Universidad Autónoma de Madrid

Instituto de Física Teórica UAM-CSIC

MULTIDARK
Multimessenger Approach for Dark Matter Detection

TAE 2024

GAMMA-RAY ASTROPHYSICS

[BRIEF INTRODUCTORY COURSE]

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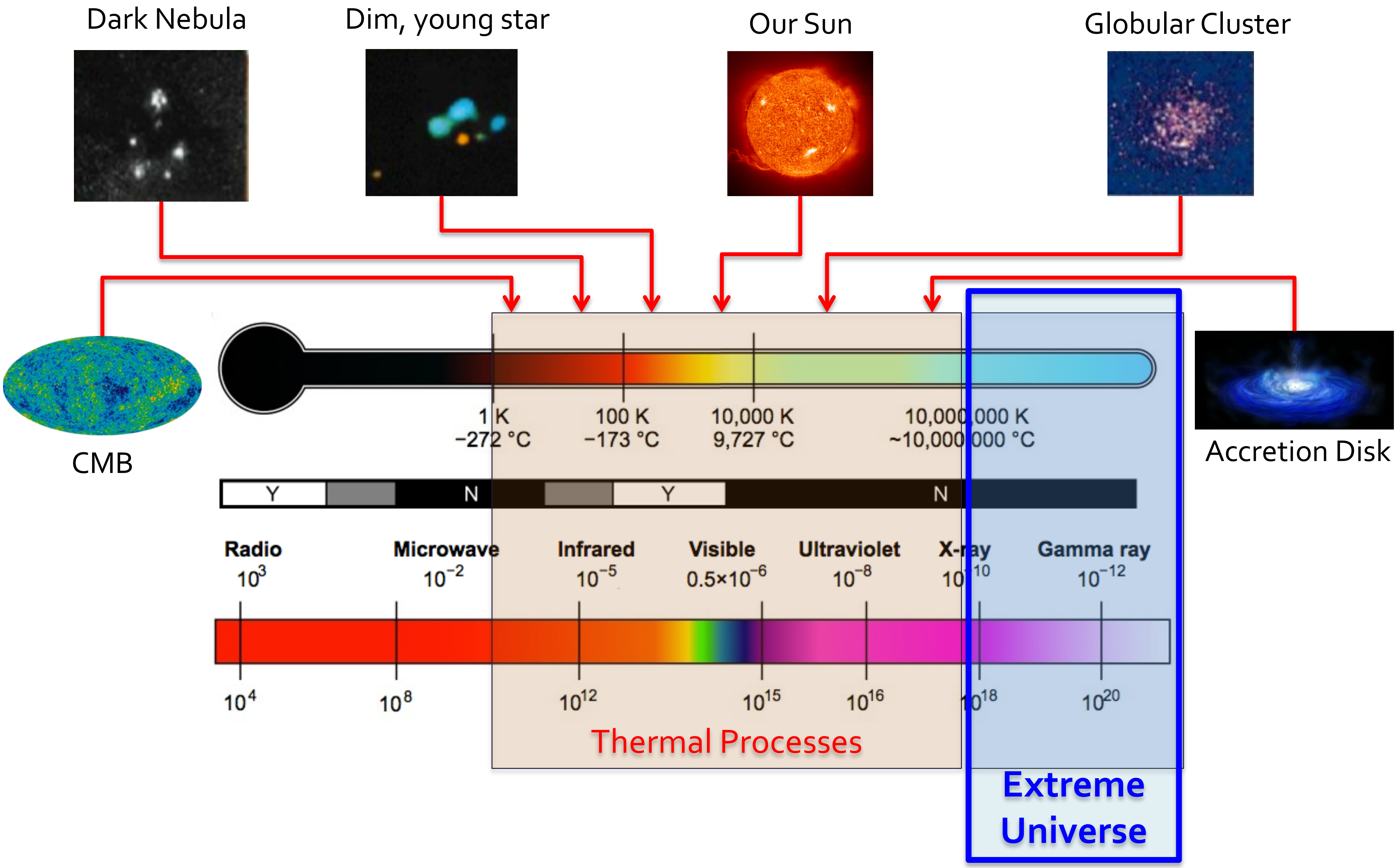
TAE2024 – International workshop on high energy physics

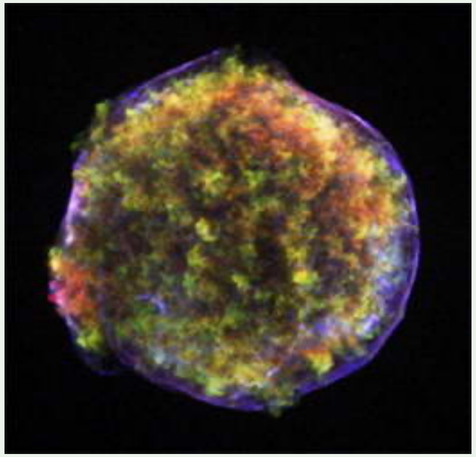
Benasque Science Center, 5 September 2024

Gamma rays probe the most violent Universe

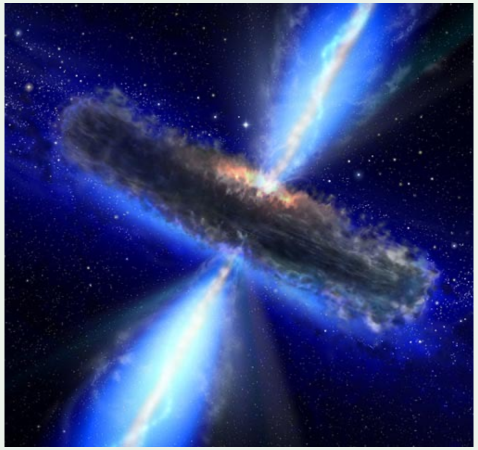


What produces gamma rays?

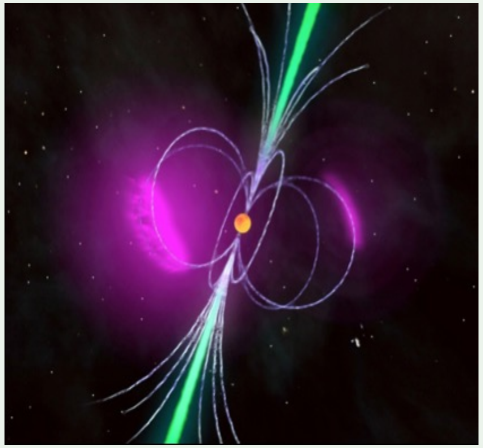
ENERGY SOURCES



Explosions

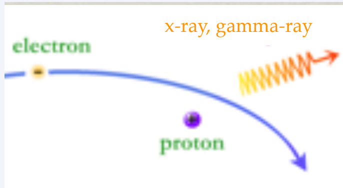


Accretion



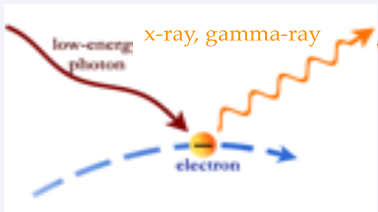
Strong magnetic fields

EMISSION MECHANISMS

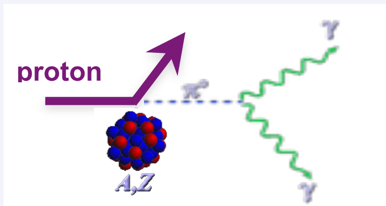


bremsstrahlung

synchrotron



inverse Compton



π^0 production

Many of these mechanisms will produce radiation at other, non γ-ray, wavelengths

High Energy Astrophysics

Gamma rays' energy domain

- High Energy (HE): 100 MeV - 100 GeV
- Very High Energy (VHE): 100 GeV – tens of TeV

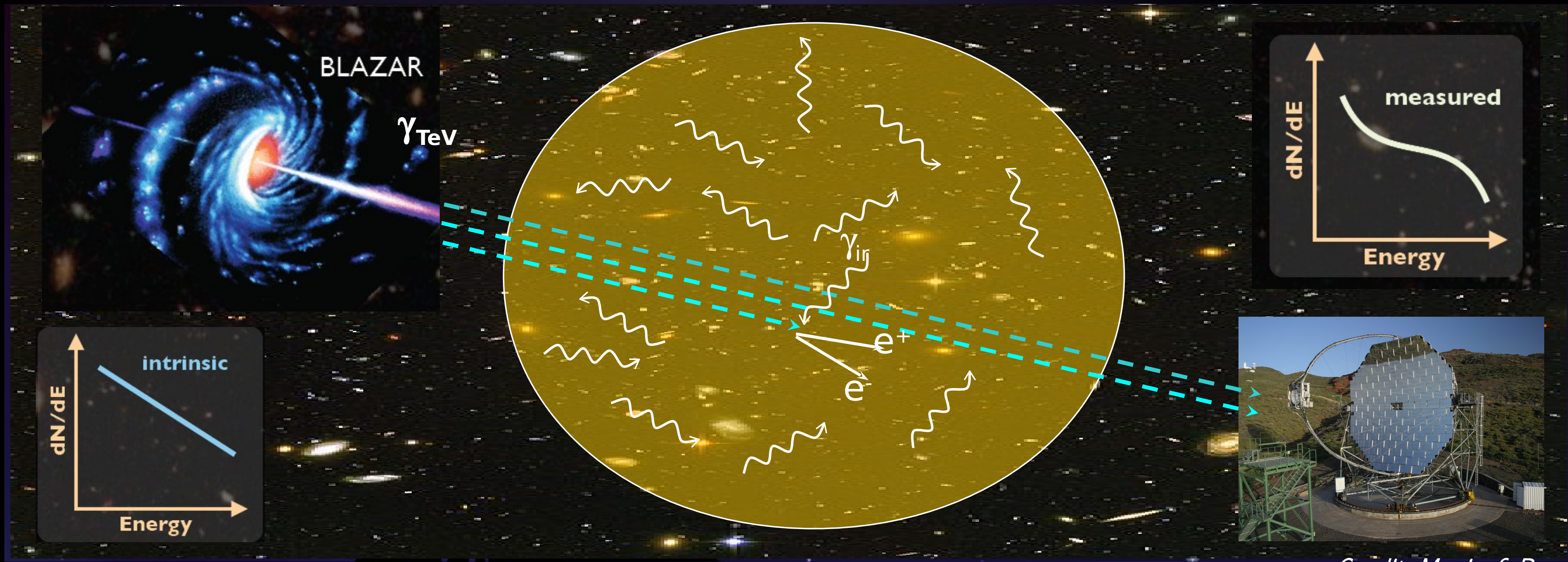
Units:

- GeV/c^2, or simply GeV (10^9 eV) with c=1. Also, MeV and TeV.
- Proton mass: 938 MeV/c^2
- Electron mass: 0,511 MeV/c^2

Non-thermal emission

- Thermal: electrons in a Maxwell-Boltzmann distribution
  → temperature, black-body radiation.
  → statistical motion of charged particles depends on temperature
- Non-thermal processes: no temperature associated. Typically, power-law spectra.

Intergalactic absorption of gamma-ray photons



Credit: Mazin & Raue

Around TeV energies:

$$\lambda \approx 1.24\left(\frac{E}{1TeV}\right)\mu m$$

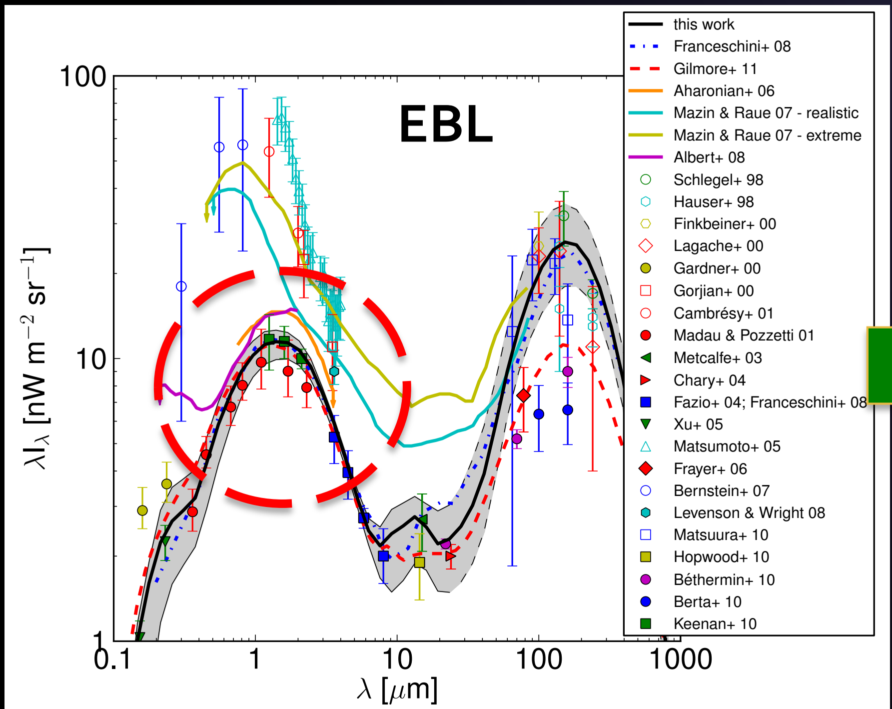
Infrared/optical/UV background photons:

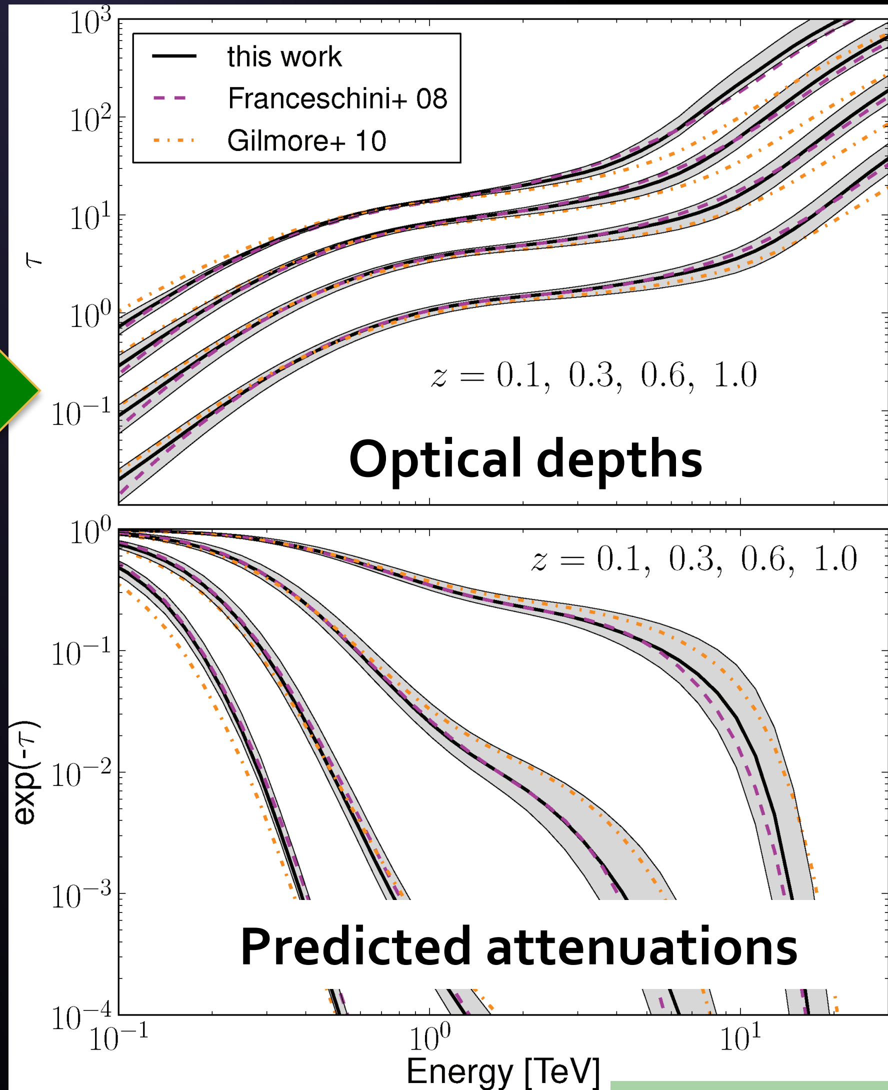
Extragalactic Background Light (EBL)

Flux attenuation: $F_{Earth} = F_{source}\ Exp[-\tau(E,z)]$ with τ = optical depth

Example: for a source at redshift 0.5 and 0.5 TeV, attenuation ~2 orders of magnitude!!

Optical depth from state-of-the-art EBL models

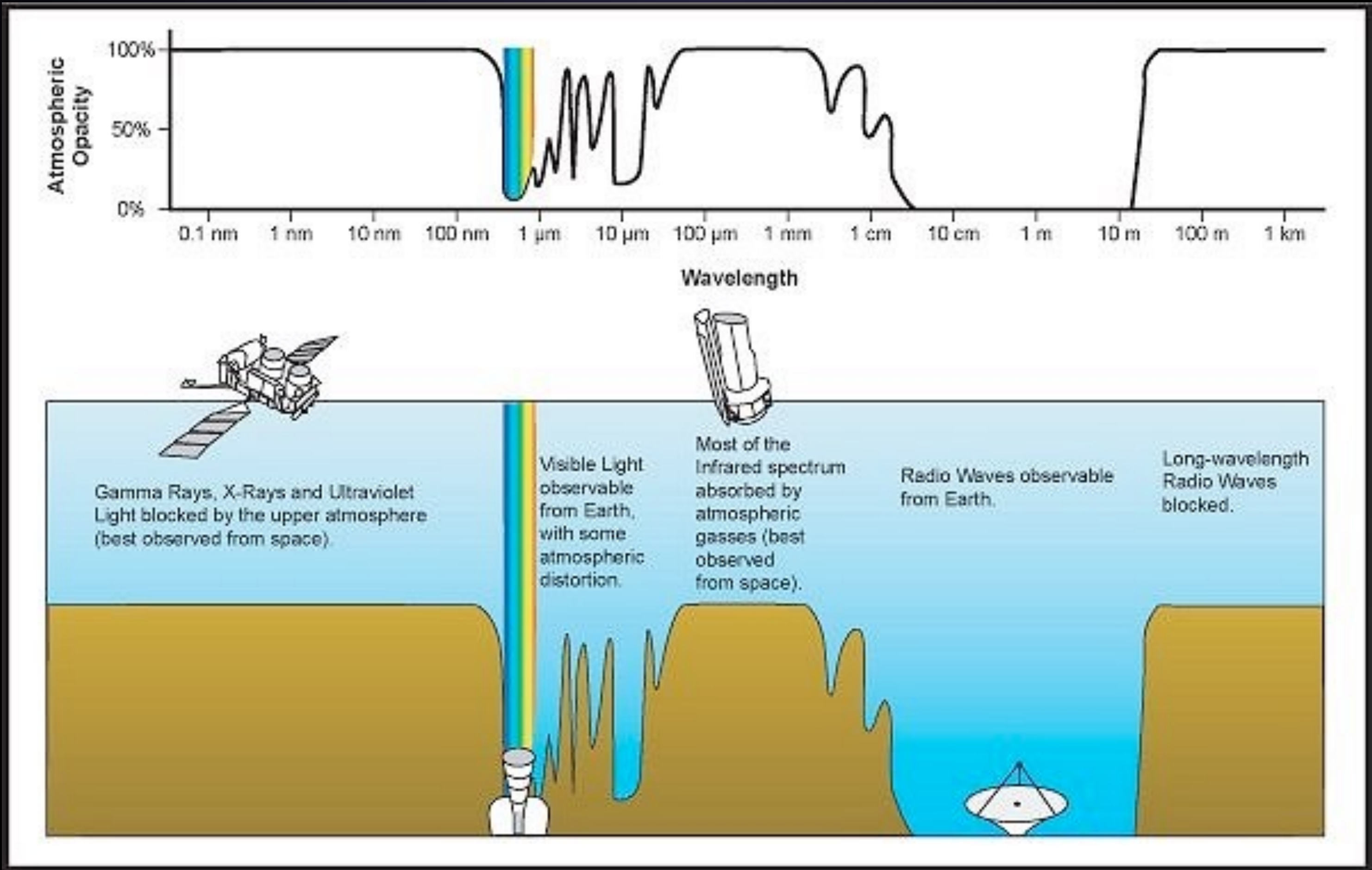




The most refined EBL models remarkably agree on their predictions for the (sub)TeV regime

Domínguez+11

Atmospheric opacity to gamma rays

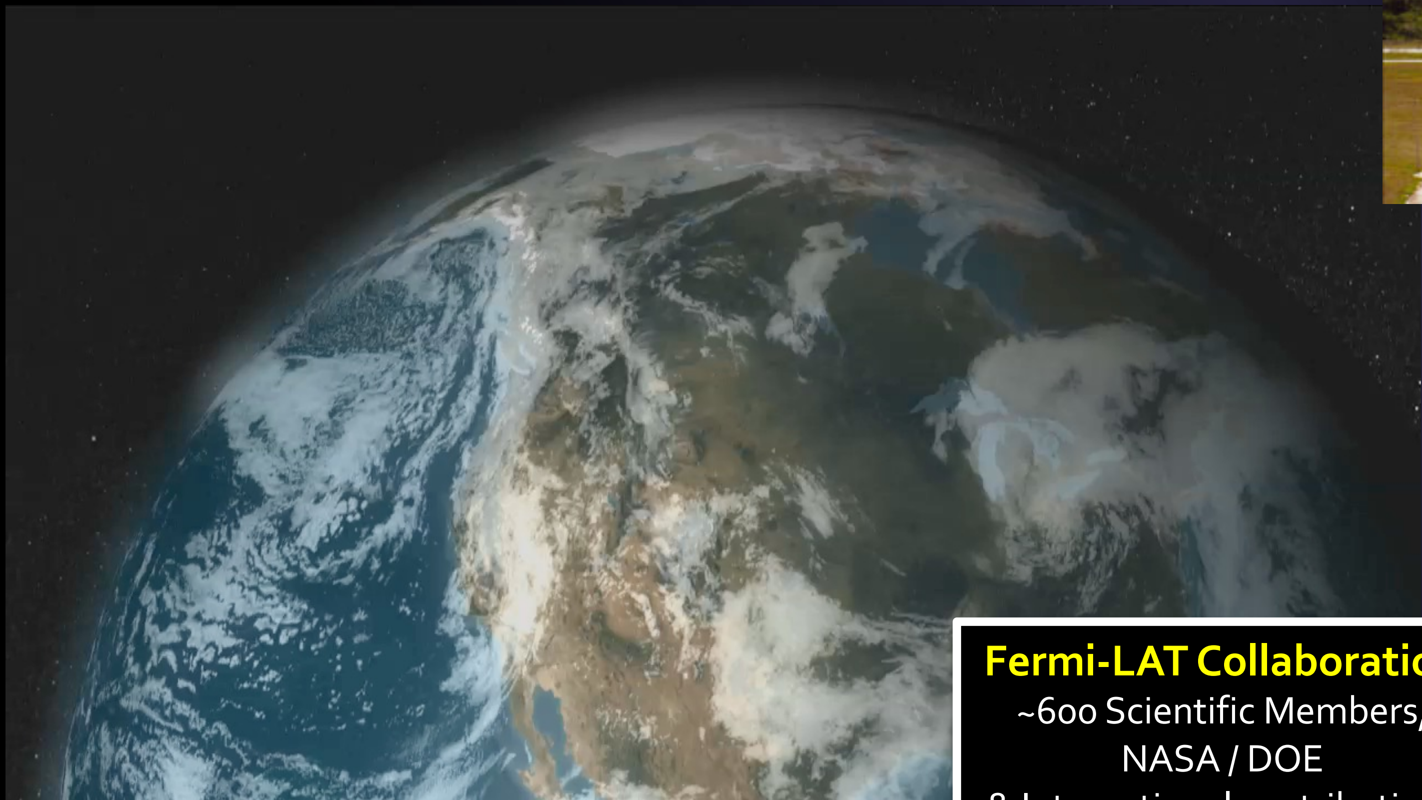


Penetration depth of gamma-rays ~ a few grams / cm².

~10km atmosphere thickness + air specific weight of ~1 mg / cm³:
→ 1000 g cm⁻²
→ The atmosphere is a thick shield!

The NASA Fermi satellite

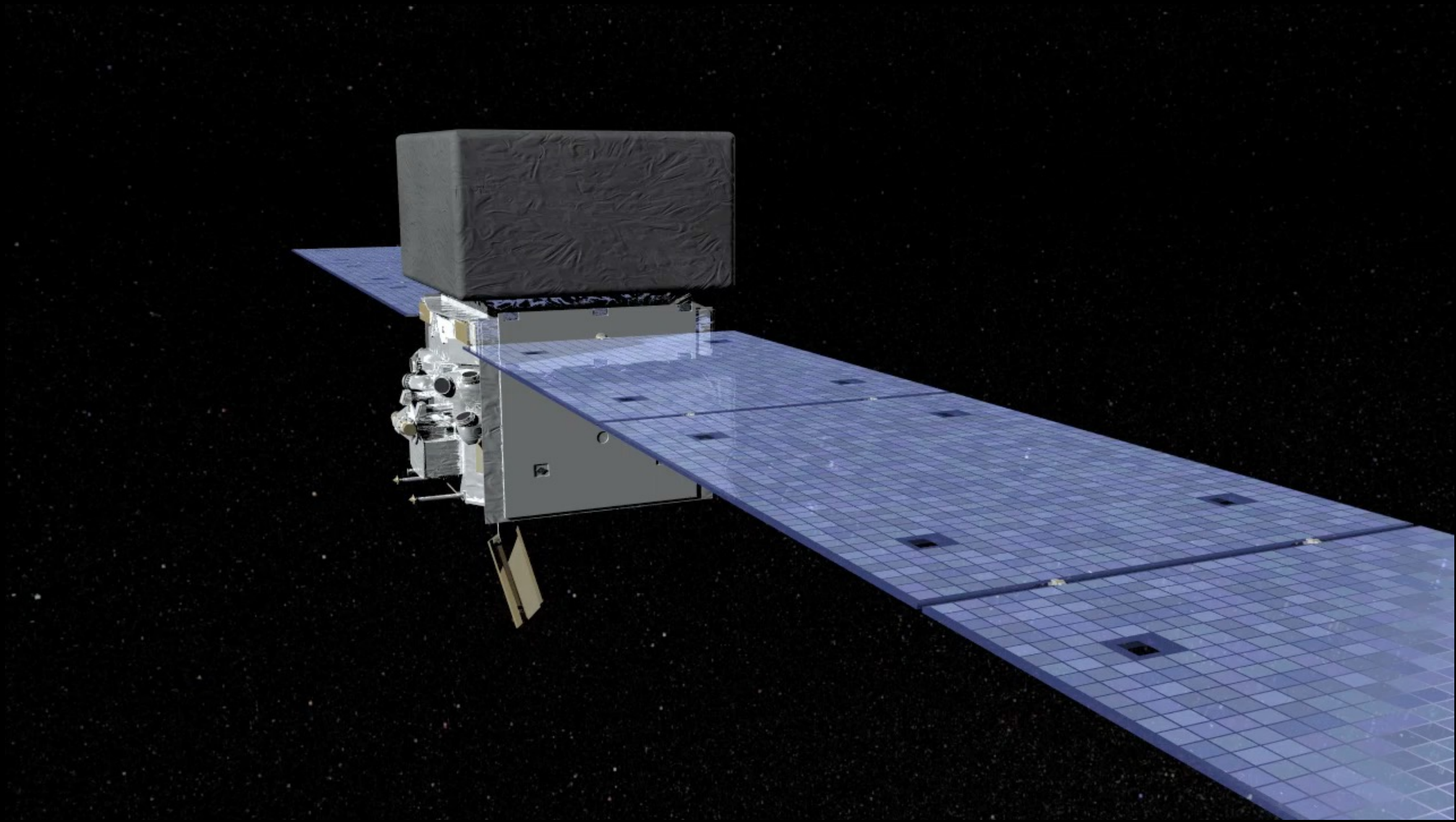
- Lauched on June 11 2008 from Cabo Cañaveral.
- $800M mission led by NASA/DOE.
- Two instruments aboard:
  - Gamma-ray Burst Monitor (GBM; 8 keV – 30 MeV)
  - **Large Area Telescope (LAT**; 20 MeV – >1 TeV)



Fermi-LAT Collaboration
~600 Scientific Members,
NASA / DOE
& International contributions

“Catching” gammas with Fermi LAT

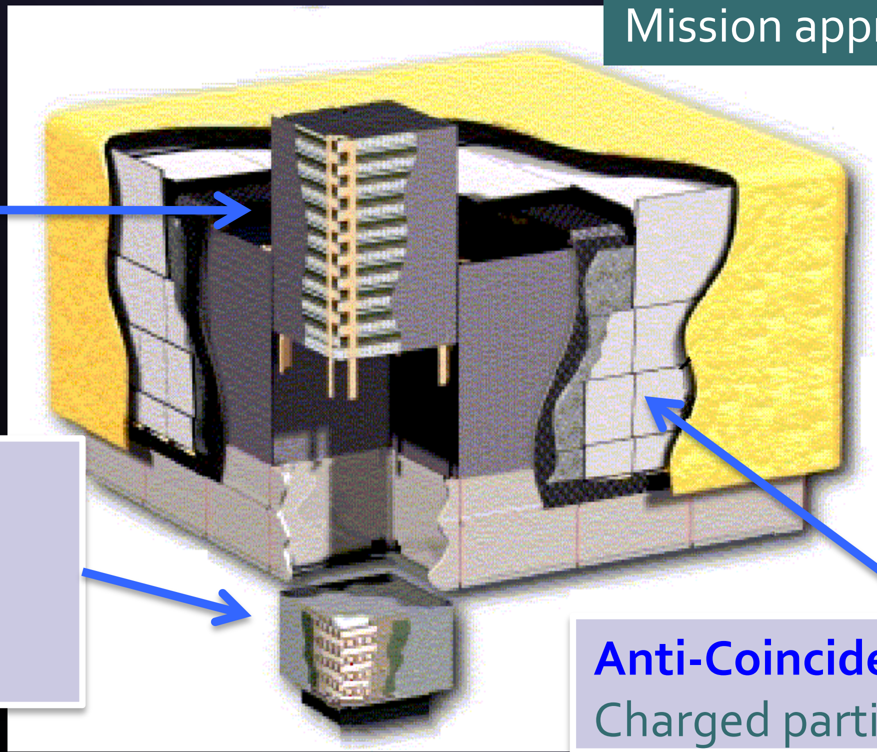
Fermi uses pair production to detect gammas.



The Fermi Large Area Telescope

LAUNCHED IN JUNE 2008
Mission approved through 2025

Si-Strip Tracker:
convert $\gamma \to e^+e^-$
reconstruct γ direction
EM v. hadron separation



[1.8 m x 1.8 m x 0.7 m]

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

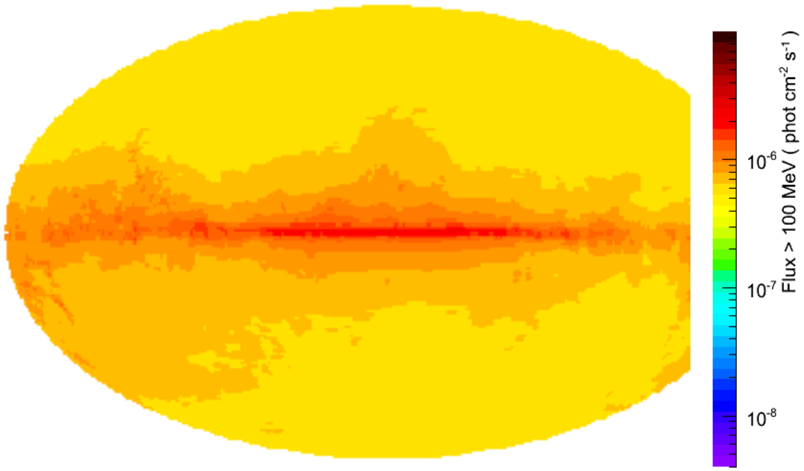
Sky Survey:
2.5 sr field-of-view
whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

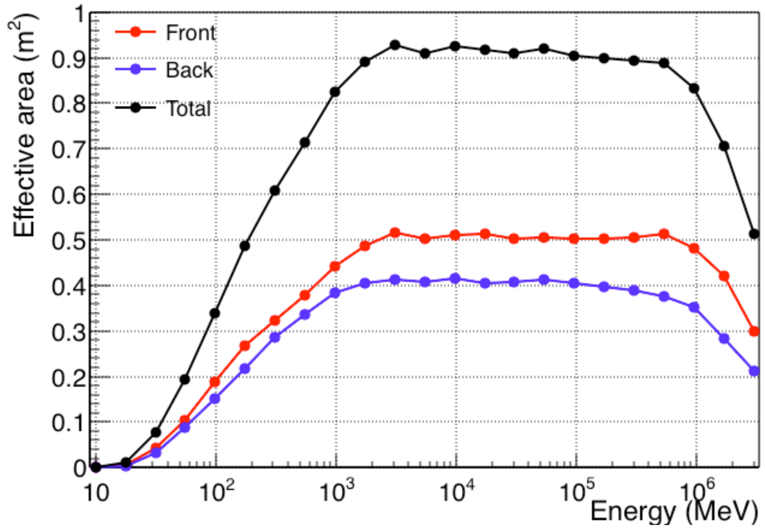
Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi-LAT performance

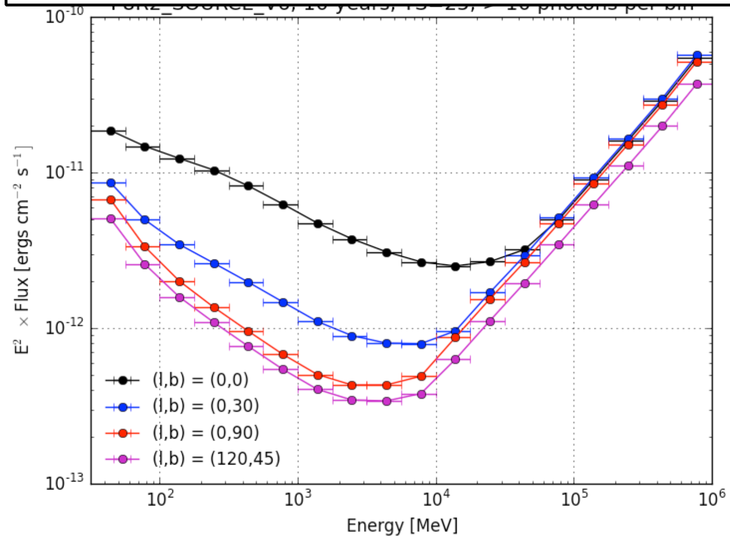
All-sky coverage



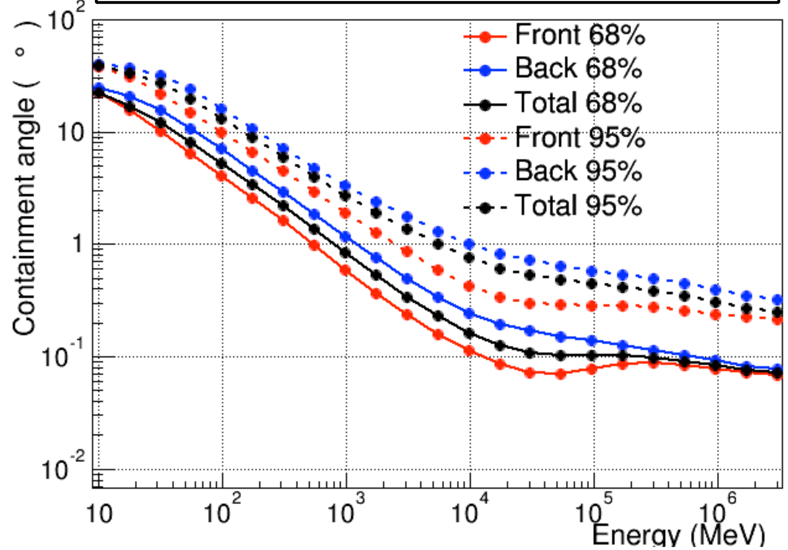
Effective area



Point source sensitivity

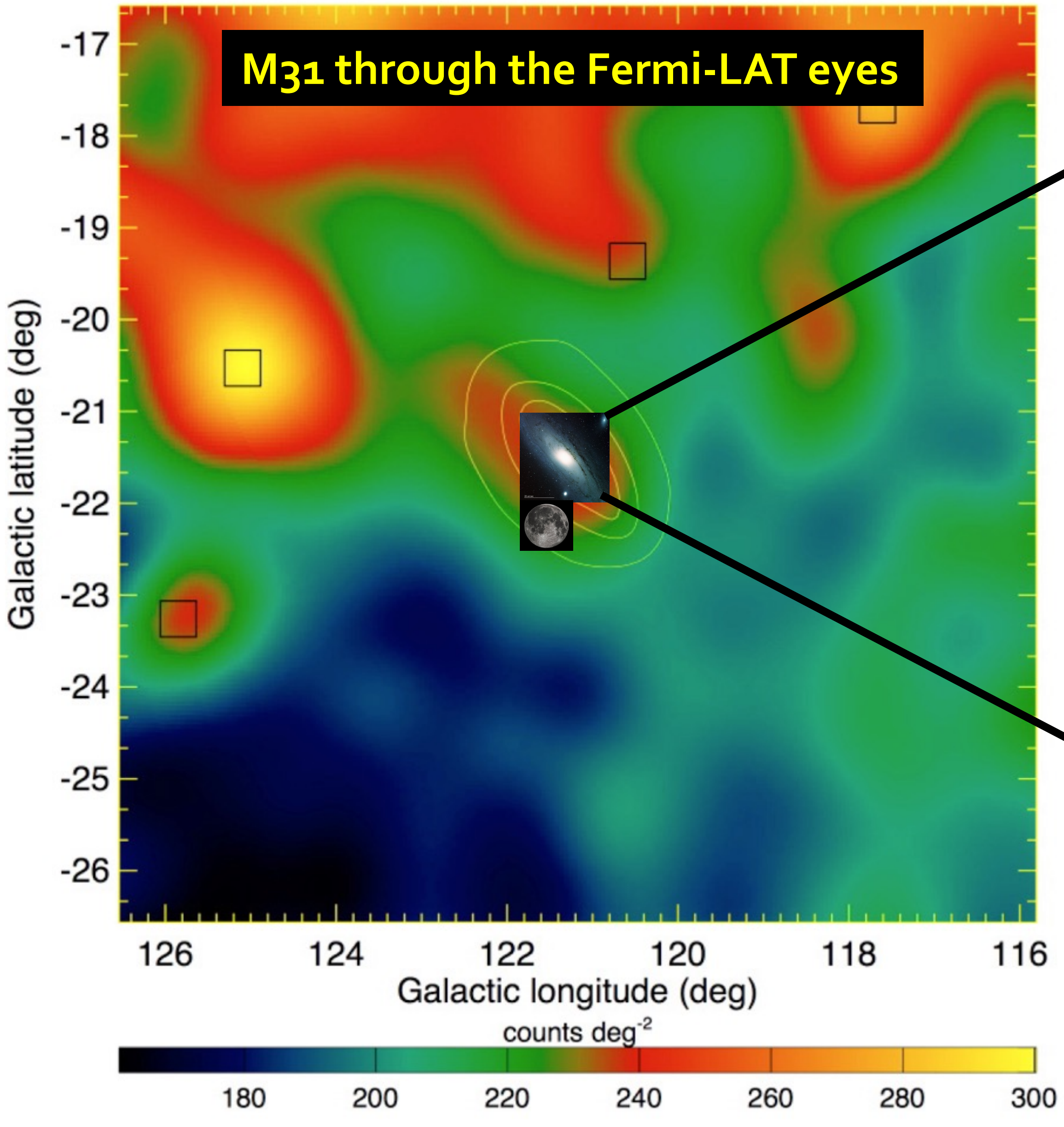


Angular resolution (PSF)



