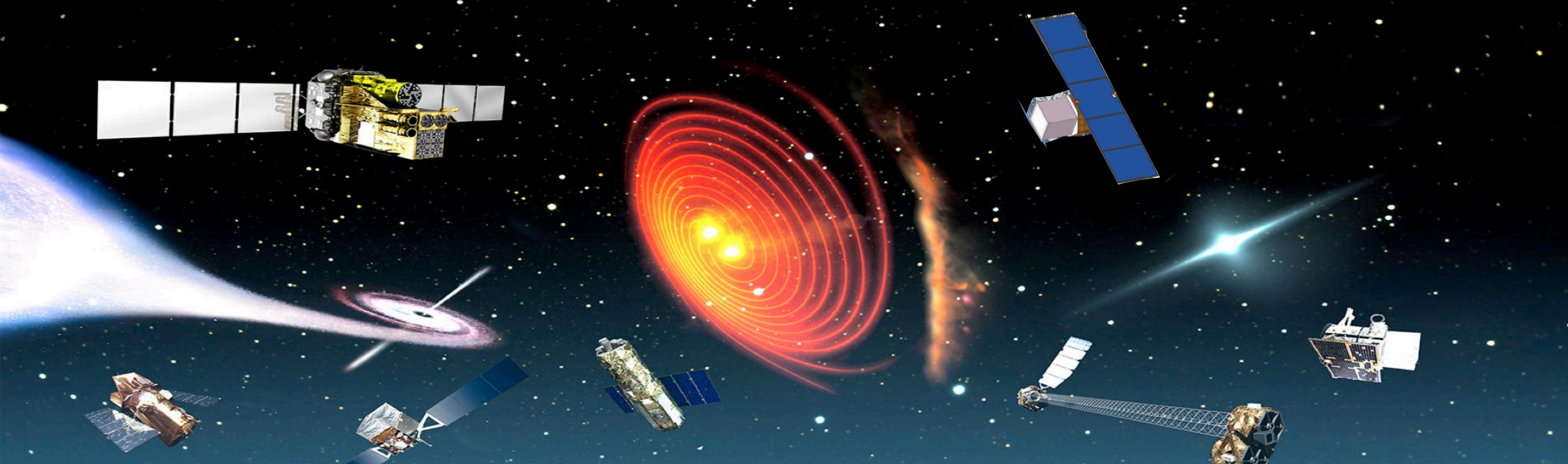
Indirect dark-matter searches with gamma-rays: experiments status and future plans from KeV to TeV



Aldo Morselli
INFN Roma Tor Vergata

Dark Side of the Universe 2016
University of Bergen
25-29 July 2016

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**

....

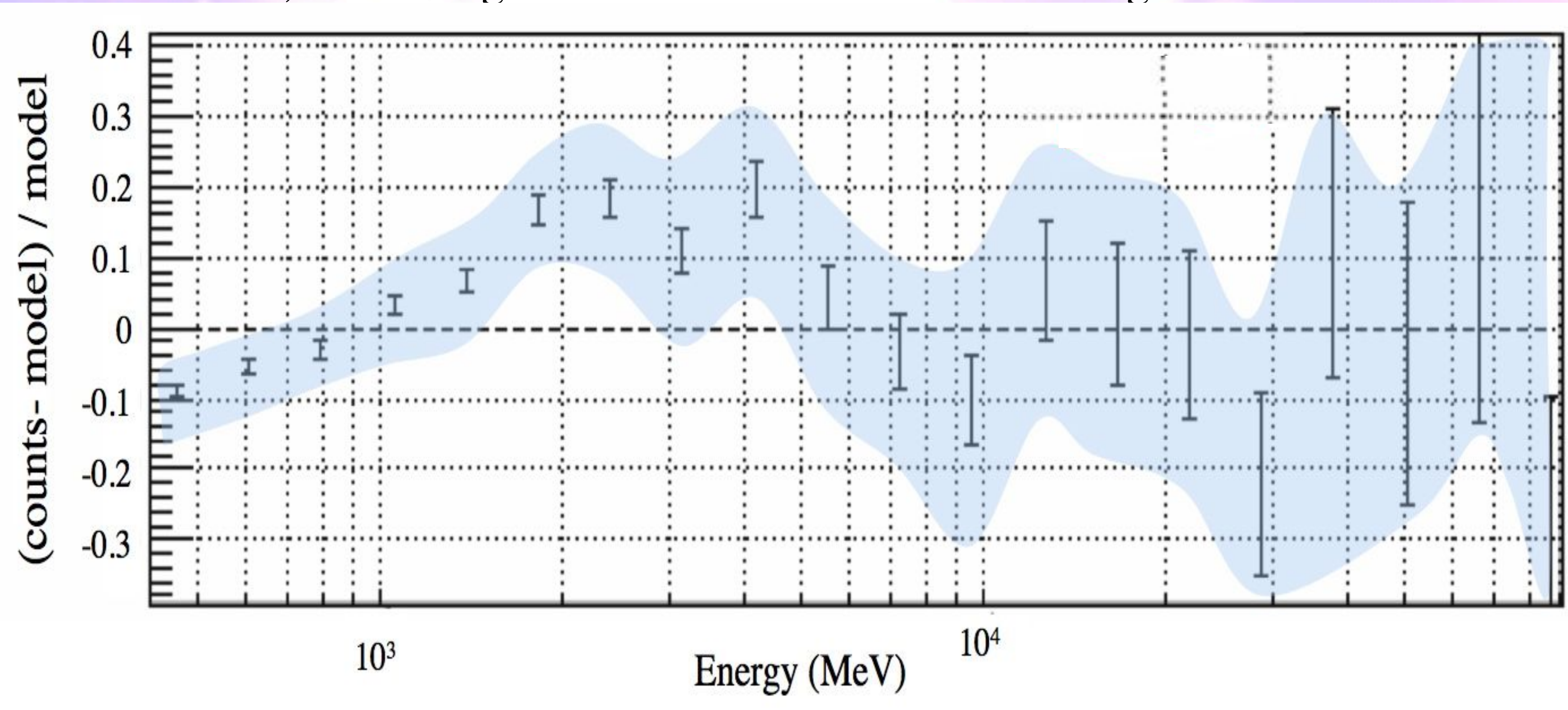
Background model systematics for the Fermi GeV excess
F.Calore, I. Cholis, C. Weniger JCAP03(2015)038 **arXiv:1409.0042v1**

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**
(using Pass7, Pass8 analysis in progress)

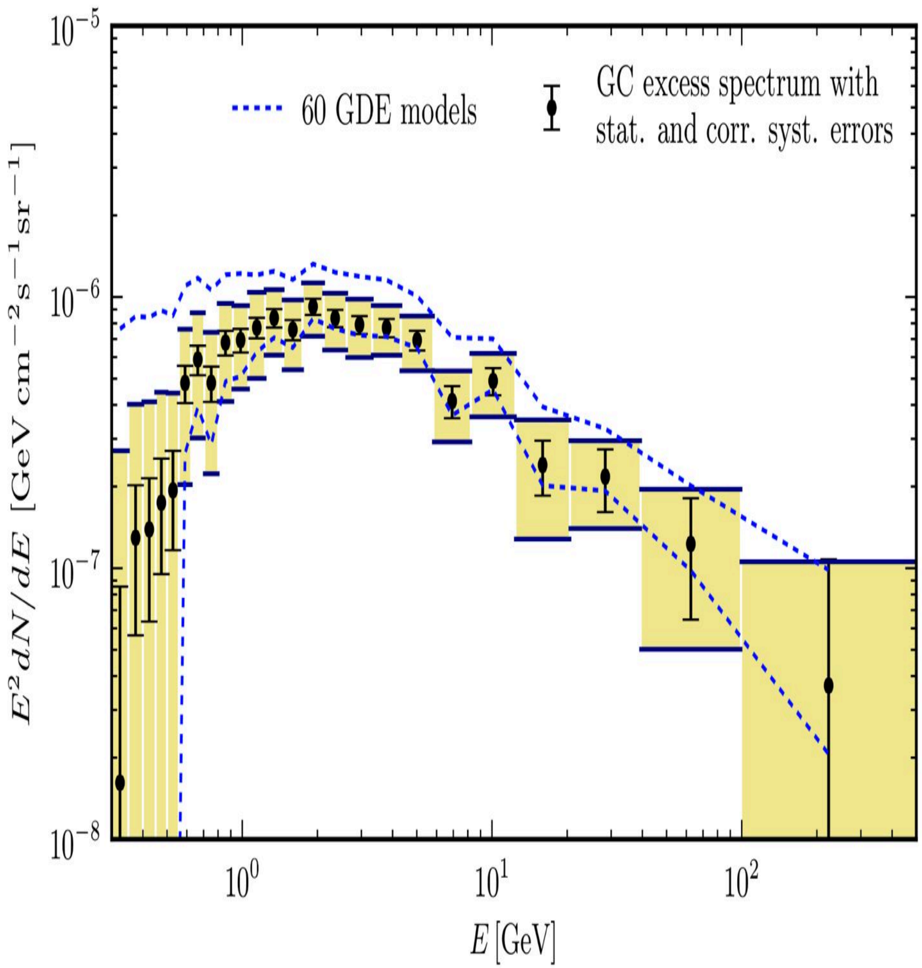
The GeV excess 7°x7°region centered on the Galactic Center

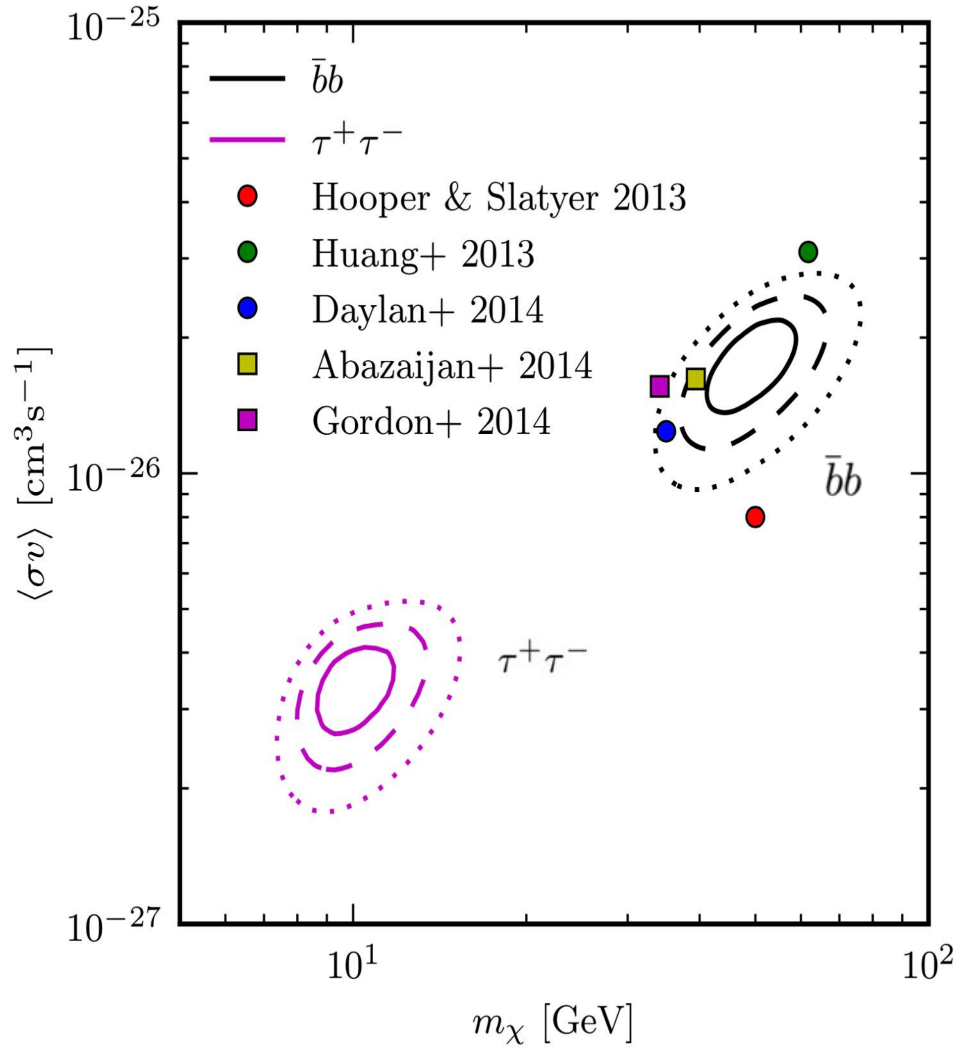
11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

- 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



The GeV excess





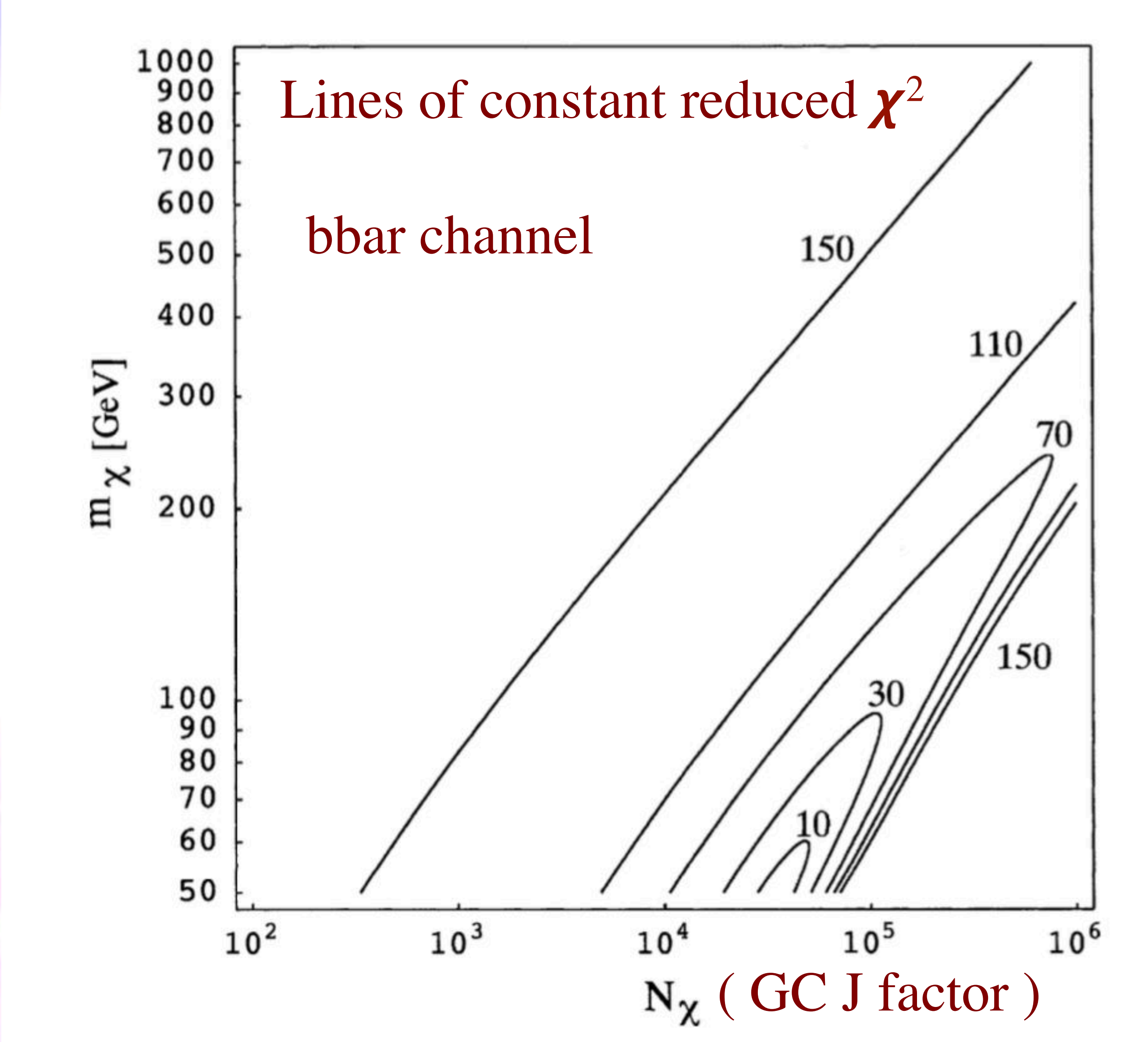
A lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center

i.e. Calore et al, arXiv:1409.0042v1

Lines of constant reduced χ^2 corresponding to best fits of the EGRET GC excess

Very similar to the mass range found with the EGRET data in 2004 !

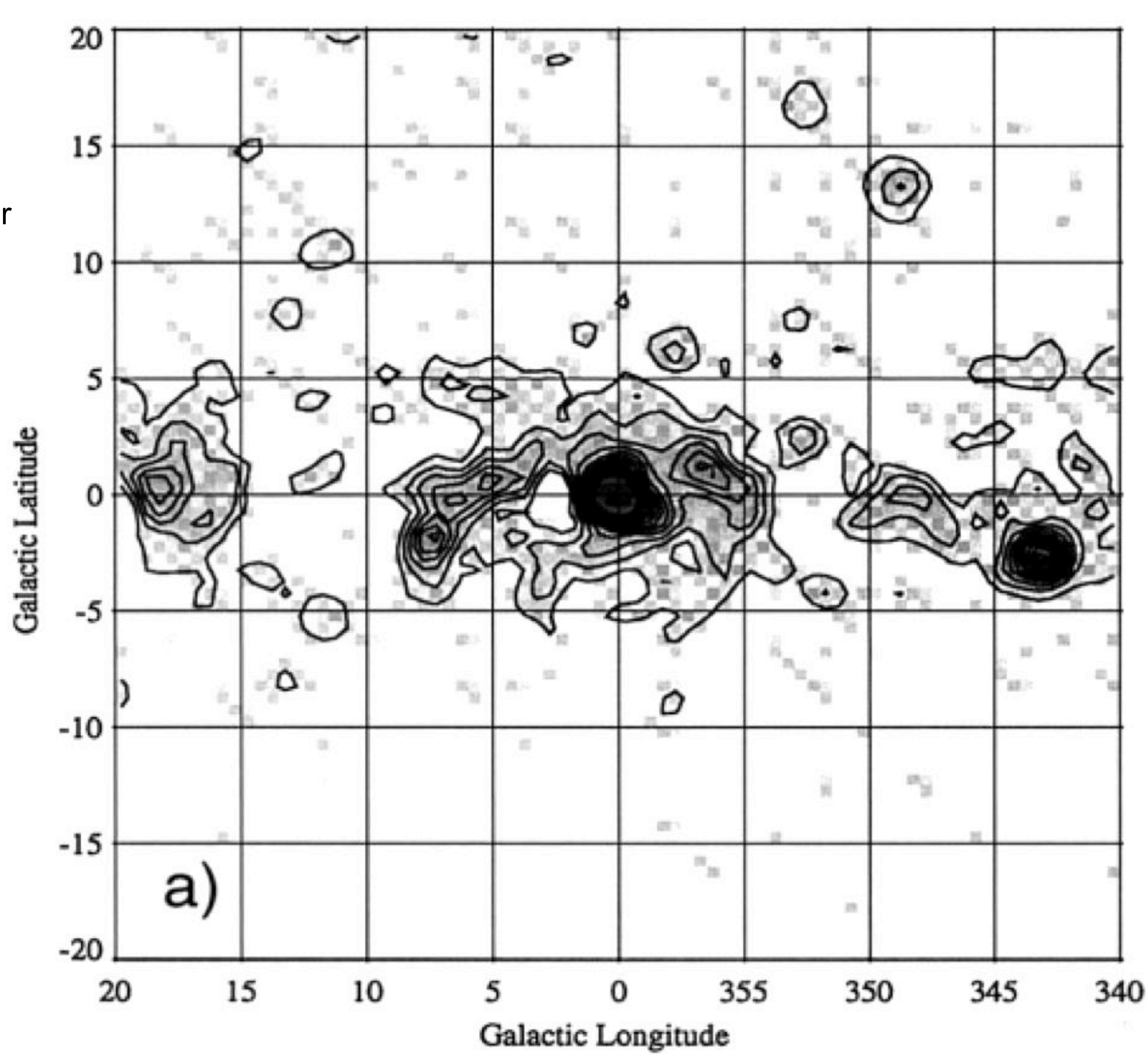
mass ~ 50- 80 GeV



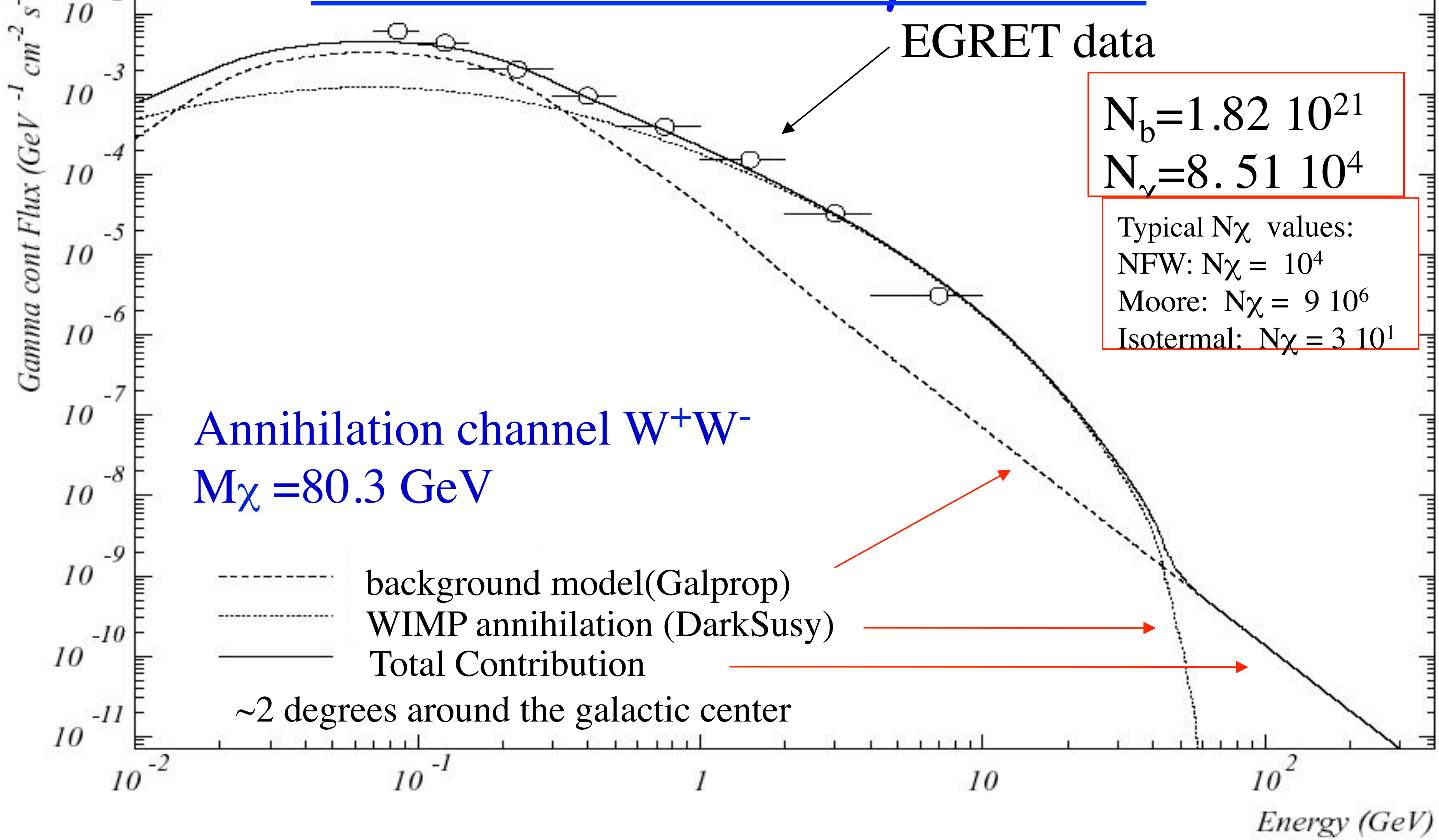
A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

