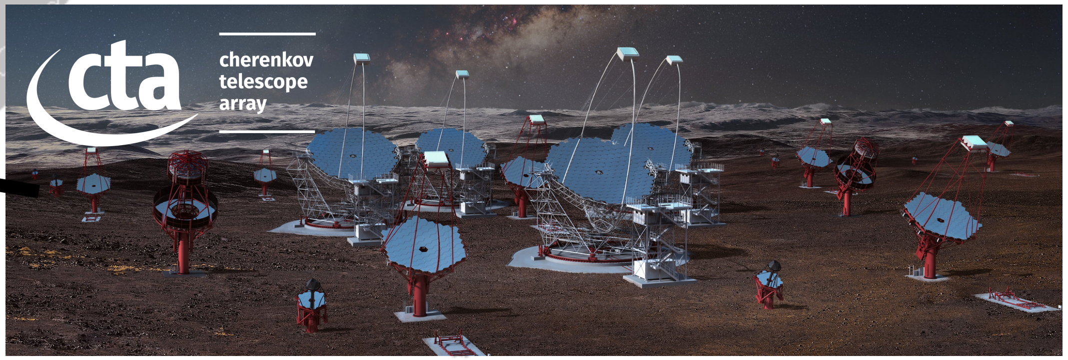
http://www.cta-observatory.org/consortium_acknowledgments

The Cherenkov Telescope Array

CTA figures of merit:
- energy range: 20 GeV - 300 TeV
- full sky coverage
- factor 10 improvement in point source sensitivity + improvement of energy and angular resolution



	# North	# South	approx. energy range (TeV)
Large-sized telescopes	4	-	0.02 - 0.2
Medium-sized telescopes	9	14	0.1 - 10
Small-sized telescopes	-	37	5 - 300



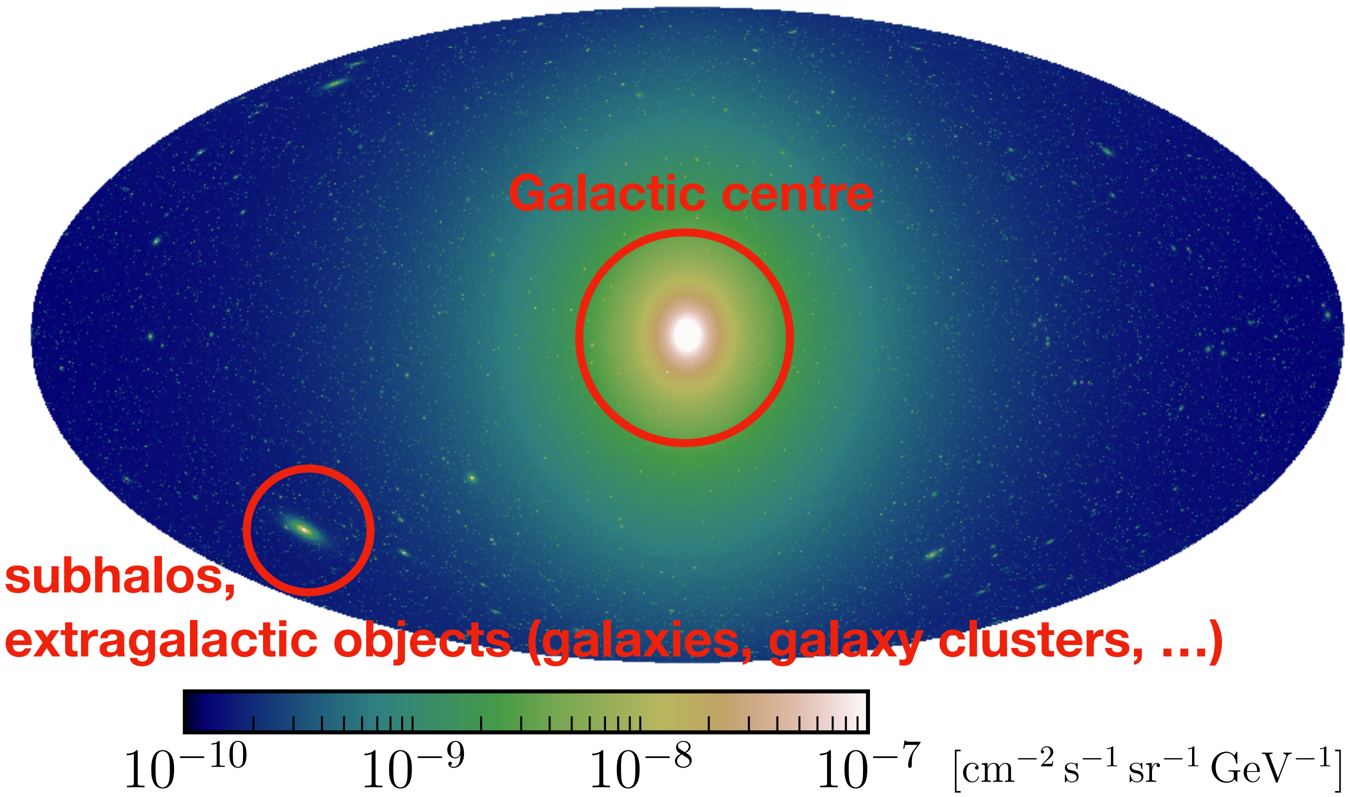
Indirect Searches for dark matter with gamma rays

Dark matter signal shape:

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

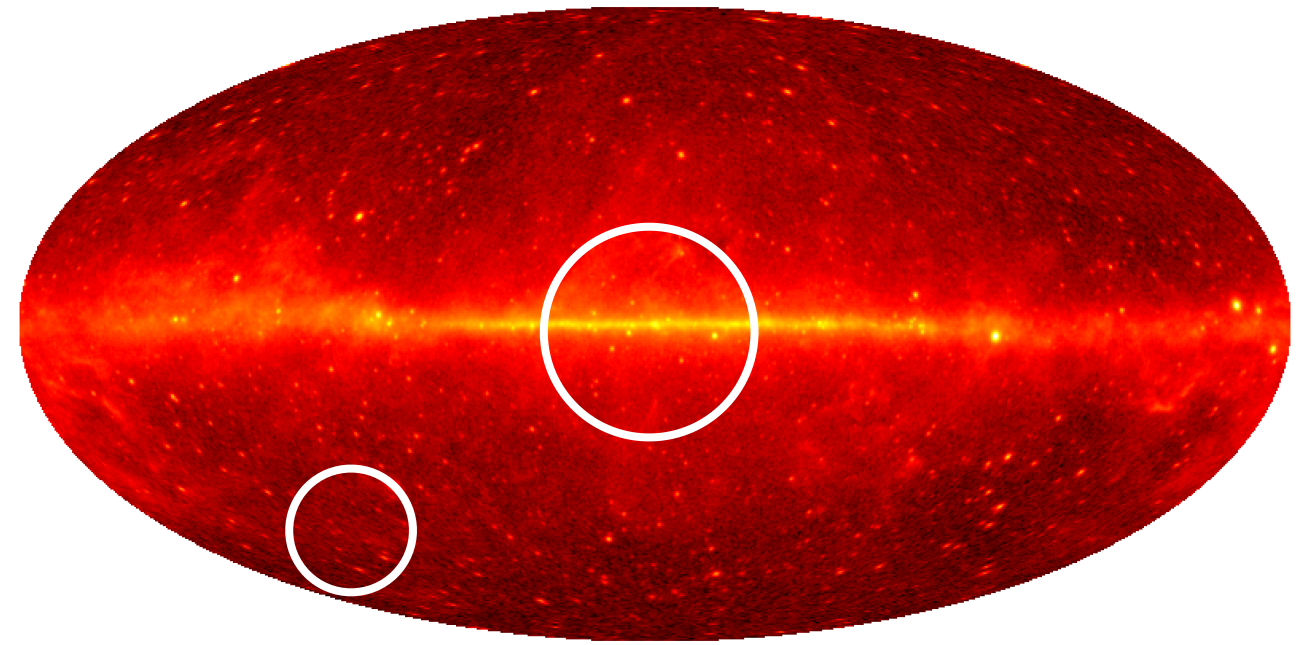
cosmology/astrophysics — particle physics

Dark matter gamma-ray diff. intensity (MW-like)



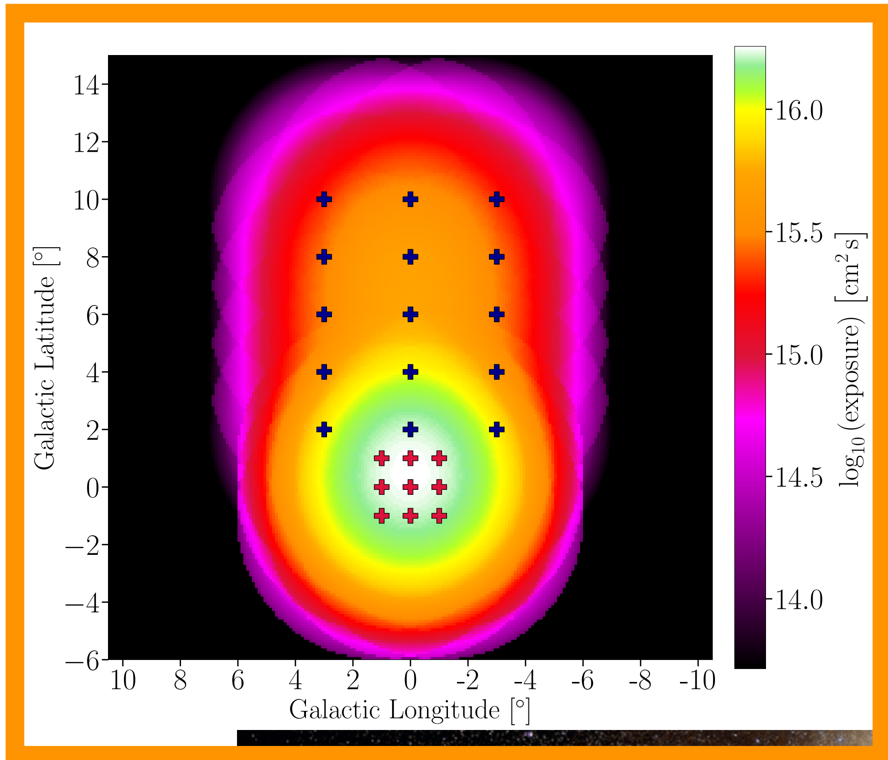
[M. Hütten et al., JCAP 1609 (2016) 047]

