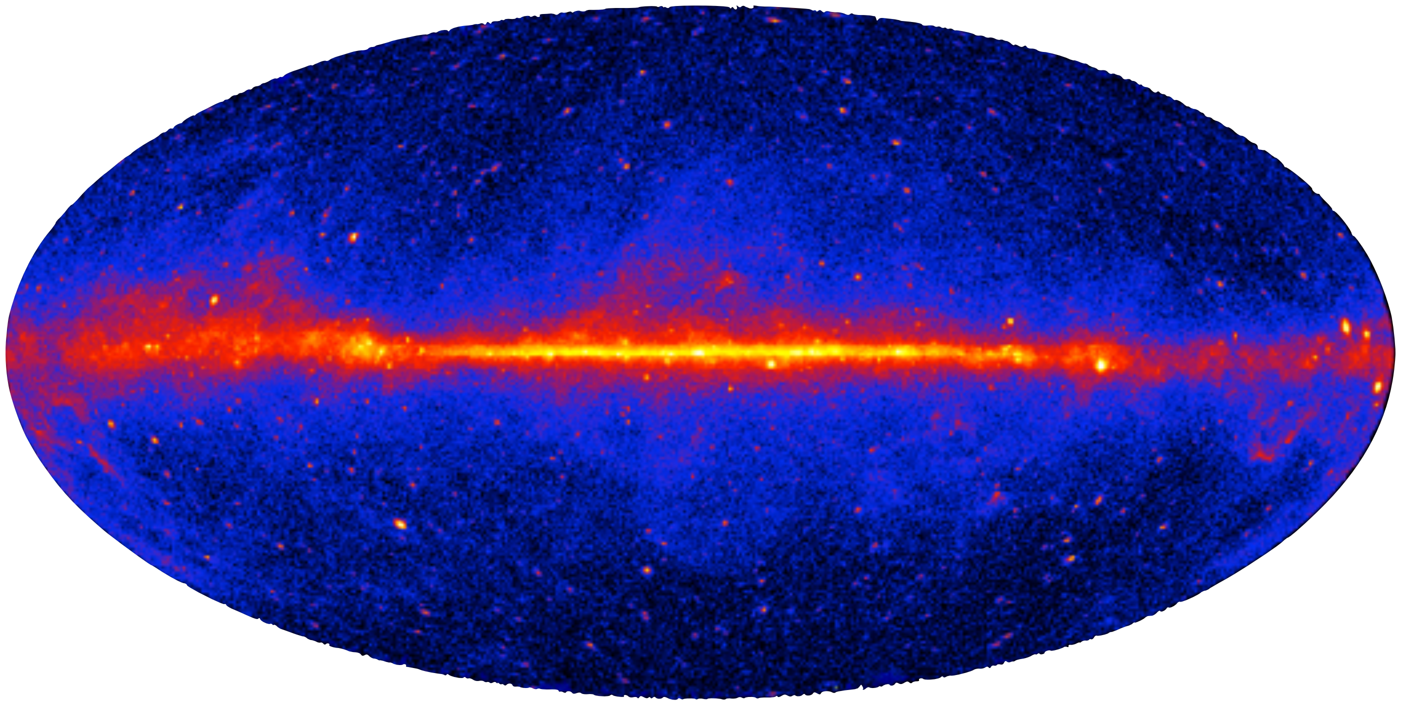
# The New Era of Spaceborne Gamma-ray Astronomy



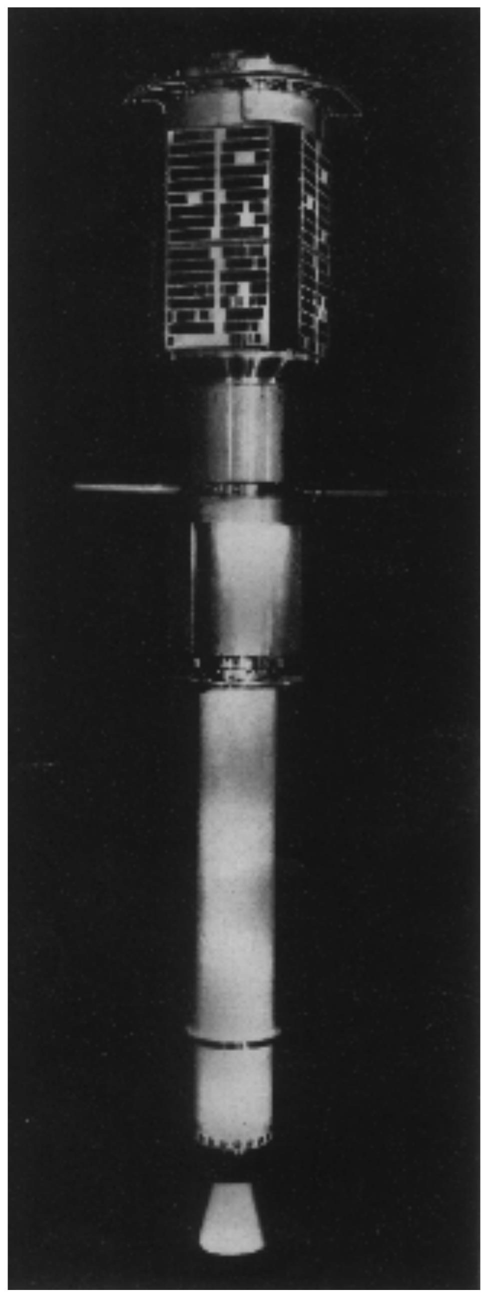
**Meng Su**

*6th HERD collaboration meeting, IHEP*

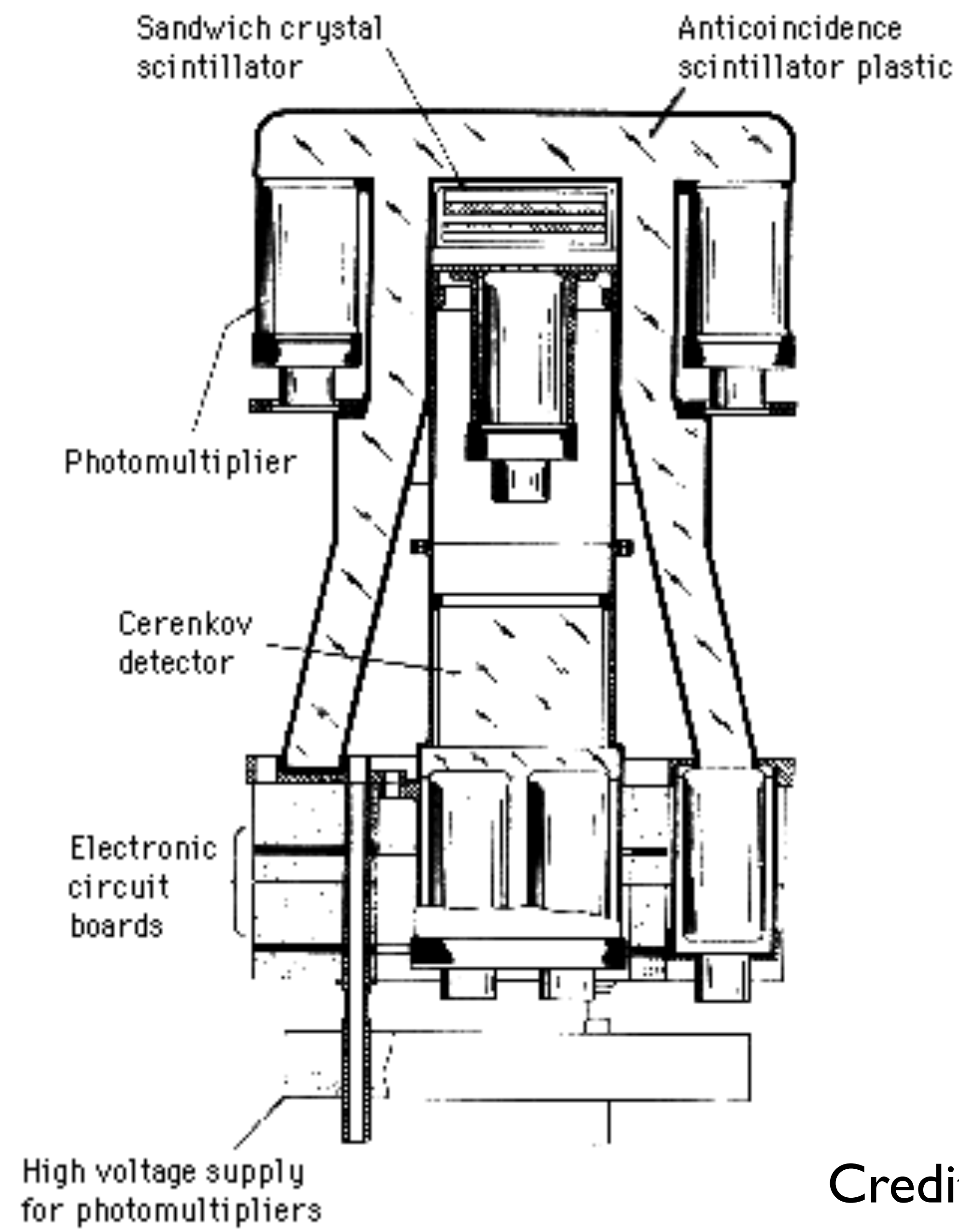
*March 26th, 2018*

# Explorer XI: the very first gamma-ray satellite

(Launched: April 1961)



Credit:NASA

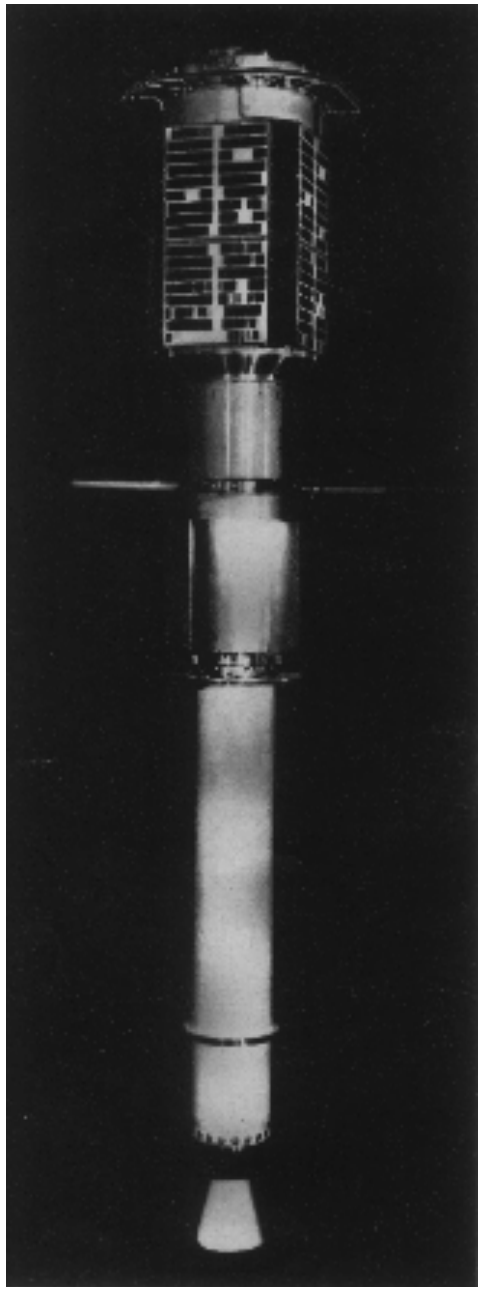



Credit:NASA

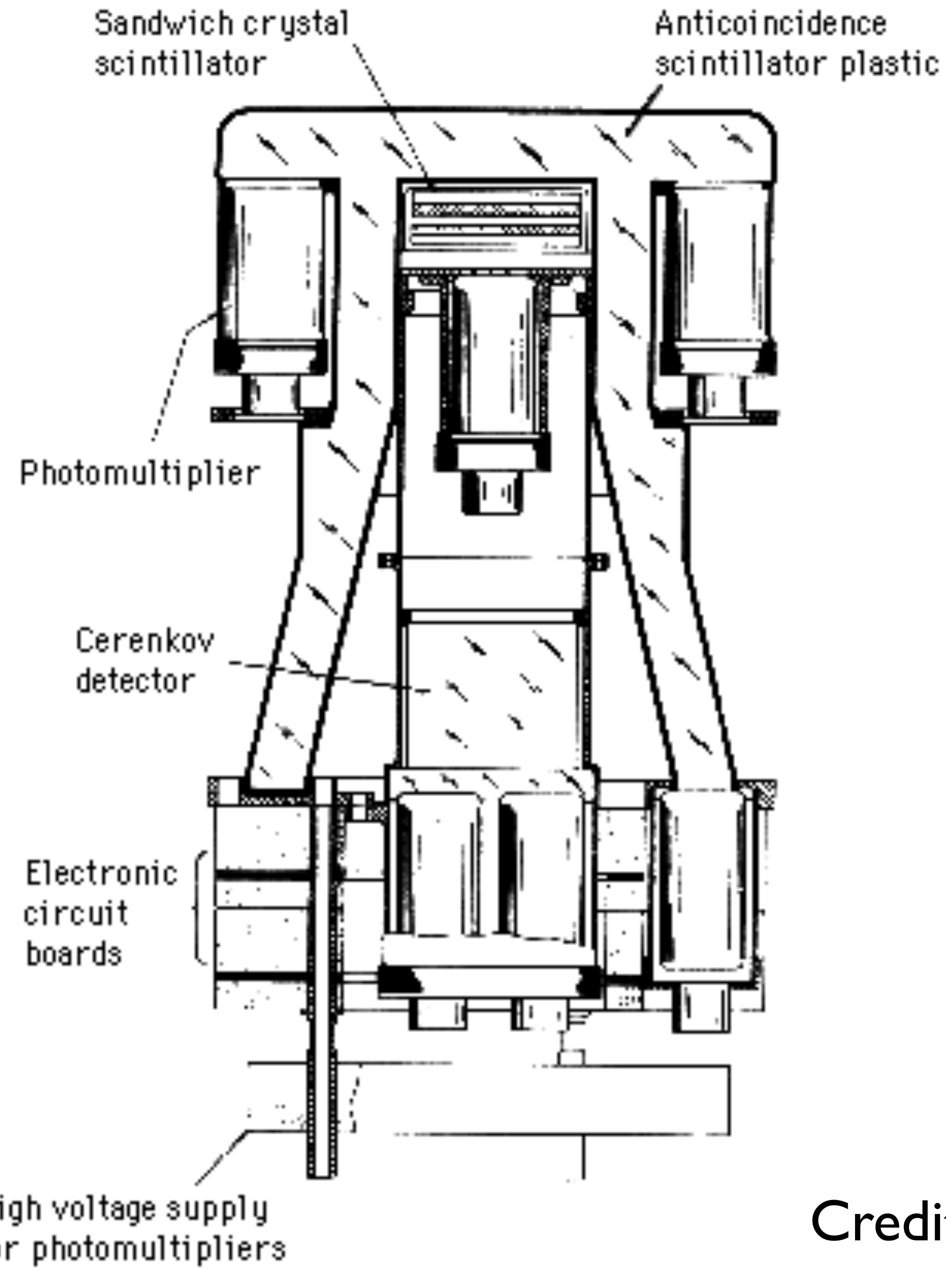
31 gamma-ray photons in its 7 month operation!

# Explorer XI:
# the very first astronomy satellite

(Launched: April 1961)



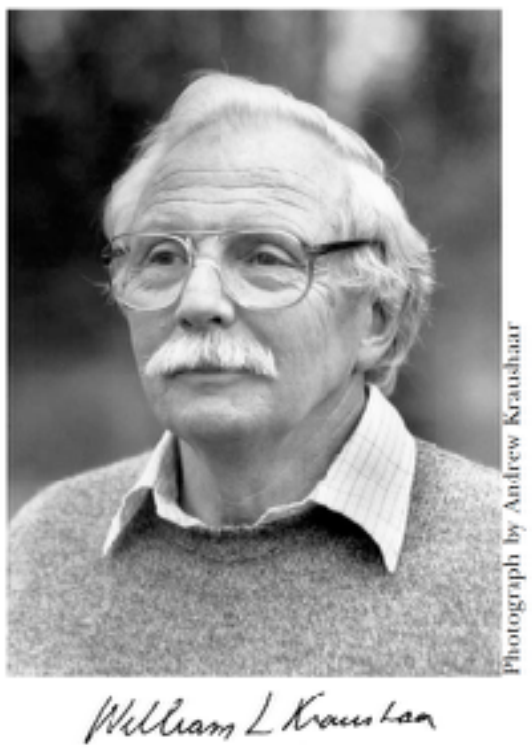
Credit:NASA



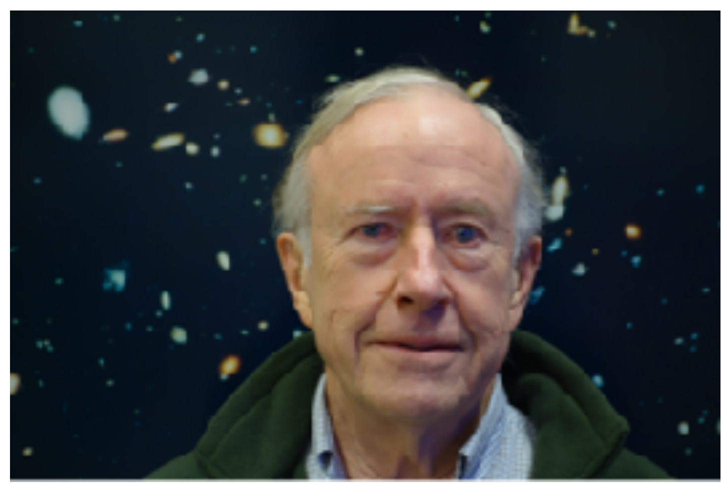

Credit:NASA

31 gamma-ray photons in its 7 month operation!

# Space gamma-ray astronomy was born at MIT




**William L. Kraushaar**
**(1 9 2 0 – 2 0 0 8)**



**George W. Clark**

*"... It is doubtful whether such a small number of particles have ever before been analyzed so intensively in an effort to extract information about the universe."*

—William L. Kraushaar and George W. Clark",
Scientific American, May 1962

# HIGH-ENERGY COSMIC GAMMA-RAY OBSERVATIONS FROM THE OSO-3 SATELLITE*

W. L. KRAUSHAAR,† G. W. CLARK, G. P. GARMIRE,‡ R. BORKEN, P. HIGBIE,§ C. LEONG, AND T. THORSOS

Laboratory for Nuclear Science,
Department of Physics and Center for Space Research,
Massachusetts Institute of Technology

*Received 1972 March 27*

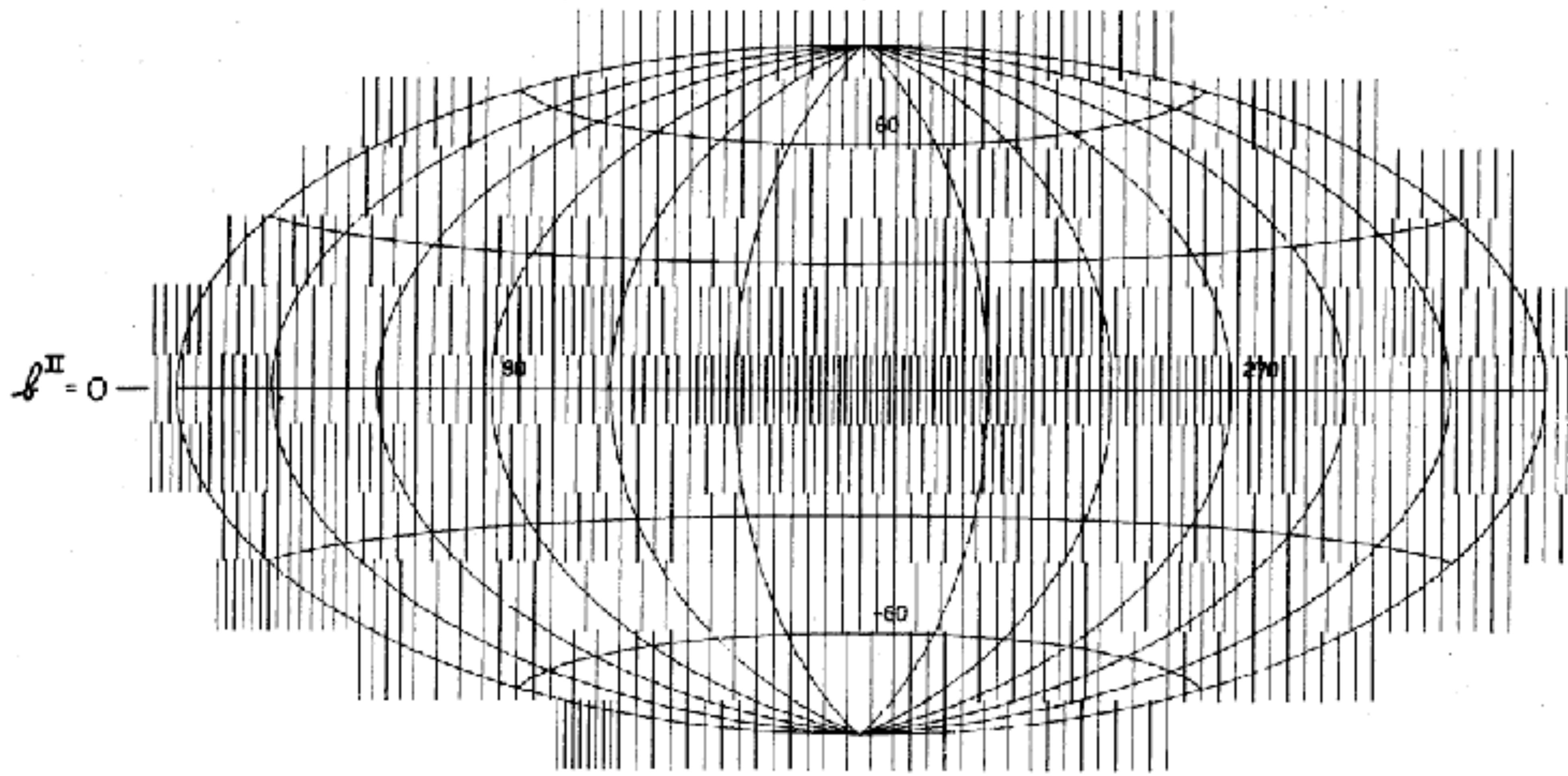
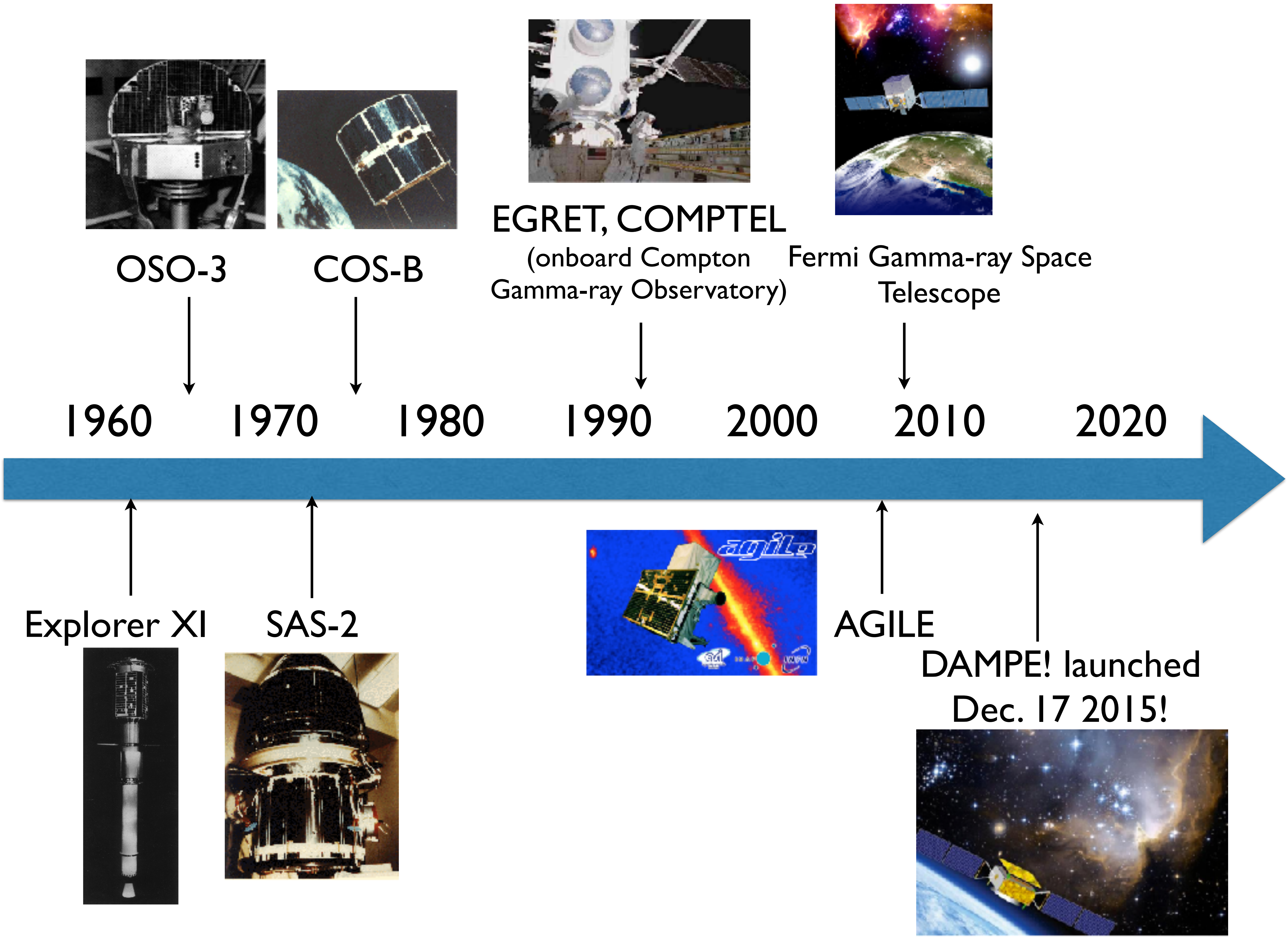



FIG. 8.—Sky map of the $\gamma$-ray intensity in galactic coordinates. The element of area on the map to which the formula given in the text applies is approximately 245 square degrees.

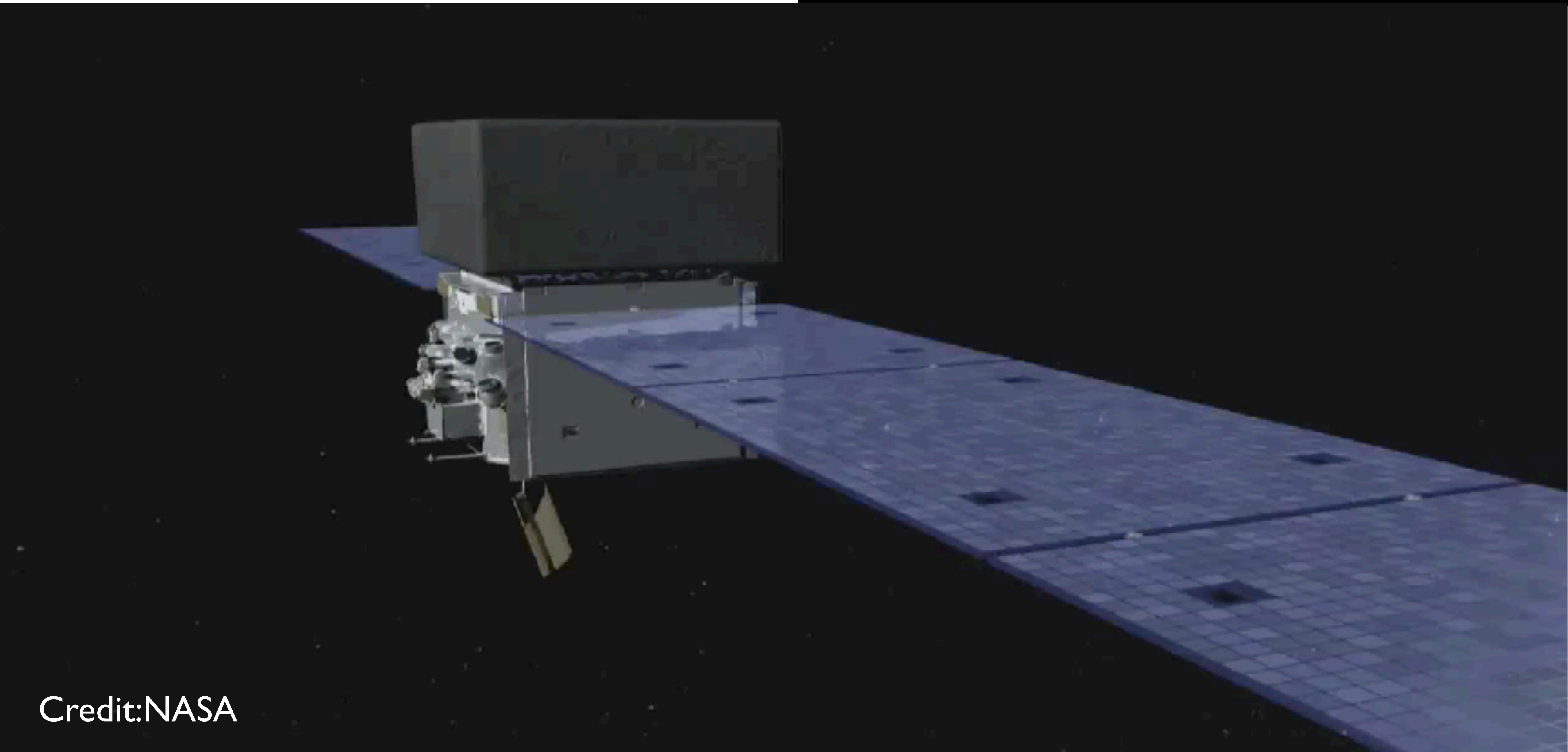
First gamma-ray sky map with 621 photons >50 MeV


OSO-3
COS-B
EGRET, COMPTEL
(onboard Compton
Gamma-ray Observatory)
Fermi Gamma-ray Space
Telescope
1960
1970
1980
1990
2000
2010
2020
Explorer XI
SAS-2
AGILE
DAMPE! launched
Dec. 17 2015!

