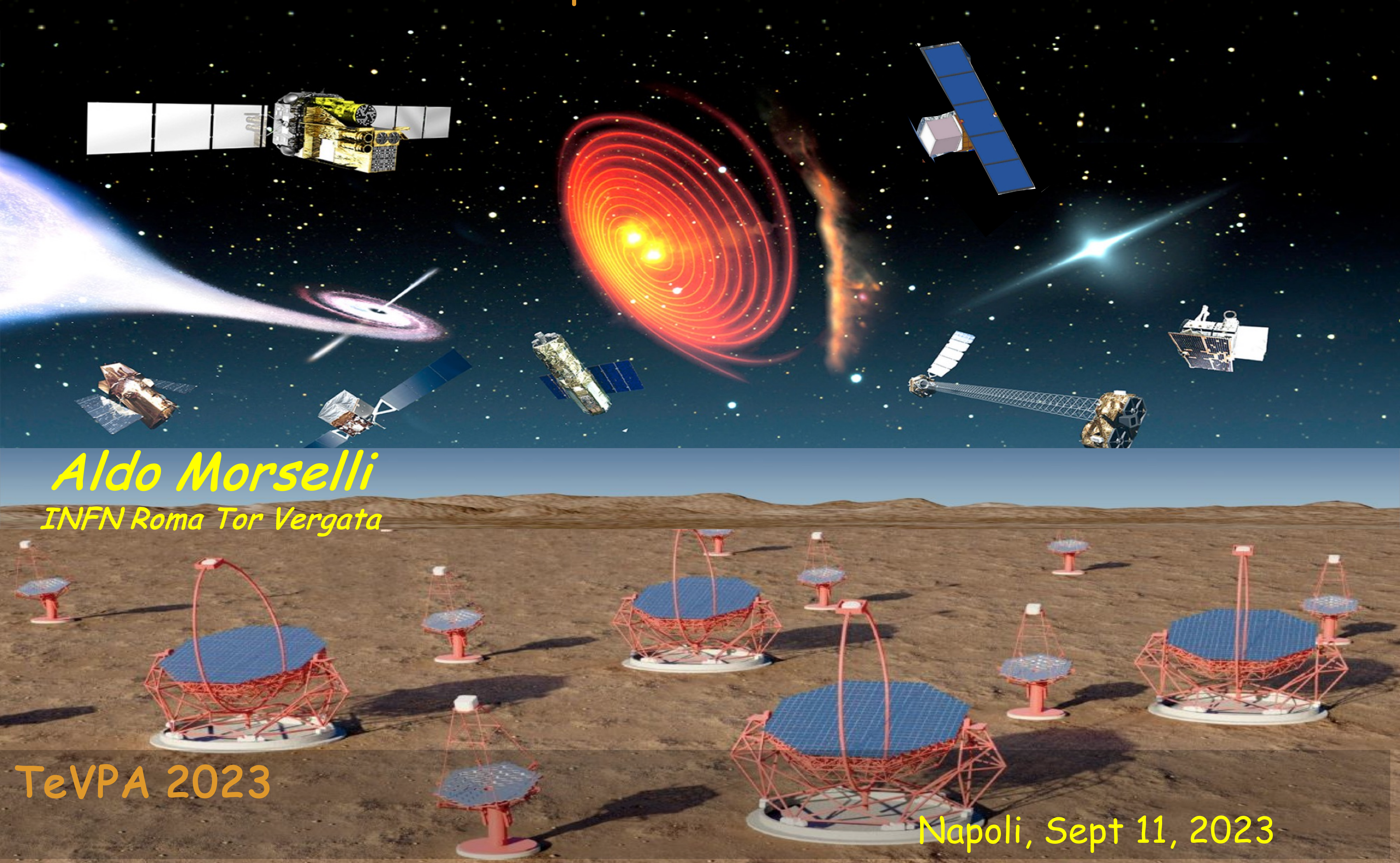
Indirect dark-matter searches with gamma-rays experiments : status and future plans from 300 KeV to 100 TeV



Aldo Morselli
INFN Roma Tor Vergata

TeVPA 2023

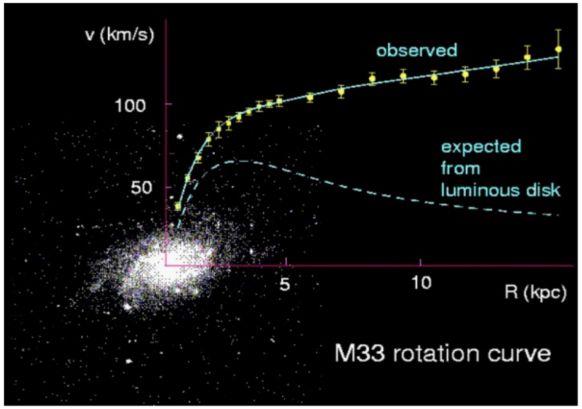
Napoli, Sept 11, 2023

Dark Matter EVIDENCE

In 1933, the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies.

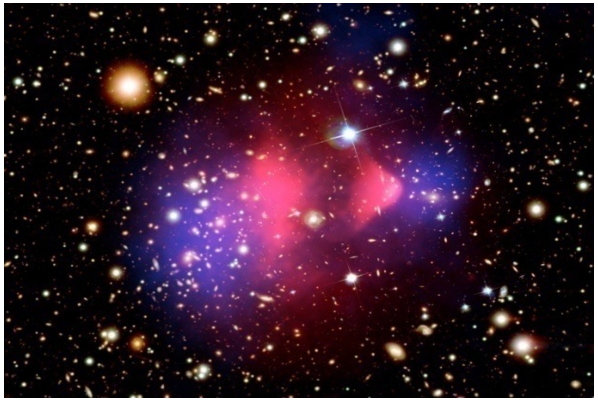
Since then, even more evidence:

Rotation curves of galaxies

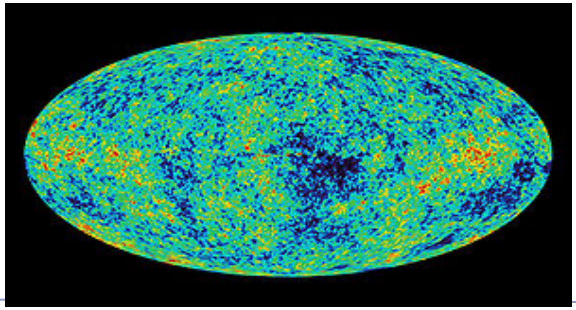


Gravitational lensing

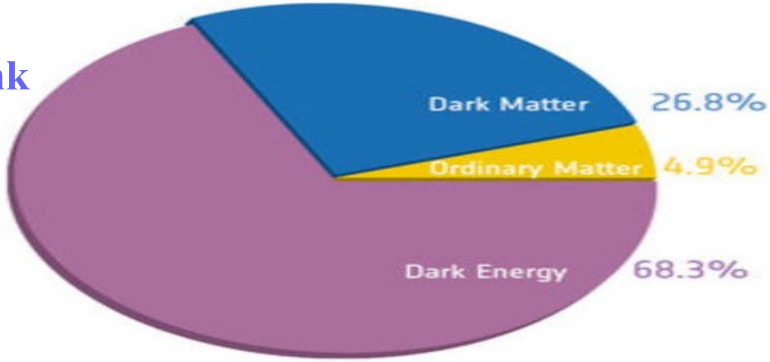
Bullet cluster



Structure formation as deduced from CMB



Data by Plank imply:



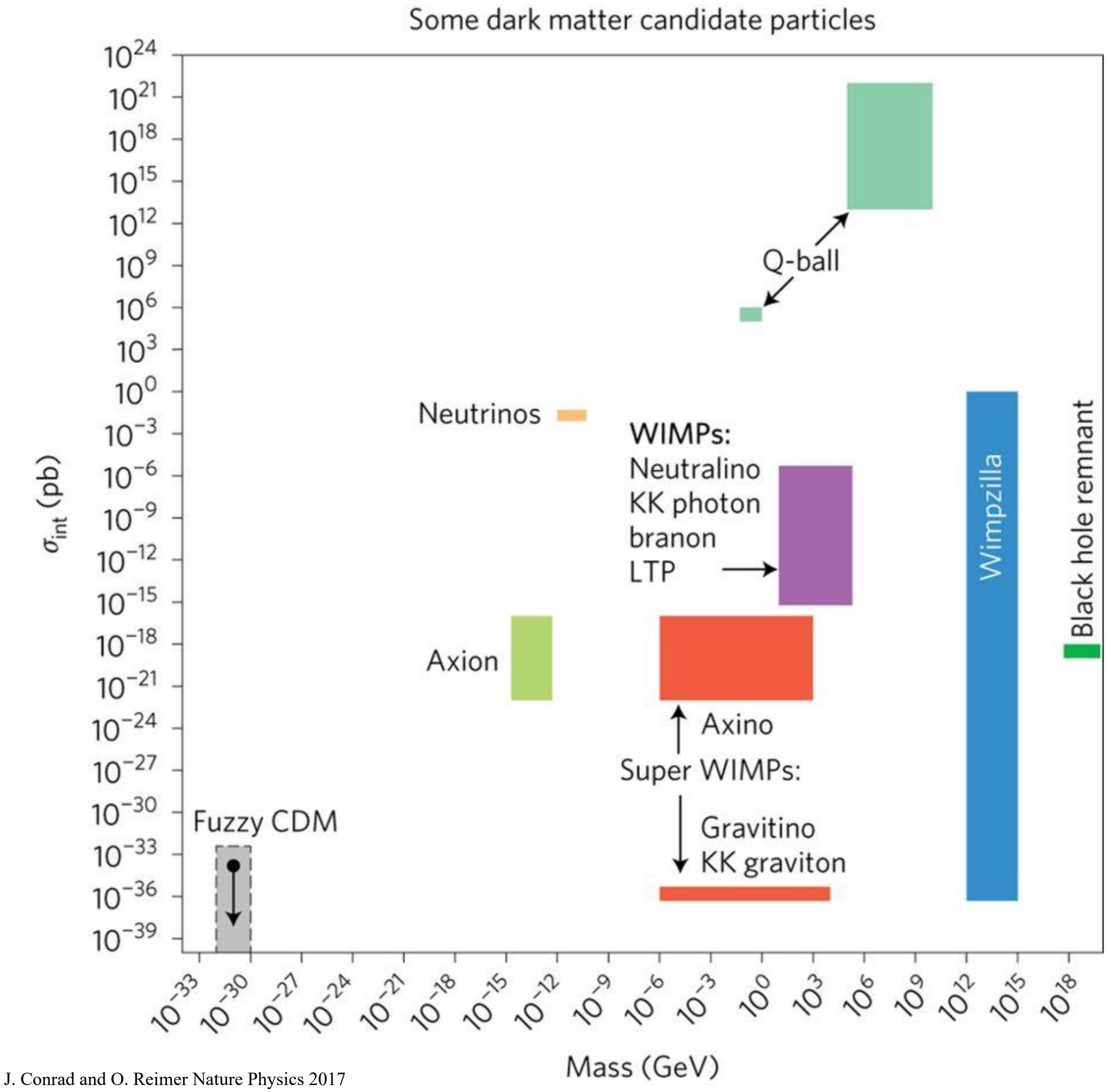
$\Omega_{DM} \approx 26.8\%$

$\Omega_{M} \approx 4.9\%$


Dark Matter

Dark Matter Candidates

- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworld DM
- Heavy neutrino
- WIMP
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes



J. Conrad and O. Reimer Nature Physics 2017

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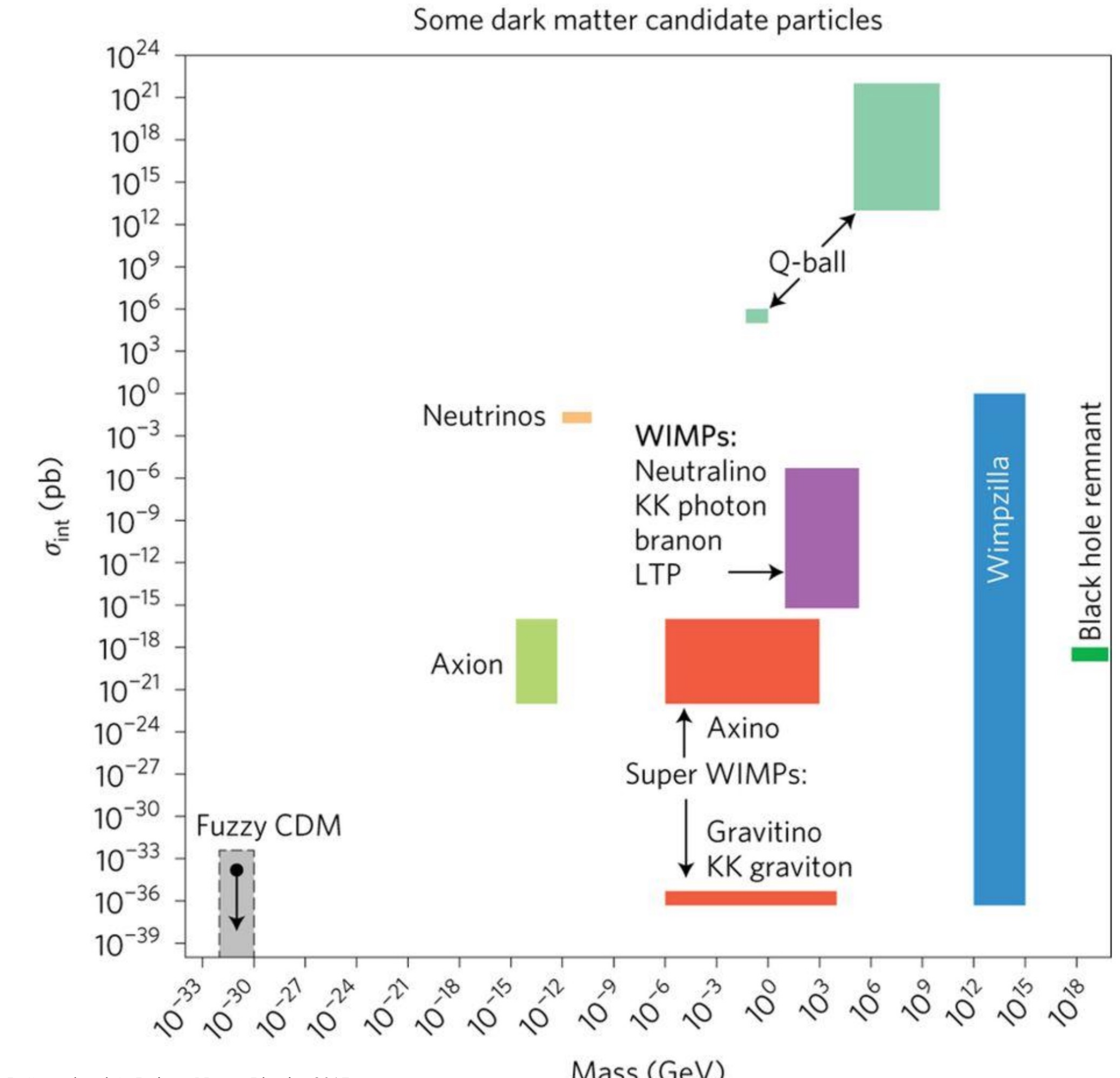
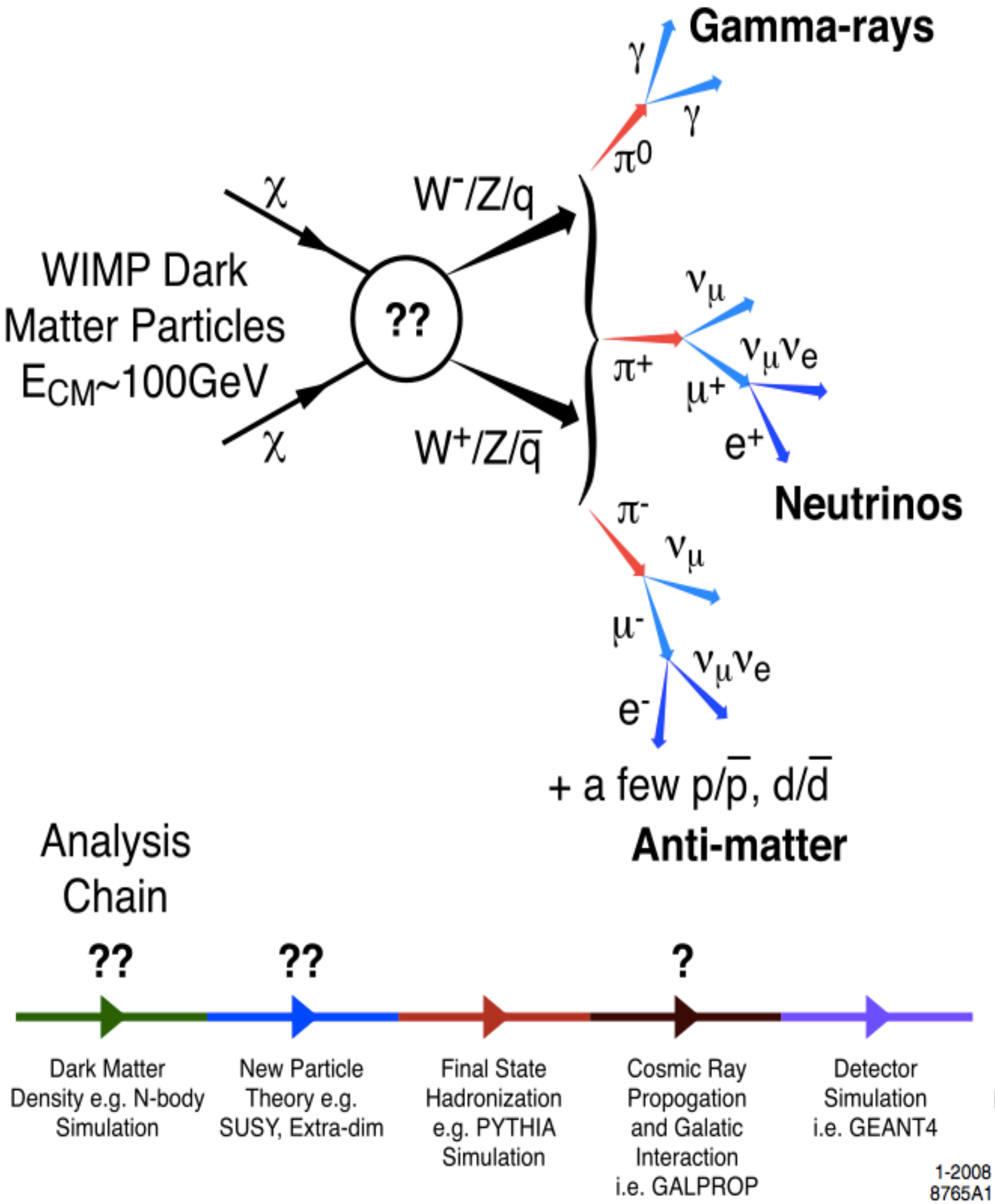
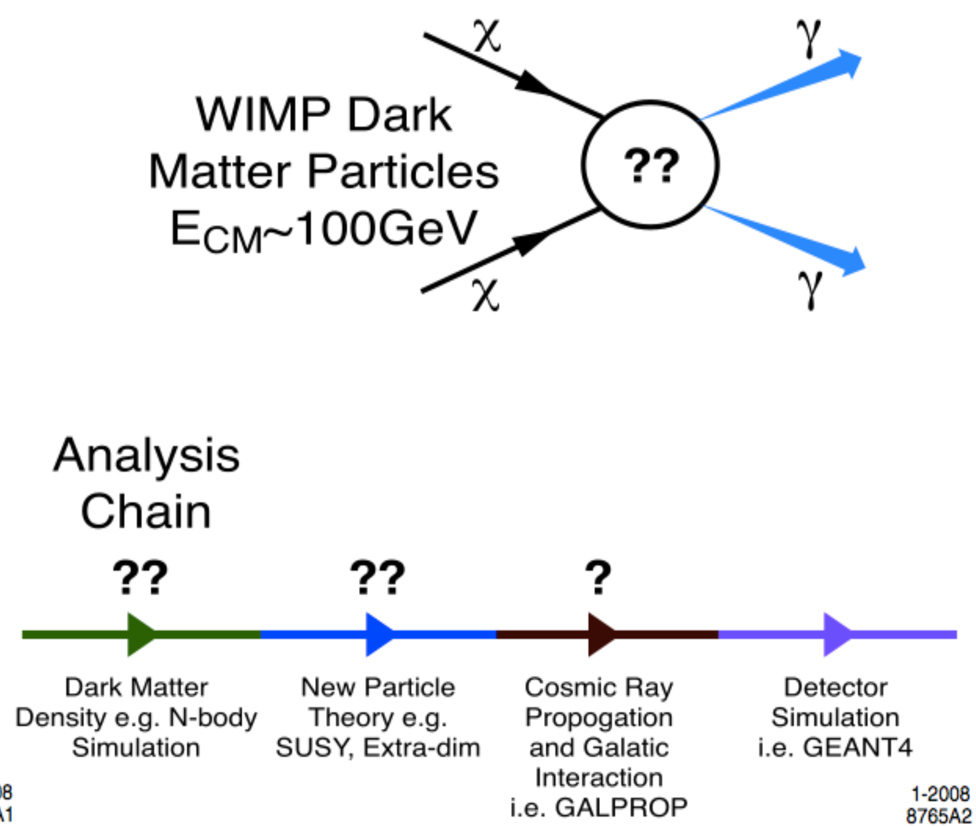


