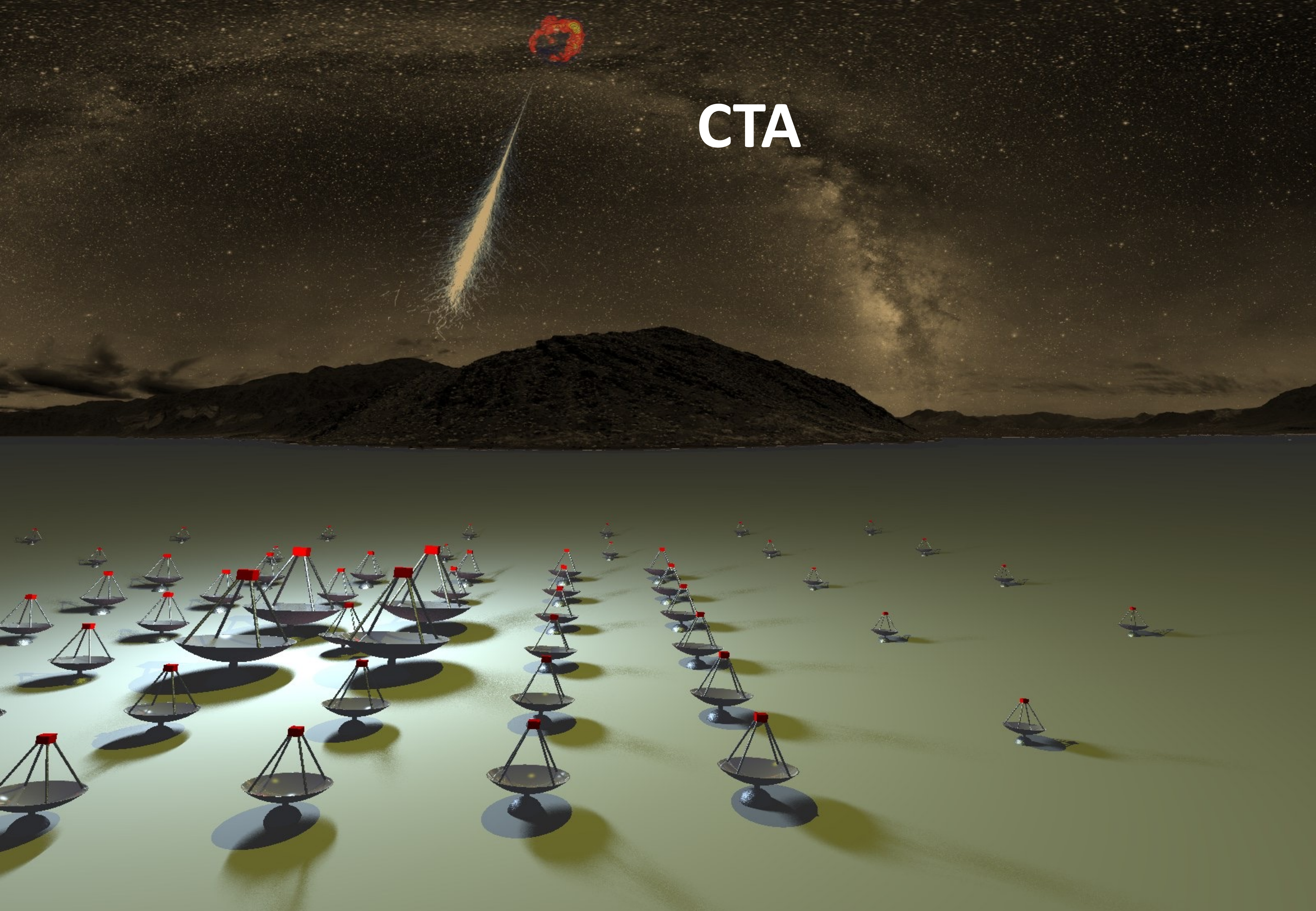
Search for dark matter with IACTs and the Cherenkov Telescope Array

Aldo Morselli

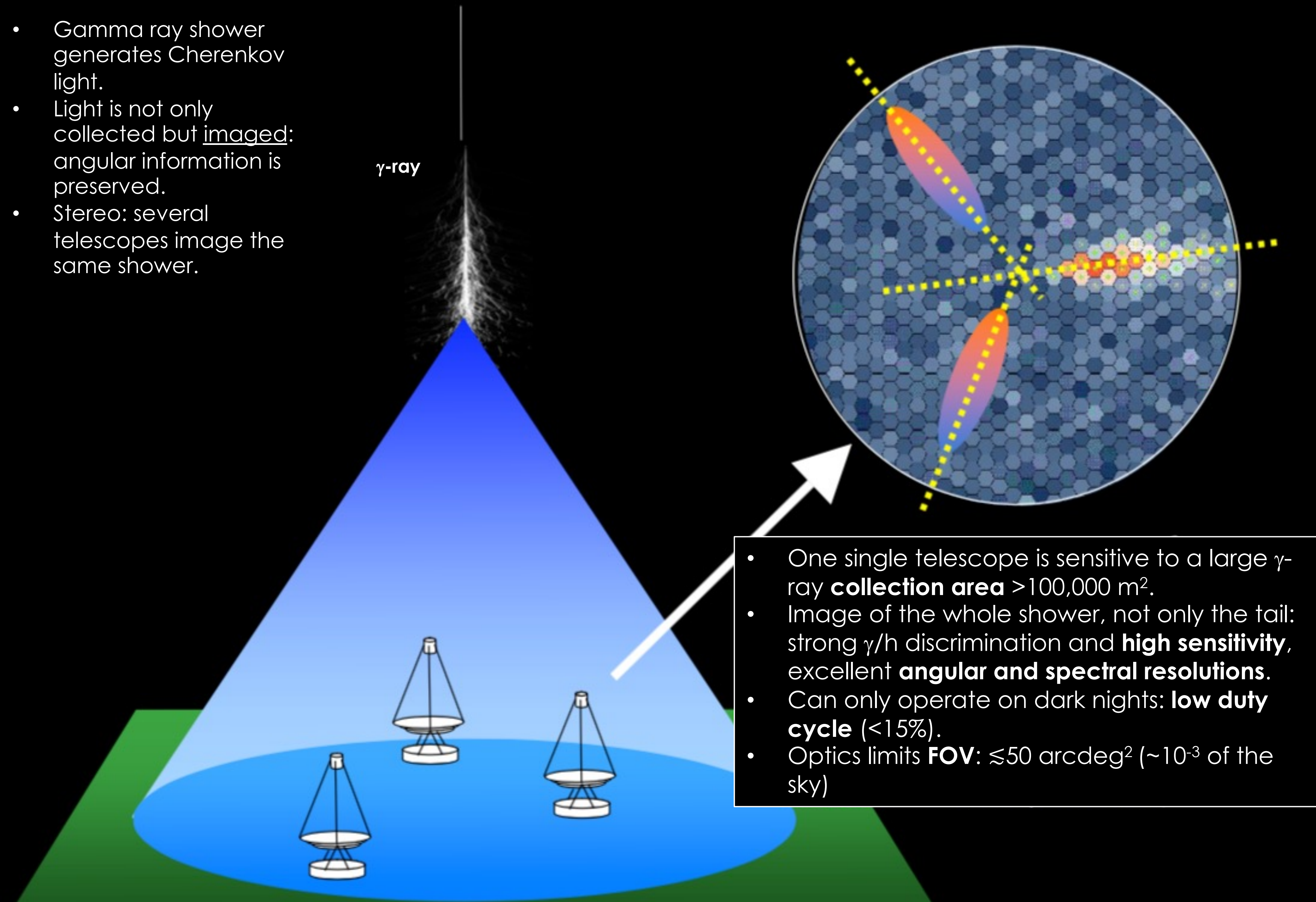
INFN Roma Tor Vergata

12th Cosmic Ray International Seminar - CRIS 2022

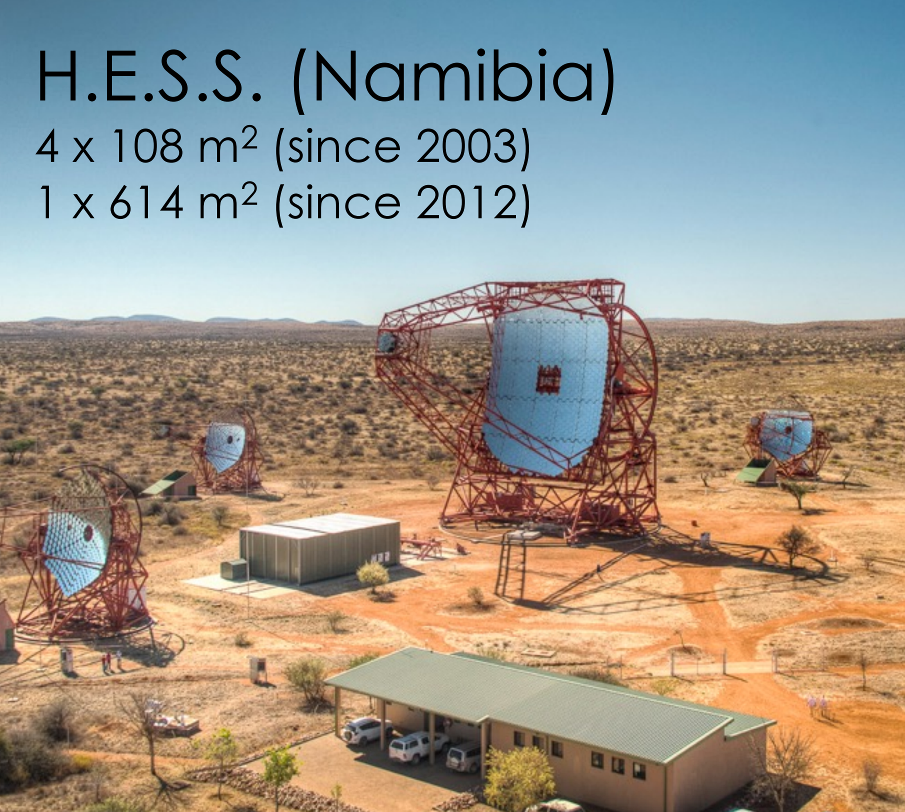
Napoli, 13 September 2022

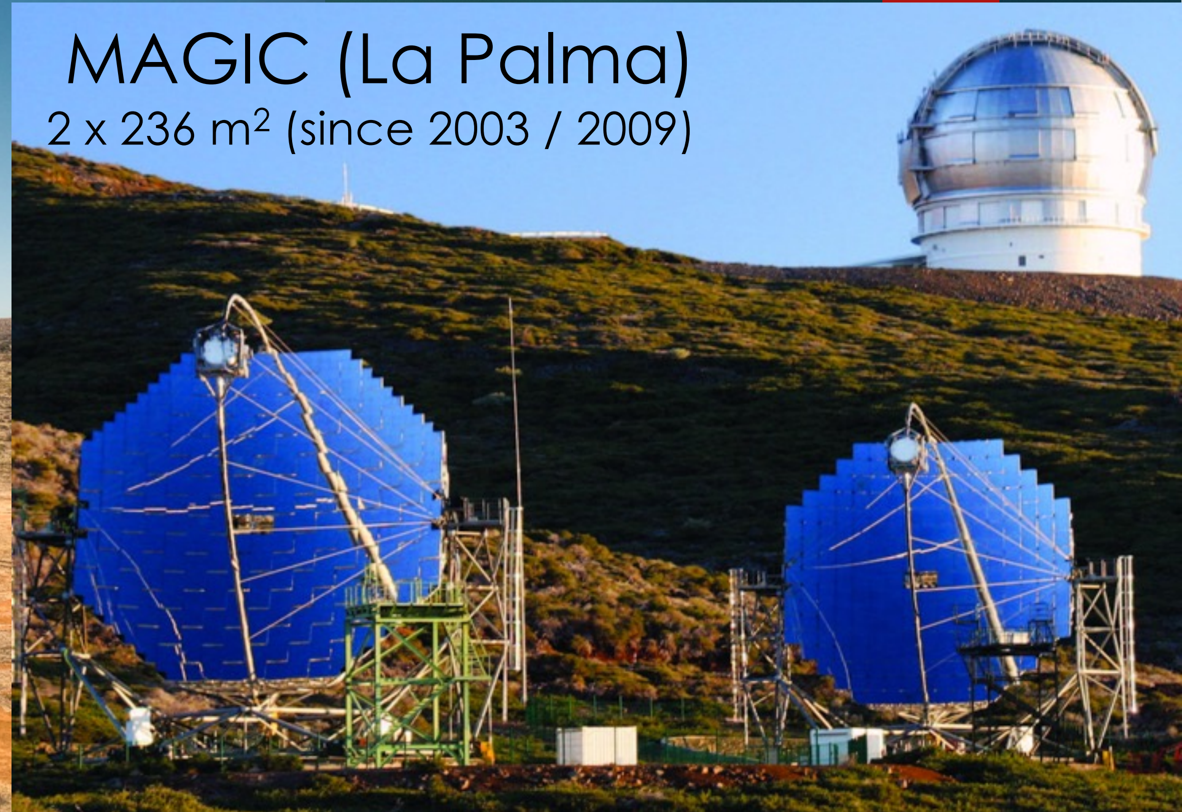

CTA

- Gamma ray shower generates Cherenkov light.
- Light is not only collected but <u>imaged</u>: angular information is preserved.
- Stereo: several telescopes image the same shower.



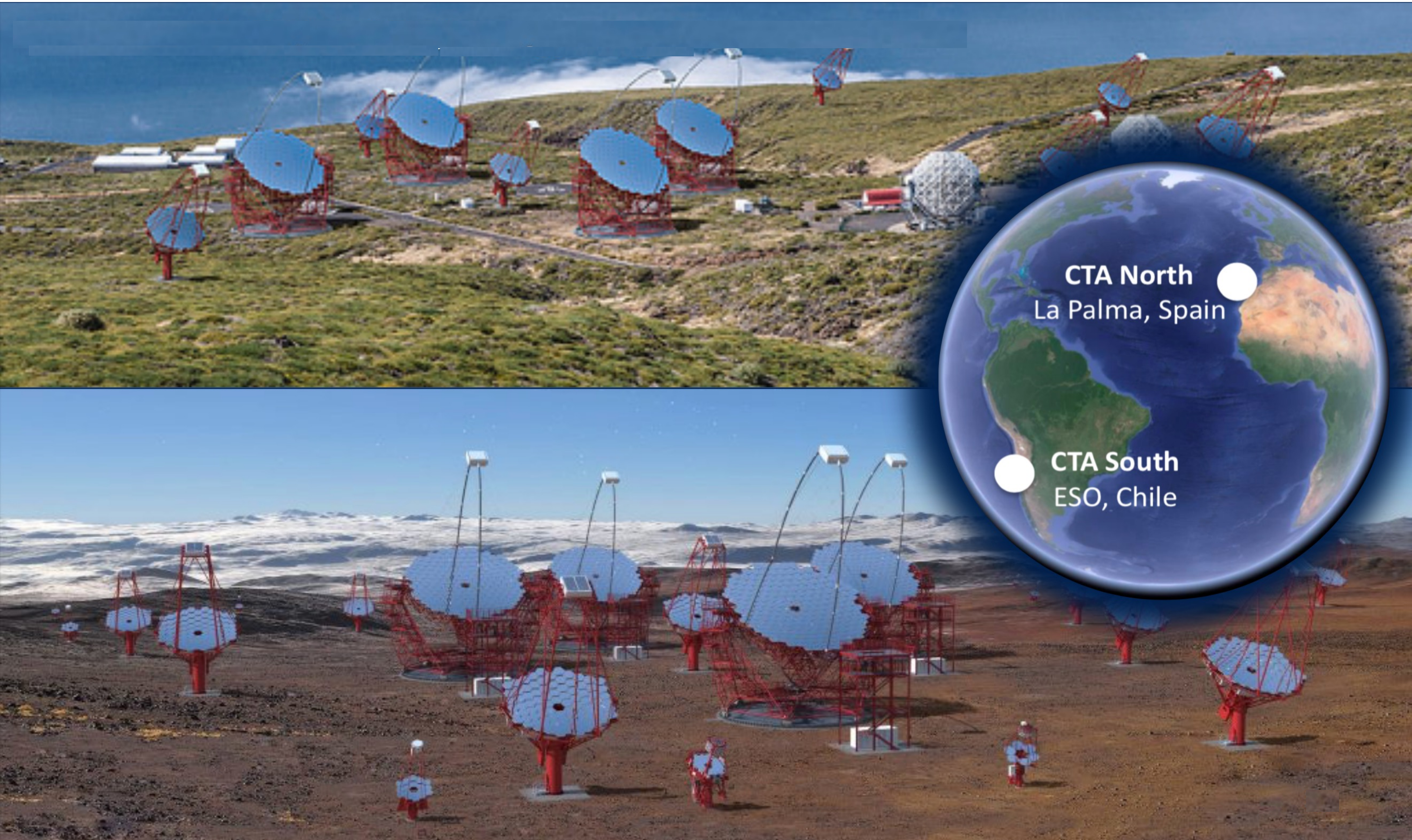
- One single telescope is sensitive to a large γ-ray **collection area** >100,000 m^2.
- Image of the whole shower, not only the tail: strong γ/h discrimination and **high sensitivity**, excellent **angular and spectral resolutions**.
- Can only operate on dark nights: **low duty cycle** (<15%).
- Optics limits **FOV**: ≲50 $arcdeg^2$ (~10^{-3} of the sky)

