“Pre-construction estimates of the CTA sensitivity to a DM signal from the GC”

summary of the upcoming CTA Consortium paper

context

- What is dark matter?

- answer will arise by observations selecting the correct hypothesis

- it's important to precisely understand what info various instruments can provide on dark matter exec summary

- updated assessment of CTA to test γ-ray signals of thermally produced, annihilating dark matter at TeV scale from the GC
- CTA will open a new window of discovery significantly extending the range of tested DM models
- this is due to CTA’s unprecedented sensitivity, angular and energy resolution, and the planned observational strategy

“This article treats a range of rather different topics, from DM to conventional astrophysics and instrumental properties. While we put an effort in covering all relevant aspects, which makes a certain overall length unavoidable, we deliberately organised it in a way that allows to directly skip to the (mostly self-contained) sections of interest without the need to read all preceding parts.”

intro

- thermally produced, annihilating dark matter at TeV scale ~ WIMP (weakly interacting massive particle - strong theory motivation)
- WIMP detection via γ-rays from GC is promising (huge literature)
- CTA is exceptionally positioned to search for such a signal
- new in this study
  - exploring a novel template fitting approach (vs. ‘ON’ and ‘OFF’ regions)
  - realistic modelling of Galactic diffuse emission background (sys limited)
  - varying assumptions of dark matter galactic distribution
  - …

