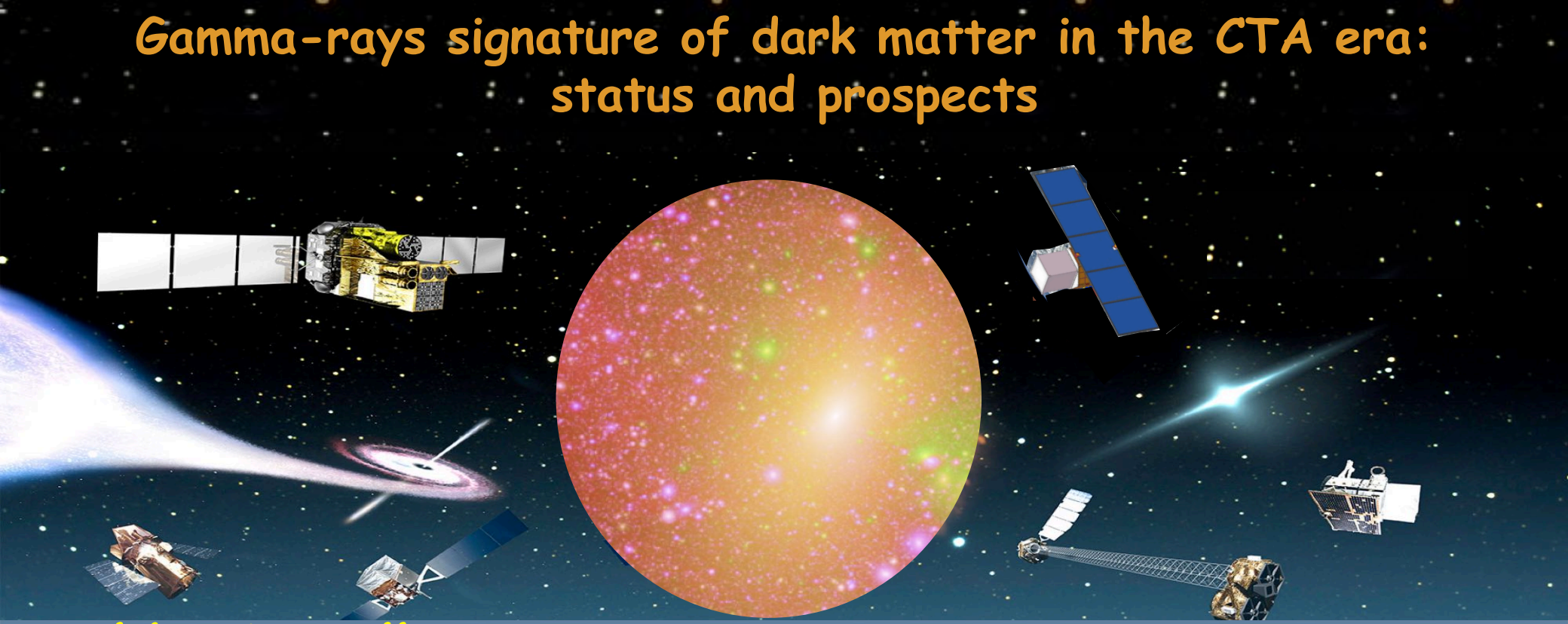
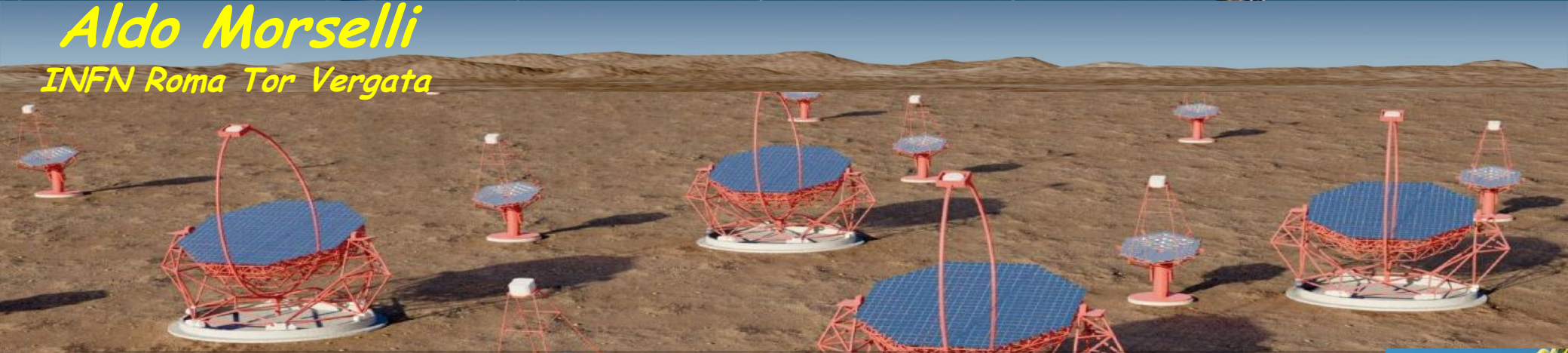
# Gamma-rays signature of dark matter in the CTA era: status and prospects




**Aldo Morselli**

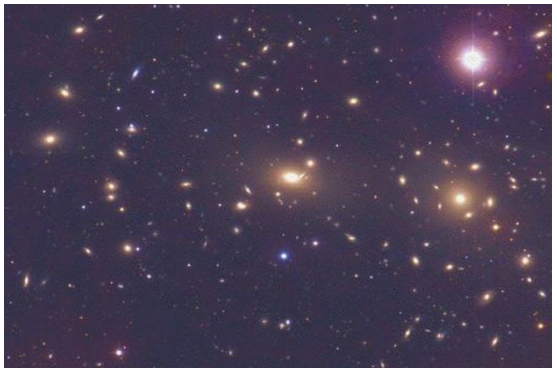
*INFN Roma Tor Vergata*

2nd World Summit: Exploring the Dark Side of the Universe

25-29 June 2018 University of Antilles

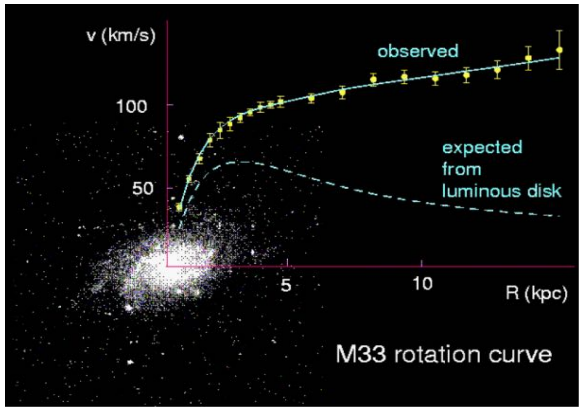
# Dark Matter EVIDENCE



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.

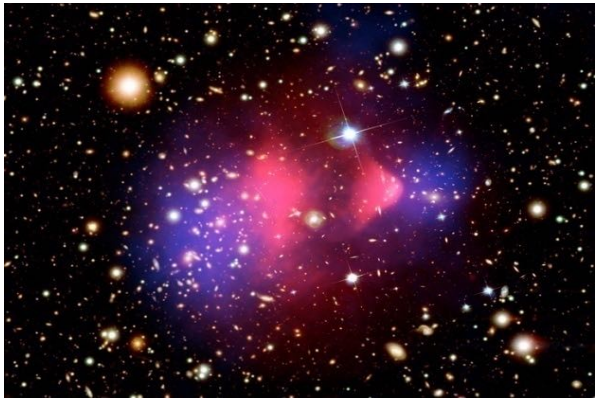
Since then, even more evidence:

