Dark Matter in the multi-messenger era

Workshop on High-energy astrophysics in the multi-messenger era

May 2023
Erlangen - Germany

Aion Viana
Instituto de Física de São Carlos - USP

Outline

1. Indirect detection of dark matter: basic principles

2. Indirect searches for dark matter with gamma-rays (and neutrinos): instruments and recent results

3. Indirect searches for dark matter with neutrinos: instruments and recent results

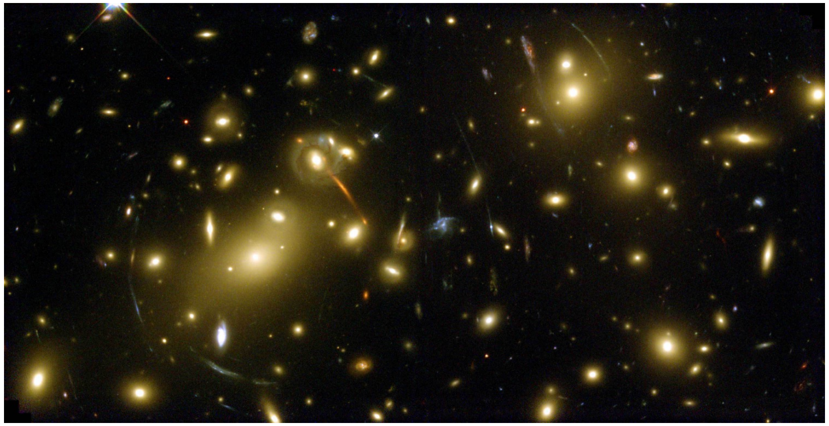
4. Indirect searches for dark matter with charged cosmic-rays: instruments and recent results

Disclaimer: Very large topic. Here I present a personal selection of recent results

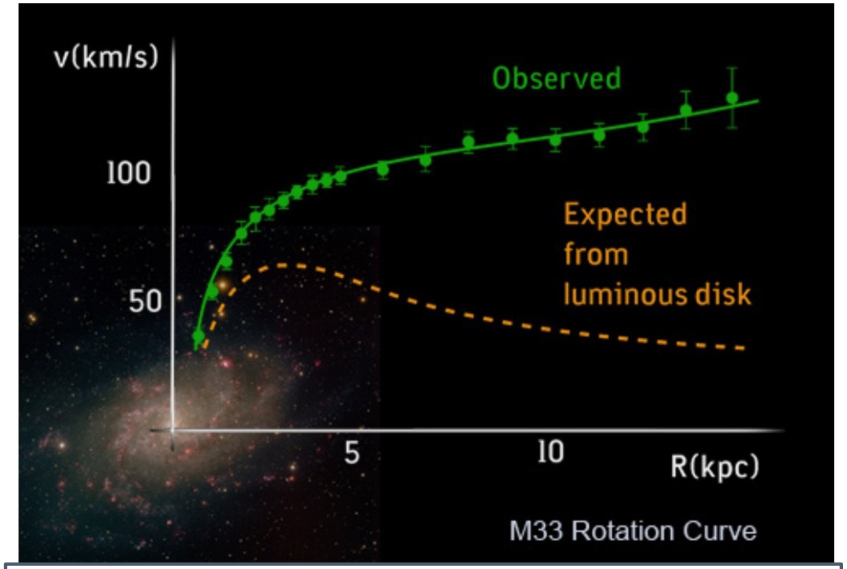
Introduction

Two hypothesis:

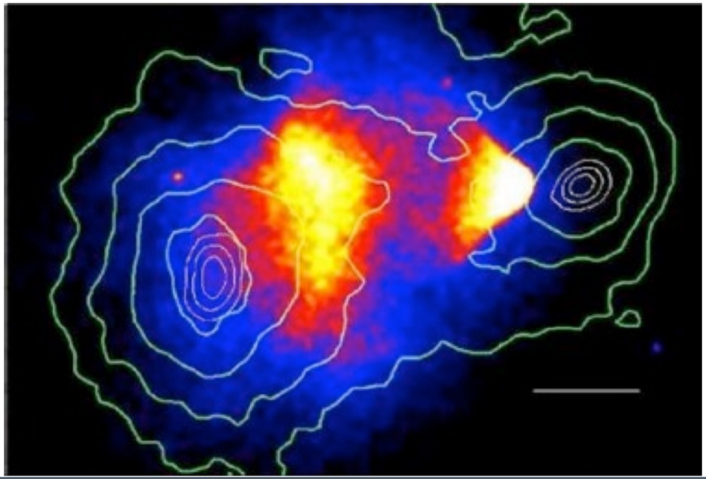
1. Dark matter does exist



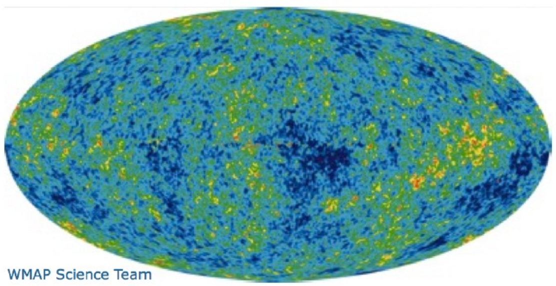
Most **gravitational mass** of galaxies and galaxy clusters (Zwicky 1937)

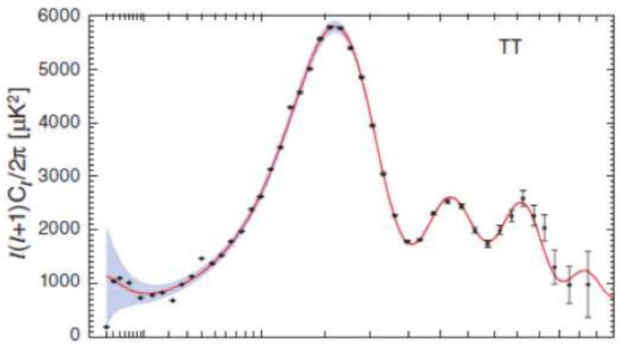


Large halos em around Galaxies: rotation curves (Rubin+ 1980)



Pratically **non-collisional**: Bullet Cluster (Clowe+ 2006)





Non-barionic: Big bang nucleosynthesis, barionic accoustic oscillations, WMAP(2010), Planck(2015)

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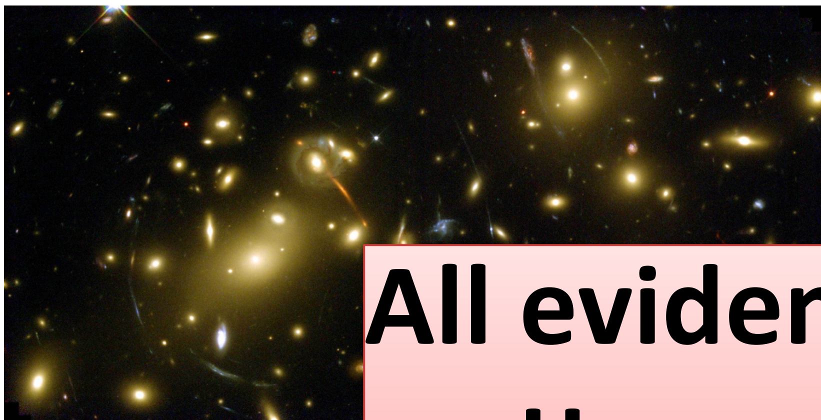

Most **gravitatior**
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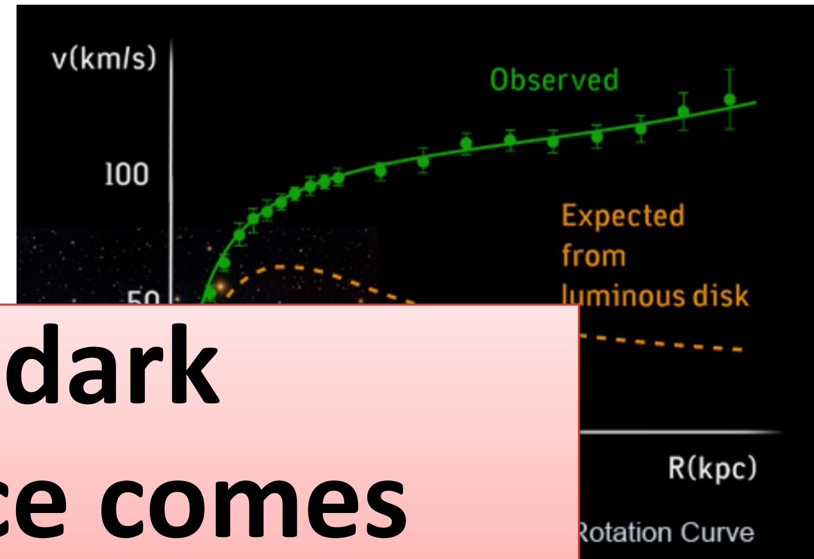
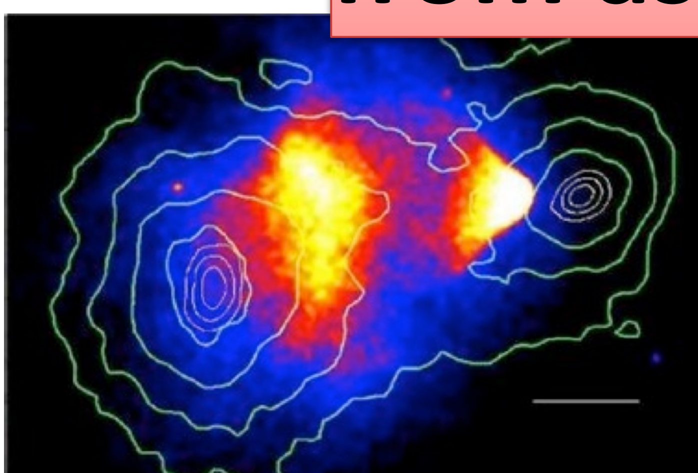


laxies:
80)

All evidence of dark matter existence comes from astrophysics!



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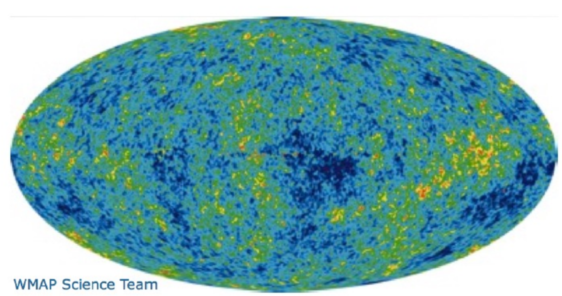

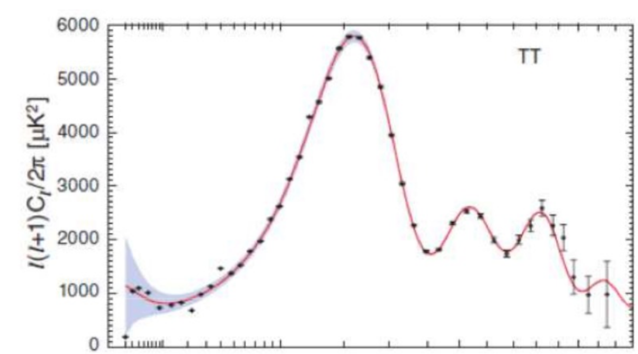

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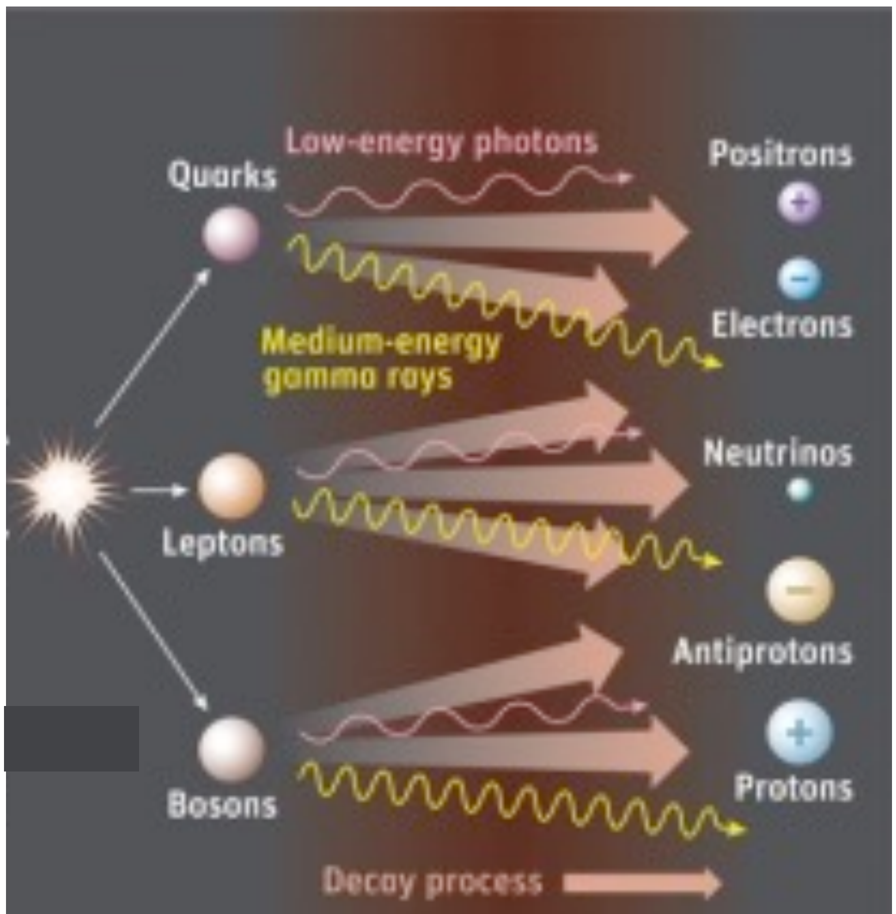
Introduction

Two hypothesis:

1. Dark matter does exist

2. Dark matter is a particle that **couples** non-gravitationally **to Standard Model particles**

$$\chi\chi \rightarrow$$
$$\chi \rightarrow$$

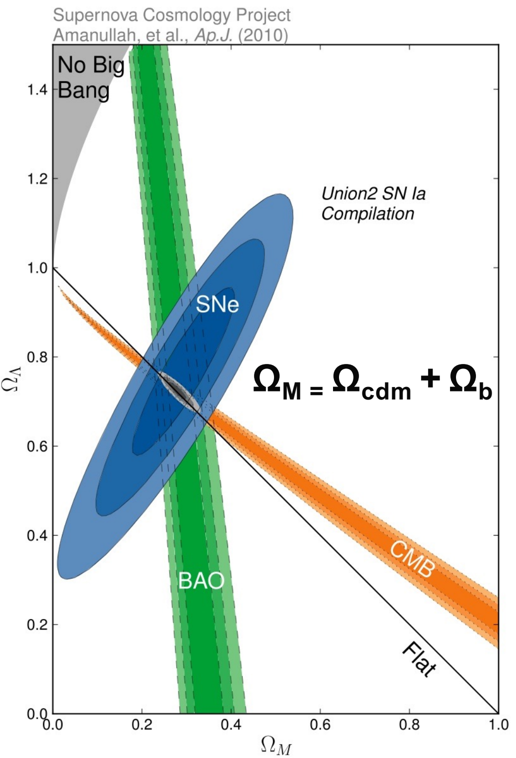


Annihilation or decay of DM leads to the production of stable particles of Standard Model

Relic density and WIMP *miracle*

Standard Cosmology Model: ΛCDM

Observation constraints



$\Omega_b = 0.048 \pm 0.001$

$\Omega_{cdm} = 0.258 \pm 0.006$

$\Omega_\Lambda = 0.691 \pm 0.006$

Relic density and WIMP *miracle*

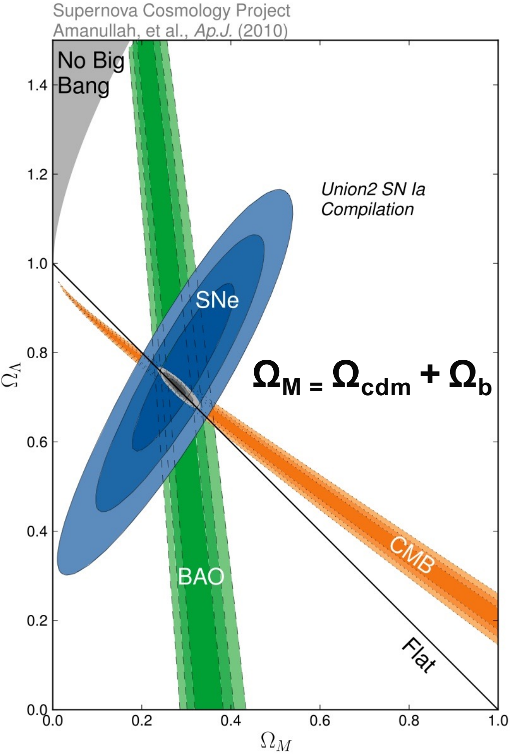
Standard Cosmology Model: ΛCDM

Boltzman equation in comoving volume

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

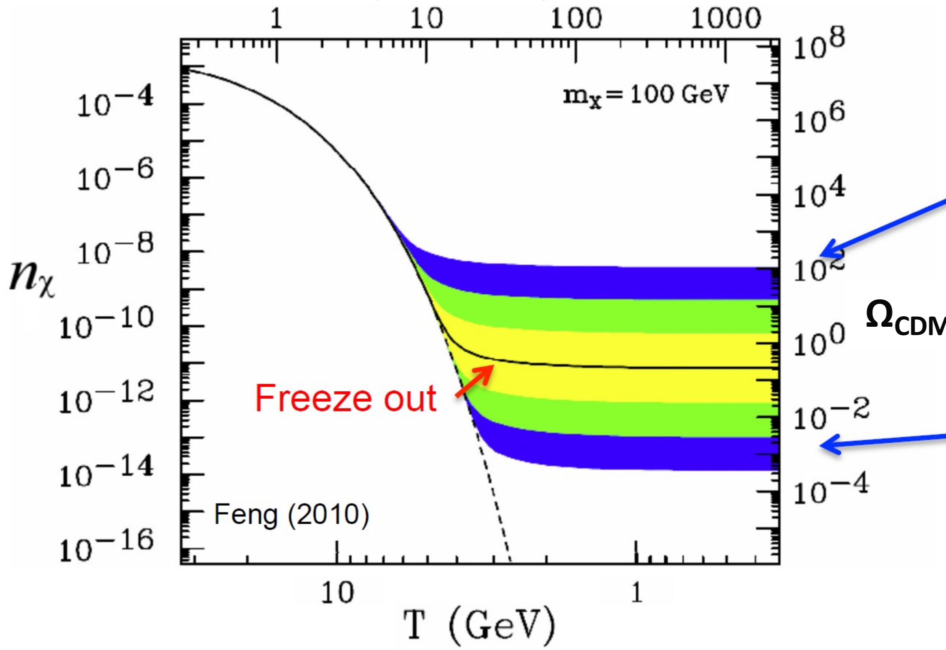
$$\chi + \bar{\chi} \leftrightarrow l + \bar{l}$$

Observation constraints



$\Omega_M = \Omega_{cdm} + \Omega_b$

DM density vs Temperature



Small cross-section: early freeze-out, too much DM

Large cross-section: late freeze-out, too little DM

$$\Omega_{CDM} \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_{ann} v \rangle} \Rightarrow \langle \sigma_{ann} v \rangle \sim 2.8 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

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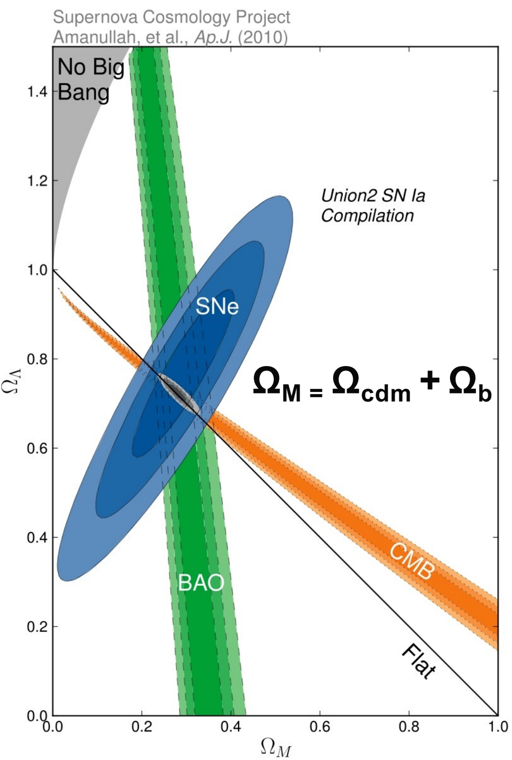

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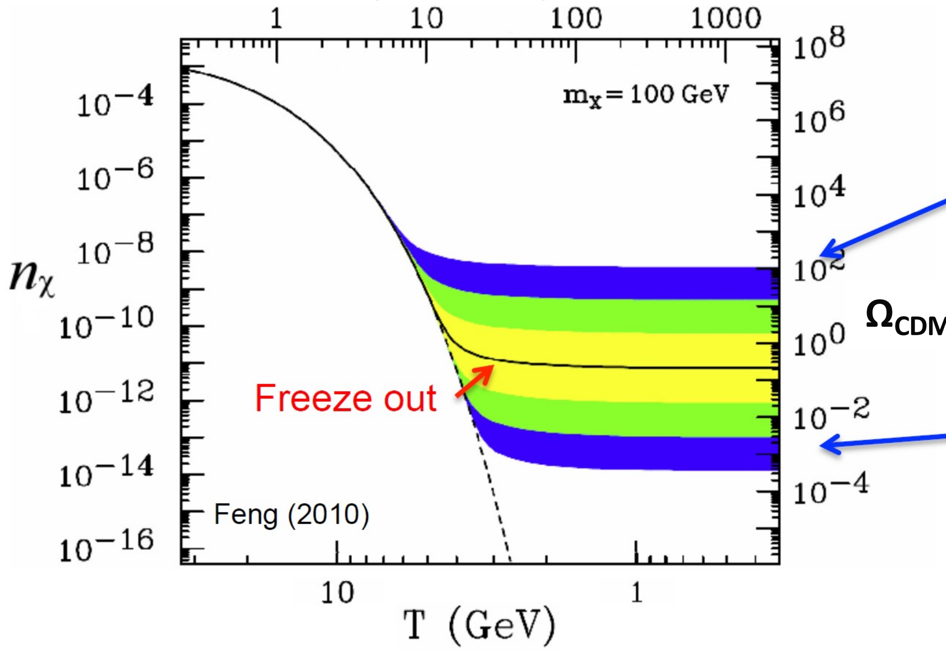

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Weakly Interacting Particle (WIMP)

- weak scale mass (10 GeV - 1 TeV)
- electroweak interaction ~ 3×10^{-26} $\mathrm{cm}^3 \mathrm{s}^{-1}$
- **Produces observed relic density**

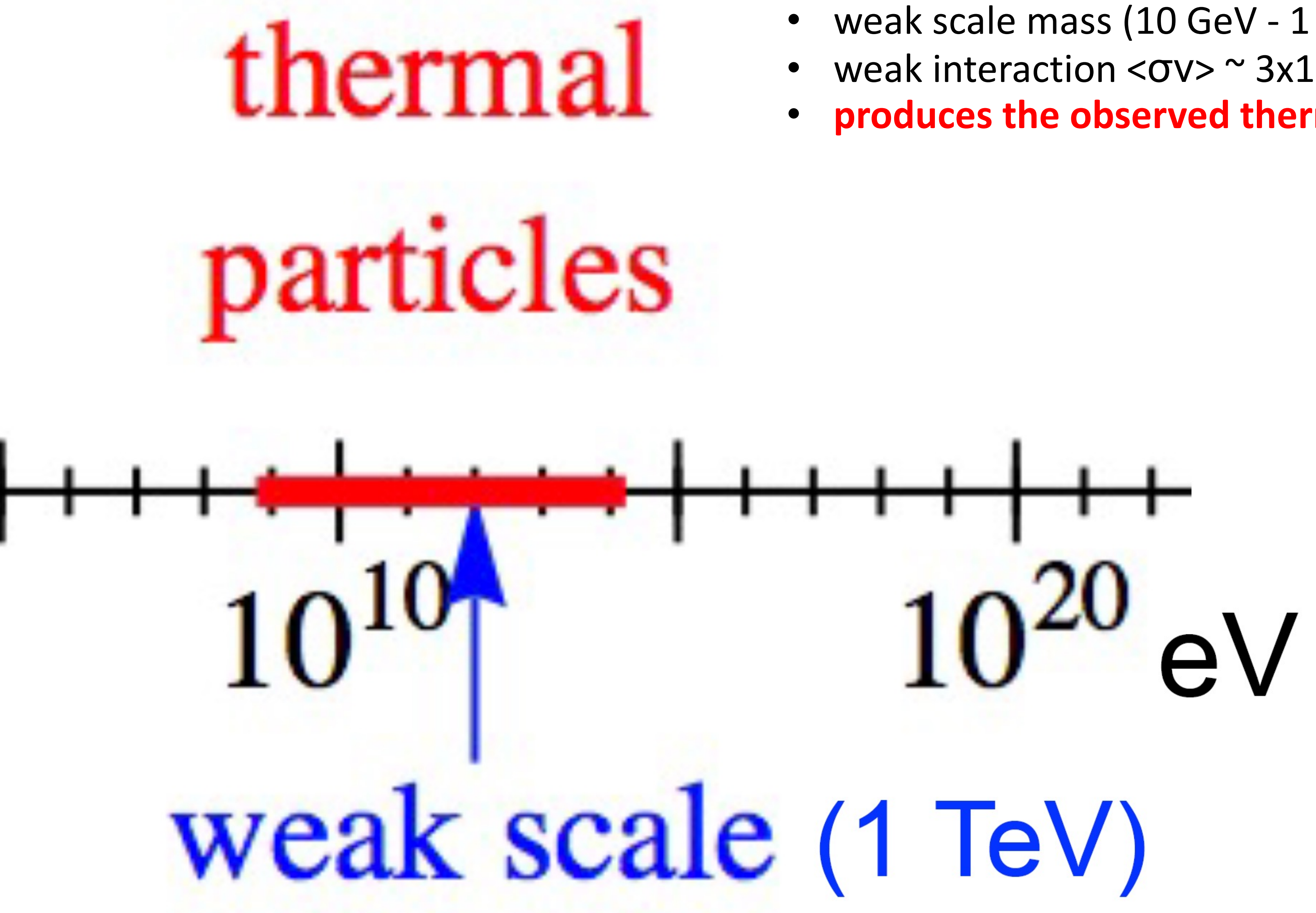
We believe in miracles!

Dark matter particle candidates

A question of pespective: plausible mass scale

Weakly Interacting Massive Particles (WIMPs)

- weak scale mass (10 GeV - 1 TeV)
- weak interaction <σv> ~ 3x10^{-26} cm^{3}s^{-1}
- **produces the observed thermal relic density**



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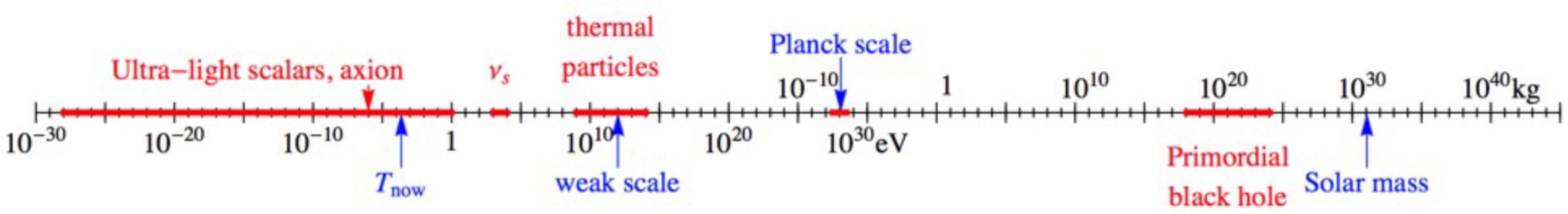
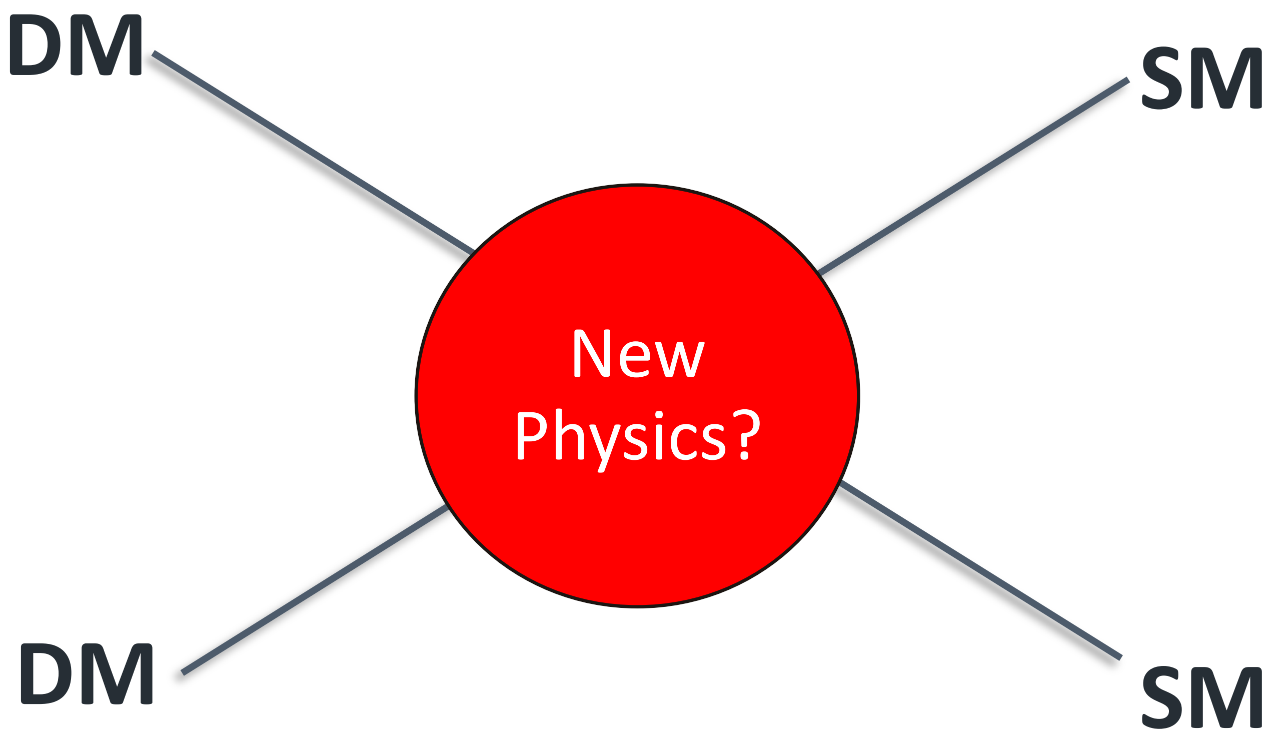


"only" 90 orders of magnitude!

Lots of Beyond Standard Model theories predict the existence of one of more WIMPs, and other dark matter particle candidates

How to detect the dark matter particle?



DM = Dark Matter
SM = Standard Model (of Particle Physics)

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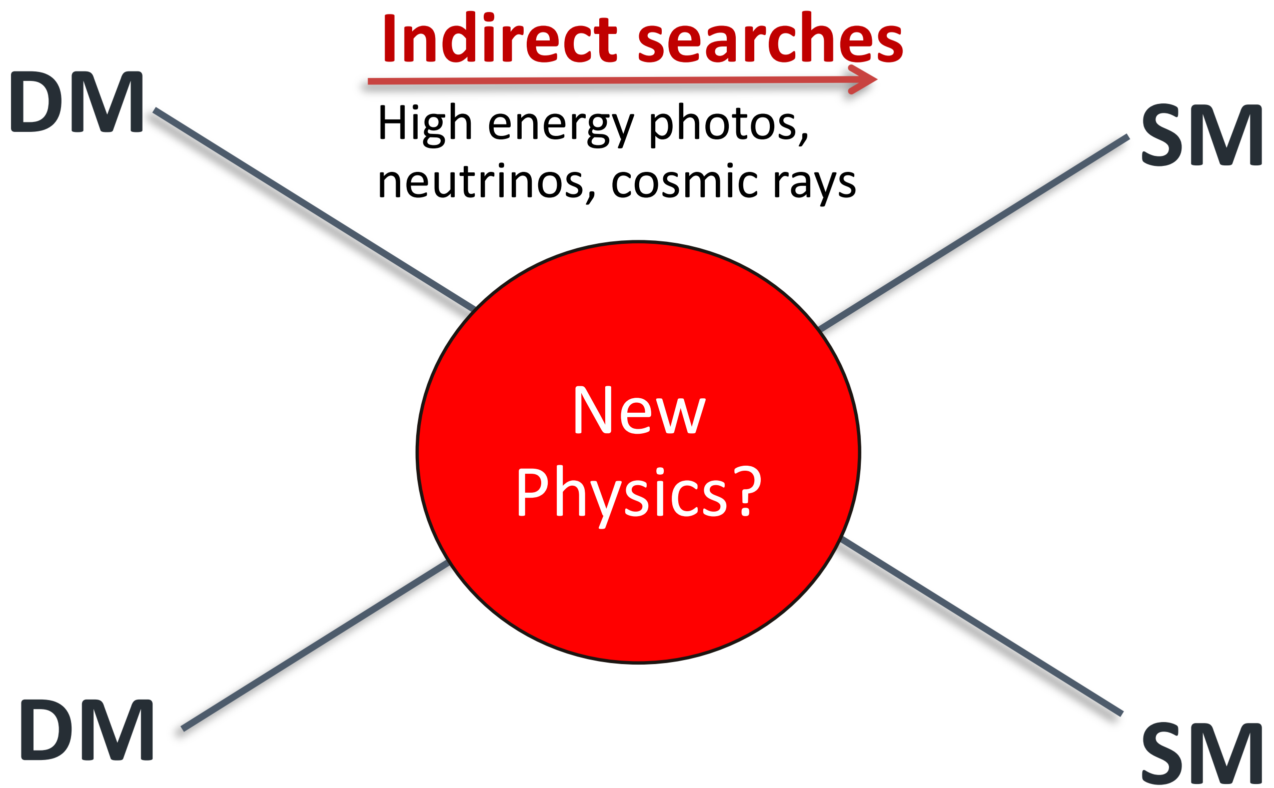

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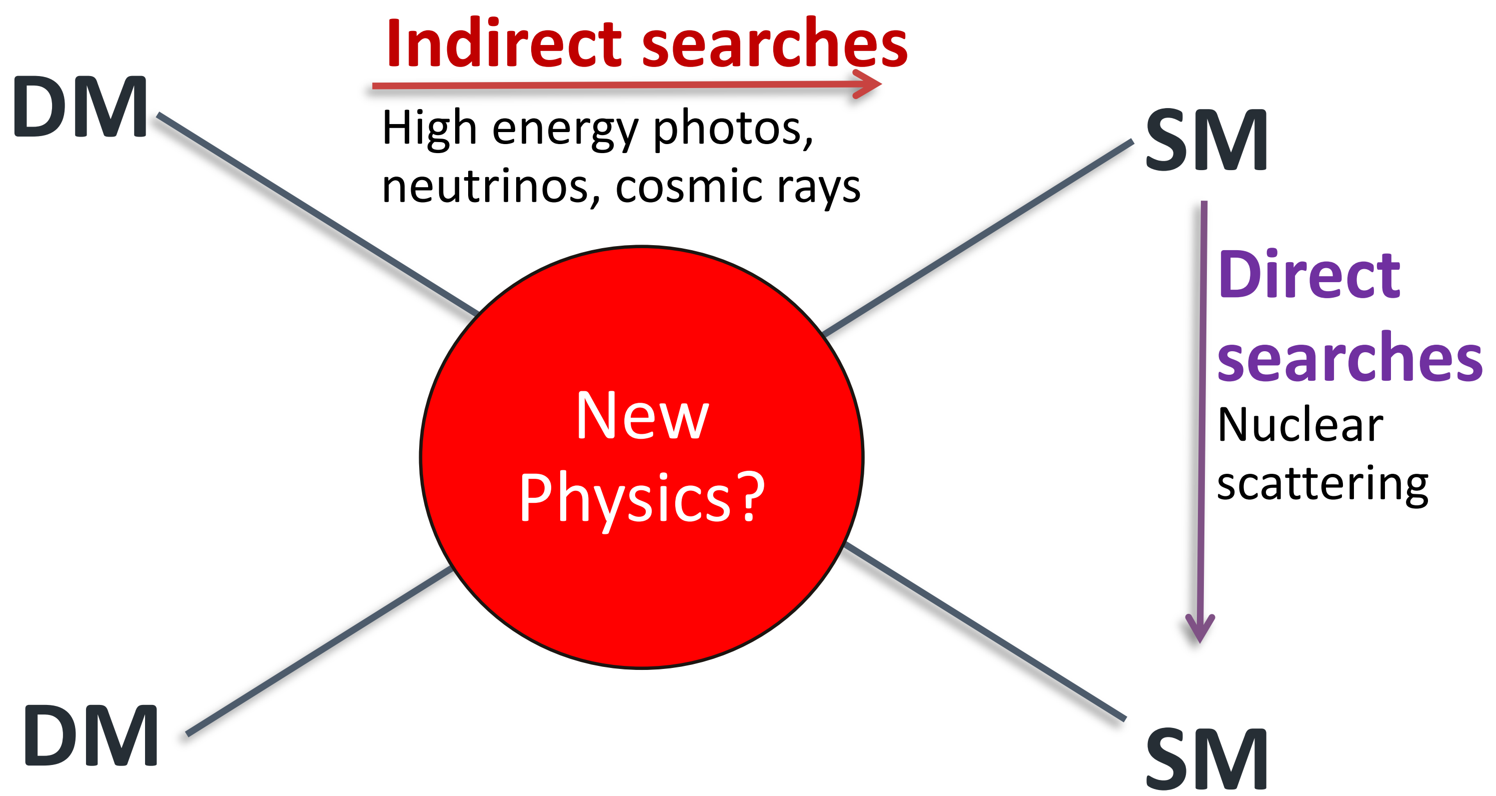

