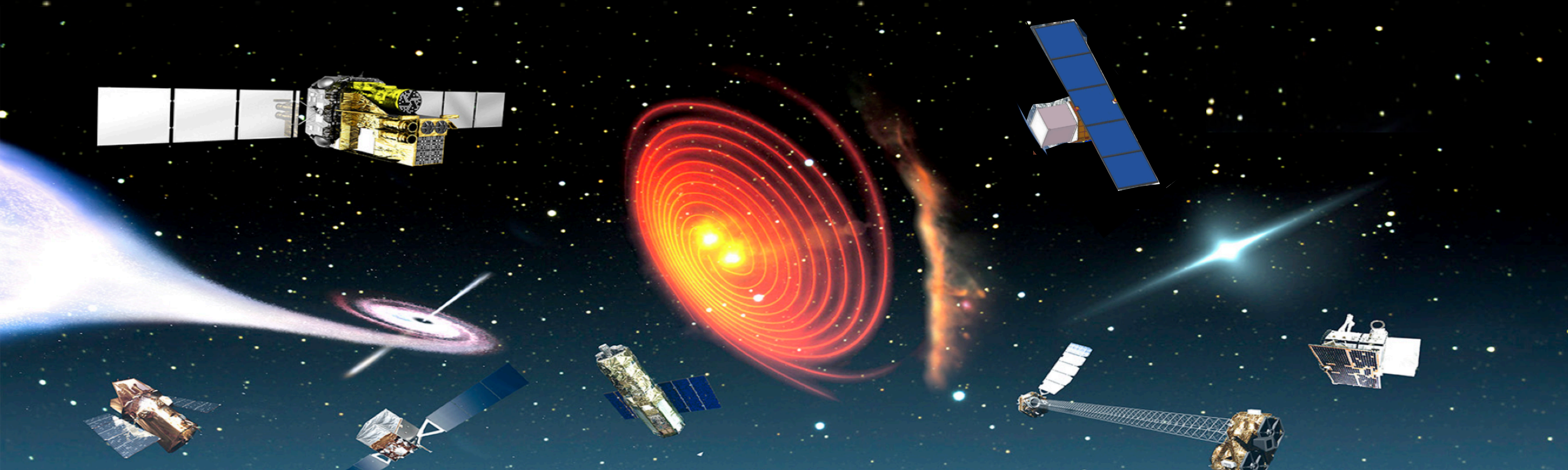
Indirect dark-matter searches with gamma-rays: experiments status and future plans from KeV to TeV



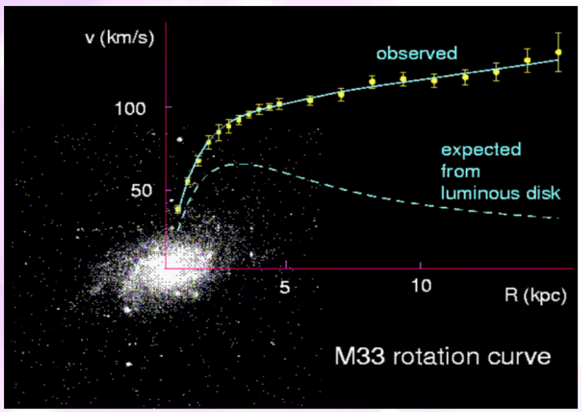
Aldo Morselli
INFN Roma Tor Vergata

CRIS 2016
"New eyes on the Universe"
10th Cosmic Ray International Seminar
Ischia (NA) Italy, July 4-8, 2016

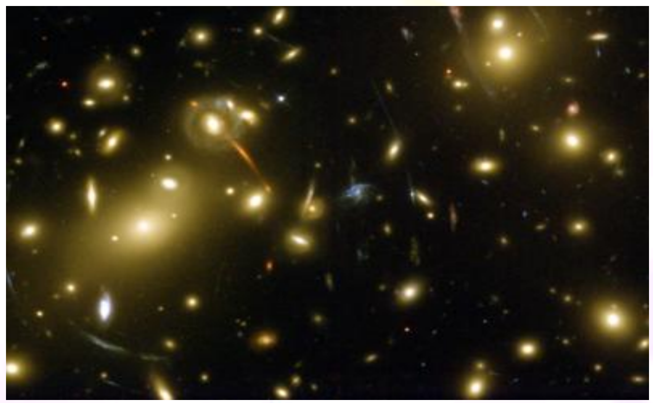
Dark Matter EVIDENCES

- 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, many other evidences:

Rotation curves of galaxies

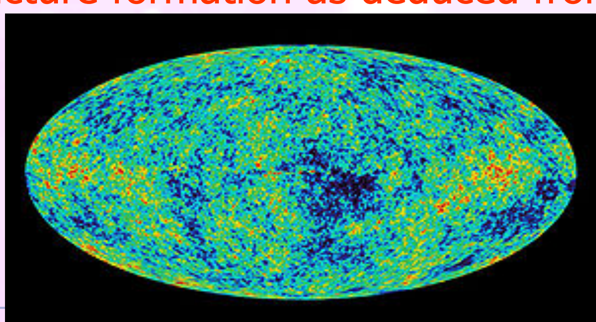


Gravitational lensing

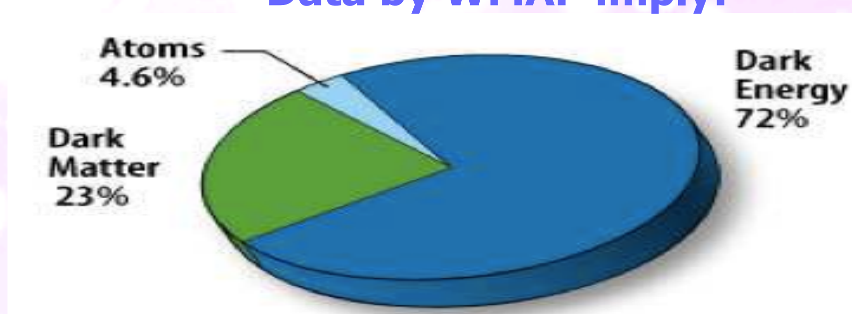


Bullet cluster

Structure formation as deduced from CMB



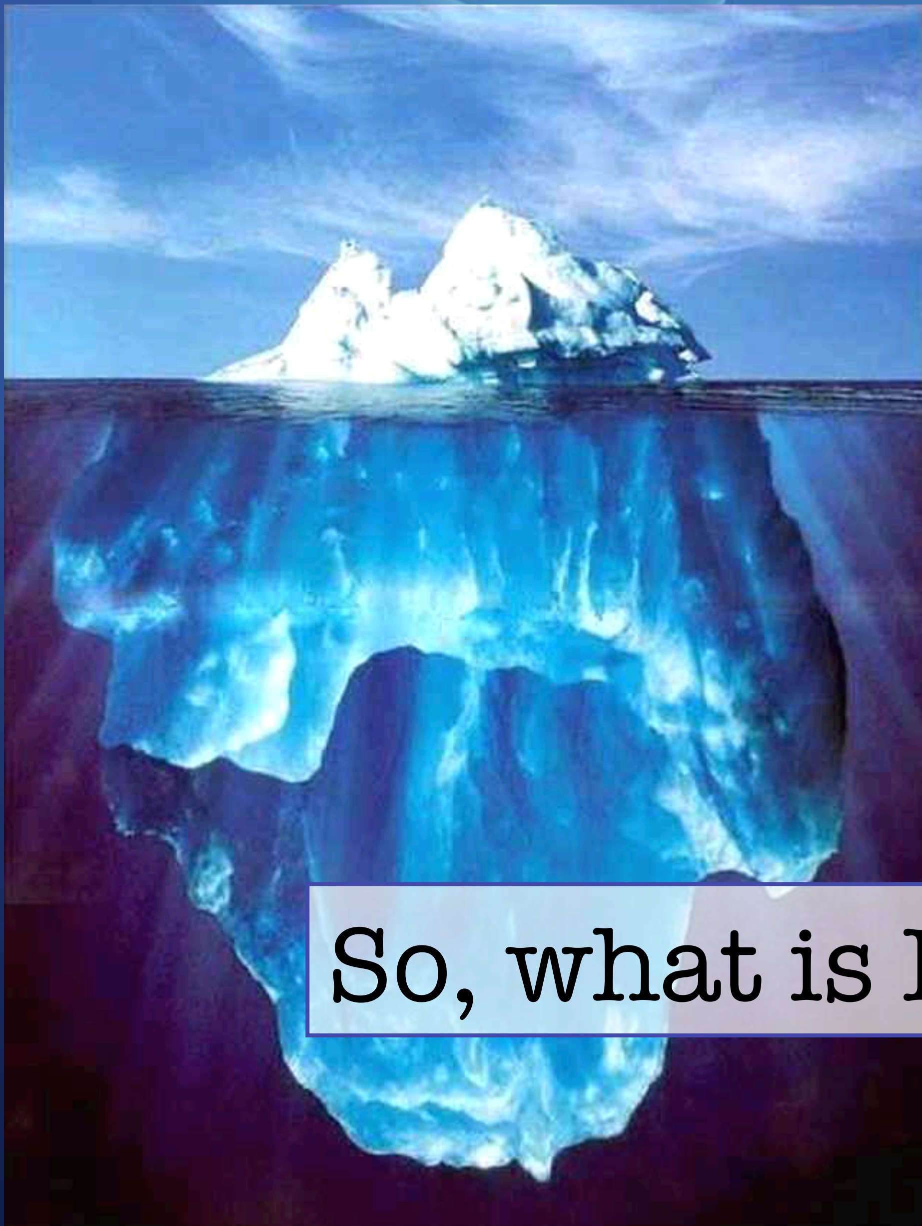
Data by WMAP imply:

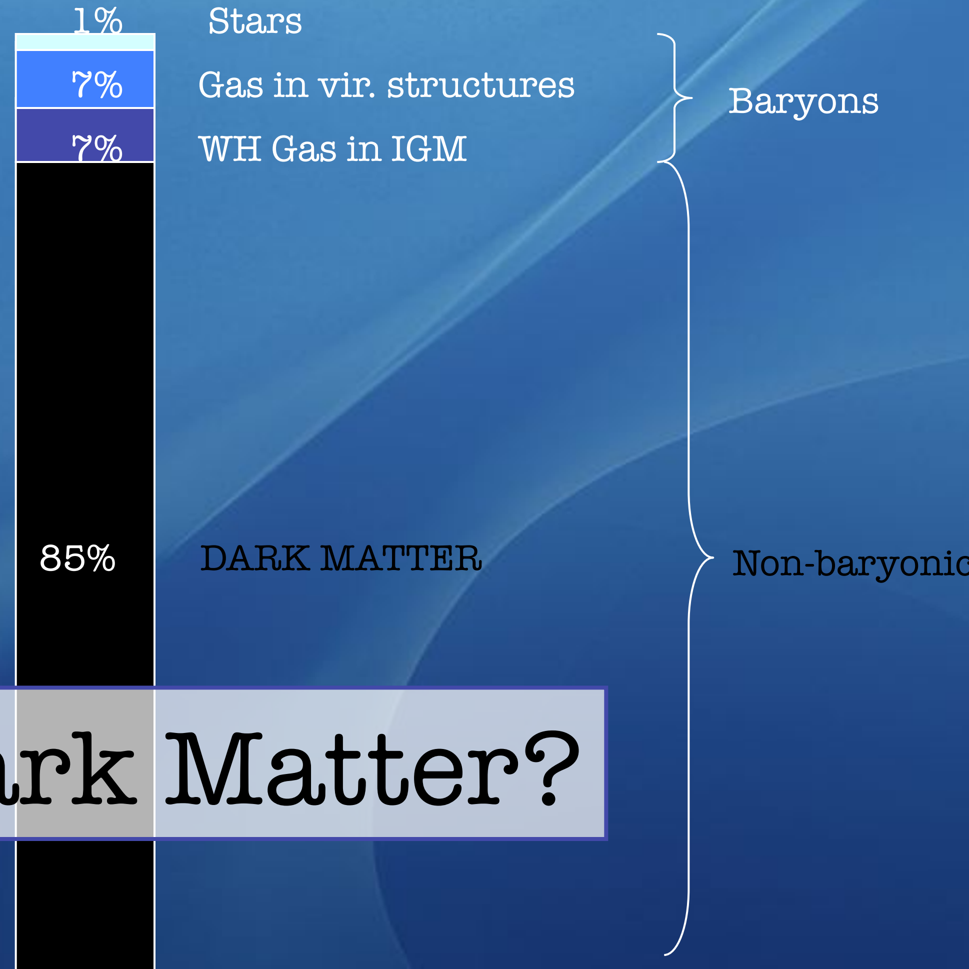


$\Omega_b h^2 \approx 0.02$

$\Omega_{DM} h^2 \approx 0.1$

An Inventory of Matter in the Universe

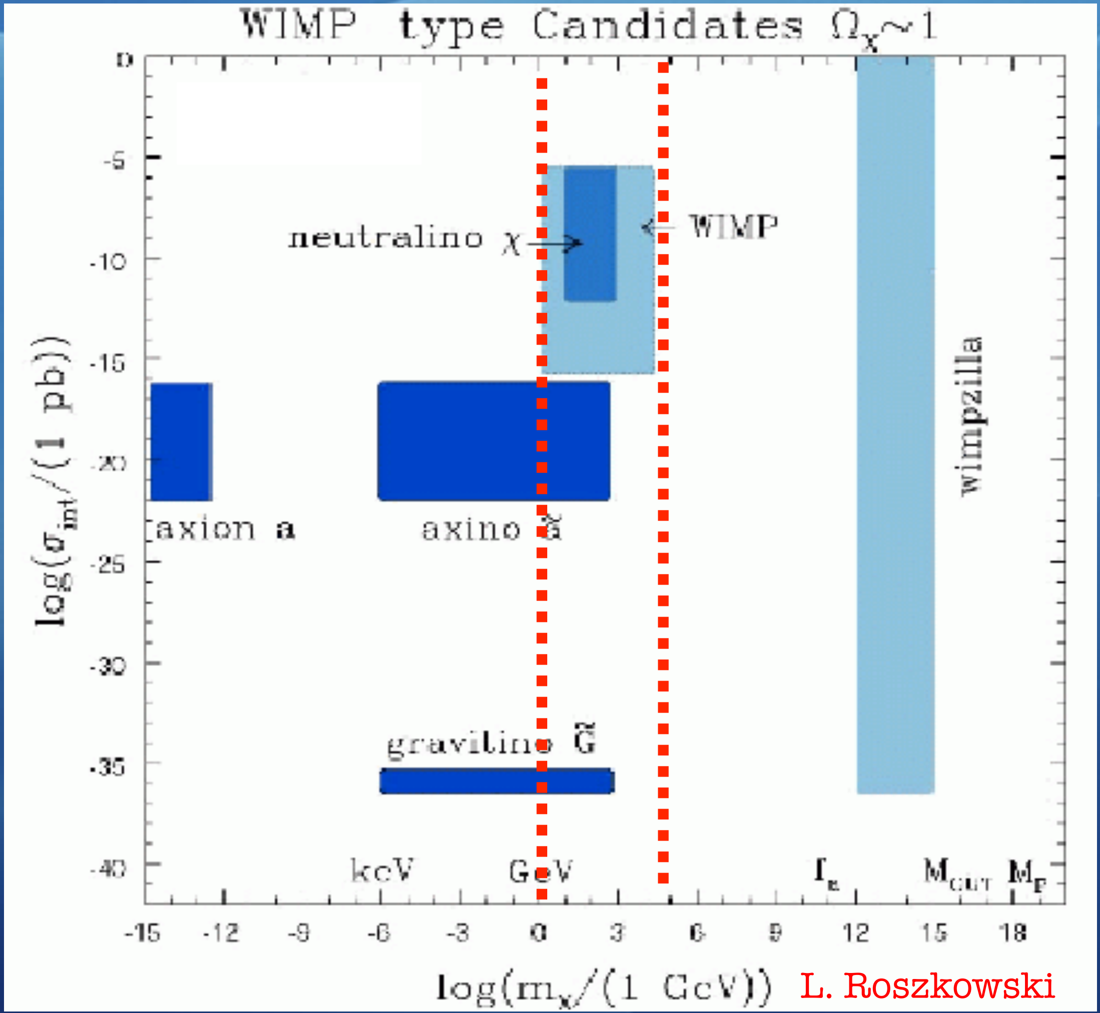




So, what is Dark Matter?

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



L. Roszkowski

Dark Matter Candidates

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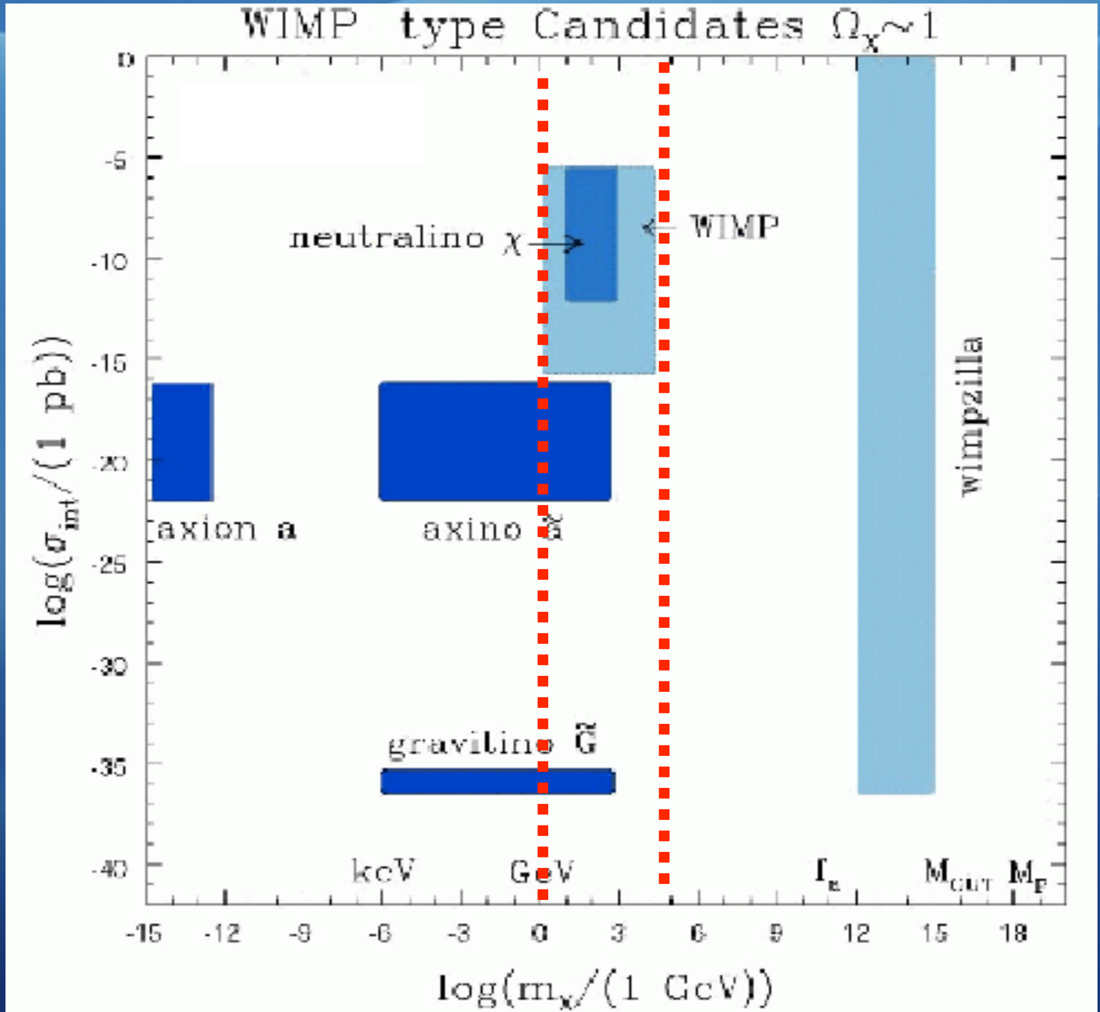
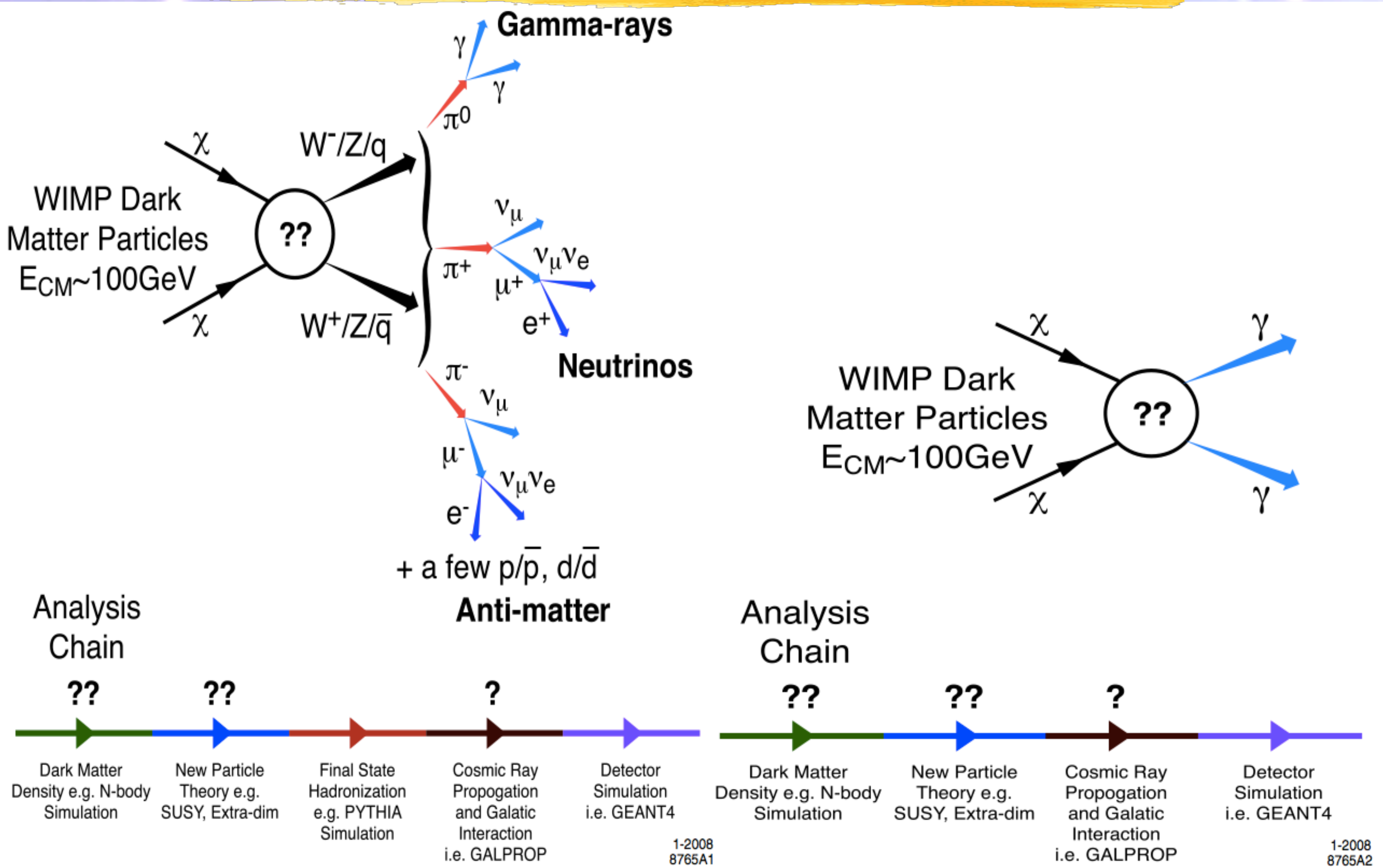


Neutralino WIMPs

Assume χ present in the Galactic halo

- χ is its own antiparticle **=>** can annihilate in galactic halo producing gamma-rays, antiprotons, positrons….
- Antimatter not produced in large quantities through standard processes (secondary production through p + p **-->** anti p + X)
- So, any extra contribution from exotic sources ($\chi\,\chi$ annihilation) is an interesting signature
- ie: $\chi\,\chi$ --> anti p + X
- Produced from (e. g.) $\chi\,\chi$ **-->** q / g / gauge boson / Higgs boson and subsequent decay and/ or hadronisation.