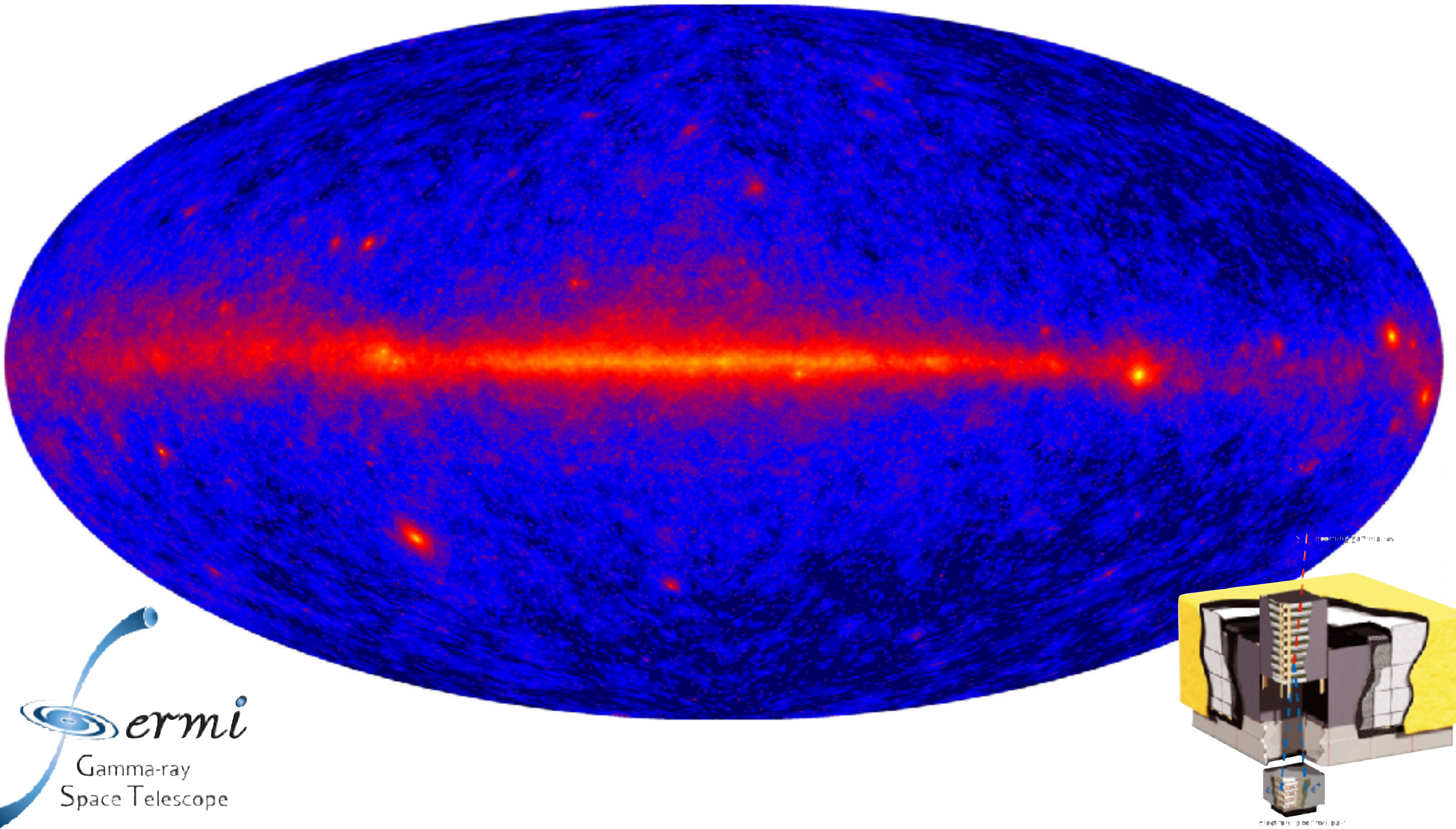

National Aeronautics and Space Administration
NASA
Fermi
Gamma-ray Space Telescope
www.nasa.gov/fermi

Credit:NASA

# Launch of Fermi Gamma-ray Space Telescope (June 2008)!

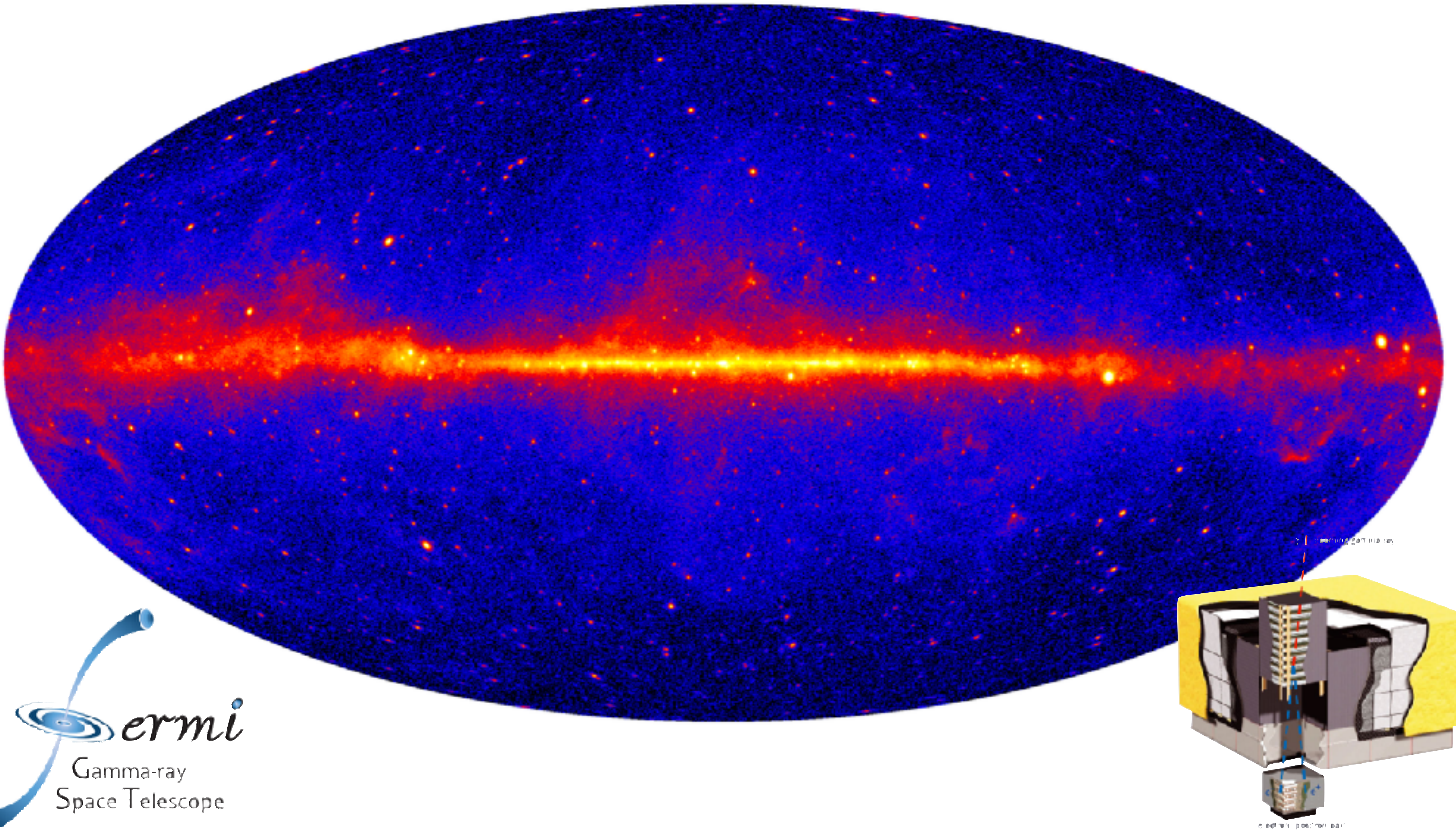


# The First LAT All-sky Map



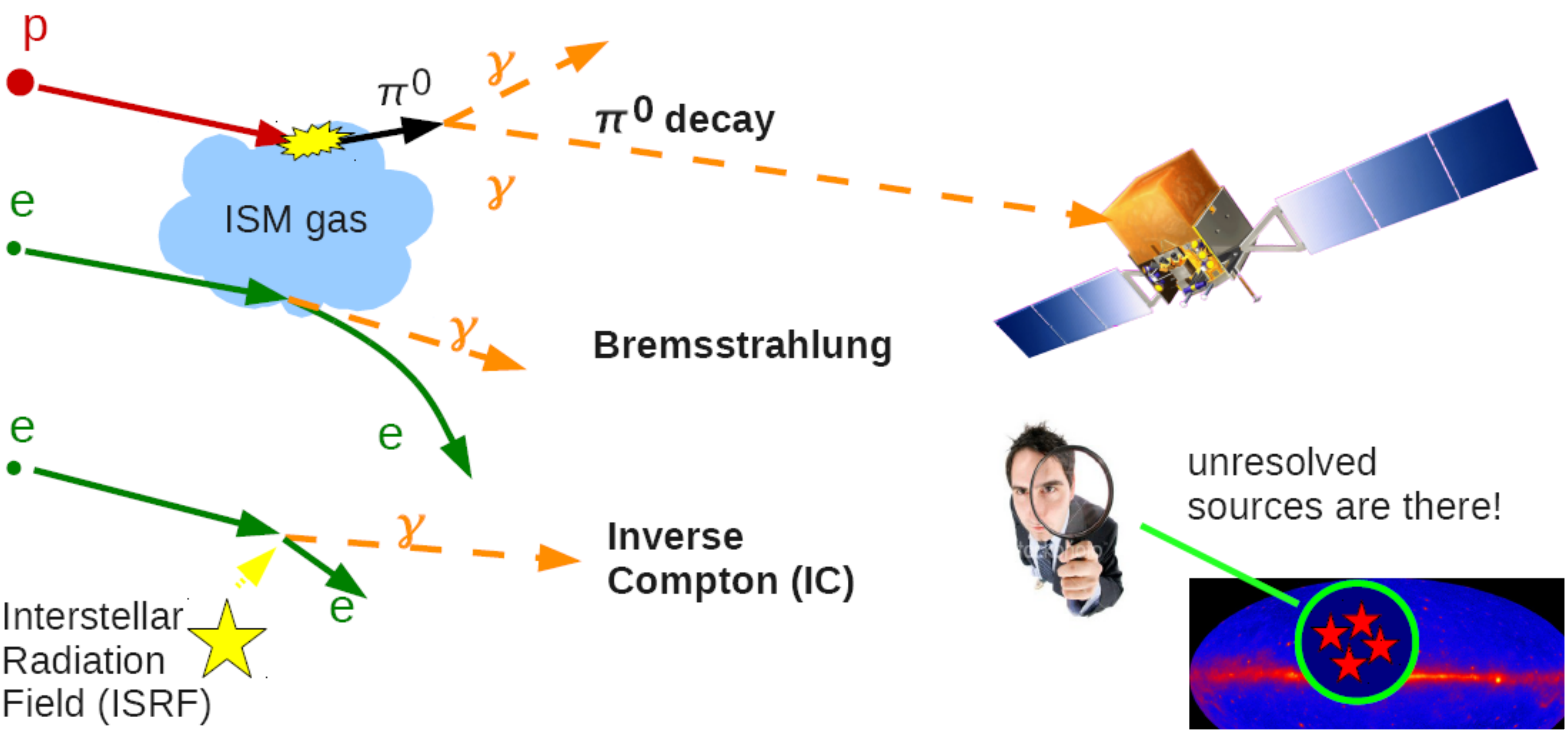
Fermi
Gamma-ray
Space Telescope

# The 3FGL All-sky Map



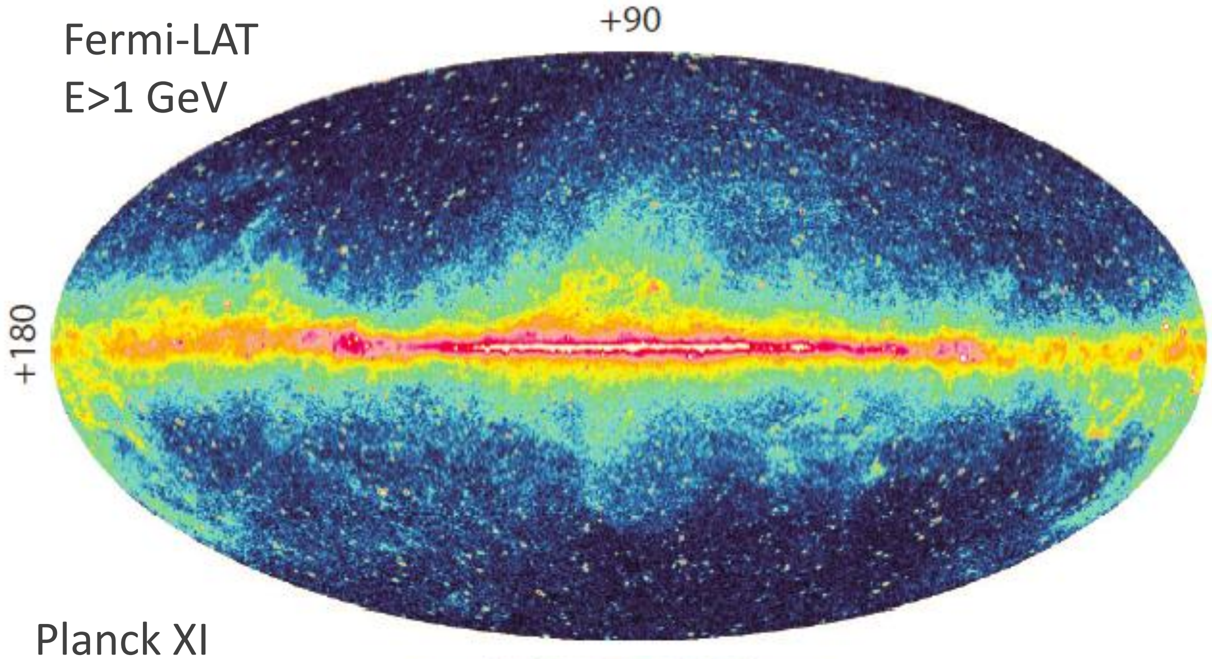
Fermi
Gamma-ray
Space Telescope

# Galactic Diffuse Gamma-ray Emission

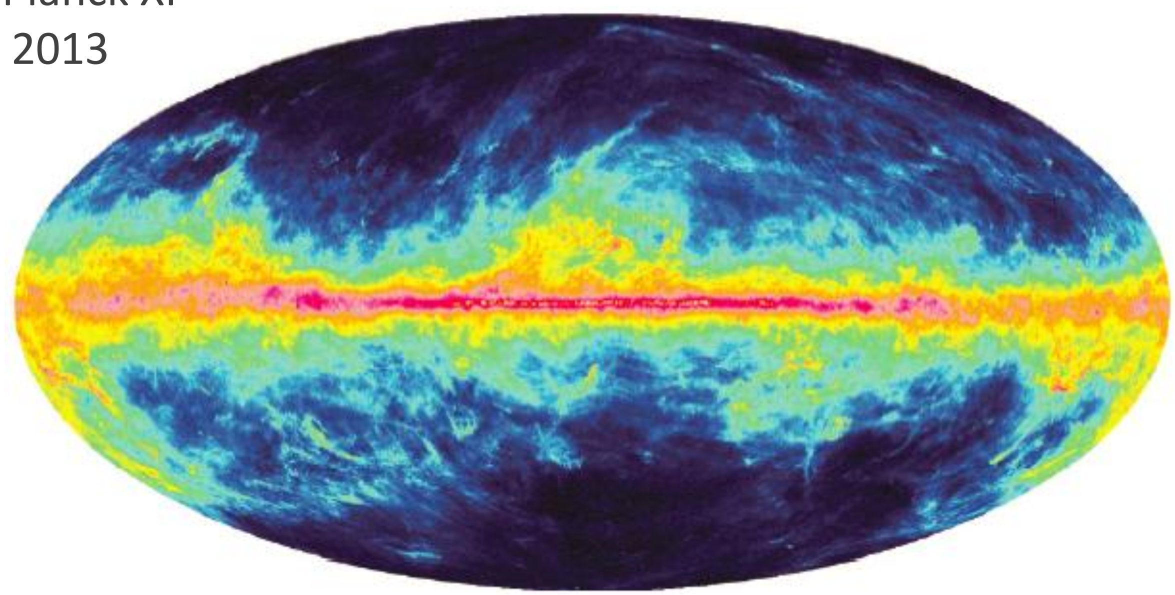


# Total gas tracers

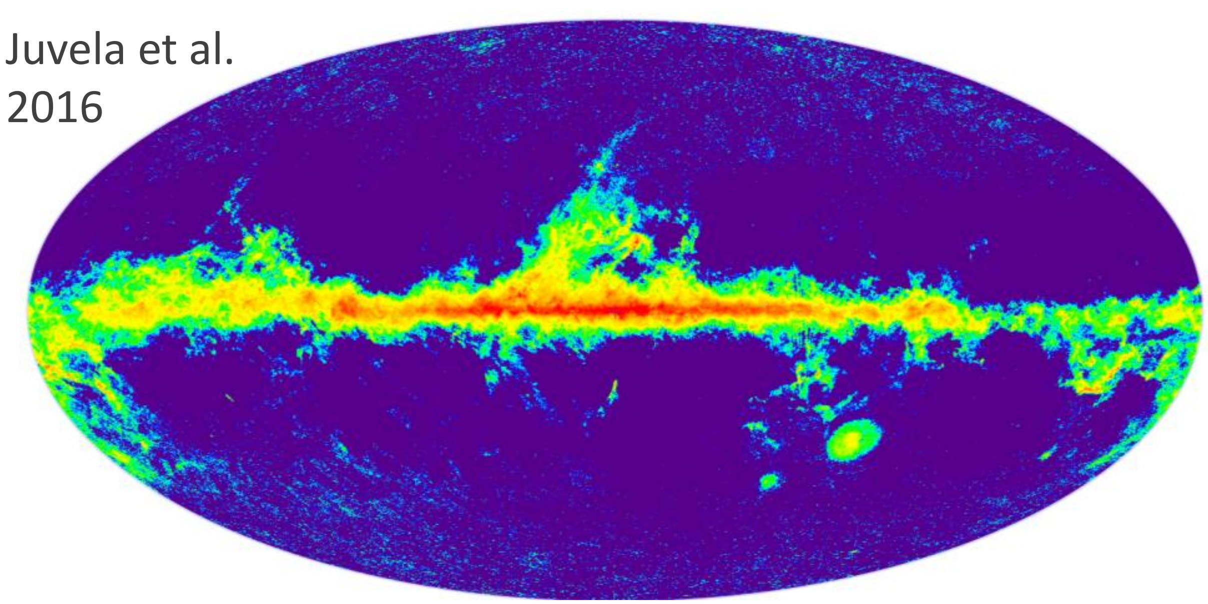
Fermi-LAT
E>1 GeV




Planck XI
2013



Juvela et al.
2016



- γ rays of interstellar origin

Cosmic-Ray interactions with gas

$$p_{CR} + p_H \rightarrow \pi_0 \rightarrow 2\,\gamma$$

$$I_\gamma \;\alpha \int n_{CR}\, n_H\, dl$$

- Dust thermal emission from large dust grains mixed with gas

$$I_\nu = \tau_\nu B_\nu(T)$$

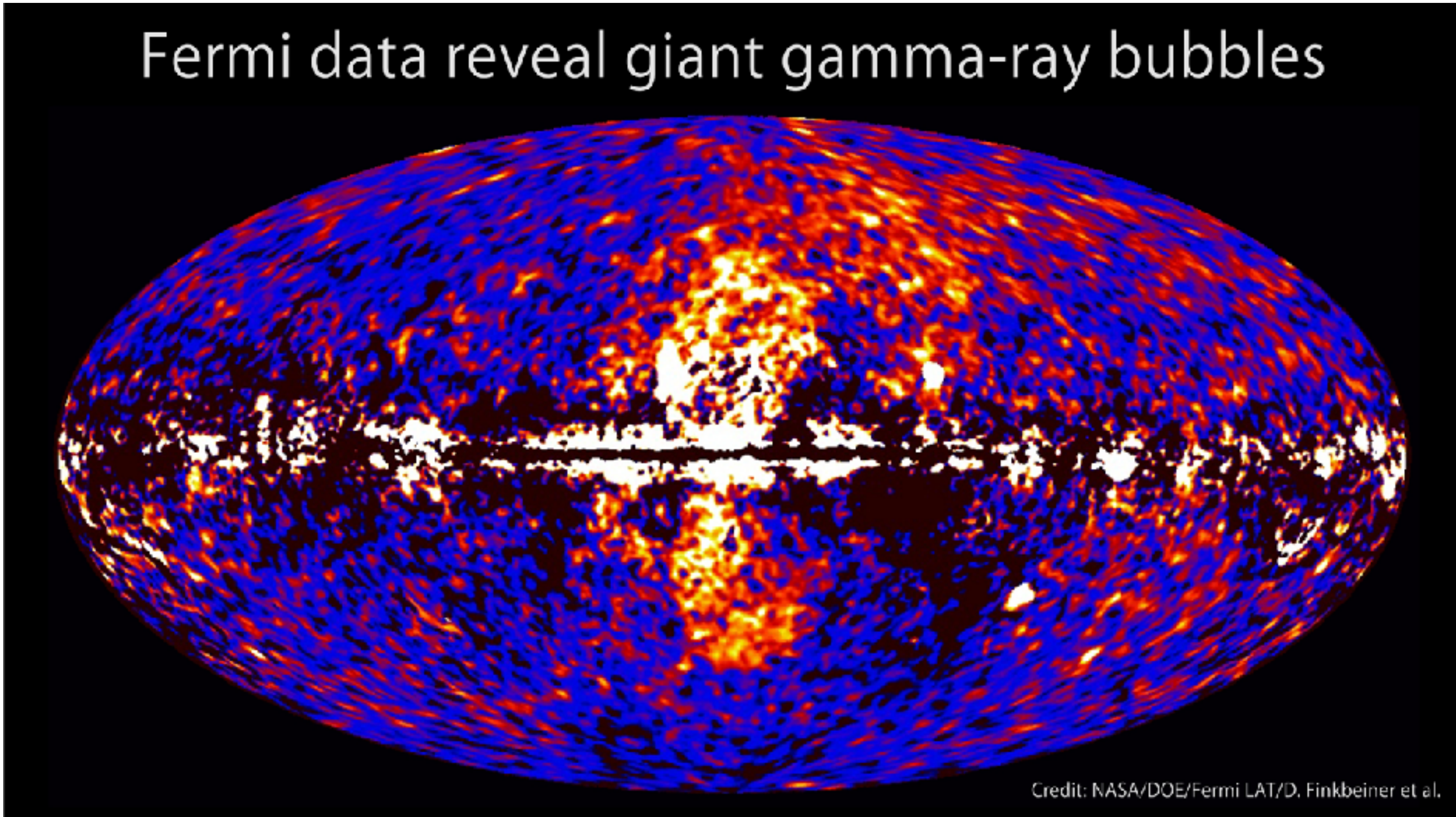
Dust optical depth $\tau_\nu = \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta R_{\rm DG}\, \mu_{\rm H} N_{\rm H}$

- Extinction caused by large dust grains mixed with gas

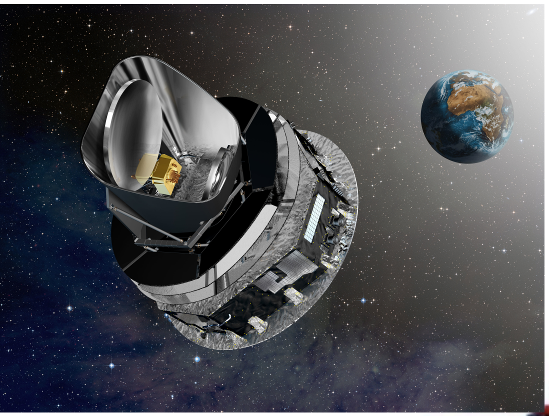
$$A_\lambda = 1.086\tau_\lambda^{\rm ext} = 1.086 \int n_{\rm dust}\sigma_\lambda^{\rm ext} {\rm ds}$$

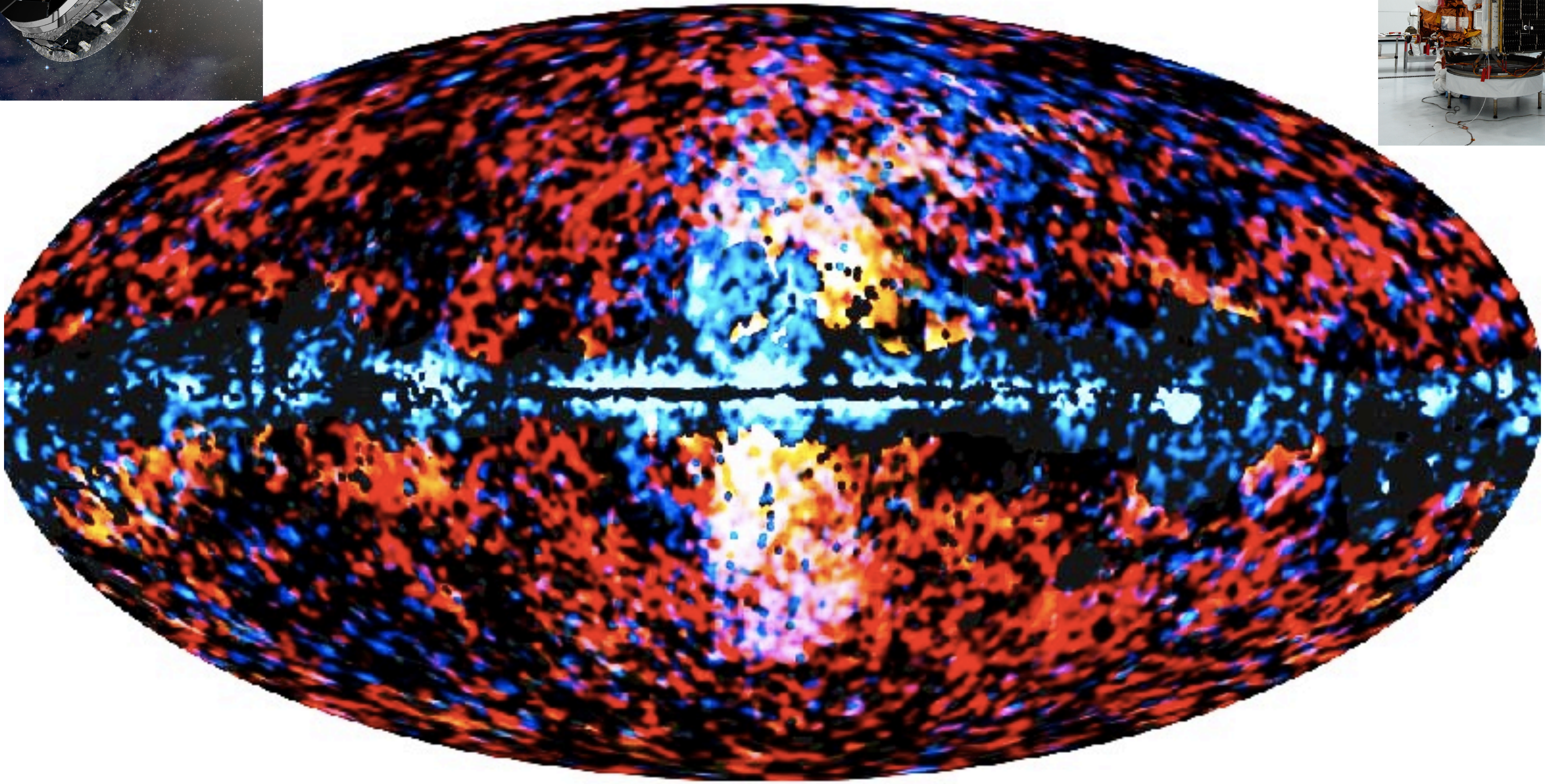
Stellar reddening: $E(B\text{-}V) = A_V / R_V$

# NASA press release: Fermi bubbles (FB)



# Haze superimposed over the FB

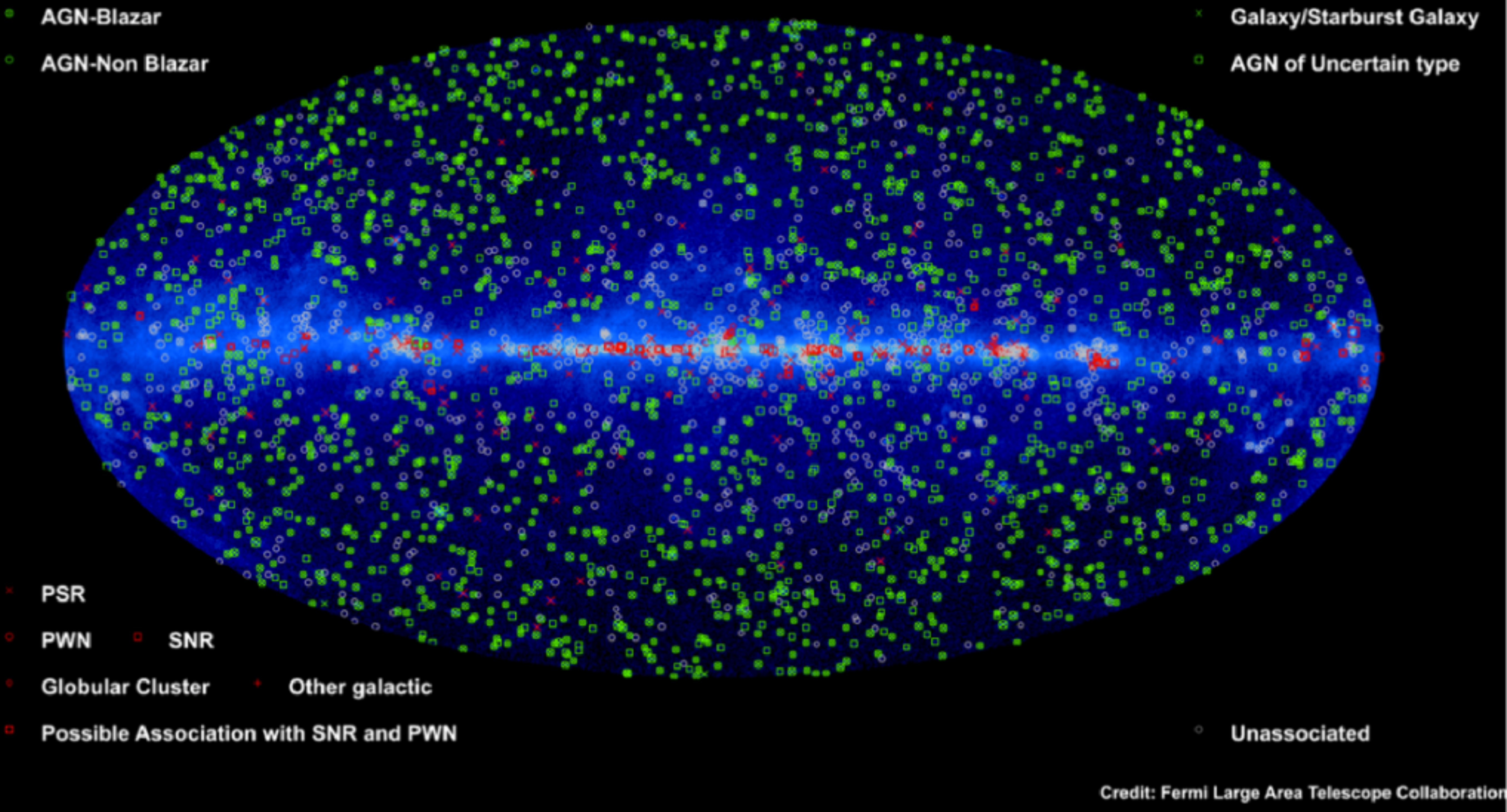


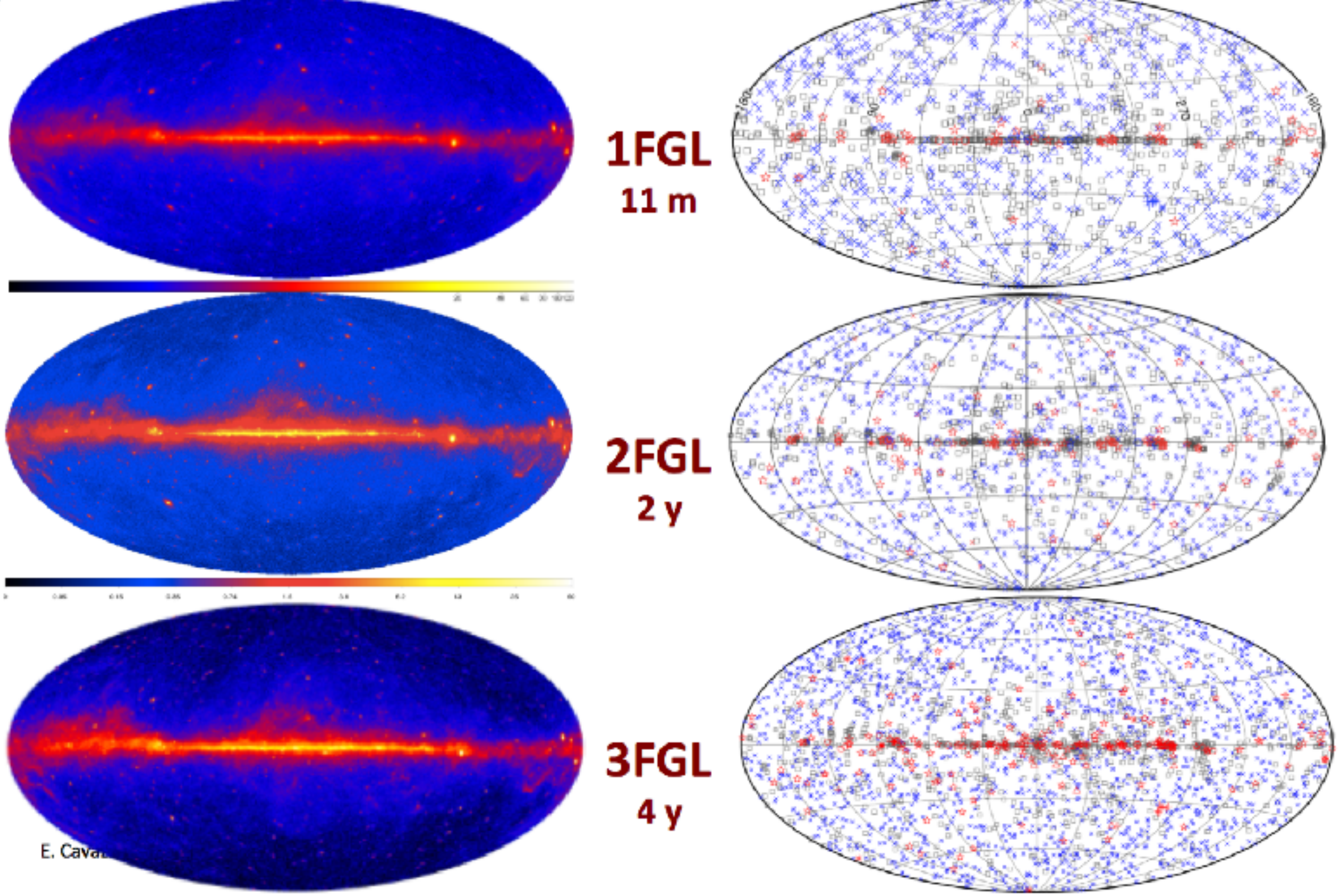


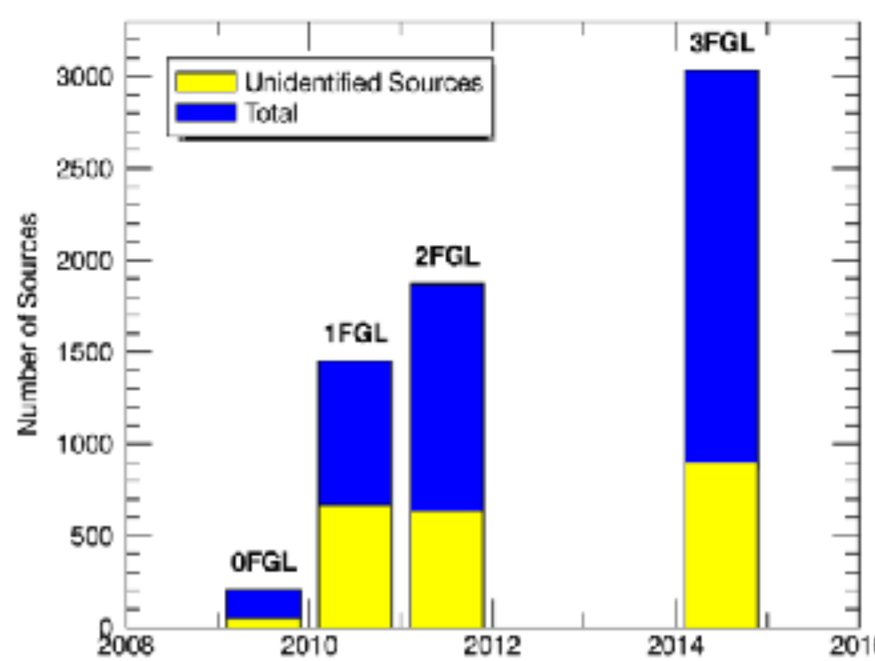
Credits: ESA/Planck Collaboration.