while I have your full attention: 5.1 Expected dark matter limits

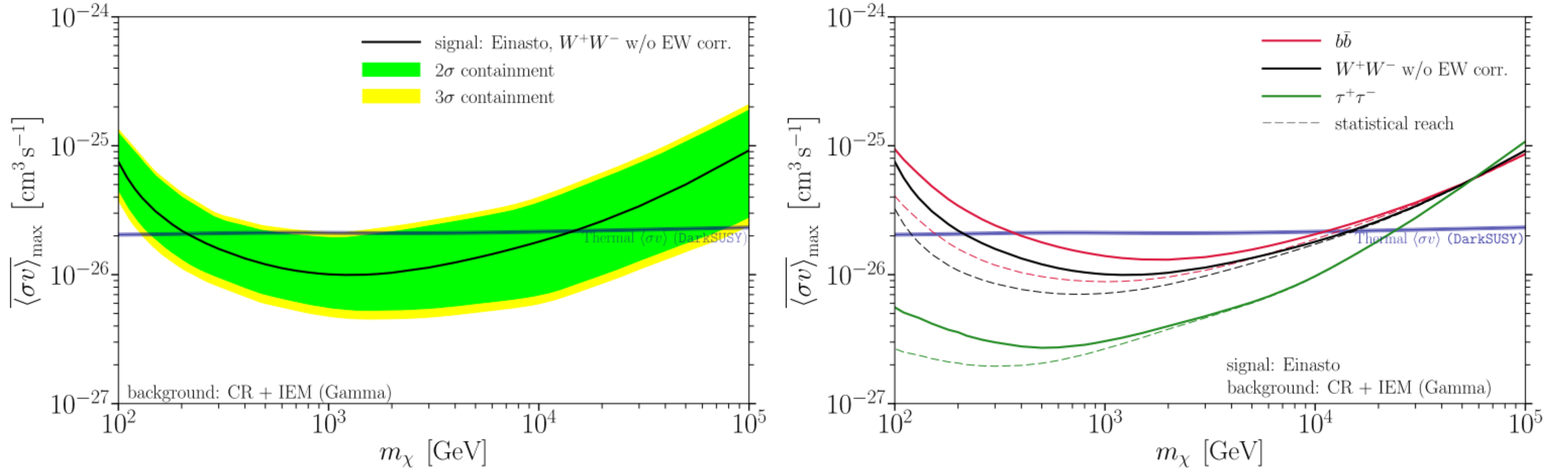

Figure 5: Mean projected upper limits on the DM annihilation cross section, at 95% C.L., based on our benchmark treatment of the expected instrumental systematic uncertainty. We also indicate the 'thermal' cross section that for the simplest DM models leads to a relic density within the 3σ range observed by Planck [1, 142]. *Left panel:* DM annihilation into W^+W^- final states, without electroweak corrections (see Section 3.1 for a discussion). The green (yellow) band indicates the 2σ (3σ) scatter of the projected limits (based on Monte Carlo realisations). *Right panel:* DM annihilation into $\bar{b}b$, W^+W^- and $\tau^+\tau^-$, respectively. Solid lines as in the left panel, while dotted lines show the reach assuming no systematic uncertainty in the spatial templates.

baseline assumptions (used for main results)

- DM self-annihilates 100% into W^+W^- (or $b\bar{b}$, $\tau\bar{\tau}$) pair
- Galactic DM distribution: Einasto
- GC survey obs. strategy: masking bright sources (cf. Fig. 1.)
- diffuse background: Asimov mock data set based on CR background and IE Gamma model templates
- template fitting analysis: based on $0.1^\circ \times 0.1^\circ$ spatial bins and 55 energy bins between 30 GeV and 100 TeV (and a width corresponding to the energy resolution at the 2σ level)

analysis of main results

- CTA can test ‘thermal’ annihilation for a wide range of DM mass
- this is the biggest deal for W^+W^- final states with slightly harder γ-ray spectrum
- this makes CTA potentially the most promising instrument to test the WIMP paradigm for TeV DM masses
- grain of salt: benchmark treatment of systematic uncertainties of “an instrument yet to be built” (compare with stat only reach – note that at high mass reach is stat limited duel too low γ flux)

less DM model independent results

- main results could be used by phenomenologists for a DM candidate with given mass and annihilation rate, but
- actual DM spectra may not coincide with those shown above
- this paper gives bin-by-bin integrated flux sensitivities, obtained by applying the likelihood function

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

- this is extremely useful for a more sophisticated indirect detection analysis of a generic DM model (cf. GAMBIT)