EGRET, E > 1GeV

Mayer-Hasselwander et al, 1998



EGRET data & Susy models



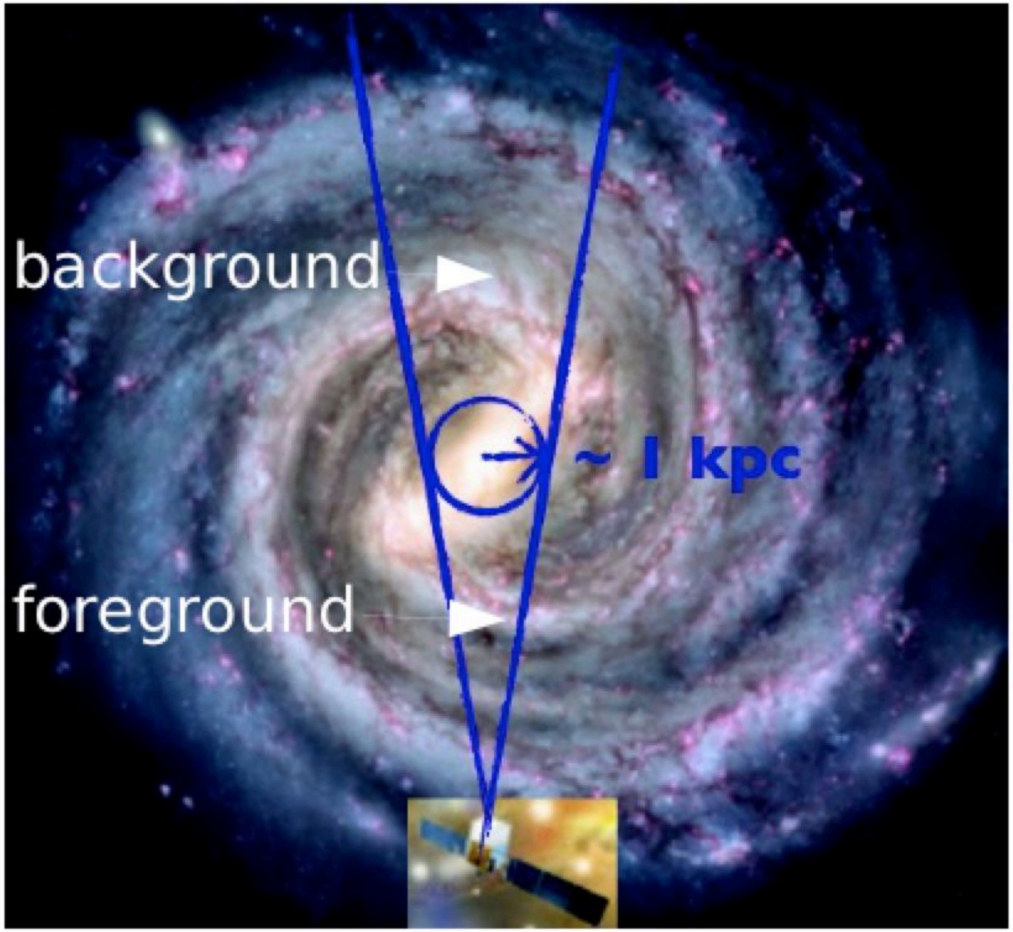
A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, Nucl. Phys. B 113B (2002) 213-220 [astro-ph/0211327]

The Galactic Center with Fermi-LAT

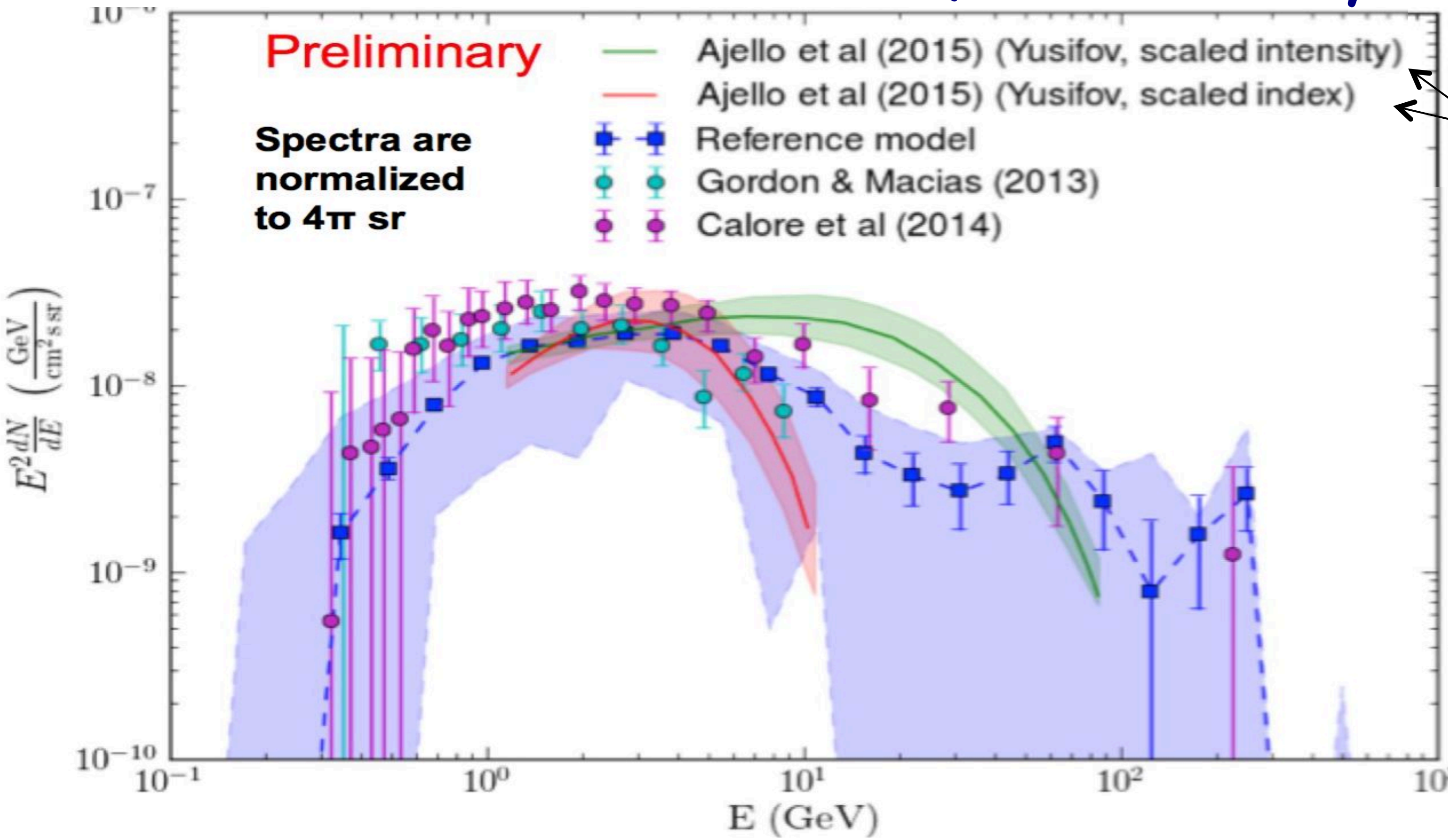
Fore/background modeling is critical to studying IG
- ~80% of the emission (1-100 GeV) in the line of sight is from fore/background

LAT counts = sum of:

- Galactic Center diffuse emission
  - Interaction of Cosmic Rays (density?) with gas (distribution?) and interstellar radiation fields (intensity?
- Foreground/background (all-sky analysis)
  - Interaction of Cosmic Rays with gas and interstellar radiation fields
- Individual sources (~catalog analysis)
- Additional components ?



The GeV excess (Pass8 analysis)



M. Ajello et al.
[Fermi-LAT Coll.]
Apj 819:44 2016
arXiv:1511.02938

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

D. Malyshev al.[Fermi-LAT Collaboration] **Fermi Symposium 2015**

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)

- Population of millisecond Pulsars around the Galactic Center

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

See Weniger's talk

- Series of Leptonic Cosmic-Ray Outbursts

Cholis et al. arXiv:1506.05119

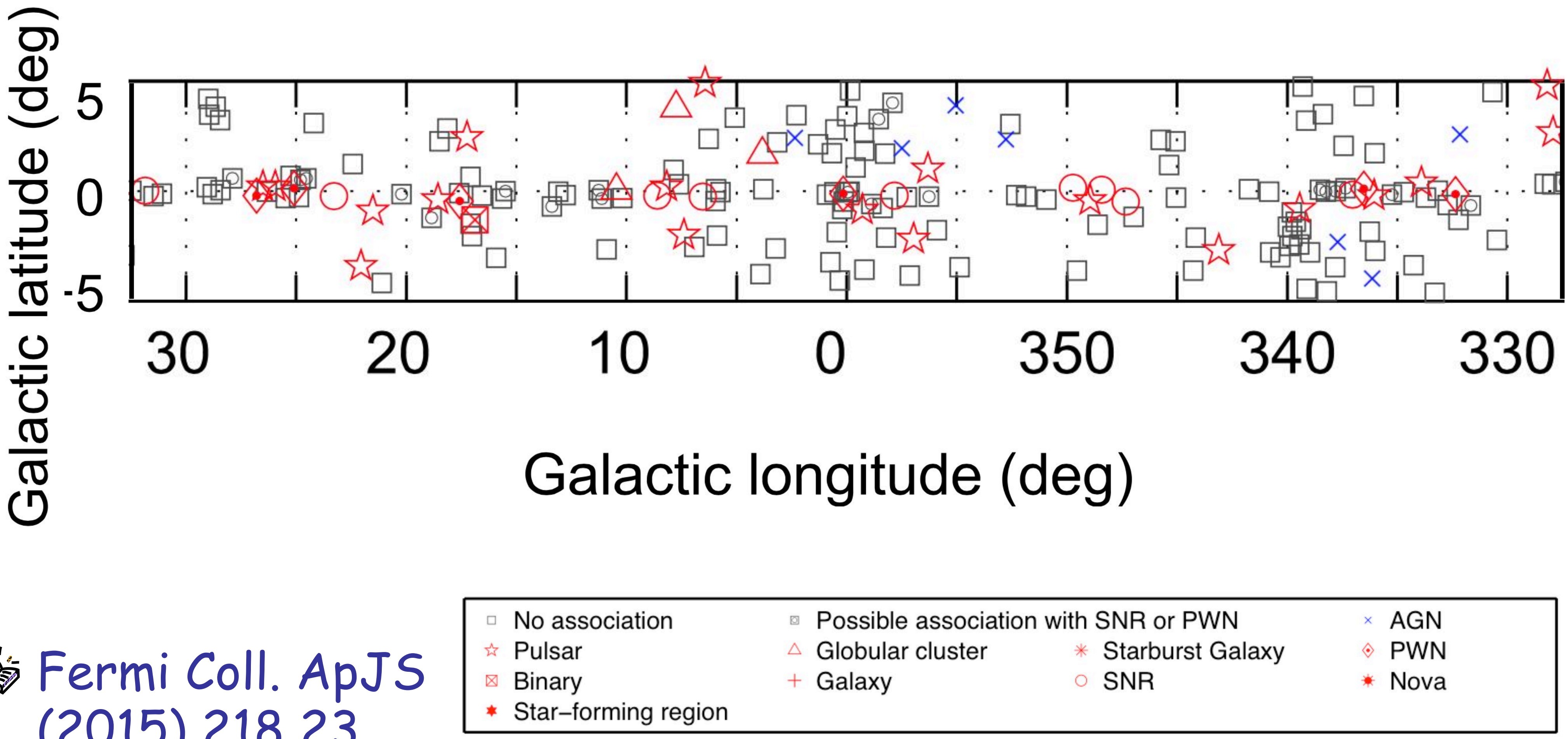
- Different diffusion coefficent in the GC region
-

How to discriminate between different hypothesis ?

The Fermi LAT 3FGL Inner Galactic Region

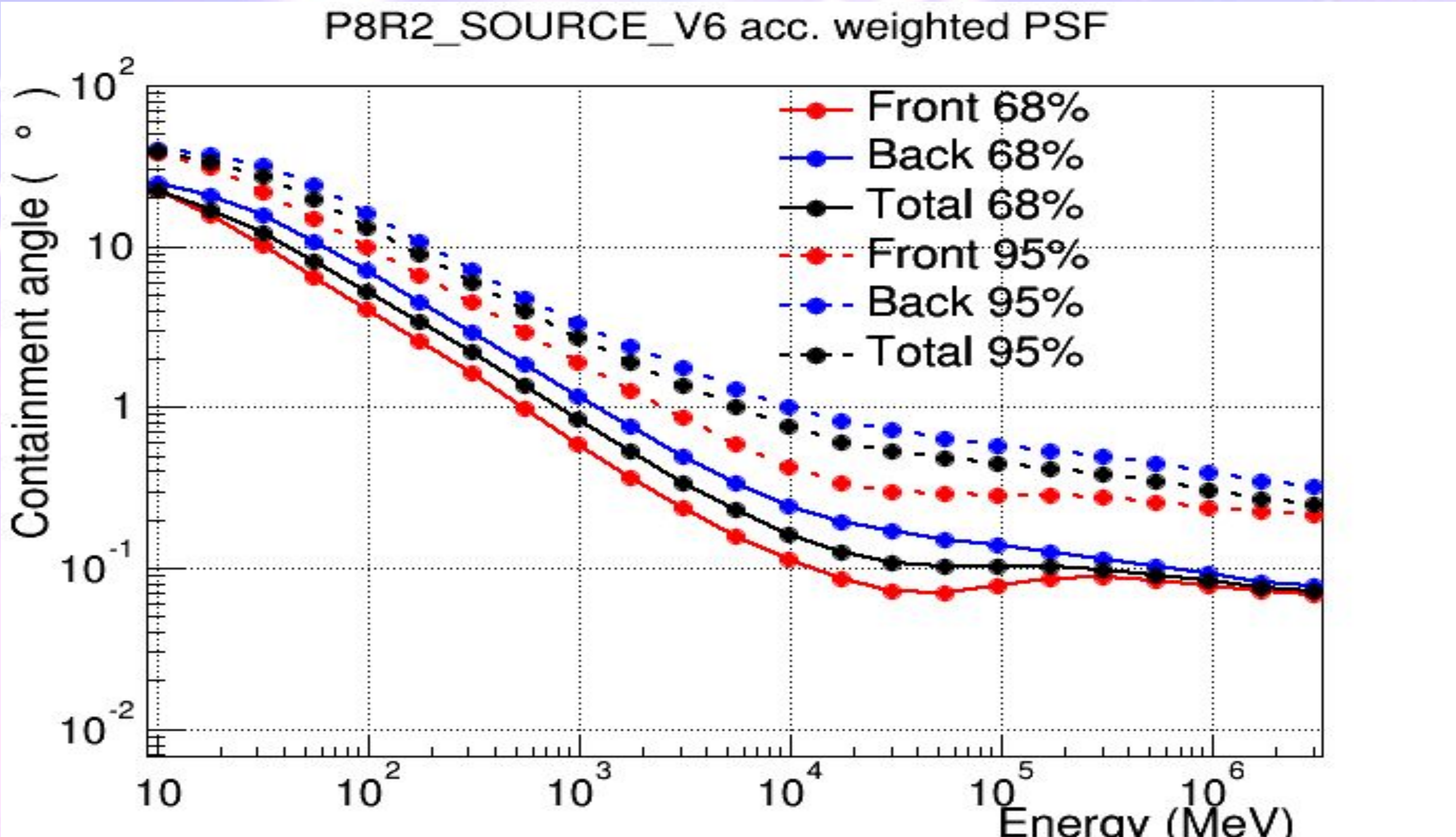
August 4, 2008, to July 31, 2010

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



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

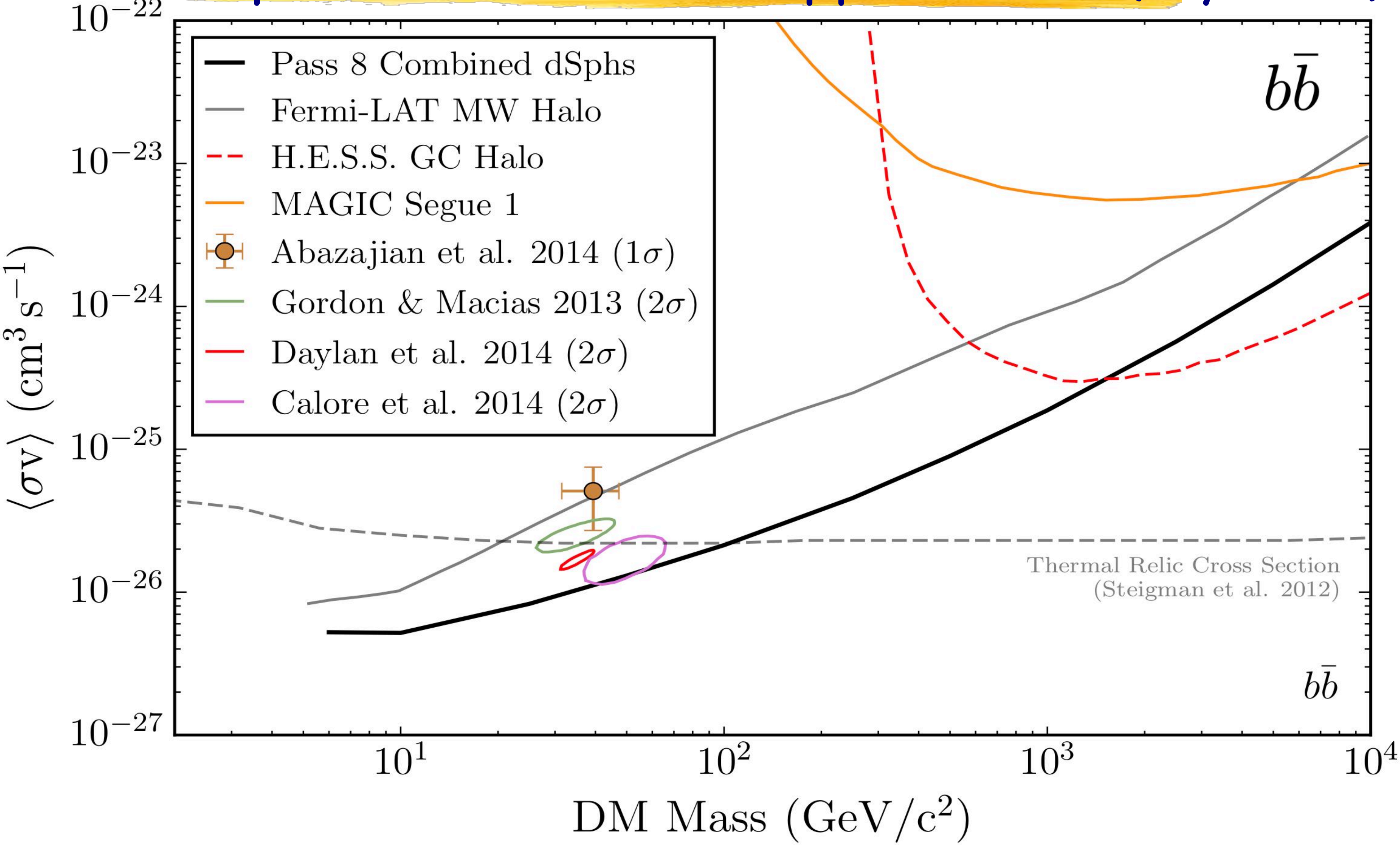
- Look for correlated synchrotron emission near the GC