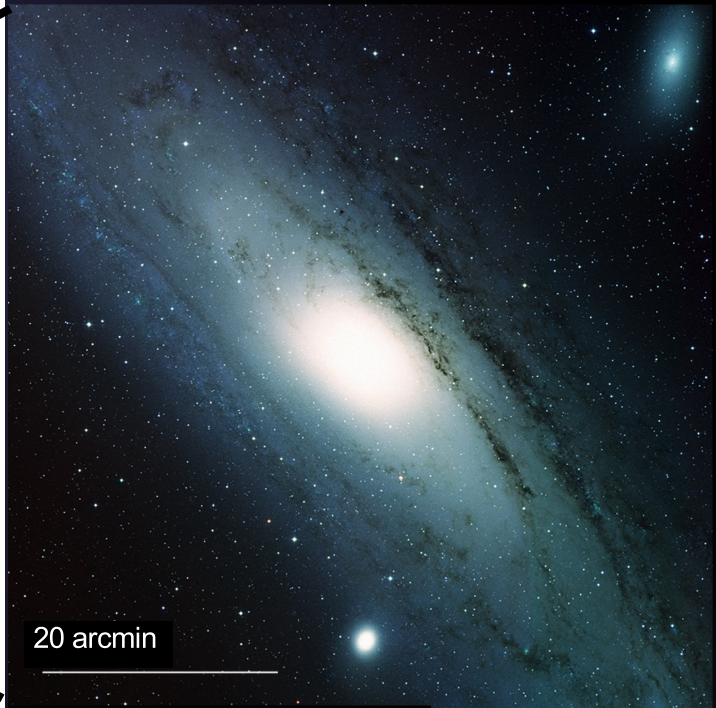
Angular resolution in gammas (aka 'source confusion')

[Abdo+10]



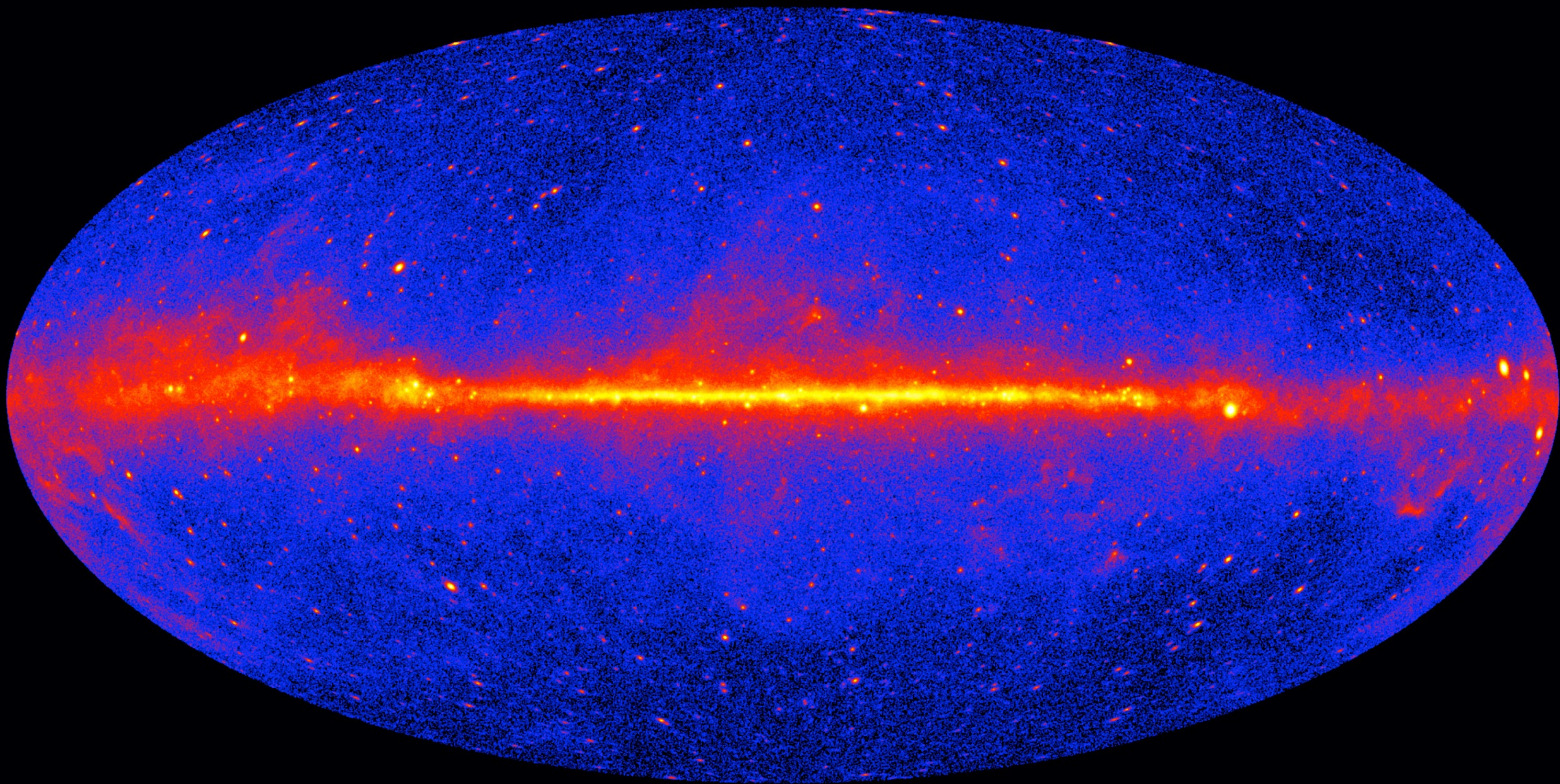
Andromeda (M31)

Optical DSS Image

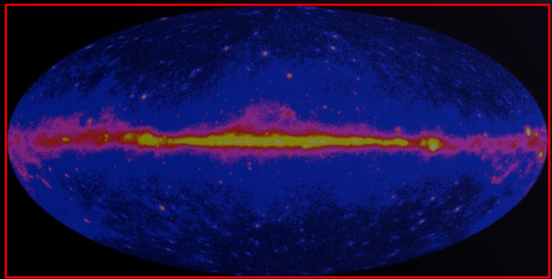


THE GAMMA-RAY SKY above 1 GeV

Fermi LAT data



The complexity of the gamma-ray sky



DATA

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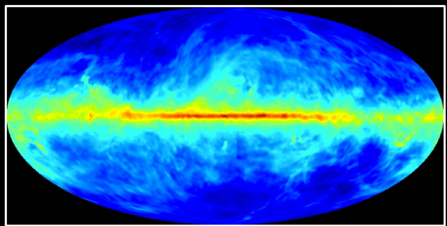
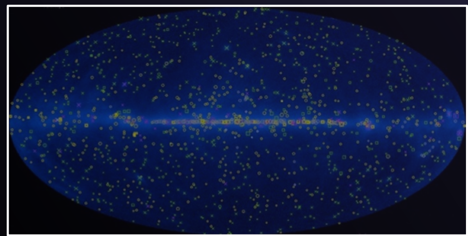


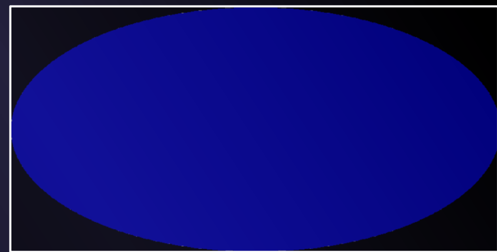
Galactic Diffuse

+



Point Sources

+

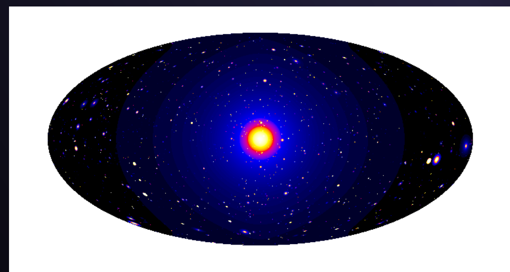


Isotropic (IGRB)

+

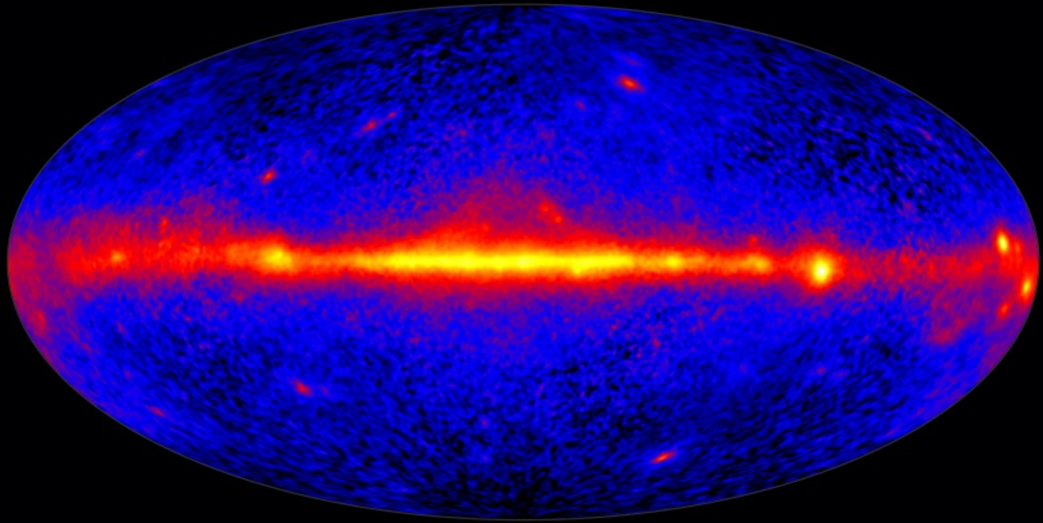
Bubbles
Loop I
Earth limb
Sun
etc

+



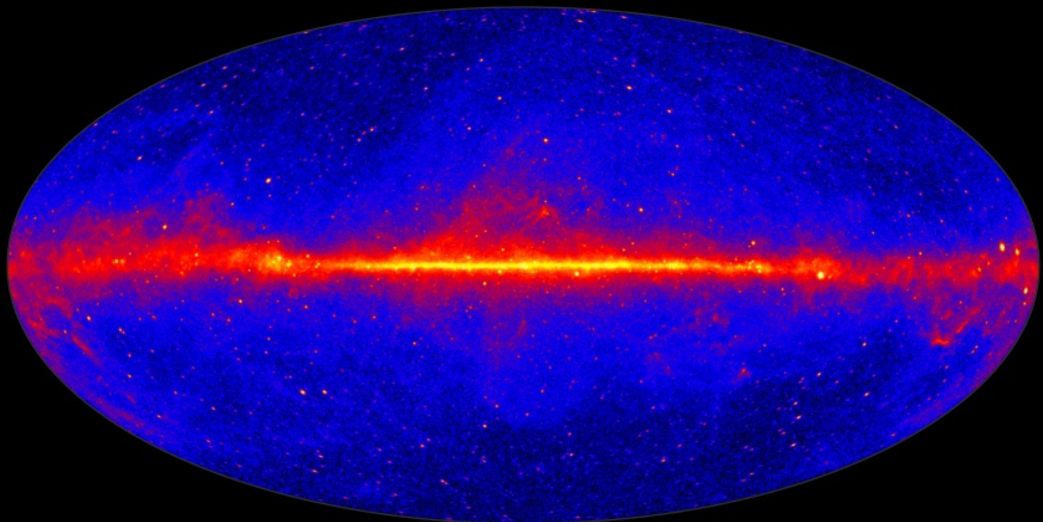
Dark matter ?

The Fermi LAT revolution



EGRET all-sky map of gamma rays above 100 MeV

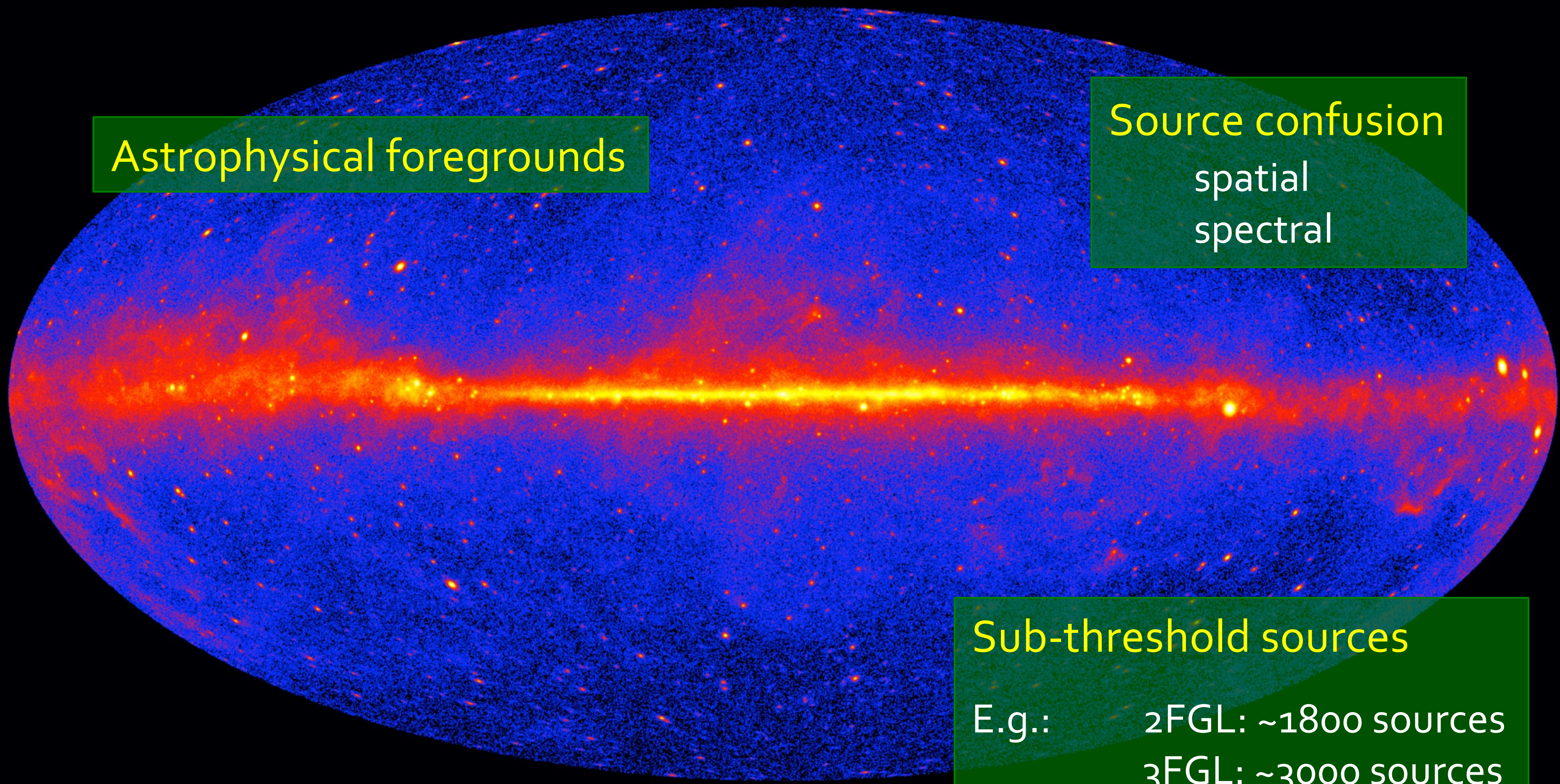
EGRET
[Fermi predecessor, 1991-1996]

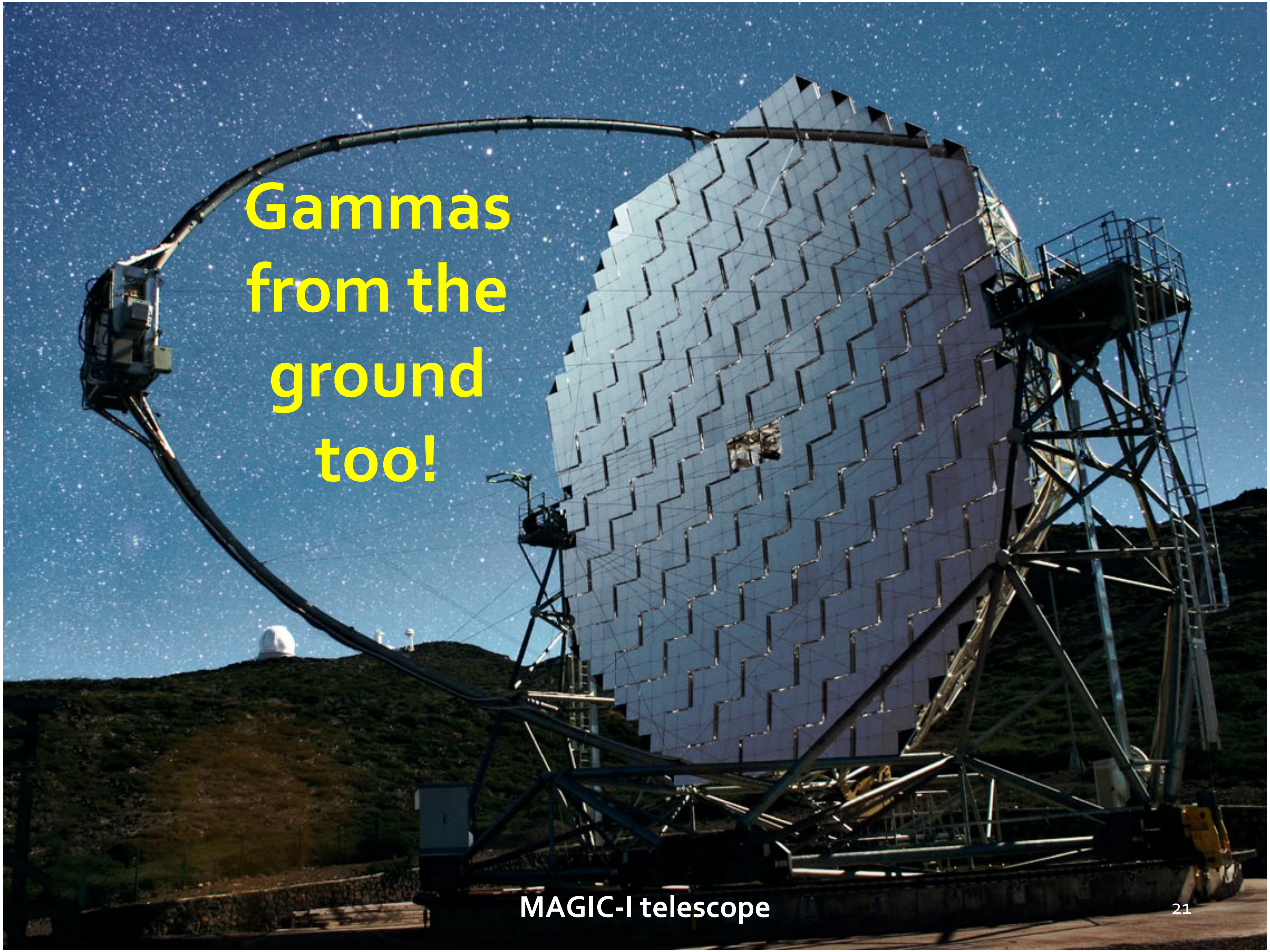


Fermi LAT 12-year all-sky map of gamma rays above 1 GeV

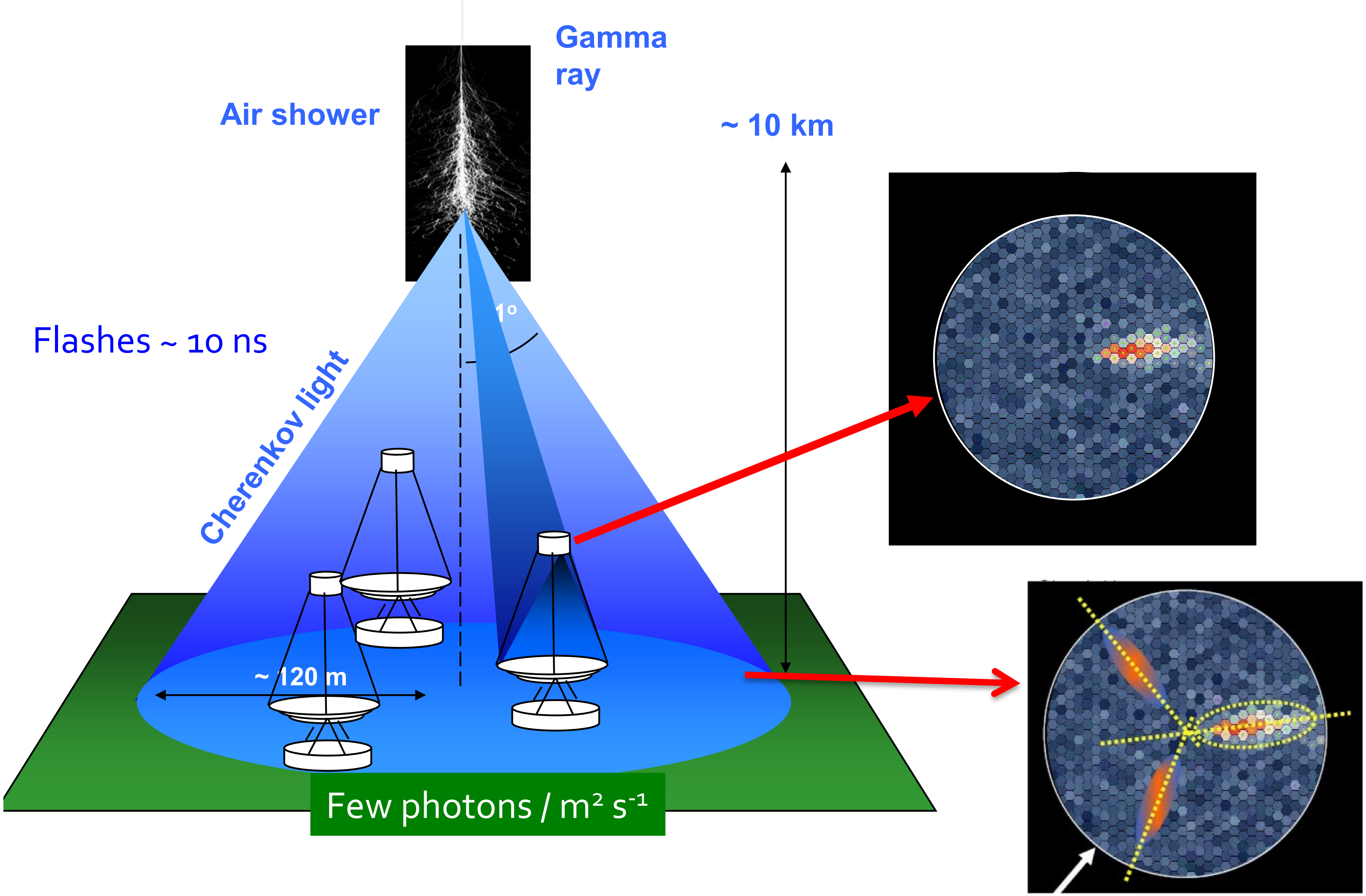
Fermi LAT
[2008-present]

Data analysis challenges



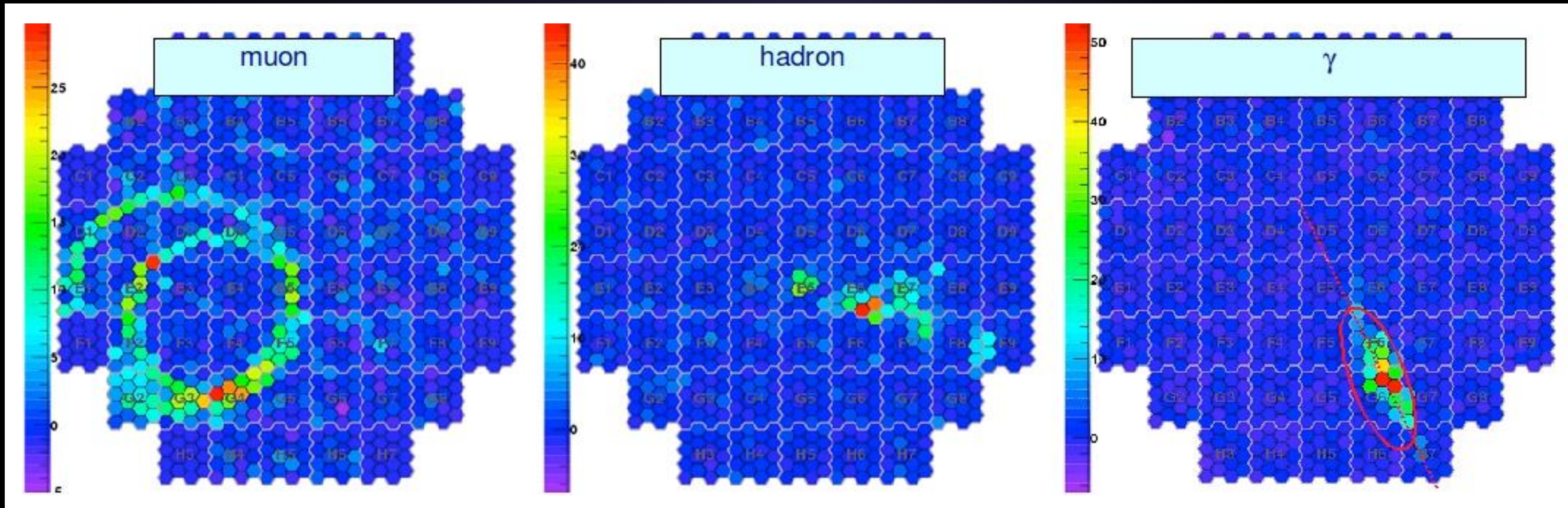

Gammas from the ground too!
MAGIC-I telescope

IACT technique



Stereoscopic system improves background discrimination and arrival direction reconstruction

IACT technique (II)



1. Primary particle ID based on "shape" discrimination.
2. Image intensity → energy of primary
3. Image orientation –> arrival direction of primary

   → All this can be improved with more telescopes.

Massive MonteCarlo production needed for the analysis.

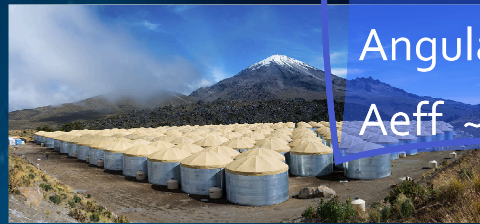
→ Selection cuts applied based on expected performance.

Present gamma-ray observatories

E. range: 20 MeV → >1 TeV
E. resolution: ~10% @ GeV
FoV: ≈ 2.4 sr
Angular res.: ~0.2°@10 GeV
Aeff ~ m^2

Fermi LAT
[>2008]

HAWC
[>2015]



E. range: 0.1 → >300 TeV
E. resolution: ~20% @ 10 TeV
FoV: ≈ 2 sr
Angular res.: ~0.2°@10 TeV
Aeff ~22,000 m^2

LHAASO
[>2023]

MAGIC
[>2003]

HESS
[>2002]

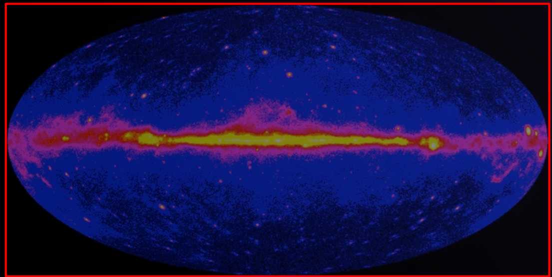
VERITAS
[>2006]

IACTs

E. range: 50 GeV → >10TeV
E. resolution: ~20%
FoV: ≈ 4 deg.
Angular res.: ≈ 0.1°
Aeff ~ 10^5 m^2

DESY/Milde Science Comm./Exozet

The complexity of the gamma-ray sky



DATA

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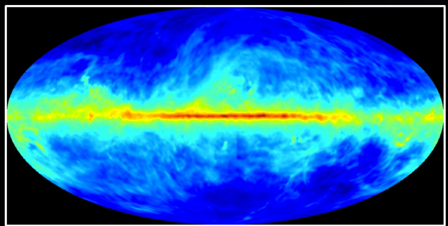
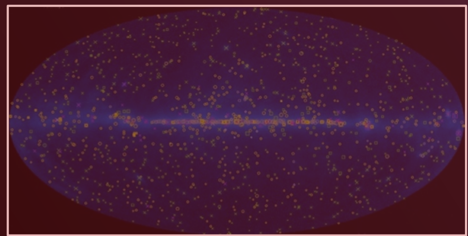


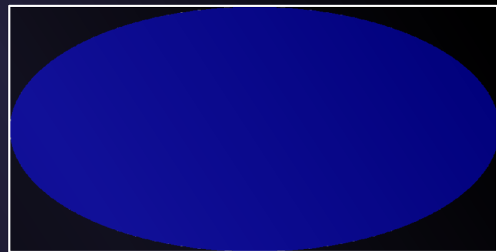
Galactic Diffuse

+



Point Sources

+

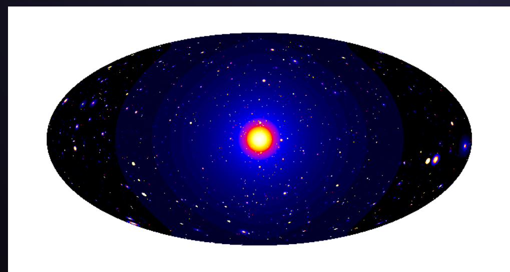


Isotropic (IGRB)

+

Bubbles
Loop I
Earth limb
Sun
etc

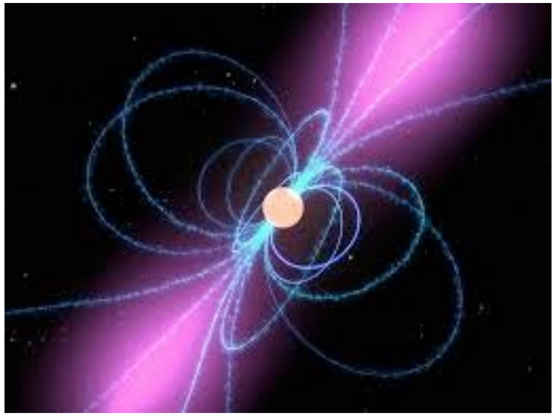
+



Dark matter ?

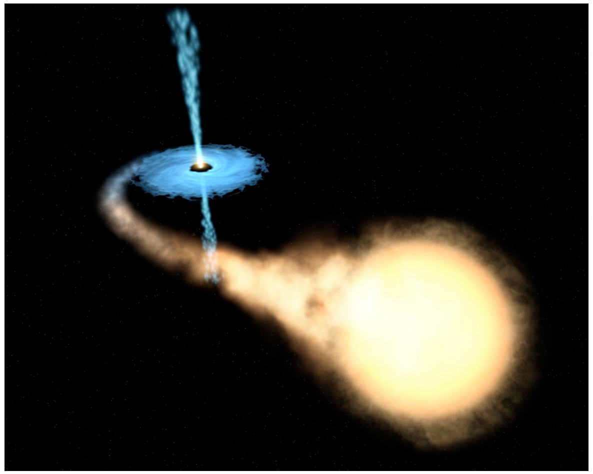
Sources: the gamma-ray zoo

Black holes



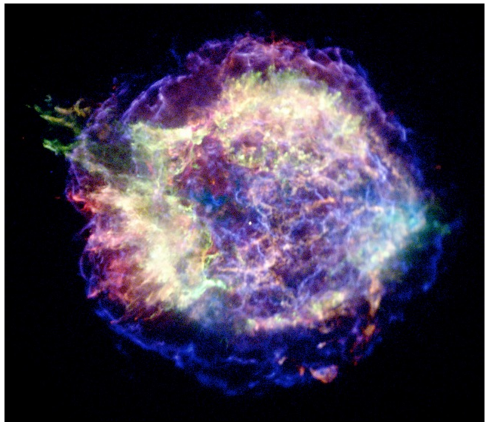
Pulsars

Radio galaxies



Binary star systems

Star-forming galaxies

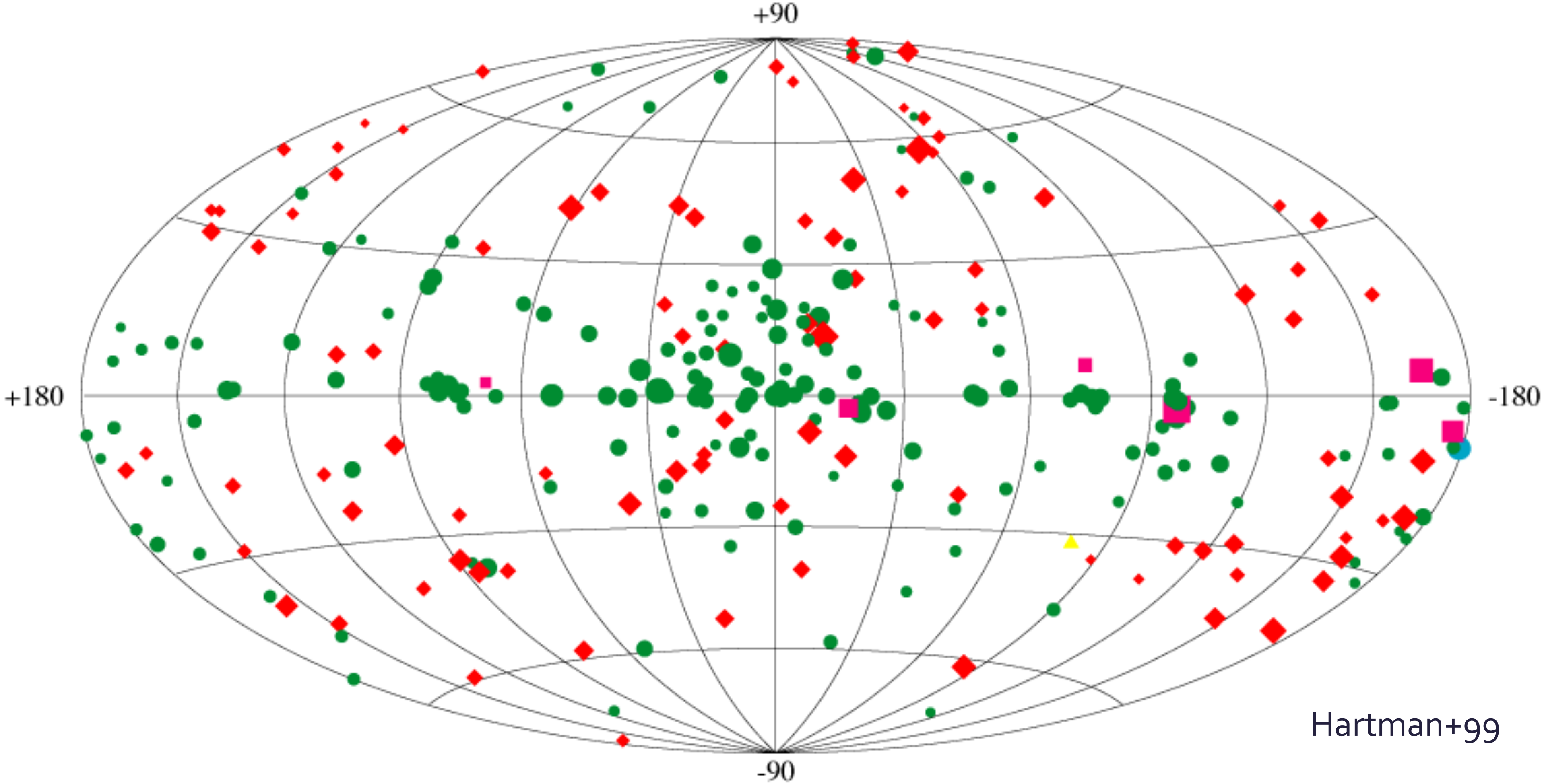


Supernova remnants

+ Unknown!