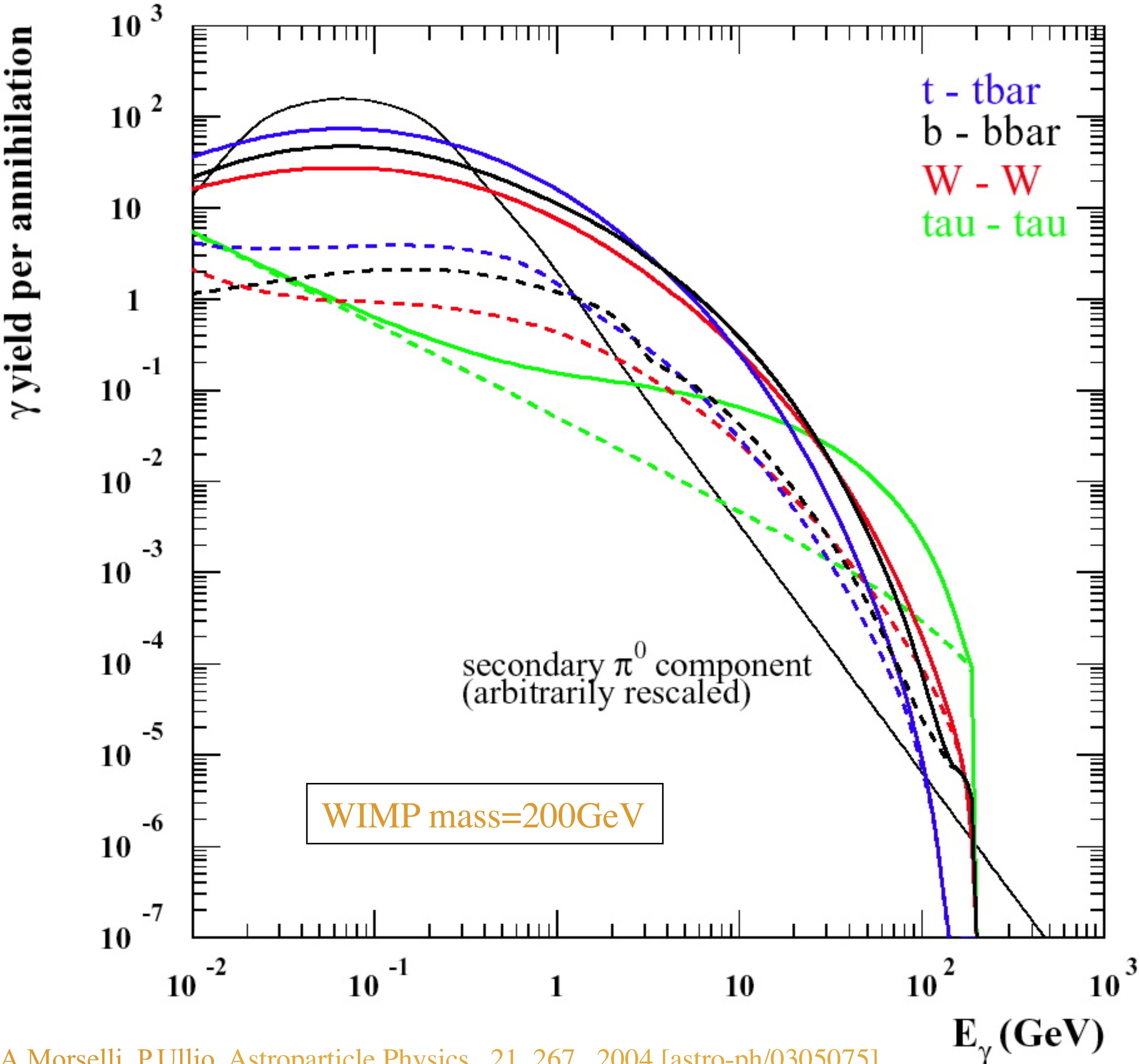
Annihilation channels



Differential yield for each annihilation channel

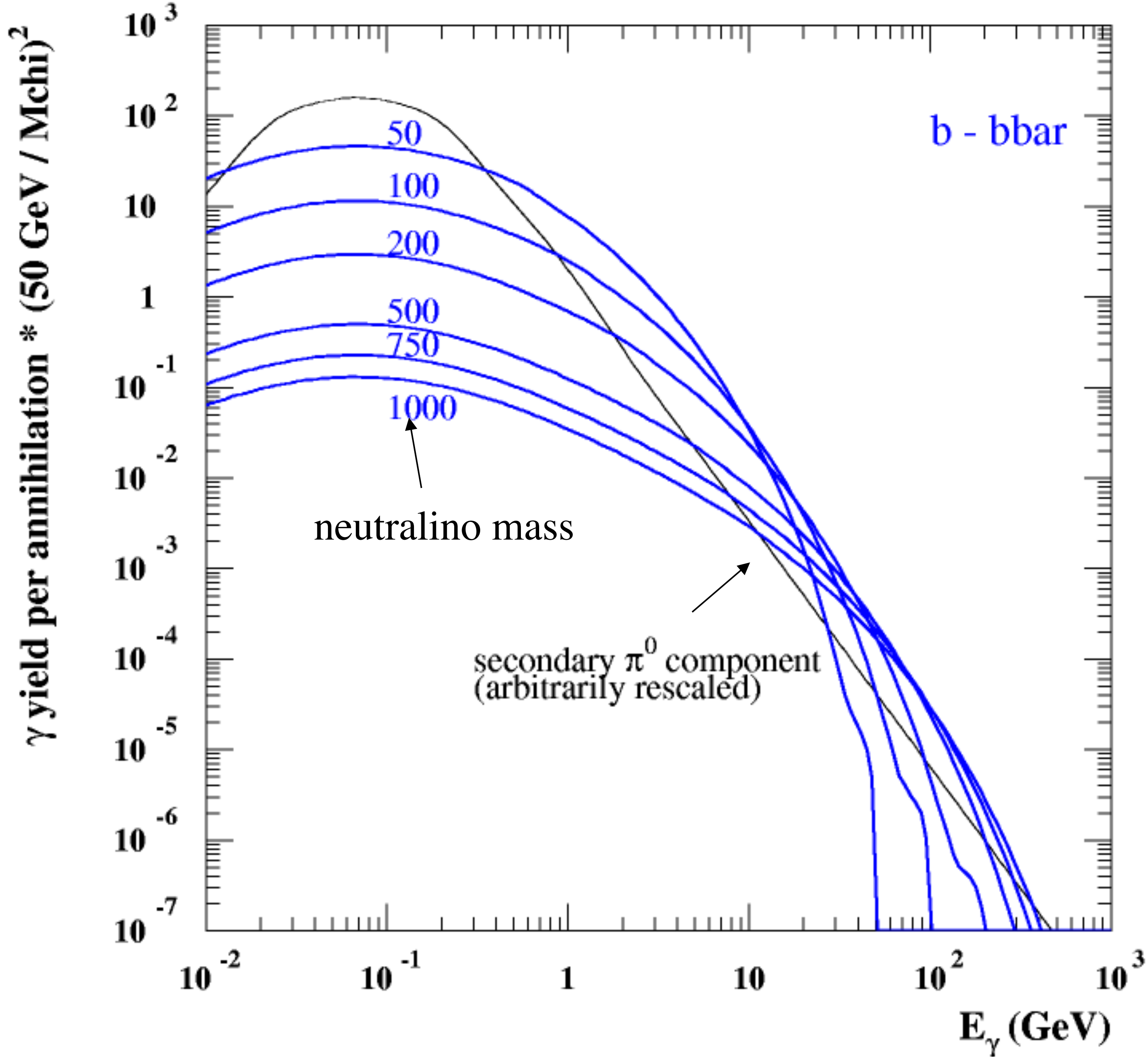
- Quite distinctive spectrum (no power-law)

- solid lines are the total yields, while the dashed lines are components not due to π^0 decays

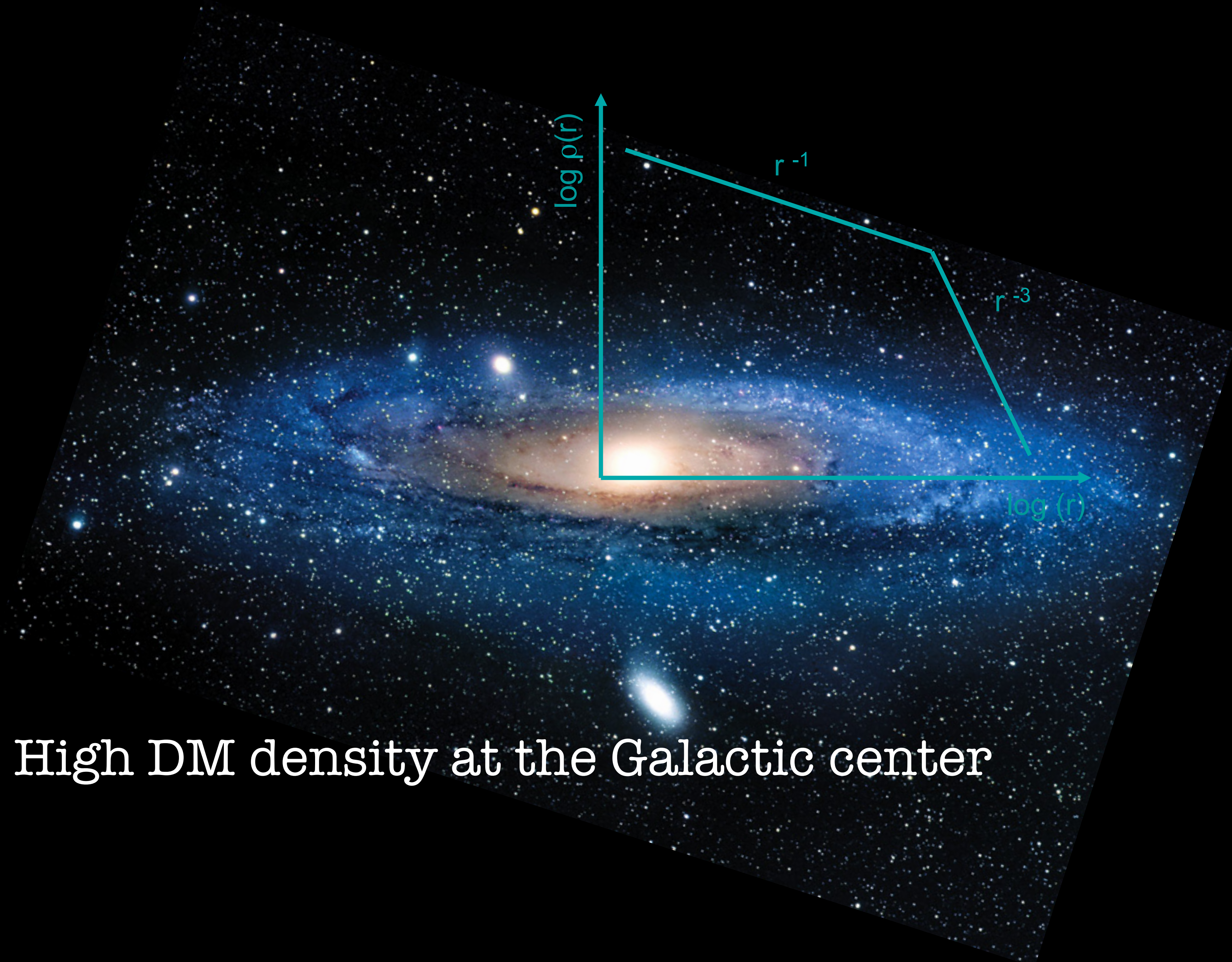


A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

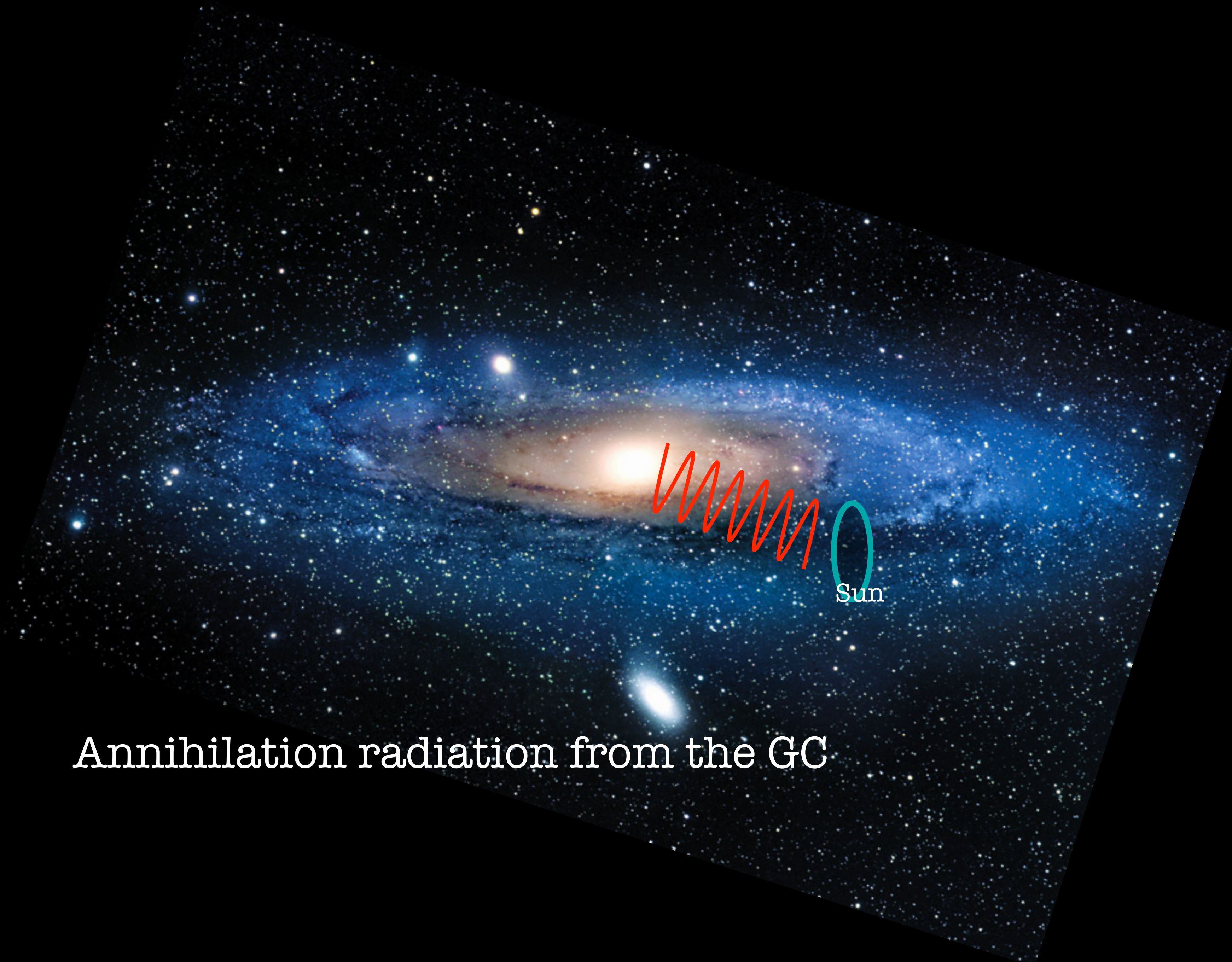
Differential yield for b bar for different neutralino mass



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



High DM density at the Galactic center



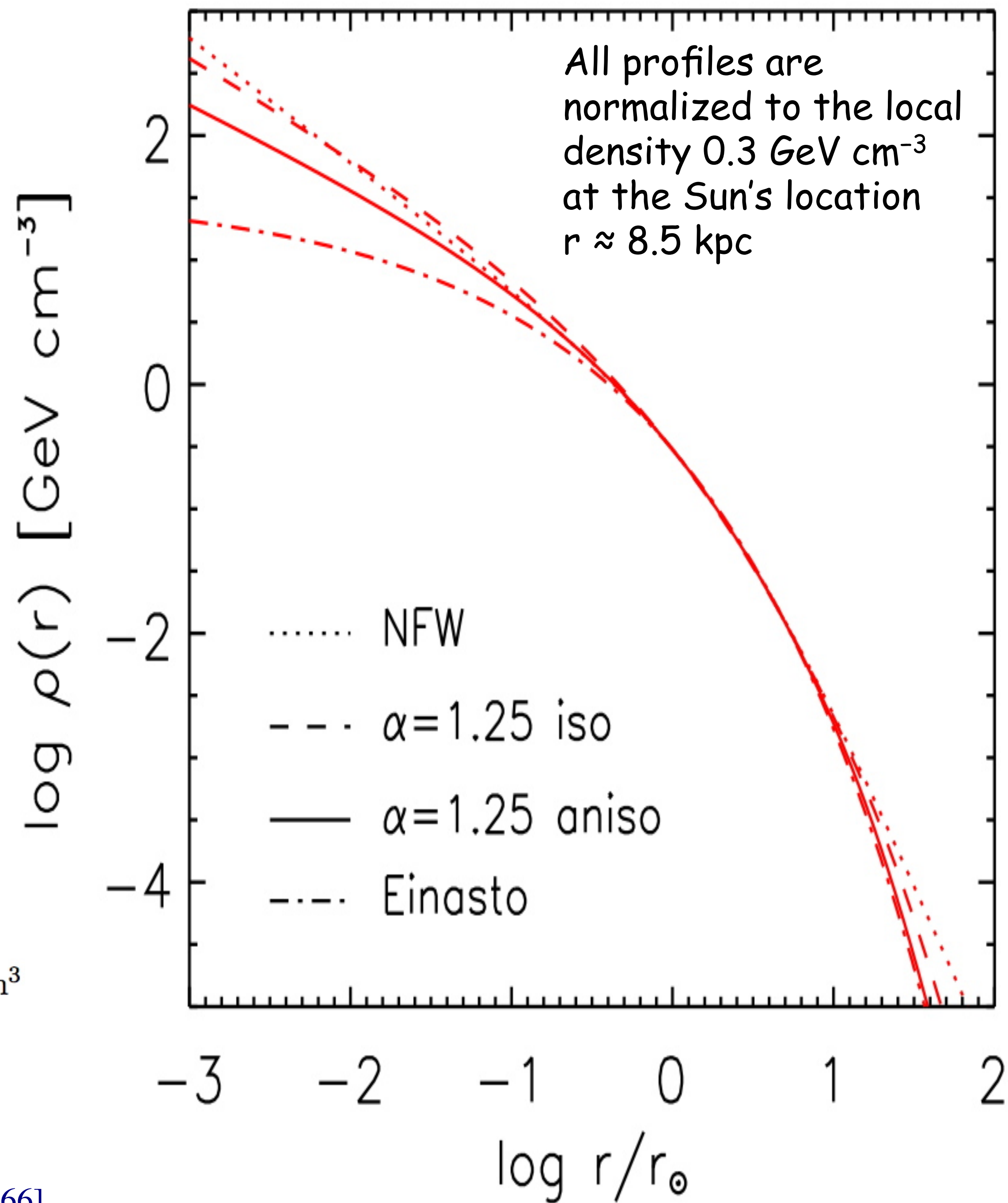
Annihilation radiation from the GC

Milky Way Dark Matter Profiles

$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

Einasto | $\alpha = 0.17$ $r_s = 20\,\text{kpc}$ $\rho_s = 0.06\,\text{GeV/cm}^3$



A.Lapi, A.Paggi, A.Cavaliere, A.Lionetto, A.Morselli, V.Vitale. A&A 510, A90 (2010) [arXiv:0912.1766]

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**

....

