Search for dark matter in the multimessenger era

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Multimessenger Data analysis in the era of CTA

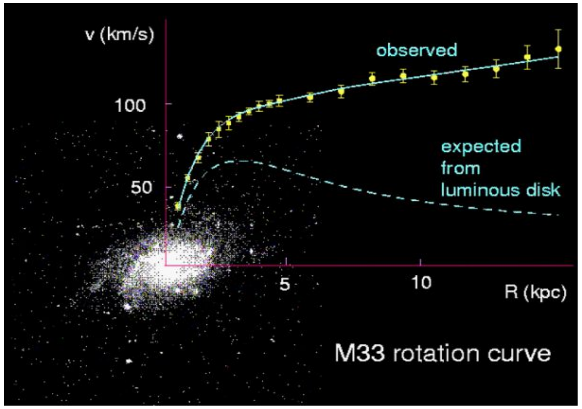
Sexen Center for Astrophysics, 27June 2019

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.

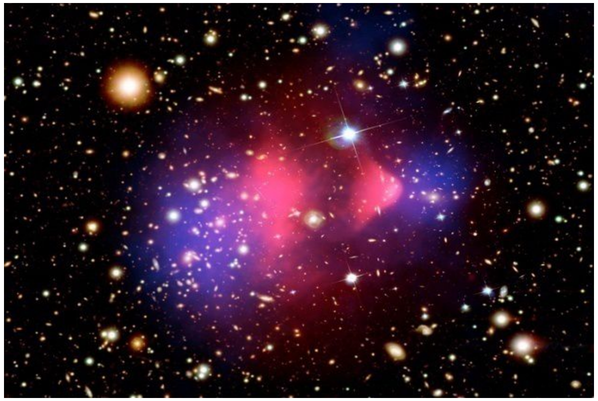
Since then, even more evidence:

Rotation curves of galaxies

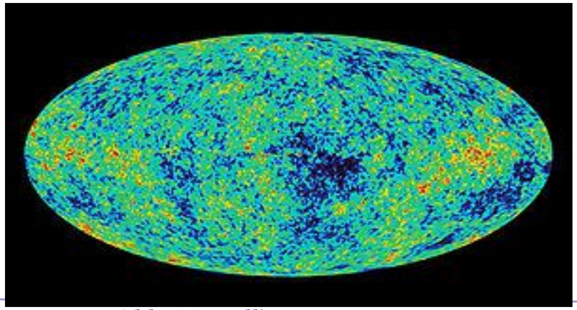


Gravitational lensing

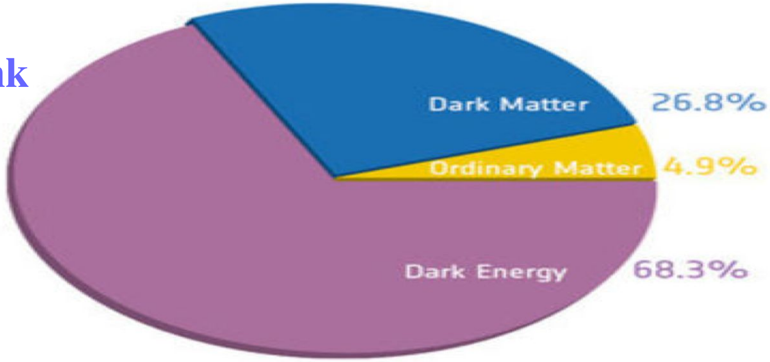
Bullet cluster



Structure formation as deduced from CMB



Data by Plank imply:



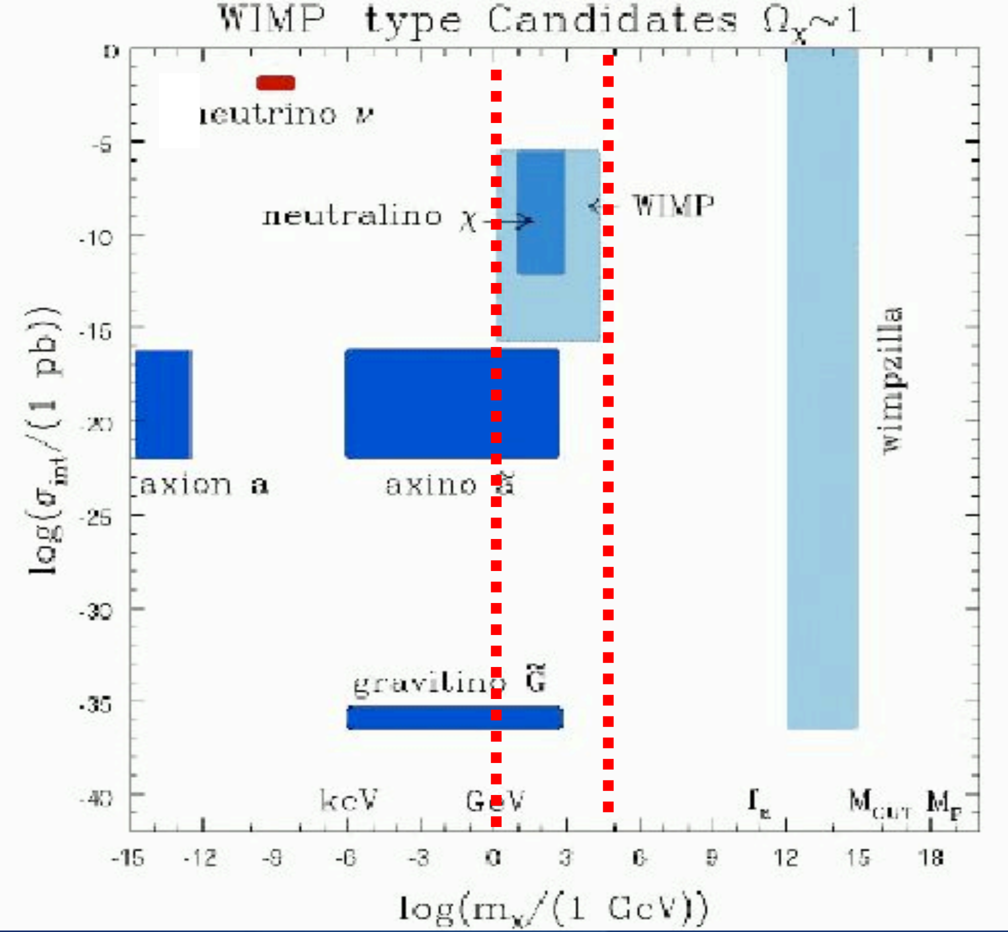
$\Omega_{Dm} \approx 26.8\%$

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

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
- NEUTRALINO
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes



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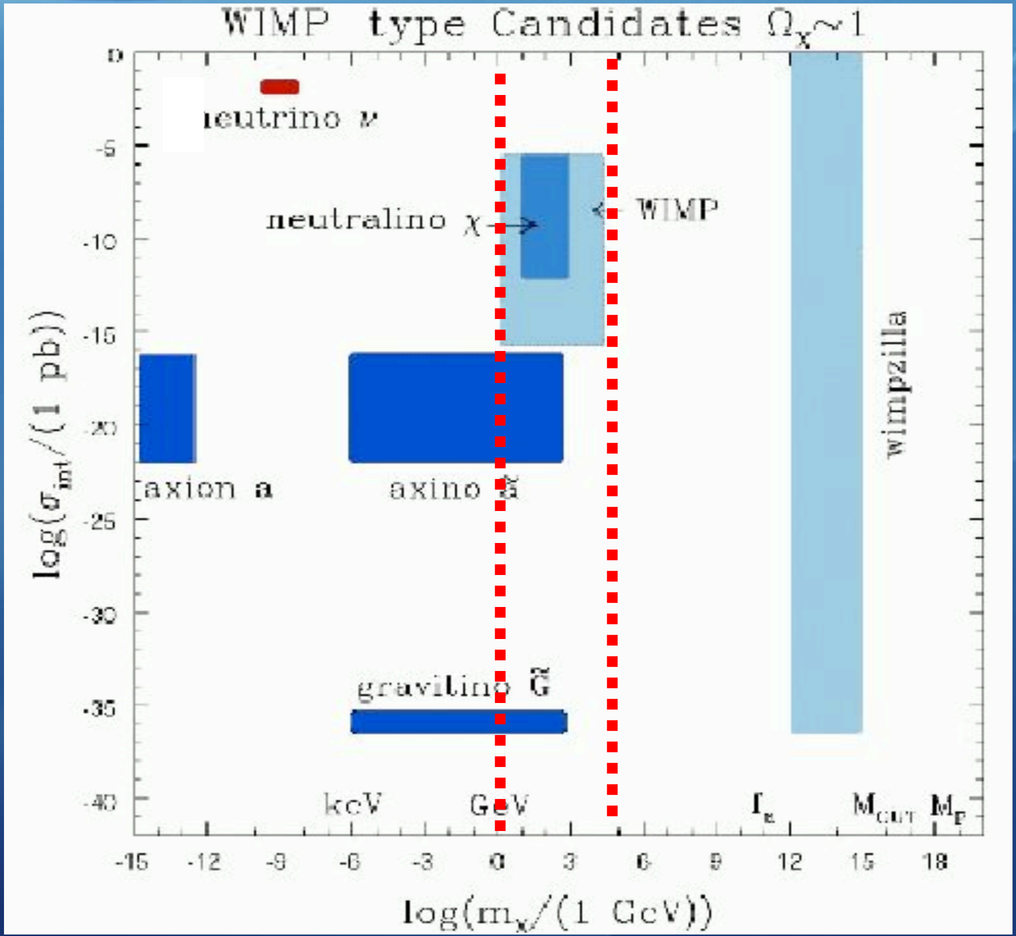
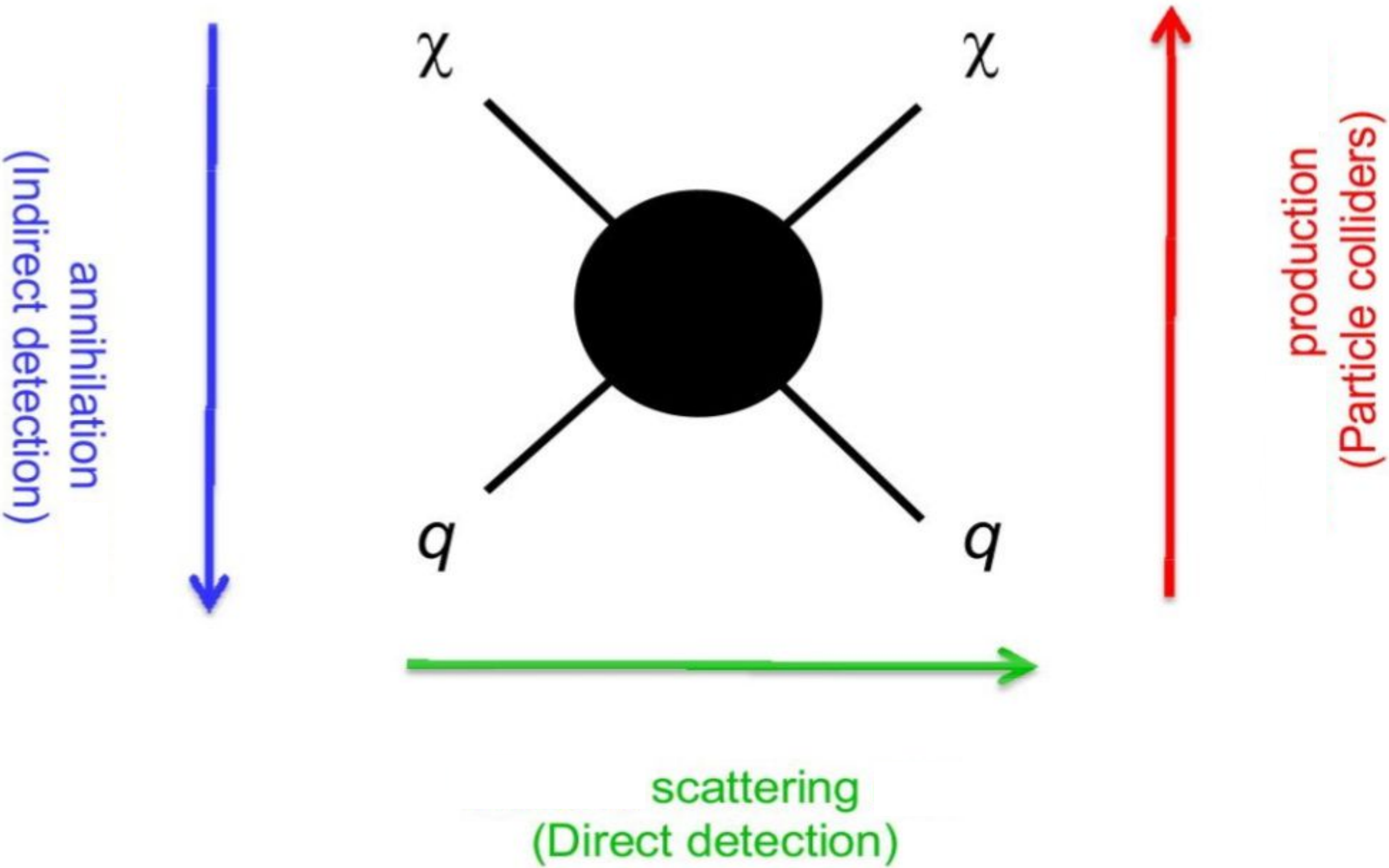
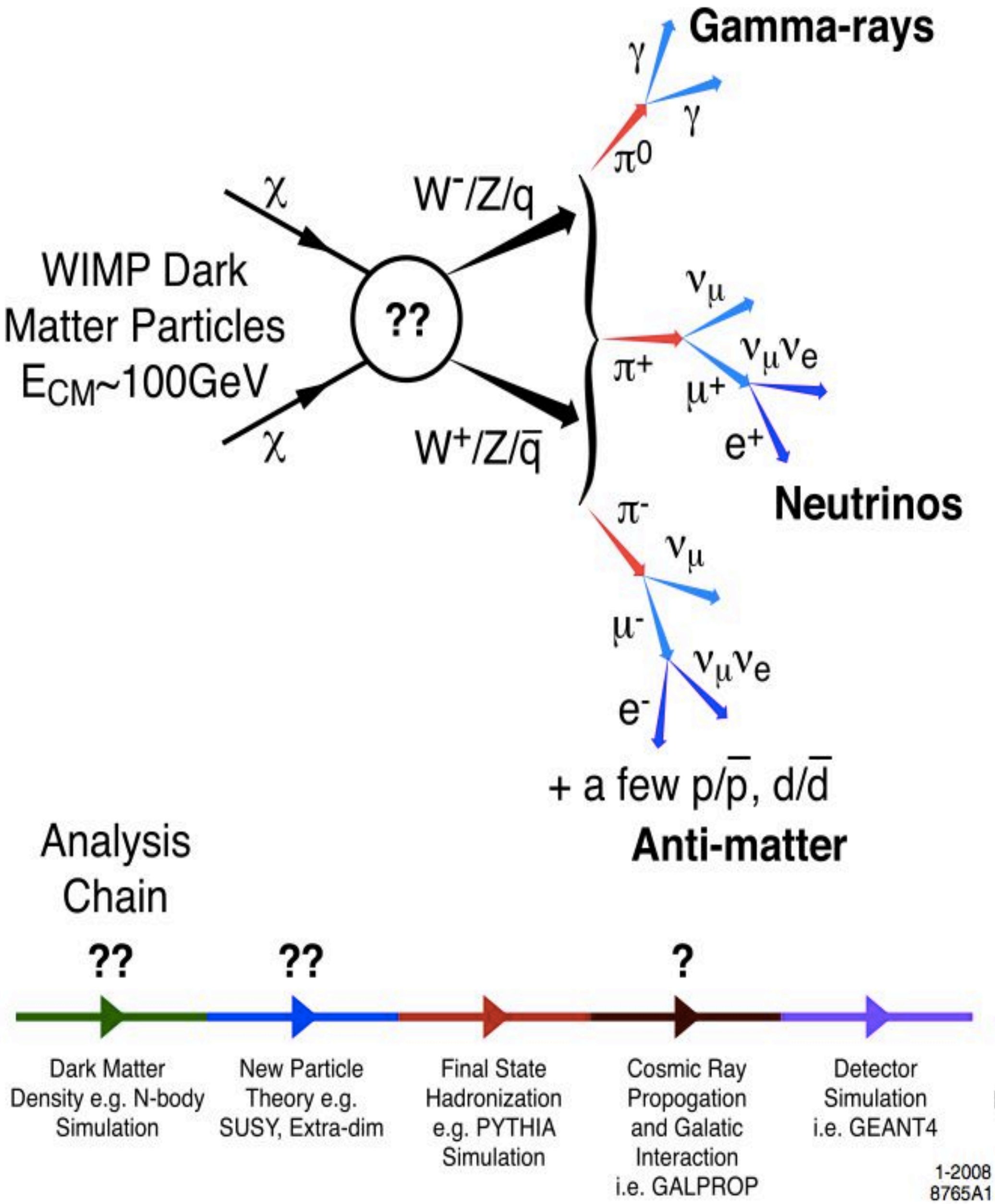
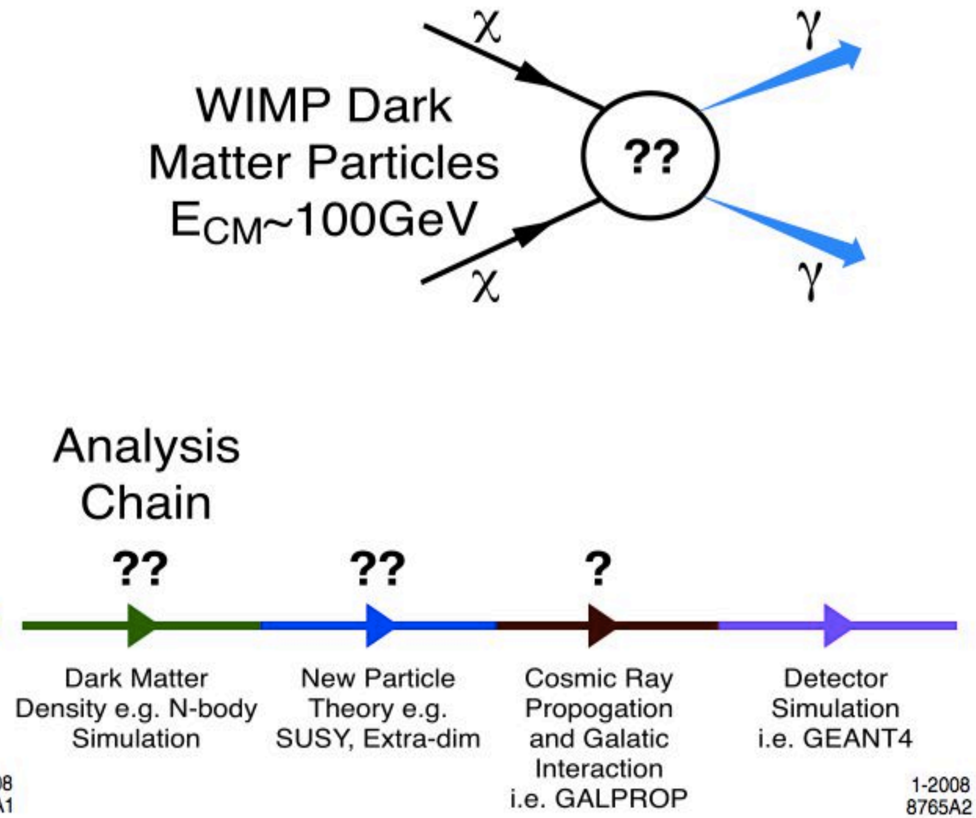


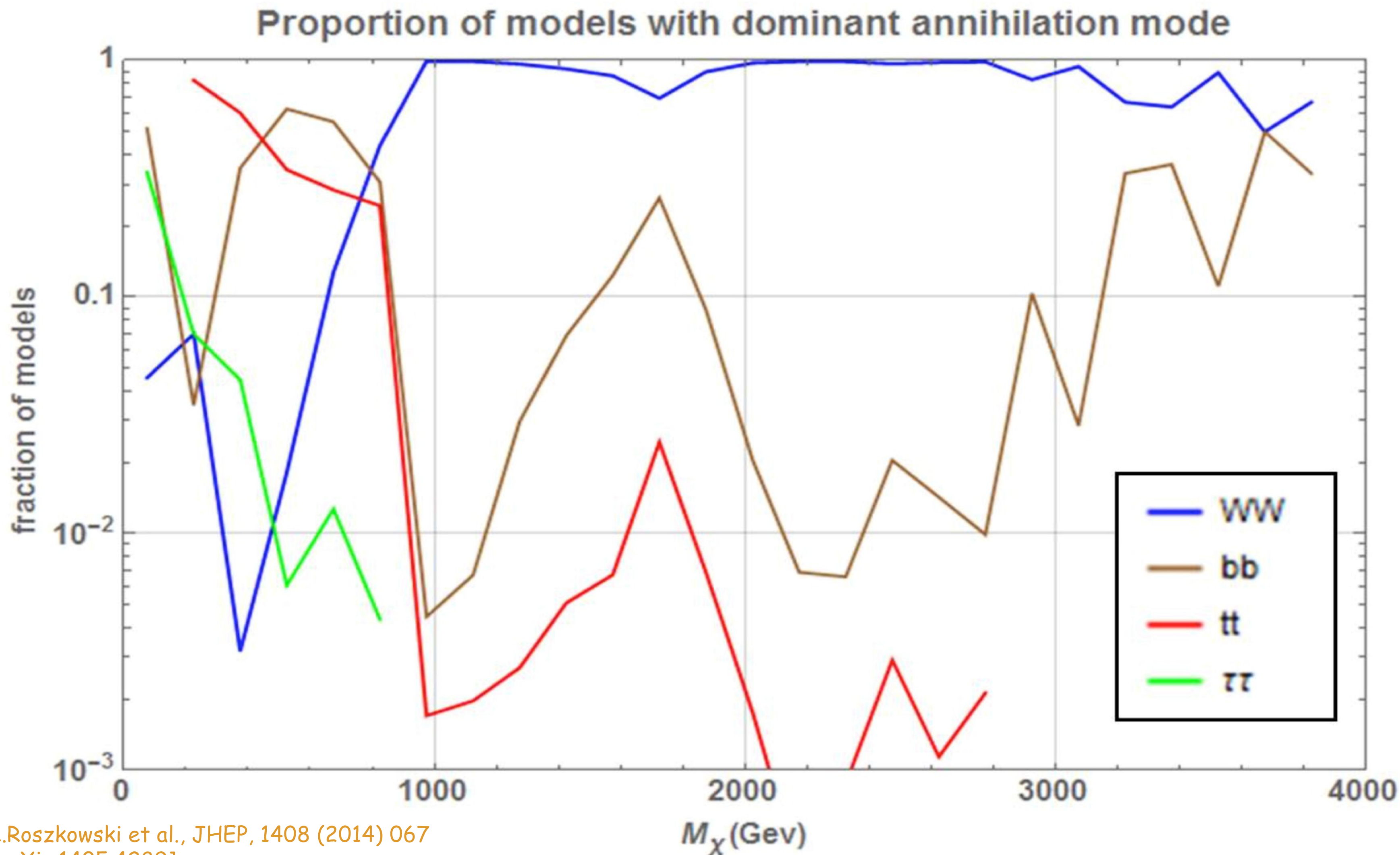

χ
χ
q
q
annihilation
(Indirect detection)
production
(Particle colliders)
scattering
(Direct detection)

Annihilation channels



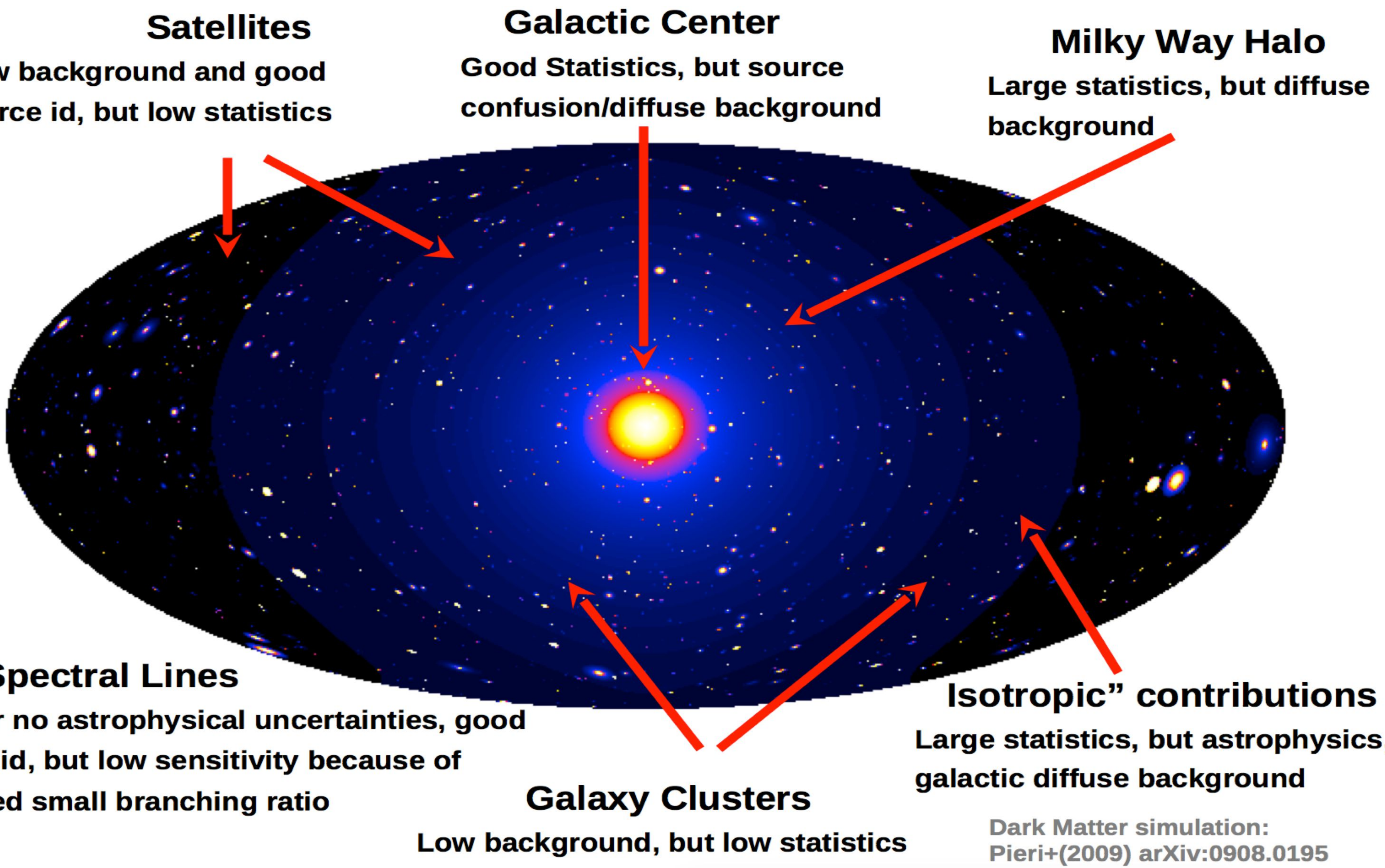


Which channel to choose?
Example: The dominant annihilation modes in the pMSSM scan



L.Roszkowski et al., JHEP, 1408 (2014) 067
[arXiv:1405.4289]

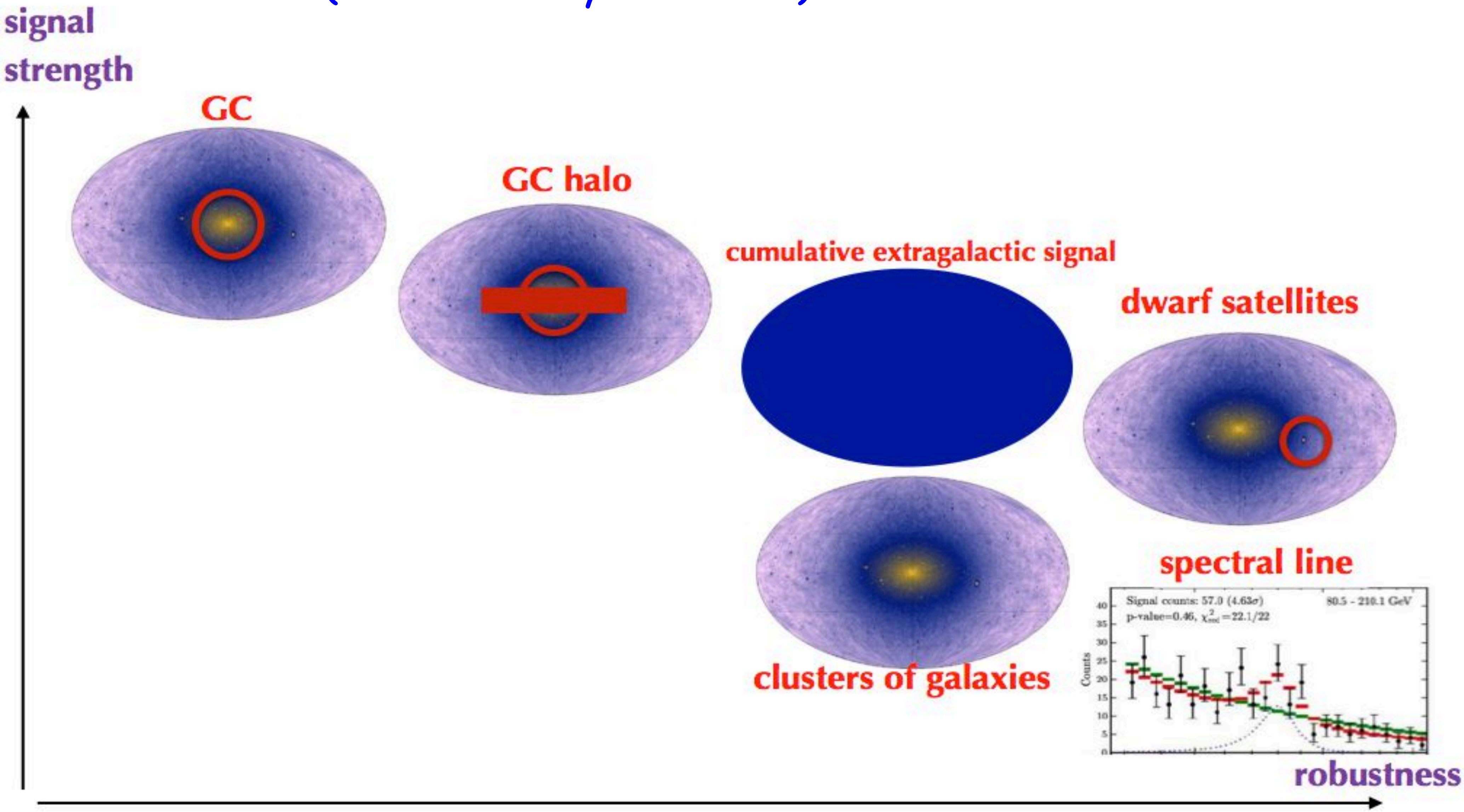
Dark Matter Search: Targets and Strategies