Rotation curves of galaxies

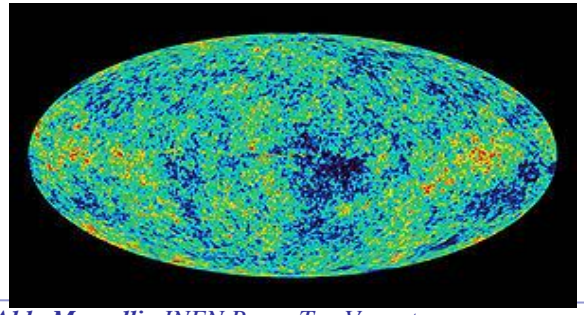



Gravitational lensing

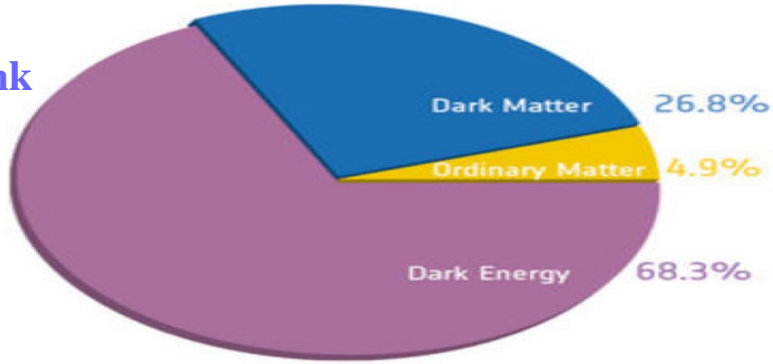
Bullet cluster



Structure formation as deduced from CMB



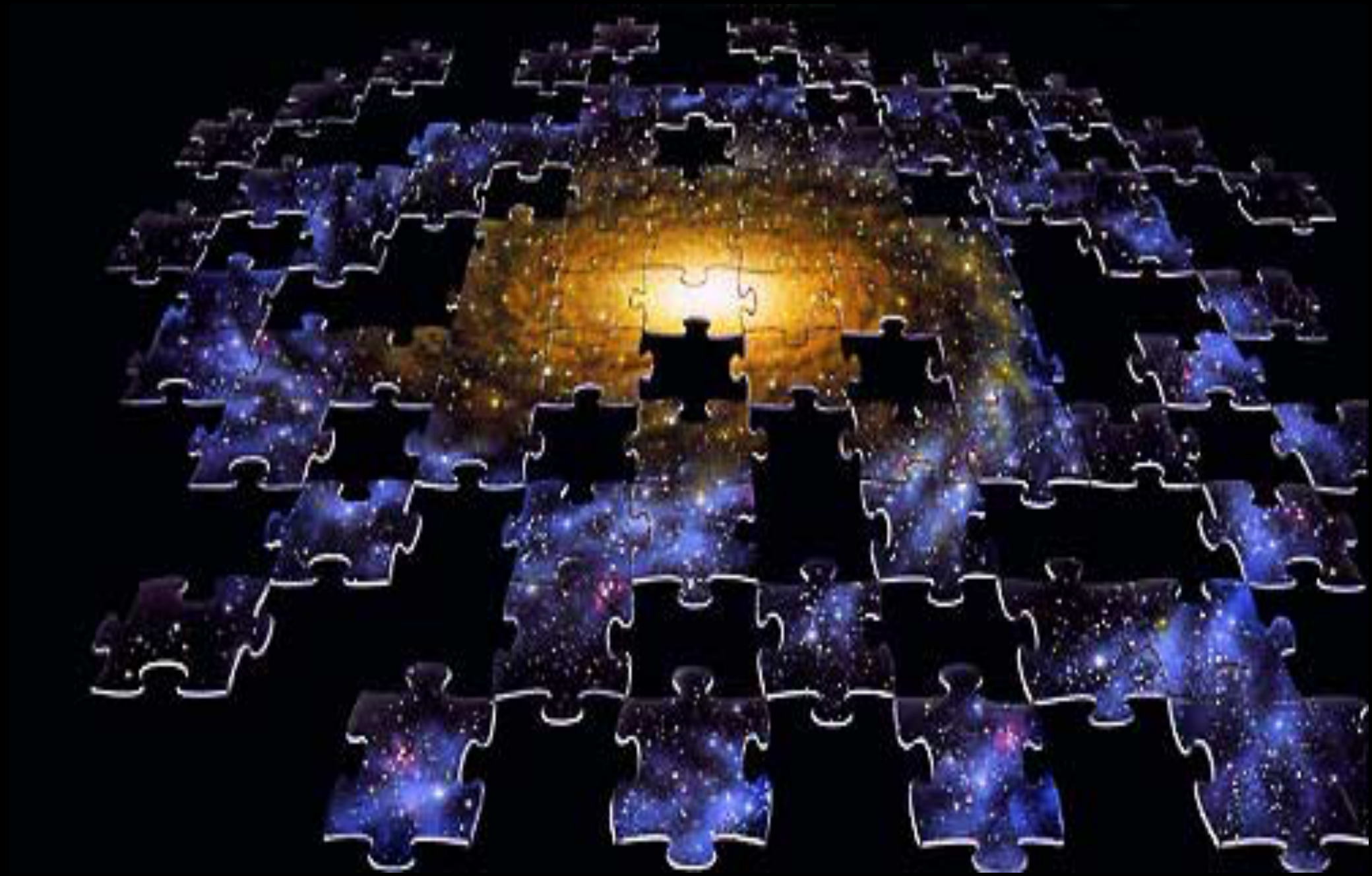
**Data by Plank imply:**



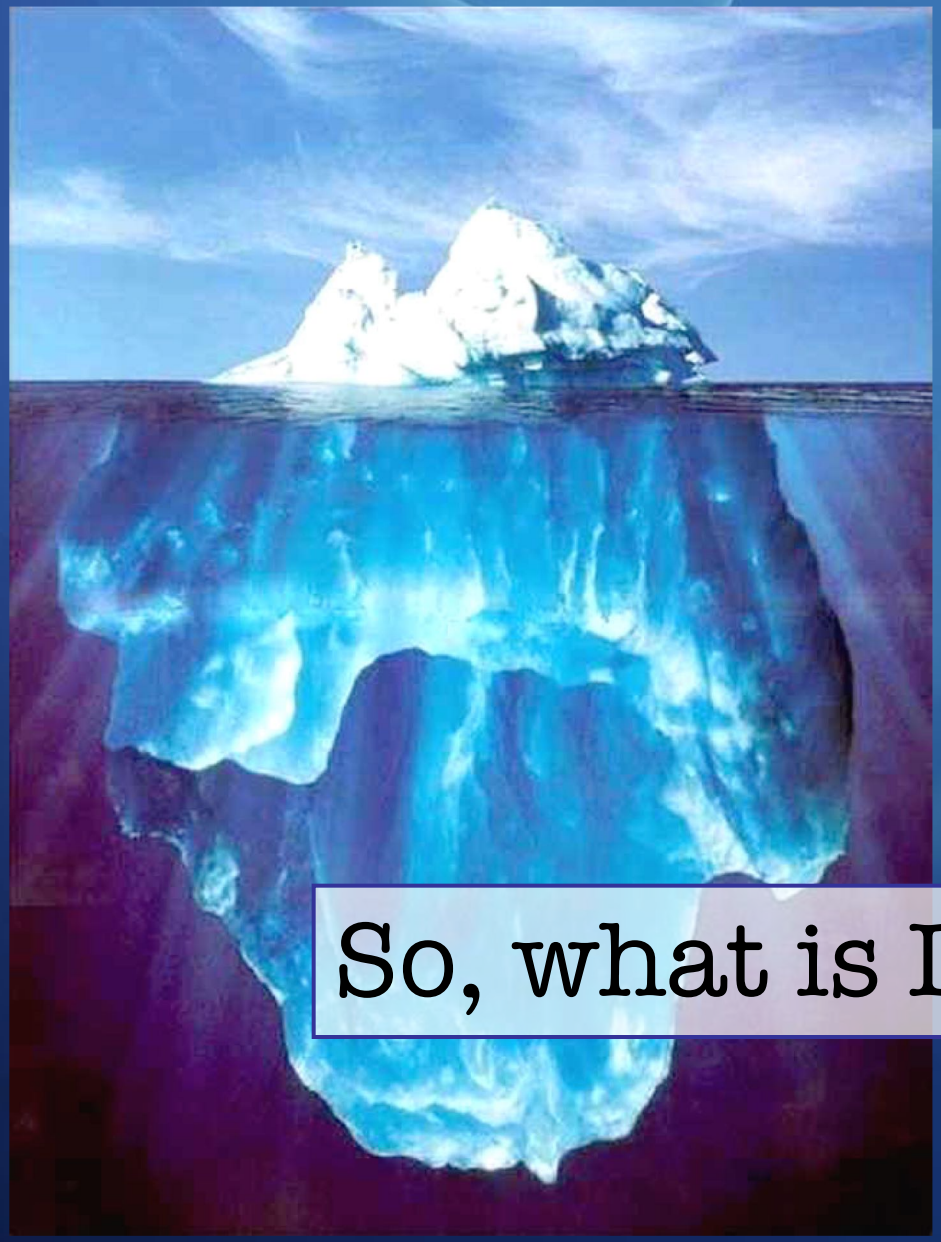

**$\Omega_{Dm} \approx 26.8\%$**

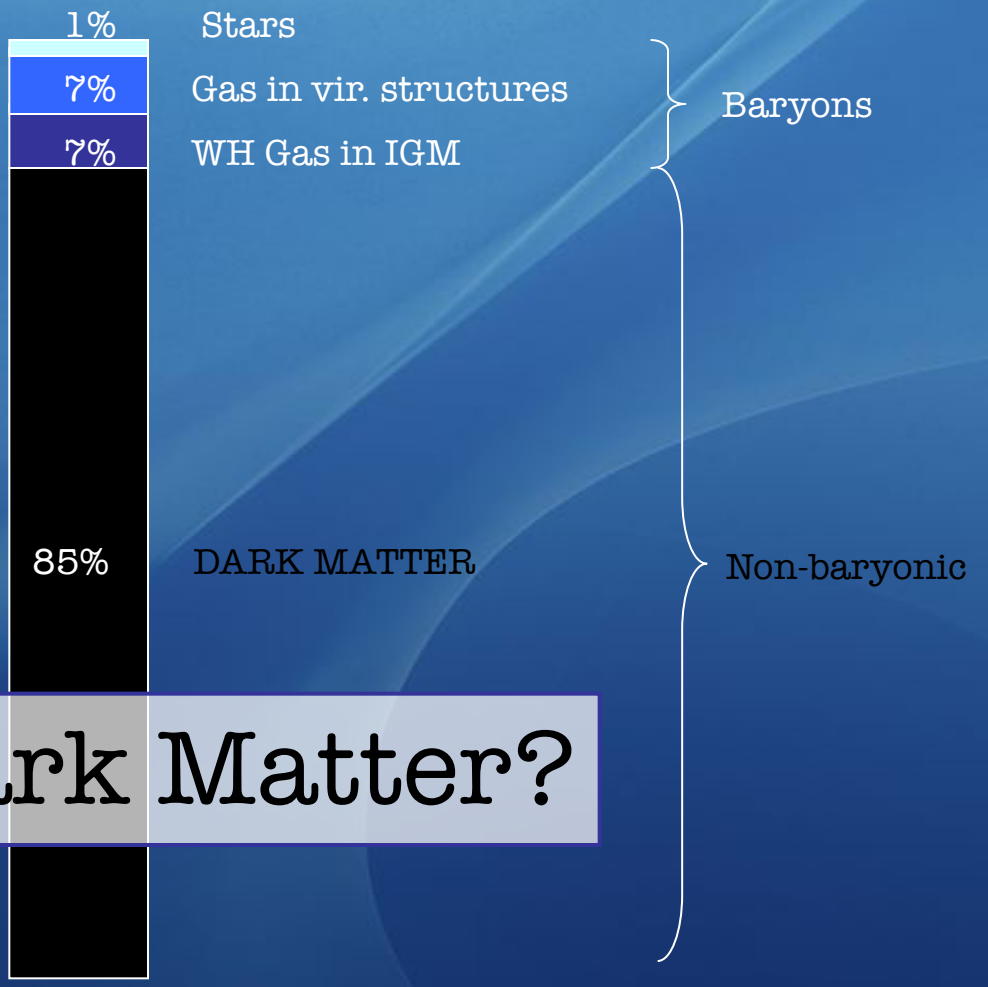
**$\Omega_{Om} \approx 4.9\%$**

# Dark Matter



# An Inventory of Matter in the Universe

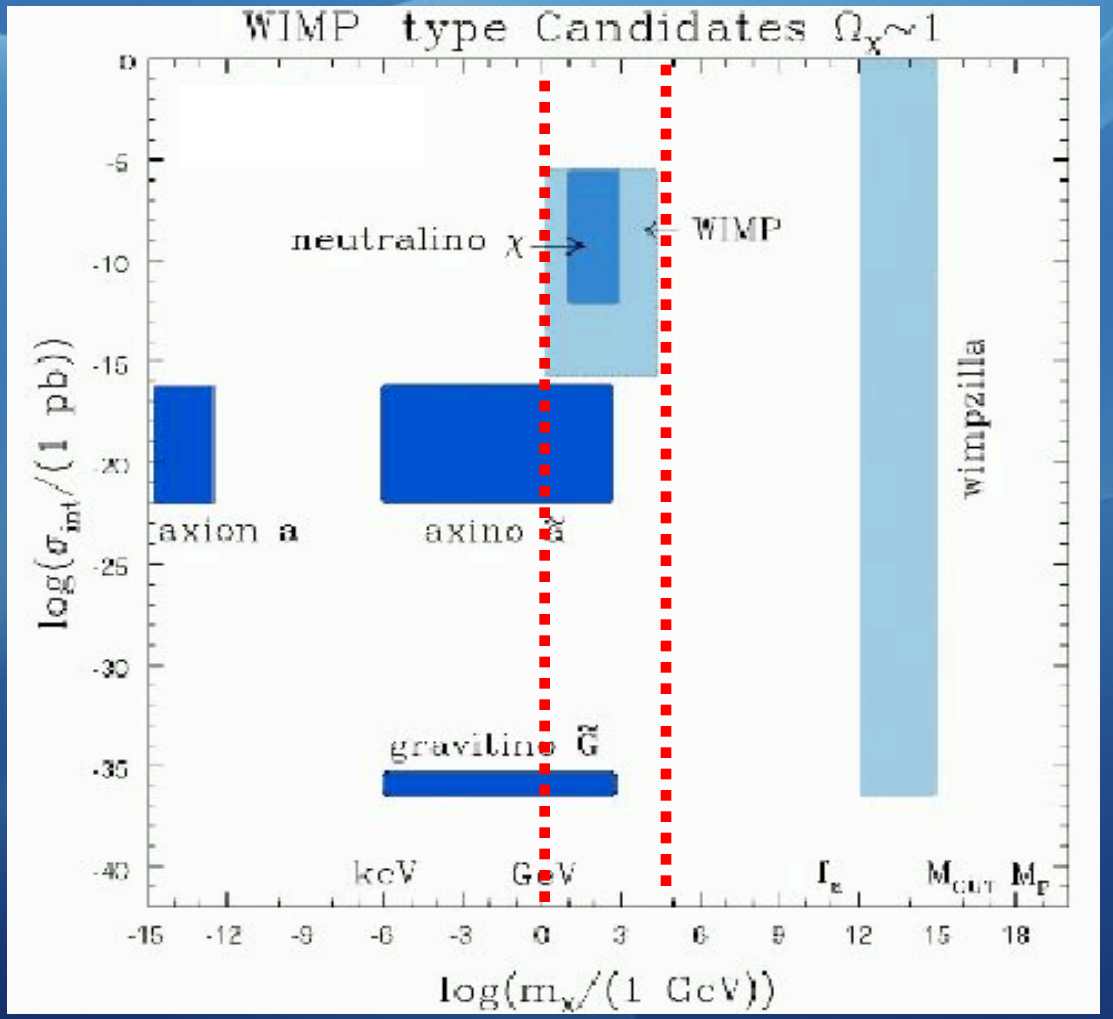





## So, what is Dark Matter?

# 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



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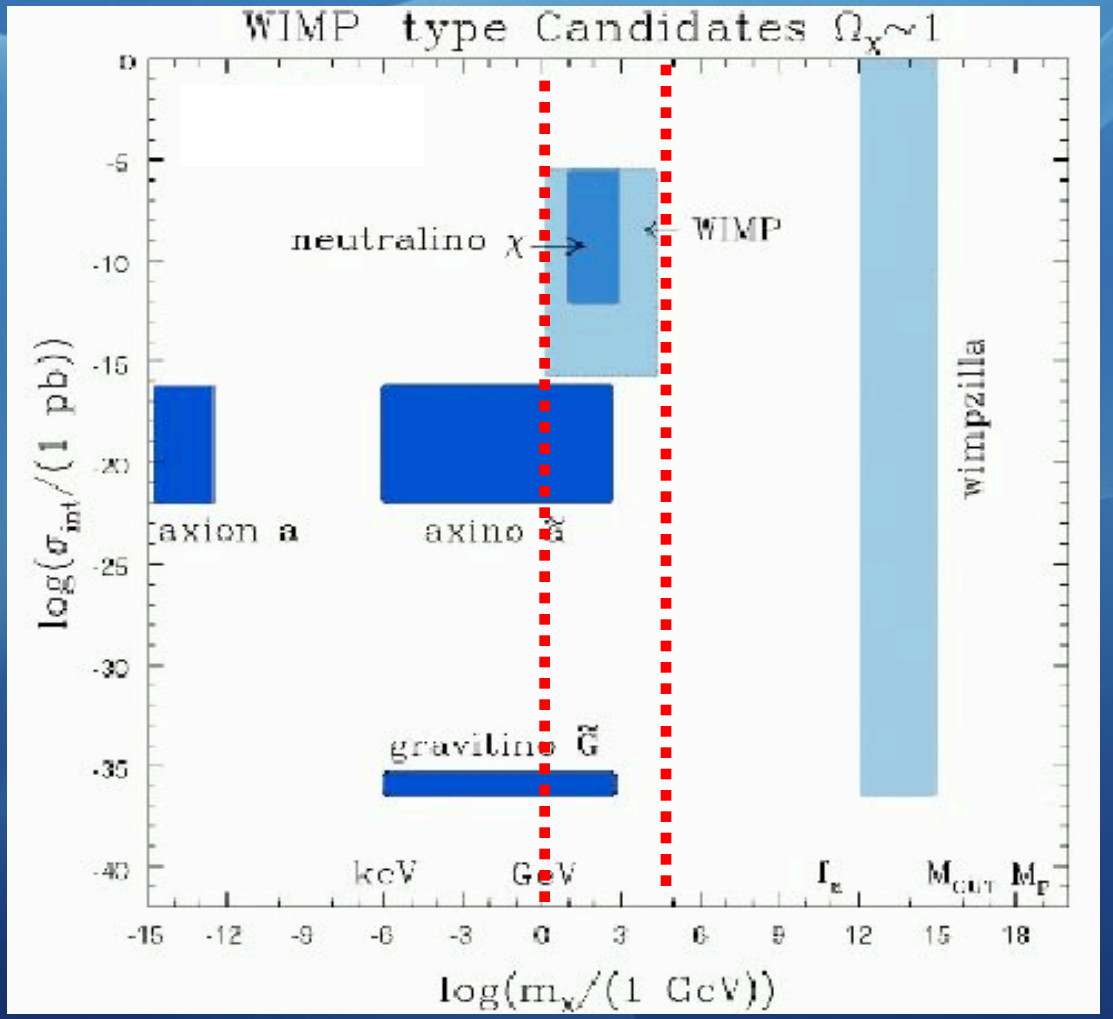
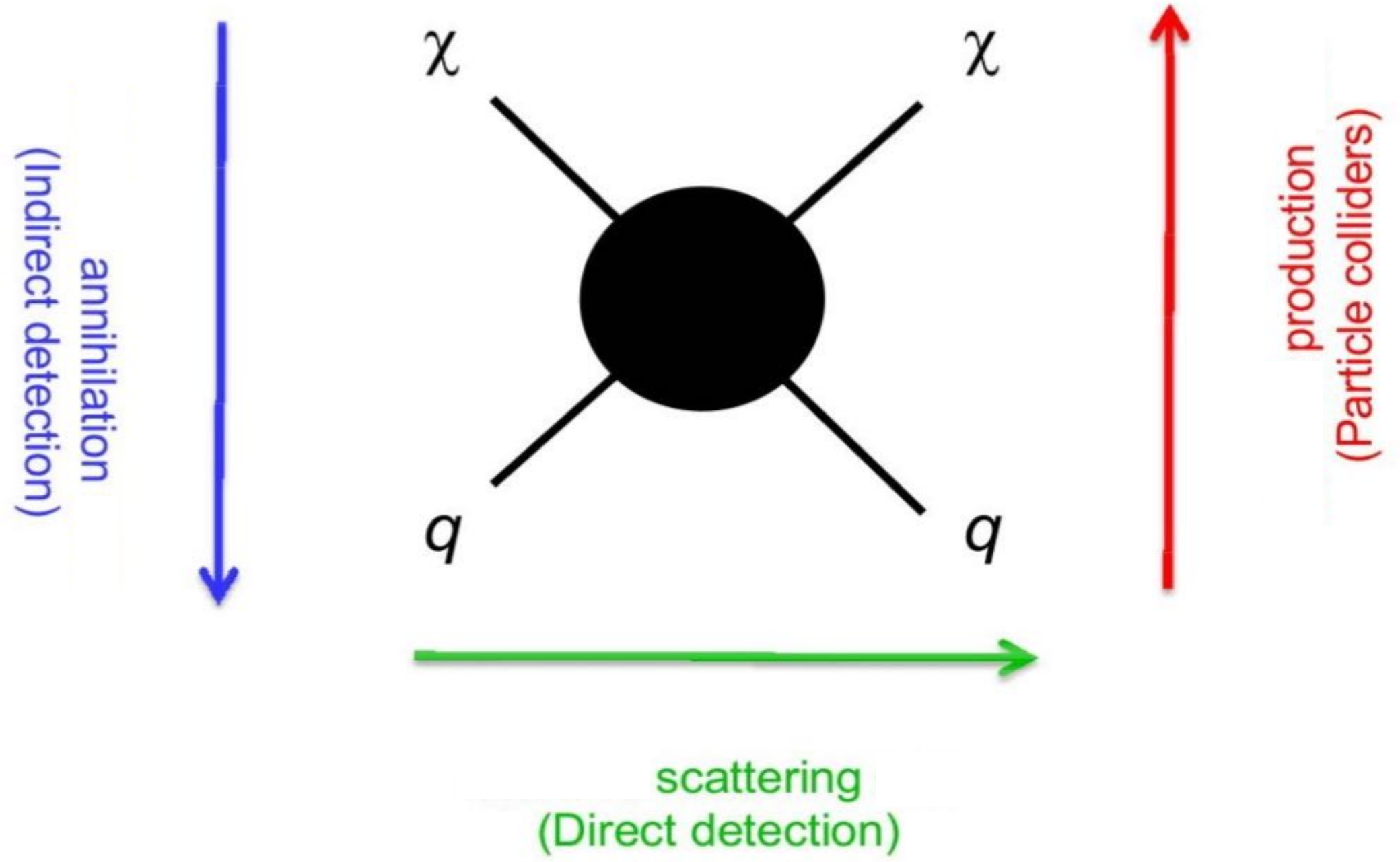
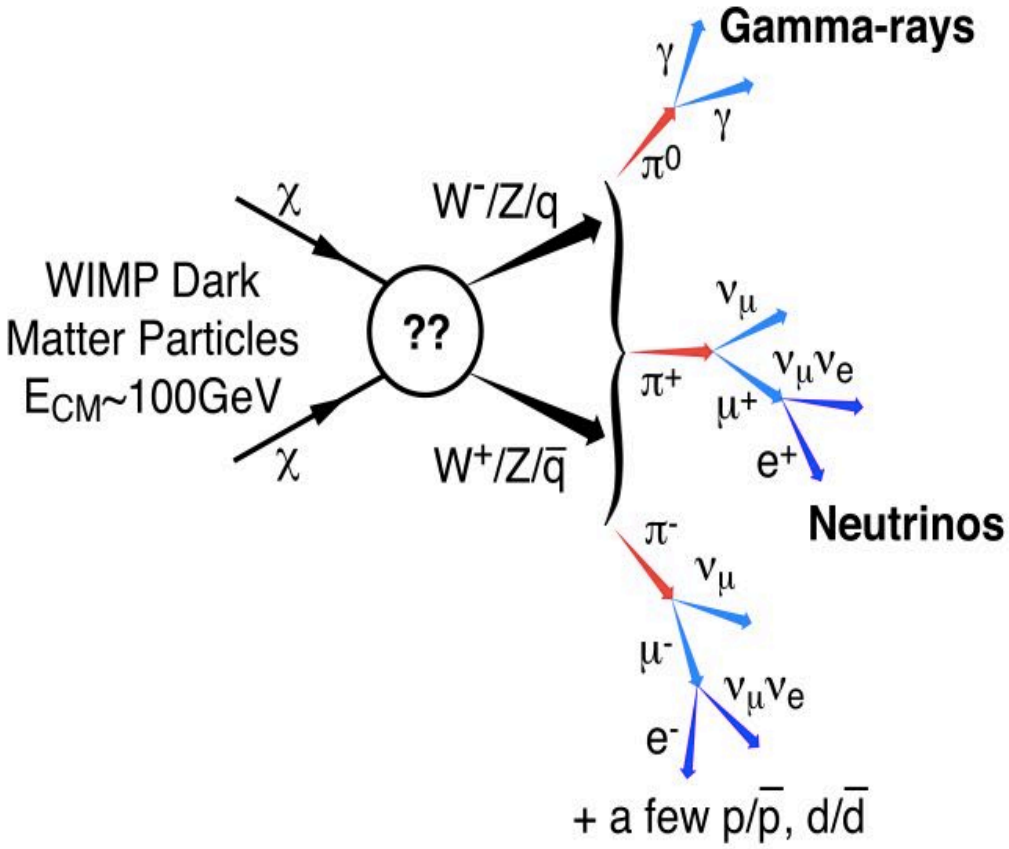
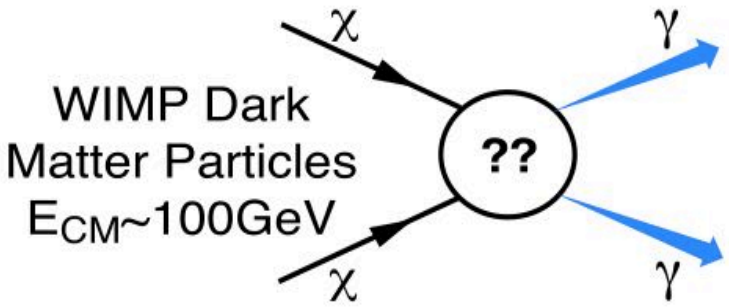
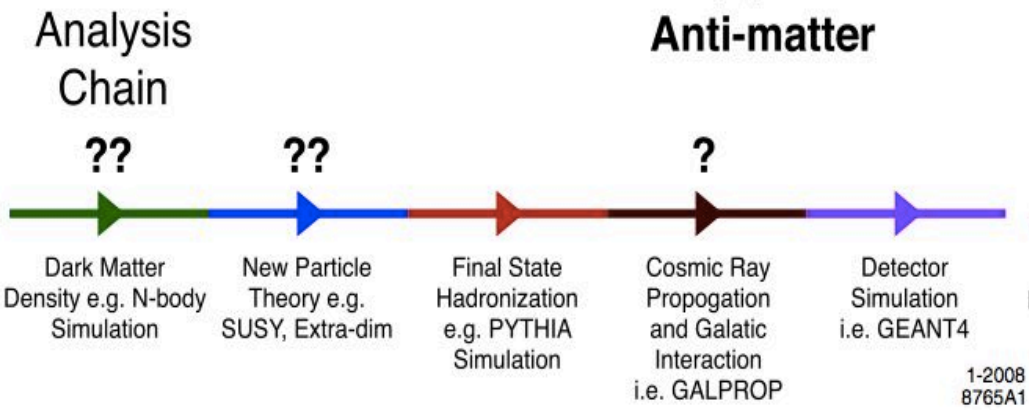


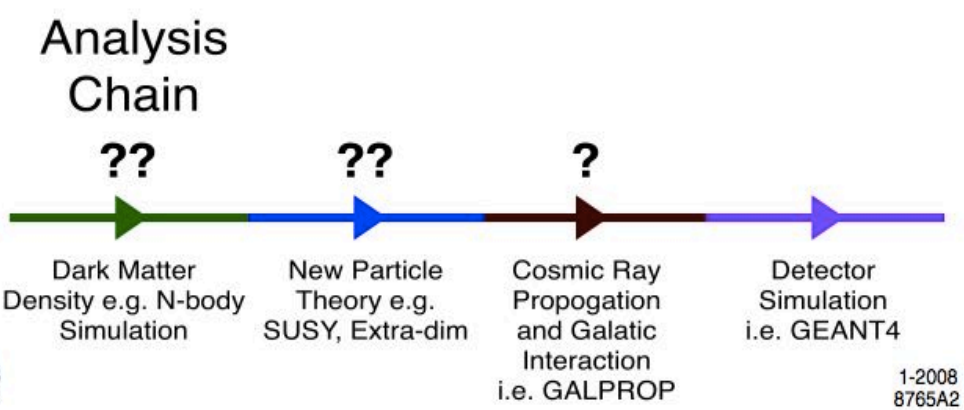

χ
χ
q
q
annihilation
(Indirect detection)
production
(Particle colliders)
scattering
(Direct detection)

# Annihilation channels

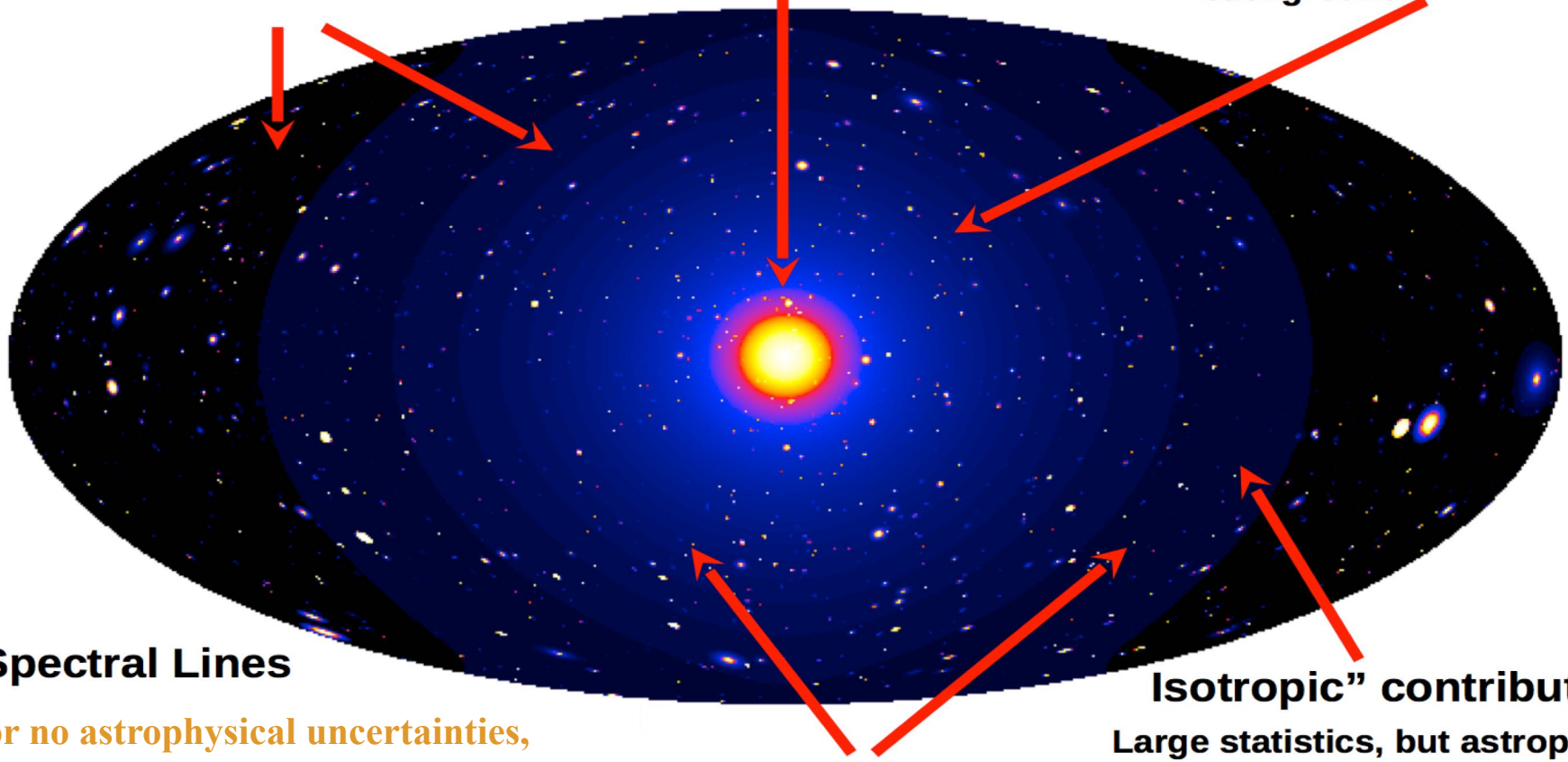


# Dark Matter Search: Targets and Strategies



**Satellites**

Low background and good source id, but low statistics

**Galactic Center**

Good Statistics, but source confusion/diffuse background

**Milky Way Halo**

Large statistics, but diffuse background

**Spectral Lines**

Little or no astrophysical uncertainties, but low sensitivity because of expected small branching ratio

**Isotropic" contributions**

Large statistics, but astrophysics, galactic diffuse background

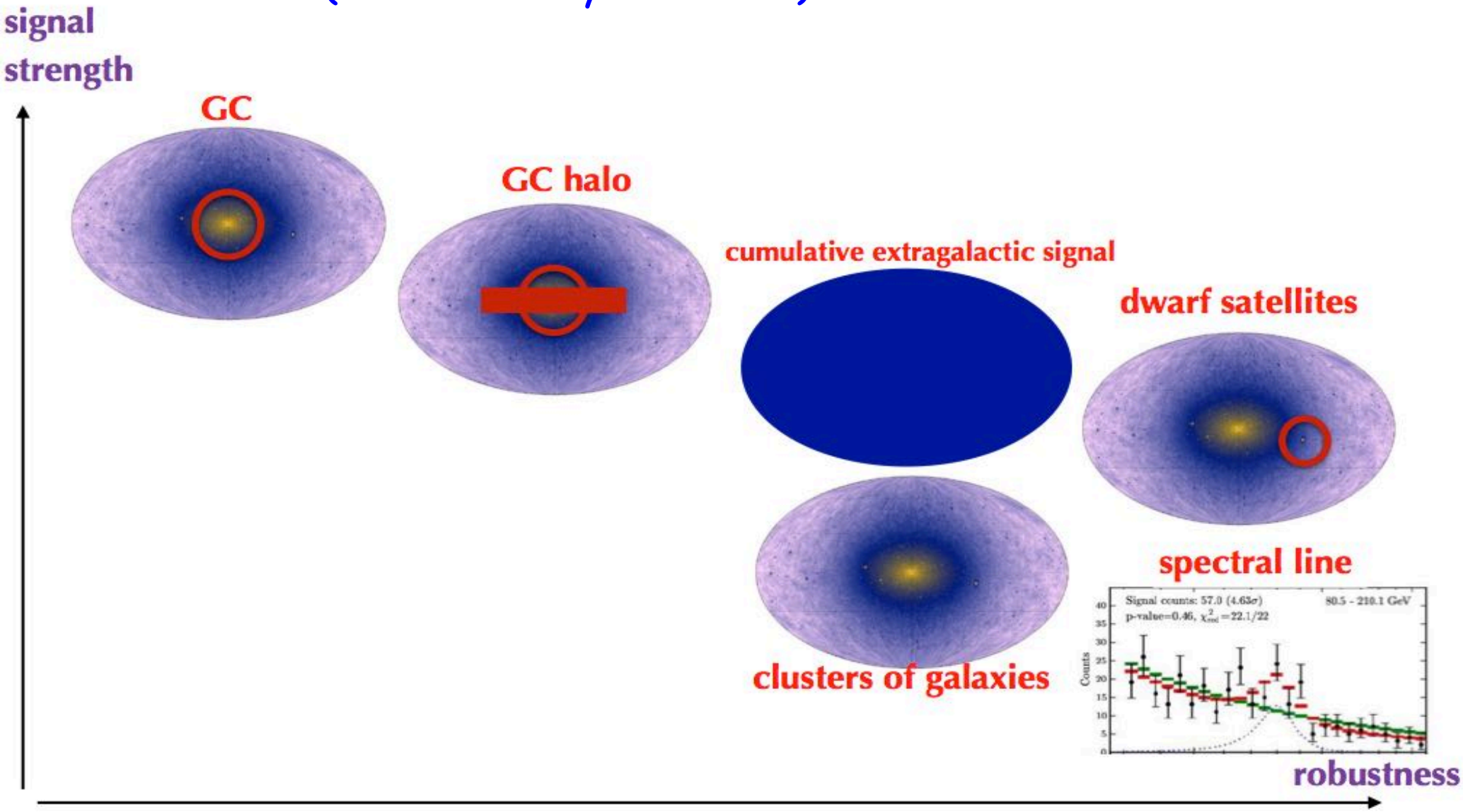
**Galaxy Clusters**

Low background, but low statistics

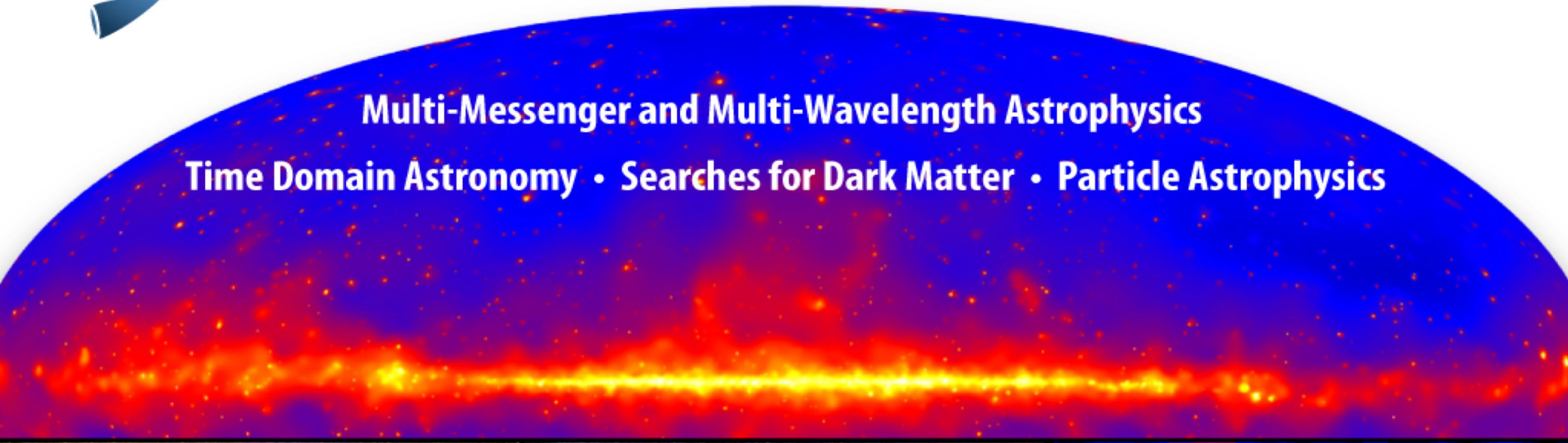
Dark Matter simulation: Pieri+(2009) arXiv:0908.0195

# Dark Matter Search: Targets and Strategies

## (Another way to see it)

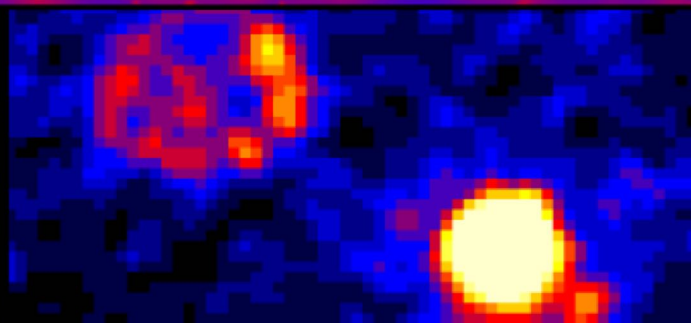


# Fermi Gamma-Ray Space Telescope



**Multi-Messenger and Multi-Wavelength Astrophysics**

**Time Domain Astronomy • Searches for Dark Matter • Particle Astrophysics**



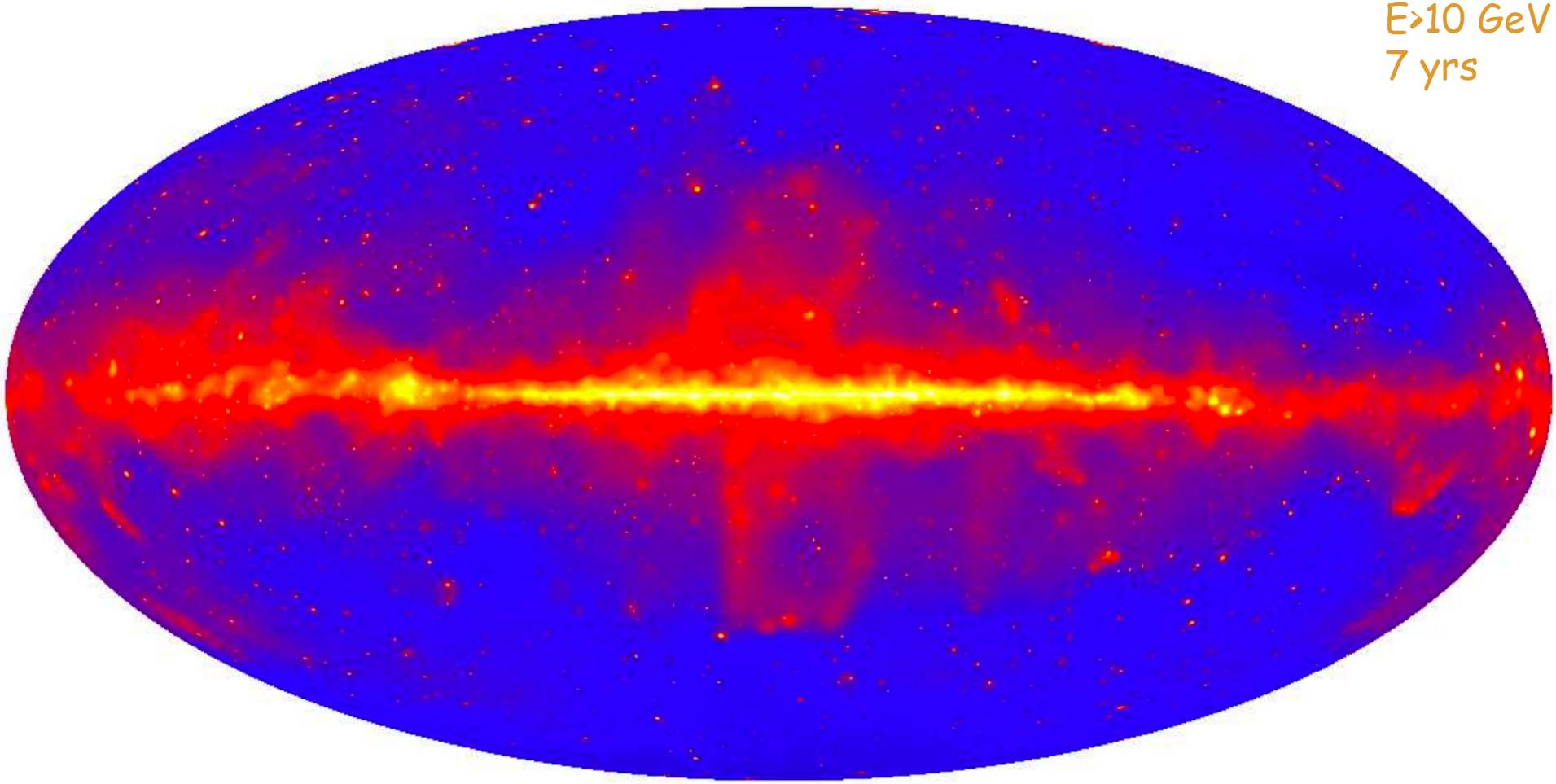
Fermi
Gamma-ray
Space Telescope

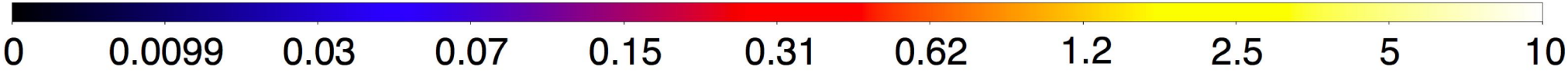
# Happy 10th Birthday Fermi !!

