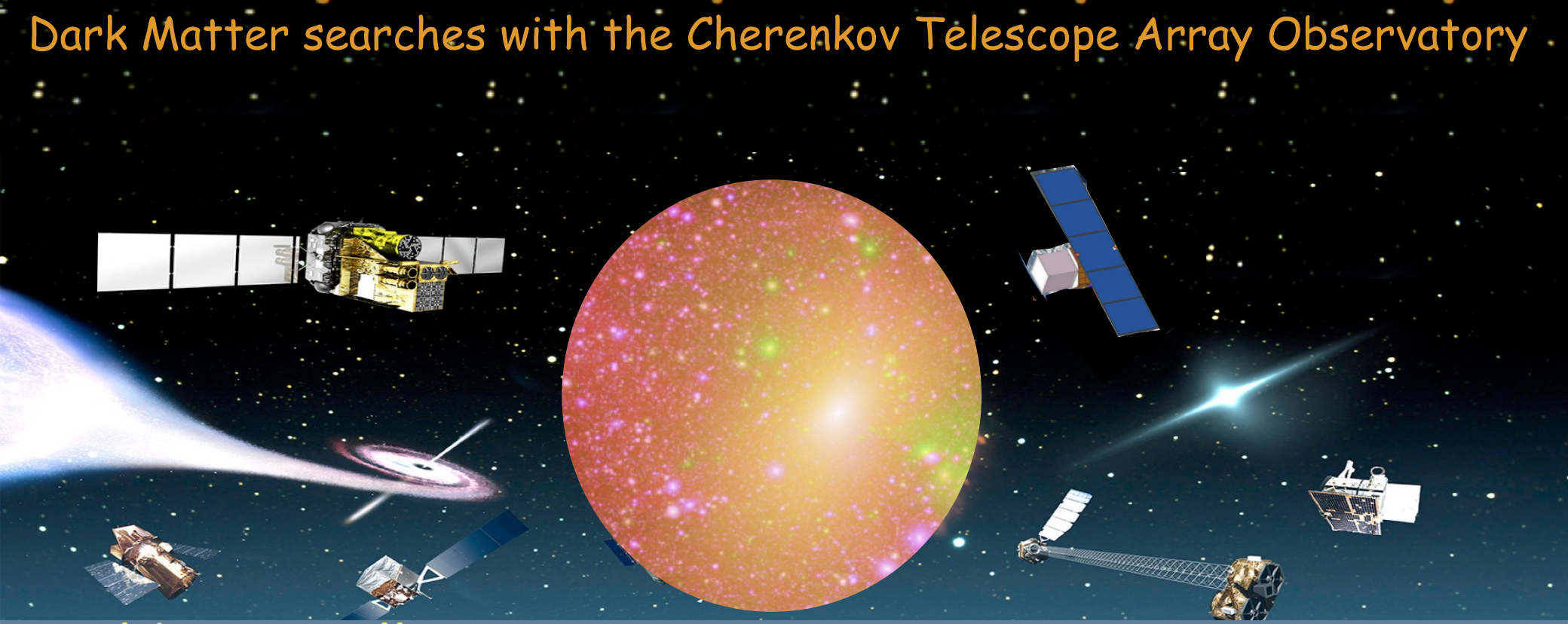
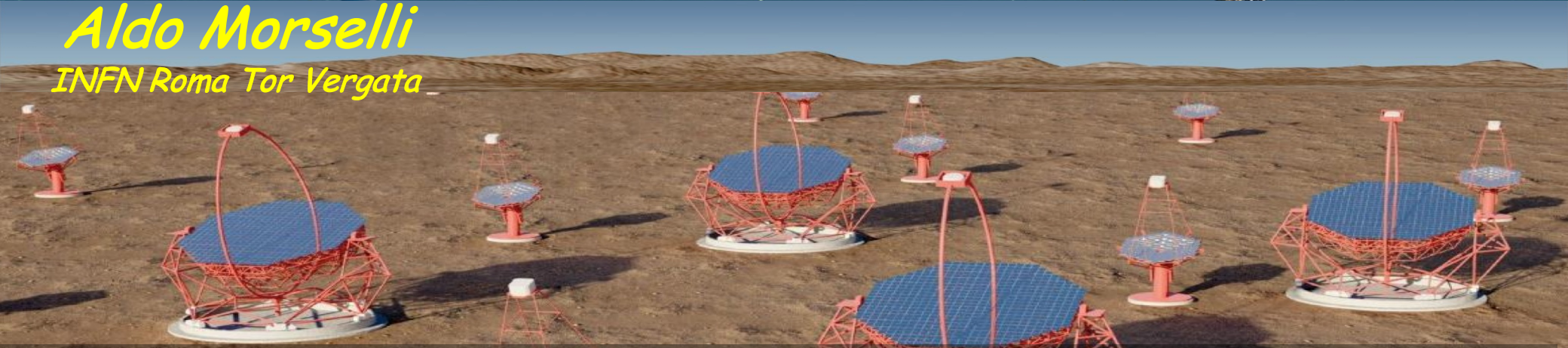
Dark Matter searches with the Cherenkov Telescope Array Observatory



Aldo Morselli

INFN Roma Tor Vergata



Hands-on the Extreme Universe with High Energy Gamma-ray Data

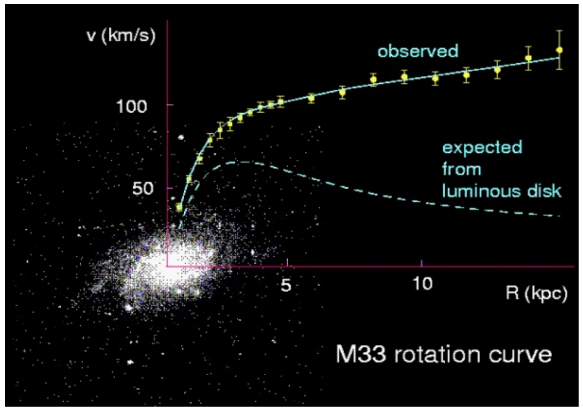
Sexen Center for Astrophysics, 20 July 2022

Dark Matter EVIDENCE

In 1933, the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies.

Since then, even more evidence:

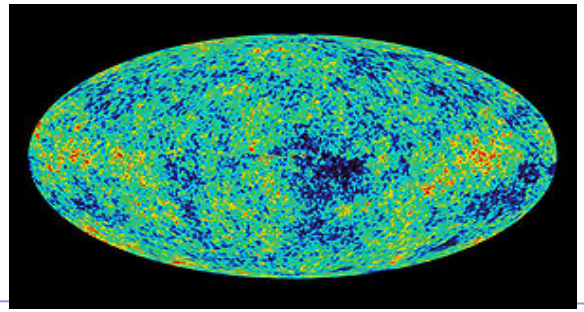
Rotation curves of galaxies



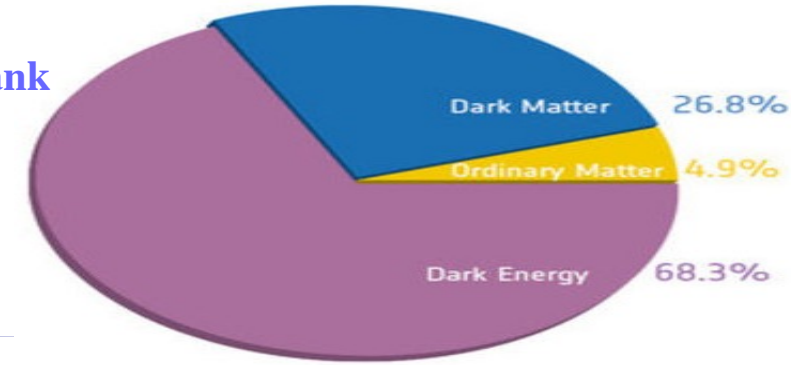
Gravitational lensing

Bullet cluster

Structure formation as deduced from CMB



Data by Plank imply:



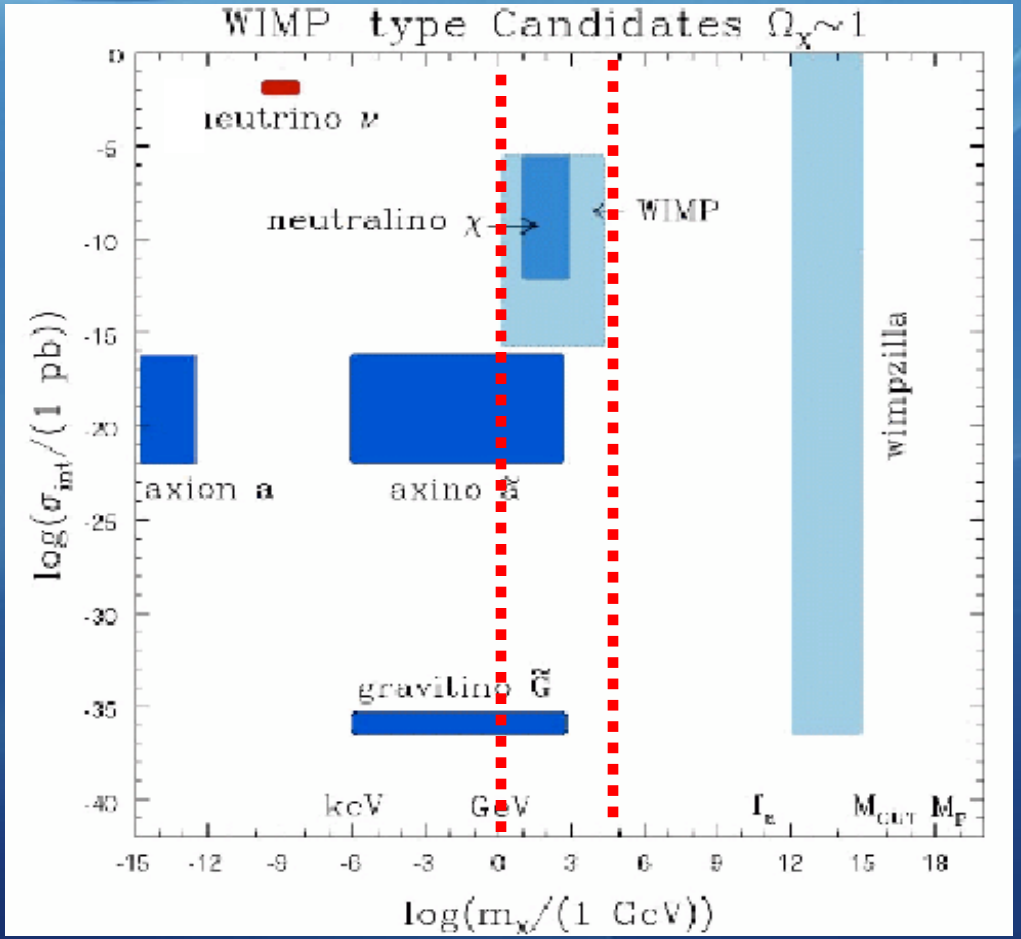
$\Omega_{Dm} \approx 26.8\%$

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


Dark Matter

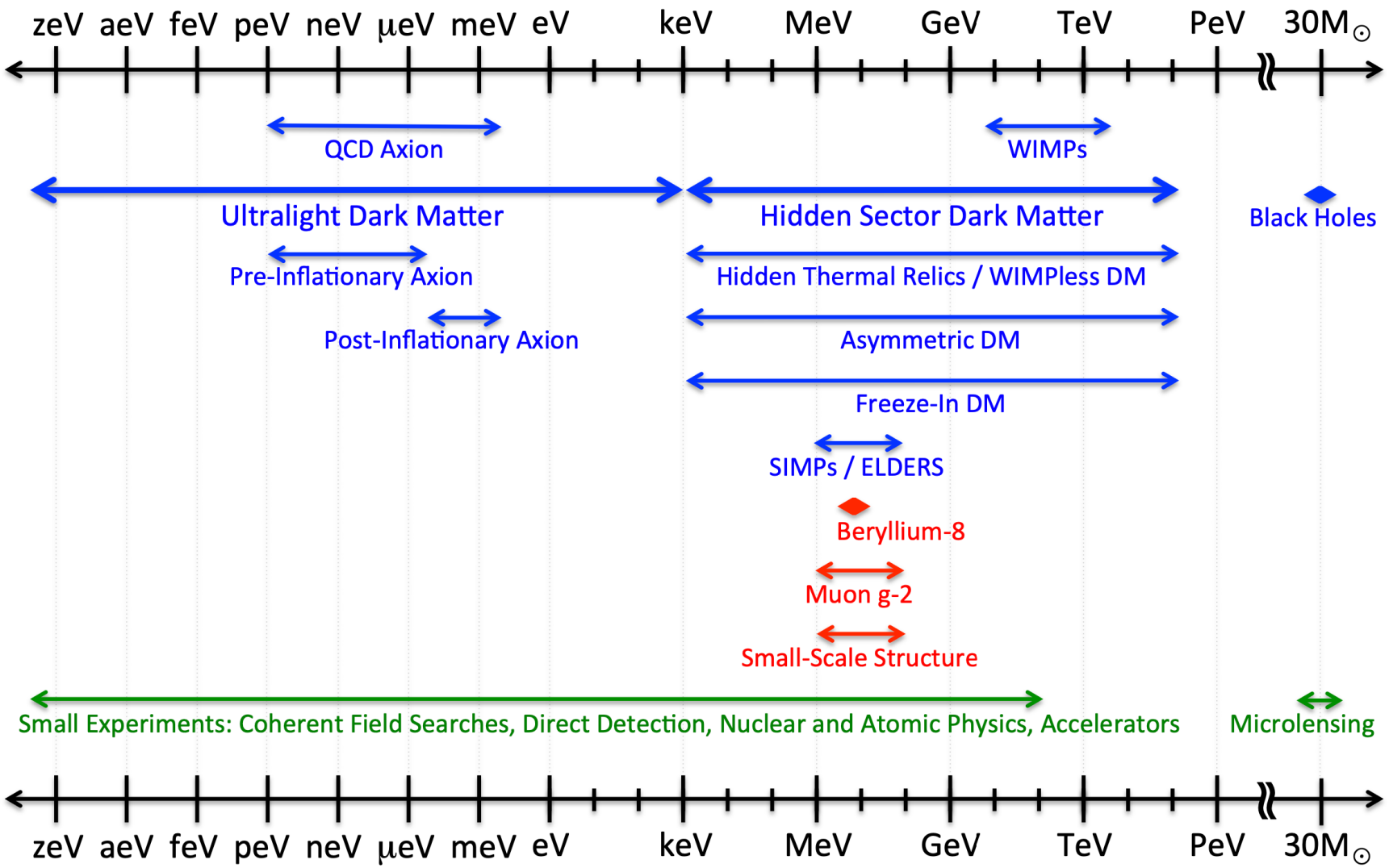
Dark Matter Candidates

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



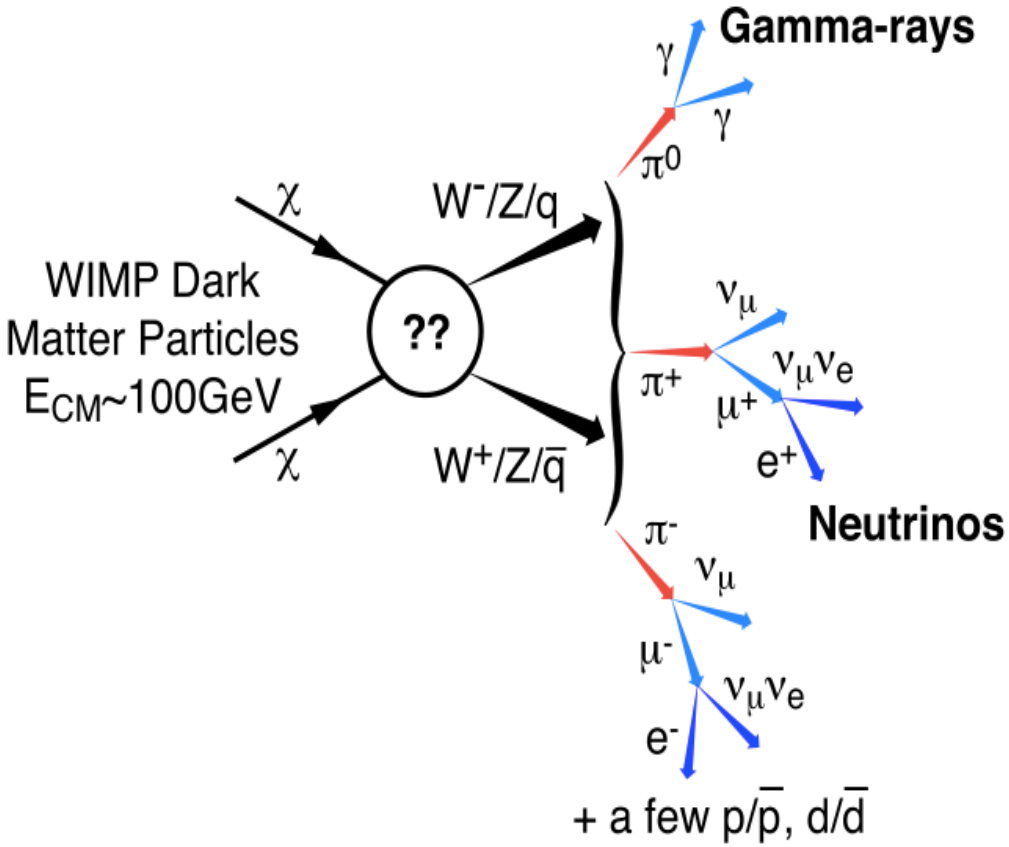
Dark Sector Candidates, Anomalies, and Search Techniques

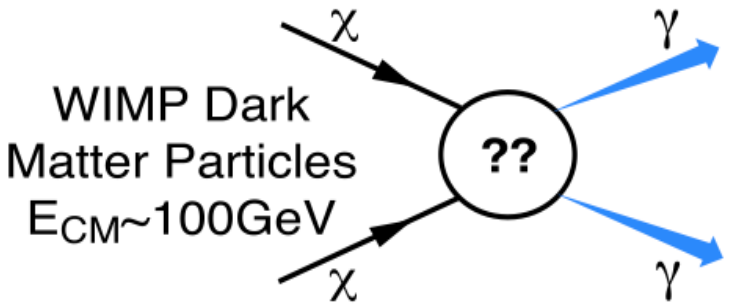
Dark Sector Candidates, Anomalies, and Search Techniques

