Cherenkov Telescope Array Sensitivity to the Putative Millisecond Pulsar Population responsible for the Galactic Center Excess

ICRC 2021: The Astroparticle Physics Conference, Berlin, Germany.

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arXiv:2102.05648, Accepted by MNRAS

July 21, 2021

Kavli IPMU (Tokyo U.) & GRAPPA (Amsterdam U.)

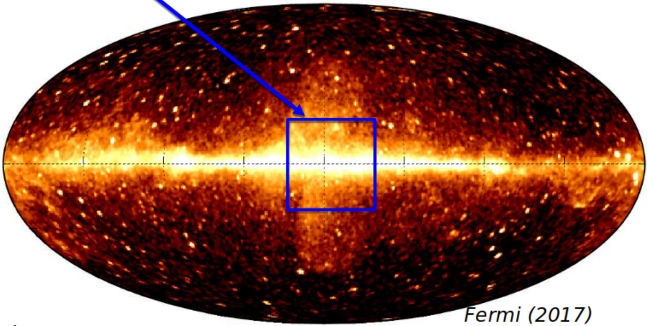
The Galactic Center Excess

From the Galactic Center out to mid-latitudes

Goodenough & Hooper (2009)
Vitale & Morselli, Phys.Lett.B (2009)
Hooper & Goodenough, PRD (2011)
Hooper & Linden, PRD (2011)
Boyarsky et al. PRD (2011)
Abazajian & Kaplinghat, PRD (2012)
Gordon & Macias, PRD (2013)
Hooper & Slatyer PRD (2013)
Huang et al. PRD (2013)
Macias & Gordon, PRD (2014)
Abazajian et al. PRD (2014, 2015)
Calore et al. JCAP (2014)
Zhou et al. PRD (2014)
Daylan et al. PRD (2014)
Macias et al. MNRAS (2016)
Selig et al. JCAP (2015)
Huang et al. PRD (2015)
Gaggero et al. PRD (2015)
Carlson et al. PRD (2015, 2016)
Yang & Aharonian, A&A (2016)
Horiuchi et al. JCAP (2016)
Lee et al. PRL (2016)
Linden et al. PRD (2016)
Ackermann et al. ApJ (2017)
Ajello et al. ApJ (2017)
Macias et al. Nat. Astr. (2018)
Bartels et al. Nat. Astr. (2018)
Macias et al. JCAP (2019)
Abazajian et al. (2020)
... (not a complete list)

Method

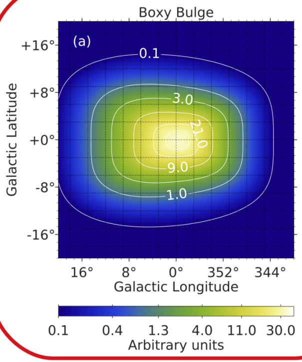
Found by morphological template fitting



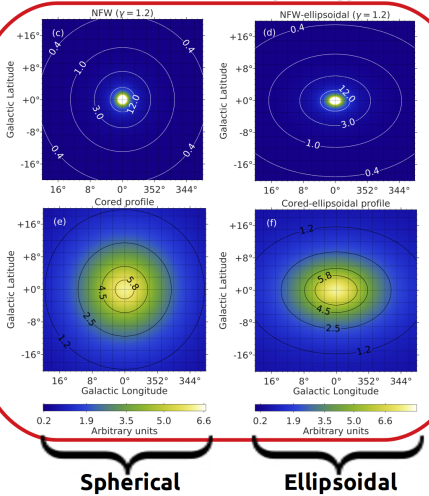
Fermi (2017)

The spatial morphology of Dark Matter is distinct from that of Millisecond Pulsars

