Searching for Dark Matter with the Southern Wide-field Gamma-ray Observatory (SWGO)

37th International Cosmic Ray Conference (ICRC) 2021, July 2021

Aion Viana
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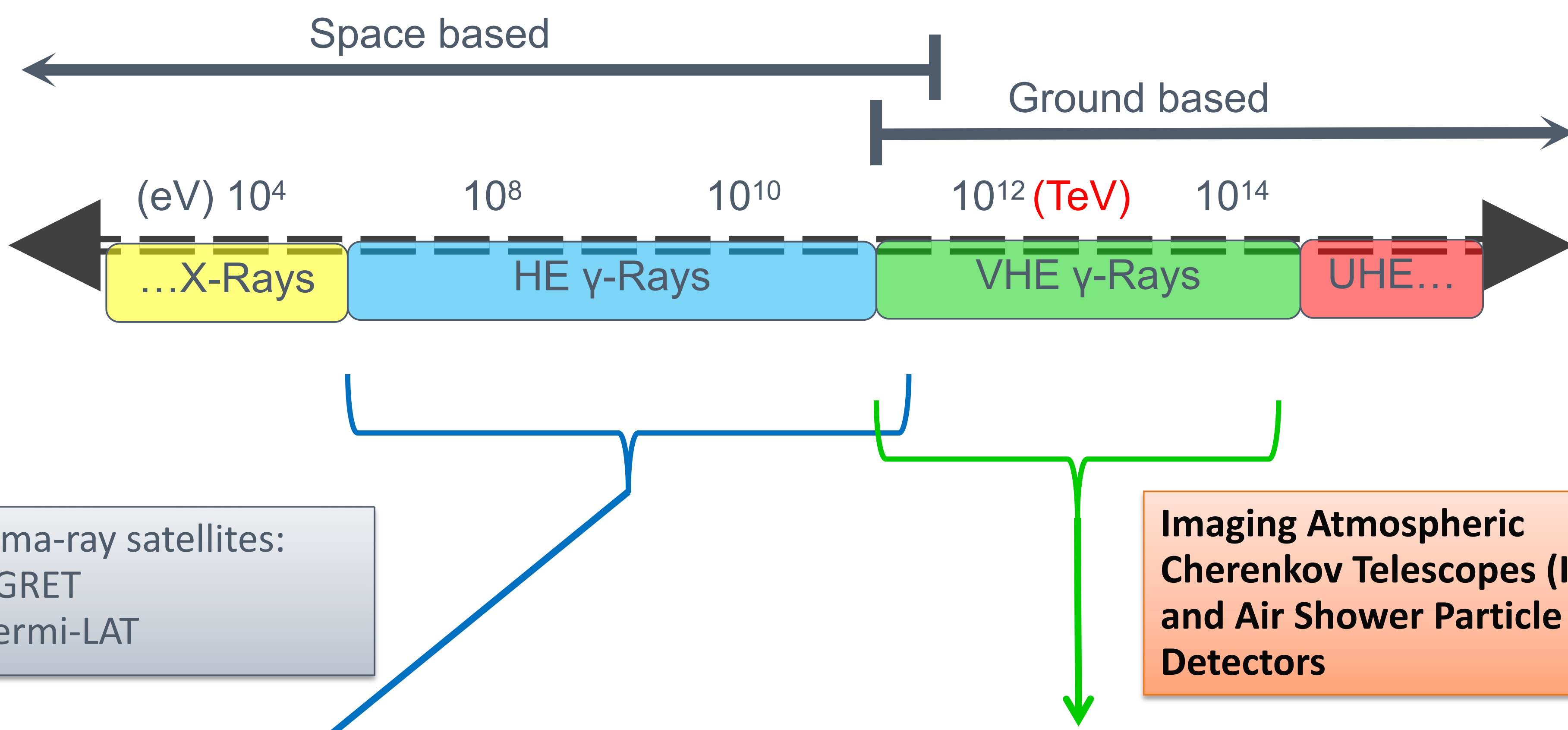
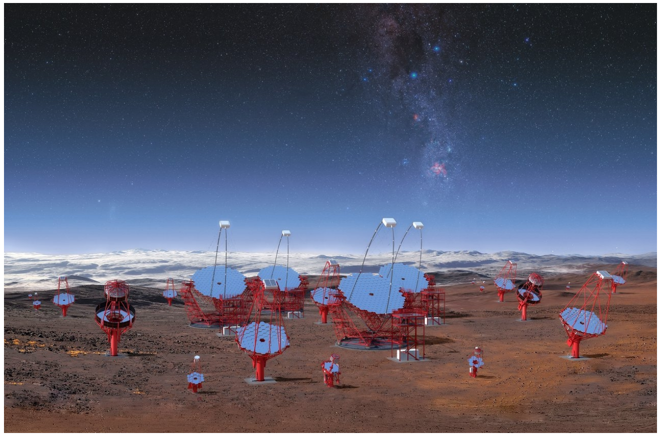
References:
- *AV, H. Schoorlemmer, A. Albert, V. de Souza, J. P. Harding, J. Hinton JCAP 2019 [arXiv:1906.03353]*
- *White paper: Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere, SGSO-alliance [arXiv:1902.08429]*

The extreme electromagnetic universe

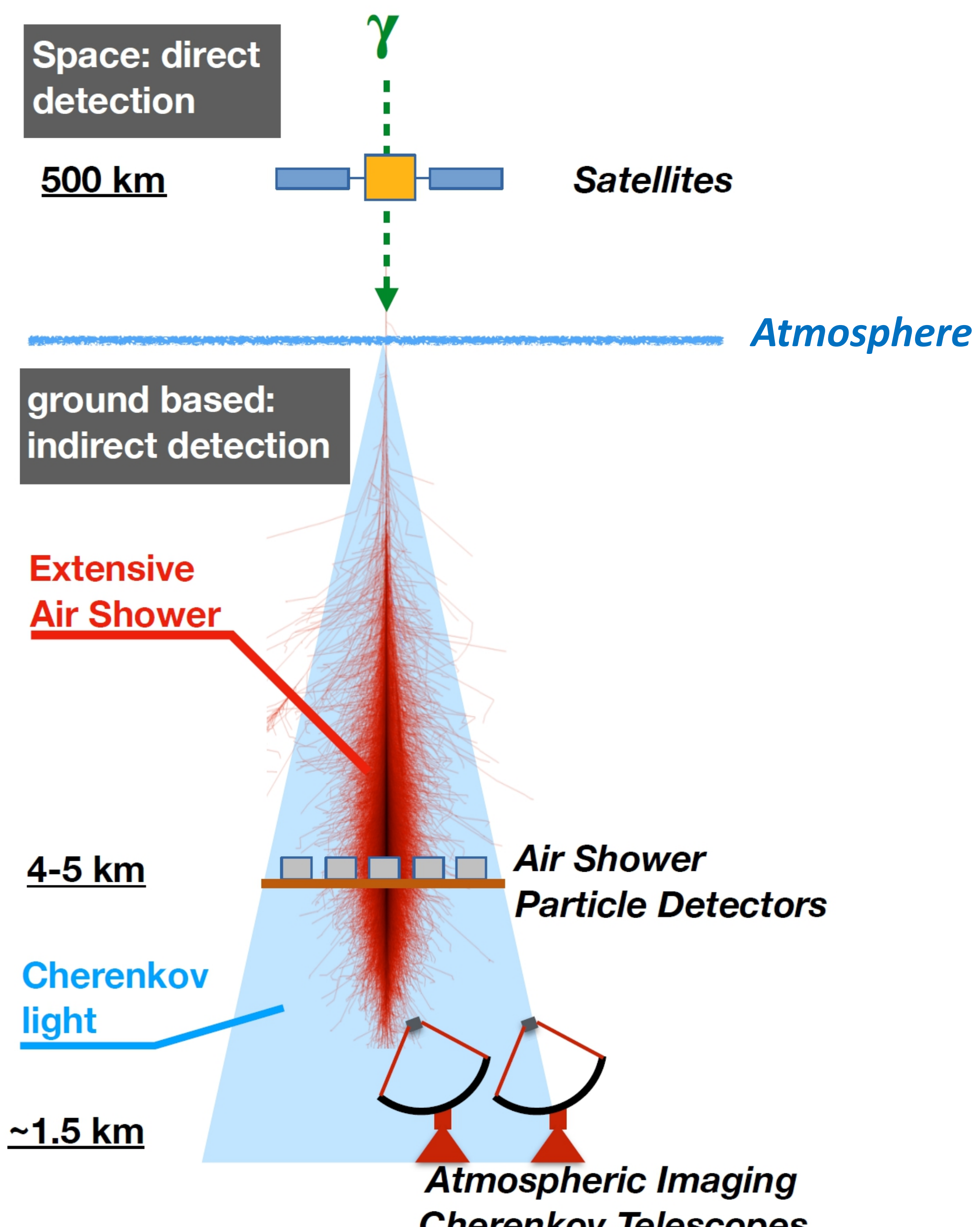


Gamma-ray satellites:
- EGRET
- Fermi-LAT

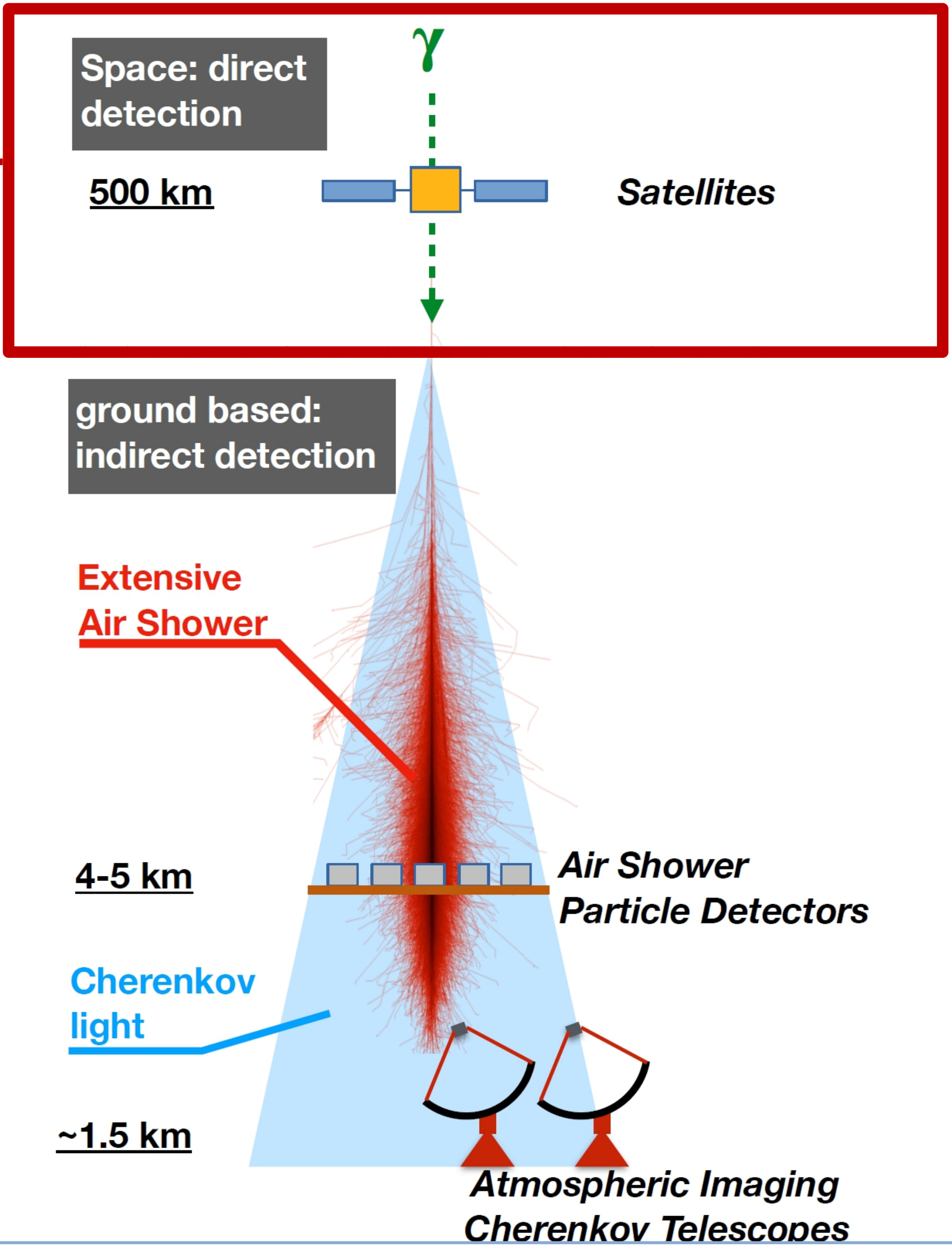
Imaging Atmospheric Cherenkov Telescopes (IACT) and Air Shower Particle Detectors



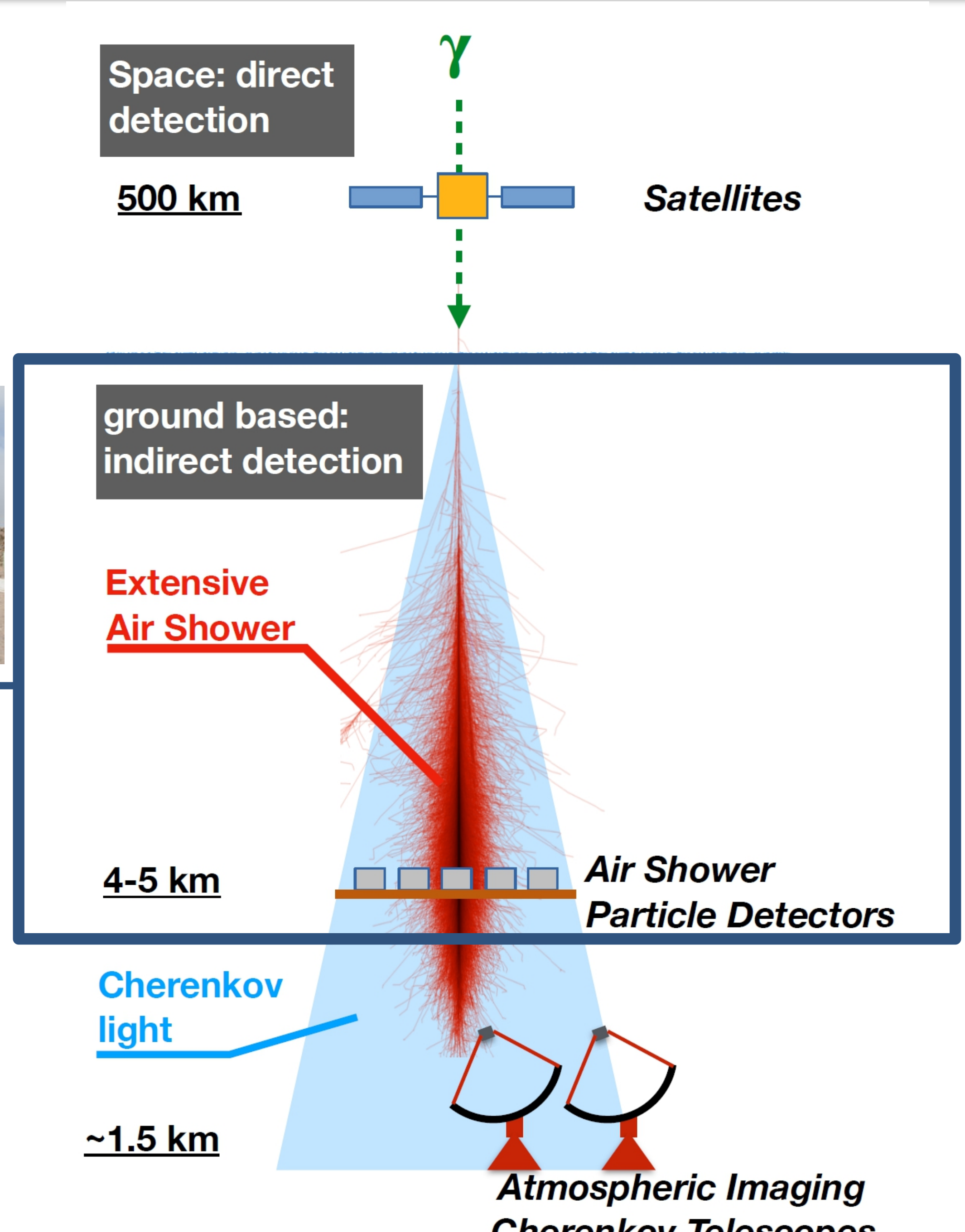
Detection techniques in gamma-ray astronomy



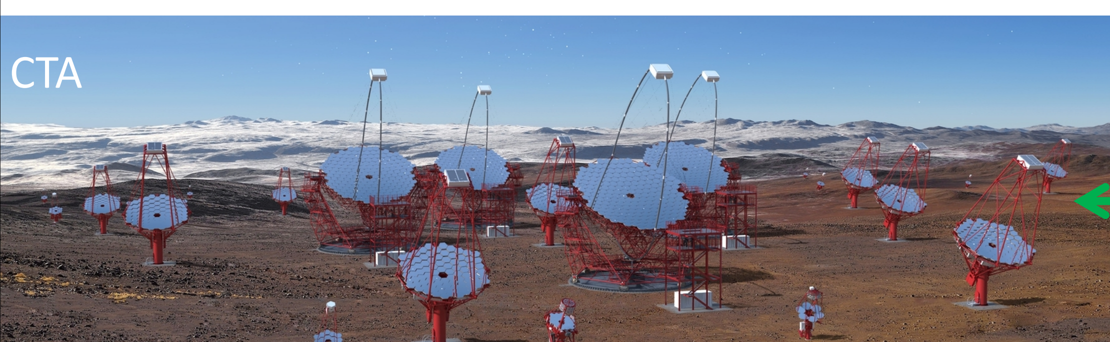
Detection techniques in gamma-ray astronomy