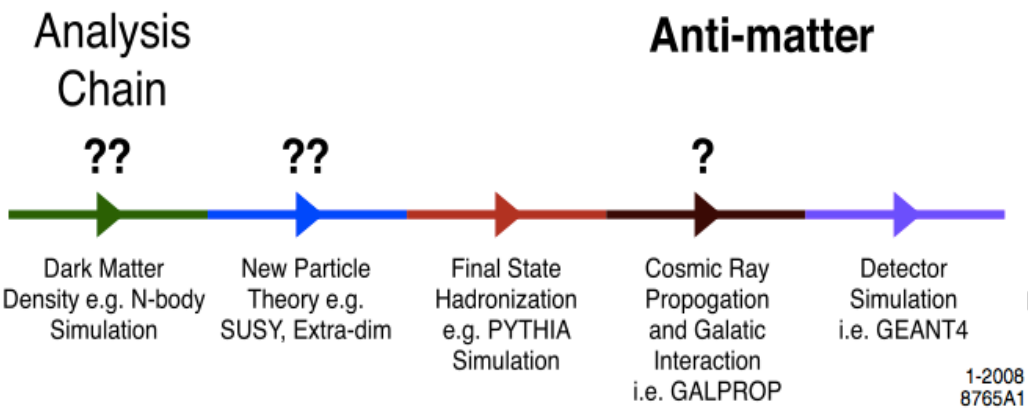


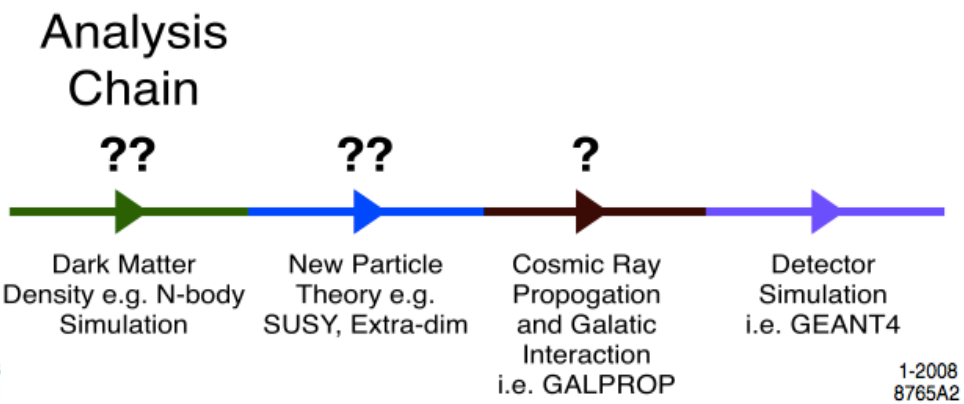
New Ideas in Dark Matter 2017 : Community Report arXiv:1707.04591

Annihilation channels

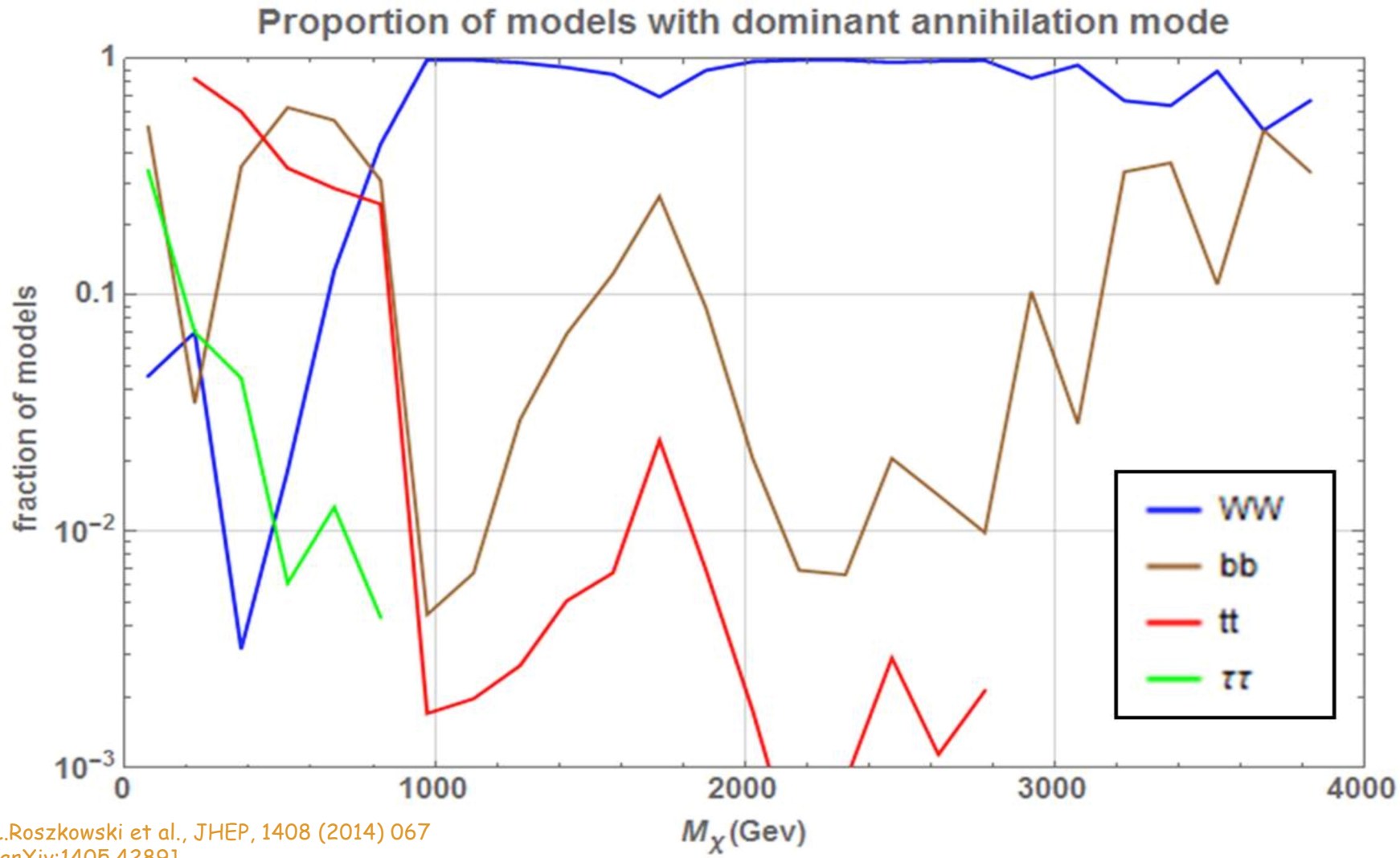






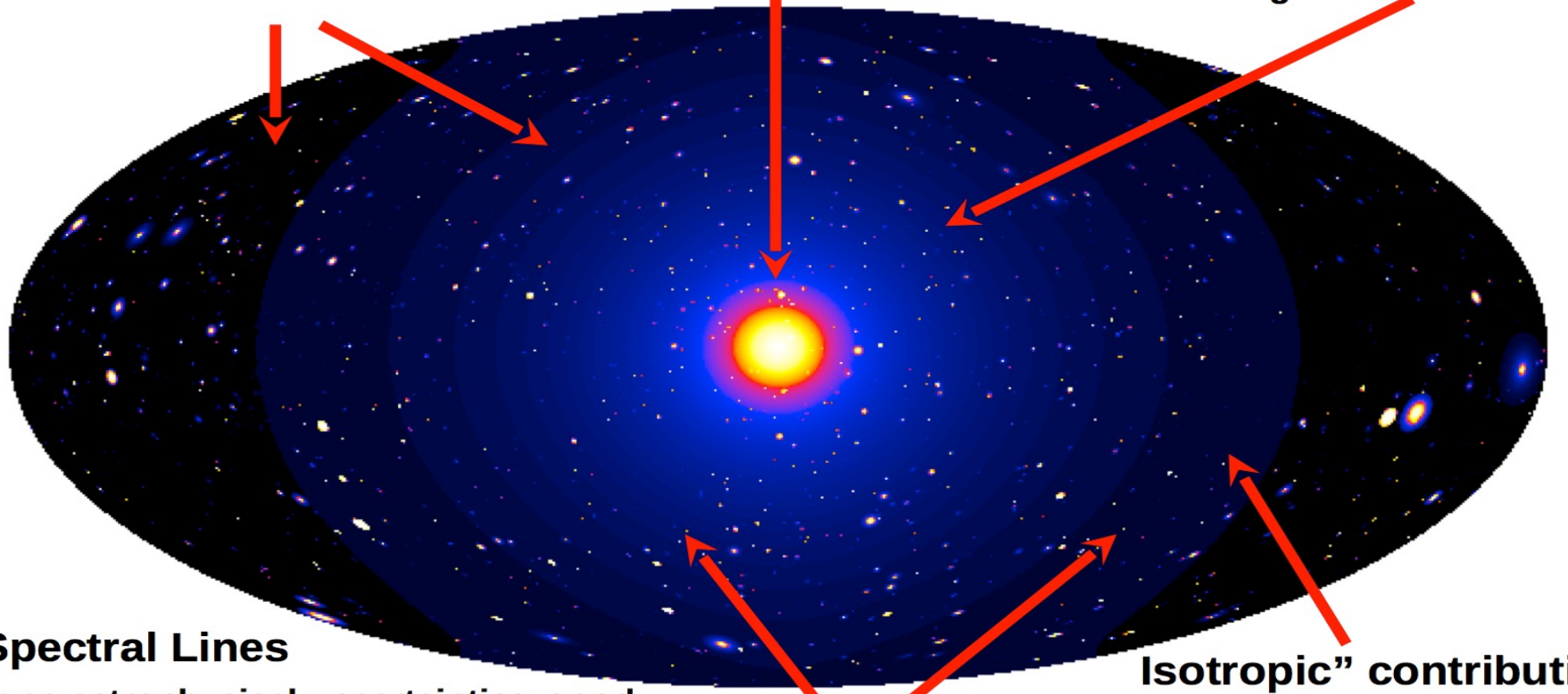


Which channel to choose?
Example: The dominant annihilation modes in the pMSSM scan



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

Dark Matter Search: Targets and Strategies



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, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics

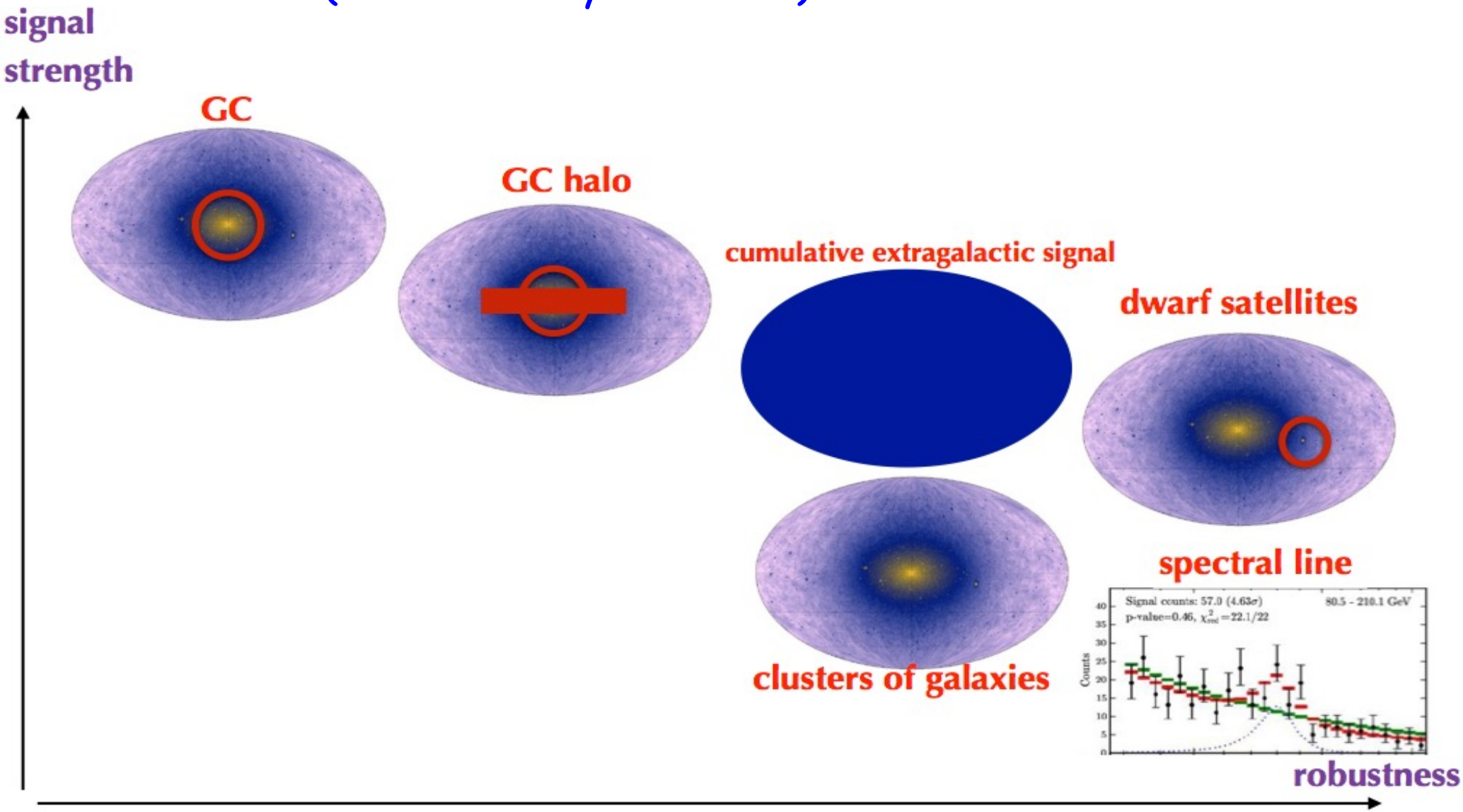
Isotropic" contributions

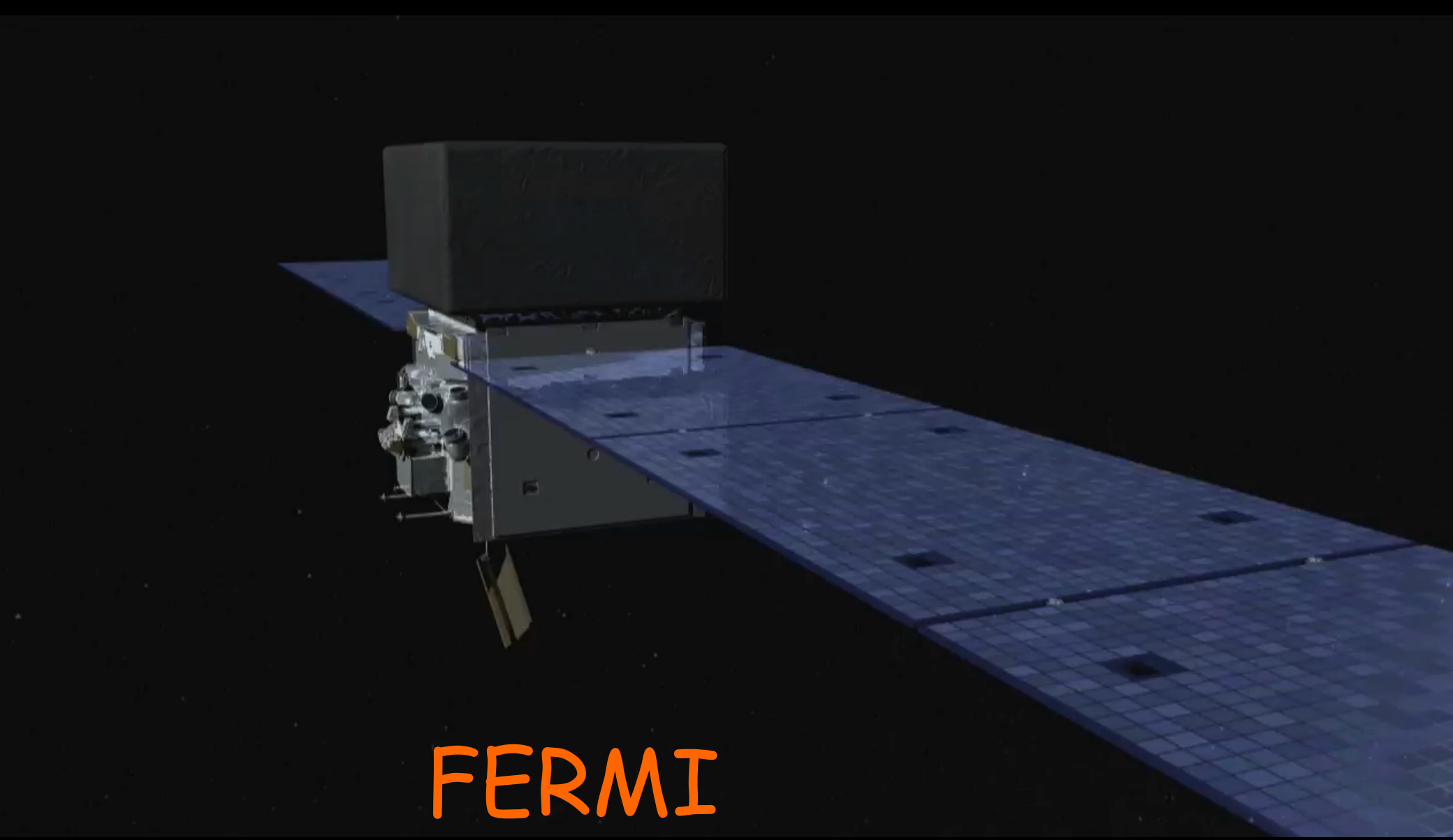
Large statistics, but astrophysics, galactic diffuse background

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

Dark Matter Search: Targets and Strategies

(Another way to see it)