Millisecond Pulsars distribution

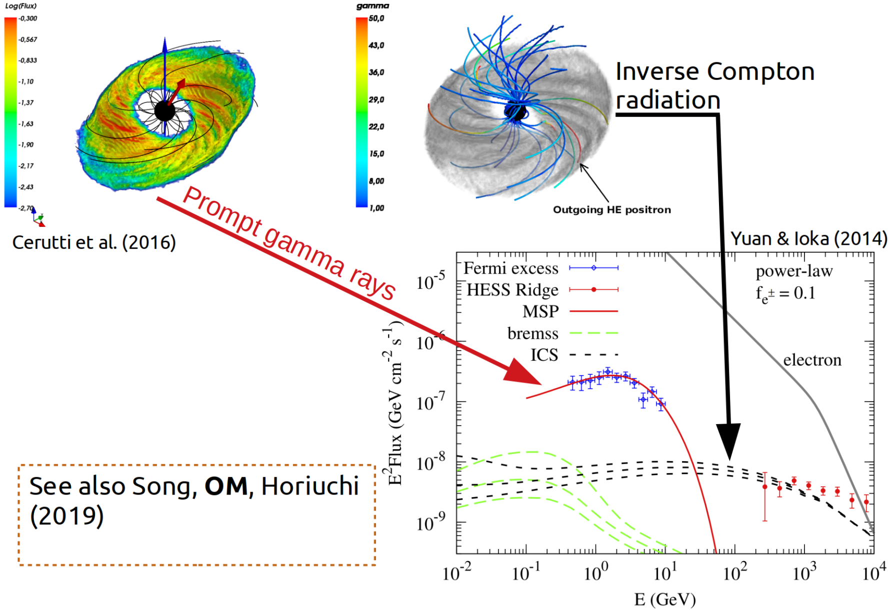


Dark Matter morphology



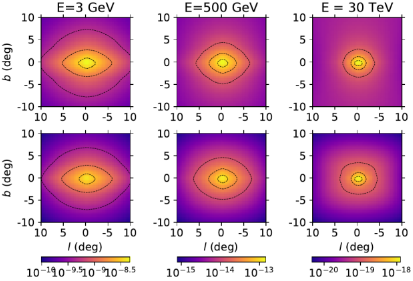
Abazajian, Horiuchi, Kaplinghat, Keeley, **OM** (2020), arXiv:2003.10416

Millisecond pulsar emission at the ∼ GeV–TeV energy scale



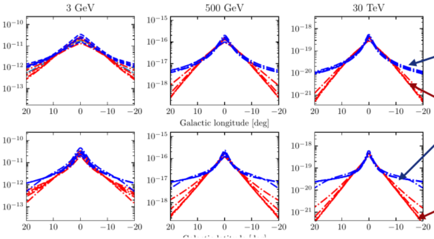
See also Song, **OM**, Horiuchi (2019)

MSPs and dark matter predicted inverse Compton maps



Inverse Compton from dark matter following spherical distribution

Inverse Compton from MSPs following a boxy bulge distribution



Spherical distribution

Peanut bulge distribution

Song, OM, Horiuchi [PRD 99 (2019) 12, 123020]

Specifications of the Analysis

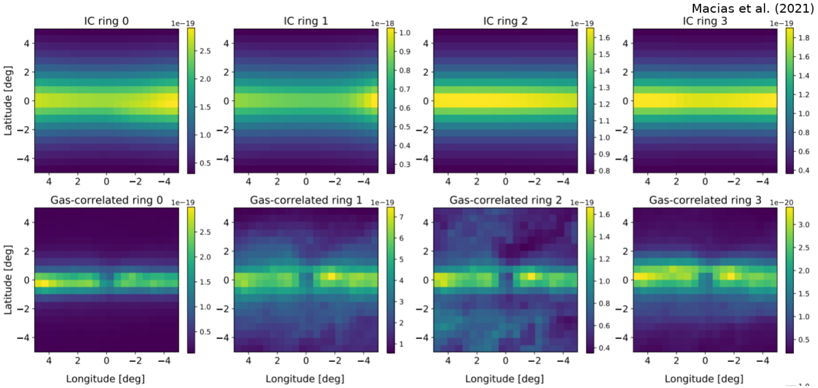
Data reduction procudure:

- Size of region of interest: $10^\circ \times 10^\circ$ around the Galactic Center.
- Mask: Galactic plane $|b| \leq 0.3^\circ$, point sources 3FHL catalog, and extended TeV sources.
- Instrument Response Function: `CTA-Performanceprod 3bv1-South-20deg-average-50h.root3`.
- Exposure: 500 hours.
- Energy range: 16 GeV - 158 TeV.
- Spatial bins: $0.5^\circ \times 0.5^\circ$.

Statistical Analysis:

- Spectrum: Binned maximum-likelihood procedure applied to each individual energy bin.
- Morphology: Maps divided in Galactocentric rings.