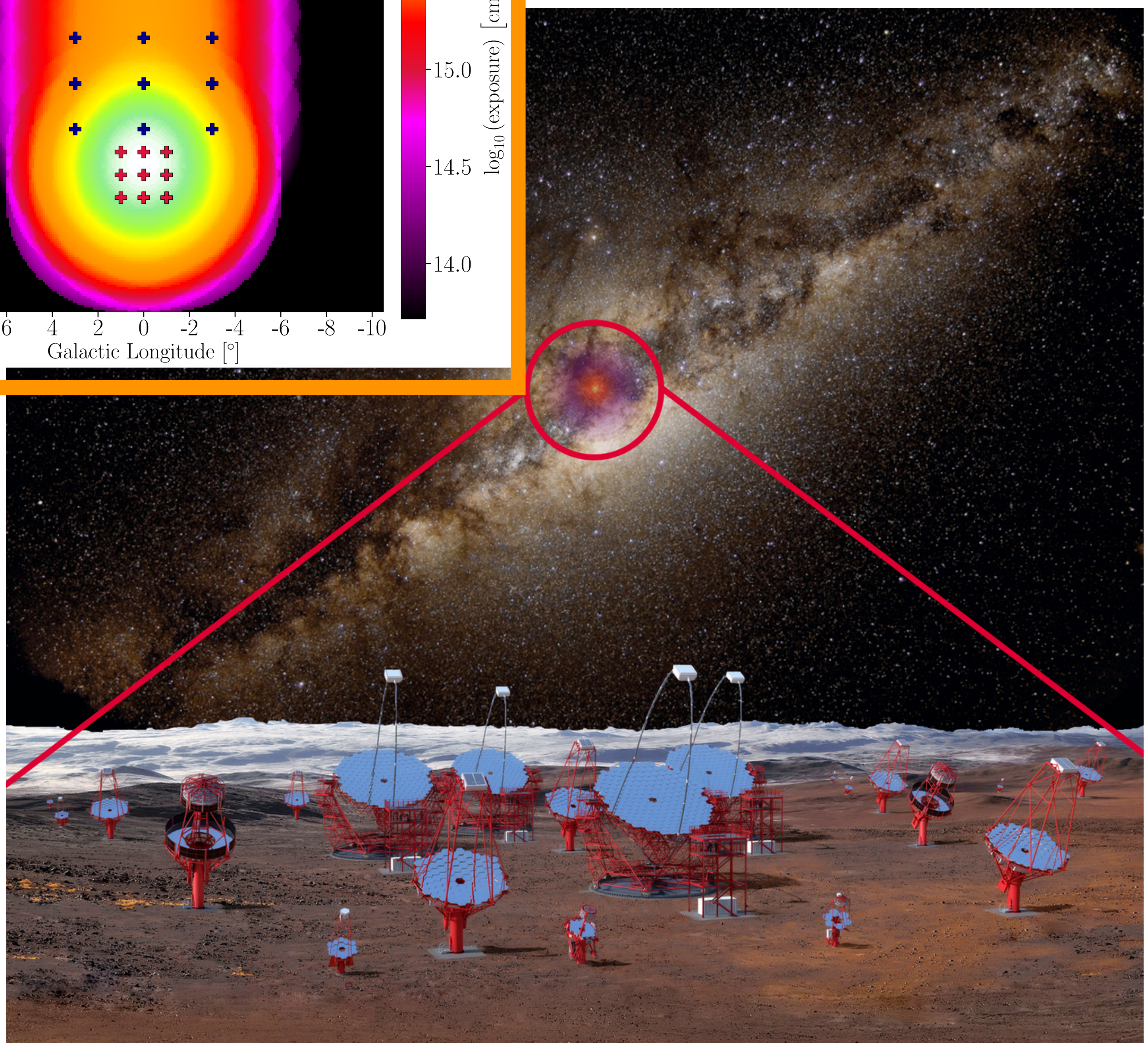
Astrophysical gamma-ray emission (Fermi-LAT gamma-ray sky)



strong signal **high background** **Galactic centre**	…	**moderate signal** **moderate background** **LMC, Andromeda galaxy**	…	**moderate/low signal** **low background** **Milky Way dwarf satellites**

Dark matter at the TeV scale with CTA





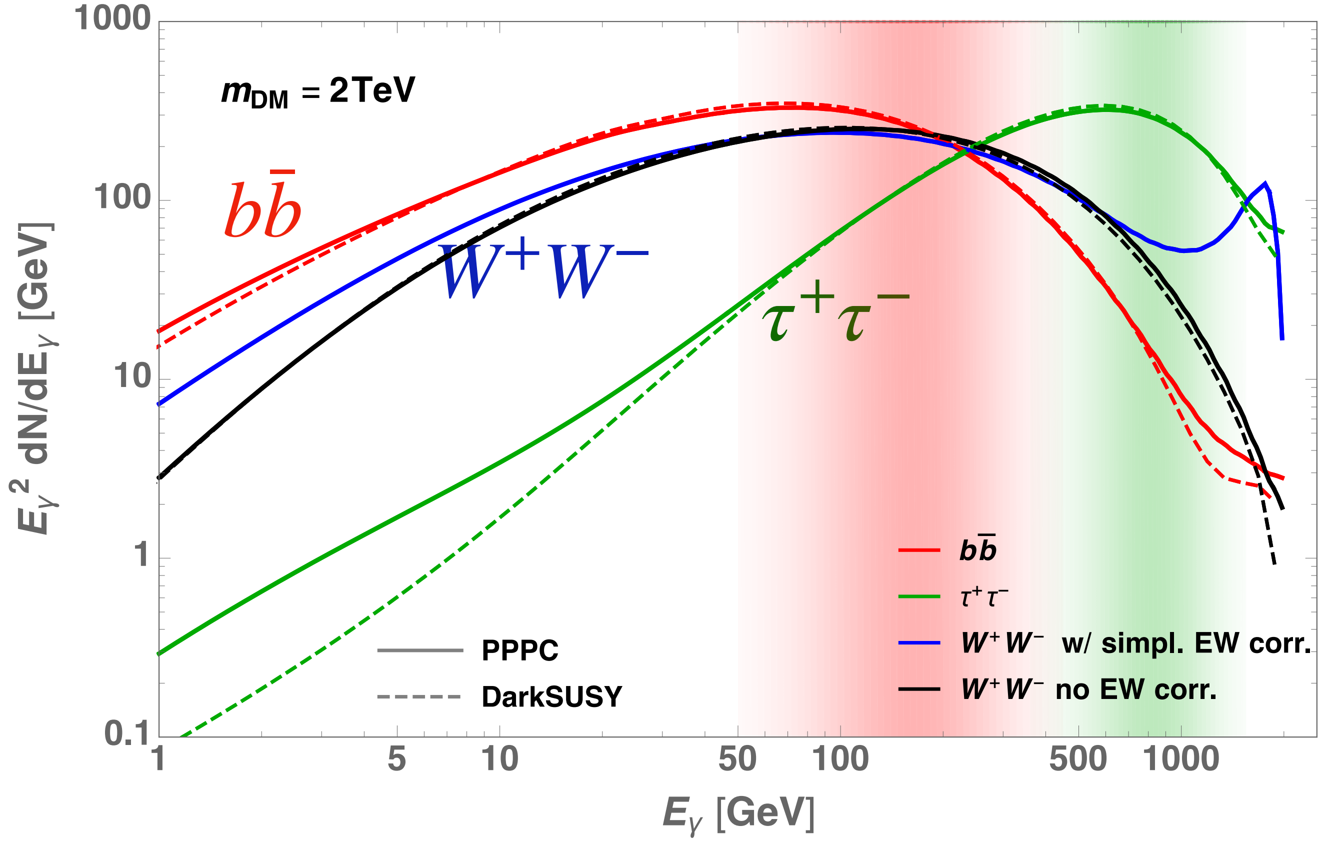
What do we want?

1. Define the **most promising data analysis and observational strategy** for CTA DM searches in the Galactic centre, **using state-of-the-art modelling of astrophysical and instrumental backgrounds**.
2. Develop a **realistic assessment** of CTA's sensitivity to a DM annihilation signal from the Galactic centre.
3. Define **requirements in terms of systematic uncertainty** to reach the thermal annihilation cross-section for various realisations of DM parameters.

CTA is a unique instrument capable of testing thermal WIMP models in the TeV energy range!

