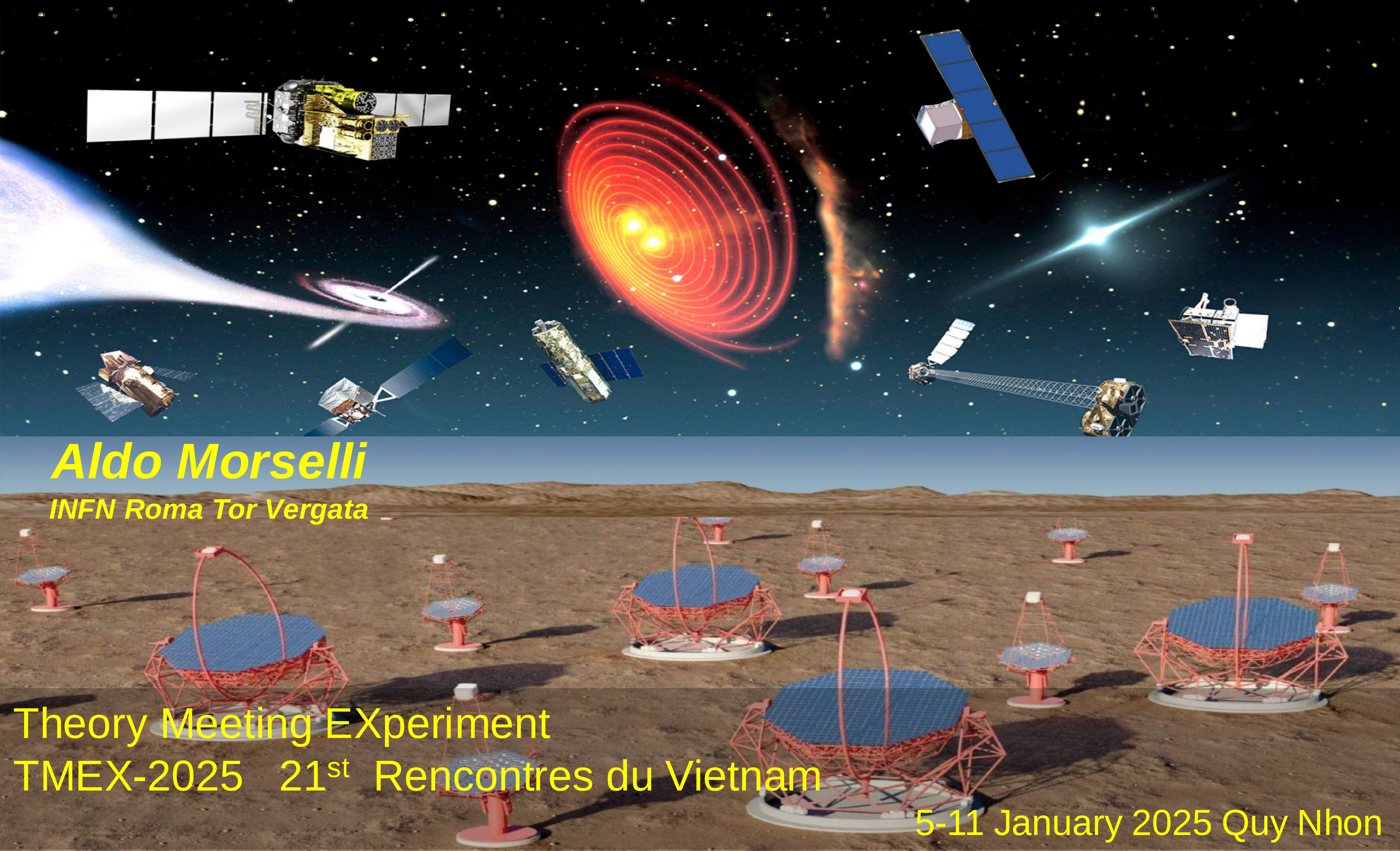
Indirect dark-matter searches with gamma-rays experiments : status and future plans from 300 KeV to 100 TeV



Aldo Morselli

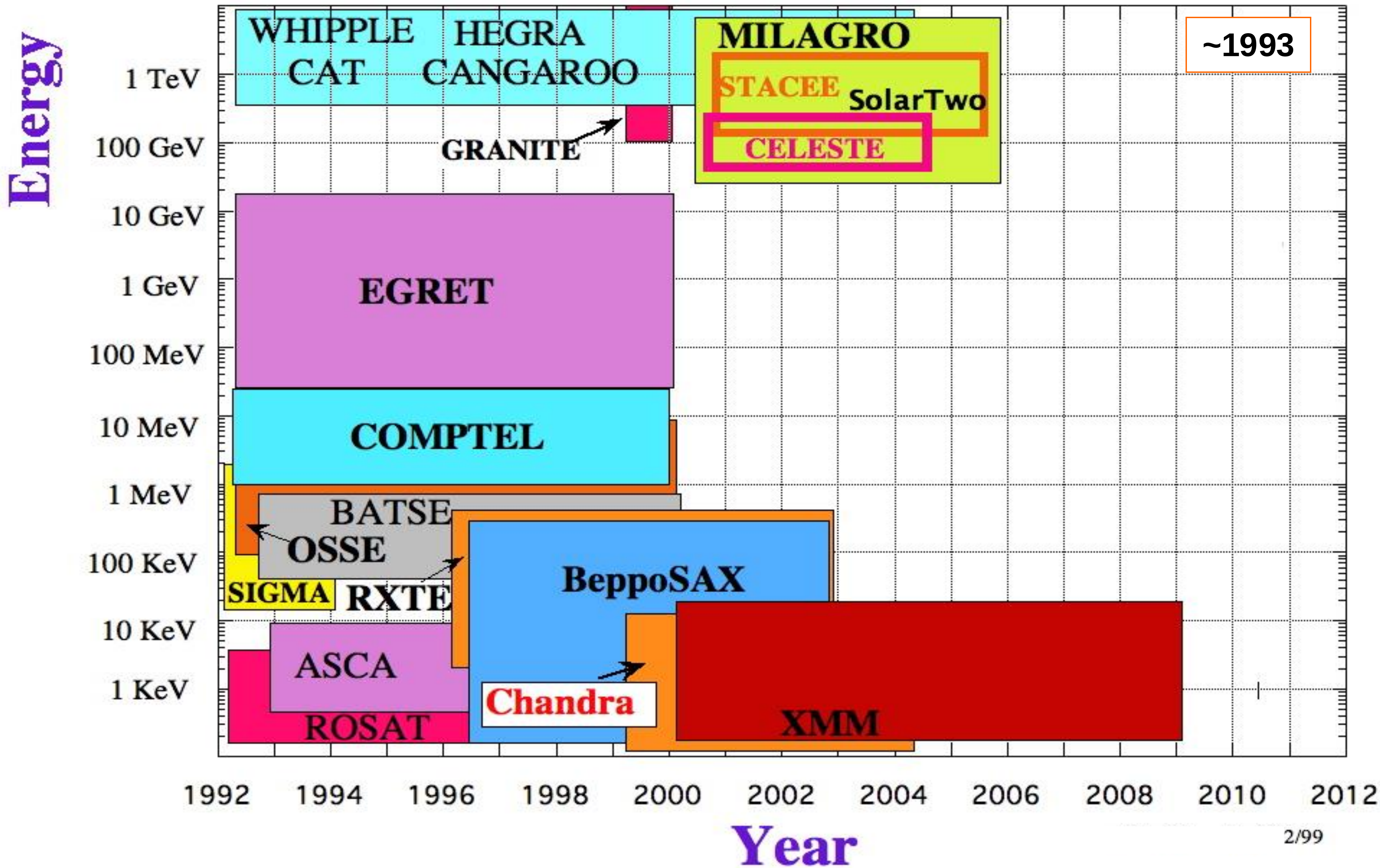
INFN Roma Tor Vergata

Theory Meeting EXperiment

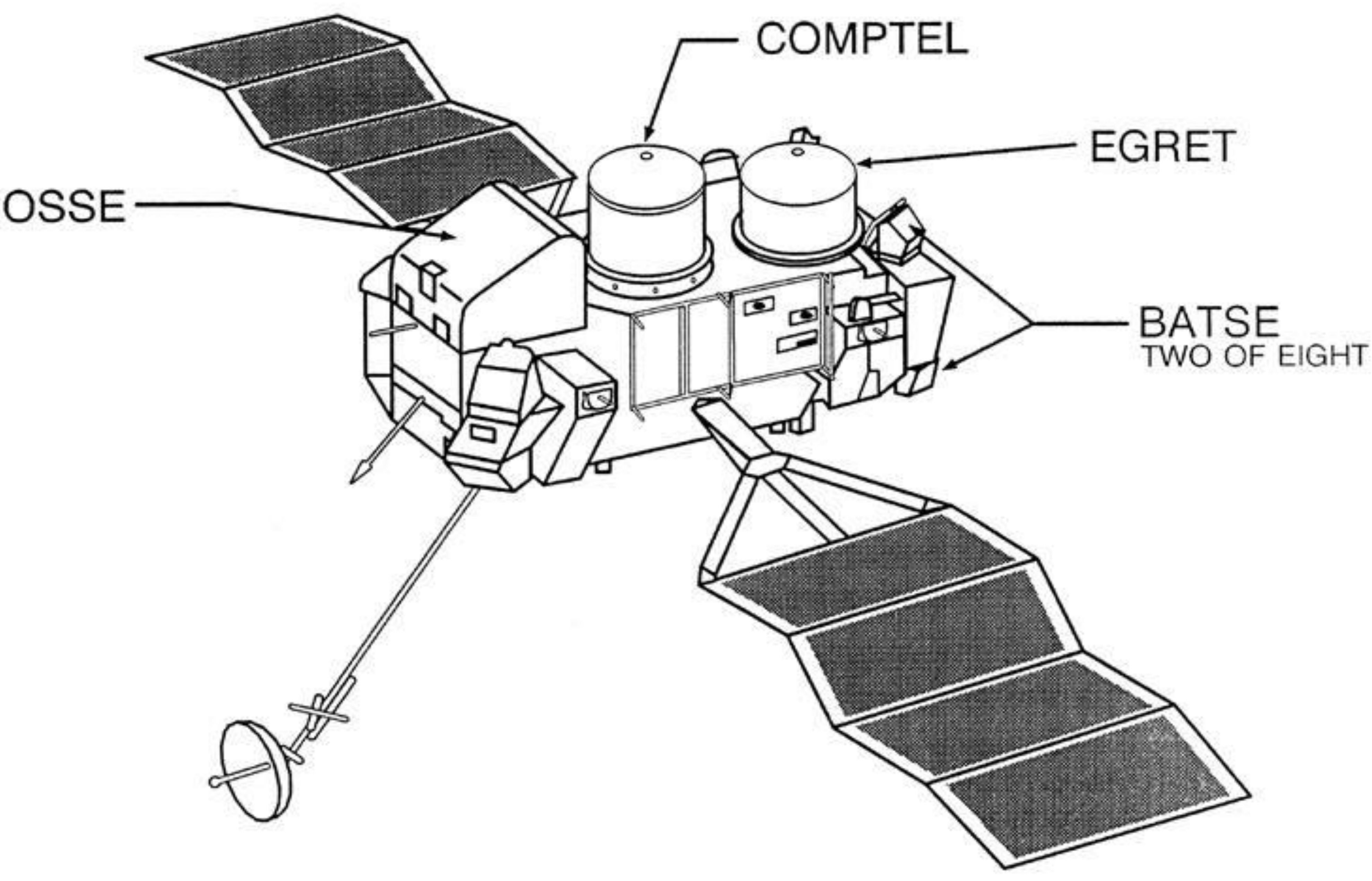
TMEX-2025 21st Rencontres du Vietnam

5-11 January 2025 Quy Nhon

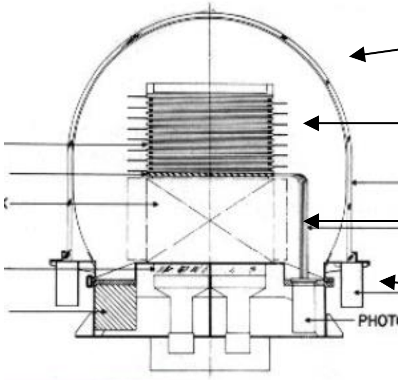
High Energy Gamma Experiments



COMPTON OBSERVATORY INSTRUMENTS



The gamma-ray missions



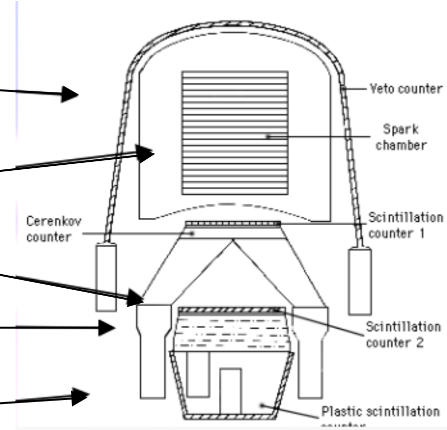
Anti-Coincidence Dome

Spark Chamber

Trigger Telescope

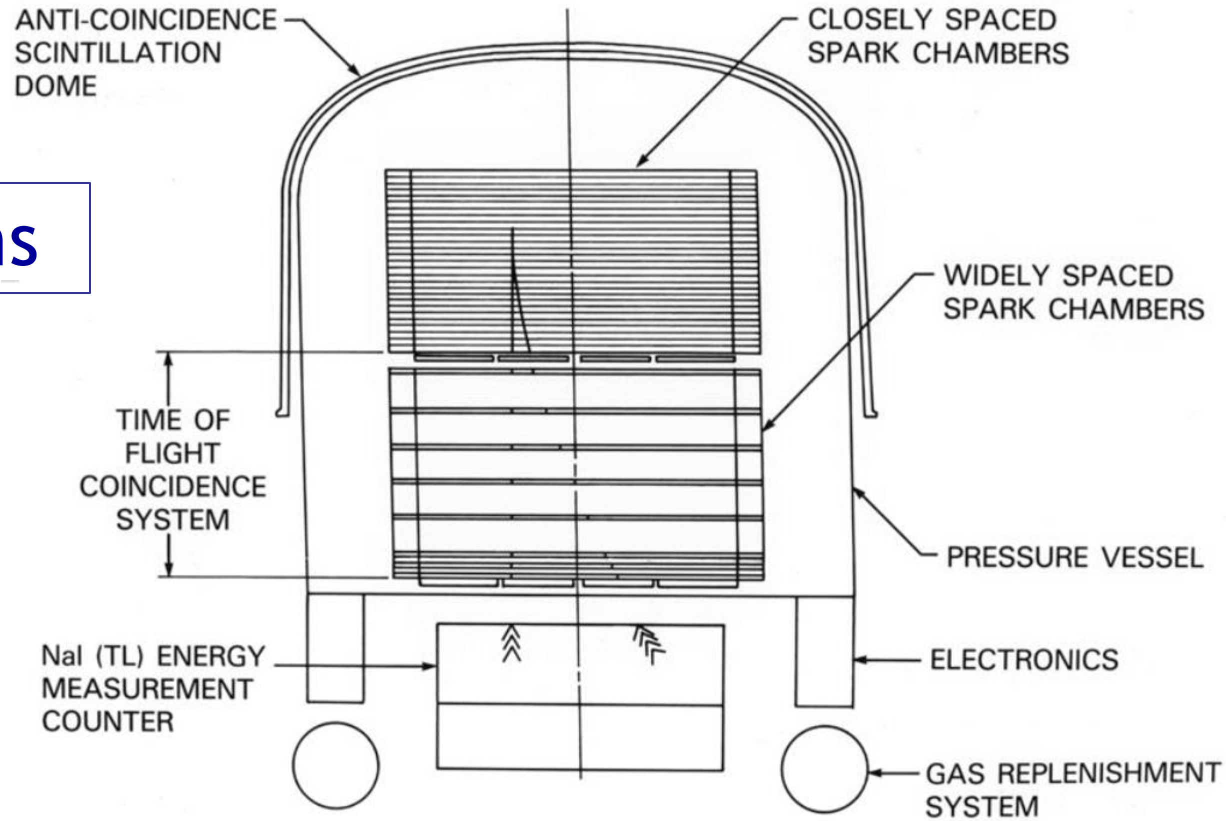
Cerenkov Counter

Energy Calorimeter



SAS-2 11/1972-7/1973

Cos-B 8/1975-4/1982

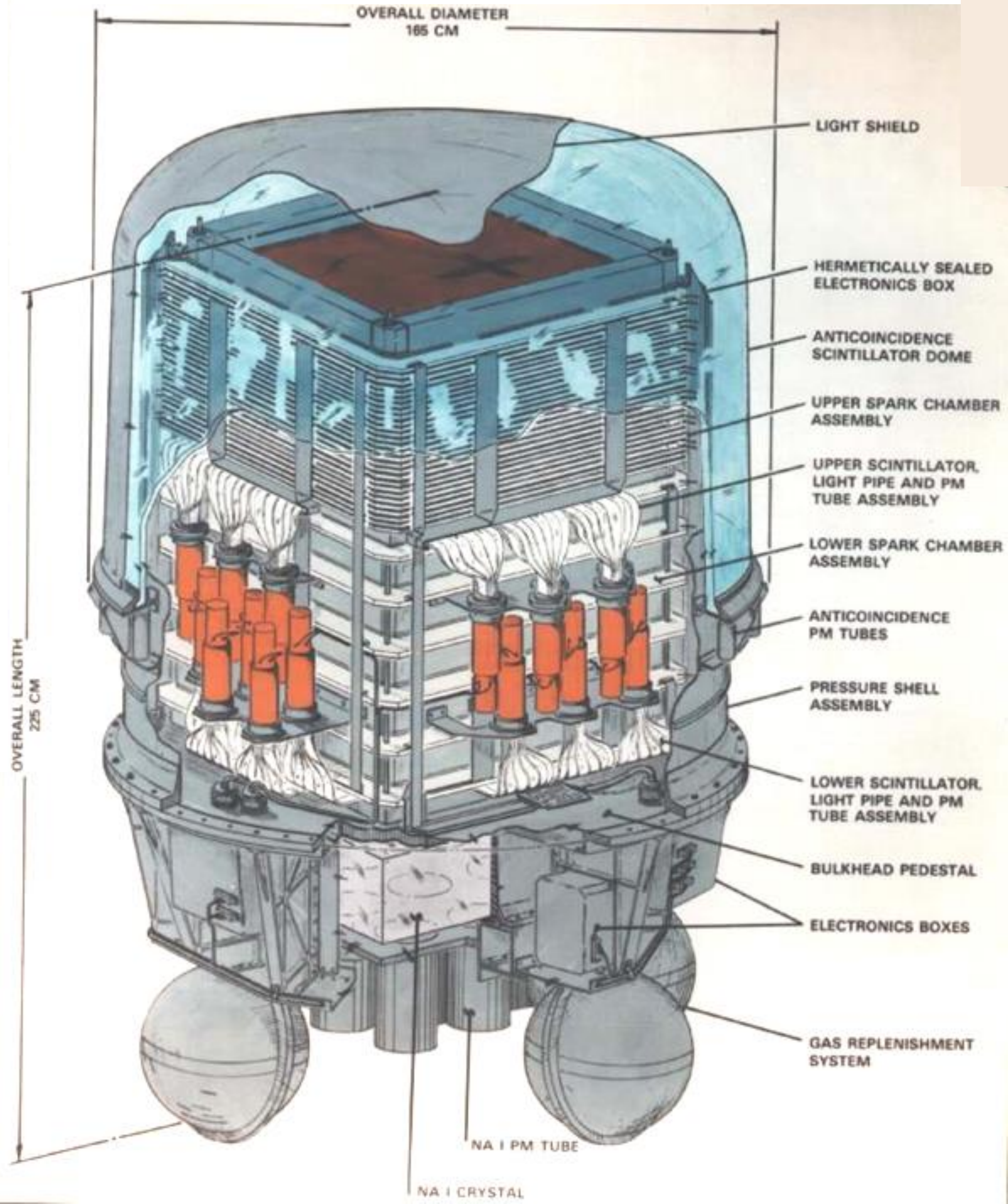


EGRET 4/1991-1999

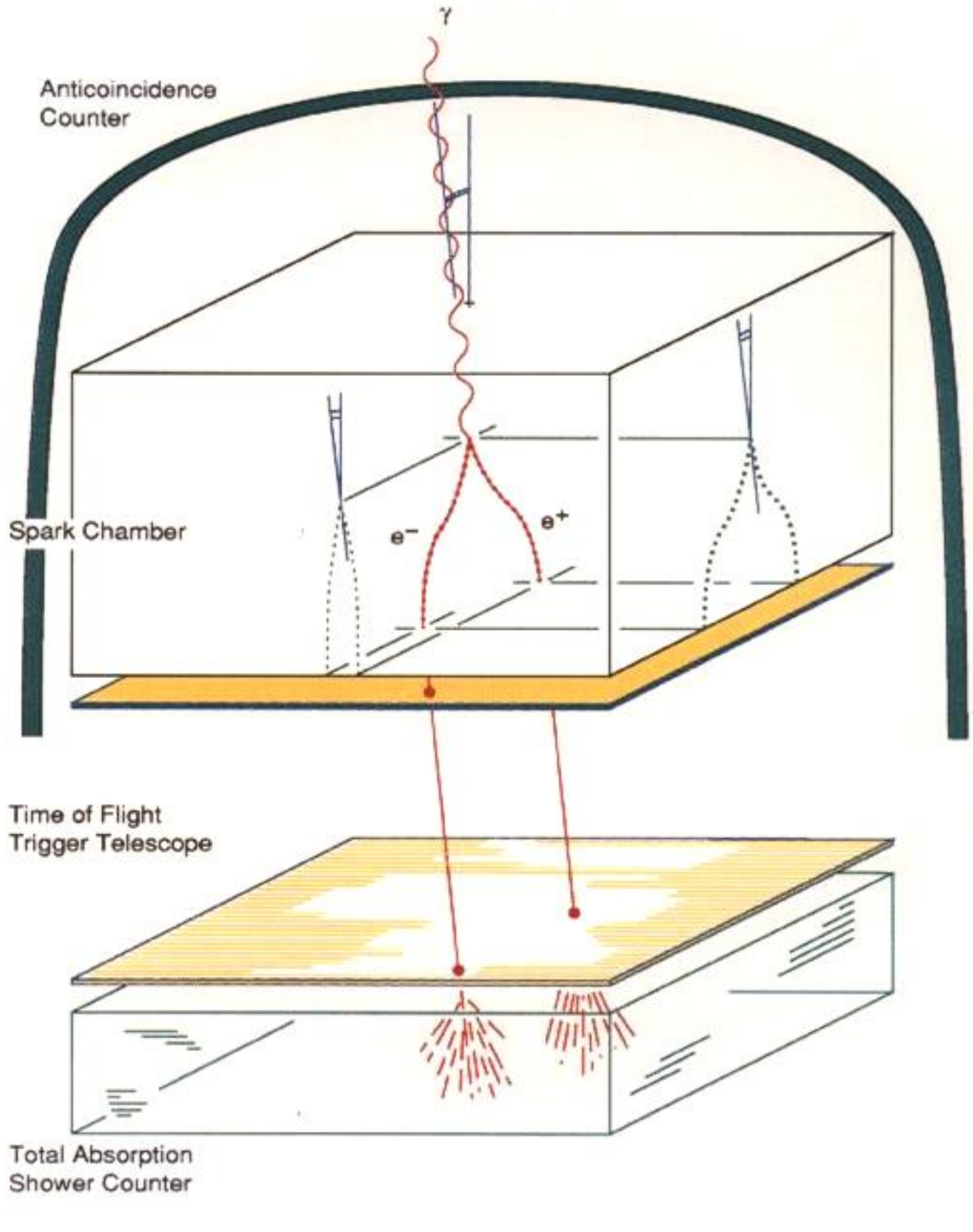
EGRET:the detector

Energy range:	20 MeV - 30 GeV	
Weight:	1820 Kg	
Power:	160 W	
Field of view:	0. 5 sr	
Dead Time:	100 ms	
Effective Area (@1GeV)	1200 cm^2	
Angular resolution (@100MeV)	5.8	

Sensitivity	0.1 GeV	$5x10^{-8}$
for point	1 GeV	$1x10^{-8}$
sources	10 GeV	$2x10^{-8}$
(ph cm-2 s-1)*		



EGRET – Principle of gamma ray detection



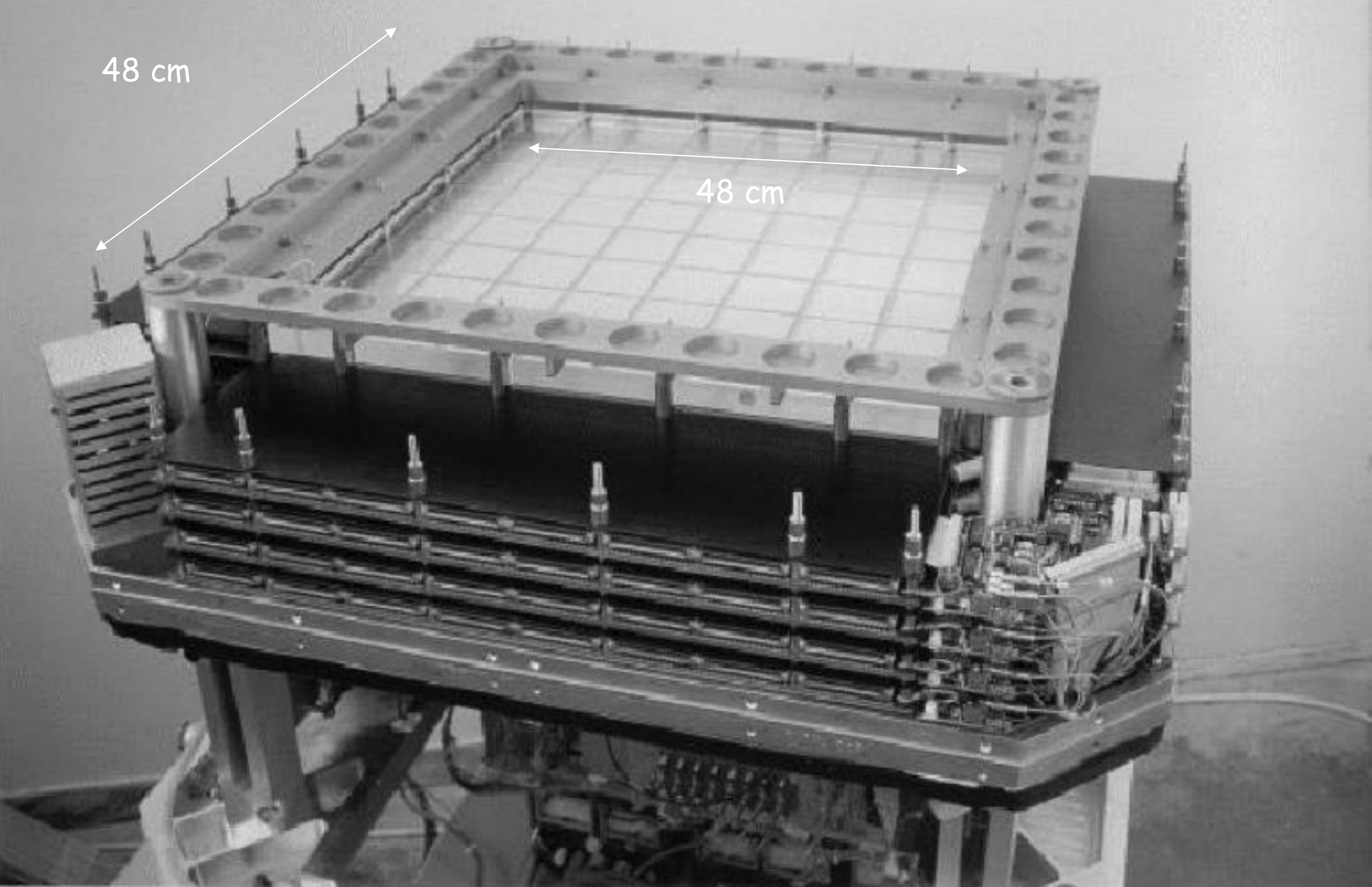
EGRET: Principle of Detection of High Energy Gamma Rays

A γray which enters the top of the EGRET instrument will pass undetected through the large anticoincidence scintillator surrounding the spark chamber and has a probability 33% of converting into an electronpositron pair in one of the thin tantalum (Ta) sheets interleaved between the 28 closely spaced spark chambers in the upper portion of the instrument.

Below the conversion stack are two 4 x 4 arrays of plastic scintillation detector tiles spaced 60 cm apart which register the passage of charged particles. If the timeofflight delay indicates a downward moving particle which passed through a valid combination of upper and lower scintillator tiles, and the anticoincidence system has not been triggered by a charged particle, the track information is recorded digitally. In this manner, a three dimensional picture of the path of the electronpositron pair is measured.

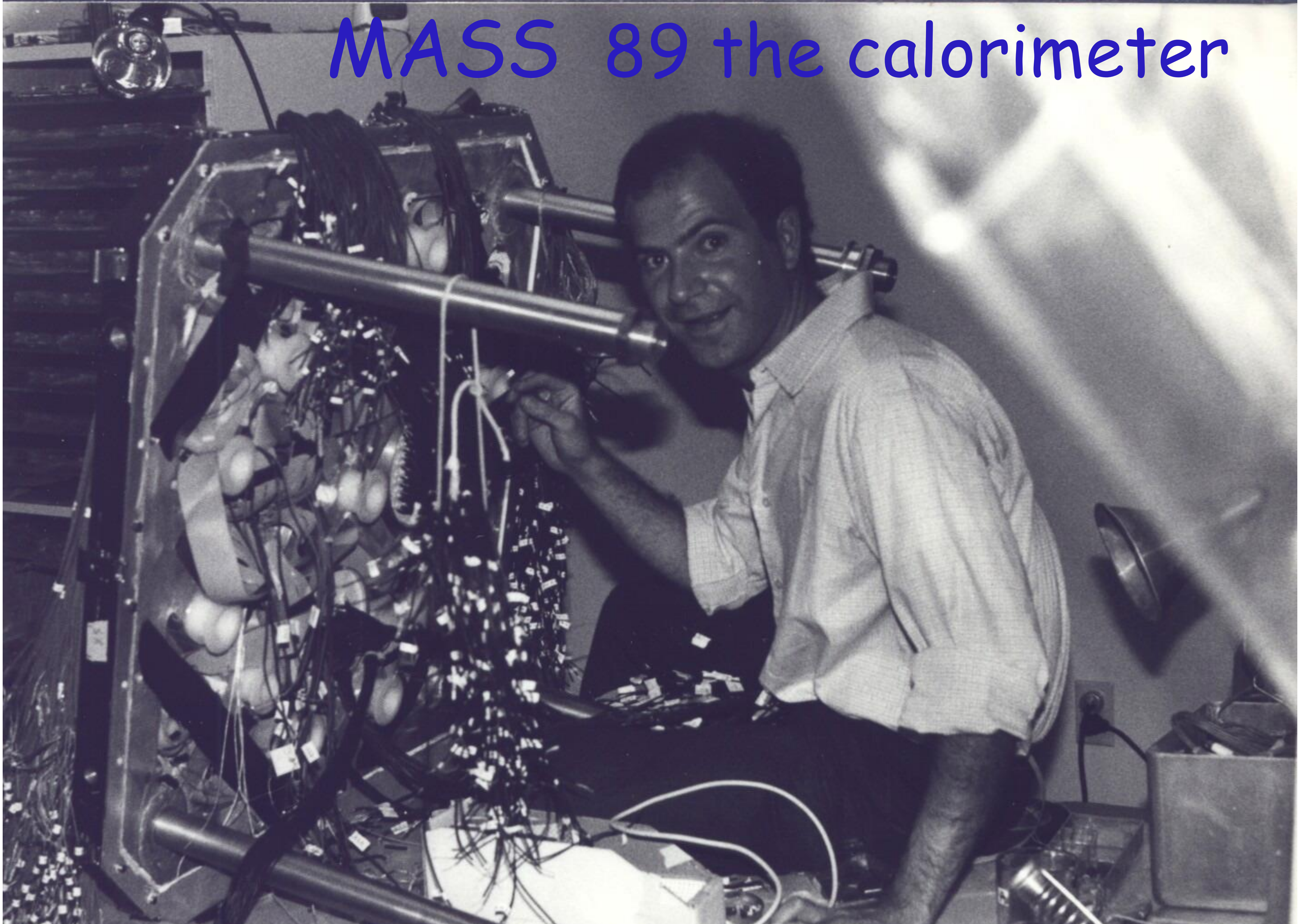
The energy deposition in the NaI(Tl) Total absorption Shower Counter (TASC) located directly below the lower array of plastic scintillators is used to estimate the photon energy.

The TS93 and CAPRICE silicon-tungsten imaging calorimeter.




The CAPRICE 94
flight

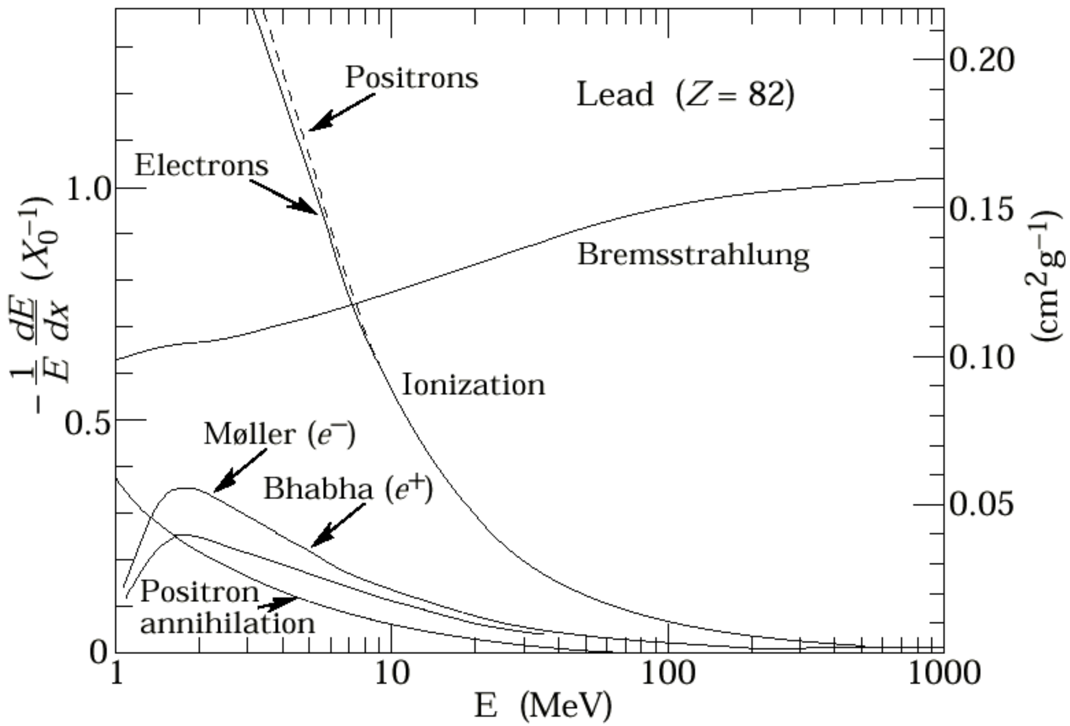
MASS 89 the calorimeter



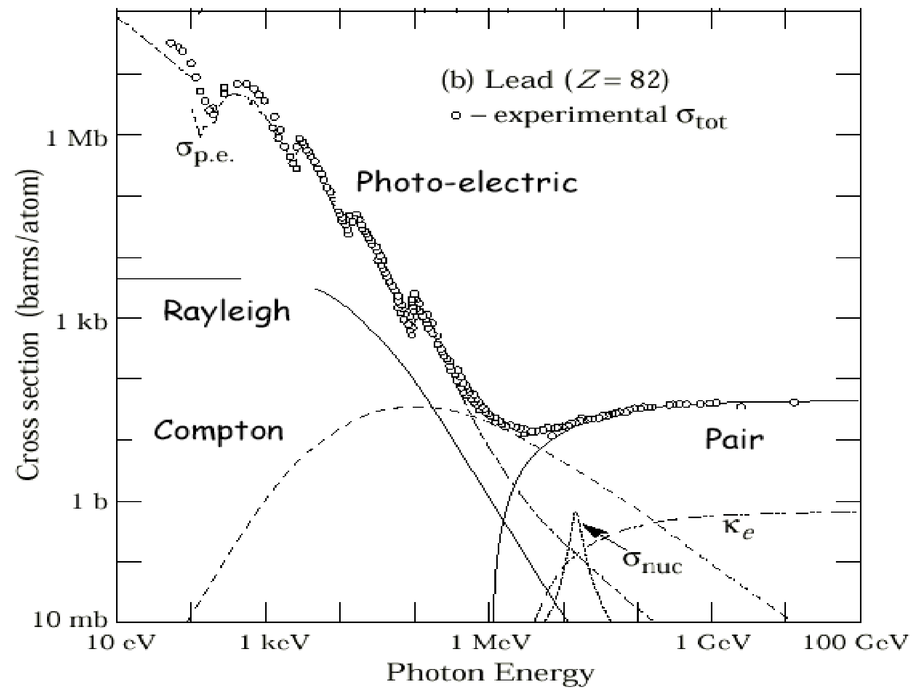

HOLD

Interaction of photons with matter

Fractional energy loss for e^+ and e^- in lead



Photon total cross sections



$$\left.\frac{dE}{dx}\right._{Brems} = -\frac{E}{X_0} \Rightarrow E(x) = e^{-\frac{x}{X_0}}$$

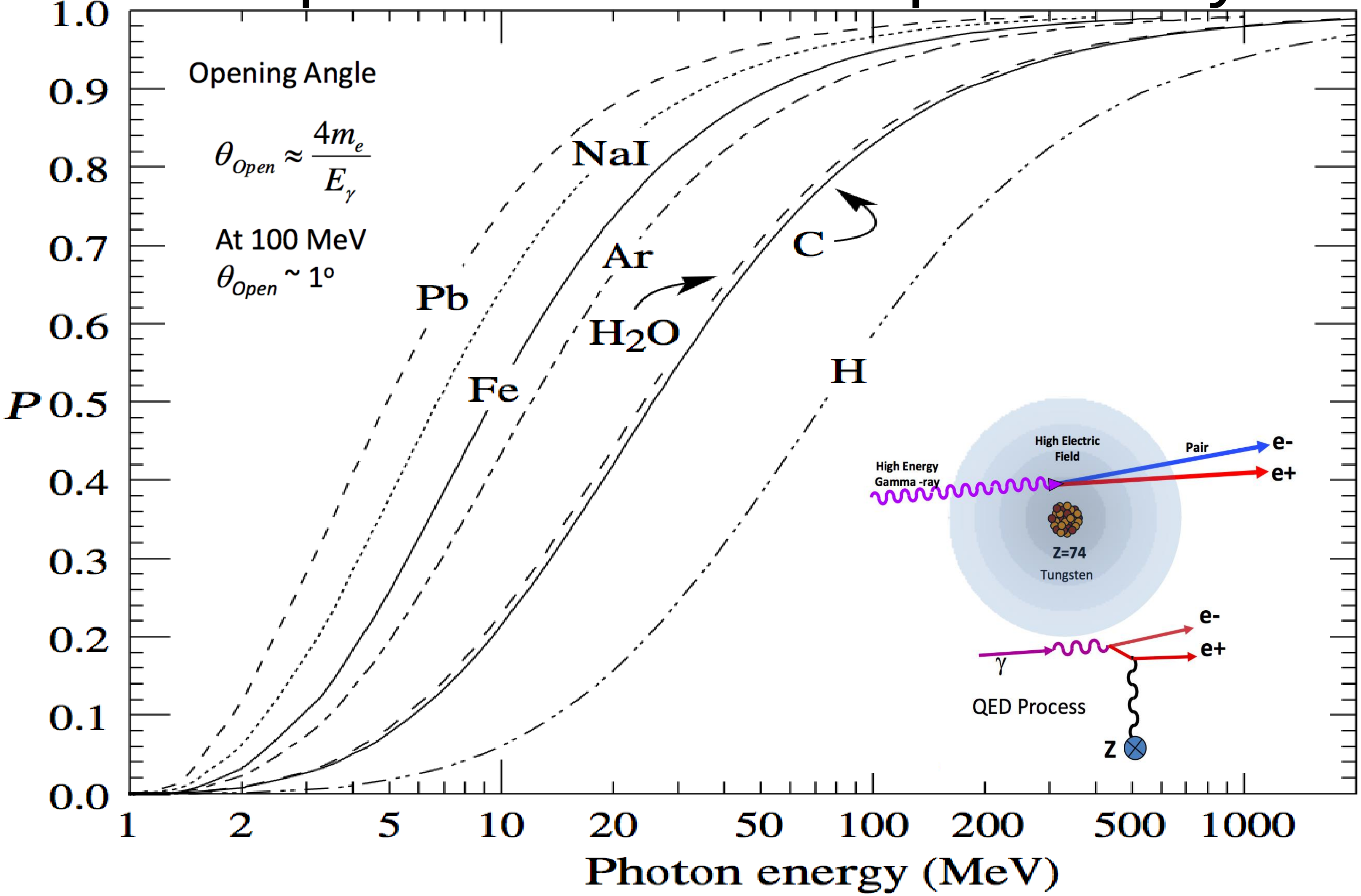
with X_0 = radiation length

$$X_0 = 716.4\ \mathrm{g\,cm^{-2}} \frac{A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

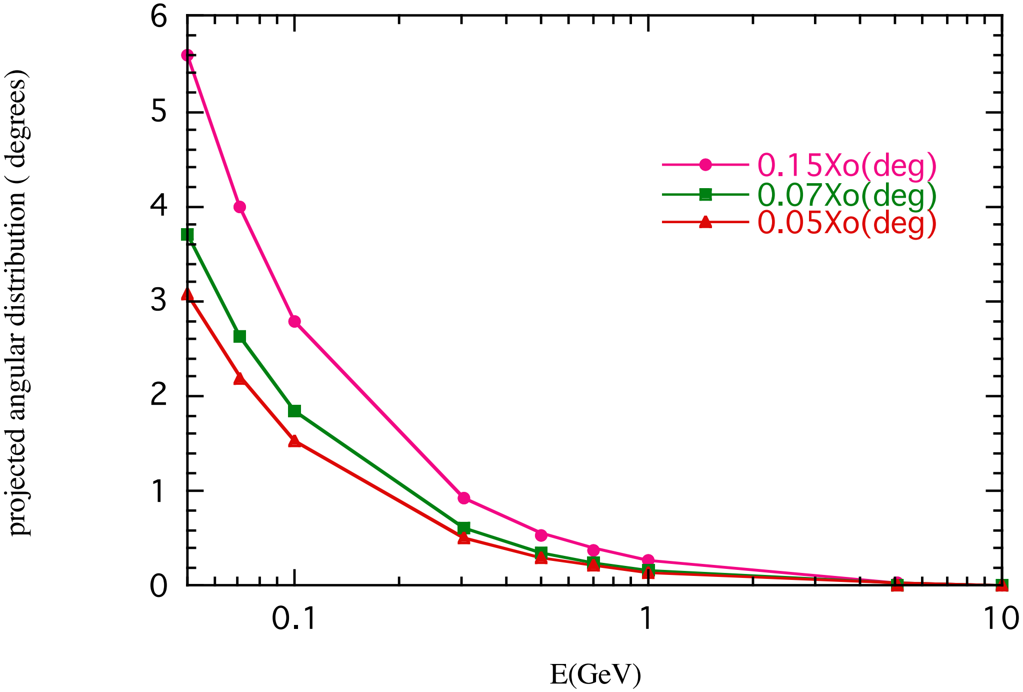
$$\text{Prob. of Int.} = 1 - \exp^{-\frac{7}{9}\frac{x}{X_0}}$$