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

Dark Matter Search: Targets and Strategies

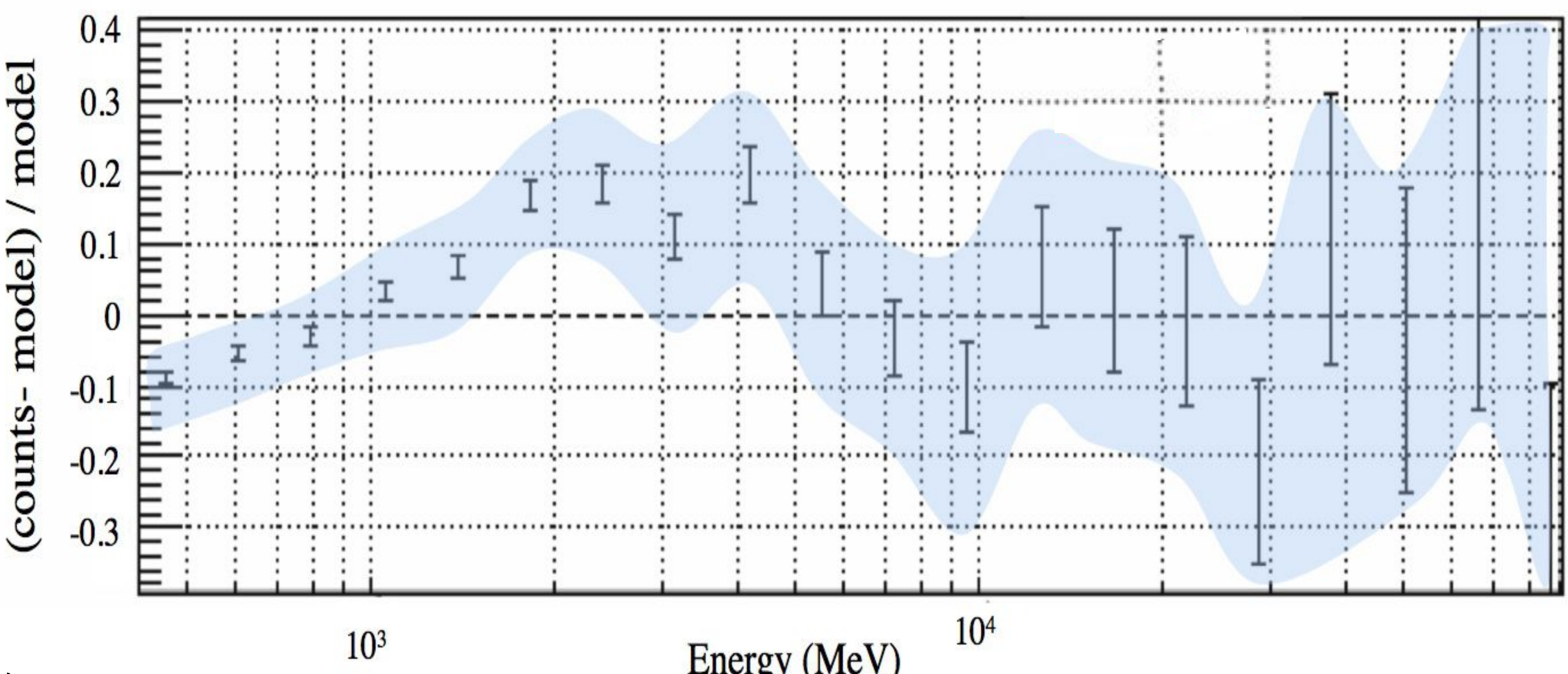
(Another way to see it)



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

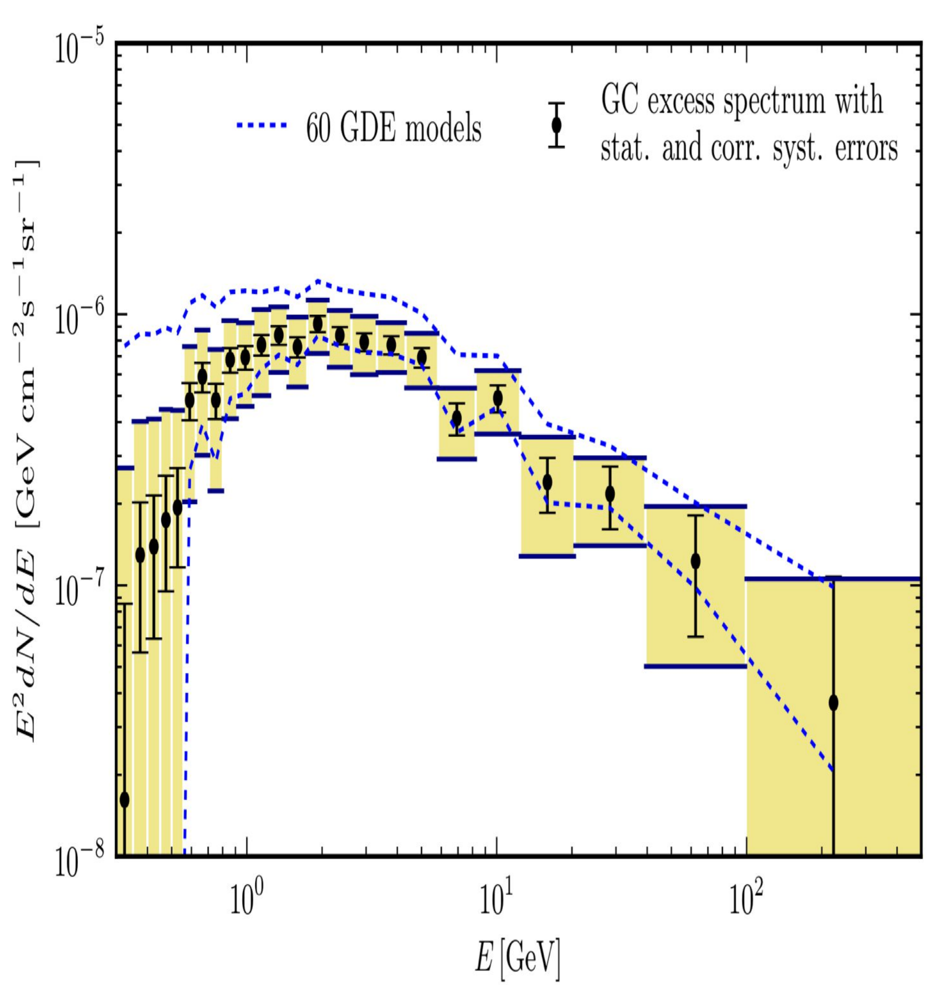
11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

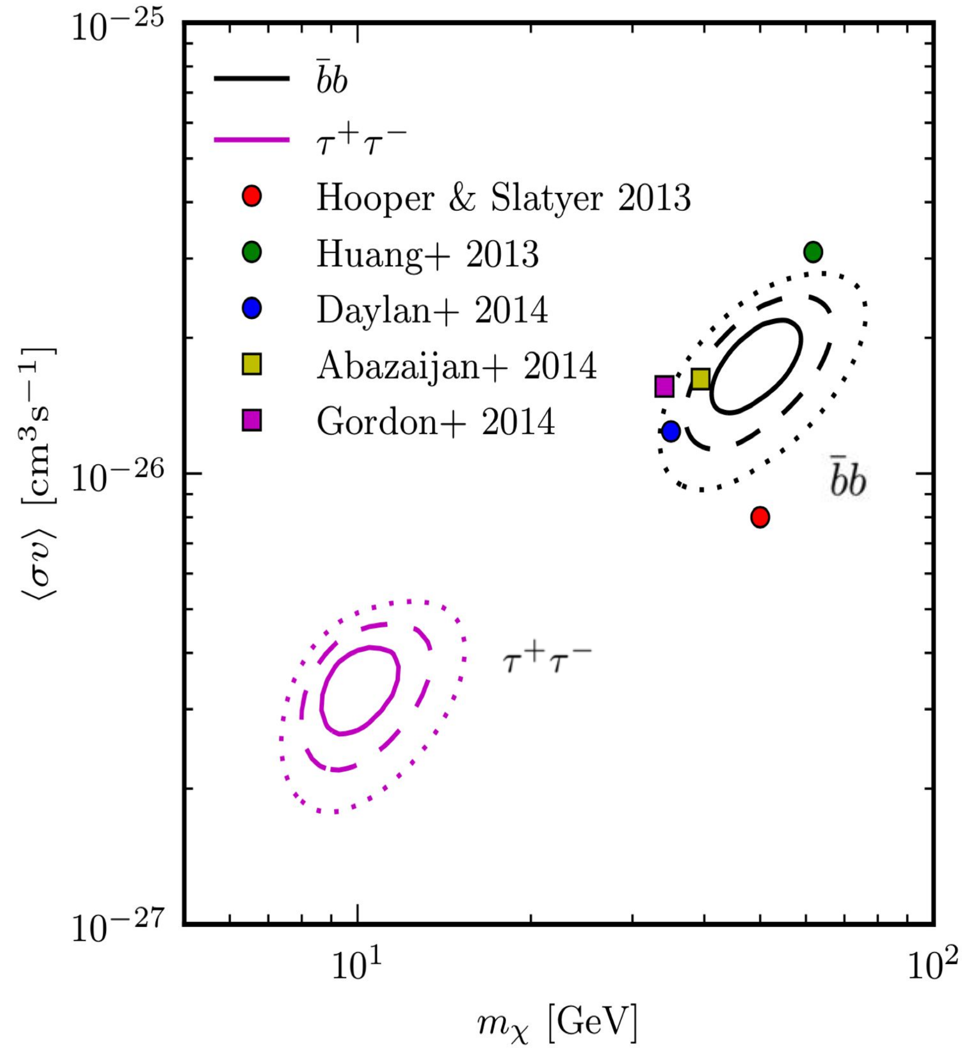
- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV



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

The GeV excess





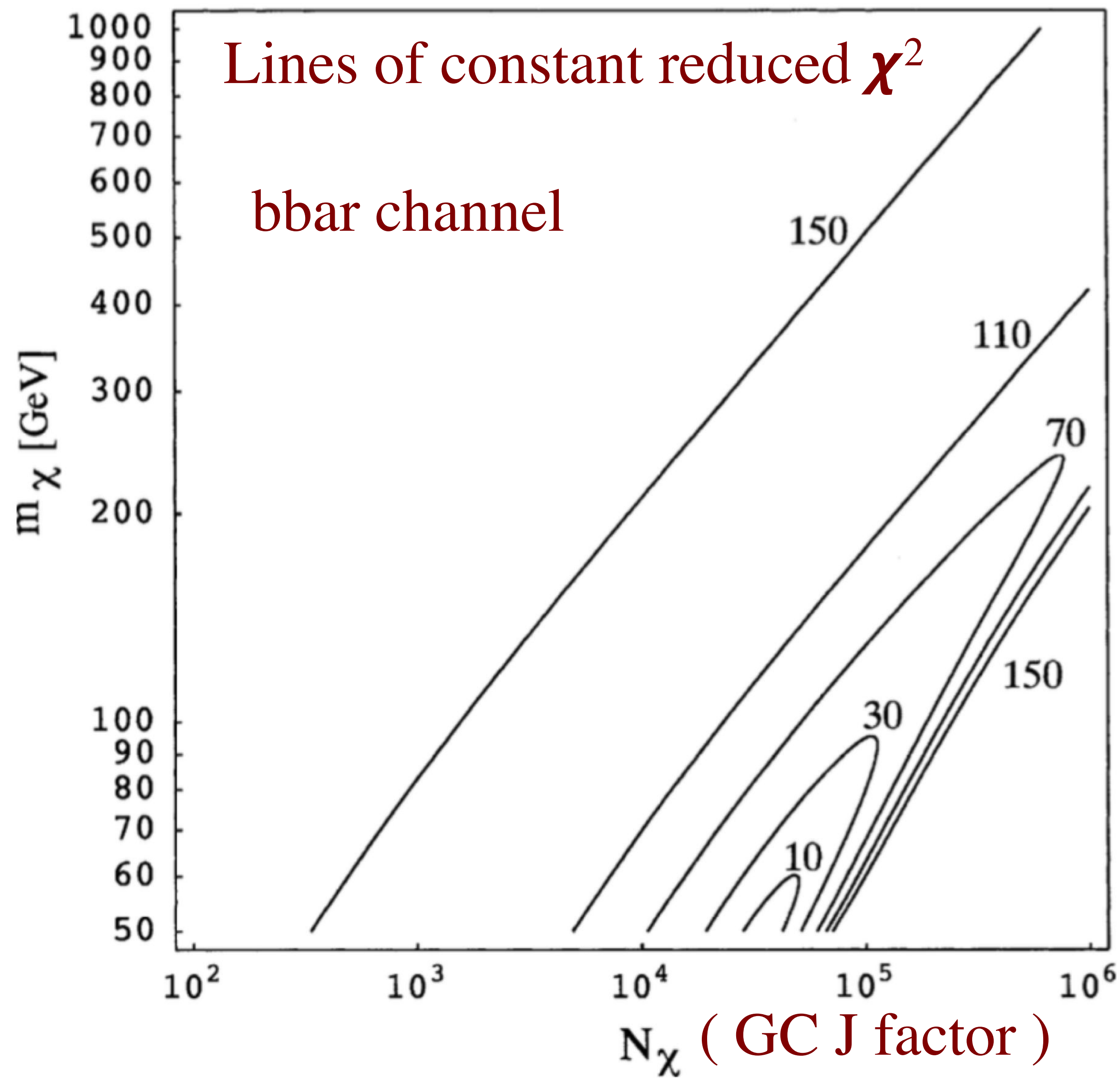
A lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center

Calore et al, arXiv:1409.0042v1

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 !

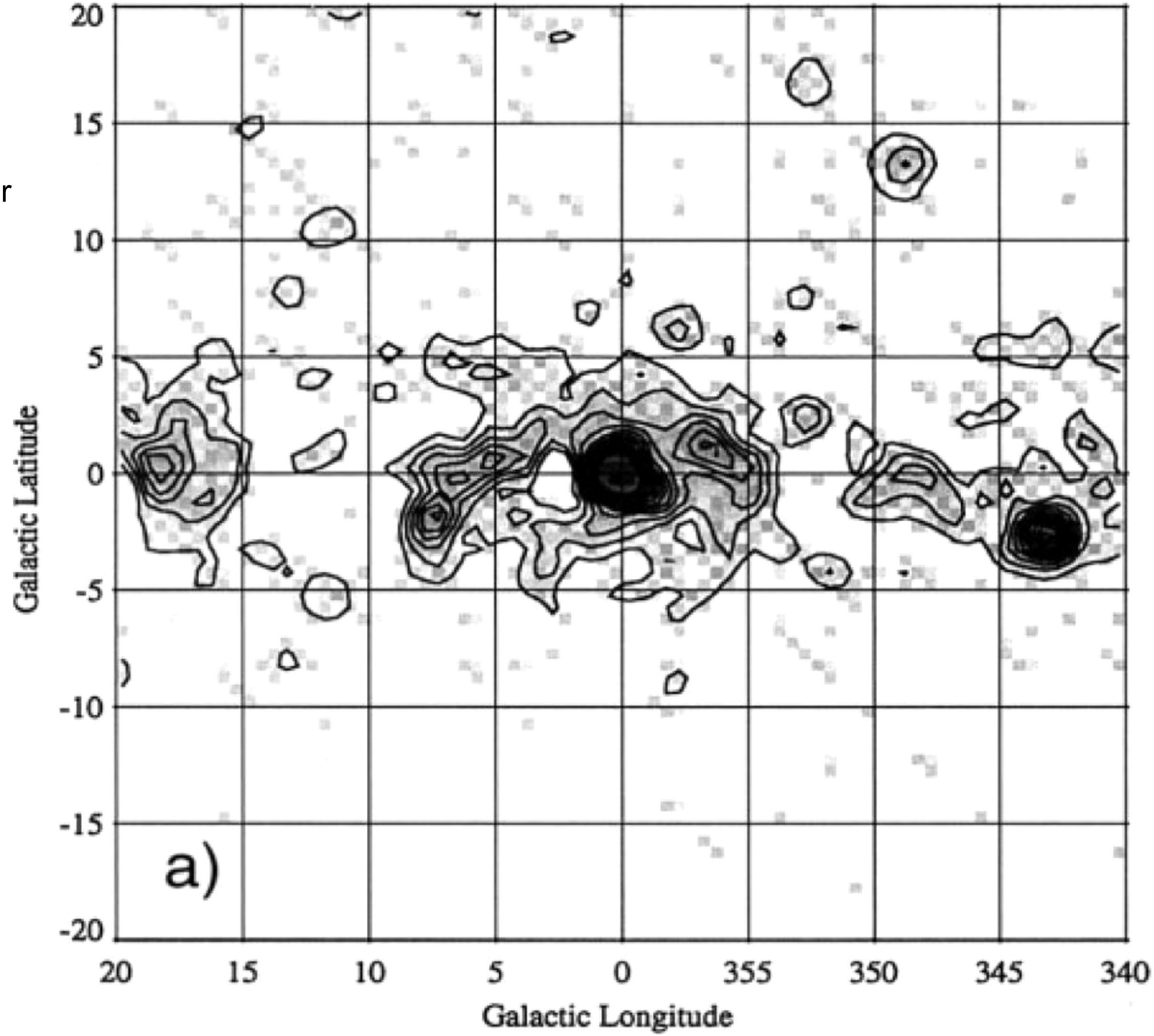
mass ~ 50- 80 GeV



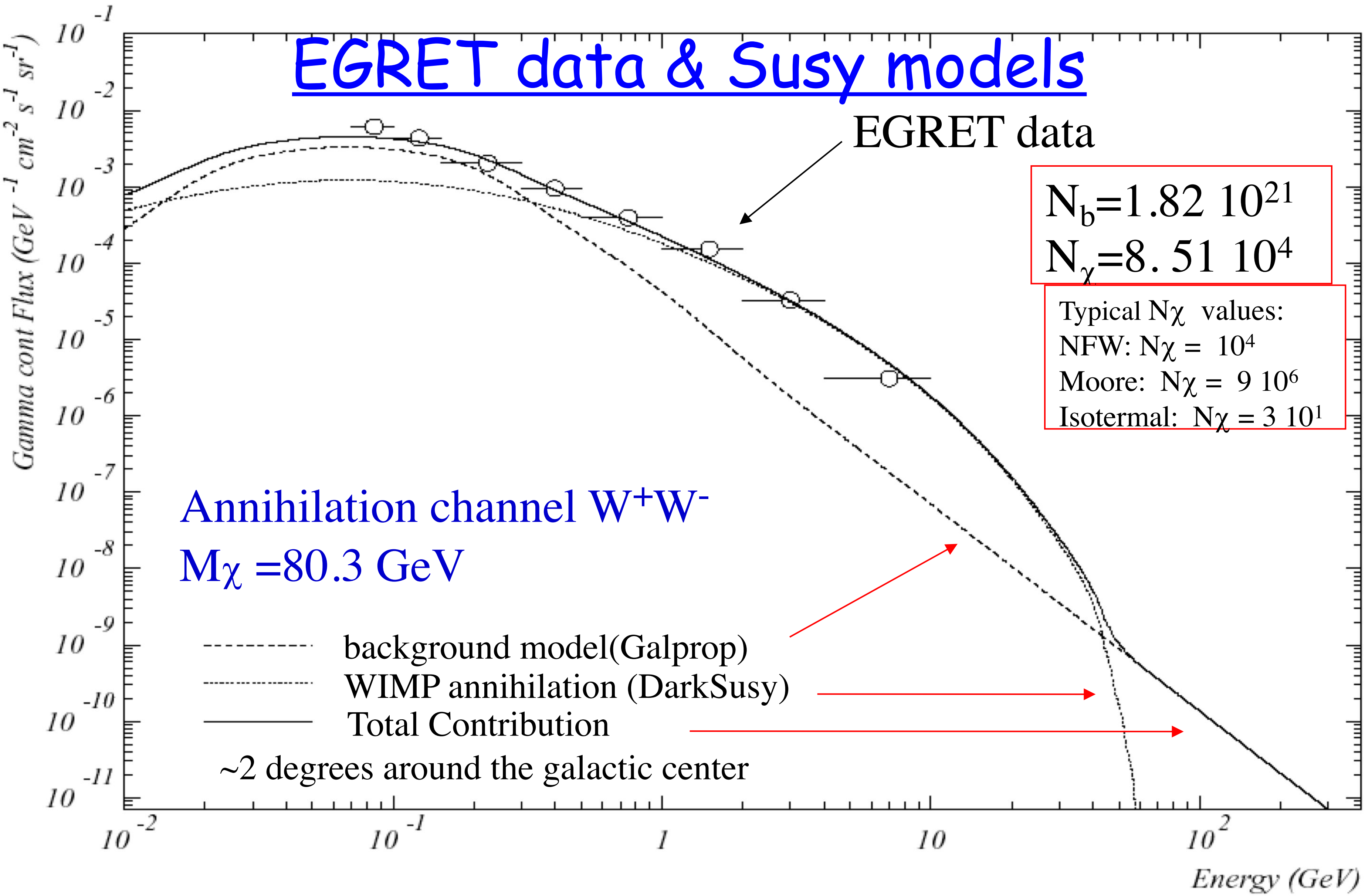
A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

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 : 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)

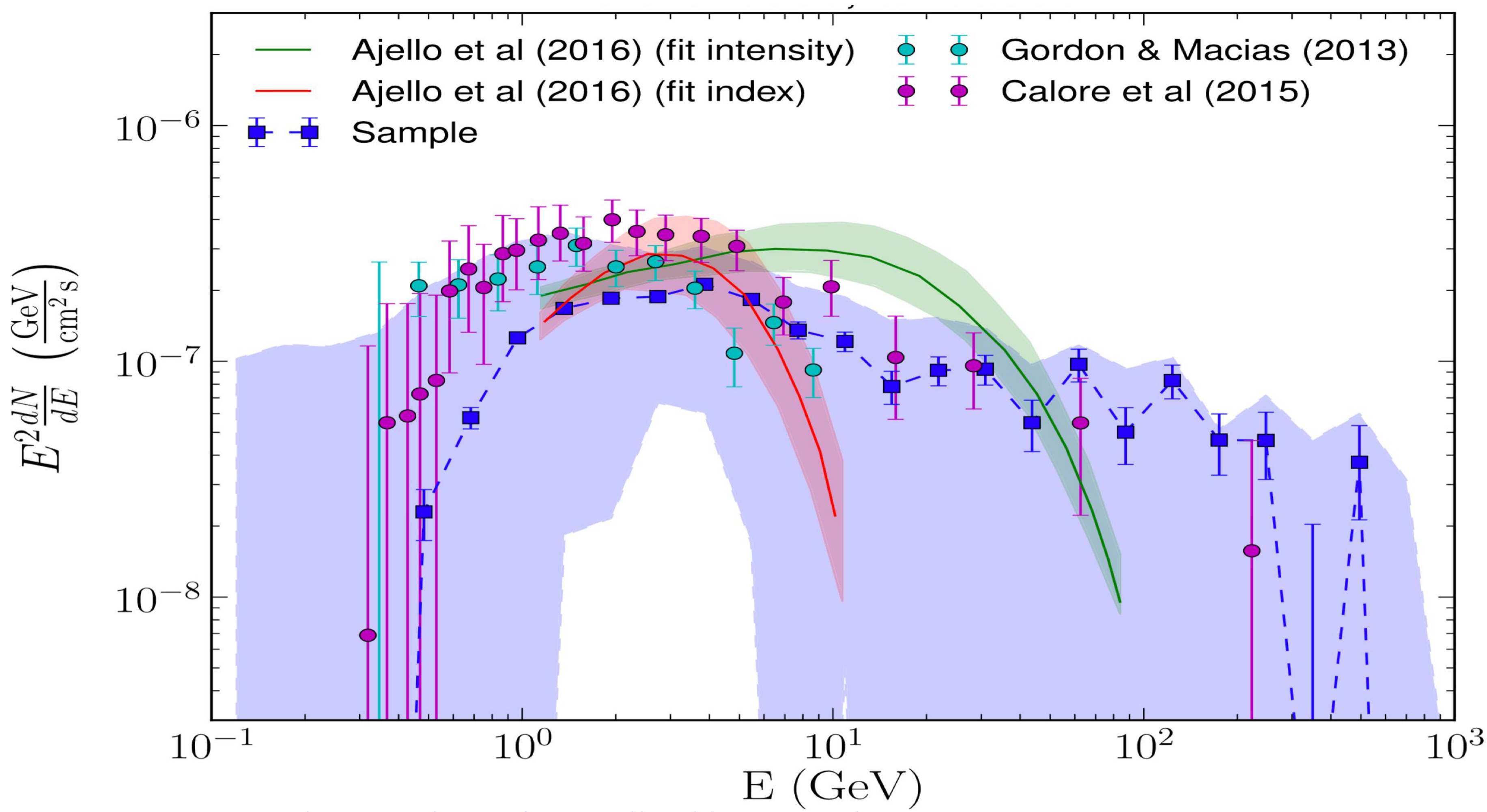
Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope
Dan Hooper , Lisa Goodenough . (21 March 2011). 21 pp. **Phys.Lett. B697 (2011) 412-428**

....

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 (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 : 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

- Molecular Clouds in the disk

De Boer et al. arXiv:1610.08926, arXiv:1707.08653

- 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 ?

The GeV excess

in 2016 two papers on Strong support for millisecond pulsars:

S. K. Lee et al., Evidence for Unresolved γ-Ray Point Sources in the Inner Galaxy, Phys. Rev. Lett. 116 (2016) 051103, [arXiv:1506.05124].

R. Bartels et al., Strong support for the millisecond pulsar origin of the Galactic center GeV excess Phys. Rev. Lett. 116 (2016) 051102, [arXiv:1506.05104].

but in R. Leane et al., Dark Matter Strikes Back at the Galactic Center, arXiv:1904.08430 it is shown that "large artificial injected dark matter signals are completely misattributed to point sources." so dark matter may provide a dominant contribution to the GCE after all.

then:
The Return of the WIMP: Missing Energy Signals and the Galactic Center Excess,
Carena et al., arXiv:1905.03768
excess in tri-lepton events plus missing energy observed by the ATLAS experiment at the LHC could be interpreted as a signal of low energy supersymmetry. $M\chi$ =60 GeV (bb) compatible with the muon anomalous magnetic moment and consistent with the requirement of obtaining the correct Higgs mass in the Minimal Supersymmetric Standard Model (MSSM)

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

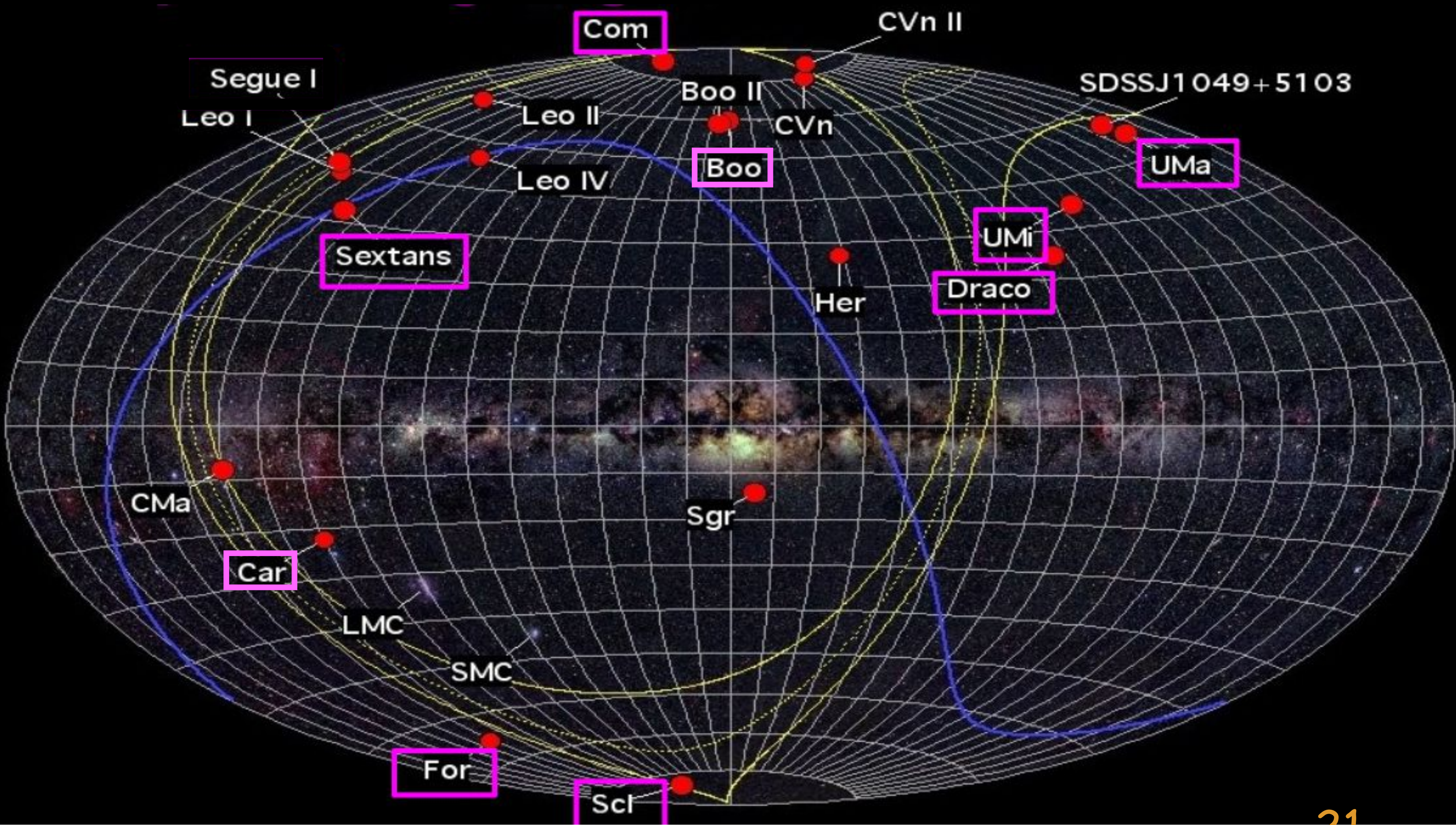
- Look for correlated synchrotron emission near the GC