11 June 2008


Pisa 15 March 2018

# The sky in gamma-rays




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

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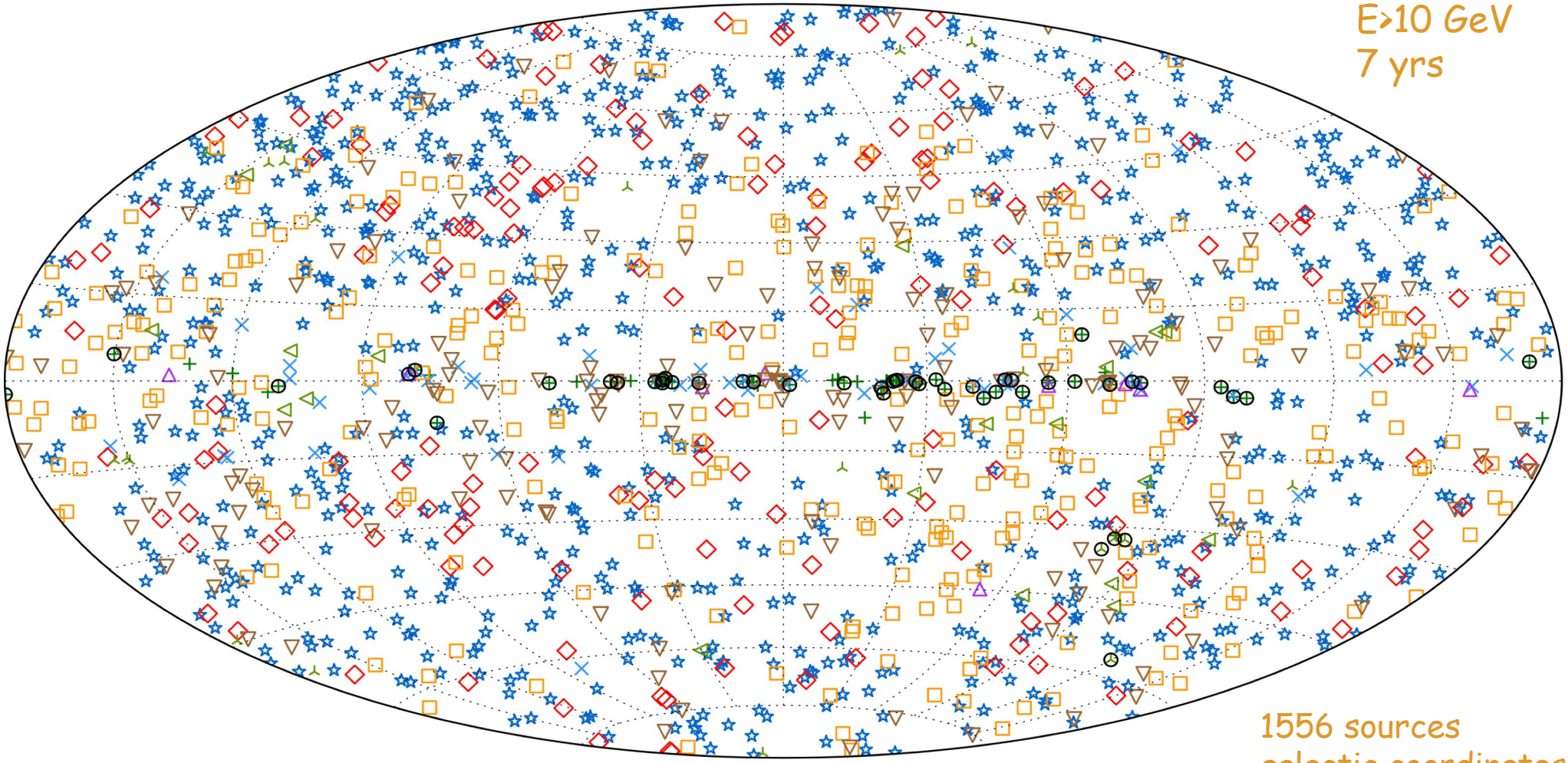



M.Ackermann et al. [Fermi Coll.] 3FHL: The Third Catalog of Hard Fermi-LAT Sources arXiv:1702.00664

# GW170817

## Fermi

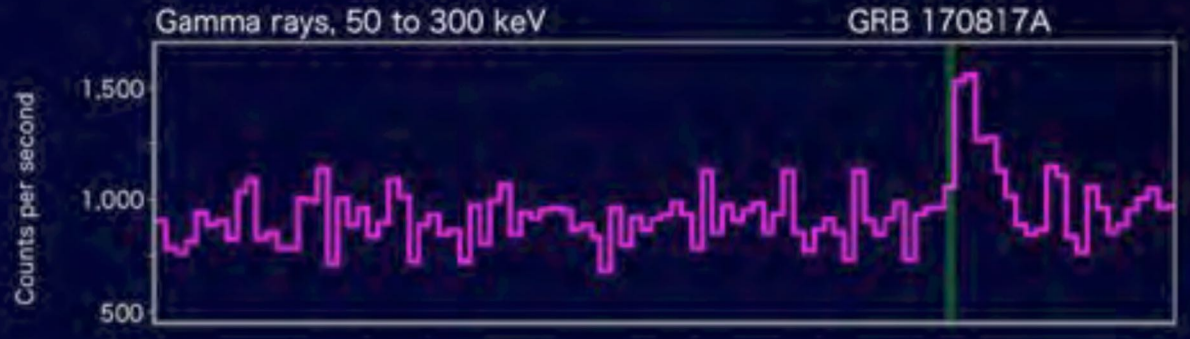
Reported 16 seconds after detection

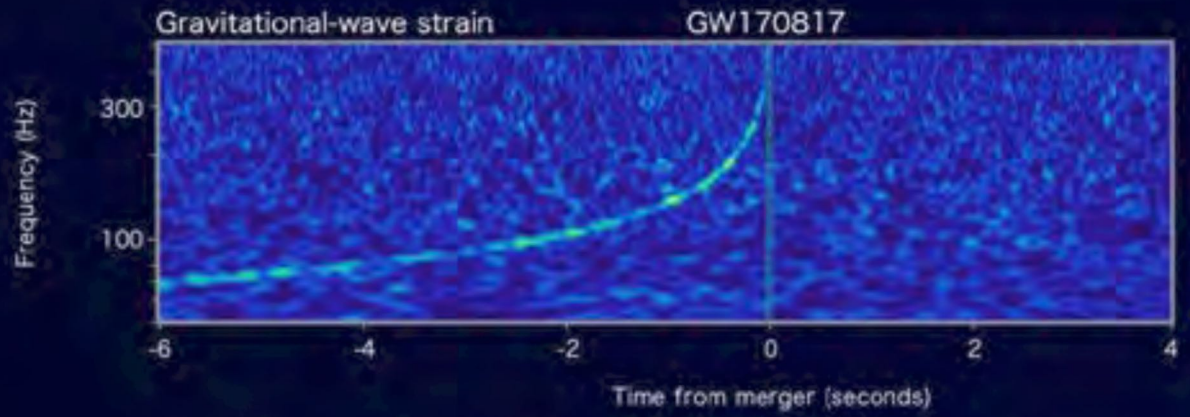
## LIGO-Virgo

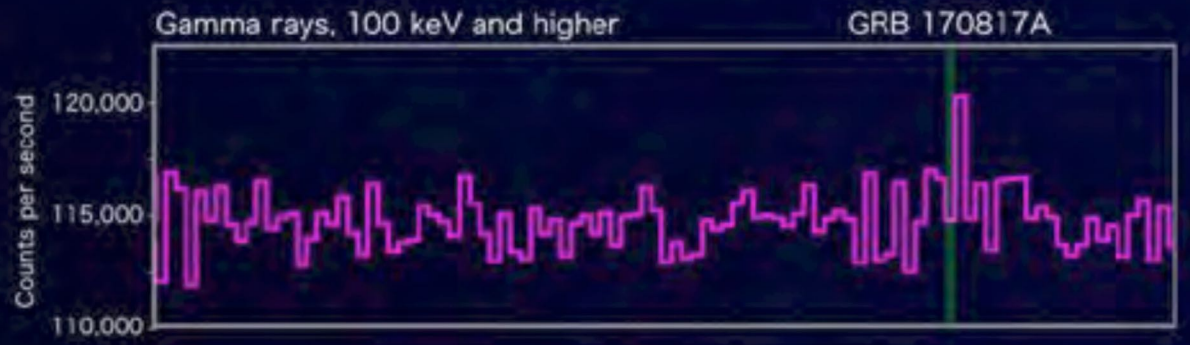
Reported 27 minutes after detection

## INTEGRAL

Reported 66 minutes after detection



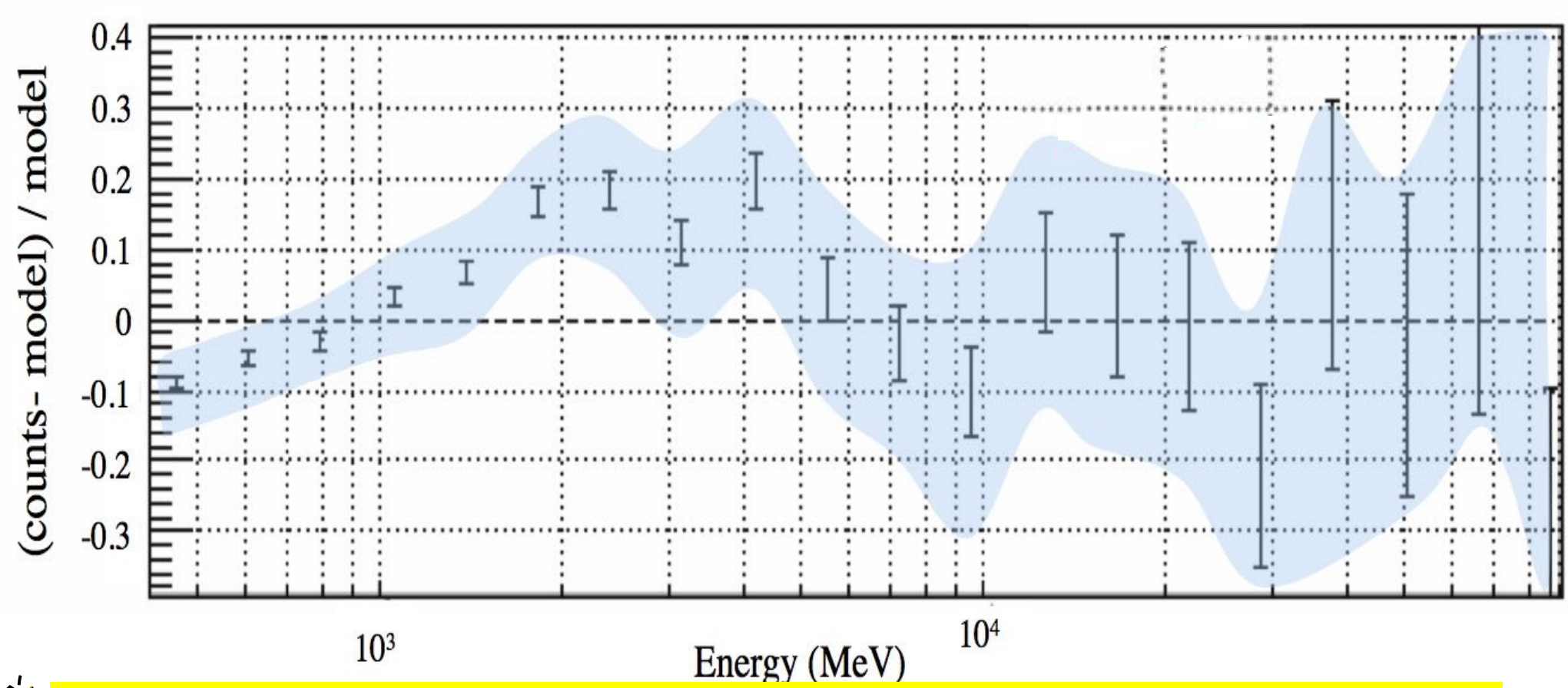

Multi-messenger Observations of a Binary Neutron Star Merger ApjL 848 L12 2017 [arXiv:1710.05833] 3656 authors !

# The GeV excess

7° x7° region centered on the Galactic Center

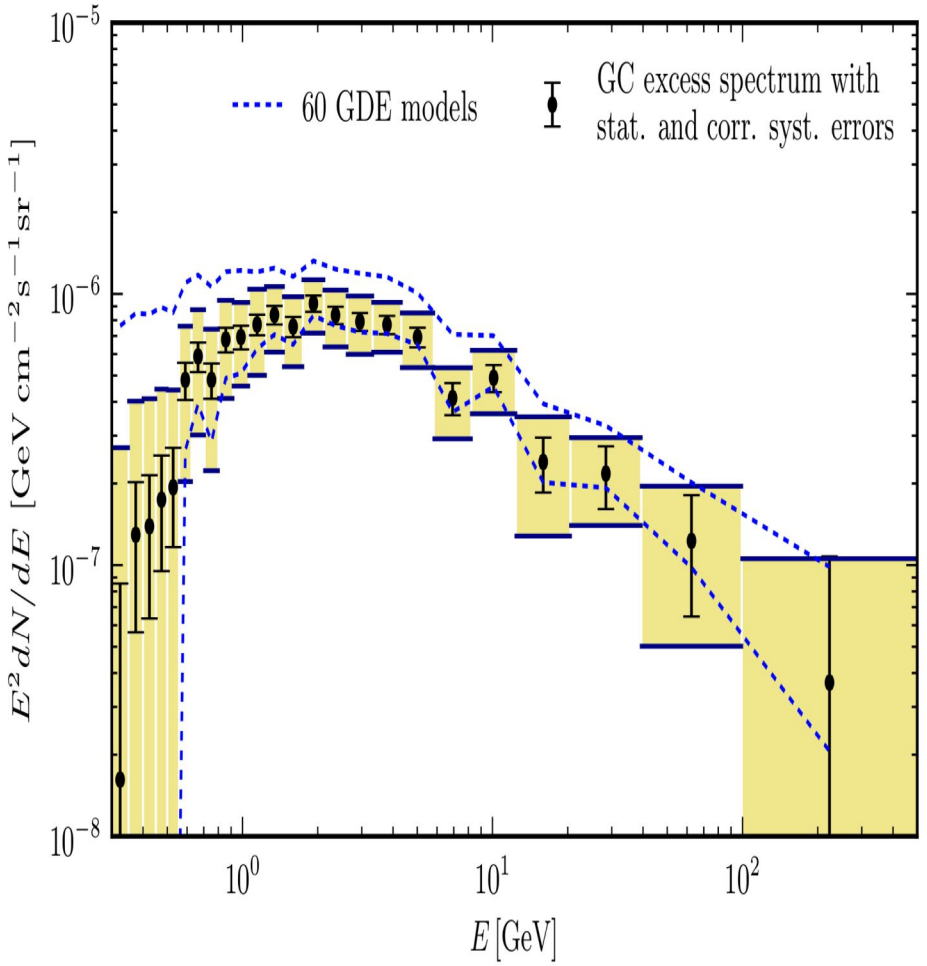
11 months of data, E >400 MeV, front-converting events
analyzed with binned likelihood analysis )

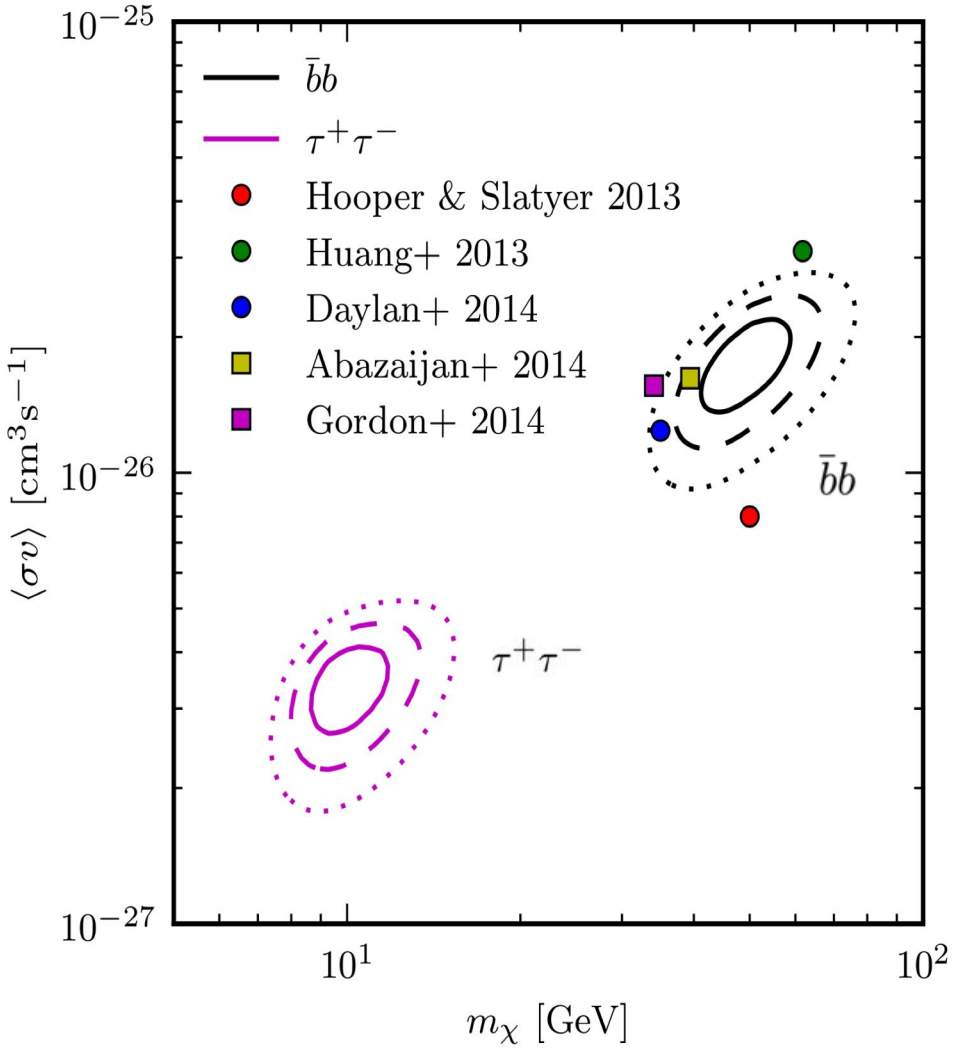
- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV




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

# The GeV excess



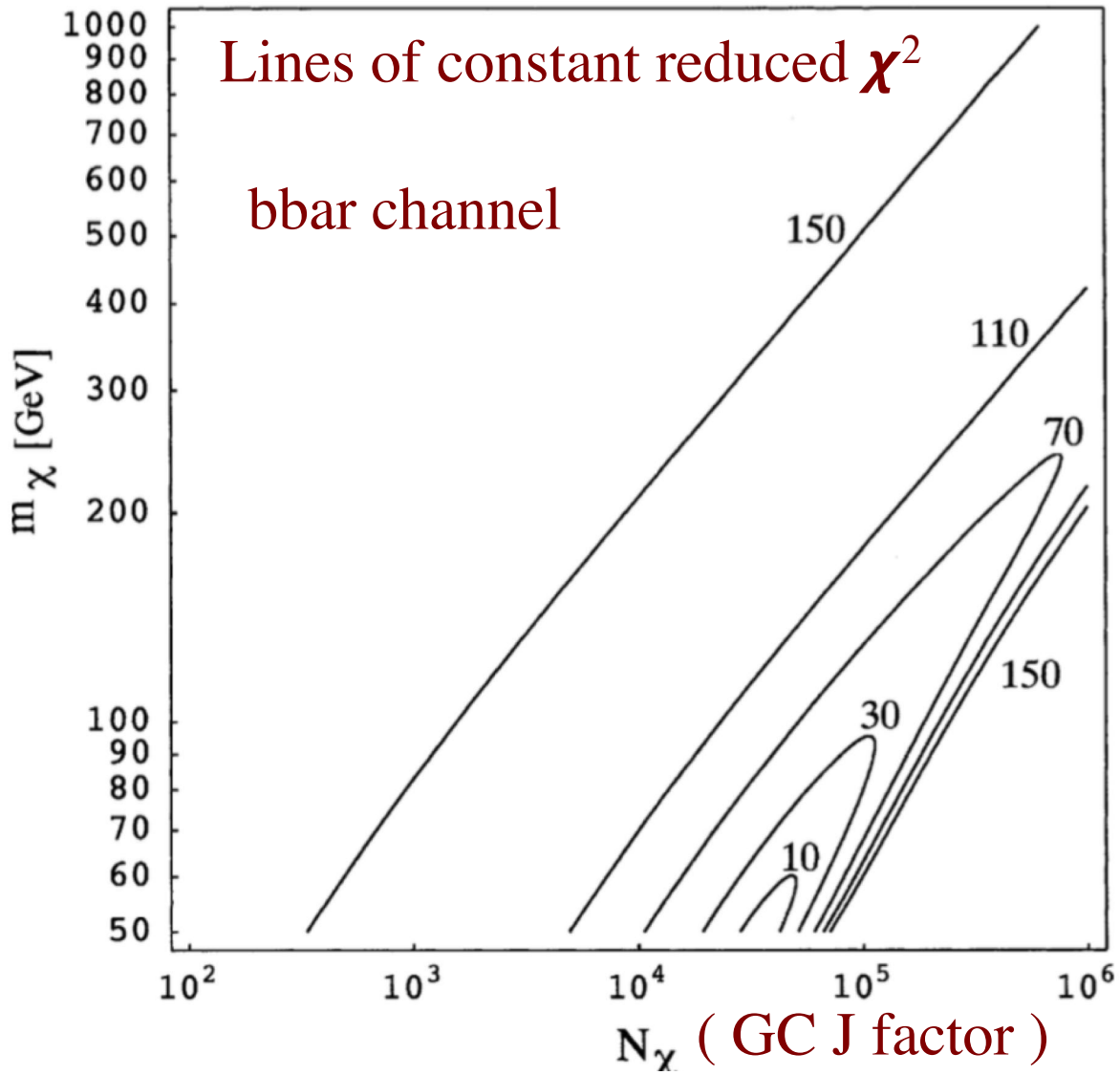

A lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center

Calore et al, arXiv:1409.0042v1

# Lines of constant reduced $\chi^2$ corresponding to best fits of the EGRET GC excess

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

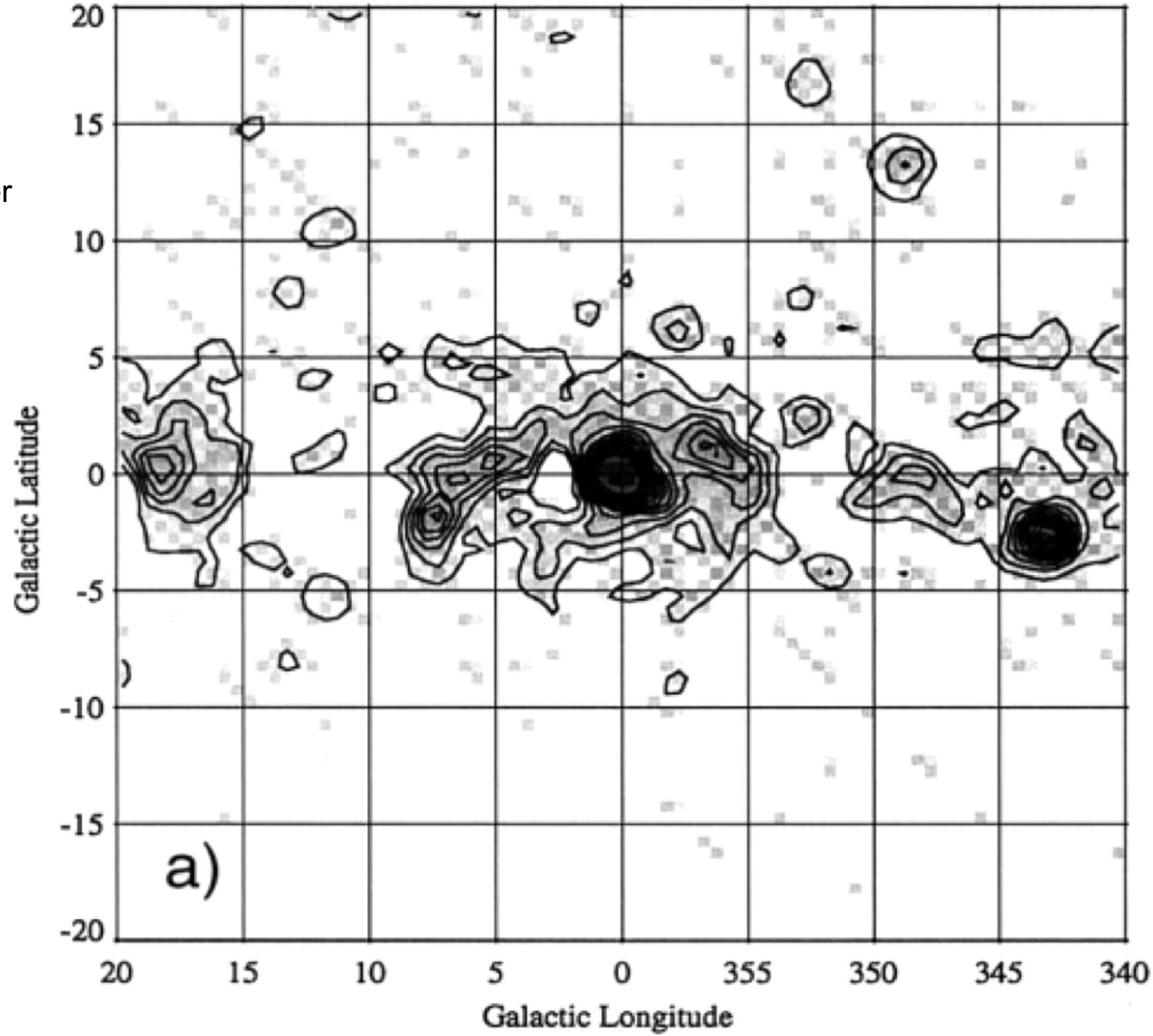
mass ~ 50- 80 GeV



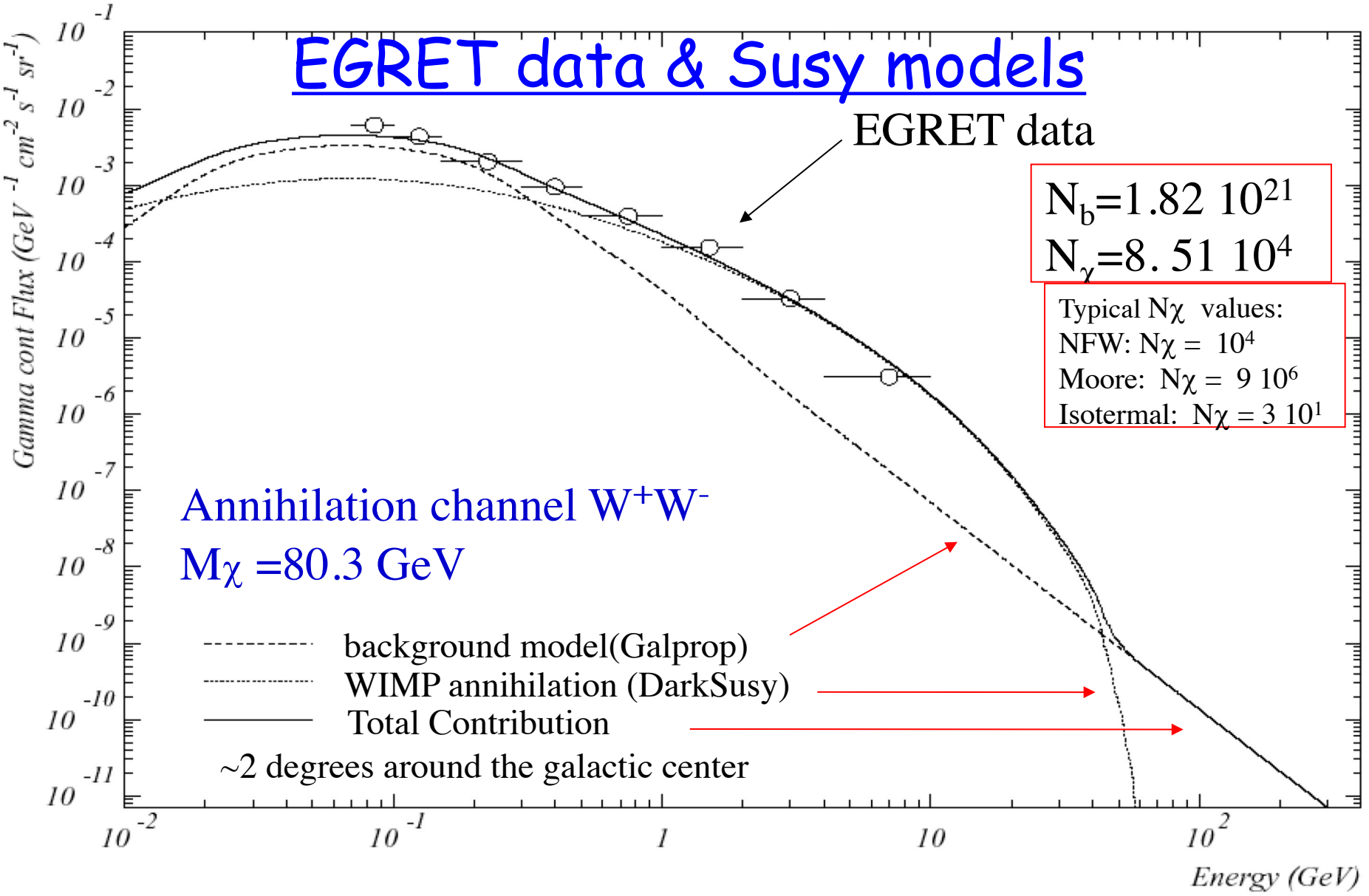

A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

# 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)

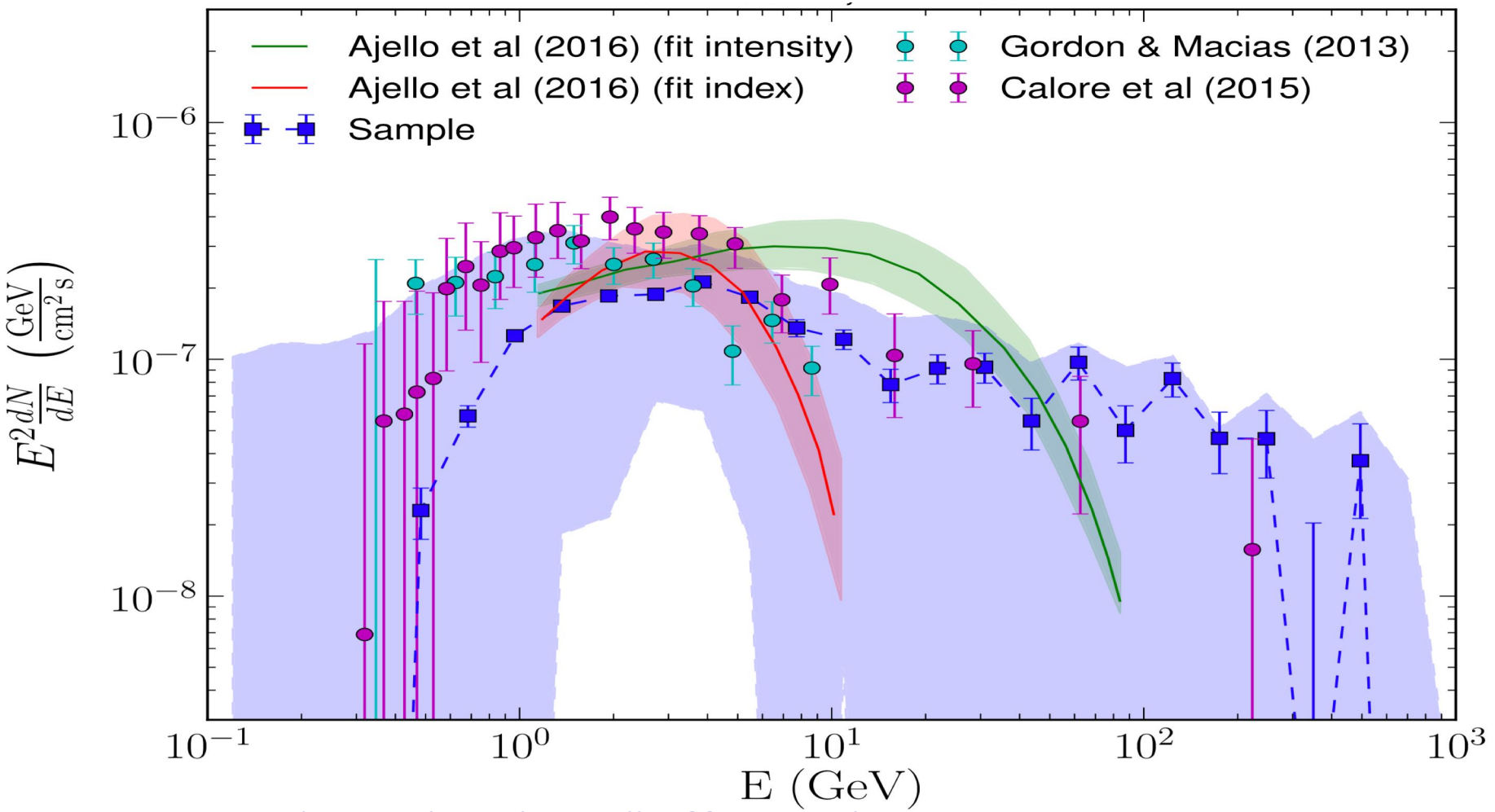
**Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope**
Dan Hooper , Lisa Goodenough . (21 March 2011 ). 21 pp. **Phys.Lett. B697 (2011) 412-428**

.....

**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

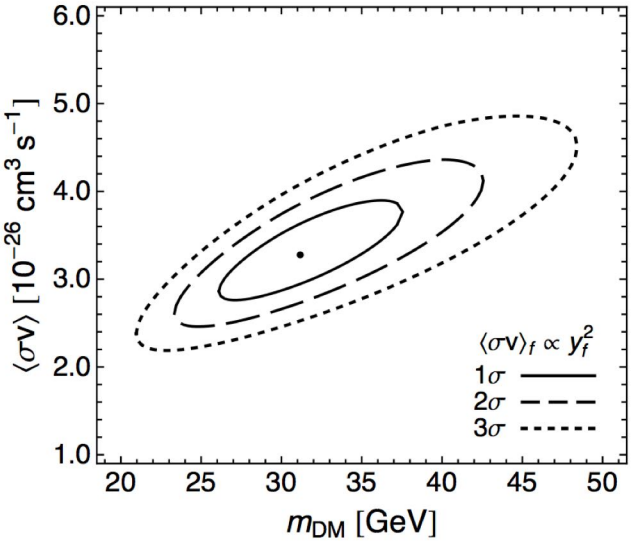
- **Most significant sources of uncertainty are:**

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

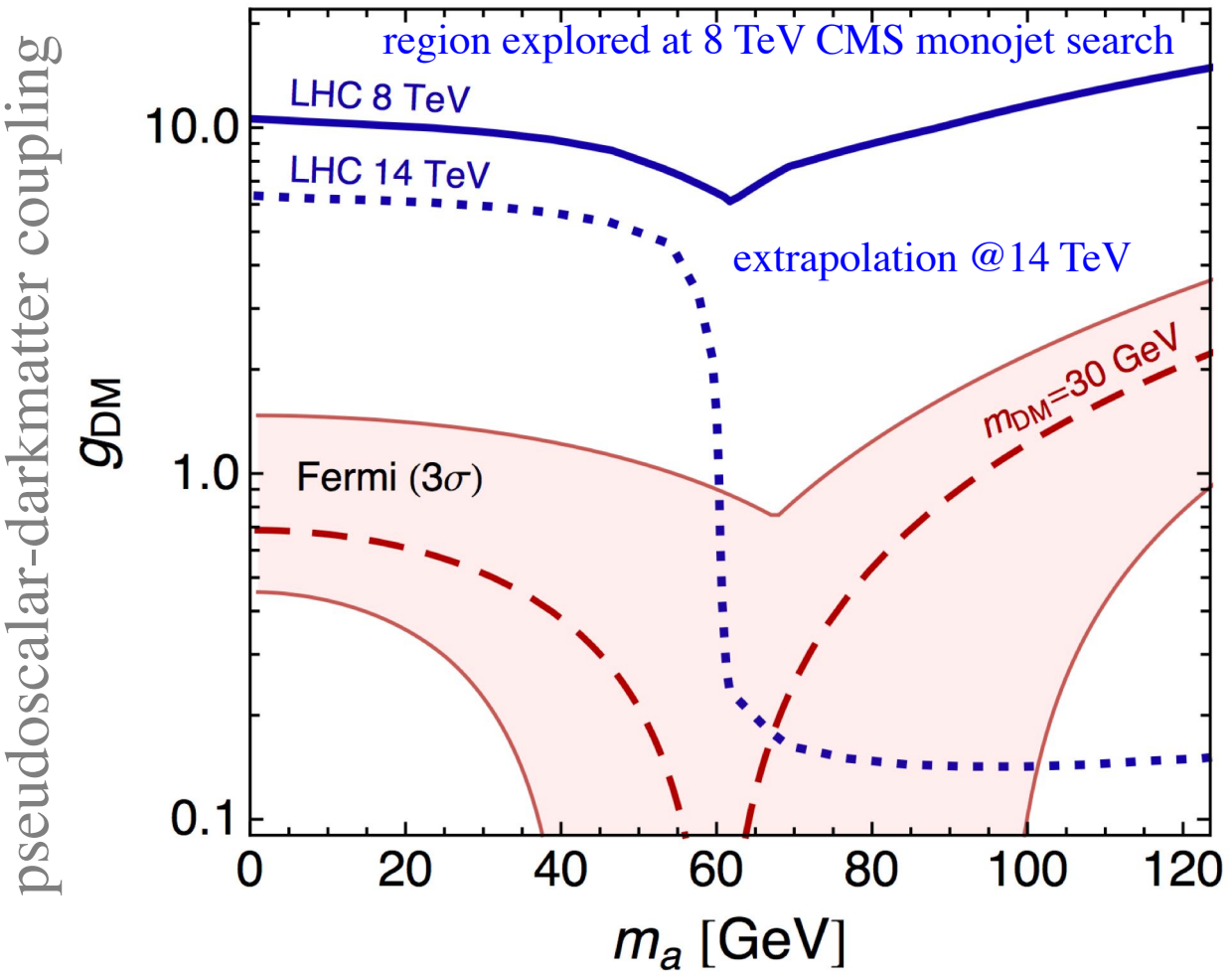
Fermi-LAT Collaboration Apj 840:43 2017 May 1 arXiv:1704.03910

# Galactic Center and Dark Matter

GeV excess fit




note:this plot is valid only for a particular model of coy Dirac dark matter that annihilates primarily into b quarks via a pseudoscalar




*Se non è vero è ben trovato*

*( If it is not true, it is well conceived )*

Bœhm et al. JCAP05(2014)009

arXiv:1401.6458

# 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]

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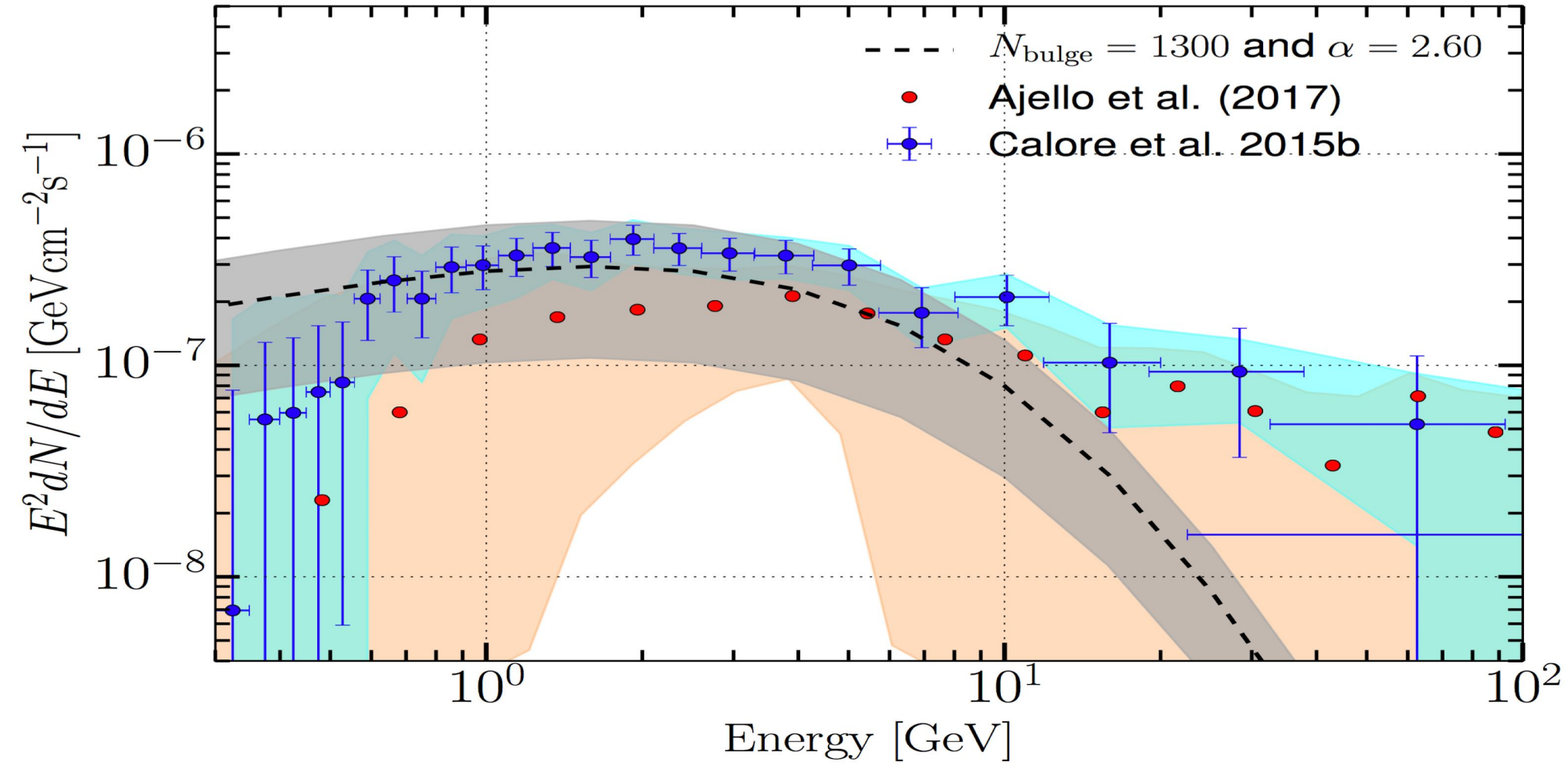
How to discriminate between different hypothesis ?

# Population of pulsars in the Galactic bulge and the GeV excess



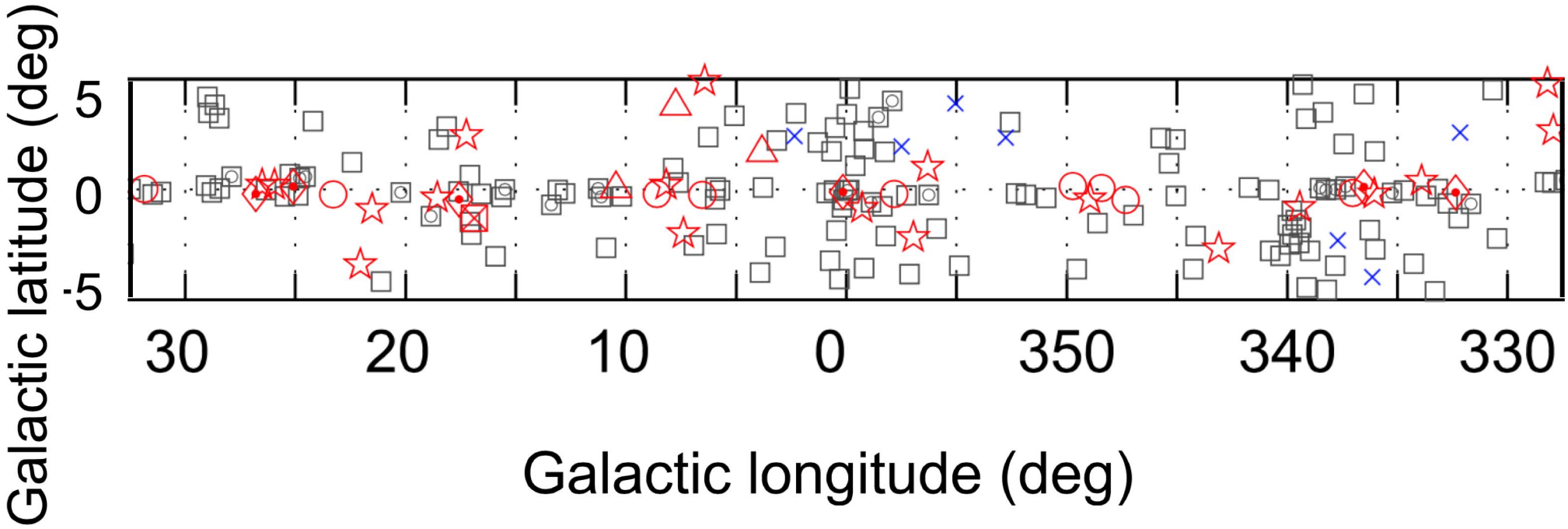

the Galactic bulge must include 800-3600 pulsars ( most of them unresolved) in order to explain the GC excess

M.Ajello et al. [Fermi-LAT Coll.] Apj sub. [arXiv:1705.00009]

# The Fermi LAT 3FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

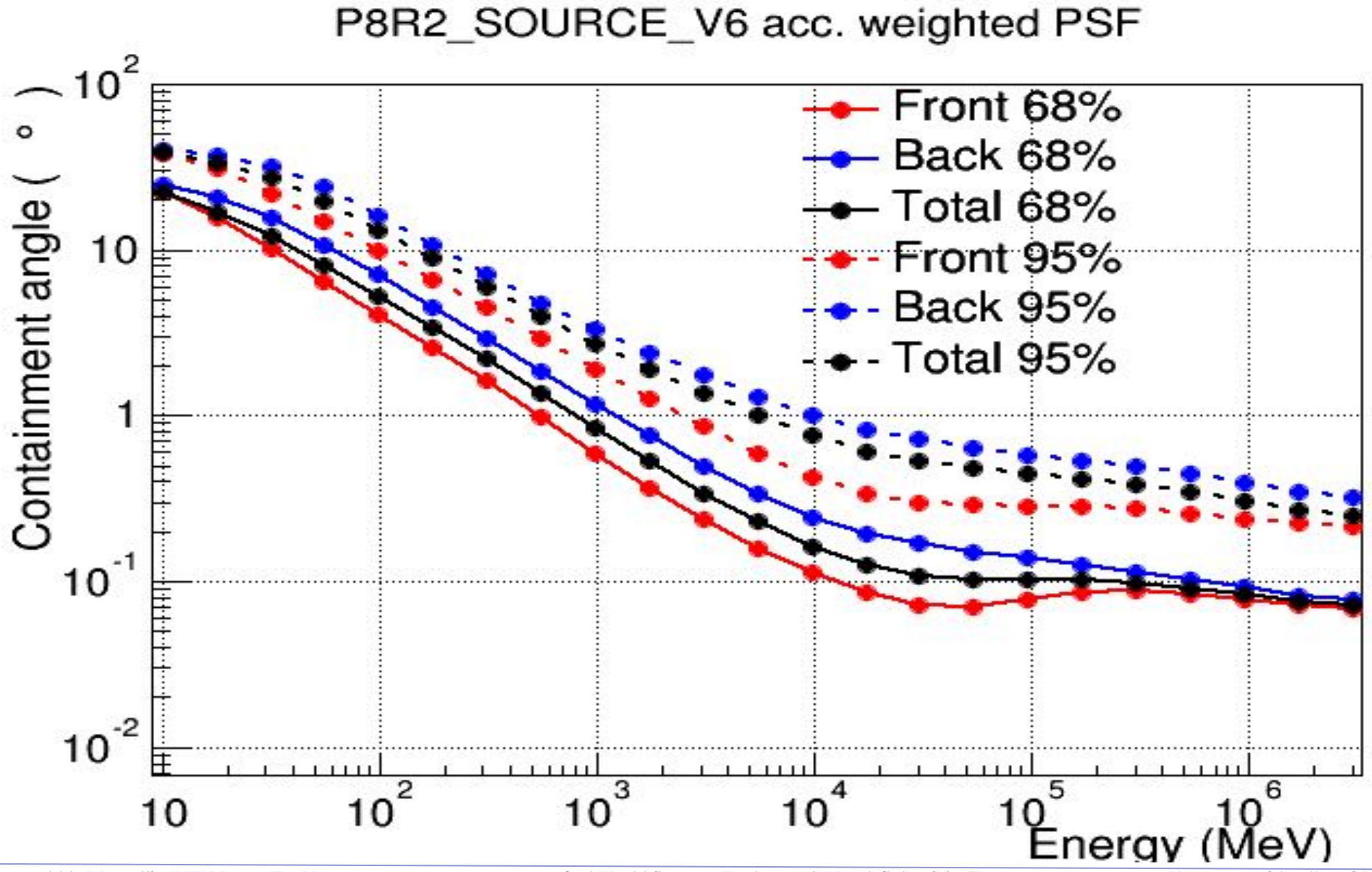
100 MeV to 300 GeV energy range




| | | |
|---|---|---|
| No association | Possible association with SNR or PWN | AGN |
| Pulsar | Globular cluster | Starburst Galaxy | PWN |
| Binary | Galaxy | SNR | Nova |
| Star–forming region | | |