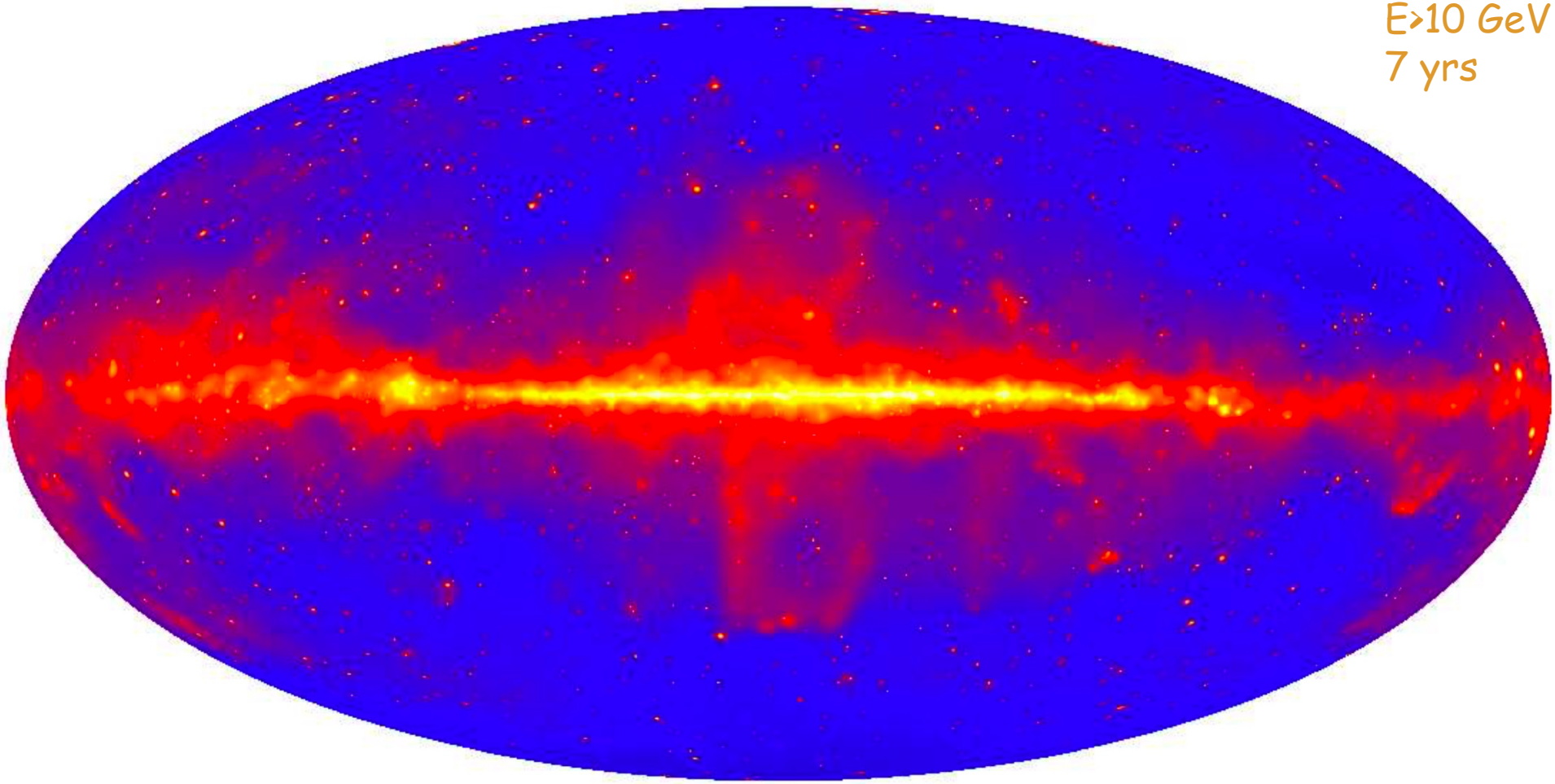

FERMI
Large Area Telescope

Fermi
Gamma-ray
Space Telescope

11 June 2008


Fermi
Gamma-ray
Space Telescope
Happy 14th Birthday Fermi !!
11 June 2008

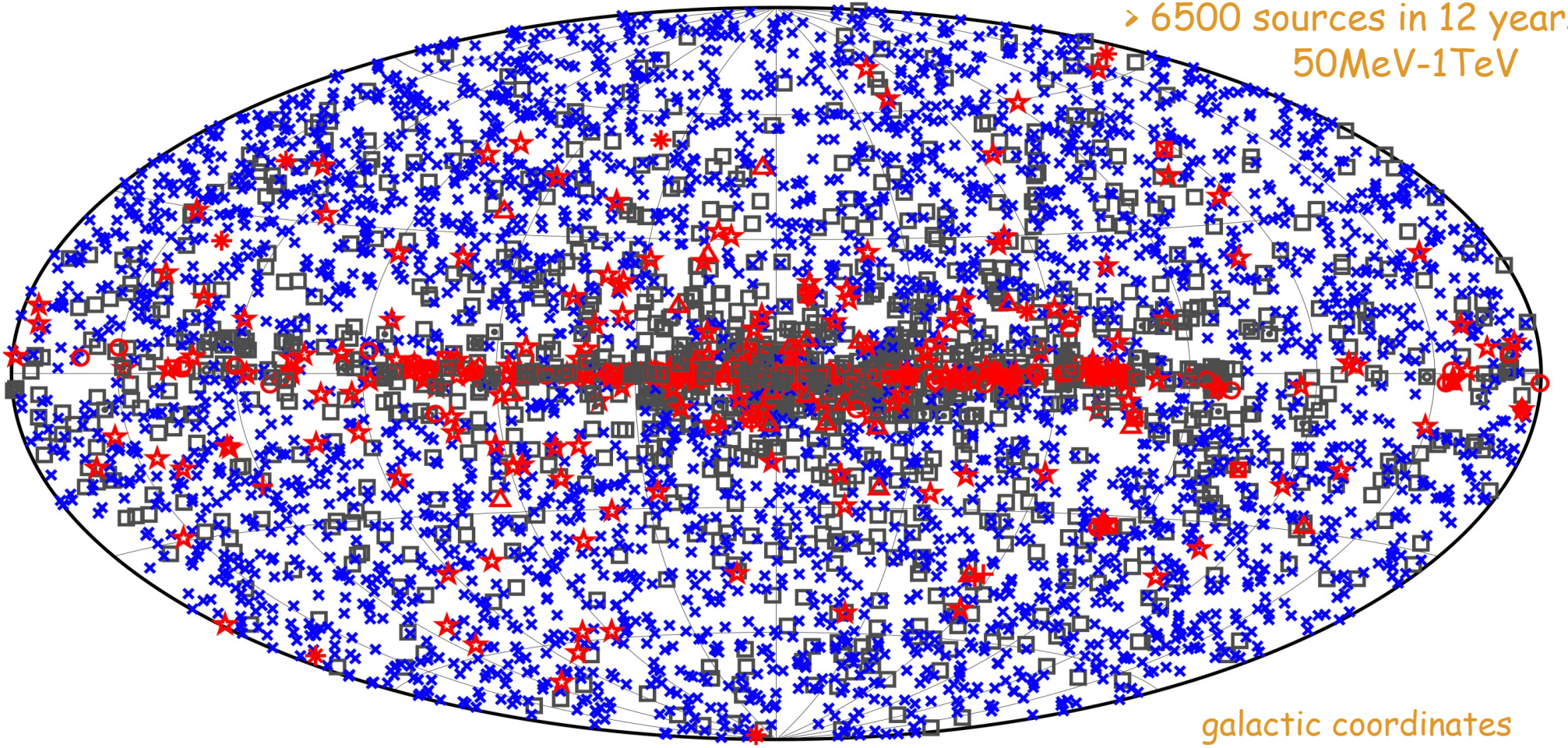
The sky in gamma-rays



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

The sky in gamma-rays 4th source catalog

> 6500 sources in 12 years
50MeV-1TeV

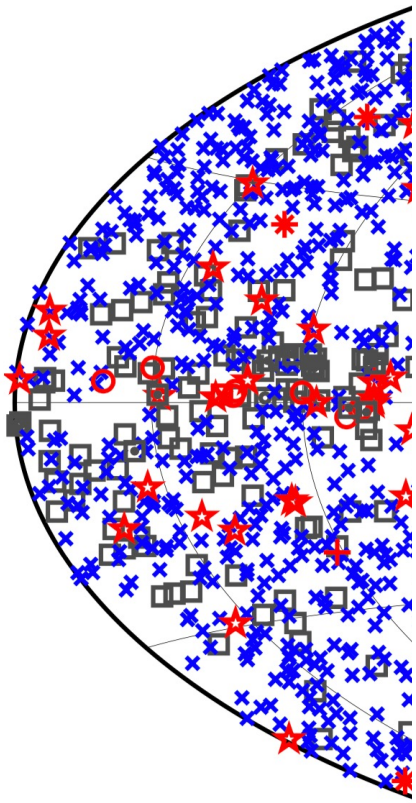


galactic coordinates

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

Fermi Fourth Source Catalog, The Astrophysical Journal ss, 247; 33 March 2020 [arXiv:1902.10045]
+ Incremental Fermi Large Area Telescope Fourth Source Catalog arXiv:2201.11184

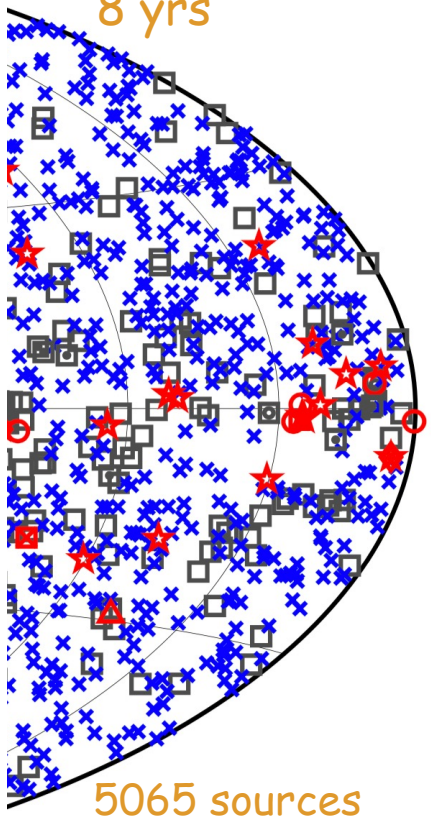
The sky in gamma-rays 4th source catalog



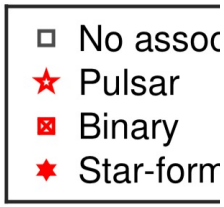
Description	Identified		Associated	
	Designator	Number	Designator	Number
Pulsar, identified by pulsations	PSR	229	···	···
Pulsar, no pulsations seen in LAT yet	···	···	psr	10
Pulsar wind nebula	PWN	12	pwn	6
Supernova remnant	SNR	24	snr	16
Supernova remnant / Pulsar wind nebula	SPP	0	spp	90
Globular cluster	GLC	0	glc	30
Star-forming region	SFR	3	sfr	0
High-mass binary	HMB	5	hmb	3
Low-mass binary	LMB	1	lmb	1
Binary	BIN	1	bin	0
Nova	NOV	1	nov	0
BL Lac type of blazar	BLL	22	bll	1094
FSRQ type of blazar	FSRQ	42	fsrq	644
Radio galaxy	RDG	6	rdg	36
Non-blazar active galaxy	AGN	1	agn	17
Steep spectrum radio quasar	SSRQ	0	ssrq	2
Compact Steep Spectrum radio source	CSS	0	css	5
Blazar candidate of uncertain type	BCU	3	bcu	1327
Narrow line Seyfert 1	NLSY1	4	nlsy1	5
Seyfert galaxy	SEY	0	sey	1
Starburst galaxy	SBG	0	sbg	7
Normal galaxy (or part)	GAL	2	gal	2
Unknown	UNK	0	unk	92
Total	···	356	···	3388
Unassociated	···	···	···	1323

NOTE—The designation 'spp' indicates potential association with SNR or PWN. Designations shown in capital letters are firm identifications; lower case letters indicate associations.

50MeV-1TeV
8 yrs



5065 sources
galactic coordinates

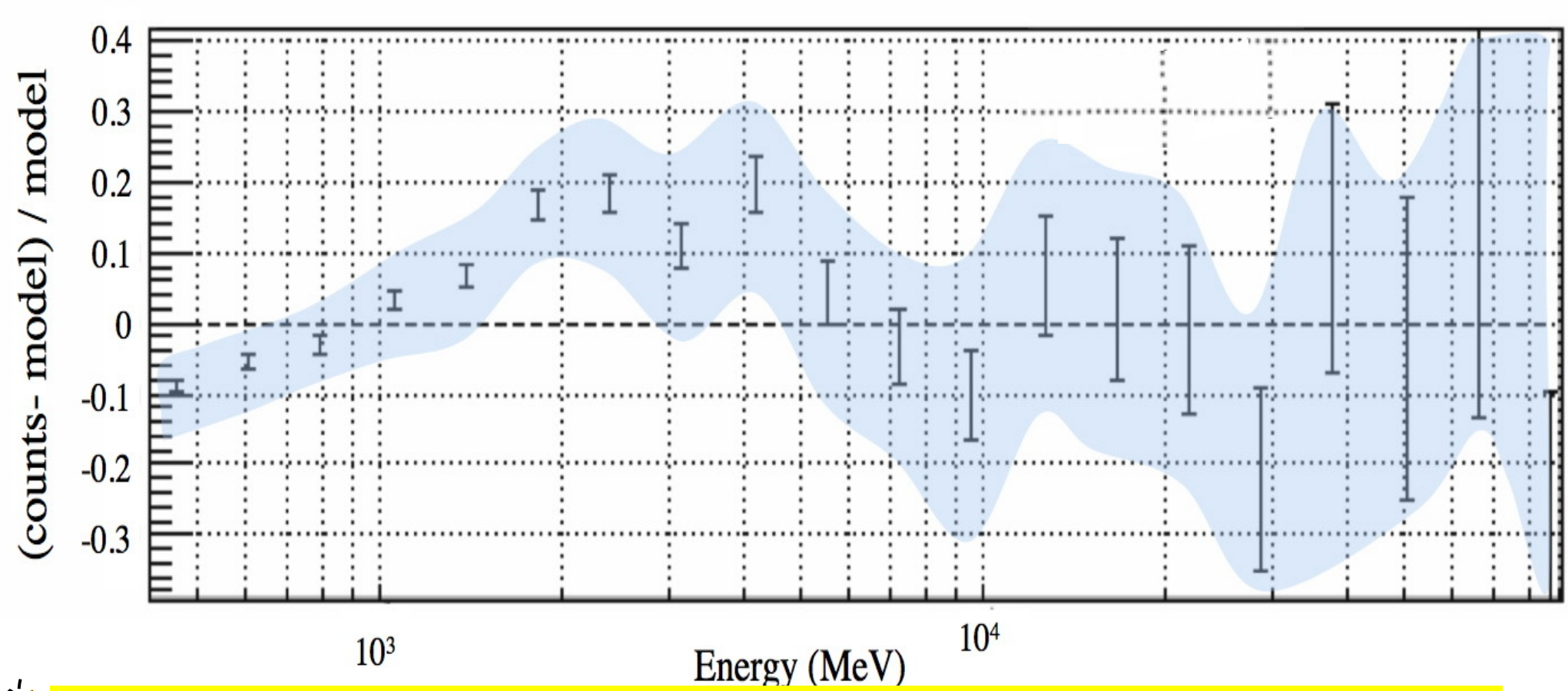


Fermi Fourth Source Catalog, The Astrophysical Journal ss, 247: 33 March 2020 [arXiv:1902.10045]

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

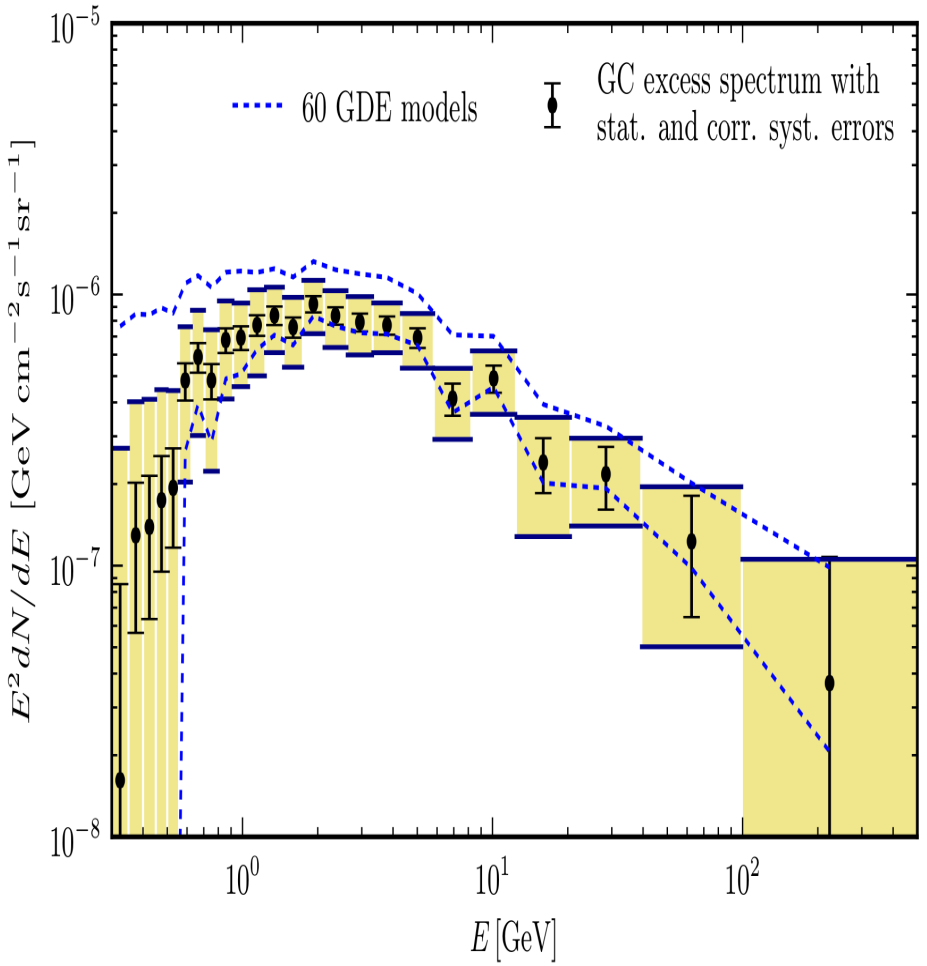
11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