More Fermi LAT analysis

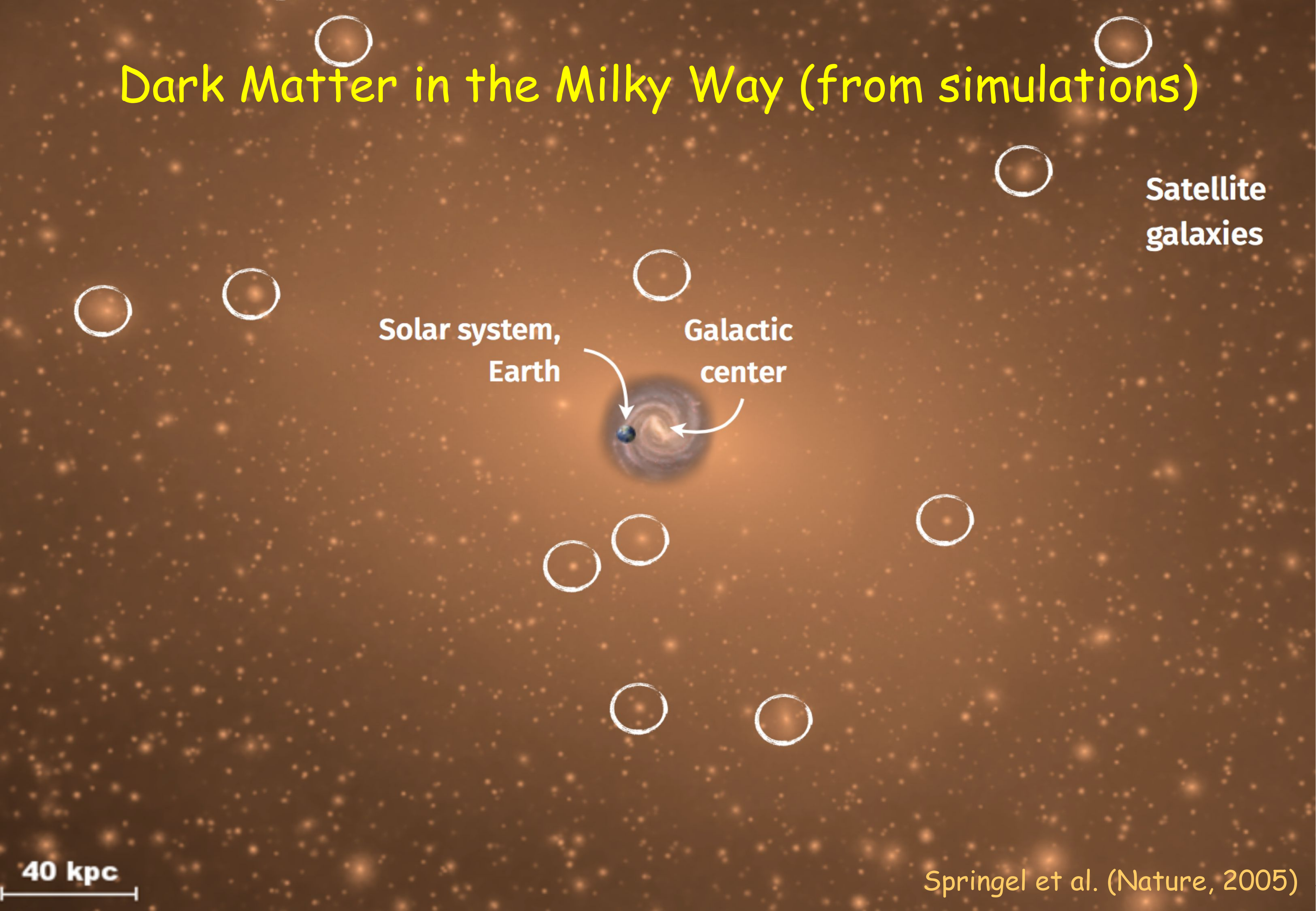
- Diffuse emission modeling
- Analysis of point sources near the GC

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

Classical Dwarf spheroidal galaxies: promising targets for DM detection

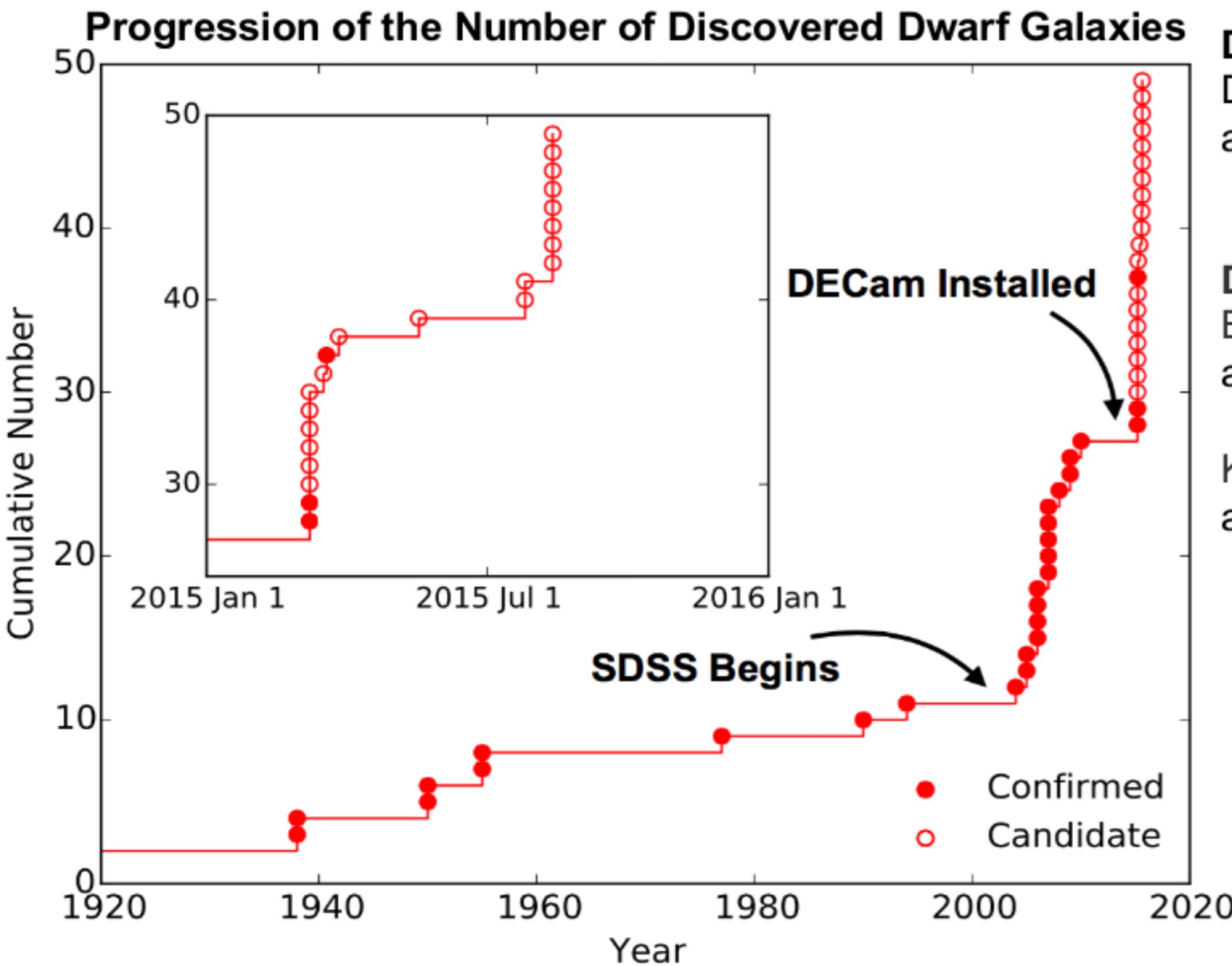


Dark Matter in the Milky Way (from simulations)



Springel et al. (Nature, 2005)

Dwarf Spheroidal Galaxies: Growing number of known targets

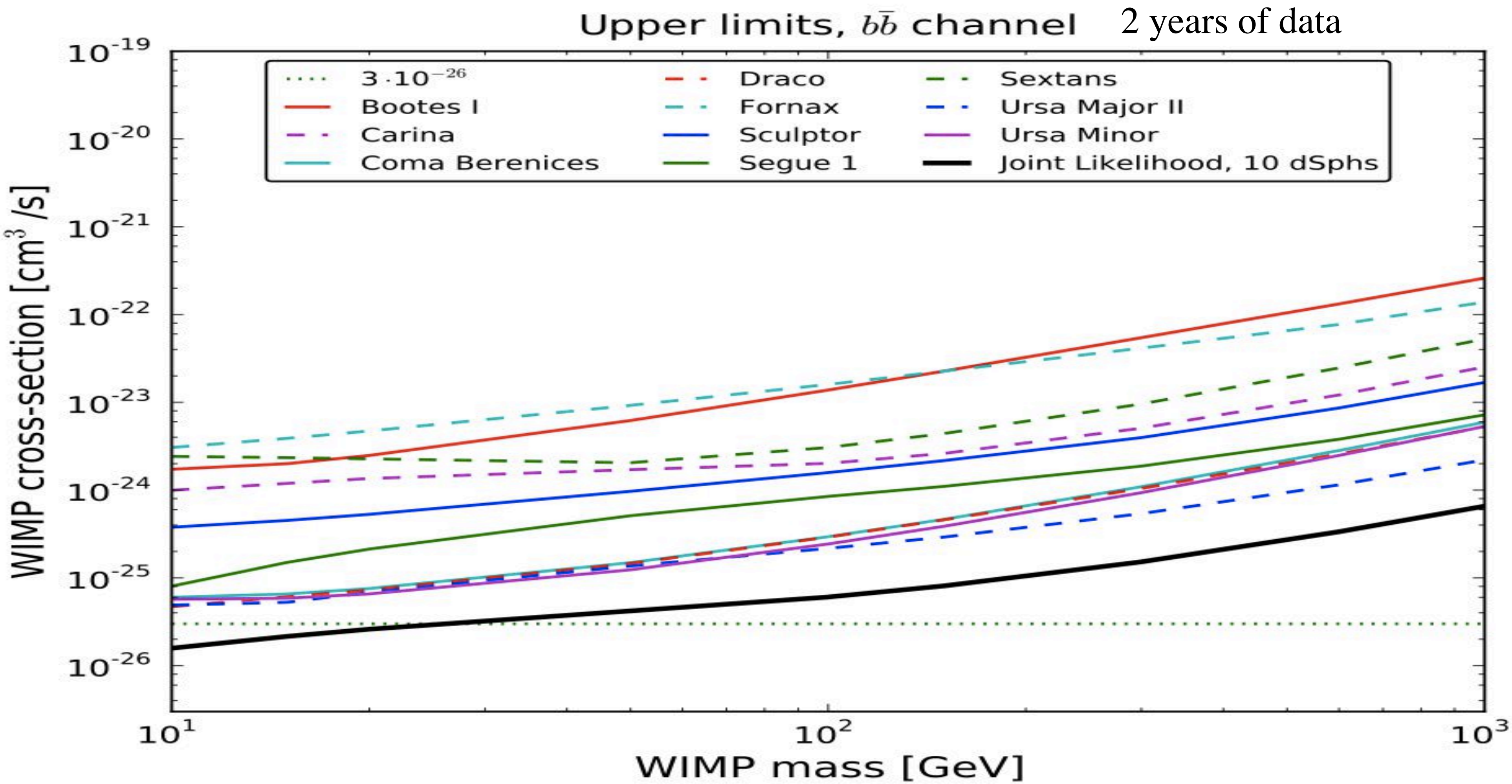


DES Year 2 Data:
Drlica-Wagner+,
arXiv:1508.03622

DES Year 1 Data:
Bechtol+:
arXiv:1503.02584

Koposov+:
arXiv:1503.02079

Dwarf Spheroidal Galaxies combined analysis

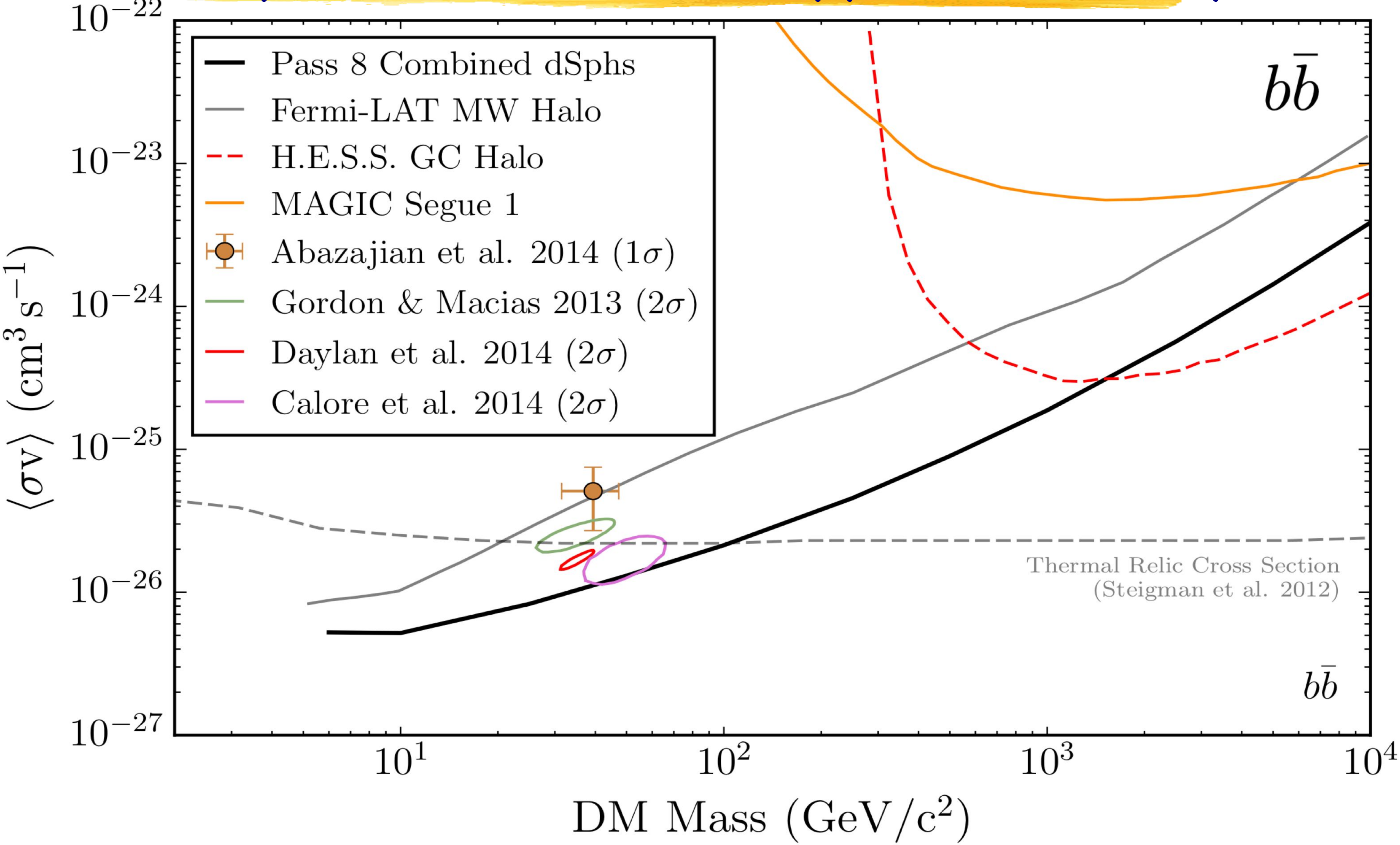


robust constraints including J-factor uncertainties from the stellar data statistical analysis

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]

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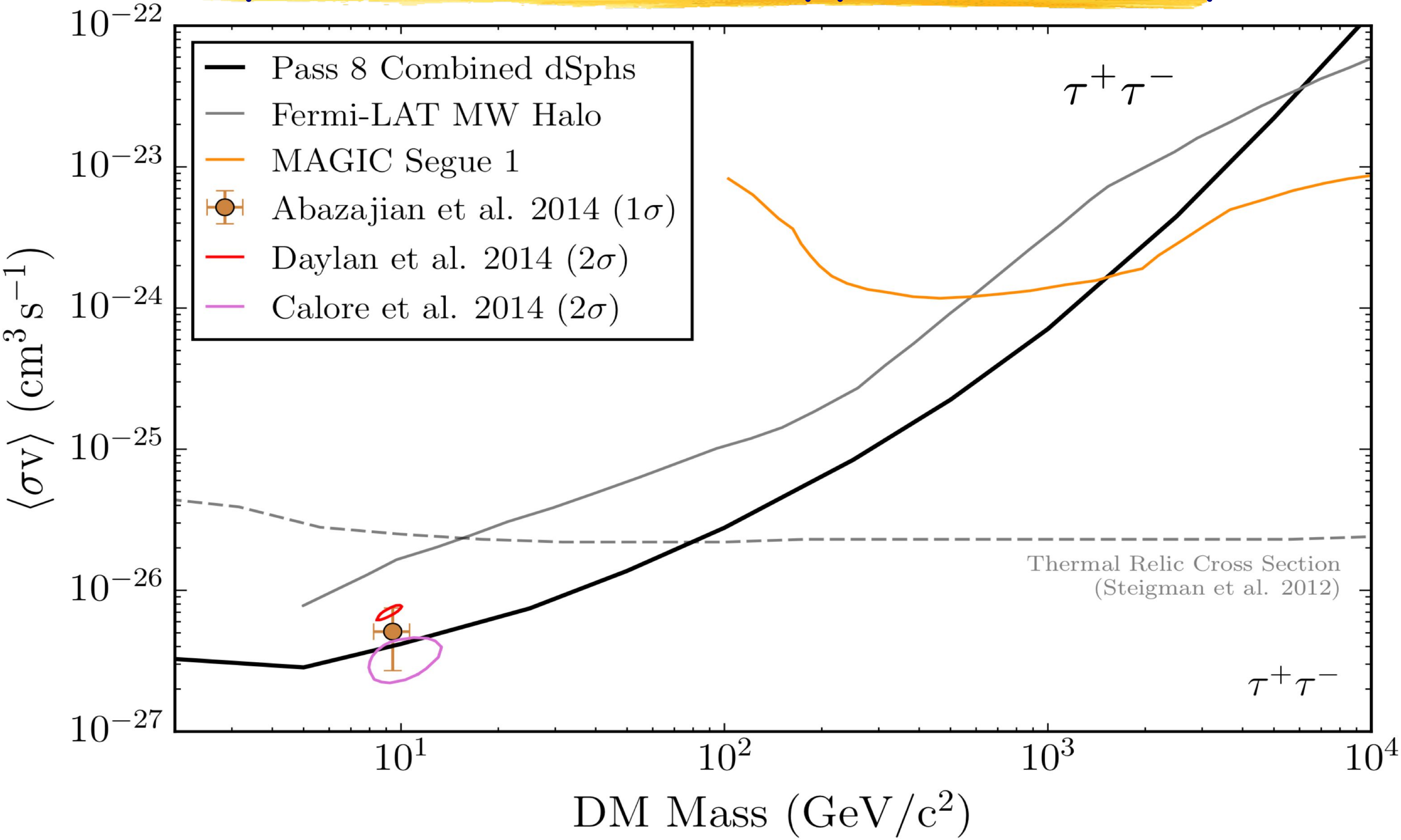
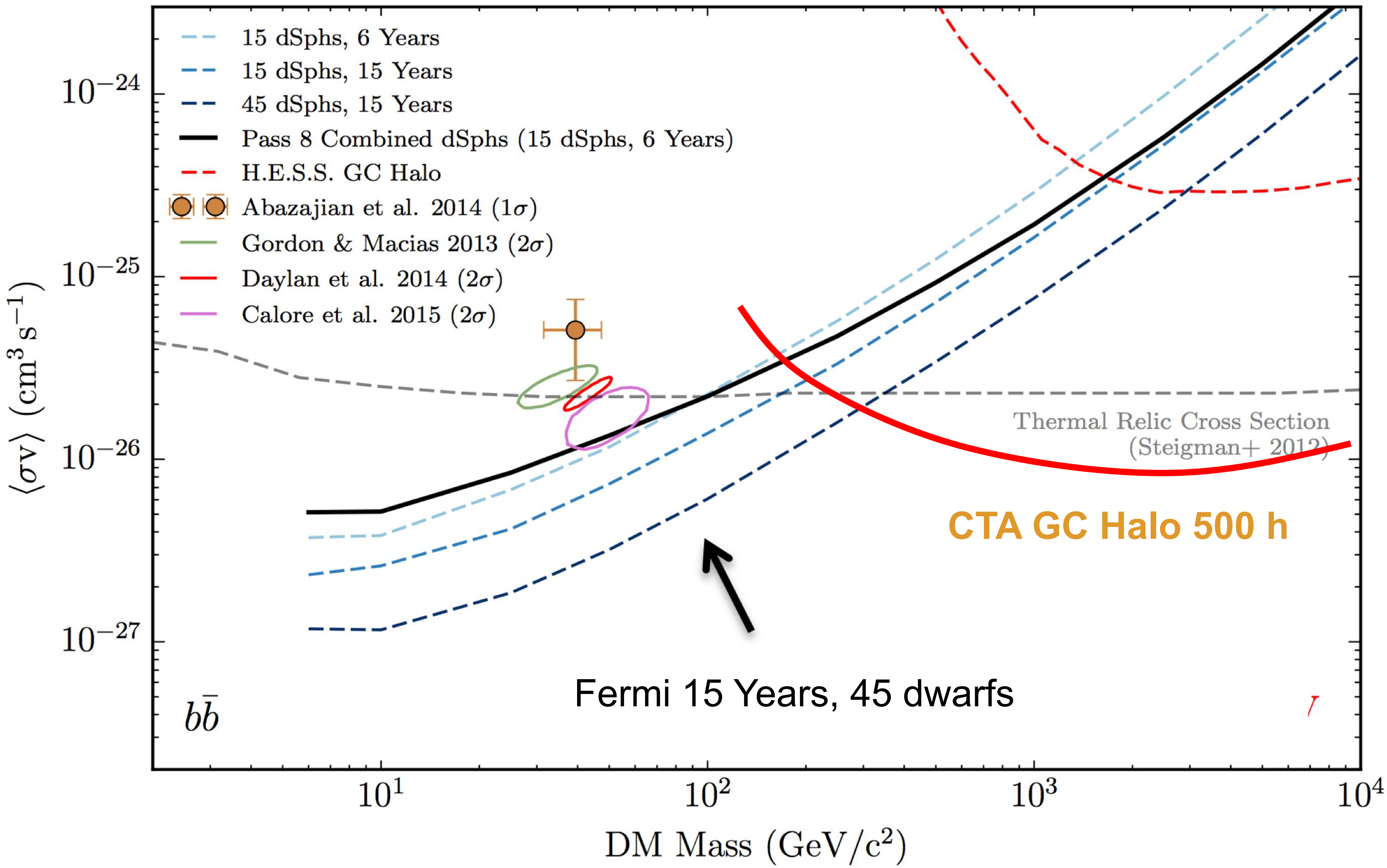
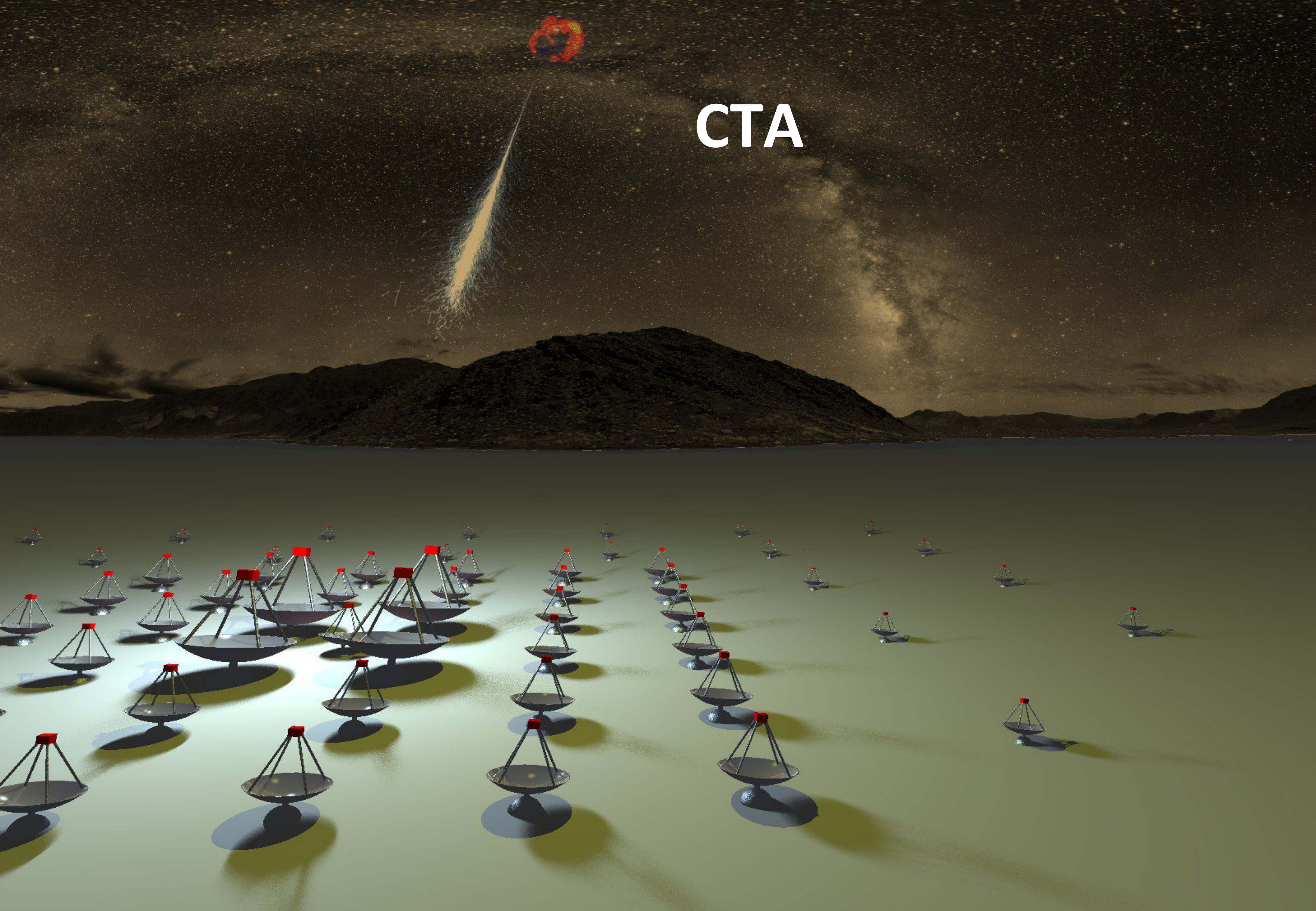


M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

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

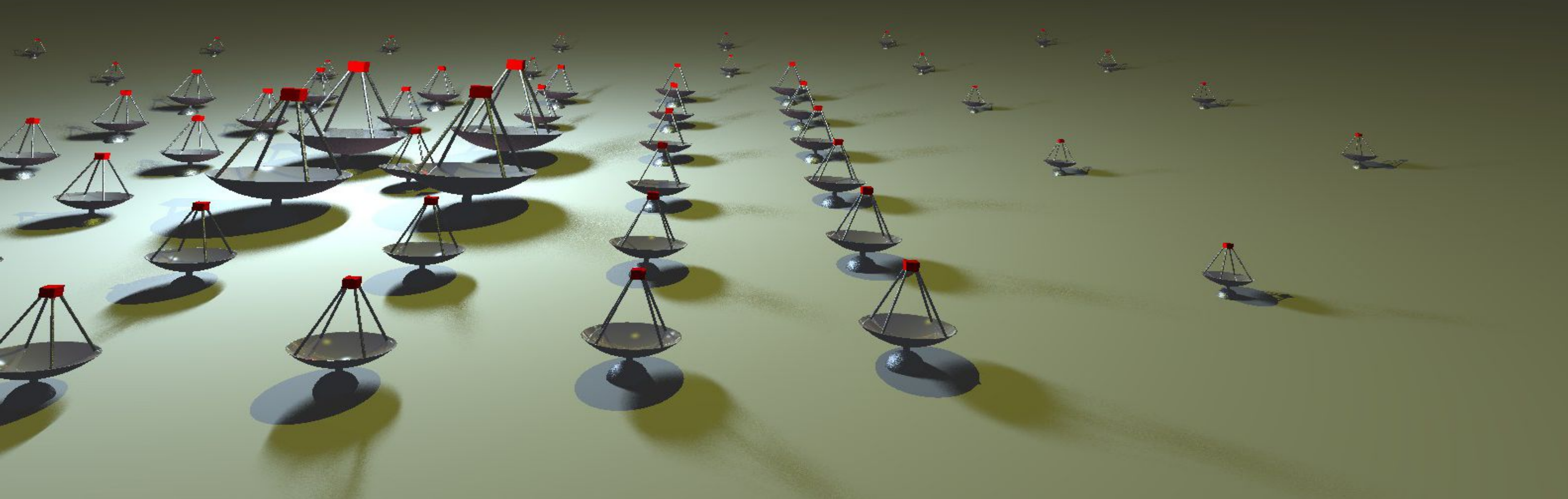


Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section


CTA

CTA PROJECT

- Next generation ground based Gamma-ray observatory
- Open observatory
- Two sites with more than 100 telescopes
  - Southern Site: Near Paranal, Chile
  - Northern Site: La Palma, Canary Islands, Spain
- 31 nations, ~300M€ project +100M€ manpower

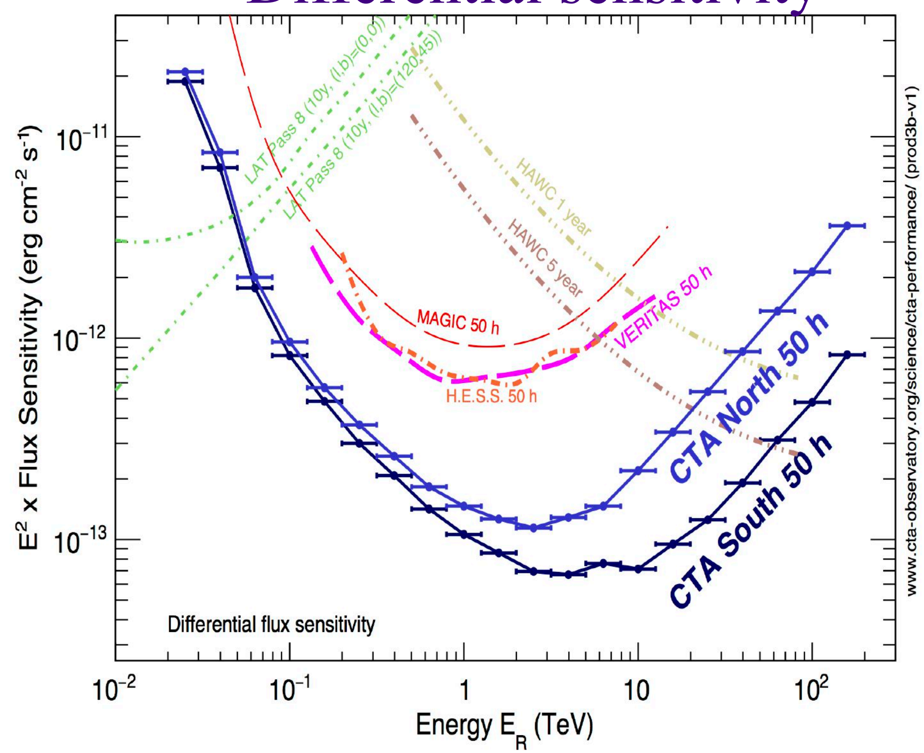


CTA PERFORMANCE

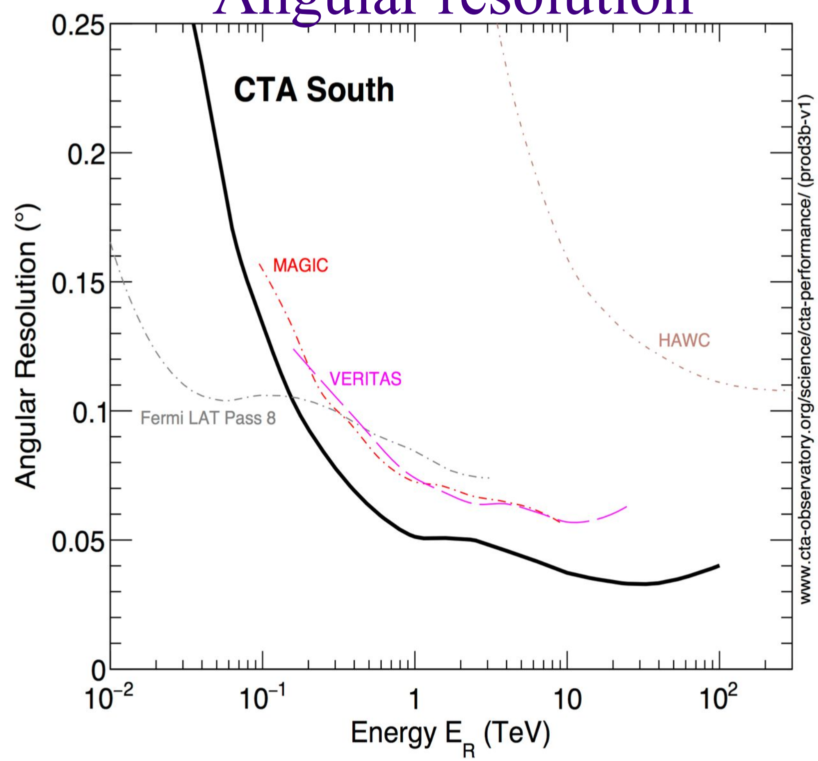
Southern Site:
- 4 Large-size telescopes
- 25 Medium-size telescopes
- 70 Small-size telescopes

