WIMPs @ CTA

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special thanks to:

Torsten Bringmann (Oslo)

Christopher Eckner (Annecy)

Sergio Cadena Hernández (Mexico City)

image: https://www.cta-observatory.org/the-dark-side-of-the-matter/

outline

WIMPs as gamma ray sources

projected CTA sensitivity for generic WIMPs

Bayesian backbone of our toolchain

prelim results

WIMPs producing cosmic gamma rays

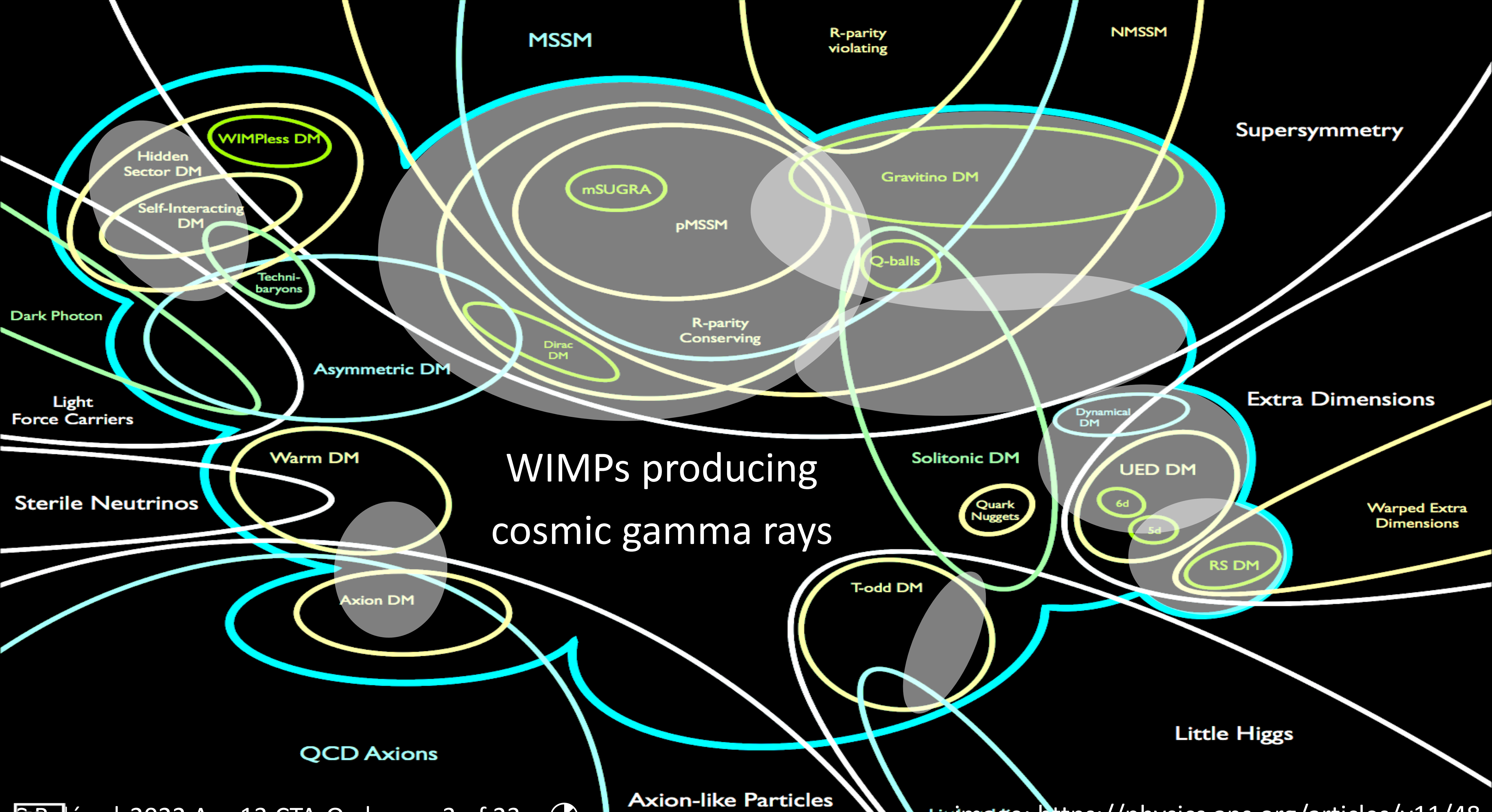
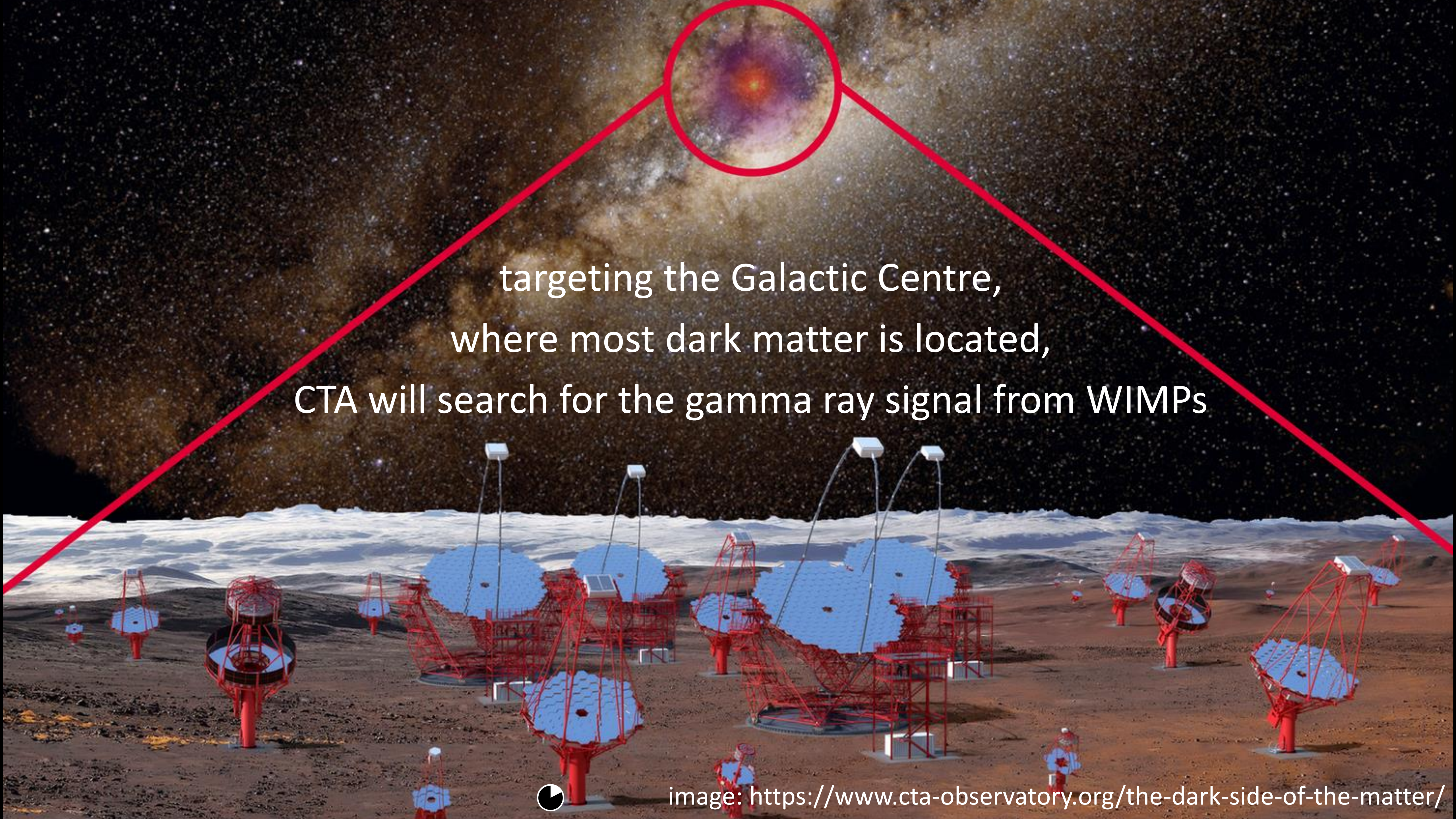