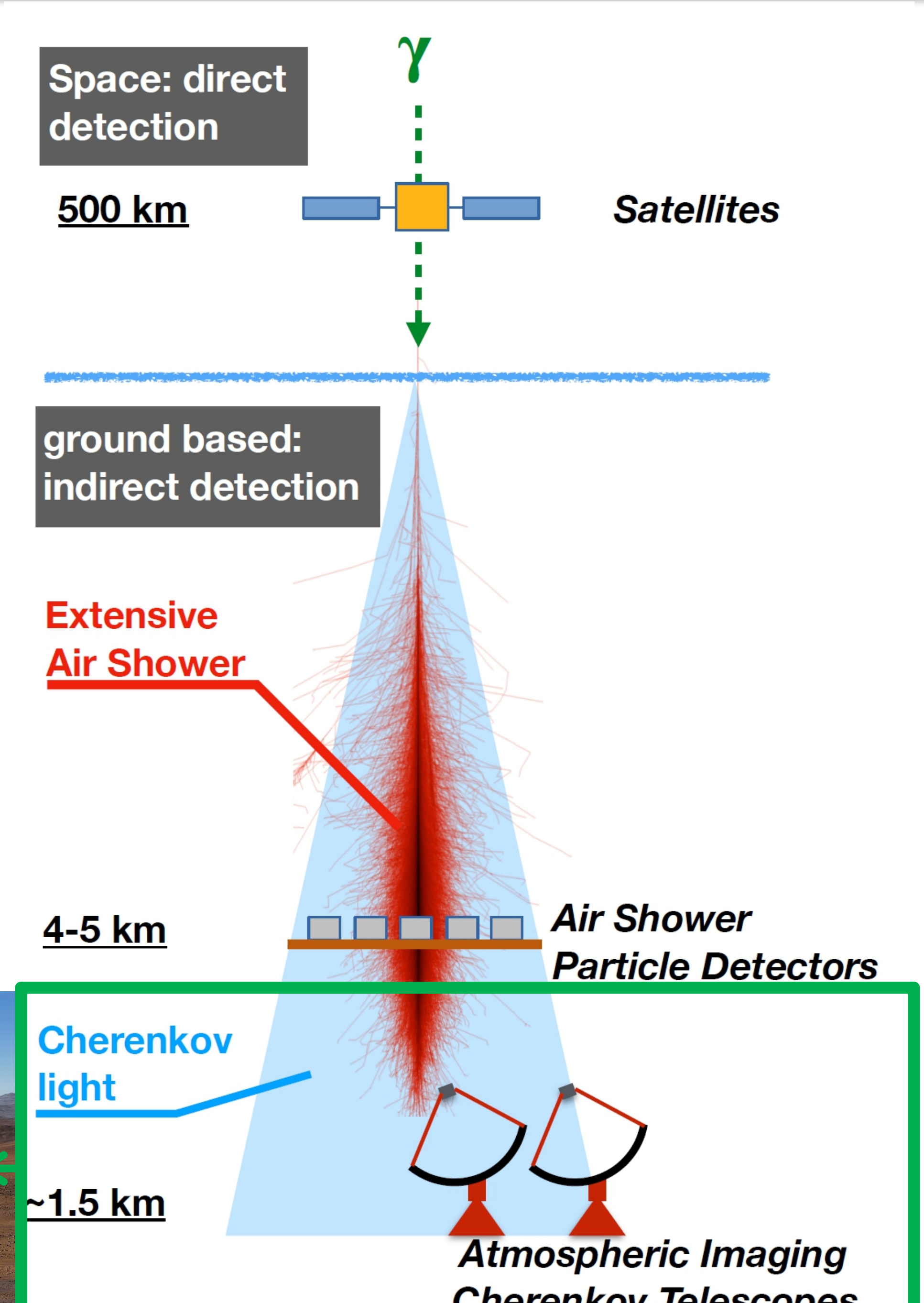


Detection techniques in gamma-ray astronomy



Detection techniques in gamma-ray astronomy



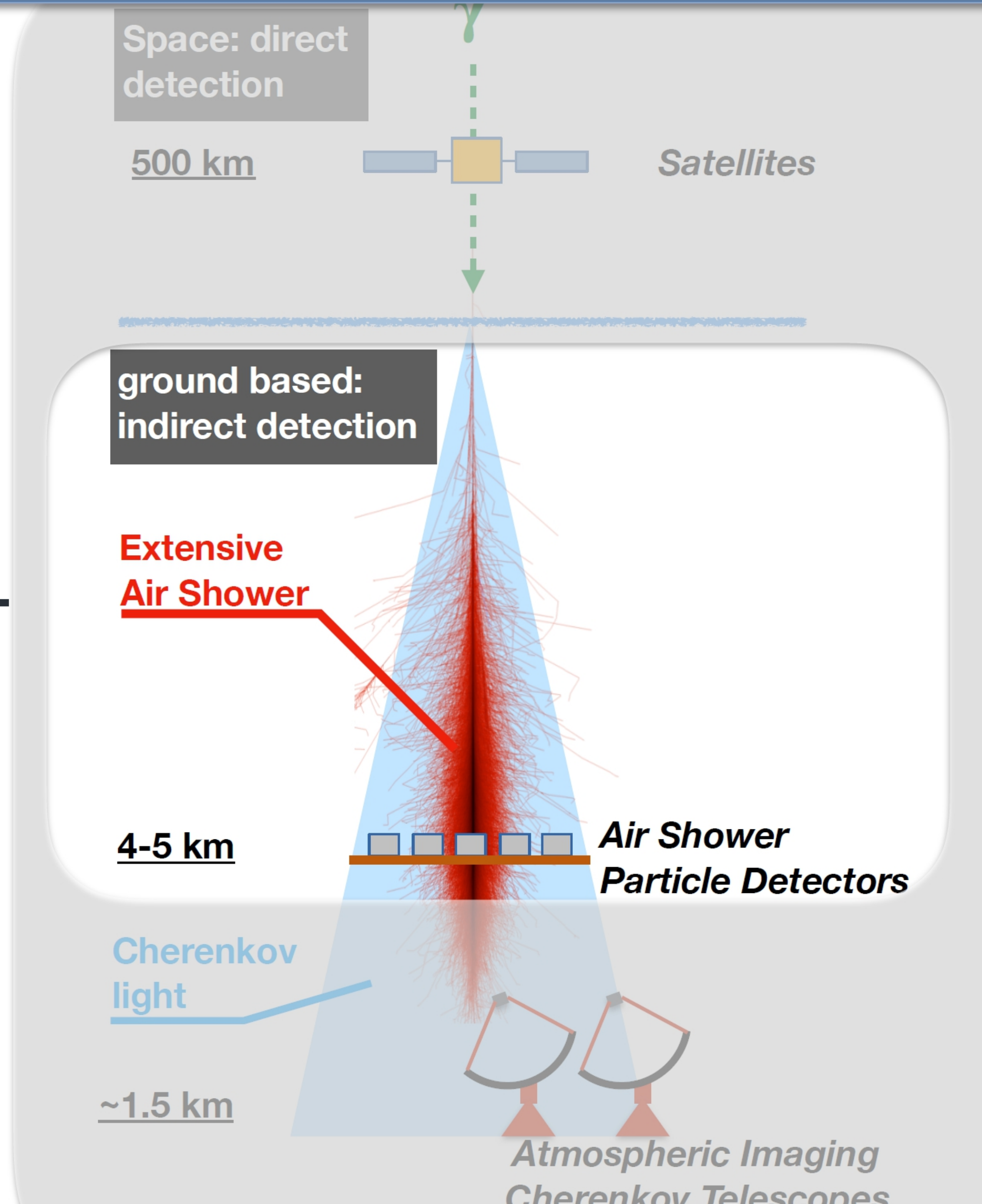


Southern Wide-field Gamma-ray Observatory (SWGO)

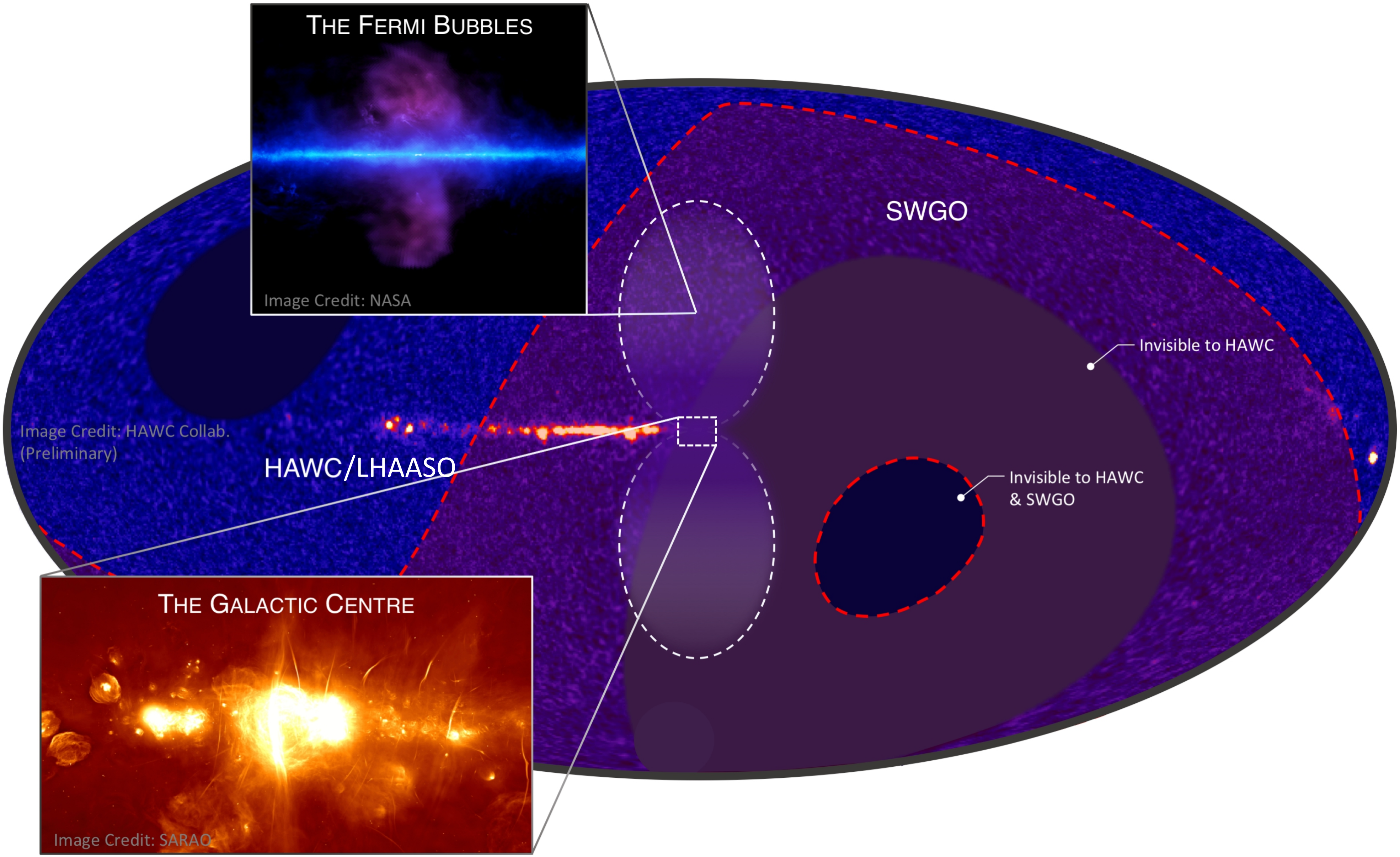
SWGO

The Southern Wide-field Gamma-ray Observatory

- Wide-angle air shower particle detector, complementary to CTA South
- Located at a high-altitude site in South America,
- Covering the energy range 100 GeV to 100 TeV,
- Significant sensitivity improvement over HAWC
- Various detector concepts under study



The Southern gamma-ray sky

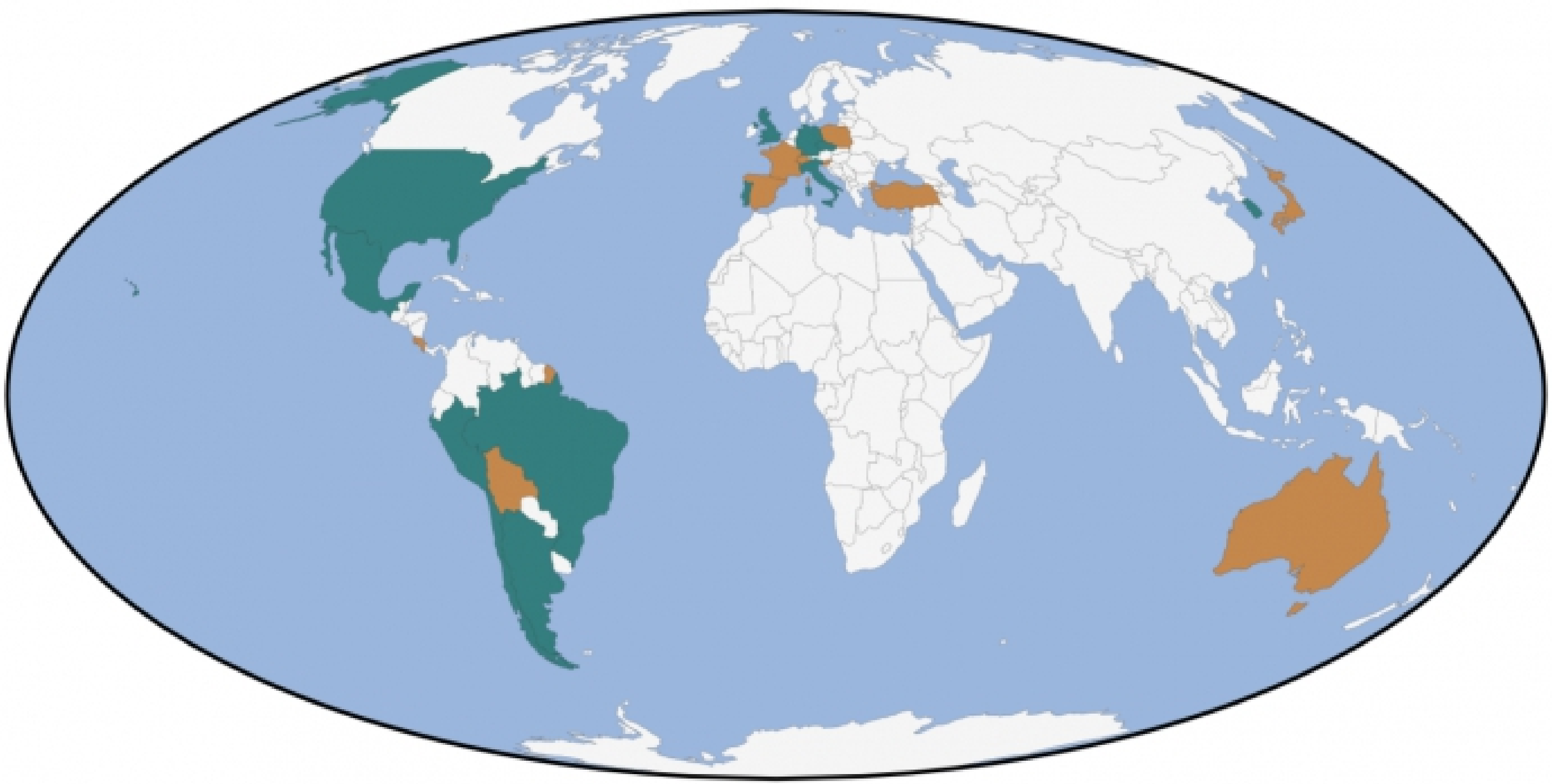


Gamma-ray sky image as seen by the (current) HAWC and (future) SWGO observatories (Credit: Richard White, MPIK)

The SWGO collaboration

- **R&D collaboration founded on July 1st 2019 by 54 partner institutes in 12 countries + supporting scientists from 11 more countries**

- **Aims of the collaboration:** development, over the next three years, of a detailed proposal for the implementation of such an observatory, including site selection and technology choice



Countries in SWGO

Institutes

Argentina*, Brazil, Chile, Czech Republic, Germany*, Italy, Mexico, Peru, Portugal, South Korea, United Kingdom, United States*