Northern Site:
- 4 Large-size telescopes
- 15 Medium-size telescopes

Differential sensitivity



Angular resolution



CTA PERFORMANCE

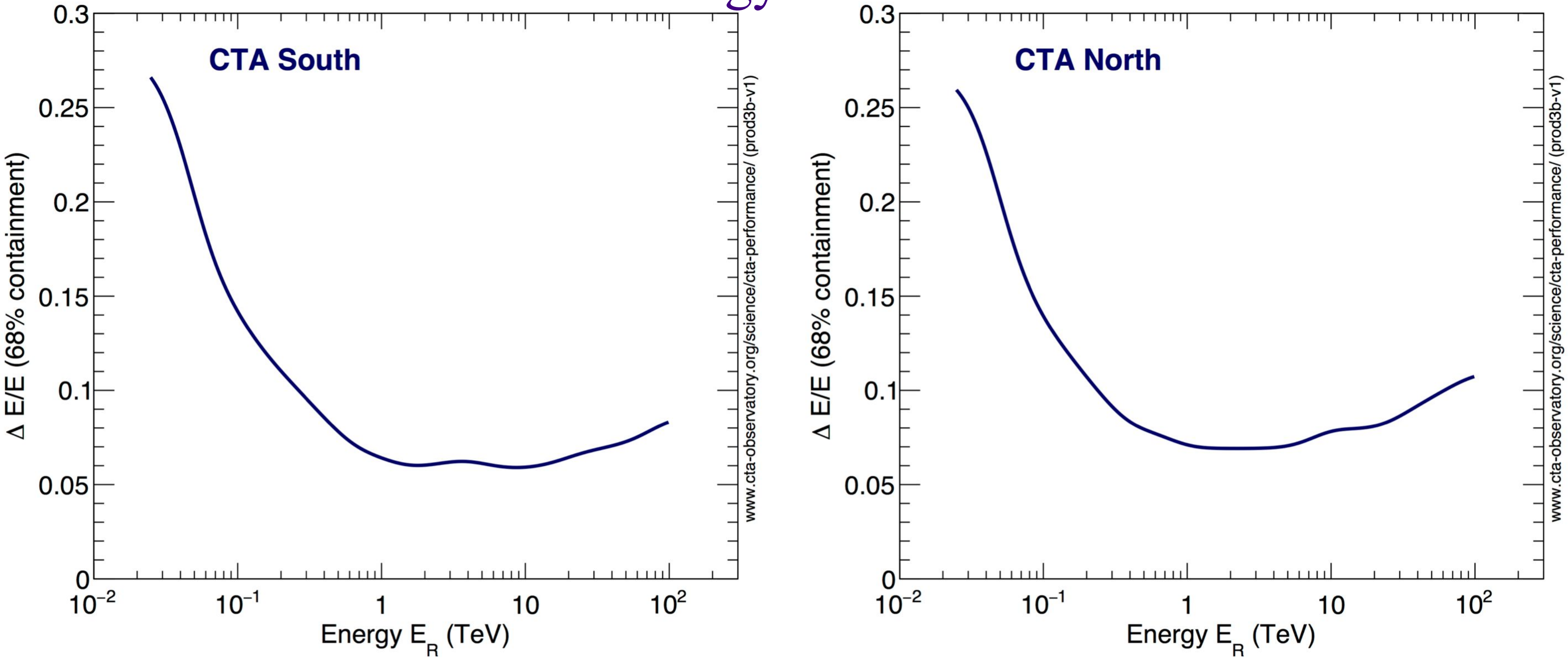
Southern Site:

4 Large-size telescopes
25 Medium-size telescopes
70 Small-size telescopes

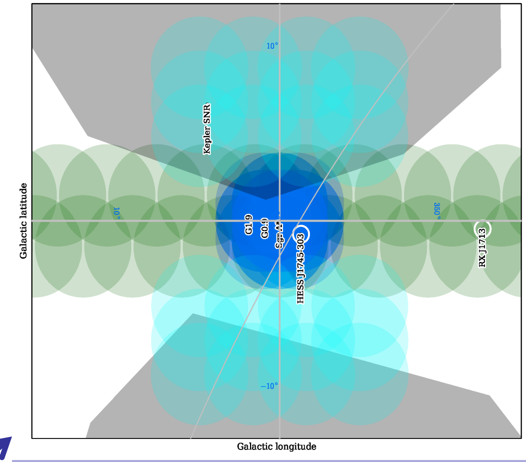
Northern Site:

4 Large-size telescopes
15 Medium-size telescopes

Energy Resolution



The Survey Key Science Projects

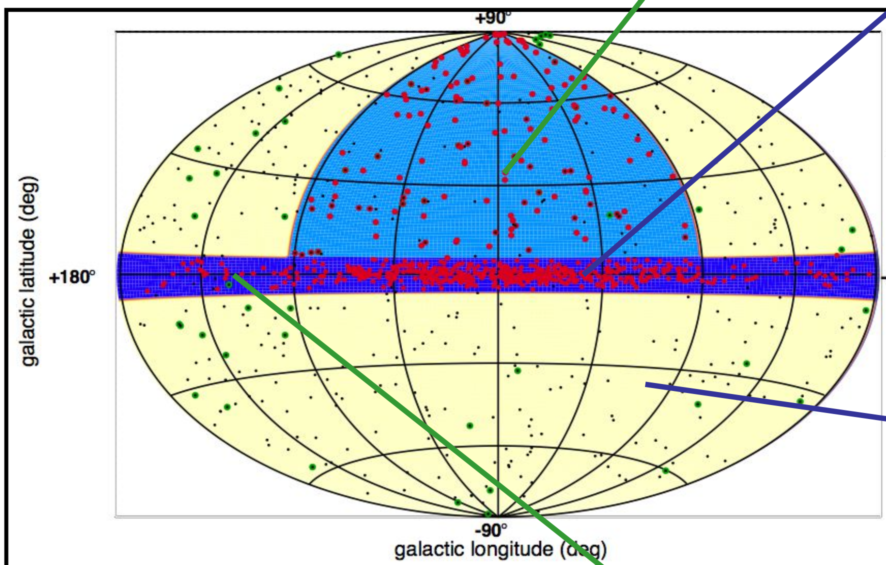


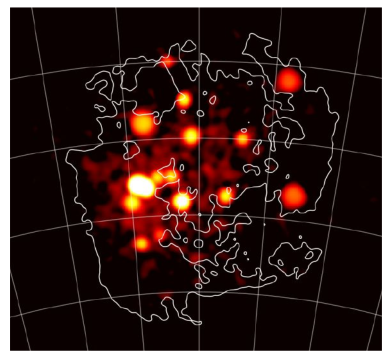
Extragalactic Survey:

Unbiased survey of ¼ sky to ~6 mCrab
VHE population study, duty cycle
New, unknown sources; 1000 h

Galactic Centre Survey:

ID of the central source
Spectrum, morphology of diffuse emission
Deep DM search
Central exposure: 525 h, 10°x10° : 300 h





Science with the Cherenkov Telescope Array
World Scientific
https://doi.org/10.1142/10986
[arXiv:1709.07997] ~364 pp.

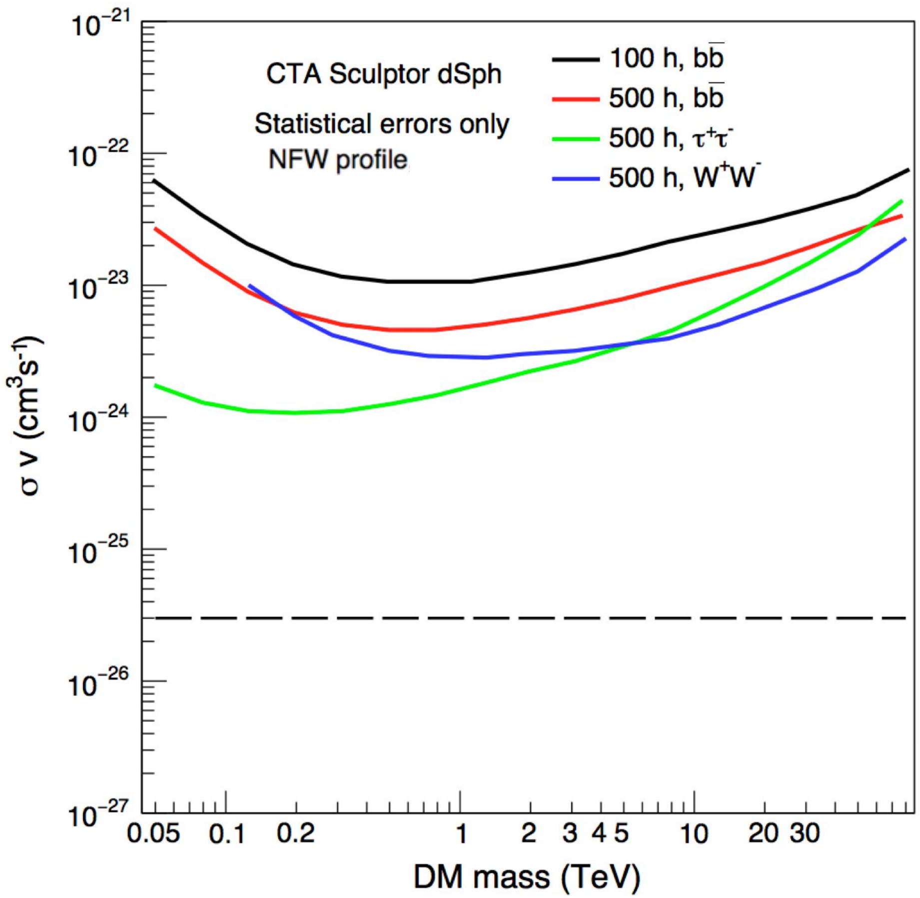
Galactic Plane Survey:

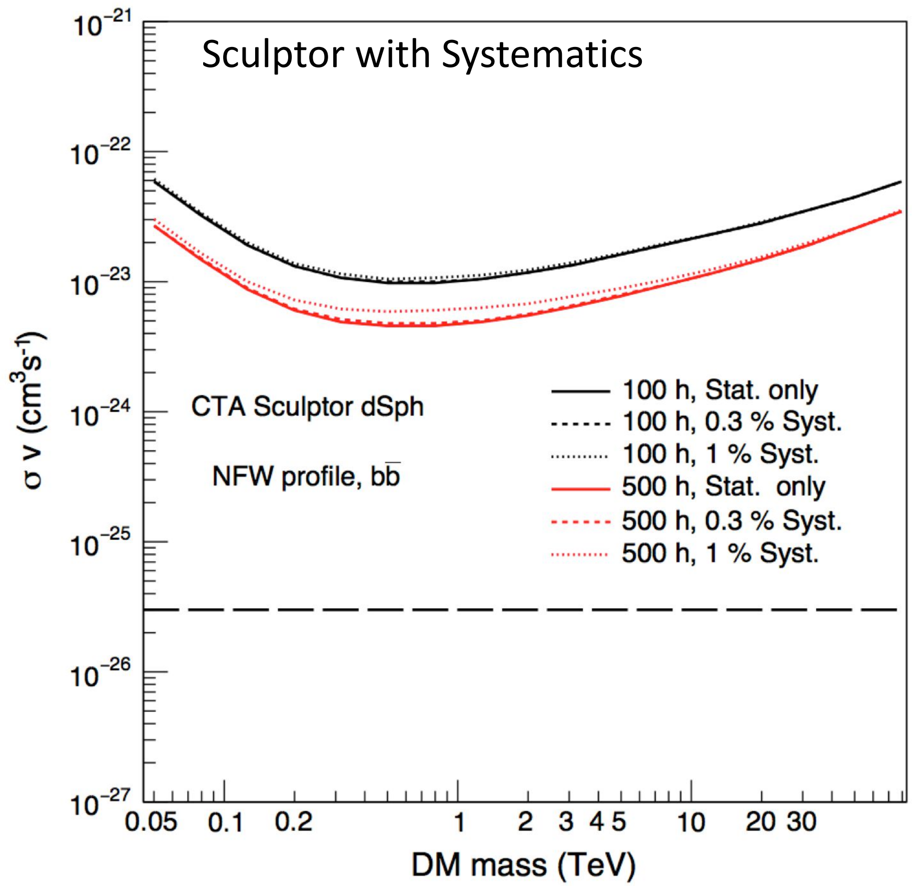
Survey of entire plane to ~2 mCrab
Galactic source population: SNRs, PWNe, etc.
PeVatron candidates, early view of GC, 1620 h

Large Magellanic Cloud Survey:

Face-on satellite galaxy with high SFR
Extreme Gal. sources, diffuse emission (CRs)
DM search; 340 h in six pointings

Dwarf Spheroidal Galaxies: CTA Sensitivity

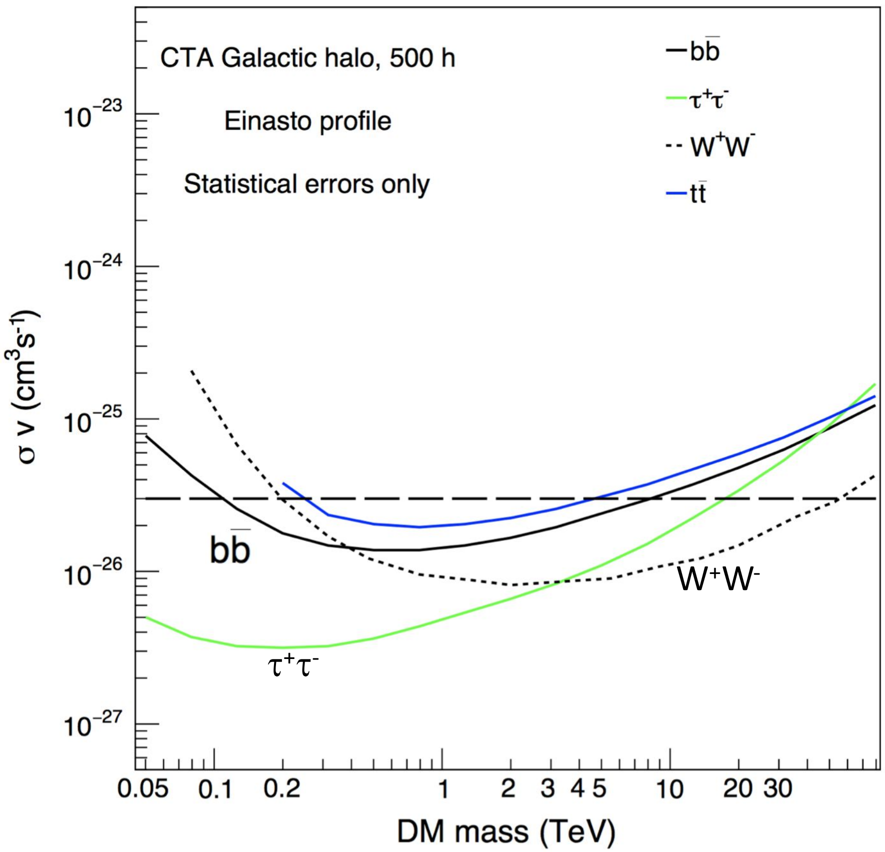


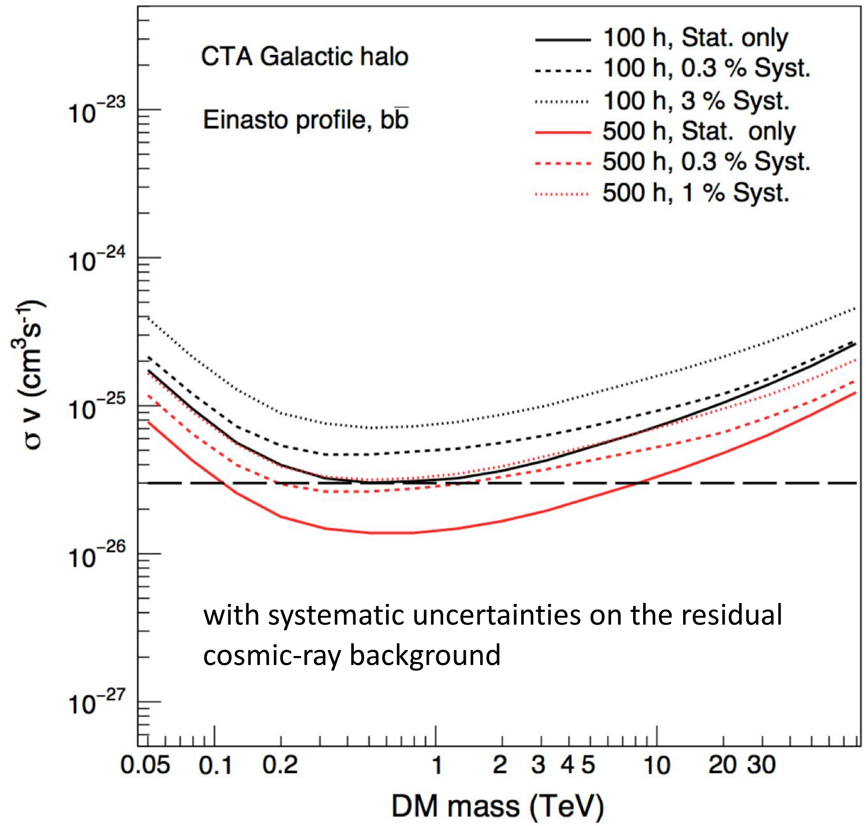


There are several of the newly discovered dSph that have a better case for being a promising target,

Will choose most promising targets before observations with the latest knowledge.

CTA Galactic Halo DM upper-limits



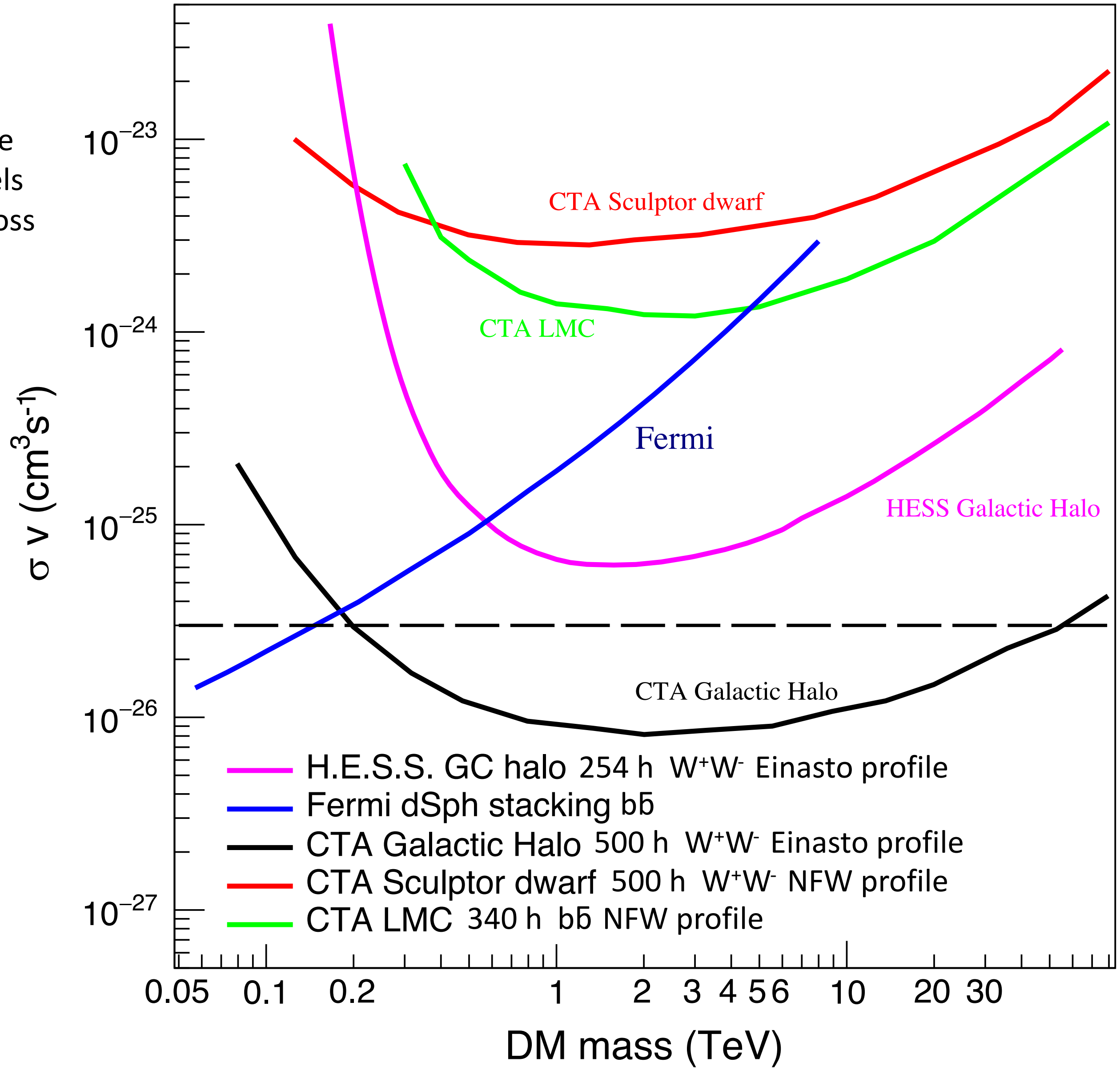


The predictions shown here can be considered optimistic, even when systematics errors are included, as we do not consider the effect of the Galactic diffuse emission as background for DM searches that can affect the results by ~ 50%

This will be investigated in detail in a forthcoming publication by the CTA Consortium.

CTA, Fermi,HESS DM upper-limits

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section
The expectation for CTA for the Galactic Halo
is for the Einasto profile and is optimistic as includes
only statistical errors.
The effect of the Galactic diffuse emission can affect
the results by ~ 50%
As we saw in the previous slides the limits from dwarfs are much less dependent from the systematic uncertanties



CTA, HESS, FERMI, PLANK DM upper-limits

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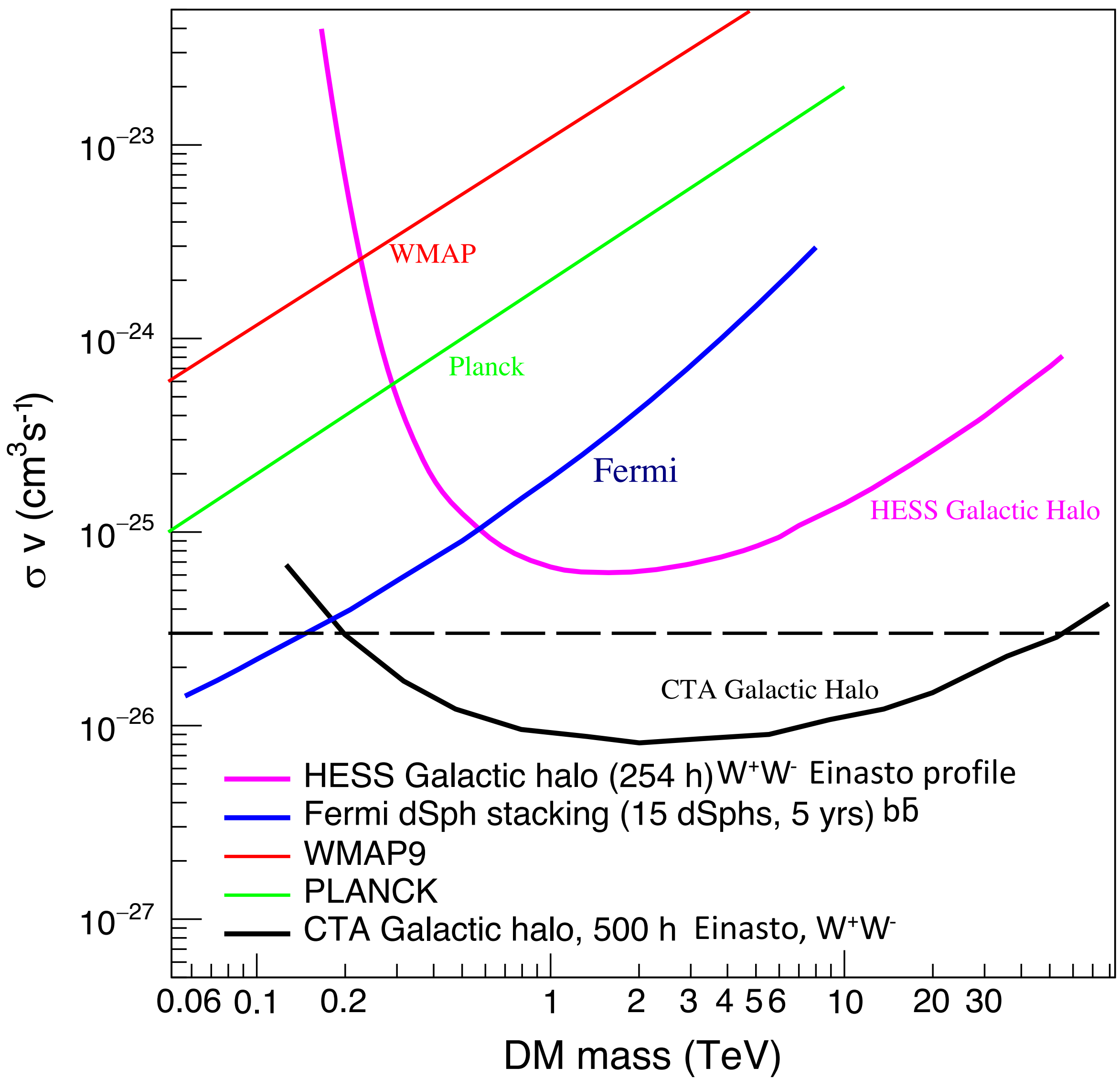


CTA DM Detection Strategy

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

First 3 years

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

Next 7 years

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

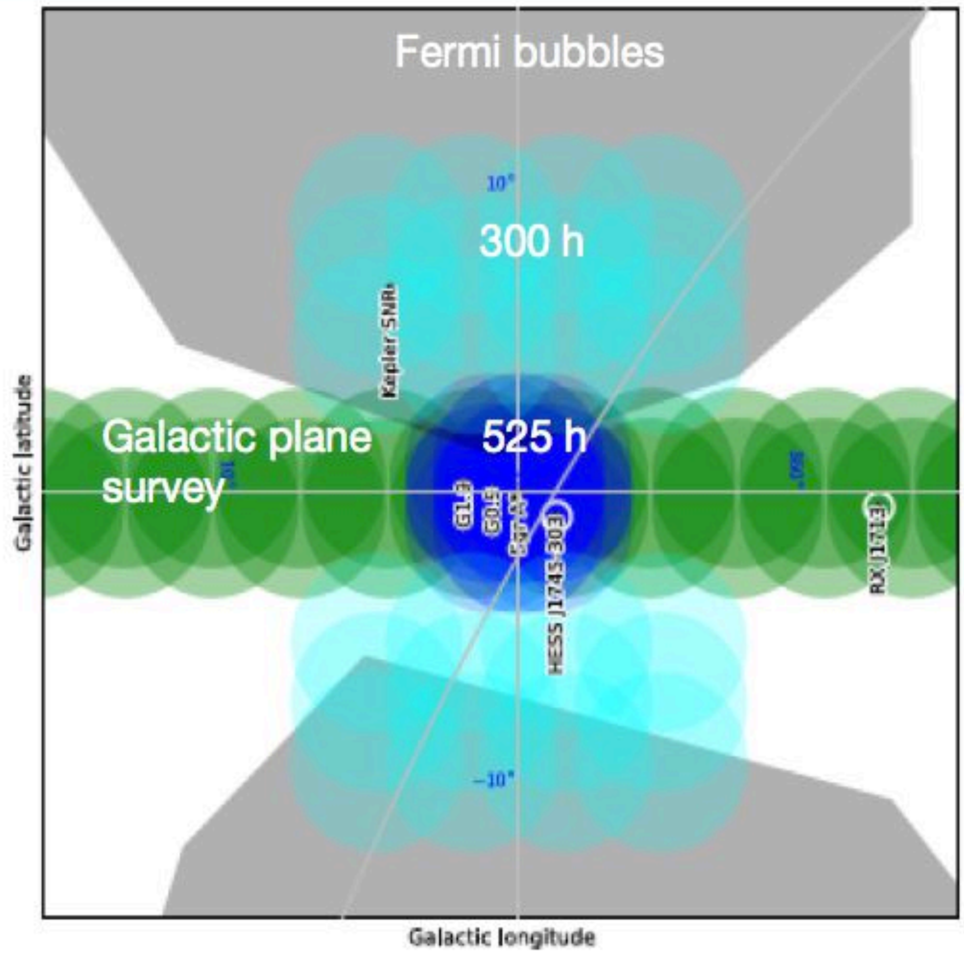
DEEP OBSERVATIONS OF GC REGION

Deep 525 h exposure in the inner 5° around Sgr A*;

Extended 300 h survey of 10°x10° region;

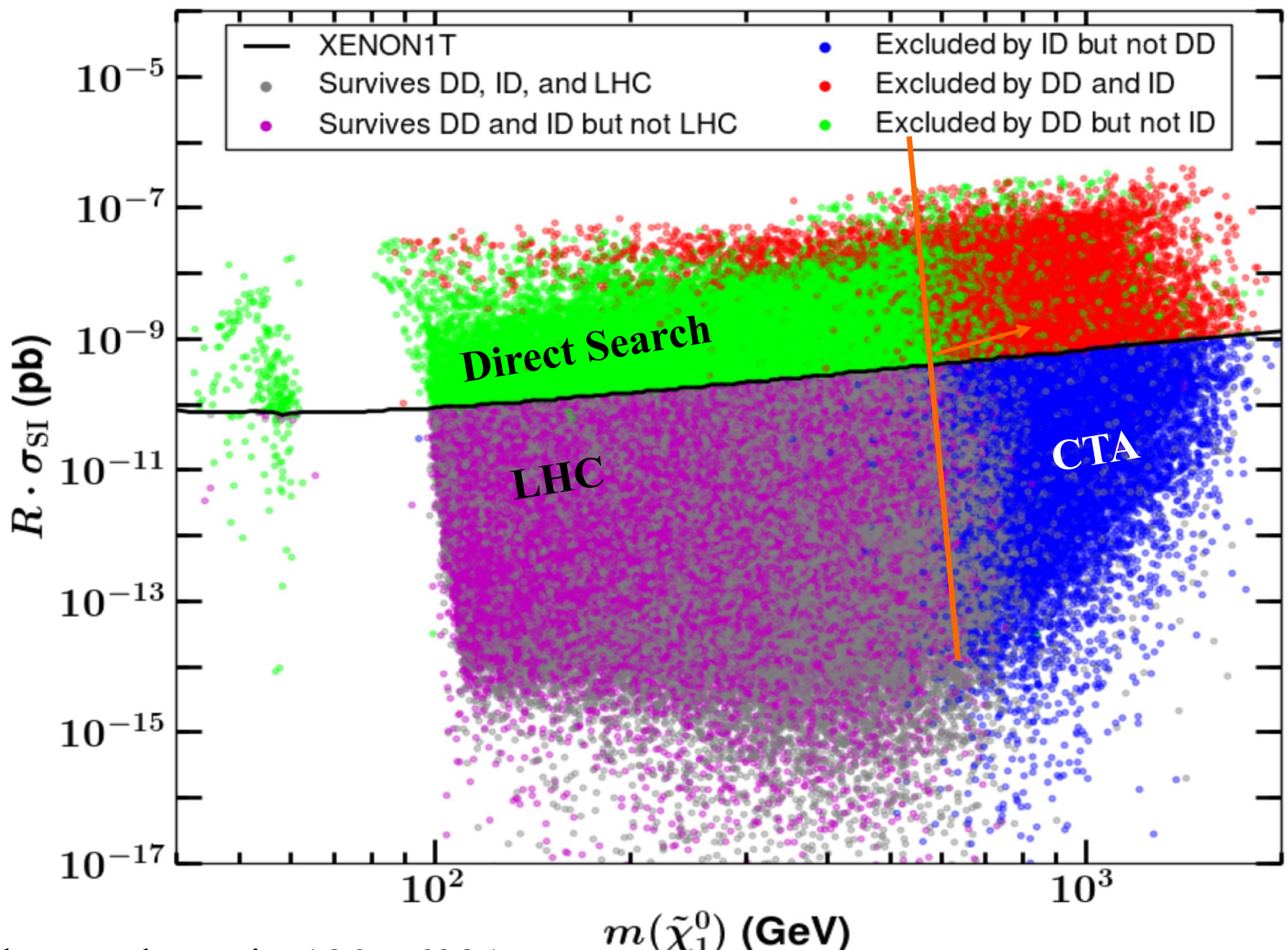
Produce CTA legacy data set for large range of scientific topics, which include

- GC and GC DM halo
- Understand "backgrounds" pin down VHE sources and map diffuse emission
- Astrophysics of SNRs (multiple sources, e.g. G1.9, …)
- Astrophysics of PWNe and Pulsars
- Extended objects such as Central Radio lobes (central ±1°) and arc features.