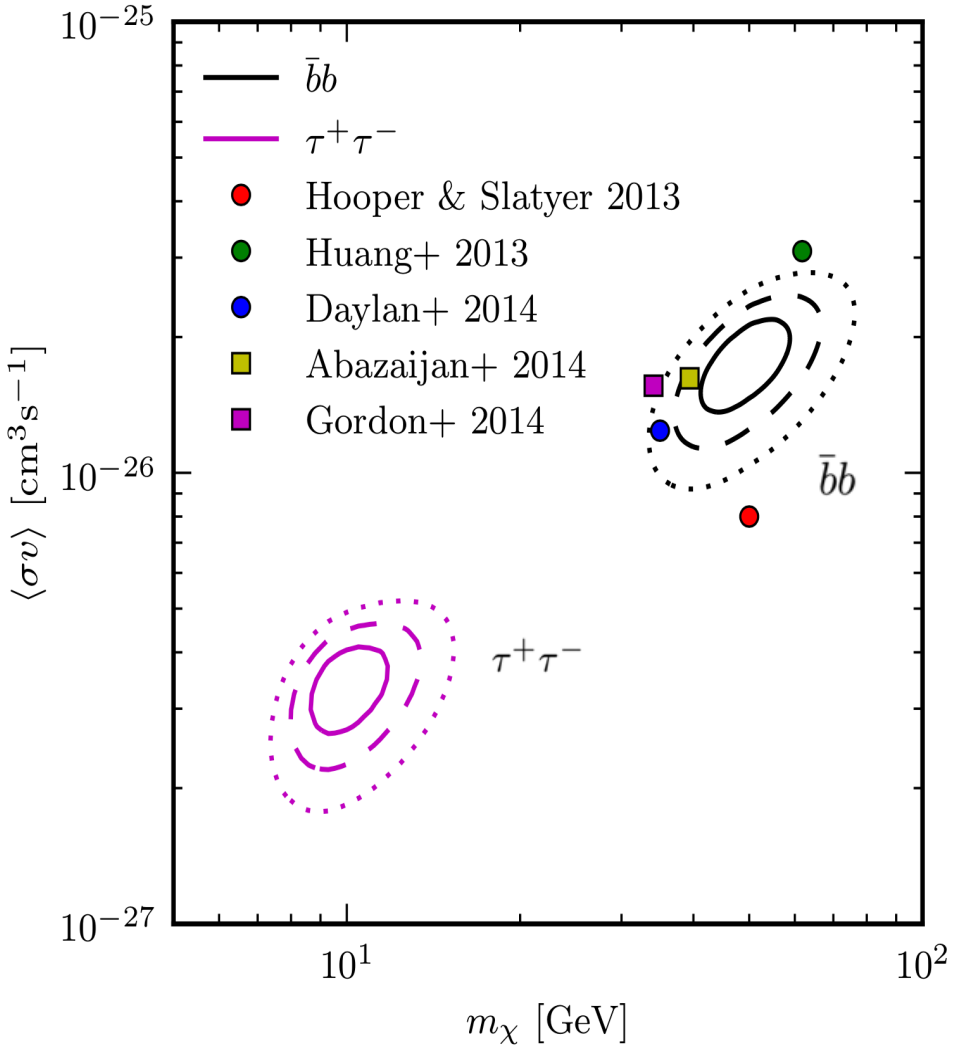
- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV



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

The GeV excess

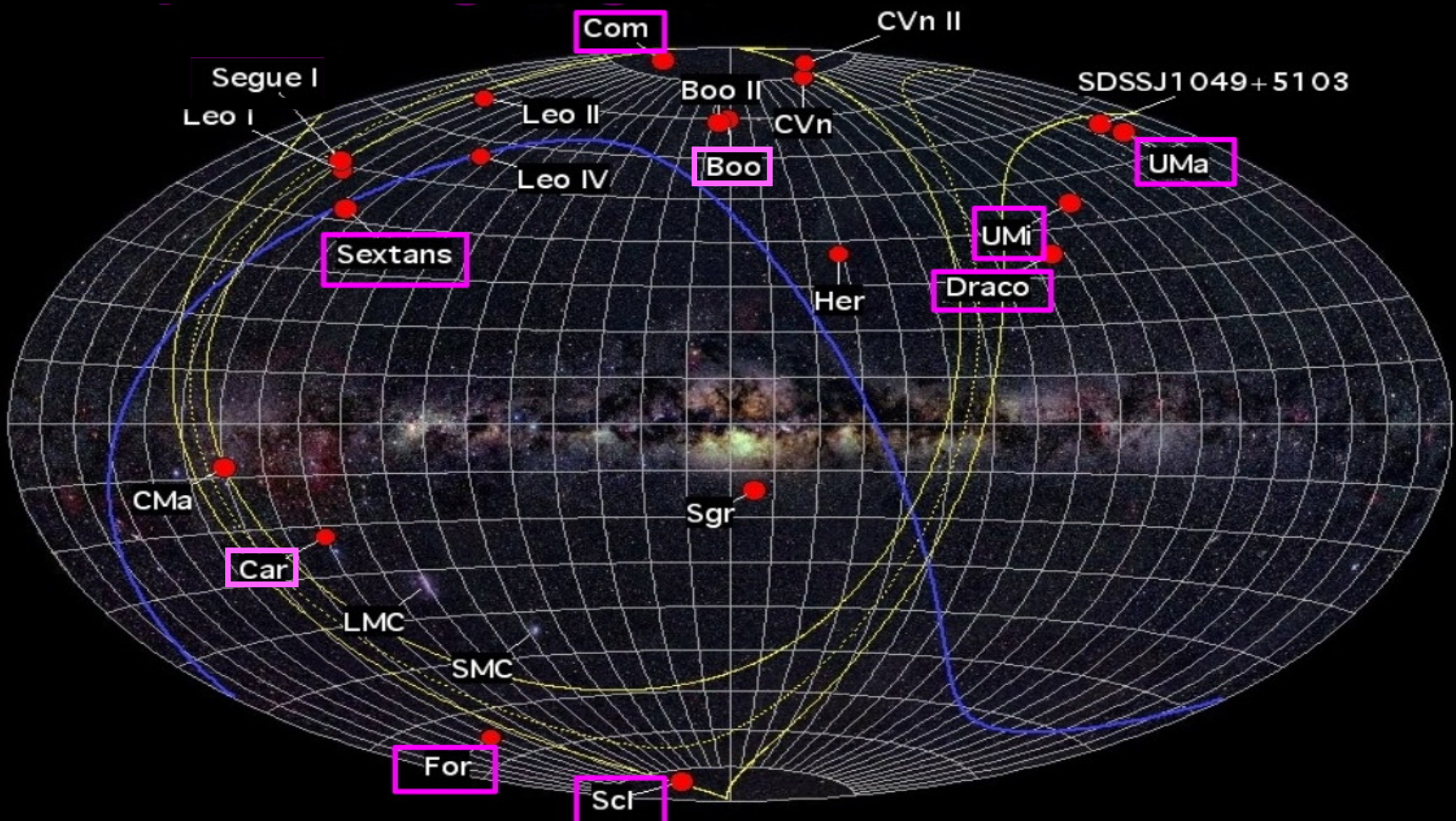




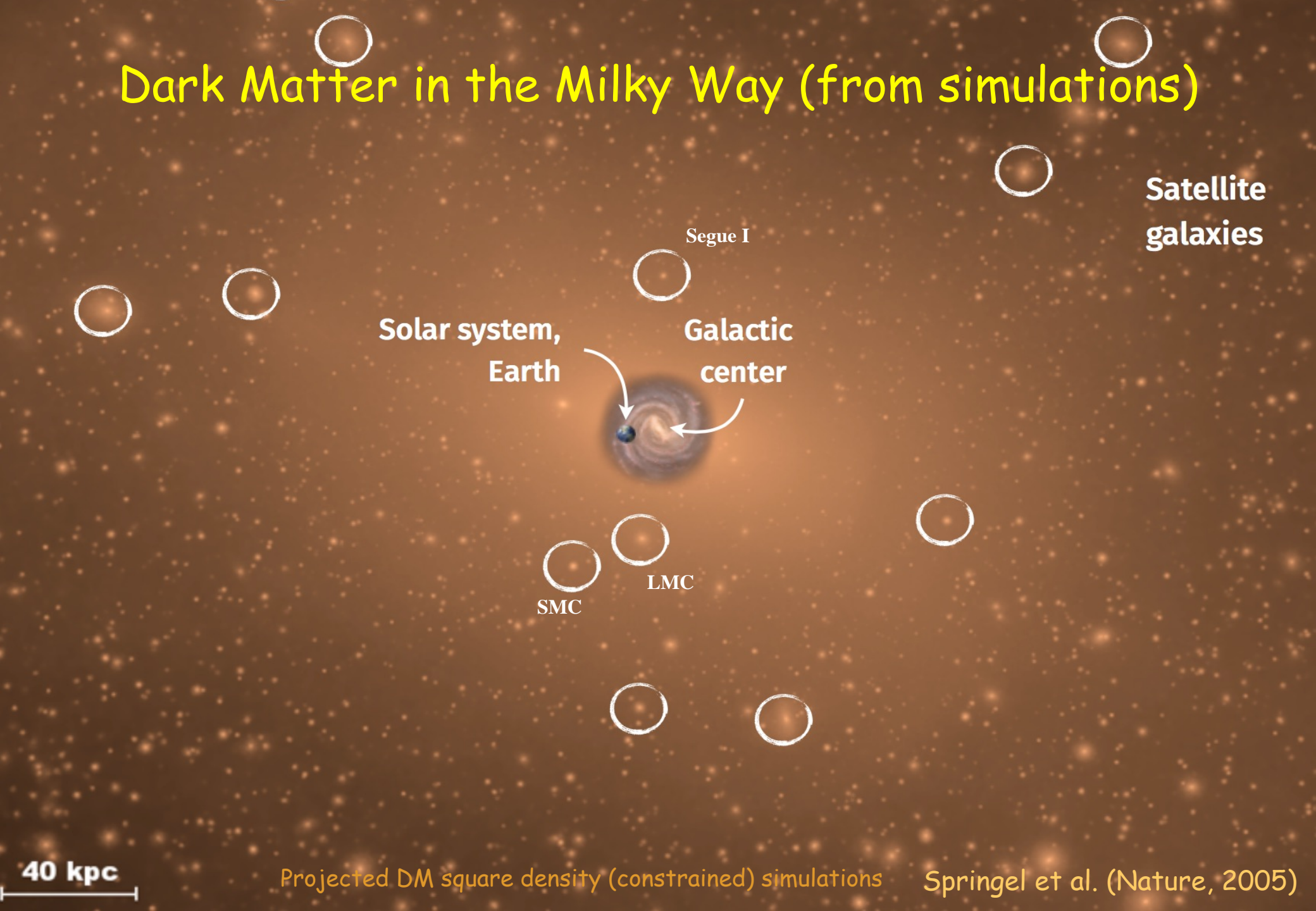
A lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center

Calore et al, arXiv:1409.0042v1

Classical Dwarf spheroidal galaxies: promising targets for DM detection



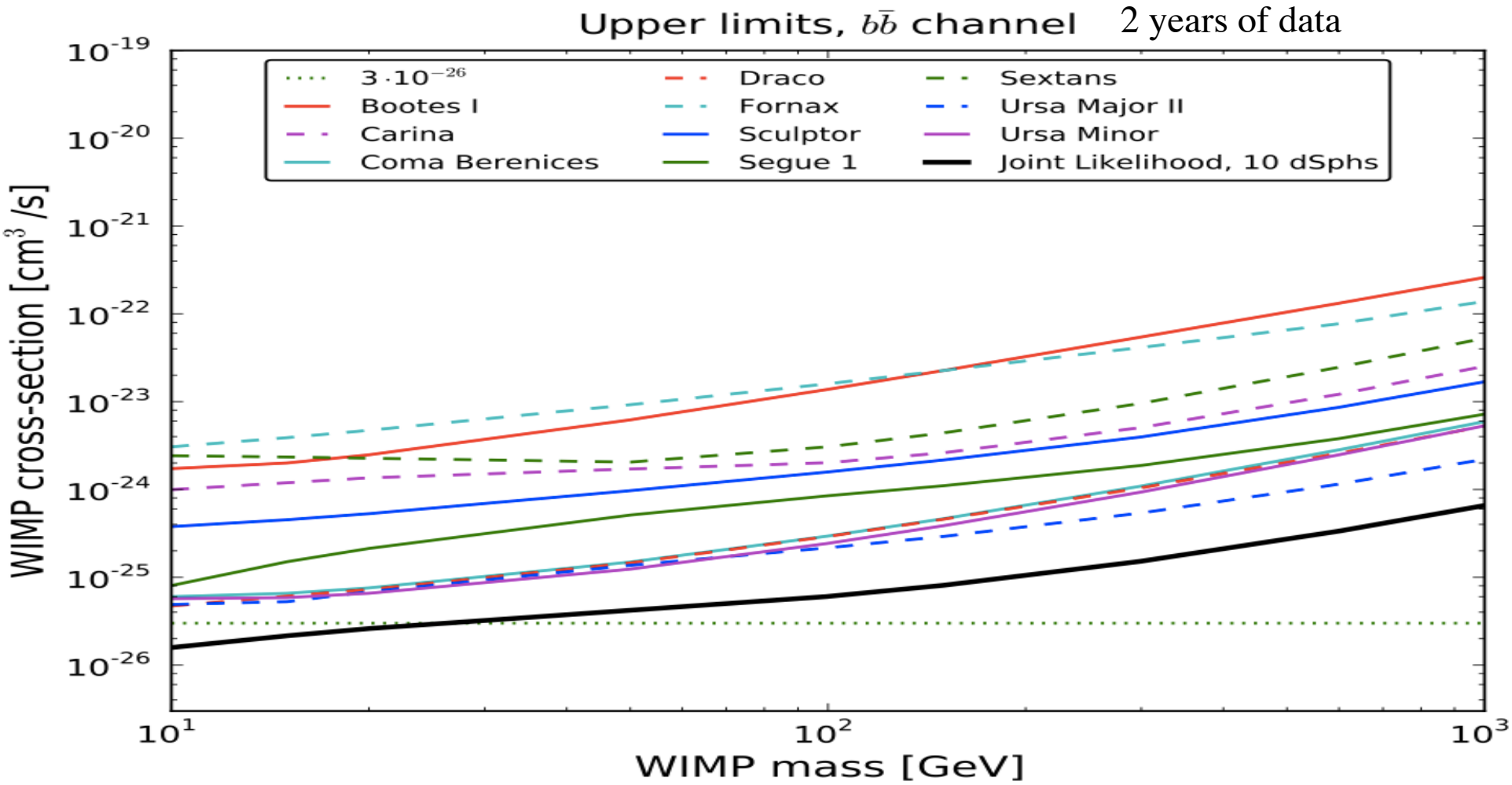
Dark Matter in the Milky Way (from simulations)



Projected DM square density (constrained) simulations

Springel et al. (Nature, 2005)

Dwarf Spheroidal Galaxies combined analysis

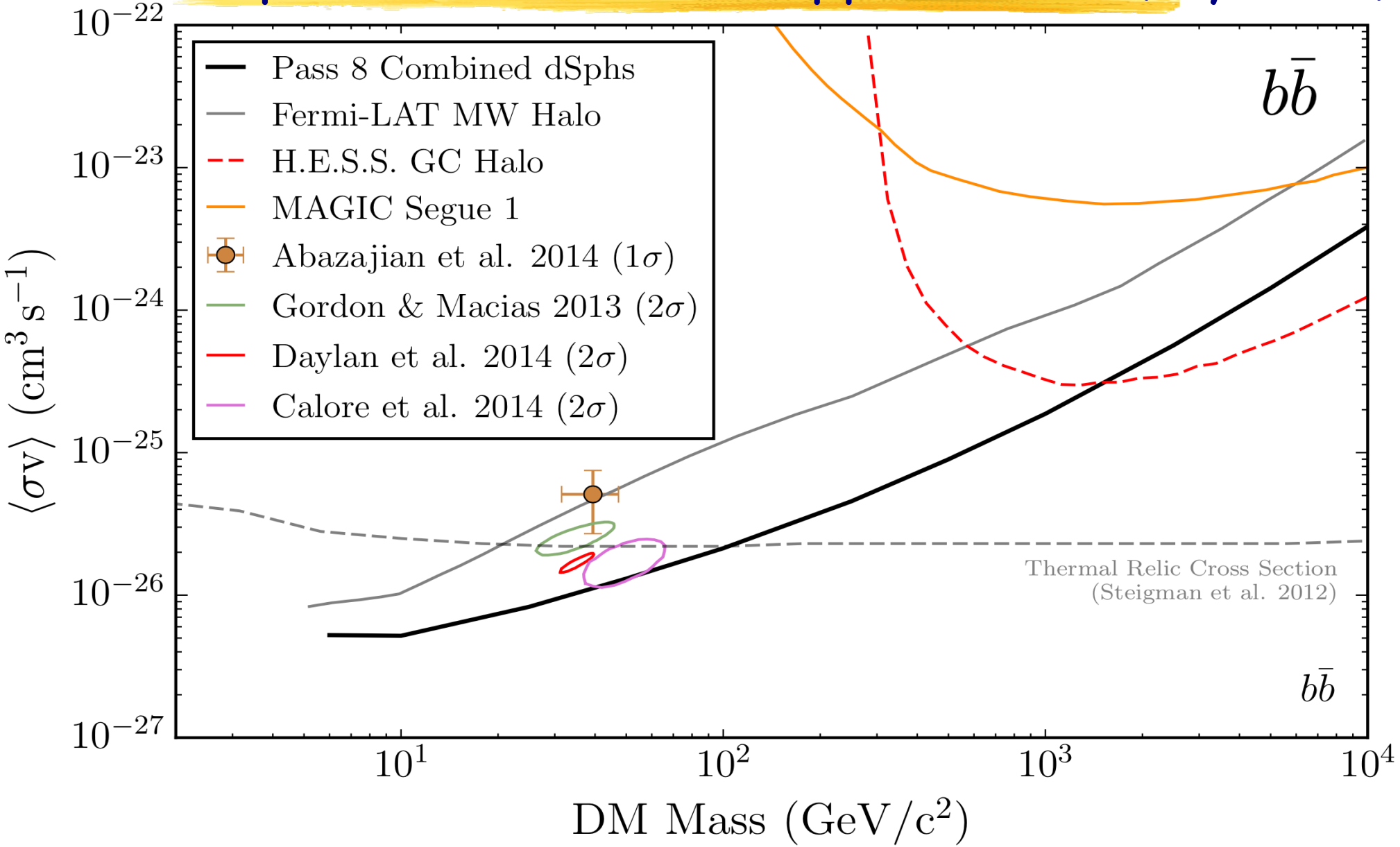


robust constraints including J-factor uncertainties from the stellar data statistical analysis