Image: https://physics.aps.org/articles/v11/48



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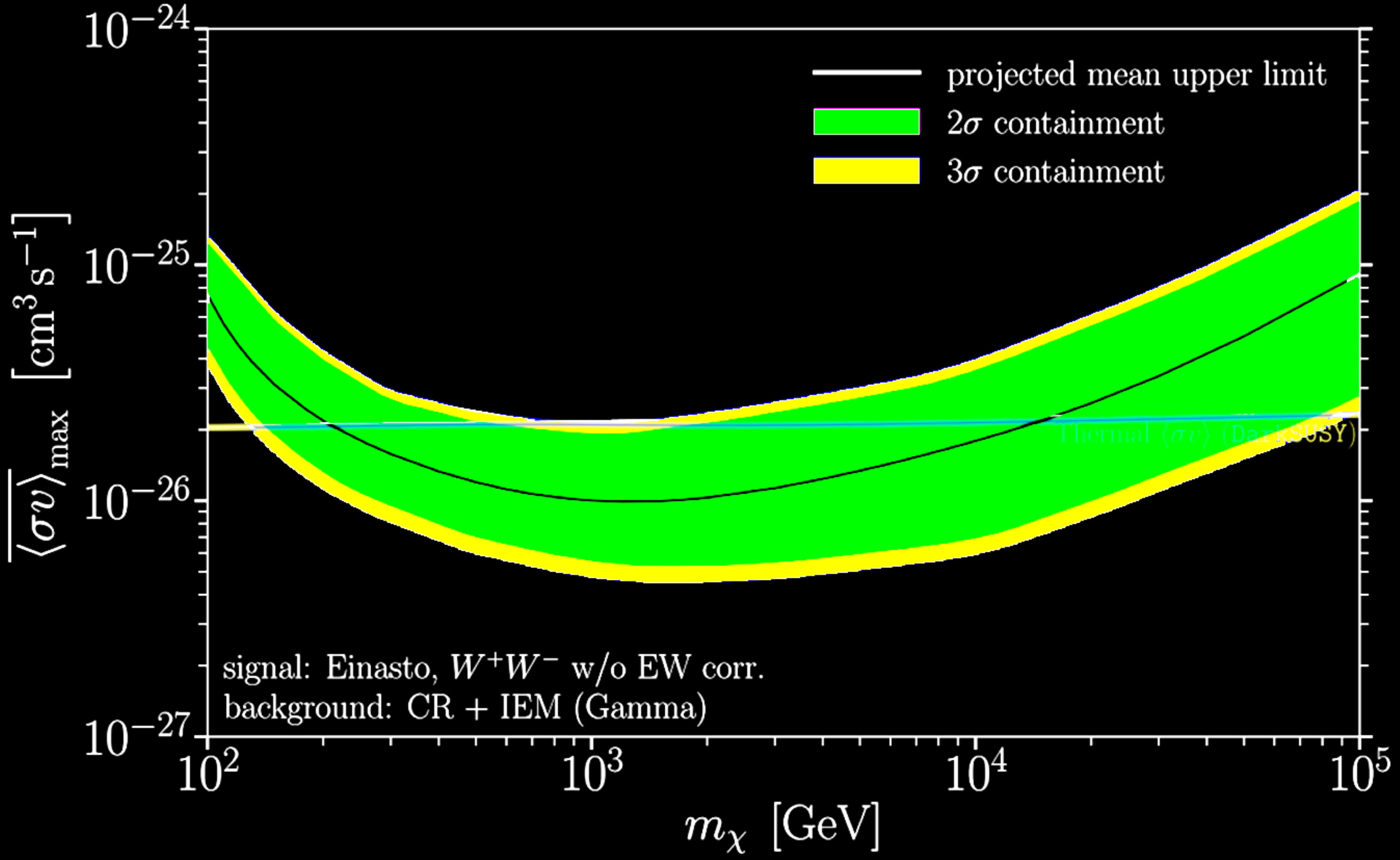


the DM WG published sensitivity of CTA for a generic WIMP

our goal is to generalize these limits for specific DM models

plot: CTA Consortium JCAP 01 (2021) 057

Bayesian inference – the inverse problem

hypothesis A: given dark matter model

measurement B: gamma ray events in CTA

prediction: ‘easy’ to calculate $P(B|A)$

but CTA will give us data B and we want to infer $P(A|B)$

we need to invert $P(B|A)$ to obtain $P(A|B)$

Bayesian inference – hierarchical inversion

measurement level B: given CTA data

truth level A: true values of measured quantities

calibration: 'easy' to construct instrument response $P(B|A)$

but CTA will give us data B and we want to infer $P(A|B)$

we need to invert $P(B|A)$ to obtain $P(A|B)$

Bayes' theorem

we use Bayes' theorem

$$P(A|B) = P(B|A) * P(A)/P(B)$$

to update our prior knowledge on A and B

$$P(A)/P(B)$$

with newly acquired likelihood info

$$P(B|A)$$

to infer the posterior probability of A occurring given that B occurred

measurement vs truth

CTA “data”: measured sky location and energy of i^{th} gamma ray event

$$d_i = \{\Omega_m^i \ E_m^i\}$$

the true sky location and energy of the event, however, is

$$\{\Omega^i \ E^i\}$$

the true and measured values are connected by likelihood functions

$$\mathcal{L}(\Omega_m^i | \Omega^i \ E^i) \quad \text{and} \quad \mathcal{L}(E_m^i | E^i)$$

likelihood of an event

the likelihood of CTA measuring E^i_m, given a true value of E^i, is

$$\mathcal{L}(E^i_m|E^i)$$

the likelihood of CTA measuring Ω^i_m, given $\{\Omega^i\ E^i\}$, is

$$\mathcal{L}(\Omega^i_m|\Omega^i\ E^i)$$

the likelihood of CTA measuring $\{\Omega^i_m\ E^i_m\}$, given $\{\Omega^i\ E^i\}$, is

$$\mathcal{L}(\Omega^i_m\ E^i_m|\Omega^i\ E^i) = \mathcal{L}\left(E^i_m|E^i\right)\mathcal{L}(\Omega^i_m|\Omega^i\ E^i)$$