CTA legacy data set

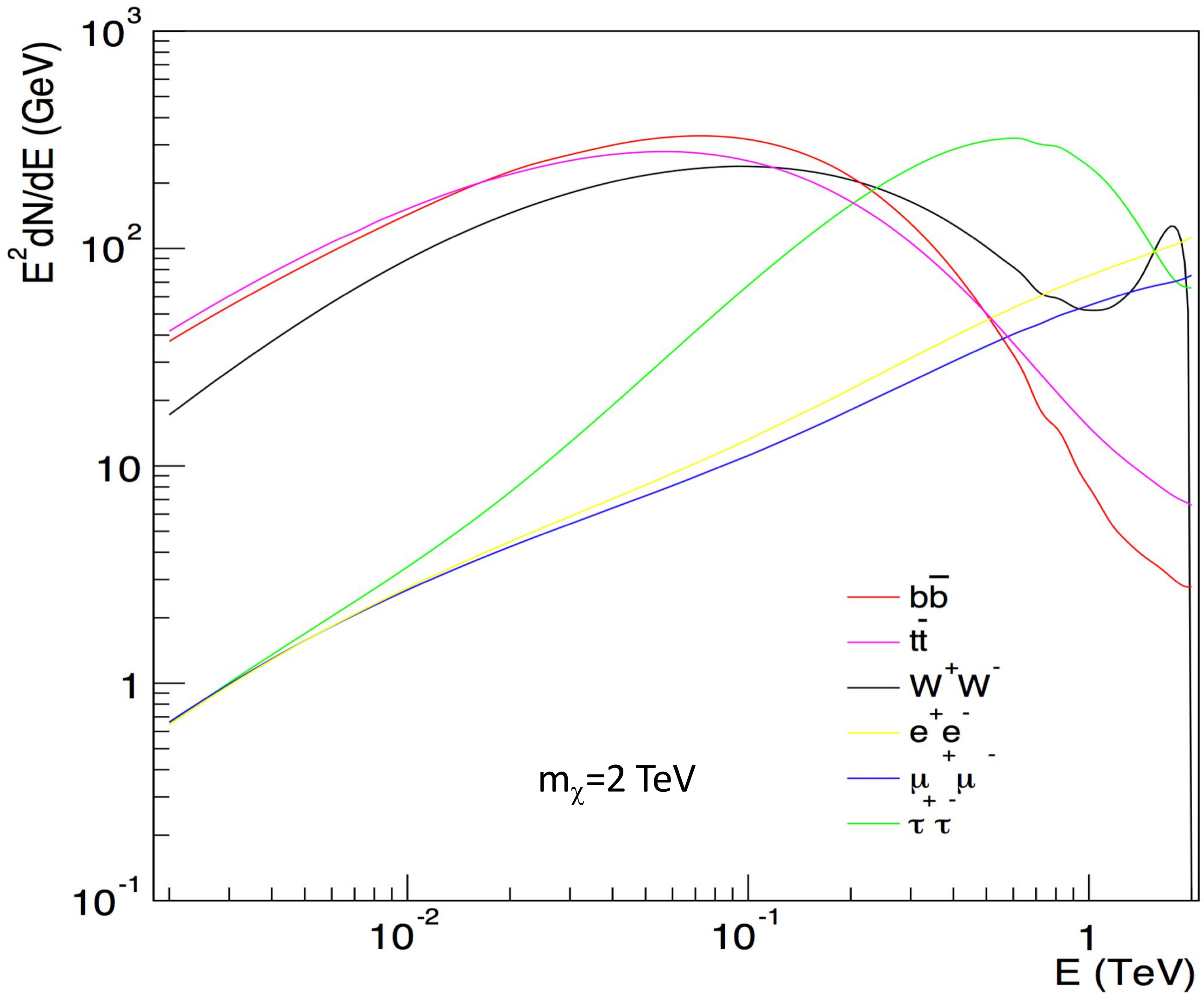
Complementarity and Searches for Dark Matter in the pMSSM



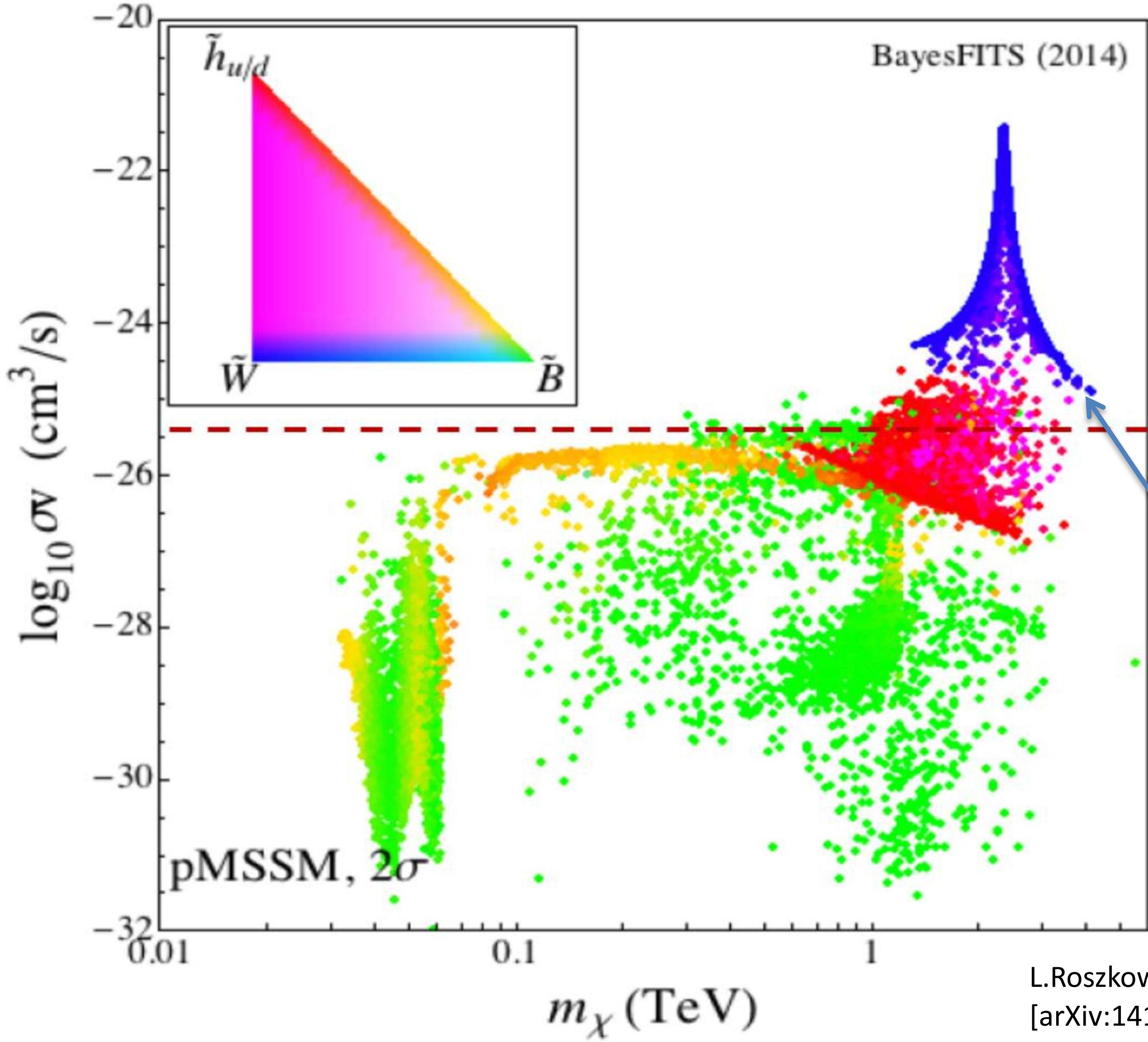
Cahill-Rowley et al. arXiv:1305.6921

Annihilation spectra for the continuum signals from the quark, lepton and gauge boson primary channels

The line-like feature expected from the virtual internal Bremsstrahlung process contribution is particularly prominent for the W^+W^- channel



note:the “thermal” cross section is only a reference value. The real cross section can be higher or lower



Example: Annihilation cross-section points from a 19 dimensional pMSSM fit

Note that a strong enhancement of the annihilation cross section occurs for winos around 2-3 TeV due to Sommerfeld enhancement.

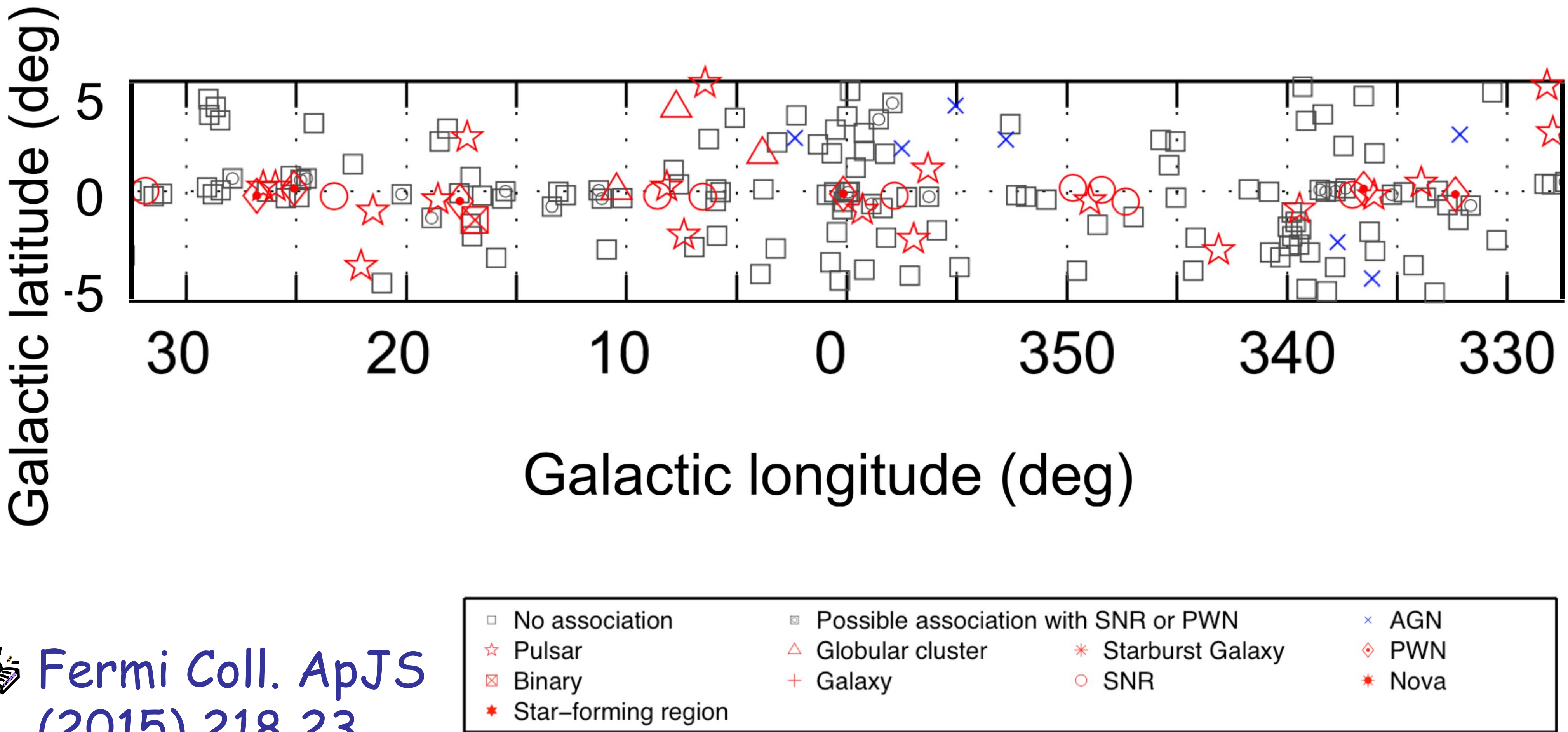
L.Roszkowski et al., JHEP 1502 (2015) 014 [arXiv:1411.5214]

The Low Energy Frontier

The Fermi LAT 3FGL Inner Galactic Region

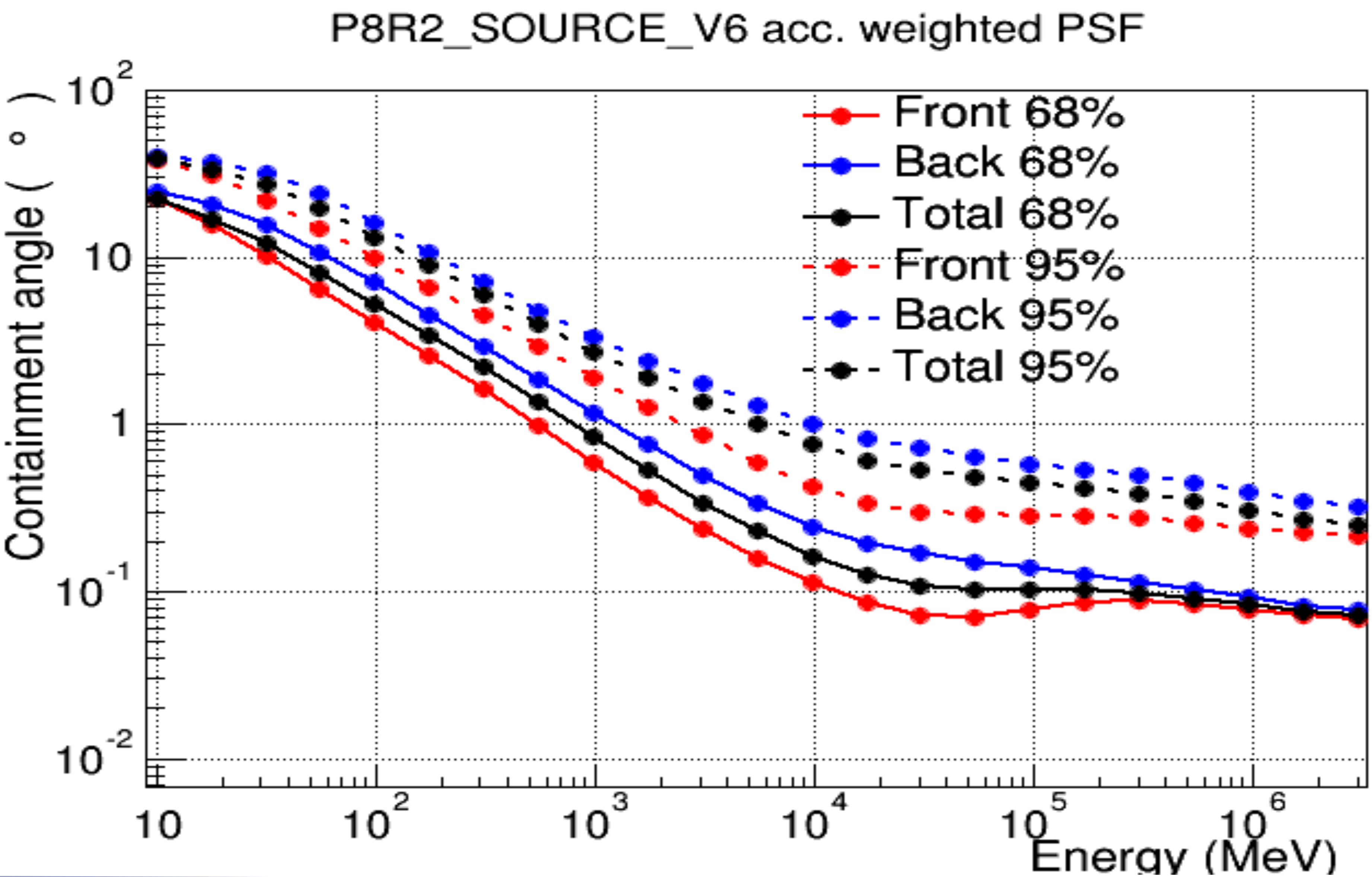
August 4, 2008, to July 31, 2010

100 MeV to 300 GeV energy range

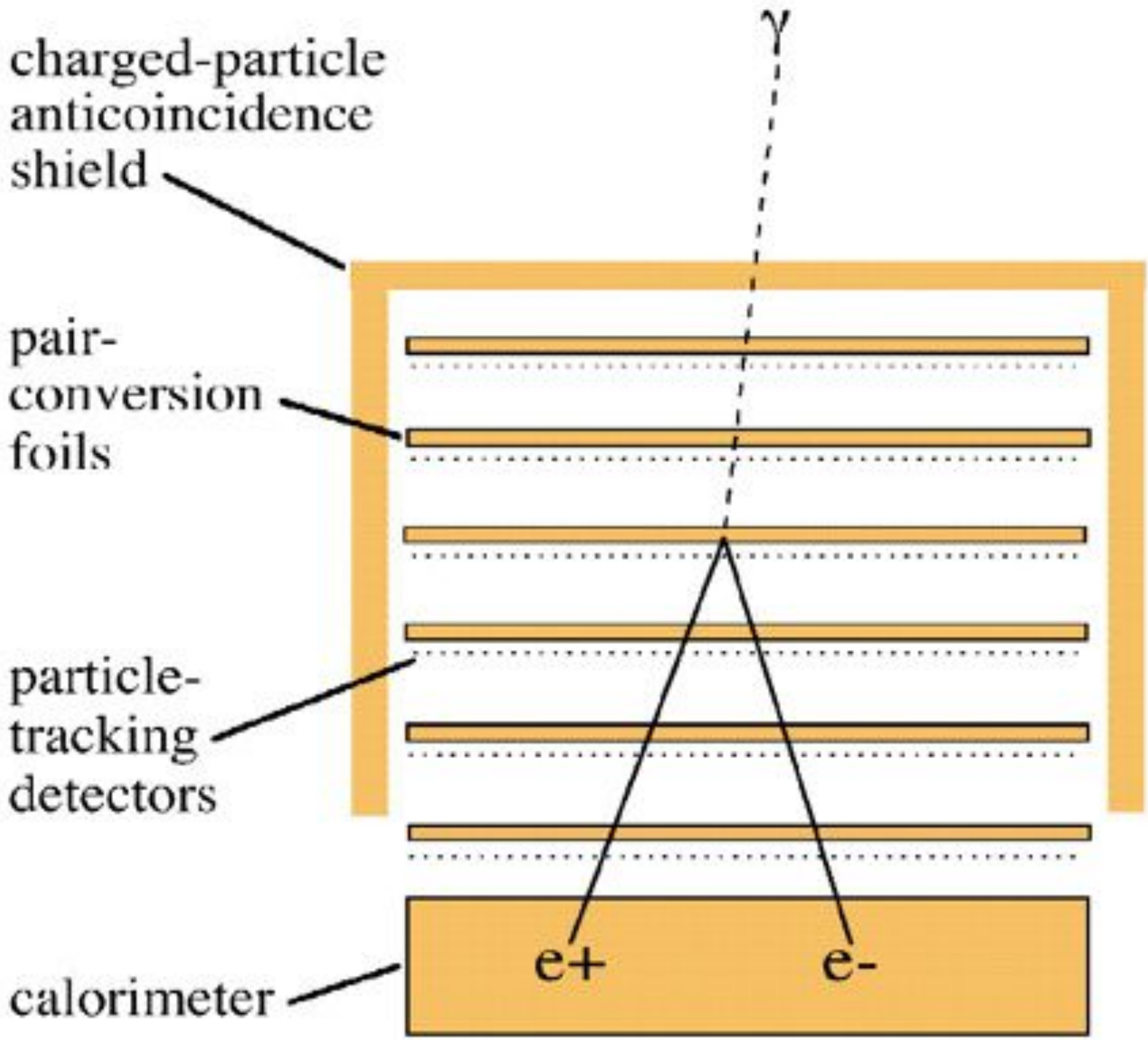


Fermi Coll. ApJS (2015) 218 23
arXiv:1501.02003

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



Elements of a pair-conversion telescope

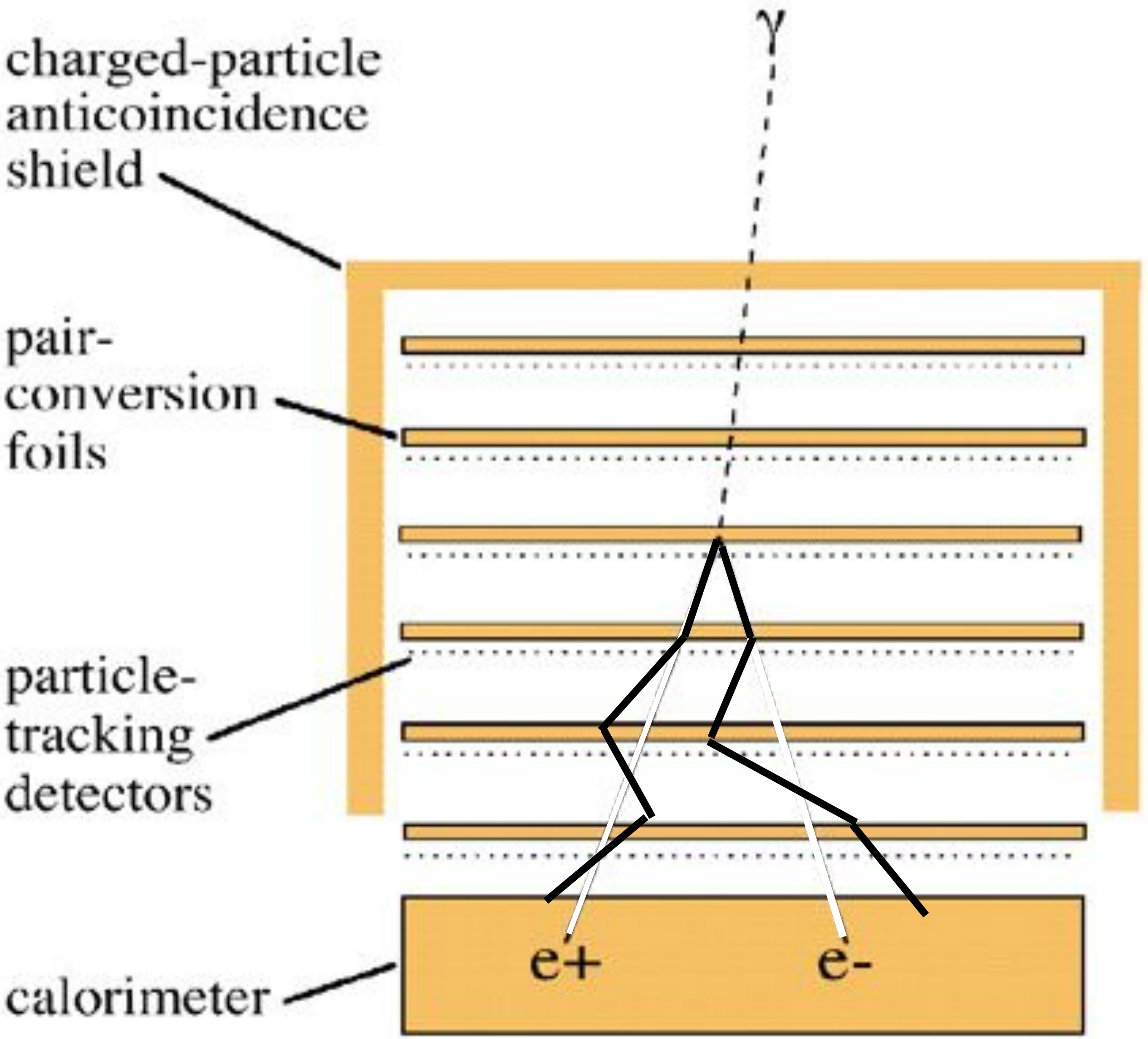


(energy measurement)

- 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

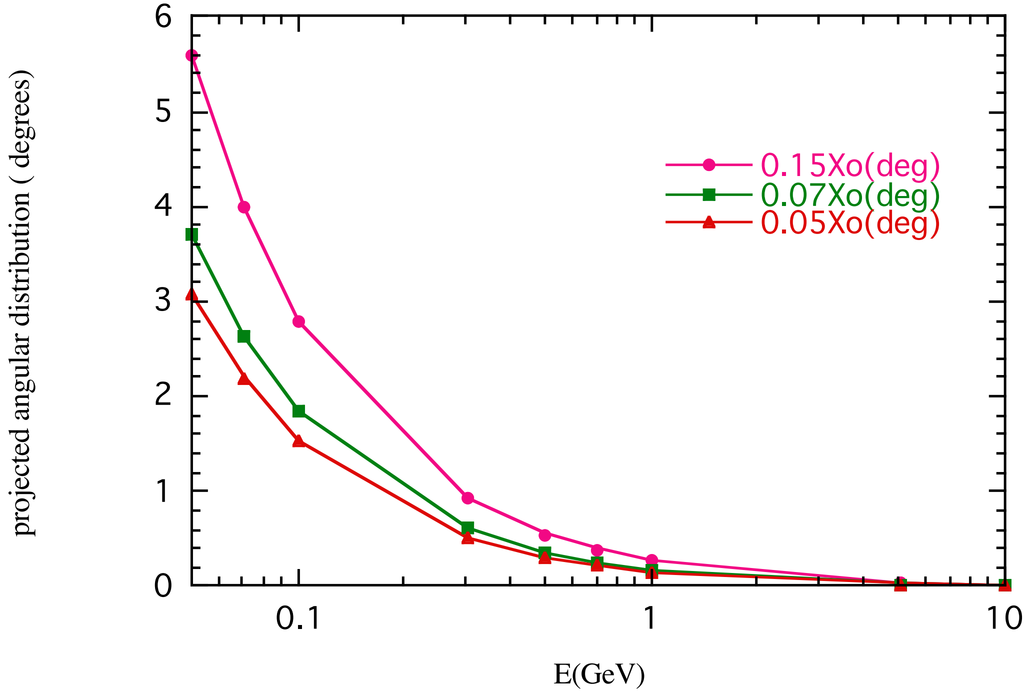
Elements of a pair-conversion telescope

(more realistic scheme)

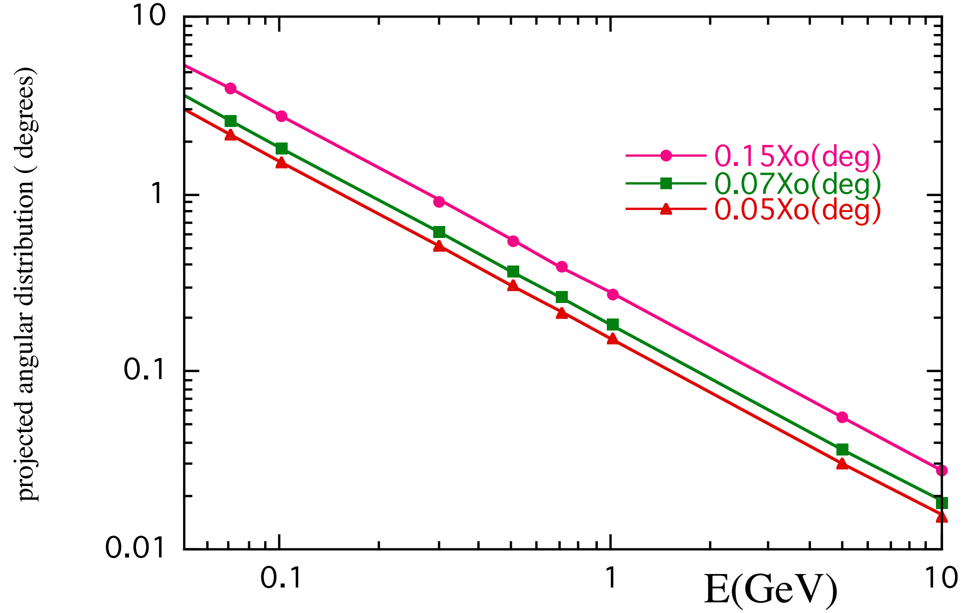


(energy measurement)