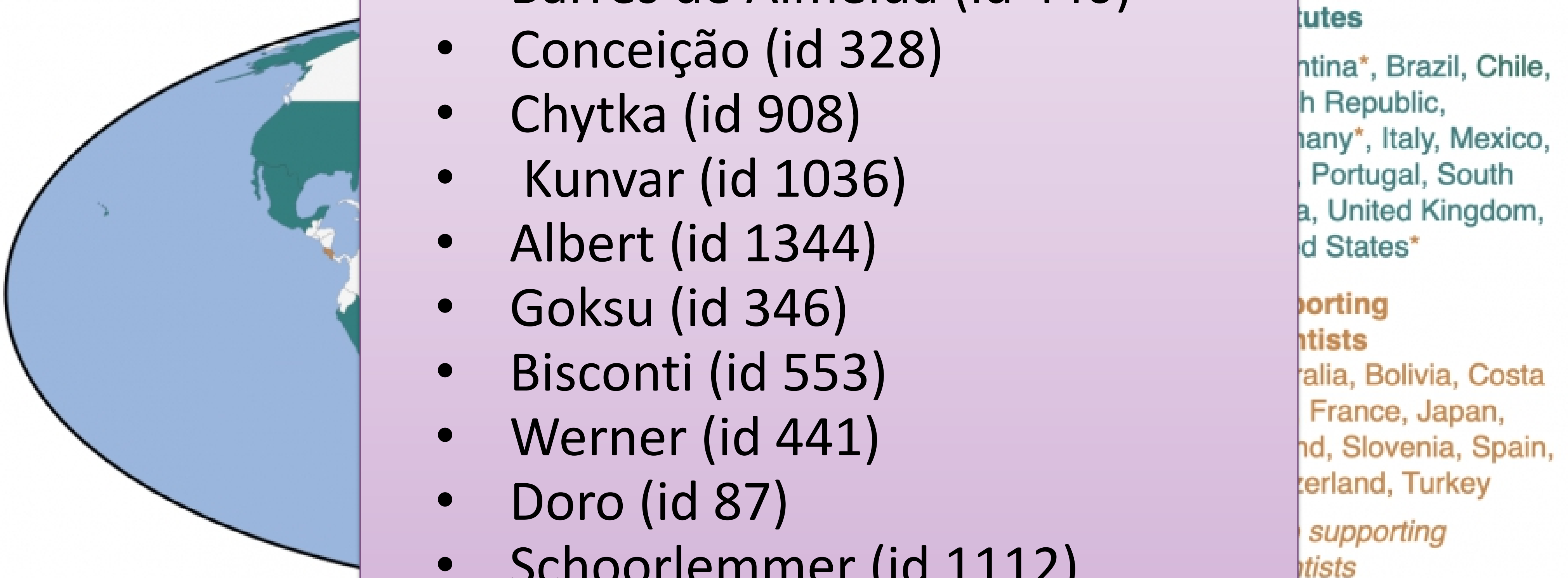
Supporting scientists

Australia, Bolivia, Costa Rica, France, Japan, Poland, Slovenia, Spain, Switzerland, Turkey

**also supporting scientists*

The SWGO collaboration

- **R&D collabo… r institutes in 12 countrie… es**
- **Aims of the …** ee years, of a detailed pro… vatory, including sit…

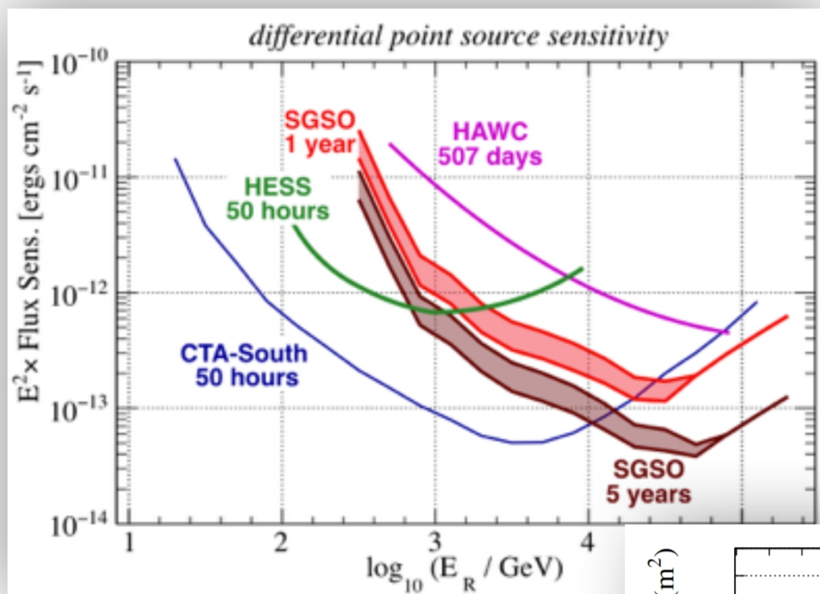


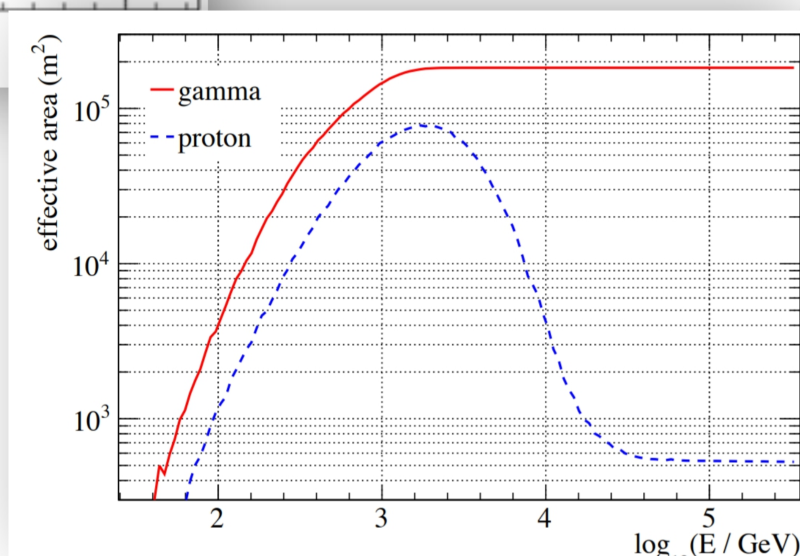
To know more (instrument and science):

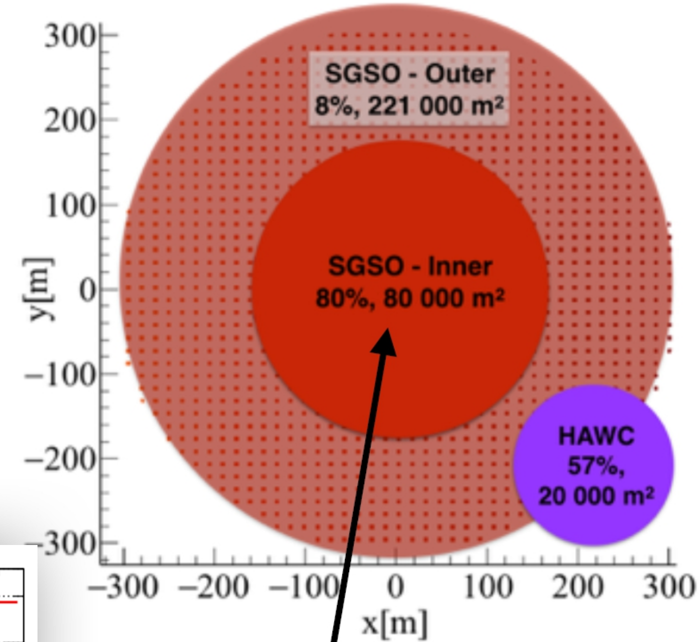
- Plenary: J. Hinton (id 1117)
- Discussions:
  - Taylor (id 304),
  - Barres de Almeida (id 440)
  - Conceição (id 328)
  - Chytka (id 908)
  - Kunvar (id 1036)
  - Albert (id 1344)
  - Goksu (id 346)
  - Bisconti (id 553)
  - Werner (id 441)
  - Doro (id 87)
  - Schoorlemmer (id 1112)

A straw man design for SWGO

- Based on established performances (e.g. HAWC)
- CORSIKA + simple detecctors; altitude of 5000m; larger + denser array







e.g. stations with circular footprint
3m diameter: ~4500 stations

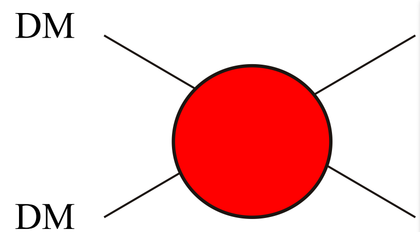
White paper: Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere, SGSO-alliance [arXiv:1902.08429]

H. Schoorlemmer

Indirect dark matter searches through gamma-rays

DM self-annihilation rate :

$$\Gamma_{\mathrm{DM}} \approx \sigma v \frac{\rho_{\mathrm{DM}}^2}{m_{\mathrm{DM}}^2}$$



SM: b, W^+, Z, μ^+

Primary channels

SM: $\bar{b}$, W^-, Z, μ^-

Hadronisation and/or decay

=> γ, $e^\pm$, p, ν

Final states

=> γ, $e^\pm$, $\bar{p}$, $\bar{\nu}$

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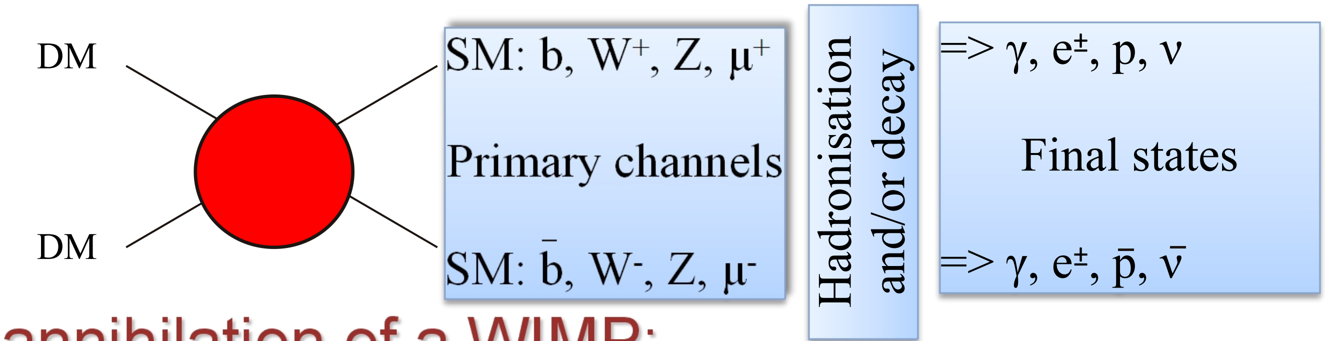

Gamma-ray flux from annihilation of a WIMP:

$$\frac{\mathrm{d}\Phi_\gamma(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{1}{8\pi} \underbrace{\frac{\langle \sigma v \rangle}{m_{\mathrm{DM}}^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}}_{\text{Particle Physics}} \times \underbrace{\bar{J}(\Delta\Omega)\Delta\Omega}_{\text{Astrophysics}} \quad \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$$

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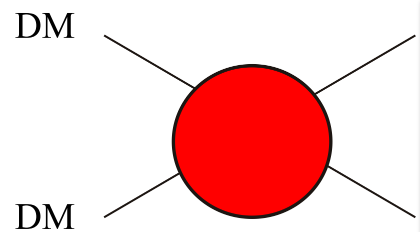

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Gamma-ray flux from annihilation of a WIMP:

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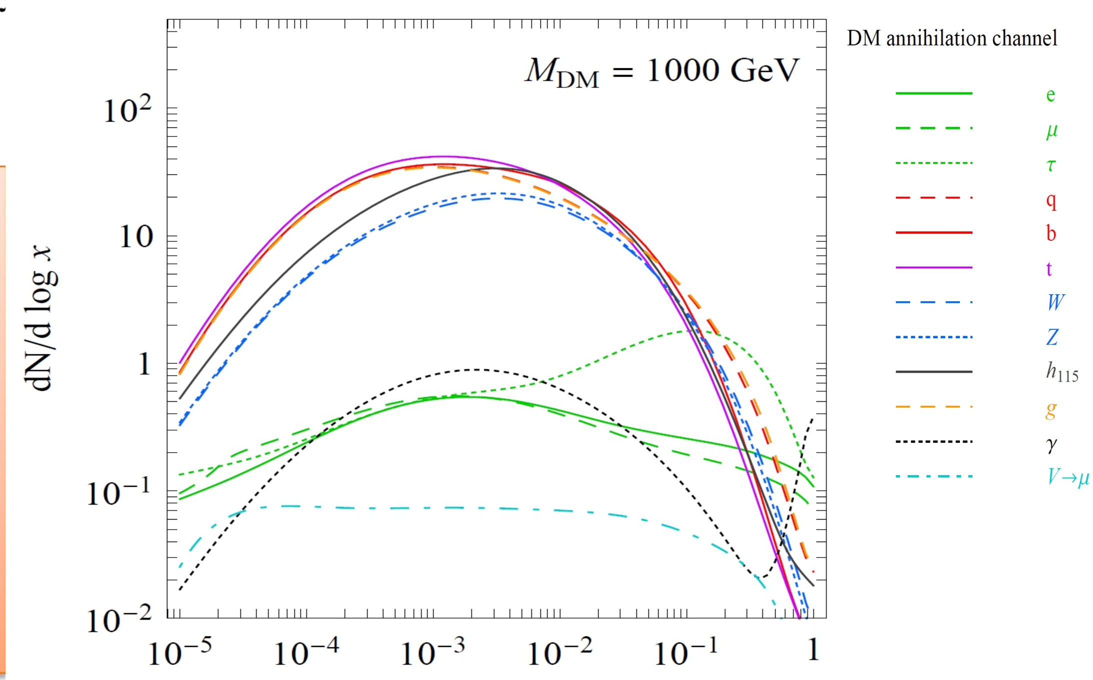
where

Gamma spectrum:

- typically a continuum with an energy cut-off at the DM particle mass
- Mono-energetic line signal :
  - χχ → γγ, γZ : line at or close to DM particle mass
  - χχ → ll, WW: Internal Bremsstrahlung



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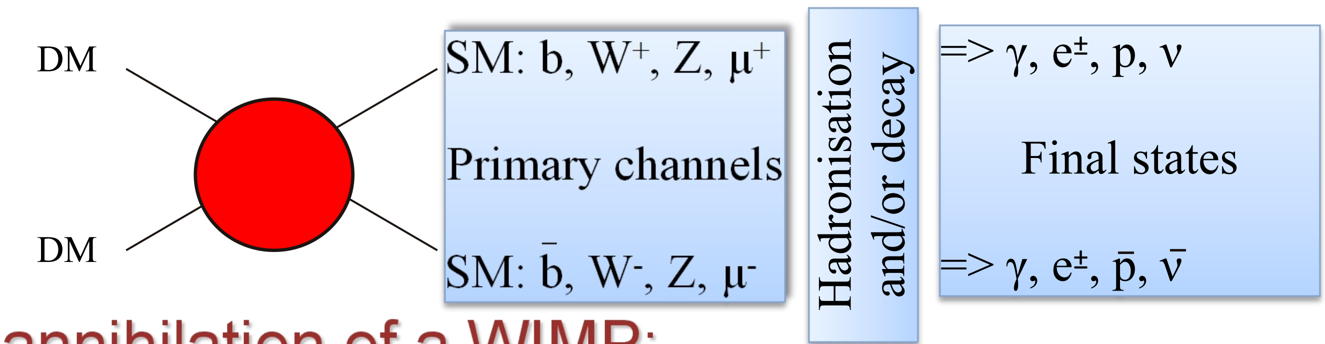

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where

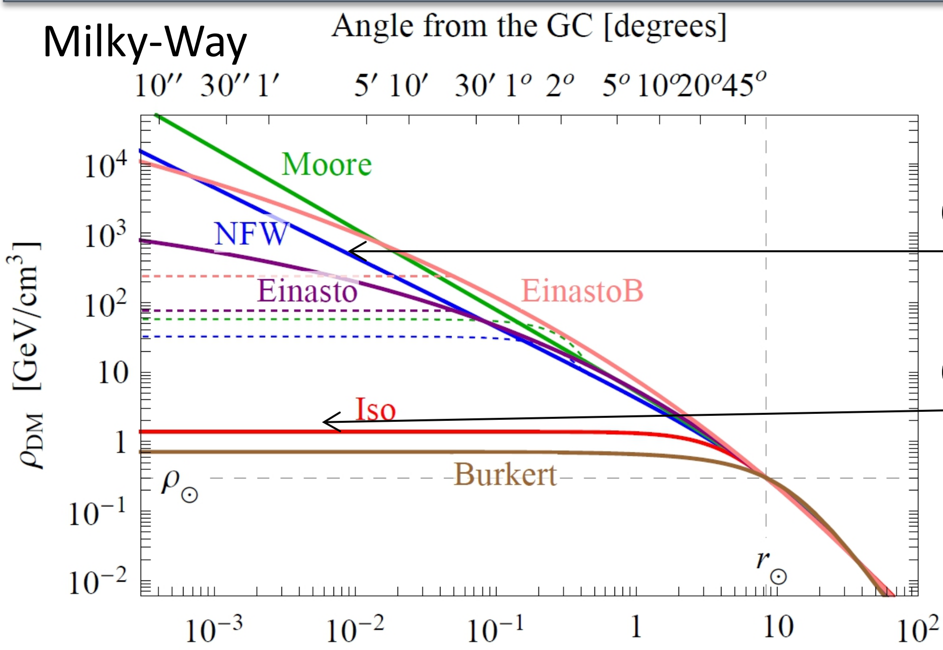
$$\bar{J}(\Delta\Omega) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} {\rm d}\Omega \int_{\rm l.o.s.} \rho^2[r(s)]{\rm d}s$$

- Line of sight integral
- Density profile model is needed
- Dependence **dark matter halo** modeling

Dark Matter halo modeling

- Cosmological N-body numerical simulations => Cusp profile
- Observation of galaxies dynamics => Cored profile

Milky-Way



Cirelli et al 2011

Examples:

Cuspy

$$\rho_{\rm NFW}(r) = \frac{\rho_s (r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$$

std NFW $\gamma = 1$
baryons steepens profile: $\gamma = 1.2$-1.5

Cored

$$\rho_{\rm iso}(r) = \rho_0 \frac{r_c^2}{(r_c^2 + r^2)}$$

- The parameters are found from observation of some tracer dynamics(luminous density, star velocity dispersion, velocity anisotropy…)
- The DM density at small scale is poorly known
  - necessity to take in account both class of models