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

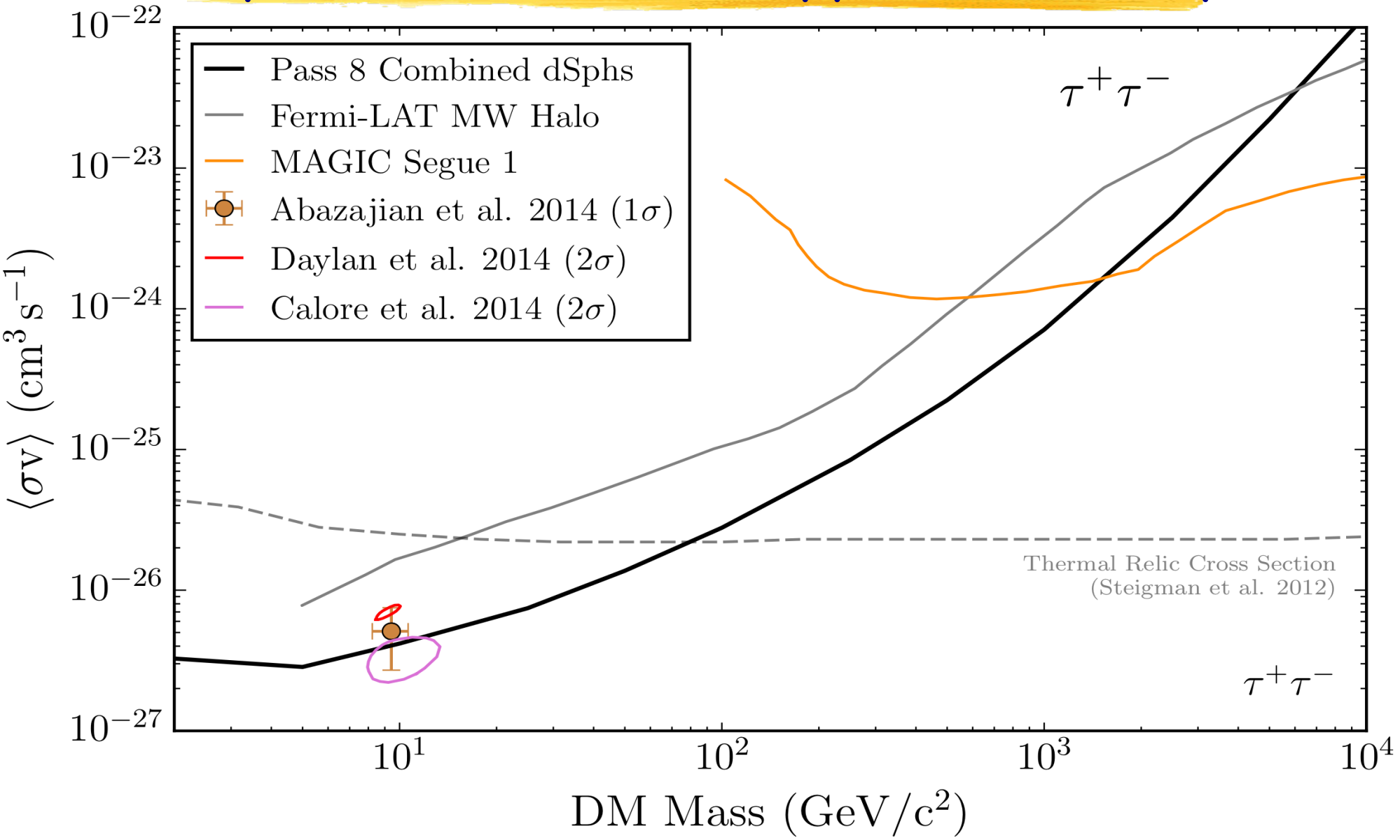
Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

Dwarf Spheroidal Galaxies upper-limits (6 years)



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

Dwarf Spheroidal Galaxies upper-limits (6 years)



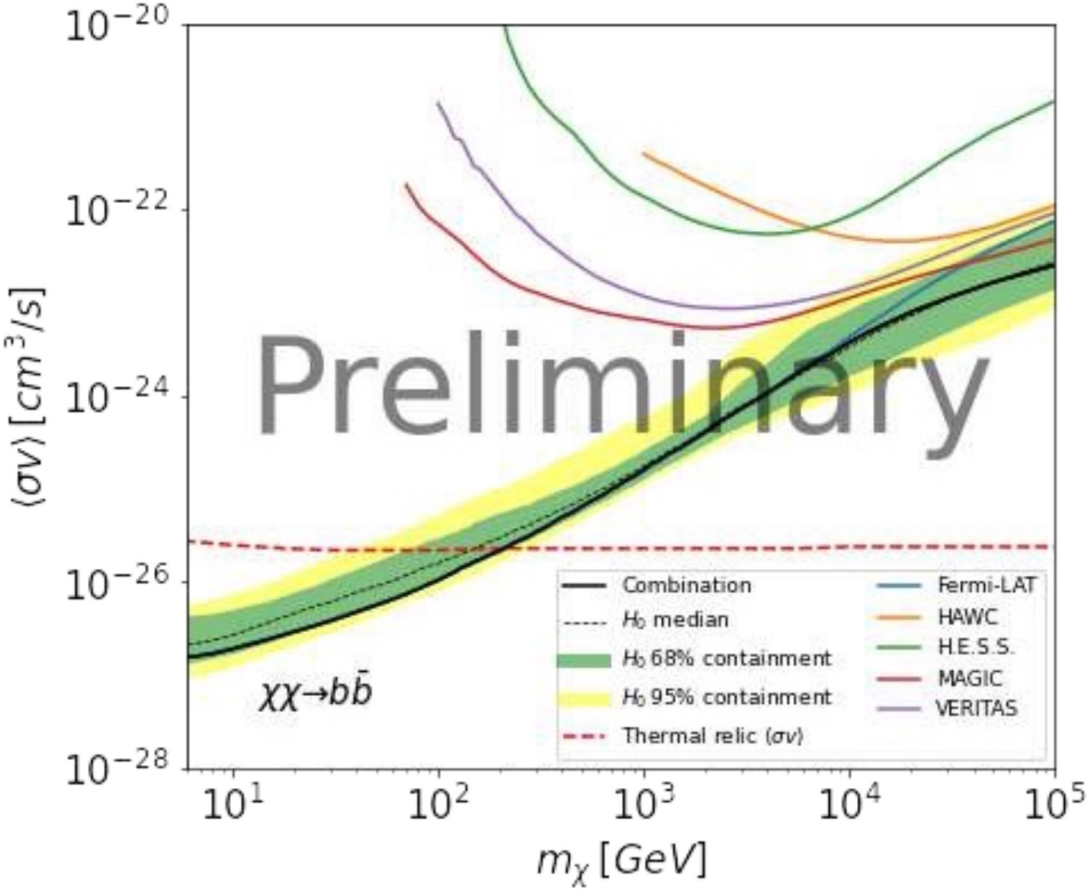
M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

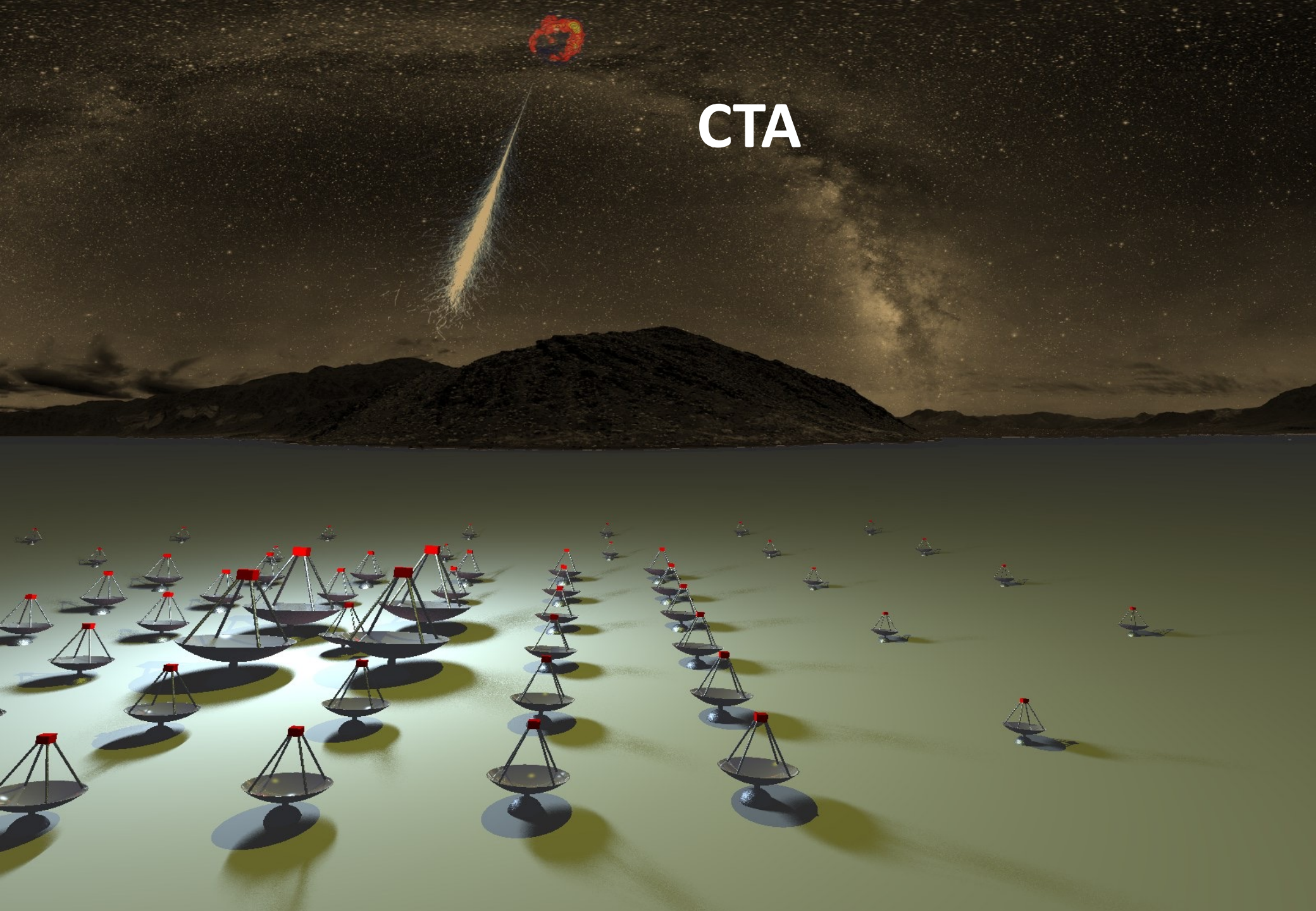
Combining all dSph observations

- Combination of the observation results towards 20 dwarf spheroidal galaxies (dSphs)
  - Significant increase of the statistics

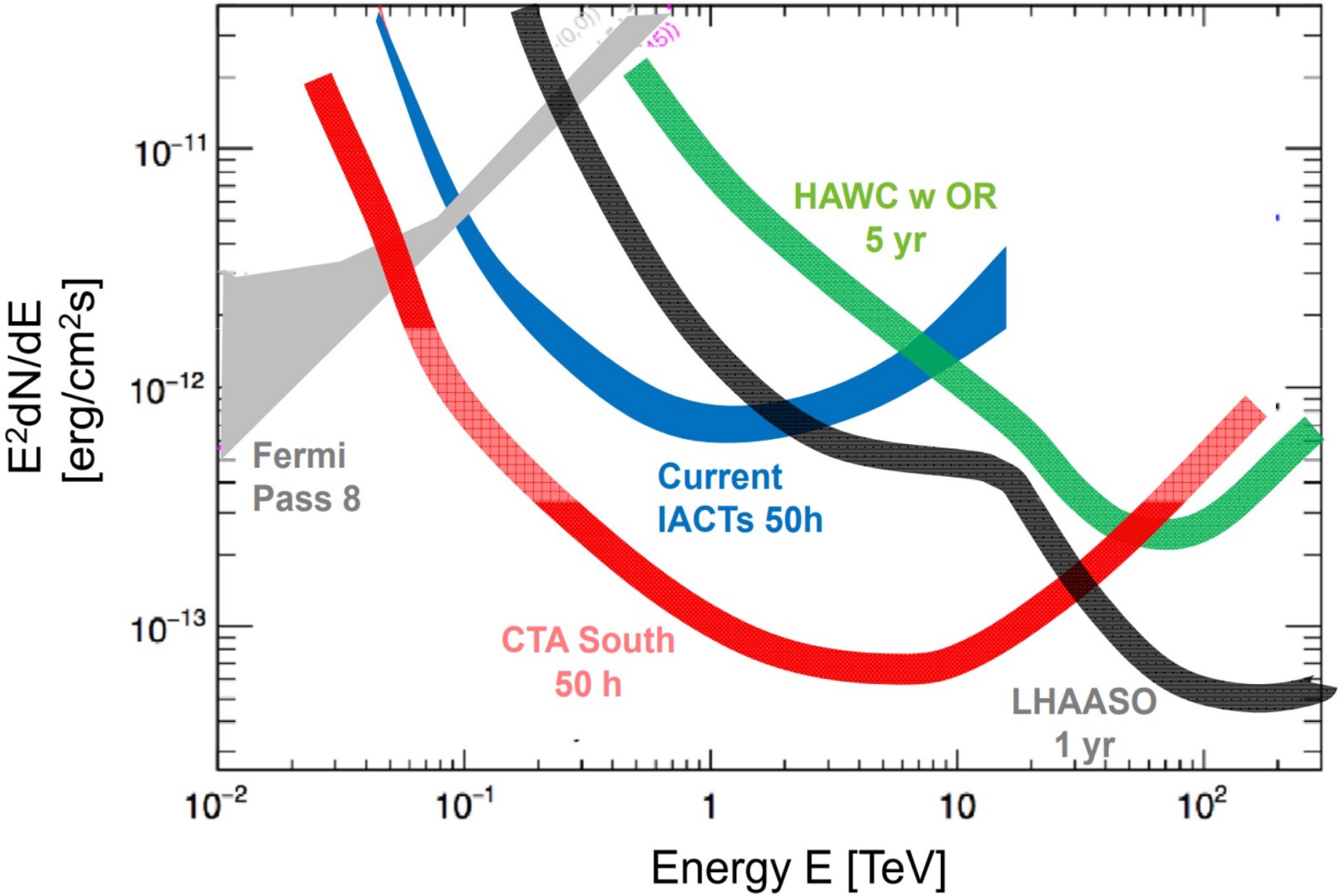
-> Increase the sensitivity to potential dark matter signals
  - Cover the widest energy range ever investigated : 20 MeV – 80 TeV

- Common elements :
  - Agreed model parameters
  - Sharable likelihood table formats
  - Joint likelihood test statistic

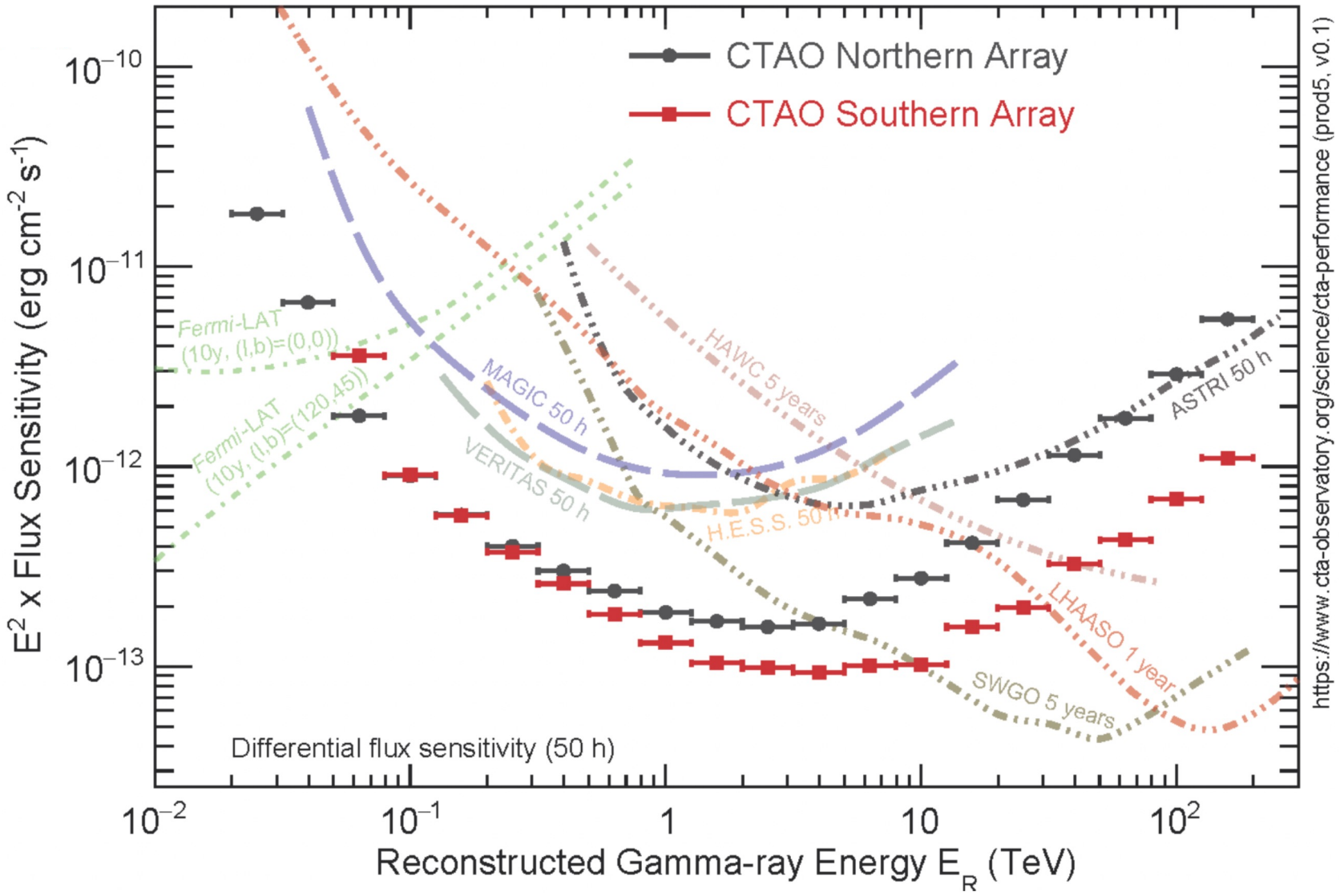



CTA

γ-ray detectors sensitivities



(more detailed) γ-ray detectors sensitivities



Key Science Project Targets

- Galactic Center

high DM density but high astrophysical emissions

- dSph

no background but low signal

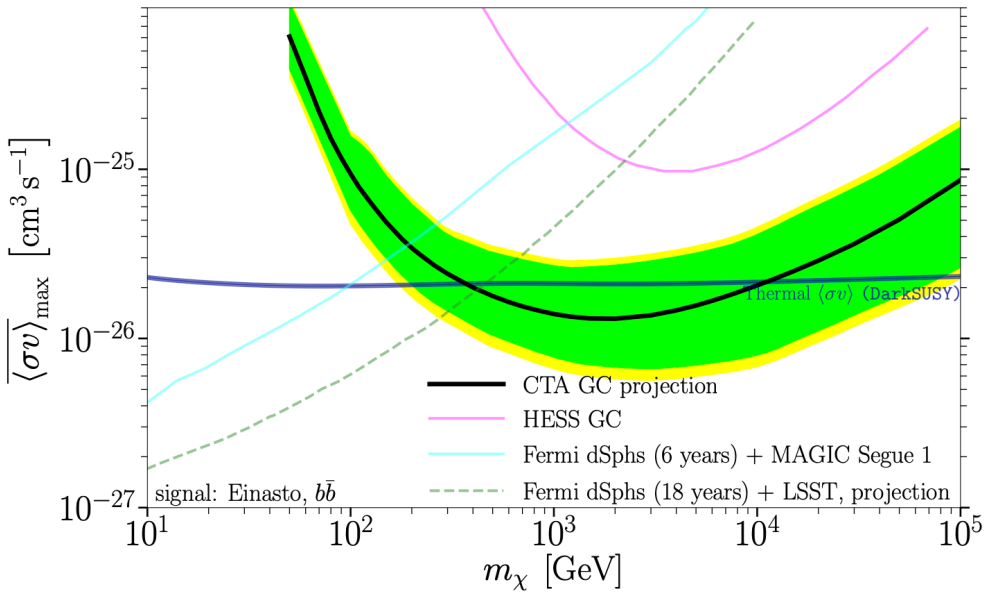
- LMC

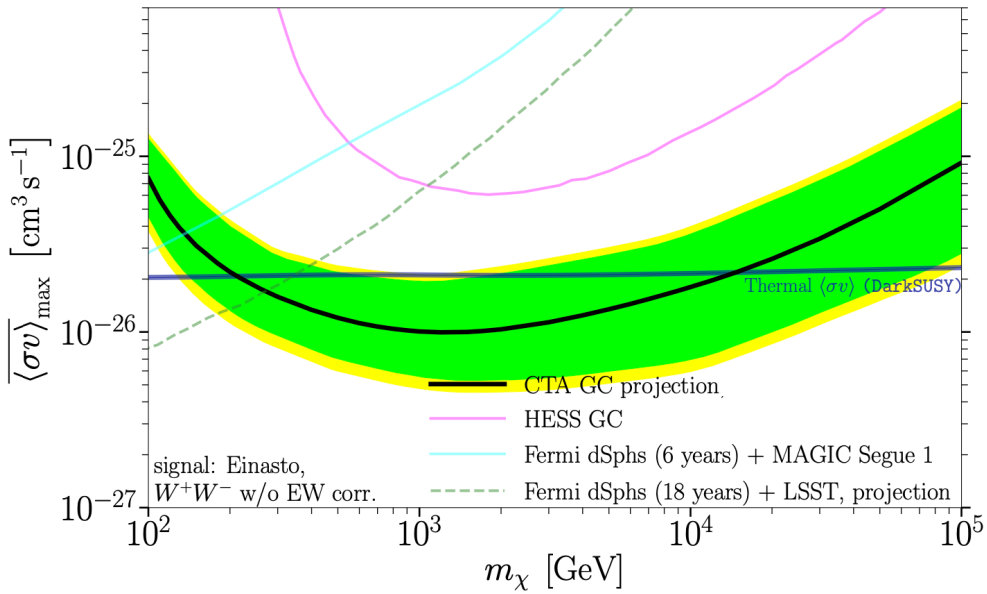
neaby & massive but astrophysical emissions