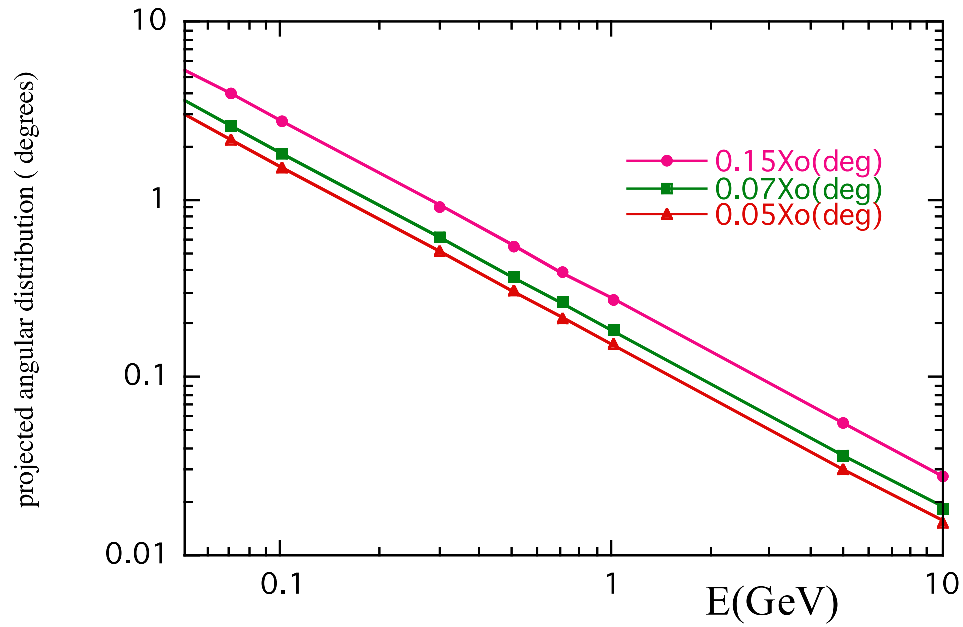
x/X_0	Prob Int.
0.5	0.40
1	0.54
2	0.79
7	0.995

Pair photon interaction probability



Multiple Scattering



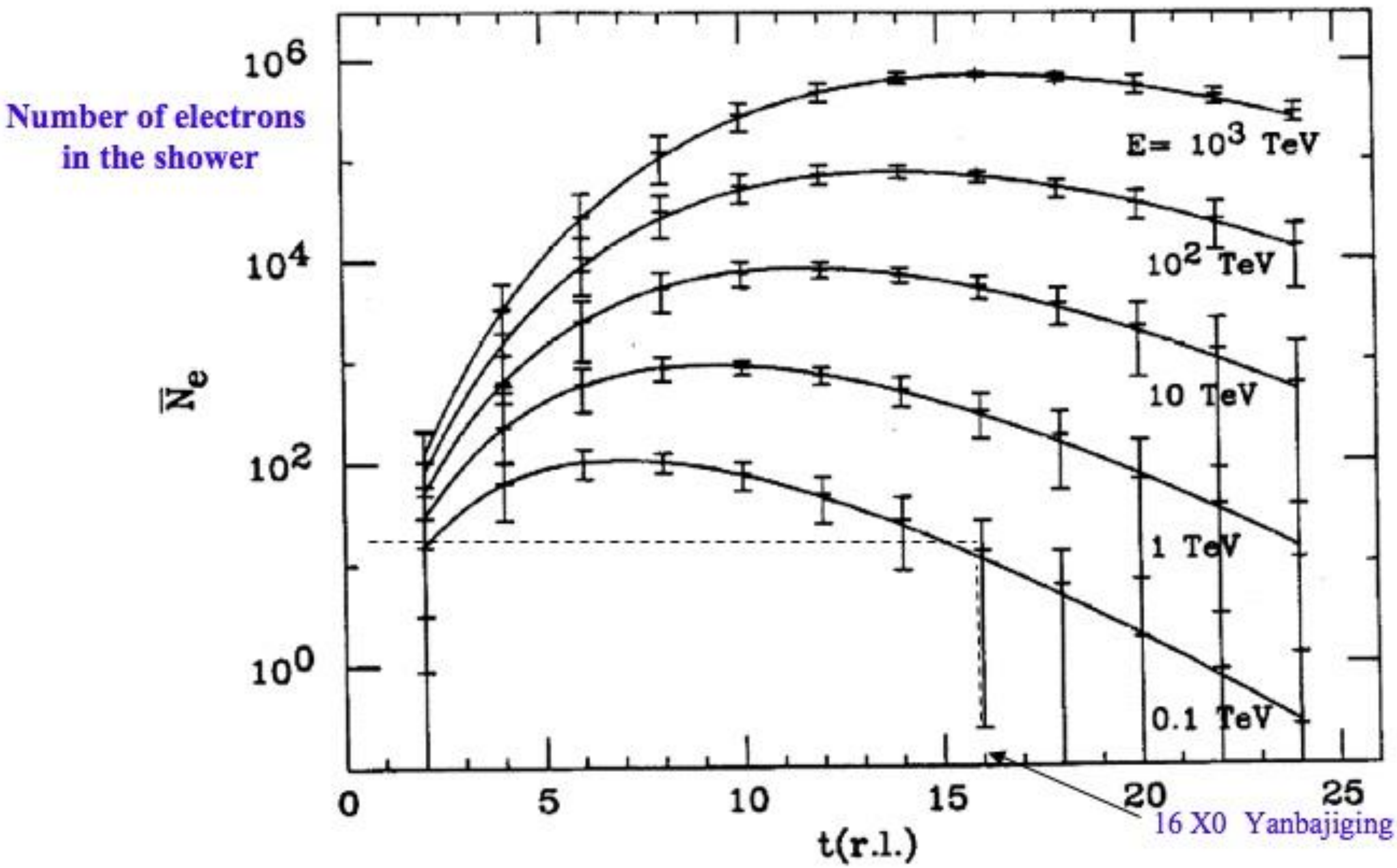


$$\theta_0 = \theta^{rms}_{plane} = \frac{1}{\sqrt{2}}\theta^{rms}_{space}$$

$$\theta_0 = \frac{13.6MeV}{\beta cp} z\sqrt{x/X_0}\,\left[1 + 0.038\ln\left(x/X_0\right)\right]$$

Longitudinal development of the electron component of photon initiated shower

(with electron threshold energy of 5 MeV and fluctuations superimposed)



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Nuclear Physics B (Proc. Suppl.) 43 (1995) 253–256

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

A wide aperture telescope for high energy gamma rays detection

G. Barbiellini[a], M. Boezio [a],M.Candusso [b], M.Casolino[b], M. P. De Pascale[b], C. Fuglesang[c], A. M. Galper [d], A. Moiseev [d], A. Morselli[b*], Yu. V. Ozerov [d], P. Picozza[b], A. V. Popov [d], M. Ricci[e], R. Sparvoli[b], P. Spillantini[f], A. Vacchi[a], S.A. Voronov [d], V. M. Zemskov [d], V. G. Zverev[d]

[a] Dept. of Physics, Univ. of Trieste and INFN, Italy

[b] Dept. of Physics, Univ. of Rome "Tor Vergata" and INFN, Italy

[c] Royal Institute of Technology, Stockholm, Sweden

[d] Moscow Engineering Physics Institute, Moscow, Russia

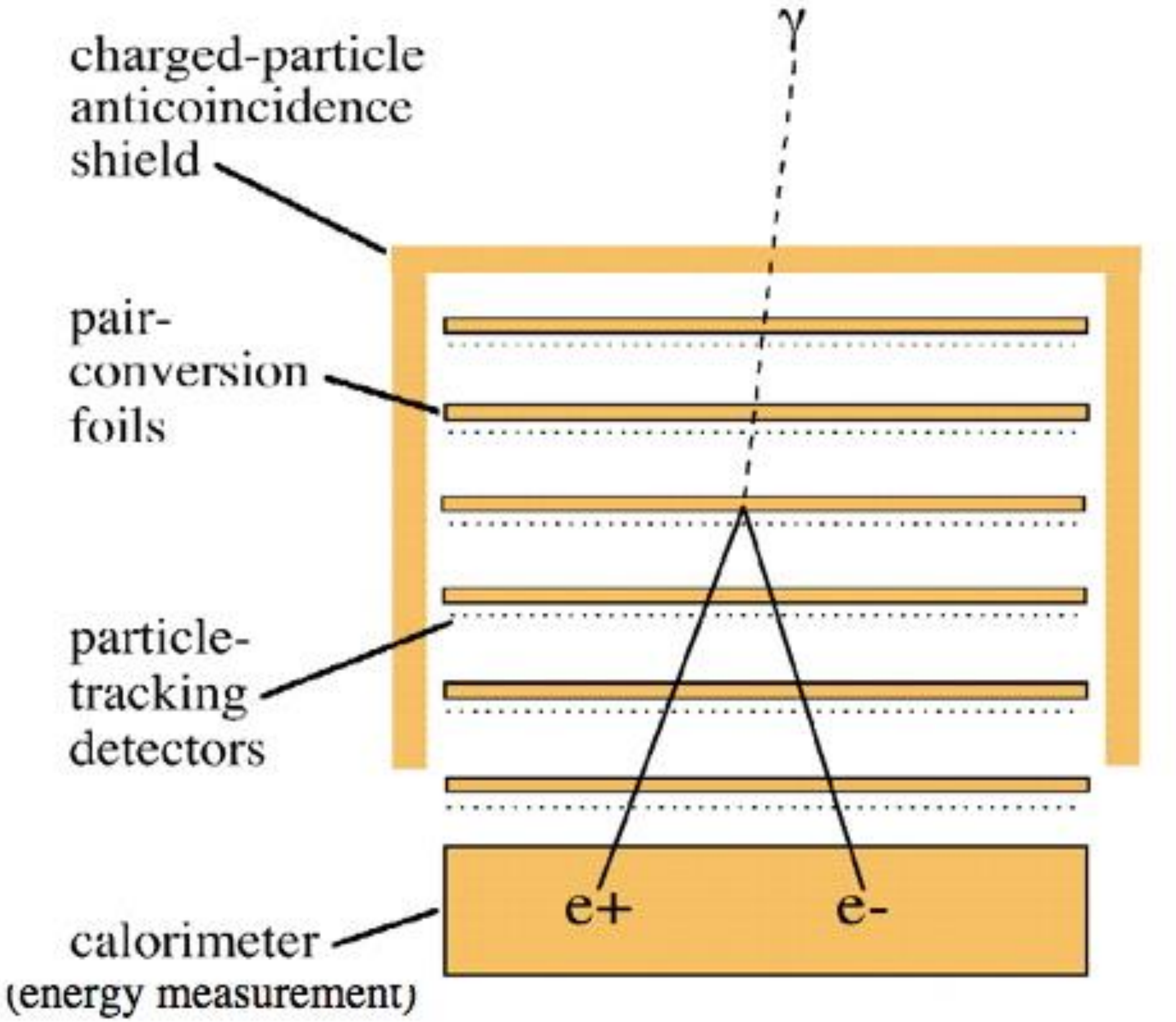
[e] INFN Laboratori Nazionali di Frascati, Italy

[f] Dept. of Physics, Univ. of Firenze and INFN, Italy

In this paper new techniques for the realization of a high energy gamma-ray telescope are presented, based on the adoption of silicon strip detectors and lead scintillating fibers. The simulated performances of this instrument show that the silicon strip technology adopted by GILDA (Gamma-ray Imaging Large Detector for Astrophysics) could improve the performance of EGRET, which is so far the most successful experiment of a high energy gamma-ray telescope, though having less volume and weight.

* Corresponding author.

Elements of a pair-conversion telescope



- photons materialize into matter-antimatter pairs:

  E_γ --> $m_{e^+}c^2 + m_{e^-}c^2$

- electron and positron carry information about the direction, energy and polarization of the γ-ray

N·H
ELSEVIER
Nuclear Instruments and Methods in Physics Research A 354 (1995) 547–552
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

The GILDA mission: a new technique for a gamma-ray telescope in the energy range 20 MeV–100 GeV

G. Barbiellini [a], M. Boezio [a], M. Casolino [b], M. Candusso [b], M.P. De Pascale [b], A. Morselli [b,*], P. Picozza [b], M. Ricci [d], R. Sparvoli [b], P. Spillantini [c], A. Vacchi [a]

[a] *Dept. of Physics, Univ. of Trieste and INFN, Italy*
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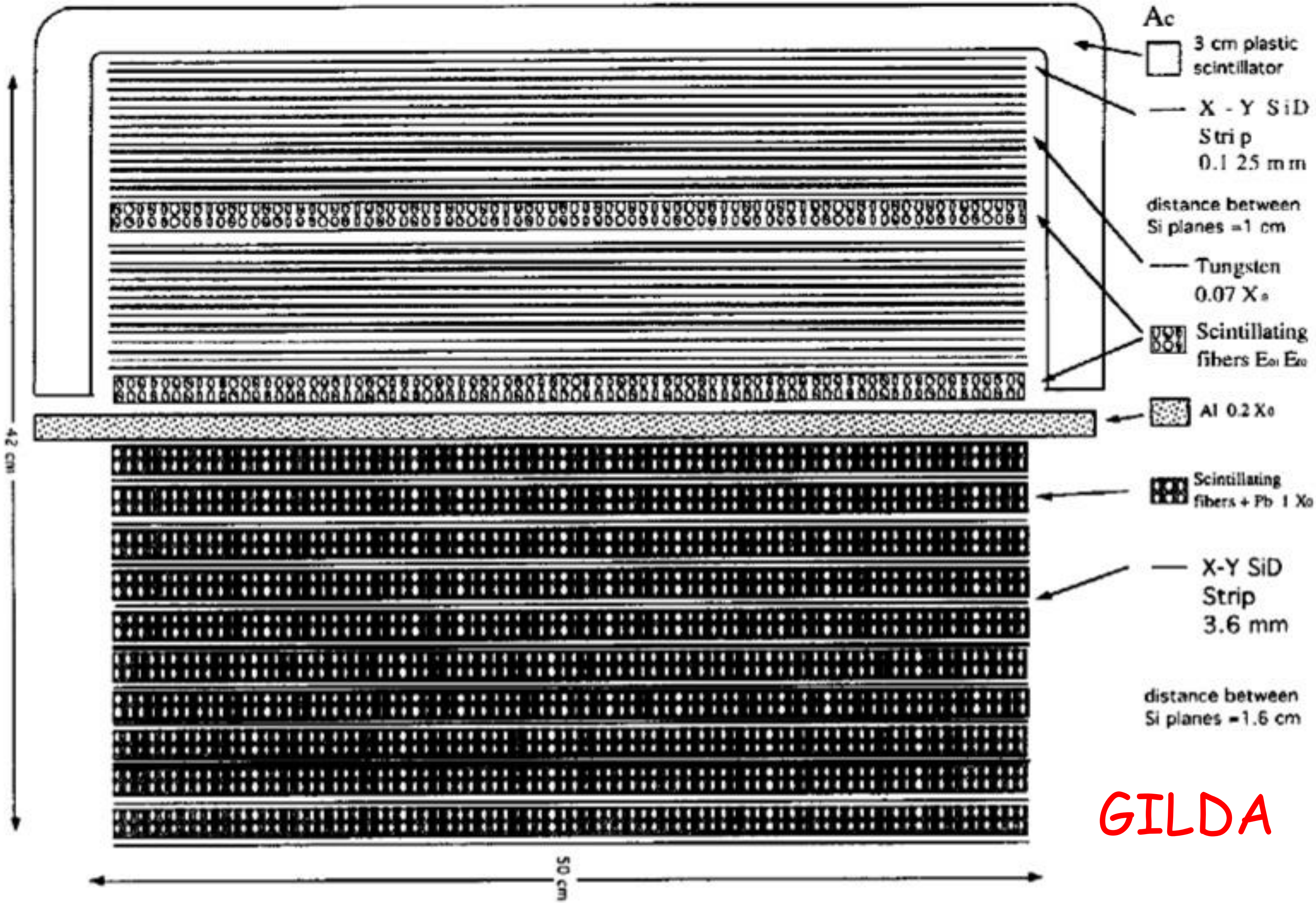
Received 5 August 1994

Abstract

In this article a new technique for the realization of a high energy gamma-ray telescope is presented, based on the adoption of silicon strip detectors and lead scintillating fibers. The simulated performances of such an instrument (GILDA) are significatively better than those of EGRET, the last successful experiment of a high energy gamma-ray telescope, launched on the CGRO satellite, though having less volume and weight.

* Corresponding author.



Ac
3 cm plastic scintillator
X - Y SiD Strip 0.125 mm
distance between Si planes =1 cm
Tungsten 0.07 X_0
Scintillating fibers E_{01} E_{02}
Al 0.2 X_0
Scintillating fibers + Pb 1 X_0
X-Y SiD Strip 3.6 mm
distance between Si planes =1.6 cm
42 cm
50 cm

GILDA

Proposta per la *Call for Ideas* ASI per Piccole Missioni (Scienze dell'Universo)
26 giugno 1997

AGILE: Rivelatore a immagini gamma leggero

M. Tavani[1,2], G. Barbiellini[3], M. Boezio[3], P. Caraveo[1], M. Casolino[4], M. P. De Pascale[4], S. Mereghetti[1], A. Morselli[4], A.Perrino[4], P. Picozza[4], P. Schiavon[3], R. Sparvoli[4], A. Vacchi[3]

1. Istituto di Fisica Cosmica e Tecnologie Relative, CNR, Milano
2. Columbia Astrophysics Laboratory, Columbia University, New York, USA
3. Dipartimento di Fisica, Universitá di Trieste e INFN
4. Dipartimento di Fisica, Universitá di Roma II, "Tor Vergata" e INFN

Introduzione

L'astrofisica gamma delle alte energie nella banda 30 MeV–10 GeV beneficierebbe enormemente durante i primi anni del 2000 dall'esistenza di un rivelatore al silicio a largo campo e con sensibilita' e accuratezza confrontabili o migliore di EGRET. Presentiamo qui il concetto di tale missione leggera, AGILE (*Astro-rivelatore Gamma a Immagini LEggero*) dalle dimensioni e peso (inferiore ai 50 kg) ridotte ma dall'elevata e unica capacita' di rivelare sorgenti gamma galattiche e extragalattiche. La tecnologia al silicio permette di rivelare radiazione gamma con enormi vantaggi rispetto a EGRET. AGILE non presenterá problemi di rifornimento di gas, non necessita di alti valori di tensione, e' caratterizzata da un tempo morto breve ($1\mu s$) e da un trigger fornito esclusivamente dai piani di silicio. L'assenza di un calorimetro non consente di avere informazione spettrale dettagliata. Tuttavia, l'enorme vantaggio di realizzare uno strumento molto leggero e dalle elevate prestazioni di rivelazione (sia di risoluzione angolare che di flusso) rende AGILE altamente competitivo rispetto a future missioni astrofisiche di alta energia. AGILE sfrutta l'esperienza del gruppo proponente nella realizzazione di satelliti astrofisici con tecnologia al silicio. L'intero rivelatore e' da realizzarsi in Italia con un costo dello strumento inferiore ai 10 miliardi e costo complessivo della missione inferiore ai 25 miliardi di lire.

Proposta per la *Call for Ideas* ASI per Piccole Missioni (Scienze dell'Universo)
26 giugno 1997

GILDA40: rivelatore di raggi gamma al Silicio

A. Morselli[1], G. Barbiellini[2], M. Boezio[2], P. Caraveo[3], M. Casolino[1], M. P. De Pascale[1], S. Mereghetti[3], A.Perrino[2], P. Picozza[1], P. Schiavon[2], R. Sparvoli[1], M. Tavani[3,4], A. Vacchi[2]

1. Dipartimento di Fisica, Universitá "Tor Vergata" e INFN.
2. Dipartimento di Fisica, Universitá di Trieste e INFN.
3. Istituto di Fisica Cosmica e Tecnologie Relative, CNR, Milano.
4. Columbia Astrophysics Laboratory, Columbia University, New York, USA.

Introduzione

La proposta del telescopio gamma GILDA40 nasce dall'attivita' consolidata della collaborazione internazionale denominata WiZard che prevede le missioni *Nina* (prevista volare per l'autunno 1997) e *Pamela* (programmata per la seconda meta' del 2000). Cio' significa che esiste un contesto scientifico in cui GILDA40 si inserisce naturalmente. Costi e tempi di sviluppo possono essere realisticamente e sensibilmente bassi visto che e' possibile attingere a tutto il lavoro di progettazione, realizzazione e test gia' esistente (vedi descrizione tecnica). Il telescopio GILDA40 fa infatti uso di rivelatori al silicio ad alta risoluzione spaziale. Questi offrono grandi vantaggi per la rivelazione astrofisica di radiazione gamma: non presentano problemi di rifornimento di gas, non necessitano di alti valori di tensione nè di fotomoltiplicatori per l'analisi del segnale, presentano un tempo morto breve ($1\mu s$) e un trigger dato esclusivamente dai piani di silicio. Lo strumento consiste in un tracciatore al silicio e di un calorimetro di dimensioni e peso opportunamente configurati in base all'orbita scelta. GILDA40 puo' volare sia su un satellite a puntamento con orbita equatoriale, che in *scanning mode* su un satellite elio-sincrono. GILDA40 puo' essere realizzata interamente in Italia entro tre anni con un costo dello strumento inferiore ai 10 miliardi di lire.

AGILE

Phase A Report
Italian Space Agency Program for Small Scientific Missions
October 1998

AGILE

Astrorivelatore Gamma a Immagini LEggero

Principal Investigator:

M. Tavani	IFC - CNR, Milano Columbia University, New York

Co-Investigators:

G. Barbiellini	University of Trieste and INFN, Trieste
P. Caraveo	IFC - CNR, Milano
S. Di Pippo	ASI
F. Longo	University of Trieste and INFN, Trieste
S. Mereghetti	IFC - CNR, Milano
A. Morselli	University "Tor Vergata" and INFN, Roma
A. Pellizzoni	IFC - CNR, Milano
P. Picozza	University "Tor Vergata" and INFN, Roma
S. Severoni	University "Tor Vergata" and INFN, Roma
F. Tavecchio	IFC - CNR, Milano
A. Vacchi	University of Trieste and INFN, Trieste
S. Vercellone	IFC - CNR, Milano

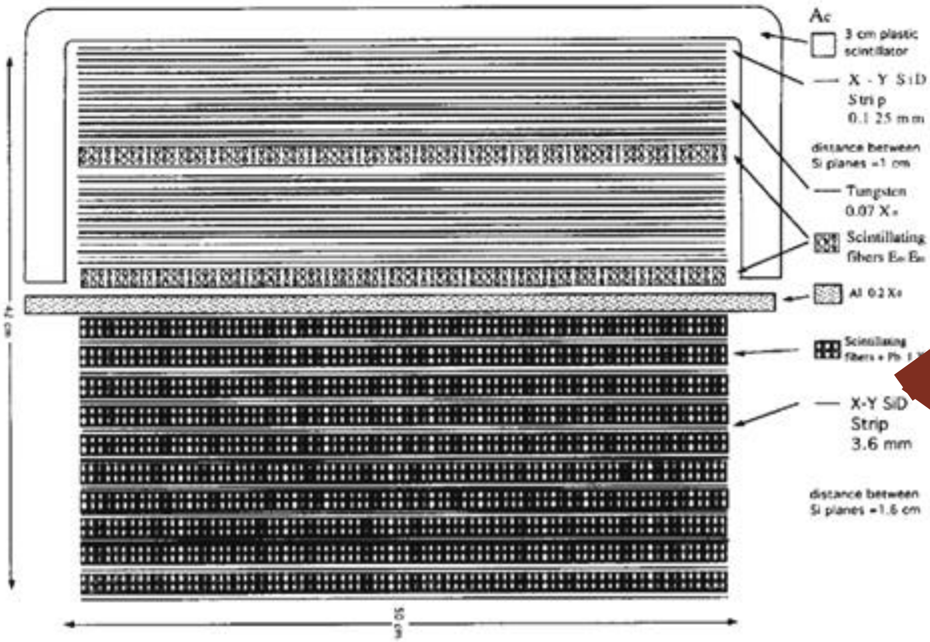
Scientific Editors:

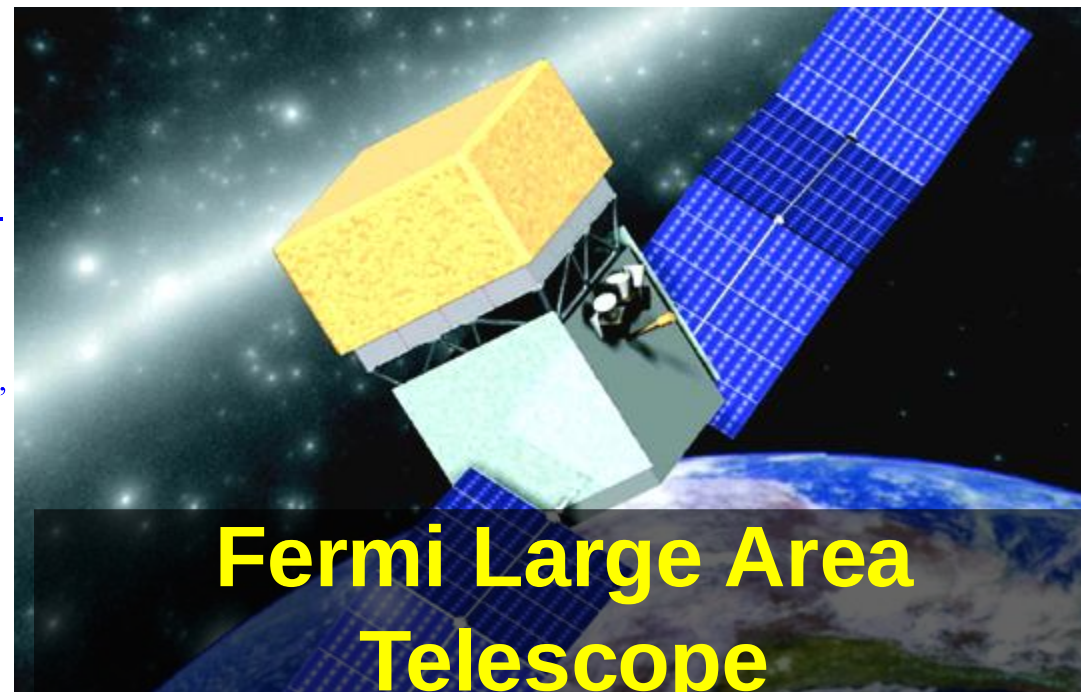
Sandro Mereghetti

Aldo Morselli

Marco Tavani

GILDA





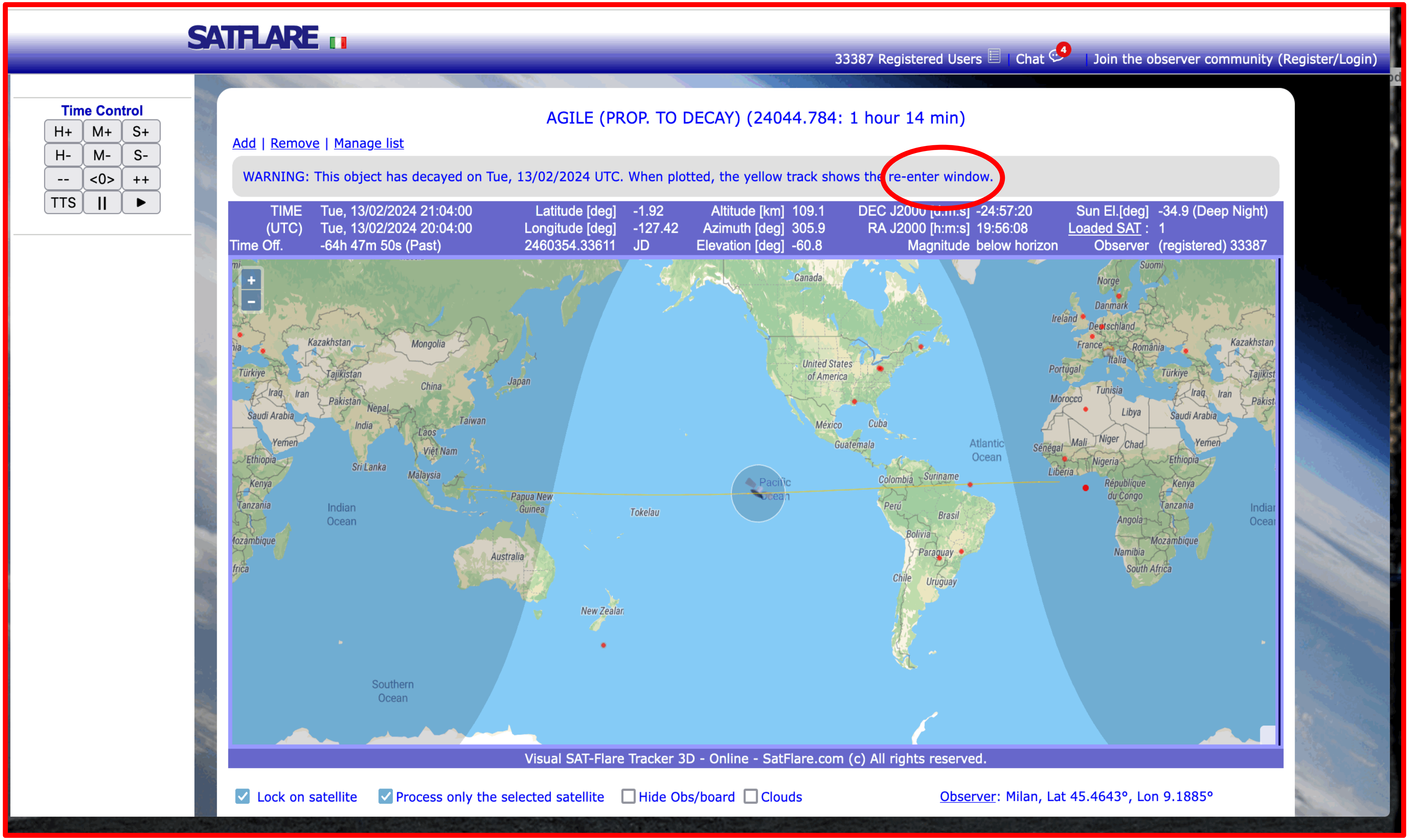
Development of GLAST, a broadband High-Energy Gamma-Ray Telescope using Silicon Strip Detectors

P.Michelson, W.Atwood, E.Bloom, G.Godfrey, Y.Lin, P.Nolan, D.Bertsch, N.Gehrels, R.Hartman, S.Hunter, J.Norris, J.Ormes, R.Streitmatter, D.Thompson, E.Grove, P.Hertz, W.N.Johnson, M.Lovellette, G.H.Share, M.Wolff, K.S.Wood, R.Johnson, C.Couvault, R.Ong, M.Oreglia, J.Mattox, T.Burnett, C.Chenette, G.Nakano, L.Cominsky, H.A.Mayer-Hasselwander, G.Barbiellini, A.Colavita, A.Morselli, T.Kamae, K.Kasahara

Proposal presented to NASA, Space Physics Division in response to "Proposal for High Energy Astrophysics Supporting Research and Technology Program", NRA 95-OSS-17


AGILE
23 April 2007
16 years and 10 month in orbit


AGILE
23 April 2007- 23 April 2022
Happy 15th Birthday Agile !!


SATFLARE
33387 Registered Users | Chat | Join the observer community (Register/Login)
Time Control
H+ M+ S+
H- M- S-
-- <0> ++
TTS || ▶
AGILE (PROP. TO DECAY) (24044.784: 1 hour 14 min)
Add | Remove | Manage list
WARNING: This object has decayed on Tue, 13/02/2024 UTC. When plotted, the yellow track shows the re-enter window.
TIME Tue, 13/02/2024 21:04:00
(UTC) Tue, 13/02/2024 20:04:00
Time Off. -64h 47m 50s (Past)
Latitude [deg] -1.92
Longitude [deg] -127.42
2460354.33611 JD
Altitude [km] 109.1
Azimuth [deg] 305.9
Elevation [deg] -60.8
RA J2000 [h:m:s] 19:56:08
Magnitude below horizon
Sun El.[deg] -34.9 (Deep Night)
Loaded SAT : 1
Observer (registered) 33387
Visual SAT-Flare Tracker 3D - Online - SatFlare.com (c) All rights reserved.
Lock on satellite
Process only the selected satellite
Hide Obs/board
Clouds
Observer: Milan, Lat 45.4643°, Lon 9.1885°

Summary of AGILE results in >16 years of operations

- **Publications:** the scientific production of the AGILE Team consists of **> 800 bibliographic references in ADS, of which> 160 refereed articles.**
- The monitoring of the sky with a rapid and efficient alert system led to the publication of **>240 ATels** and **>300 GCNs**. From May 2019, **101 MCAL GCN automatic notices** have been published.

- The Quick Look system developed by INAF-OAS, distributed between the data center at SSDC and INAF-OAS in Bologna, produced **scientific results within ~ 25 min** from the data downlink to the ASI Malindi ground station: an absolute record for gamma astrophysics. The Team has also developed **AGILEScience - App on Google Play and App Store** to monitor and follow the observations of the AGILE satellite on mobile devices.

- **AGILE and the search for GW counterparts:** participation of Team members with shifts 24/7 during LIGO-VIRGO observational runs. AGILE follow-up of all **pre-O4 GW events**, with **96 GW-AGILE type GCNs published during O3** and collected in a dedicated web page in SSDC**:** *https://agile.ssdc.asi.it/news_gw.html* AGILE completed the follow-up of all GW events **up to the end of LVK O4a (first part) on Jan 16, 2024**.

- AGILE contribution to **Fast Radio Bursts** science: **very important discovery** on April 28, 2020 published in **Nature, Tavani et al. 2021** (2021NatAs...5..401T)

THE AGILE LEGACY

AGILE archives and catalogs are available to the community through the ASI SSDC.

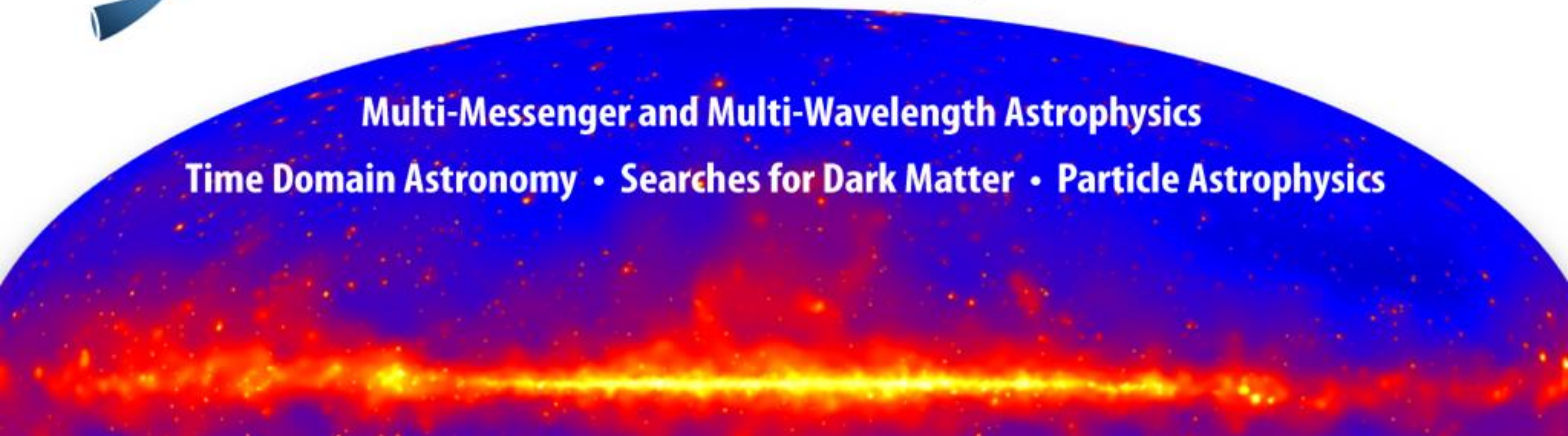
Science activities continue. We have just published on Feb. 29, 2024 all AGILE-GRID data **up to January 15, 2024. A data reprocessing is in progress.**

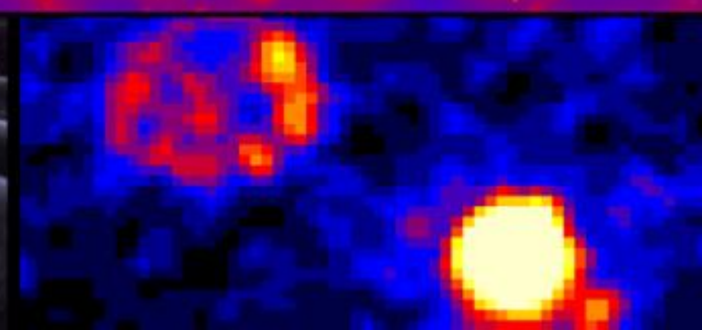
Open-source Python software package **Agilepy** (INAF-OAS) and/or **SSDC AGILE-LV3 online data analysis tool.**

With AGILE's re-entry, the in-orbit operational phase ended, but a new phase of scientific work on the satellite legacy data archive opens.

Work in progress on new catalogs with and without **Machine Learning** techniques. **Stay tuned for further results**.

Fermi Gamma-Ray Space Telescope






Fermi
Gamma-ray
Space Telescope
Happy 16th Birthday Fermi !!
11 June 2008

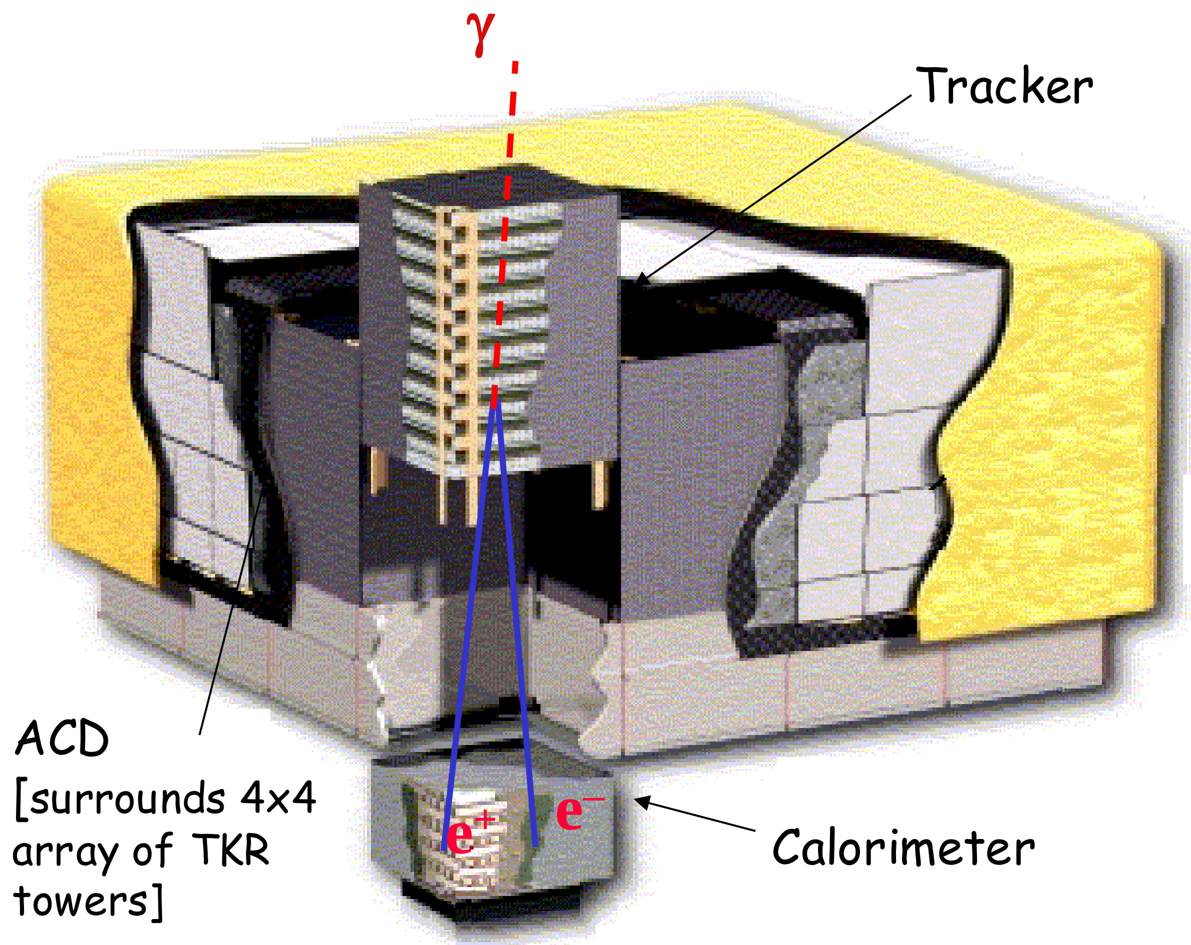
Fermi LAT: A Telescope Without Lenses

- Precision Si-strip Tracker (TKR) 70 m^2 of silicon detectors arranged in 36 planes. 880,000 channels.

- Hodoscopic CsI Calorimeter(CAL) 1536 CsI(Tl) crystals in 8 layers, total mass 1.5 tons.

- Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles.

- Electronics System Includes flexible hardware trigger and onboard computing.