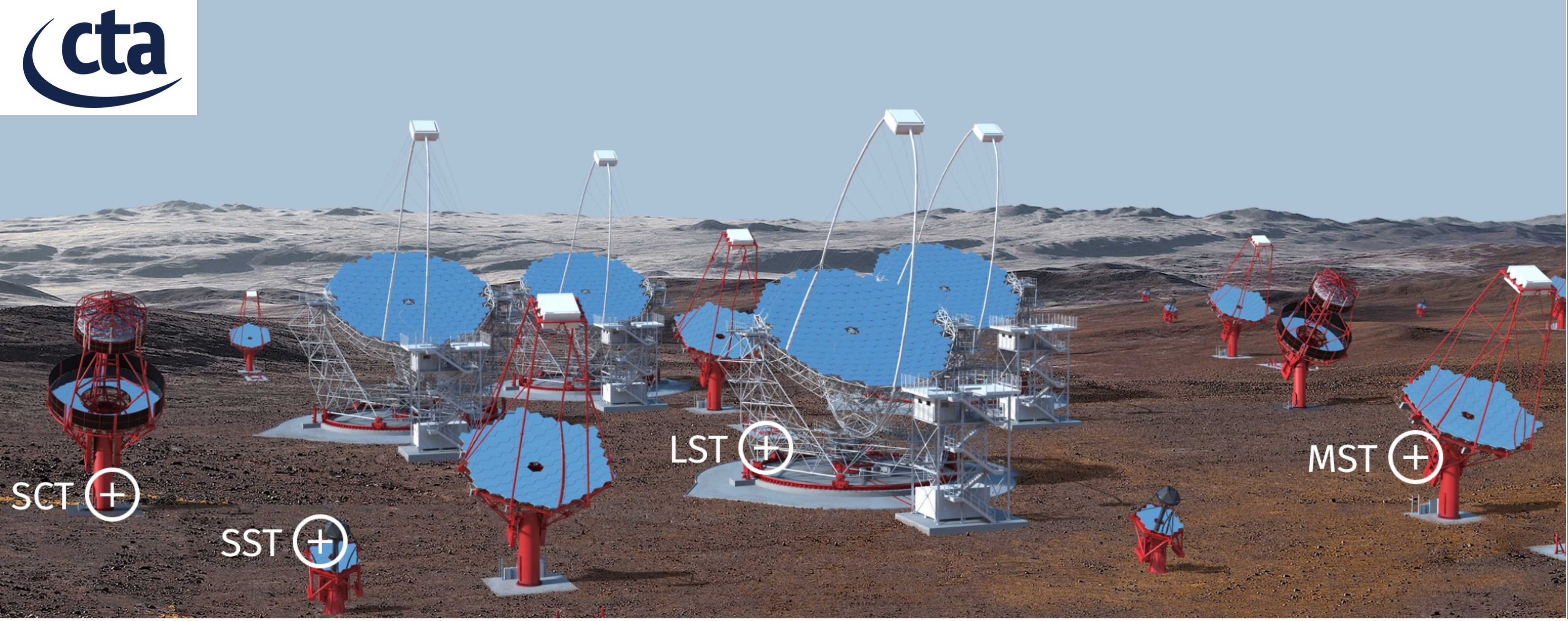

H.E.S.S. (Namibia)
4 x 108 m² (since 2003)
1 x 614 m² (since 2012)


MAGIC (La Palma)
2 x 236 m² (since 2003 / 2009)


VERITAS (Arizona)
4 x 110 m² (since 2007)

1 Observatory - 2 array sites





The Alpha Configuration

CTAO Northern Array

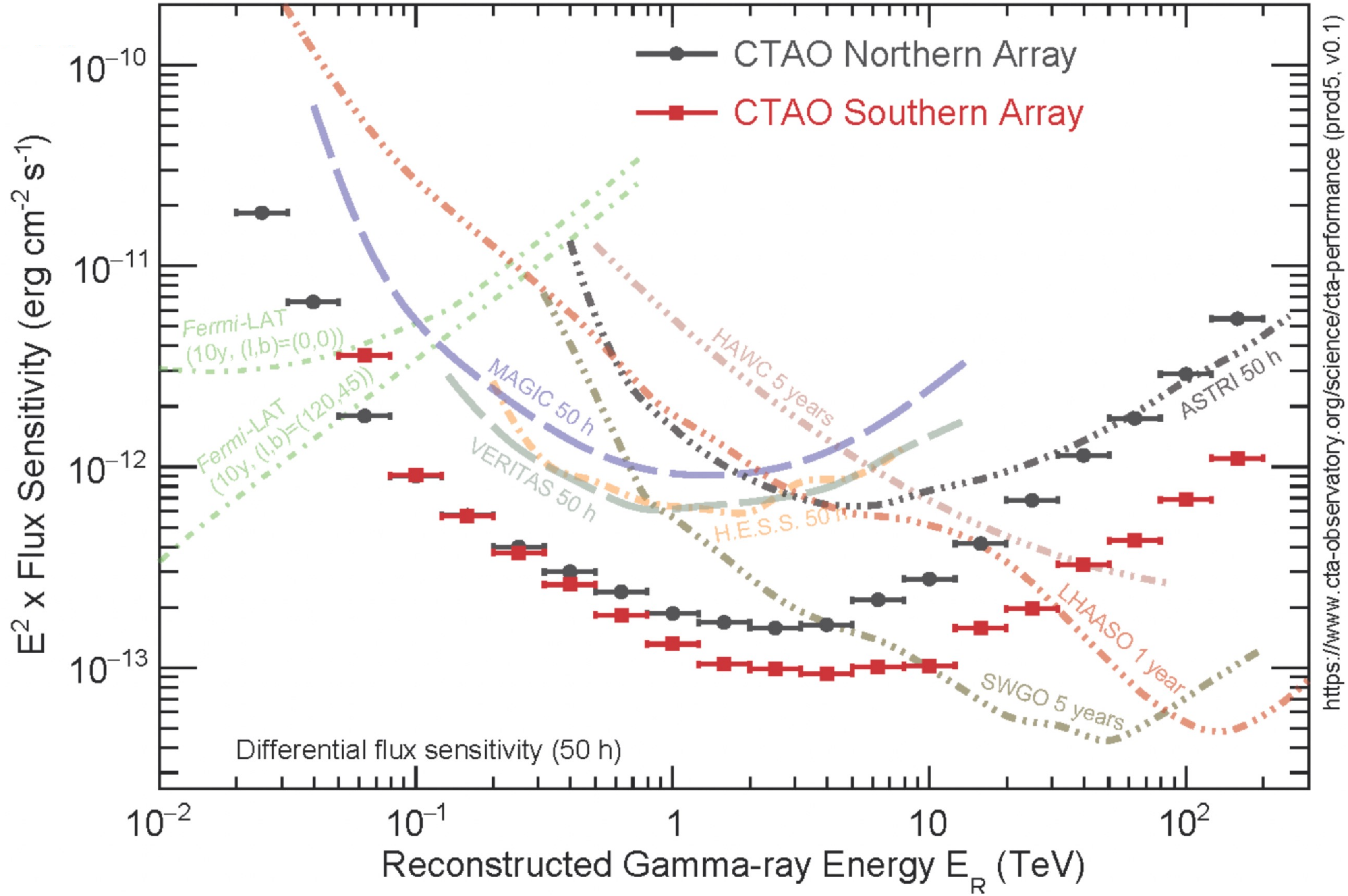
- **4 LSTs + 9 MSTs**
- 0,25 km² footprint
- focus on extra-Galactic science

CTAO Southern Array

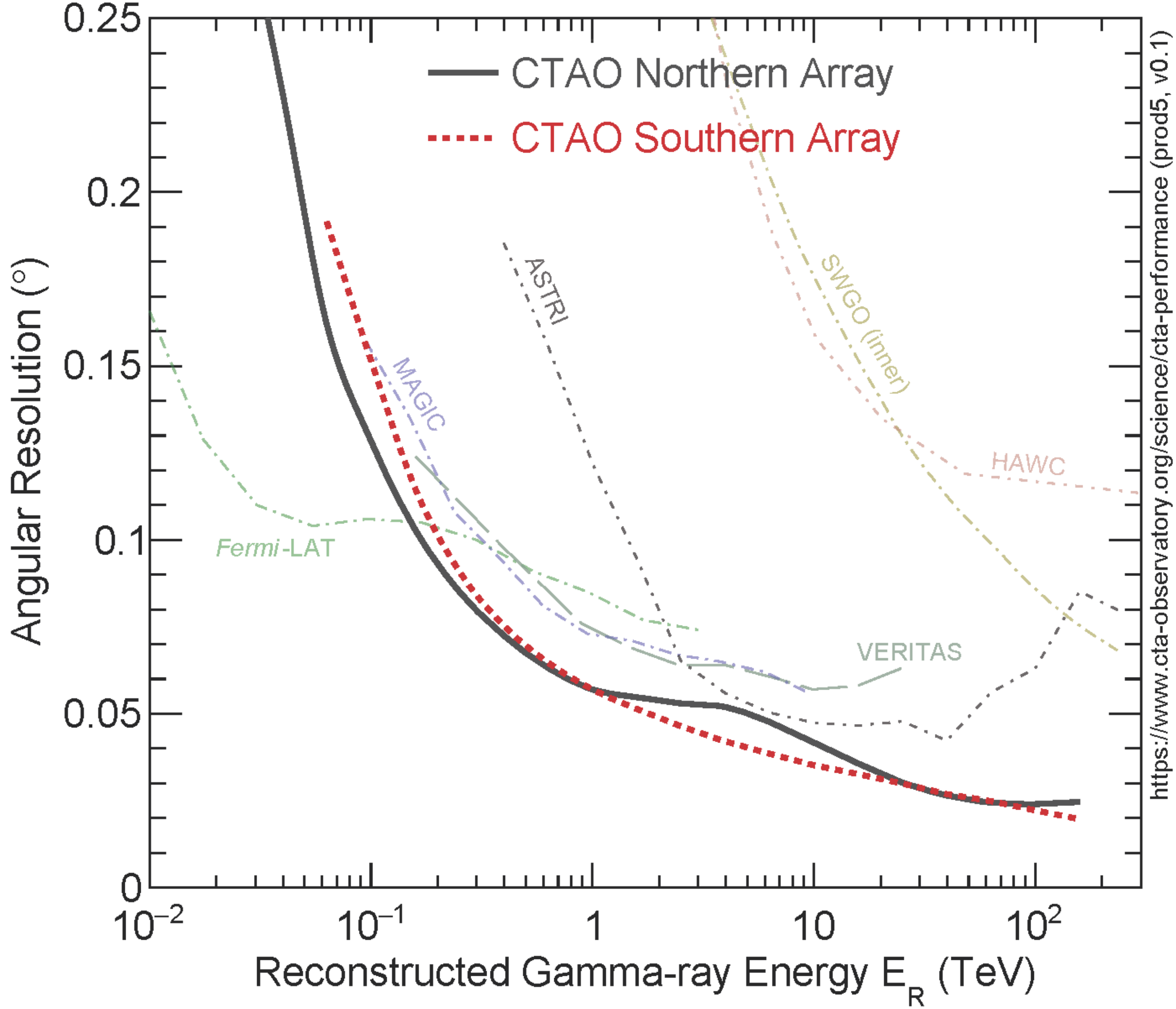
- **14 MSTs + 37 SSTs**
- 3 km² footprint
- focus on Galactic science

and a good news: INAF+INFN have secured funding for 2 LST in the South

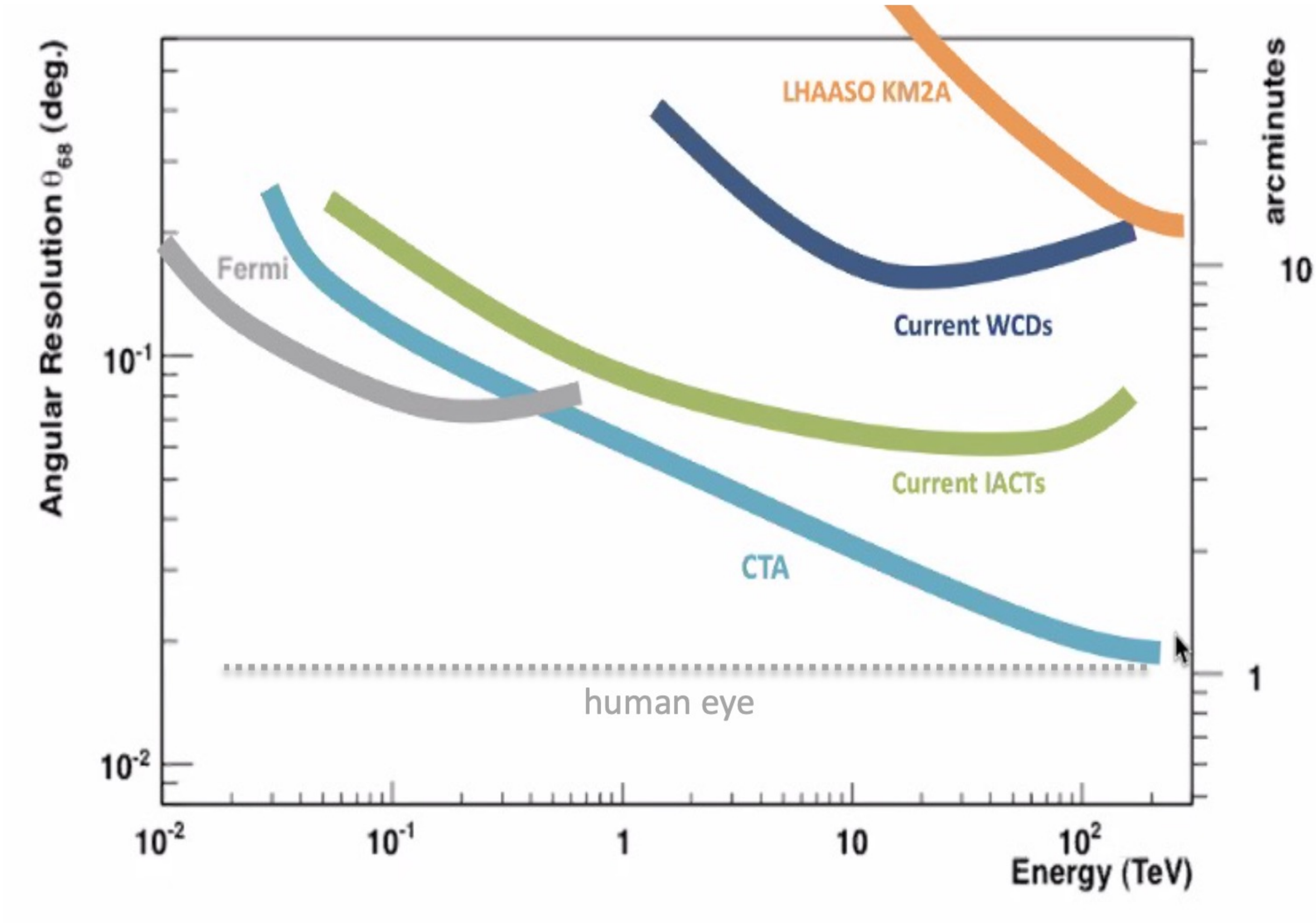
(more detailed) γ-ray detectors sensitivities