Dark Matter halo modeling

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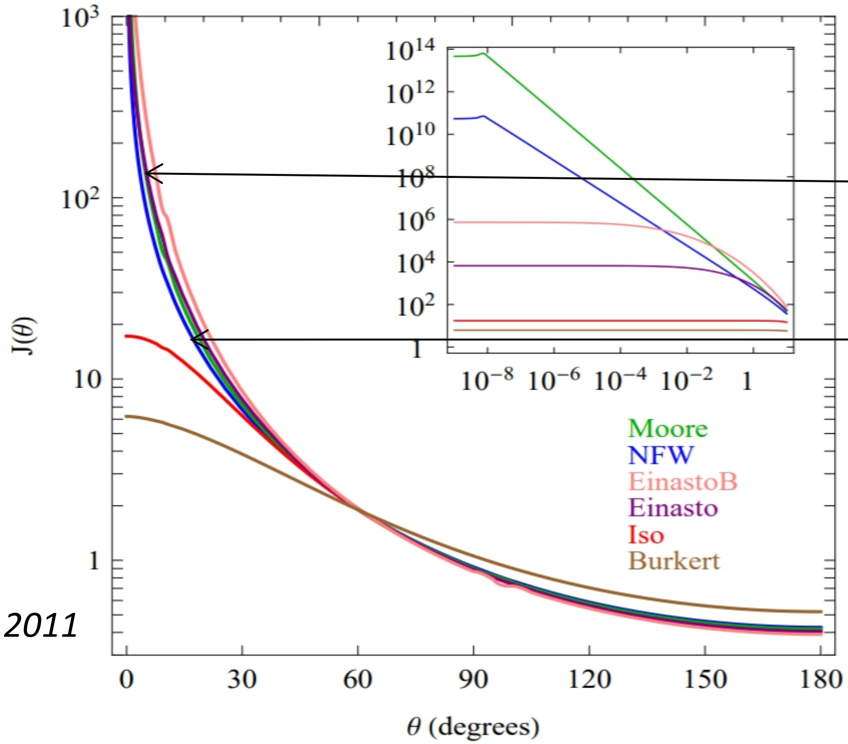
Milky-Way: morphology



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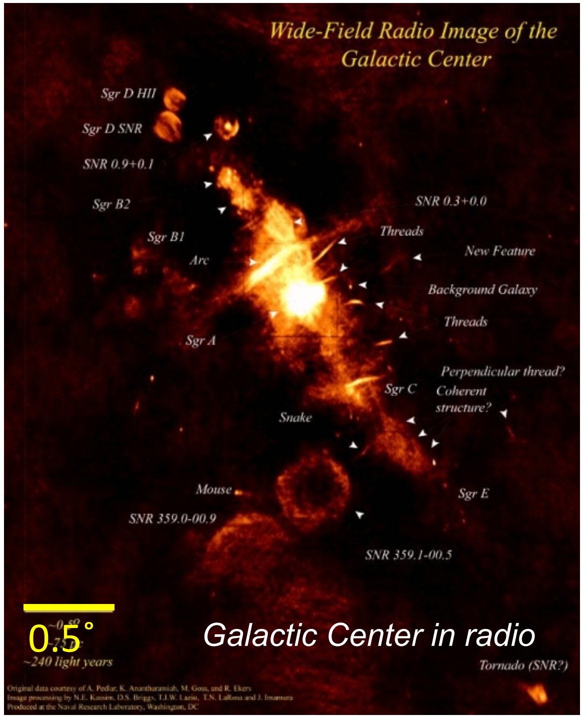
Dark matter targets

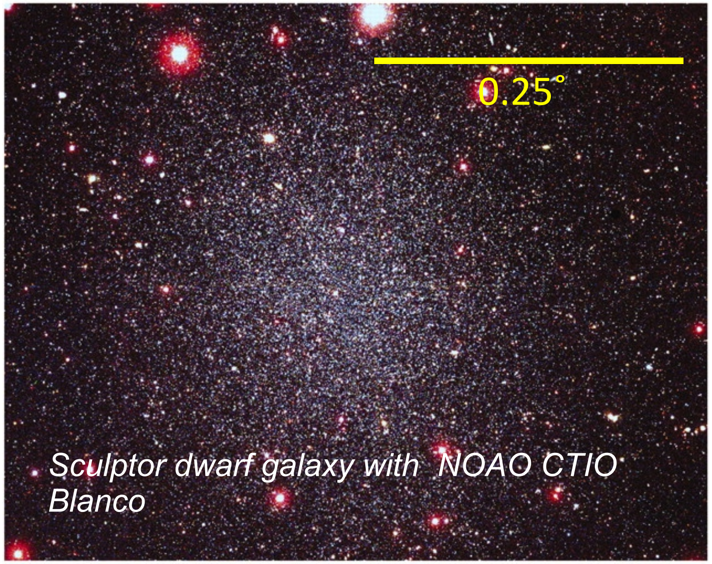


Galactic Center in radio

Galactic Centre

- ❑ Proximity (~8kpc)
- ❑ High (possibly) central DM concentration :

  DM profile : core? cusp?
- ❑ High astrophysical background in gamma-rays

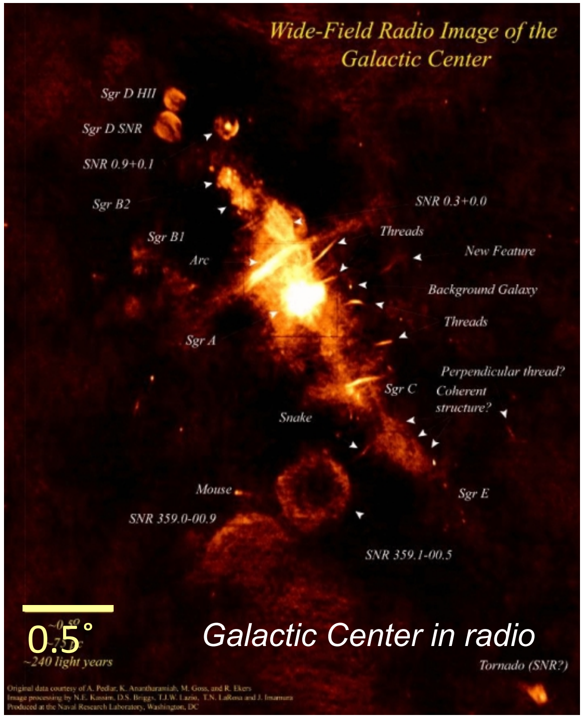


Sculptor dwarf galaxy with NOAO CTIO Blanco

Dwarf galaxies of the Milky Way

- ❑ Many of them within the 100 kpc from Sun
- ❑ Extremely DM-dominated environment
- ❑ Expected low astrophysical background

Dark matter targets



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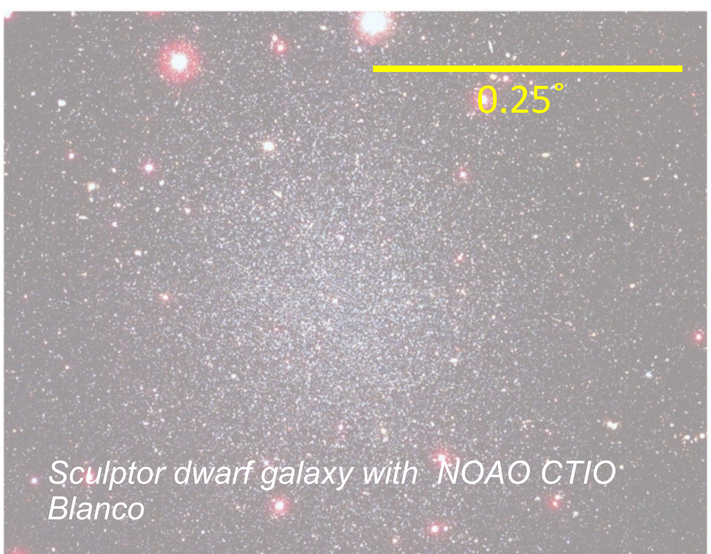

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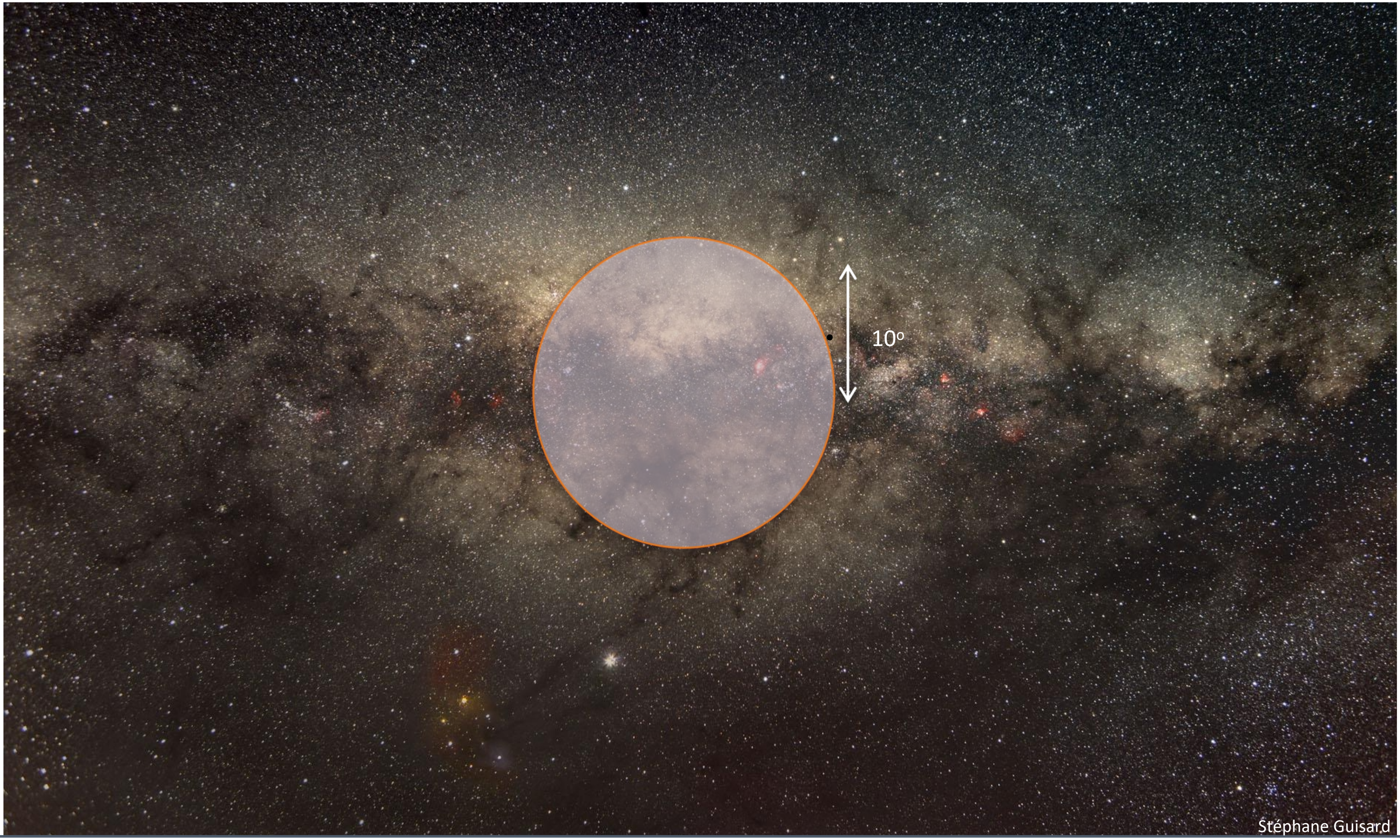
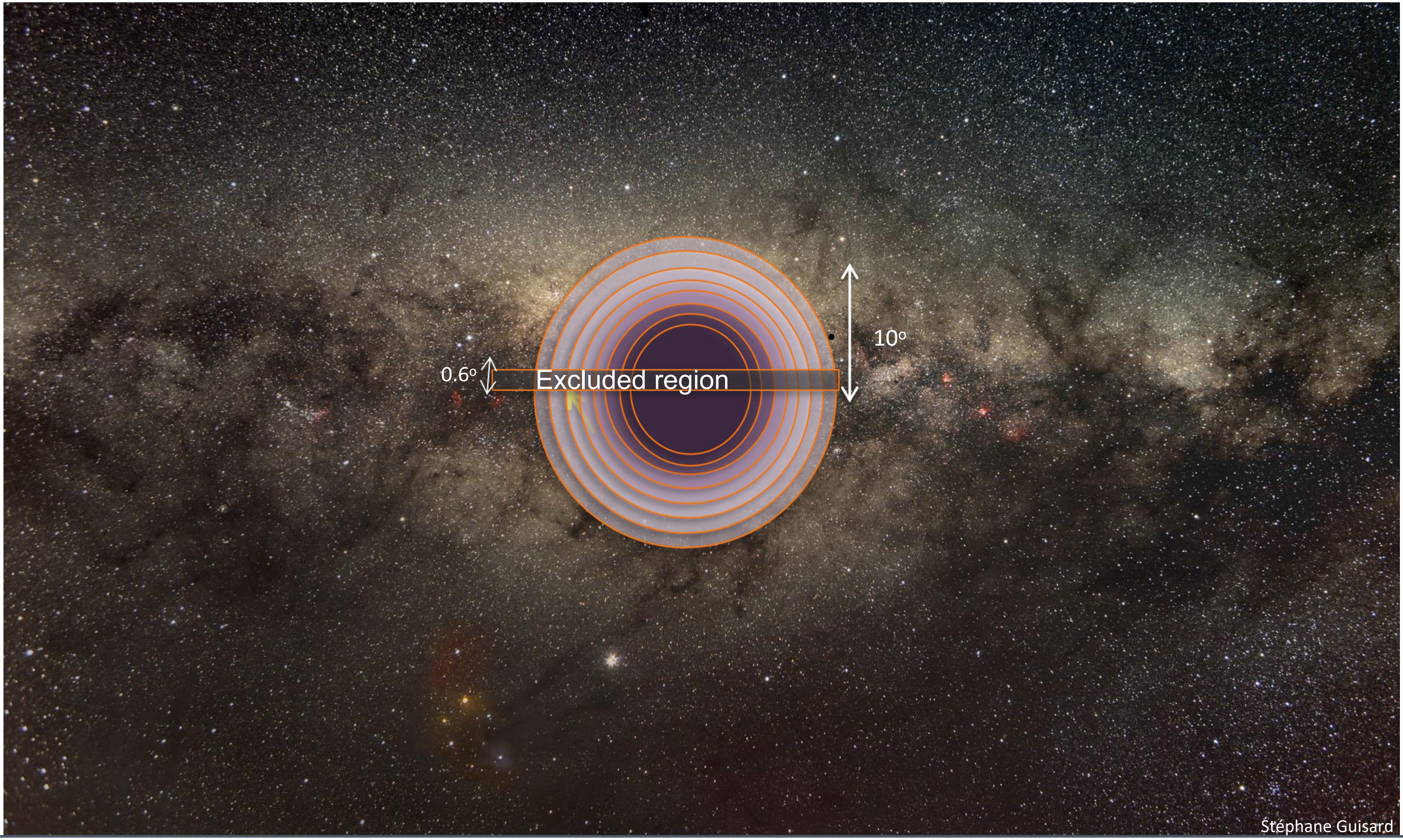
GC halo: DM annihilation sensitivity

- Search for signal in the inner 10^{o} of the Galaxy

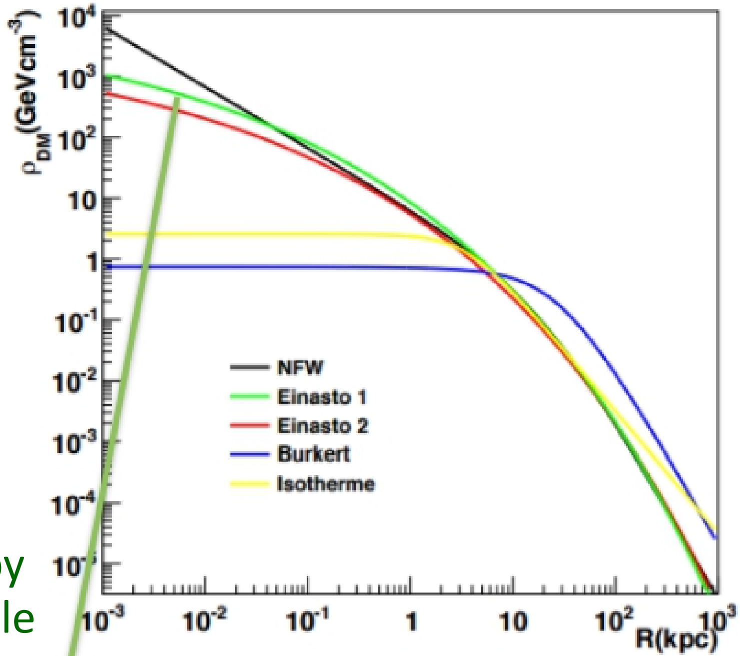


GC halo: DM annihilation sensitivity

- Search for signal in the inner 10º of the Galaxy
- Exclusion of +-0.3º band in latitude to avoid strong astrophysical background
- 2D likelihood analysis with spectral and spatial information of signal: 30 energy bins between [500 GeV, 100 TeV] and 48 bins spatial bins