energy dispersion function

the likelihood

$$\mathcal{L}\left(E_m^i \middle| E^i\right)$$

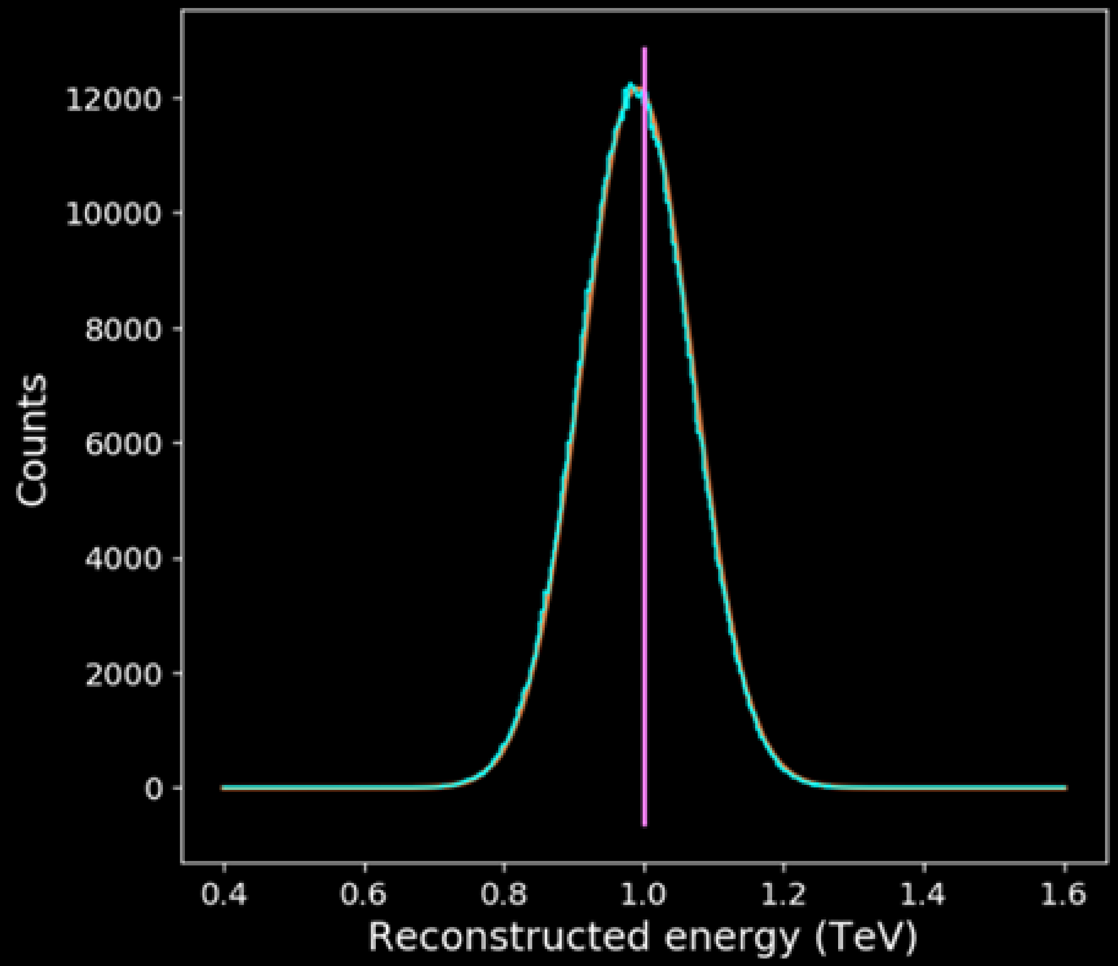
is called “energy dispersion function”

(instrument response function for energy)

