SUSY 2024

Theory meets Experiment

Madrid
10-14 June 2024

SUSY24: The 31st International Conference on Supersymmetry and Unification of Fundamental Interactions

10–14 Jun 2024
IFT (Madrid, Spain)
Europe/Madrid timezone

INDIRECT DM SEARCHES

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DM NET Sep 2023 Padova (Italy)

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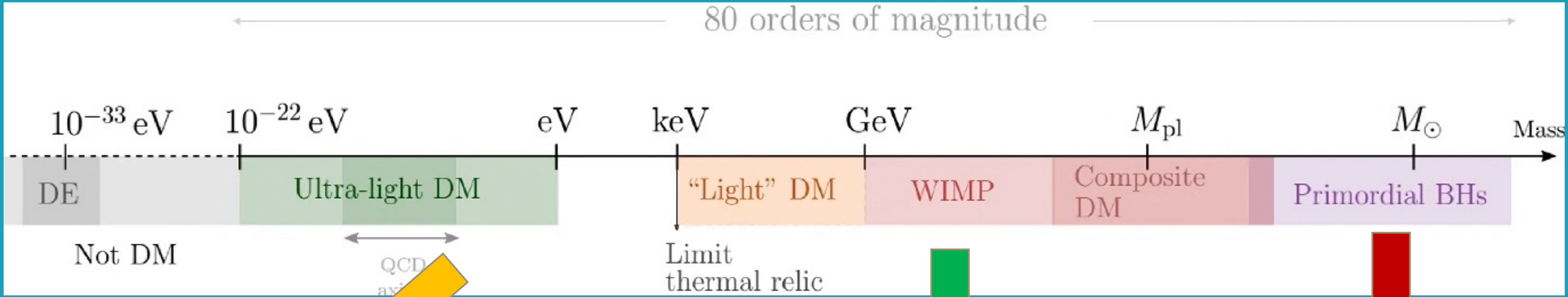
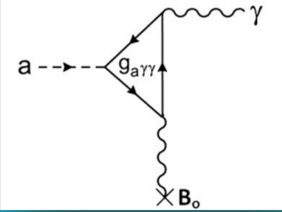
DISCLAIMER #1

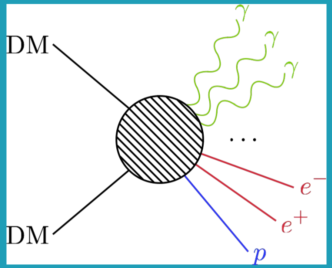
Elisa Ferreira 2021



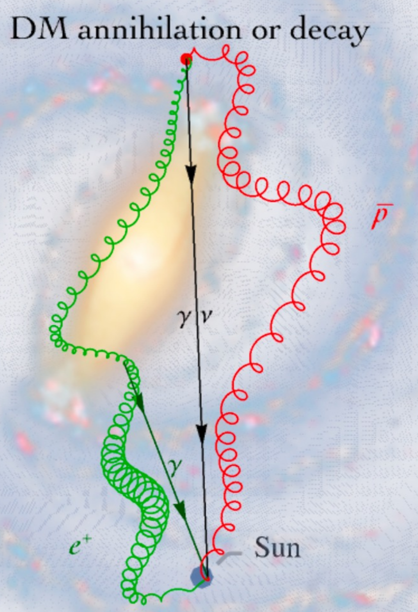
Axion-like particles leave imprint in g-ray spectra. Only on backup slides

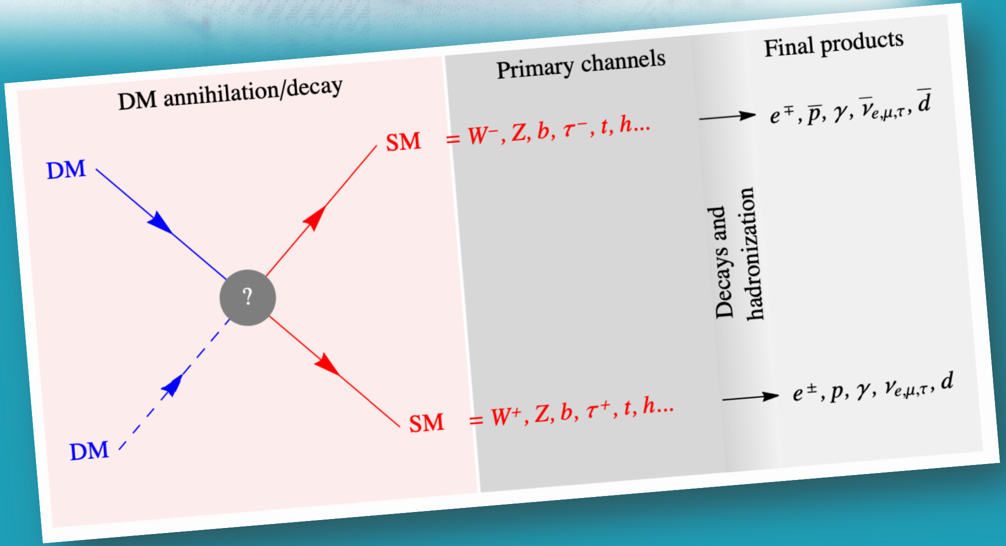


Annihilation/Decay of GeV-TeV DM in space



TeV emission during PBH evaporation. Not discussed here, but can do on coffee breaks





DISCLAIMER #2

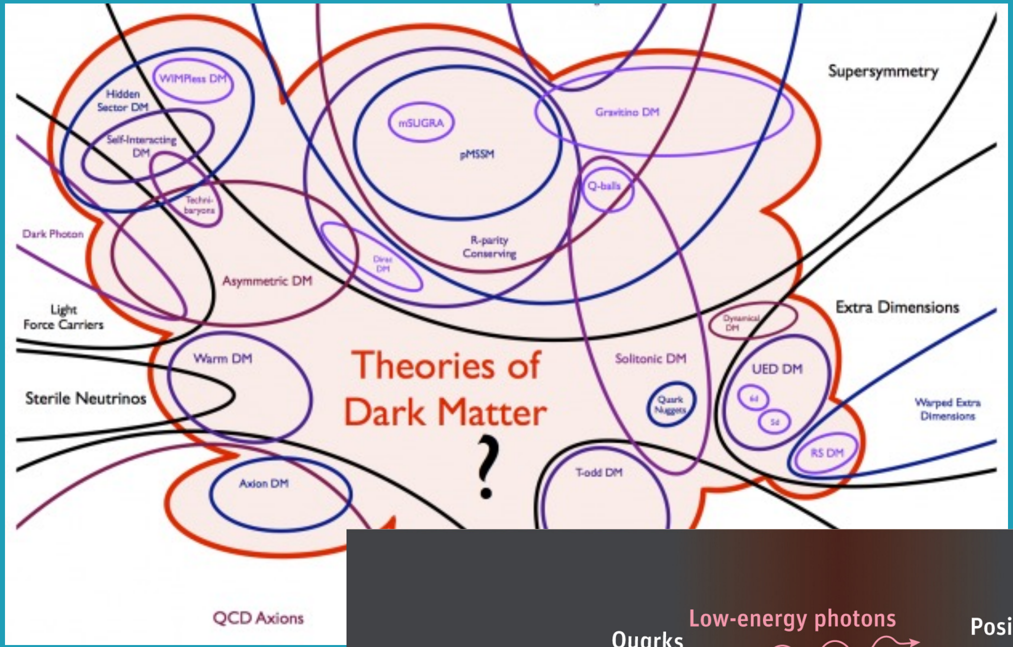
- Neutral particles ← trace-back origin
  - **Prompt Gamma-ray**
  - Reprocessed X-radio
  - Neutrinos

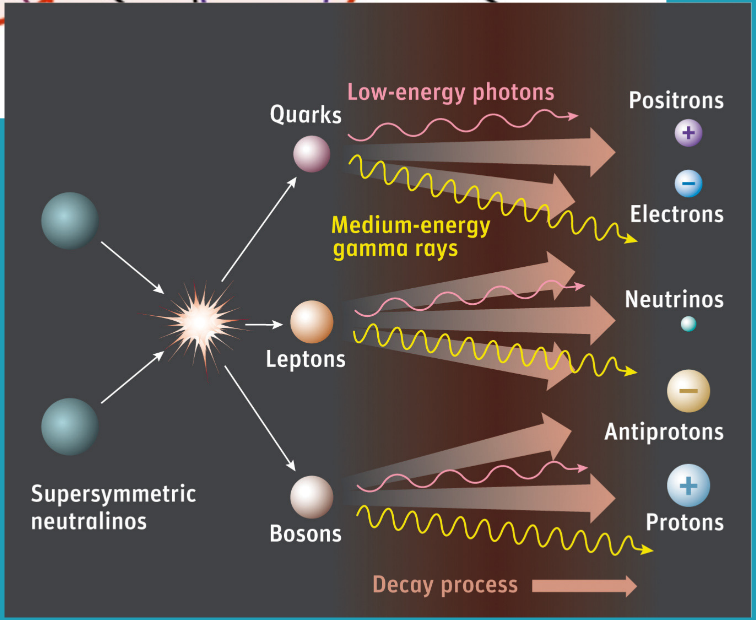
- Charged particles: all but most interesting are antiparticles (less background) ← overall abundances
  - Positron
  - Antiprotons
  - antideuterons

Recently Cirelli+ 2406.01705 made a nice review. I have shamelessly taken several summary plots

#1 WHY G-RAYS ARE IMPORTANT DM PROBES

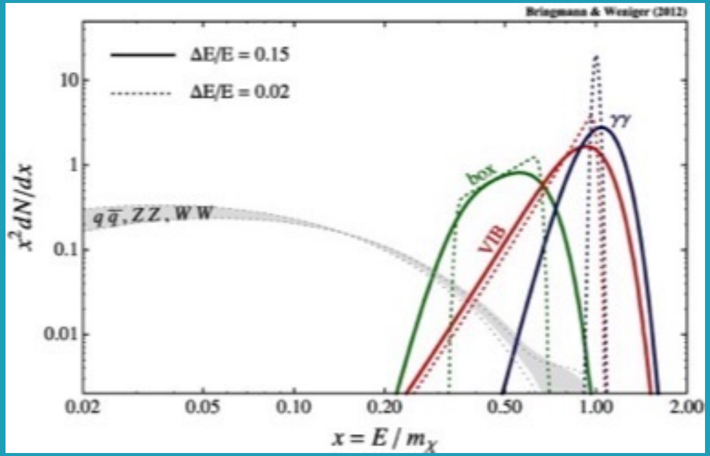
IN GAMMA-RAYS WE TRUST



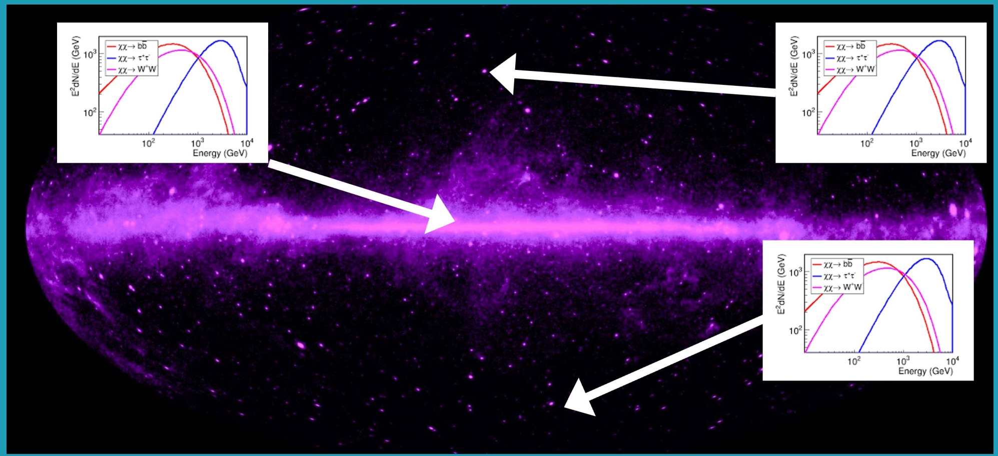


#0 Gamma-rays expected in HE interactions

#1 Peculiarity of gamma-ray spectra (no astro-like)



#2 Same signal at different targets



#3 Know where to point

G-RAY SIGNAL MODEL

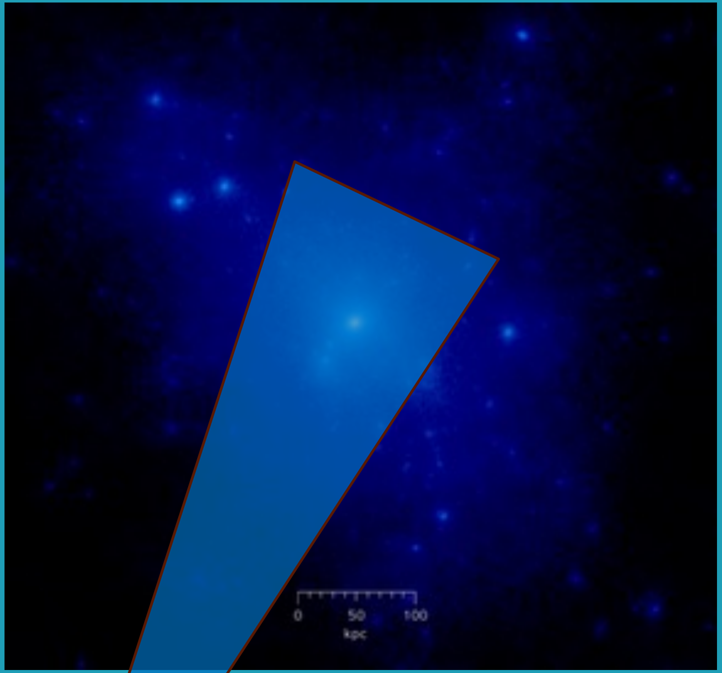
$$\frac{d\Phi_\gamma}{dE_\gamma} = \begin{cases} \frac{\langle\sigma v\rangle}{4k\pi\ m_\chi^2} \sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma} \cdot J_{\mathrm{ann}}(\Delta\Omega) & \text{Annihilating DM} \\ \frac{1}{4\pi\, m_\chi} \sum_i \Gamma_i \frac{dN_\gamma^i}{dE_\gamma} \cdot J_{\mathrm{dec}}(\Delta\Omega) & \text{Decaying DM} \end{cases}$$

Particle physics to understand the process from DM to SM

+

Astrophysics to guess the amount of DM in the sky or an object

$$\begin{cases} J_{\mathrm{ann}}(\Delta\Omega) = \int_{\Delta\Omega} \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2(\ell,\Omega)\, d\ell\, d\Omega & \text{Annihilating DM} \\ J_{\mathrm{dec}}(\Delta\Omega) = \int_{\Delta\Omega} \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}(\ell,\Omega)\, d\ell\, d\Omega & \text{Decaying DM} \end{cases}$$



1. How much DM?
2. How much astro?

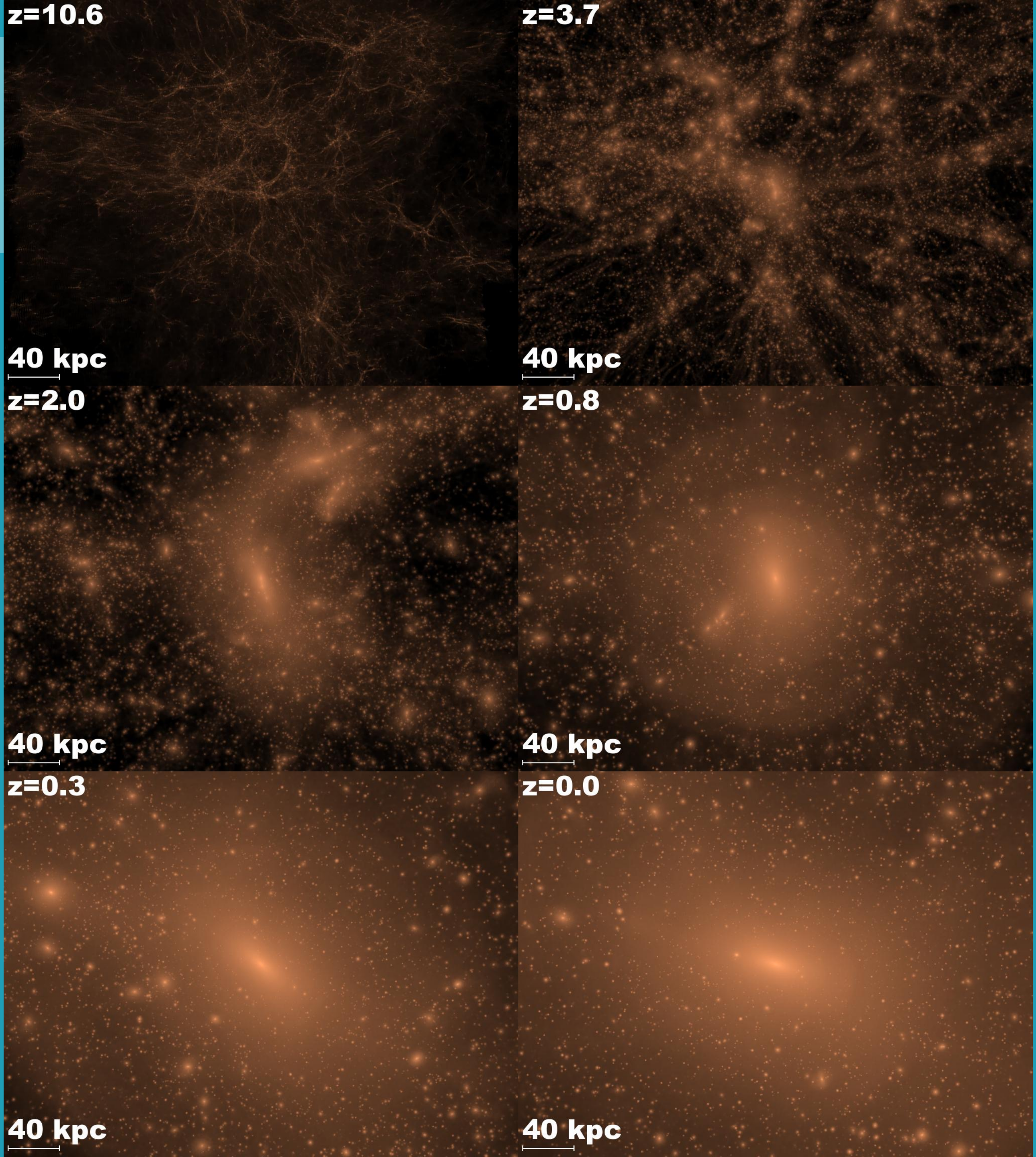
HOW MUCH DM?
N-BODY SIMULATIONS

- Provide relations M(r), N(M), N(r) of DM subhaloes required to make the signal model

- Provide DM density $\rho(r)$

$$\begin{cases} J_{\mathrm{ann}}(\Delta\Omega) = \int_{\Delta\Omega} \int_{\mathrm{l.o.s.}} \rho^2_{\mathrm{DM}}(\ell,\Omega)\, d\ell\, d\Omega & \text{Annihilating DM} \\ J_{\mathrm{dec}}(\Delta\Omega) = \int_{\Delta\Omega} \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}(\ell,\Omega)\, d\ell\, d\Omega & \text{Decaying DM} \end{cases}$$

- Light tracks matter to fit DM profile parameters



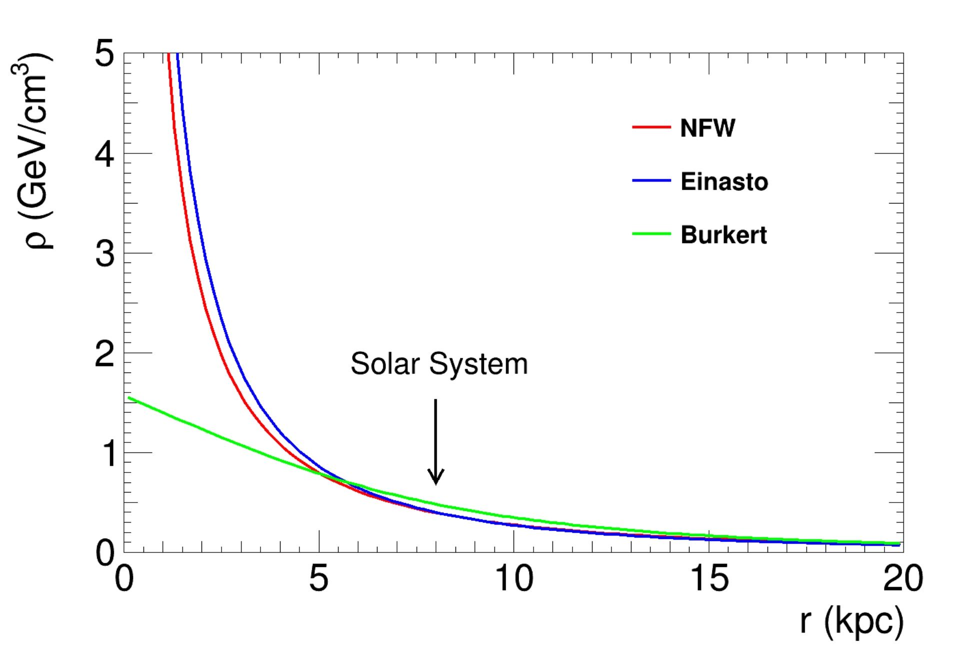
ASTROPHYSICAL FACTOR

$$\begin{cases} J_{\rm ann}(\Delta\Omega) = \int_{\Delta\Omega}\int_{\rm l.o.s.} \rho^2_{\rm DM}(\ell,\Omega)\, d\ell\, d\Omega & \text{Annihilating DM} \\ J_{\rm dec}(\Delta\Omega) = \int_{\Delta\Omega}\int_{\rm l.o.s.} \rho_{\rm DM}(\ell,\Omega)\, d\ell\, d\Omega & \text{Decaying DM} \end{cases}$$

DM halo	Functional form
NFW	$\rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$
Generalized NFW	$\rho_{\rm gNFW}(r) = \rho_s \left(\frac{r_s}{r}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{\gamma-3}$
Einasto	$\rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha_{\rm Ein}}\left[\left(\frac{r}{r_s}\right)^{\alpha_{\rm Ein}}-1\right]\right\}$
Cored Isothermal	$\rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$
Burkert	$\rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$.

Table 2.1: *Plausible spherical density profiles $\rho(r)$ for DM halos in galaxies.*

Cirelli+ 2406.01705



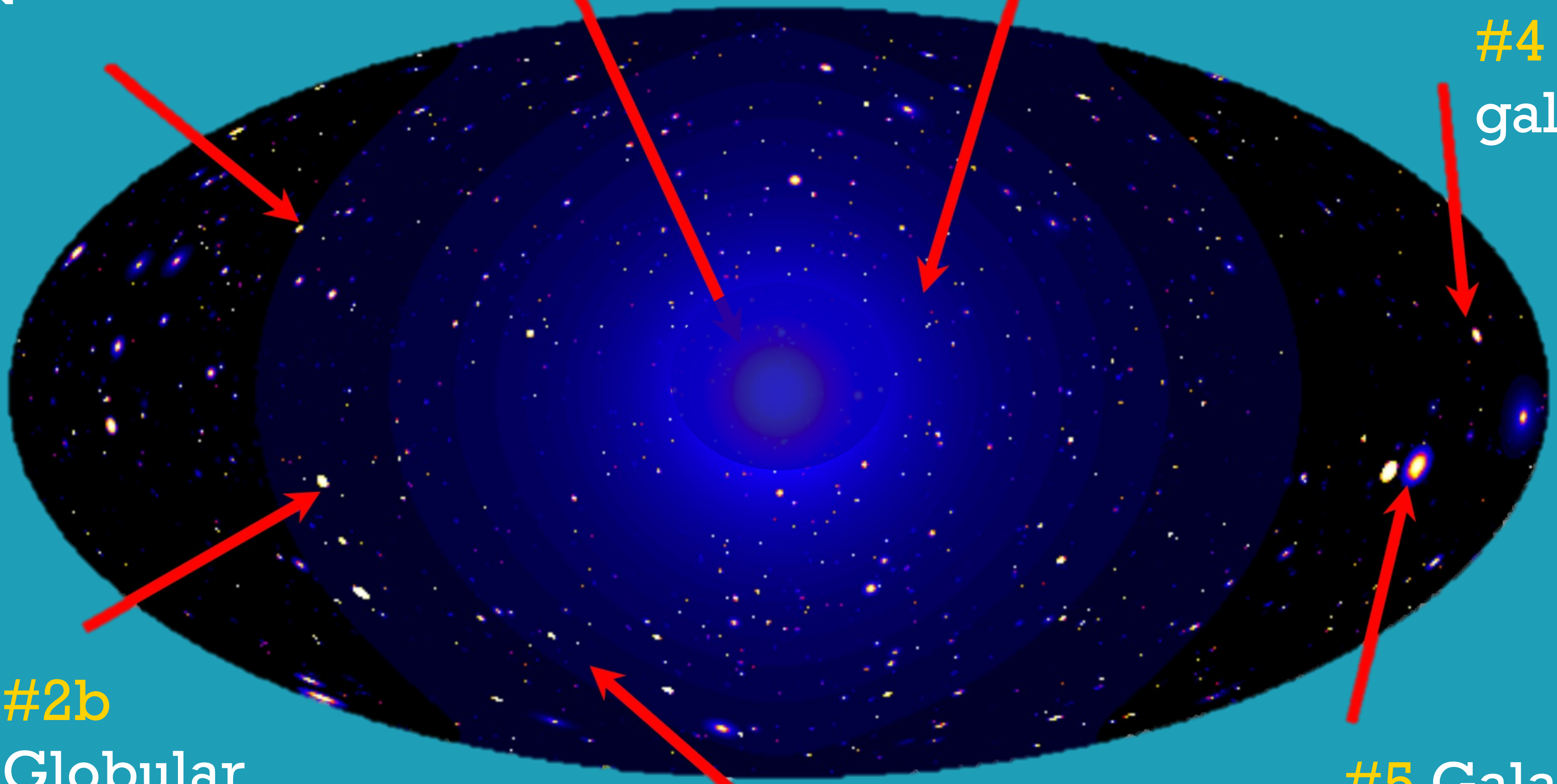
- Implicit form from N-body simulation:
  - Cuspy DM profiles
  - Cored DM profiles: preferred by observation
- Parameters adjusted from Jeans equilibrium equation using stellar velocity dispersion