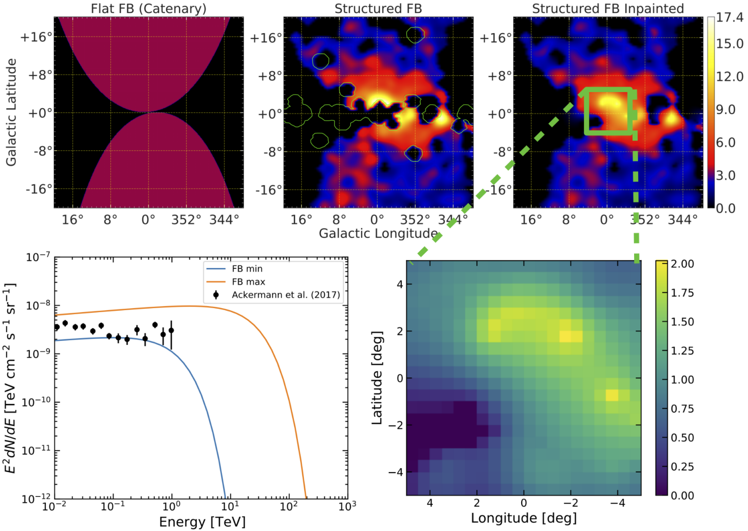
Galactic Diffuse Emission Model (γ-ray energy ≈ 11 TeV)



GALPROP simulation details:

- Assumed propagation parameter setup F98-SA50 in Johannesson et al. (2018)
- ['ring 0','ring 1', 'ring 2', 'ring 3']:=[0 – 3.5, 3.5 – 8.0, 8.0 – 10.0, 10.0 – 50.0] kpc.

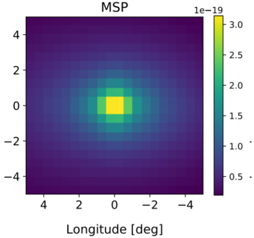
Low-Latitude Fermi Bubbles Model



Method:

Followed the same approach as in Rinchuso et al. (2020) [arXiv:2008.00692].

Simulation of the MSPs IC signals



Macias et al. (2021)

Model Name	Γ	$E_{\rm cut}$ (TeV)
Baseline	2.0	50
Inj1	1.5	50
Inj2	2.5	50
Inj3	2.0	10
Inj4	2.0	100

The injection spectrum of $e^{\pm}$:

$$\frac{dN_{e^\pm}}{dE} \propto E^{-\Gamma} \exp\left(-\frac{E}{E_{\rm cut}}\right)$$

Injection luminosity:

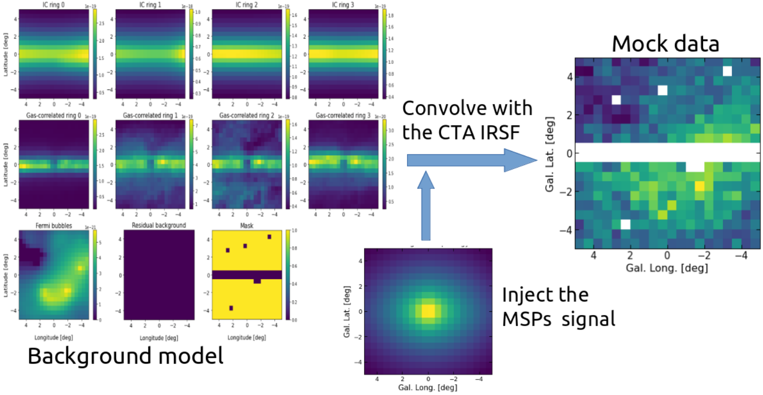
The γ-ray efficiency $f_\gamma \equiv L_{\gamma,\rm prompt}/\dot{E} \simeq 10\%$, with $\dot{E}$ the MSPs spin-down lominosity.

$$L_{e^\pm} = f_{e^\pm}\dot{E} = \frac{f_{e^\pm}}{f_\gamma} L_{\gamma,\rm prompt} \simeq 10 f_{e^\pm} L_{\gamma,\rm prompt},$$

$L^{\rm bulge}_{\gamma,\rm prompt} = (2.2 \pm 0.4) \times 10^{37}$ erg s^{-1} and $L^{\rm NB}_{\gamma,\rm prompt} = (3.9 \pm 0.5) \times 10^{36}$ erg s^{-1}. So, we can finally write:

