SENSITIVITY OF CTA TO THE DETECTION OF A DARK MATTER SIGNAL

in comparison with DIRECT DETECTION AND COLLIDER EXPERIMENTS

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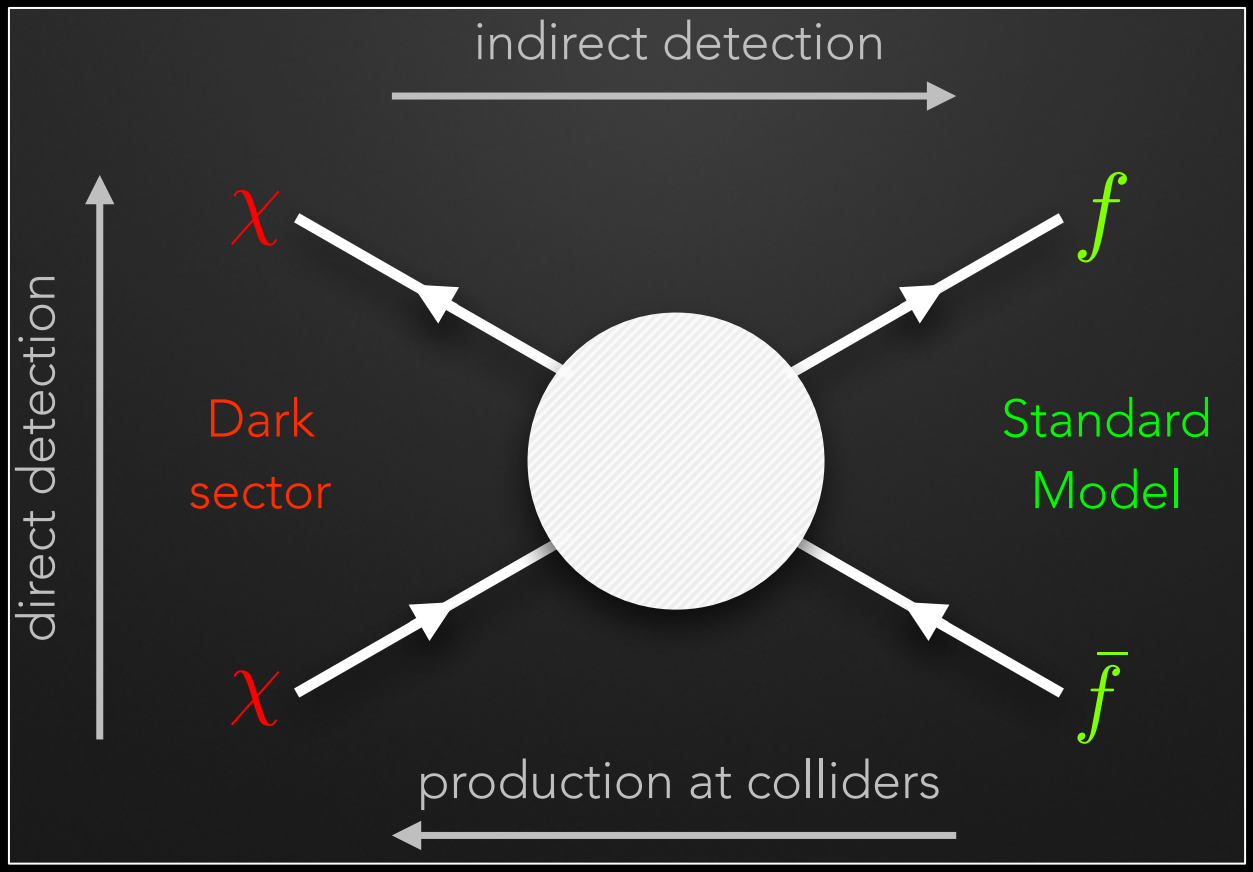
[In collaboration with Balazs, Conrad, Farmer, Jacques, Li, Meyer, Queiroz]

"Dark matter at the dawn of discovery?" workshop
Heidelberg University, April 9-11 2018

Complementarity is critical

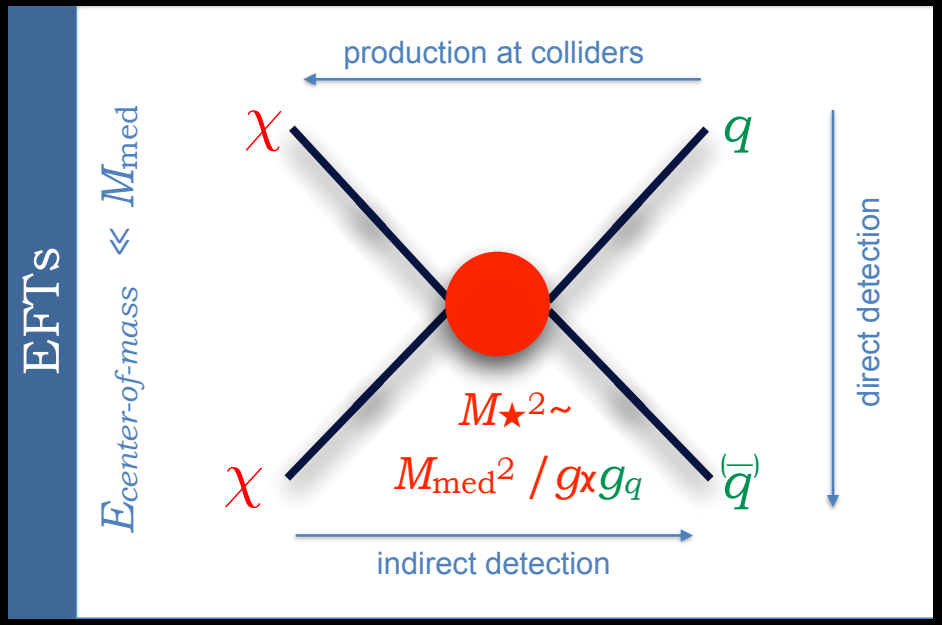


Only a COMBINED effort of all experimental techniques can unravel the nature of WIMP DM.

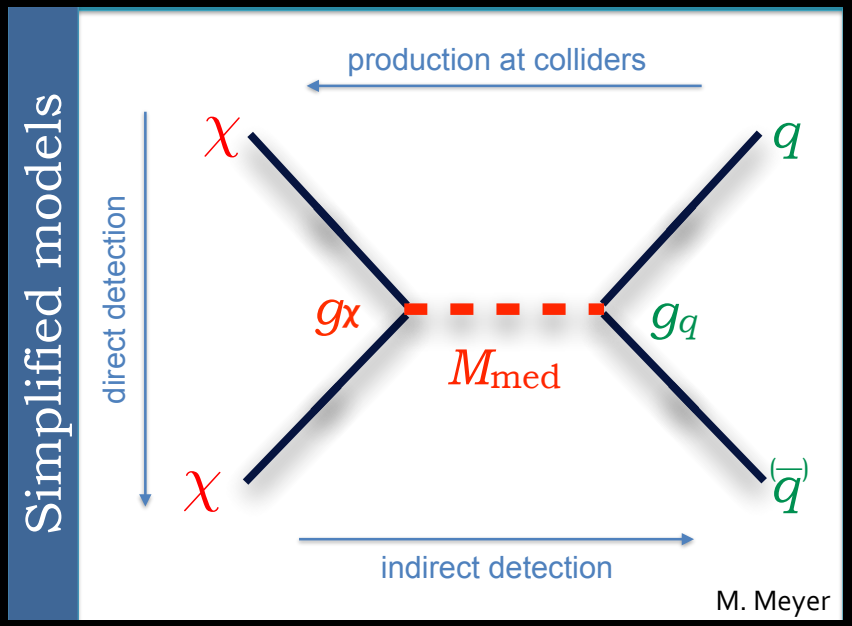
Complementarity: scope of our work

[arXiv:1706.01505]

- Compare the DM detection sensitivity of CTA to that of colliders and DD.
- Efective field theories (EFT) and Simplified Models to perform such comparison.
- Dirac fermion DM that interacts with SM quarks through different mediators.