A POSSIBLE G-RAY DM SKY

#1 Galactic Center and halo

#3 Dark objects

#4 Other galaxies



#2 Dwarf galaxies (MW satellites) Spheroidal and Irregular

#2b Globular clusters

#6 Diffuse signal, lines, streams, …

#5 Galaxy clusters

#2
INSTRUMENTS

Experiment	Location	Operation	Technology	Main focus	Energy range	Home	Ref.
HEAO-1	satellite	1977 → 1979	X-ray detectors	X/γ-rays	0.2 keV – 10 MeV	web	[466]
BAKSAN	Russia	1978 →	scintillation	neutrinos	1 GeV – 1 TeV	web	[467]
ROSAT	satellite	1990 → 1999	X-ray detectors	X-rays	0.1 – 2.5 keV	web	[468]
COMPTEL	satellite	1991 → 2000	HEP detectors	γ-rays	1 – 30 MeV	web	[469]
EGRET	satellite	1991 → 2000	HEP detectors	γ-rays	30 MeV – 30 GeV	web	[470]
CANGAROO	Australia	1992 → 2012	air Čerenkov	γ-rays	200 GeV – 3 TeV	web	[471]
HEAT	balloon	1994, 1995	HEP detectors	e^- & e^+	1 – 100 GeV	–	[472]
SUPER-KAM.	Japan	1996 →	water Čerenkov	neutrinos	few MeV – $\gtrsim$100 GeV	web	[473]
AMANDA	South Pole	1996 → 2005	ice Čerenkov	neutrinos	50 GeV – $\gtrsim$10 TeV	web	[474]
AMS-01	Space shuttle	1998	HEP detectors	charged CRs	0.1 – 200 GeV	web	[475]
BAIKAL-NT	Siberia	1998 →	water Čerenkov	neutrinos	10 GeV – few TeV	web	[476]
CHANDRA	satellite	1999 →	X-ray detectors	X-rays	0.1 – 100 keV	web	[477]
XMM-NEWTON	satellite	2000 →	X-ray detectors	X-rays	0.15 – 15 keV	web	[478]
MILAGRO	New Mexico	2001 → 2008	water Čerenkov	γ-rays	100 GeV – 100 TeV	web	[479]
INTEGRAL	satellite	2002 →	HEP detectors	X-/γ-rays	15 keV – 20 MeV	web	[480]
HESS	Namibia	2003 →	air Čerenkov	γ-rays	30 GeV – 100 TeV	web	[481]
VERITAS	Arizona	2004 →	air Čerenkov	γ-rays	50 GeV – 50 TeV	web	[482]
MAGIC	Canary Islands	2004 →	air Čerenkov	γ-rays	30 GeV – 100 TeV	web	[483]
SWIFT	satellite	2004 →	X-ray detectors	X-rays	0.2 – 10 keV	web	[484]
CREAM	Antarctic balloon	2004 → 2010	HEP detectors	CR nuclei	10 GeV – 100 TeV	web	[485]
SUZAKU	satellite	2005 → 2015	X-ray detectors	X-rays	0.2 – 600 keV	web	[486]
ICECUBE	South Pole	(2005) 2010 →	ice Čerenkov	neutrinos	$\gtrsim$ 100 GeV	web	[487]
ANITA	Antarctic balloon	2006 →	Askaryan effect	neutrinos	0.1 – 100 EeV	web	[488]
PAMELA	satellite	2006 → 2016	HEP detectors	charged CRs	50 MeV – 1 TeV	web	[489]
FERMI	satellite	2008 →	HEP detectors	γ-rays	20 MeV – 500 GeV	web	[490]
ANTARES	French riviera	2008 → 2021	water Čerenkov	neutrinos	10 GeV – 1 PeV	web	[491]
AMS-02	ISS	2011 →	HEP detectors	charged CRs	500 MeV – 2 TeV	web	[492]
NUSTAR	satellite	2012 →	X-ray detectors	X-rays	3 – 79 keV	web	[493]
TAIGA	Siberia	~2012 →	air Čerenkov	γ-rays/CRs	few TeV – 100 PeV	web	[494]
HAWC	Mexico	2014 →	water Čerenkov	γ-rays	100 GeV – 100 TeV	web	[495]
TIBET AS	Tibet	2014 →	air shower/water Č.	γ-rays/CRs	$\geq$ 100 TeV	web	[496]
CALET	ISS	2015 →	HEP detectors	charged CRs	1 GeV – 20 TeV	web	[497]
HITOMI	satellite	2016	X-ray detectors	X-rays	0.3 – 80 keV	web	[498]
DAMPE	satellite	2016 →	HEP detectors	charged CRs	5 GeV – 10 TeV	web	[499]
COSI-SPB	balloon	2016	Compton telescope	γ-rays	0.2 – 5 MeV	web	[500]
HXMT	satellite	2017 →	X-ray detectors	X/γ-rays	1 – 250 keV	web	[501]
ISS-CREAM	ISS	2017 →	HEP detectors	charged CRs	10 GeV – 100 TeV	web	[502]
MACE	Himalaya	2017 →	air Čerenkov	γ-rays	40 GeV – 20 TeV	–	[503]
MICRO-X	New Mexico	2018	X-ray detectors	X-rays	0.2 – 3 keV	web	[504]
EROSITA	satellite	2019 →	X-ray detectors	X/γ-rays	0.3 – 10 KeV	web	[505]
LHAASO	China	2020 →	air shower/water Č.	γ-rays/CRs	100 GeV – EeV	web	[506]
GAPS	Antarctic balloon	2022?	nuclear physics	$\bar{d}$	0.1 – 0.3 GeV/n	web	[507]
KM3NET	Mediterranean	2022?	water Čerenkov	neutrinos	$\gtrsim$ 1 TeV	web	[508]
CTA	North+South	2020s?+?	air Čerenkov	γ-rays	50 GeV – 50 TeV	web	[509]
XRISM	satellite	2023?	X-ray detectors	X-rays	0.3 – 13 keV	web	[510]
ADEPT	balloon	2024?	HEP detectors	γ-rays	5 – 200 MeV	–	[511]
BAIKAL-GVD	Siberia	2024?	water Čerenkov	neutrinos	100 GeV – few PeV	web	[512]
GAMMA-400	satellite	2025?	HEP detectors	γ-rays	100 MeV – 3 TeV	web	[513]
DUNE	USA	2026?	liquid Argon	neutrinos	$\gtrsim$ 10 MeV	web	[514]
COSI	satellite	2027?	Compton telescope	γ-rays	0.2 – 5 MeV	web	[515]
HYPER-KAM.	Japan	2027?	water Čerenkov	neutrinos	few MeV – $\gtrsim$100 GeV	web	[516]
HERD	Chinese SS	2020s?	HEP detectors	charged CRs	50 GeV – 1 PeV	web	[517]
SKA	S.Africa+Australia	2020s?	radio telescope	radio	50 MHz – 30 GHz	web	[518]
INO-ICAL	India	2020s?	calorimeter	neutrinos	1 – 100 GeV	web	[519]
AMEGO	satellite	late 2020s?	HEP detectors	γ-rays	0.2 MeV – 10 GeV	web	[520]
APT	satellite	late 2020s?	HEP detectors	γ-rays	60 MeV – 1 TeV	–	[521]
ATHENA	satellite	early 2030s?	X-ray detectors	X/γ-rays	0.2 – 12 keV	web	[522]
AS-/E-ASTROGAM	satellite	2030s?	HEP detectors	γ-rays	0.1 MeV – 3 GeV	–	[523]
GRAND	high altitude deserts	2030s?	radio telescopes	neutrinos	100 PeV – 100 EeV	web	[524]
ALADINO	L2 point?	2035?	HEP detectors	charged CRs	→ 10 TeV	–	[525]
AMS-100	L2 point	2039?	HEP detectors	charged CRs	sub-GeV – 10 TeV	–	[526]
GECCO	satellite	proposed	HEP detectors	X/γ-rays	100 keV – 10 MeV	–	[527]
MAST	satellite	proposed	LAr satellite	γ-rays	100 MeV – 1 TeV	–	[528]
GRAMS	balloon/satellite	proposed	LAr detector	γ-rays/$\bar{d}$	200 keV – 200 MeV	–	[529]
SWGO	South America	proposed	water Č.	γ-rays	100 GeV – 1 PeV	web	[530]

WE HAVE OUR TOOLBOX

Gamma-rays

X-rays

Neutrinos

Charged particles

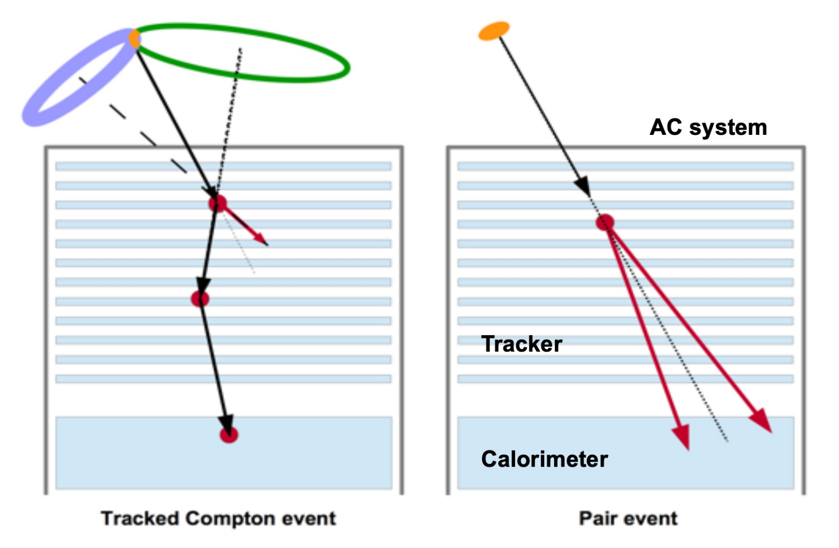
Cirelli+ 2406.01705


agile
Gamma-rays
2000 → X-ray detectors X-rays 0.15 – 15 keV web [478]
100 GeV – 100 TeV web [479]
MAGIC Canary Islands
SWIFT satellite
COSI-SPB balloon
COSI satellite 2027? Compton telescope γ-rays
100 GeV – 1 PeV web [530]
Palma (Canary Islands, Spain)
North: 19 telescopes
Cerro Paranal (Atacama, Chile)
South: 99 telescopes
Gabriel Pérez Diaz, IAC, SMM
We focus on a selection of more-constraining gamma-ray instruments

SATELLITE-BORNE TRACKER + CALORIMETERS

IN SPACE: Compton + Pair Production

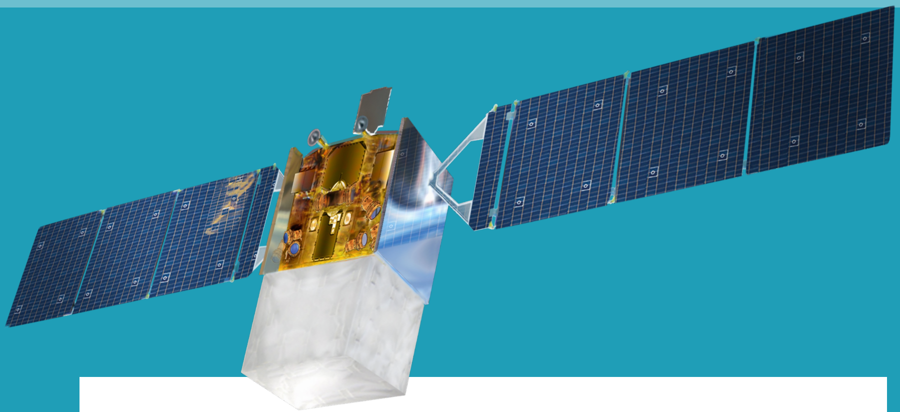
→ Mev – GeV



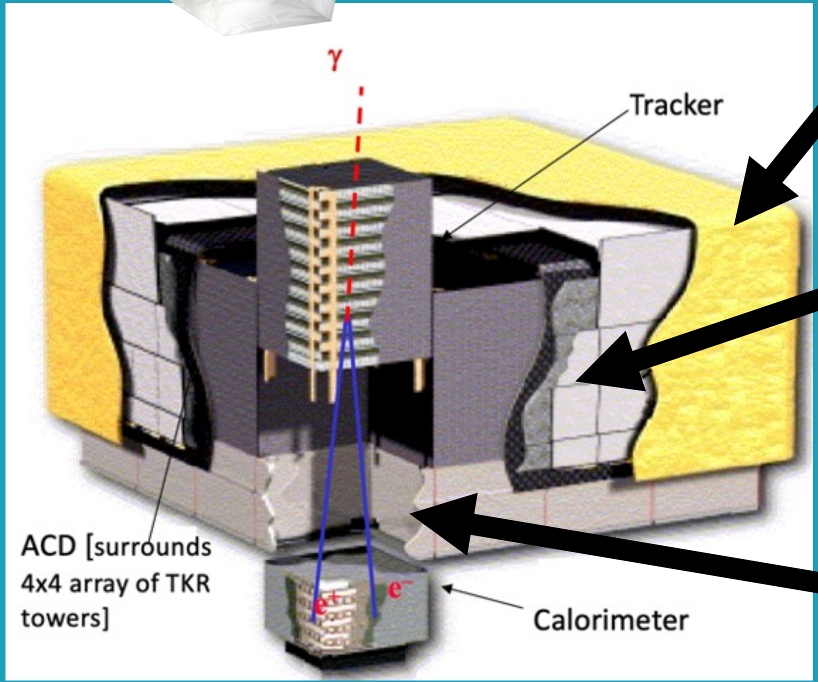
Past: CGRO, EGRET, AGILE

Present: Fermi-LAT, INTEGRAL, DAMPE

Future: HERD, e-ASTROGAM, AMEEGO, COSI,…



FERMI-LAT 2006--



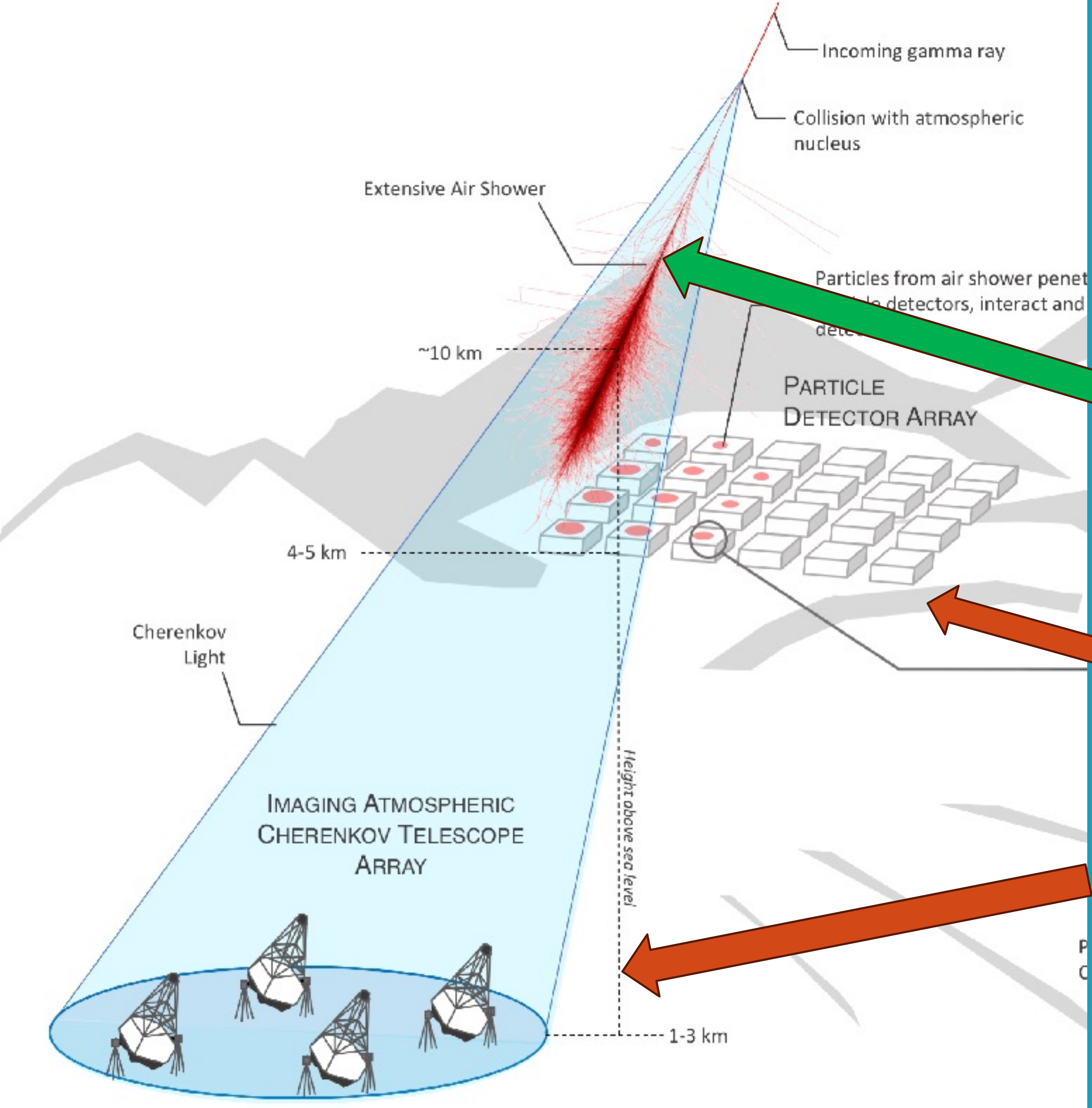
Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles.

Precision Si-strip Tracker (TKR) 70 m² of silicon detectors arranged in 36 planes. 880,000 channels.

Hodoscopic CsI Calorimeter(CAL) 1536 CsI(Tl) crystals in 8 layers, total mass 1.5 tons.

NOTE: All-sky instrument (every 3h). 100% duty cycle.

GROUND-BASED



Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

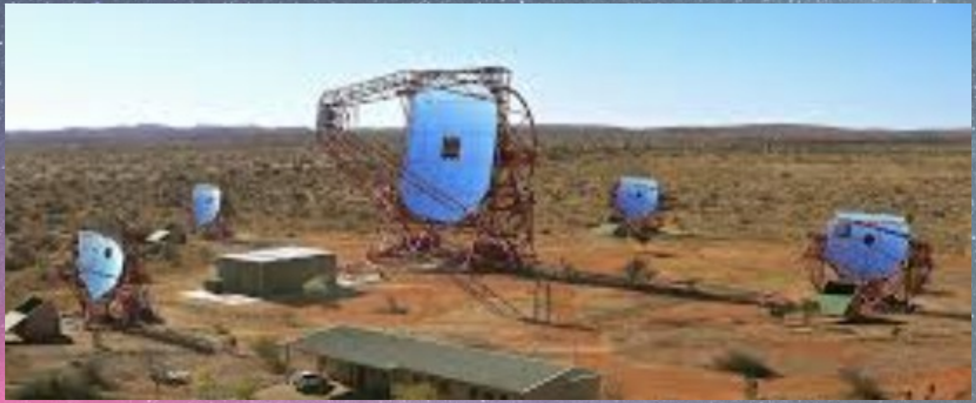
AT GROUND: Particle showers + Cherenkov
→ 100 Gev – 10 PeV

GAMMA-RAYS creates atmospheric showers of particles at 5-25km height

Shower front detectors (SFDs) samples the shower particles
- 24h/7d
- large FOV – 1 sr

Imaging Atmospheric Cherenkov Telescopes (IACTs) sample the seconday Cherenkov light
- work at night
- small FOV ~ 10deg
- sensitive area 10^5 m^2 >> telescope area

IACTS



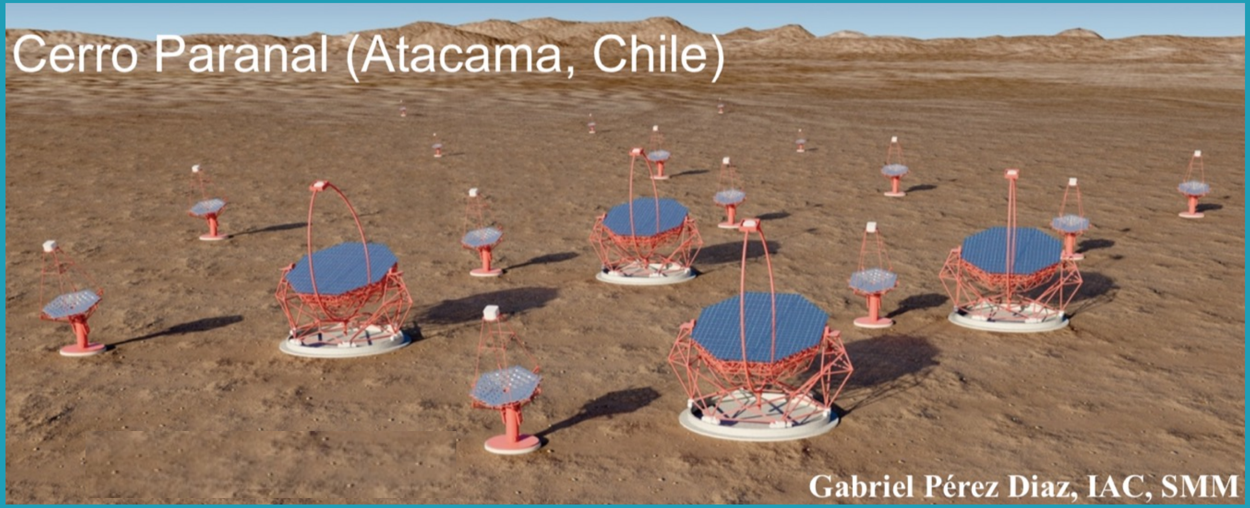
IACT	Year	Nr. tels & diameter	Location
Whipple	1968	1×12 m	Arizona, USA
H.E.S.S.	2003	4×12 m+1×28 m	Gambserg, Namibia
MAGIC	2004	2×17 m	La Palma, Spain
VERITAS	2007	4×12 m	Arizona, USA

Table 1: Current major operating ground-based Cherenkov telescopes. Given are the starting year, the array multiplicity and dish diameter *in the latest configuration*, and the location.

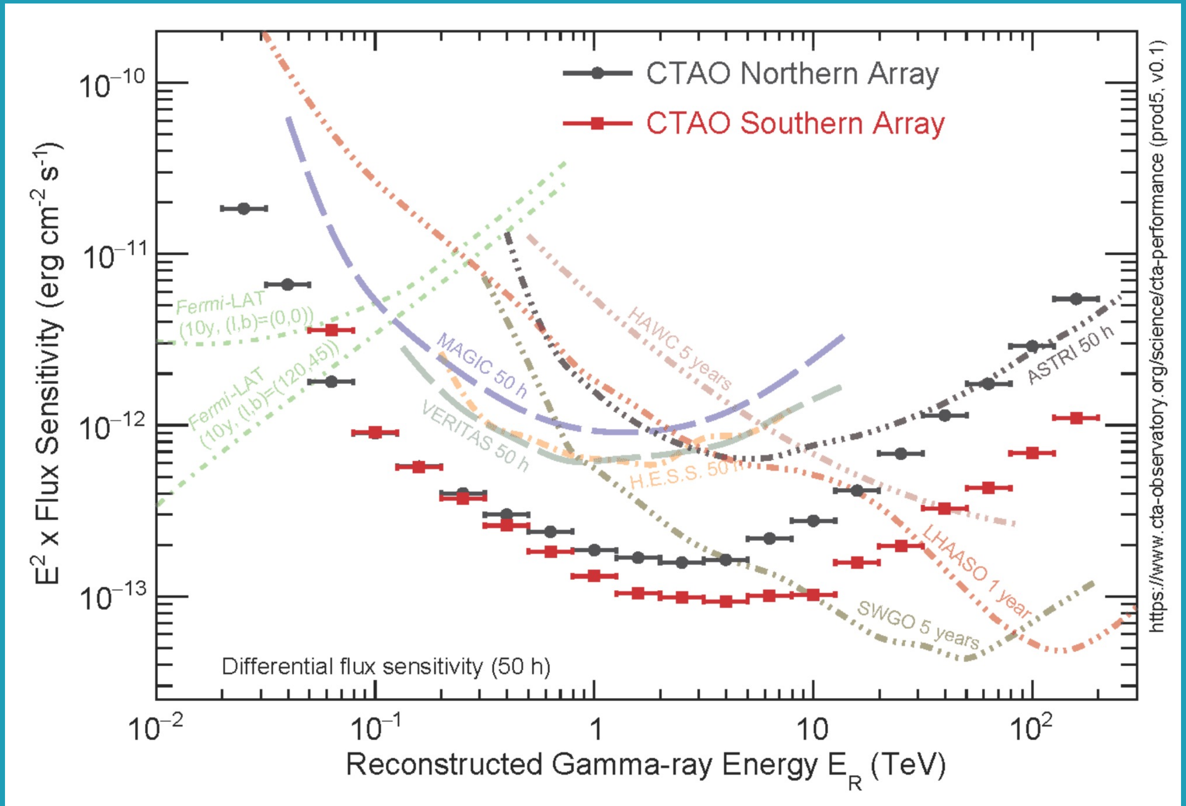
Cherenkov flash (blue/UV, few ns) → telescopes work at night, need fast electronics

Few photons/dm^2 → diameters 12--23 m (huge!),

FUTURE: CHERENKOV TELESCOPE ARRAY OBSERVATORY



CTA-NORTH 15 telescopes, low-energy focus
CTA-SOUTH 70 telescopes, all-energy focus

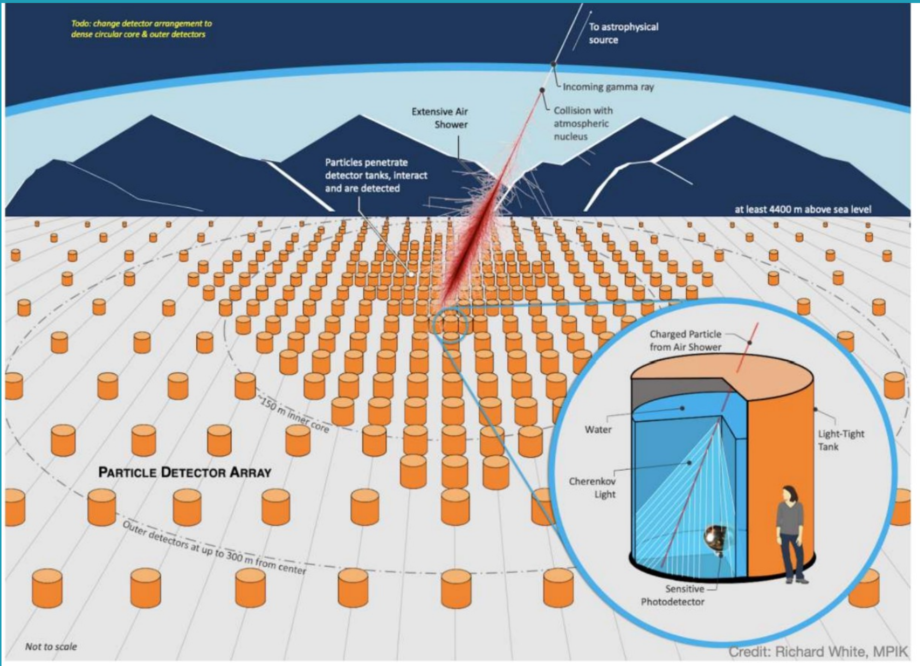


Tremendous sensitivity boost
Larger energy reach
Better energy and angular resolution
Observatory-based: proposal-based programs