- 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



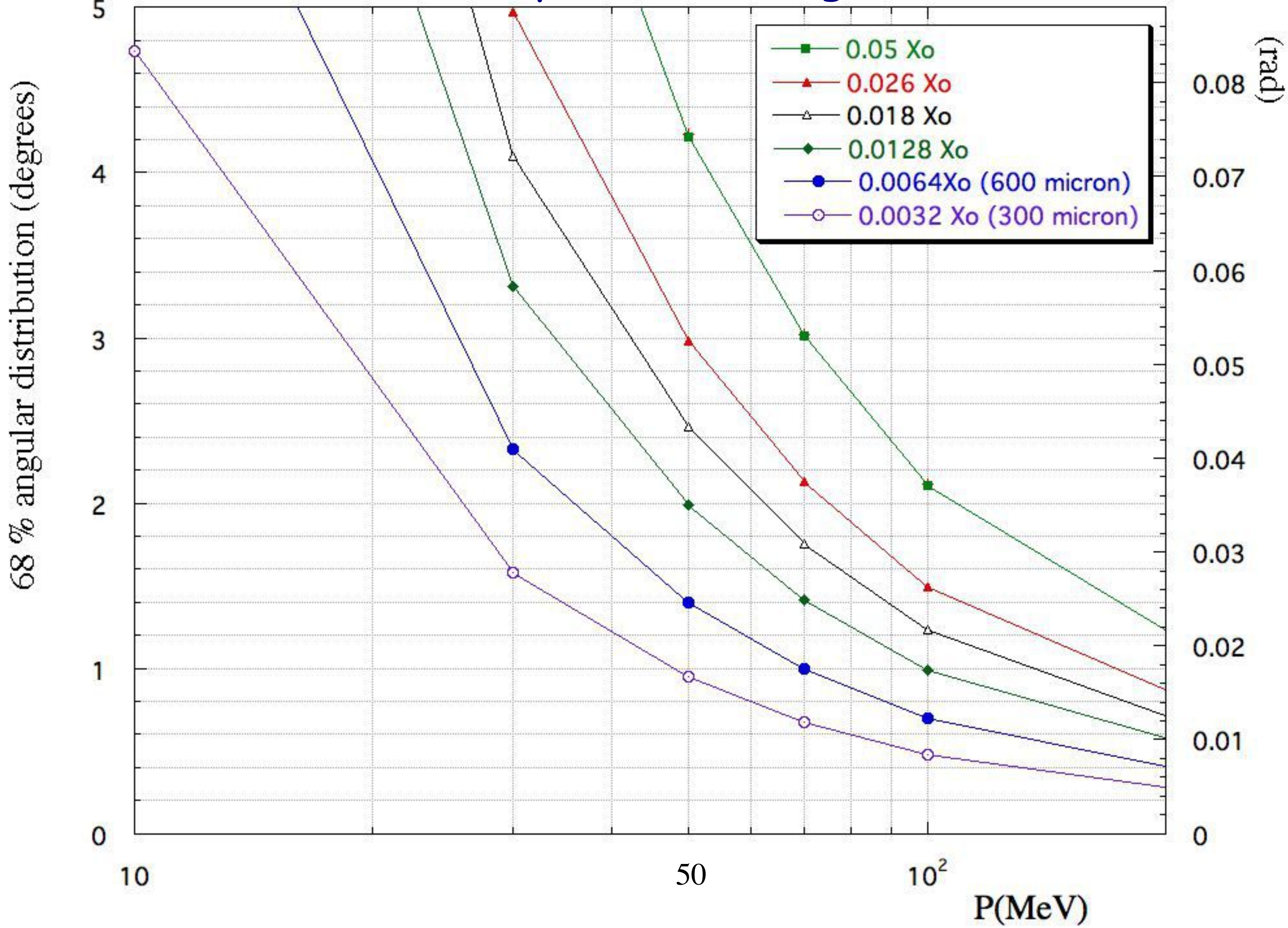
Multiple Scattering



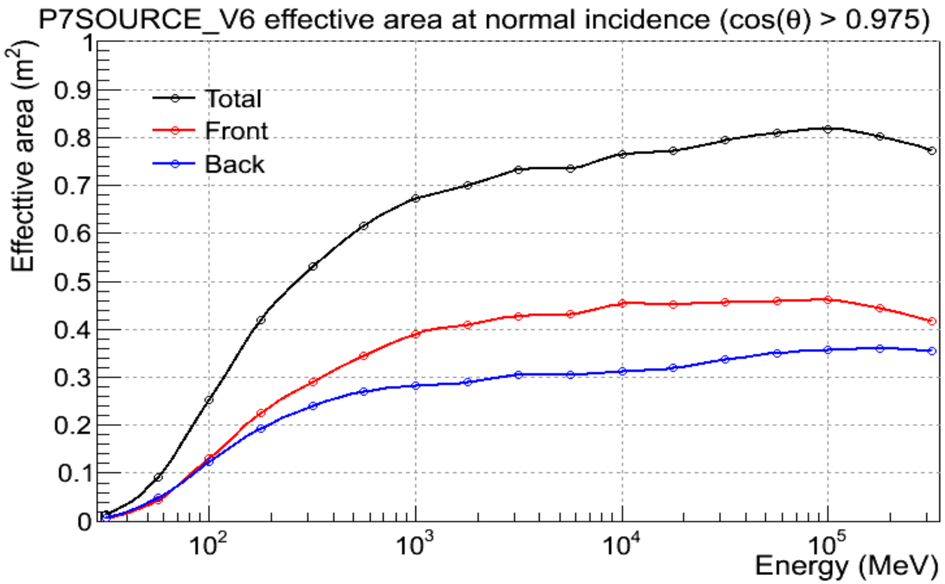
$$\theta_0 = \theta_{plane}^{rms} = \frac{1}{\sqrt{2}}\theta_{space}^{rms}$$

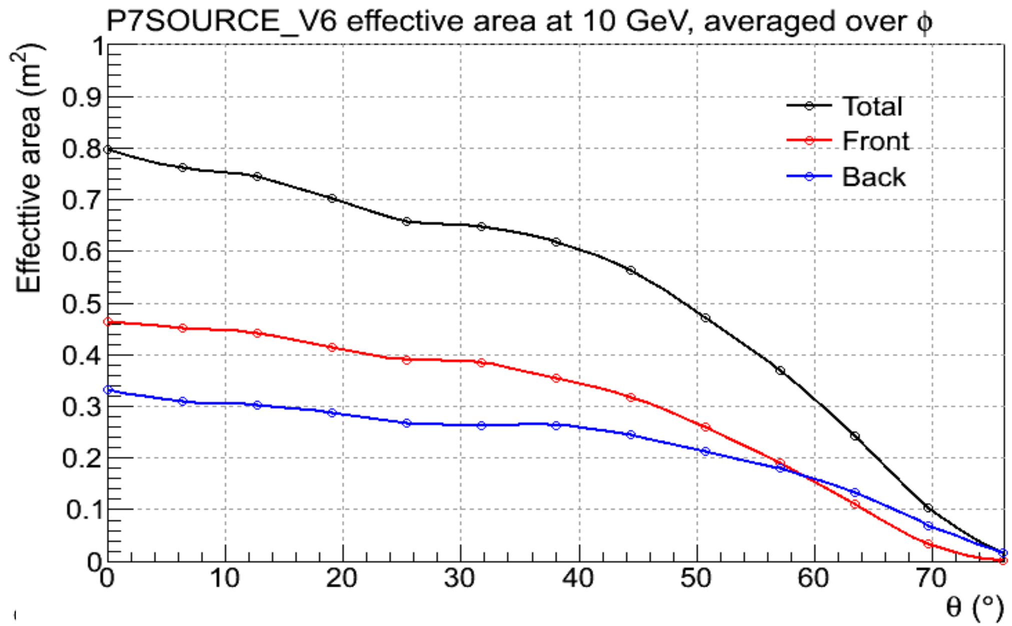
$$\theta_0 = \frac{13.6 MeV}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038 \ln (x/X_0)]$$

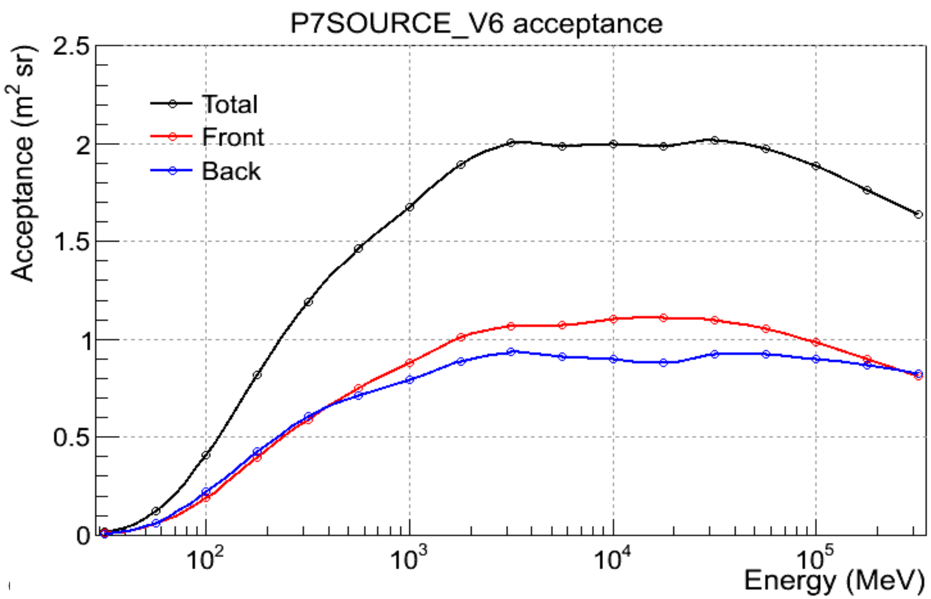
Multiple Scattering

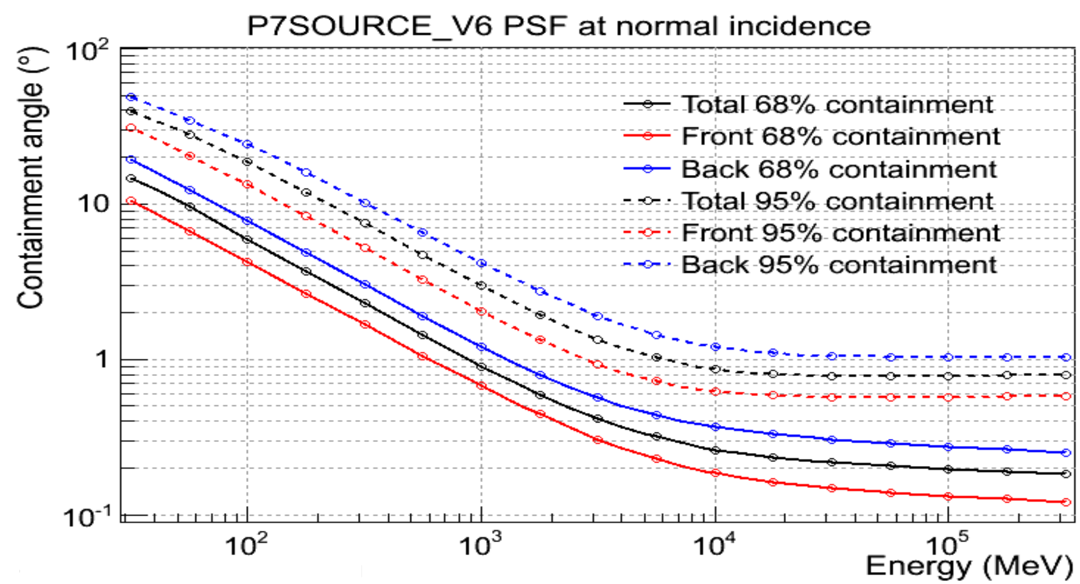


Fermi Instrument Response Function



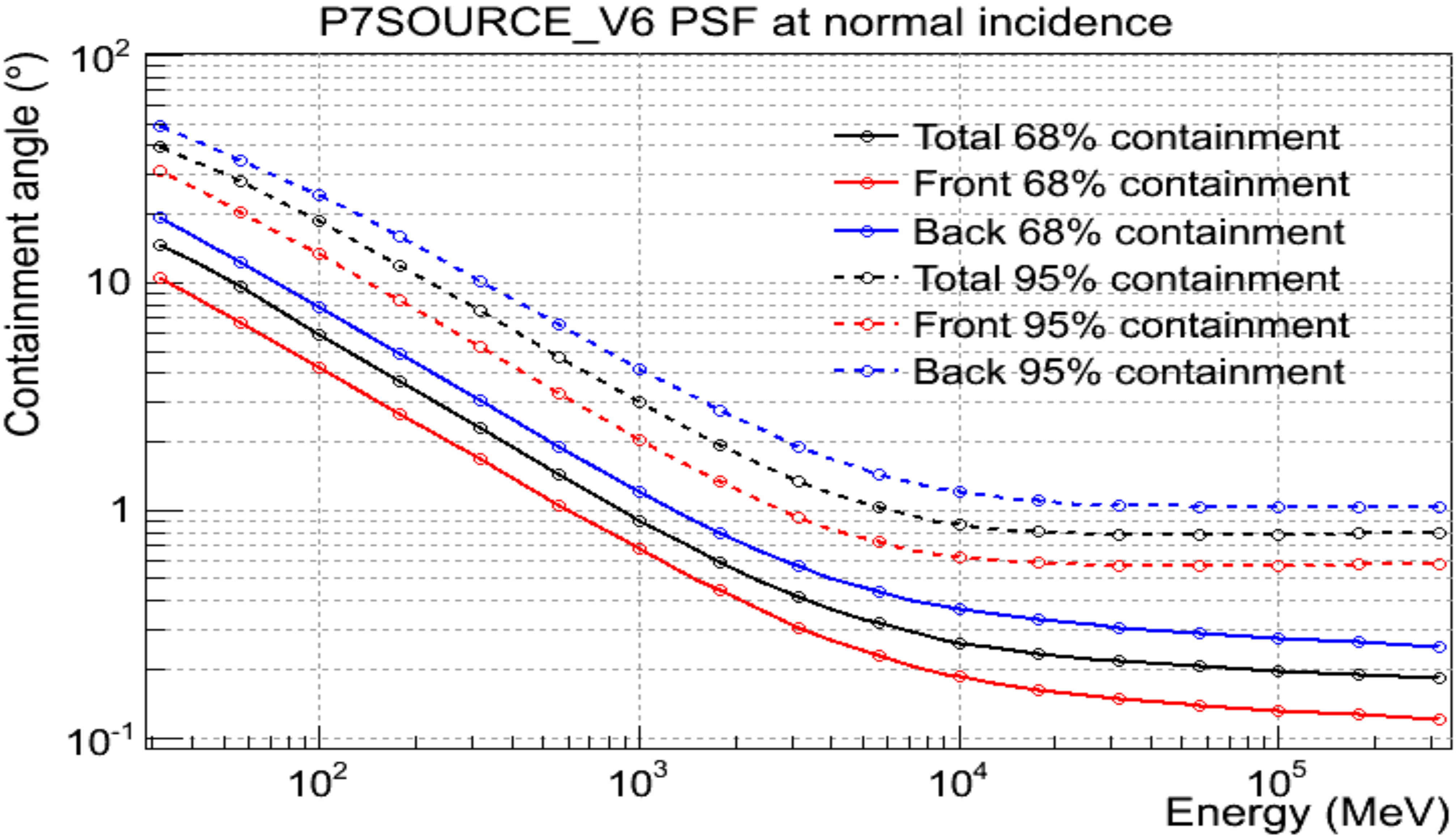






http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Fermi Instrument Response Function



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

$N\gamma_s$= number of photons from source
$N\gamma_B$= number of photons from background
$\Delta\Omega$ = solid angle around dth source
A_{eff} = Effective area (Area* efficiency)
x = converter plane in radiation lengh

Sensitivity

depends on field of view

$$N_{\gamma s} = \Phi_s(cm^{-2}) * A_{eff} * \Delta T$$

$$N_{\gamma B} = \Phi_B(cm^{-2} sr^{-1}) * \Delta\Omega * A_{eff} * \Delta T$$

depends on angular resolution

Sensitivity

number of σ

$$N_{\gamma s} \geq 5(N_{\gamma B})^{-\frac{1}{2}}$$

$$\Delta\Omega \sim \pi\theta^2 \sim \pi E^{-2} x$$

$$\Phi_s \geq \frac{5}{E}\left(\frac{\Phi_B * x}{A_{eff} * \Delta T}\right)^{-\frac{1}{2}}$$

good detector

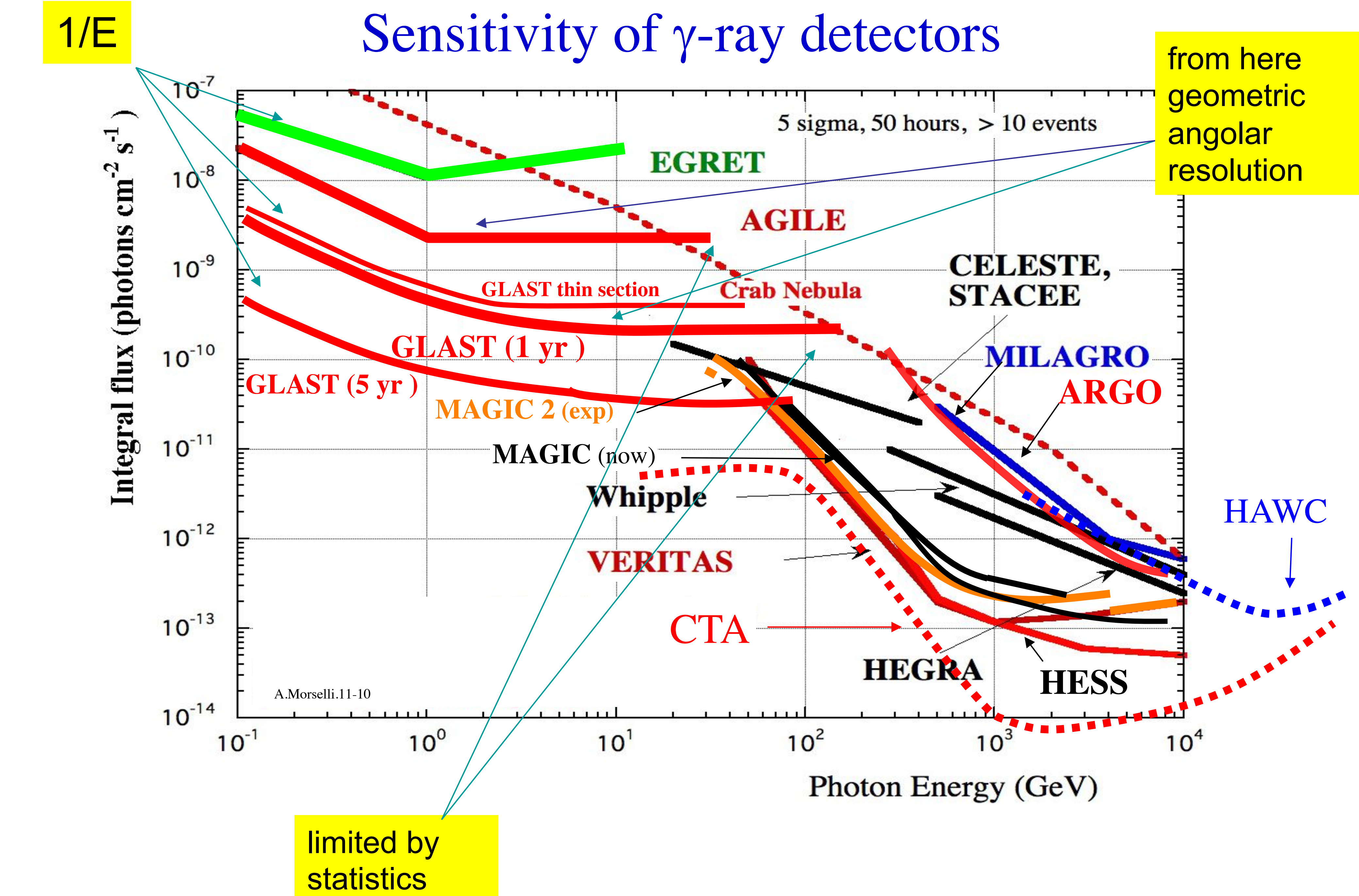
small converter plane

$$\Phi_s \geq \frac{5}{E}\left(\frac{\Phi_B * x}{A_{eff} * \Delta T}\right)^{-\frac{1}{2}}$$

large effective area
(large geometric area and large total conversion efficiency)

large field of view

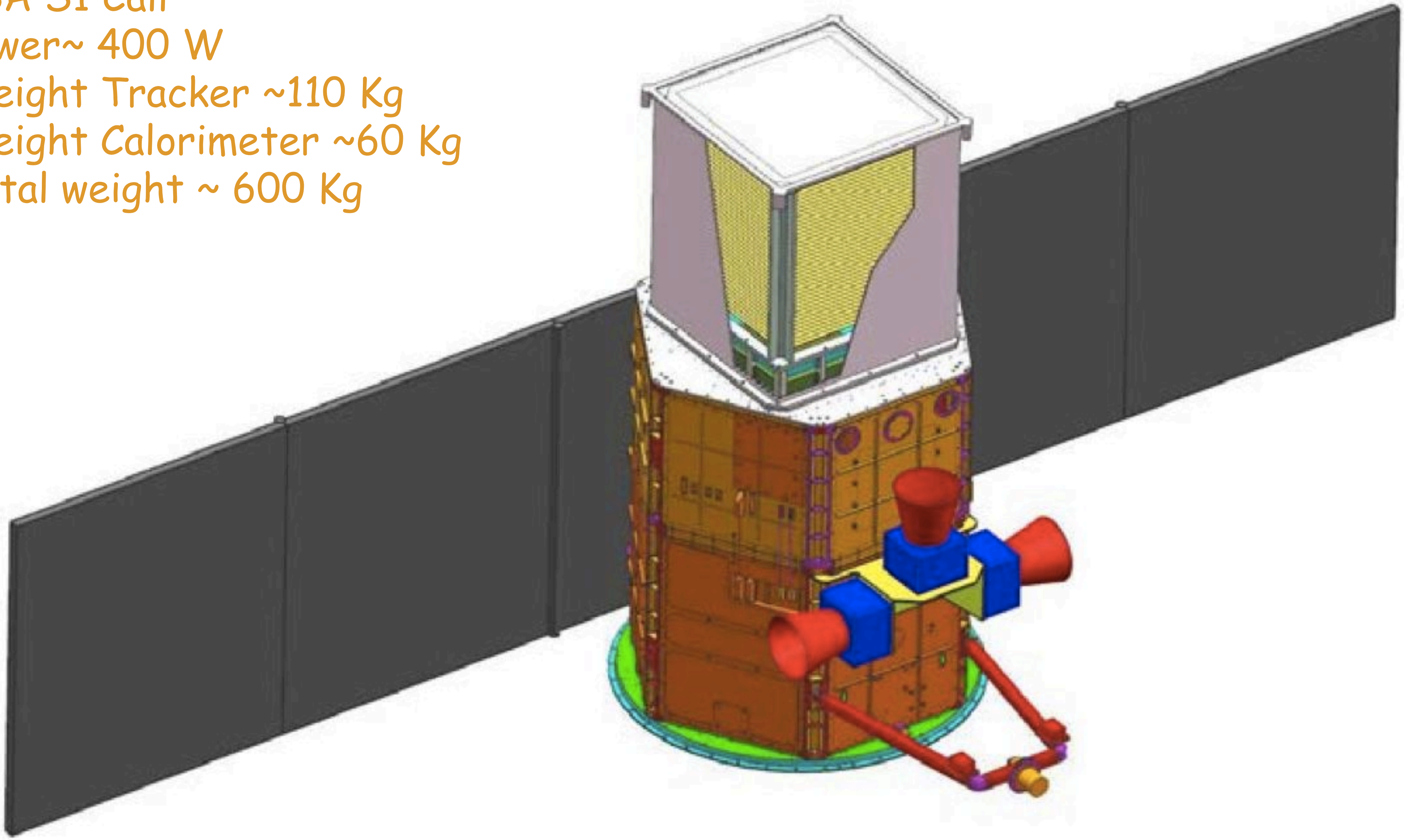
Sensitivity of γ-ray detectors



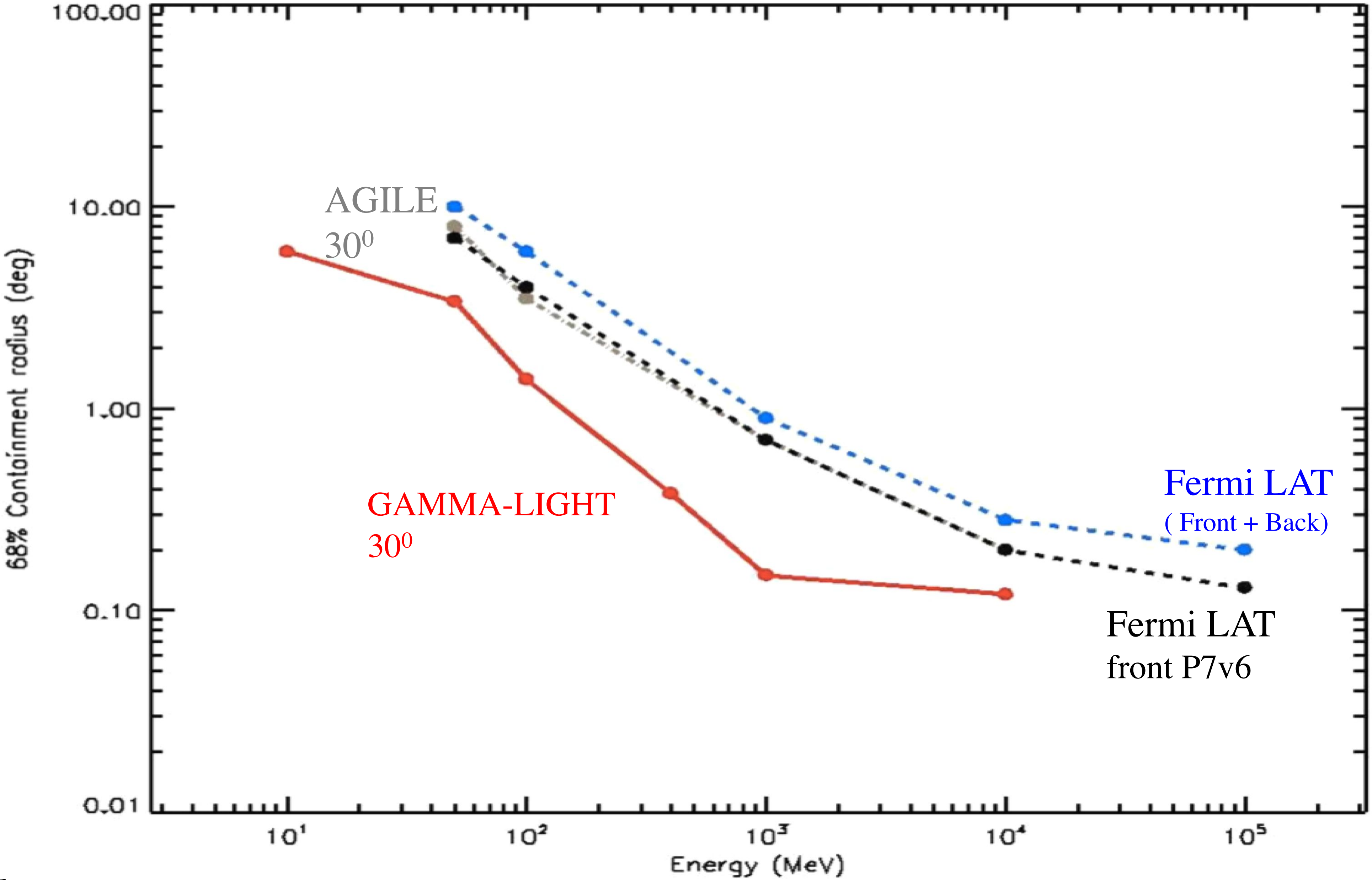
- 1-100 MeV unexplored domain for
  - Dark Matter searches
  - Galactic compact stars and nucleosynthesis
  - Cosmic rays
  - Relativistic jets, microquasars
  - Blazars
  - Gamma-Ray Bursts
  - Solar physics
- and…
  - Terrestrial Gamma-Ray Flashes

