Lecture 2:
Gamma-ray Astrophysics

Ultra High Energy \\ Cosmic Rays

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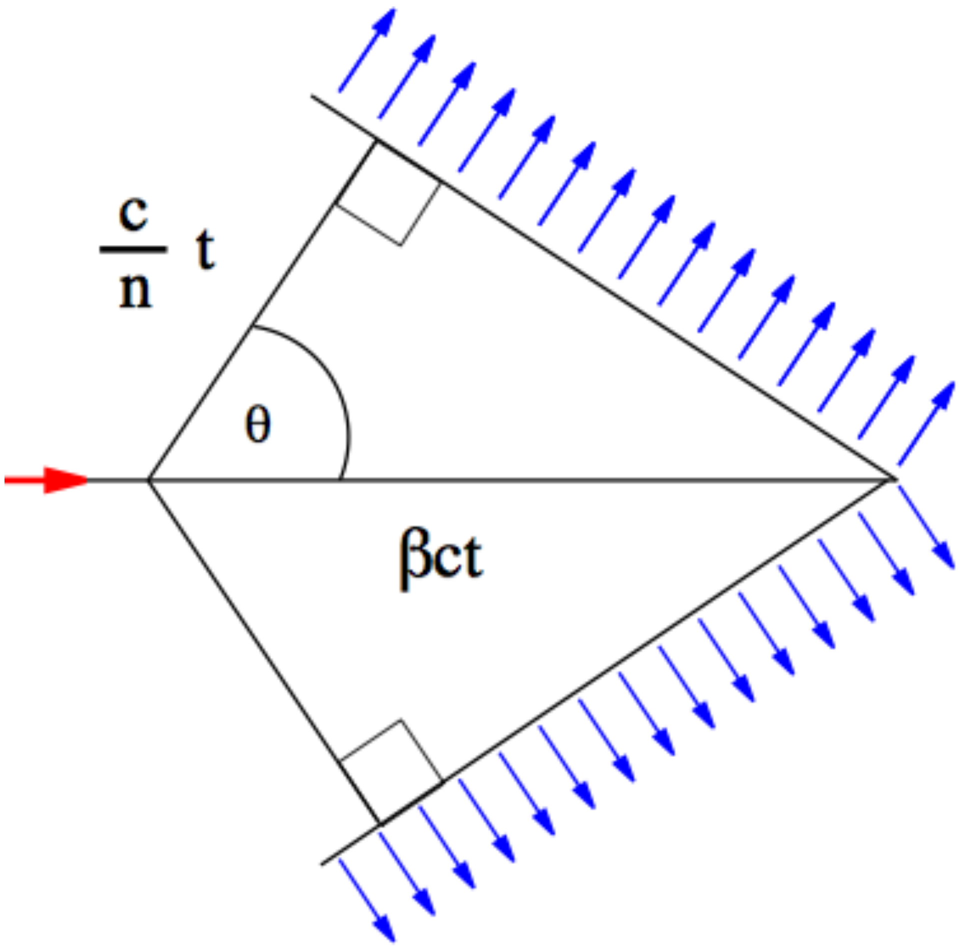
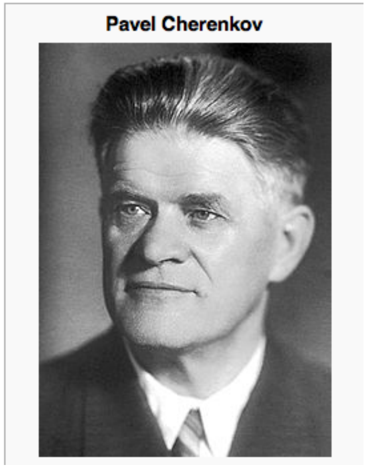
Overview:

- Cherenkov radiation
- Detection technics
- Present and future experiments
- Galactic gamma-ray sources and diffused background
- Extragalactic sources and backgrounds
- Study of intergalactic magnetic fields
- Indirect detection of Dark Matter
- Conclusions

Cherenkov radiation

Cherenkov radiation





Discovery 1934

Nobel prize 1958

Cherenkov radiation

$$V > V_m = c / n$$

n is refractive index of medium

$n = 1.008$ air

$n = 1.33$ water

The charged particles polarize the molecules, which then turn back rapidly to their ground state, emitting prompt radiation