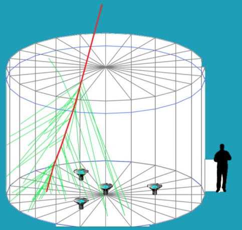
SHOWER FRONT DETECTORS

SWGO 2030?—
~10k water Cherenkov tanks

→ SOUTHERN HEMISPHERE



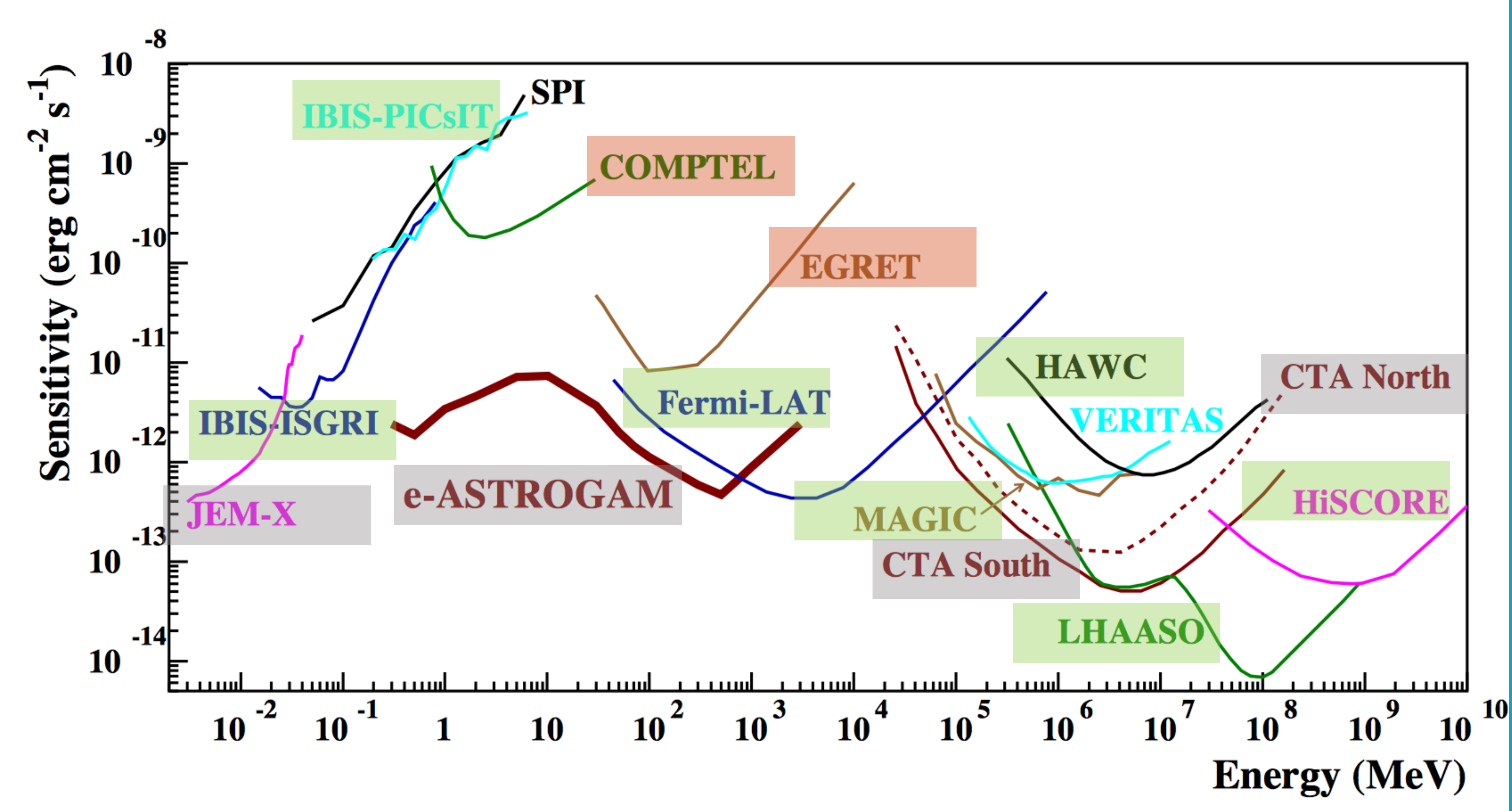
HAWC Mexico—
4100 m a.sl.
300 large tanks in the core array
350 small tanks in the sparse array



LHAASO China—
~5200 scintillator counters
~1200 muon detectors
~3000 water Cherenkov tanks
~12 wide-field-of view IACTs

COMPARING EXPERIMENTS

Plot from https://arxiv.org/abs/1611.02232



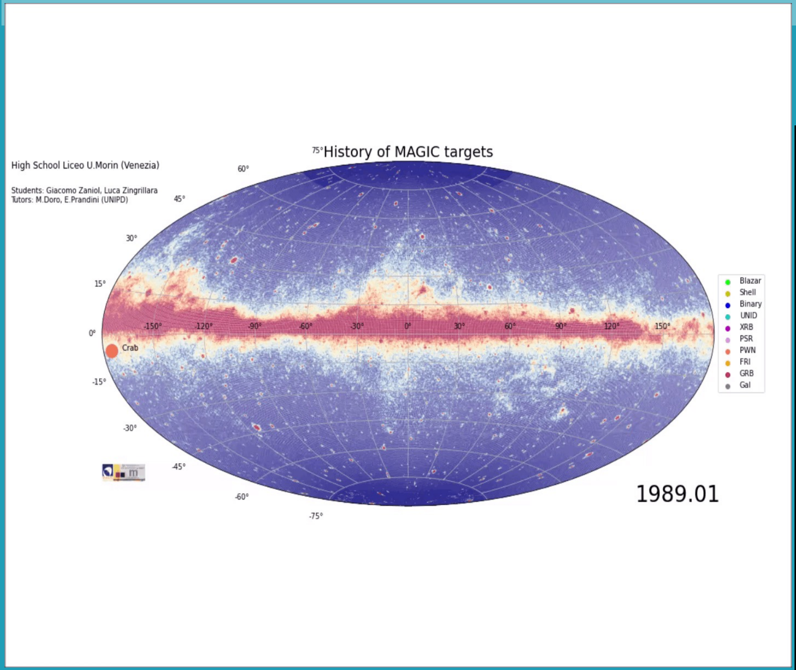
Past

Present

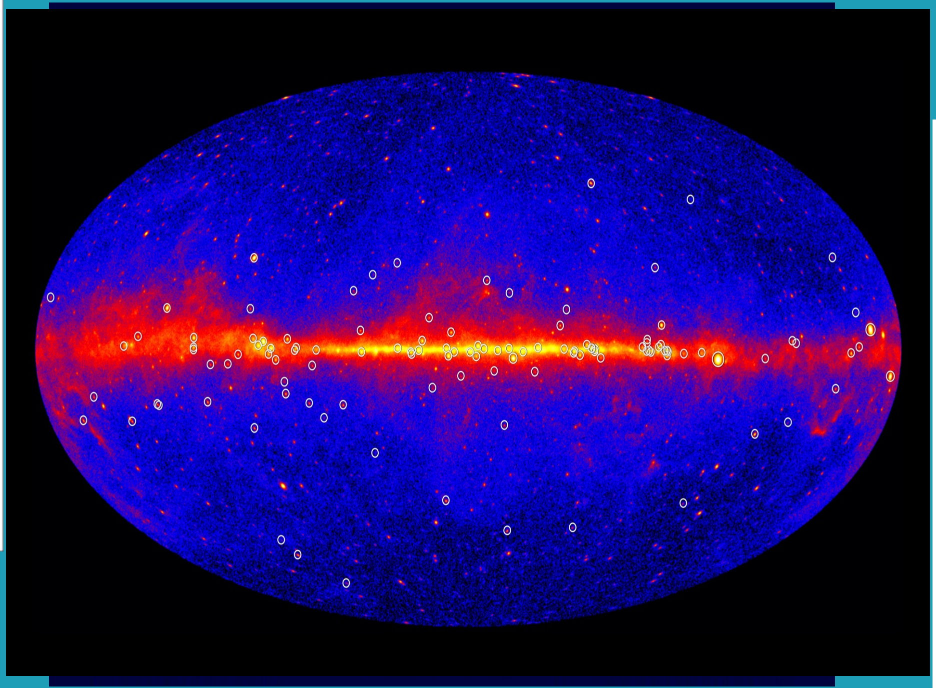
Future

GAMMA-RAY SKY: "3 REVOLUTIONS IN 3 DECADES"

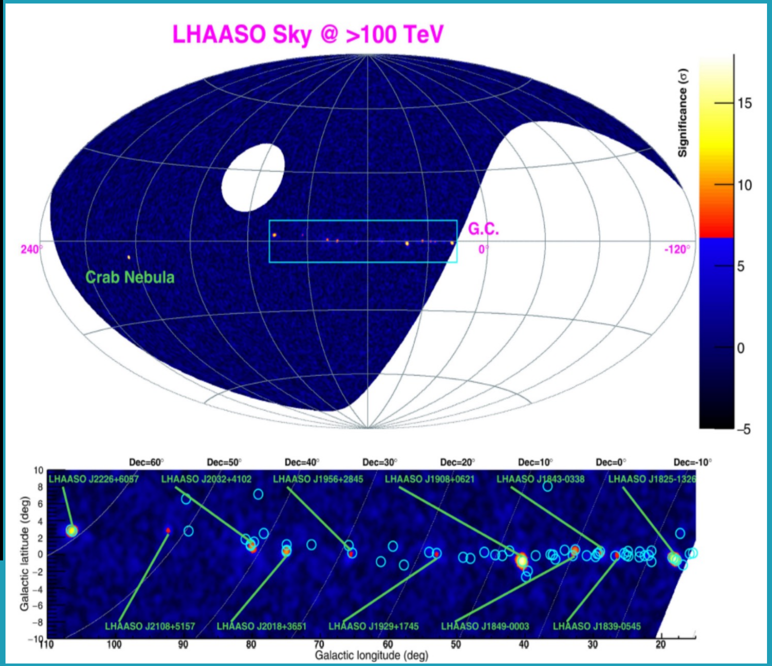
Cit. F. Aharonian



TeV revolution (IACT, 2000)

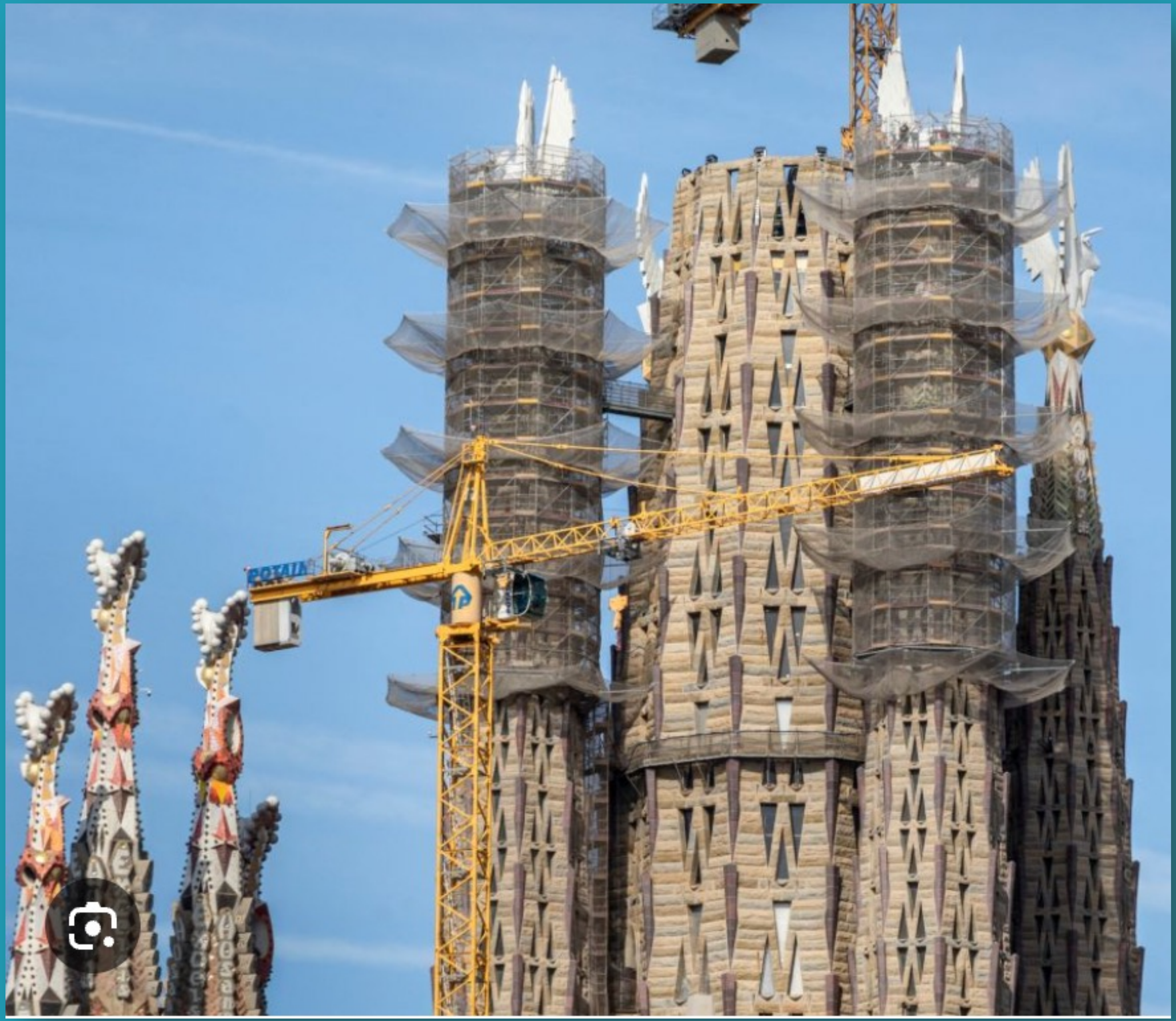


GeV revolution (AGILE, FERMI, 2010)



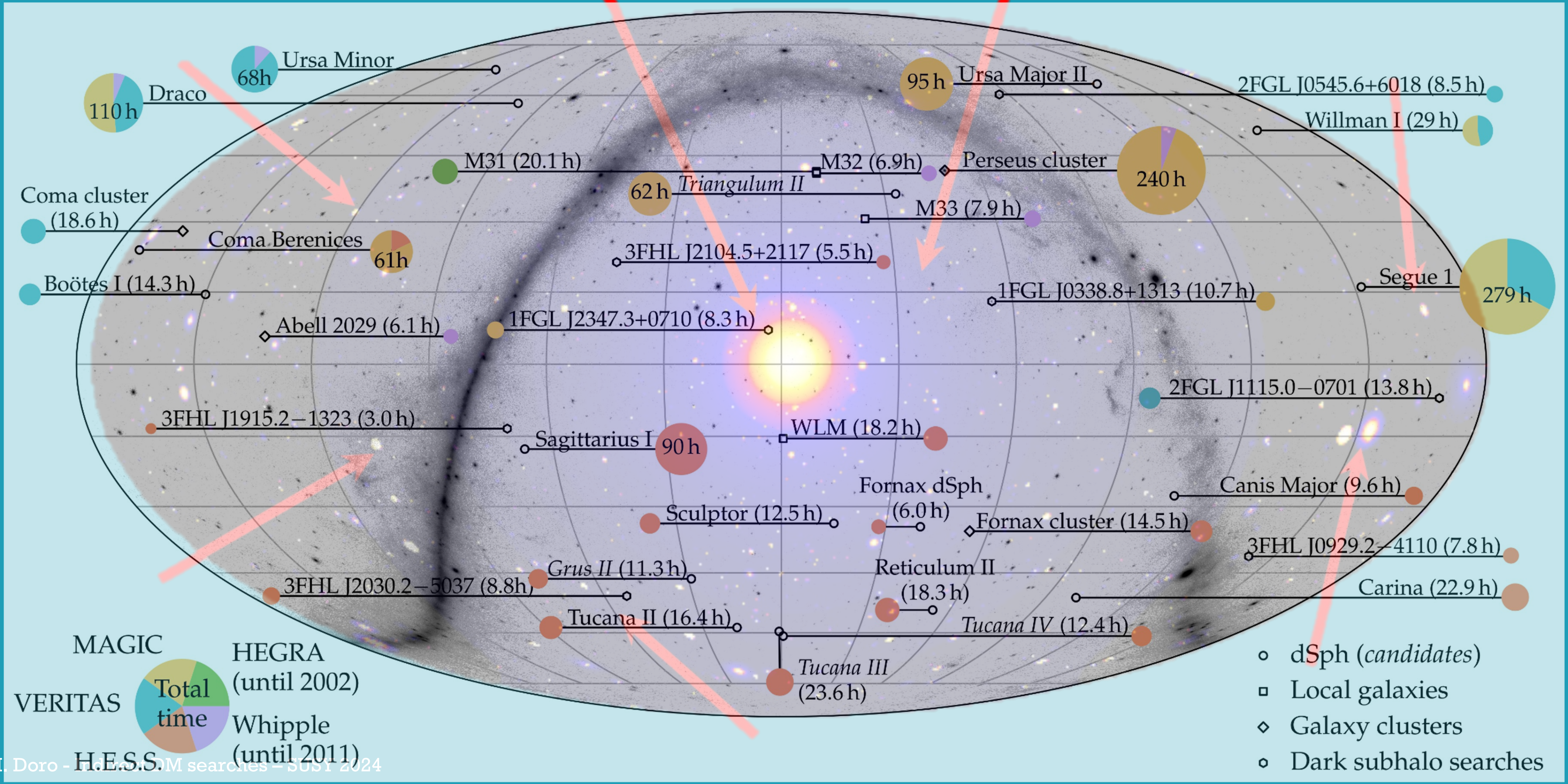
PeV revolution (LHAASO, 2020)

#3 WHAT DONE/ WHAT AHEAD

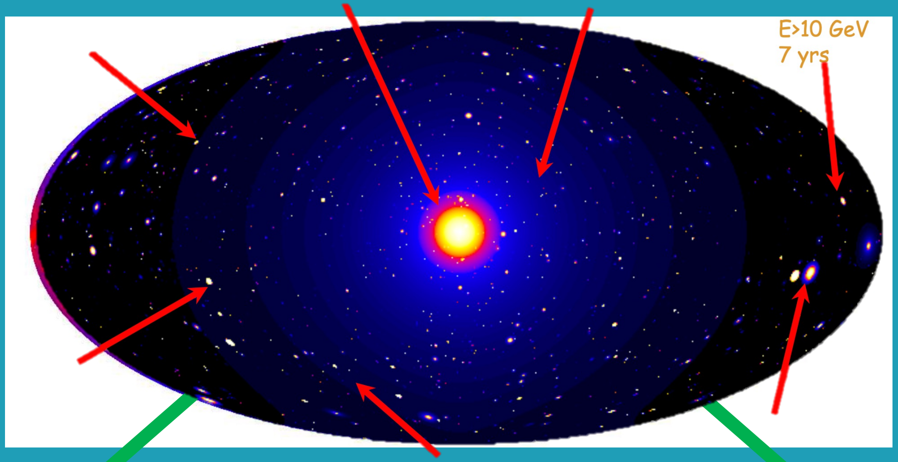


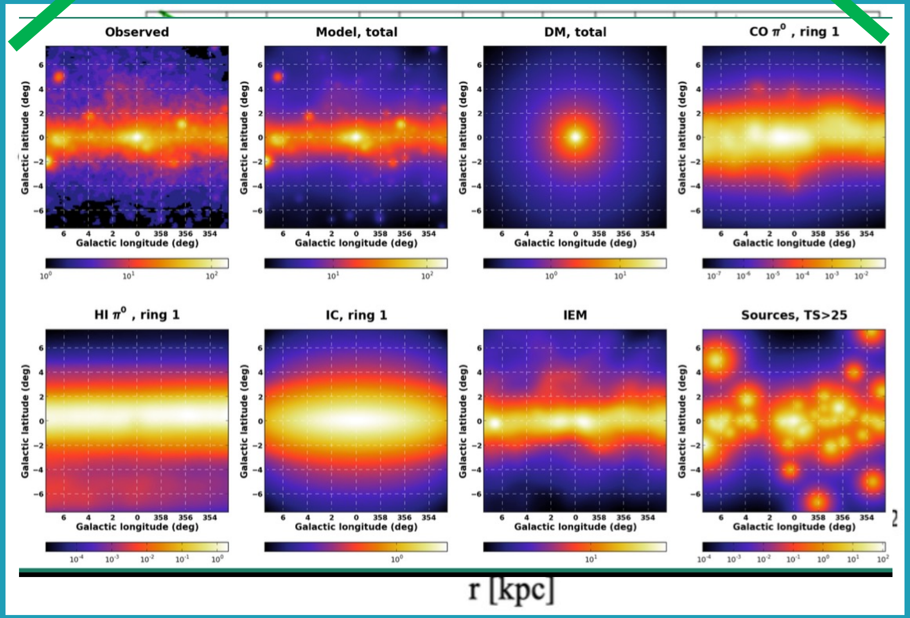
WE LOOKED AROUND

Galaxies **2022**, *10*(5), 92



#3.1 GALACTIC CENTER





Largest predicted accumulation of DM close to us (8 kpc) in the baricenter of the Milky Way

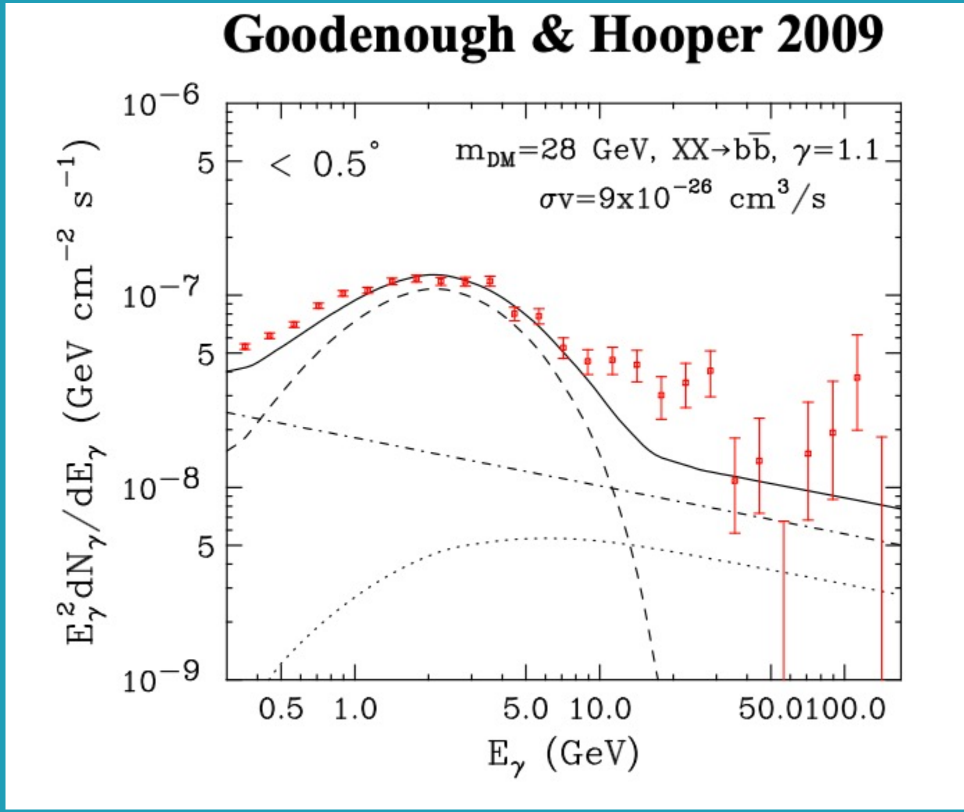
J-factor 10^{22} GeV^{2}cm-5

Can outshine all other DM targets BUT unknown interplay with baryons:
- gravitational contraction → more DM
- stellar outward finds → less DM

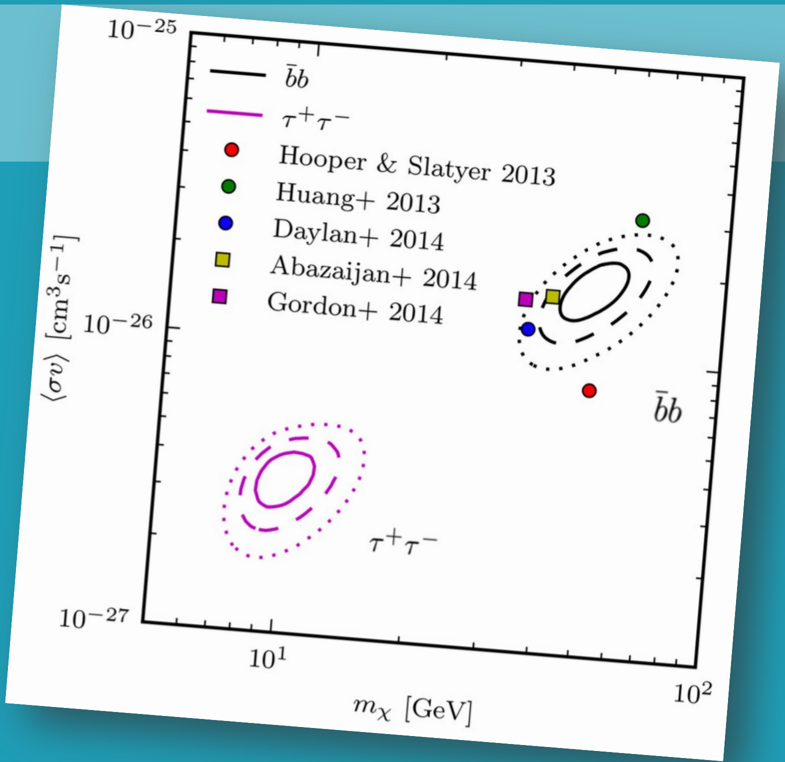
Also several 'astrophysics' backgrounds: BH, ridge, unresolved targets, galactic plane, etc.