# Fermi Large Area Telescope 3FGL catalog

**Fermi-LAT (1FGL, 2FGL, 3FGL) catalogs do an excellent job in characterizing variability and energetics of sources detected in the 0.1-100 GeV band**




1FGL
11 m
2FGL
2 y
3FGL
4 y


Unidentified Sources
Total
0FGL
1FGL
2FGL
3FGL
Number of Sources
0
500
1000
1500
2000
2500
3000
2008
2010
2012
2014
2016

# HERD's gamma-ray science goals

- Search for signatures of dark matter
- Studies of Galactic and extragalactic gamma-ray sources
- Galactic and extragalactic diffuse emission
- Gamma-ray transients, e.g. gamma-ray bursts, flares

# Scientific Objectives of the High Energy cosmic Radiation Detection facility (HERD)*

Gamma-ray Science Workshop Group†

(Dated: March 26, 2018)

I. Gamma Ray Observatory

A. Galactic and extragalactic gamma-ray origins of diffuse emission and the nature of unidentified sources

1. Unidentified EGRET/FERMI sources
2. Interstellar emission originated from the Milky Way, nearby galaxies, and galaxy clusters
3. Extragalactic diffuse emission

B. Galactic and extragalactic cosmic rays

1. The origin of Galactic cosmic rays
2. Galactic winds and the Fermi bubbles
3. Cosmic-ray transport
4. Origin of the ultra high-energy cosmic rays

C. Mechanisms of particle acceleration in celestial sources

1. The Galactic center region
2. Isolated pulsars and their wind nebula
3. Black holes and binaries
4. Active Galactic Nuclei(AGN)
5. Gamma-ray binaries

D. gamma-ray emission from the Sun and solar system bodies

1. Solar flares
2. Terrestrial gamma-ray flashes

E. High-energy behavior or GRBs and transients

F. Nature of Dark Matter

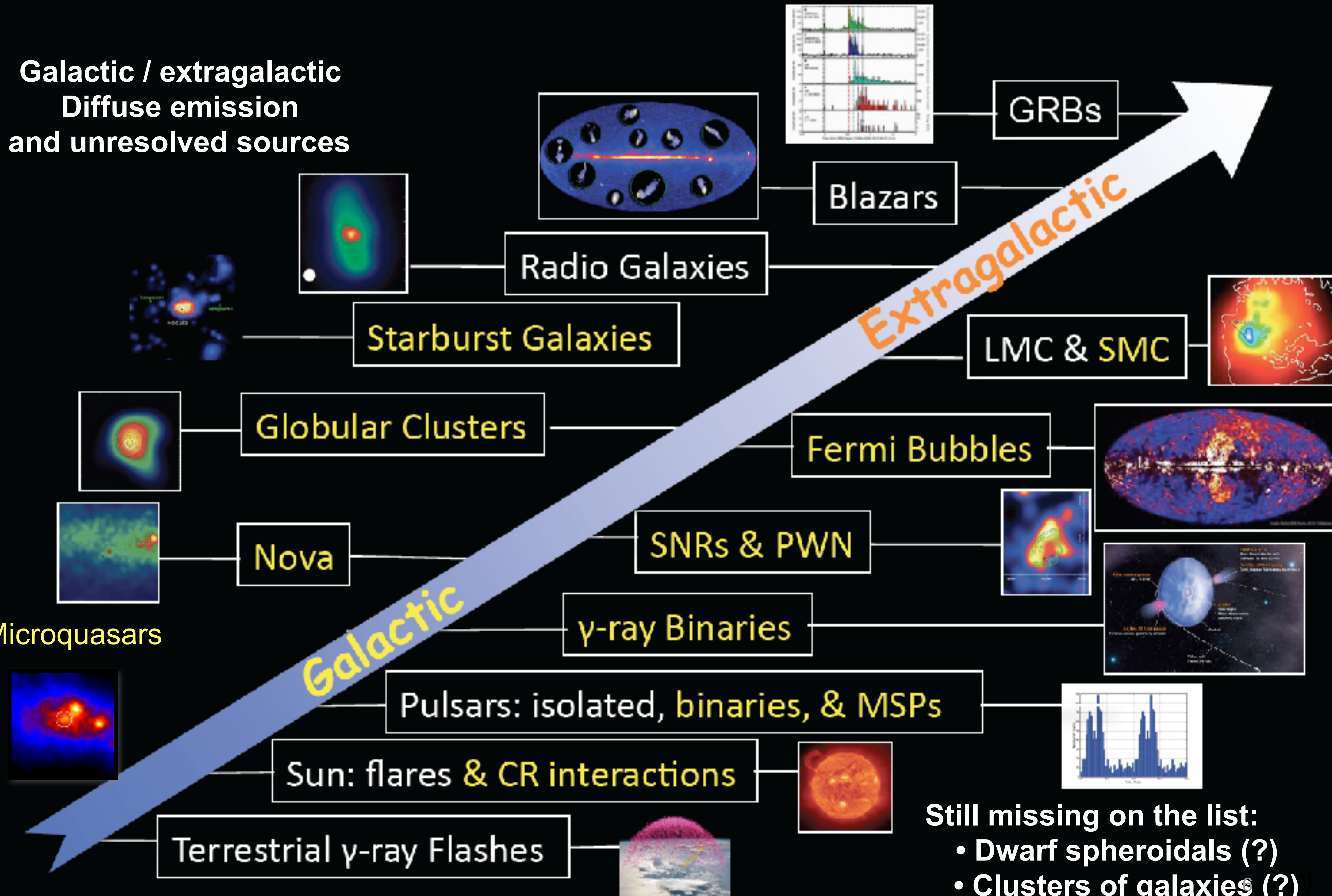
G. Cosmology and the early universe

1. Gamma-ray background and baryon asymmetry
2. Evaporation of primordial black holes
3. Quantum-gravity and the structure of space-time

H. Future of multi-messenger astronomy

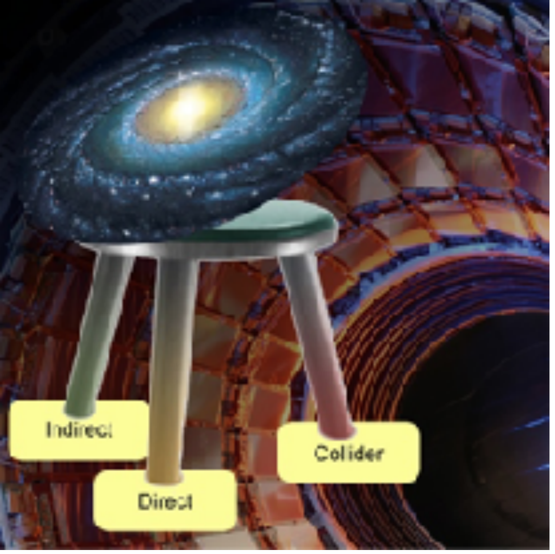
# The GeV-TeV sky is rich!

**Galactic / extragalactic**
**Diffuse emission**
**and unresolved sources**

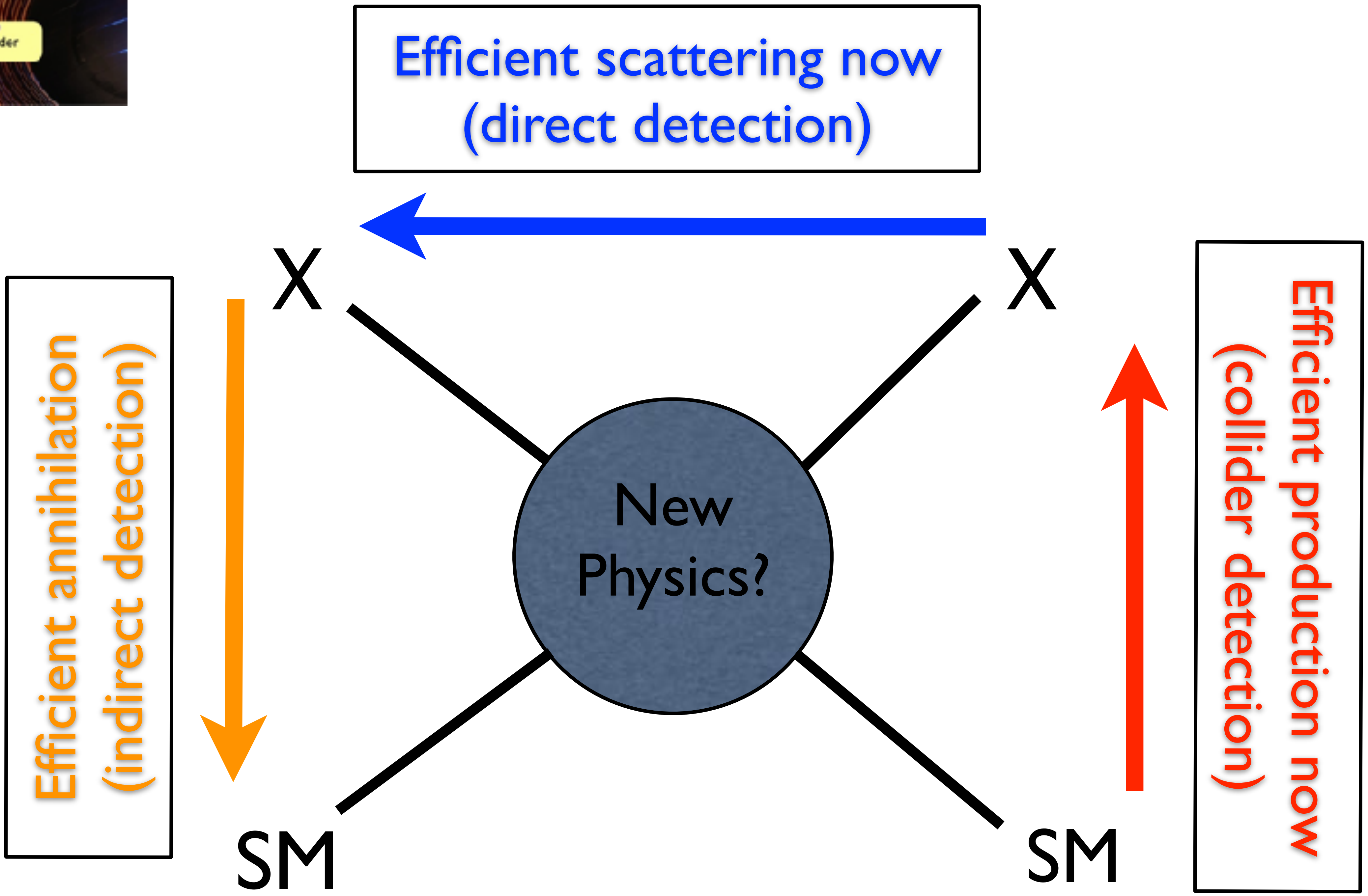



**Still missing on the list:**

- **Dwarf spheroidals (?)**
- **Clusters of galaxies (?)**

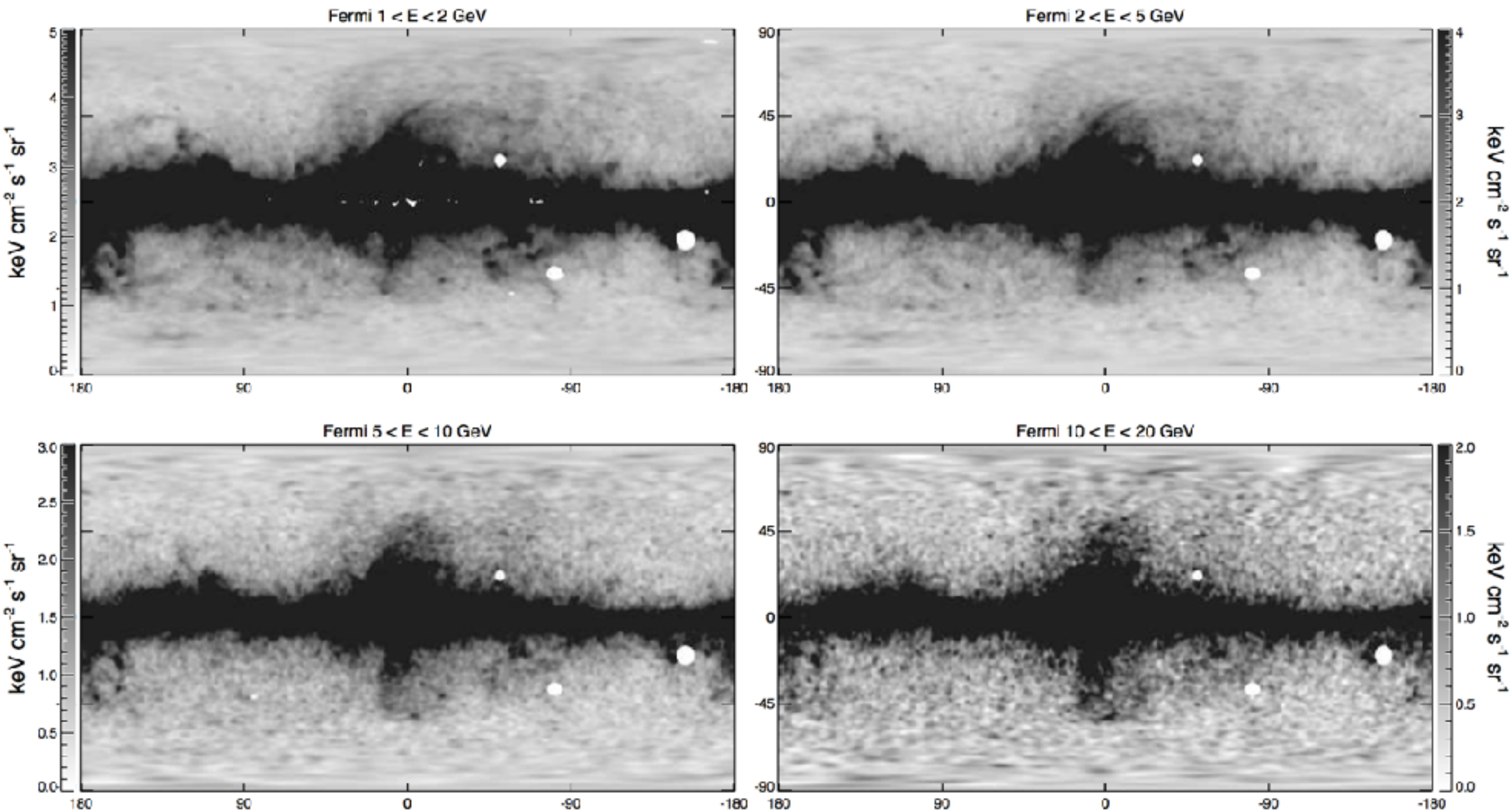



# Dark Matter: a grand challenge for both fundamental physics and astronomy.

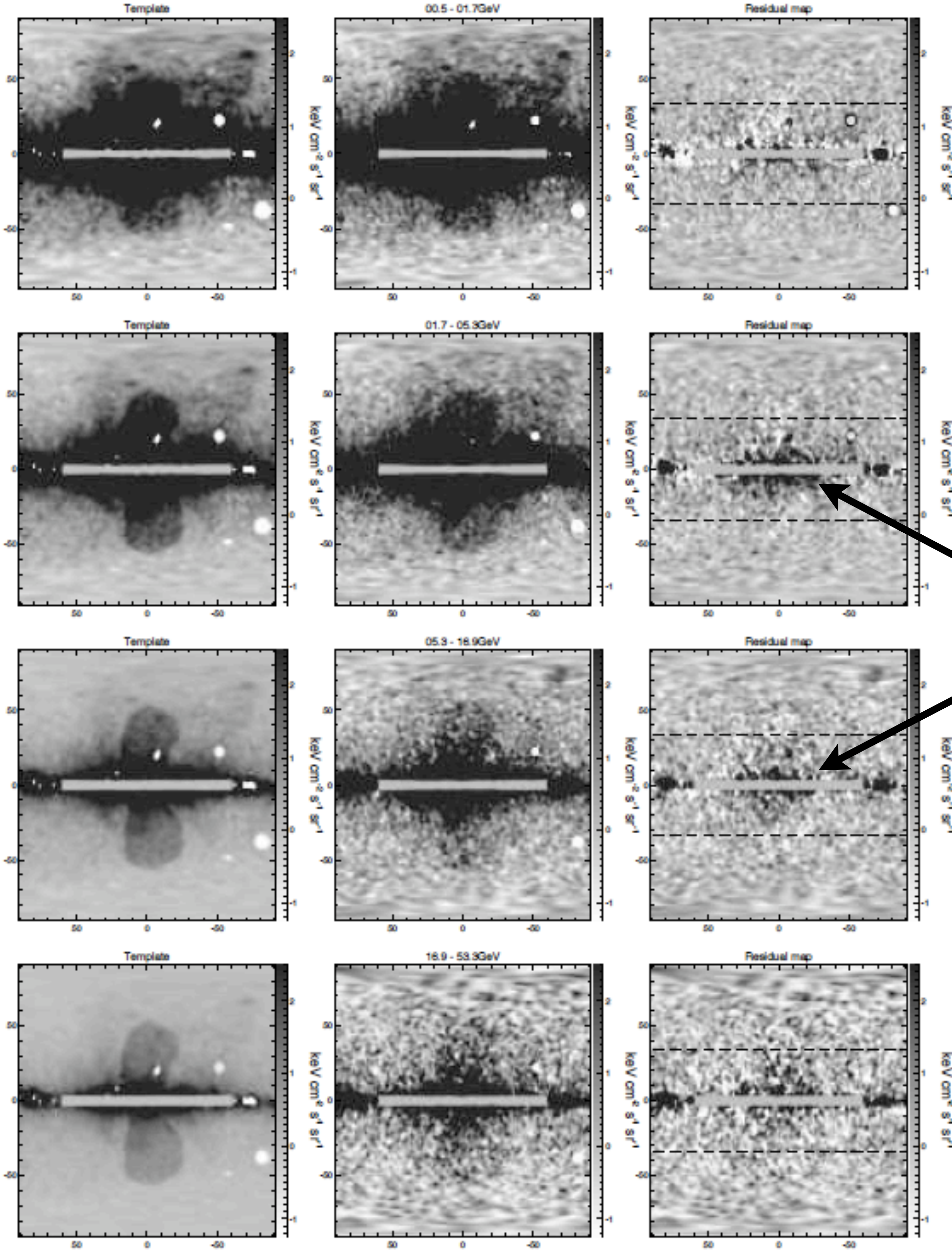



Groundbreaking ***complementarity*** experiments are set to transform the field of dark matter in the coming decade!

# Almost ten years Fermi data



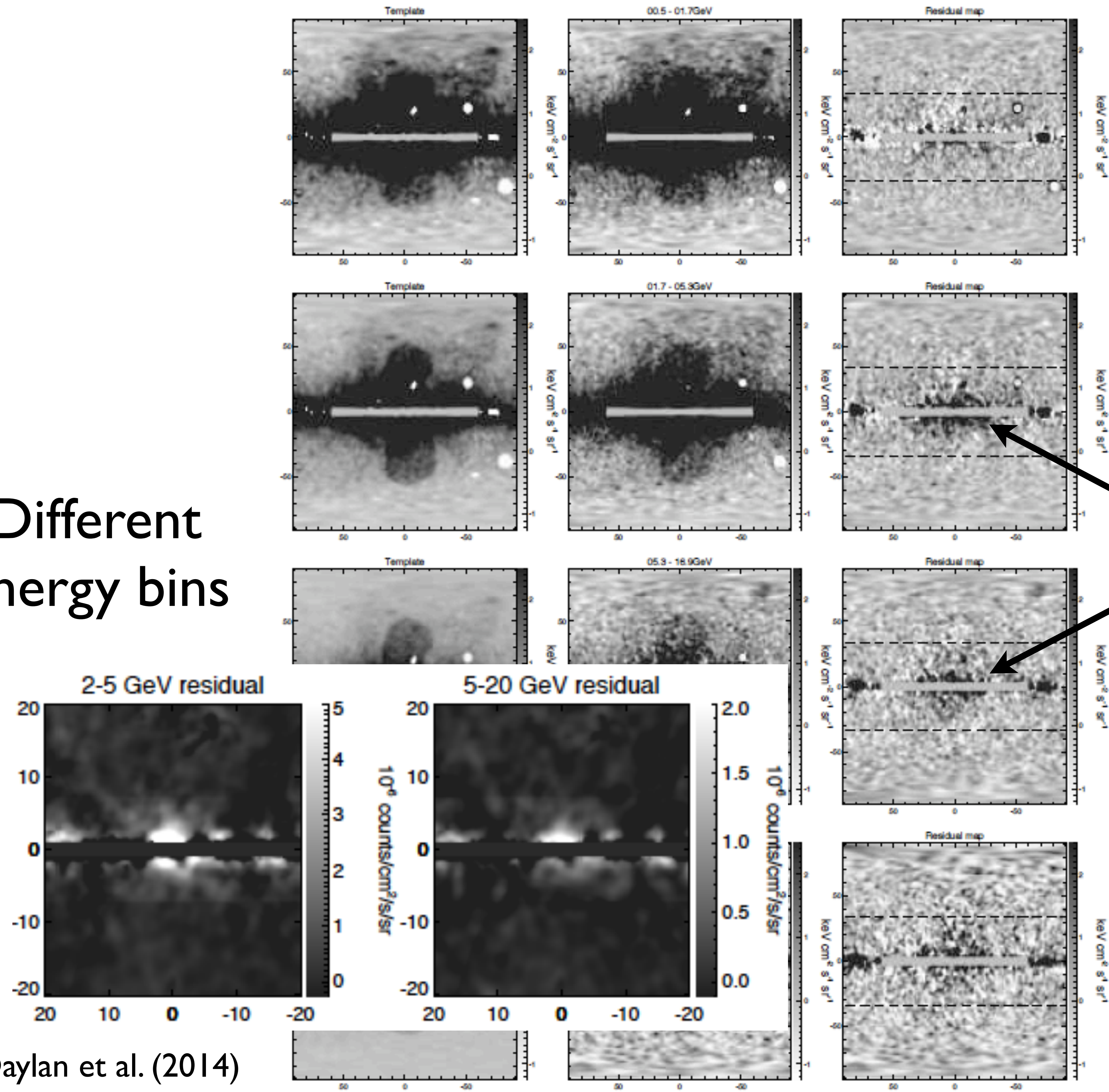
Different energy bins




What's this?

MS, Slatyer, Finkbeiner (2010)

Different energy bins

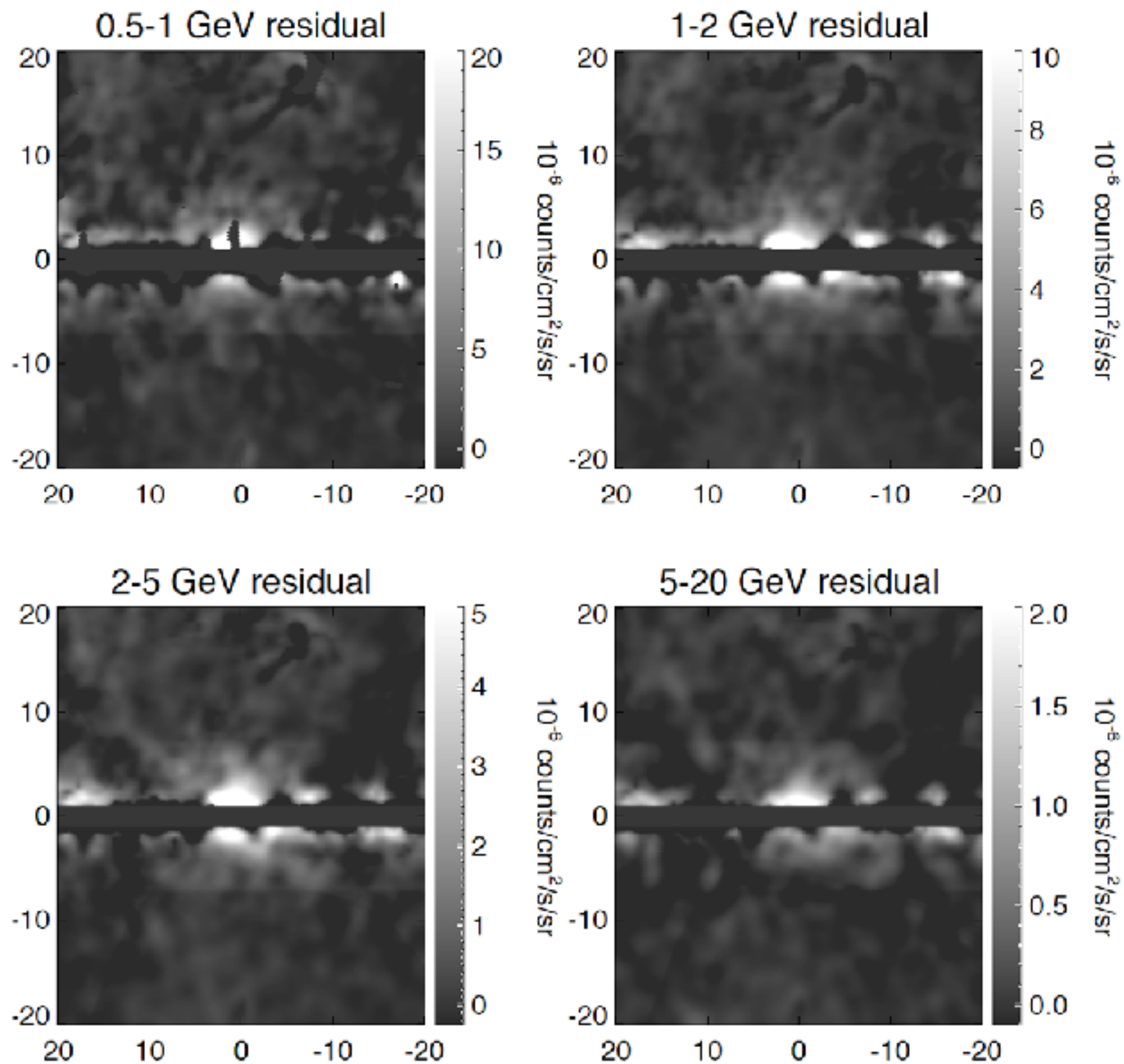



What's this?

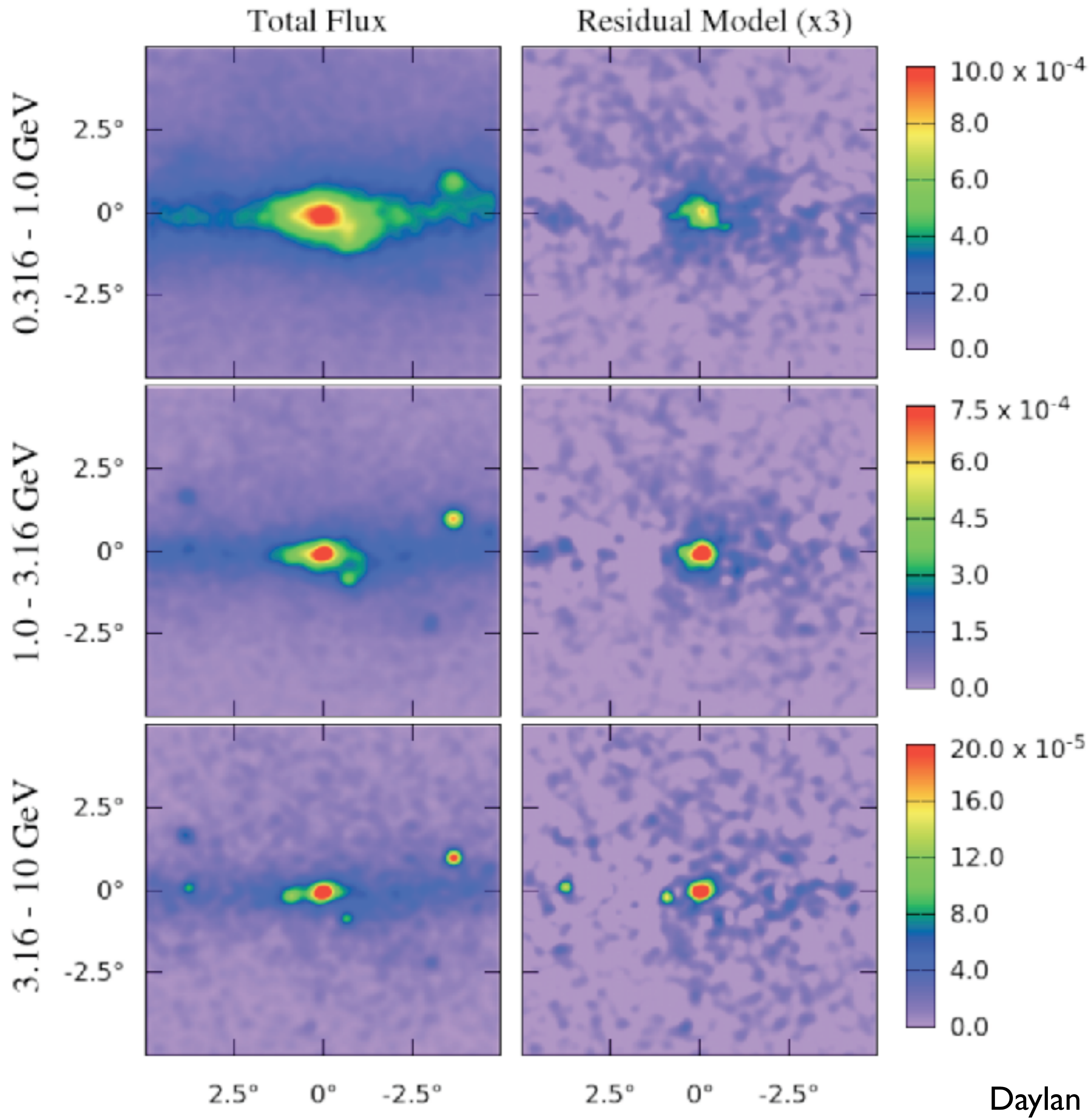
Daylan et al. (2014)

MS, Slatyer, Finkbeiner (2010)