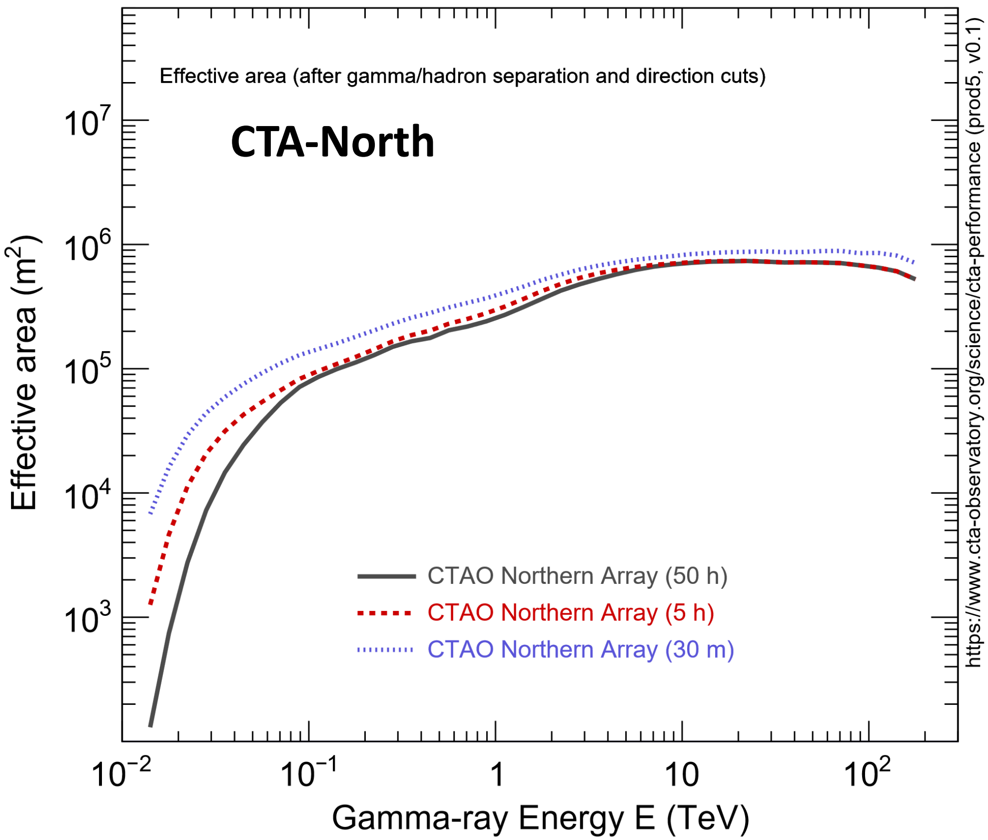
Angular resolution

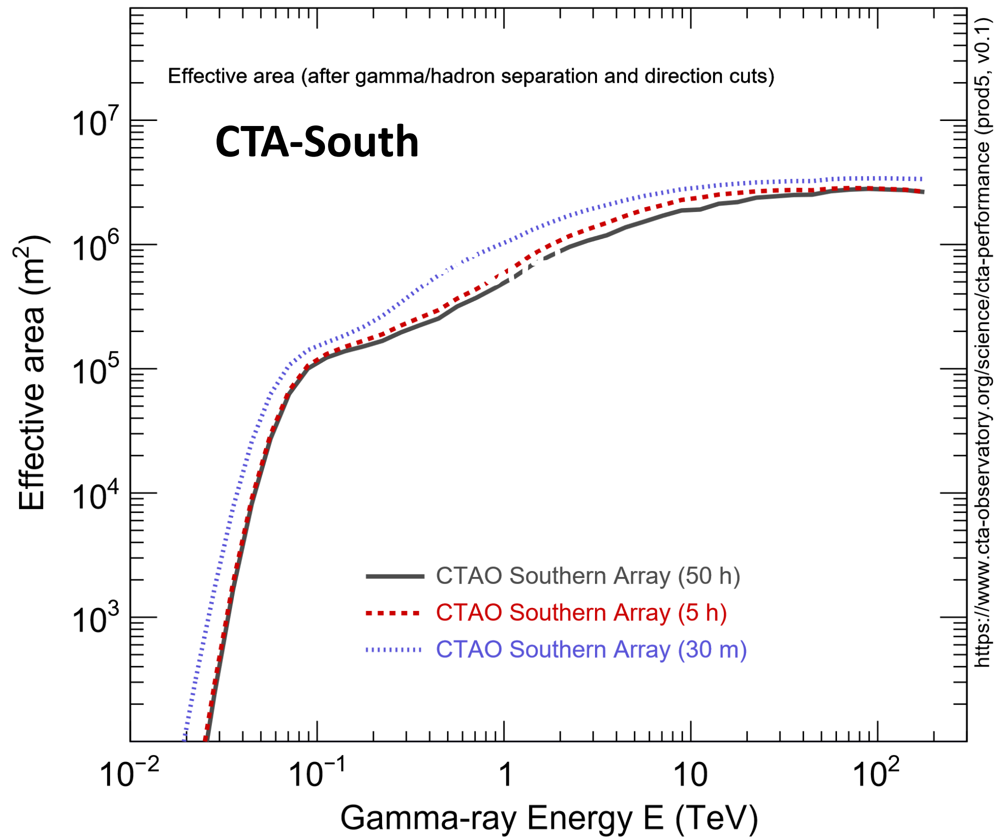


Angular resolution

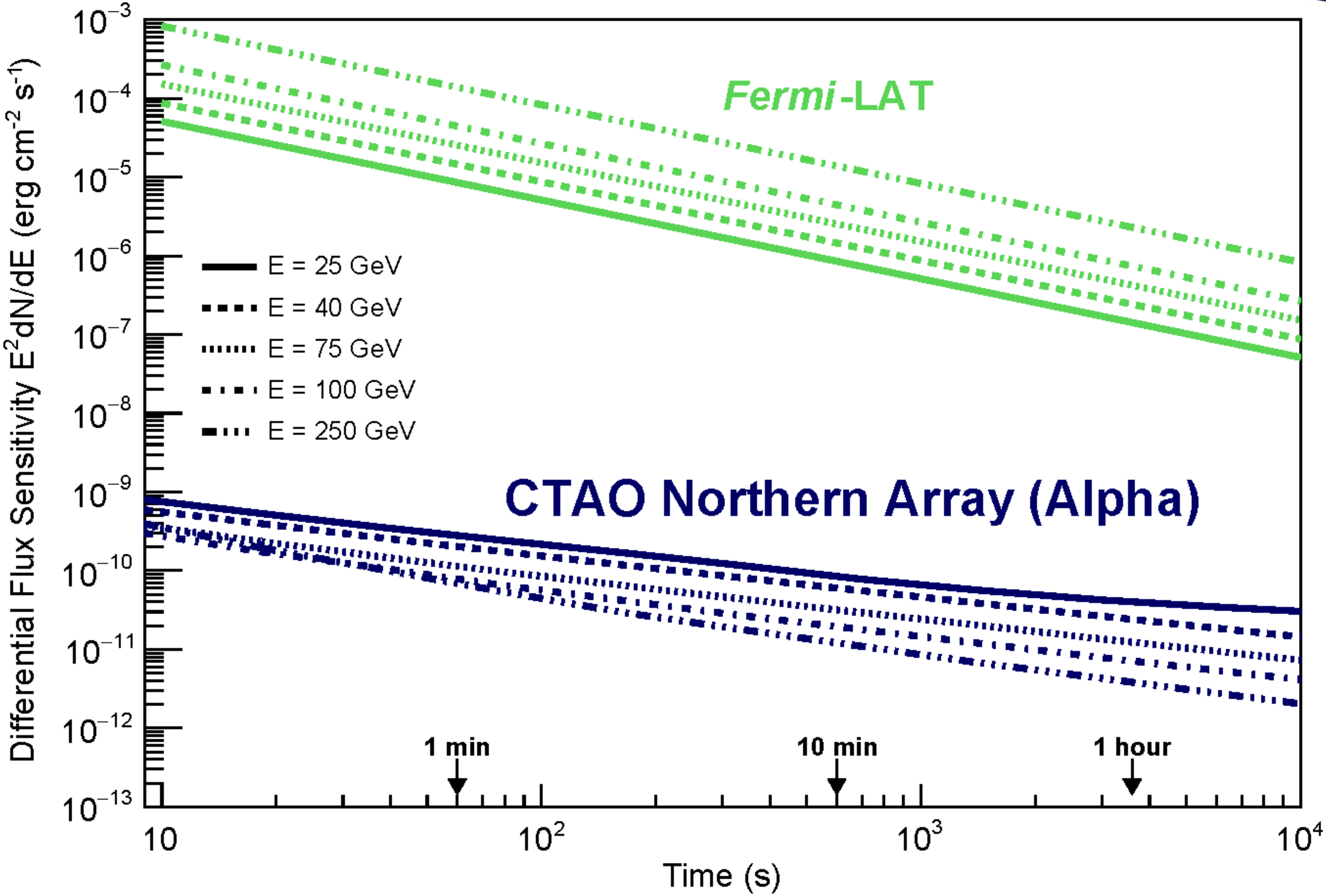


Collection areas





Sensitivity for short observations



CTA LST Status   talk by Federico Di Pierro

CTA pSCT Status talk by Francesca Romana Pantaleo

The Science of CTA

CTA will target major science questions in high-energy astrophysics, through a large observational programme.

Sky Surveys

- Galactic and X-Gal Scan
- Dark Matter Programme
- Magellanic Clouds

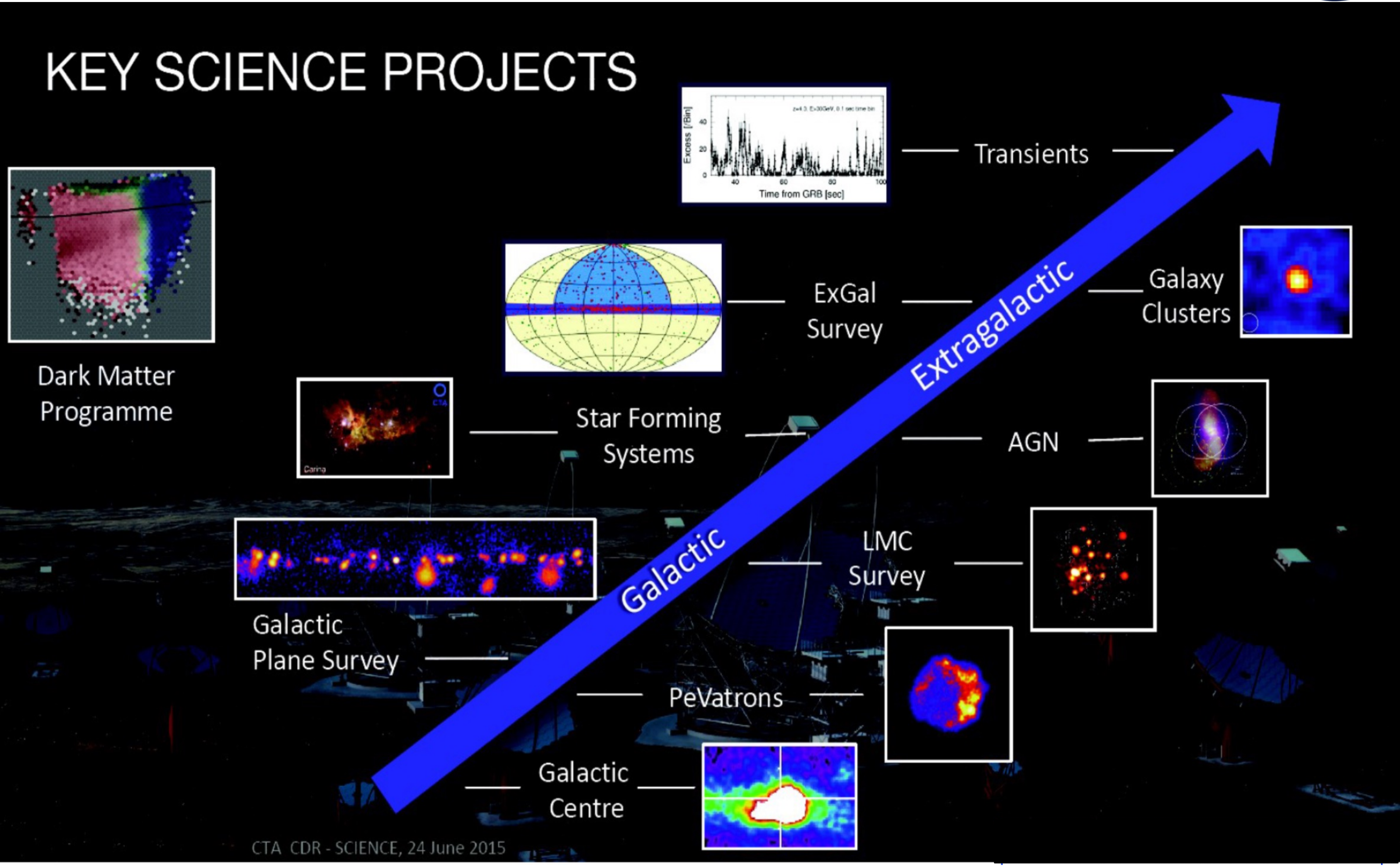
Deep Targeted Observations

- PeVatrons
- Star-forming Systems
- Radio Galaxies & Clusters

Follow-ups of Transient and Multi-messenger events

Monitoring of Variability notably of AGN

A Census of particle accelerators across all cosmic scales



Key Science Project Targets related to Dark Matter search

- Galactic Center

high DM density but high astrophysical emissions

- Dwarf Spheroidal Galaxies (dSph)

no background but low signal

- LMC

neaby & massive but astrophysical emissions

- galaxy cluster

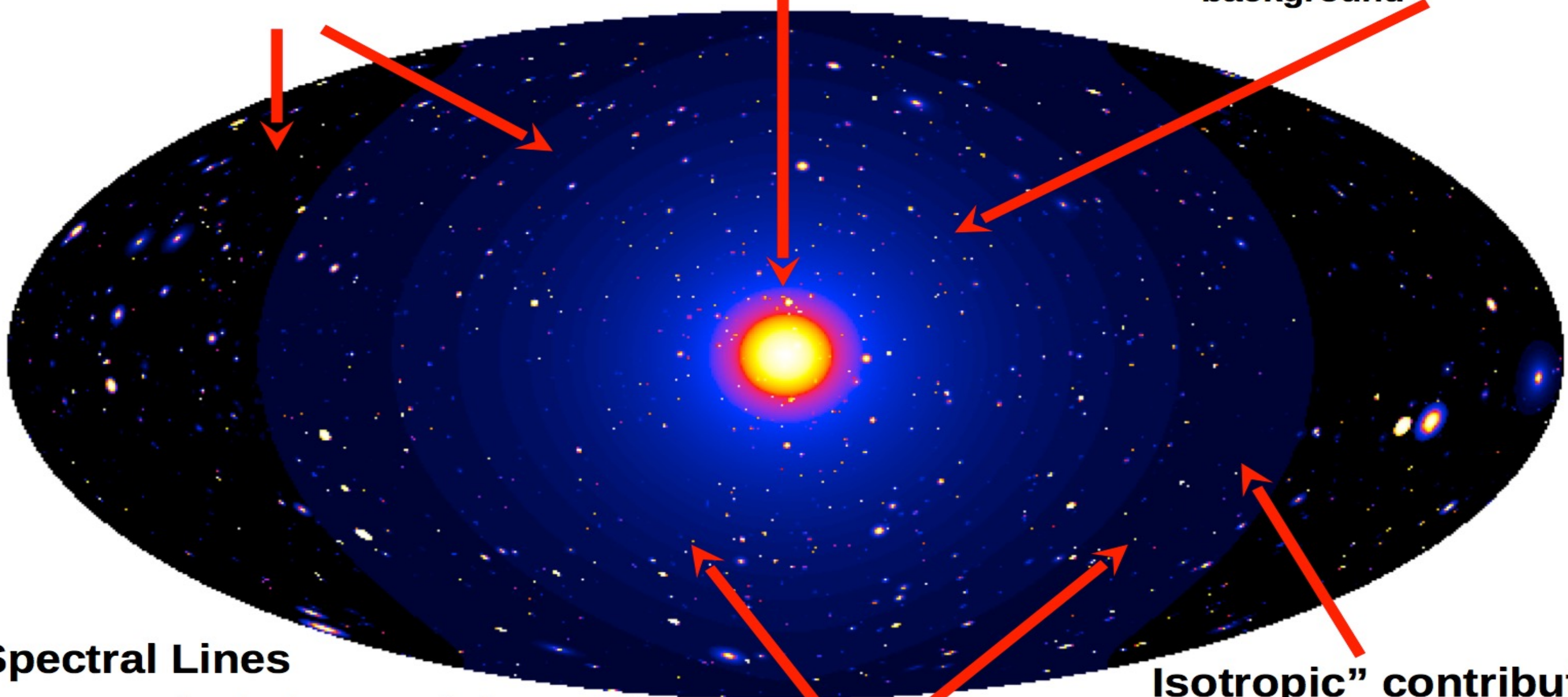
very massive (best for decay)

Dark Matter Search: Targets and Strategies

Satellites
Low background and good source id, but low statistics

Galactic Center
Good Statistics, but source confusion/diffuse background

Milky Way Halo
Large statistics, but diffuse background



Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

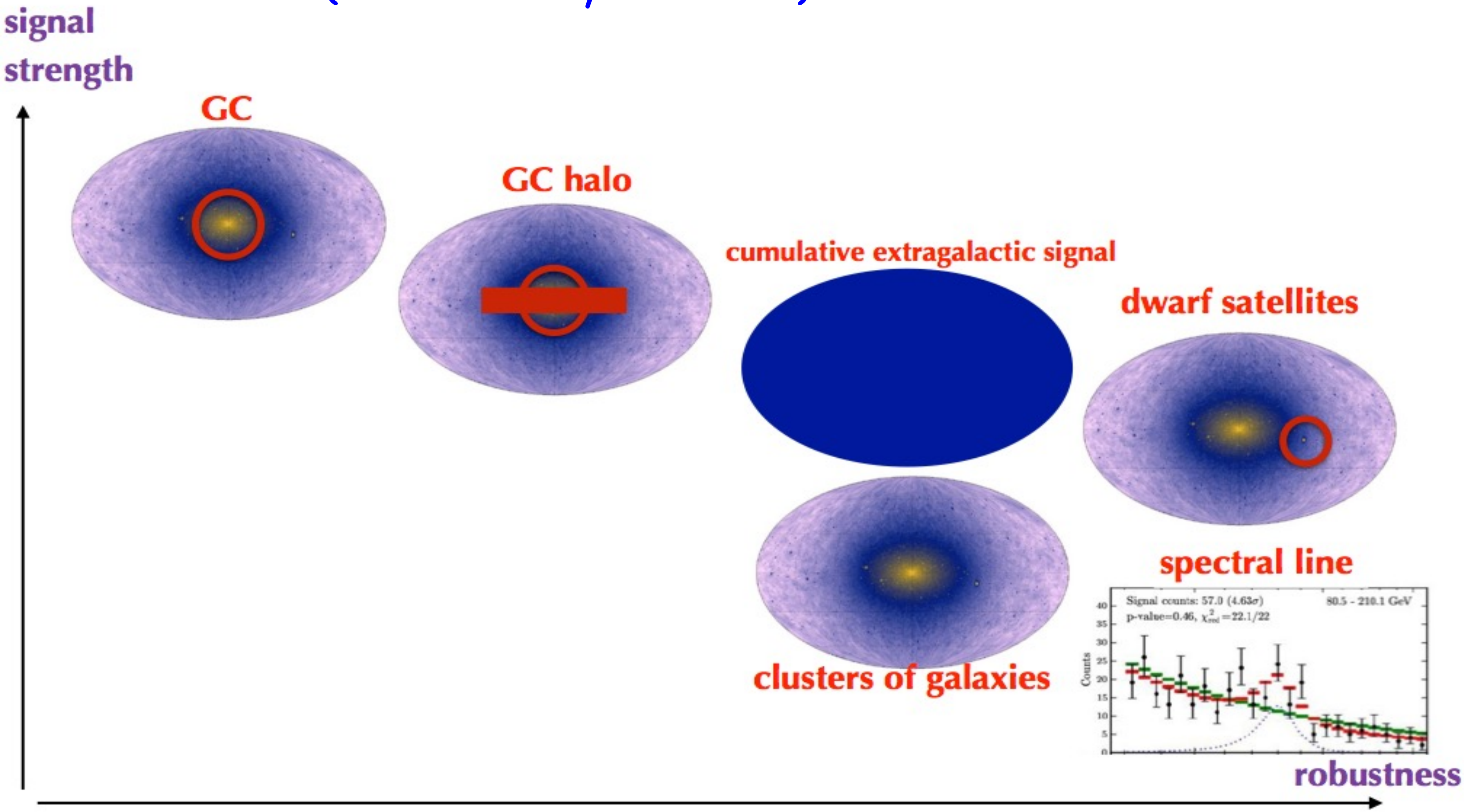
Galaxy Clusters
Low background, but low statistics

Isotropic" contributions
Large statistics, but astrophysics, galactic diffuse background