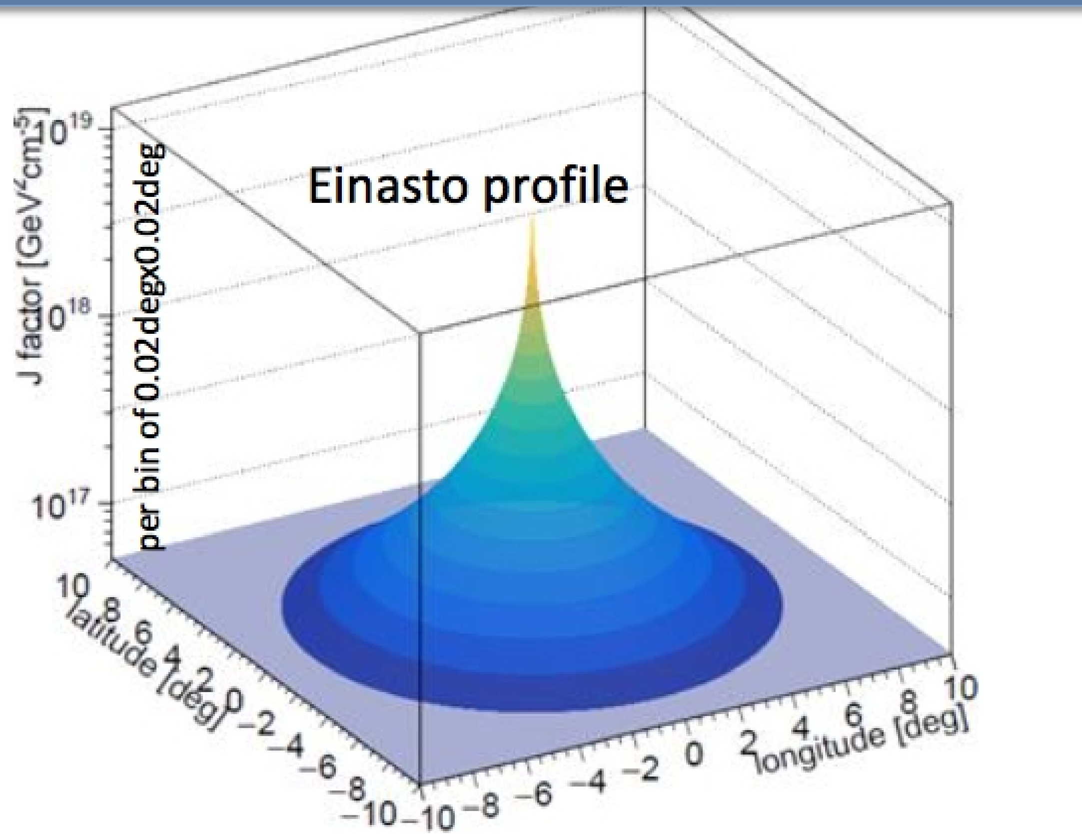
Dark Matter distribution in the GC



Cuspy profile

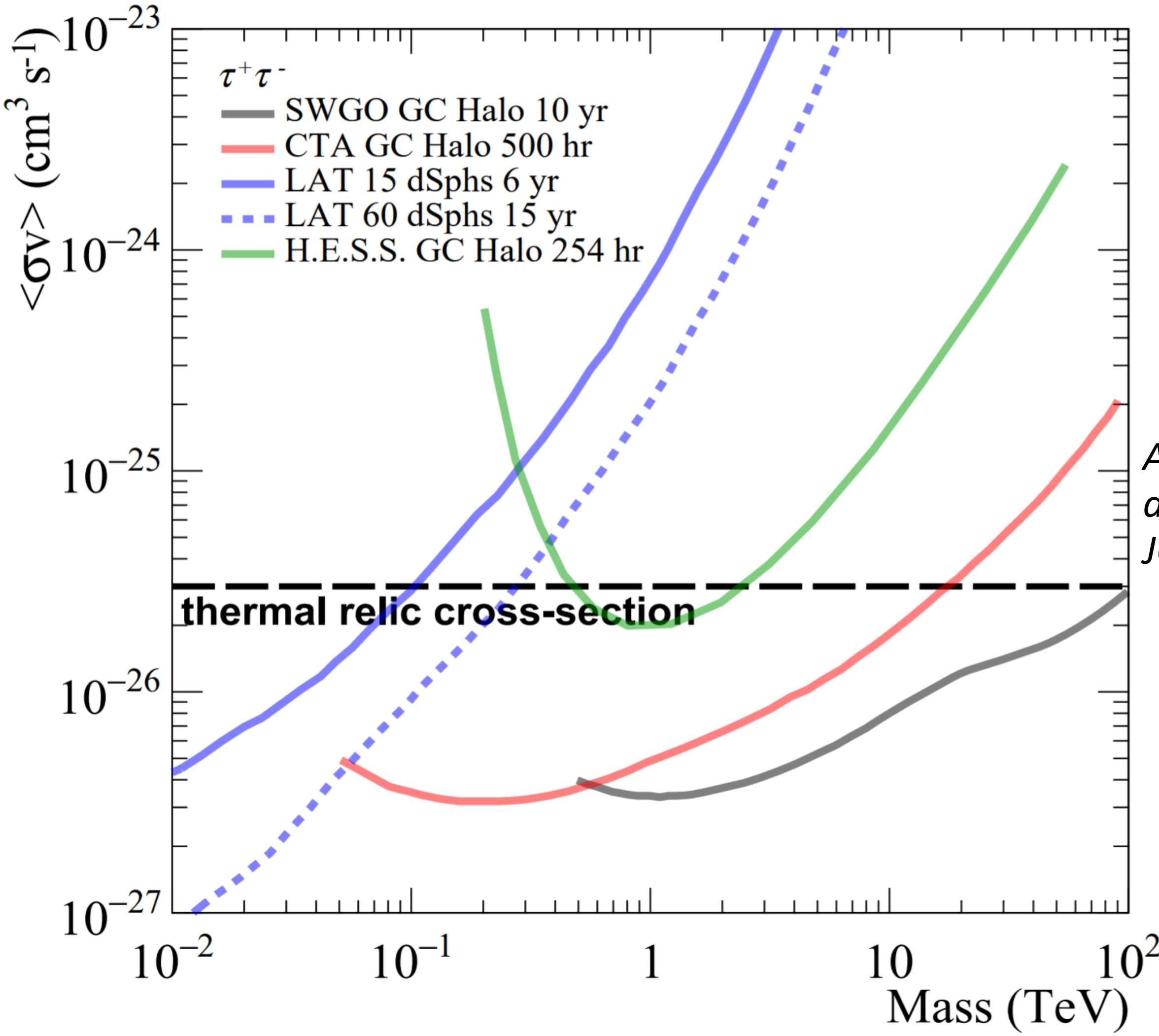
$$\rho_{Ein1}(r) = \rho_s \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

parametrized with
$\alpha = 0.17$
$r_s = 21\ kpc$
$\rho_s = 0.07\ GeV cm^{-3}$



- We assumed an Einasto profile
- The spatial morphology can be used to discriminate between a DM gamma-ray signal and the residual isotropic hadronc background

GC halo: DM annihilation sensitivity



$\tau^+\tau^-$ channel

AV, H. Schoorlemmer, A. Albert, V. de Souza, J. P. Harding, J. Hinton JCAP 2019 [arXiv:1906.03353]

- For $\tau^+\tau^-$ channel: more sensitive than CTA for masses > 600 GeV
- Combined (LAT,CTA,SWGO) sensitivity smaller than thermal relic cross-section (3×**10^{-26} cm^{-3} s^{-1}**) for all masses below 100 TeV

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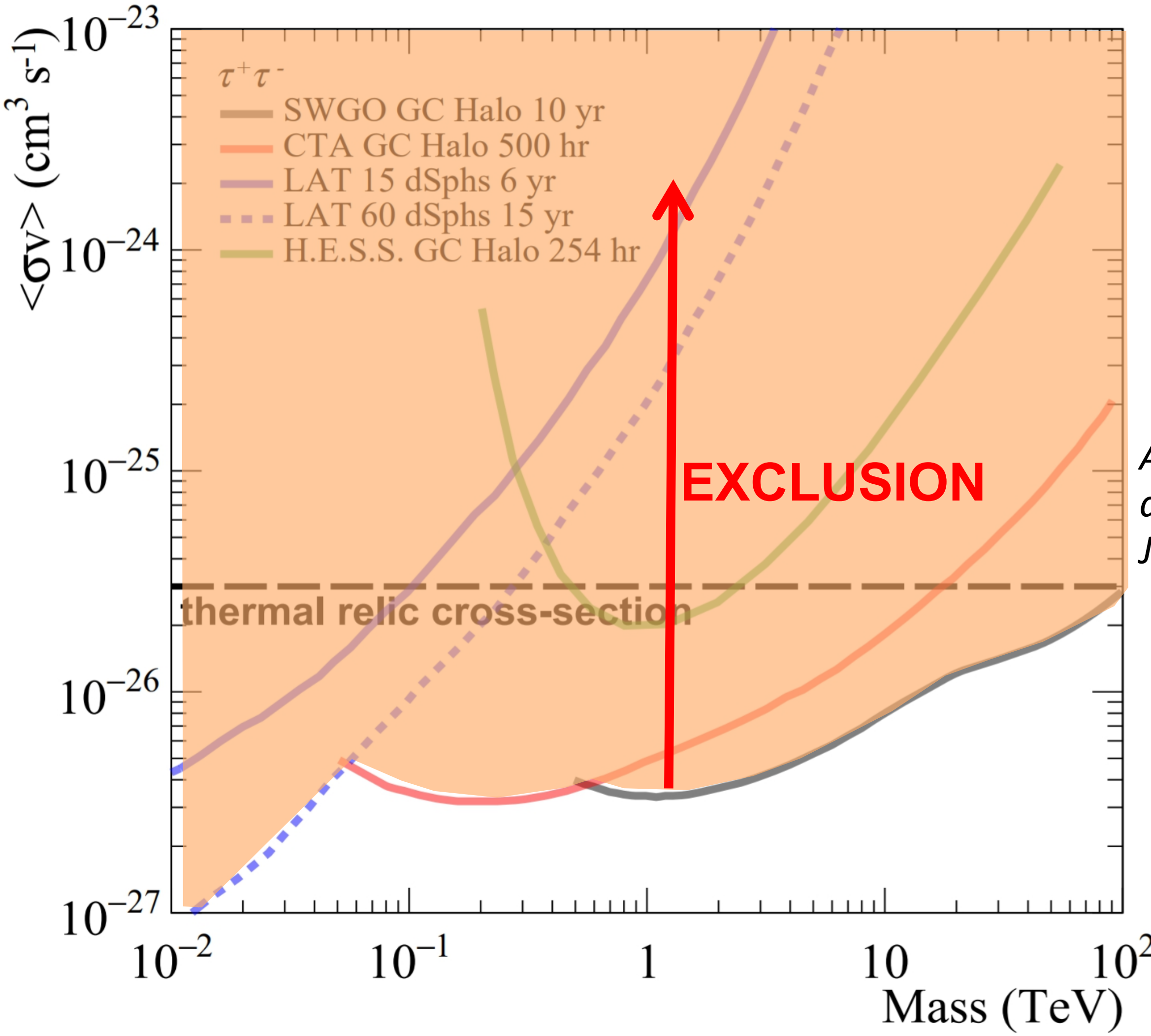

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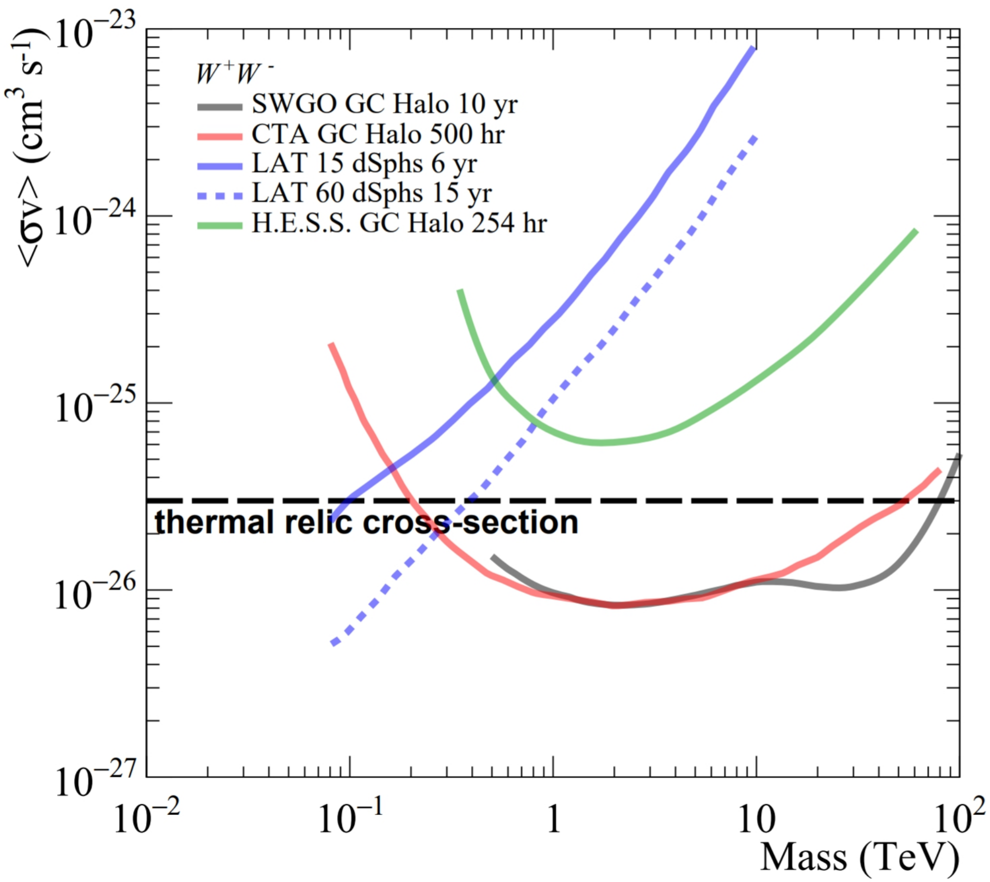
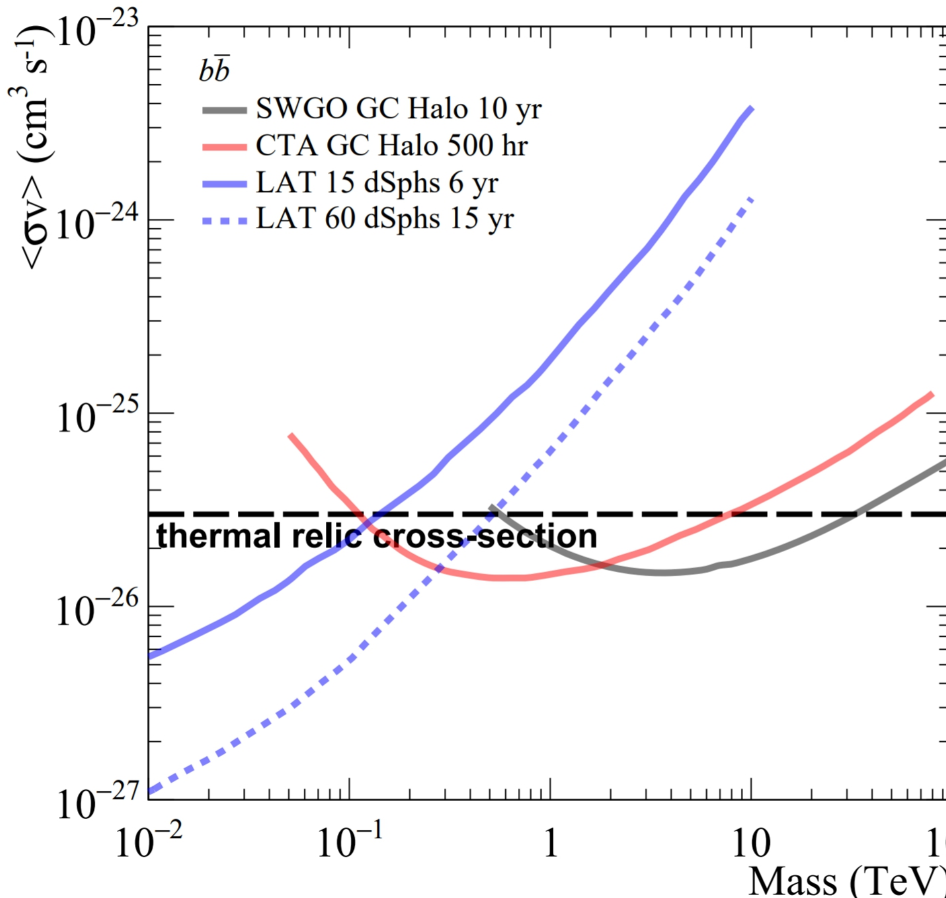
W^+W^- channel