J. Conrad and O. Reimer Nature Physics 2017

Annihilation channels



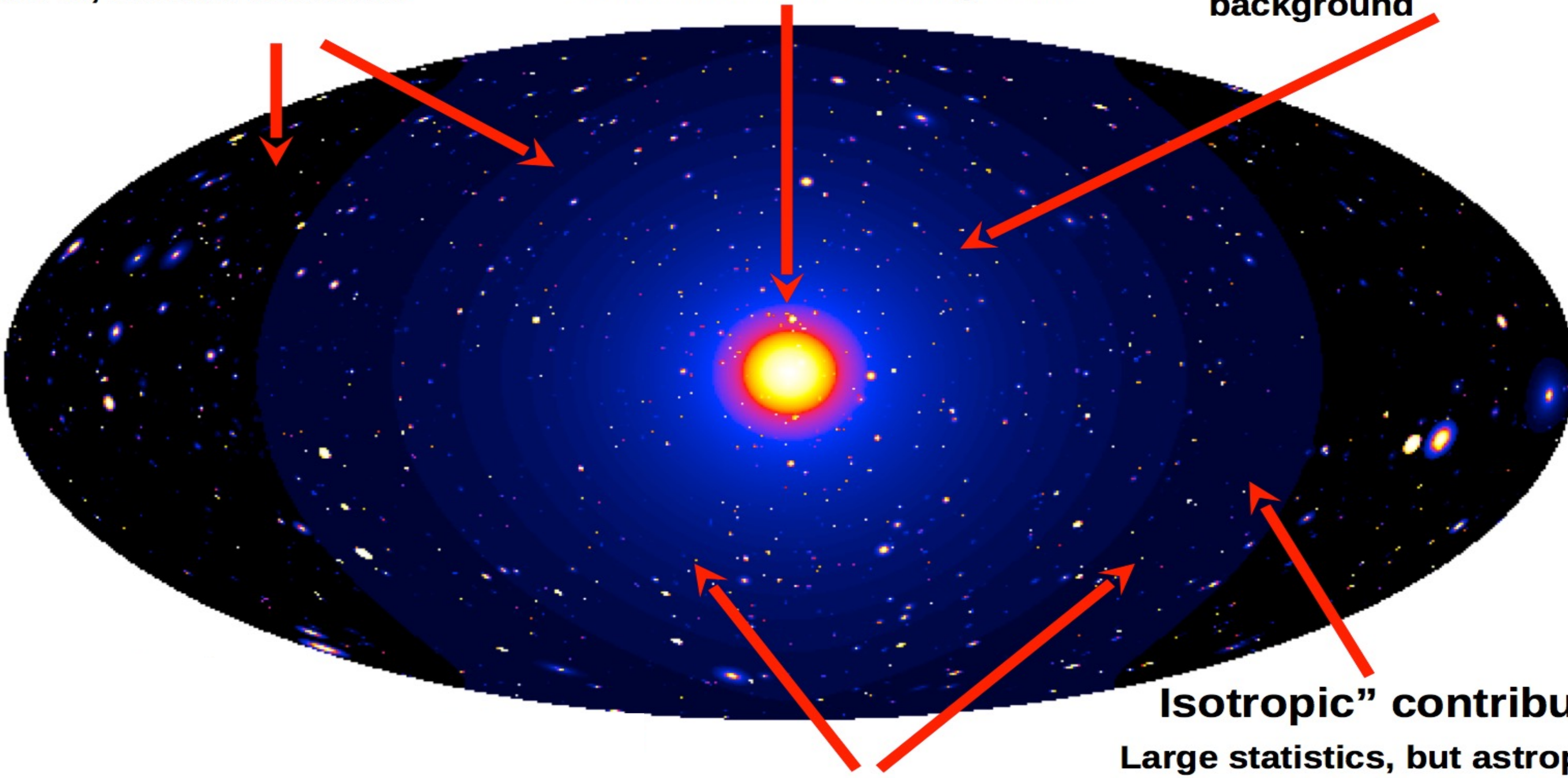


Dark Matter Search: Targets and Strategies

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

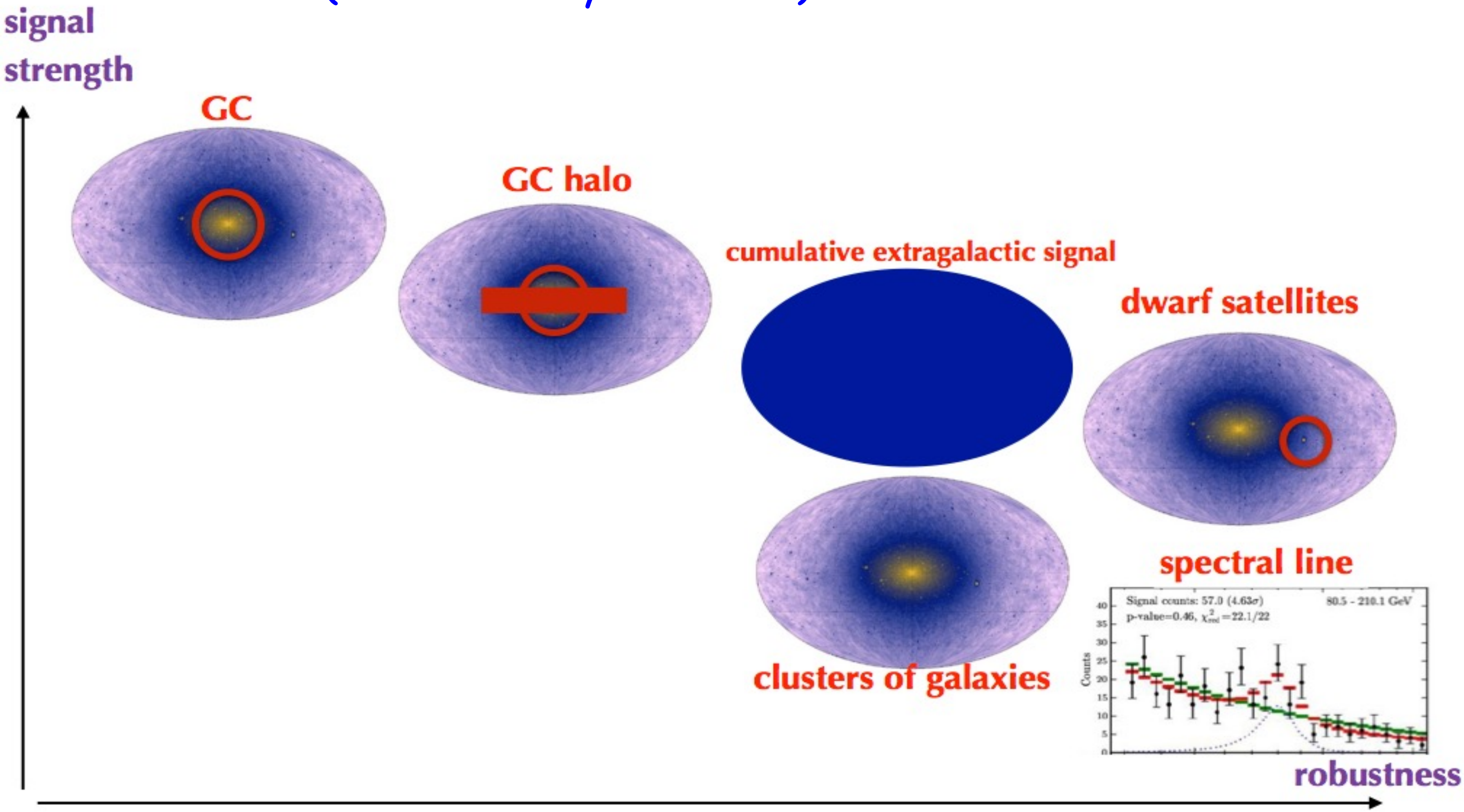


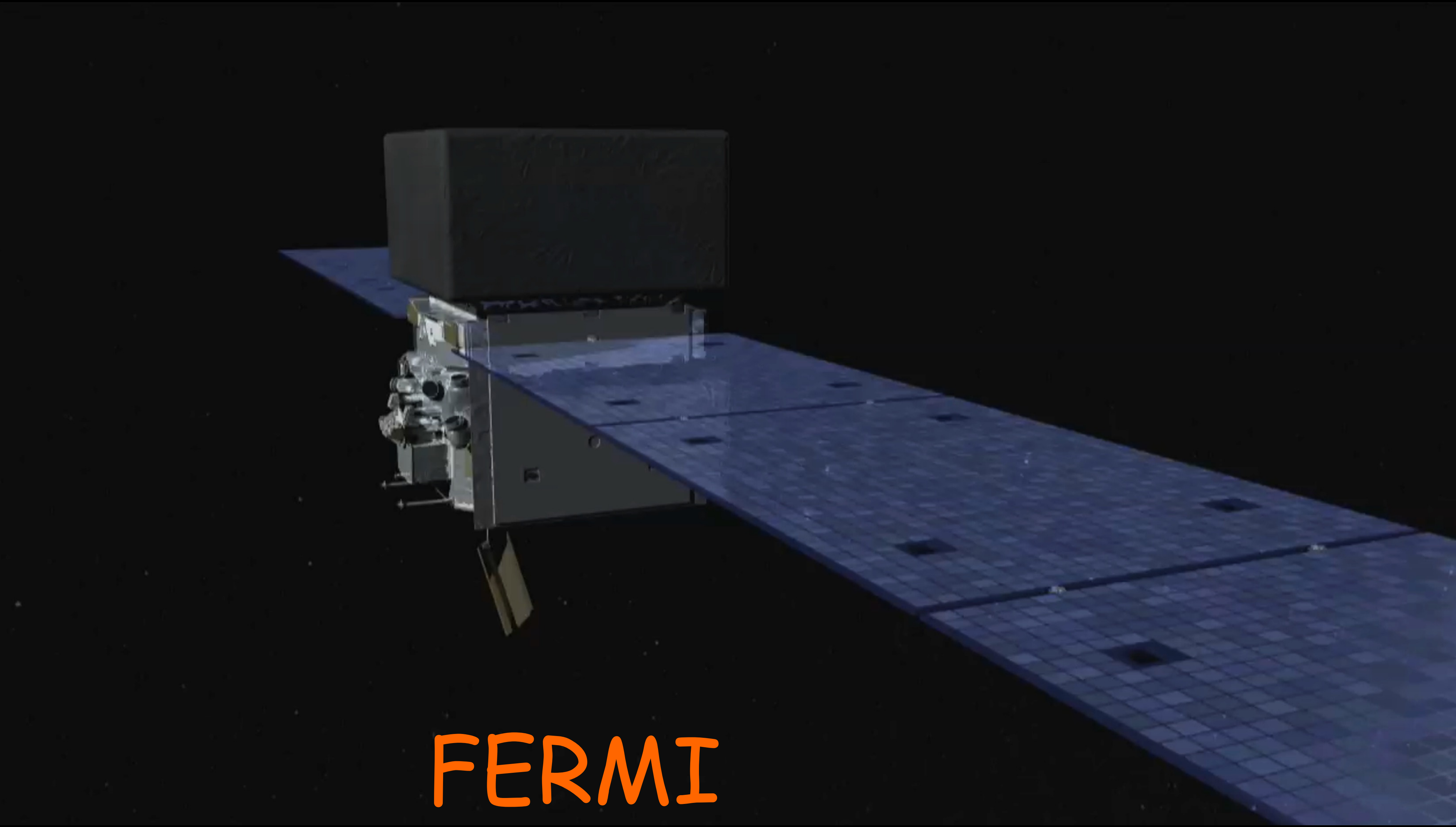
Isotropic" contributions
Large statistics, but astrophysics, galactic diffuse background

Galaxy Clusters
Low background, but low statistics

Dark Matter Search: Targets and Strategies

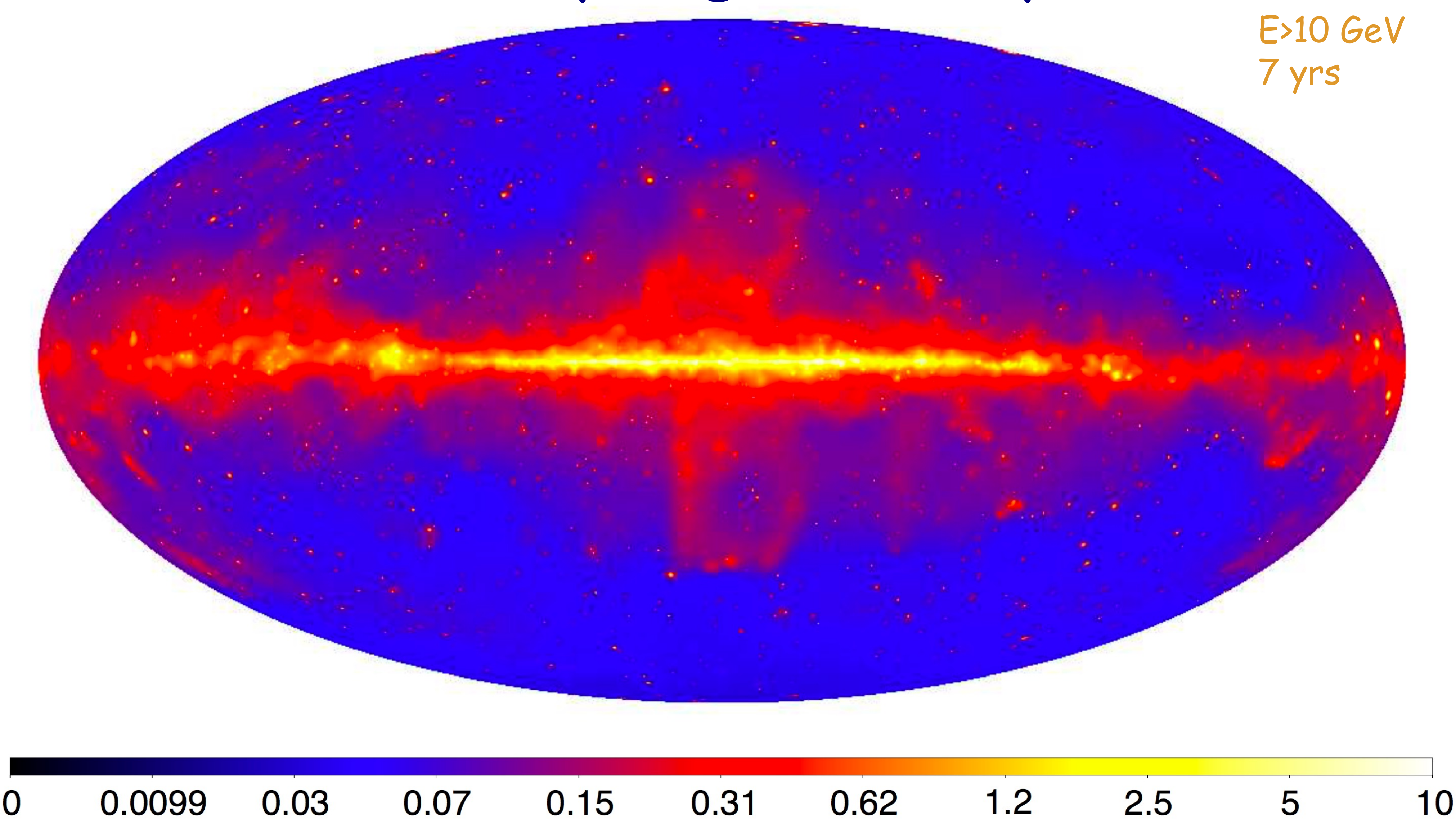
(Another way to see it)





FERMI
Large Area Telescope

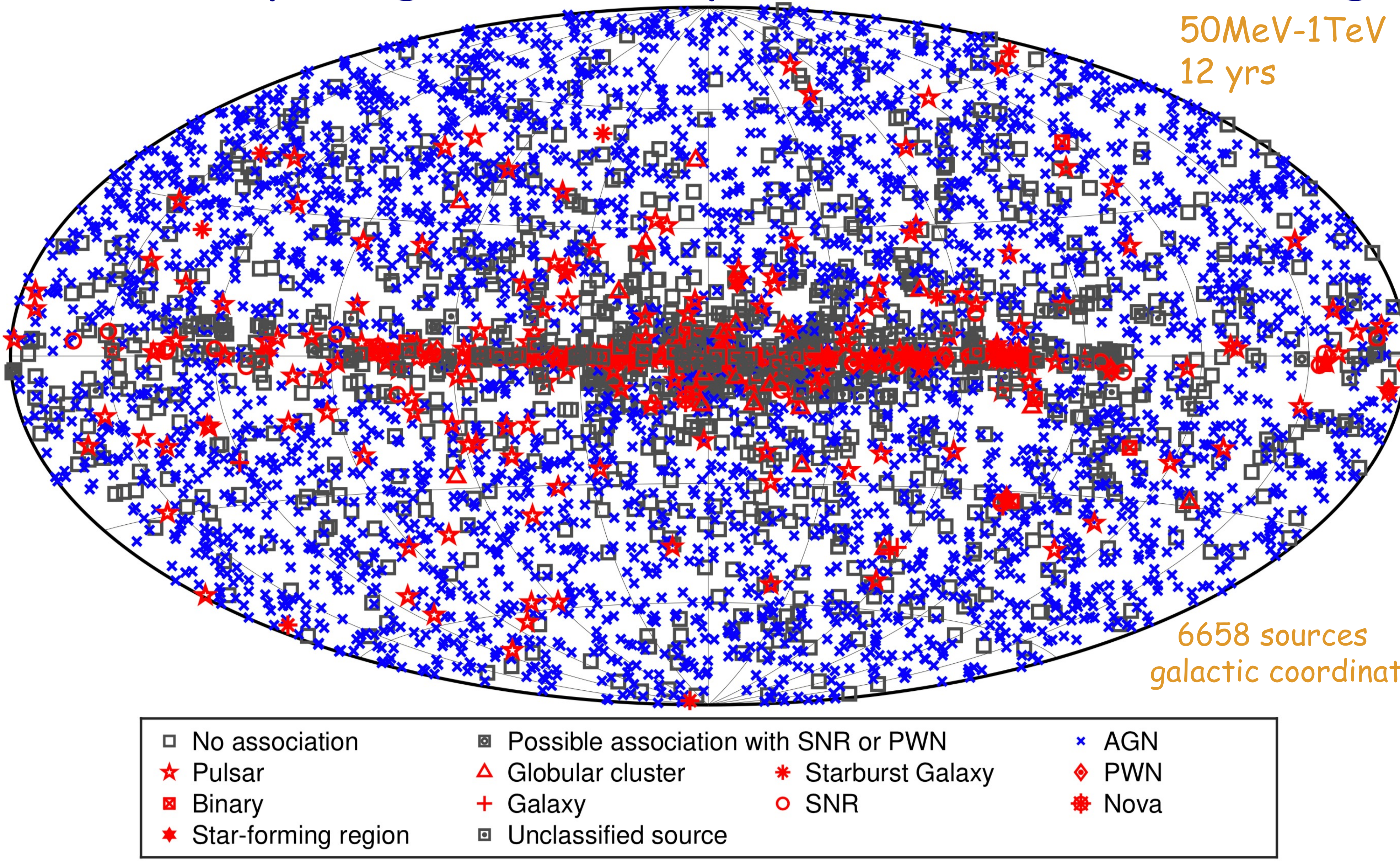
The sky in gamma-rays



M.Ackermann et al. [Fermi Coll.] 3FHL: The Third Catalog of Hard Fermi-LAT Sources ApJS 2017 232 arXiv:1702.00664

The sky in gamma-rays 4th source catalog

50MeV-1TeV
12 yrs



6658 sources
galactic coordinates

Incremental Fermi Fouth Source Catalog, ApJS 260, 53 (2022) arXiv: 2201.11184 see Dario Gasparrini's talk

the GALACTIC CENTER : any hints of Dark Matter?

the beginning of the history :

The Galactic Center as a Dark Matter Gamma-Ray Source
A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, Nuclear Physics B 113B (2002) 213-220 [astro-ph/0211327]
A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio Astroparticle Physics 21, 267-285, 2004 [astro-ph/0305075]

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope
Lisa Goodenough, Dan Hooper arXiv:0910.2998

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope
Vincenzo Vitale, Aldo Morselli, the Fermi/LAT Collaboration
Proceedings of the 2009 Fermi Symposium, 2-5 November 2009, eConf Proceedings C091122 **arXiv:0912.3828 21 Dec 2009**

Search for Dark Matter with Fermi Large Area Telescope: the Galactic Center
V.Vitale, A.Morselli, the Fermi-LAT Collaboration NIM A 630 (2011) 147–150 (Available online 23 June 2010)

Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope
Dan Hooper, Lisa Goodenough. (21 March 2011). 21 pp. **Phys.Lett. B697 (2011) 412-428**
....

Background model systematics for the Fermi GeV excess
F.Calore, I. Cholis, C. Weniger JCAP03(2015)038 **arXiv:1409.0042v1**

Fermi–LAT observations of high-energy γ-ray emission toward the galactic centre
M. Ajello et al.[Fermi-LAT Coll.] **Apj 819:44 2016 arXiv:1511.02938**

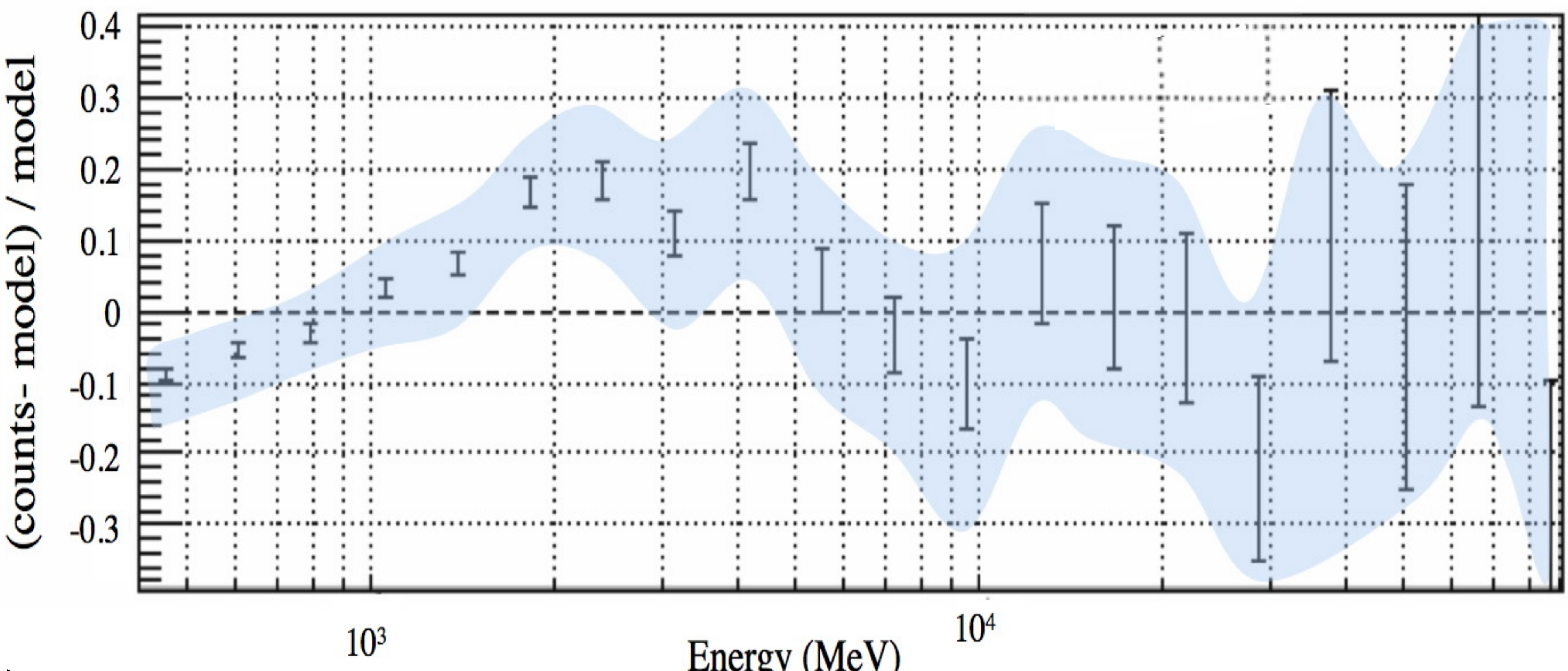
The Fermi galactic center GeV excess and implications for dark matter
M. Ajello et al.[Fermi-LAT Coll.] **Apj 819:44 2016 arXiv:1511.02938**

Revisiting the Gamma-Ray Galactic Center Excess with Multi-Messenger Observations
IC, Zhong, McDermott, Surdutovich, PRD 105, 103023 (2022)

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

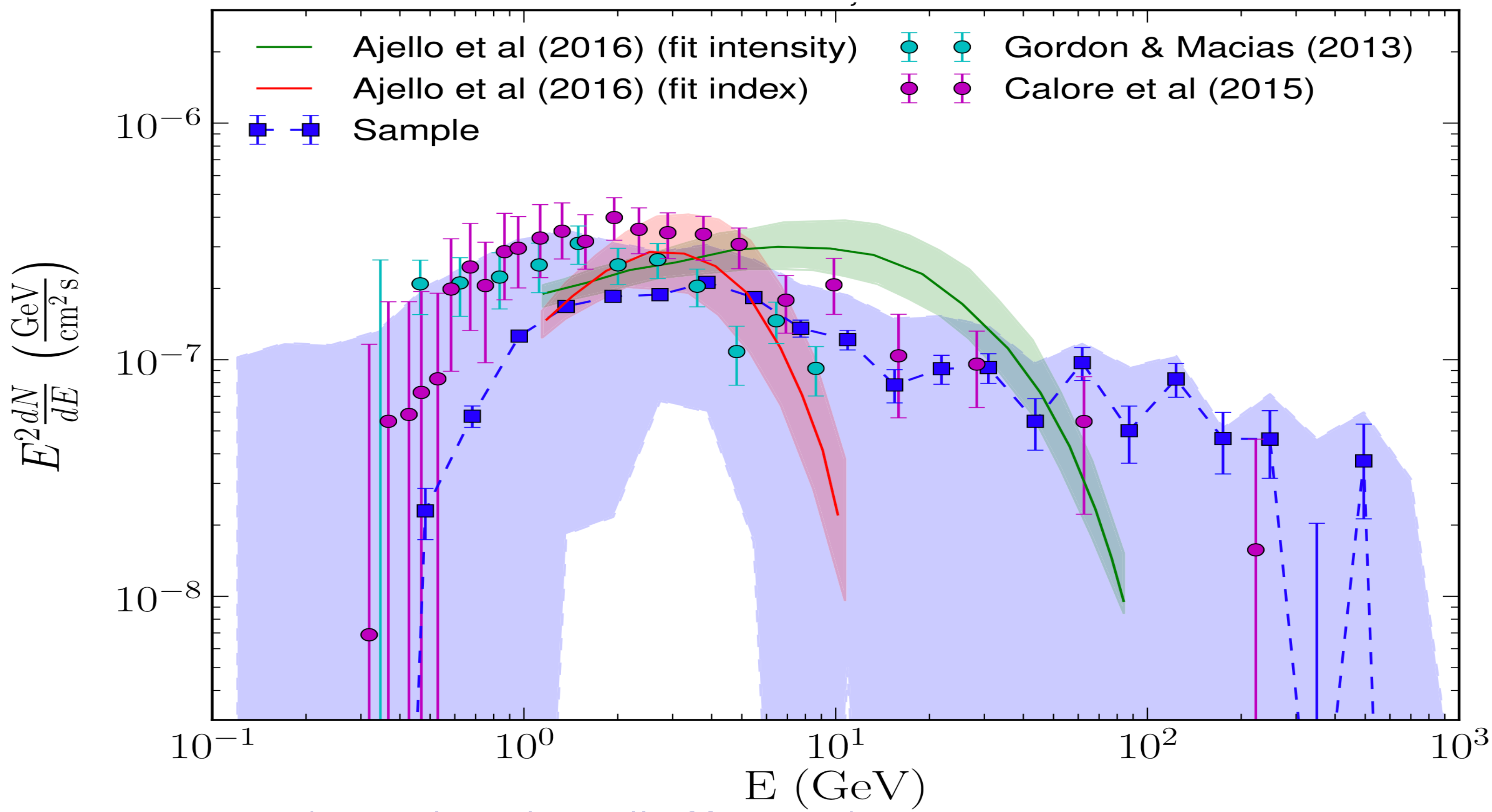
11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

- 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 (Pass8 analysis)



following uncertainties have relatively small effect on the excess spectrum

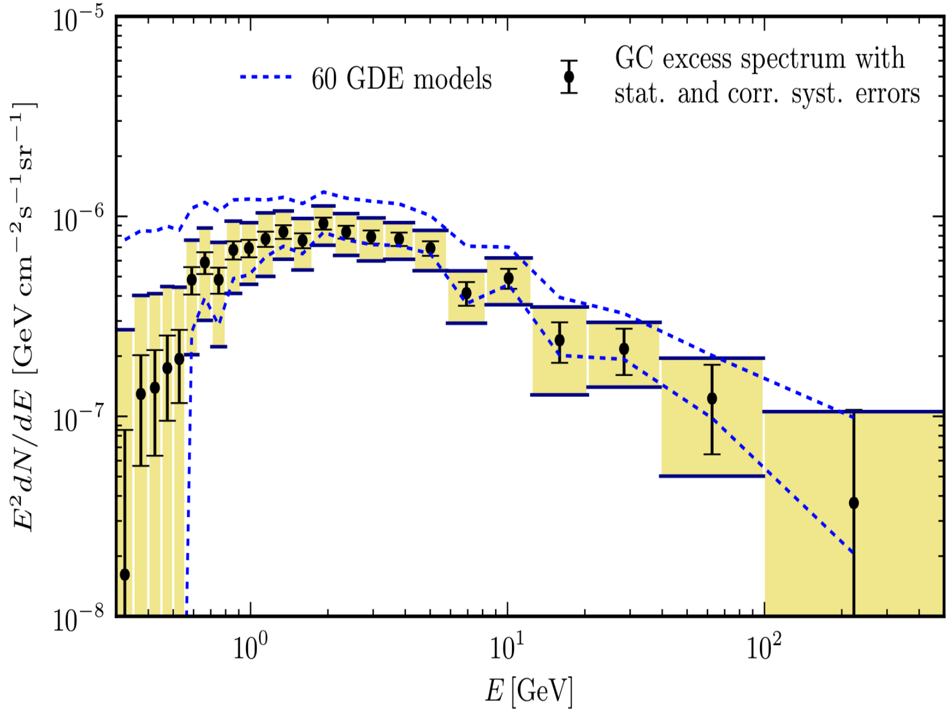
- Variation of GALPROP models – Distribution of gas along the line of sight

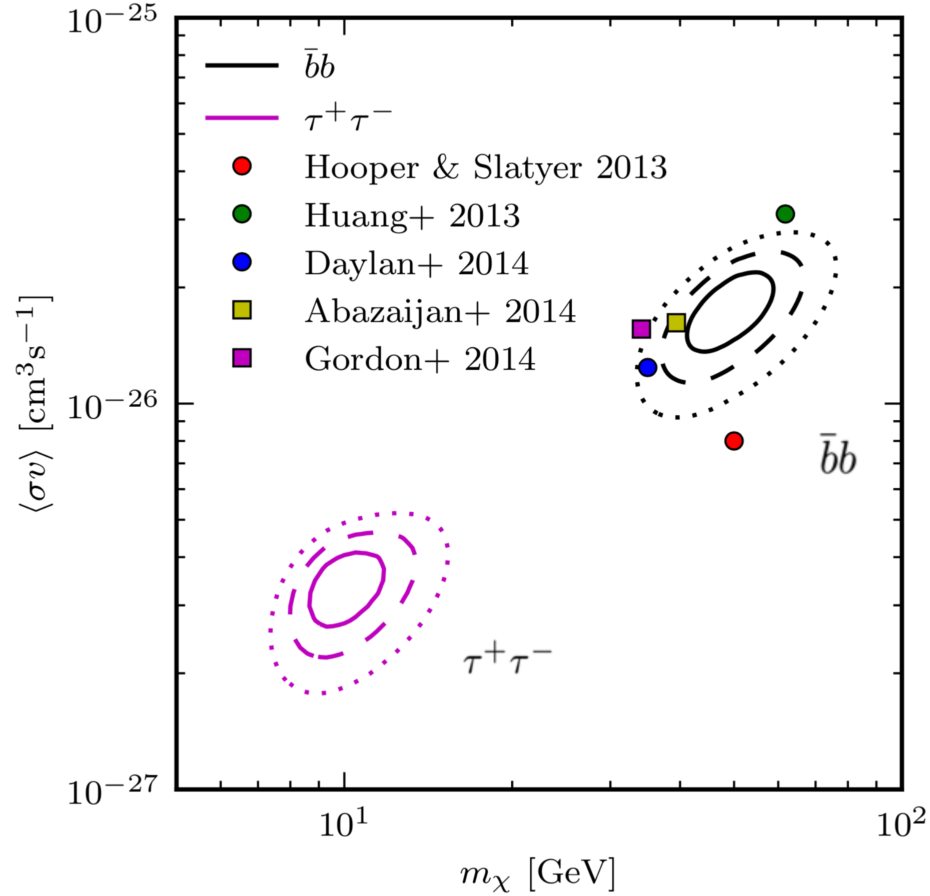
- **Most significant sources of uncertainty are:**

- Fermi bubbles morphology at low latitude – Sources of CR electrons near the GC

Fermi-LAT Collaboration Apj 840:43 2017 May 1 arXiv:1704.03910

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:1409.0042
Cholis et al., Phys. Rev. D 105, 103023 (2022) arXiv:2112.09706

The GeV excess : Other explanations exist

• past activity of the Galactic center

(e.g. Petrovic et al., arXiv:1405.7928, Carlson & Profumo arXiv:1405.7685)

• Series of Leptonic Cosmic-Ray Outbursts

Cholis et al. arXiv:1506.05119

• Stellar population of the X-bulge and the nuclear bulge

Macias et al. arXiv:1611.06644

• Population of pulsars in the Galactic bulge

e.g. , Yuan and Zhang arXiv:1404.2318v1, Lee et al. arXiv:1506.05124, Bartels et.al. 1506.05104

M.Ajello et al. [Fermi-LAT Coll.] Phys. Rev. D 95, 082007 (2017) [arXiv:1704.07195]

....