More Fermi LAT analysis

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

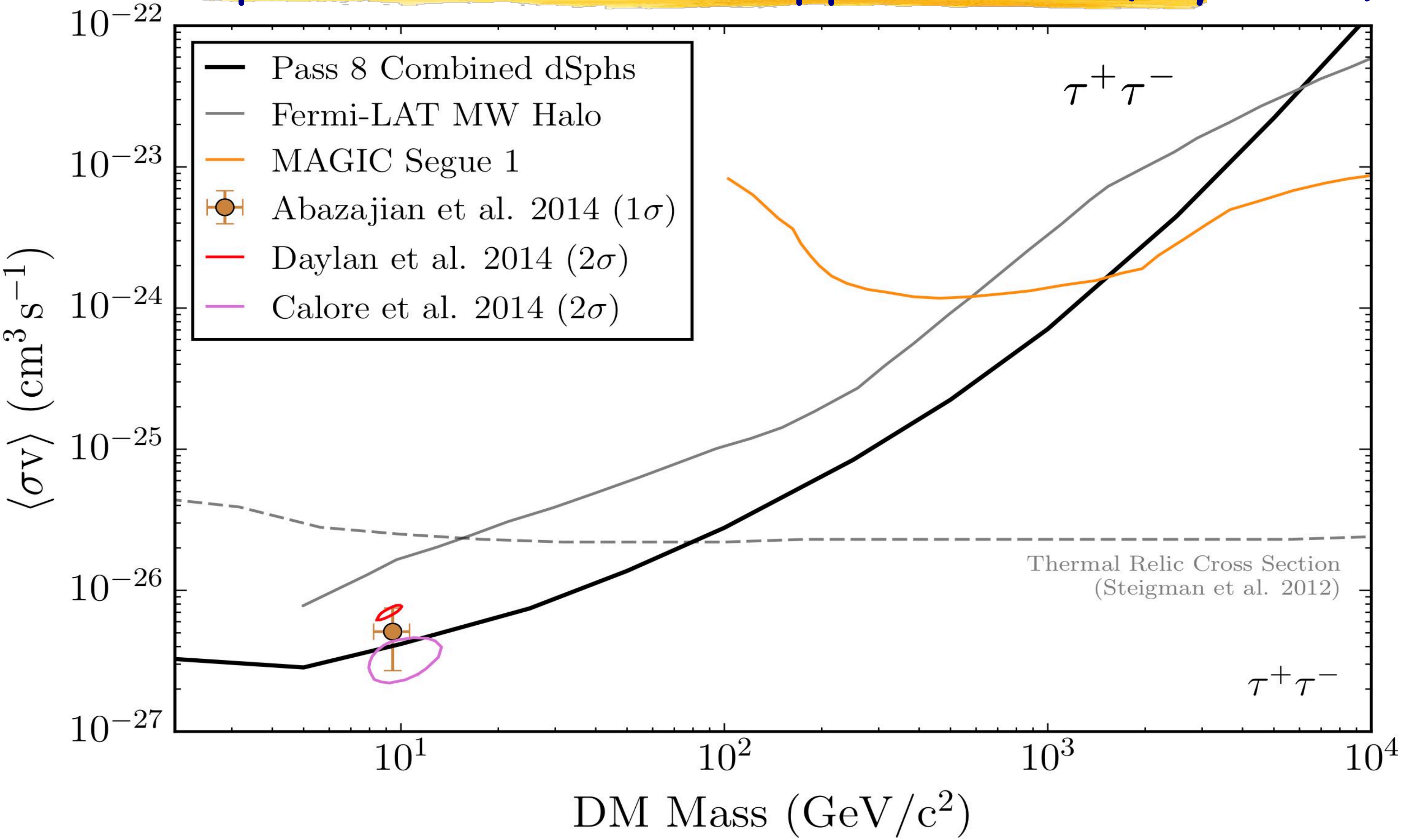
But ultimately We need a new experiment with better angular resolution below 100 MeV

Dwarf Spheroidal Galaxies upper-limits (6 years)



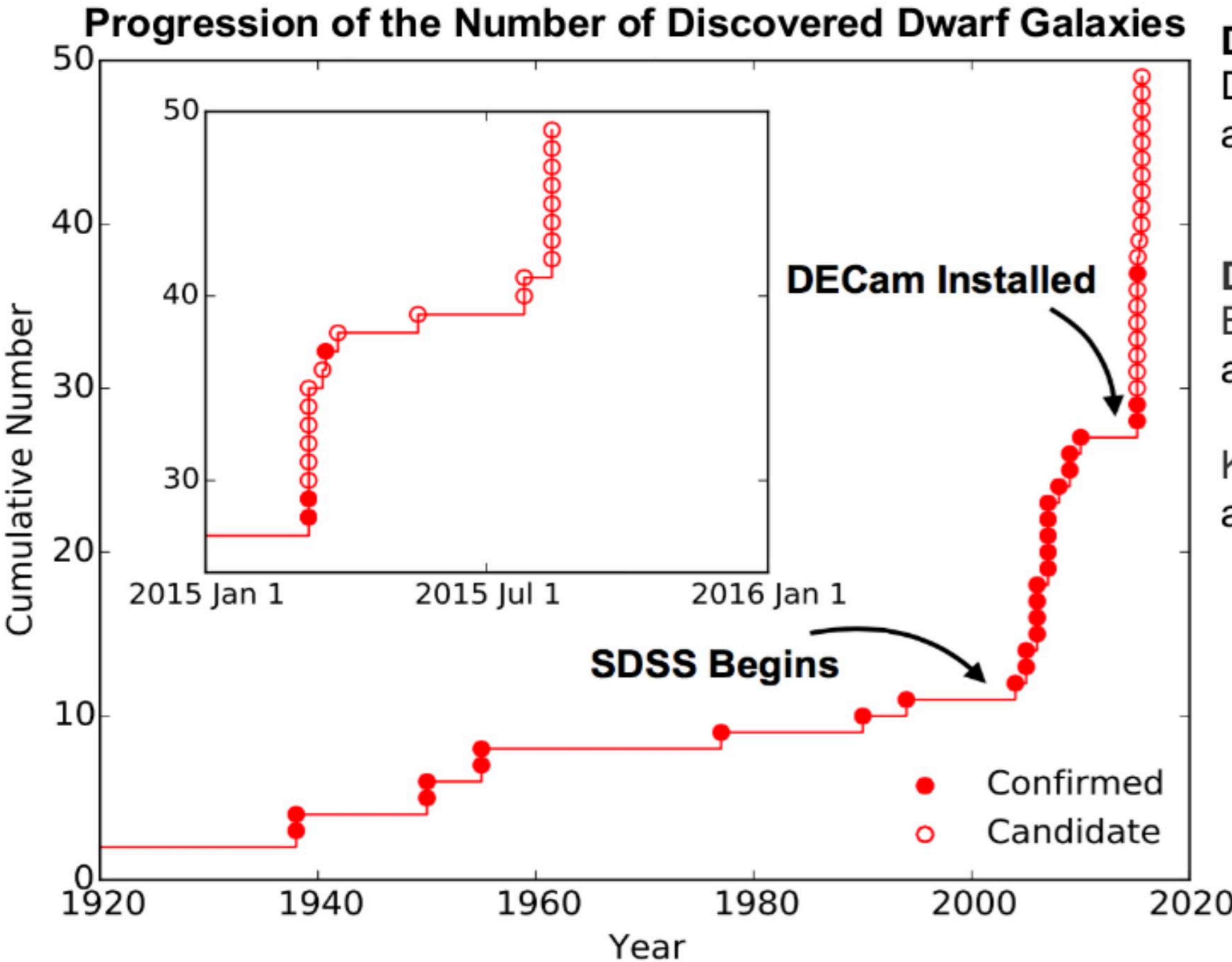
M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

Dwarf Spheroidal Galaxies upper-limits (6 years)



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

Dwarf Spheroidal Galaxy: Growing number of known targets

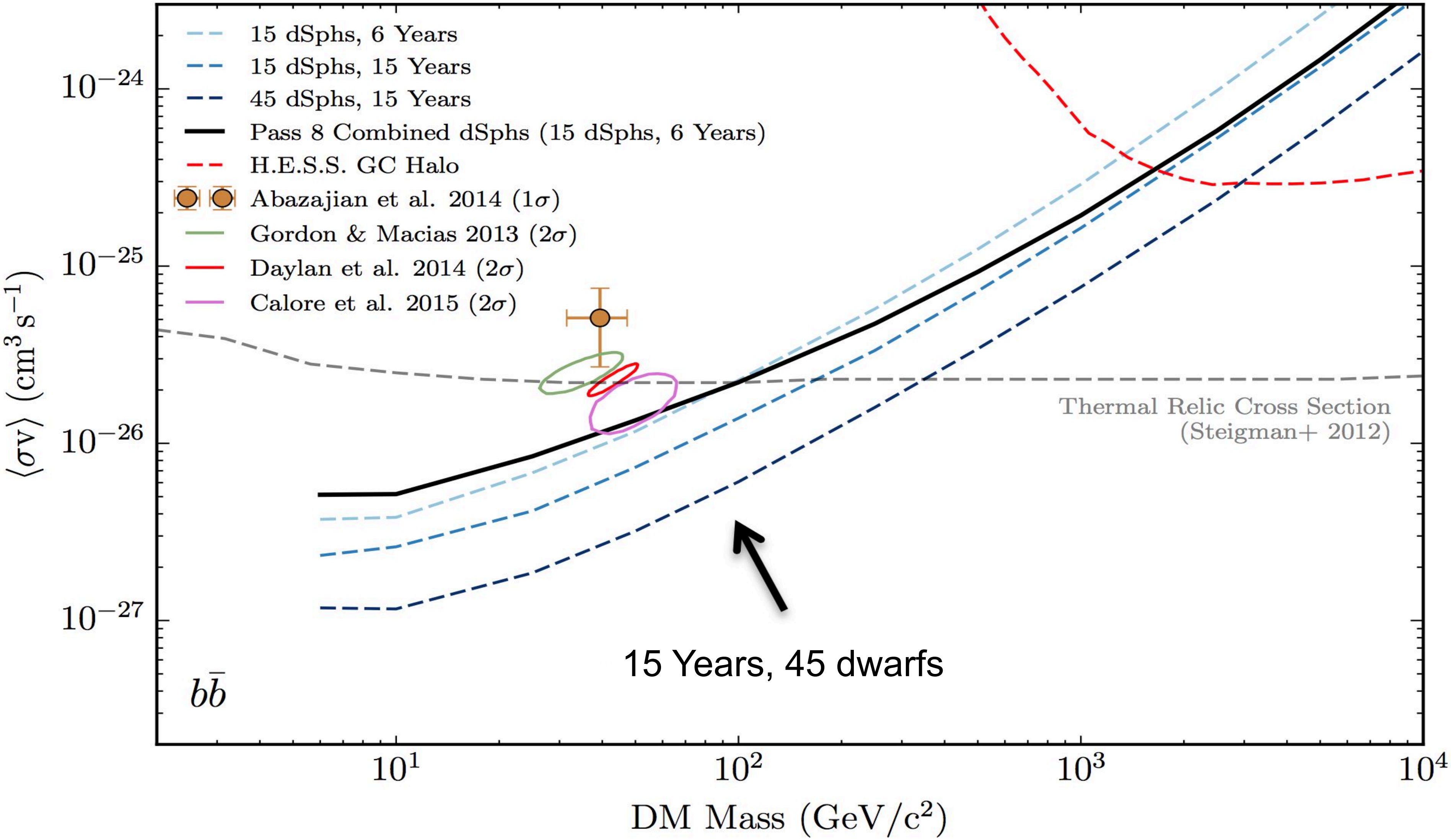


DES Year 2 Data:
Drlica-Wagner+,
arXiv:1508.03622

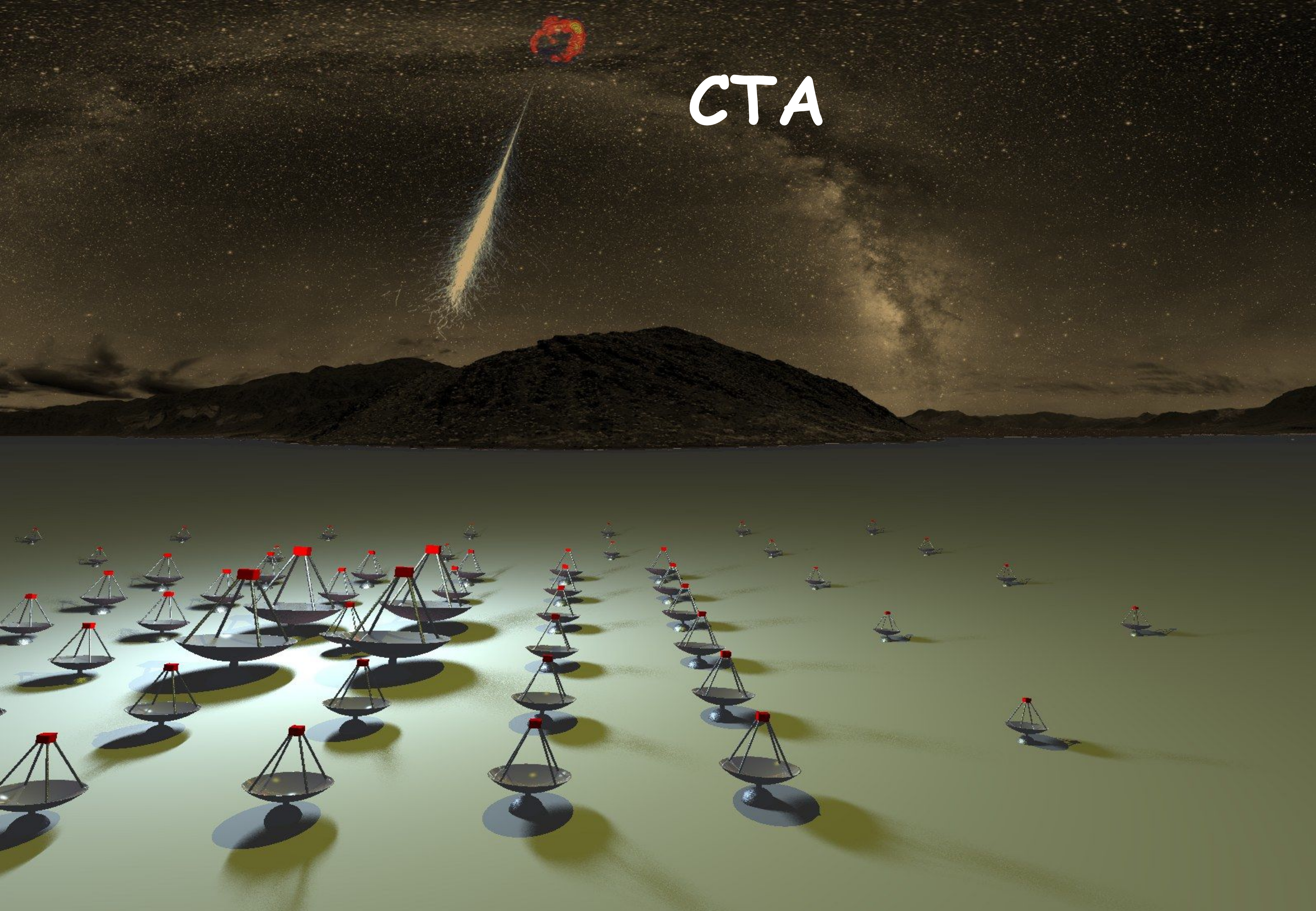
DES Year 1 Data:
Bechtol+:
arXiv:1503.02584

Koposov+:
arXiv:1503.02079

DM limit improvement estimate in 15 years with the composite likelihood approach (2008- 2023)



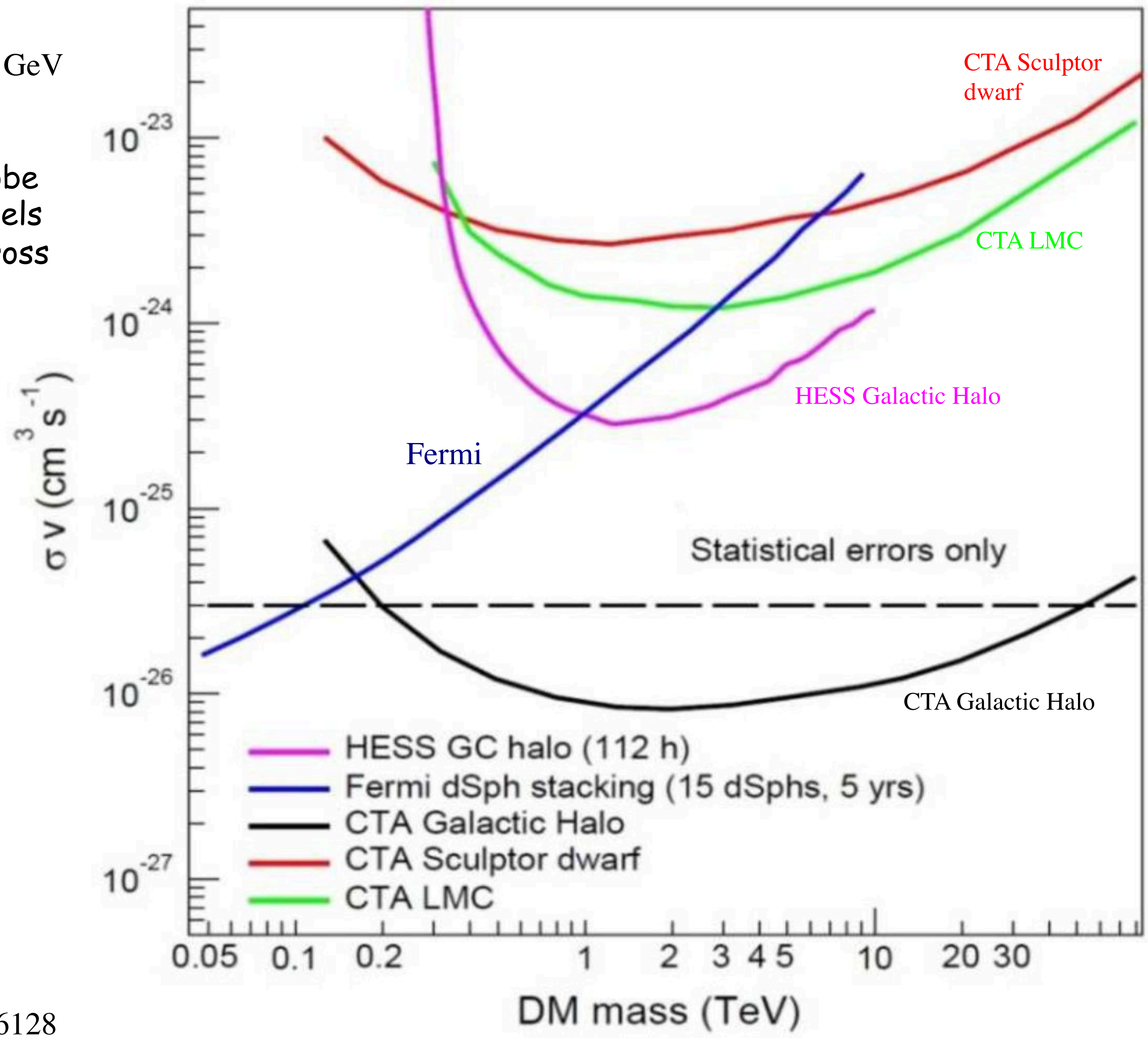
E. Charles et.al, Phy Rep. 636 2016, arXiv:1605.02016