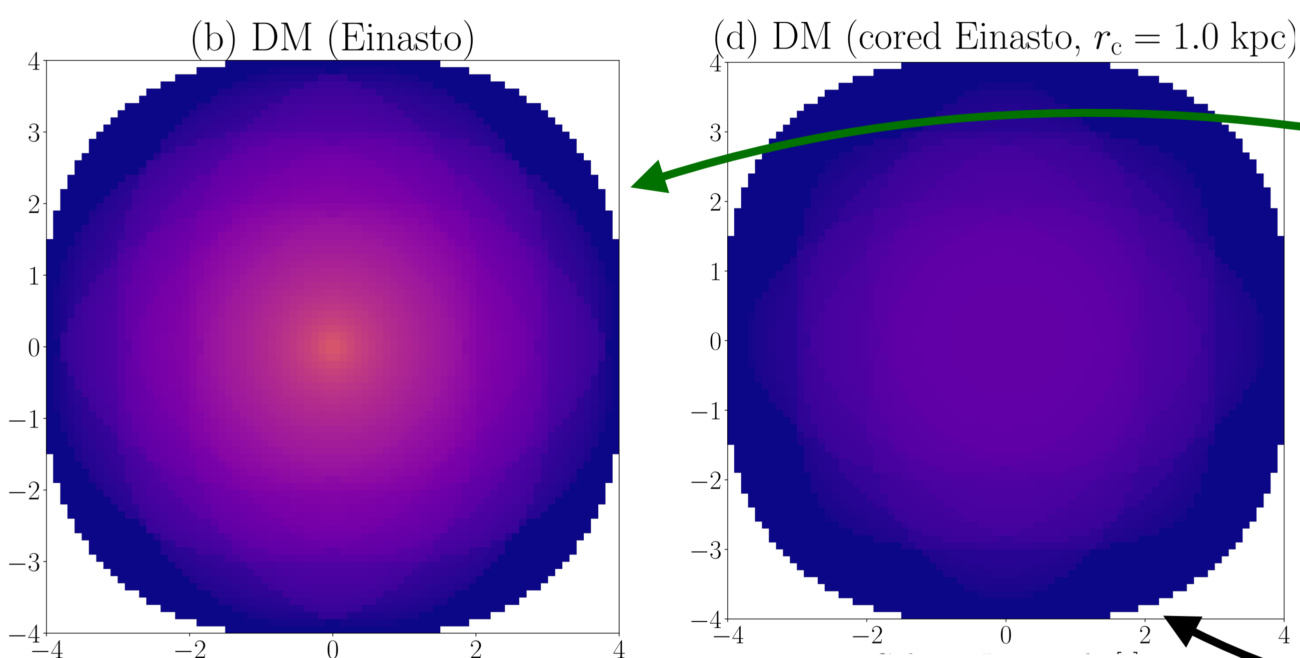
Dark matter signal setup

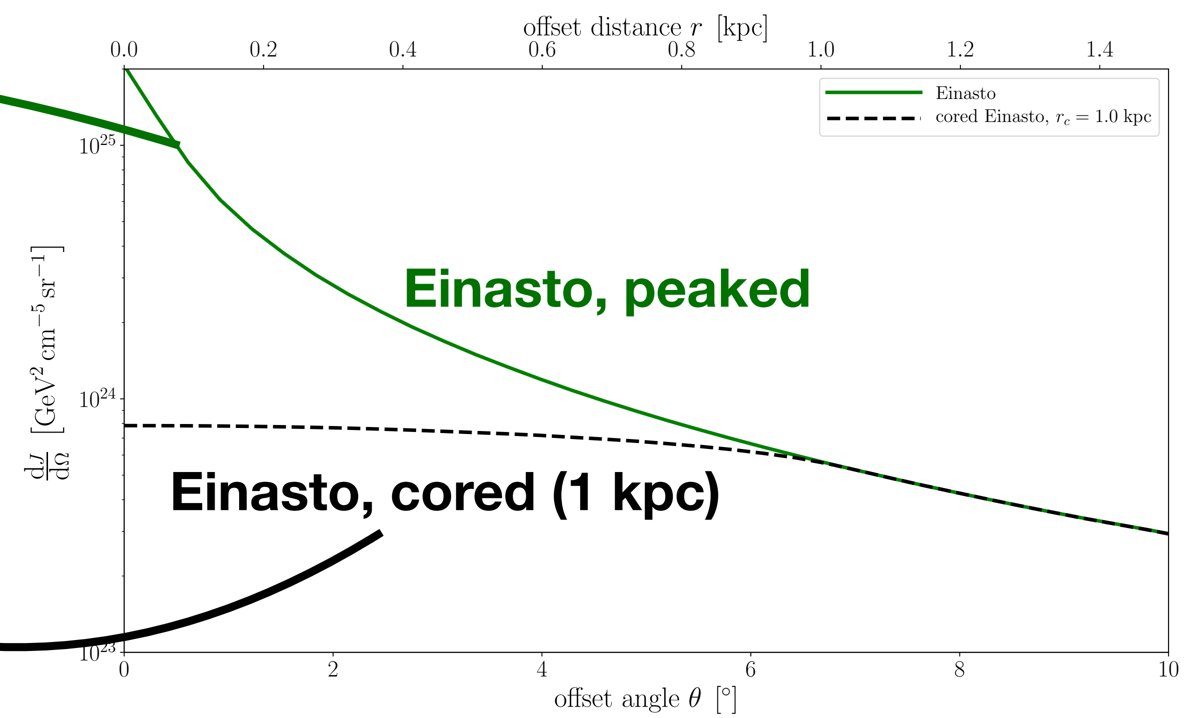
Spectral Shape: various annihilation channels (DarkSUSY/ PPPC [Cirelli et al., JCAP 1103 (2011) 051])



- standard/vanilla WIMP channels
- the harder the spectrum, the better CTA's sensitivity
- shaded regions: most constraining power
  —> good agreement between DarkSUSY and PPPC

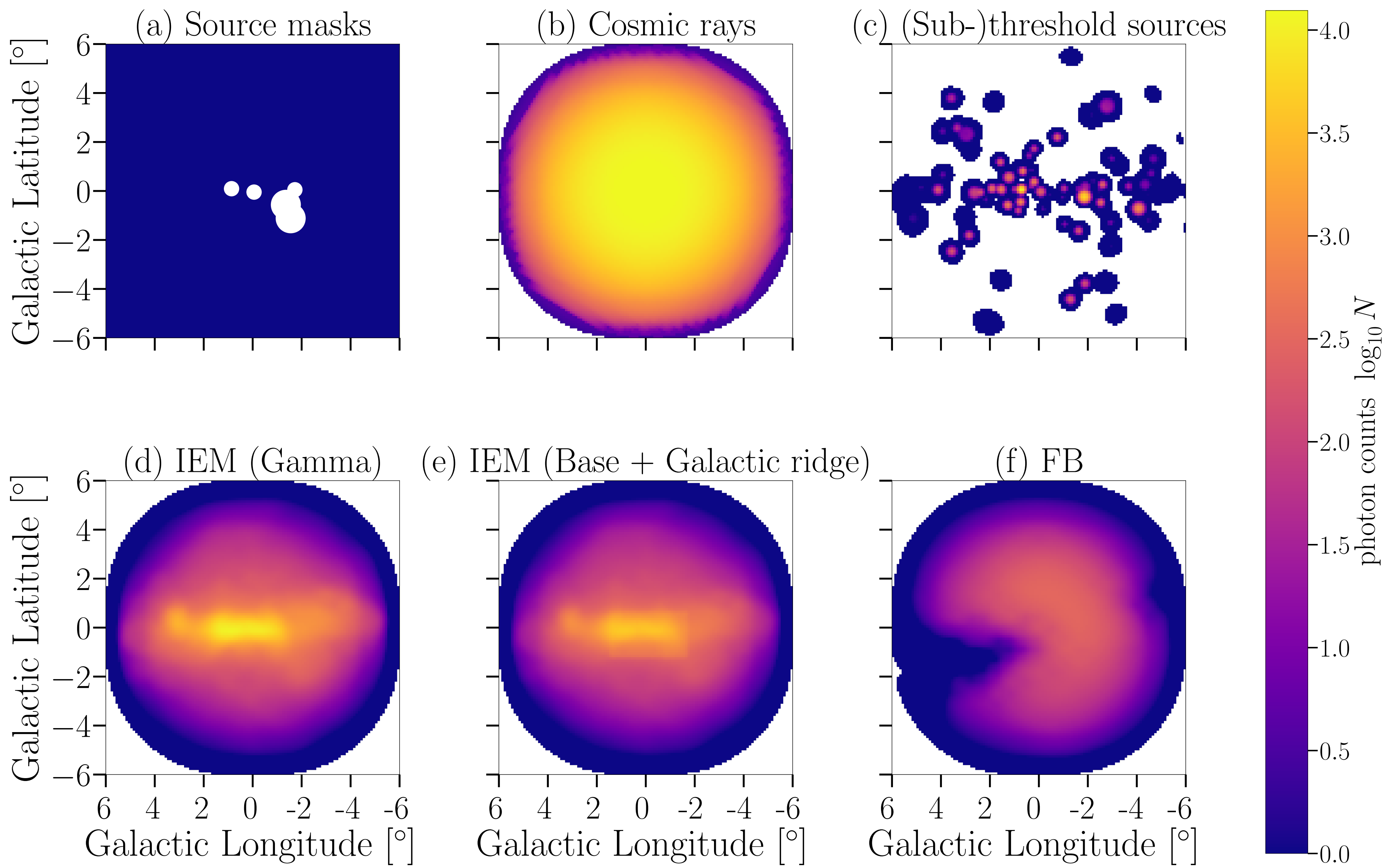
Signal Morphology





Astrophysical background components

We consider a variety of astrophysical emission components relevant at TeV energies.



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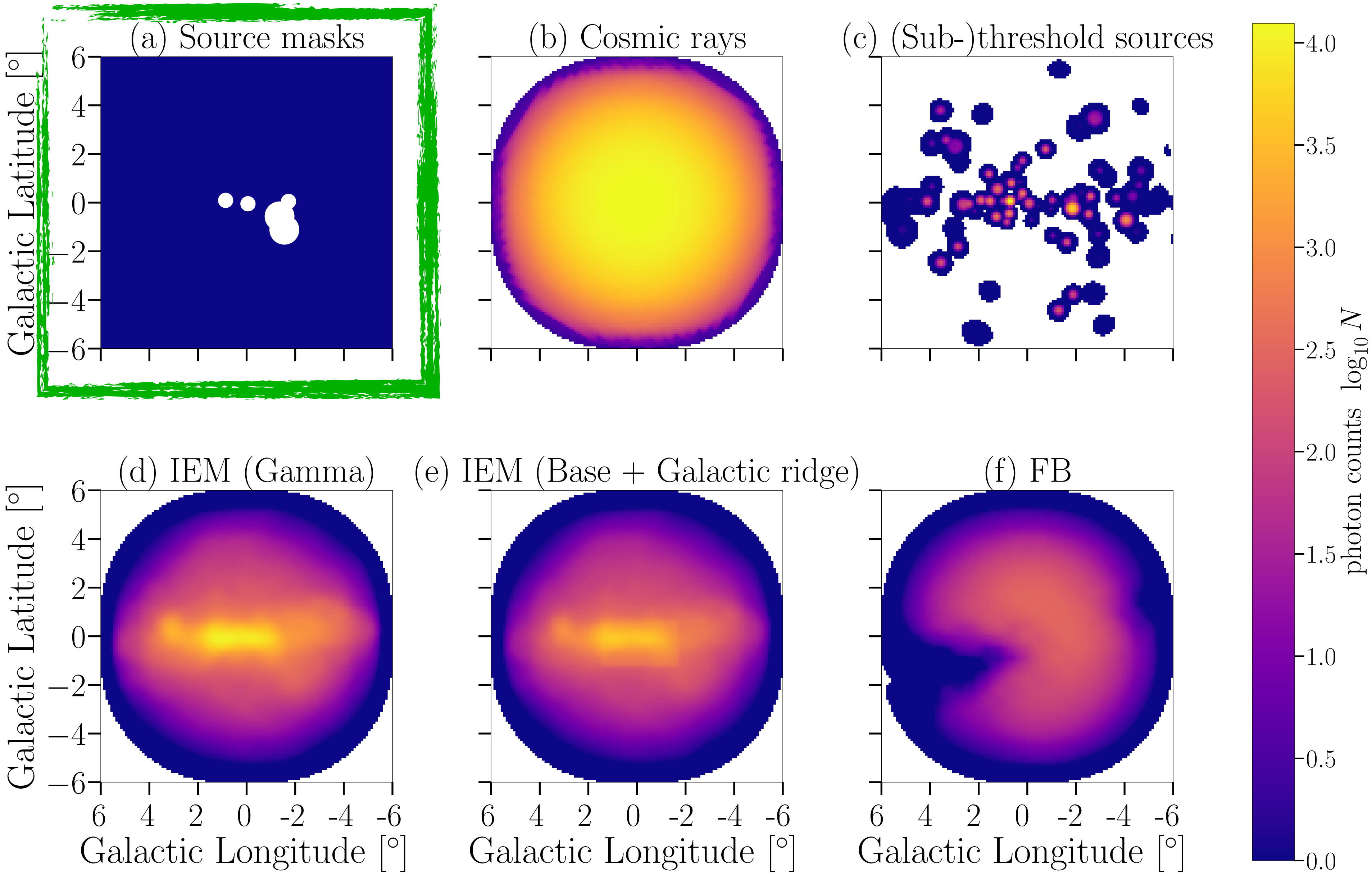

Detected/established TeV emitters:

—> Localised sources that have been detected by current-generation Cherenkov telescopes.

—> We mask a region around their location based on their intrinsic extension and CTA's resolution.