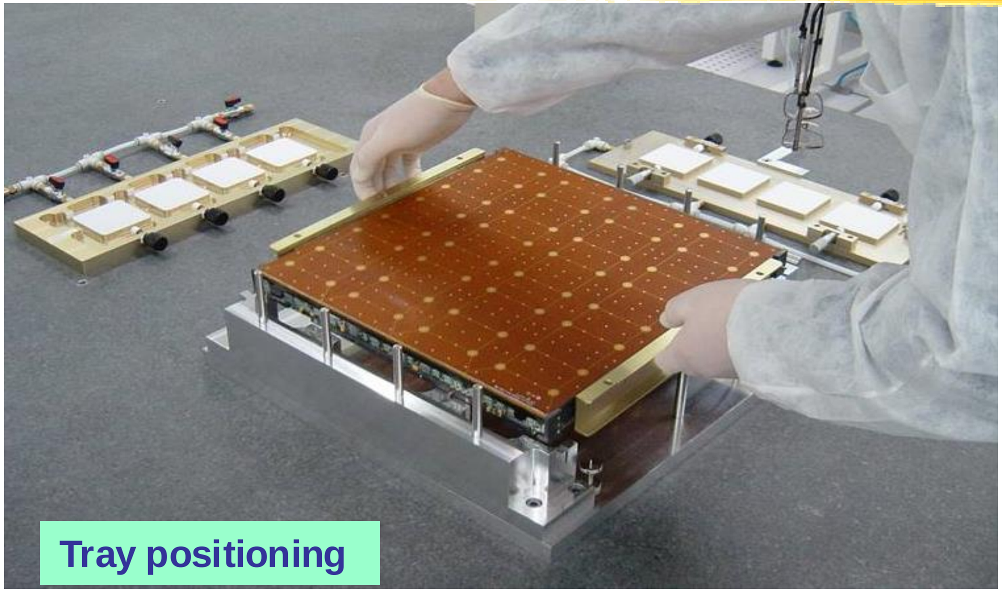
The Fermi Observatory

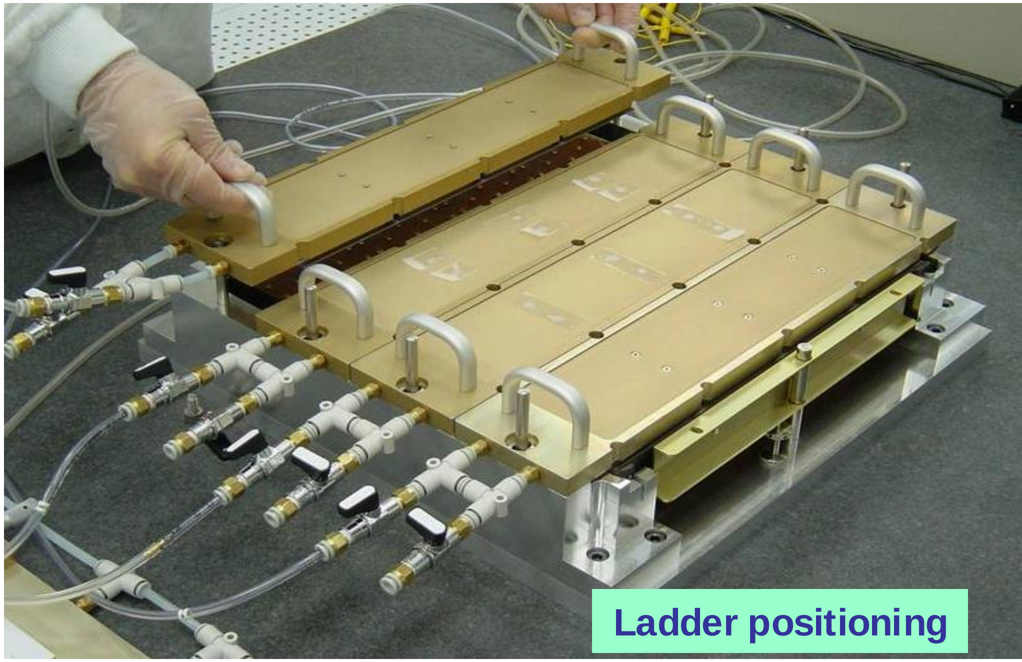
LAT
Large
Area
Telescope

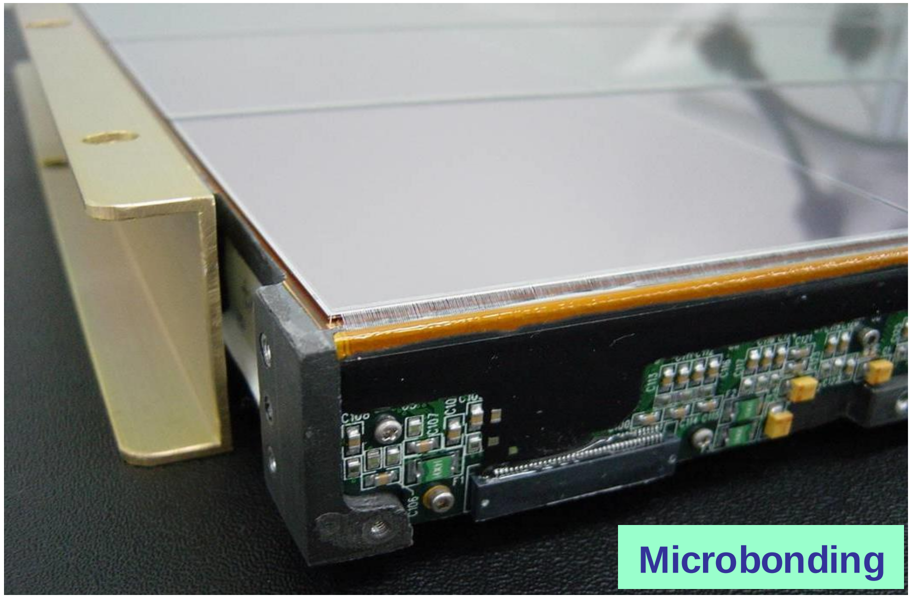
GBM
Sodium Iodide
Detector

GBM
Bismuth
Germanate
Detector

Tray assembly in G&A



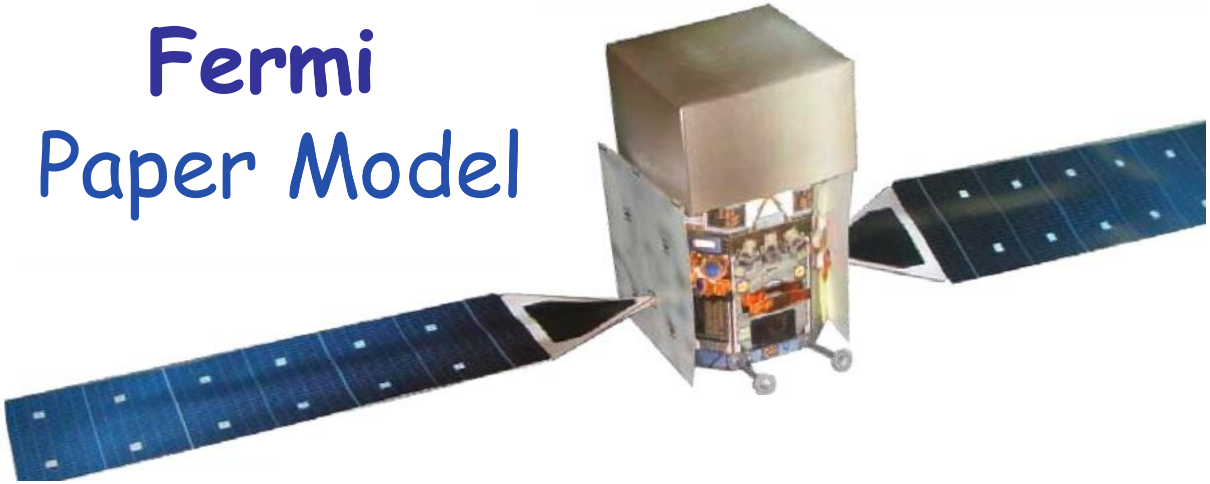


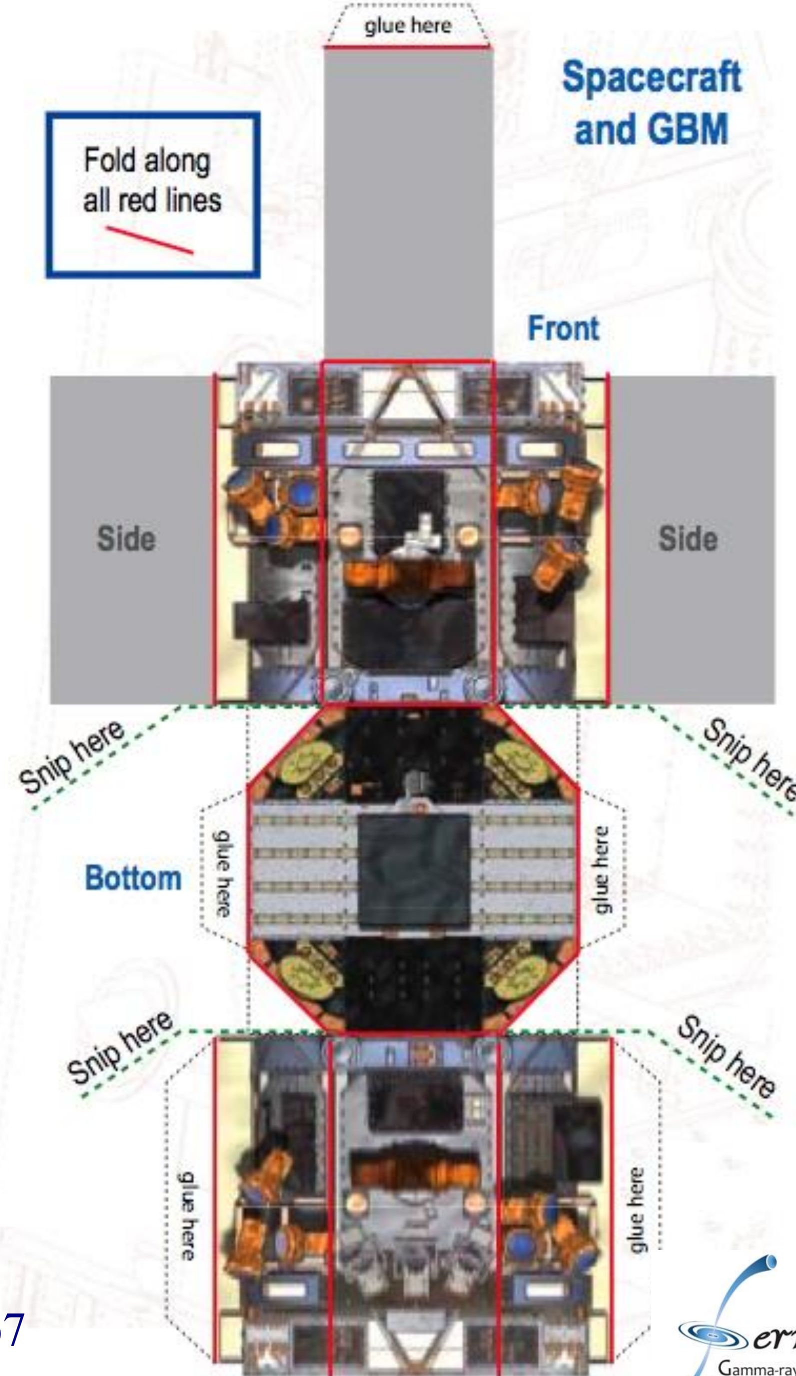


- 160 bare panels produced
- 100 tested and qualified for integration with ladders
- completed trays for 3.3 towers
- 6 assembly chain ready
- Max assembly rate : 3 trays/day/shift


EMERGENCY STOP

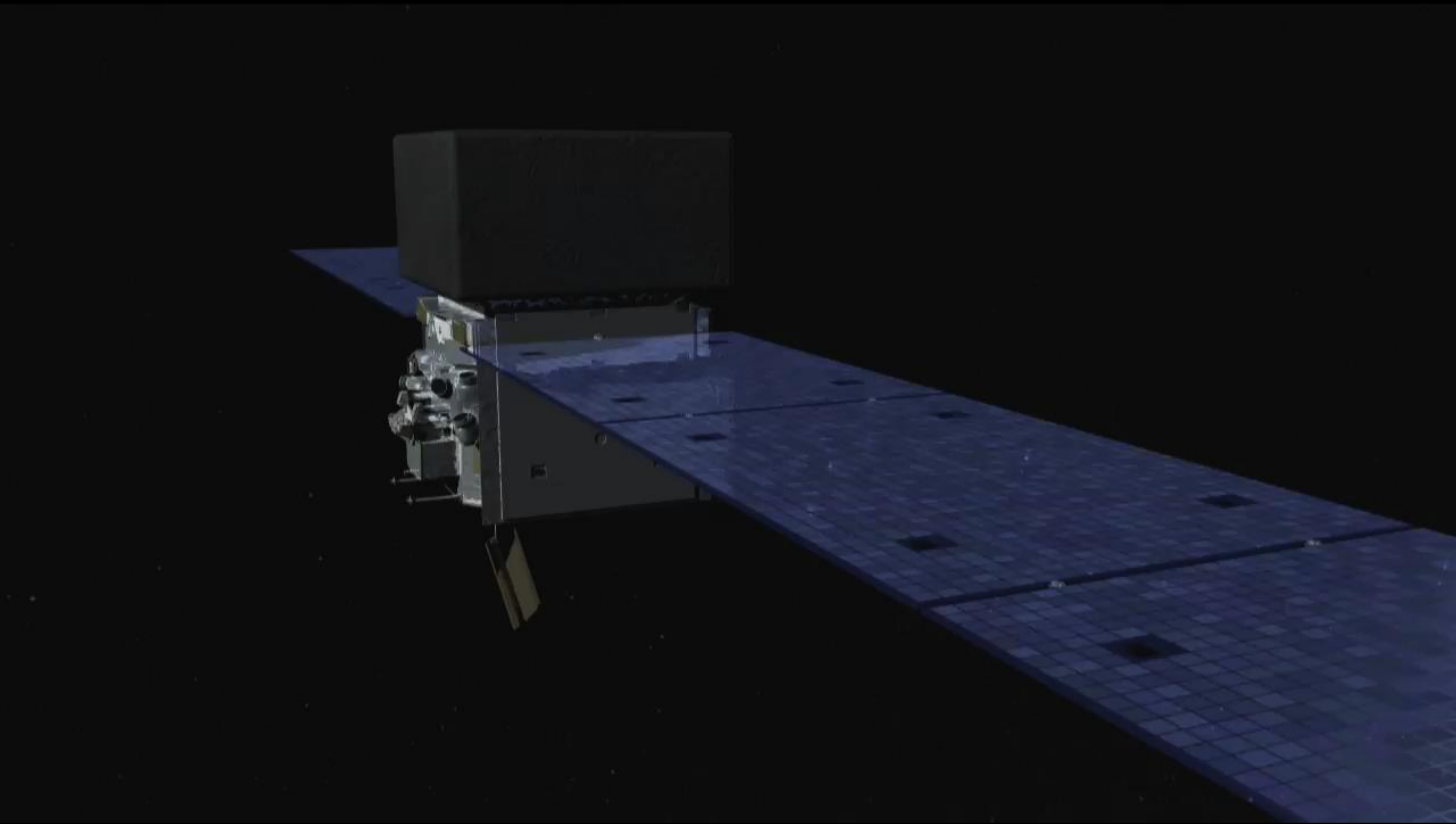
Fermi
Paper Model

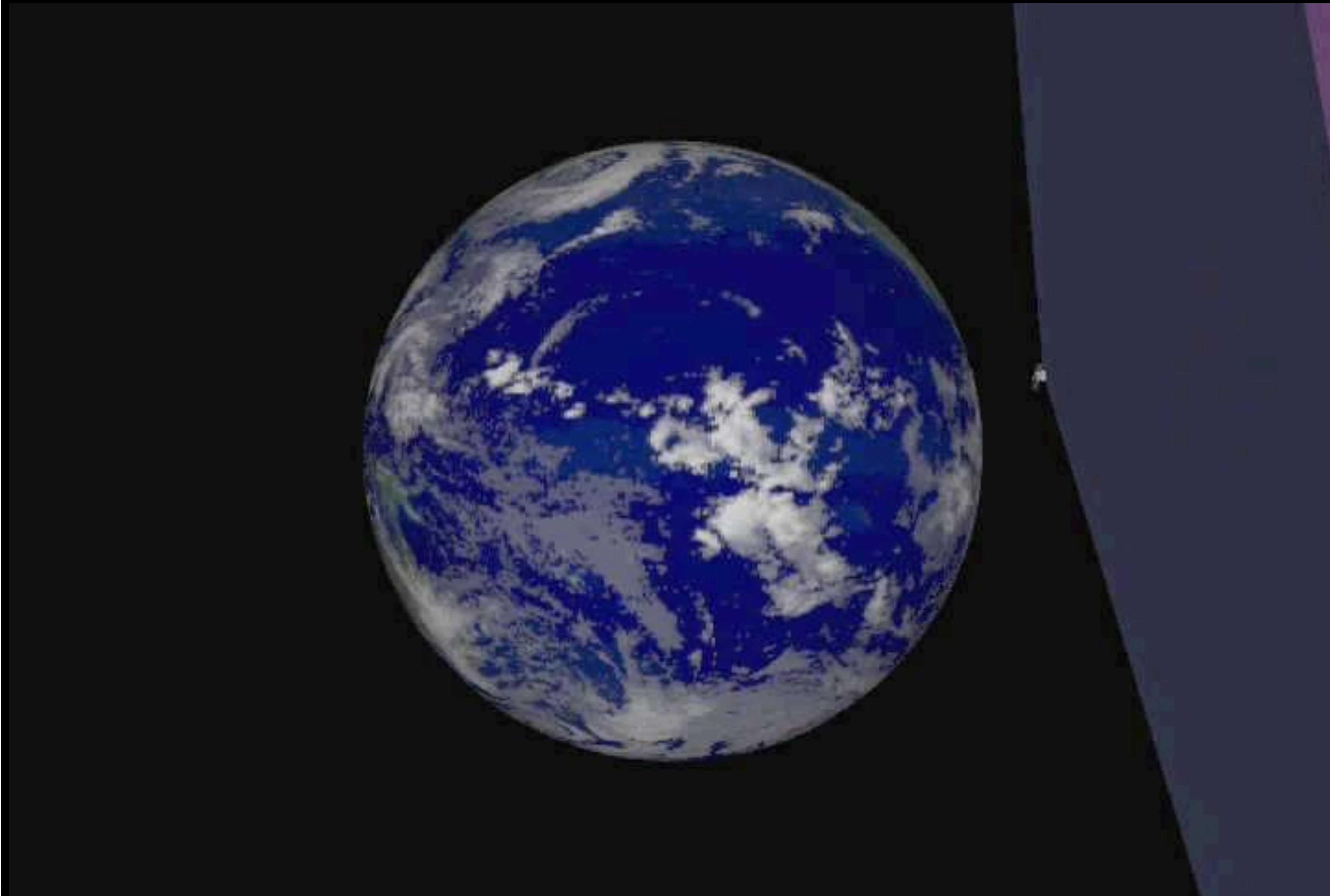




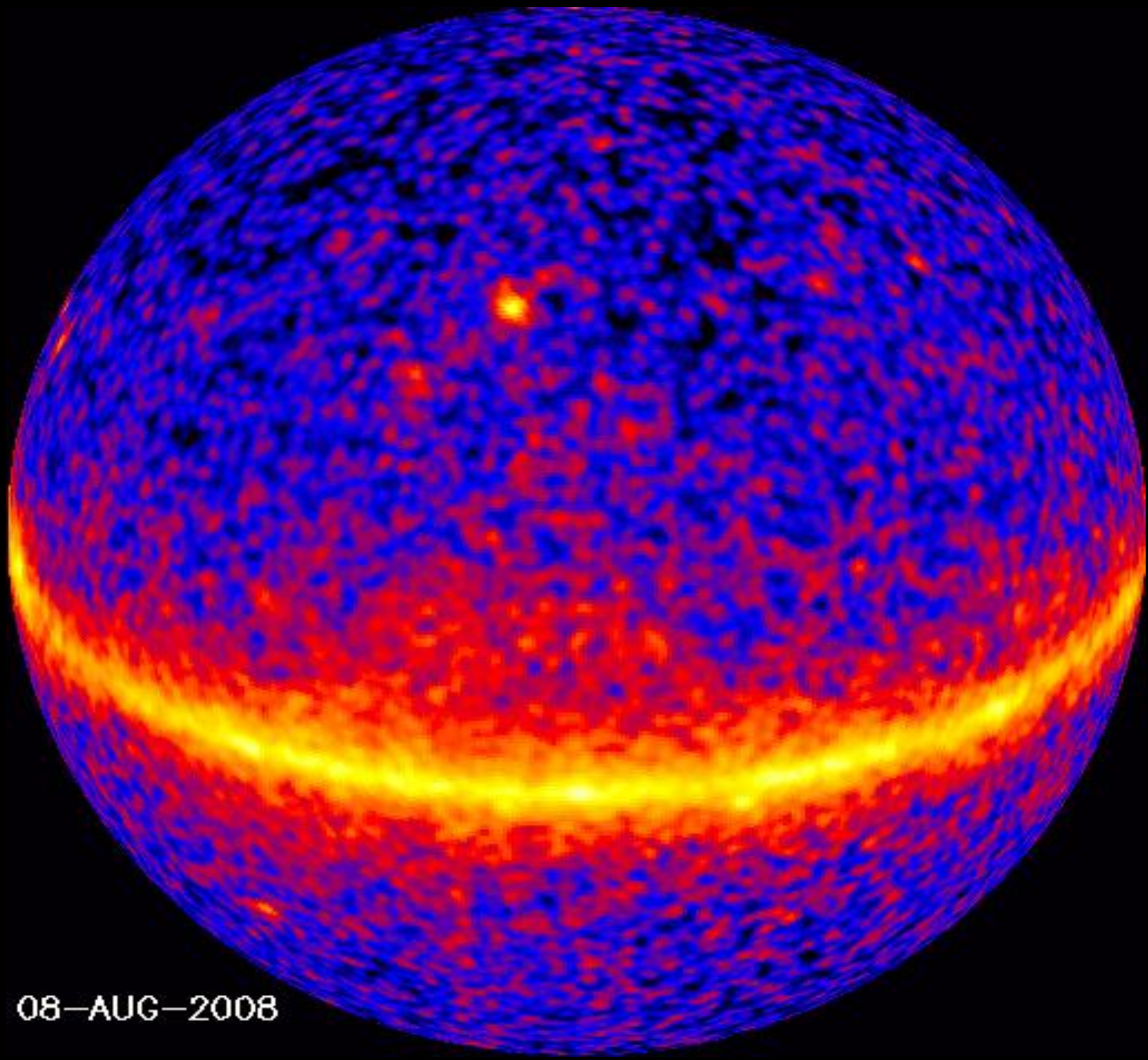
https://owncloud.roma2.infn.it/index.php/s/yvpYj8NMDV2Bip7

Fermi Gamma-ray Space Telescope

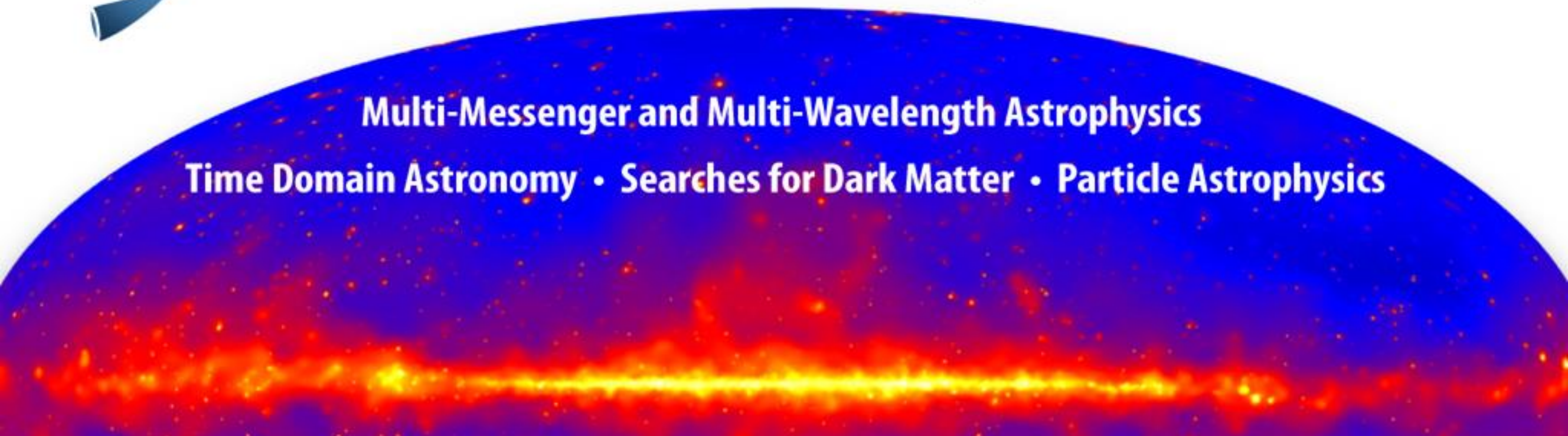


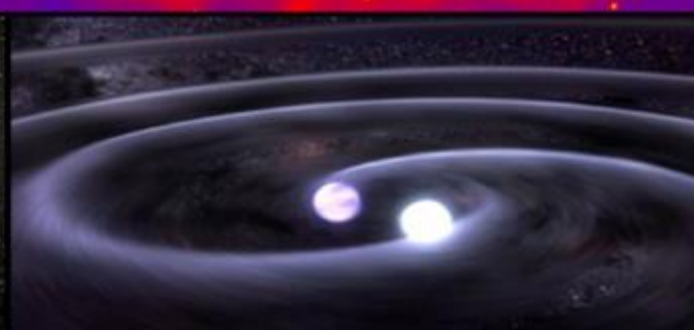


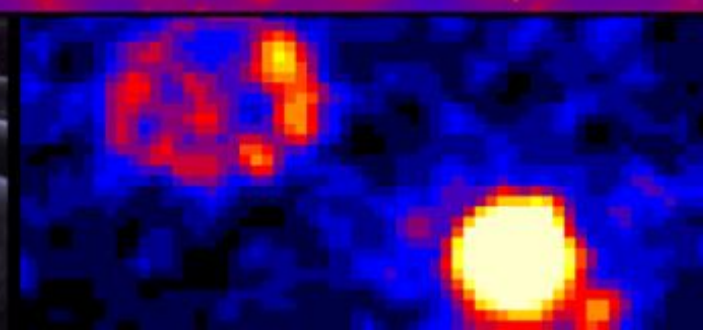
Daily Gamma-ray Sky



Fermi Gamma-Ray Space Telescope

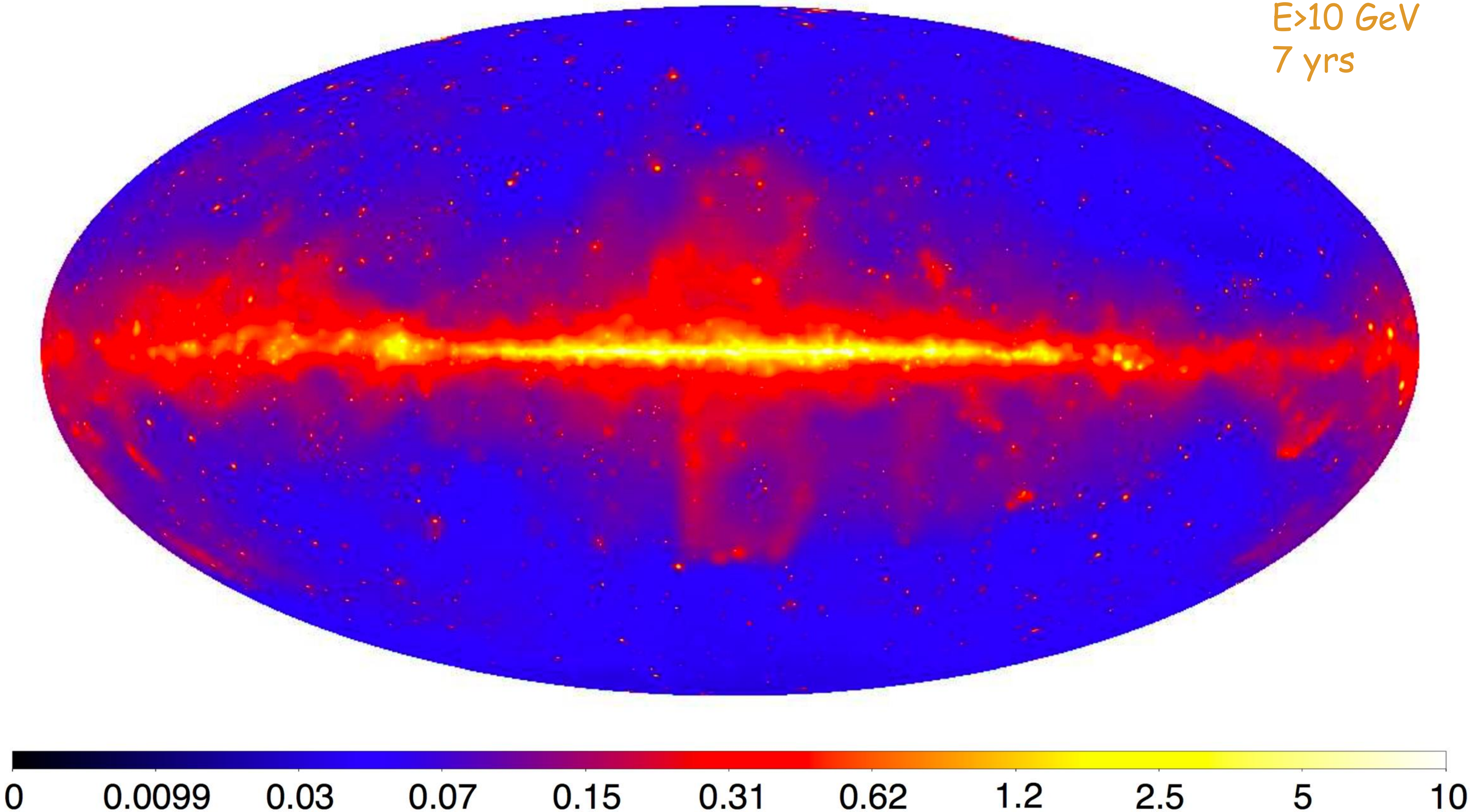






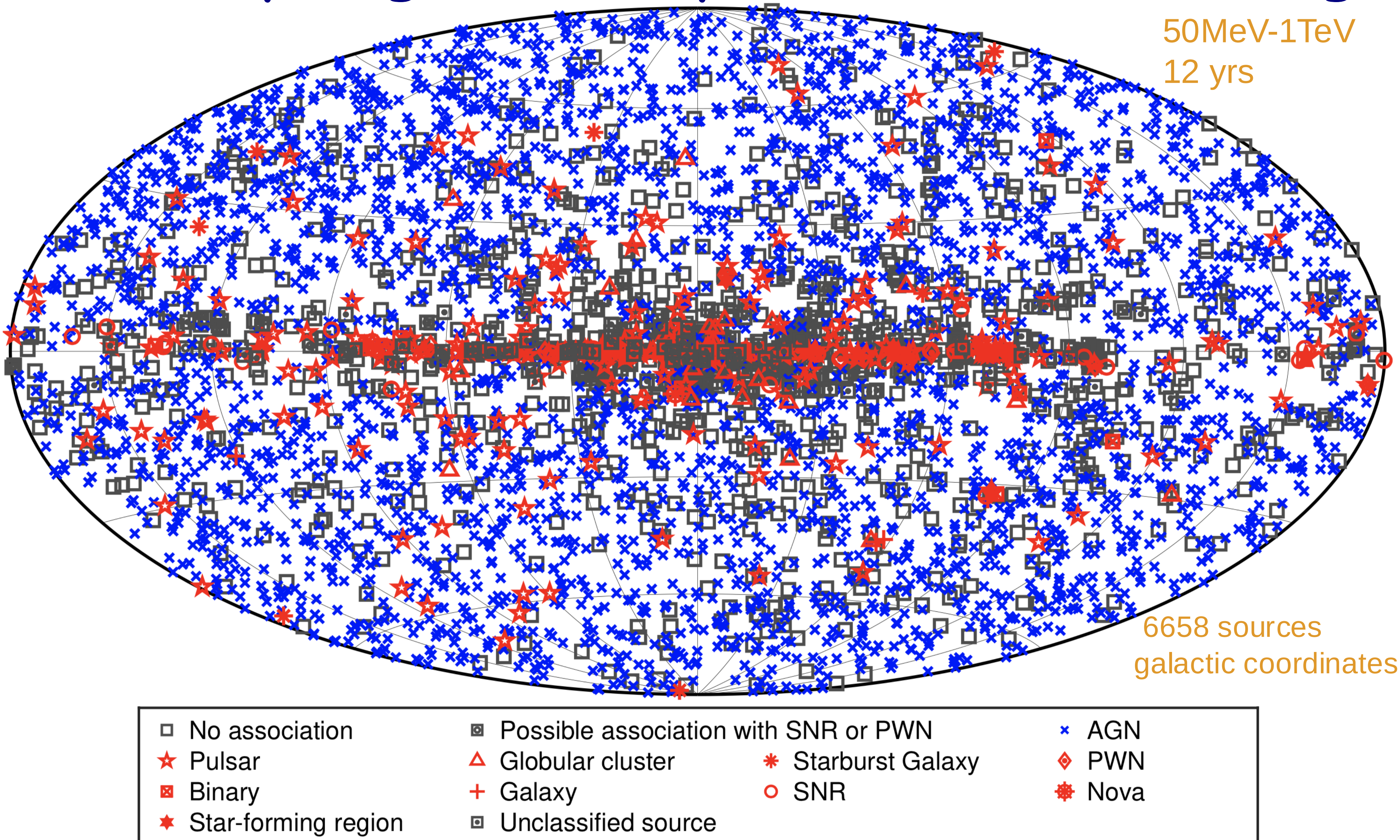
The sky in gamma-rays

E>10 GeV
7 yrs



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

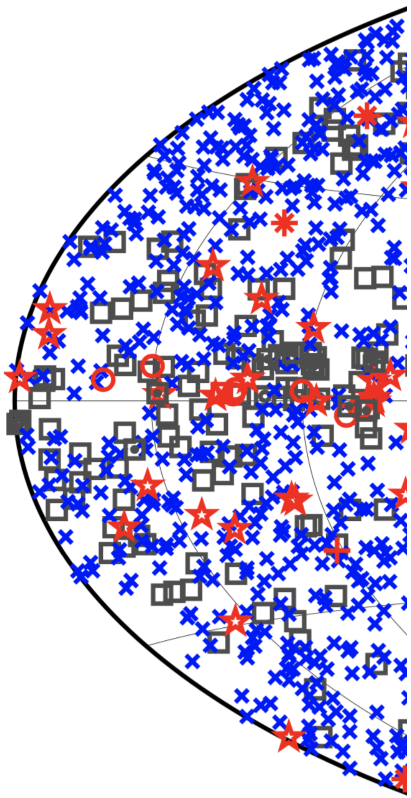
The sky in gamma-rays 4th source catalog



Incremental Fermi Fouth Source Catalog, ApJS 260, 53 (2022) [arXiv: 2201.11184]

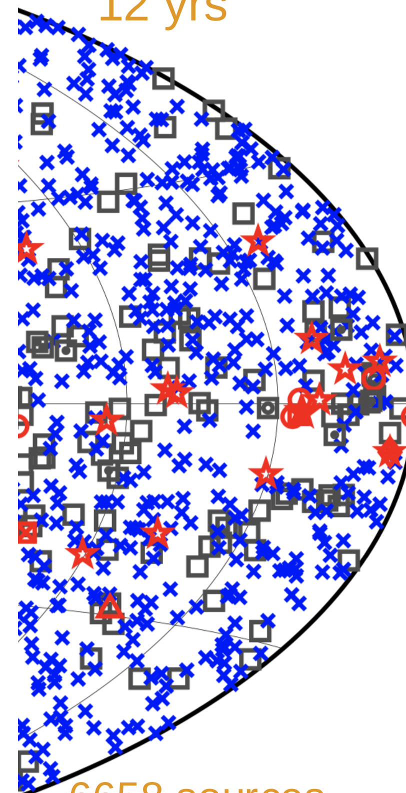
The sky in gamma-rays 4th source catalog

50MeV-1TeV
12 yrs



Description	Identified		Associated	
	Designator	Number	Designator	Number
Galactic center	GC	1	...	...
Young pulsars, identified by pulsations	PSR	135	...	...
Young pulsars, no pulsations seen in LAT yet	...	...	psr	2
Millisecond pulsars, identified by pulsations	MSP	120	...	...
Millisecond pulsars, no pulsations seen in LAT yet	...	...	msp	35
Pulsar wind nebula	PWN	11	pwn	8
Supernova remnant	SNR	24	snr	19
Supernova remnant / Pulsar wind nebula	SPP	0	spp	114
Globular cluster	GLC	0	glc	35
Star-forming region	SFR	3	sfr	2
High-mass binary	HMB	8	hmb	3
Low-mass binary	LMB	2	lmb	6
Binary	BIN	1	bin	6
Nova	NOV	4	nov	0
BL Lac type of blazar	BLL	22	bll	1435
FSRQ type of blazar	FSRQ	44	fsrq	750
Radio galaxy	RDG	6	rdg	39
Nonblazar active galaxy	AGN	1	agn	8
Steep spectrum radio quasar	SSRQ	0	ssrq	2
Compact steep spectrum radio source	CSS	0	css	5
Blazar candidate of uncertain type	BCU	1	bcu	1491
Narrow-line Seyfert 1	NLSY1	4	nlsy1	4
Seyfert galaxy	SEY	0	sey	2
Starburst galaxy	SBG	0	sbg	8
Normal galaxy (or part)	GAL	2	gal	4
Unknown	UNK	0	unk	134
Total	...	389	...	4112
Unassociated	...	...	...	2157

NOTE—The designation 'spp' indicates potential association with SNR or PWN. 'Unknown' are $|b| < 10^\circ$ sources solely associated with the likelihood-ratio method from large radio and X-ray surveys. Designations shown in capital letters are firm identifications; lower-case letters indicate associations.

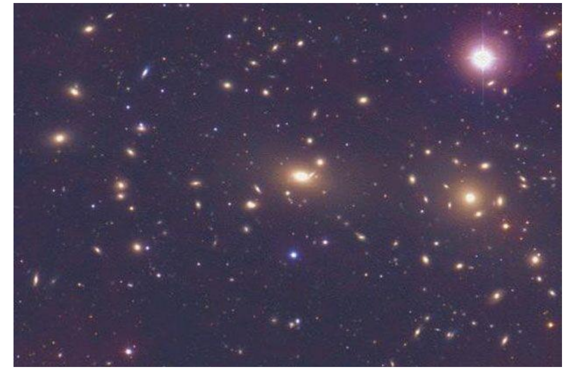


6658 sources
galactic coordinates

No asso
Pulsar
Binary
Star-forn
GN
WN
ova

Incremental Fermi Fouth Source Catalog, ApJS 260, 53 (2022) arXiv: 2201.11184

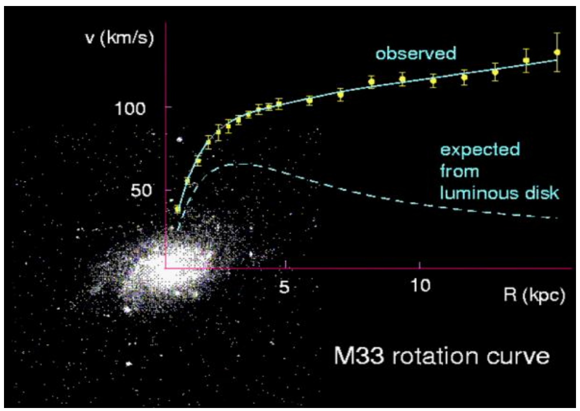
Dark Matter EVIDENCE



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.

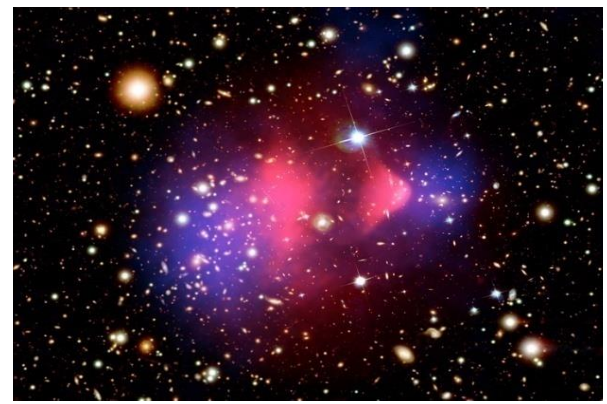
Since then, even more evidence:

Rotation curves of galaxies

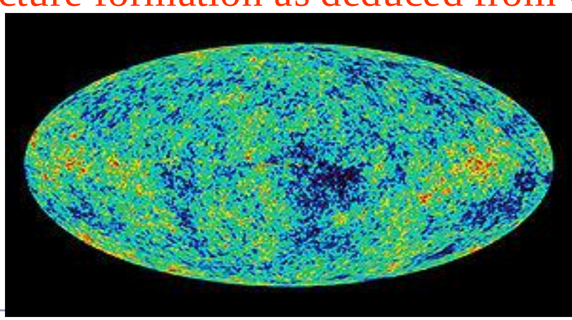


Gravitational lensing

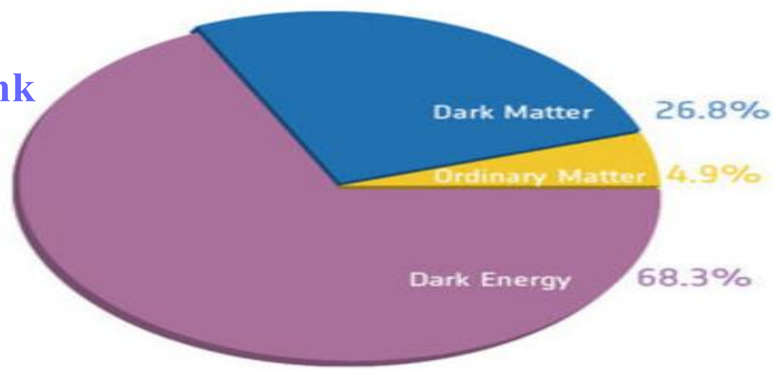
Bullet cluster



Structure formation as deduced from CMB



Data by Plank imply:

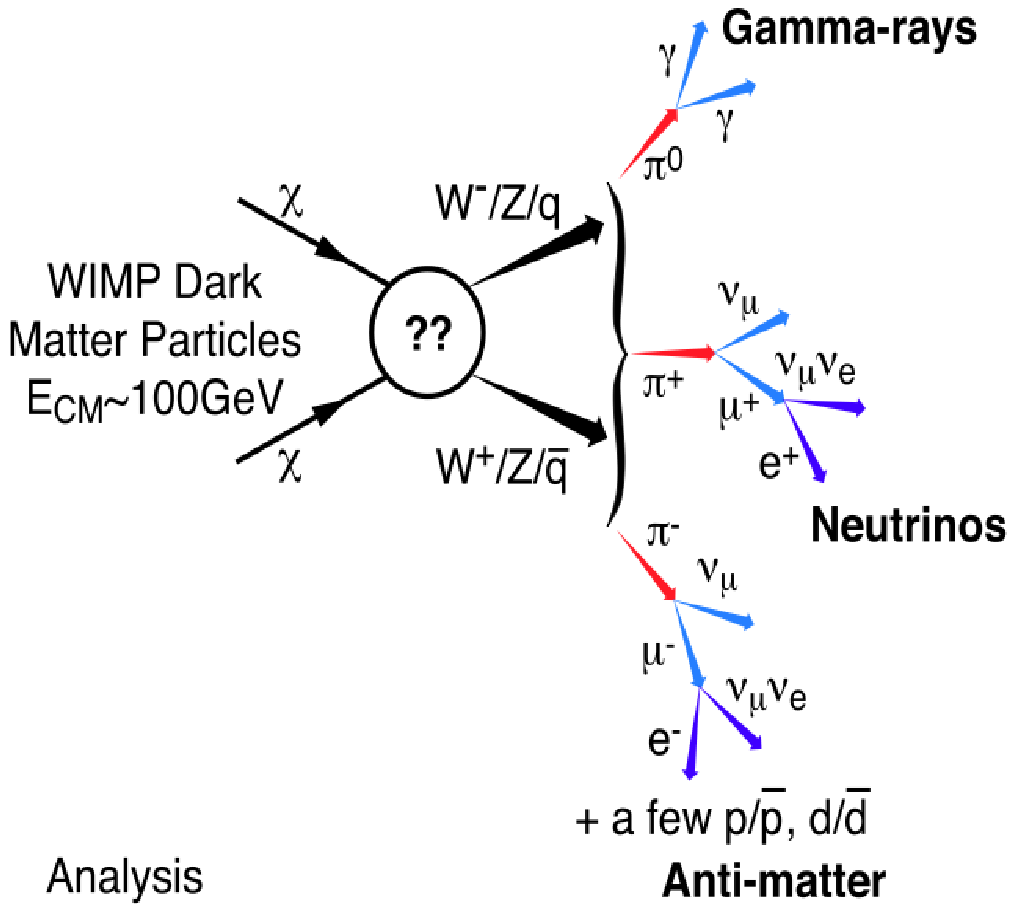


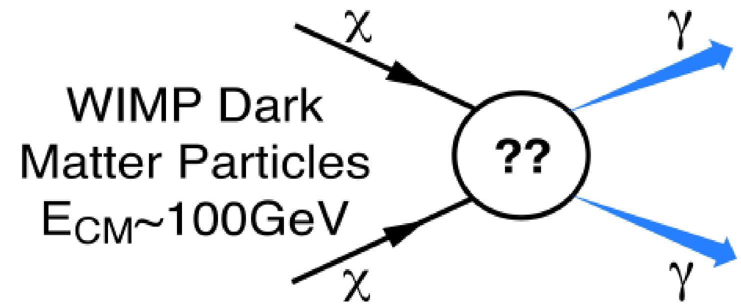
$\Omega_{DM} \approx 26.8\%$

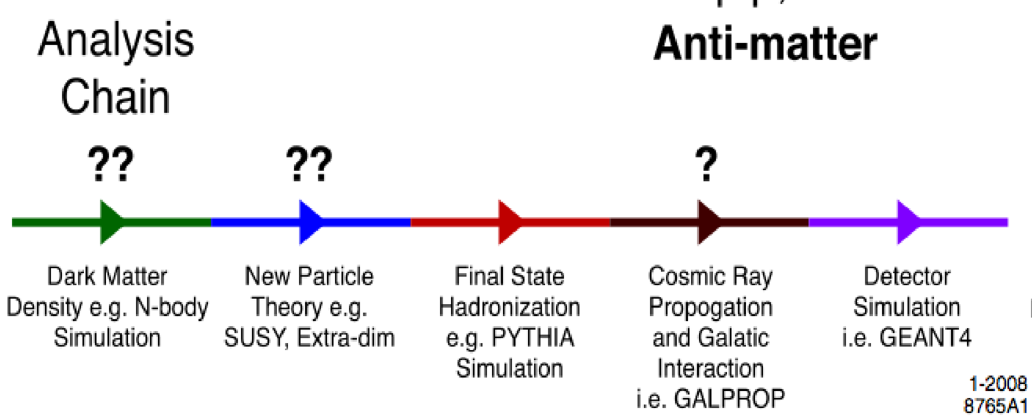
$\Omega_M \approx 4.9\%$

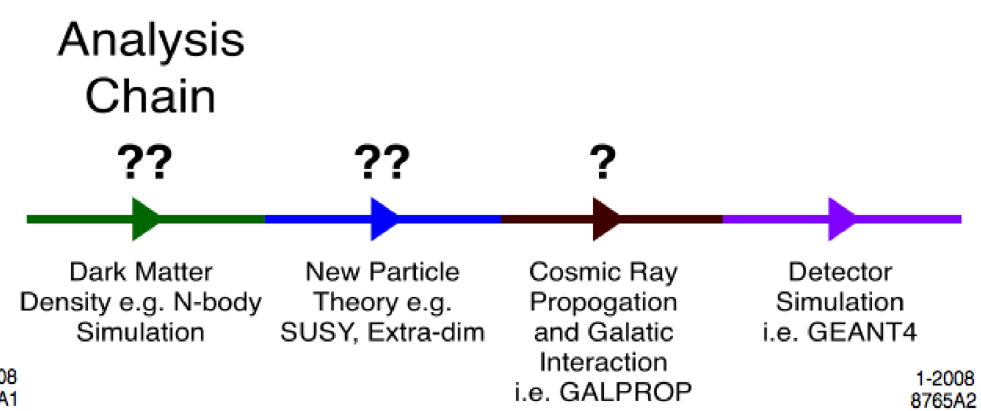
Dark Matter

Annihilation channels









Signal rate from WIMP annihilation

gamma-ray flux from
WIMP annihilation

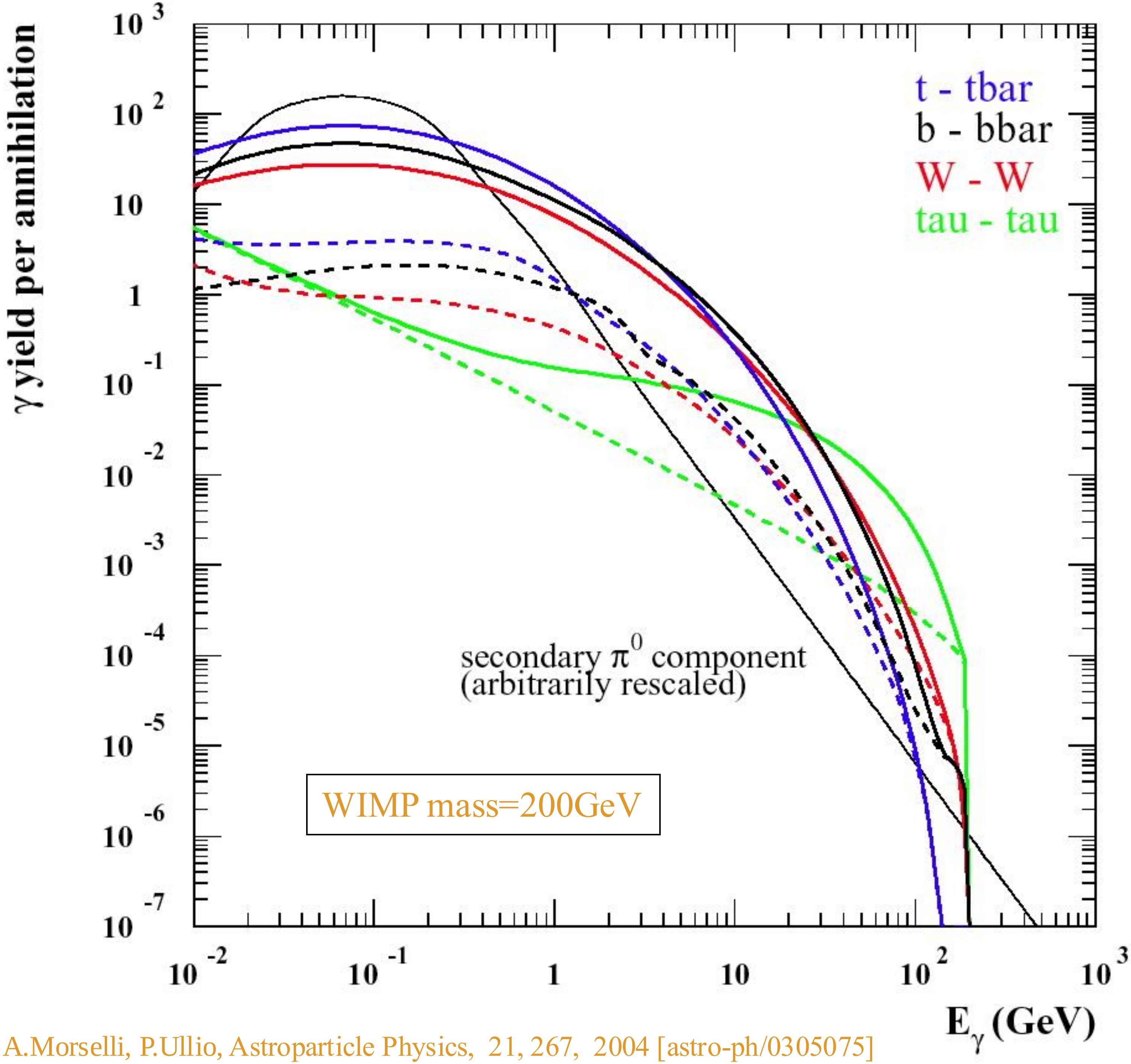
$$\phi(E,\Delta\Omega) \propto \left(\frac{\sigma v}{m_\chi^2}\right) \int_{l.o.s} \int_{\Delta\Omega} \rho^2(l)\, dl\, d\Omega$$

governed by
particle physics
(supersymmetric
parameters .. etc)

J(φ):

governed by
halo distribution

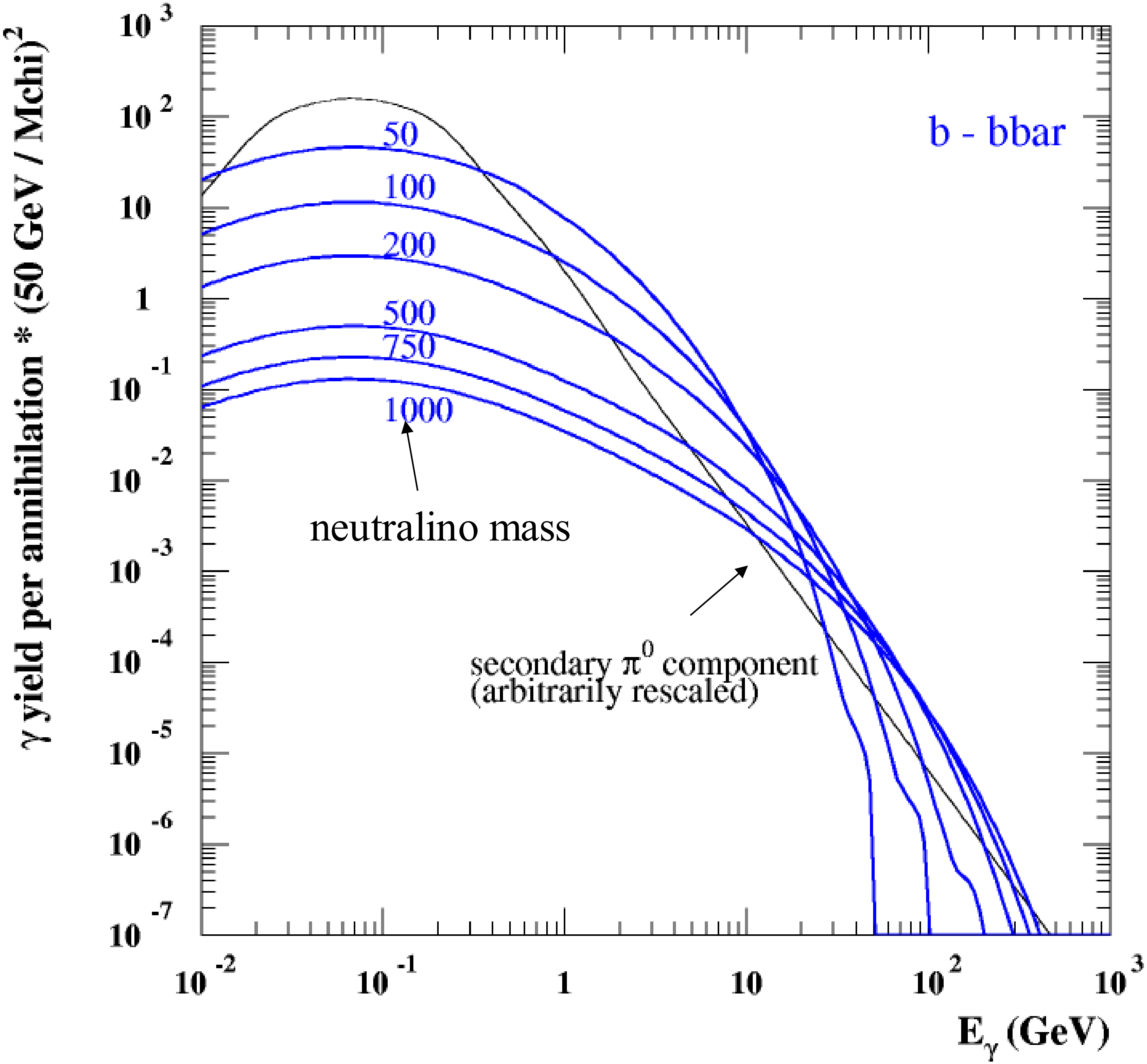
Differential yield for each annihilation channel



dashed lines are components not due to π^0 decay.

A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

Differential yield for b bar



A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267-285, 2004 [astro-ph/0305075]

Dark Matter Search: Targets and Strategies

Satellites

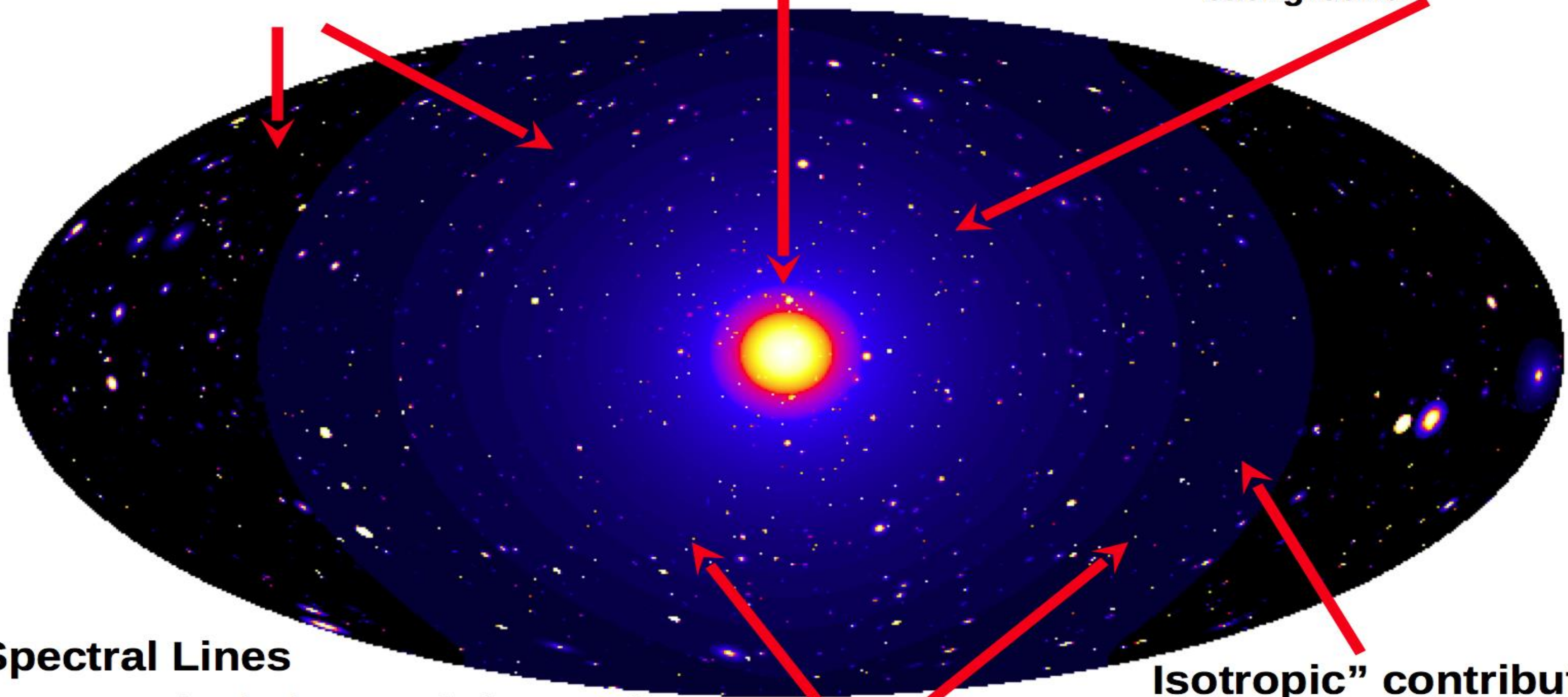
Low background and good source id, but low statistics

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

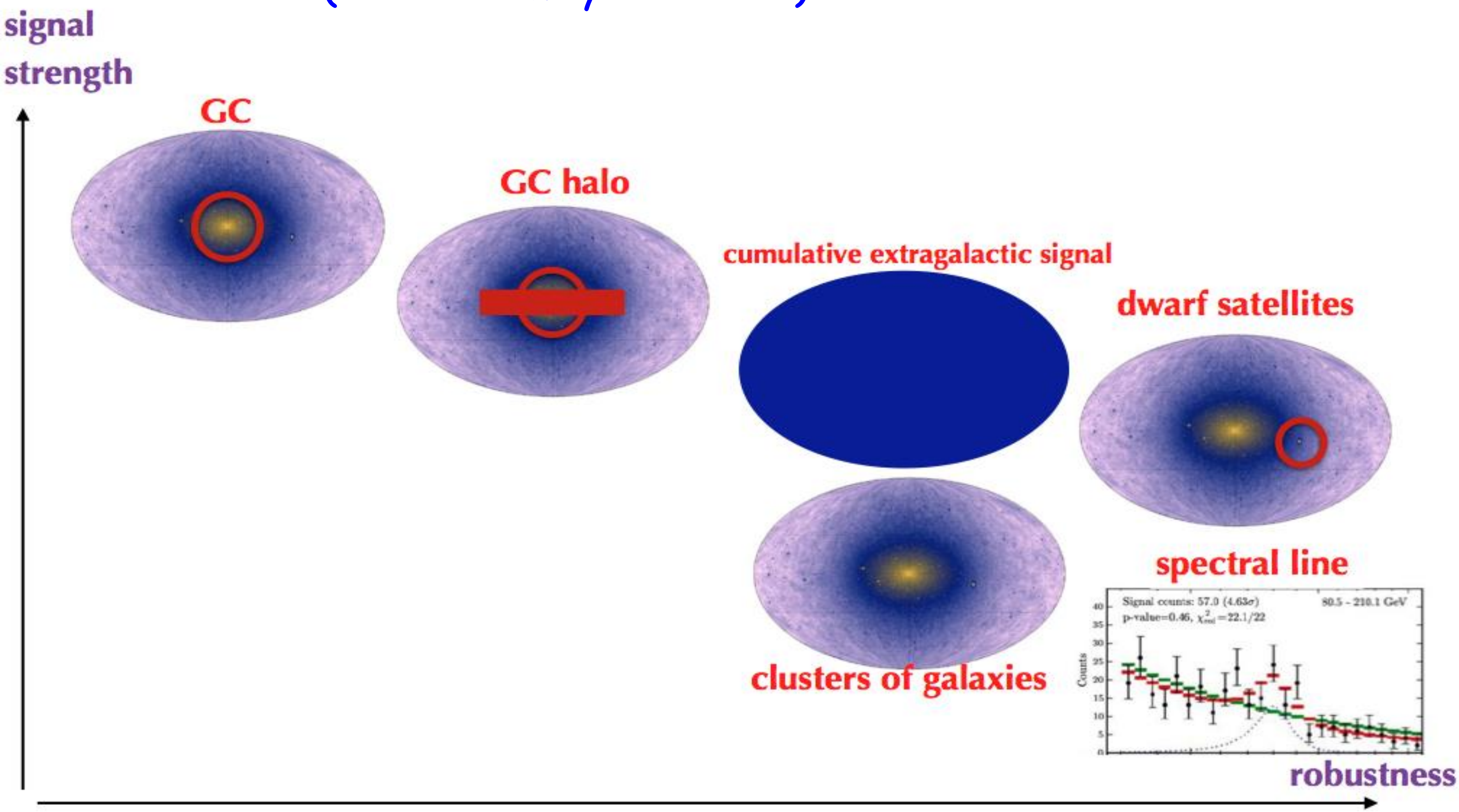
Isotropic" contributions

Large statistics, but astrophysics, galactic diffuse background

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

Dark Matter Search: Targets and Strategies

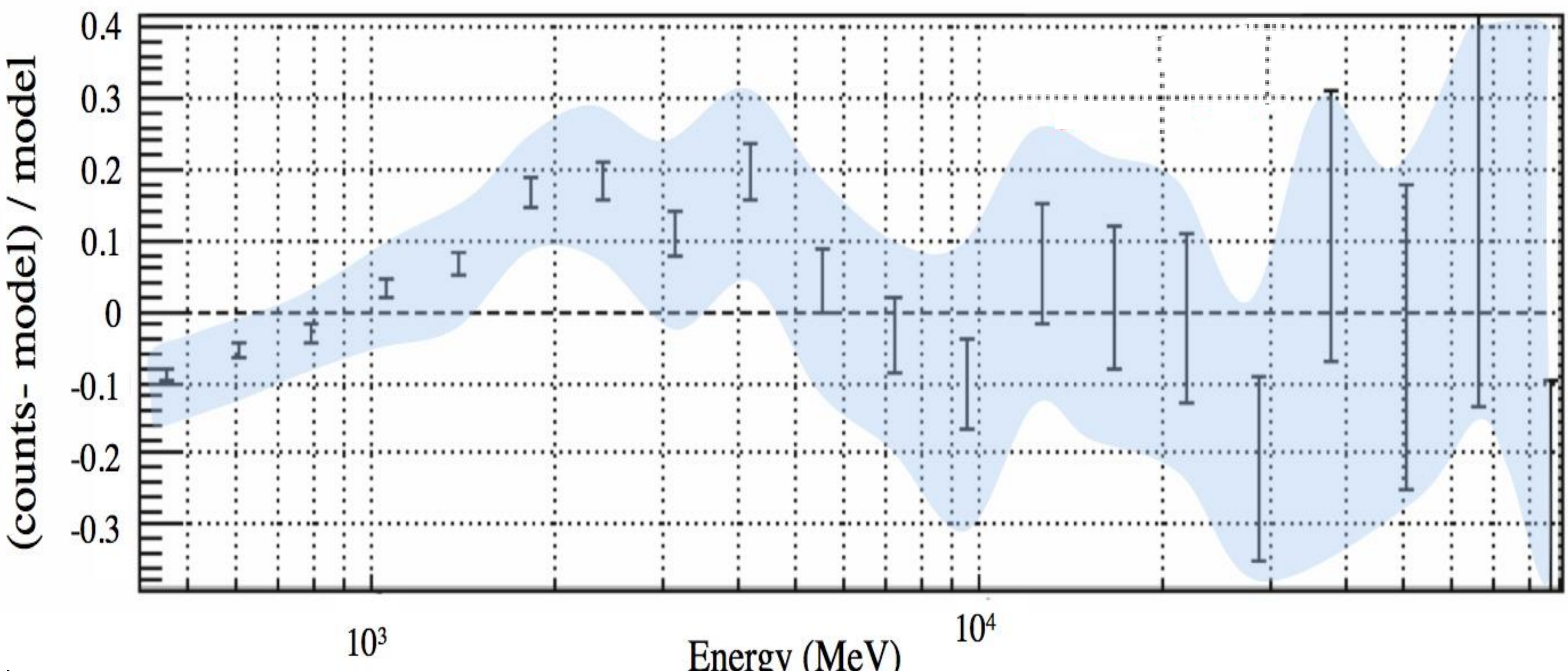
(Another way to see it)



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 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**
....

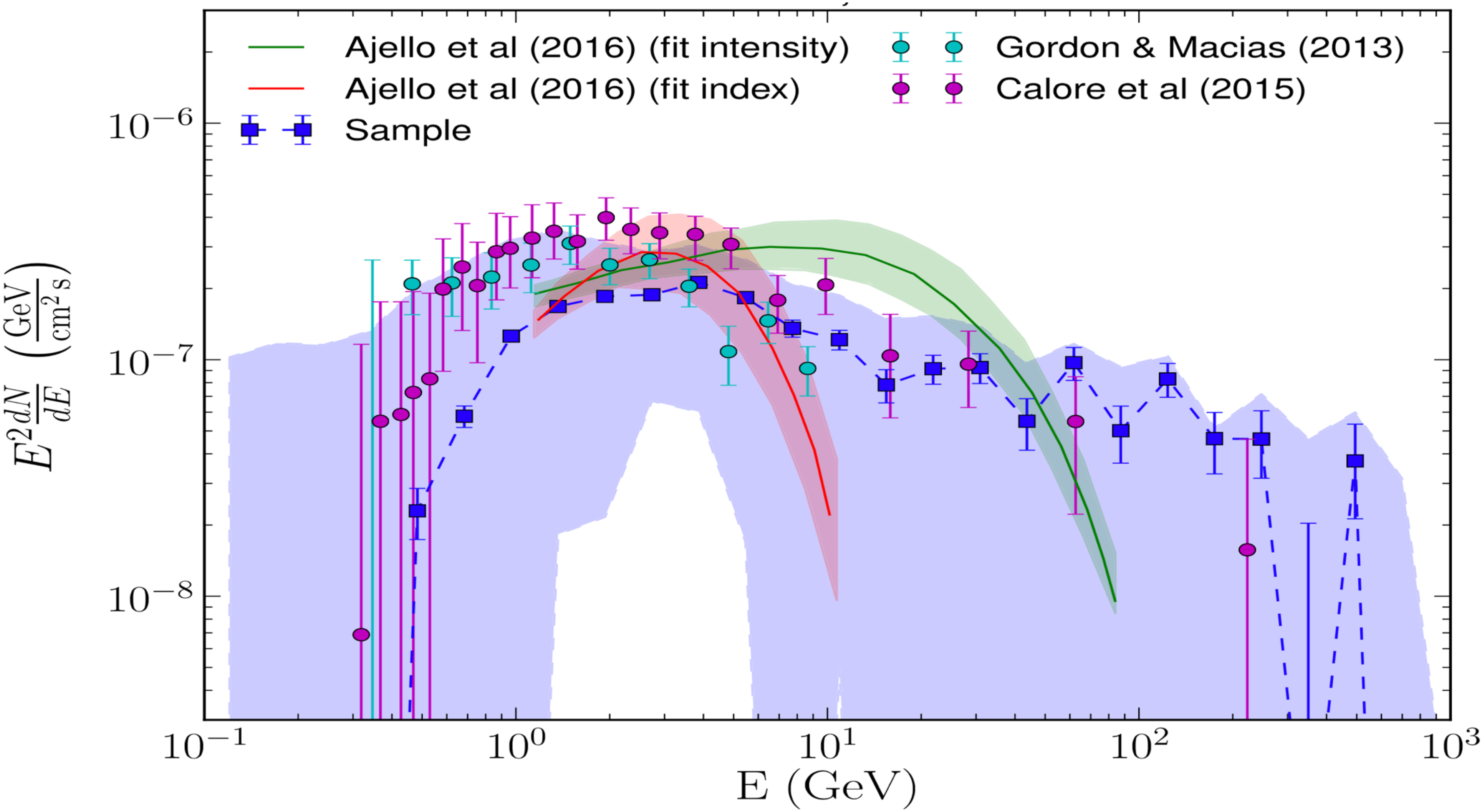
Background model systematics for the Fermi GeV excess
F.Calore, I. Cholis, C. Weniger JCAP03(2015)038 **arXiv:1409.0042v1**

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 (Pass8 analysis)



following uncertainties have relatively small effect on the excess spectrum

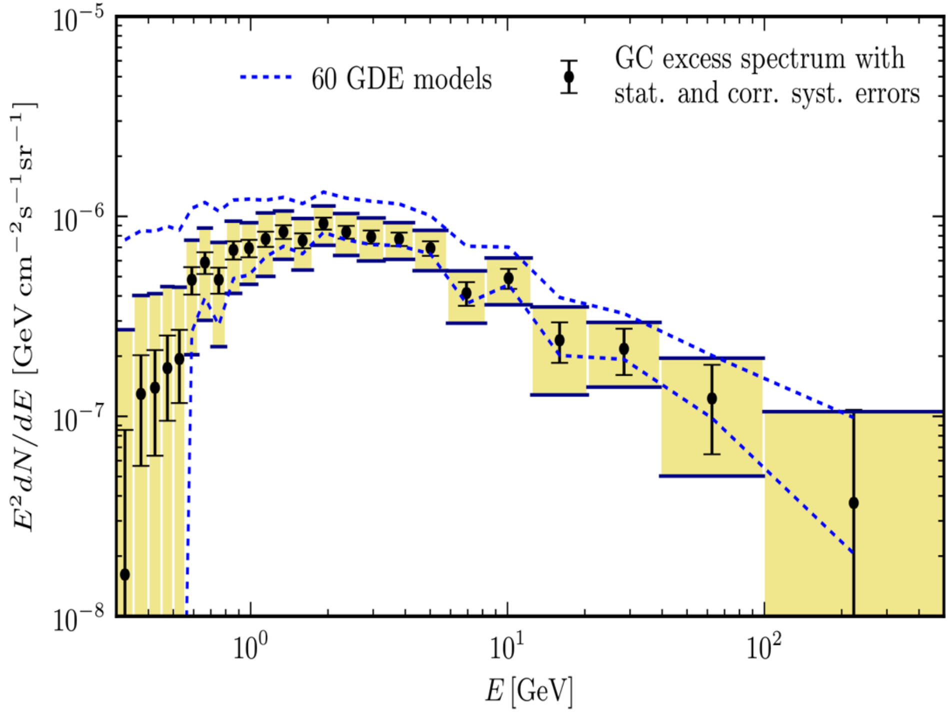
- Variation of GALPROP models - Distribution of gas along the line of sight

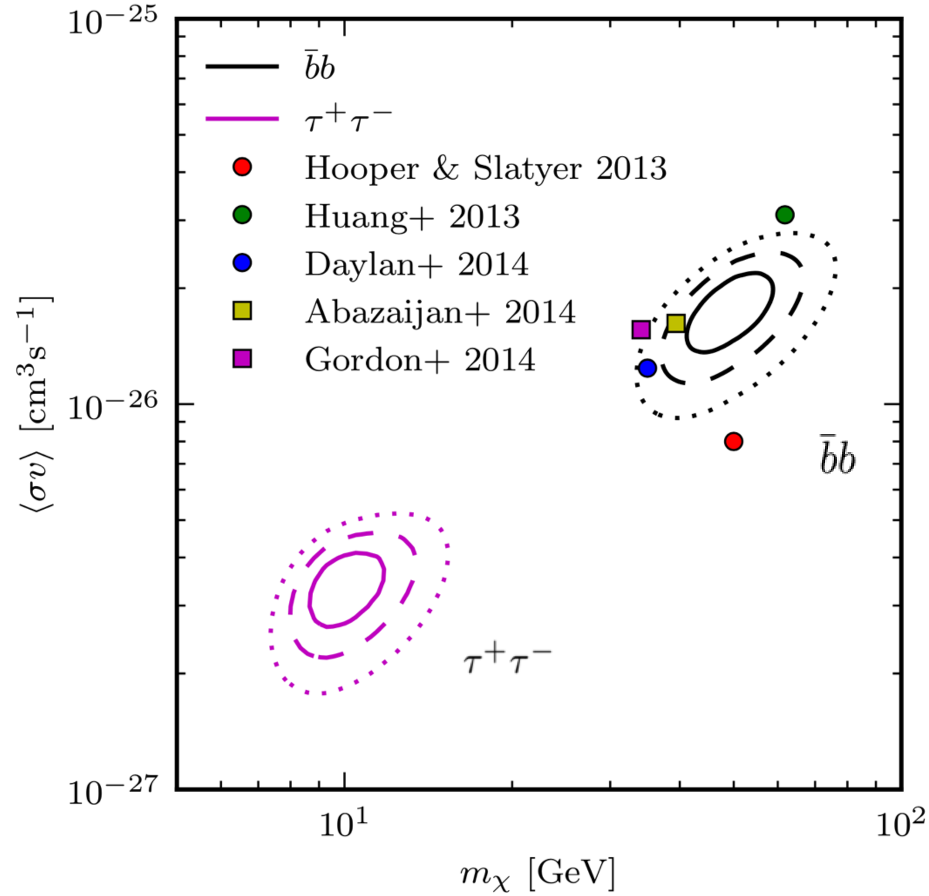
- **Most significant sources of uncertainty are:**

- 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]

....

see also the talk of Deheng Song

- Robustness of the Galactic Center Excess

leading explanations being annihilating dark matter or an unresolved population of millisecond pulsars Zhong & Cholis arXiv:2401.02481

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

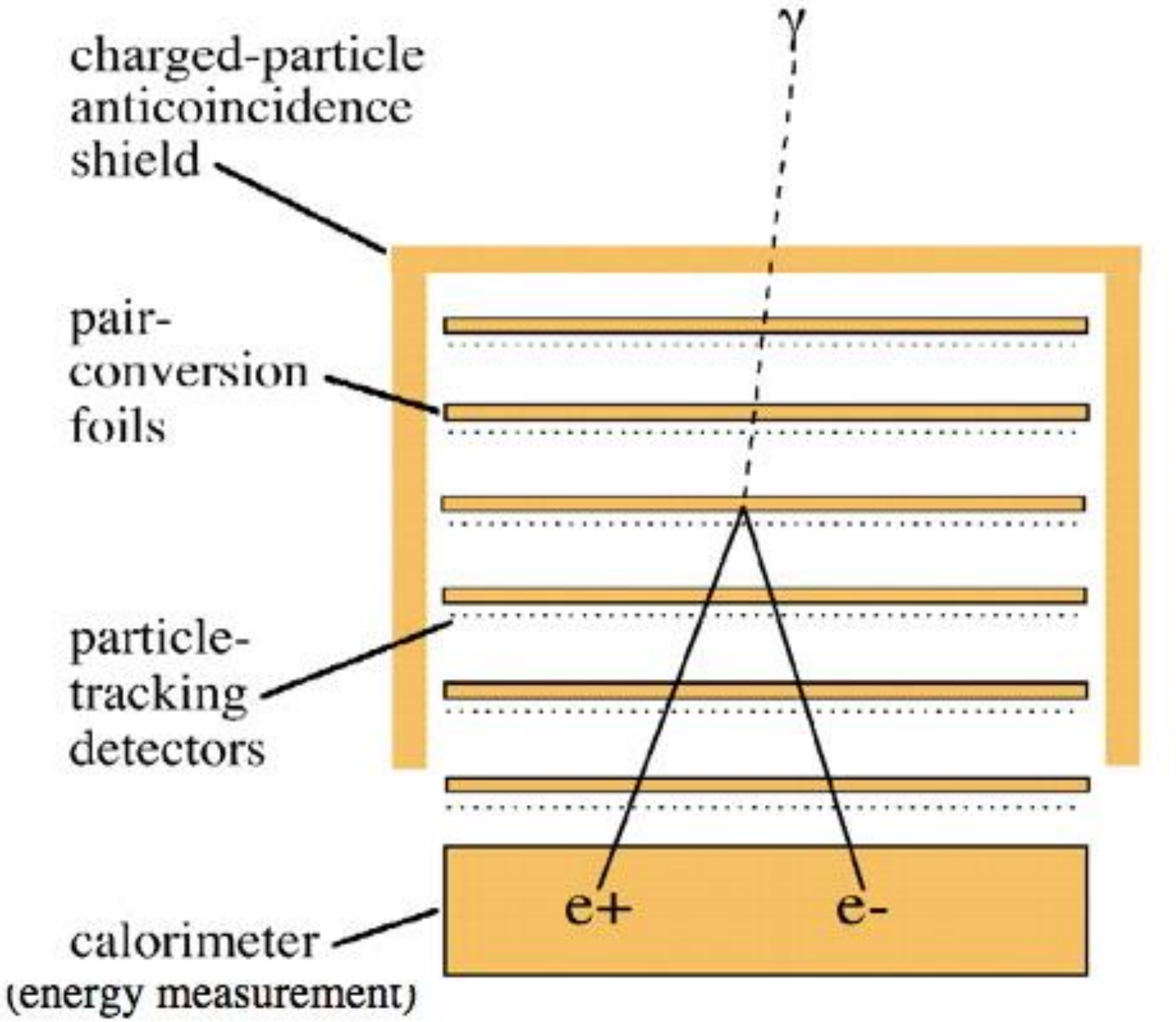
Look for correlated synchrotron emission near the GC

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

Elements of a pair-conversion telescope



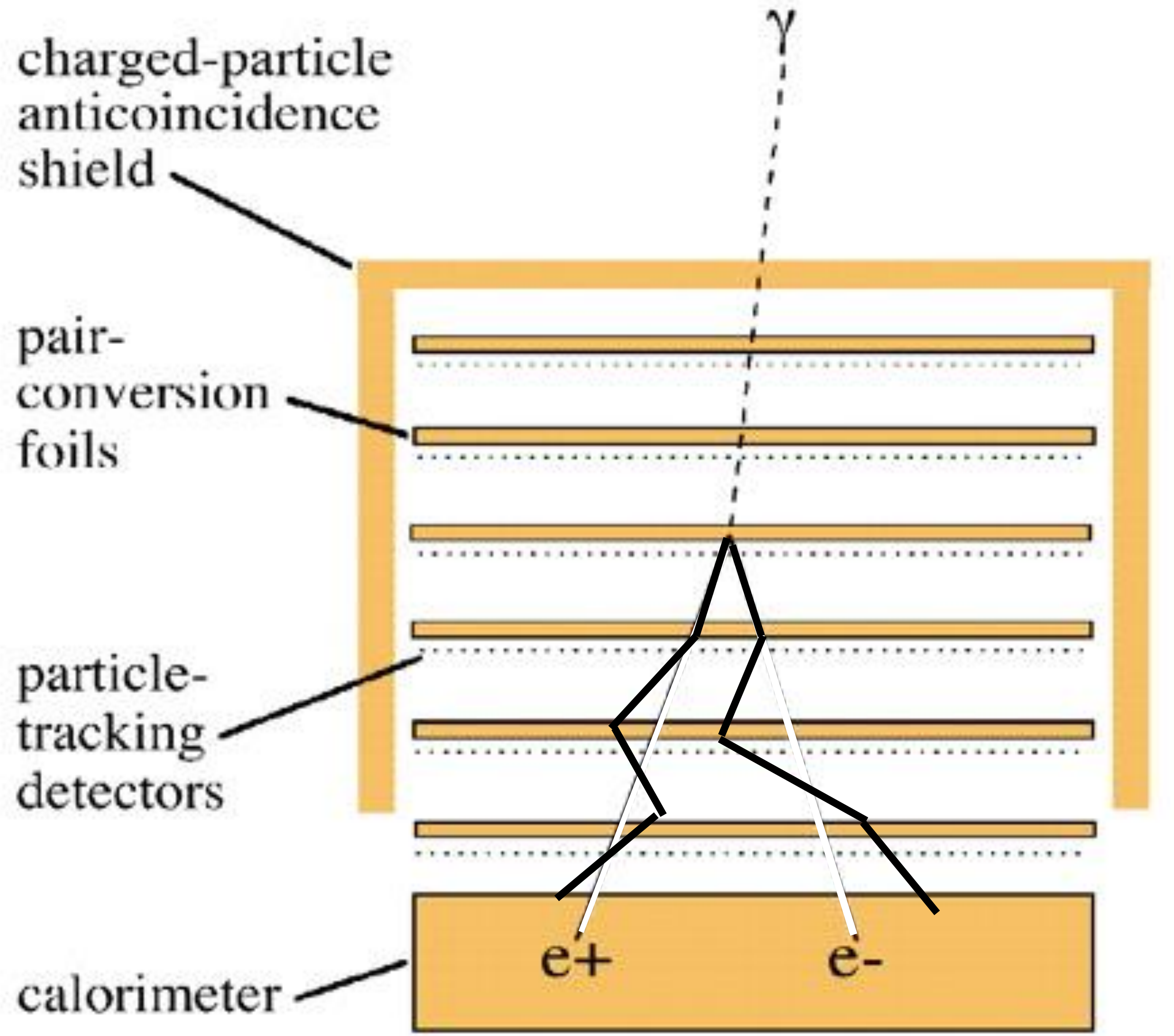
- photons materialize into matter-antimatter pairs:

  E_γ --> $m_{e^+}c^2 + m_{e^-}c^2$

- electron and positron carry information about the direction, energy and polarization of the γ-ray

Elements of a pair-conversion telescope

(more realistic scheme)



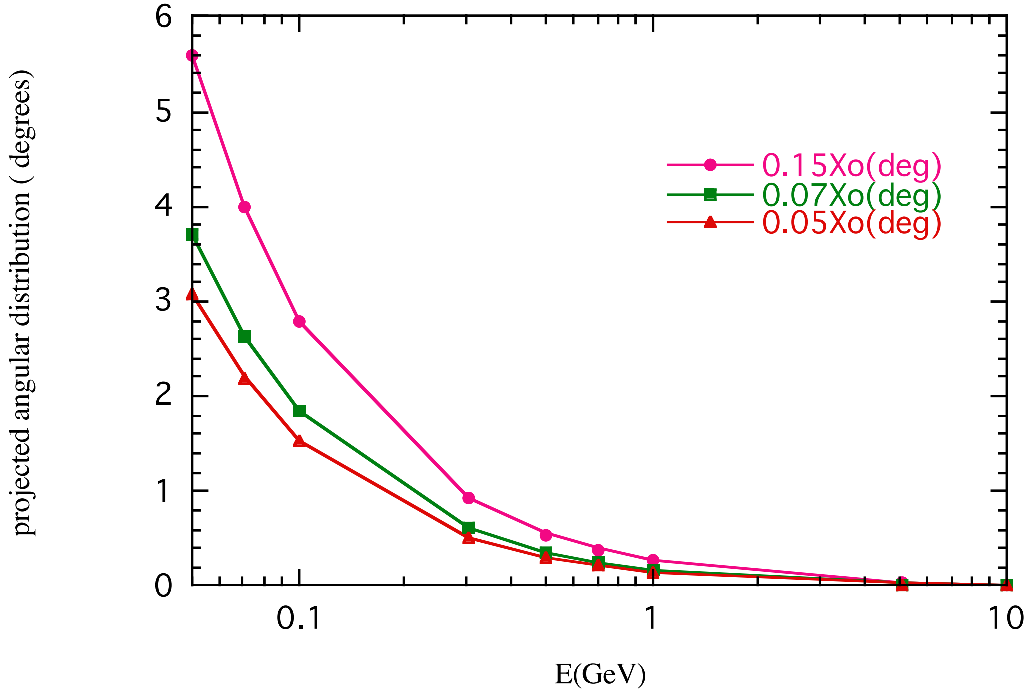
(energy measurement)

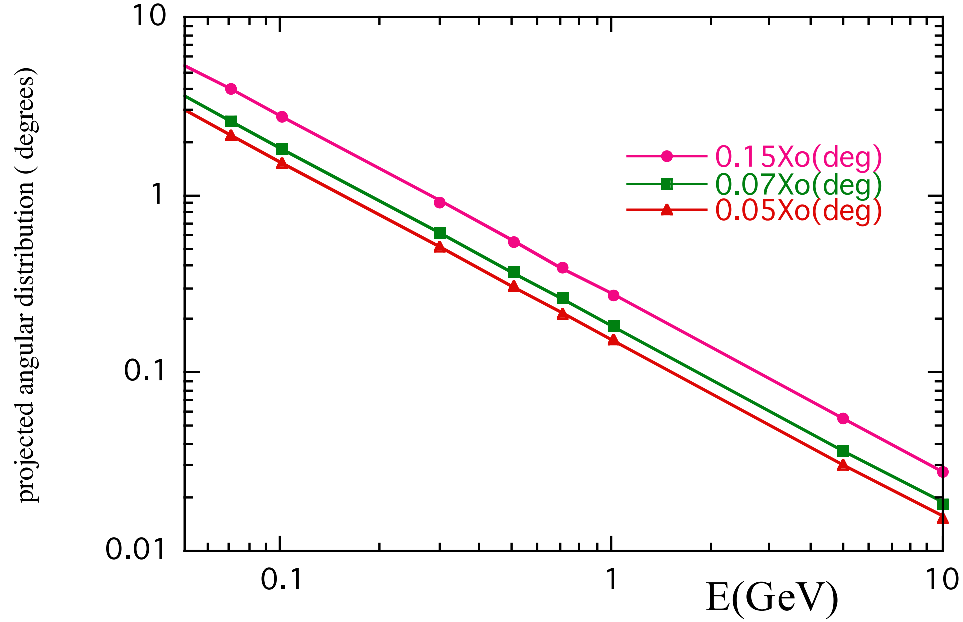
- photons materialize into matter-antimatter pairs:

  E_γ --> $m_{e^+}c^2 + m_{e^-}c^2$

- electron and positron carry information about the direction, energy and polarization of the γ-ray

