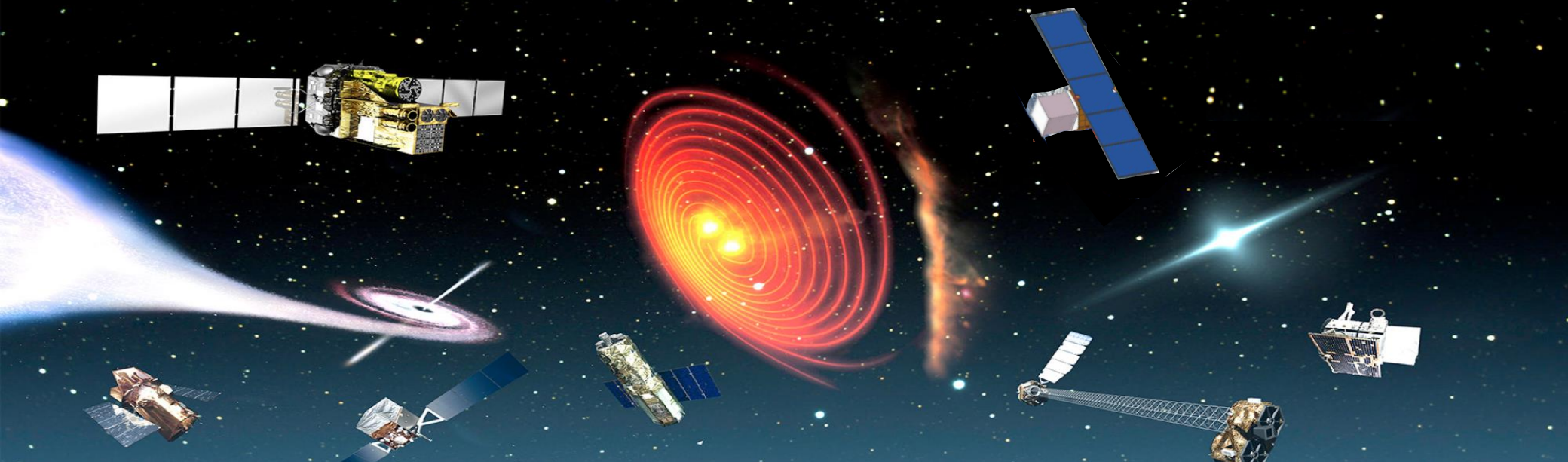
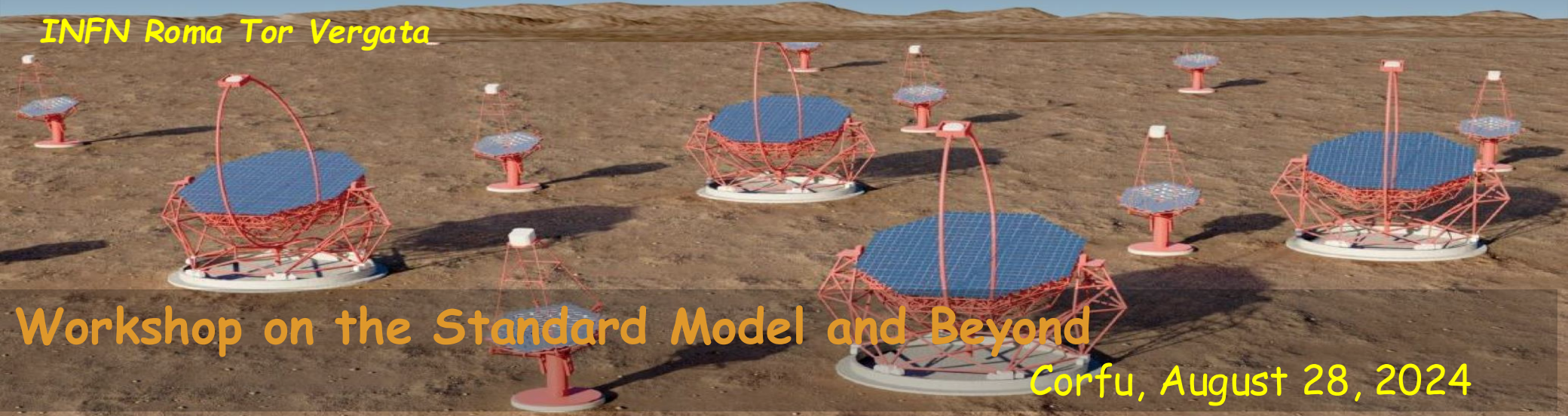


# Indirect dark-matter searches with gamma-rays experiments : status and future plans from 300 KeV to 100 TeV



**Aldo Morselli**

*INFN Roma Tor Vergata*



**Workshop on the Standard Model and Beyond**

**Corfu, August 28, 2024**



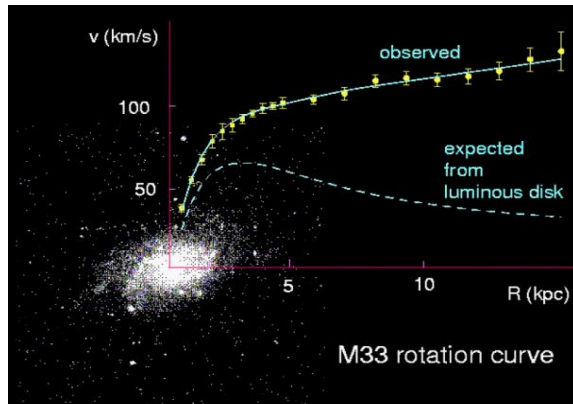
# Dark Matter EVIDENCE

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



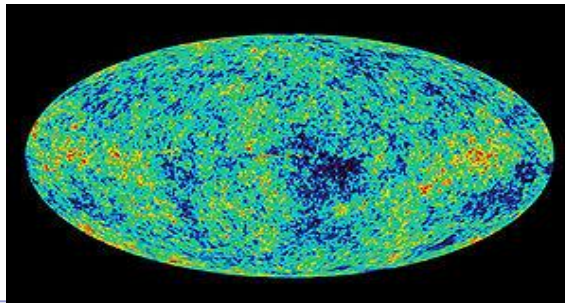
## Gravitational lensing



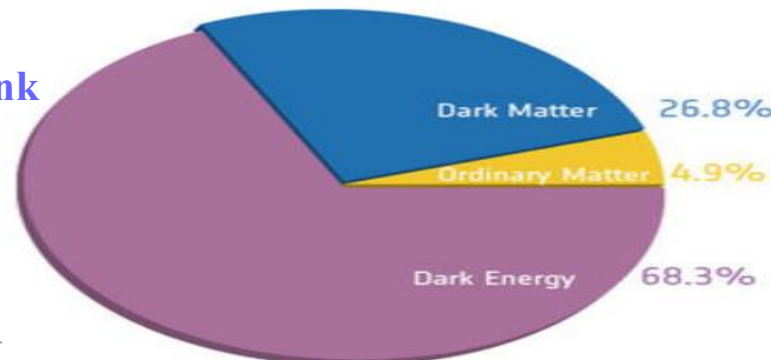
## Bullet cluster



## Structure formation as deduced from CMB



Data by Planck imply:



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

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

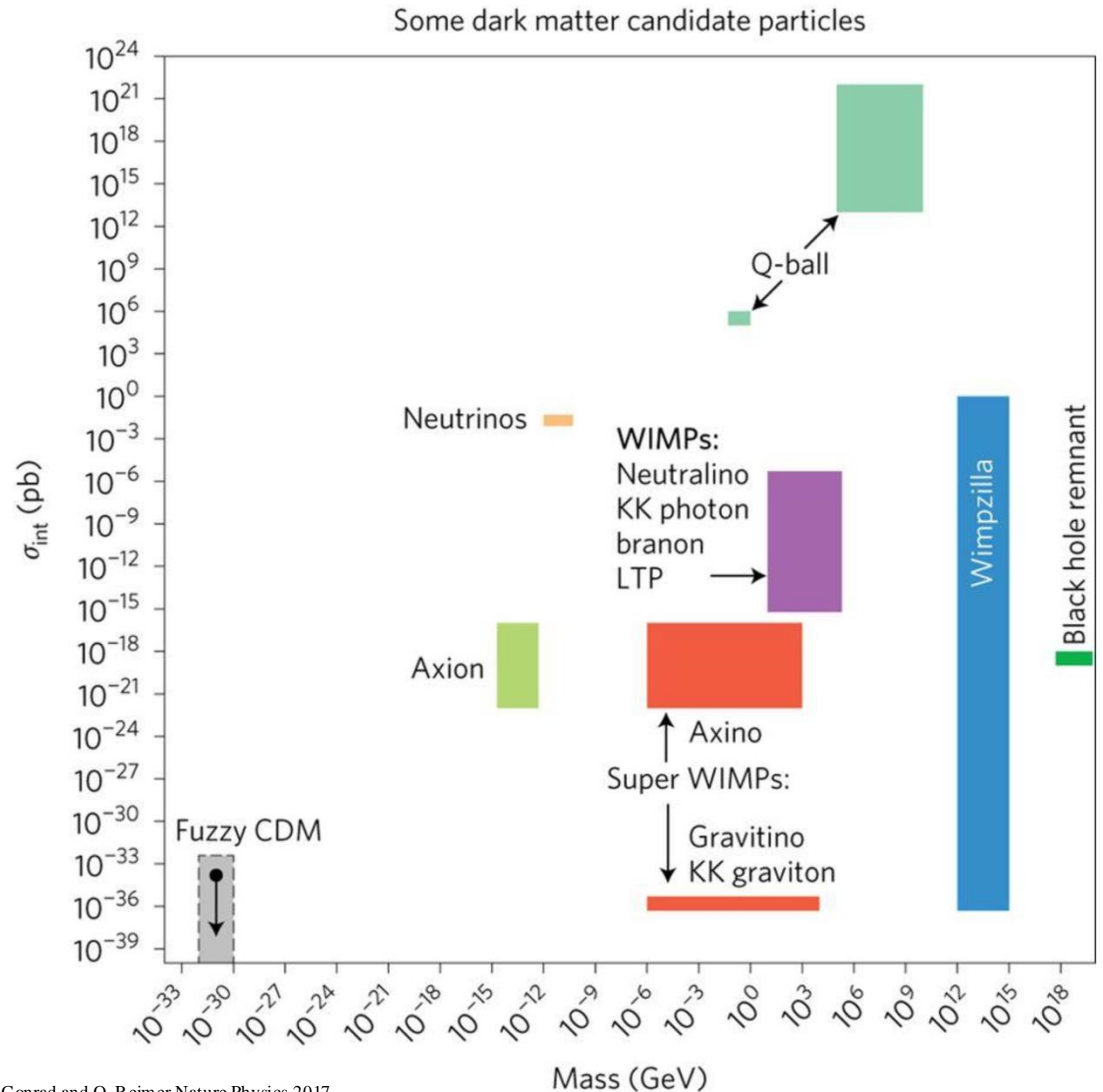
Dark er





# Dark Matter Candidates

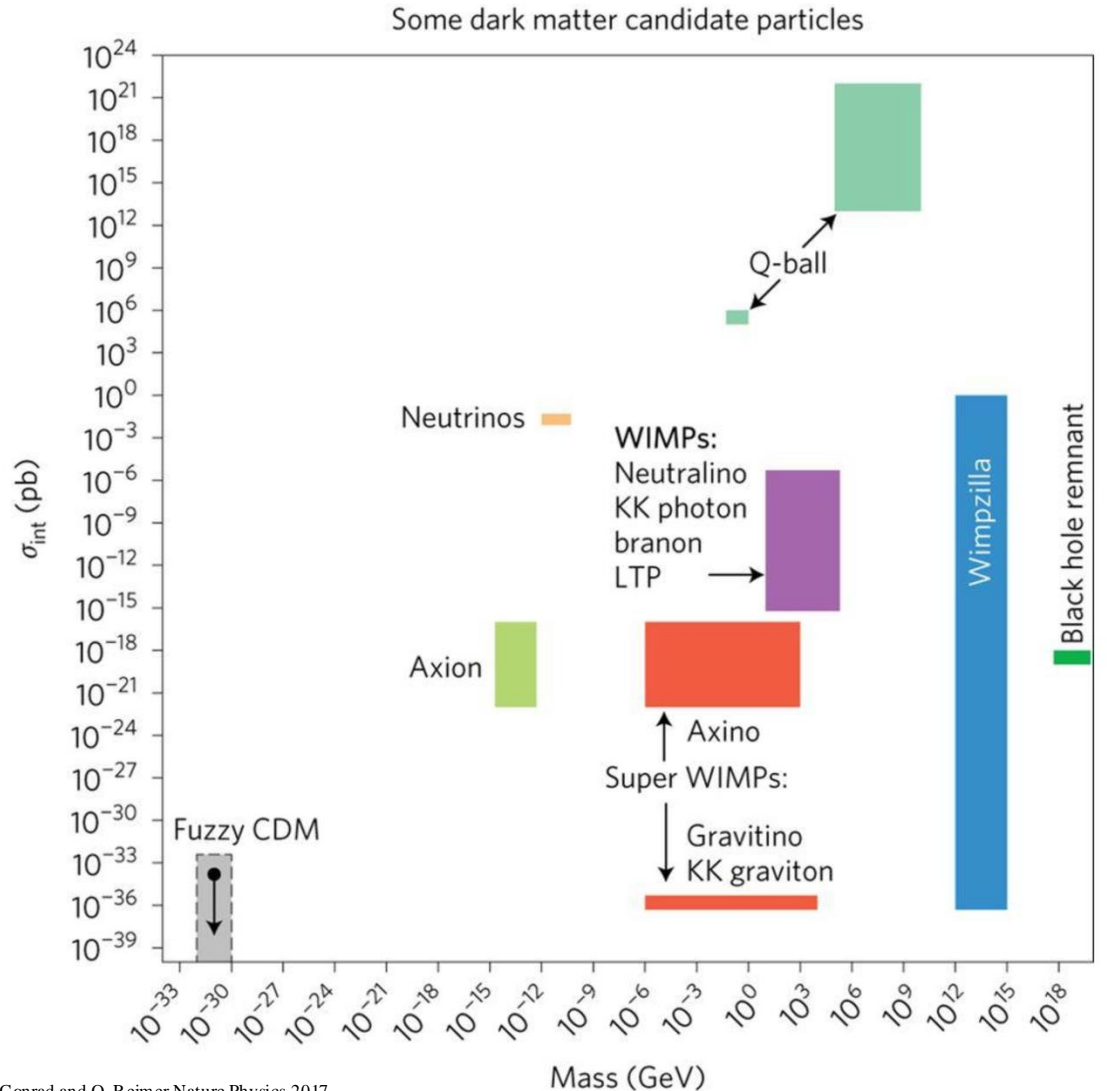
- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworld DM
- Heavy neutrino
- WIMP
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes





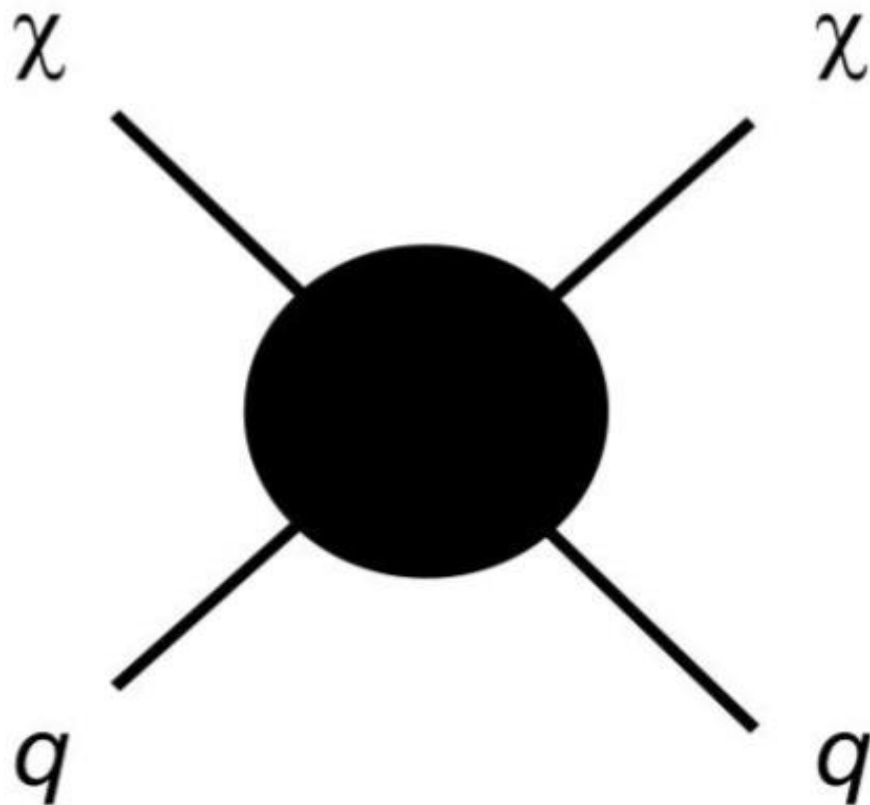
# Dark Matter Candidates

- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
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- Heavy neutrino
- **WIMP**
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes



(Indirect detection)

annihilation



production  
(Particle colliders)

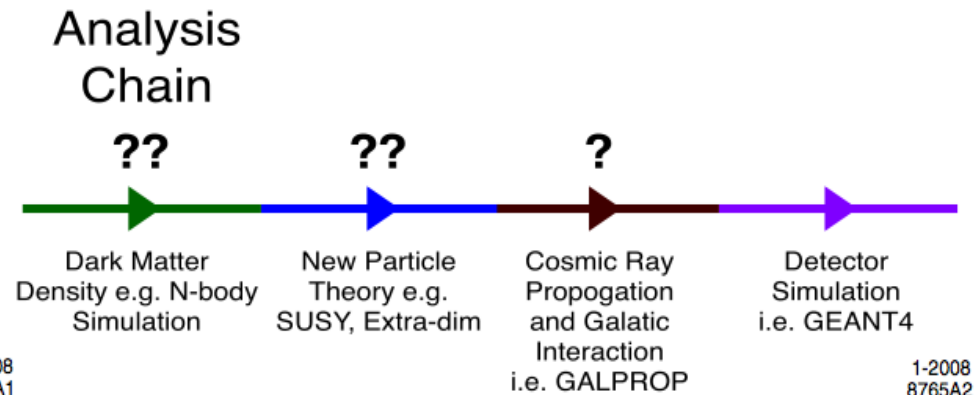
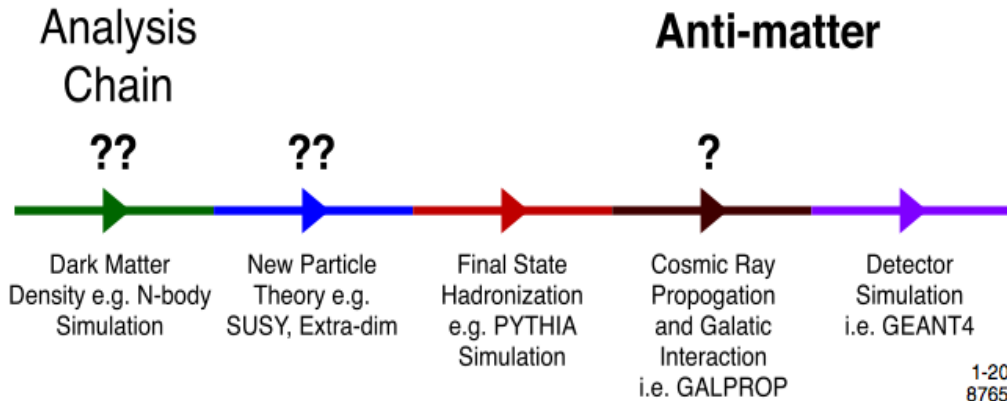
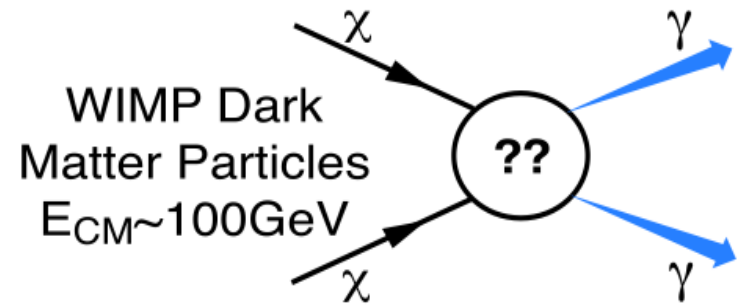
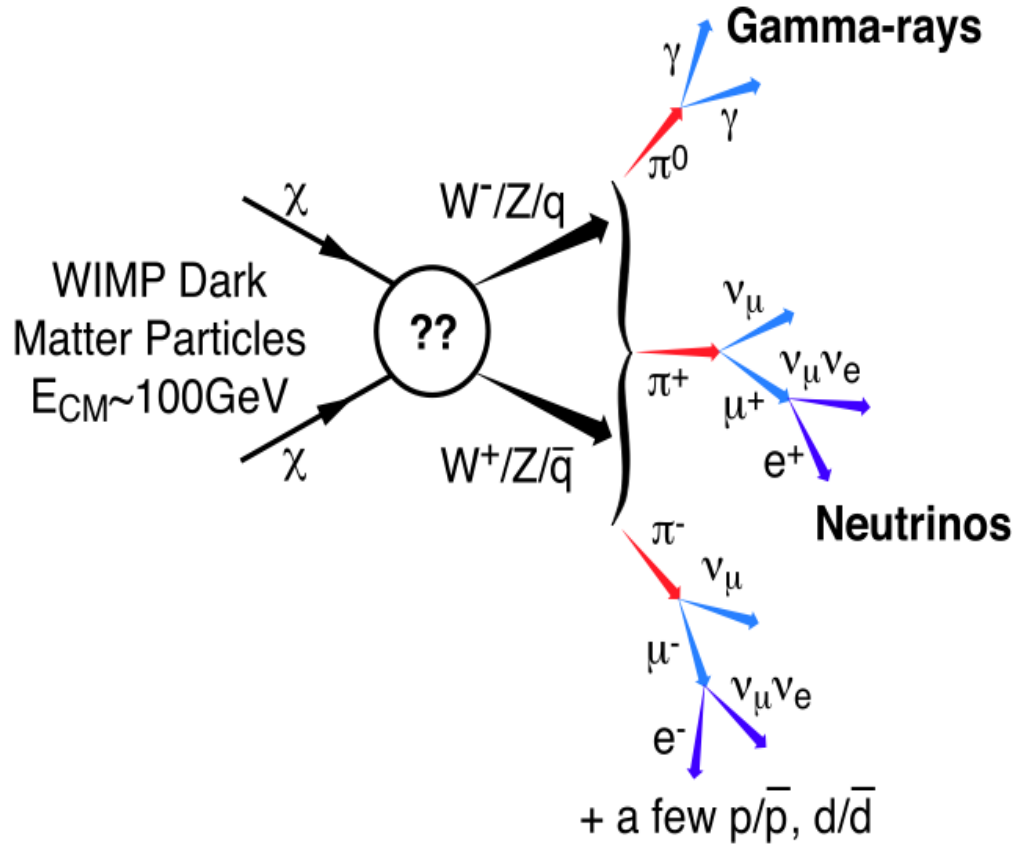


scattering  
(Direct detection)





# Annihilation channels



# Signal rate from WIMP annihilation

gamma-ray flux from  
WIMP annihilation

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

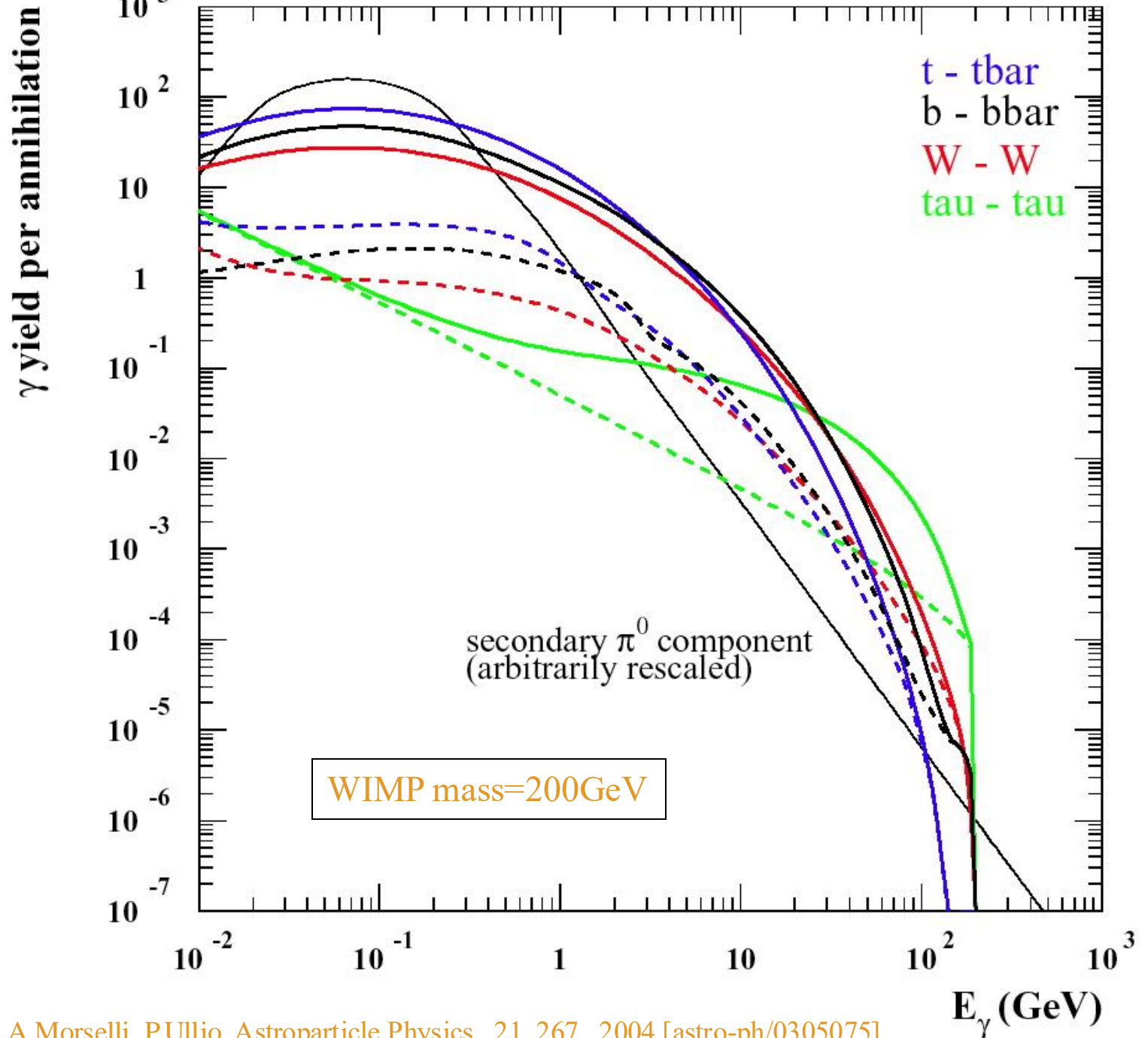
governed by  
particle physics  
(supersymmetric  
parameters .. etc )

$J(\varphi)$ :

governed by  
halo distribution

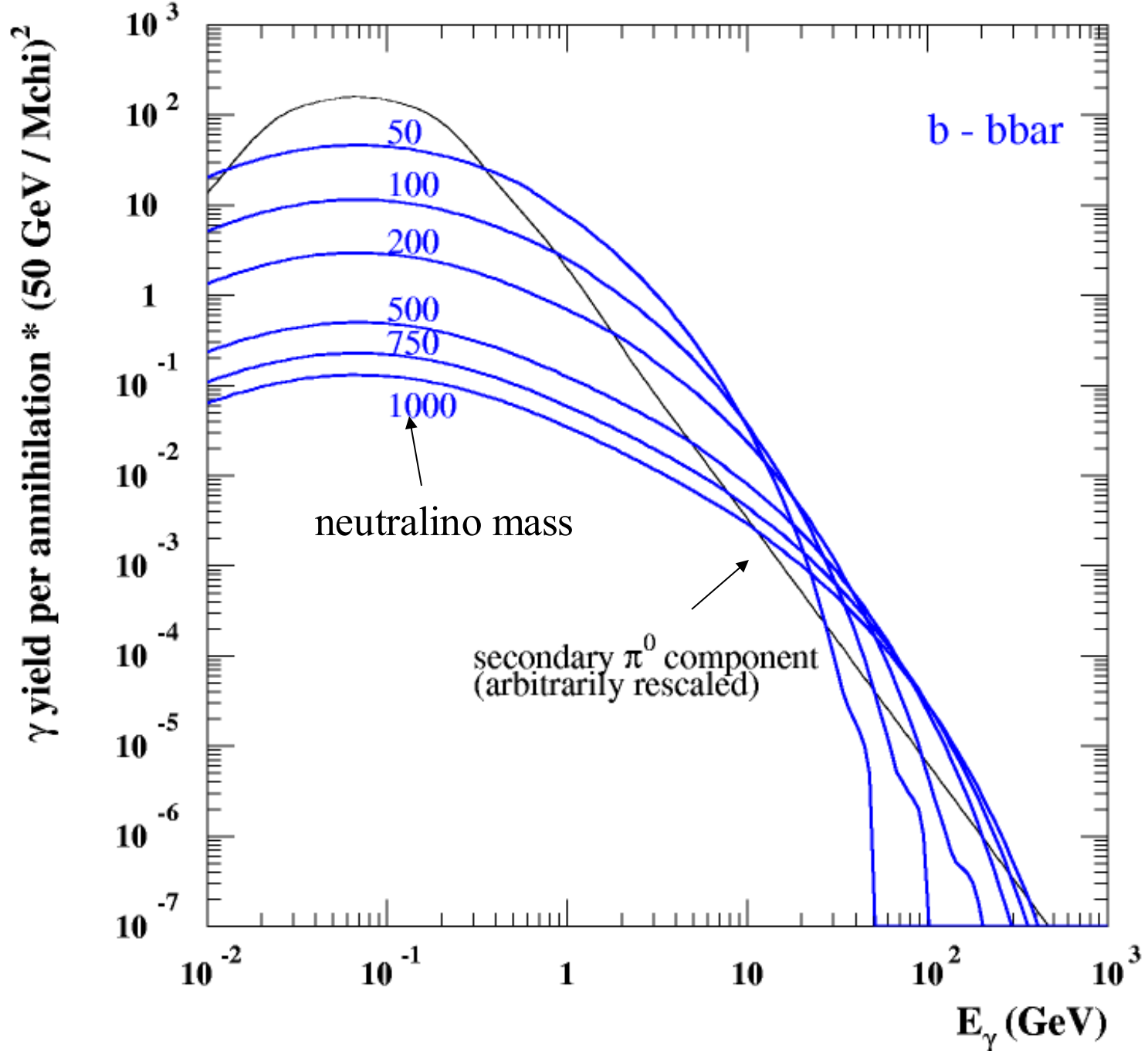


Differential yield for each annihilation channel



dashed lines are components not due to  $\pi^0$  decay.