Third EGRET Catalog (271 sources)

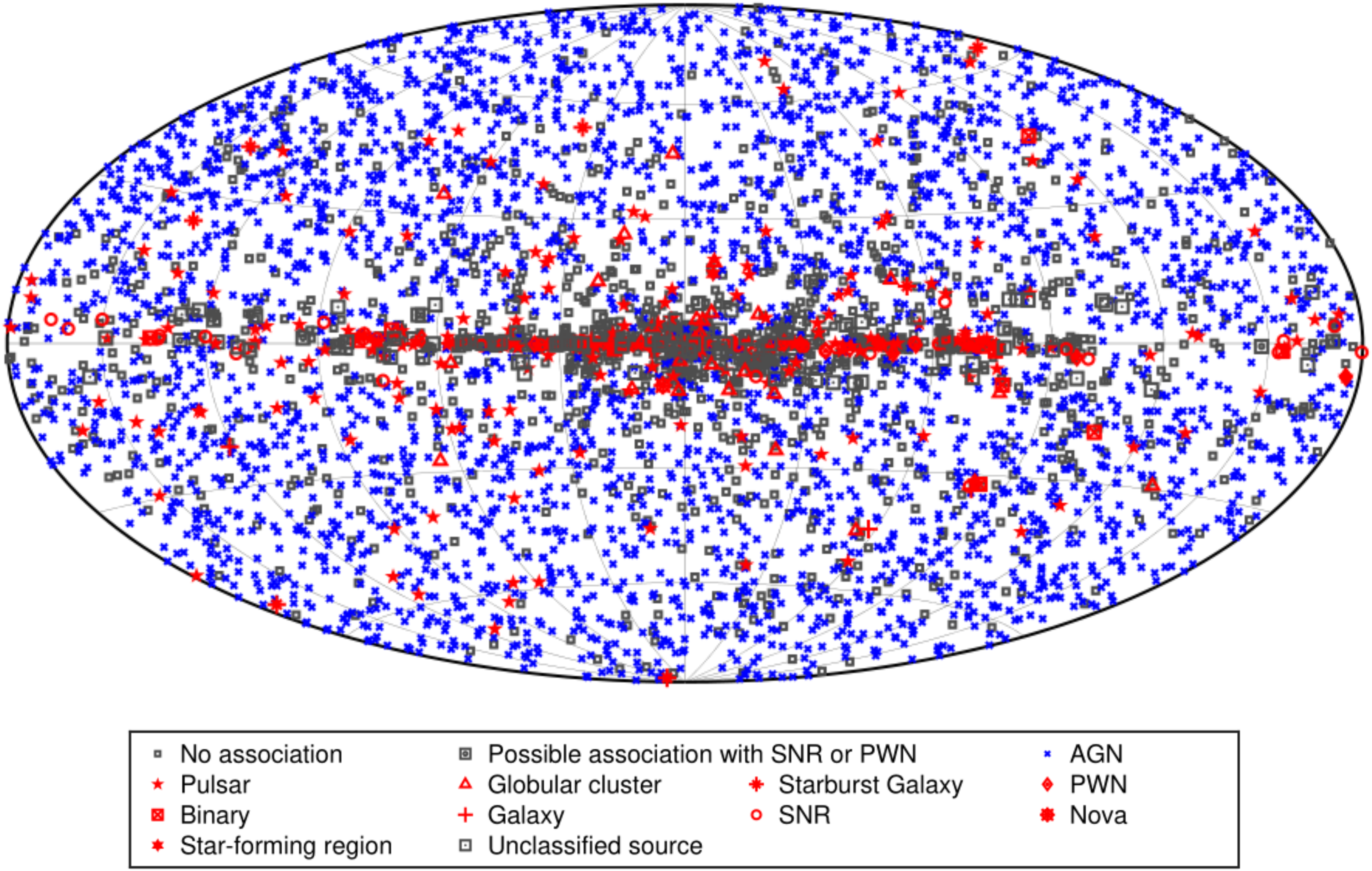
E > 100 MeV



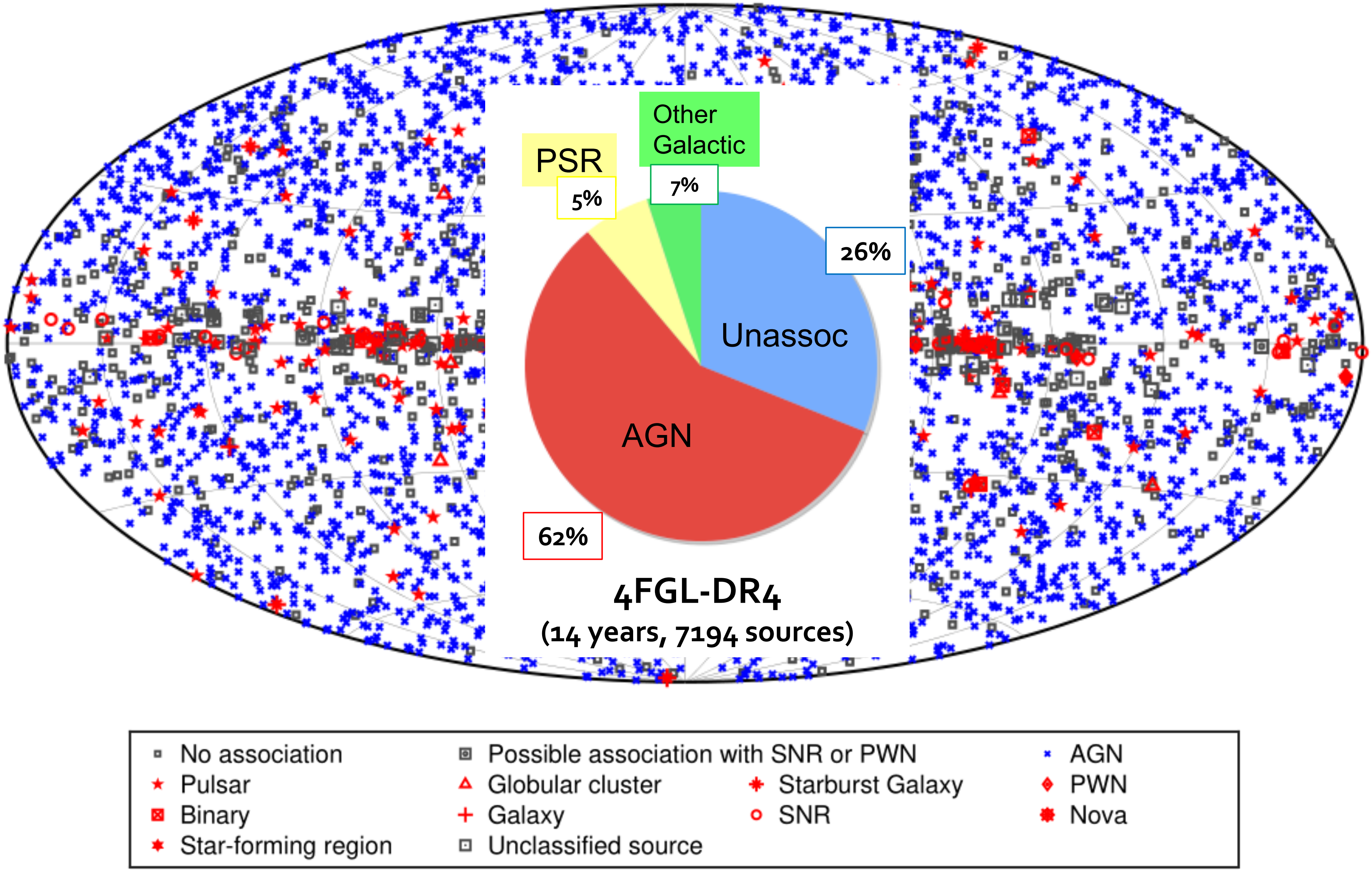
Hartman+99

◆ Active Galactic Nuclei
● Unidentified EGRET Sources
■ Pulsars
▲ LMC
● Solar FLare

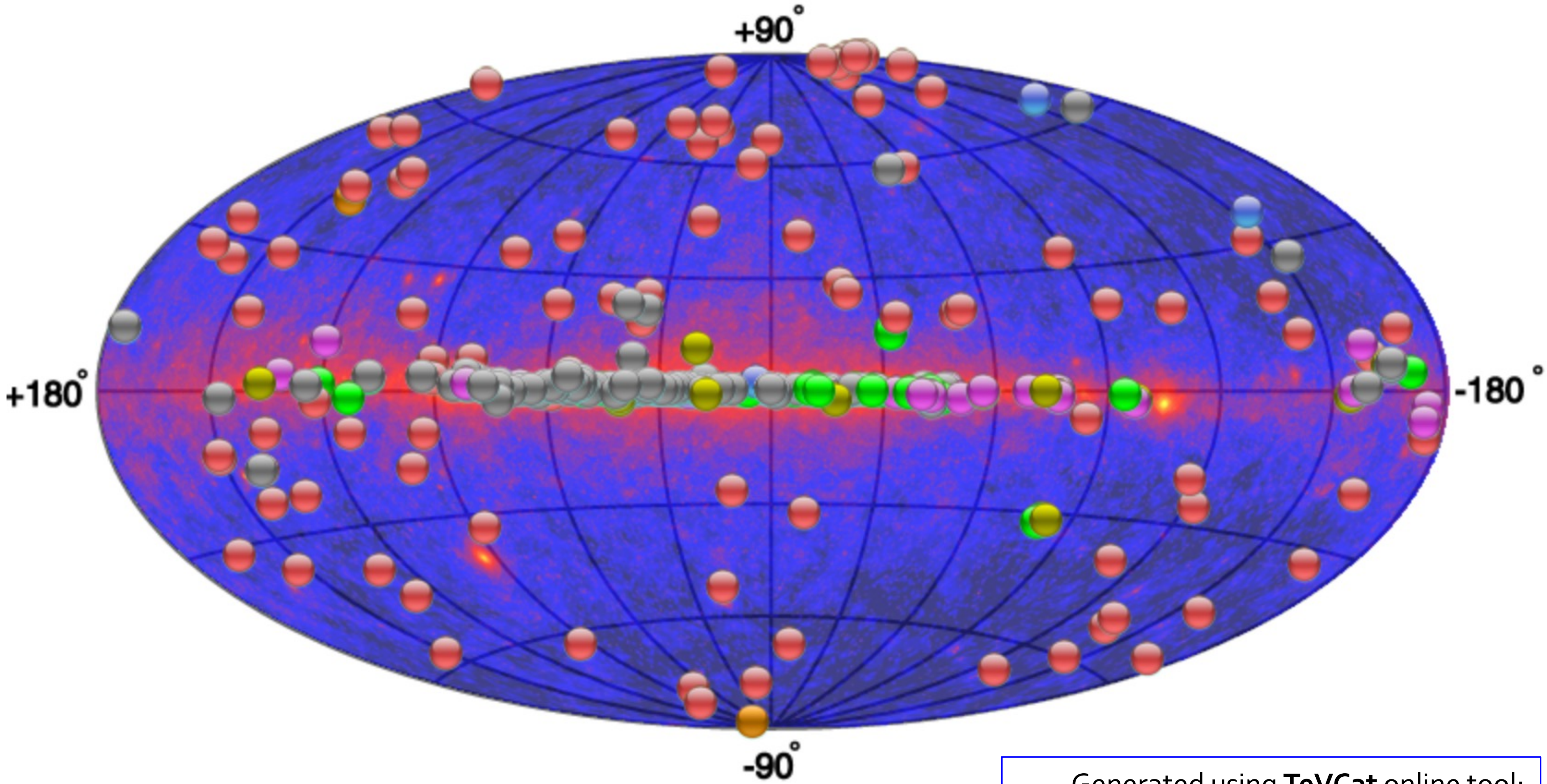
The 4FGL-DR4 Fermi-LAT point-source catalog



The 4FGL-DR4 Fermi-LAT point-source catalog



Gamma-ray sources above ~50 GeV

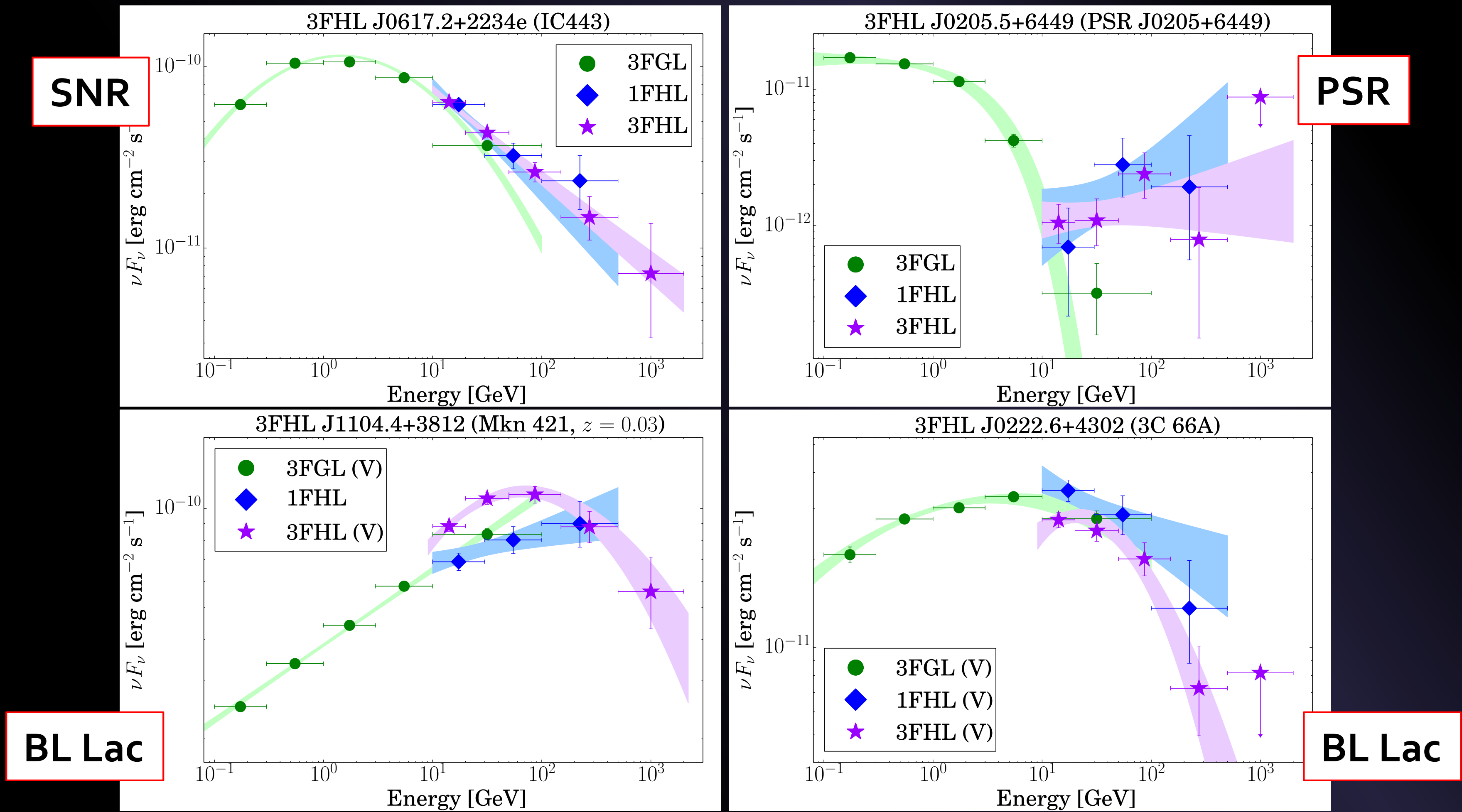


304 objects (April 29 2024)
Mostly AGNs
97 unIDs (~32%)

Generated using **TeVCat** online tool:
http://tevcat.uchicago.edu/

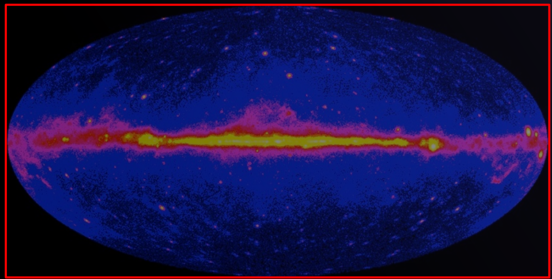
Source gamma-ray spectra

Each source type has a characteristic spectrum.
Source ID also at other wavelengths (optical, IR, radio…)



Ajello+17 [Fermi-LAT collab.]

The complexity of the gamma-ray sky



DATA

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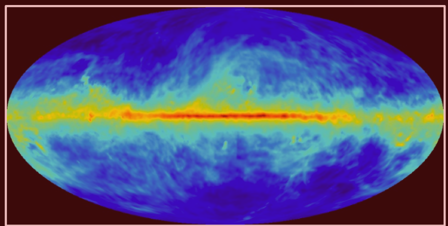
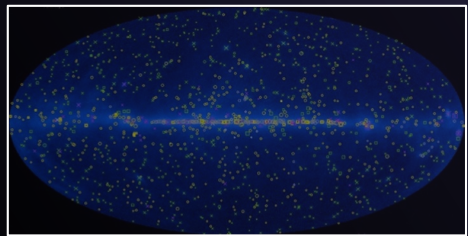


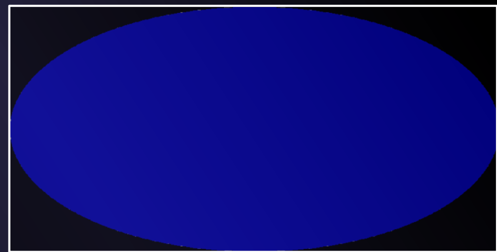
Galactic Diffuse

+



Point Sources

+



Isotropic (IGRB)

+

Bubbles
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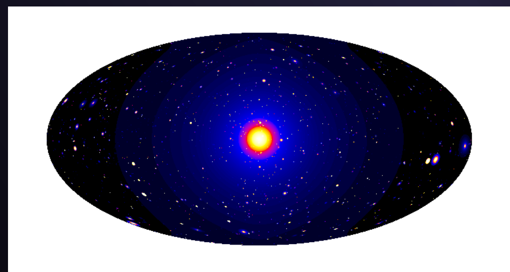
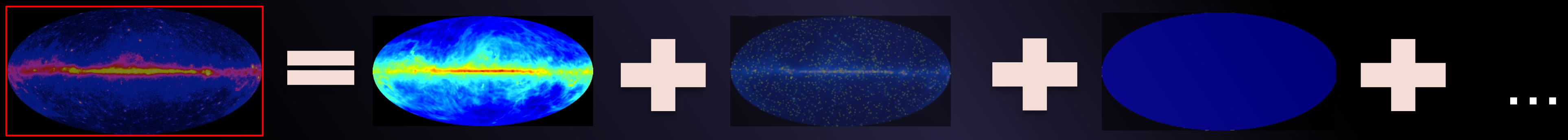
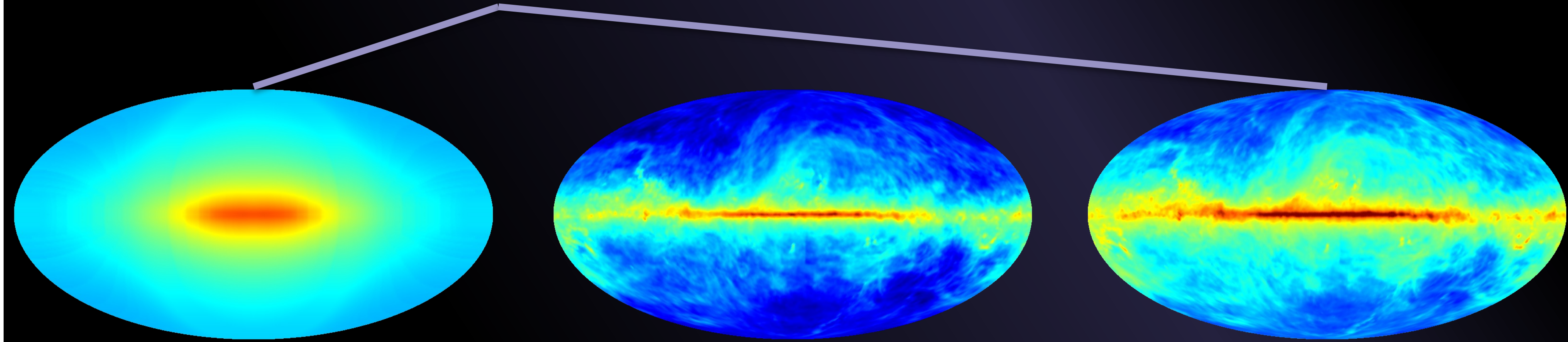


Dark matter ?

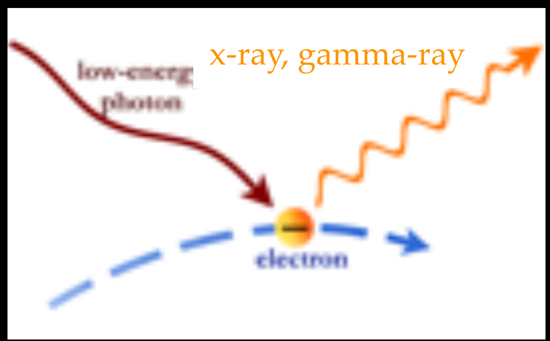
Galactic diffuse emission

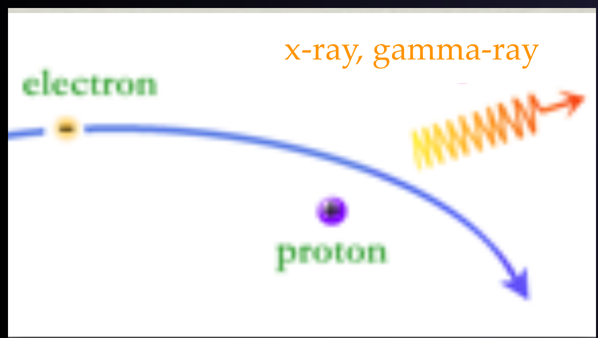


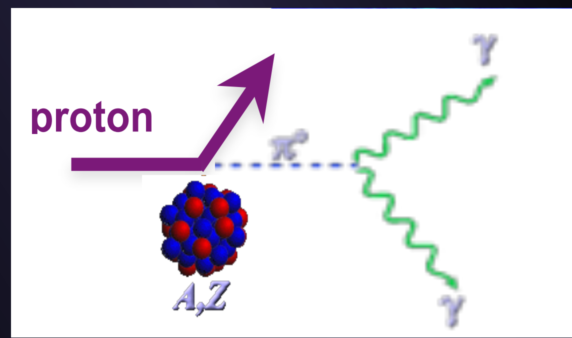
Galactic Diffuse | Point Sources | Isotropic



Inverse Compton | Bremsstrahlung | π^0 decay

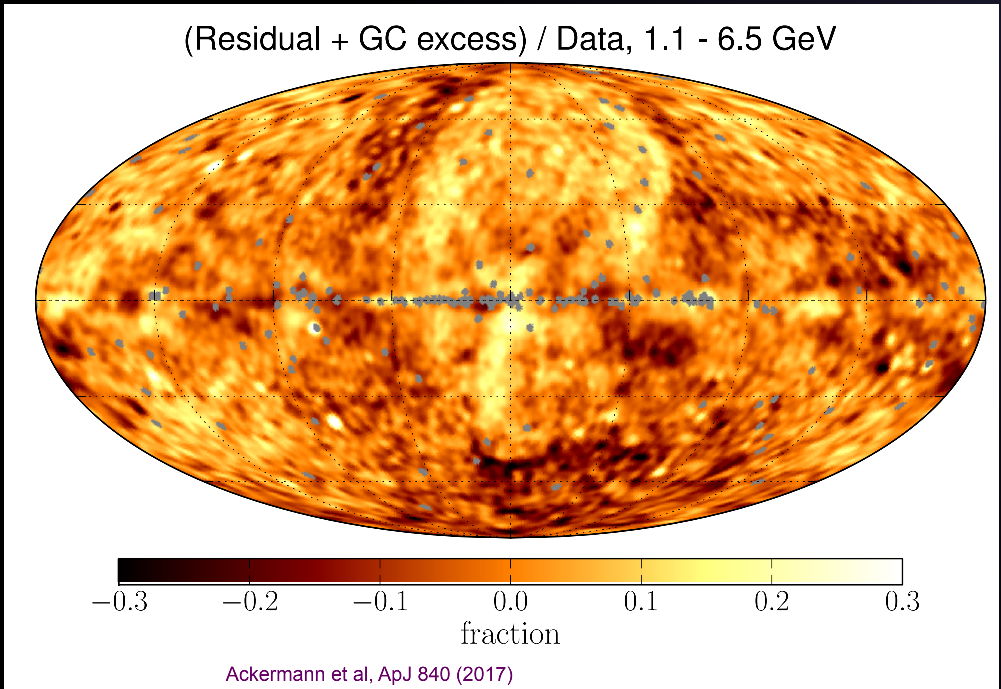






All-sky diffuse modeling

- Model cosmic-ray (CR) sources and propagation in the Galaxy, distribution of gas, resolved point sources.
  - → Generate models varying CR source distribution, halo size, gas distribution… (e.g. using GALPROP or DRAGON codes).
  - → CR origin, propagation and ISM properties constrained by comparing to data!



Example of residuals at few GeV [Ackermann+17]

On a large scale agreement is good between data and model.

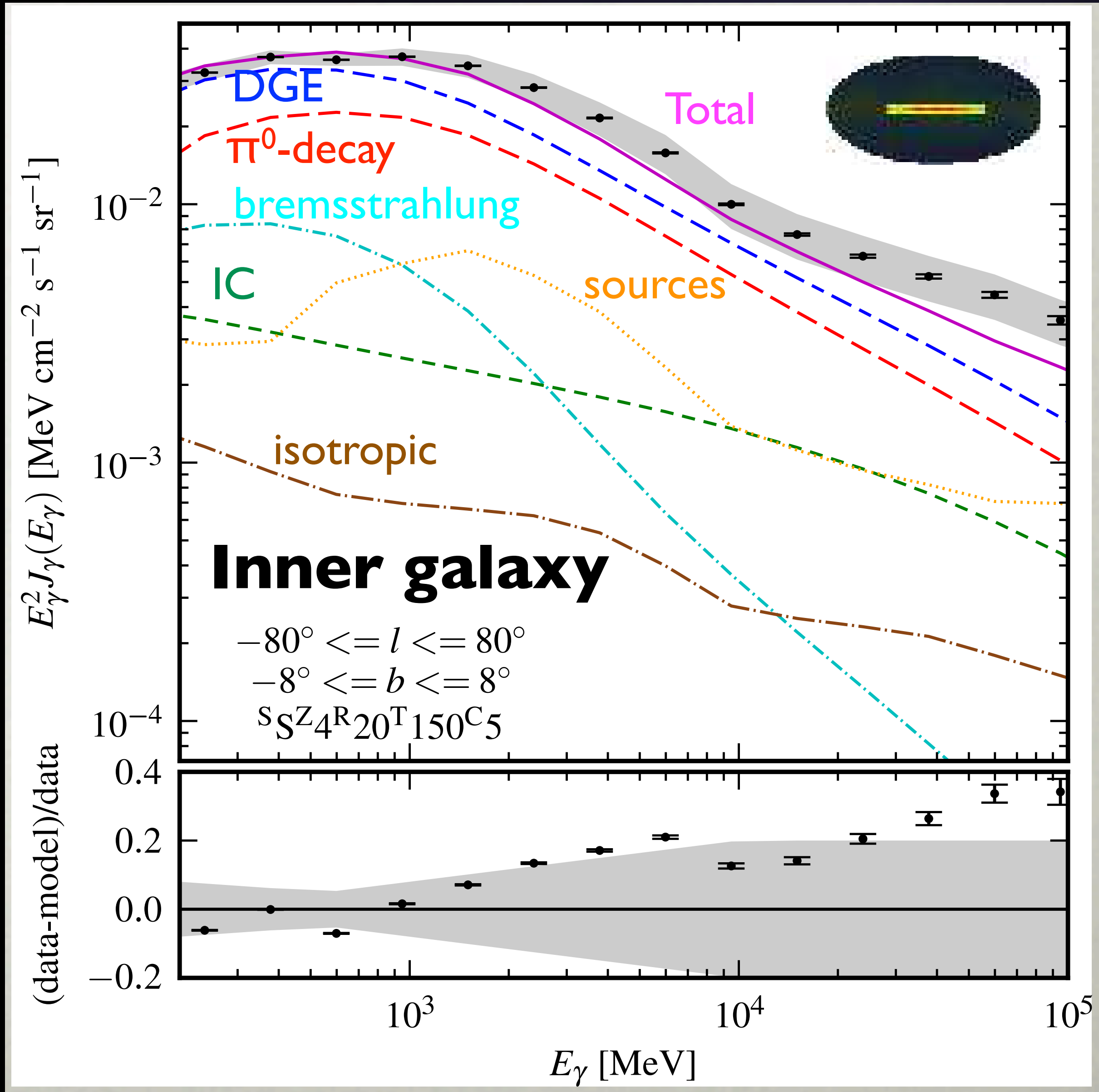
→Some extended excesses remain

Large uncertainties may be present at small scales, depending on sky position.

→ fake sources due to background mismodeling.

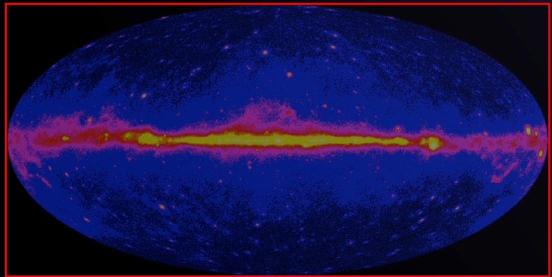
Typical residuals ~3 % (spatial & spectral), but they can be much larger (~30%)

Example of non-thermal spectra



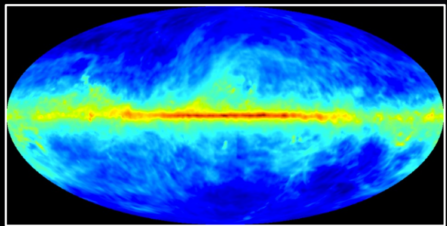
Ackermann+12
(Fermi-LAT Collaboration, astro-ph/1202.4039)

The complexity of the gamma-ray sky



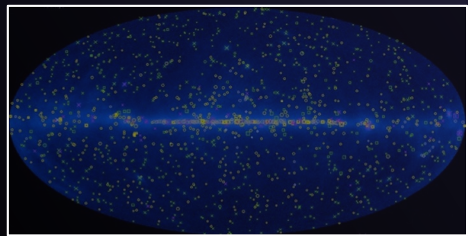
DATA

=



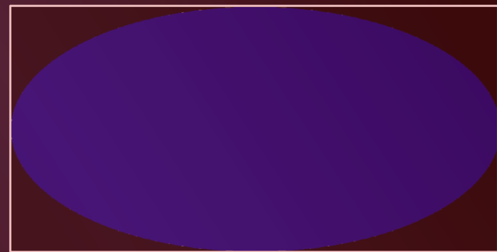
Galactic Diffuse

+



Point Sources

+

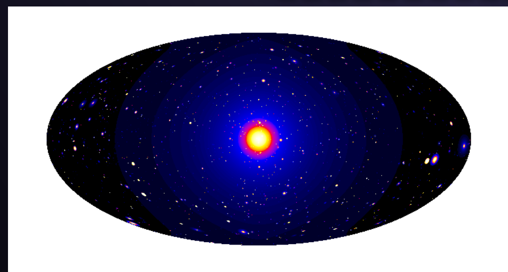


Isotropic (IGRB)

+

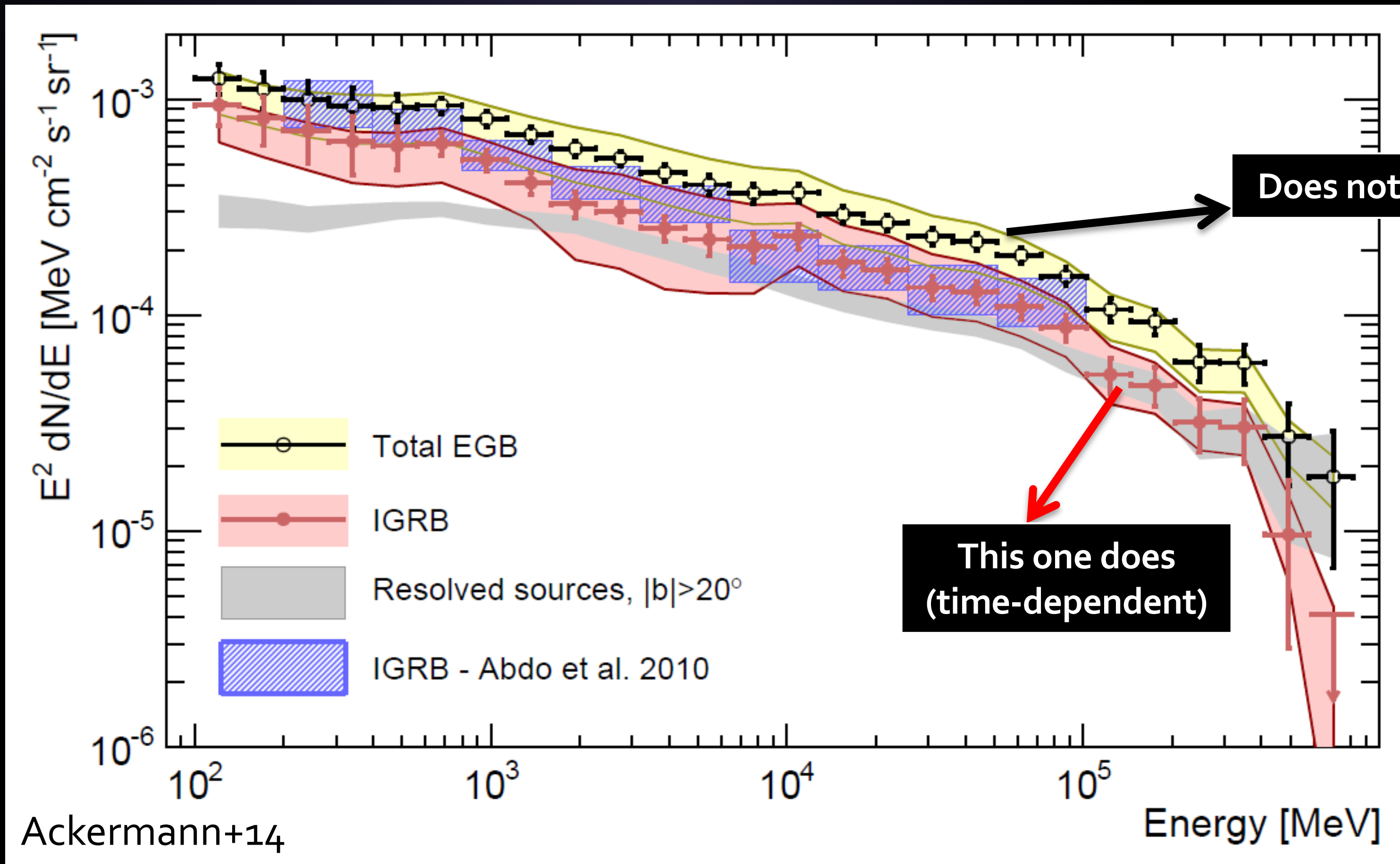
Bubbles
Loop I
Earth limb
Sun
etc

+



Dark matter ?

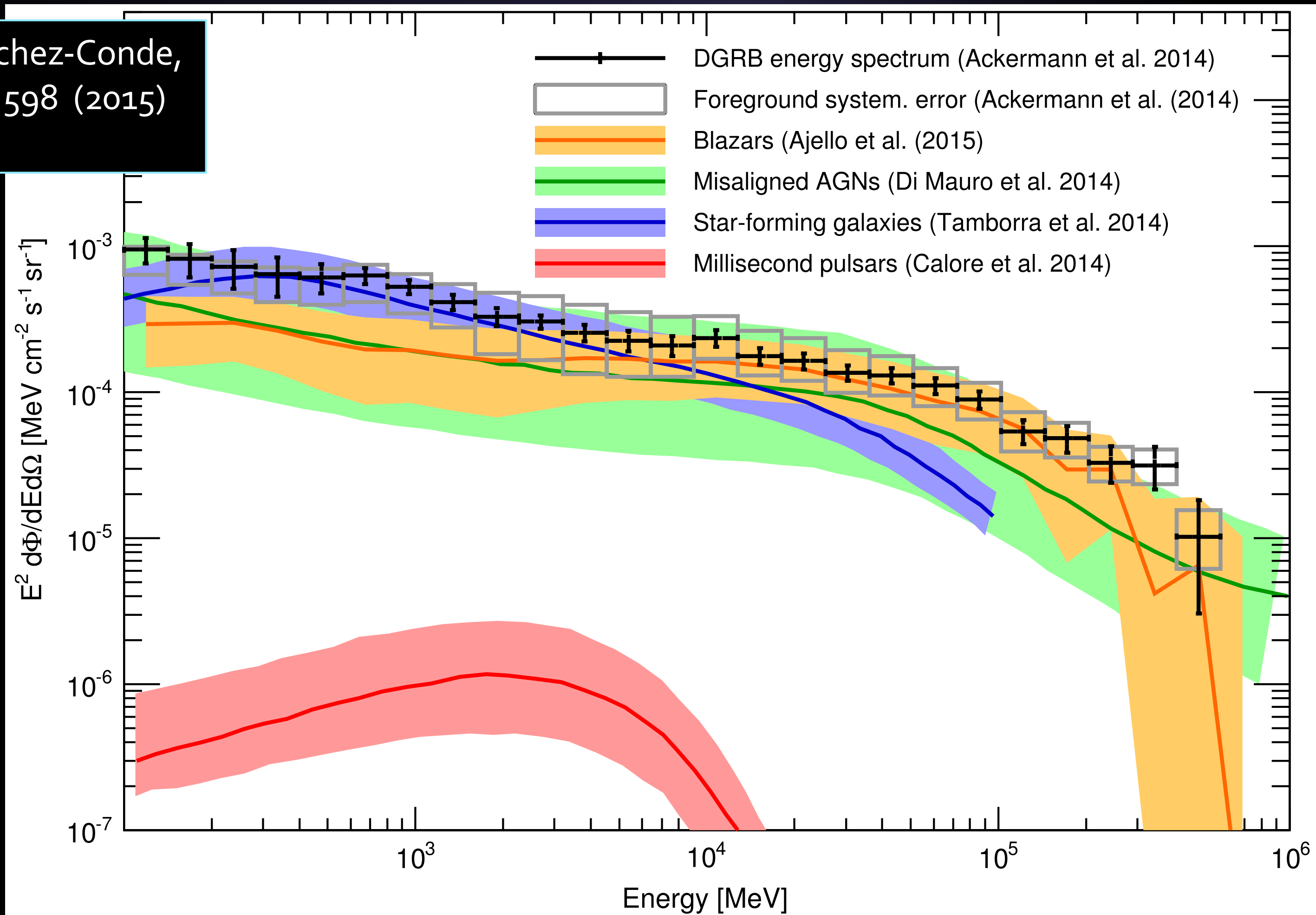
The Fermi LAT IGRB intensity spectrum



- Energy range: **100 MeV – 820 GeV**
- Significant **high-energy cutoff** feature in IGRB spectrum, consistent with simple source populations attenuated by EBL
- **~50% of total EGB** above 100 GeV now **resolved into individual LAT sources**

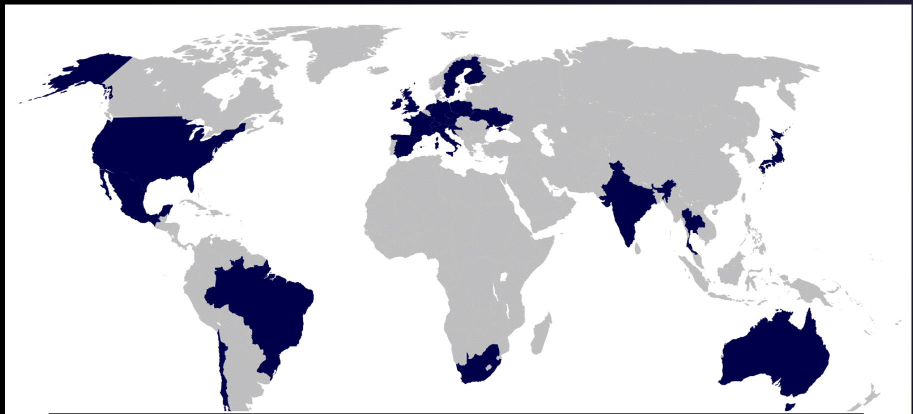
Origin of the IGRB

Fornasa & Sánchez-Conde,
Phys. Reports, 598 (2015)
[1502.02866]

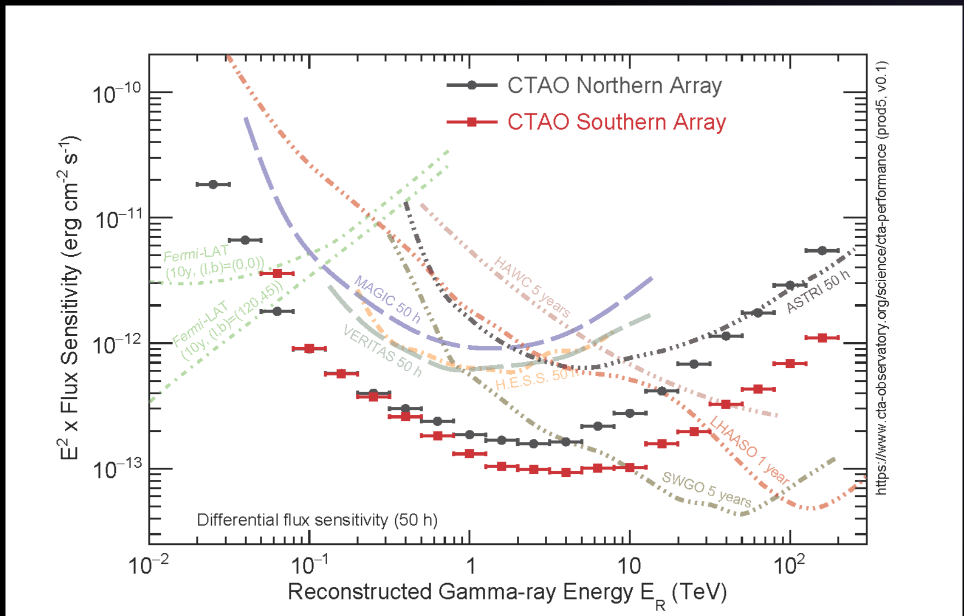


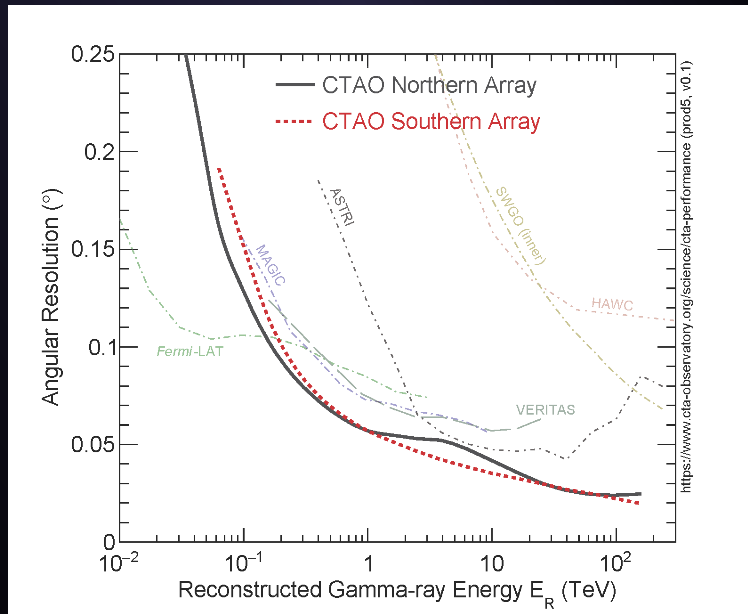
Cumulative emission of unresolved sources.