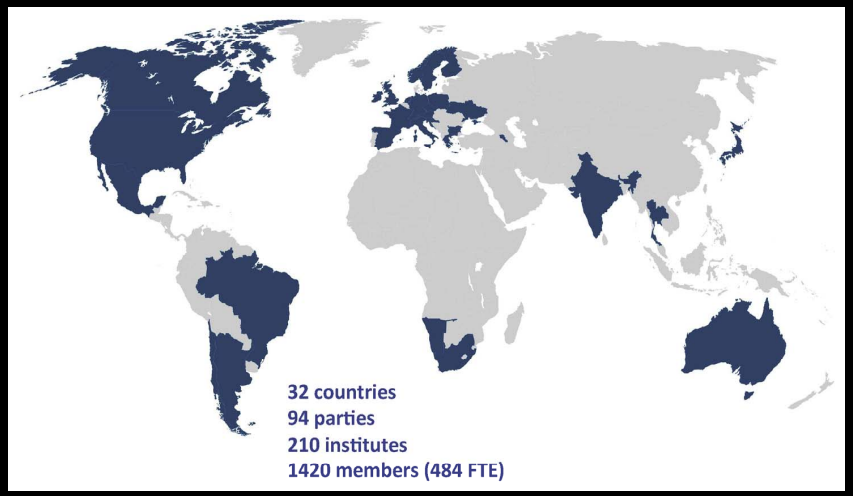


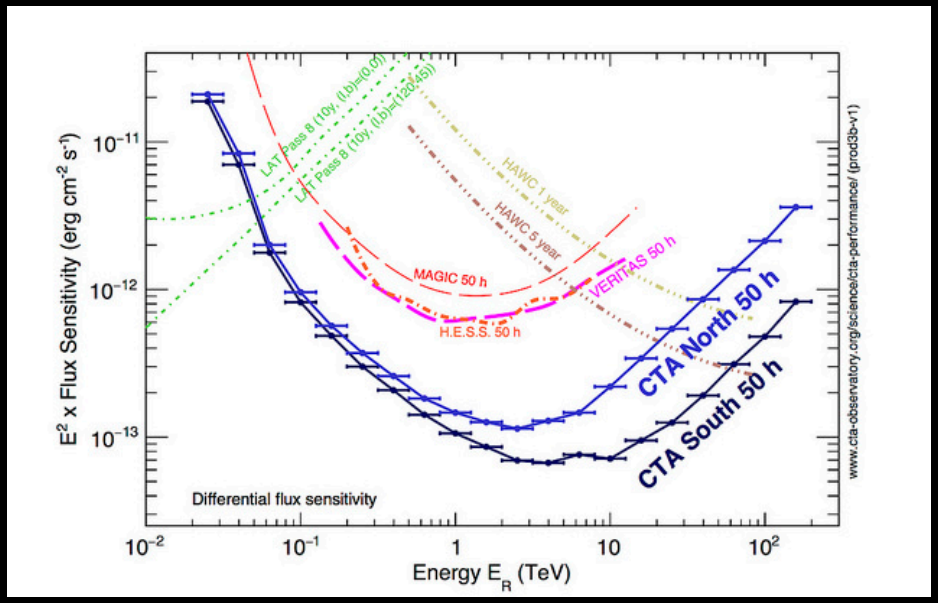
- DM mass the only additional d.o.f.
- Any DM-SM mediator assumed to be heavy.
- Bad approx. for LHC

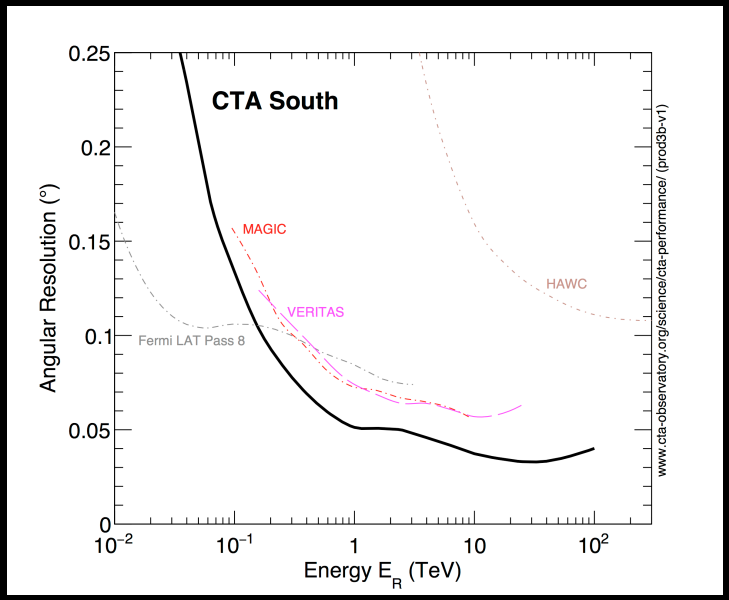


- At least one additional particle introduced that mediates

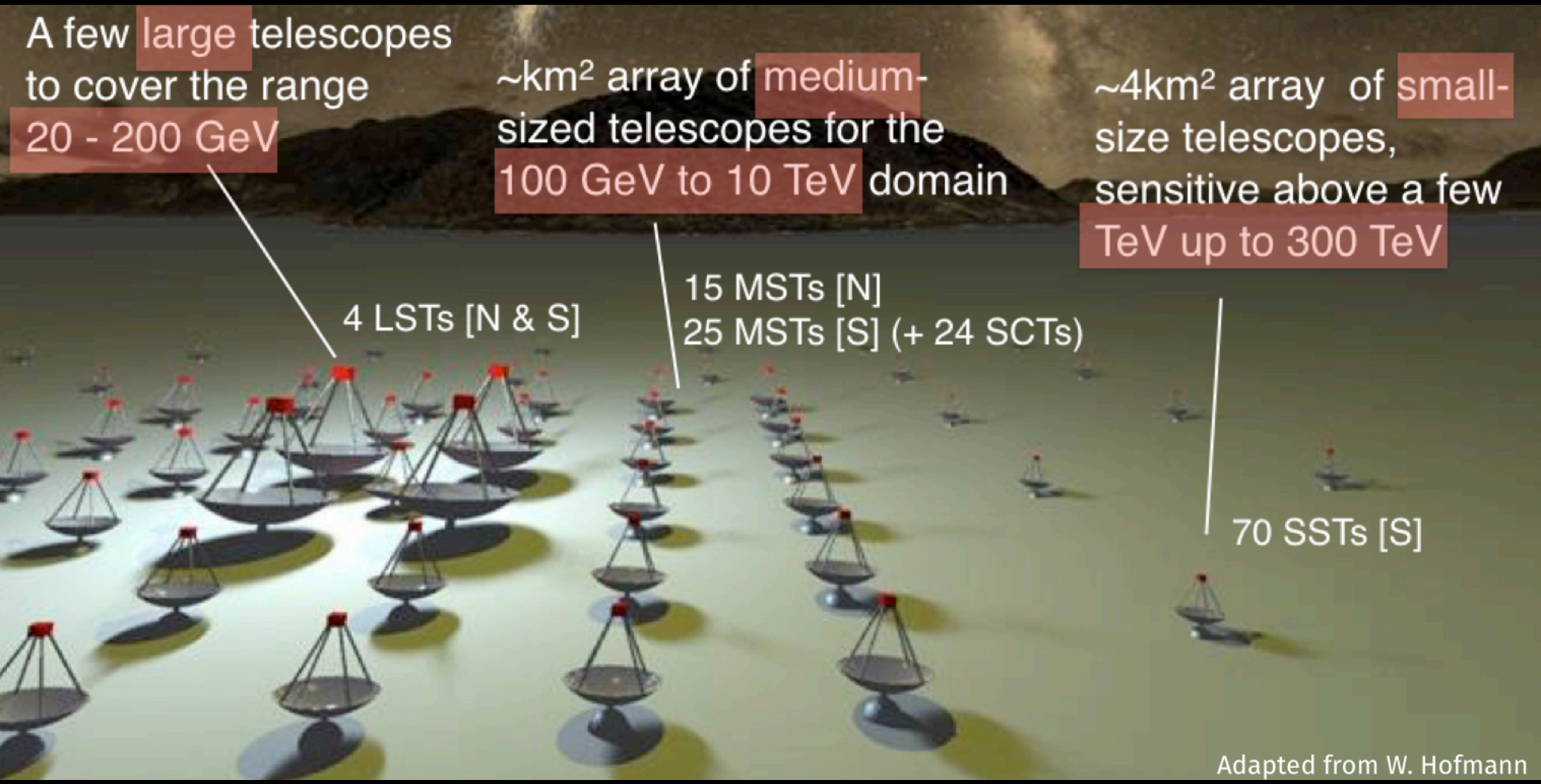
Cherenkov Telescope Array (CTA) essentials







CTA layout


A few large telescopes to cover the range 20 - 200 GeV
~km² array of medium-sized telescopes for the 100 GeV to 10 TeV domain
~4km² array of small-size telescopes, sensitive above a few TeV up to 300 TeV
4 LSTs [N & S]
15 MSTs [N]
25 MSTs [S] (+ 24 SCTs)
70 SSTs [S]
Adapted from W. Hofmann