How to discriminate between different hypothesis ?

How to discriminate between different hypothesis ?

eROSITA

- Modeling of the Fermi bubbles
- Look for correlated features near the Galactic center

HESS, MAGIC, CTA

- Fermi bubbles near the GC are much brighter
- Possible to see with Cherenkov telescopes?

Radio observations, MeerKAT, SKA

- Search for individual pulsars in the halo around the GC

Radio surveys, Planck

- Look for correlated synchrotron emission near the GC

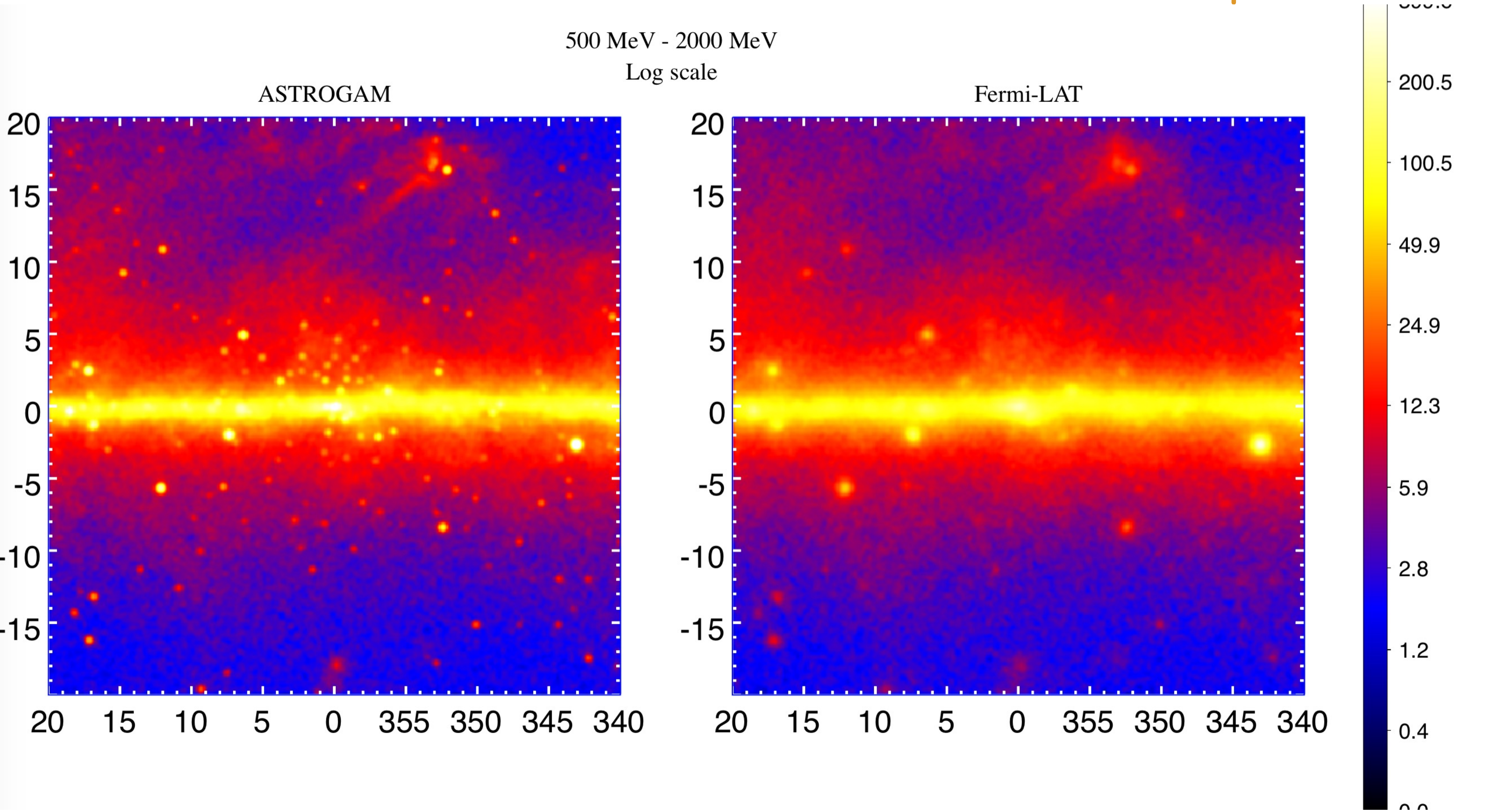
More Fermi LAT analysis

- Diffuse emission modeling
- Analysis of point sources near the GC

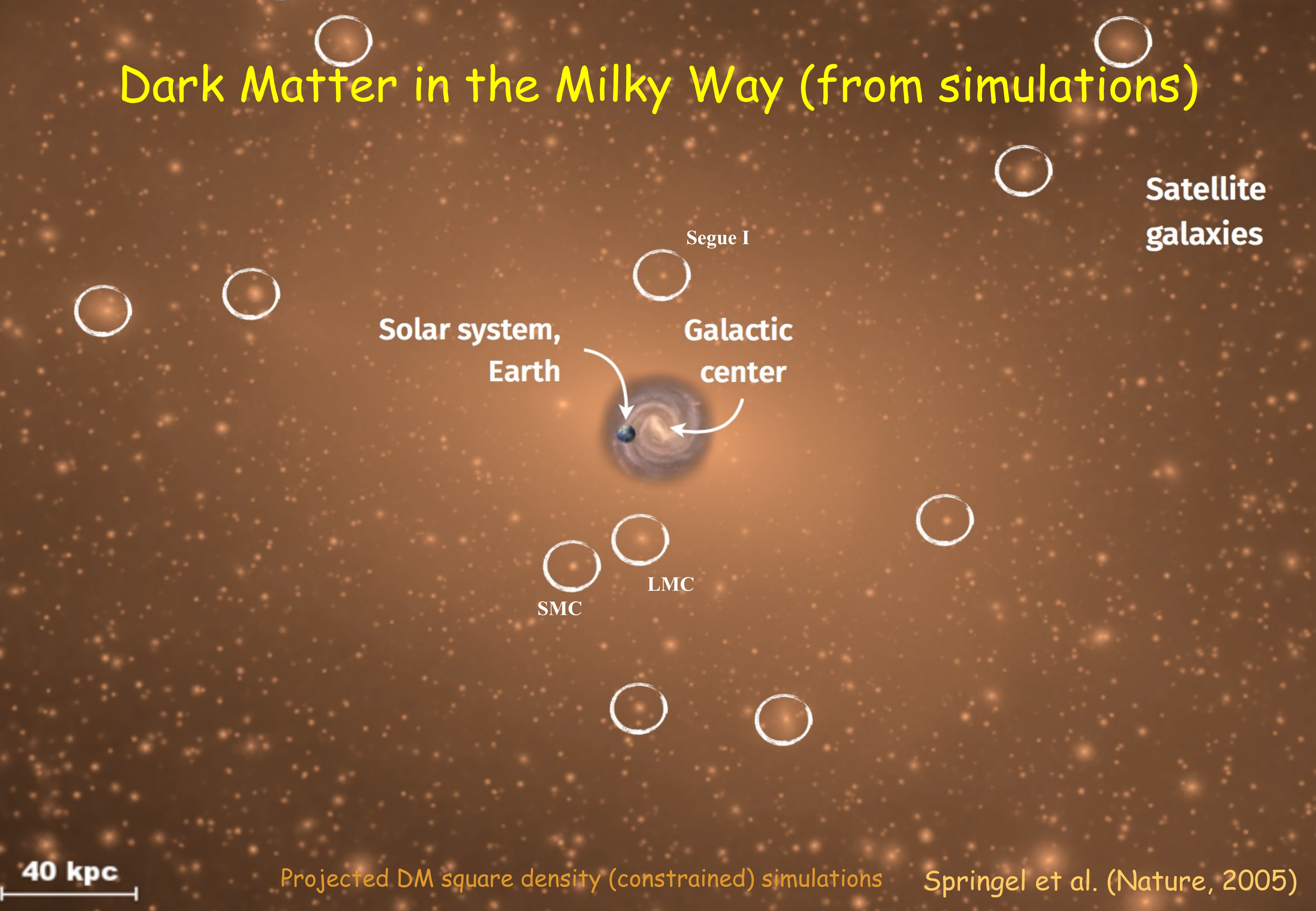
But ultimately We need a new experiment with better angular resolution below 100 MeV

Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source



Dark Matter in the Milky Way (from simulations)

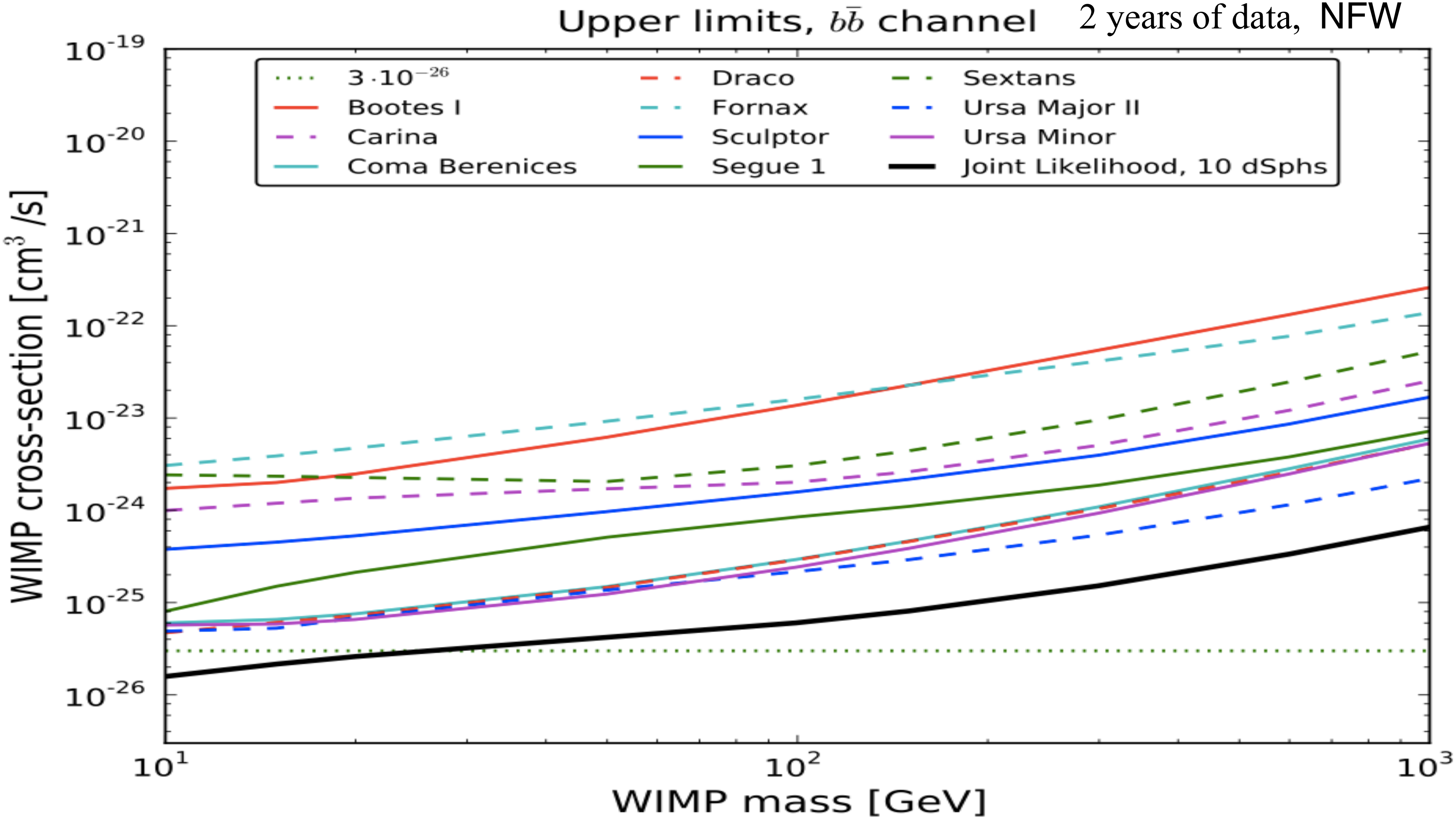


Projected DM square density (constrained) simulations

Springel et al. (Nature, 2005)

Dwarf Spheroidal Galaxies combined analysis

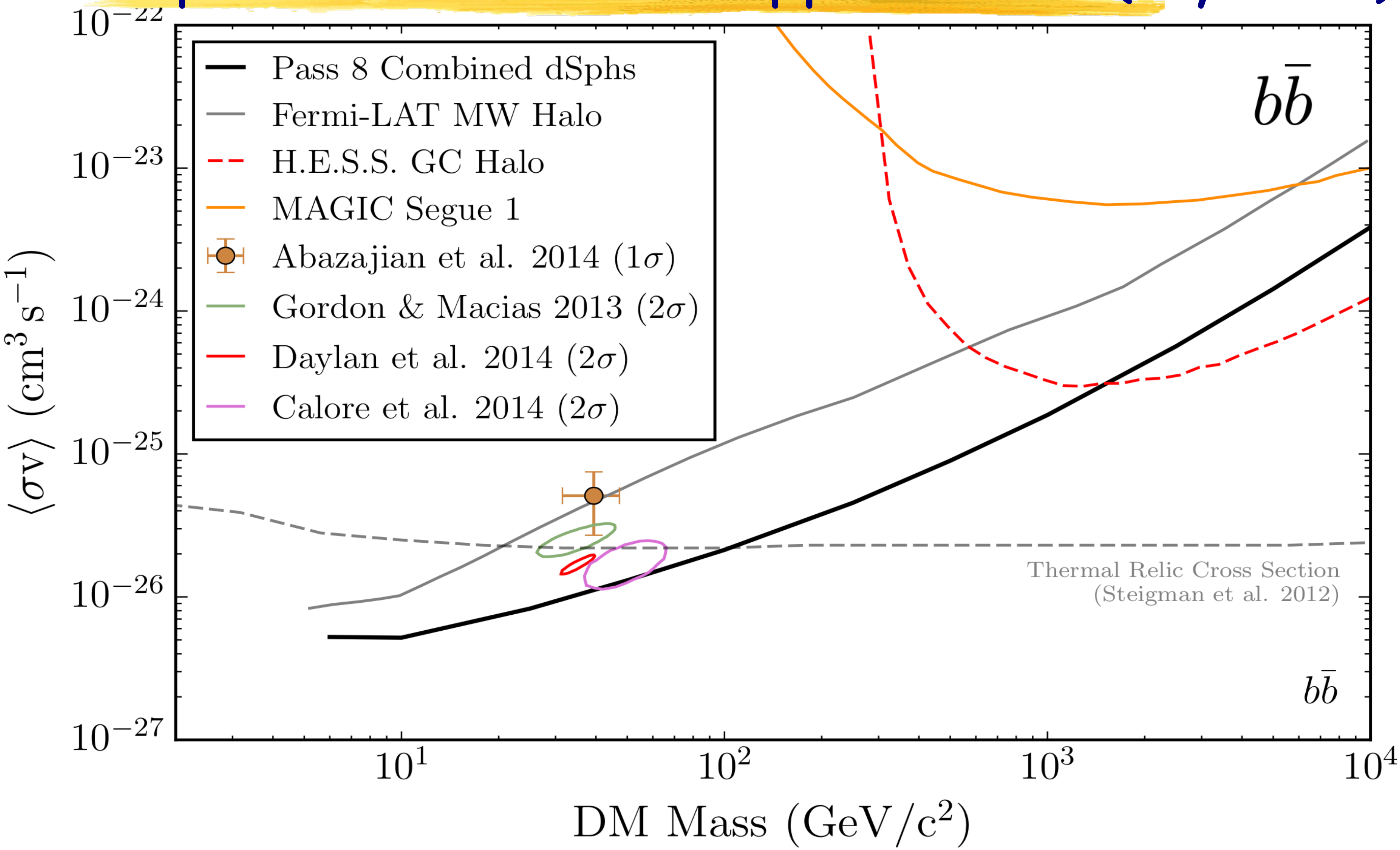
2 years of data, NFW



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

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]

see Alex McDaniel's talk

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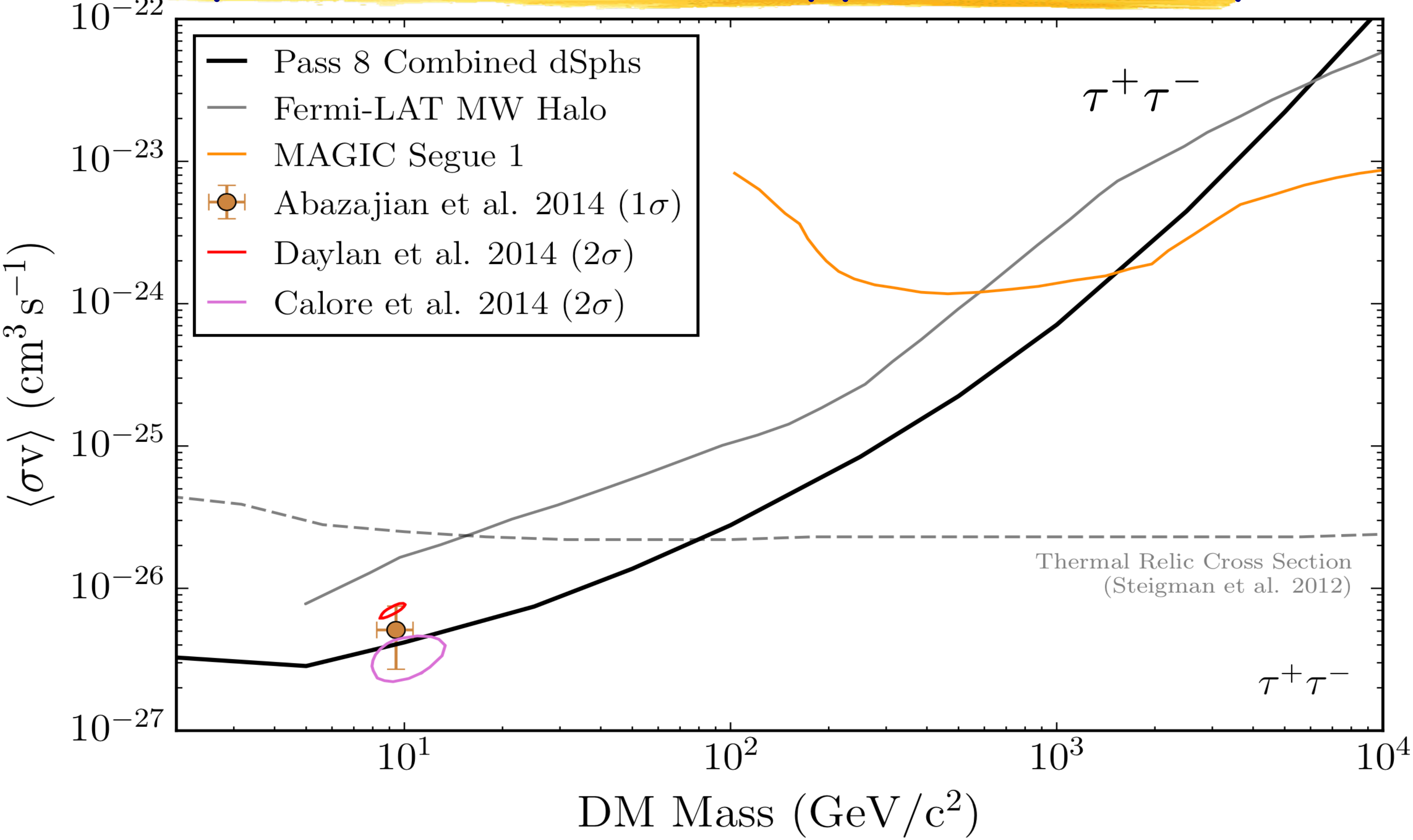


M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

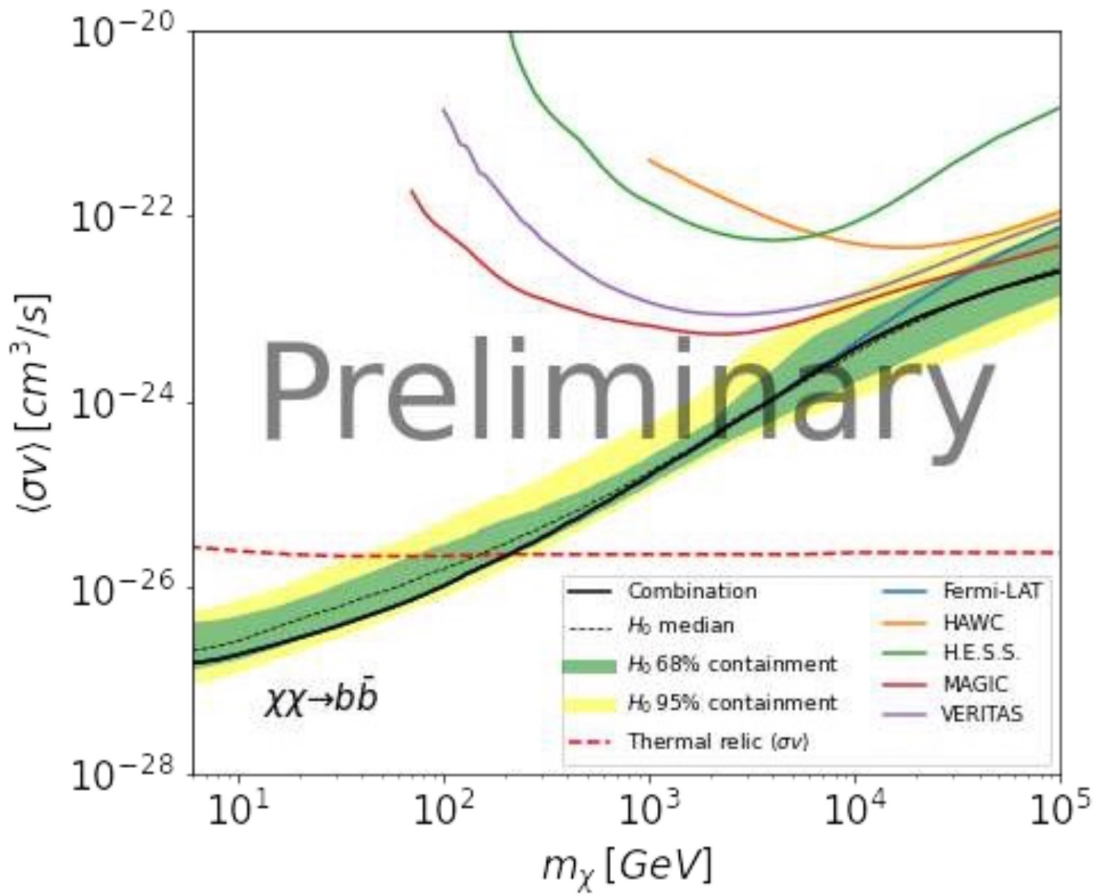
see the update in Alex McDaniel' s talk

Combining all dSph observations

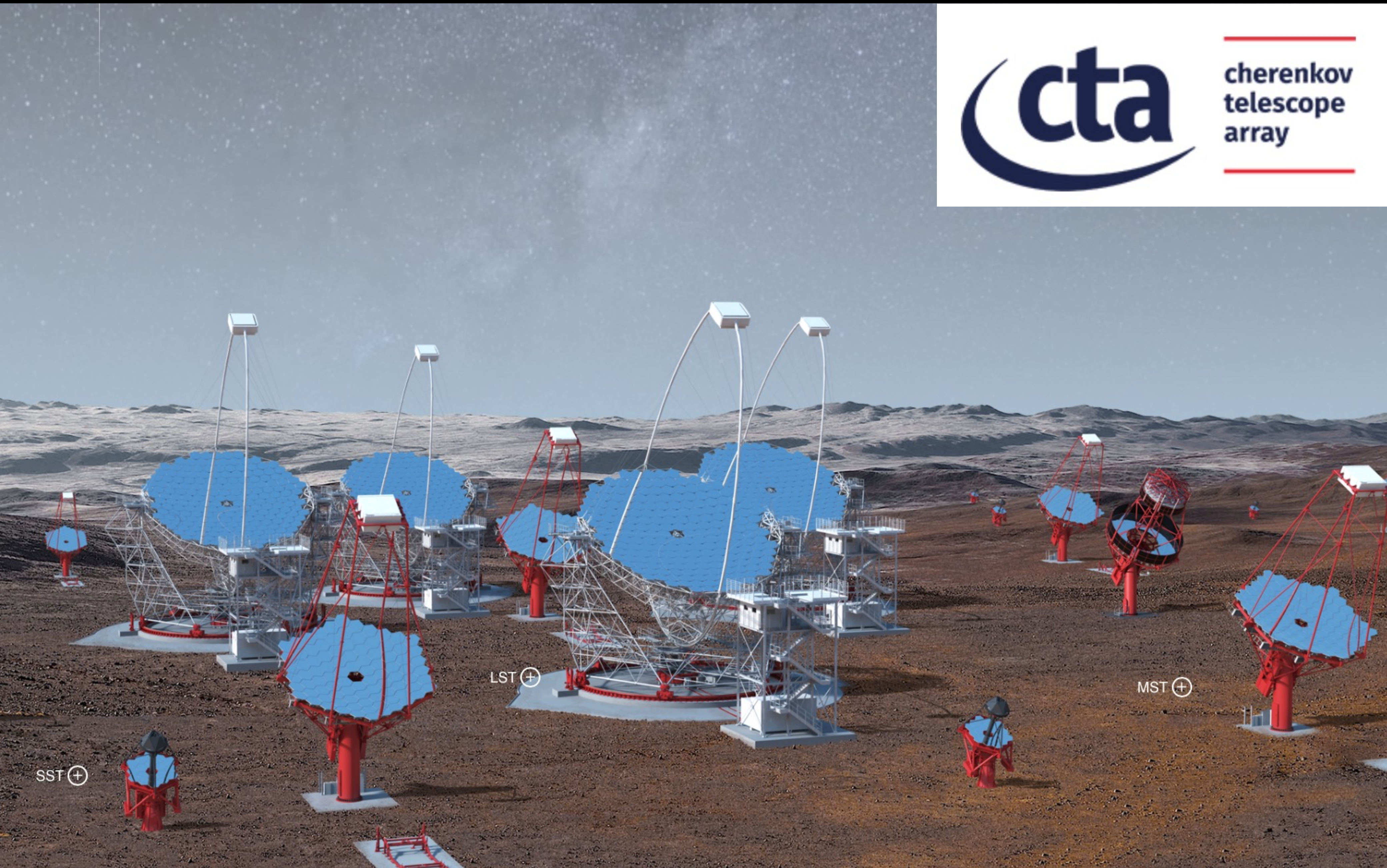
Fermi Gamma-ray Space Telescope | HAWC High Altitude Water Cherenkov Gamma-Ray Observatory | H.E.S.S. | MAGIC | VERITAS