$b\bar{b}$ channel



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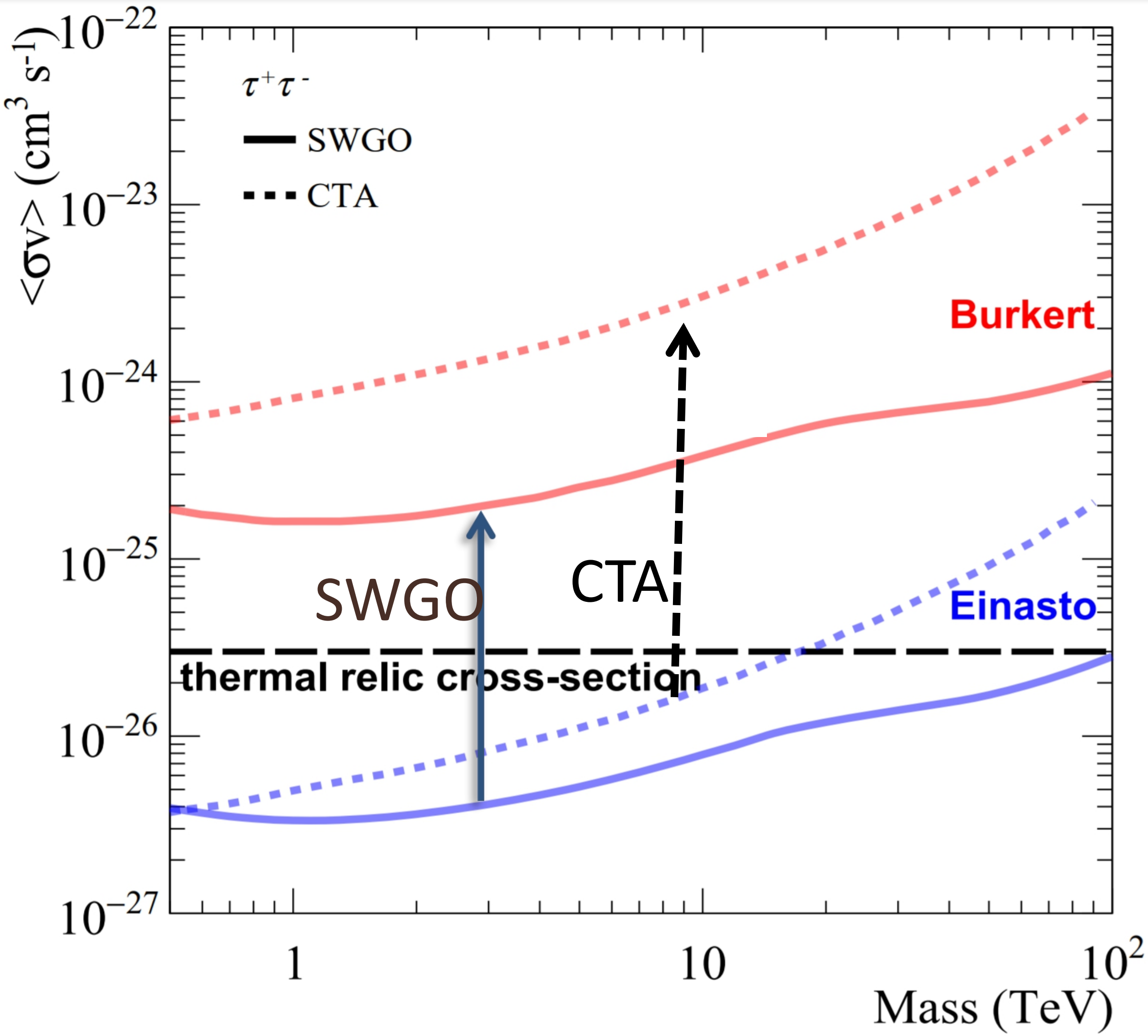
JCAP 2019 [arXiv:1906.03353]

- For W+W- channel: combined sensitivity smaller than relic-thermal cross-section ($3\times\mathbf{10^{-26}}$ **cm^{-3} s^{-1}**) for all masses below 80 TeV
- For **$b\bar{b}$** channel: combined sensitivity smaller than thermal relic cross-section ($3\times\mathbf{10^{-26}}$ **cm^{-3} s^{-1}**) for all masses below 30 TeV

GC halo: DM annihilation sensitivity



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- **Cored profiles** are best observed using a wide FOV instrument: better sensitivity and background measurements
- SWGO can observe cores larger than 2 kpc (r_θ>15°)
- CTA will be limited by the fov (r_c< 700 pc)

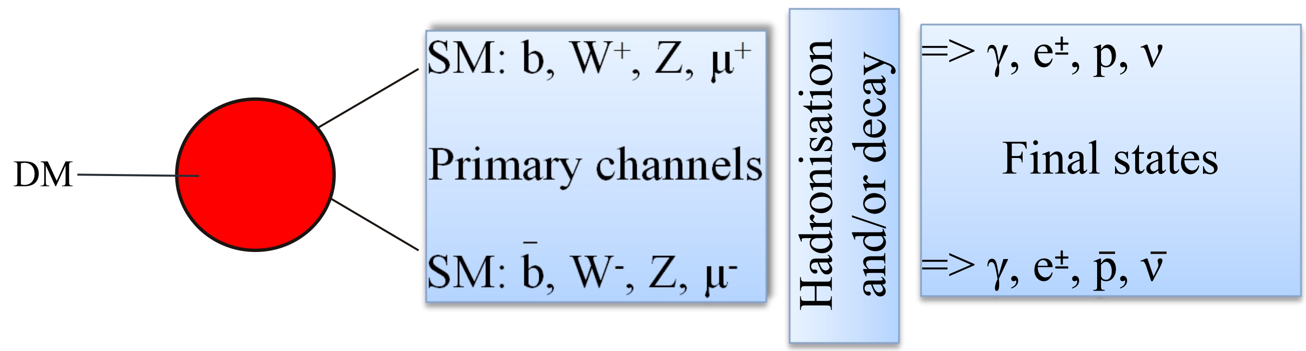
GC halo: DM decay sensitivity

DM self-annihilation rate :

$$\Gamma_{\mathrm{DM}} \approx \sigma v \frac{\rho_{\mathrm{DM}}^2}{m_{\mathrm{DM}}^2}$$

DM decay rate :

$$\Gamma_{\mathrm{DM}} \approx \frac{\rho_{\mathrm{DM}}}{\tau_{\mathrm{DM}}\, m_{\mathrm{DM}}}$$



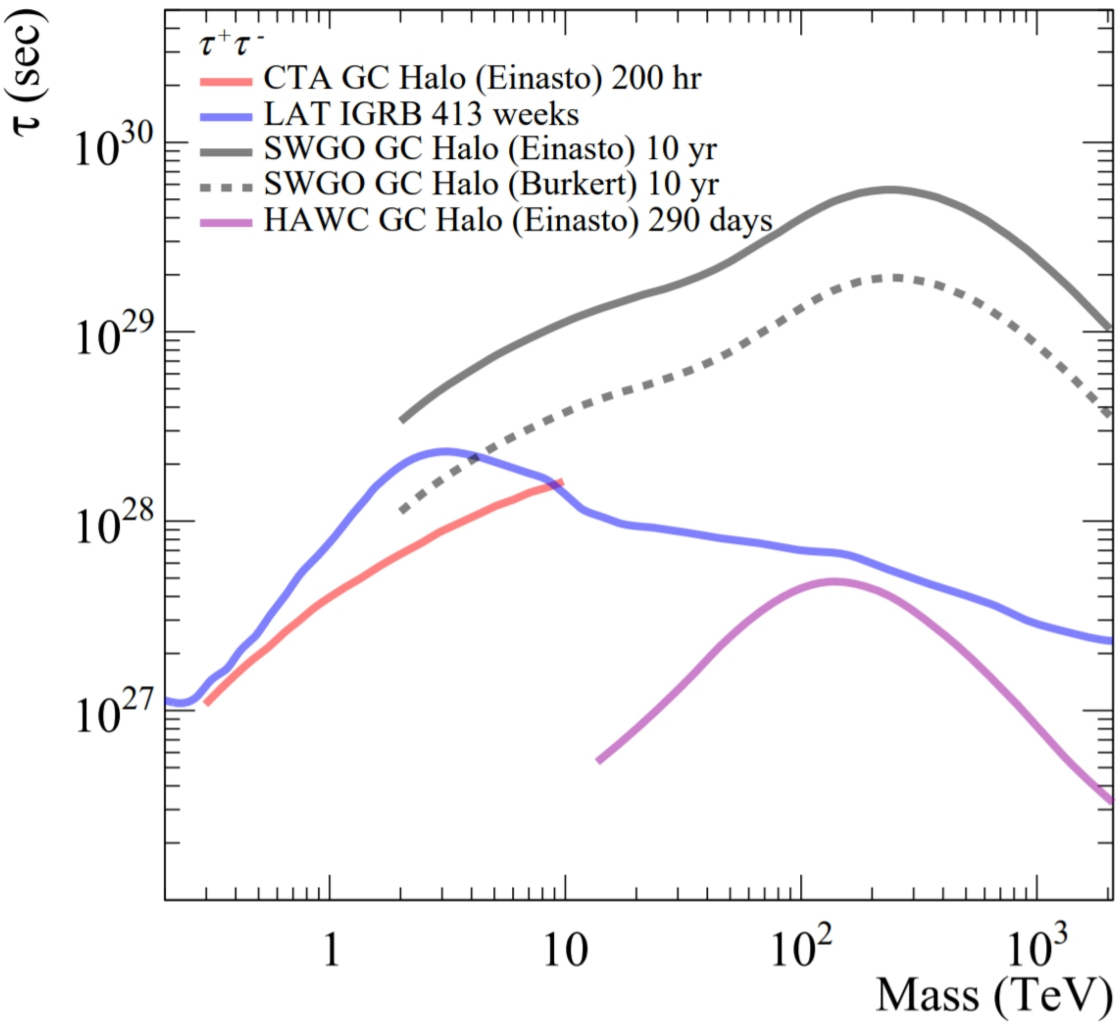
Gamma-ray flux from decay of a WIMP:

$$\frac{\mathrm{d}\Phi_{\mathrm{Dec}}(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \left(\frac{1}{4\pi}\,\frac{1}{\tau_{\mathrm{DM}} M_{\mathrm{DM}}}\,\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\right) \times \left(D(\Delta\Omega)\right)$$

where

$$D(\Delta\Omega) = \int_{\Delta\Omega}\int_{\mathrm{l.o.s.}} \mathrm{d}\Omega\,\mathrm{d}s\ \rho_{\mathrm{DM}}[r(s,\Omega)]$$

GC halo: DM decay sensitivity



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- Unprecedented sensitivity in the TeV mass range
- Better than CTA and Fermi-LAT for all DM particle masses above ~ 1 TeV
- Less sensitive to diference in density profile shape

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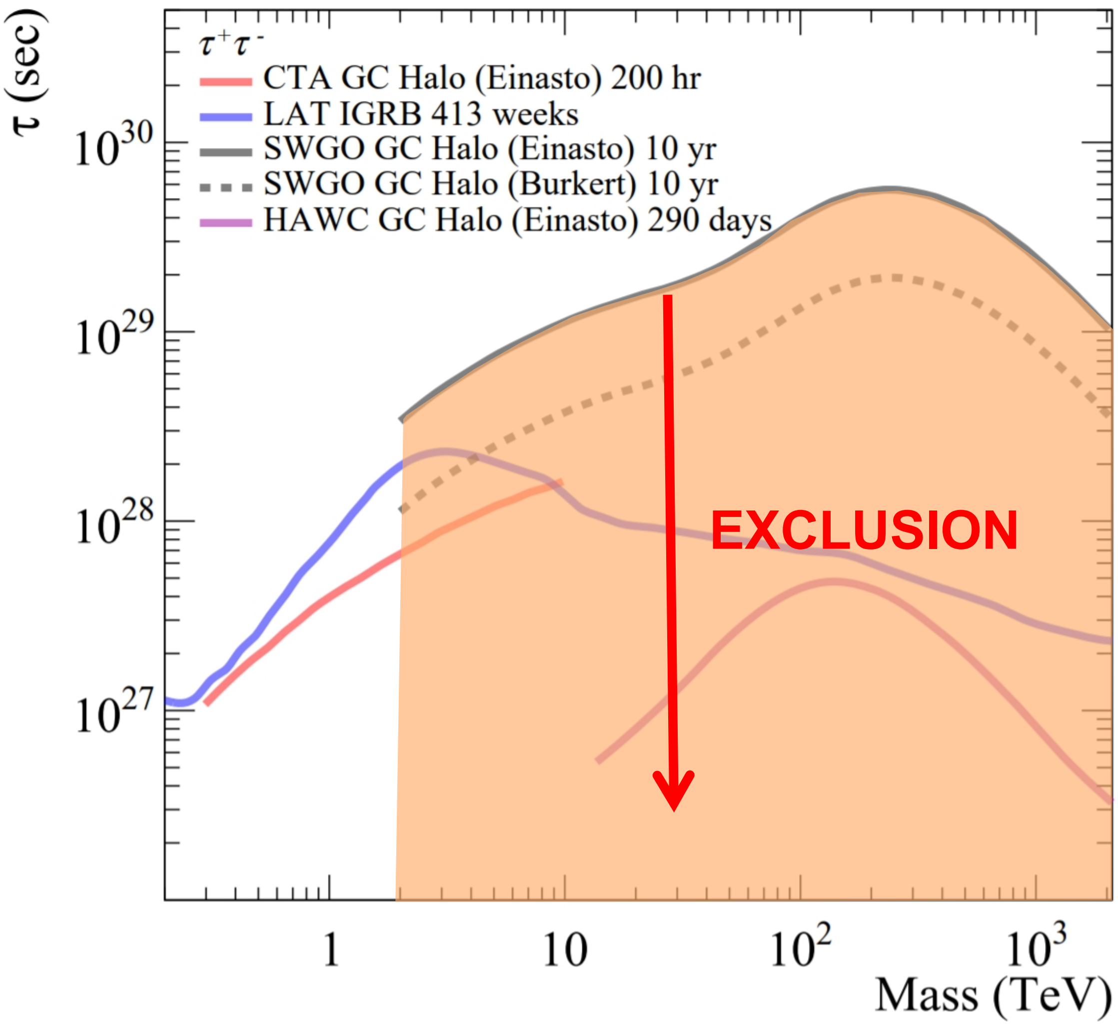

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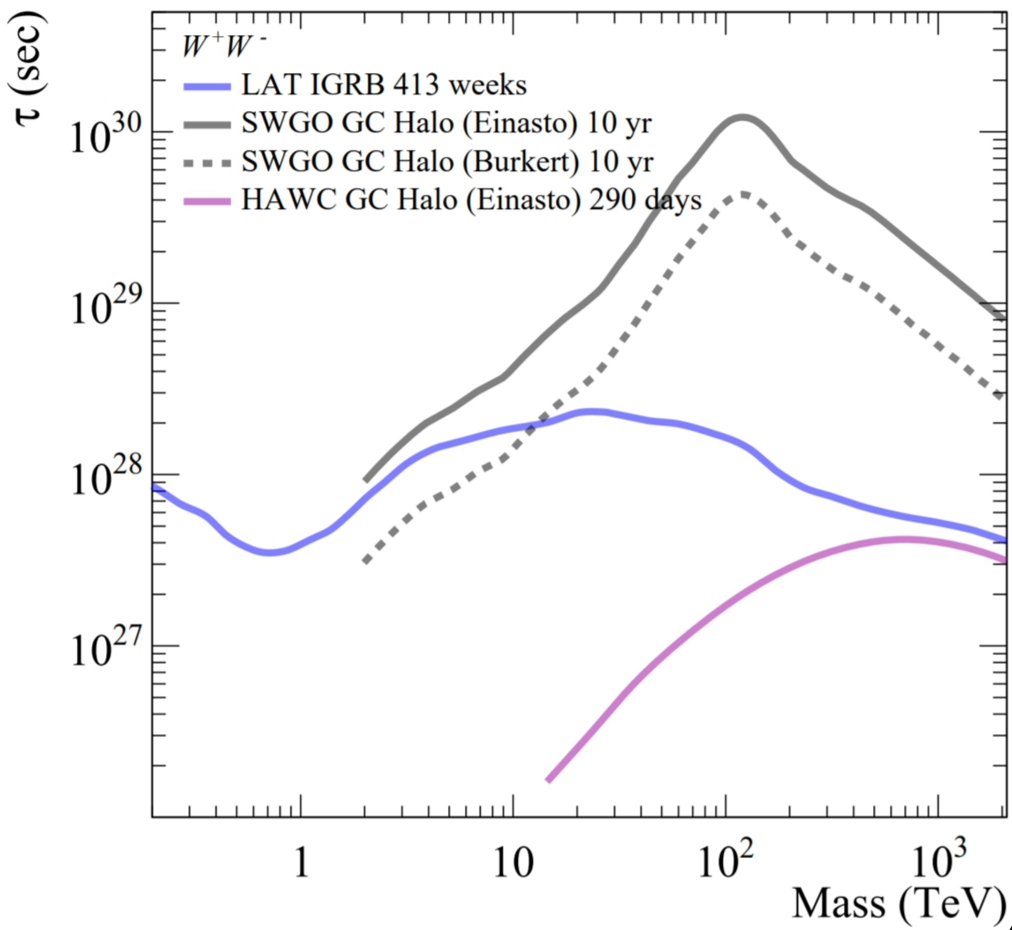

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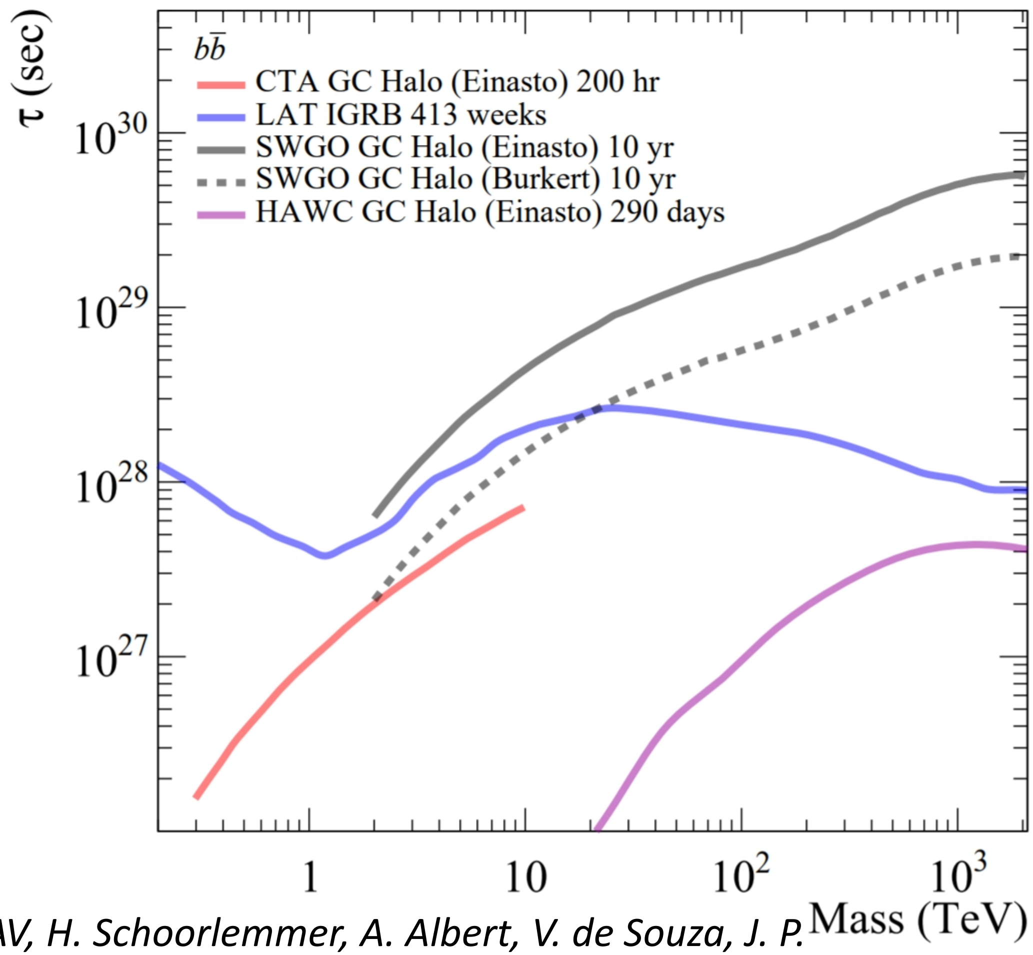