$$L_{e^\pm} \simeq [(2.7 \pm 0.4) \times 10^{38}] f_{e^\pm} \quad [\rm erg/s]$$

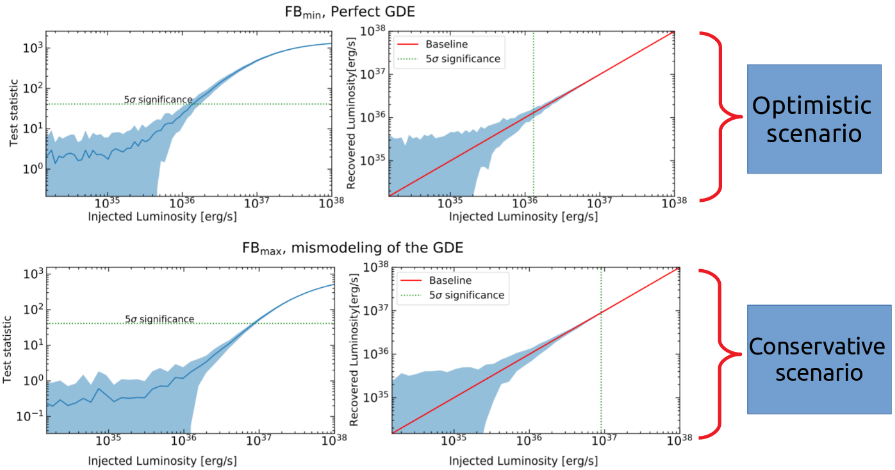
Summary of the Analysis pipeline



Fitting approach:

1. Optimistic Scenario: Fit the mock data with the same maps used in the simulations.
2. Conservative Scenario: Fit the mock data with an independent map (not used in the simulations).

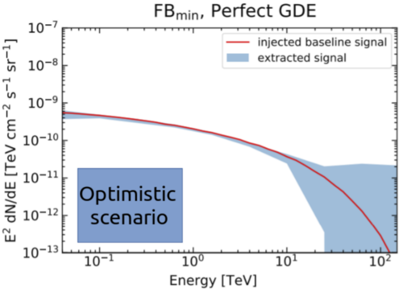
Results: signal recovery tests

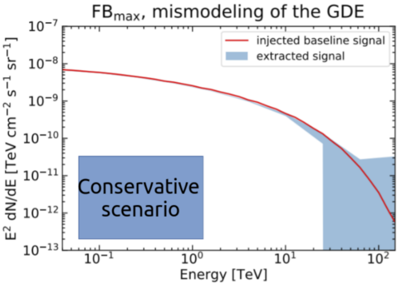


Main Result:

The signal sensitivity is highly dependent on how well the diffuse emission is modeled and the characteristics of the $e^{\pm}$ injection spectra.

Results: sensitivity to the putative population of GC MSPs



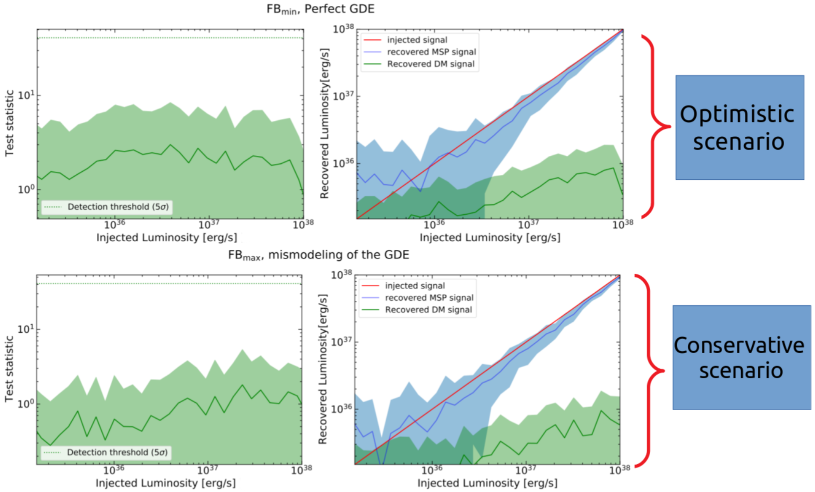


$$\frac{d^2N}{dE\,dt} \propto E^{-\Gamma} \exp(-E/E_{\rm cut}),$$

Model Name	Γ	$E_{\rm cut}$ (TeV)
Baseline	2.0	50
Inj1	1.5	50
Inj2	2.5	50
Inj3	2.0	10
Inj4	2.0	100

Minimum $f_{e^\pm}$ for detection [%]				
Baseline	**Inj1**	**Inj2**	**Inj3**	**Inj4**
FB$_{\rm min}$, perfect GDE.				
10.5%	2.9%	158.4%	24.3%	8.2%
FB$_{\rm max}$, mismodeling of the GDE.				
72.9%	51.8%	326.7%	70.4%	74.1%

Results: distinguishing MSPs from DM emission in the GC



Main Result:

CTA is capable of distinguishing whether the inverse Compton signal emanates from dark matter or MSPs based on the spatial morphology of the radiating source.