less DM model independent results

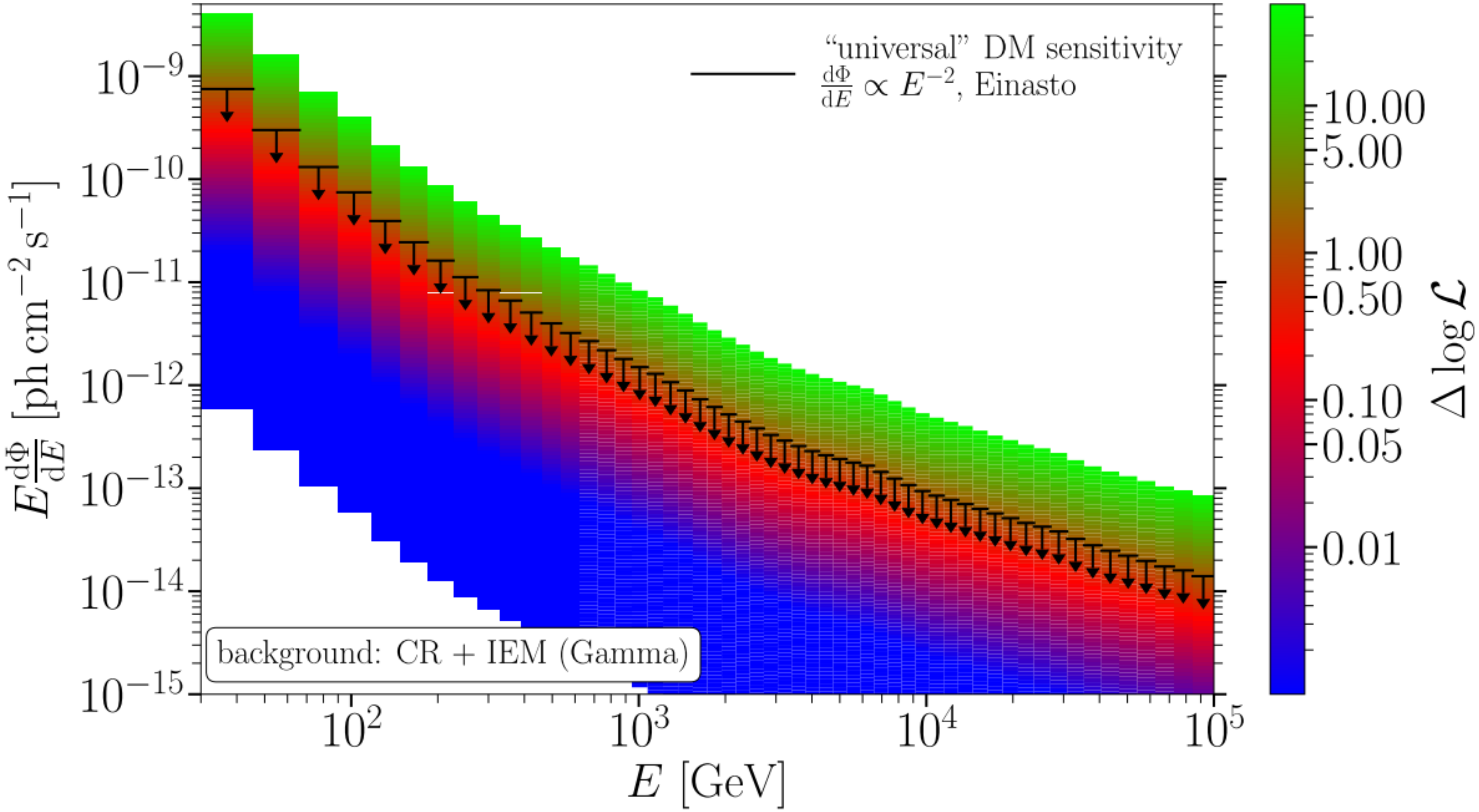

Figure 6: Per-bin sensitivity, corresponding to 2σ upper limits, and full binned likelihood for a DM template assuming a flux (locally) scaling as $d\Phi/dE \propto E^{-2}$. From this, limits on DM models with arbitrary spectra can be approximated as in Eq. (5.1).

analysis of less DM model independent results

- “To a reasonable approximation, this allows to constrain the signal normalisation, at 95% C.L., of an almost arbitrary smooth DM spectrum dN_γ/dE_γ, where N_γ is the number of photons per annihilation process.”
- assumption: the photon flux from DM annihilation is described by a power-law $\frac{d\Phi}{dN} \sim E^{-2}$ (checked that this has small effect)
- even for a DM spectrum very strongly varying with energy, integrating over the energy inside each bin would provide a reasonable estimate
- we need to add likelihood fn. to GAMBIT to be able to utilize it

impact of assumed DM galactic distribution

- baseline study assumed Einasto distribution profile

$$\rho_{\mathrm{Einasto}}(r) = \rho_s \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right)$$

- but no consensus on the Galactic DM distribution within the inner few kpc which is crucial for estimating the DM signal
- conservative case: 1 kpc inner core of constant DM density
- limits weaken because expected profile steepens
  - a signal degenerate with the misidentified CR background constitutes a blind spot for morphological analyses
  - J-factor somewhat decreases