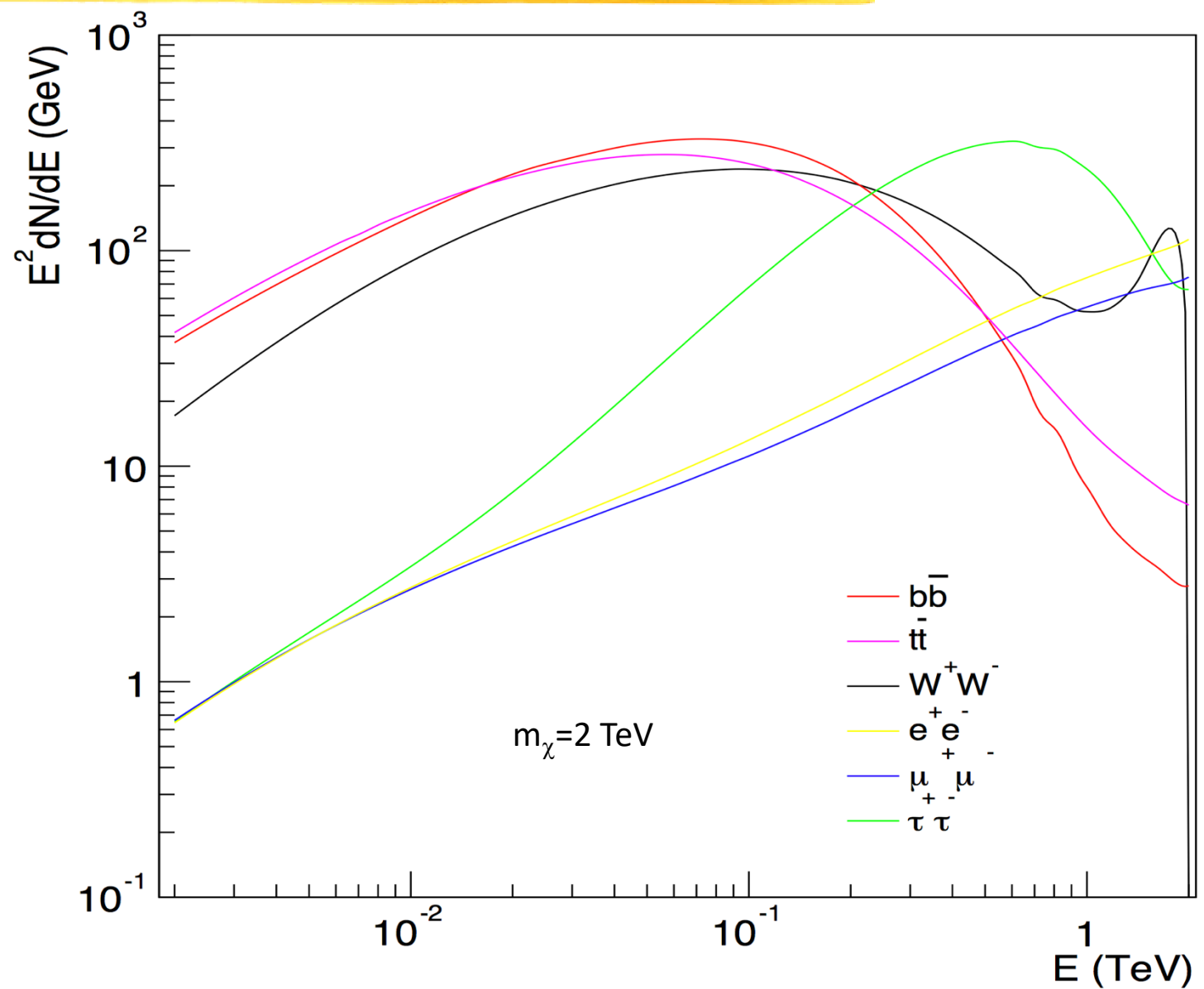
Differential yield  
for b bar



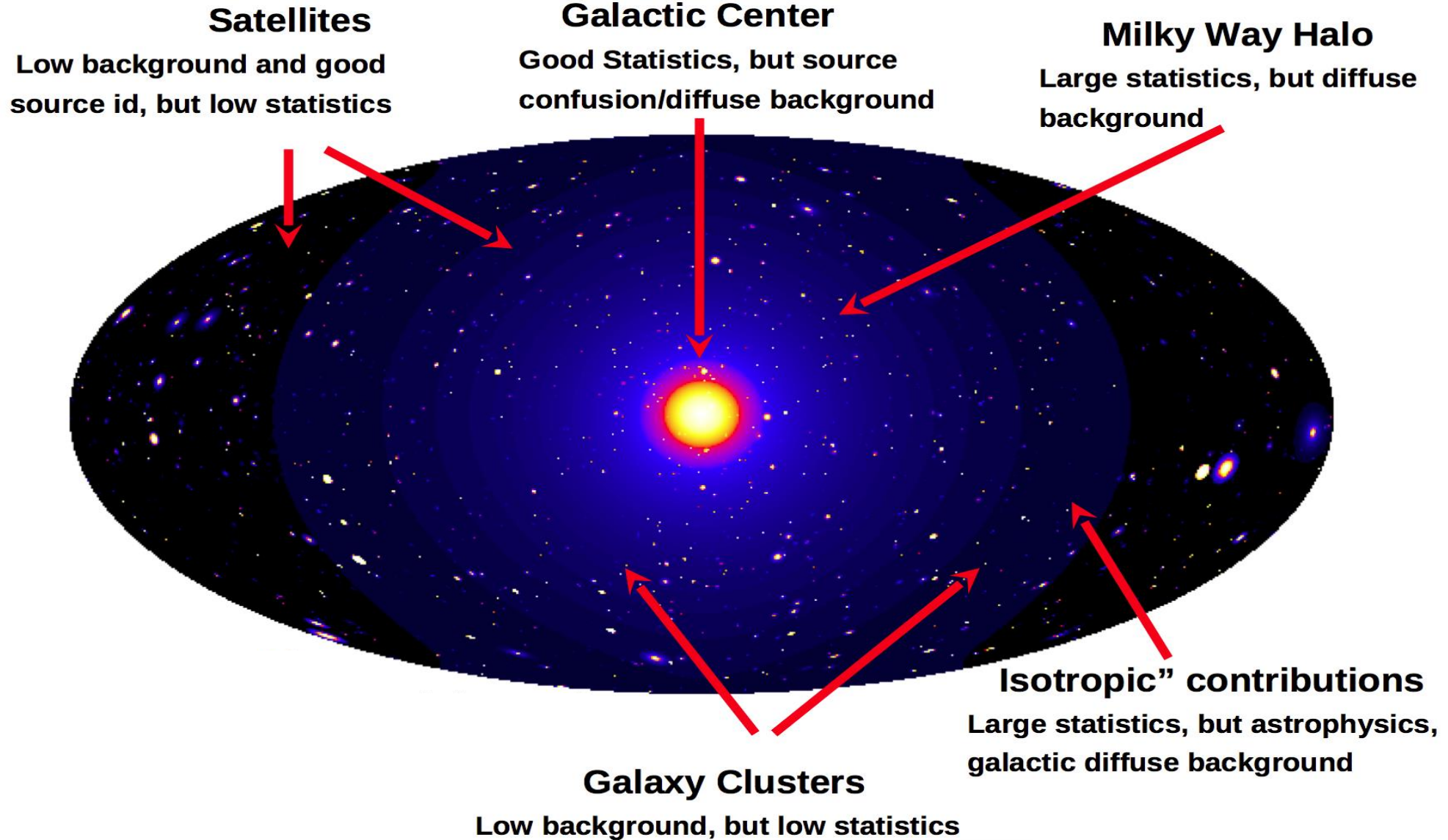


# Annihilation spectra for the continuum signal from the quark, lepton and gauge boson primary channels

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

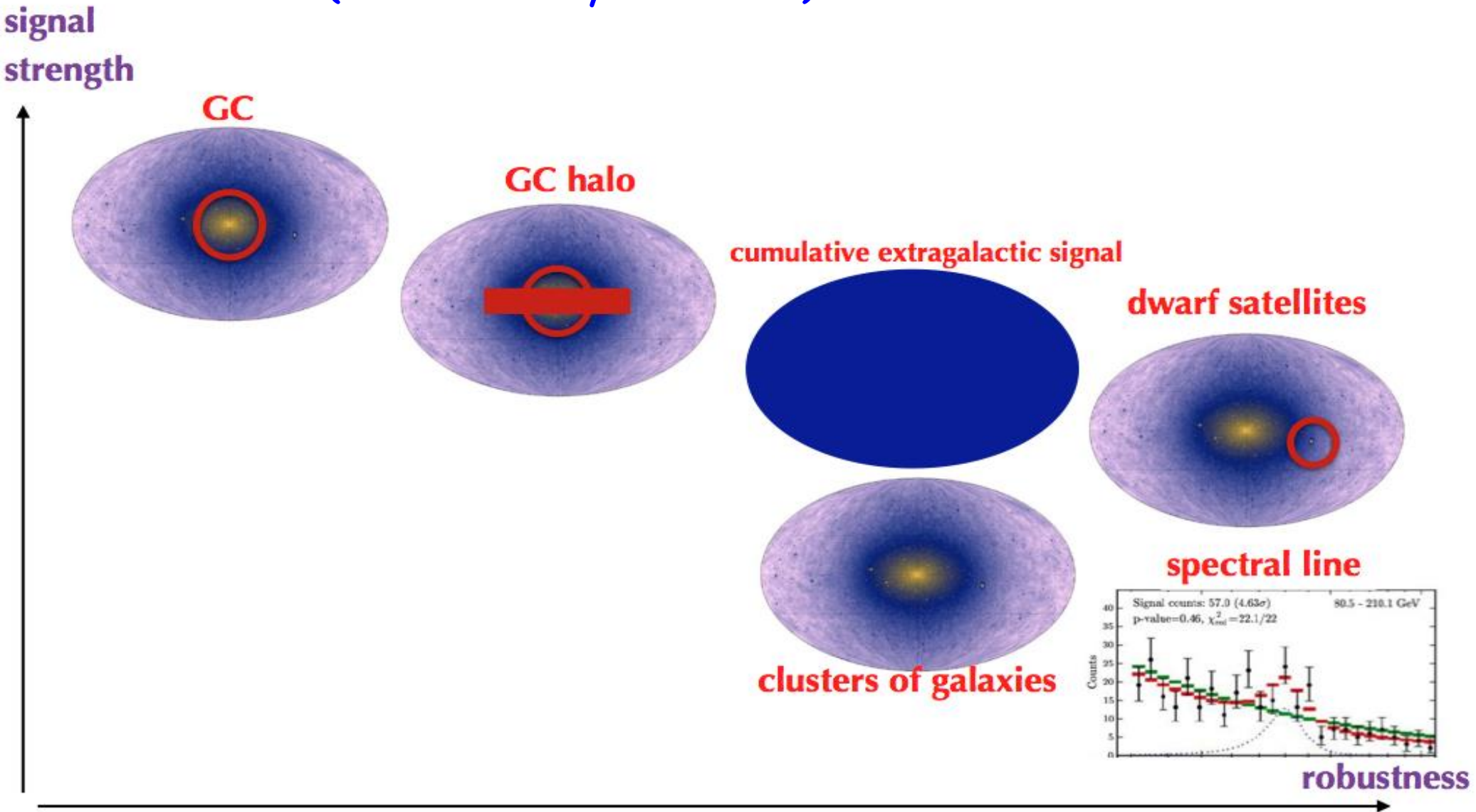


# Dark Matter Search: Targets and Strategies

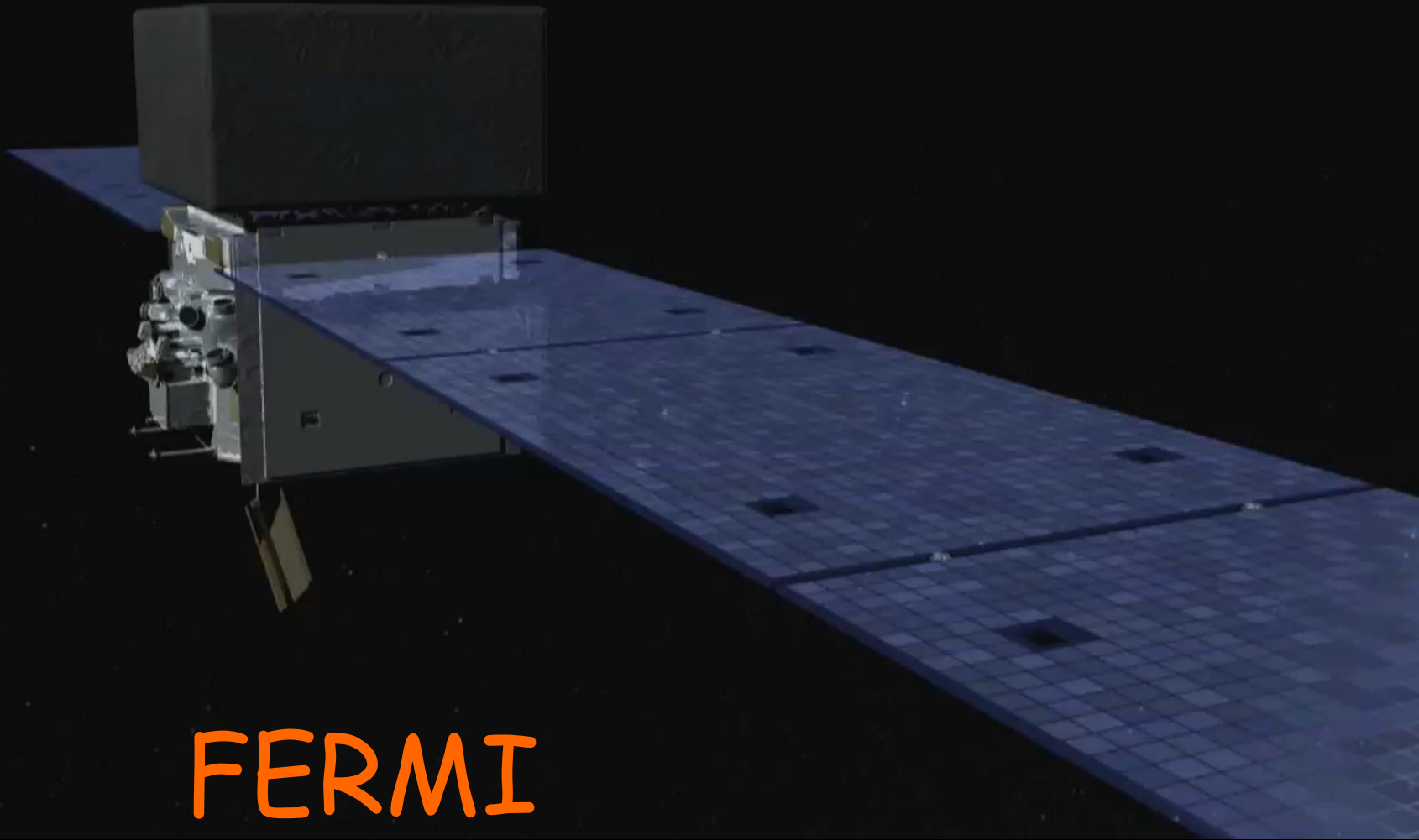


# Dark Matter Search: Targets and Strategies

(Another way to see it)

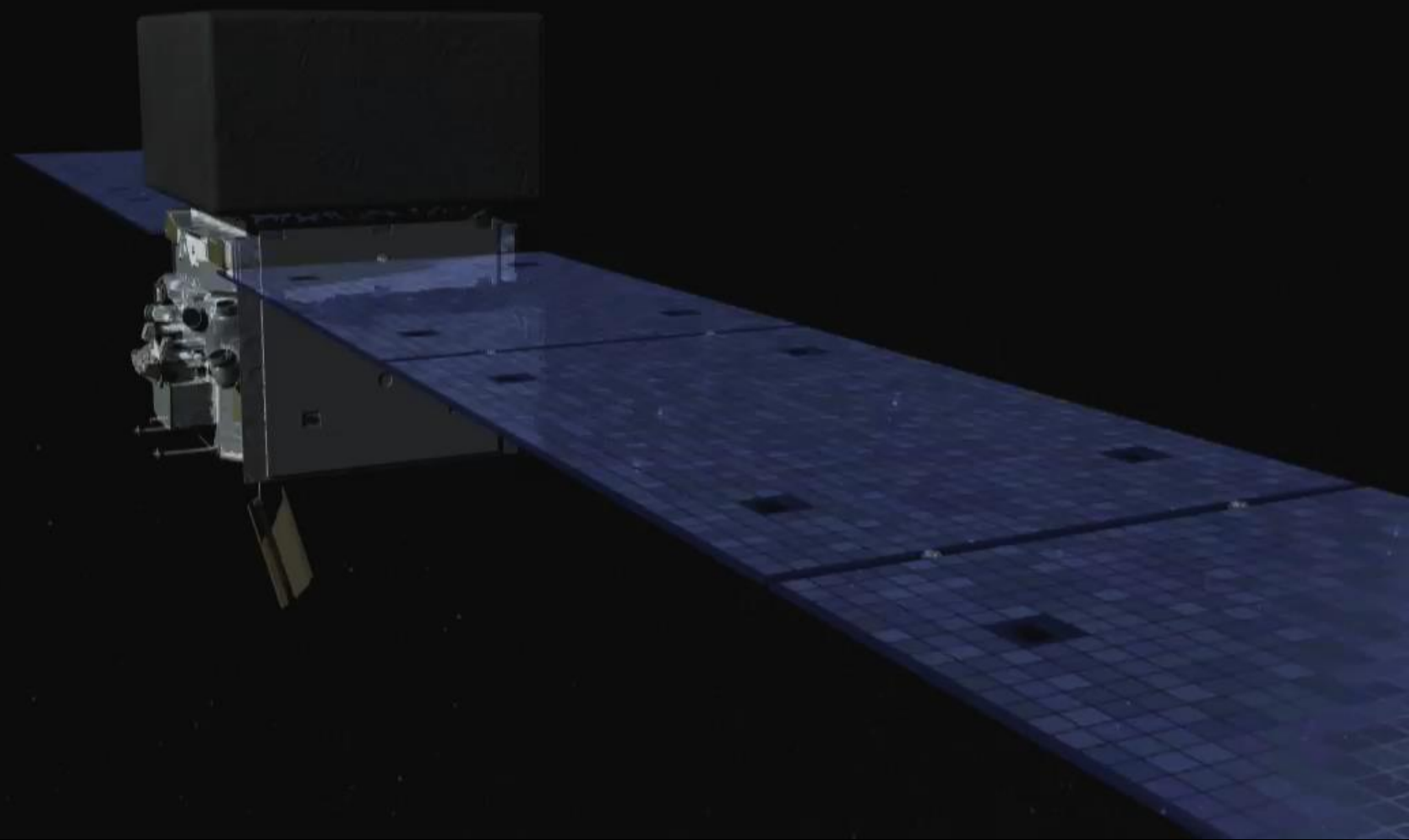


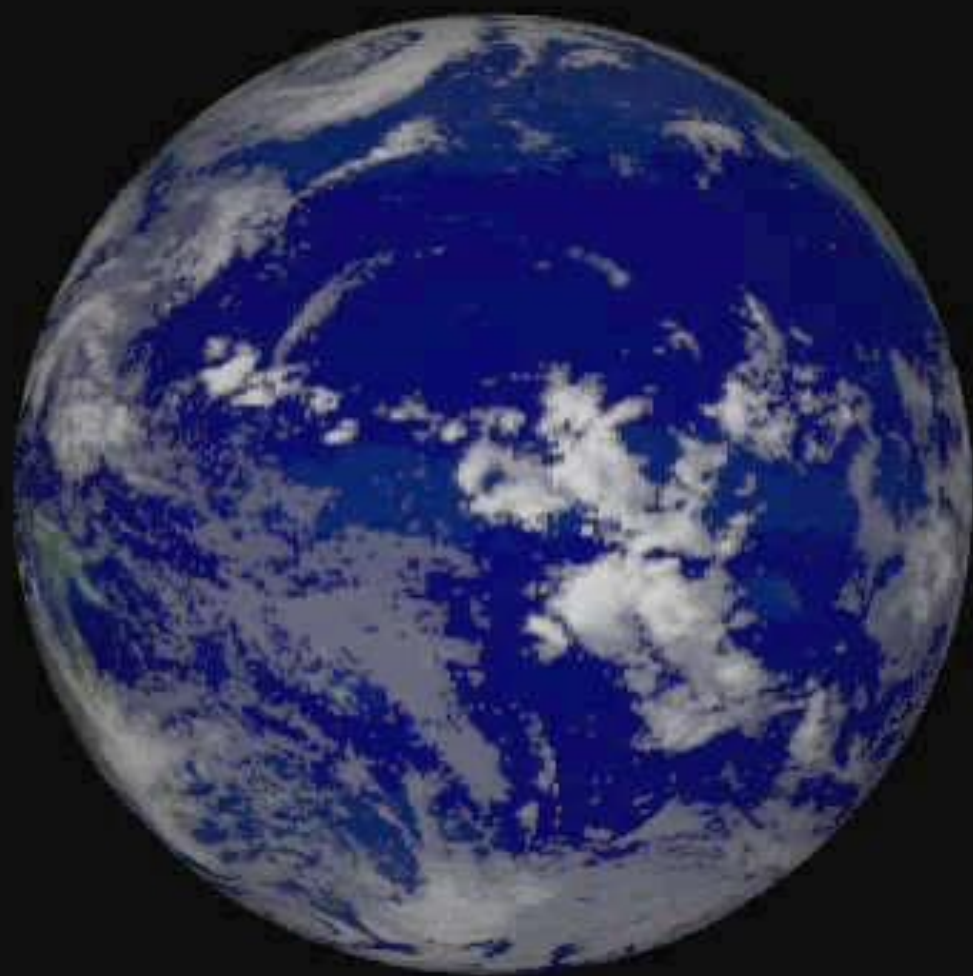




# FERMI

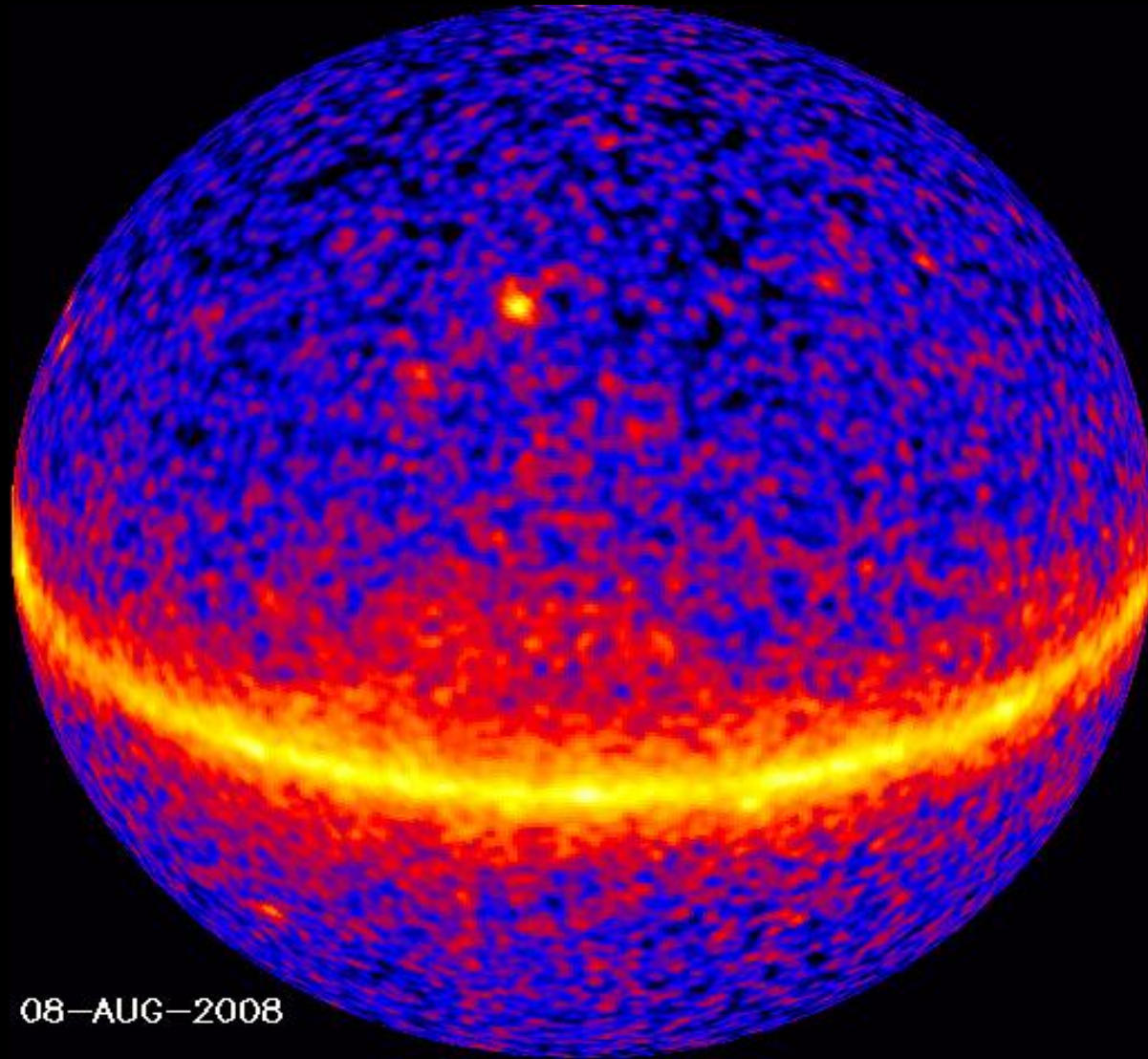
## Large Area Telescope







# Daily Gamma-ray Sky



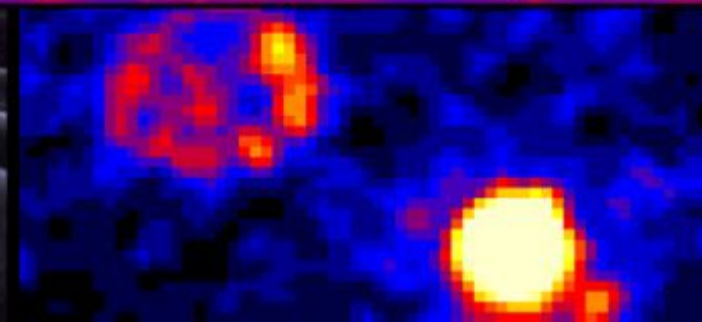
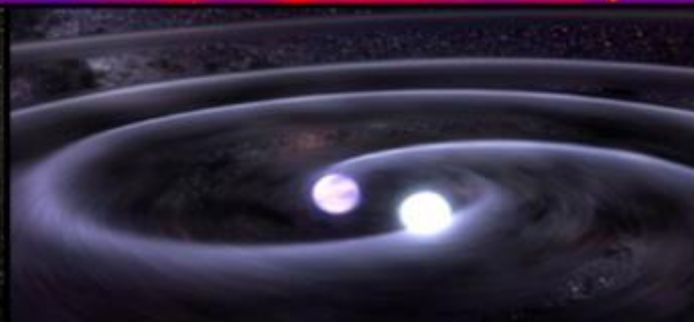
08-AUG-2008



# *Fermi* Gamma-Ray Space Telescope

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

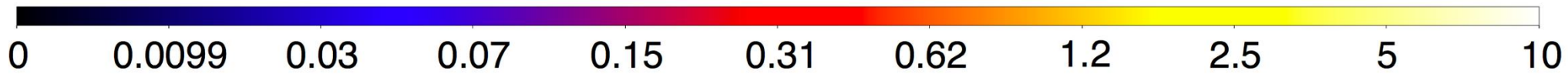
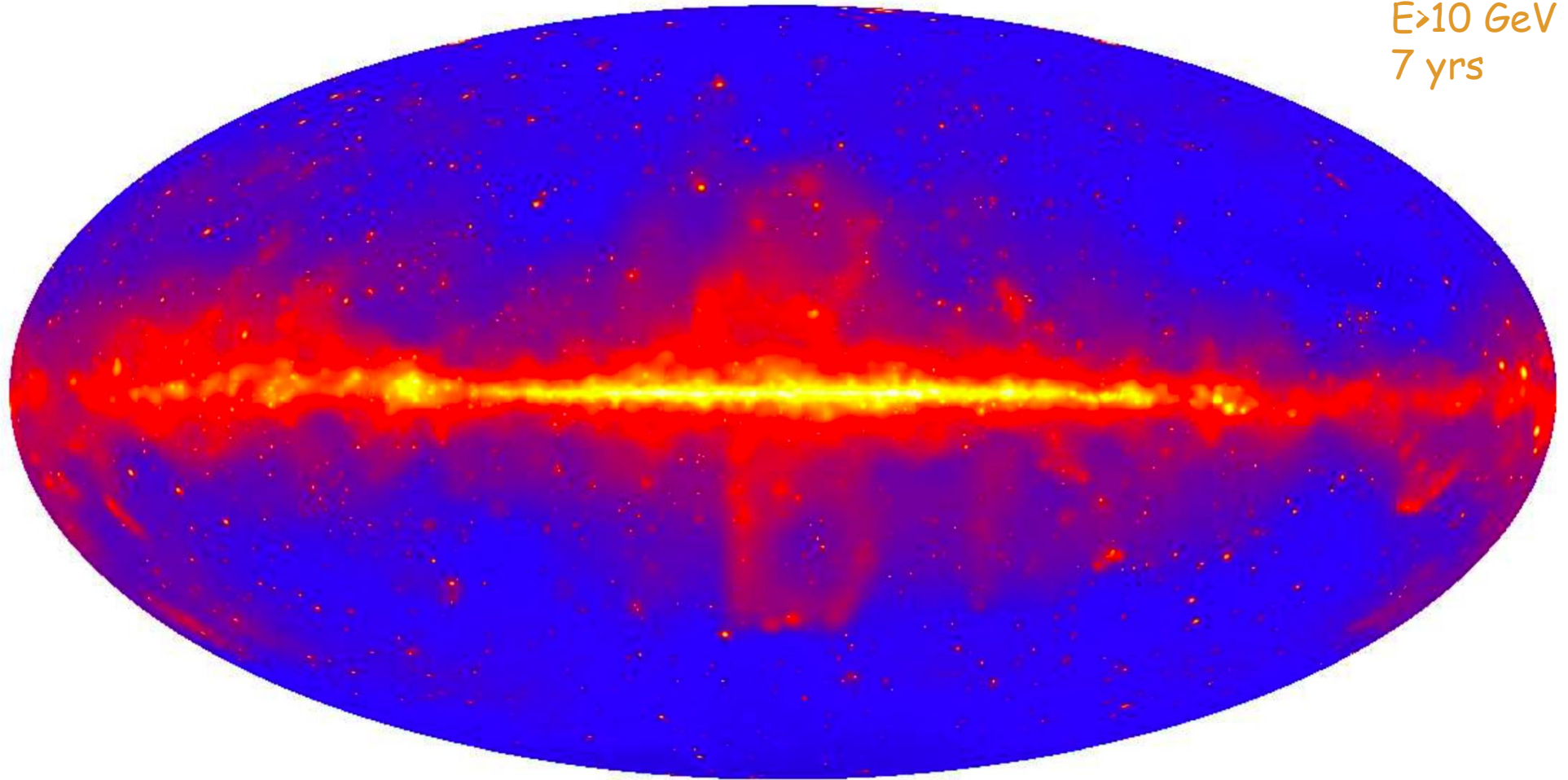
**Time Domain Astronomy • Searches for Dark Matter • Particle Astrophysics**





# The sky in gamma-rays

$E > 10 \text{ GeV}$   
7 yrs



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

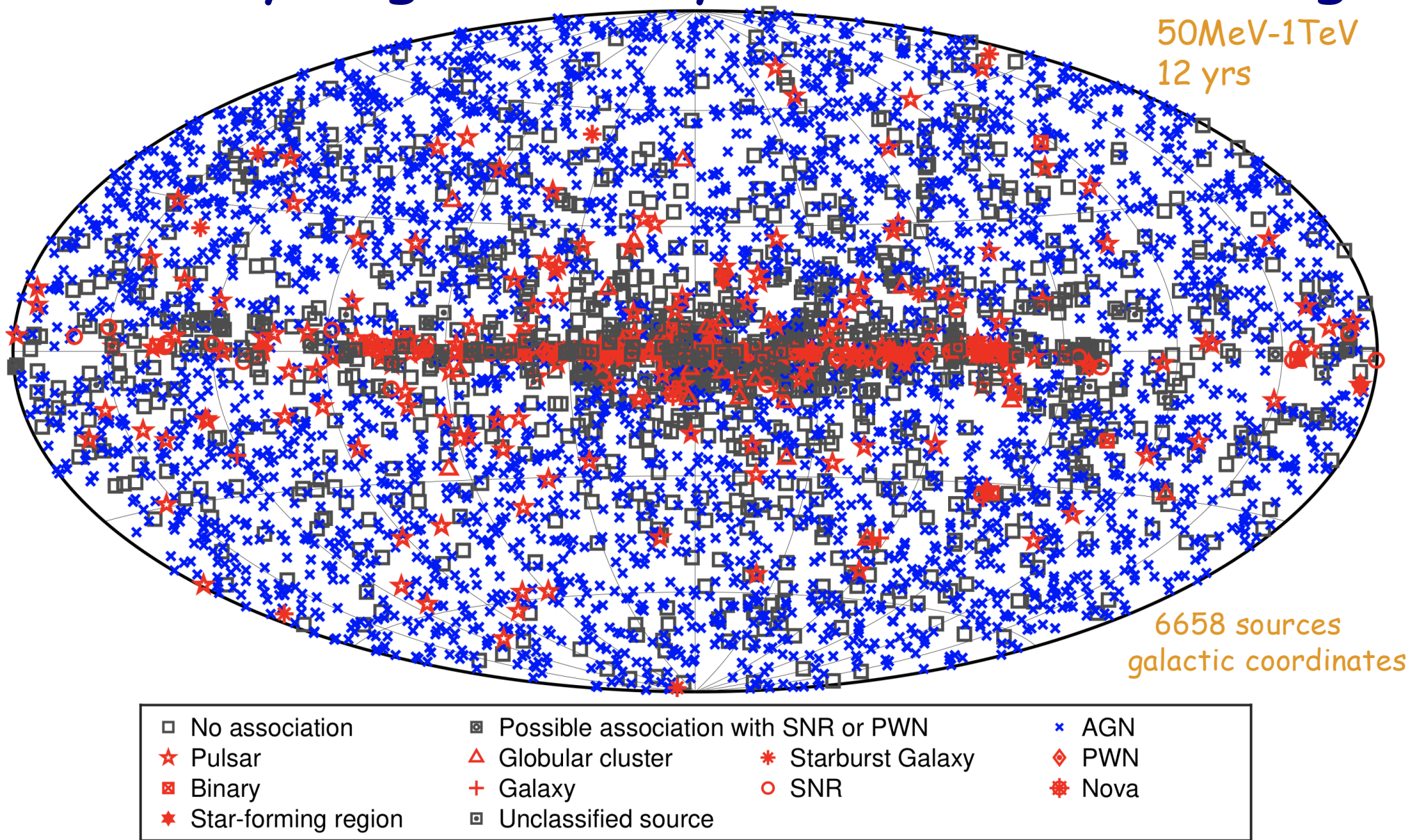




**Happy 16<sup>th</sup> Birthday Fermi !!**

**11 June 2008**

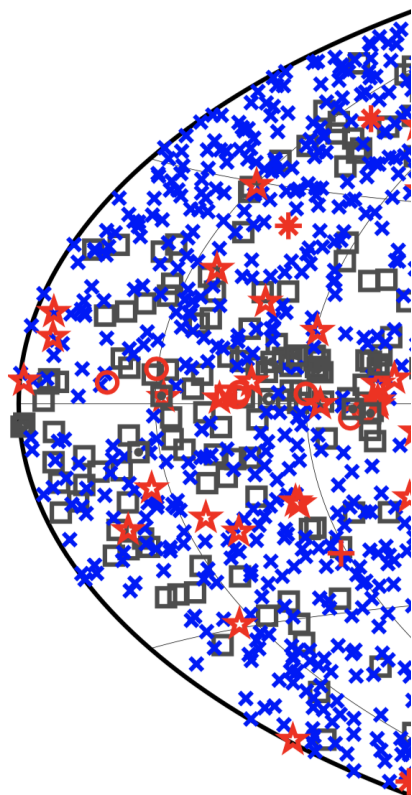
# The sky in gamma-rays 4<sup>th</sup> source catalog



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



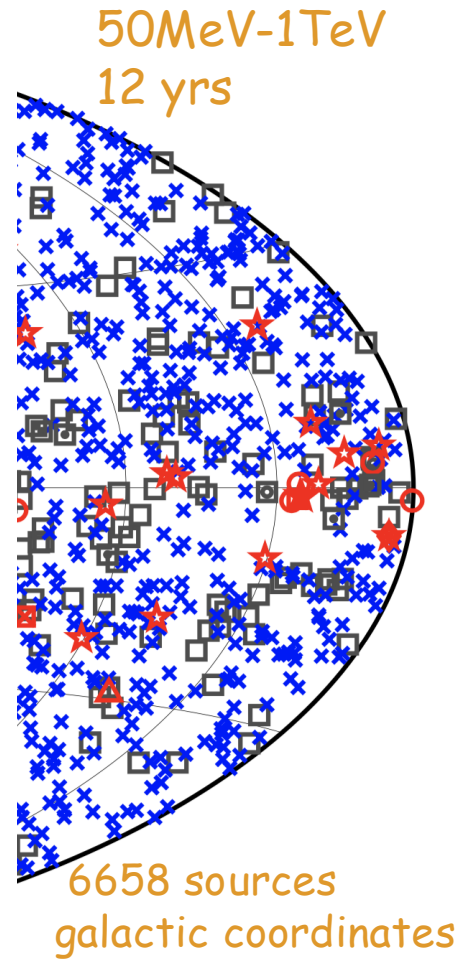
# The sky in gamma-rays 4<sup>th</sup> source catalog



- No asso
- ★ Pulsar
- ▣ Binary
- ★ Star-form

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

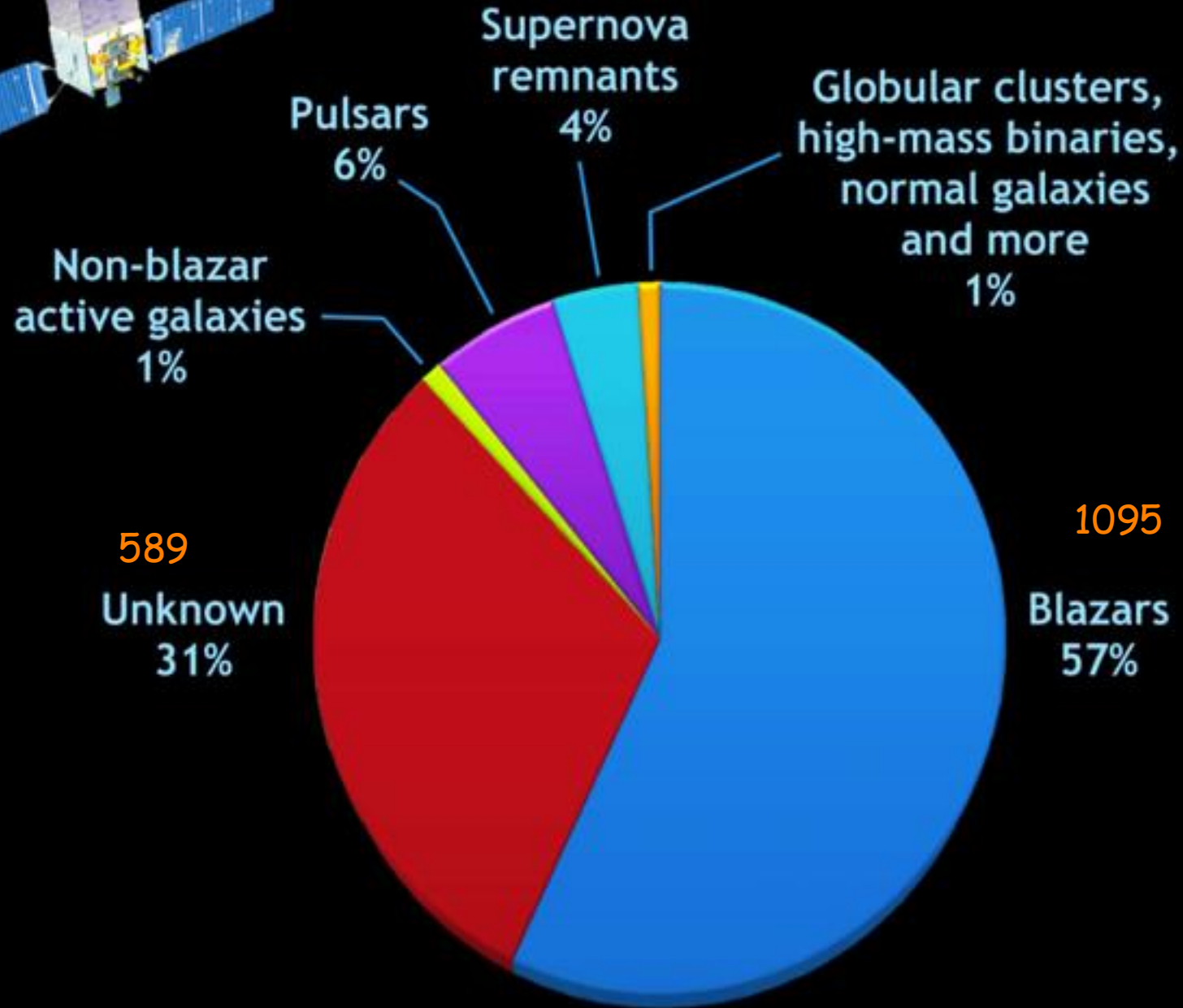
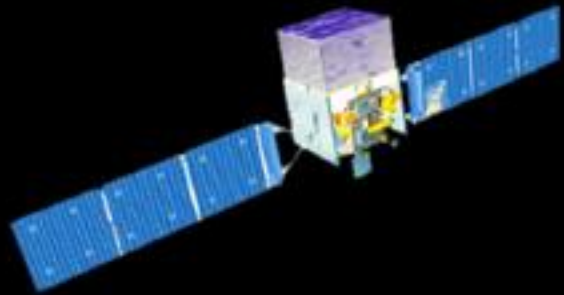
NOTE—The designation ‘spp’ indicates potential association with SNR or PWN. ‘Unknown’ are  $|b| < 10^\circ$  sources solely associated with the likelihood-ratio method from large radio and X-ray surveys. Designations shown in capital letters are firm identifications; lower-case letters indicate associations.



- GN
- WN
- ova



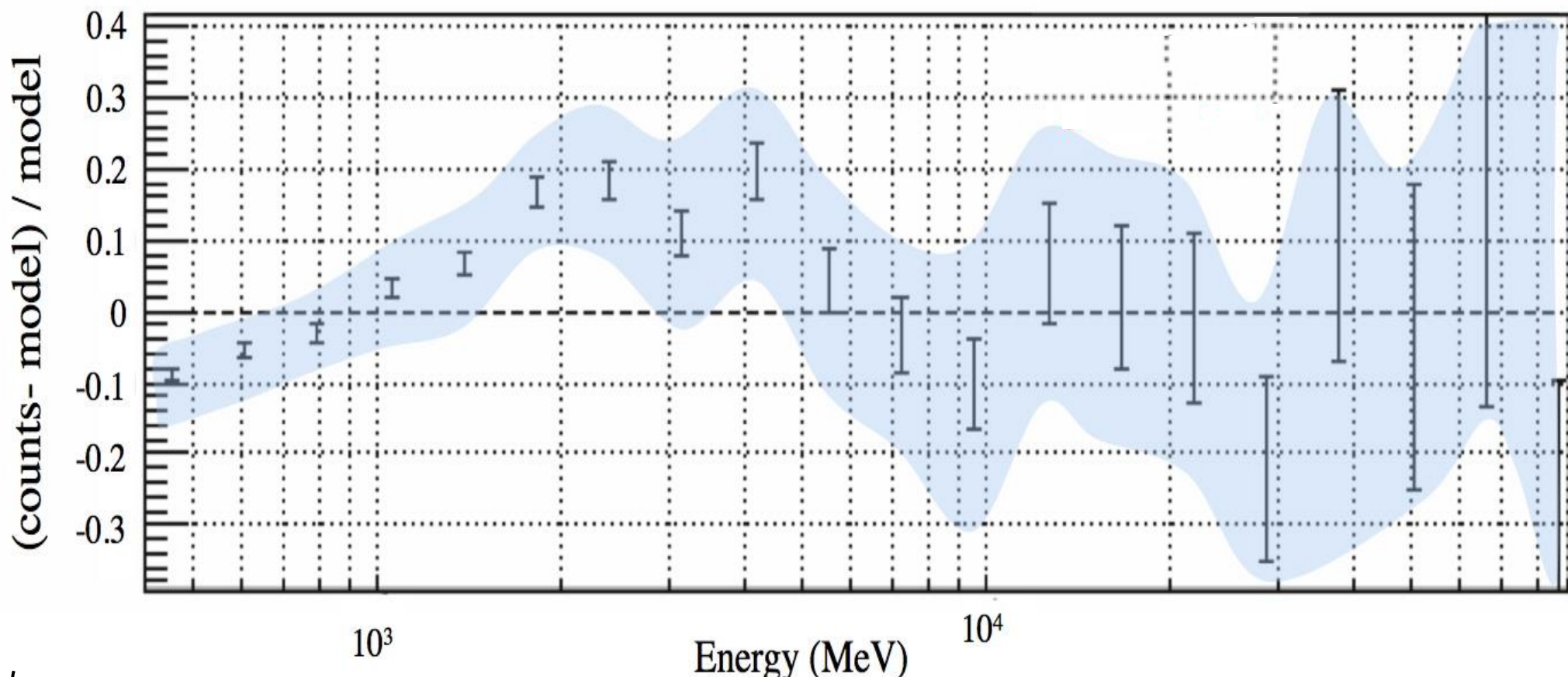
# What has Fermi found: The LAT two-year catalog



# The GeV excess

$7^\circ \times 7^\circ$  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  $\sim 10\%$  at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV



V.Vitale, A.Morselli, Fermi Coll. 2009 arXiv:0912.3828 [Fermi Symposium eConf Proceedings C091122](#)

# the GALACTIC CENTER : any hints of Dark Matter?

the beginning of the history :

## The Galactic Center as a Dark Matter Gamma-Ray Source

A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, Nuclear Physics B 113B (2002) 213-220 [astro-ph/0211327]  
A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio Astroparticle Physics 21, 267-285, 2004 [astro-ph/0305075]

## Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough, Dan Hooper arXiv:0910.2998

## Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

Vincenzo Vitale, Aldo Morselli, the Fermi/LAT Collaboration

Proceedings of the 2009 Fermi Symposium, 2-5 November 2009, eConf Proceedings C091122 arXiv:0912.3828 21 Dec 2009

## Search for Dark Matter with Fermi Large Area Telescope: the Galactic Center

V.Vitale, A.Morselli, the Fermi-LAT Collaboration NIM A 630 (2011) 147-150 (Available online 23 June 2010)

## Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope

Dan Hooper, Lisa Goodenough. (21 March 2011 ). 21 pp. Phys.Lett. B697 (2011) 412-428

.....