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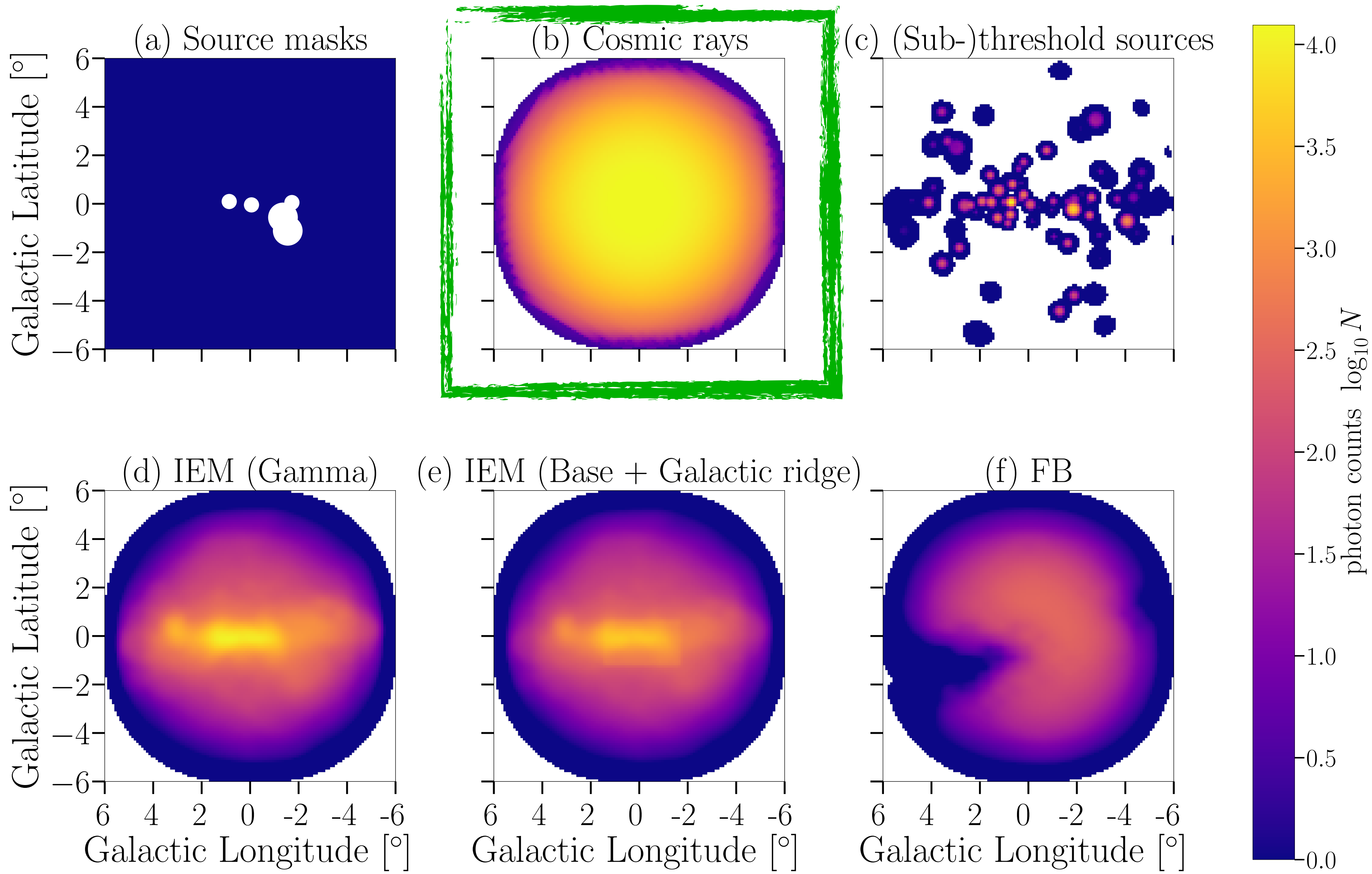

Instrumental irreducible cosmic-ray background (CR):

—> Mainly due to misclassified charged cosmic-ray events (leptonic/hadronic)

—> Expected spectrum and spatial structure simulated by CTA's Monte Carlo group (w.r.t. to particular array layout).

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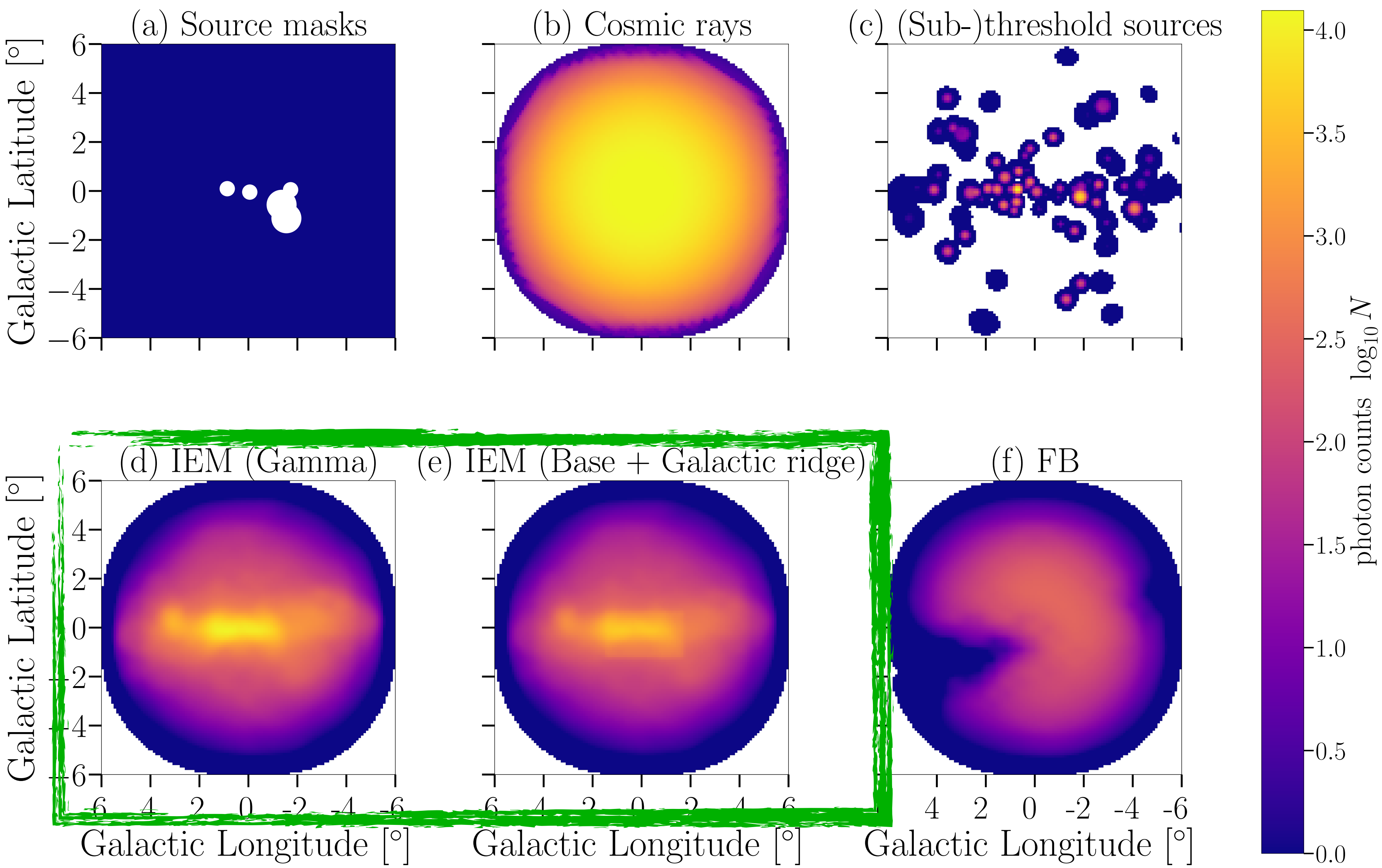
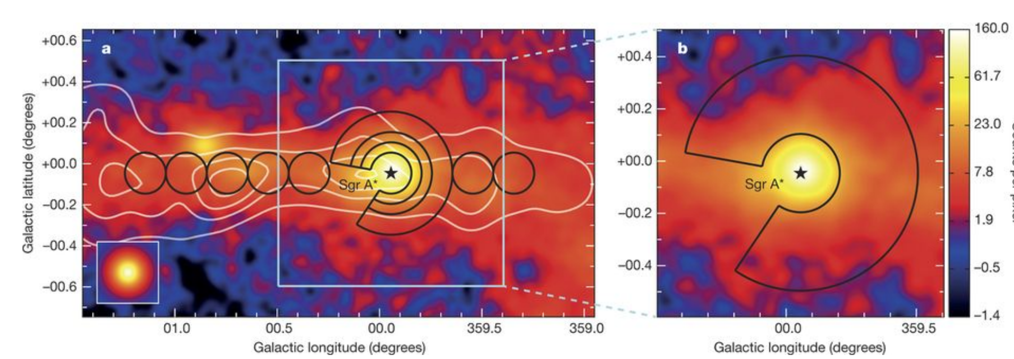


Interstellar emission (IE):

— **Galactic ridge** emission measured by H.E.S.S.

— **Larger scale emission** (b > 0.3°) not probed at TeV scale

—> tested via 3 different models



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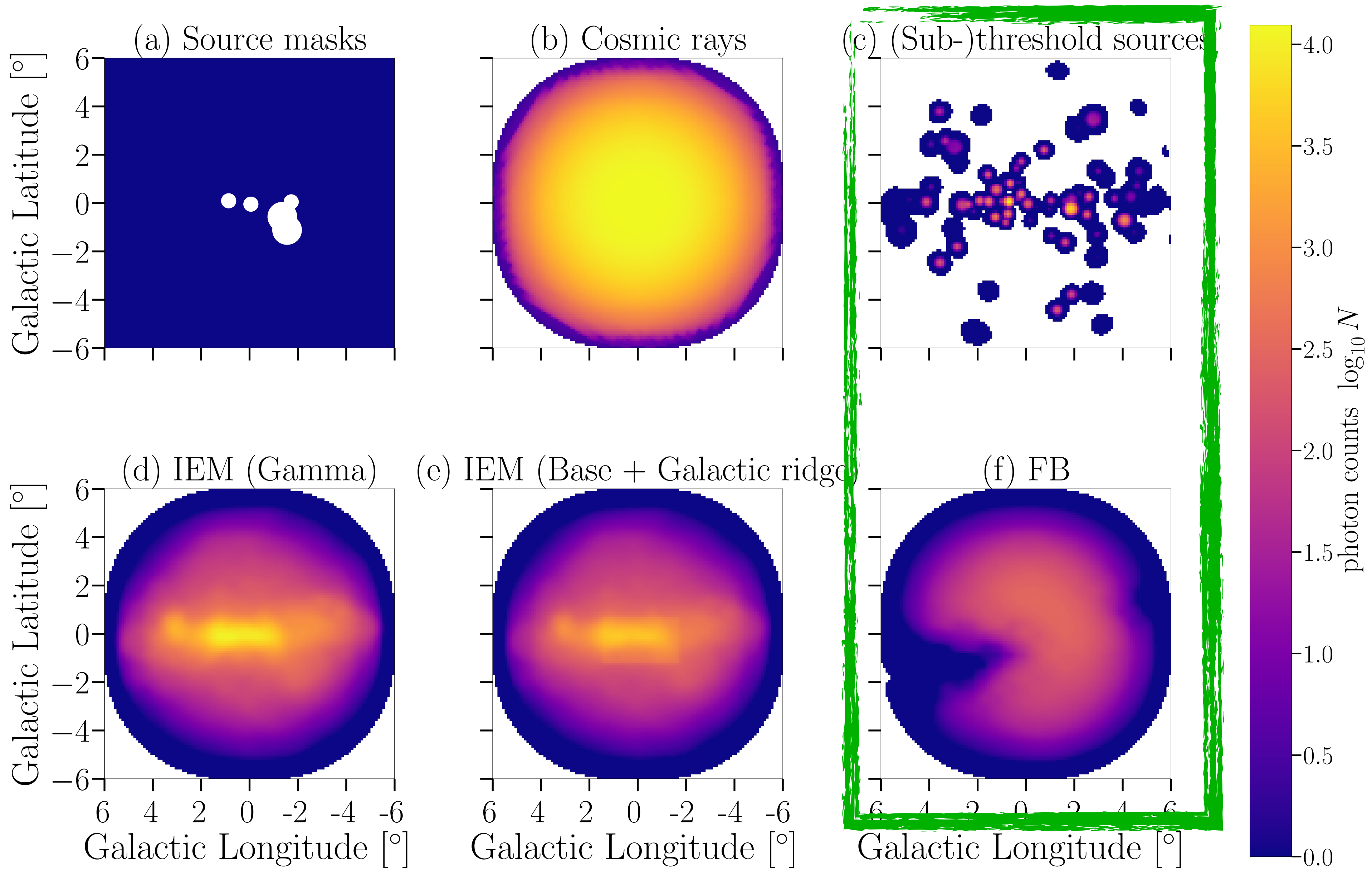


Low-latitude Fermi Bubbles and (yet) unresolved sources:

—> Their properties are hardly known; their impact is examined in less detail than the other components.