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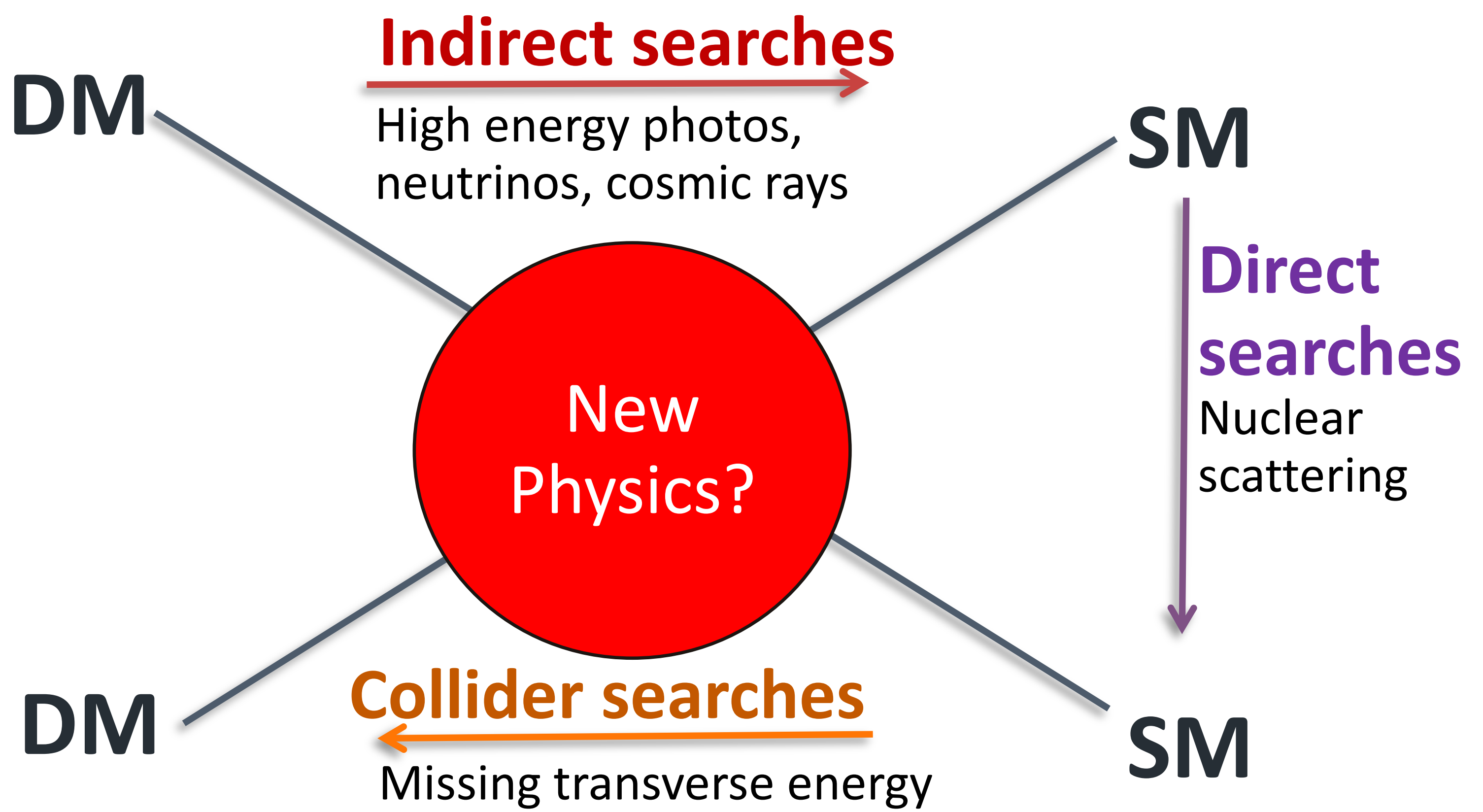

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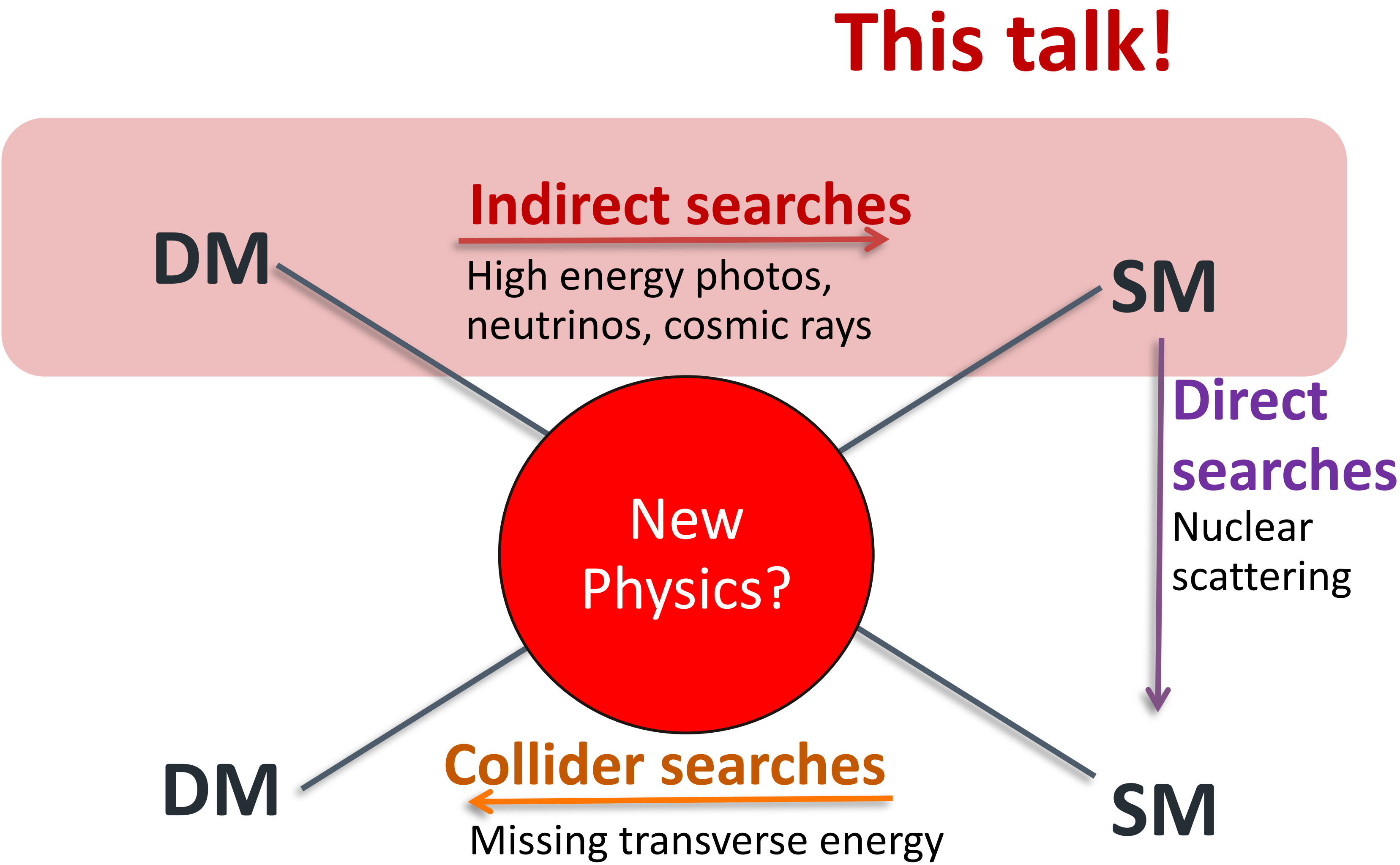

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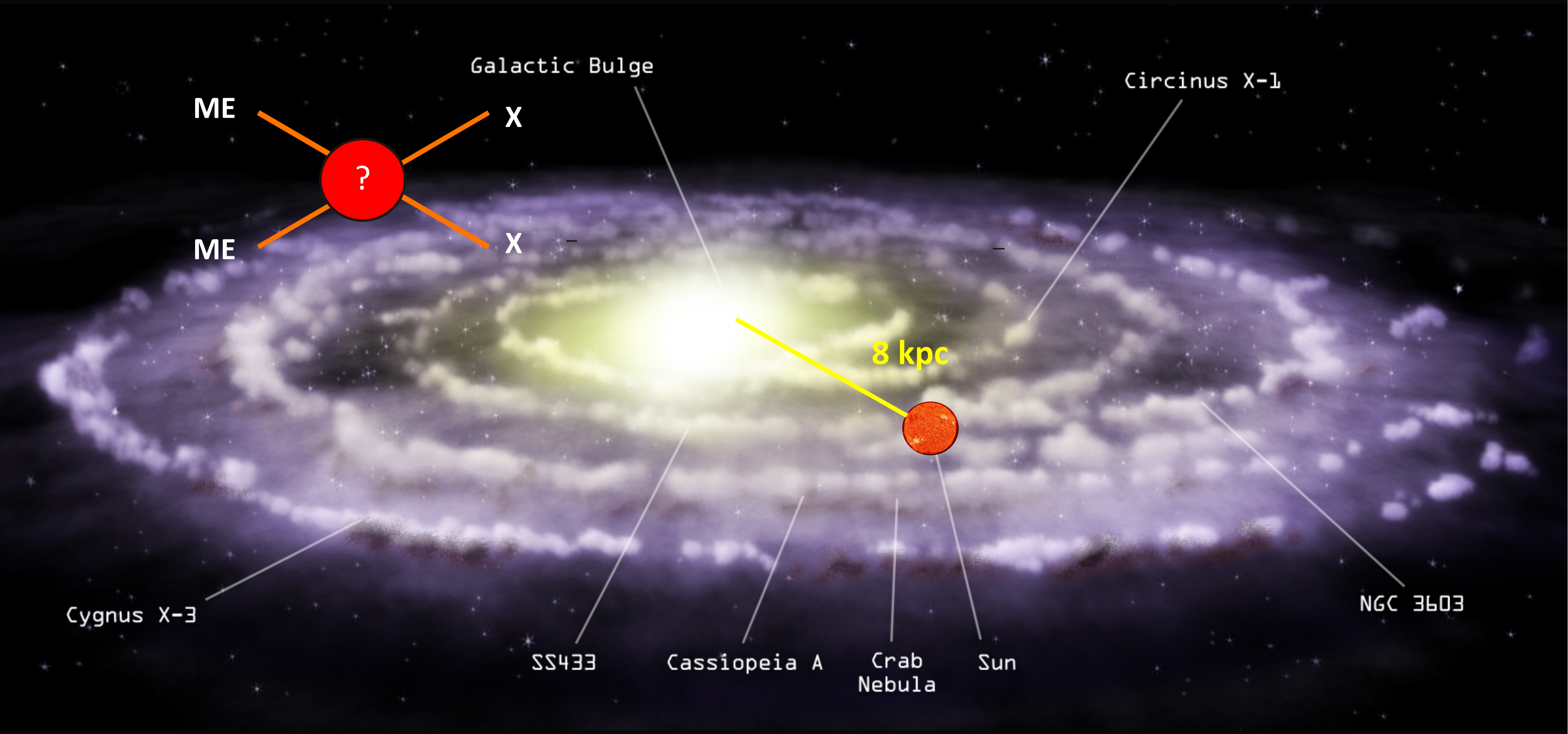
Dark matter messengers in the Galaxy



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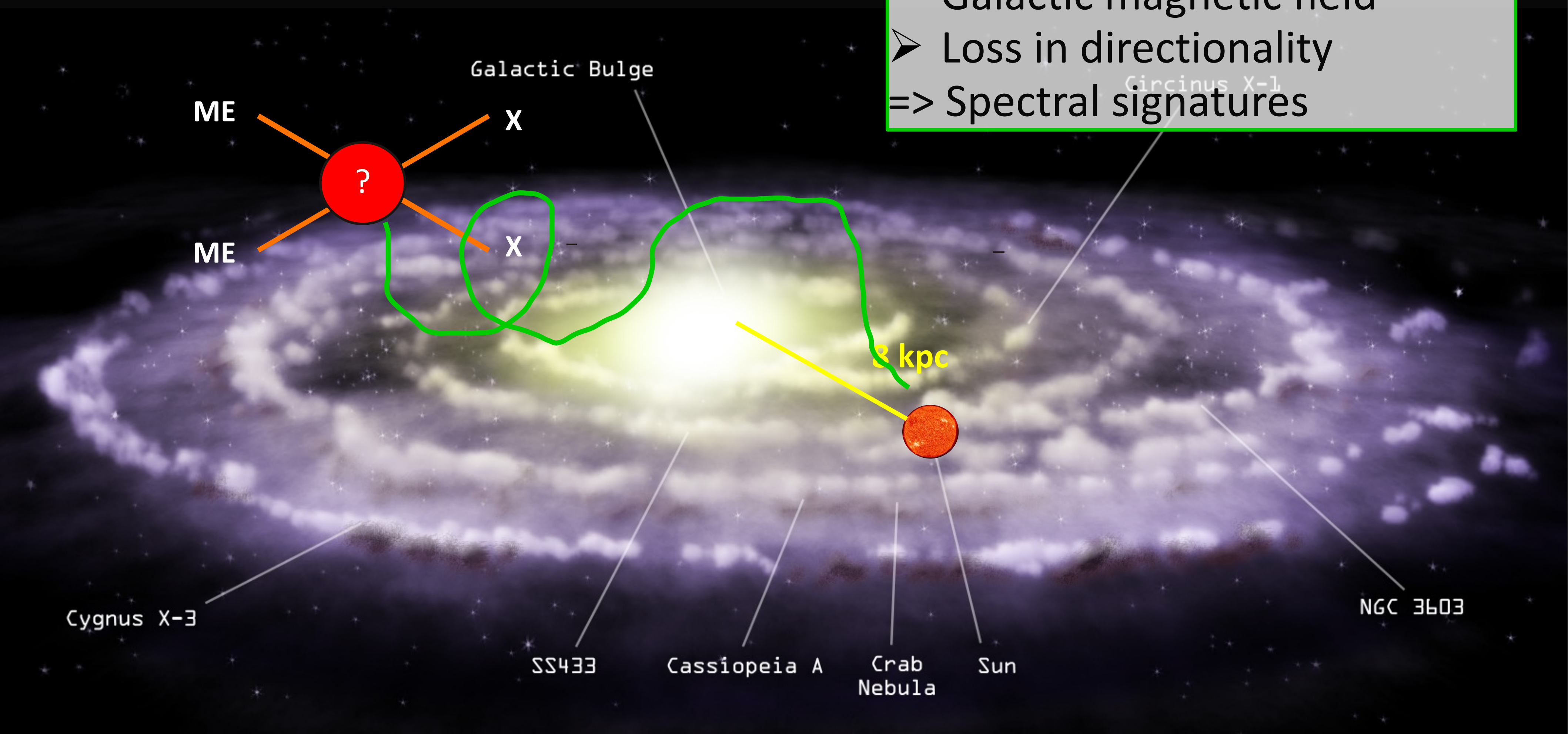
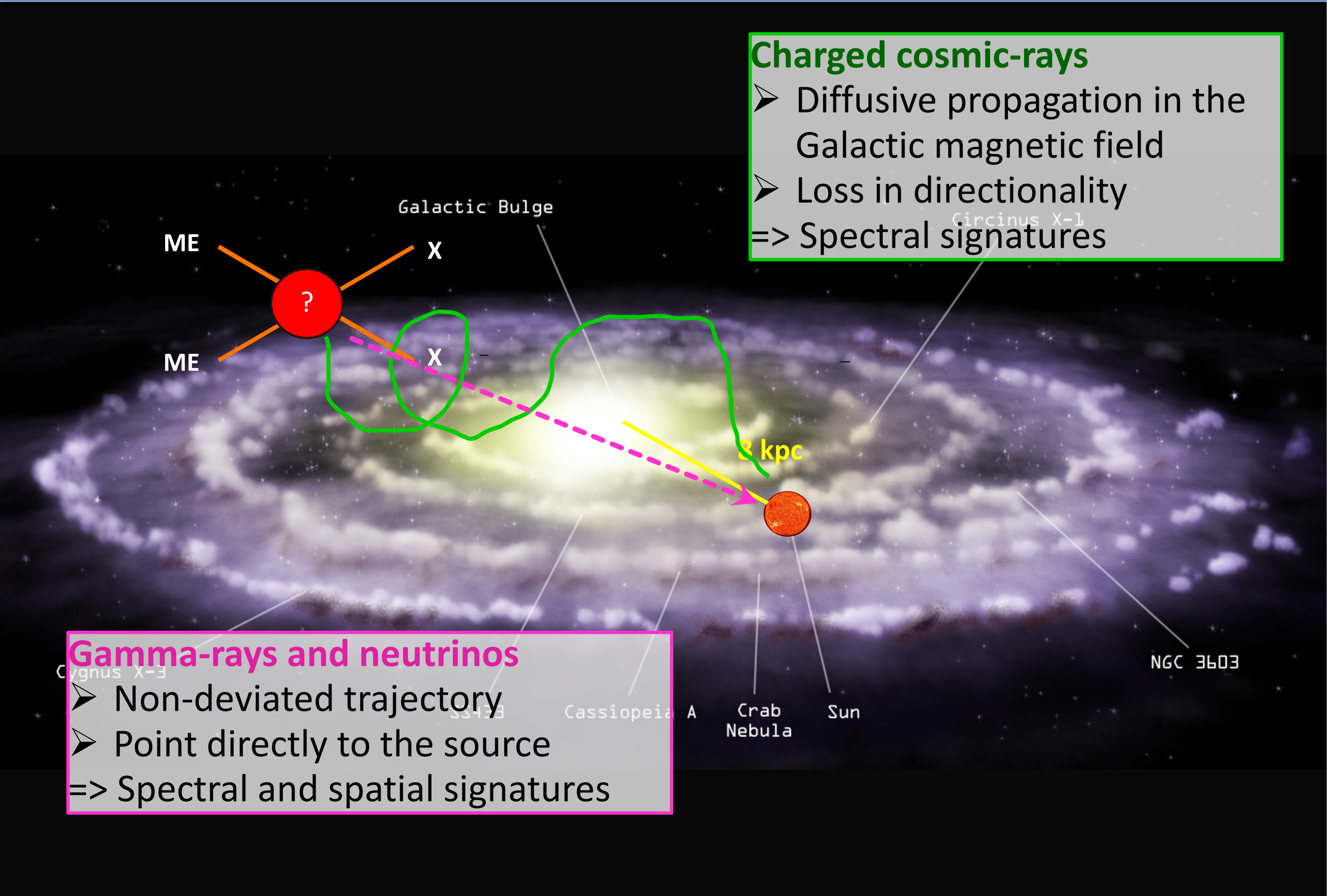


Charged cosmic-rays

- Diffusive propagation in the Galactic magnetic field
- Loss in directionality

=> Spectral signatures

Dark matter messengers in the Galaxy



Charged cosmic-rays
- Diffusive propagation in the Galactic magnetic field
- Loss in directionality

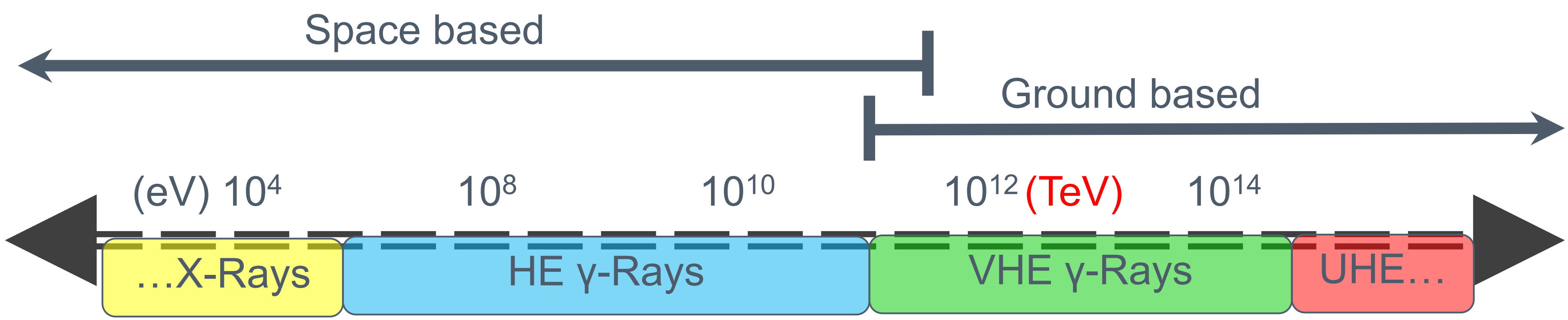
=> Spectral signatures

Gamma-rays and neutrinos
- Non-deviated trajectory
- Point directly to the source

=> Spectral and spatial signatures

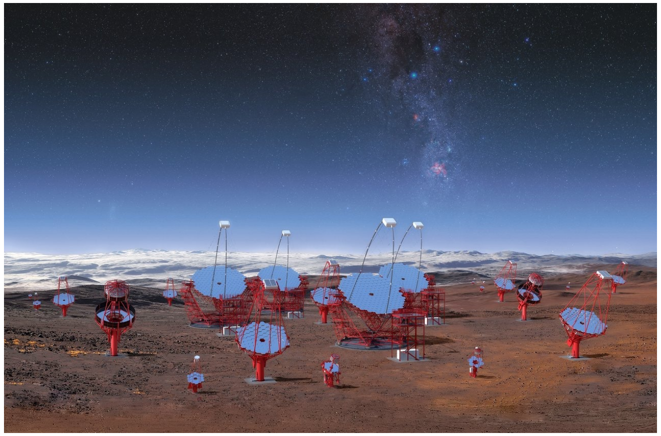
Dark Matter searches with gamma rays

The extreme electromagnetic universe

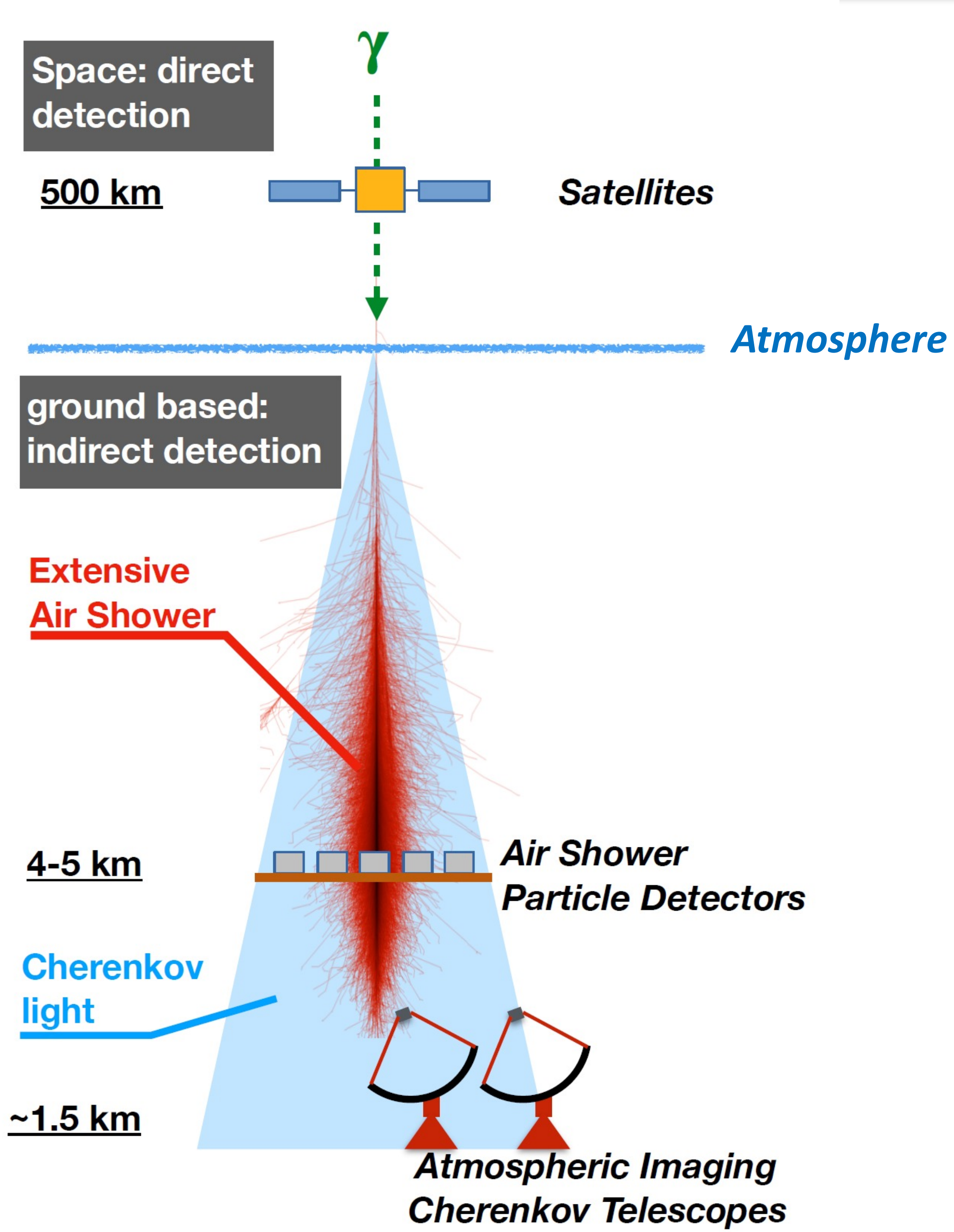


Gamma-ray satellites:
- EGRET
- Fermi-LAT

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



Detection techniques in gamma-ray astronomy



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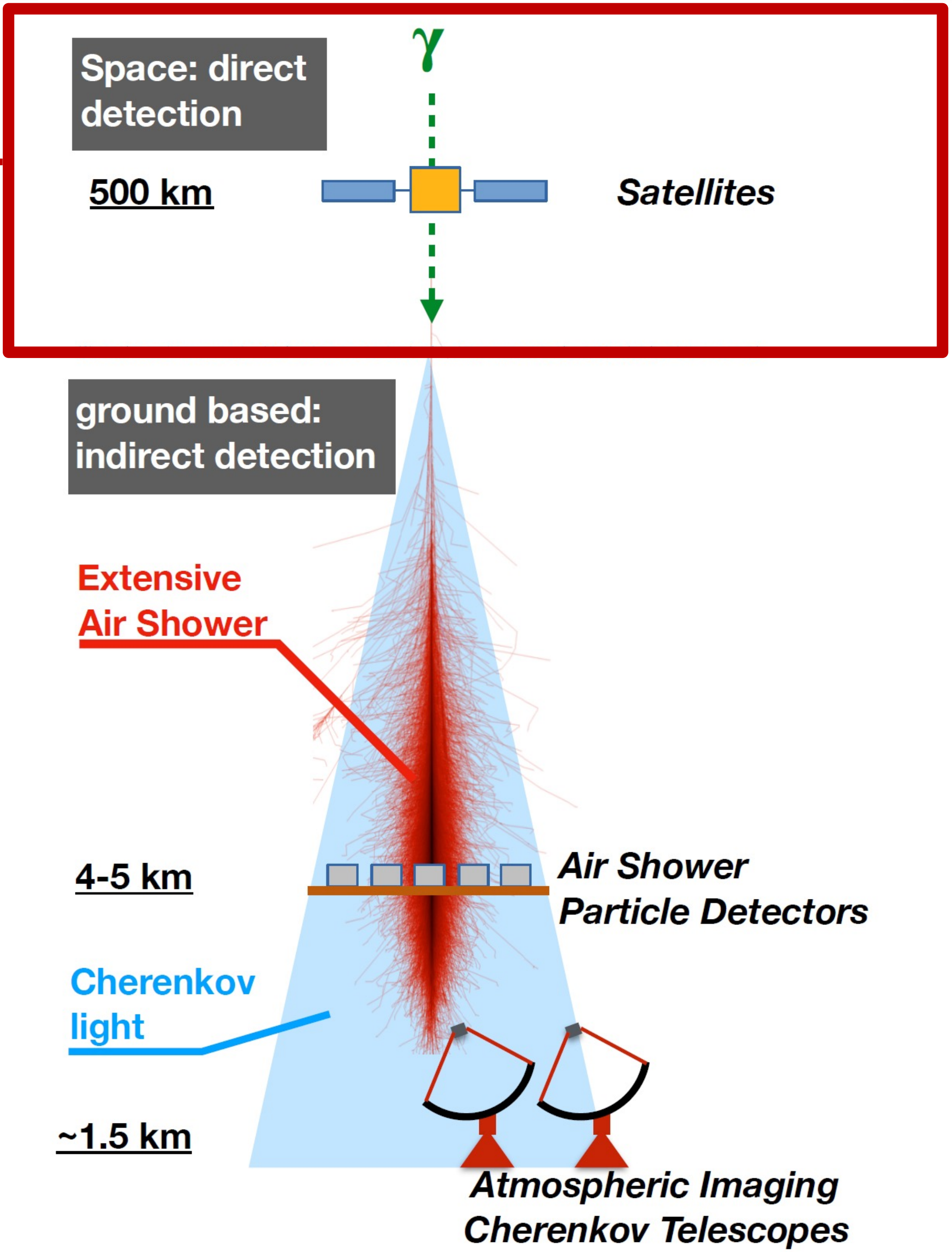

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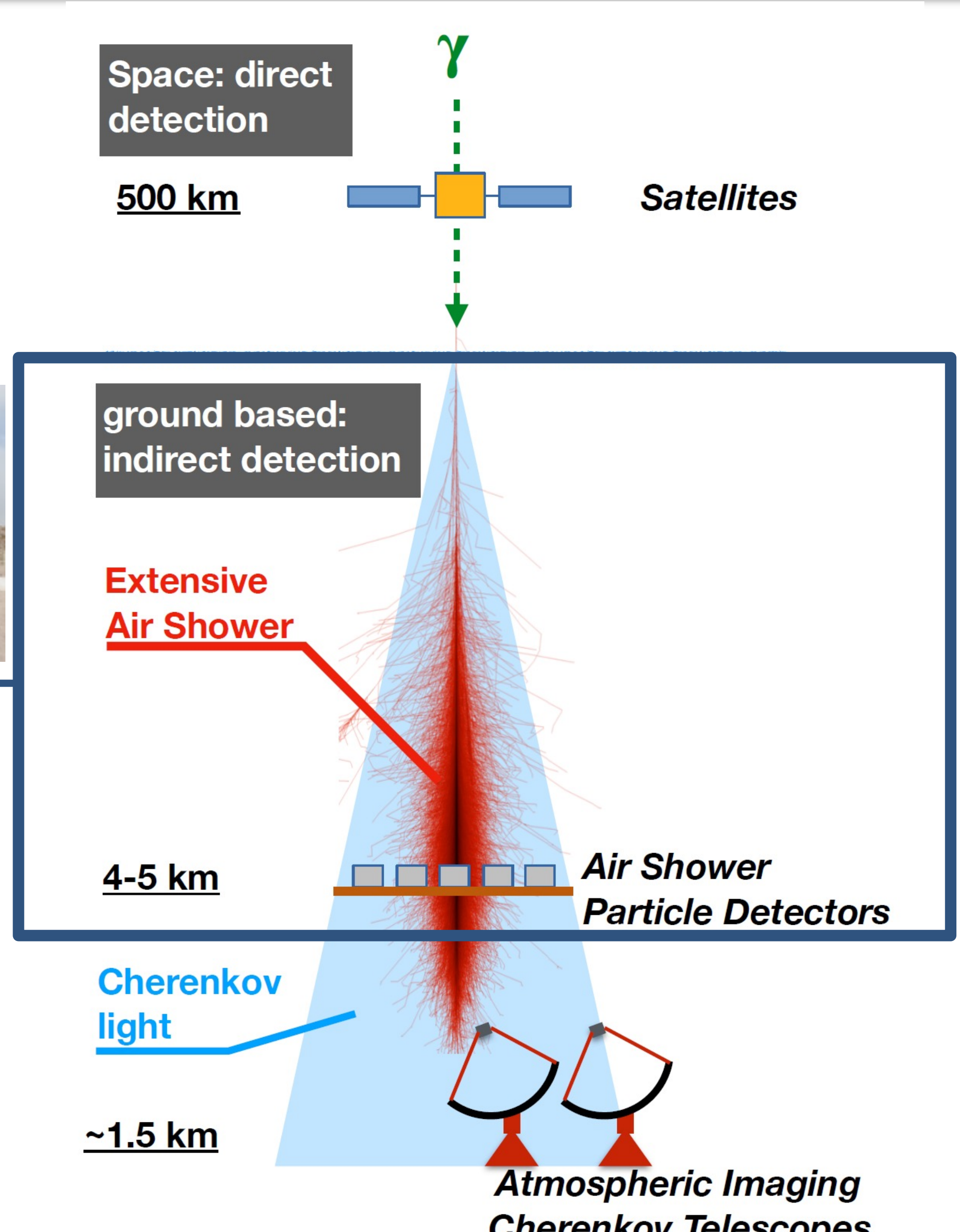