- 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

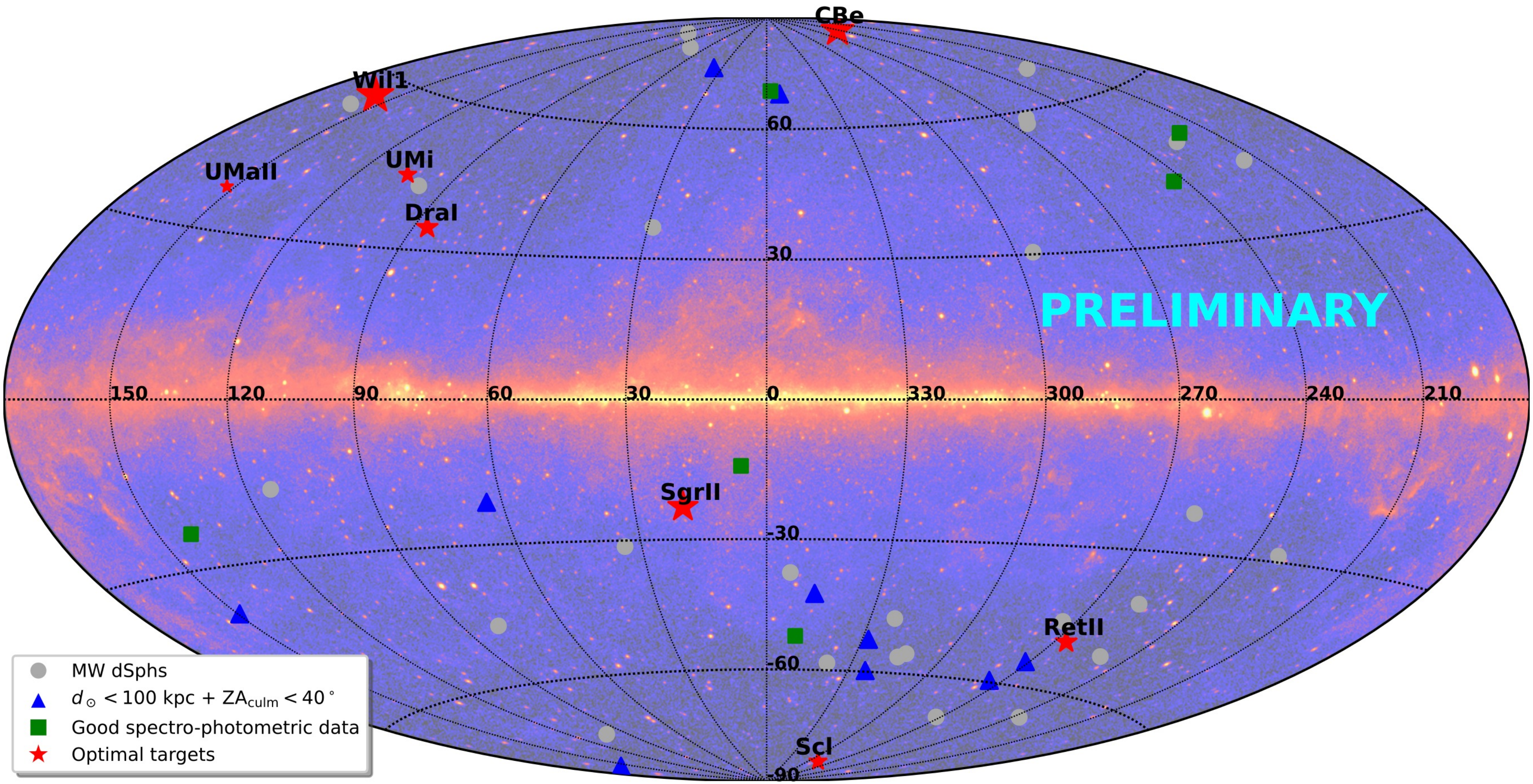
- Common elements :
- Agreed model parameters
- Sharable likelihood table formats
- Joint likelihood test statistic



see Daniel Kerszberg's talk


cta
cherenkov
telescope
array
LST
MST
SST

Dwarf Spheroidal Galaxies: Selection of optimal candidates for CTA



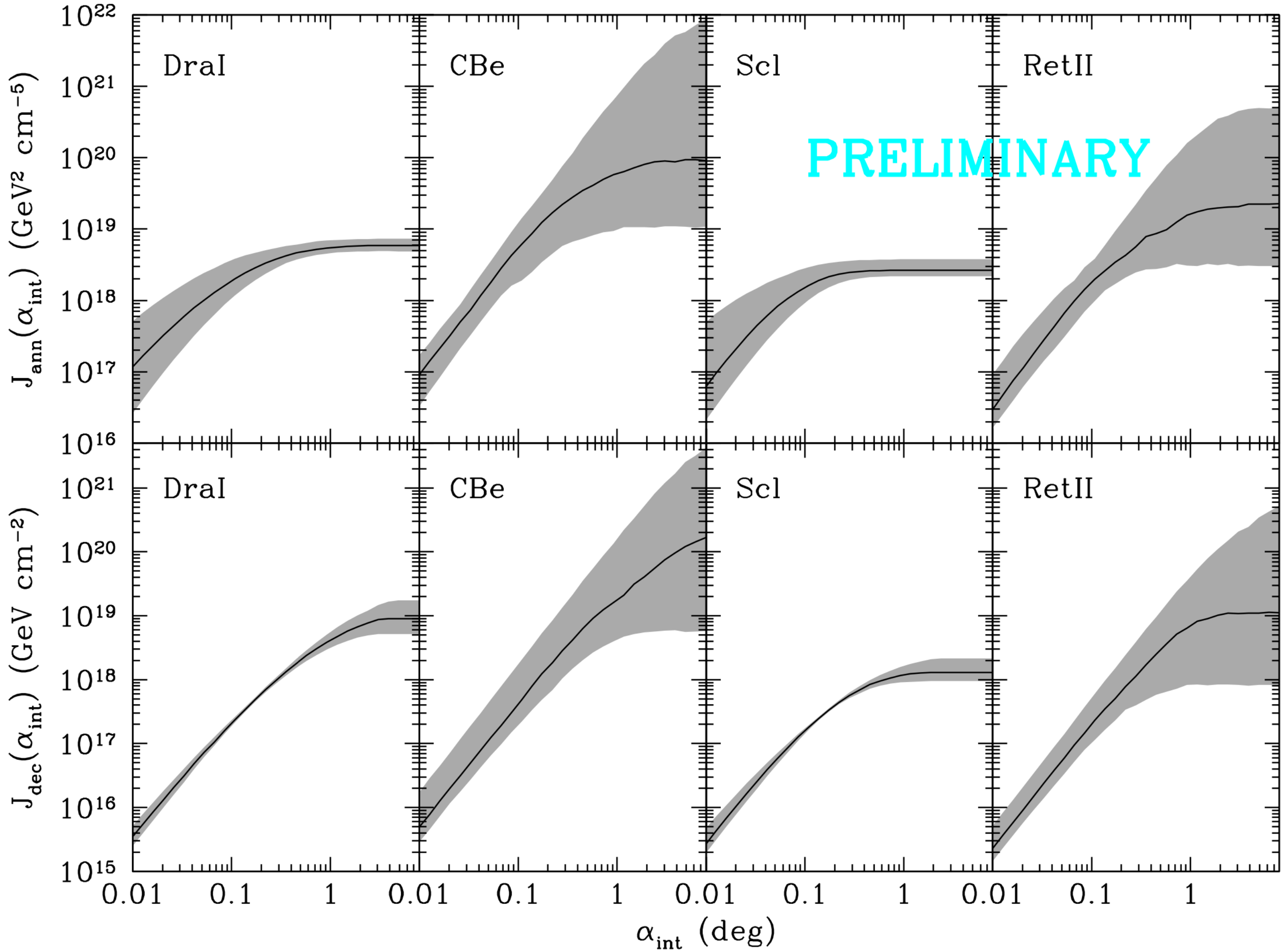
Optimal dSphs selected according to:

1.distance (d < 100 pc) 2. culmination zenith angle (ZA < 40°) 3. availability of good spectro-photometric data.

Surviving sample: 8 Northern dSphs (2 classical + 6 ultra-faint) 6 Southern dSphs (3 classical + 3 ultra-faint)

CTA Consortium paper in prep. and ICRC 2023 by the dSph task force F. G. Saturni, M. Doro, A. Morselli, G. Rodríguez-Fernández

Measuring Dark Matter densities in dSph halos: MCMC Jeans analysis of dSph data



annihilation

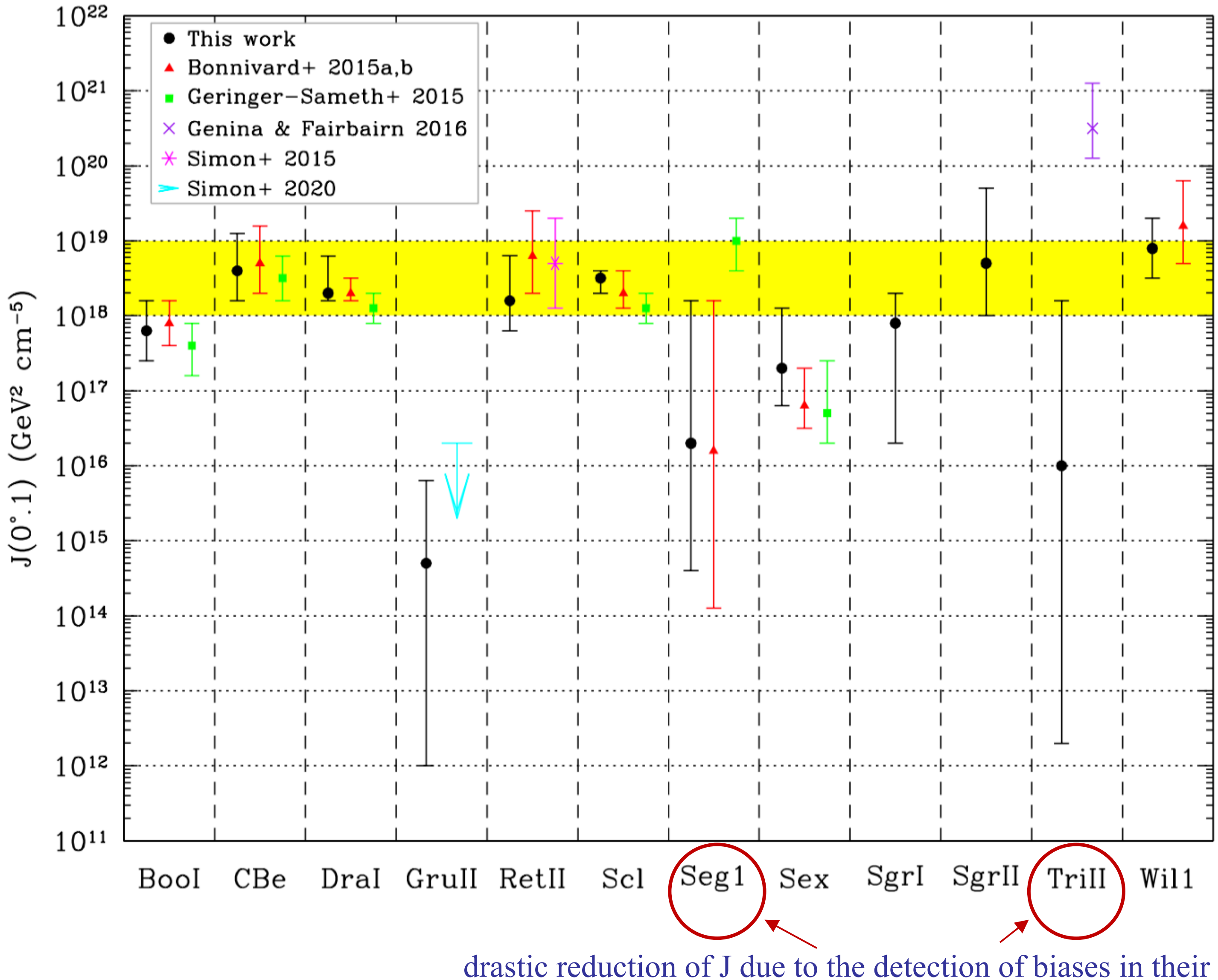
decay

Astrophysical factors (Einasto profile) for DM annihilation and decay computed from posterior distributions of best-fit parameters as a function of the integration angle

CTA Consortium paper in prep. and ICRC 2023 by the dSph task force F. G. Saturni, M. Doro, A. Morselli, G. Rodríguez-Fernández

Measuring Dark Matter densities in dSph halos

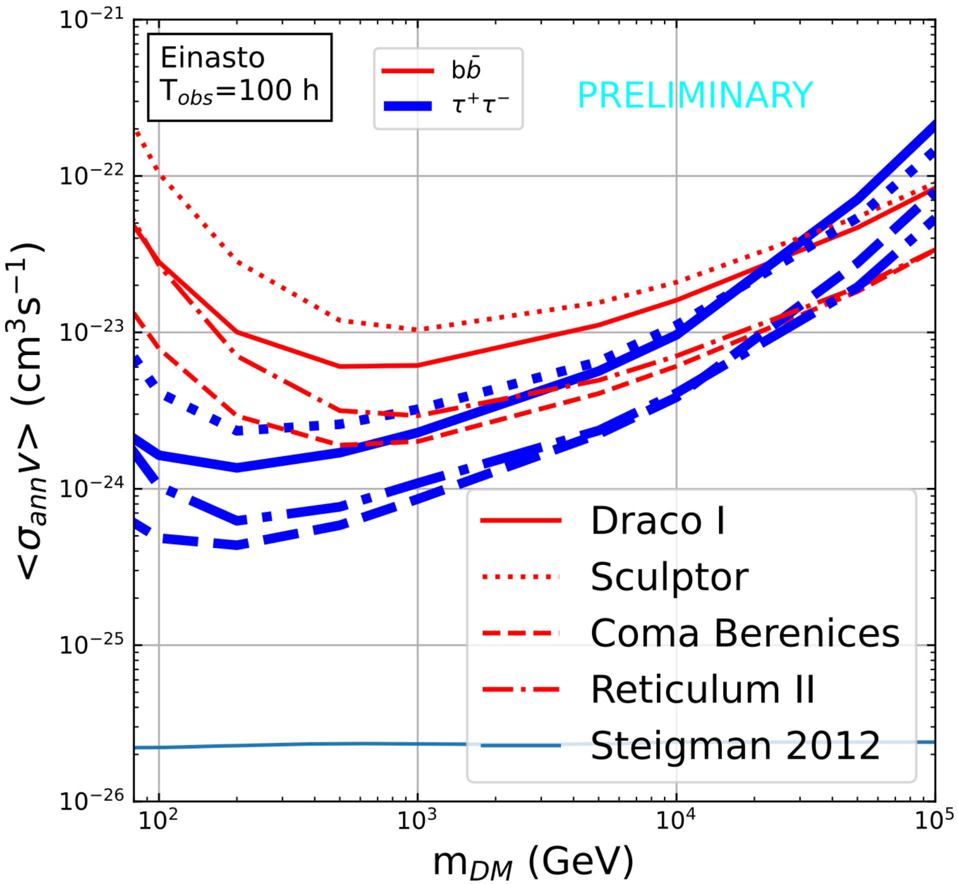
Comparison of astrophysical factor for DM annihilation within 0.1 deg of integration



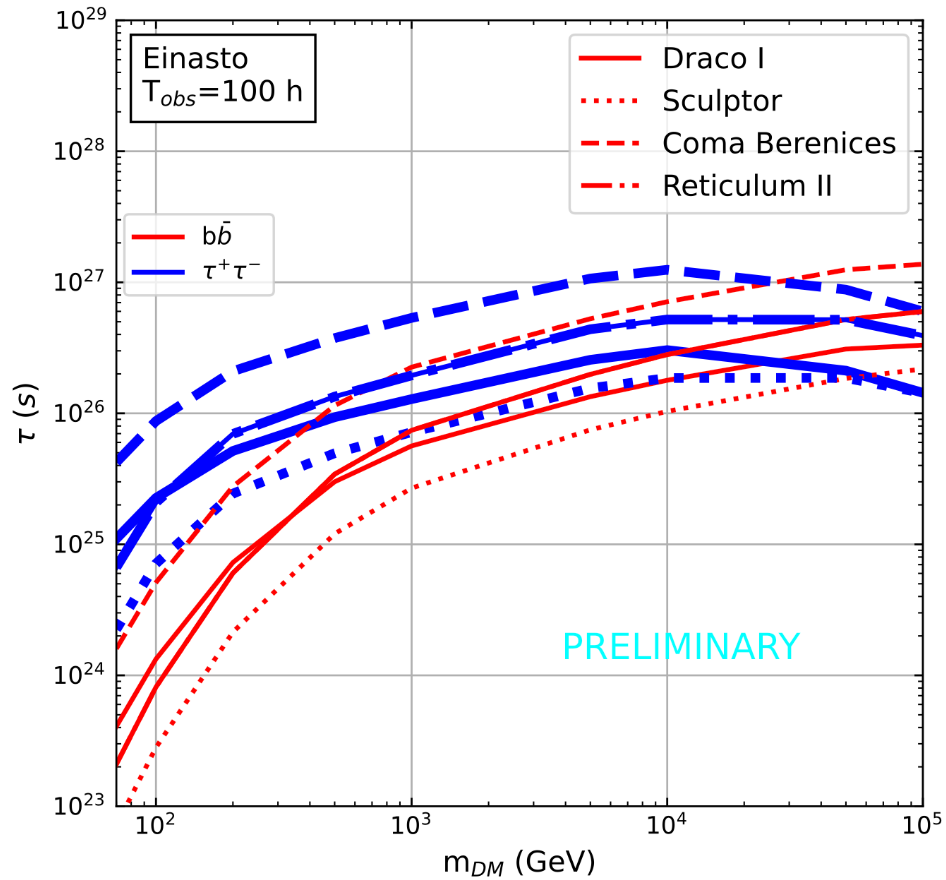
CTA Consortium paper in prep. and ICRC 2023 by the dSph task force F. G. Saturni, M. Doro, A. Morselli, G. Rodríguez-Fernández

Dwarf Spheroidal Galaxies: CTA Sensitivity

computed upper limits on annihilating DM cross sections



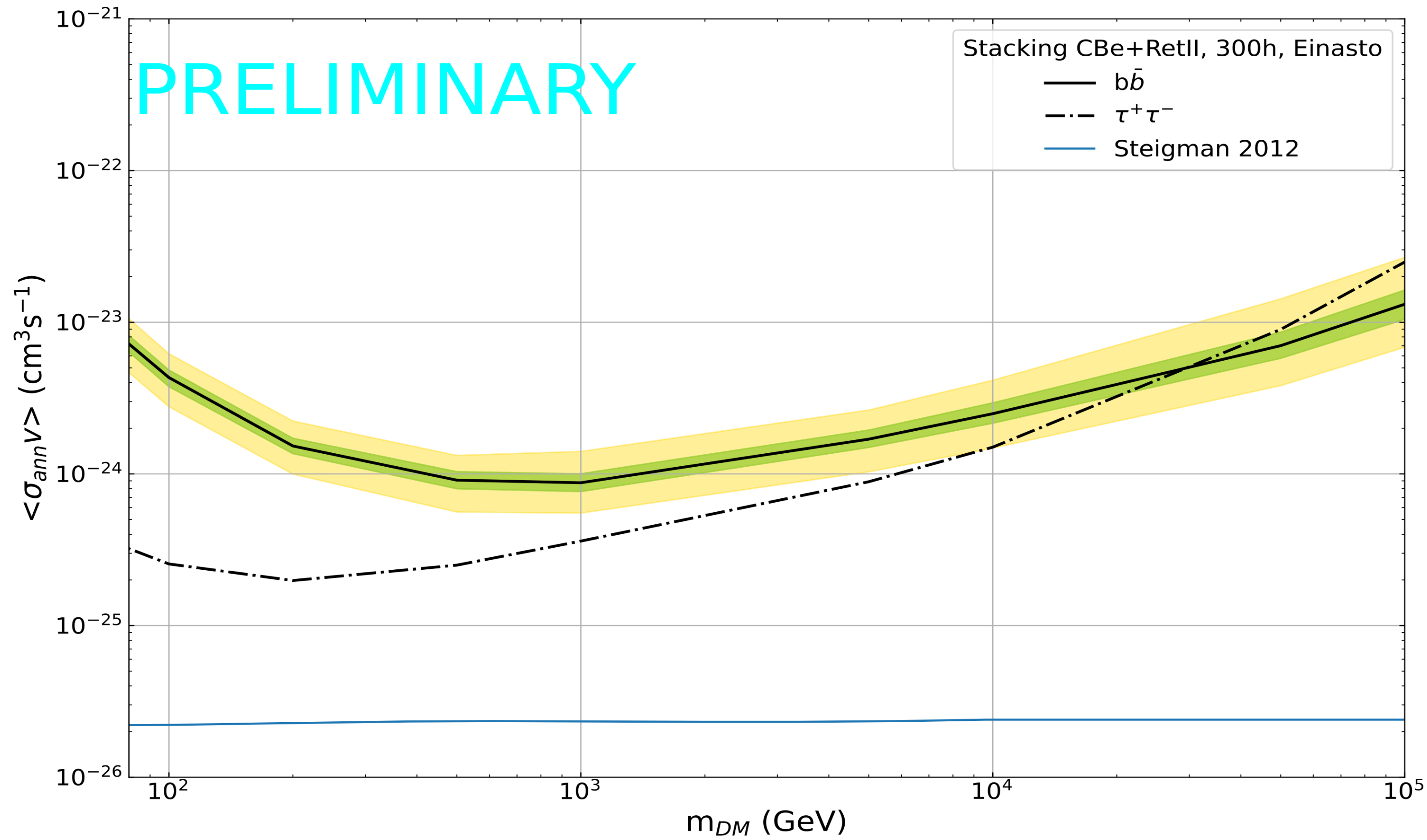
computed lower limits on the particle lifetime



computed with the Einasto DM density profile derived by CLUMPY,
assuming 100 h of observation for annihilation in the two pure DM channels $b\bar{b}$ and $\tau^+\tau^-$

CTA Consortium paper in prep. and ICRC 2023 by the dSph task force F. G. Saturni, M. Doro, A. Morselli, G. Rodríguez-Fernández

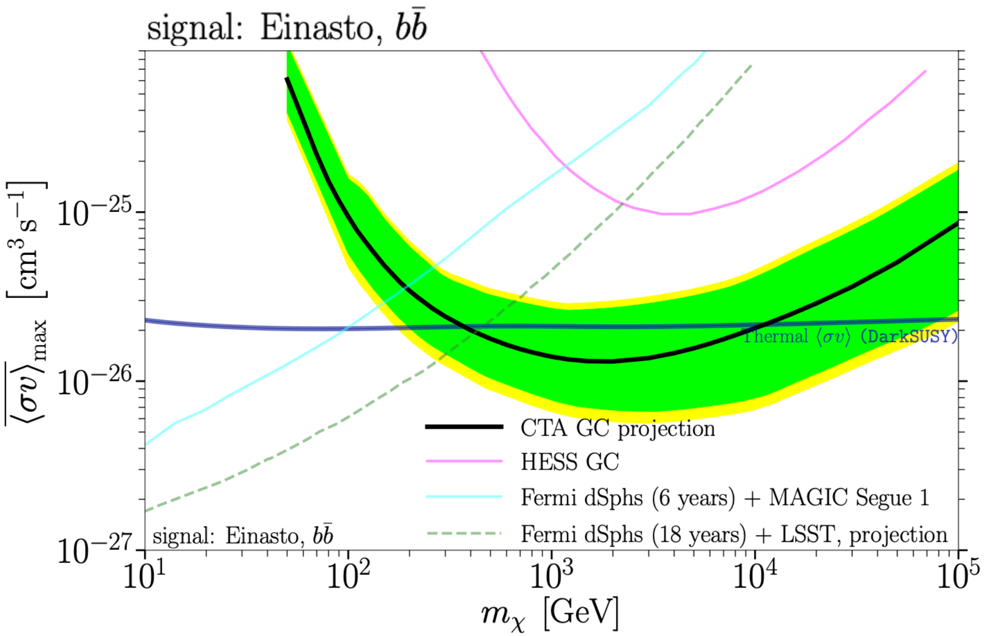
Dwarf Spheroidal Galaxies: Stacking analysis

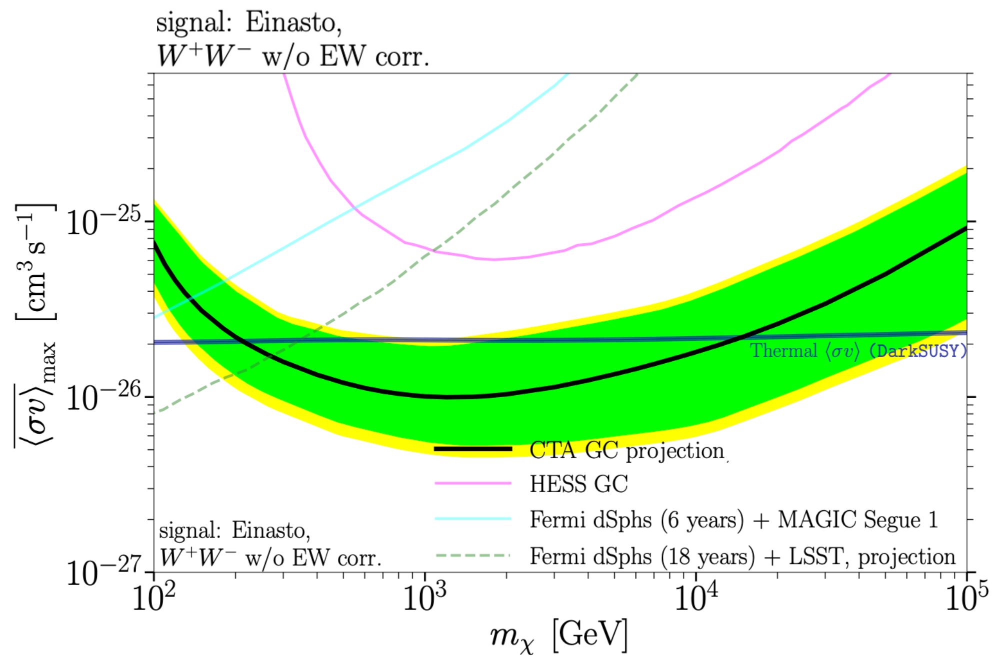


- Stacking analysis performed on 600 h of CBe+RetII observations (300 h each) for the DM annihilation into $bb^{-}$and $\tau+\tau-$
- Depending on the choice of target and the interaction channel, CTA can reach x-sections <10- 24 cm3 s-1 for DM particle masses >1 TeV.