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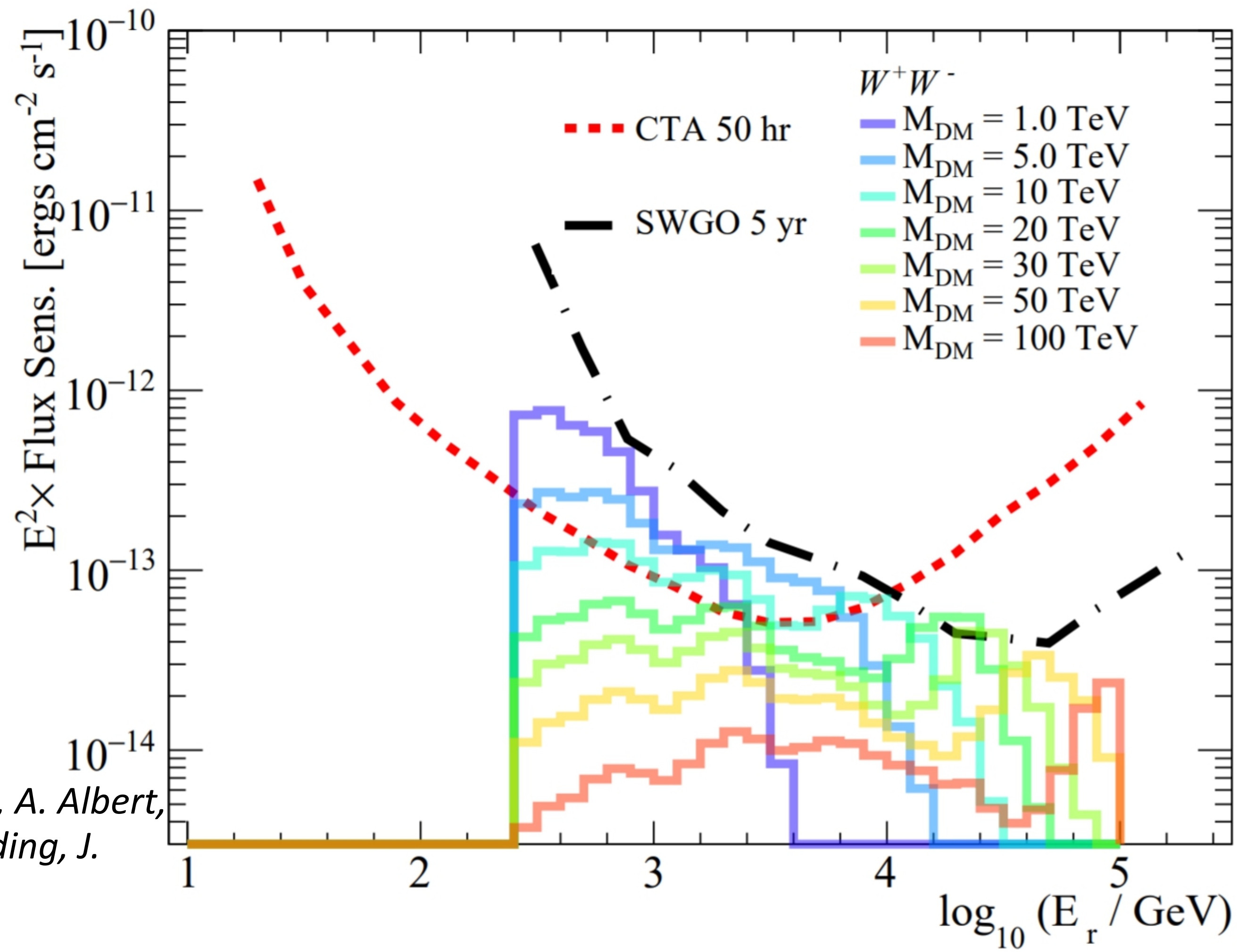
Complemetarity to CTA



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➢ For masses > 10 TeV, SWGO can be complementary to CTA -> confirmation of a spectrum cut-off

Summary

Search for Dark Matter with SWGO

1. GC halo: combination of Fermi-LAT, CTA and SWGO will be sensitive cross-section below the thermal relic value for:
   - M_{DM} <~100 TeV in τ+τ- channel
   - M_{DM} <~80 TeV in W+W- channel
   - M_{DM} <~30 TeV in $b\bar{b}$ channel

2. SWGO well suited for observation of cored DM density profiles

3. DM decay: SWGO will reach unprecedented sensitivity in the TeV mass range

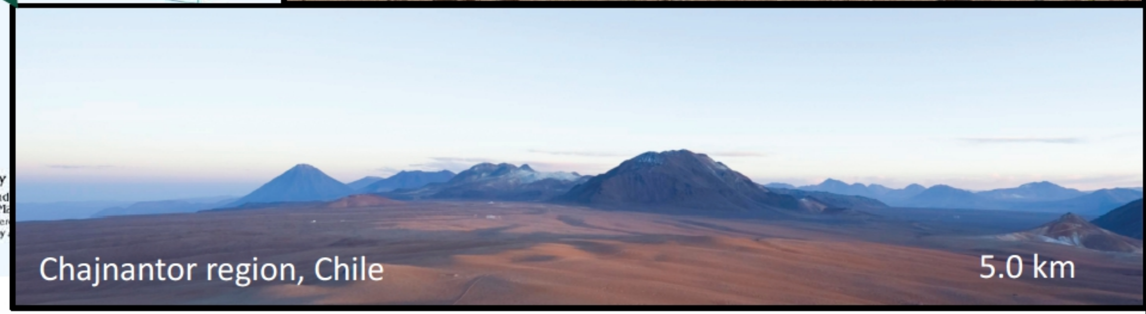
4. For masses > 10 TeV, SWGO can be complementary to CTA -> confirmation of a spectrum cut-off

5. Future developments: DM searches towards dwarf galaxies
   - preliminary estimates shown in white paper and proceedings
   - x10 improvement when compared to current instruments

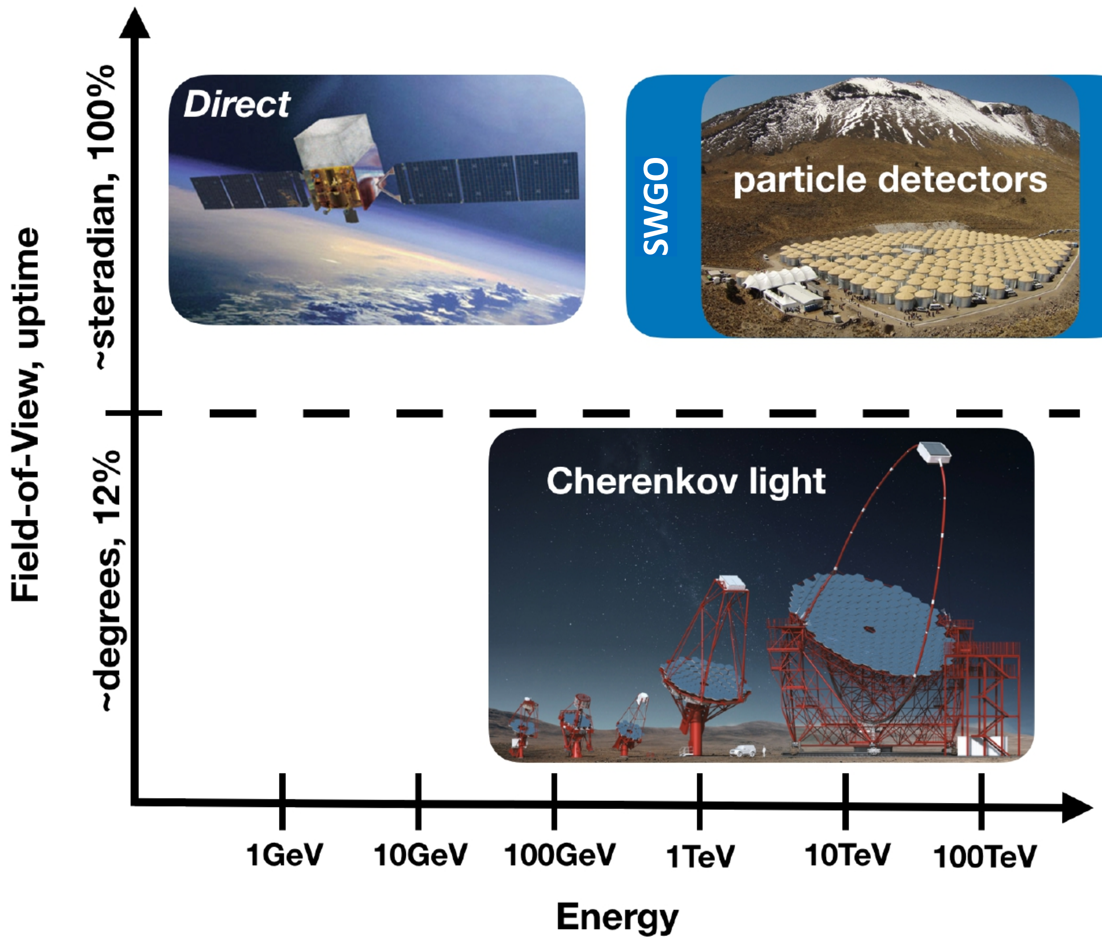
Extras

Potential SWGO Sites

- **Proposal: Build it in the Andes**
- **Above 4.7 km to reach sub-TeV sensitivities**



Overlap and complementarity



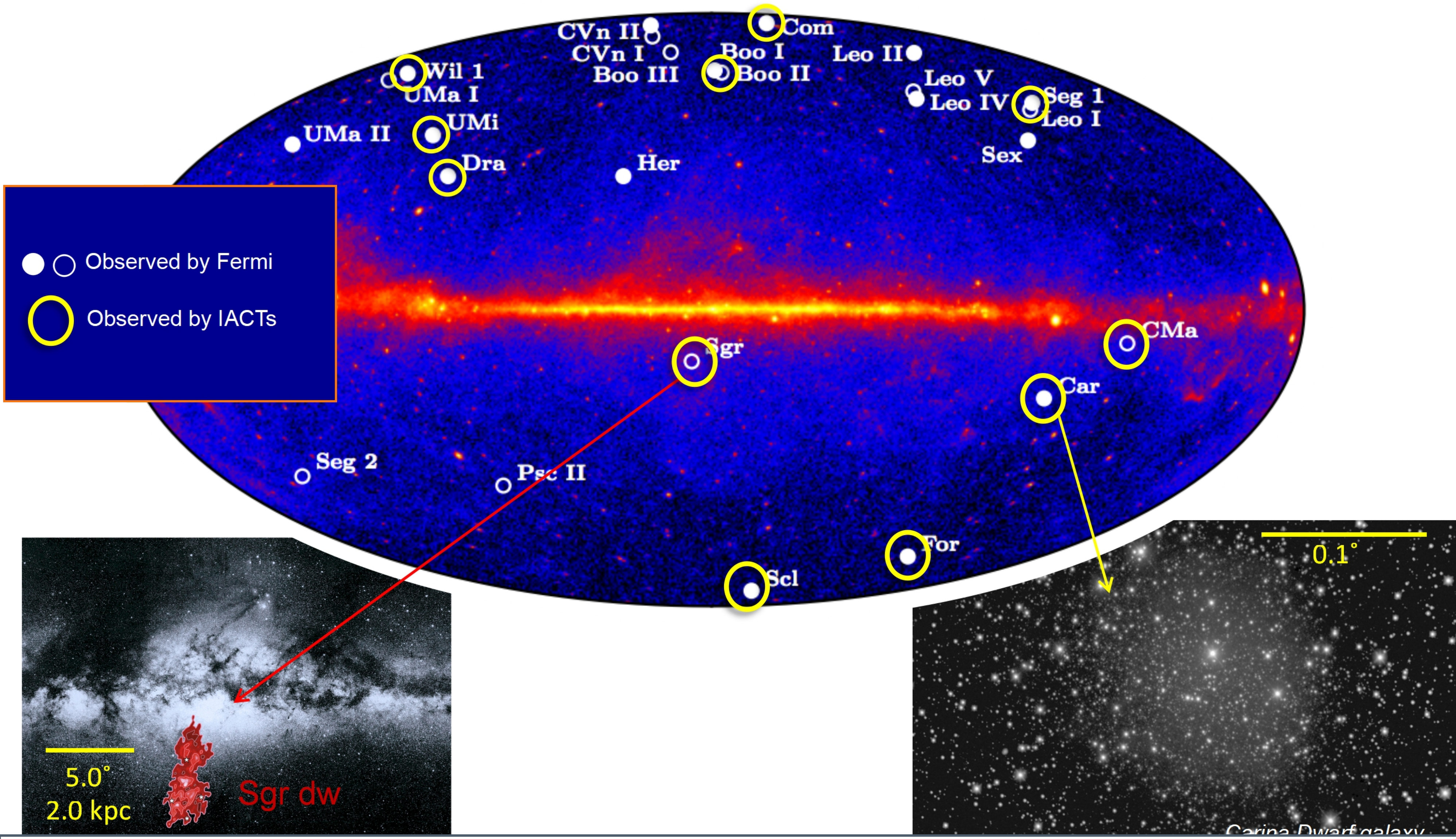
Particle Detectors

Pros*	Cons*
Accurate Background estimation	Poorer enegy resolution
Large Aperture	Poorer angular resolution
Continuous monitoring	Lower instataneus sensitivity
High Energy Reach	Higher Energy threshold
Archival Data	