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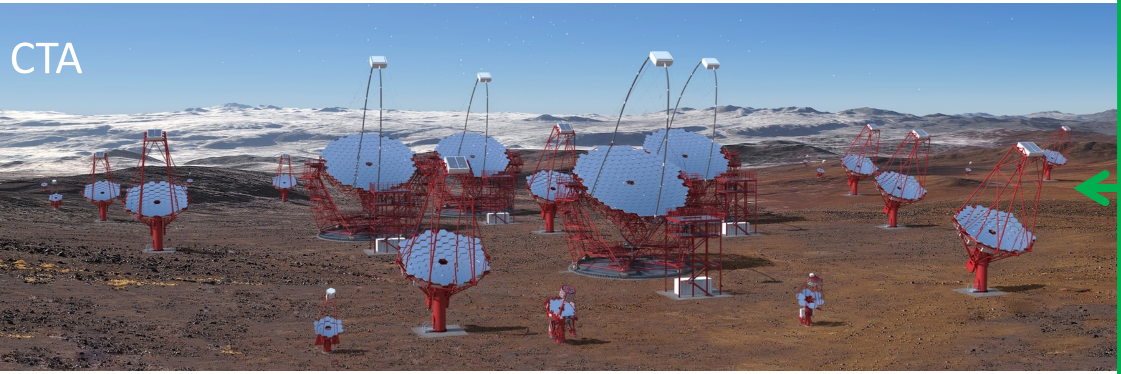
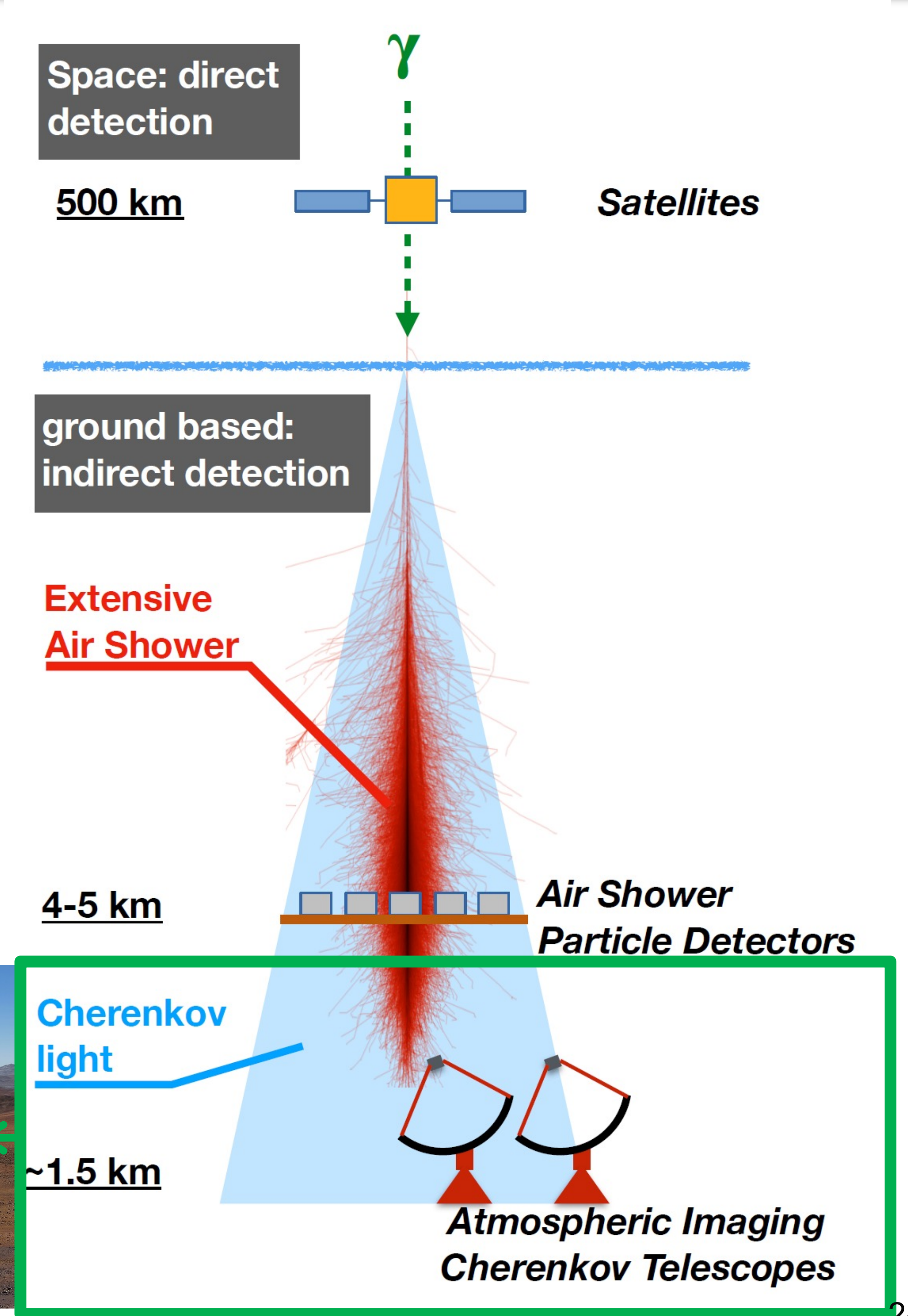
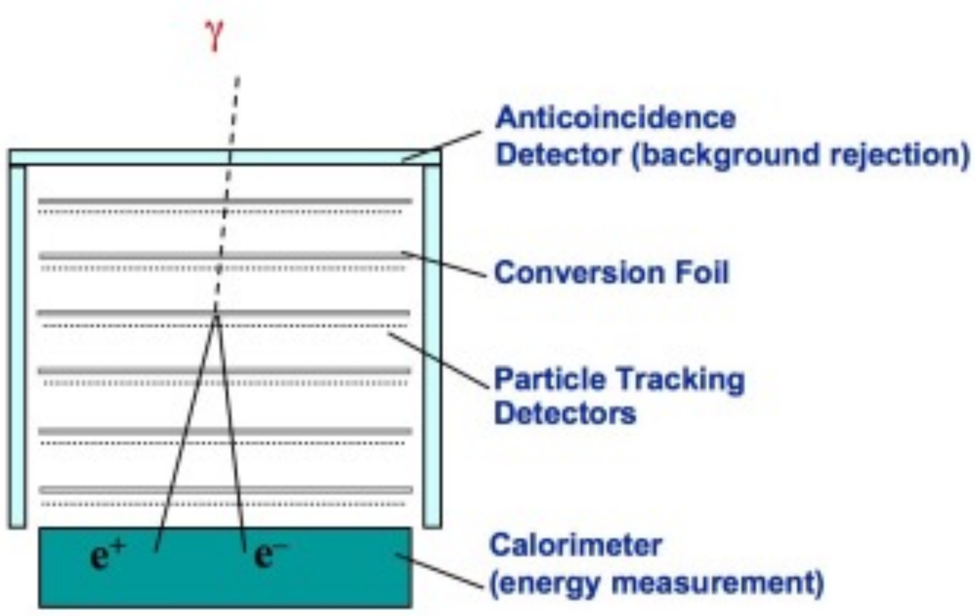


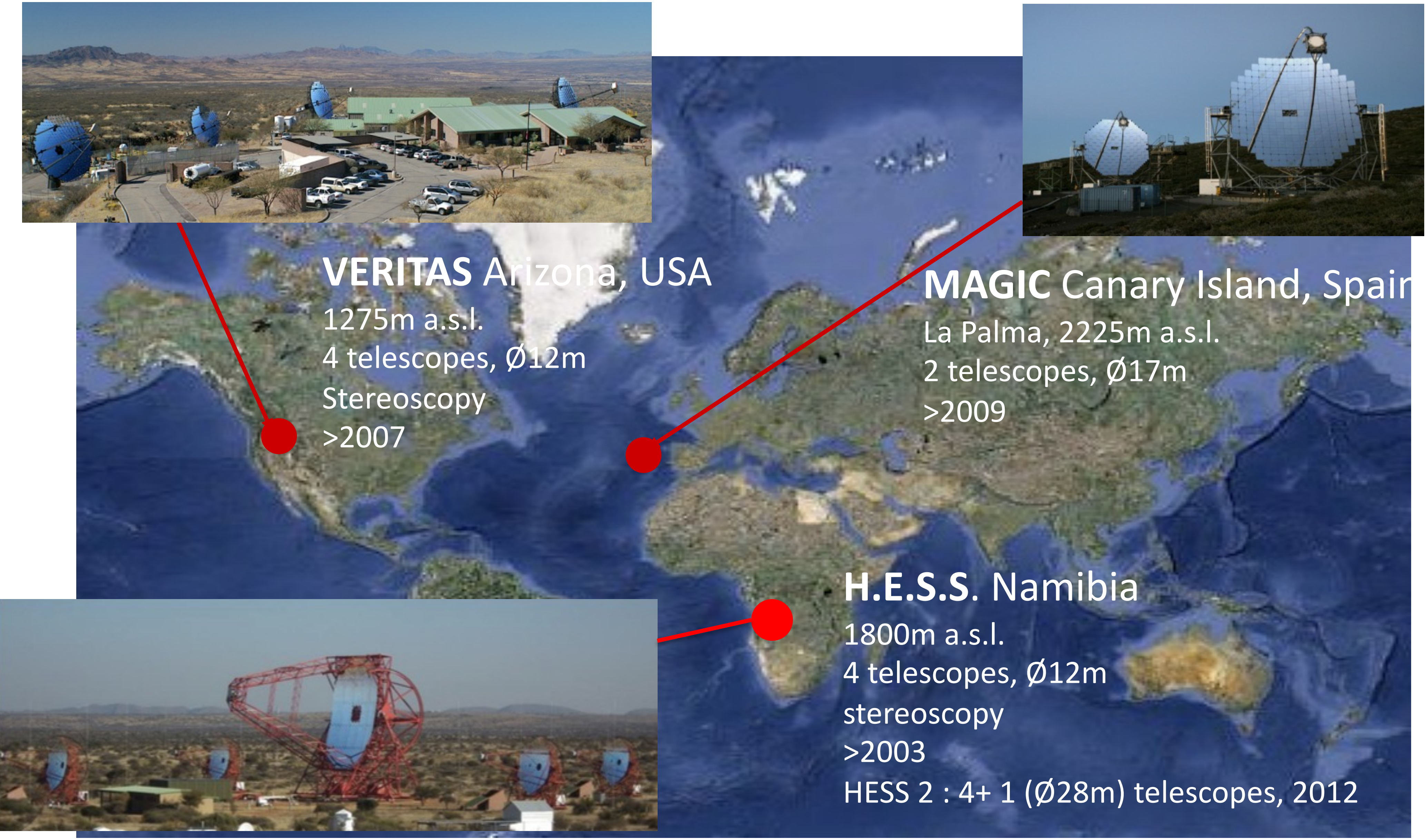


Fermi telescope: 2008 - Present

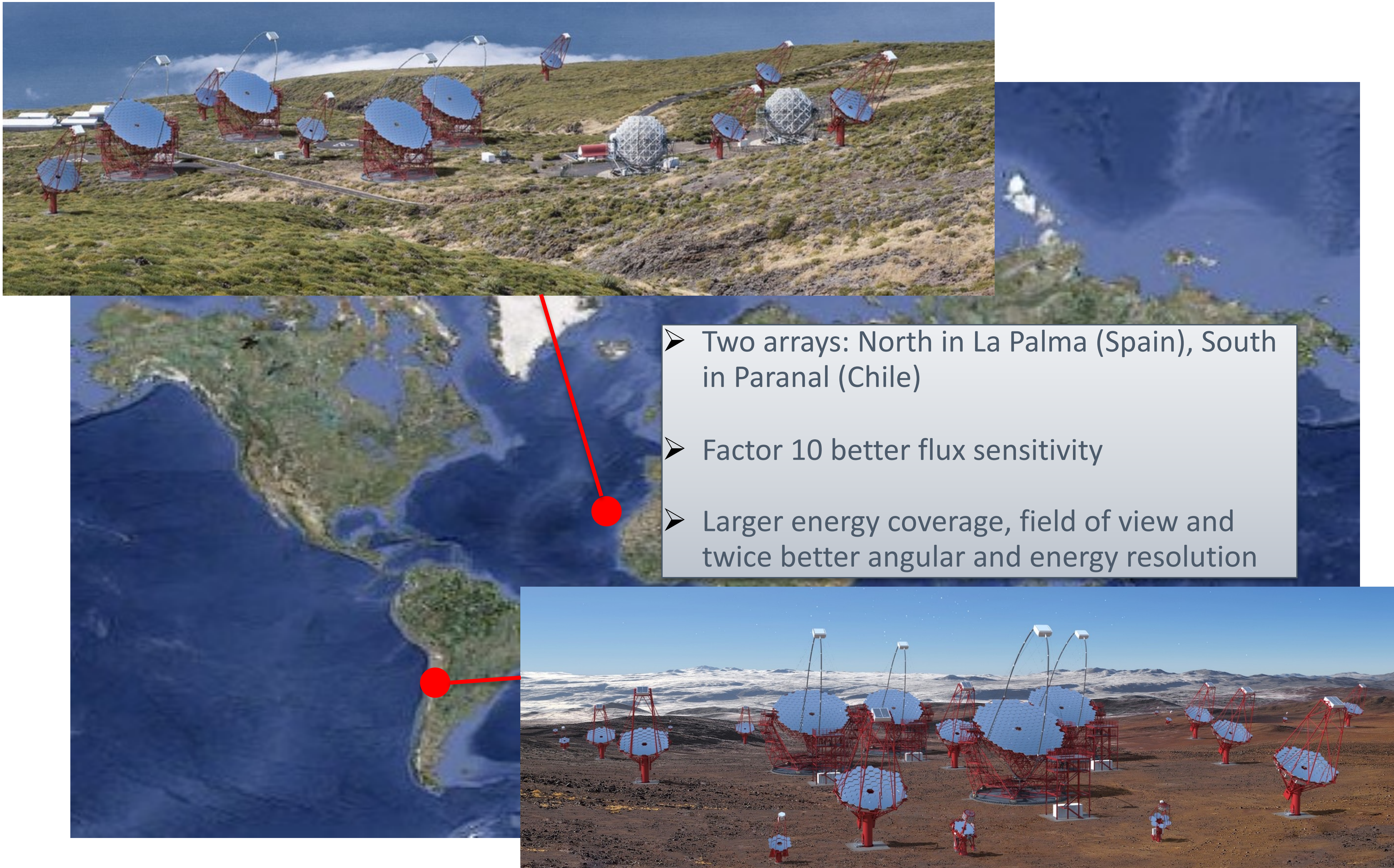
- Energy range: 20 MeV – 300 GeV
- Effective area ~ 0.9 m^2
- Energy resolution ~ 10%
- Angular resolution ~0.15^o (GeV)
- Pair conversion detector:



The current IACT world



The future IACT world: Cherenkov Telescope Array



- Two arrays: North in La Palma (Spain), South in Paranal (Chile)
- Factor 10 better flux sensitivity
- Larger energy coverage, field of view and twice better angular and energy resolution

The future IACT world: Cherenkov Telescope Array

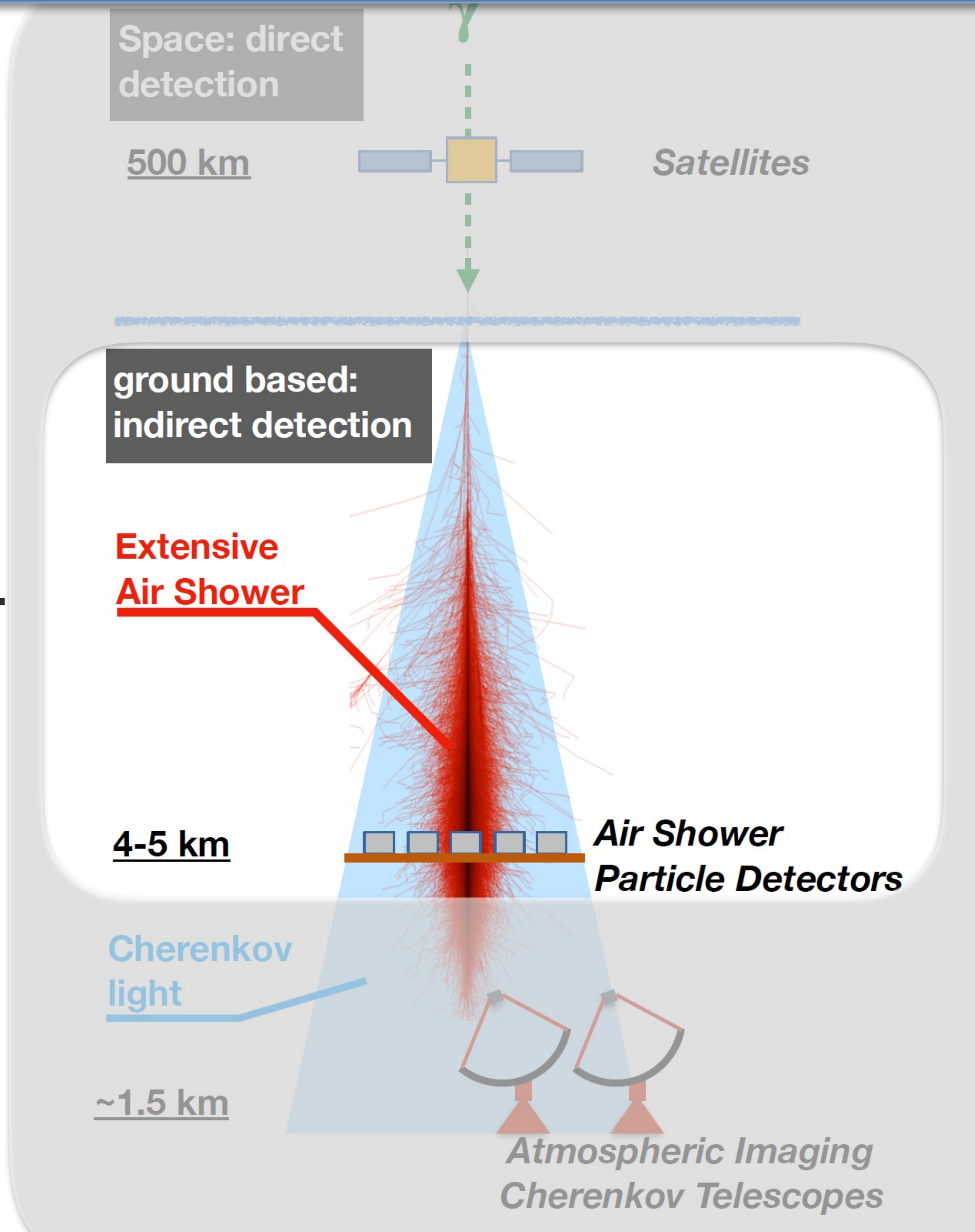
- CTA is a global effort with more than 1,350 scientists and engineers from 210 institutes in 32 countries involved in directing CTA's science goals and array design.

- Brazilian participation:
  - Centro Brasileiro de Pesquisas Físicas
  - Centro de Ciências Naturais e Humanas – Universidade Federal do ABC
  - Departamento de Engenharias e Exatas, Universidade Federal do Parana
  - Escola de Artes, Ciências e Humanidades, Universidade de São Paulo
  - Escola de Engenharia de Lorena, Universidade de São Paulo
  - Instituto de Astronomia, Geofísico, e Ciências Atmosféricas
  - Instituto de Física de São Carlos, Universidade de São Paulo
  - Instituto de Física – Universidade de São Paulo
  - International Centre for Theoretical Physics, Universidade Estadual Paulista
  - Nucleo de Astrofisica Teorica, Universidade Cruzeiro do Sul
  - Núcleo de Formação de Professores – Universidade Federal de São Carlos

Southern Wide-field Gamma-ray Observatory (SWGO)

The Southern Wide-field Gamma-ray Observatory

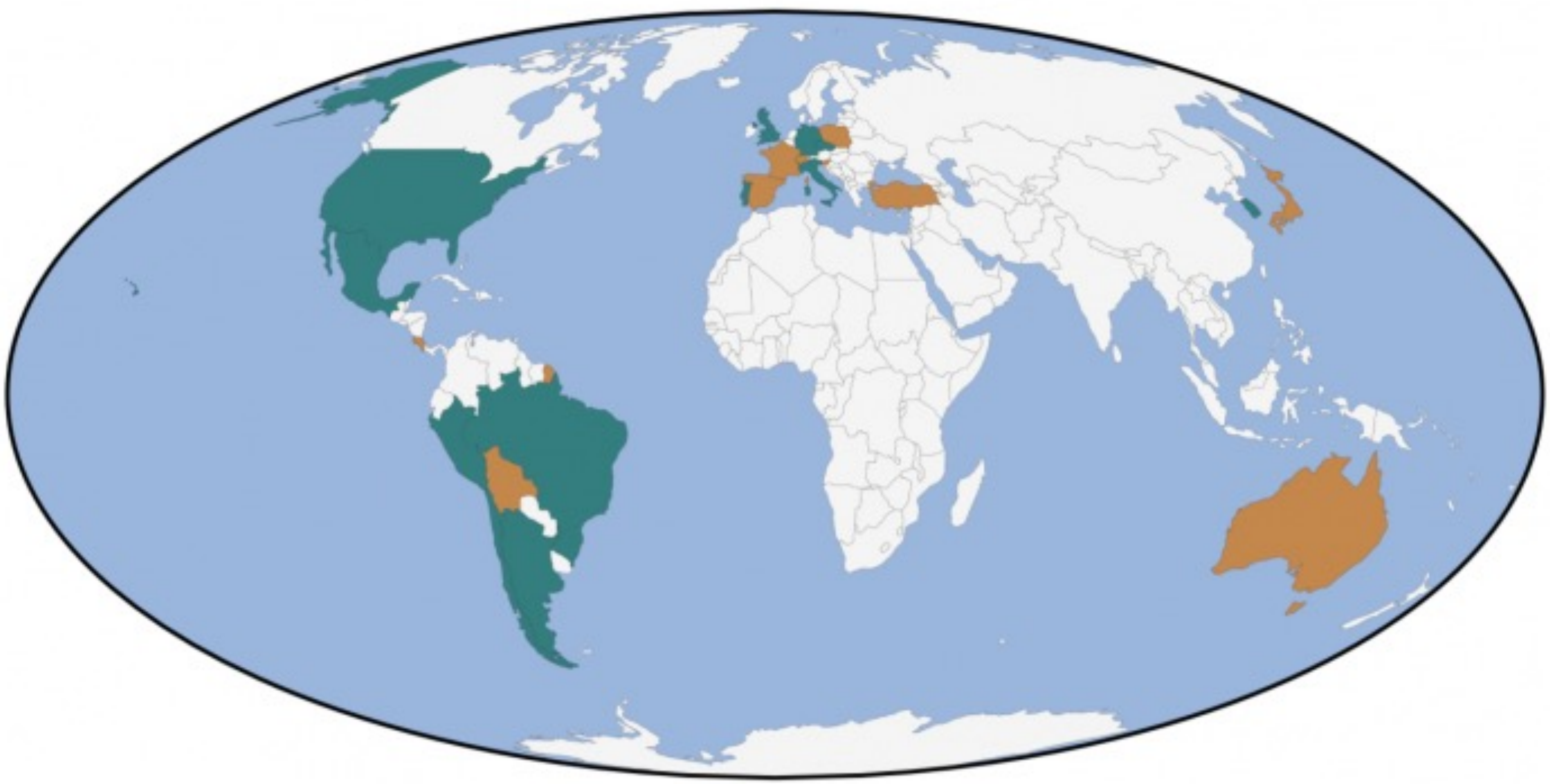
- Wide-angle air shower particle detector, complementary to CTA South
- Located at a high-altitude site in South America,
- Covering the energy range 100 GeV to 100 TeV,
- Significant sensitivity improvement over HAWC
- Various detector concepts under study



The 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*

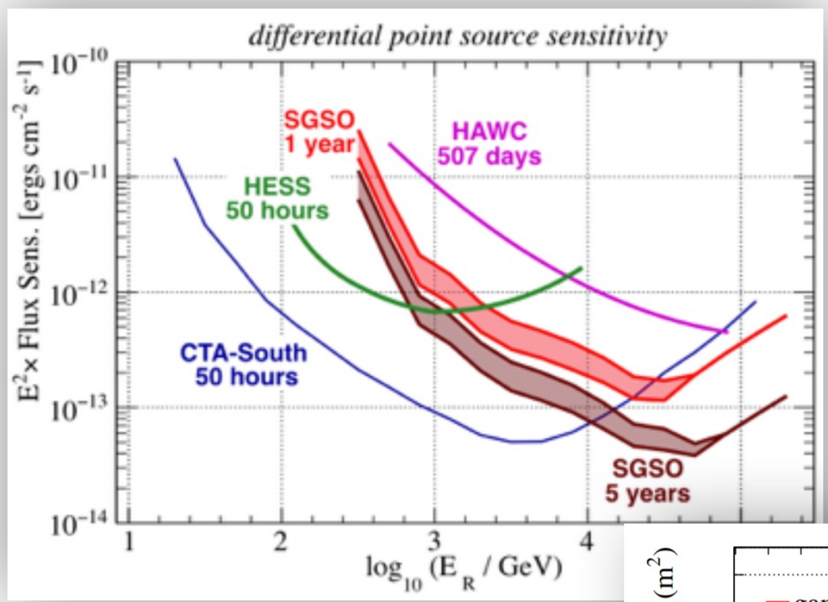
Supporting scientists

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

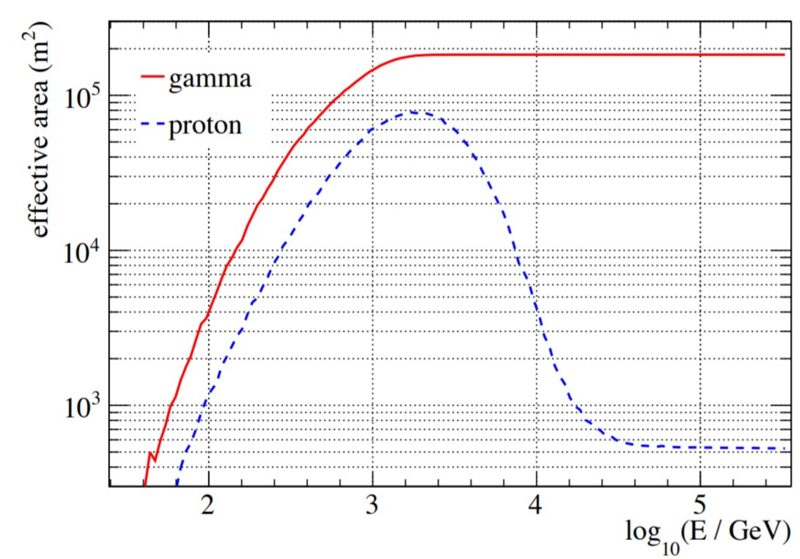
**also supporting scientists*

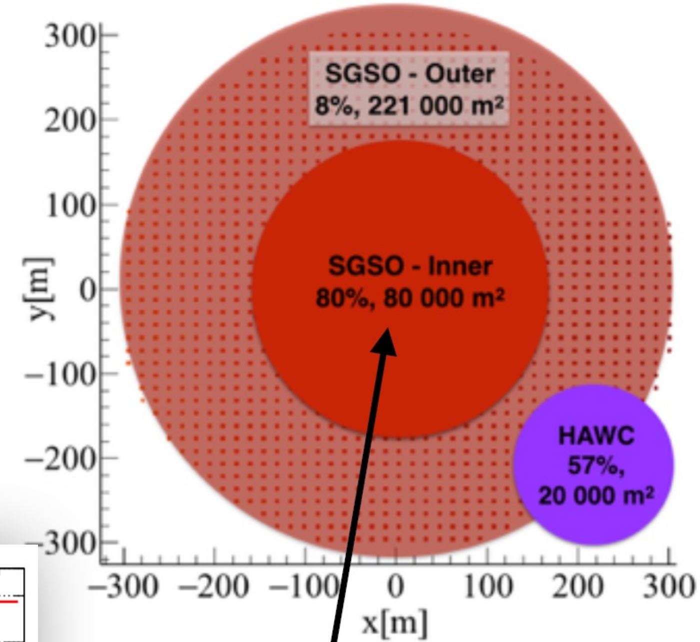
A straw man design for SWGO

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



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]





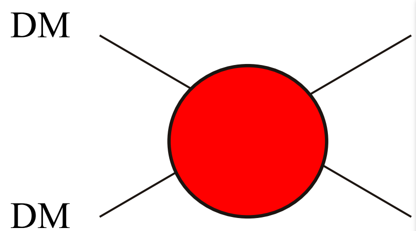
e.g. stations with circular footprint 3m diameter: ~4500 stations

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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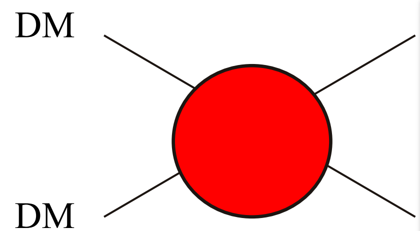

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Gamma-ray flux from annihilation of a WIMP:

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

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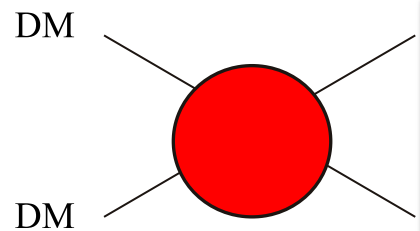

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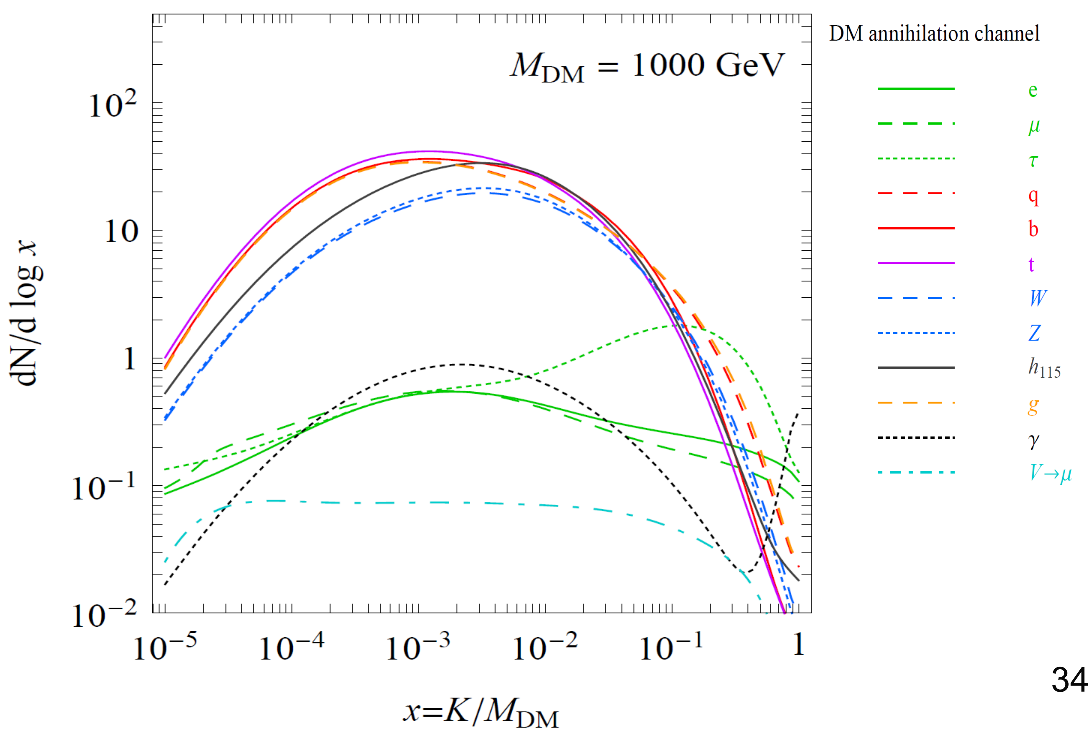
where

Gamma spectrum:

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



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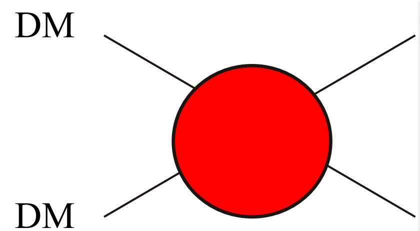

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where

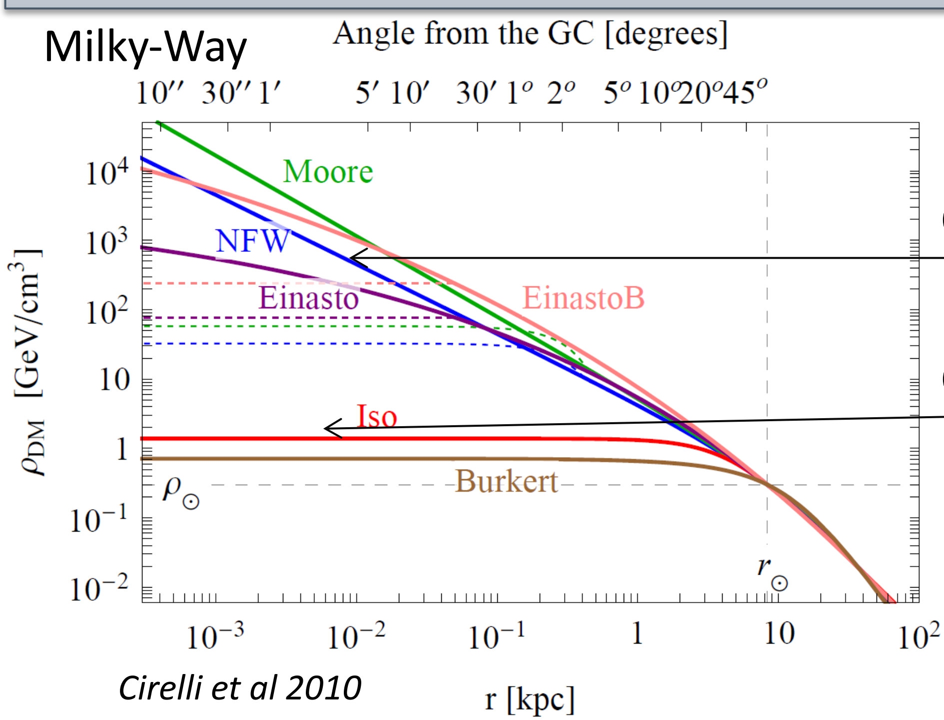
$$\bar{J}(\Delta\Omega) = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \rho^2[r(s)]\,\mathrm{d}s$$

- 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 2010

Examples:

Cuspy

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

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

Cored

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

- 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

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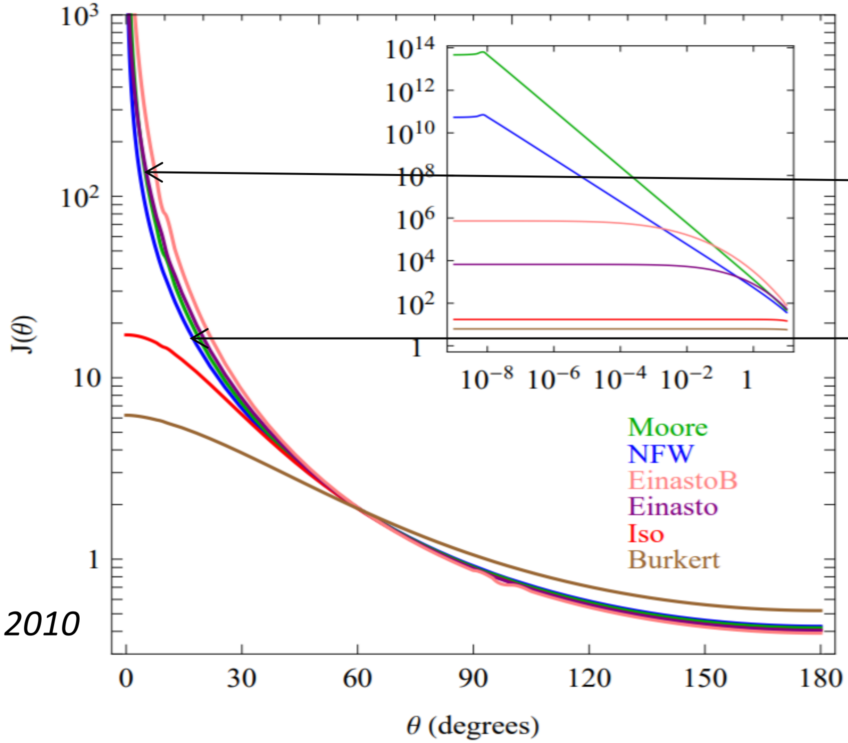
Milky-Way: morphology



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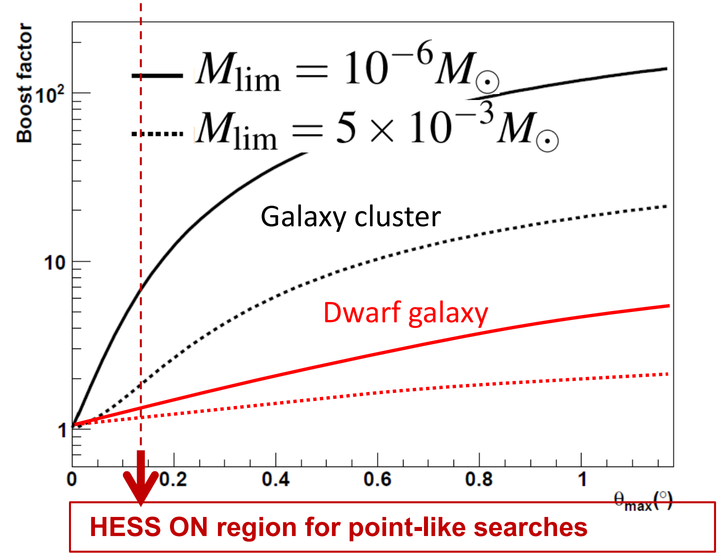
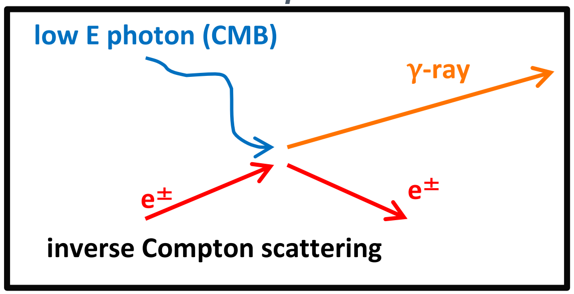
Additional contributions to the DM annihilation flux

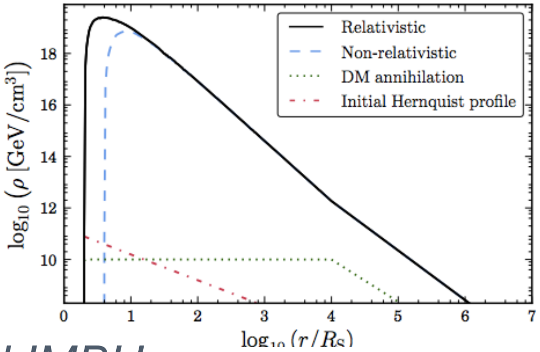
➢ From astrophysics:

- Contribution of the substructures(sub-halos) to the overall density <= flux ~ ρ^2



- Inverse compton scattering emission on CMB



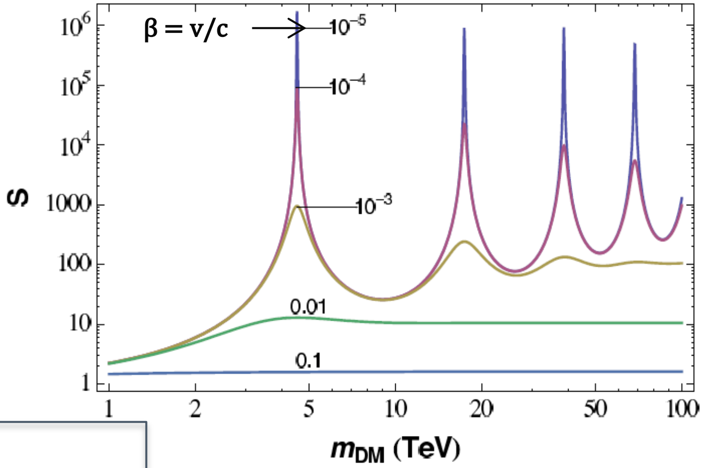


- Adiabatic growth aroundSMBH and IMBH

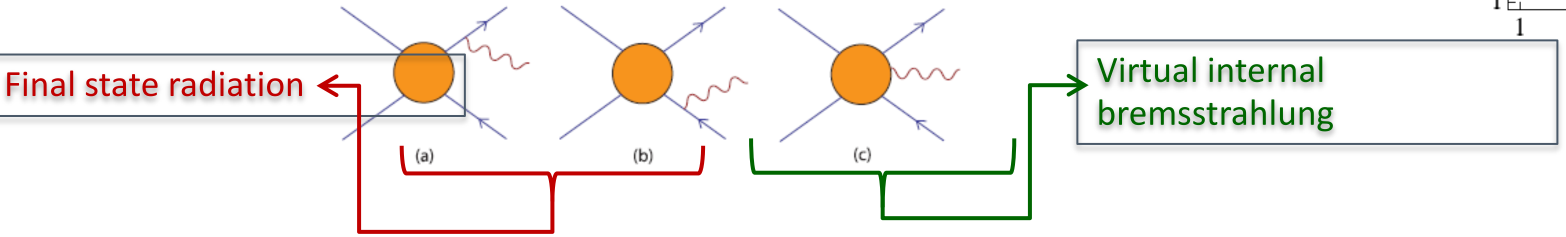
➢ From particle physics:

- Boost in the annihilation cross-section: ***Sommerfeld effect***

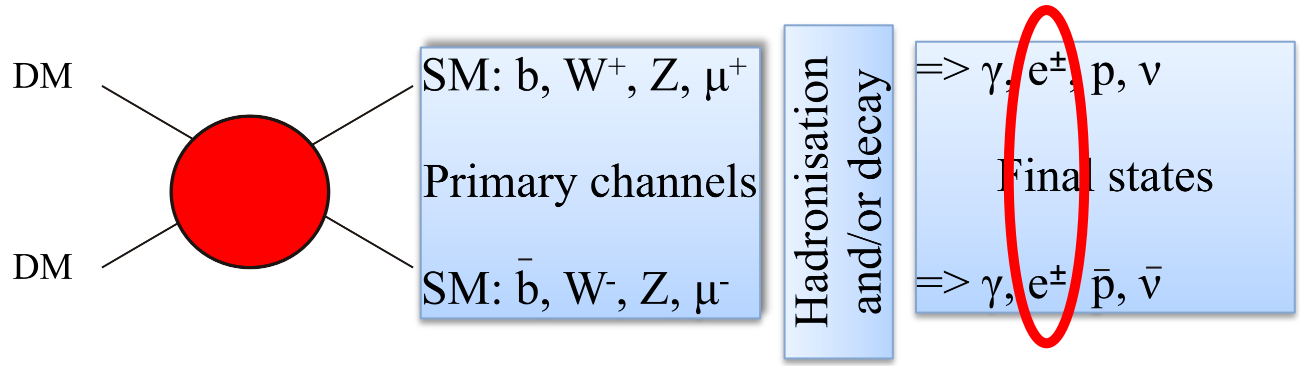
Latanzzi and Silk , PRD 79 (2009)

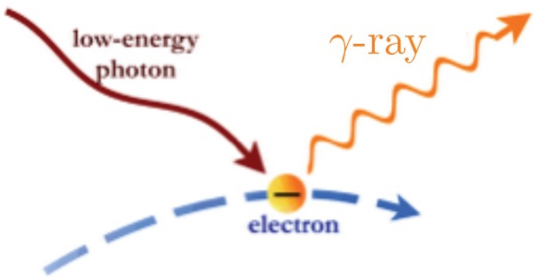


- Radiative corrections to the annihilation spectrum



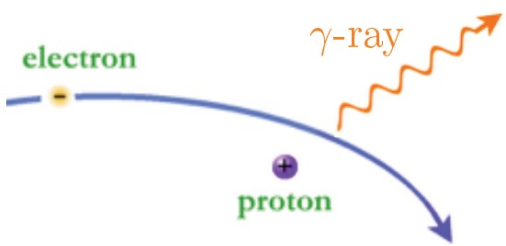
Secondary radiation from DM





Inverse Compton scattering

- on CMB, star-light, infrared-light



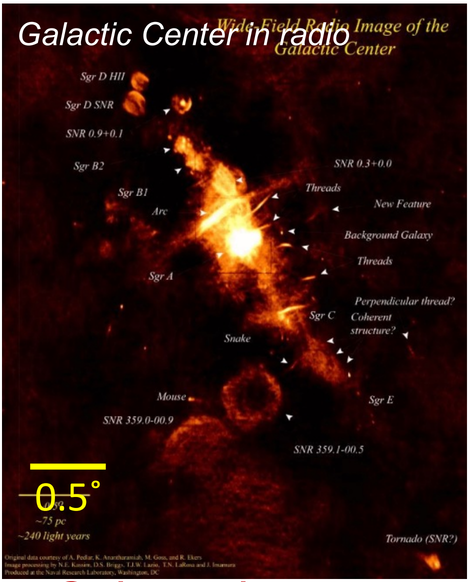
Bremsstrahlung

- onto gas of interstellar medium

Synchrotron radiation

- magnetic field O(μGauss)
- for $e^{\pm}$ of GeV-TeV
- —> MHz-GHz radio signal

Dark matter targets



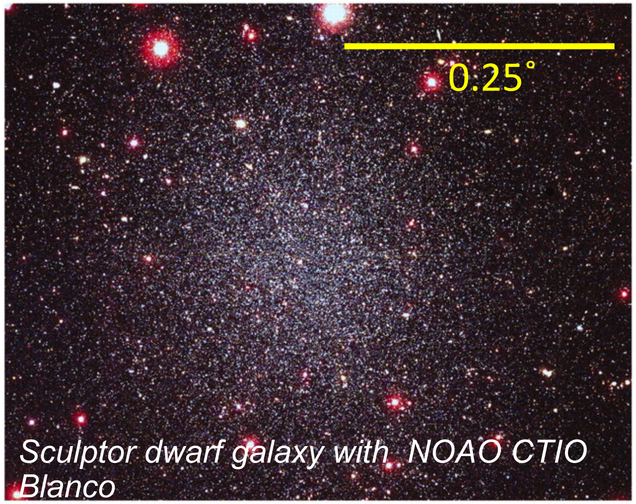
Galactic Center in radio

Galactic Centre

- ❑ Proximity (~8kpc)
- ❑ High (possibly) central DM concentration :
  DM profile : core? cusp?
- ❑ High astrophysical background in gamma-rays

Dwarf galaxies of the Milky Way

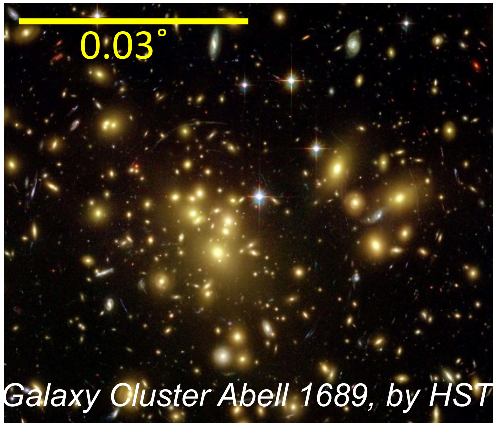
- ❑ Many of them within the 100 kpc from Sun
- ❑ Extremely DM-dominated environment
- ❑ Potential low astrophysical background



Sculptor dwarf galaxy with NOAO CTIO Blanco

Galaxy clusters

- ❑ High DM annihilation luminosity
- ❑ Substructures contribution to the overall DM flux
- ❑ Astrophysical background may be important



Galaxy Cluster Abell 1689, by HST

Andromeda Galaxy

Local Group Galaxies

- ❑ Relatively close
- ❑ Large DM mass
- ❑ Secondary radiation may be important

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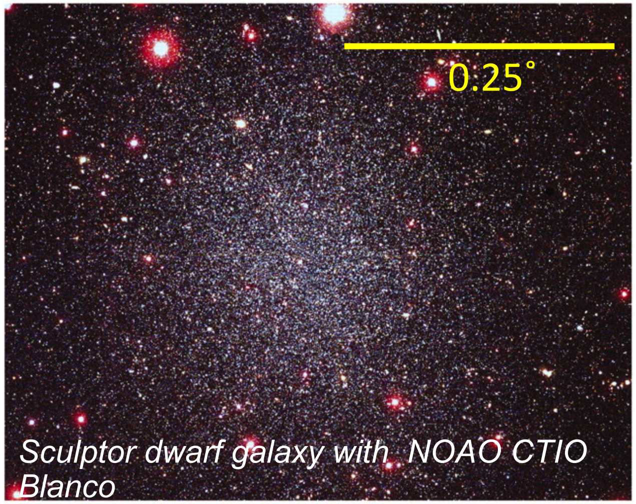

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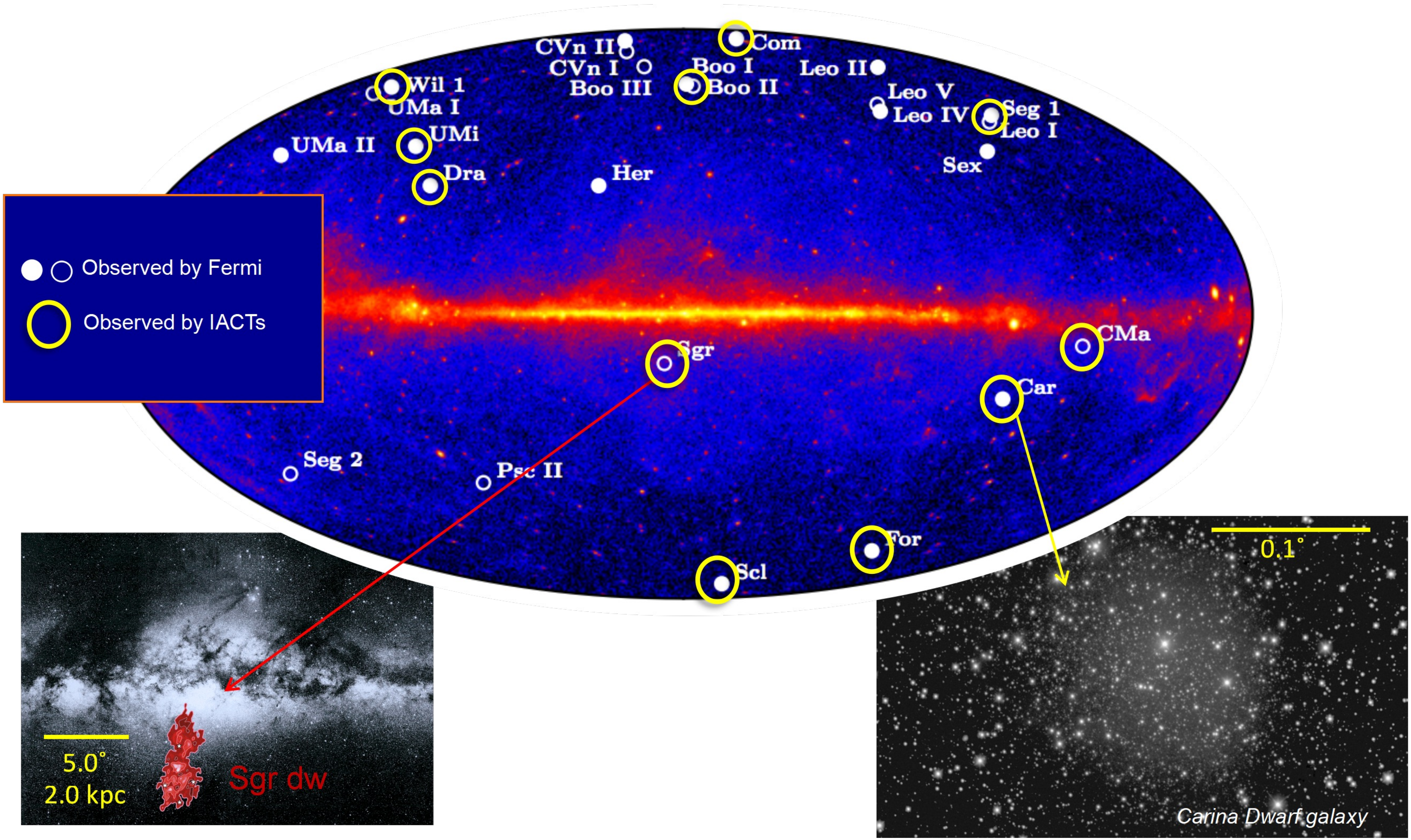
➢ Most DM-dominated systems in the Universe



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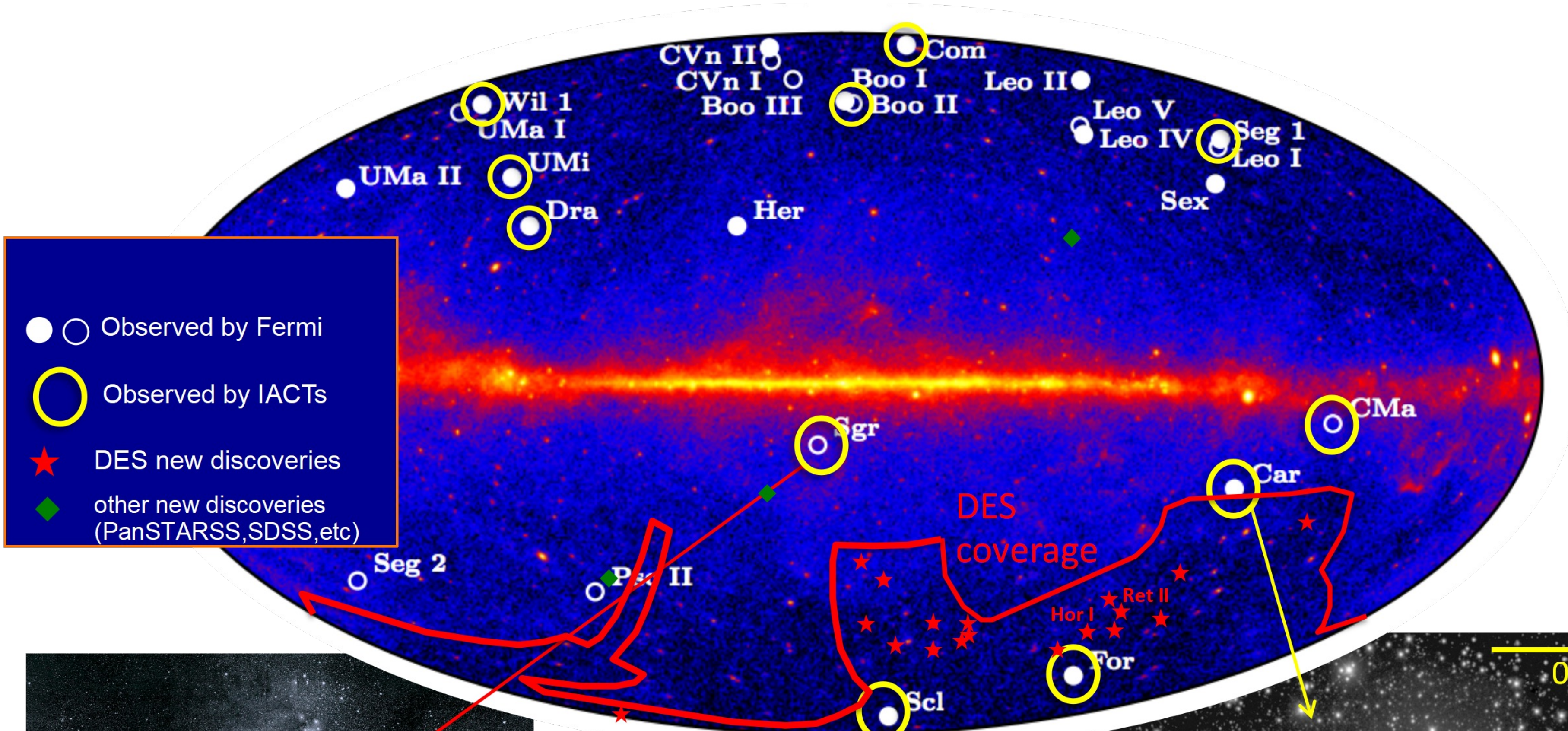
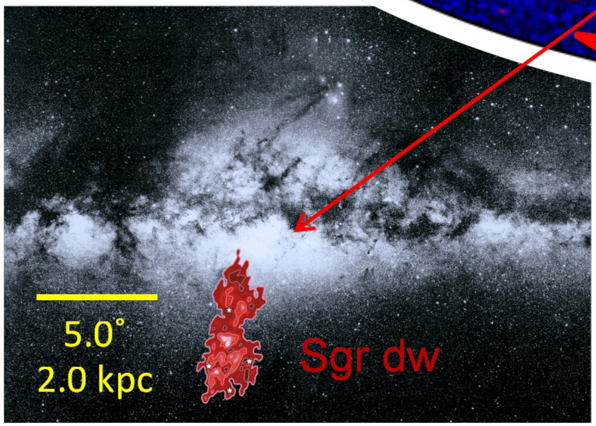
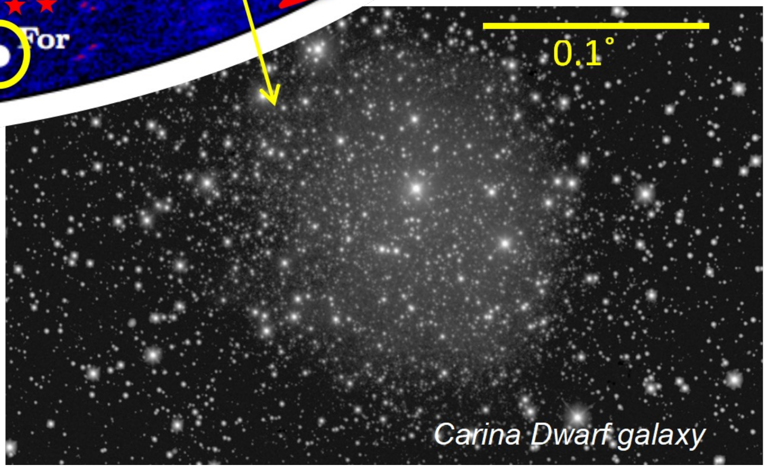


DES collaboration, ApJ 813, 109, 2015





Combined Dark Matter Searches with gamma-ray observatories

➢ Twenty dwarf spheroidal galaxies observed by Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS

- *Armand et al arXiv:2108.13646*

Source name	Experiments	Distance (kpc)
Bootes I	*Fermi*-LAT, HAWC, VERITAS	66
Canes Venatici I	*Fermi*-LAT	218
Canes Venatici II	*Fermi*-LAT, HAWC	160
Carina	*Fermi*-LAT, H.E.S.S.	105
Coma Berenices	*Fermi*-LAT, HAWC, H.E.S.S., MAGIC	44
Draco	*Fermi*-LAT, HAWC, MAGIC, VERITAS	76
Fornax	*Fermi*-LAT, H.E.S.S.	147
Hercules	*Fermi*-LAT, HAWC	132
Leo I	*Fermi*-LAT, HAWC	254
Leo II	*Fermi*-LAT, HAWC	233
Leo IV	*Fermi*-LAT, HAWC	154
Leo T	*Fermi*-LAT	417
Leo V	*Fermi*-LAT	178
Sculptor	*Fermi*-LAT, H.E.S.S.	86
Segue I	*Fermi*-LAT, HAWC, MAGIC, VERITAS	23
Segue II	*Fermi*-LAT	35
Sextans	*Fermi*-LAT, HAWC	86
Ursa Major I	*Fermi*-LAT, HAWC	97
Ursa Major II	*Fermi*-LAT, HAWC, MAGIC	32
Ursa Minor	*Fermi*-LAT, VERITAS	76

➢ In the case of no signal detection -> Joint likelihood analysis

➢ Limits on the plane $\langle\sigma v\rangle$ x m_{DM}

Combined Dark Matter Searches with gamma-ray observatories

- Three channels $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, using the J factors from Geringer Sameth et al.

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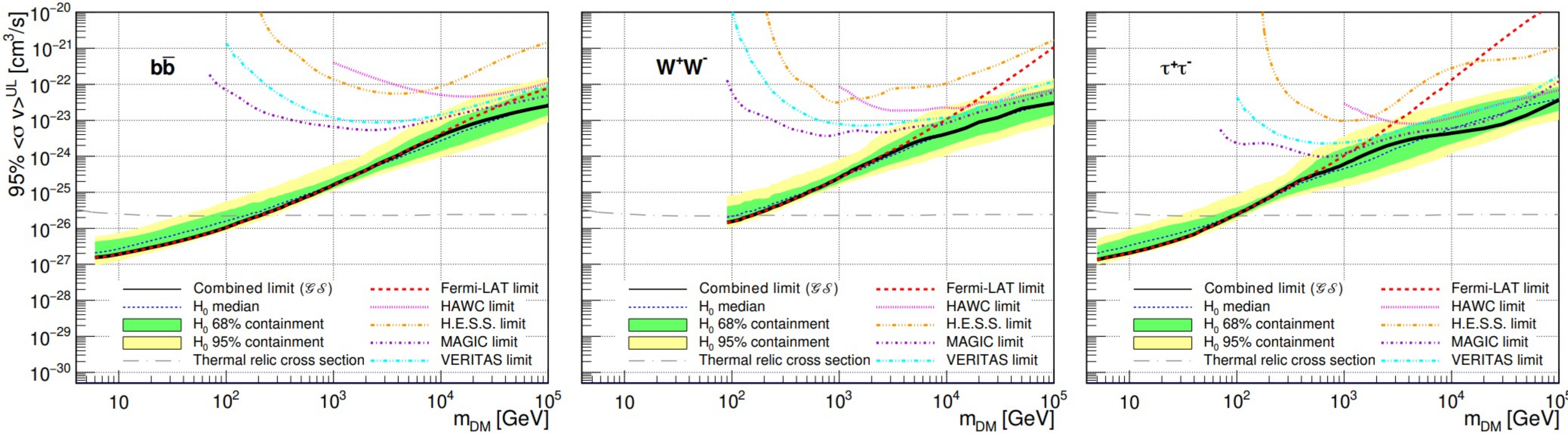

- Combined upper limits are up to 3 times more constraining, depending on the annihilation channel and the mass

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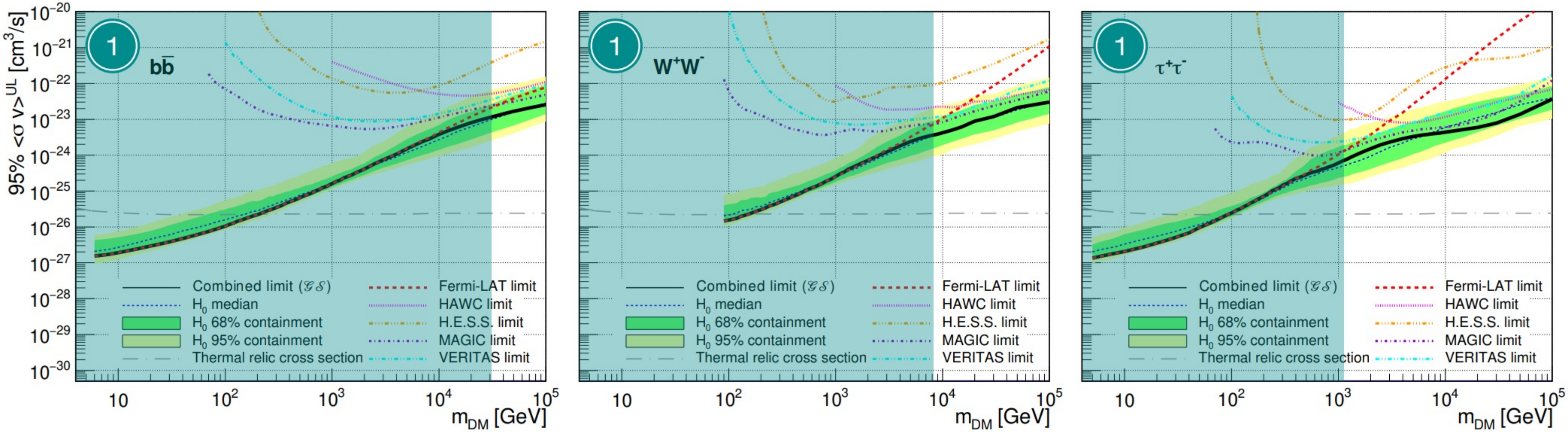

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- **Below ~2 - 30 TeV** - DM limits largely dominated by Fermi-LAT

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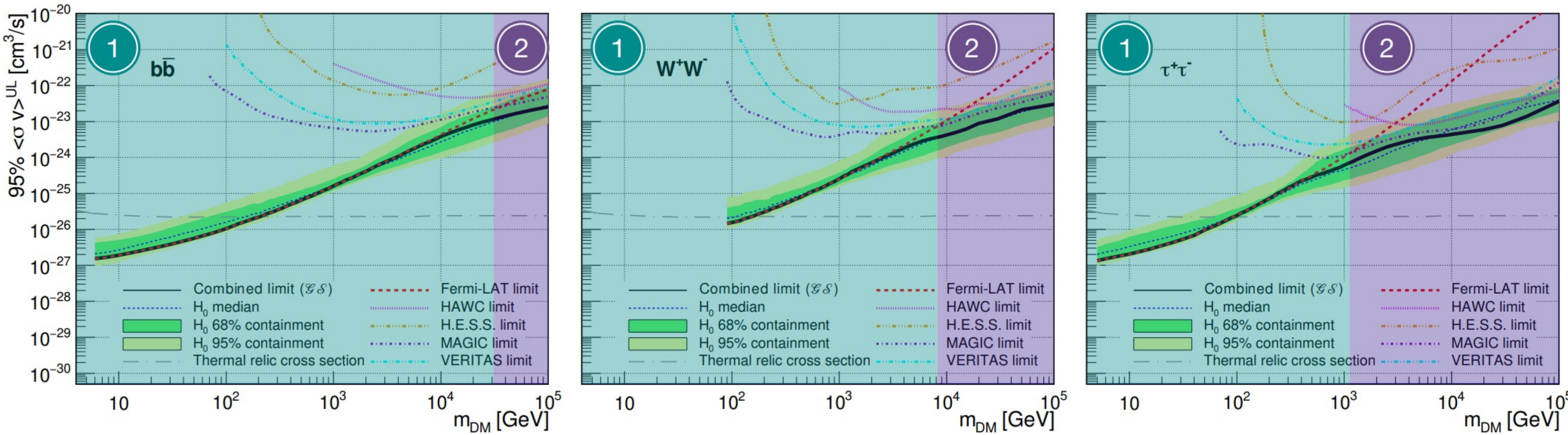

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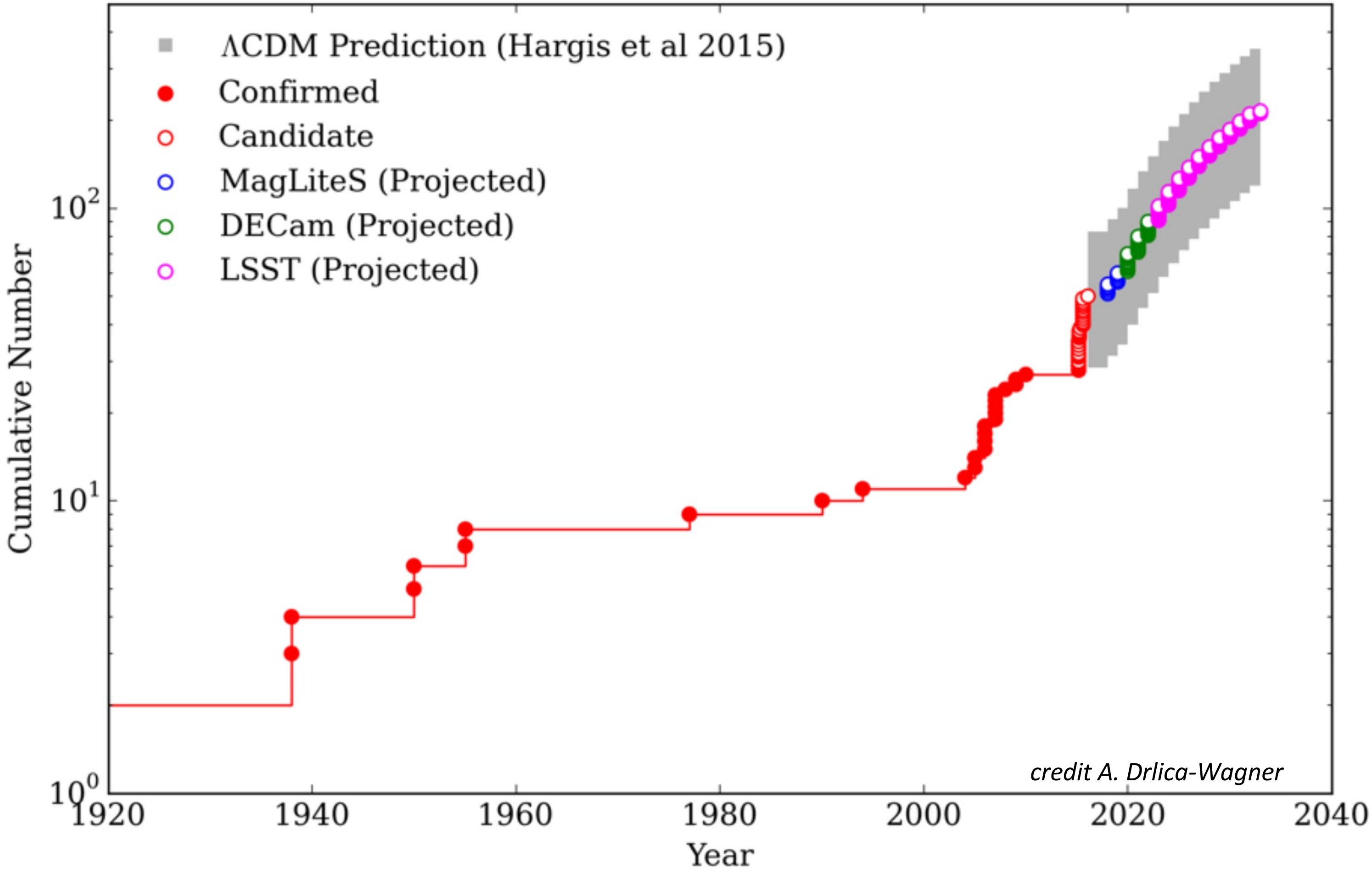
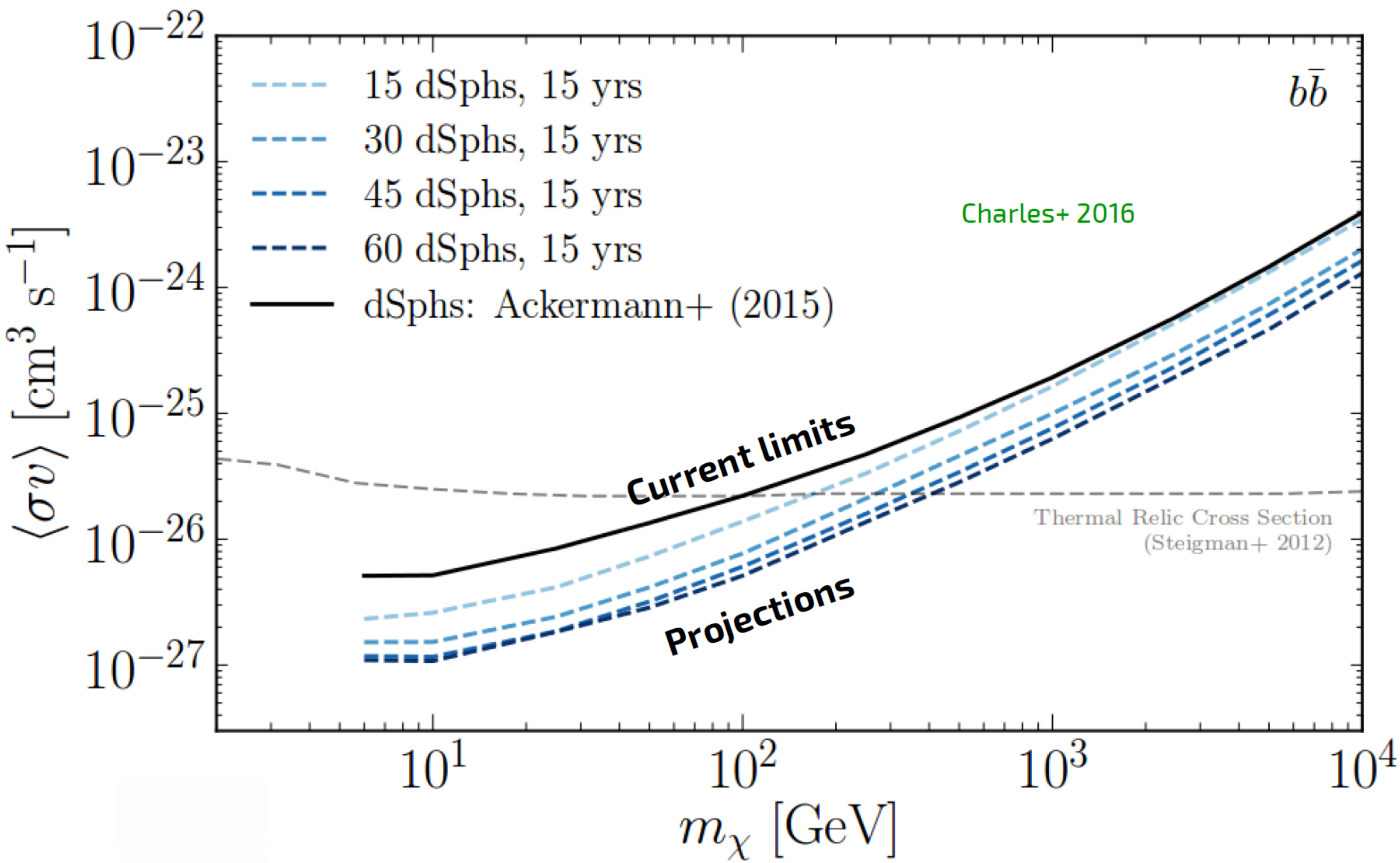
- **Above ~2 - 30 TeV** - IACTs and HAWC take over

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 Fermi-LAT at these locations could easily and immediately be analysed when new dSphs are found.**

Future prospects on dSphs



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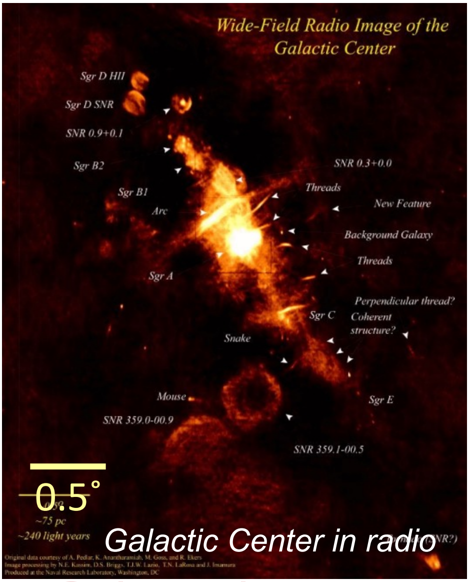

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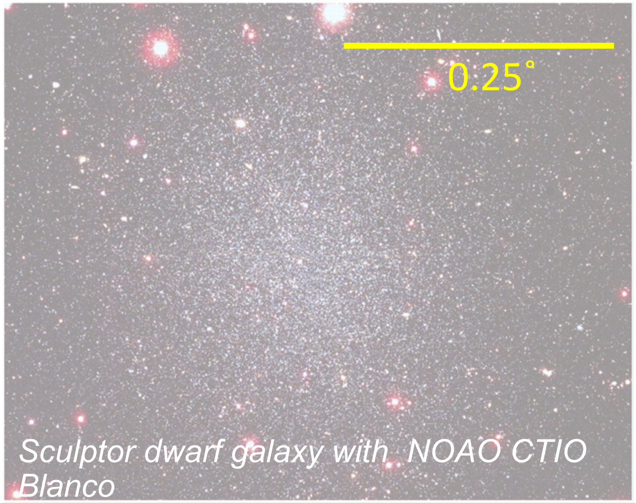