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

**H.E.S.S., 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**

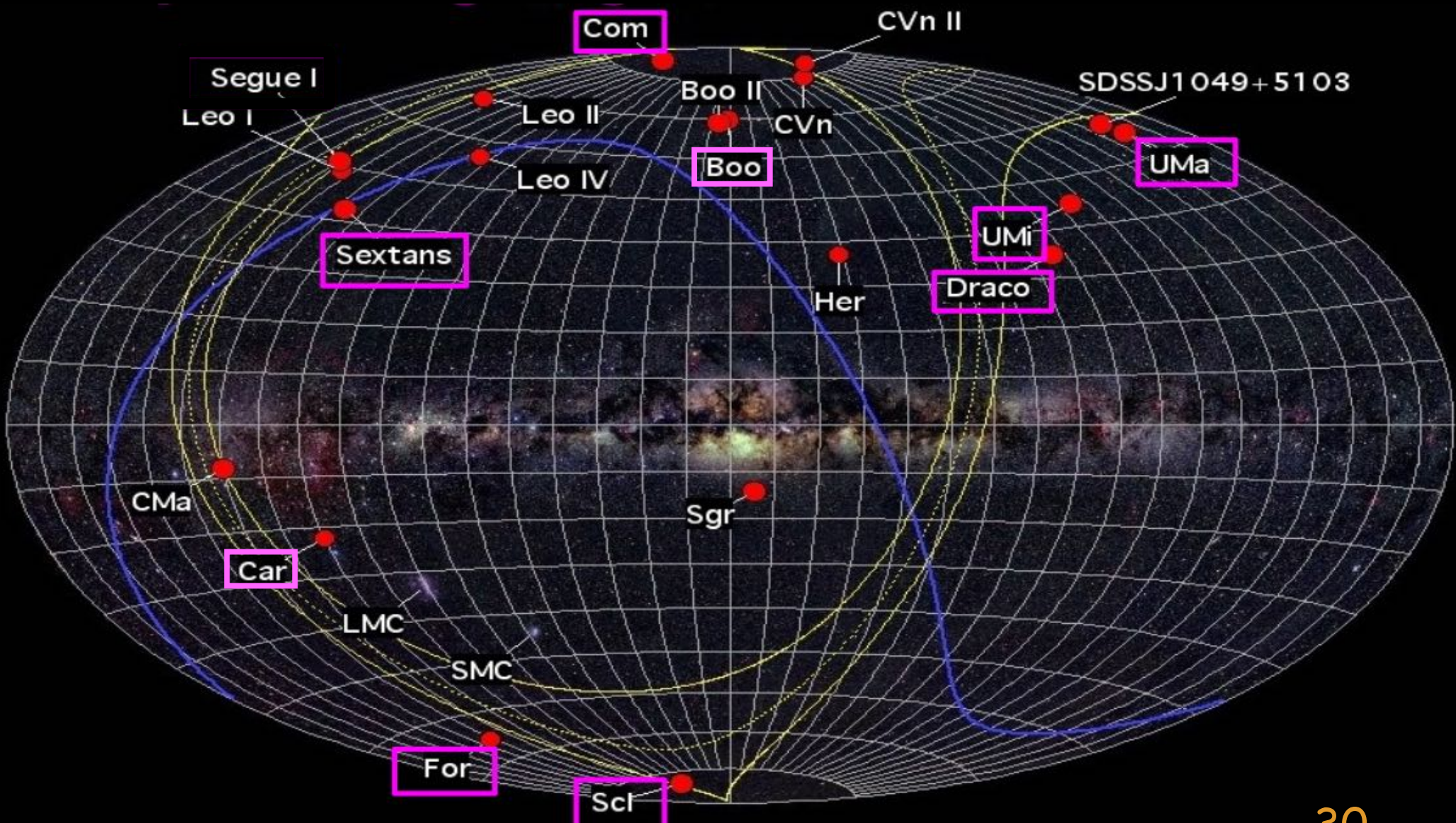
- Look for correlated synchrotron emission near the GC

**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**

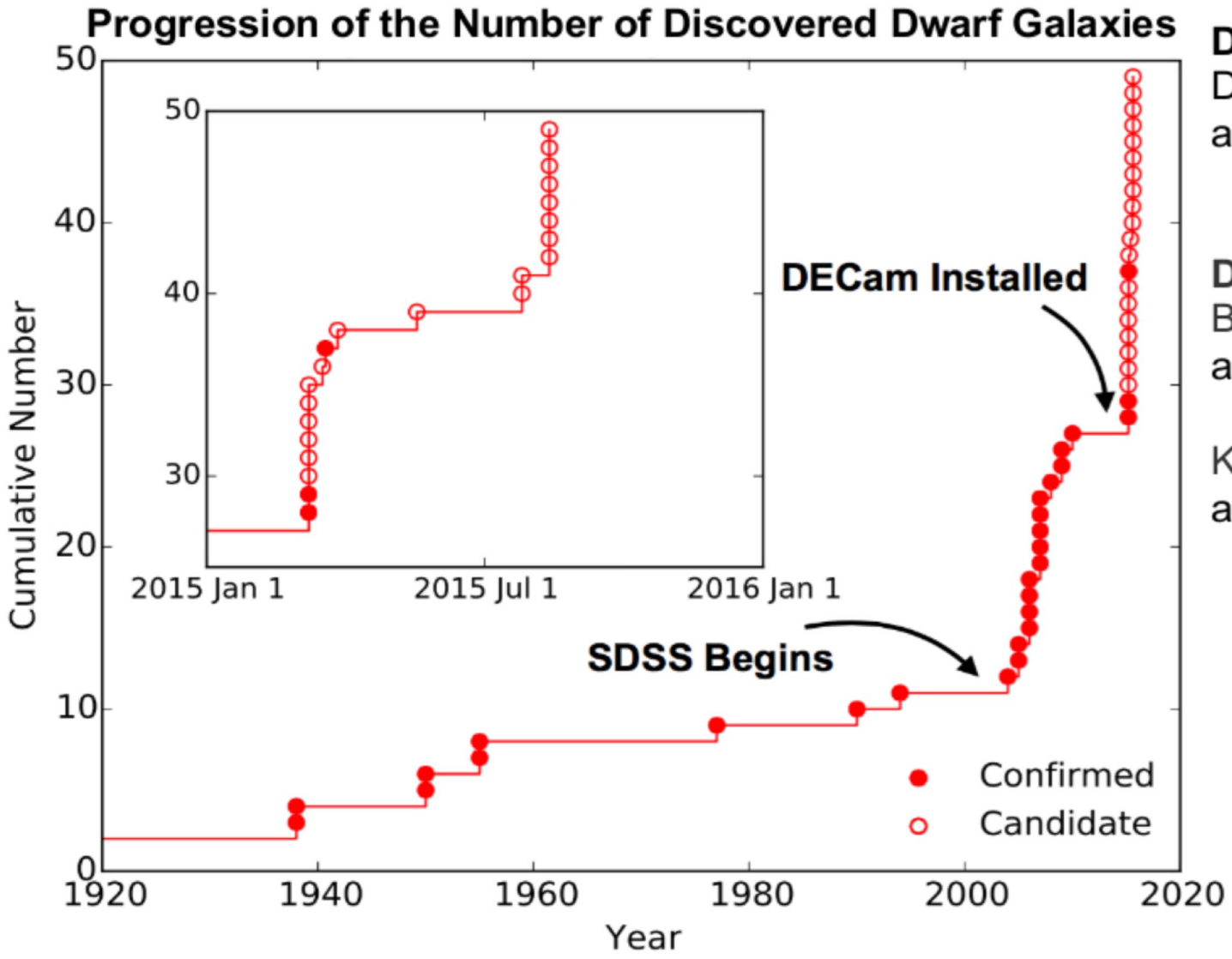
# Classical Dwarf spheroidal galaxies: promising targets for DM detection



# Dark Matter in the Milky Way (from simulations)


Springel et al. (Nature, 2005

# Dwarf Spheroidal Galaxies: Growing number of known targets

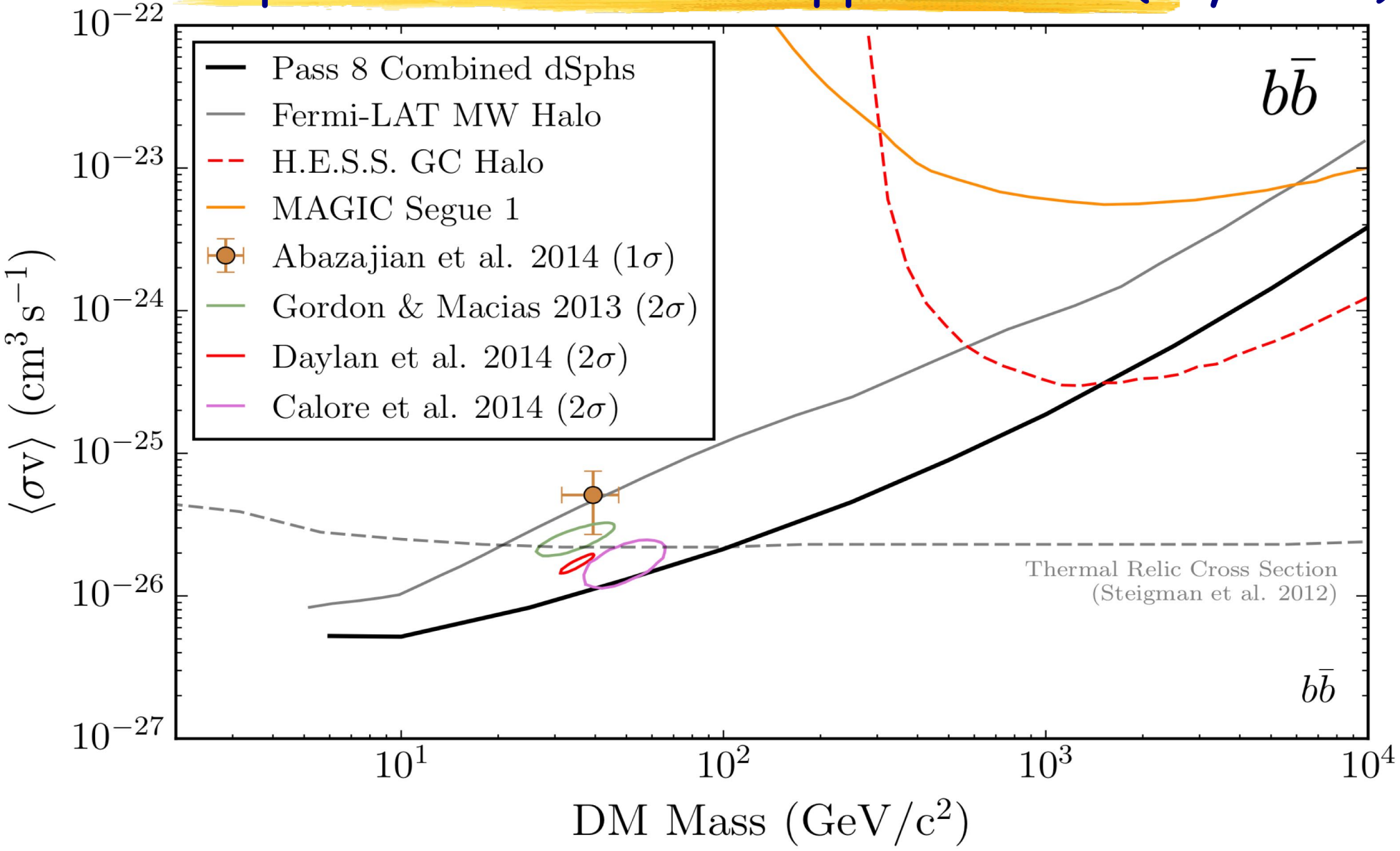



**DES Year 2 Data**:
Drlica-Wagner+,
arXiv:1508.03622

**DES Year 1 Data**:
Bechtol+:
arXiv:1503.02584

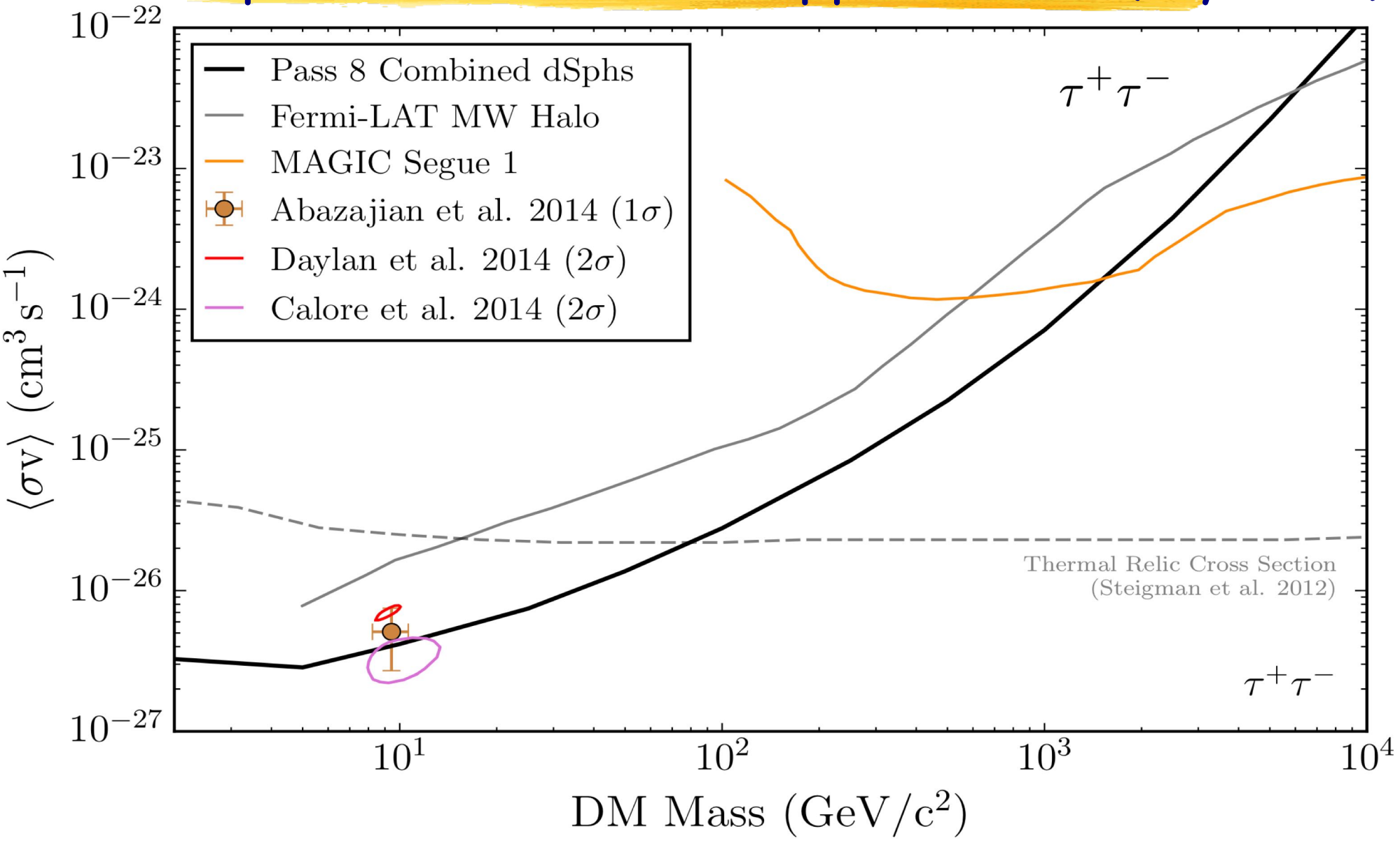
Koposov+:
arXiv:1503.02079

# Dwarf Spheroidal Galaxies upper-limits (6 years )




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

# Dwarf Spheroidal Galaxies upper-limits (6 years )



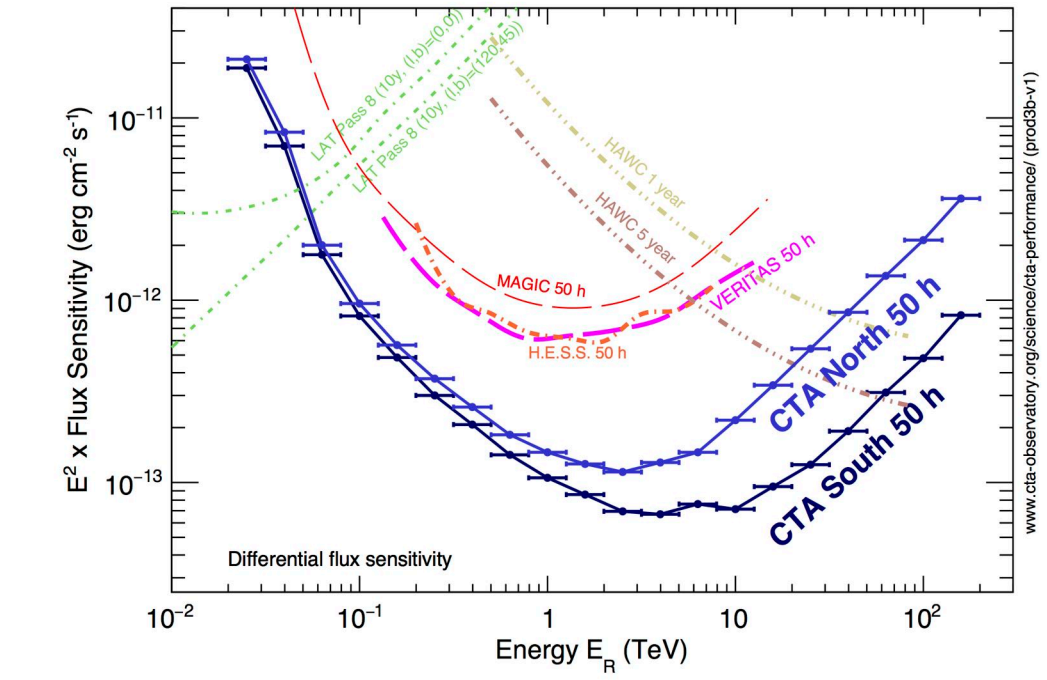

M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

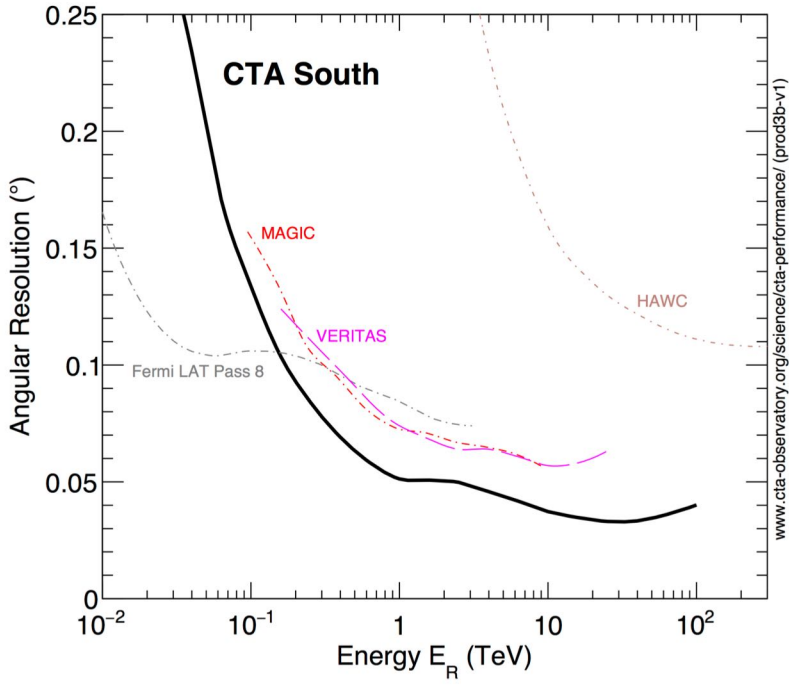

CTA
See talk by Germán Gómez-Vargas

# CTA PERFORMANCE

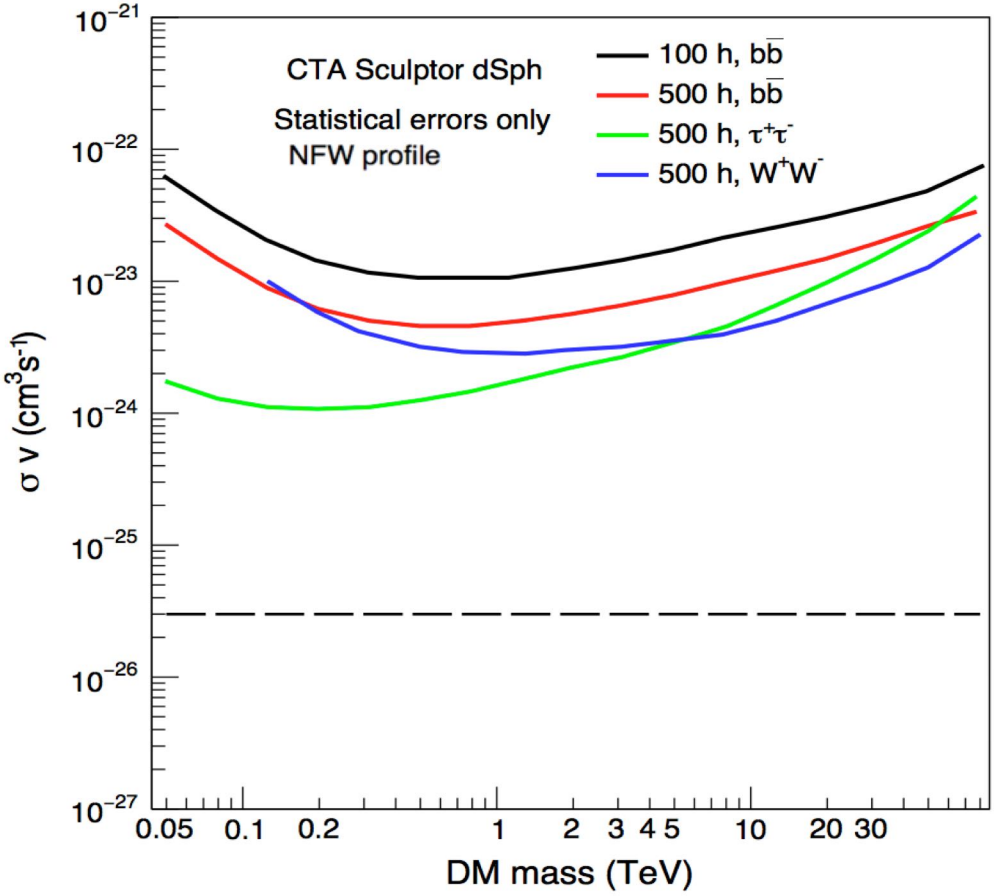
Southern Site:
- 4 Large-sized (23m) telescopes
- 25 Medium-sized (10-12m )telescopes
- 70 Small-sized (~4m ) telescopes