Cherenkov light is emitted under a constant Cherenkov angle with the particle trajectory, given by

$$\cos\delta = \frac{V_m}{V} = \frac{c}{nV} = \frac{1}{\beta n}$$

- Minimal energy of charge particle

$$\gamma_{\min} = \frac{n}{\sqrt{n^2 - 1}}$$

Main processes used in gamma-ray astrophysics

$$\gamma + \gamma_B \Rightarrow e^- + e^+$$

$$e^\pm + \gamma_B \Rightarrow e^\pm + \gamma$$

$$e^\pm + B \Rightarrow e^\pm + \gamma_{synch}$$

$$e^\pm + A_B \Rightarrow e^\pm + A_B + \gamma_{brems}$$

$$P + \gamma_B \Rightarrow N + \pi$$

$$P + P_B \Rightarrow N + N + \sum \pi$$

$$\pi^0 \Rightarrow 2\gamma$$

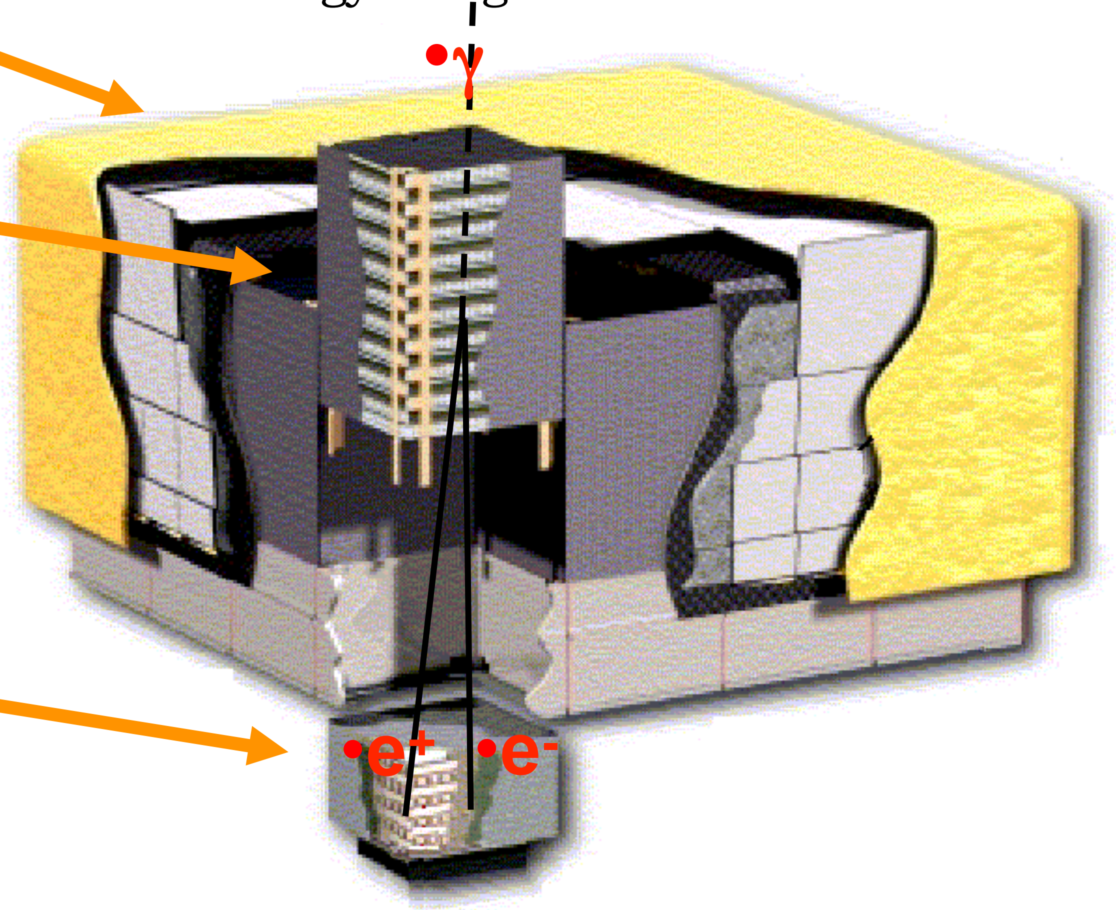
Detection technics

Fermi Large Area Telescope (LAT)