Summary of *main* CTA science opportunities

arXiv: 1709.07997

The DM-induced gamma-ray flux

$$F(E_\gamma > E_{th}, \Psi_0) = J(\Psi_0) \times f_{PP}\left(E_\gamma > E_{th}\right)$$

photons cm^{-2} s^{-1}

Astrophysics | **Particle physics**

l.o.s. integration of the squared DM density

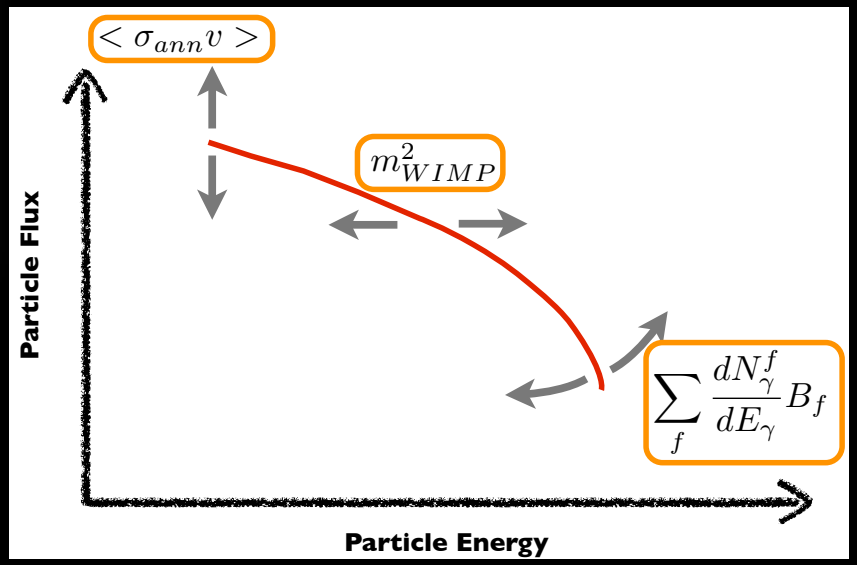
$$J(\Psi_0) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho^2_{DM}[r(\lambda)] d\lambda$$

$$f_{PP} \propto \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f \frac{\langle \sigma \cdot v \rangle}{m_\chi{}^2}$$

N_γ: photons/annihilation
$<\sigma v>$: thermal cross section
m_χ: WIMP mass

Where to search?

- Galactic Center
- Dwarf spheroidal galaxies
- Local galaxy clusters
- Nearby galaxies...



Particle Physics term:

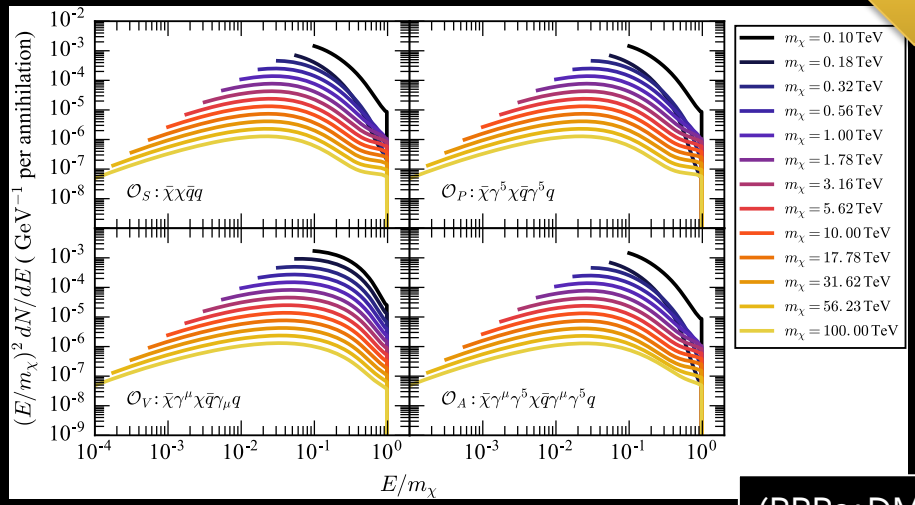
EFT and Simplified Models

Operators chosen to illustrate different levels of suppression

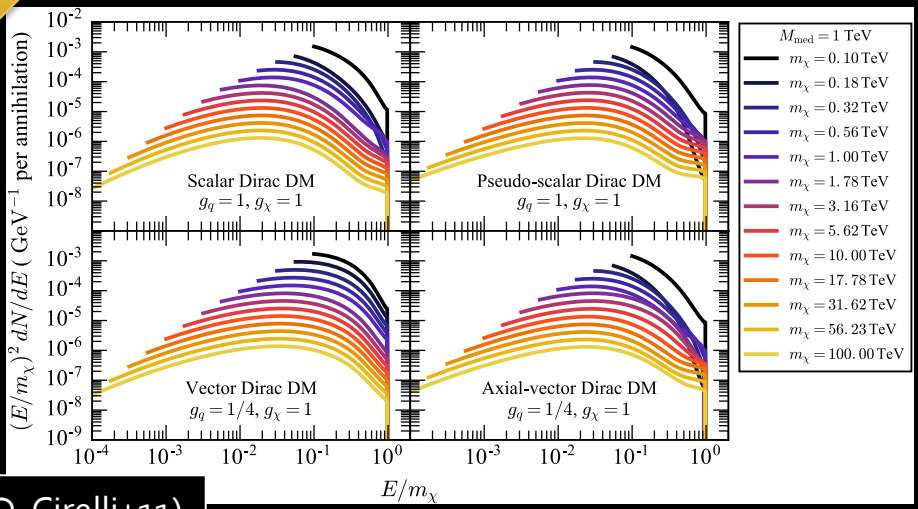
LEVELS OF SUPPRESSION

Operator/Mediator	Indirect detection	Direct detection
SCALAR	v^2	1
PSEUDOSCALAR	1	$(\vec{s}_\chi \cdot \vec{q})\,(\vec{s}_N \cdot \vec{q})$
VECTOR	1	1
AXIAL VECTOR	$m_q^2,\ v^2$	$\vec{s}_\chi \cdot \vec{s}_N$

Annihilation into quarks

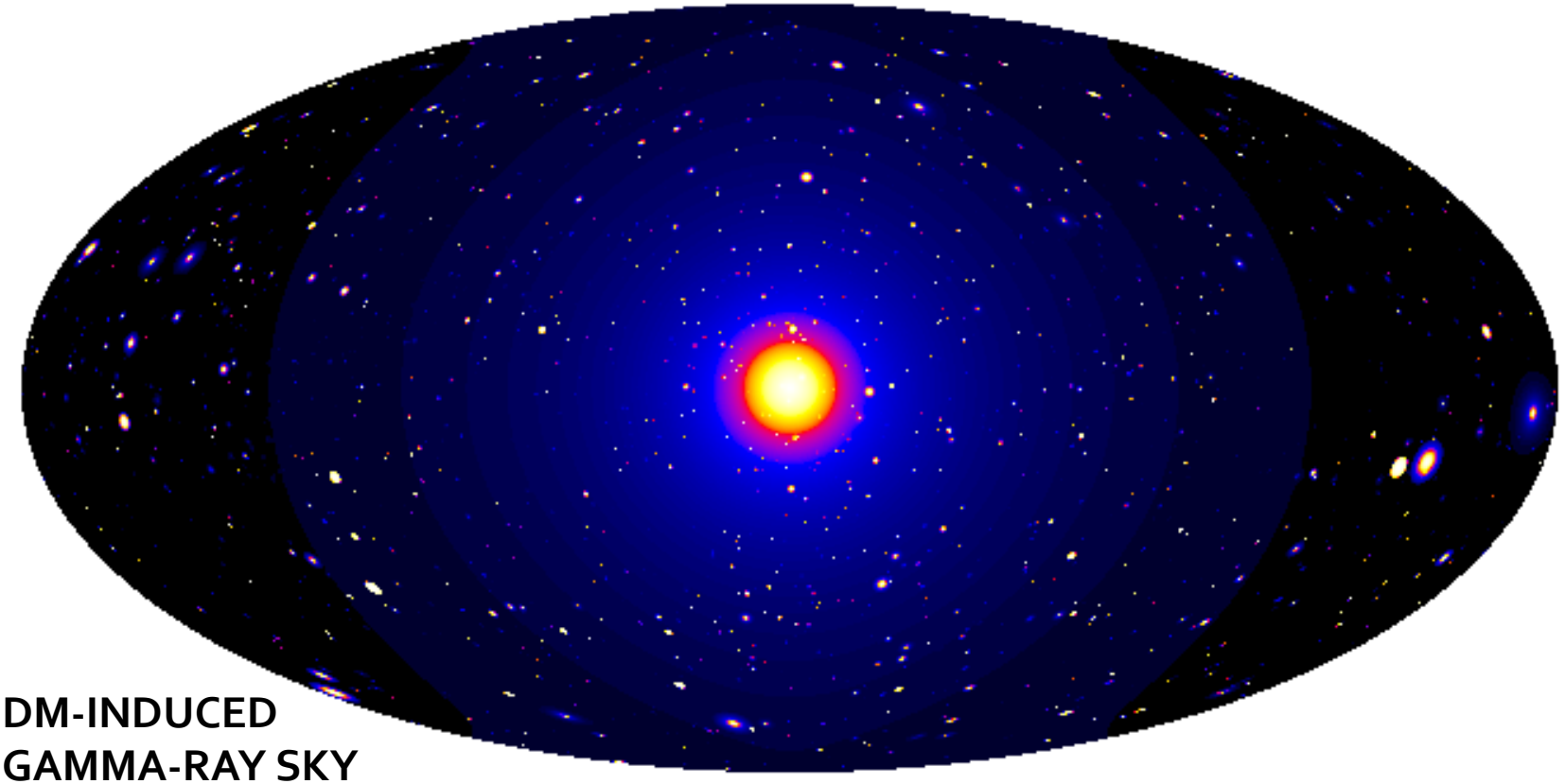


Simplified model for M_{med} = 1 TeV



(PPPC4DMID, Cirelli+11)