CTA

HESS, FERMI, CTA DM upper-limits

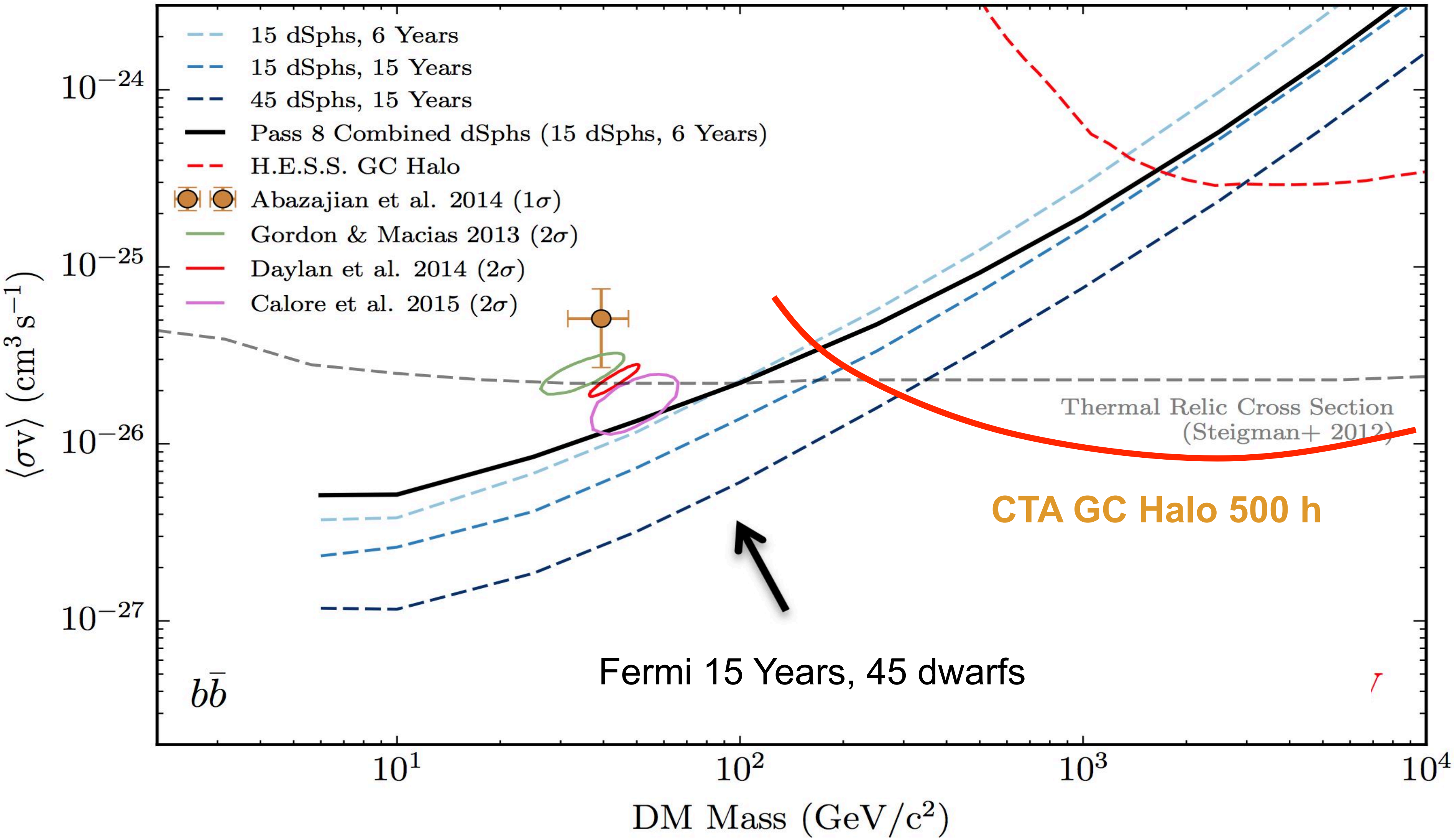
CTA 500 hr, statistical only, NFW, 30 GeV

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section



Carr et al. 2015 arXiv:1508.06128

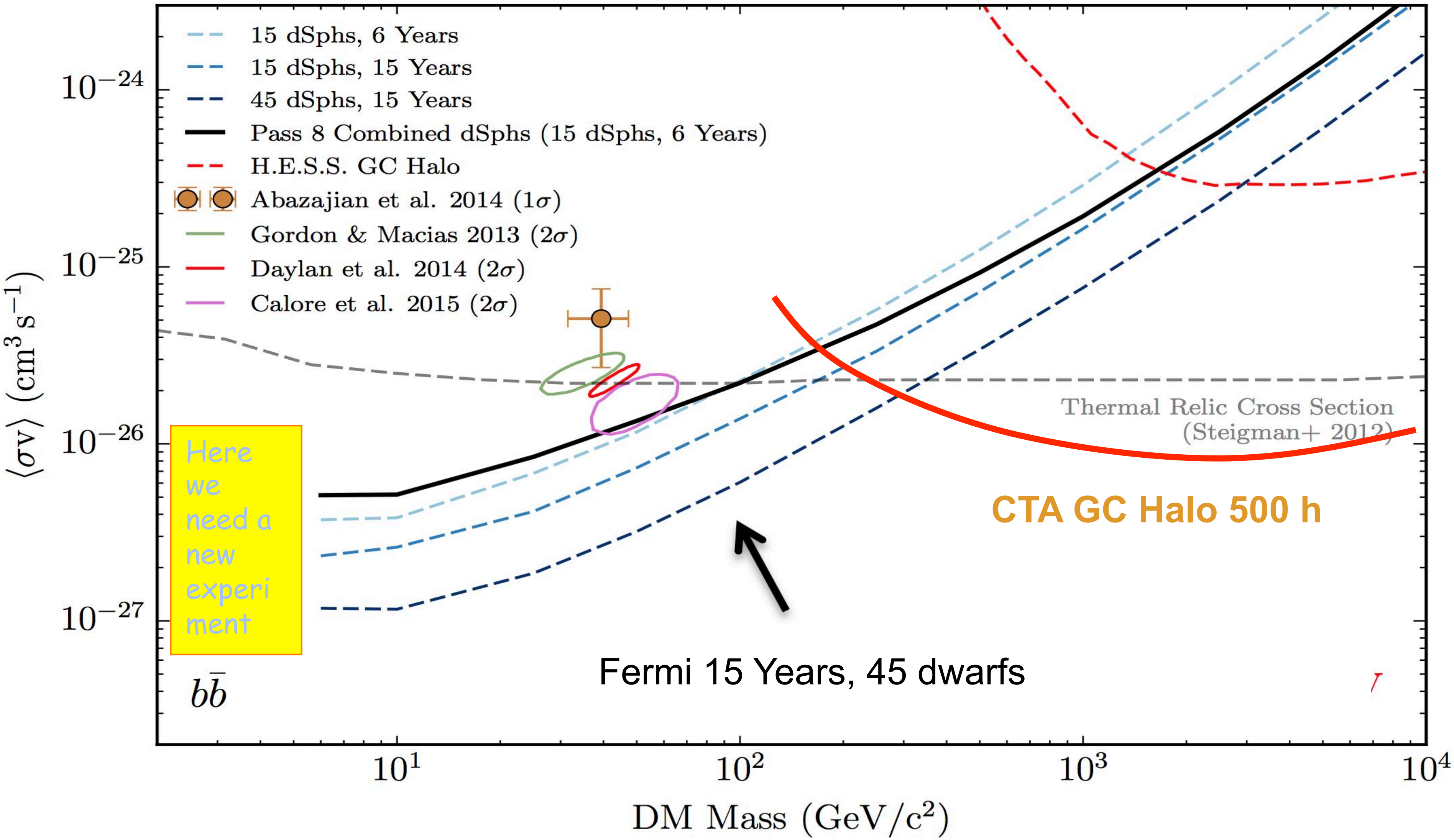
DM limit improvement estimate in 15 years (2008- 2023)



CTA sensitivity curve from Carr et al. 2015 500 hr, statistical only, NFW, 30 GeV threshold arXiv:1508.06128

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

DM limit improvement estimate in 15 years (2008- 2023)



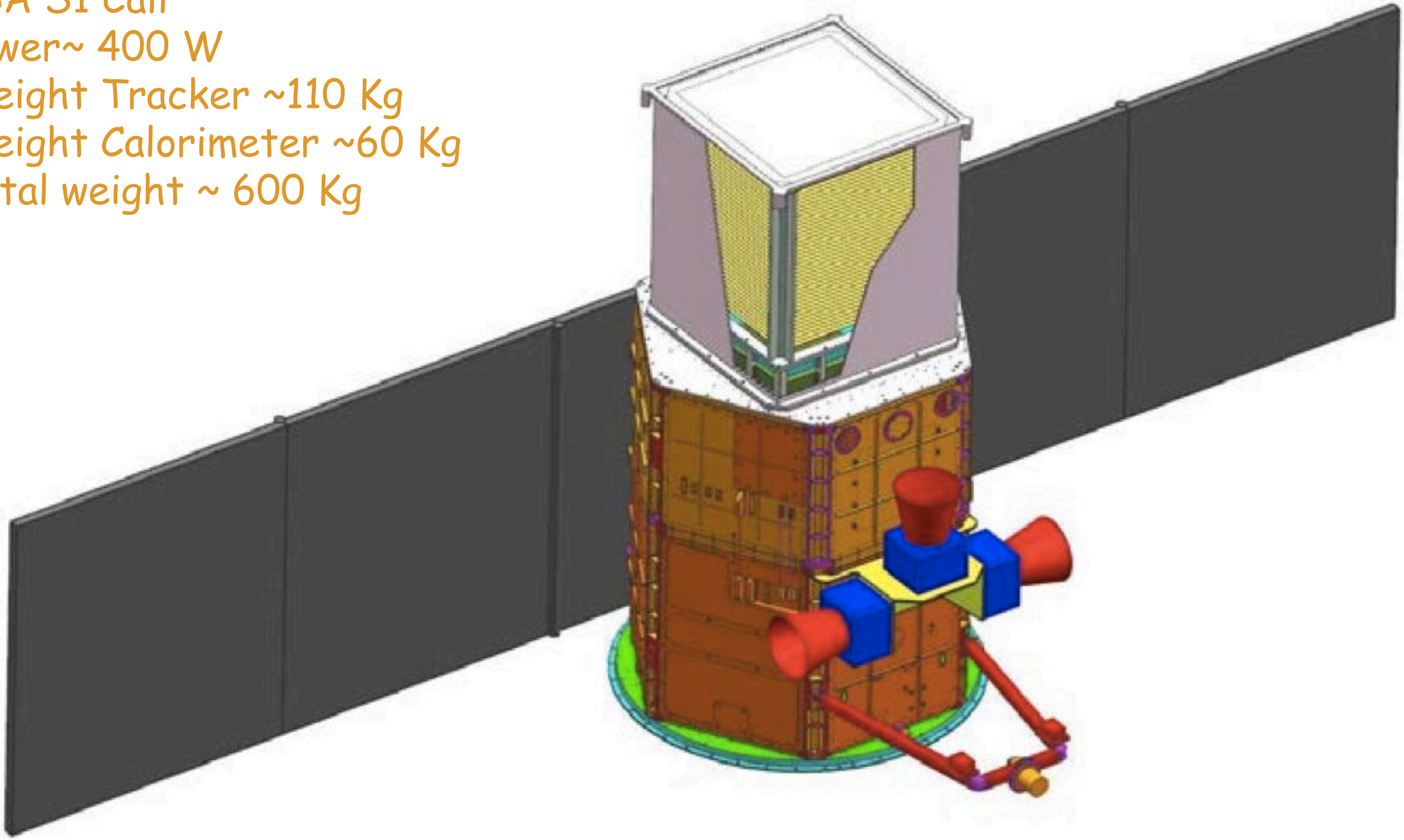
CTA sensitivity curve from Carr et al. 2015 500 hr, statistical only, NFW, 30 GeV threshold arXiv:1508.06128

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

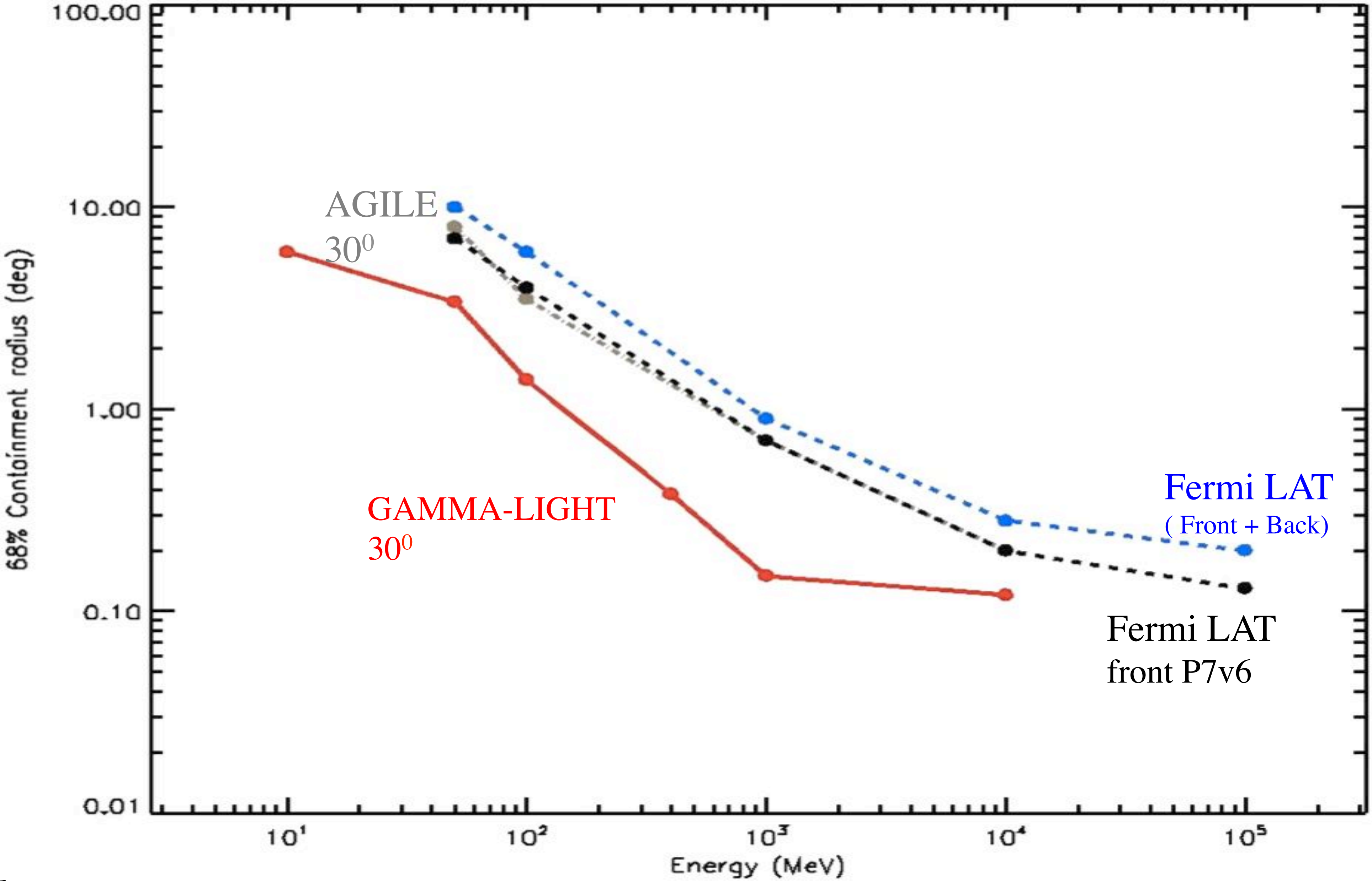
- 1-100 MeV unexplored domain for
  - Dark Matter searches
  - Galactic compact stars and nucleosynthesis
  - Cosmic rays
  - Relativistic jets, microquasars
  - Blazars
  - Gamma-Ray Bursts
  - Solar physics
- and…
  - Terrestrial Gamma-Ray Flashes

Gamma-light project

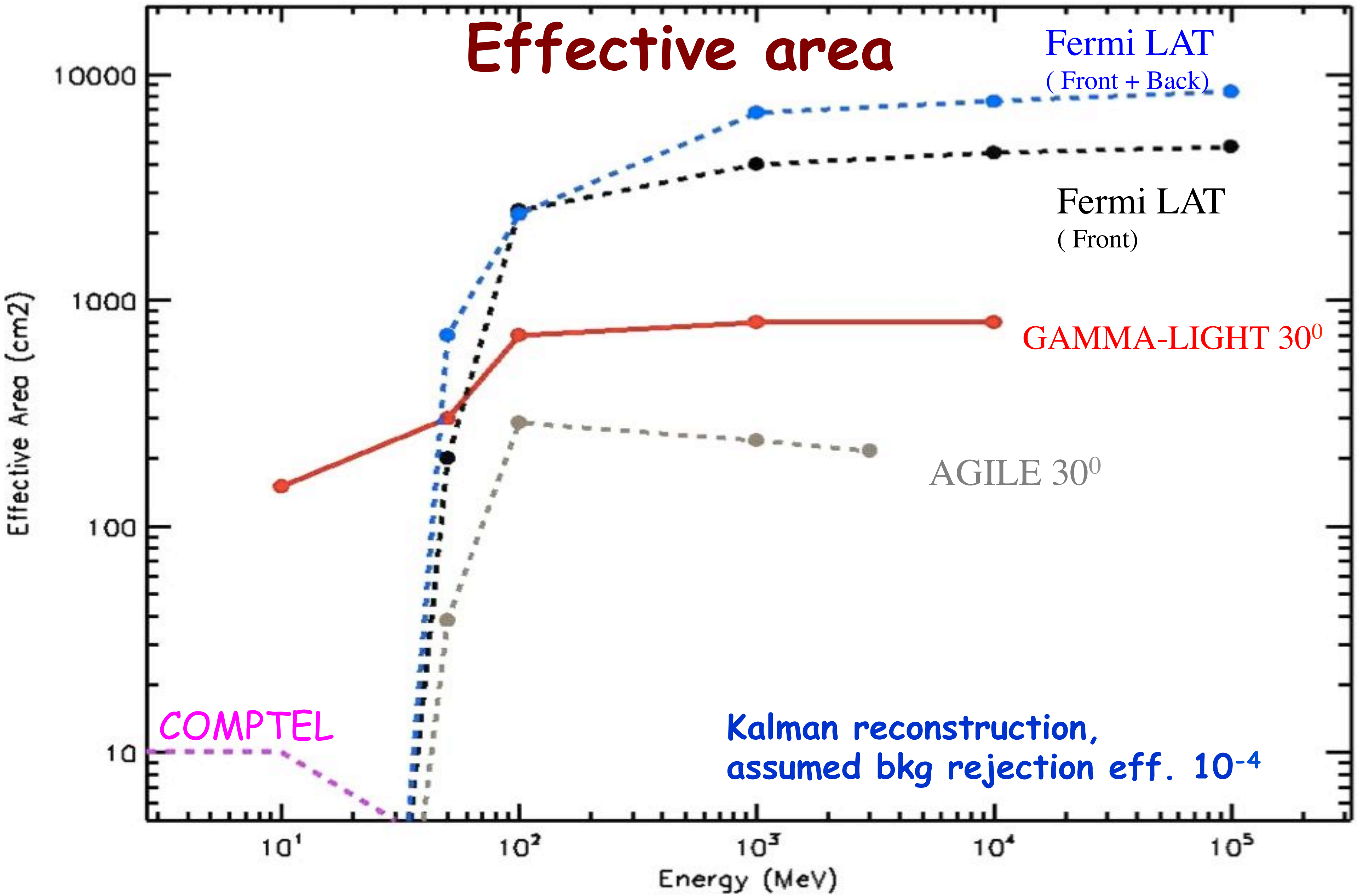
ESA S1 Call
Power~ 400 W
Weight Tracker ~110 Kg
Weight Calorimeter ~60 Kg
Total weight ~ 600 Kg



Gamma-Light Point Spread Function (angular resolution)