## Background model systematics for the Fermi GeV excess

F.Calore, I. Cholis, C. Weniger JCAP03(2015)038 arXiv:1409.0042v1

## Fermi-LAT observations of high-energy $\gamma$ -ray emission toward the galactic centre

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

## The Fermi galactic center GeV excess and implications for dark matter

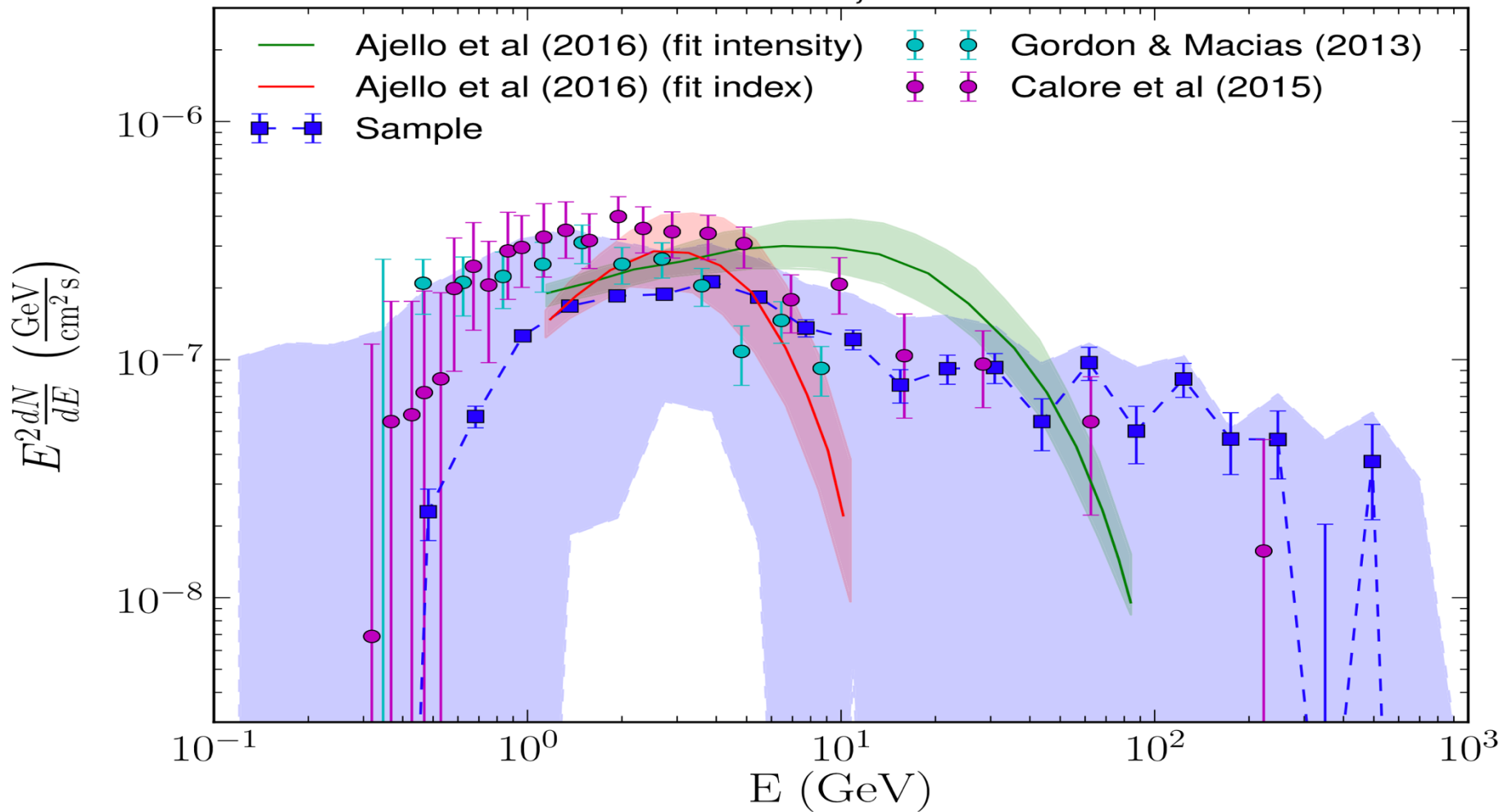
M. Ajello et al. [Fermi-LAT Coll.] Apj 819:44 2016 arXiv:1511.02938

## Revisiting the Gamma-Ray Galactic Center Excess with Multi-Messenger Observations

IC, Zhong, McDermott, Surdutovich, PRD 105, 103023 (2022)



# The GeV excess (Pass8 analysis)



following uncertainties have relatively small effect on the excess spectrum

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

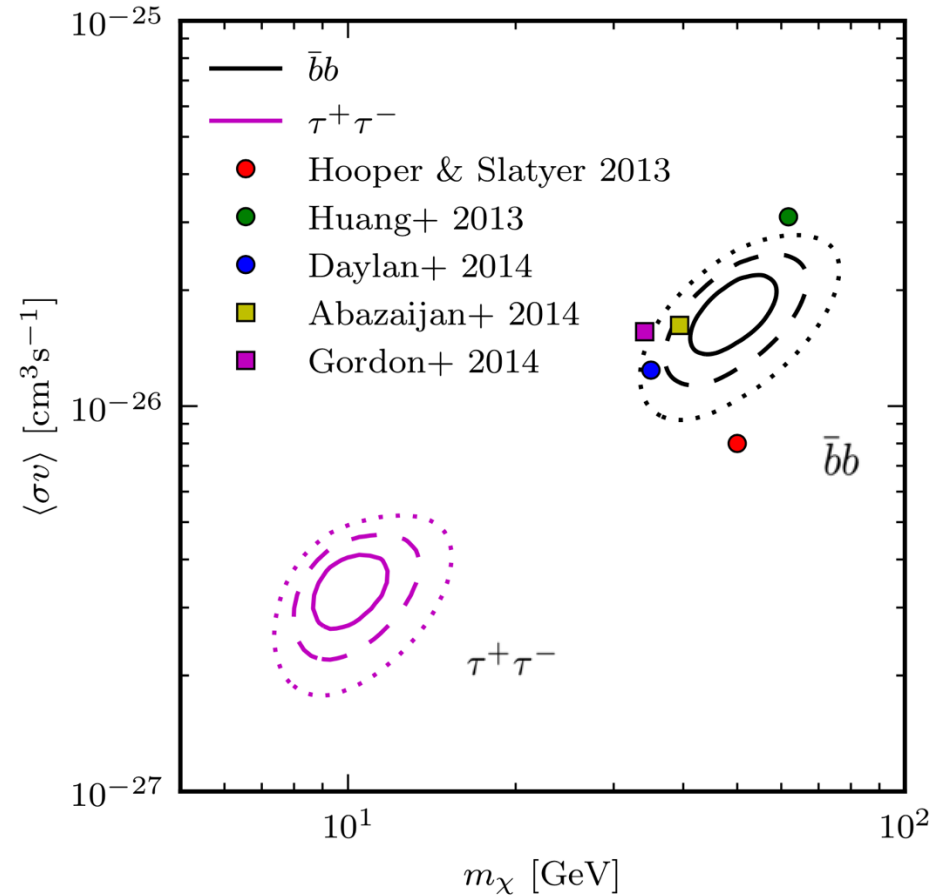
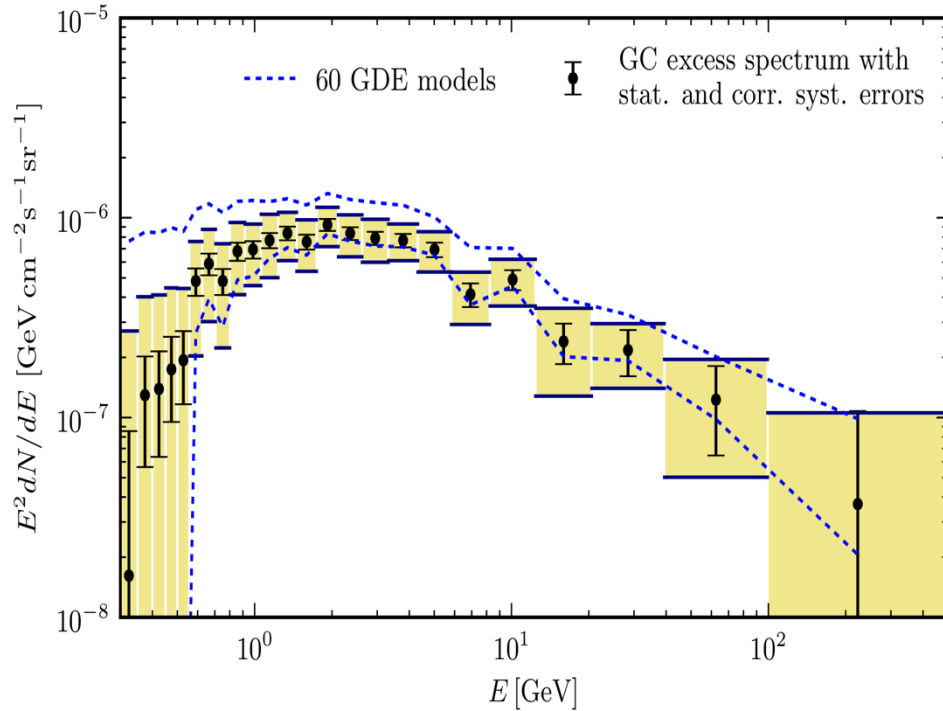
• **Most significant sources of uncertainty are:**

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



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

# The GeV excess



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

Calore et al., arXiv:1409.0042

Cholis et al., Phys. Rev. D 105, 103023 (2022) arXiv:2112.09706

# The GeV excess : Other explanations exist

- past activity of the Galactic center

(e.g. Petrovic et al., arXiv:1405.7928, Carlson & Profumo arXiv:1405.7685)

- Series of Leptonic Cosmic-Ray Outbursts

Cholis et al. arXiv:1506.05119

- Stellar population of the X-bulge and the nuclear bulge

Macias et al. arXiv:1611.06644

- Population of pulsars in the Galactic bulge

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

M.Ajello et al. [Fermi-LAT Coll.] Phys. Rev. D 95, 082007 (2017) [arXiv:1704.07195]

.....

## 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**

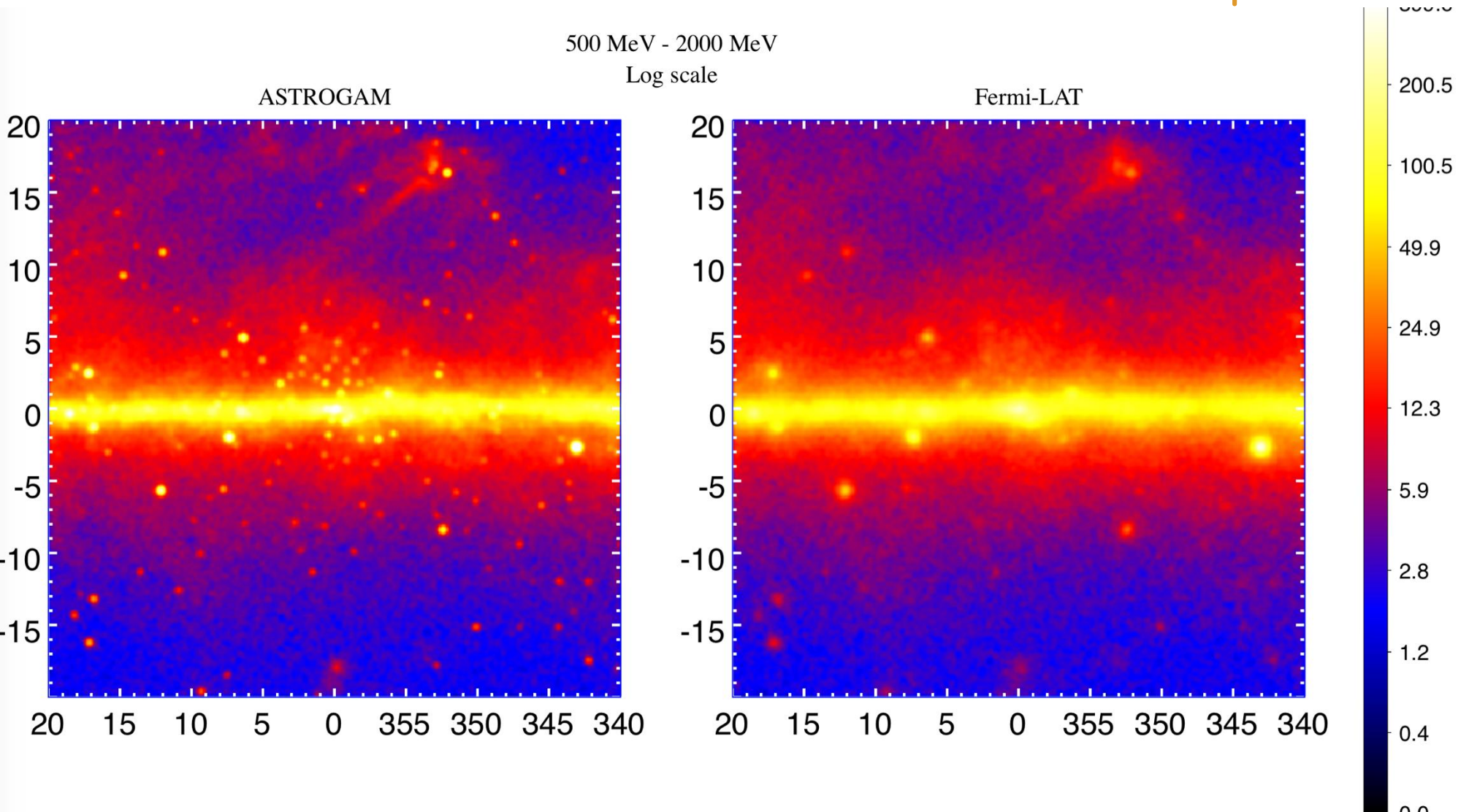
Diffuse emission modeling

Analysis of point sources near the GC

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

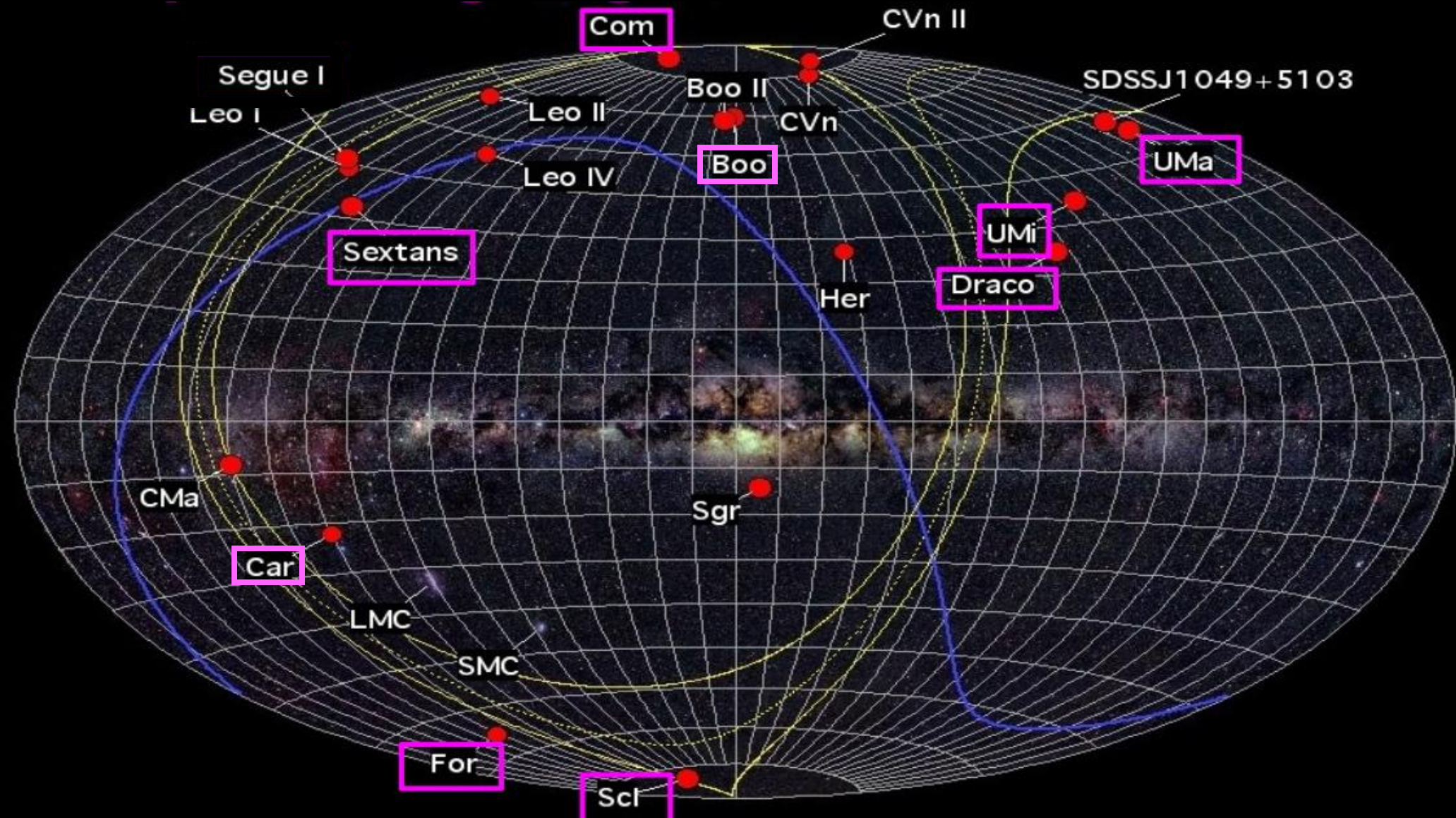
# Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source





# Classical Dwarf spheroidal galaxies: promising targets for DM detection





# Dark Matter in the Milky Way (from simulations)



40 kpc

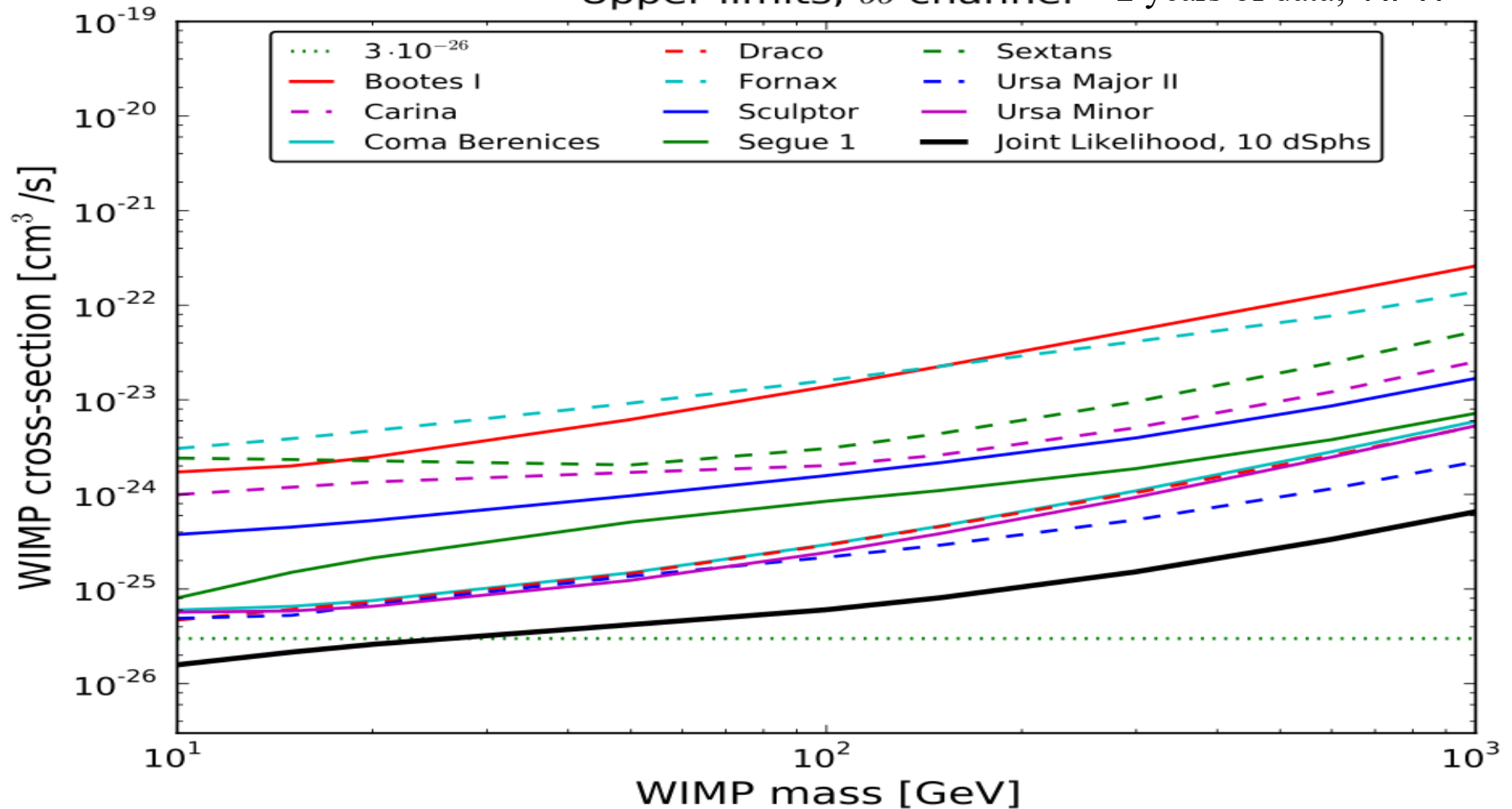
Projected DM square density (constrained) simulations

Springel et al. (Nature, 2005)



# Dwarf Spheroidal Galaxies combined analysis

Upper limits,  $b\bar{b}$  channel 2 years of data, NFW

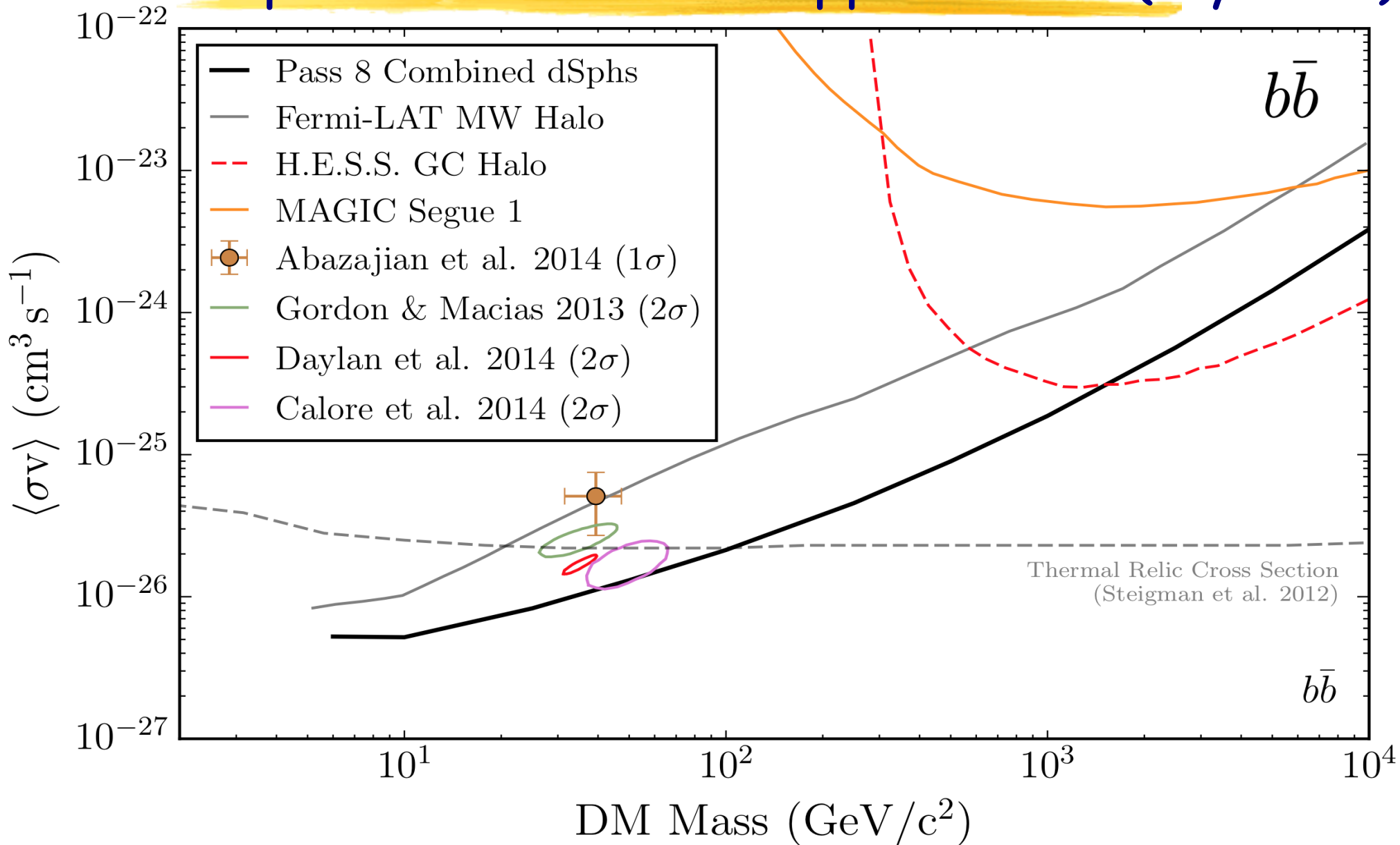


robust constraints including J-factor uncertainties from the stellar data statistical analysis



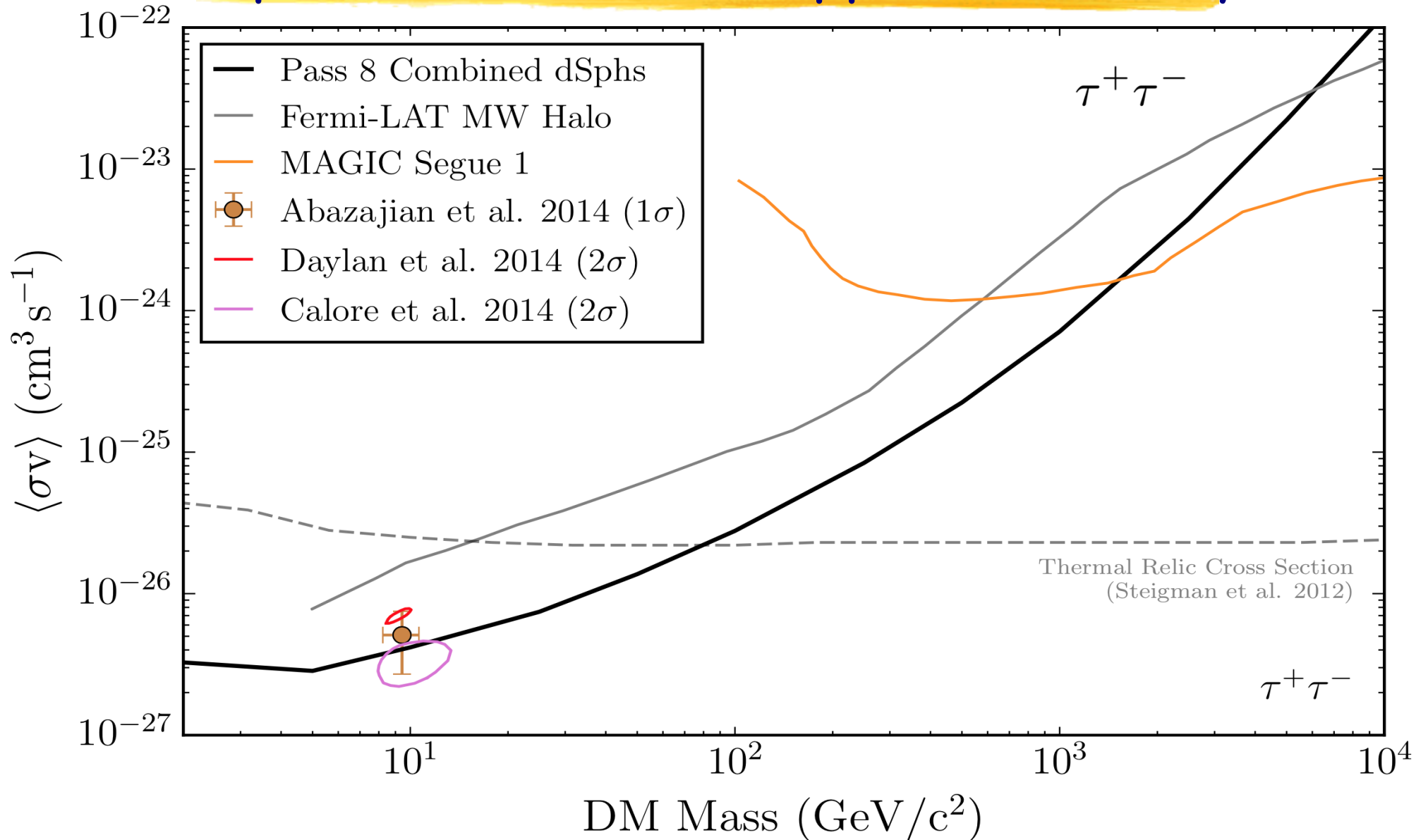
Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

# Dwarf Spheroidal Galaxies upper-limits (6 years)



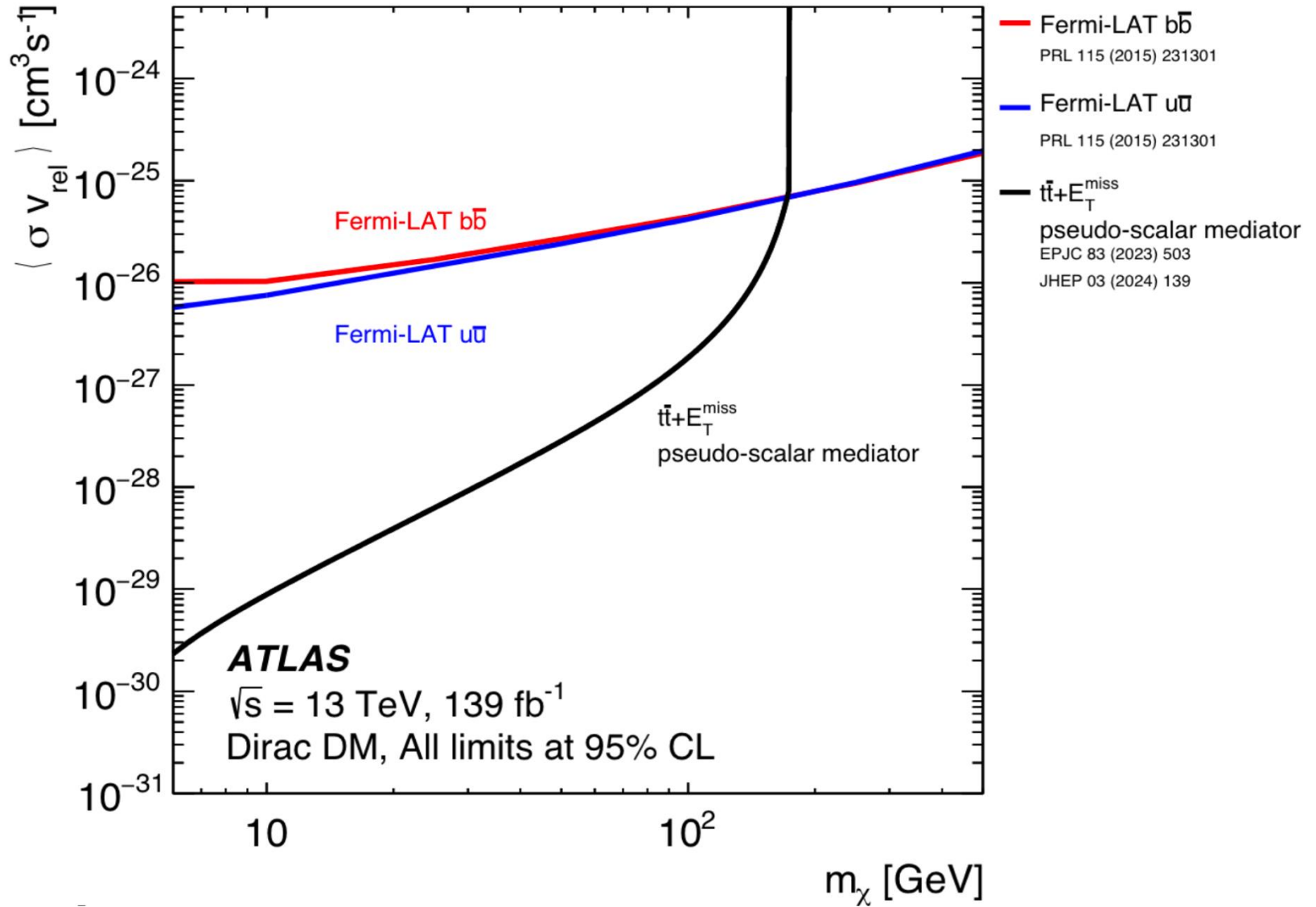
M. Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

# Dwarf Spheroidal Galaxies upper-limits (6 years)



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

# Comparison of ATLAS scalar/pseudo-scalar results with Fermi LAT indire



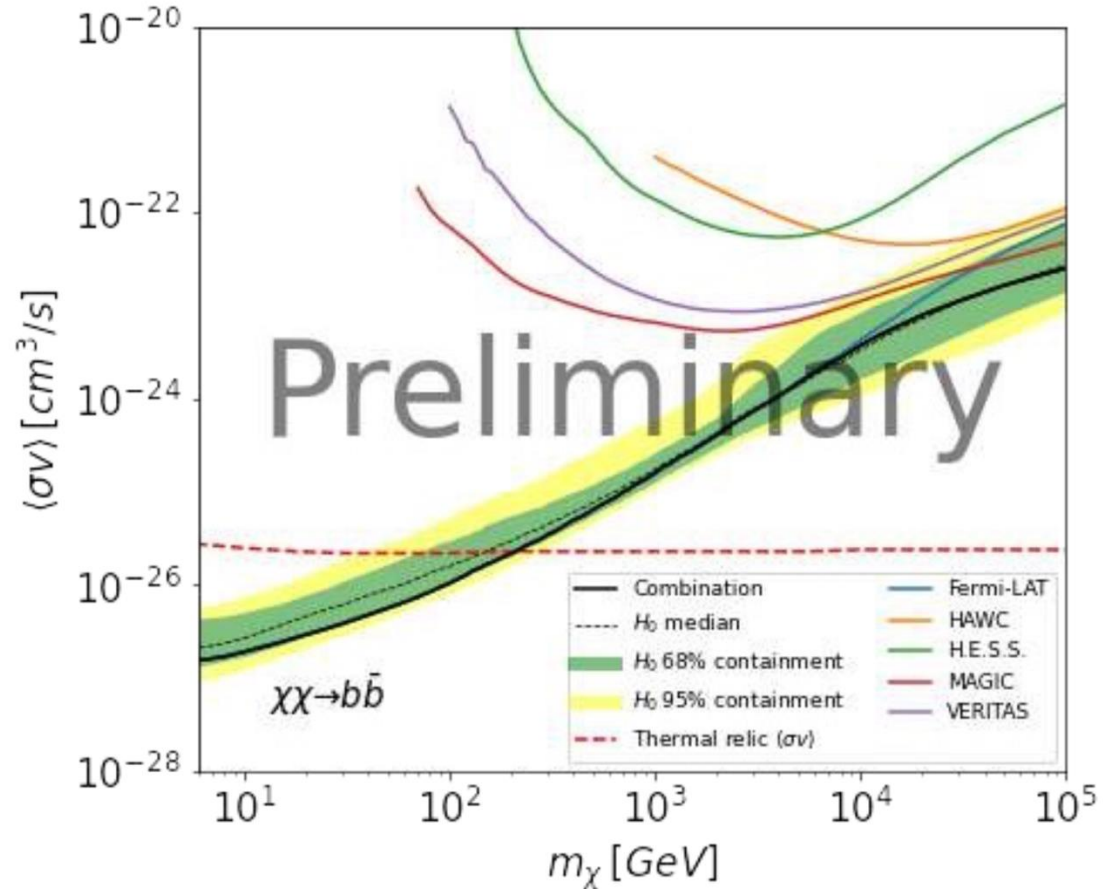
**Annihilation cross section** (cross-section  $\times$  relative velocity  $v_{rel}$ ) averaged over the DM velocity distribution for a pseudo-scalar mediator