Data analysis — "benchmark" setup

Template Fitting (3D analysis)

$$(\mu_K)_k = \mu_k^{CR} + \mu_k^{GDE} + \Delta B_k + A^{DM}\mu_k^{DM}$$

Generic setup:

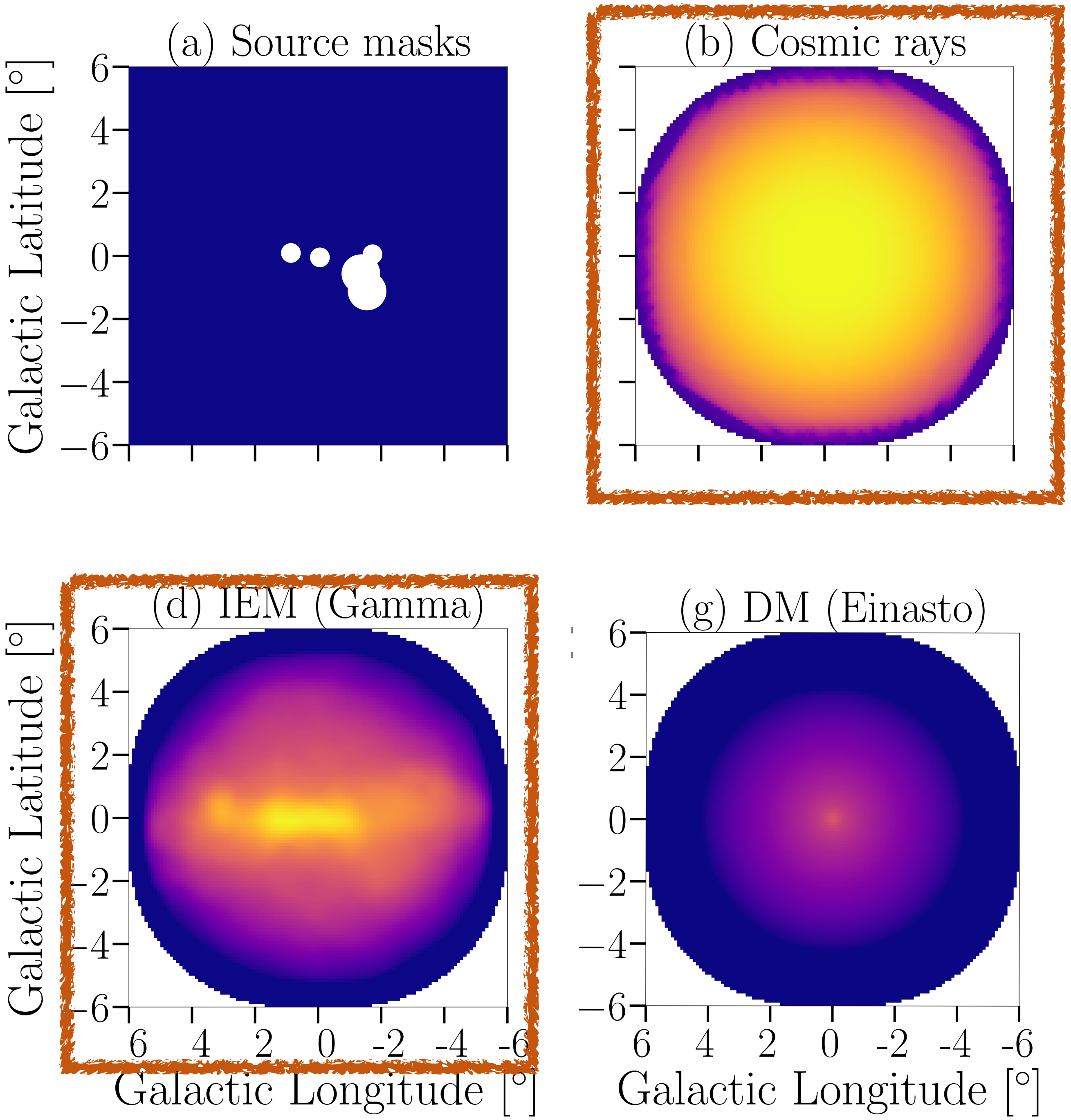
CTA Mock Data:
- **Asimov** data set
- **CR + IEM**
- spatial binning: 0.1°
- spectral binning: 54 bins (width corresponding to 2σ energy resolution of CTA) from [0.03, 100] TeV
- PS mask

Model Data:
- template preparation like mock data
- **CR + IEM + DM**

  —> systematic uncertainty added via covariance matrix

$$(K_S)_{jj'} = \sigma_S^2 \exp\left(-\frac{1}{2}\frac{\|\vec{r}_j - \vec{r}_{j'}\|^2}{\ell_S^2}\right)$$

Implementation via python package swordfish [Edwards & Weniger; arXiv:1712.05401]