- galaxy cluster

very massive (best for decay)

Galactic center CTA Sensitivity





- Einasto profile

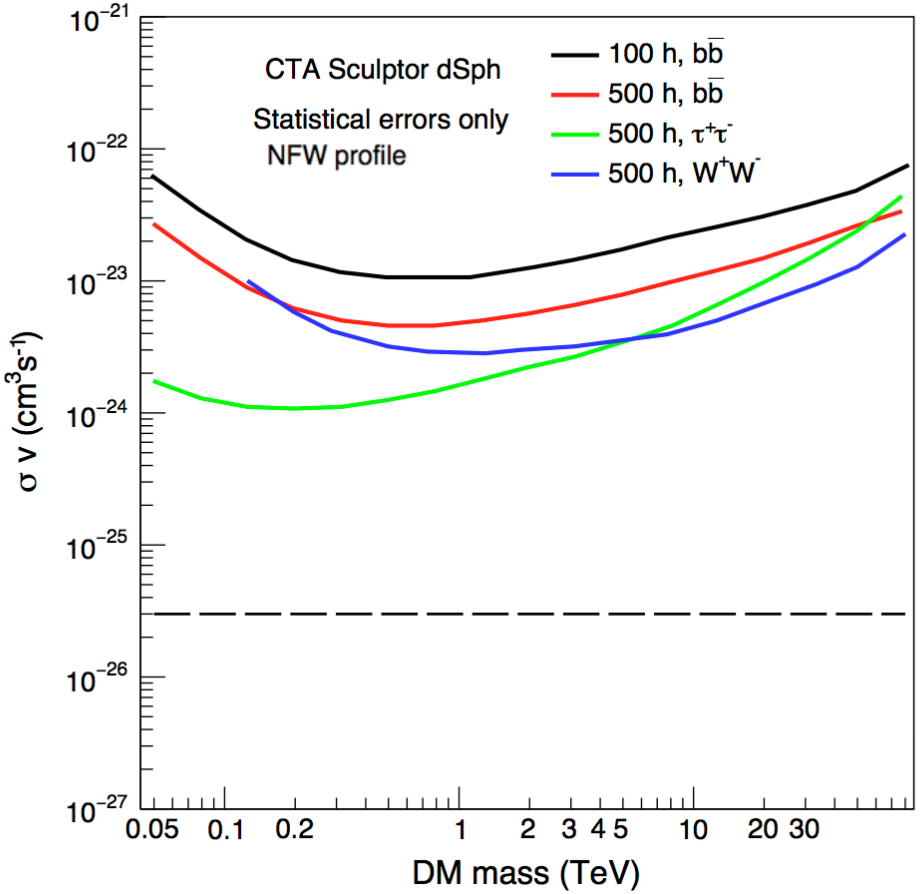
520 h

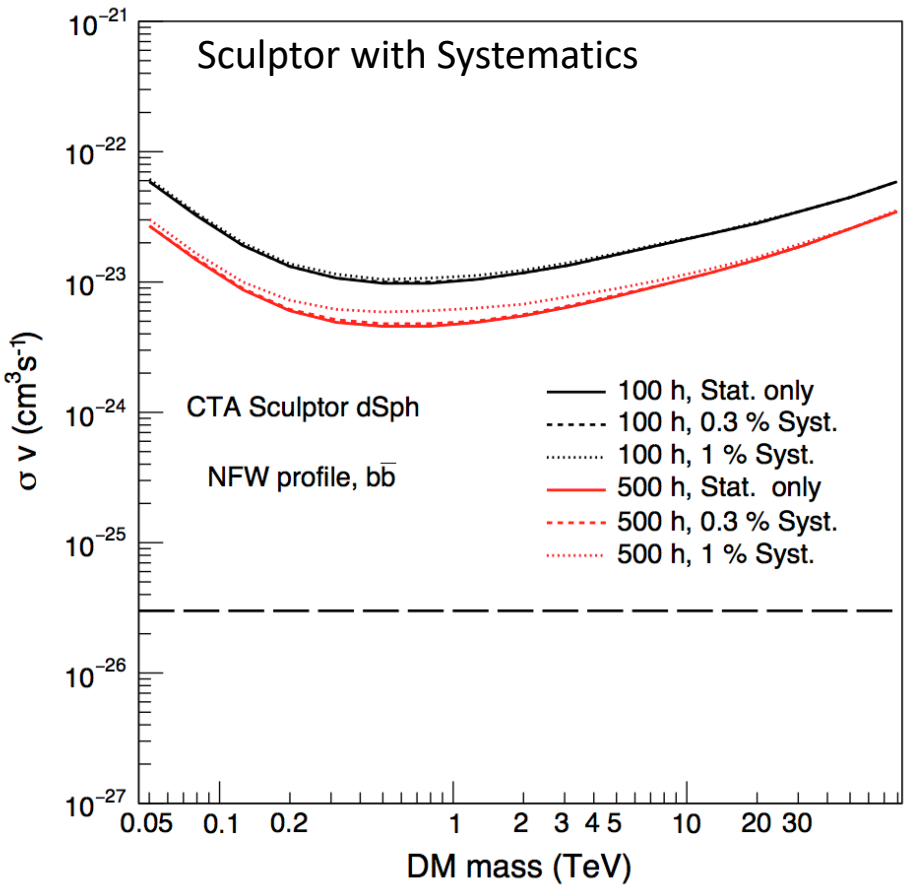
$$\rho_{\rm DM} = \rho_s \exp\left[-\frac{\alpha}{2}\left(\frac{r}{r_s}\right)^{\alpha} - 1\right], \; J \sim 7.1 \times 10^{22} {\rm GeV}^2/{\rm cm}^5$$

- Main source of background : sources, Fermi Bubble, interstellar γ, residual CR

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

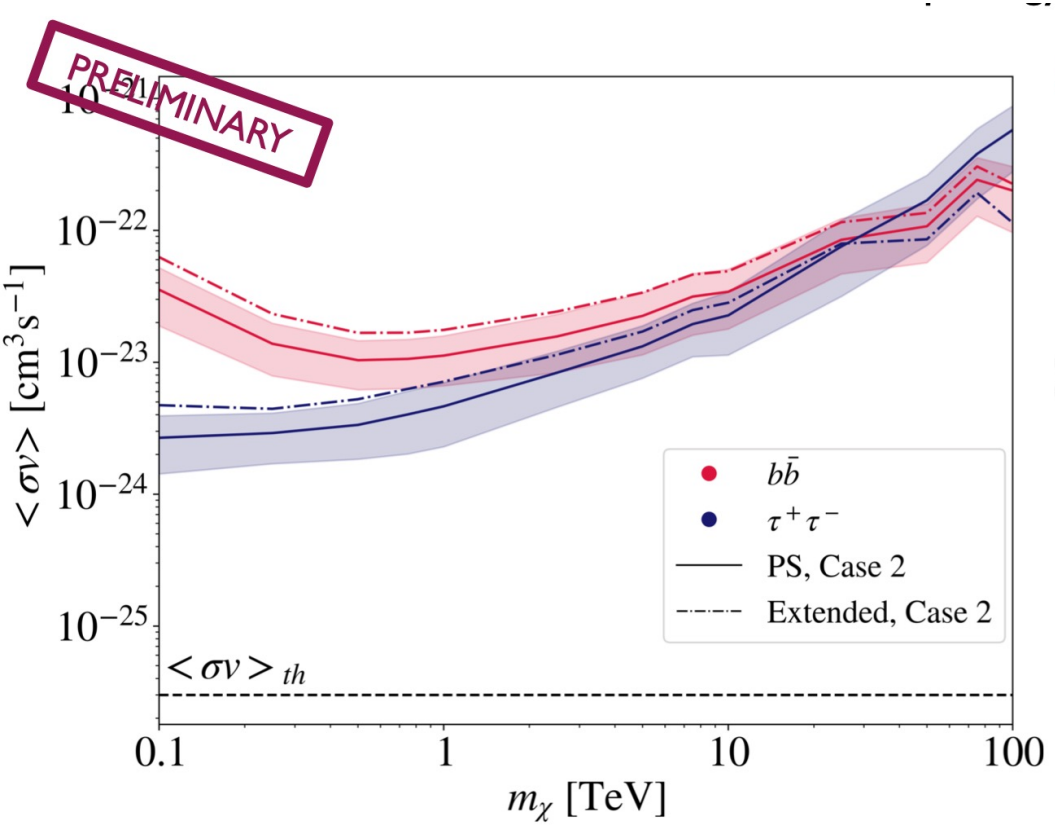
Dwarf Spheroidal Galaxies: CTA Sensitivity

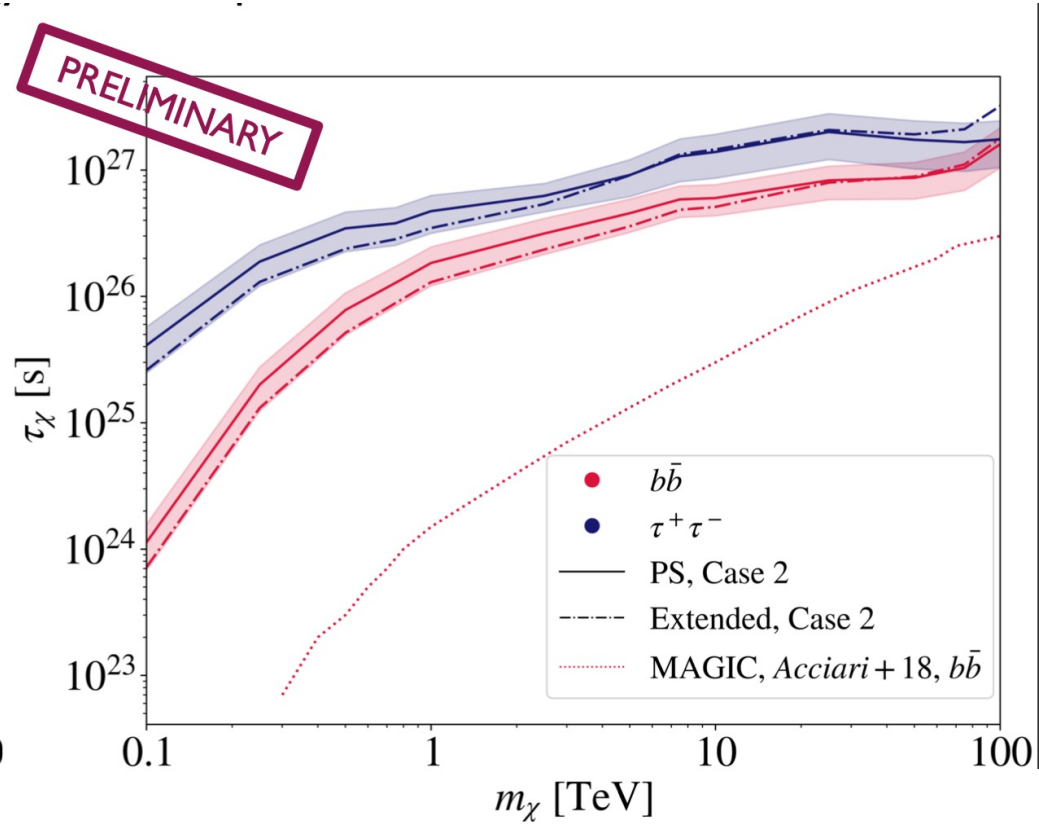




updated & dedicated collaboration paper soon from the CTA dSph task force

Perseus Cluster : CTA Sensitivity





Judit Pérez-Romero et.al CTA Consortium in preparation

CTA DM Detection Strategy

(from the CTA science book, numbers can change)

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

First 3 years

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

Next 7 years

- If there is detection in GC halo data set (525h)
  - Strong signal: continue with GC halo in parallel with best dSph to provide robust detection
  - Weak signal: focus on GC **halo** 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 Search for Dark Matter beyond WIMP

Axion Like Particle (ALP) search prospects

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

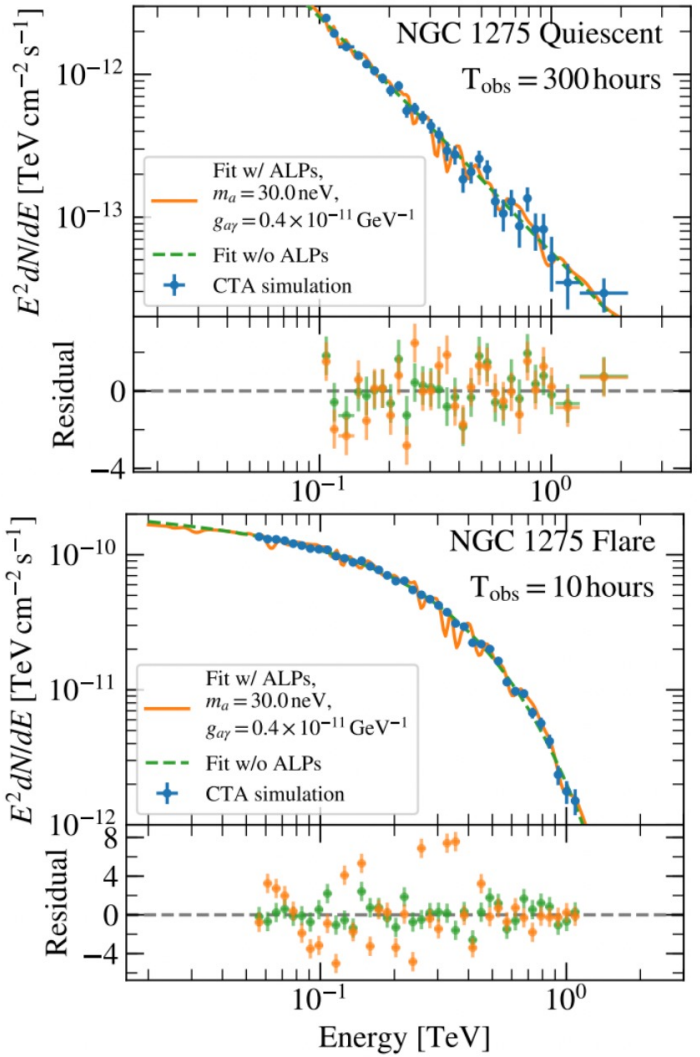
conversion probability ($E > E_{crit}$)

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

$$E_{crit} \sim 2.5\ \text{GeV} \times \left(\frac{|m_a - \omega_{pl}|}{1\text{neV}}\right)^2 \left(\frac{B}{1\mu\text{G}}\right)^{-1} \left(\frac{g_{a\gamma}}{10^{-11}\text{GeV}^{-1}}\right)^{-1}$$