Large Field of View >2.4 sr

Broad Energy Range 20 MeV - >300 GeV

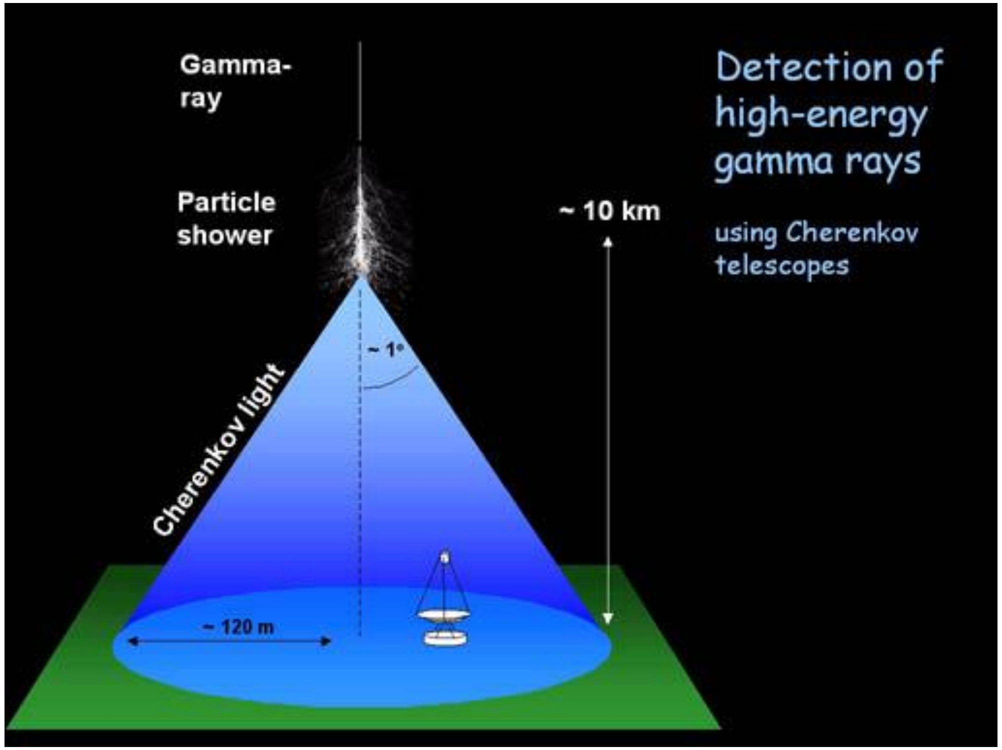
- **ACD**
- scintillator
- 89 tiles
- **Tracker**
- Si strip detectors
- Tungsten foil converters
- pitch = 228 um
- 8.8×10^5 channels
- 18 planes
- **Calorimeter**
- CsI crystals
- hodoscopic array
- 6.1×10^3 channels
- 8 layers



Cherenkov telescopes

Very high energies, above 50 GeV

- Crab nebula: flux(E > 1 TeV) = 2 x 10^{-11} cm^{-2} s^{-1}
- Large effective detection areas (>30 000 m^2) needed
- -> Back to the ground
- Use the atmosphere as a
- huge calorimeter and
- detect γ-ray-induced
- atmospheric showers
- through Cherenkov light