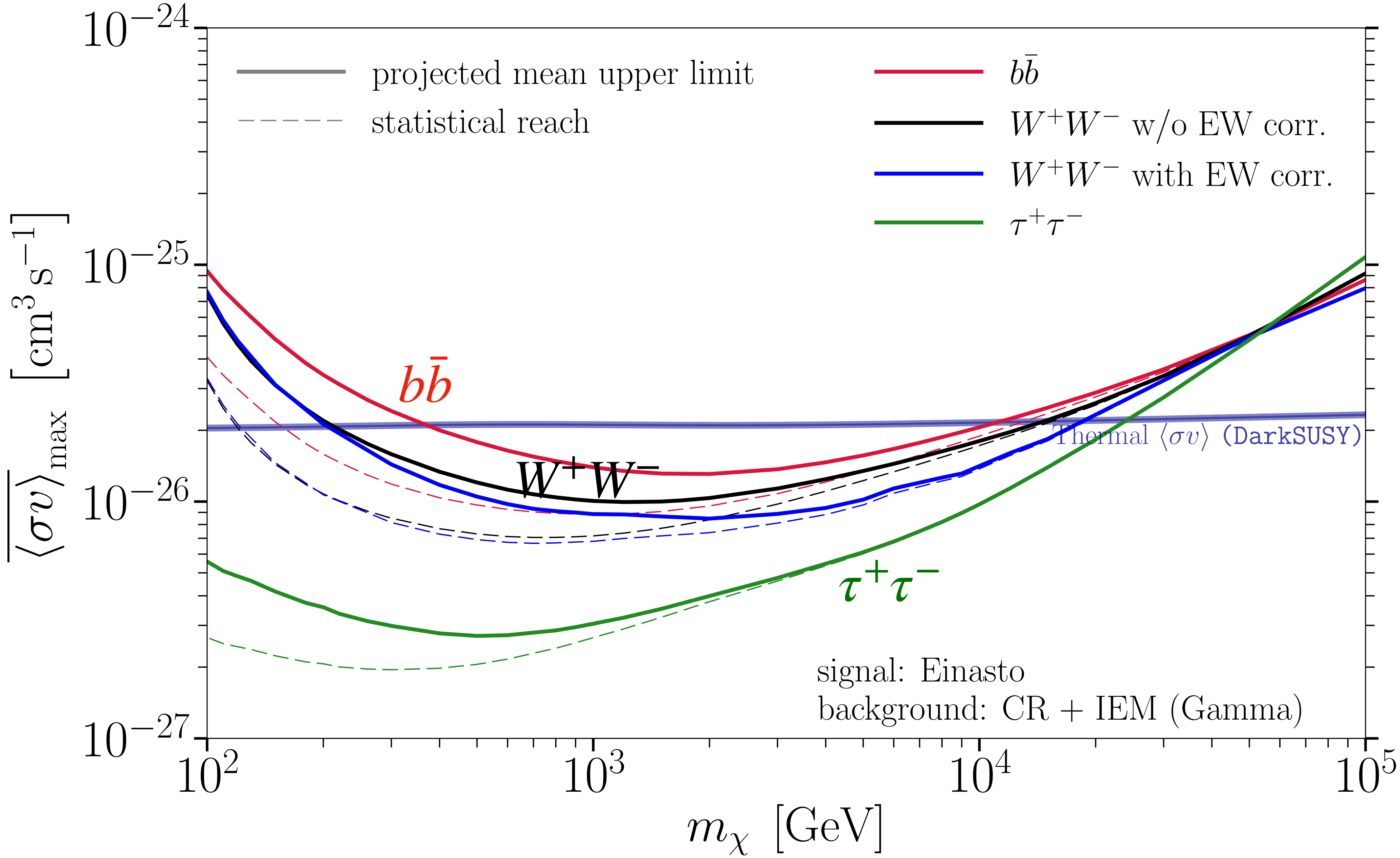


Results — DM particle models

Sensitivity to various DM annihilation channels

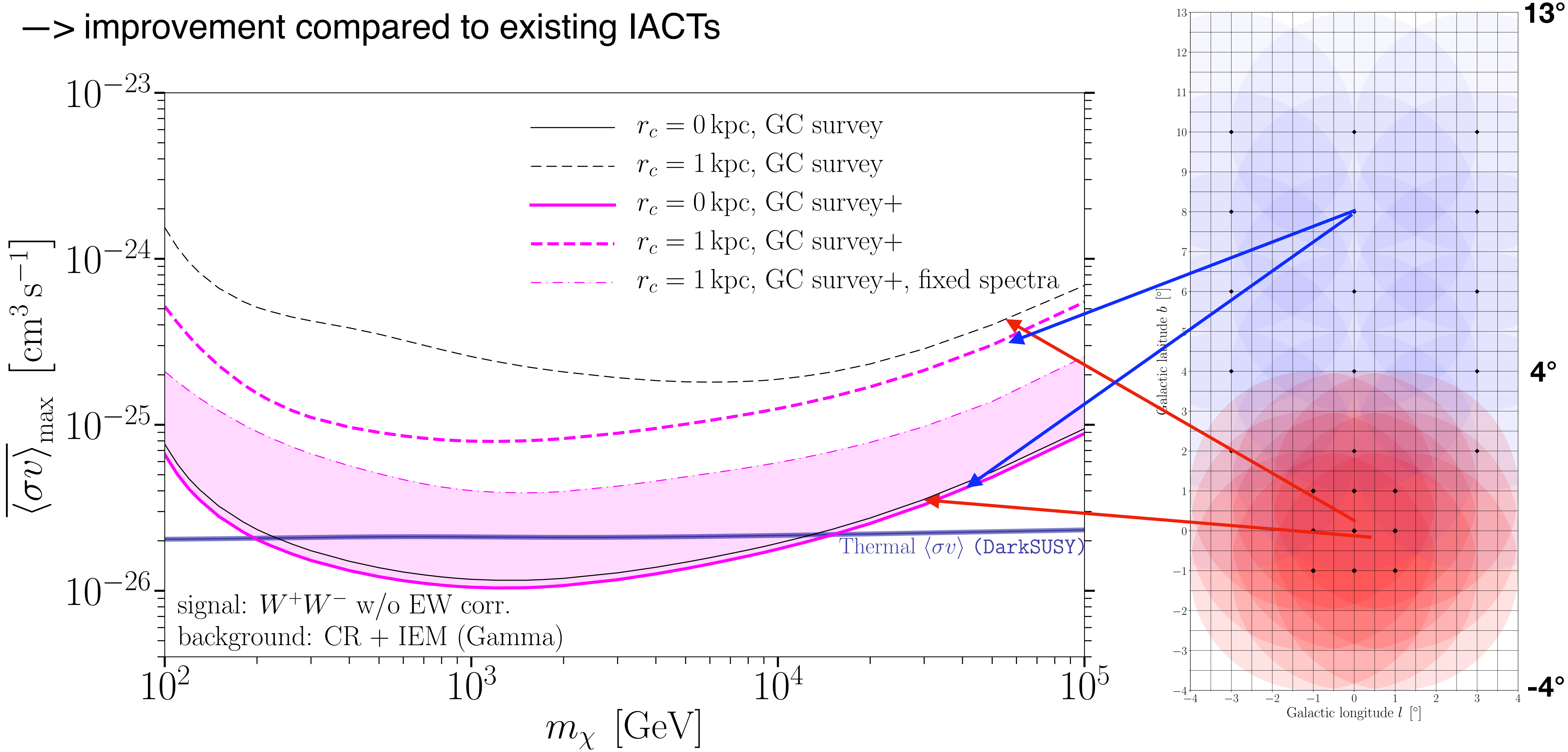
Reminder — Benchmark setup:

- GC survey
- Mock data: **CR + IEM** and **source mask**
- Model data: same + DM (Einasto)
- **instrumental systematic error: 1% with 0.1° spatial correlation length ("benchmark choice")**



Results — sensitivity to DM cored profiles

- ✦ Extensive DM cores are a blind spot for CTA (high degeneracy with the CR component).
- ✦ The additional **extended GC survey** (observation positions up to 10° in latitude) **significantly improves the prospects** regarding cored profiles.
- ✦ A careful **inclusion of spectral information** is crucial to explore the full potential of CTA to constrain extensive DM cores.
  —> improvement compared to existing IACTs



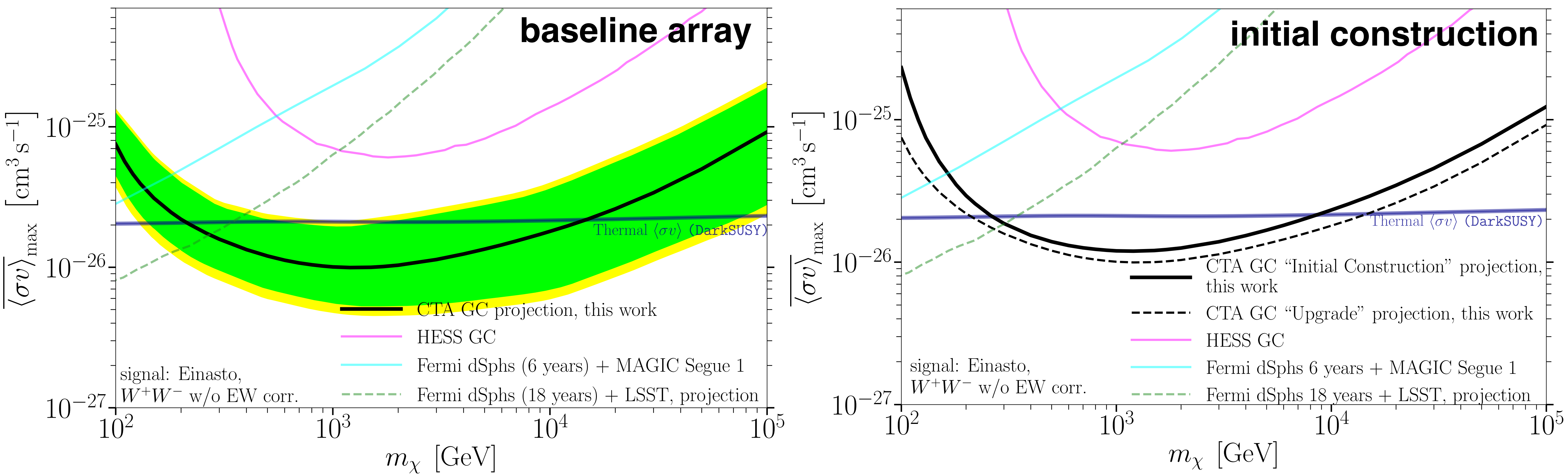
Summary

We derive the CTA's sensitivity to a DM signal in the Galactic centre by

— defining the **most promising data analysis approach** (template-based analysis),

— **studying the impact of instrumental systematic uncertainties** in an agnostic manner (for a possible input of future CTA performance optimisation),

— **quantifying the robustness** of the expected limits with respect to uncertainties of astrophysical emission components like the interstellar emission.



CTA offers the opportunity to probe the uncharted territory of the WIMP parameter space beyond the thermal annihilation cross-section at the TeV scale!

Backup Slides

Data analysis in a template-based approach

Template Fitting (3D analysis)

► **template:** binned 3D component cube with 2D sky map per energy bin

PROs:

- template fitting proved to be a **powerful technique with the LAT** data
- **ON/OFF—type analysis** (see published H.E.S.S. analyses of the Galactic centre) **might fail** with the CTA due to its sensitivity to a large-scale diffuse emission

CONs:

- **systematic uncertainties** in the templates become the **limiting factor** of the analysis

Likelihood function

systematic uncertainties directly implemented via covariance matrix

$$-2\ln\mathcal{L}(\boldsymbol{\mu_K}|\,\boldsymbol{n}) = \min_{\boldsymbol{\Delta B}}\left\{\sum_{k=1}^{\mathcal{N}}\left[n_k\ln\left(\mu_K\right)_k - \left(\mu_K\right)_k\right] - \frac{1}{2}\sum_{k,l=1}^{\mathcal{N}}\left[\Delta B_k\left(K^{-1}\right)_{kl}\Delta B_l\right]\right\}$$

$$\left(\mu_K\right)_k = \mu_k^{\mathrm{CR}} + \mu_k^{\mathrm{GDE}} + \Delta B_k + A^{\mathrm{DM}}\mu_k^{\mathrm{DM}}$$

Covariance matrices parametrise **spatial correlation** (ℓ_{S} spatial correlation length) and **spectral correlation** (ℓ_{E} spectral correlation length) of template pixels.

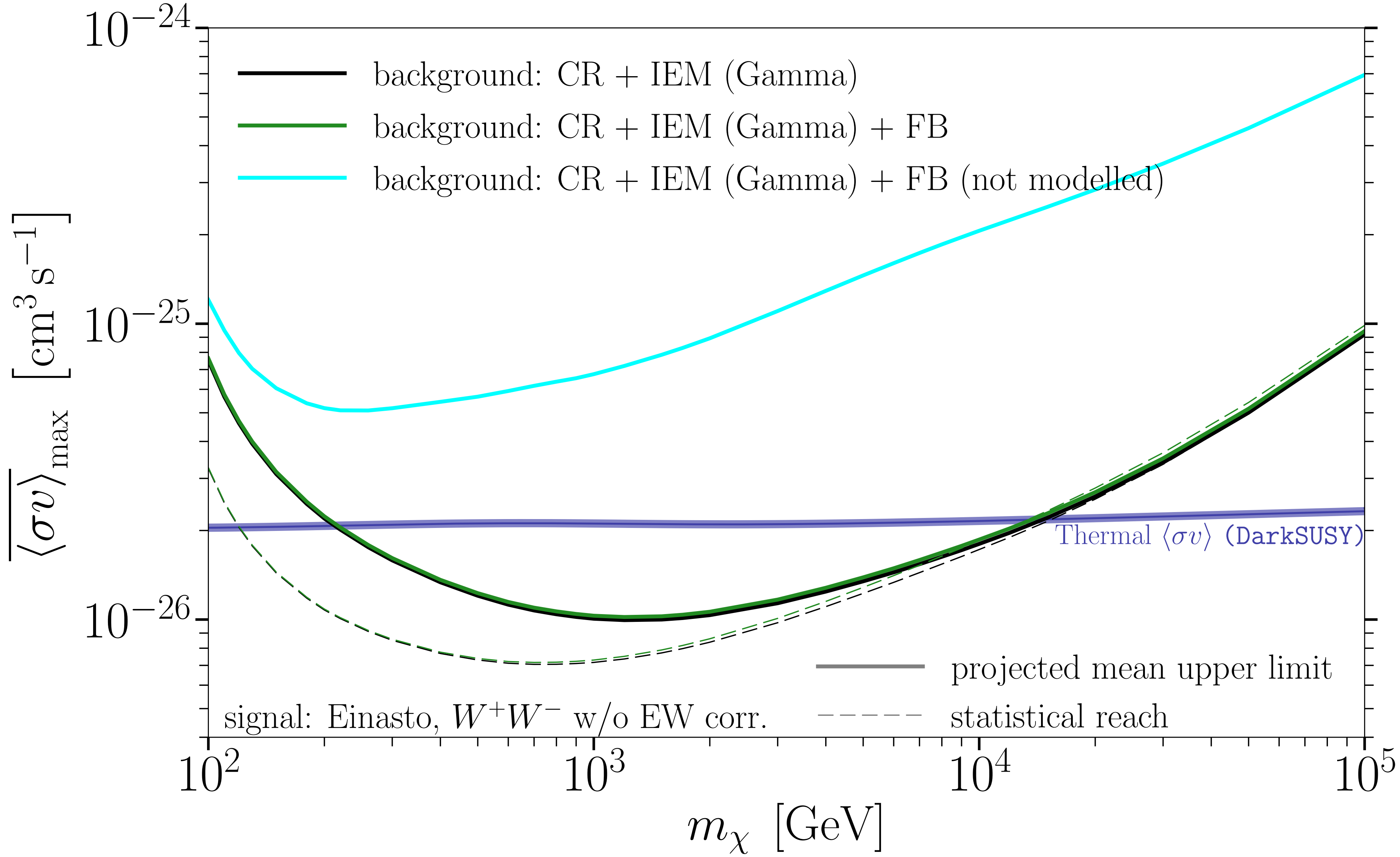
Implementation via python package **Swordfish** [Edwards & Weniger, arXiv: 1712.05401].