The future:
Cherenkov Telescope Array Observatory (CTAO)



The CTAO Consortium includes 1,500 members from more than 150 institutes in 25 countries.



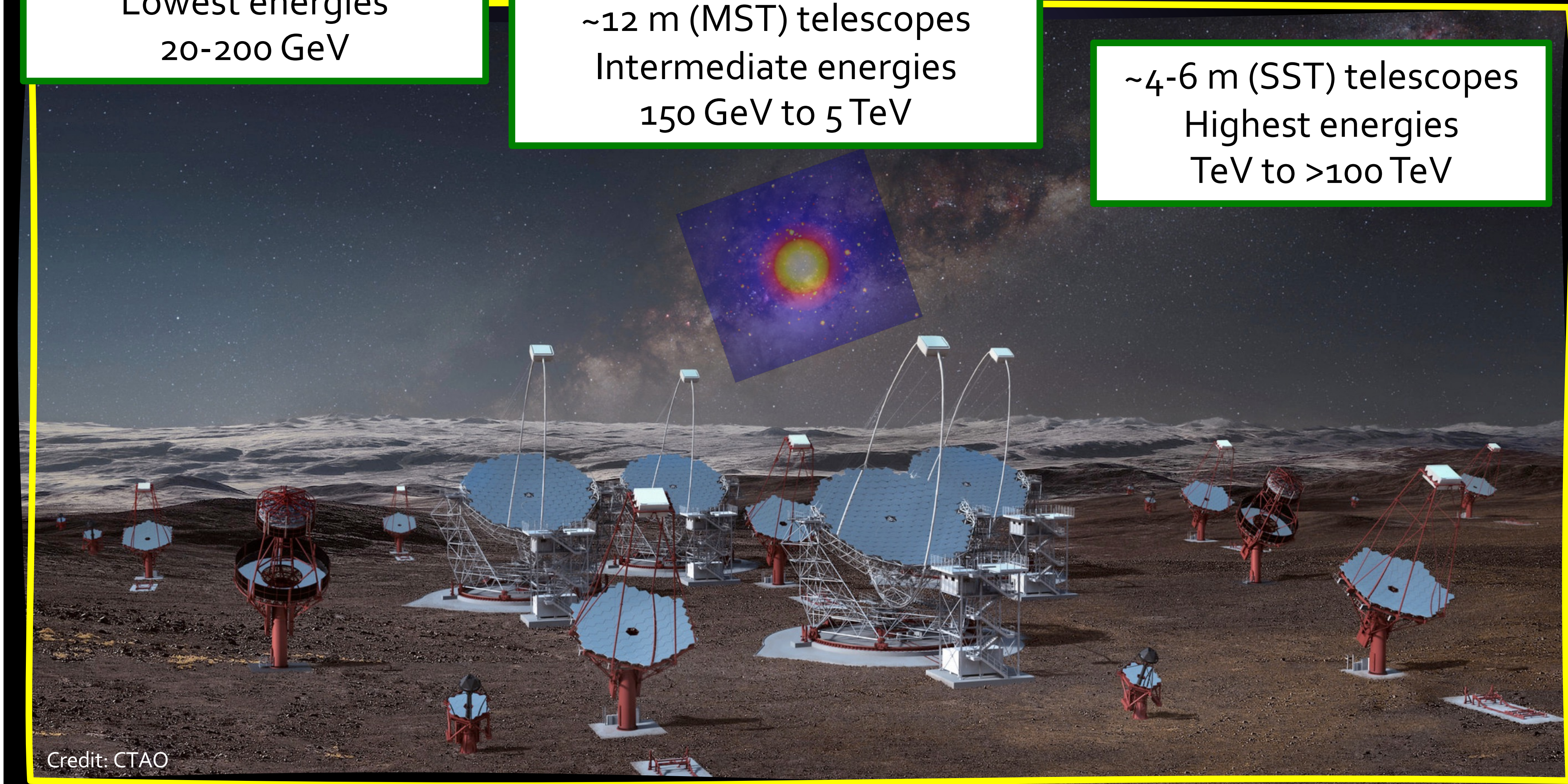


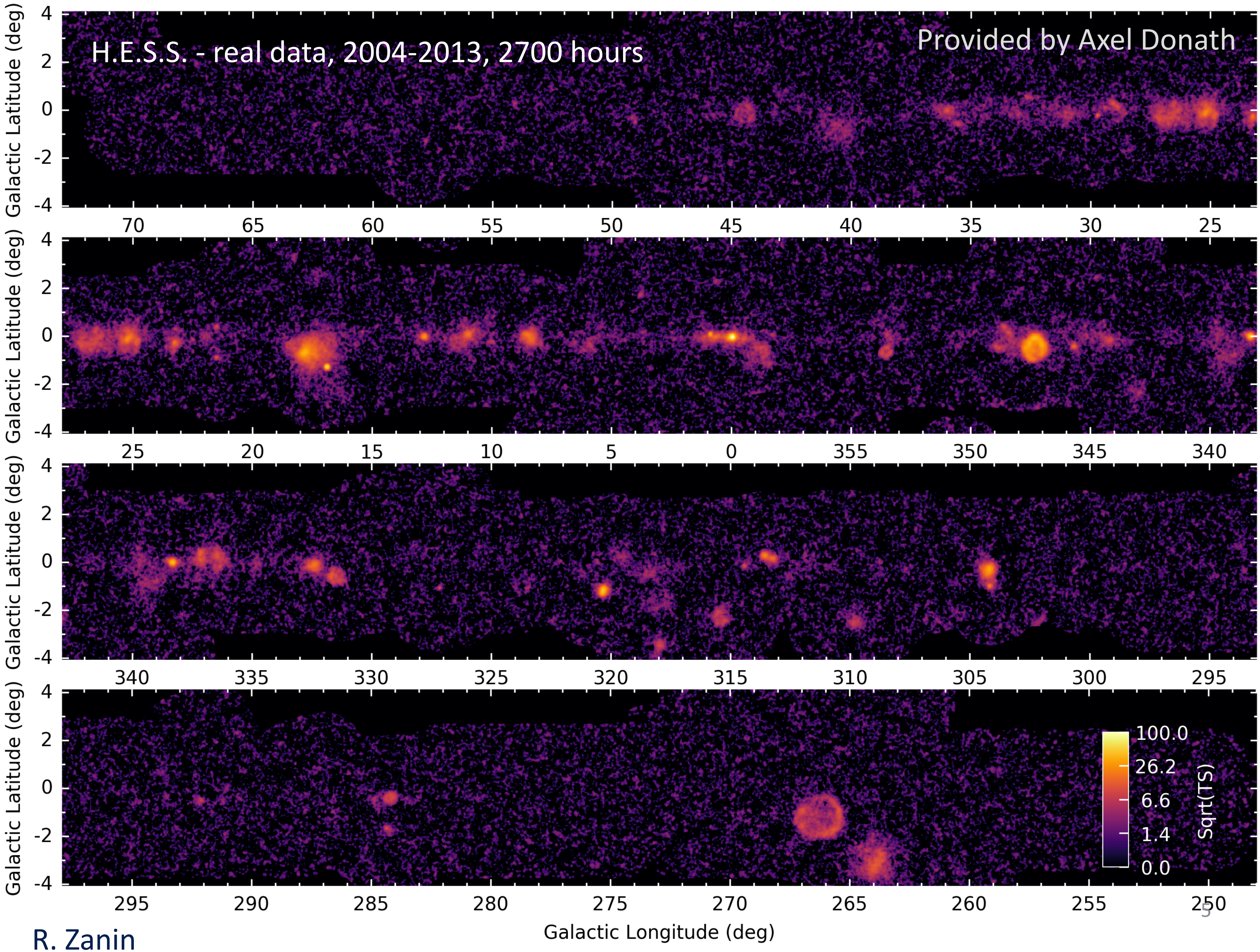
The future:
Cherenkov Telescope Array Observatory (CTAO)

23 m (LST) telescopes
Lowest energies
20-200 GeV

~12 m (MST) telescopes
Intermediate energies
150 GeV to 5 TeV

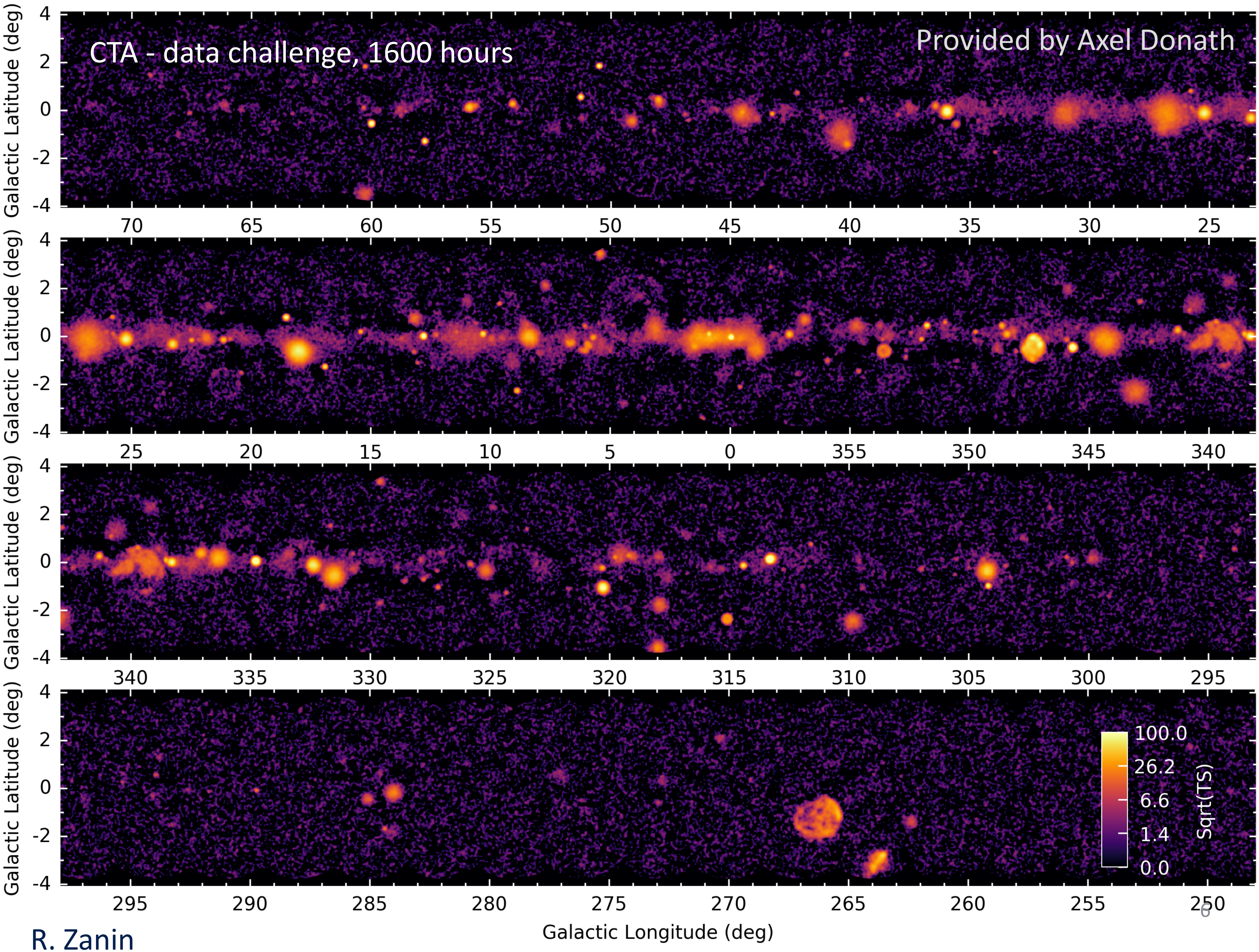
~4-6 m (SST) telescopes
Highest energies
TeV to >100 TeV





H.E.S.S. - real data, 2004-2013, 2700 hours
Provided by Axel Donath
Galactic Latitude (deg)
Galactic Longitude (deg)
Sqrt(TS)
100.0
26.2
6.6
1.4
0.0

R. Zanin



CTA - data challenge, 1600 hours
Provided by Axel Donath
Galactic Latitude (deg)
Galactic Longitude (deg)
Sqrt(TS)
100.0
26.2
6.6
1.4
0.0

R. Zanin

Summary of *main* CTA science opportunities

arXiv: 1709.07997

GAMMA-RAY
DARK MATTER SEARCHES

[BONUS TRACK]


Visible matter is just the tip of the iceberg
Credit: Hubble Ultra Deep Field – NASA

OBSERVATIONAL EVIDENCE OF DARK MATTER (DM)

Evidence has been reported at all scales, and it is only astrophysical as of today.

Galactic scales

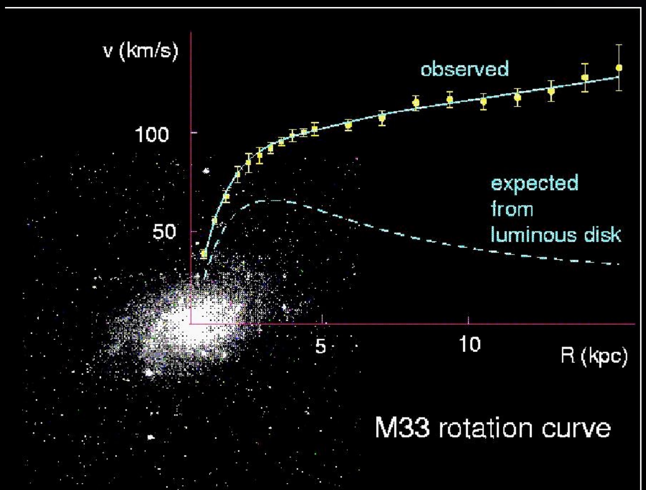
a) Rotation curves of spirals
b) Weak lensing
c) Velocity dispersions of satellite galaxies
d) Velocity dispersions in dwarfs

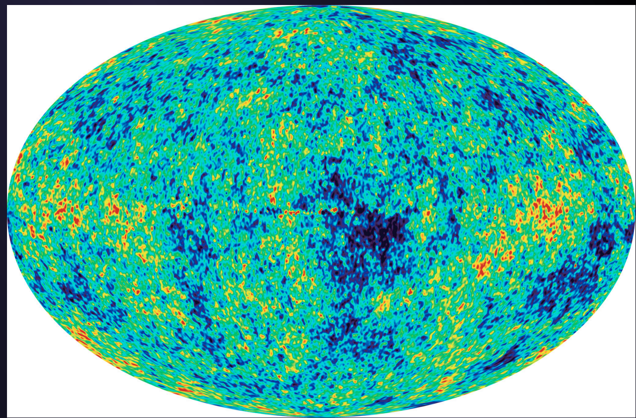
Galaxy cluster scales

a) Velocity dispersions of individual galaxies
b) Strong and weak lensing
c) Peculiar velocity flows
d) X-ray emission

Cosmological scales

a) CMB anisotropies
b) Growth of structure
c) LSS distribution
d) BAOs
e) SZ effect



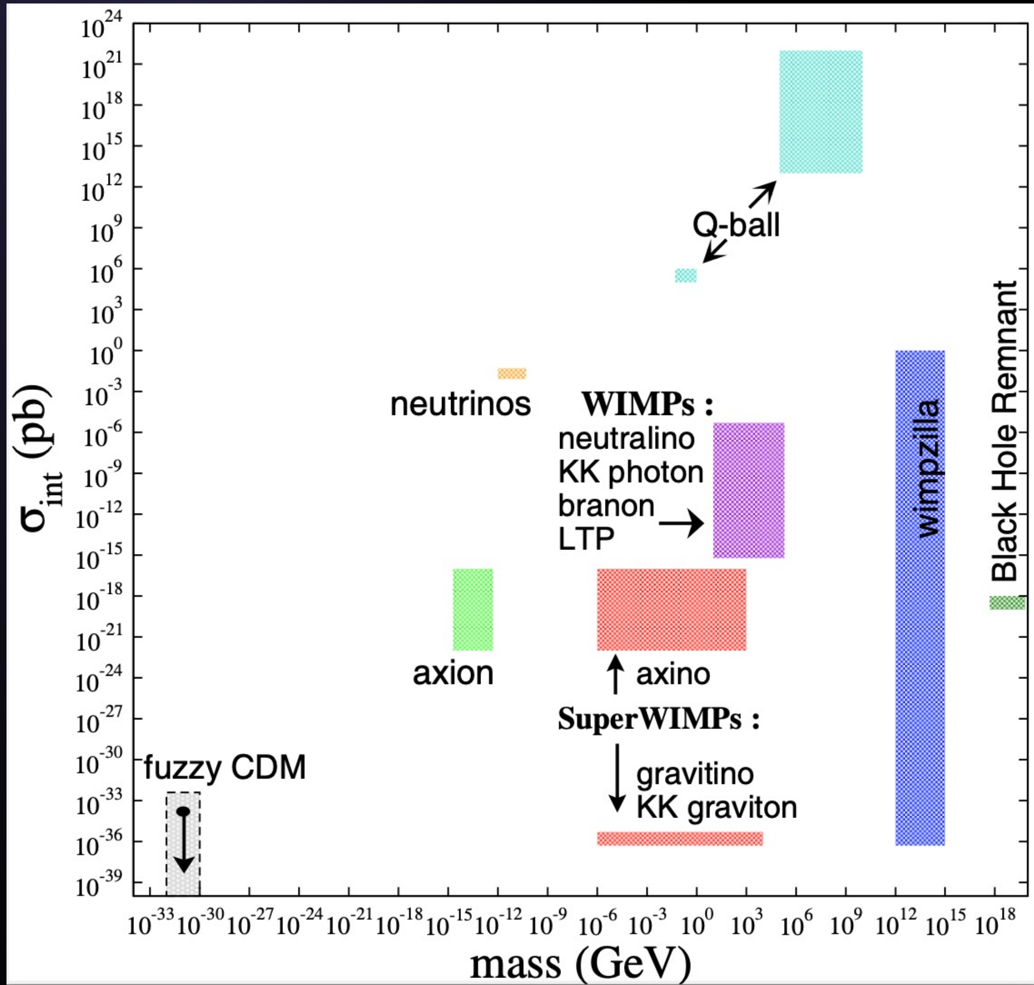


What could the DM be made of?

Most of the matter in the Universe must be in the form of non-baryonic DM.

- No viable candidate in the Standard Model
  - ✓ The neutrino, the only non-baryonic DM candidate known to exist, is excluded.
- Huge plethora of possible candidates beyond the Standard Model
- Requisites:

1) Neutral.
2) Stable/long-lived.
3) Cold.
4) Reproduce the measured DM amount



[DMSAG 2007; Baer+14; Conrad+17]

What could the DM be made of?

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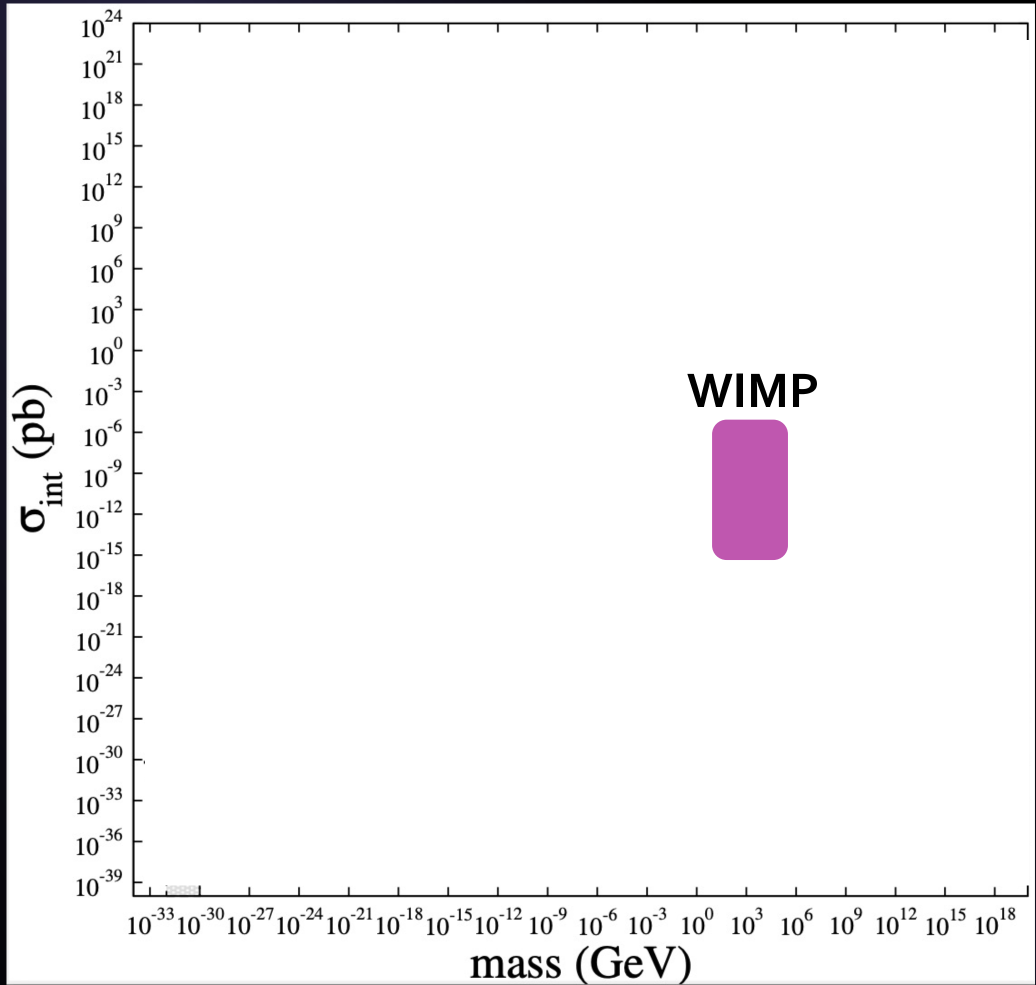
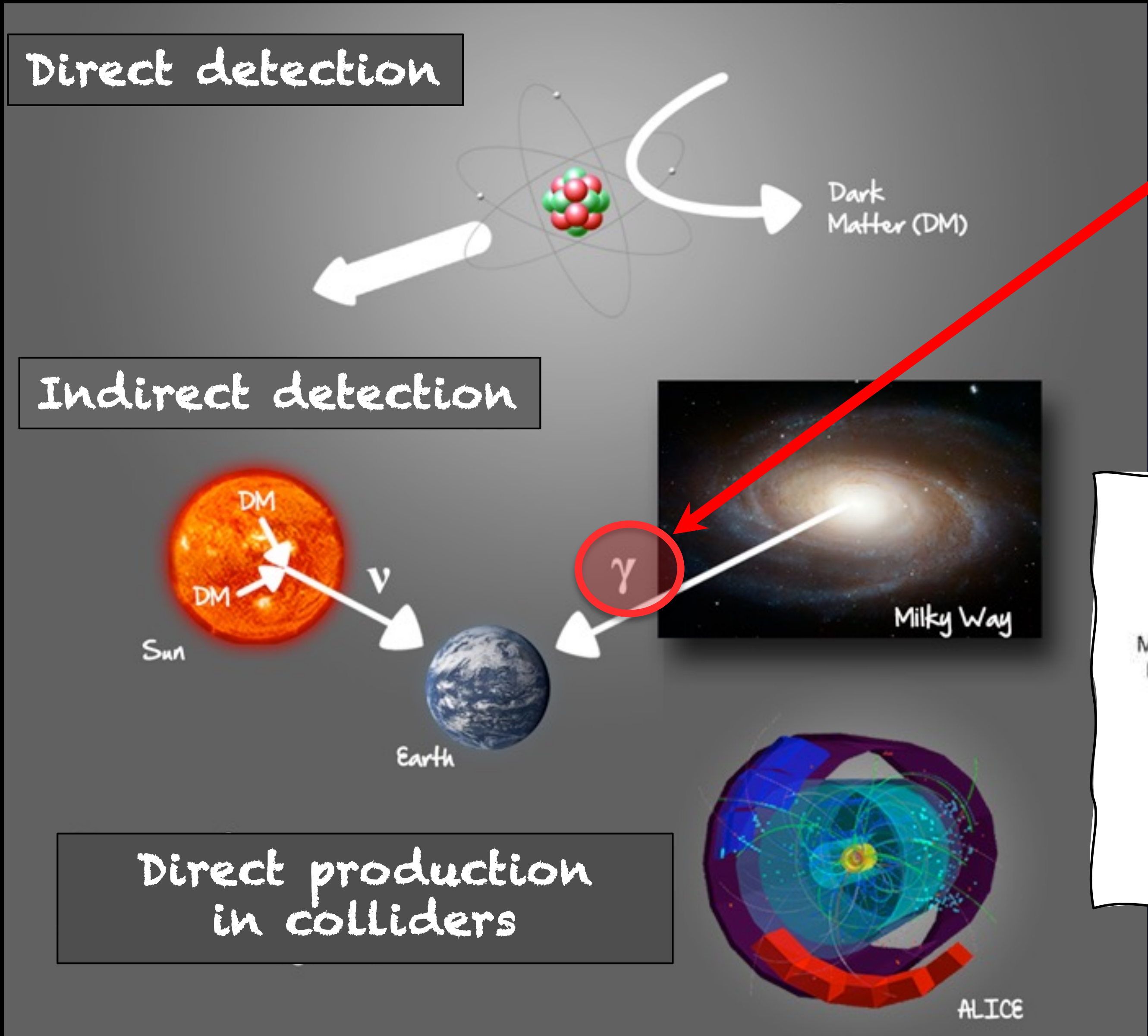
THIS LECTURE

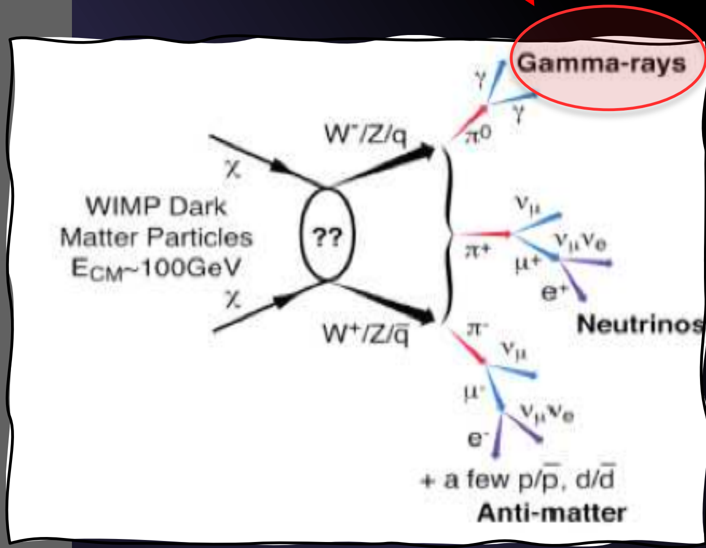


[DMSAG 2007; Baer+14; Conrad+17]

WIMP DM SEARCH STRATEGIES



Gamma rays are one of the possible **WIMP annihilation** products



Adapted from HAP / A. Chantelauze

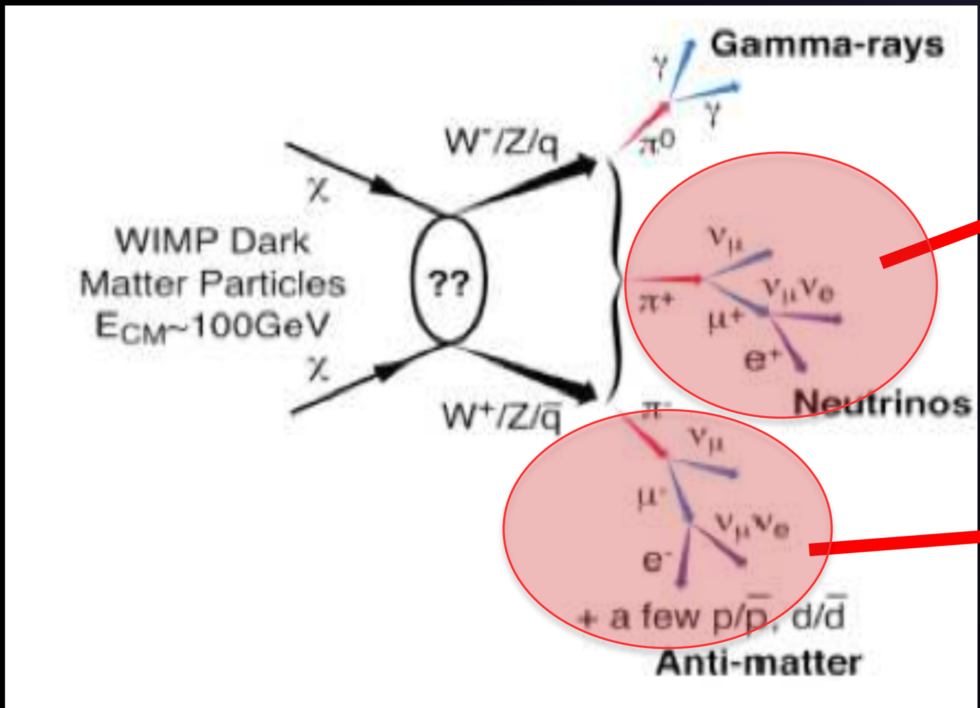
The 'golden channel': GAMMAS

Why gammas?

✓Energy scale of annihilation products set by DM particle mass
→ favored models ~GeV-TeV

✓Gamma-rays travel following straight lines
→ source can be known

✓[In the local Universe] Gamma-rays do not suffer from attenuation
→ spectral information retained.



Neutrinos
- ✓ No deflection
- ✓ No absorption
- ✓ BUT difficult to detect

Antimatter
- ✓ Low background in some cases
- ✓ BUT deflected by B fields
- ✓ BUT energy loses

The DM-induced gamma-ray flux

$$F(E_\gamma > E_{th}, \Psi_0) = J(\Psi_0) \times f_{PP}\left(E_\gamma > E_{th}\right)$$ photons cm^{-2} s^{-1}

Astrophysics

l.o.s. integration of the squared DM density

$$J(\Psi_0) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_{DM}^2[r(\lambda)]\, d\lambda$$

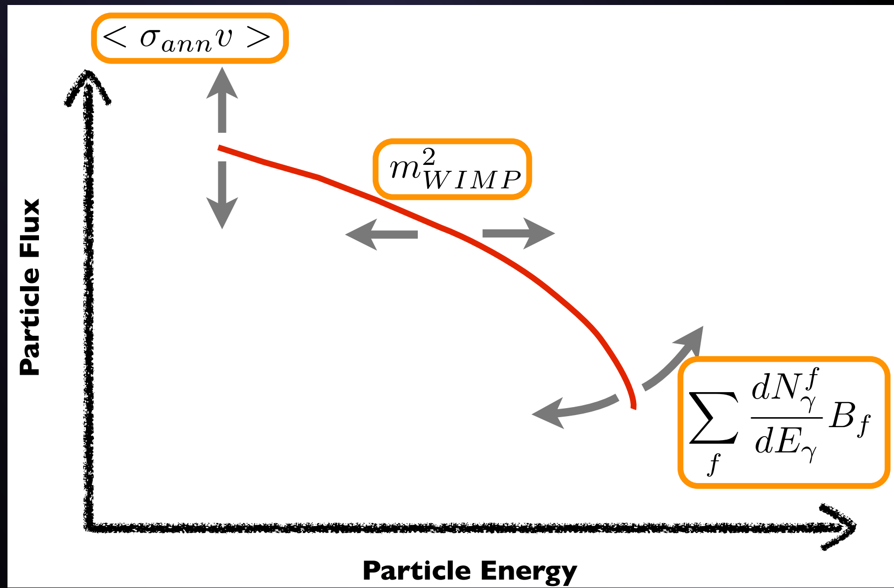
Where to search?

- Galactic Center
- Dwarf spheroidal galaxies
- Local galaxy clusters
- Nearby galaxies...

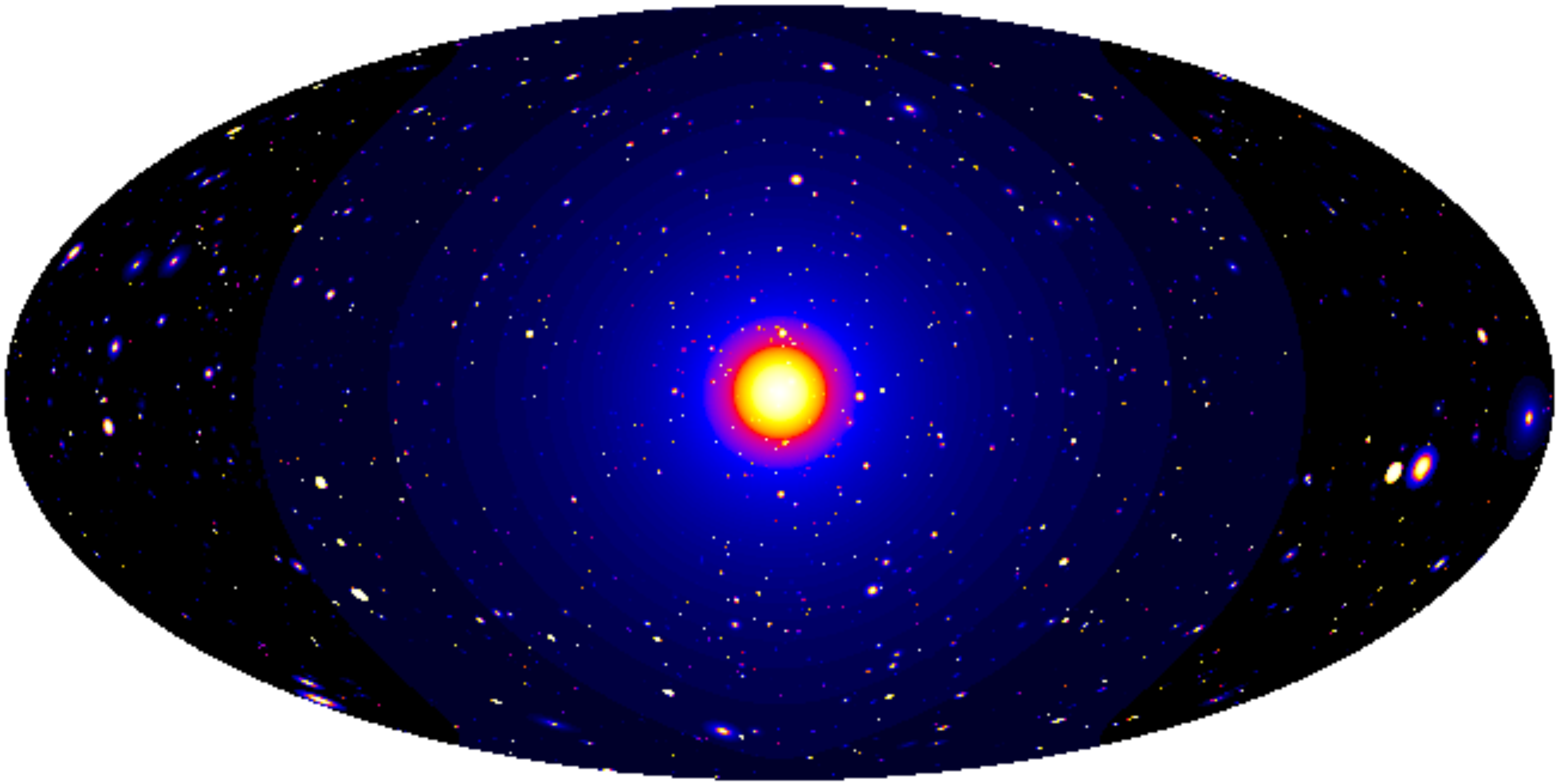
Particle physics

$$f_{PP} \propto \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f \frac{\langle \sigma \cdot v \rangle}{m_\chi^2}$$

- *N_γ: photons/annihilation*
- *$<\sigma v>$: thermal cross section*
- *m_χ: WIMP mass*