# What we are looking at

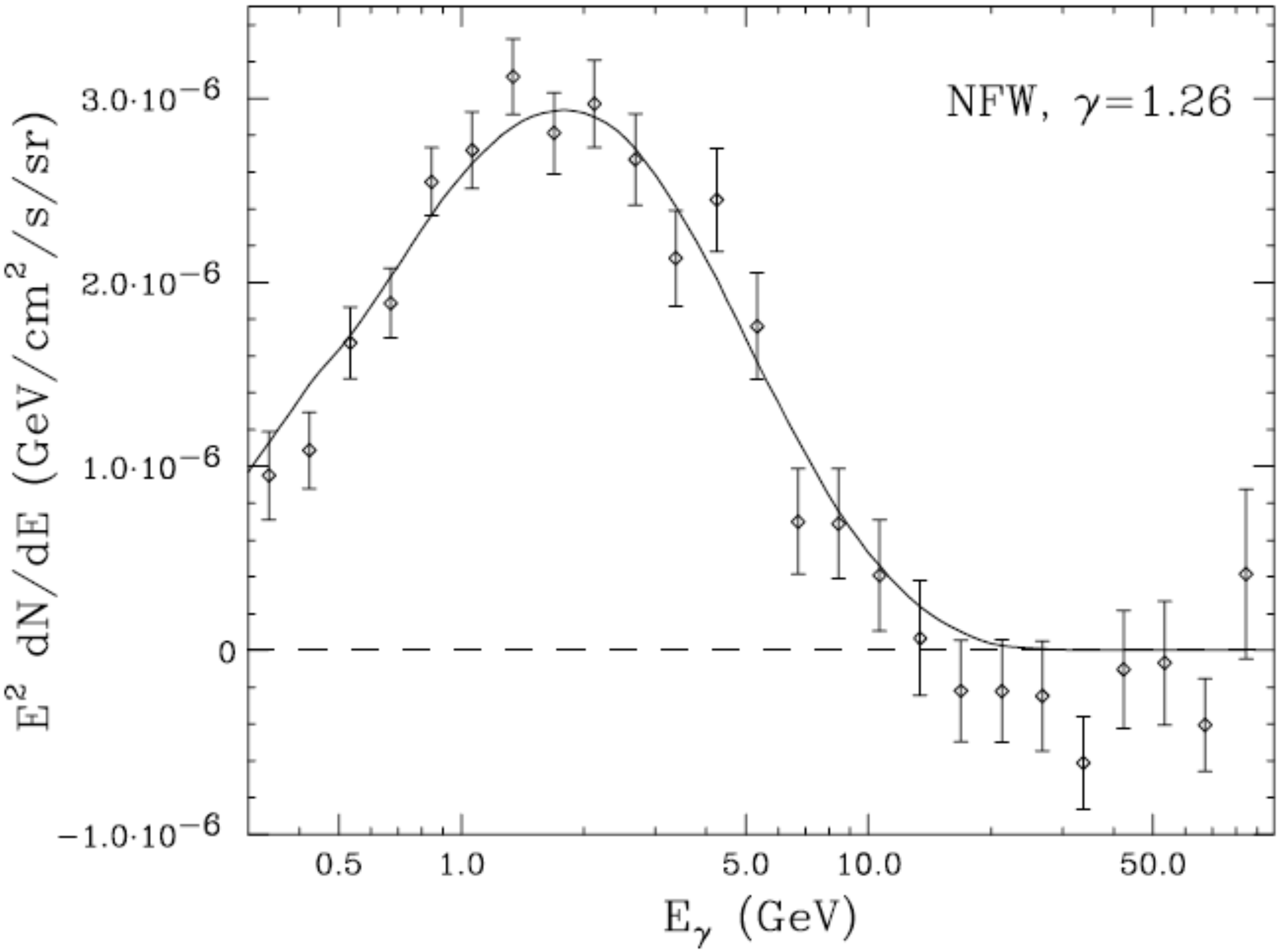



Daylan et al. (2014)




Daylan et al. (2014)

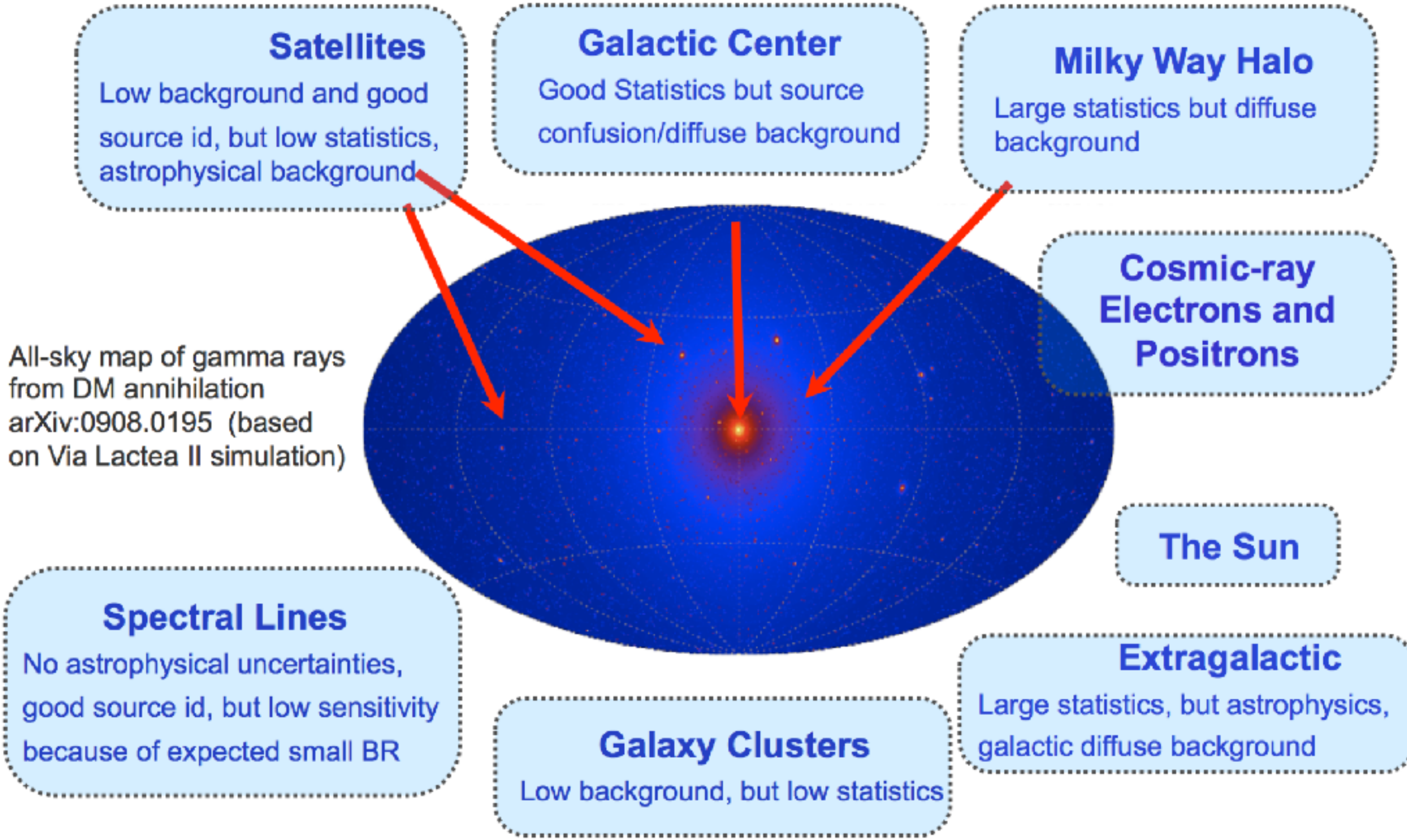
# Best fit spectrum



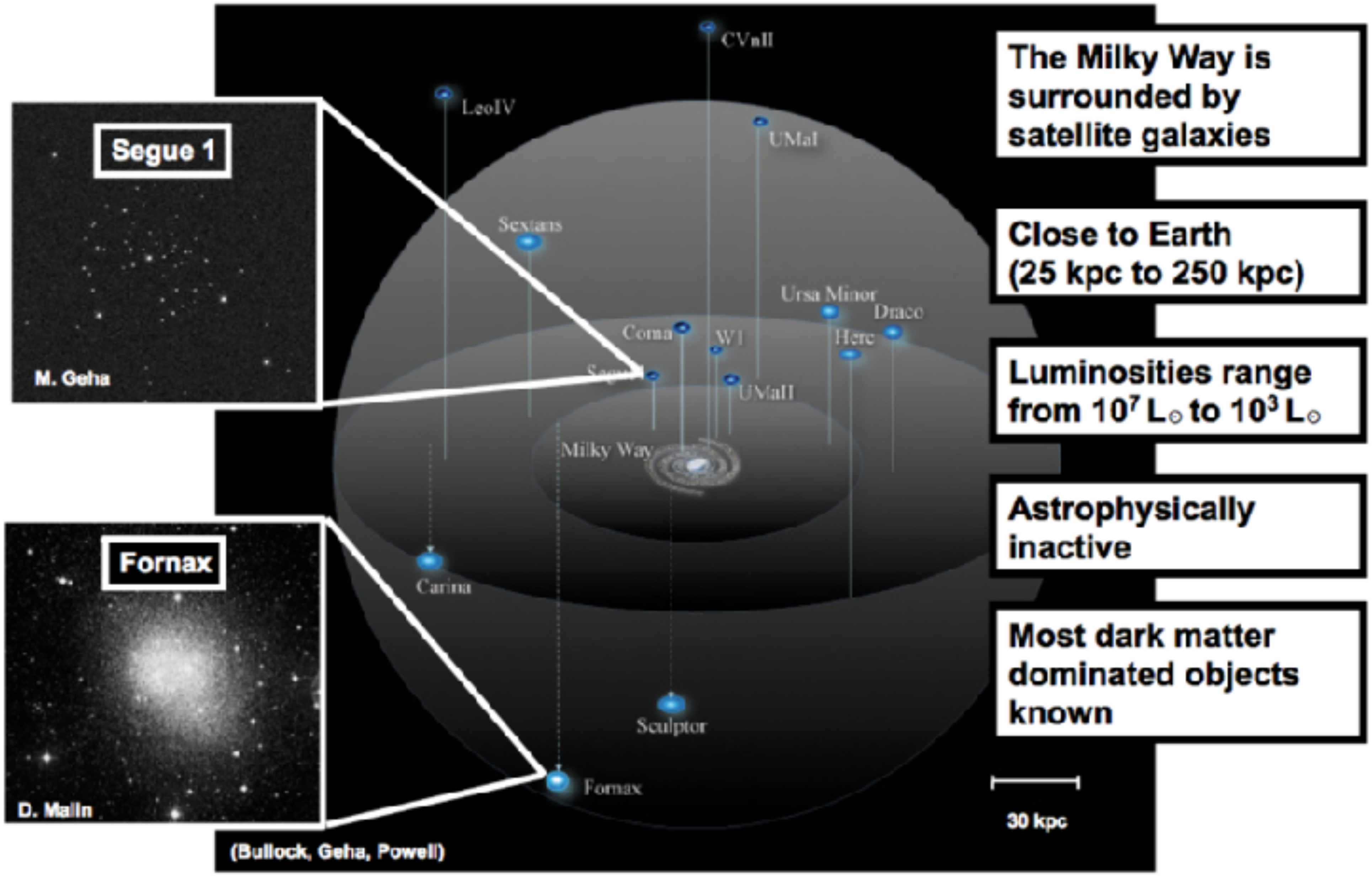

A ~35 GeV dark matter particle annihilating to bbar

$$\sigma v = 1.7 \times 10^{-26}\ \mathrm{cm^3/s}\ \times [(0.3\,\mathrm{GeV/cm^3})/\rho_{\mathrm{local}}]^2$$

Daylan et al. (2014)


Satellites
Low background and good source id, but low statistics, astrophysical background
Galactic Center
Good Statistics but source confusion/diffuse background
Milky Way Halo
Large statistics but diffuse background
Cosmic-ray Electrons and Positrons
All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)
The Sun
Spectral Lines
No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR
Extragalactic
Large statistics, but astrophysics, galactic diffuse background
Galaxy Clusters
Low background, but low statistics

# Dwarf spheroidal galaxies (dSphs) are highly DM-dominated systems orbiting the MW at typical distances of 25-100 kpc



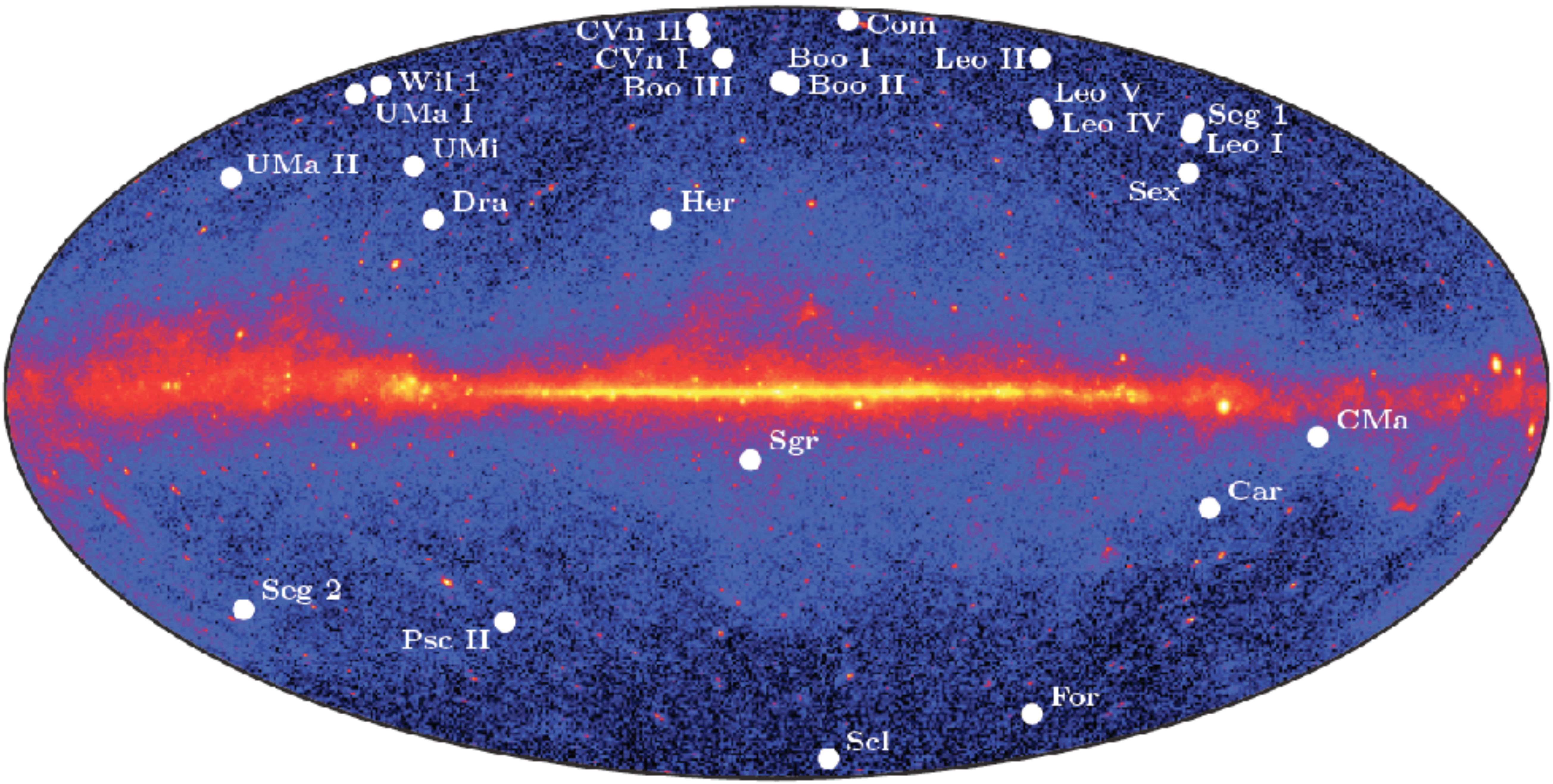

THEORETICAL YIELD

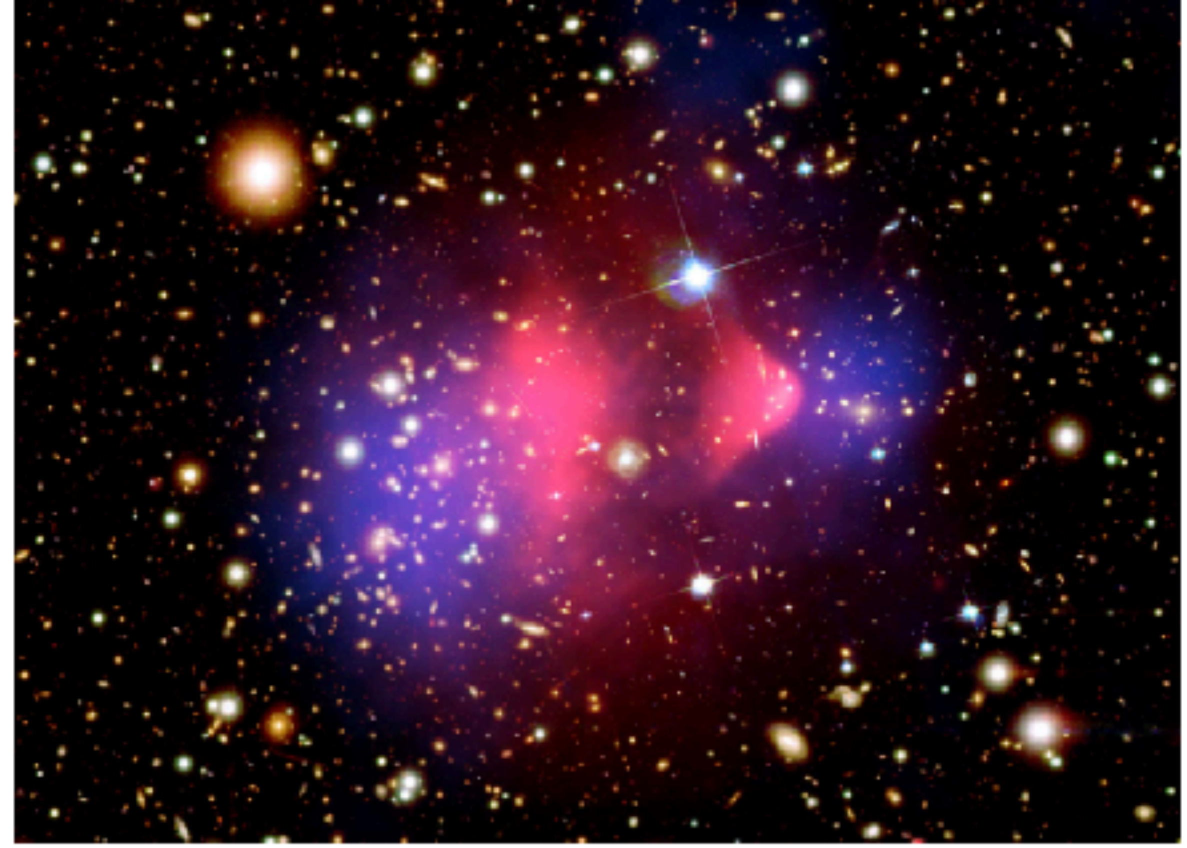
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f \int_{\Delta\Omega} d\Omega \int_{los} \rho^2(l)\, dl(\psi)\, d\Omega$$

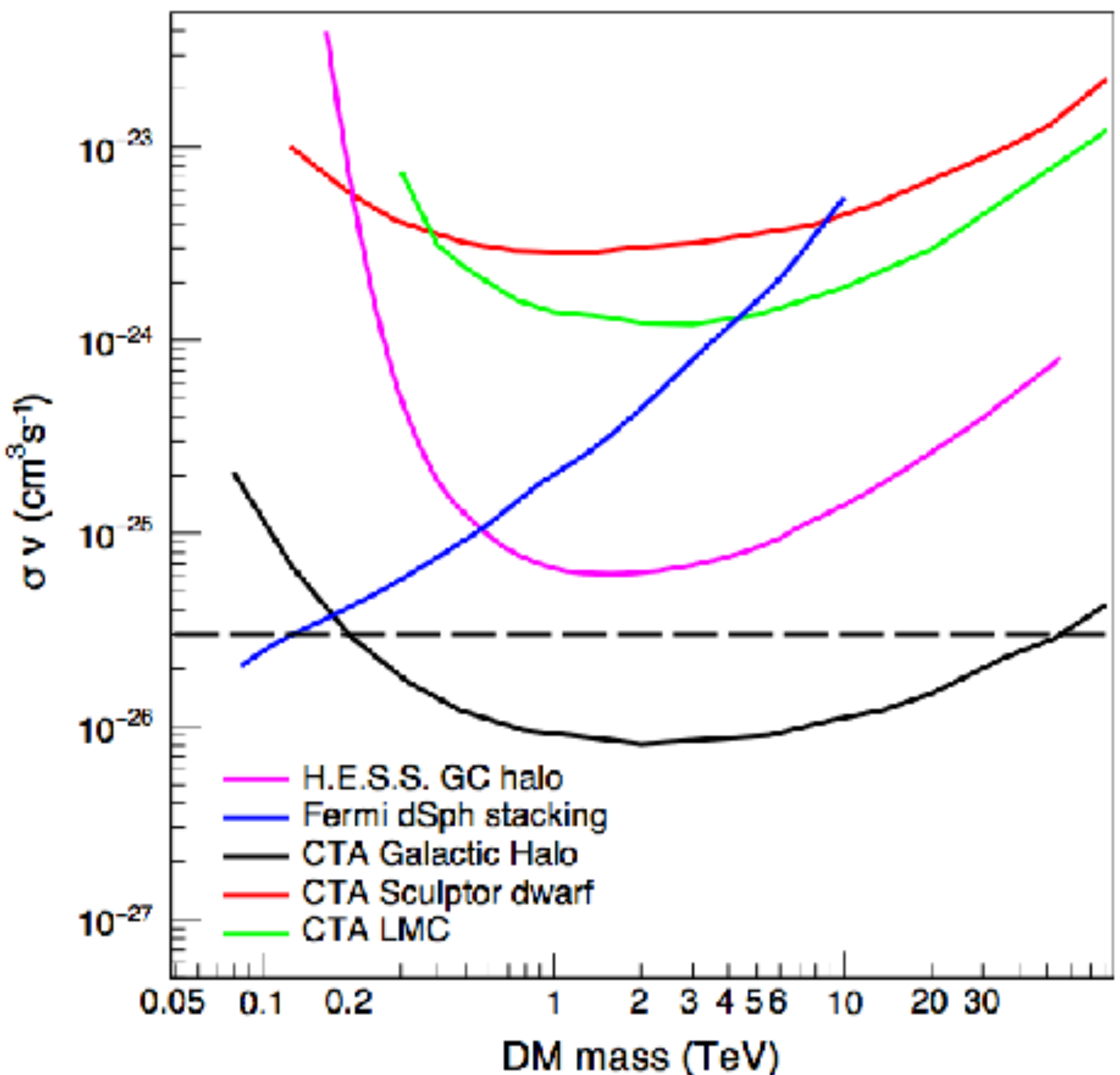
particle

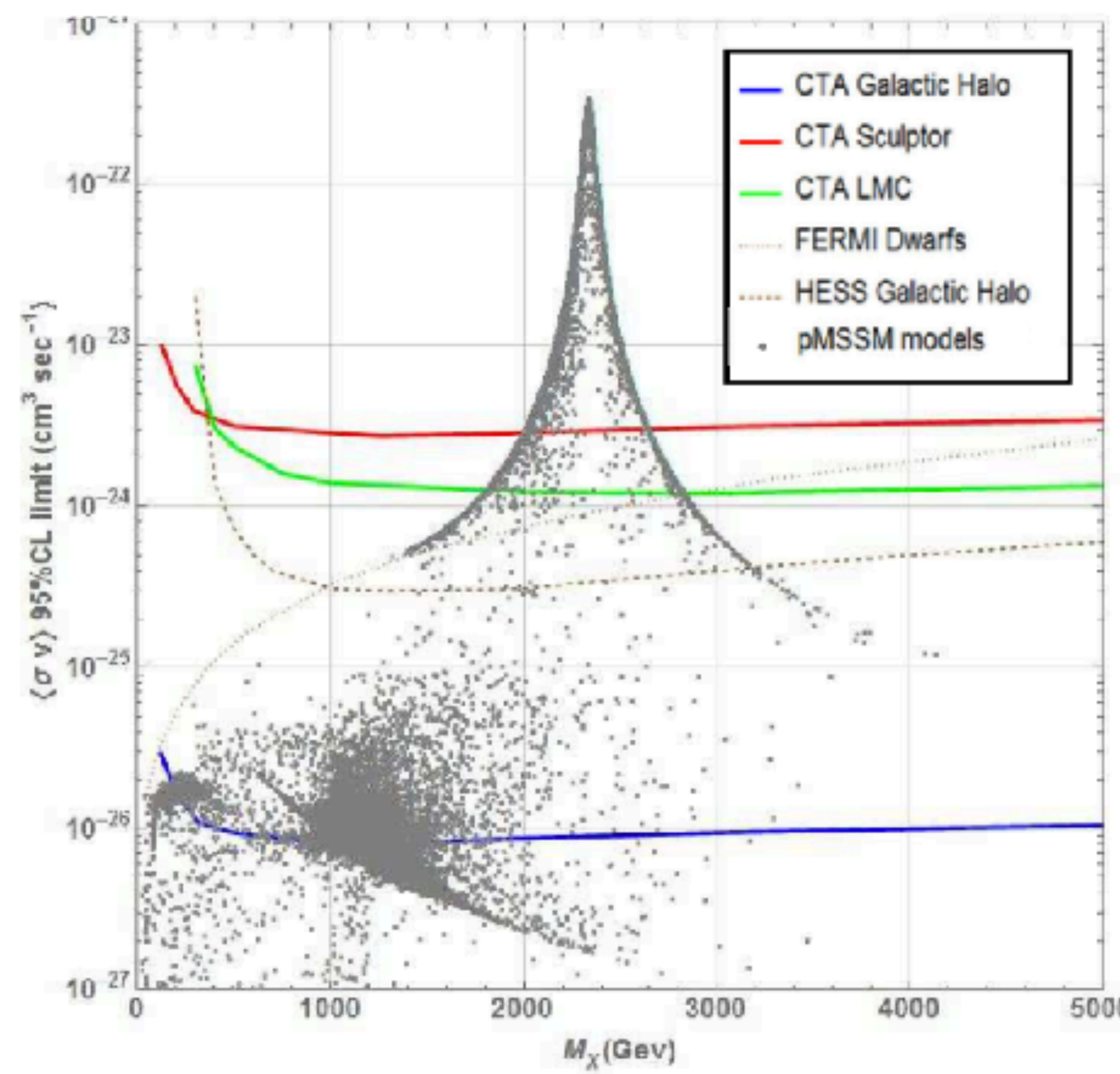
astro ("J-factor")

# Dwarf Spheroidal Galaxies on top of Fermi map



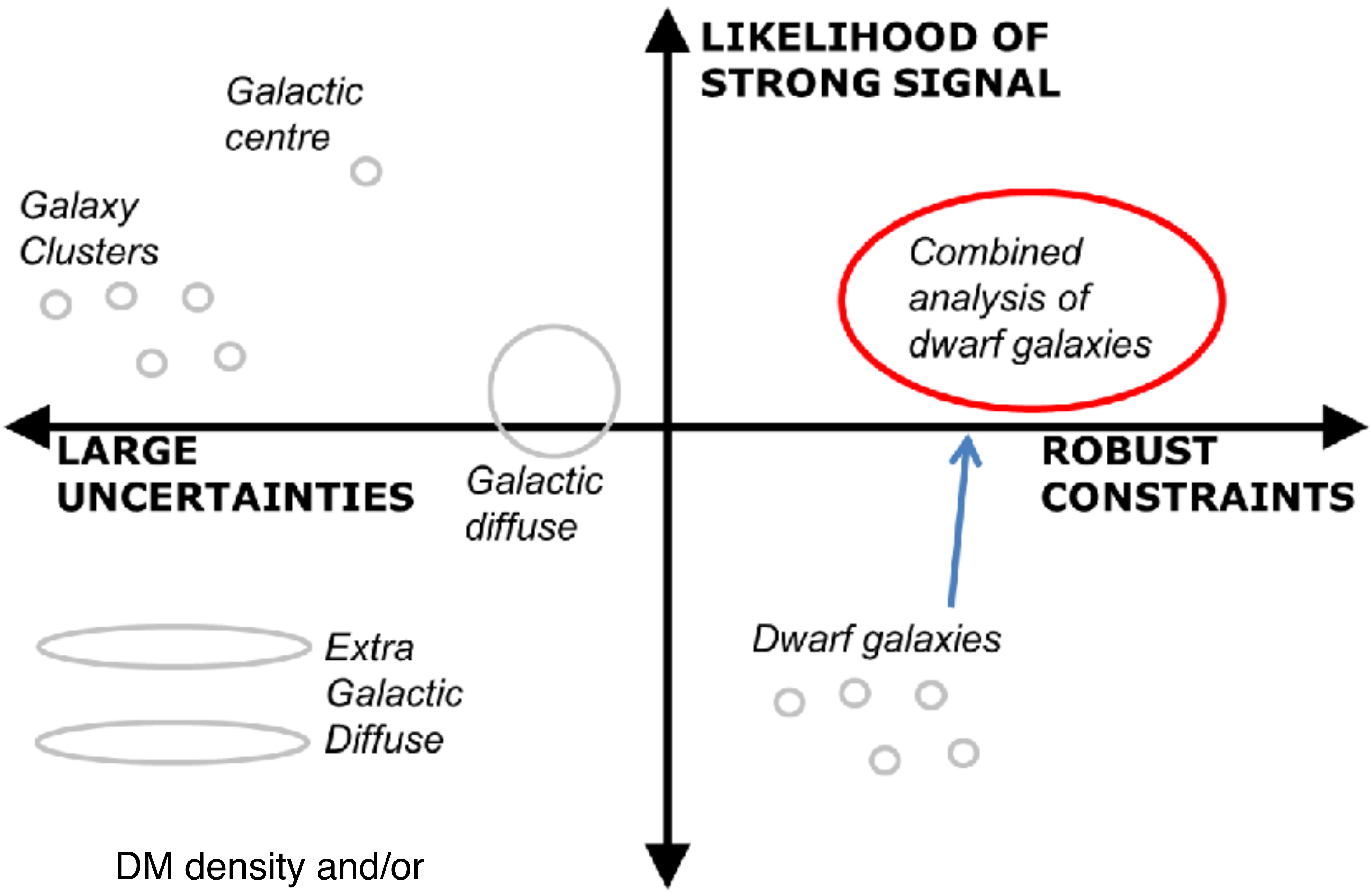



σ v (cm$^3$s$^{-1}$)
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
$10^{-27}$
H.E.S.S. GC halo
Fermi dSph stacking
CTA Galactic Halo
CTA Sculptor dwarf
CTA LMC
0.05 0.1 0.2 1 2 3 4 5 6 10 20 30
DM mass (TeV)


⟨σ v⟩ 95%CL limit (cm$^3$ sec$^{-1}$)
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
$10^{-27}$
CTA Galactic Halo
CTA Sculptor
CTA LMC
FERMI Dwarfs
HESS Galactic Halo
pMSSM models
0 1000 2000 3000 4000 5000
$M_\chi$ (Gev)

| | |
|---|---|
| Galactic Centre | Strongest expected signal, but hard background sources<br>Poorly understood diffuse background.<br>Uncertain DM distribution. |
| Dwarf Galaxies | Weak signal<br>small background<br>relatively well determined DM distribution<br>best for constraints |
| Galaxy Clusters | Boost factor gives potential for detection<br>DM distribution not well understood<br>bad for constraints, maybe good for detection |
| Galactic halo | Spatial and spectral signature<br>backgrounds not well constrained<br>(in Fermi-LAT energy range).<br>most promising venue for IACTs |
| Extragalactic | Dependent on many unknowns<br>(DM model, EBL †absorption, cosmology)<br>good as target for anisotropy studies |
| Lines | Smoking gun<br>weak signal<br>potential instrumental systematics |

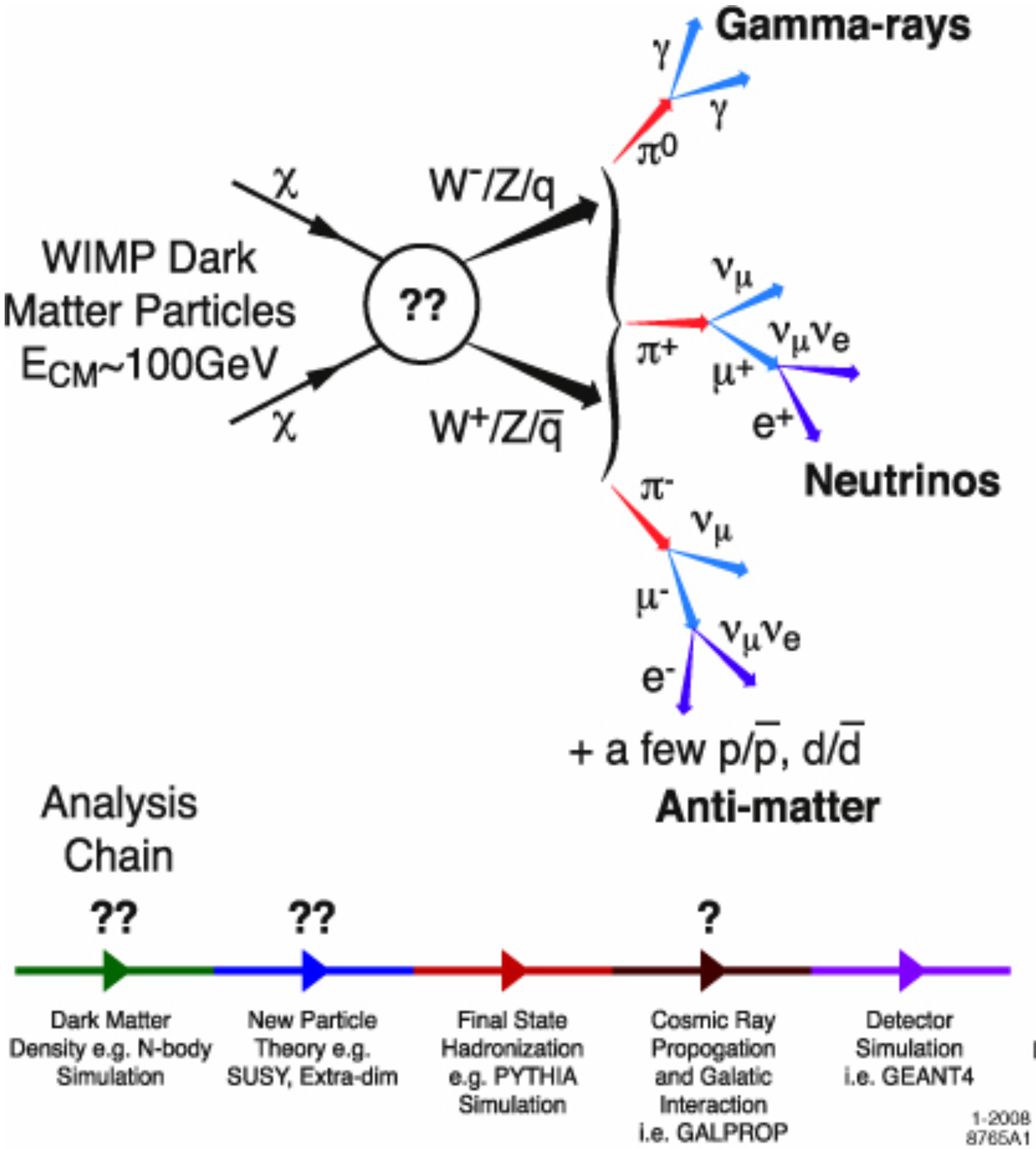
# Relative benefits and drawbacks of different targets