Gamma-light project

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

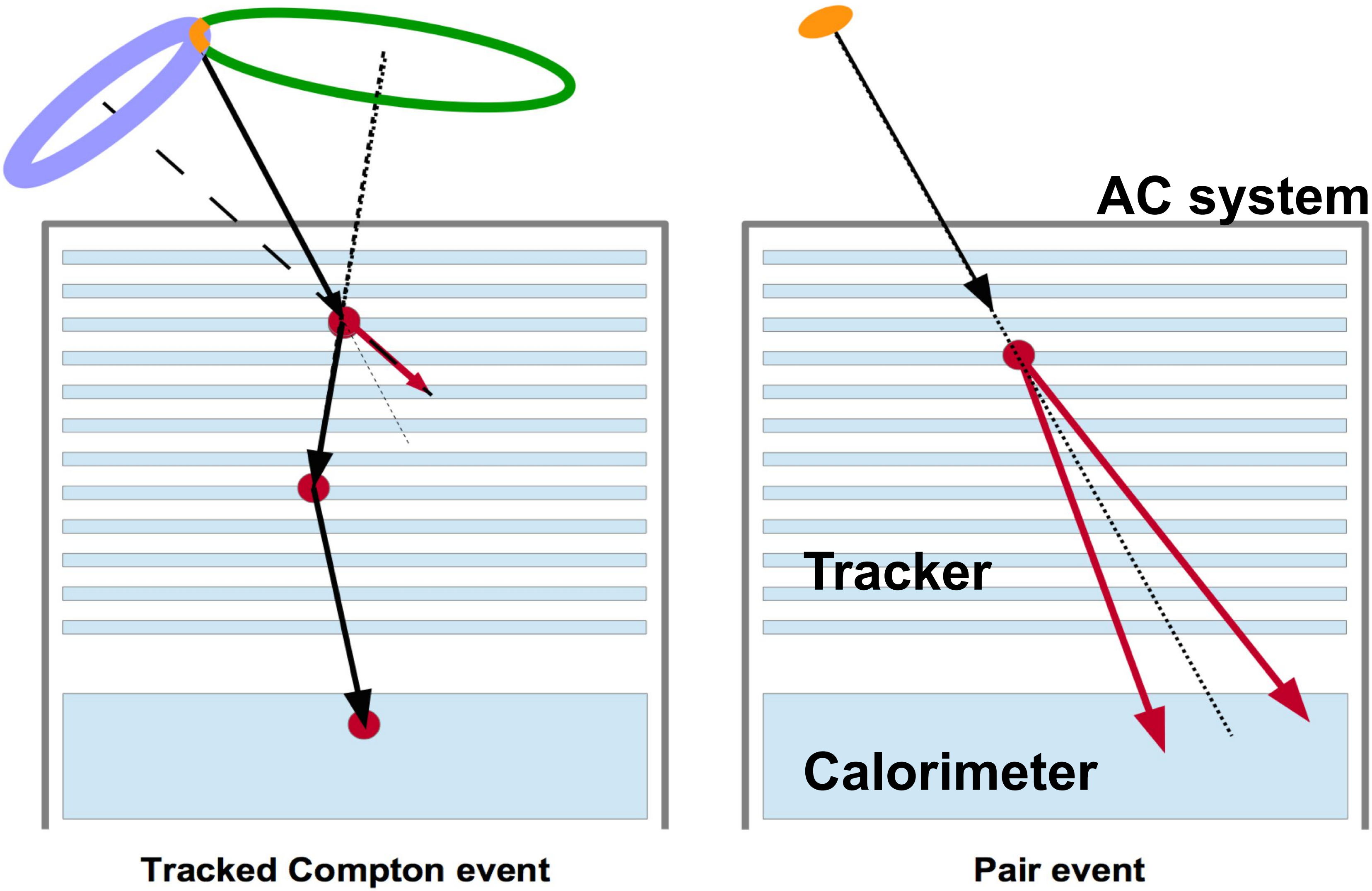


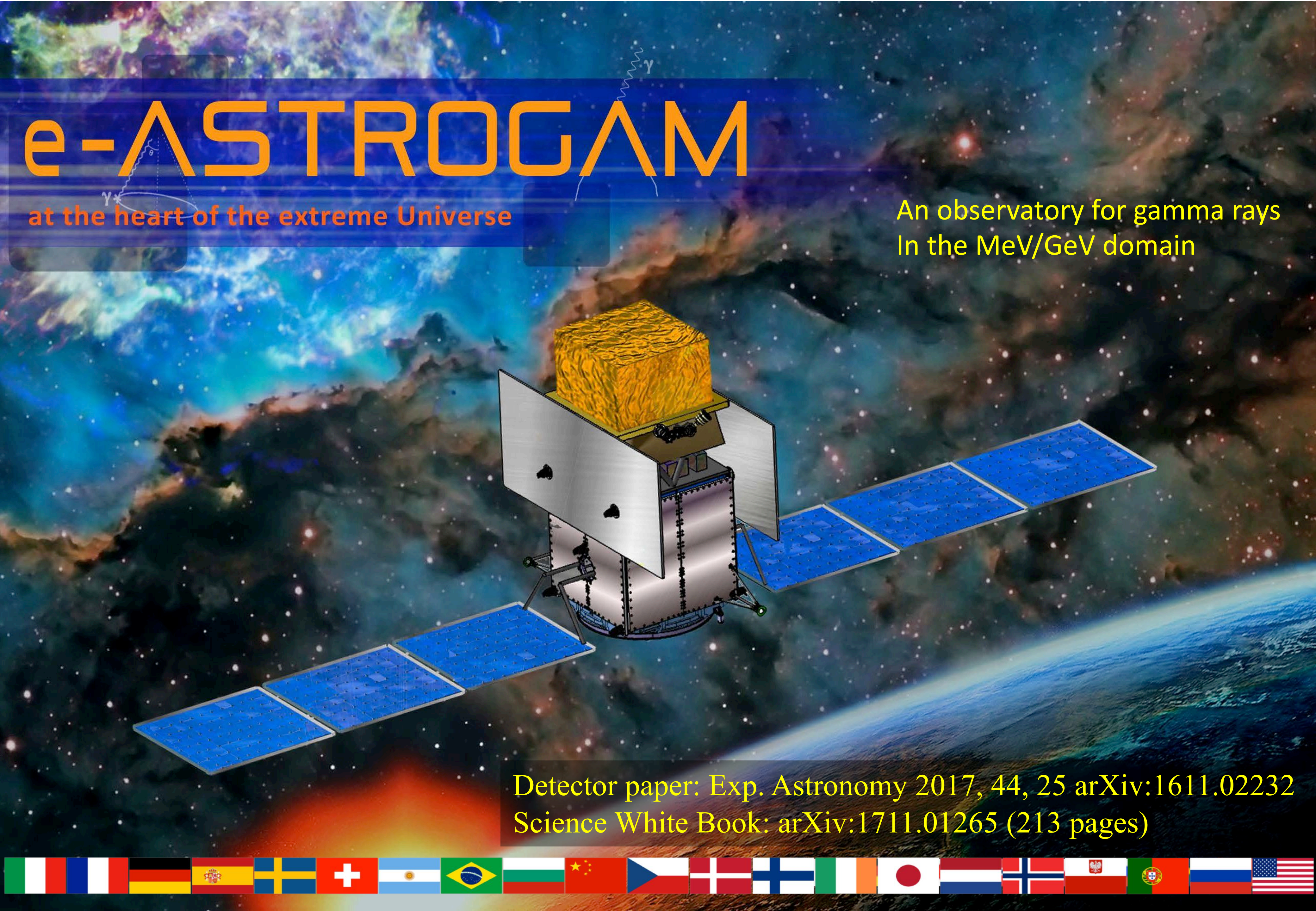
Gamma-Light Point Spread Function (angular resolution)



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

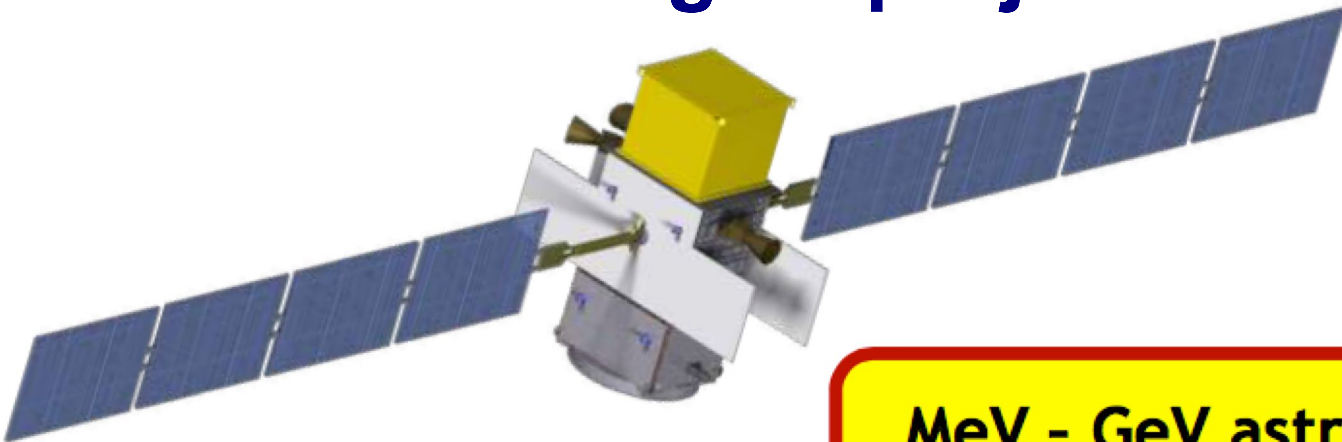
An instrument that combine two detection techniques



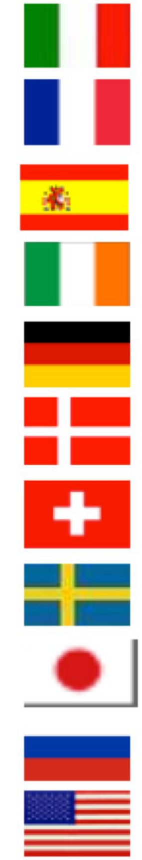

e-ASTROGAM
at the heart of the extreme Universe
An observatory for gamma rays
In the MeV/GeV domain
Detector paper: Exp. Astronomy 2017, 44, 25 arXiv:1611.02232
Science White Book: arXiv:1711.01265 (213 pages)

The next gamma-ray MeV-GeV mission:

the e-Astrogam project

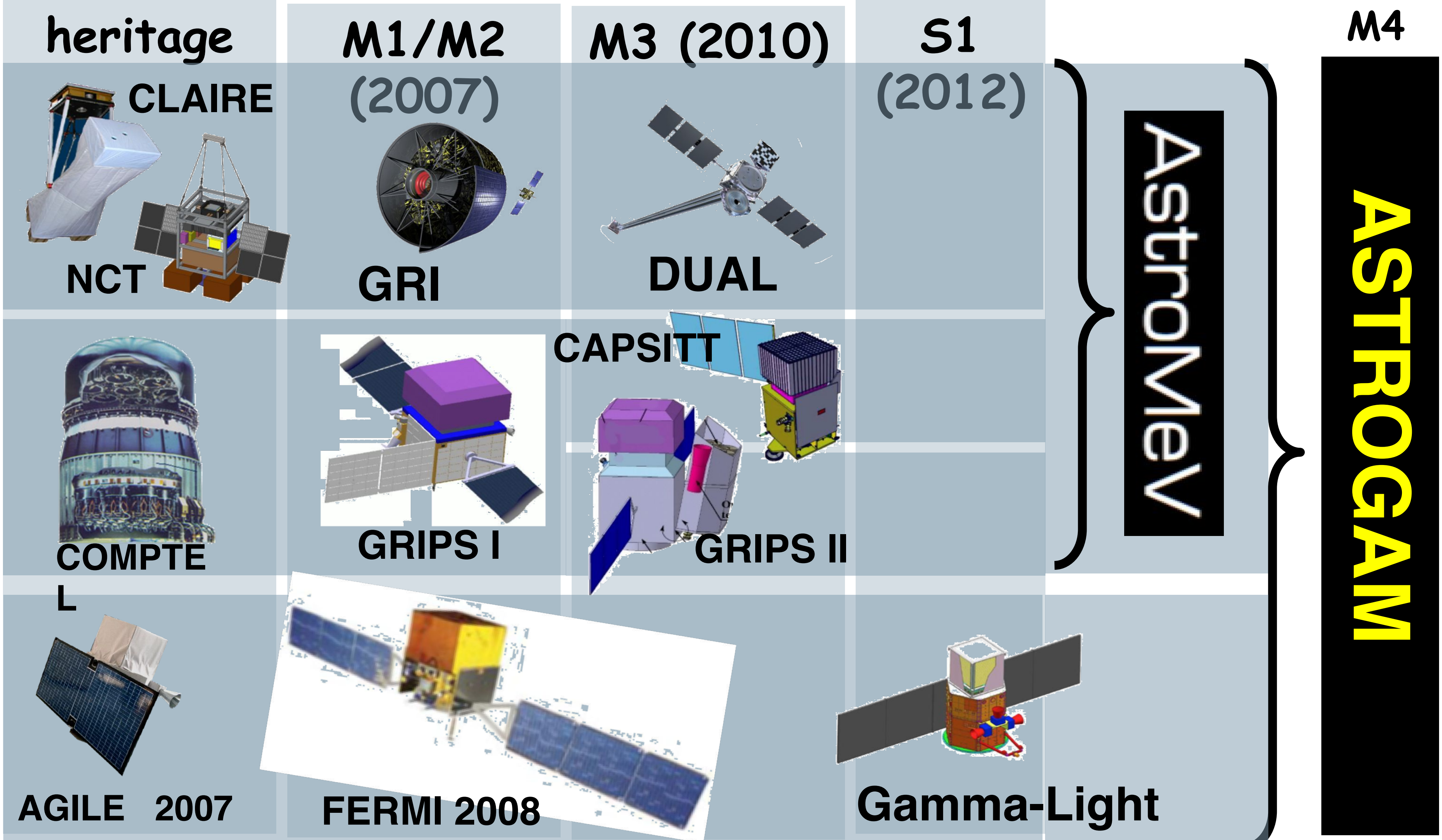


MeV - GeV astrophysics
MeV - GeV community

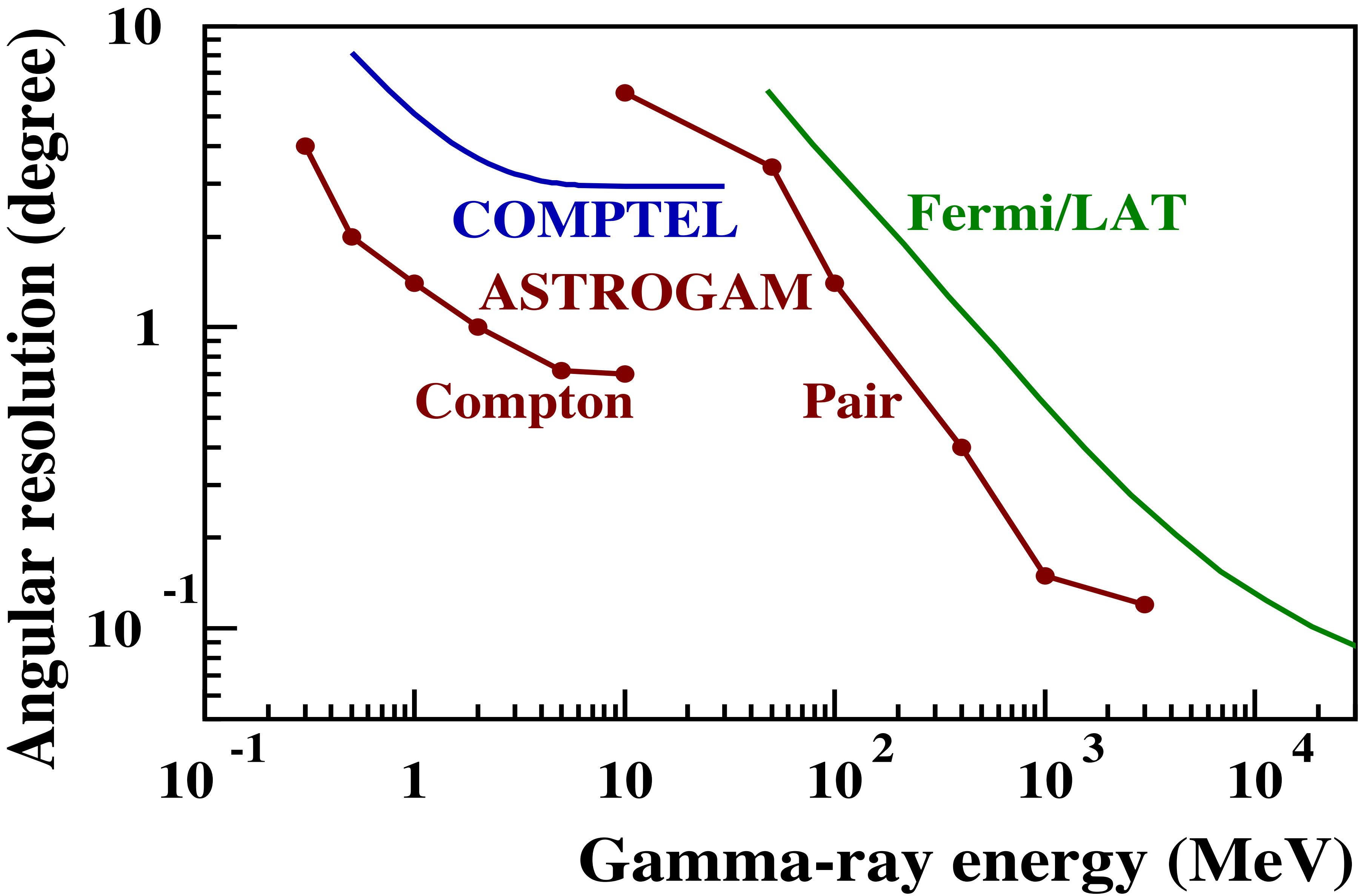


e-ASTROGAM is focused on gamma-ray astrophysics in the range 0.3-100 MeV.

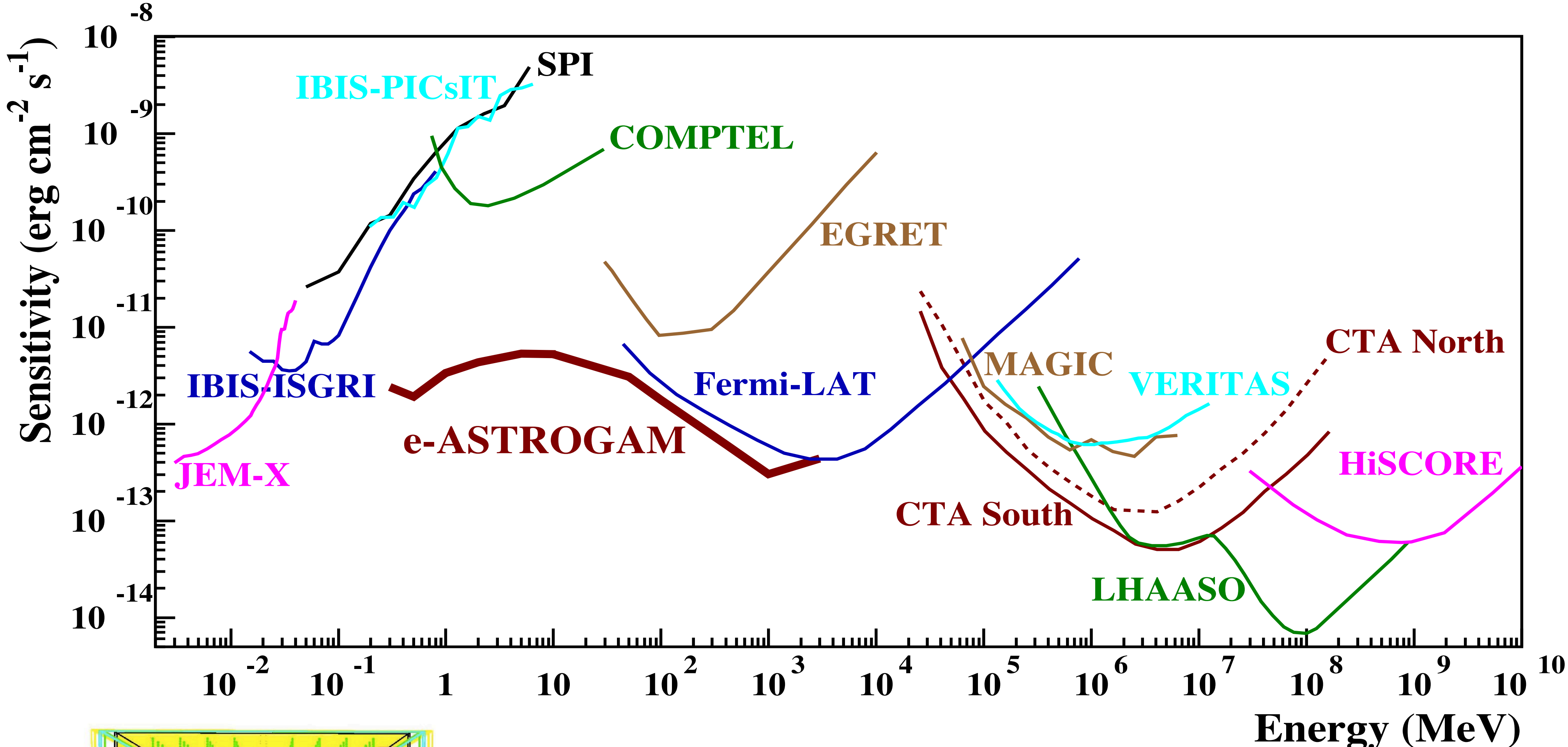
ASTROGAM a unified proposal from the entire gamma-ray community

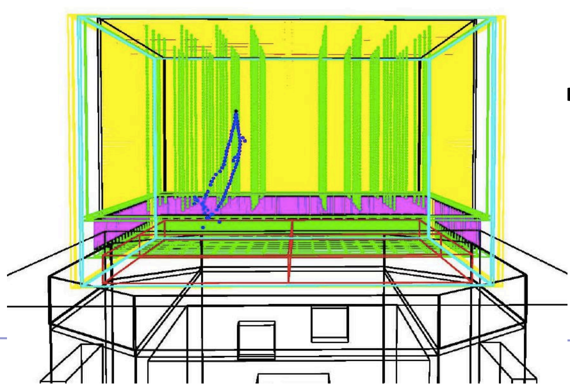


ASTROGAM Angular Resolution



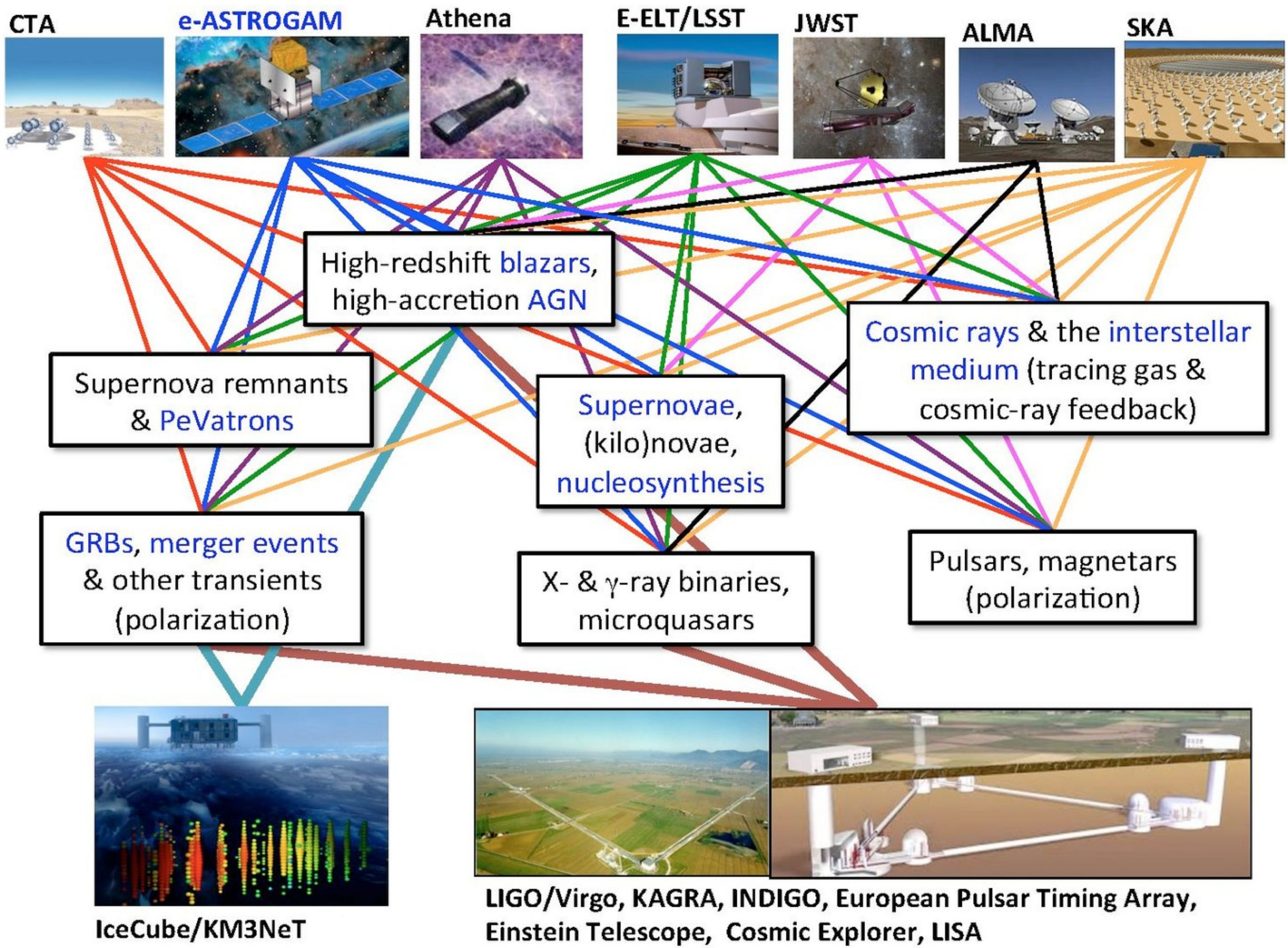
e-ASTROGAM Performance assessment





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

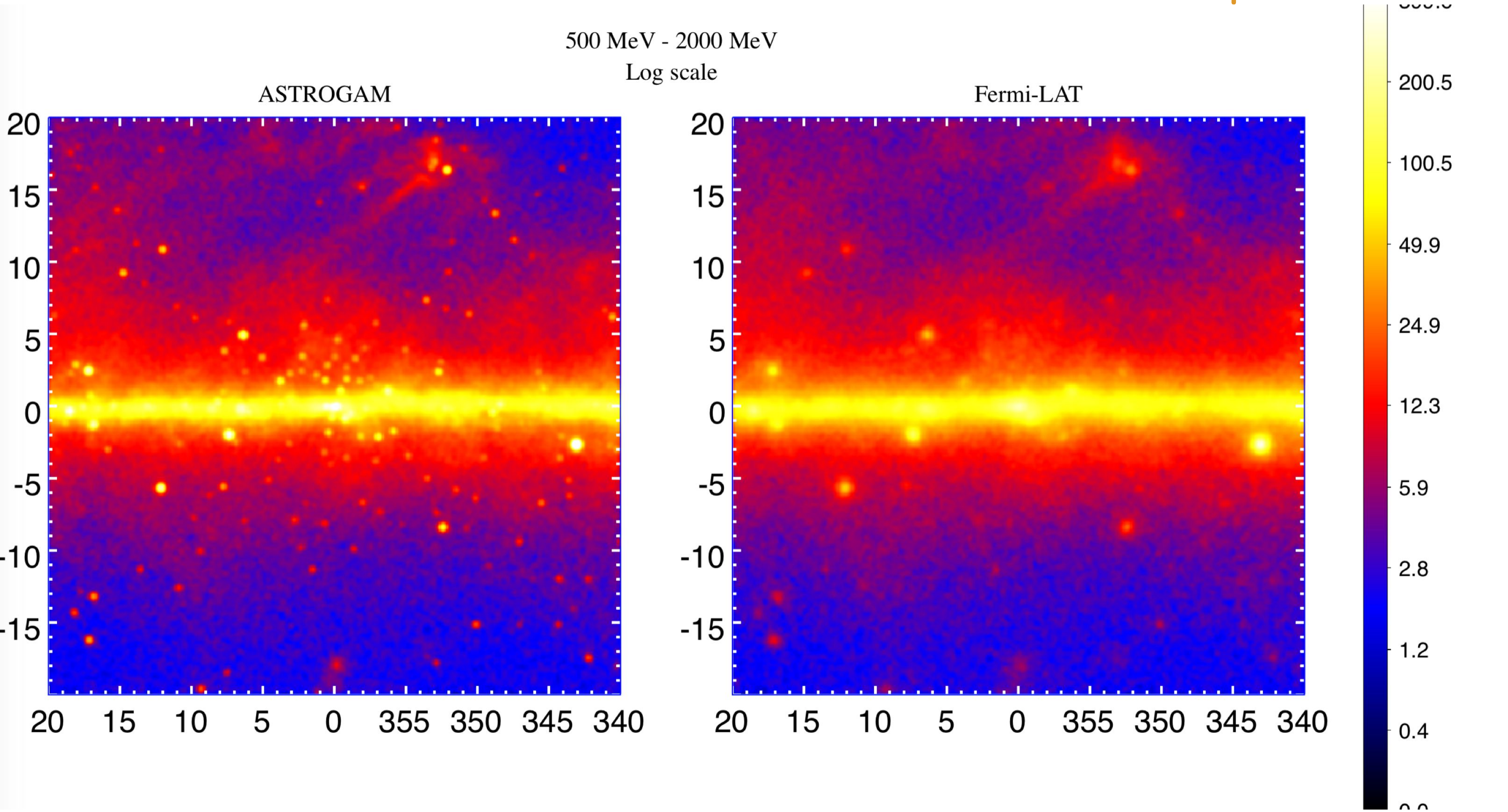
e-Astrogam: arXiv:1611.02232



CTA
e-ASTROGAM
Athena
E-ELT/LSST
JWST
ALMA
SKA
High-redshift blazars, high-accretion AGN
Supernova remnants & PeVatrons
Supernovae, (kilo)novae, nucleosynthesis
Cosmic rays & the interstellar medium (tracing gas & cosmic-ray feedback)
GRBs, merger events & other transients (polarization)
X- & γ-ray binaries, microquasars
Pulsars, magnetars (polarization)
IceCube/KM3NeT
LIGO/Virgo, KAGRA, INDIGO, European Pulsar Timing Array, Einstein Telescope, Cosmic Explorer, LISA

Galactic Center Region 0.5-2 GeV

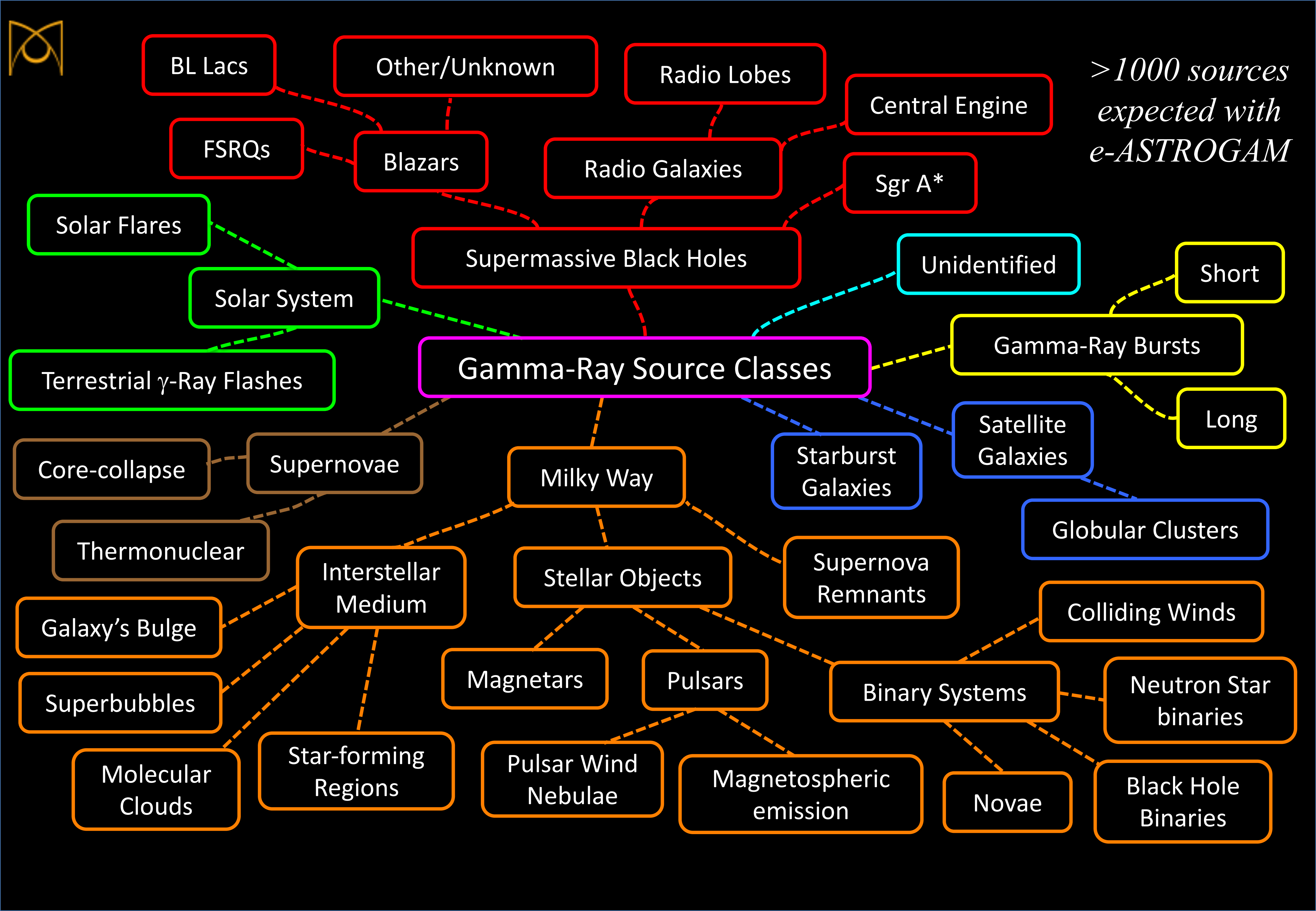
Fermi PSF Pass7 rep v15 source



Morselli, Gomez Vargas, preliminary

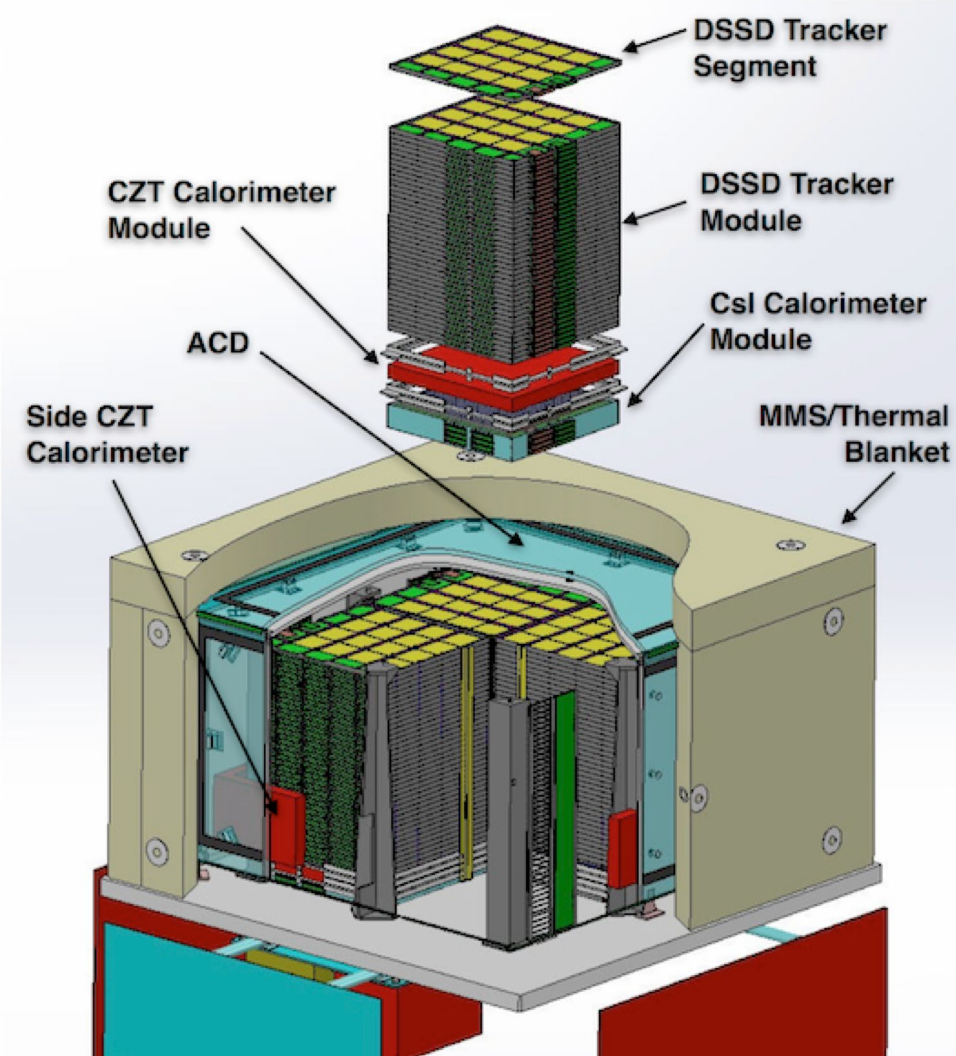
Why eAstrogam is important for IceCube and KM3Net