Sculptor dwarf galaxy with NOAO CTIO Blanco

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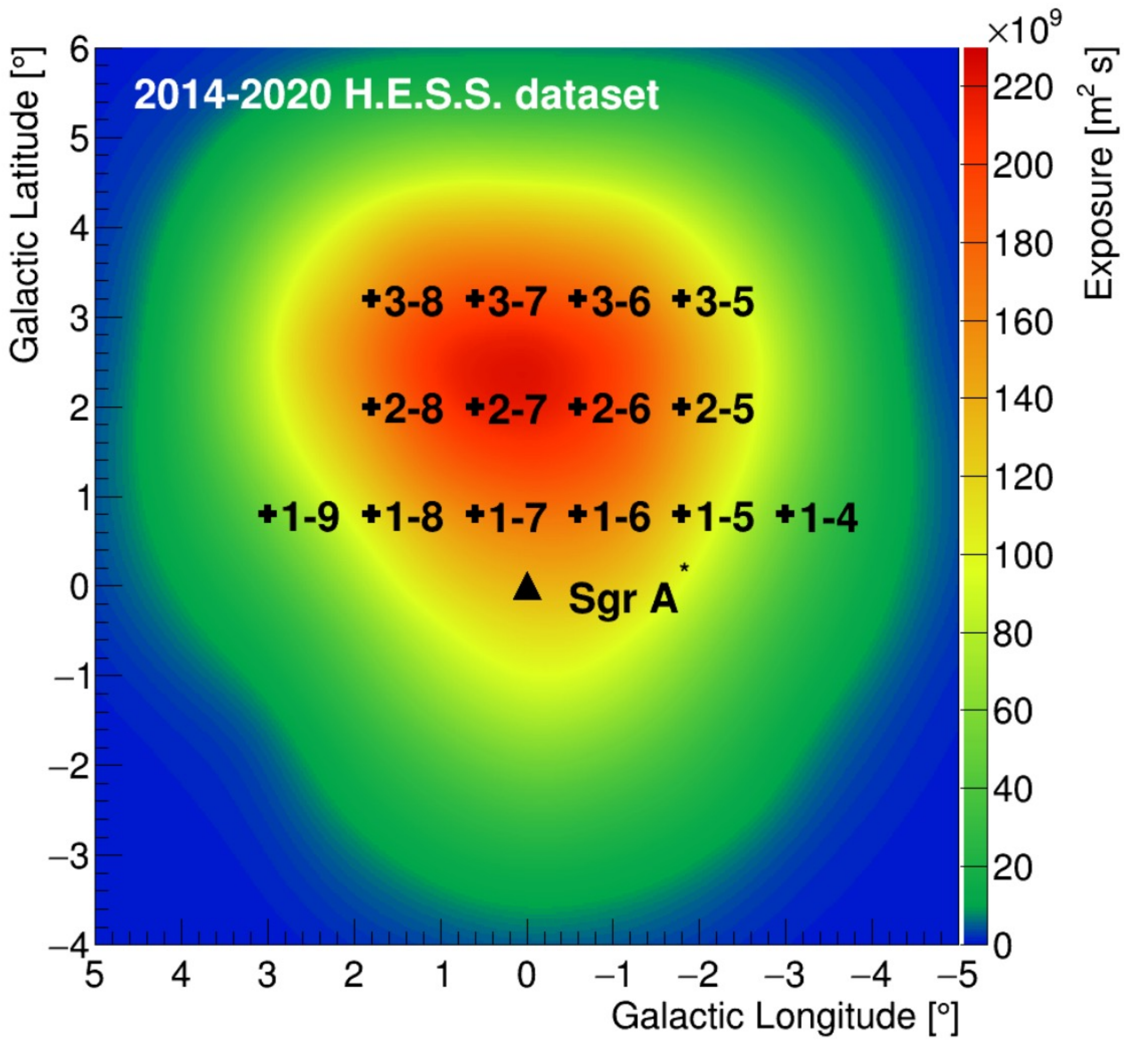
H.E.S.S. Inner Galaxy Survey

- First-ever conducted deep VHE gamma-ray survey of the Galactic Center region (b < +3.2)
- 2014-2020 dataset amounts to 546 hours (livetime) towards the GC



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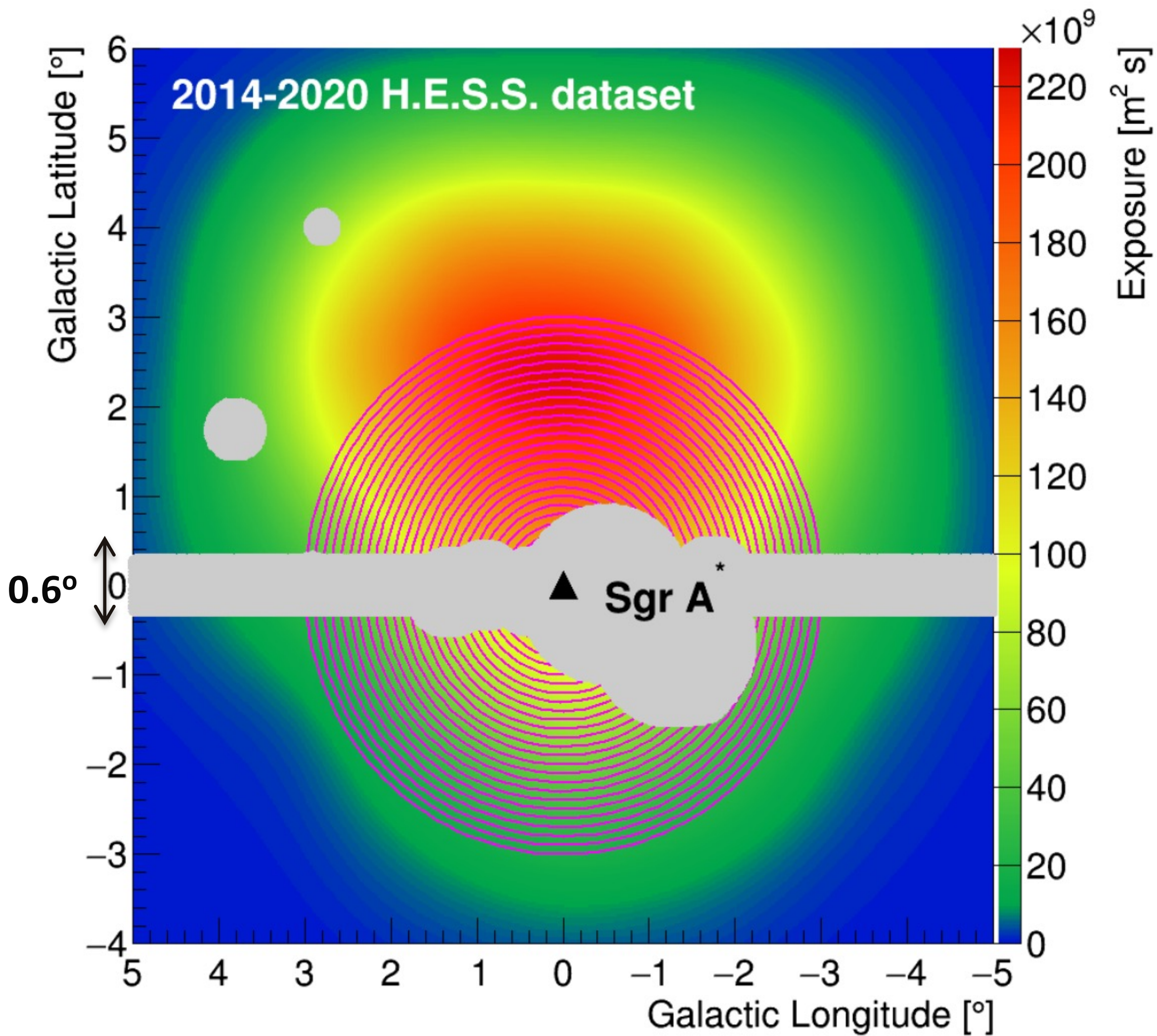
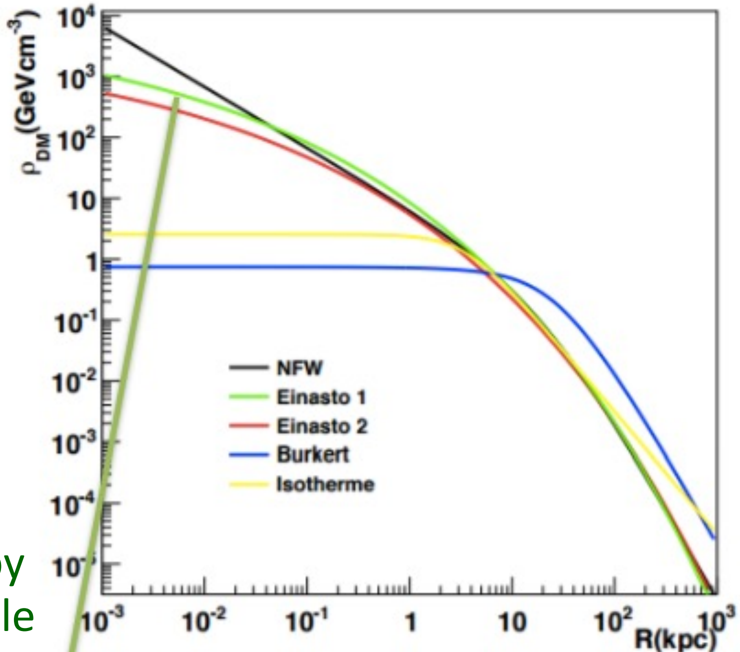
- Analysis method : 2D likelihood analysis with spectral and spatial information of signal and background



Dark Matter distribution in the GC



Cuspy profile

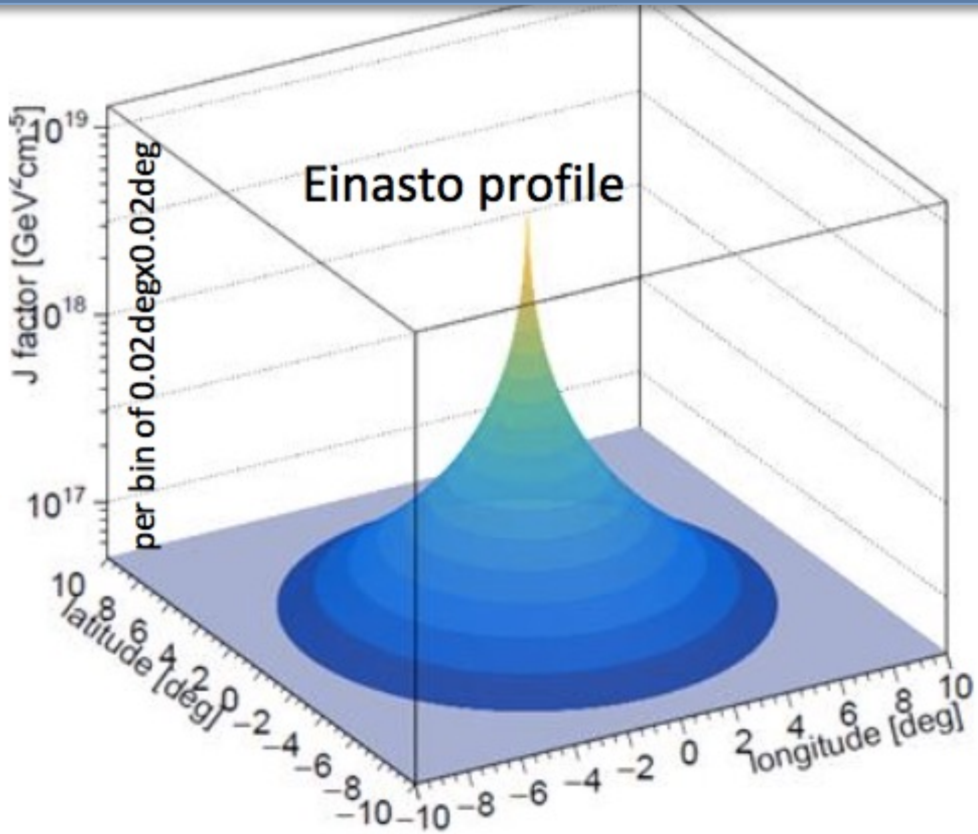
$$\rho_{Ein1}(r) = \rho_s \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

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

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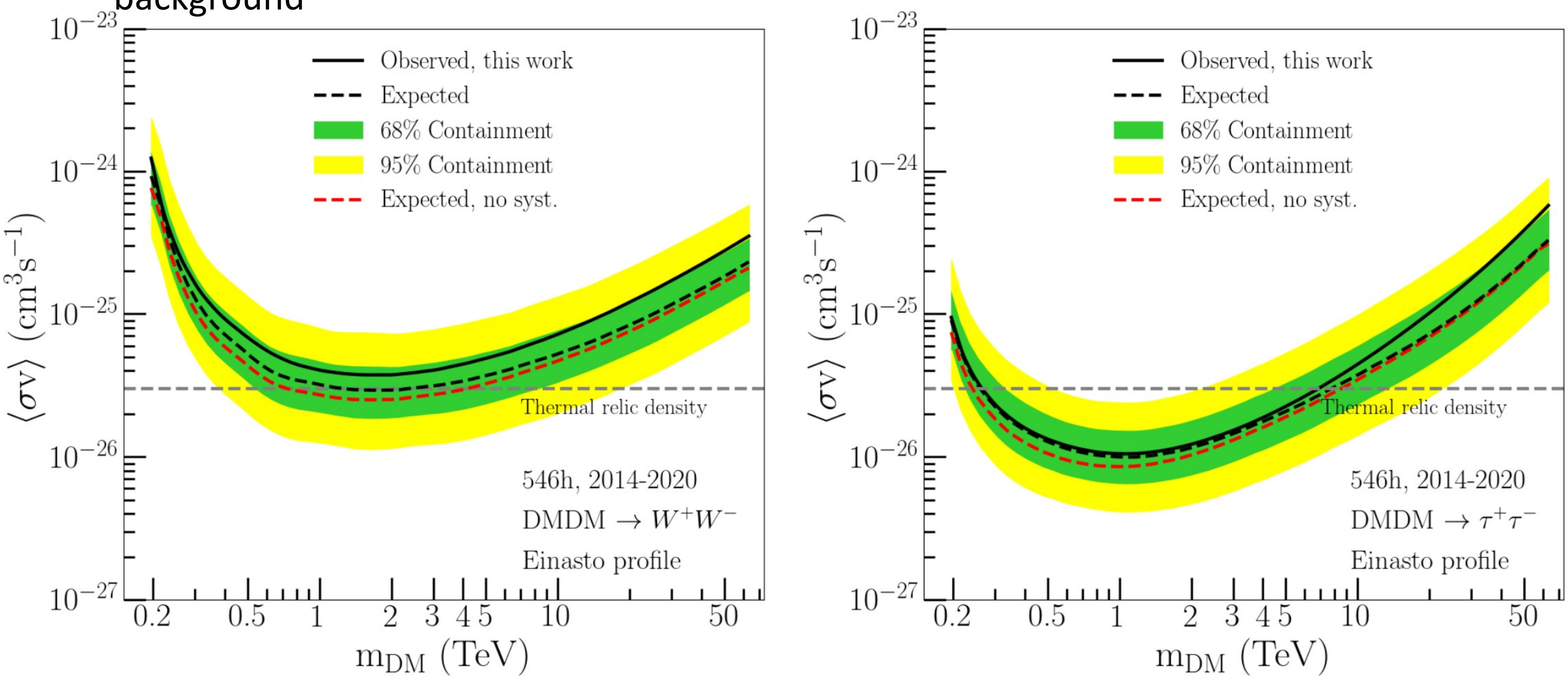
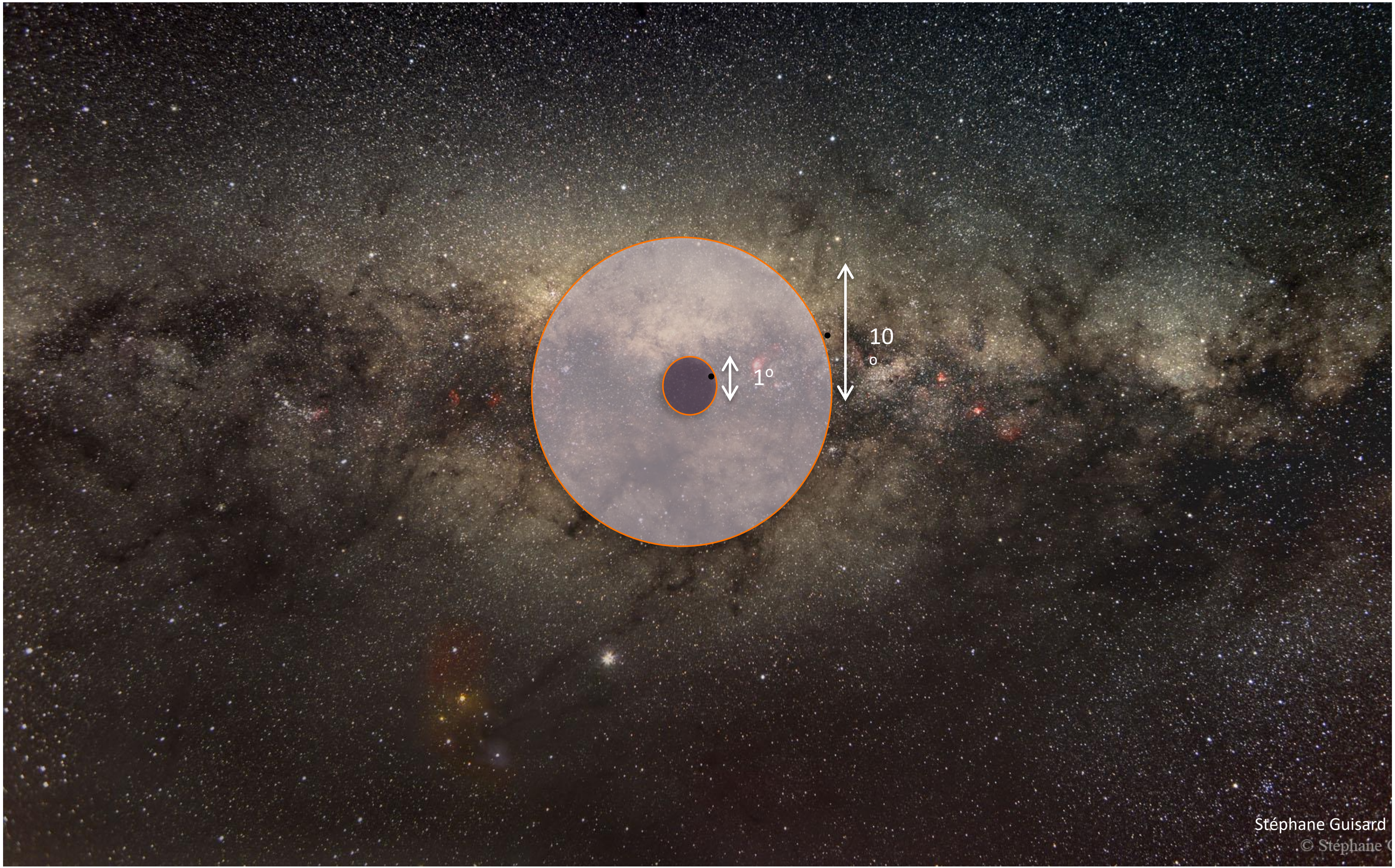


For the Einasto profile, strongest limits so far in the TeV mass range:

- in the WW channel: **3.7×10^{-26} cm^{-3} s^{-1}** at 1.5 TeV
- in the ττ channel: **1.2×10^{-26} cm^{-3} s^{-1}** at 700 GeV

GC halo: DM annihilation future sensitivity

- Search for signal in the inner 1^{o} (CTA) and 10^{o} (SWGO) of the Galaxy



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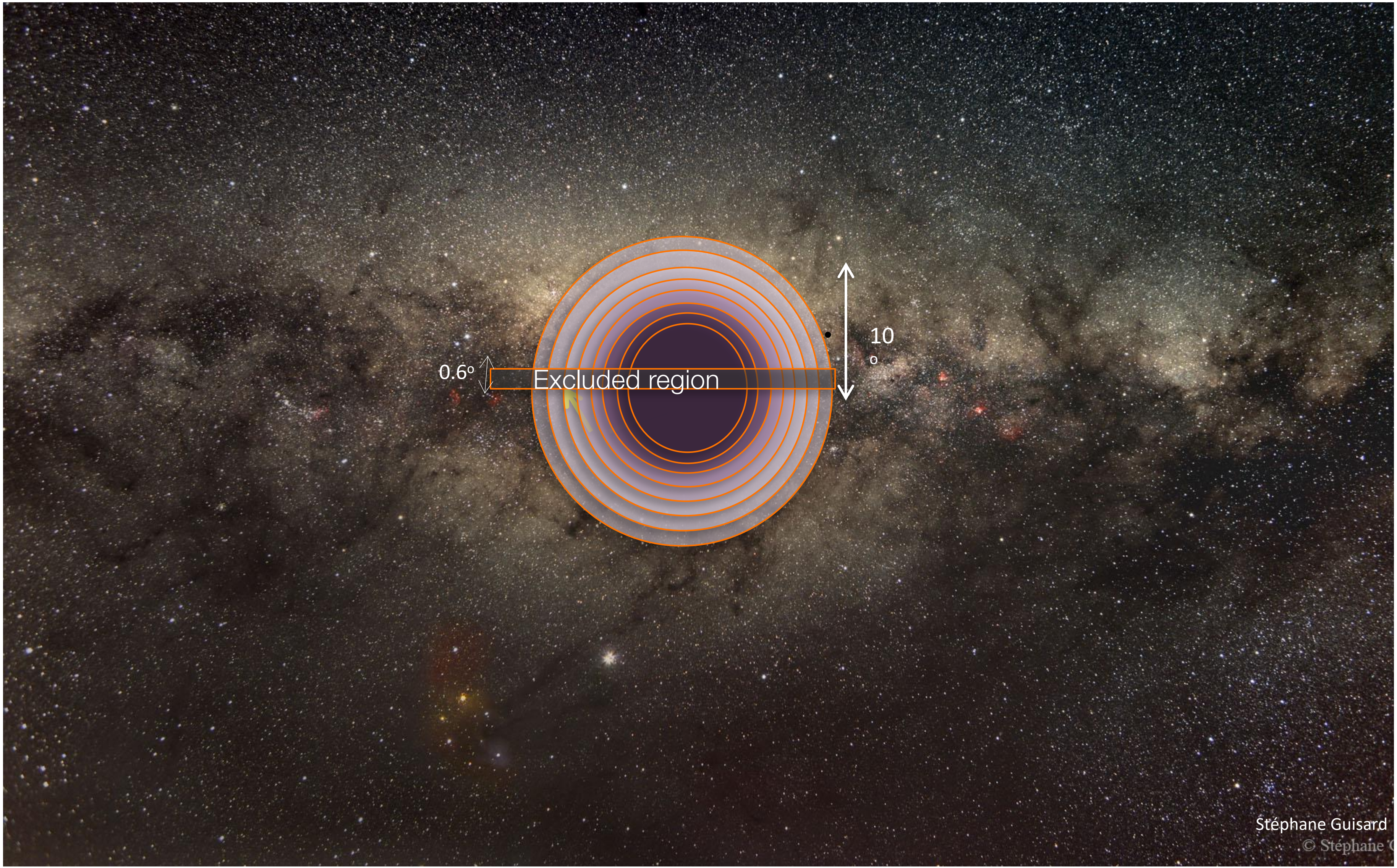
- Search for signal in the inner 1° (CTA) and 10° (SWGO) of the Galaxy
- Exclusion of +-0.3° band in latitude to avoid strong astrophysical background
- 2D likelihood analysis with spectral and spatial information of signal and background



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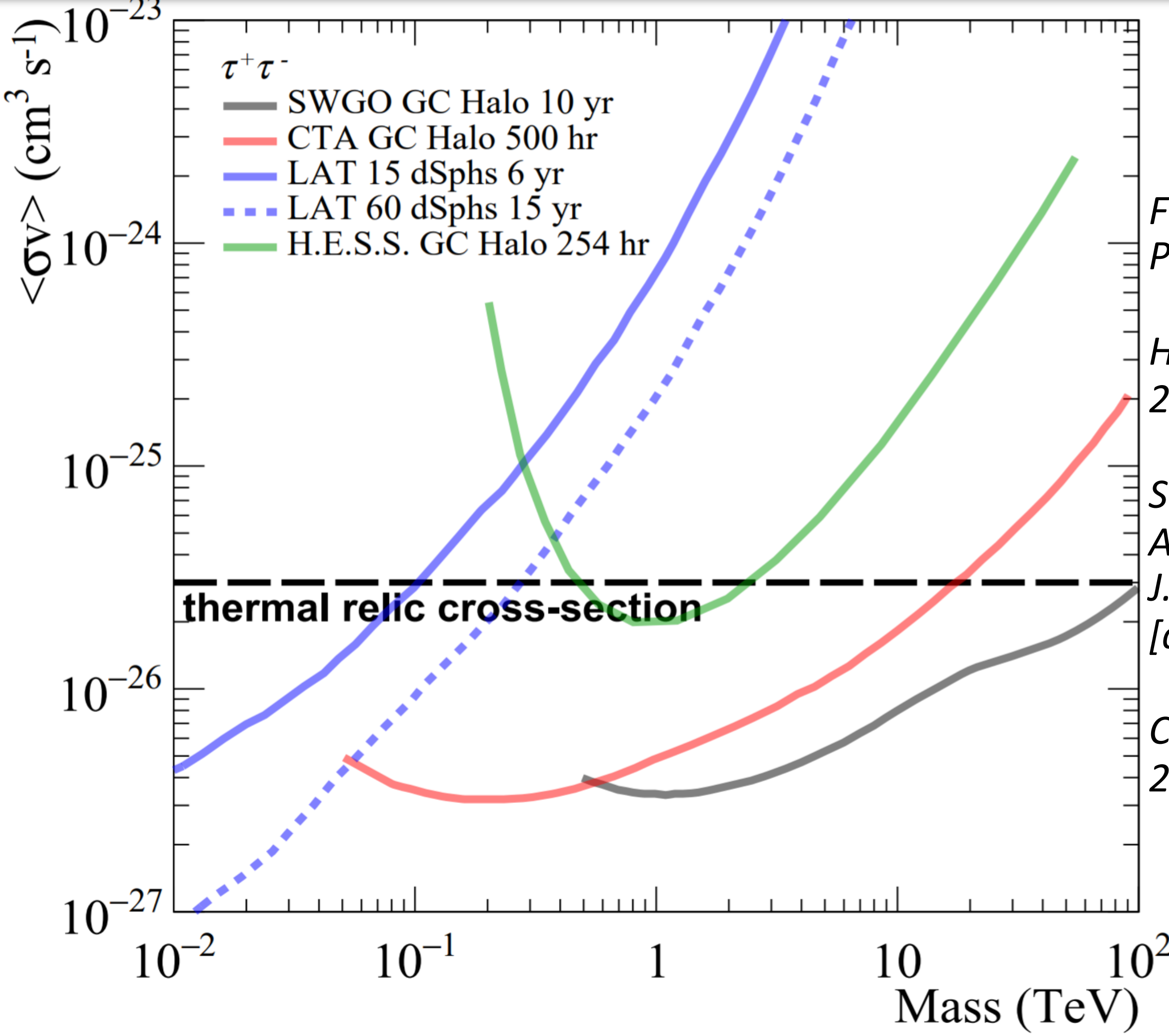

$\tau^+\tau^-$ channel

Fermi: Fermi-LAT Collaboration PRL 2015 [arXiv:1503.02641]

HESS: HESS Collaboration PRL 2016 [arXiv:1607.08142]

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

CTA: The CTA Consortium JCAP 2021 [arXiv:2007.16129]

- For $\tau^+\tau^-$ channel: SWGO more sensitive than CTA for masses > 600 GeV
- Combined (LAT,CTA,SWGO) future sensitivity smaller than thermal relic cross-section for all masses below 100 TeV

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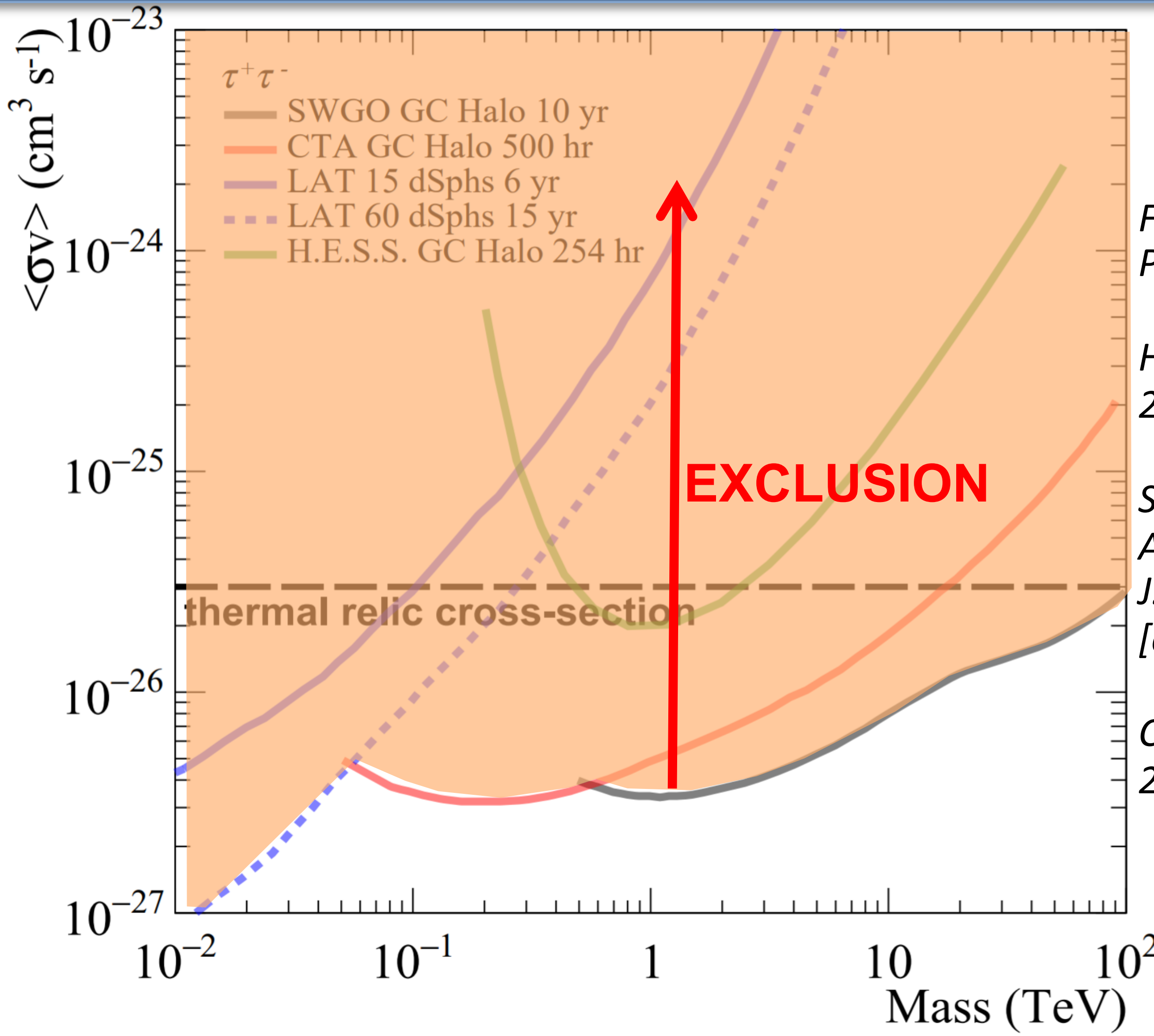

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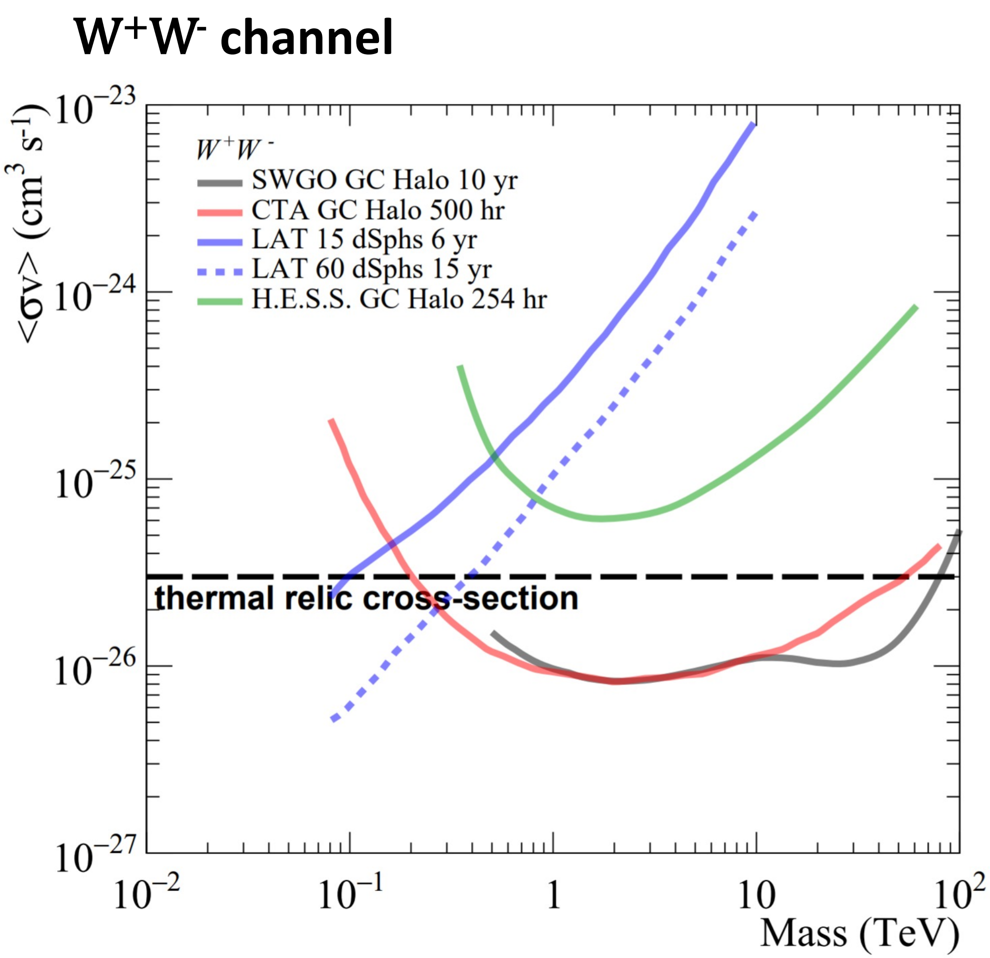
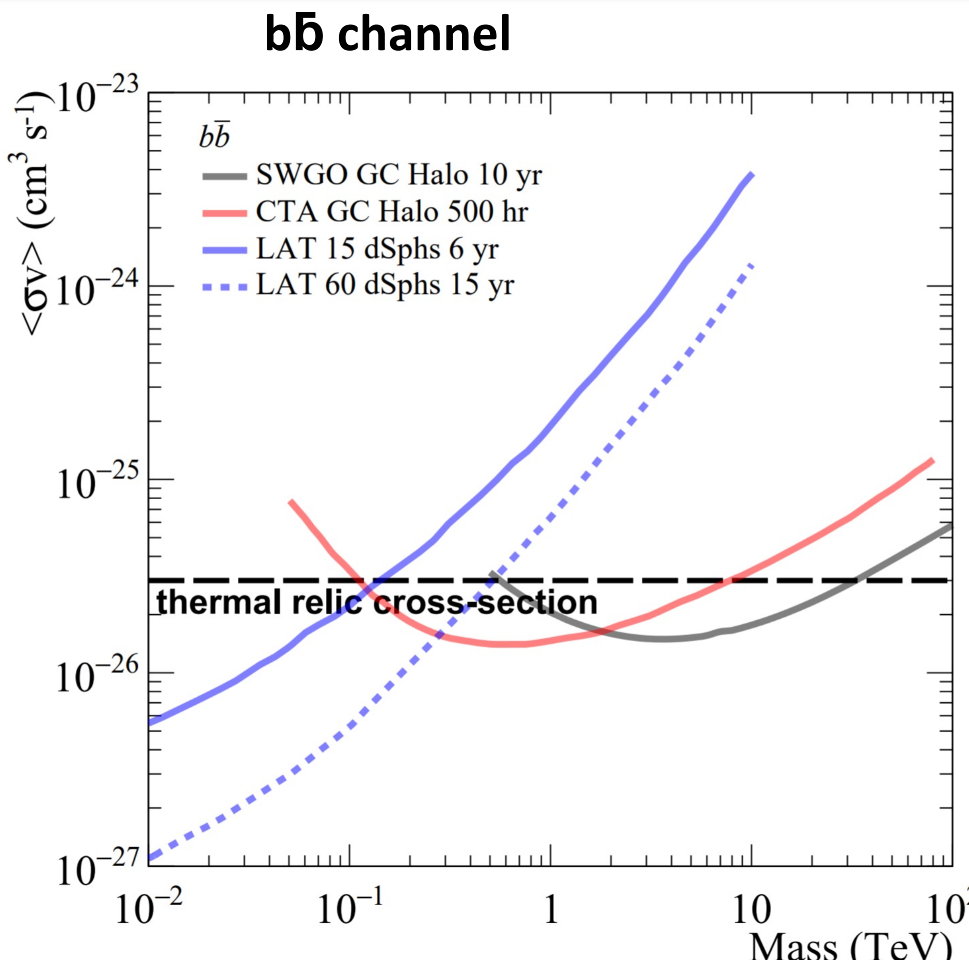
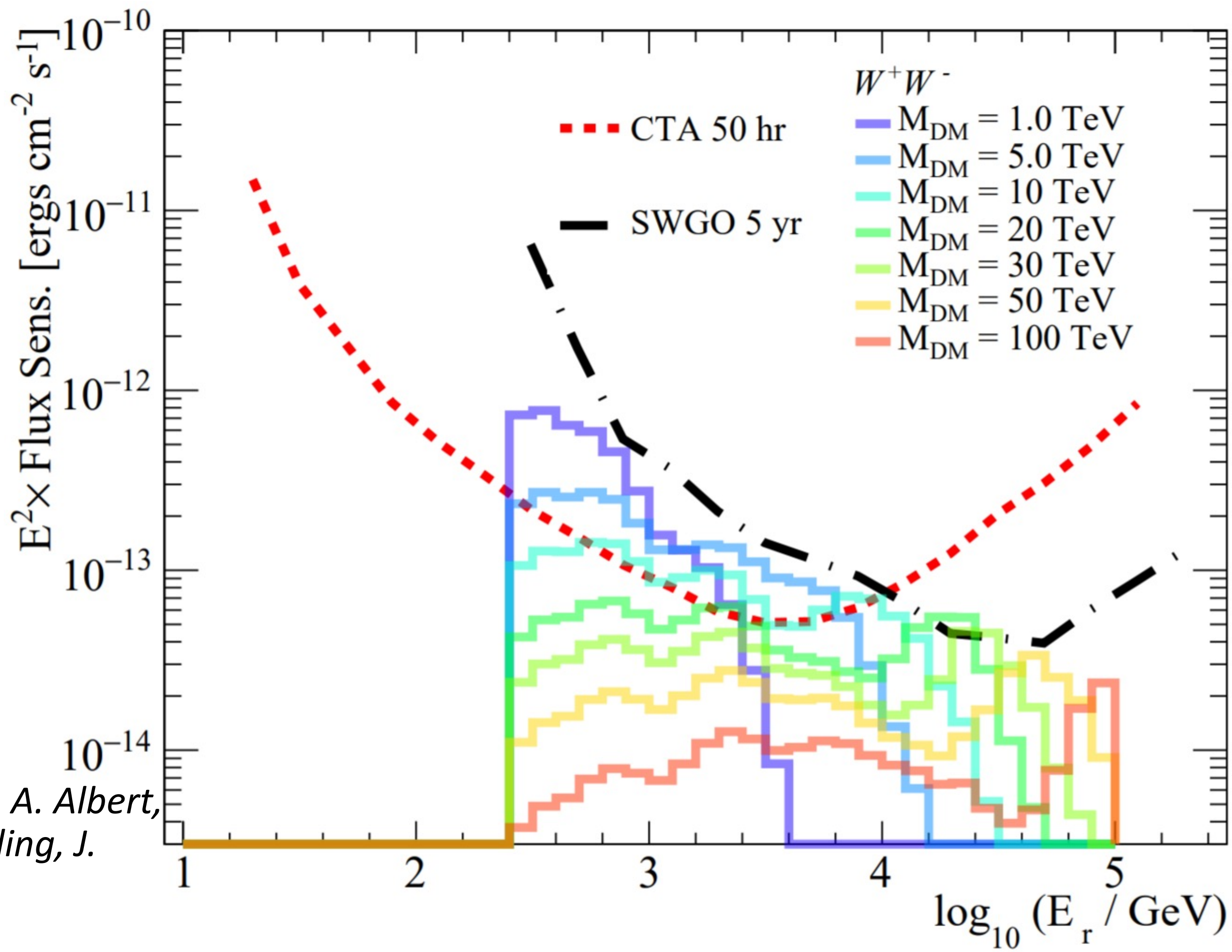