it relates the measured energy E_m^i to the true energy E^i

it comes from test_sim_edisp of gammalib within ctools

energy dispersion function we use



point spread function

the likelihood

$$\mathcal{L}(\Omega_m^i|\Omega^i\ E^i)$$

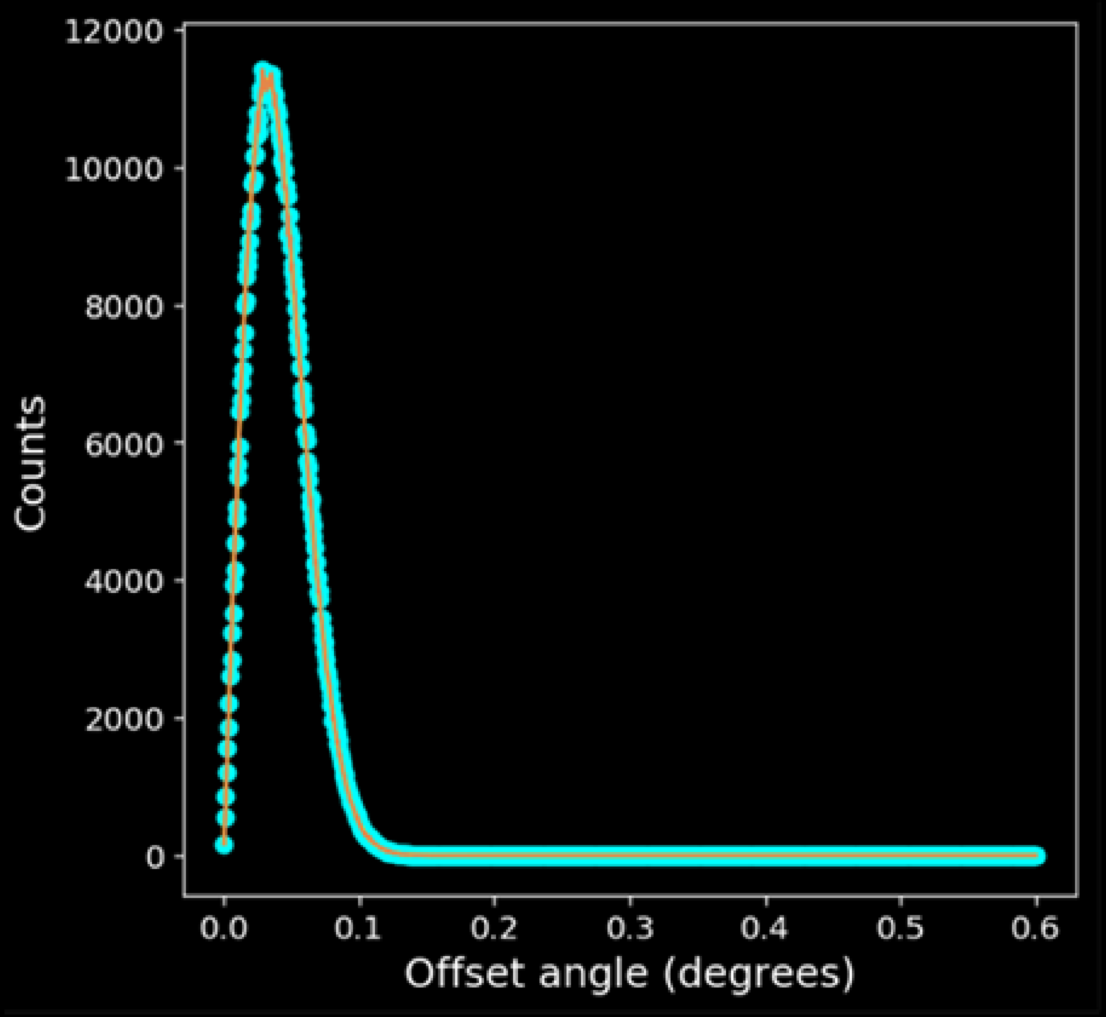
is called “point spread function”

(instrument response function in angle)

it relates the measured sky location Ω_m^i to the true location Ω^i

it comes from test_sim_psf of gammalib within ctools

point spread function we use



posteriors

to infer the presence of dark matter particles

for each event we calculate two posteriors

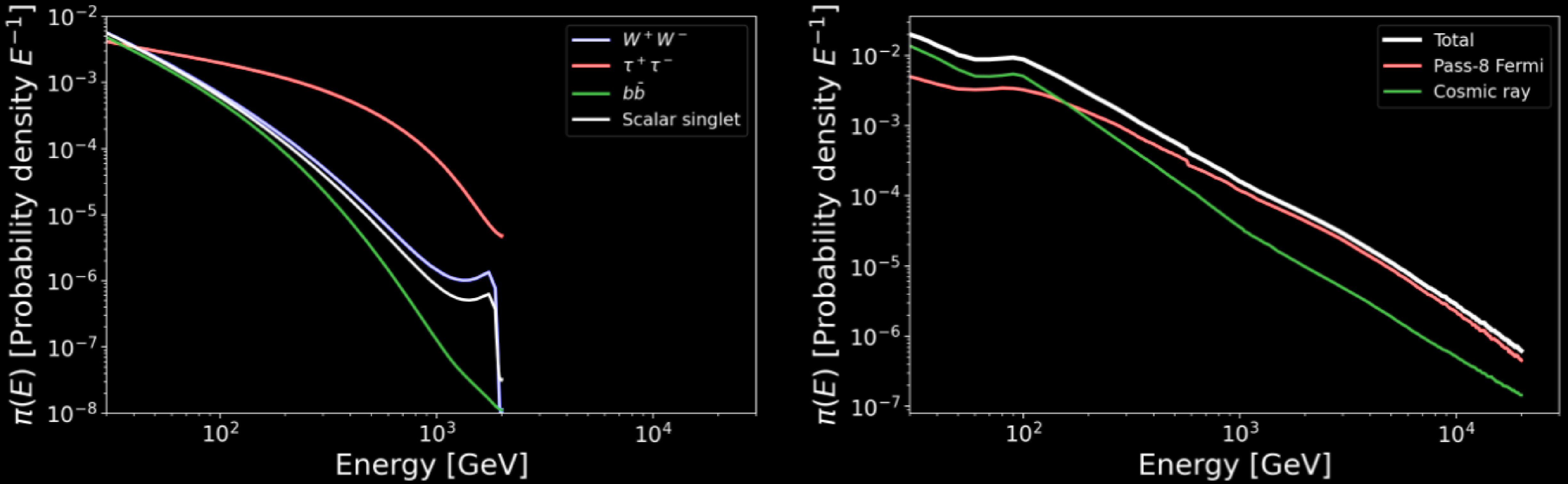
one assuming the signal hypothesis

$$\mathcal{L}(d^i|\mathcal{S}) = \int d\hat{\Omega}^i \int dE^i \, \mathcal{L}(d_i|\Omega^i E^i) \, \pi(\Omega^i, E^i|\mathcal{S})$$