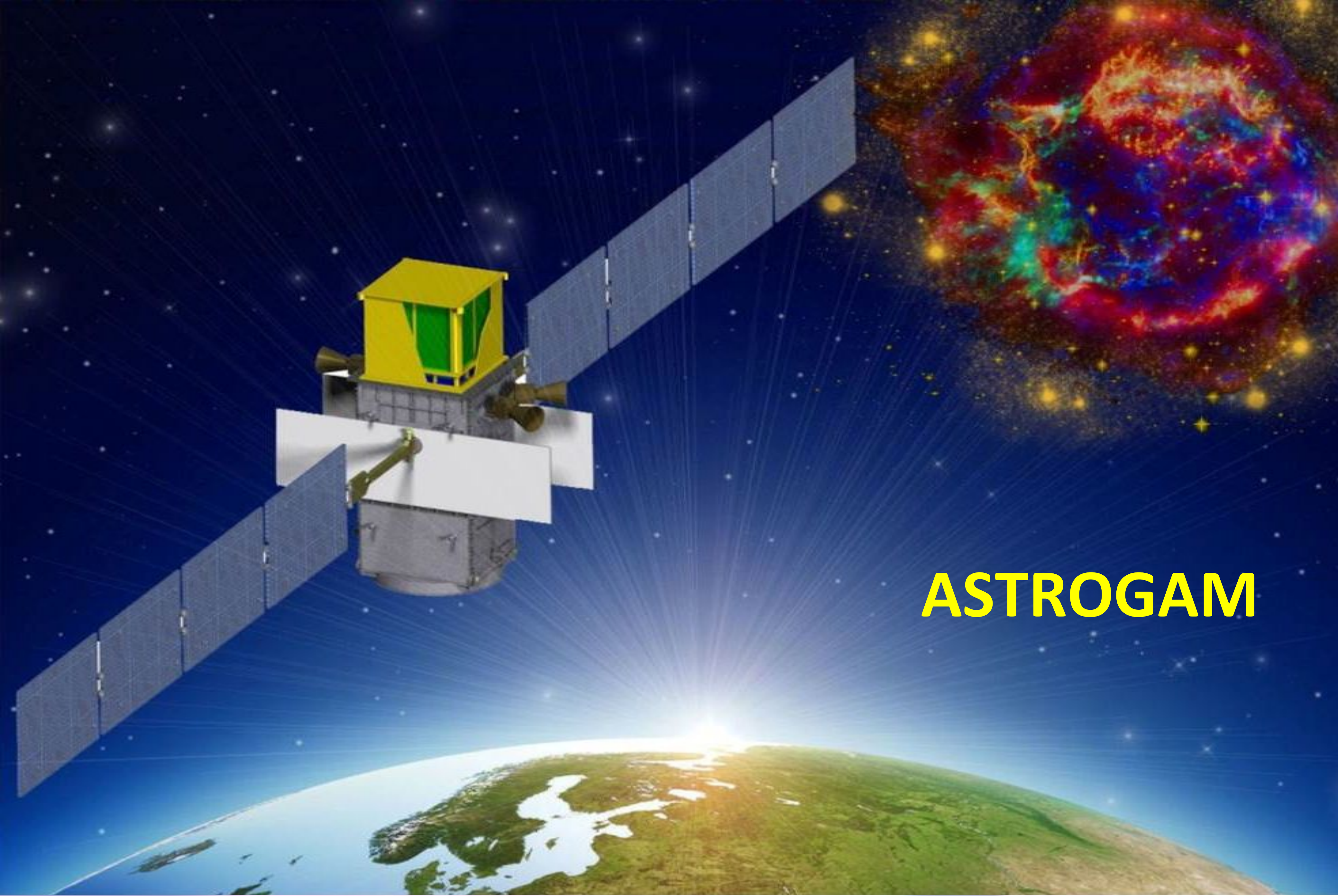
A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198 [arXiv:1406.1071]



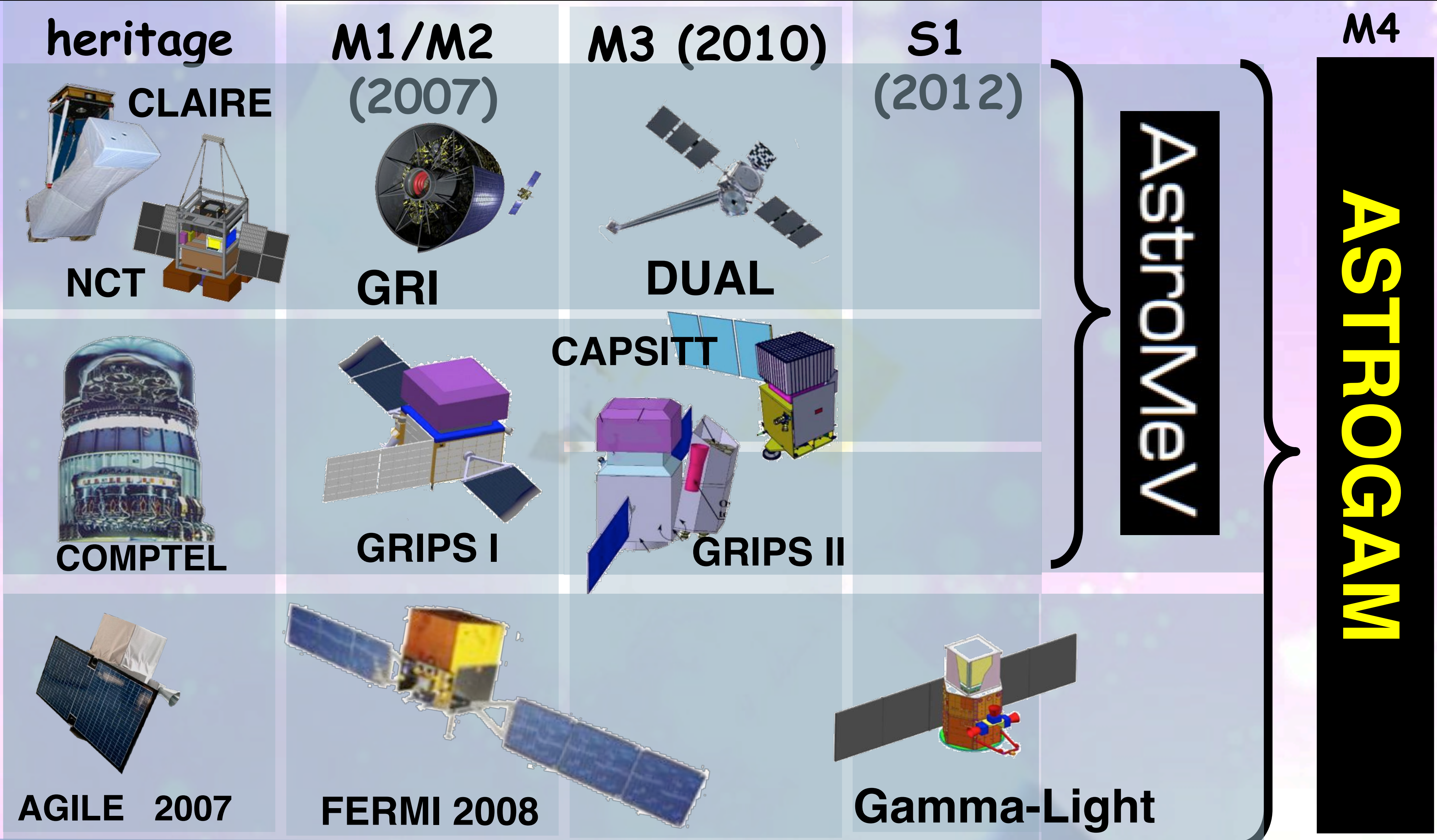
A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198 [arXiv:1406.1071]

ESA M-4 Call

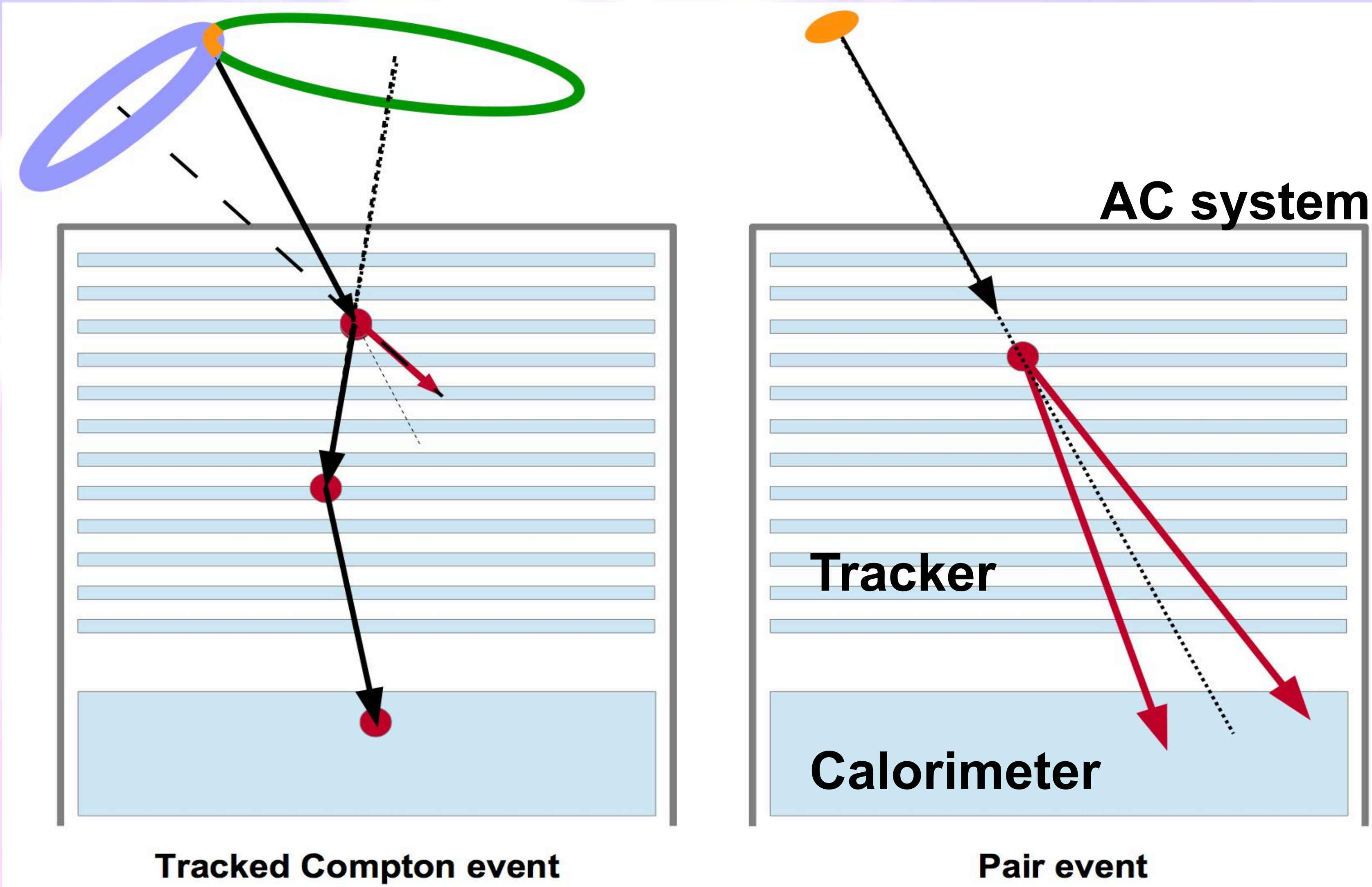
- quite different from previous Medium-sized Mission Calls (Solar Orbiter, EUCLID, PLATO);
- total ESA budget: 450 Meuro.
- guidelines for an ‘‘ESA-only’’ mission:
  - Payload mass: 300 kg;
  - total spacecraft mass: 800 kg.


ASTROGAM

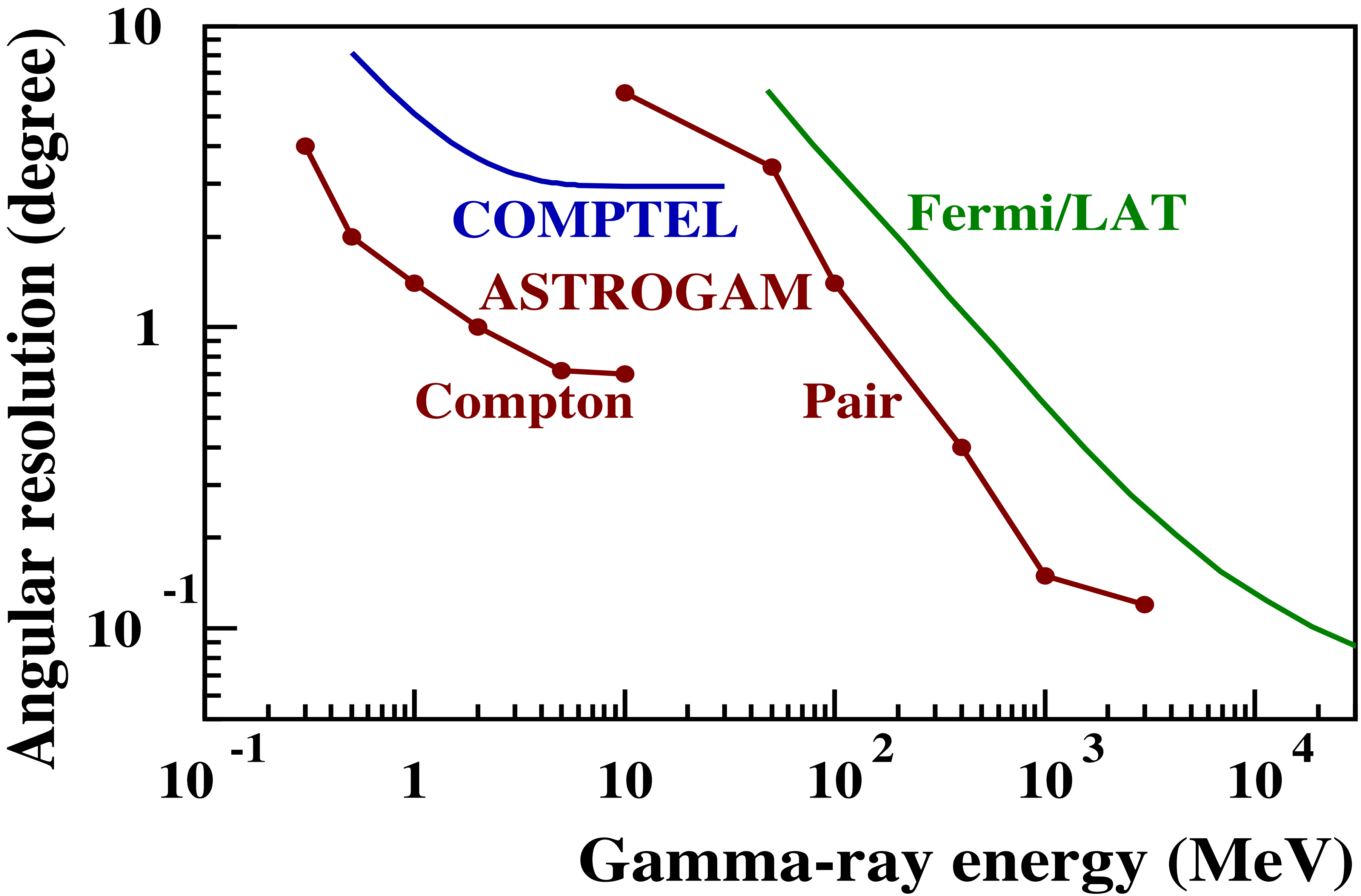
ASTROGAM a unified proposal from the entire gamma-ray community



An instrument that combine two detection techniques

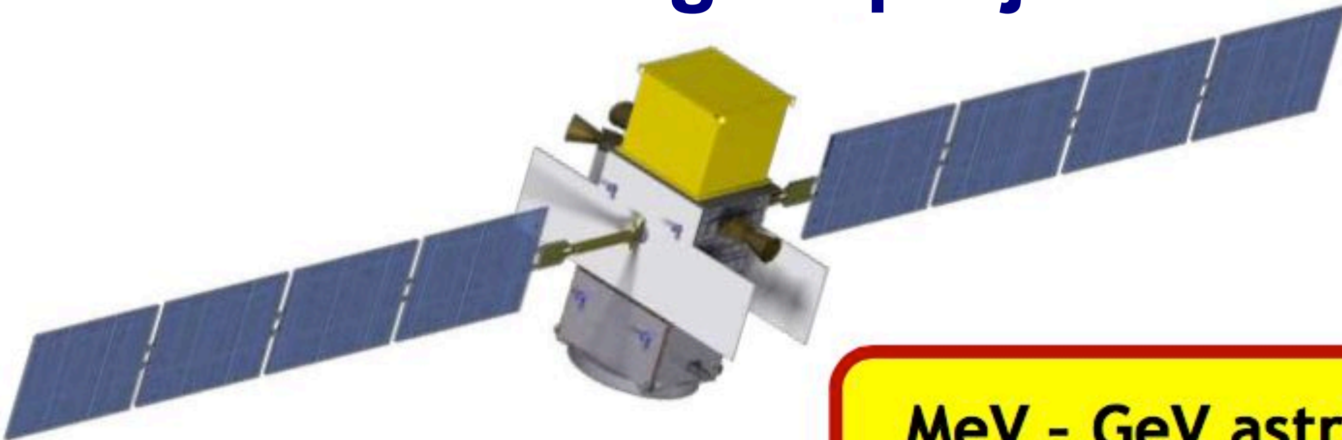


ASTROGAM Angular Resolution



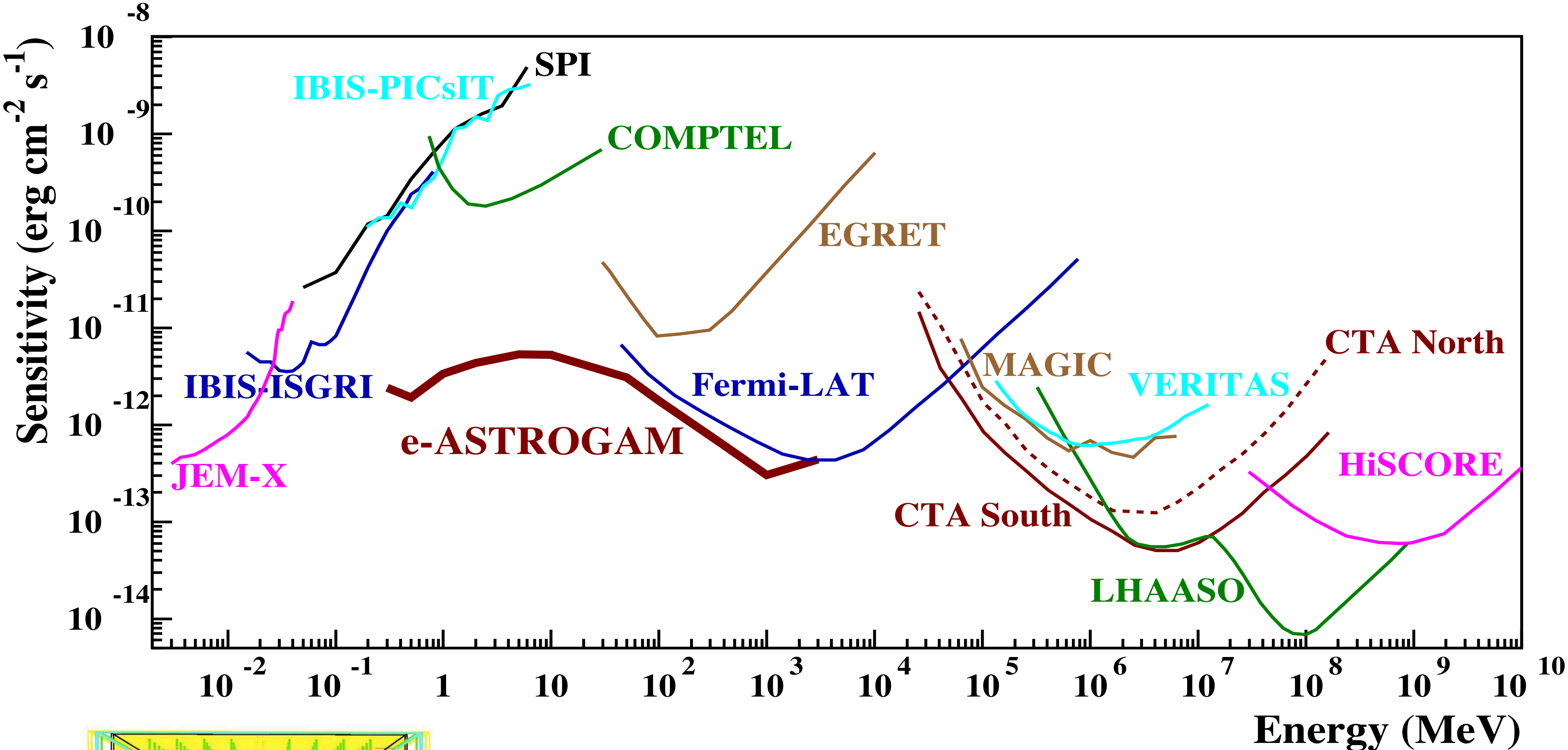
The next gamma-ray MeV-GeV mission:

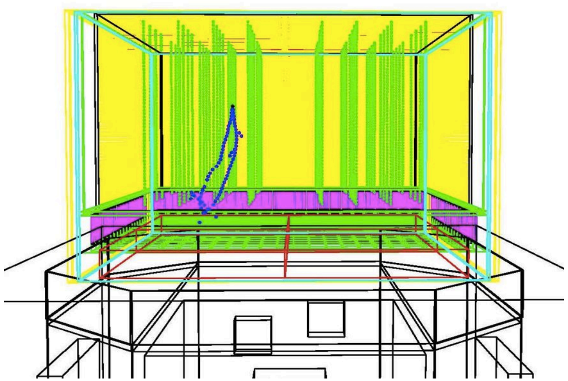
the e-Astrogam project



MeV - GeV astrophysics
MeV - GeV community

Proposed for the ESA M4 call; currently under study for enhancement and reconfiguration for the ESA M5 call. ASTROGAM is **focused on gamma-ray astrophysics in the range 0.3-100 MeV** with excellent capability also at GeV energies.