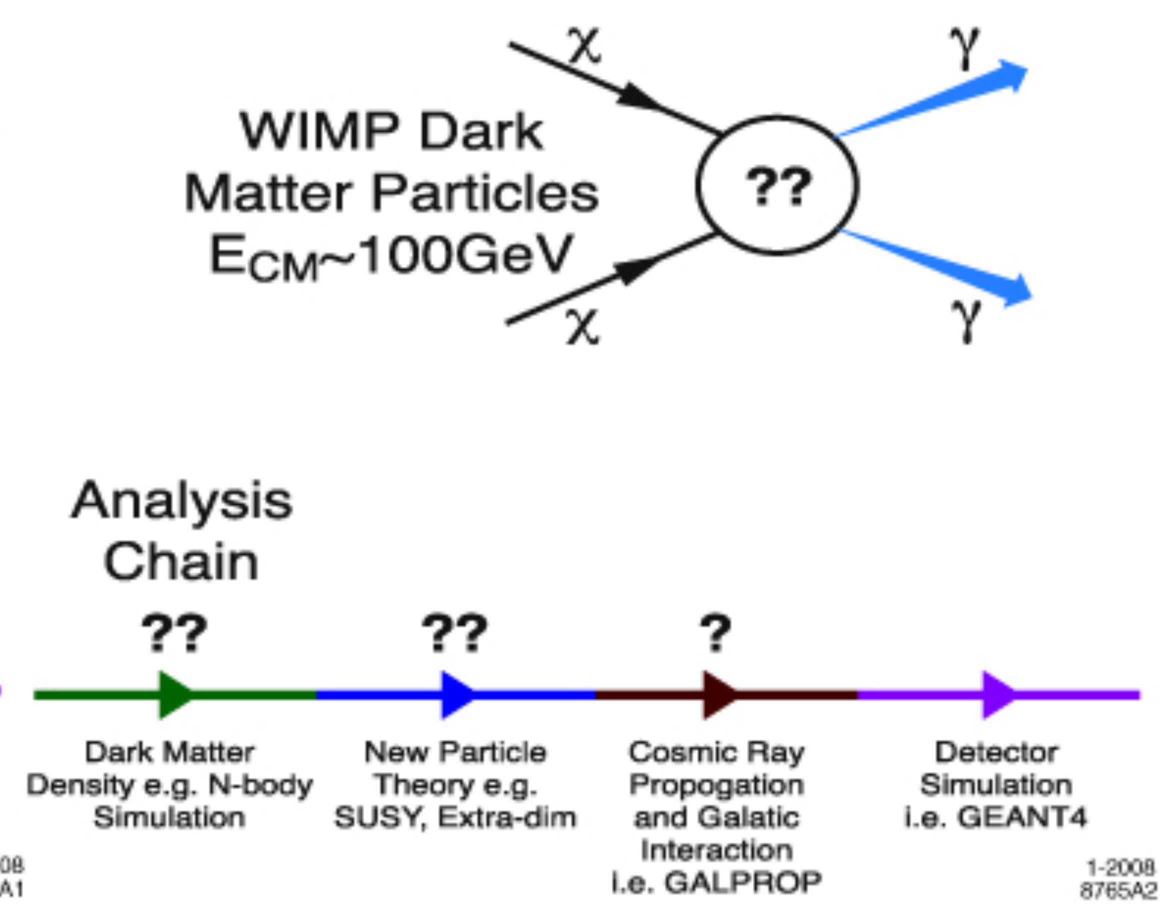



DM density and/or

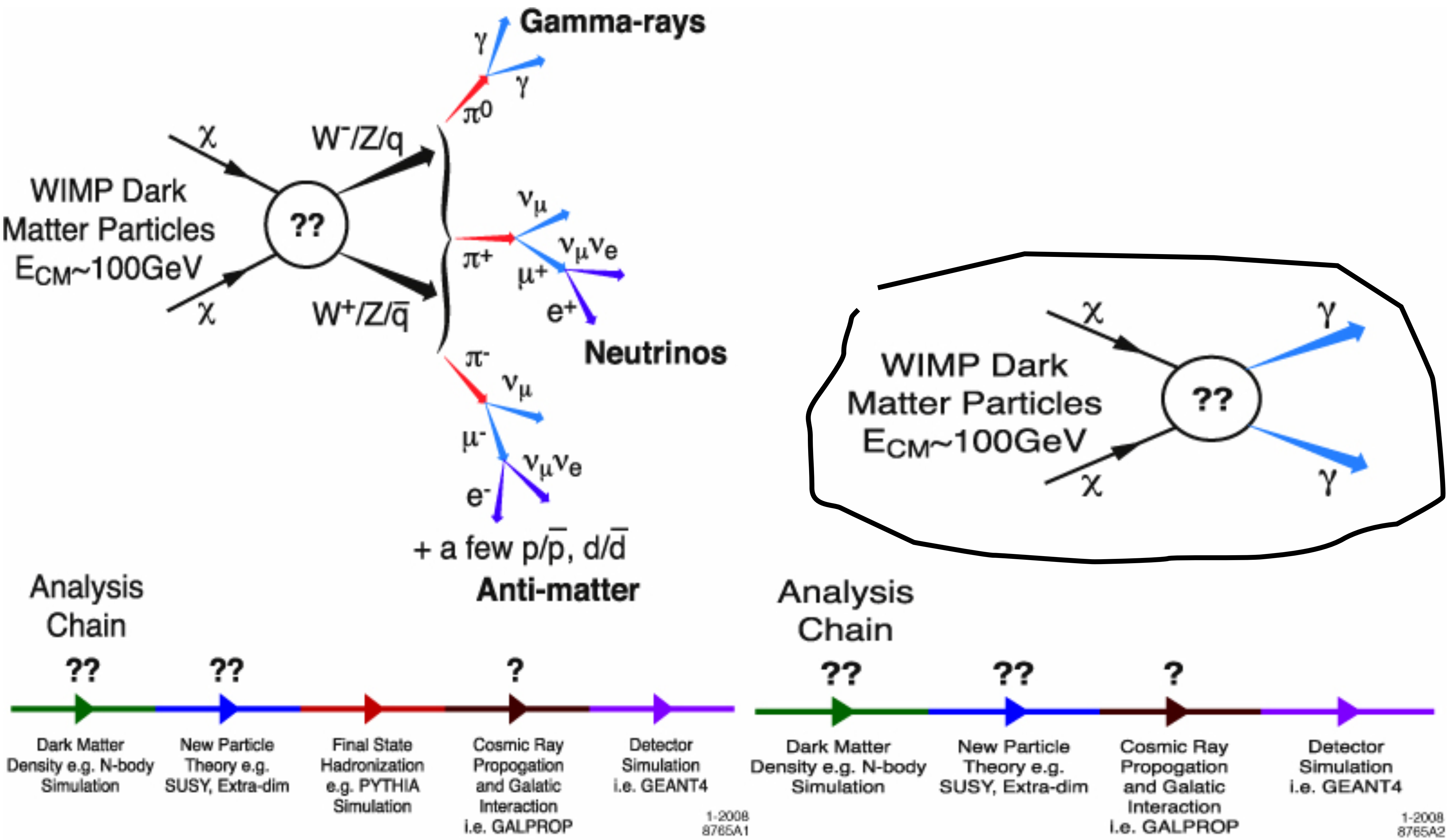
uncertainties in background modeling

# Searching for DM produced gamma-ray

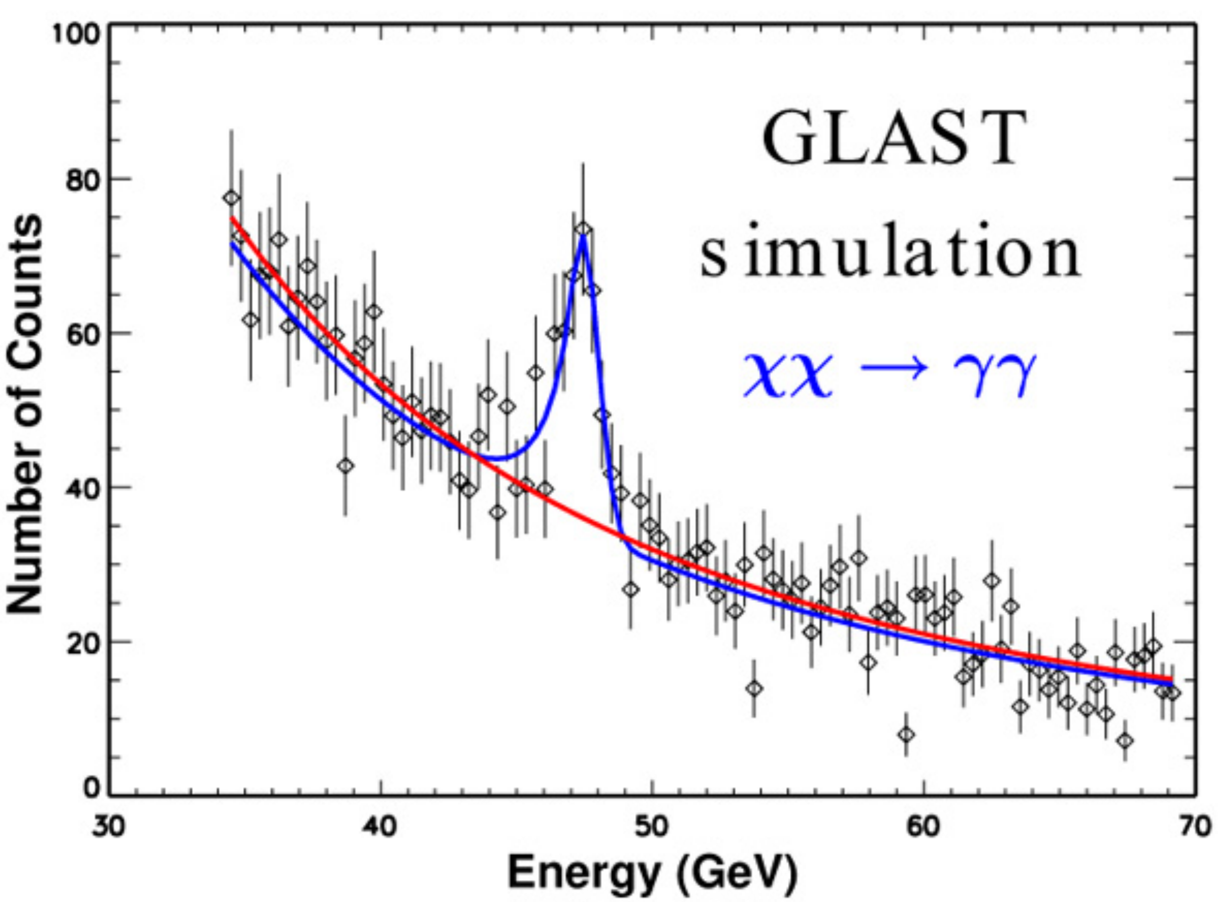


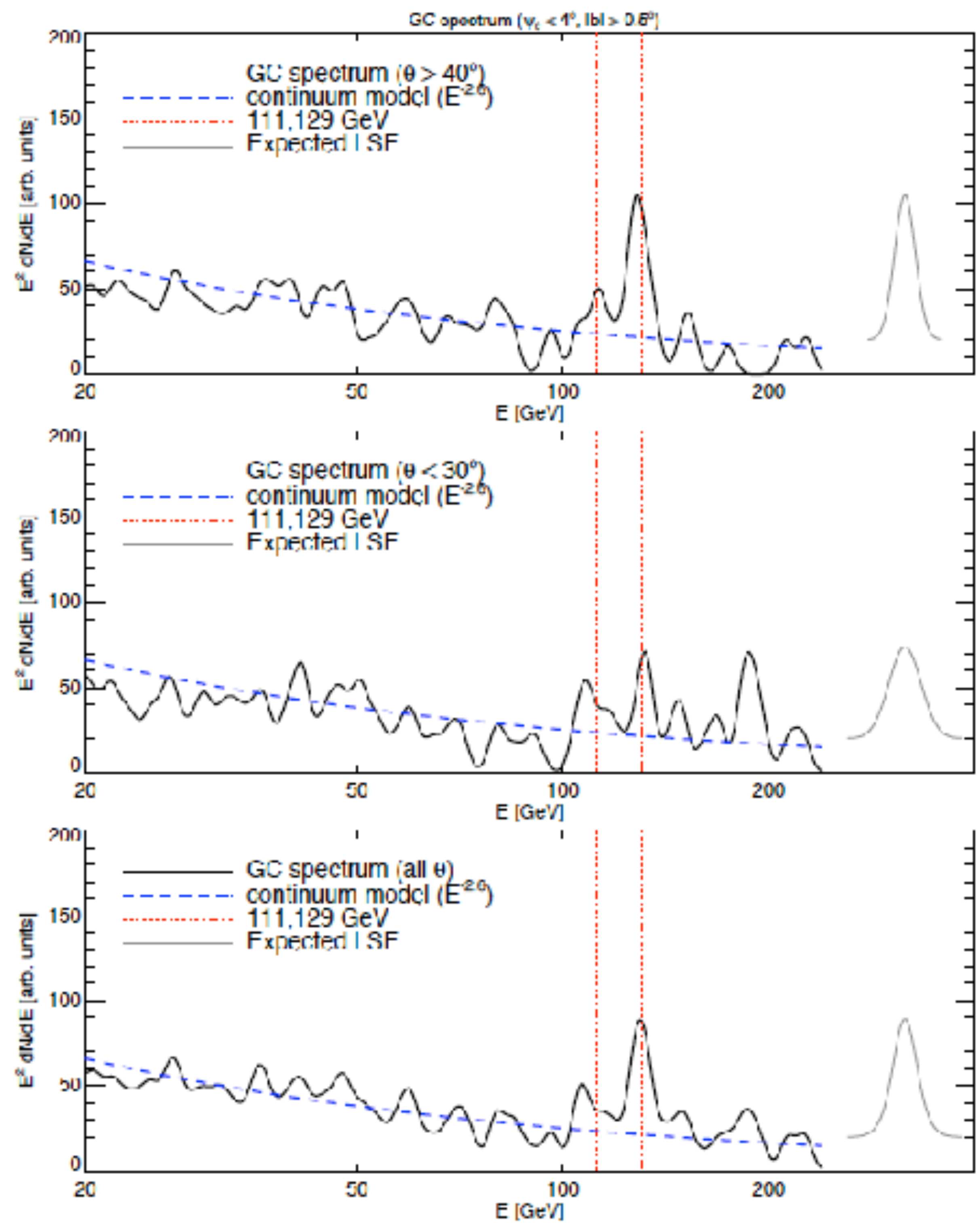



# Searching for DM produced gamma-ray



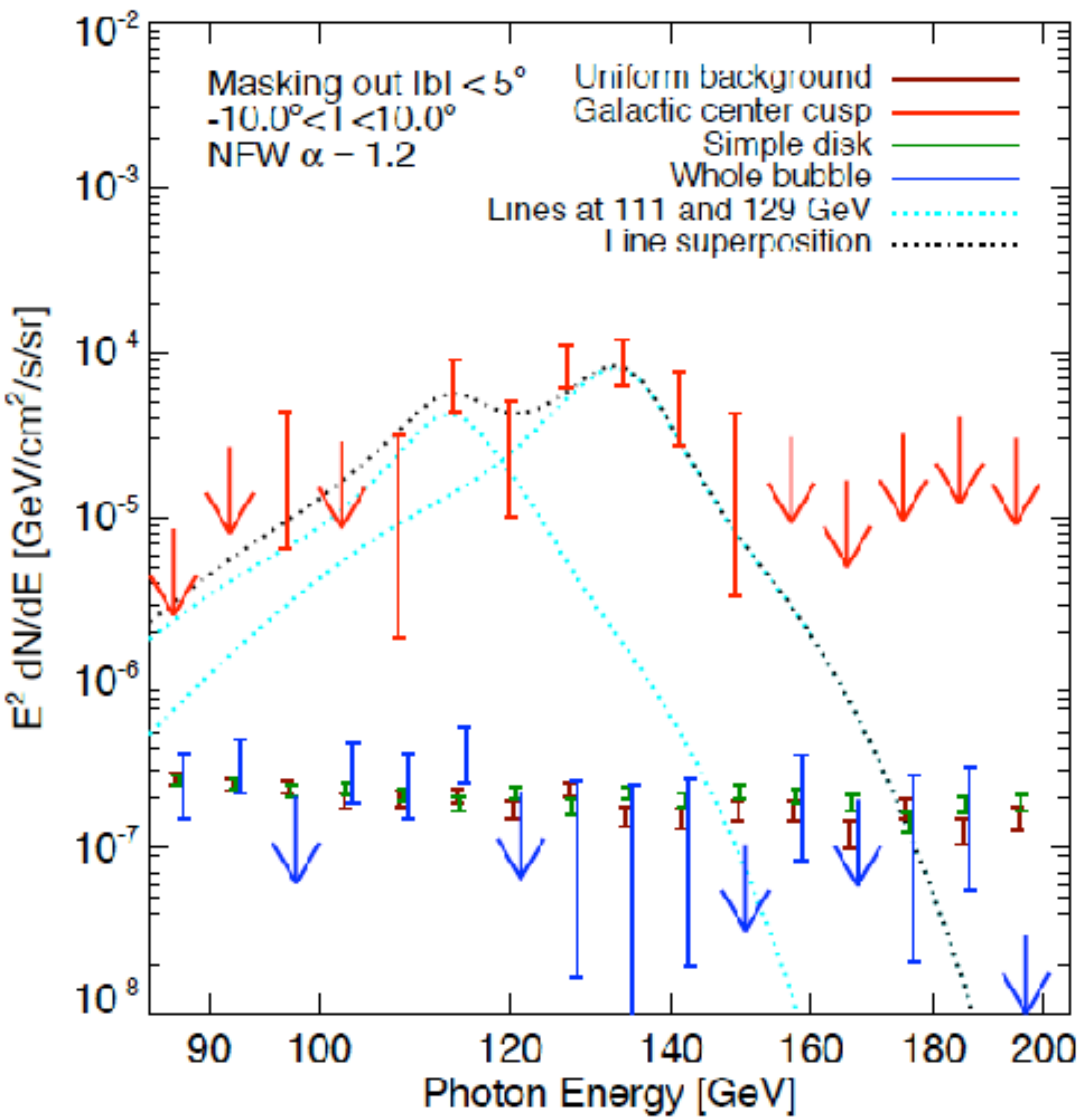
# Smoking gun signature of dark matter particle




MS & Finkbeiner (2012)

# Offset dark matter profile fits better




$$E_\gamma = m_\chi \left(1 - \frac{m_X^2}{4m_\chi^2}\right)$$

1) $\chi+\chi \rightarrow \gamma+\gamma$

2):$\chi+\chi \rightarrow Z^0+\gamma$

$E\gamma = m_x - M_z^2/4m_x$

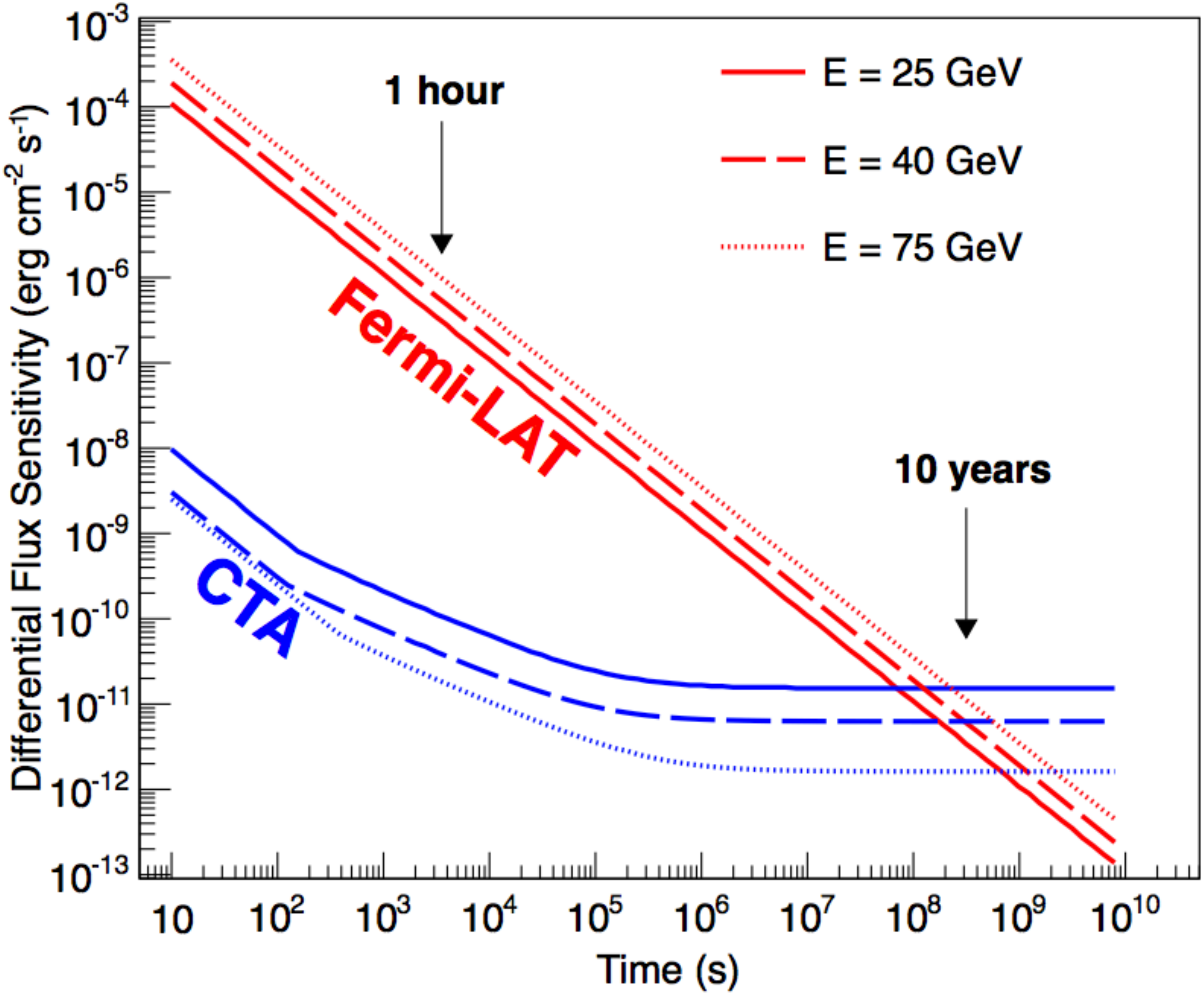
A pair of lines at

110.8±4.4 GeV and 128.8±2.7 GeV

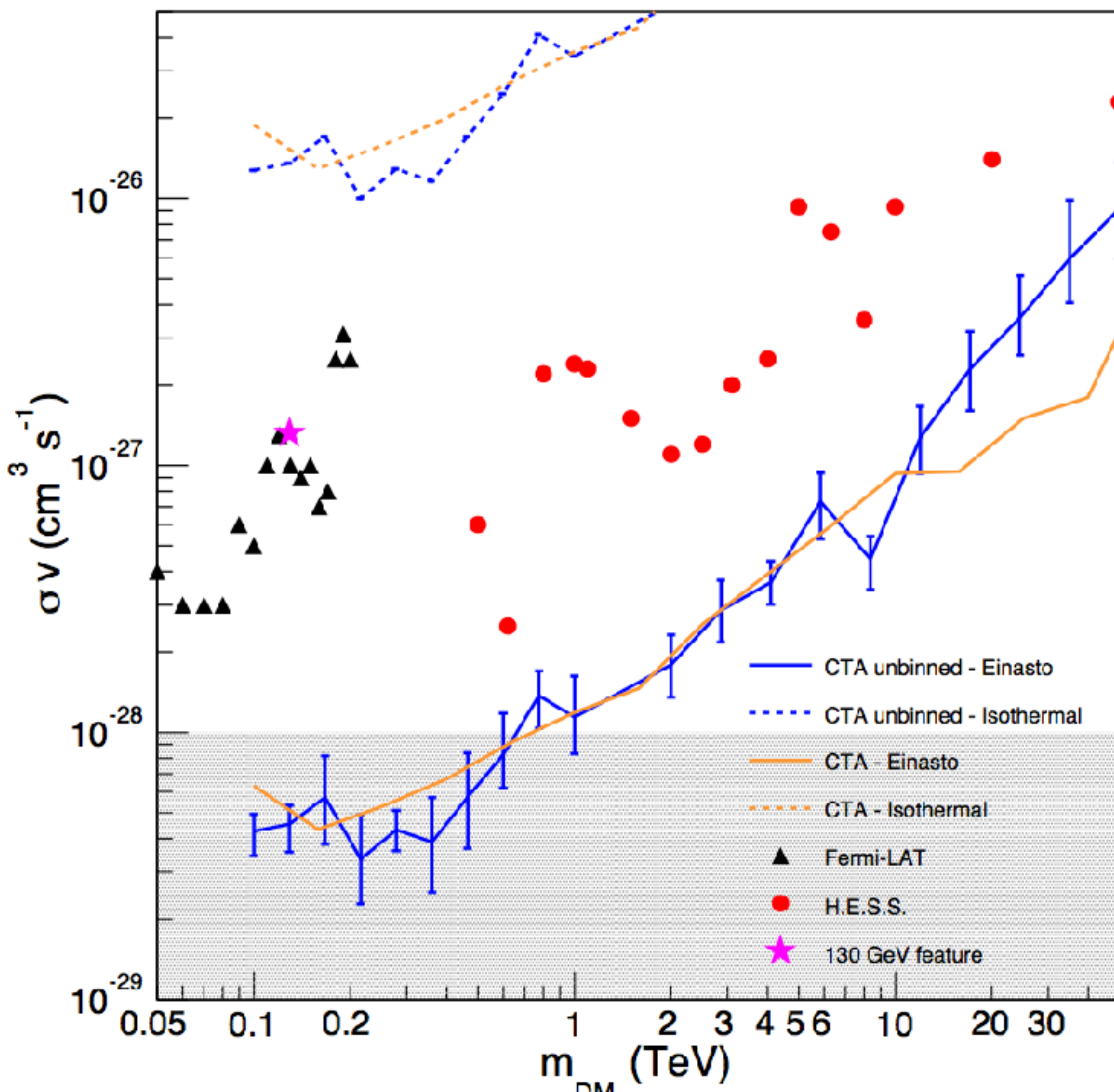
Consistent with single line at

127.3 ± 2.7 GeV

MS & Finkbeiner (2012)

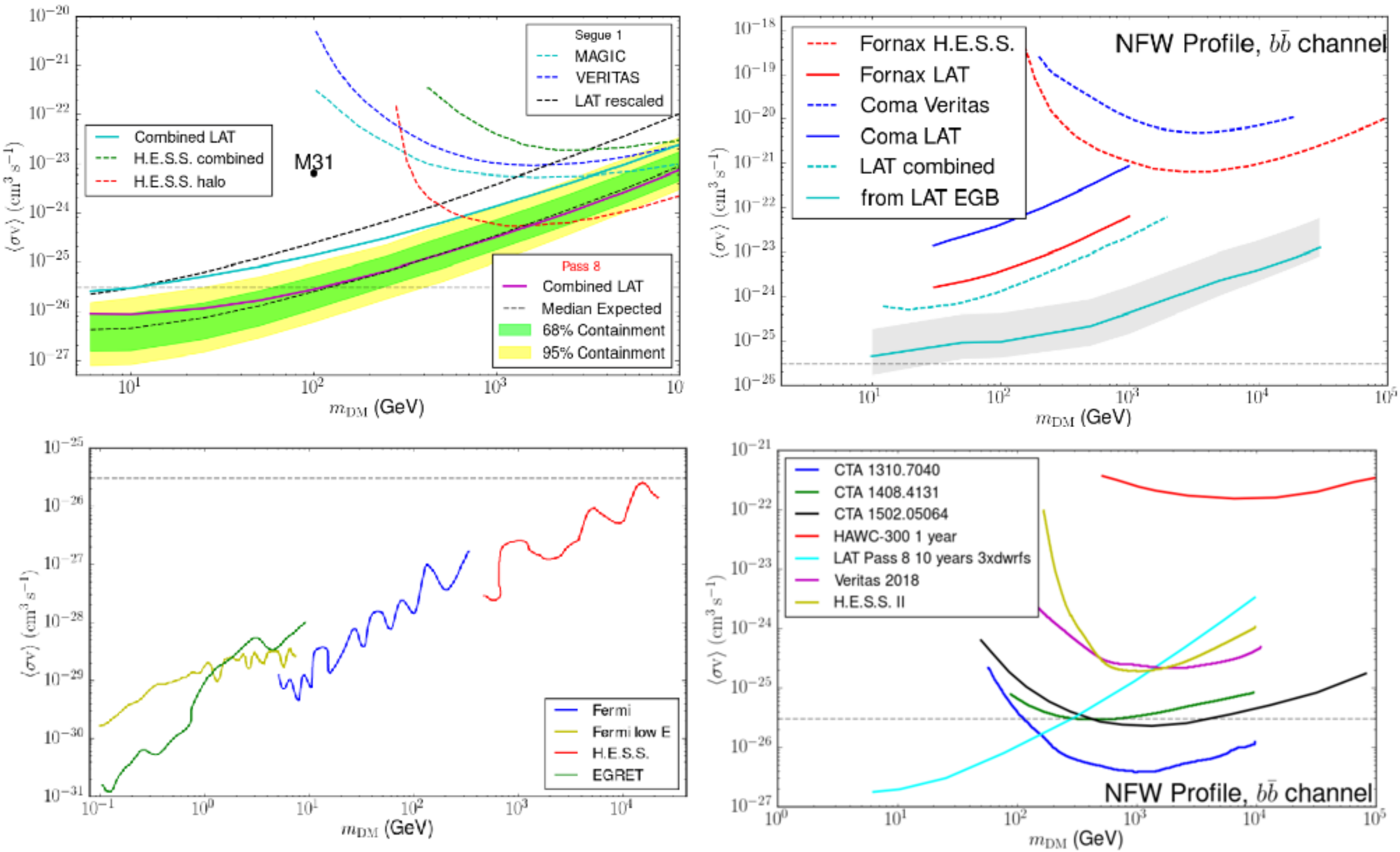


E = 25 GeV
E = 40 GeV
E = 75 GeV
1 hour
10 years
Fermi-LAT
CTA
Differential Flux Sensitivity (erg cm$^{-2}$ s$^{-1}$)
Time (s)