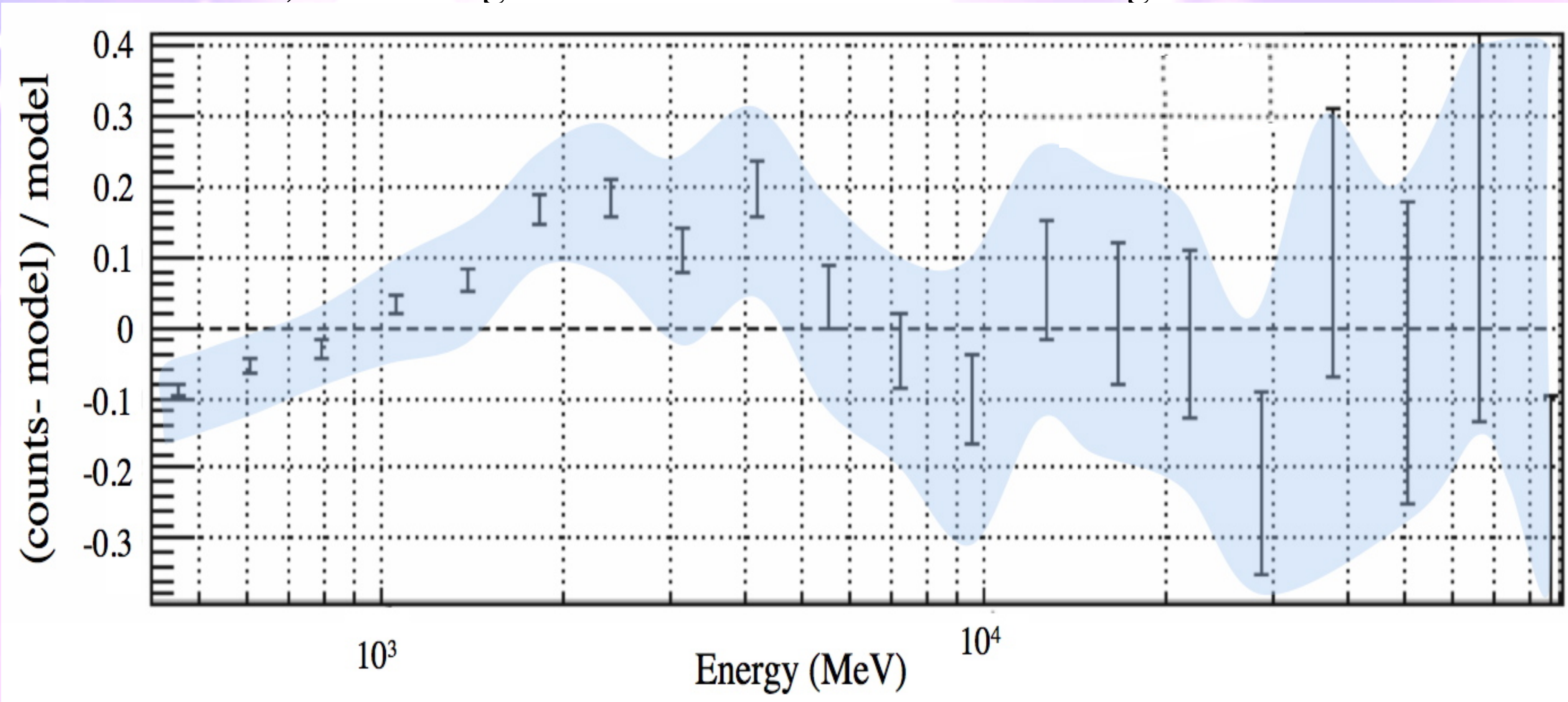
Background model systematics for the Fermi GeV excess
F.Calore, I. Cholis, C. Weniger JCAP03(2015)038 **arXiv:1409.0042v1**

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)

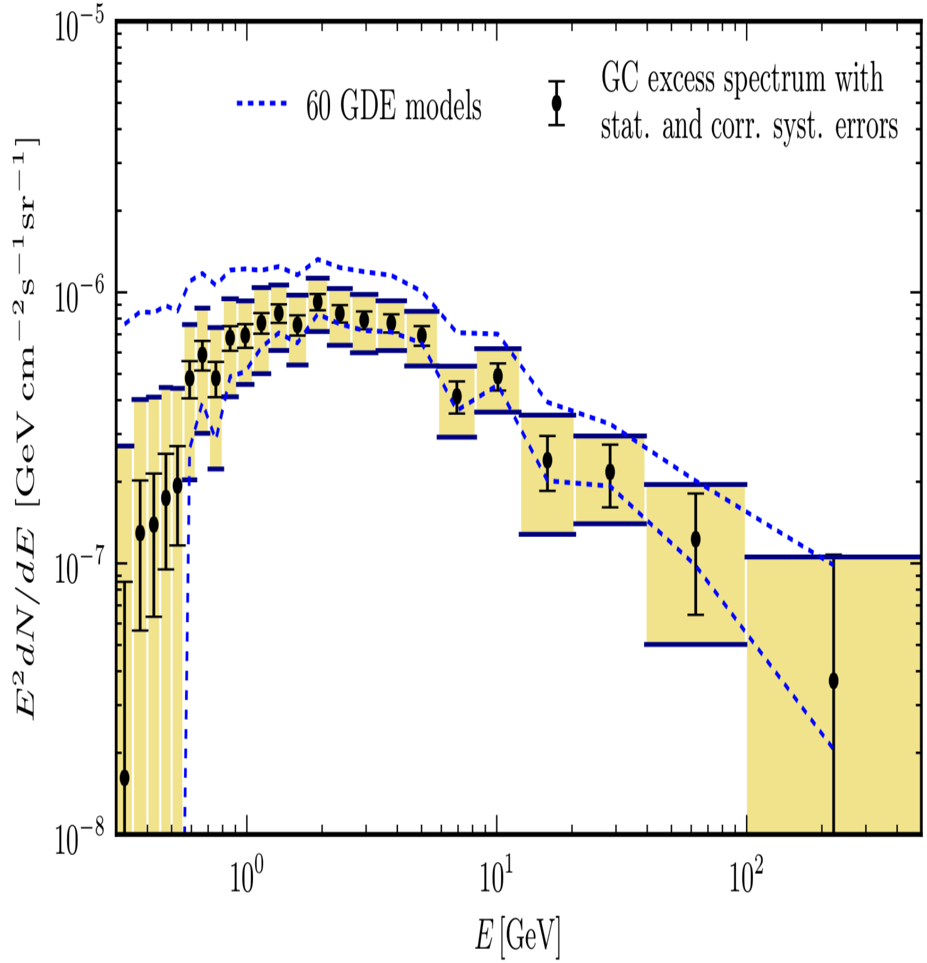
The GeV excess

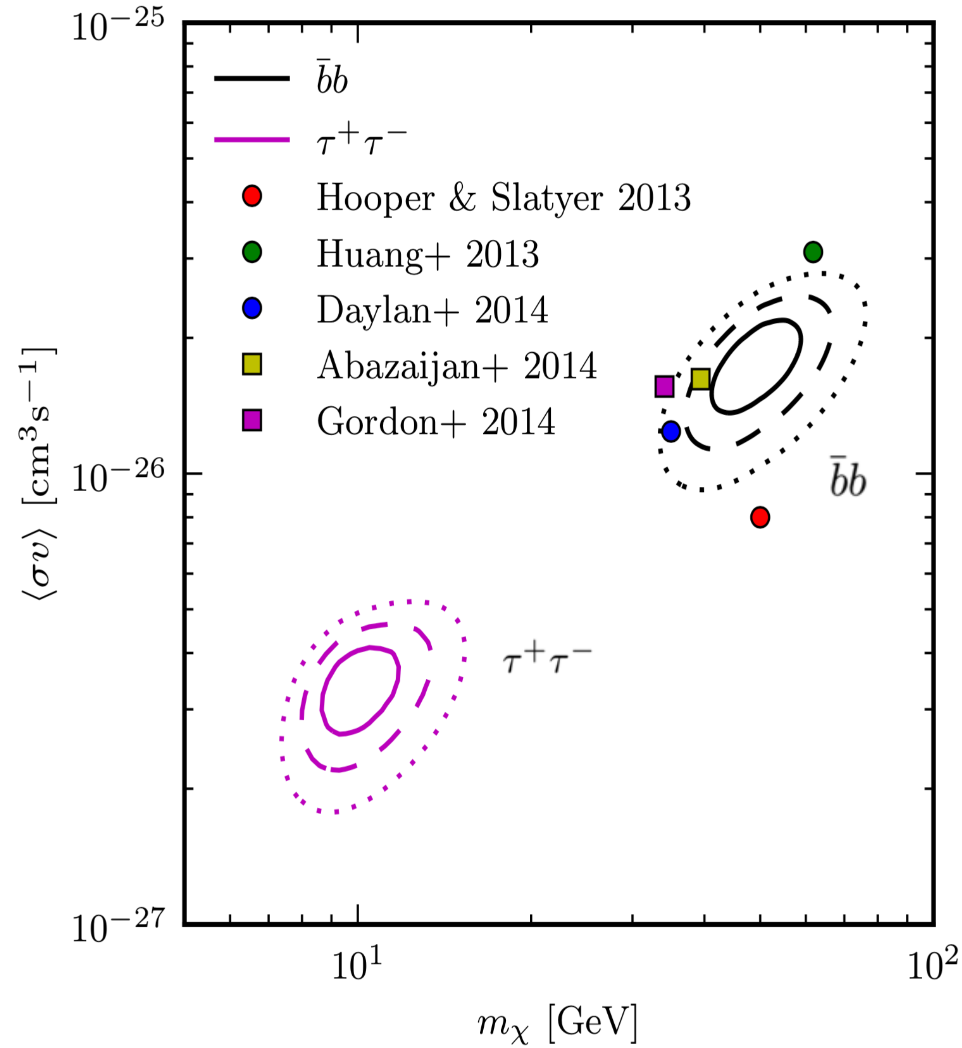
7°x7°region centered on the Galactic Center
11 months of data, E >400 MeV, front-converting events
analyzed with binned likelihood analysis)

- 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





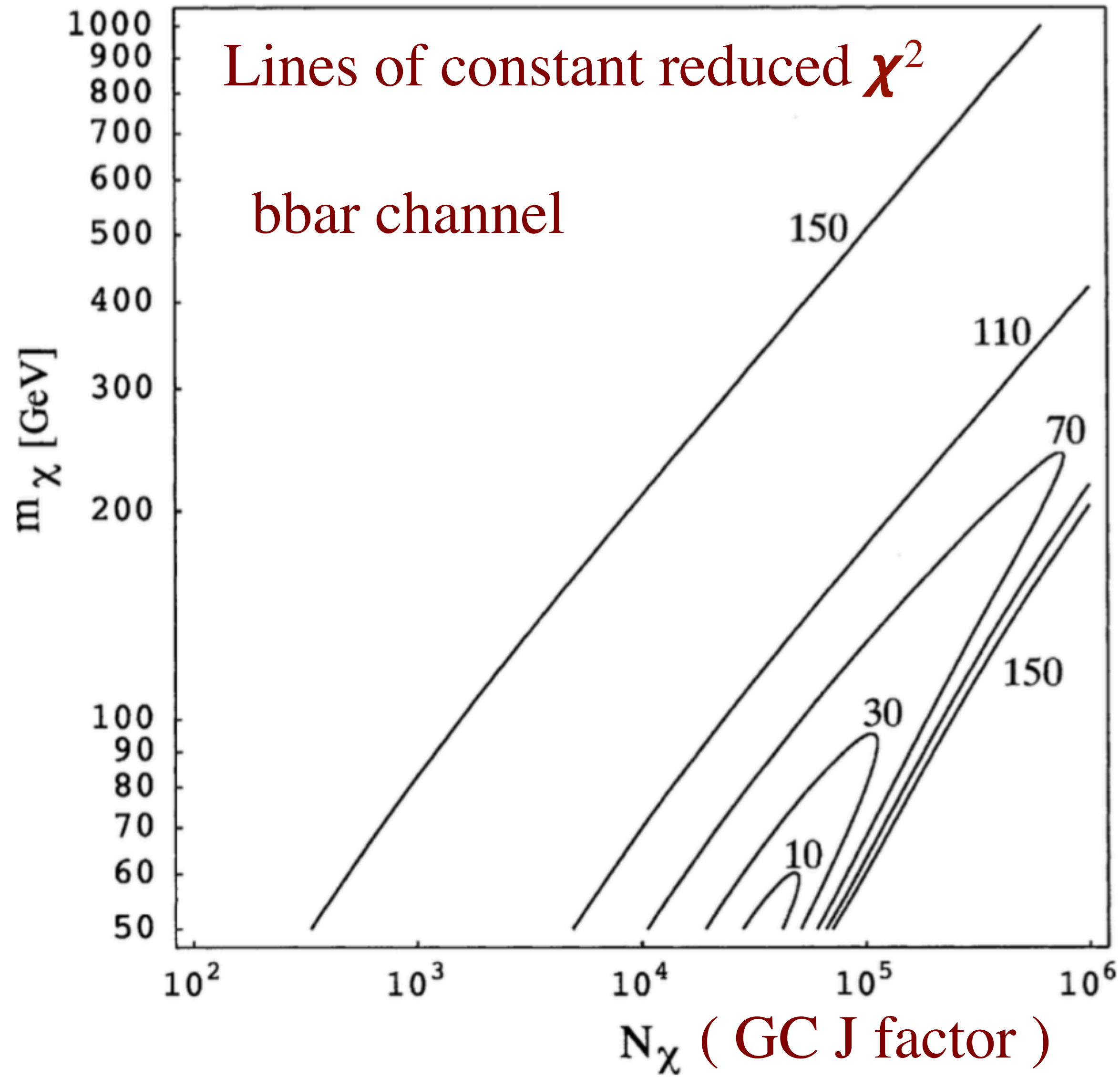
A lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center

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 !

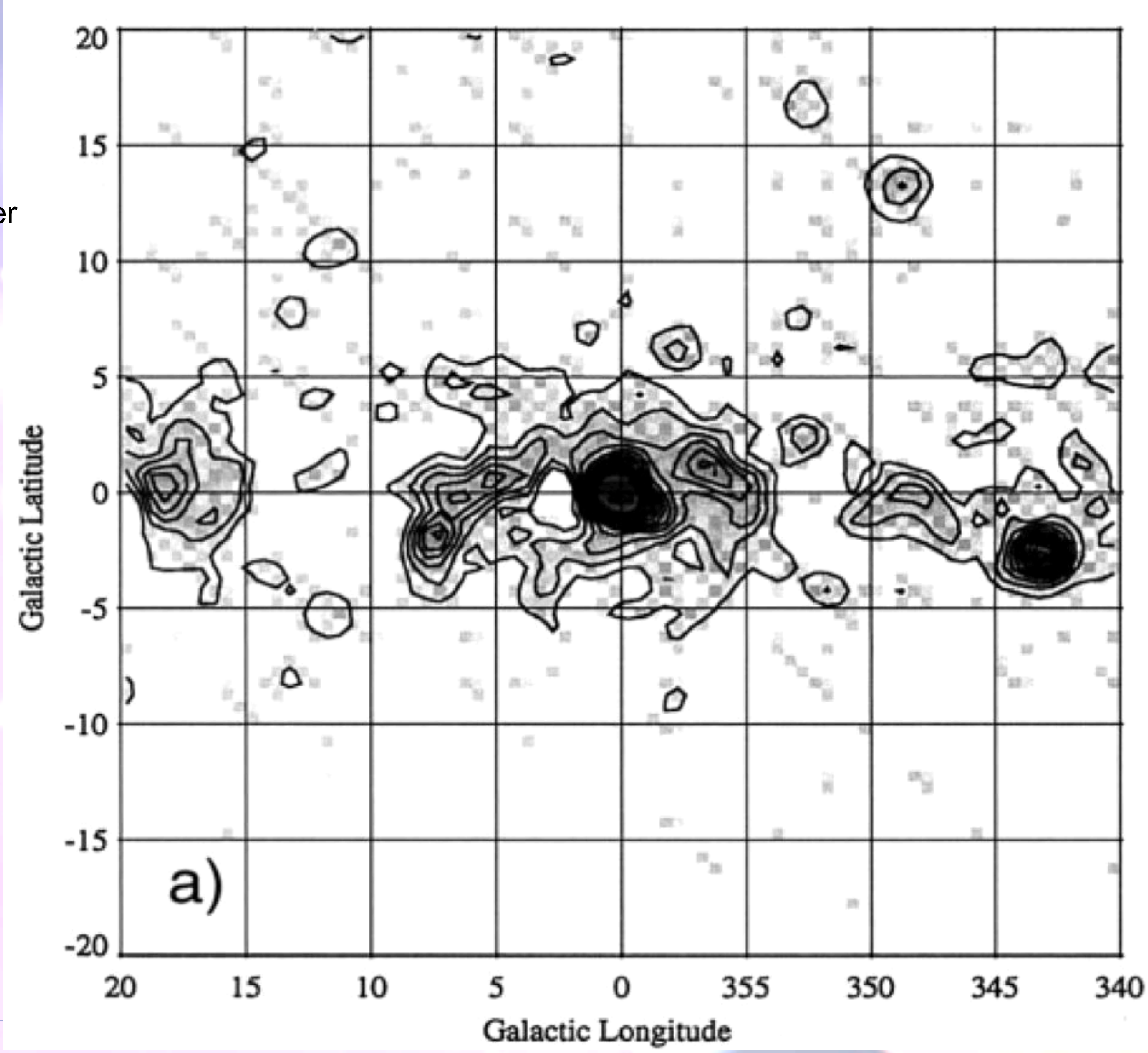
mass ~ 50- 80 GeV



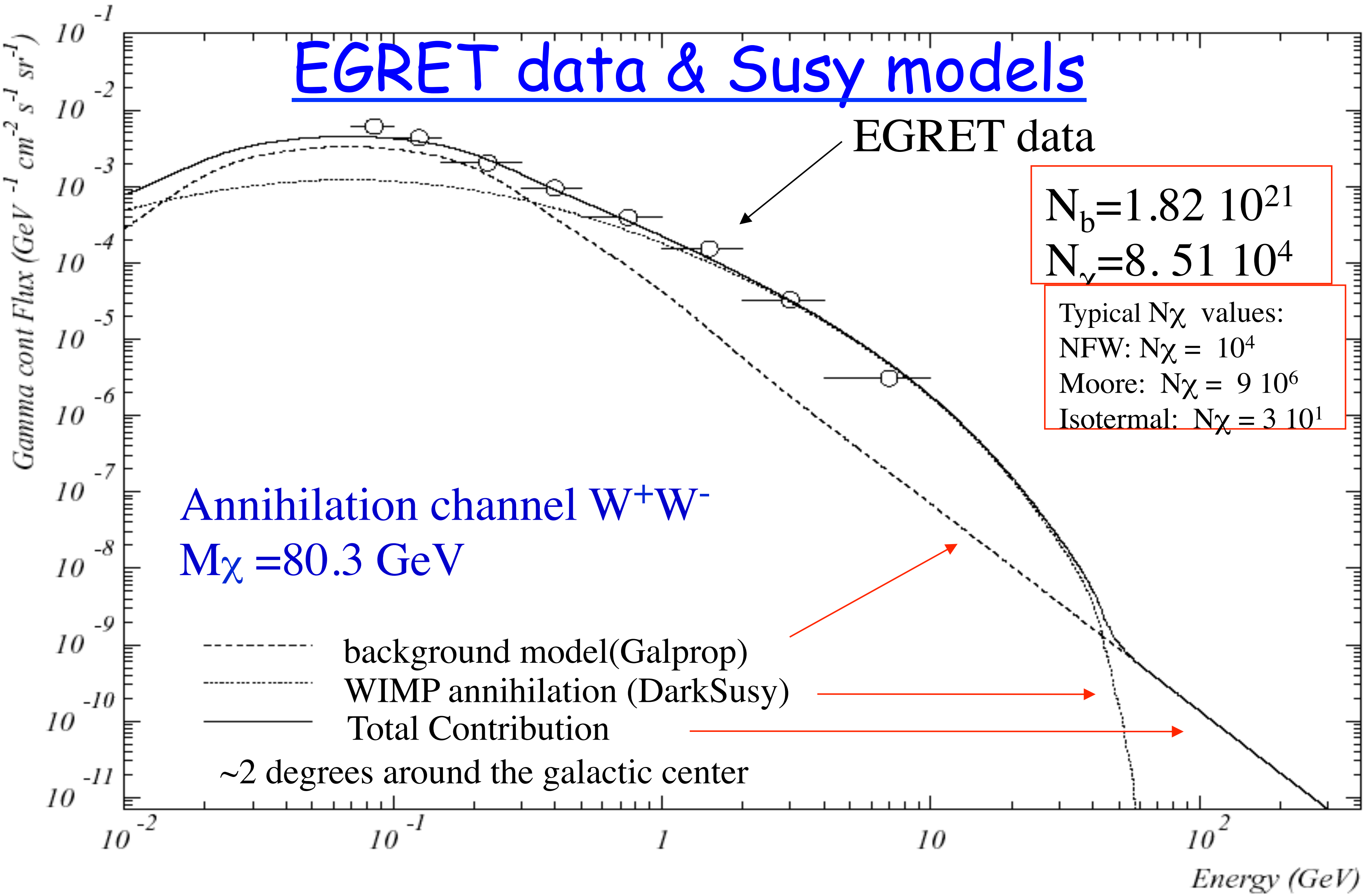
A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

EGRET, E > 1GeV

Mayer-Hasselwander et al, 1998



EGRET data & Susy models



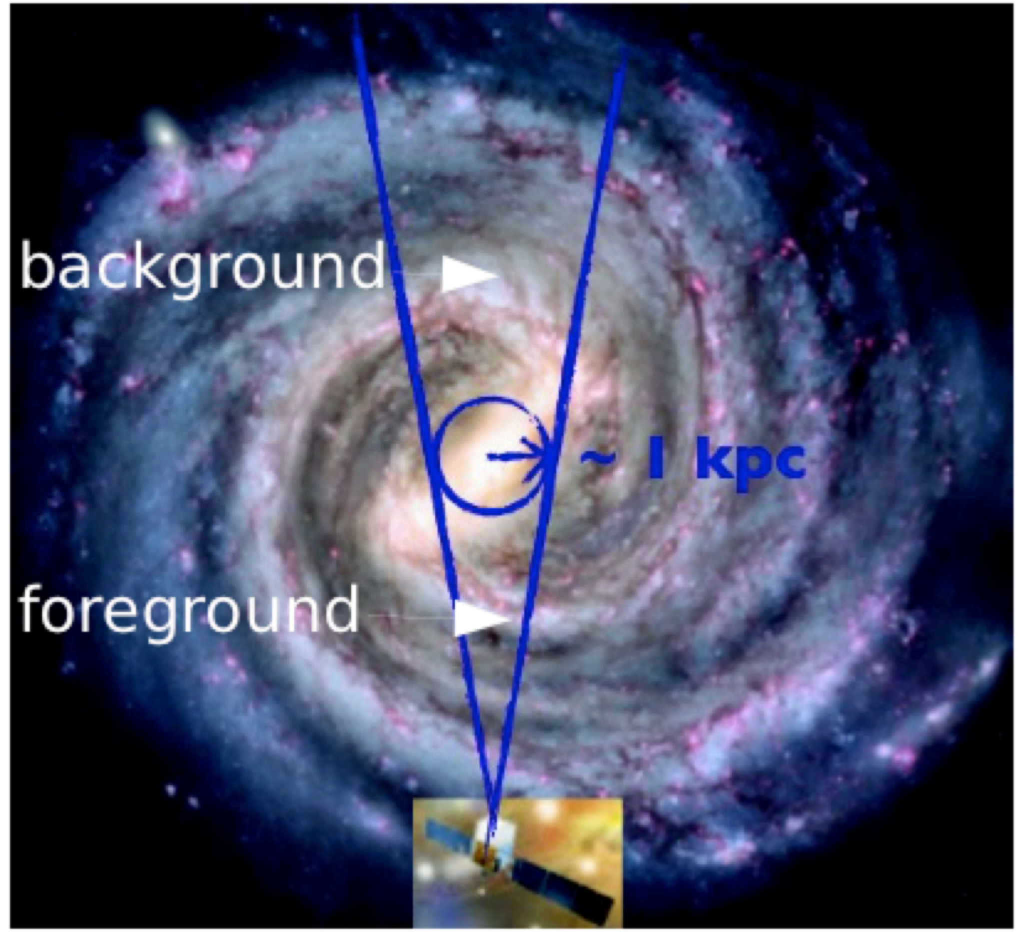
A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, Nucl. Phys. B 113B (2002) 213-220 [astro-ph/0211327]