HINTS OF DM?

Found excess in the vicinities of the GC,



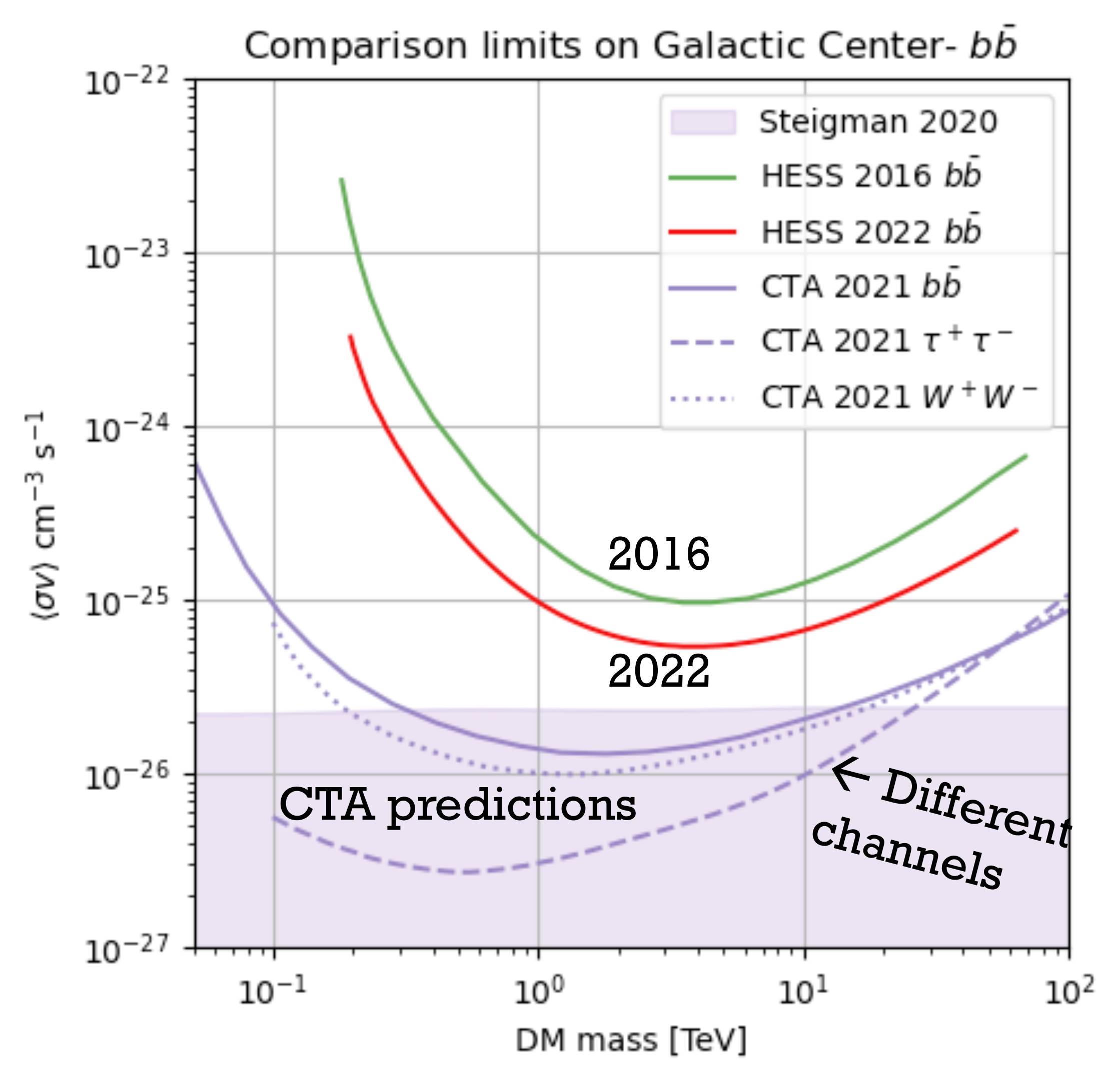
Compatible with
- DM signal at few GeV
- 1+ pulsars



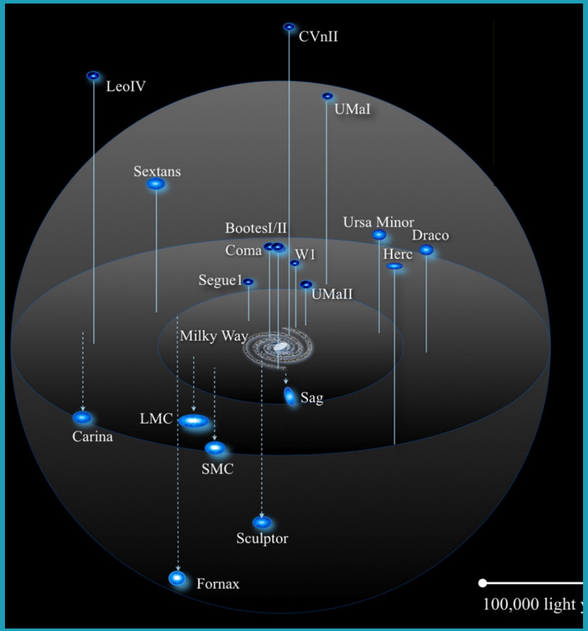
- The Galactic Center as a Dark Matter Gamma-Ray Source
- A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, Nuclear Physics B 113B (2002) 213-220 [astro-ph/0211327] A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio Astroparticle Physics 21, 267-285, 2004 [astro-ph/0305075]
- Possible Evidence 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
- 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)

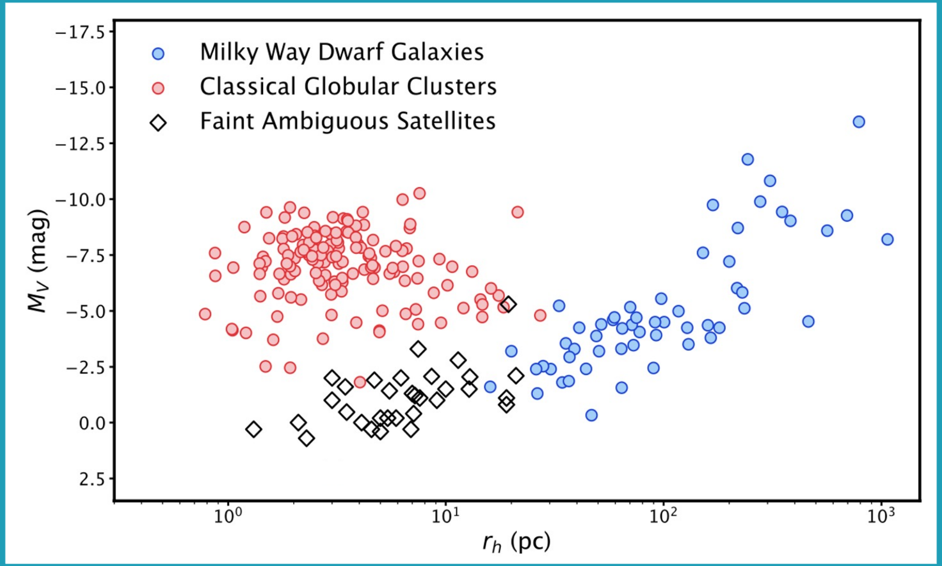
GC: IACTS (LESS BKG THAN AT GEV)

- Primary target for H.E.S.S., located in Southern-Hemisphere: 546h
- Also investigated by MAGIC, Veritas
- Obvious candidate for CTA!



#3.2 DWARF SPHEROIDAL GALAXIES



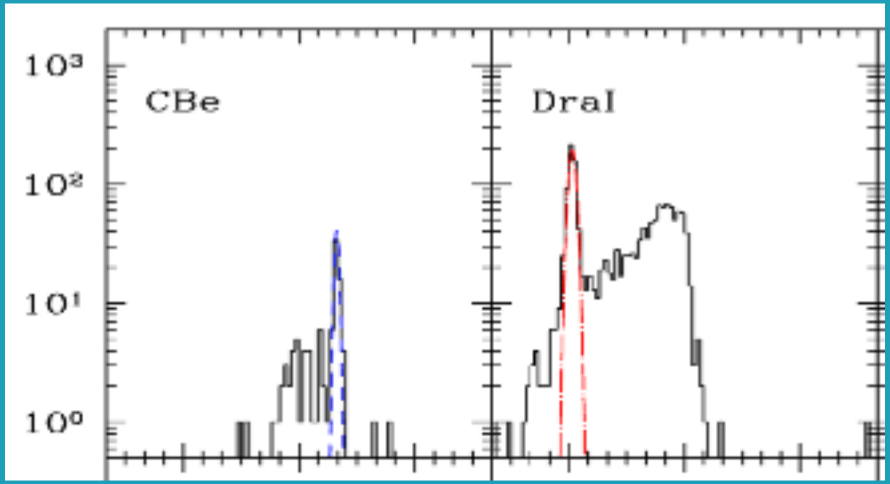


- Gravitationally bound to MW halo
- Pressure supported system
- DM density given by velocity dispersion (Jeans equation)

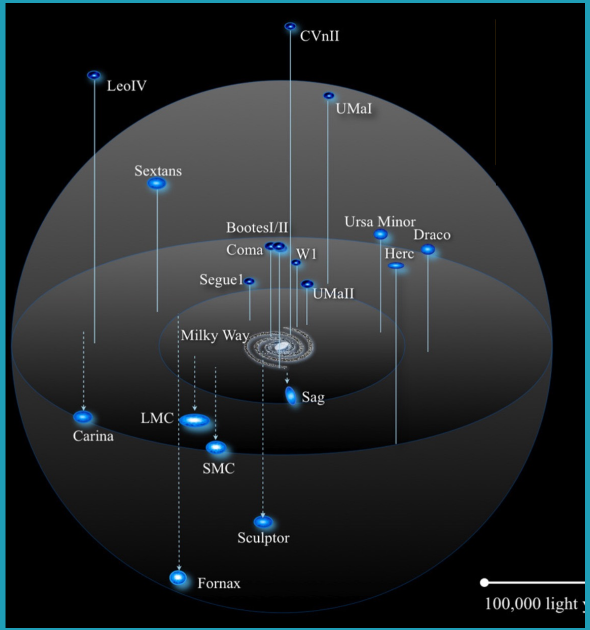
$$\rightarrow \rho(r) = \frac{\sigma^2}{2\pi G r^2}.$$

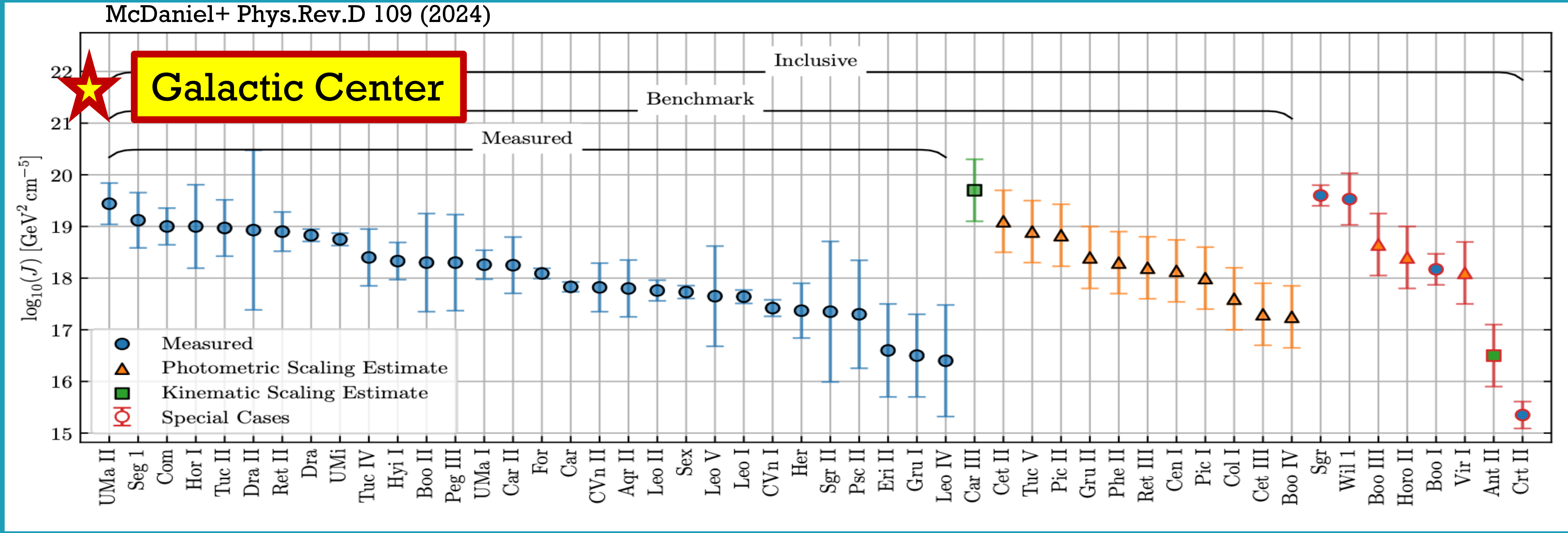
- Size, concentration and metallicity different than globular clusters
- Mass to light ratio ~100/1000 that of Sun
- Clean targets: no astrophysical background

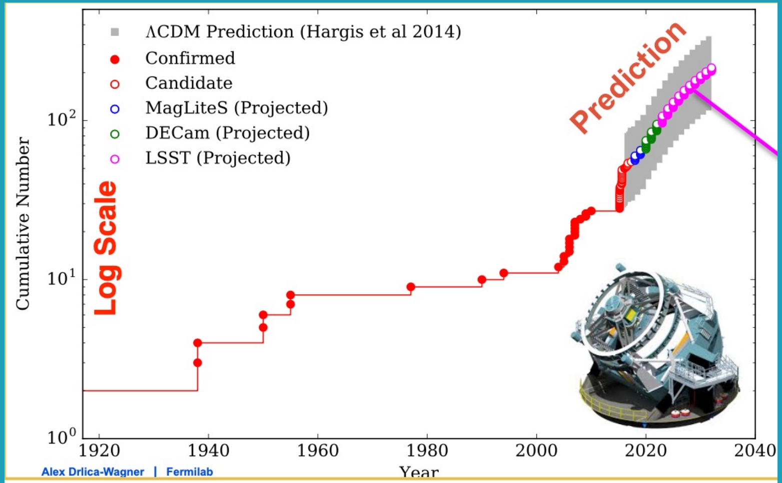
velocity dispersion : Issue with stellar association…very few candidates



#3.2 THE DWARF MW GALAXIES

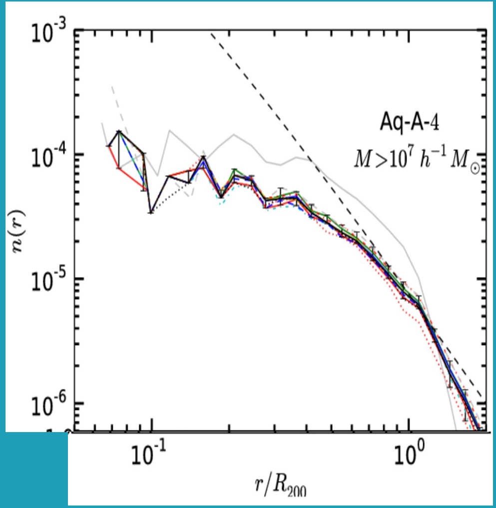


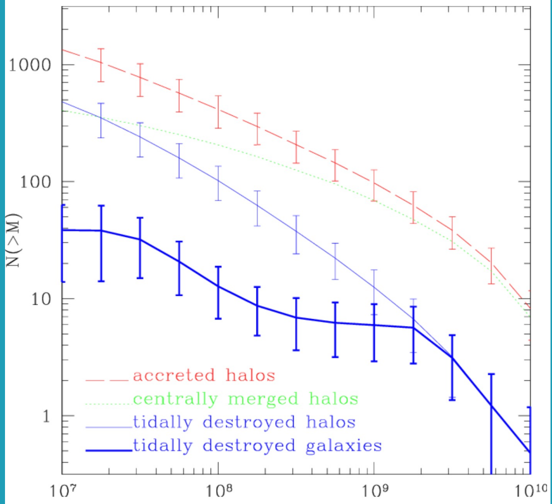




About 150 expected before 2050

Home message: 1+ big guy expected from theory!





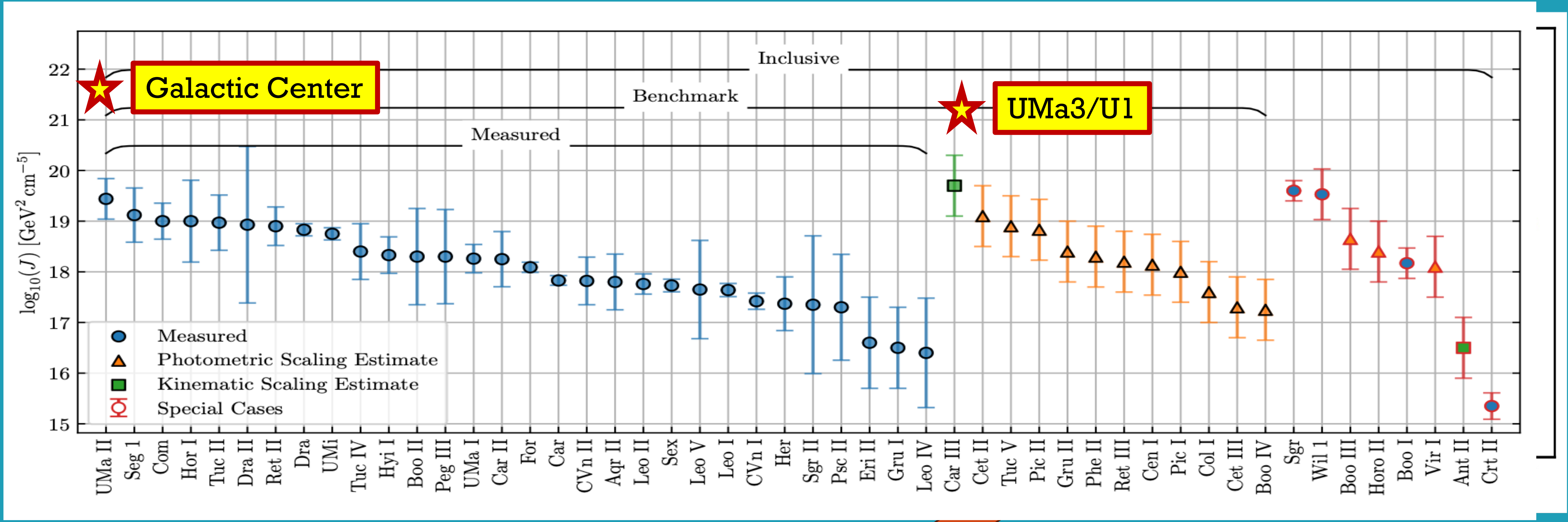
THE BIG GUY?

https://arxiv.org/abs/2311.10147

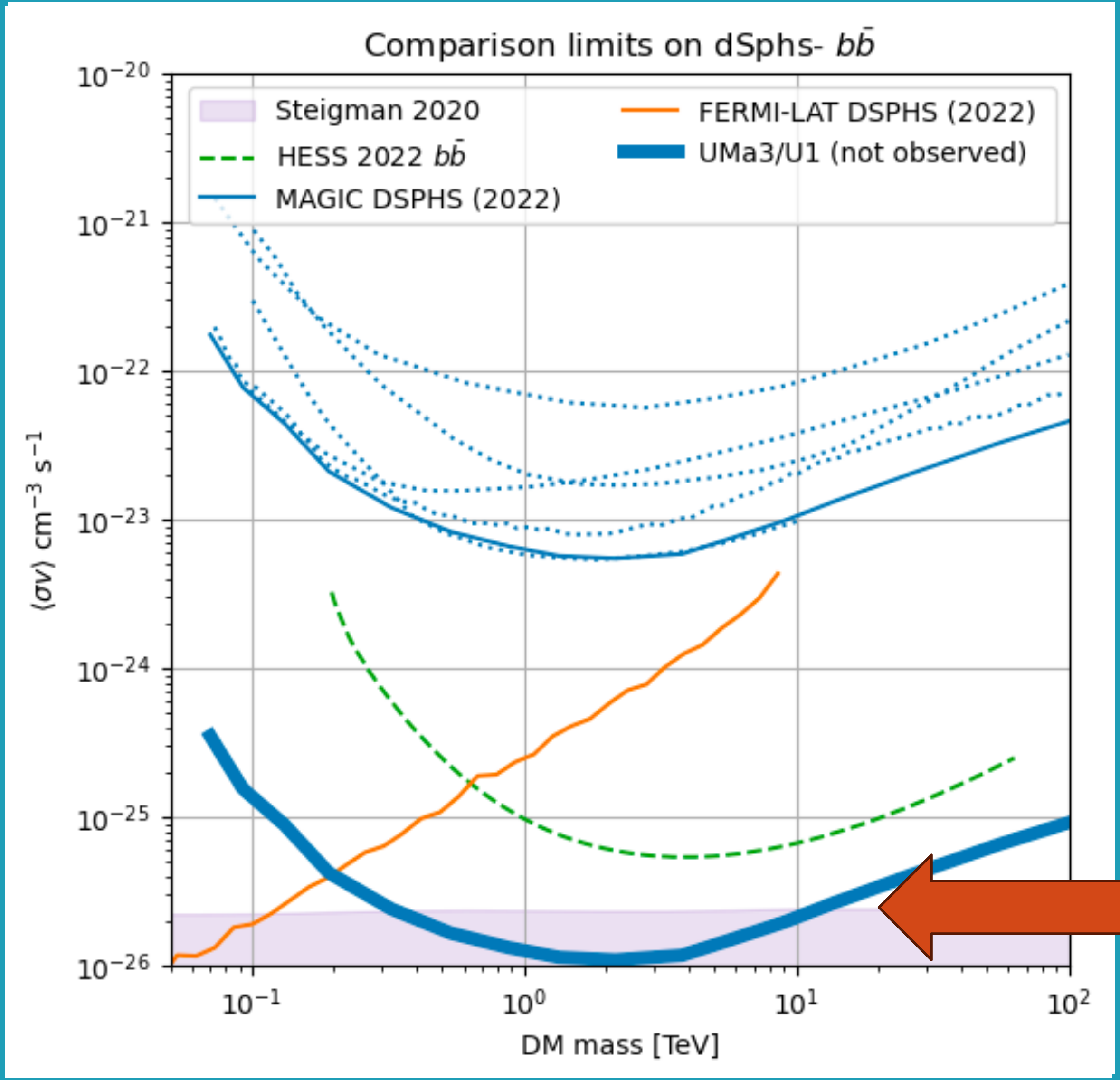
McDaniel+ Phys.Rev.D 109 (2024)

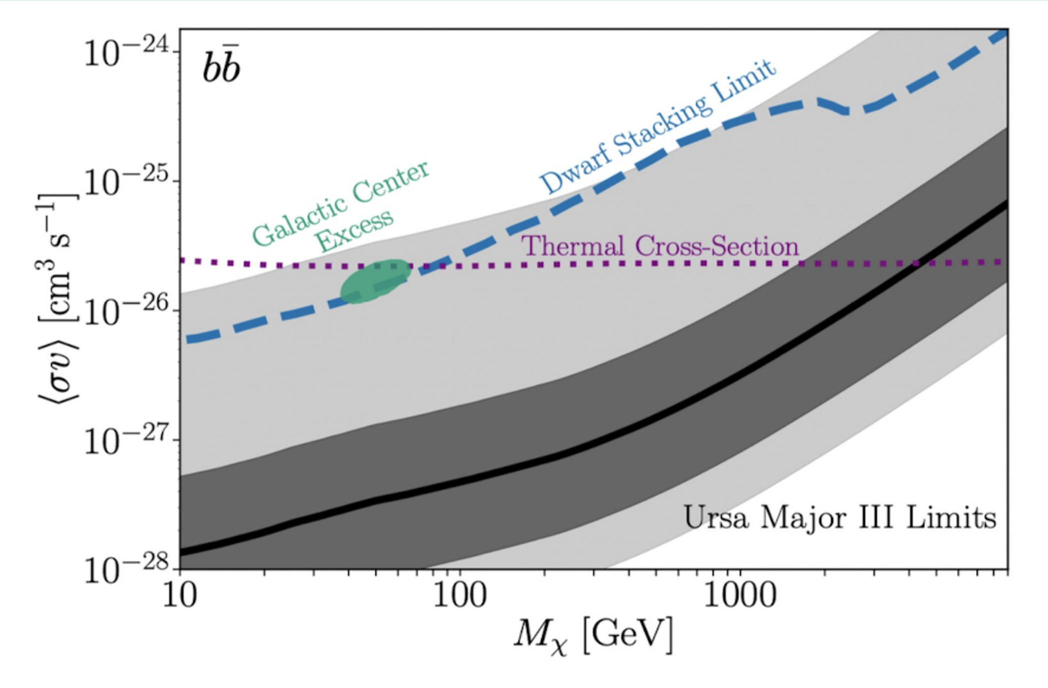
The discovery of the faintest known Milky Way satellite using UNIONS

Simon E. T. Smith,[1] William Cerny,[2] Christian R. Hayes,[3] Federico Sestito,[1] Jaclyn Jensen,[1] Alan W. McConnachie,[3,1] Marla Geha,[2] Julio Navarro,[1] Ting S. Li,[4] Jean-Charles Cuillandre,[5] Raphaël Errani,[6] Ken Chambers,[7] Stephen Gwyn,[3] Francois Hammer,[8] Michael J. Hudson,[9,10,11] Eugene Magnier,[7] and Nicolas Martin[6,12]



DSPH LIMITS FROM IACTS AND FERMI

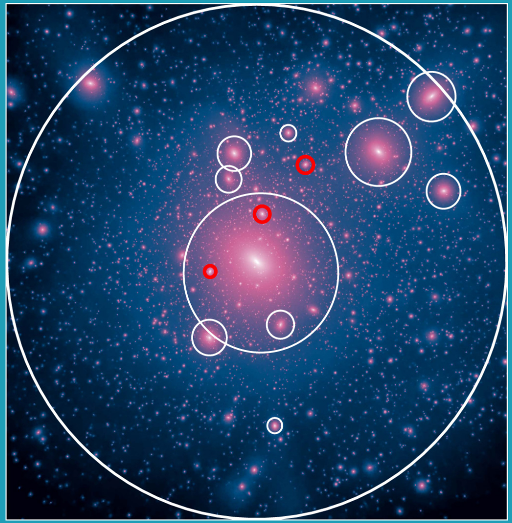




out

- If UMa3/U1 confirmed dSph (and observed) huge jump in constraints

3.3 THE DARK SUBHALOES



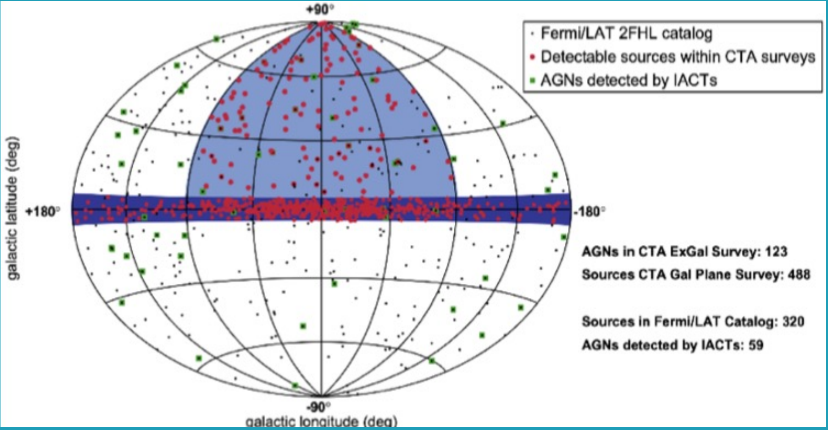
It is possible that a fraction of DM subhalos did not accrete baryons. This would result:

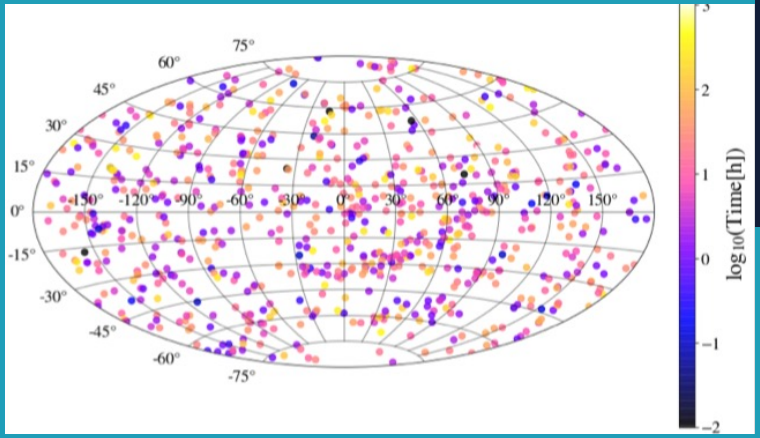
- more likely high density in the center (DM spikes)
- no visible from stars

Detectable through gravitational interaction: stellar streams gaps or micro-lensing?. For small FOV instrument it's hard to spot them other than serendipitously.