and one assuming the background hypothesis

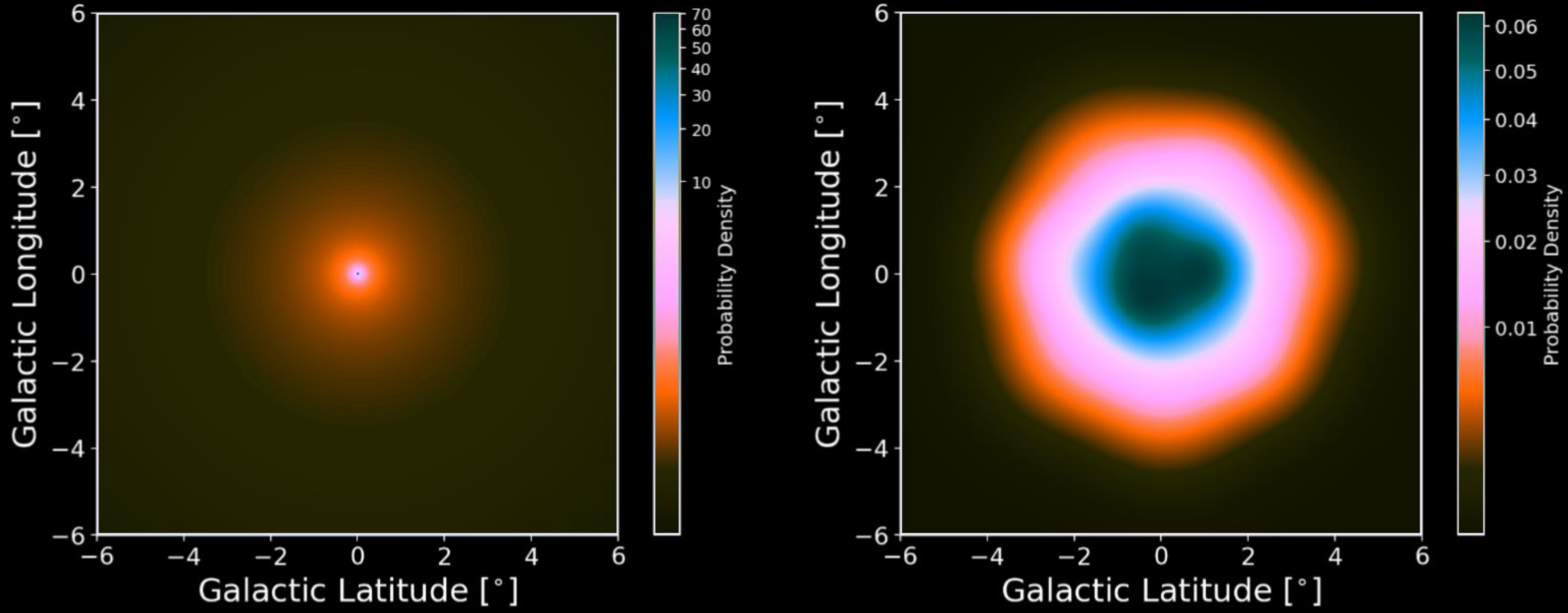
$$\mathcal{L}(d_i|\mathcal{B}) = \int d\hat{\Omega}_i \int dE_i \, \mathcal{L}(d_i|\Omega^i E^i)\pi(\Omega^i, E^i|\mathcal{B})$$

priors for energy



energy priors for signal and background hypotheses

priors for sky location



sky location priors for signal and background hypotheses

posterior of full dataset

the likelihood of the complete dataset is

$$\mathcal{L}(\vec{d}|\lambda) = \prod_{i}^{N} \lambda \mathcal{L}(d_i|\mathcal{S}) + (1-\lambda)\mathcal{L}(d_i|\mathcal{B})$$

λ is the probability that an event is drawn from the signal population

equivalently, λ is the proportion of events drawn from the signal

$$\lambda = \frac{N_\mathcal{S}}{N} \approx \frac{N_\mathcal{S}}{N_\mathcal{B}}$$

number of signal events

N_S is proportional to the gamma ray source flux

$$N_S = T \int \frac{d\Phi}{d\Omega dE}(E,\psi) A(E) dE d\Omega$$

which is proportional to the annihilation cross section

$$\frac{d\Phi}{d\Omega dE}(E,\psi) = \frac{1}{4\pi} \int_{l.o.s} dl(\psi) \rho_\chi^2(\mathbf{r}) \left(\frac{\langle \sigma v \rangle}{2m_\chi^2} \sum B_f \frac{dN}{dE} \right)$$