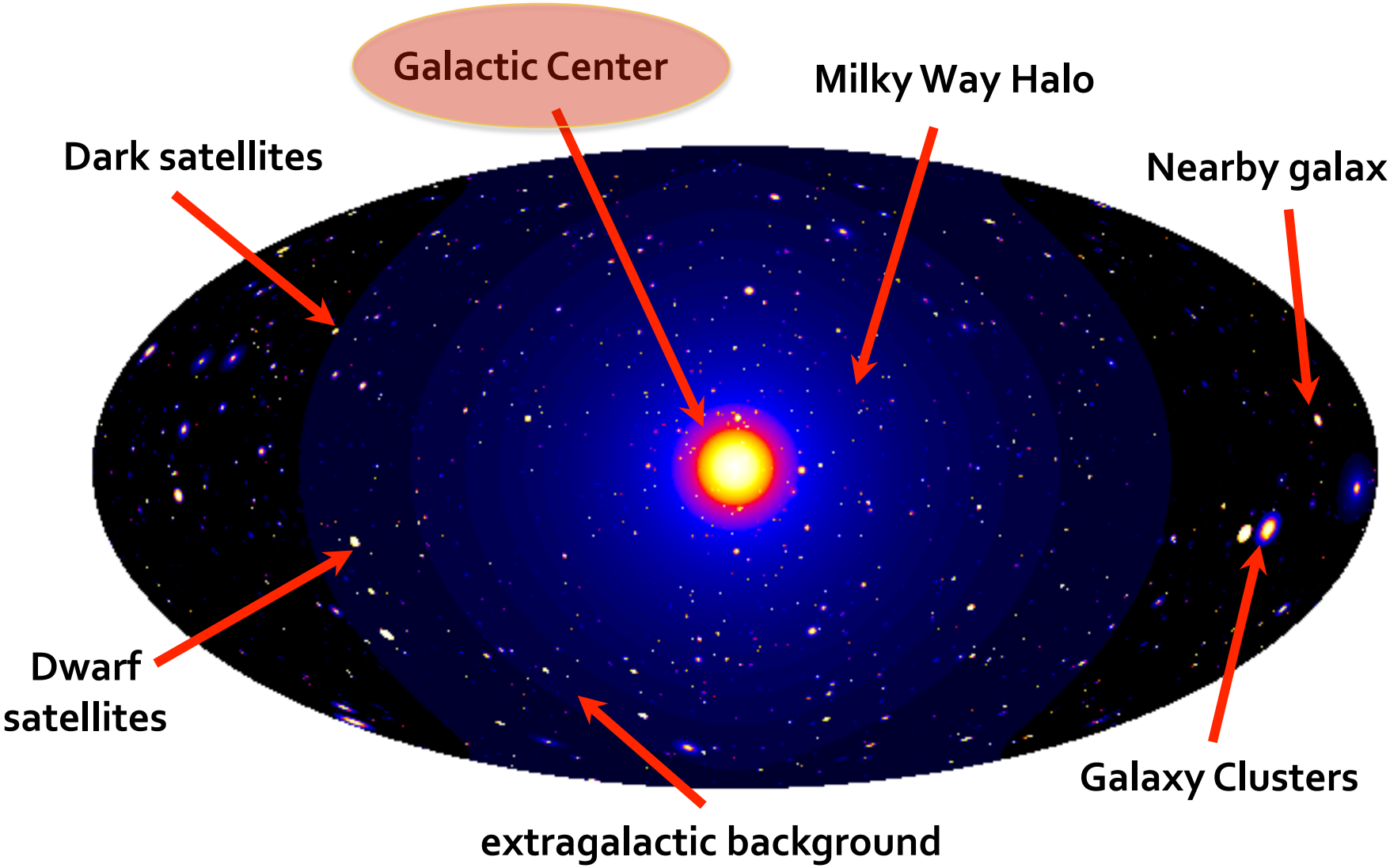
Target selection



DM-INDUCED GAMMA-RAY SKY

Dark Matter simulation:
Pieri+(2009) arXiv:0908.0195

Target selection

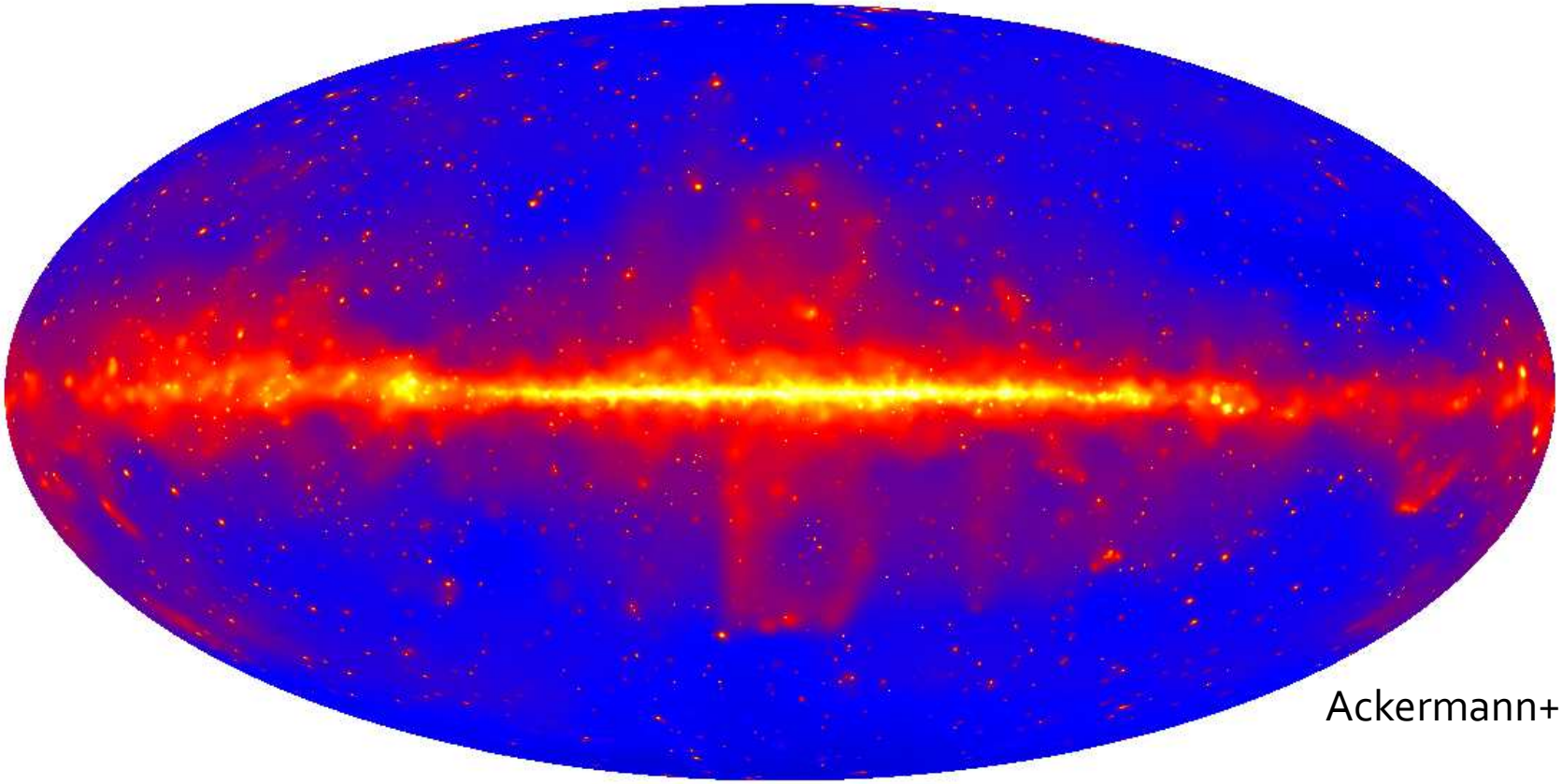


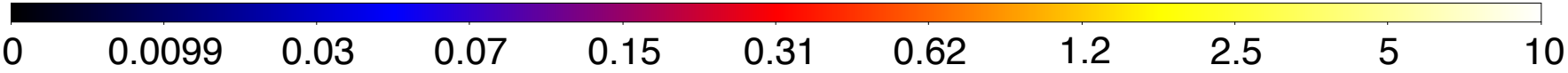
+ Spectral Lines

Dark Matter simulation: Pieri+(2009) arXiv:0908.0195

Gamma ray sky above 10 GeV

[7 years of Fermi LAT data]





Need to disentangle dark matter annihilations from 'conventional' astrophysics.