- 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 Core science

1. Jet astrophysics: a unique link to new astronomies (gravitational waves, neutrinos, ultra-high energy cosmic rays)

2. The high-energy mysteries of the Galactic center region

3. Supernovae, nucleosynthesis and Galactic chemical evolution

e-ASTROGAM Collaboration

INFN, INAF, University Tor Vergata, University of Udine

CSNSM, IRAP, APC, CEA, LLR, LUPM, IPNO

Univ. Mainz, Univ. Wuerzburg, MPE, RWTH, DESY, Univ. Erlangen

ICE (CSIC-IEEC), IMB-CNM (CSIC), IFAE-BIST, Univ. Barcelona

University College Dublin, DIAS

DTU

University of Geneva

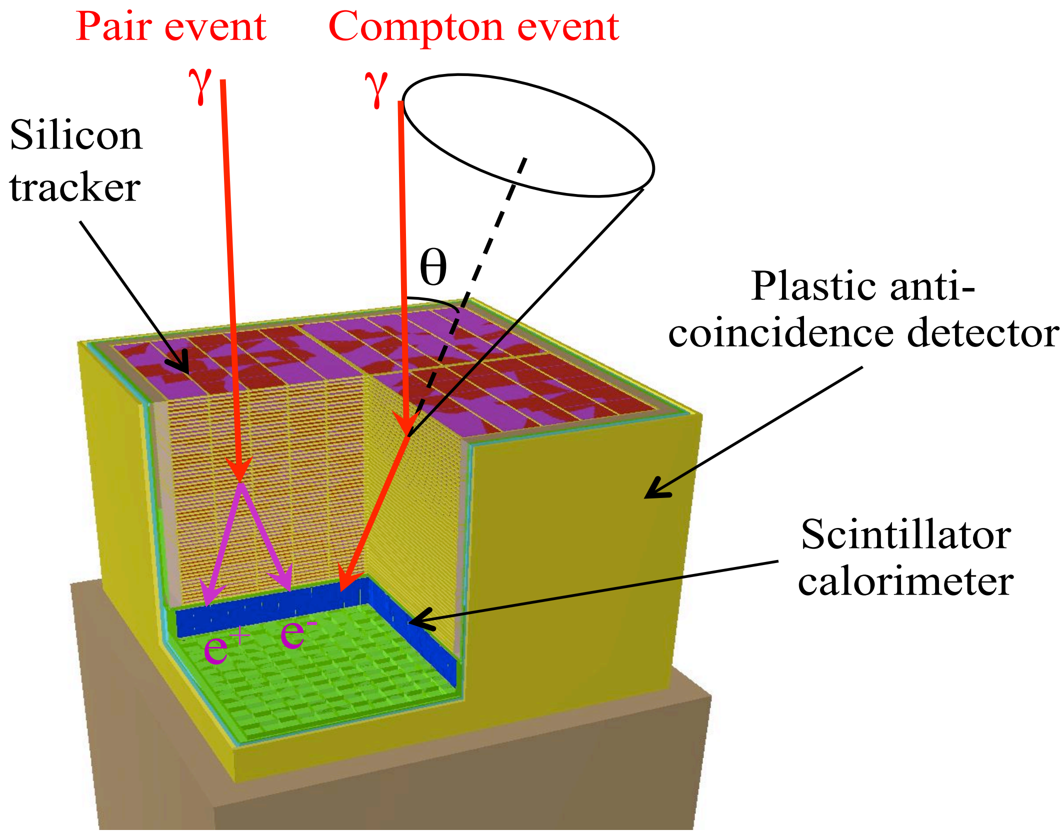
Jagiellonian University, CBK, NCAC

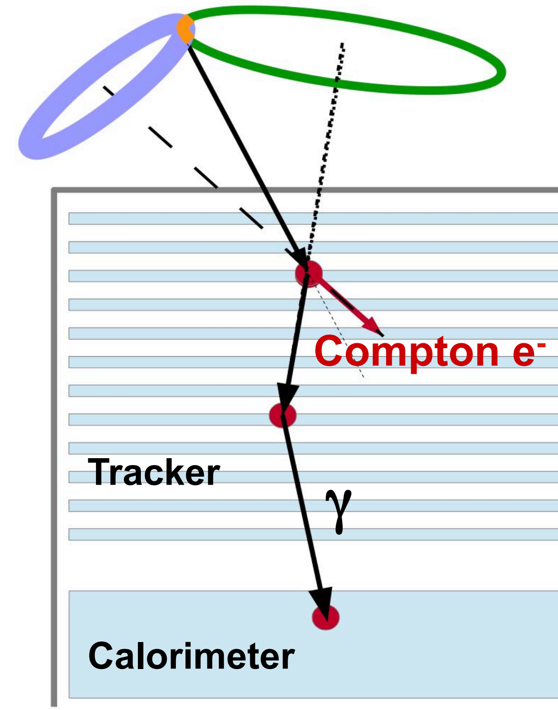
NASA GSFC, NRL, Clemson Univ., Washington Univ., Yale Univ., UC Berkeley

Ioffe Institute

University of Tokyo

Measurement principle

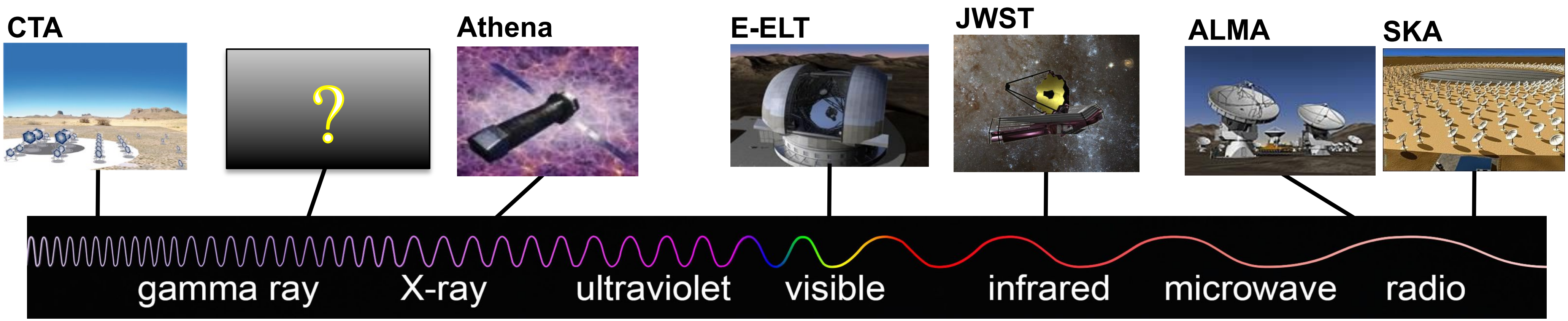




Tracked Compton event

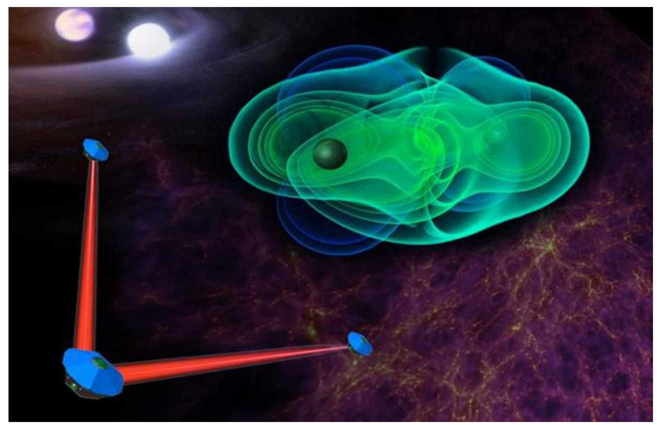
- **Tracker** – Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution
- **Calorimeter** – High-Z material for an efficient absorption of the scattered photon ⇒ CsI(Tl) scintillation crystals readout by Si Drift Diodes for better energy resolution
- **Anticoincidence detector** to veto charged-particle induced background ⇒ plastic scintillators readout by Si photomultipliers

e-ASTROGAM γ-ray astronomy in context

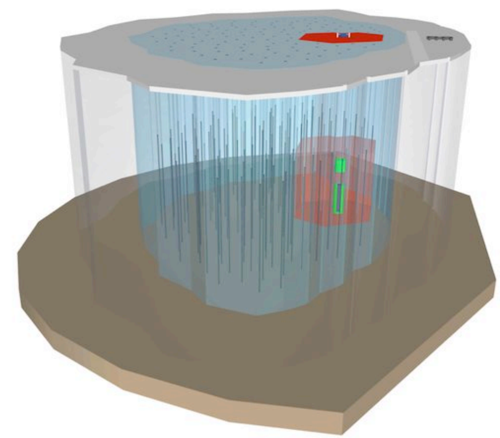


New Astronomies:
gravitational waves
neutrinos

eLISA – Gravitational waves



IceCube-Gen2 – Neutrinos

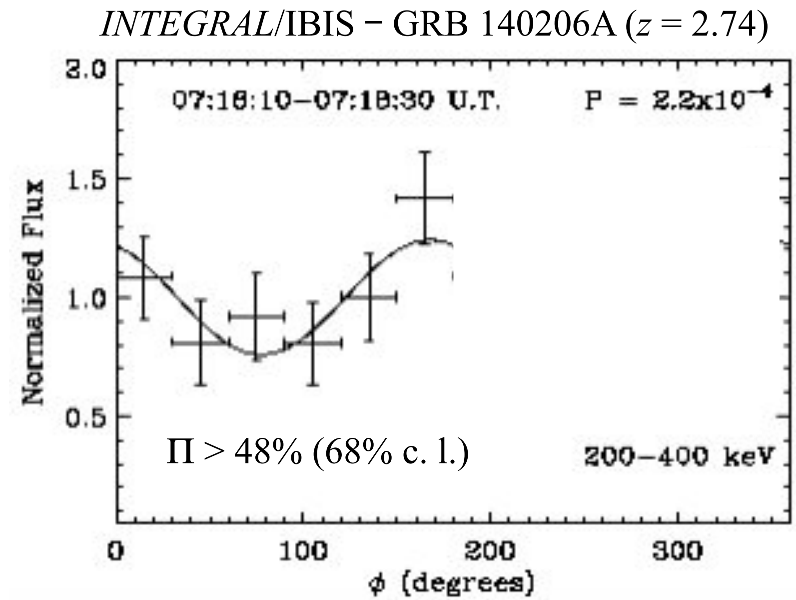


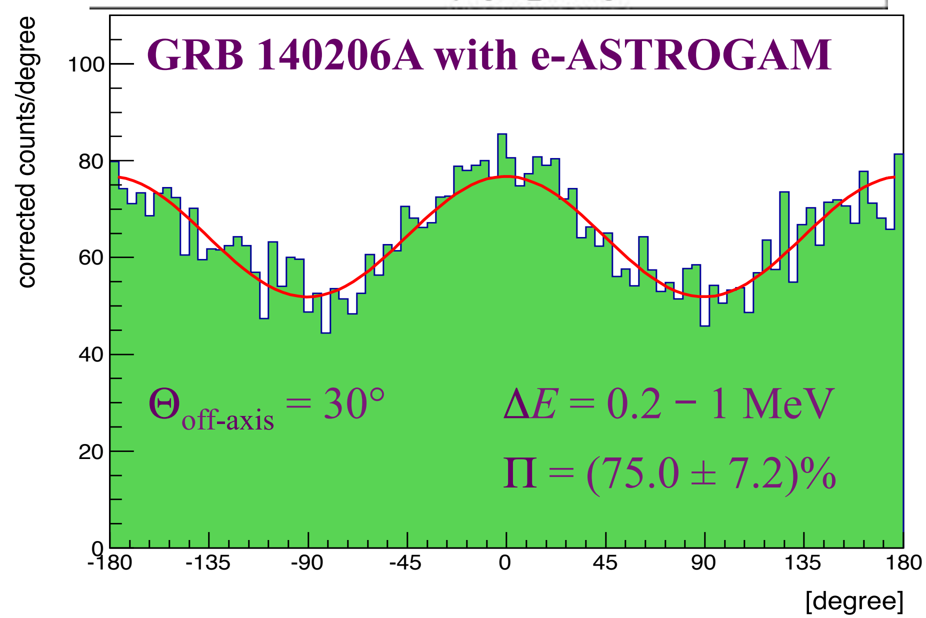
- Need for a sensitive, wide-field γ-ray space observatory operating at the same time as facilities like SKA and CTA, as well as eLISA and neutrino detectors, to get a coherent picture of the transient sky and the sources of gravitational waves and high-energy neutrinos

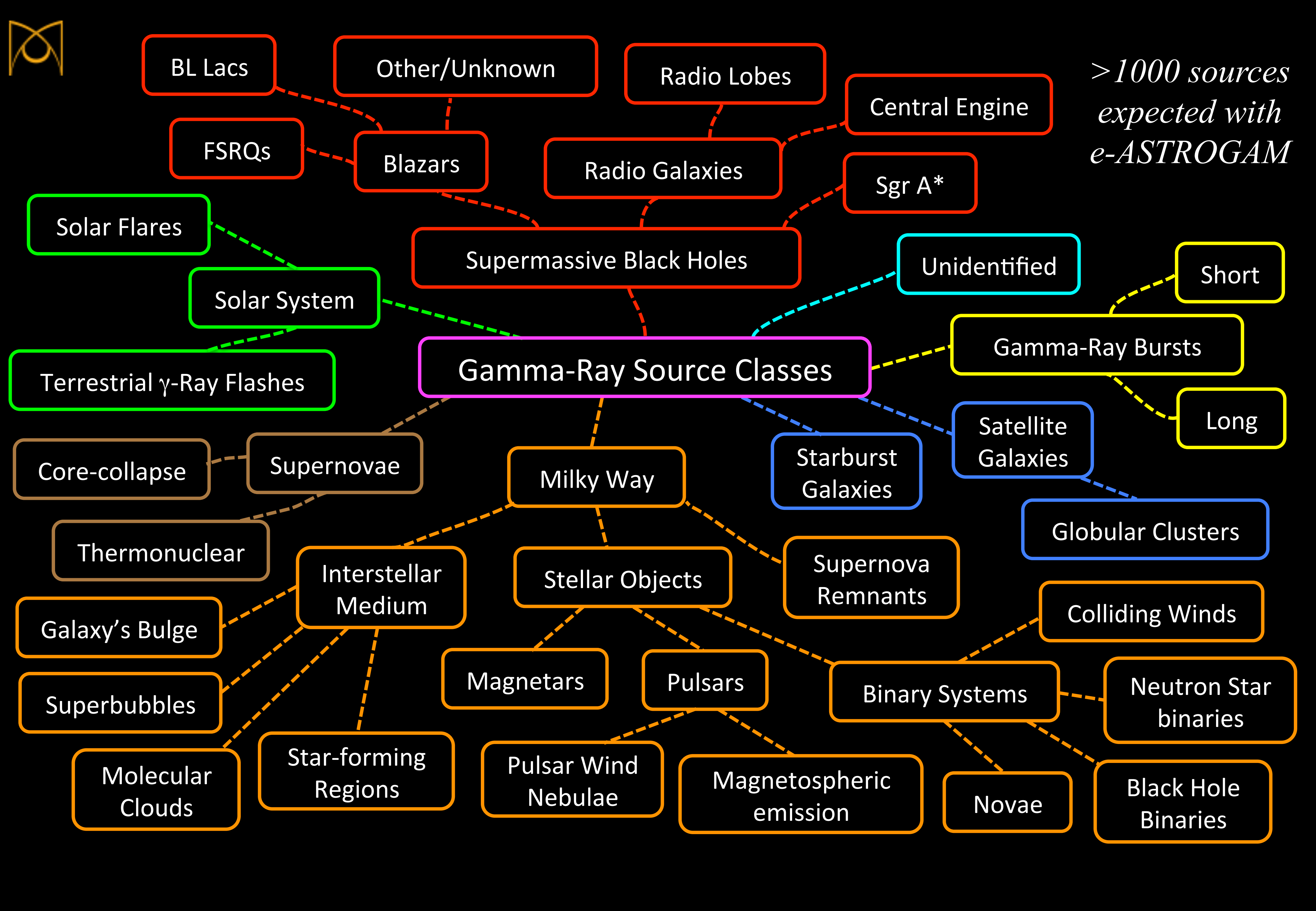
e-ASTROGAM Gamma-ray polarization

- γ-ray polarization in **objects emitting jets** (GRBs, Blazars, X-ray binaries) or with **strong magnetic field** (pulsars, magnetars) ⇒ magnetization and content (hadrons, leptons, Poynting flux) of the outflows + radiation processes
- γ-ray polarization from **cosmological sources** (GRBs, Blazars) ⇒ fundamental questions of physics related to Lorentz Invariance Violation (vacuum birefringence)

✓ e-ASTROGAM will measure the γ-ray polarization of ∼ **100 GRBs per year** (promising candidates for highly γ-ray polarized sources)



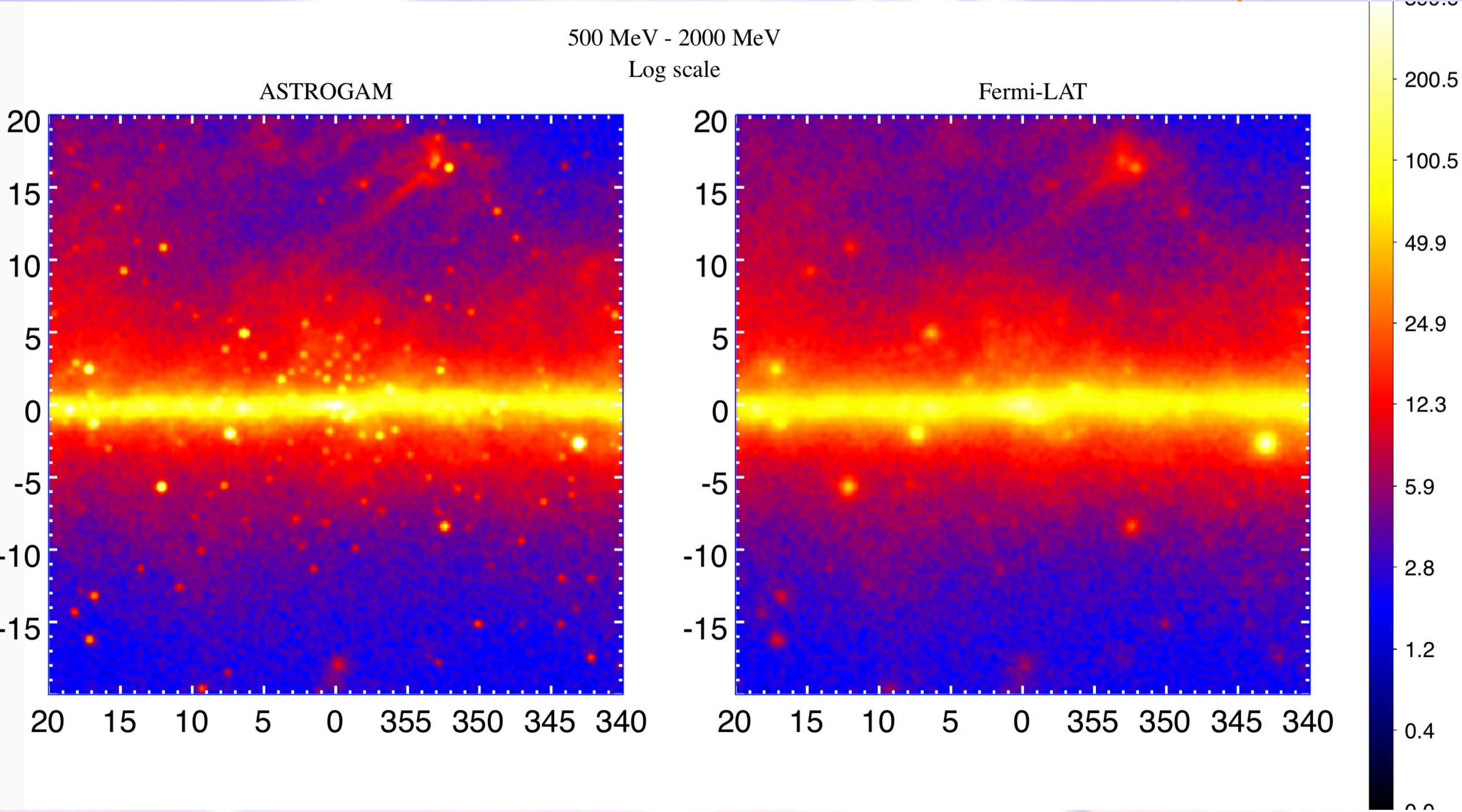




BL Lacs
Other/Unknown
Radio Lobes
Central Engine
FSRQs
Blazars
Radio Galaxies
Sgr A*
Solar Flares
Supermassive Black Holes
Unidentified
Short
Solar System
Gamma-Ray Bursts
Terrestrial γ-Ray Flashes
Gamma-Ray Source Classes
Satellite Galaxies
Long
Core-collapse
Supernovae
Milky Way
Starburst Galaxies
Globular Clusters
Thermonuclear
Interstellar Medium
Stellar Objects
Supernova Remnants
Colliding Winds
Galaxy's Bulge
Magnetars
Pulsars
Binary Systems
Neutron Star binaries
Superbubbles
Molecular Clouds
Star-forming Regions
Pulsar Wind Nebulae
Magnetospheric emission
Novae
Black Hole Binaries
>1000 sources expected with e-ASTROGAM

Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source



Morselli, Gomez Vargas, preliminary

Conclusions

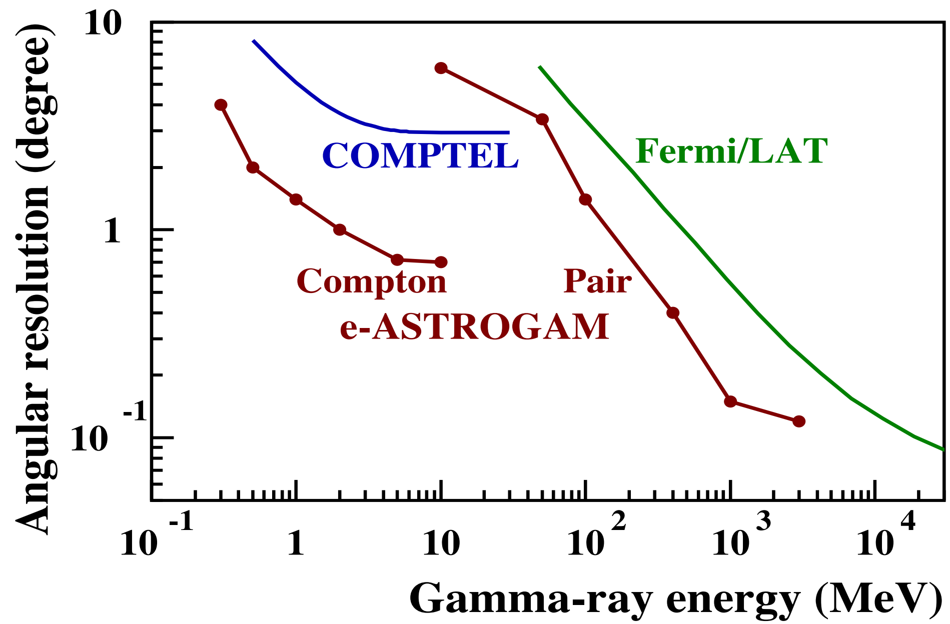
Detection of gamma rays from the annihilation or decay of dark matter particles is a promising method for identifying dark matter, understanding its intrinsic properties, and mapping its distribution in the universe (in synergy with the experiments at the LHC and in the underground laboratories).
In the future it would be extremely important to extend the energy range of experiments at lower energies (compared to the Fermi energies) (AstroGAM)
and higher energies (CTA, HAWC, LHAASO, HERD)

Thank you !