Multiple Scattering

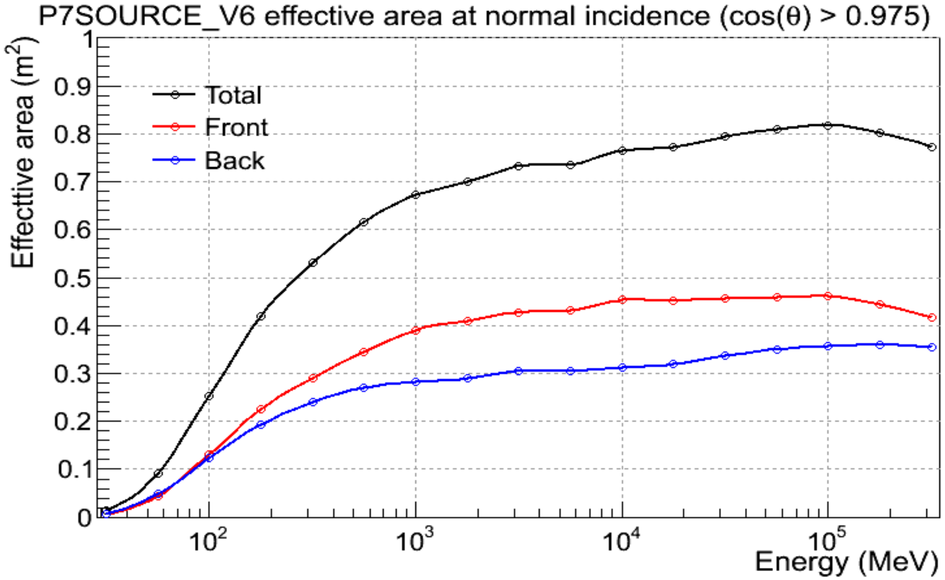


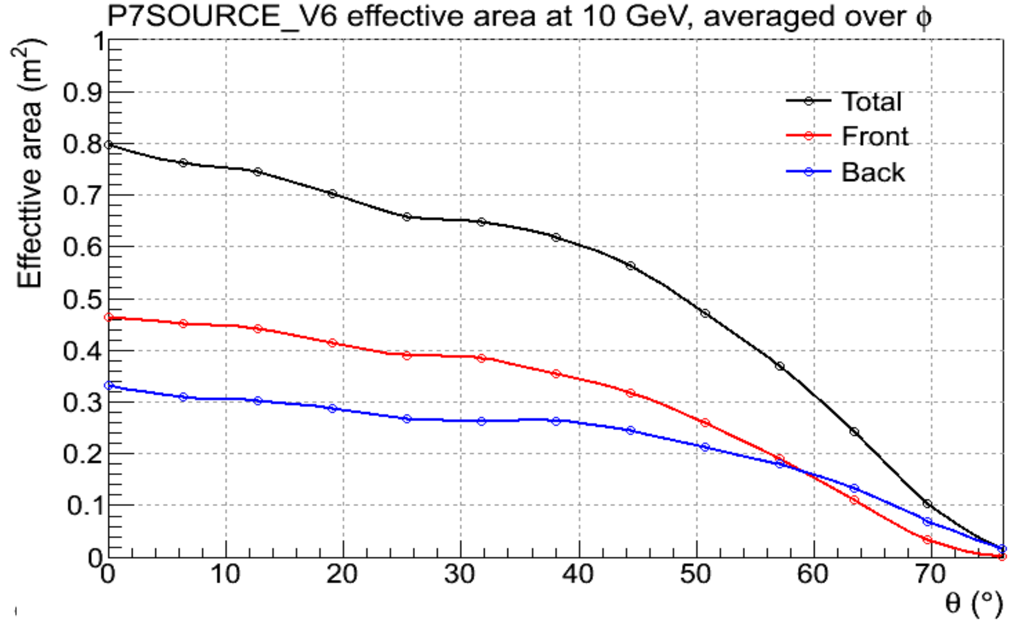


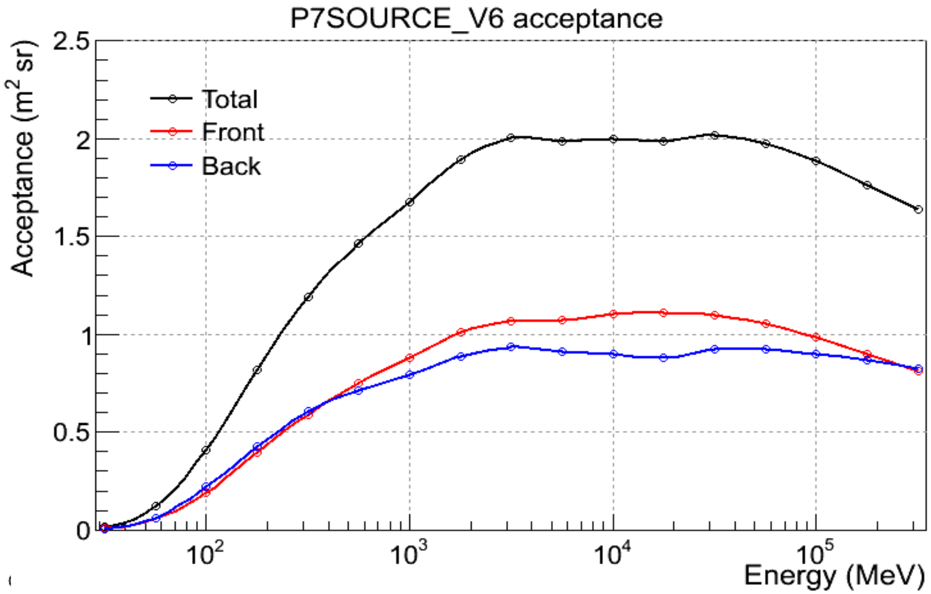
$$\theta_0 = \theta_{plane}^{rms} = \frac{1}{\sqrt{2}}\theta_{space}^{rms}$$

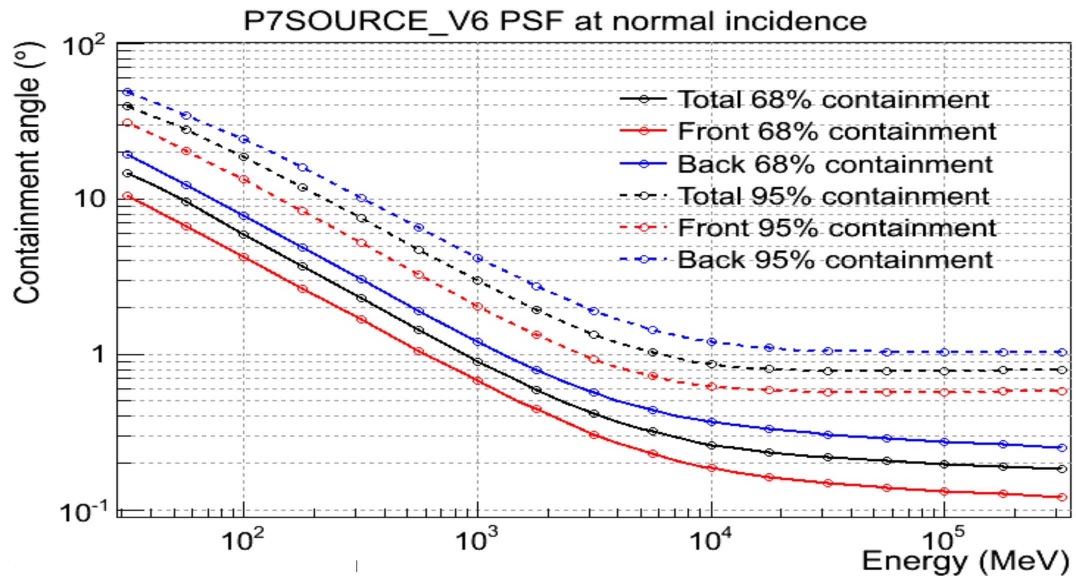
$$\theta_0 = \frac{13.6MeV}{\beta cp} z\sqrt{x/X_0}\left[1 + 0.038\ln\left(x/X_0\right)\right]$$

Fermi Instrument Response Function



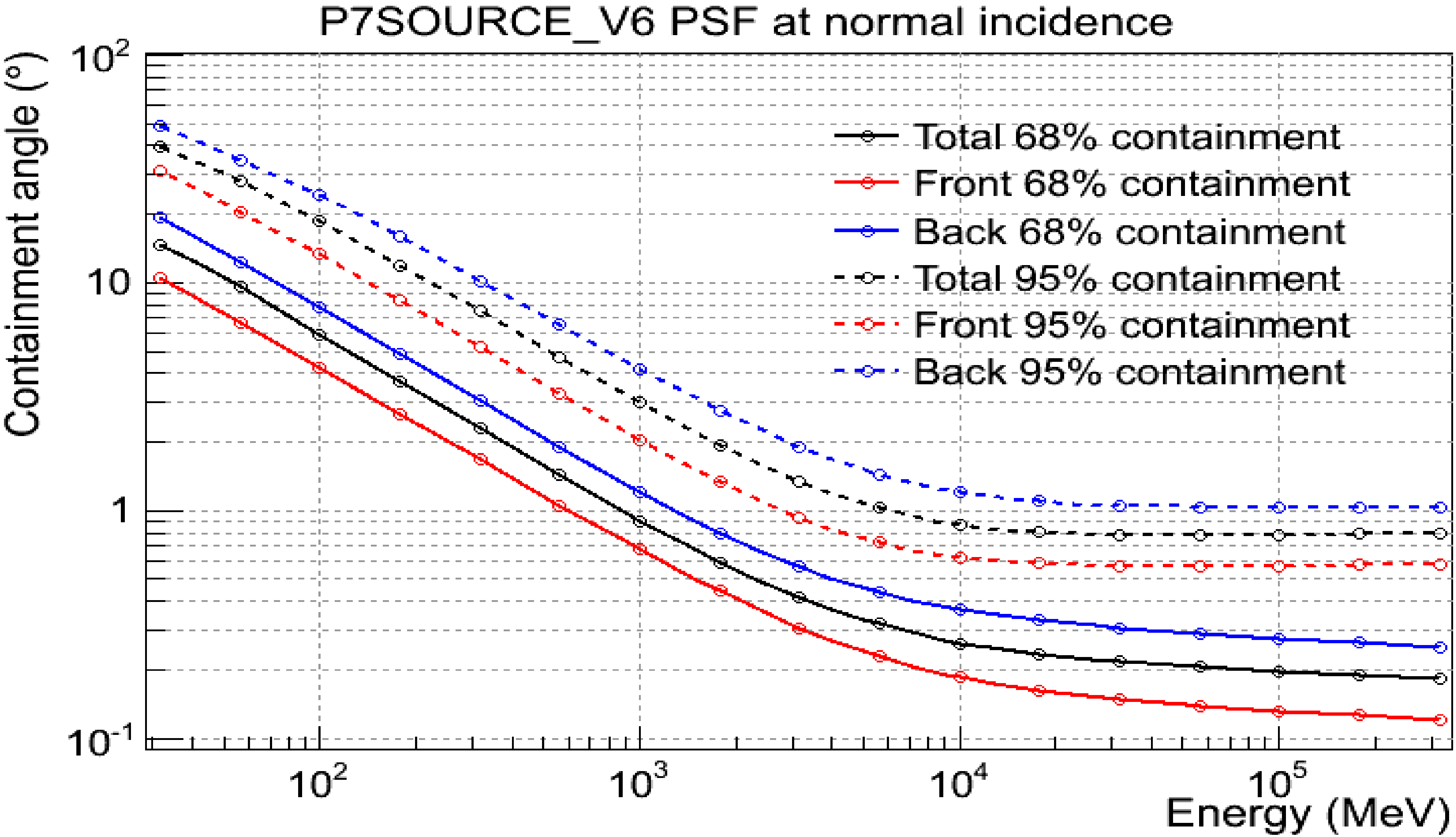






http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Fermi Instrument Response Function

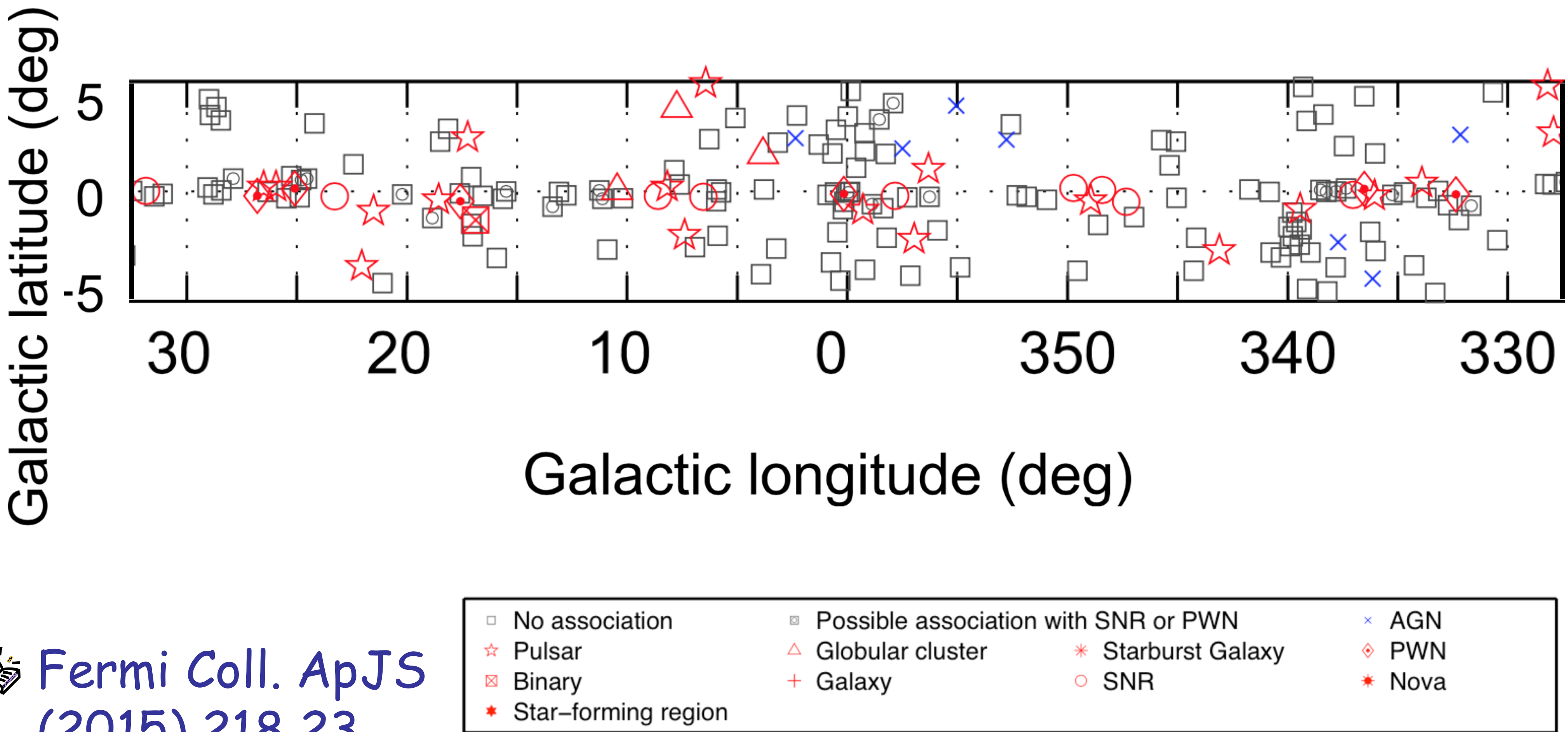


http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

The Fermi LAT 3FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

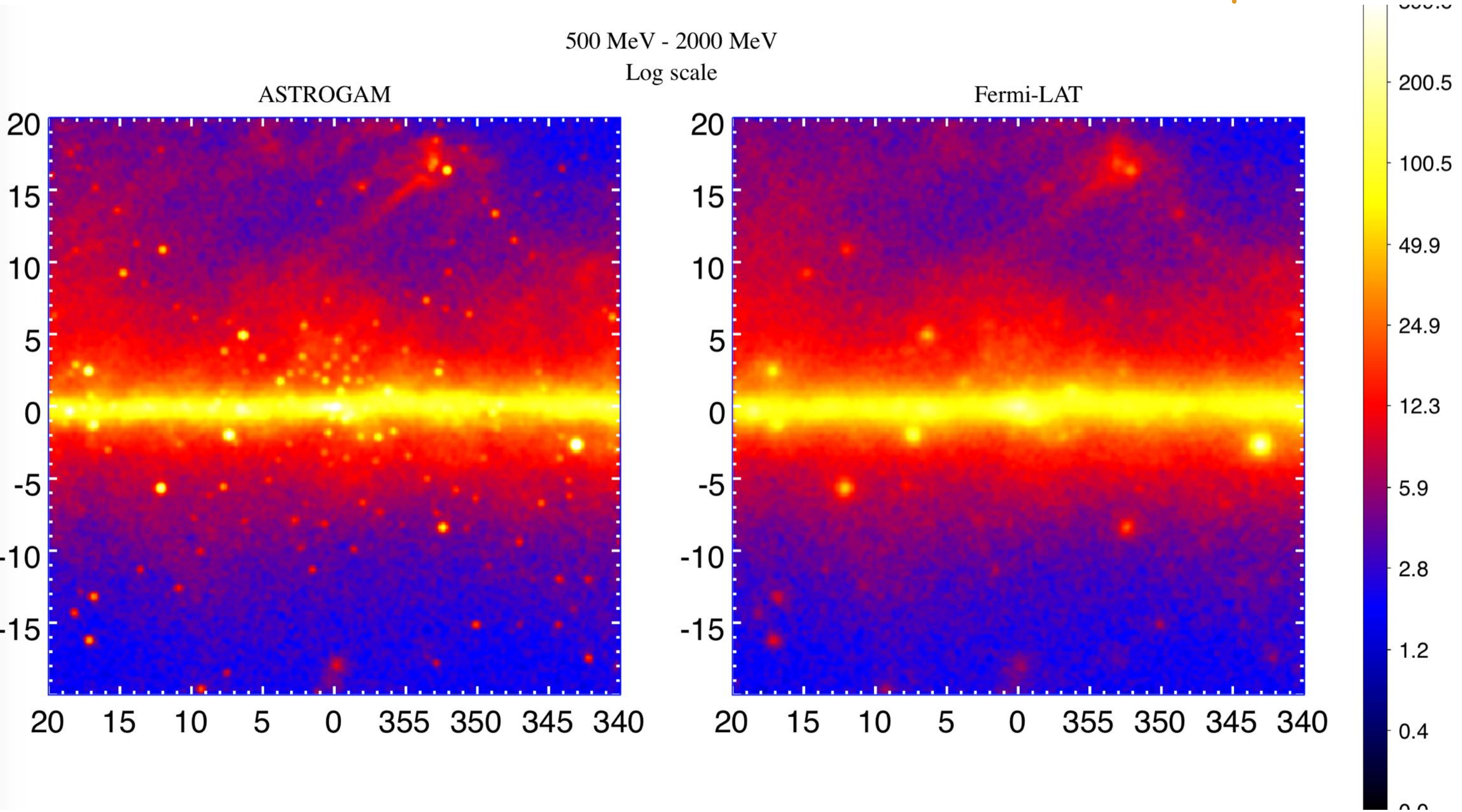
100 MeV to 300 GeV energy range



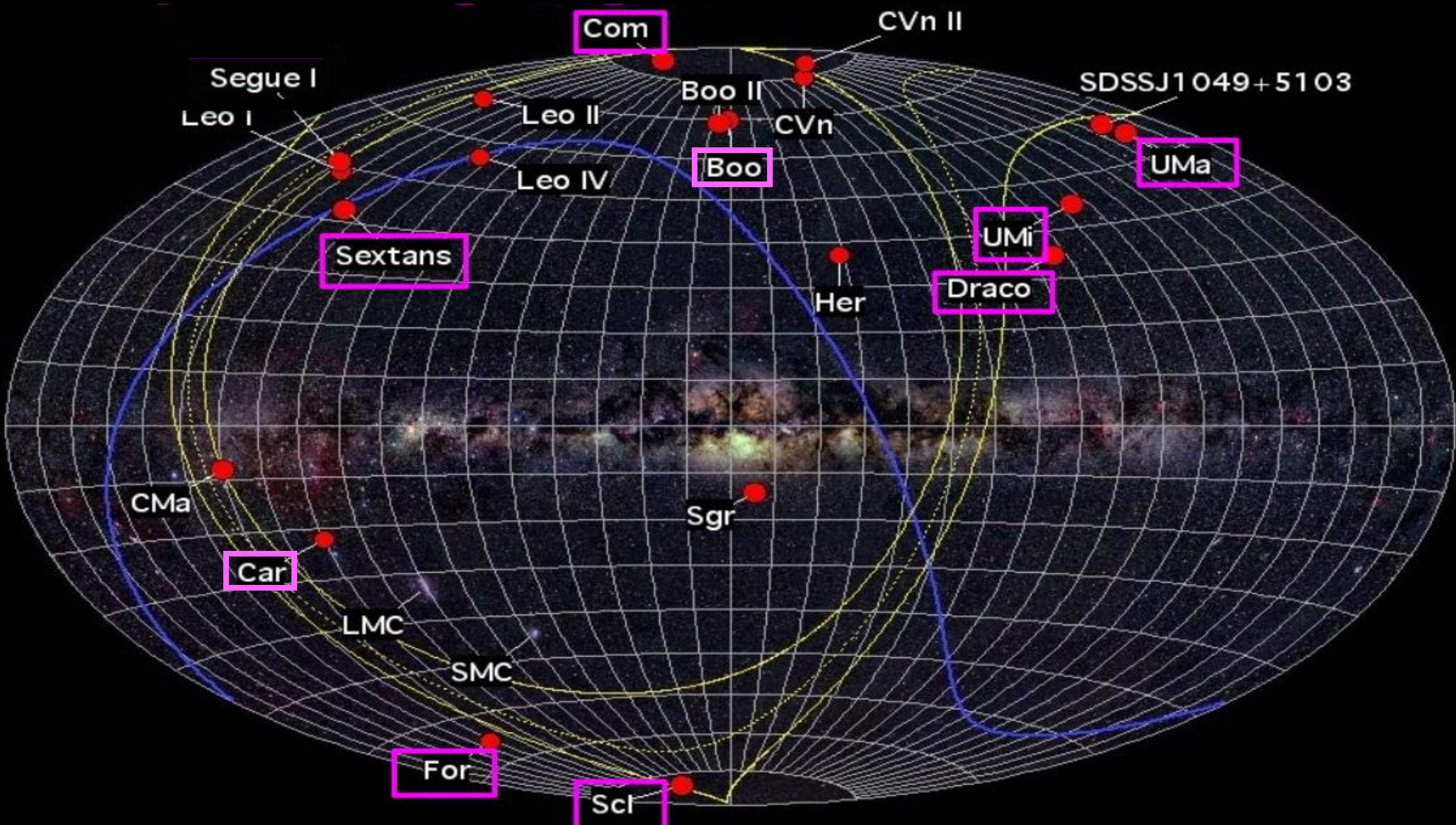
Fermi Coll. ApJS (2015) 218 23
arXiv:1501.02003

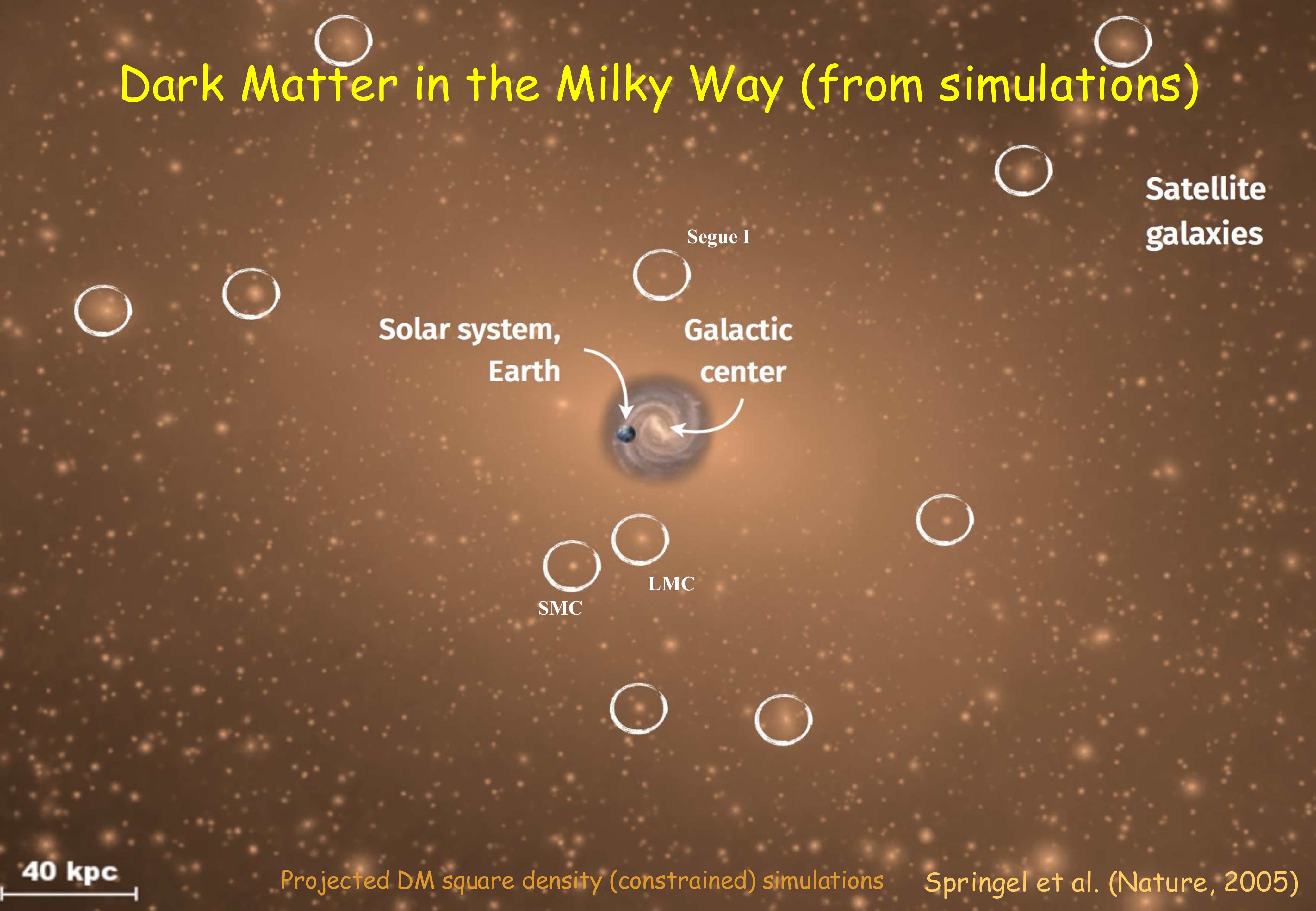
Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source

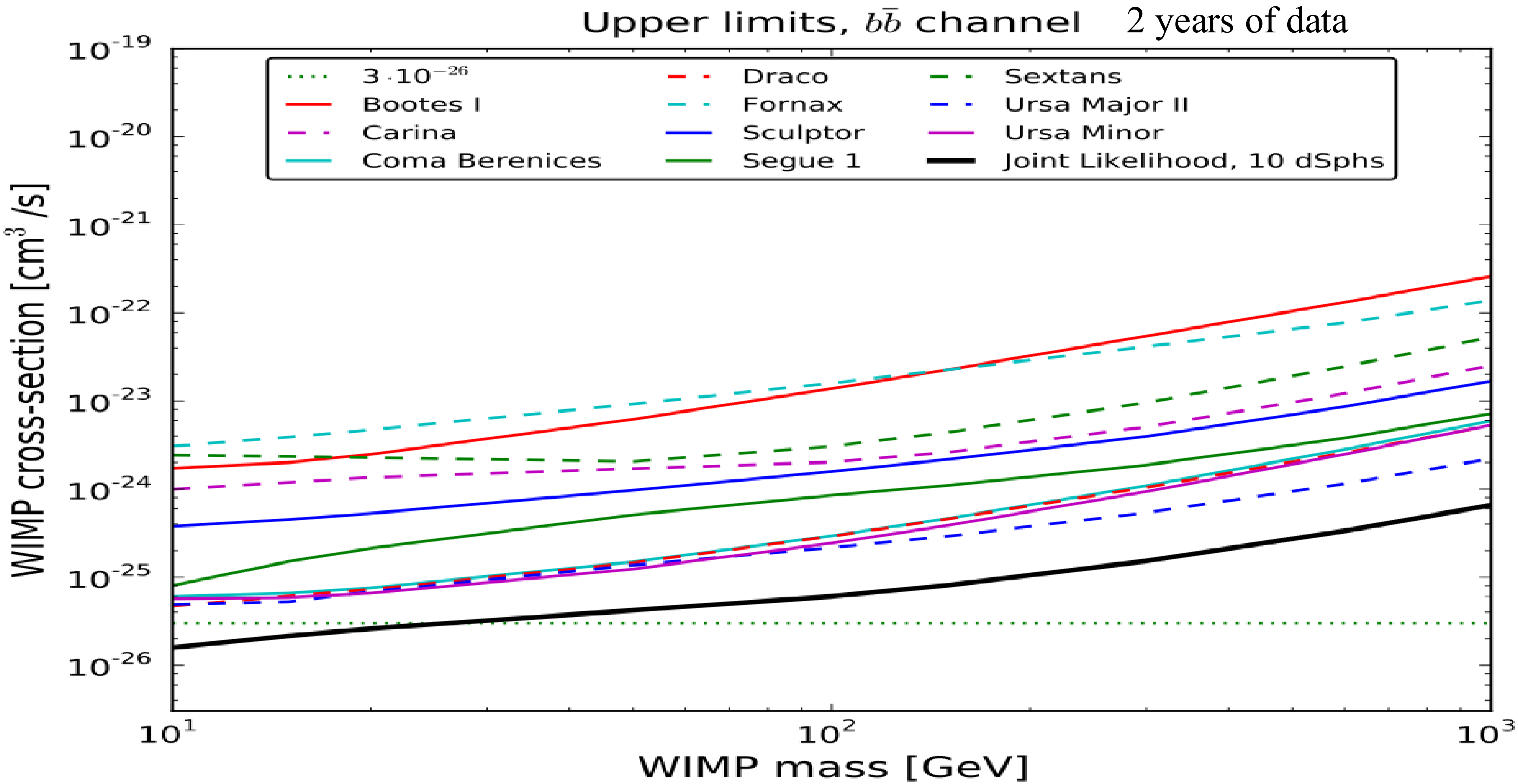


Classical Dwarf spheroidal galaxies: promising targets for DM detection




Dark Matter in the Milky Way (from simulations)
Satellite galaxies
Segue I
Solar system, Earth
Galactic center
LMC
SMC
40 kpc
Projected DM square density (constrained) simulations
Springel et al. (Nature, 2005)

Dwarf Spheroidal Galaxies combined analysis

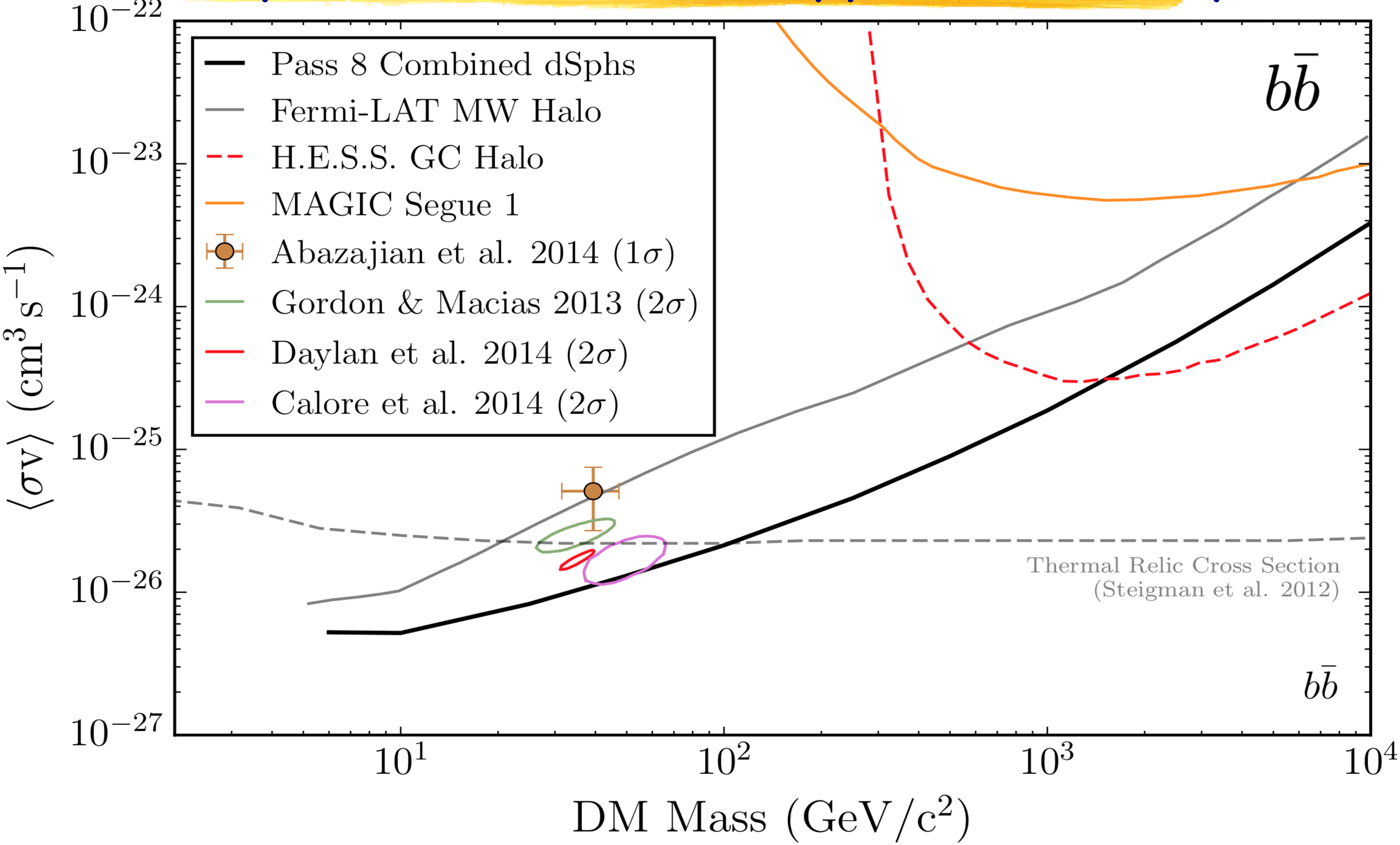


robust constraints including J-factor uncertainties from the stellar data statistical analysis

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

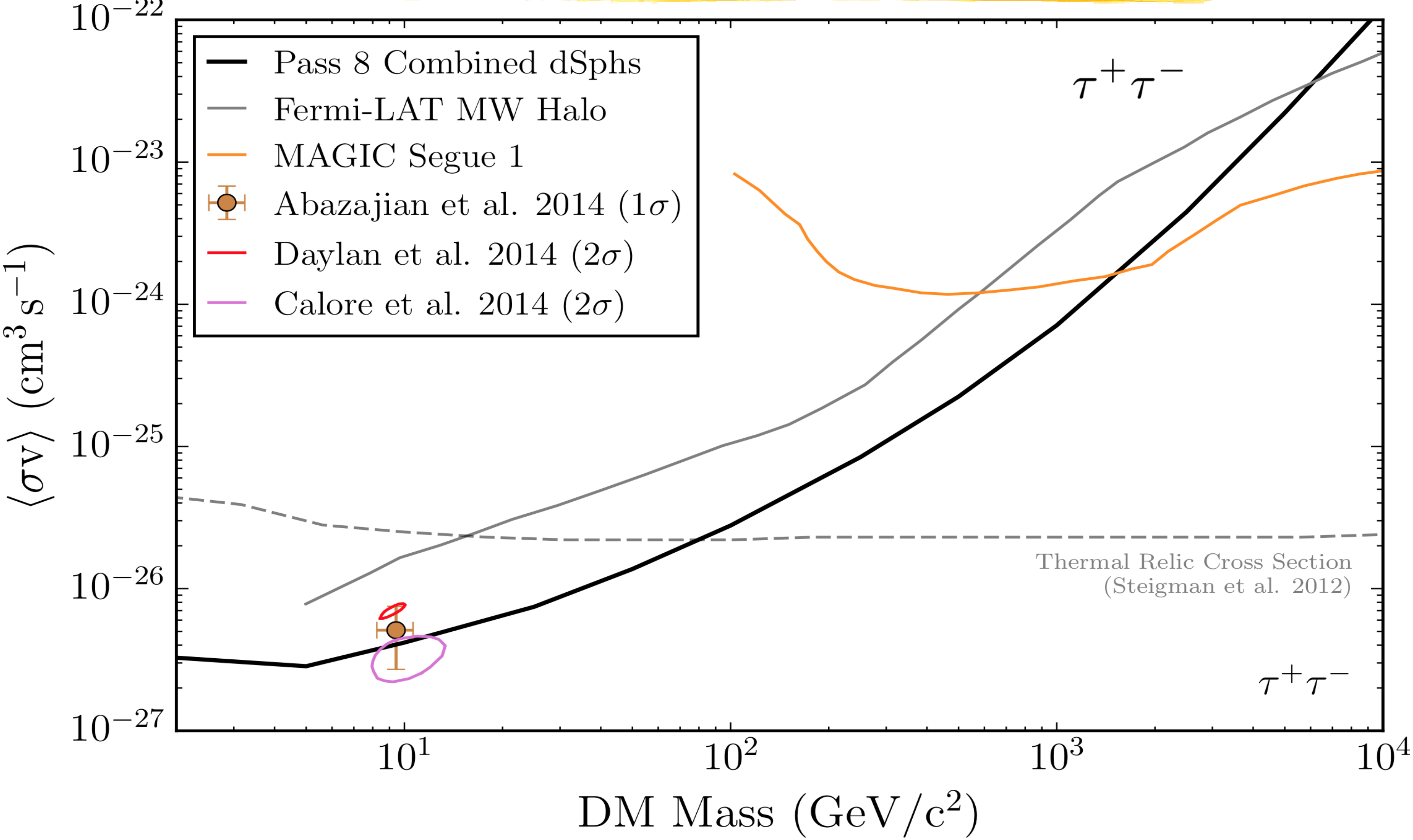
Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

Dwarf Spheroidal Galaxies upper-limits (6 years)



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

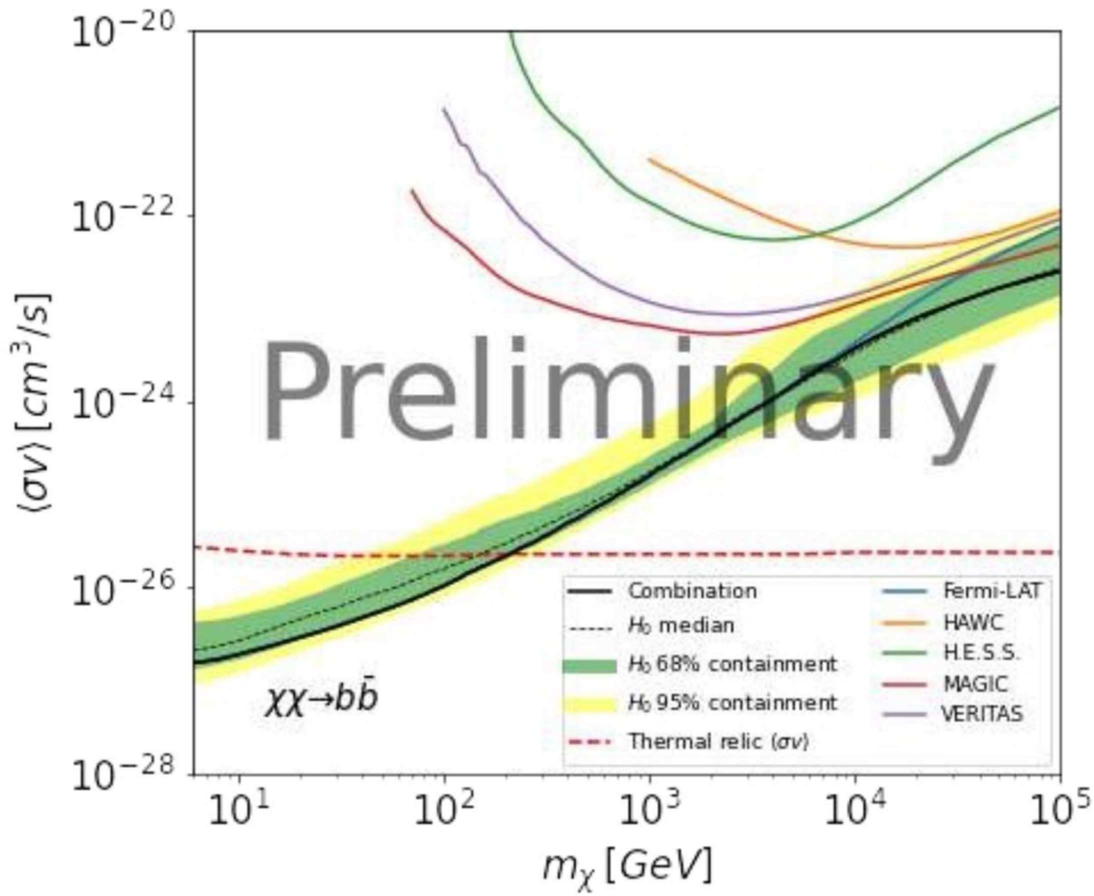
Dwarf Spheroidal Galaxies upper-limits (6 years)



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

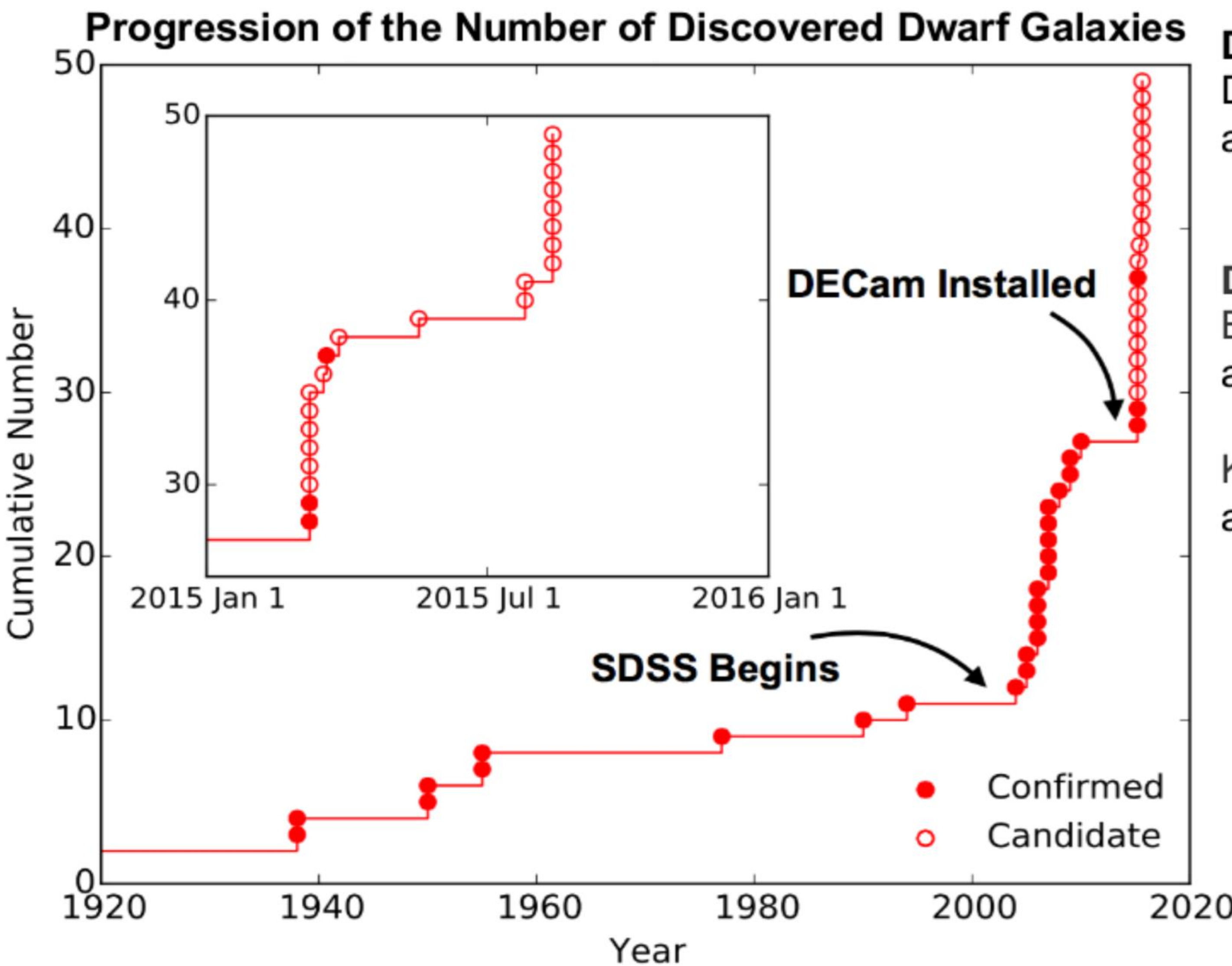
Combining all dSph observations

• 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

Dwarf Spheroidal Galaxies: Growing number of known targets



DES Year 2 Data:
Drlica-Wagner+,
arXiv:1508.03622

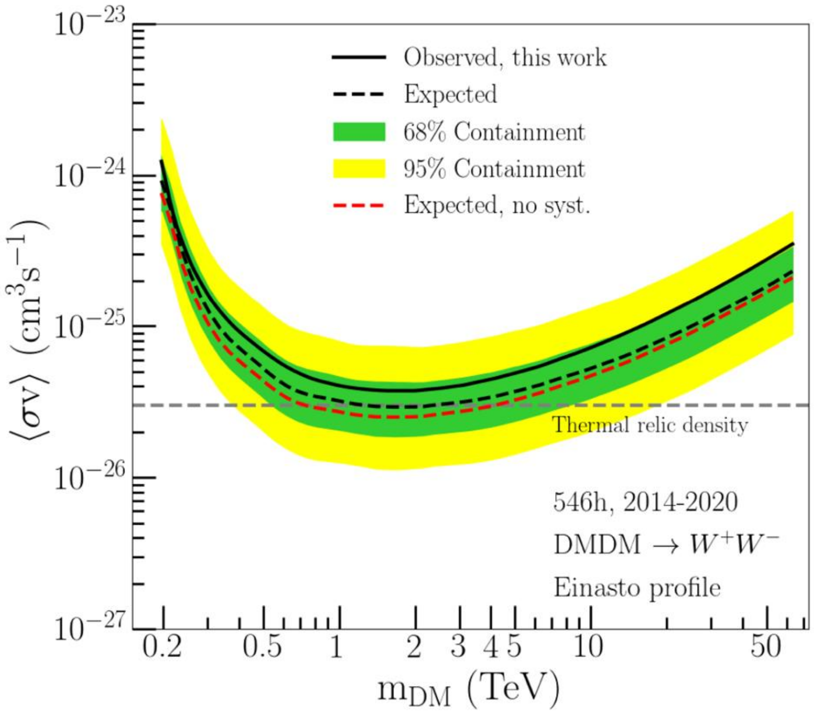
DES Year 1 Data:
Bechtol+:
arXiv:1503.02584

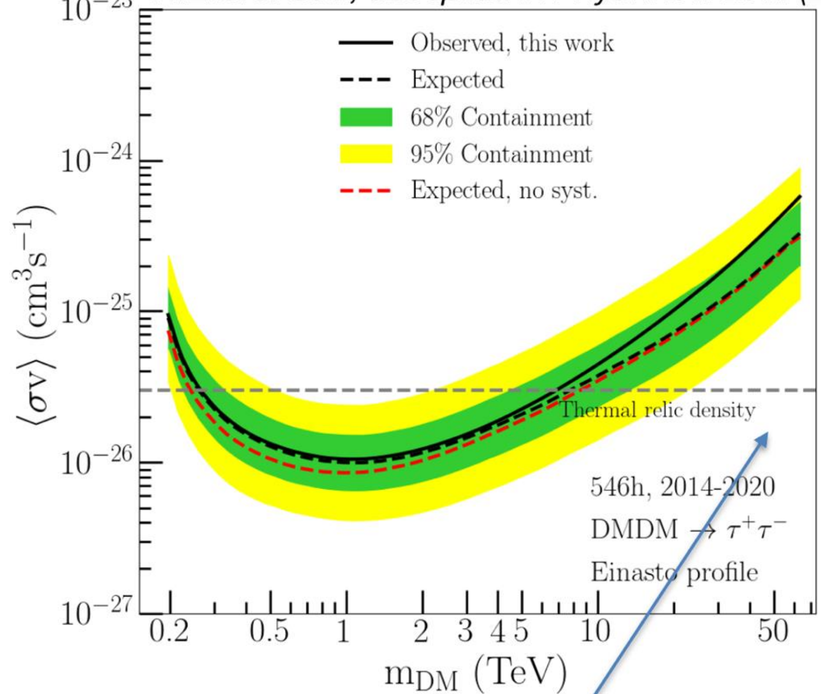
Koposov+:
arXiv:1503.02079

Galactic center with H.E.S.S.