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

Dark Matter Search: Targets and Strategies

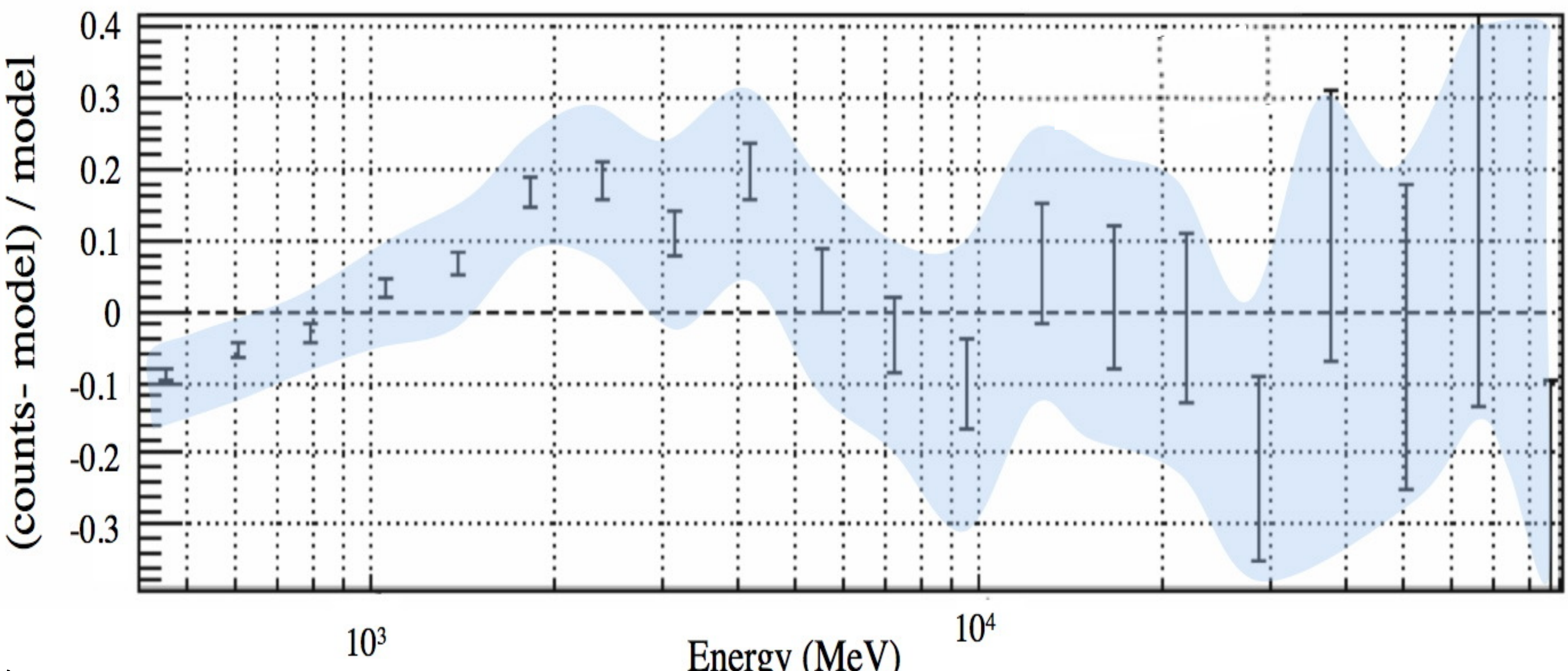
(Another way to see it)



The GeV excess 7° x7° region centered on the Galactic Center

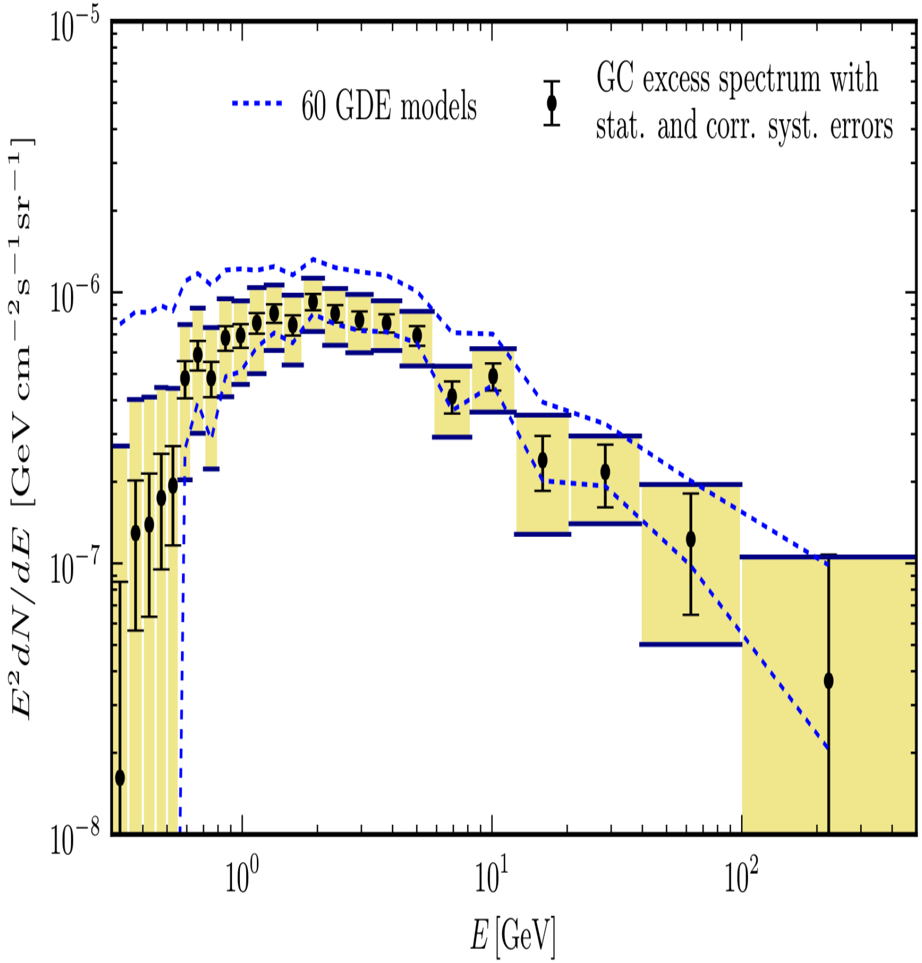
11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

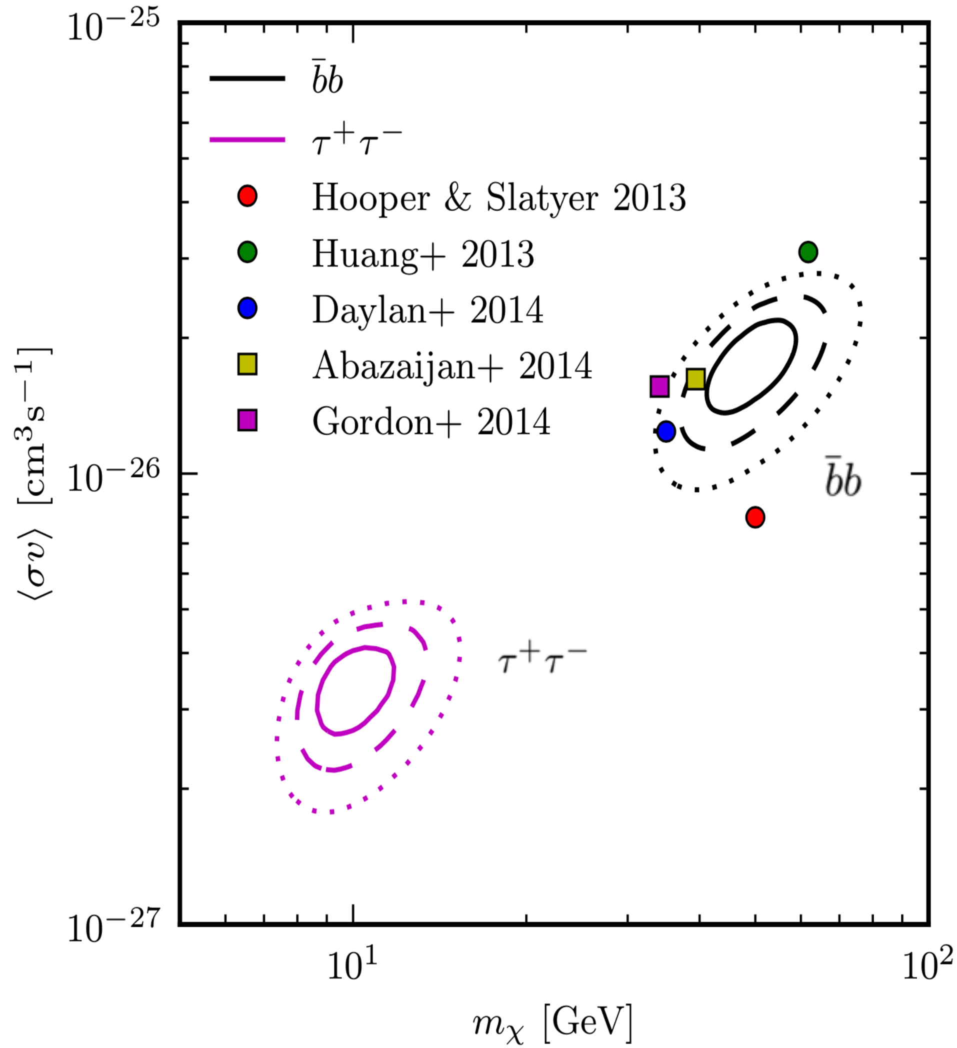
- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV



V.Vitale, A.Morselli, Fermi Coll. 2009 arXiv:0912.3828 Fermi Symposium eConf Proceedings C091122

The GeV excess

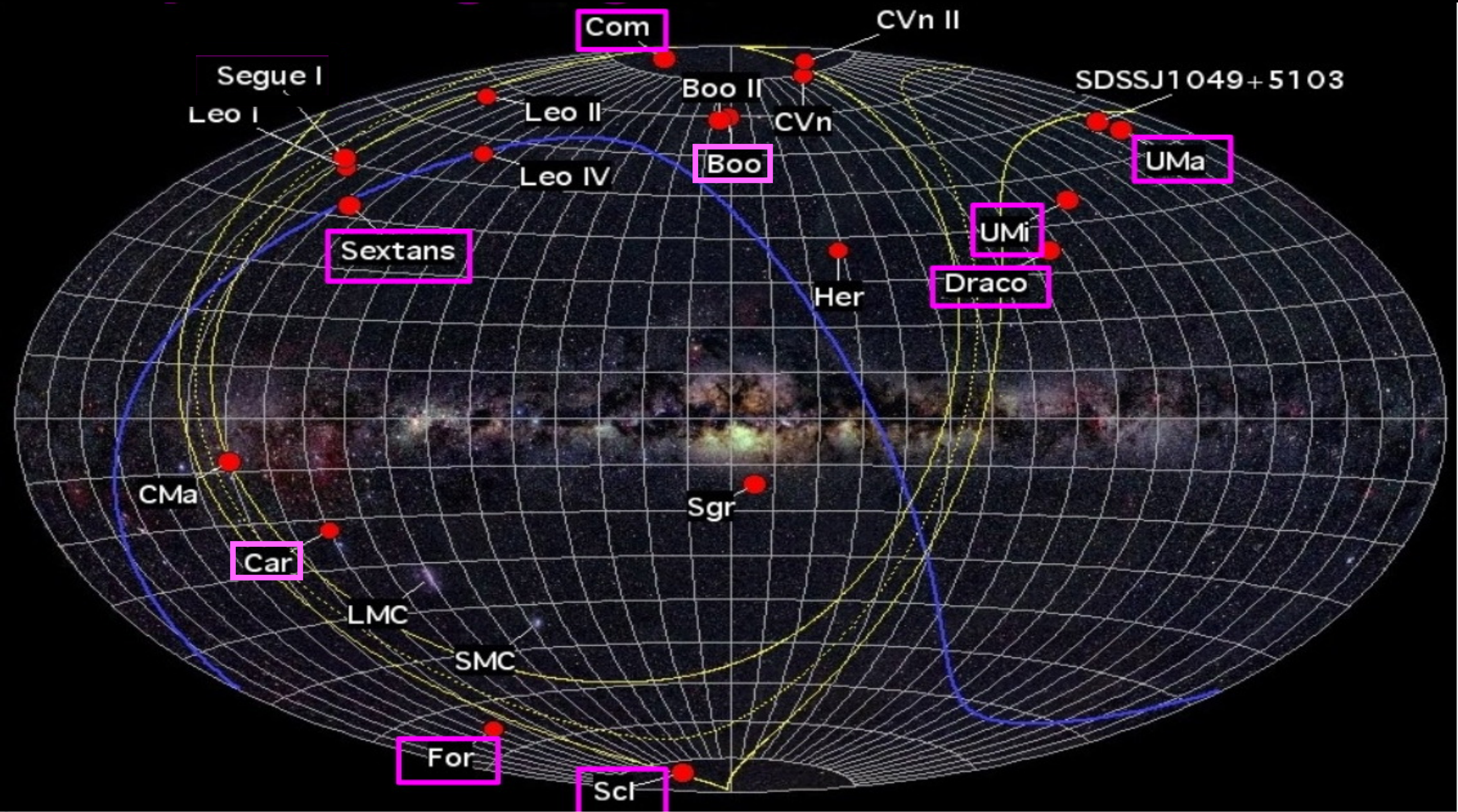




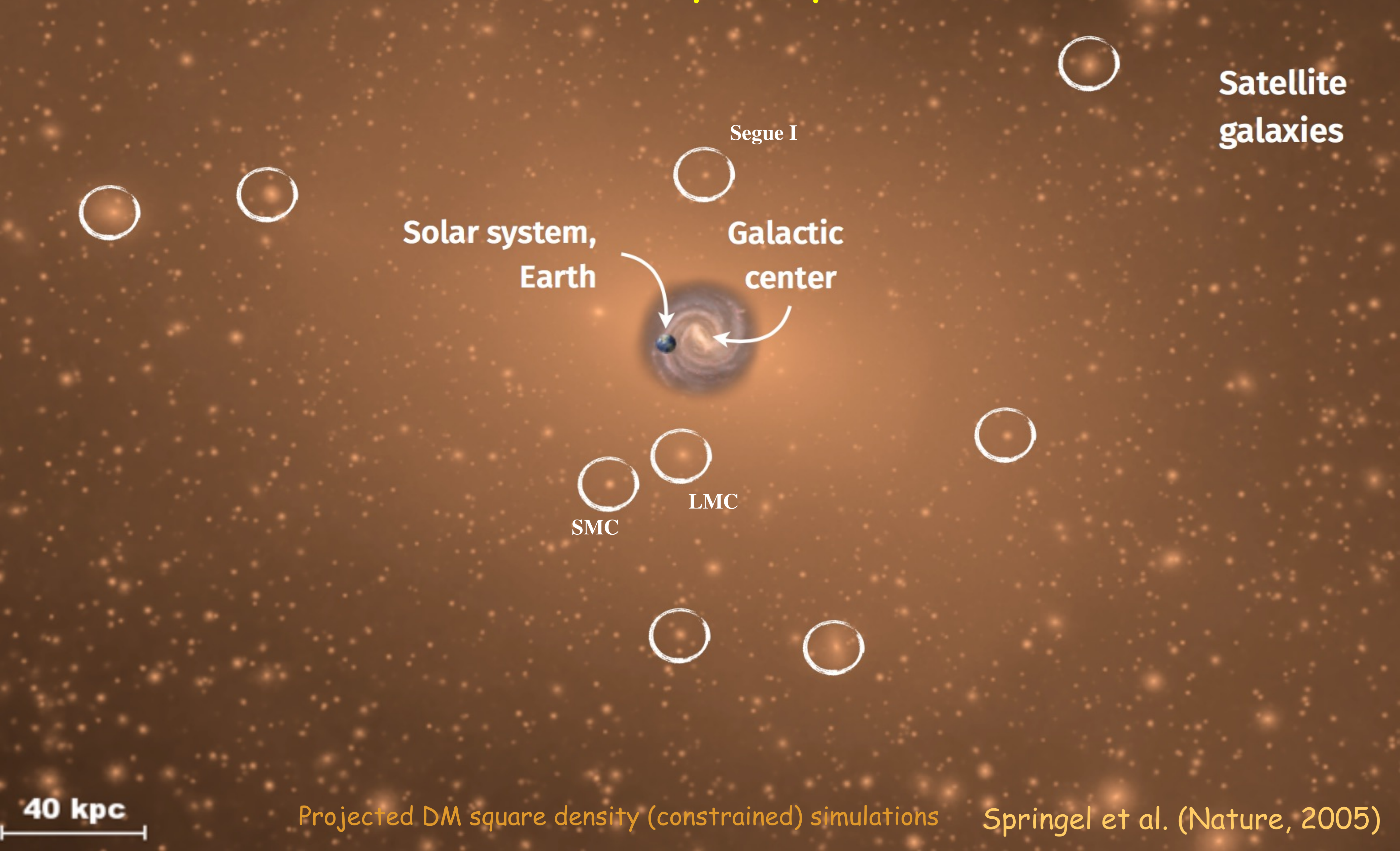
A lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center

Calore et al, arXiv:1409.0042v1

Classical Dwarf spheroidal galaxies: promising targets for DM detection

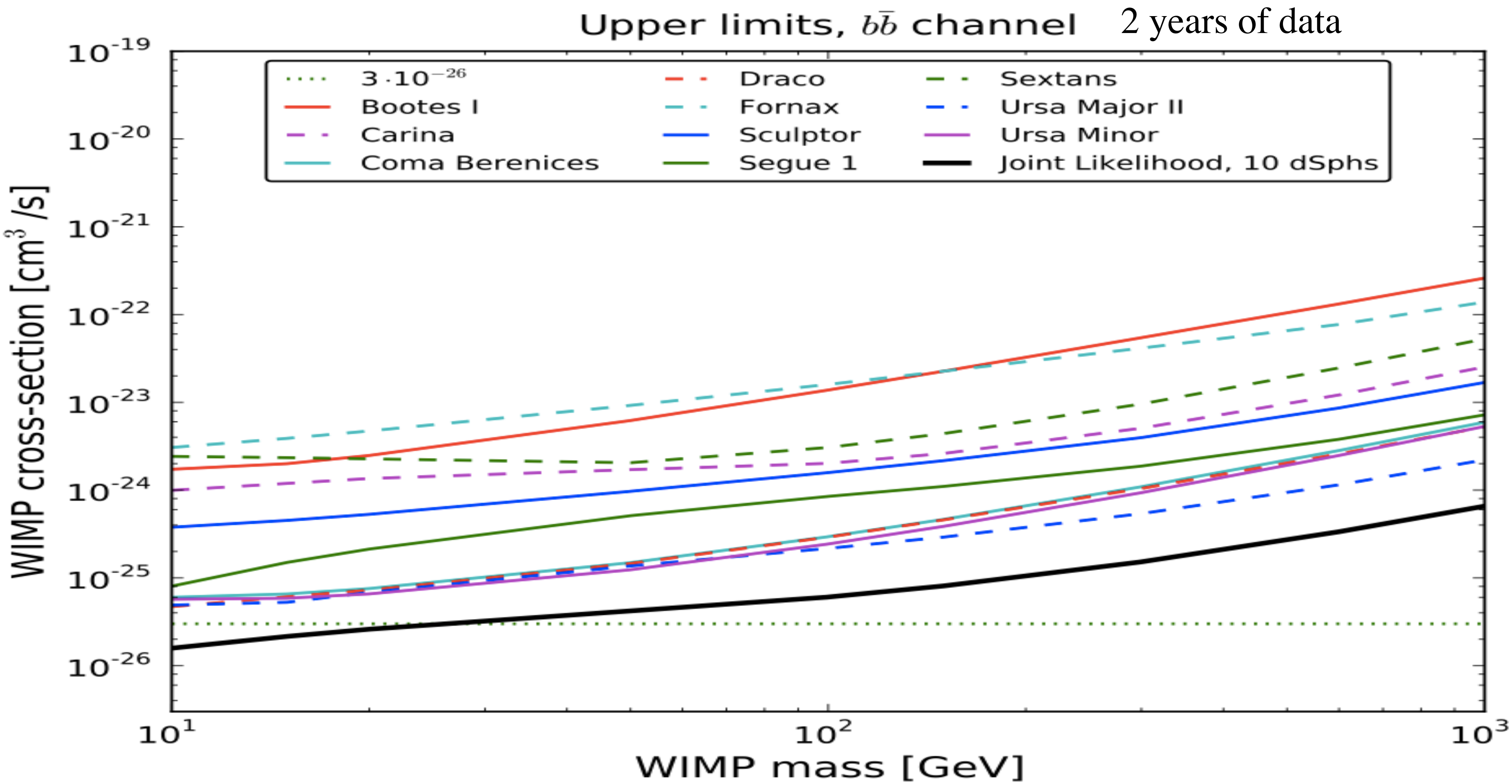


Dark Matter in the Milky Way (from simulations)