Crucial to understand the astrophysical processes in great detail.

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MORE IN WENIGER'S TALK

Galactic Center J-factors

$$J(\Psi_0) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho^2_{DM}[r(\lambda)] d\lambda$$

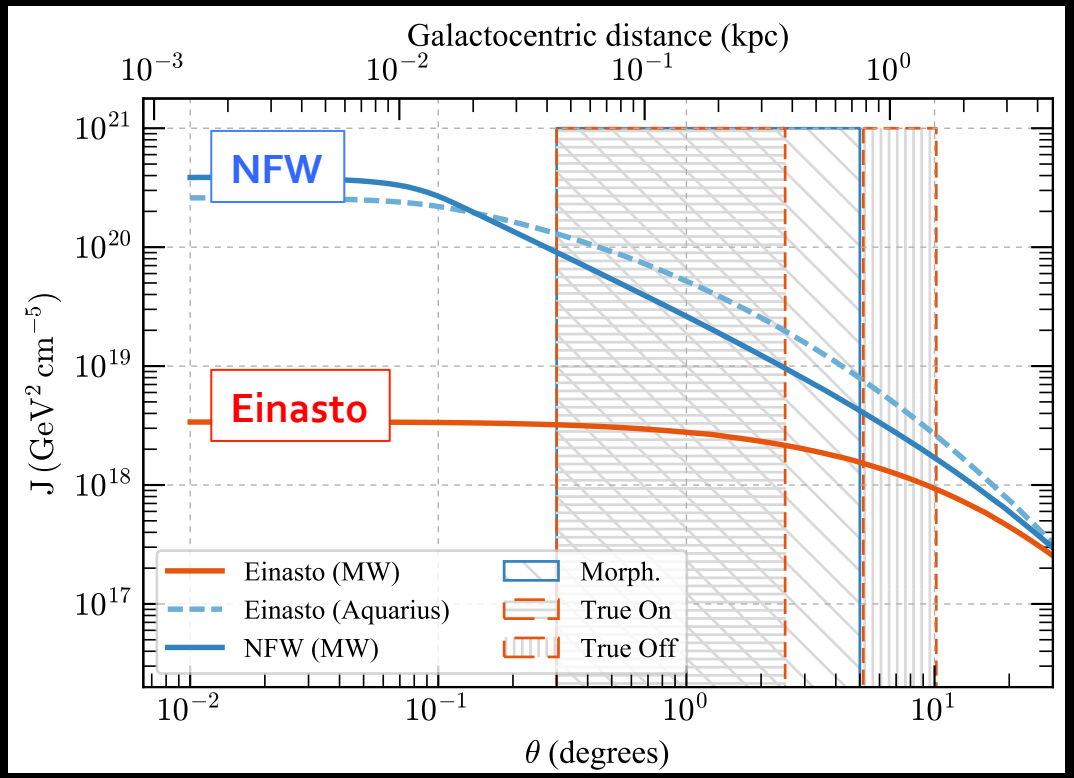
Two different DM density profiles with best-fit parameters from Milky Way rotation curves [Pato+15]

Navarro-Frenk-White (NFW):

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)\right]^2}$$

Einasto:

$$\rho_{\rm Ein}(r) = \rho_0 \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$$



[ρ_{local} = 0.42 GeV/cm^3; r_s = 20 kpc; α = 0.36]

CTA analysis strategy

- We simulate 100h of CTA observations of the GC between 30 GeV – 100 TeV
- Likelihood analysis in spectral and spatial bins.

DM SIGNAL

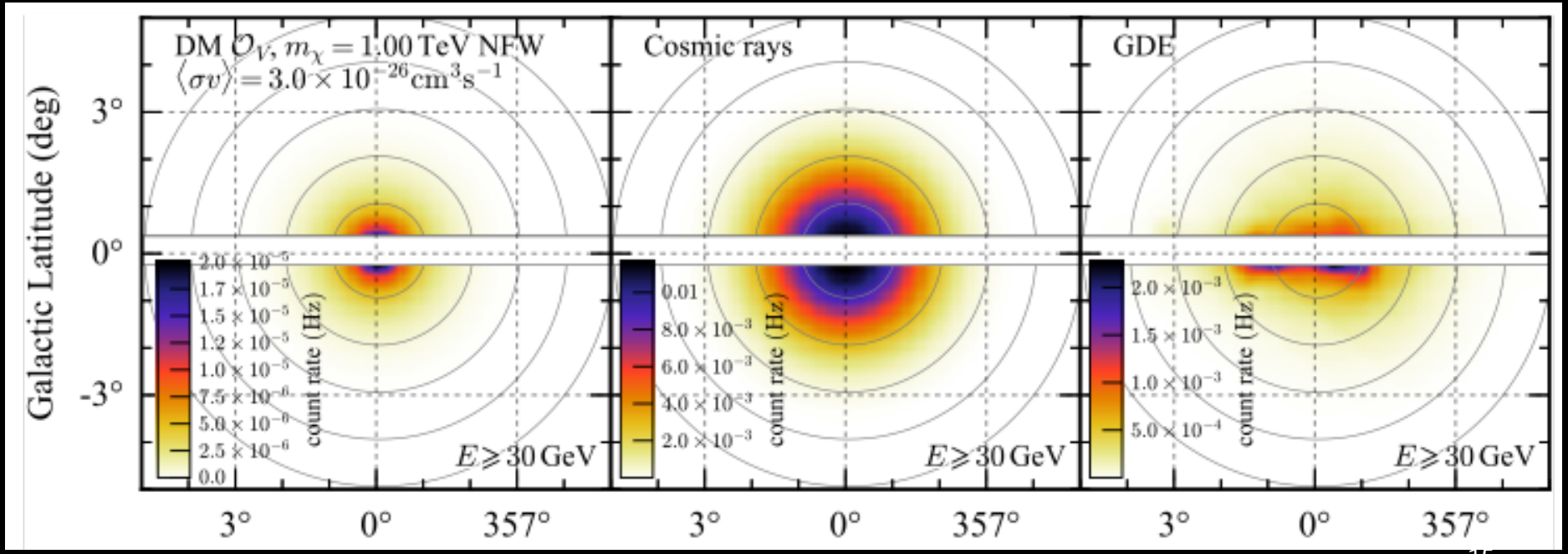
Spectra from EFT / Simplified models + J-factors from NFW / Einasto profiles