impact of assumed DM galactic distribution

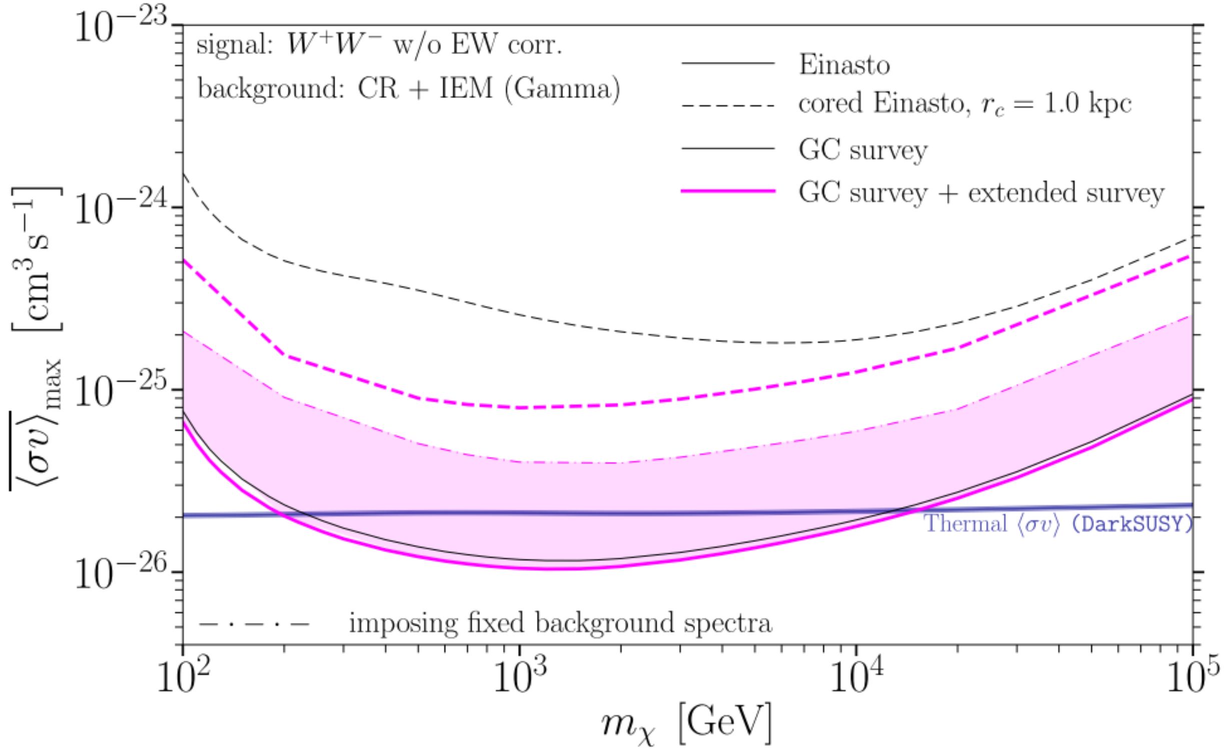

Figure 7: Black lines show how the expected DM sensitivity to the W^+W^- channel, resulting from GC survey observations, deteriorates when going from an Einasto profile (solid), to a 1 kpc core (dashed). Magenta lines show the improvement in sensitivity from adding extended survey observations. Modelling the spectral information with greater care may lead to a further improvement of the sensitivity to a cored profile, as indicated by the magenta dash-dotted line (see text for more details). Due to limitations in computational resources, the sensitivity predictions in this figure are based on only 20 (equally log-spaced) energy bins.

impact of assumed DM galactic distribution

- limit for the W^+W^- channel worsen by about one order of magnitude when assuming cored DM distribution
- planned extended GC survey helps (see next slide for “extended”)
- note: for Einasto the effect of extending the survey is minimal (the template discrimination already good for standard survey)
- further improvement is possible using spectral correlations (thin magenta dash-dot)
- in summary: a large core in the DM distribution would worsen the CTA sensitivity to DM annihilation but much less severely than naively expected