EGAL survey
CTA KSP, 25% of the sky, 3h per pointing

Pros: large area, uniform exposure
Cons: only 3h of exposure



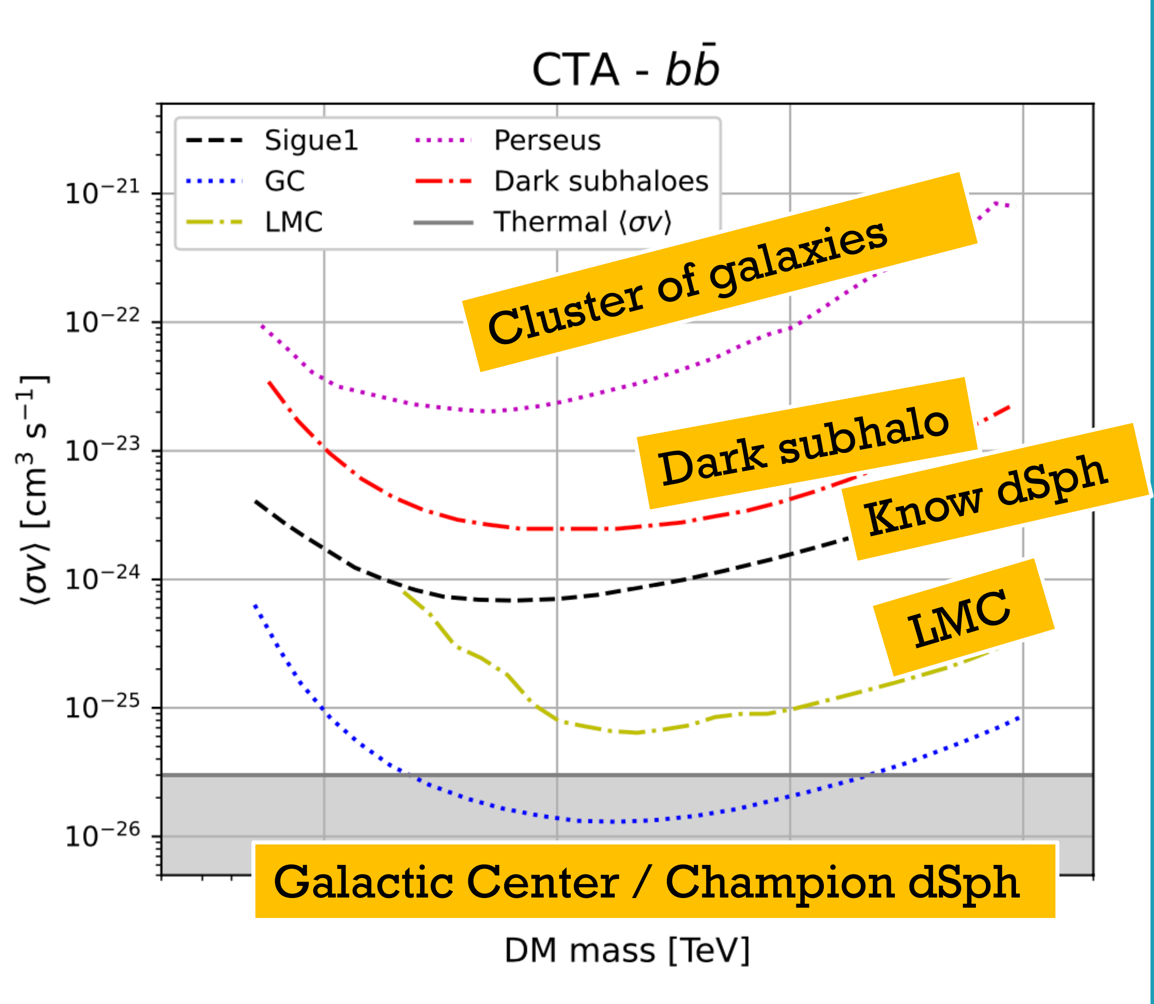


Overall exposure
Serendipitous discovery in the FoV of any CTA pointing

Pros: larger area, larger exposures
Cons: difficult to estimate time+area, off-axis sensitivity

J. Coronado-Blázquez, MD, M.A. Sanchez Conde.

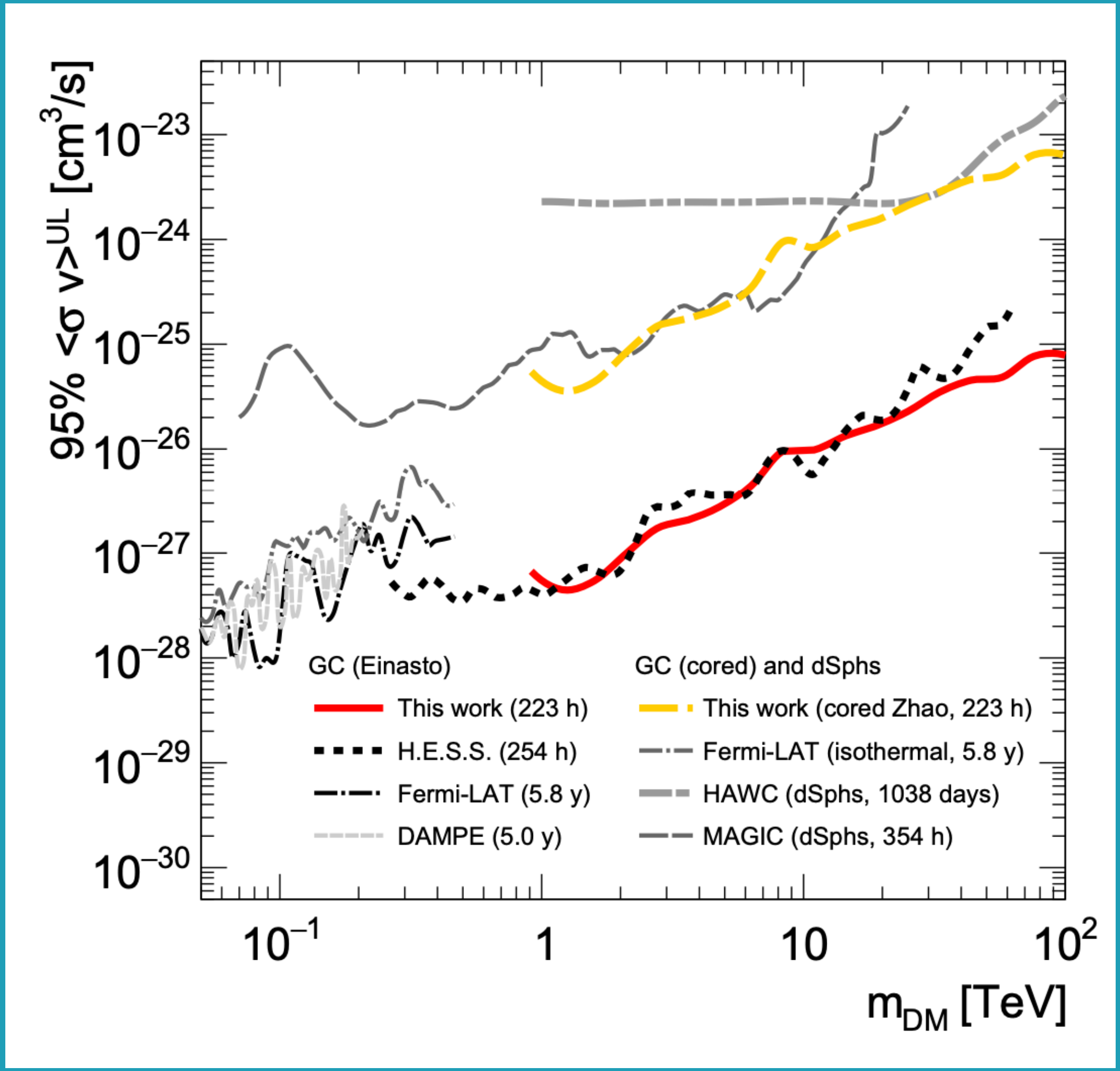
CONSIDERATION 1: HUNTING THE BEST TARGETS

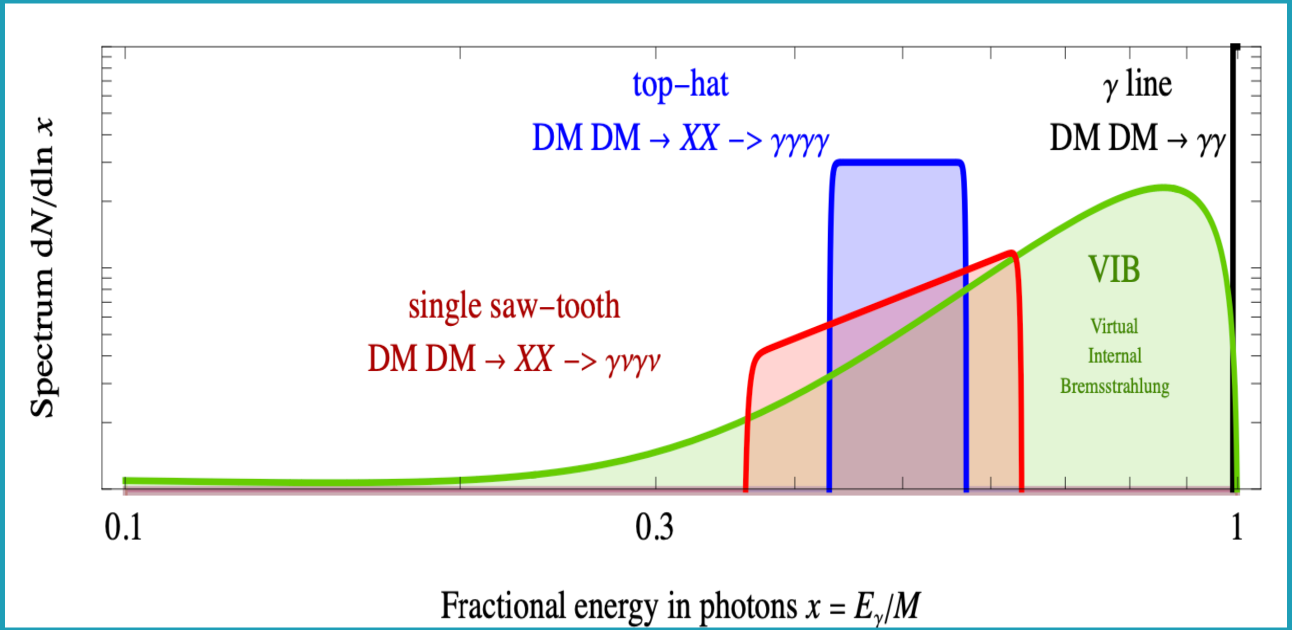


Astrophysical search of DM is also a hunt for the champion target

- Free of astrophysical background
- Most DM dominated

3.5 SEARCH FOR DM LINES AND BOXES





- Smoking gun evidence for DM
- DM mass determination

3.6 DECAY DM SEARCHES

- Best done on object with ‘a lot of DM’ as opposed to ’highly-dense’ such as galaxy clusters

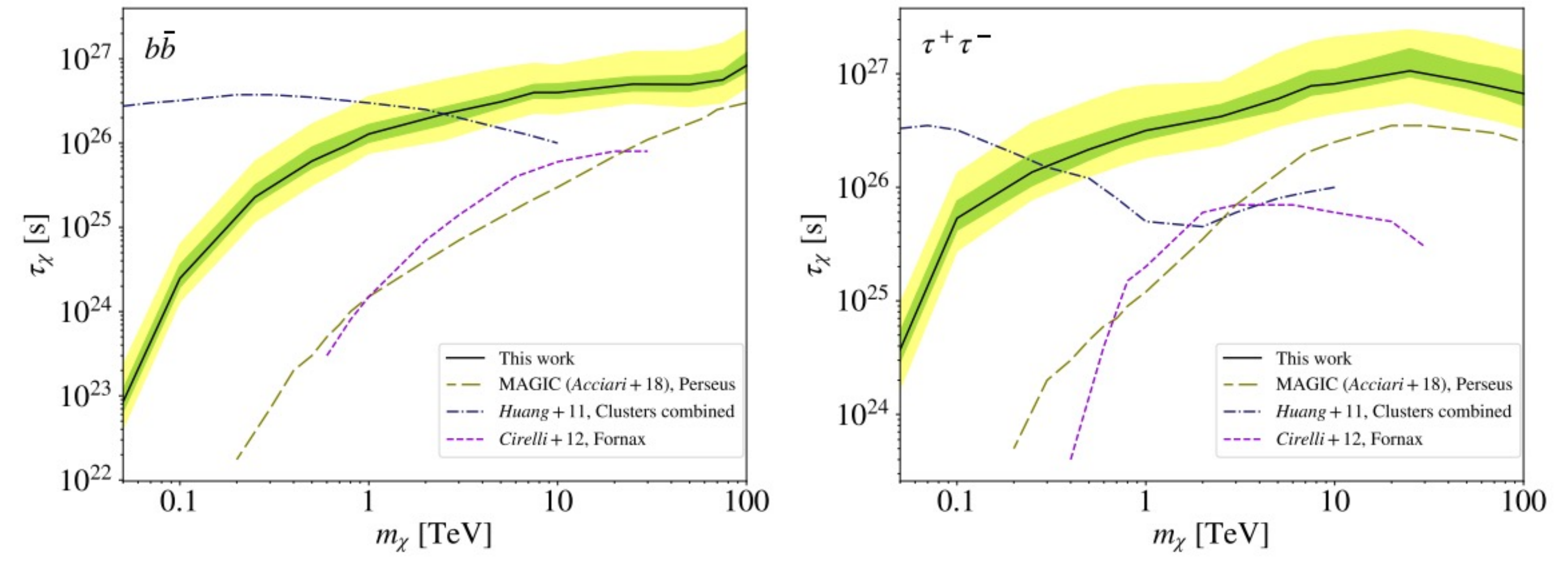
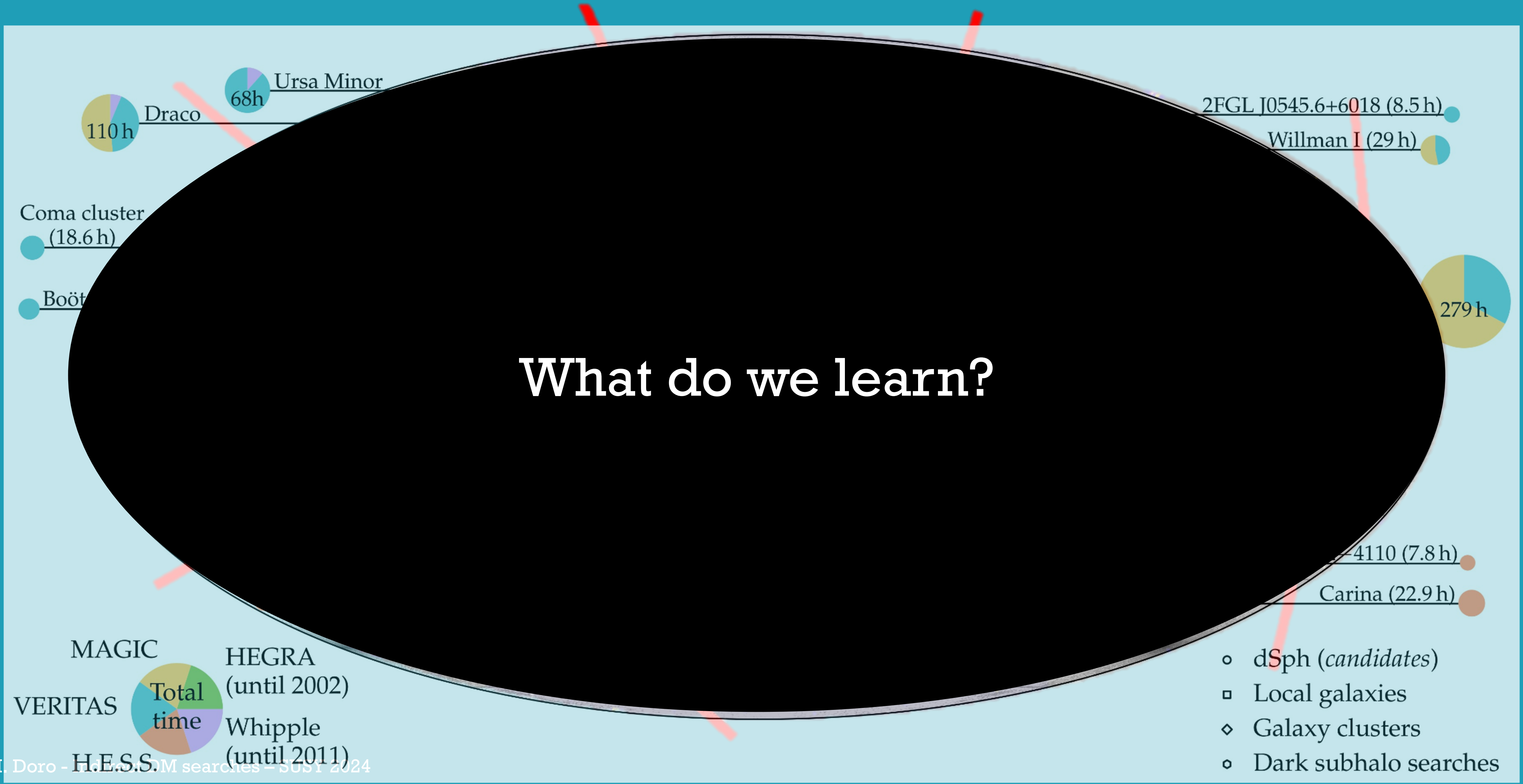


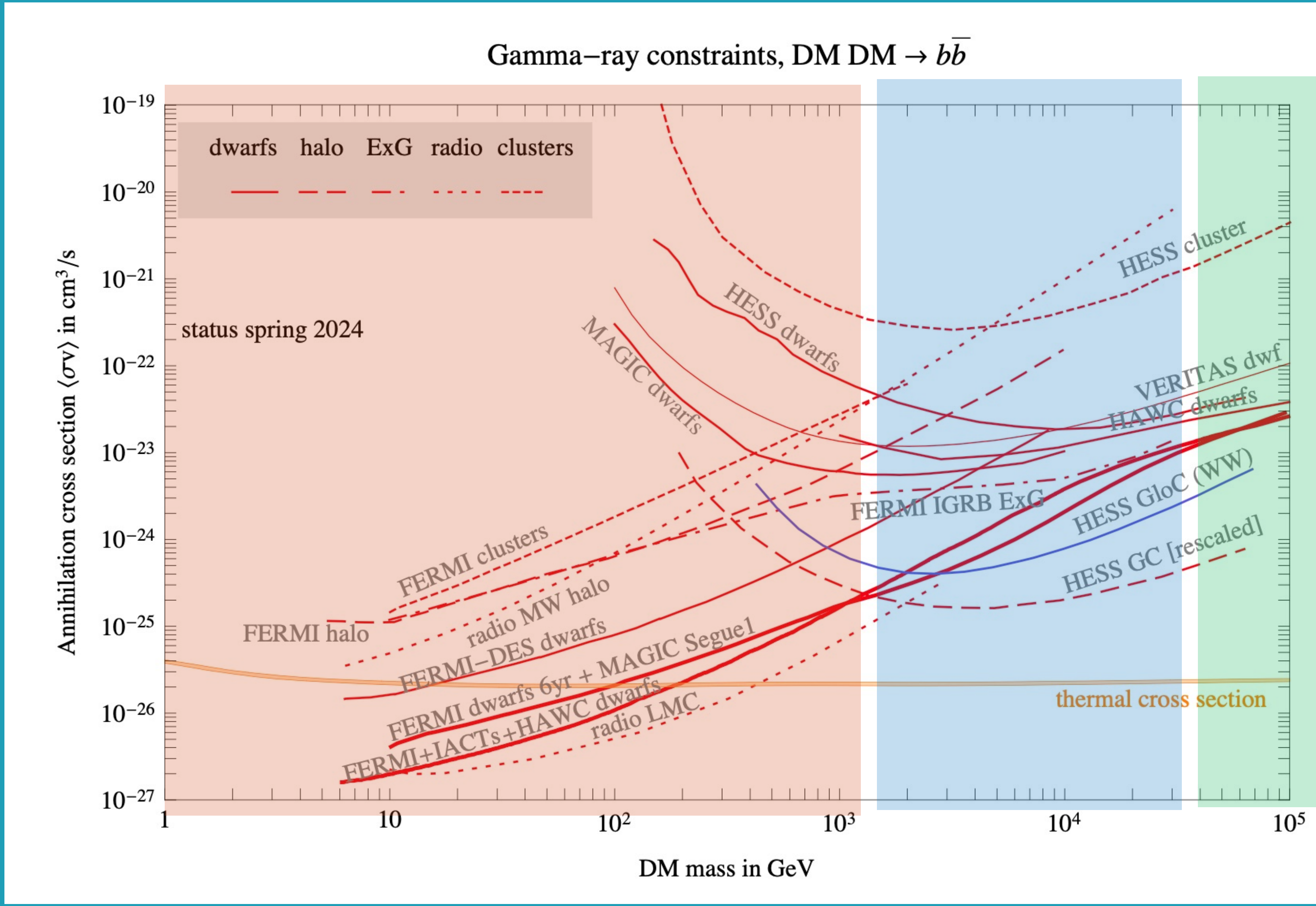
Figure 21. Sensitivity of CTA to a DM decay signal from the Perseus cluster, at 95% C.L., in terms

CLOSING REMARKS



What do we learn?