CTA Consortium paper in prep. and ICRC 2023 by the dSph task force F. G. Saturni, M. Doro, A. Morselli, G. Rodríguez-Fernández

Galactic center CTA Sensitivity





- Einasto profile

525 h

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

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

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

CTA Key Science Project Targets

- Galactic Center

high DM density but high astrophysical emissions

- dSph

no background but low signal

- LMC

neaby & massive but astrophysical emissions

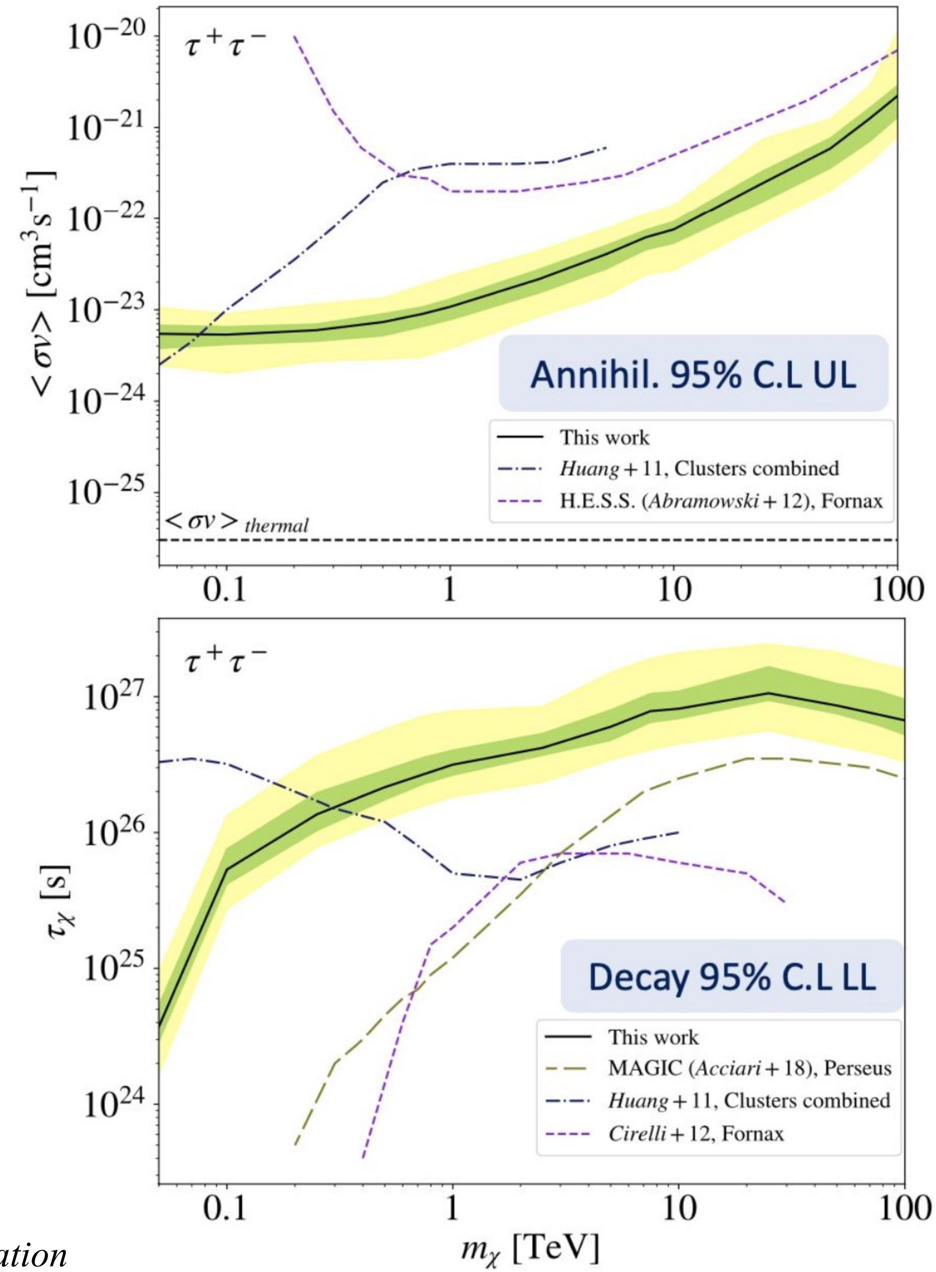
- galaxy clusters

very massive (best for decay)

Perseus cluster

Expected CTA sensitivity

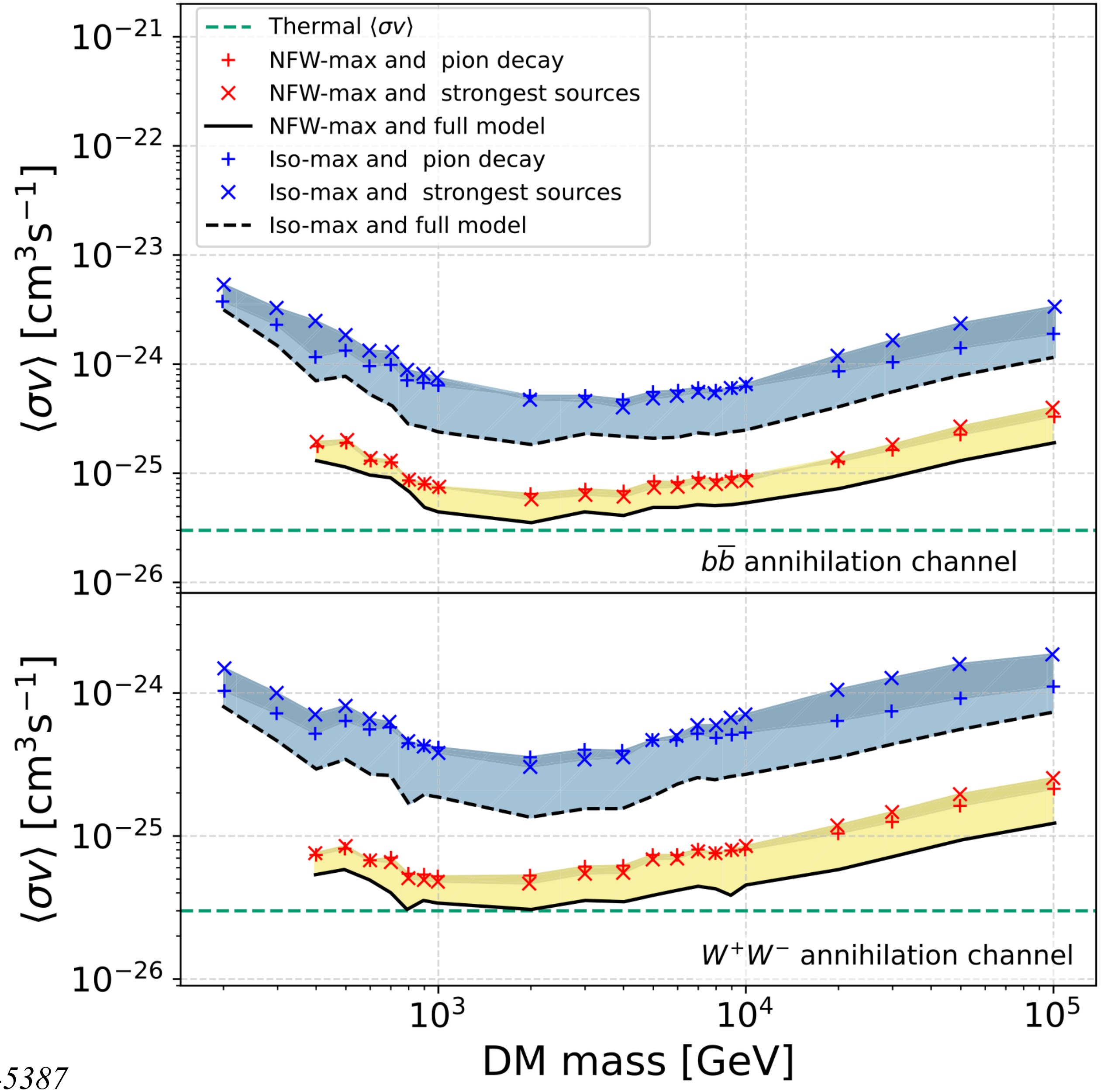
- Distance: 75 Mpc
- Dark matter content: $\log_{10}J$ [GeV^{2}cm^{-5}] =18.43
  $\log_{10}D$[GeV^{2}cm^{-2}] =19.20
- Observation time: 300 h
- Astrophysical gamma-ray sources:
  - Active Galactic Nuclei
  - diffuse emission (CR interactions)



The CTA Consortium, in preparation

DM searches in the Large Magellanic Cloud

- Distance: 50.1 kpc
- Dark matter content: $\log_{10} J[\mathrm{GeV}^2 \mathrm{cm}^{-5}] = 21.14$
- Observation time: 340 h
- Astrophysical gamma-ray sources:
  - 4 known sources: SNR, PWN
  - diffuse emission (CR interactions)



The CTA Consortium, MNRAS 523 (2023) 4, 5353-5387

CTA Search for Dark Matter beyond WIMP

Axion Like Particle (ALP) search prospects

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

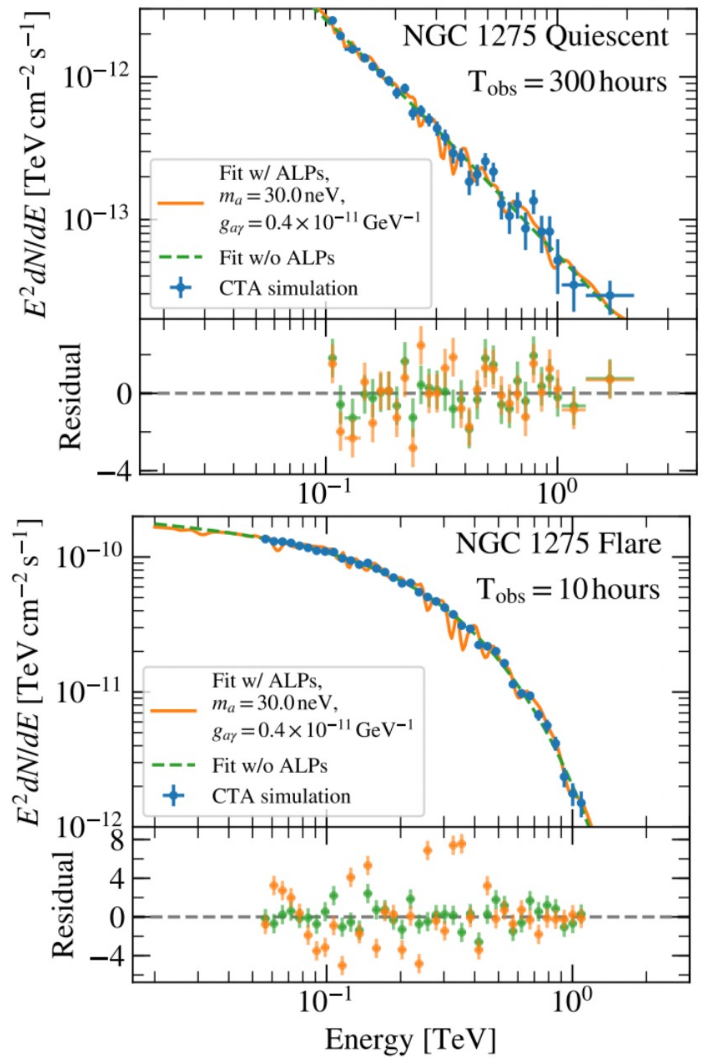
conversion probability ($E > E_{crit}$)

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

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

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



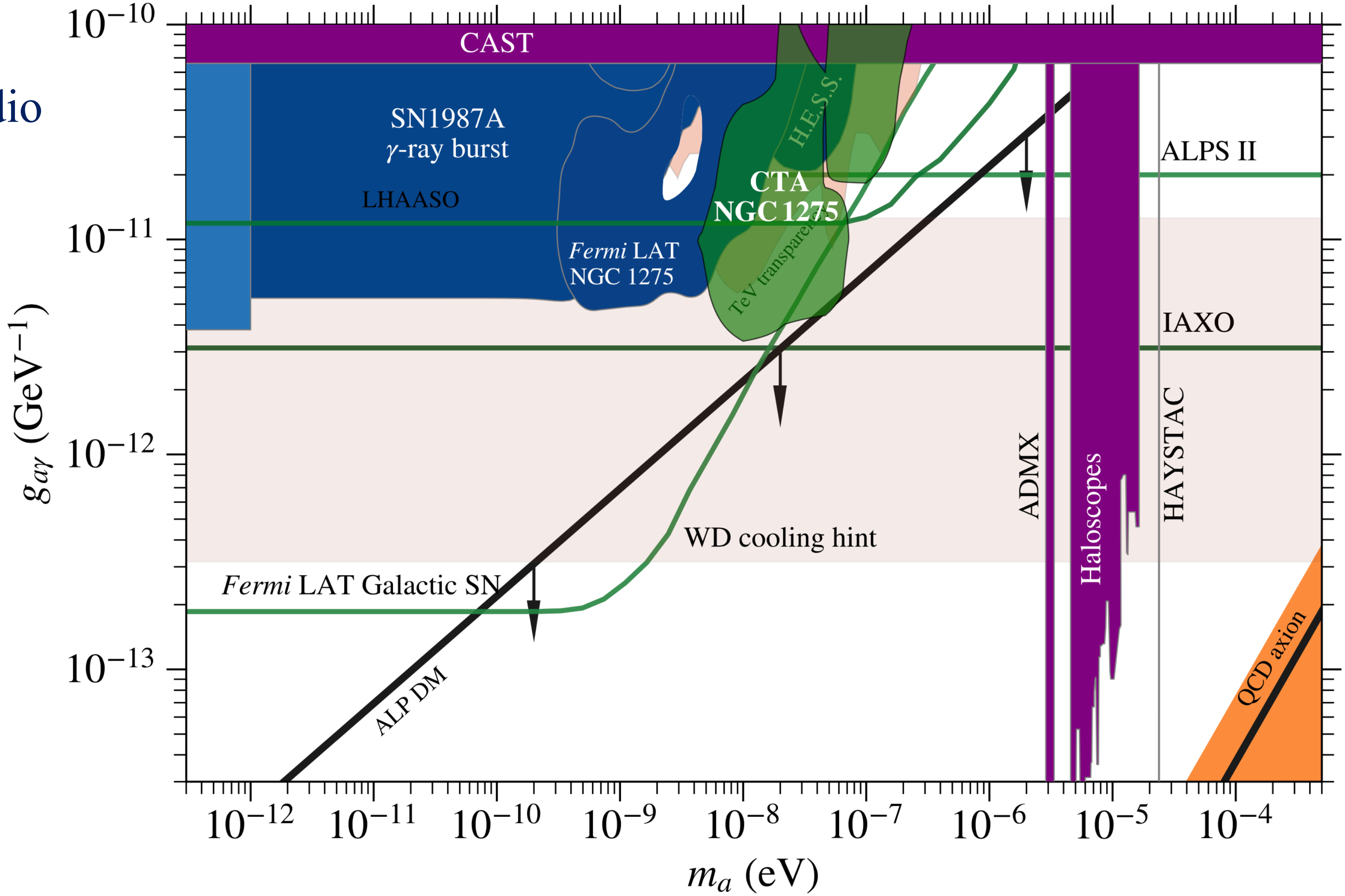
The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]

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.

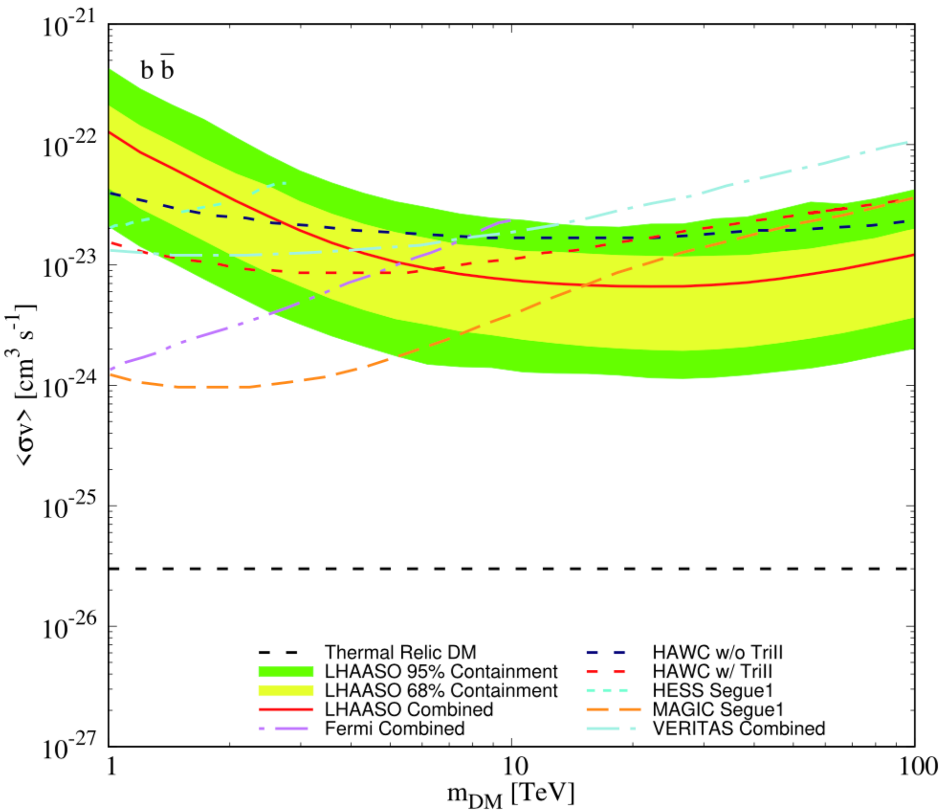


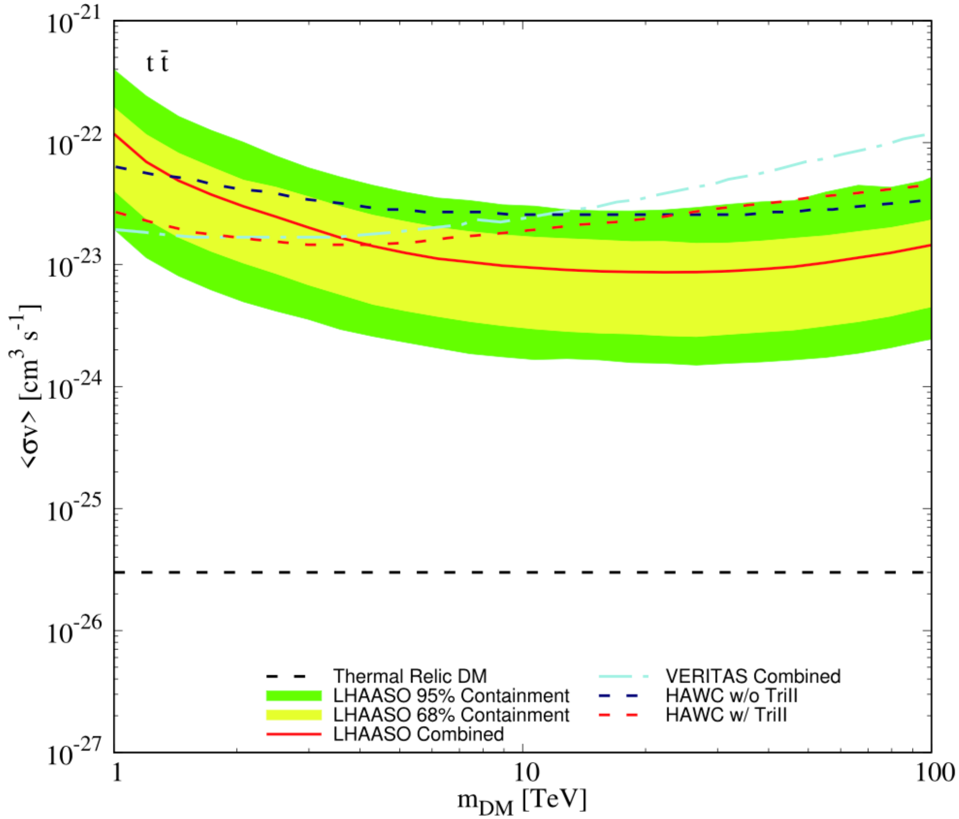
The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]

LHAASO

Mt. Haizi 4410 altitude

Combined one-year LHAASO sensitivities

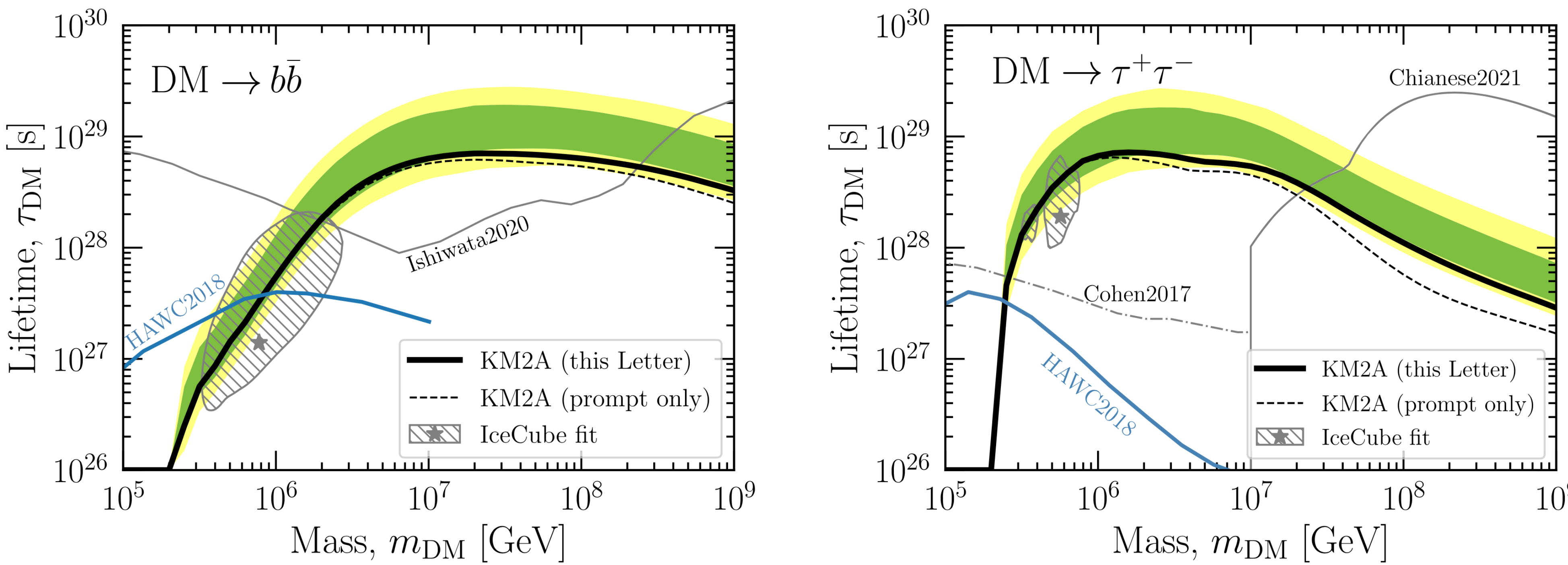




The LHAASO median combined sensitivities (red solid lines) and related two-sided 68% (yellow bands) and 95% (green bands) containment bands of one year for the bb̄, t̄t for 19 dSphs within the LHAASO FOV

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

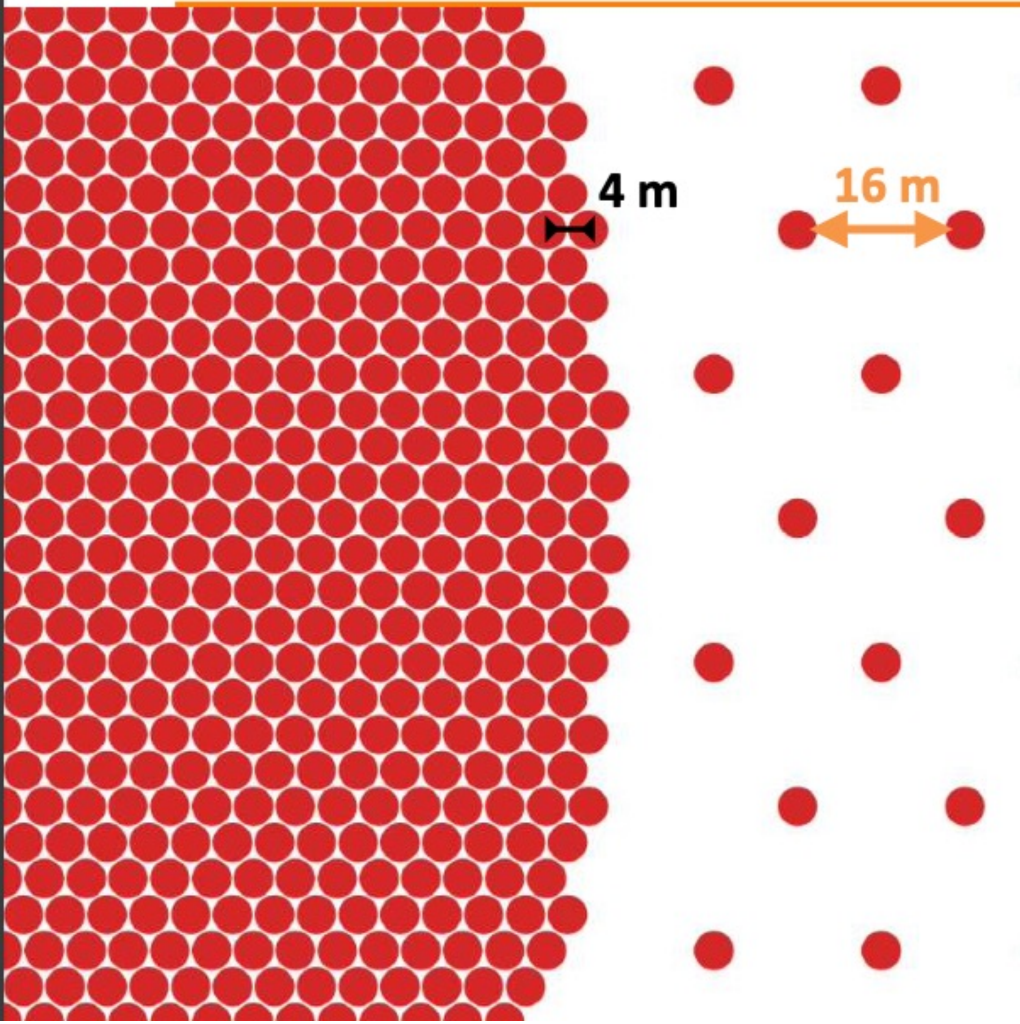
Constraints on Heavy Decaying Dark Matter from 570 Days of LHAASO Observations



95% one-sided lower limits on DM lifetime obtained with the profile likelihood analysis (thick black lines), for DM decaying into b quarks (left) or τ leptons (right). The black dashed line shows the limit for prompt DM contribution only. The green and yellow bands correspond to the expected 68% and 95% limit ranges from Monte Carlo simulations with the background-only hypothesis. Previous limits are shown with gray and blue lines. The hatched regions show the 1σ DM parameter space favored by IceCube high-energy neutrino flux

Z. Cao et al. (LHAASO Collaboration) Phys. Rev. Lett. 129, 261103 (2022)

The baseline detector concept

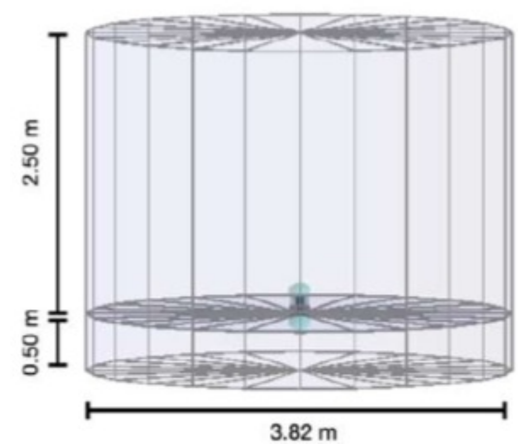


Core: Ø 320 m, FF = 80%
5,700 WCD units

Outer: Ø 600 m, FF = 5%
880 WCD units

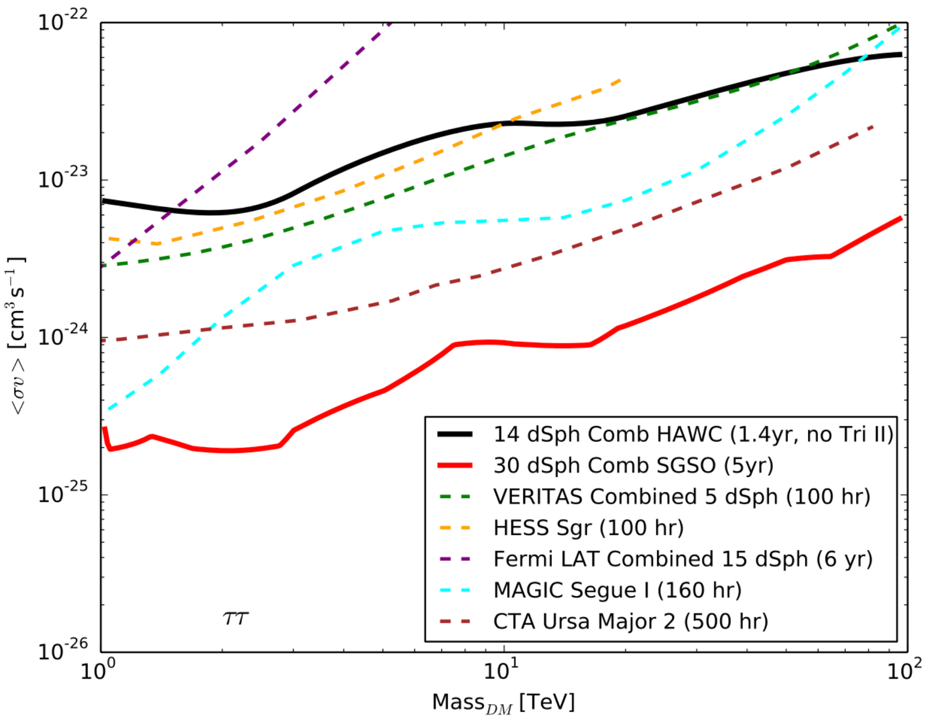
Altitude: 4,700 m a.s.l.