2.2 Observational strategy of the GC

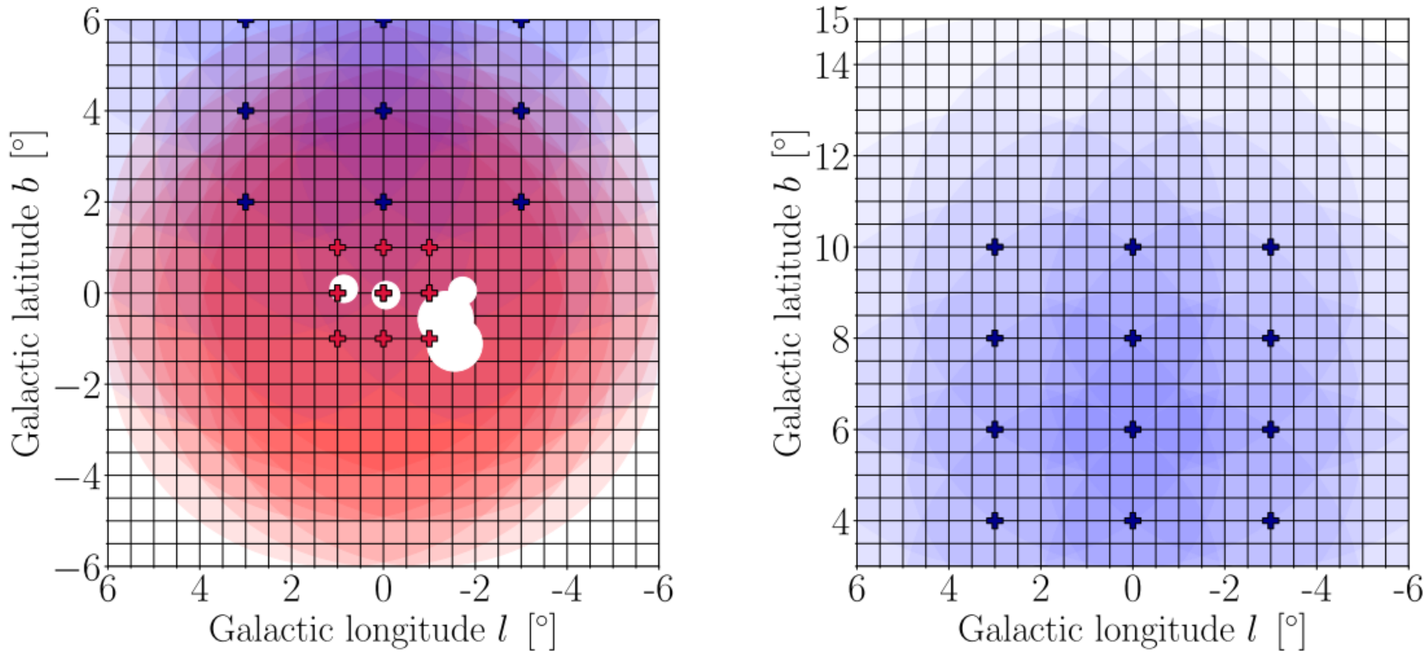

Figure 1: Schematic visualisation of CTA's Galactic centre (GC) and extended GC surveys. The nine pointing positions of the GC survey mode are marked with red crosses and the respective FoVs are shaded in red with circles of 5° radius; the observation time for each position will be 58.3 h. The 15 pointing positions belonging to the extended survey north of the Galactic plane are marked with blue crosses, with the circular 5° FoVs shaded in blue; the observation time for each position will be 20 h in this case. Note the different latitude range in left and right panel, and that we display a 0.5° grid only to guide the eye here; our benchmark binning in the actual analysis is 0.1°. Finally, we also indicate the source masks that we apply in our analysis (white circles, c.f. Section 3.2).