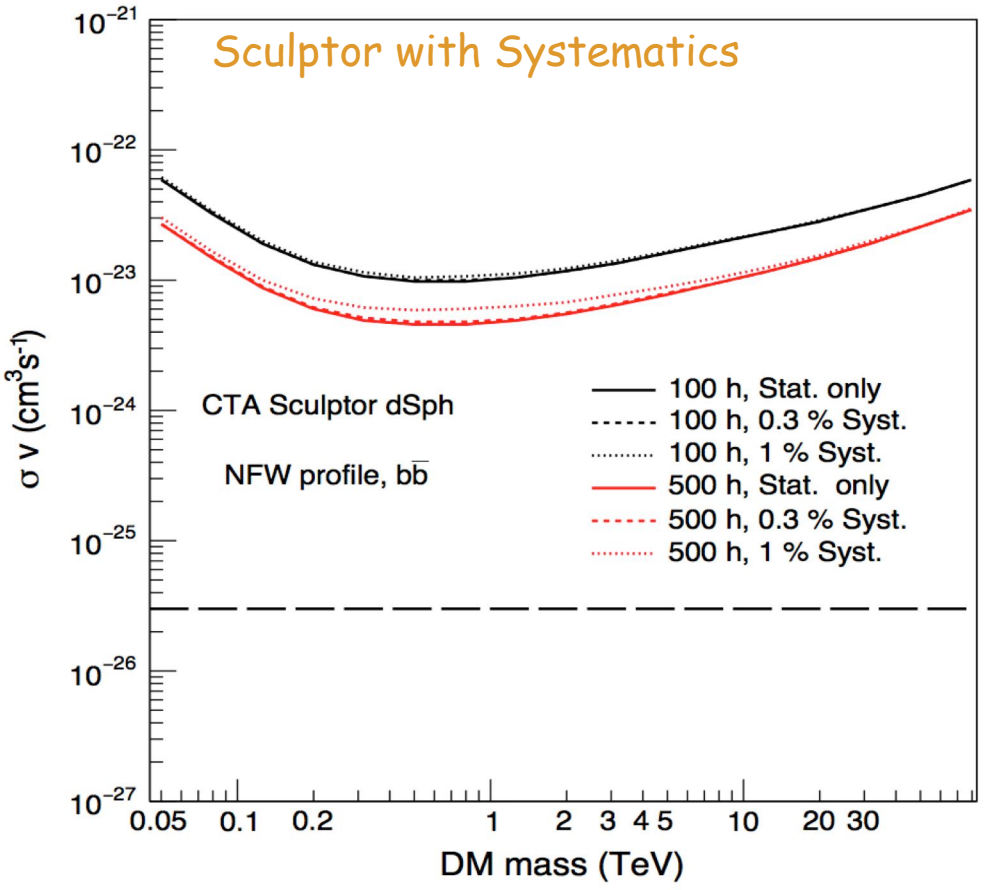
Northern Site:
- 4 Large-sized (23m) telescopes
- 15 Medium-sized (10-12m ) telescopes



# Dwarf Spheroidal Galaxies: CTA Sensitivity

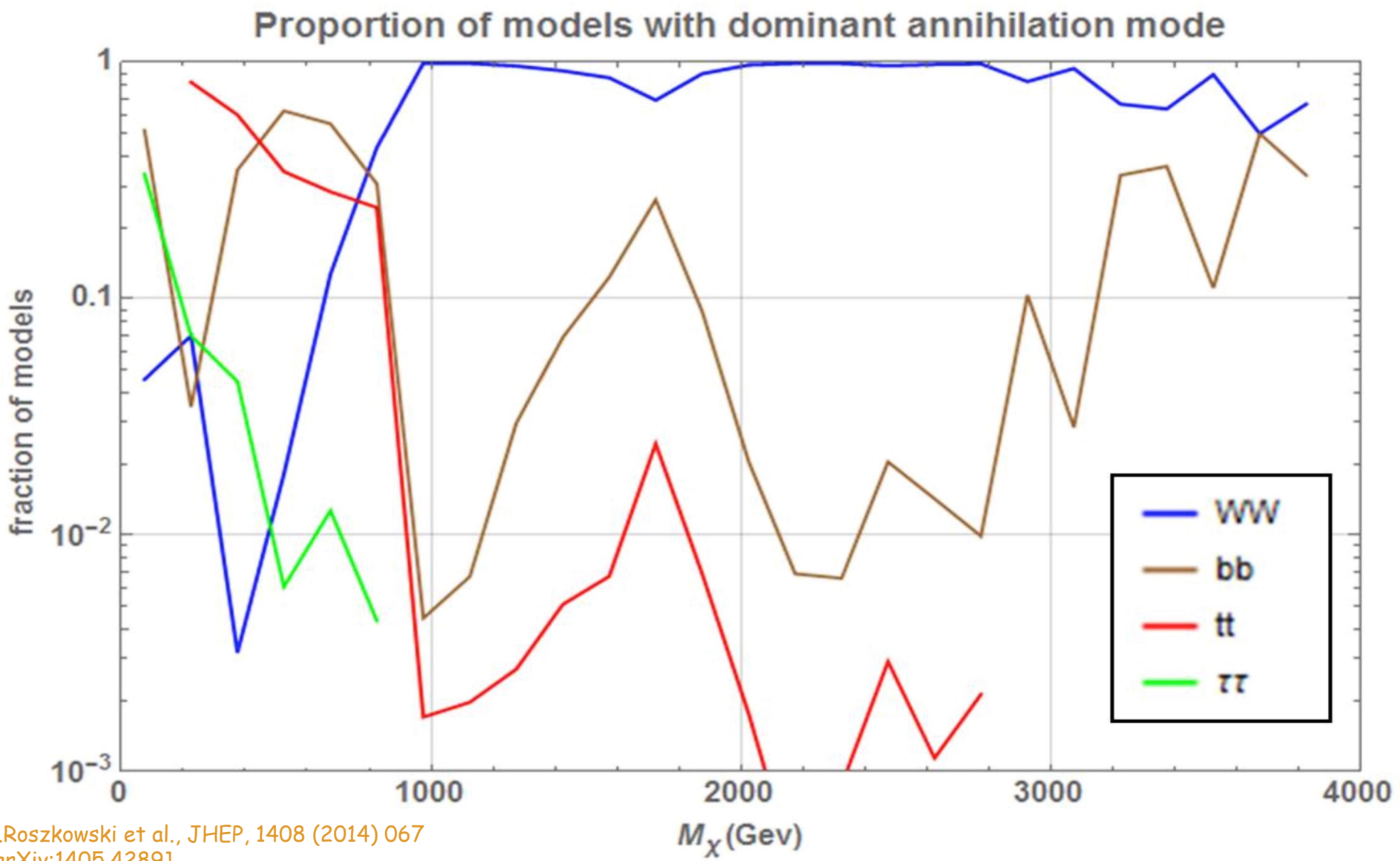



There are several of the newly discovered dSph that have a better case for being a promising target,

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

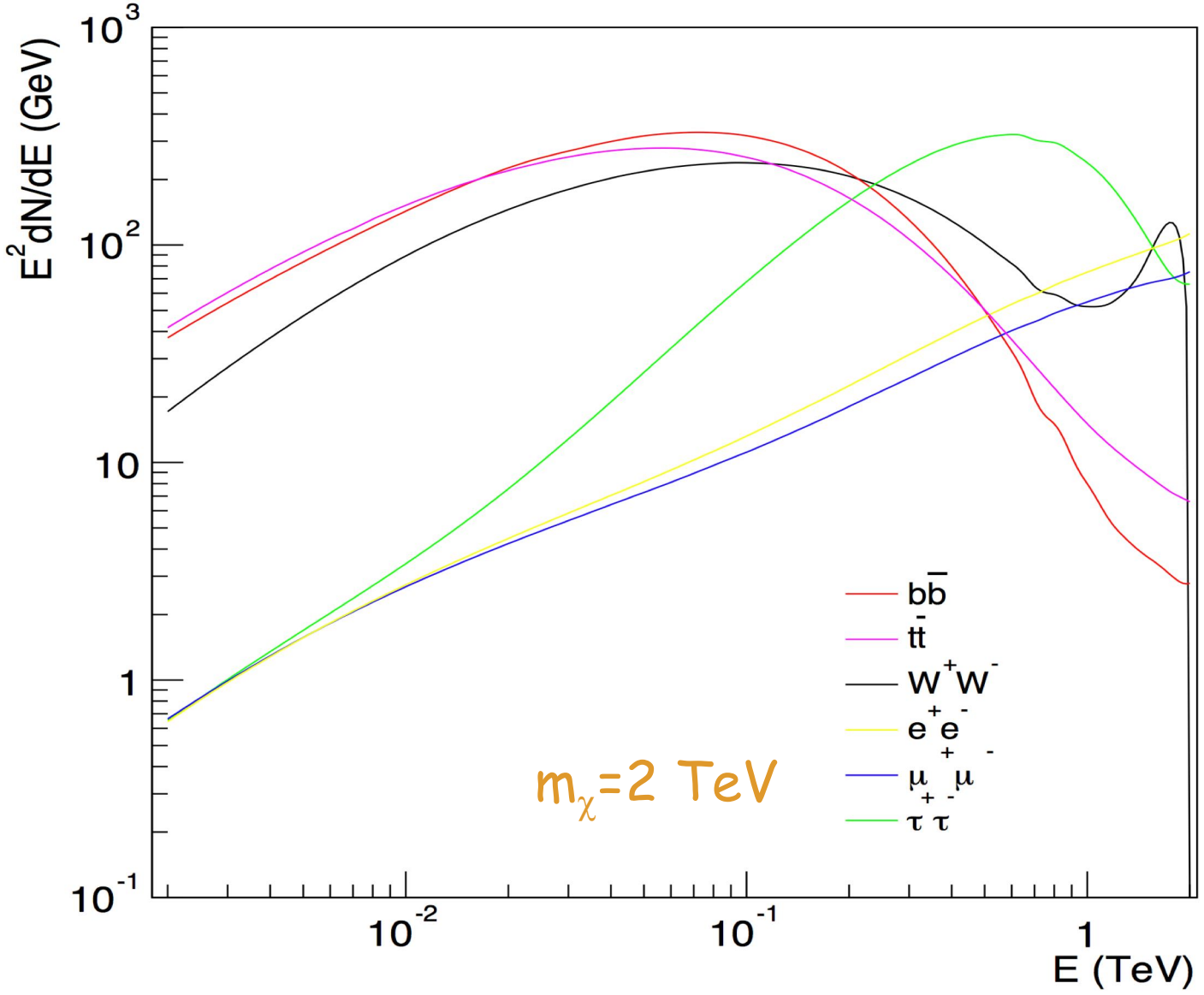
# Which channel to choose?
# Example: The dominant annihilation modes in the pMSSM scan



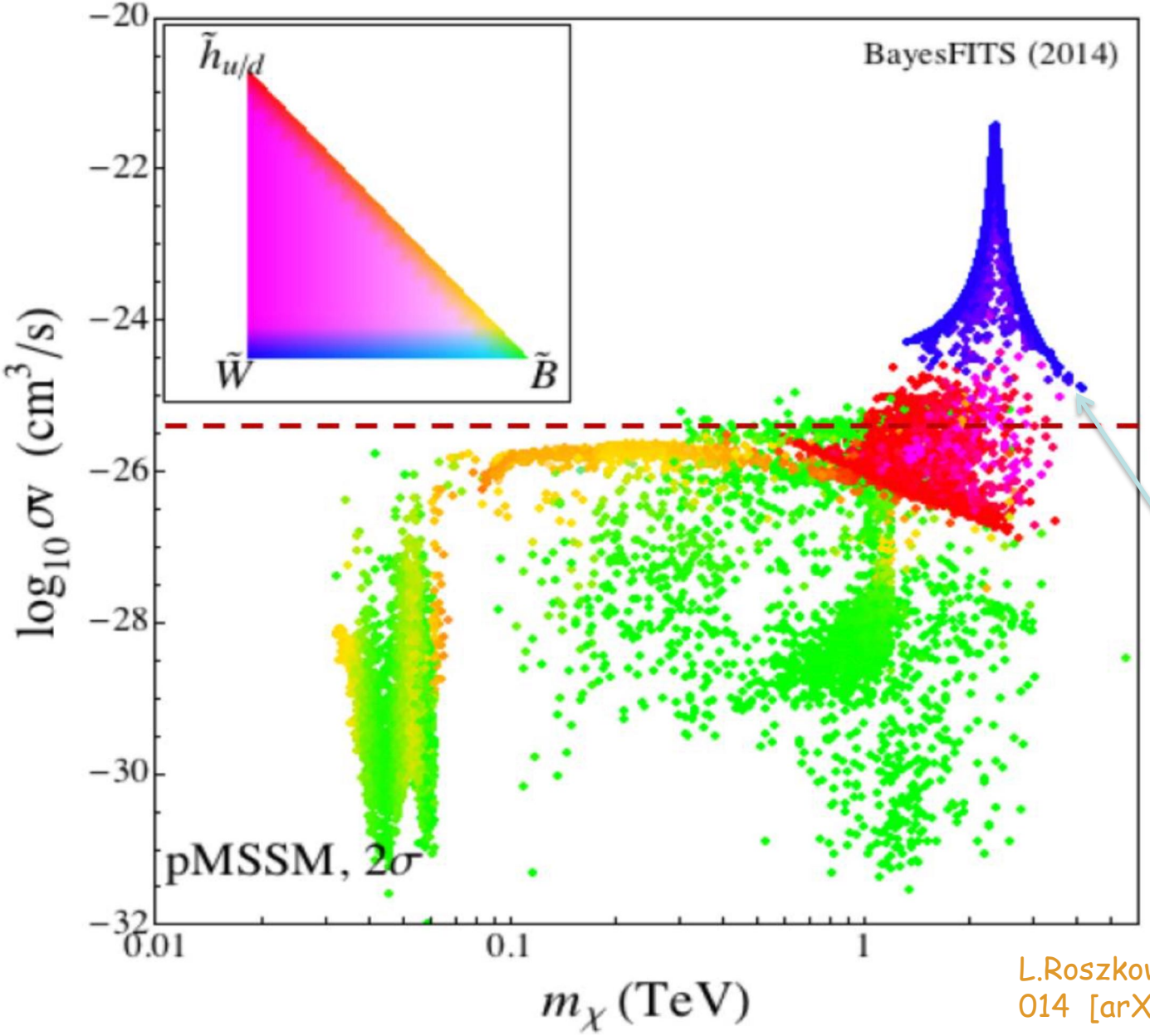

L.Roszkowski et al., JHEP, 1408 (2014) 067 [arXiv:1405.4289]

# 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

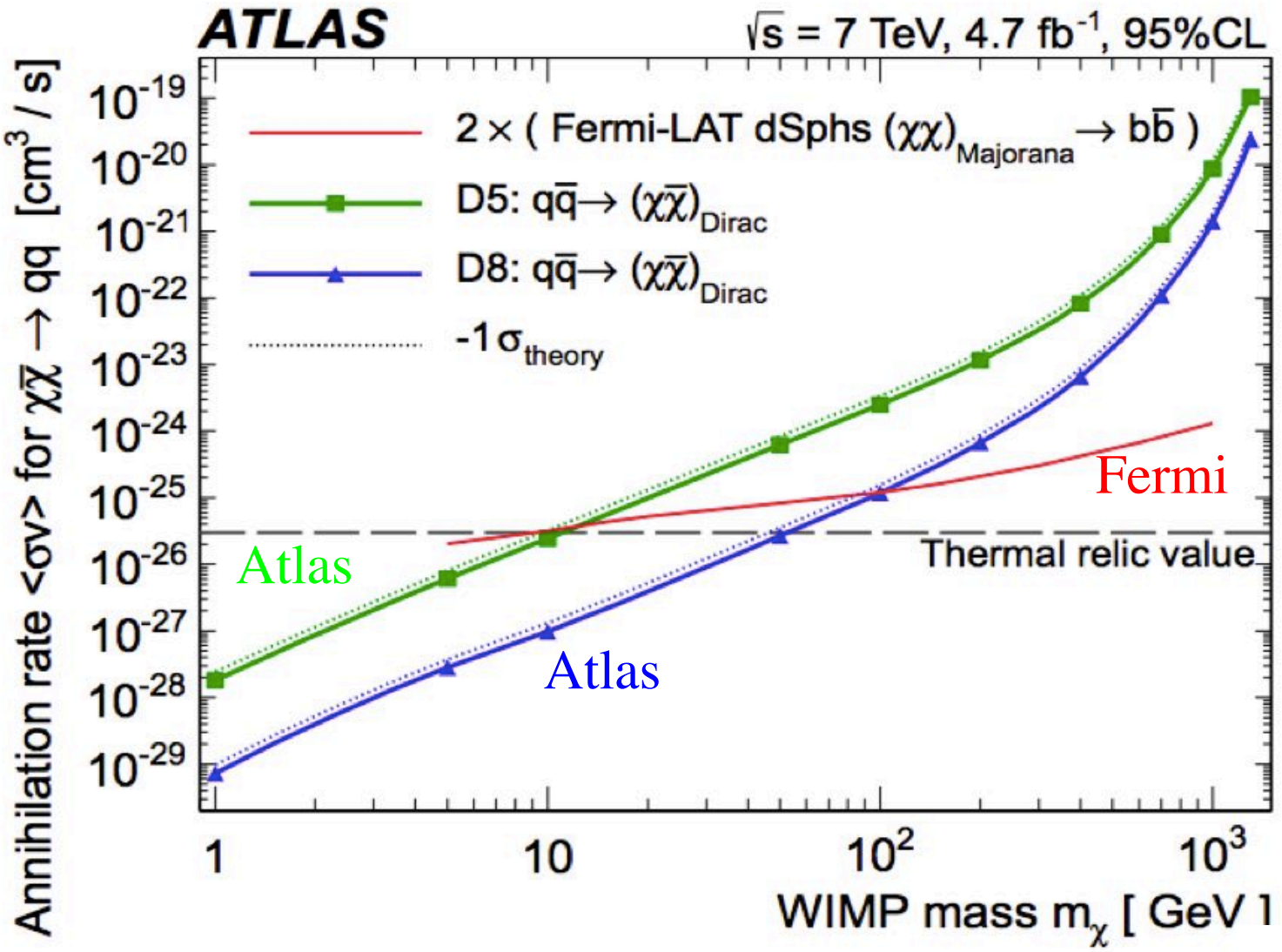



Example: Annihilation cross-section points from a 19 dimensional pMSSM fit

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]

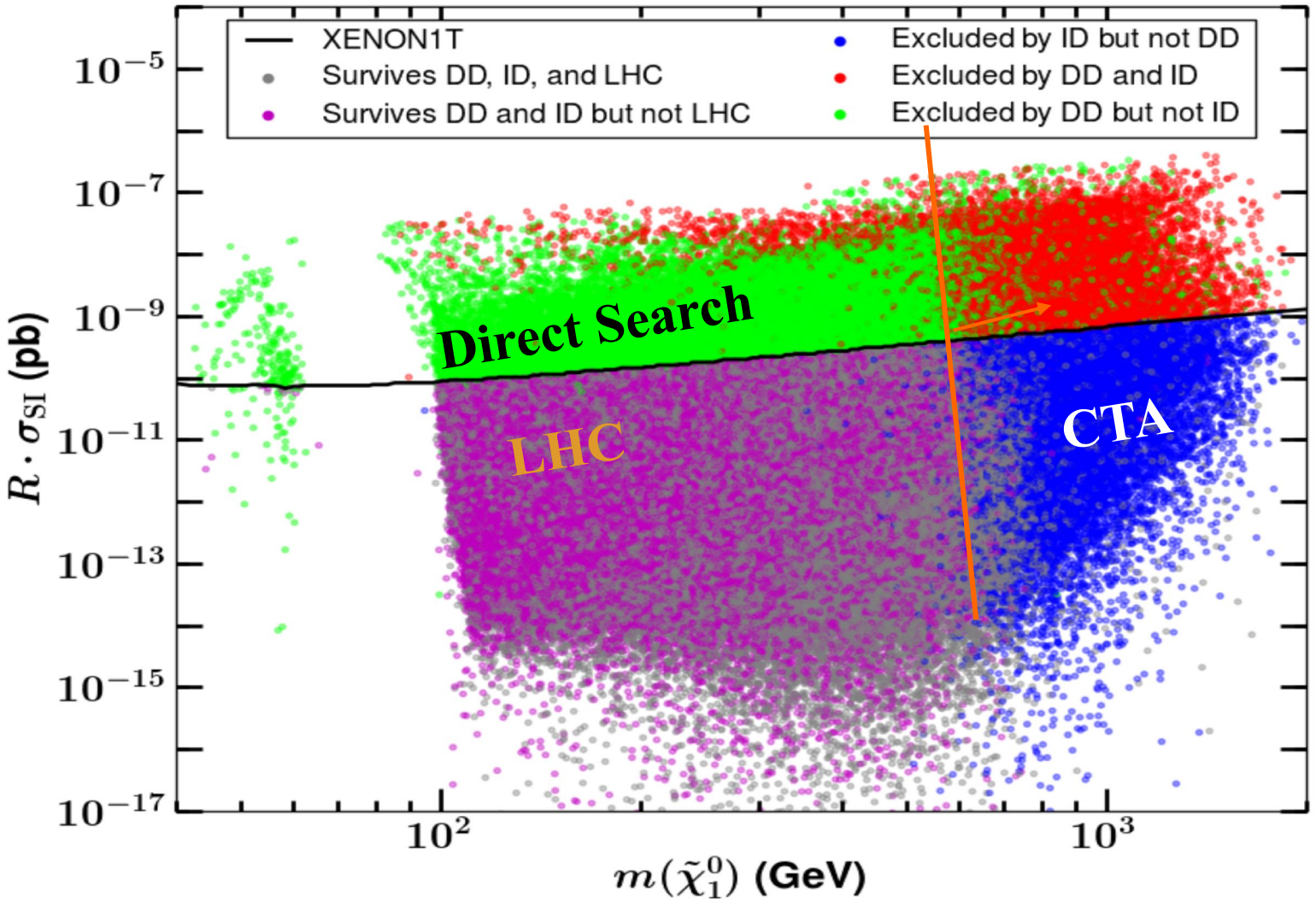
# ATLAS-Fermi Results




note: ATLAS limits are for the four light quark flavours assuming equal coupling strengths for all quark flavours to the WIMPs

Atlas Coll. JHEP 1304 (2013) 075 arXiv:1210.4491

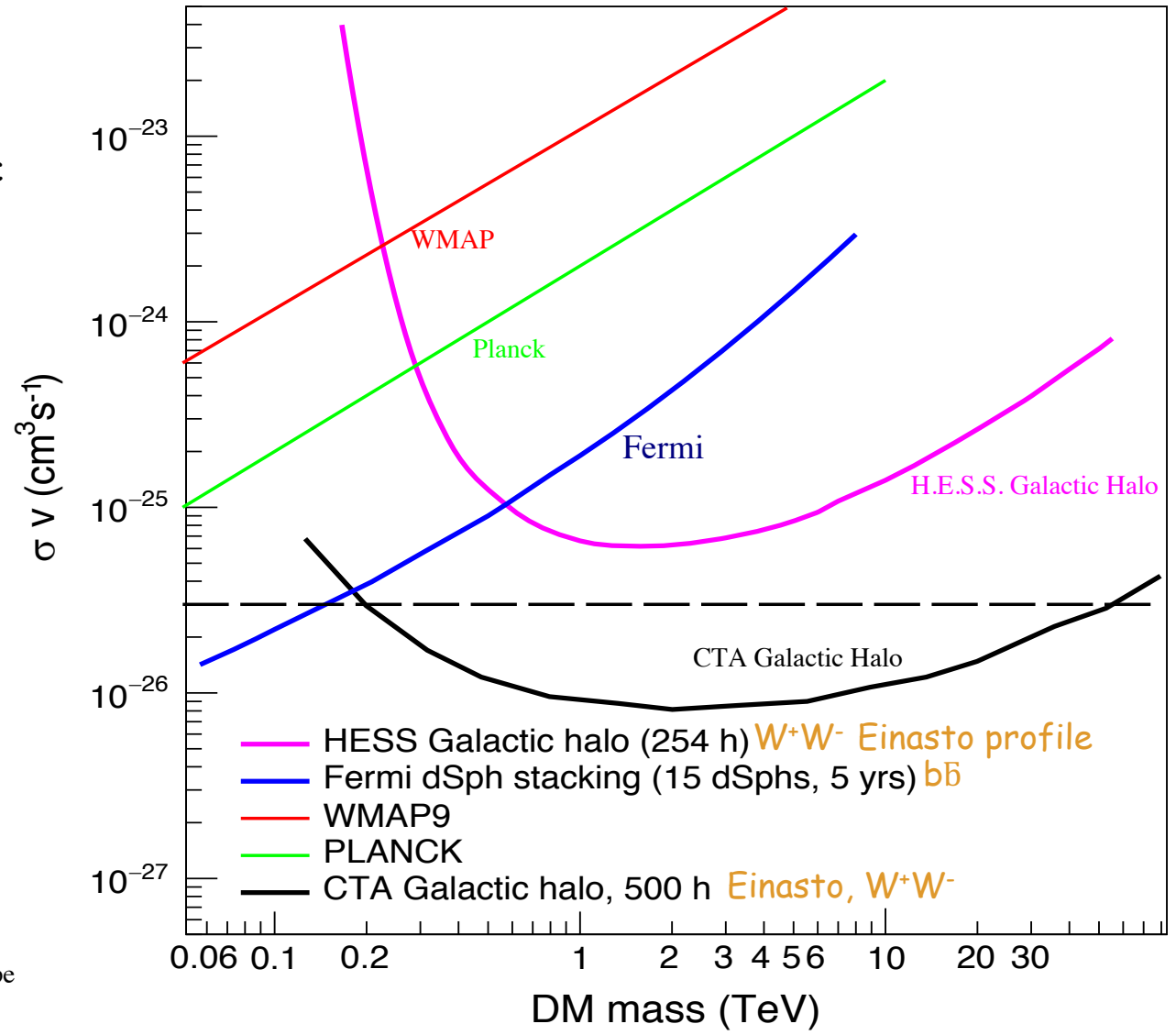
# Complementarity and Searches for Dark Matter in the pMSSM