# Combining all dSph observations

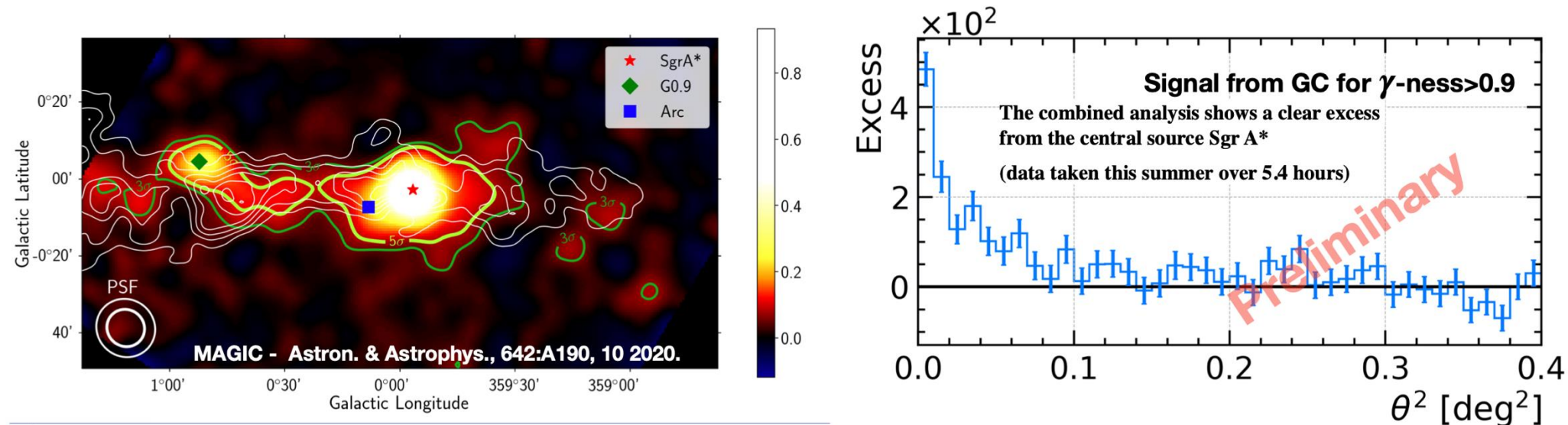


- Combination of the observation results towards 20 dwarf spheroidal galaxies (dSphs)
  - Significant increase of the statistics
  - > Increase the sensitivity to potential dark matter signals
  - Cover the widest energy range ever investigated : 20 MeV – 80 TeV
- Common elements :
  - Agreed model parameters
  - Sharable likelihood table formats
  - Joint likelihood test statistic



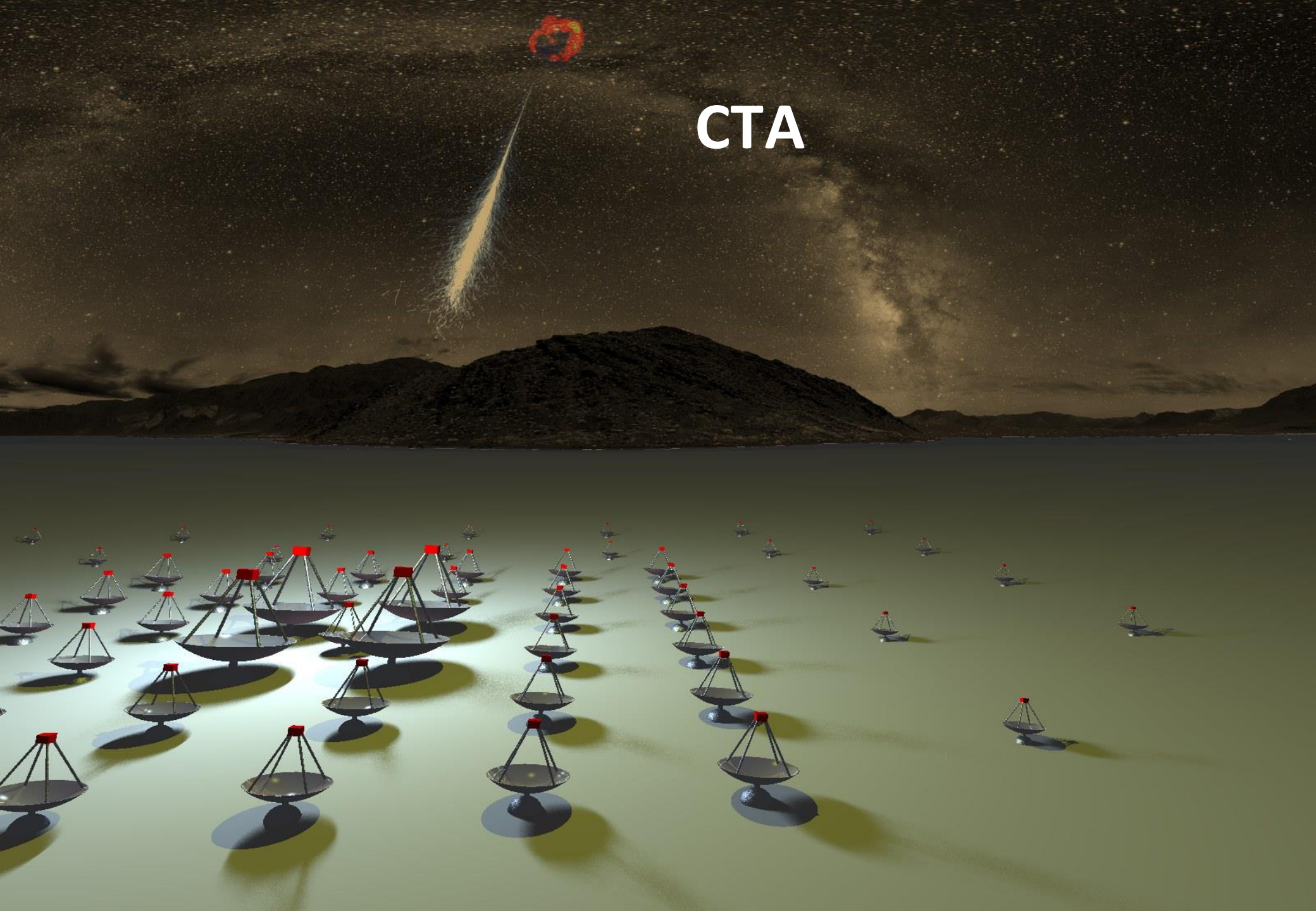
# Joint MAGIC –LST 1 observation of Galactic Center

- The Galactic Center (GC) is one of the target regions for MAGIC + LST-1 observations, given the abundance of science targets (Sgr A\*, Gal. diffuse emission and Dark Matter)
- The GC region culminates at large zenith angle of 58 degree seen at La Palma, thus enlarging the light pool and increasing the efficiency of the stereo triggering of LST array
- At the same time, the complexity of the area, requires improved the angular resolution in order to understand/constrain the origin of the gamma-ray emission [SEP]

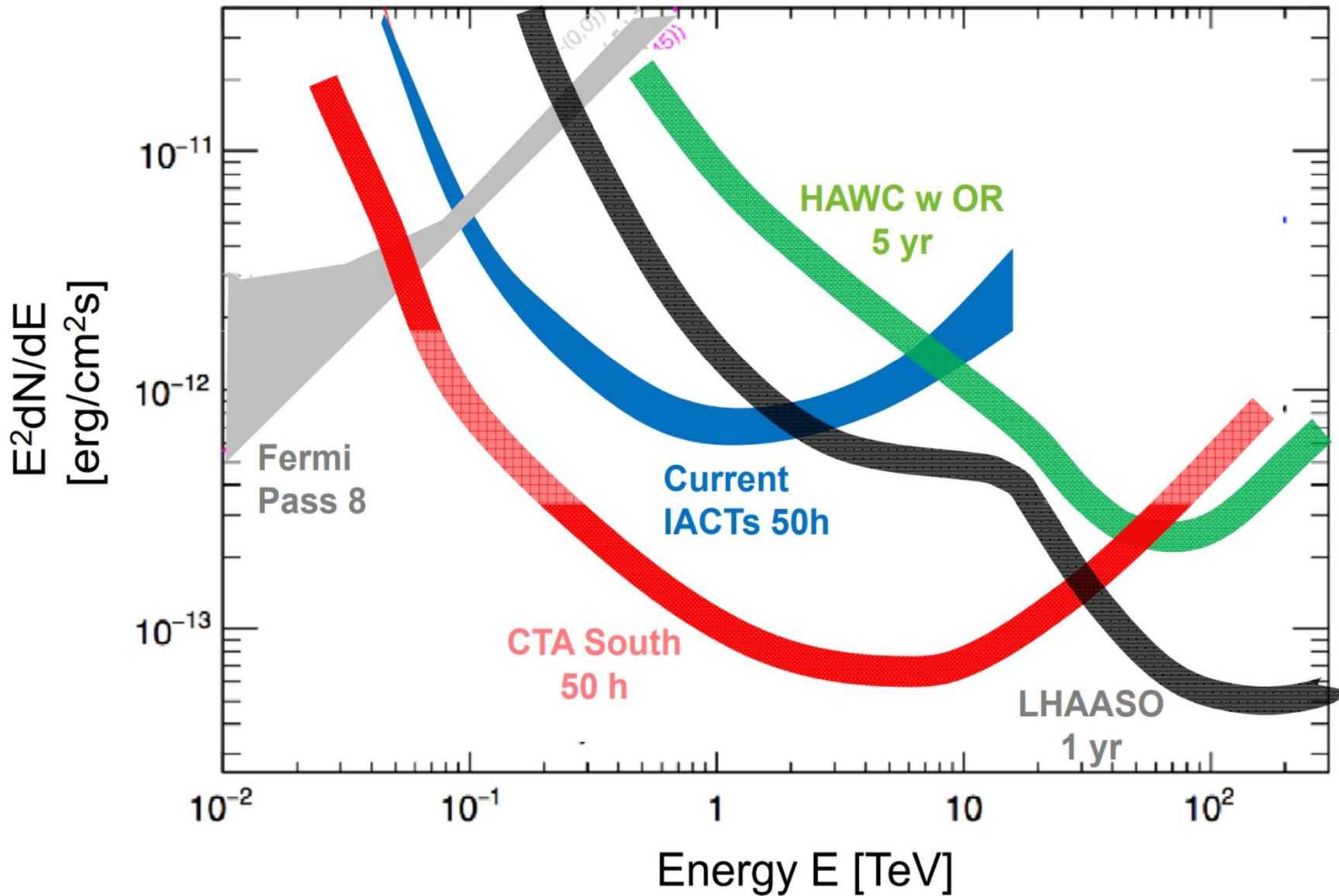




CTA

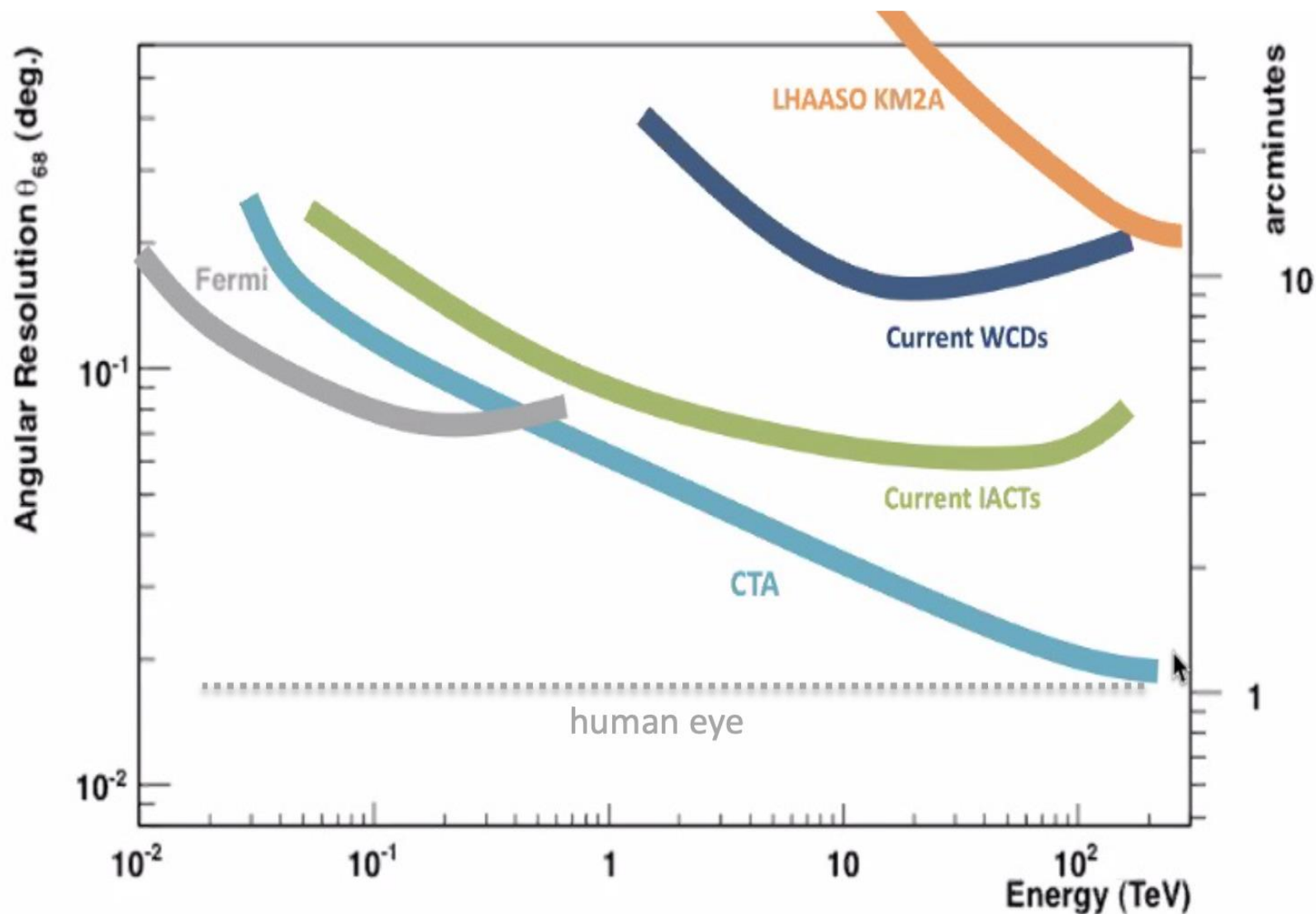


# $\gamma$ -ray detectors sensitivities





# Angular resolution



# Measuring DM densities in dSph halos

Optimal dSphs selected according to:

1. Distance ( $d < 100 \text{ pc}$ )
2. Culmination zenith angle ( $Z_{\text{Amin}} < 30^\circ$ )

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

Surviving sample:

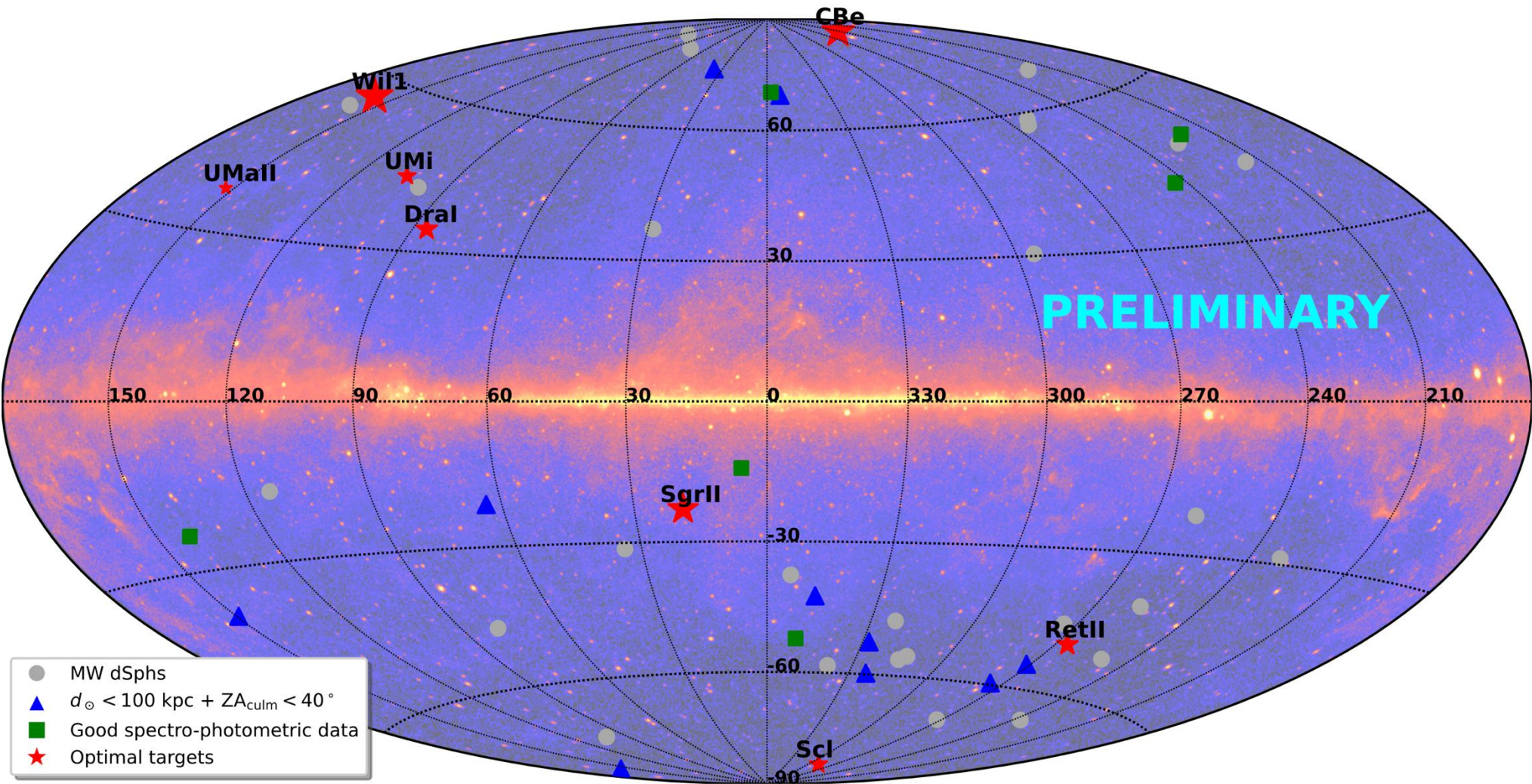
— 6 Northern dSphs (1 classical + 5 ultra-faint)

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

Name	Abbr.	Type	R.A. (hh mm ss)	dec. (dd mm ss)	Distance (kpc)	$Z_{\text{Aculm N}}$ (deg)	$Z_{\text{Aculm S}}$ (deg)	Month
Andromeda XVIII	AndXVIII	uft	00 02 14.5	+45 05 20	$1330 \pm 104$	16.3	69.7	Sep
Aquarius	Aqr	uft	20 46 51.8	-12 50 53	$1030 \pm 57$	41.6	11.8	Aug
<b>Boötes I</b>	BoöI	uft	14 00 06.0	+14 30 00	$65 \pm 3$	14.3	39.1	Apr
<b>Boötes II</b>	BoöII	uft	13 58 00.0	+12 51 00	$39 \pm 2$	15.9	37.5	Apr
<b>Boötes III</b>	BoöIII	uft	13 57 12.0	+26 48 00	$46 \pm 2$	2.0	51.4	Apr
Canes Venatici I	CVnI	uft	13 28 03.5	+33 33 21	$216 \pm 8$	4.8	58.2	Apr
Canes Venatici II	CVnII	uft	12 57 10.0	+34 19 15	$159 \pm 8$	5.6	58.9	Apr
Carina	Car	cls	06 41 36.7	-50 57 58	$106 \pm 1$	79.7	26.3	Dec
Cetus I	CetI	uft	00 26 11.0	-11 02 40	$748 \pm 31$	39.8	13.6	Sep
<i>Cetus II</i>	CetII	uft	01 17 52.8	-17 25 12	$30 \pm 3$	46.2	7.2	Oct
Columbia I	ColI	uft	05 31 26.4	-28 01 48	$182 \pm 18$	56.8	3.4	Dec
<b>Coma Berenices</b>	CBe	uft	12 26 59.0	+23 54 15	$42 \pm 2$	4.9	48.5	Mar
<b>Draco I</b>	DraI	cls	17 20 12.4	+57 54 55	$75 \pm 4$	29.2	82.5	Jun
Draco II	DraII	uft	15 52 47.6	+64 33 55	$20 \pm 3$	35.8	89.2	May
Eridanus II	EriII	uft	03 44 21.5	-43 31 48	$330 \pm 16$	72.3	18.9	Nov
<i>Eridanus III</i>	EriIII	uft	02 22 45.5	-52 16 48	$95 \pm 27$	81.0	27.7	Oct
Fornax	For	cls	02 39 59.3	-34 26 57	$146 \pm 1$	63.2	9.8	Oct
Grus I	GruI	uft	22 56 42.4	-50 09 48	$120 \pm 17$	75.9	25.5	Sep
<i>Grus II</i>	GruII	uft	22 04 04.8	-46 26 24	$53 \pm 5$	75.2	21.8	Aug
Hercules	Her	uft	16 31 02.0	+12 47 30	$137 \pm 11$	16.0	37.4	May
<i>Horologium I</i>	HorI	uft	02 55 28.9	-54 06 36	$87 \pm 23$	82.9	29.5	Oct
Hydra II	HyaII	uft	12 21 42.1	-31 59 07	$134 \pm 10$	60.7	7.4	Mar
<i>Indus I</i>	IndI	uft	21 08 48.1	-51 09 36	$69 \pm 16$	79.9	26.5	Aug
Indus II	IndII	uft	20 38 52.8	-6 09 36	$214 \pm 16$	74.9	21.5	Aug
<b>Laevens 3</b>	Lae3	uft	21 06 54.5	+4 58 48	$67 \pm 3$	13.8	39.6	Aug
Leo I	LeoI	cls	11 58 28.1	+12 18 23	$272 \pm 10$	16.5	36.9	Feb
Leo II	LeoII	cls	11 13 28.8	+22 09 06	$240 \pm 9$	6.6	46.8	Mar
Leo IV	LeoIV	uft	11 32 57.0	-00 32 00	$151 \pm 4$	29.3	24.1	Mar
Leo V	LeoV	uft	11 31 09.6	+02 13 12	$169 \pm 5$	26.5	26.9	Mar
Leo T	LeoT	uft	09 34 53.4	+17 03 05	$377 \pm 28$	11.7	41.7	Feb
Phoenix I	PheI	uft	01 51 06.3	-44 26 41	$427 \pm 31$	73.2	19.8	Oct
<i>Phoenix II</i>	PheII	uft	23 39 57.6	-54 24 36	$95 \pm 18$	83.2	29.8	Sep
Pictor I	PicI	uft	04 43 48.0	-50 16 48	$126 \pm 24$	79.0	25.7	Nov
Pisces II	PscII	uft	22 58 31.0	+05 57 09	$182 \pm 13$	22.8	30.6	Sep
<i>Reticulum II</i>	RetII	uft	03 35 40.9	-54 03 00	$32 \pm 2$	82.8	29.4	Nov
Reticulum III	RetIII	uft	03 45 26.3	-60 27 00	$92 \pm 13$	89.2	35.8	Nov
<i>Sagittarius I</i>	SgrI	dis	18 55 19.5	-30 32 43	$31 \pm 1$	59.3	5.9	Jul
<i>Sagittarius II</i>	SgrII	uft	19 52 40.5	-22 04 05	$67 \pm 5$	50.8	2.6	Jul
<i>Sculptor</i>	Scl	cls	01 00 09.4	-33 42 33	$84 \pm 2$	62.5	9.1	Oct
<b>Segue 1</b>	Seg1	uft	10 07 04.0	+16 04 55	$23 \pm 2$	12.7	40.7	Feb
<b>Segue 2</b>	Seg2	uft	02 19 16.0	+20 10 31	$36 \pm 2$	8.6	44.8	Oct
<i>Sextans</i>	Sex	cls	10 13 03.0	-01 36 53	$84 \pm 3$	30.4	23.0	Feb
<b>Triangulum II</b>	TriII	uft	02 13 17.4	+36 10 42	$30 \pm 2$	7.4	60.8	Oct
Tucana I	TucI	uft	22 41 49.6	-64 25 10	$855 \pm 35$	—	39.8	Sep
Tucana II	TucII	uft	22 52 16.7	-58 33 36	$58 \pm 6$	87.3	33.9	Sep
Tucana III	TucIII	uft	23 56 35.9	-59 36 00	$25 \pm 2$	88.4	35.0	Sep
Tucana IV	TucIV	uft	00 02 55.3	-60 51 00	$48 \pm 4$	89.6	36.2	Sep
Ursa Major I	UMaI	uft	10 34 52.8	+51 55 12	$105 \pm 2$	23.2	76.6	Mar
Ursa Major II	UMaII	uft	08 51 30.0	+63 07 48	$35 \pm 2$	34.4	87.8	Feb
Ursa Minor	UMi	cls	15 09 08.5	+67 13 21	$68 \pm 2$	38.5	—	May
<b>Willman 1</b>	Will	uft	10 49 21.0	+51 03 00	$38 \pm 7$	22.3	75.7	Mar



# Dwarf Spheroidal Galaxies: Selection of optimal candidates for CTA

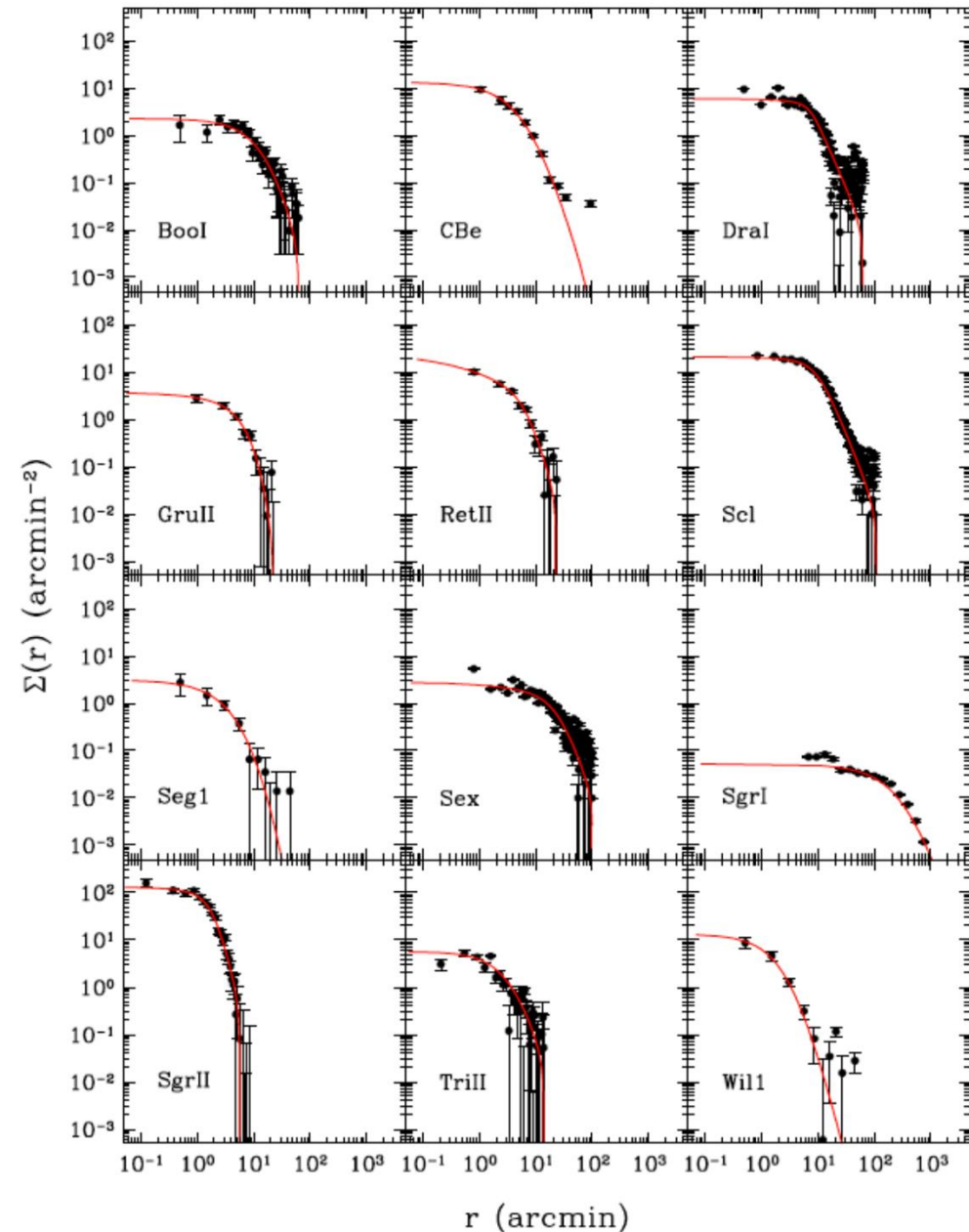


Optimal dSphs selected according to:

- 1. distance ( $d < 100 \text{ pc}$ )
  - 2. culmination zenith angle ( $ZA < 40^{\circ}$ )
  - 3. availability of good spectro-photometric data.
- Surviving sample: 8 Northern dSphs (2 classical + 6 ultra-faint) 6 Southern dSphs (3 classical + 3 ultra-faint)

# Measuring Dark Matter densities in dSph halos

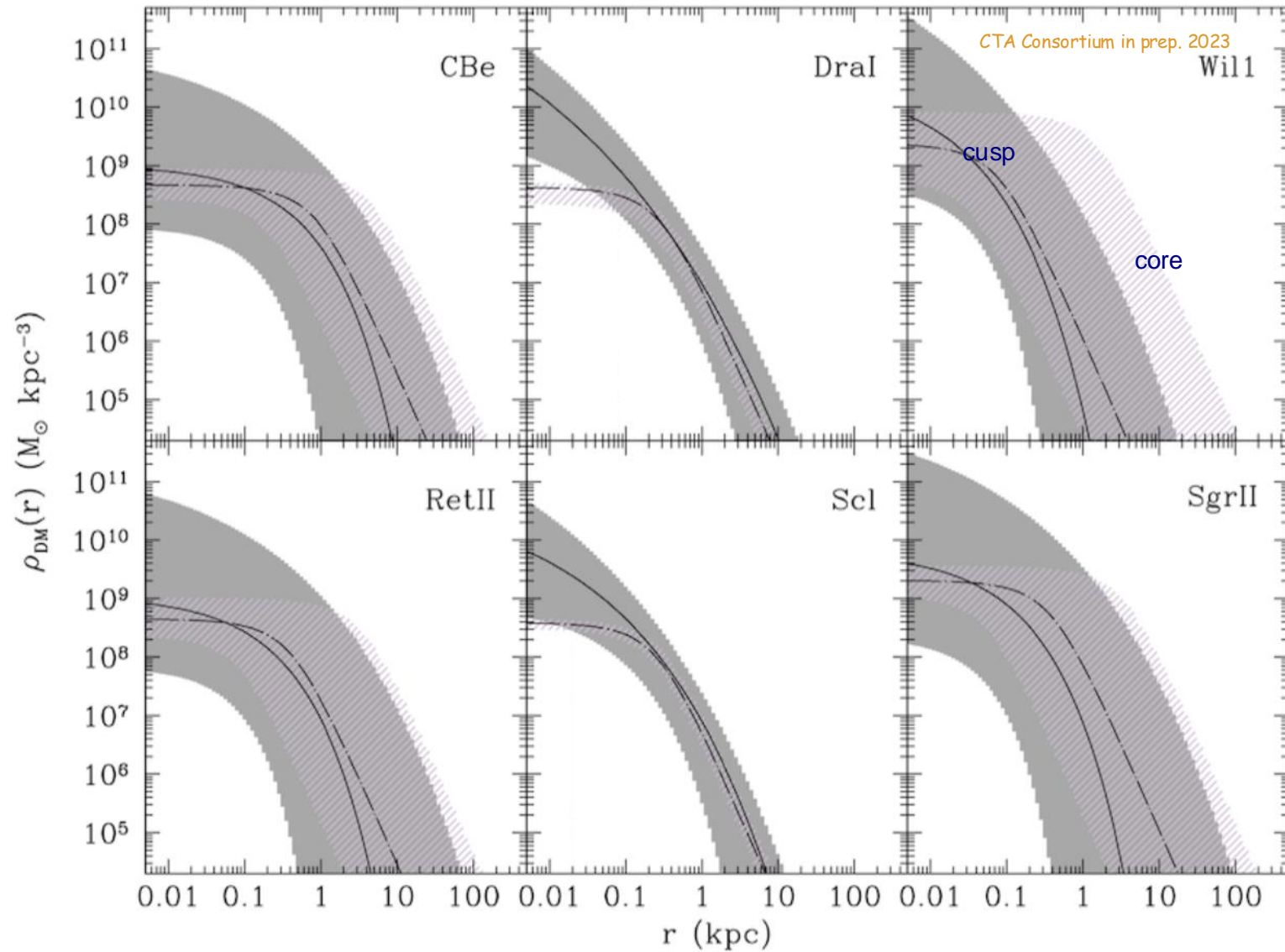
Best-fit brightness profiles  $\Sigma(r)$  of the analyzed dSphs as a function of the object's projected (2D) radial coordinate  $r$  from the dSph centroid



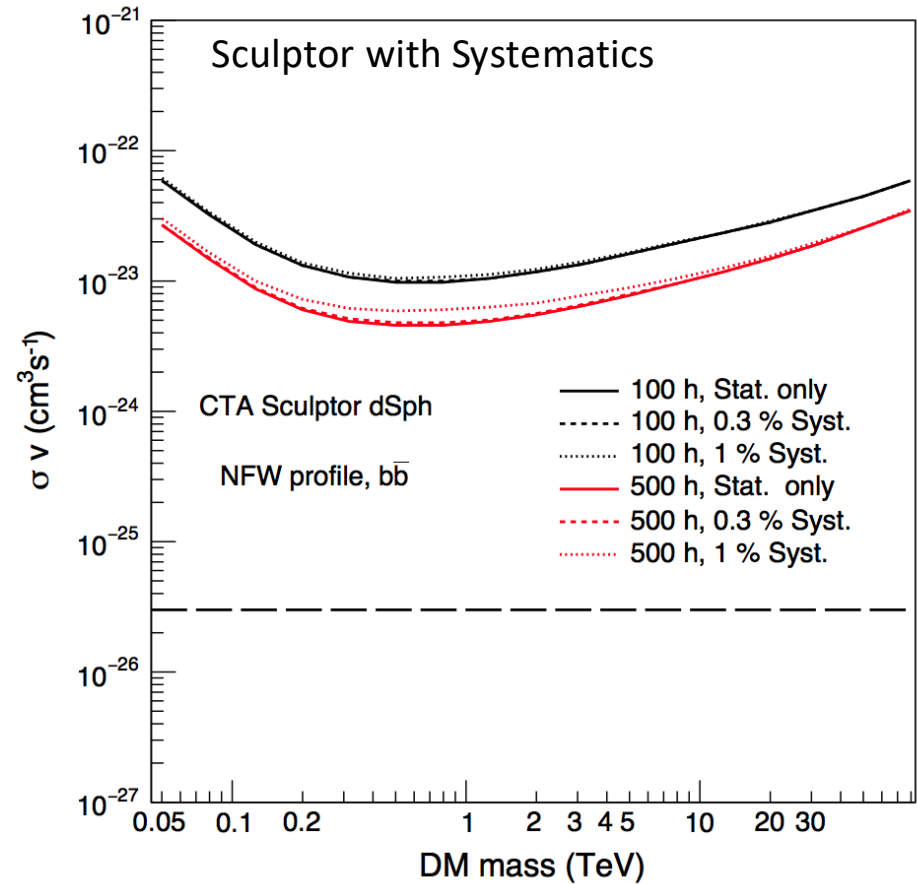
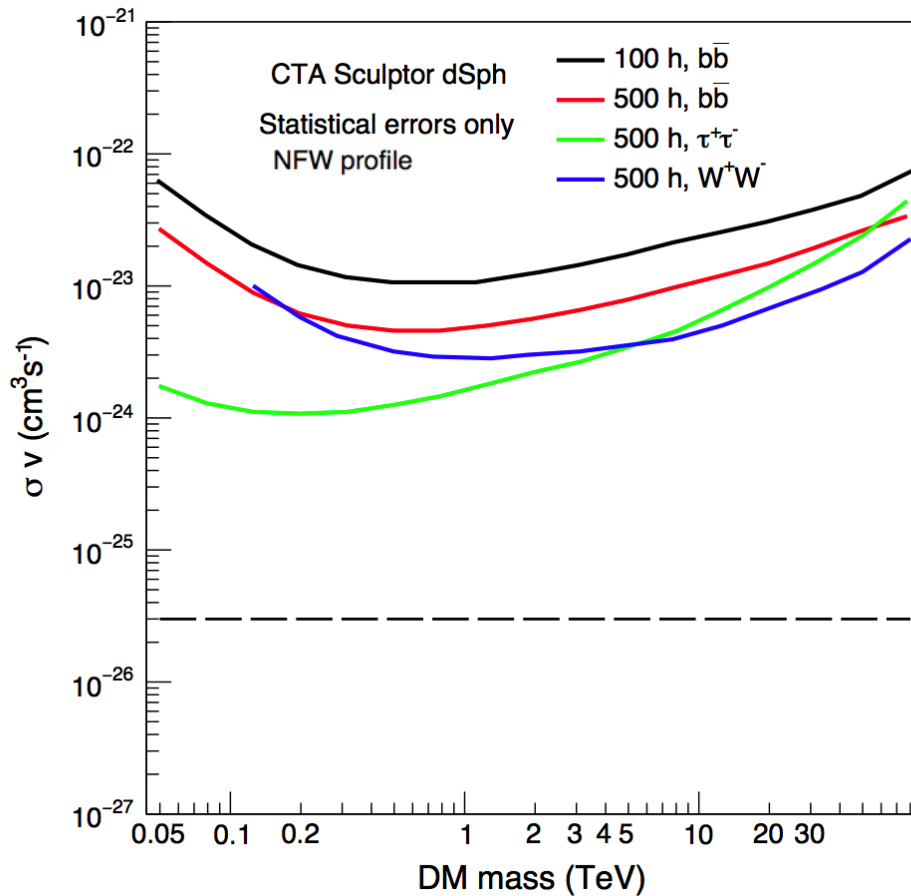


# Measuring Dark Matter densities in dSph halos

## Core and cusp DM density profiles for 6 dSph targets



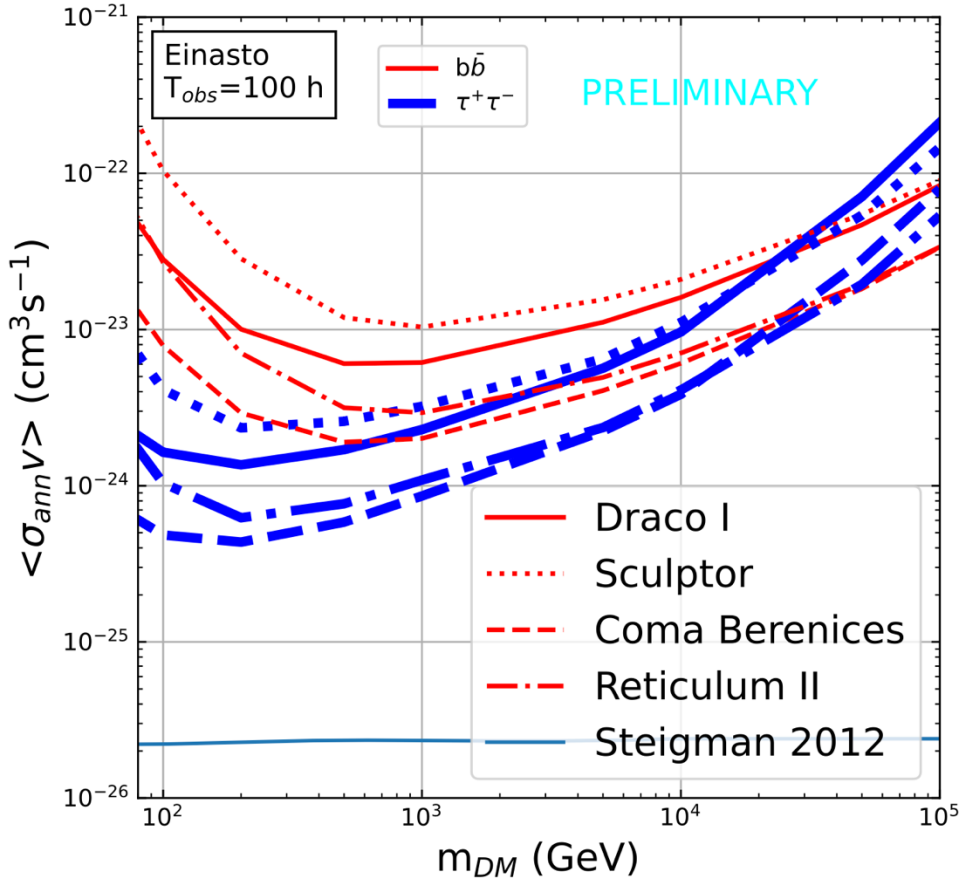
# Dwarf Spheroidal Galaxies: CTA Sensitivity



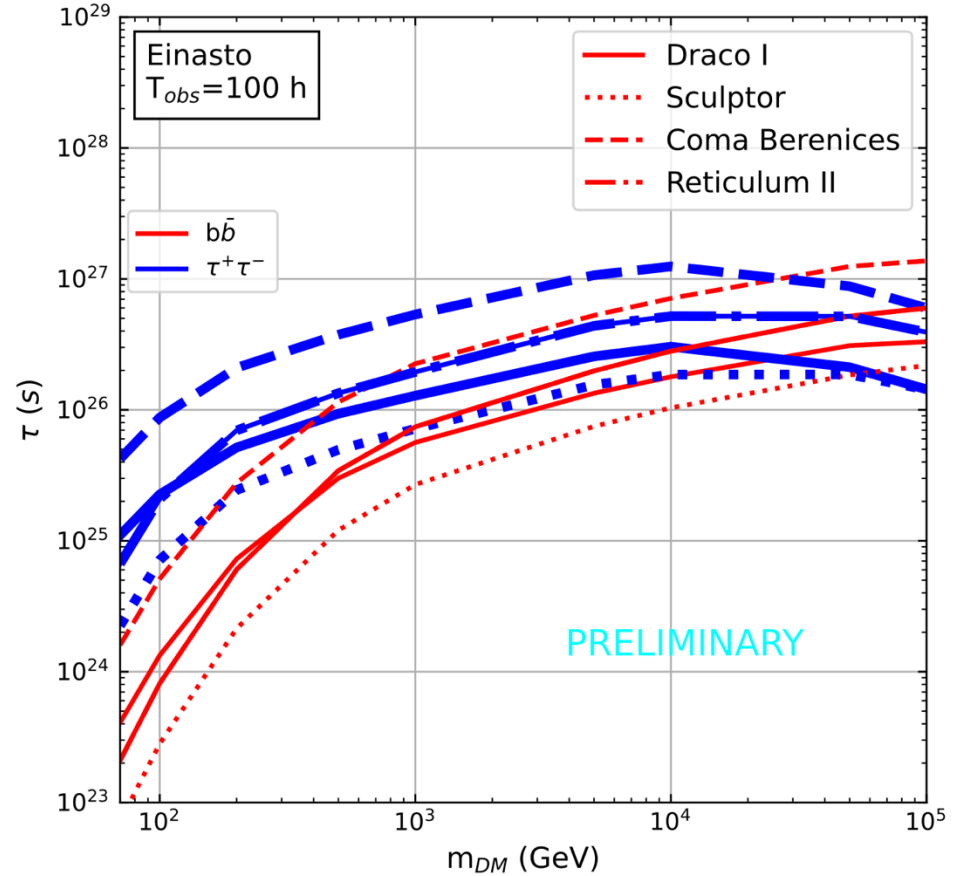
There are several of the newly discovered dSph that have a better case for being a promising target,  
 Will choose most promising targets before observations with the latest knowledge.