I skipped most of the paper including

- 6.1 Instrumental systematics
- 6.2 Uncertainties in astrophysical components
  - IE template uncertainty
  - Localised sources: Non-diffuse sources, Fermi bubbles
- A Phase 1 telescope configuration
- B Details of IE models
  - B.1 Spectral differences in the Galactic Ridge region
  - B.2 Morphological differences
  - B.3 Effect of masking
- C Further analysis details

conclusion: Phase 1 projection and comparison to HESS and Fermi

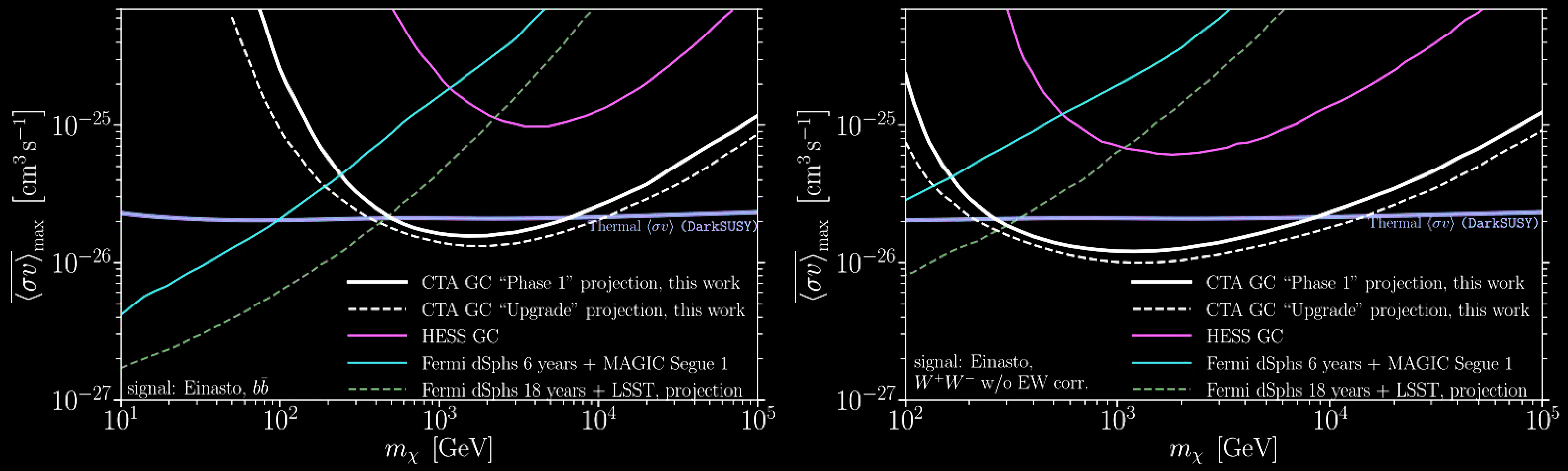

Figure 15: Same as Fig. 14, but the solid black line now shows the sensitivity projection for the reduced phase 1 configuration (while the dashed black line shows the result for the benchmark analysis setting presented in the main text).