COMPLEMENTARITY. IN GAMMA-RAYS

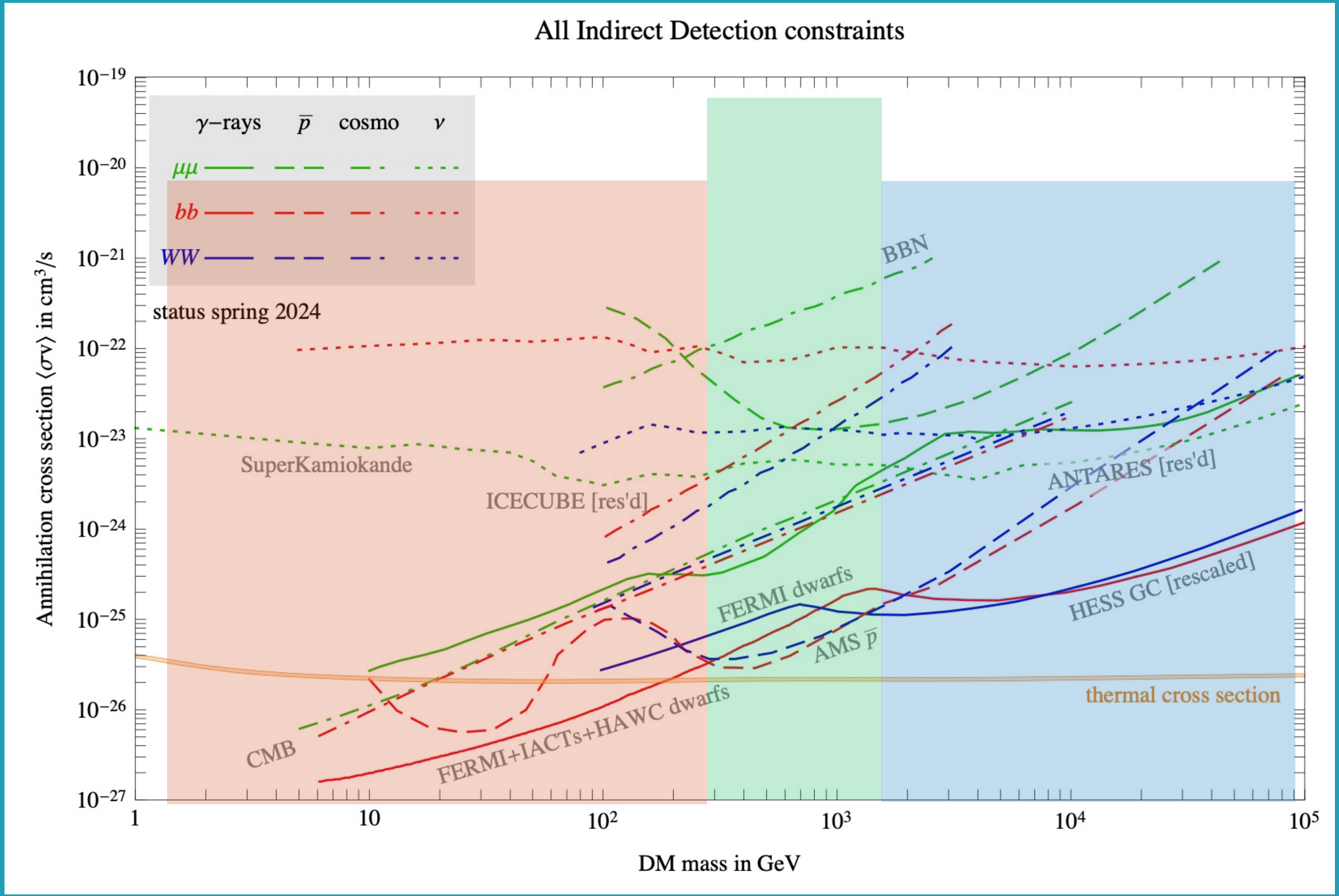


Satellites-borne experiment

Ground-Based Experiments

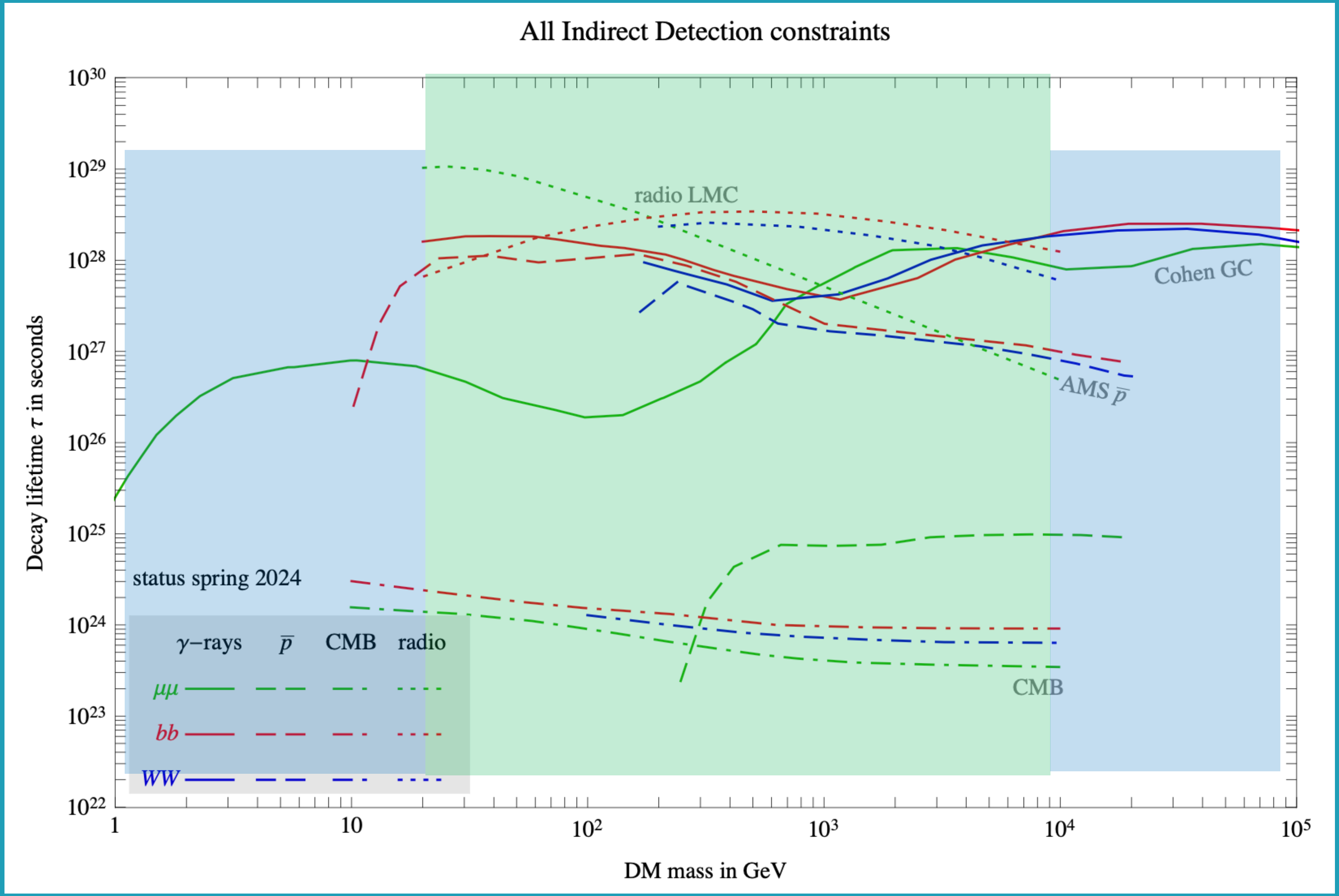
Shower Front Detectors

COMPLEMENTARY RADIATION/PARTICLES



Antiparticles

COMPLEMENTARITY IN WAVELENGHTS



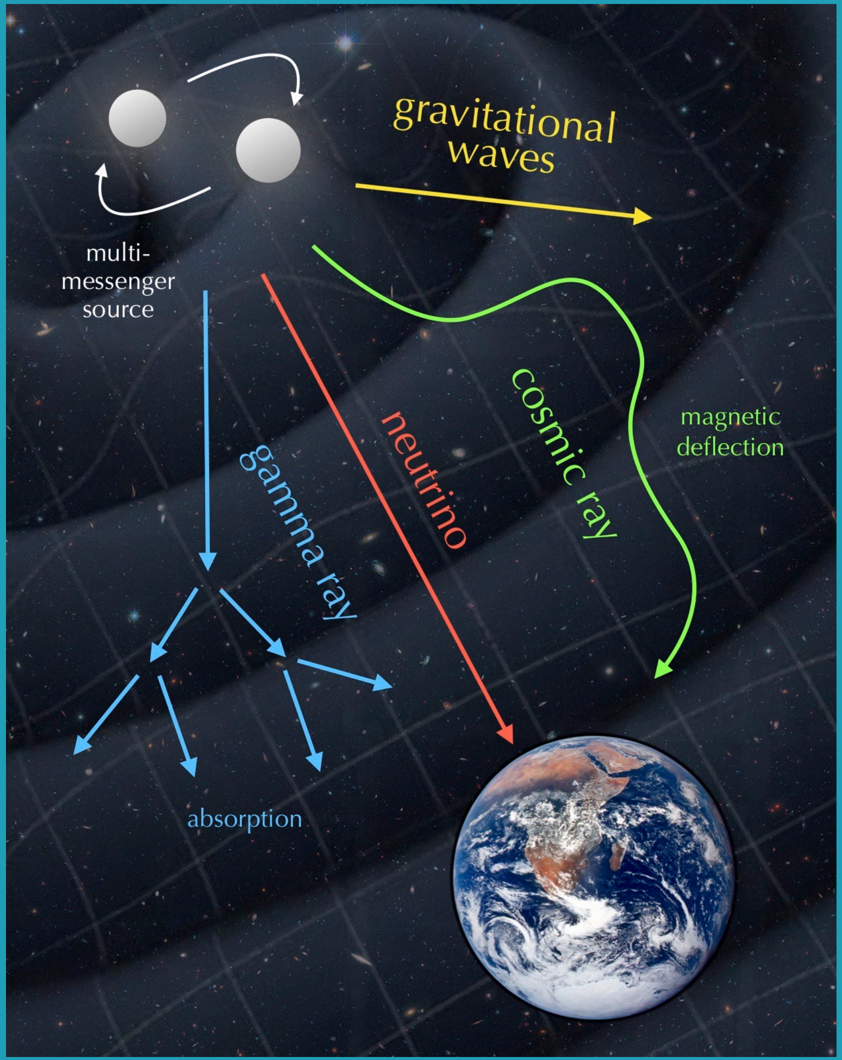
Gammas

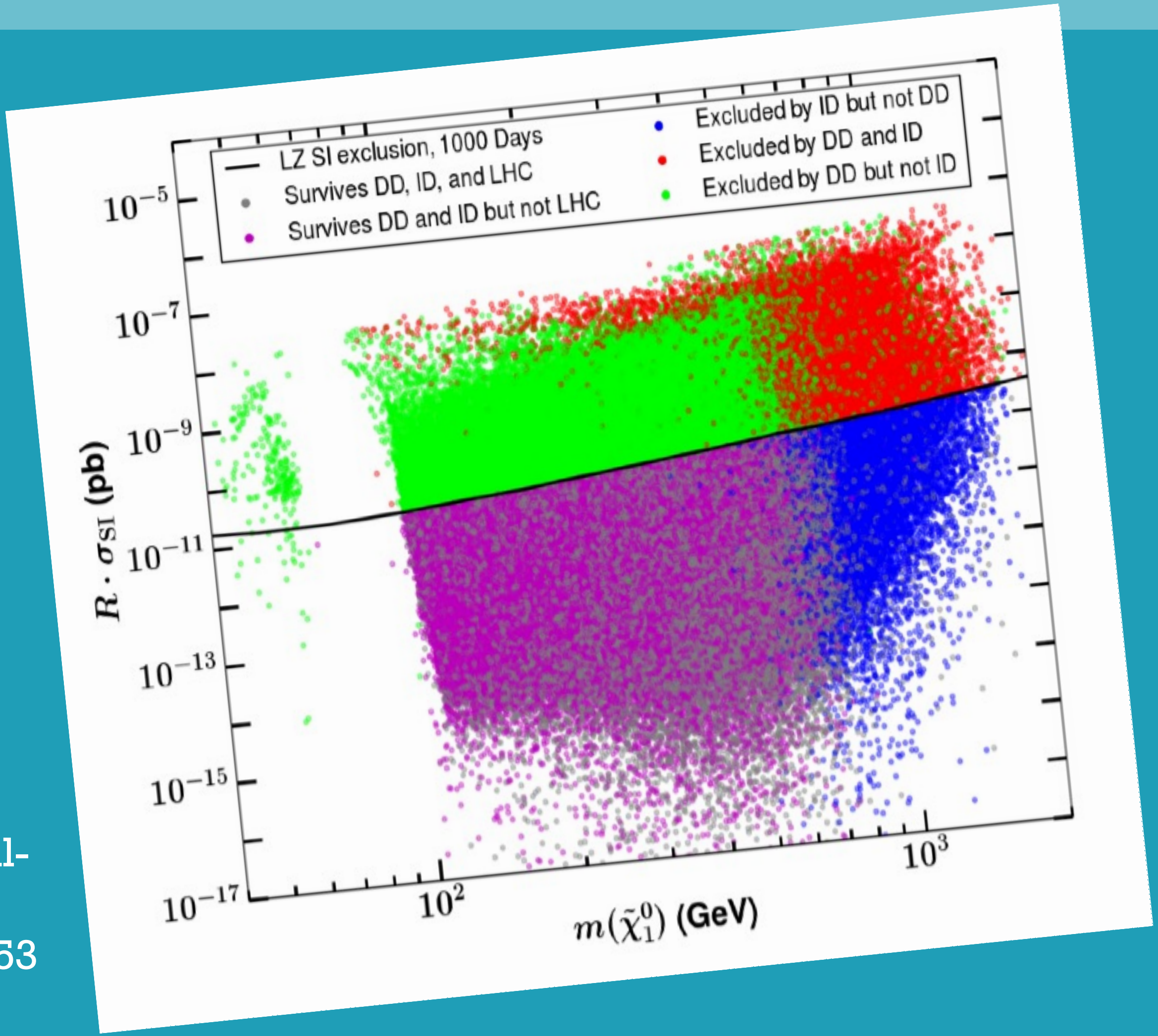
Radio

Gammas

CONSIDERATION #2 DM IS MULTI-MESSENGER

AND G-RAYS UNIQUE PROBES

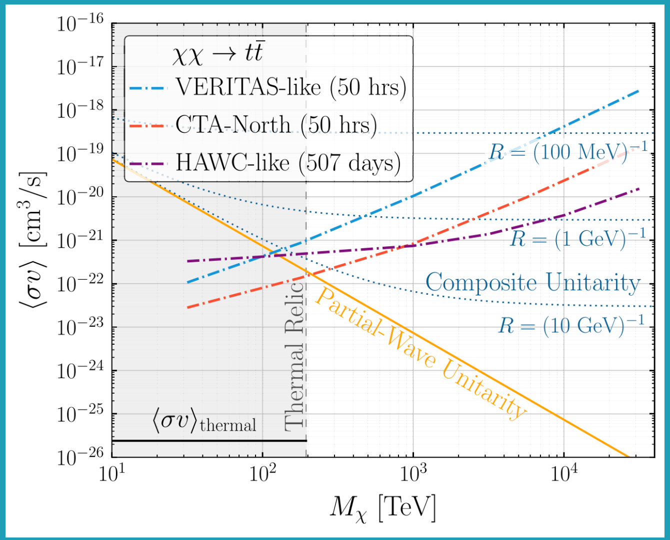




M. Cahill-Rawley 1411.3353

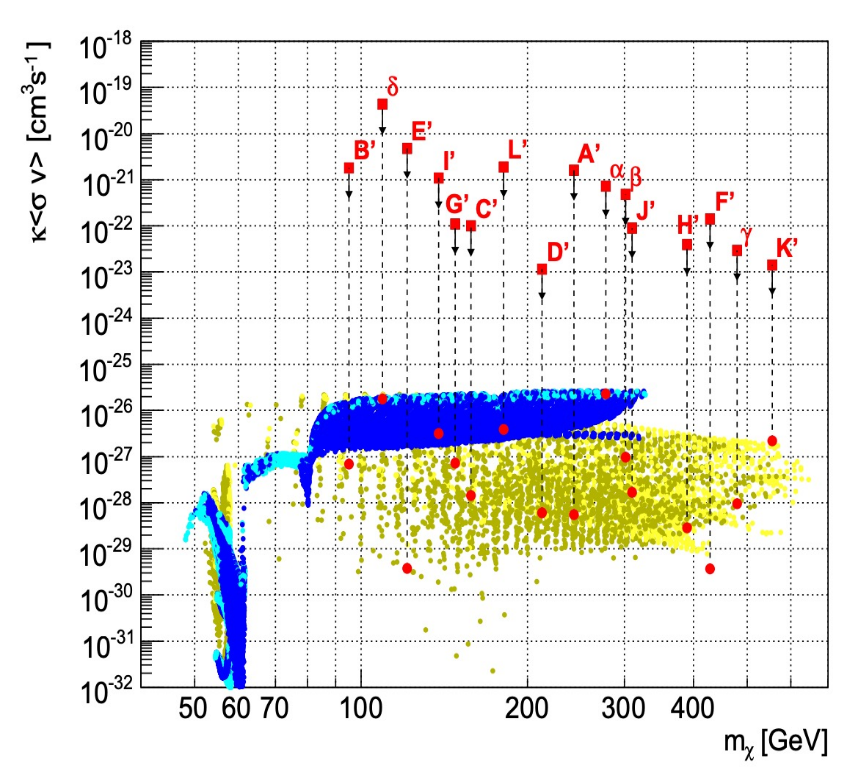
CONSIDERATION #3 ARE WE CLOSE OR FAR?

- From the astrophysical point of view: A coherent picture of astrophysical DM gives us yet the possibility to find a super-target, very DM dominated

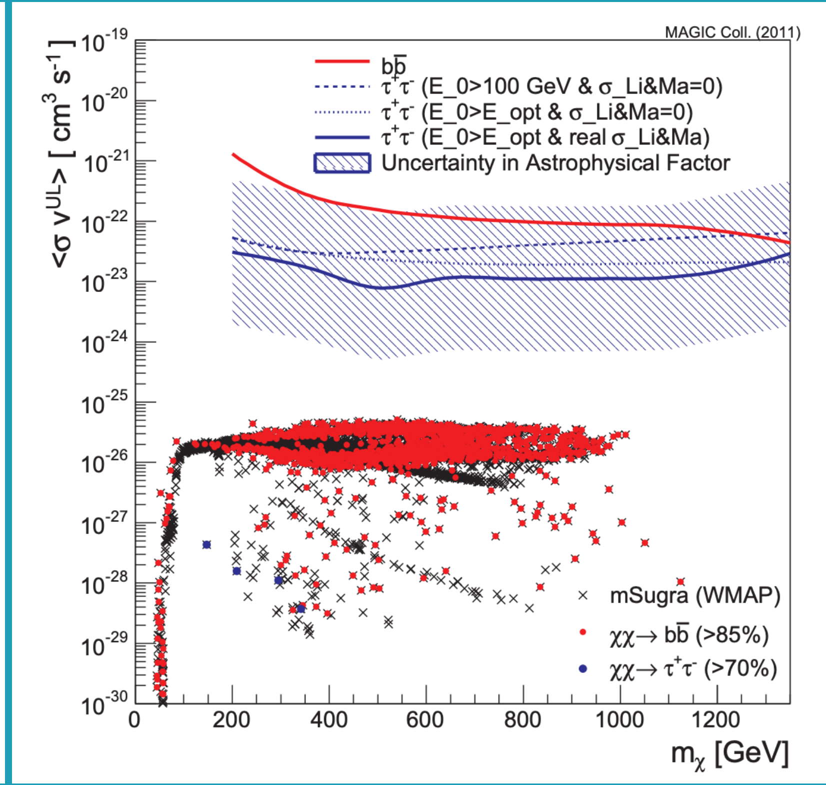


- From the particle physics point of view, gamma-rays are rather 'model independent' therefore any null result maybe a relevant limit

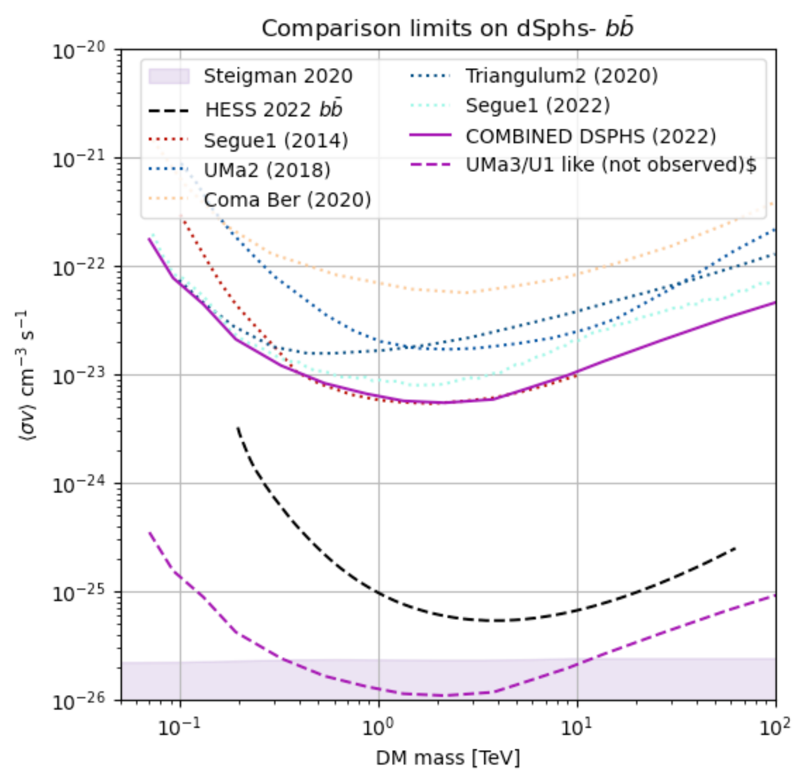
#3B. ARE WE PROBING ANY MODEL?



MAGIC 2009: benchmarks

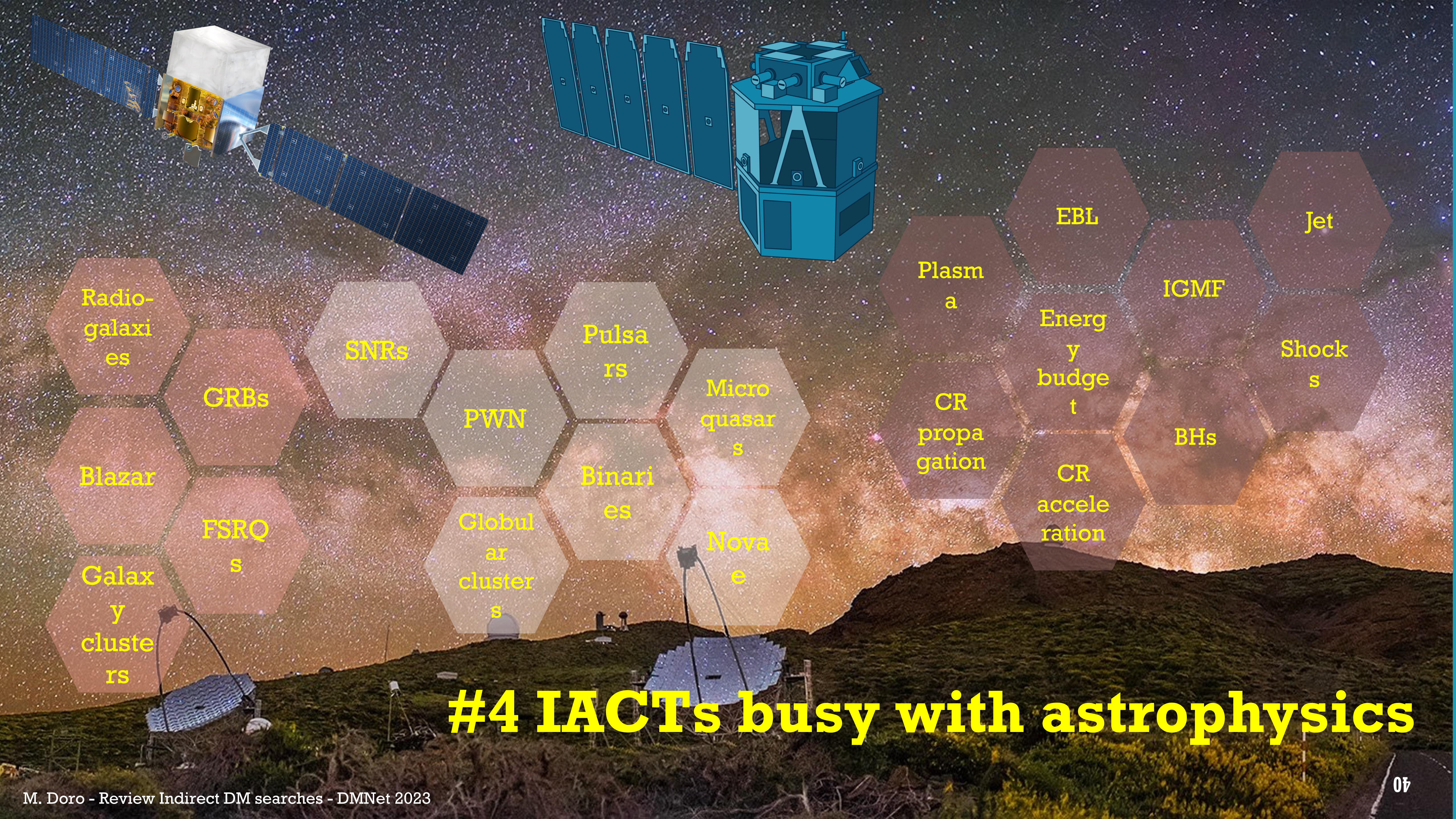


MAGIC 2011: scan

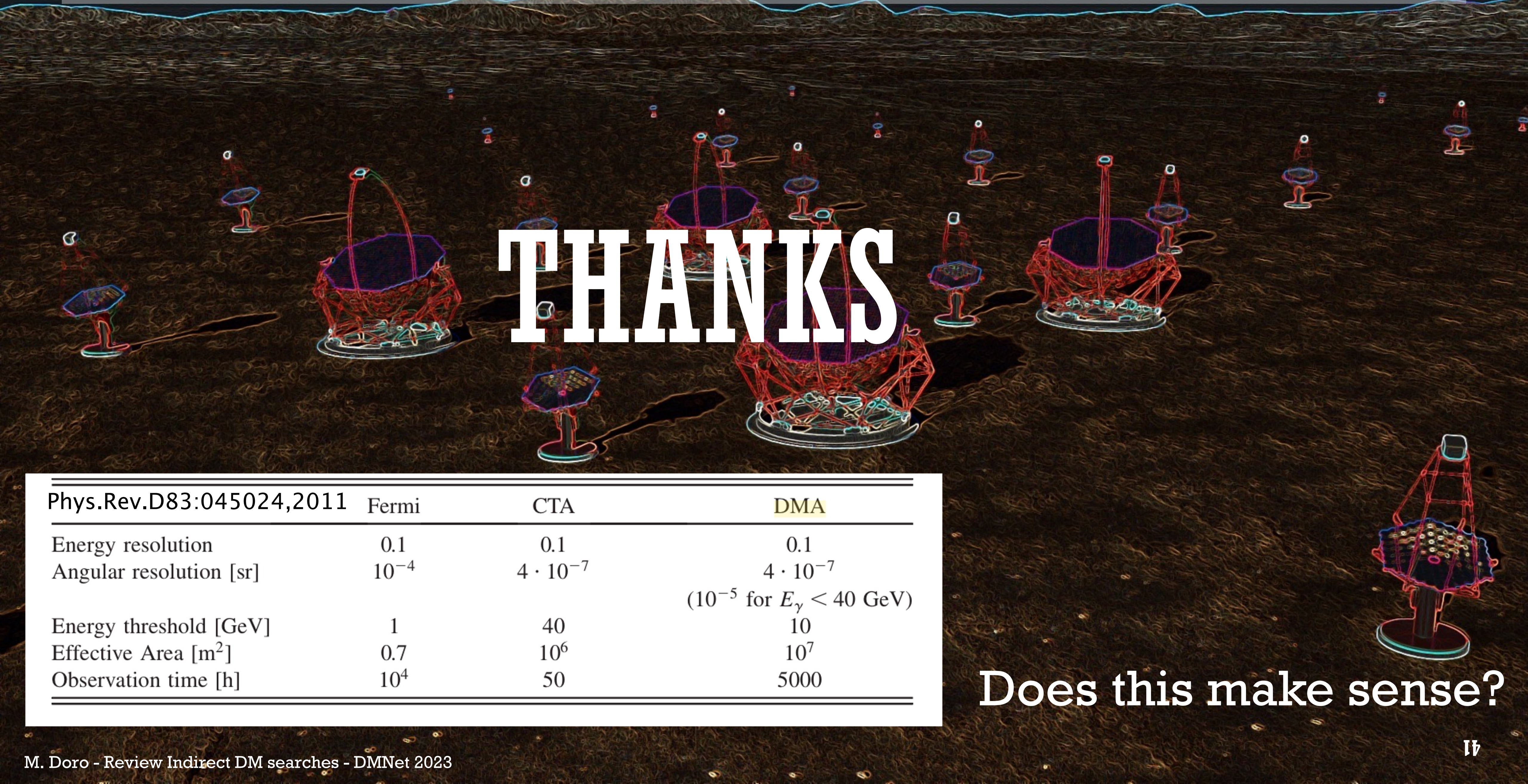


All>2012, just thermal value

Do we need to update our prediction on parameters spaces given certain DM models to check predicitivity?