# Dwarf Spheroidal Galaxies: CTA Sensitivity

upper limits on annihilating DM cross sections



lower limits on the particle lifetime

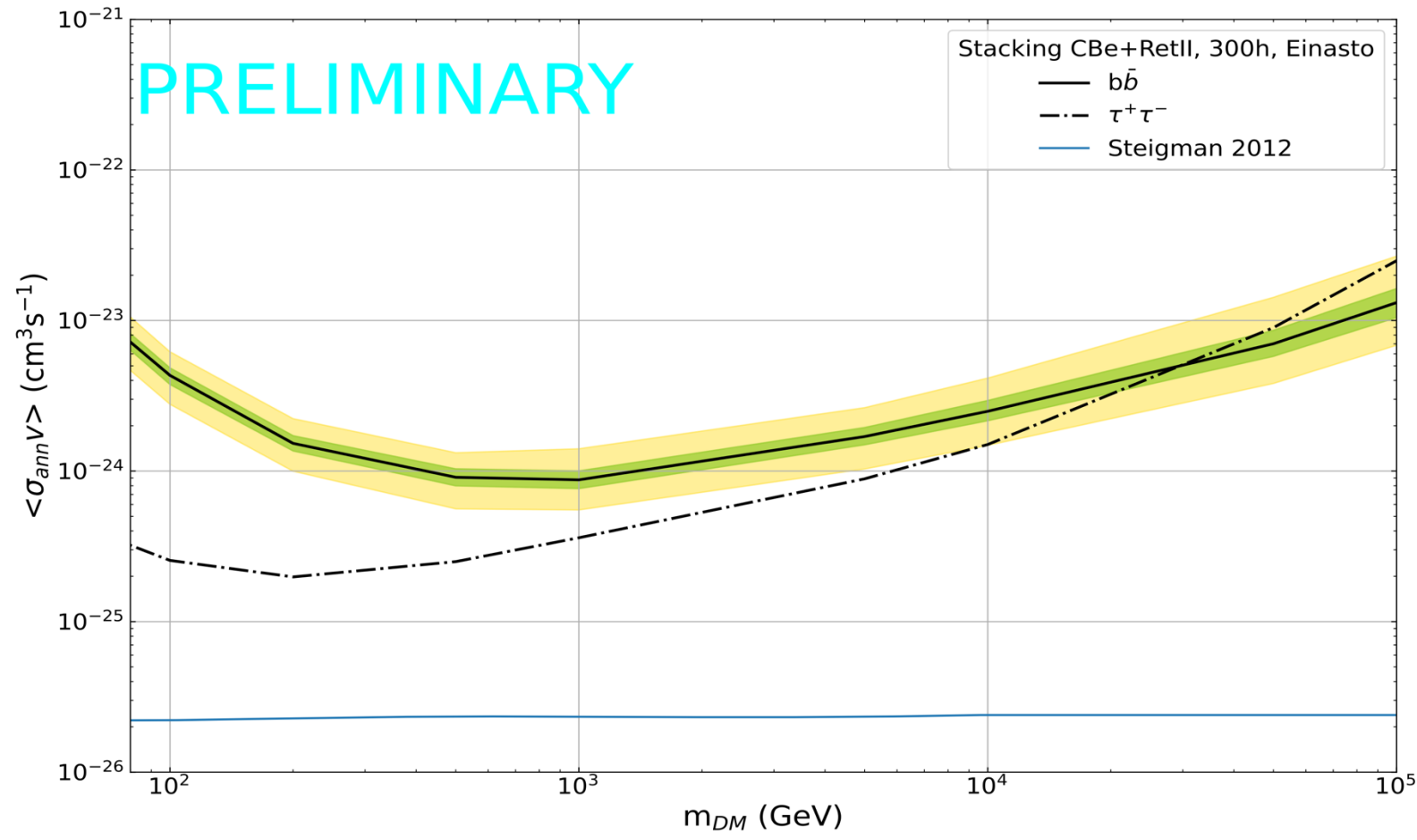


computed with the Einasto DM density profile derived by CLUMPY, computed assuming 100 h of observation for annihilation in the two pure DM channels  $b\bar{b}$  and

$\tau^+\tau^-$

CTA Consortium paper in prep. and ICRC 2023 by the dSph task force F. G. Saturni, M. Doro, A. Morselli, G. Rodríguez-Fernández

# Dwarf Spheroidal Galaxies: Stacking analysis

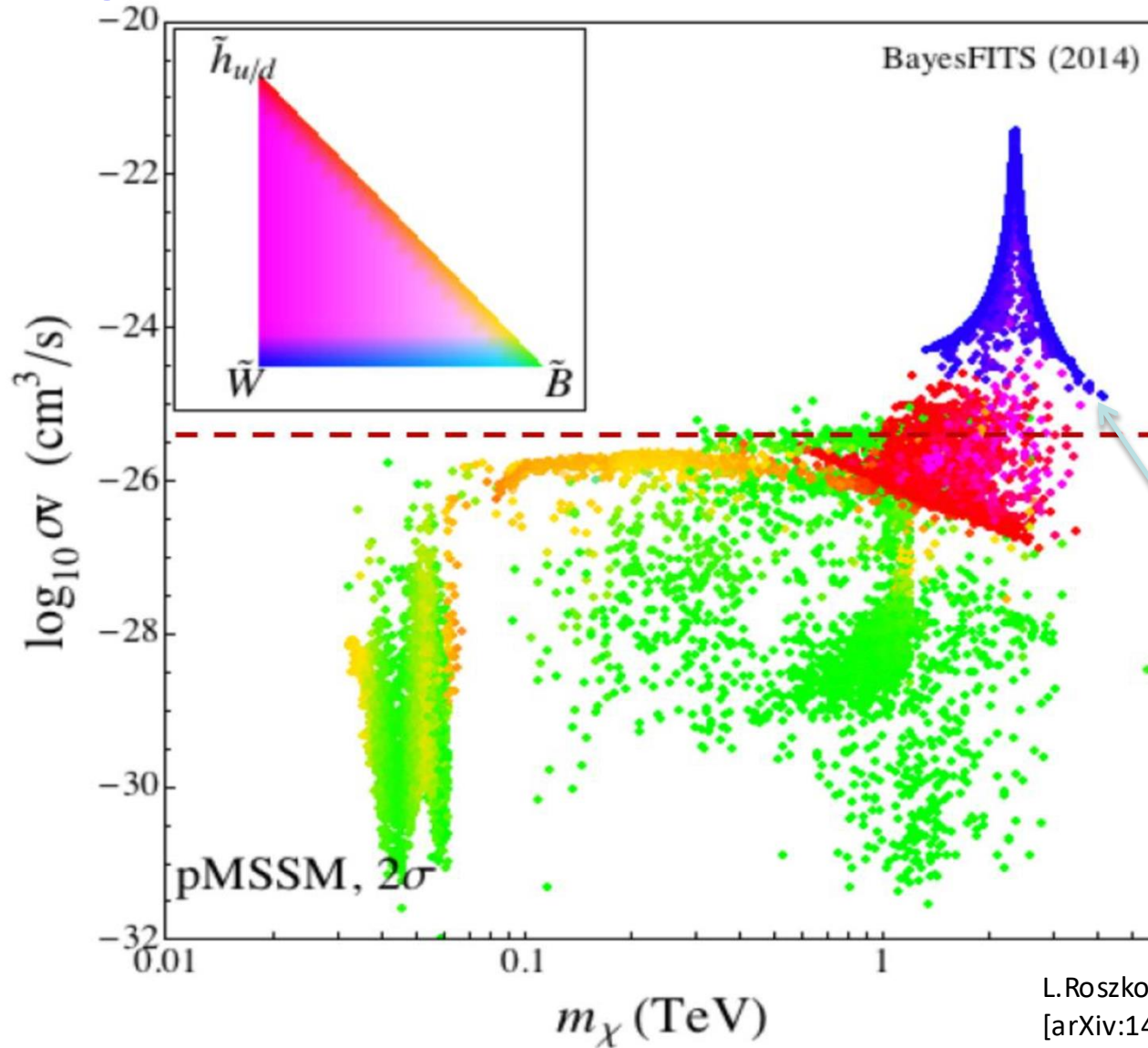


- Stacking analysis performed on 600 h of CBe+RetII observations (300 h each) for the DM annihilation into  $b\bar{b}$  and  $\tau^+\tau^-$
- Depending on the choice of target and the interaction channel, CTA can reach x-sections  $< 10^{-24} \text{ cm}^3 \text{ s}^{-1}$  for DM particle masses  $> 1 \text{ TeV}$ .

CTA Consortium paper in prep. and ICRC 2023 by the dSph task force F. G. Saturni, M. Doro, A. Morselli, G. Rodríguez-Fernández



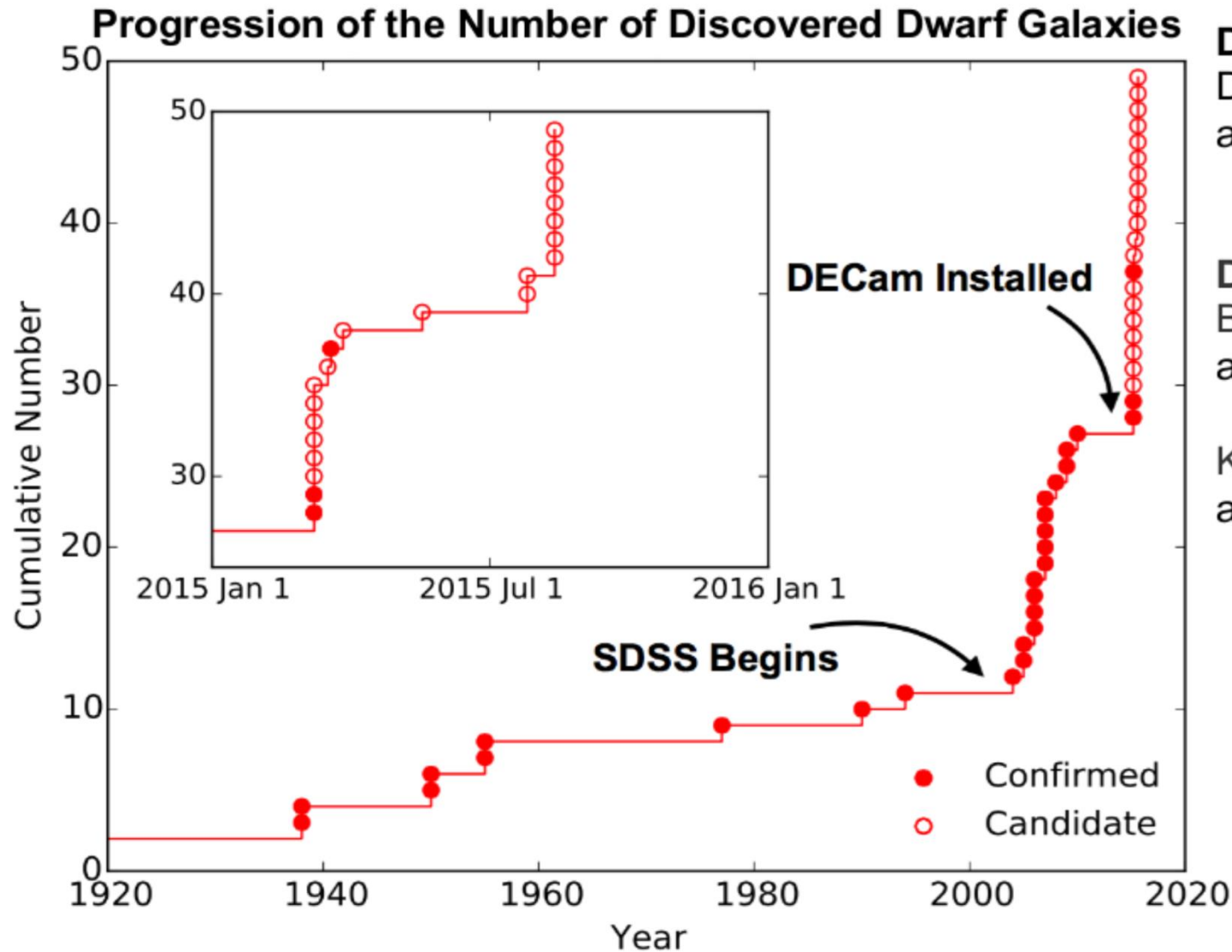
note:the “thermal” cross section is only a reference value. The real cross section can be higher or lower



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

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

# Dwarf Spheroidal Galaxies: Growing number of known targets

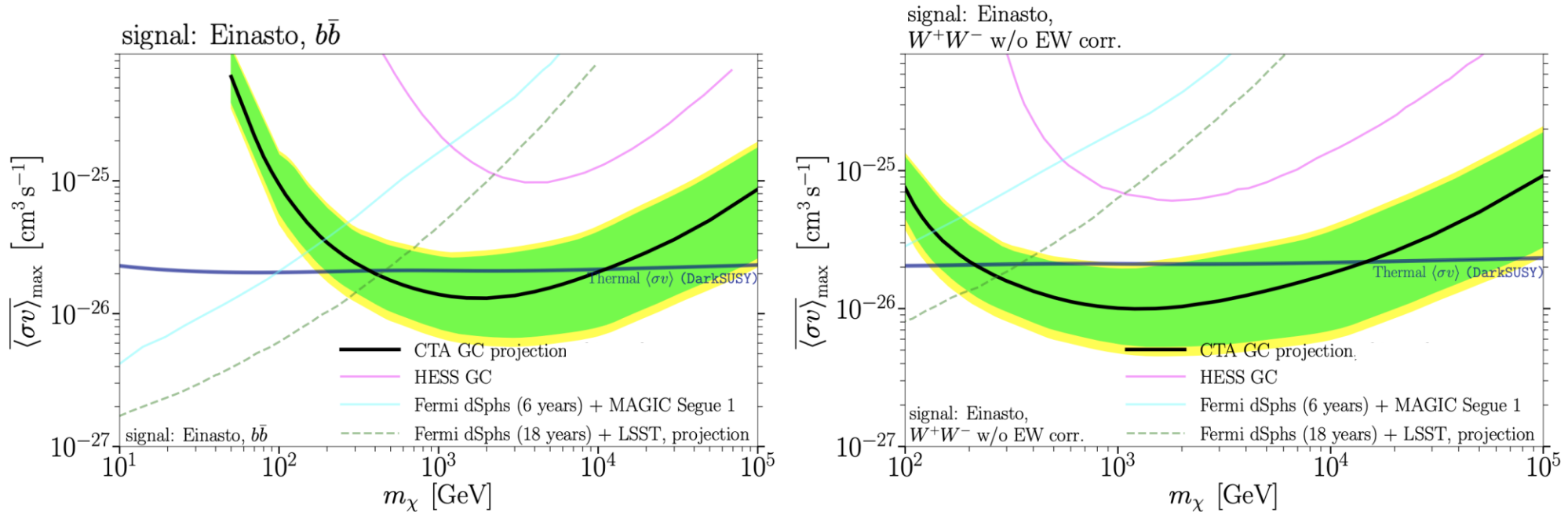


**DES Year 2 Data:**  
Drlica-Wagner+,  
arXiv:1508.03622

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

Koposov+:  
arXiv:1503.02079

# Galactic center CTA Sensitivity



## • Einasto profile

525 h

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

• Main source of background : sources, Fermi Bubble, interstellar  $\gamma$ , residual CR



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



# 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							
<i>in case of detection at GC, large <math>\sigma v</math></i>										
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
<i>in case of detection at GC, small <math>\sigma v</math></i>										
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
<i>in case of no detection at GC</i>										
<i>Best Target</i>				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.

# CTA Key Science Project Targets



- Galactic Center

high DM density but high astrophysical emissions

- dSph

no background but low signal

- LMC

neaby & massive but astrophysical emissions

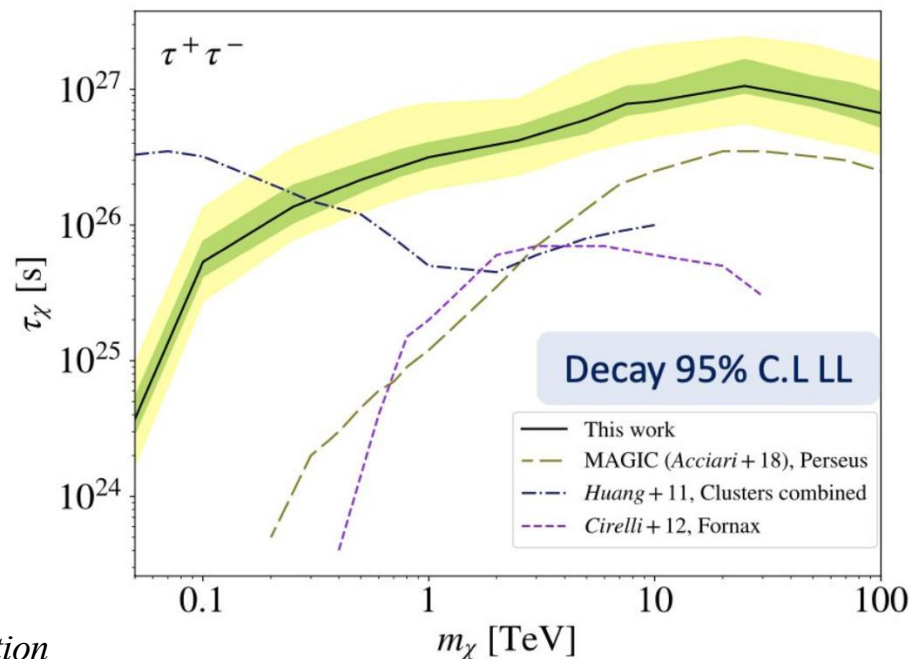
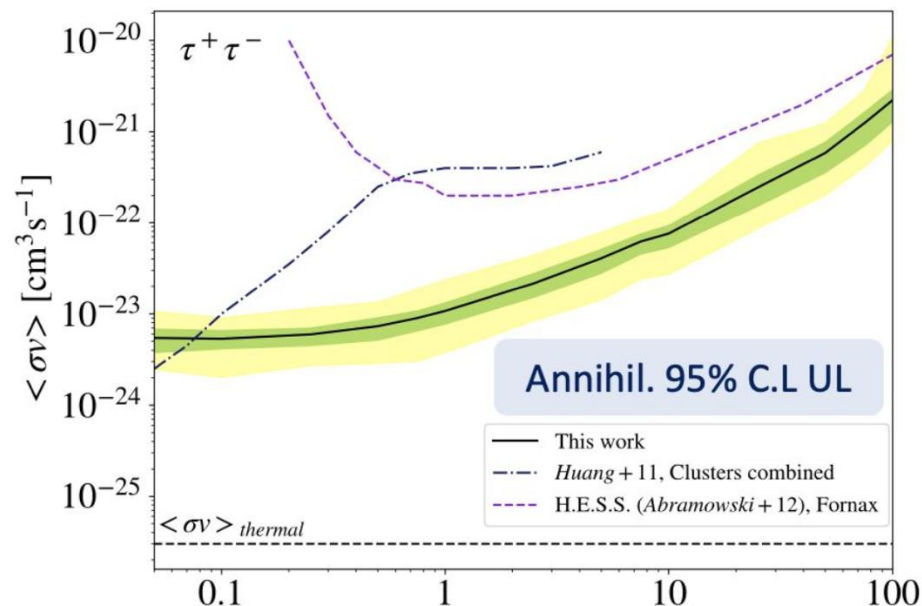
- galaxy cluster

very massive (best for decay )

# Perseus cluster

## Expected CTA sensitivity

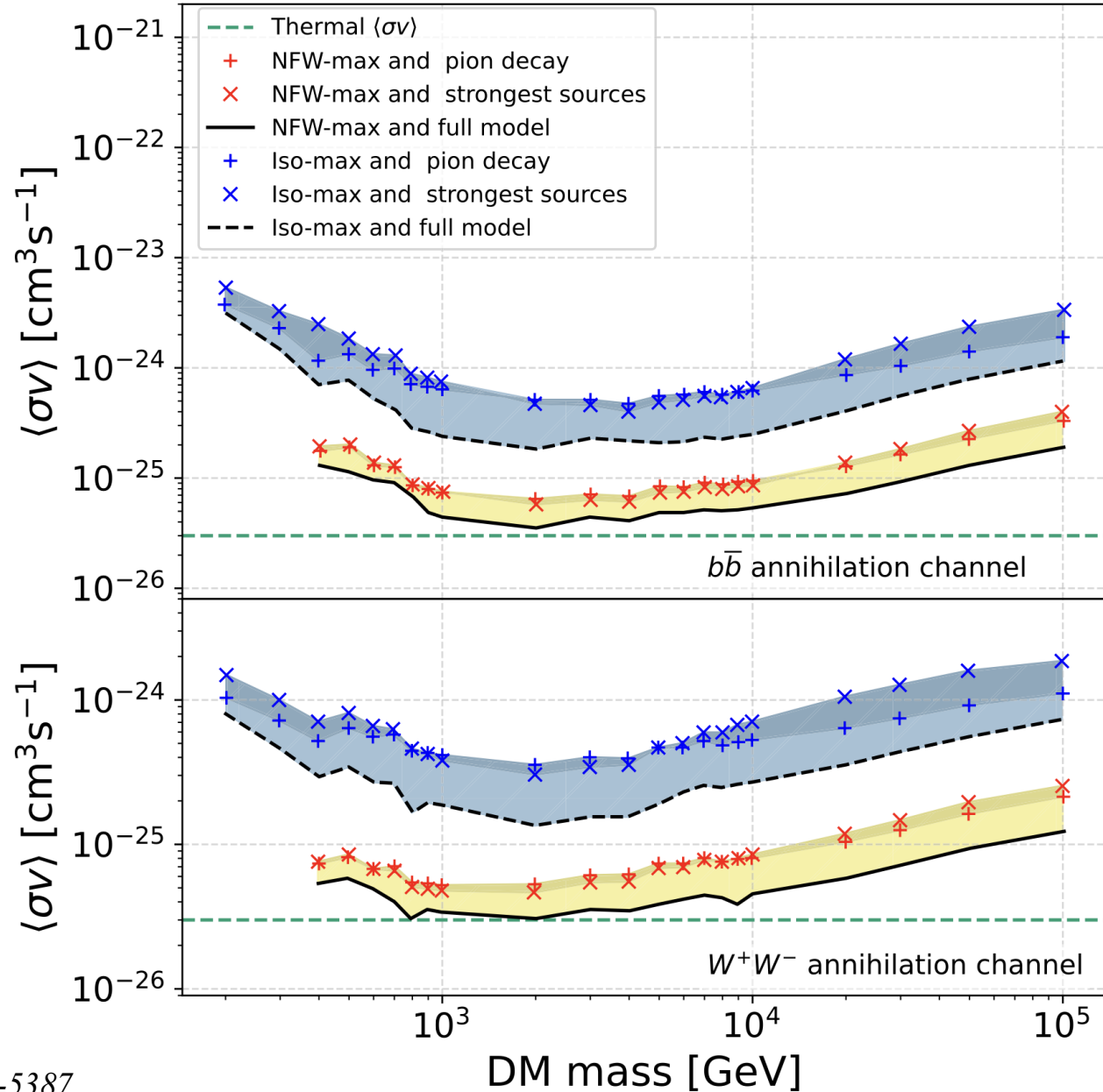
- Distance: 75 Mpc
- Dark matter content:  $\log_{10} \Omega [\text{GeV}^2 \text{cm}^{-5}] = 18.43$   
 $\log_{10} D [\text{GeV}^2 \text{cm}^{-2}] = 19.20$
- Observation time: 300 h
- Astrophysical gamma-ray sources:
  - Active Galactic Nuclei
  - diffuse emission (CR interactions)



The CTA Consortium, in preparation

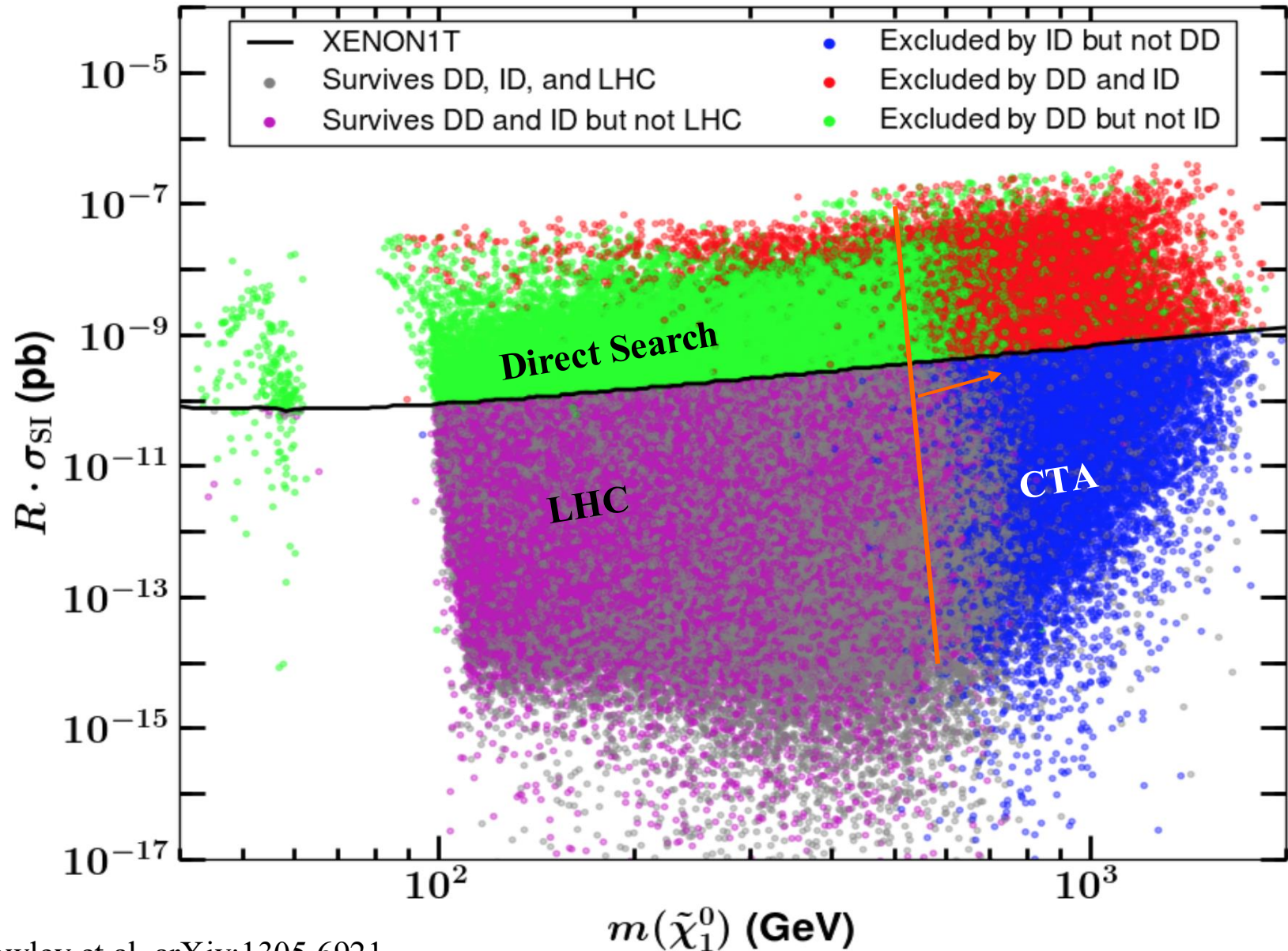
# DM searches in the Large Magellanic Cloud

- Distance: 50.1 kpc
- Dark matter content:  
 $\log_{10}[\text{GeV}^2\text{cm}^{-5}] = 21.14$
- Observation time: 340 h
- Astrophysical gamma-ray sources:
  - 4 known sources: SNR, PWN
  - diffuse emission (CR interactions)





# Complementarity and Searches for Dark Matter in the pMSSM



# CTA Search for Dark Matter beyond WIMP

## Axion Like Particle (ALP) search prospects

$$\gamma + B \rightarrow a + B \rightarrow \gamma' + \dots$$

conversion probability ( $E > E_{\text{crit}}$ )

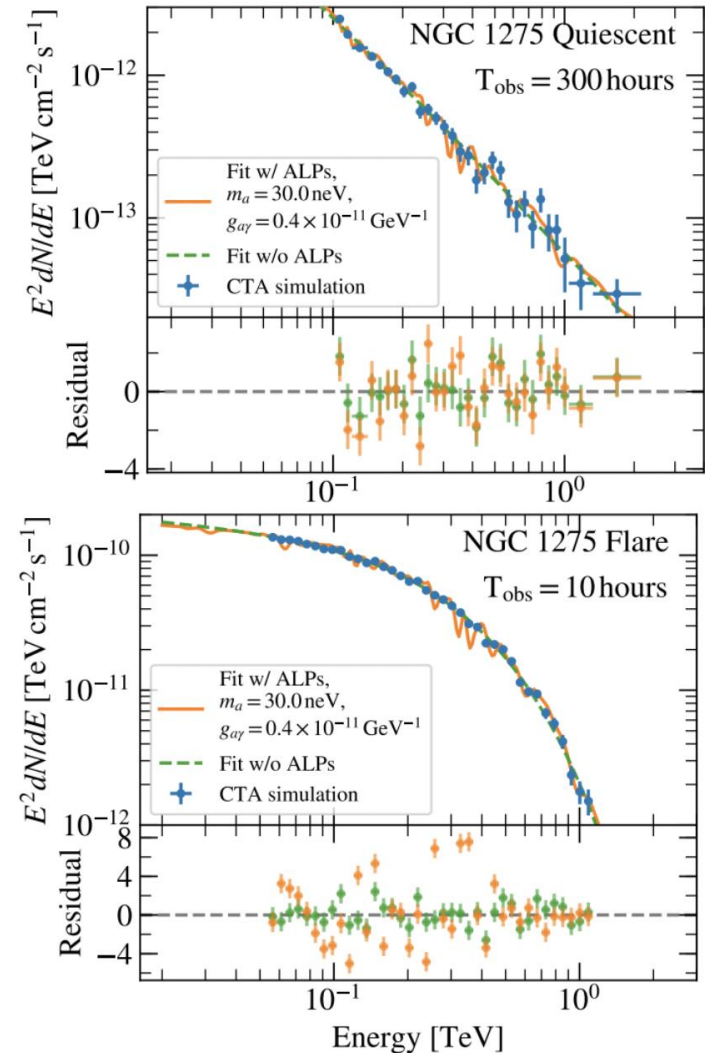
$$P_{a\gamma} \sim \sin^2 \left( \frac{g_{a\gamma} B l}{2} \right),$$

$$E_{\text{crit}} \sim 2.5 \text{ GeV}$$

$$\times \left( \frac{|m_a - \omega_{\text{pl}}|}{1 \text{ neV}} \right)^2 \left( \frac{B}{1 \mu\text{G}} \right)^{-1} \left( \frac{g_{a\gamma}}{10^{-11} \text{ GeV}^{-1}} \right)^{-1}$$

the observation is simulated without an ALP effect and is modeled both without ALPs and with a fixed set of magnetic-field realization and ALP parameters that are excluded at 95 % confidence level by the flaring state simulation