Springel et al. (Nature, 2005)

Fermi LAT Dwarf Spheroidal Galaxies combined analysis

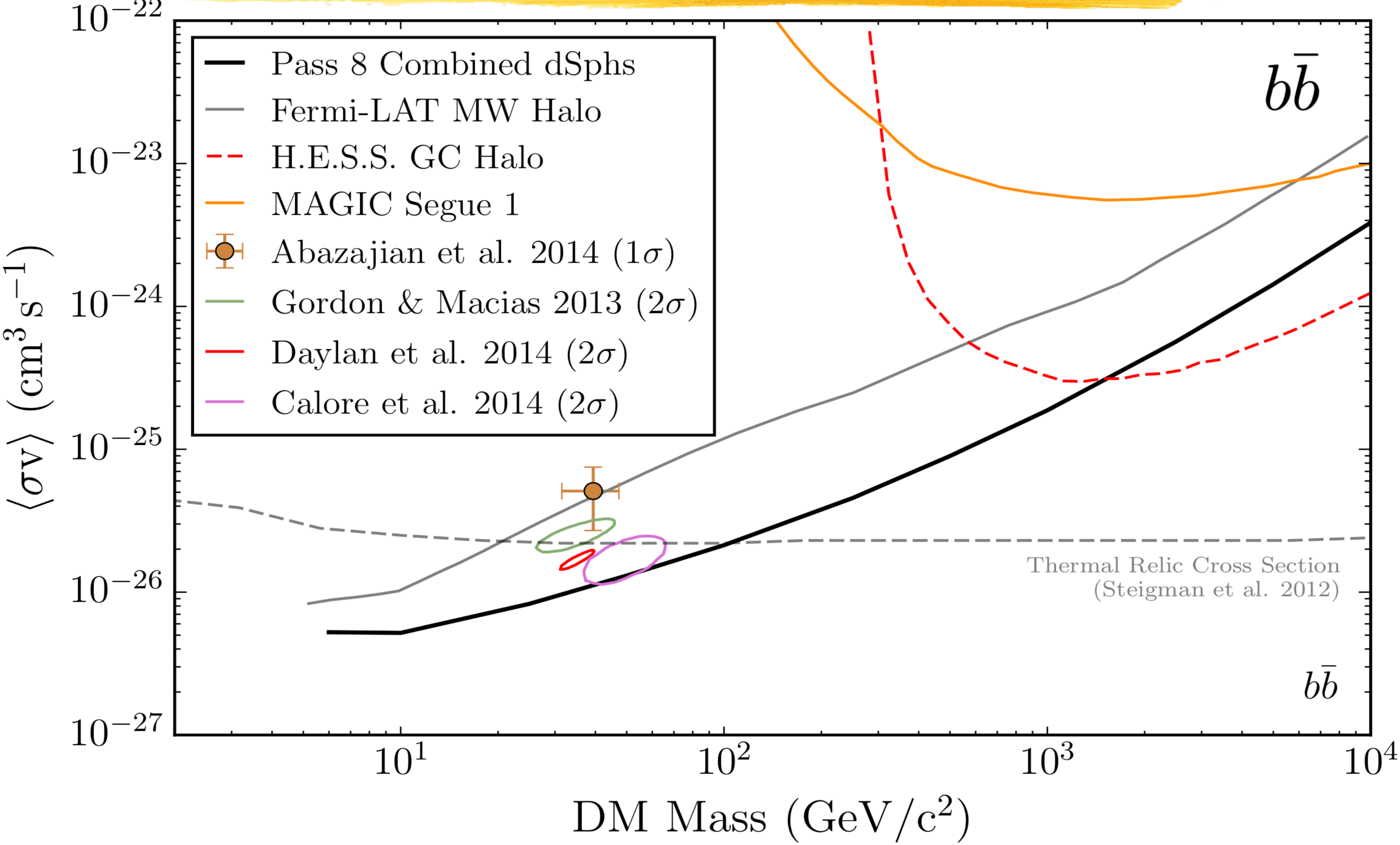


robust constraints including J-factor uncertainties from the stellar data statistical analysis

NFW. For cored dark matter profile, the J-factors for most of the dSphs would either increase or not change much

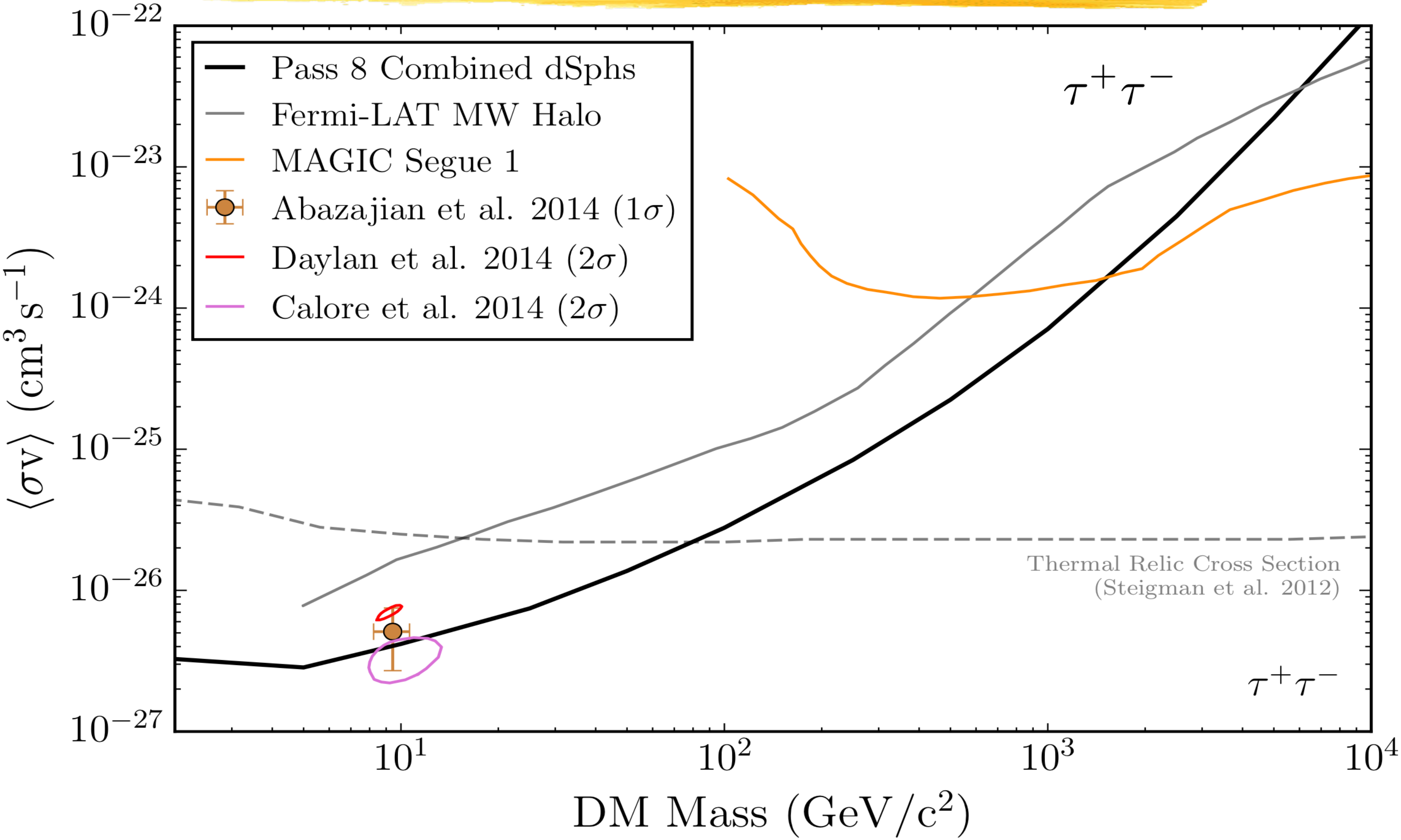
Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

Dwarf Spheroidal Galaxies upper-limits (6 years)



M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

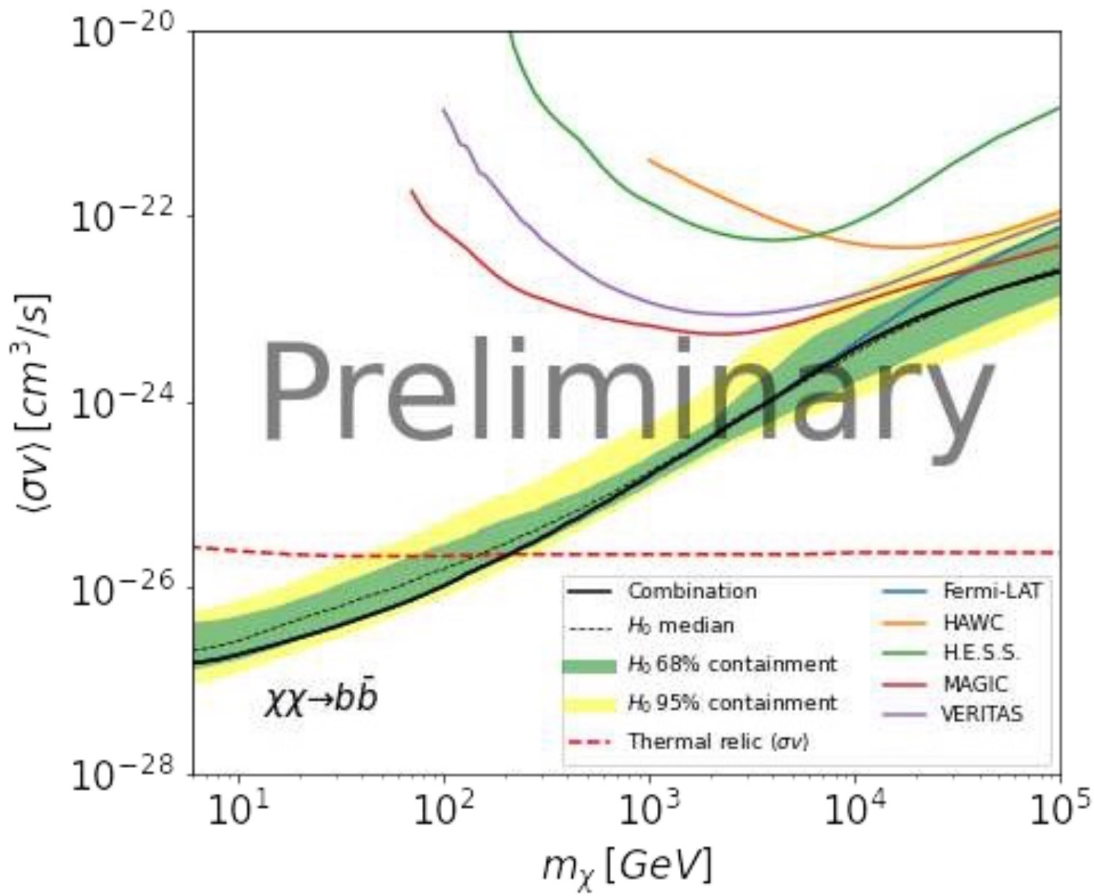
Dwarf Spheroidal Galaxies upper-limits (6 years)



M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

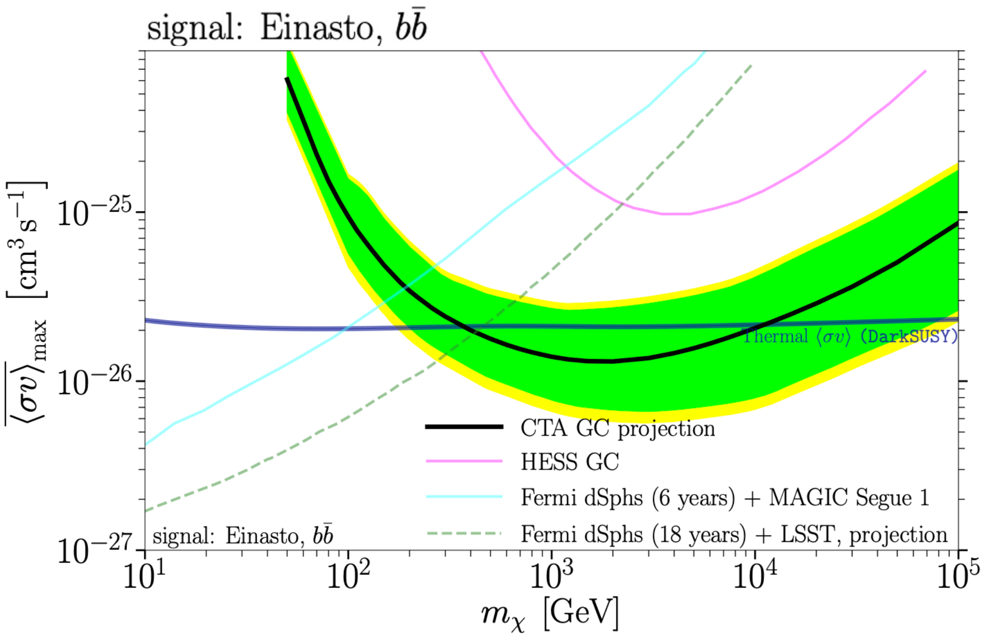
Combining all dSph observations

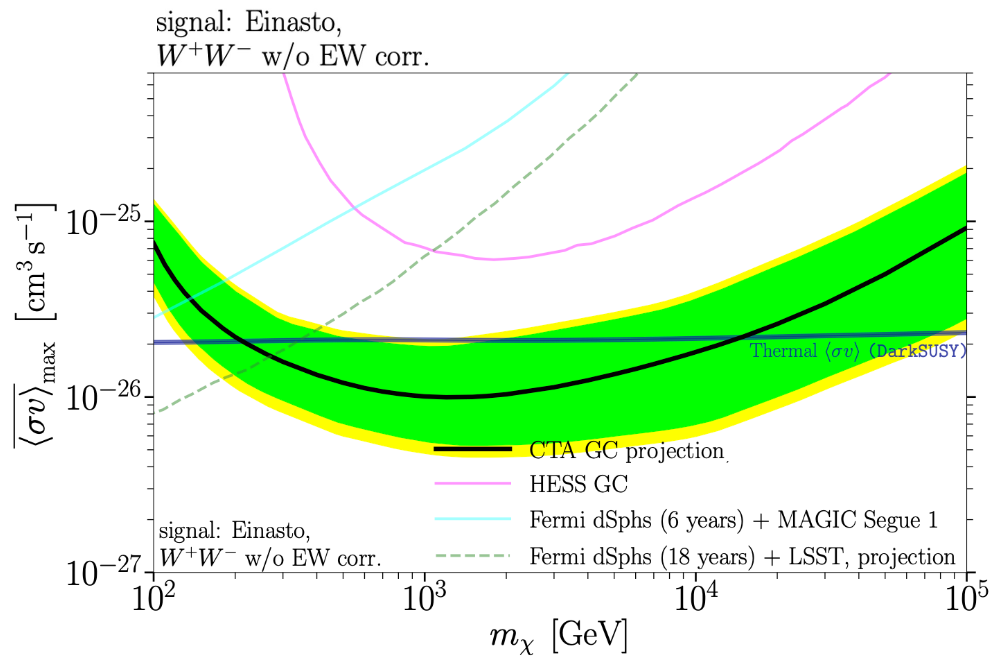
- Combination of the observation results towards 20 dwarf spheroidal galaxies (dSphs)
  - Significant increase of the statistics -> Increase the sensitivity to potential dark matter signals
  - Cover the widest energy range ever investigated : 20 MeV – 80 TeV



- Common elements :
  - Agreed model parameters
  - Sharable likelihood table formats
  - Joint likelihood test statistic