Radio-galaxies
GRBs
Blazar
FSRQs
Galaxy clusters
SNRs
PWN
Globular clusters
Pulsars
Binaries
Microquasars
Novae
Plasma
EBL
CR propagation
Energy budget
CR acceleration
IGMF
BHs
Jet
Shocks
#4 IACTs busy with astrophysics

A DEDICATED DARK MATTER ARRAY?



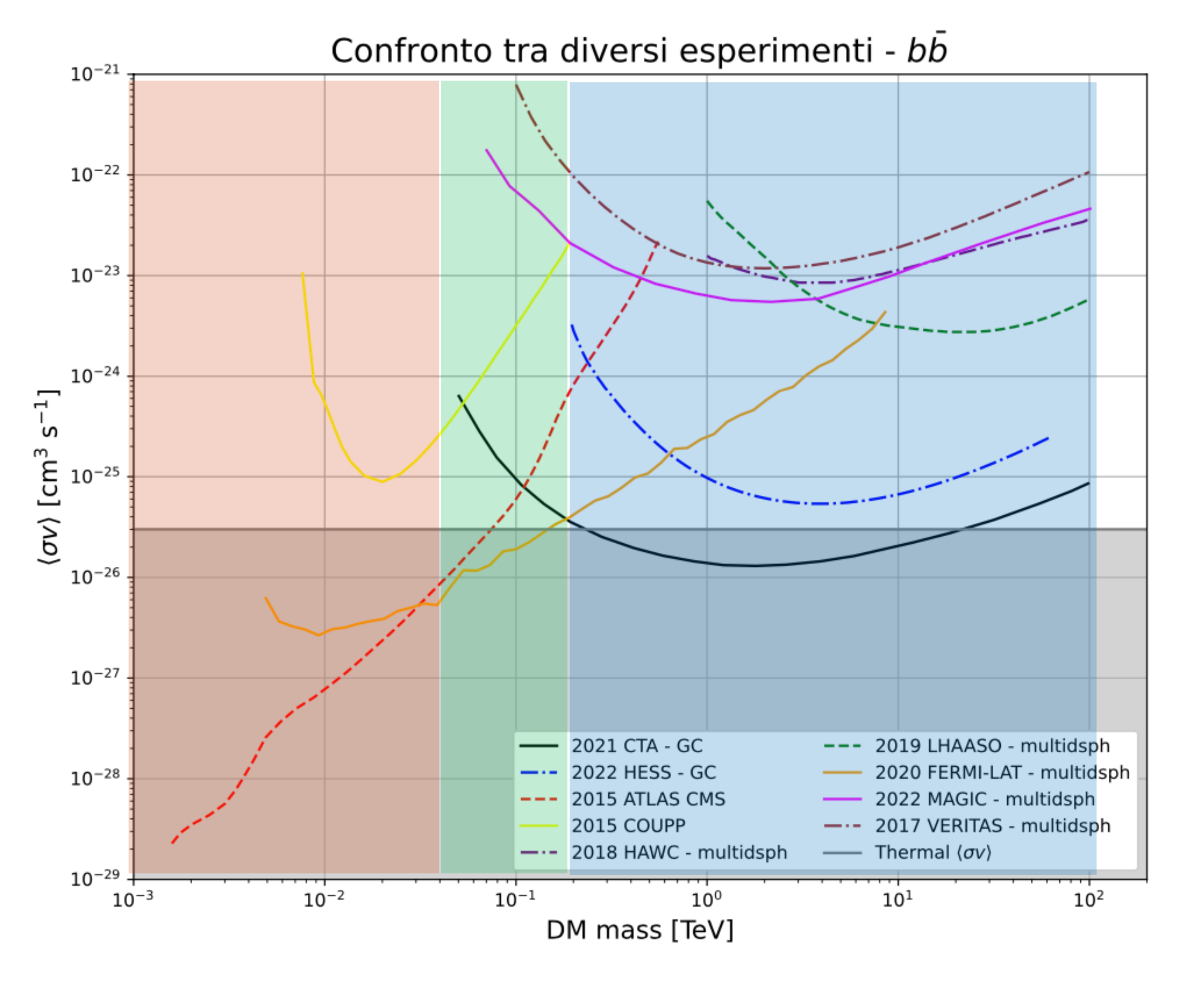
THANKS

Phys.Rev.D83:045024,2011	Fermi	CTA	DMA
Energy resolution	0.1	0.1	0.1
Angular resolution [sr]	10^{-4}	$4 \cdot 10^{-7}$	$4 \cdot 10^{-7}$ (10^{-5} for $E_\gamma < 40$ GeV)
Energy threshold [GeV]	1	40	10
Effective Area [m^2]	0.7	10^6	10^7
Observation time [h]	10^4	50	5000

Does this make sense?

BACKUPS

COMPILATION FOR DIFFERENT EXPERIMENTS



k-MeV DM (production, generation)

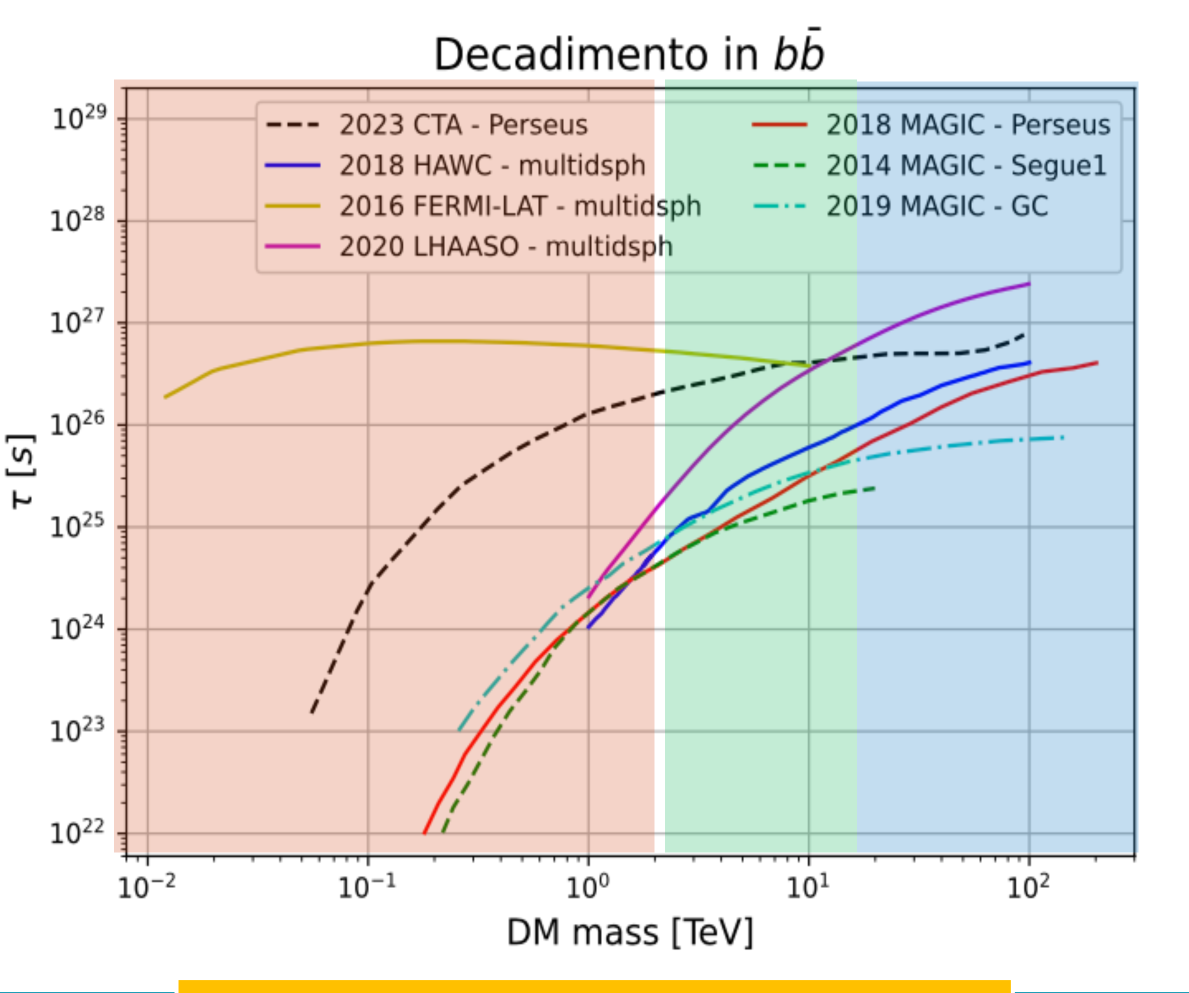
GeV DM (satellites) e.g. Fermi-LAT

TeV DM (ground-baed IACTs) e.g. MAGIC, HESS, VERITAS, CTA

100TeV DM (ground-based SFD) e.g. HAWC, LHAASO, SWGO

COMPILATION FOR TARGETS – DECAYING DM

GeV DM (satellites)
e.g. Fermi-LAT



100TeV DM (ground-based SFD)
e.g. HAWC, LHAASO, SWGO

TeV DM (ground-baed IACTs)
e.g. MAGIC, HESS, VERITAS, CTA

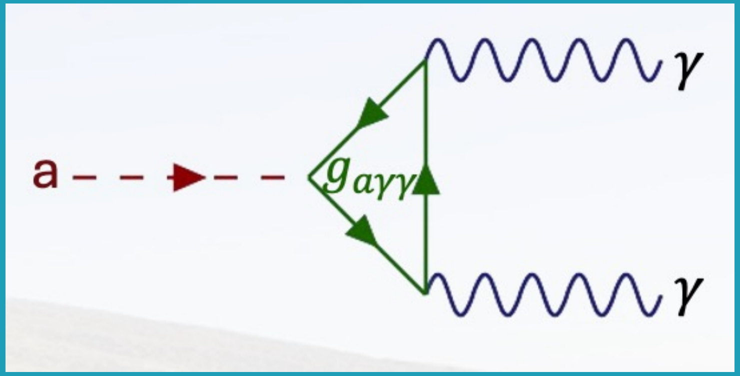
ALPS

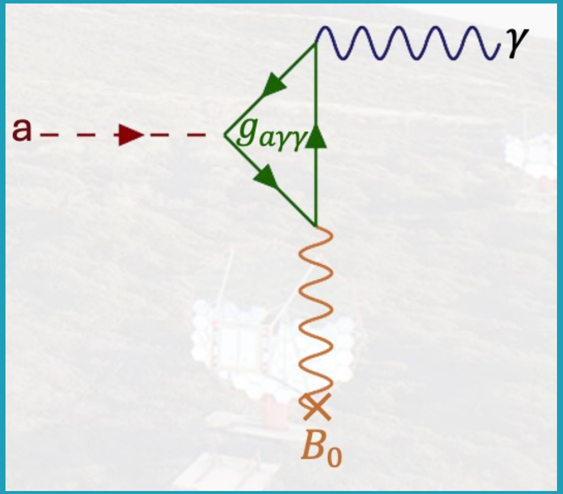
AXION AND AXION-LIKE PARTICLES

$$m_a \simeq 6 \times 10^{-6} \frac{10^{12}\text{GeV}}{f_a}$$

$$g_{a\gamma\gamma} < \left(\frac{m_a}{1\ \text{neV}}\right)^{\frac{1}{2}} \text{GeV}^{-1}$$

- Visible axion (eV), a new boson proposed by Peccei and Quinn (1977) to solve CP problem
- Axion-like particles (mass and coupling independent) more general, arise in many BSM theories, also explains (part of) DM





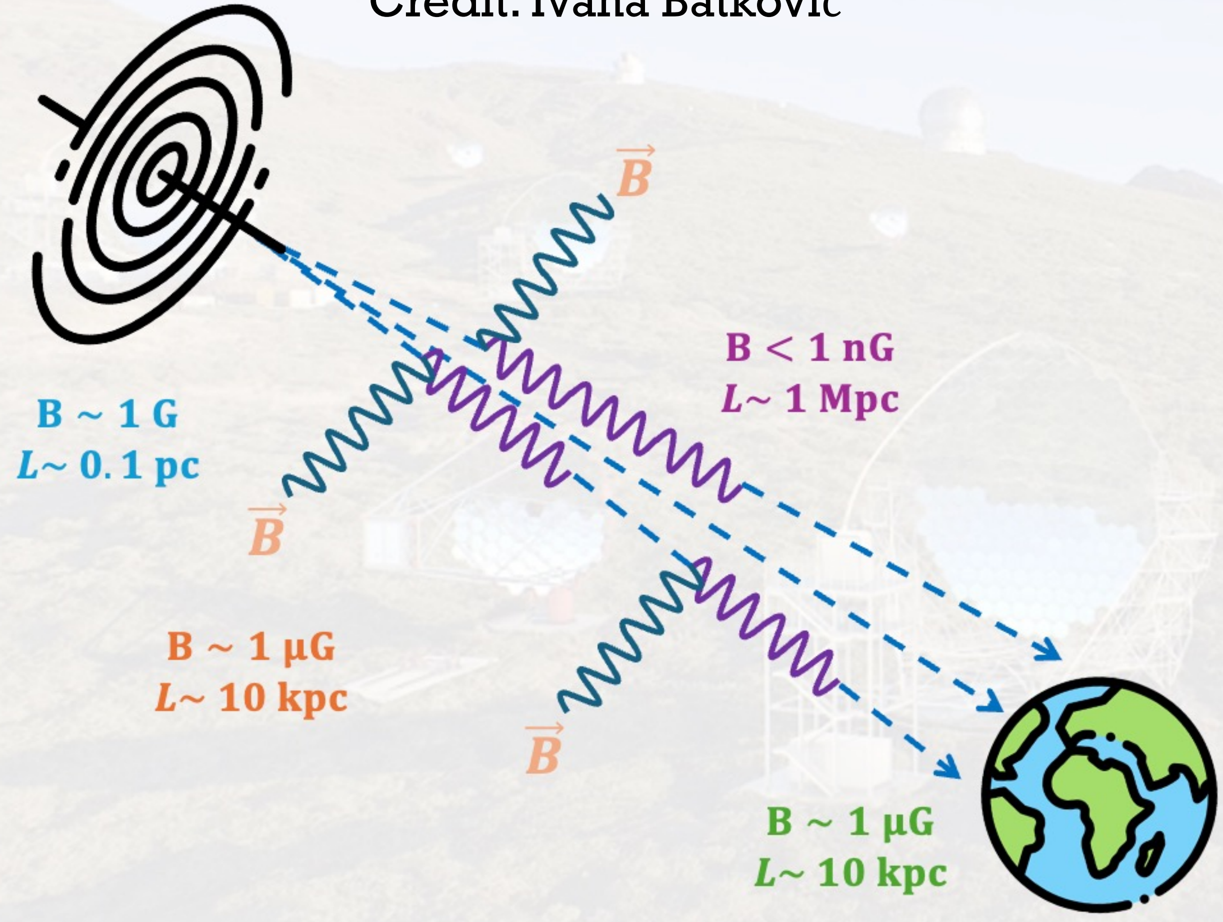
$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma\gamma} \vec{E} \cdot \vec{B} a$$

ALP-gamma-ray oscilllations in external B-field

$$\frac{d\Phi_{obs}}{dE} = \frac{d\Phi_{int}}{dE} \times P^{a,EBL}_{\gamma\gamma}(E_\gamma; m_a, g_{a\gamma}, B; z)$$

Observed flux · Intrinsic flux · Gamma-ray energy · Ambient magnetic field · Source's redshift

Credit: Ivana Batković



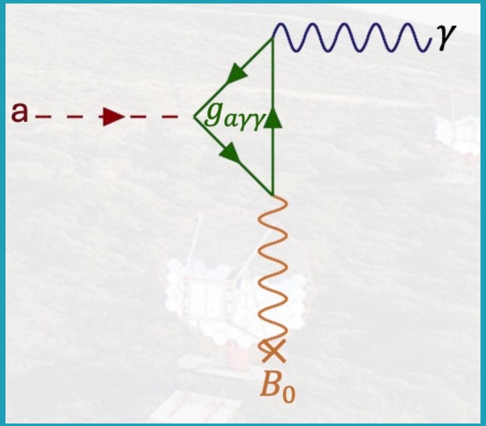
1. **Source and jet magnetic field**
   - ✧ Helical and tangled jet magnetic field model by Potter & Cotter

2. **Galaxy cluster magnetic field**
   - ✧ Negligible due to the much stronger field in the jet causing the mixing
   - ✧ Not observed for the source under scrutiny

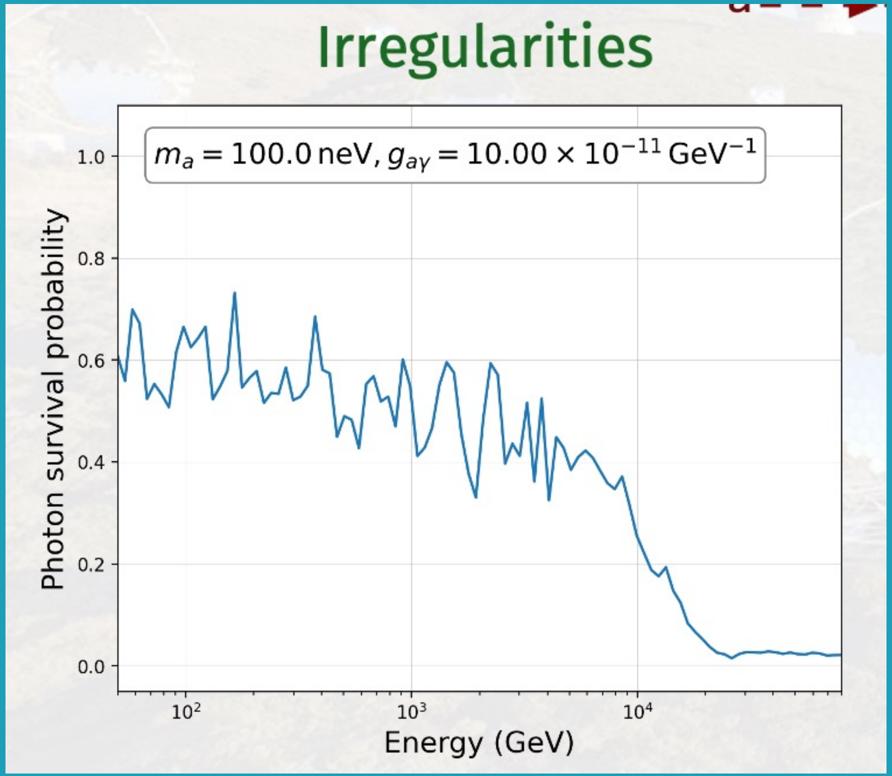
3. **Intergalactic magnetic field:**
   - ✧ Negligible mixing for the choice of ALPs parameters and the source, EBL only

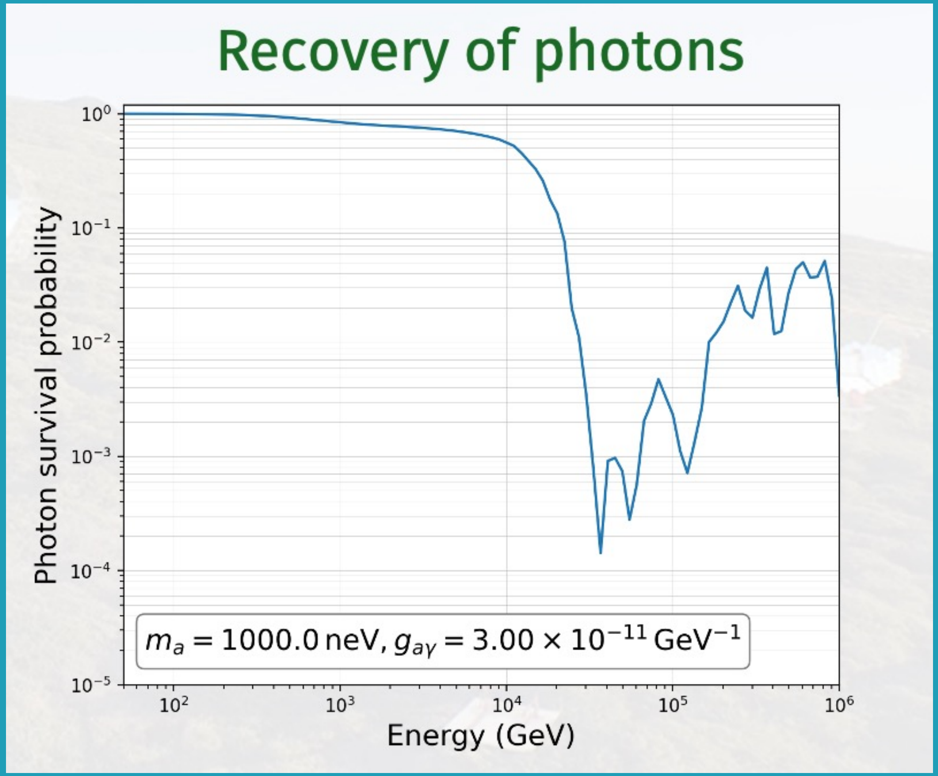
4. **Milky Way magnetic field:**
   - ✧ Modelled with a turbulent and regular component

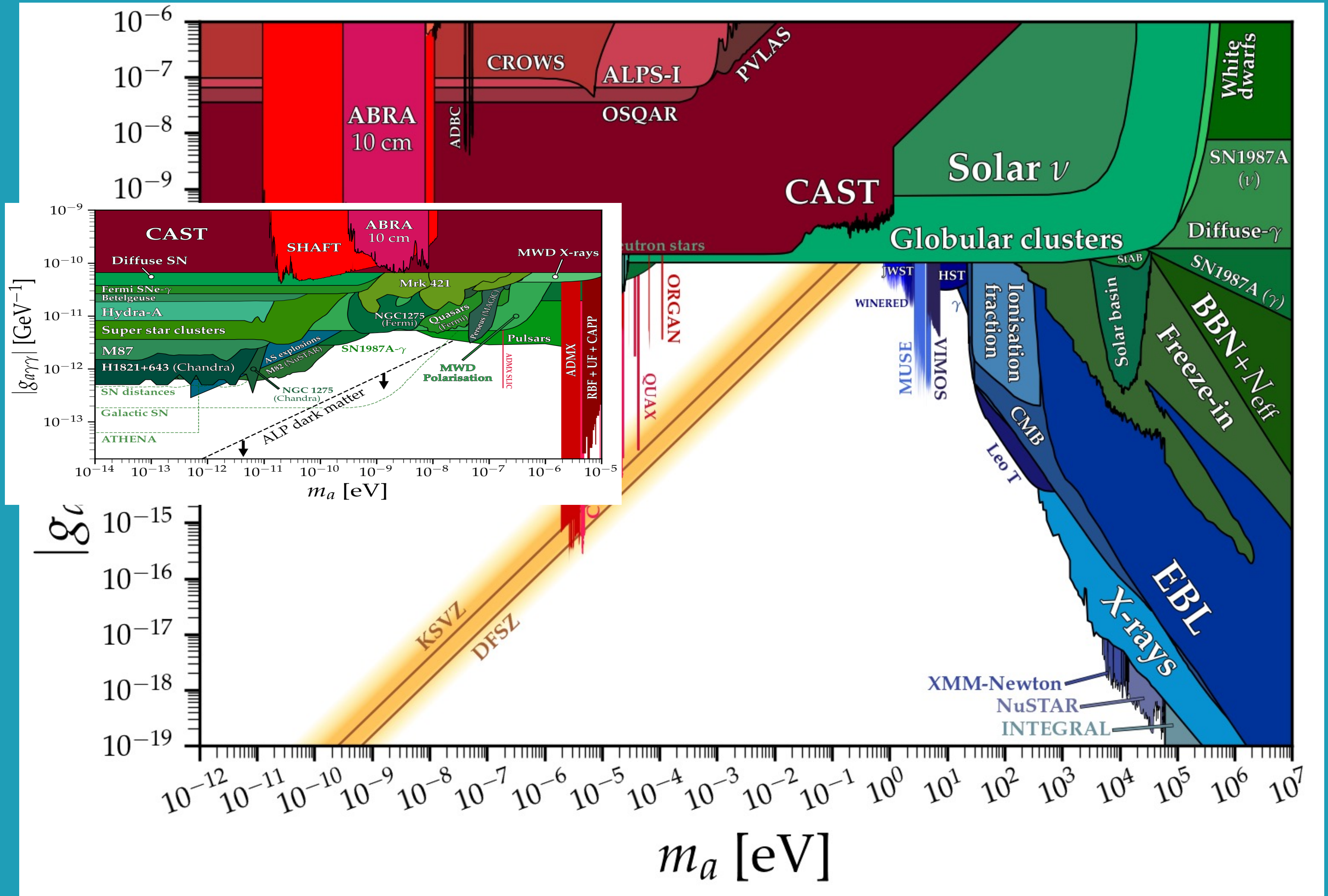
SPECTRAL WIGGLES AND PHOTON RECOVERY



$$E_{crit} = 2.5\ \text{GeV}\frac{\left|m^2_{a,\text{neV}} - \omega^2_{pl,\text{neV}}\right|}{G_{11} B_{\mu\text{G}}}$$






CROWS
ALPS-I
PVLAS
OSQAR
ABRA 10 cm
ADBC
CAST
Solar ν
Globular clusters
White dwarfs
SN1987A (ν)
Diffuse-γ
SN1987A (γ)
StAB
Solar basin
BBN+N_{eff}
Freeze-in
Neutron stars
ORGAN
QUAX
JWST
HST
WINERED
MUSE
VIMOS
Ionisation fraction
CMB
Leo T
EBL
X-rays
XMM-Newton
NuSTAR
INTEGRAL
KSVZ
DFSZ
m_a [eV]
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
CAST
SHAFT
ABRA 10 cm
MWD X-rays
Diffuse SN
Fermi SNe-γ
Betelgeuse
Mrk 421
Hydra-A
NGC1275 (Fermi)
Quasars (Fermi)
Perseus (MAGIC)
Super star clusters
Pulsars
M87
AS explosions
M82 (NuSTAR)
SN1987A-γ
H1821+643 (Chandra)
NGC 1275 (Chandra)
MWD Polarisation
ADMX SLIC
ADMX
RBF + UF + CAPP
SN distances
Galactic SN
ATHENA
ALP dark matter