Simulated spectra of the radio galaxy NGC 1275

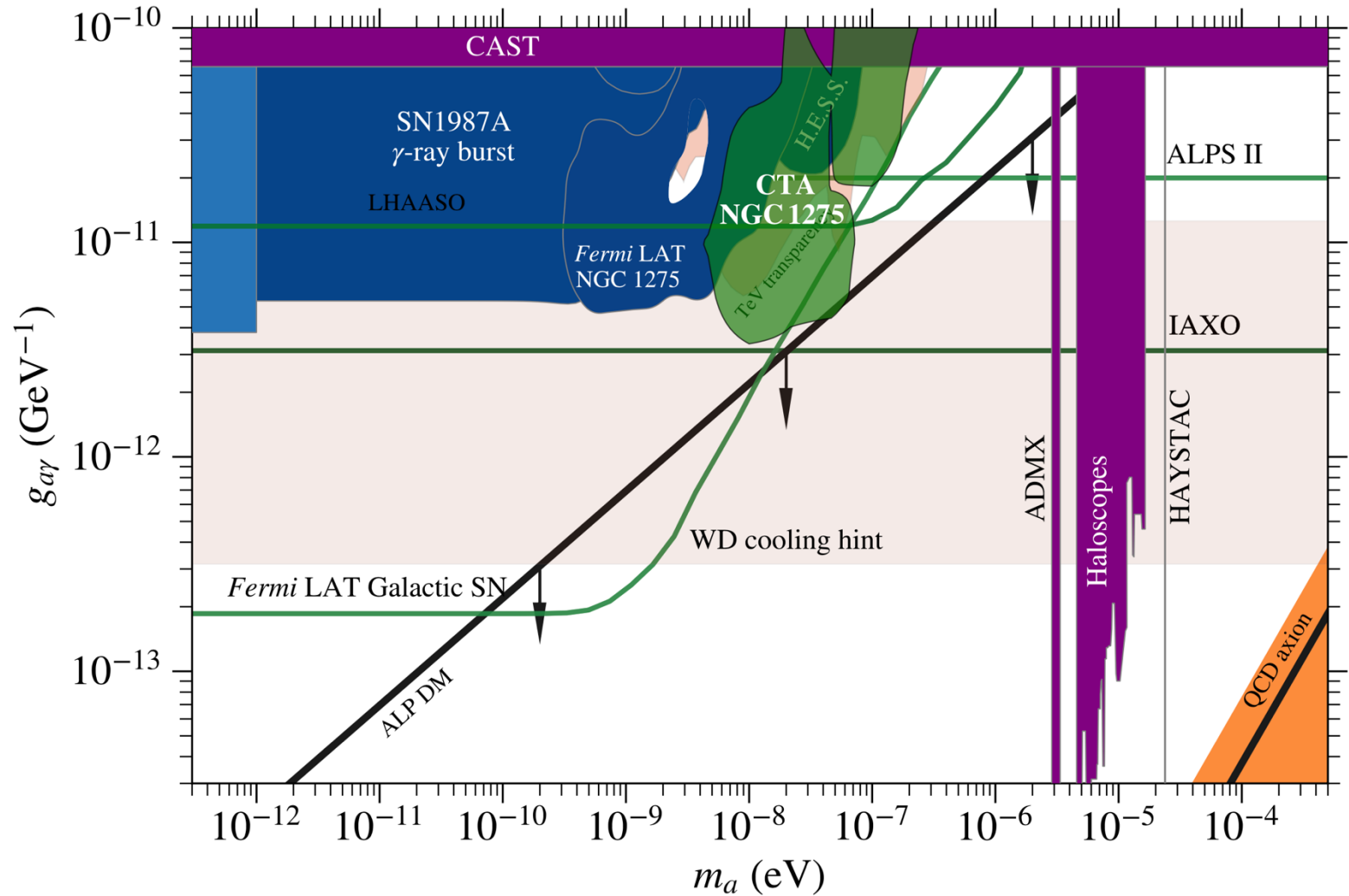


The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]

# Search for Dark Matter beyond WIMP

## Axion Like Particle (ALP) search prospects

- Observation of a flaring state of the radio galaxy NGC 1275 inside the Perseus cluster



The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]



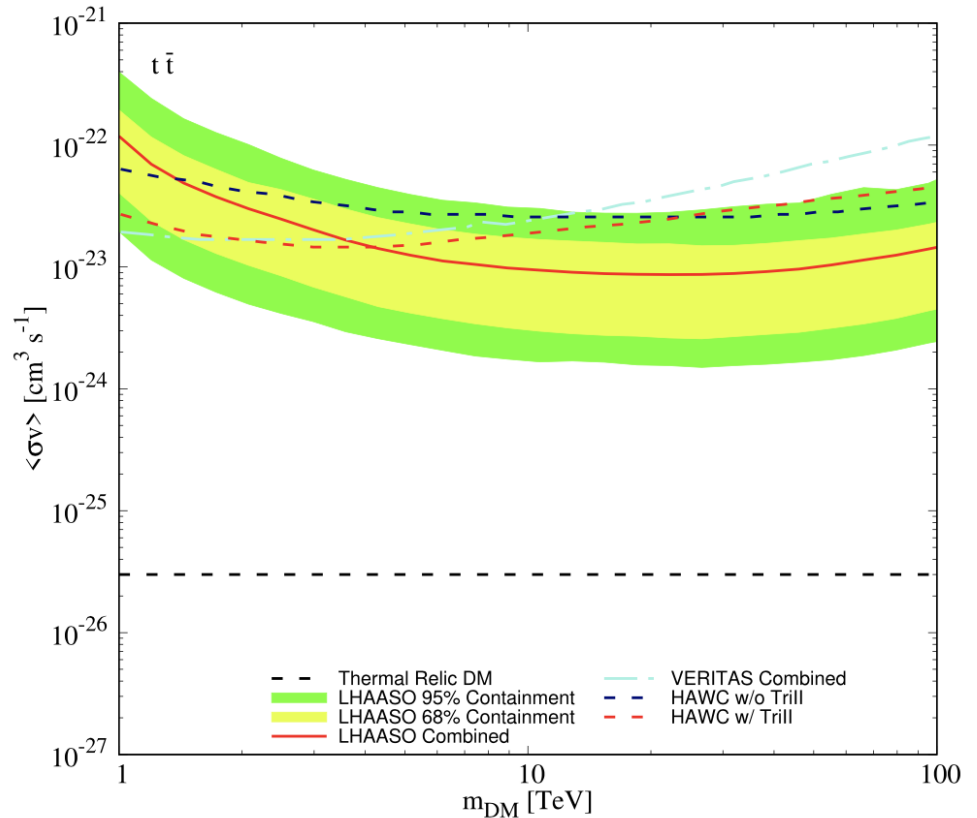
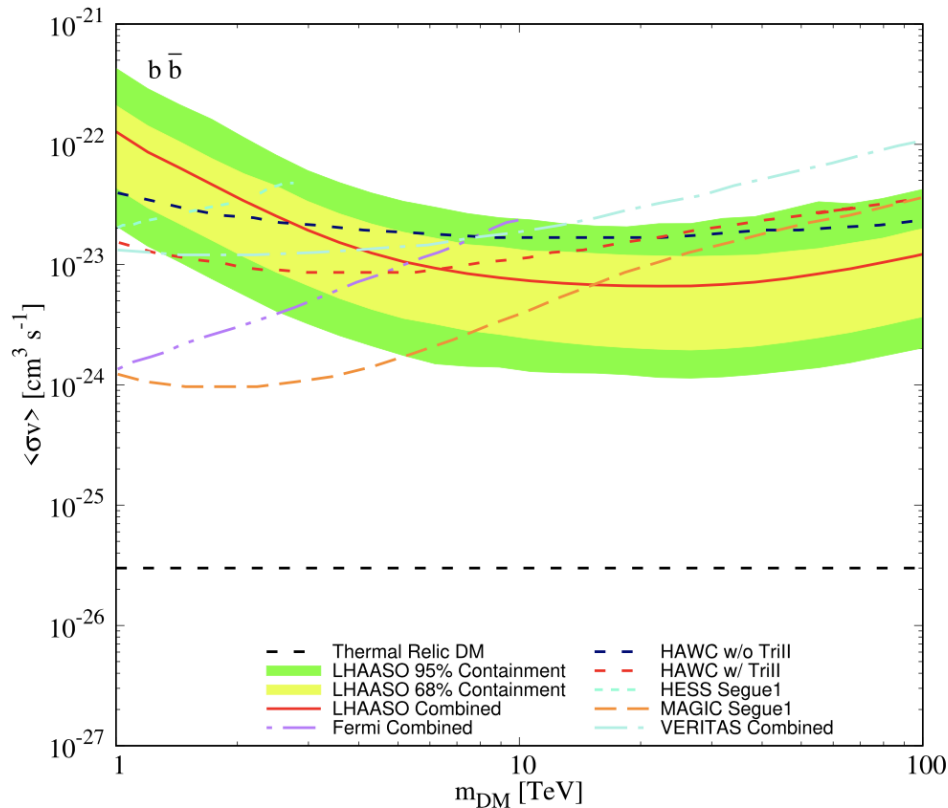
LHAASO



Mt. Haizi 4410 altitude



# Combined one-year LHAASO sensitivities

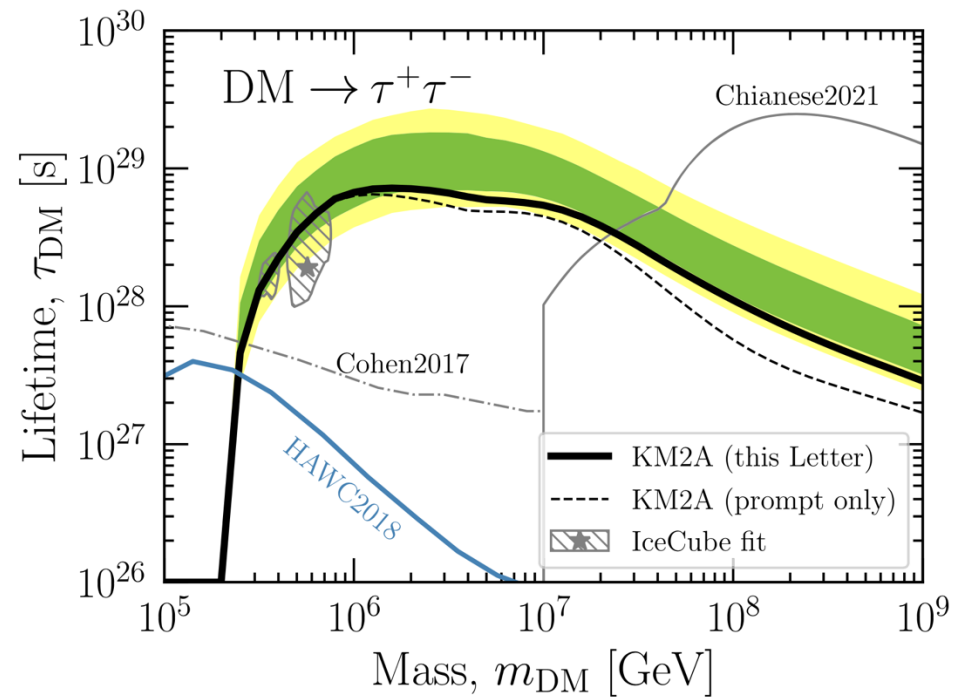
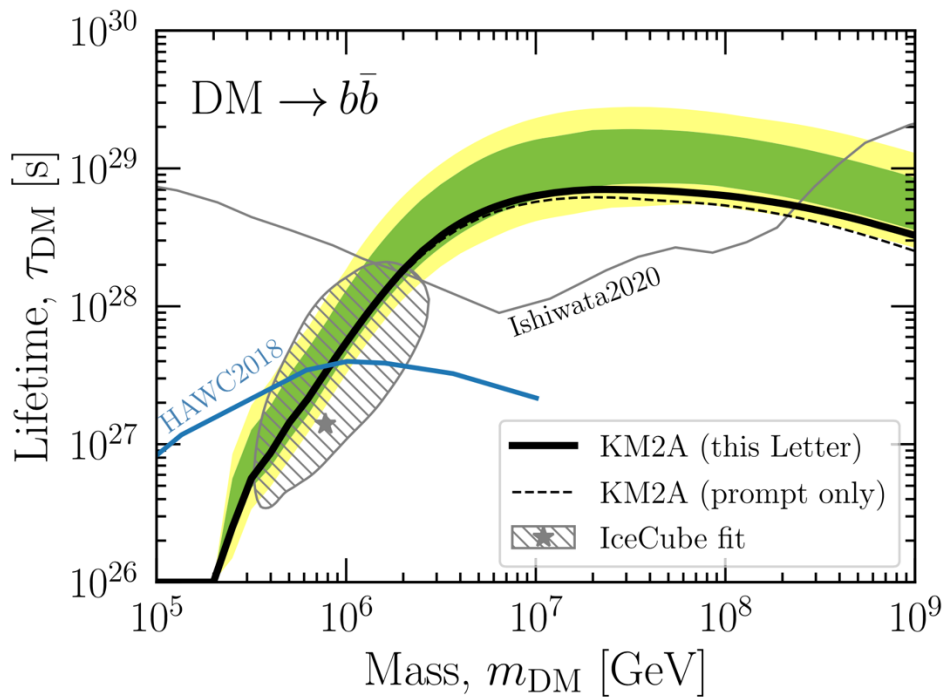


The LHAASO median combined sensitivities (red solid lines) and related two-sided 68% (yellow bands) and 95% (green bands) containment bands of one year for the  $b\bar{b}$ ,  $t\bar{t}$  for 19 dSphs within the LHAASO FOV



Dong-Ze He et al., Phys. Rev. D 100, 083003 (2019)

# Constraints on Heavy Decaying Dark Matter from 570 Days of LHAASO Observations

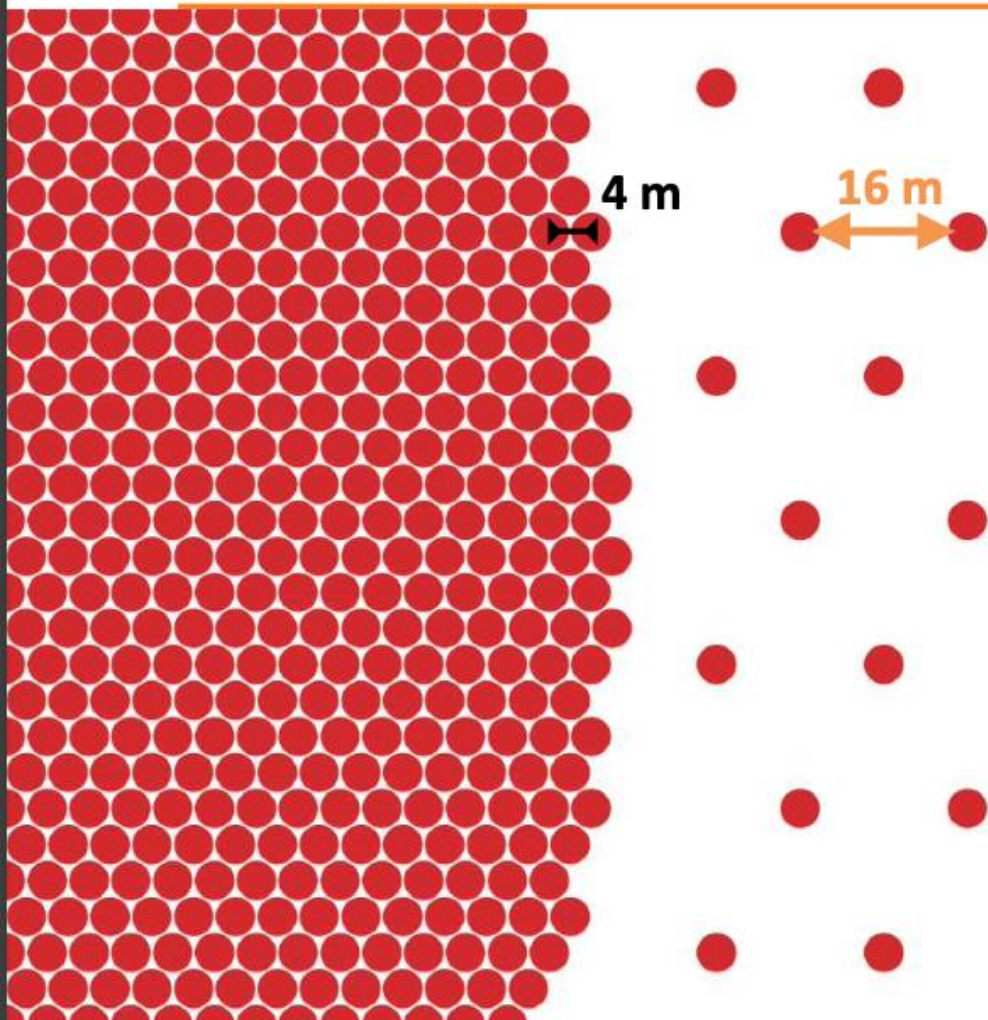


95% one-sided lower limits on DM lifetime obtained with the profile likelihood analysis (thick black lines), for DM decaying into b quarks (left) or  $\tau$  leptons (right). The black dashed line shows the limit for prompt DM contribution only. The green and yellow bands correspond to the expected 68% and 95% limit ranges from Monte Carlo simulations with the background-only hypothesis. Previous limits are shown with gray and blue lines. The hatched regions show the  $1\sigma$  DM parameter space favored by IceCube high-energy neutrino flux



Z. Cao et al. (LHAASO Collaboration) Phys. Rev. Lett. 129, 261103 (2022)

# The baseline detector concept

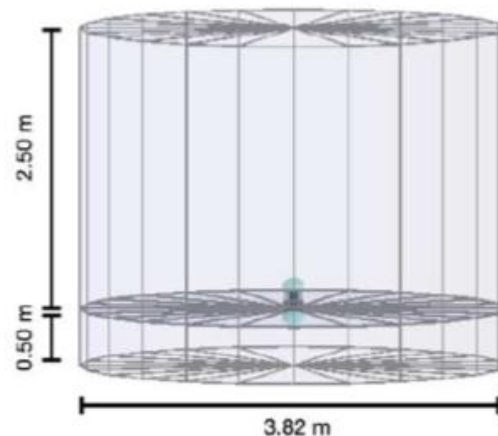


**Core:**  $\varnothing$  320 m, FF = 80%  
5,700 WCD units

**Outer:**  $\varnothing$  600 m, FF = 5%  
880 WCD units

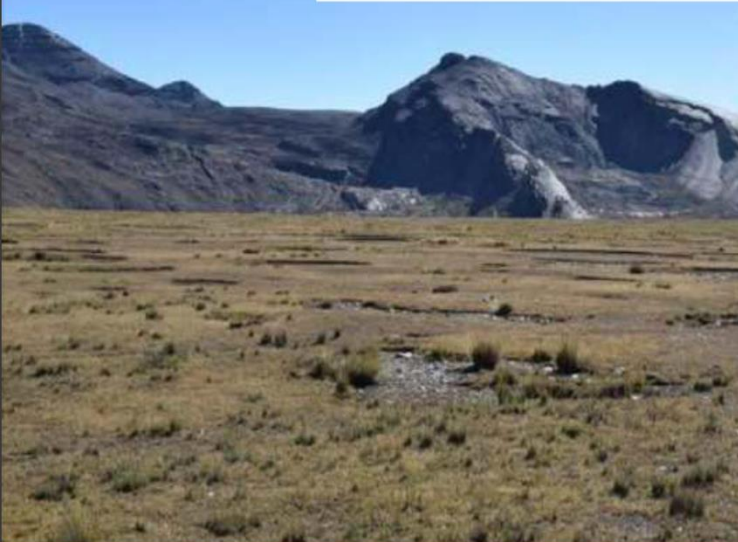
**Altitude:** 4,700 m a.s.l.

✧ muon counting





# A Wide-field Gamma-ray Observatory in the South





# A Wide-field Gamma-ray Observatory in the South



**Shortlisting: Fall 2022**  
**Site visits: October**  
**Site selection: Fall 2023**

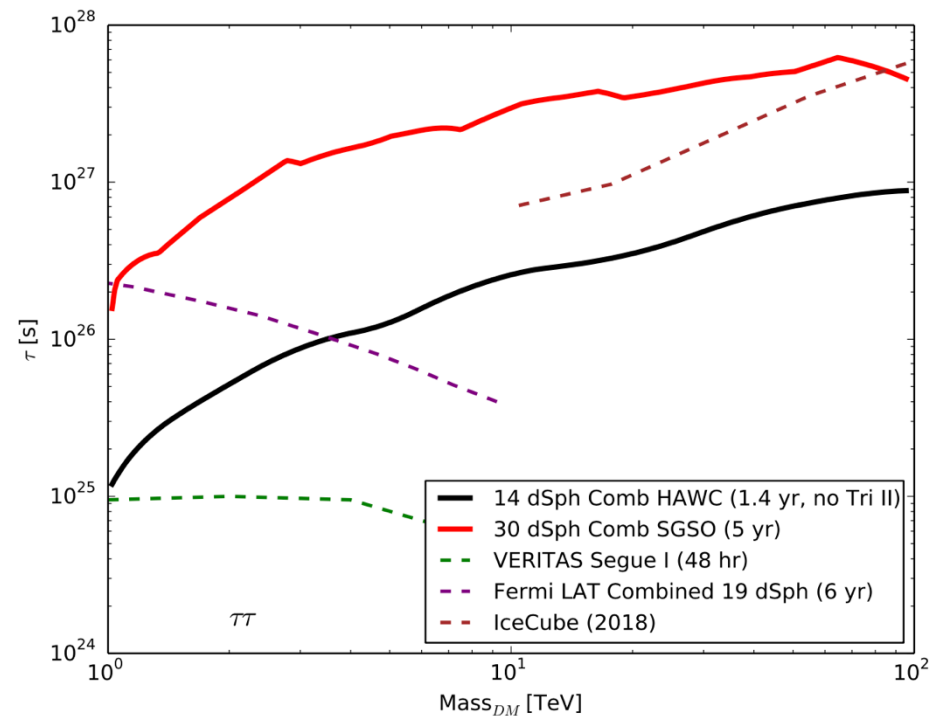
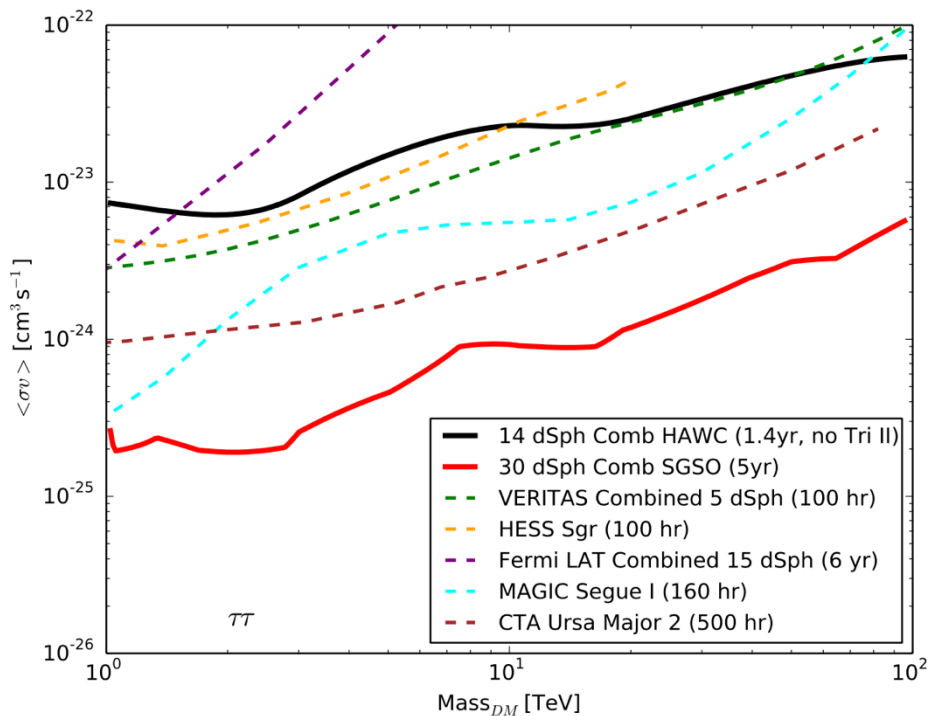
Country	Elevation	Location:
Peru	4900	Laguna Sibinacocha
Peru	4450	Imata
Peru	4450	Yanque
Argentina	4800	Cerro Vecar
Argentina	4450	Alto Tocomar
Chile	4700	<b>ALMA Pampa La Bola</b>
Chile	4400	AAP Pajonales
Bolivia	4700	ALPACA area



**Selected as Preferred Site for SWGO Aug.24**



# SWGGO sensitivities

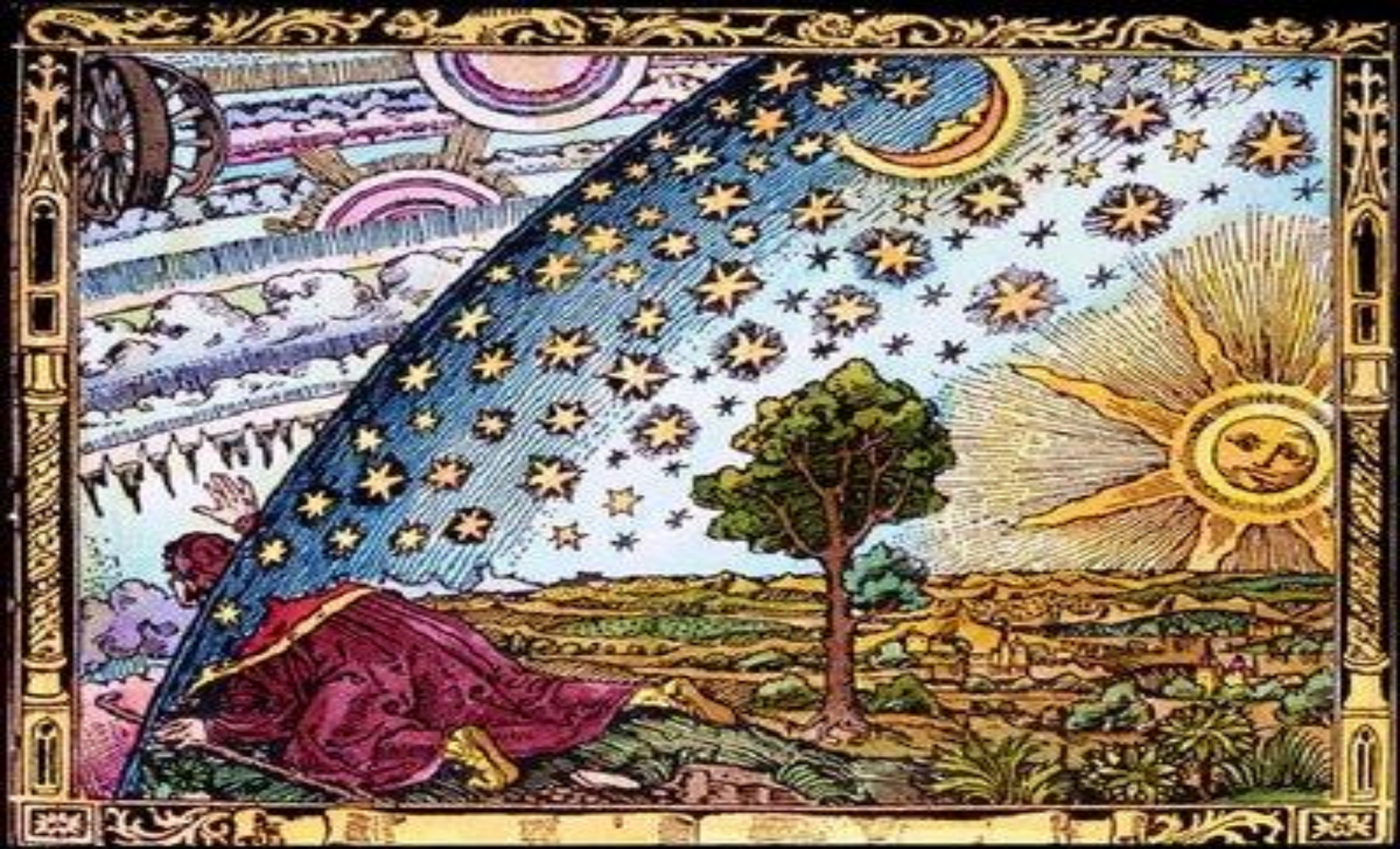


Assumed new dSph discovery and J-factor and D-factor distributions of the new dSphs matches that of the previously known dSphs

 [SWGGO White paper arXiv:1902.08429](https://arxiv.org/abs/1902.08429)



# The Low Energy Frontier

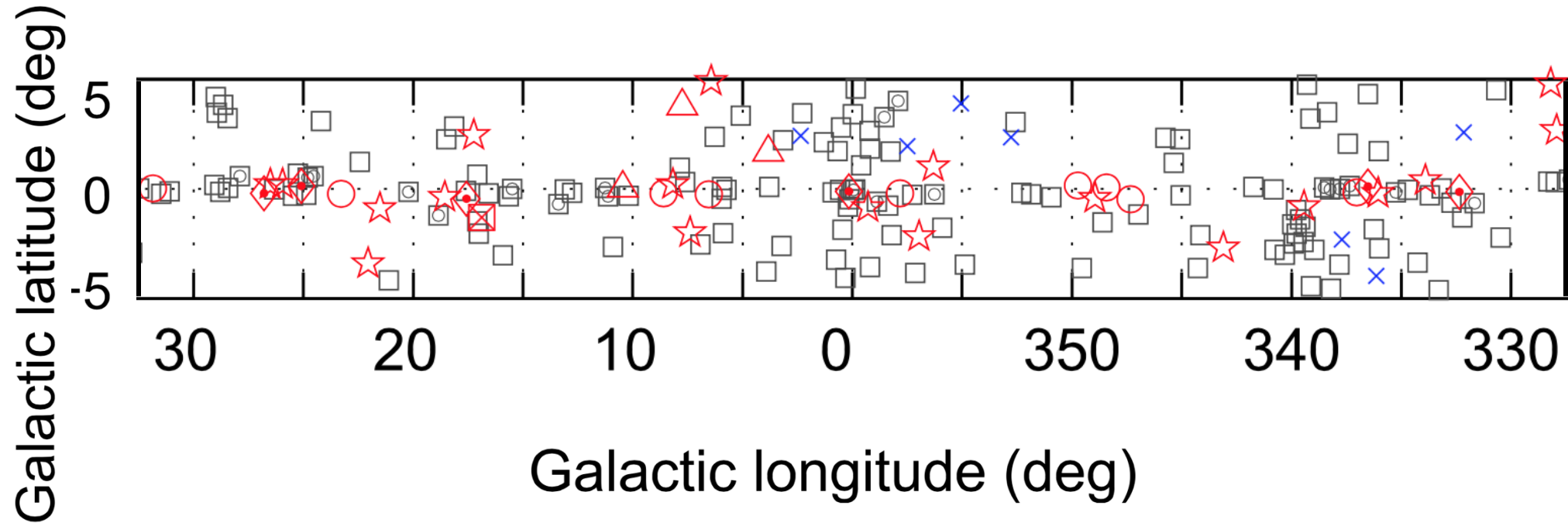





# The Fermi LAT 3FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

100 MeV to 300 GeV energy range



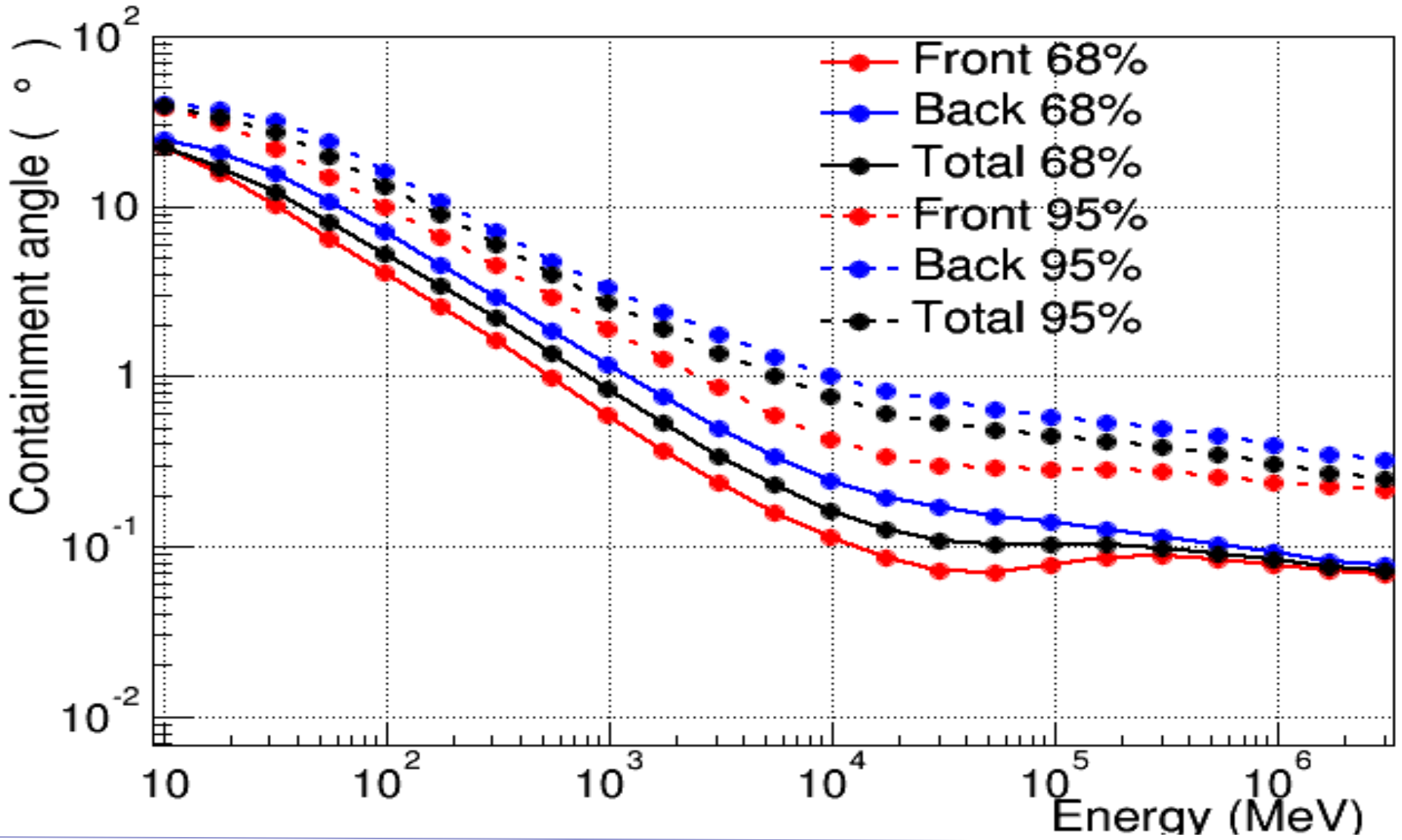
□ No association	◻ Possible association with SNR or PWN	× AGN
☆ Pulsar	△ Globular cluster	* Starburst Galaxy
⊠ Binary	+ Galaxy	○ SNR
★ Star-forming region		◇ PWN
		★ Nova

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

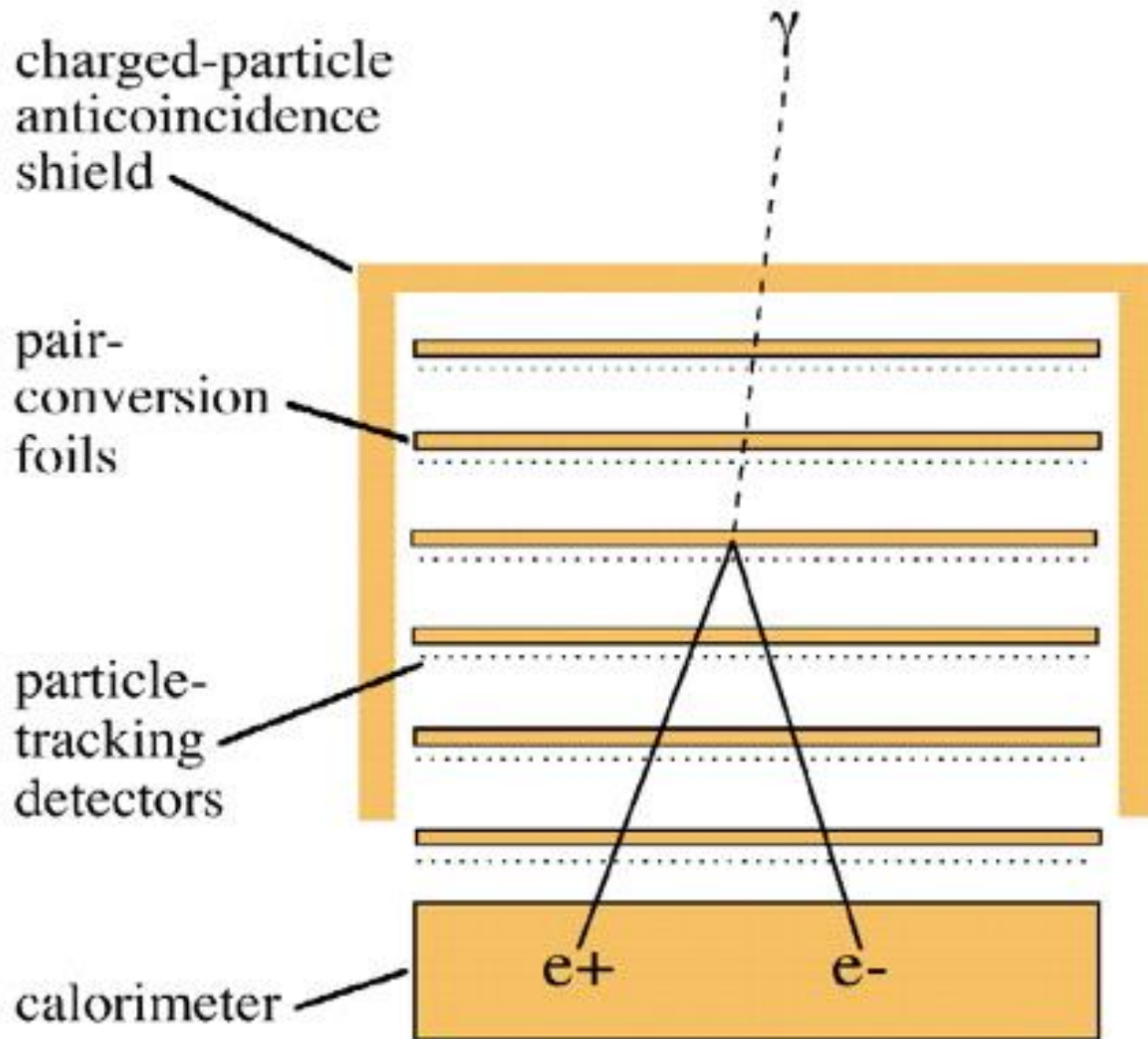


# Fermi-LAT Instrument Response Functions (Pass 8) Angular Resolution

P8R2\_SOURCE\_V6 acc. weighted PSF



# Elements of a pair-conversion telescope



- photons materialize into matter-antimatter pairs:

$$E_{\gamma} \rightarrow m_{e^+}c^2 + m_{e^-}c^2$$

- electron and positron carry information about the direction, energy and polarization of the  $\gamma$ -ray

calorimeter  
(energy measurement)