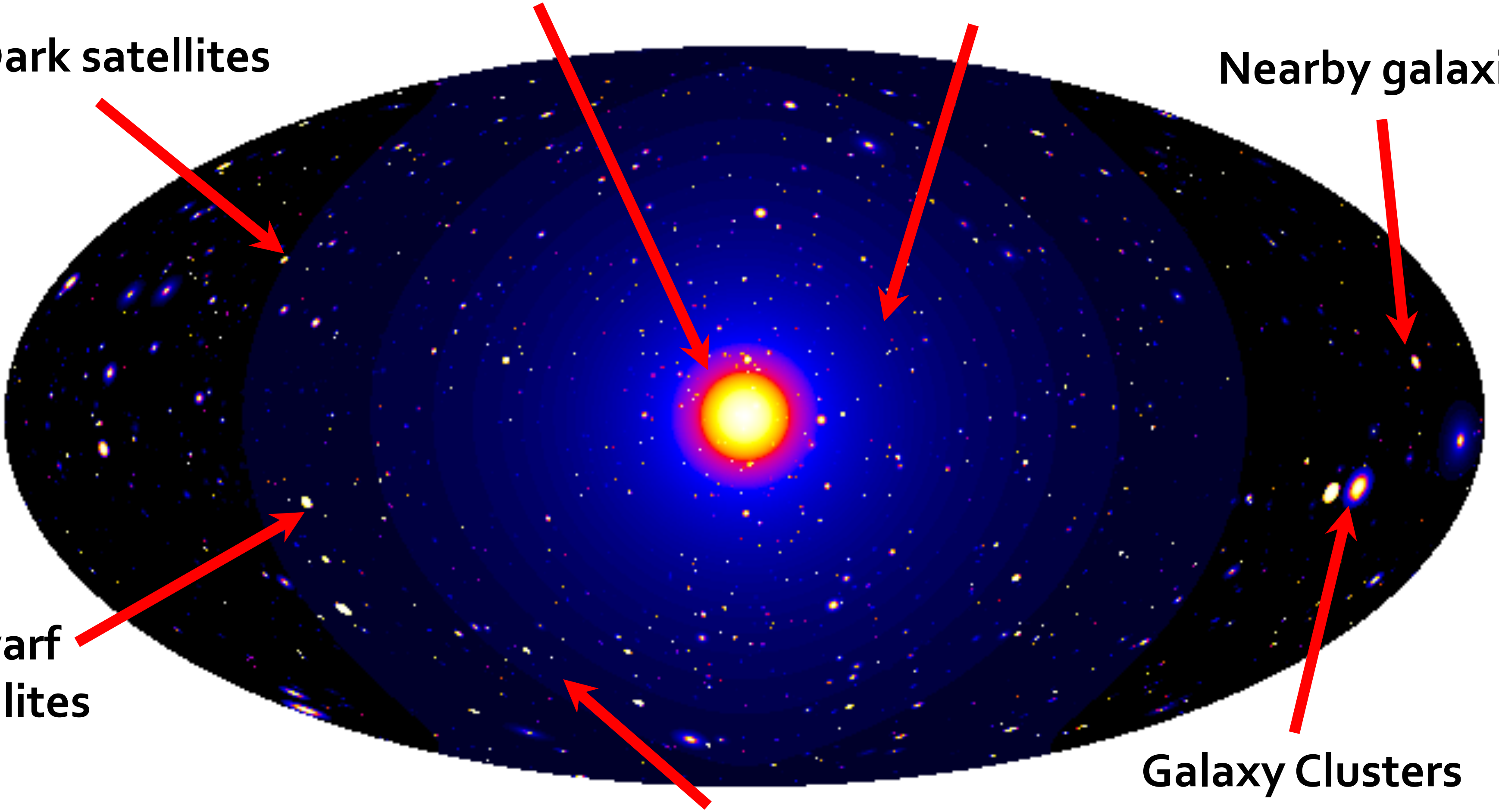


The dark matter-induced gamma-ray sky



Dark Matter simulation:
Pieri+09, arXiv:0908.0195

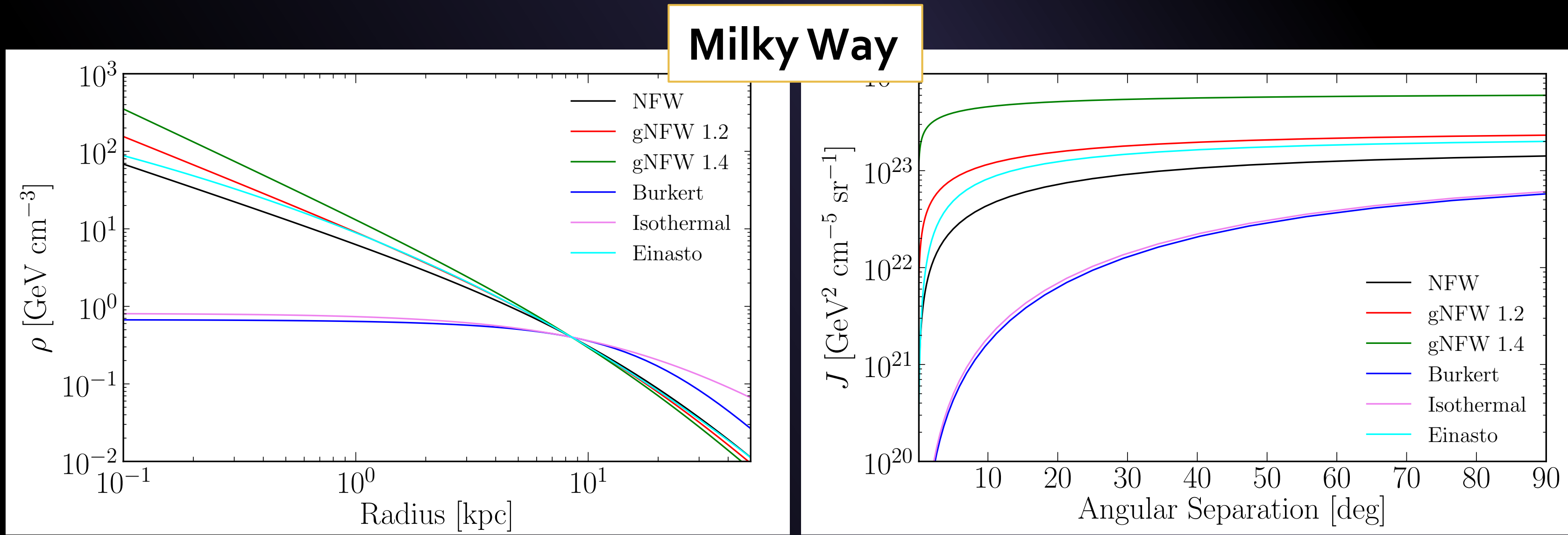
Dark Matter search strategies



+ Spectral Lines

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

Typical J-factors

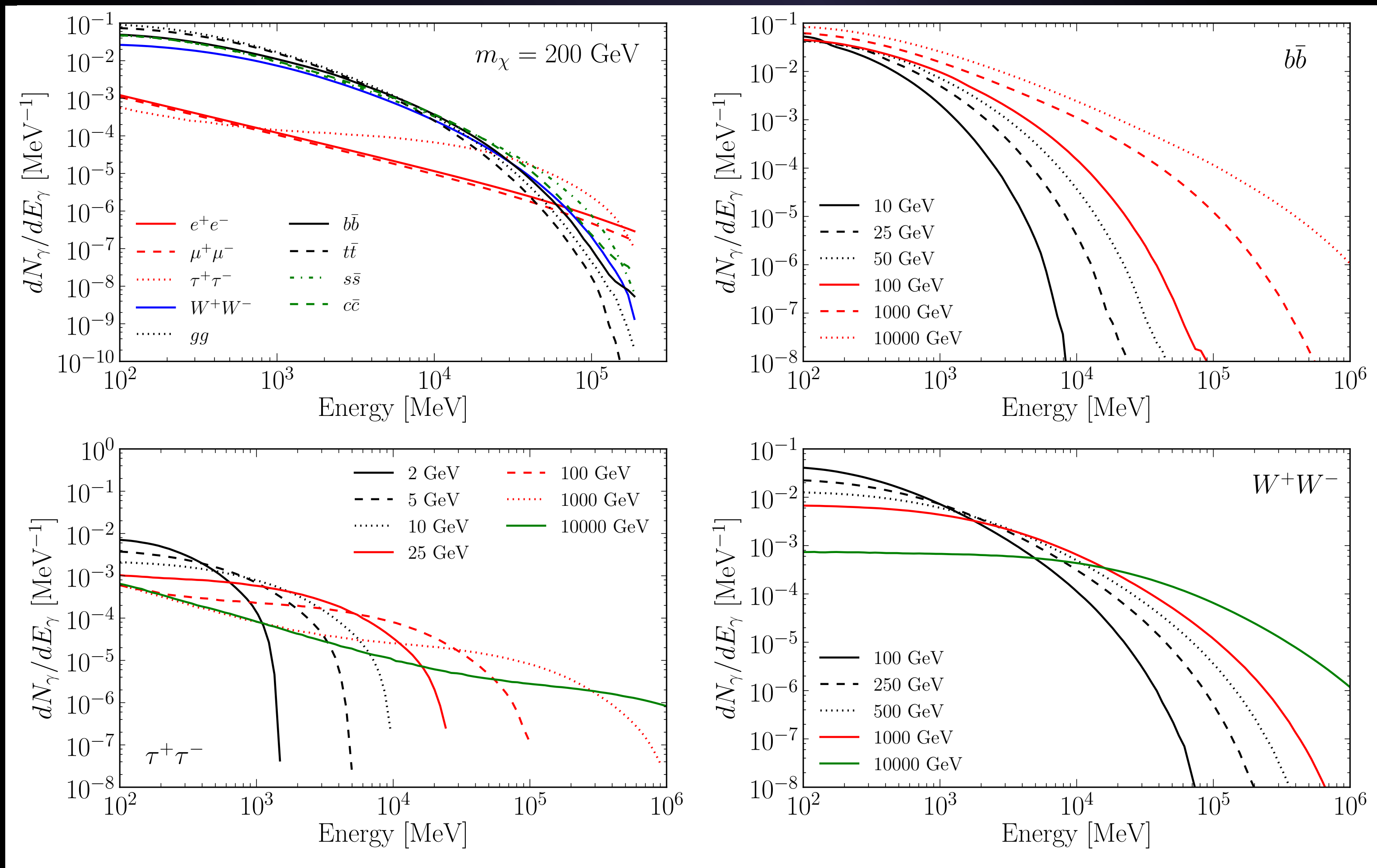


Target	Distance (kpc)	J factor ($\mathrm{GeV}^2\,\mathrm{cm}^{-5}$)	Angular Extent (°)
Galactic center / halo (§4.4)	8.5	3×10^{22} to 5×10^{23}	>10
Known Milky Way satellites (§4.5)	25 to 300	3×10^{17} to 3×10^{19}	<0.5
Dark satellites (§4.6)	up to 300	up to 3×10^{19}	<0.5
Galaxy Clusters (§4.7)	$>5\times10^{4}$	up to 1×10^{18}	up to ~ 3
Cosmological DM (§4.8)	$>10^{6}$	-	Isotropic

Charles, MASC+16, astro-ph/1605.02016

Annihilation spectra

1. Cut-off at the DM particle mass
2. Spectra of leptonic channels "harder" (i.e., "fall slower") than hadronic ones.



Charles, MASC+16, astro-ph/1605.02016

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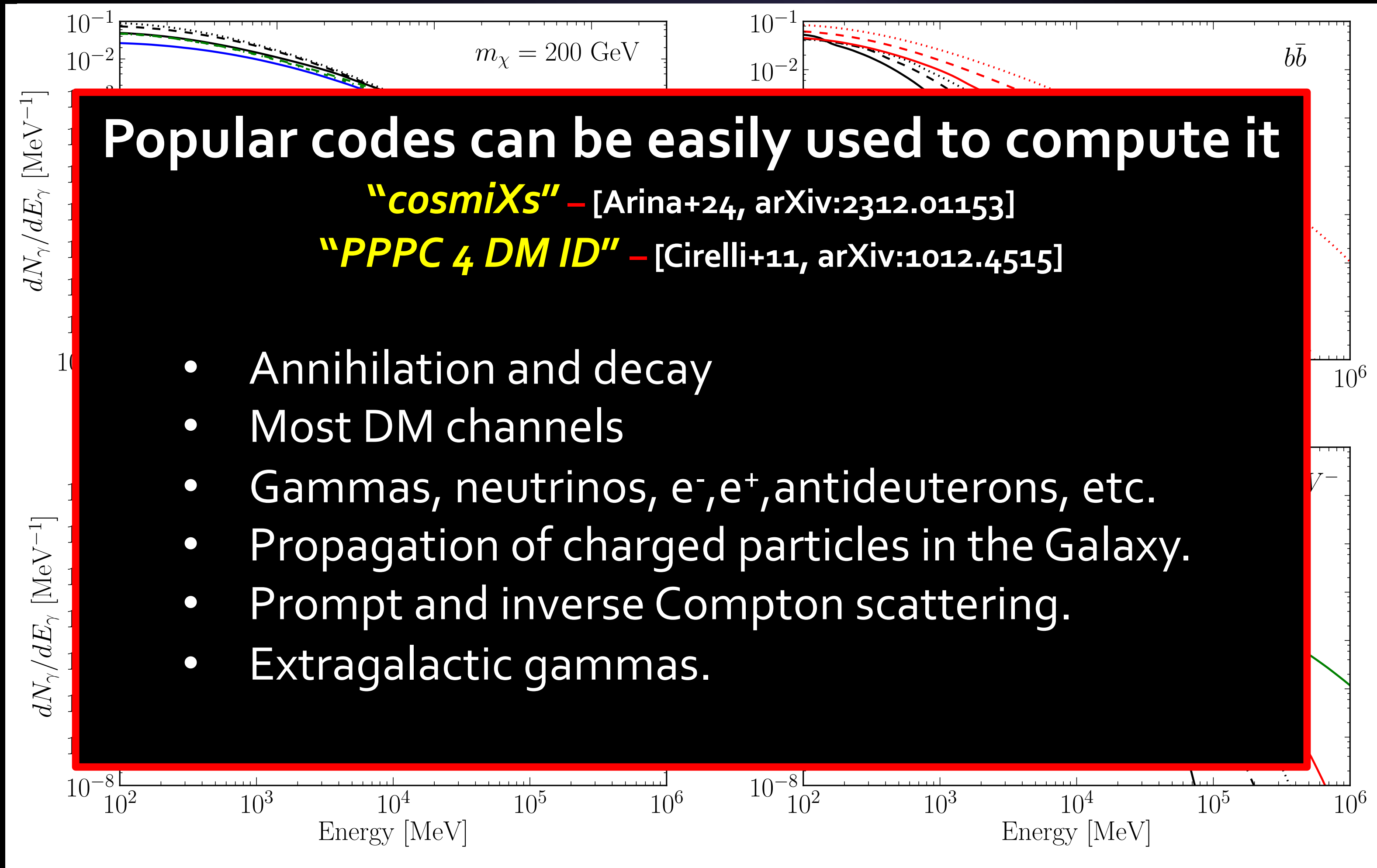


Popular codes can be easily used to compute it

“cosmiXs” – **[Arina+24, arXiv:2312.01153]**

“PPPC 4 DM ID” – **[Cirelli+11, arXiv:1012.4515]**

- Annihilation and decay
- Most DM channels
- Gammas, neutrinos, e^-,e^+,antideuterons, etc.
- Propagation of charged particles in the Galaxy.
- Prompt and inverse Compton scattering.
- Extragalactic gammas.

Charles, MASC+16, astro-ph/1605.02016

DM fluxes computation: CLUMPY

CLUMPY: multi-purpose code for indirect DM detection modelling and analysis

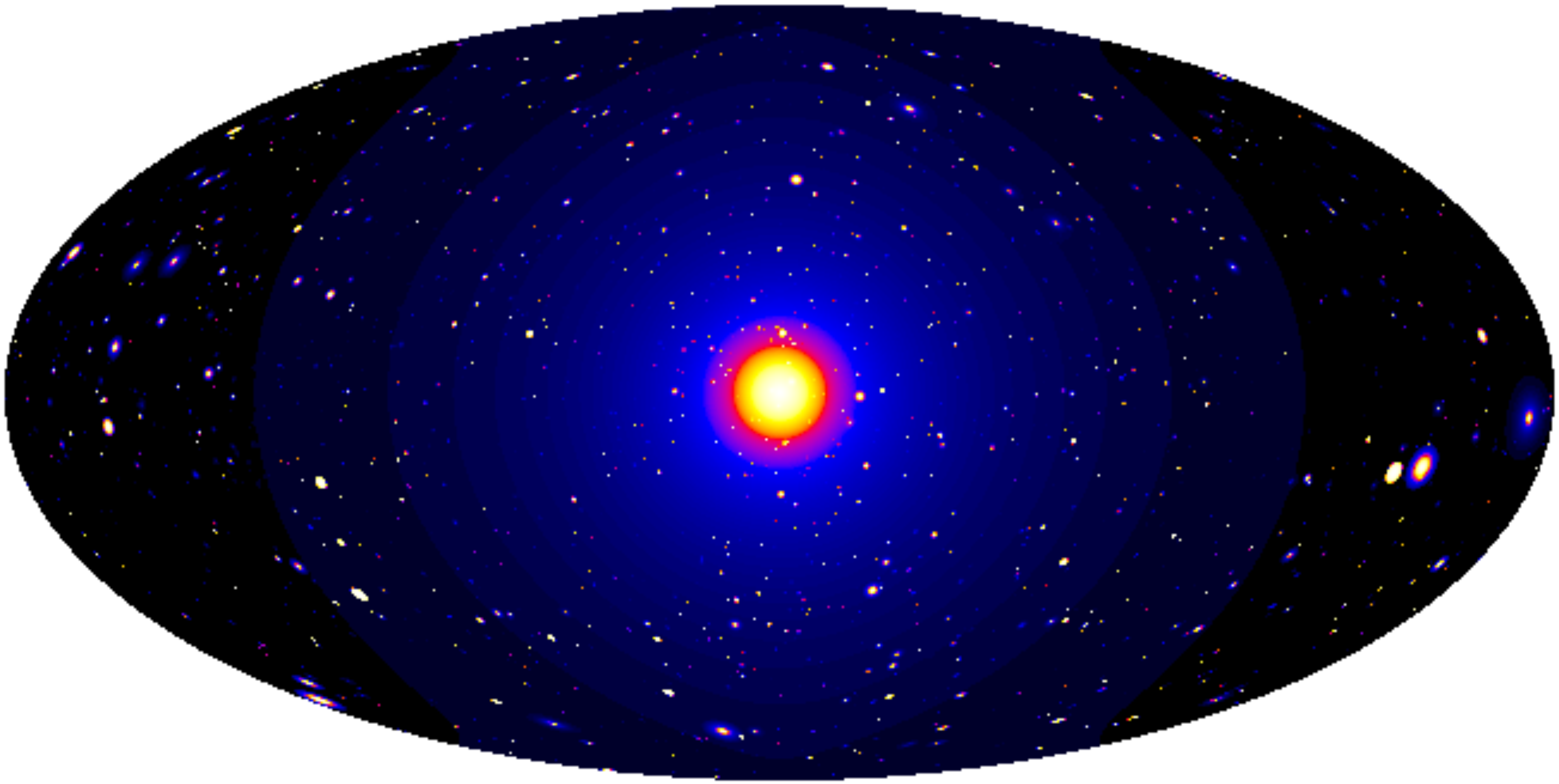
- Code distribution and usage:
  - Open-source: reproducible and comparable $\mathcal{J}$-factor calculations
  - User-friendly Sphinx documentation, lots of examples & tests to run
  - All runs from single parameter file or command line (profiles, concentration, spectra…)
- Fast computation of:
  - Annihilation or decay astrophysical factors using any DM profile
  - Boost from substructures and its uncertainty
  - Integrated/differential fluxes in γ-rays and neutrinos, mixing user-defined branching ratios
- Four main modules / physics cases:
  I. DM emission from list of objects (dSph galaxies, galaxy clusters)
  II. Full-sky map mode for Galactic DM emission with substructure + additional objects from list
  III. Jeans module: full analysis from kinematic data to $\mathcal{J}$-factors for dSph
  IV. Full-sky map mode for extragalactic DM emission

Growing use in the community for state-of-the-art DM studies for many targets (dSphs, cluster, dark clumps…) and by various collaborations (MAGIC, CTA, HAWC)

Download from **https://lpsc.in2p3.fr/clumpy/**

[Courtesy of M. Hütten]

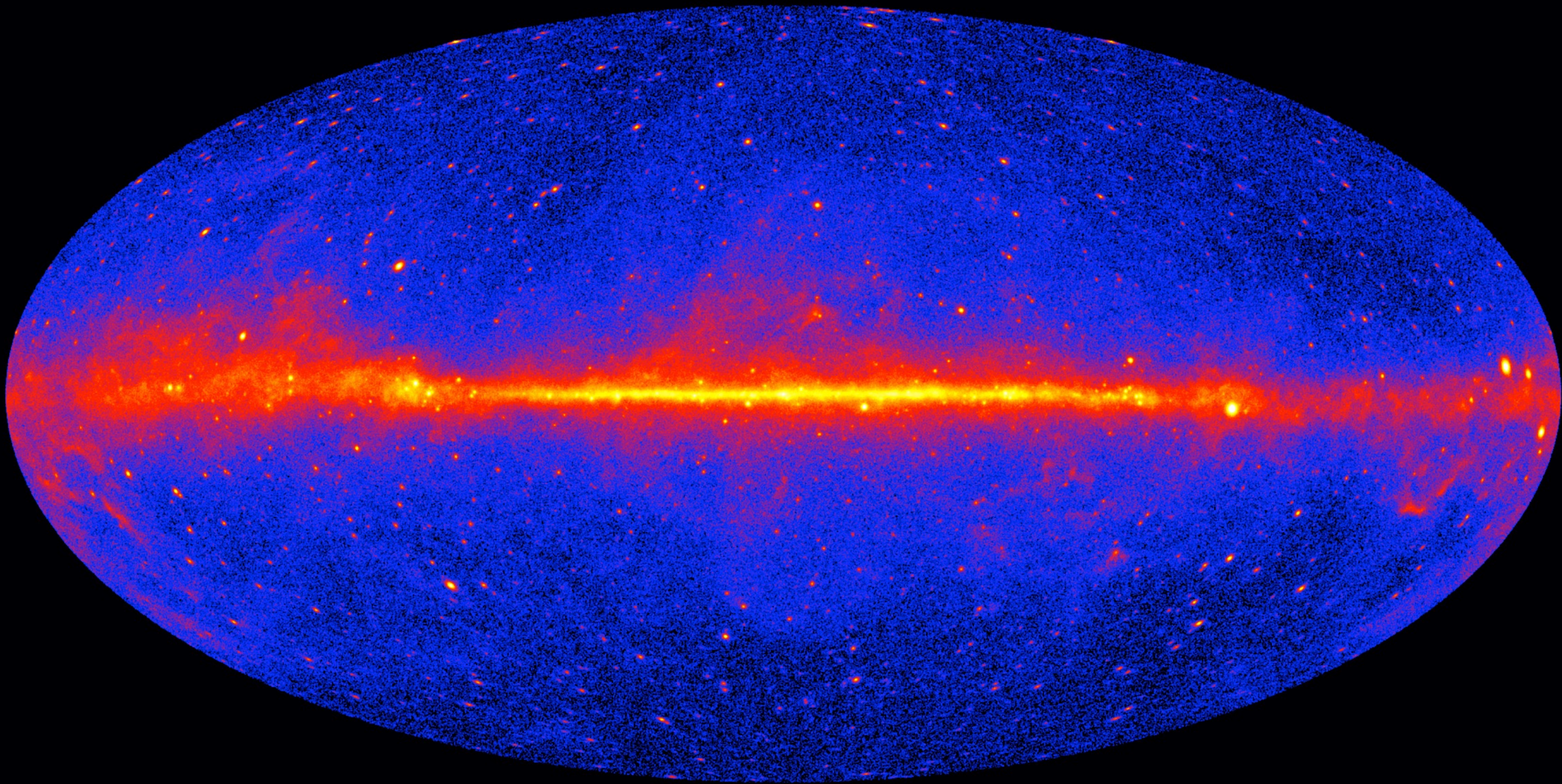
The dark matter-induced gamma-ray sky



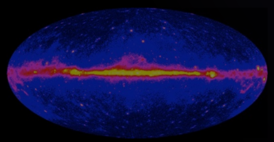
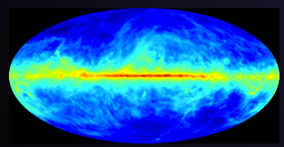
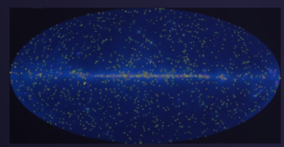
Dark Matter simulation:
Pieri+09, arXiv:0908.0195

THE GAMMA-RAY SKY above 1 GeV

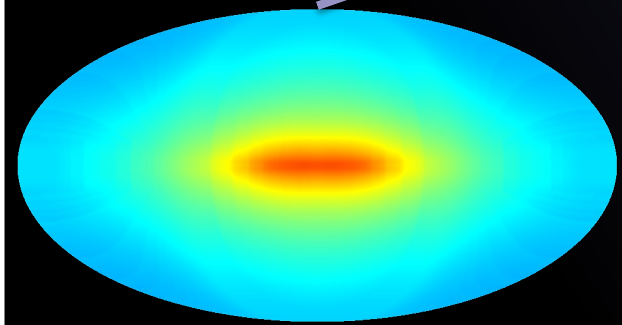
5 years of Fermi LAT data



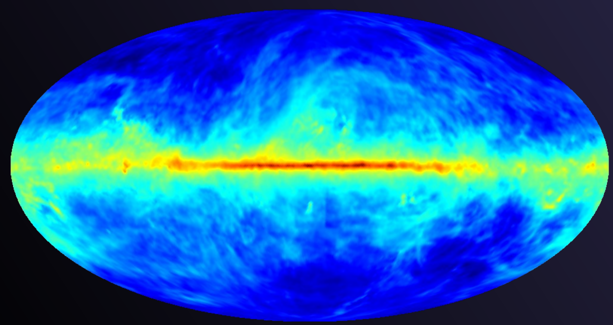
The complexity of the gamma-ray sky

 =  +  +  + ???

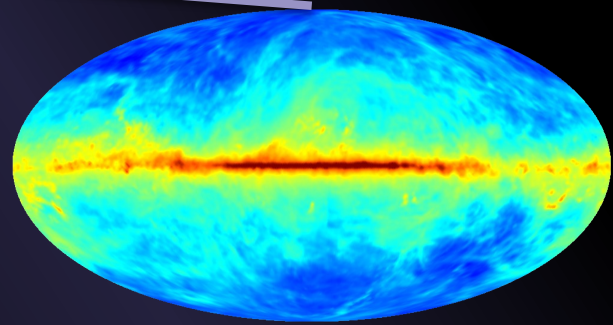
Galactic | Point Sources | Isotropic



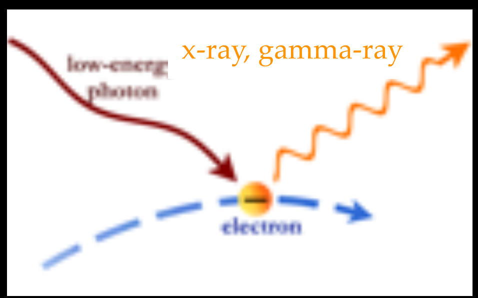
Inverse Compton

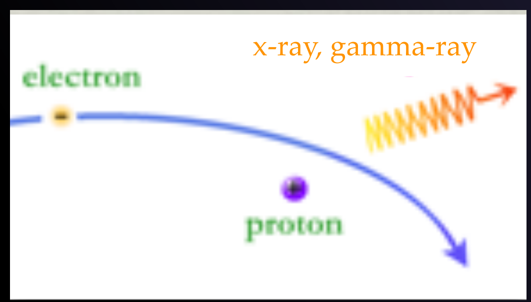


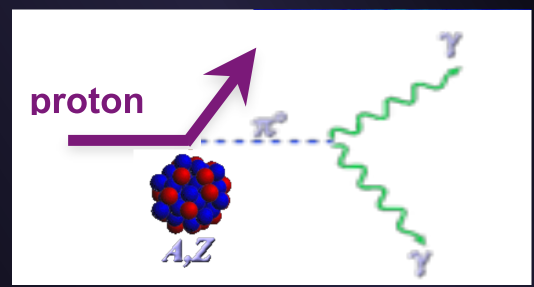
Bremsstrahlung



π^0 decay



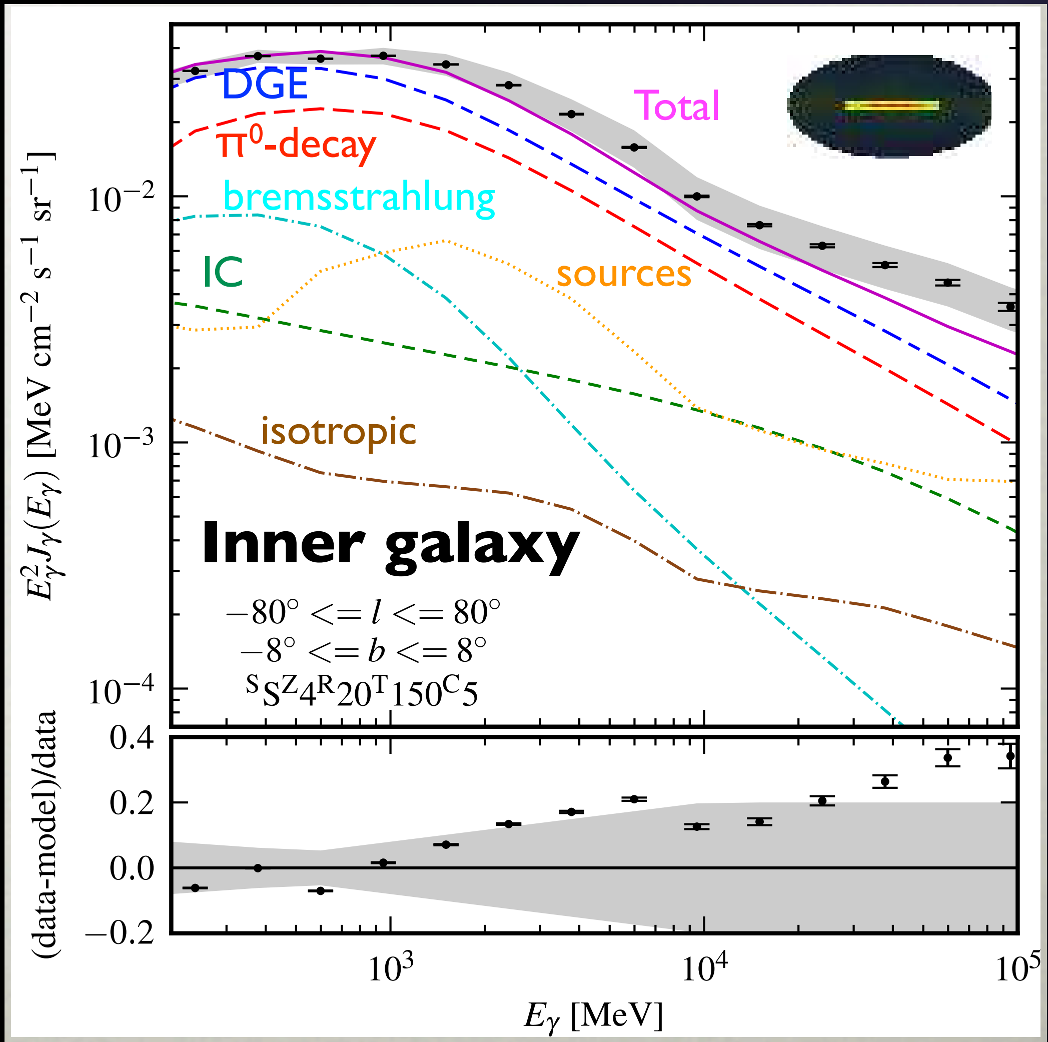




Need to disentangle dark matter annihilations from 'conventional' astrophysics.

Crucial to understand the astrophysical processes in great detail.

Putting all the astrophysics together



Fermi-LAT Collaboration, astro-ph/1202.4039

Galactic diffuse

+

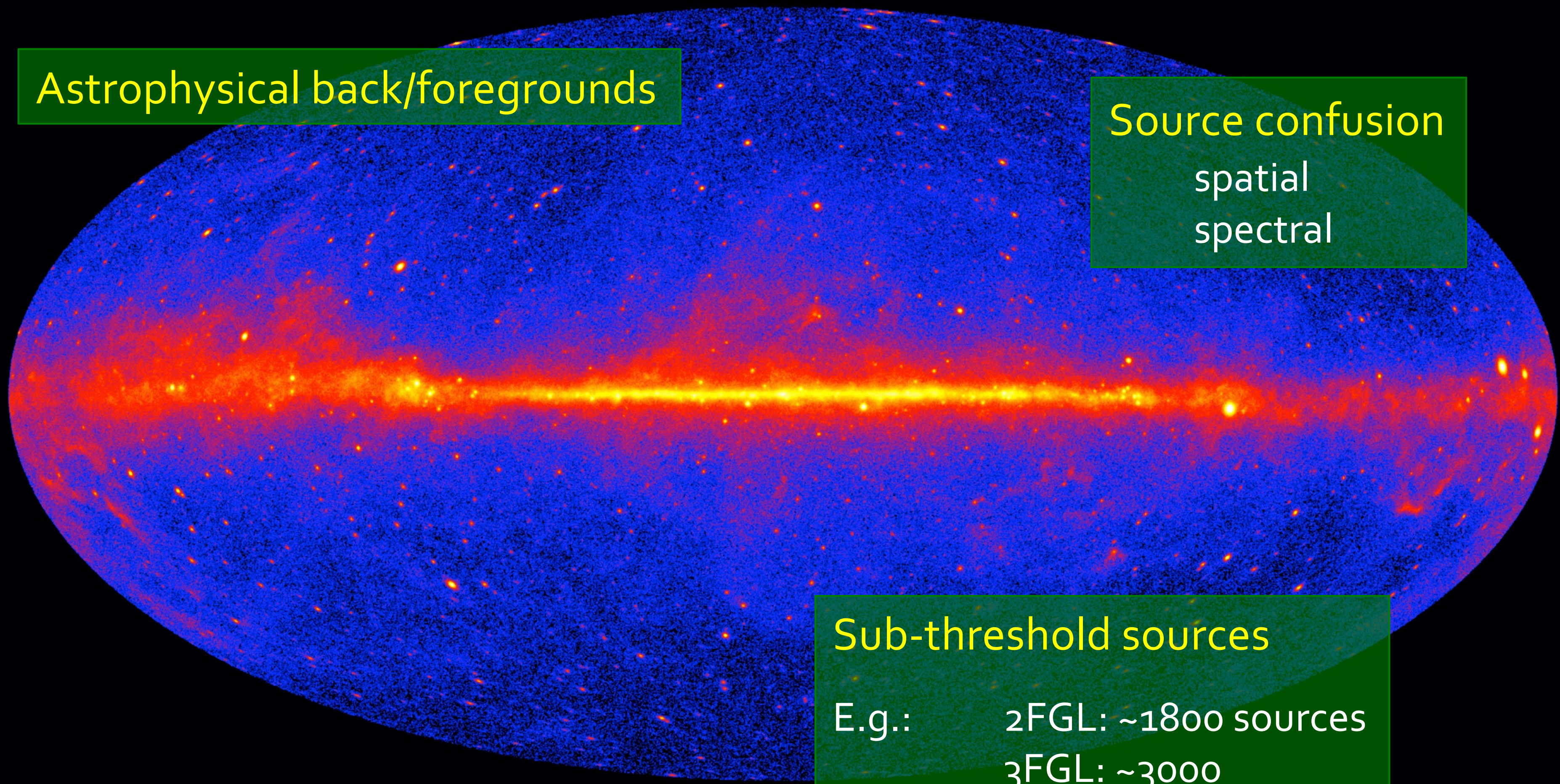
Point sources

+

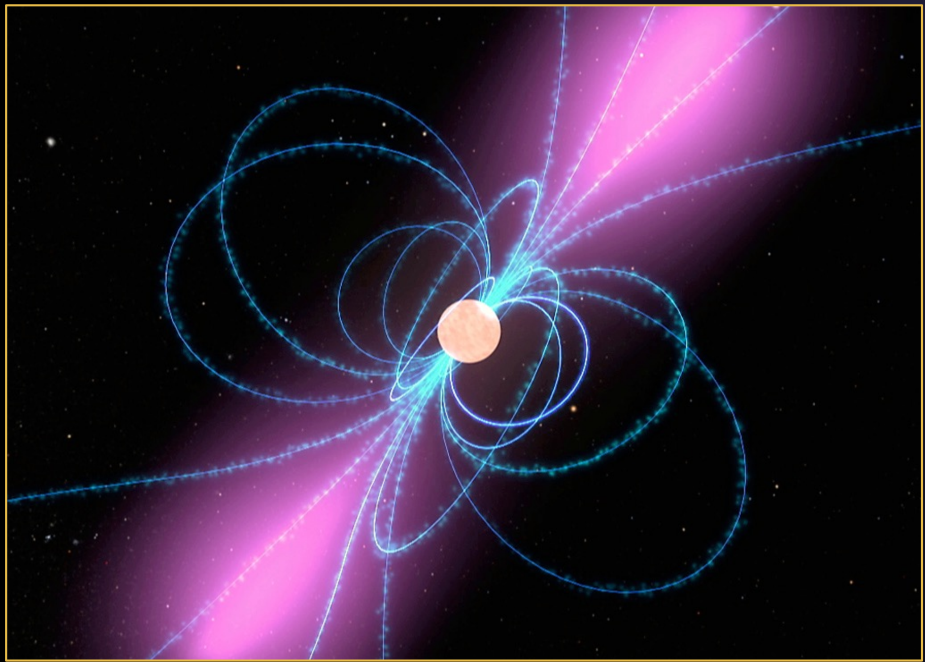
isotropic

Room for dark matter only
in the residuals of the best-fit…

Gamma-ray DM analysis challenges

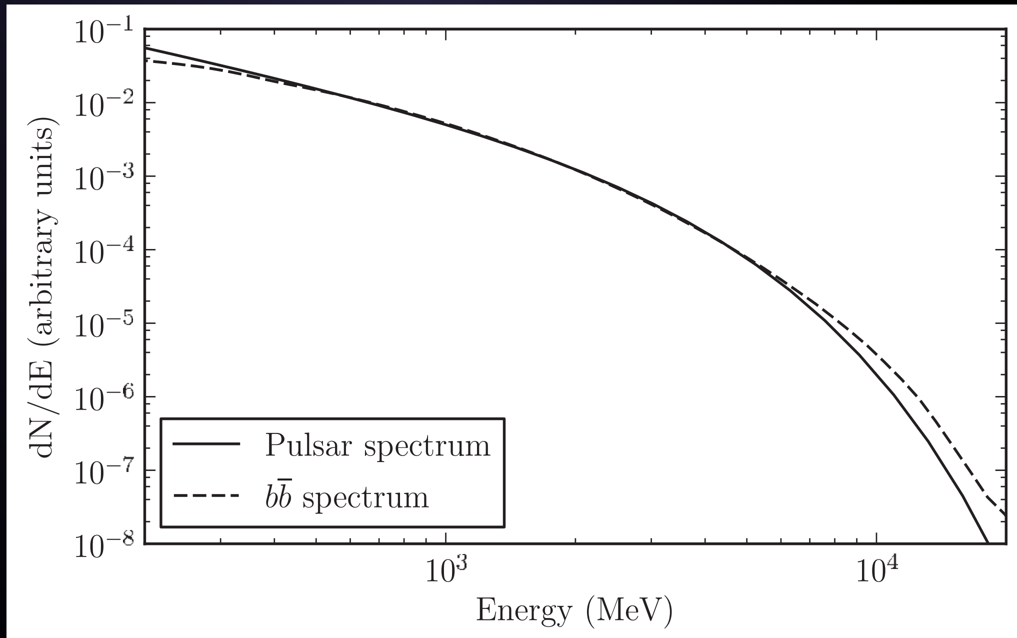


Example of source confusion:
Dark matter or Pulsars?



NASA/Fermi

Highly magnetized, rotating neutron star that emits beams of EM radiation (from radio to gamma-rays)



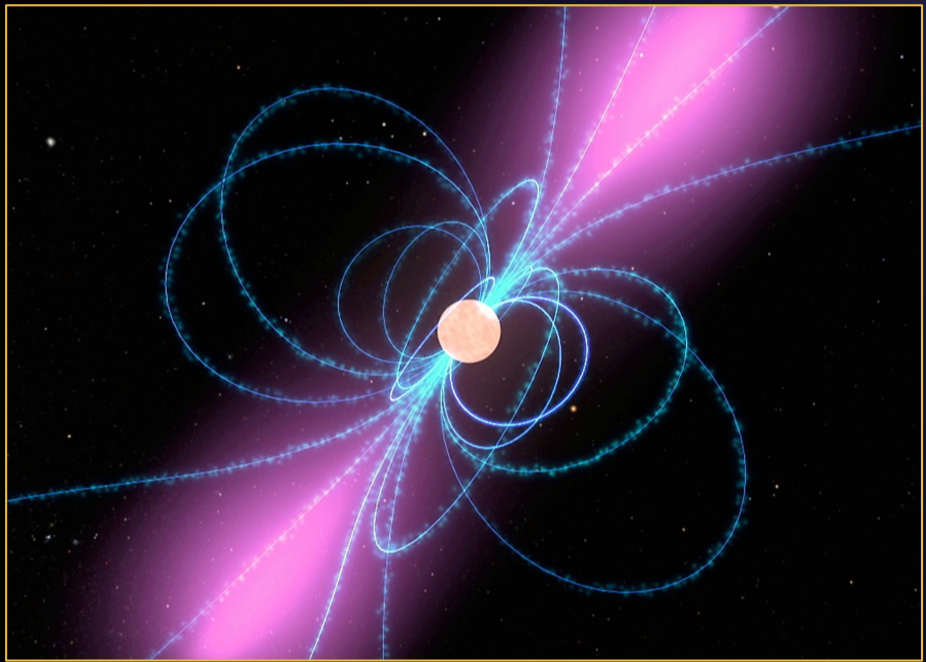
1FGL J0030+0451 Millisecond Pulsar

The best-fit DM spectrum and the best-fit pulsar spectrum can be very similar.