**with respect to IACTs*

Dwarf galaxies of the Milky Way

➢ Most DM-dominated systems in the Universe



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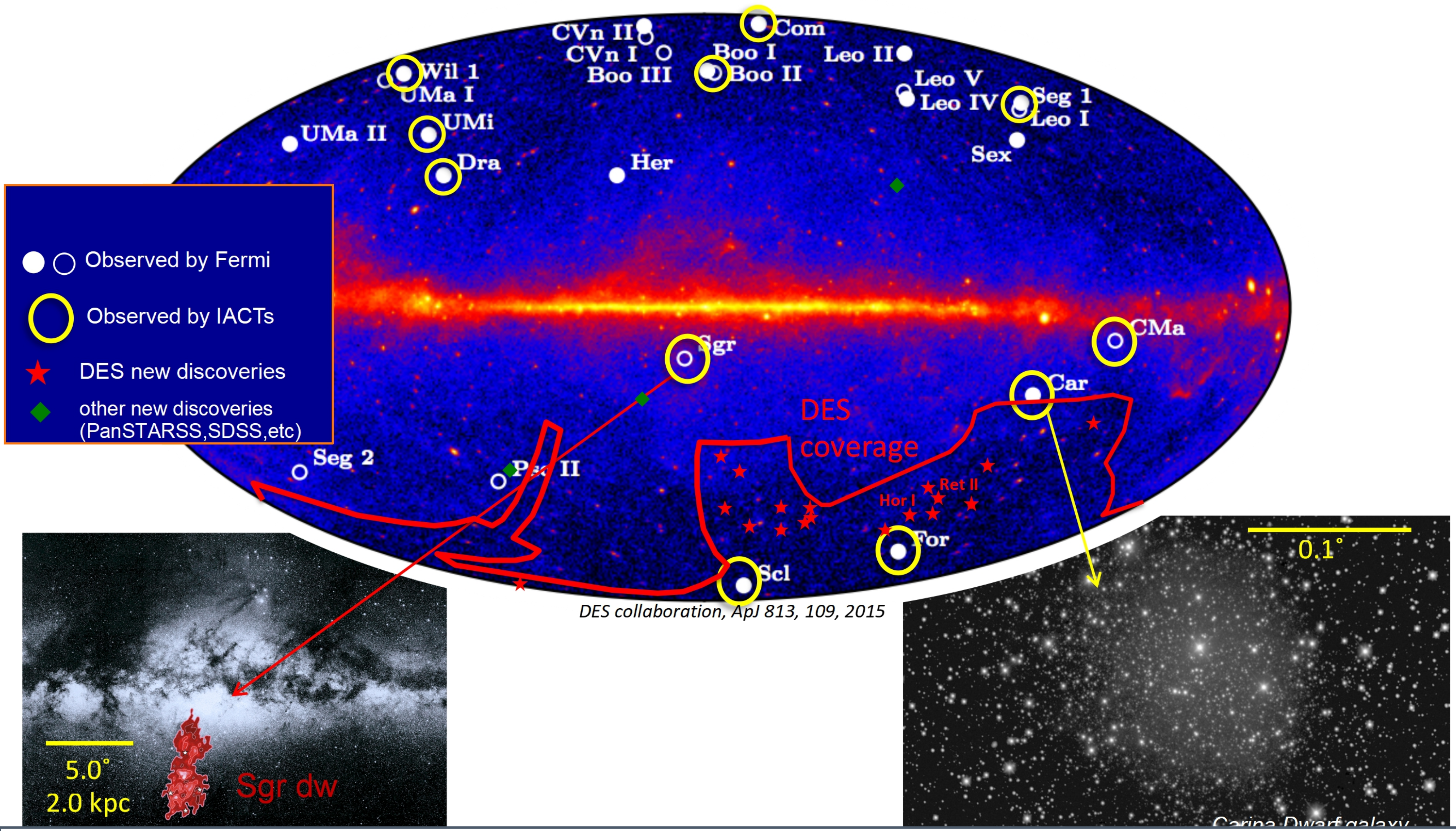
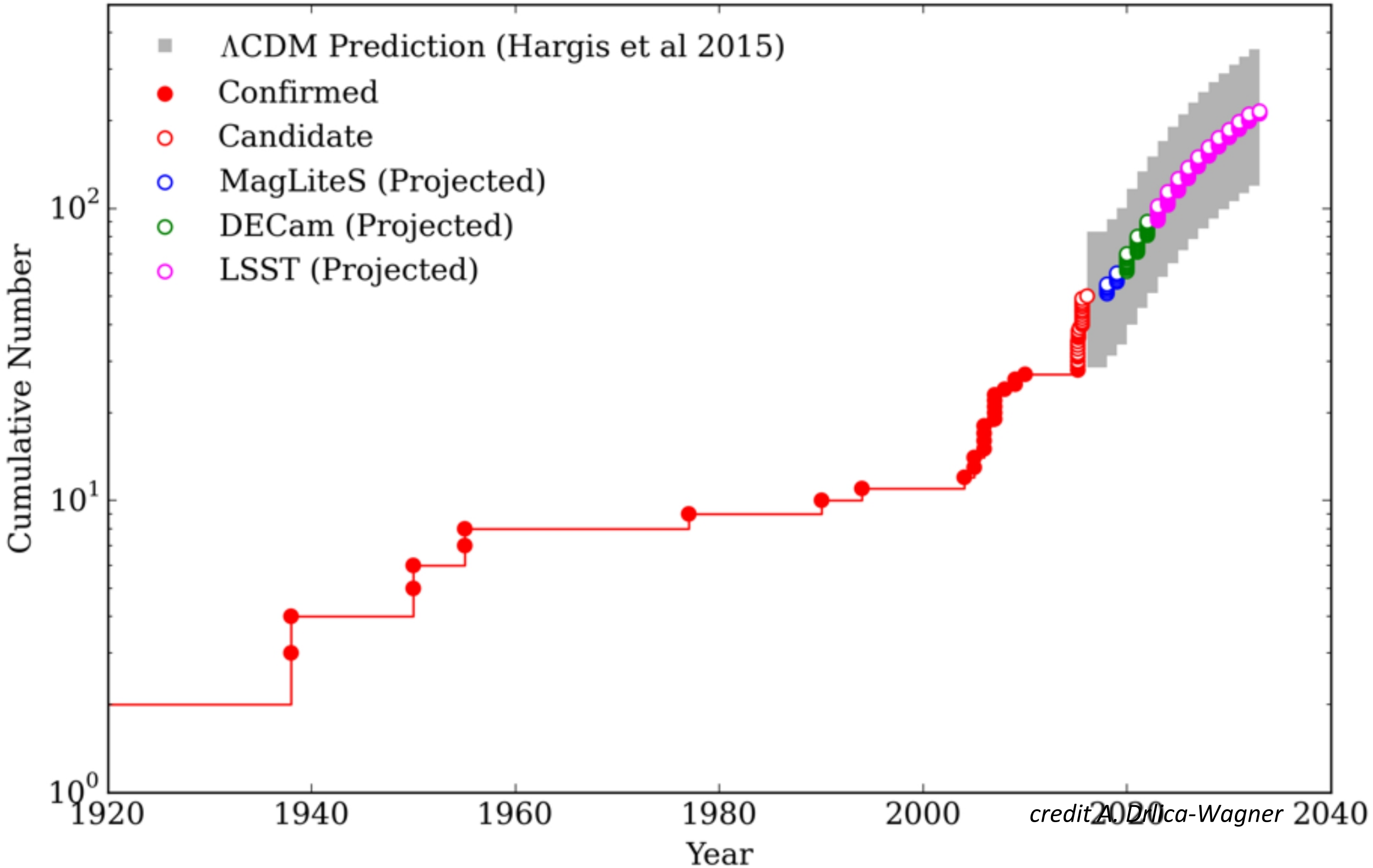


DES collaboration, ApJ 813, 109, 2015

Future prospects on dSphs

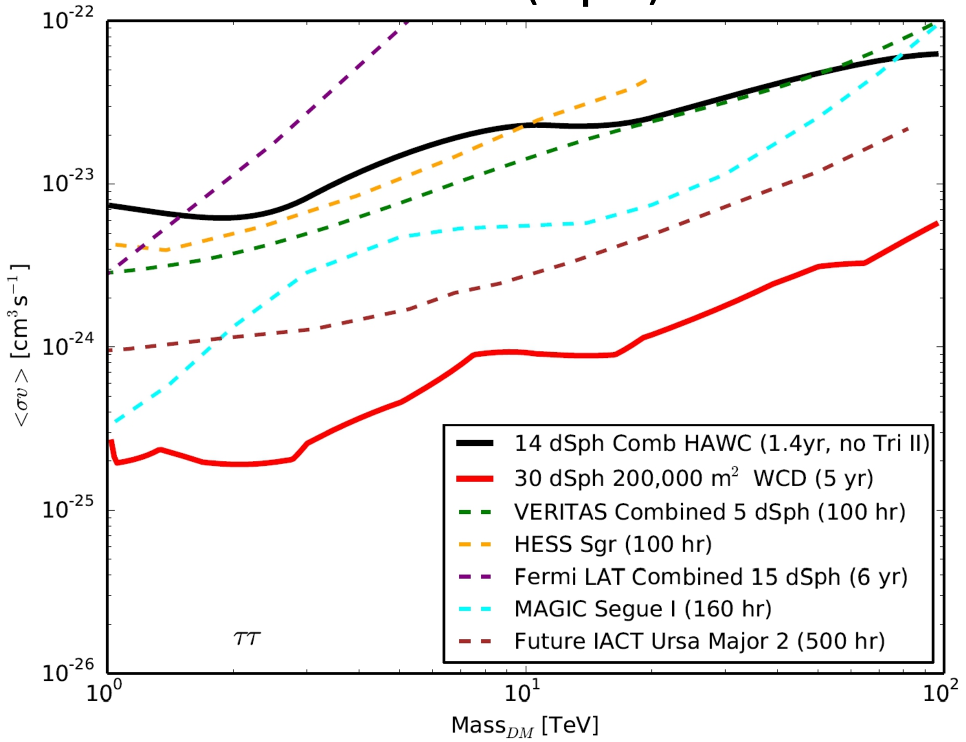


- Recent deep observations with wide-field optical imaging surveys have already discovered 33 new ultra-faint Milky Way satellites
- The next generation of surveys (i.e., The Rubin Observatory) should complete our census of the ultra-faint dwarfs out to the virial radius of the Milky Way.
- **Legacy data from SWGO at these locations could easily and immediately be analysed when new dSphs are found.**

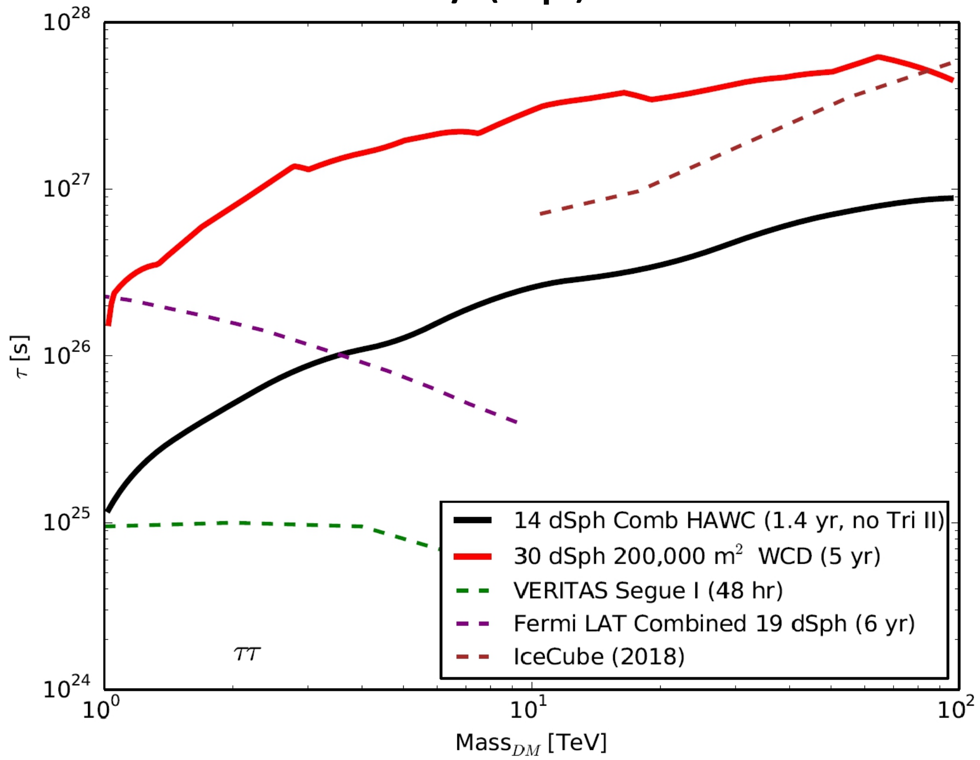
dSph galaxies: sensitivities

White paper: Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere, SGSO-alliance, arXiv:1902.08429

annihilation($\propto\rho^2$)



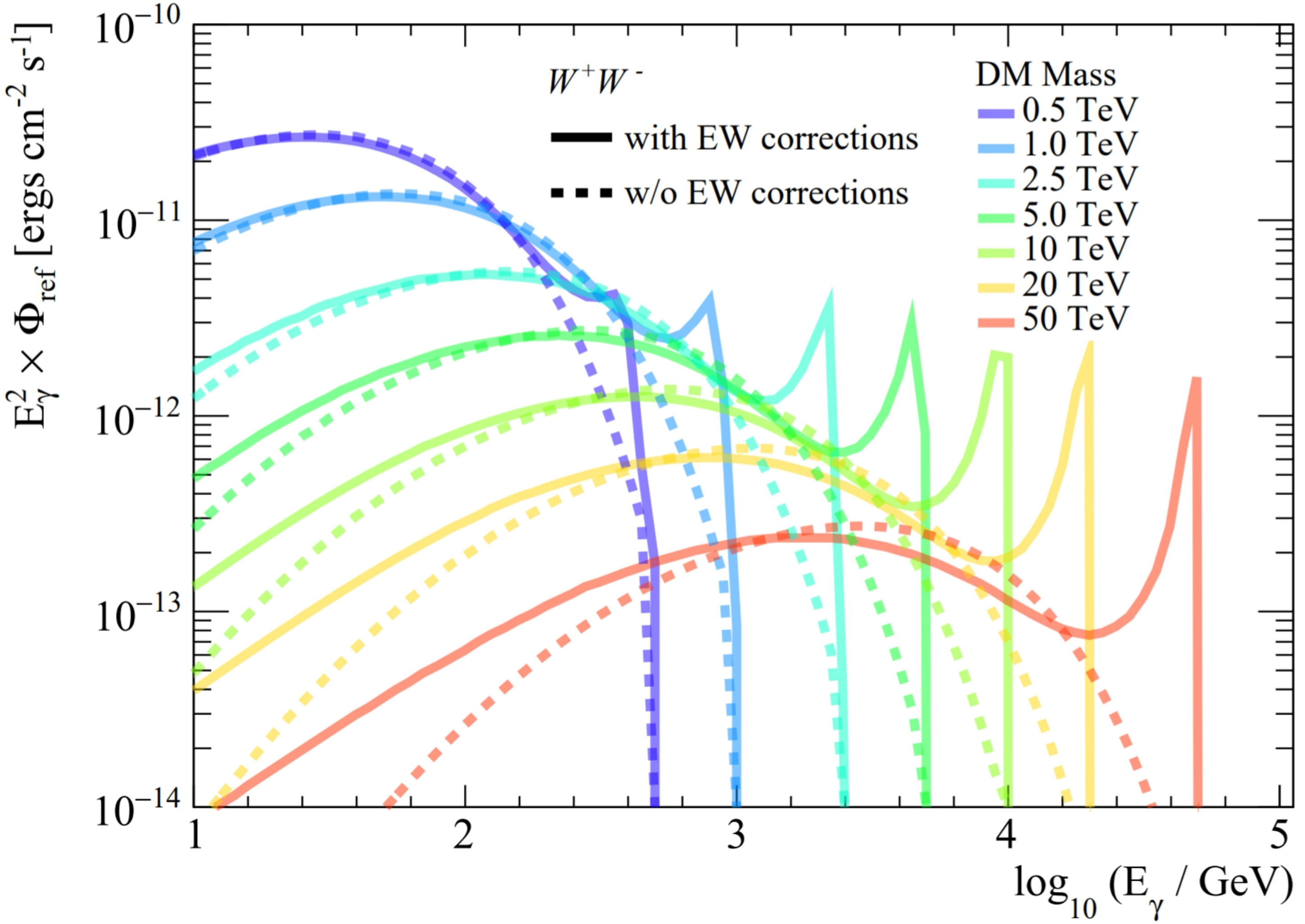
decay ($\propto\rho$)



- Assumed J-factor and D-factor distributions of the new dSphs matches that of the previously known dSphs
- **Improvement by an order of magnitude when compared to HAWC**
- **SWGO dSph searches to be more sensitive than dSph searches from current and future IACTs like H.E.S.S. and CTA.**

Electroweak corrections at TeV

- Electroweak corrections important for annihilation/decay of DM particle with masses well above electroweak-scale
- In W+W- channel -> production of hard photons in final state (gamma peak close to DM mass)



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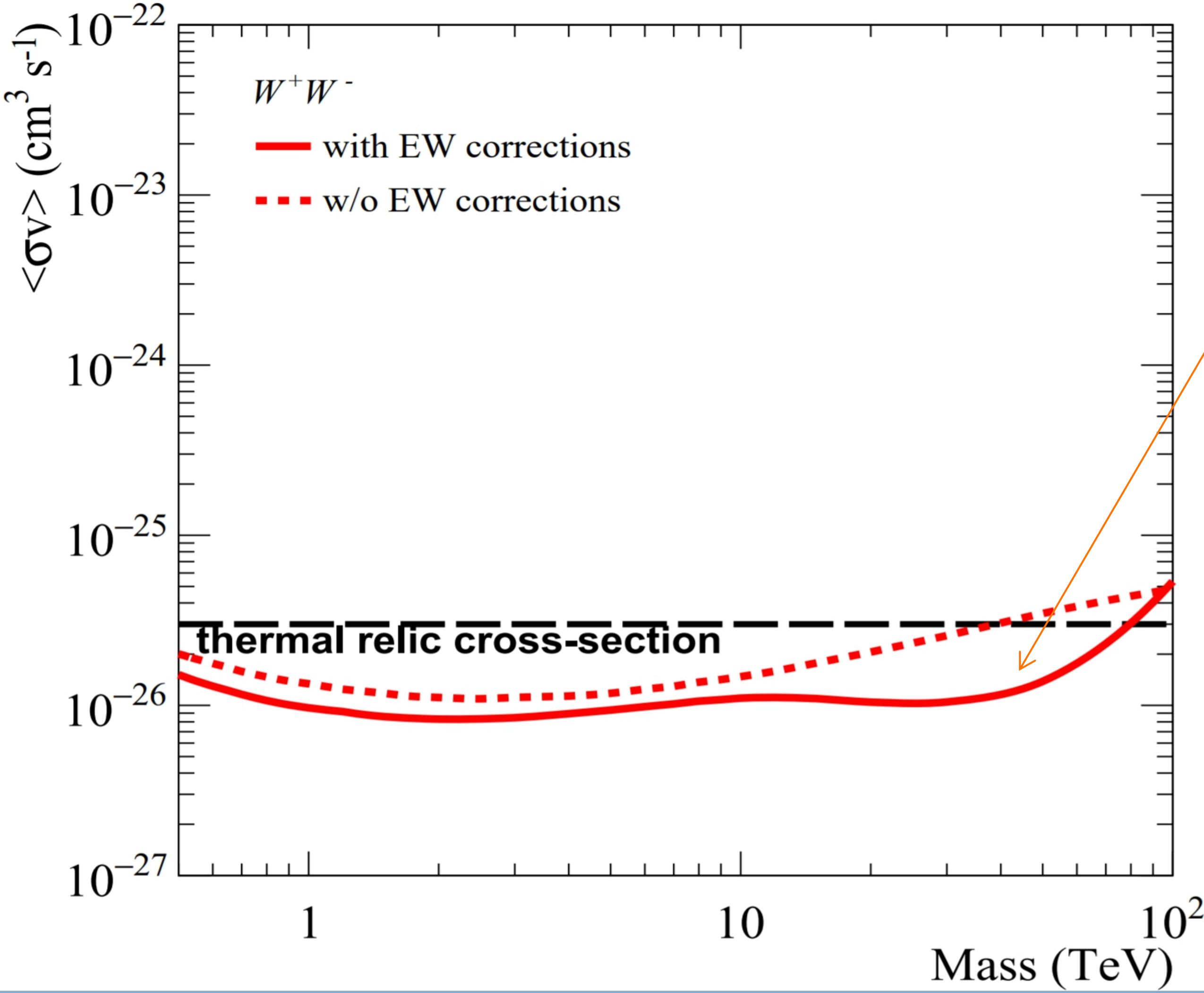

Effect particularly relevant for DM masses > 10 TeV