# Elements of a pair-conversion telescope

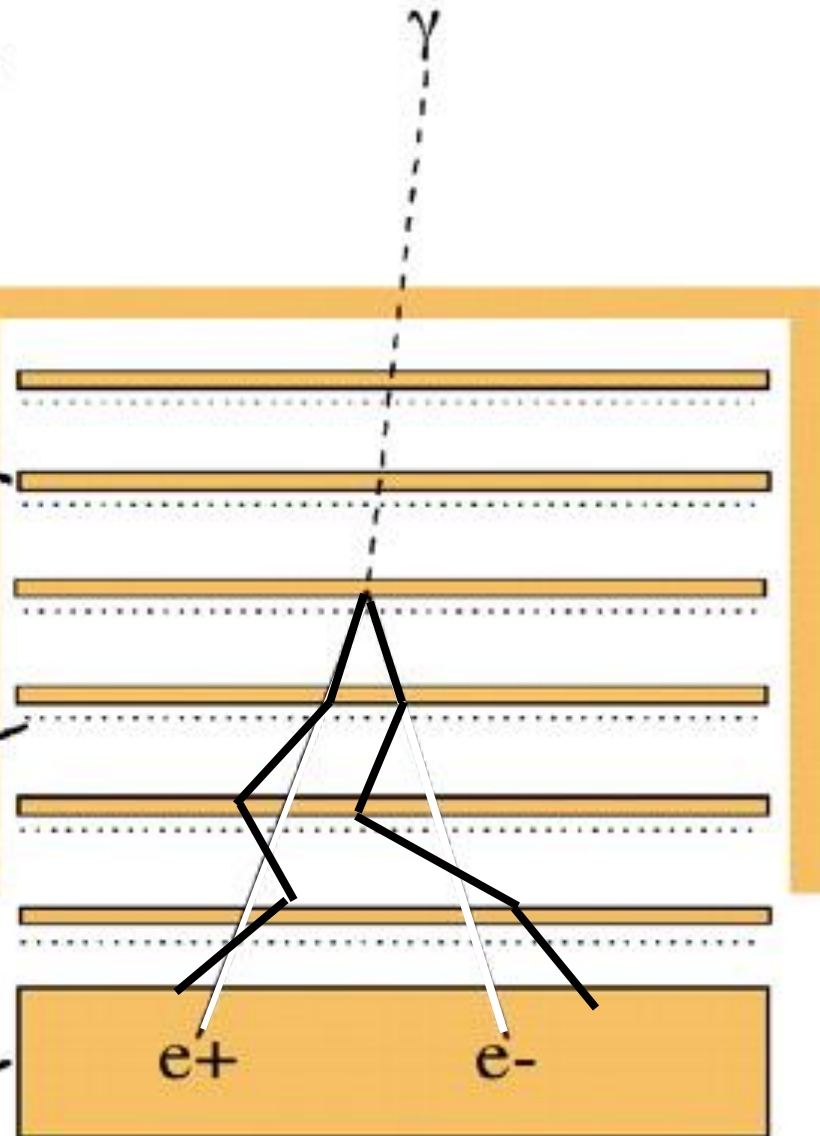
(more realistic scheme)

charged-particle  
anticoincidence  
shield

pair-  
conversion  
foils

particle-  
tracking  
detectors

calorimeter



- photons materialize into matter-antimatter pairs:

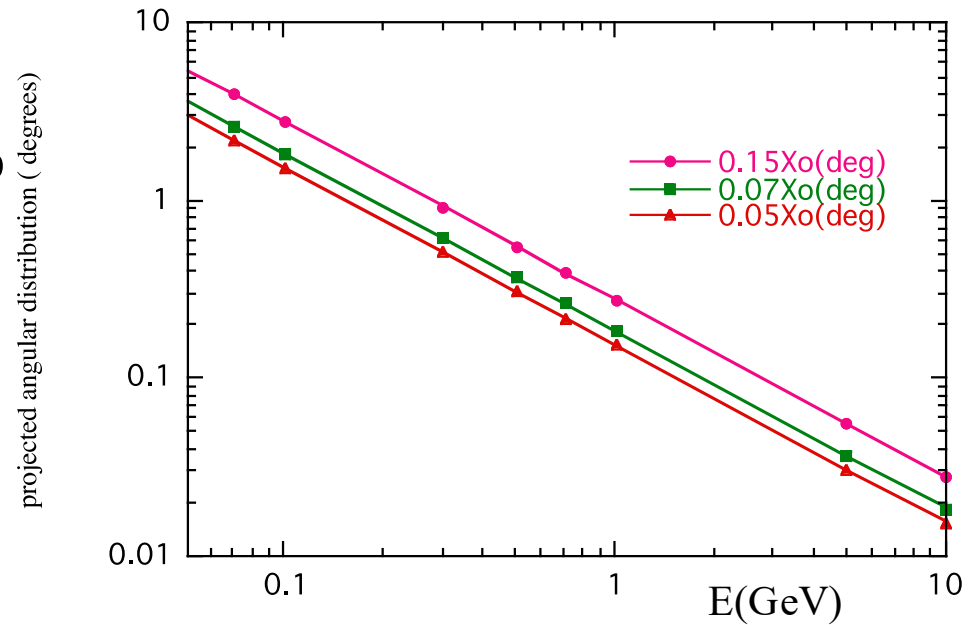
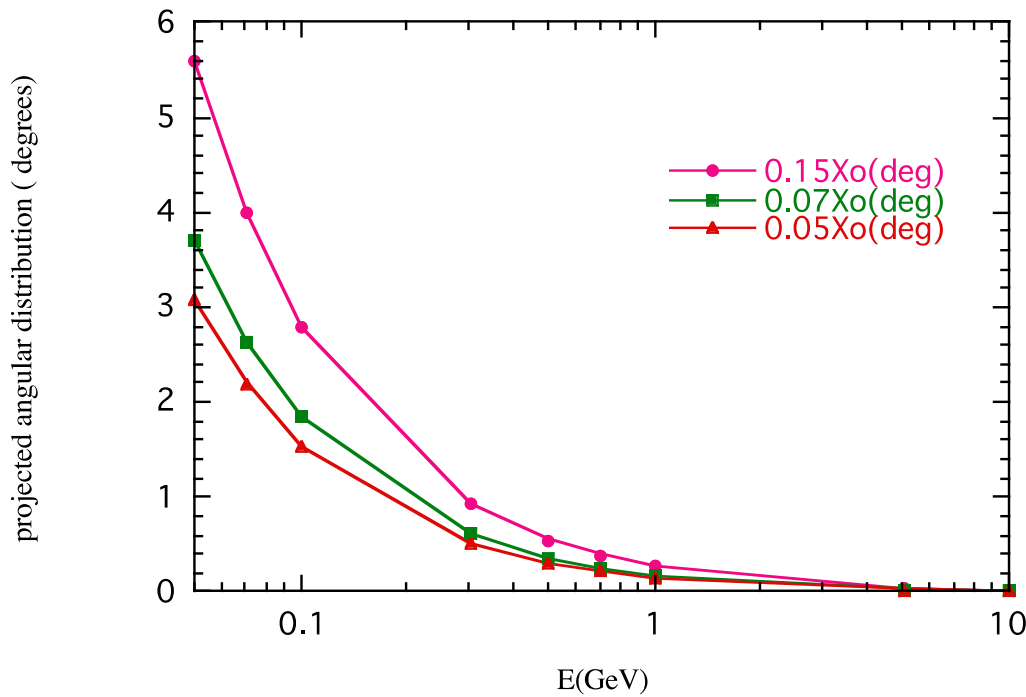
$$E_{\gamma} \rightarrow m_{e^{+}}c^2 + m_{e^{-}}c^2$$

- electron and positron carry information about the direction, energy and polarization of the  $\gamma$ -ray

(energy measurement)



# Multiple Scattering

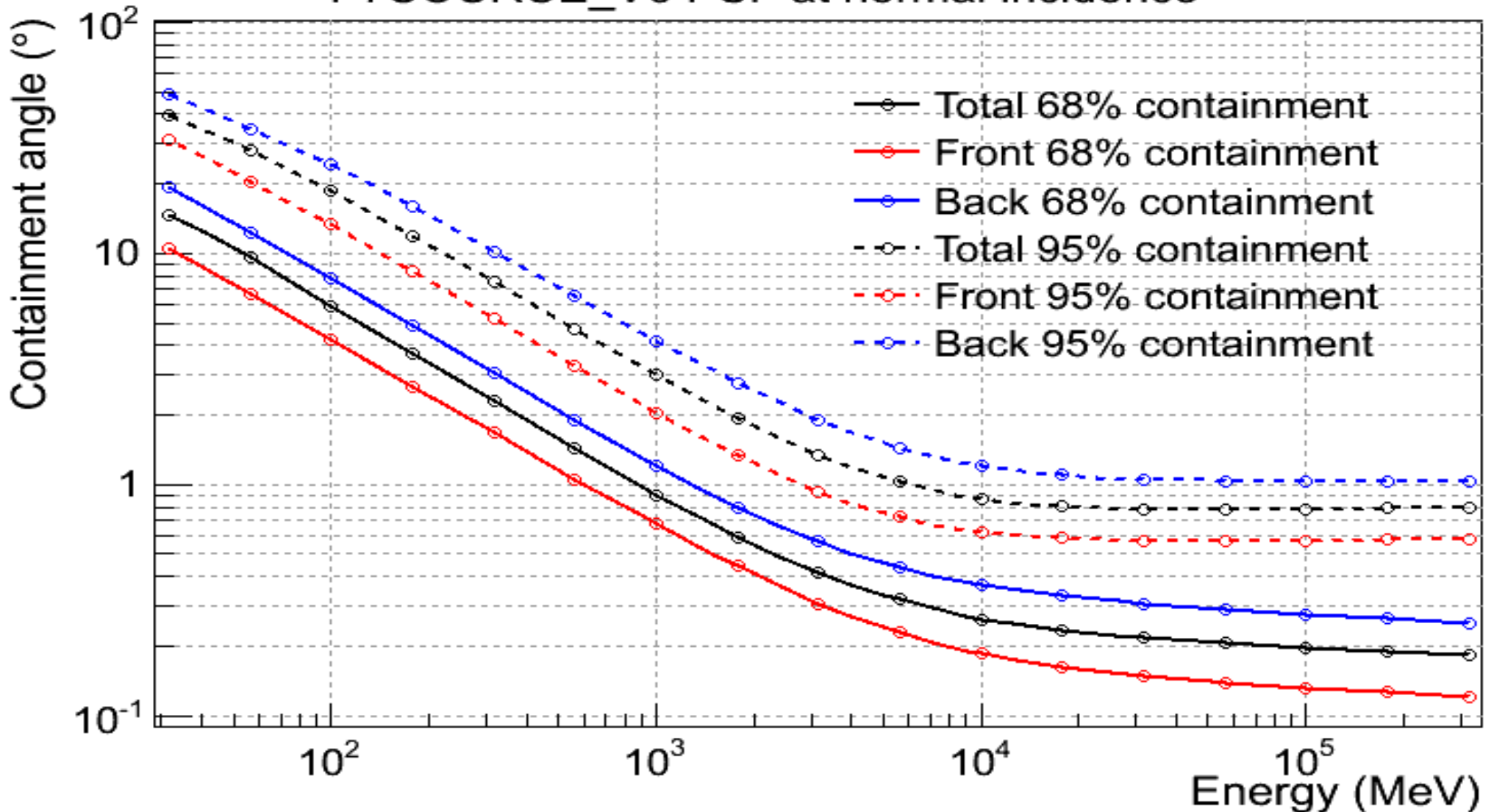


$$\theta_0 = \theta_{plane}^{rms} = \frac{1}{\sqrt{2}} \theta_{space}^{rms}$$

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

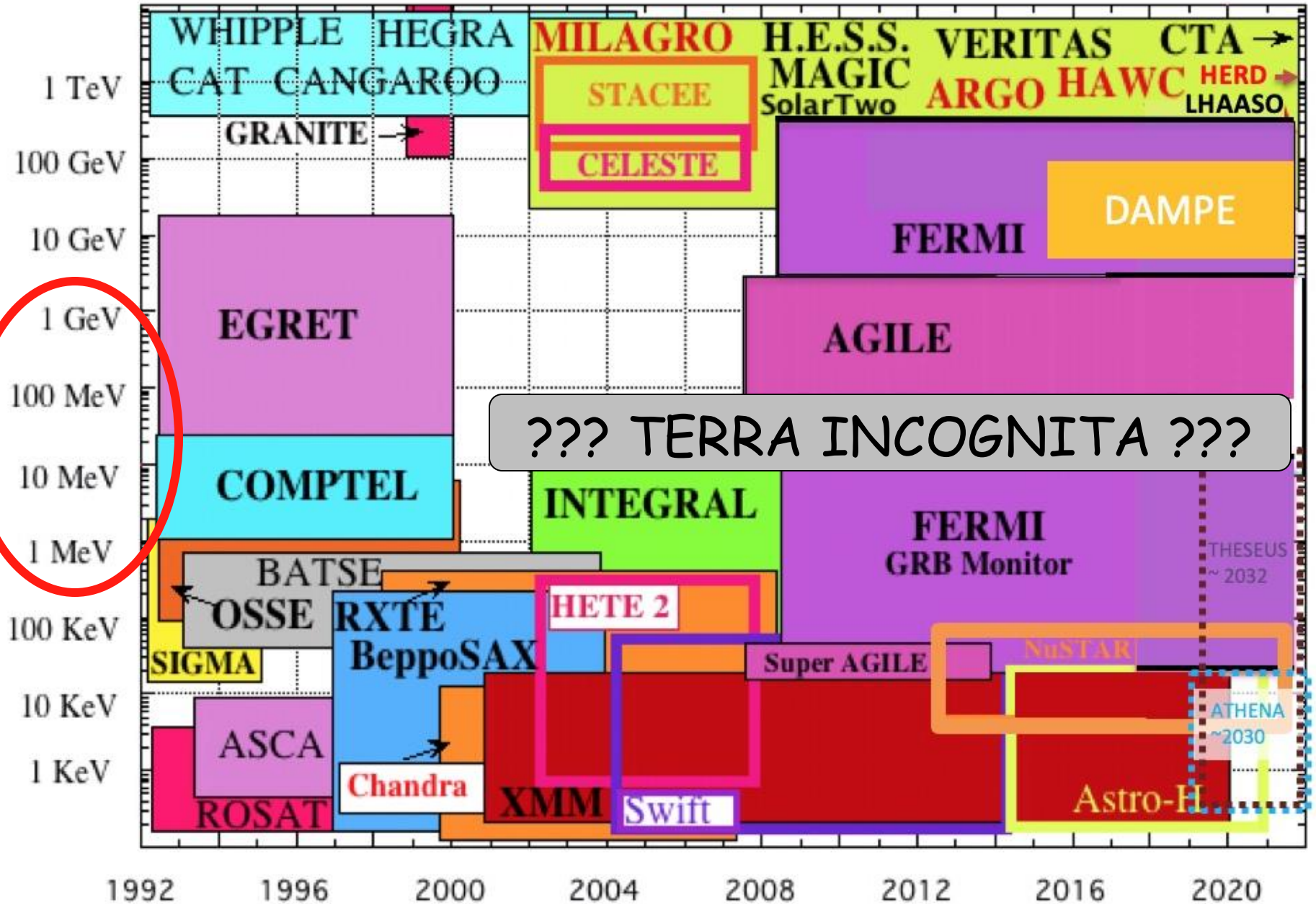
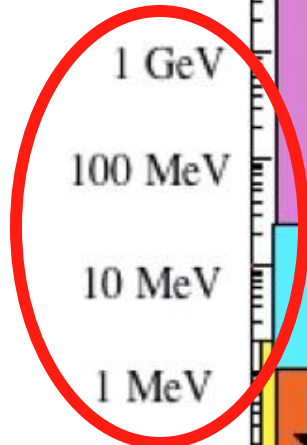
# Fermi Instrument Response Function

P7SOURCE\_V6 PSF at normal incidence



[http://www.slac.stanford.edu/exp/glast/groups/canda/lat\\_Performance.htm](http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm)

Energy



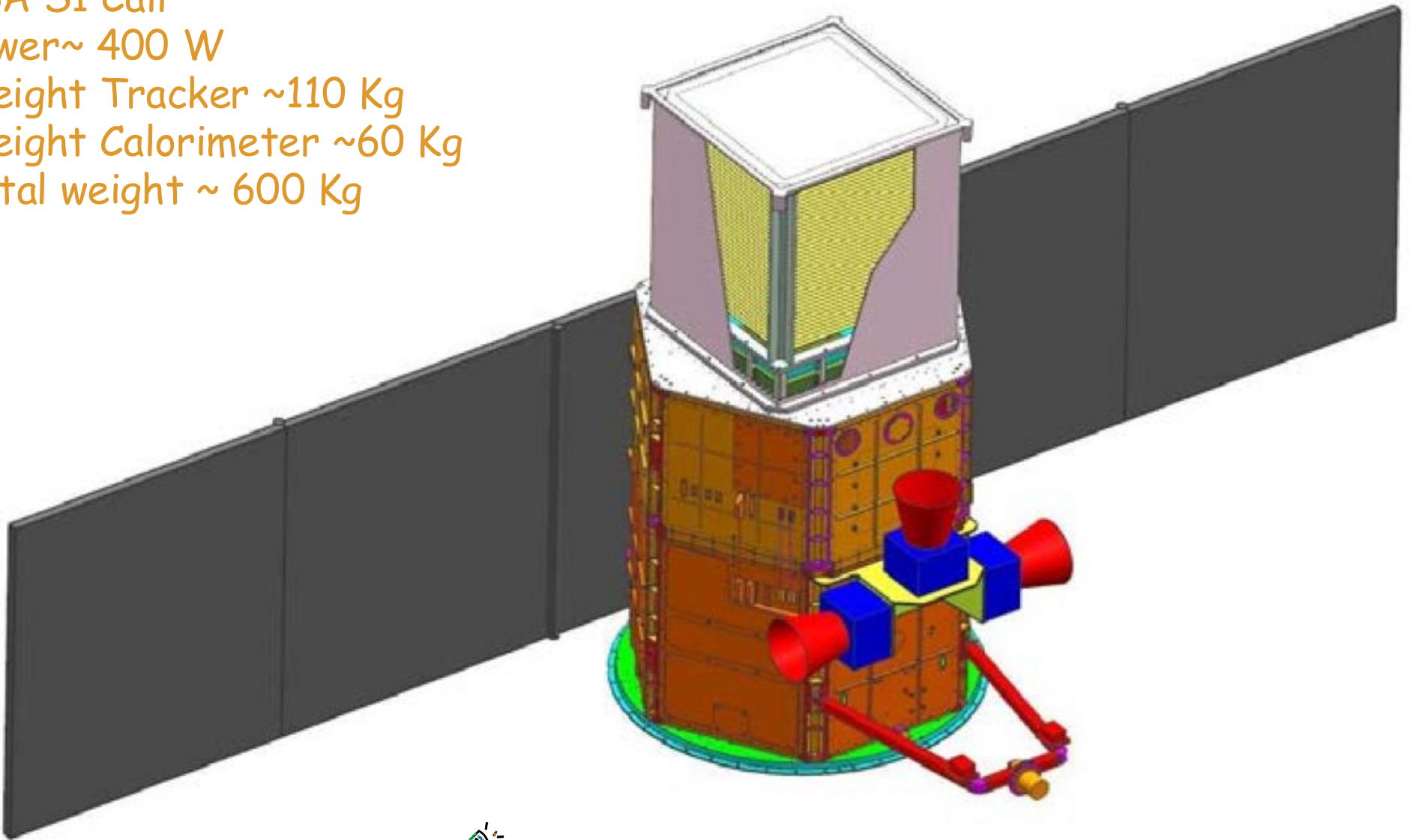
Year



- **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

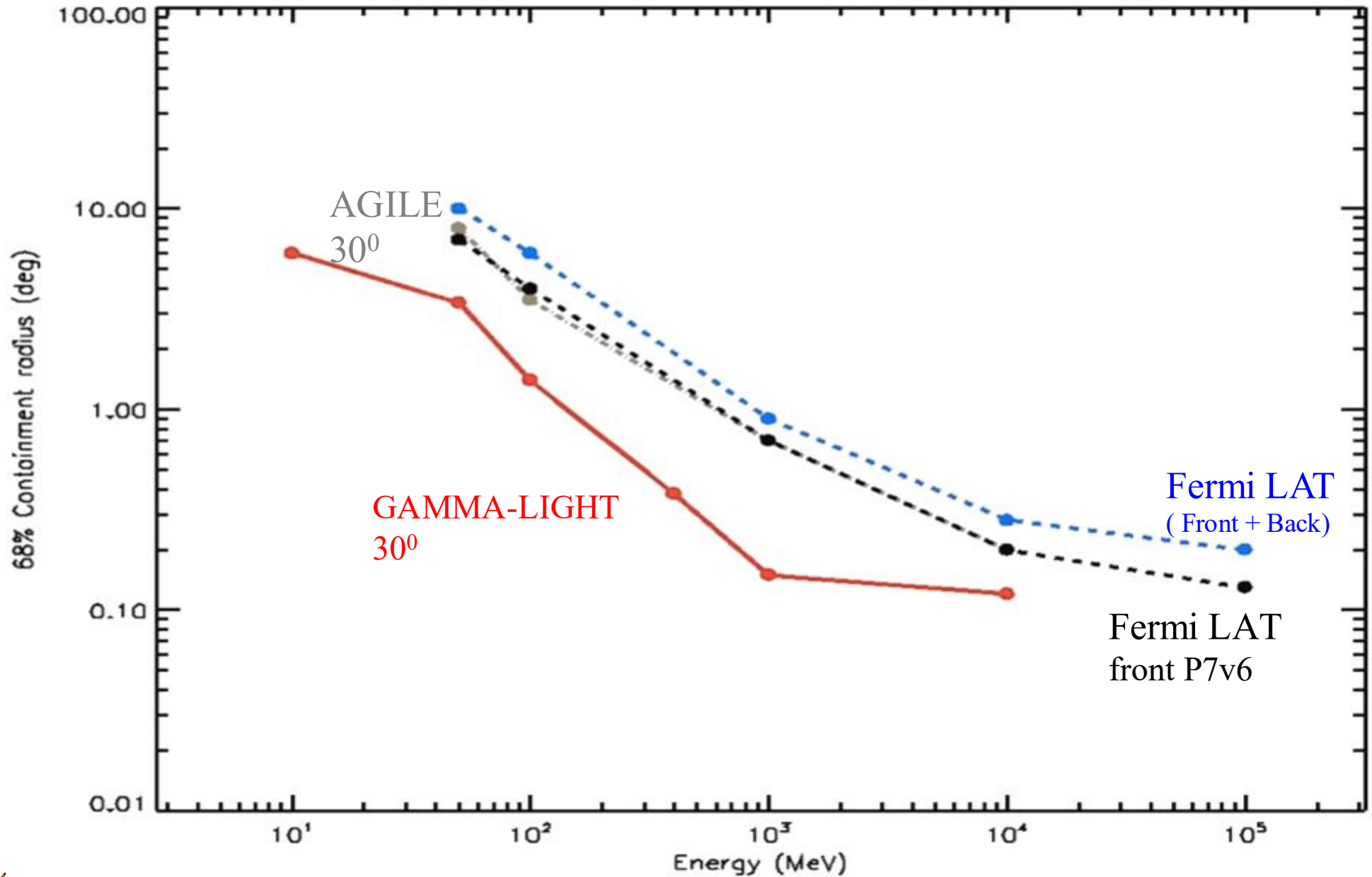
# Gamma-light project

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



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

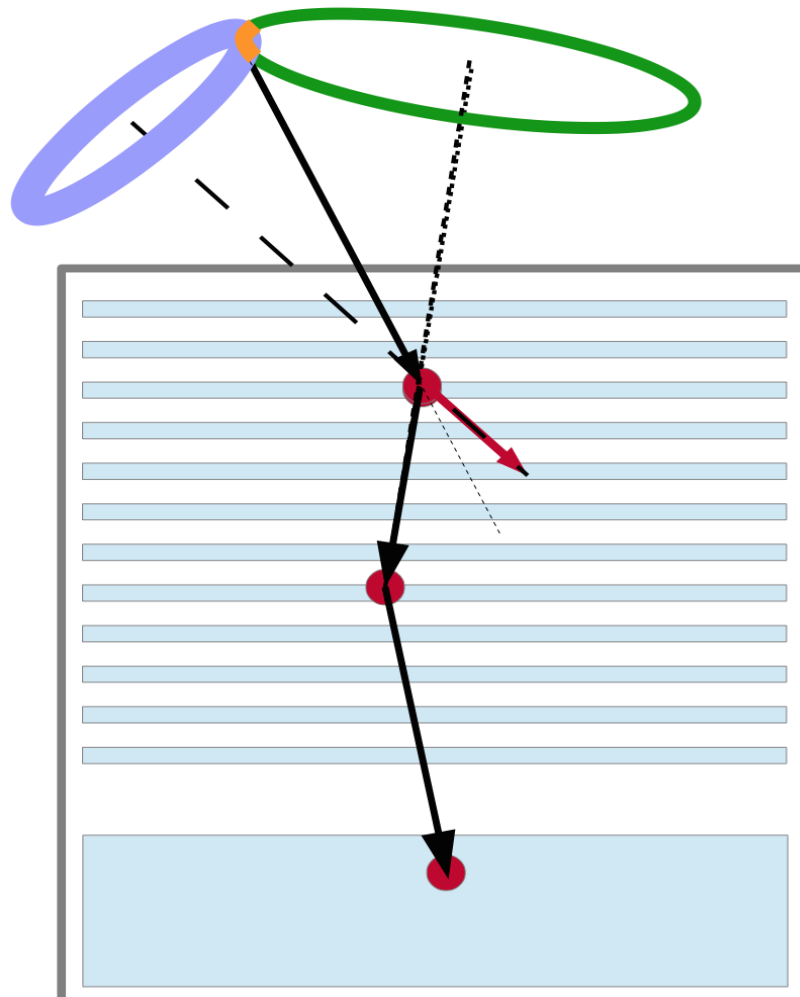
# Gamma-Light Point Spread Function (angular resolution)



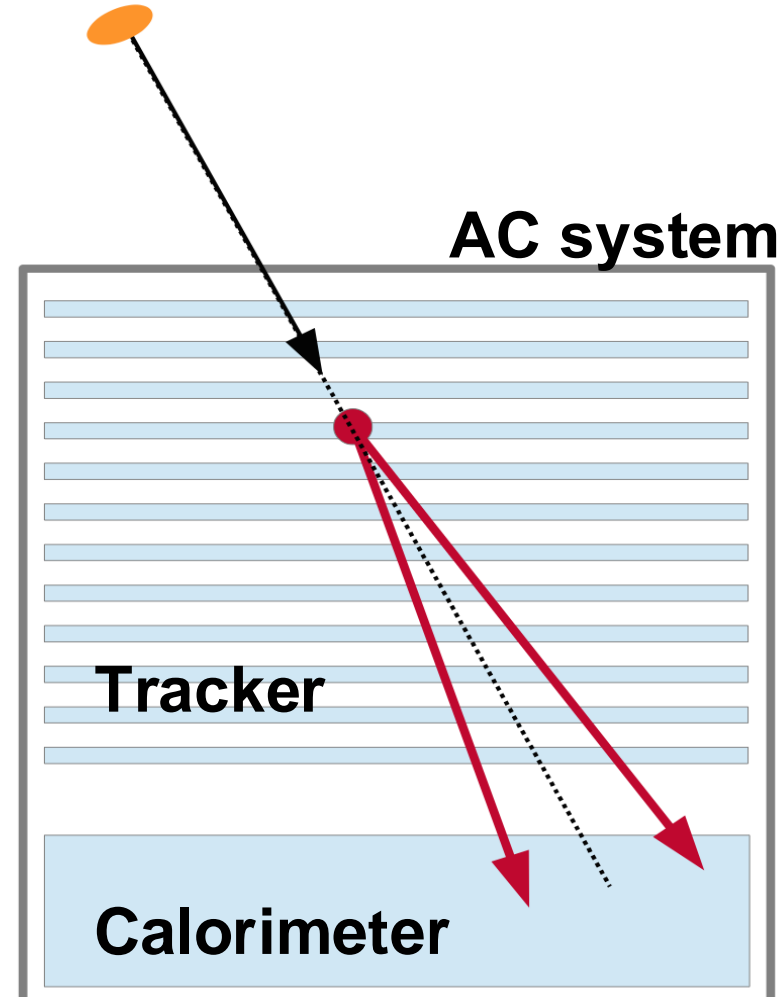
A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198 [arXiv:1406.1071]



# An instrument that combine two detection techniques



Tracked Compton event

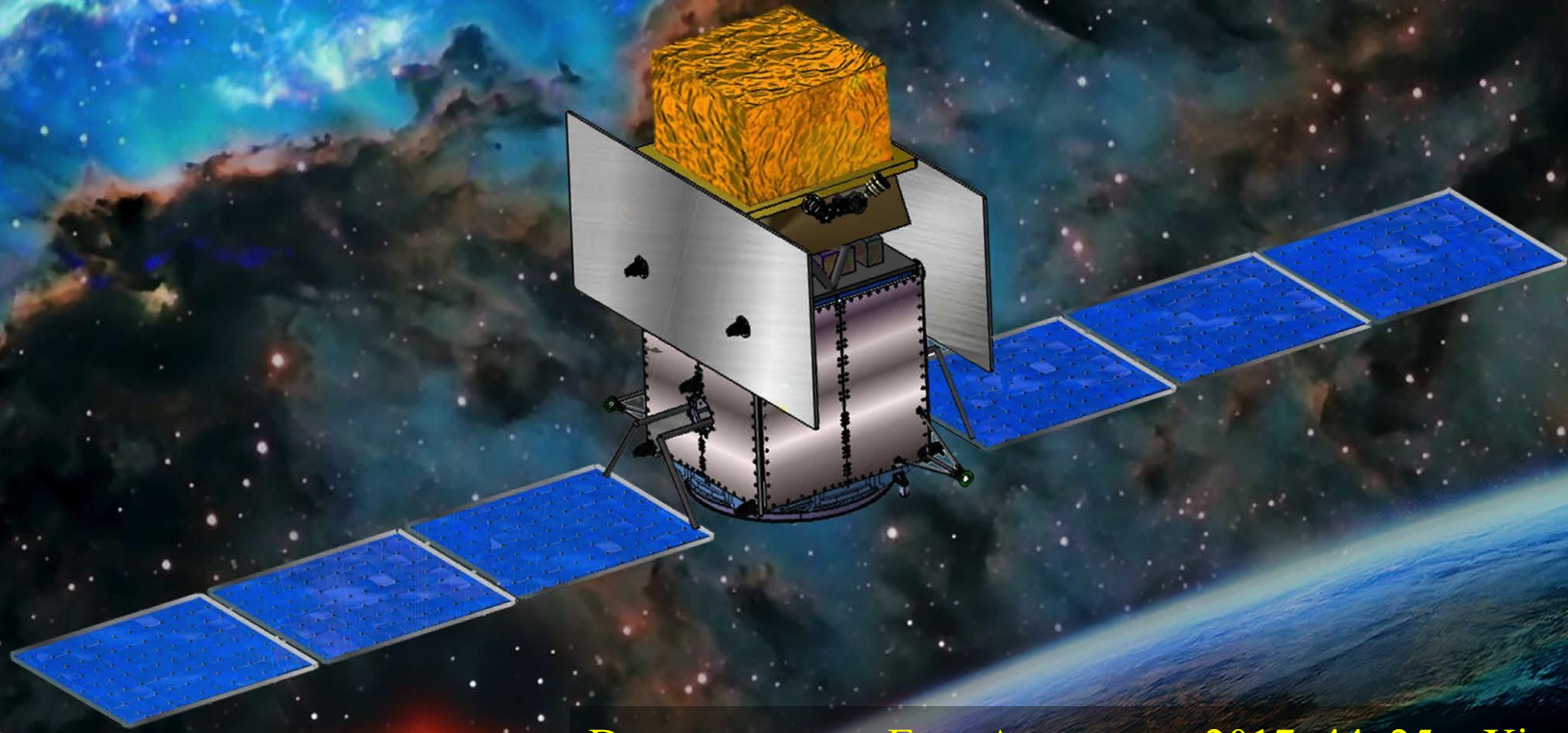


Pair event

# e-ASTROGAM

at the heart of the extreme Universe

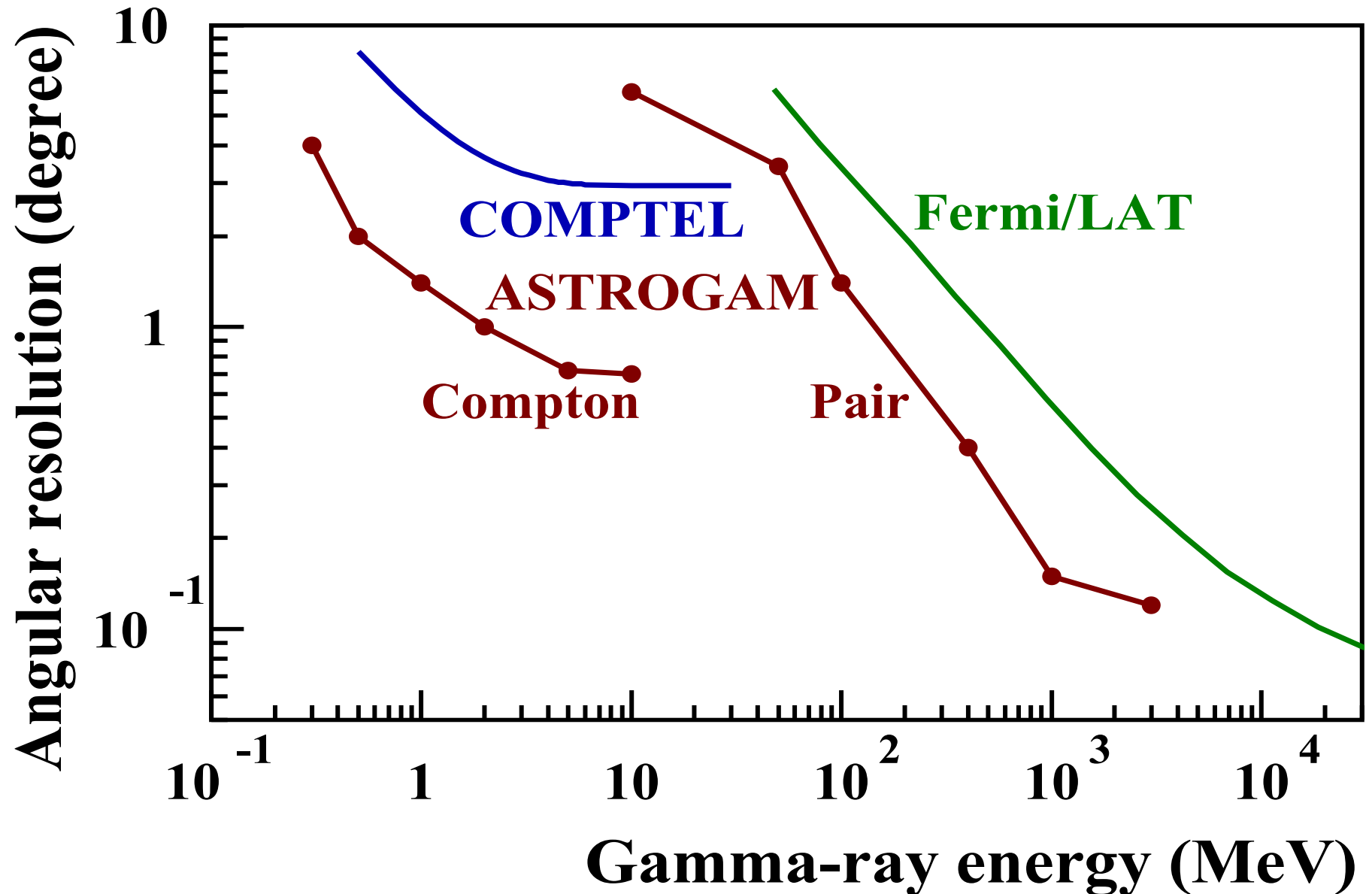
An observatory for gamma rays  
In the MeV/GeV domain



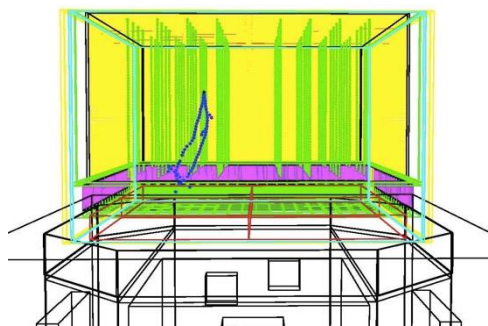
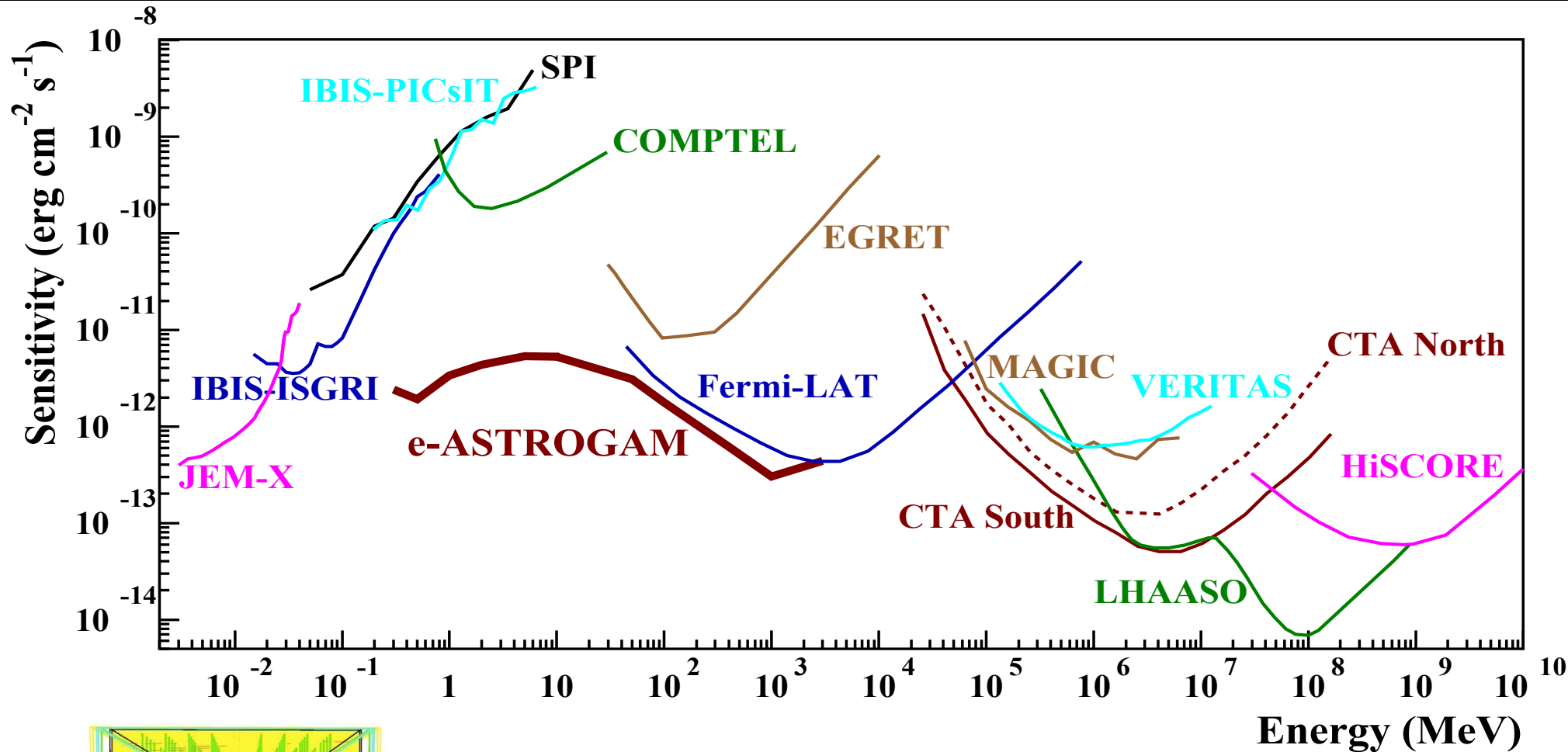
Detector paper: Exp. Astronomy 2017, 44, 25 arXiv:1611.02232  
Science White Book: arXiv:1711.01265 (213 pages)