→ Very specially for bb channel.

→ Low WIMP masses.

Example of source confusion:
Dark matter or Pulsars?



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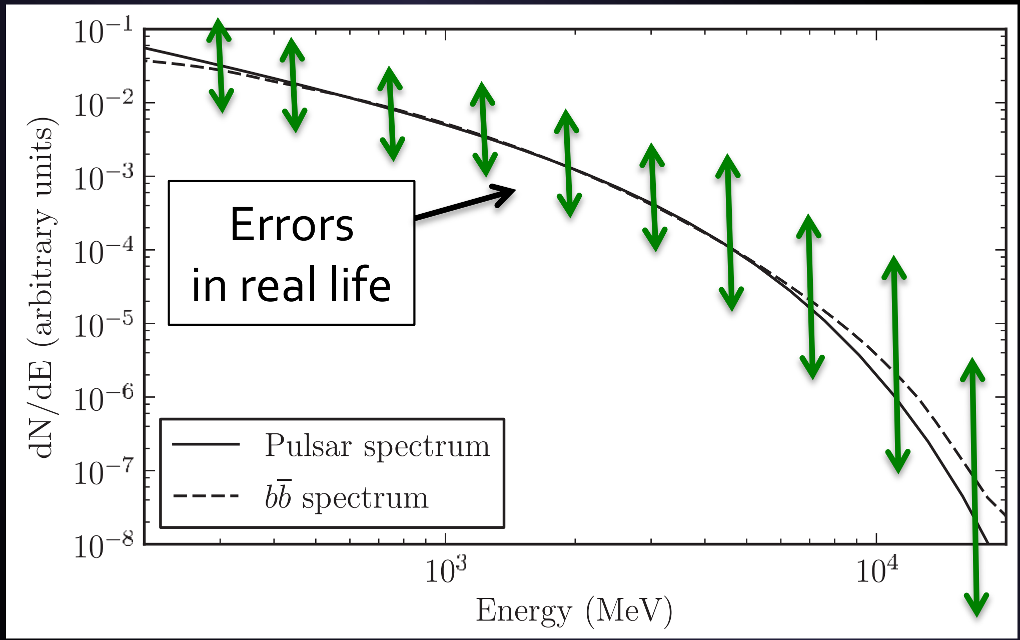
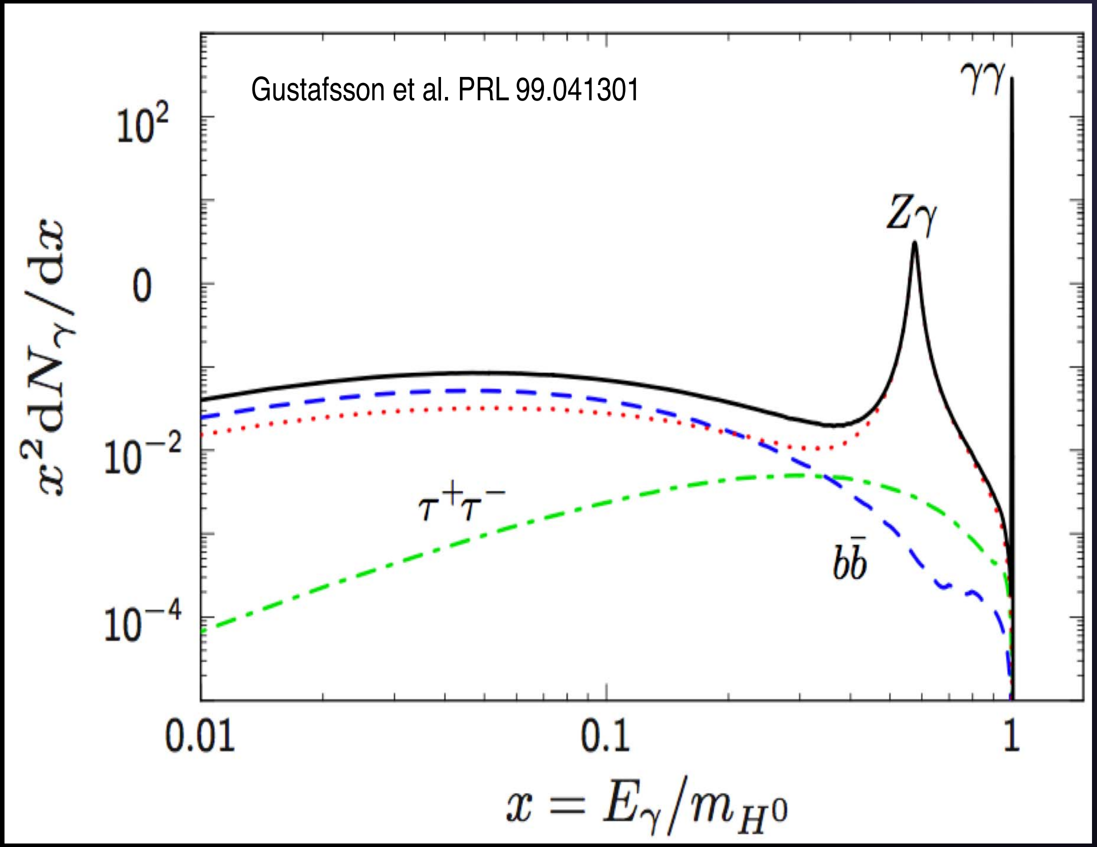


1FGL J0030+0451 Millisecond Pulsar

How to be sure?

Critical features in the spectrum should be universal:

1) Continuum gamma-ray spectrum with a cut-off at the particle mass
2) Mono-energetic lines → smoking gun (but loop suppressed)
3) Signal in several targets



Plus complementarity with other detection techniques!

DM search in real life

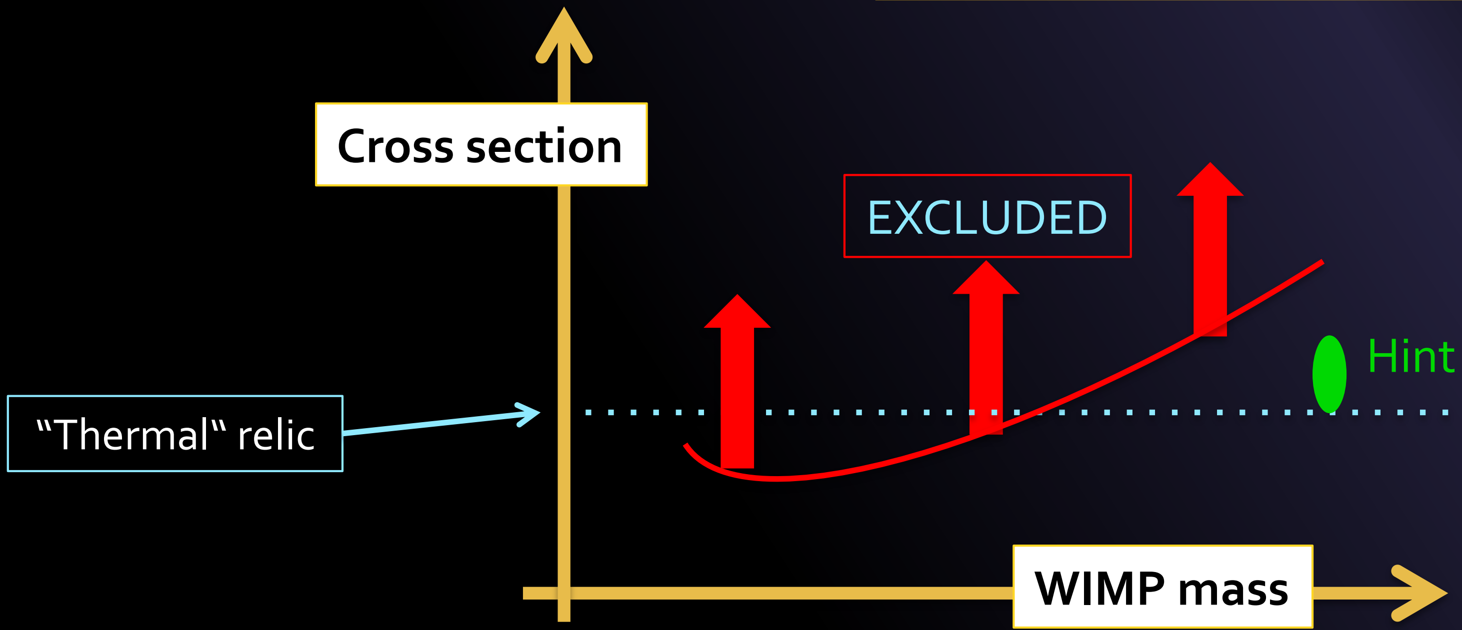
- Search for a DM signal in the data:
  - → No significant signal is found.
  - → Some signal is found but not sure it is real ('hints'; more later!)
- In both cases, we can set **limits on the DM parameter space.**

$$F(E > E_{th}) = J_{factor} * f_{pp}(E > E_{th})$$

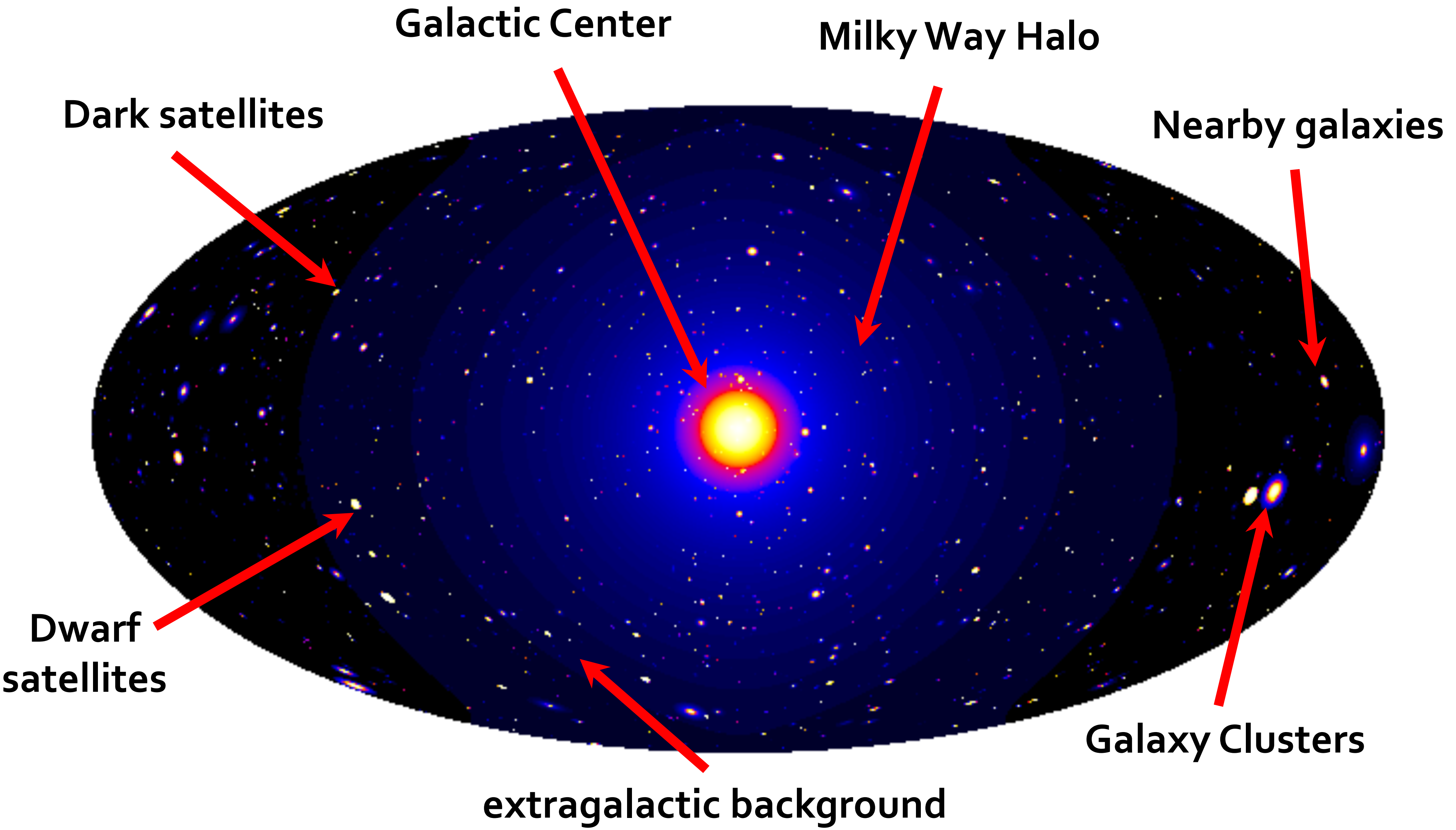
Astrophysics (Density profile, distance…) — **Particle Physics** (channel, annihilation spectra…)

$$\langle \sigma v \rangle \propto \frac{m_\chi^2 \cdot F_{min}}{J_{factor} \cdot \int_{E_{th}}^{E} \left(\frac{dN}{dE}\right) dE} = \frac{m_\chi^2 \cdot F_{min}}{J_{factor} \cdot N_\gamma}$$

Instrument (F_{min}) — Theory (N_γ) — Sims / Observations (J_{factor})



Dark Matter search strategies

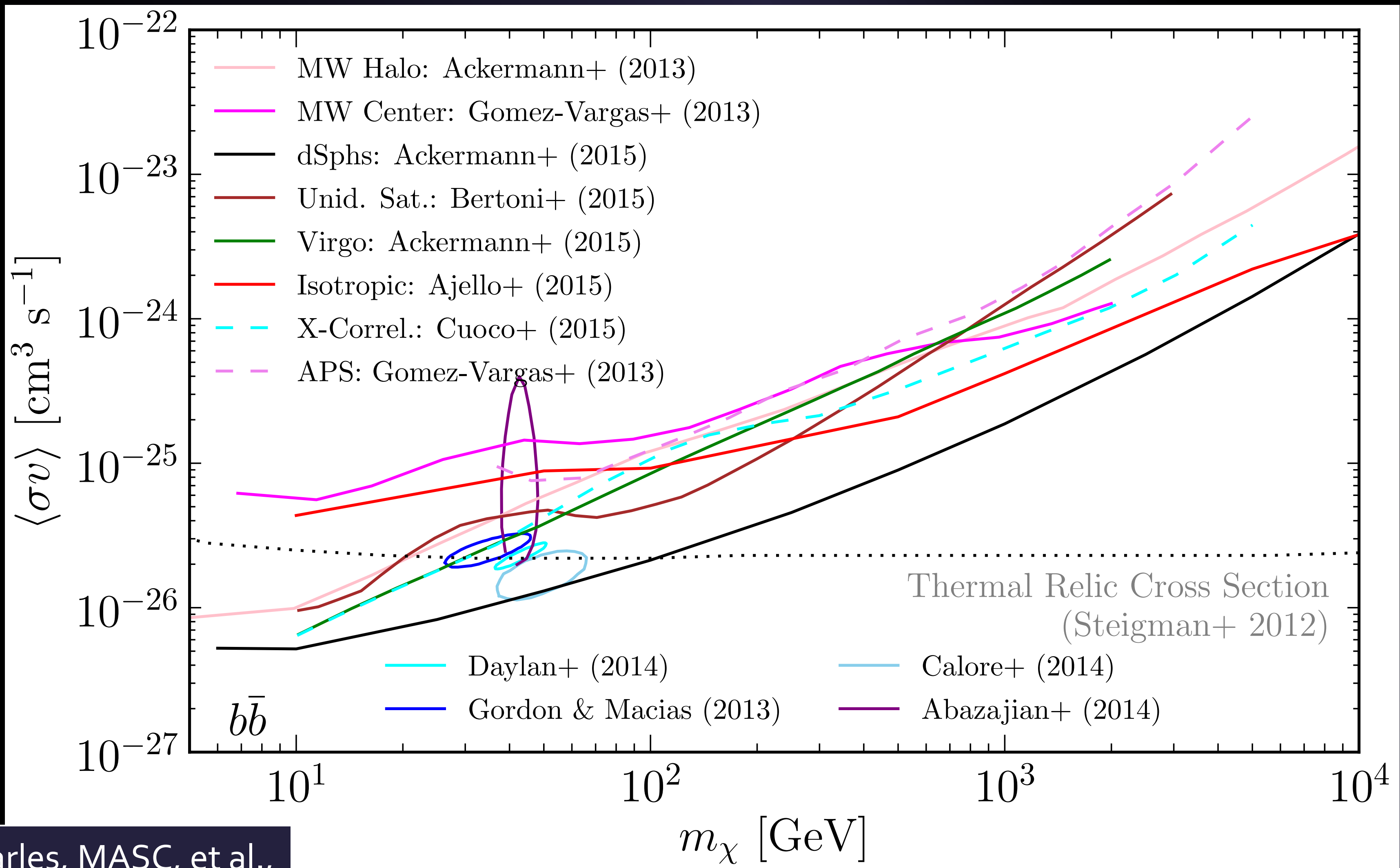


+ Spectral Lines

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

Fermi-LAT : a lot of DM targets explored so far

[many DM limits and some signal hints]



Charles, MASC, et al., [1605.02016]

IACTs : a lot of DM targets explored so far

[many DM limits and some signal hint]

Dwarf galaxies, GC halo, dark satellites, local galaxies, galaxy clusters…

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.
				Ann.	Ahnen et al.
	2010 – 2018	184	VERITAS	–	Kelley-Hoski
Boötes 1	2009	14.3	VERITAS	Ann.	Acciari et al.
		(14.0)		Ann.	Archambault (2017)
Coma Berenices	2010 – 2013	(8.6)	H.E.S.S.	Ann.	Abramowski
	2010 – 2013	10.9		Ann.	Abdalla et al
	< 2018	37	VERITAS	–	Kelley-Hoski
	2018	50.2	MAGIC	Ann.	Maggio et al.
Fornax	2010	6.0	H.E.S.S.	Ann.	Abramowski
				Ann.	Abdalla et al
Ursa Major II	2014 – 2016	94.8	MAGIC	Ann.	Ahnen et al.
Triangulum II*	2014 – 2016	62.4	MAGIC	Ann.	Acciari et al.
	< 2018	181	VERITAS	–	Kelley-Hoski
Segue II	< 2018	19	VERITAS	–	Kelley-Hoski
Canes Ven I	< 2018	14	VERITAS	–	Kelley-Hoski
Canes Ven II	< 2018	14	VERITAS	–	Kelley-Hoski
Hercules	< 2018	13	VERITAS	–	Kelley-Hoski
Sextans	< 2018	13	VERITAS	–	Kelley-Hoski
Draco II	< 2018	10	VERITAS	–	Kelley-Hoski
Leo I	< 2018	7	VERITAS	–	Kelley-Hoski
Leo II	< 2018	16	VERITAS	–	Kelley-Hoski
Leo IV	< 2018	3	VERITAS	–	Kelley-Hoski
Leo V	< 2018	3	VERITAS	–	Kelley-Hoski
Reticulum II	2017 – 2018	18.3	H.E.S.S.†	Ann.	Abdalla et al
Tucana II	2017 – 2018	16.4	H.E.S.S.†	Ann.	Abdalla et al
Tucana III*	2017 – 2018	23.6	H.E.S.S.†	Ann.	Abdalla et al
Tucana IV*	2017 – 2018	12.4	H.E.S.S.†	Ann.	Abdalla et al
Grus II*	2018	11.3	H.E.S.S.†	Ann.	Abdalla et al
Dark satellites					
1FGL J2347.3+0710	2010	8.3	MAGIC	–	Nieto et al. (
1FGL J0338.8+1313	2010-2011	10.7	MAGIC	–	Nieto et al. (
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
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

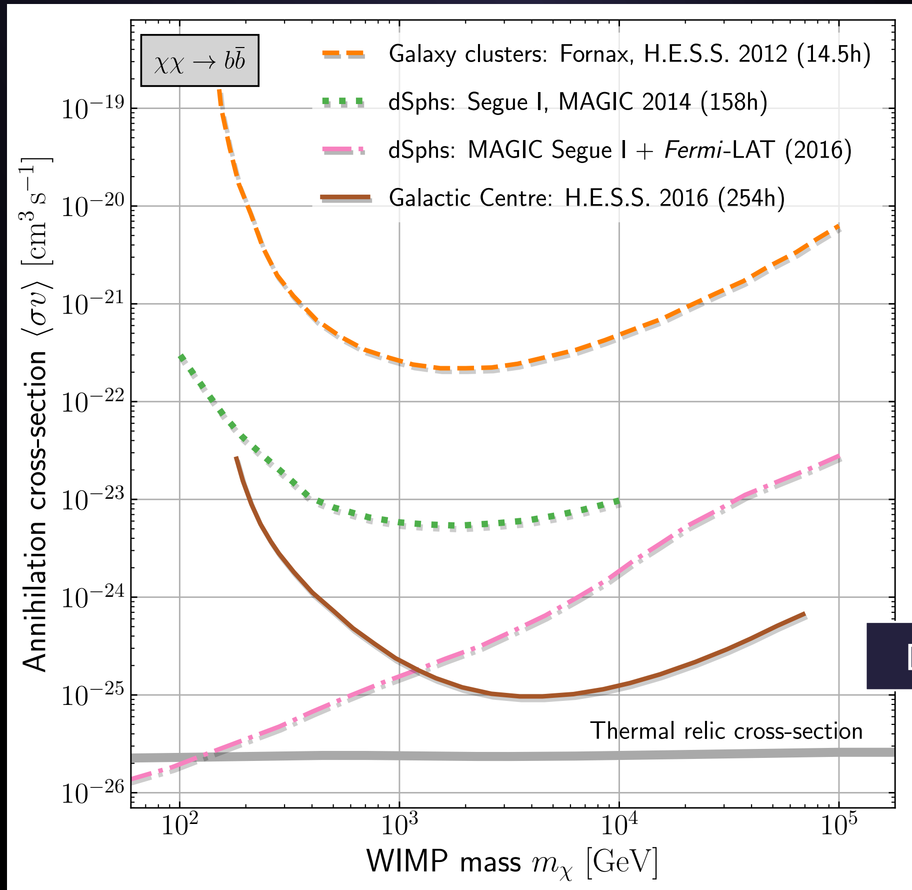
Table 8.1 – continued from previous page

Target	Year	Time [h]	IACT	Limit	Ref.
Intermediate Mass Black Holes					
Galactic Plane Survey	2004 – 2007	400	H.E.S.S.	Ann.	Aharonian
	2005 – 2006	25	MAGIC‡	Ann.	Doro et al.
Globular Clusters					
M15	2002	0.2	Whipple	Ann.	Wood et al.
	2006 – 2007	15.2	H.E.S.S.	Ann.	Abramowsk
NGC 6388	2008 – 2009	27.2	H.E.S.S.	Ann.	Abramowsk
Other galaxies					
M33	2002 – 2004	7.9	Whipple	Ann.	Wood et al.
M32	2004	6.9	Whipple	Ann.	Wood et al.
WLM	2018	18.2	H.E.S.S.†	Ann.	Abdallah et
Galaxy Clusters					
Abell 2029	2003 – 2004	6.1	Whipple	–	Perkins et a
Perseus (Abell 426)	2004 – 2005	13.5	Whipple	–	Perkins et a
	2008	24.4	MAGIC‡	Ann.	Aleksić et a
	2009 – 2017	202.2	MAGIC	Decay	Acciari et a
Fornax (Abell S0373)	2005	14.5	H.E.S.S.	Ann.	Abramowsk
Coma (Abell 1656)	2008	18.6	VERITAS	Ann.	Arlen et al.
Line searches					
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowsk (2013c)
	2014	15.2	H.E.S.S.†	Ann.	Abdalla et
	2004 – 2014	(254)	H.E.S.S.	Ann.	Abdalla et
	2013 – 2019	204	MAGIC	Ann.	Inada et al.
Segue 1 dSph	2010 – 2013	(157.9)	MAGIC	A.+D.	Aleksić et a
Five dSph galaxies	2006 – 2012	(137.1)	H.E.S.S.	Ann.	Abdalla et
Five dSph galaxies	2007 – 2013	(229.8)	VERITAS	Ann.	Archambau (2017)
WLM	2018	(18.2)	H.E.S.S.†	Ann.	Abdallah et
Charged particles					
All-electron	2004 – 2007	239	H.E.S.S.	–	Aharonian 2009b)
	2009 – 2012	296	VERITAS	–	Archer et al
	2009 – 2010	14	MAGIC	–	Borla Trido
Moon shadow	2010 – 2011	20	MAGIC	–	Colin et al.
	2014	1.2	VERITAS	–	Bird et al.

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)

[Doro, MASC, Hütten – 2111.01198]

γ-ray DM annihilation searches: today



Doro, MASC, Hütten (2021)

Different targets observed, different DM scenarios explored.

→ No DM-induced gamma-ray signal (unequivocally) detected.

→ Fermi LAT ruling out thermal WIMPs below ~100 GeV.

→ GC excess persists (M31 too?). Dwarfs the best independent way to test it.

→ IACTs and HAWC/LHAASO competitive in the TeV energy range.

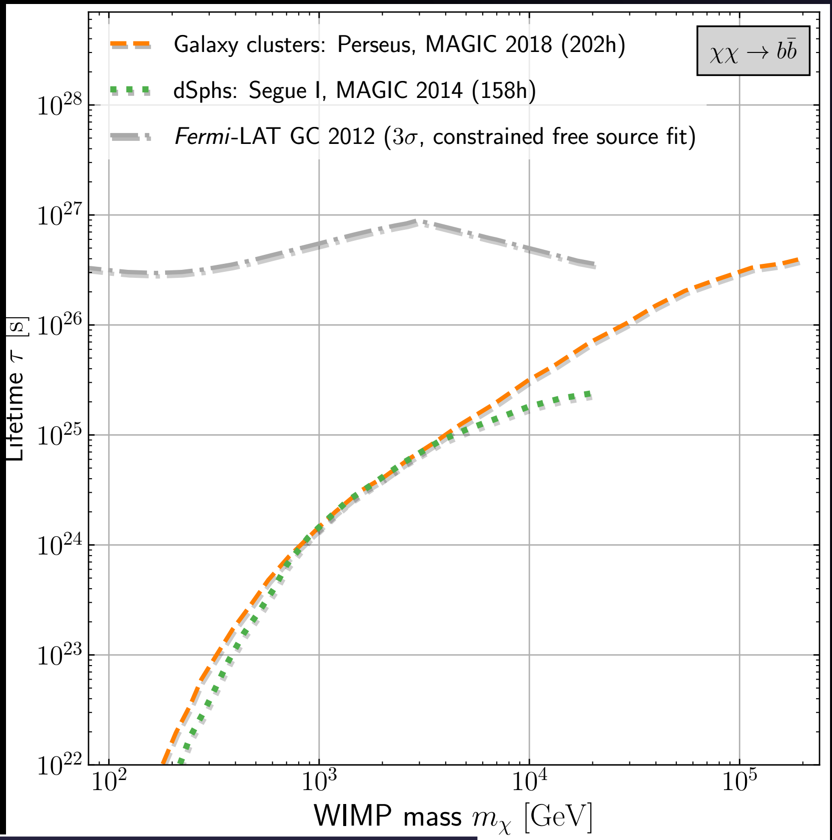
γ-ray DM decay searches: today

Annihilating DM	$\frac{d\Phi_{ann}}{dE_\gamma} = \frac{1}{k}\frac{\langle\sigma v\rangle}{4\pi\, m_{DM}^2}\sum_i BR_i \frac{dN_\gamma^i}{dE} \times J_{\Delta\Omega}$
Decaying DM	$\frac{d\Phi_{dec}}{dE_\gamma} = \frac{1/\tau}{4\pi\, m_{DM}}\sum_i \Gamma_i \frac{dN_\gamma^i}{dE} \times D_{\Delta\Omega}$

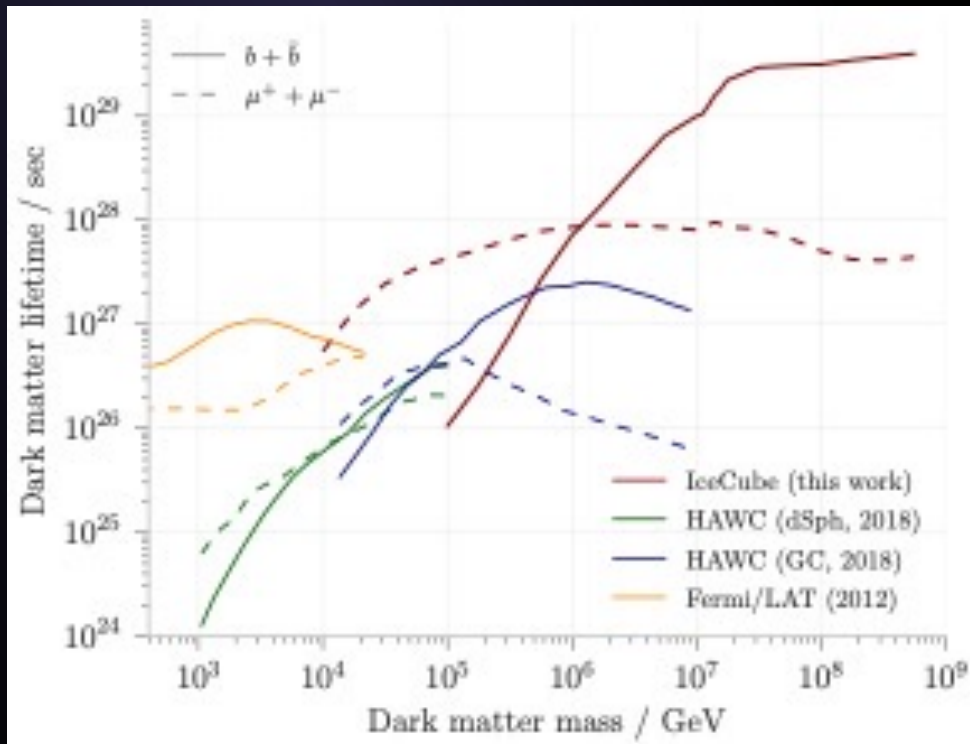
with

$$J_{\Delta\Omega} = \int_{\Delta\Omega}\int_{l.o.s.} \rho_{DM}^2(\ell,\Omega)\, d\ell\, d\Omega$$

$$D_{\Delta\Omega} = \int_{\Delta\Omega}\int_{l.o.s.} \rho_{DM}(\ell,\Omega)\, d\ell\, d\Omega$$

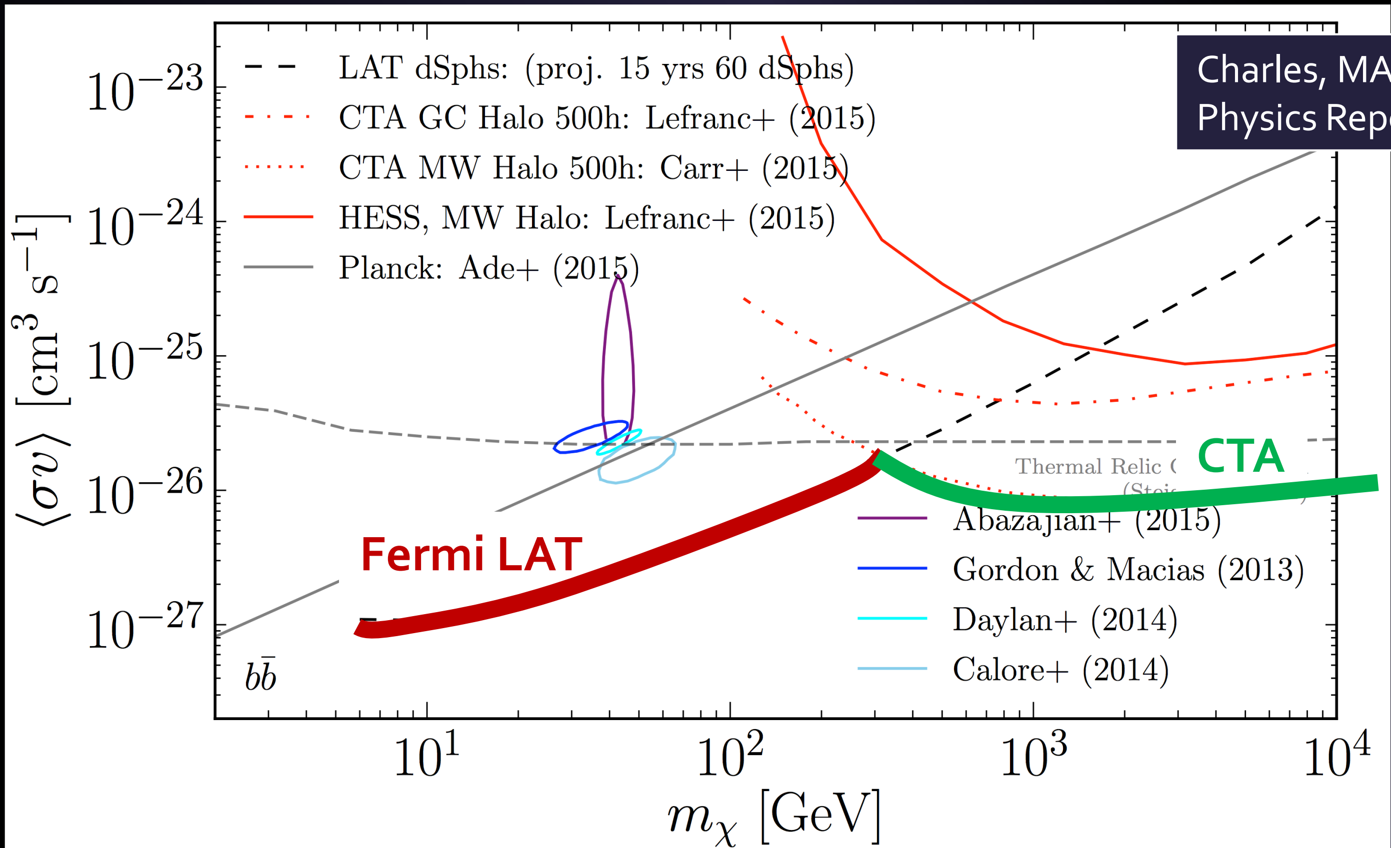


Doro, MASC, Hütten (2021)



[Aartsen+18]

(γ-ray) DM searches: tomorrow



Charles, MASC, et al., Physics Reports [1605.02016]

- → Discovery of **new dwarfs** the best tool to improve upon the current DM limits.
- → Origin of the **GC excess possibly settled** (more dwarfs, radio and MeV measurements)
- → **Fermi + CTA** will (fully?) test the WIMP miracle (by ~2025?)
- → Critical to **keep the diversity** of targets, experiments, messengers, DM particle candidates.
- → New **analysis** techniques (e.g., Machine Learning)

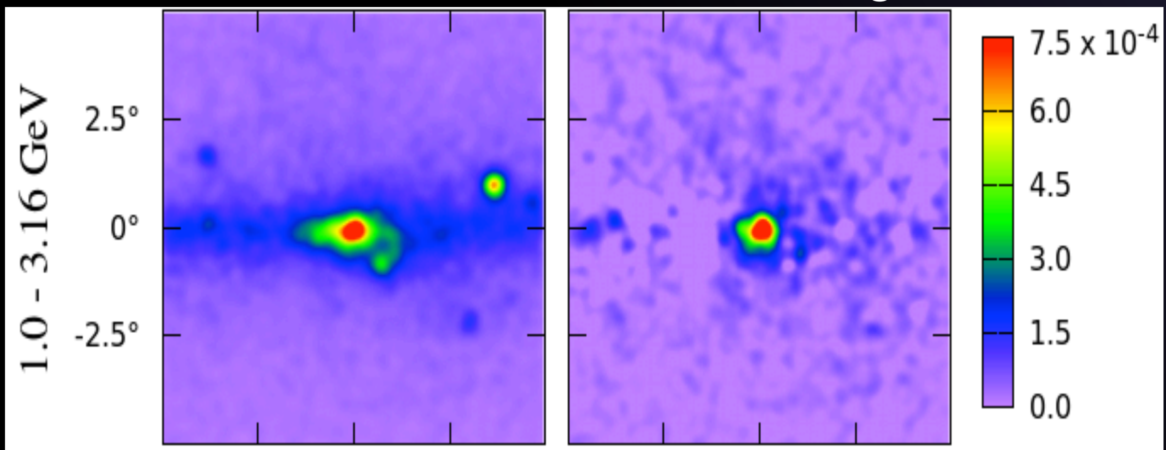
MAIN BATTLEGROUNDS_______________

[GALACTIC CENTER, DWARF GALAXIES AND DARK SATELLITES]

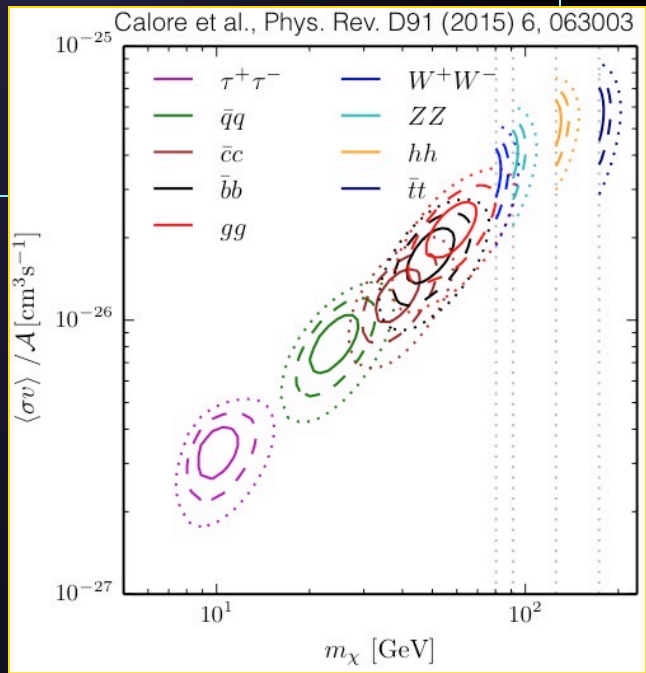
'GeV excess' in the Galactic center

- **Several groups** reported an excess of GeV photons from the GC region
  (e.g., Goodenough & Hooper 09, 11; Daylan+14, Abazajian+14, Calore+14; Gordon & Macías 14, Ajello+16)
- General agreement on the excess **peaking at a few GeV** above the ***standard*** diffuse emission models.
- **Interpretation difficult** due to complicated foreground/background modeling.
- **DM annihilation** (still) a plausible and exciting possibility
  - Spatially consistent with gNFW
  - Approx. half the thermal cross section
  - Around 50 GeV DM particle mass (bb)

Total flux Residuals (x3)



[Daylan+14]

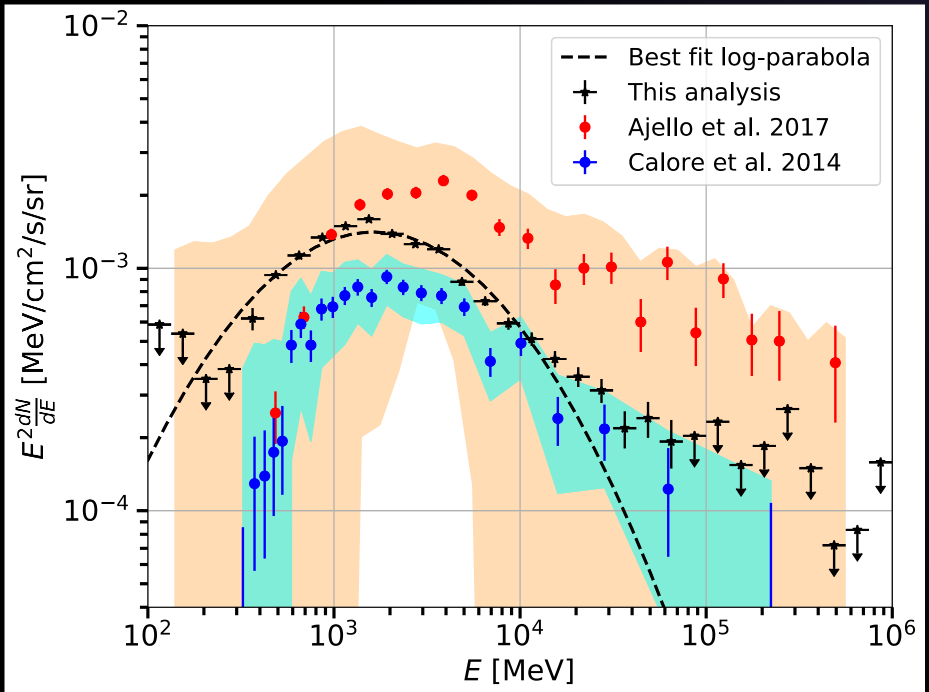


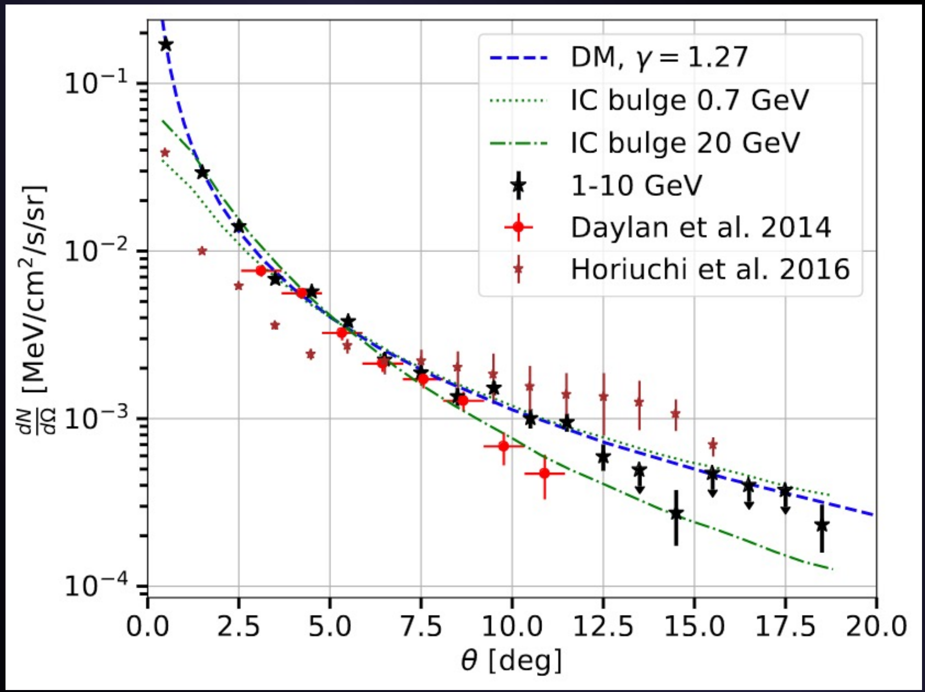
[Calore+14]

GC excess *circa* 2024

- Excess persists. Different explanations possible: pulsars, CR outbursts, DM.
- Pulsar interpretation is strenghtening:
  - Photon counts suggest a point source origin (Bartels+15, Lee+15; Buschmann+20; Malyshev+24; but see also Leane&Slatyer 20).
  - GCE seems to trace stellar densities (Bartels+18; Macias+18)
- Similar excesses at other longitudes along the Galactic Plane (Ackermann+17)

  → not expected from DM; diffuse emission residuals can mimic a DM signal.