- No significant DM signal found in any ROI
  → 95% C.L. upper limits on <σv>

H.E.S.S. coll., accepted in Phys. Rev. Lett. (2022)



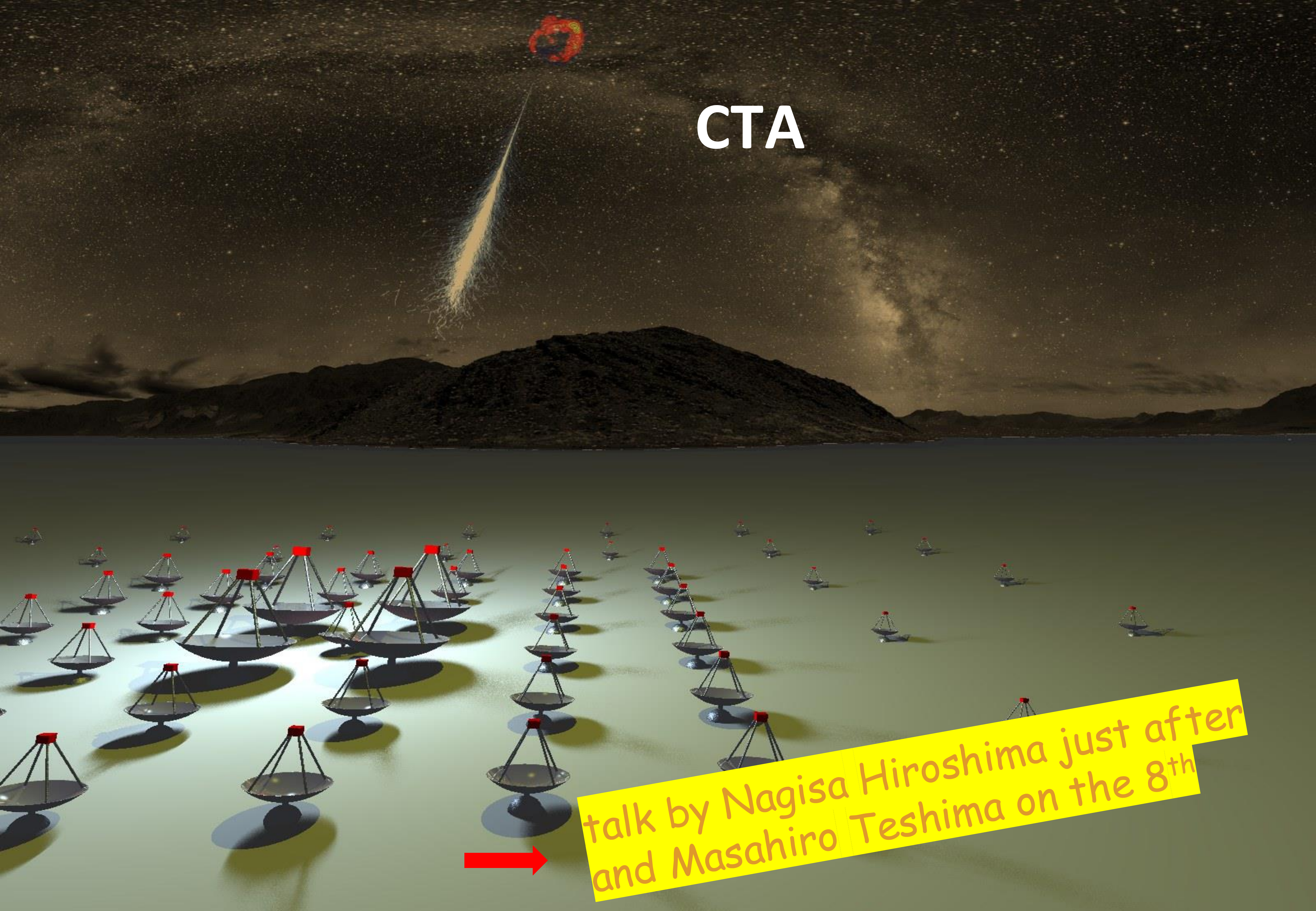


- Systematic uncertainty included in the limit computation

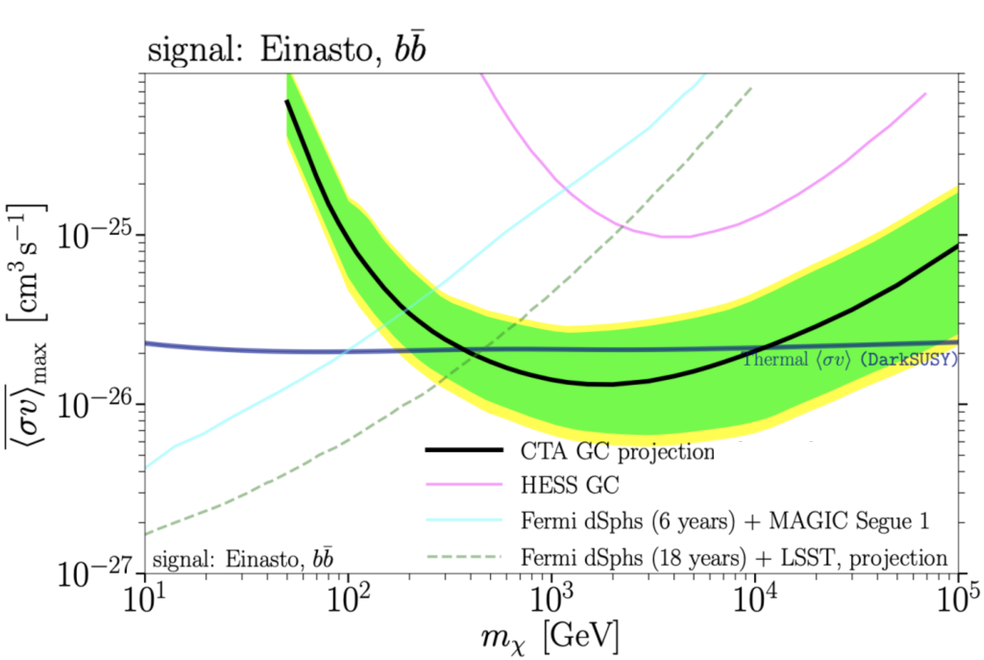
Thermal cross-section expected for vanilla (s-wave) annihilating WIMPs that account for 100% of DM

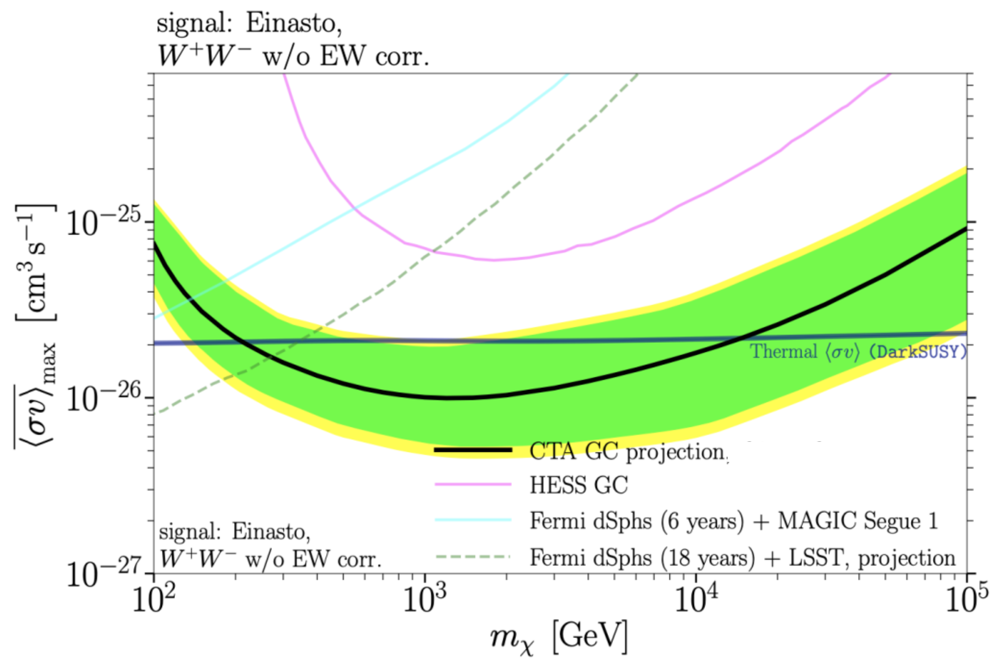
H.E.S.S.

Emmanuel Moulin – RICAP 2022 17


CTA
talk by Nagisa Hiroshima just after
and Masahiro Teshima on the 8th

Galactic center CTA Sensitivity





- Einasto profile

520 h

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

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

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

Measuring DM densities in dSph halos

Optimal dSphs selected according to:
1. Distance(d<100pc)
2. Culmination zenith angle (ZAmin < 30°)

Targets with no/poor brightness and/ or kinematic data excluded from the MCMC Jeans analysis.

Surviving sample:

— 6 Northern dSphs (1 classical + 5 ultra-faint)

— 6 Southern dSphs (3 classical + 3 ultra-faint)

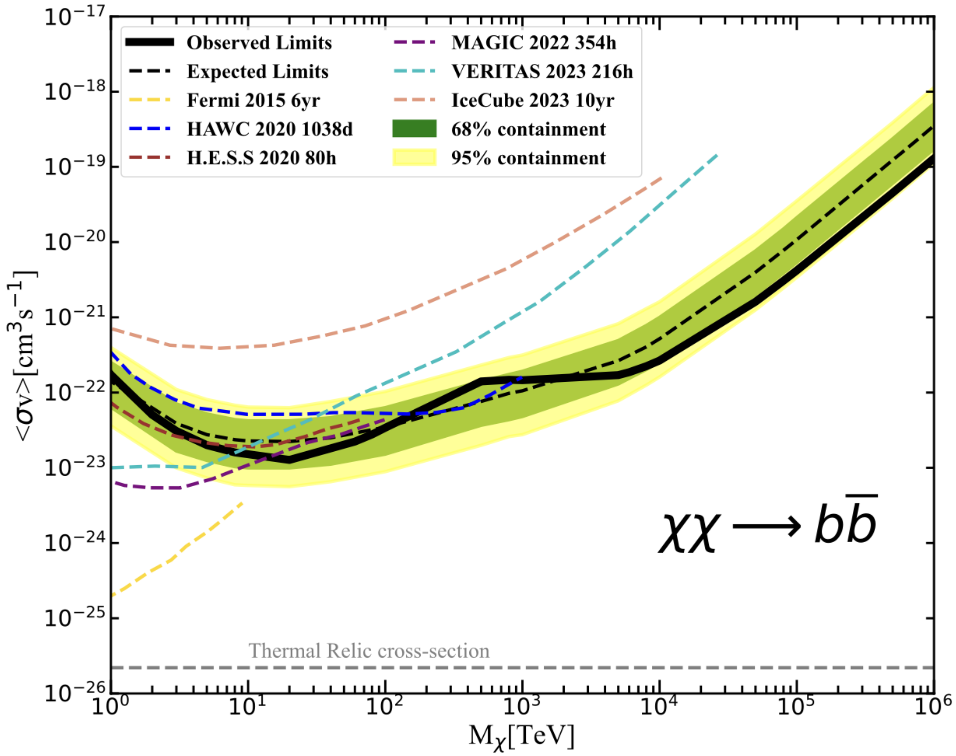
Name	Abbr.	Type	R.A. (hh mm ss)	dec. (dd mm ss)	Distance (kpc)	ZA_{culm} N (deg)	ZA_{culm} S (deg)	Month
Andromeda XVIII	AndXVIII	uft	00 02 14.5	+45 05 20	1330 ± 104	16.3	69.7	Sep
Aquarius	Aqr	uft	20 46 51.8	−12 50 53	1030 ± 57	41.6	11.8	Aug
Boötes I	BoöI	uft	14 00 06.0	+14 30 00	65 ± 3	14.3	39.1	Apr
Boötes II	BoöII	uft	13 58 00.0	+12 51 00	39 ± 2	15.9	37.5	Apr
Boötes III	BoöIII	uft	13 57 12.0	+26 48 00	46 ± 2	2.0	51.4	Apr
Canes Venatici I	CVnI	uft	13 28 03.5	+33 33 21	216 ± 8	4.8	58.2	Apr
Canes Venatici II	CVnII	uft	12 57 10.0	+34 19 15	159 ± 8	5.6	58.9	Apr
Carina	Car	cls	06 41 36.7	−50 57 58	106 ± 1	79.7	26.3	Dec
Cetus I	CetI	uft	00 26 11.0	−11 02 40	748 ± 31	39.8	13.6	Sep
Cetus II	CetII	uft	01 17 52.8	−17 25 12	30 ± 3	46.2	7.2	Oct
Columba I	ColI	uft	05 31 26.4	−28 01 48	182 ± 18	56.8	3.4	Dec
Coma Berenices	CBe	uft	12 26 59.0	+23 54 15	42 ± 2	4.9	48.5	Mar
Draco I	DraI	cls	17 20 12.4	+57 54 55	75 ± 4	29.2	82.5	Jun
Draco II	DraII	uft	15 52 47.6	+64 33 55	20 ± 3	35.8	89.2	May
Eridanus II	EriII	uft	03 44 21.5	−43 31 48	330 ± 16	72.3	18.9	Nov
Eridanus III	EriIII	uft	02 22 45.5	−52 16 48	95 ± 27	81.0	27.7	Oct
Fornax	For	cls	02 39 59.3	−34 26 57	146 ± 1	63.2	9.8	Oct
Grus I	GruI	uft	22 56 42.4	−50 09 48	120 ± 17	78.9	25.5	Sep
Grus II	GruII	uft	22 04 04.8	−46 26 24	53 ± 5	75.2	21.8	Aug
Hercules	Her	uft	16 31 02.0	+12 47 30	137 ± 11	16.0	37.4	May
Horologium I	HorI	uft	02 55 28.9	−54 06 36	87 ± 13	82.9	29.5	Oct
Hydra II	HyaII	uft	12 21 42.1	−31 59 07	134 ± 10	60.7	7.4	Mar
Indus I	IndI	uft	21 08 48.1	−51 09 36	69 ± 16	79.9	26.5	Aug
Indus II	IndII	uft	20 38 52.8	−46 09 36	214 ± 16	74.9	21.5	Aug
Laevens 3	Lae3	uft	21 06 54.3	+14 58 48	67 ± 3	13.8	39.6	Aug
Leo I	LeoI	cls	10 08 28.1	+12 18 23	272 ± 10	16.5	36.9	Feb
Leo II	LeoII	cls	11 13 28.8	+22 09 06	240 ± 9	6.6	46.8	Mar
Leo IV	LeoIV	uft	11 32 57.0	−00 32 00	151 ± 4	29.3	24.1	Mar
Leo V	LeoV	uft	11 31 09.6	+02 13 12	169 ± 5	26.5	26.9	Mar
Leo T	LeoT	uft	09 34 53.4	+17 03 05	377 ± 28	11.7	41.7	Feb
Phoenix I	PheI	uft	01 51 06.3	−44 26 41	427 ± 31	73.2	19.8	Oct
Phoenix II	PheII	uft	23 39 57.6	−54 24 36	95 ± 18	83.2	29.8	Sep
Pictor I	PicI	uft	04 43 48.0	−50 16 48	126 ± 24	79.[illegible]	25.7	Nov
Pisces II	PscII	uft	22 58 31.0	+05 57 09	182 ± 13	22.8	30.6	Sep
Reticulum II	RetII	uft	03 35 40.9	−54 03 00	32 ± 2	82.8	29.4	Nov
Reticulum III	RetIII	uft	03 45 26.3	−60 27 00	92 ± [illegible]	89.2	35.8	Nov
Sagittarius I	SgrI	dis	18 55 19.5	−30 32 43	31 ± 1	59.3	5.9	Jul
Sagittarius II	SgrII	uft	19 52 40.5	−22 04 05	67 ± 5	50.8	2.6	Jul
Sculptor	Scl	cls	01 00 09.4	−33 42 3[illegible]	84 ± 2	62.5	9.1	Oct
Segue 1	Seg1	uft	10 07 04.0	+16 04 55	23 ± 2	12.7	40.7	Feb
Segue 2	Seg2	uft	02 19 16.0	+20 10 31	36 ± 2	8.6	44.8	Oct
Sextans	Sex	cls	10 13 03.[illegible]	−01 36 53	84 ± 3	30.4	23.0	Feb
Triangulum II	TriII	uft	02 13 17.4	+36 10 42	30 ± 2	7.4	60.8	Oct
Tucana I	TucI	uft	22 41 49.6	−64 25 10	855 ± 35	—	39.8	Sep
Tucana II	TucII	uft	22 52 16.7	−58 33 36	58 ± 6	87.3	33.9	Sep
Tucana III	TucIII	uft	23 56 35.9	−59 36 00	25 ± 2	88.4	35.0	Sep
Tucana IV	TucIV	uft	00 02 55.3	−60 51 00	48 ± 4	89.6	36.2	Sep
Ursa Major I	UMaI	uft	10 34 52.8	+51 55 12	105 ± 2	23.2	76.6	Mar
Ursa Major II	UMaII	uft	08 51 30.0	+63 07 48	35 ± 2	34.4	87.8	Feb
Ursa Minor	UMi	cls	15 09 08.5	+67 13 21	68 ± 2	38.5	—	May
Willman 1	Wil1	uft	10 49 21.0	+51 03 00	38 ± 7	22.3	75.7	Mar

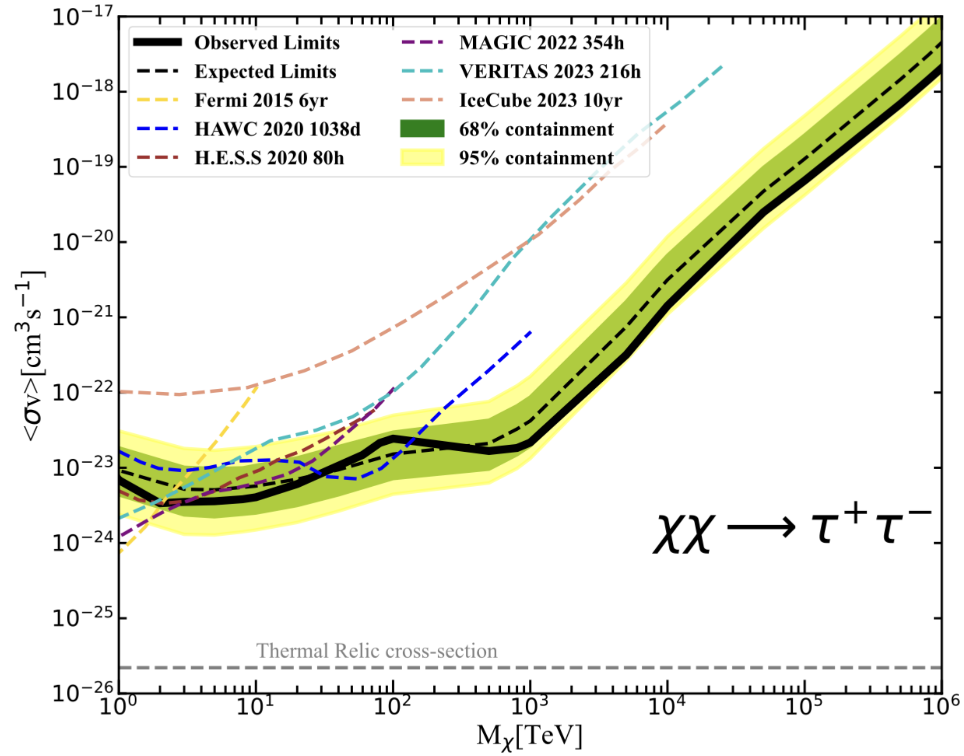
LHAASO

Mt. Haizi 4410 altitude

Constraints on Ultra Heavy Dark Matter Properties from Dwarf Spheroidal Galaxies with LHAASO Observations

DM annihilation cross-section



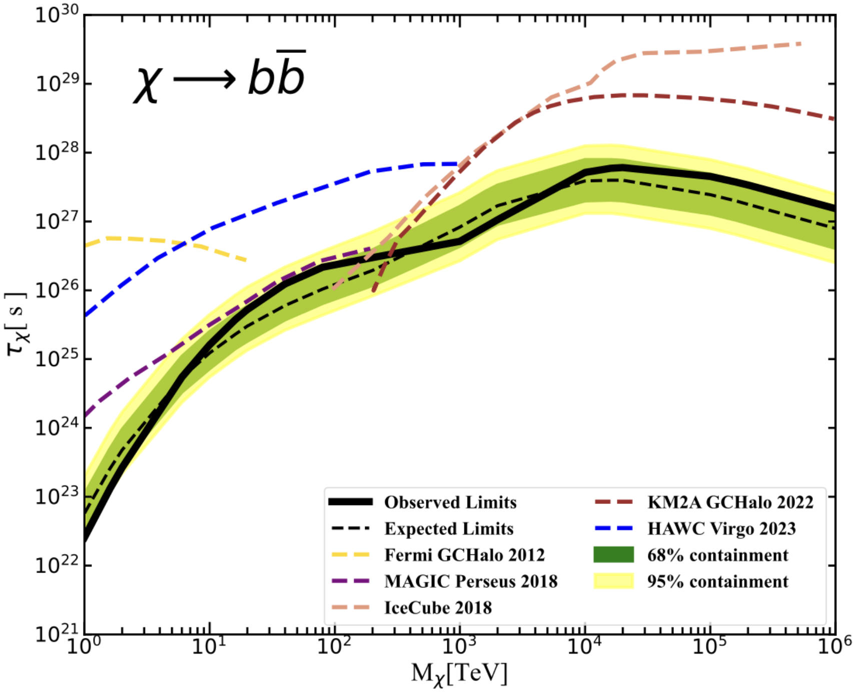


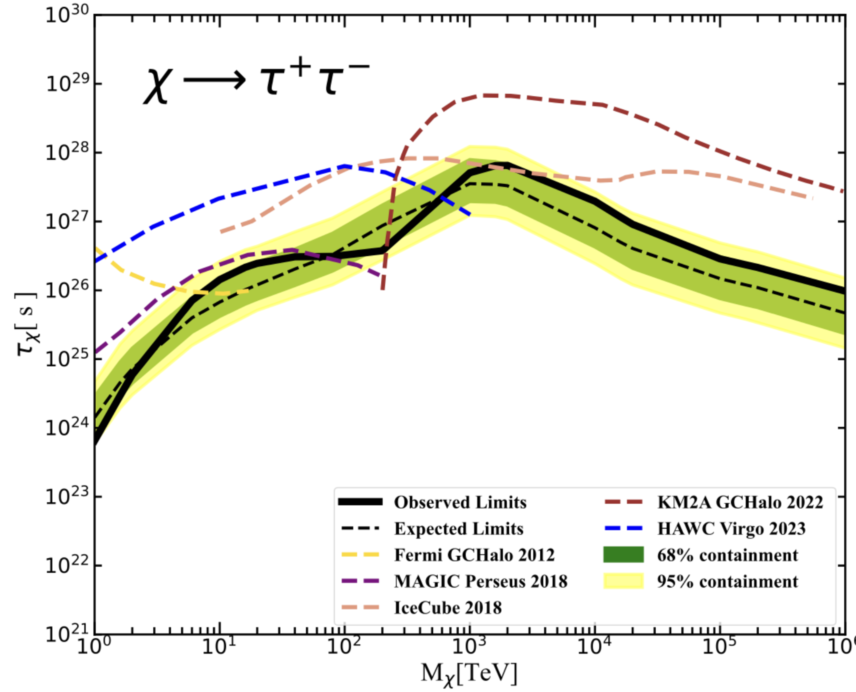
700 days, 16 dwarf spheroidal galaxies

LHAASO Coll. 2406.08698v1

Constraints on Ultra Heavy Dark Matter Properties from Dwarf Spheroidal Galaxies with LHAASO Observations

DM decay lifetime

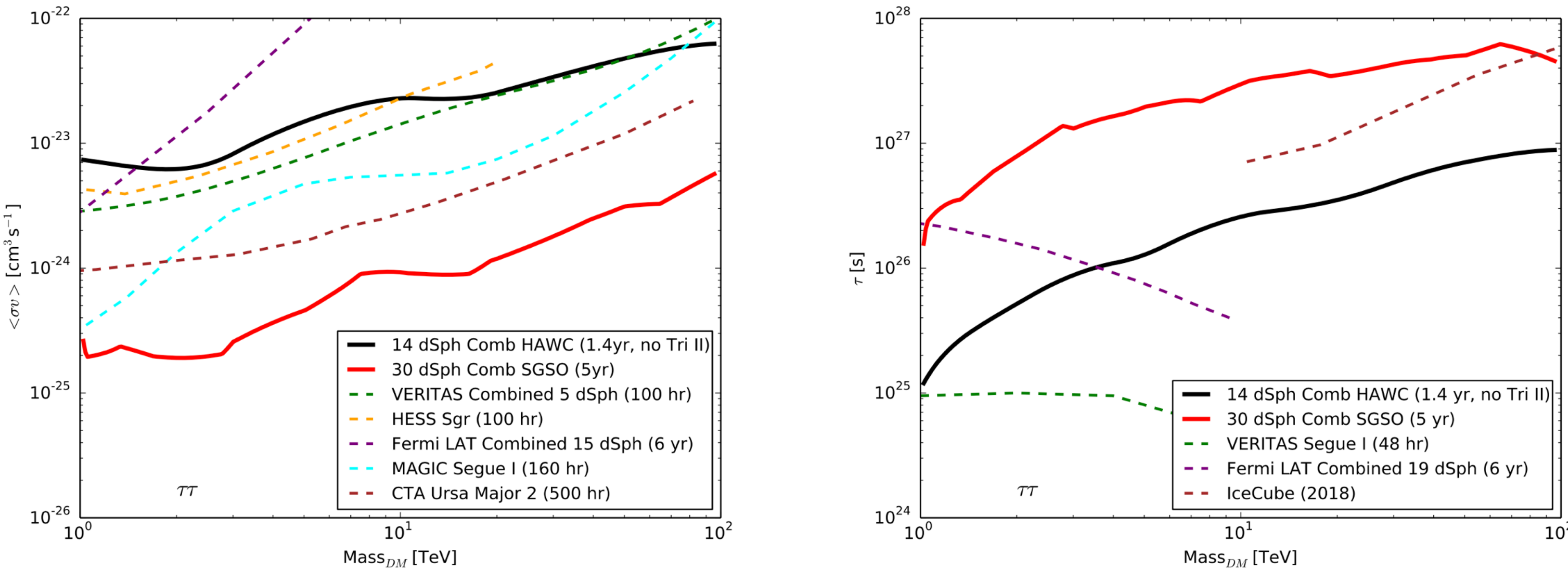




700 days, 16 dwarf spheroidal galaxies

LHAASO Coll. 2406.08698v1

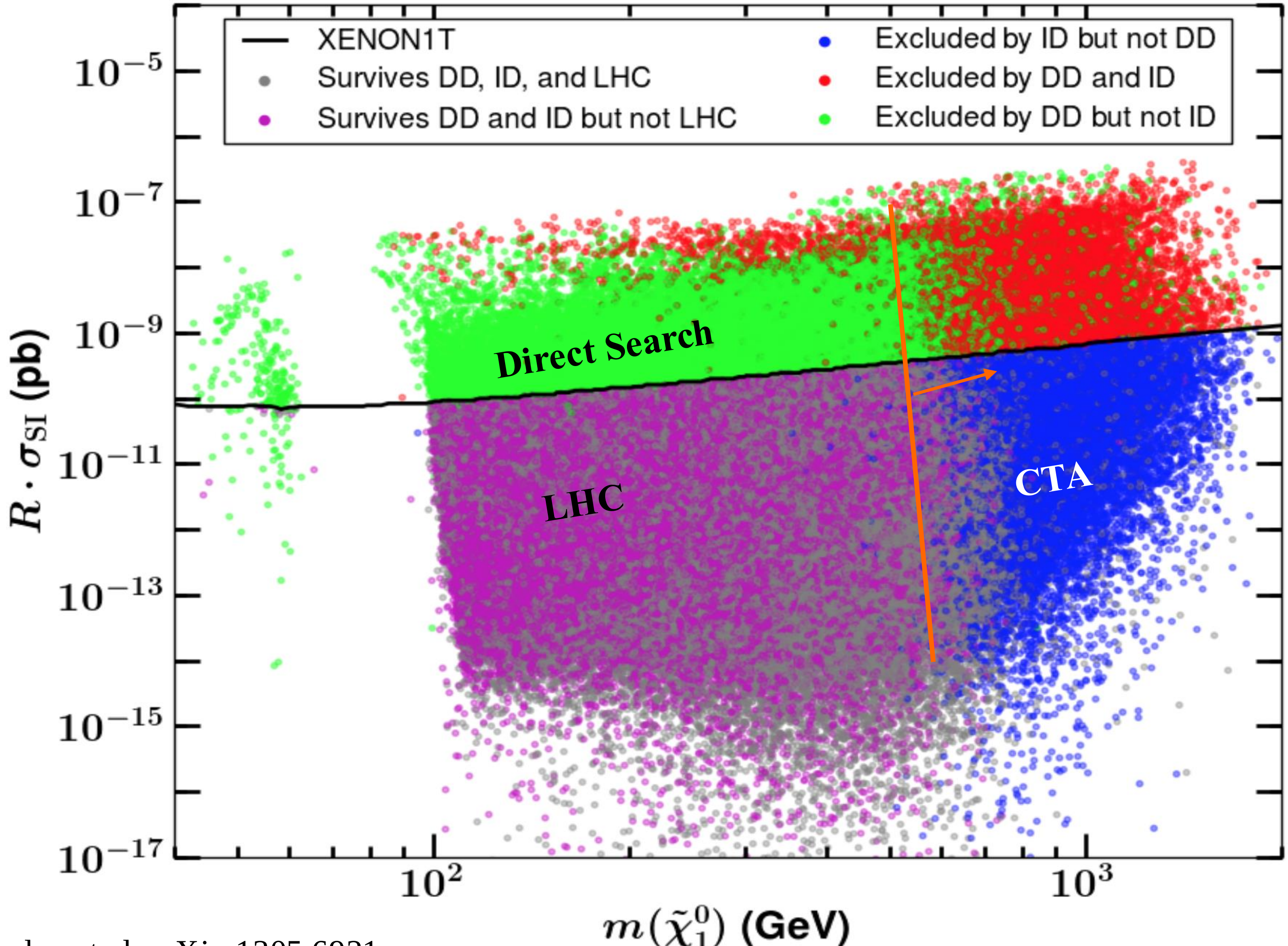
SWGO sensitivities



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

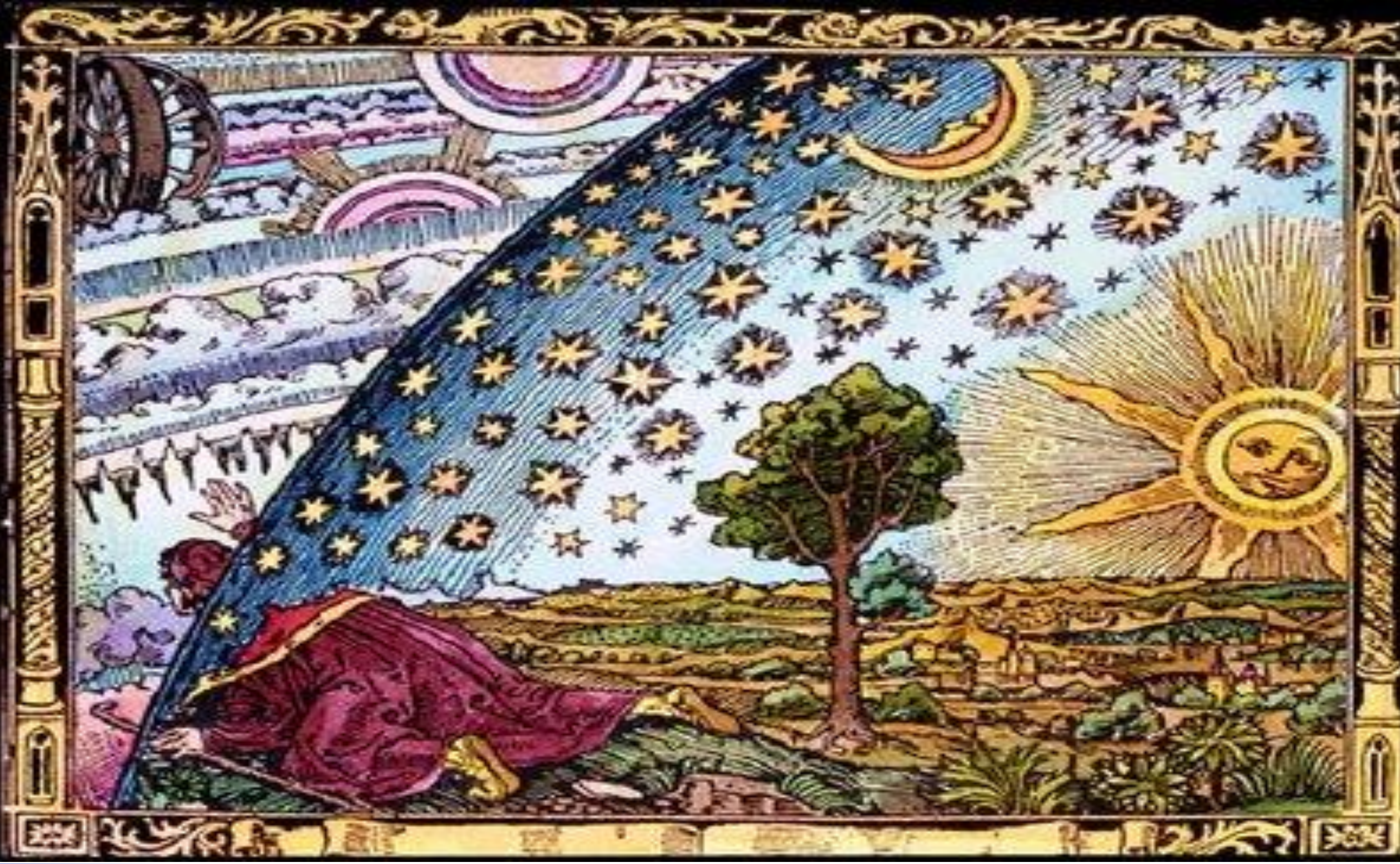
SWGO White paper arXiv:1902.08429

Complementarity and Searches for Dark Matter in the pMSSM

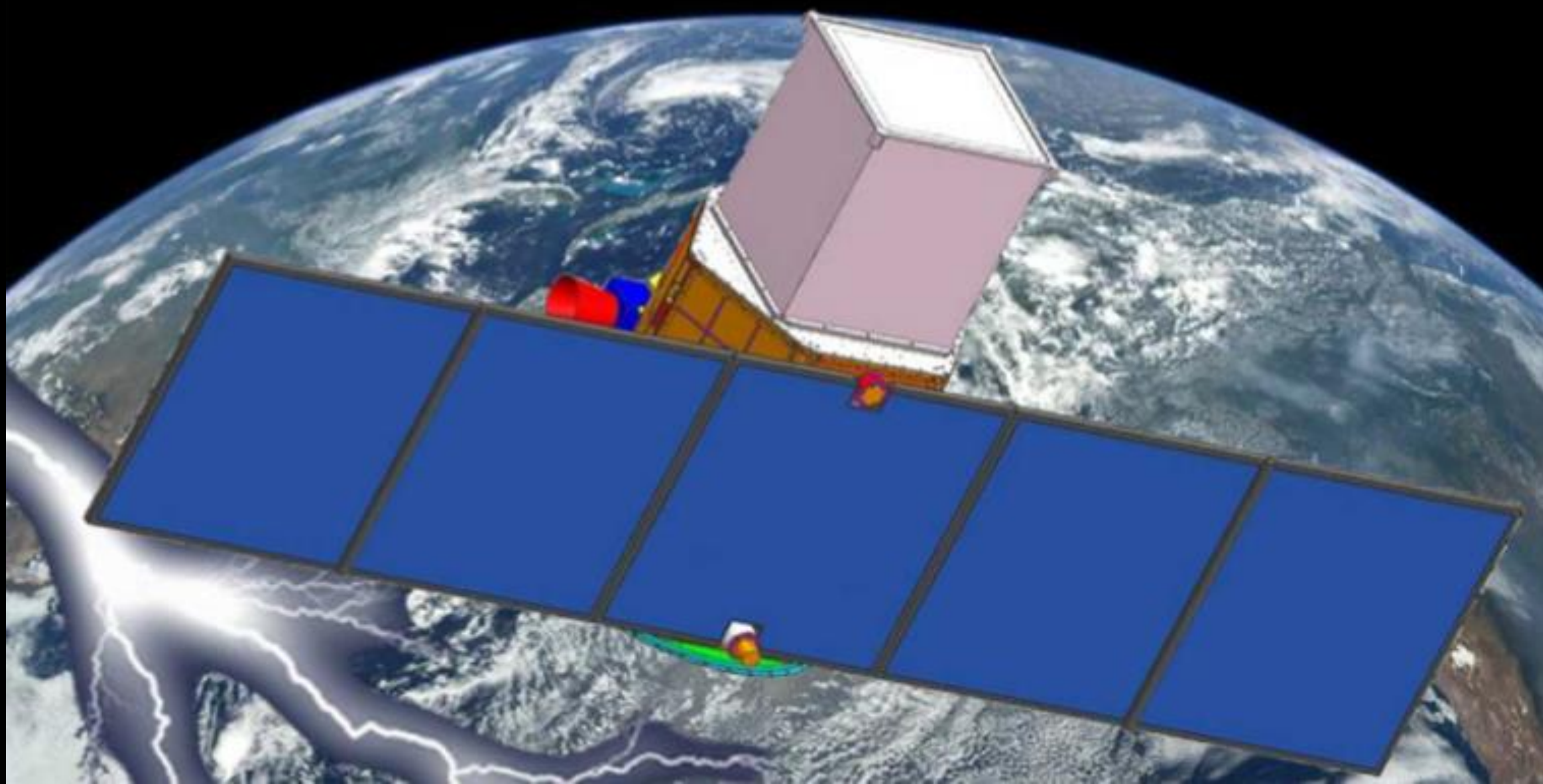


Cahill-Rowley et al. arXiv:1305.6921

The Low Energy Frontier

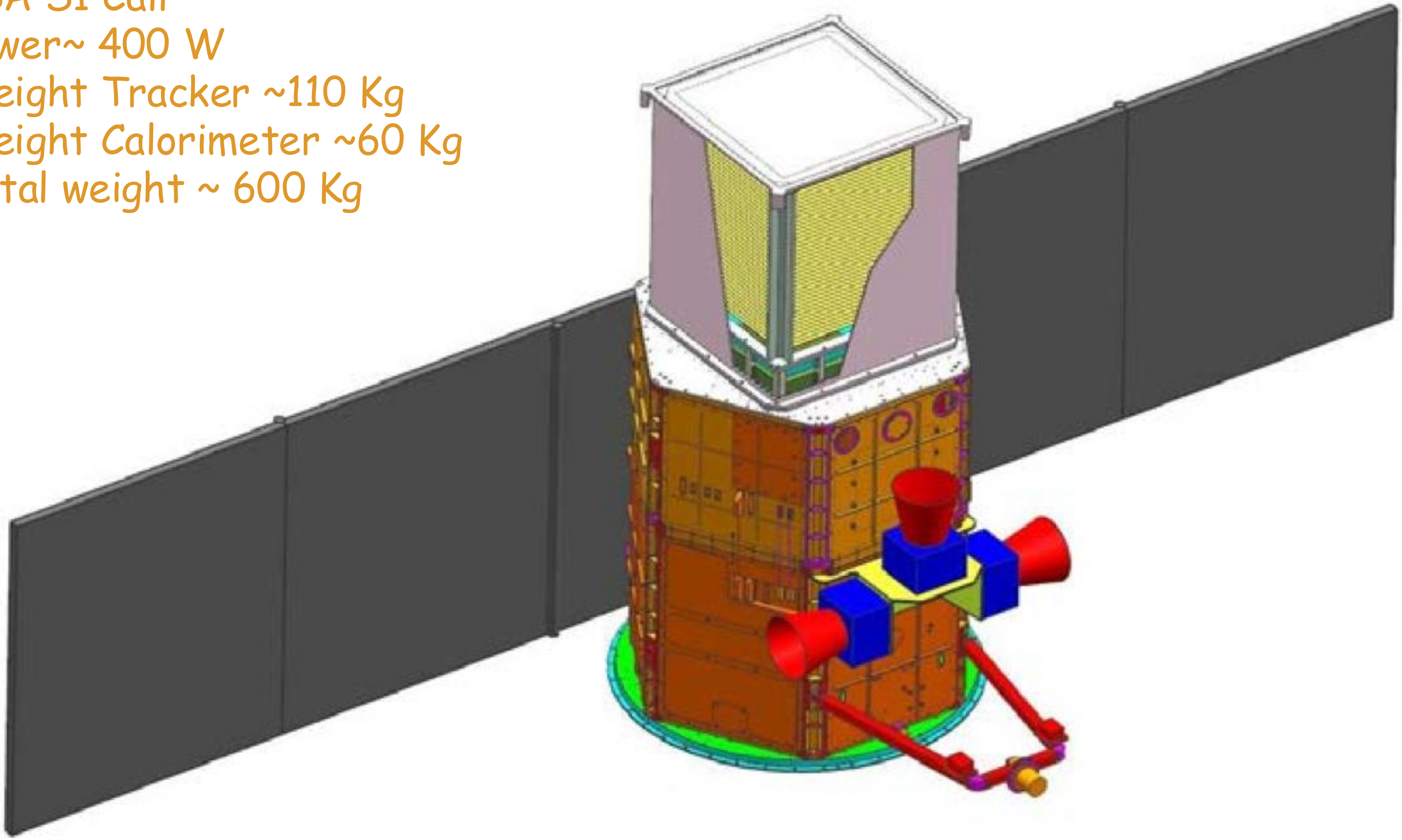


Gamma-Light



Gamma-light project

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



Gamma-light scheme

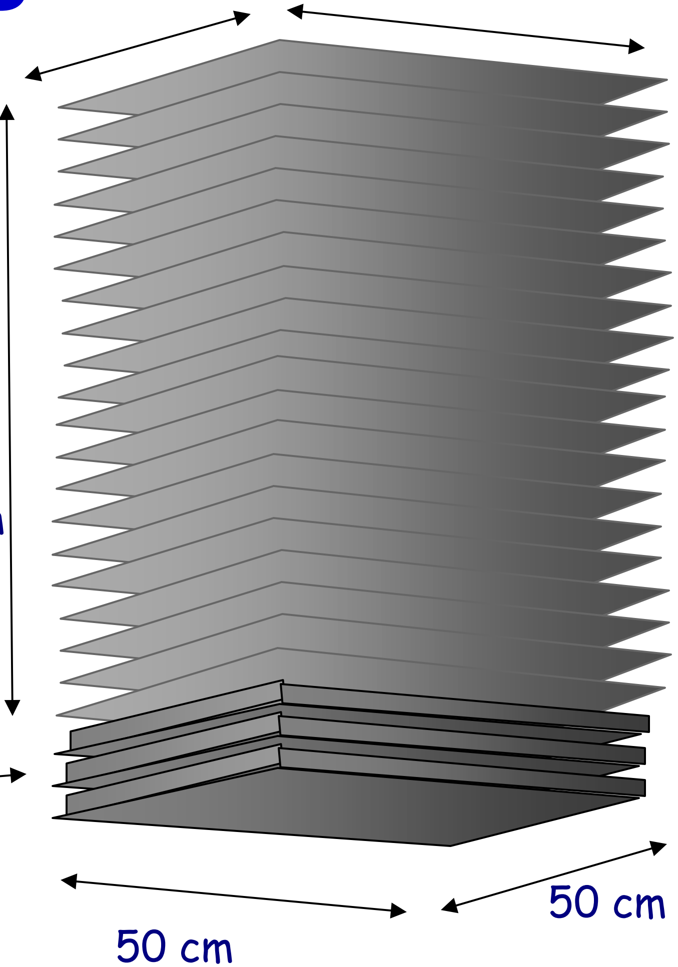
40+1 x-y planes
100 μm pitch
each
~0.025 X_0