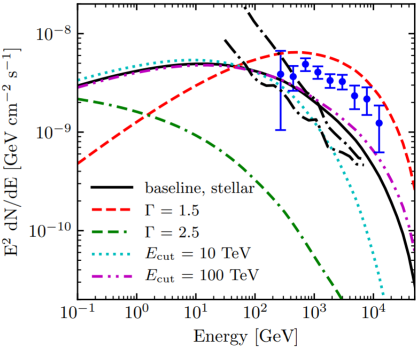
Conclusions

- CTA will potentially be able to probe the MSPs hypothesis for the Galactic center excess, for physically plausible $f_{e^\pm}$ values.

- CTA will have the sensitivity to disentangle a MSPs signal from a dark matter self-annihilation signal.

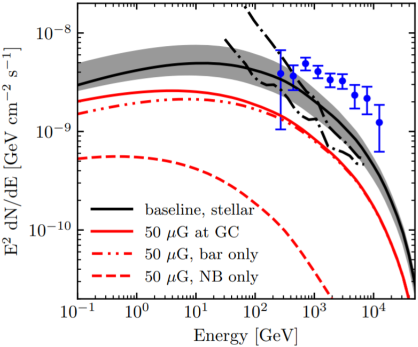
- We obtained reliable and well behaved fit results using a bin-by-bin analysis and breaking the gas maps in different Galactocentric rings.

Limits by H.E.S.S. measurements of the Galactic ridge.



Predictions at the Galactic ridge:

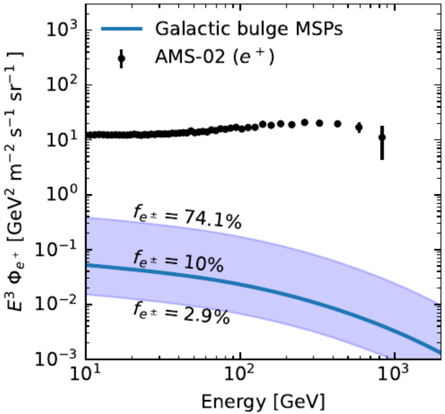
- Assume $f_{e^\pm} = 10\%$.
- Assume $B = 10; \mu$G at the GC.
- See Song et al. (2019).



Impact of the magnetic field:

- Assume $B = 50; \mu$G in the nuclear bulge .
- Contribution of the nuclear bulge drastically reduced, while not for the boxy bulge.

Implications for local CR measurements

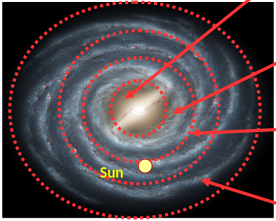


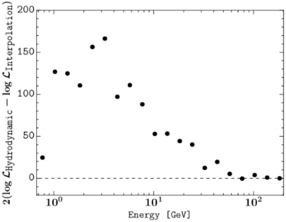
Predicted $e^\pm$ fluxes at Earth:

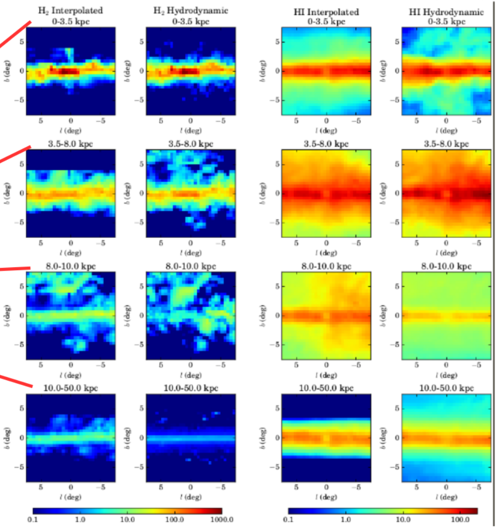
- Even for very high $f_{e^\pm}$ values, the $e^\pm$ accelerated by Galactic bulge MSPs are not expected to be observed by local CR detectors.

Astrophysical background: Interstellar gas.