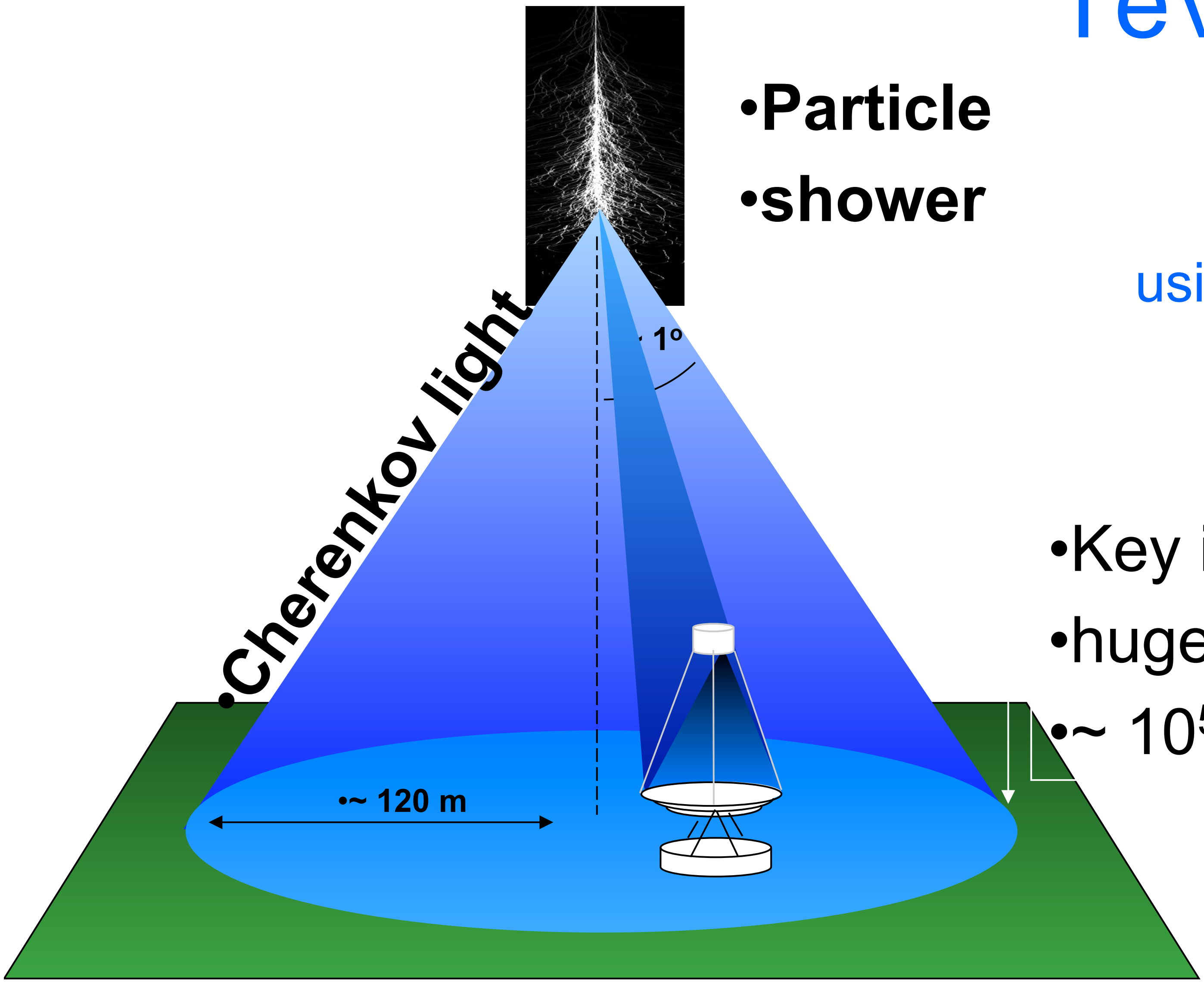
Experimental challenges

- Reduce the energy threshold as much as possible

  Try to get some overlap region with space observations
- Increase flux sensitivity
- **Remove the huge background** of showers induced by charged particles **(cosmic ray protons, ions and electrons)**

Detection of TeV gamma rays

using Cherenkov telescopes



- Key issue:
- huge detection area
- ~ 10^5 m^2

From W.Hofman

Hardonic rejection

- Image shape:

  Electromagnetic showers:

  elongated, quasi-elliptic shape

  Hadronic showers:

  more irregular shape

- Image direction:

  Electromagnetic showers:

  point to the source (the center of the field of view)