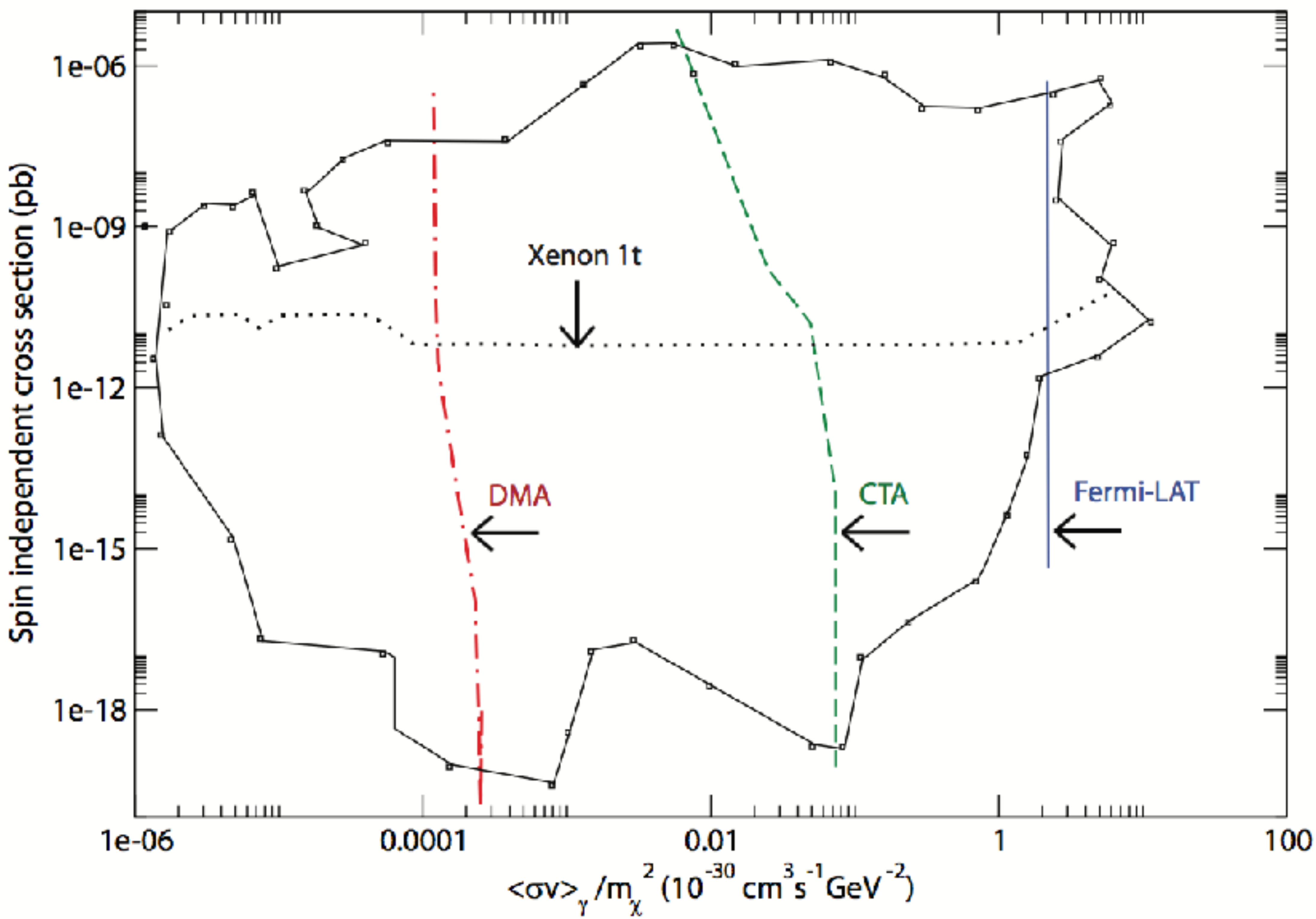


CTA unbinned - Einasto
CTA unbinned - Isothermal
CTA - Einasto
CTA - Isothermal
Fermi-LAT
H.E.S.S.
130 GeV feature
σv (cm³ s⁻¹)
10⁻²⁶
10⁻²⁷
10⁻²⁸
10⁻²⁹
0.05
0.1
0.2
1
2
3
4 5 6
10
20
30
m_DM (TeV)

# LAT combined analysis of 15 dwarf galaxies, galaxy clusters, GC, and EGB



# Little correlation between scattering cross section and annihilation cross-section in phenomenological Minimal Supersymmetry

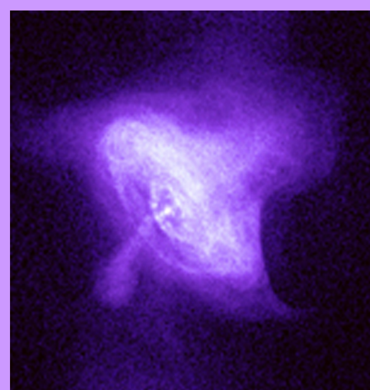


# Gamma-Ray Astrophysics

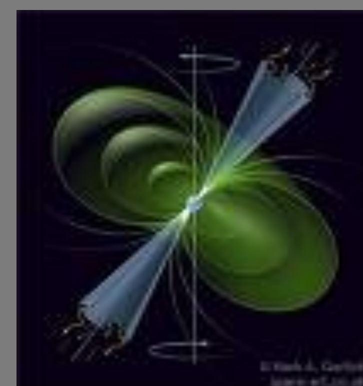
Galactic

- Positrons near Earth?
- TeV pulsed emission
- PeVatrons accelerating cosmic rays?
- Pulsar wind vs. microquasar scenarios

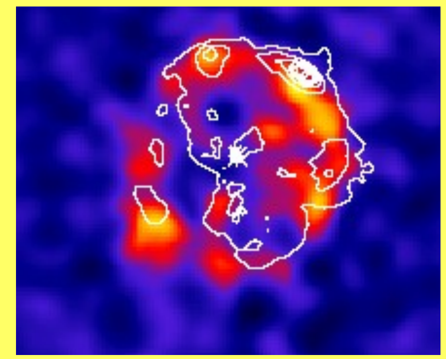
Pulsars Wind Nebula



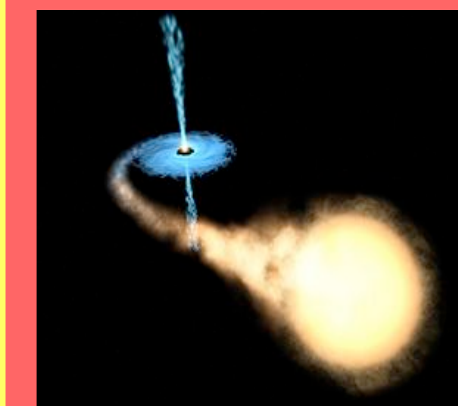
Pulsars



Supernova Remnant

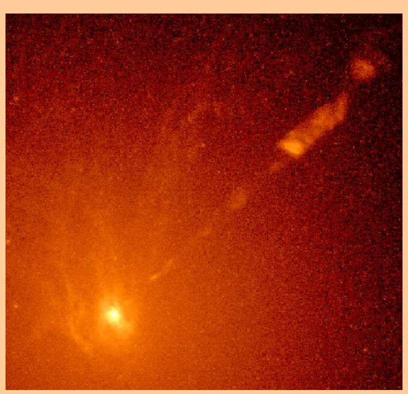


X-ray Binaries



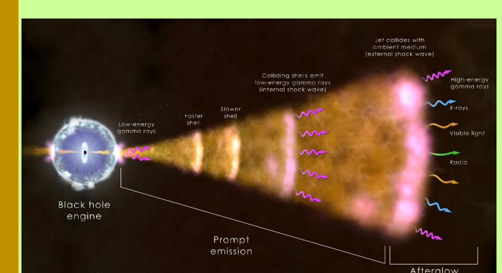
Extragalactic

Active Galactic Nuclei



Starburst Galaxies

Gamma-Ray Burst




Indirect Dark Matter

- flare strength and timescale
- acceleration mechanism/efficiency
- cosmic ray accelerators?
- no >100GeV detection yet
- neutrino / gravitational wave counterparts?
- Galactic center?

# Fermi Status: Catalogs

•LAT

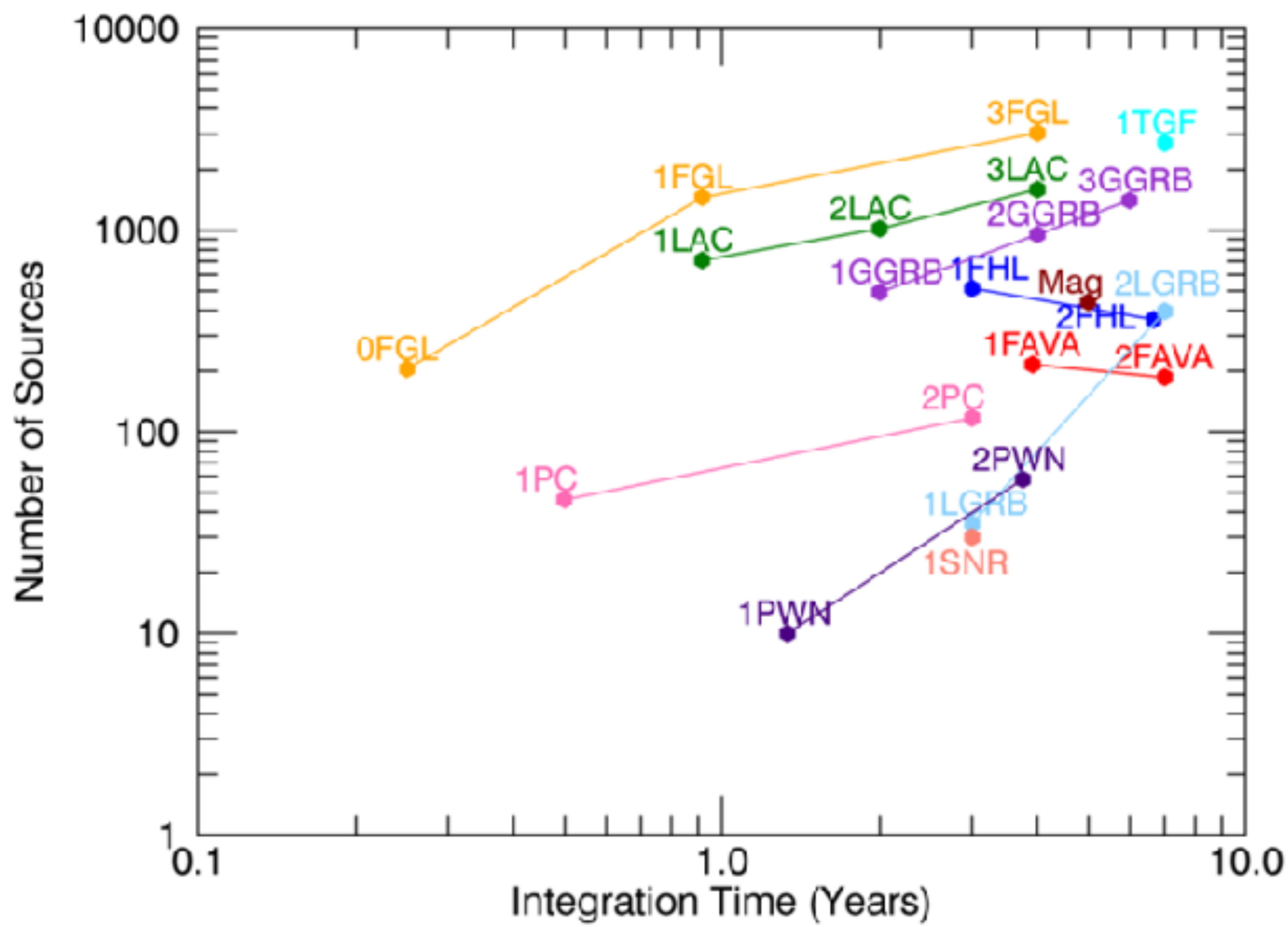
- FGL (General)
- FHL (High-energy)
- LAC (AGN)
- PC (Pulsars)
- LGRB (GRBs)
- FAVA (Flaring sources)
- SNR (supernova remnants)
- Solar flares (upcoming)

• GBM

- GGRB (GRBs)
- Mag (Magnetar bursts)
- TGF

. Gamma-ray Burst Monitor (GBM)

- New localization contours
- Ongoing work to improve automation (RoboBA)



# Rich Menu of Catalogs

GBM

- 6-yr Trigger Catalog (3FGBM)
- 8-yr Terrestrial Gamma-ray Flashes Catalog (submitted)
- 8-yr Trigger and Spectral Catalog (in preparation)

LAT

- Extended Sources in the Galactic Plane (FGES)
- Second *Fermi* All-sky Variability Analysis catalog (2FAV)
- Third high-energy source catalog (3FHL)
- 2$^{nd}$ GRB catalog, extended source catalog (FHES), 4FGL and 4LAC in preparation

# What we have learned for HERD's concern

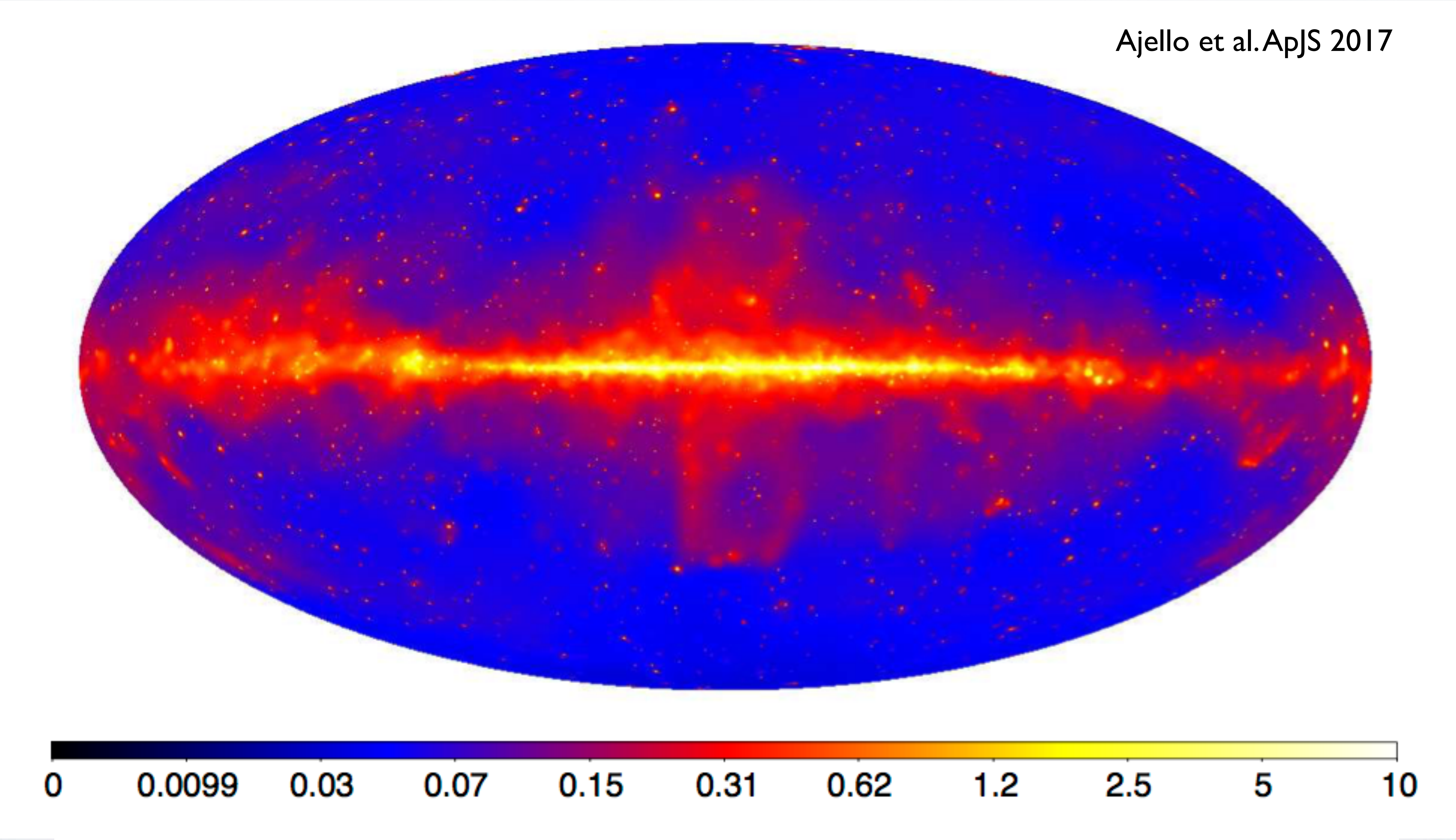
- Pass 8 performance improvements (angular resolution + acceptance) and 10 years of exposure allow the characterization of sources directly at E>50 GeV and even higher

- Excellent angular resolution allows detailed studies of the Galactic plane and its sources

- Increased acceptance provides more photons from sources which enables studies of the EBL and of the SEDs of sources

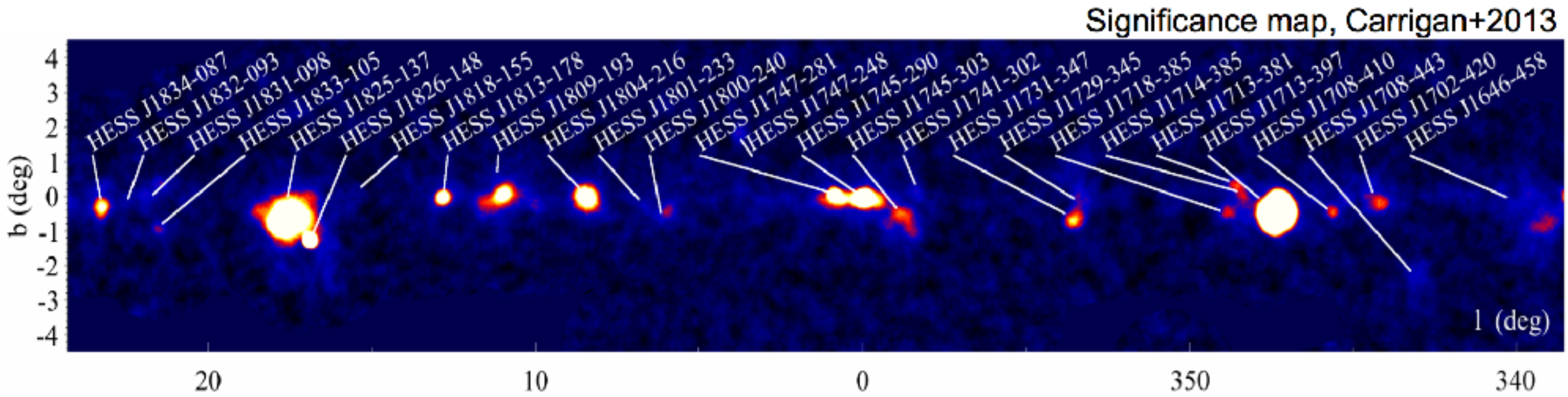
- A survey of >50 GeV gamma-ray sources connects well to ACTs, HAWC, CTA, and LHAASO in the future

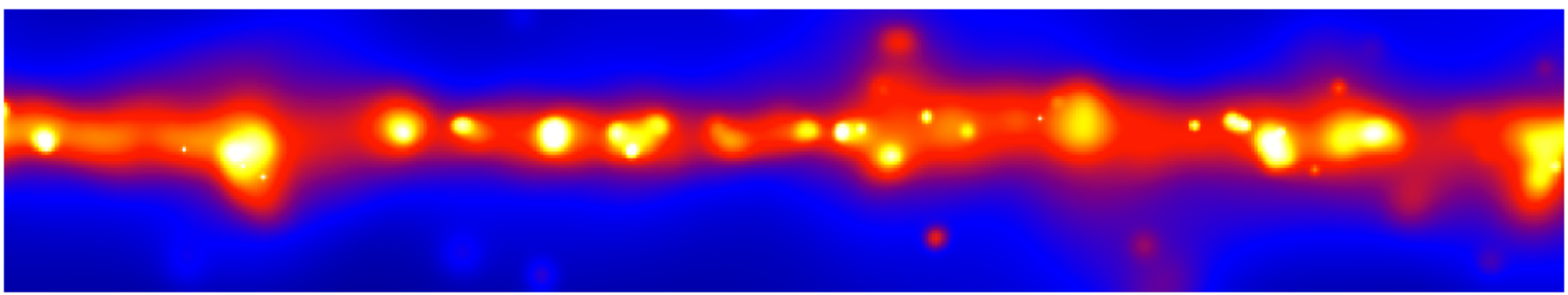
# GeV - TeV Sky Survey




Fermi-LAT count map 10 GeV — 2 TeV with >1500 objects in 84 months of data.

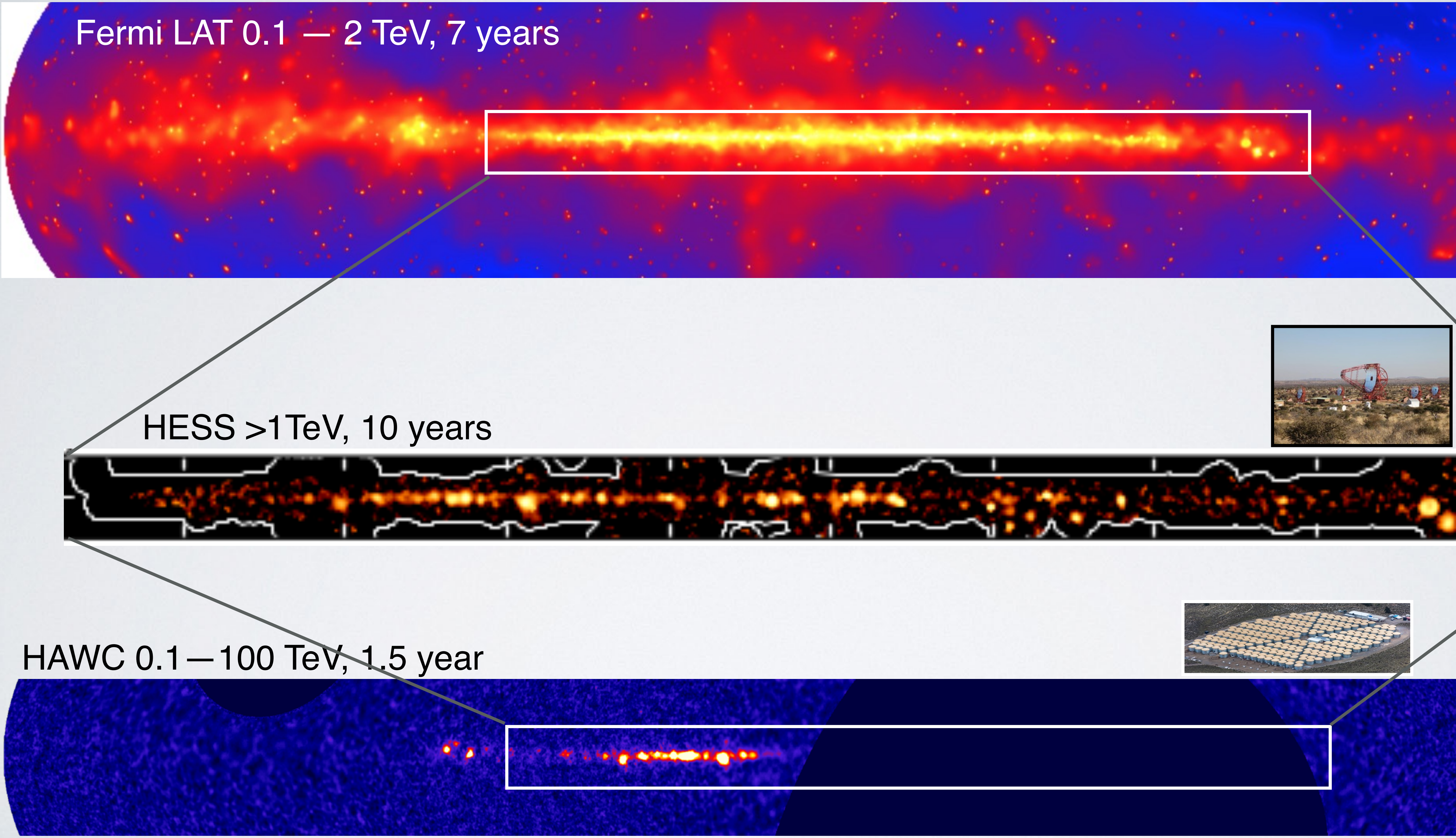
Good match between HESS and Fermi (50 GeV-2TeV) maps



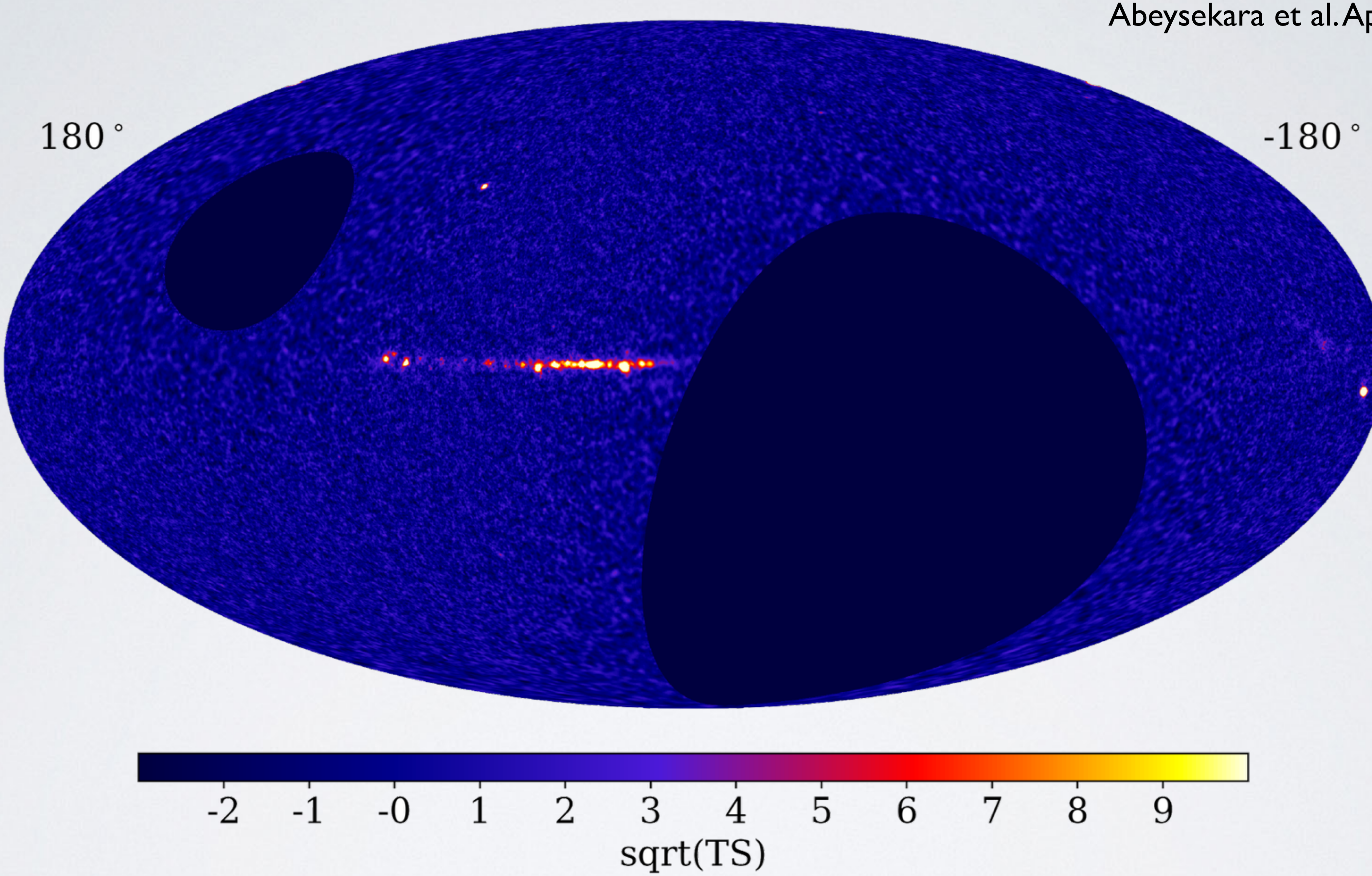
HERD will improve this map by a factor of >10!

# Gamma-ray view of our Galaxy



# TeV Sky Survey

Abeysekara et al. ApJ 2017




- HAWC TeV skymap in 17 months of data.
- 39 2HWC sources: 2 blazars, 5 UID off the Galactic plane, 19 are unassociated with any known TeV source.

# HERD’s improvement over Fermi

## PROS of Fermi:

- Excellent characterization in energy/variability of the gamma-ray sky
- Serendipitous survey over a large energy band

## CONS of Fermi (opportunities for HERD)

- ‘coarse’ 5-bin spectra, good for intermediate-brightness sources
- Spectra ‘biased’ by the larger statistics of low energy photons
- 0.1-100 GeV fit might not be representative of the spectrum at high energy

# Prospects for HERD

• For most of the sky and most of >10GeV energy range, the current Fermi-LAT is limited by photon counting statistics, not background. Linear scaling of HERD improvement with acceptance.

• HERD increases the energy reach to 10 TeV, improves the statistical precision, and enhances variability measurements.

• The extreme phenomena seen with Fermi are often rare, so the HERD increases the chances of seeing activity that gives meaningful insight of physics behind a variety of high energy phenomenon.

# Prospects for HERD

HERD is set to continue operating probably beyond 10 years

Continues producing new products and catalogs from the HERD operation (a lot of work for gamma-ray working group)

We will take advantage of all the information and tools that are already out there, in particular heritage from Fermi-LAT, but we need to improve to the precession by a few factors.

Please let us know if you have ideas for things that will make our gamma-ray science better

# Highlights of HERD Potential Contributions

- **High energy extension in gamma rays:**
  * **GeV**-TeV mapping of the diffuse gamma-ray emission (Galactic and extragalactic, isotropic and anisotropic)
  * Extragalactic Background Light (together with stacked HE sources)
  * GeV-TeV source spectrum (including search for exotic potential sources)
  * Monitoring for transients complementary to Fermi (GRB, GW events, flares, TGF etc.)
  * Extended sources Fermi Bubbles, Cen A lobes, Cygnus region, Supernova remnants
  * TeV point sources!

- **Synergy with other high energy missions:** (gamma-ray, neutrino, multi-wavelength, GW detector etc.)

# How you learn about AGN physics from HERD observations

- AGN Physics of HERD:
  - Investigation of blazar spectral properties (correlation of photon index with blazar class, spectral breaks) and variability time scales (observed ranging from sub-day to several months)
  - Gamma-ray flares from gravitationally lensed blazars discovered!
  - Some cases with evidence for large distances gamma-ray emission regions from BH, although the location of the gamma-ray emitting region in the jet is still ambiguous
  - Radio-to-gamma-ray SEDs are forcing us to look for models beyond the standard one-zone leptonic models
  - Many multifrequency studies have provided time-resolved SEDs and interband (radio, optical, X-ray, TeV) temporal correlation

# Extreme Electrodynamics

TeV variation in AGN jets

Rapid variation from 100pc?

Rapid acceleration in jets

Currents filament in plasmas
(reconnection, shocks, pinches)

Concentrate energy in small volume
(impulsive flares)

Astrophysical detection
- Galactic Nuclei
- X-ray binaries
- Gamma-ray Bursts

Disks and Jets
- Common and robust
- Many unstable modes!

- How are they made?
  - Accretion rate crucial
  - Magnetic field crucial
  - Spin crucial

# Development of the Galactic Diffuse Emission Model is required for the HERD gamma-ray analysis

- For source detection and characterization in gamma-ray data we want to model as accurately as possible everything other than the sources

- The Milky Way is rather bright in ~GeV gamma rays
  – ~65% of the celestial gamma rays detected by the LAT originate in diffuse processes in the Milky Way
  – ~25% is isotropic extragalactic background
  – ~10% is resolved into point and small extended sources

- Especially on the faint end of the source distribution (where most of the sources are), an accurate foreground model will result in a deeper, more accurate and reliable catalog

- Other diffuse components include residual charged-particle background, residual Earth limb emission, and the effectively diffuse emission from the moving quiet Sun and Moon.