bonus material

fun fact: MSTs are most sensitive to DM

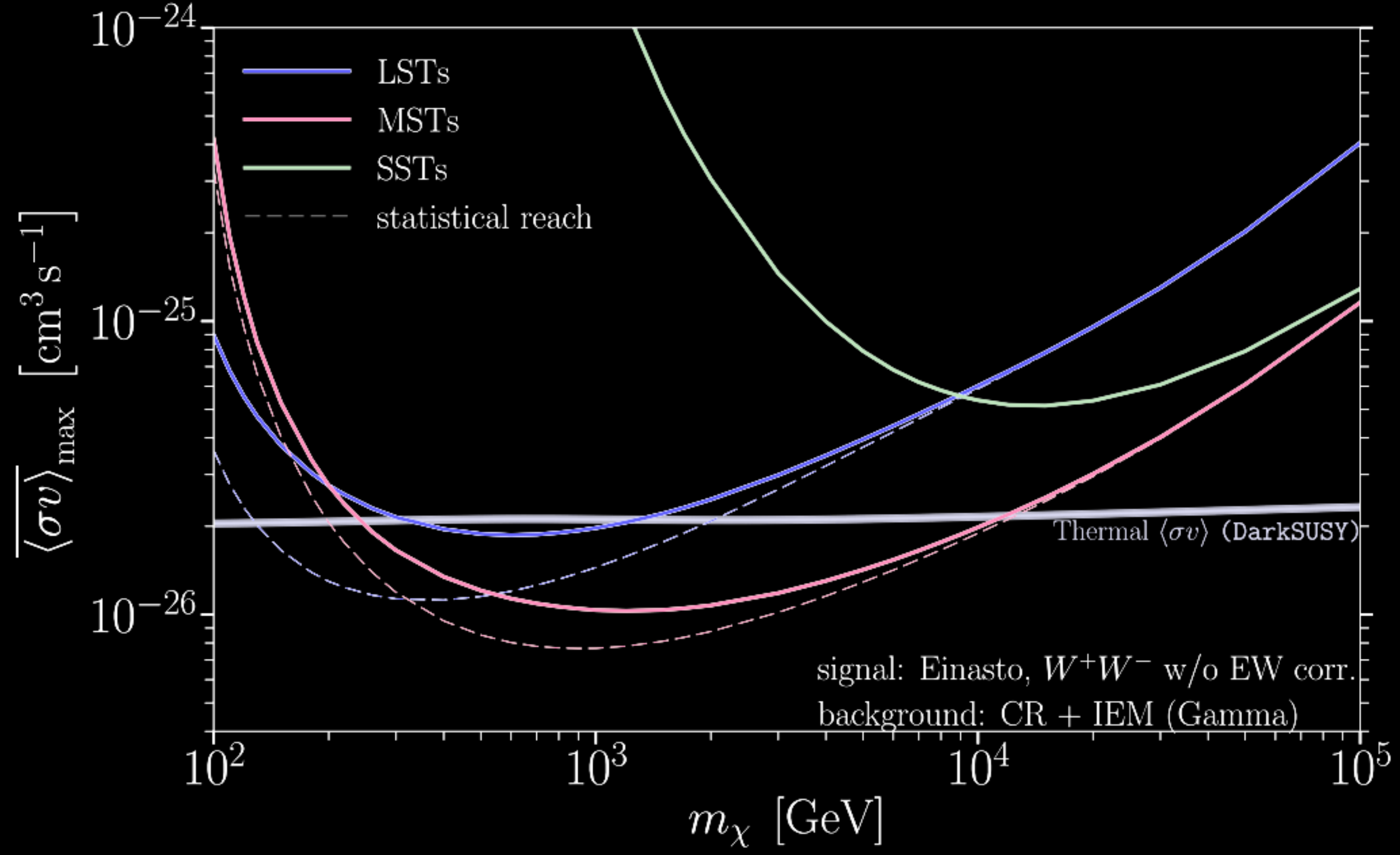

Figure 24: Mean expected upper limits on annihilating DM for the three telescope types of CTA according to the Southern Array layout, both for our standard analysis pipeline (solid) and when neglecting systematic uncertainties (dashed). Note that in the case of SSTs the solid and dashed lines are overlapping.

fun fact: DM distribution might be more favorable for CTA

generalized NFW profile

$$\rho_{\rm gNFW}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

note: sensitivities are calculated for the extended survey, but without spectral information