AV, H. Schoorlemmer, A. Albert, V. de Souza, J. P. Harding, J. Hinton
JCAP 2019 [arXiv:1906.03353]

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

Complementarity at the highest energies



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

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

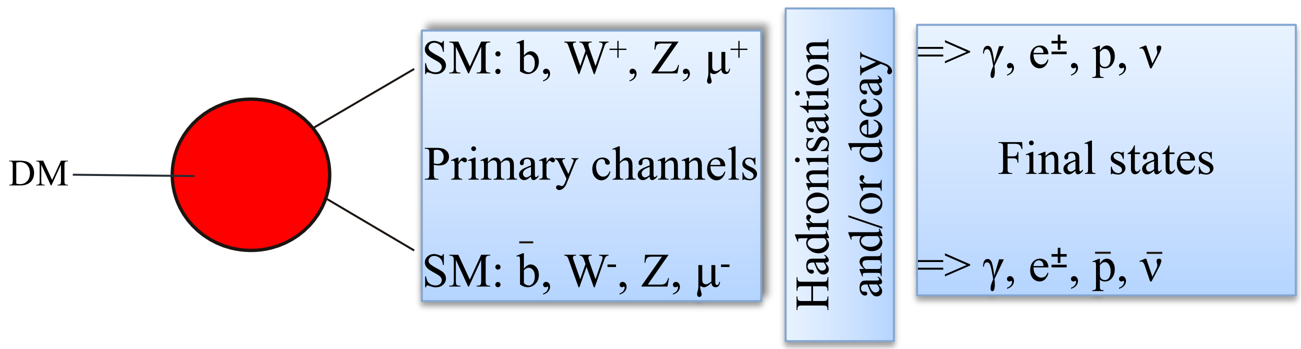
DM decay sensitivity

DM self-annihilation rate :

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

DM decay rate :

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



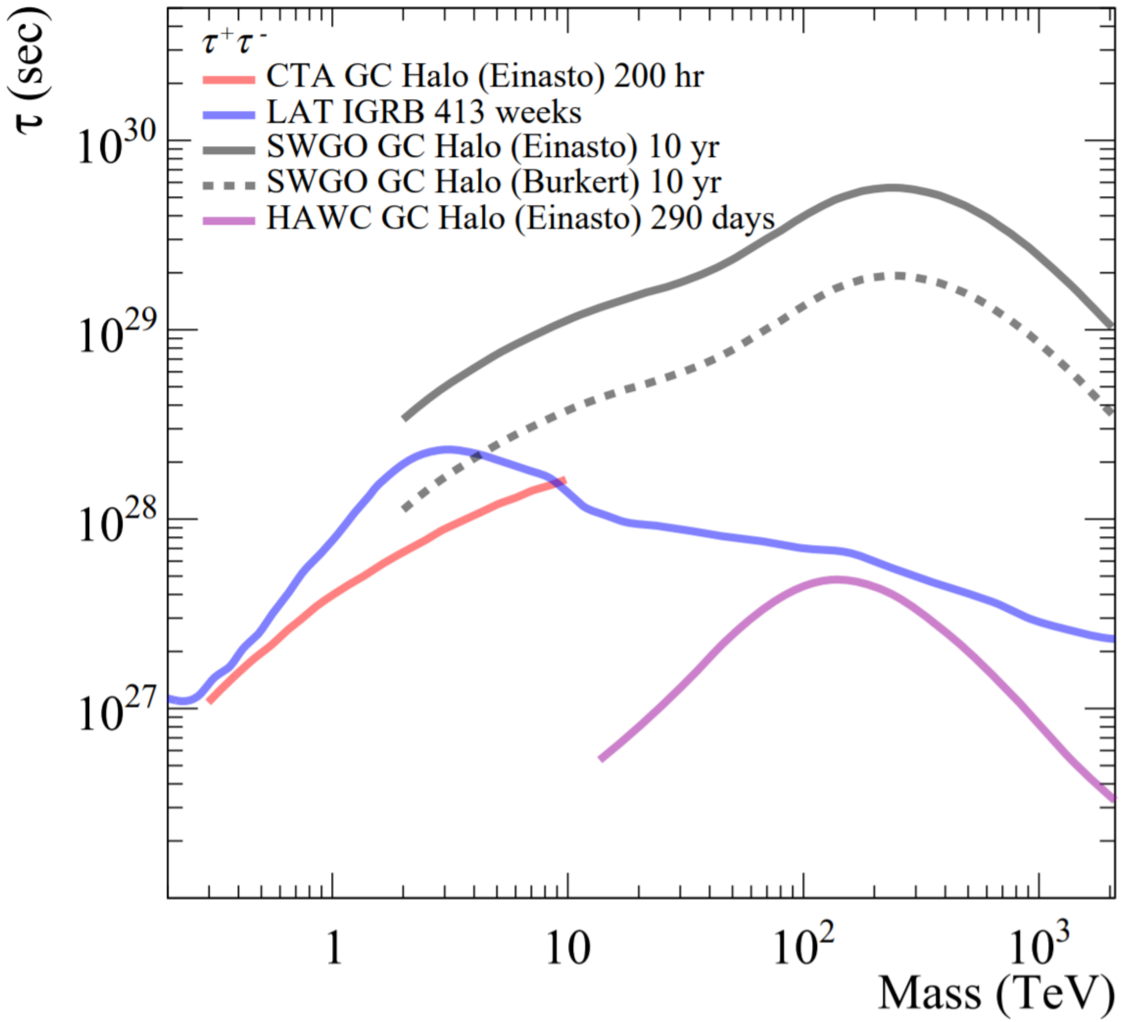
Gamma-ray flux from decay of a WIMP:

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

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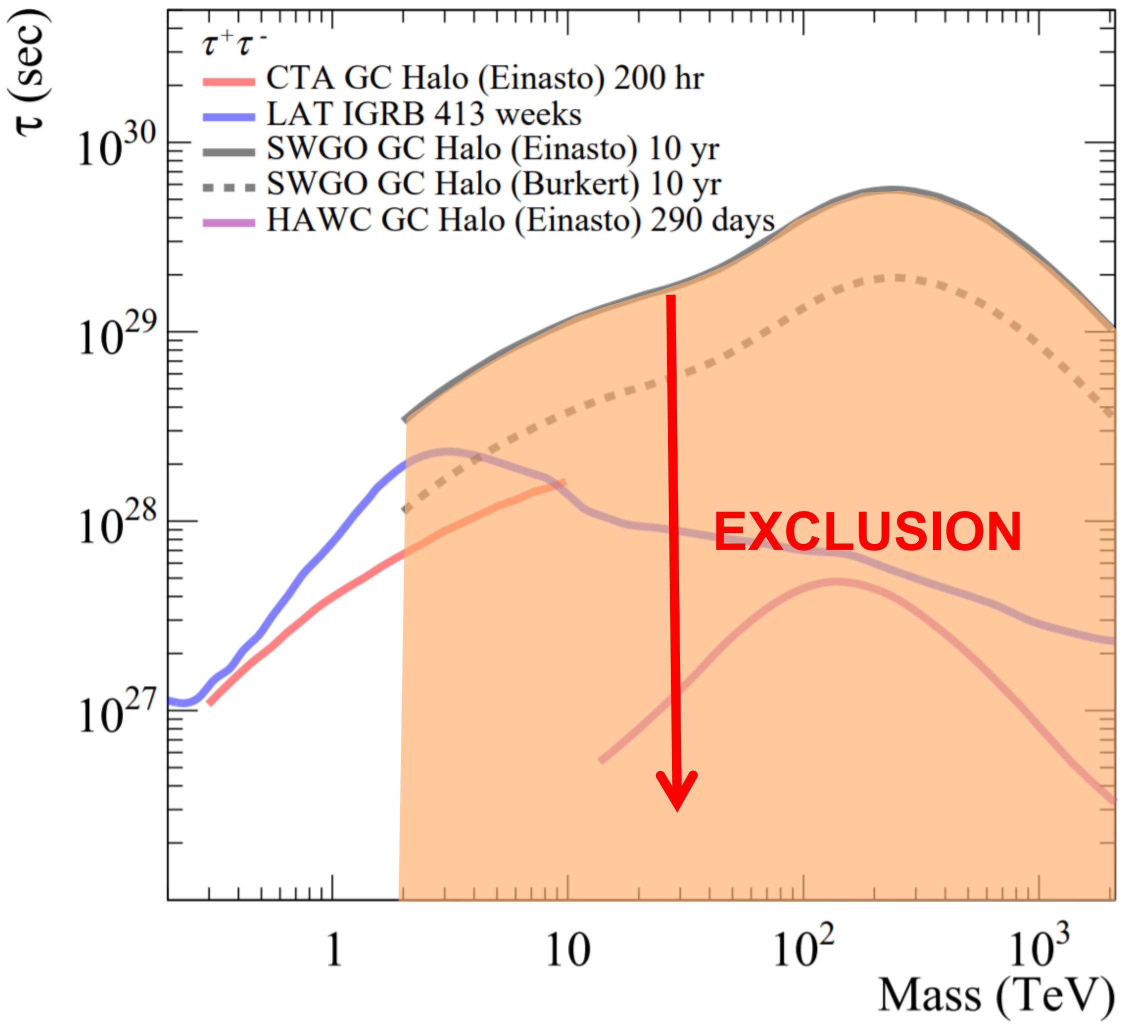
AV, H. Schoorlemmer, A. Albert, V. de Souza, J. P. Harding, J. Hinton JCAP 2019 [arXiv:1906.03353]

- ➢ SWGO will have 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

GC halo: DM decay sensitivity



$\tau^+\tau^-$ channel

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

- ➢ SWGO will have 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

Dark matter targets

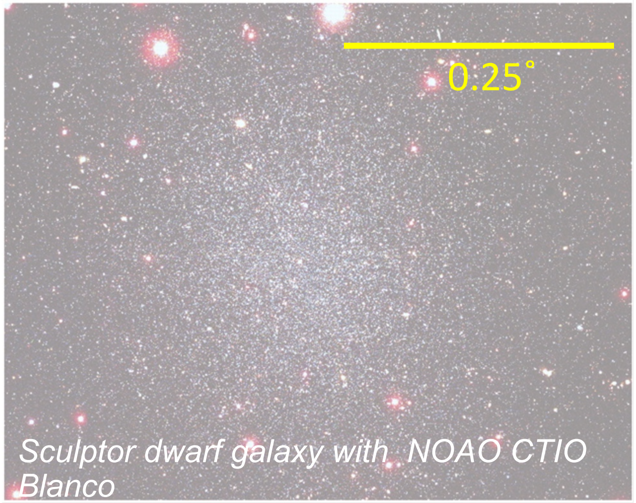
Galactic Center in radio

Galactic Centre

- ❑ Proximity (~8kpc)
- ❑ Possibly high central DM concentration :
  DM profile : core? cusp?
- ❑ High astrophysical background in gamma-rays

Dwarf galaxies of the Milky Way

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



Sculptor dwarf galaxy with NOAO CTIO Blanco

Galaxy clusters

- ❑ High DM annihilation luminosity
- ❑ Substructures contribution to the overall DM flux
- ❑ Astrophysical background may be important

Galaxy Cluster Abell 1689

Andromeda galaxy

Local Group Galaxies

- ❑ Large DM mass
- ❑ Relatively close
- ❑ Secondary radiation may be important location

Large Magellanic Cloud

- Large dark matter content
  $M_{vir} \sim 10^{11}\ M_{Sun}$

- Proximity to Earth
  $D \sim 50$ kpc

Credit: David Darling

Large Magellanic Cloud observed by ASKAP

- Large dark matter content
  $M_{vir} \sim 10^{11}\ M_{Sun}$
- Proximity to Earth
  $D \sim 50$ kpc

Credit: David Darling

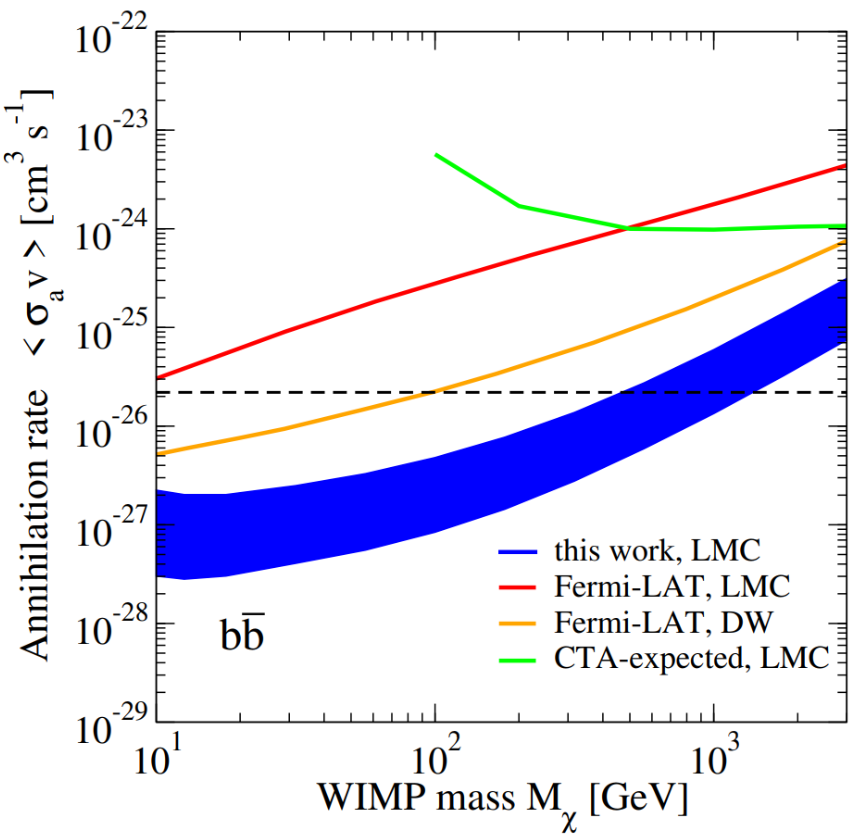
- **Australian Square Kilometre Array Pathfinder (ASKAP)**
  36 antennas, each 12 m in diameter
  Commissioning and early science
- **Evolutionary Map of the Universe (EMU)**
  Survey of the Southern sky ($3 \times 10^4\ deg^2$) at ~ 1 GHz with ~10'' resolution and sensitivity of 30 mJy/beam

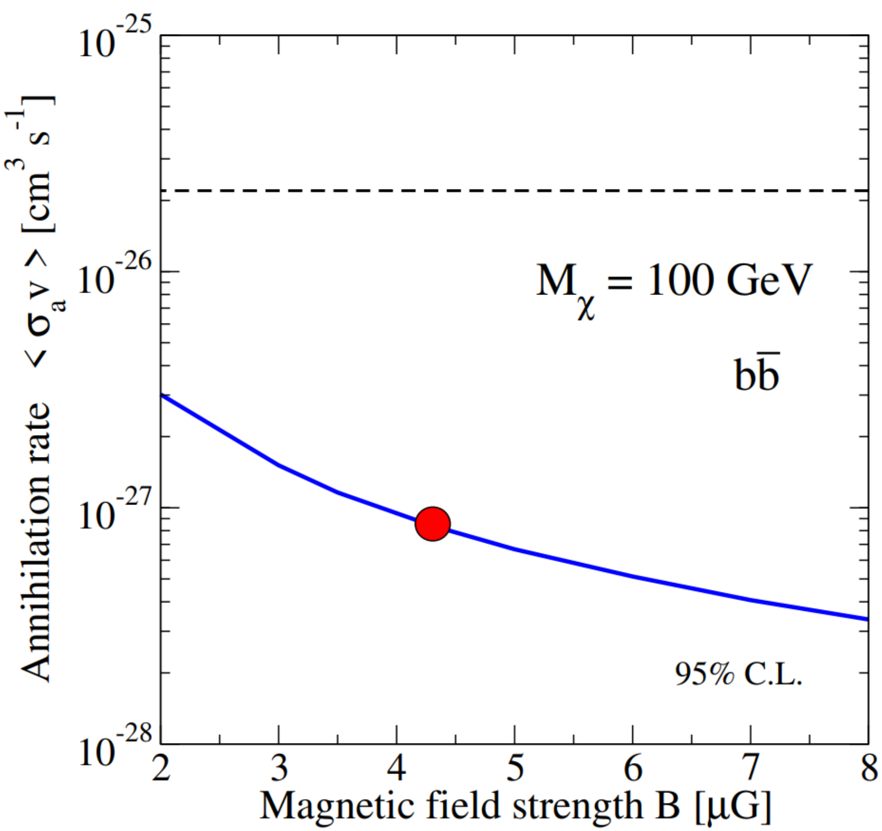
Credit: ATNF-CSIRO

Limits to DM from LMC by ASKAP

Synchrotron radiation

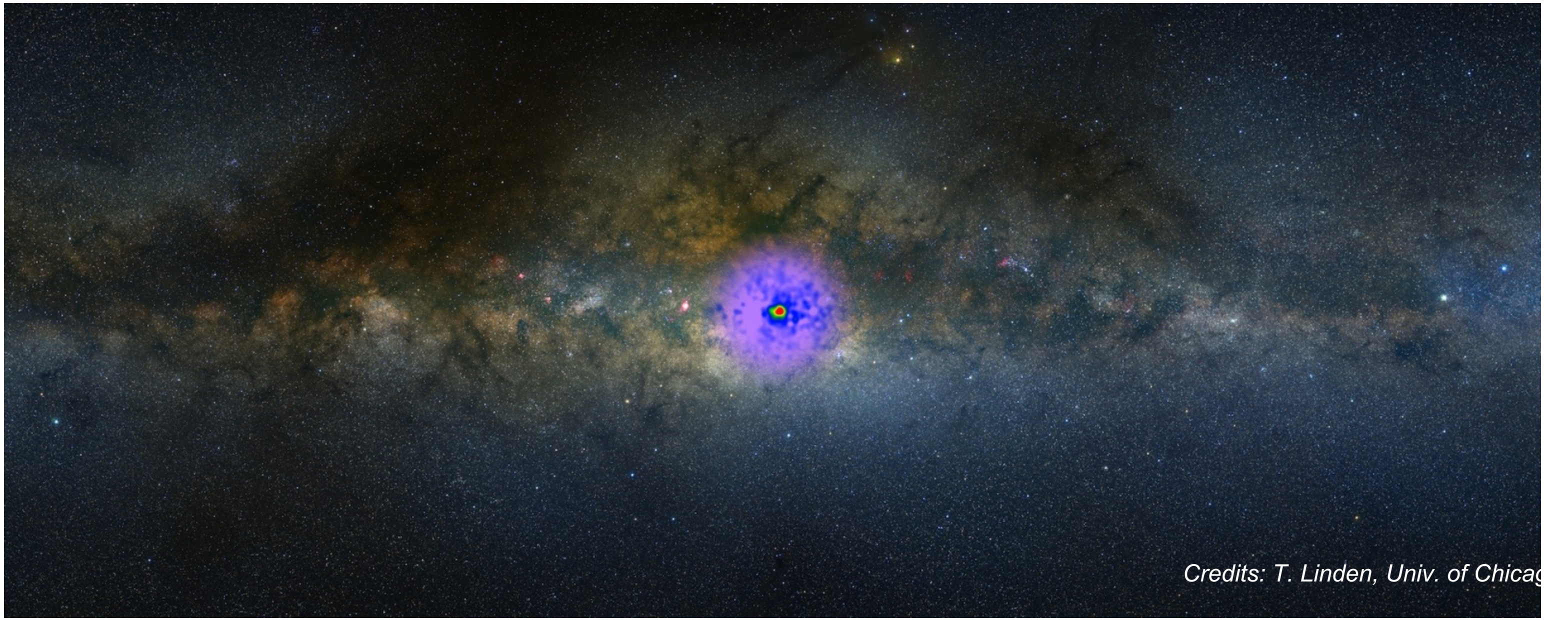
- Dependent on the magnetic field (lower limit > 1 μG)
- Total magnetic field strength estimated as 4.3 μG [Gaensler+, Science 2005]





- Very strong bounds
- Thermal cross-section excluded for DM masses below 480 GeV (bb), 358 GeV (W+W-), 192 GeV (τ+τ-) , 164 GeV (μ+μ-)

"Galactic Center GeV Excess"



Residual GeV emission in the Galactic Center by Fermi-LAT

- Initial claims by Goodenough & Hooper (2009) [see also Vitale & Morselli (2009)]
- Controversial discussion in the community for six years
- In 2015, the existence of "GeV excess" finally got the blessing of the Fermi-LAT collaboration
- Is it a sign of DM?

Literature overview

Slide adapted from C. Weniger

Papers that looked at data

- Goodenough & Hooper, arXiv:0910.2998
- Vitale & Morselli, 2009
- Hooper & Goodenough, Phys. Lett. B697 (2011) 412
- Hooper & Linden, Phys. Rev. D84 (2011) 123005
- Boyarsky, Malyshev & Ruchayskiy, Phys. Lett. B705 (2011) 165
- Abazajian & Kaplinghat, PRD 86 (2012) 083511
- Hooper & Slatyer, Phys. Dark Univ. 2 (2013) 118
- Gordon & Macias, Phys. ReV. D88 (2013) 083521
- Macias & Gordon, PRD 89 (2014) 063515
- Abazajian, Canac, Horiuchi, Kaplinghat, Phys. Rev. D90 (2014) 023526
- Cholis, Evoli, Calore, Linden, Weniger, Hooper, JCAP 1512 (2015) 12
- Calore, Cholis & Weniger, JCAP 1503 (2015) 038
- Zhou, Liang, Huang, Li, Fan, Chang, Phys. Rev. D91 (2015) 123010
- Gaggero, Taoso, Urbano, Valli & Ullio, JCAP 1512 (2015) 056
- Daylan, Finkbeiner, Hooper, Linden, Portillo et al., Physics of Dark Universe 12 (2016) 1
- De Boer, Gebauer, Neumann, Biermann, arXiv:1610.08926 (ICRC 2016 proceedings)
- Huang, Ensslin & Selig, JCAP 1604 (2016) 030
- Carlson, Linden, Profumo, Phys. Rev. D94 (2016) 063504
- Bartels, Krishnamurthy, Weniger, Phys. Rev. Lett. 116 (2016) 5
- Macis, Gordon, Crocker, Coleman, Paterson, arXiv:1611.06644
- Lee, Lisanti, Safdi, Slatyer, Xue, Phys. Rev. Lett. 116 (2016) 5
- Ajello et al. 2016, Astrophys. J. 819, 44
- Ackermann et al., 2017, Astrophys. J. 840, 43
- Ajello et al., 2017, arXiv:1705.00009
- Macias, Horiuchi, Kaplinghat,Gordon, Crocker, Nataf, JCAP arXiv:1901.03822
- Leane & Slatyer, PRL arXiv:1904.08430
- Cholis, Zhong, McDermott, Surdutovich PRD arXiv:2112.09706
- Martin Pohl, Macias, Coleman, Gordon, ApJ arXiv:2203.11626

Excess is likely DM

Excess is there

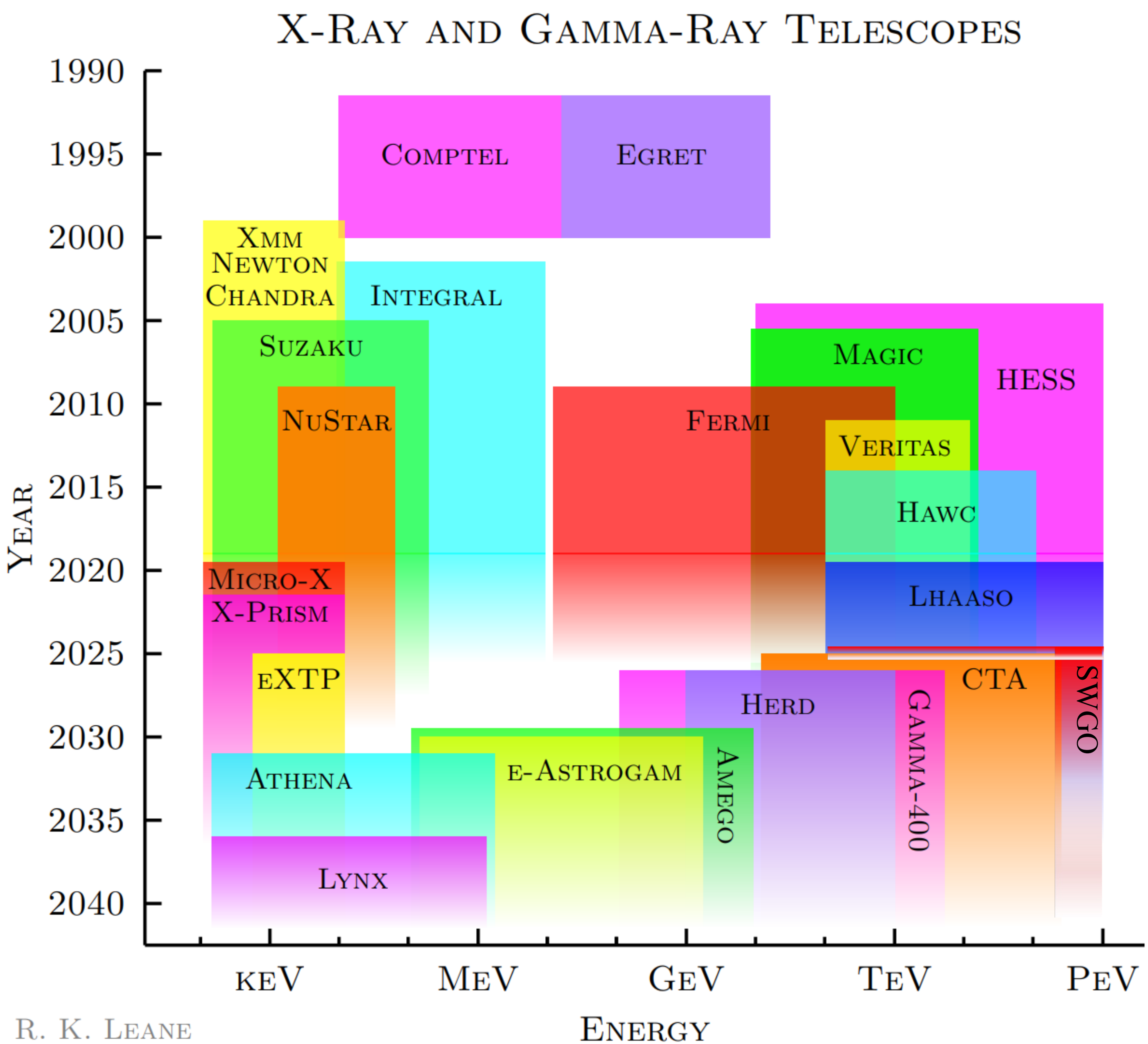
Excess is likely not DM

Excess is not there

+hundreds of DM theory papers

+a few papers missed

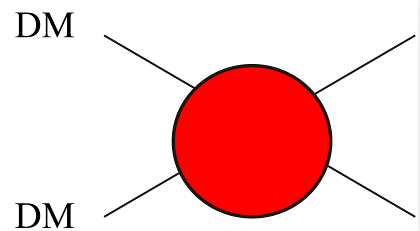
High-energy telescopes: past-present-future



What about neutrinos?

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

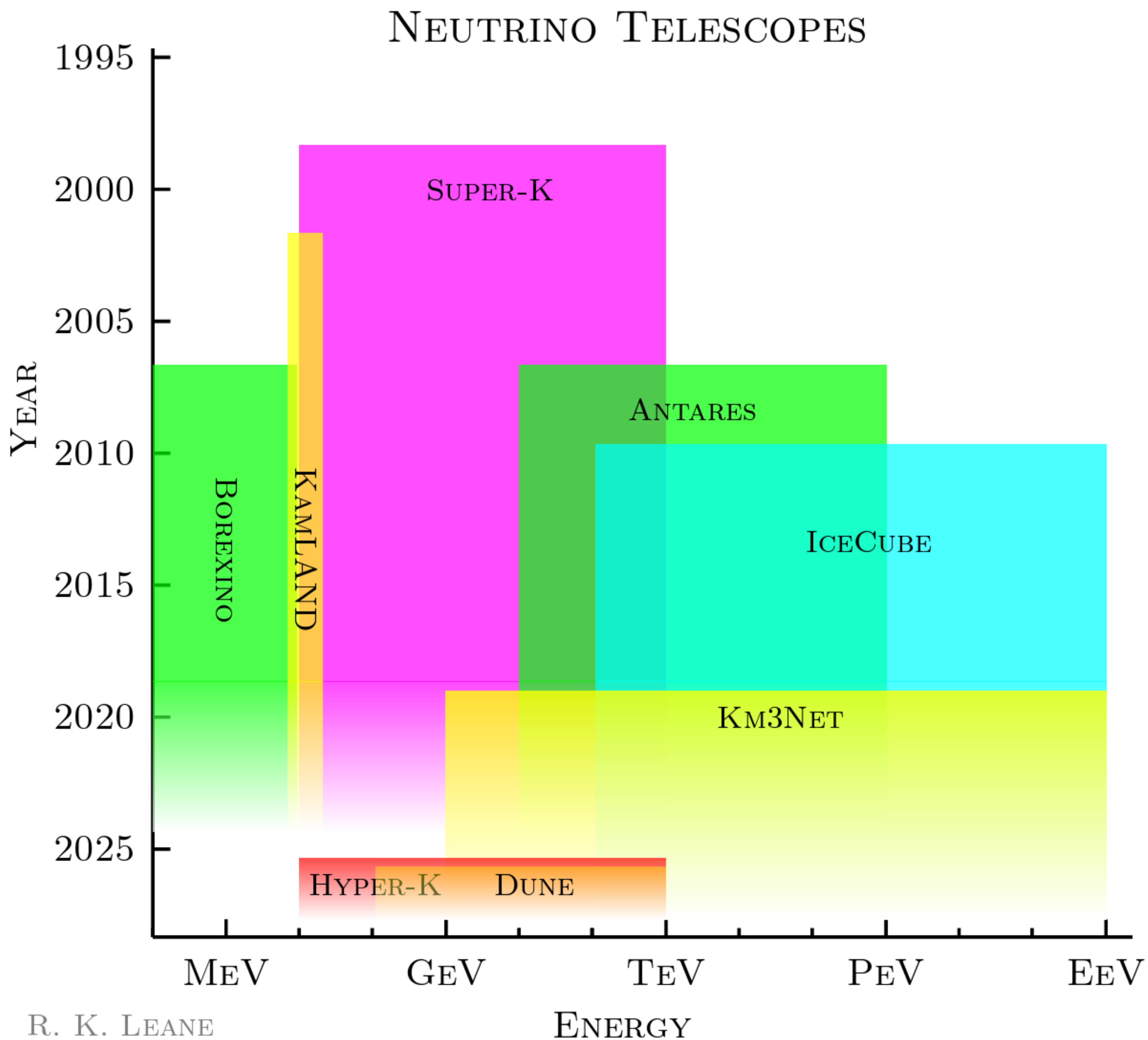
Final states

=> γ, $e^\pm$, $\bar{p}$, $\bar{\nu}$

Neutrino flux from annihilation of a WIMP:

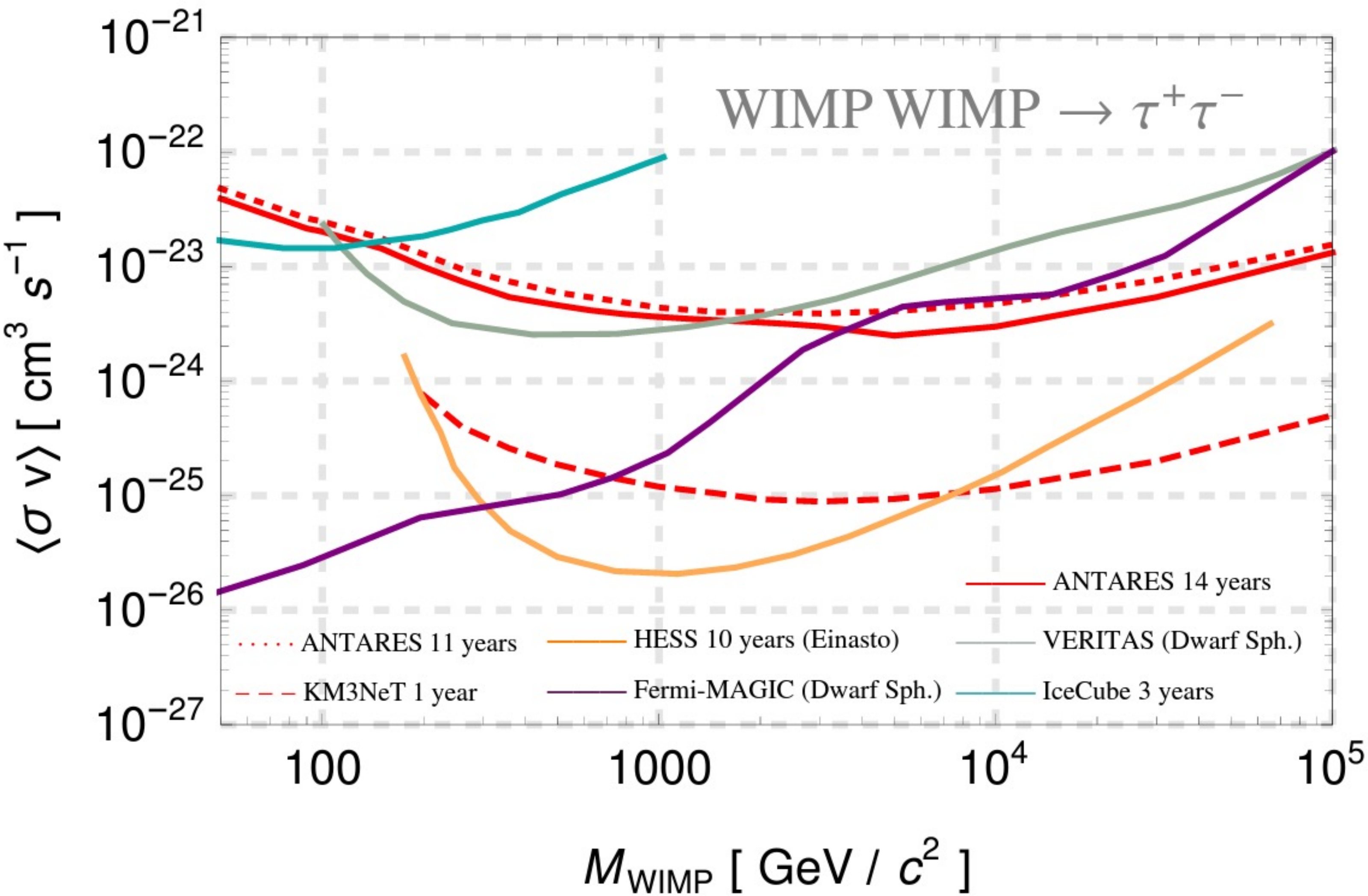
$$\frac{\mathrm{d}\Phi_\nu(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\nu} = \frac{1}{8\pi} \underbrace{\frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}^2} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}}_{\text{Particle Physics}} \times \underbrace{\bar{J}(\Delta\Omega)\Delta\Omega}_{\text{Astrophysics}} \quad \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$$