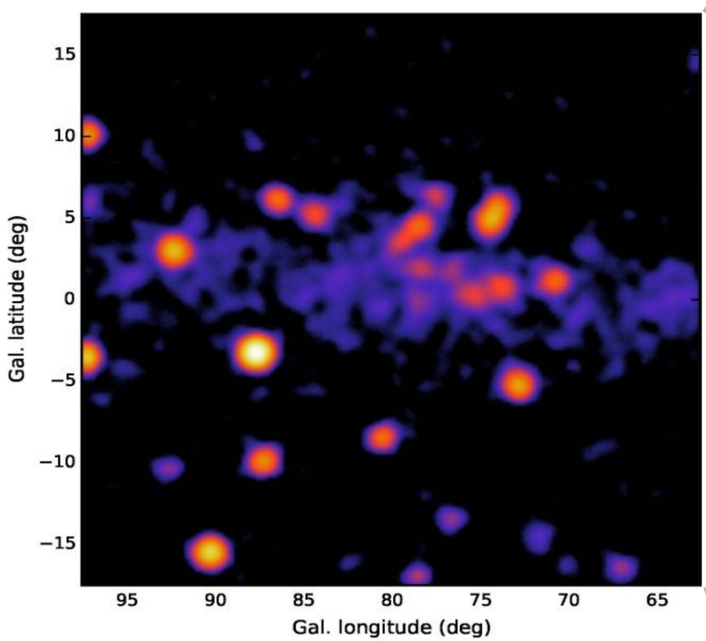
Extra slides

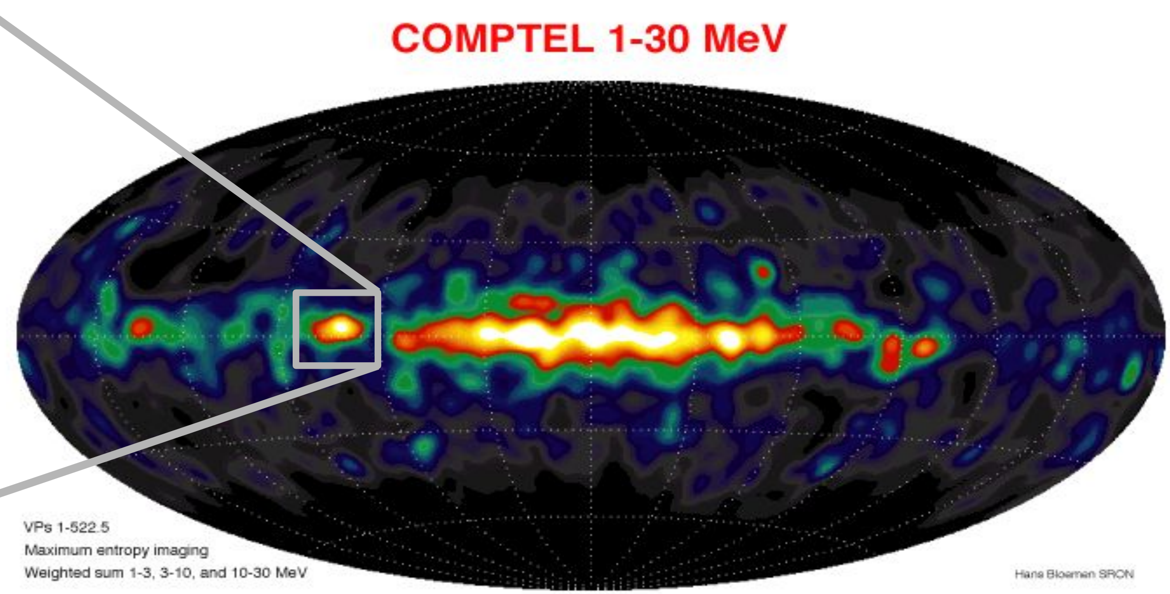
Angular resolution

- Angular resolution needs to be improved close to the physical limits (Doppler broadening, nuclear recoil)



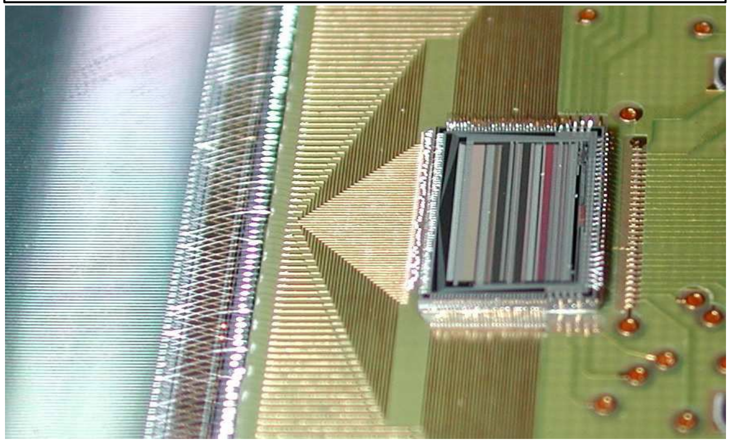
Cygnus region in the 1 - 3 MeV energy band with the e-ASTROGAM PSF (extrapolation of the 3FGL source spectra to low energies)

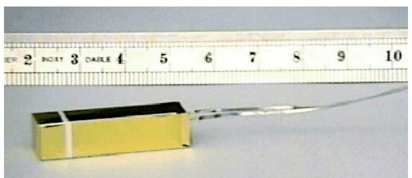




e-ASTROGAM Payload

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

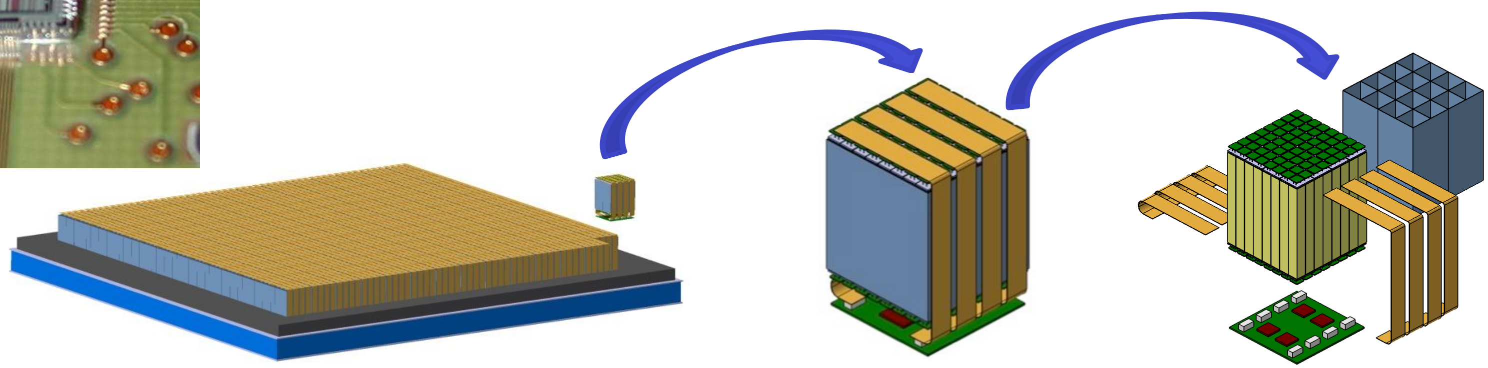




PICSiT CsI(Tl) pixel

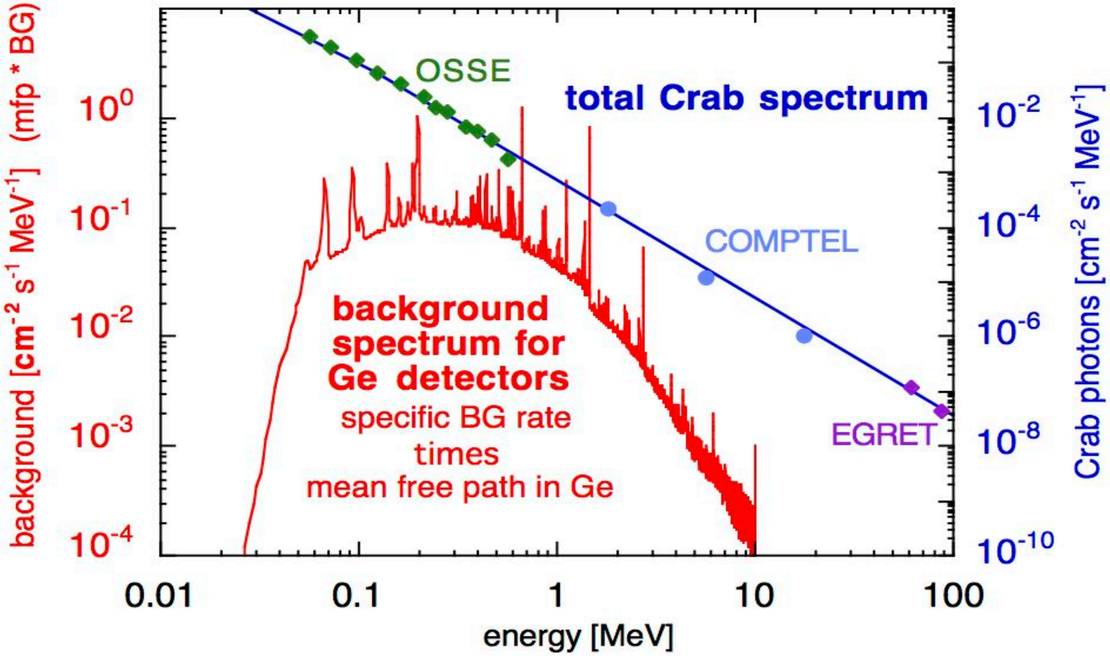
Fermi/LAT AC system

- **Tracker**: 56 layers of 4 times 5×5 DSSDs (5 600 in total) of 500 μm thickness and 240 μm pitch
- DSSDs bonded strip to strip to form 5×5 ladders
- Light and stiff mechanical structure
- Ultra low-noise front end electronics



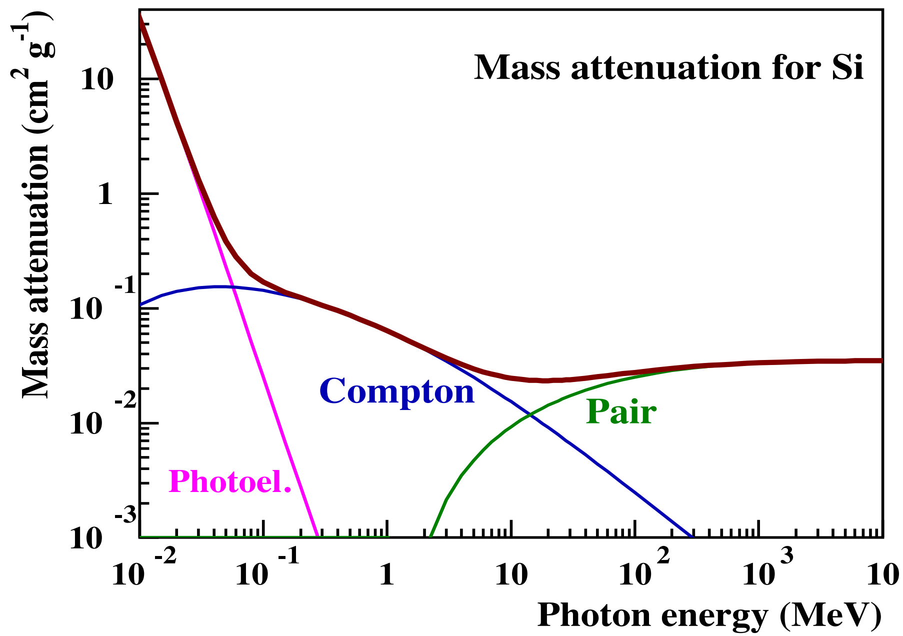
- **Calorimeter**: 33 856 CsI(Tl) bars coupled at both ends to low-noise Silicon Drift Detectors
- **ACD**: segmented plastic scintillators coupled to SiPM by optical fibers
- **Heritage**: AGILE, Fermi/LAT, AMS-02, INTEGRAL, LHC/ALICE…

e-ASTROGAM Observational challenges



☺ The MeV range is the domain of nuclear γ-ray lines (radioactivity, nuclear collision, positron annihilation, neutron capture)

☹ Strong instrumental background from activation of space-irradiated materials

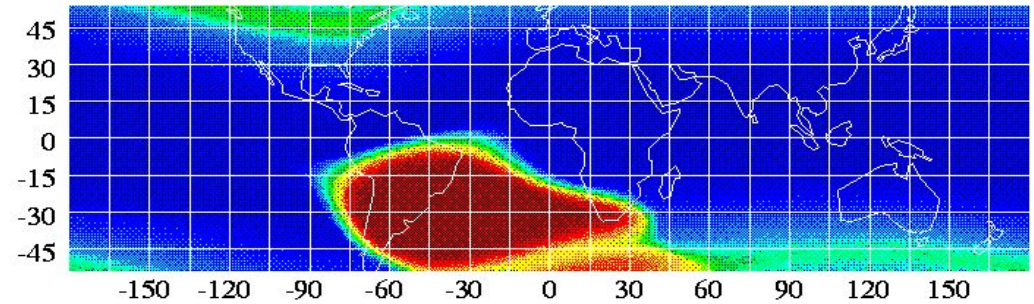


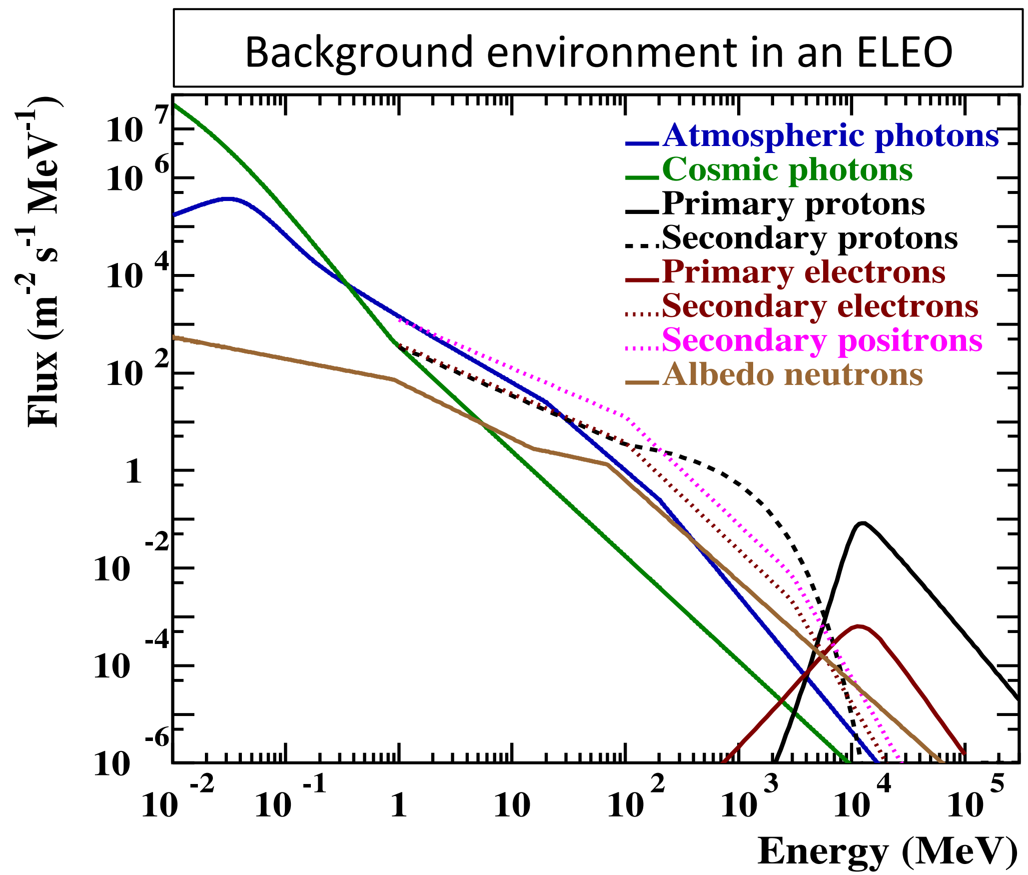
☹ Photon interaction probability reaches a minimum at ~ 10 MeV

☹ Three competing processes of interaction, Compton scattering being dominant around 1 MeV ⇒ complicated event reconstruction e-ASTROGAM

Mission profile

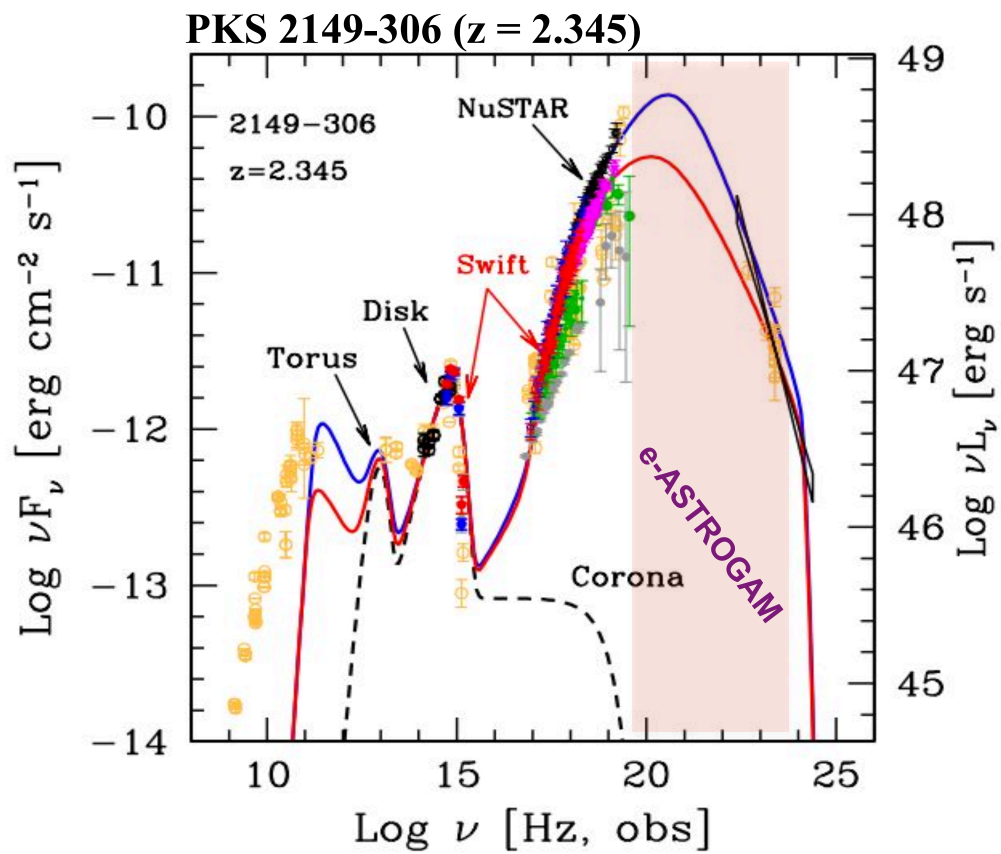
- **Orbit** – Equatorial (inclination $i < 2.5°$, eccentricity $e < 0.01$) low-Earth orbit (altitude in the range 550 - 600 km)
- **Launcher** – Ariane 6.2
- **Satellite communication** – ESA ground station at Kourou + ASI Malindi station (Kenya)
- **Data transmission** – via X-band (available downlink of 10 Mbps)
- **Observation modes** – (i) zenith-pointing sky-scanning mode, (ii) nearly inertial pointing, and (iii) fast repointing to avoid the Earth in the field of view
- **In-orbit operation** – 3 years duration + provisions for a 2+ year extension