The Galactic Center with Fermi-LAT

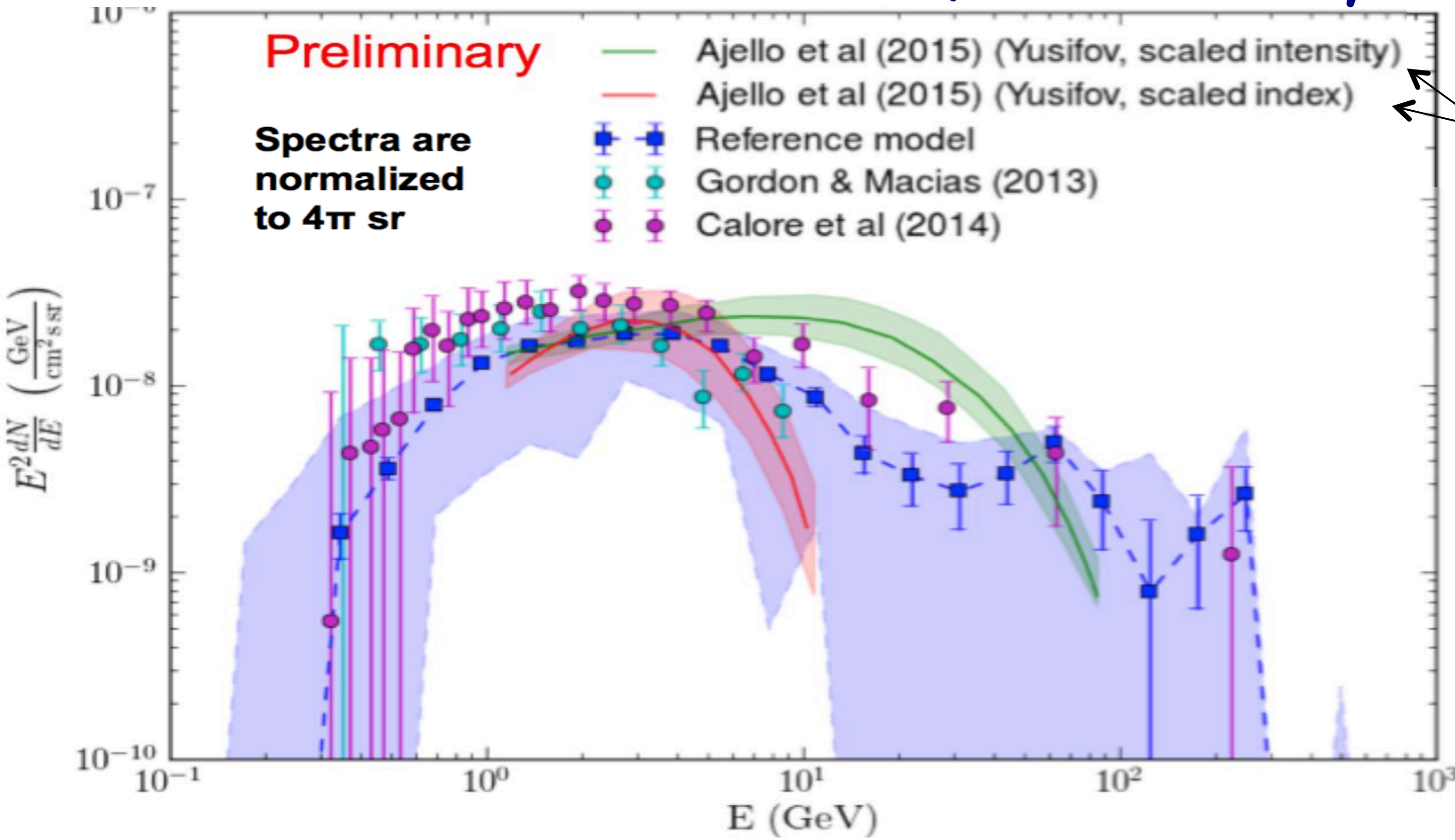
Fore/background modeling is critical to studying IG
- ~80% of the emission (1-100 GeV) in the line of sight is from fore/background

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) (however see Hooper & Linden arXiv:1606.09250)

- 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 ?

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

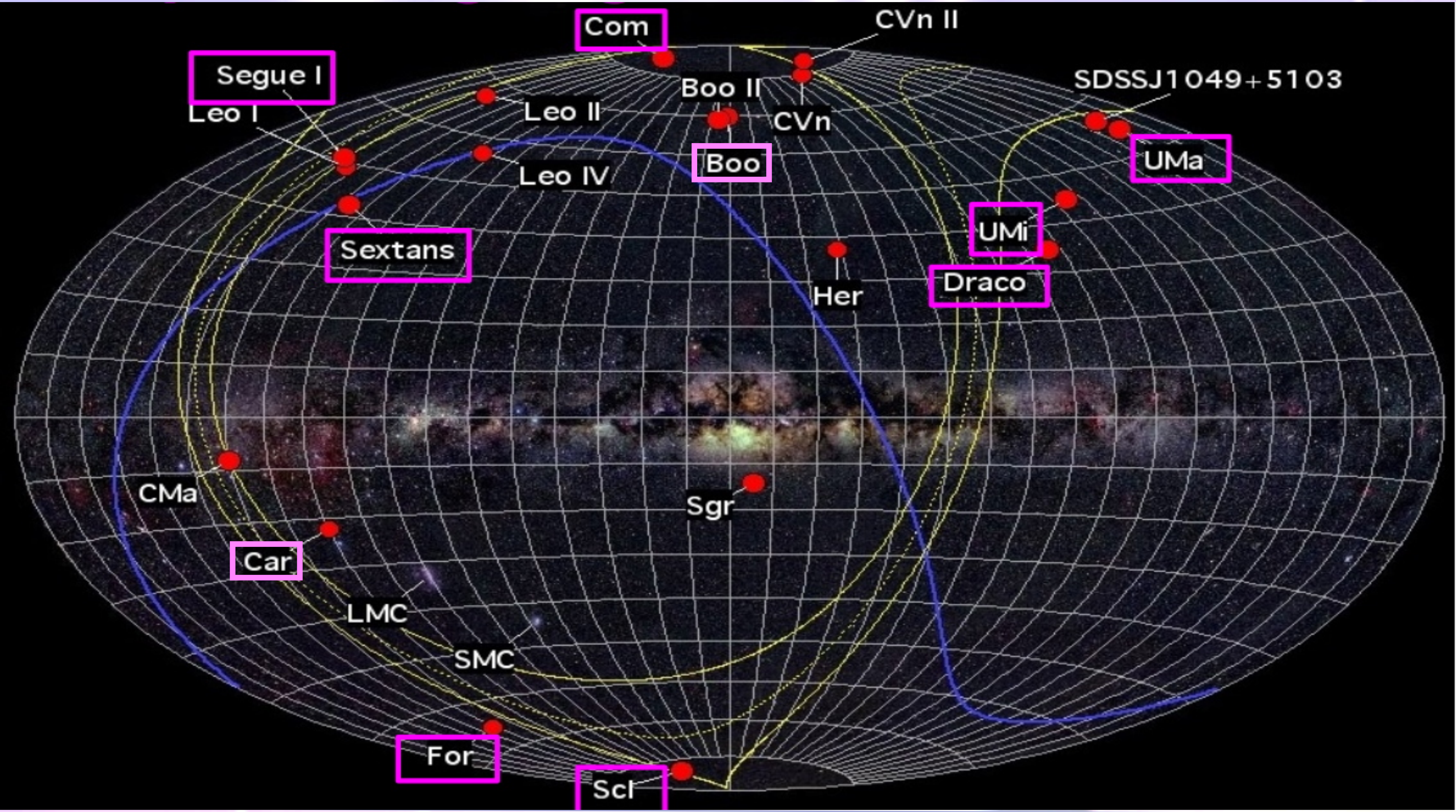
- Look for correlated synchrotron emission near the GC

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 (dSph) : promising targets for DM detection

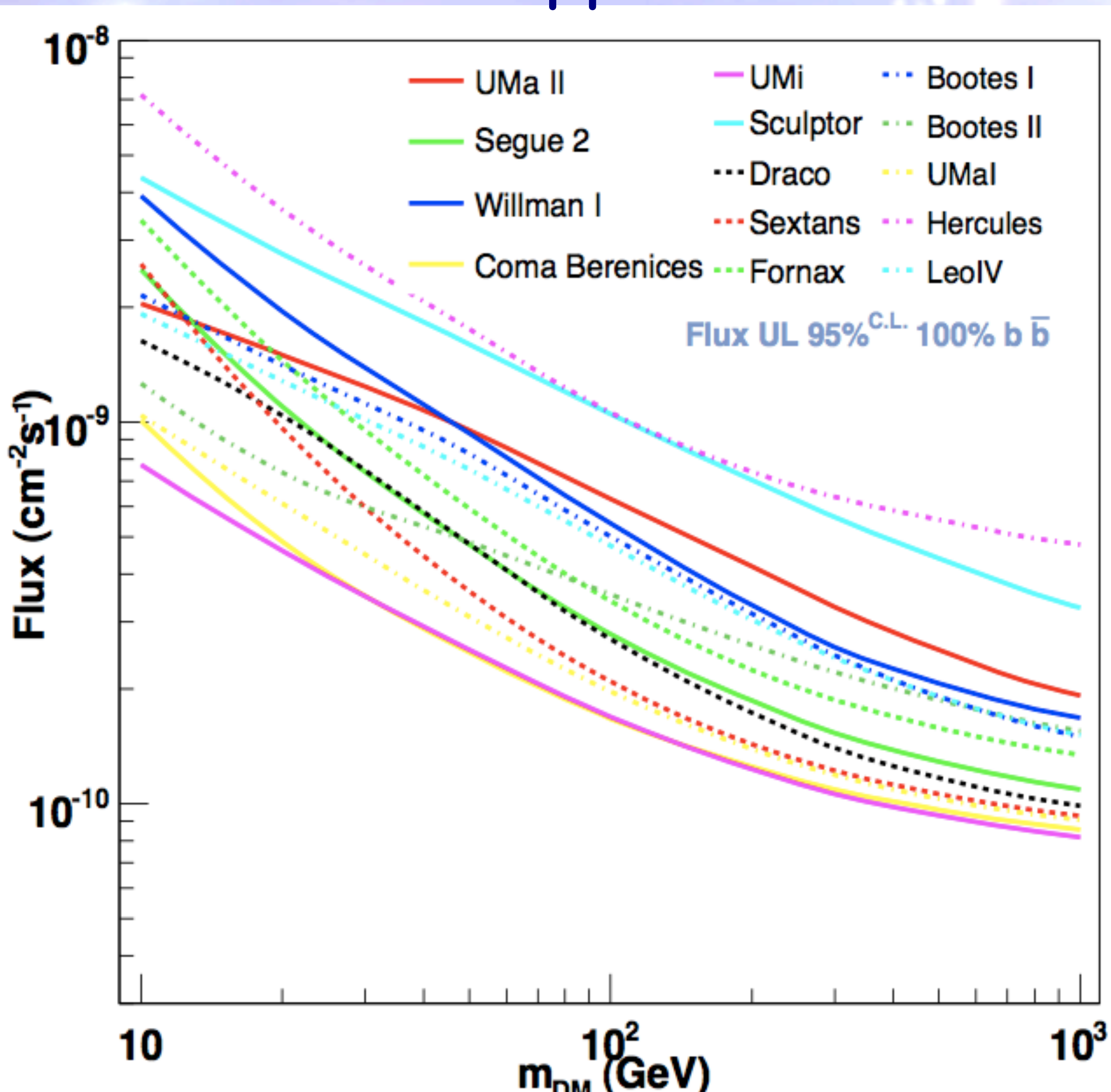


Dwarf Spheroidal Galaxies upper-limits

No detection by Fermi with 11 months of data. 95% flux upper limits are placed for several possible annihilation final states.

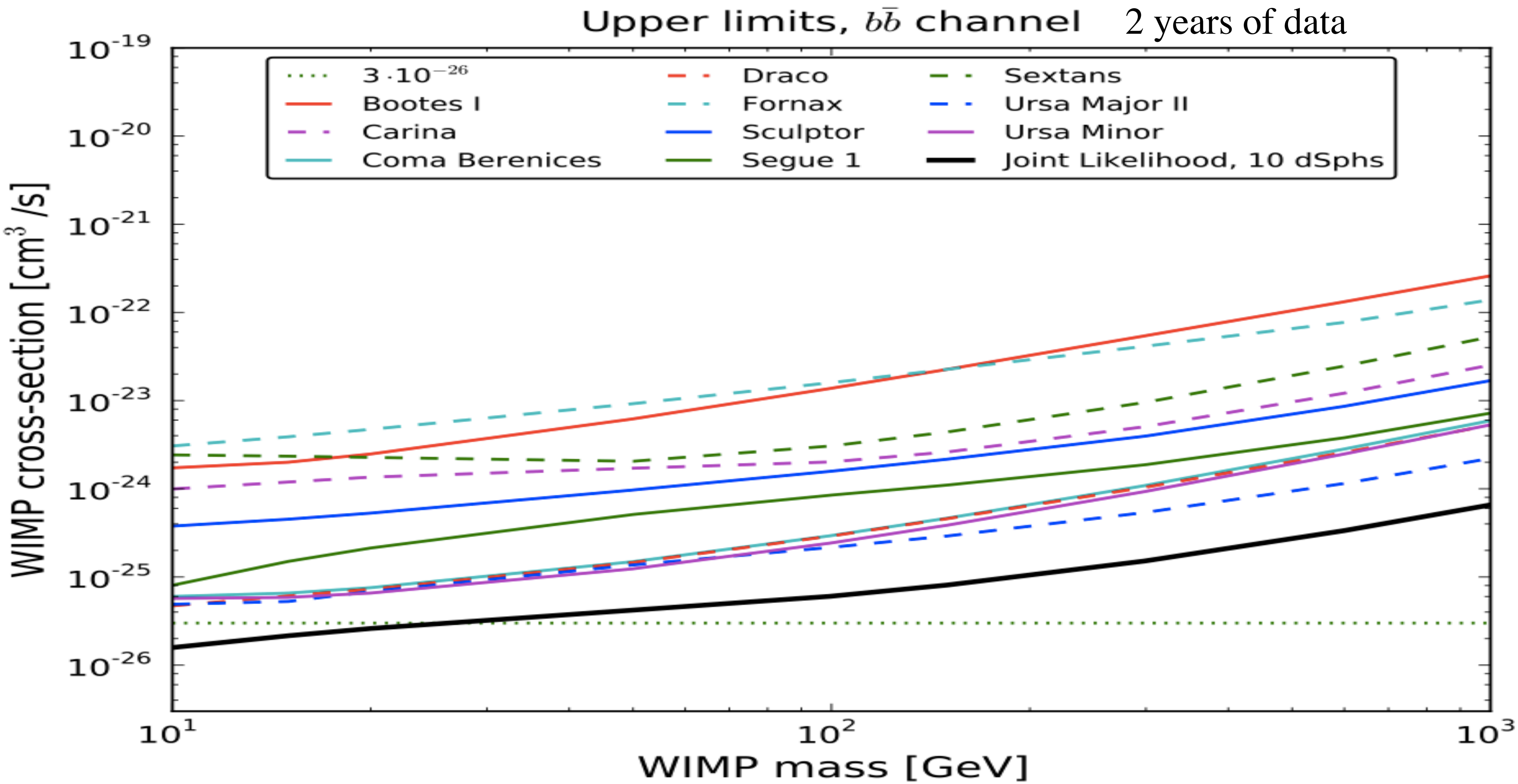
- Flux upper limits are combined with the DM density inferred by the stellar data(*) for a subset of 8 dSph (based on quality of stellar data) to extract constraints on < σ v> vs WIMP mass for specific DM models

(*) stellar data from the Keck observatory (by Martinez, Bullock, Kaplinghat)



Fermi Coll. ApJ 712 (2010) 147-158 [arXiv:1001.4531]

Dwarf Spheroidal Galaxies combined analysis

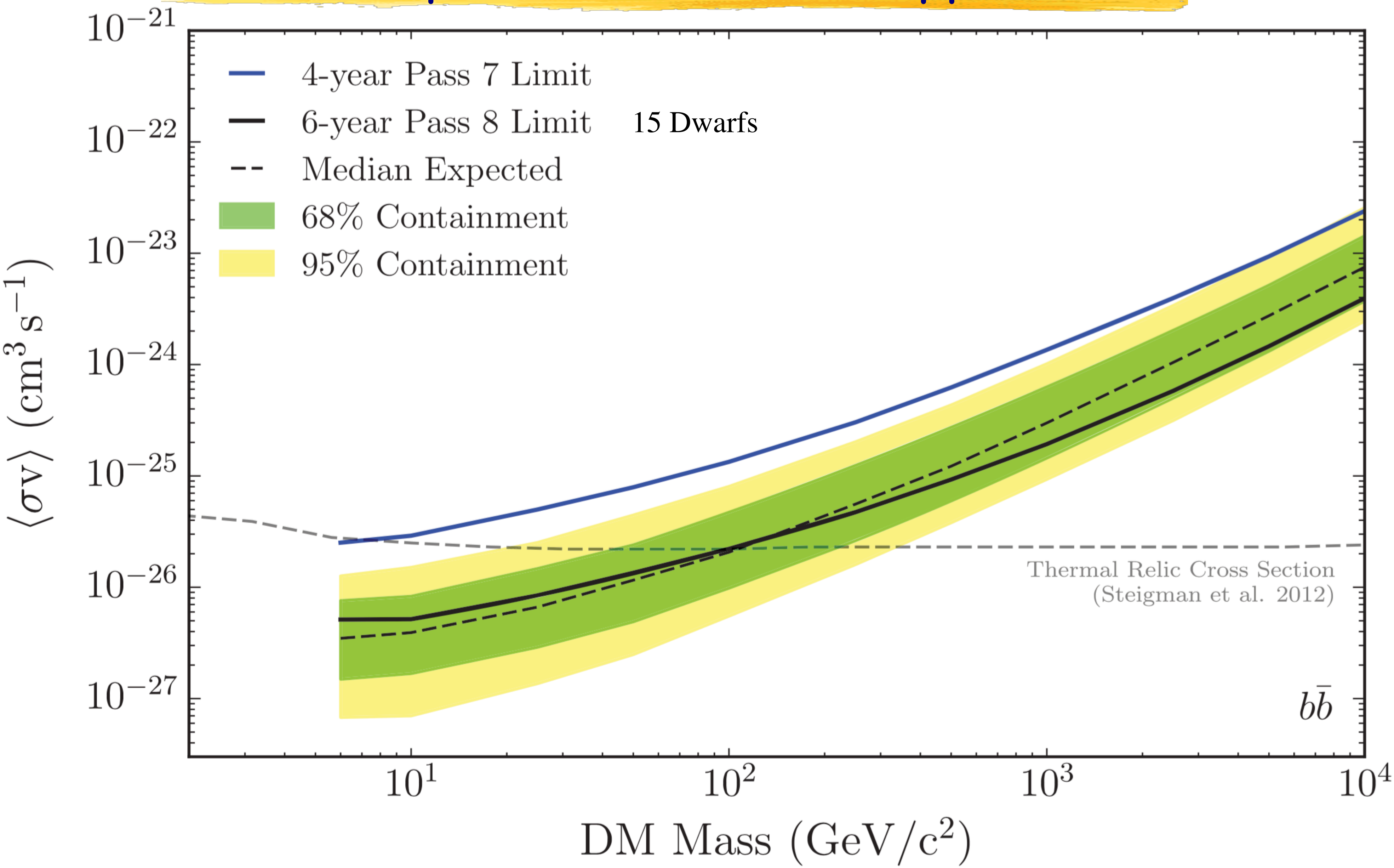


robust constraints including J-factor uncertainties from the stellar data statistical analysis