Cahill-Rowley et al. arXiv:1305.6921

# CTA, H.E.S.S., FERMI, PLANK DM upper-limits

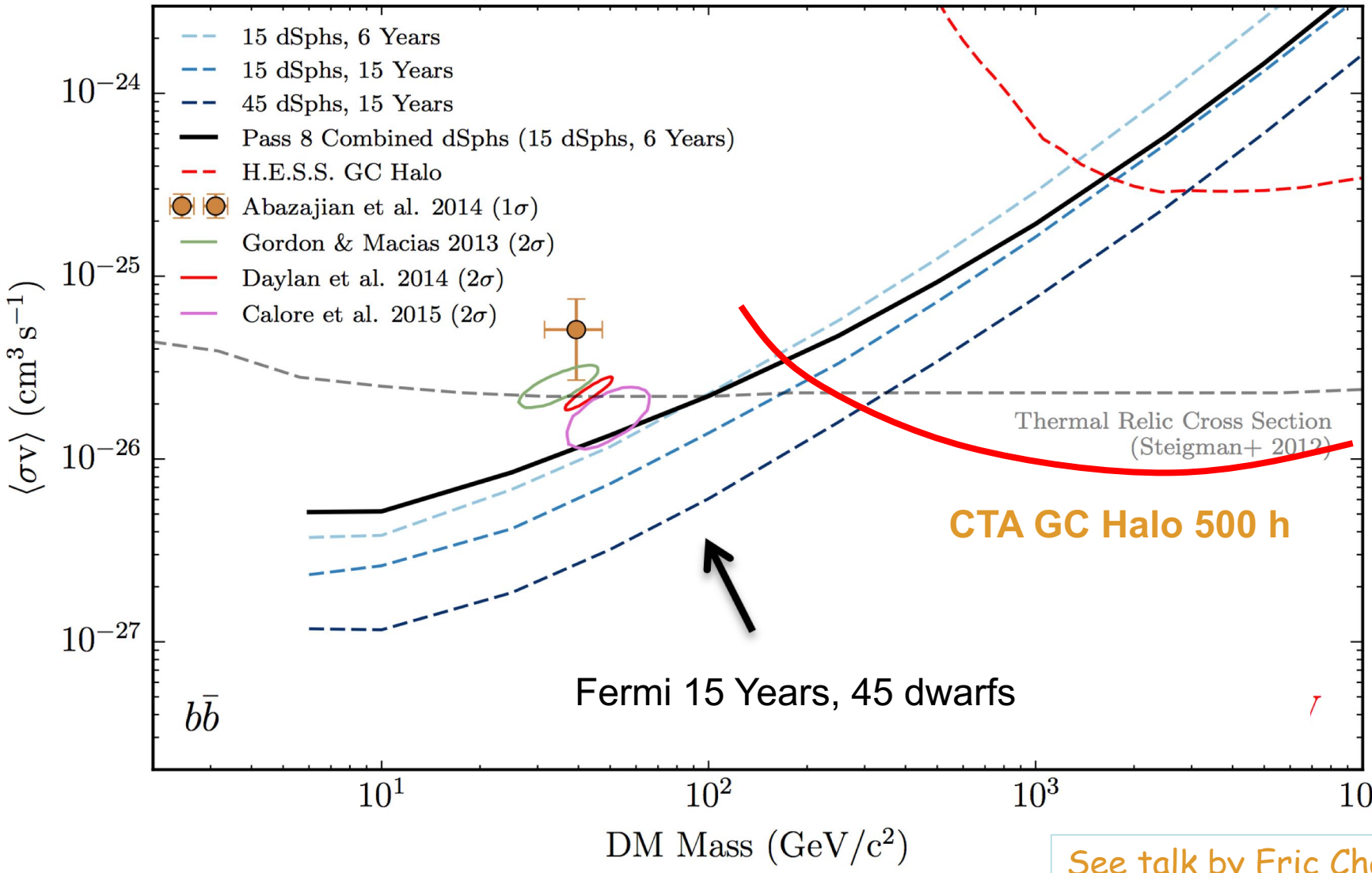
- Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section.
- The expectation for CTA for the Galactic Halo is for the Einasto profile and is optimistic as includes only statistical errors.
- The effect of the Galactic diffuse emission can affect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





A.Morselli, CTA Cons, PoS(ICRC2017)921 [arXiv:1709.01483]
CTA Cons, Science with the Cherenkov Telescope Array, arXiv:1709.07997

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




See talk by Eric Charles

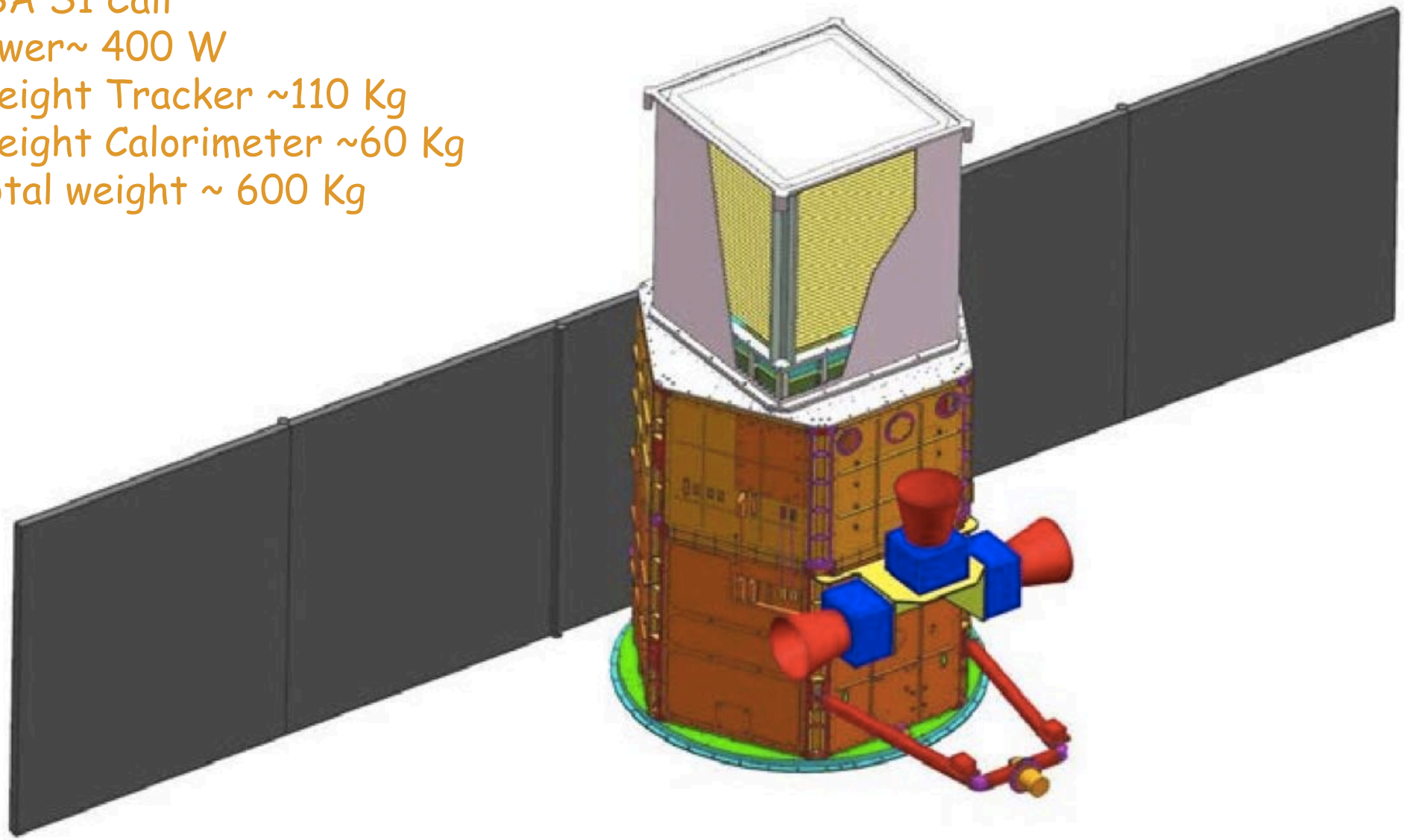
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

# The Low Energy Frontier

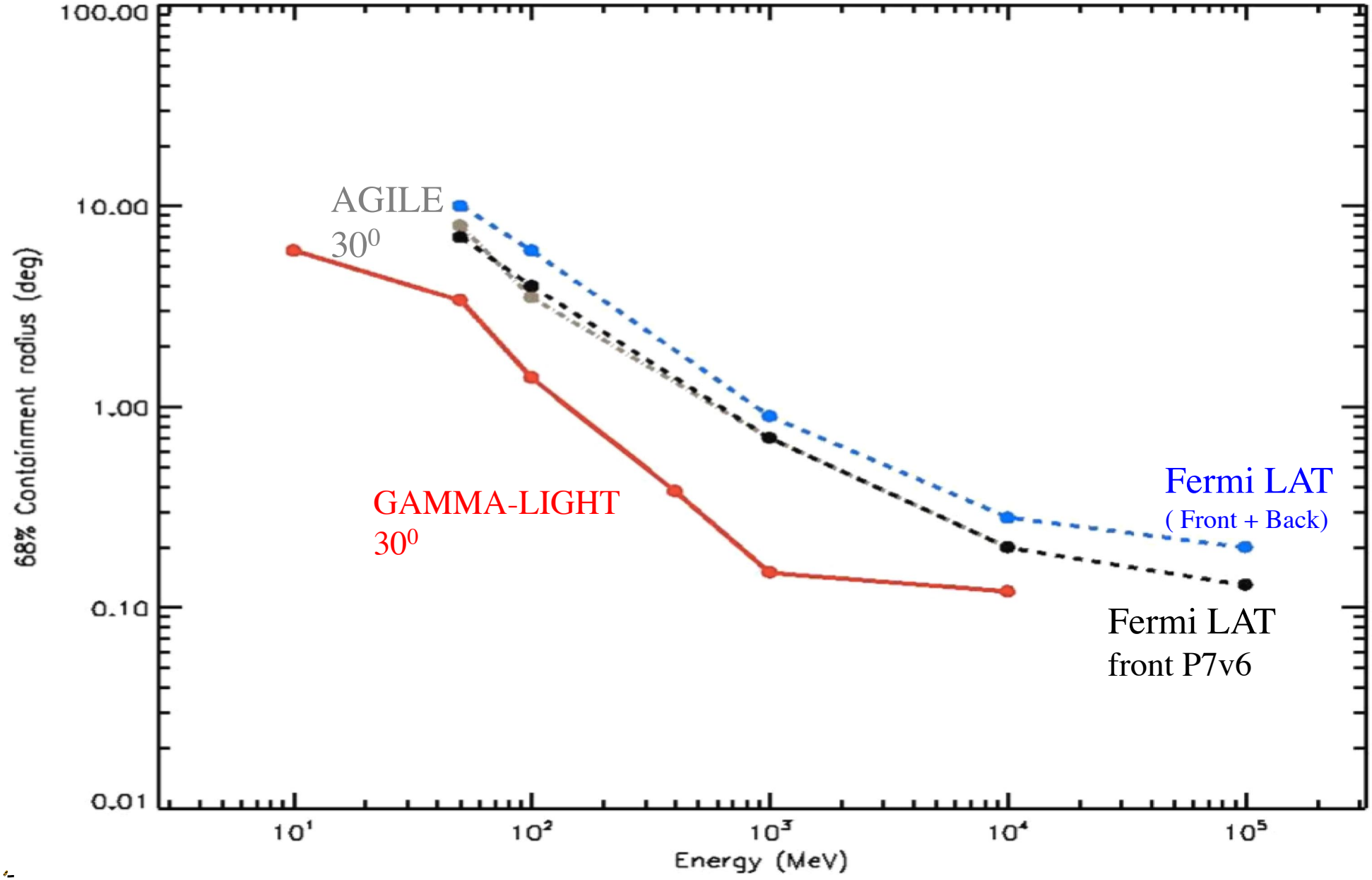
- 1-100 MeV unexplored domain for
  - Dark Matter searches
  - Galactic compact stars and nucleosynthesis
  - Cosmic rays
  - Relativistic jets, microquasars
  - Blazars
  - Gamma-Ray Bursts
  - Solar physics
- and…
  - Terrestrial Gamma-Ray Flashes

# Gamma-light project

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

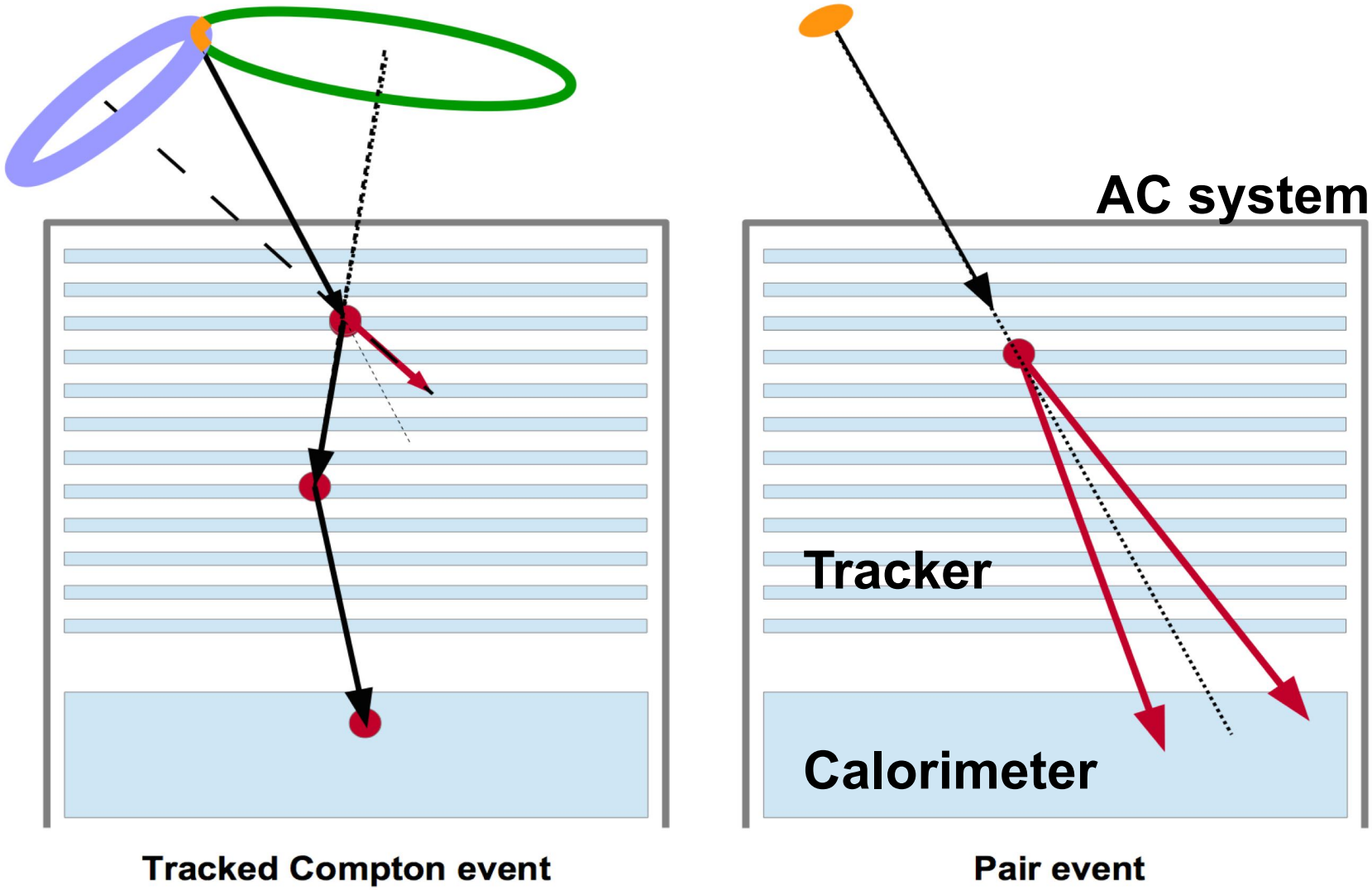


# Gamma-Light Point Spread Function (angular resolution)



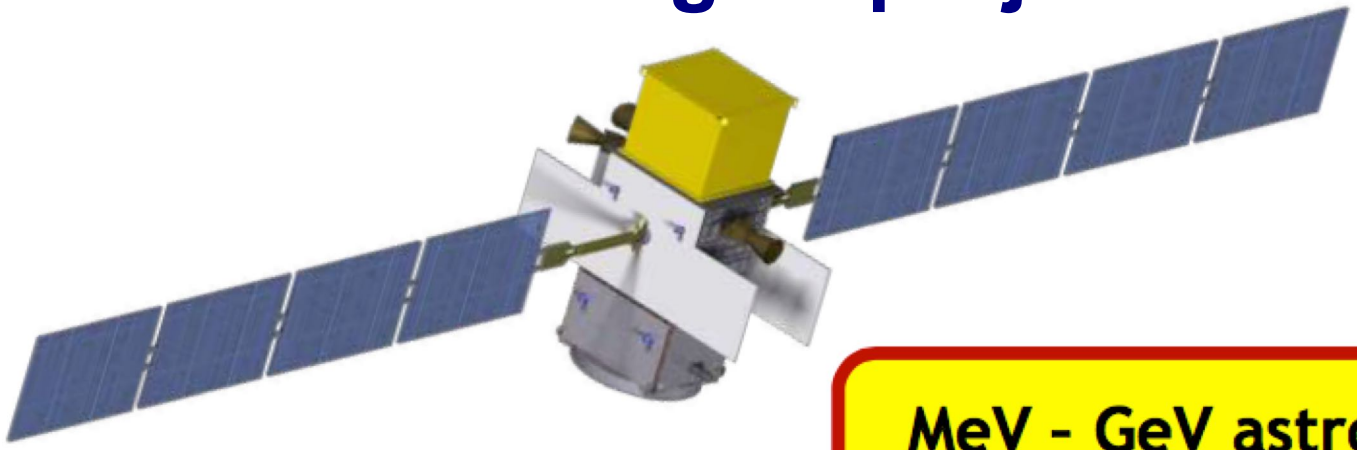

A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198 [arXiv:1406.1071]

# An instrument that combine two detection techniques



# The next gamma-ray MeV-GeV mission:

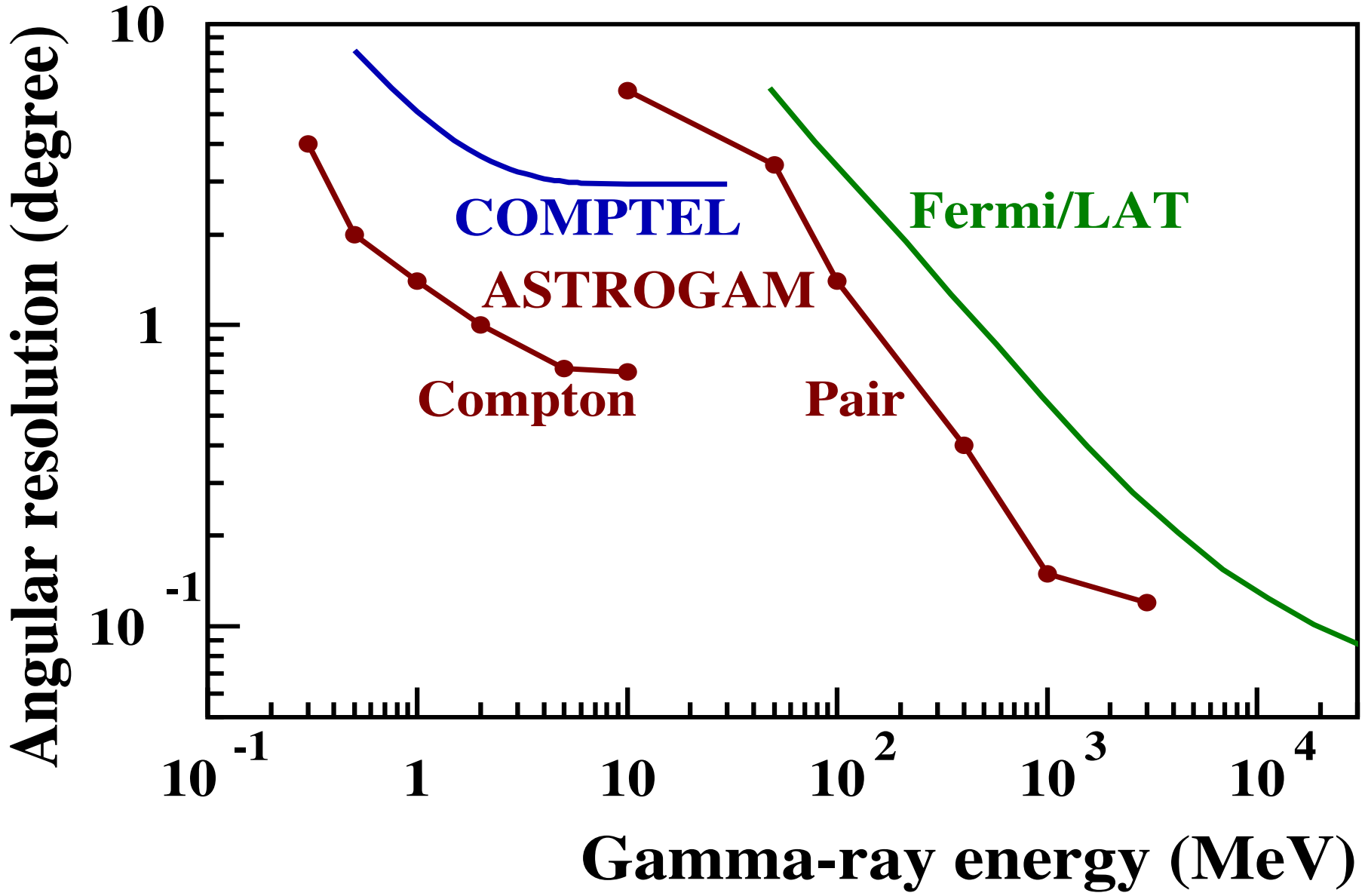
## the e-Astrogam project



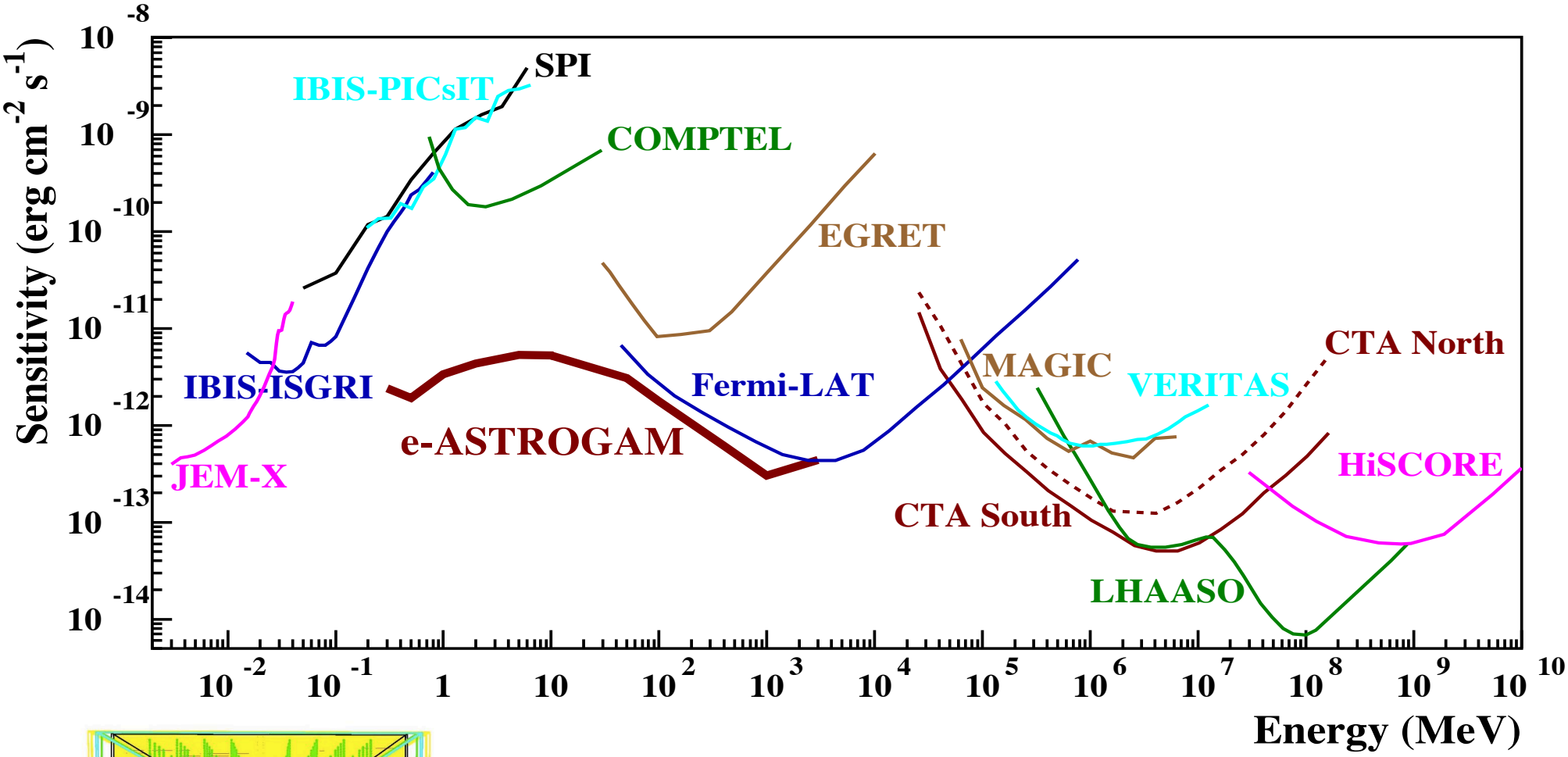
**MeV - GeV astrophysics**
**MeV - GeV community**

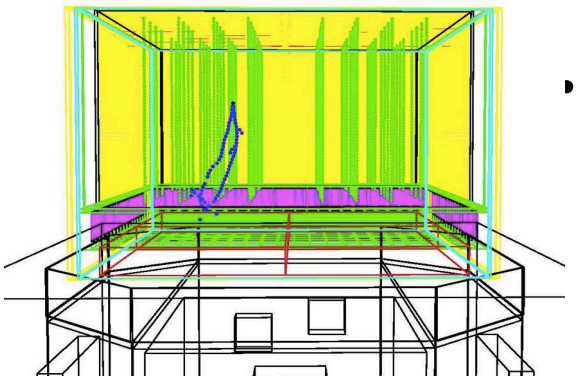
e-ASTROGAM is focused on gamma-ray astrophysics in the range 0.3-100 MeV.