COSMIC-RAY BACKGRD

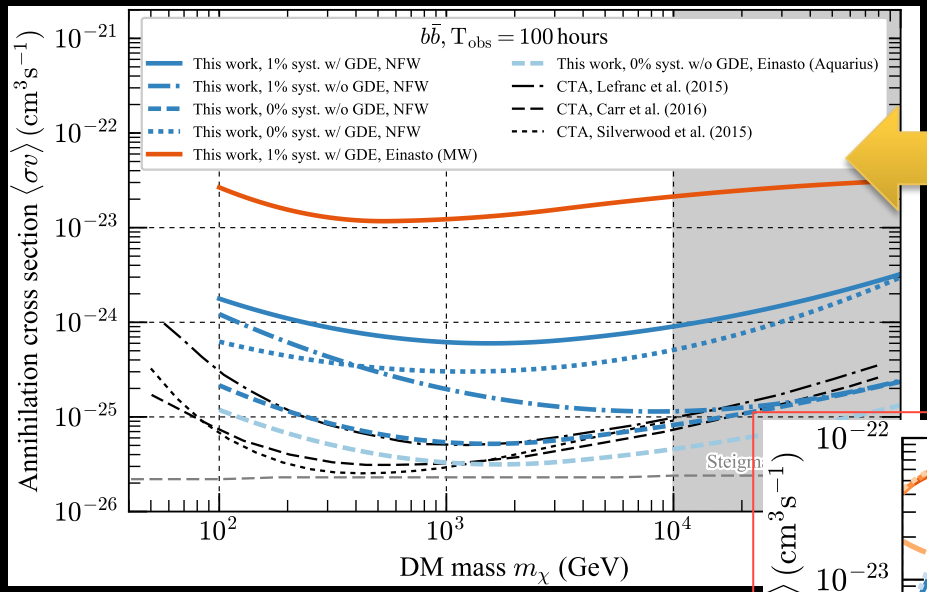
From CTA Monte Carlo simulations

GAL. DIFFUSE EMISSION

Extrapolation of Fermi LAT GDE models at high energies



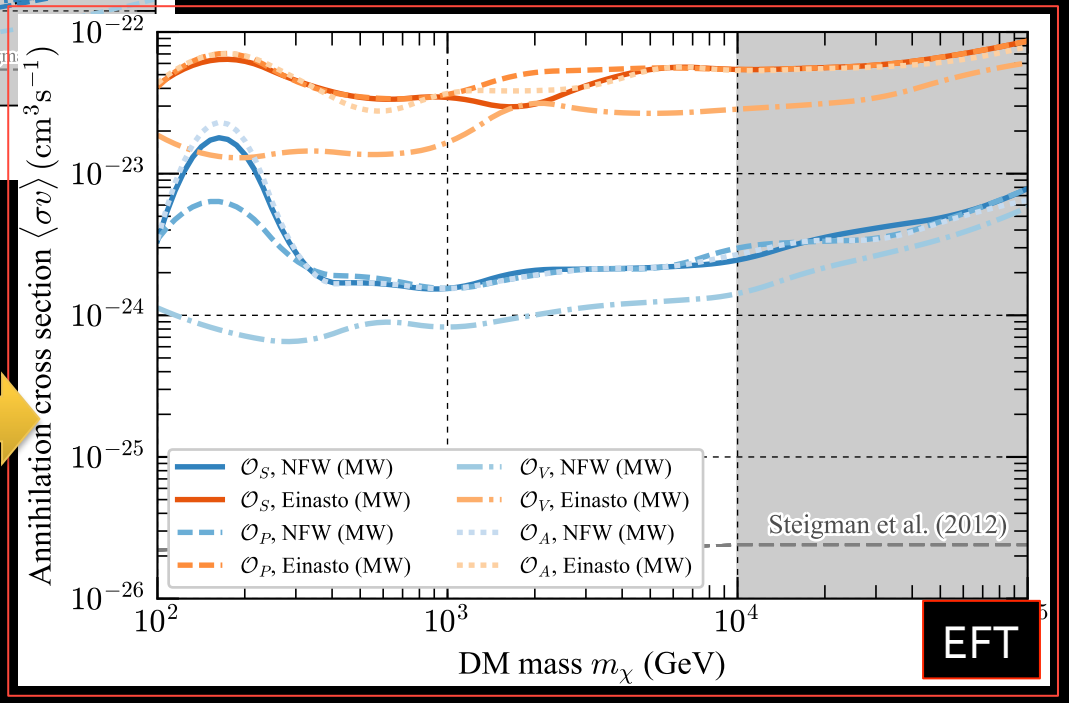
Limits to annihilation cross section



Comparison with previous work for annihilation to bb

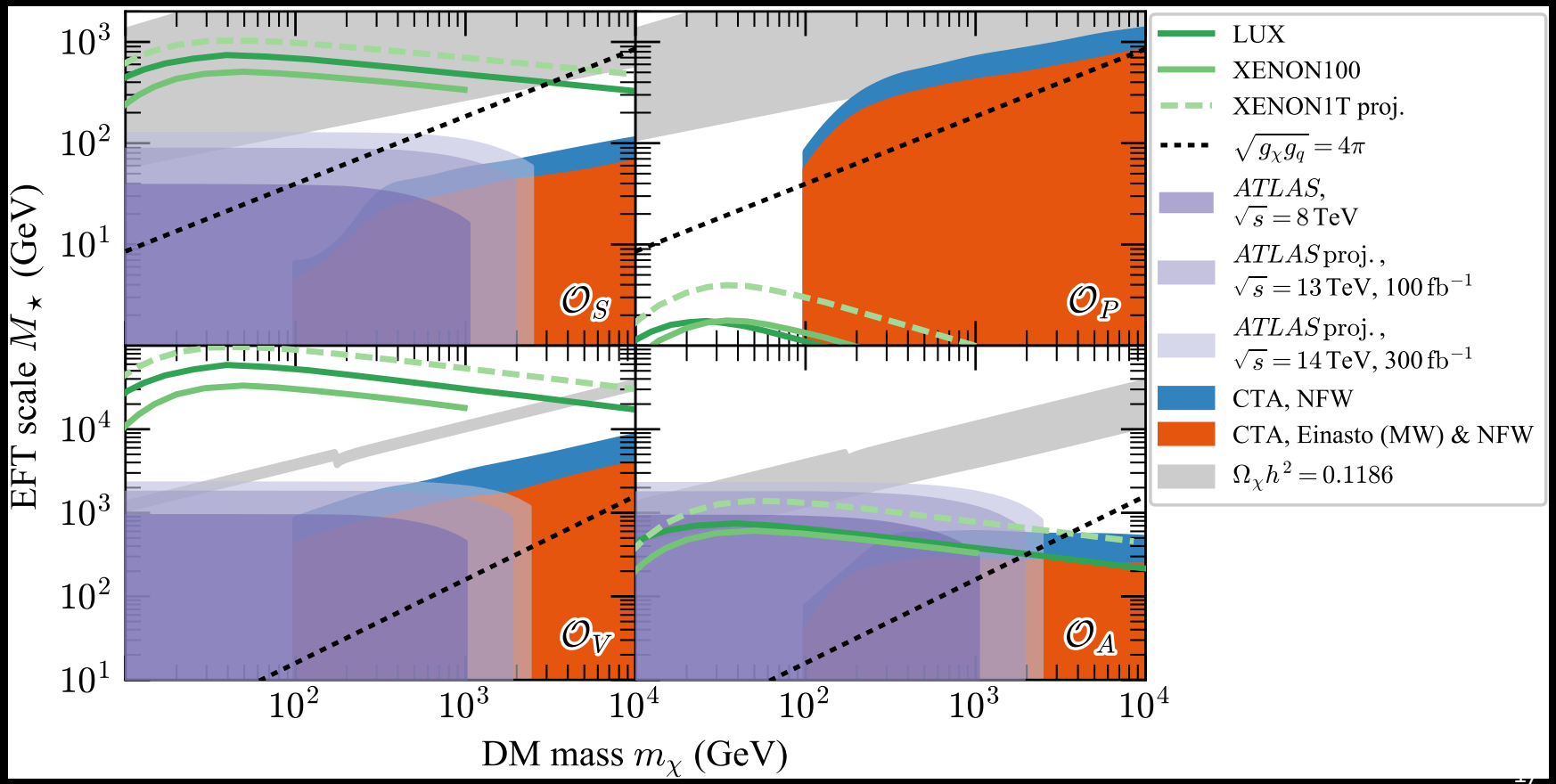
Same procedure to derive limits for EFT and Simplified Models.

Later converted into limits on EFT scale or limits on DM mass vs. mediator mass.



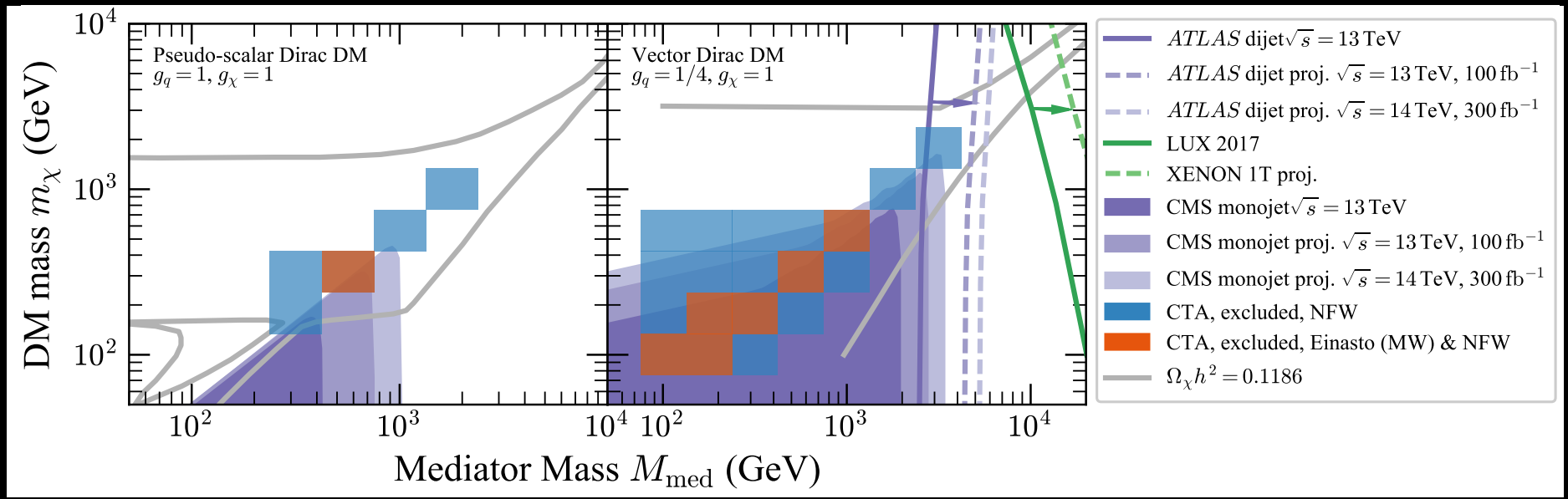
Lower limits on EFT scale

- Limits only valid above black dashed line
- Vector and pseudo-scalar case: CTA probes DM masses partially out of reach of LHC and DD experiments.