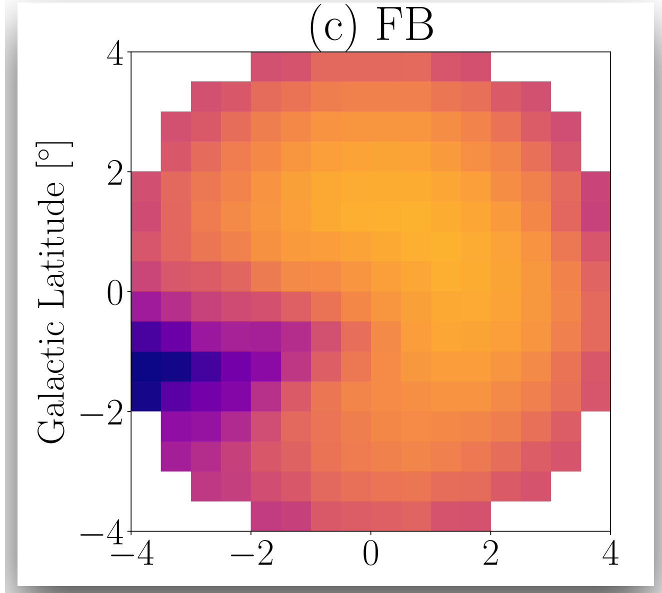
Impact of the Fermi Bubbles

Reminder — Benchmark setup:

- GC survey
- Mock data: **CR + GDE + FB** (PS perfectly masked)
- Model data: same + DM (Einasto, $b\bar{b}$)
- instrumental systematic error: 1% with 0.1° spatial correlation length

—> Impact turns out to be minor (provided that we can derive a flux template)!

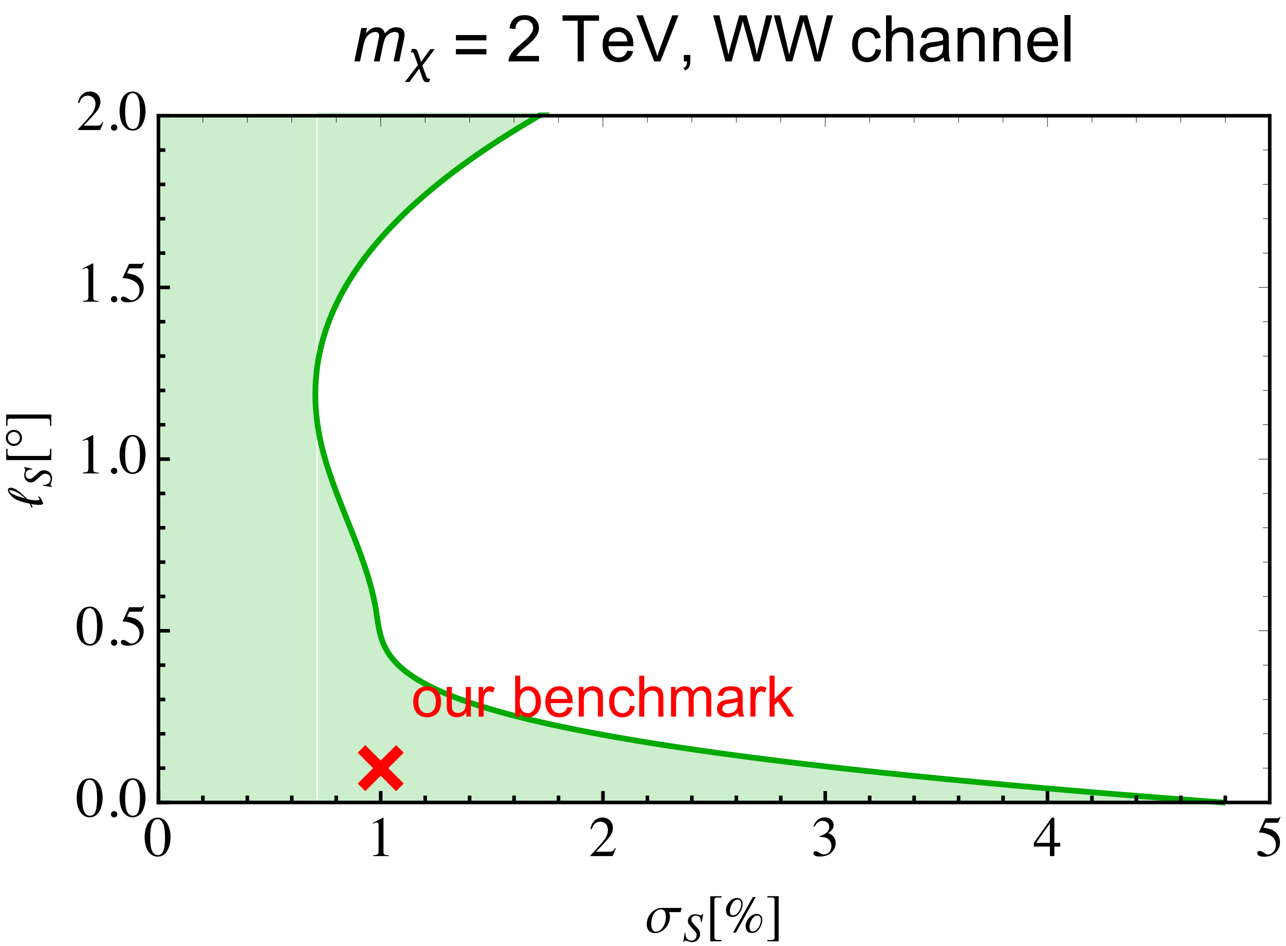


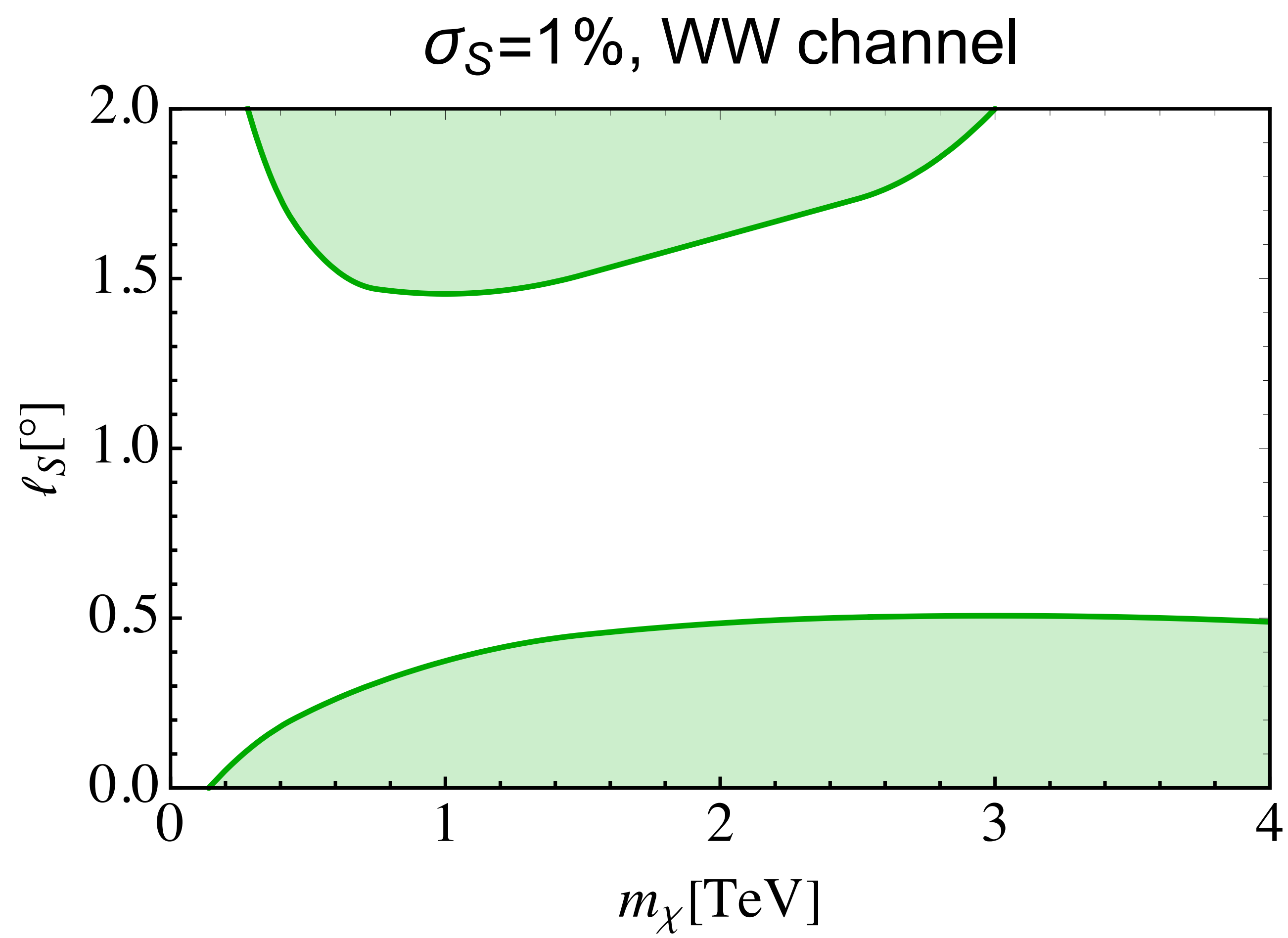


Results — instrumental requirements

Turn the issue around - what level of systematic errors can we tolerate and still reach the thermal cross-section (i.e. test the WIMP hypothesis)?

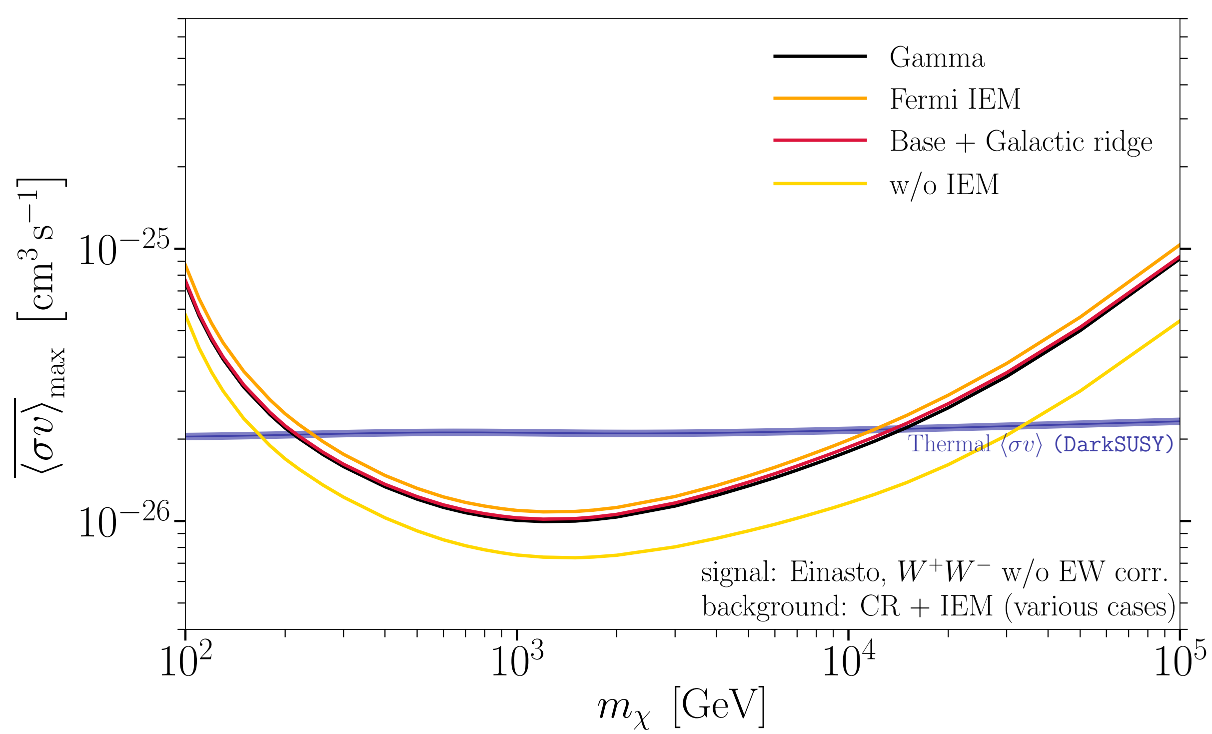
- Our benchmark point is ‘reasonable’ and not an isolated case
- **Deterioration of sensitivity happens when the correlation length coincides with the typical length scale of the dark matter signal (~0.5° to ~1°).**
- When real data becomes available, CTA might produce a subset of IRFs that satisfies this criterion.