# ASTROGAM Angular Resolution





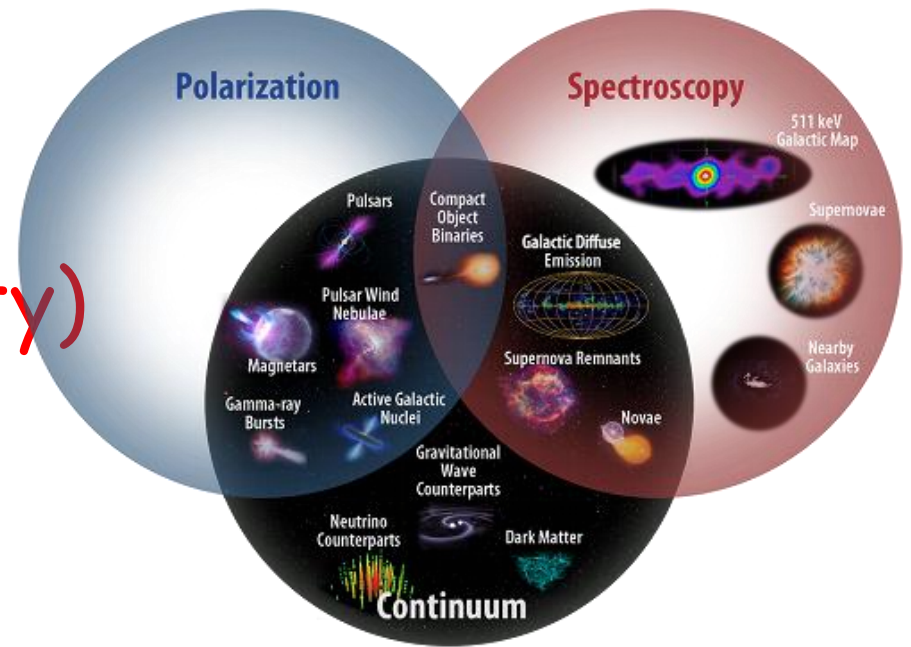
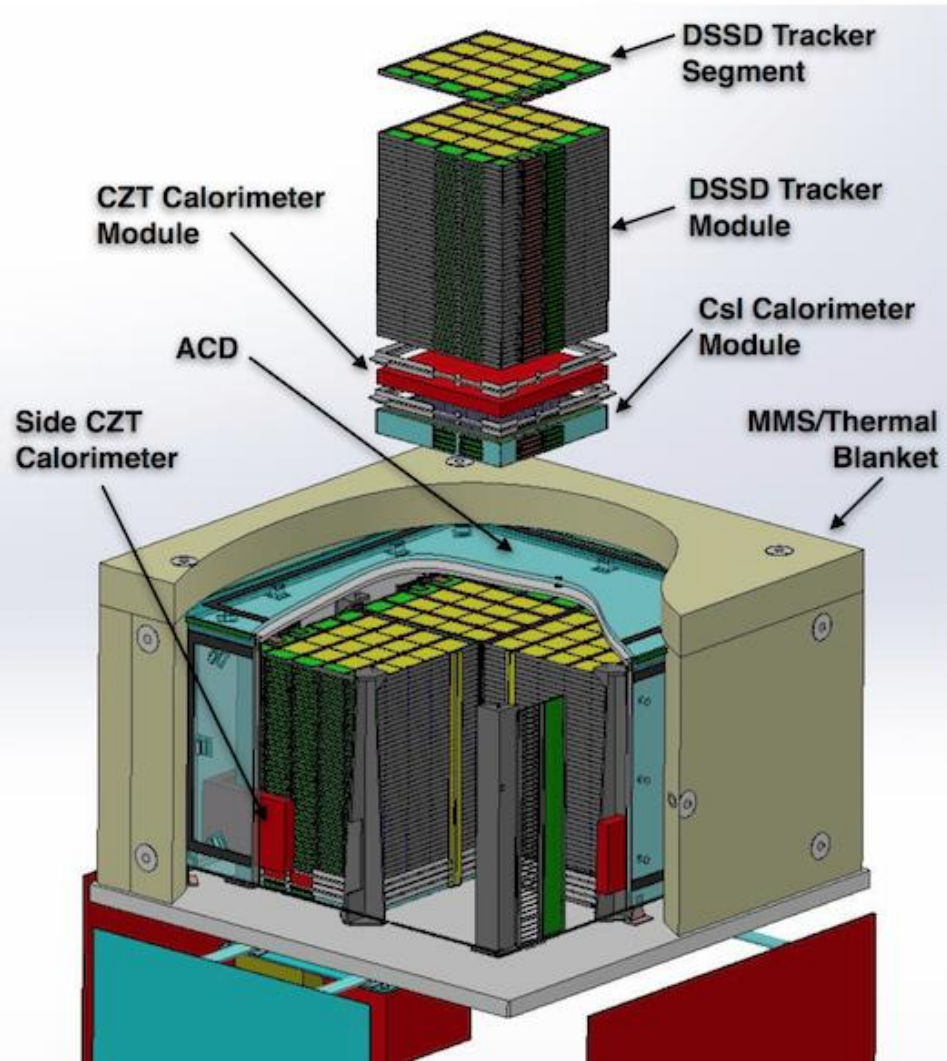


- e-ASTROGAM performance evaluated with **MEGALib** and – both tools based on Geant4 – and a **detailed numerical mass model** of the gamma-ray instrument



e-Astrogam: arXiv:1611.02232

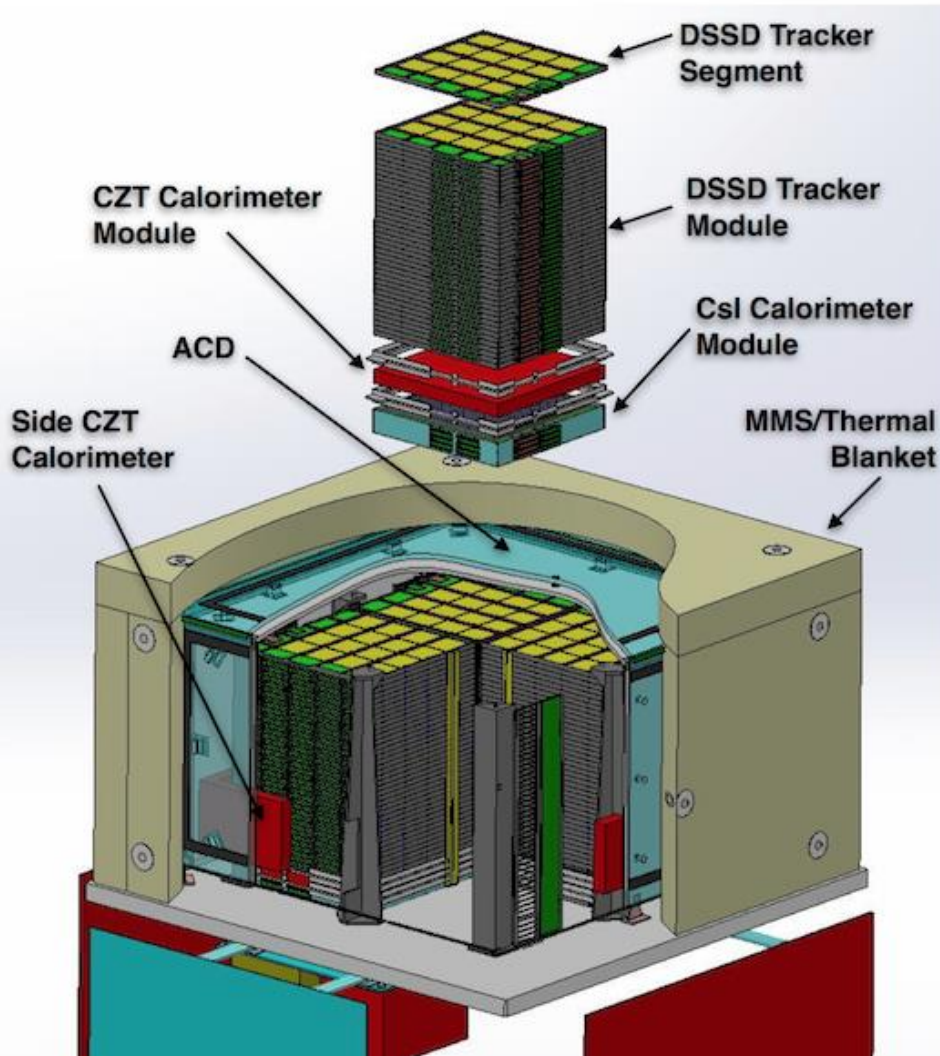
# Our sister experiment: AMEGO (NASA) (two brands, one community)



- ~20% smaller tracker
- CZT calorimeter layer

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

# Our sister experiment: AMEGO (NASA)



Status and Plans :

Resubmit in the next MIDEX round  
(~2027)

*in the meantime:*

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

- Science gaps:

<https://pcos.gsfc.nasa.gov/physpag/science-gaps/science-gaps.php>

- Technology gaps: [https://pcos.gsfc.nasa.gov/news/2024/6\\_Technology\\_Gaps\\_Submissions\\_Due.php](https://pcos.gsfc.nasa.gov/news/2024/6_Technology_Gaps_Submissions_Due.php)

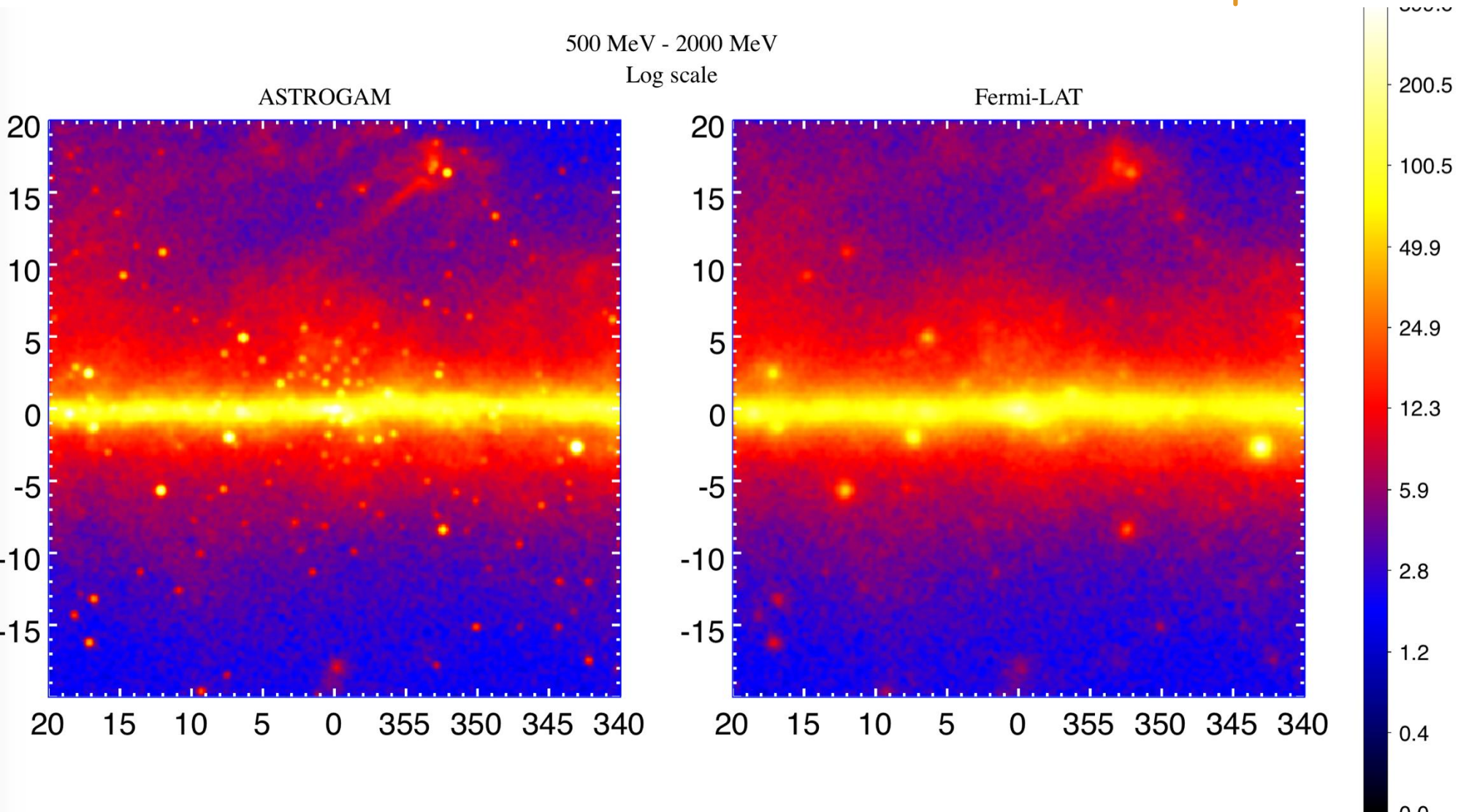
- Join the Gamma-ray Science Interest Group (GammaSIG)

- <https://pcos.gsfc.nasa.gov/sigs/grsig.php>



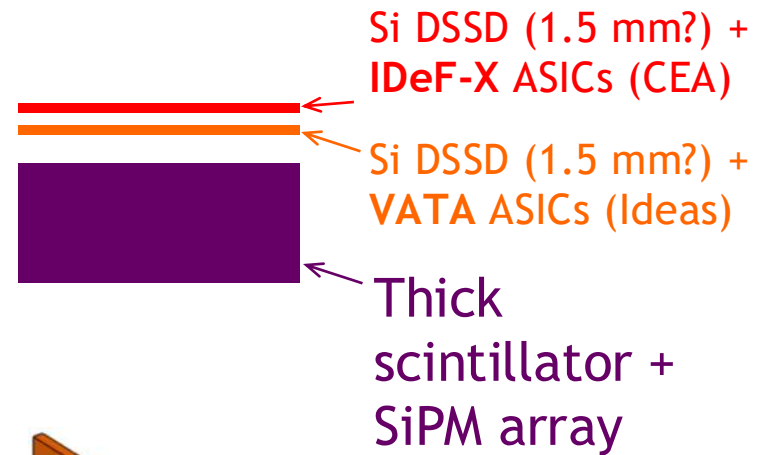
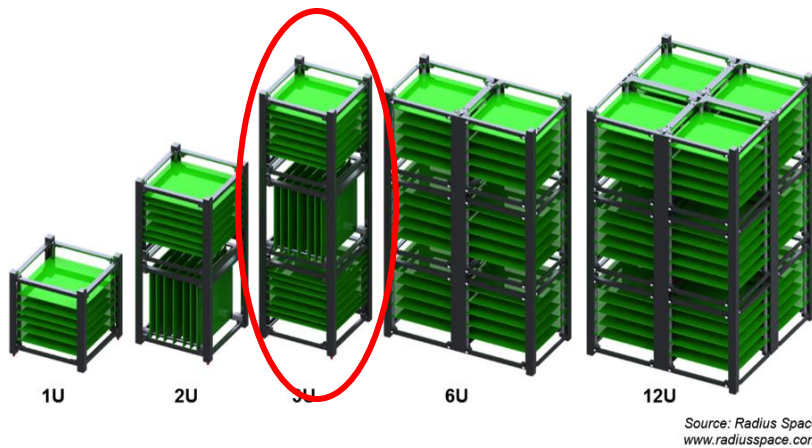
# Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source

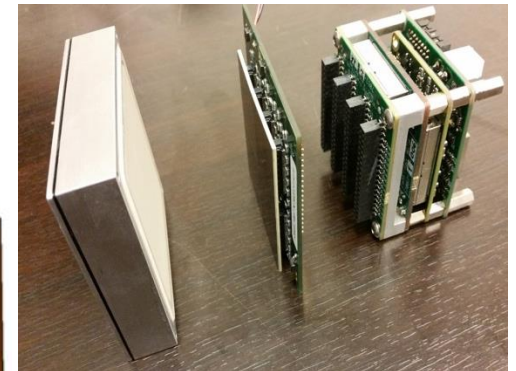
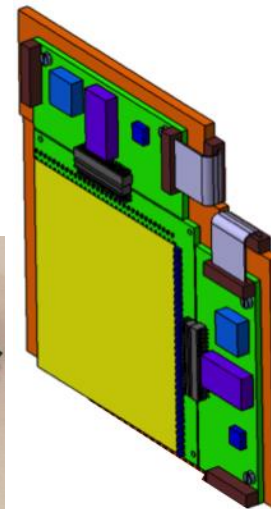
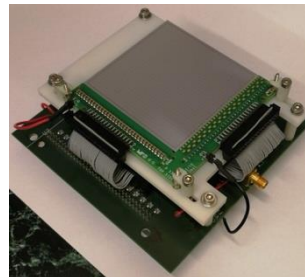


# COMCUBE Nanosat sub-WP

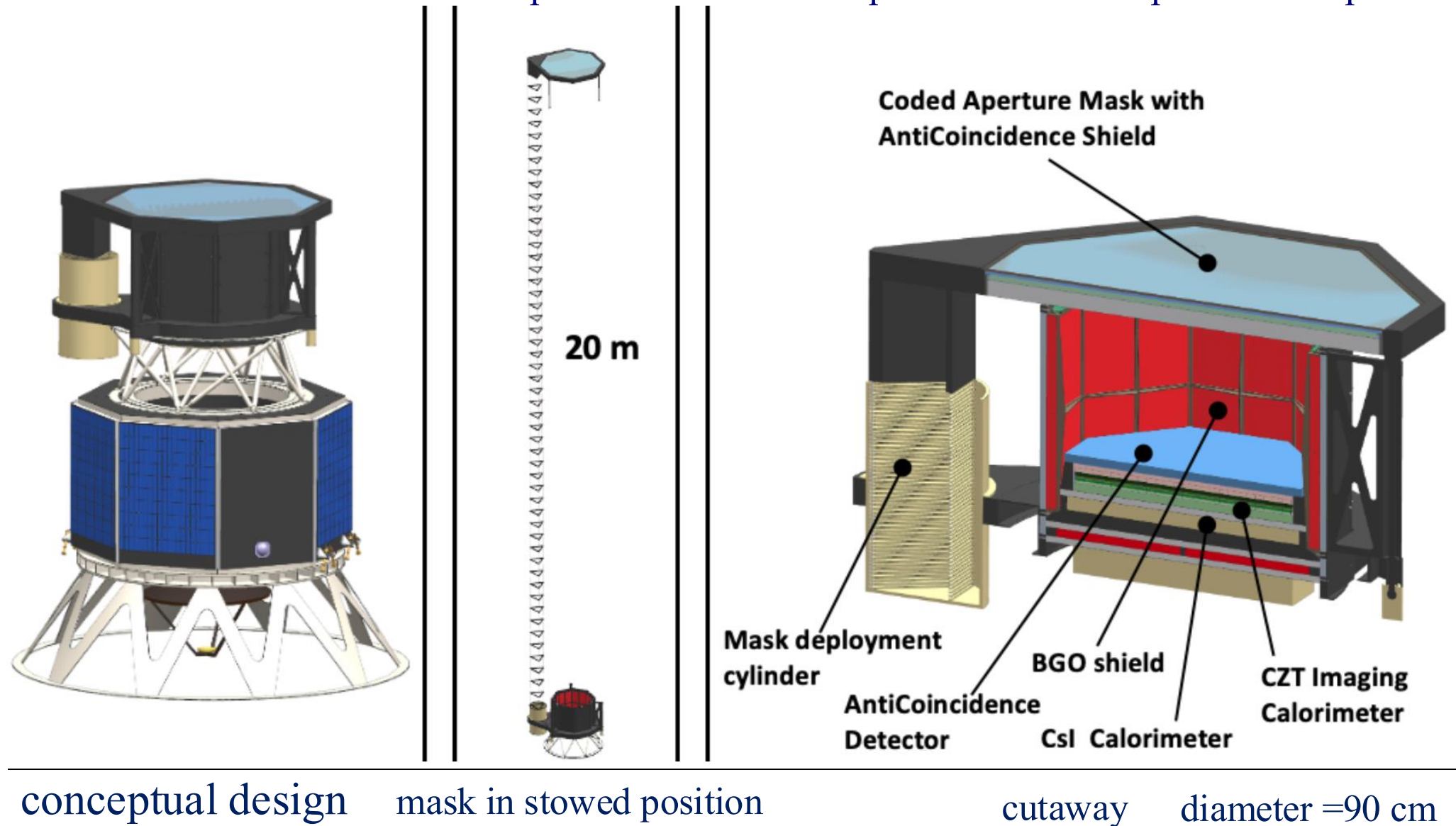
Development of a 3U (?) Compton nanosat for the polarimetry of GRBs + qualification of the e-ASTROGAM technologies



- Cubesat : standard unit  $\Rightarrow$  1U
- Size : 10 x 10 x 10 cm
- Weight : 1kg
- Power: ~ 1.3 W



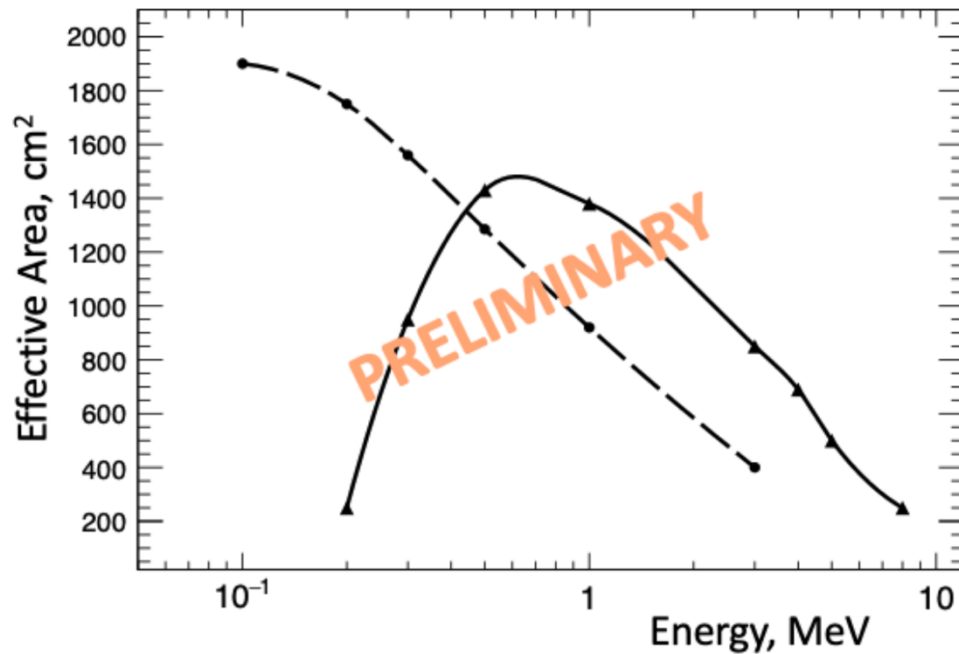
# GECCO The Galactic Explorer with a Coded Aperture Mask Compton Telescope



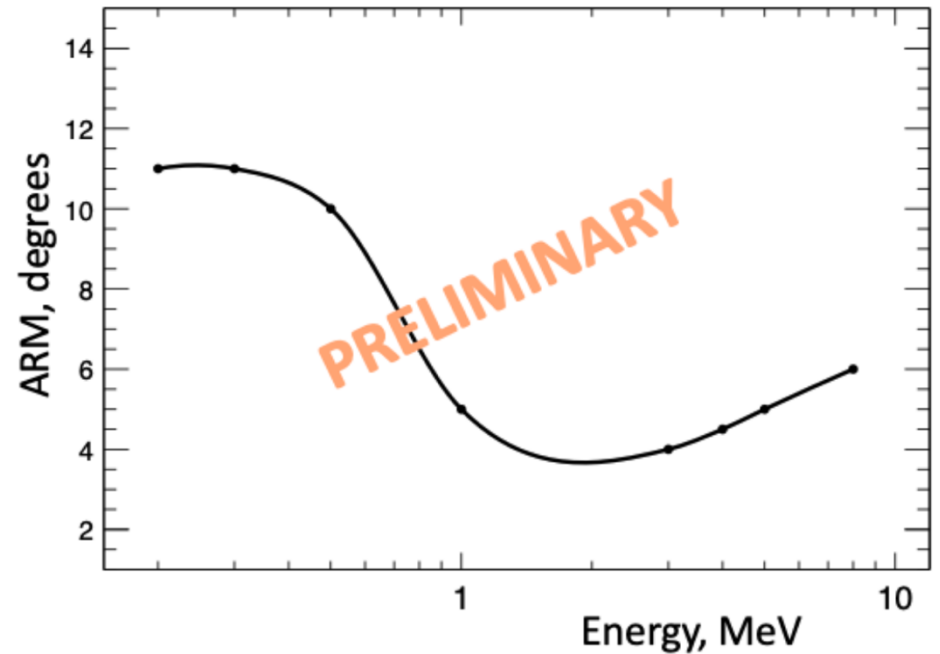
GECCO Team, JCAP07(2022)036 arXiv:2112.07190



# GECCO The Galactic Explorer with a Coded Aperture Mask Compton Telescope



effective area for the CA mask imaging; the solid line is for Compton pointing used, and the dashed line is for classical mask analysis.



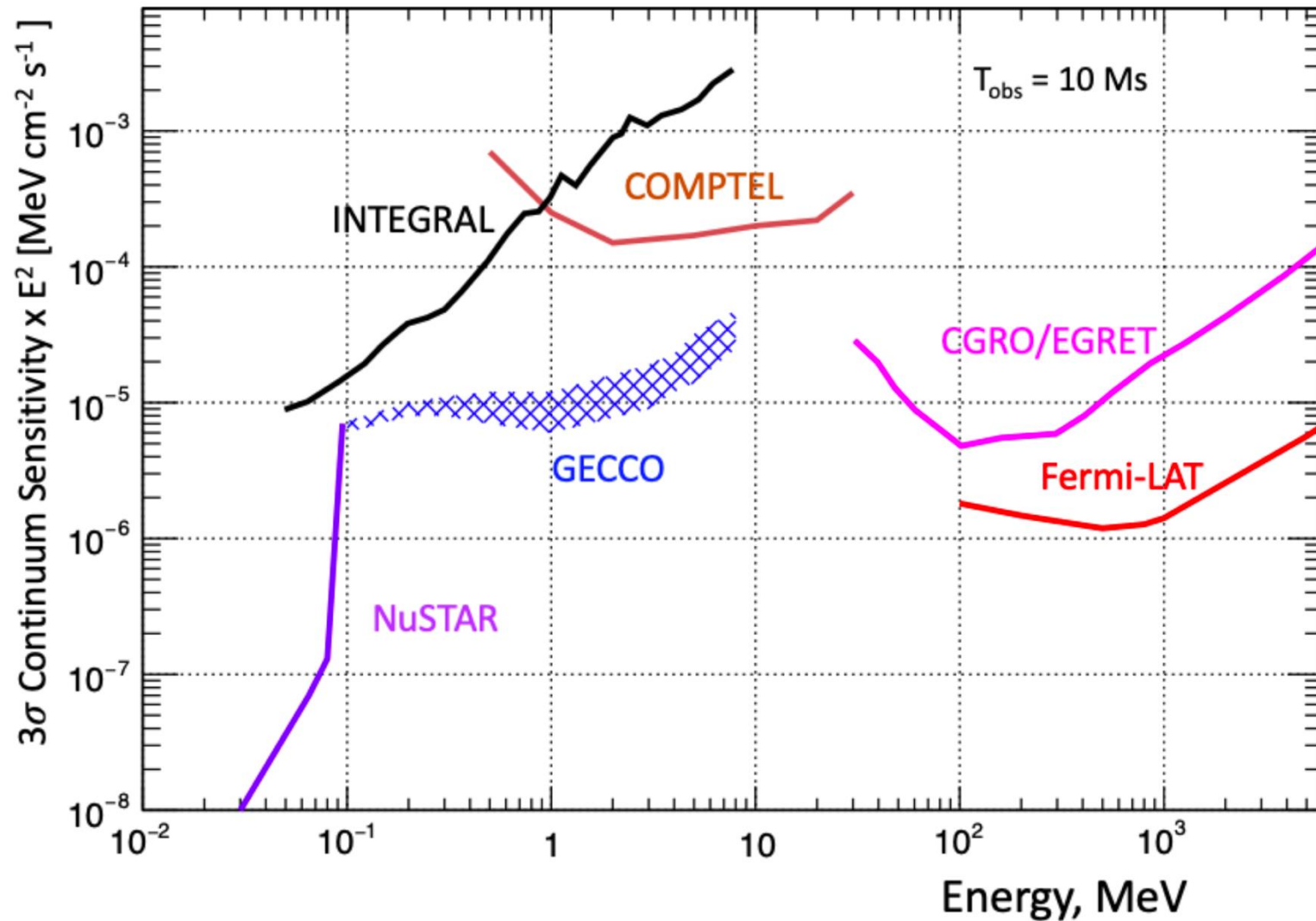
ARM (angular resolution measure) for the ImCal standalone Compton telescope.



GECCO Team, in preparation

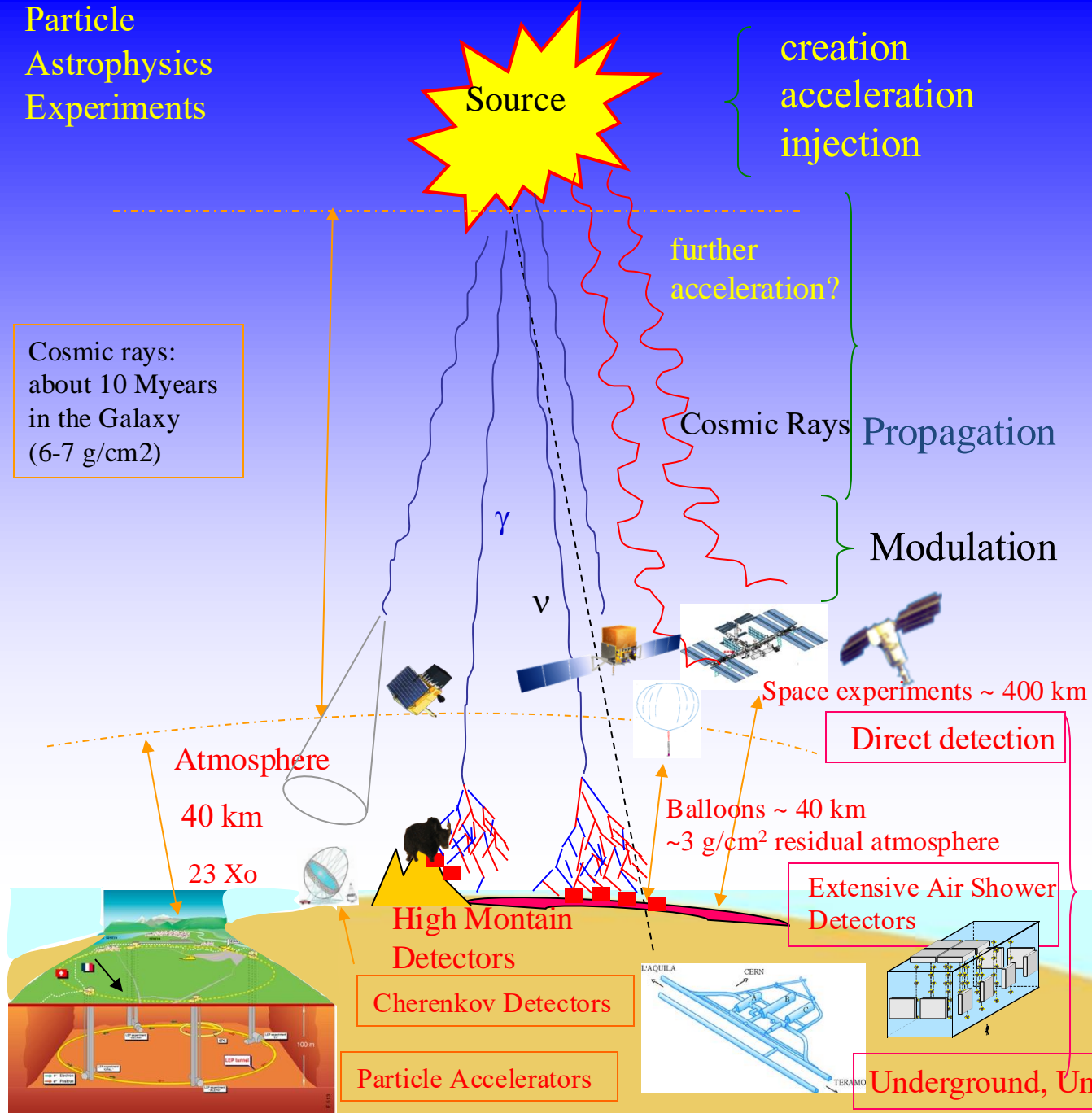
# GECCO The Galactic Explorer with a Coded Aperture Mask Compton Telescope

## Sensitivity

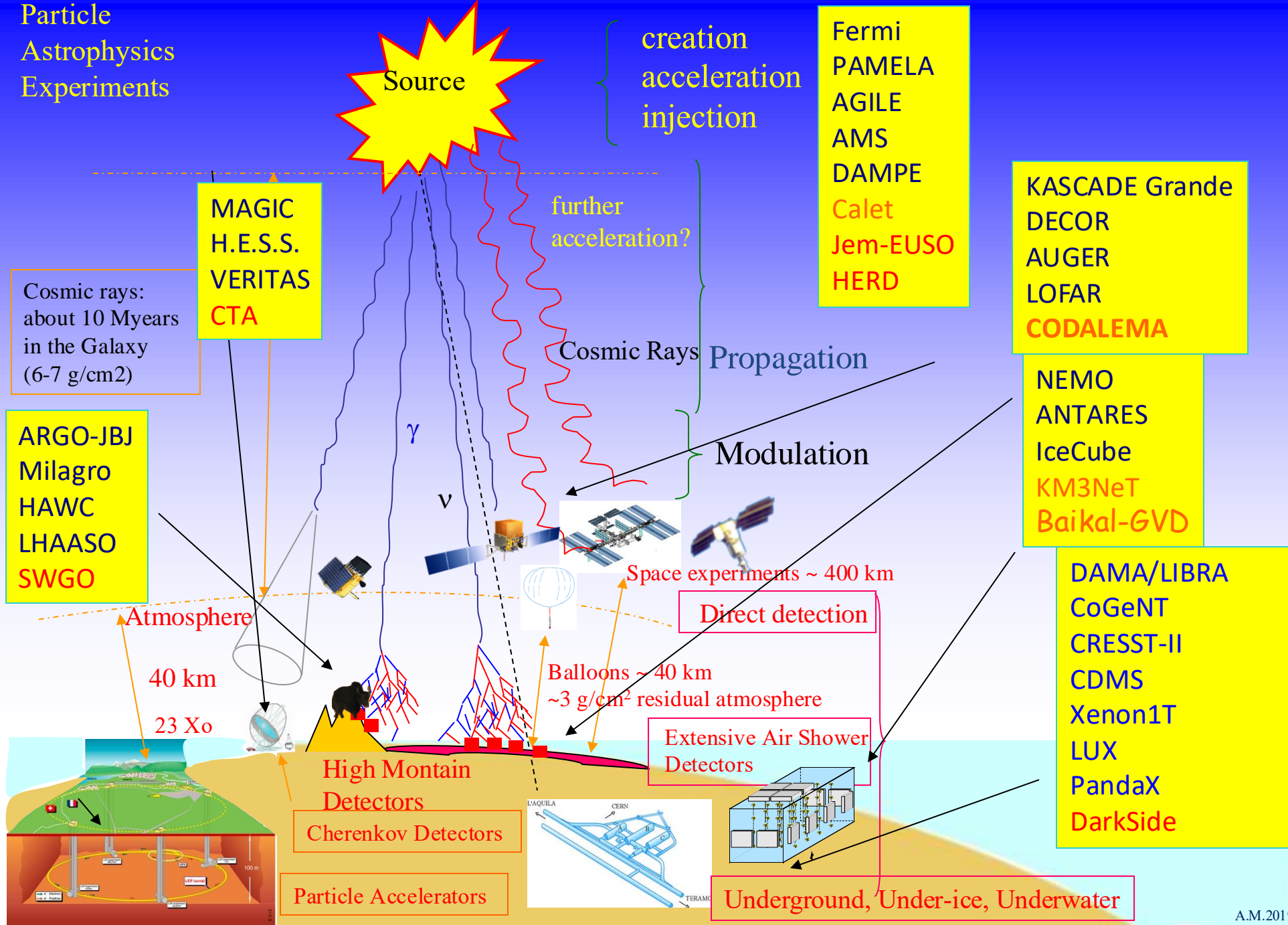


GECCO Team, JCAP07(2022)036 arXiv:2112.07190

# Indirect, Direct and Accelerator Searches for Dark Matter







# Summary

- Indirect search of Dark Matter with gamma rays is complementary to all other research in the underground laboratories and at LHC
- CTA, SWGO and LHAASO can explore the high -energy domain
- Fermi is still in orbit but we need a new mission with a focus in the low energy range ( below 100 MeV)
- Because the flux is high it can be at the AGILE scale (like Gamma-Light) i.e. also a National Space Agency (or two) can support the development and launch

thank you!