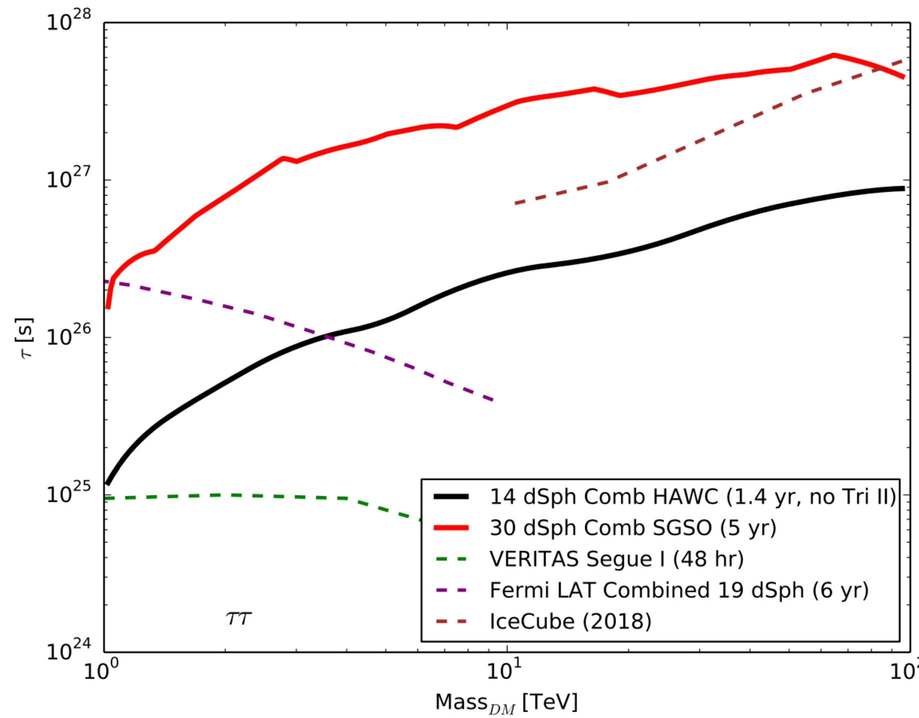
✧ **muon counting**



SWGO White paper arXiv:1902.08429

SWGO sensitivities





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

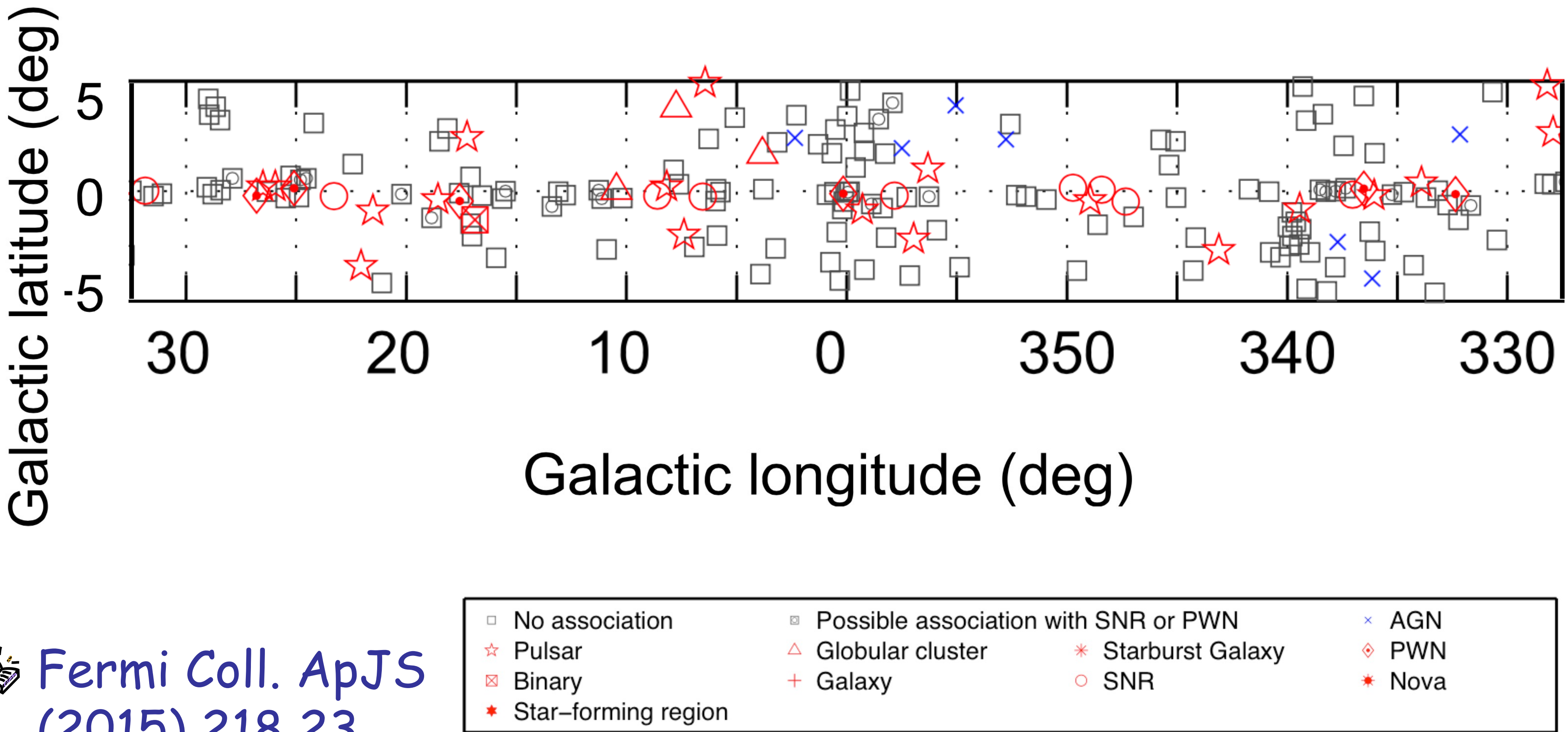
SWGO White paper arXiv:1902.08429

The Low Energy Frontier

The Fermi LAT 3FGL Inner Galactic Region

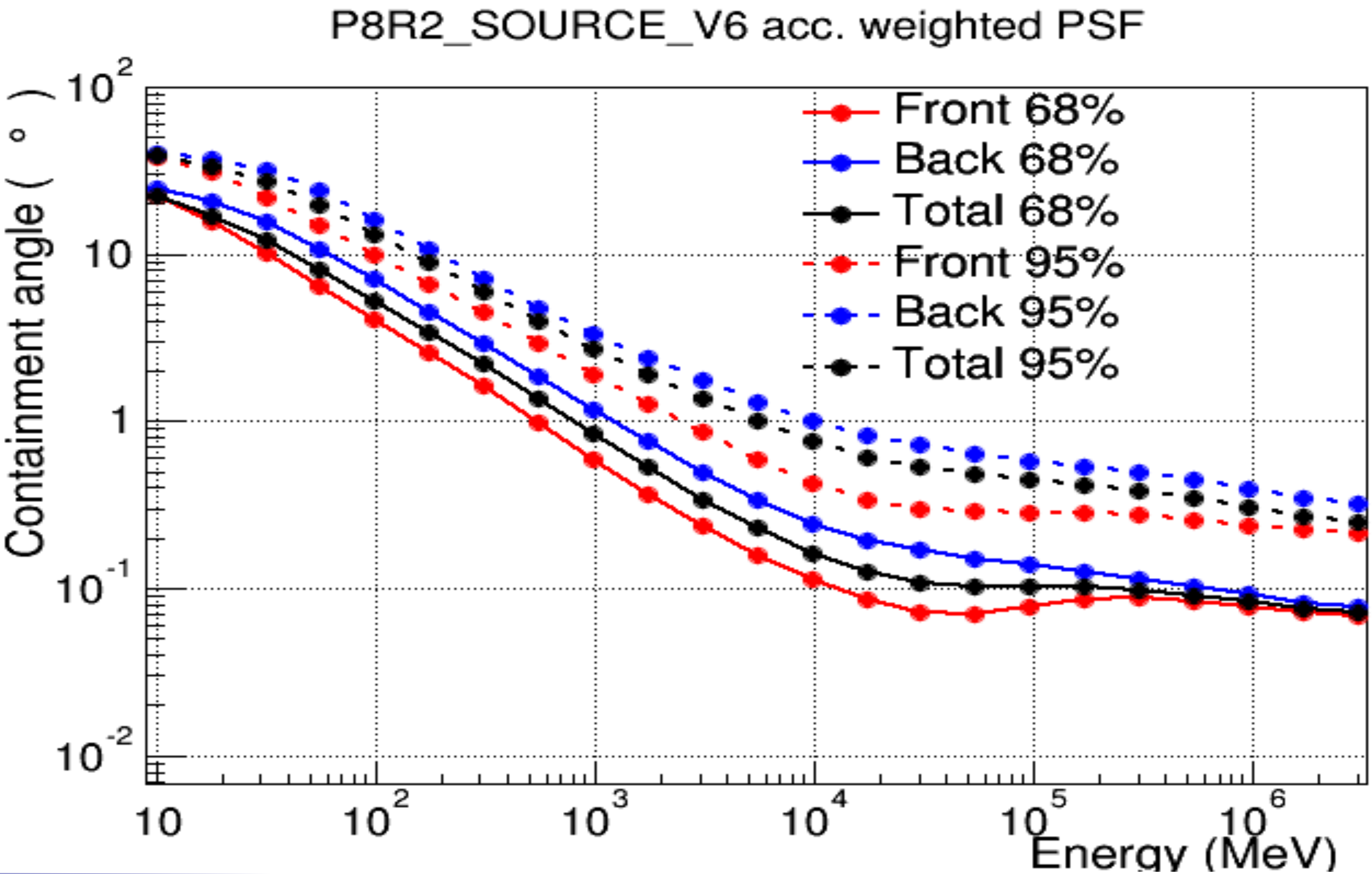
August 4, 2008, to July 31, 2010

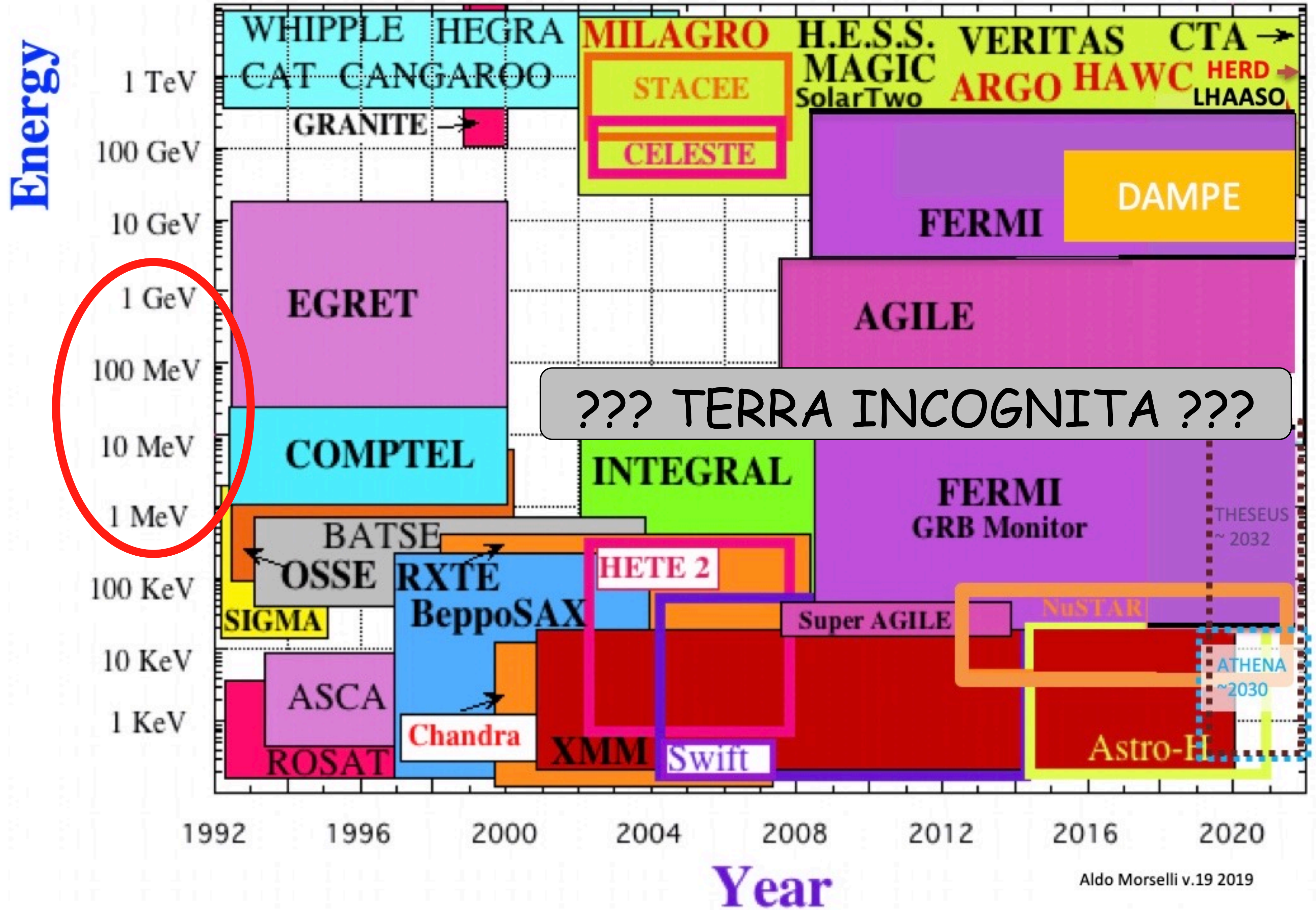
100 MeV to 300 GeV energy range



Fermi Coll. ApJS (2015) 218 23
arXiv:1501.02003

Fermi-LAT Instrument Response Functions (Pass 8) Angular Resolution

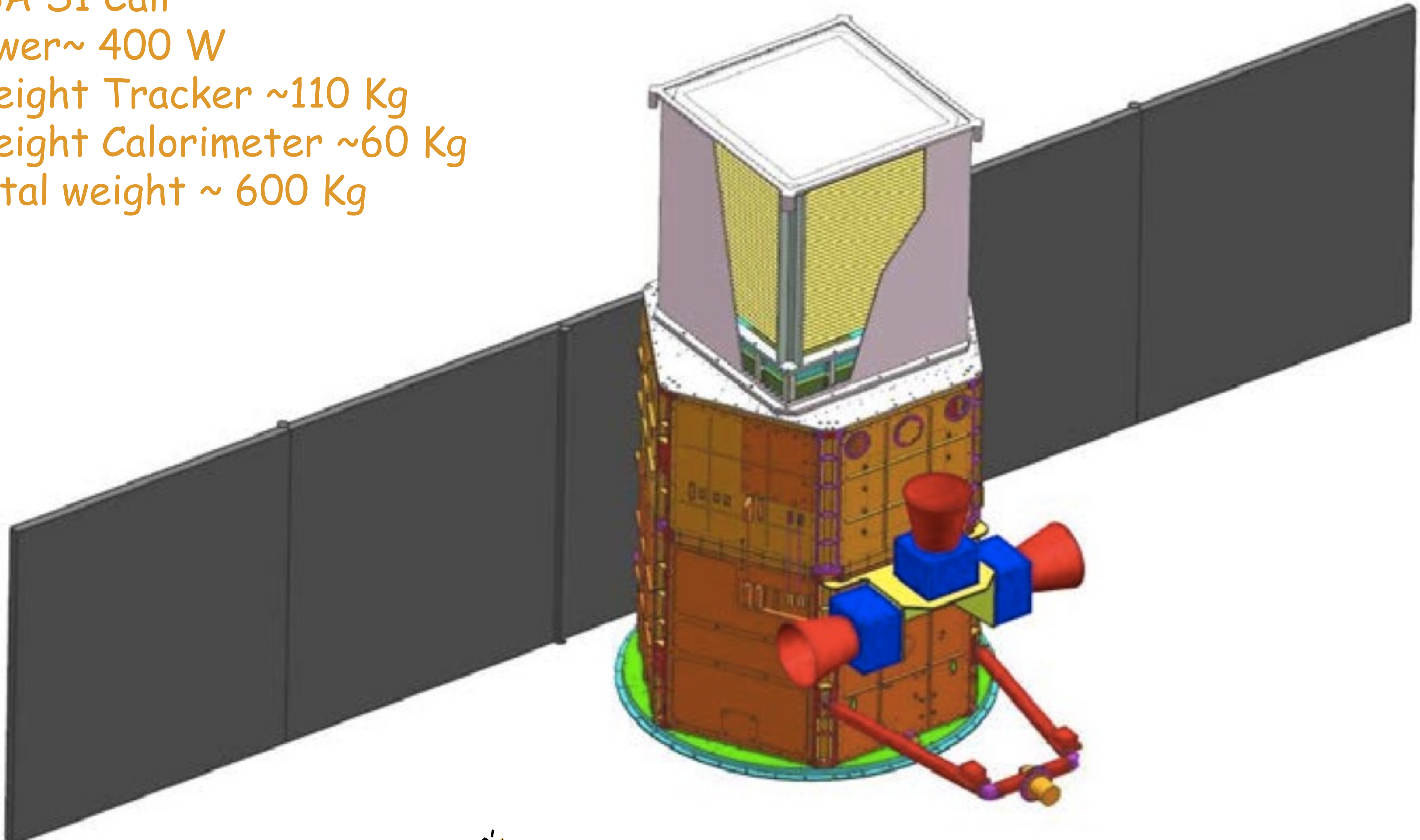



Energy
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 KeV
10 KeV
1 KeV
WHIPPLE HEGRA
CAT CANGAROO
GRANITE
MILAGRO
STACEE
CELESTE
H.E.S.S.
MAGIC
SolarTwo
VERITAS
ARGO
HAWC
CTA
HERD
LHAASO
FERMI
DAMPE
EGRET
AGILE
??? TERRA INCOGNITA ???
COMPTEL
INTEGRAL
FERMI
GRB Monitor
THESEUS
~ 2032
BATSE
OSSE
RXTE
BeppoSAX
HETE 2
SIGMA
Super AGILE
NuSTAR
ASCA
ATHENA
~2030
Chandra
XMM
Swift
Astro-H
ROSAT
1992
1996
2000
2004
2008
2012
2016
2020
Year
Aldo Morselli v.19 2019

- 1-100 MeV unexplored domain for
  - Dark Matter searches
  - Galactic compact stars and nucleosynthesis
  - Cosmic rays
  - Relativistic jets, microquasars
  - Blazars
  - Gamma-Ray Bursts
  - Solar physics
- and…
  - Terrestrial Gamma-Ray Flashes

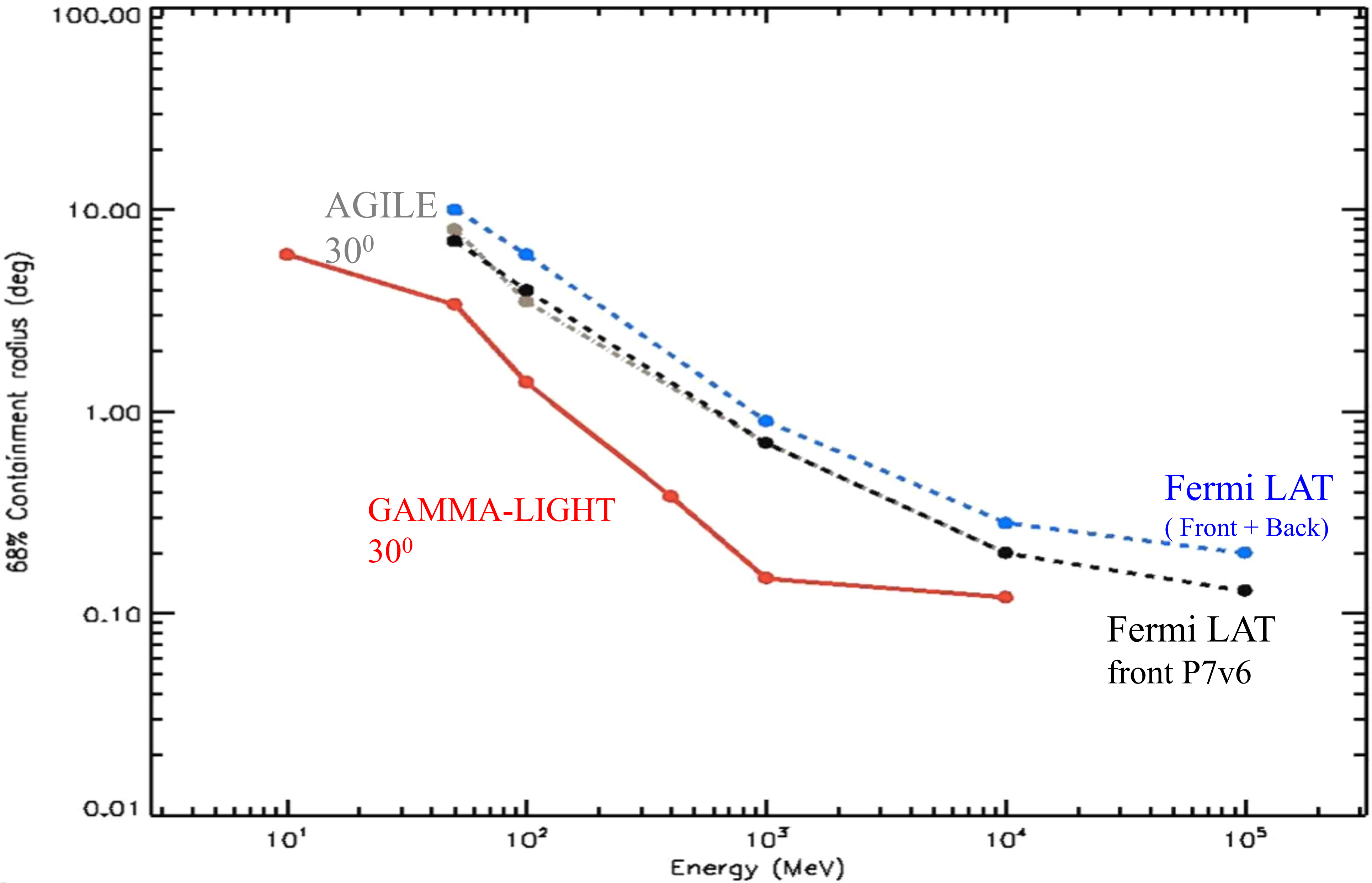
Gamma-light project

ESA S1 Call
Power~ 400 W
Weight Tracker ~110 Kg
Weight Calorimeter ~60 Kg
Total weight ~ 600 Kg



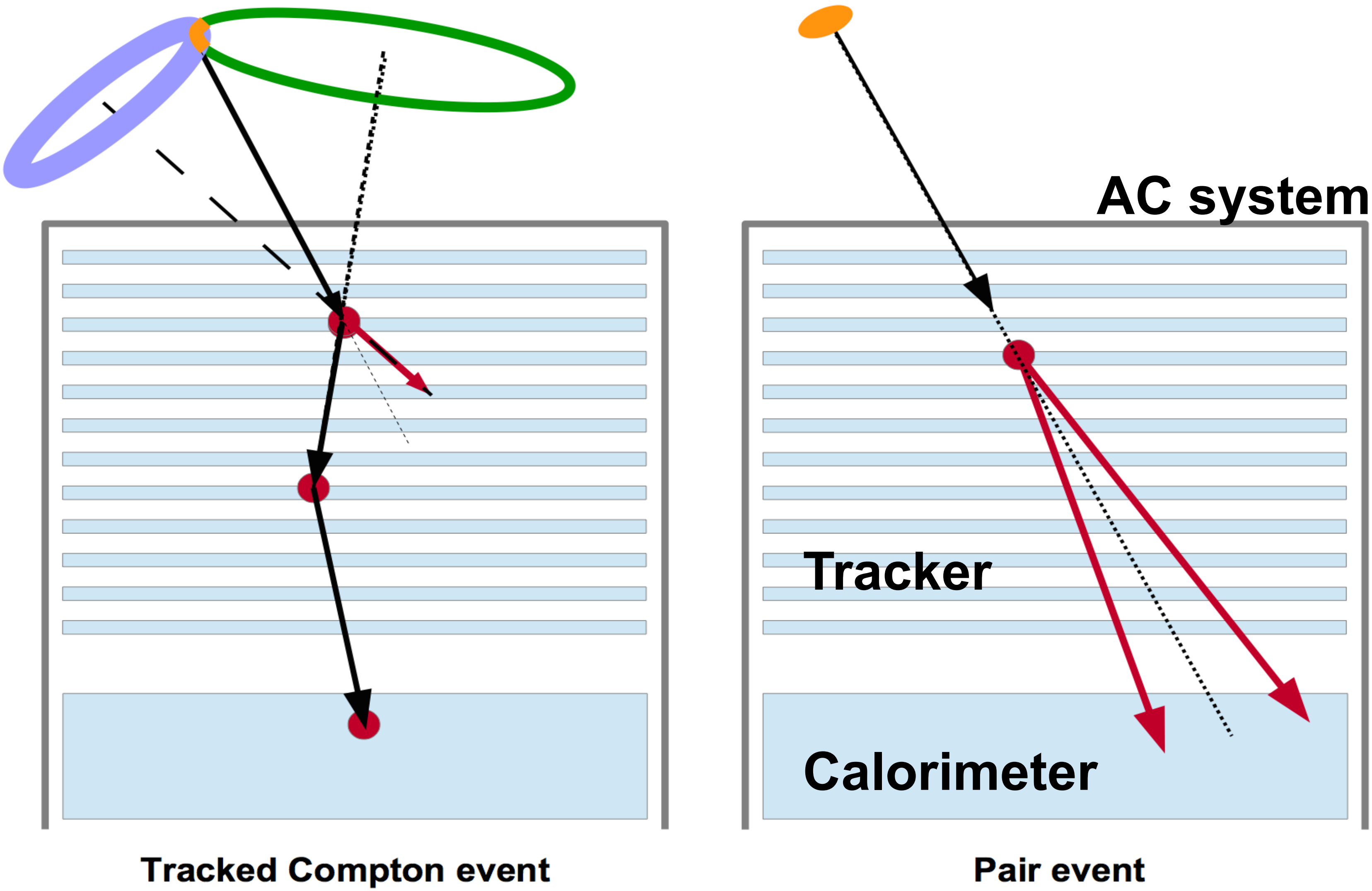
A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198 [arXiv:1406.1071]