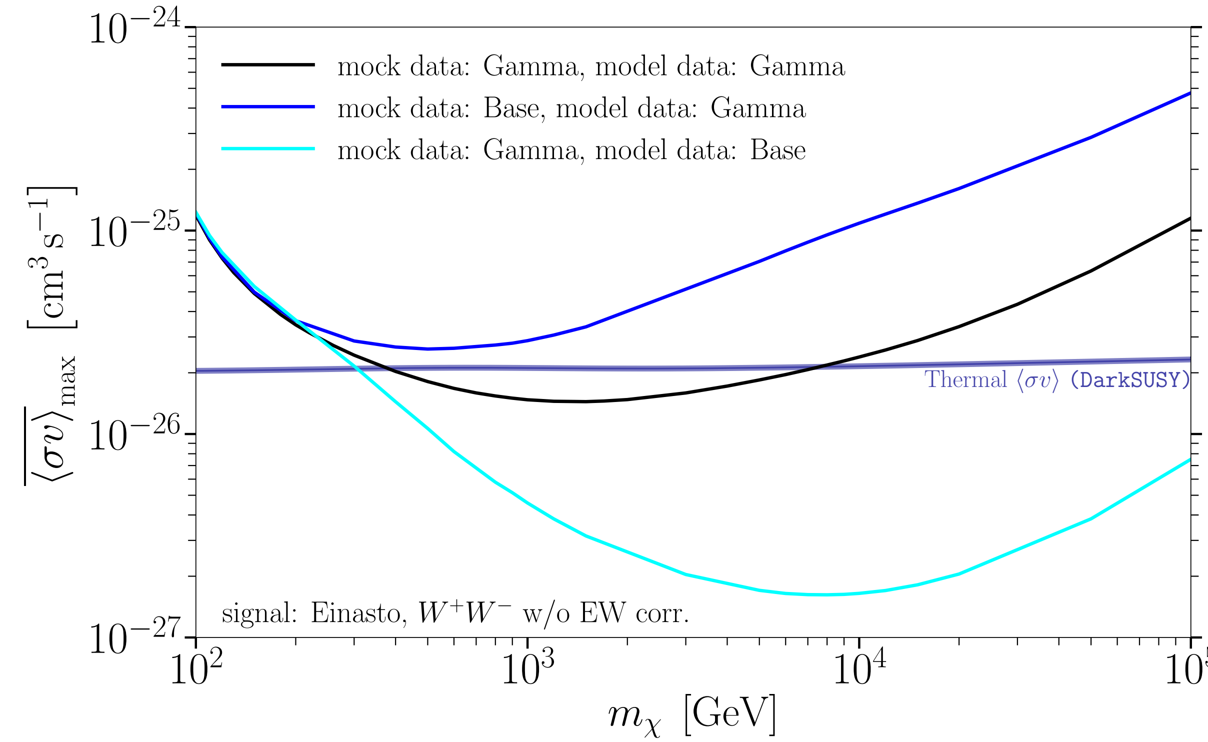




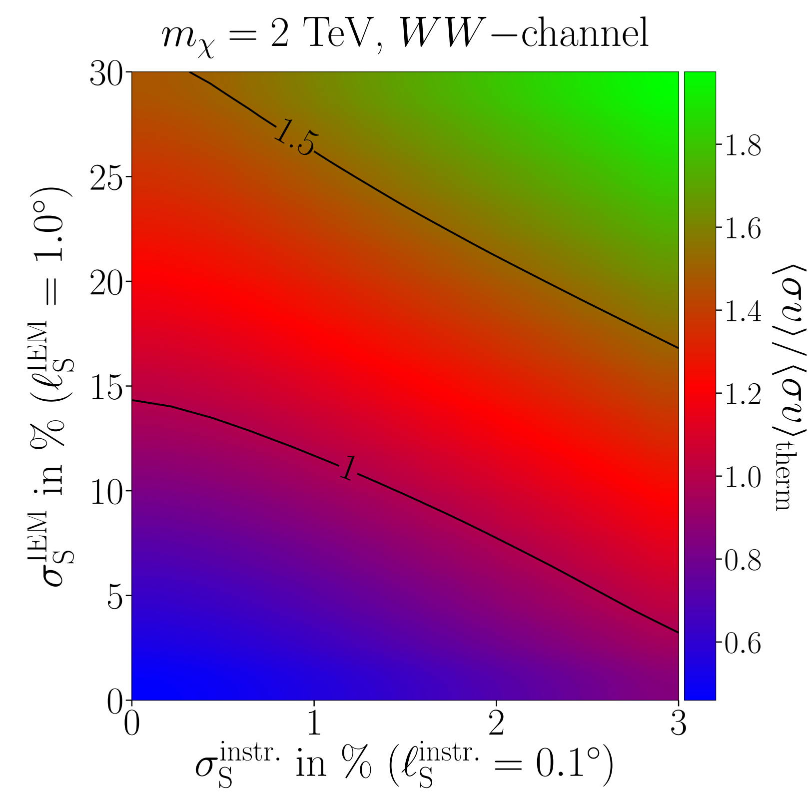
Results — impact of interstellar emission

The interstellar emission is still poorly mapped in the TeV range. CTA will probably change this, but what influence do modelling uncertainties have on the results?





- Results are rather robust regarding different IEMs.
- IEM confusion (fitting a model that does not necessarily correspond with reality in all details) can heavily bias the upper limits
  —> analyse structure of fit residuals
- Thermal cross-section remains in reach for IEM uncertainties of up to ~10% in presence of instrumental systematic uncertainties!

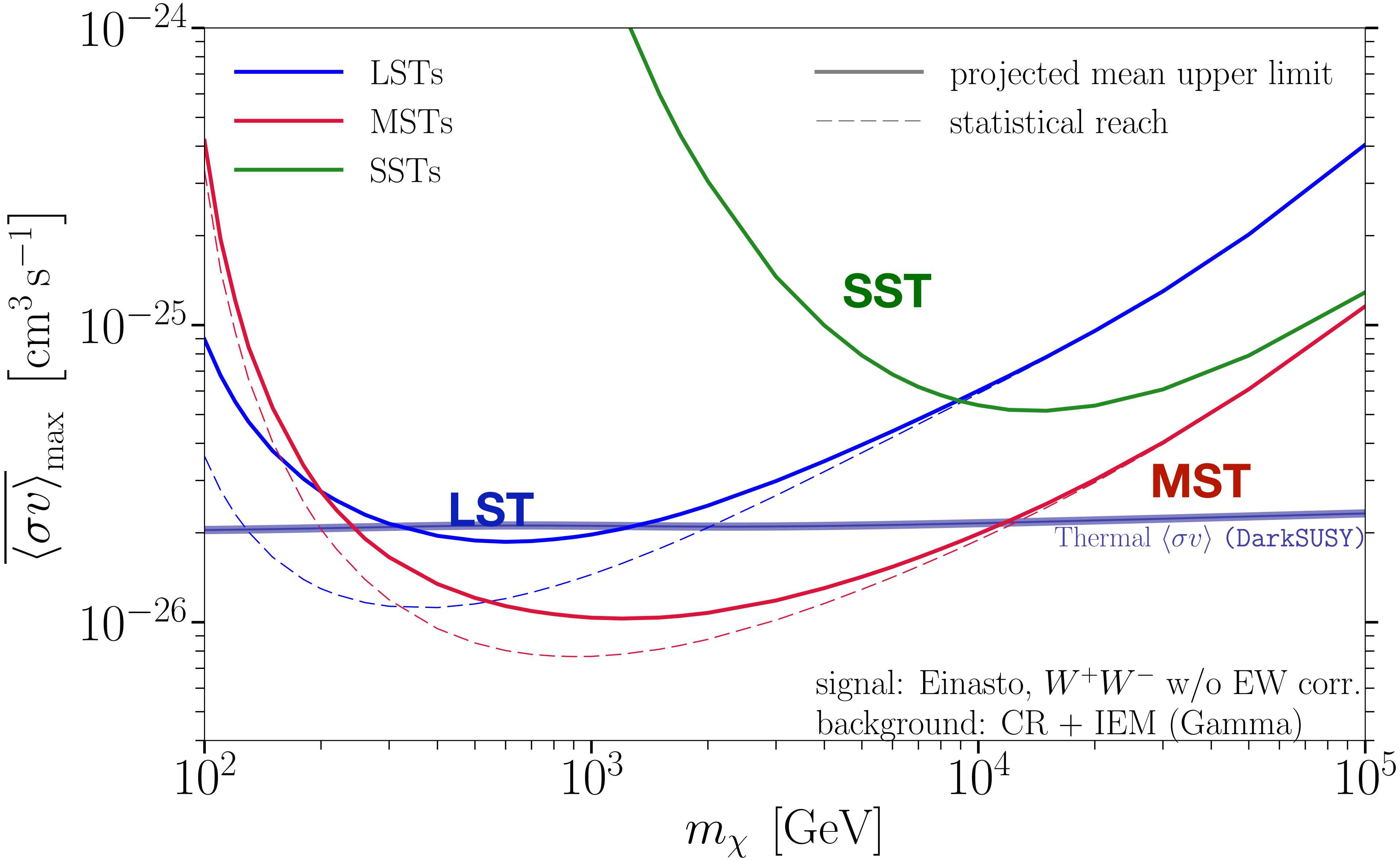


Results — Sensitivity Per Telescope Type

Sensitivity with respect to the Southern array's telescopes

- CTA South will most likely start operating with a smaller telescope subset (no LSTs).
- Full GC survey time not necessarily needed for all types.

—> In terms of DM limits, CTA South is a one-man show of the MST.
—> LSTs important nevertheless to fix spectra of point sources!



Comparison with ON/OFF Approach

Comparison with the ON/OFF analysis technique

- ON/OFF technique works as long as there is no substantial structured astrophysical emission component besides the instrumental background in the ROI.
  => This might be a limiting factor for CTA!
- If the **interstellar emission is weak at TeV energies** —> ON/OFF approach performs comparably to a template-based analysis or even better.
- **With substantial IE**: strong contamination, ON/OFF region construction might fail.