Neutrinos experiments: past-present-future



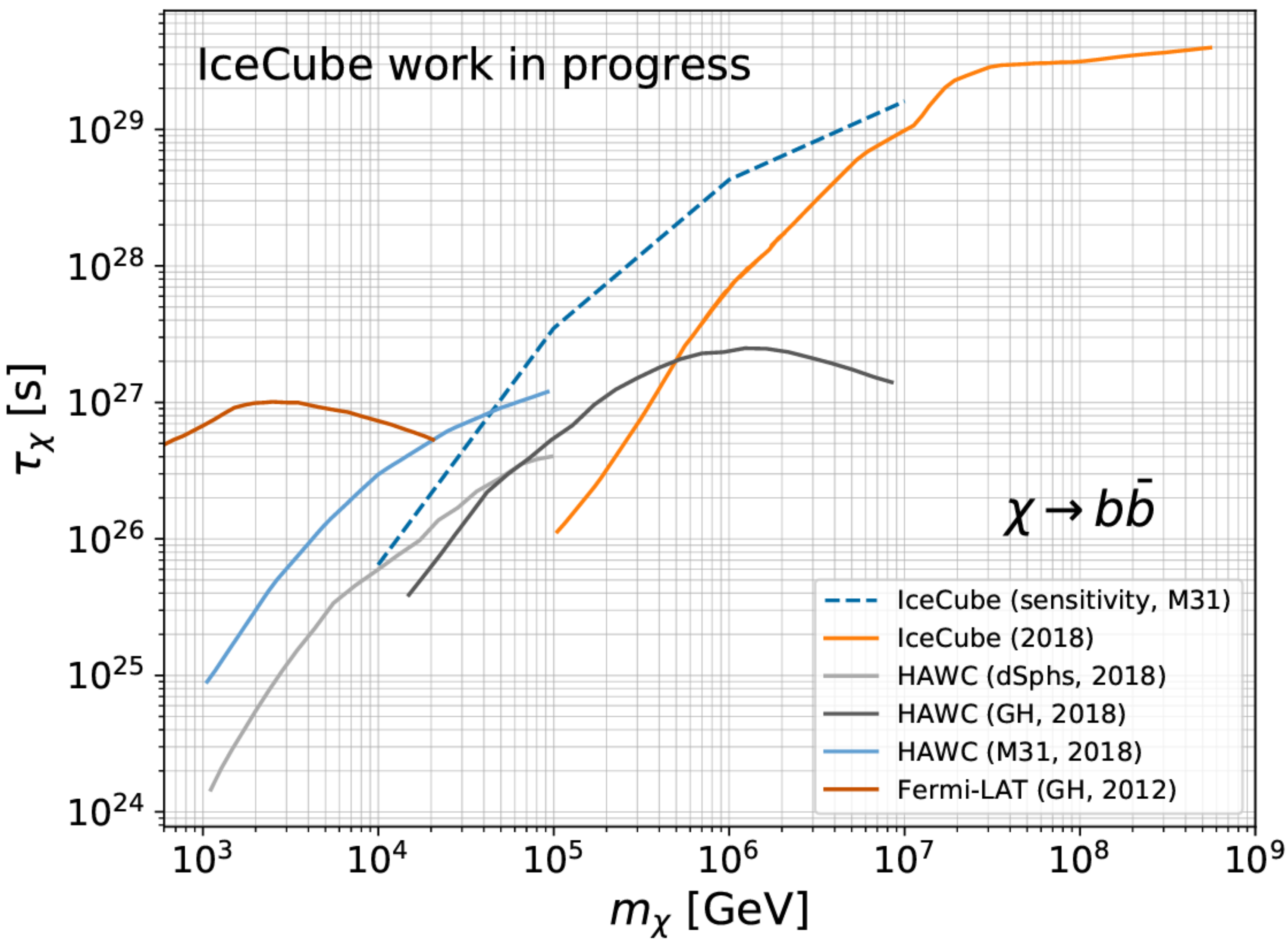
Neutrino constraints to annihilation

The ANTARES Collaboration arXiv:1912.05296



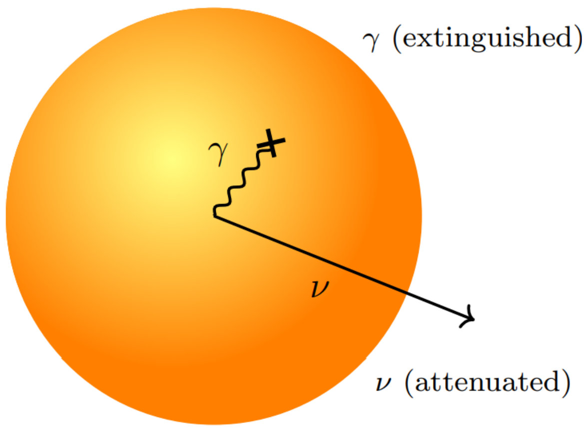
Neutrino constraints to decay

The IceCube Collaboration arXiv:1804.03848 & arXiv:2107.11527



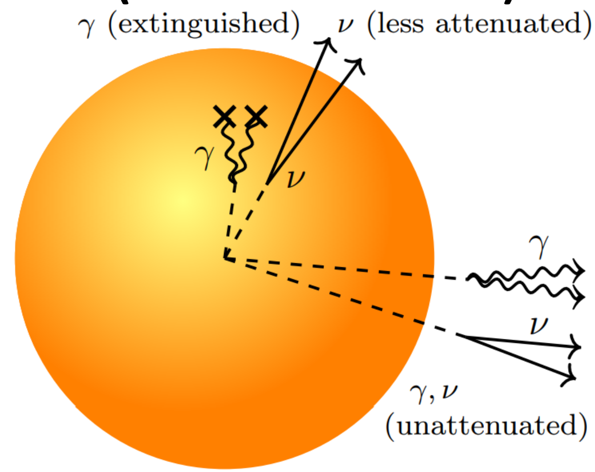
Dark matter capture in the Sun

DM decay into neutrinos



Short-lived mediators

DM ann/dec into new mediator (secluded models)



Long-lived mediators

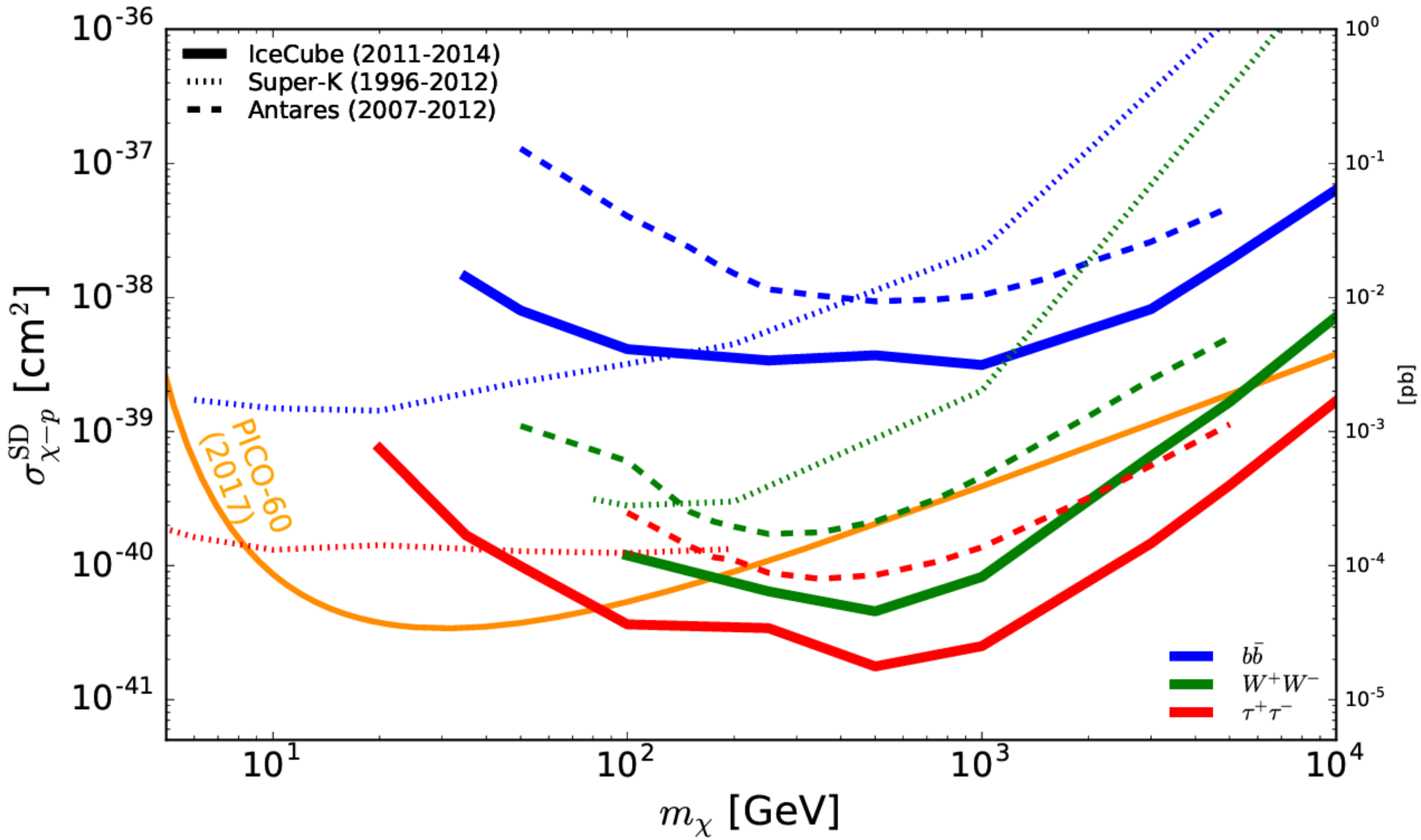
$$\frac{d\Phi}{dE} = \frac{\Gamma_{ann}}{4\pi D_{\oplus}^2} \times \frac{dN}{dE} \times Br\,(Y \rightarrow SM) \times P_{surv}$$

EQUILIBRIUM

$$\Gamma_{ann} = \frac{1}{2}\Gamma_C \propto \sigma_{\chi p}^{SD}$$

capture rate

Neutrinos constraint to scattering cross-section



- Limits from IceCube and ANTARES comparable to DM direct detection experiments

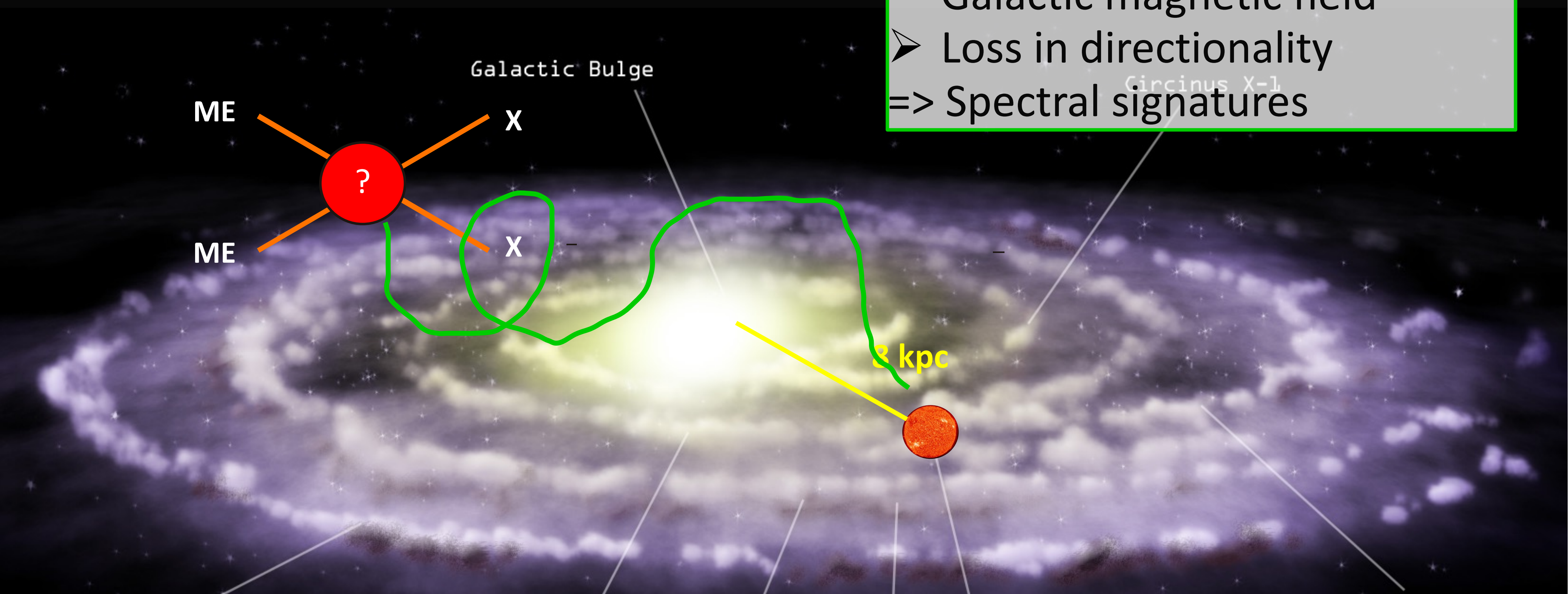
Dark Matter searches with charged cosmic rays

Transport equation of charged CRs

Charged cosmic-rays

- Diffusive propagation in the Galactic magnetic field
- Loss in directionality

=> Spectral signatures



Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun… '90s, '00s

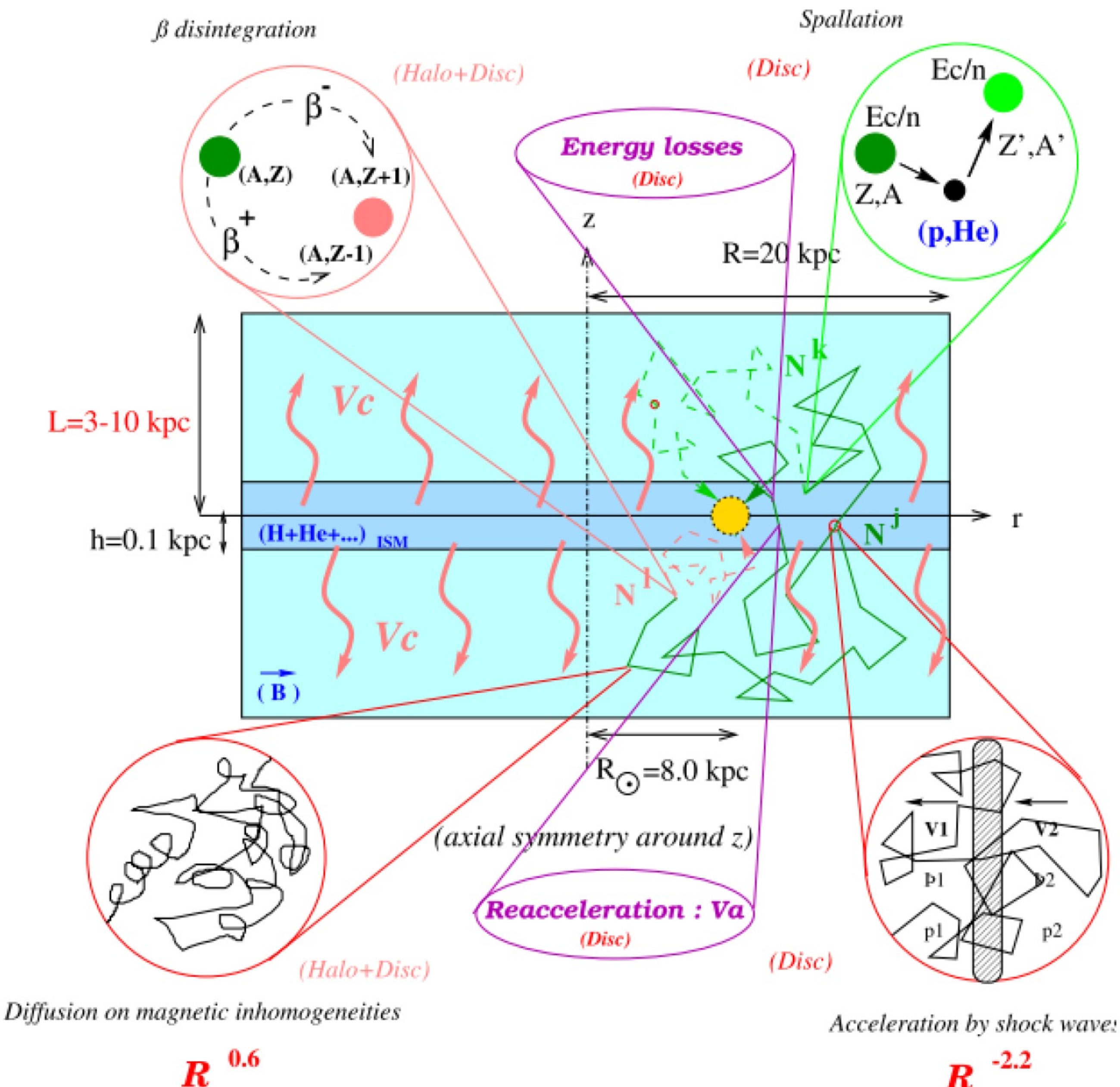
spectrum

$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion | energy loss | convective wind | source | spallations

[uncert]

Illustration of CRs propagation



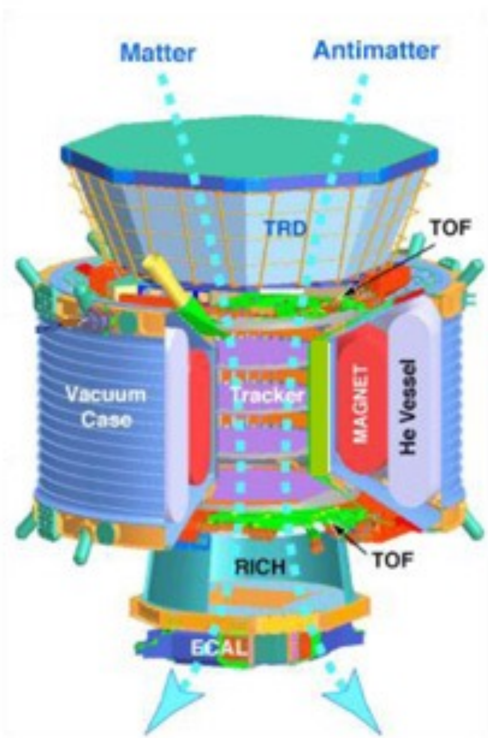
Most relevant assumption:
- Cylindrical symmetry
- Homogeneous diffusion coefficient

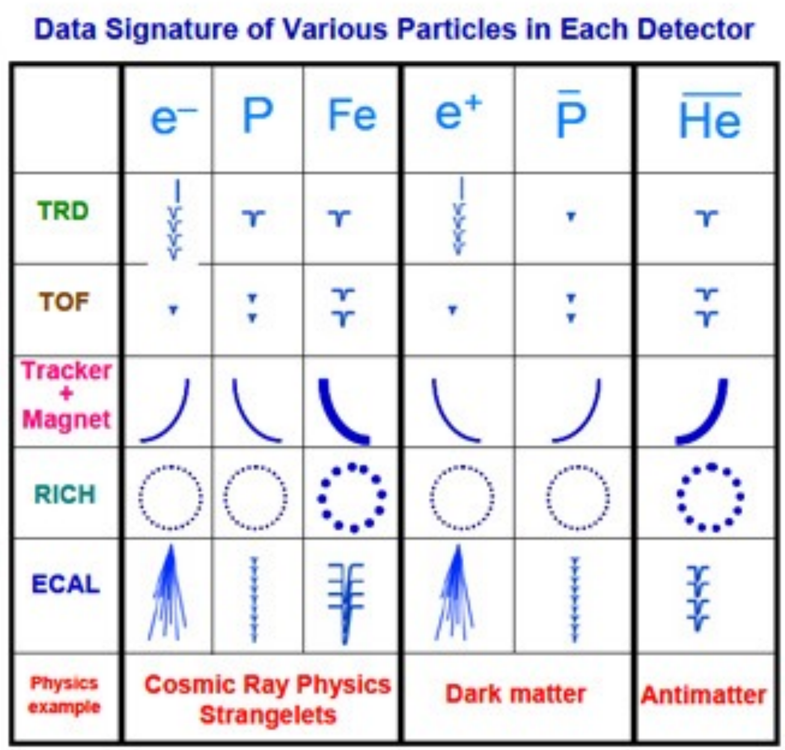
Most relevant parameters:
- Diffusion zone height, L
- Diffusion constant, D

[excellent review: Lavalle & Salati (2012)]

Detecting charged CRs at GeV-TeV

- Cosmic-ray detector at International Space Station: AMS-2
- Taking data since 2011



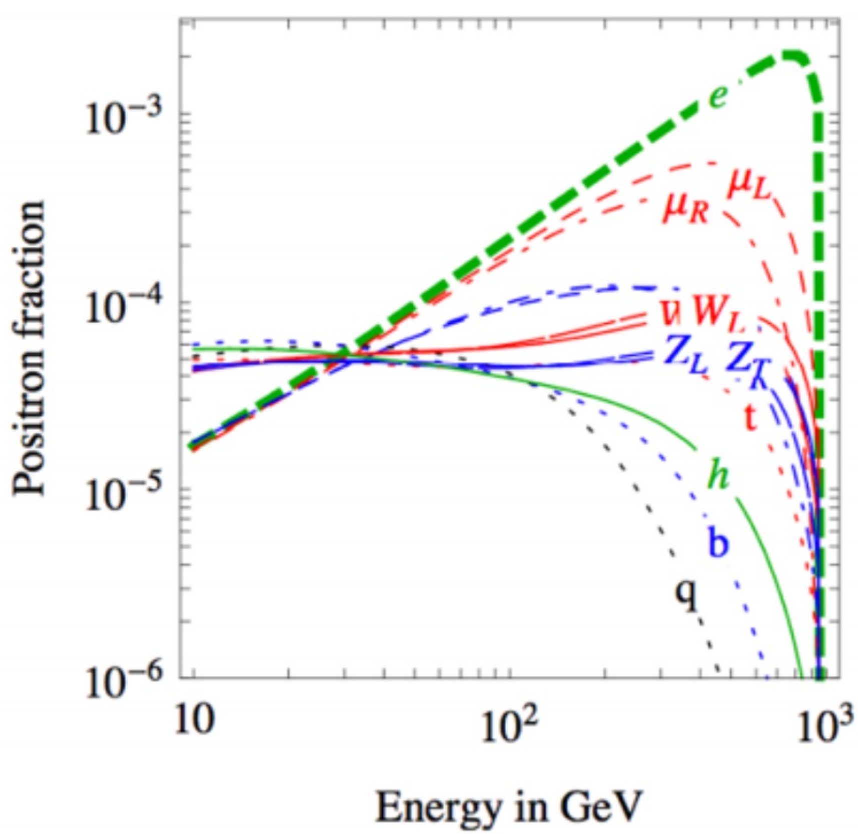


Primary production of CRs from dark matter

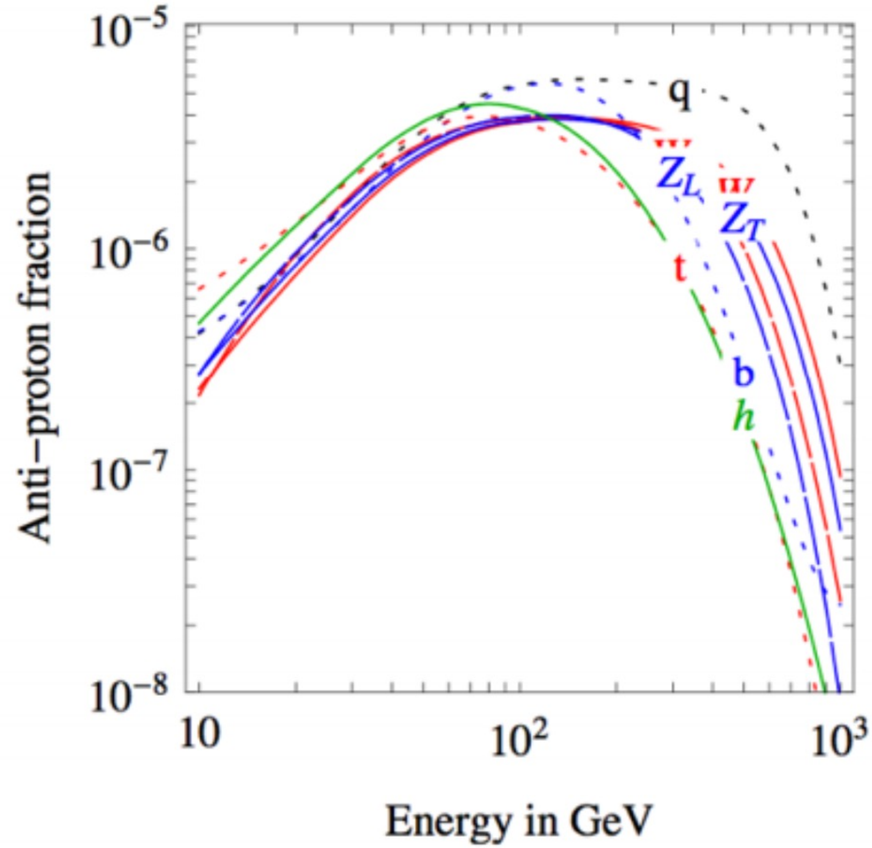
$$\chi\chi \to \begin{Bmatrix} ZZ,\ W^+W^-,\ \gamma\gamma \\ q\bar{q},\ l^+l^-,\ \nu\bar{\nu} \end{Bmatrix} \xrightarrow[\text{decays}]{\text{hadronization}} \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}, \ldots$$

$$Q^j_{\mathrm{DM}}(r, z, E) = \langle\sigma v\rangle \frac{dN_j}{dE_j}\left(\frac{\rho_\chi(r,z)}{m_\chi}\right)^2$$

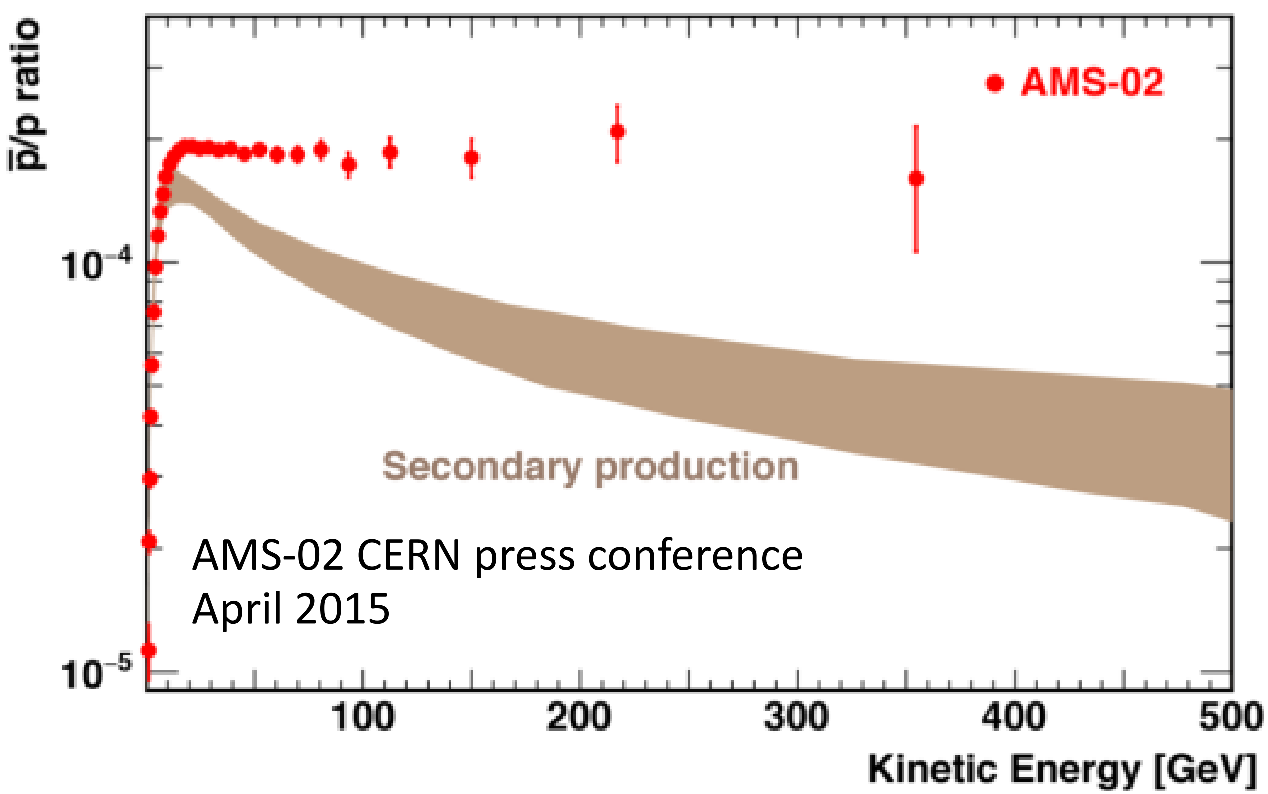
e^+



$\overline{p}$



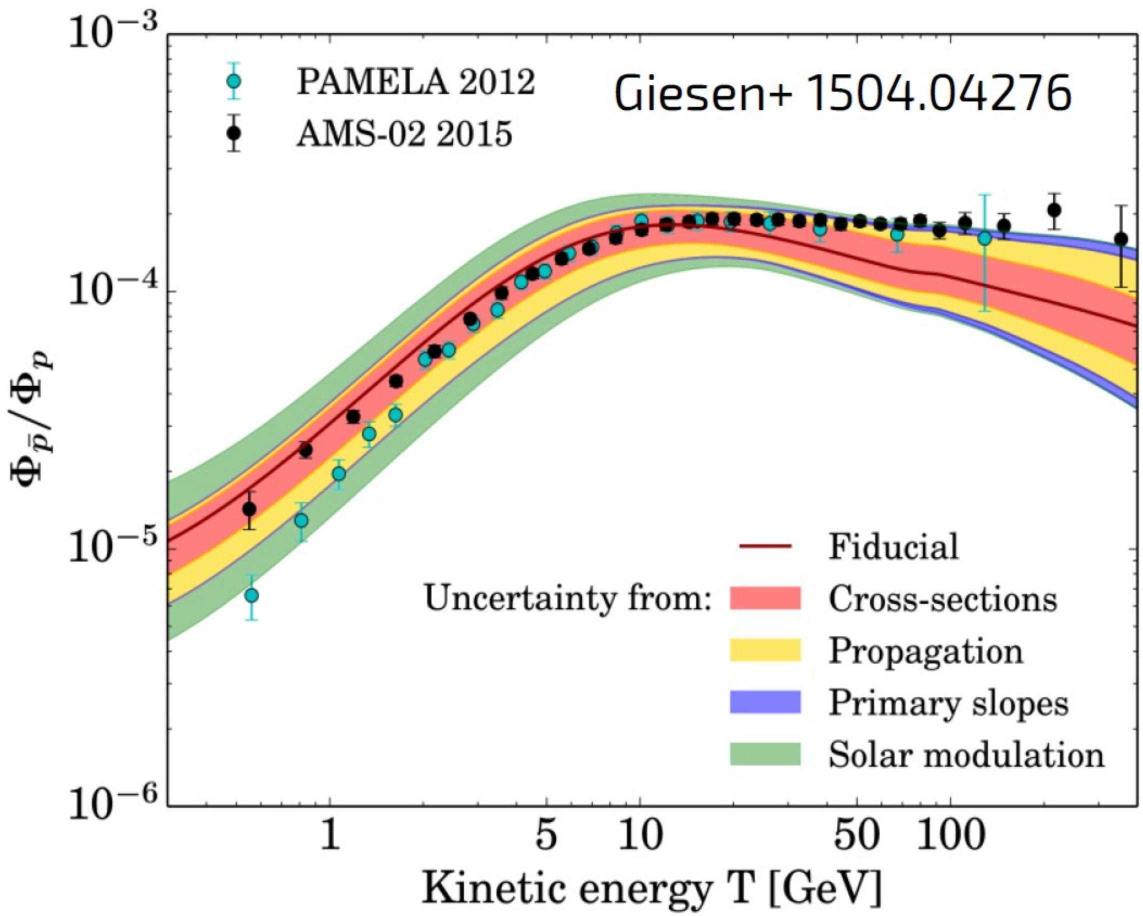
Proton/anti-proton ratio



- Shown as excess above the expectations from secondary production (**ICRC 2015: "Theoretical prediction based on pre-AMS knowledge of cosmic ray propagation"**)

- Antiprotons traditionally well modelled by our CR knowledge
- —> Useful to set stringent constraints on DM contribution.

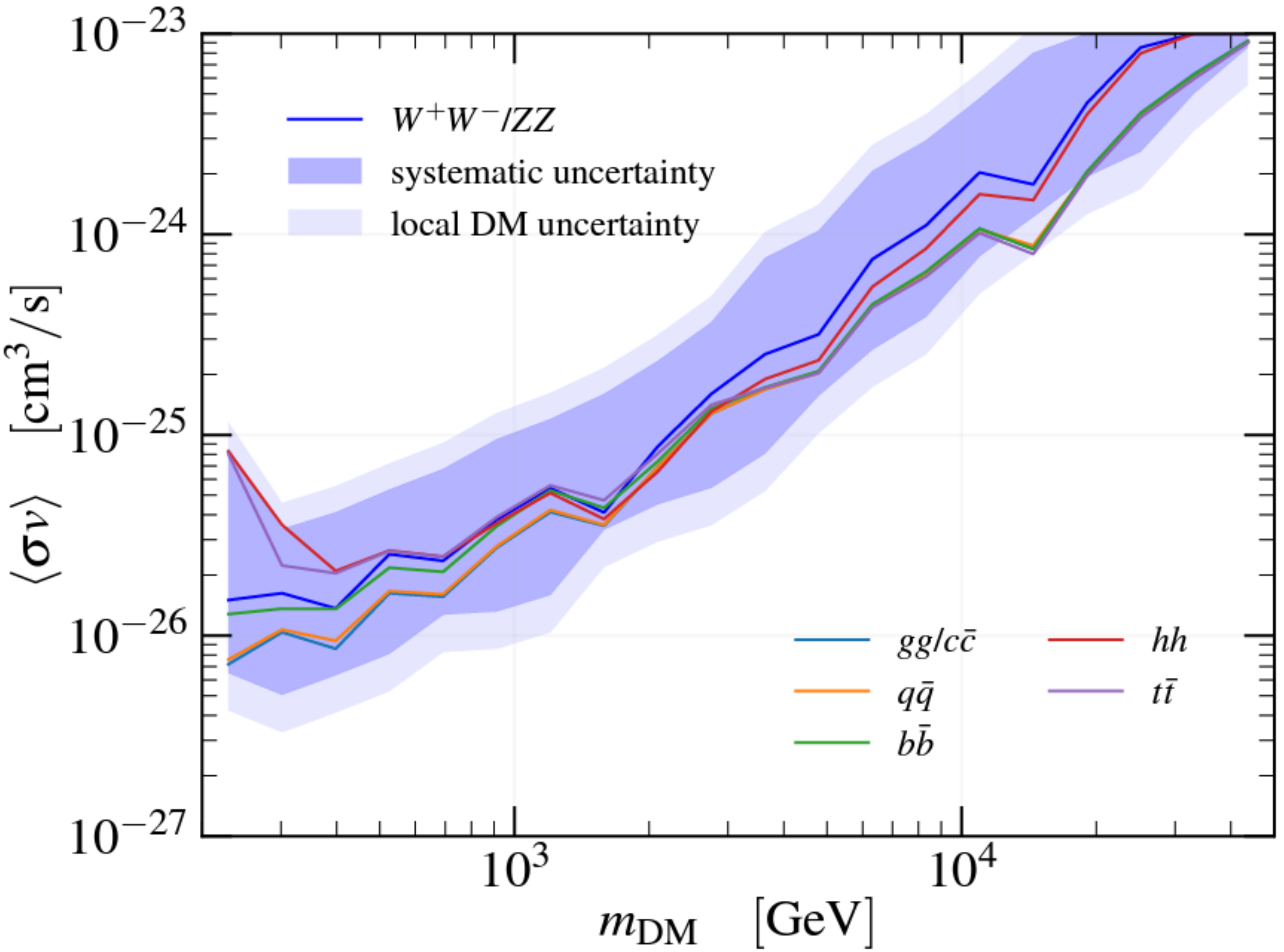
Proton/anti-proton ratio



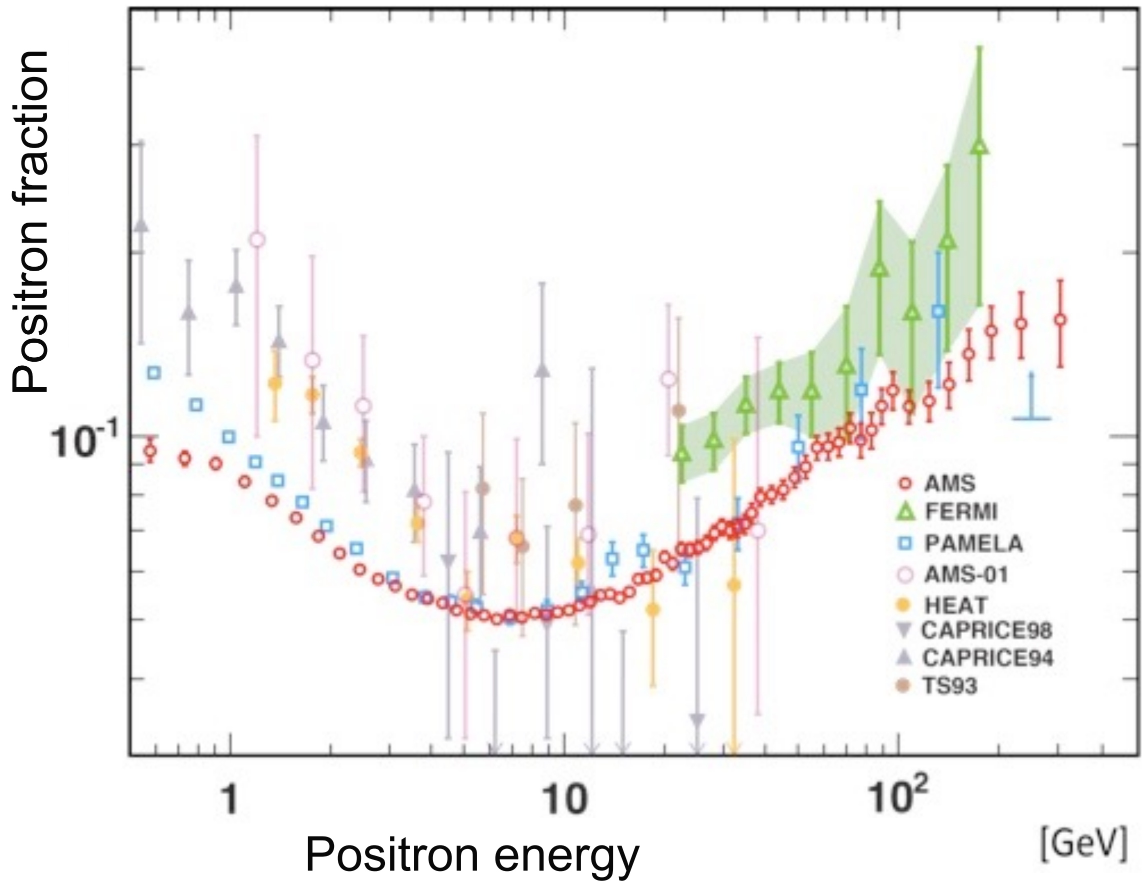
- However quite some uncertainty affects the prediction of the astro only antiproton signal.
- Situation: No excess observed above astrophysical background, when all uncertainties are taken into account
- Only upper limits

Constraints to annihilation from antiprotons

Cuoco et al. arXiv:1711.05274.