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

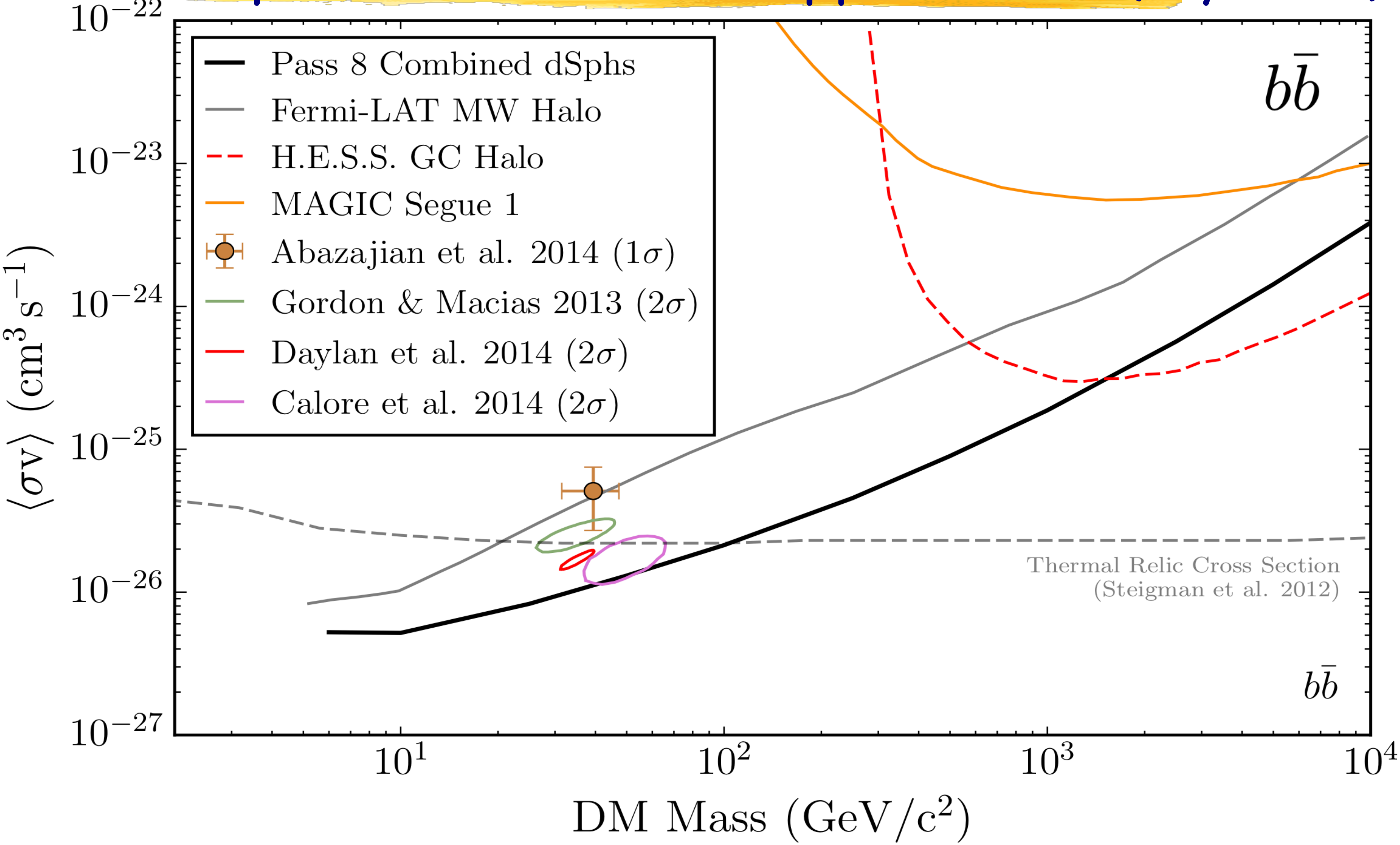
Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

Dwarf Spheroidal Galaxies upper-limits



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

Dwarf Spheroidal Galaxies upper-limits (6 years)



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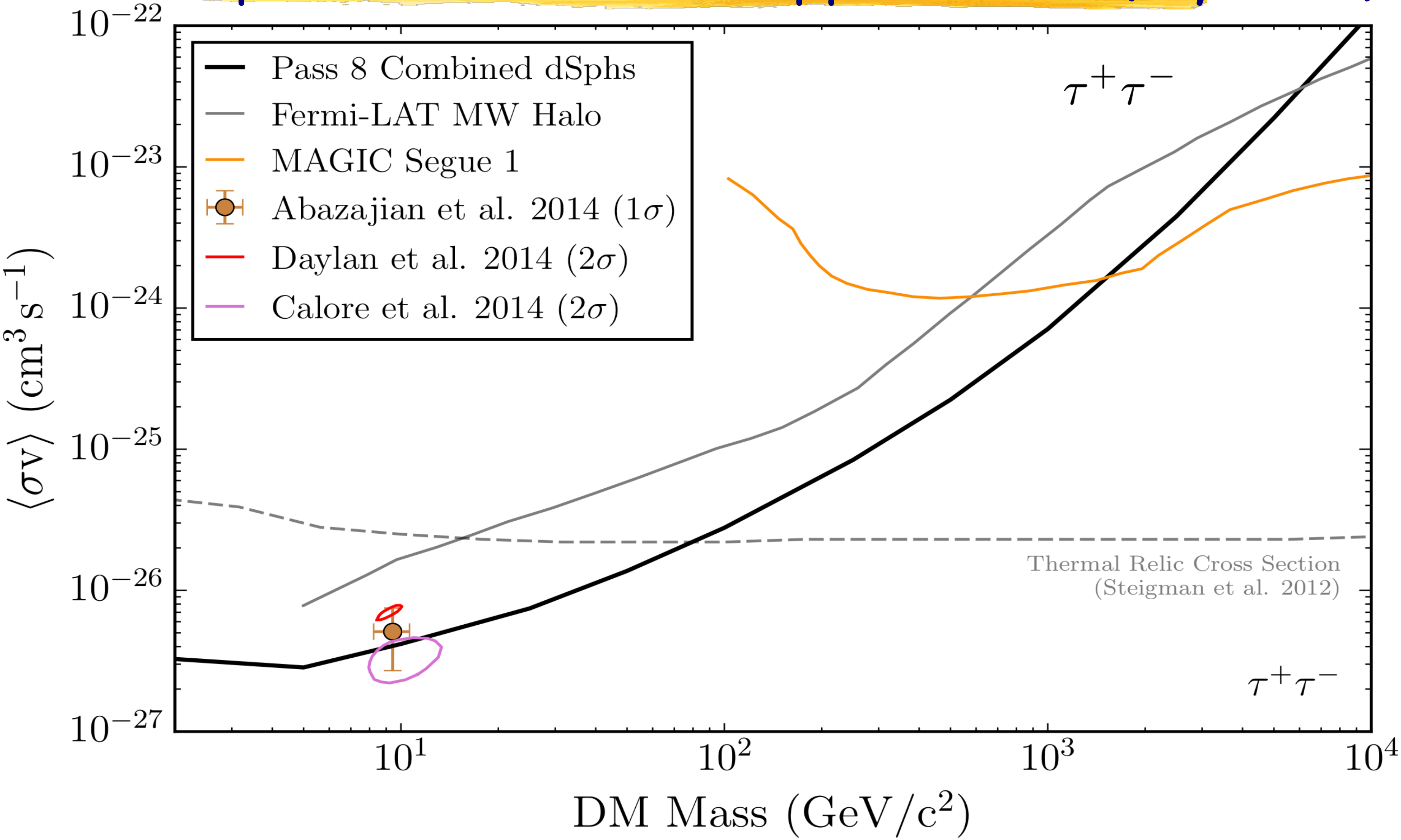
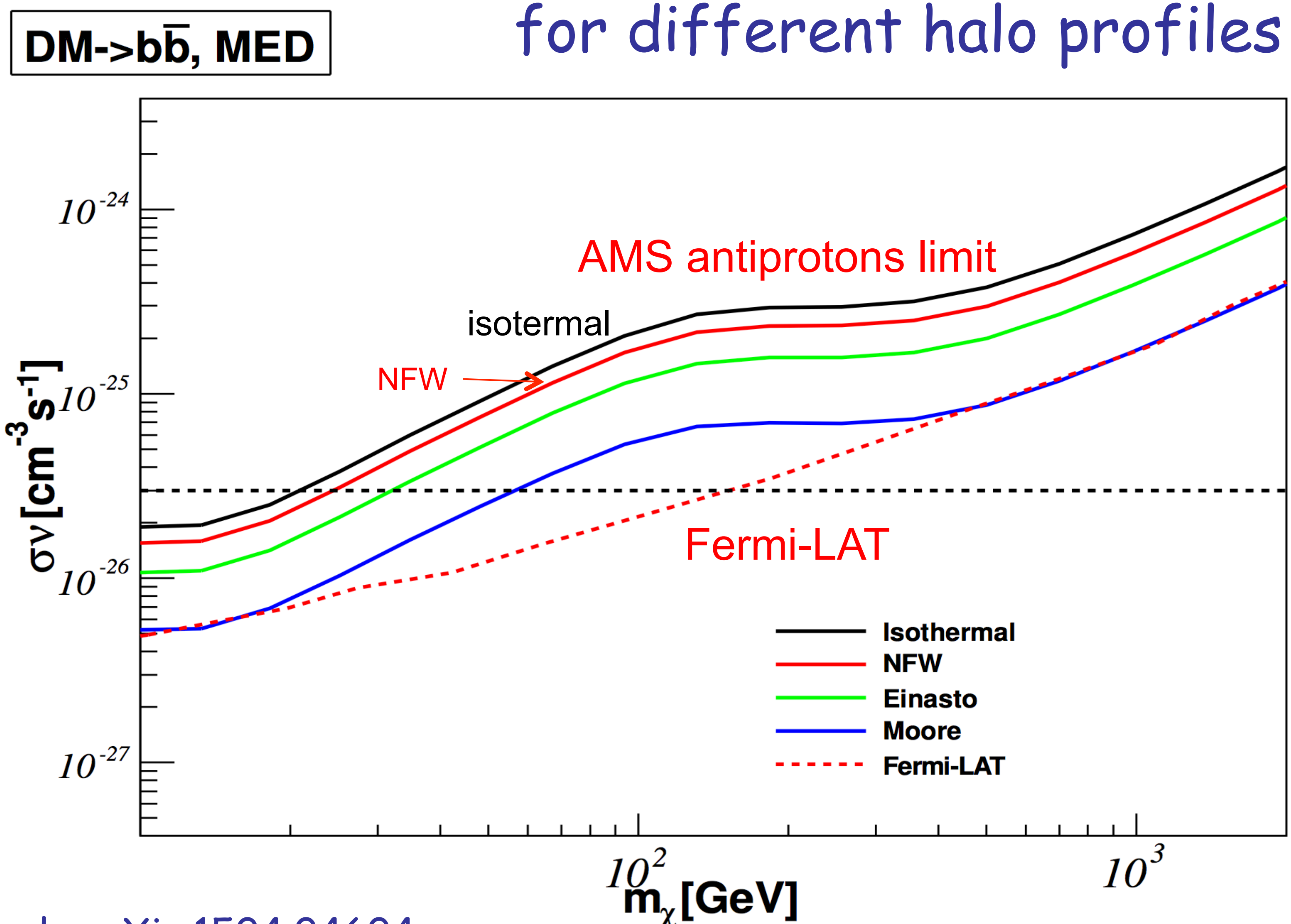


M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

Upper limits from AMS antiprotons and Fermi LAT

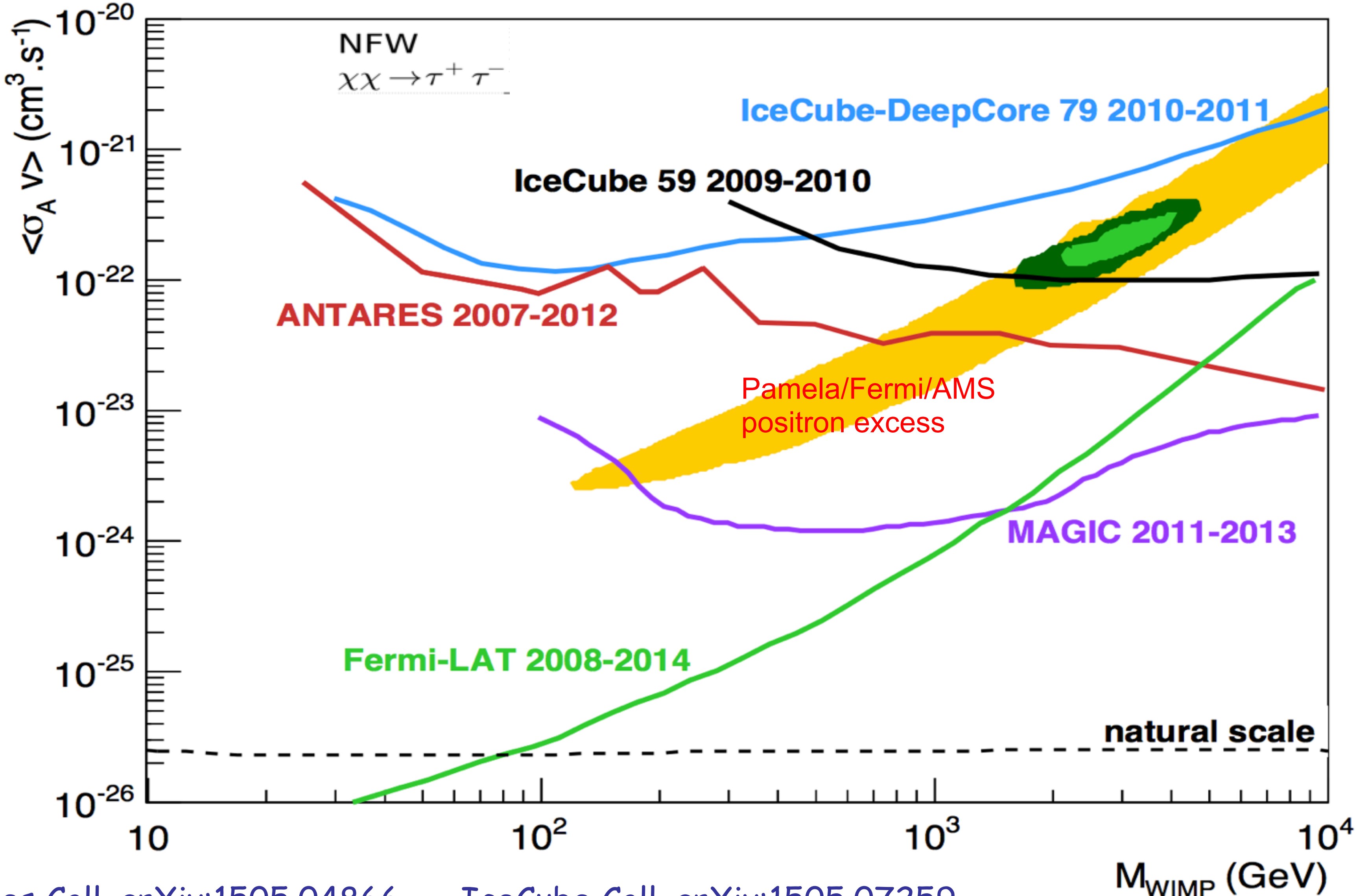
for different halo profiles



Jin et al., arXiv:1504.04604

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

Upper limits from Fermi LAT, Antares, IceCube, Magic



Antares Coll. arXiv:1505.04866 IceCube Coll. arXiv:1505.07259

Fermi limits are the best limits below 2 TeV

2015: New DES Dwarf Spheroidal Galaxy Candidates

The Washington Post

Speaking of Science

Nine new dwarf galaxies full of dark matter found just chilling around the Milky Way

By **Rachel Feltman** March 10

For the first time in a decade, astronomers have found new dwarf galaxies -- ones with just billions of stars or even less compared with the hundreds of billions in our own -- orbiting the Milky Way. And they've found *nine* of them. That's the most that have ever turned up at once. The findings were published Tuesday in the Astrophysical Journal.

LAT Collaboration – DES Collaboration agreement – Feb 2015

- first joint paper "Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data" ApJL 2015, 809,L4,arXiv:1503.02632

- analysis of observations of 8 new Dwarf Spheroidal Galaxies found by DES:

  Bechtol, et al. arXiv:1503.02584

  also found by Koposov, et al. arXiv:1503.02079

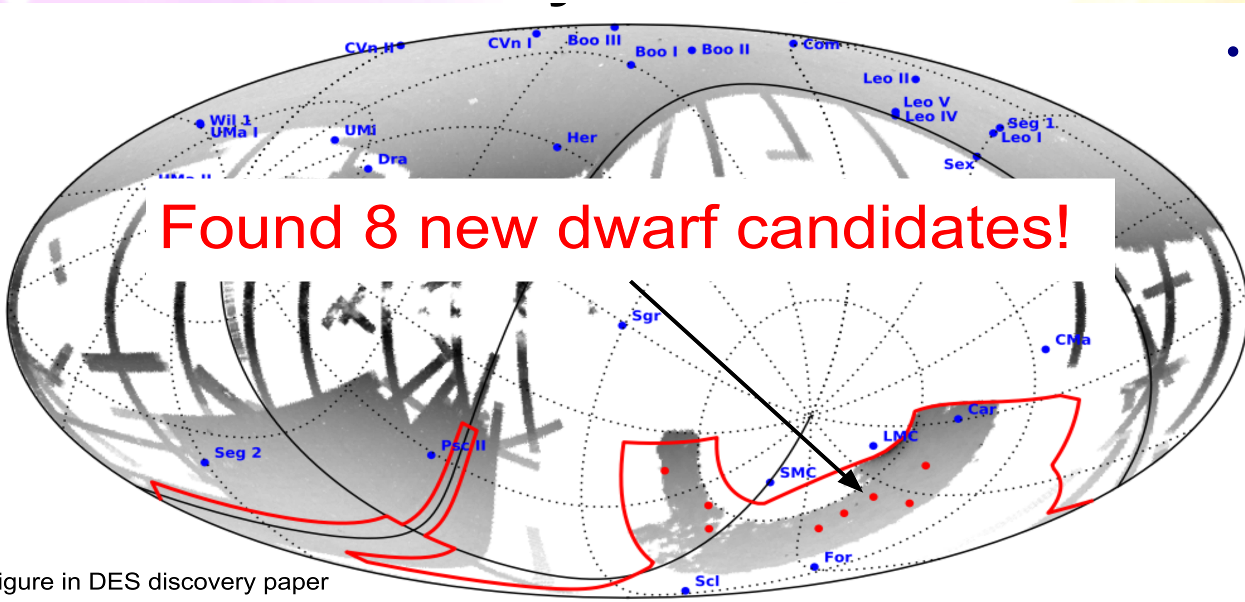
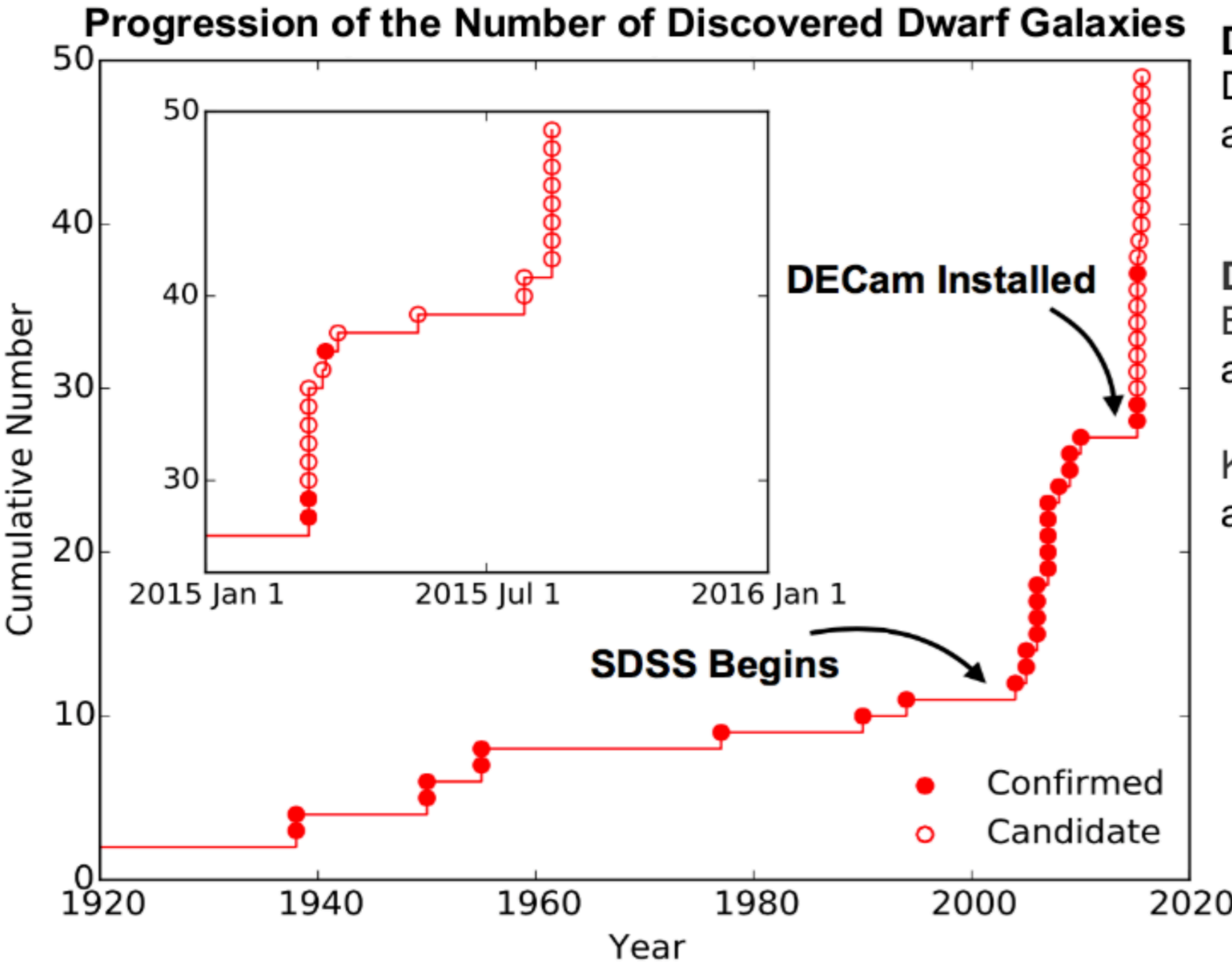