# ASTROGAM Angular Resolution



# Performance assessment



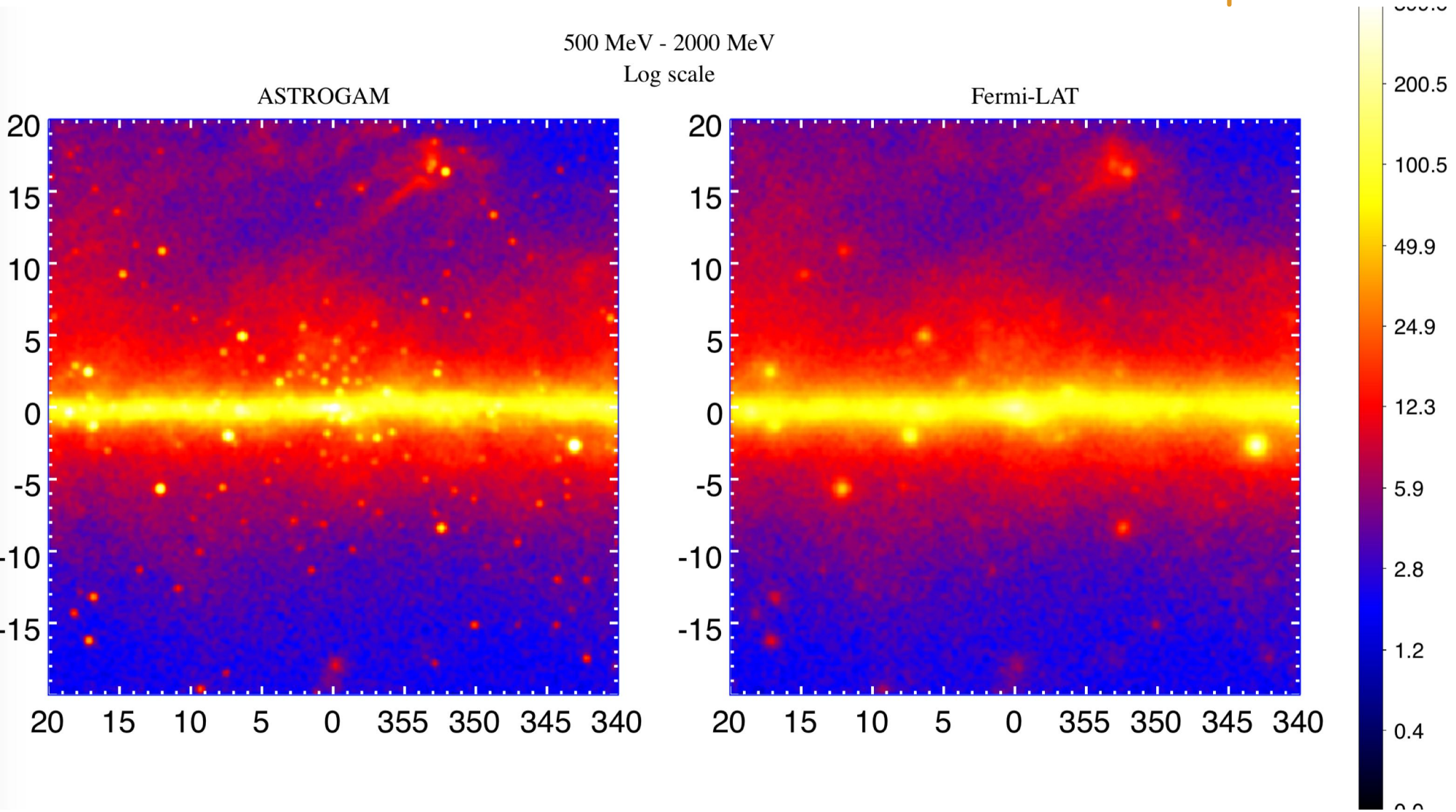



- e-ASTROGAM performance evaluated with **MEGAlib** and – both tools based on Geant4 – and a detailed numerical mass model of the gamma-ray instrument

e-Astrogam: arXiv:1611.02232

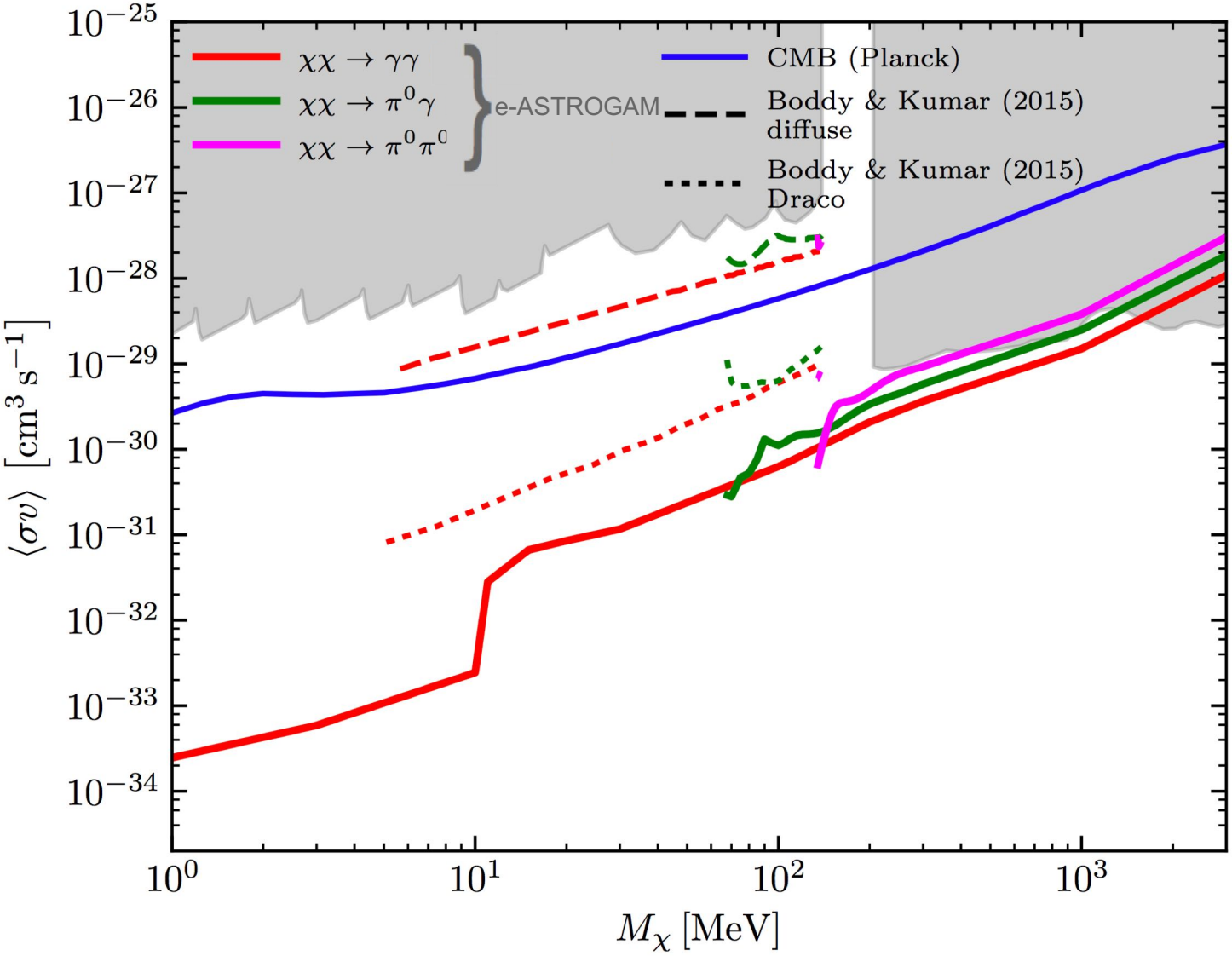
# Galactic Center Region 0.5-2 GeV

## Fermi PSF Pass7 rep v15 source

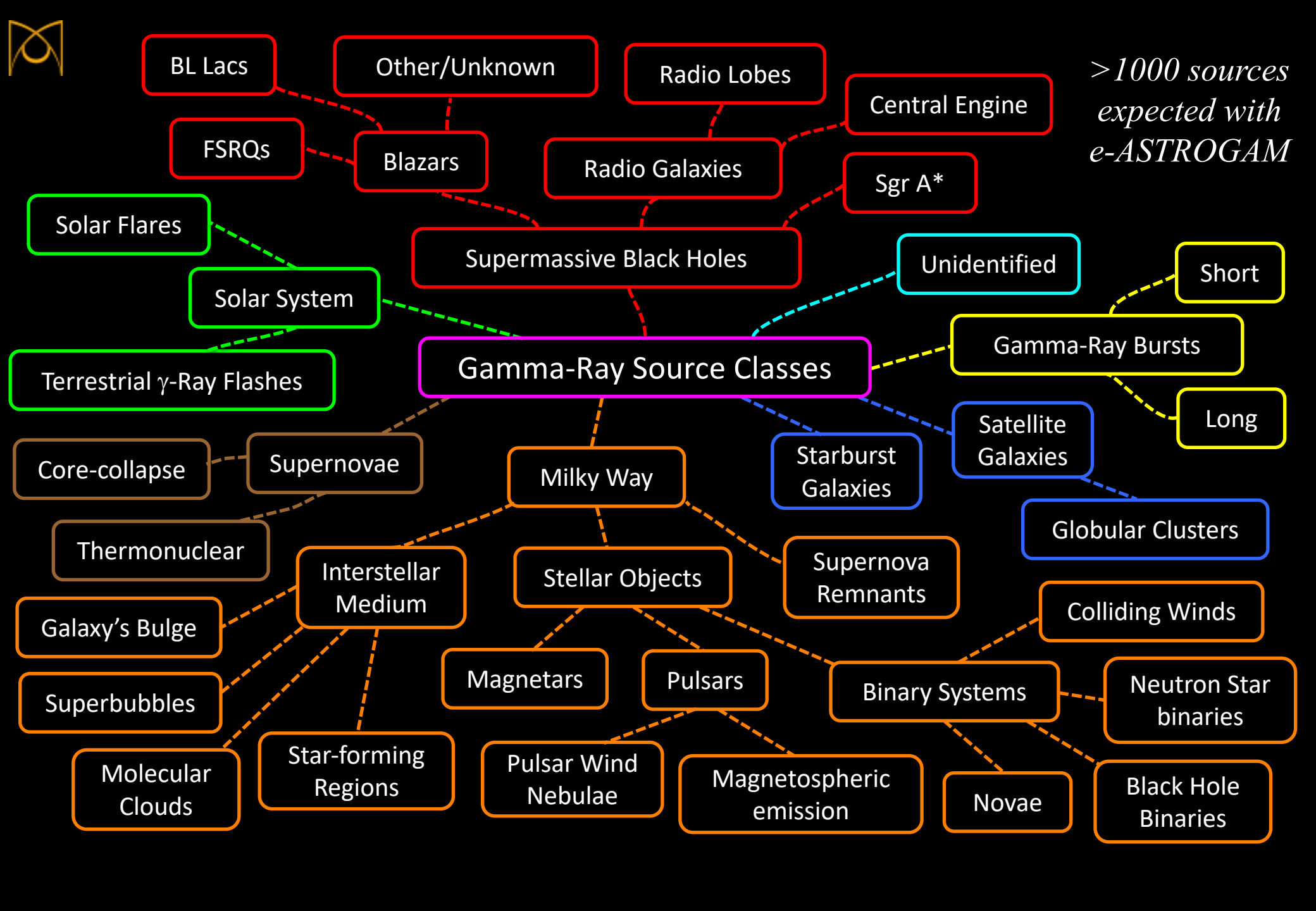



Morselli, Gomez Vargas, preliminary

# DM limits with e-ASTROGAM in the MeV region

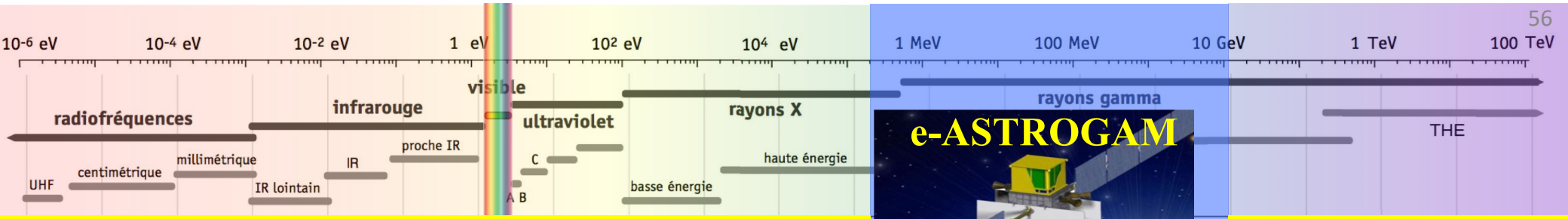



e-ASTROGAM White Book arXiv:1711.01265


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

# An instrument to complete the coverage of the electromagnetic spectrum

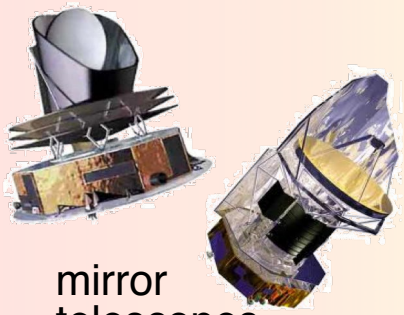




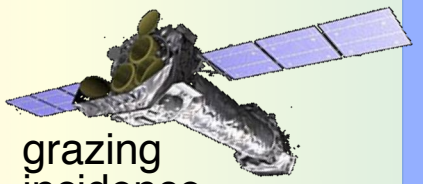

total external reflection

Cerenkov

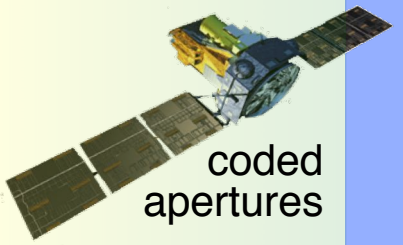
1 m 1 cm 0.1 mm 1 μm 10 nm 1 Å $10^{-12}$ m $10^{-14}$ m $10^{-16}$ m $10^{-18}$ m $10^{-20}$ m



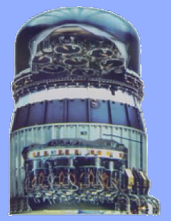
mirror telescopes



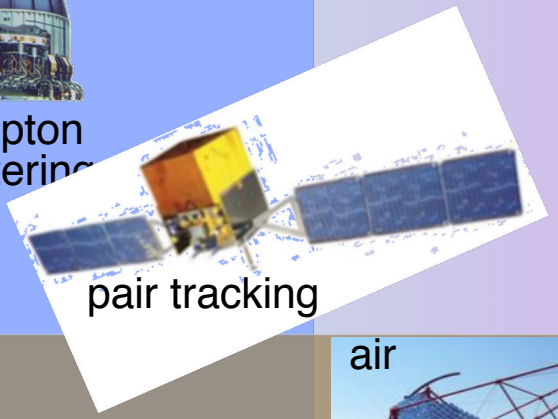
grazing incidence



coded apertures



Compton scattering



pair tracking

sub-mm/IR UV x-rays gamma-ray

air

water

# Particle Astrophysics Experiments

Source

creation
acceleration
injection

MAGIC
H.E.S.S.
VERITAS
CTA

Fermi
PAMELA
AGILE
AMS
DAMPE
Calet
Gamma-400
Jem-EUSO

KASCADE Grande
DECOR
AUGER
LOFAR
CODALEMA

Cosmic rays:
about 10 Myears
in the Galaxy
(6-7 g/cm2)

further
acceleration?

Cosmic Rays

Propagation

Modulation

NEMO
ANTARES
IceCube
KM3NeT
Baikal-GVD

ARGO-JBJ
Milagro
HAWC
LHAASO

$\gamma$

$\nu$

Space experiments ~ 400 km

Direct detection

Atmosphere

40 km

23 Xo

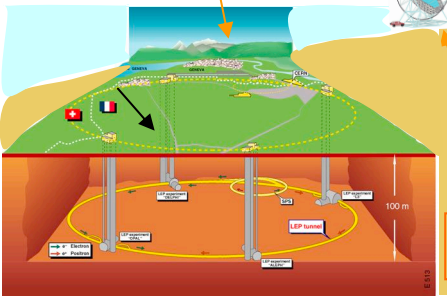
Balloons ~ 40 km
~3 g/cm$^2$ residualatmosphere

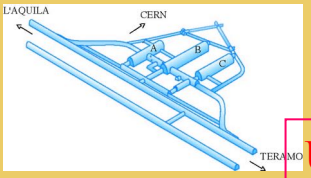
Extensive Air Shower
Detectors

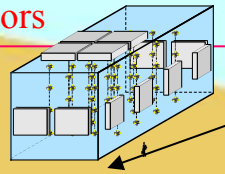
High Montain
Detectors

Cherencov Detectors

Particle Accelerators



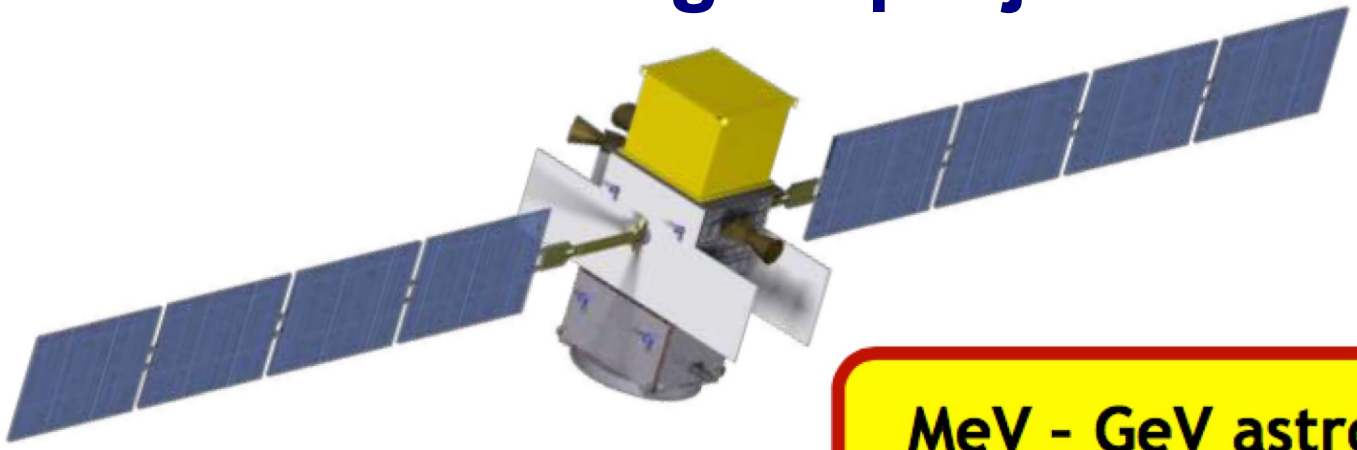



Underground, Under-ice, Underwater

DAMA/LIBRA
CoGeNT
CRESST-II
CDMS
Xenon1T
LUX
PandaX
DarkSide
...

# 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.
Proposed for ESA M5 call but not selected for Fase A study.
We need to find other opportunity
With NASA (AMEGO) ? With China ?
Different possibilities under evaluation

# 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).

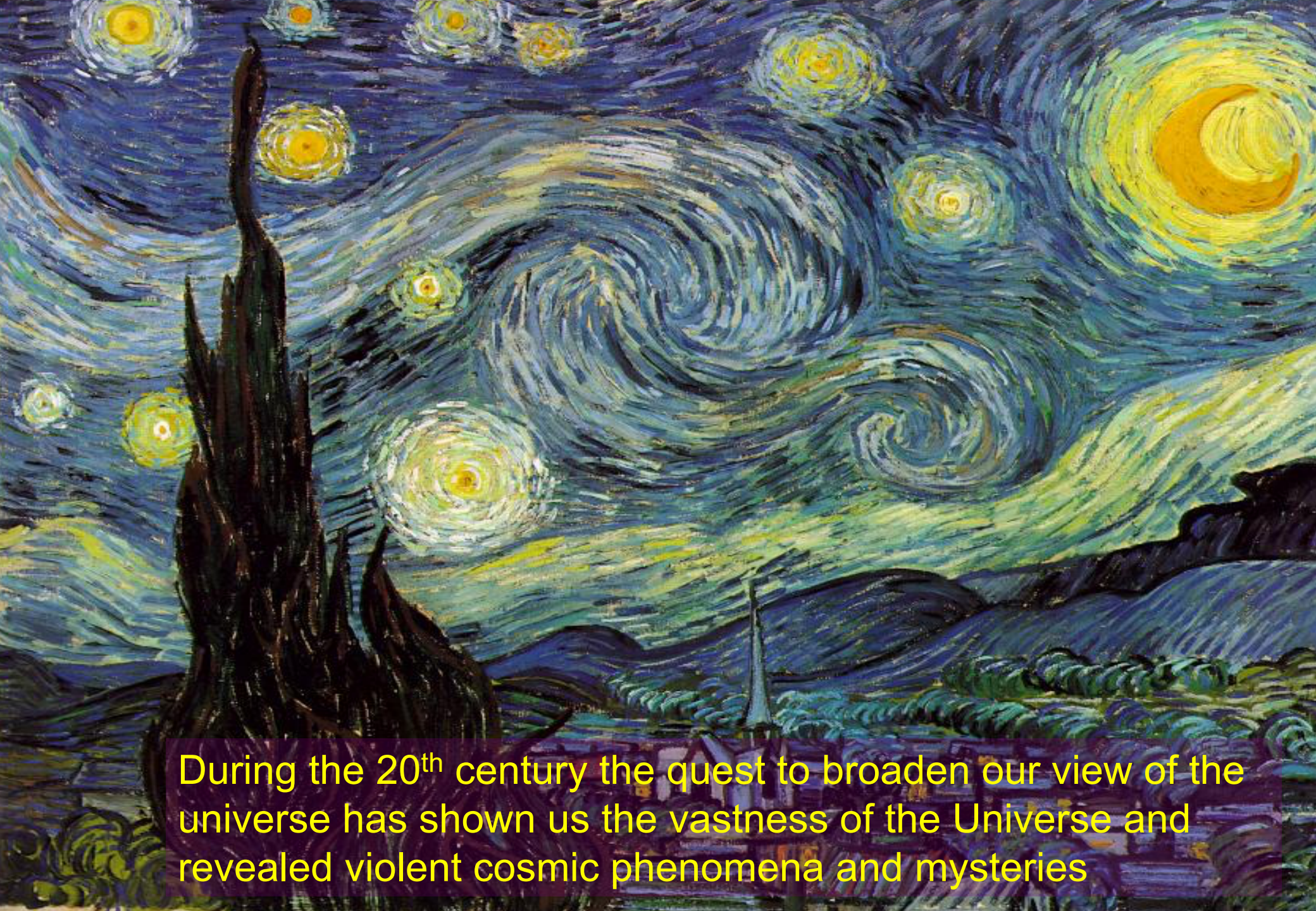
In the future it would be extremely important to extend the energy range of experiments at lower energies (compared to the Fermi energies)

(e-AstroGAM, AMEGO)

and higher energies (CTA, HAWC)

Thank you !


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 !