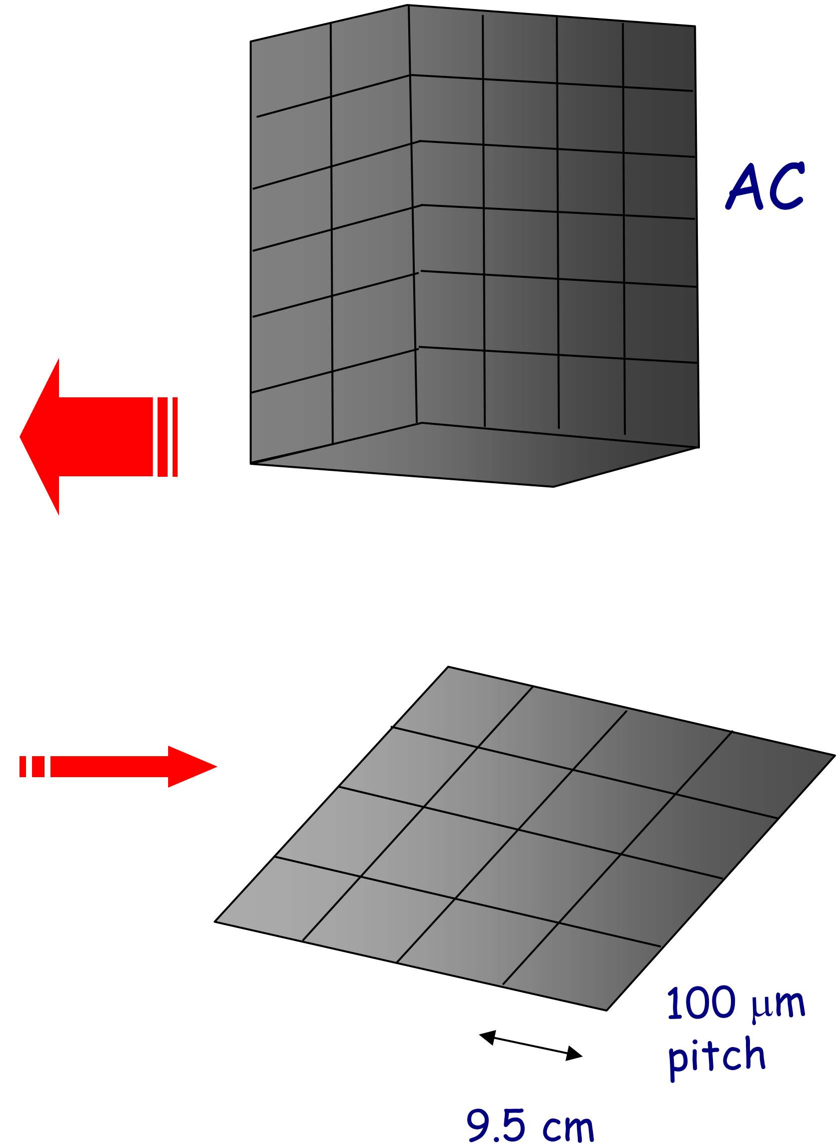
Tot~ 1 X_0

54.7 cm

height of a plane 1.3 cm

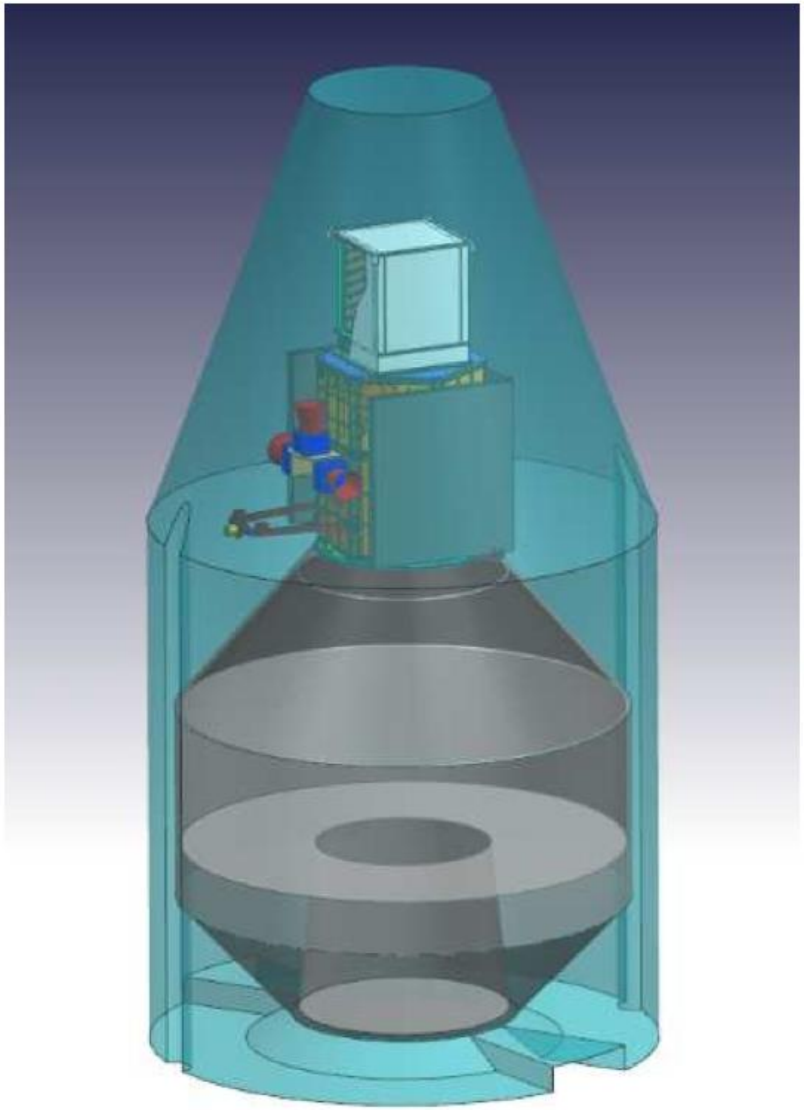
2 Xo Calorimiter

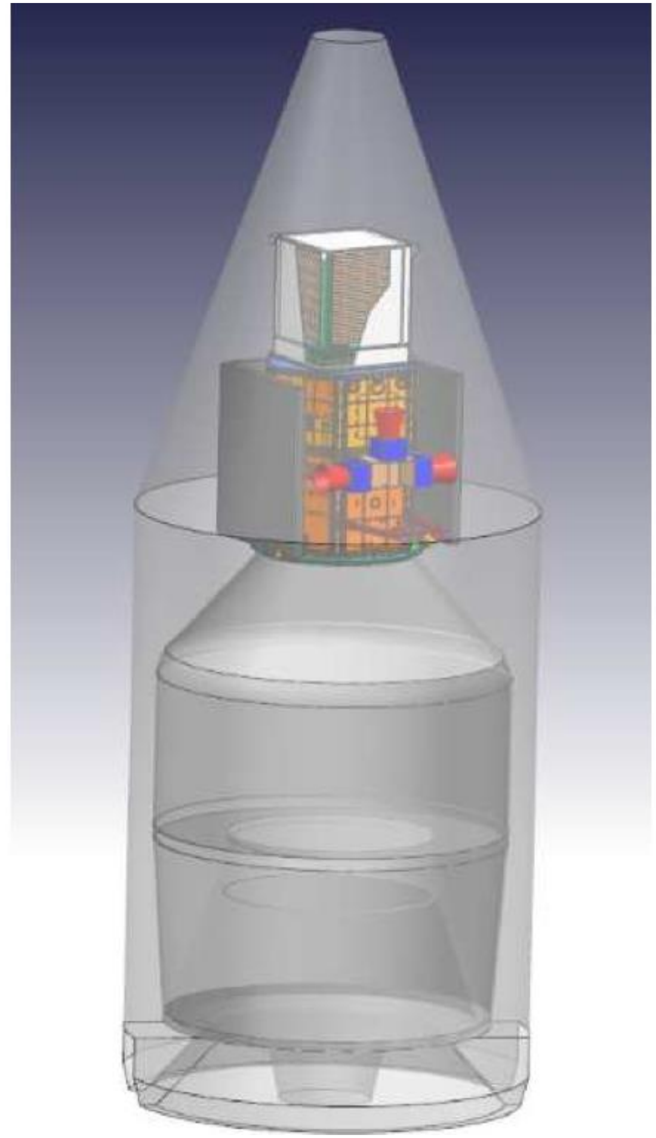




Compton scattering ***and*** *pair production telescope*

GAMMA-LIGHT satellite launch configurations for the PSLV and VEGA

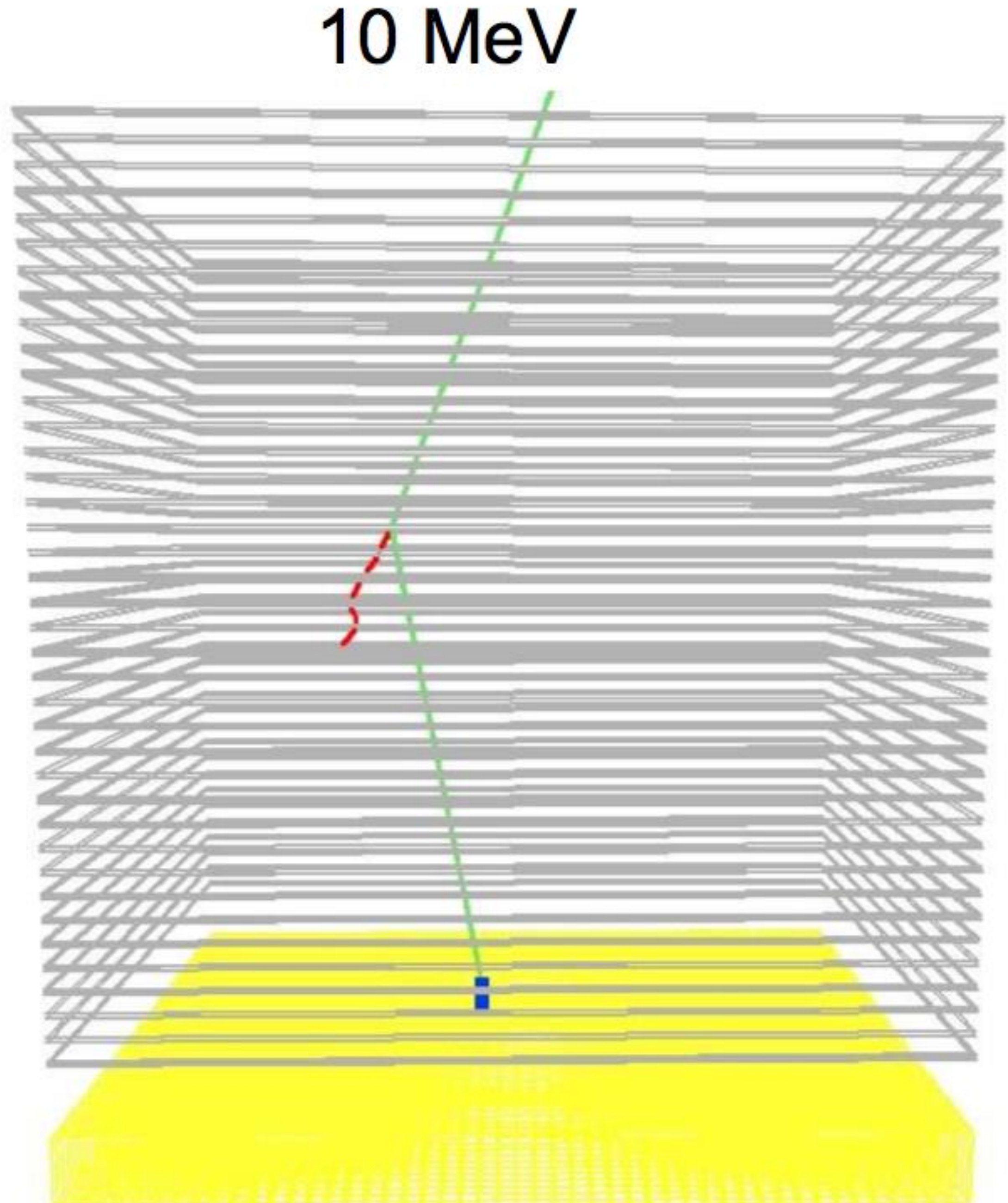




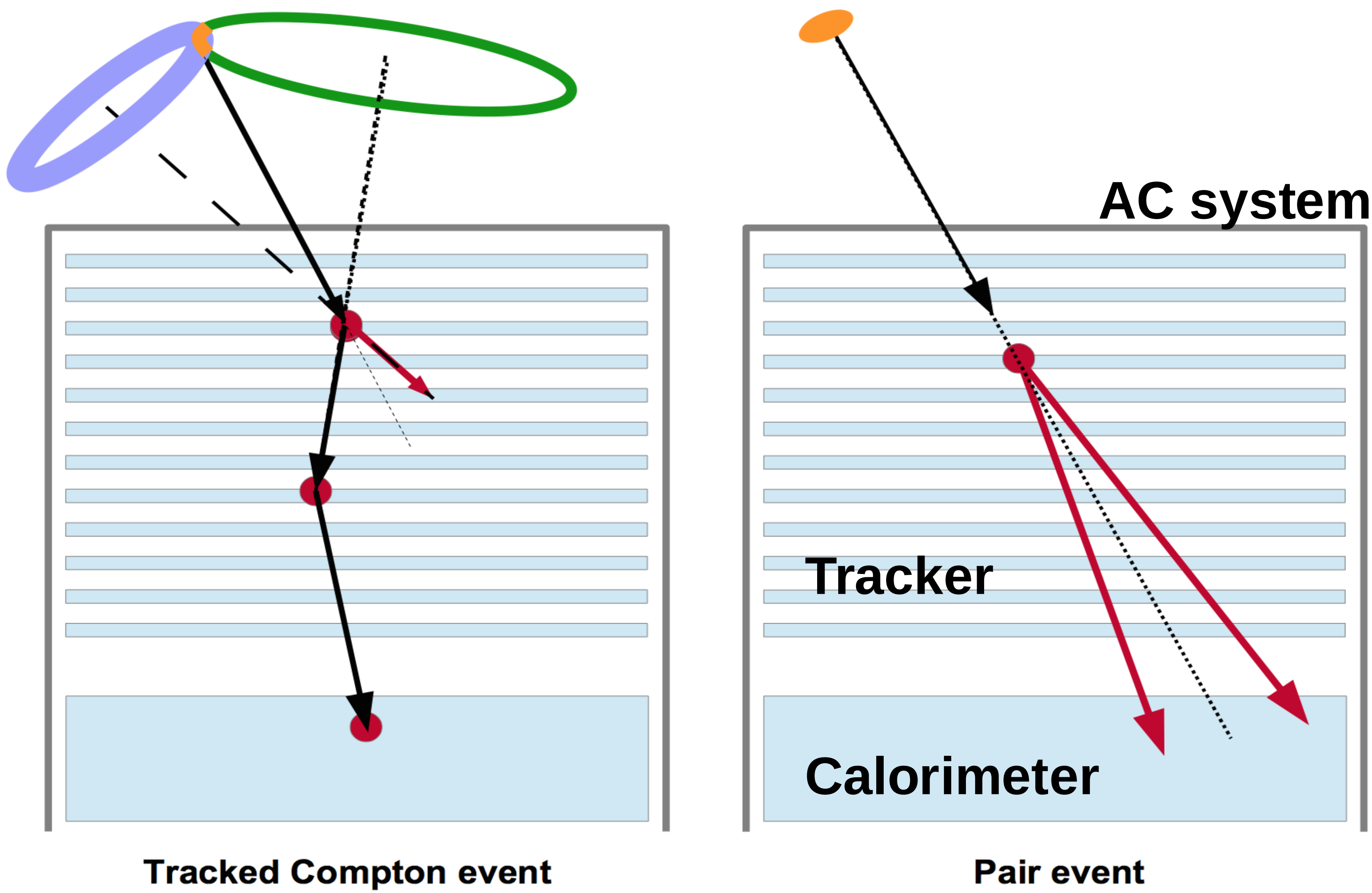
- a companion satellite similar to G-LIGHT can be accomodated.

G-LIGHT Simulation

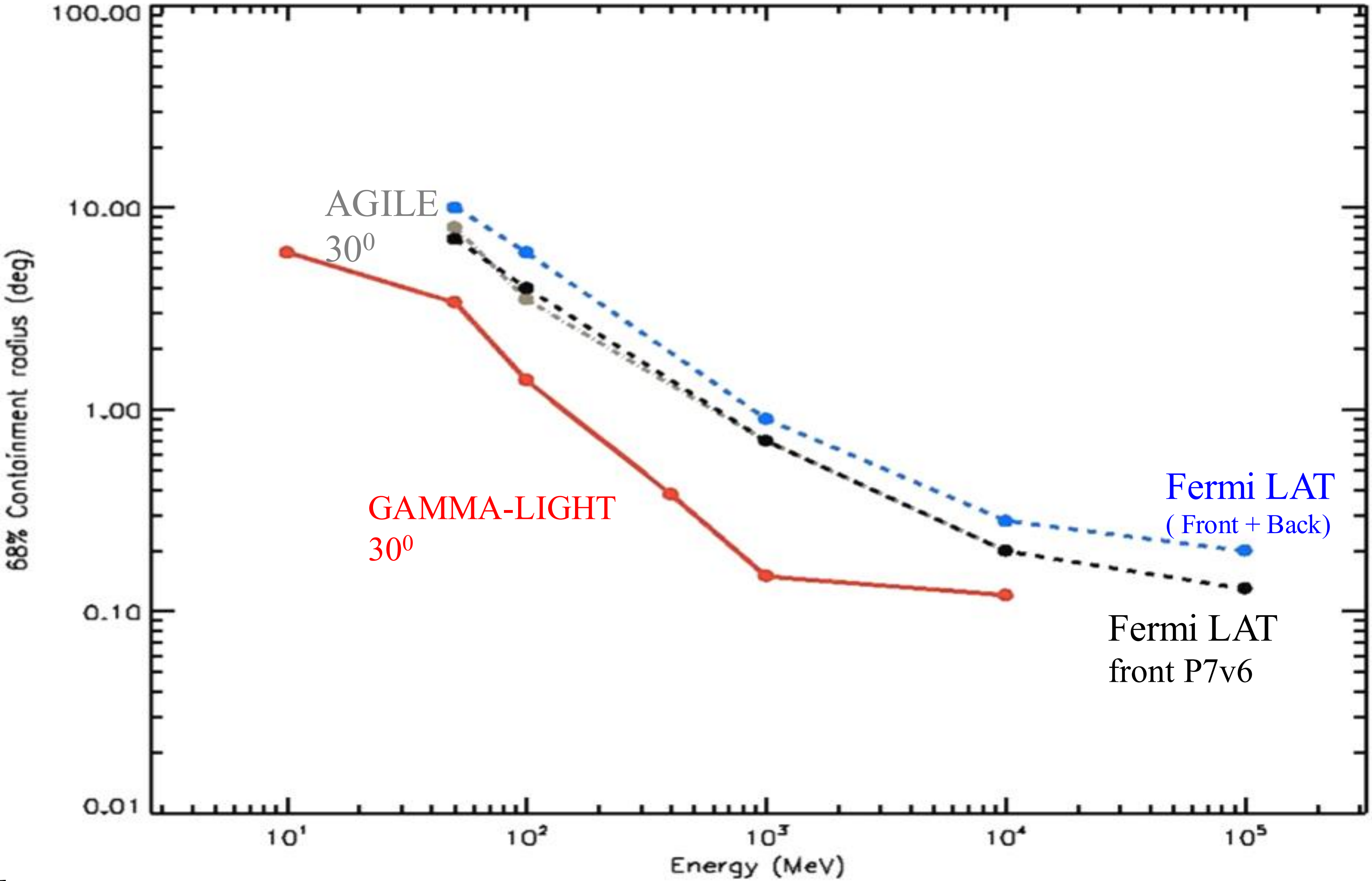
Compton interaction of a 10 MeV photon producing a low-energy single-track electron, and depositing energy in the Calorimeter for a 30^0 incidence



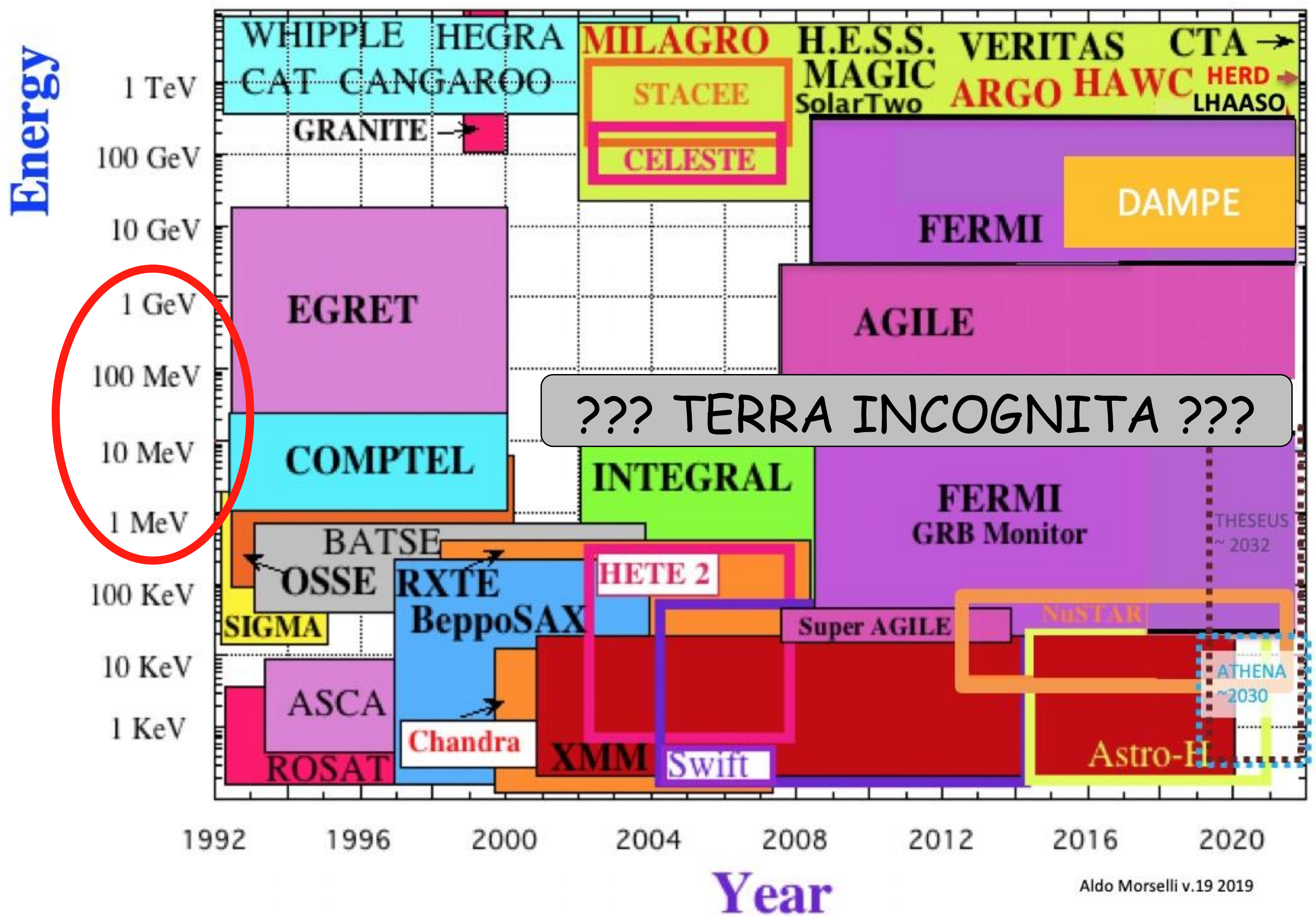
An instrument that combine two detection techniques



Gamma-Light Point Spread Function (angular resolution)



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


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
DAMPE
FERMI
EGRET
AGILE
??? TERRA INCOGNITA ???
COMPTEL
INTEGRAL
FERMI
GRB Monitor
THESEUS
~ 2032
BATSE
OSSE
RXTE
HETE 2
SIGMA
BeppoSAX
Super AGILE
NuSTAR
ATHENA
~2030
ASCA
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


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)

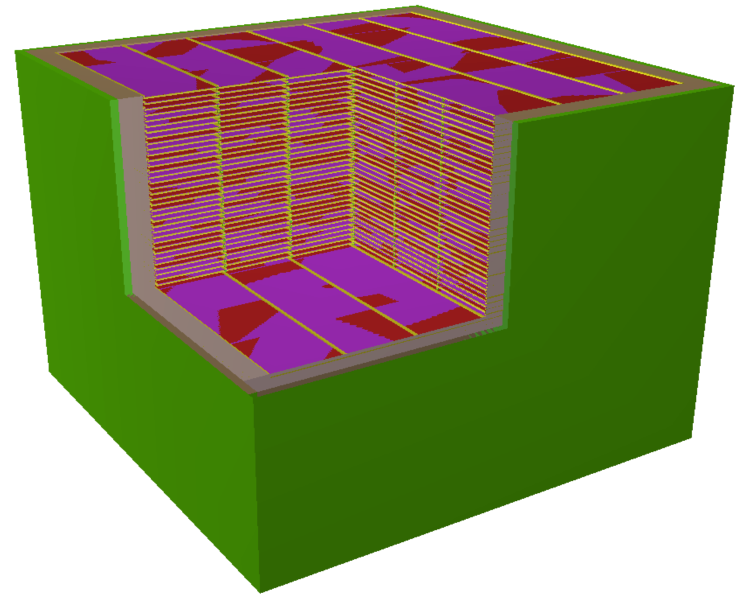
ASTROGAM Silicon Tracker

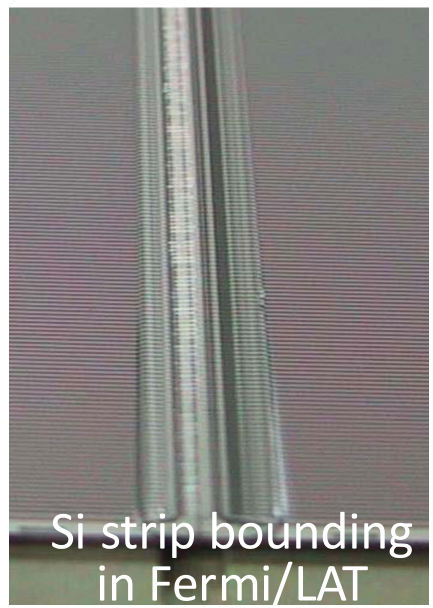
- 70 layers of 6 × 6 double sided Si strip detectors = 2520 DSSDs
- Each DSSD has a total area of 9.5 × 9.5 cm^2, a thickness of 400 μm, a strip width of 100 μm and pitch of 240 μm (384 strips per side), and a guard ring of 1.5 mm
- Spacing of the Si layers: 7.5 mm
- The DSSDs are wire bonded strip to strip to form 2-D ladders

⇒ 322 560 electronic channels

- DSSD strips connected to ASICs (32 channels each) through a pitch adapter (DC coupling)
- 144 ASICs (IDeF-X HD) per layer (72 per DSSD side)

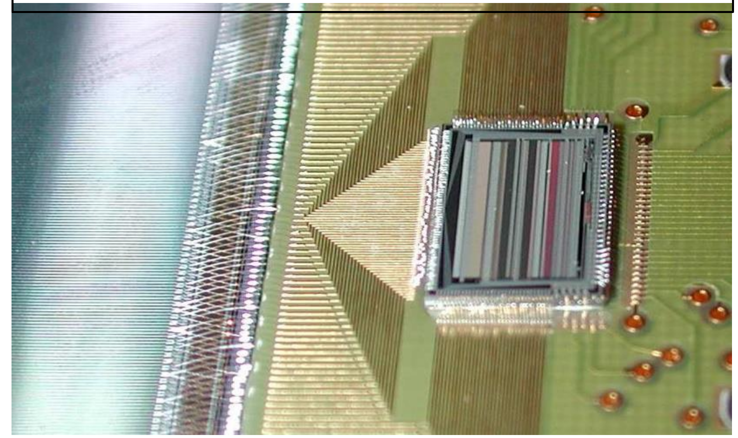
⇒ 10 080 ASICs total



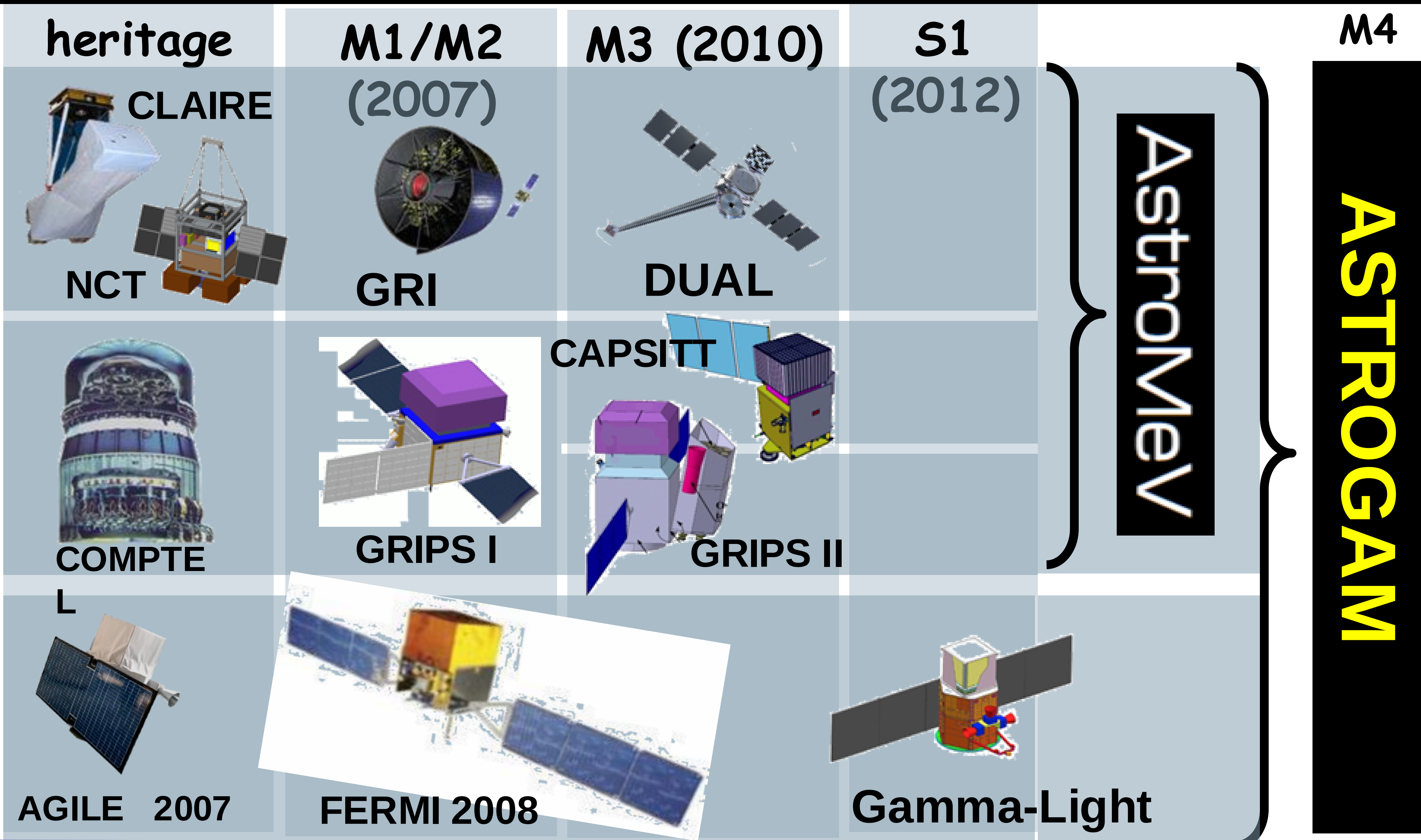


Si strip bounding in Fermi/LAT

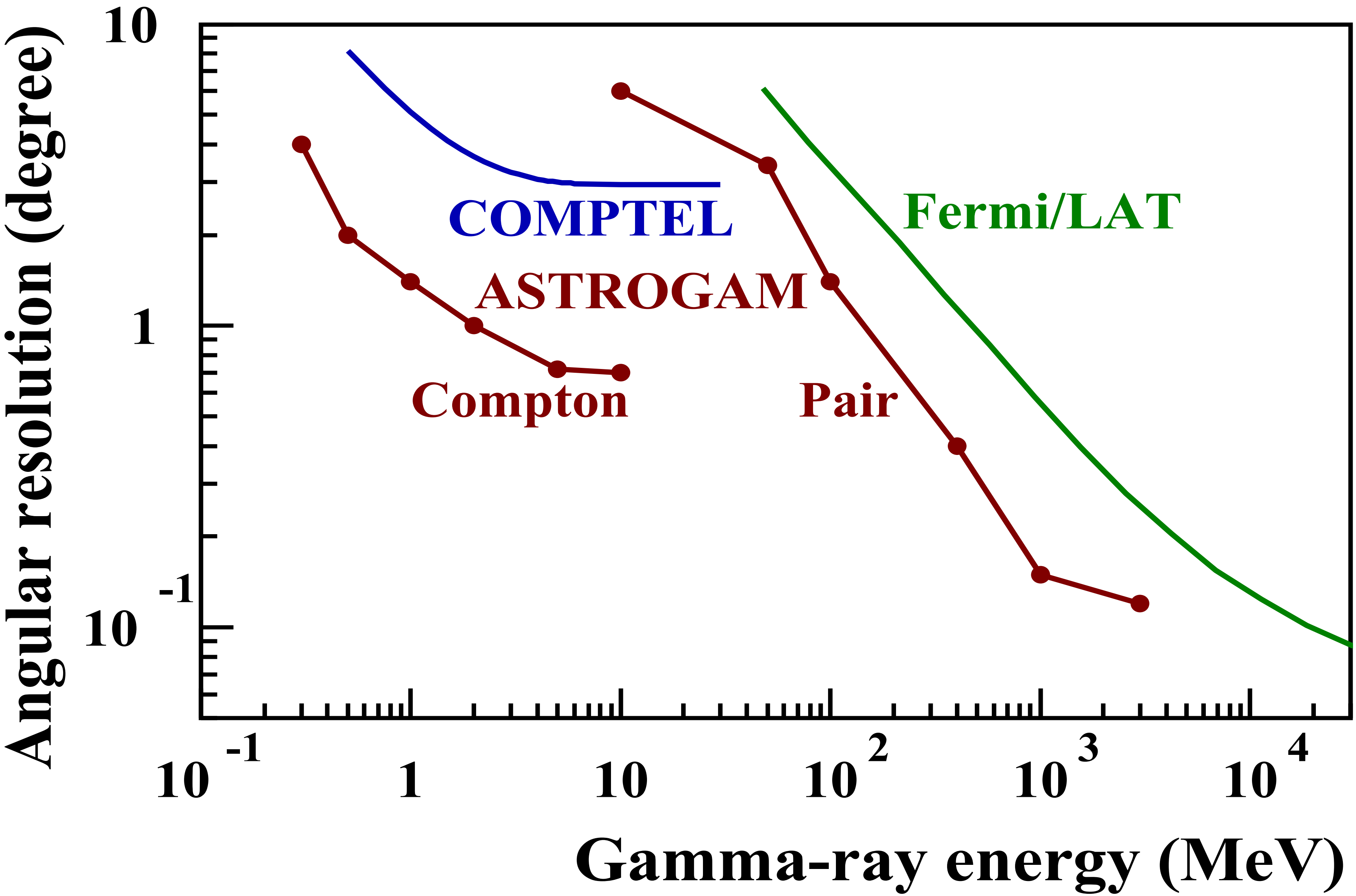
Detail of the detector-ASIC bonding in the AGILE Si Tracker



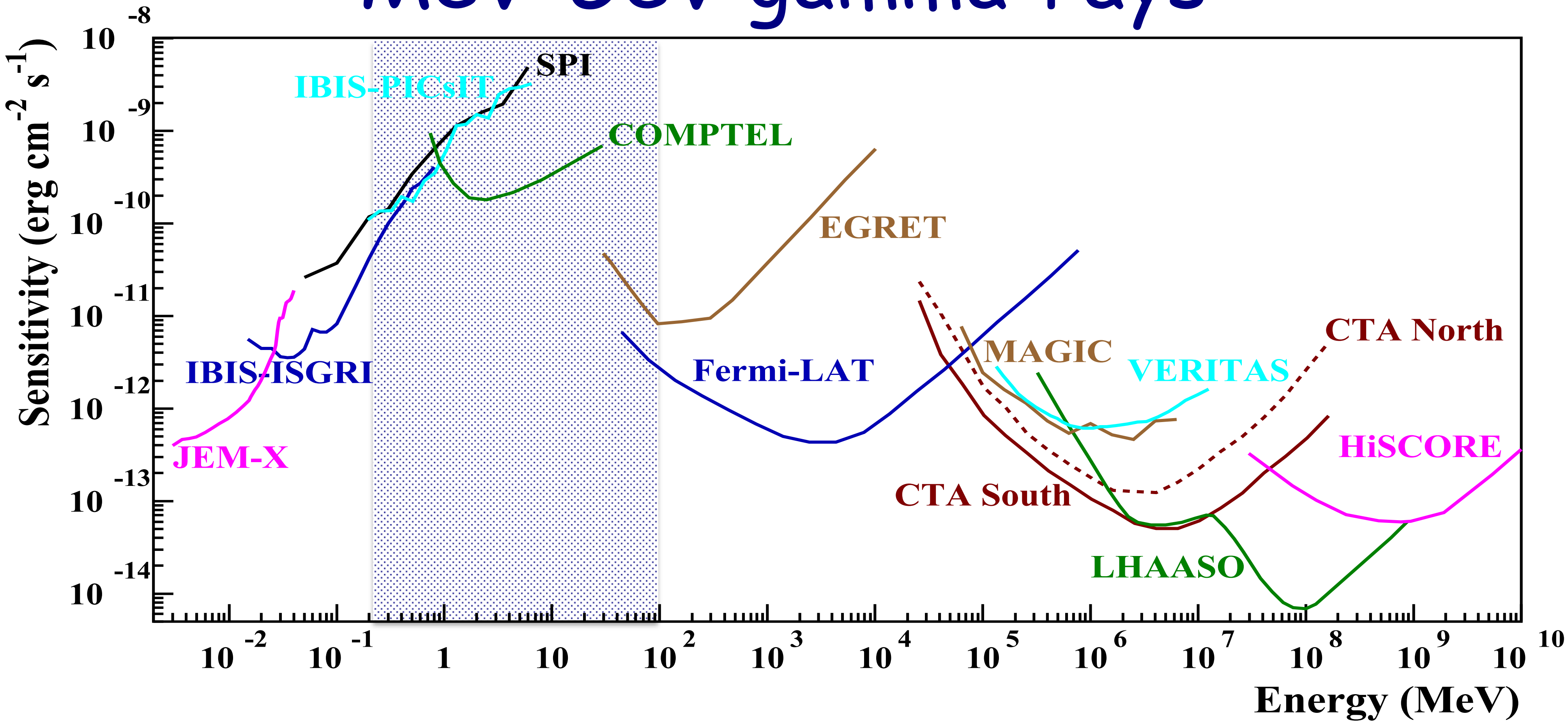
ASTROGAM a unified proposal from the entire gamma-ray community