figure in DES discovery paper

Dwarf Spheroidal Galaxy: Growing number of known targets

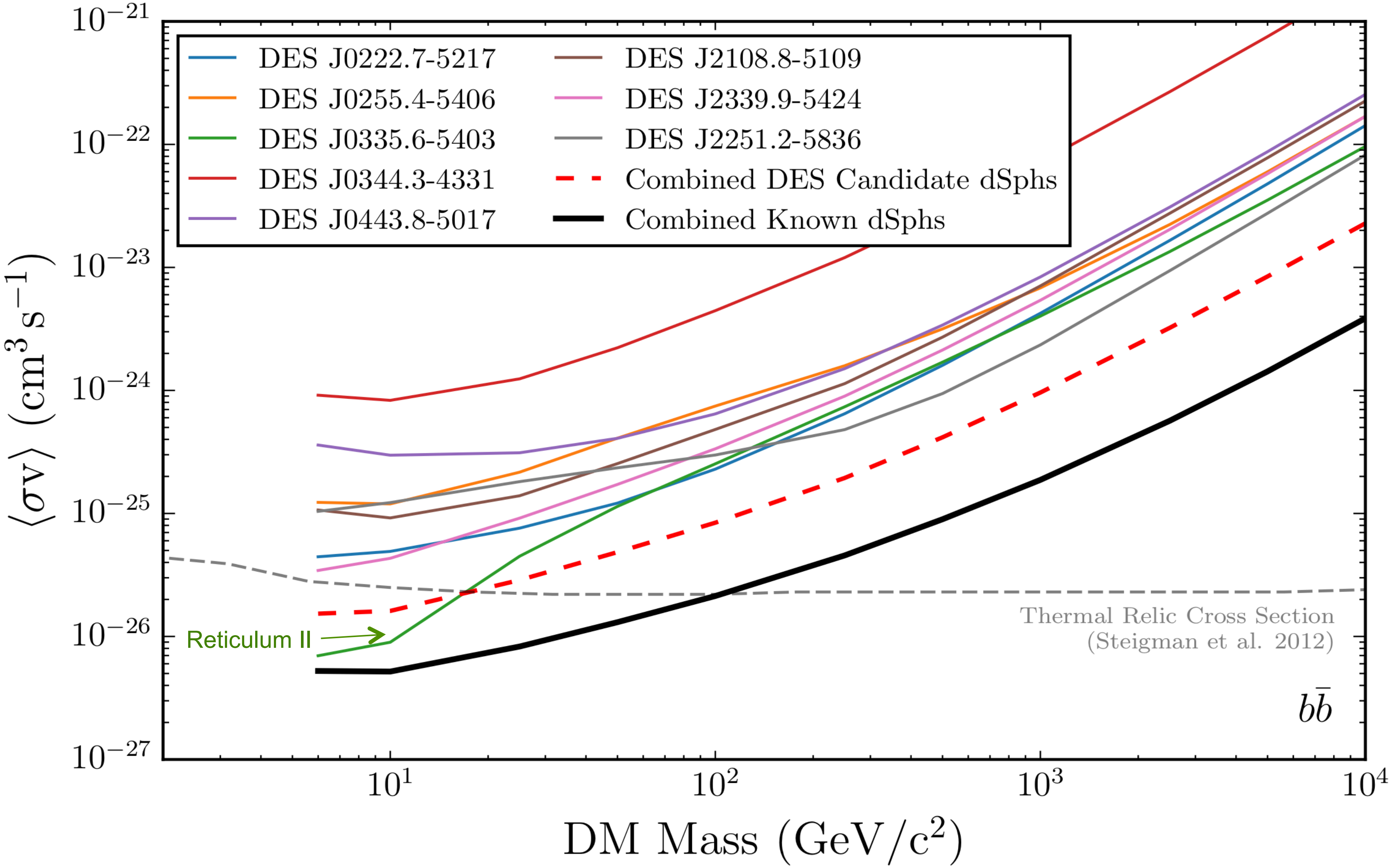


DES Year 2 Data:
Drlica-Wagner+,
arXiv:1508.03622

DES Year 1 Data:
Bechtol+:
arXiv:1503.02584

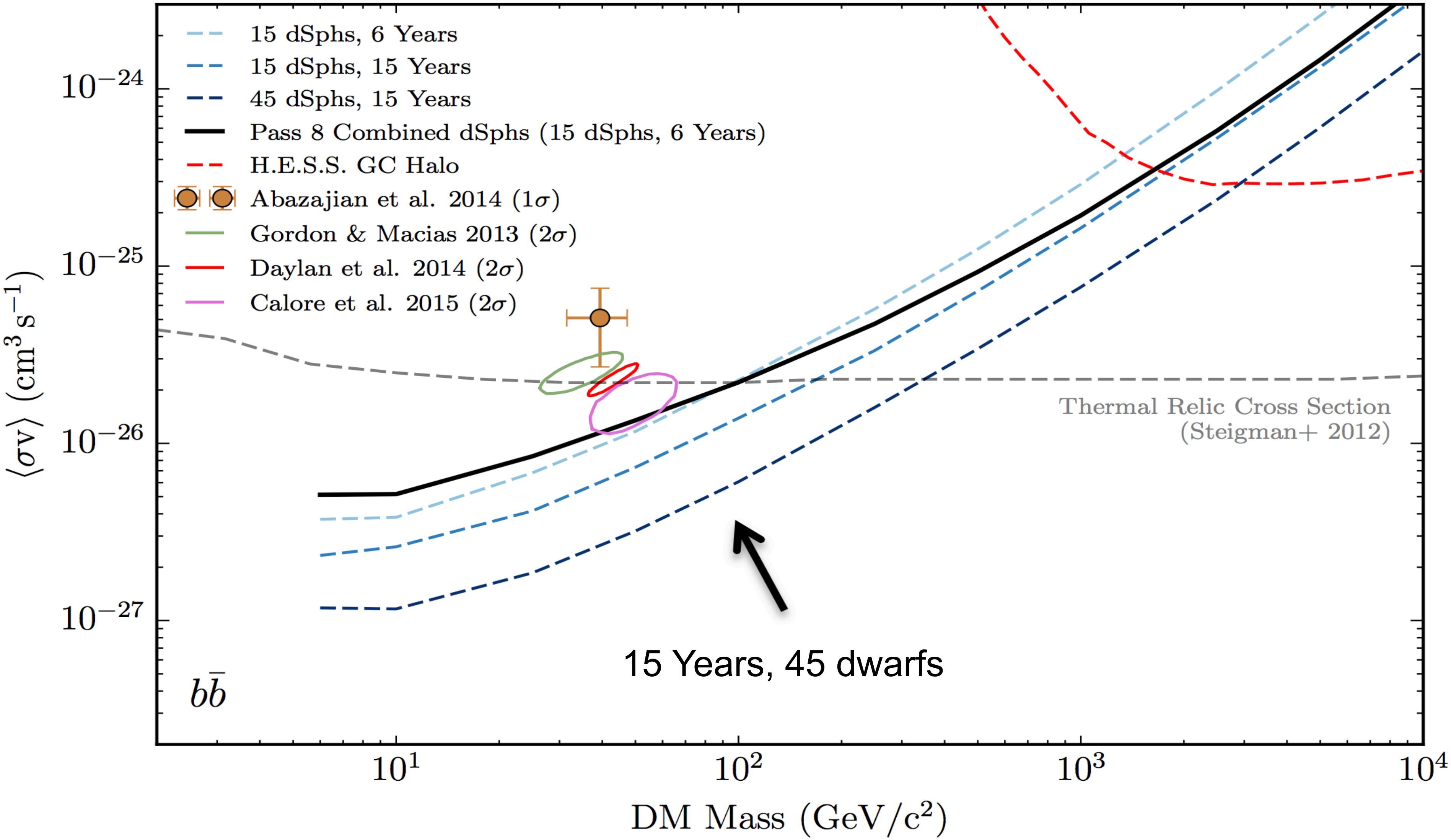
Koposov+:
arXiv:1503.02079

New DES Dwarf Spheroidal Galaxy Candidates

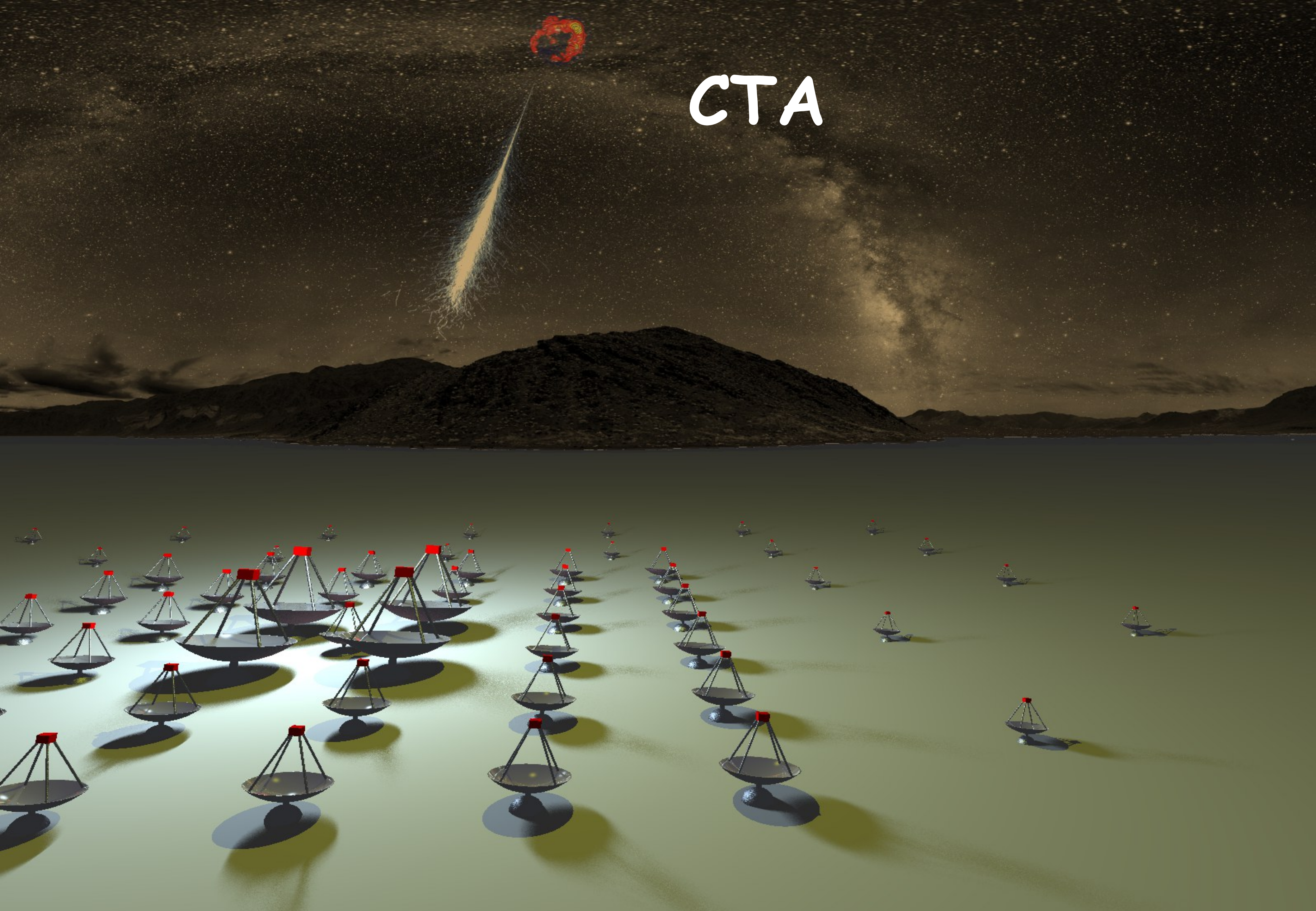


A.Drlica-Wagner et al. [Fermi and DES Coll.] ApJL 2015, 809, L4 [arXiv:1503.02632]

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



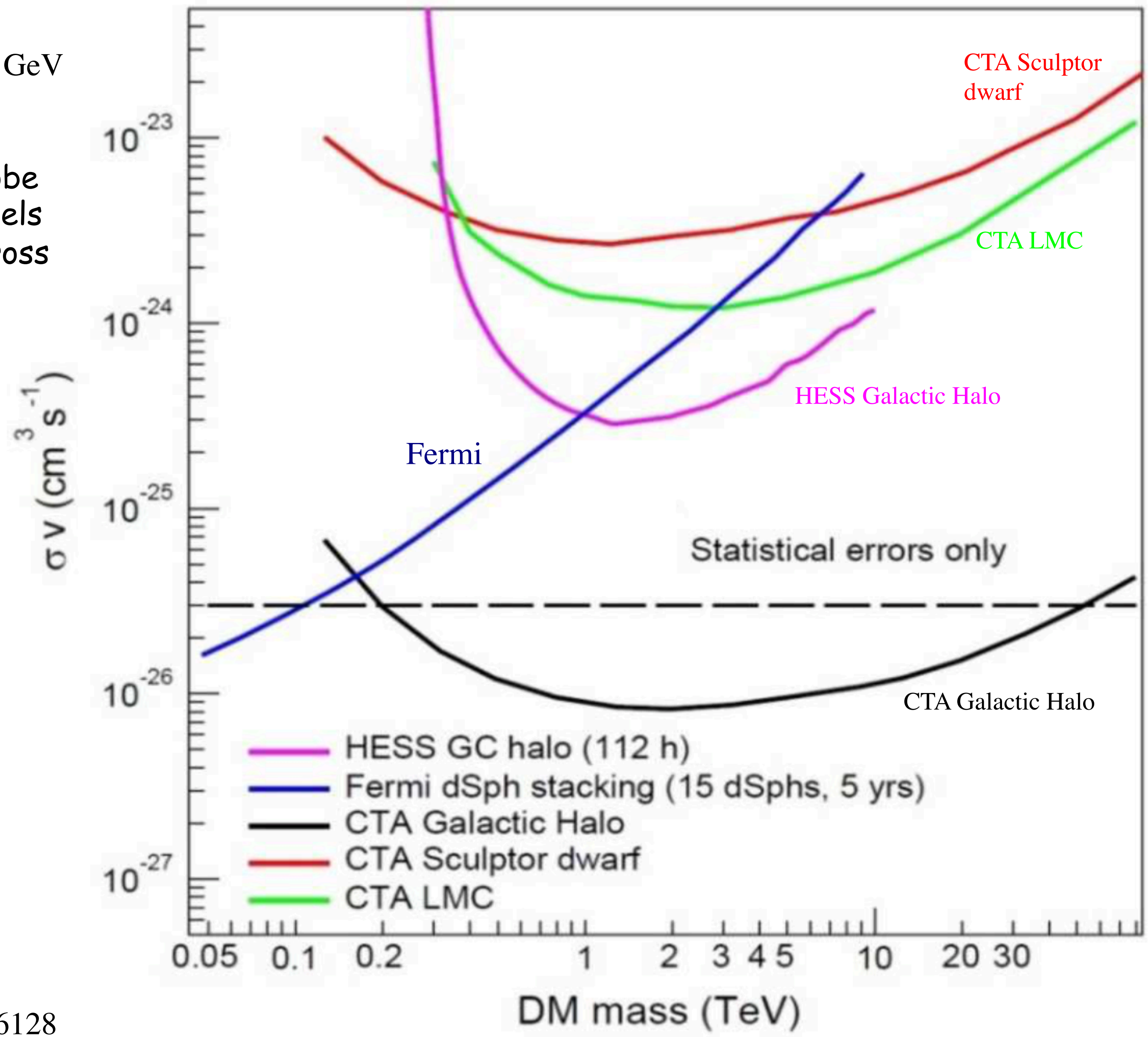
E. Charles et.al, arXiv:1605.02016


CTA

HESS, FERMI, CTA DM upper-limits

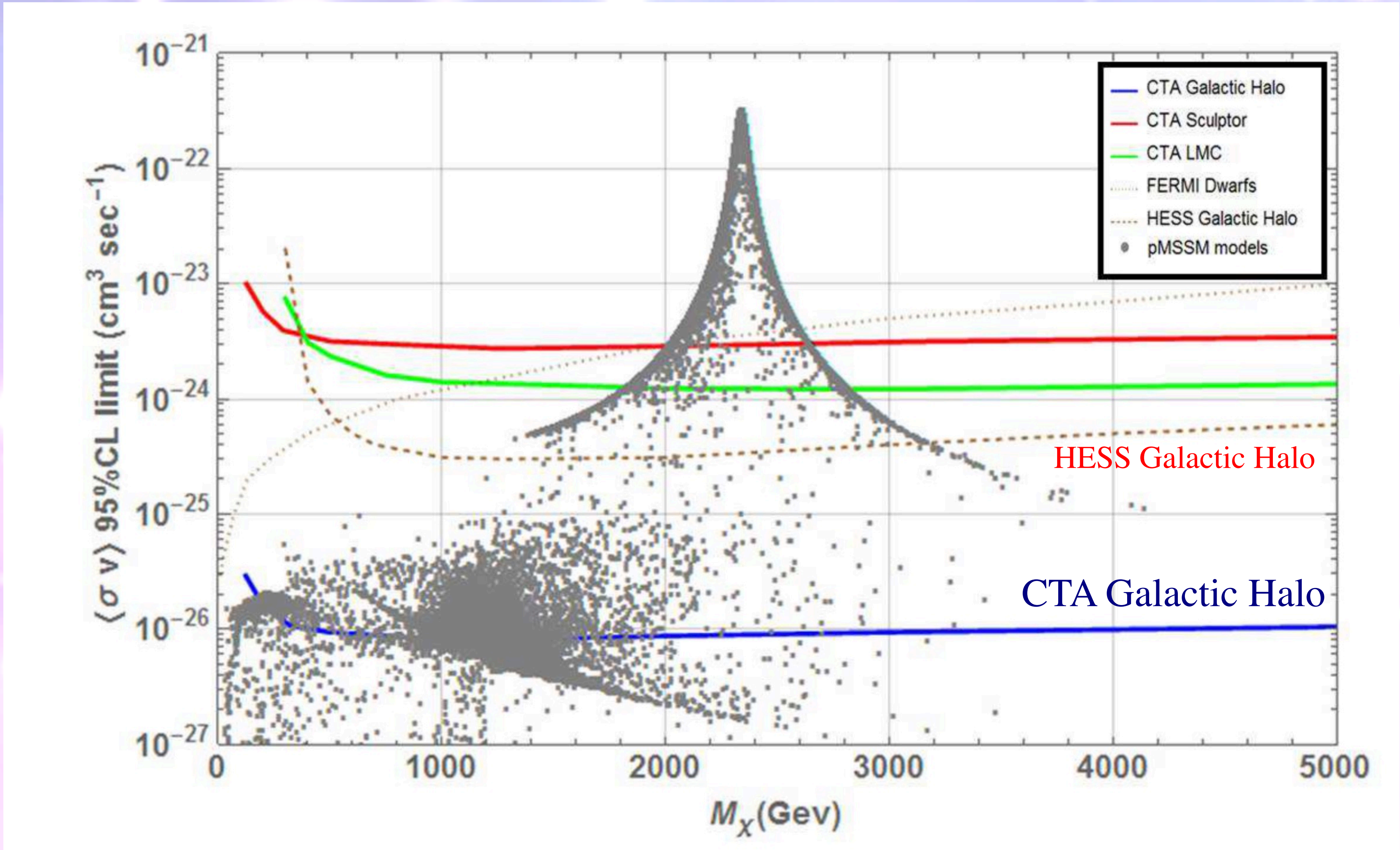
CTA 500 hr, statistical only, NFW, 30 GeV