# The Future: Multi-messenger Synergies

## Advanced LIGO/Virgo

- HERD large-sky monitoring could also provide coincident transient source

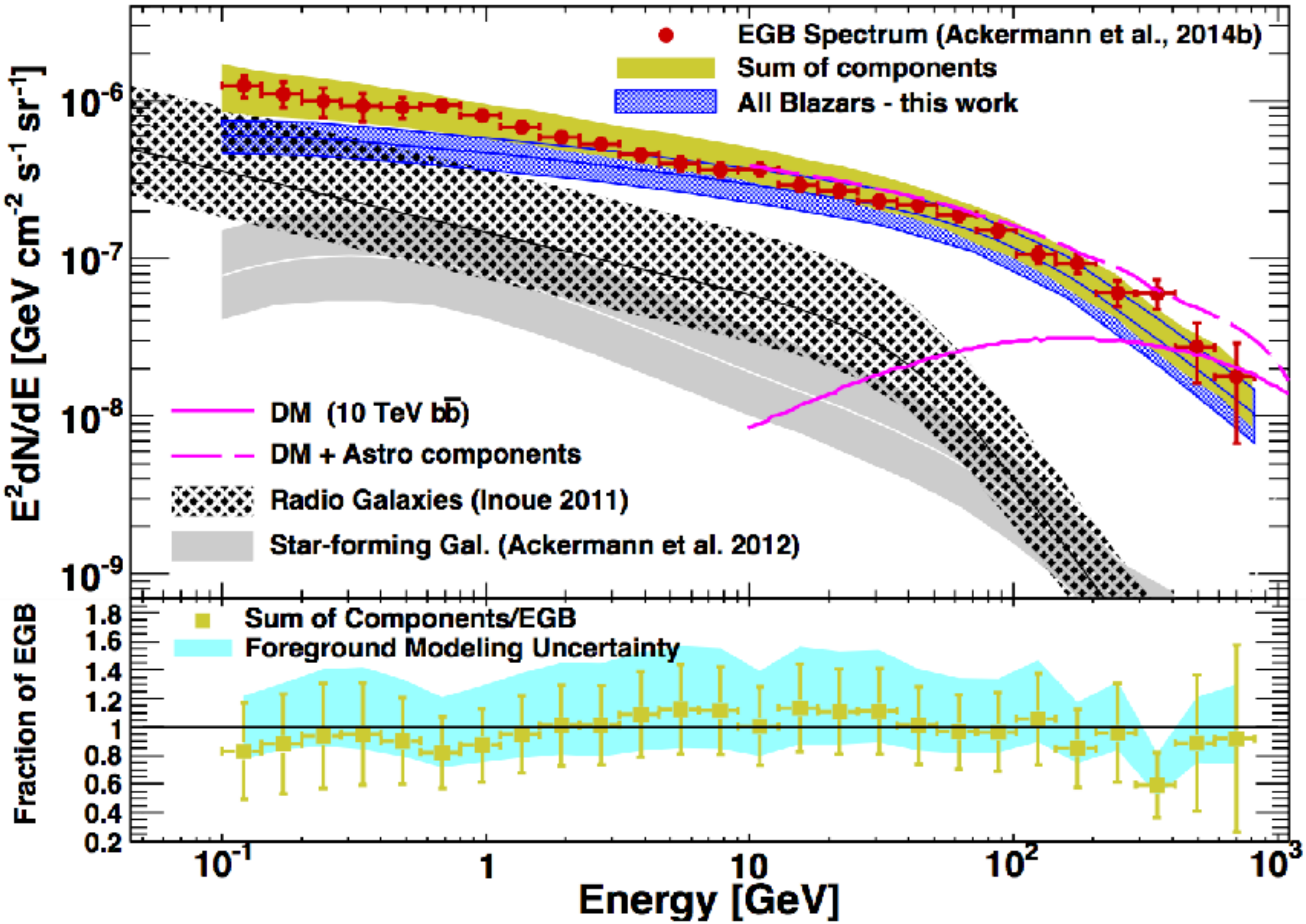
## IceCube PeV Neutrinos

• HERDs wide sky coverage provides unique capability to search for contemporaneous flaring in photon data and neutrinos

## Pulsar Timing Arrays

- HERD might help to detect high energy gamma-ray emitting pulsars, and putative gravitational wave sources like possible SMBH binary PG 1553+113
- SMBH binary with periods of ~years are in frequency range of PTAs, and evenly sampled all-sky data is ideal for searching for these periodicities

# Extragalactic Gamma-ray Background

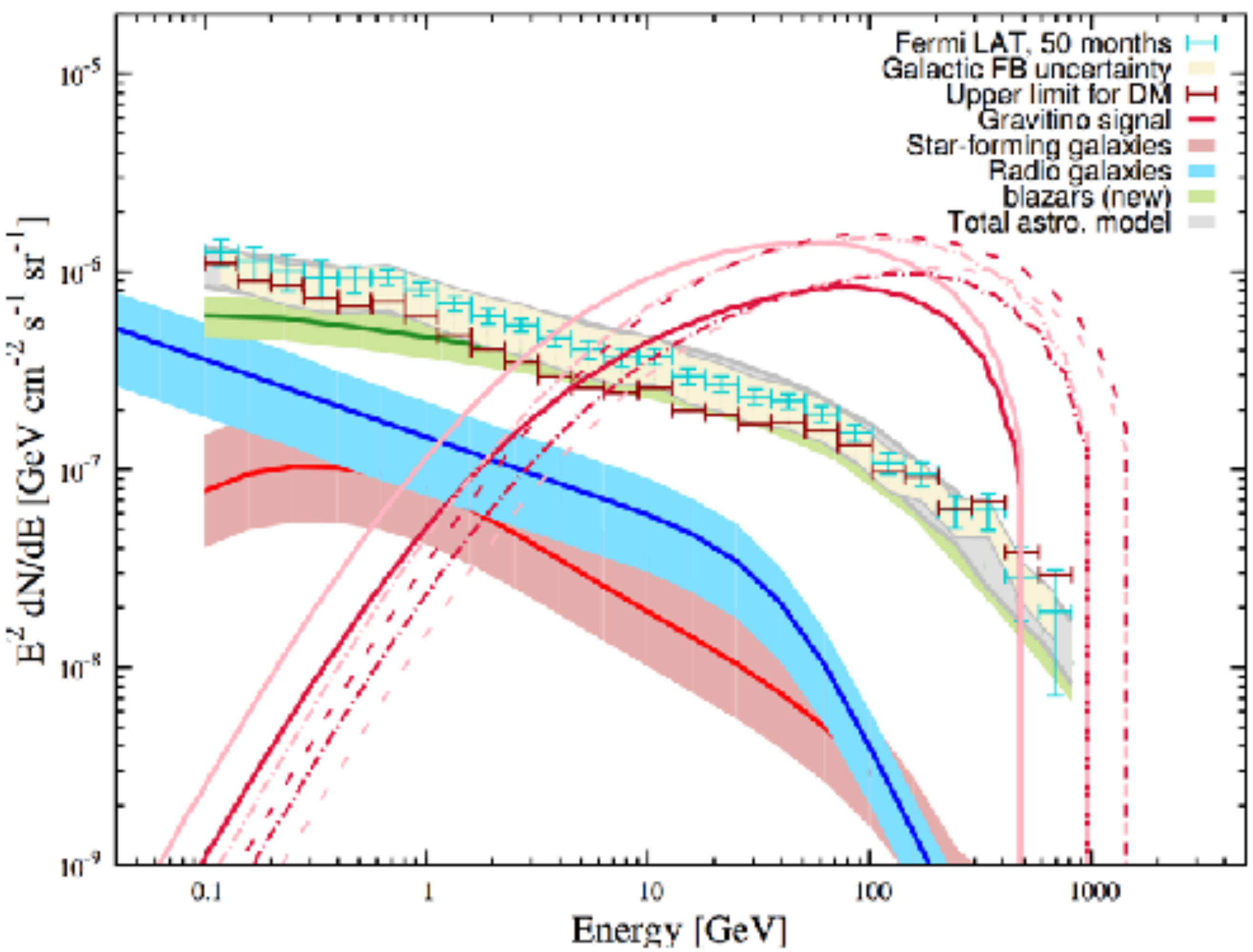


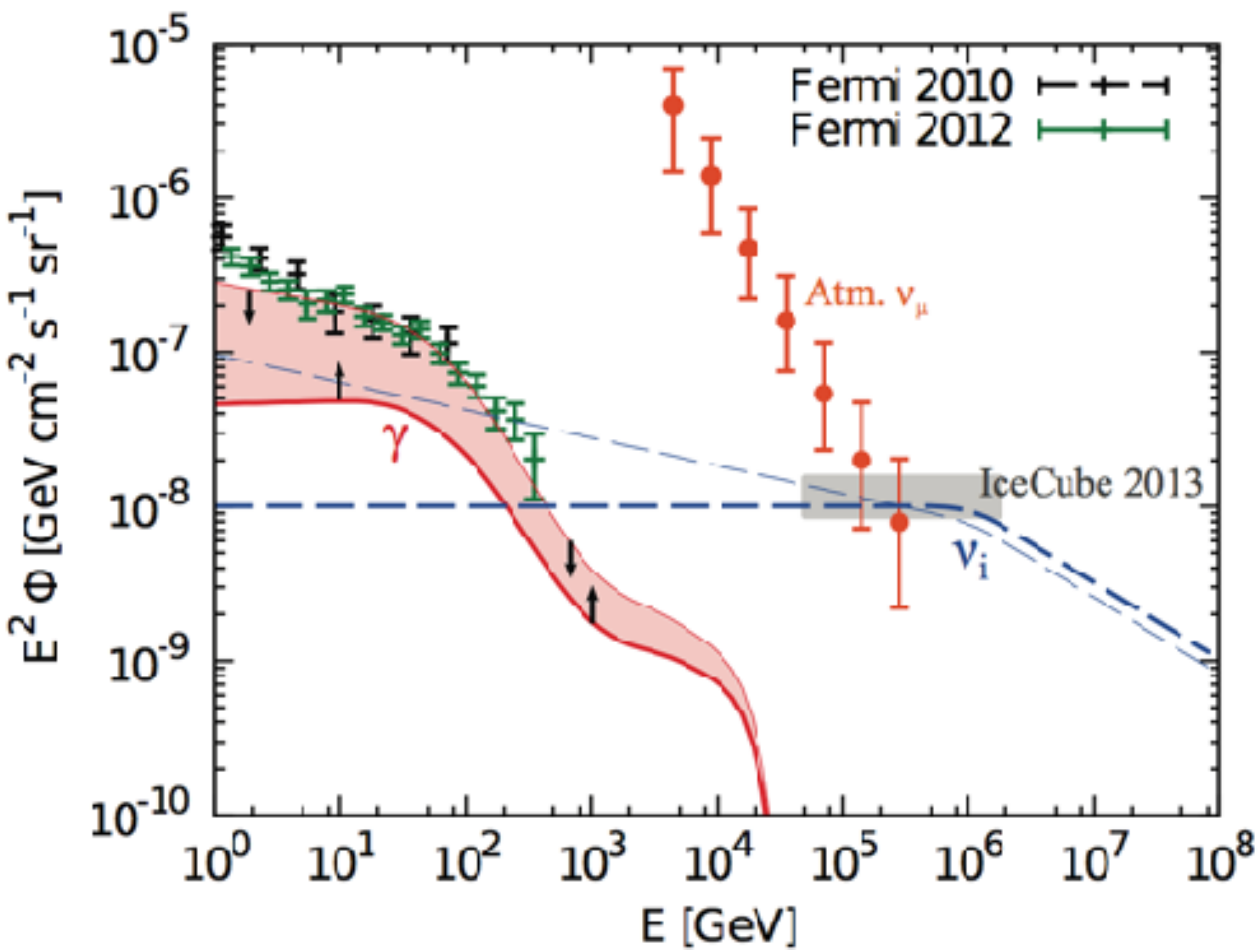
Isotropic gamma-ray background (IGRB) from 100MeV to > 500 GeV

Spectral rollover above 100 GeV

Unresolved blazars, other AGN & starburst galaxies appear to account for most of the IGRB

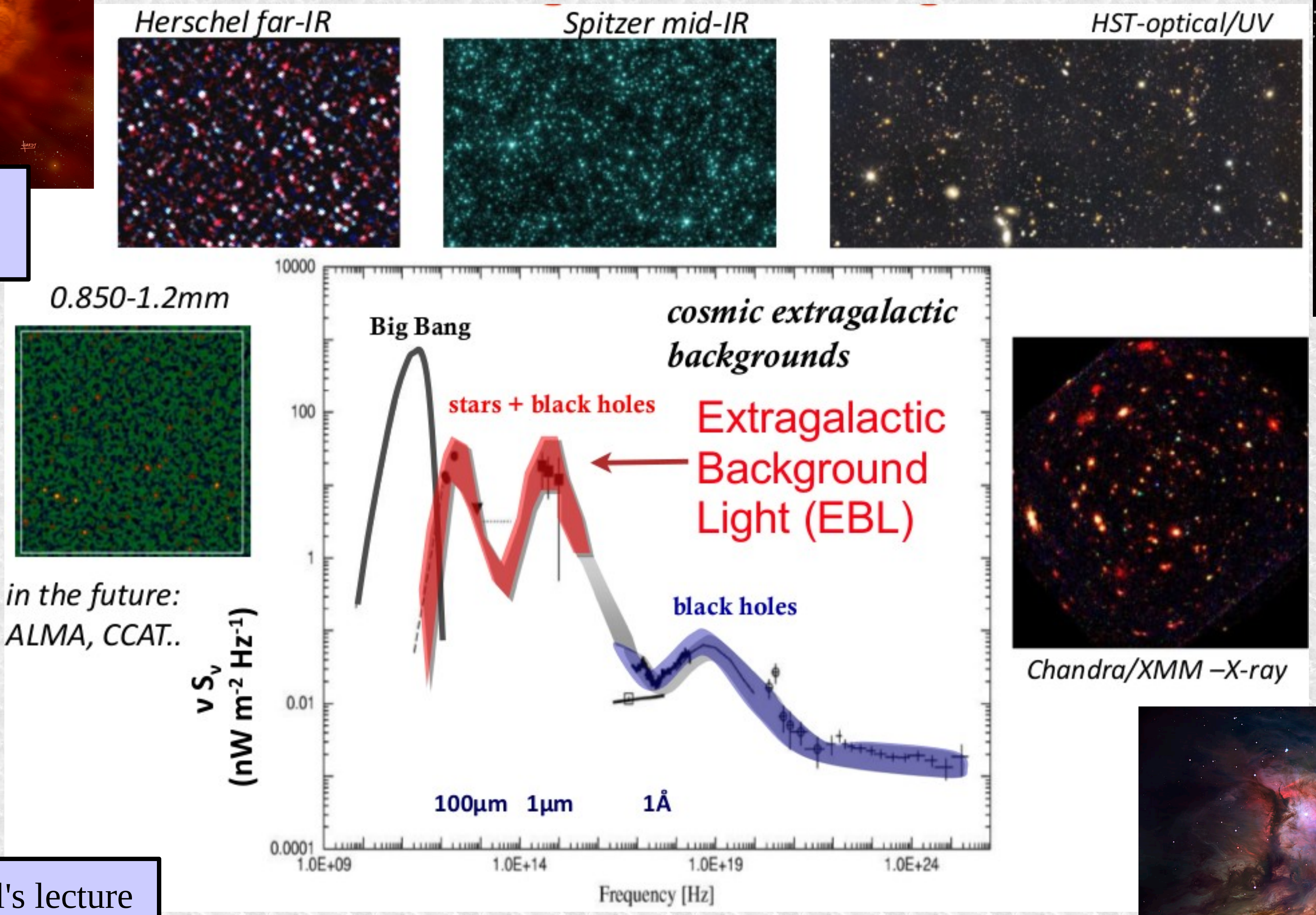
More information can be obtained from anisotropy or cross-correlation analyses

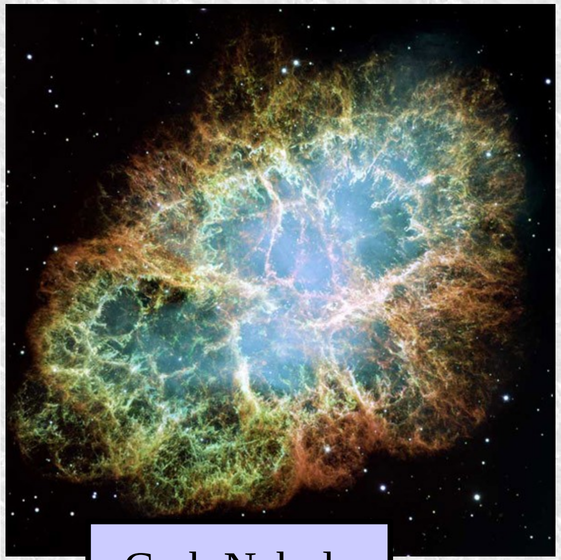


# The Extragalactic Background Light

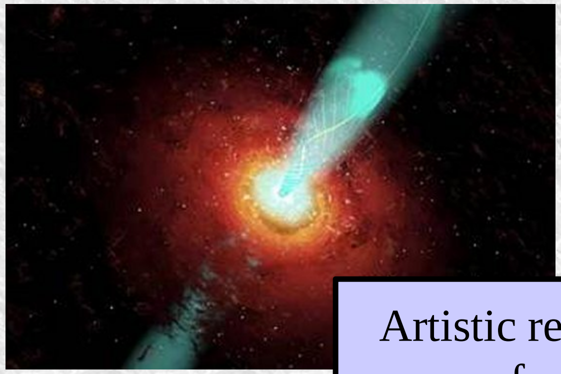
Artistic representation of a binary system



Crab Nebula

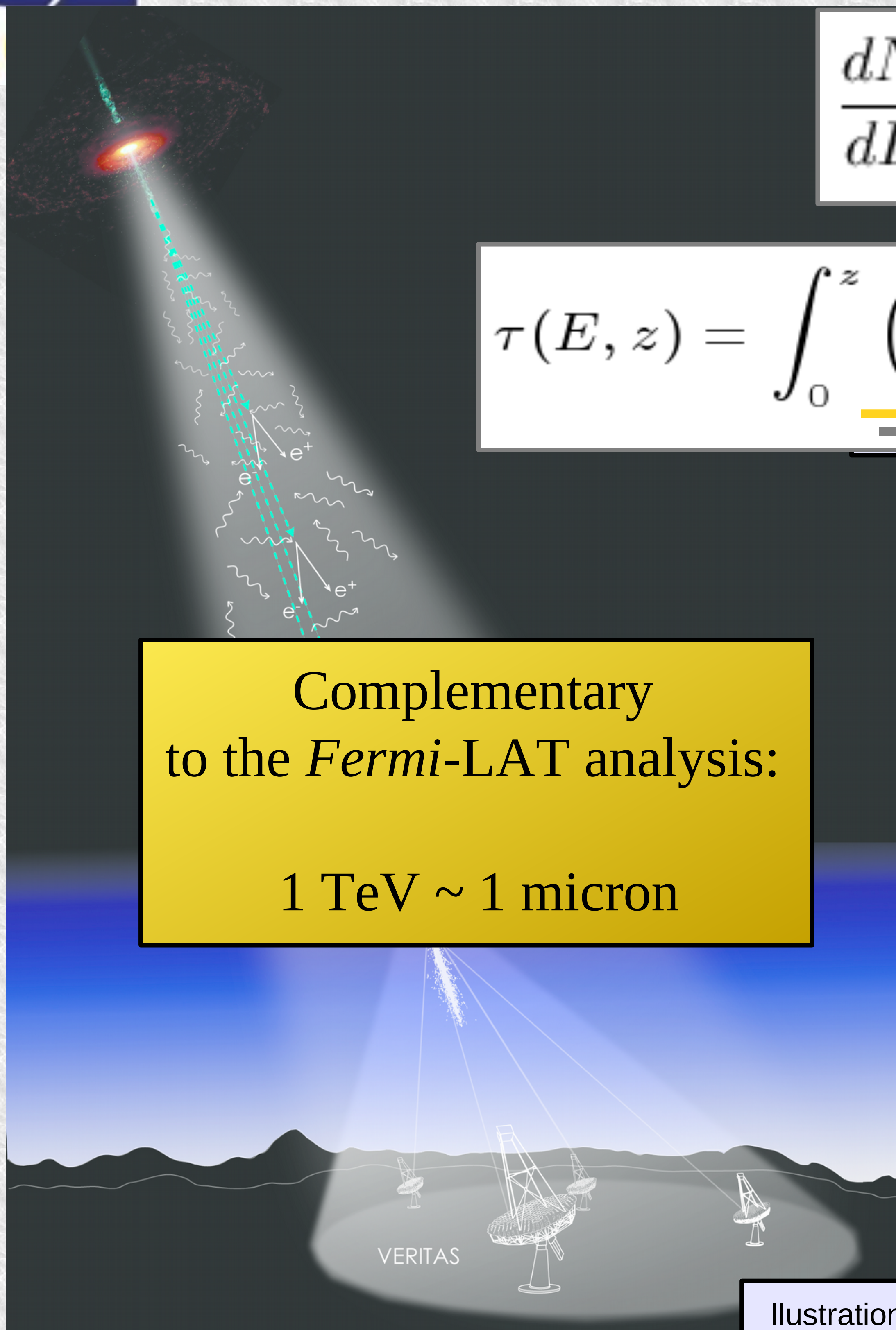
From Genzel's lecture @ 2013 Jerusalem Winter School



Artistic representation of a blazar

Orion Nebula (birth place of stars)

# Extragalactic Background Light Study Using gamma-ray Attenuation




Complementary to the *Fermi*-LAT analysis:

1 TeV ~ 1 micron

Ilustration: Nina McCur

$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

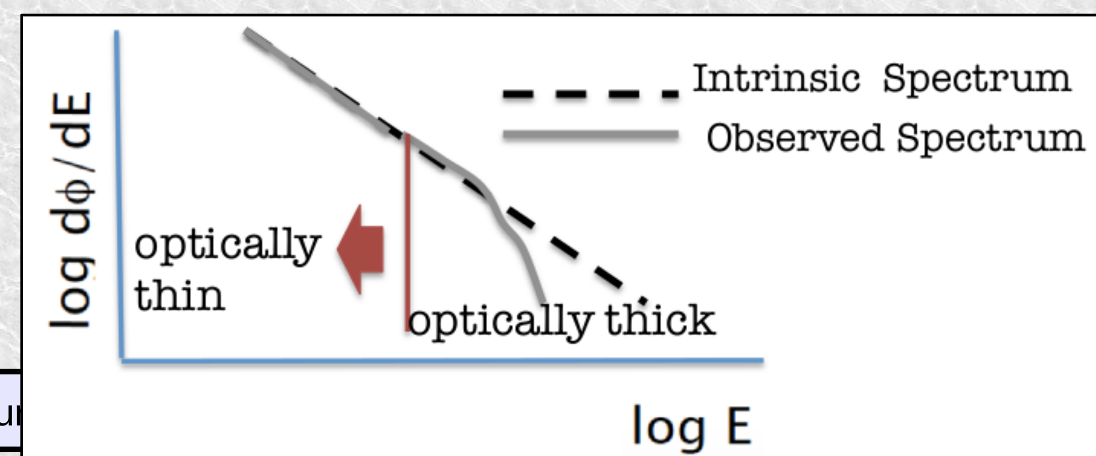
$$\tau(E,z) = \int_0^z \left(\frac{dl'}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{min}}^{\infty} d\varepsilon' \, \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$

distance

Interaction angle

cross section

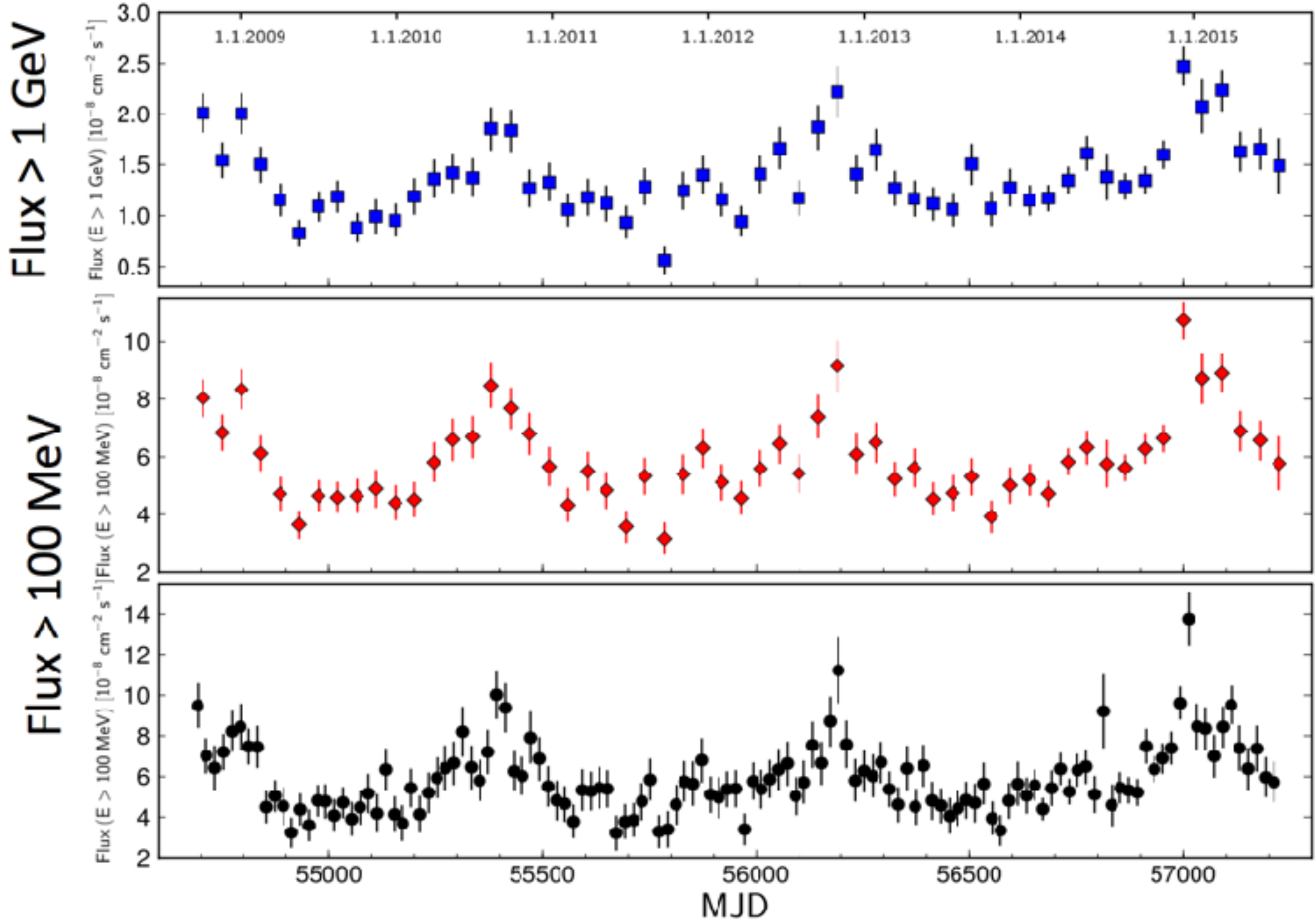
EBL photon density evolution



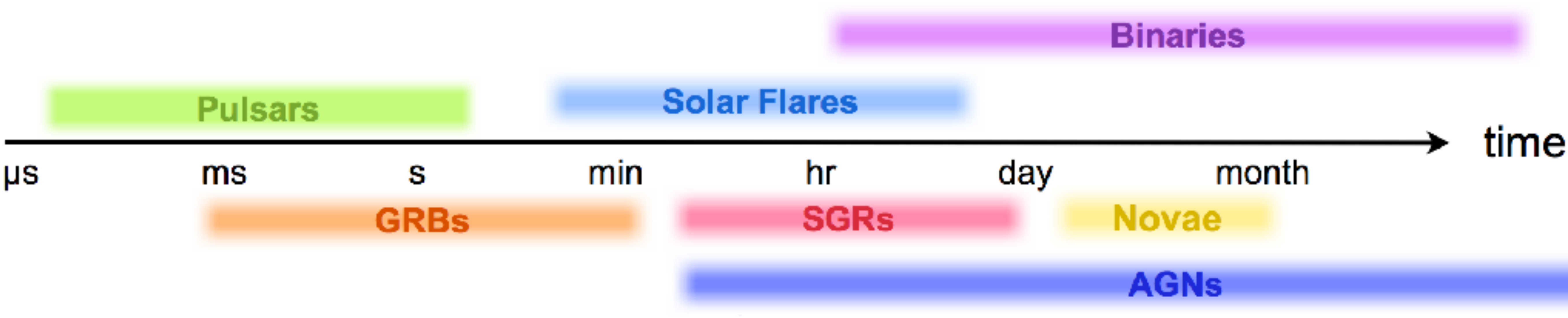
# Long-term Variability – Periodic Blazar?

*Fermi* LAT sees apparent quasi-periodic variability from BL Lac object PG 1553+113

If this ~2-yr pattern continues, it might suggest a binary supermassive black hole system.



# Variability in gamma rays in HERD era




– New sources detected or identified through their variability

– HERD will provide continuous (unique) sky monitoring for the multi-wavelength community (impact to the astronomy community). Pulsed emission from Crab detected by MAGIC up to ~2 TeV, Pulsations from Vela observed above 50 GeV

– We probably need automated data processing, based on daily peak finder and likelihood analysis for ATels (Fermi triggered 301 Astronomers Telegrams)

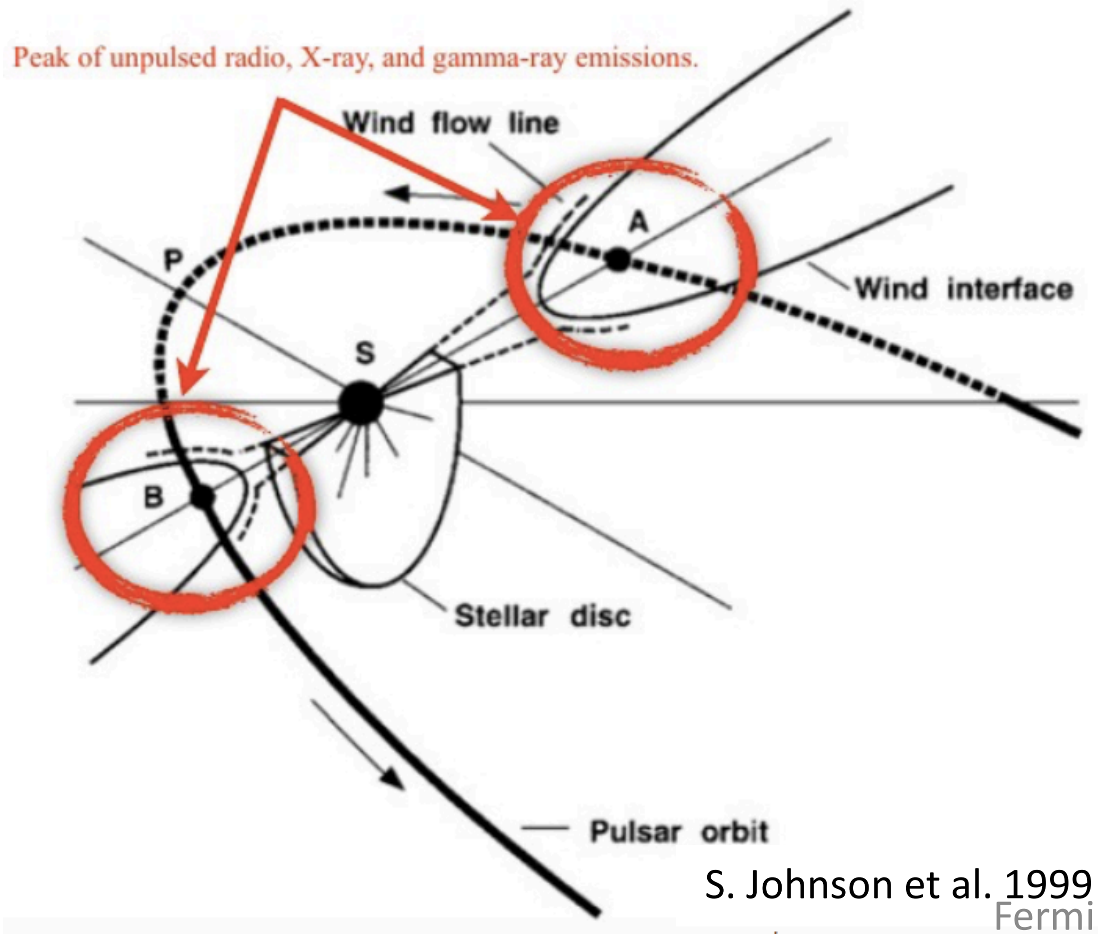
# The Sky Is Busier Than Ever

- LAT Target of Opportunity observations in past year
  - Flaring blazars (CTA 102) and MW campaigns (e.g. EHT campaign on M87)
  - Galactic Novae
  - Crab Nebula
- 2 gamma-ray binaries near periastron
- IceCube neutrino events

Report campaigns that depend on Fermi coverage to guarantee consideration when planning observatory activities.
https://fermi.gsfc.nasa.gov/ssc/observations/multi/reporting/

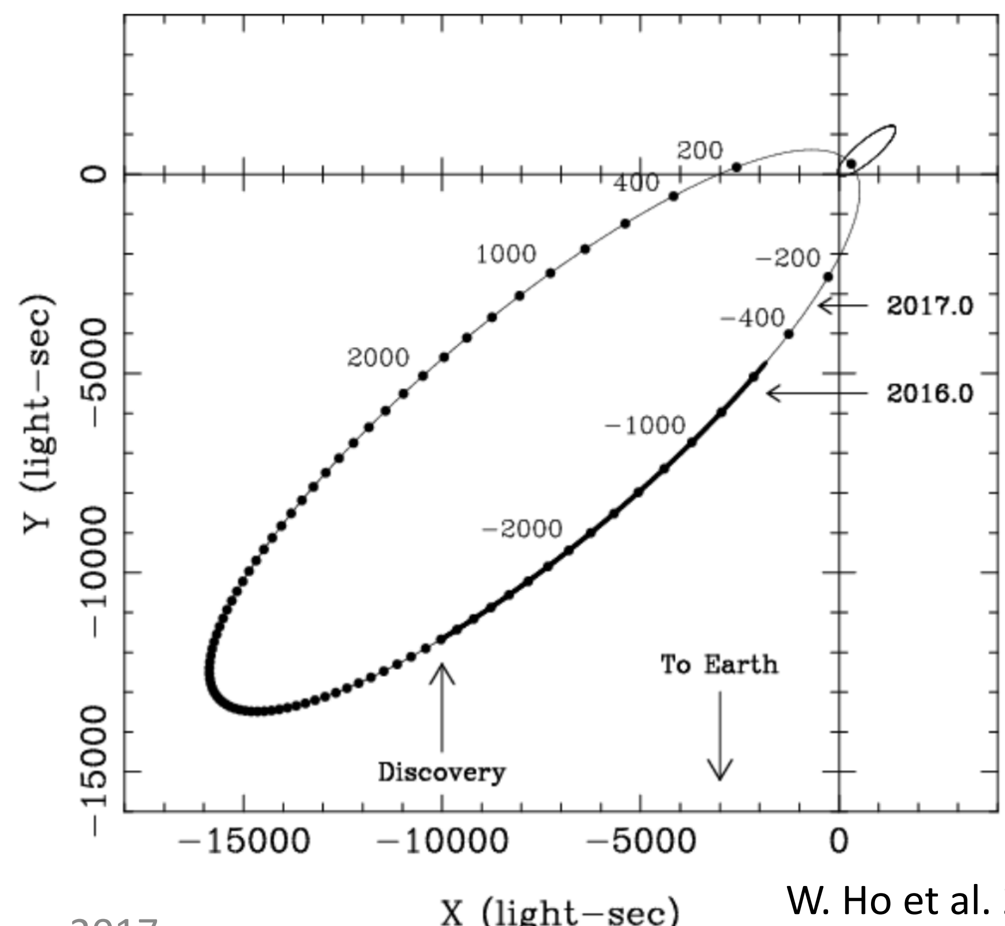
# Two Binaries at Close Approach

PSR B1259-63   3.4 yr orbital period
Periastron Sept. 22, 2018




S. Johnson et al. 1999

PSR J2032+4127  ~50 yr orbital period
Periastron Nov. 13, 2018




W. Ho et al. 2017

# Neutrino Follow-up

- *Fermi*-LAT reported an active gamma-ray blazar in the error region of an IceCube extremely high-energy neutrino, 170922A

**Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.**

ATel #10791; ***Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration***
*on* ***28 Sep 2017; 10:10 UT***
*Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)*

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845

Tweet Recommend 3

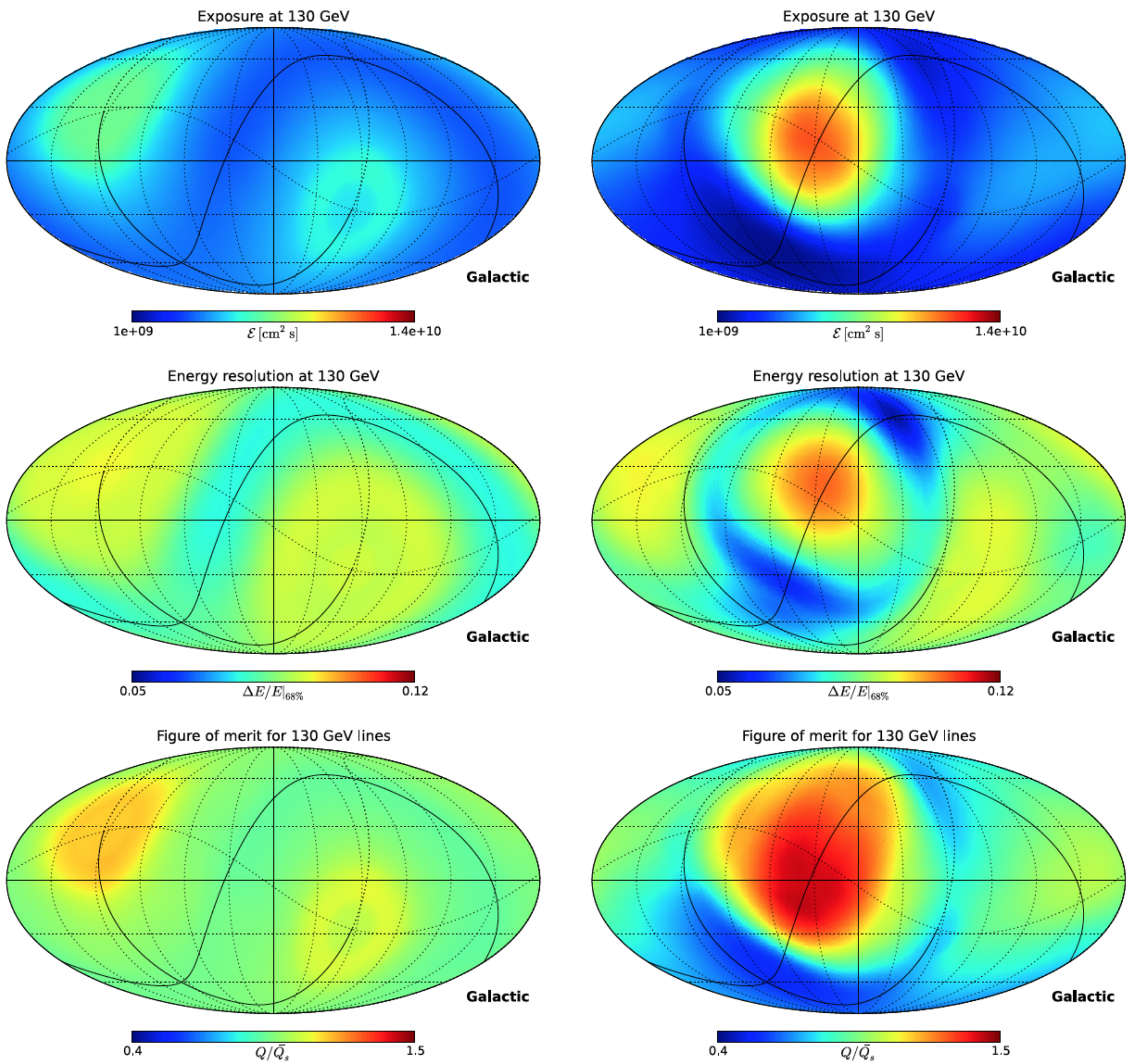
We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL J0509.4+0542), is located inside the IceCube error region. The FAVA (Fermi All-sky Variability Analysis) light curve at energies above 800 MeV shows a flaring state recently (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27). Indeed, the LAT 0.1--300 GeV flux during 2018

# Observations with modified strategy of Fermi started Dec. 5th 2013

Exposure map:

Energy resolution:

Figure of merit:

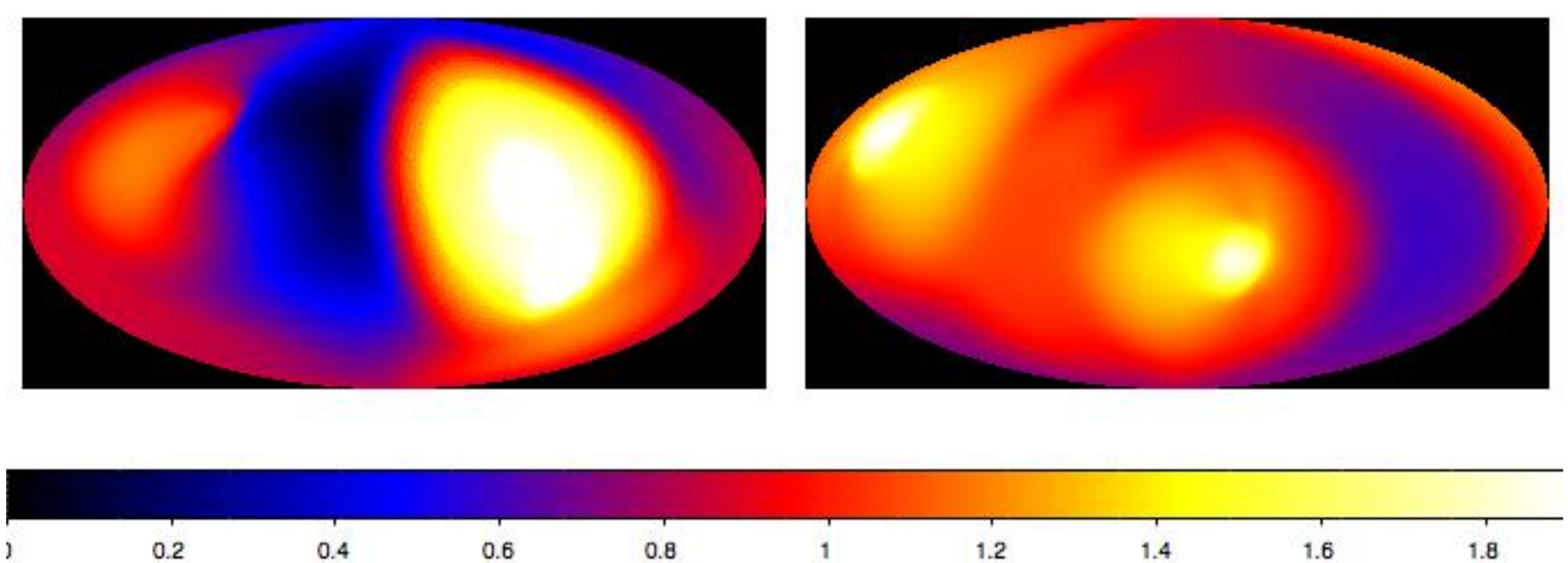


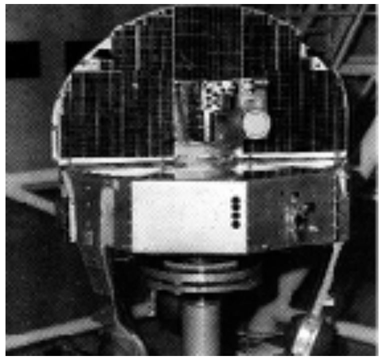

Weniger, MS, et al. (2013)

Sky survey provides optimal monitoring of multiple objects of interest.

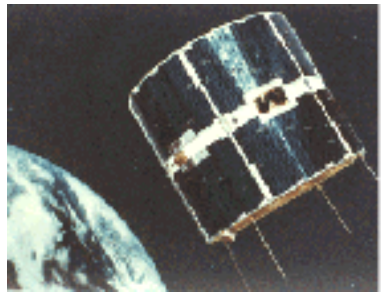
HERD has no consumables, no degradation of science performance

Observations not in sky survey mode, no pointed observations for autonomous repoints and target of opportunity requests

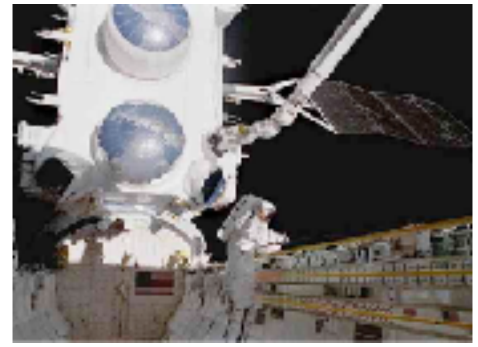




OSO-3

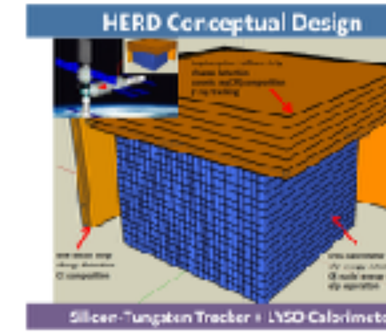


COS-B



EGRET, COMPTEL
(onboard Compton Gamma-ray Observatory)

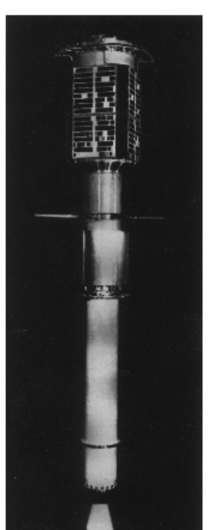
Fermi Gamma-ray Space Telescope



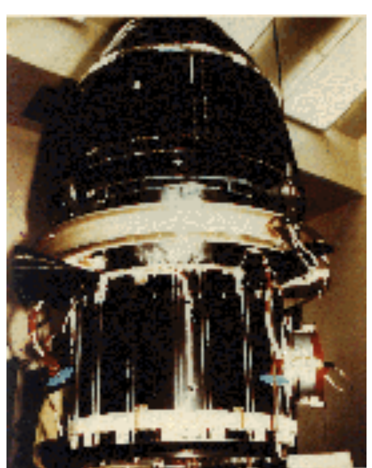

HERD!

1960 1970 1980 1990 2000 2010 2020 2025

Explorer XI



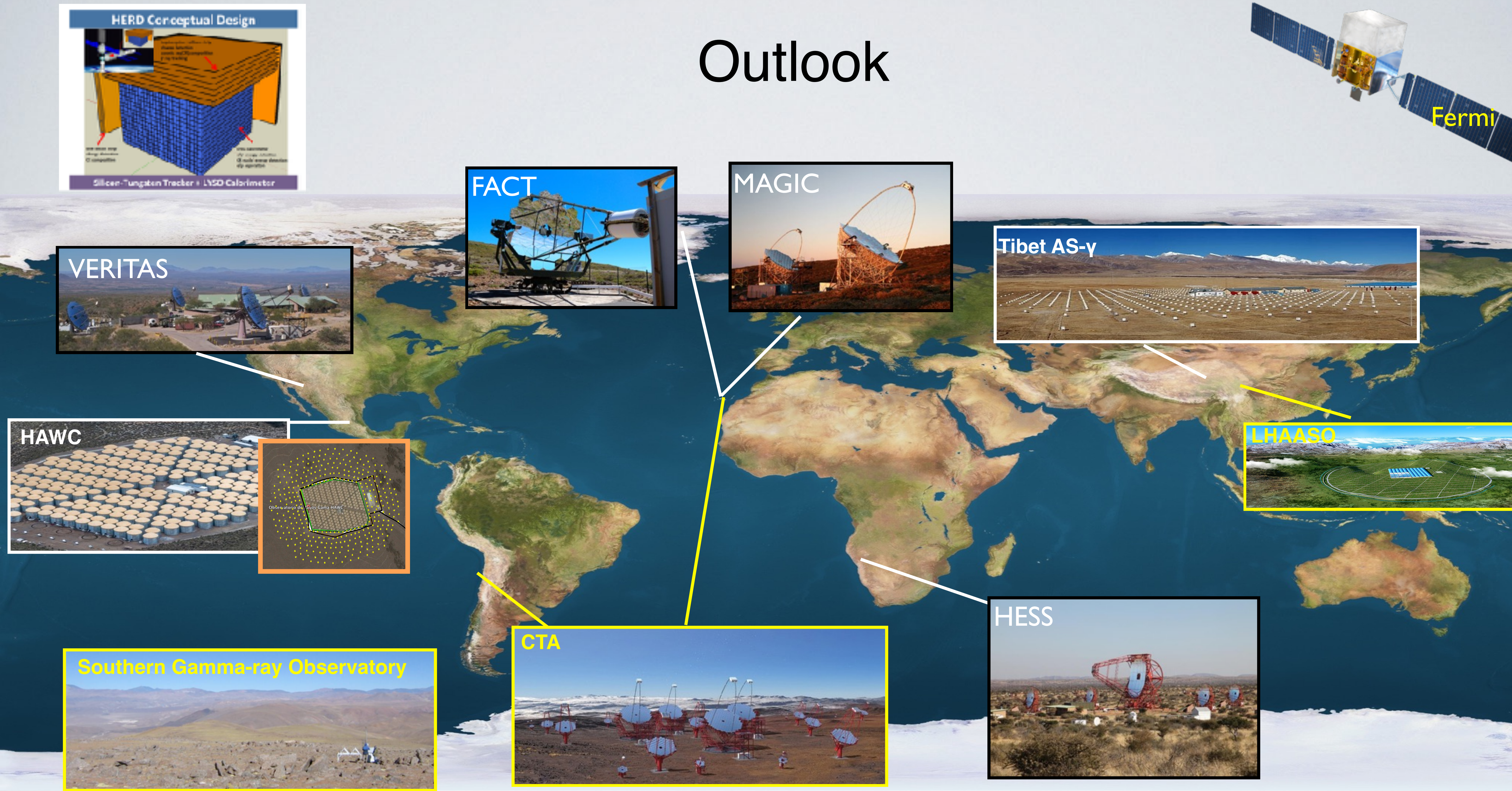
SAS-2




AGILE

DAMPE! launched Dec. 17 2015!

# Outlook




- The gamma-ray sky is currently well-monitored with good survey coverage.
- Many instruments from different waveband/messenger (X rays, gamma rays, neutrinos, gravitational waves) available for simultaneous observations.
- Both wide-field and pointing instruments in development and coming online in the next decade.

HERD completely overlaps the energy range of Cherenkov telescopes by measuring the photons in situ!

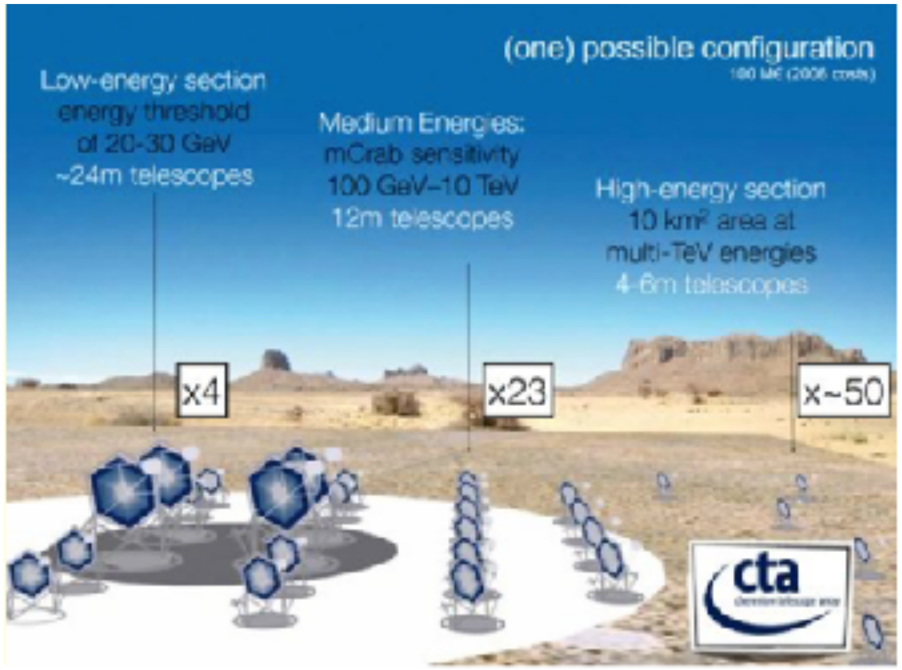
HERD + LHAASO + CTA!

- HERD extends the Fermi source spectrum to higher energy
- Significantly enhance the detection from Fermi data and reveal NEW sources (especially 1FHL catalog)
- HERD >50 GeV catalog, >100 GeV catalog)
- HERD will improve the significance of Fermi sources over a large energy range, improve the source location
- HERD is crucial to provide targets

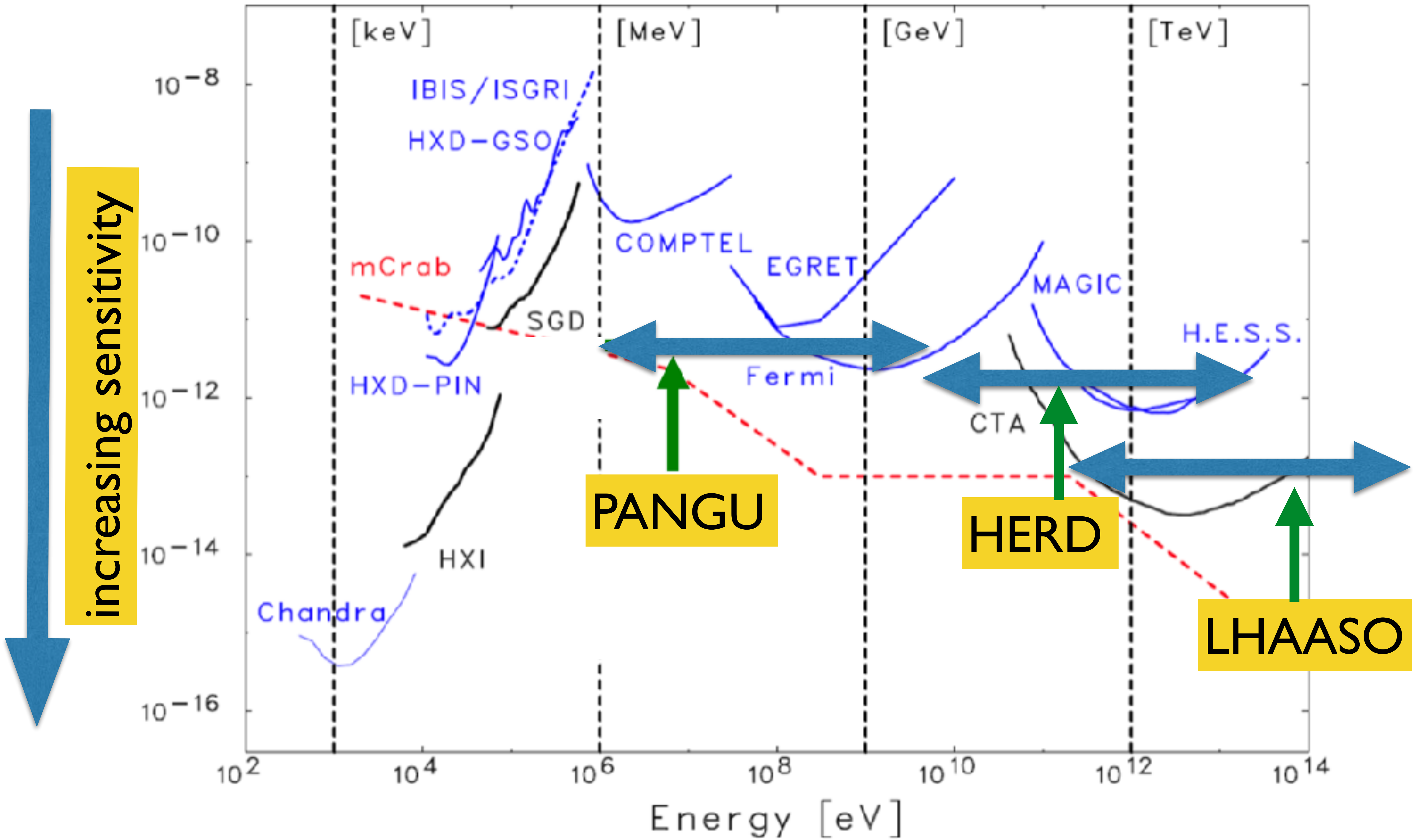
  for existing Cherenkov telescopes

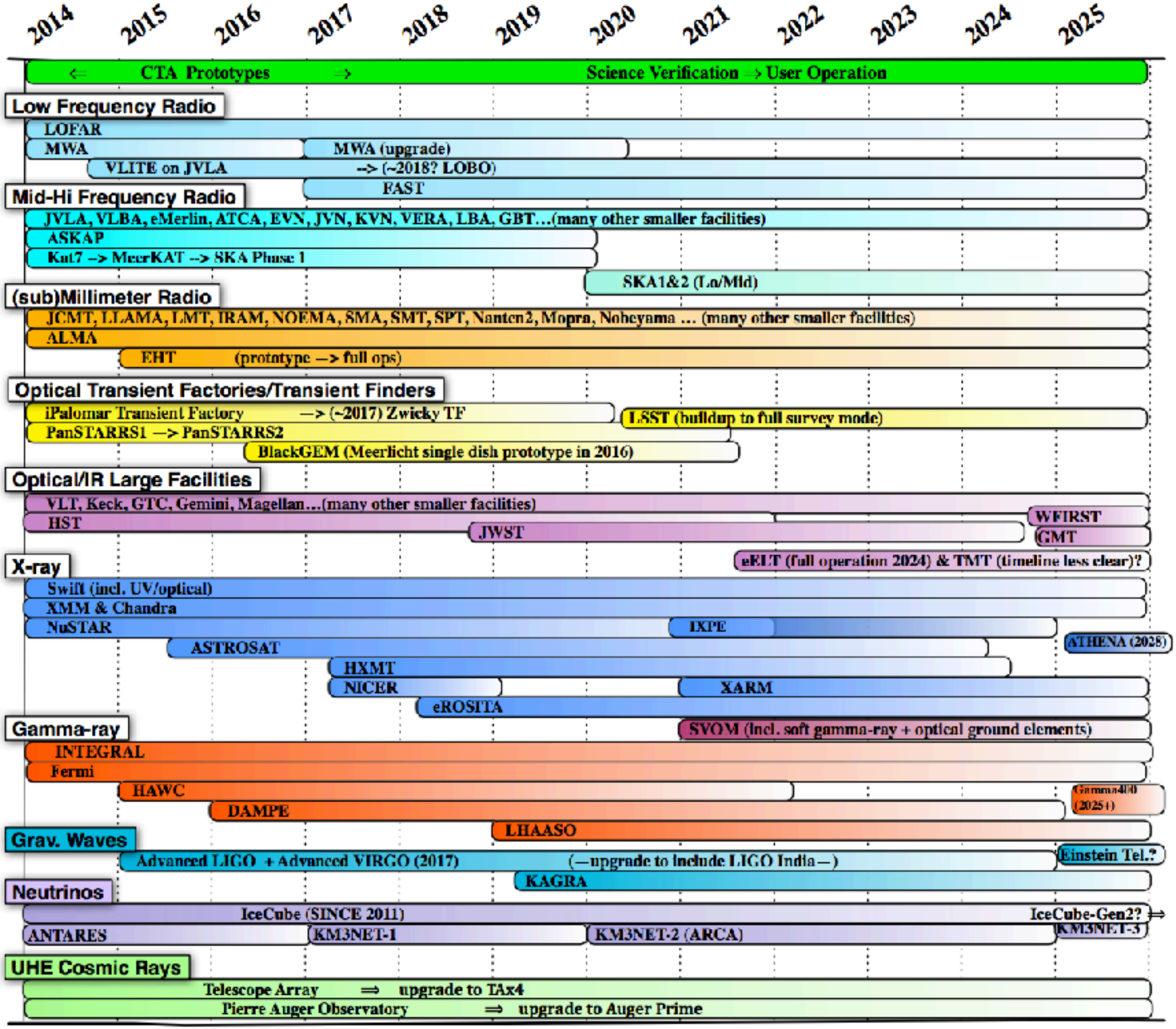
  and future CTA/LHAASO

  - HERD ToO requests:
  - Sun, AGN, Crab, Novae, binary systems



# Bright future!
# We could cover nine decades of energy from MeV-PeV




2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
CTA Prototypes
Science Verification → User Operation
Low Frequency Radio
LOFAR
MWA
MWA (upgrade)
VLITE on JVLA
--> (~2018? LOBO)
FAST
Mid-Hi Frequency Radio
JVLA, VLBA, eMerlin, ATCA, EVN, JVN, KVN, VERA, LBA, GBT…(many other smaller facilities)
ASKAP
Kat7 --> MeerKAT --> SKA Phase 1
SKA1&2 (Lo/Mid)
(sub)Millimeter Radio
JCMT, LLAMA, LMT, IRAM, NOEMA, SMA, SMT, SPT, Nanten2, Mopra, Nobeyama … (many other smaller facilities)
ALMA
EHT
(prototype --> full ops)
Optical Transient Factories/Transient Finders
iPalomar Transient Factory
--> (~2017) Zwicky TF
LSST (buildup to full survey mode)
PanSTARRS1 --> PanSTARRS2
BlackGEM (Meerlicht single dish prototype in 2016)
Optical/IR Large Facilities
VLT, Keck, GTC, Gemini, Magellan…(many other smaller facilities)
WFIRST
HST
JWST
GMT
eELT (full operation 2024) & TMT (timeline less clear)?
X-ray
Swift (incl. UV/optical)
XMM & Chandra
NuSTAR
IXPE
ATHENA (2028)
ASTROSAT
HXMT
NICER
XARM
eROSITA
Gamma-ray
SVOM (incl. soft gamma-ray + optical ground elements)
INTEGRAL
Fermi
HAWC
Gamma400 (2025+)
DAMPE
LHAASO
Grav. Waves
Advanced LIGO + Advanced VIRGO (2017)
(—upgrade to include LIGO India—)
Einstein Tel.?
KAGRA
Neutrinos
IceCube (SINCE 2011)
IceCube-Gen2?
ANTARES
KM3NET-1
KM3NET-2 (ARCA)
KM3NET-3
UHE Cosmic Rays
Telescope Array
⇒ upgrade to TAx4
Pierre Auger Observatory
⇒ upgrade to Auger Prime

We plan to set up a
a multi-wavelength/multi-messenger working group for HERD gamma-ray Science

# The Fermi All-Sky Cake


Credit: Judy Racusin

# Looking forward to the HERD All-Sky Cake


Credit: Judy Racusin

# The HERD all-sky cake in trans-TeV

"HERD gamma-ray diffuse model", synergy with Fermi-LAT gamma-ray diffuse model

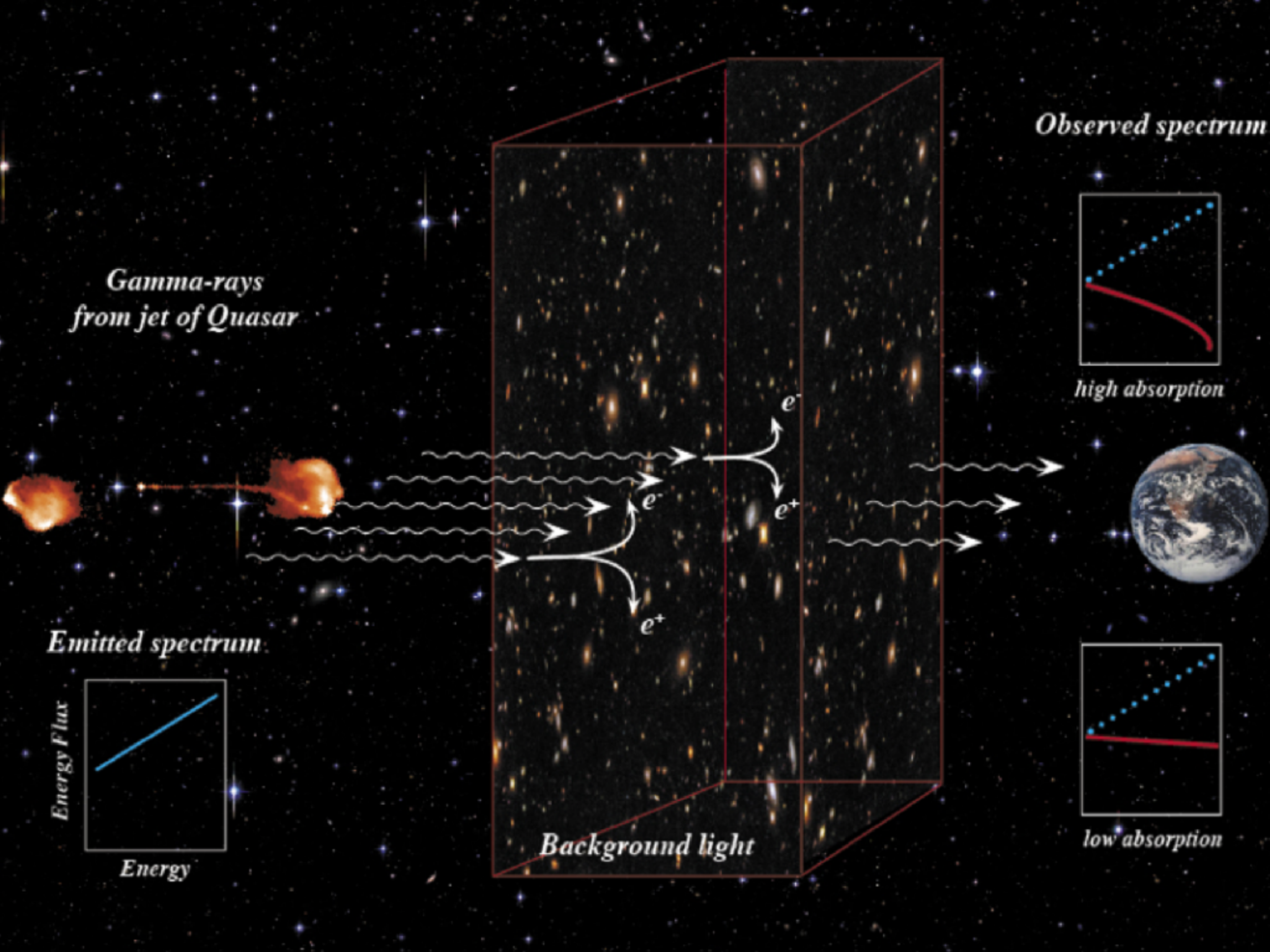
Isotropic/Anisotropic background

Extended sources Fermi Bubbles, Cen A lobes, Cygnus region, Supernova remnants

TeV point sources!

# Thank you!

Expected launch 2025, a lot of work to do!


Gamma-rays
from jet of Quasar
Emitted spectrum
Energy Flux
Energy
e-
e+
e-
e+
Background light
Observed spectrum
high absorption
low absorption

# The Gamma-ray Horizon

- EBL opacity curves (Dominguez et al. 2011) • PKS 1424+240 probes an opacity of $\tau$>5
- 3C 66A and PG 1553+113 also pushing up in opacity
- S3 0218+35 @ z=0.944 detected by MAGIC between 100-200 GeV probes < $\tau$~2.5