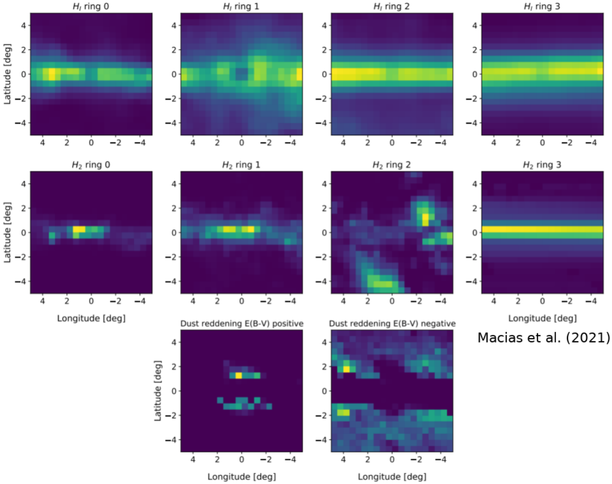
Macias et al. Nat. Astr.(2018)







Astrophysical background: Interstellar gas.

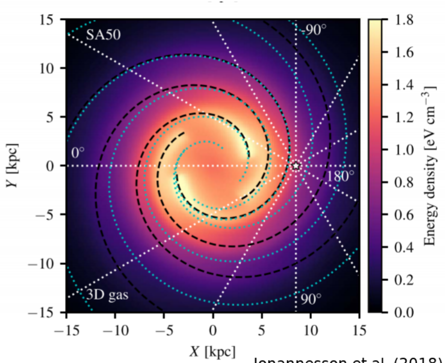


Macias et al. (2021)

Hydrodynamic gas templates:

Atomic hydrogen, molecular hydrogen and residual dust templates. These are publicly available on github https://github.com/chrisgordon1/galactic_bulge.

Astrophysical background: Alternative model.



Jonannesson et al. (2018)

GALPROP v56 setup:

- 3D spatial models for the interstellar radiation fields and interstellar gas.
- Diffusive reacceleration with $\Delta X \Delta Y \Delta Z = 0.2 \times 0.2 \times 0.1$ kpc^3 spatial resolution.

Macias et al. (2021)

Parameter	value
X_h [kpc]	±20.00
Y_h [kpc]	±20.00
Z_h [kpc]	±6.00
ΔX [kpc]	0.2
ΔY [kpc]	0.2
ΔZ [kpc]	0.1
$D_{0,xx}$ [10^{28} cm^{2}s^{-1}]	2.28
δ	0.545
$V_{\rm Alfven}$ [km s^{-1}]	5.26
γ_0	1.51
γ_1	2.35
R_1 [GV]	3.56
$\gamma_{0,H}$	1.71
$\gamma_{1,H}$	2.35
$\gamma_{2,H}$	2.19
$R_{1,H}$ [GV]	4.81
$R_{2,H}$ [GV]	200
$\gamma_{0,e}$	1.81
$\gamma_{1,e}$	2.77
$\gamma_{2,e}$	2.38
$R_{1,e}$ [GV]	5.97
$R_{2,e}$ [GV]	76

This model assumes same power of CR injection in the arms/disk (50% each).

MNRAS **000**, 1–22 (2021) Preprint 11 February 2021 Compiled using MNRAS LaTeX style file v3.0

Cherenkov Telescope Array sensitivity to the putative millisecond pulsar population responsible for the Galactic center excess

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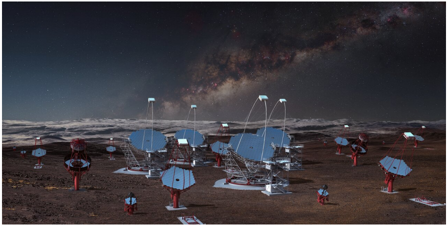
See more details in:

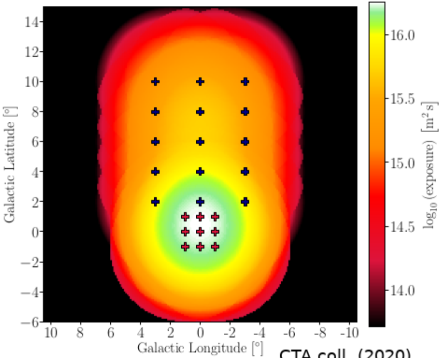
- **arXiv:2102.05648** (Accepted by MNRAS)

Sensitivity to MSPs from Galactic Center TeV-scale γ rays



Cherenkov Telescope Array:

- Beginning of observations in $\sim$ 2022.
- Energy resolution $\approx$ 10 GeV to 100 TeV.
- Angular resolution $\approx$ 0.2 to 0.02 deg.
- Southern site more sensitive to the Galactic Center.



CTA coll. (2020)

CTA observation strategy

- Multiple pointing observations of the Galactic Center.
- Diffuse observations achievable by stitching images together.