ASTROGAM Angular Resolution

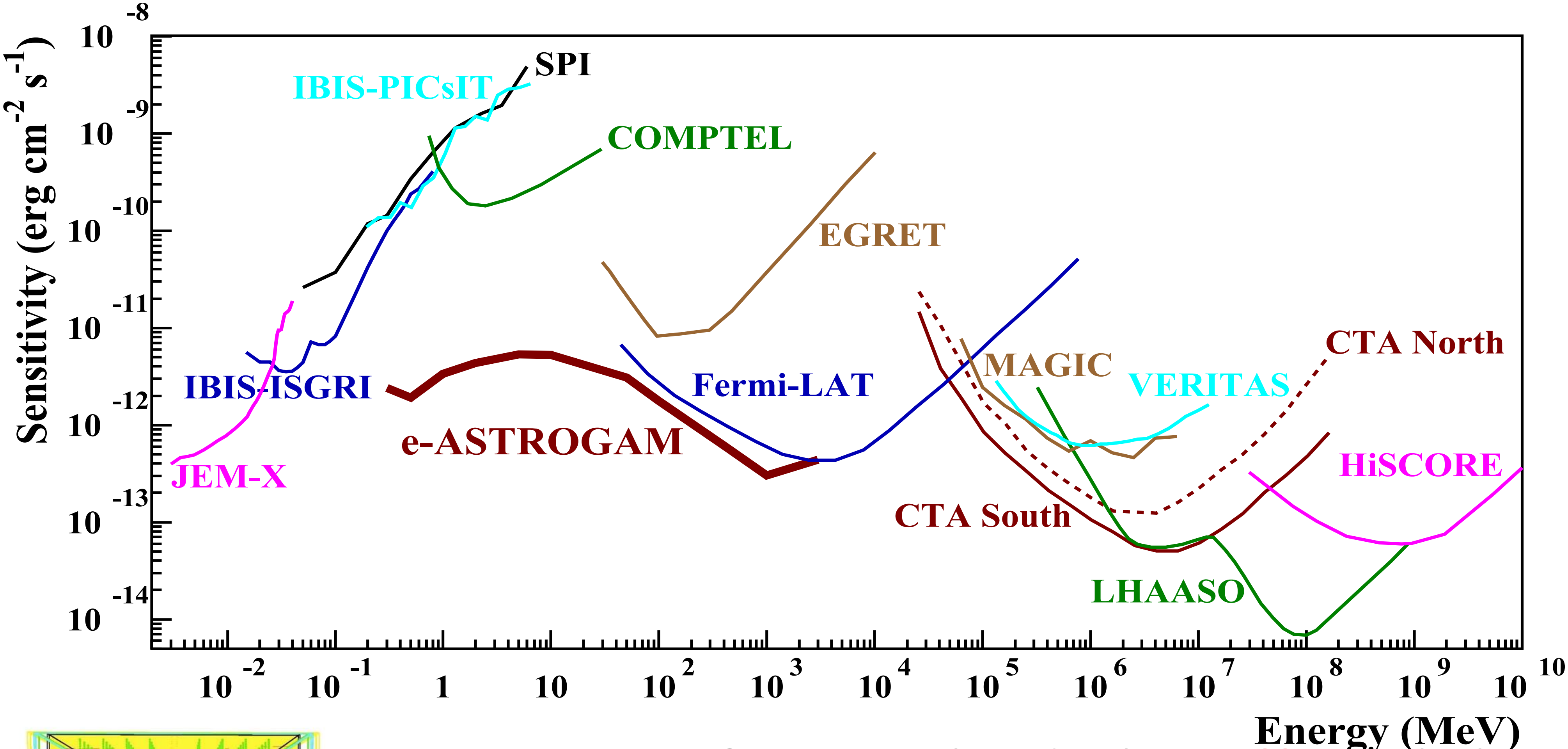


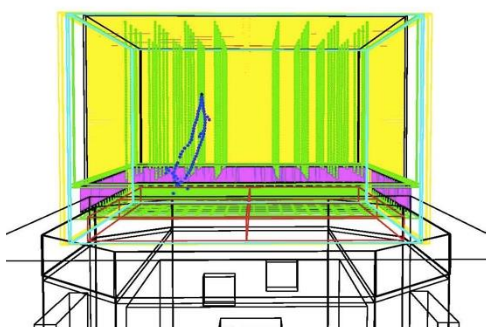
MeV-GeV gamma-rays



- Worst covered part of the electromagnetic spectrum in 0.1-100 MeV
- Many objects have their peak emissivity in this range (GRBs, blazars, pulsars...)
- The MeV range is the domain of nuclear gamma-ray lines (supernovae, nucleosynthesis and Galactic chemical evolution)

e-ASTROGAM Performance assessment



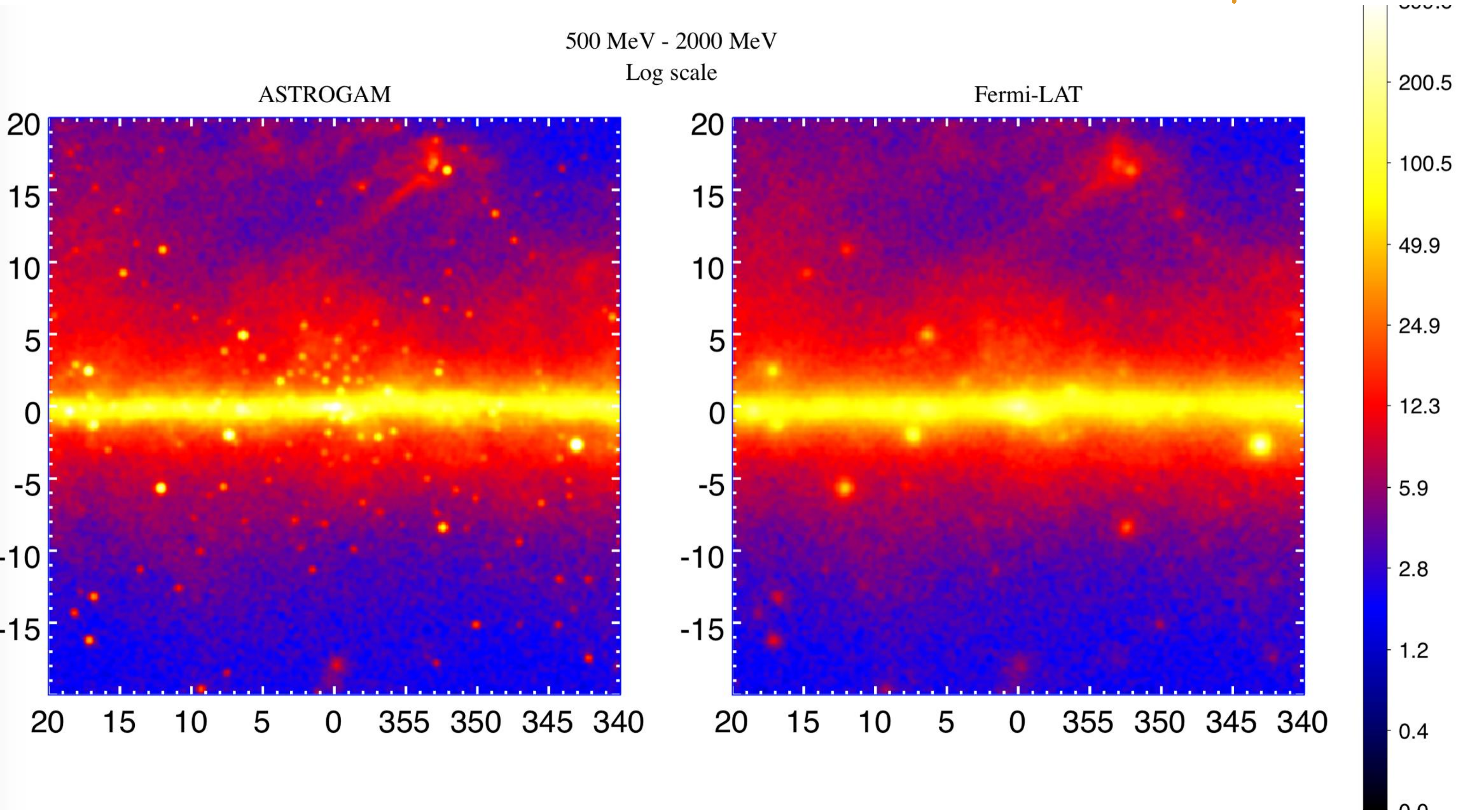


- e-ASTROGAM performance evaluated with **MEGAlib** and – both tools based on Geant4 – and a detailed numerical mass model of the gamma-ray instrument   e-Astrogam: arXiv:1611.02232

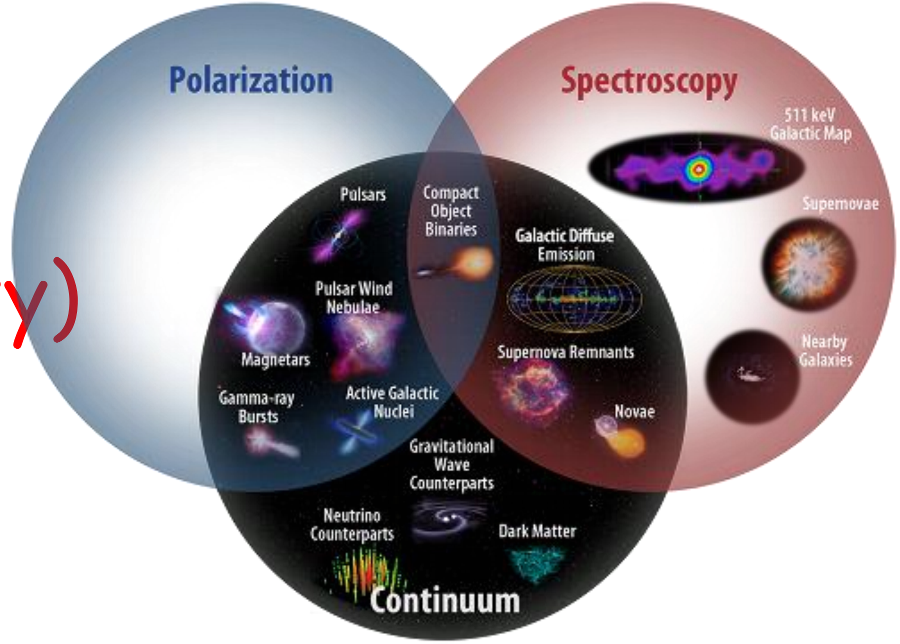
we are now preparing a proposal for ESA M8 in 2025

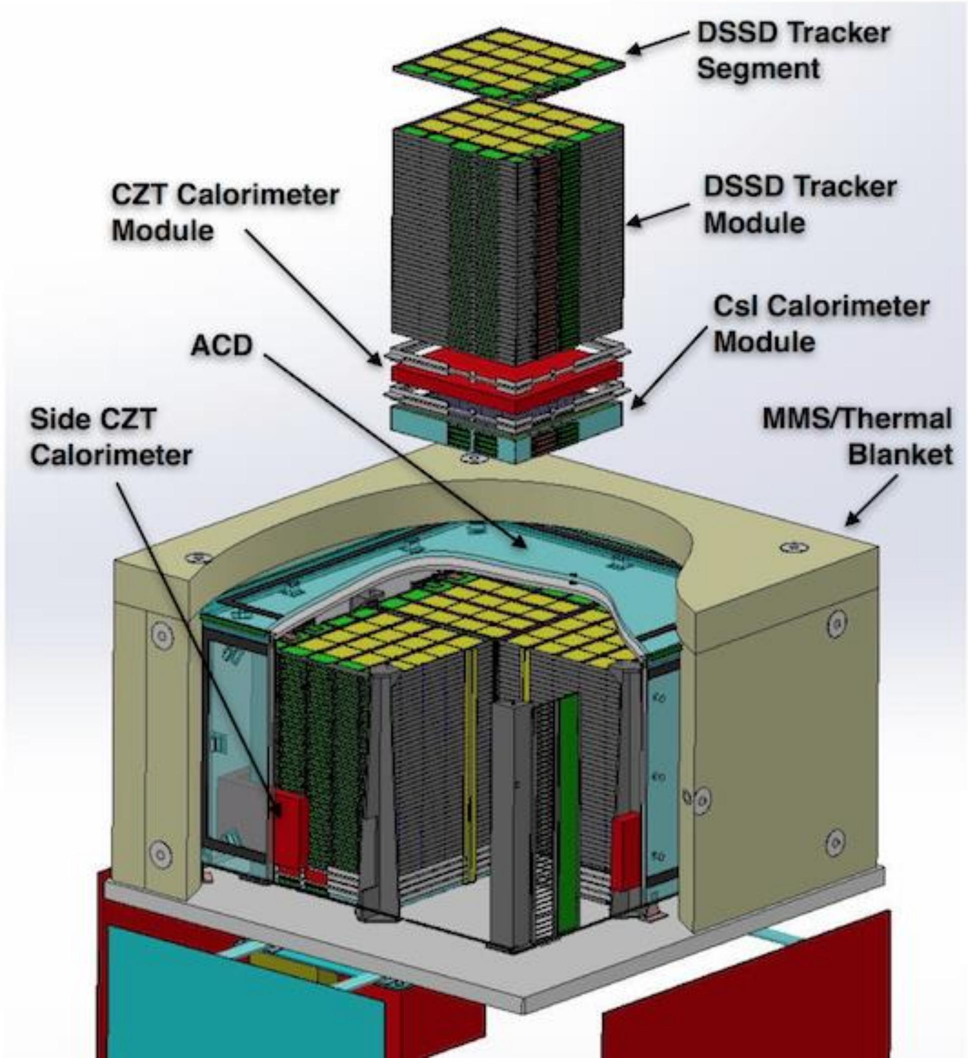
Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source



Our sister experiment: AMEGO (NASA)
(two brands, one community)

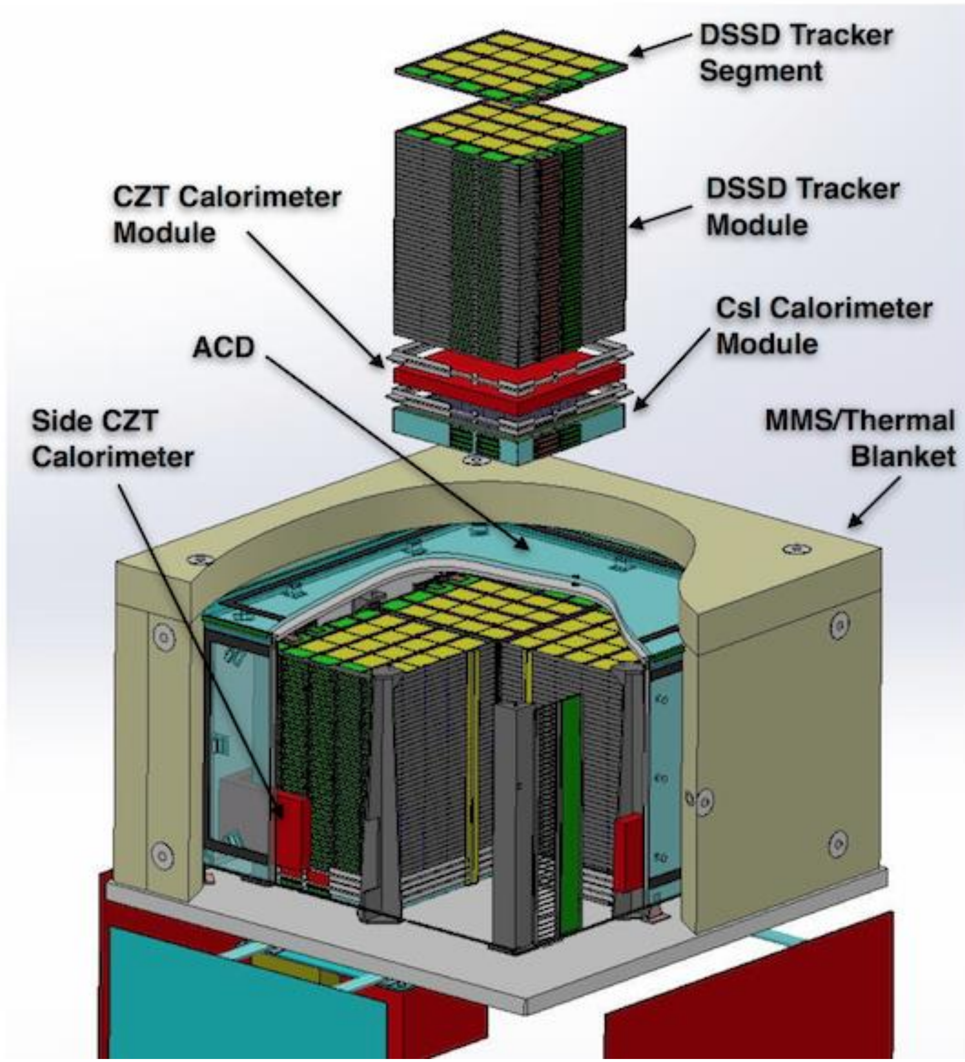




- ~20% smaller tracker
- CZT calorimeter layer

Status and Plans :
Resubmit in the next MIDEX round (~2027)

Our sister experiment: AMEGO (NASA)

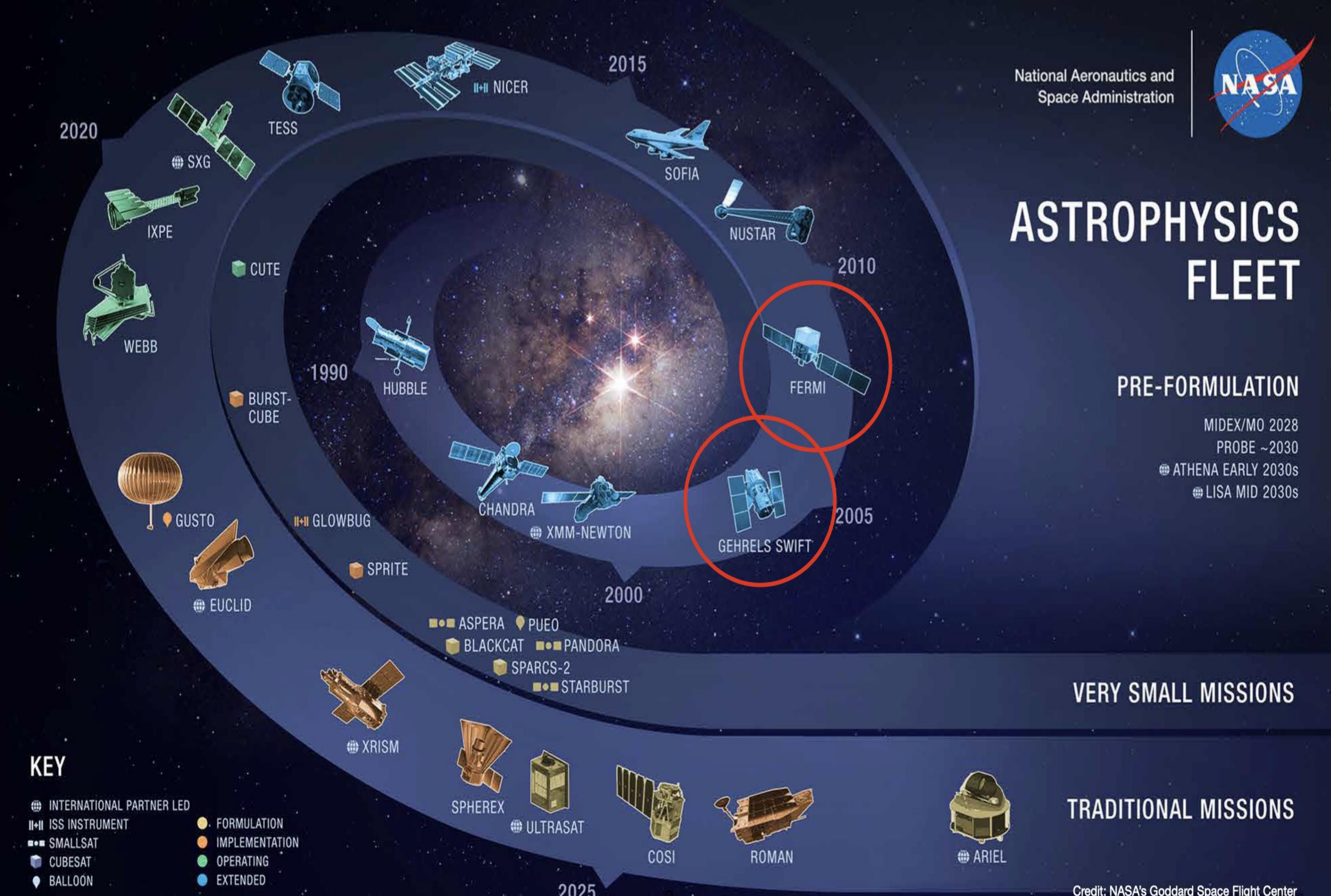


Status and Plans :
Resubmit in the next MIDEX round (~2027)

in the meantime:

Advocate to NASA via the Physics of the Cosmos Program Analysis Group (PhysPAG). This is NASA's link to the community.

- Science gaps: https://pcos.gsfc.nasa.gov/physpag/science-gaps/science-gaps.php
- Technology gaps: https://pcos.gsfc.nasa.gov/news/2024/6_Technology_Gaps_Submissions_Due.php
- Join the Gamma-ray Science Interest Group (GammaSIG)
- https://pcos.gsfc.nasa.gov/sigs/grsig.php



Updated June 2022

COSI The Compton Spectrometer and Imager

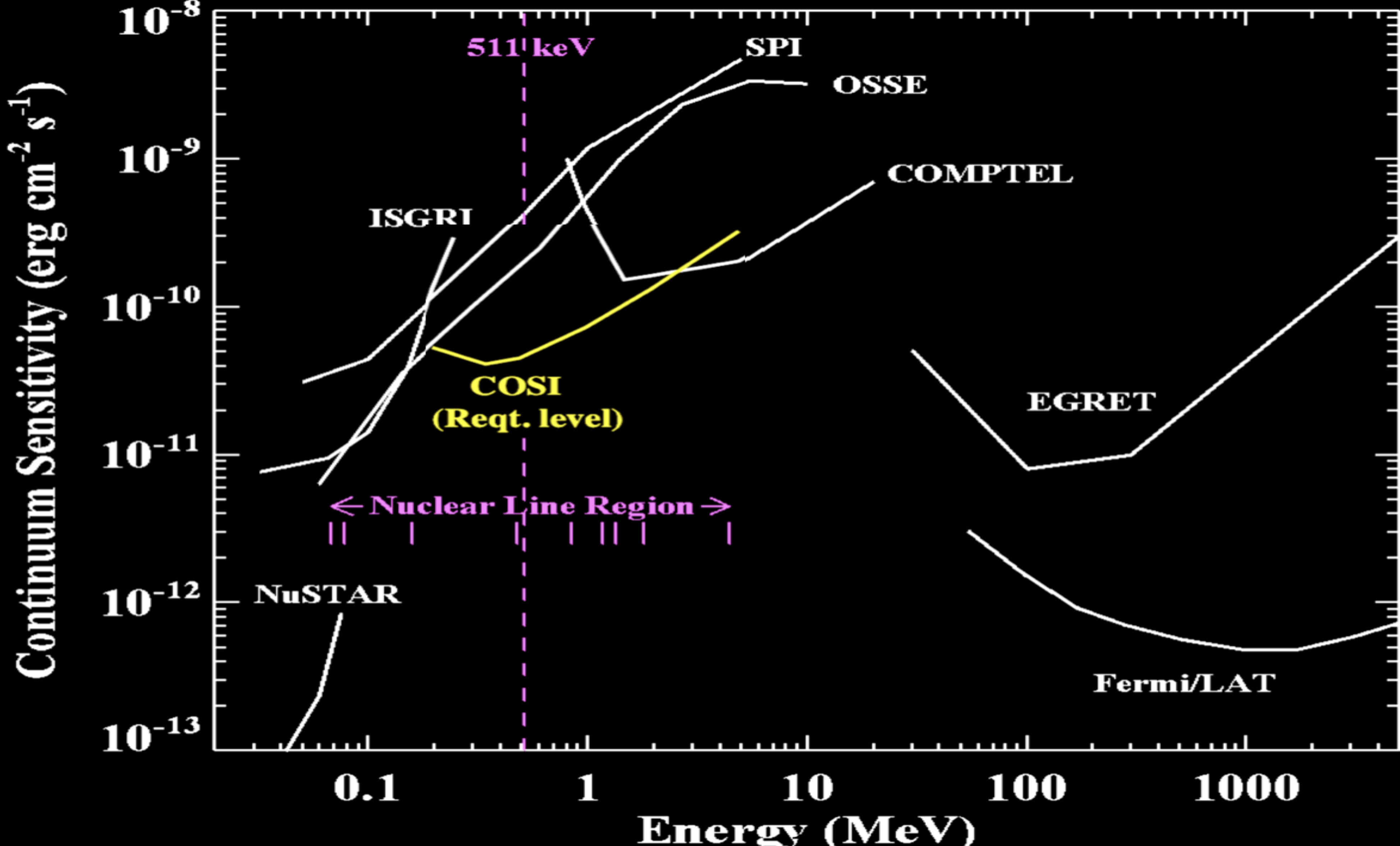
- COSI has been selected by NASA as a SMEX to launch in 2027

- a Compton telescope for observing 0.2-5 MeV gamma-rays

1. Key capabilities
   - Uses cryogenically-cooled germanium detectors (GeDs) to provide energy resolution (~1%)
   - Instantaneous field of view is >25%-sky and covers the whole sky every day

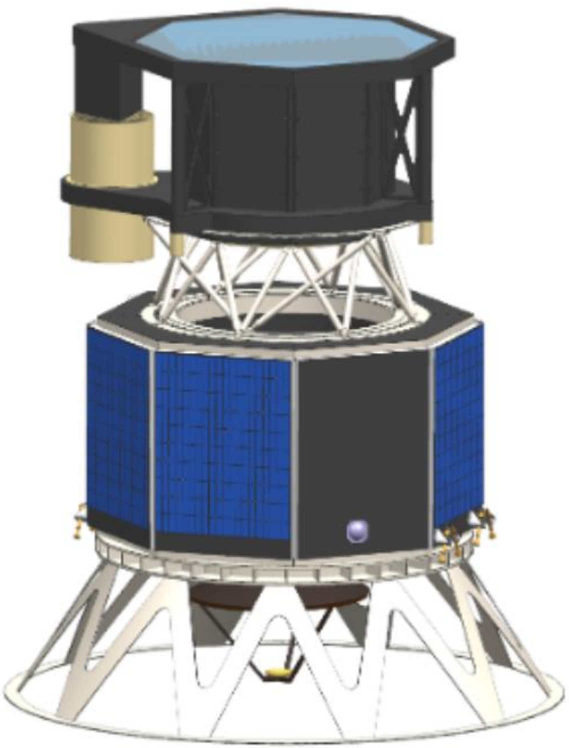
- Goal D emphasizes the connection to gravitational waves
- ▪Detects short gamma-ray bursts (GRBs) from merging neutron stars
  ▪Localizations to ~1° accuracy
  ▪Public alerts in <1 hour

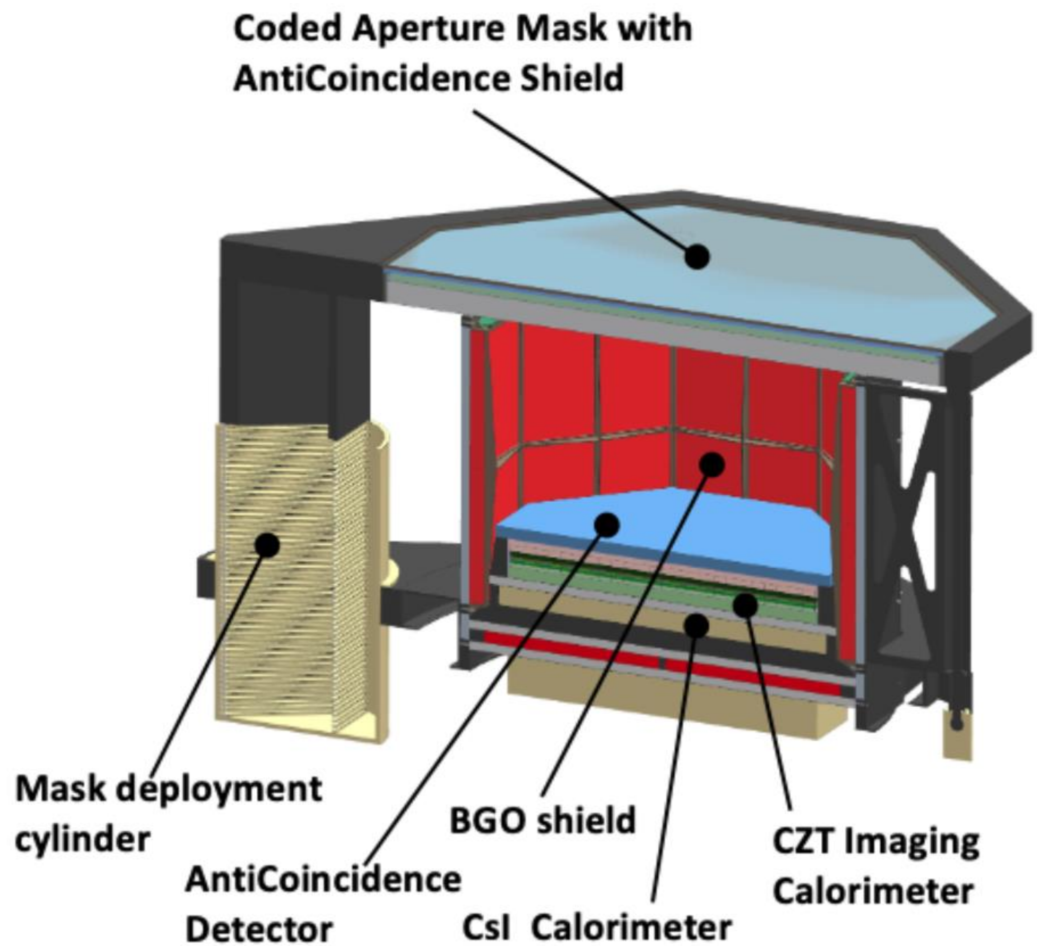
COSI



continuum emission sensitivity

GECCO The Galactic Explorer with a Coded Aperture Mask Compton Telescope

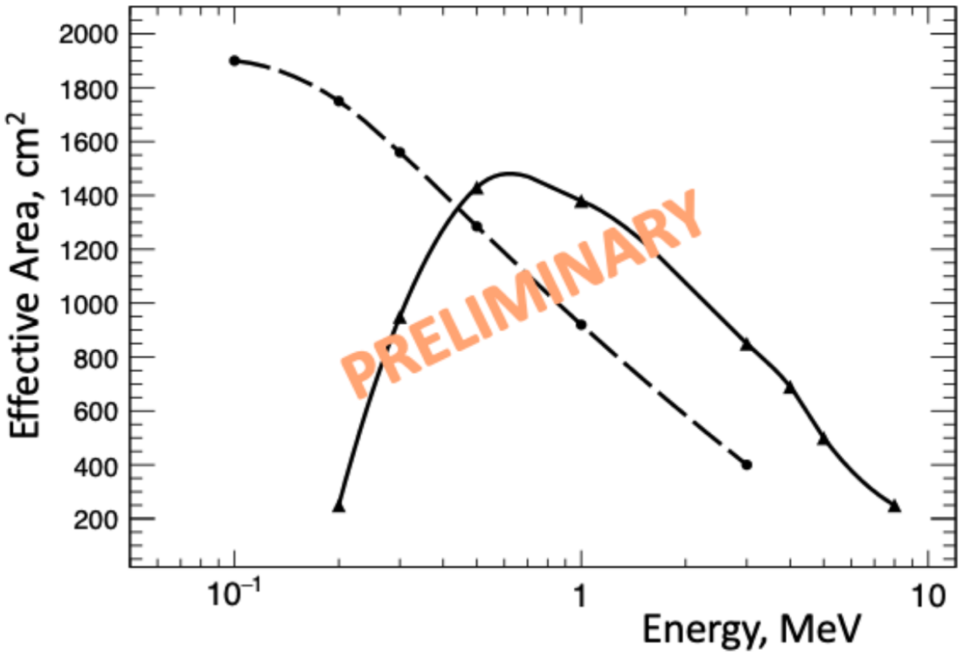




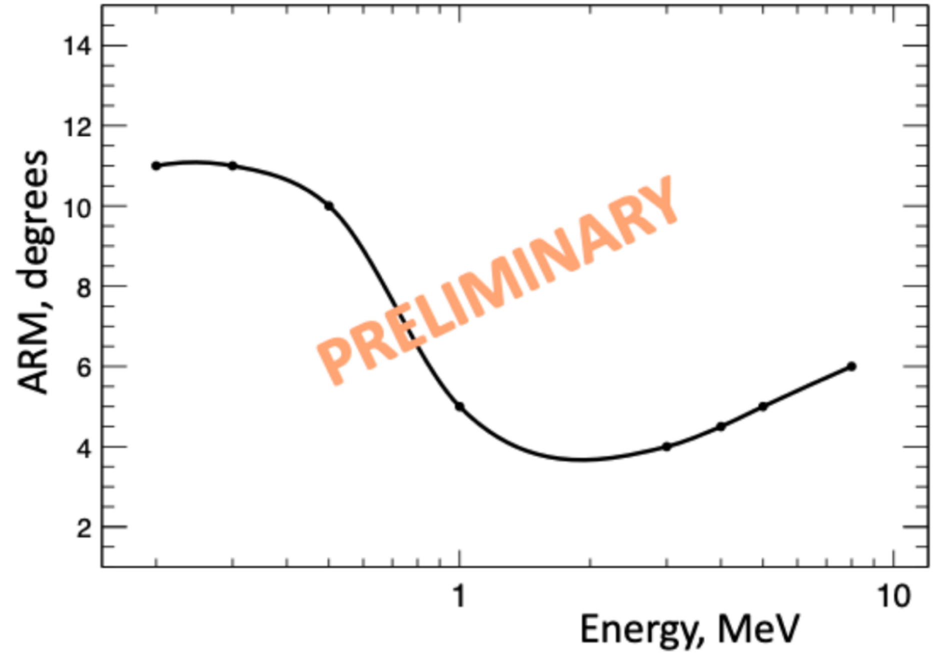
conceptual design mask in stowed position cutaway diameter =90 cm

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.

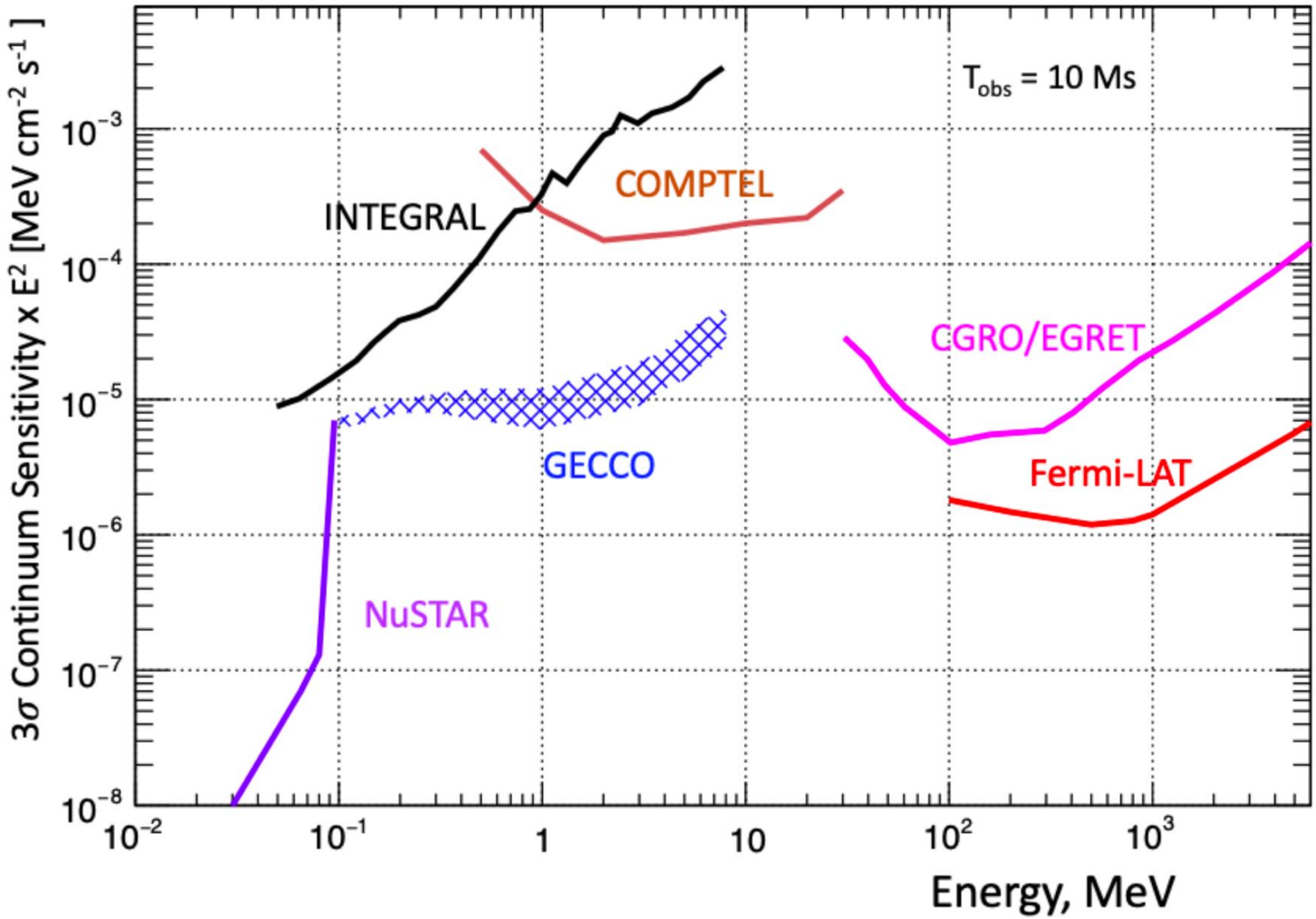


ARM (angular resolution measure) for the ImCal standalone Compton telescope.

GECCO Team, in preparation

GECCO The Galactic Explorer with a Coded Aperture Mask Compton Telescope

Sensitivity



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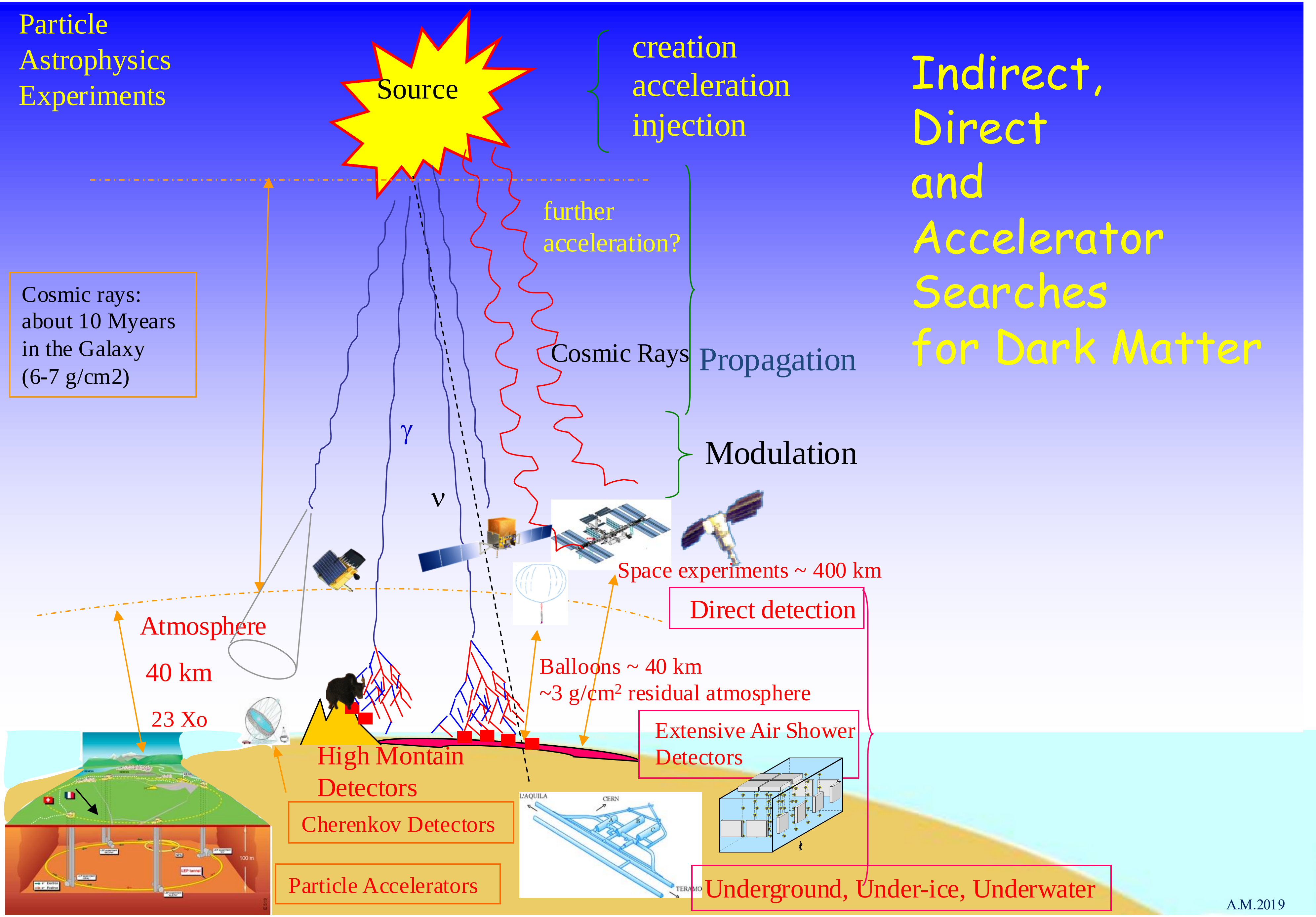
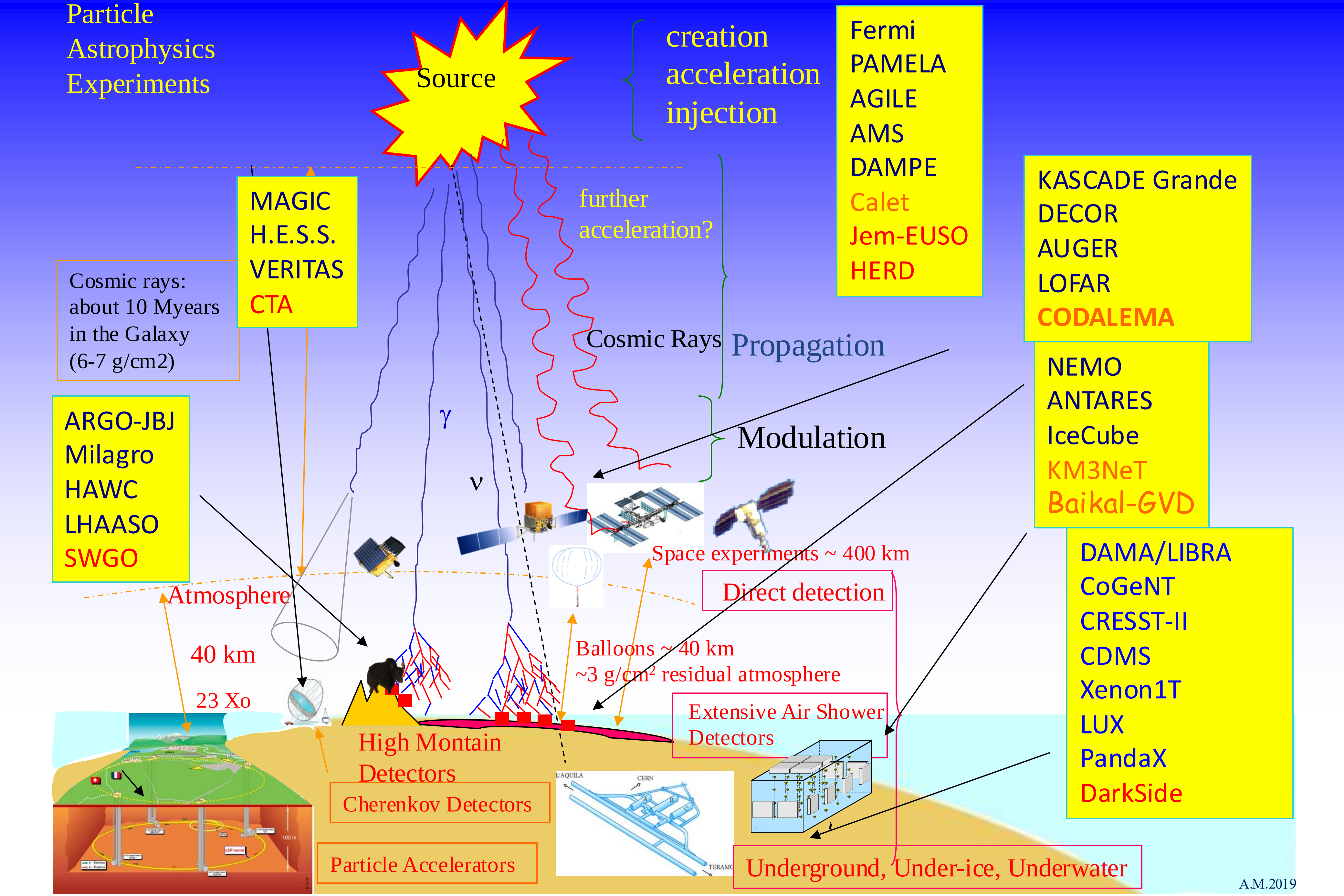
Summary

- Indirect search of Dark Matter with gamma rays is complementary to all other research in the underground laboratories and at LHC
- CTA, SWGO and LHAASO can explore the high -energy domain
- Fermi is still in orbit but we need a new mission with a focus in the low energy range (below 100 MeV)

- We are preparing a new proposal to ESA for M8 mission

Indirect, Direct and Accelerator Searches for Dark Matter




Particle Astrophysics Experiments
Source
creation
acceleration
injection
Fermi
PAMELA
AGILE
AMS
DAMPE
Calet
Jem-EUSO
HERD
KASCADE Grande
DECOR
AUGER
LOFAR
CODALEMA
MAGIC
H.E.S.S.
VERITAS
CTA
further acceleration?
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
ν
Modulation
Space experiments ~ 400 km
Direct detection
DAMA/LIBRA
CoGeNT
CRESST-II
CDMS
Xenon1T
LUX
PandaX
DarkSide
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
Underground, Under-ice, Underwater
A.M.2019