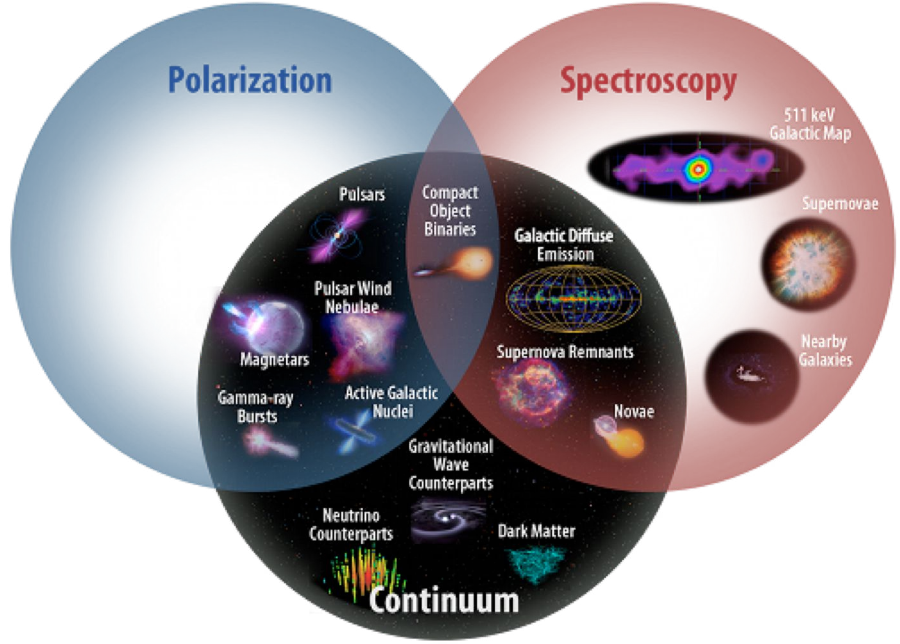
- Wide FoV (> 2.5 sr at 10 MeV) in survey mode.
- Sources of astrophysical neutrinos detected by IceCube may be opaque to 1–100 GeV gamma-rays but bright in the MeV domains (expecially if the neutrino flux originates from photo-hadronic processes)
- eAstrogam can select the best blazar candidates for a neutrino emission (looking at the MeV hump of the double-humped spectral energy distribution)
- Can constrain the population models of the EGB helping to discriminate between pγ or pp processes
-



BL Lacs
Other/Unknown
Radio Lobes
Central Engine
>1000 sources expected with e-ASTROGAM
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
Long
Satellite Galaxies
Core-collapse
Supernovae
Milky Way
Starburst Galaxies
Globular Clusters
Thermonuclear
Interstellar Medium
Stellar Objects
Supernova Remnants
Galaxy's Bulge
Colliding Winds
Superbubbles
Magnetars
Pulsars
Binary Systems
Neutron Star binaries
Molecular Clouds
Star-forming Regions
Pulsar Wind Nebulae
Magnetospheric emission
Novae
Black Hole Binaries

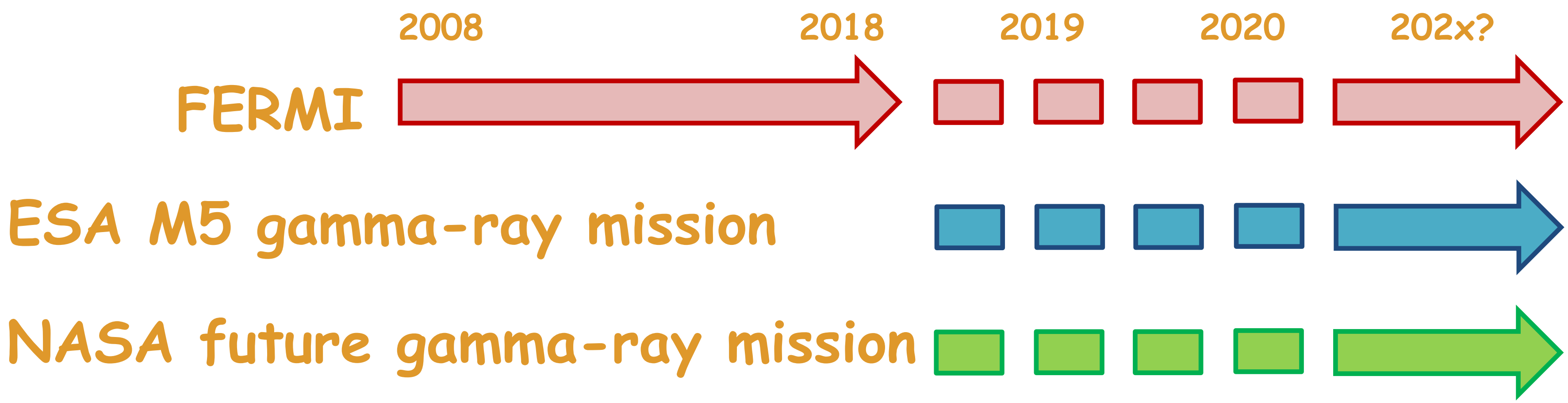
Our sister experiment: AMEGO (NASA)
(two brands, one community)





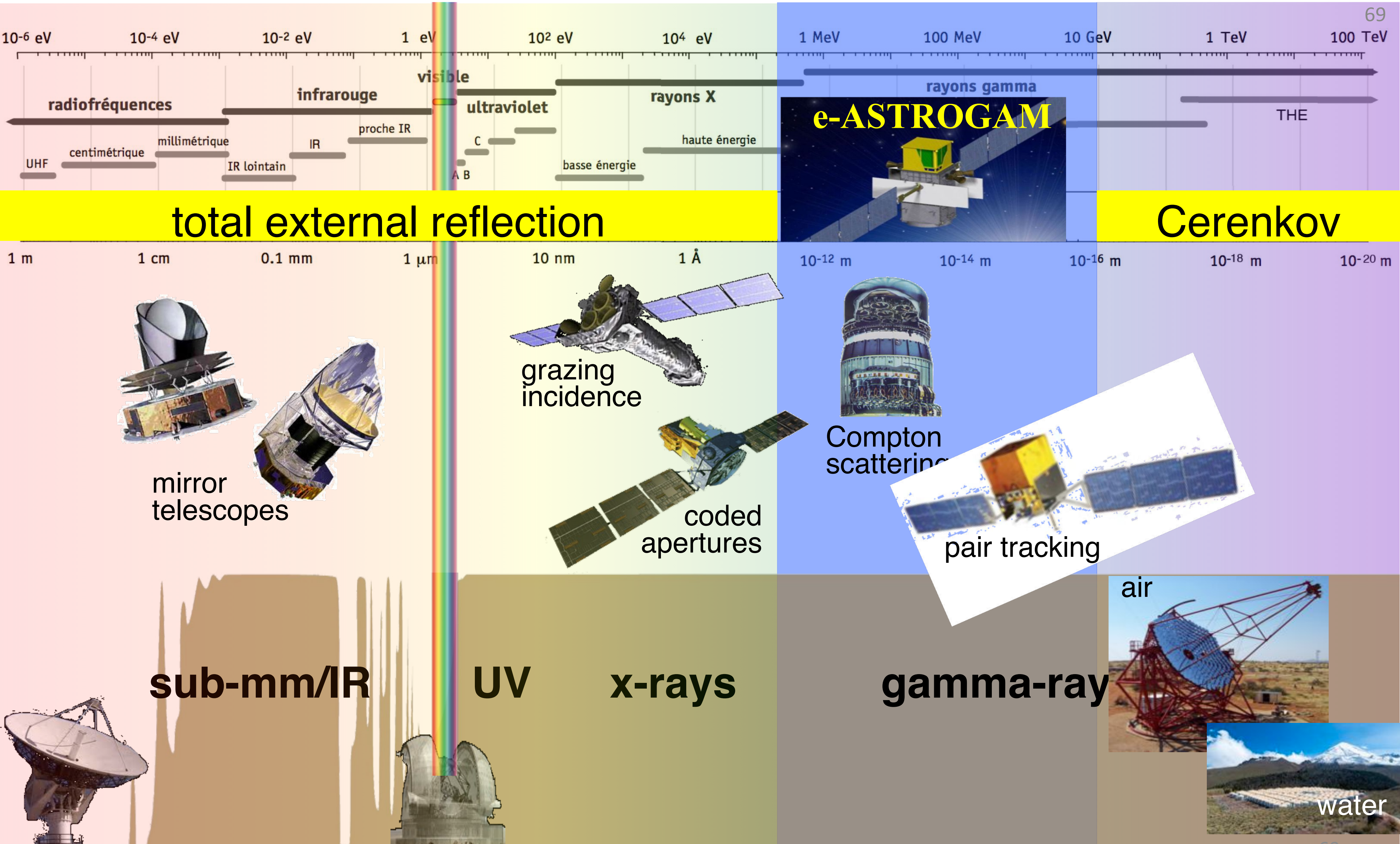
- ~20% smaller tracker
- CZT calorimeter layer
- In the decadal survey?

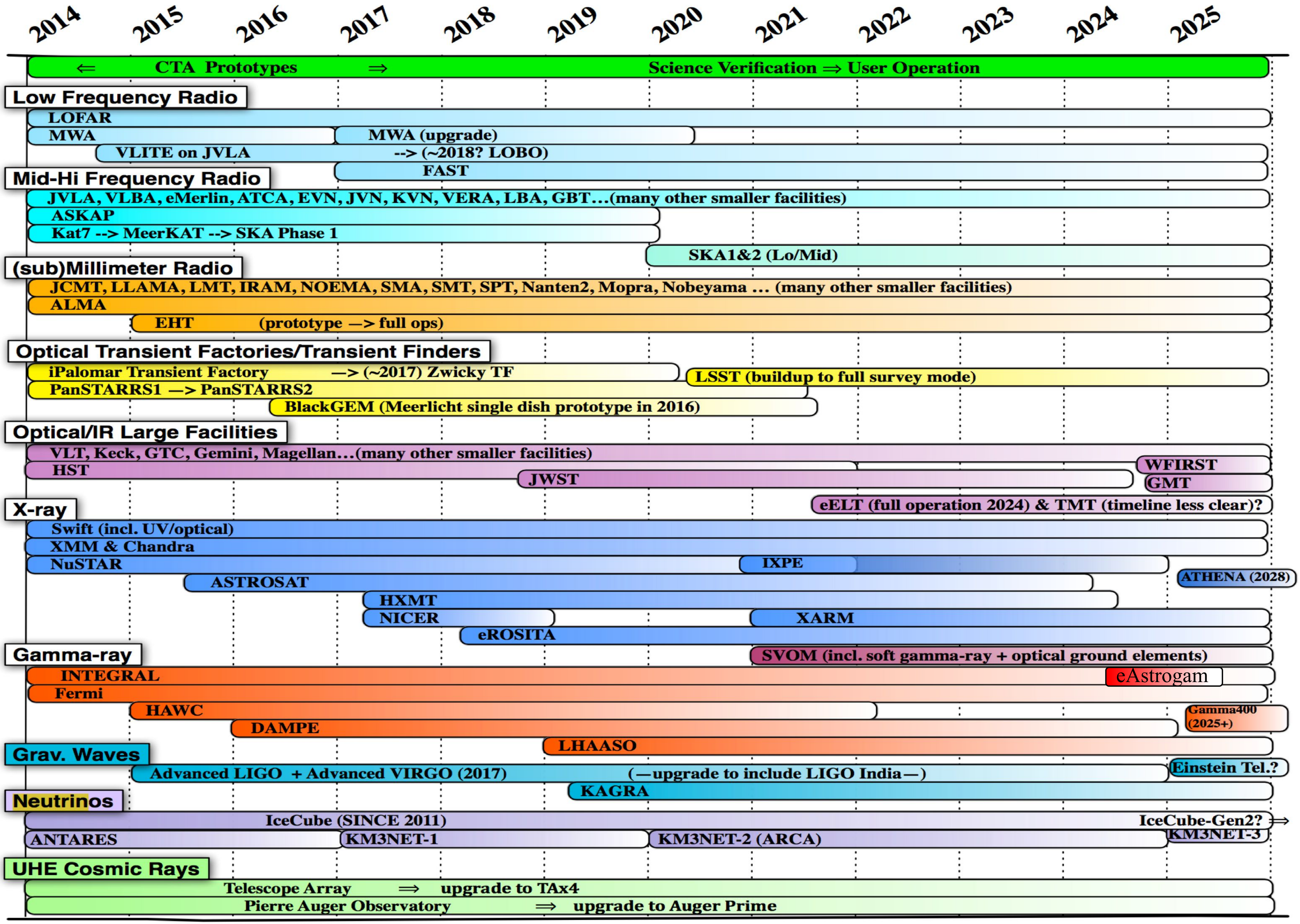
Space-based high energy gamma ray plan



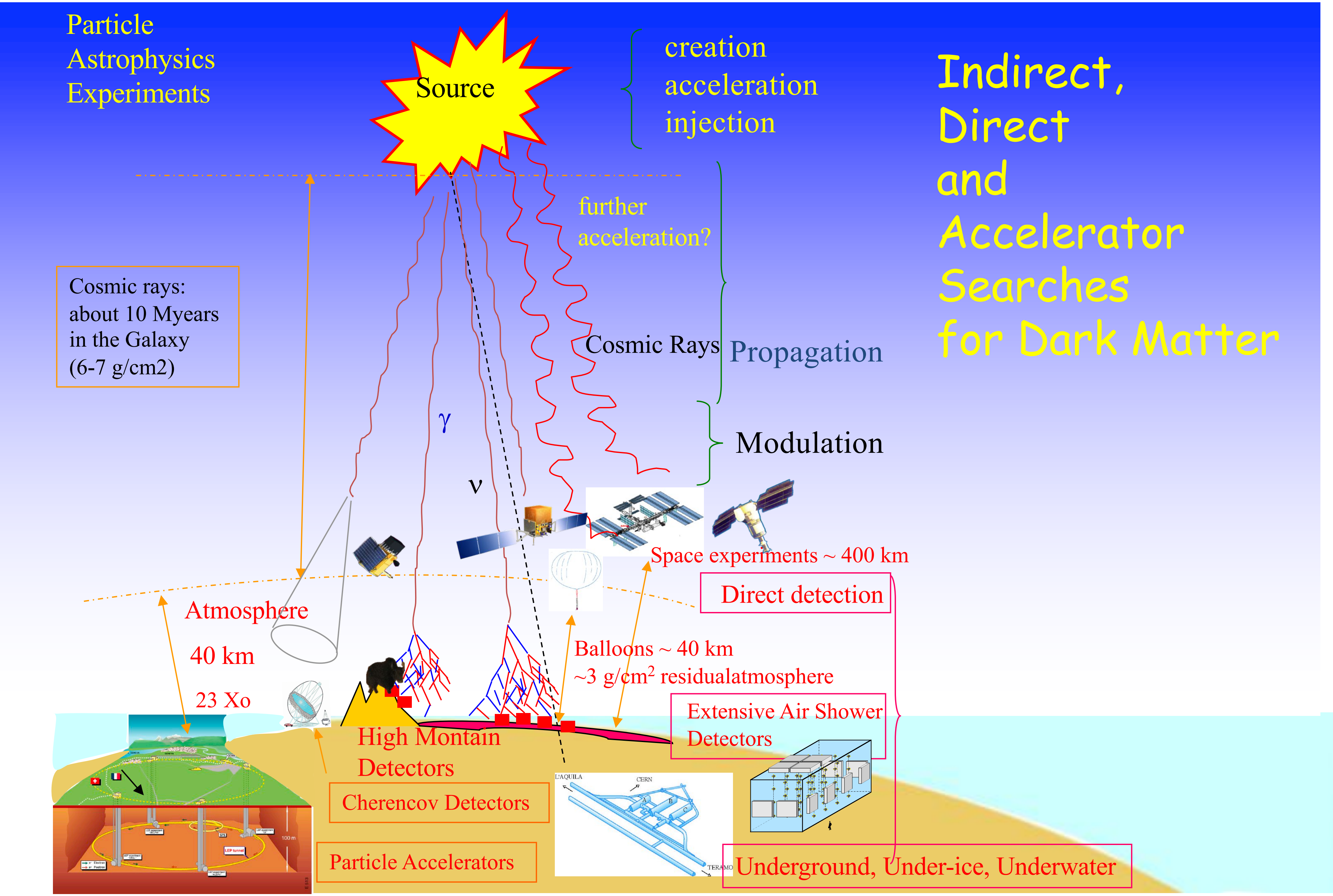
- M5 Phase A selection
  - 7 May 2018: ESA selects three new mission concepts for study:
    - A high-energy survey of the early Universe (Theseus), an infrared observatory to study the formation of stars, planets and galaxies (Spica) , and a Venus orbiter (EnVision) are to be considered for ESA's fifth medium class mission in its Cosmic Vision science programme, with a planned launch date in **2032**
  - e-ASTROGAM not selected for ESA M5
    - Excellent report, though; stressed challenging technical solutions
- Next chances:
  - AMEGO decadal review in 2019
  - Discussions for a possible integration in HERD
  - Discussions for a possible Russian launcher

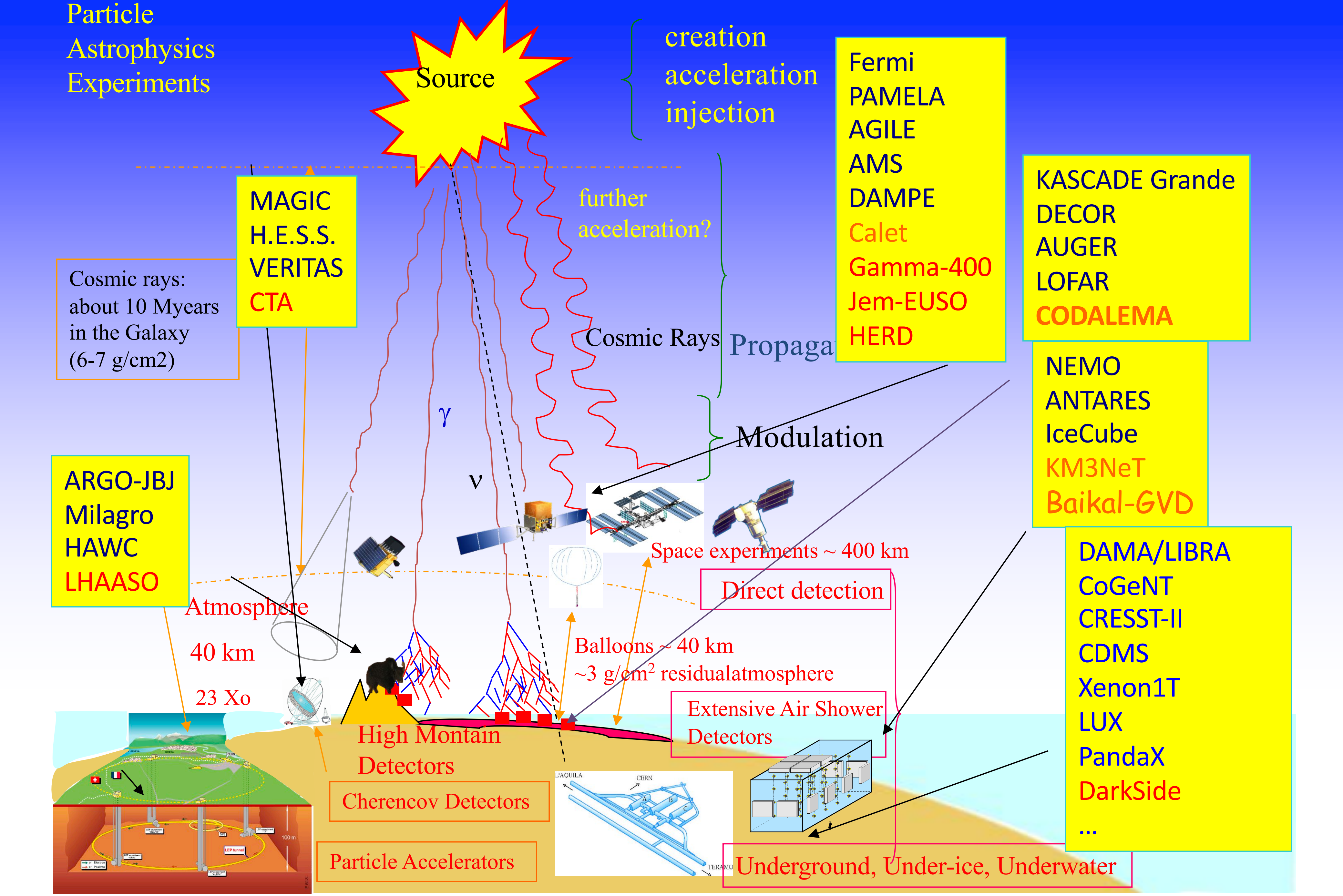
An instrument to complete the coverage of the electromagnetic spectrum





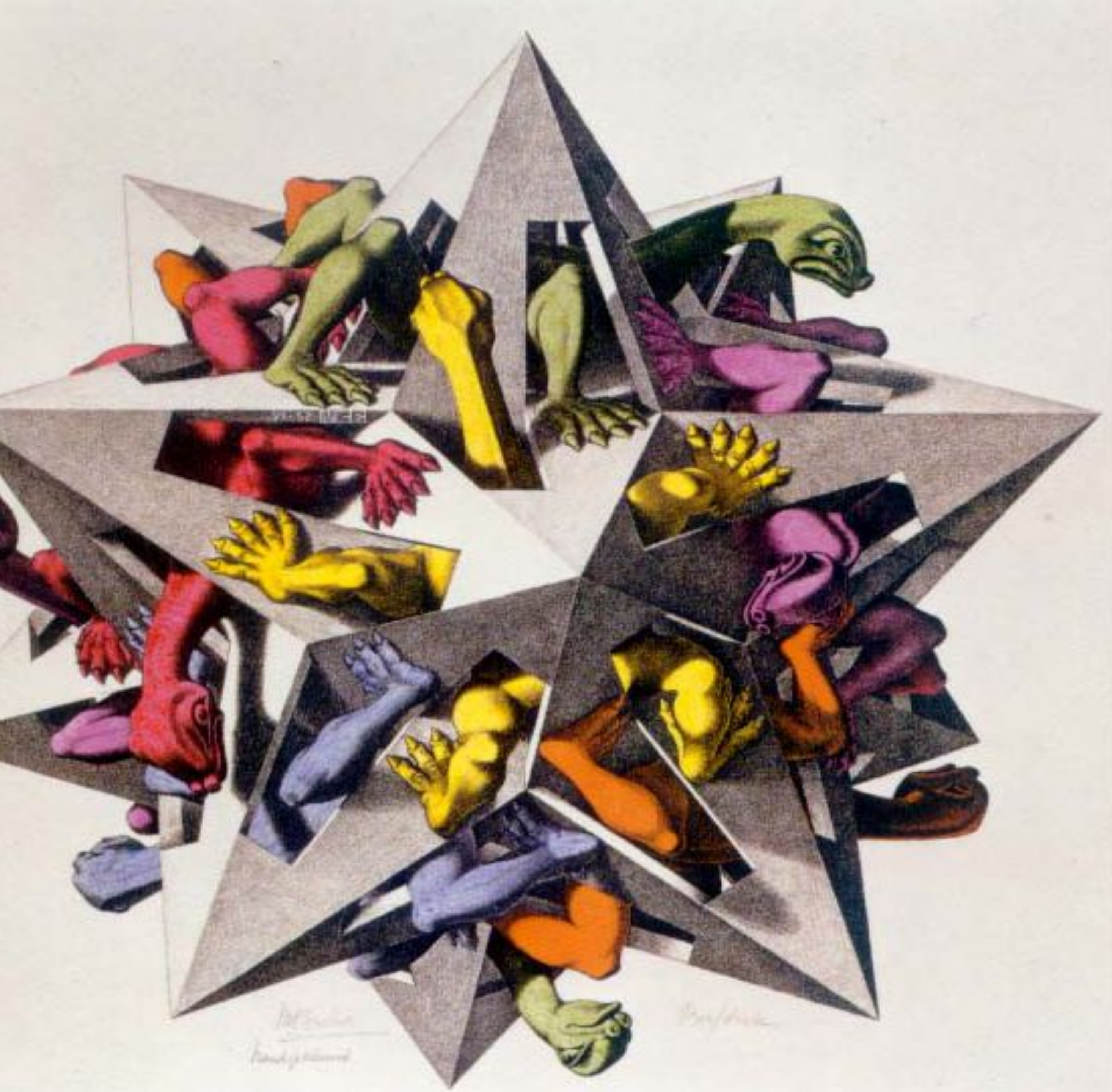
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
⇐ CTA Prototypes ⇒
Science Verification ⇒ User Operation
Low Frequency Radio
LOFAR
MWA
MWA (upgrade)
VLITE on JVLA
--> (~2018? LOBO)
FAST
Mid-Hi Frequency Radio
JVLA, VLBA, eMerlin, ATCA, EVN, JVN, KVN, VERA, LBA, GBT…(many other smaller facilities)
ASKAP
Kat7 --> MeerKAT --> SKA Phase 1
SKA1&2 (Lo/Mid)
(sub)Millimeter Radio
JCMT, LLAMA, LMT, IRAM, NOEMA, SMA, SMT, SPT, Nanten2, Mopra, Nobeyama … (many other smaller facilities)
ALMA
EHT
(prototype —> full ops)
Optical Transient Factories/Transient Finders
iPalomar Transient Factory
—> (~2017) Zwicky TF
LSST (buildup to full survey mode)
PanSTARRS1 —> PanSTARRS2
BlackGEM (Meerlicht single dish prototype in 2016)
Optical/IR Large Facilities
VLT, Keck, GTC, Gemini, Magellan…(many other smaller facilities)
HST
WFIRST
JWST
GMT
X-ray
eELT (full operation 2024) & TMT (timeline less clear)?
Swift (incl. UV/optical)
XMM & Chandra
NuSTAR
IXPE
ATHENA (2028)
ASTROSAT
HXMT
NICER
XARM
eROSITA
Gamma-ray
SVOM (incl. soft gamma-ray + optical ground elements)
INTEGRAL
eAstrogam
Fermi
HAWC
Gamma400 (2025+)
DAMPE
LHAASO
Grav. Waves
Advanced LIGO + Advanced VIRGO (2017)
(—upgrade to include LIGO India—)
Einstein Tel.?
KAGRA
Neutrinos
IceCube (SINCE 2011)
IceCube-Gen2? ⇒
ANTARES
KM3NET-1
KM3NET-2 (ARCA)
KM3NET-3
UHE Cosmic Rays
Telescope Array
⇒ upgrade to TAx4
Pierre Auger Observatory
⇒ upgrade to Auger Prime


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 residualatmosphere
Extensive Air Shower
Detectors
High Montain
Detectors
Cherencov Detectors
Particle Accelerators
L'AQUILA
CERN
TERAMO
Underground, Under-ice, Underwater


Particle
Astrophysics
Experiments
Source
creation
acceleration
injection
Fermi
PAMELA
AGILE
AMS
DAMPE
Calet
Gamma-400
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
Propaga
NEMO
ANTARES
IceCube
KM3NeT
Baikal-GVD
γ
Modulation
ν
ARGO-JBJ
Milagro
HAWC
LHAASO
Space experiments ~ 400 km
DAMA/LIBRA
CoGeNT
CRESST-II
CDMS
Xenon1T
LUX
PandaX
DarkSide
...
Direct detection
Atmosphere
40 km
23 Xo
Balloons ~ 40 km
~3 g/cm² residualatmosphere
Extensive Air Shower
Detectors
High Montain
Detectors
Cherencov Detectors
L'AQUILA
CERN
TERAMO
Particle Accelerators
Underground, Under-ice, Underwater

Through most of history, the cosmos has been viewed as eternally tranquil

During the 20th century the quest to broaden our view of the universe has shown us the vastness of the Universe and revealed violent cosmic phenomena and mysteries




The future?
Thank you !