Limits for Simplified Models

- Pseudo-scalar: may outperform colliders and DD.
  - For NFW, can probe relic density.
- Vector case: already excluded by DD (for the adopted couplings).



[No points are excluded in the scalar Dirac DM case for $g_q = g_\chi = 1$ and none of the excluded parameters of the axial-vector model obey perturbative unitarity, thus these cases are not shown.]

Remarks

- DM search complementarity critical to unveil the nature of DM.
  - EFT and Simplified Models provide a meaningful way to compare between ID, DD and LHC results.
- CTA will be competitive compared to DD and LHC.
  - Especially sensitive to pseudo-scalar and vector mediated DM.
  - For pseudo-scalar, CTA can probe parameter space not reachable by LHC and DD.
- Our results illustrate the need for different techniques (ID, DD, colliders).

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ADDITIONAL MATERIAL

Present gamma-ray observatories

E. range: 20 MeV → 1 TeV
E. resolution: ~10% @ GeV
FoV: ≈ 2.4 sr
Angular res.: ~0.2°@10 GeV
Aeff ~ m^2

Fermi LAT
[>2008]

E. range: 0.1 → 100 TeV
E. resolution: ~20% @ 10 TeV
FoV: ≈ 2 sr
Angular res.: ~0.2°@10 TeV
Aeff ~22,000 m^2

HAWC
[>2015]

MAGIC
[>2003]

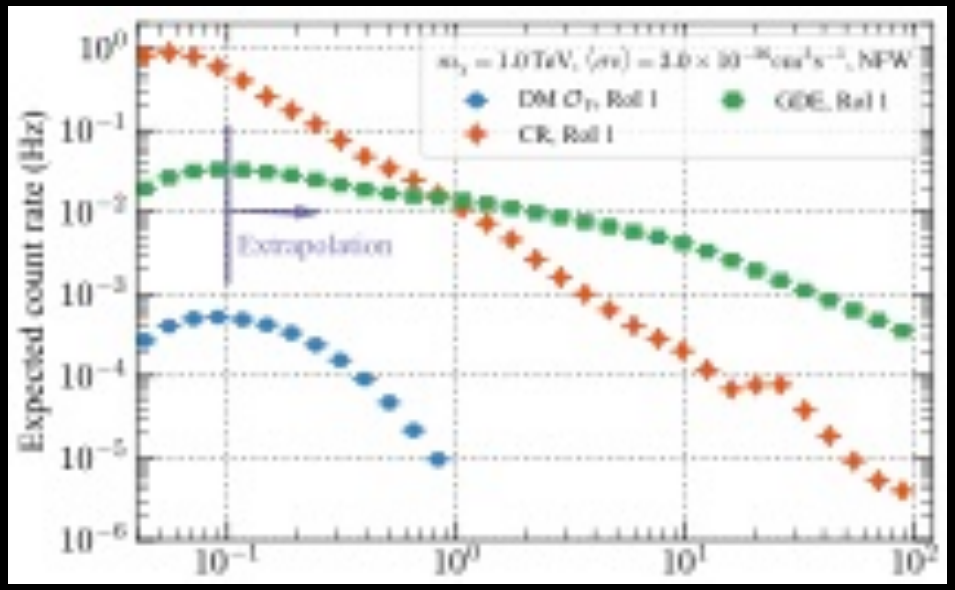
HESS
[>2002]

VERITAS
[>2006]

E. range: 50 GeV → 10TeV
E. resolution: ~20%
FoV: ≈ 4 deg.
Angular res.: ≈ 0.1°
Aeff ~ 10^5 m^2

DESY/Milde Science Comm./Exozet

ctools v1.0.1 to extract expected number of counts (Asimov data set)	
IRFs	prod 2 south 50 hrs
Energy range	30 GeV - 100 TeV
Spectral binning	10 bins per decade
Spatial binning	0.0625 deg / pixel
Assumed observation time	100 hours



LIKELIHOOD ANALYSIS

[Roughly following Silverwood et al. (2015)]

- **Likelihood given by sum over spatial and spectral bins** *i,j;* α term characterizes systematics:

$$\ln \mathcal{L} = \sum_{i,j} \left[n_{ij} \ln(\alpha_{ij} \mu_{ij}) - \mu_{ij} \alpha_{ij} - \frac{(1-\alpha_{ij})^2}{2\sigma_\alpha^2} \right] + C$$

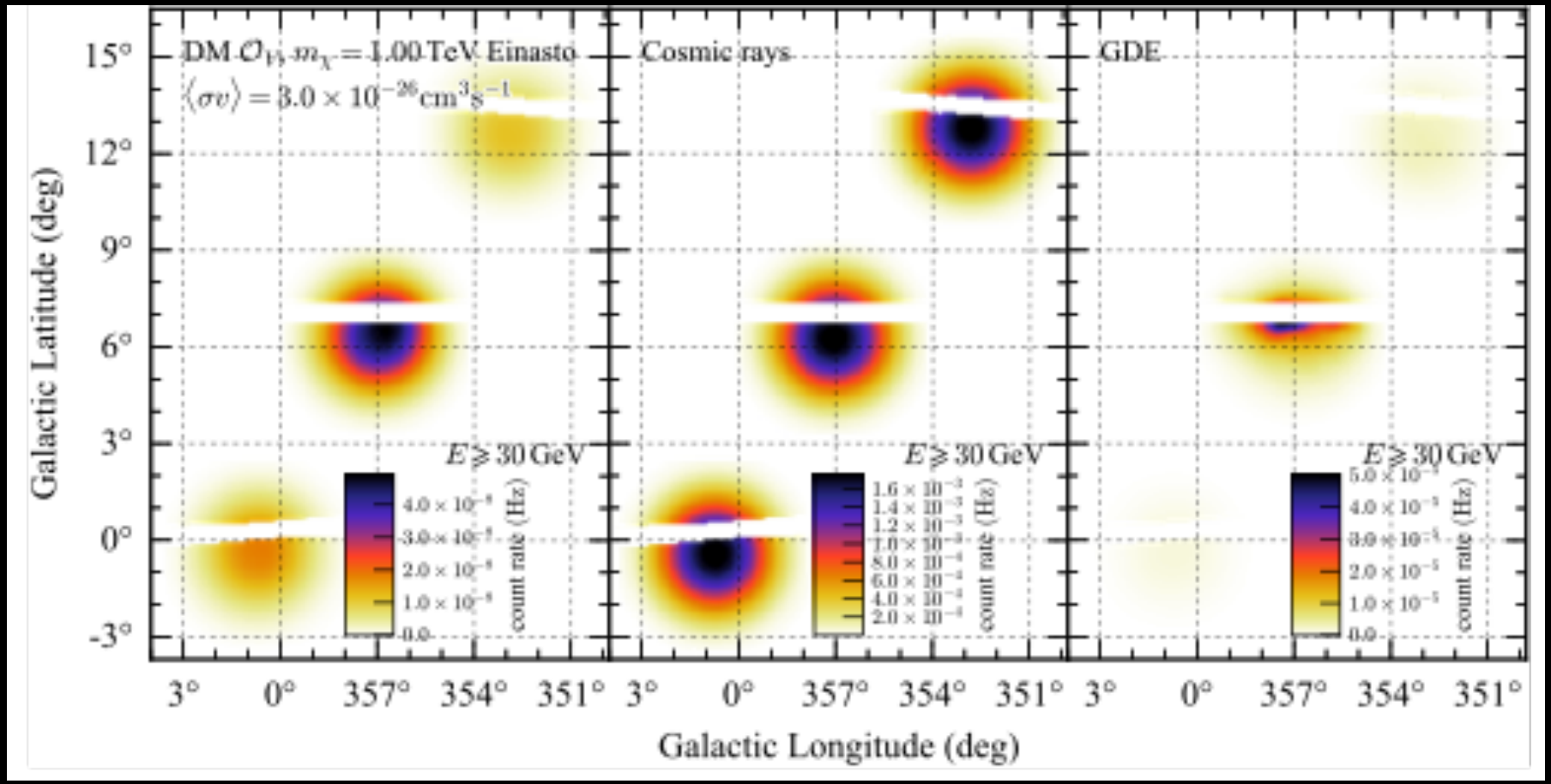
- **Expected number of counts**:

$$\mu_{ij} = \mu_{ij}^{\mathrm{DM}}(m_\chi, \langle \sigma v \rangle) + N^{\mathrm{GDE}} \mu_{ij}^{\mathrm{GDE}} + N^{\mathrm{CR}} \mu_{ij}^{\mathrm{CR}}$$