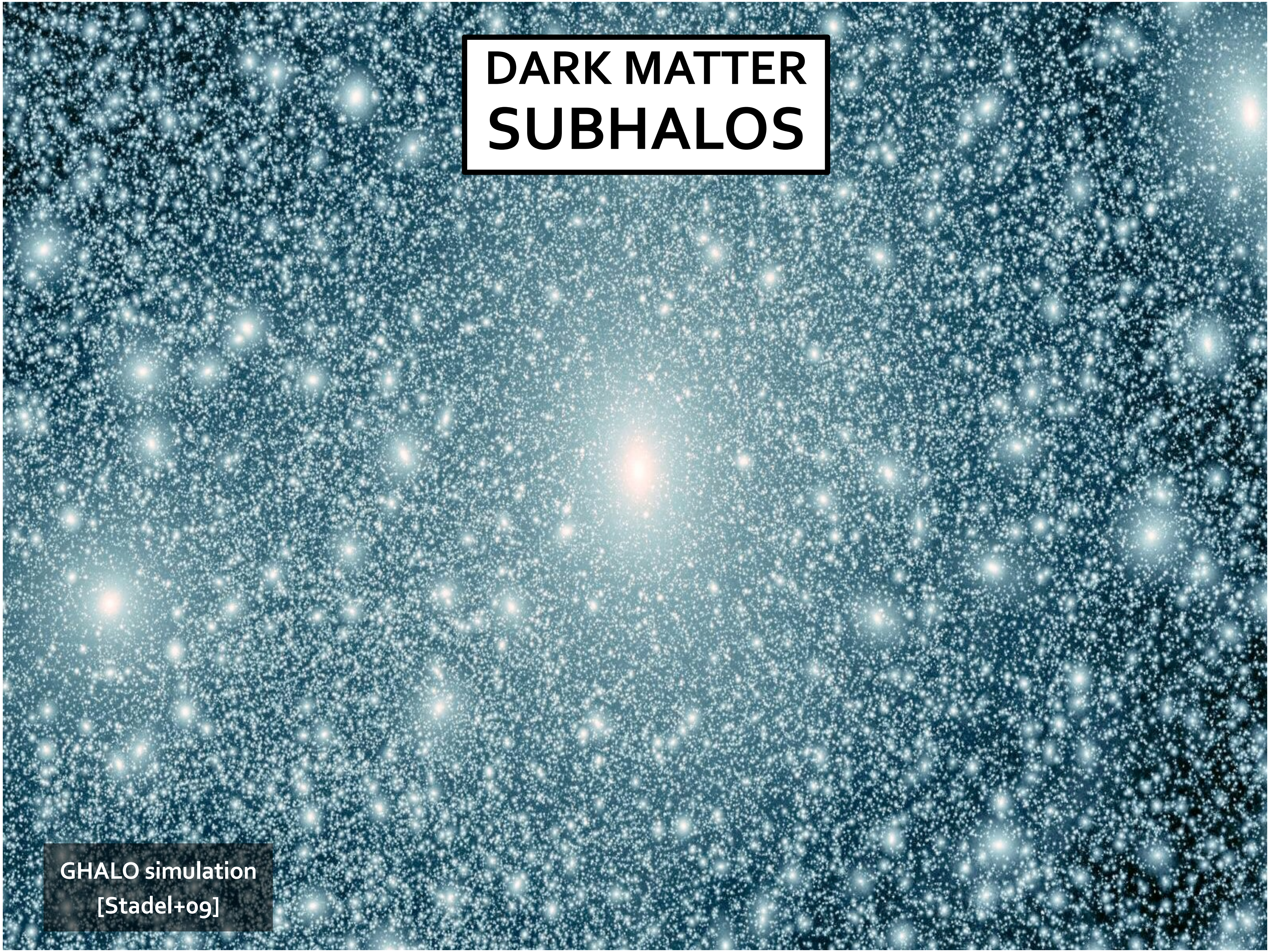


[di Mauro+21]

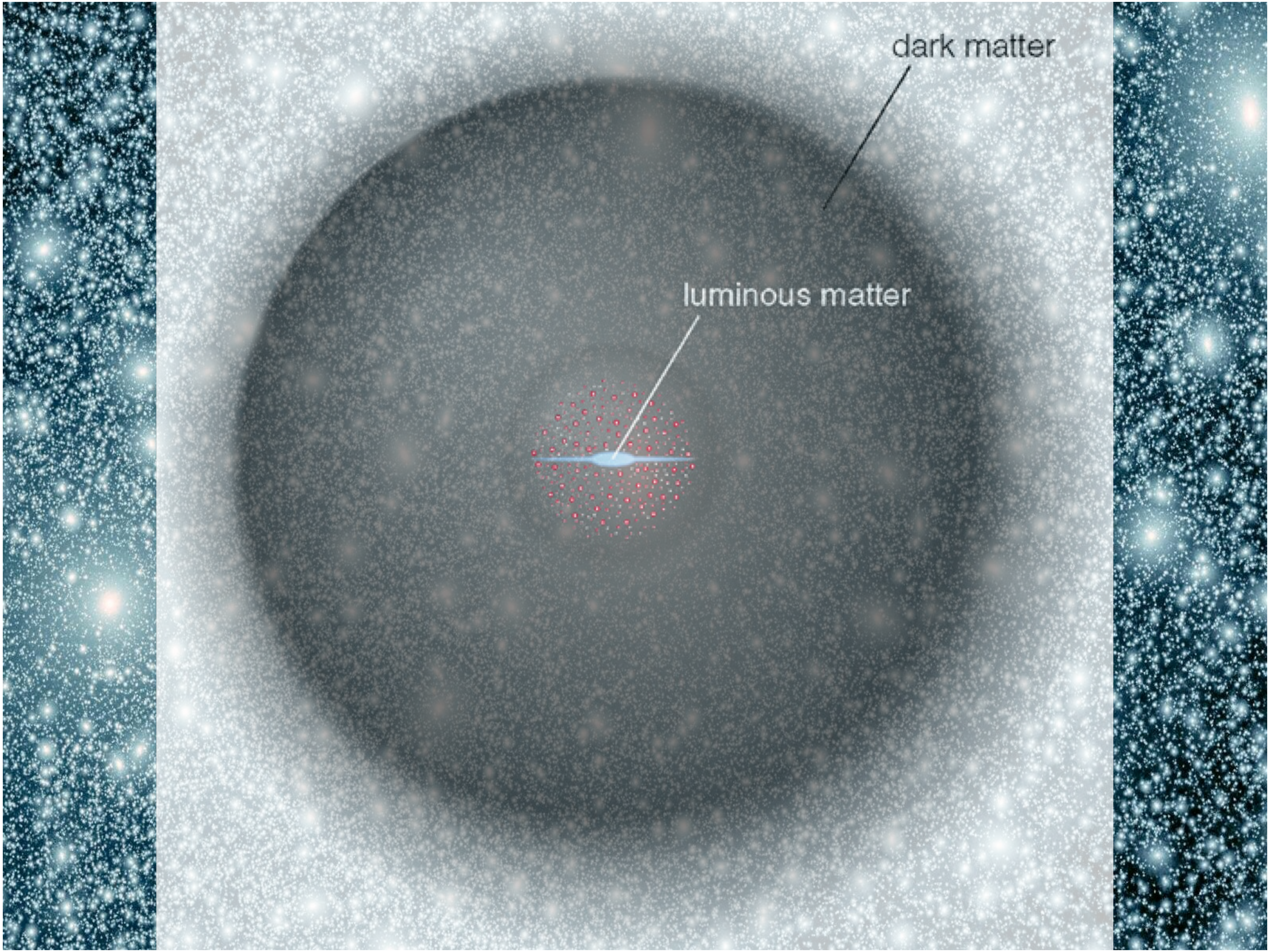
The GC is a complicated place.

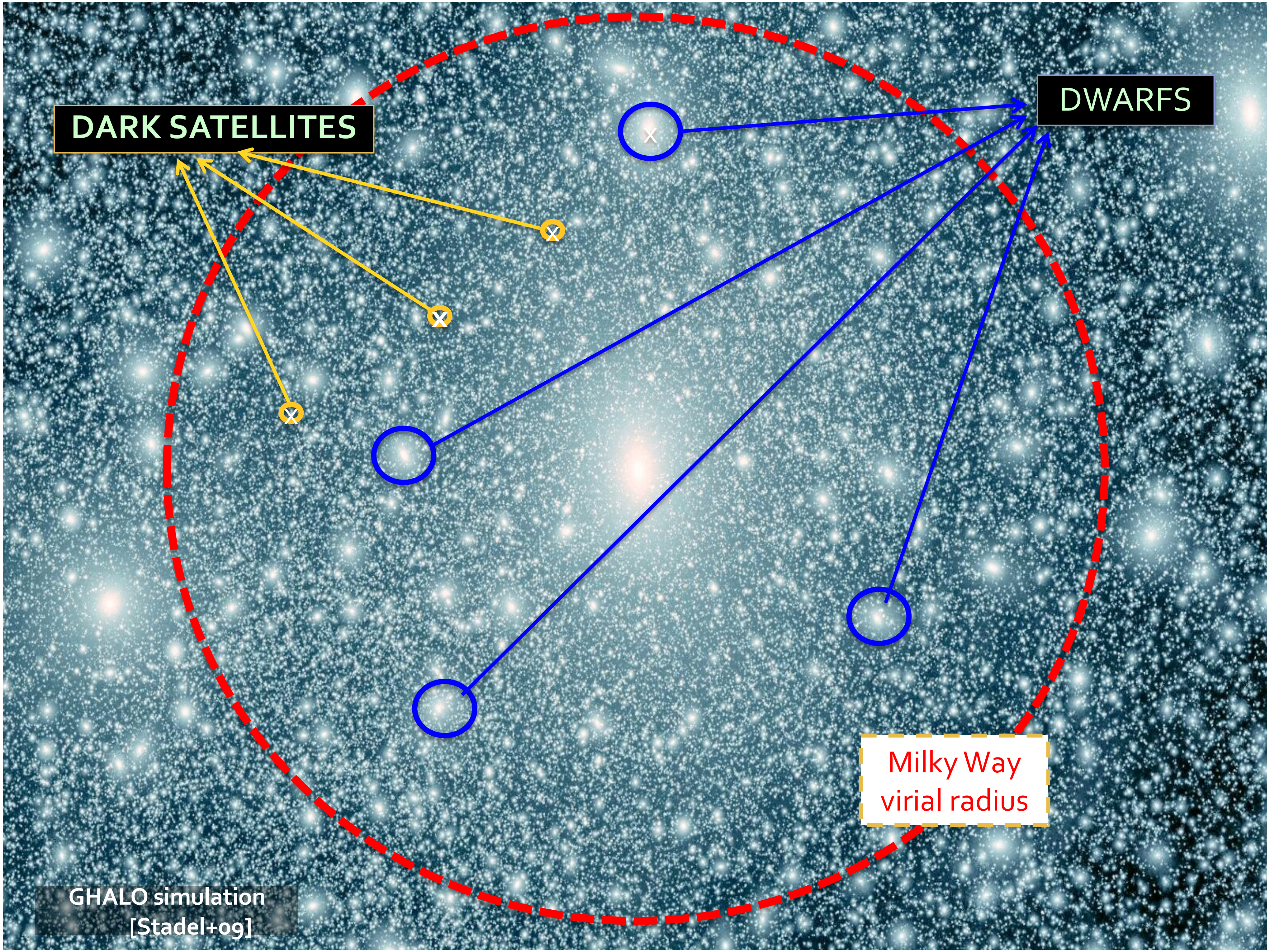
Can other targets provide an independent test of the GeV excess as being due to DM?

DARK MATTER SUBHALOS



GHALO simulation
[Stadel+09]


dark matter
luminous matter


DARK SATELLITES
DWARFS
Milky Way
virial radius
GHALO simulation
[Stadel+09]

The key role of DM halo substructure in (indirect) WIMP searches

Both visible *dwarfs* and *dark satellites* are high DM-dominated systems

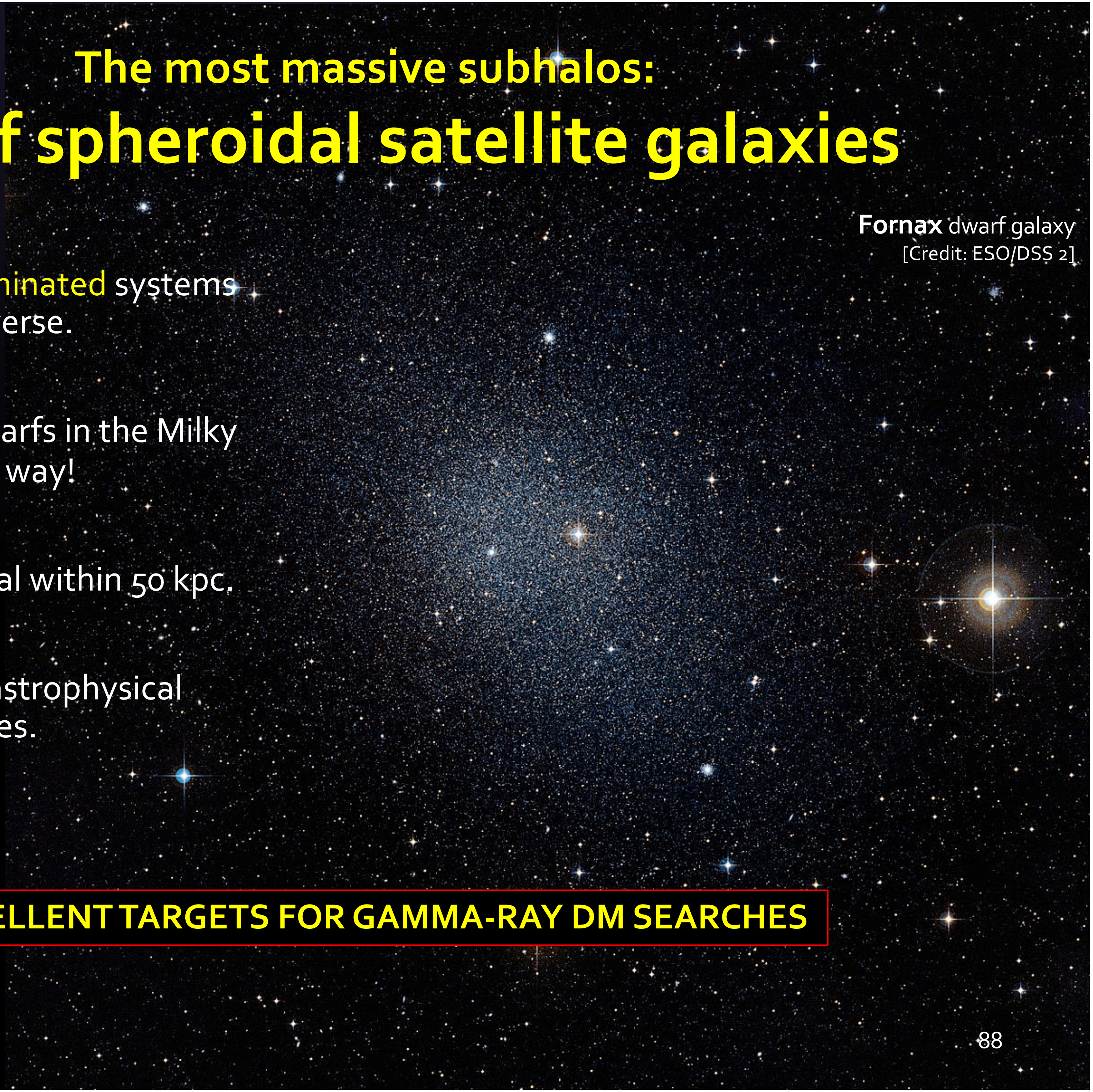
→ GREAT TARGETS

The *clumpy distribution* of subhalos inside larger halos should boost the annihilation signal importantly.

→ "SUBSTRUCTURE BOOSTS"

The most massive subhalos:

Dwarf spheroidal satellite galaxies



Fornax dwarf galaxy
[Credit: ESO/DSS 2]

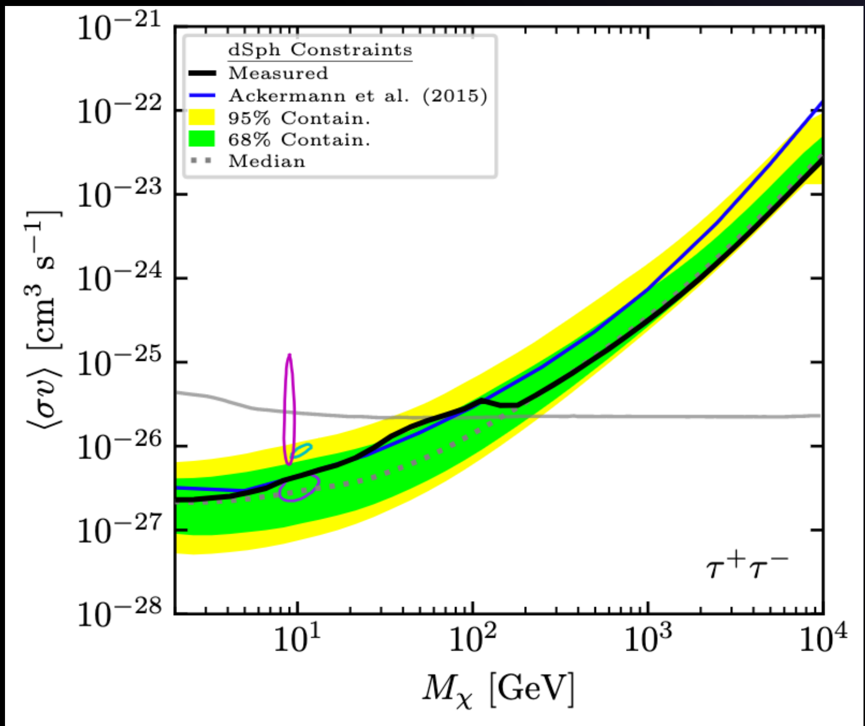
- The most DM dominated systems known in the Universe.
- ~50 confirmed dwarfs in the Milky Way. More on the way!
- Close to us. Several within 50 kpc.
- Free from bright astrophysical gamma-ray sources.

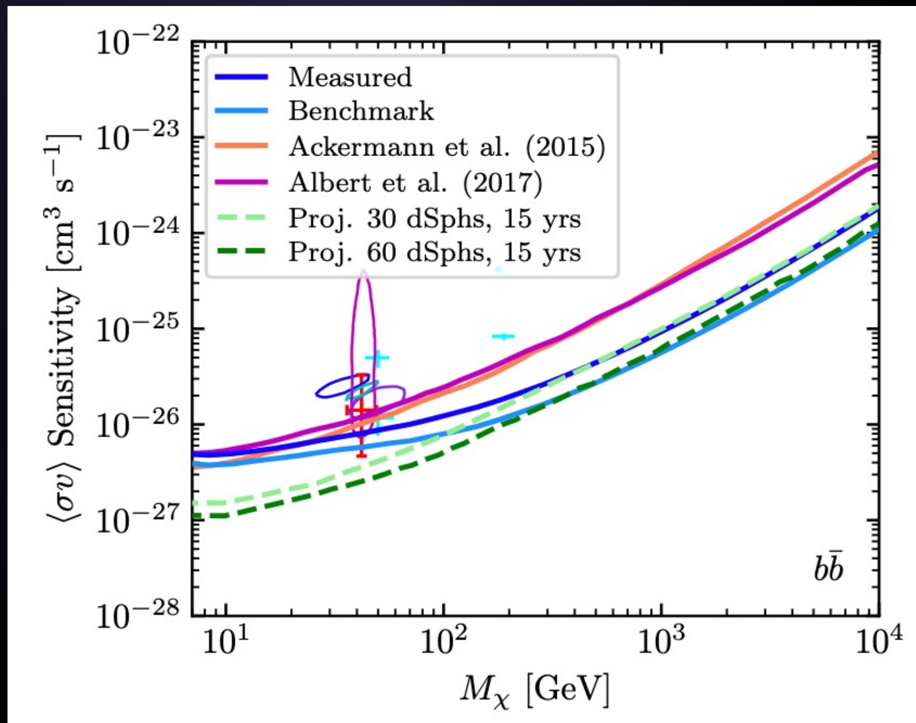
EXCELLENT TARGETS FOR GAMMA-RAY DM SEARCHES

Latest dwarf results with the Fermi LAT

[McDaniel, Ajello, Karwin, di Mauro, Drlica-Wagner, MASC (2024) – arXiv:2311.04982]

- No gamma-ray signal found in the direction of ~50 dwarfs
  → Upper limits to the gamma-ray flux → Upper limits to DM annihilation
- Most significant excess is < 1σ (global) (but see Crocker+22)
- Combined DM limits the most robust and competitive ones so far.
  → Dwarfs as a test of the GeV GC excess.



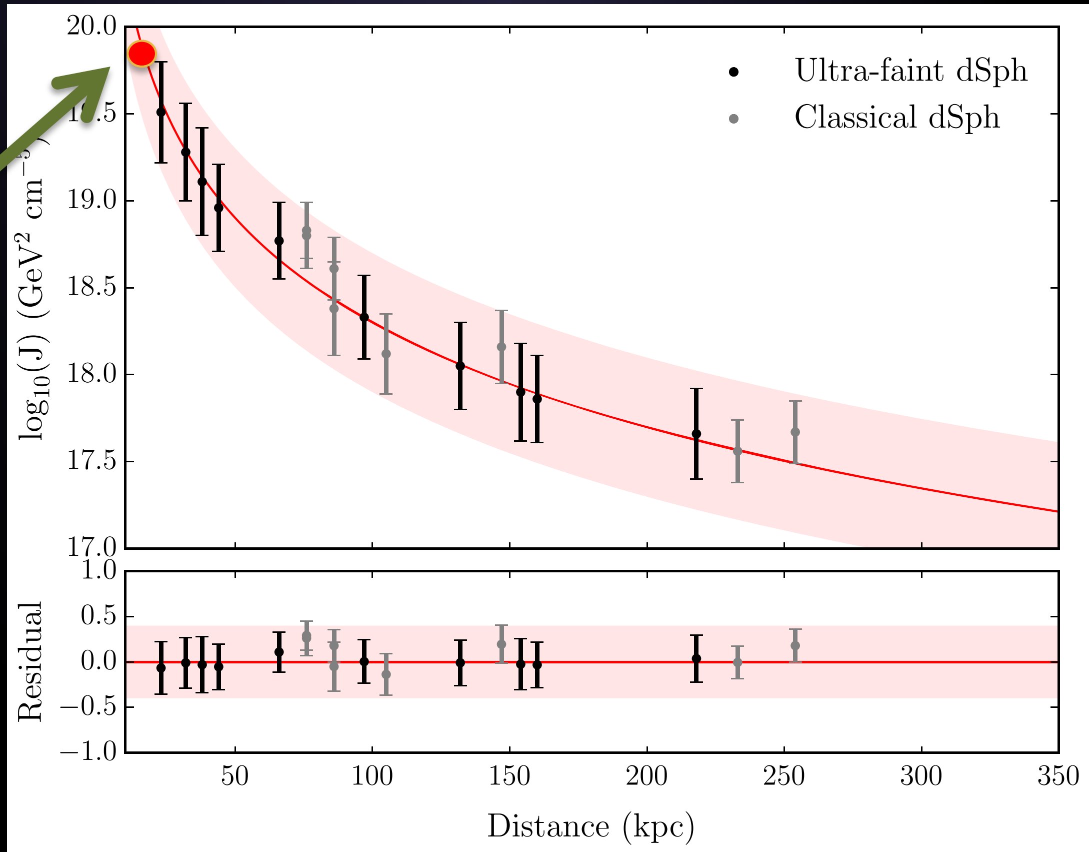


[McDaniel+24]

The least massive subhalos:
Dark satellites

- If DM is made of WIMPs → subhalo annihilates → gamma rays
- Maybe the only way to probe subhalo masses below ~10^7 solar masses
- The only type of search that provides info on the nature of the DM particle.

Should we expect any dark satellite e.g. here?



Adapted from Albert+15

Dark satellite search with gammas: general methodology

Around 1/3 of sources in gamma-ray catalogs are unidentified (unIDs)
(e.g., >2000 unIDs in the '4FGL-DR4' Fermi-LAT catalog)

Exciting possibility: some of them may be subhalos annihilating to gammas!

Search for potential DM subhalo candidates by identifying those unIDs compatible with DM subhalo annihilation.

→ Apply a series of '*filters*' based on expected DM signal properties.

Possible results:

1. A few VIP candidates → dedicated data analyses, follow-up campaigns…
2. A few more subhalo candidates (yet uncertain) → set DM constraints
3. No unIDs compatible with DM → best achievable constraints

DM constraints
from gamma-ray unID sources?

VS.

dark subhalo J-factors, number density, spatial extension...

instrument sensitivity to DM annihilation, pool of unID sources

Number of predicted detectable subhalos VS. number of unIDs compatible with DM

DM CONSTRAINTS

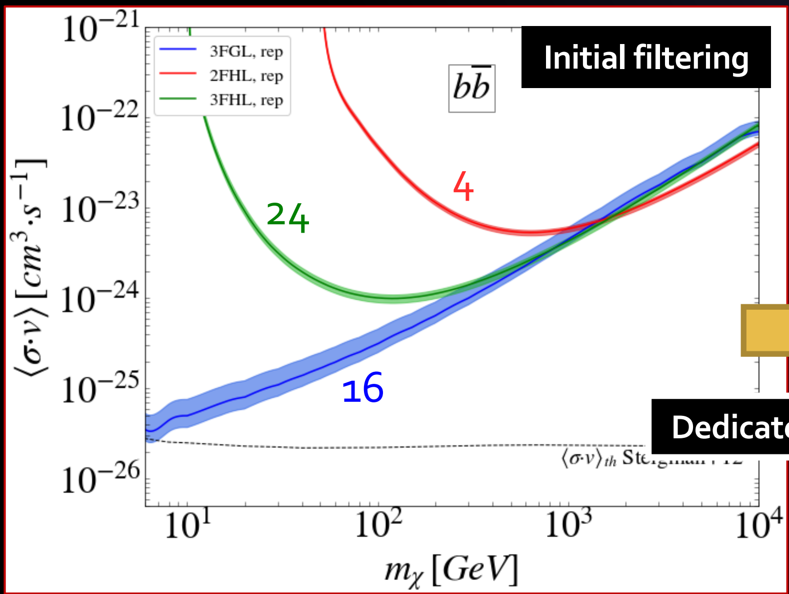
[The less DM candidates among unIDs the better the constraints]

Dark satellite search in Fermi-LAT catalogs (I)

[Coronado-Blázquez, MASC, et al. (2019 a,b) – arXiv:1906.11896; 1910.14429]

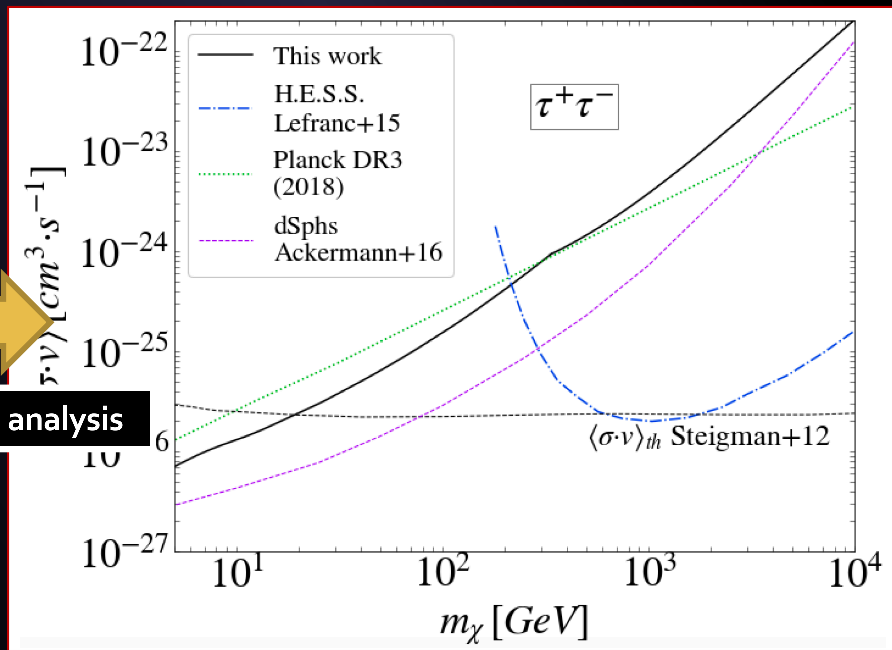
- List of O(10) VIP candidates in the 2FGL+2FHL+ 3FGL Fermi LAT catalogs.
- Dedicated **spectral analysis** of best DM subhalo candidates → improved constraints
- DM limits competitive with other targets, reach thermal cross section.
- 4FGL-DR4 search ongoing (Valenciano-Ruano & MASC, in prep.)

Initial filtering



[Coronado-Blázquez, MASC+19 – 1906.11896]

Dedicated spectral analysis



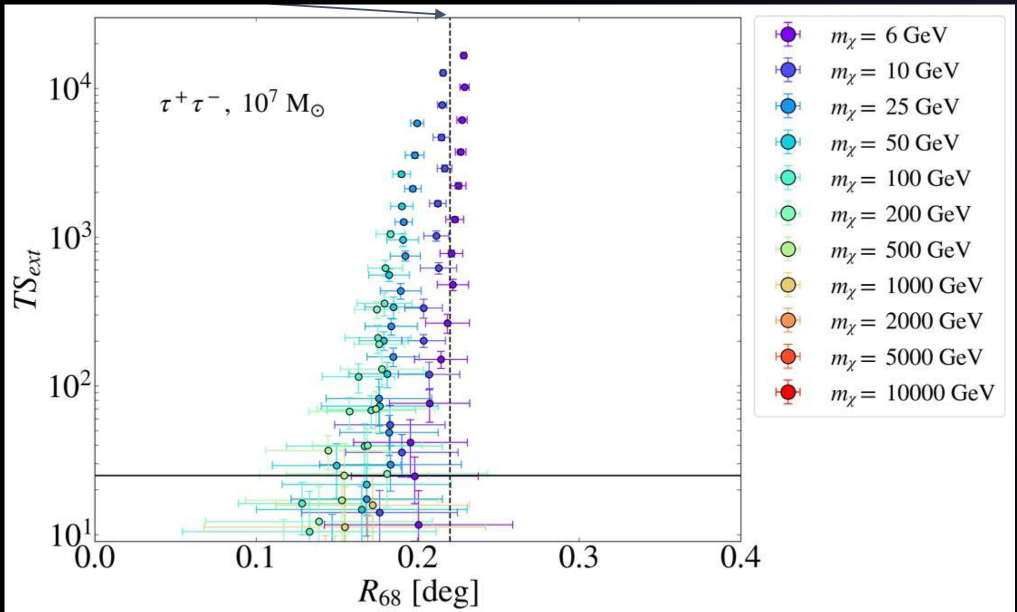
[Coronado-Blázquez, MASC+19b – 1910.14429]

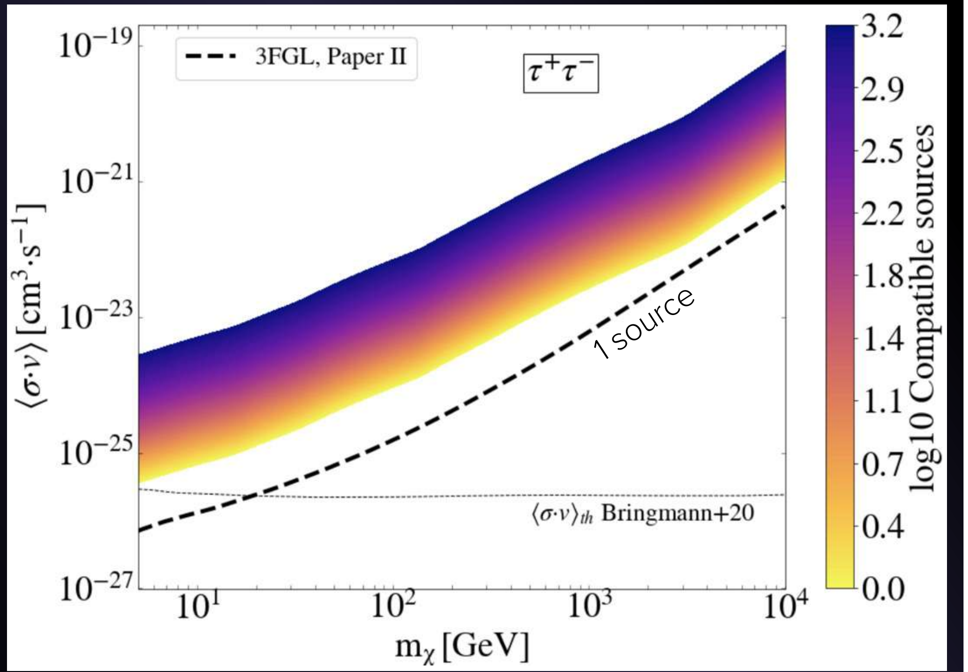
Also: Tasitsiomi&Olinto 02; Pieri+05; Kuhlen+07; Springel+08; Anderson+10; Brun+11; Belikov+12; Ackermann+12; Zechlin+12;+13; Berlin&Hooper 13; Mirabal+16; Hooper+16; Bertoni+16; Schoonenberg+16; Calore+17; Abeysekara+19

Dark satellite search in Fermi-LAT catalogs (II)

[Coronado-Blázquez, MASC, et al. (2023) – arXiv:2204.00267]

- Study of the **spatial properties** of the expected DM emission and of the implications for Fermi-LAT detectability and DM constraints.
  - Realistic LAT simulations of 'typical', extended subhalos.
  - Careful spatial analysis of previously VIP candidates.
- Typical emission **O(0.2 - 0.3 degrees)** for the LAT and for the brightest subhalos.
- DM constraints more robust/realistic but weaker than previous ones by a factor 2-3.