which means that λ is a linear function of the cross section

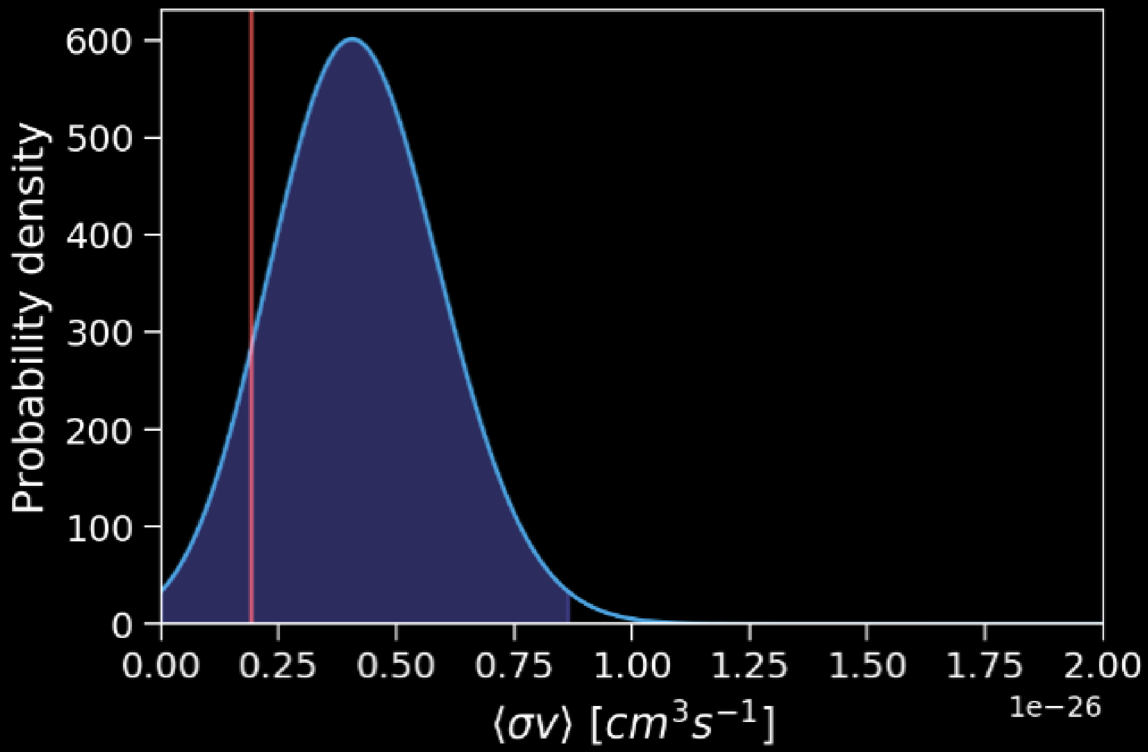
Posterior for annihilation cross section

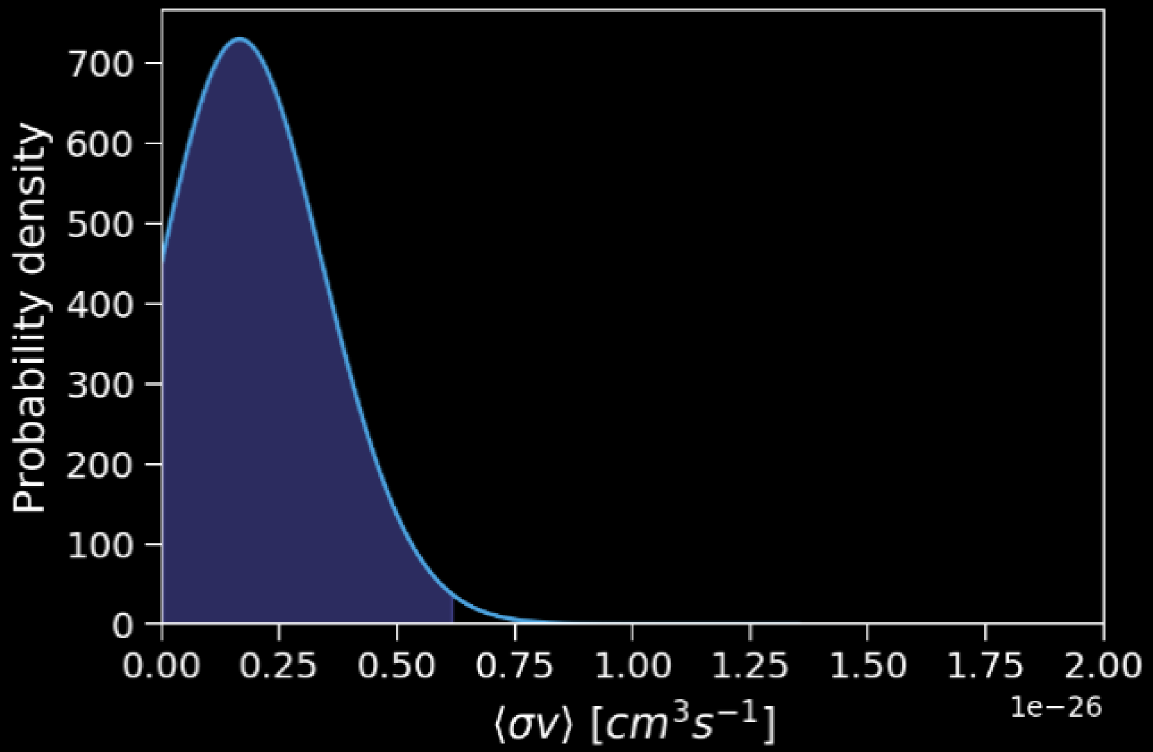
using Bayes theorem, we can invert the likelihood