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



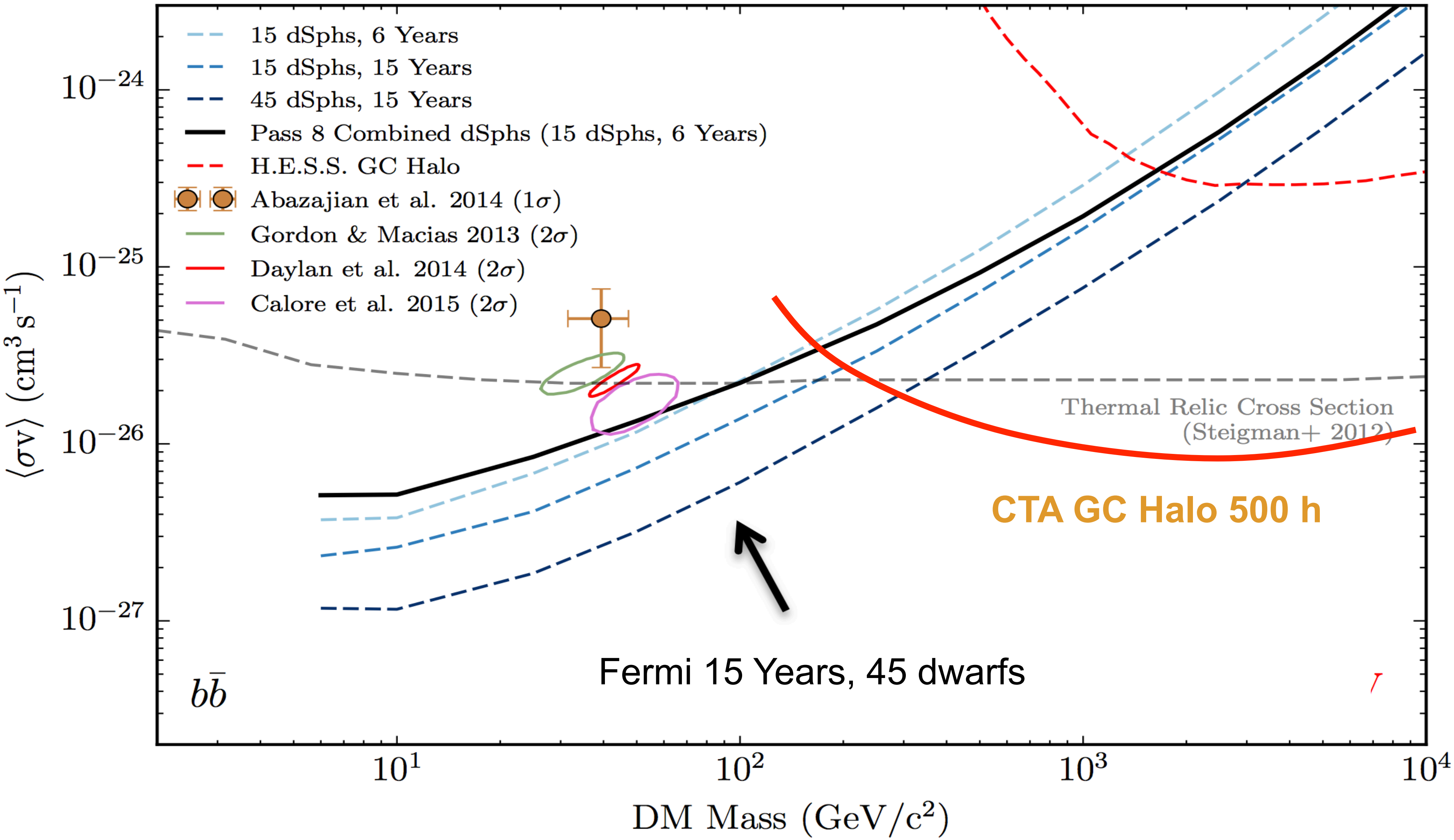
Carr et al. 2015 arXiv:1508.06128

CTA sensitivities in the TeV mass range and pMSSM models



Carr et al. 2015 arXiv:1508.06128

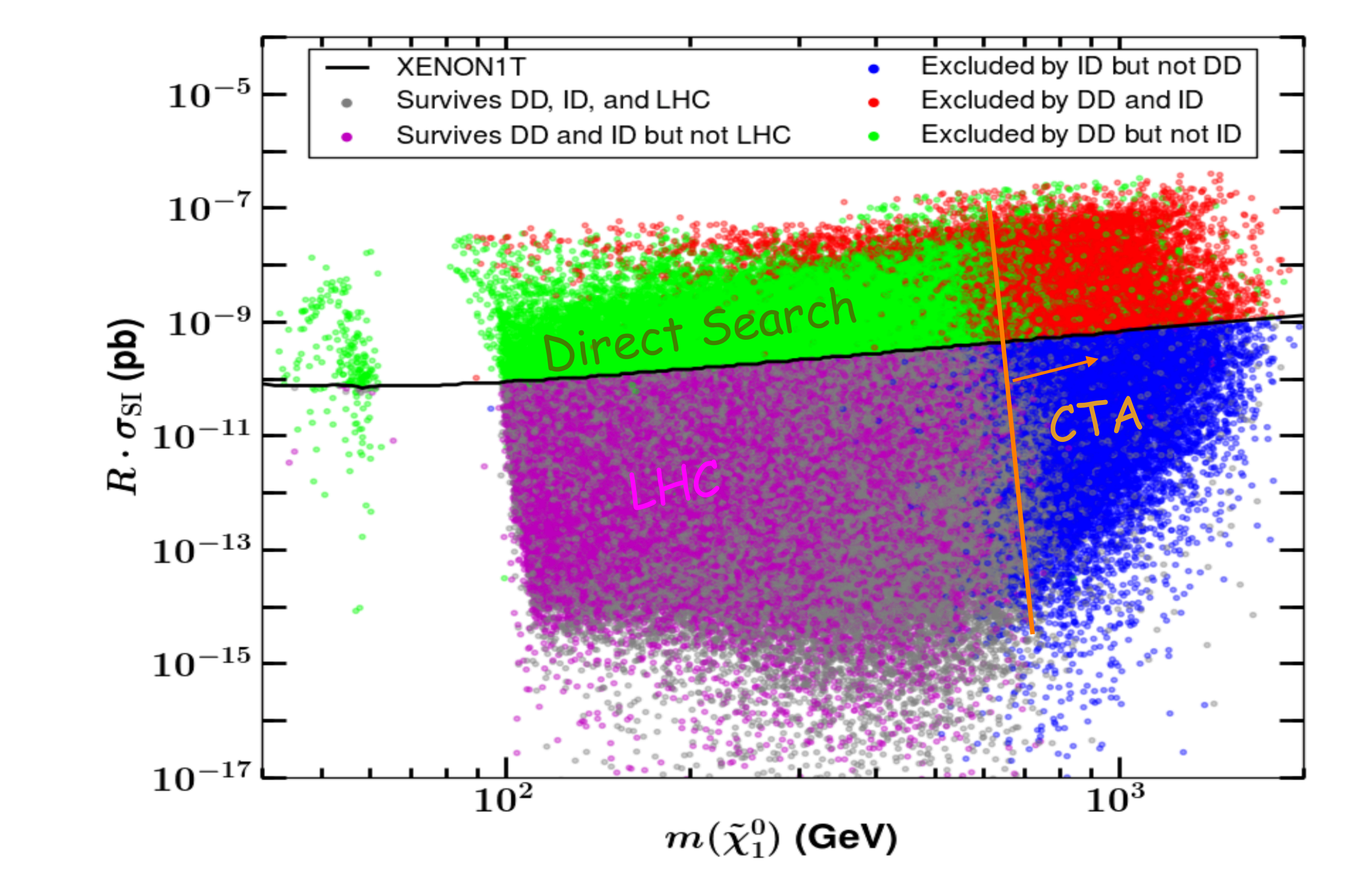
DM limit improvement estimate in 15 years (2008- 2023)



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

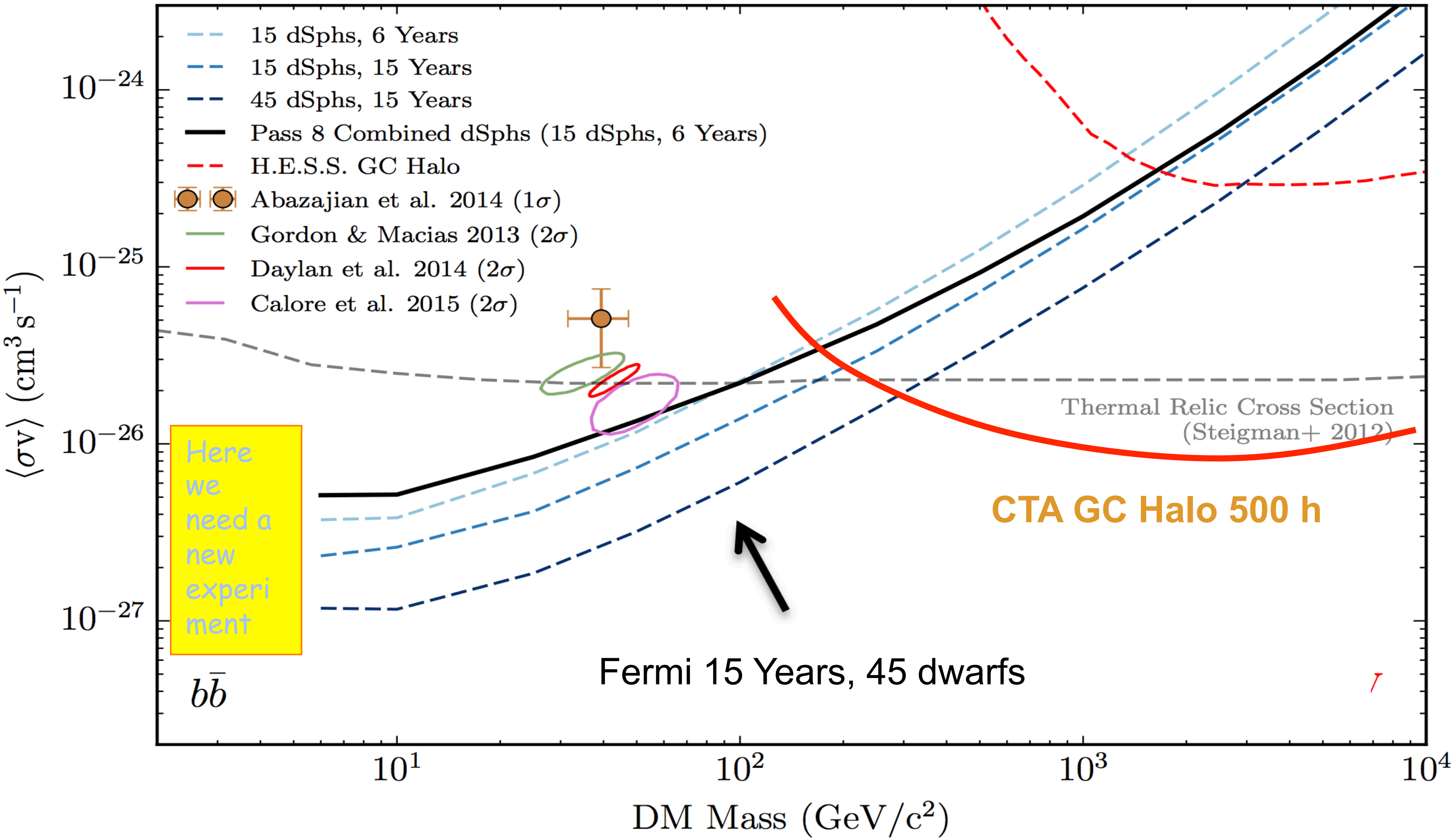
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

Complementarity and Searches for Dark Matter in the pMSSM



Cahill-Rowley et al. arXiv: 1305.6921

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



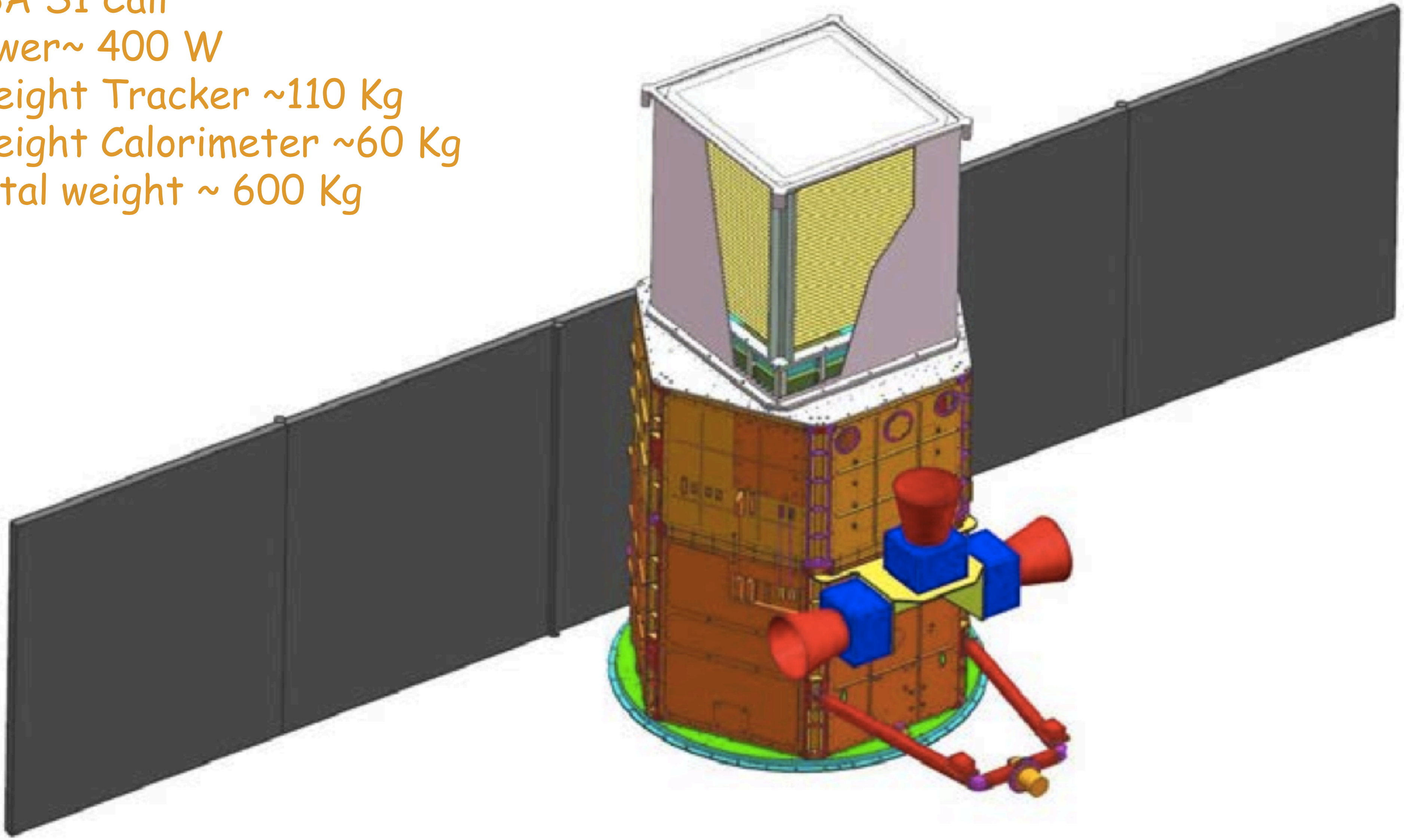
CTA sensitivity curve from Carr et al. 2015 500 hr, statistical only, NFW, 30 GeV threshold arXiv:1508.06128

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

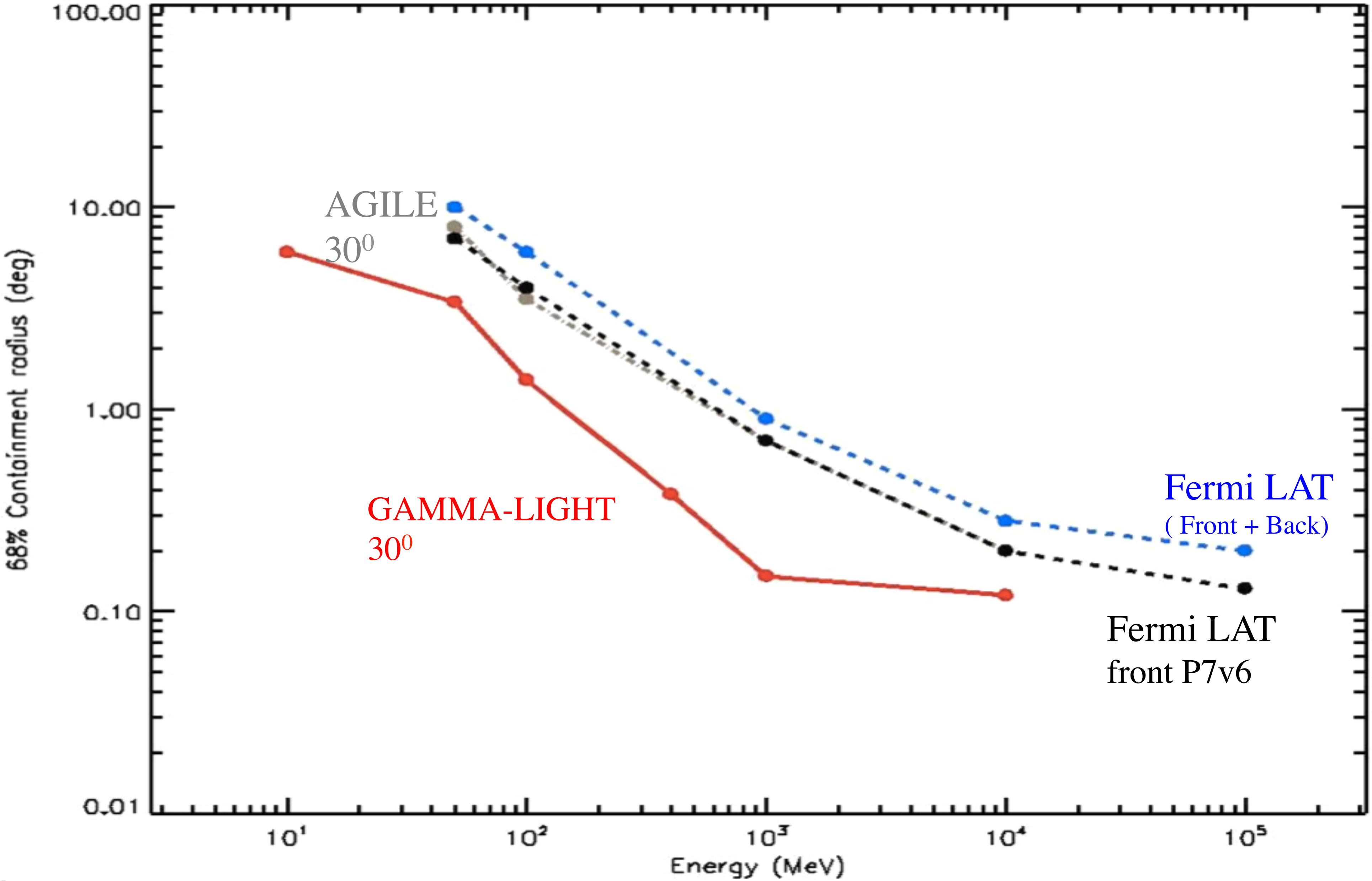
- 1-100 MeV unexplored domain for
  - Dark Matter searches
  - Galactic compact stars and nucleosynthesis
  - Cosmic rays
  - Relativistic jets, microquasars
  - Blazars
  - Gamma-Ray Bursts
  - Solar physics
- and…
  - Terrestrial Gamma-Ray Flashes

Gamma-light project

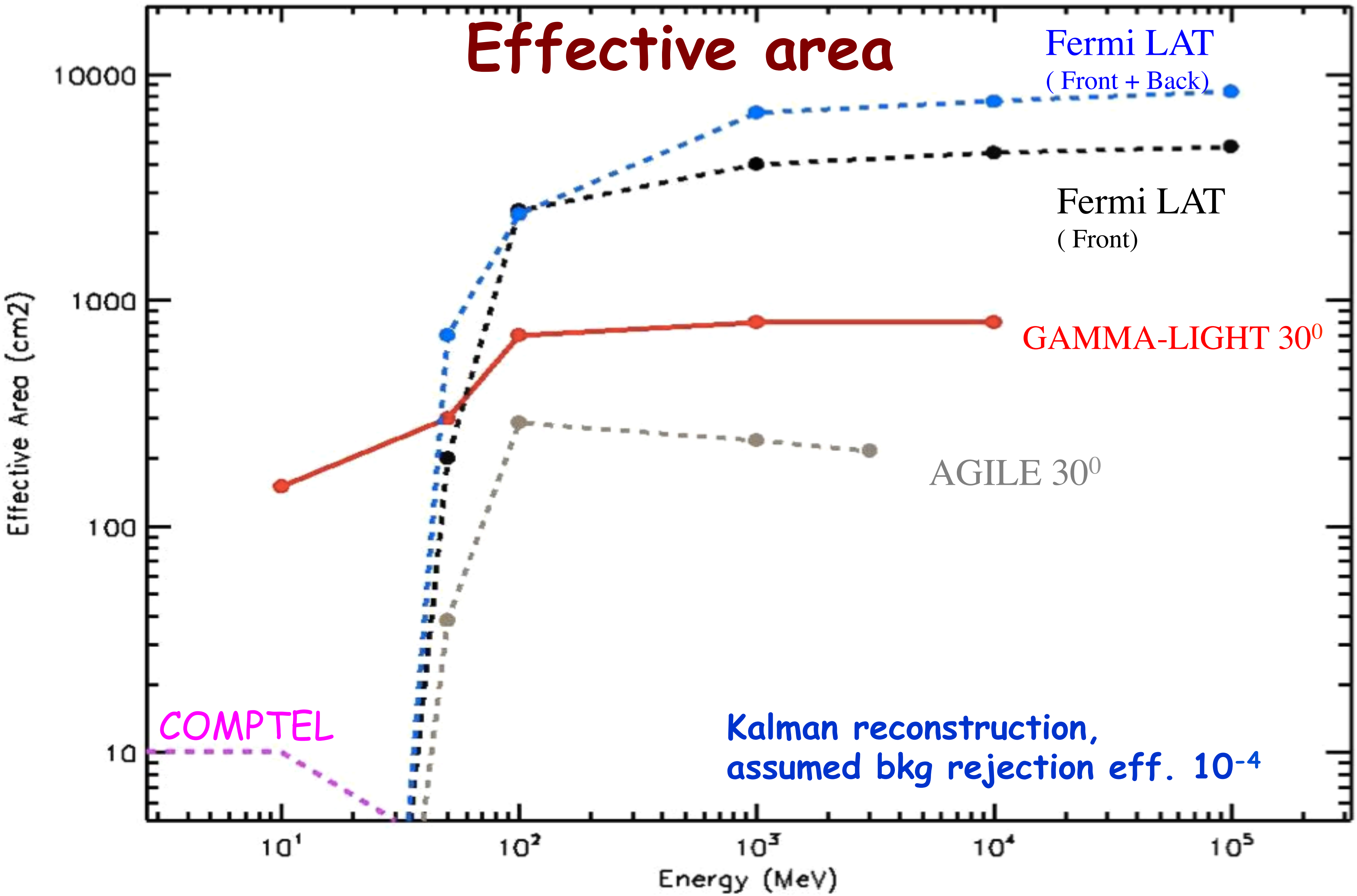
ESA S1 Call
Power~ 400 W
Weight Tracker ~110 Kg
Weight Calorimeter ~60 Kg
Total weight ~ 600 Kg



Gamma-Light Point Spread Function (angular resolution)



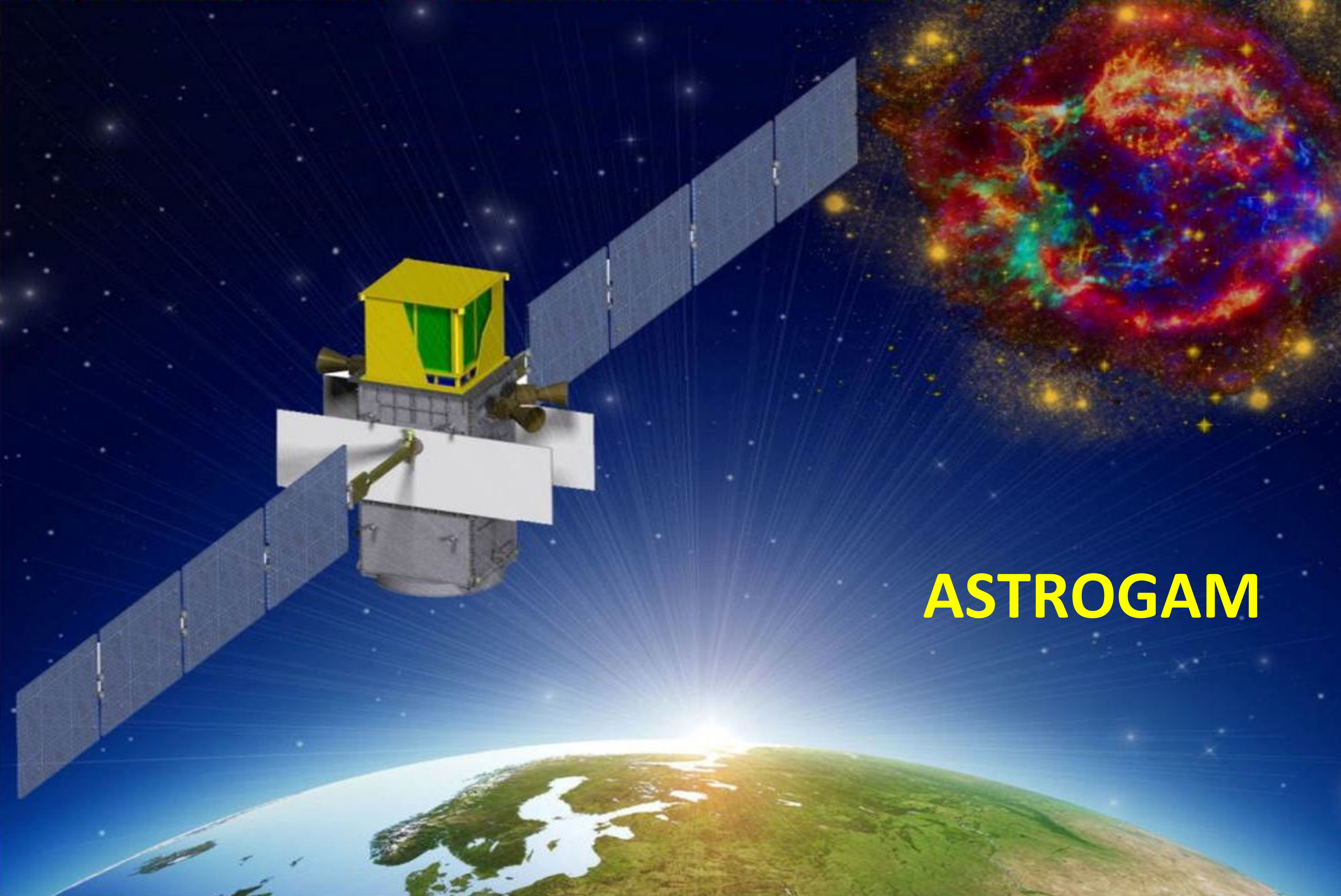
A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198 [arXiv:1406.1071]