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

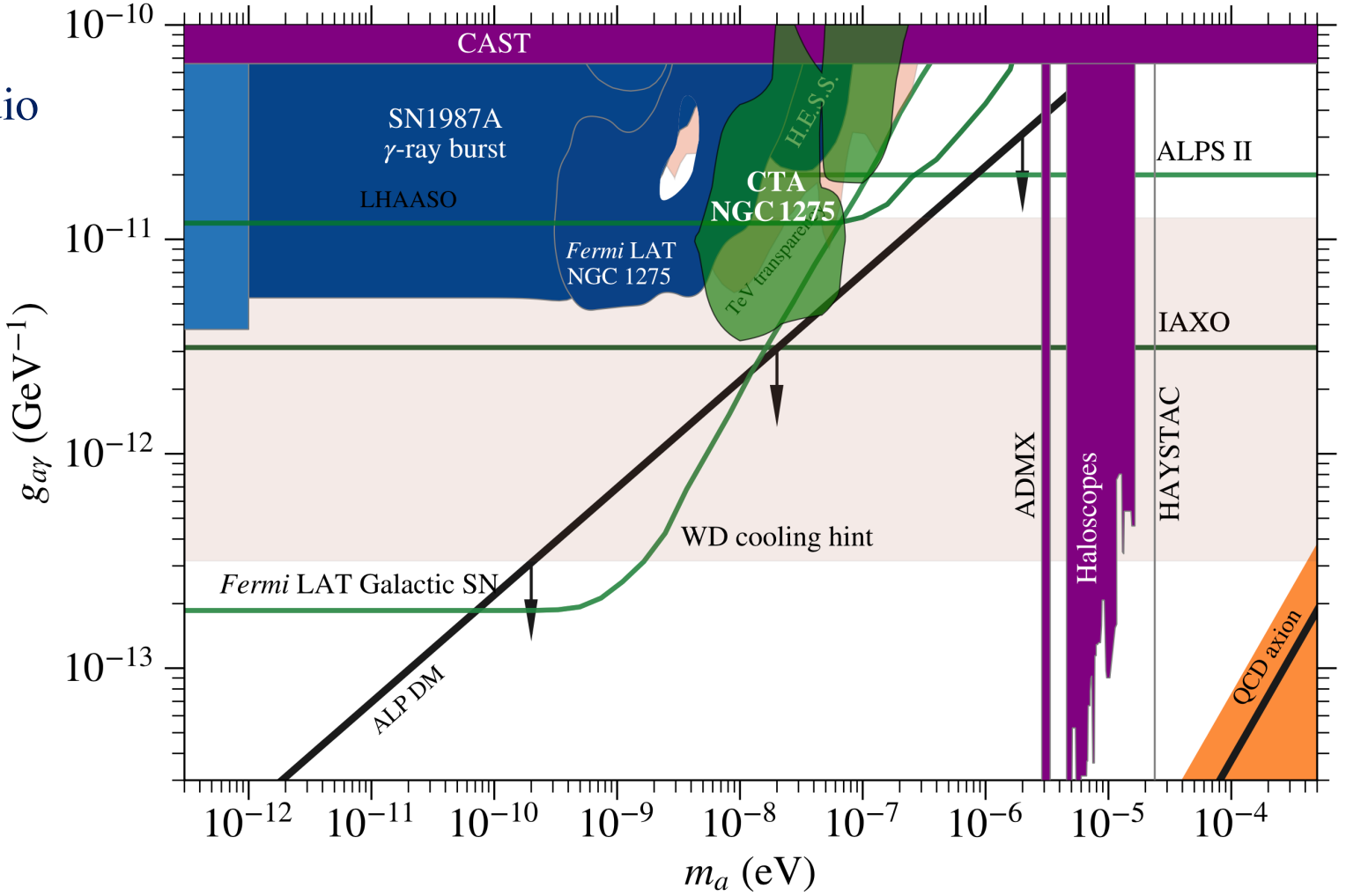


The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]

CTA Search for Dark Matter beyond WIMP

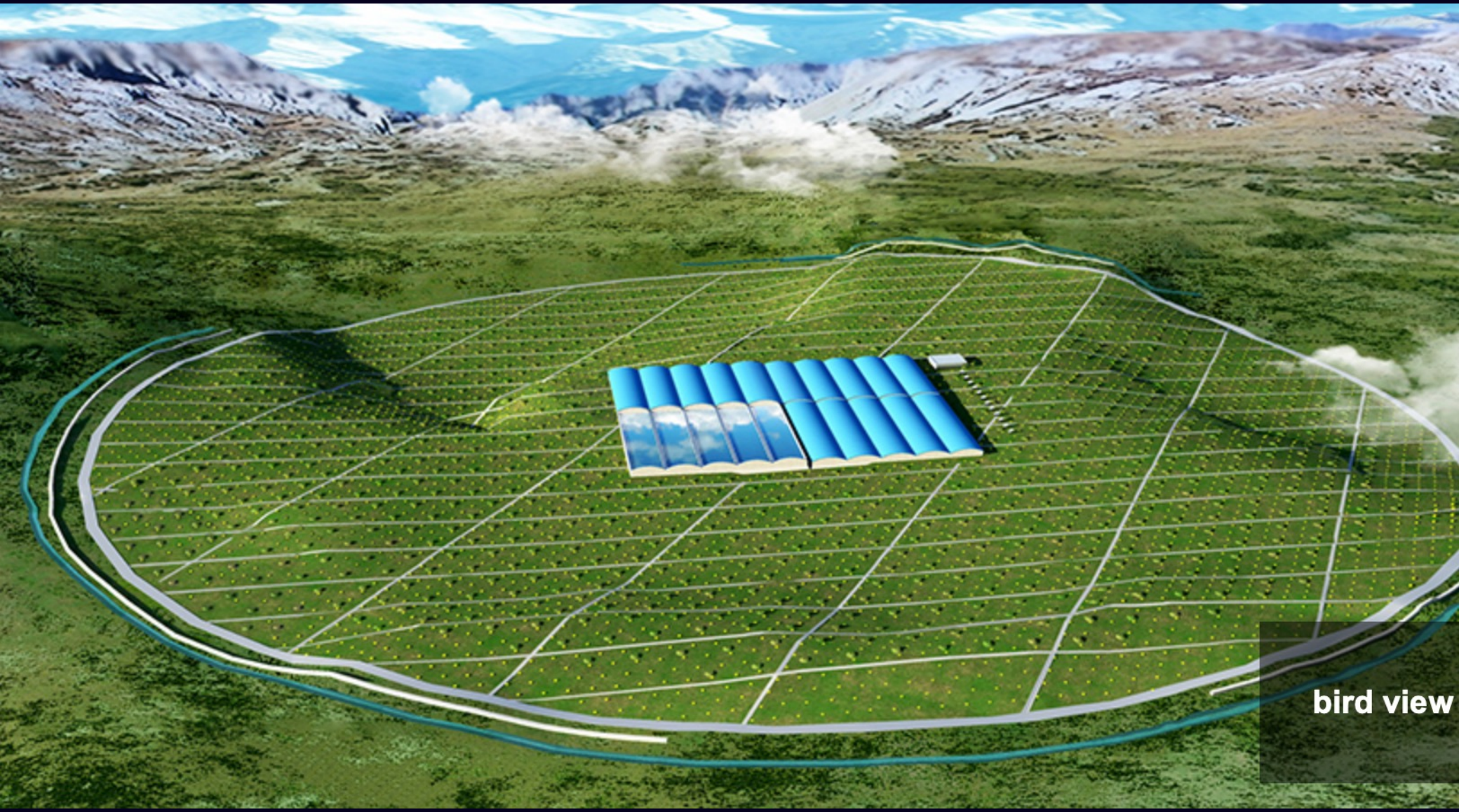
Axion Like Particle search prospects

- Observation of a flaring state of the radio galaxy NGC 1275 inside the Perseus cluster
- Observations of several AGN can be combined to further improve the CTA sensitivity.

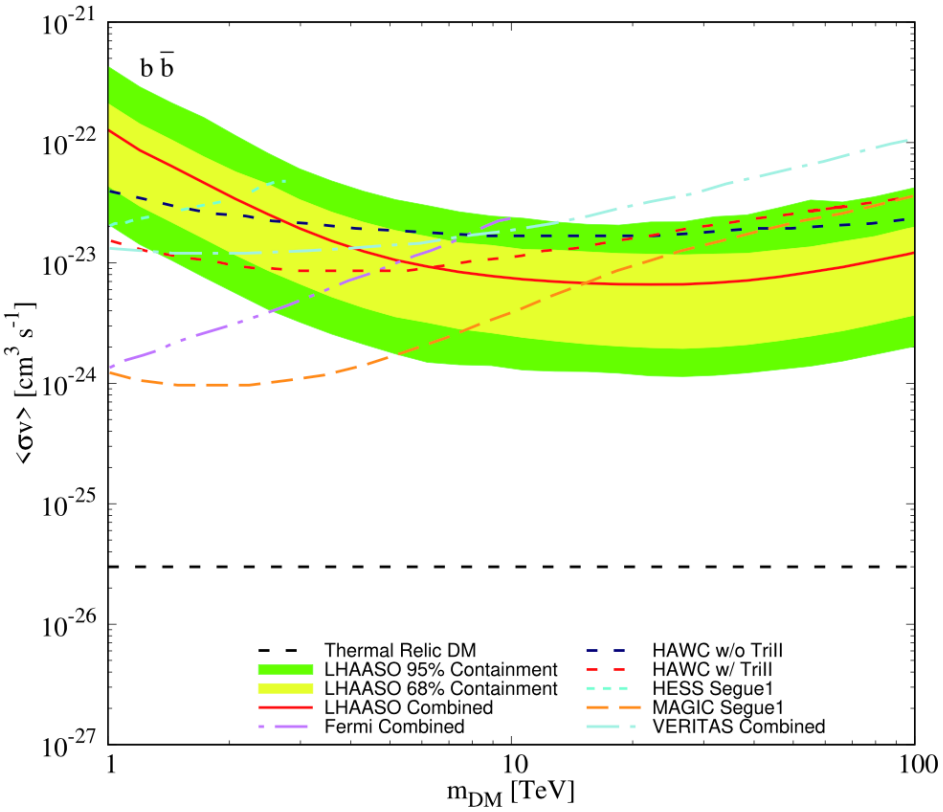


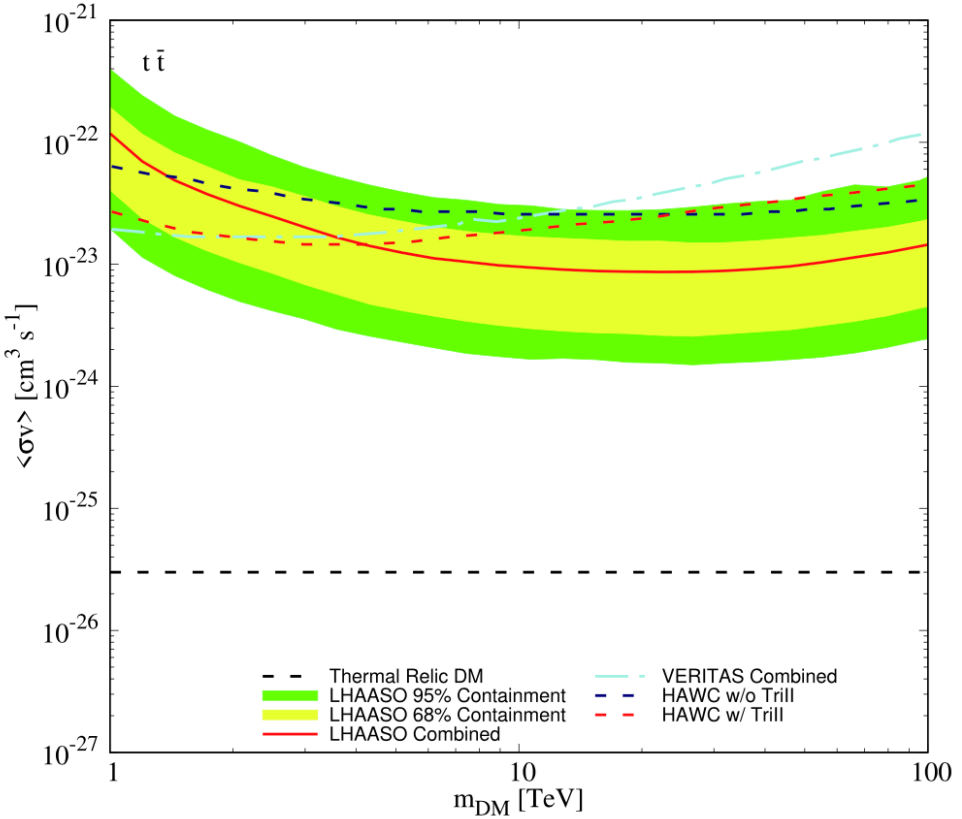
The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]

LHAASO



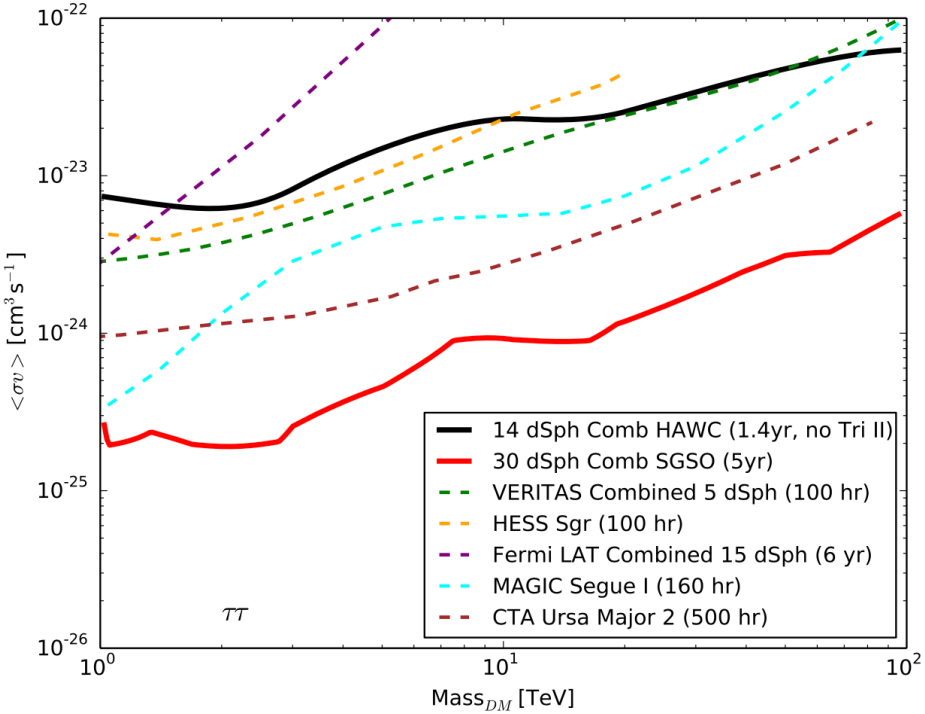
combined one-year LHAASO sensitivities

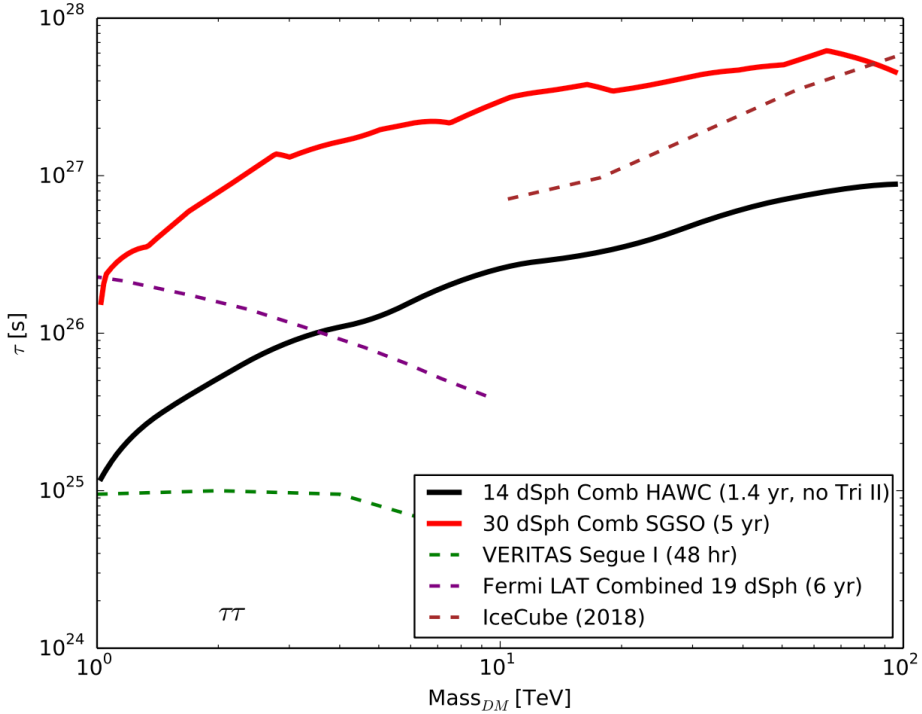




Dong-Ze He et al., Phys. Rev. D 100, 083003 (2019)