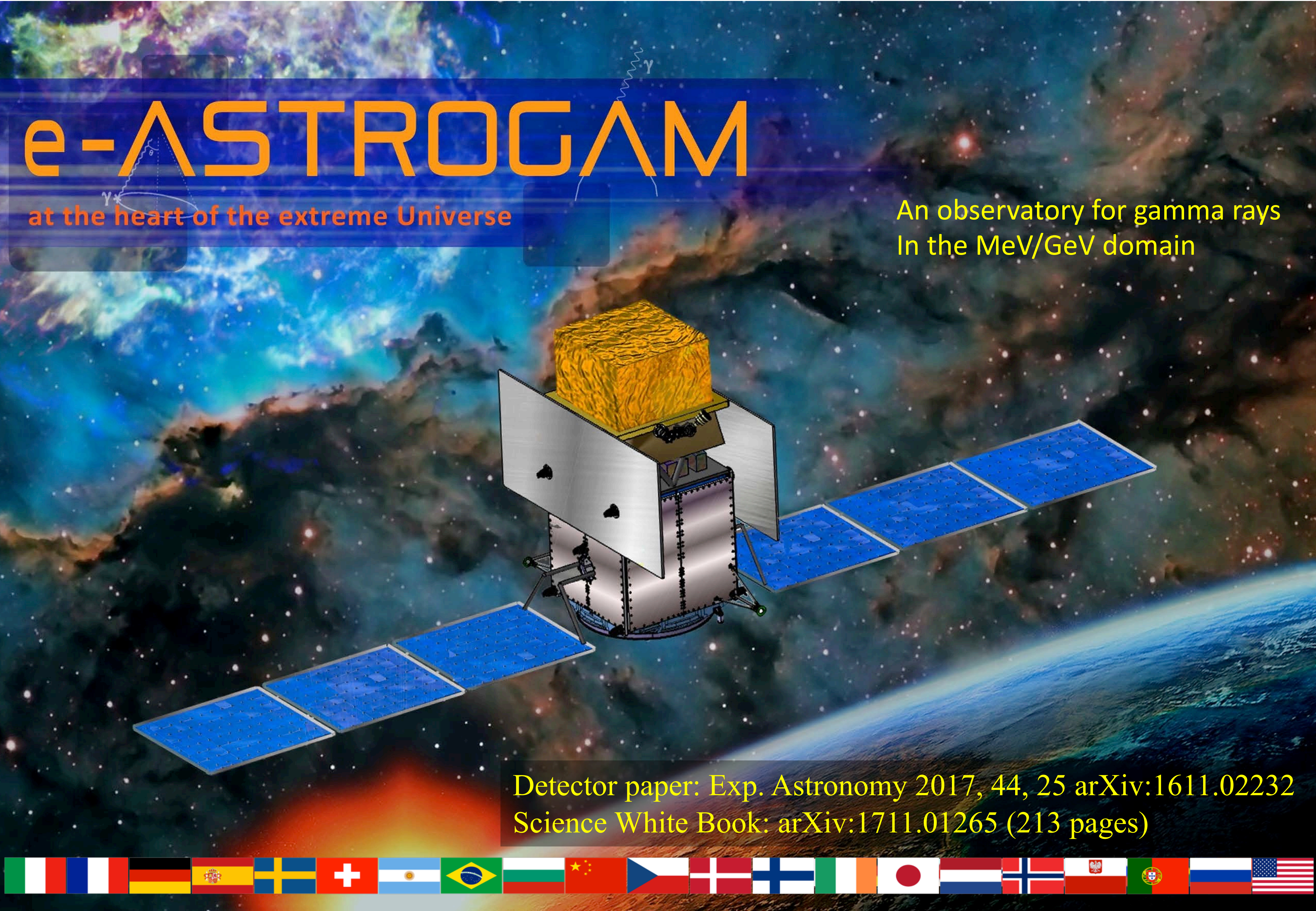
Gamma-Light Point Spread Function (angular resolution)



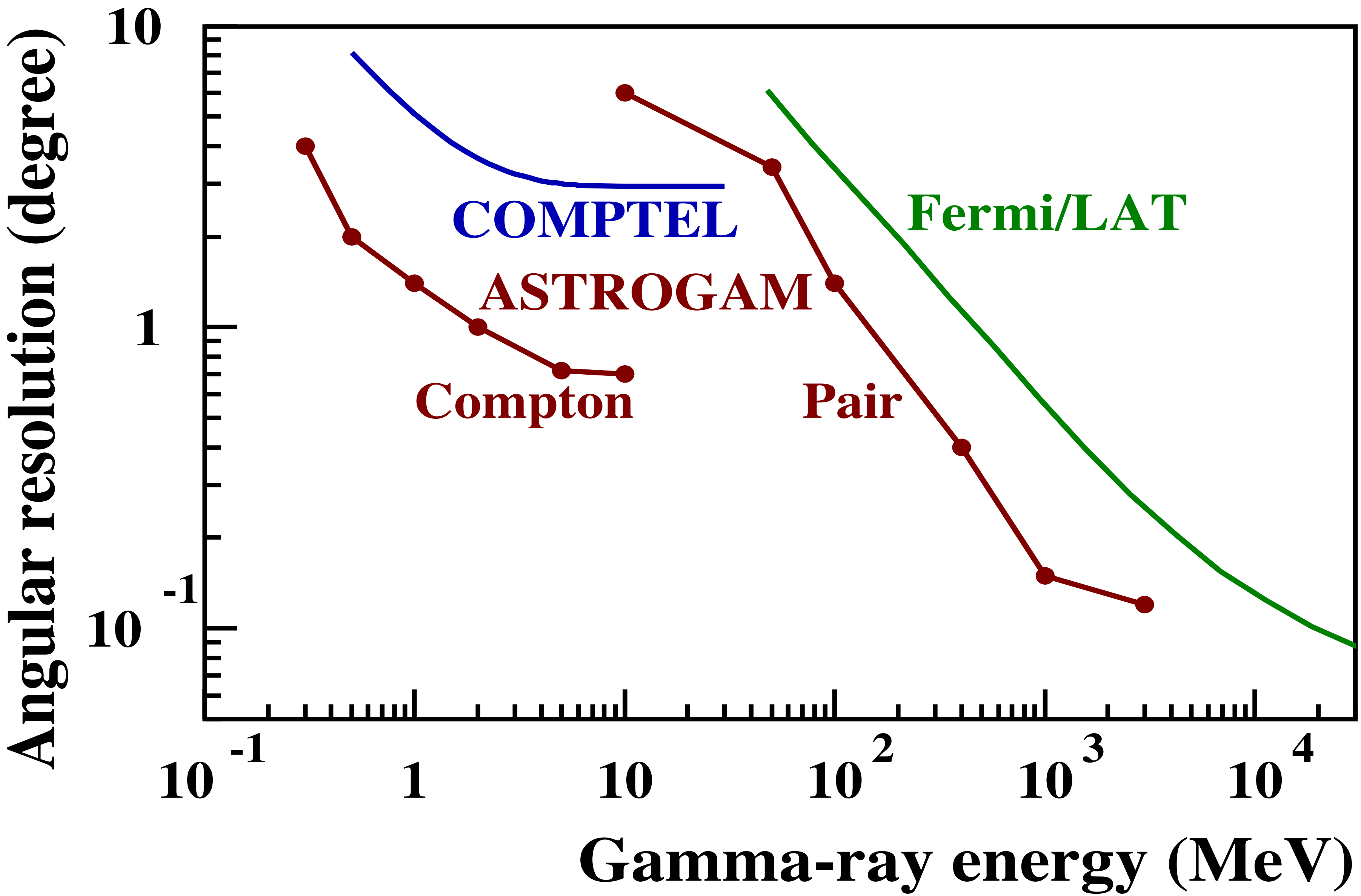
A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198 [arXiv:1406.1071]

An instrument that combine two detection techniques

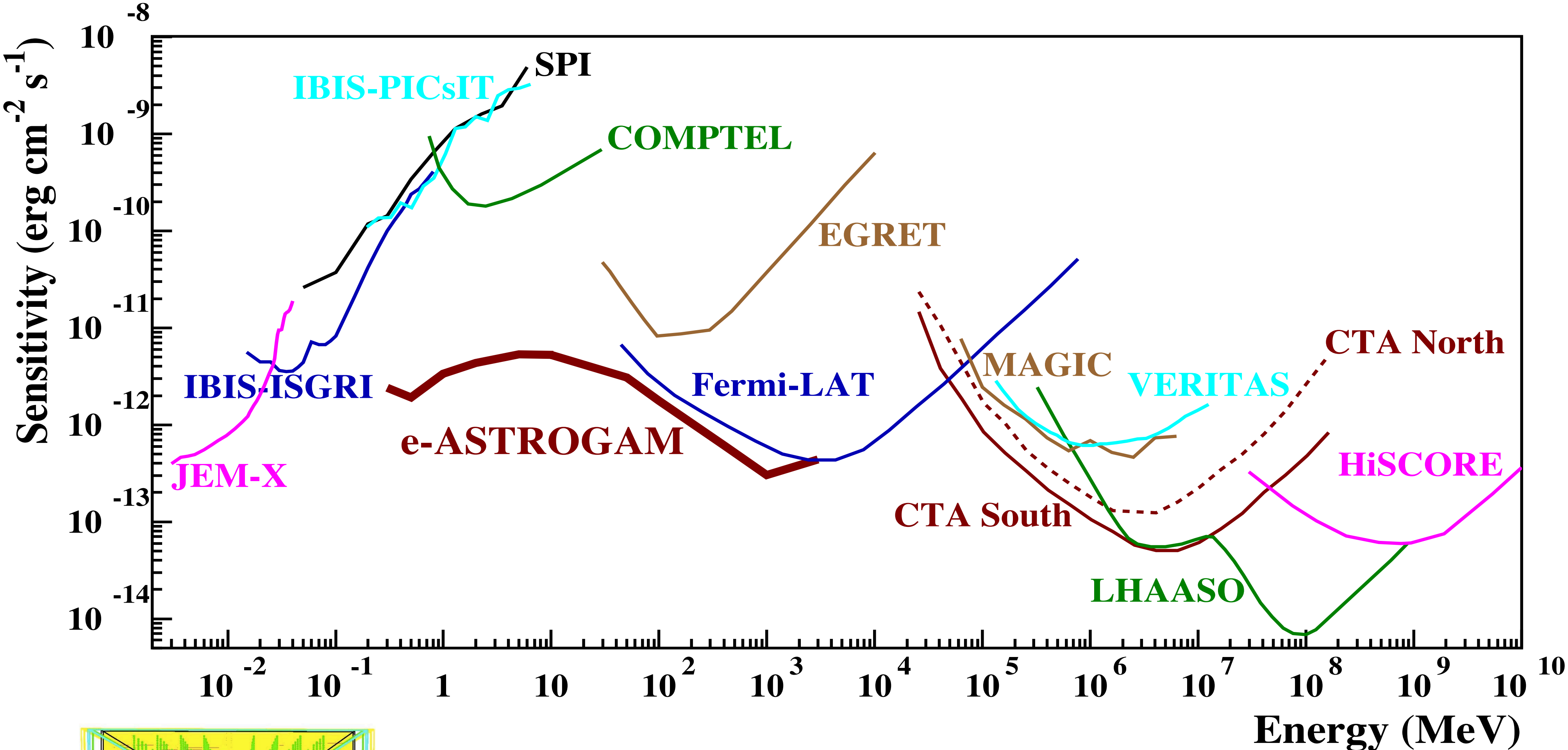


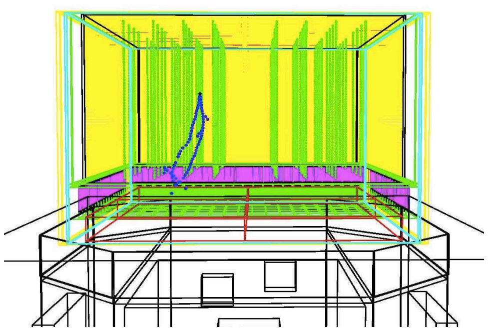

e-ASTROGAM
at the heart of the extreme Universe
An observatory for gamma rays
In the MeV/GeV domain
Detector paper: Exp. Astronomy 2017, 44, 25 arXiv:1611.02232
Science White Book: arXiv:1711.01265 (213 pages)

ASTROGAM Angular Resolution



Performance assessment



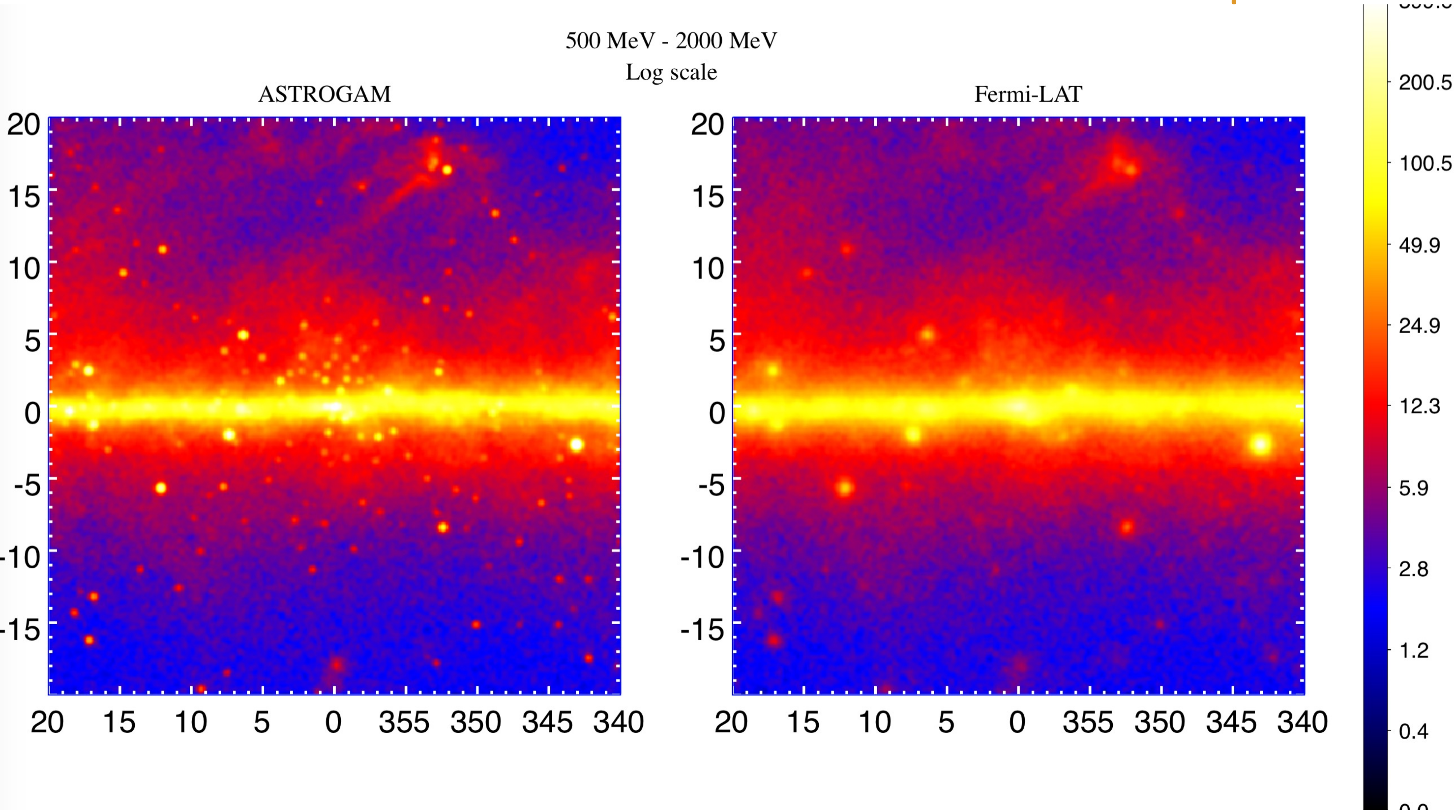


- e-ASTROGAM performance evaluated with **MEGAlib** and – both tools based on Geant4 – and a detailed numerical mass model of the gamma-ray instrument

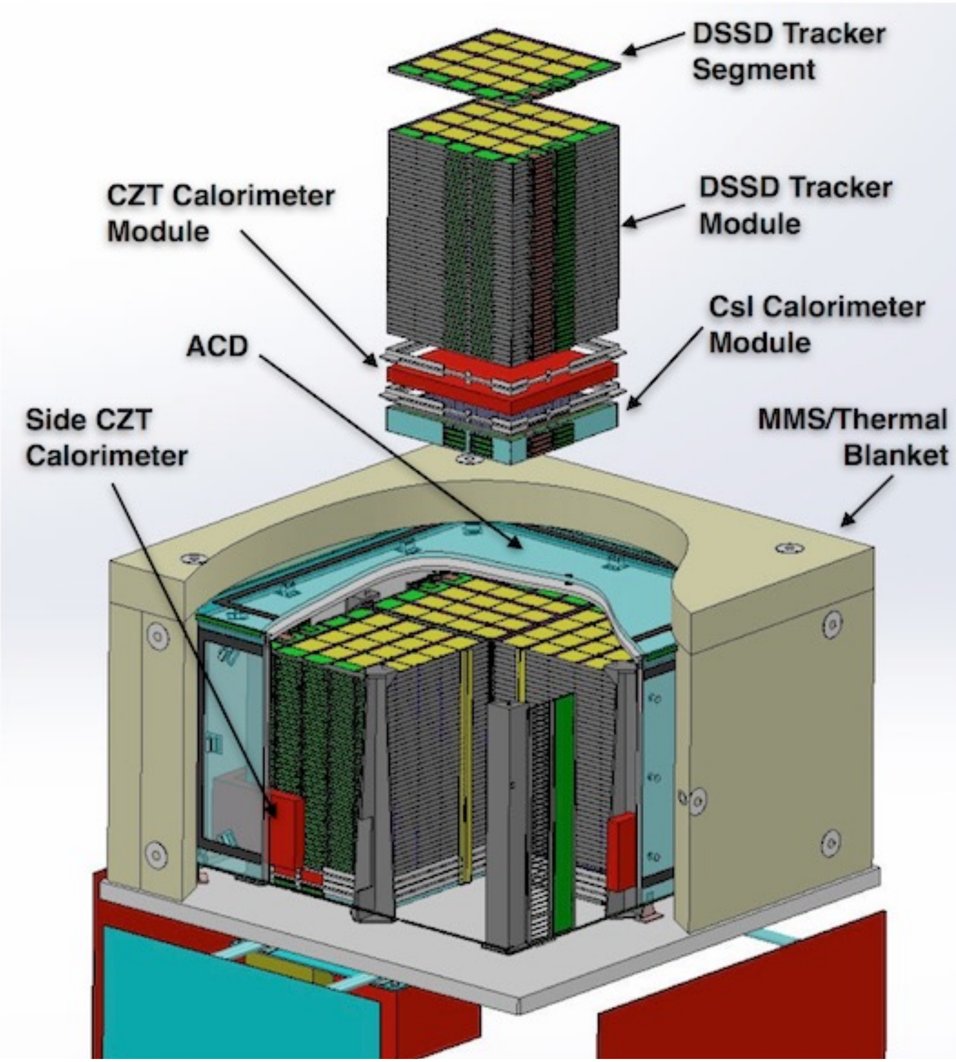
e-Astrogam: arXiv:1611.02232

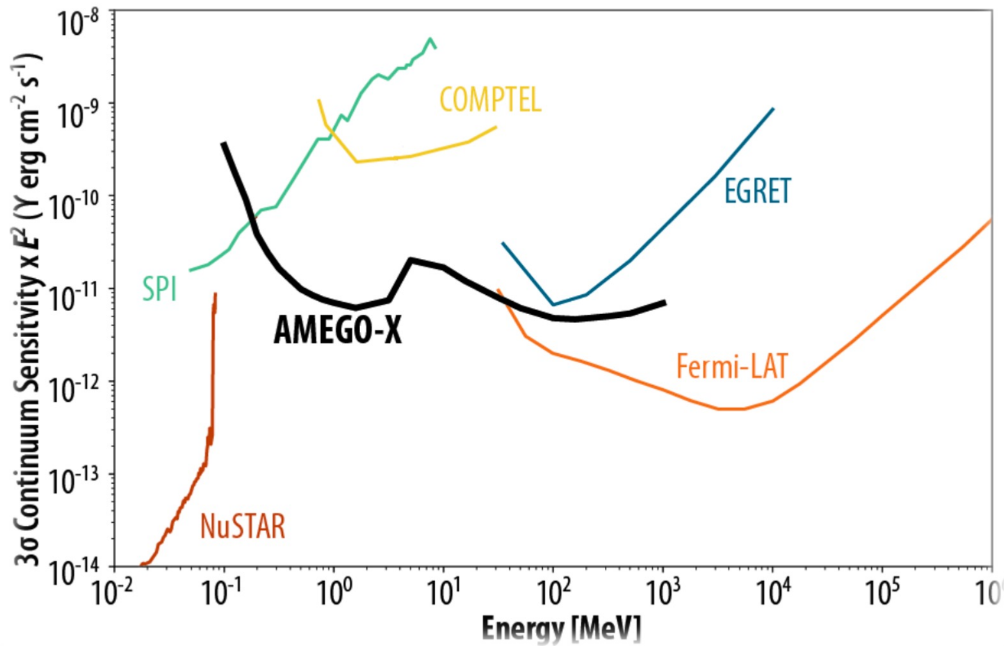
Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source



Our sister experiment: AMEGO-X mission concept for the NASA MIDEX call

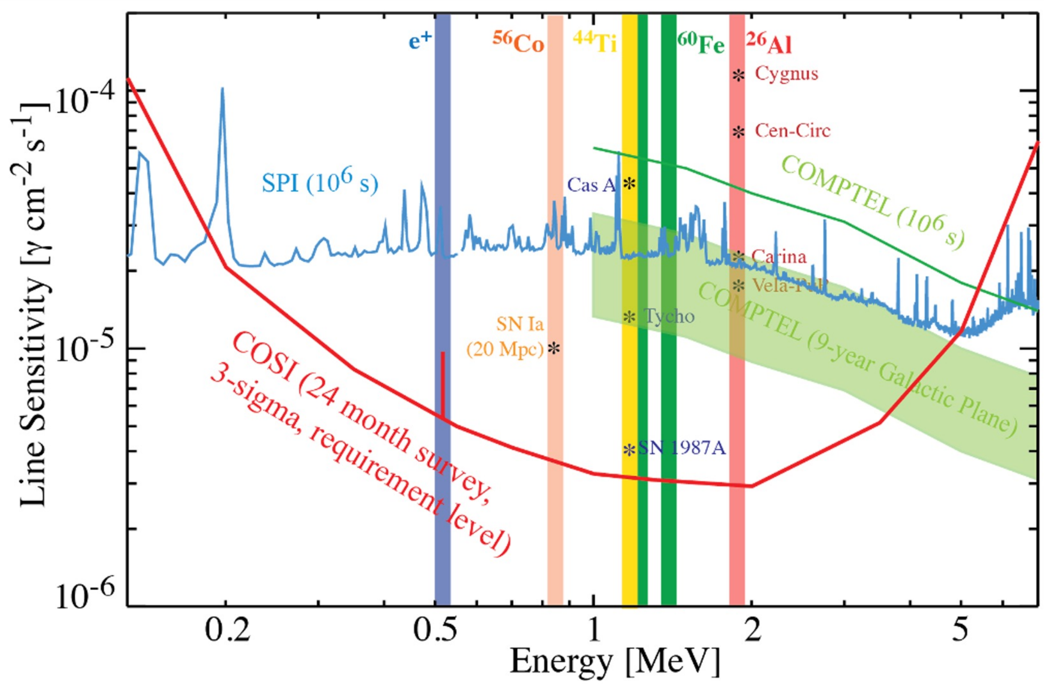


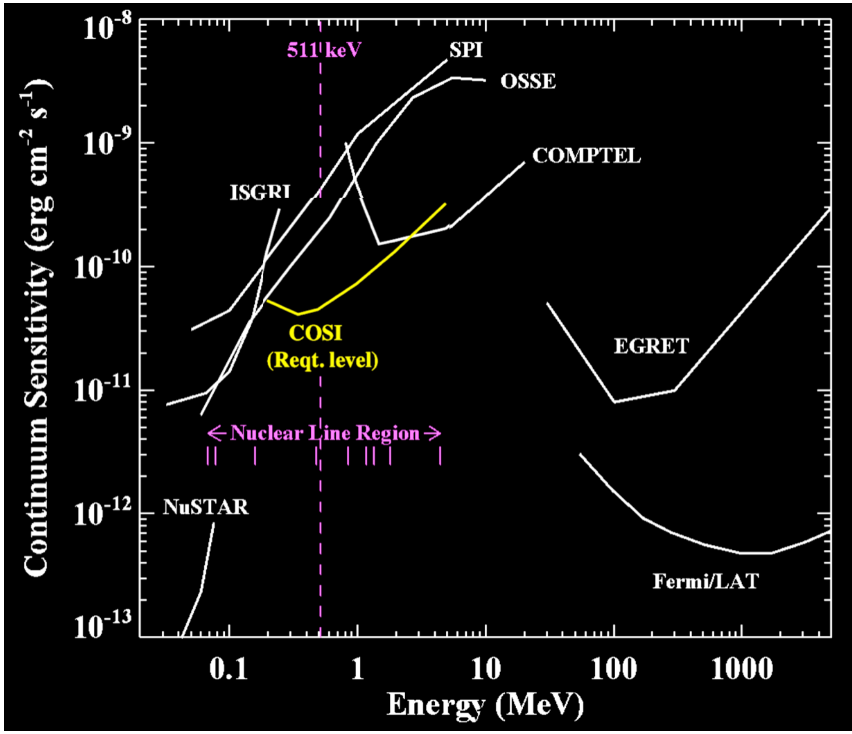


- ~20% smaller tracker
- CZT calorimeter layer

COSI The Compton Spectrometer and Imager

- COSI has been selected by NASA as a SMEX to launch in 2027



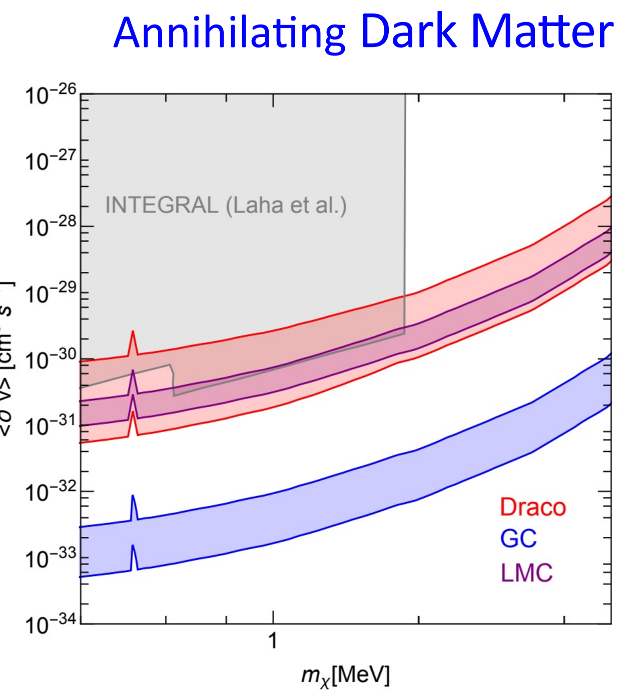


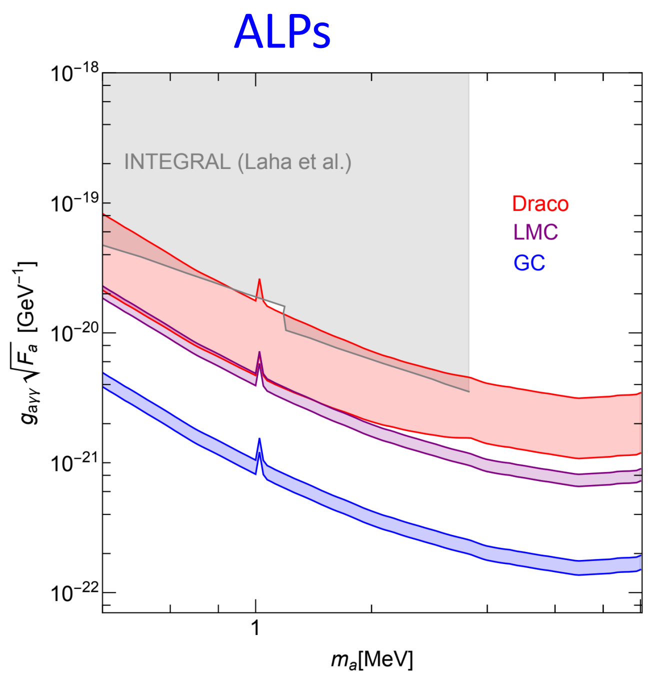
emission lines sensitivity

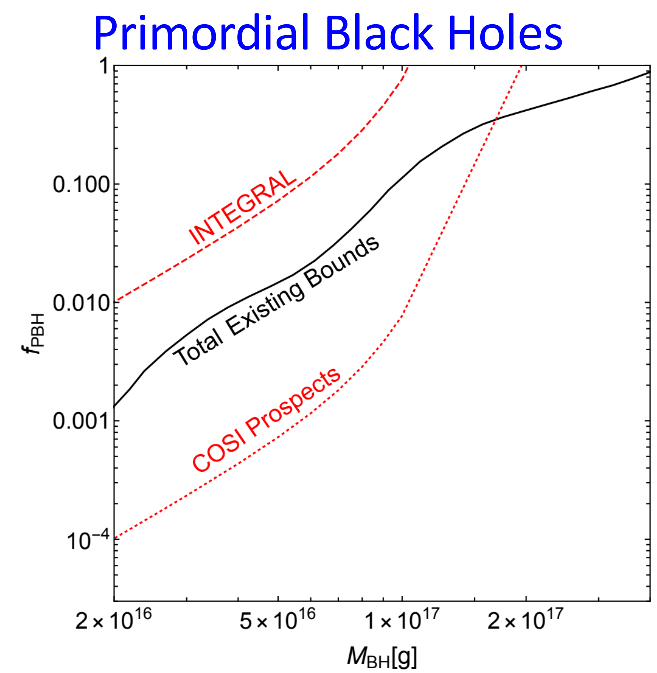
continuum emission sensitivity

Dark Matter Studies with COSI

- COSI will provide limits on annihilating/decaying DM, Axion like particles and primordial black holes