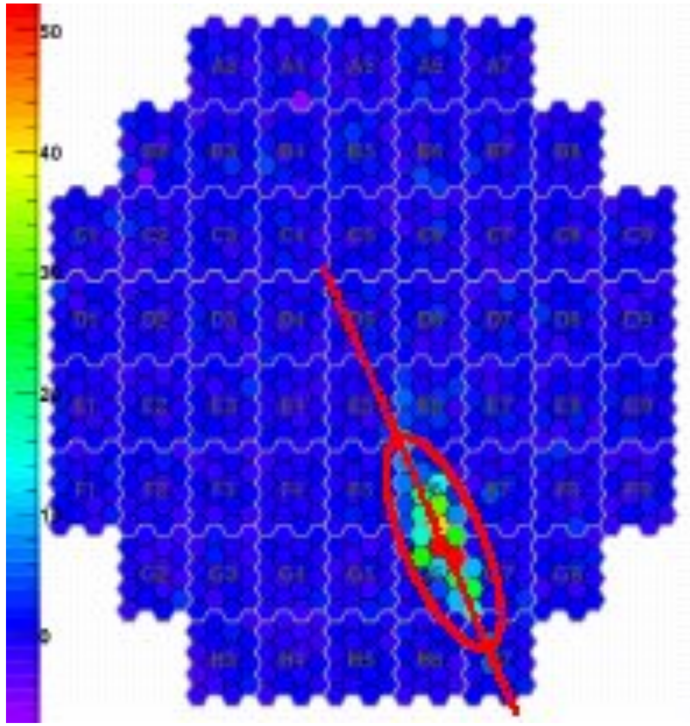
  Hadronic showers:

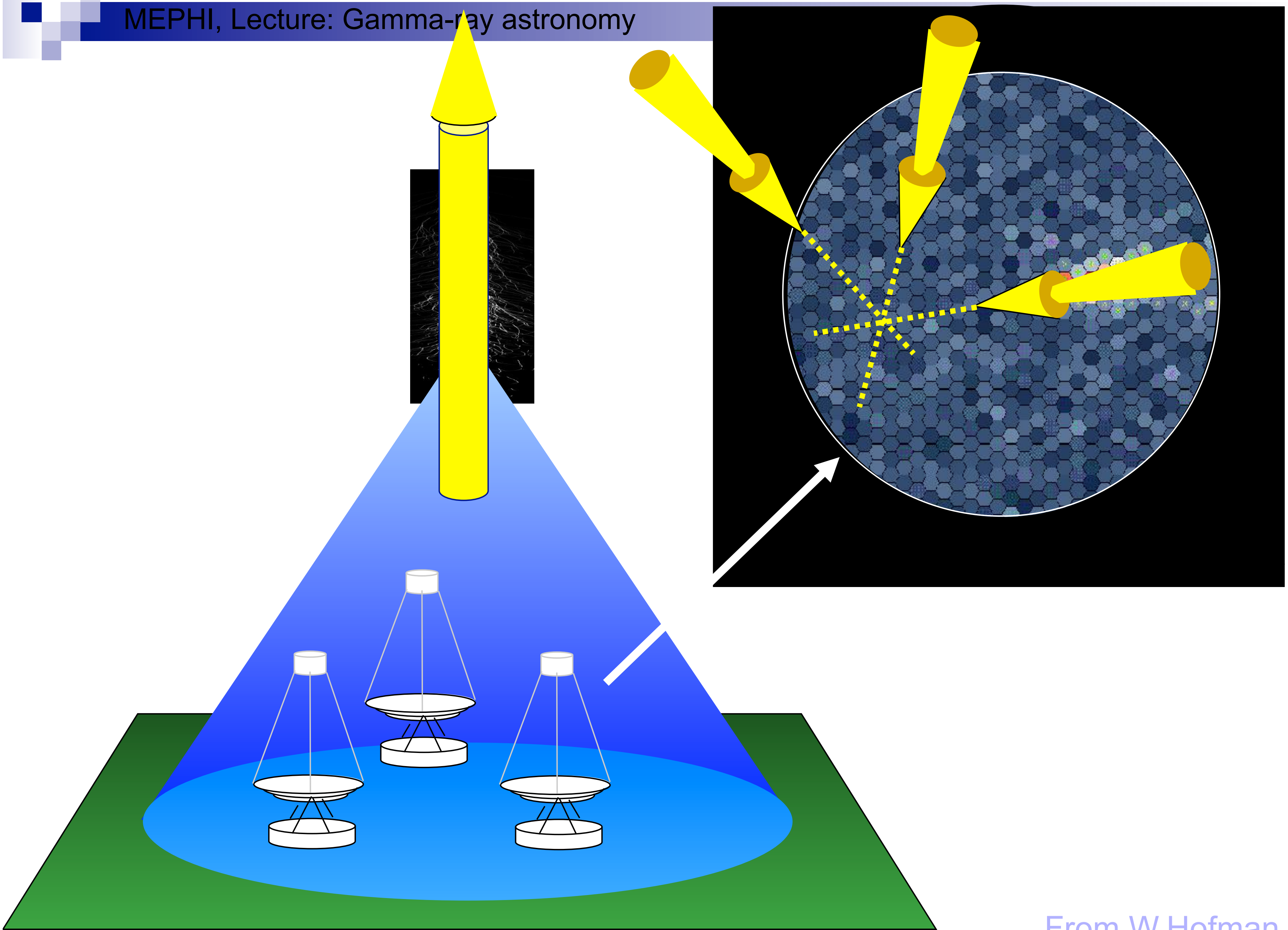
  randomly oriented in the focal plane

- Image light profiles

  (longitudinal and transverse)