SWGO sensitivities

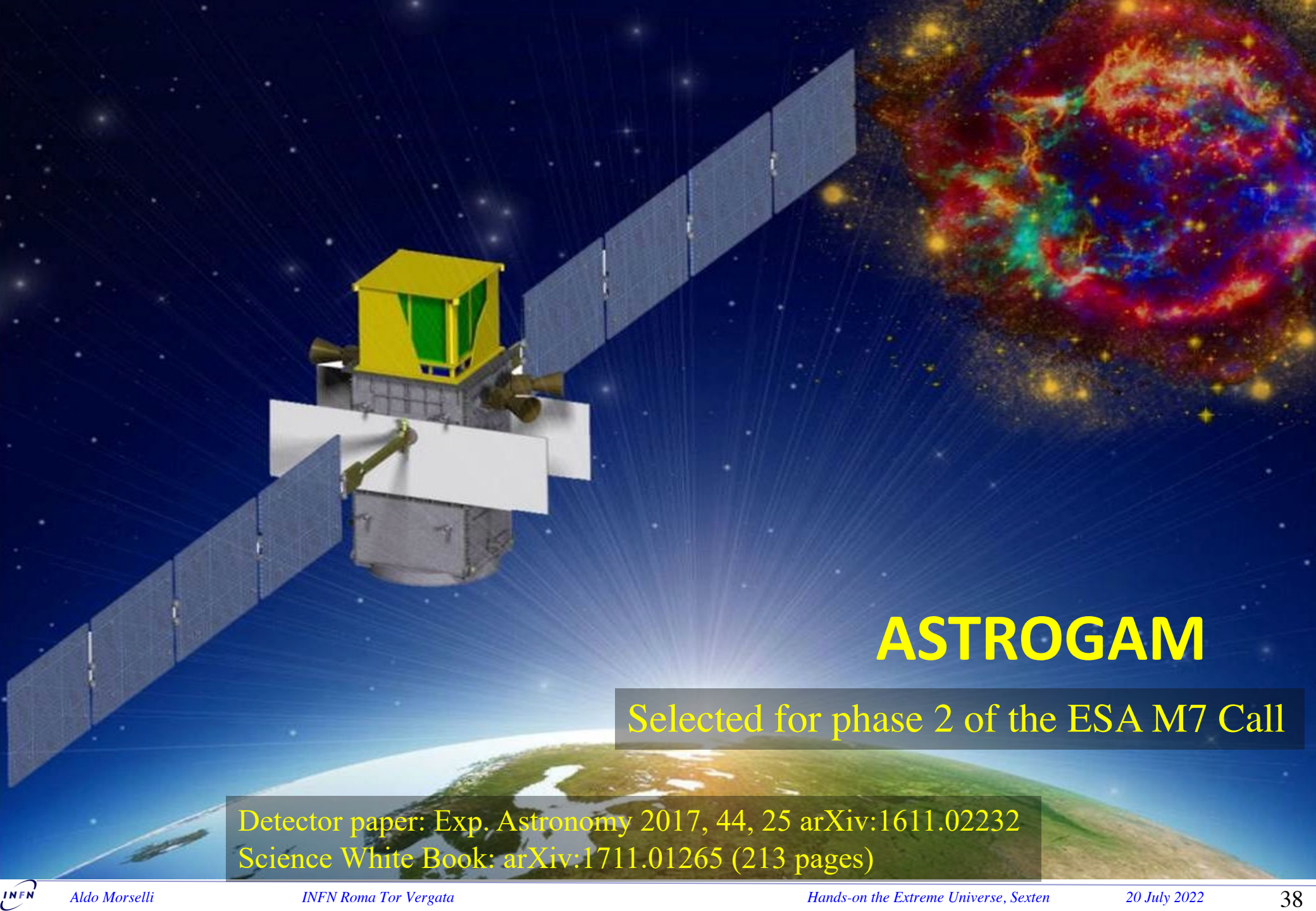




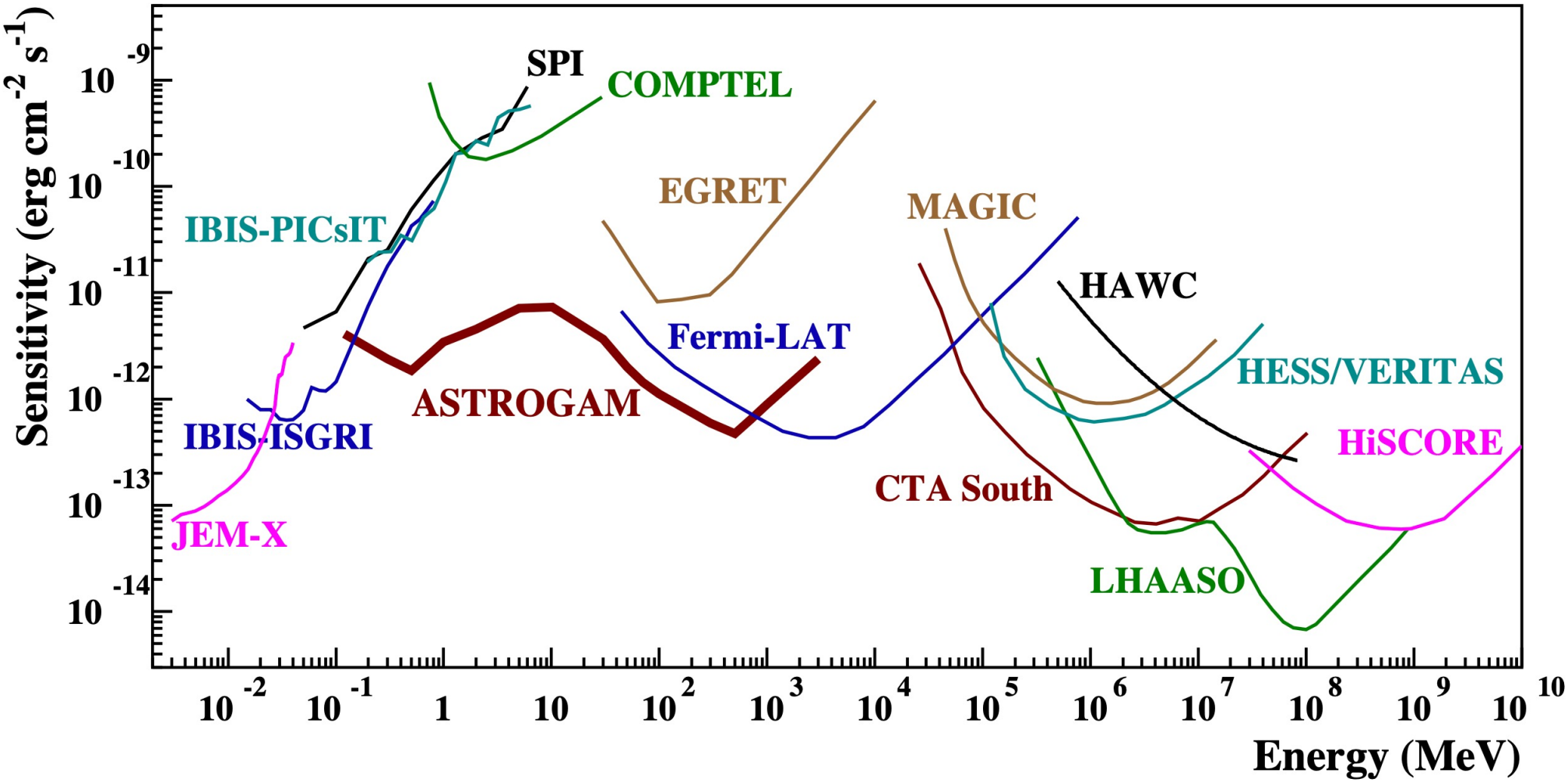
Assumed new dSph discovery and
J-factor and D-factor distributions of the new dSphs matches that of the previously known dSphs

SWGO White paper arXiv:1902.08429

The Low Energy Frontier

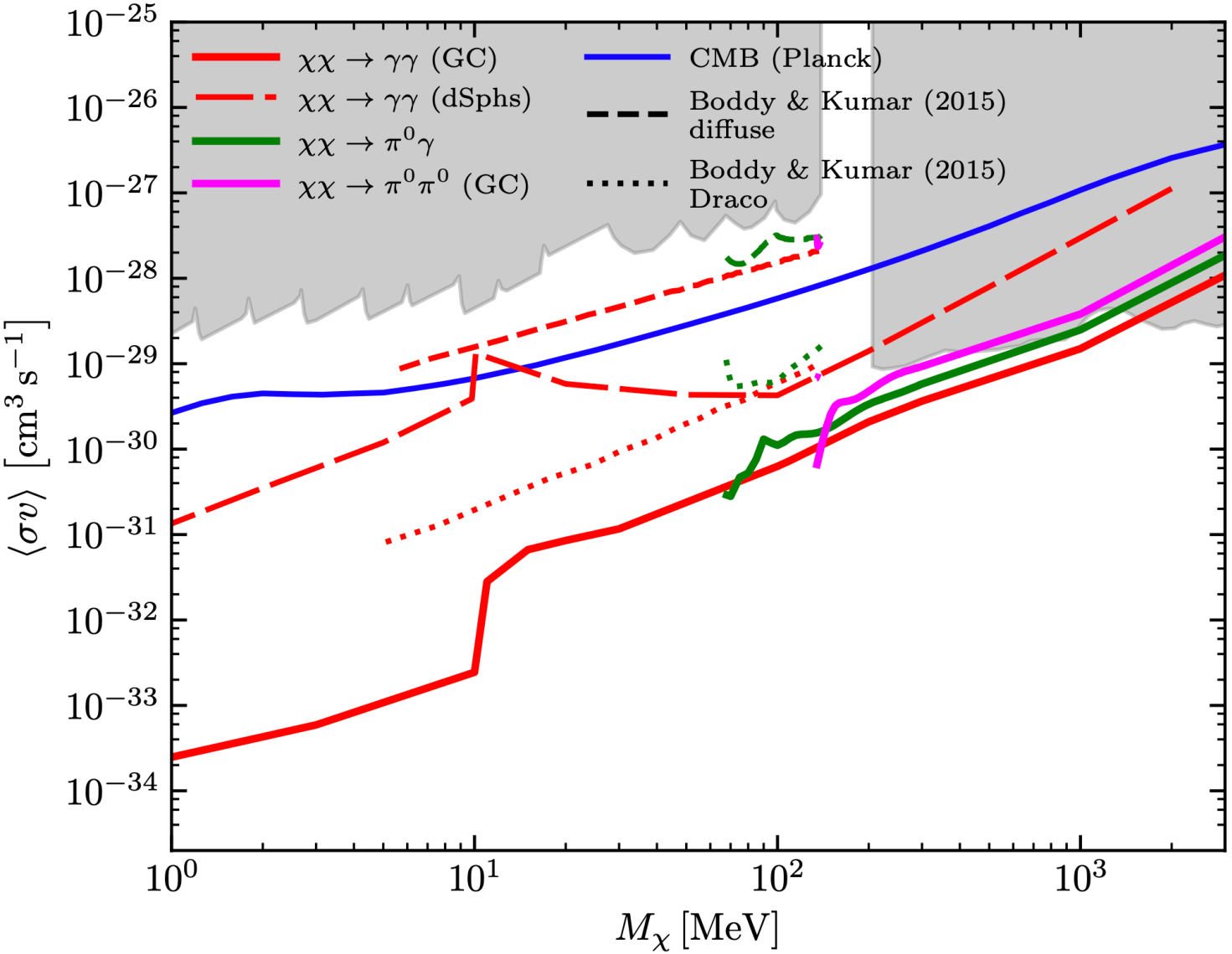

ASTROGAM
Selected for phase 2 of the ESA M7 Call
Detector paper: Exp. Astronomy 2017, 44, 25 arXiv:1611.02232
Science White Book: arXiv:1711.01265 (213 pages)

Astrogam Performance



Astrogam sensitivity for an effective exposure of two years at high galactic latitude

Astrogam Sensitivity for Dark Matter



ASTROGAM detectability of sub-GeV DM-induced gamma-ray signals from the GC and dSphs

Indirect, Direct and Accellerator Searches for Dark Matter

Source

creation
acceleration
injection

further acceleration?

Propagation

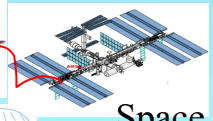
Cosmic Rays

Modulation

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

γ

ν



Space experiments ~ 400 km

Direct detection

Atmosphere

40 km

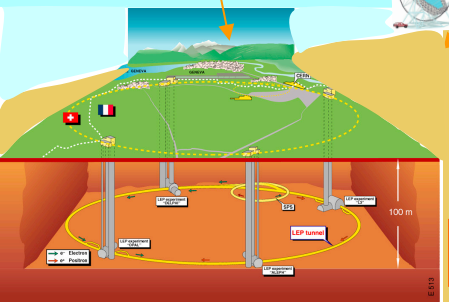
23 Xo

Balloons ~ 40 km
~3 g/cm² residual atmosphere

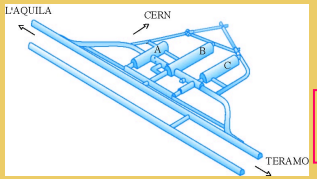
Extensive Air Shower
Detectors

High Montain
Detectors

Particle
Astrophysics
Experiments

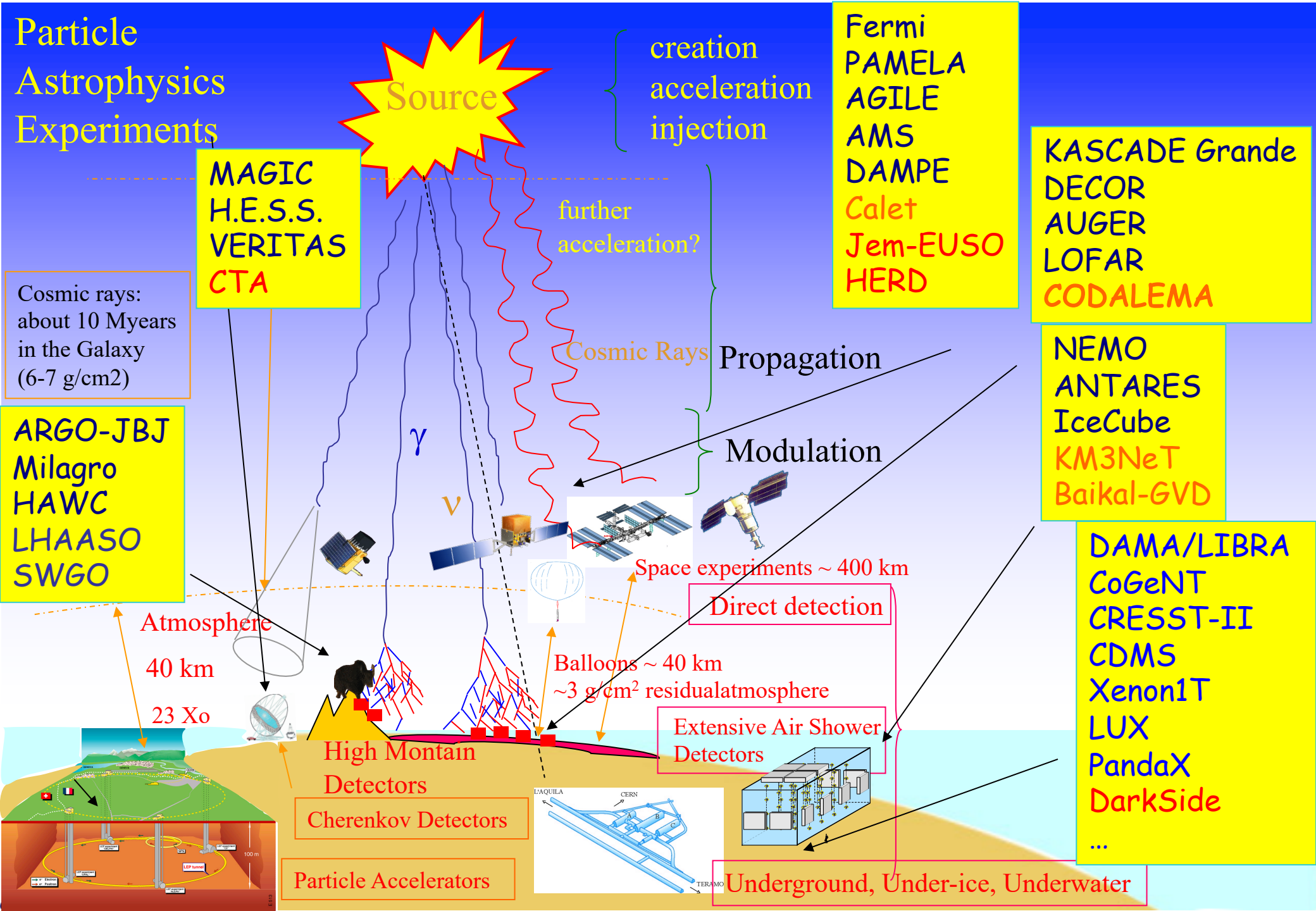


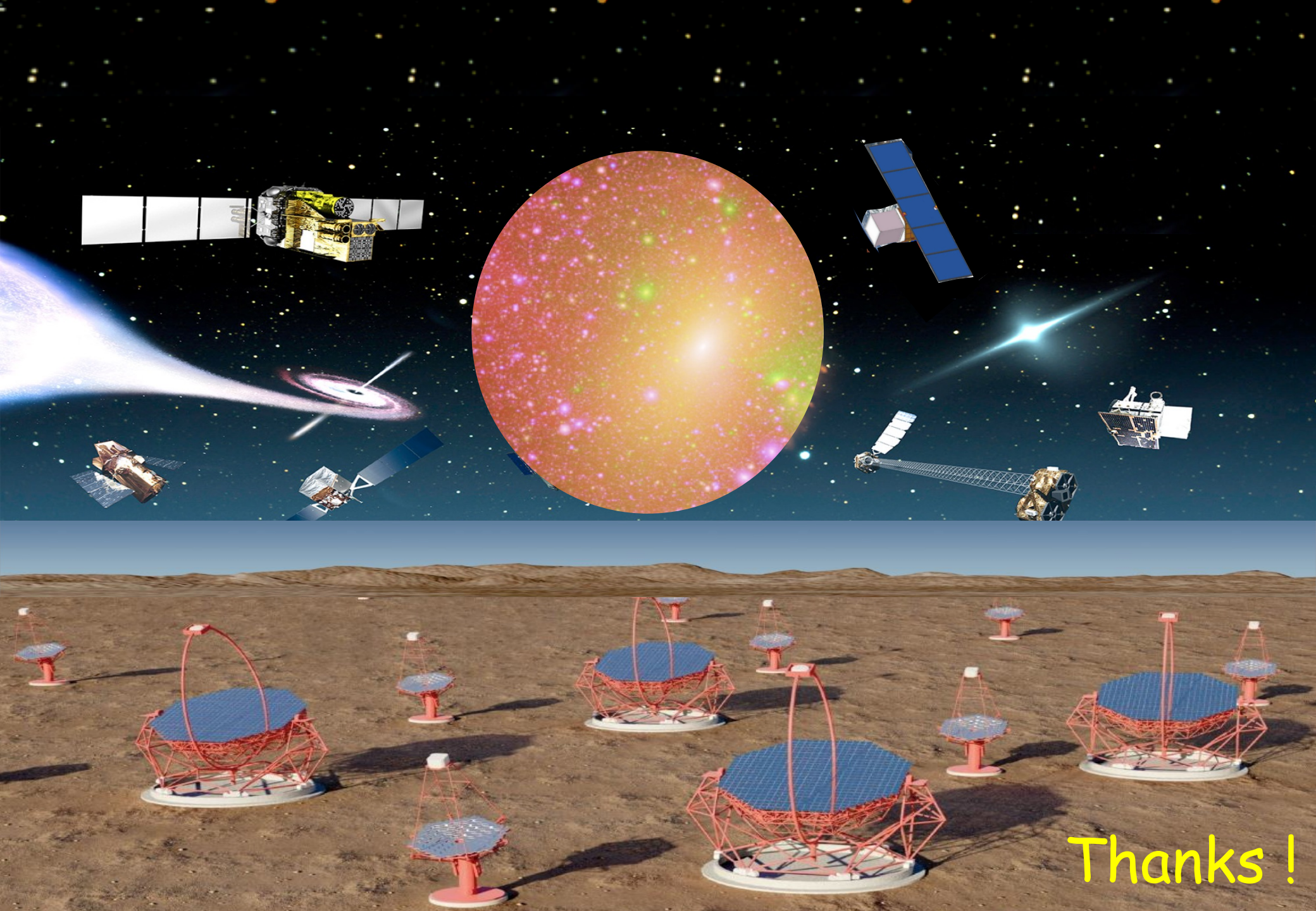
Cherenkov Detectors



Particle Accelerators

Underground, Under-ice, Underwater


Particle Astrophysics Experiments
Source
creation
acceleration
injection
Fermi
PAMELA
AGILE
AMS
DAMPE
Calet
Jem-EUSO
HERD
KASCADE Grande
DECOR
AUGER
LOFAR
CODALEMA
MAGIC
H.E.S.S.
VERITAS
CTA
further acceleration?
Cosmic rays: about 10 Myears in the Galaxy (6-7 g/cm2)
Cosmic Rays
Propagation
Modulation
NEMO
ANTARES
IceCube
KM3NeT
Baikal-GVD
ARGO-JBJ
Milagro
HAWC
LHAASO
SWGO
γ
ν
Space experiments ~ 400 km
Direct detection
DAMA/LIBRA
CoGeNT
CRESST-II
CDMS
Xenon1T
LUX
PandaX
DarkSide
...
Atmosphere
40 km
23 Xo
Balloons ~ 40 km
~3 g/cm² residualatmosphere
Extensive Air Shower Detectors
High Montain Detectors
Cherenkov Detectors
Particle Accelerators
L'AQUILA
CERN
TERAMO
Underground, Under-ice, Underwater


Thanks !