WE (IACTS) LOOKED A LOT AROUND

Table 8.1 – continued from previous page

Target	Year	Time [h]	IACT	Limit	Ref.
Segue 1	2008 – 2009	29.4	MAGIC‡	Ann.	Aleksić et al. (2011)
	2010 – 2011	(47.8)	VERITAS	A.+D.	Aliu et al. (2012)
	2010 – 2013	(92.0)		Ann.	Archambault et al. (2017)
	2010 – 2013	157.9	MAGIC	A.+D.	Aleksić et al. (2014)
				Ann.	Ahnen et al. (2016b)
	2010 – 2018	184	VERITAS	–	Kelley-Hoskins (2018)
Boötes 1	2009	14.3	VERITAS	Ann.	Acciari et al. (2010)
		(14.0)		Ann.	Archambault et al. (2017)
Coma Berenices	2010 – 2013	(8.6)	H.E.S.S.	Ann.	Abramowski et al. (2014)
	2010 – 2013	10.9		Ann.	Abdalla et al. (2018a)
	< 2018	37	VERITAS	–	Kelley-Hoskins (2018)
	2018	50.2	MAGIC	Ann.	Maggio et al. (2021)
Fornax	2010	6.0	H.E.S.S.	Ann.	Abramowski et al. (2014)
				Ann.	Abdalla et al. (2018a)
Ursa Major II	2014 – 2016	94.8	MAGIC	Ann.	Ahnen et al. (2018a)
Triangulum II*	2014 – 2016	62.4	MAGIC	Ann.	Acciari et al. (2020)
	< 2018	181	VERITAS	–	Kelley-Hoskins (2018)
Segue II	< 2018	19	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven I	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven II	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Hercules	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Sextans	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Draco II	< 2018	10	VERITAS	–	Kelley-Hoskins (2018)
Leo I	< 2018	7	VERITAS	–	Kelley-Hoskins (2018)
Leo II	< 2018	16	VERITAS	–	Kelley-Hoskins (2018)
Leo IV	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Leo V	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Reticulum II	2017 – 2018	18.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana II	2017 – 2018	16.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana III*	2017 – 2018	23.6	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana IV*	2017 – 2018	12.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Grus II*	2018	11.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Dark satellites					
1FGL J2347.3+0710	2010	8.3	MAGIC	–	Nieto et al. (2011a)
1FGL J0338.8+1313	2010-2011	10.7	MAGIC	–	Nieto et al. (2011a)
2FGL J0545.6+6018	2013-2015	8.5	VERITAS	Ann.	Nieto (2015)
2FGL J1115.0-0701	2013-2015	13.8	VERITAS	Ann.	Nieto (2015)
H3FHL J0929.2-4110	2018-2019	7.8	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J1915.2-1323	2018 – 2019	3.0	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J2030.2-5037	2018 – 2019	8.8	H.E.S.S.†	Ann.	Abdallah et al. (2021a)
3FHL J2104.5+2117	2018 – 2019	5.5	H.E.S.S.†	Ann.	Abdallah et al. (2021a)

Table 8.1 – Continued on next page

Target	Year	Time [h]	IACT	Limit	Ref.
The Milky Way central region & halo					
MW Centre	2004	(48.7)	H.E.S.S.	Ann.	Aharonian et al. (2006)
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2010	9.1		Ann.	Abramowski et al. (2015)
	2004 – 2014	254		Ann.	Abdallah et al. (2016)
	2014 – 2020	546	H.E.S.S.†	Ann.	Montanari et al. (2021)
MW Outer Halo	2018	10	MAGIC	Decay	Ninci et al. (2019)
Dwarf Satellite Galaxies					
Draco	2003	7.4	Whipple	Ann.	Wood et al. (2008)
	2007	7.8	MAGIC‡	Ann.	Albert et al. (2008b)
	2007	(18.4)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(49.8)		Ann.	Archambault et al. (2017)
	2007 – 2018	114		–	Kelley-Hoskins (2018)
	2018	52.6	MAGIC	Ann.	Maggio et al. (2021)
Ursa Minor	2003	7.9	Whipple	Ann.	Wood et al. (2008)
	2007	(18.9)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(60.4)		Ann.	Archambault et al. (2017)
	2007 – 2018	161		–	Kelley-Hoskins (2018)
Sagittarius	2006	(11.0)	H.E.S.S.	Ann.	Aharonian et al. (2008)
	2006 – 2012	90		Ann.	Abramowski et al. (2014)
	2006 – 2012	(85.5)		Ann.	Abdalla et al. (2018a)
Canis Major	2006	9.6	H.E.S.S.	Ann.	Aharonian et al. (2009a)
Willman 1	2007 – 2008	13.7	VERITAS	Ann.	Acciari et al. (2010)
		(13.6)		Ann.	Archambault et al. (2017)
	2008	15.5	MAGIC‡	Ann.	Aliu et al. (2009)
Sculptor	2008	(11.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
				Ann.	Abdalla et al. (2018a)
	2008 – 2009	12.5		Ann.	Abramowski et al. (2014)
Carina	2008 – 2009	(14.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2008 – 2009	(12.7)		Ann.	Abramowski et al. (2014)
	2008 – 2010	22.9		Ann.	Abdalla et al. (2018a)

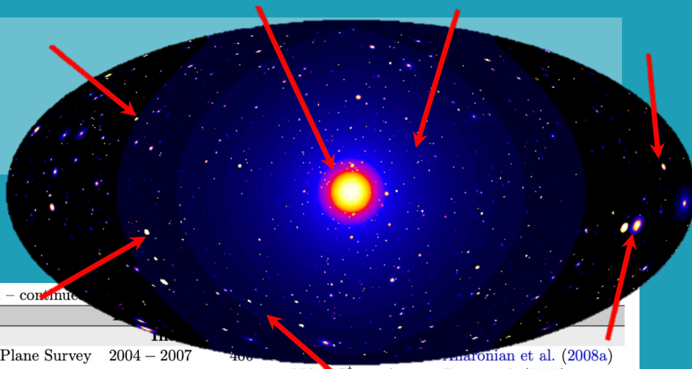


Table 8.1 – continue[illegible]

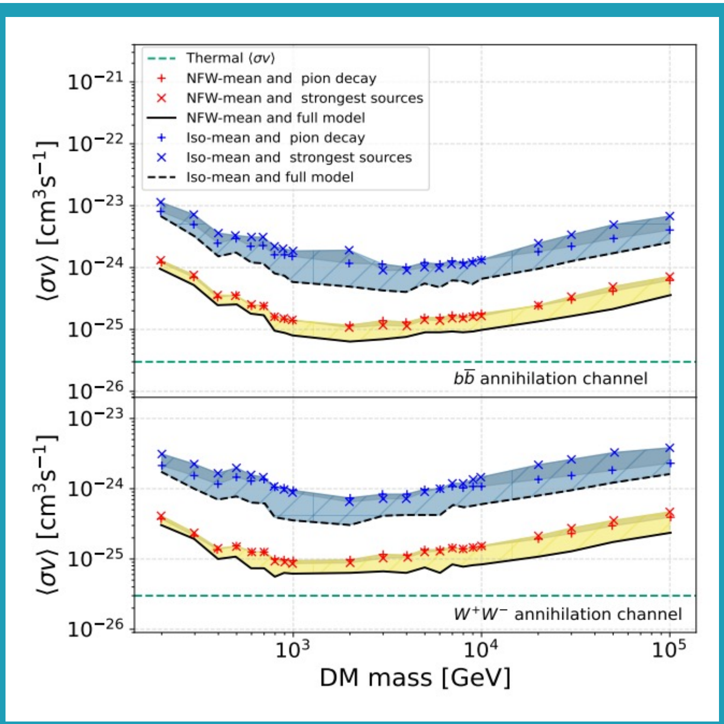
Target	Year	Time [h]	IACT	Limit	Ref.
[illegible]					
Galactic Plane Survey	2004 – 2007	[illegible]	[illegible]	[illegible]	Aharonian et al. (2008a)
	2005 – 2006	25	MAGIC‡	Ann.	Doro et al. (2007)
Globular Clusters					
M15	2002	0.2	Whipple	Ann.	Wood et al. (2008)
	2006 – 2007	15.2	H.E.S.S.	Ann.	Abramowski et al. (2011)
NGC 6388	2008 – 2009	27.2	H.E.S.S.	Ann.	Abramowski et al. (2011)
Other galaxies					
M33	2002 – 2004	7.9	Whipple	Ann.	Wood et al. (2008)
M32	2004	6.9	Whipple	Ann.	Wood et al. (2008)
WLM	2018	18.2	H.E.S.S.†	Ann.	Abdallah et al. (2021b)
Galaxy Clusters					
Abell 2029	2003 – 2004	6.1	Whipple	–	Perkins et al. (2006)
Perseus (Abell 426)	2004 – 2005	13.5	Whipple	–	Perkins et al. (2006)
	2008	24.4	MAGIC‡	Ann.	Aleksić et al. (2010)
	2009 – 2017	202.2	MAGIC	Decay	Acciari et al. (2018)
Fornax (Abell S0373)	2005	14.5	H.E.S.S.	Ann.	Abramowski et al. (2012)
Coma (Abell 1656)	2008	18.6	VERITAS	Ann.	Arlen et al. (2012)
Line searches					
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2013c)
	2014	15.2	H.E.S.S.†	Ann.	Abdalla et al. (2016)
	2004 – 2014	(254)	H.E.S.S.	Ann.	Abdalla et al. (2018b)
	2013 – 2019	204	MAGIC	Ann.	Inada et al. (2021)
Segue 1 dSph	2010 – 2013	(157.9)	MAGIC	A.+D.	Aleksić et al. (2014)
Five dSph galaxies	2006 – 2012	(137.1)	H.E.S.S.	Ann.	Abdalla et al. (2018a)
Five dSph galaxies	2007 – 2013	(229.8)	VERITAS	Ann.	Archambault et al. (2017)
WLM	2018	(18.2)	H.E.S.S.†	Ann.	Abdallah et al. (2021b)
Charged particles					
All-electron	2004 – 2007	239	H.E.S.S.	–	Aharonian et al. (2008b, 2009b)
	2009 – 2012	296	VERITAS	–	Archer et al. (2018)
	2009 – 2010	14	MAGIC	–	Borla Tridon et al. (2011)
Moon shadow	2010 – 2011	20	MAGIC	–	Colin et al. (2011)
	2014	1.2	VERITAS	–	Bird et al. (2016)

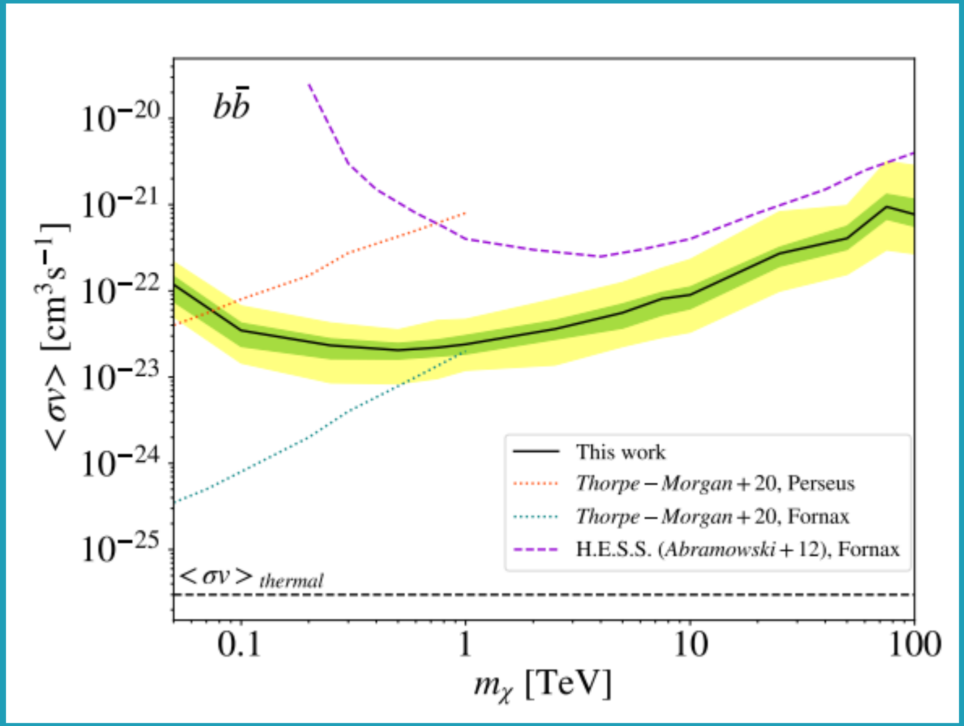
MD, M.A. Sanchez-Conde, M. Huetten.
https://arxiv.org/abs/2111.01198

#3.4 LARGE MAGELLANIC CLOUDS

A galaxy disrupted of its outer rims
by the crossing in the MW.
DM core believed intact.

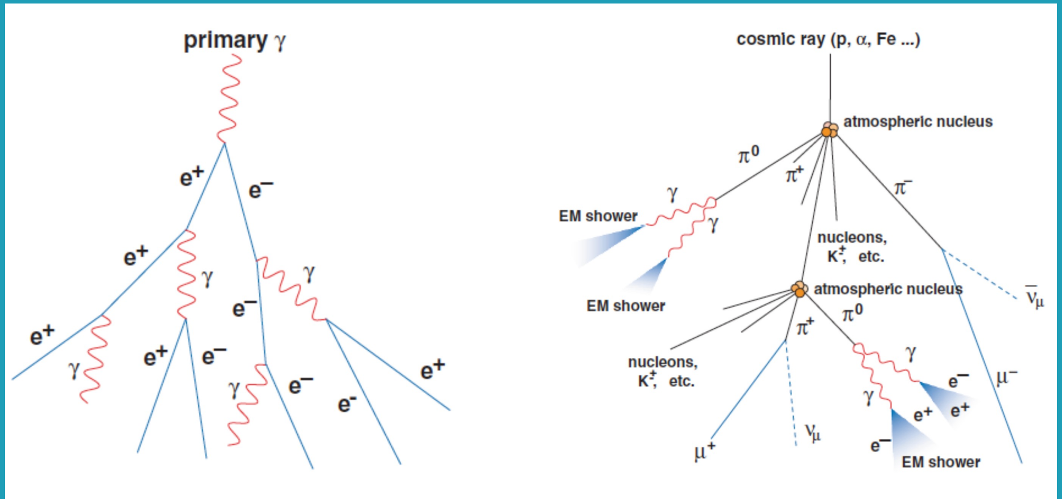
CTAO Mon.Not.Roy.Astron.Soc. 523 (2023) 4

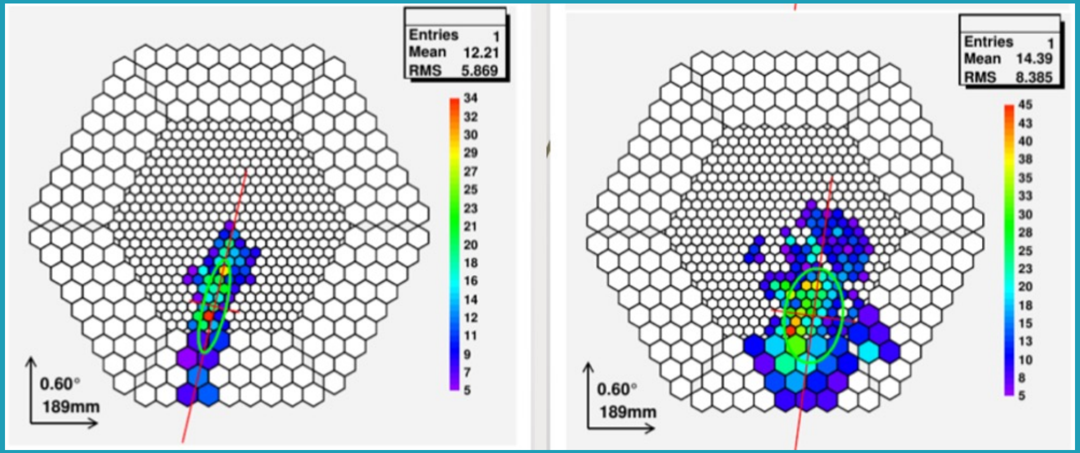


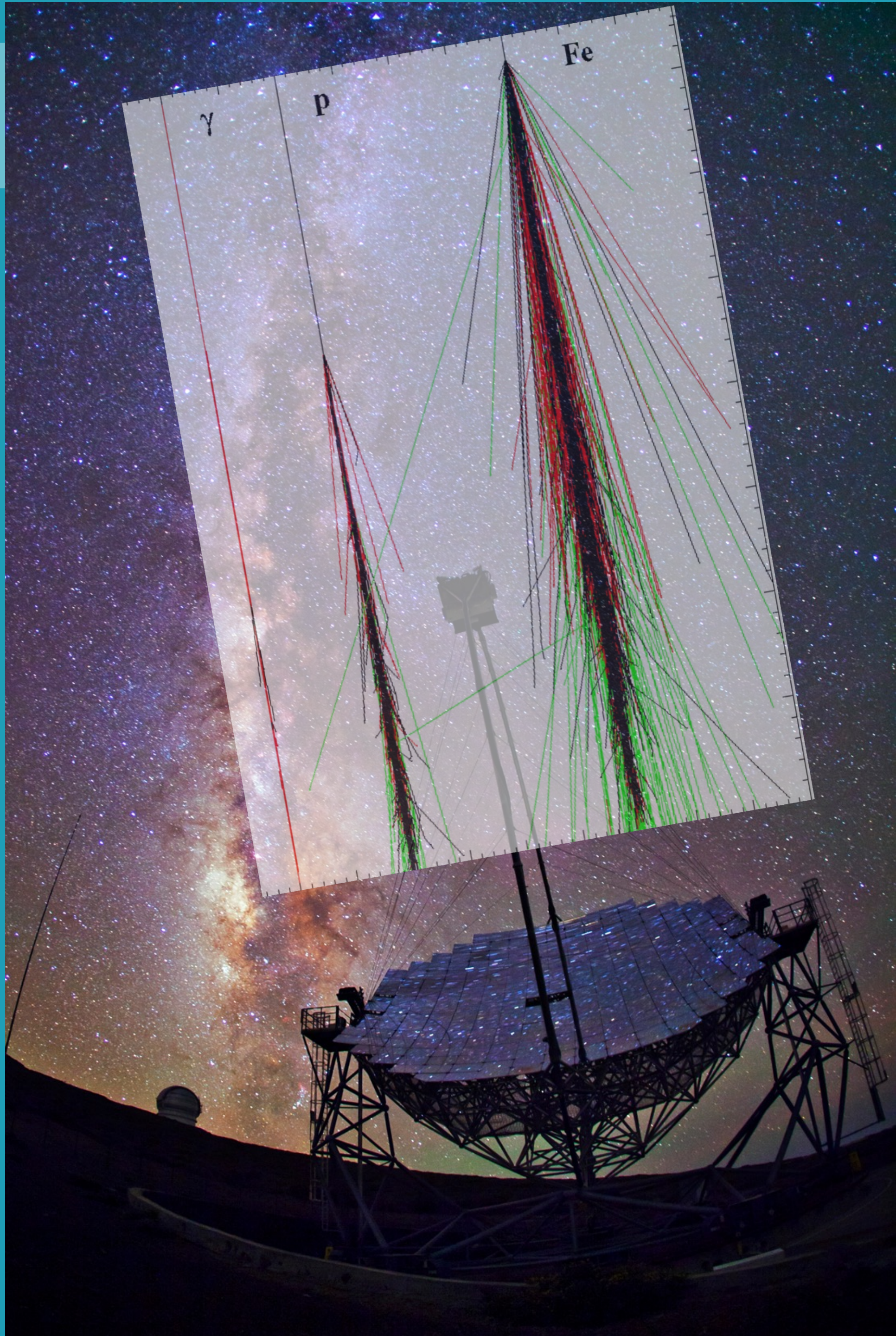


FOCUS

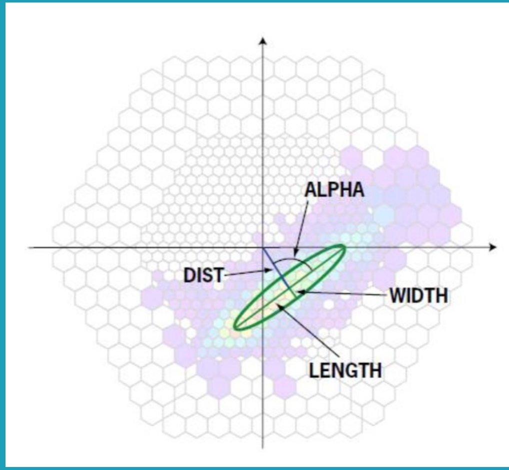
~1 gamma / 1000 protons.







EVENT TAGGING

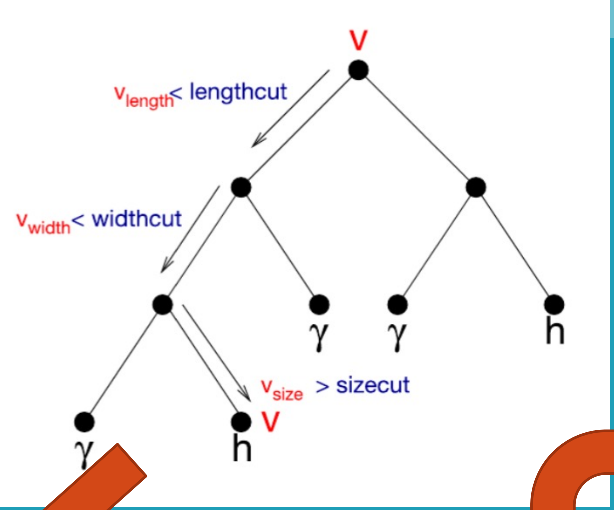


1

You "clean the image and extract shape parameters

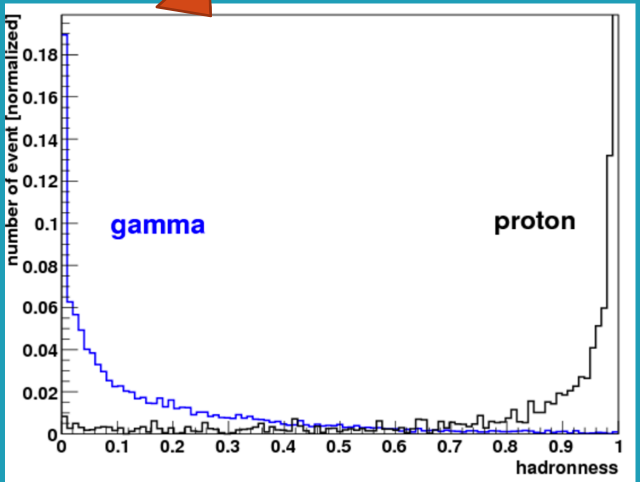
2

You make a classification by comparing with Monte Carlo



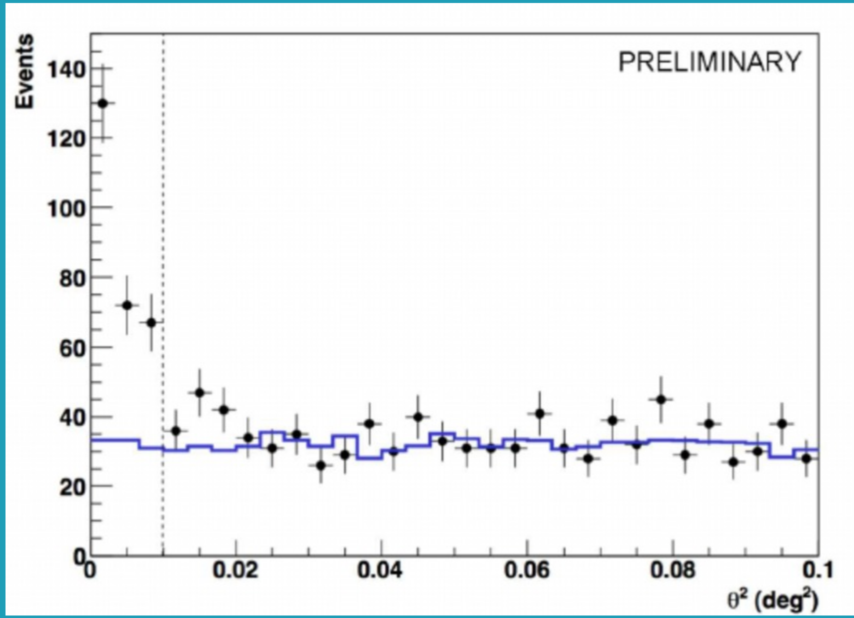
3

Cuts



4

Detection = significant number of excess events over background from region of interest



#3.7 MORE?

	GC / GCH	MW halo	Dwarfs	Clusters	Cosmological	other
DM annihilation: γ-ray searches						
continuum	Hess [532–535] (Fermi [545])	Fermi [536] Hawc [546, 547]	Magic [537–539] Hess [548, 549] Fermi [551] Fermi+Magic [554] Fermi-Des [555] Hawc [557] Veritas [558] Fermi+IActs+ +Hawc [559] McDaniel et al. [560]	Fermi [540–542] Hess [550] Veritas [552]	Fermi [543]	Fermi [544] (dark satellites) Hess [553] (GloCs) Veritas [556] (subhalos)
lines	Hess [561, 562]	Fermi [563]	Magic [537] Hess [549, 565] Veritas [558] Hawc [566]	Fermi [542, 564]		
DM annihilation: neutrino searches						
continuum	Antares [567–569] IceCube [574, 575] SuperK [578, 579] Baikal [580] Antares+ IceCube [581] Antares (heavy/ secluded DM) [582]	IceCube [570–572] Antares [576]	IceCube [573] Baikal [577]	IceCube [573]		
lines	Antares [569, 576] IceCube [574, 575] SuperK [578, 579] Baikal [580]	IceCube [570–572]	IceCube [573] Baikal [577]			
DM decay: γ-ray searches						
continuum	Cohen et al. [583] Esmaili et al. [587]	Fermi [536] Hawc [546, 547]	Veritas [584] Magic [537] Hawc [589]	Fermi [585] Magic [588] Hawc [590]	Cirelli et al. [586]	
lines		Fermi [563]	Magic [537]			