$$\mathcal{L}(\vec{d}|\lambda) = \prod_i^N \lambda \mathcal{L}(d_i|\mathcal{S}) + (1-\lambda)\mathcal{L}(d_i|\mathcal{B})$$

to obtain a probability distribution for the annihilation cross section

Posterior for annihilation cross section

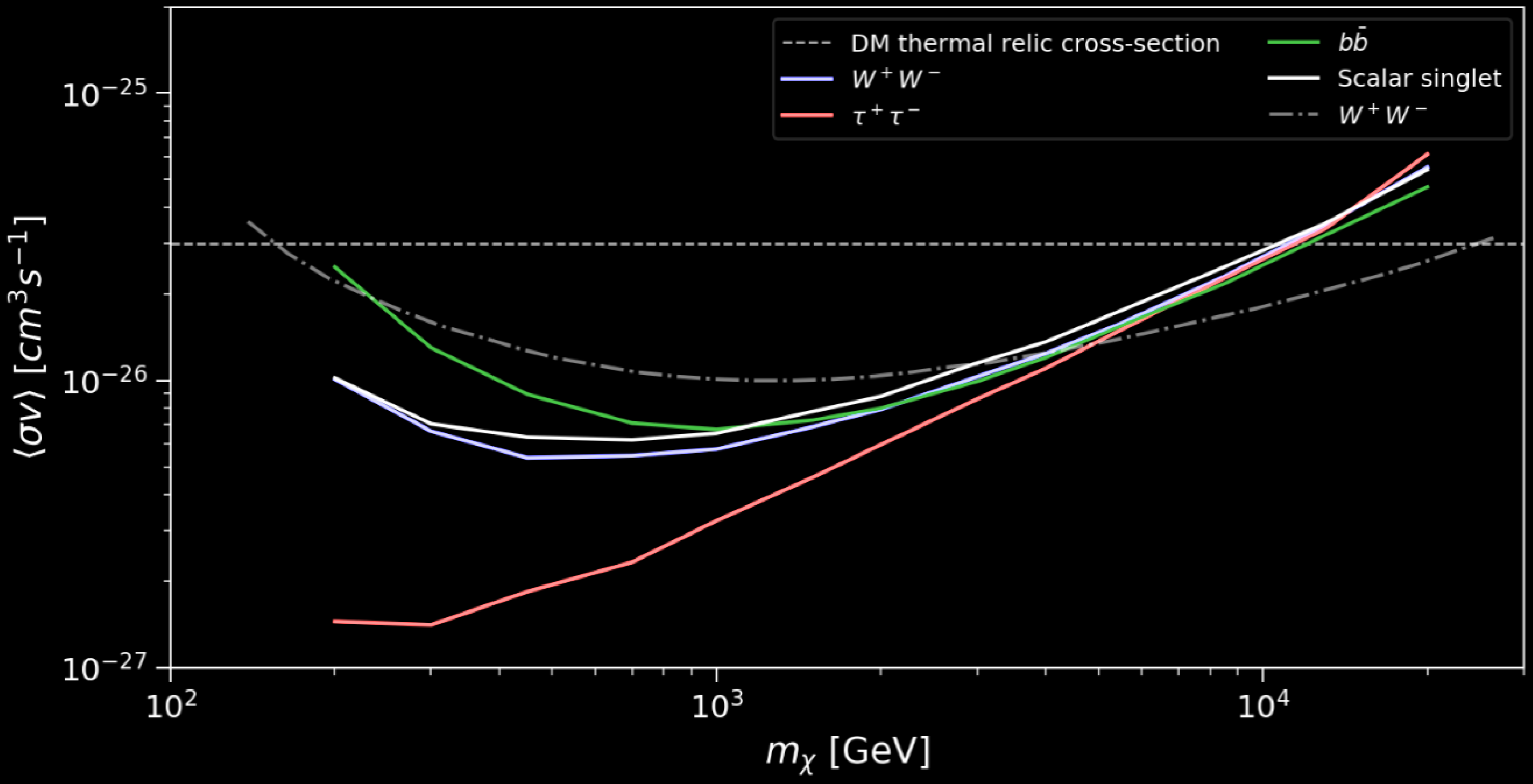




sample detection (left) and exclusion (right) at 99% C.L.

shaded region indicating credible interval (vertical line at true value)

limits for annihilation cross section



CTA will be a powerful tool to hunt for WIMPs.

It will be able to discover or rule out various WIMP candidates.

We're working on a generic numerical framework to determine the sensitivity of CTA for various WIMP models.

Interesting results are coming soon!