Jet astrophysics in the era of new astronomies

- *Launch of ultra-relativistic jets in **GRBs**? Ejecta composition, energy dissipation site, radiation processes?*
- *Can short-duration GRBs be unequivocally associated to **gravitational wave** signals?*
- *How does the accretion disk/jet transition occur around supermassive black holes in **AGN**?*
- *Are BL Lac blazars sources of **UHECRs** and high-energy **neutrinos**?*

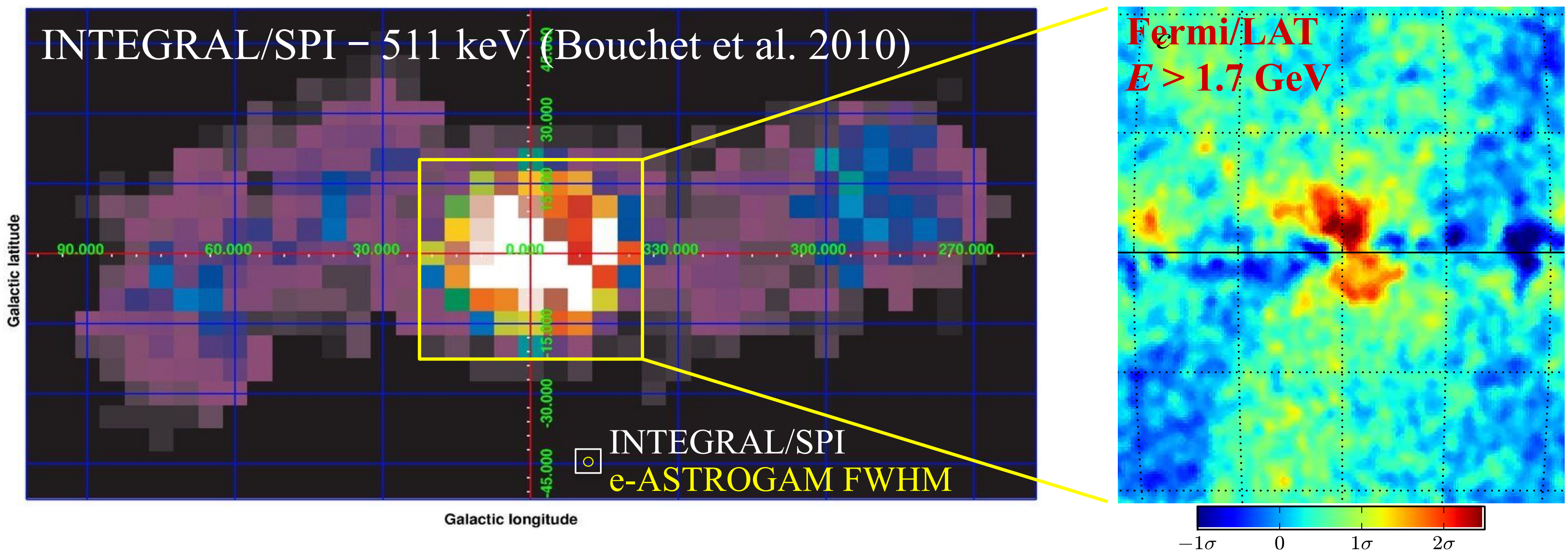


✓ With its wide **field of view**, unprecedented **sensitivity** over a large spectral band, and exceptional capacity for **polarimetry**, **e-ASTROGAM** will give access to a variety of extreme **transient** phenomena

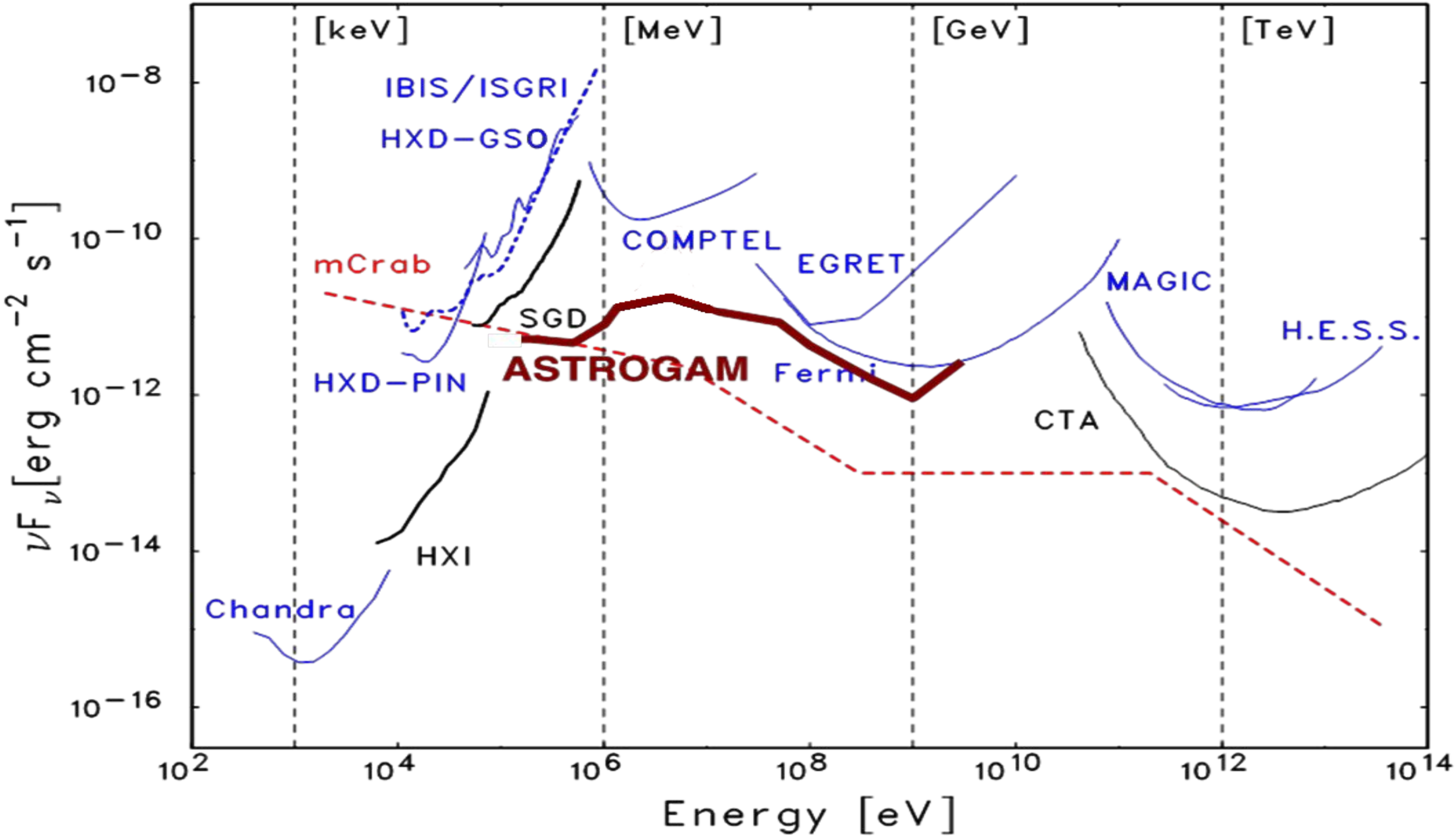
The high-energy mysteries at the Galactic Center

- *Origin of the **Fermi Bubbles** and of the **511 keV emission** from the Galaxy's bulge? Are these linked to a past activity of the central **supermassive black hole**? What is causing the **GeV excess** emission from the center region?*

✓ With a **sensitivity** and an **angular resolution** in the MeV – GeV range significantly improved over previous missions, **e-ASTROGAM** will enable a detailed **spectro-imaging** of the various high-energy components

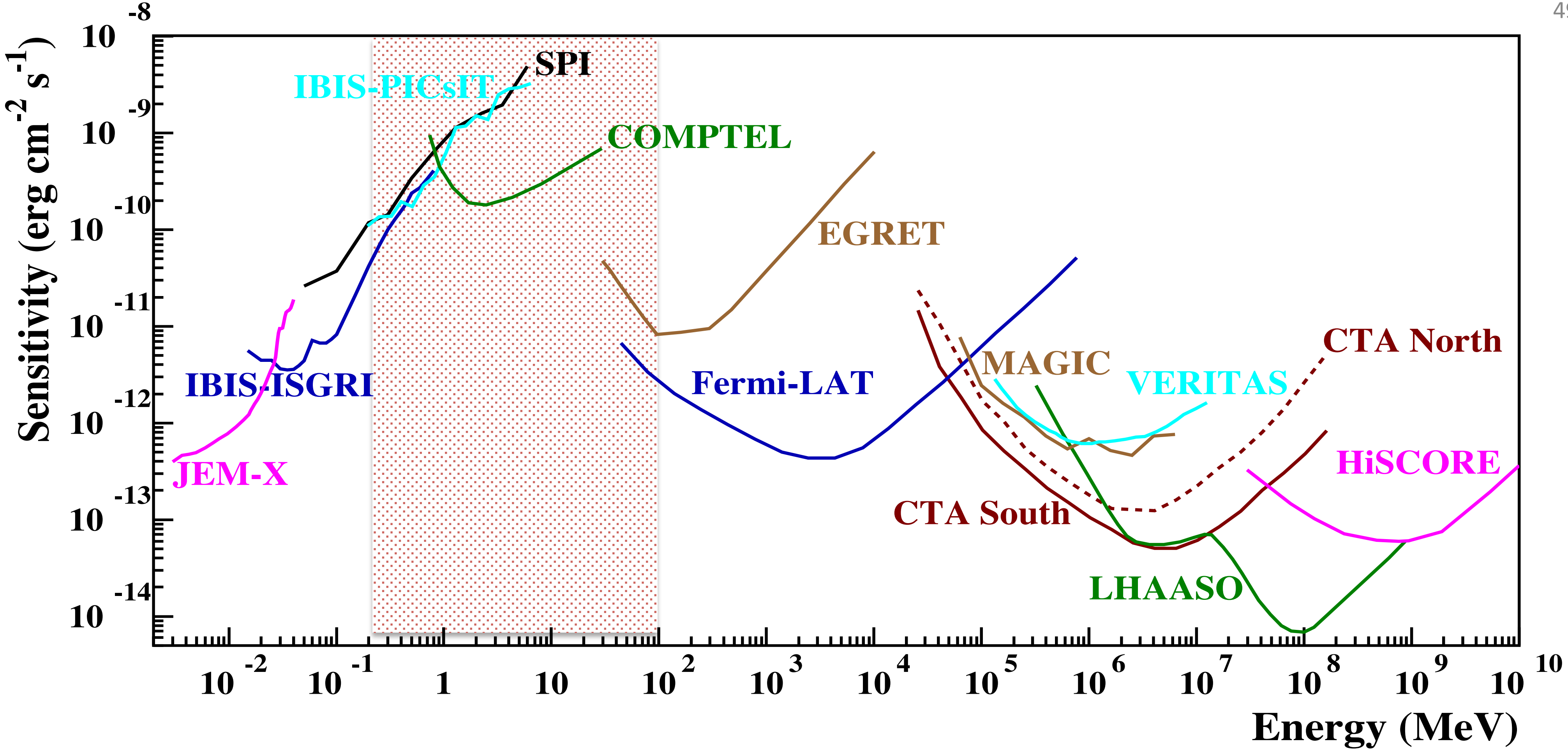


ASTROGAM 3.5 yr survey sensitivity



- **ASTRO-H/SGD** – 3σ sensitivity for 100 ks exposure of an isolated point source
- **COMPTEL** and **EGRET** – sensitivities accumulated during the whole duration of the CGRO mission (9 years)
- **Fermi/LAT** – 5σ sensitivity for a high Galactic latitude source and after 1 year observation in survey mode
- **ASTROGAM** – 5σ sensitivity for a high Galactic latitude source after 3.5 years in survey mode

The MeV/sub-GeV domain

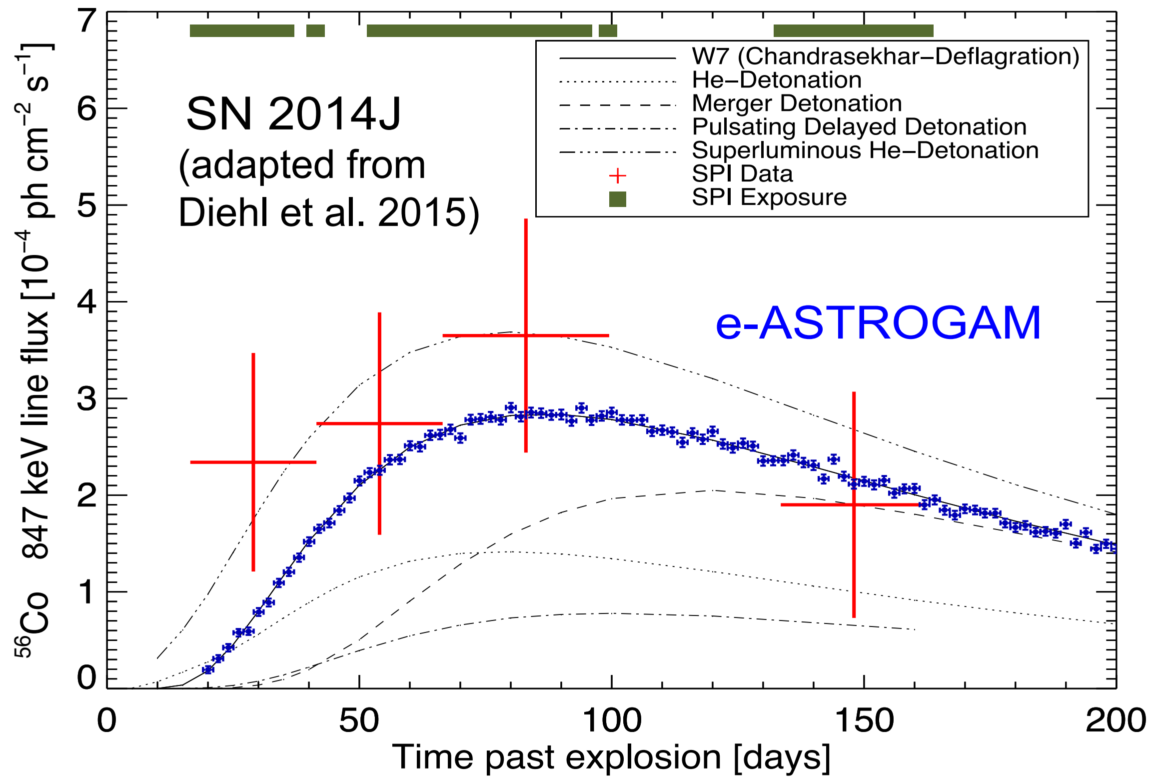


- Worst covered part of the electromagnetic spectrum (only a few tens of steady sources detected so far between 0.2 and 30 MeV)
- Many objects have their peak emissivity in this range (GRBs, blazars, pulsars...)

Supernovae, nucleosynthesis, and Galactic chemical evolution

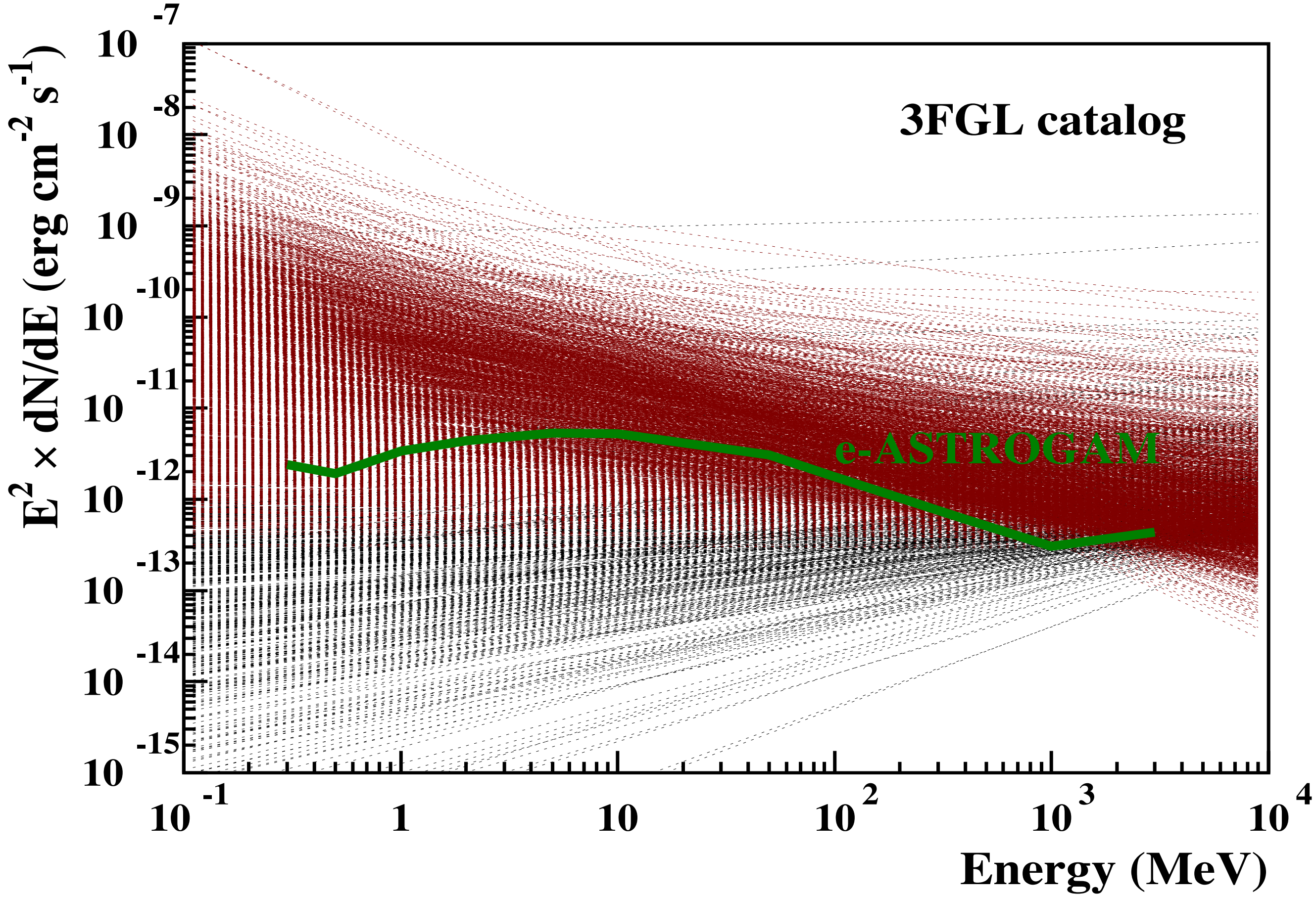
- *How do thermonuclear and core-collapse SNe explode? How are cosmic isotopes created in stars and distributed in the interstellar medium?*

✓ With a remarkable improvement in **γ-ray line sensitivity** over previous missions, **e-ASTROGAM** should allow us to finally understand the progenitor system(s) and explosion mechanism(s) of **Type Ia SNe** (^{56}Ni, ^{56}Co), the dynamics of **core collapse** in massive star explosions (^{56}Co, ^{57}Co), and the history of **recent SNe** in the Milky Way (^{44}Ti, ^{60}Fe...)



e-ASTROGAM Discovery space

- Over 3/4 of the sources from the 3rd *Fermi* LAT Catalog (3FGL), 2415 sources over 3033, have power-law spectra (E_γ > 100 MeV) steeper than E_γ^{-2}, implying that their peak energy output is below 100 MeV



- These includes more than 1200 (candidate) blazars (mostly FSRQ), about 150 pulsars, and nearly **900 unassociated sources**

- Most of these sources will be detected by **e-ASTROGAM** ⇒ large discovery space for new sources and source classes