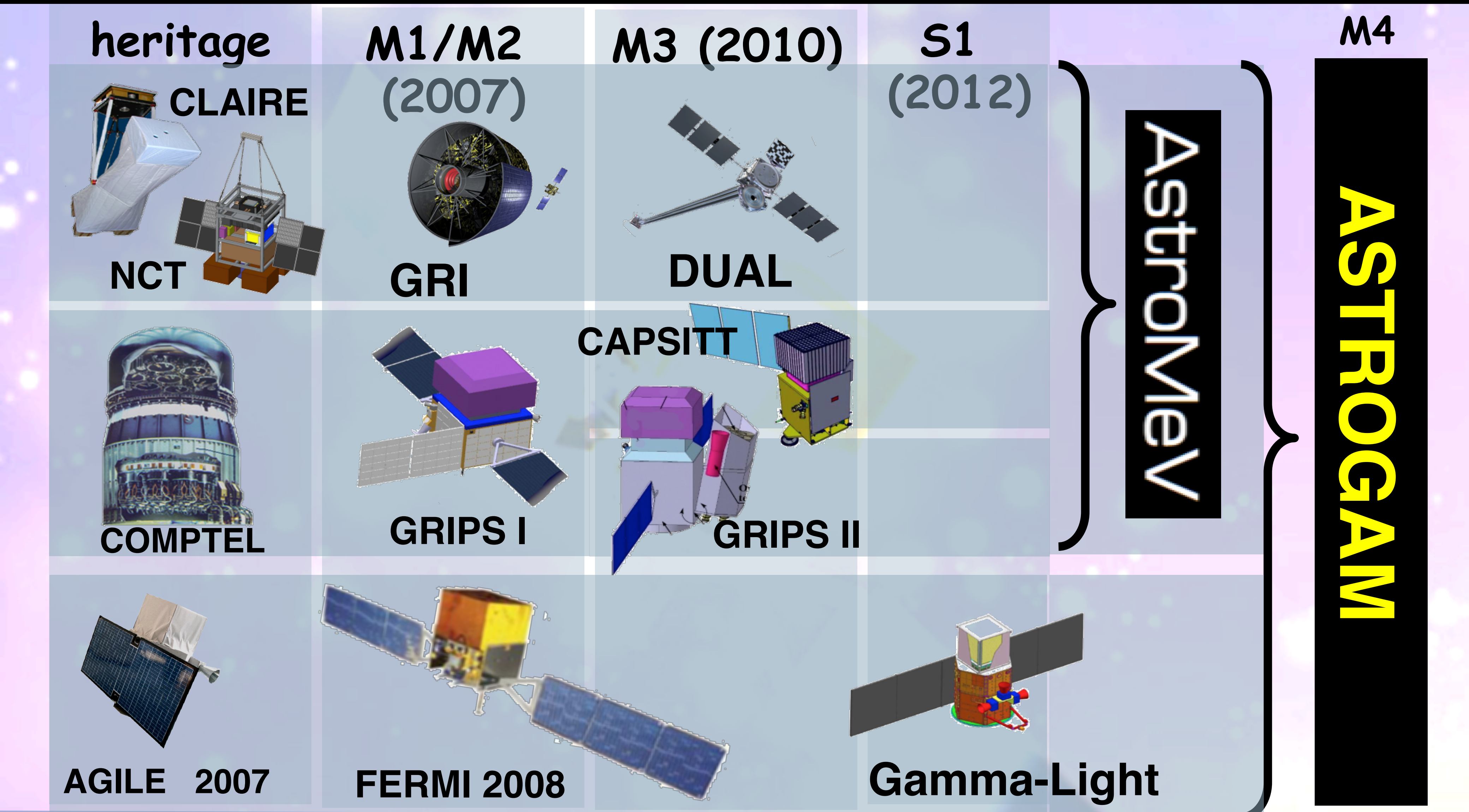
A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198 [arXiv:1406.1071]

ESA M-4 Call

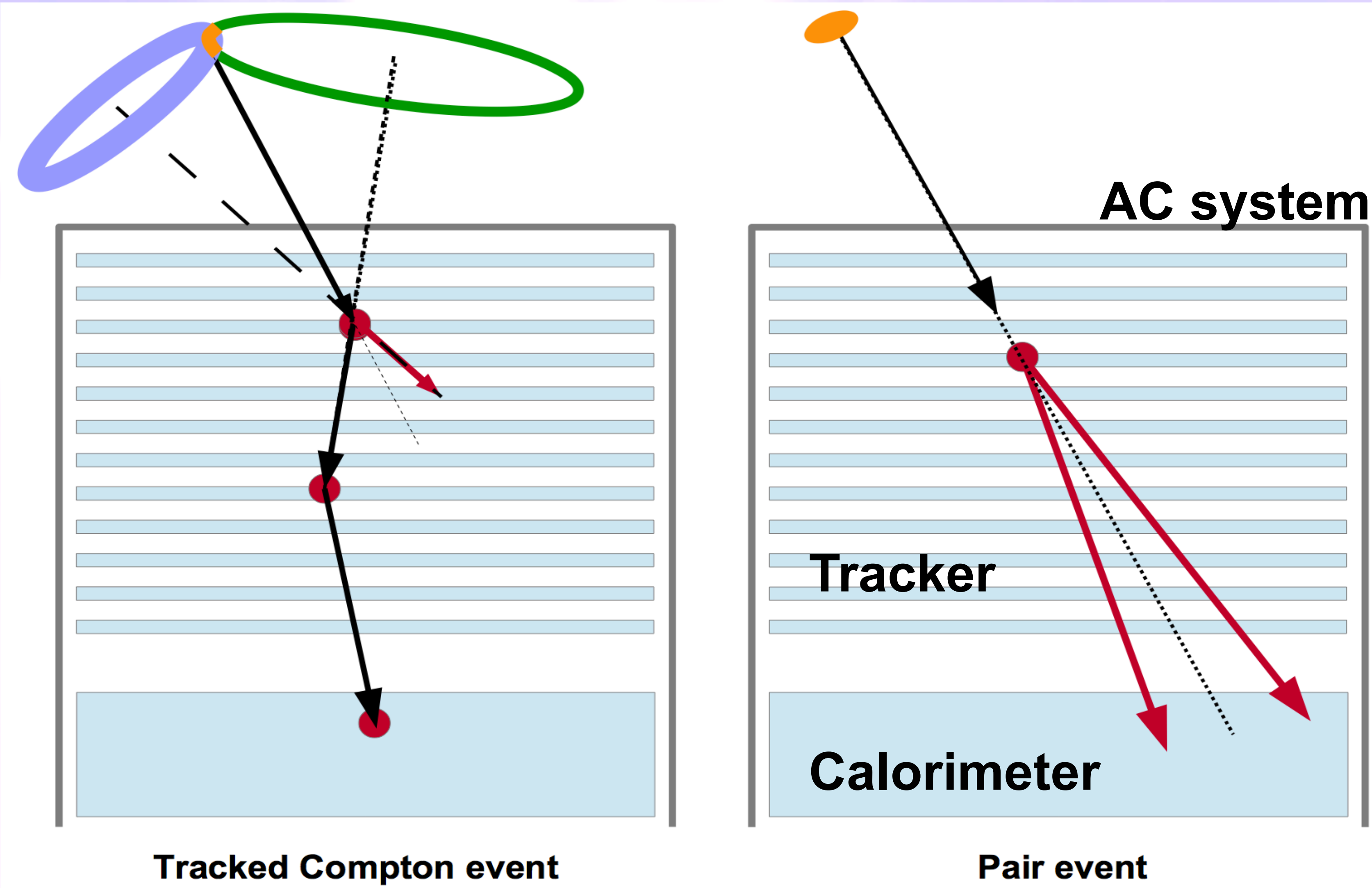
- quite different from previous Medium-sized Mission Calls (Solar Orbiter, EUCLID, PLATO);
- total ESA budget: 450 Meuro.
- guidelines for an ‘‘ESA-only’’ mission:
  - Payload mass: 300 kg;
  - total spacecraft mass: 800 kg.


ASTROGAM

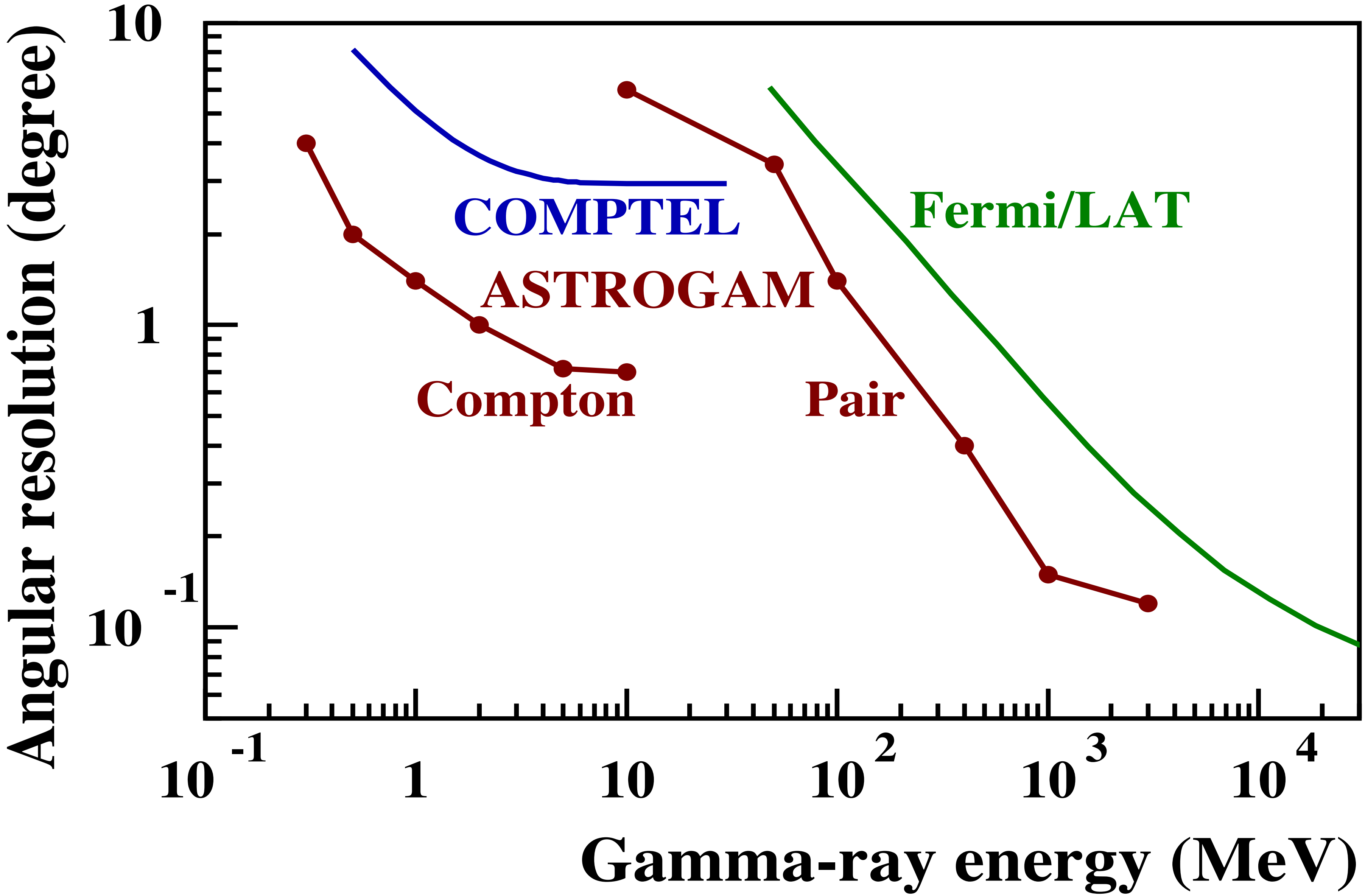
ASTROGAM a unified proposal from the entire gamma-ray community



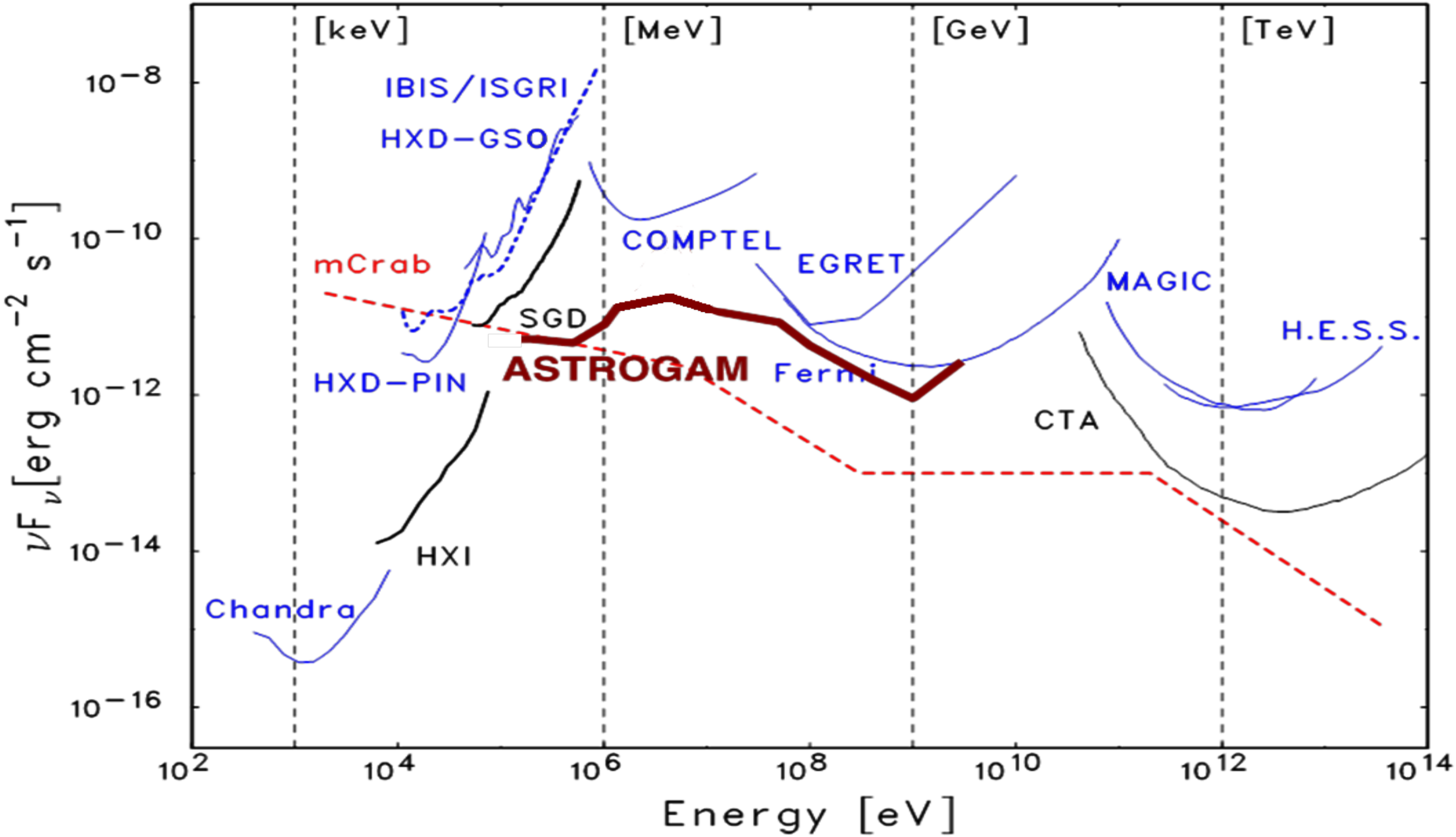
An instrument that combine two detection techniques



ASTROGAM Angular Resolution



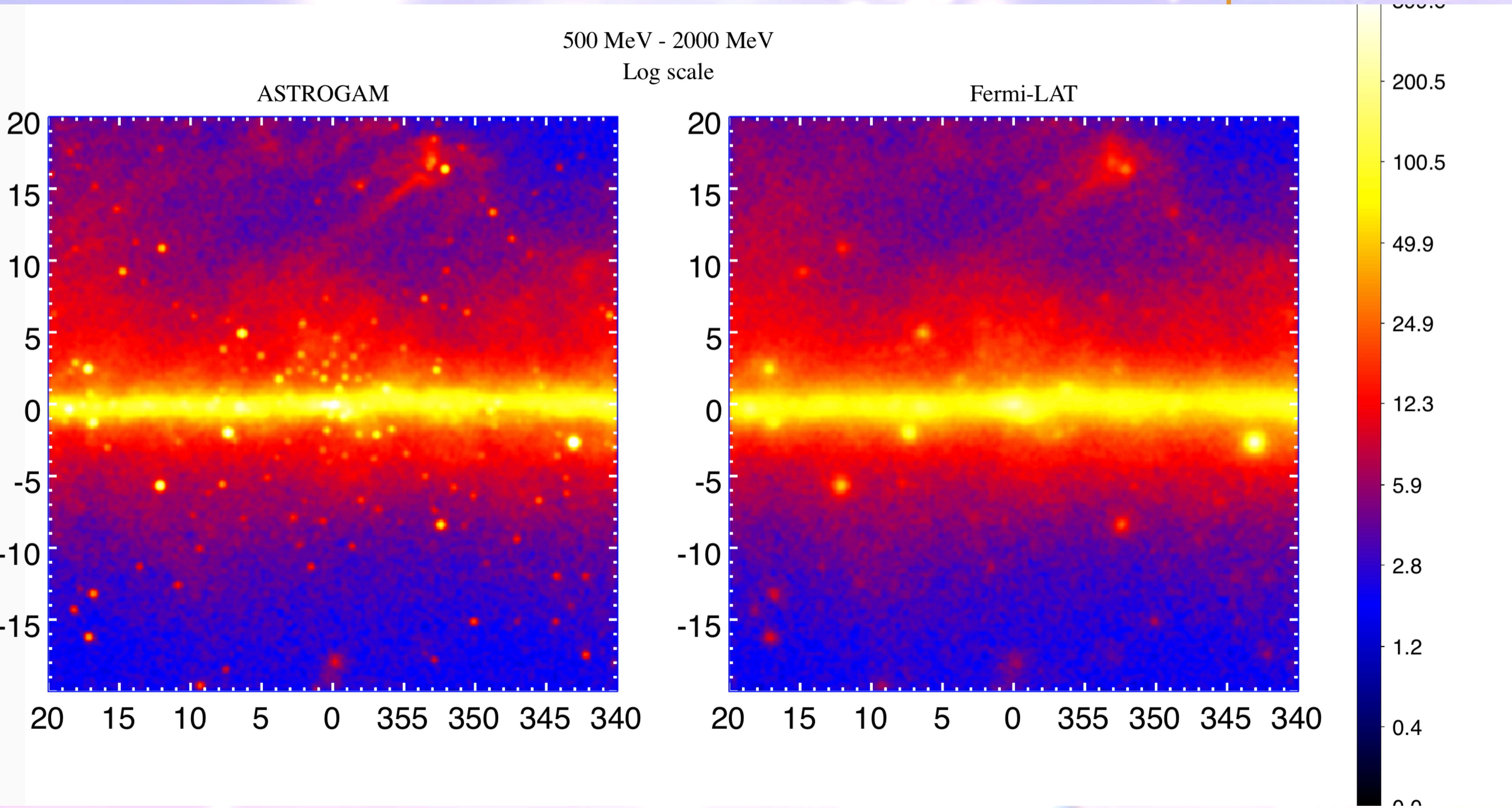
3.5 yr survey sensitivity



- **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

Galactic Center Region 0.5-2 GeV

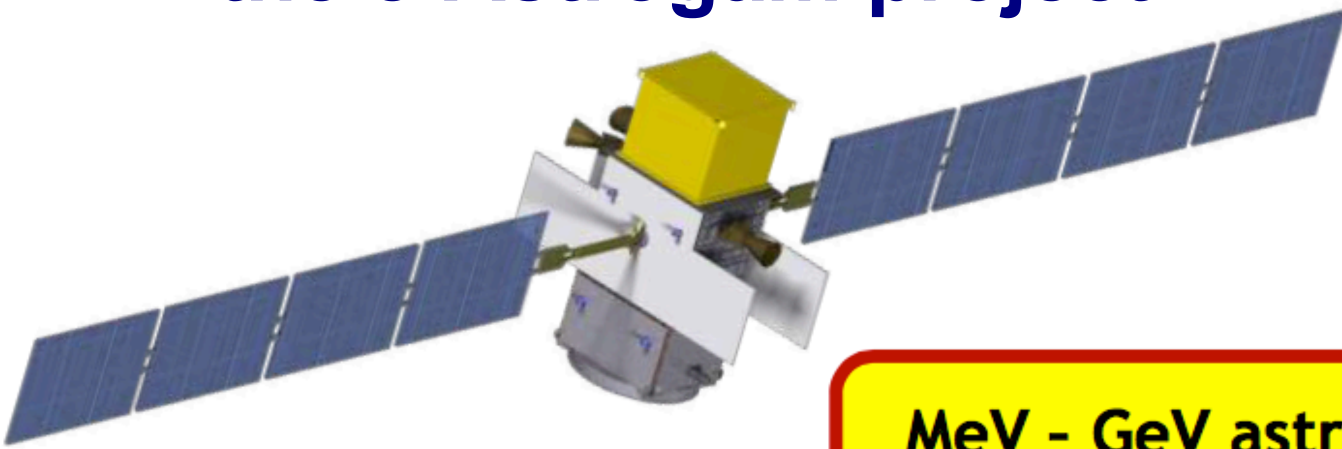
Fermi PSF Pass7 rep v15 source



Morselli, Gomez Vargas, preliminary

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.

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 !