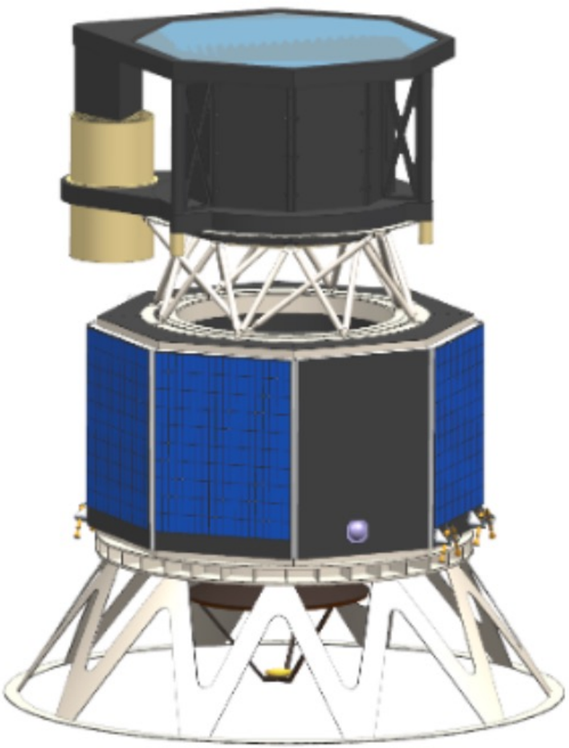


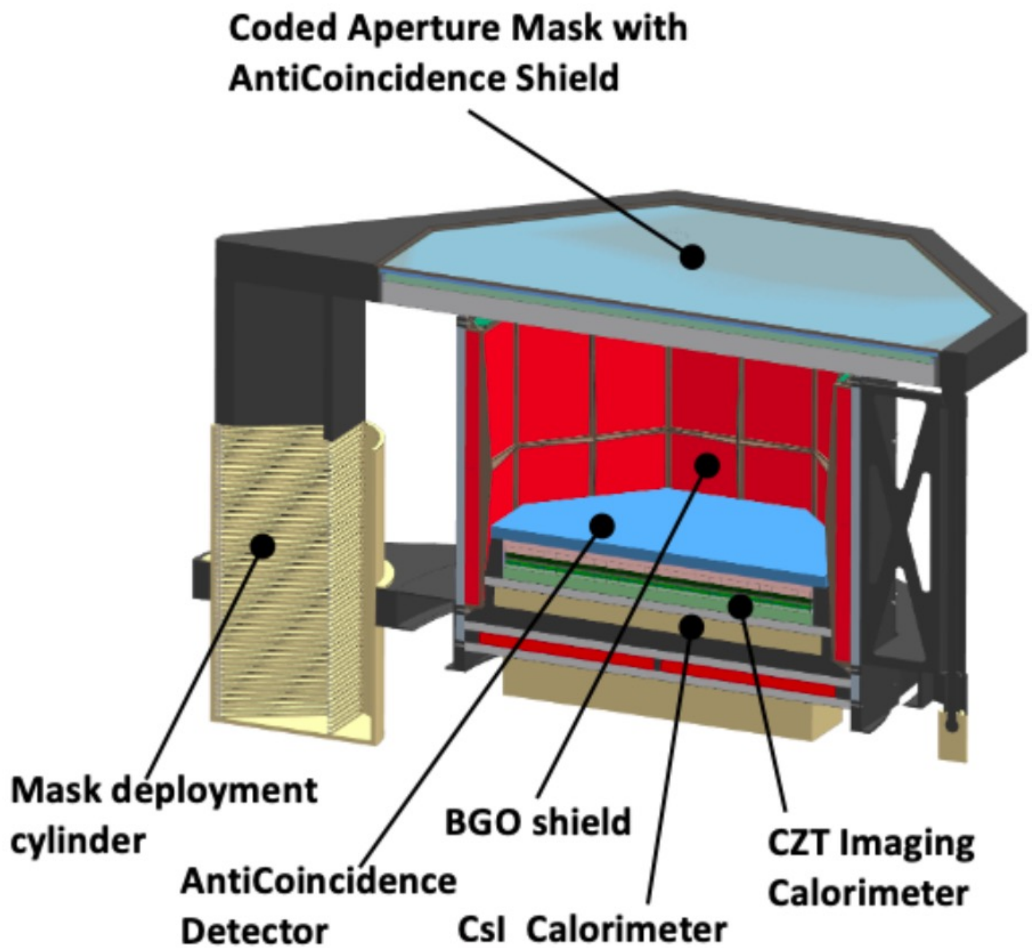




Caputo et al. 2023 arXiv2210.09310

GECCO The Galactic Explorer with a Coded Aperture Mask Compton Telescope

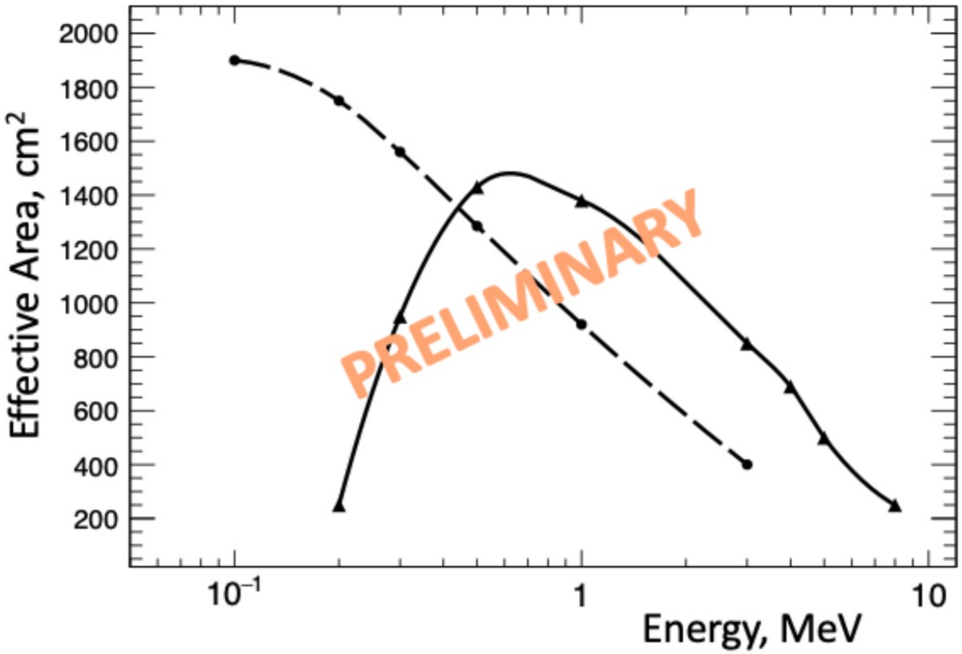


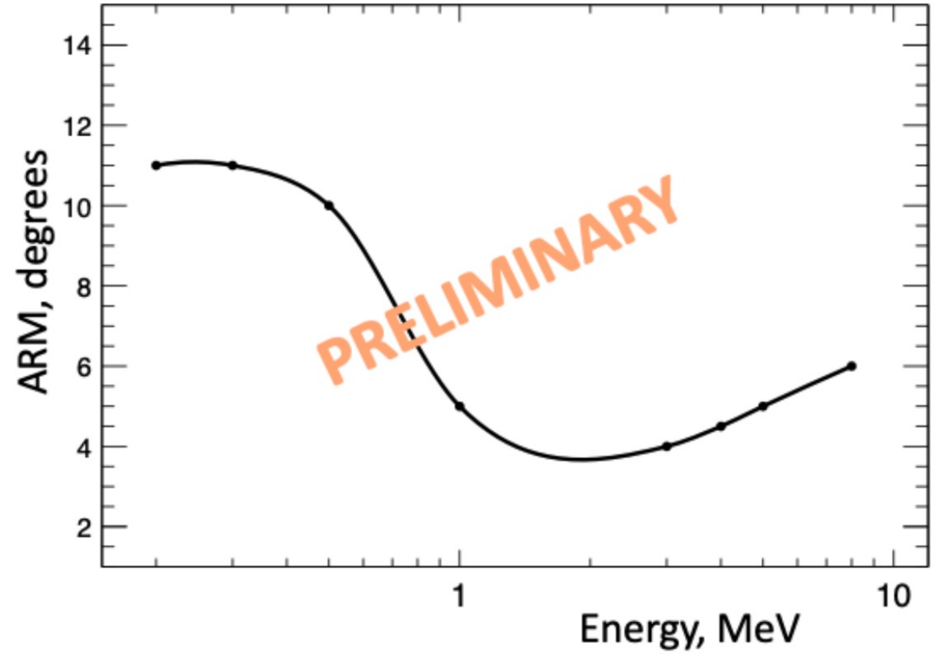


conceptual design   mask in stowed position   cutaway   diameter =90 cm

GECCO Team, JCAP07(2022)036 arXiv:2112.07190

GECCO The Galactic Explorer with a Coded Aperture Mask Compton Telescope





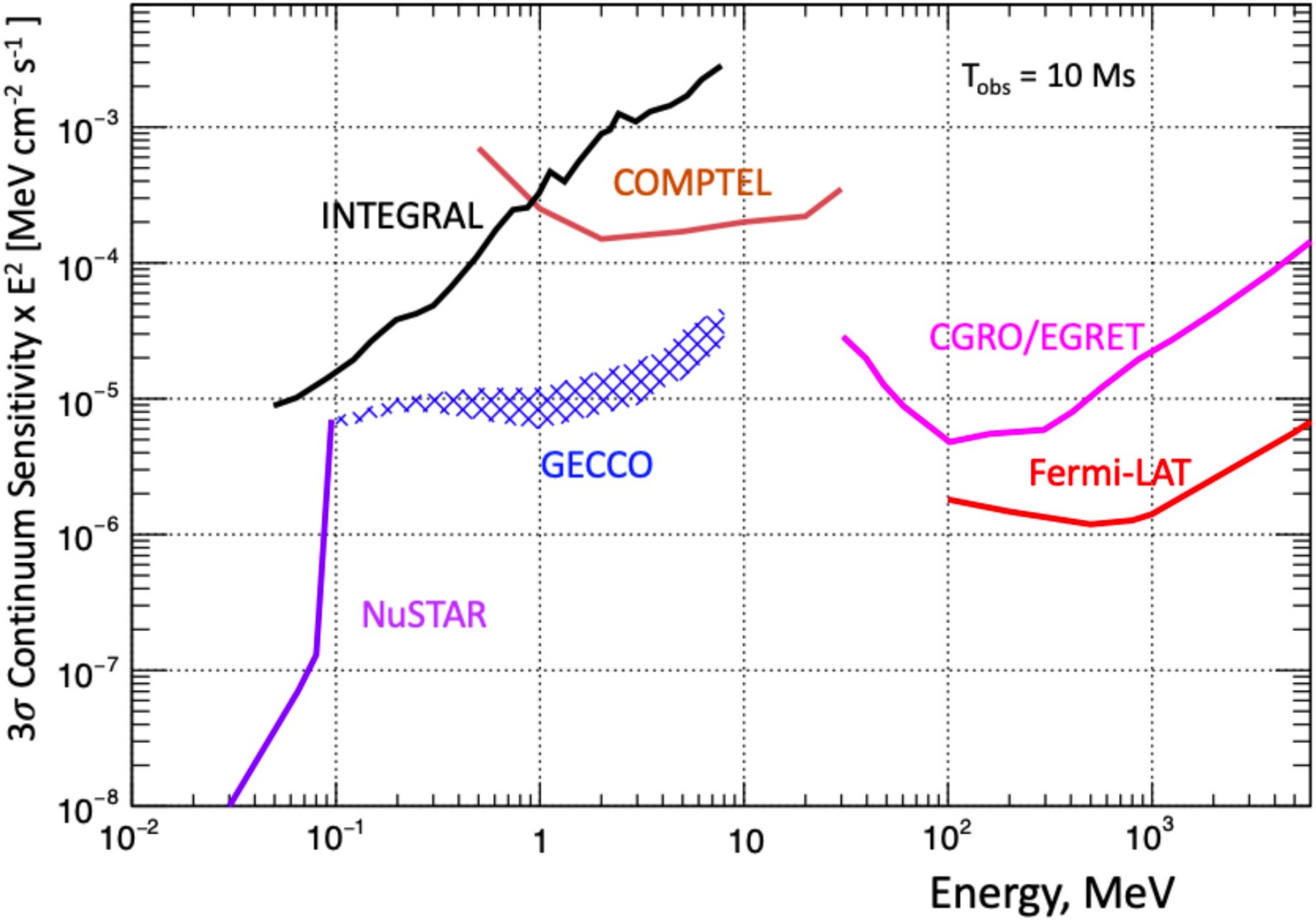
effective area for the CA mask imaging; the solid line is for Compton pointing used, and the dashed line is for classical mask analysis.

ARM (angular resolution measure) for the ImCal standalone Compton telescope.

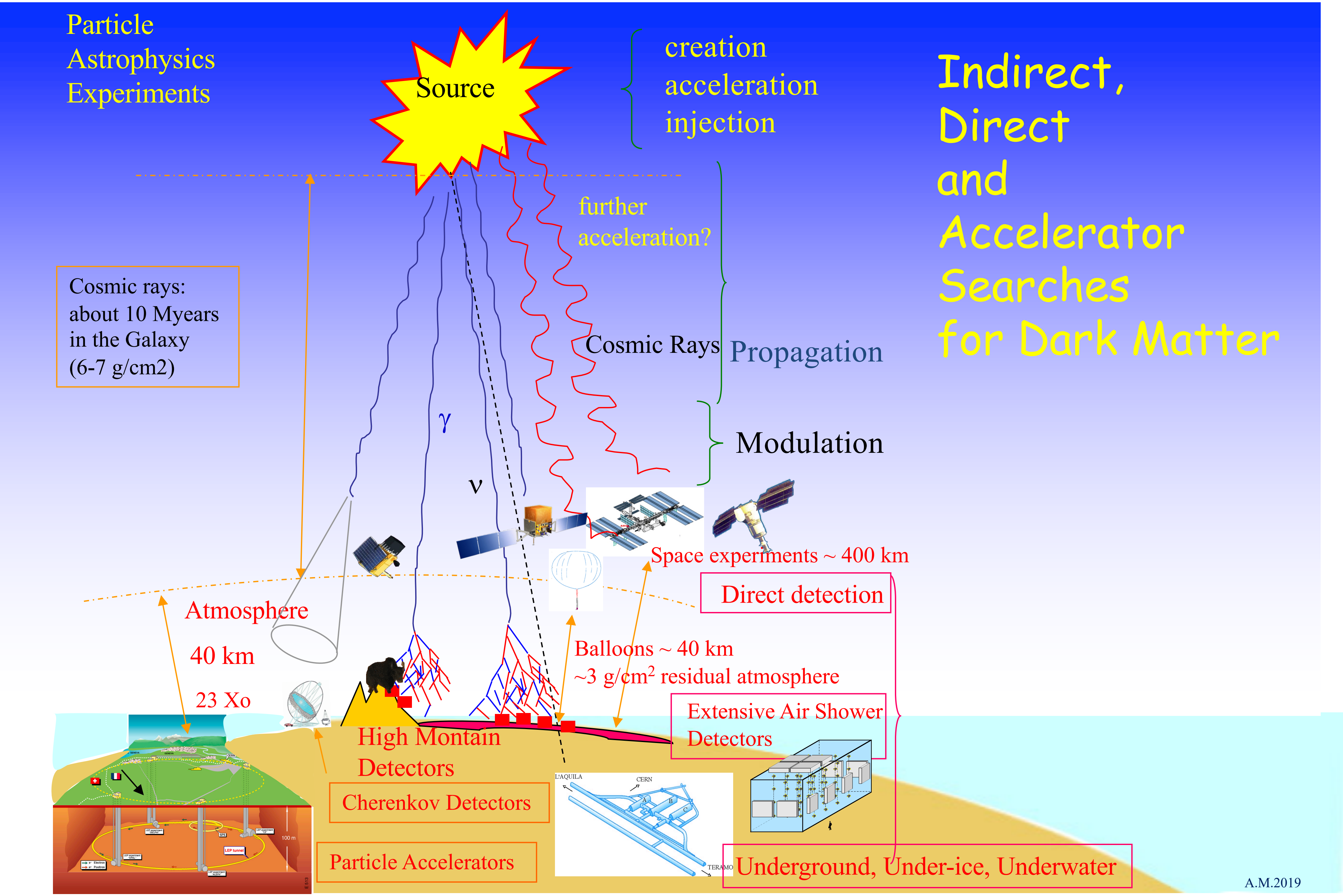
GECCO Team, in preparation

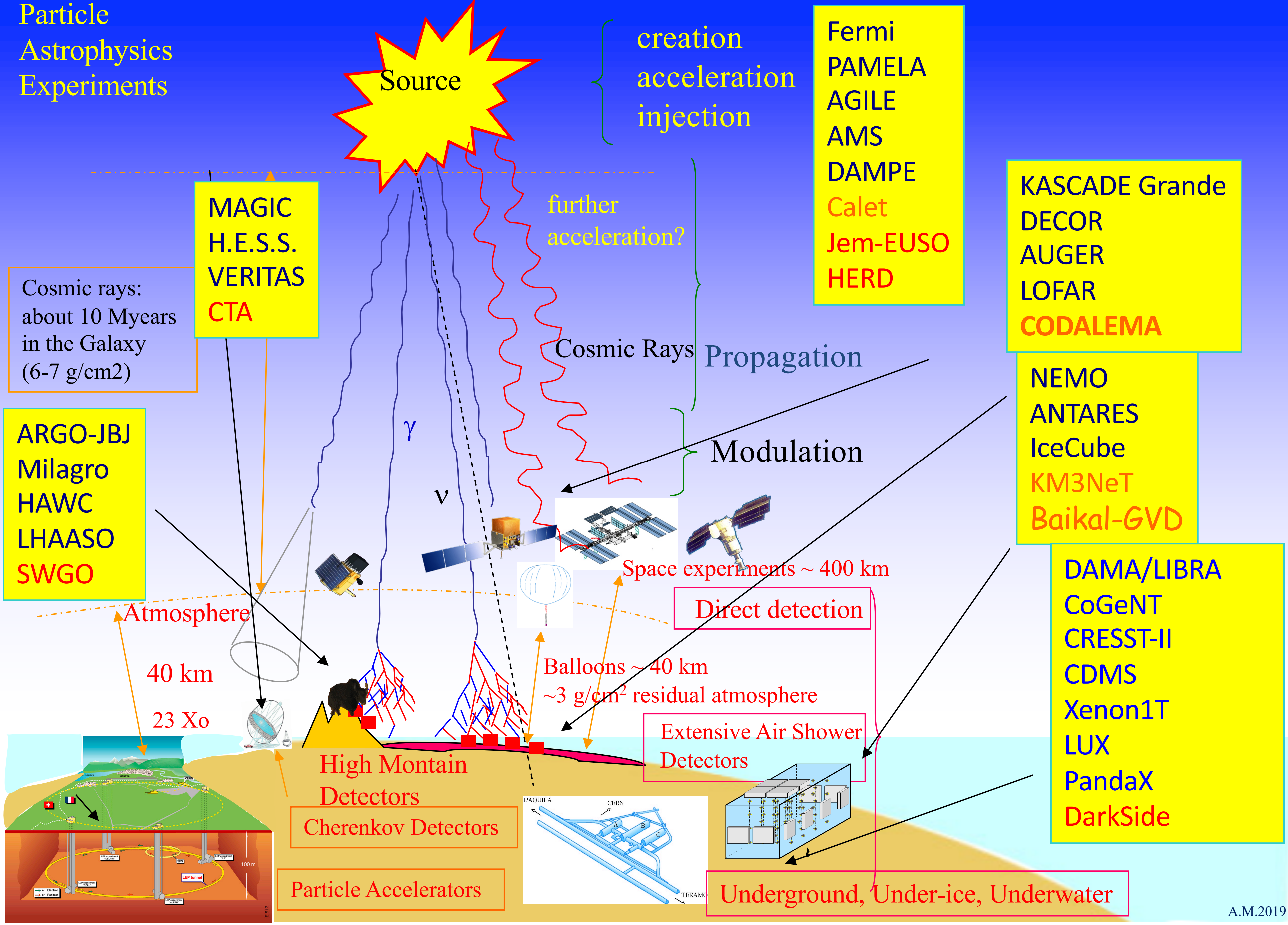
GECCO The Galactic Explorer with a Coded Aperture Mask Compton Telescope

Sensitivity



GECCO Team, JCAP07(2022)036 arXiv:2112.07190

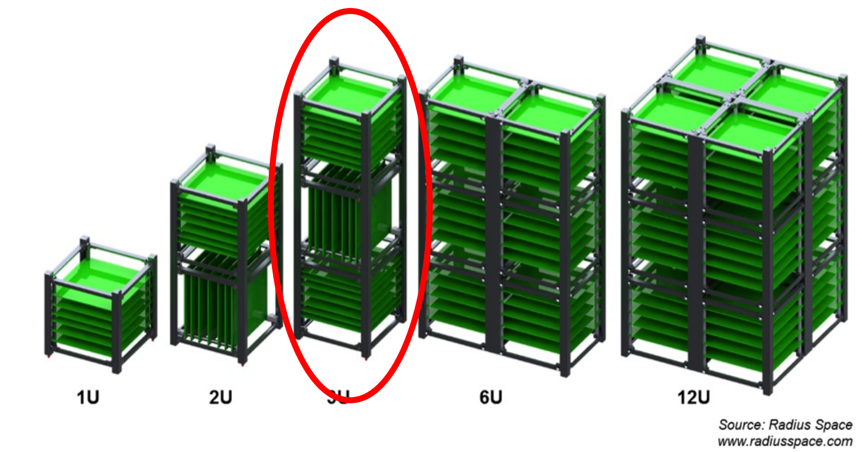

Particle
Astrophysics
Experiments
Source
creation
acceleration
injection
Indirect,
Direct
and
Accelerator
Searches
for Dark Matter
further
acceleration?
Cosmic rays:
about 10 Myears
in the Galaxy
(6-7 g/cm2)
Cosmic Rays
Propagation
γ
Modulation
ν
Space experiments ~ 400 km
Direct detection
Atmosphere
40 km
23 Xo
Balloons ~ 40 km
~3 g/cm² residual atmosphere
Extensive Air Shower
Detectors
High Montain
Detectors
Cherenkov Detectors
Particle Accelerators
L'AQUILA
CERN
TERAMO
Underground, Under-ice, Underwater
A.M.2019


Particle Astrophysics Experiments
Source
creation
acceleration
injection
Fermi
PAMELA
AGILE
AMS
DAMPE
Calet
Jem-EUSO
HERD
MAGIC
H.E.S.S.
VERITAS
CTA
further acceleration?
KASCADE Grande
DECOR
AUGER
LOFAR
CODALEMA
Cosmic rays: about 10 Myears in the Galaxy (6-7 g/cm2)
Cosmic Rays
Propagation
NEMO
ANTARES
IceCube
KM3NeT
Baikal-GVD
ARGO-JBJ
Milagro
HAWC
LHAASO
SWGO
γ
Modulation
ν
Space experiments ~ 400 km
DAMA/LIBRA
CoGeNT
CRESST-II
CDMS
Xenon1T
LUX
PandaX
DarkSide
Atmosphere
Direct detection
40 km
Balloons ~ 40 km
~3 g/cm² residual atmosphere
23 Xo
Extensive Air Shower Detectors
High Montain Detectors
Cherenkov Detectors
L'AQUILA
CERN
TERAMO
Particle Accelerators
Underground, Under-ice, Underwater
A.M.2019

additional slides

COMCUBE Nanosat sub-WP

Development of a 3U (?) Compton nanosat for the polarimetry of GRBs + qualification of the e-ASTROGAM technologies



Si DSSD (1.5 mm?) + **IDeF-X** ASICs (CEA)

Si DSSD (1.5 mm?) + **VATA** ASICs (Ideas)

Thick scintillator + SiPM array

- Cubesat : standard unit ⇒ 1U
- Size : 10 x 10 x 10 cm
- Weight : 1kg
- Power: ~ 1.3 W