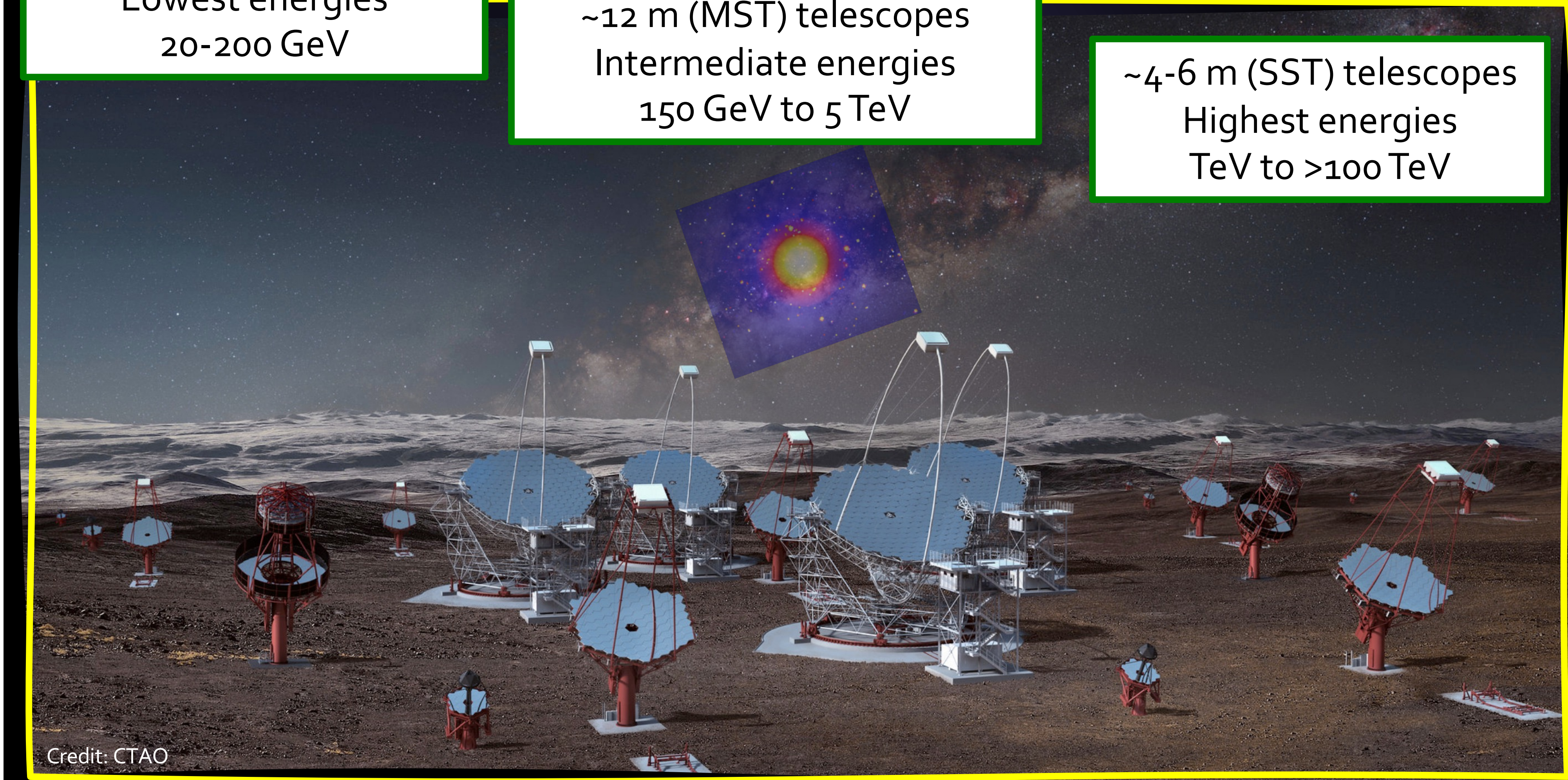


The future:
Cherenkov Telescope Array Observatory (CTAO)

23 m (LST) telescopes
Lowest energies
20-200 GeV

~12 m (MST) telescopes
Intermediate energies
150 GeV to 5 TeV

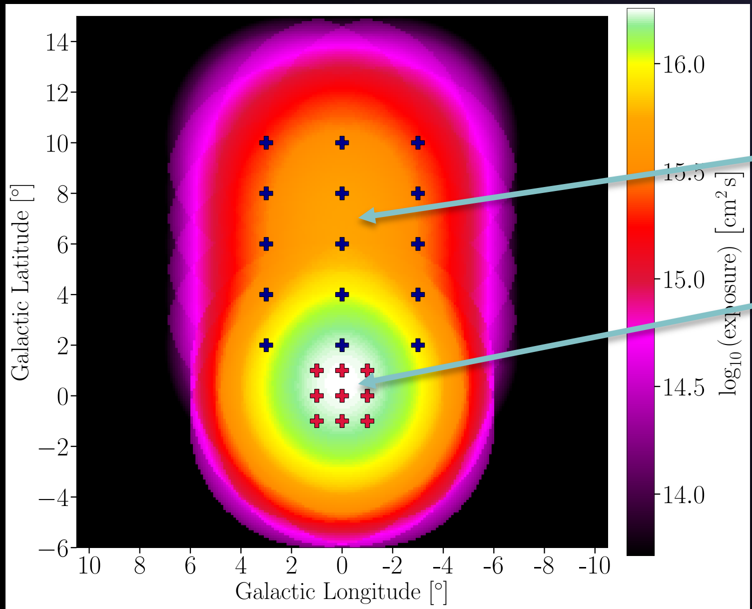
~4-6 m (SST) telescopes
Highest energies
TeV to >100 TeV



Credit: CTAO

The Galactic center with CTAO

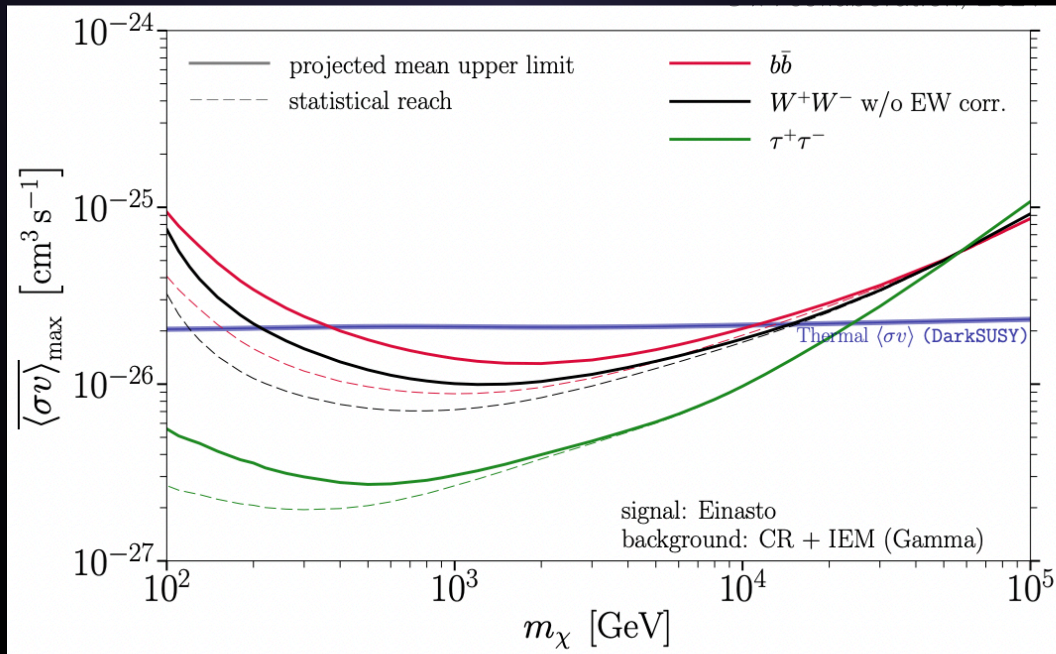
Detailed simulations critical to understand actual CTAO capabilities for DM.
CTAO observations of the GC will be of utmost importance for the DM community.



[Acharyya+21]

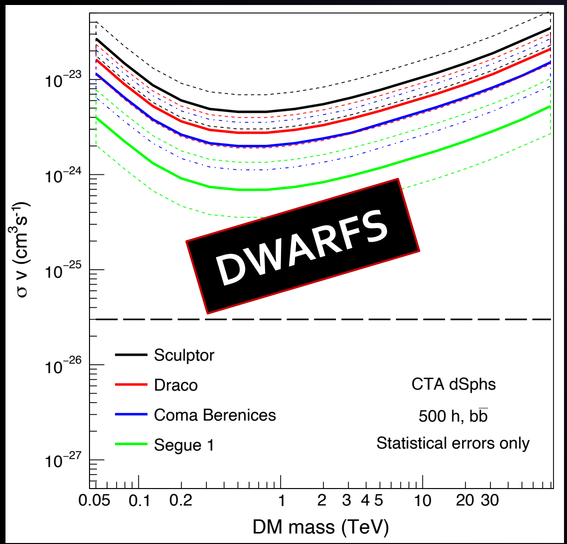
Extended survey: additional 300 hours

Galactic center survey:
525 hours over the first 10 years!

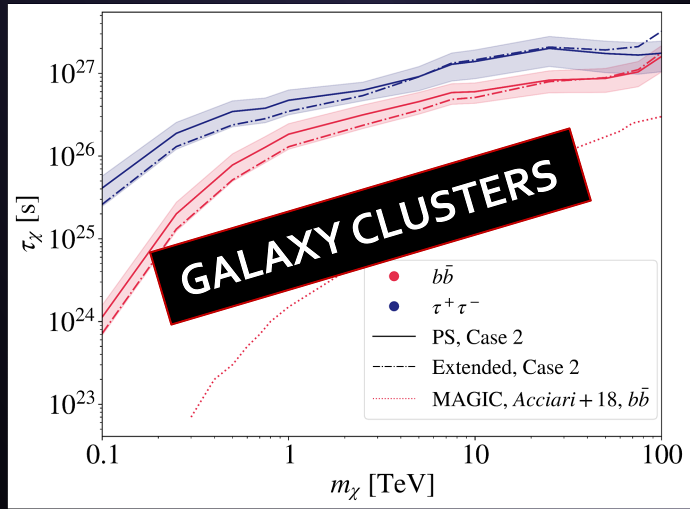


CTAO DM predictions including treatment of systematic uncertaintites and astrophysical backgrounds

... but not only the GC !

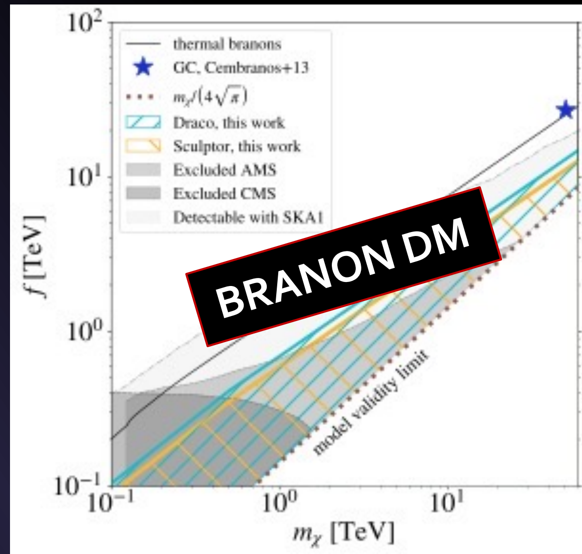


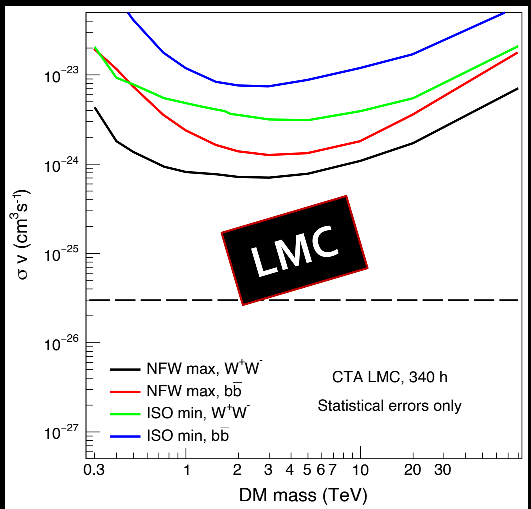
[Acharya+17]



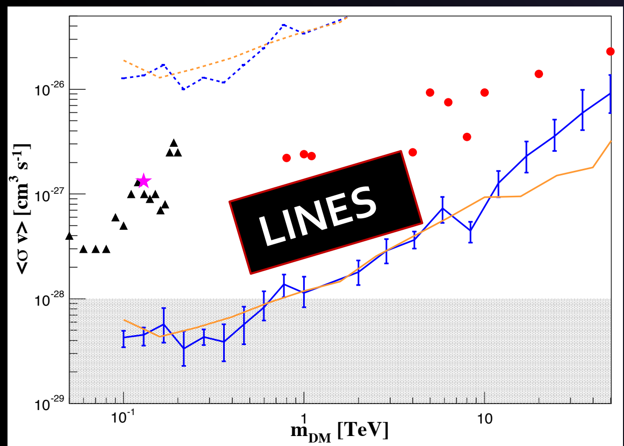
[Pérez-Romero+22]

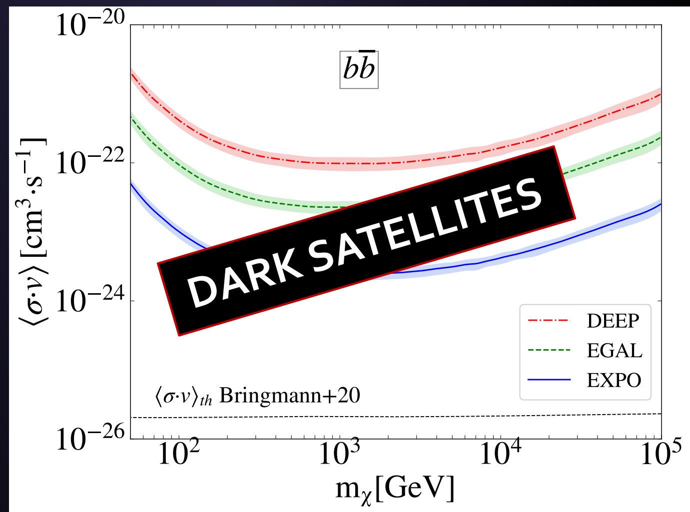
[Aguirre-Santaella+22]





[Acharya+17]



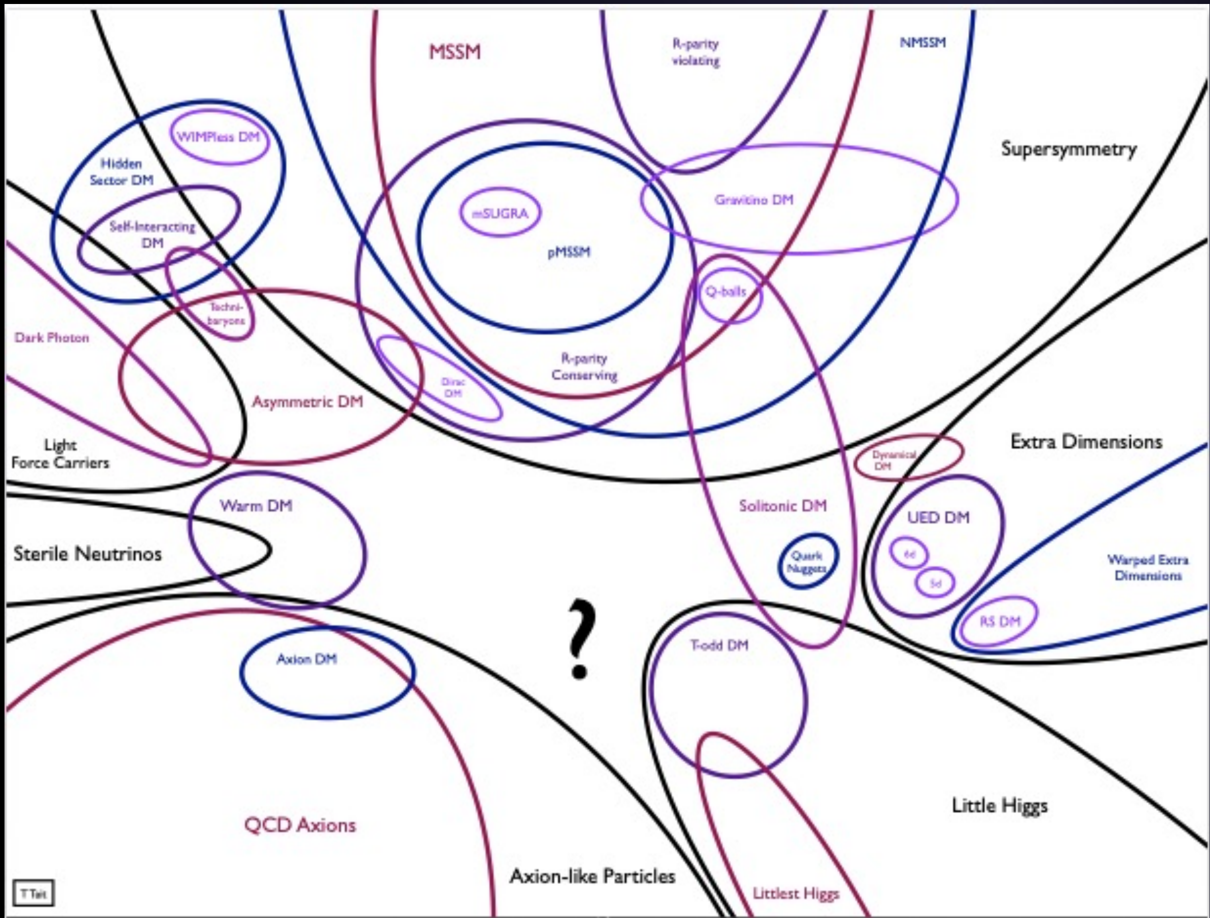


[Coronado-Blázquez+21]

Disclaimer: many other particle DM models…

(this talk was just a tiny part of the full story)

Credit: Tim Tait



Some of these models also leave imprints in the gamma-ray sky!

(e.g. ALPs)

Critical to **keep the diversity** of targets, experiments, messengers, DM particle candidates.

[Beyond WIMPs:] Axion-like particles in gamma rays

- Axions proposed as a by-product of the Peccei-Quinn solution of the strong-CP problem.
- Axion-like particle (ALP): mass and coupling not related.
- Can be suitable dark matter candidates.
- Expected to convert into photons (and vice-versa) in the presence of magnetic fields.

Probability of conversion (e.g.Raffelt & Stodolsky 88, Mirizzi+07):

$$P_0 = (\Delta_B s)^2 \frac{\sin^2(\Delta_{\rm osc} s/2)}{(\Delta_{\rm osc} s/2)^2}.$$

with

$$\Delta_B = \frac{B_t}{2M} \simeq 1.7 \times 10^{-21} M_{11} B_{\rm mG}\ {\rm cm}^{-1},$$

$$\Delta_{\rm osc}^2 \simeq (\Delta_{\rm CM} + \Delta_{\rm pl} - \Delta_a)^2 + 4\Delta_B^2,$$

Photon/axion conversions the main vehicle used in axion searches at present (ADMX, CAST…).

Some astrophysical environments fulfill the mixing requirements

$$\frac{15 \cdot B_G \cdot s_{pc}}{M_{11}} \geq 1$$

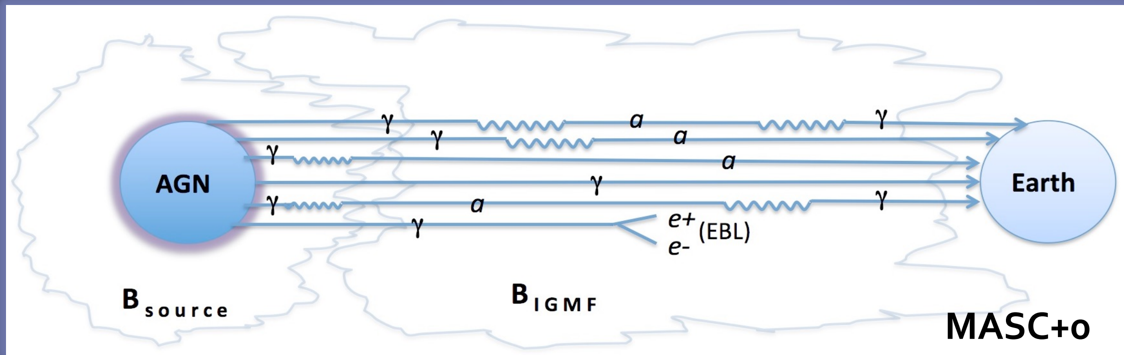
$M_{11} \geq 0.114$ GeV (CAST limit)

- M_{11}: coupling constant inverse ($g_{a\gamma}/10^{11}$ GeV)
- B_G: magnetic field (G)
- s_{pc}: size region (pc)

Photon/ALP conversions in gamma-rays

Many different scenarios already explored in the literature:

- Mixing in the AGN (e.g. Hooper & Serpico 07, Tavecchio+12)
- IGMF mixing (e.g. De Angelis+07, 09, 11)
- AGN+ IGMF mixing (e.g. MASC+09)
- IGMF + Galactic mixing (e.g. Simet+08)
- AGN + cluster+ Galactic mixing (e.g. Meyer+14)



MASC+09

Critical energy for conversion

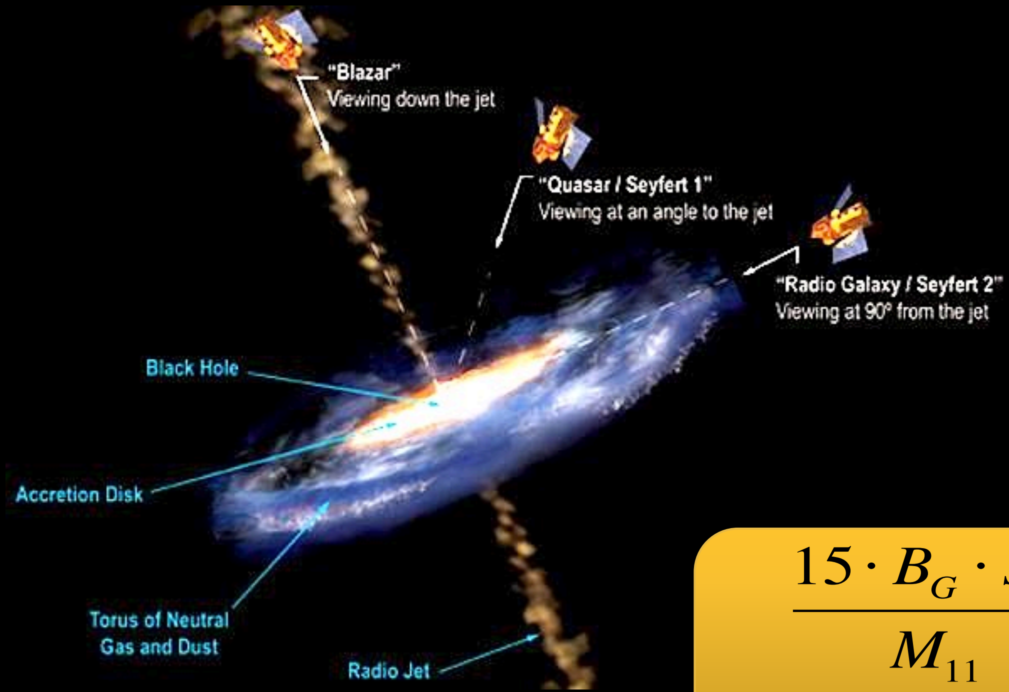
$$E_{crit}(GeV) = \frac{m_{\mu eV}^2 \; M_{11}}{0.4 \; B_G}$$

where $m_{\mu eV} = |m_{ALP} - \omega_{plasma}|$

Gamma-ray energy range → ultra-light ALPs (~10^{-9} eV).

For the same ALP properties, different E_{crit} are expected for each astrophysical scenario.

Very diverse astrophysical mixing scenarios are possible…



From Active Galactic Nuclei (AGNs)…

B ~ Gauss
s_{pc} ~ (sub)pc

$$\frac{15 \cdot B_G \cdot s_{pc}}{M_{11}} \geq 1$$

$B_G \cdot s_{pc} > 0.01$

… to Intergalactic Magnetic Fields (IGMFs)

B ~ nG
s_{pc} ~ Mpc

Astrophysical scenarios for photon/ALP conversions

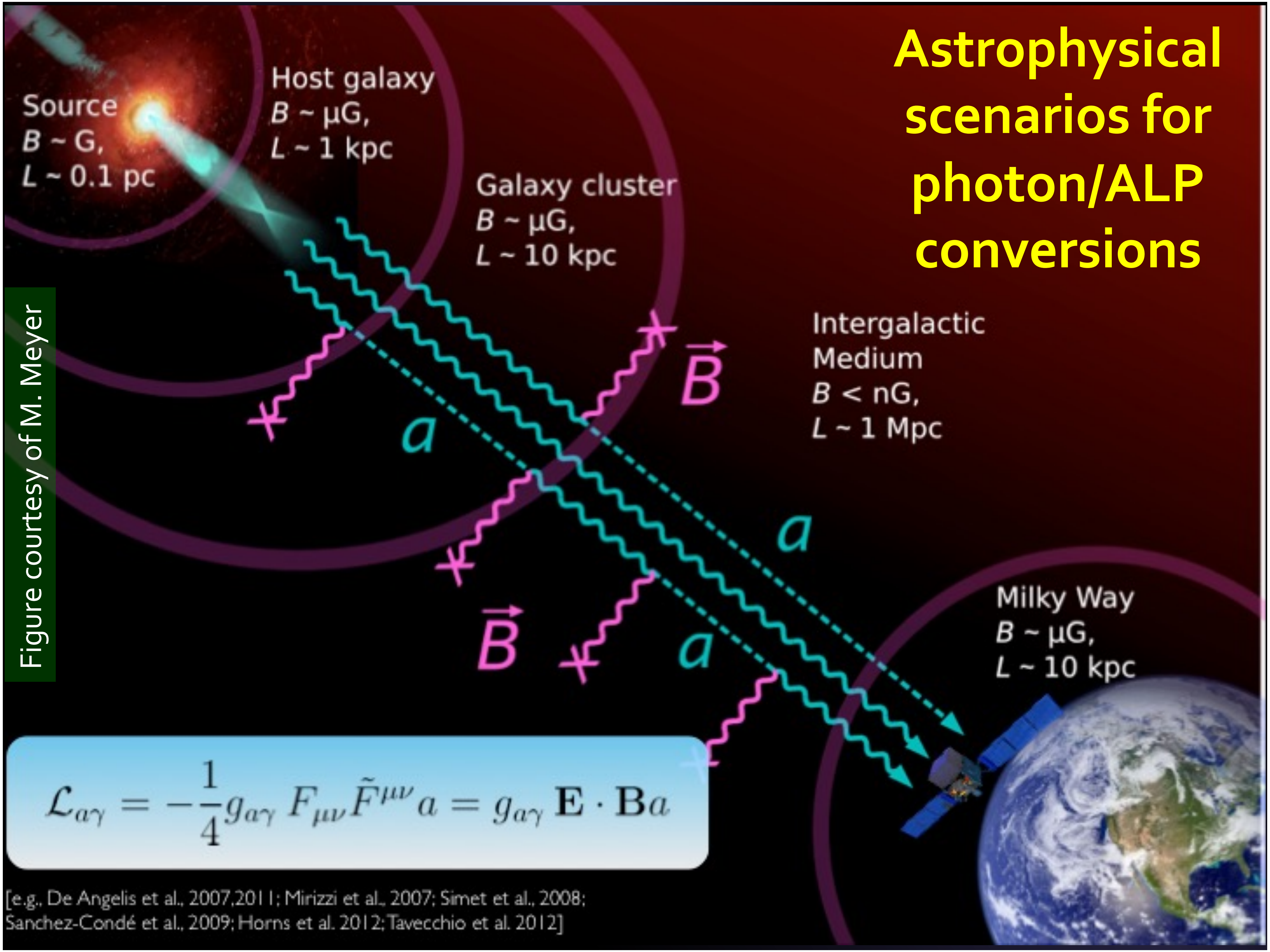


Figure courtesy of M. Meyer

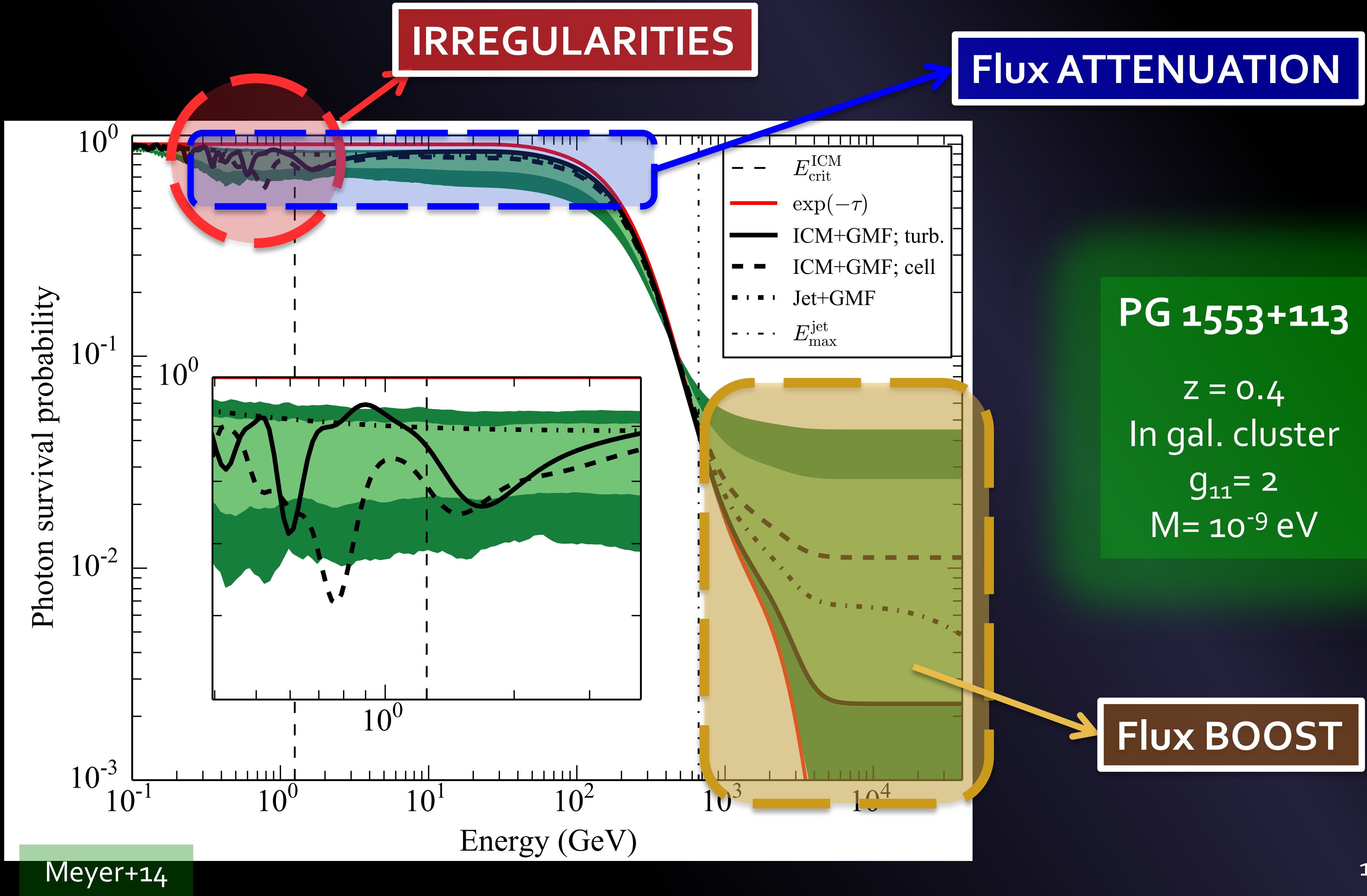
Hints of new Physics in γ-ray data?

(or why astrophysicists started to care about ALPs)

Some gamma-ray observations pose substantial challenges to the conventional astrophysical models, e.g.:

- **Lower opacity of the Universe to gamma rays** than expected
  (e.g. Aharonian+06, Albert+08, Acciari+11, De Angelis+09,11,13)
- **Too hard intrinsic spectrum of AGNs**
  (e.g. Albert+08, Wagner+10, Aleksic+11,Tanaka+13, Furniss+13)
- **Intrinsic spectrum deviates from a power-law**: pile-up problem (Dominguez, MASC+12; Furniss+13)
- **Extremely rapid and intense flares in FSRQs:** $\gamma\gamma$ absorption problem
  (Tavecchio+12).
- **GeV spectral breaks and dips**
  (Tanaka+13, Rubtsov & Troitsky 14, Mena & Razzaque 13)

ALPs modify the spectrum of AGNs



PG 1553+113

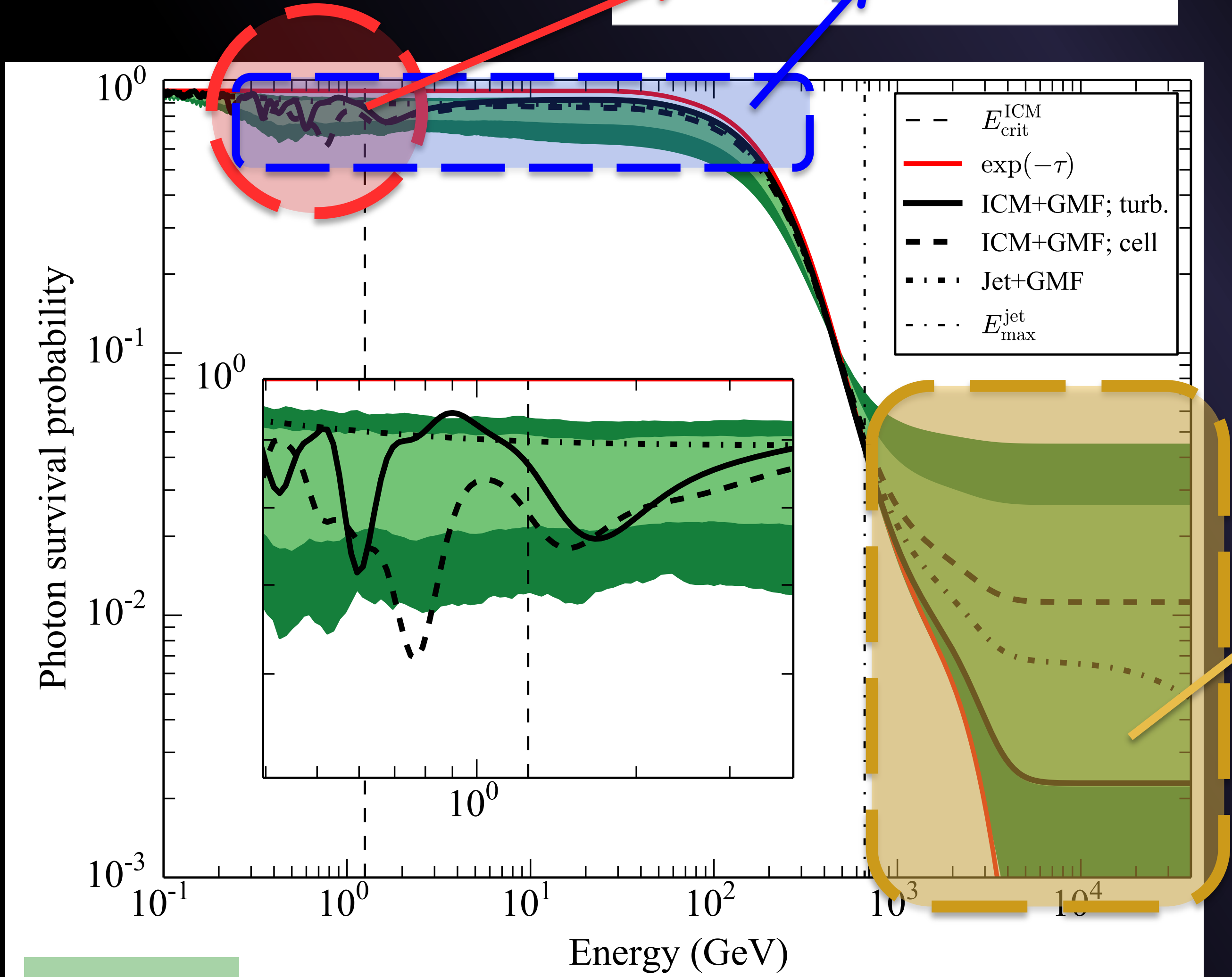
z = 0.4

In gal. cluster

g_{11} = 2

M= 10^{-9} eV

The ALP hunt with Fermi and IACTs

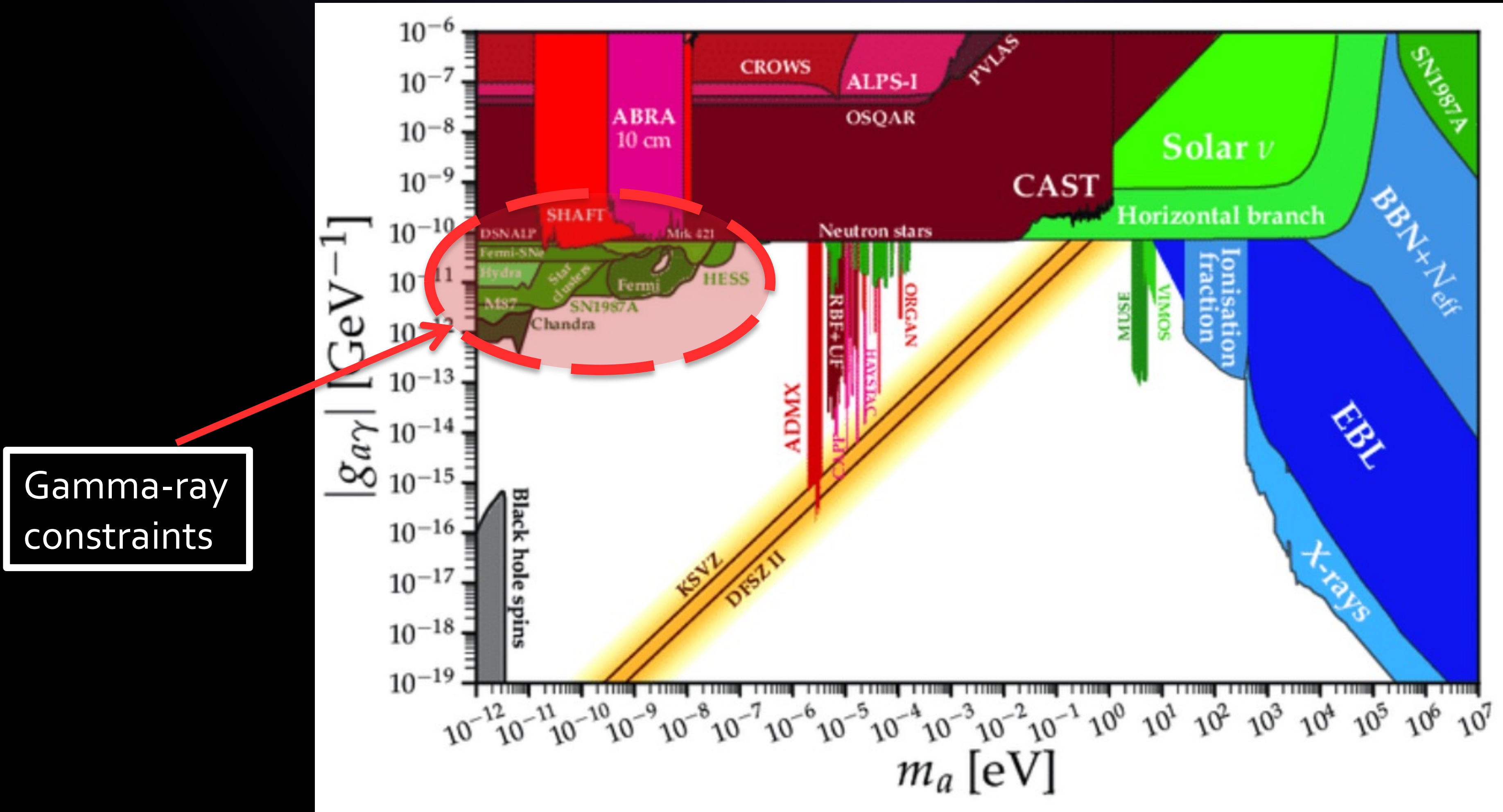


Fermi is more suitable for energies where the EBL is still not at work

Meyer+14

Current constraints on ALP properties

No clear signal found up to now after having scrutinized several targets.
In the absence of a significant detection in the data, upper limits are set.



Batkovic+21

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