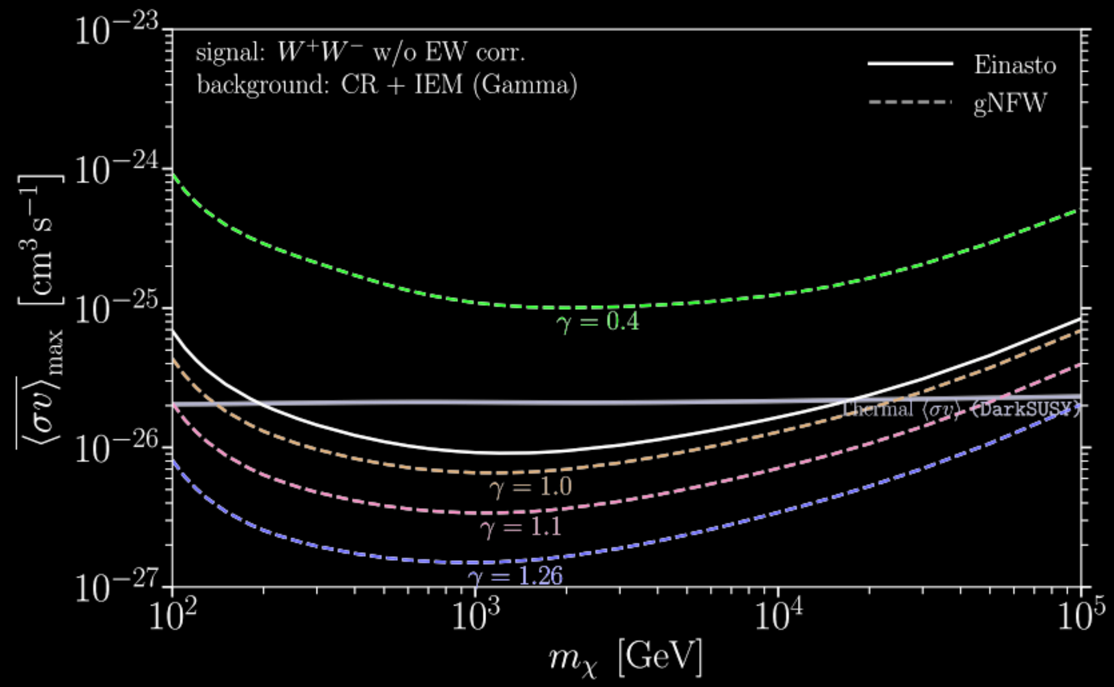

Figure 23: Upper limits on DM annihilating to W^+W^- for a gNFW DM density profile (dashed lines), for various choices choices of the slope parameter γ (and corresponding best-fit values for scale radius r_s and local DM density $\rho_\odot$ as derived in Ref. [62]). The solid black line shows, for comparison, the upper limit for our standard Einasto profile. All upper limits incorporate our benchmark settings of instrumental systematic uncertainty. We stress that the range of DM density profiles shown here does not include the possible enhancement of the DM density in the very central ($r \ll 1$ kpc) regions of the galaxy, which would further contribute to an increase of the CTA sensitivity. Possible spectral correlations (increasing the sensitivity for $\gamma \leq 1$ profiles) are also not considered here.

the likelihood function

- an upper bound on the γ-ray from DM annihilation is set based on the test statistics

$$\mathrm{TS}(A_\chi) = -2 \min_{\{A_i^X\}} \left(\ln\left[\frac{\mathcal{L}(\boldsymbol{\mu}(A^\chi, A_i^X) | \, \boldsymbol{n})}{\mathcal{L}(\hat{\boldsymbol{\mu}} | \, \boldsymbol{n})} \right] \right)$$

- μ = number of photons predicted by the theory model, and n = (modeled) number of photons detected
- The likelihood function is Poisson (with Gaussian prior on the background variations ΔB_k) in the spatial and energy bins k

$$\mathcal{L}(\boldsymbol{\mu} | \, \boldsymbol{n}) = \prod_{k=1}^{\mathcal{N}} \frac{\mu_k^{n_k}}{(n_k)!} e^{-\mu_k} \times \exp\left[-\frac{1}{2} \Delta B_k \sum_{l=1}^{\mathcal{N}} \left(K^{-1}\right)_{kl} \Delta B_l \right]$$

the likelihood function

- here the number of photons from the theoretical prediction

$$(\mu_K)_k \equiv \mu_k^{\mathrm{CR}} + \mu_k^{\mathrm{IEM}} + \Delta B_k + A^\chi \mu_k^\chi$$

includes the backgrounds

- profiling over the nuisance parameters yields a likelihood function that only depends on the signal normalization A_k

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