Galactic center CTA Sensitivity





- Einasto profile

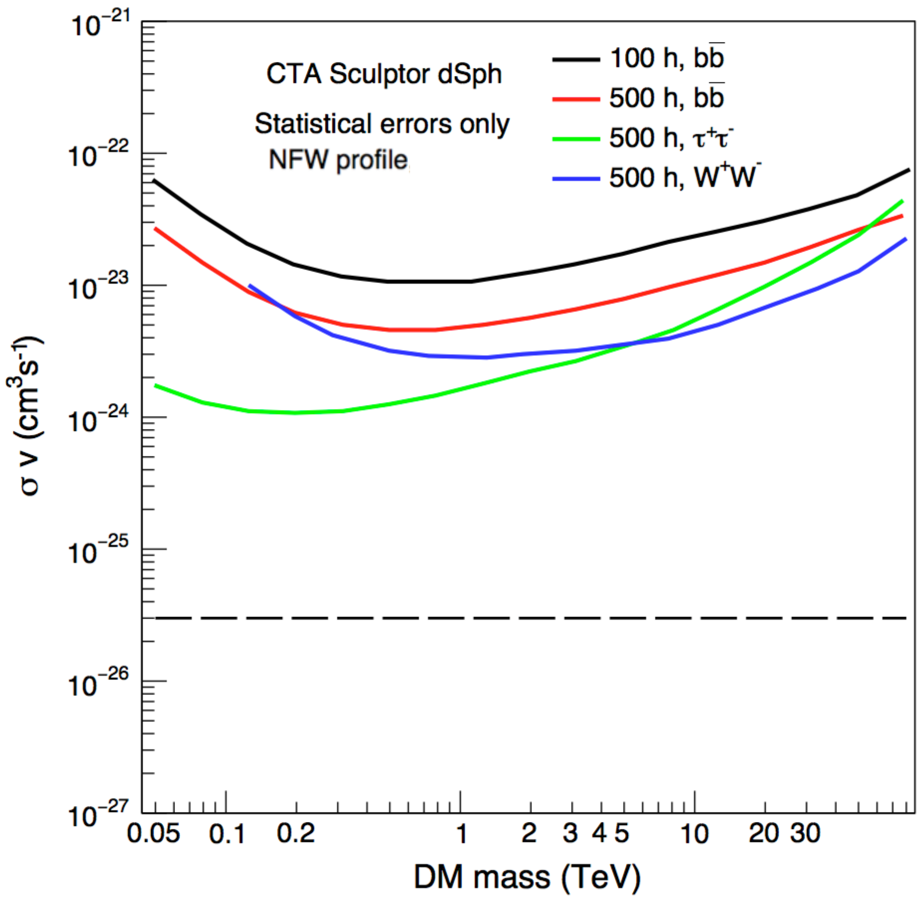
520 h

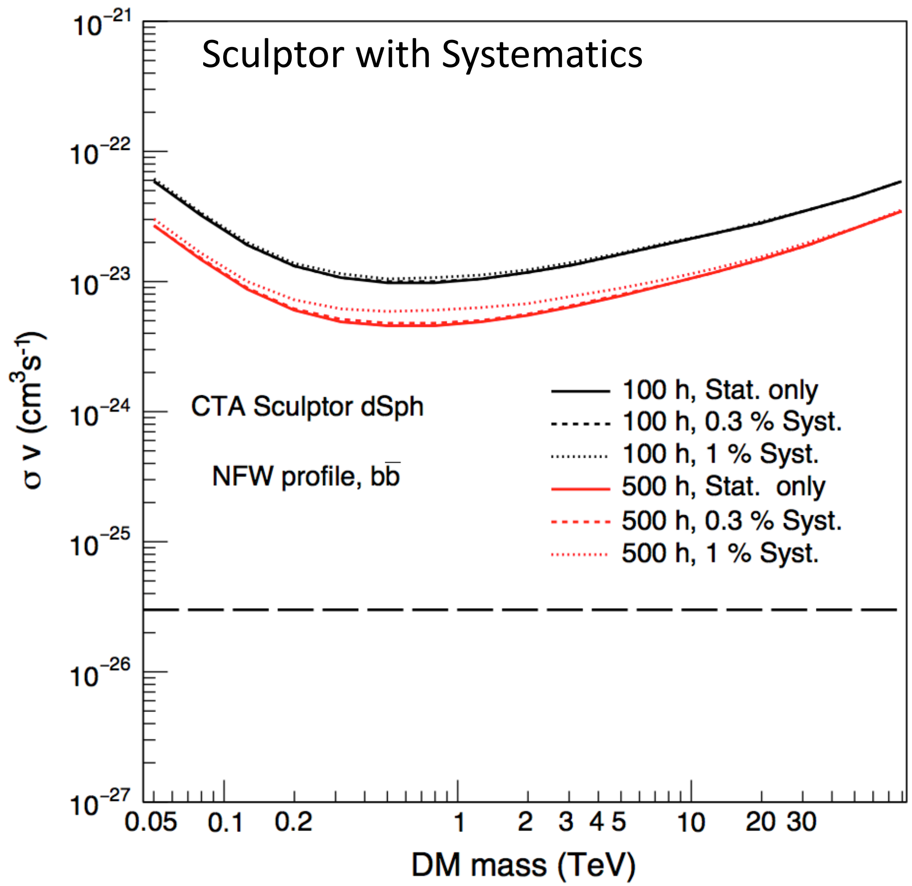
$$\rho_{DM} = \rho_s \exp\left[-\frac{\alpha}{2}\left(\frac{r}{r_s}\right)^{\alpha} - 1\right], \; J \sim 7.1 \times 10^{22} \mathrm{GeV}^2/\mathrm{cm}^5$$

- Main source of background : sources, Fermi Bubble, interstellar γ, residual CR

The CTA Consortium JCAP01(2021) 057 January 27, 2021 [arXiv:2007.16129]

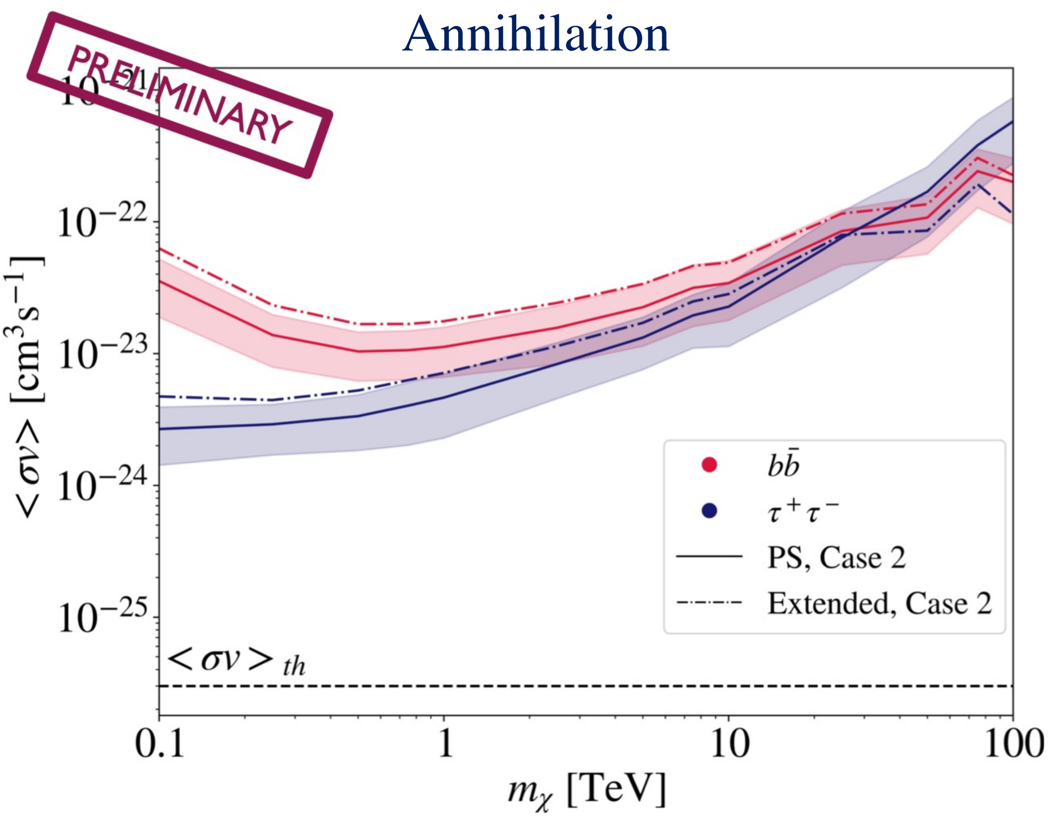
Dwarf Spheroidal Galaxies: CTA Sensitivity

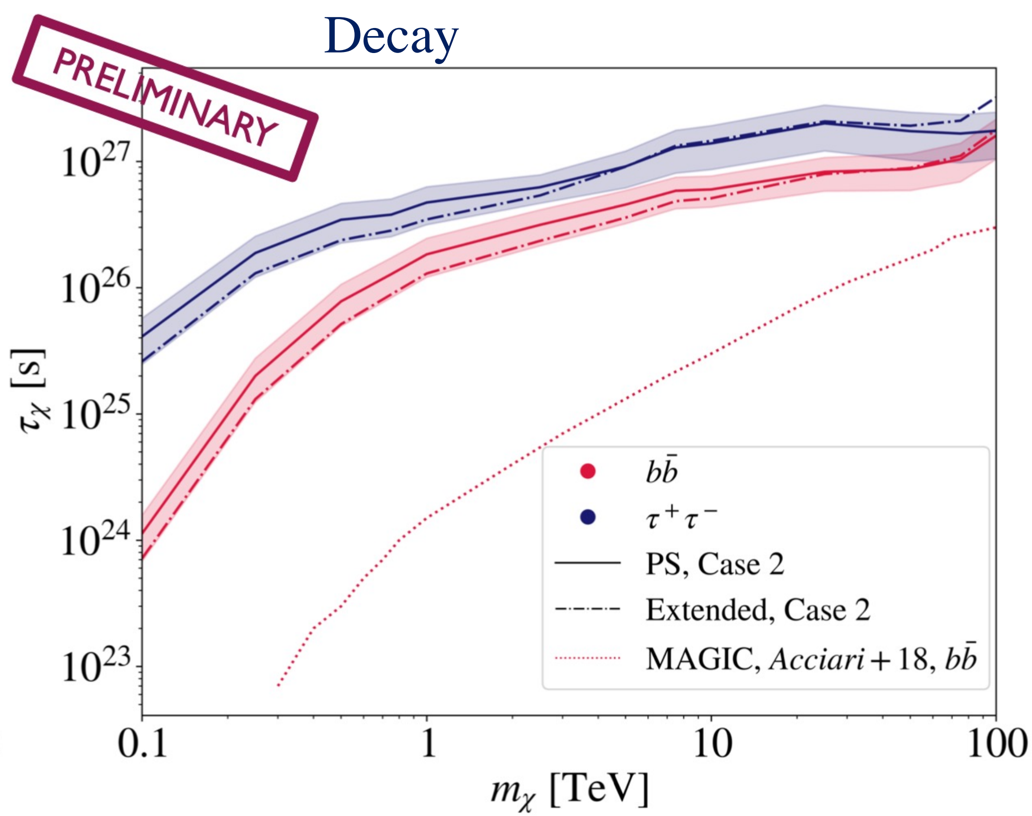




updated & dedicated collaboration paper soon from the CTA dSph task force

Perseus Cluster : CTA Sensitivity





CTA Consortium in preparation

CTA DM Detection Strategy

(from the CTA science book, numbers can change)

Year	1	2	3	4	5	6	7	8	9	10
Galactic halo	175 h	175 h	175 h							
Best dSph	100 h	100 h	100 h							
				in case of detection at GC, large σv						
Best dSph				150 h	150 h	150 h	150 h	150 h	150 h	150 h
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of detection at GC, small σv						
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of no detection at GC						
Best Target				100 h	100 h	100 h	100 h	100 h	100 h	100 h

First 3 years

- The principal target is the Galactic Center Halo (most intense diffuse emission regions removed)
- Best dSph as “cleaner” environment for cross-checks and verification (if hint of strong signal)

Next 7 years

- If there is detection in GC halo data set (525h)
  - Strong signal: continue with GC halo in parallel with best dSph to provide robust detection
  - Weak signal: focus on GC **halo** to increase data set until systematic errors can be kept under control
- If no detection in GC halo data set
  - Focus observation on the best target at that time to produce legacy limits.

CTA Search for Dark Matter beyond WIMP

Axion Like Particle (ALP) search prospects

$\gamma + B \rightarrow a + B \rightarrow \gamma' + \ldots$

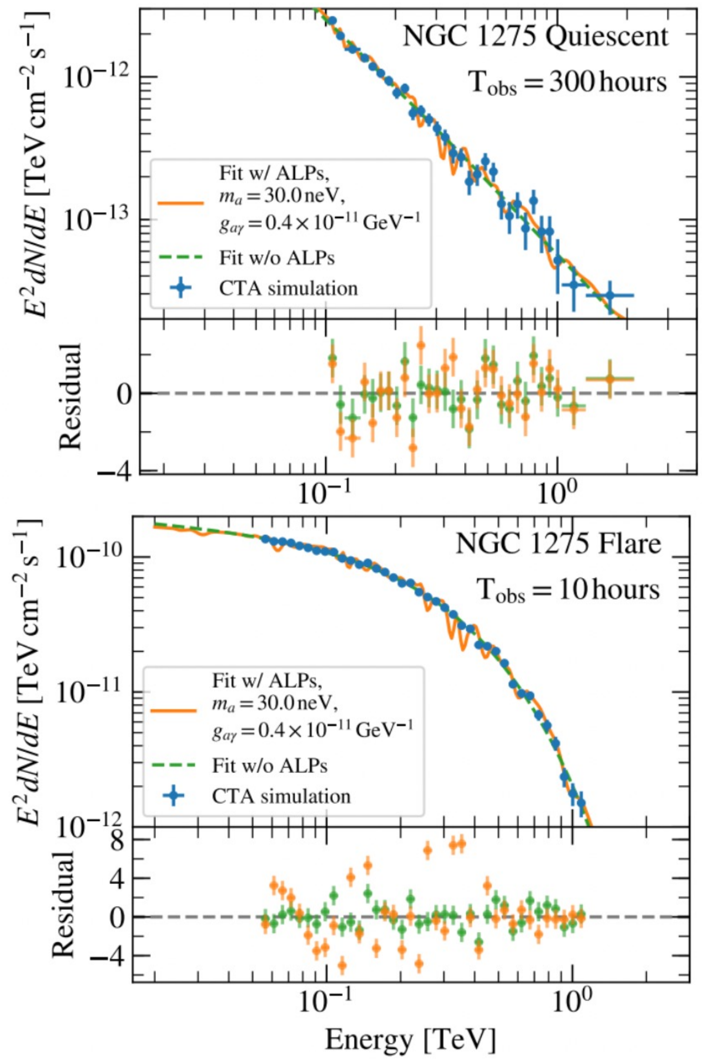
conversion probability ($E > E_{crit}$)

$$P_{a\gamma} \sim \sin^2\left(\frac{g_{a\gamma} B l}{2}\right),$$

$$E_{\mathrm{crit}} \sim 2.5\ \mathrm{GeV} \times \left(\frac{|m_a - \omega_{\mathrm{pl}}|}{1\mathrm{neV}}\right)^2 \left(\frac{B}{1\mu\mathrm{G}}\right)^{-1} \left(\frac{g_{a\gamma}}{10^{-11}\mathrm{GeV}^{-1}}\right)^{-1}$$

the observation is simulated without an ALP effect and is modeled both without ALPs and with a fixed set of magnetic-field realization and ALP parameters that are excluded at 95 % confidence level by the flaring state simulation

Simulated spectra of the radio galaxy NGC 1275

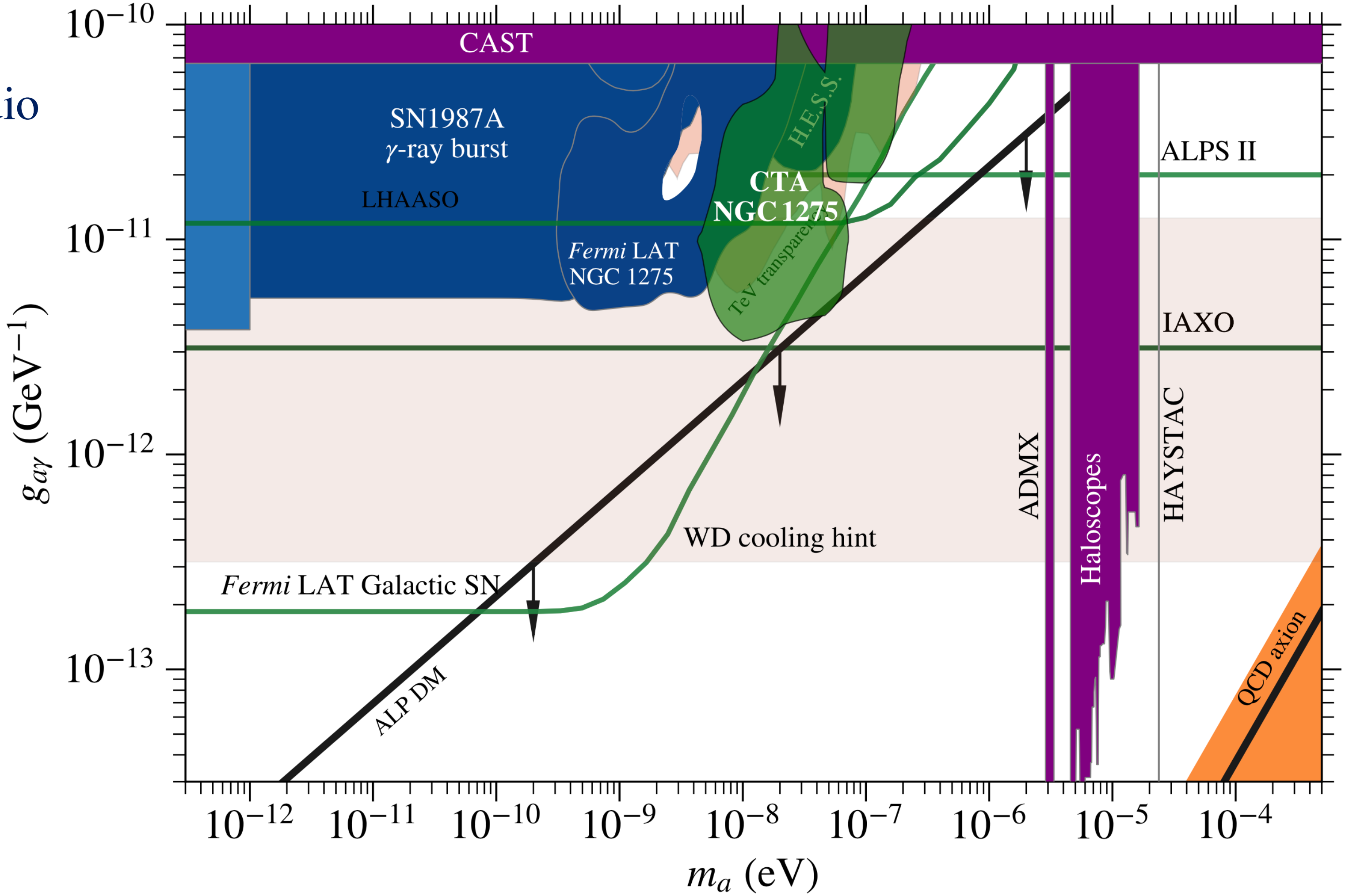


The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]