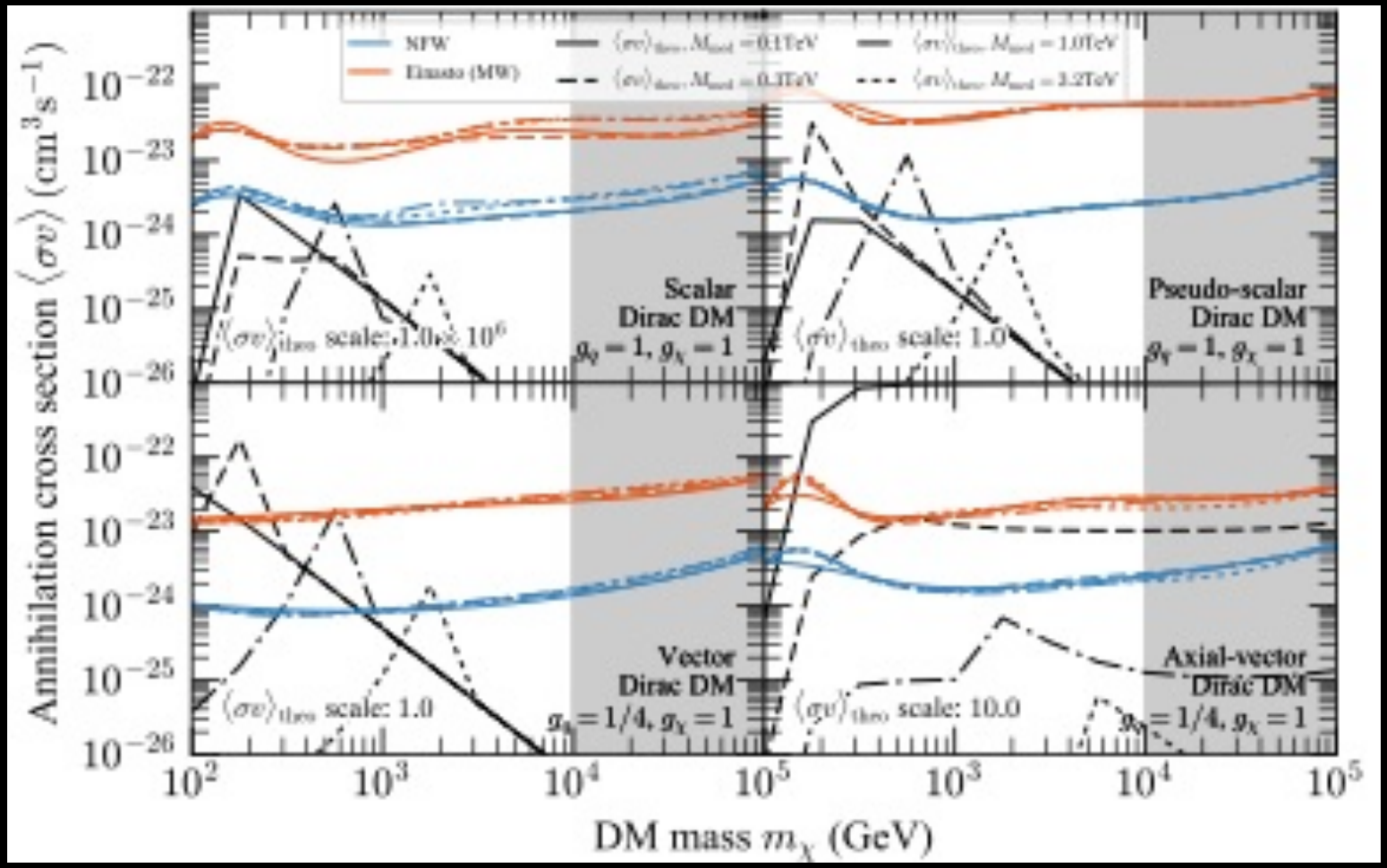
- μ^{x} ***x = DM, GDE, CR*** are expected number of counts **derived from ctools** within each energy bin and spatial bin
- Fit parameters: $\langle \sigma v \rangle$, N^{GDE}, N^{CR}, α for each energy bin
- σ_α taken to be 1% (account for systematics in e.g. acceptance)
- Using **Asimov data set**: $n_{ij} = \mu_{ij}$ with $\langle \sigma v \rangle = 0$, $N^{\mathrm{GDE}} = 1$, $N^{\mathrm{CR}} = 1$, $\alpha = 1$
- Limit on $\langle \sigma v \rangle$ found by increasing $\langle \sigma v \rangle$ from best fit until $-2\Delta\ln(\mathscr{L}) = 2.71$

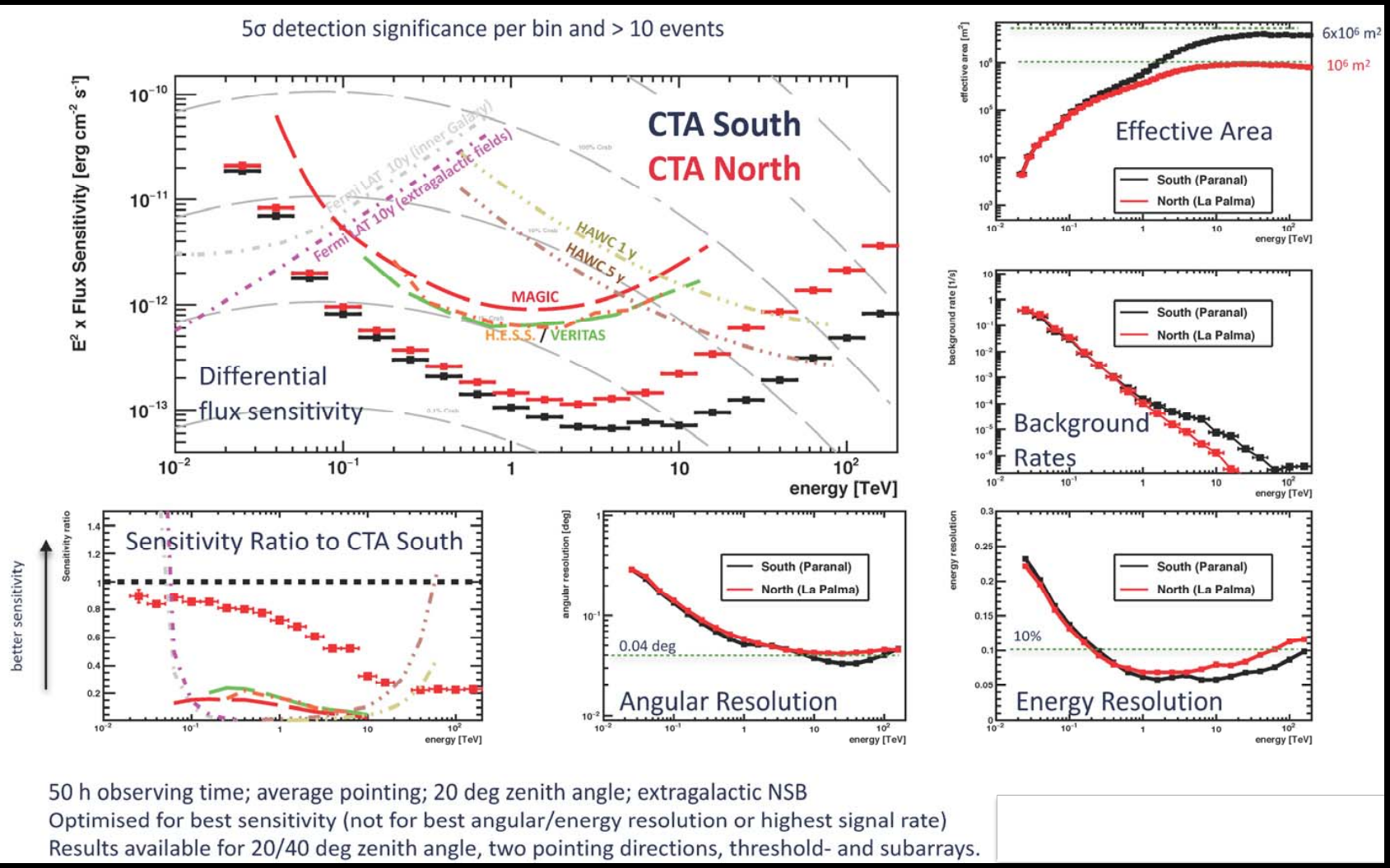
Courtesy of M. Meyer

Observation strategy for Einasto



Limits on annihilation cross section for Simplified Models





50 h observing time; average pointing; 20 deg zenith angle; extragalactic NSB
Optimised for best sensitivity (not for best angular/energy resolution or highest signal rate)
Results available for 20/40 deg zenith angle, two pointing directions, threshold- and subarrays.