Positron fraction



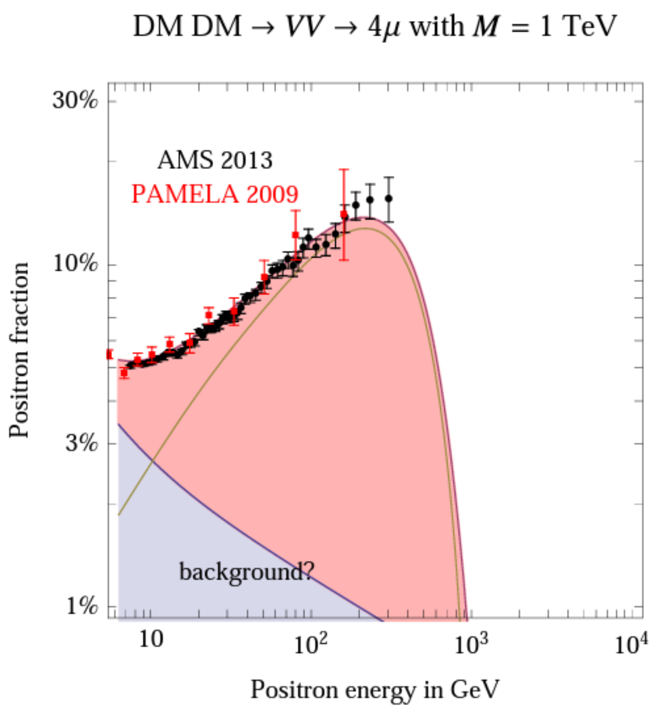
$$\frac{\Phi(e^+)}{\Phi(e^+) + \Phi(e^-)}$$

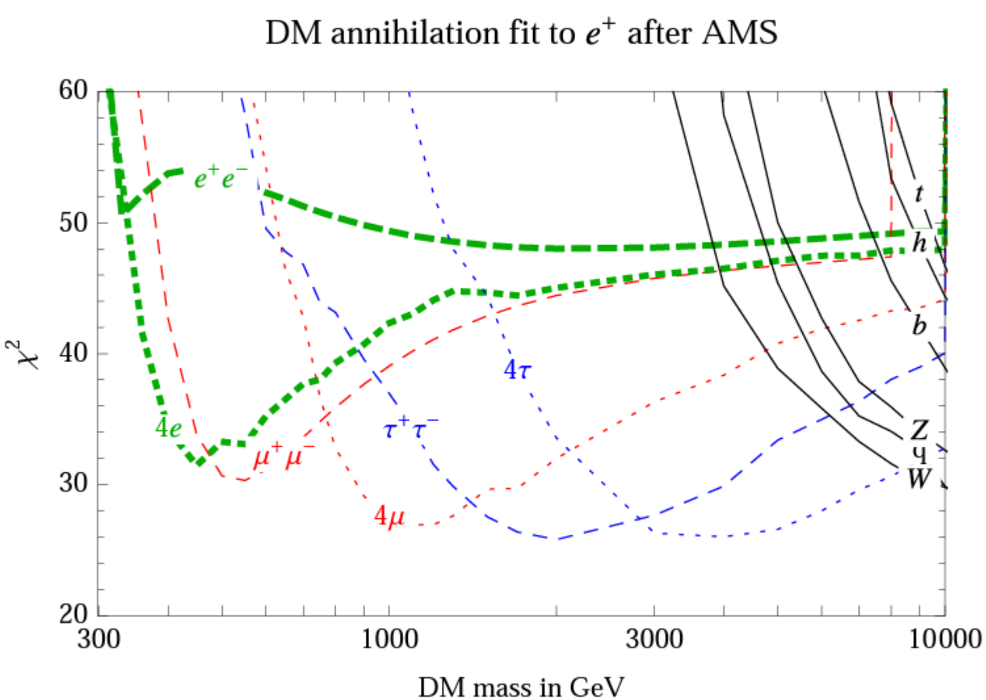
- **Anomaly**: a rise in the positron fraction for E > 10 GeV
- From CR propagation physics, the ratio is expected to decrease for all propagation models.

Positron fraction from DM

However, dark matter interpretation:

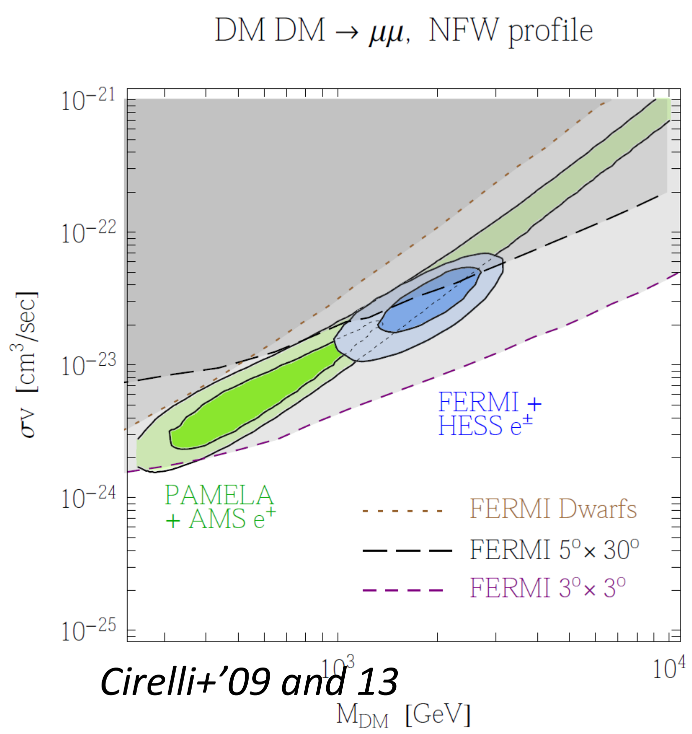
- Only annihilation into leptons ("leptophilic" DM)
- Massive particle (~TeV)
- Too large annihilation cross-section: O(10^{-21}-10^{-24} cm^{-3} s^{-1})



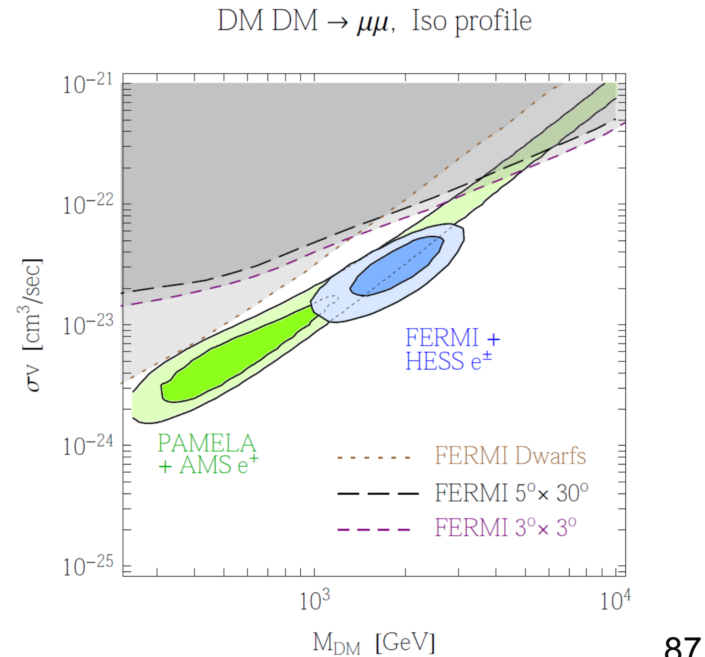


Positron fraction from DM

- Annihilation into leptons produces inverse compton emission, not seen in gamma -> gamma-ray consraints
- Tension with CMB



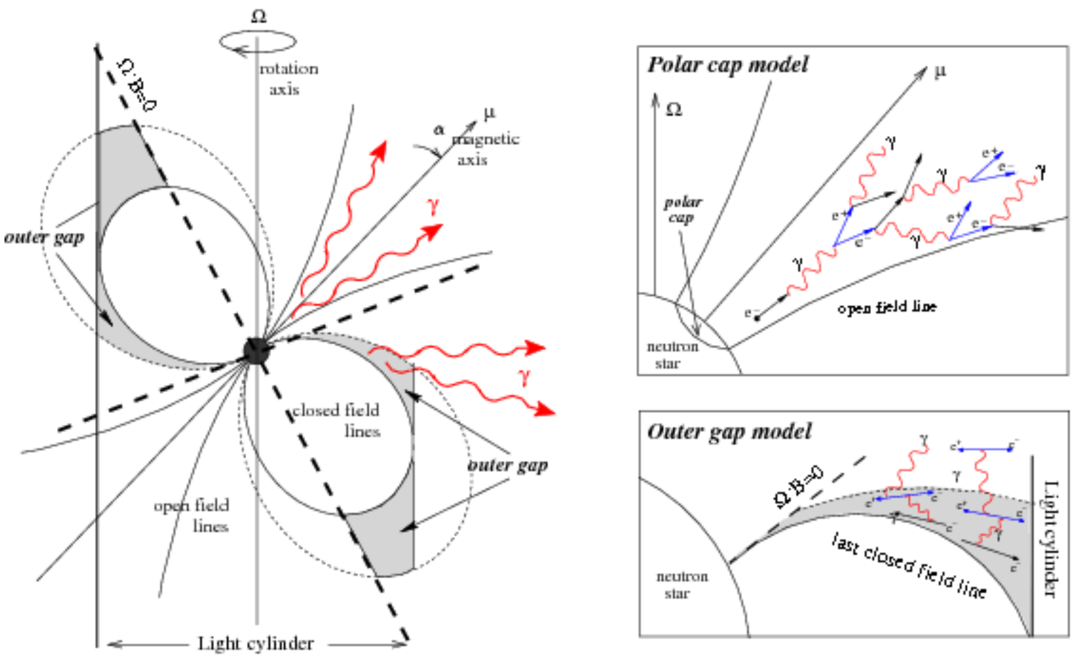
Cirelli+'09 and 13



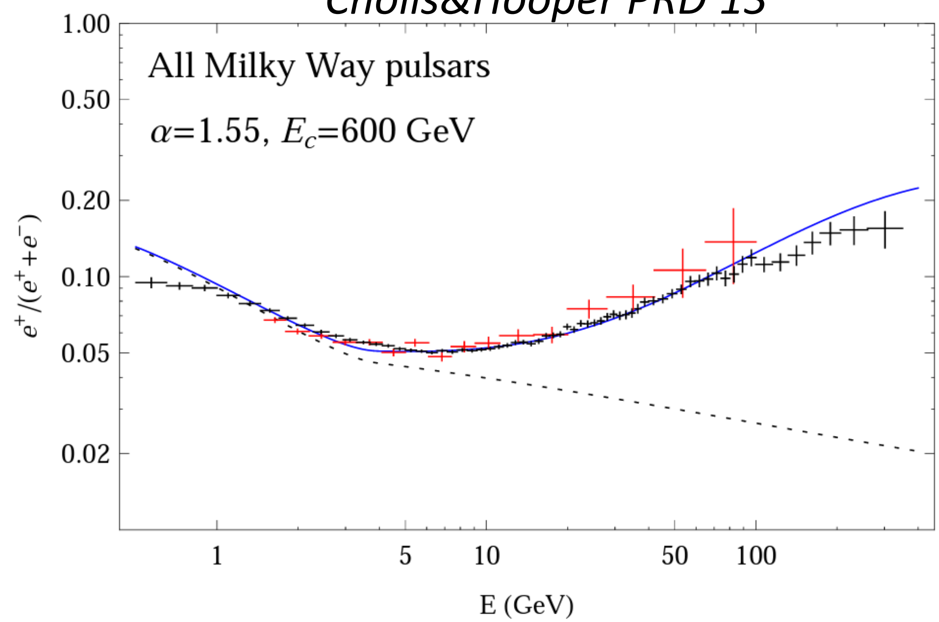
Dark matter interpretation of positron fractions seems to be in tension with gamma-ray observations!

Other explanations

Primary positrons by pair production (e+e-) in pulsars magnetosphere

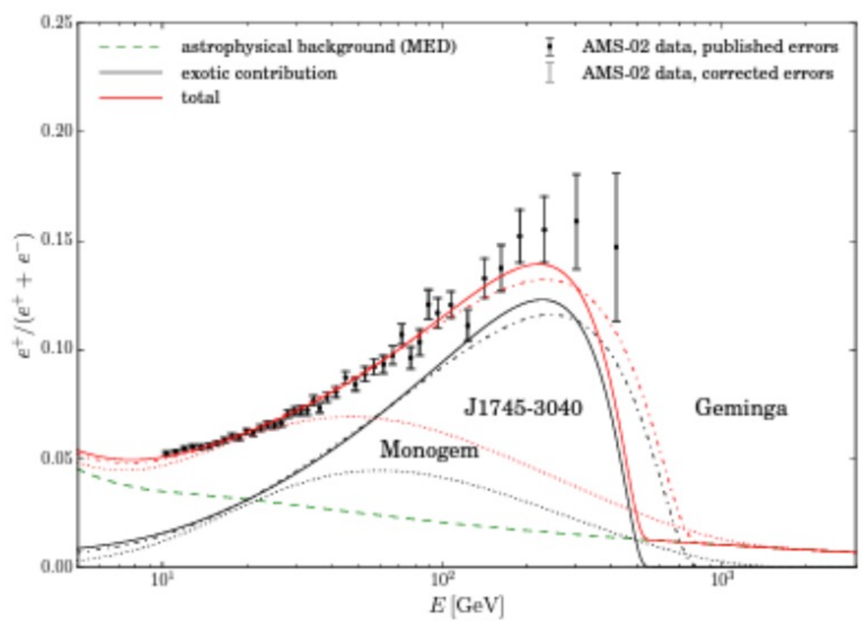


Cholis&Hooper PRD'13



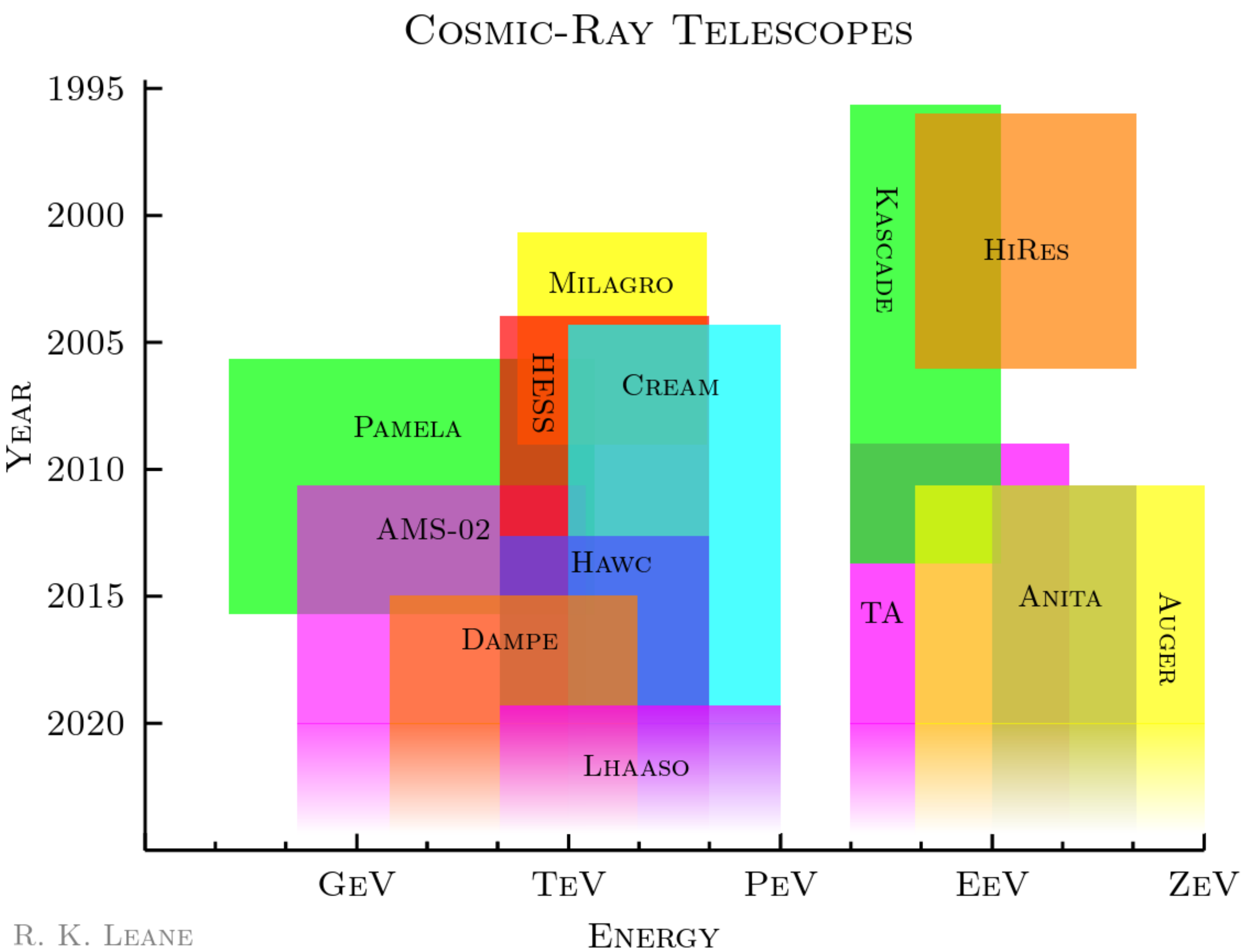
How to discriminate DM from astrophysical emission?

a. Spectrum shape(hard)
b. Anisotropy (signal direction)?

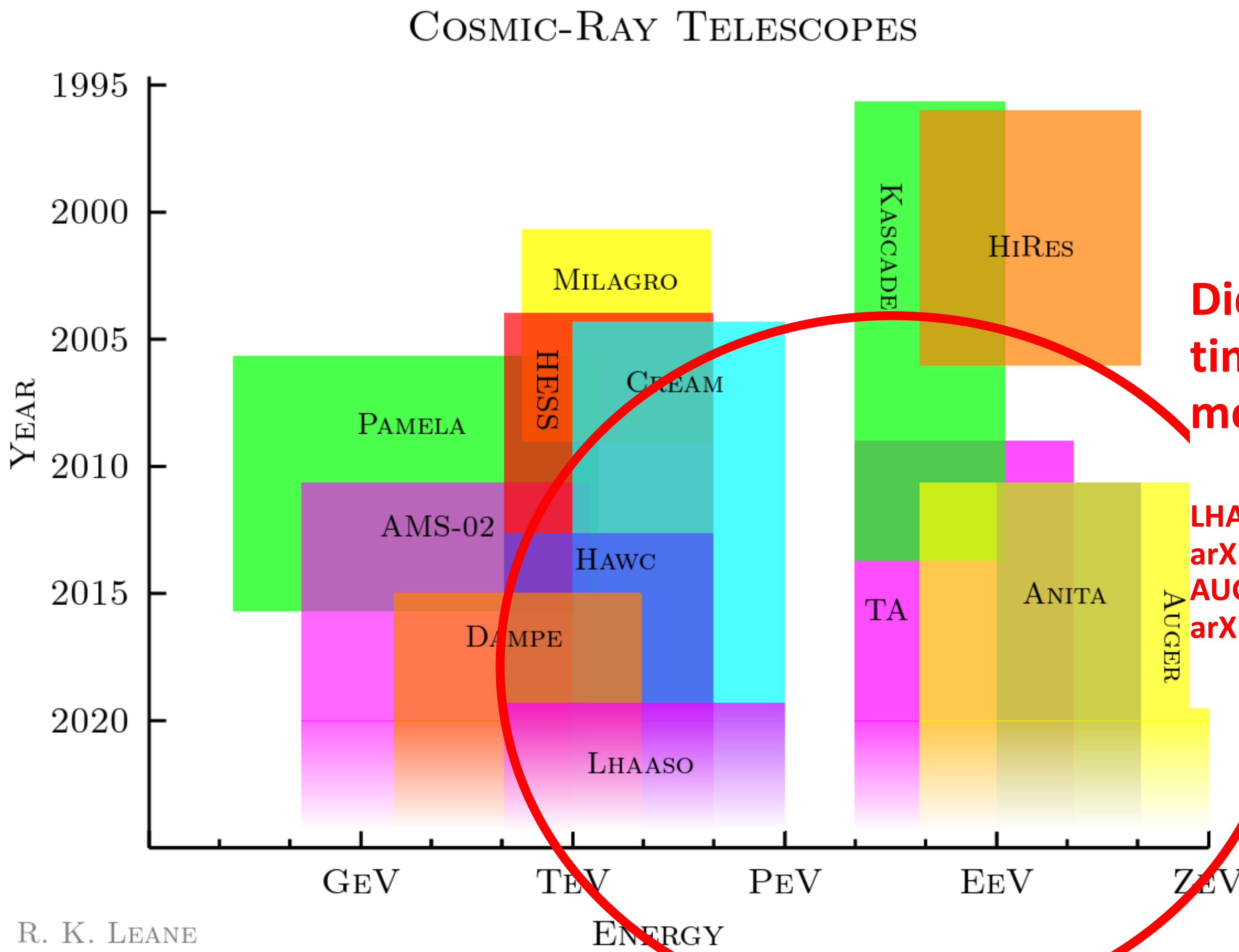


Boudaud+ A&A'14

Cosmic-ray detectors: past-present-future



Cosmic-ray detectors: past-present-future

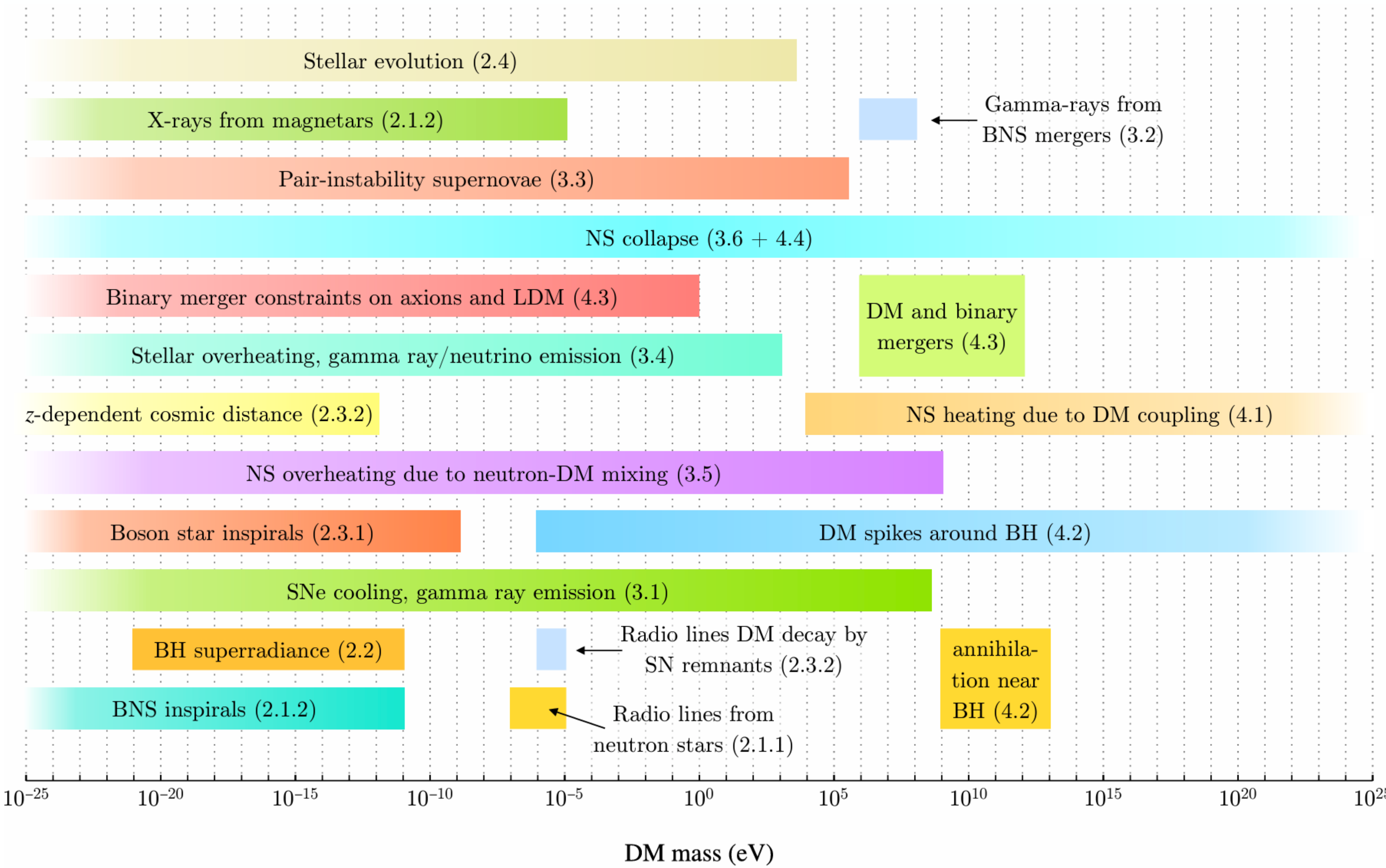


Didn't have time to mention!

LHAASO: arXiv:2210.15989
AUGER: arXiv:2203.08854

Other new interesting things I didn't mention

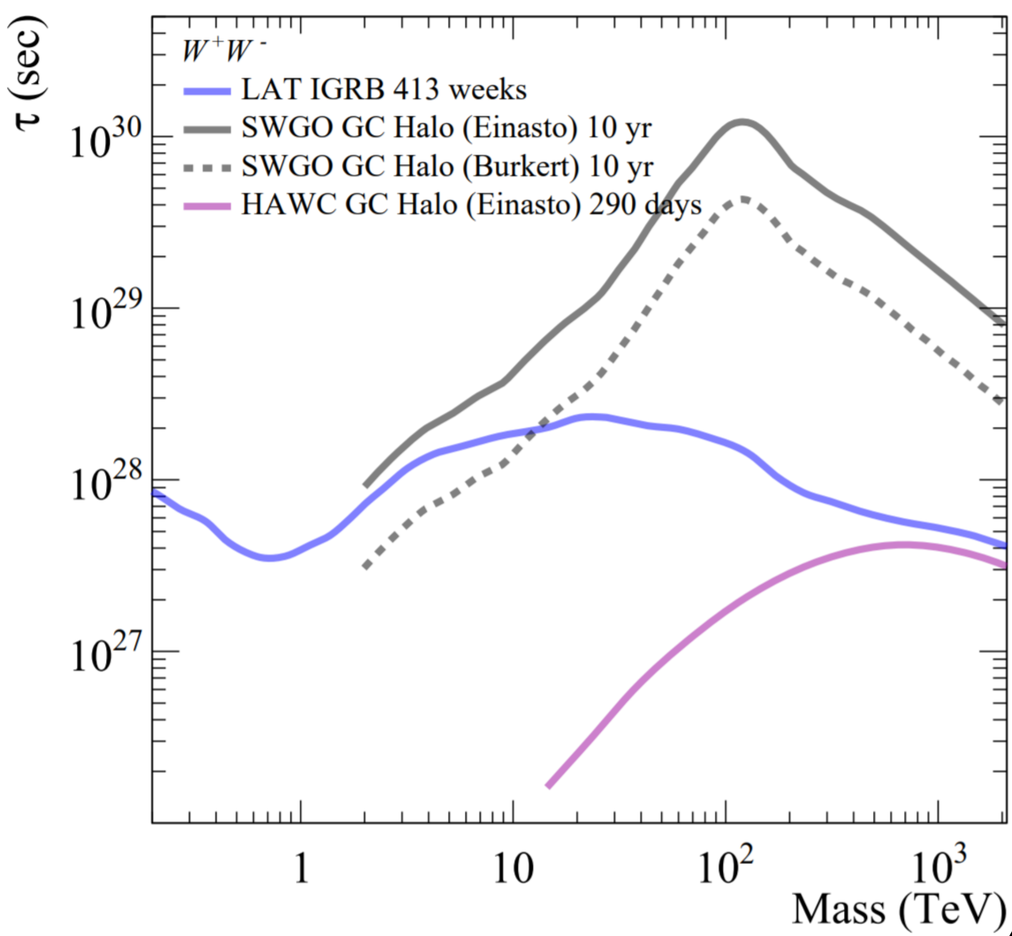
Dark Matter In Extreme Astrophysical Environments: arXiv:2203.07984



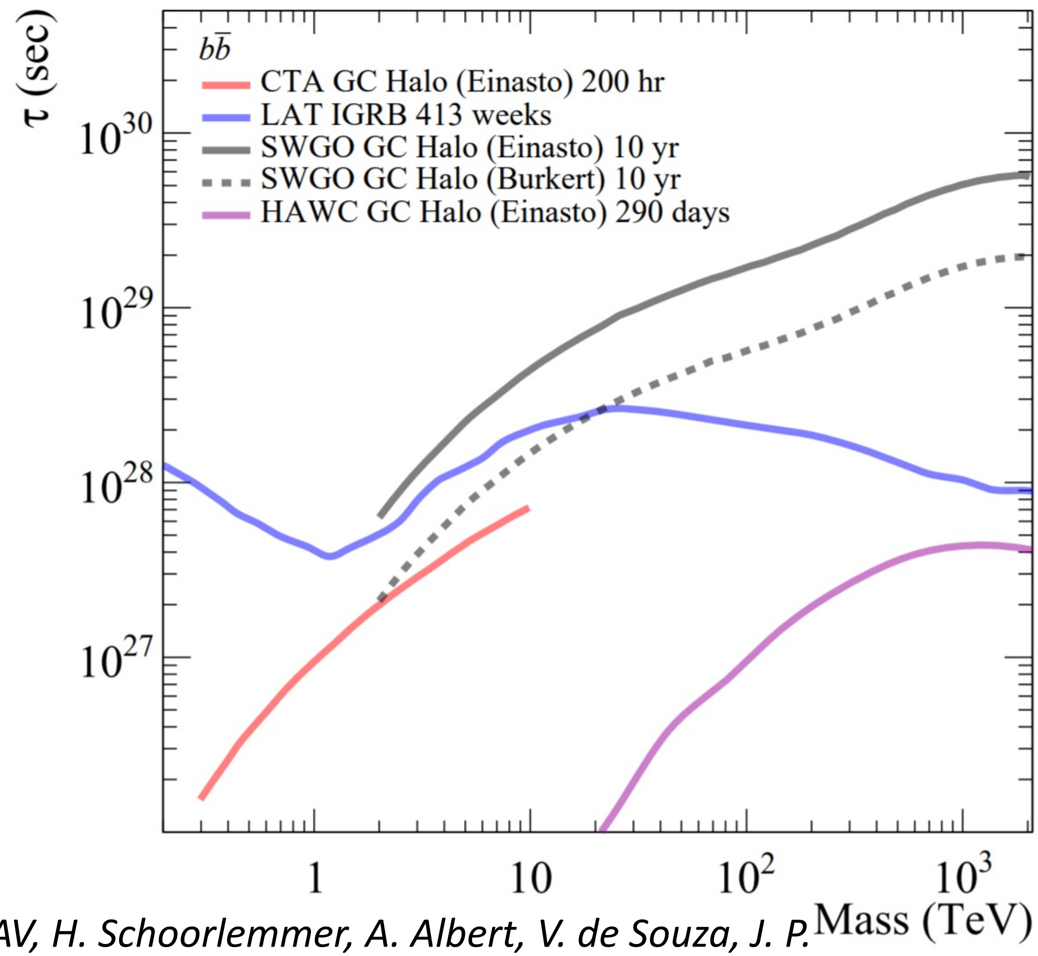
Thank you!

GC halo: DM decay sensitivity

W^+W^- channel



$b\bar{b}$ channel



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

- 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

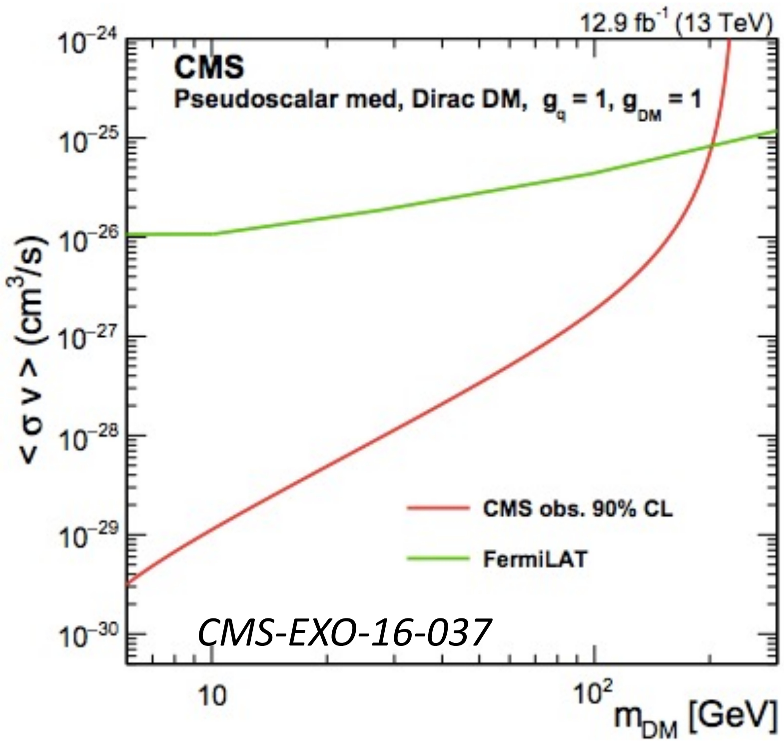
Complementarity to direct detection and accelerators

- Particle model dependent: in Simplified DM models it depends on the mediators
- Indirect detection is most sensitive for pseudo-scalar DM at >200 GeV
- **For a complete understanding of the nature of dark matter these different techniques are complementary and essential**

Table: Summary of suppression effects

OPERATOR	ID	DD
SCALAR	v^2	1
PSEUDO SCALAR	1	$(\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})$
VECTOR	1	1
AXIAL VECTOR	m_q^2, v^2	$\vec{s}_\chi \cdot \vec{s}_N$

M. Meyer



CMS-EXO-16-037