CTA Search for Dark Matter beyond WIMP

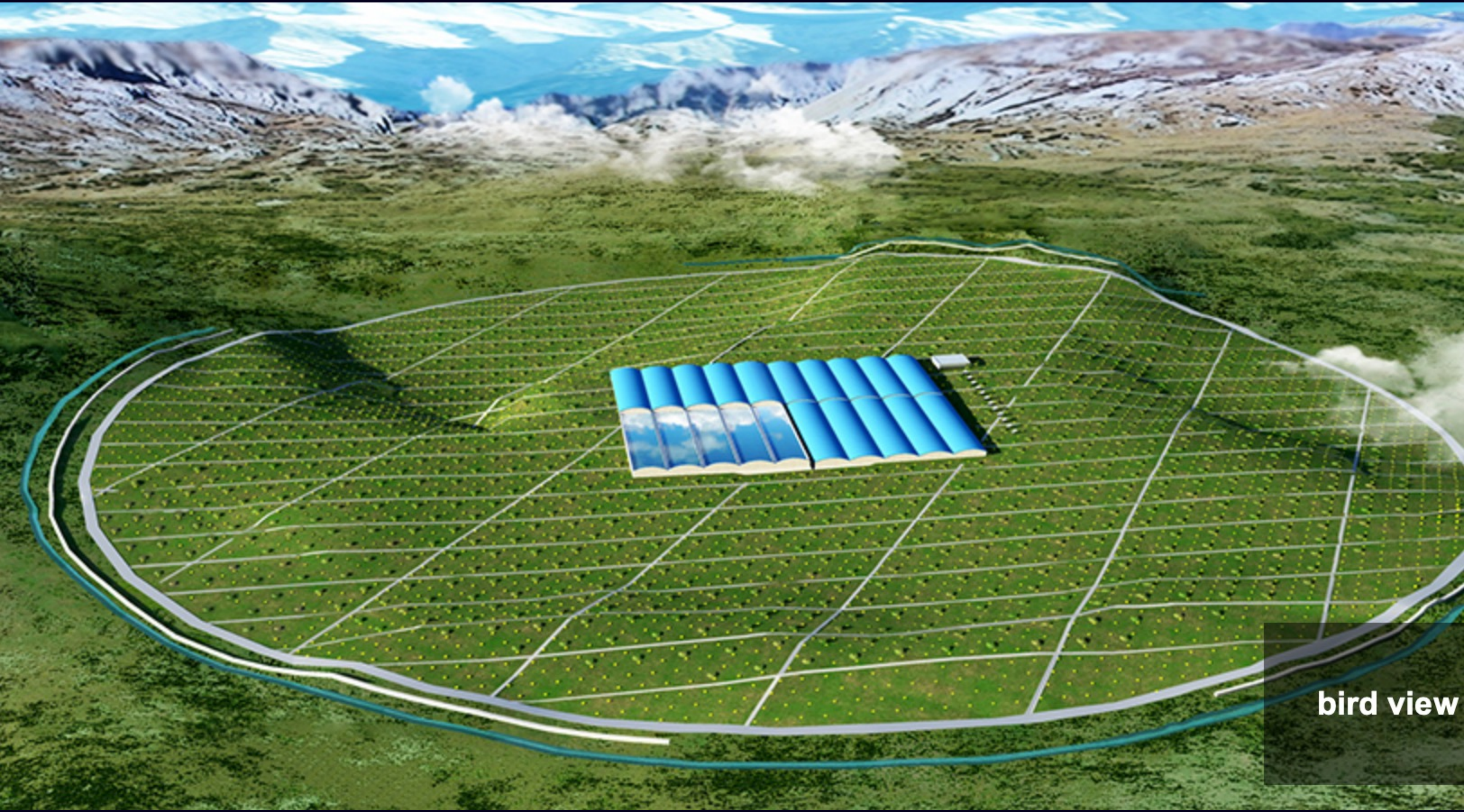
Axion Like Particle search prospects

- Observation of a flaring state of the radio galaxy NGC 1275 inside the Perseus cluster
- Observations of several AGN can be combined to further improve the CTA sensitivity.

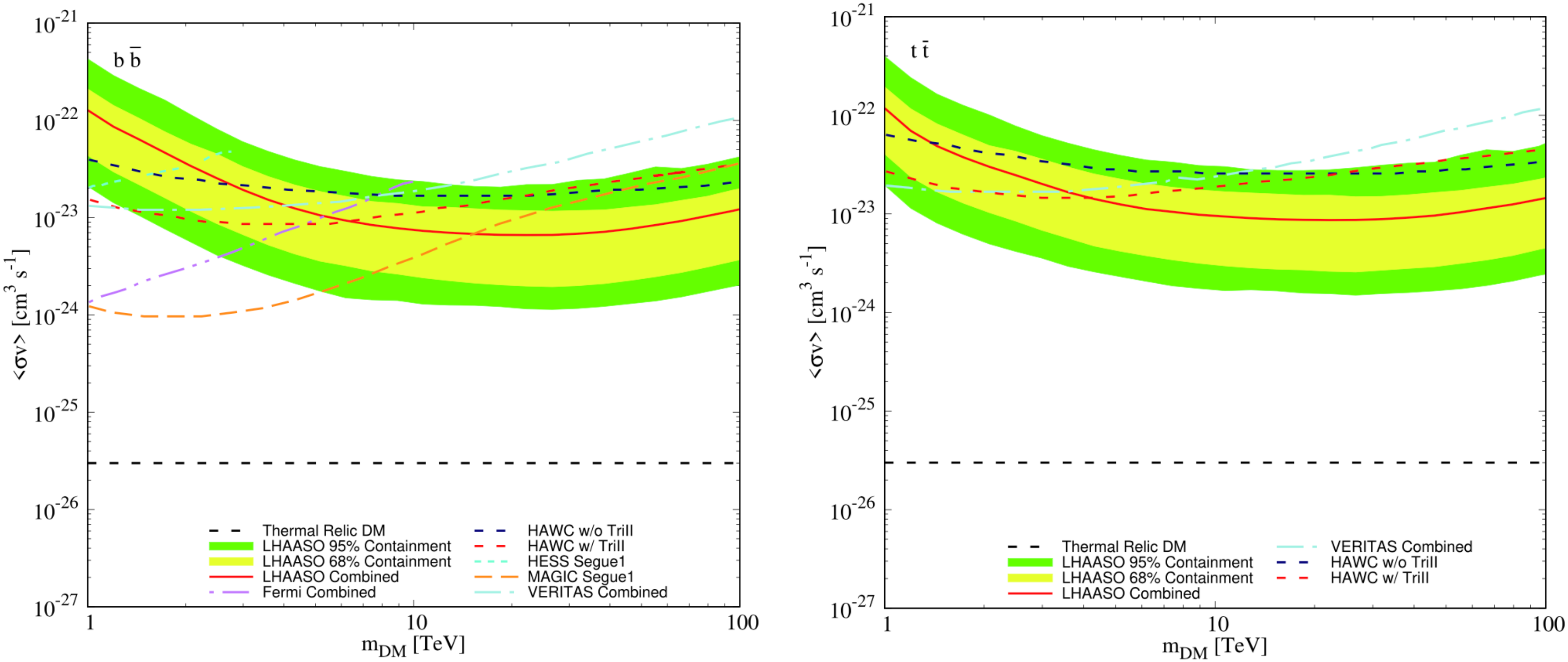


The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]

LHAASO



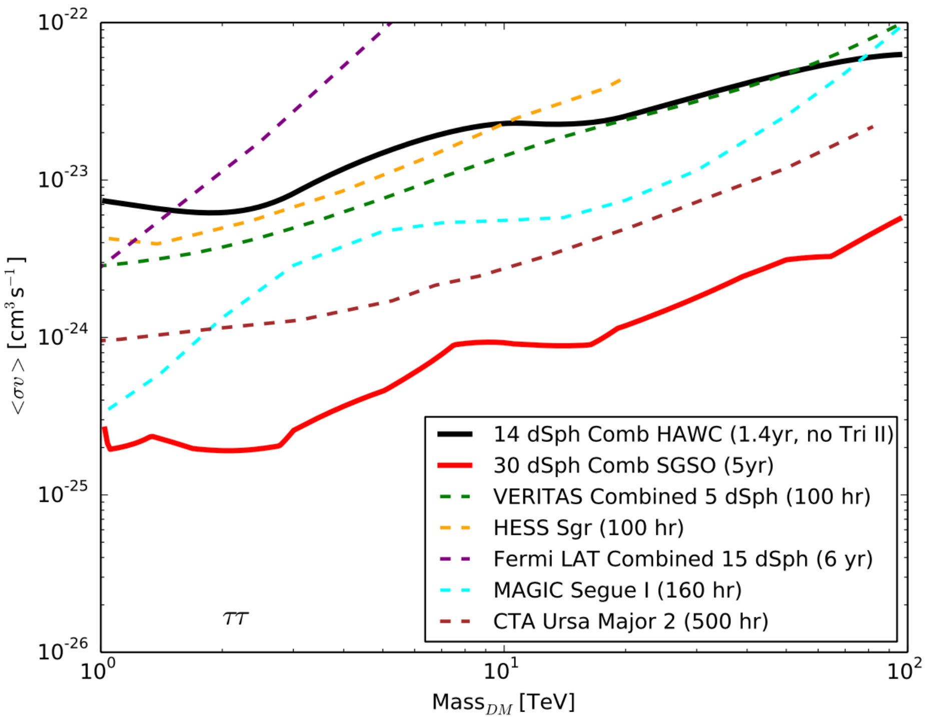
Combined one-year LHAASO sensitivities

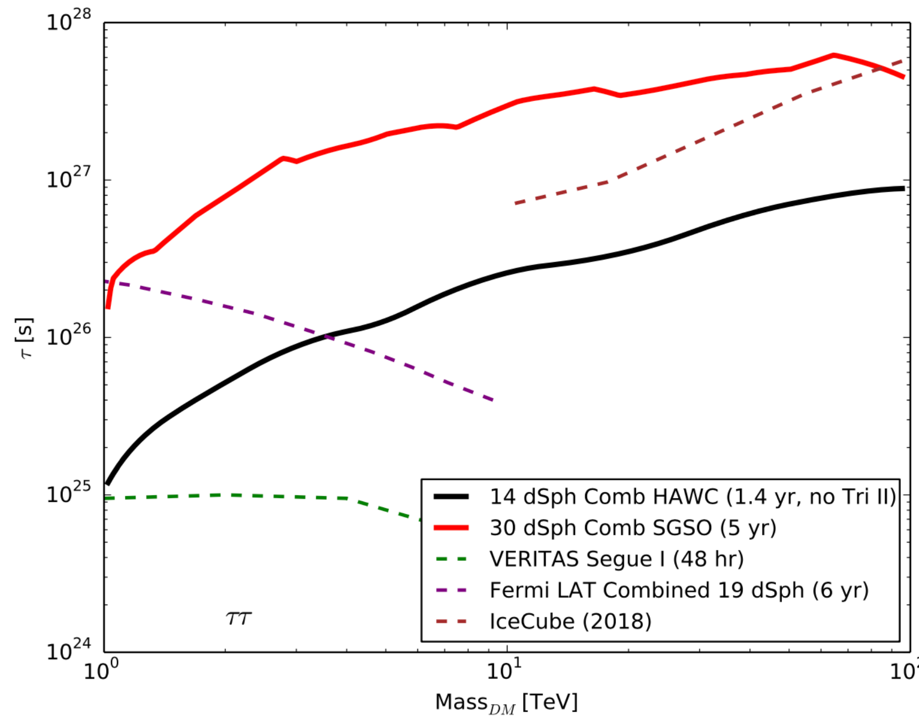


The LHAASO median combined sensitivities (red solid lines) and related two-sided 68% (yellow bands) and 95% (green bands) containment bands of one year for the $b\bar{b}$, $\bar{t}t$ for 19 dSphs within the LHAASO FOV

Dong-Ze He et al., Phys. Rev. D 100, 083003 (2019)

SWGO sensitivities





Assumed new dSph discovery and
J-factor and D-factor distributions of the new dSphs matches that of the previously known dSphs

SWGO White paper arXiv:1902.08429

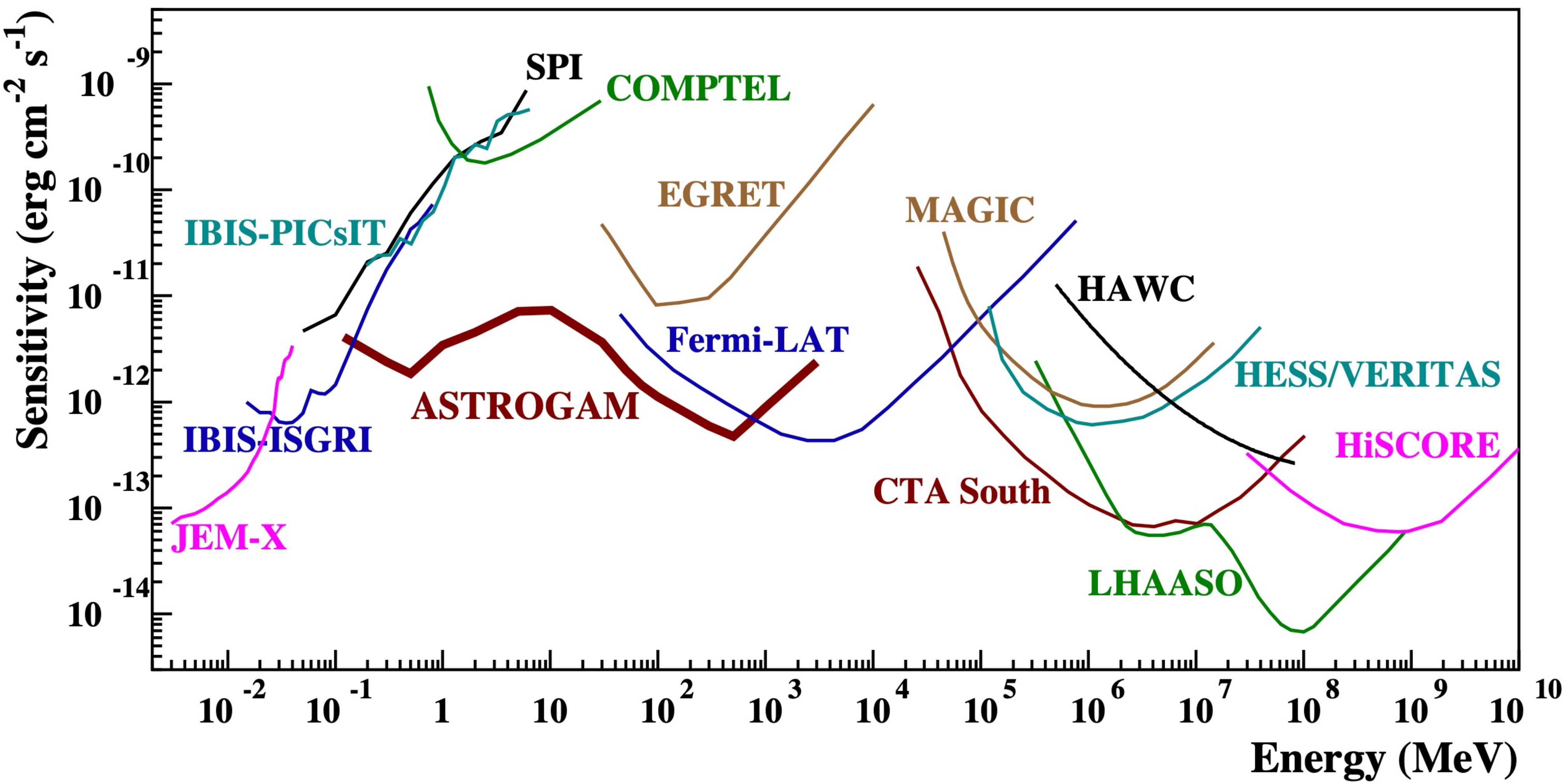
The Low Energy Frontier

ASTROGAM

Selected for phase 2 of the ESA M7 Call

Detector paper: Exp. Astronomy 2017, 44, 25 arXiv:1611.02232
Science White Book: arXiv:1711.01265 (213 pages)

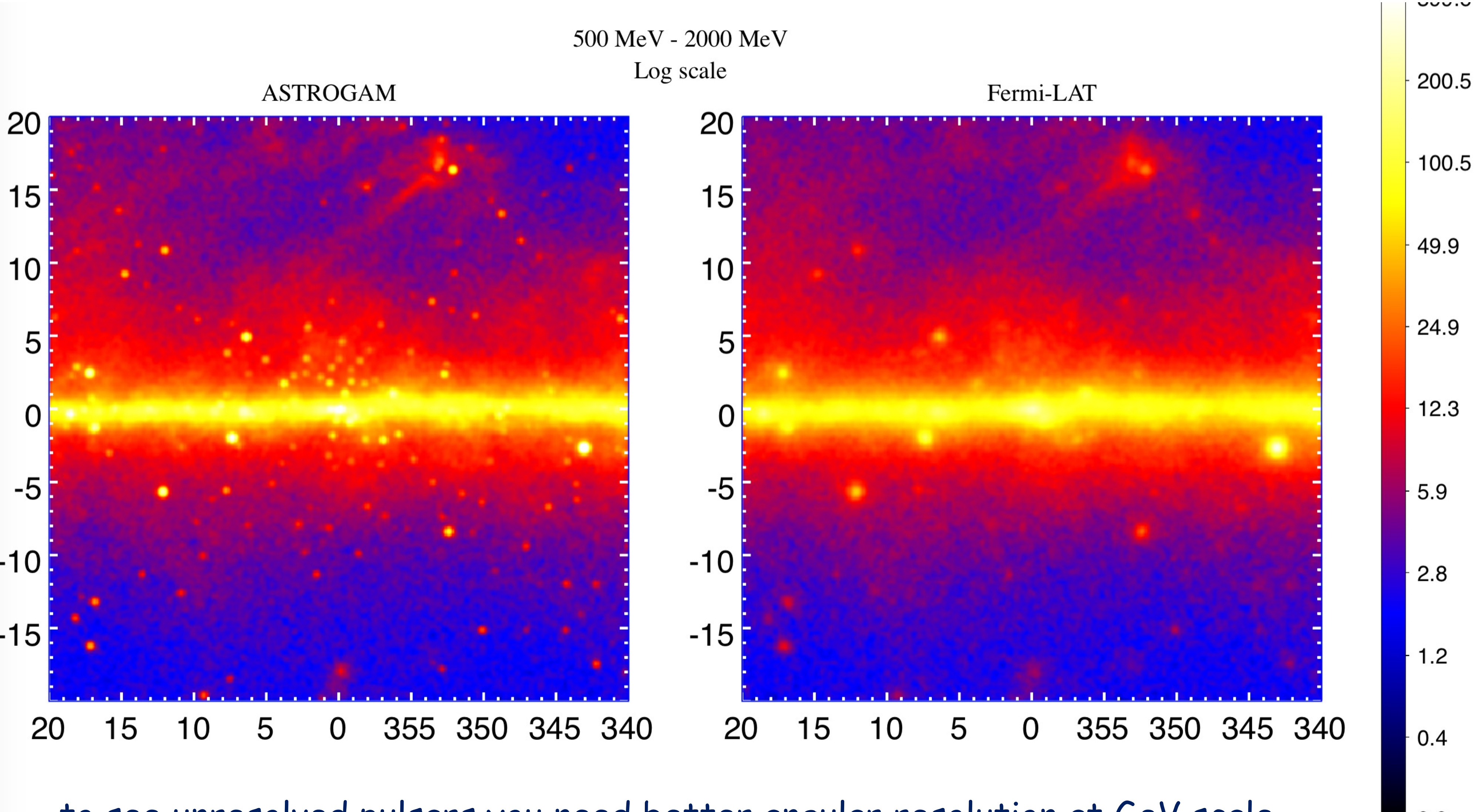
Astrogam Performance



Astrogam sensitivity for an effective exposure of two years at high galactic latitude

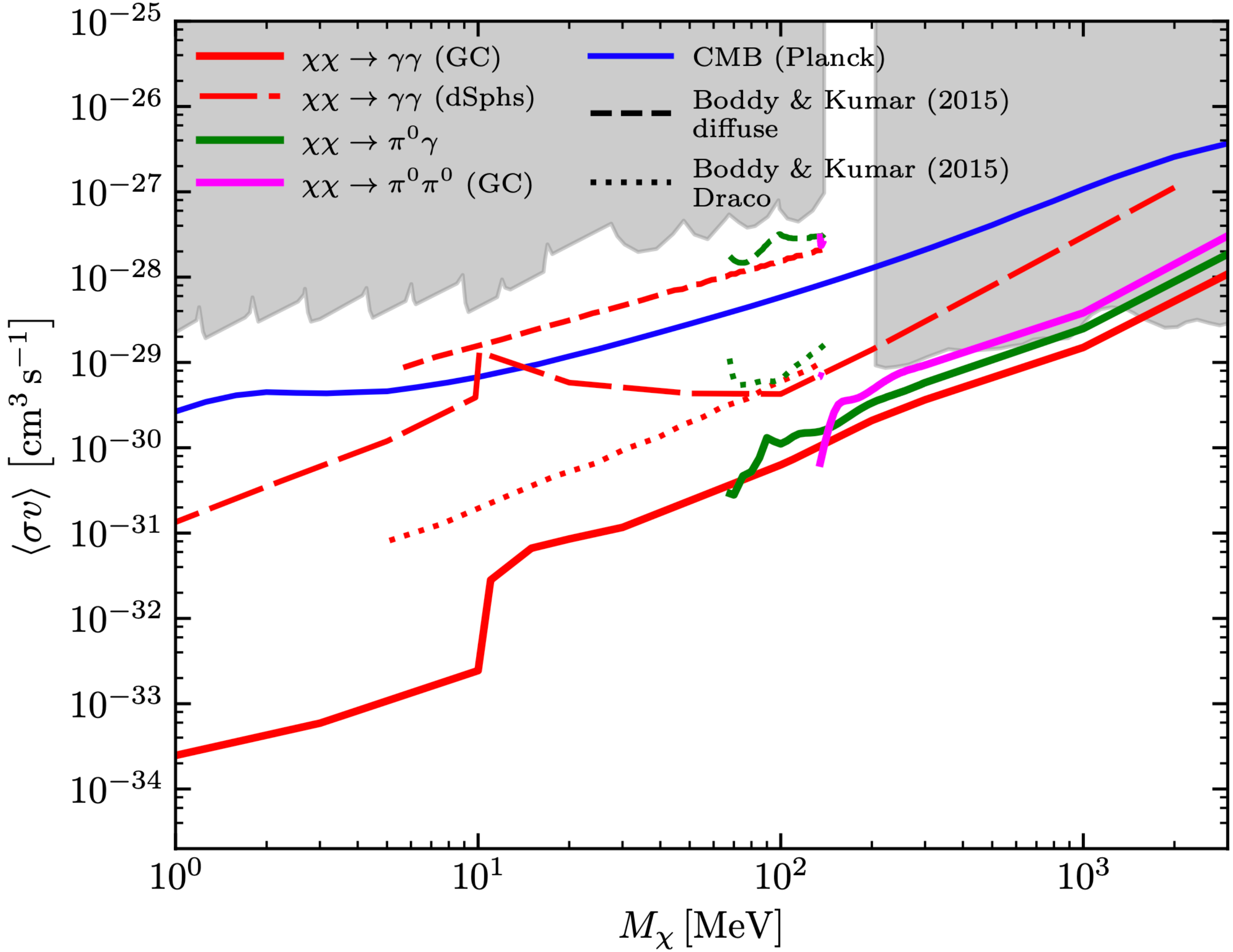
Galactic Center Region 0.5-2 GeV

Fermi PSF 8

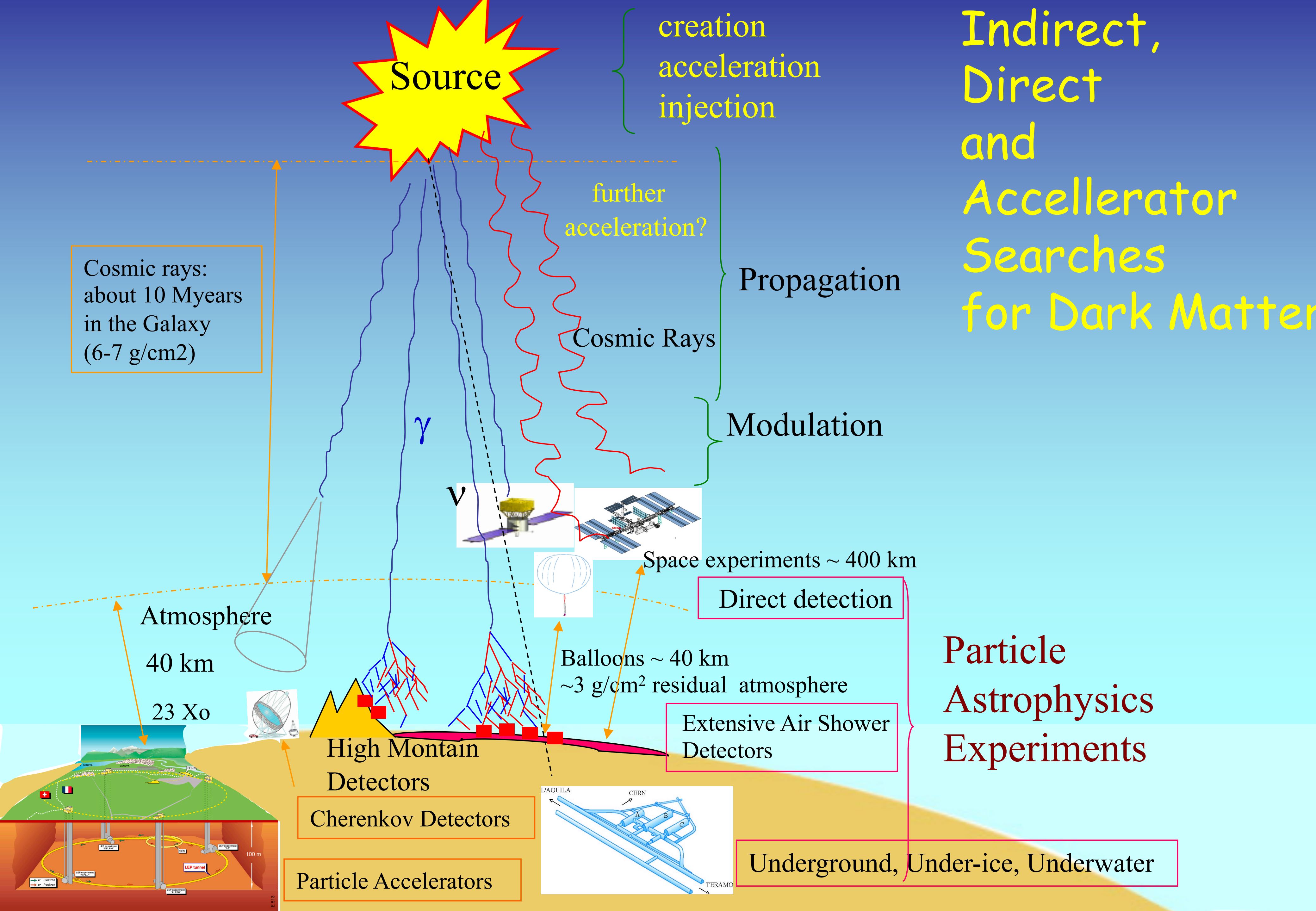


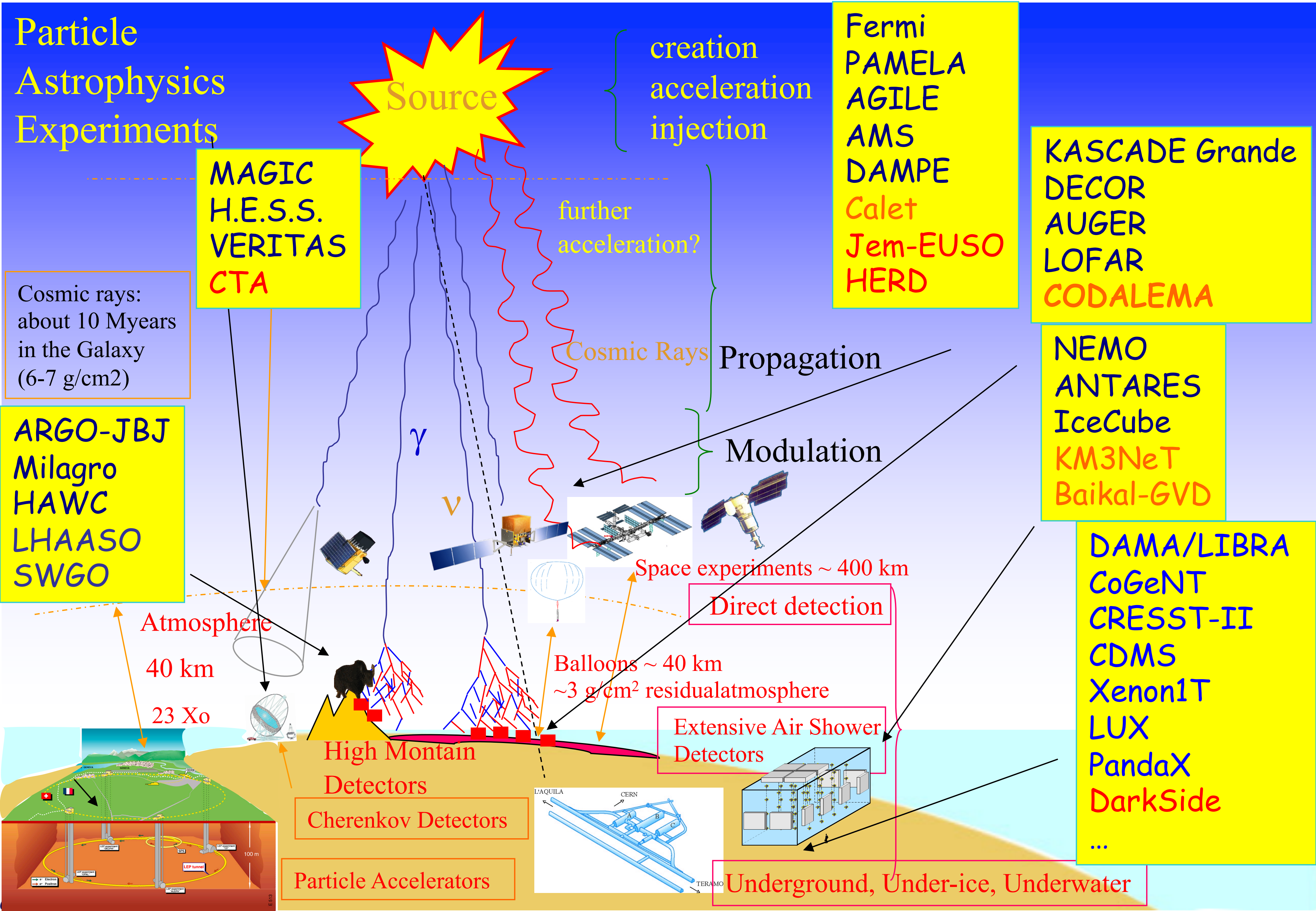
to see unresolved pulsars you need better angular resolution at GeV scale

Astrogam Sensitivity for Dark Matter



ASTROGAM detectability of sub-GeV DM-induced gamma-ray signals from the GC and dSphs


Indirect,
Direct
and
Accellerator
Searches
for Dark Matter
Source
creation
acceleration
injection
further
acceleration?
Propagation
Cosmic Rays
Modulation
Cosmic rays:
about 10 Myears
in the Galaxy
(6-7 g/cm2)
γ
ν
Space experiments ~ 400 km
Direct detection
Atmosphere
40 km
23 Xo
Balloons ~ 40 km
~3 g/cm² residual atmosphere
Extensive Air Shower
Detectors
Particle
Astrophysics
Experiments
High Montain
Detectors
Cherenkov Detectors
Particle Accelerators
L'AQUILA
CERN
TERAMO
Underground, Under-ice, Underwater


Particle
Astrophysics
Experiments
Source
creation
acceleration
injection
Fermi
PAMELA
AGILE
AMS
DAMPE
Calet
Jem-EUSO
HERD
KASCADE Grande
DECOR
AUGER
LOFAR
CODALEMA
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Cosmic rays:
about 10 Myears
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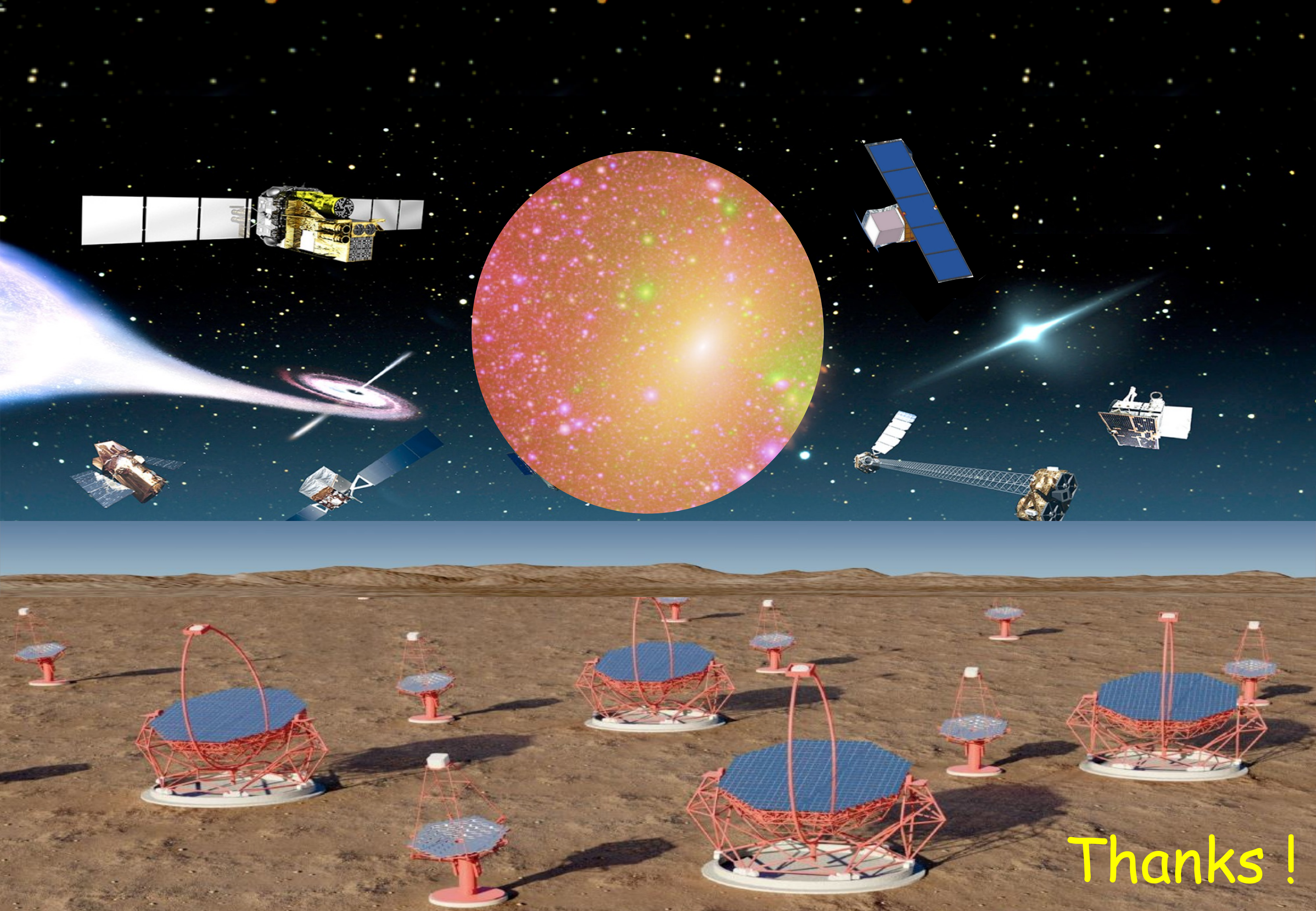
Cosmic Rays
Propagation
NEMO
ANTARES
IceCube
KM3NeT
Baikal-GVD
ARGO-JBJ
Milagro
HAWC
LHAASO
SWGO
γ
Modulation
ν
DAMA/LIBRA
CoGeNT
CRESST-II
CDMS
Xenon1T
LUX
PandaX
DarkSide
...
Space experiments ~ 400 km
Direct detection
Atmosphere
40 km
23 Xo
Balloons ~ 40 km
~3 g/cm² residualatmosphere
Extensive Air Shower
Detectors
High Montain
Detectors
Cherenkov Detectors
Particle Accelerators
L'AQUILA
CERN
TERAMO
Underground, Under-ice, Underwater


Thanks !