  help finding the source position

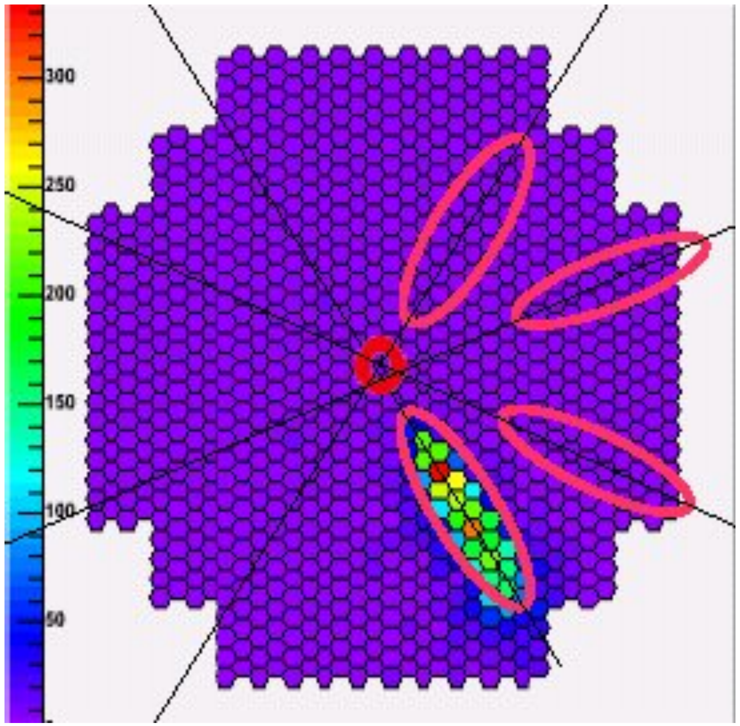


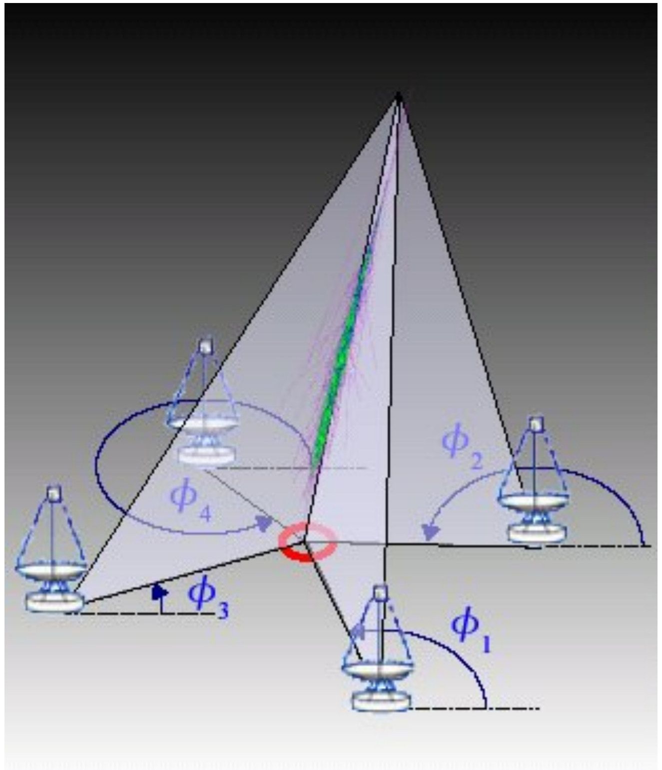


From W.Hofman

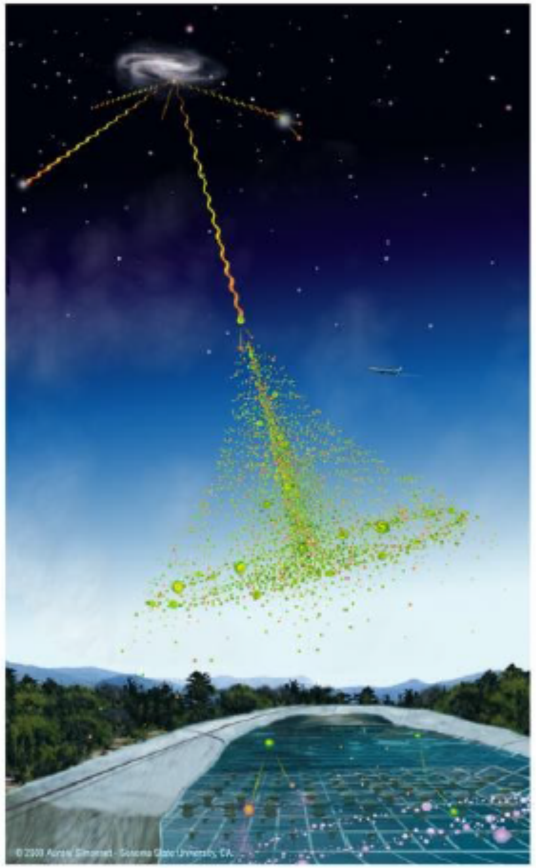
Stereoscopic measurement (e.g. HEGRA, H.E.S.S. VERITAS, MAGIC)

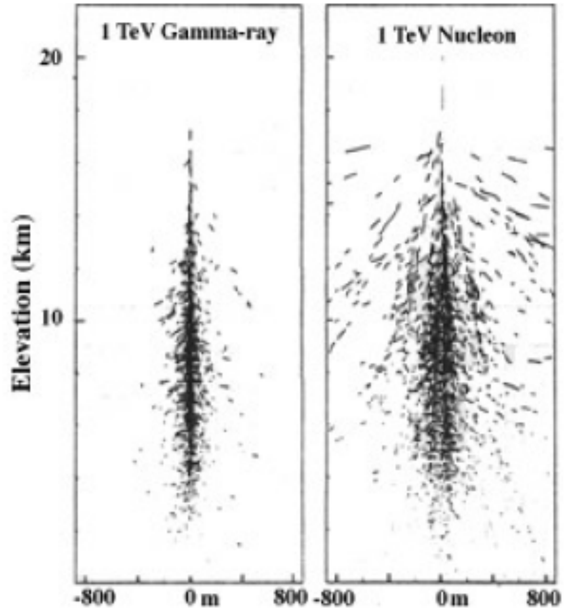
- Direct measurement of the **γ-ray origin** in the field of view (important for extended sources)
- Direct measurement of the **impact on the ground** (important for energy measurement)
- Better hadronic rejection
- Much better angular resolution

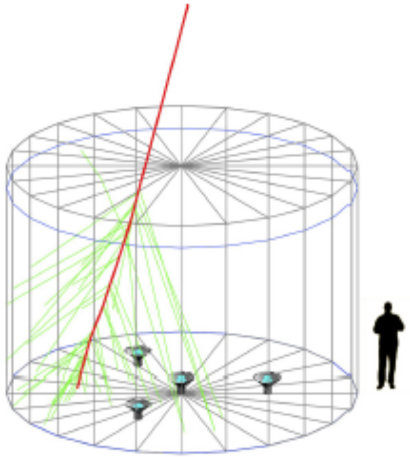




Detection Technique of the EAS Arrays



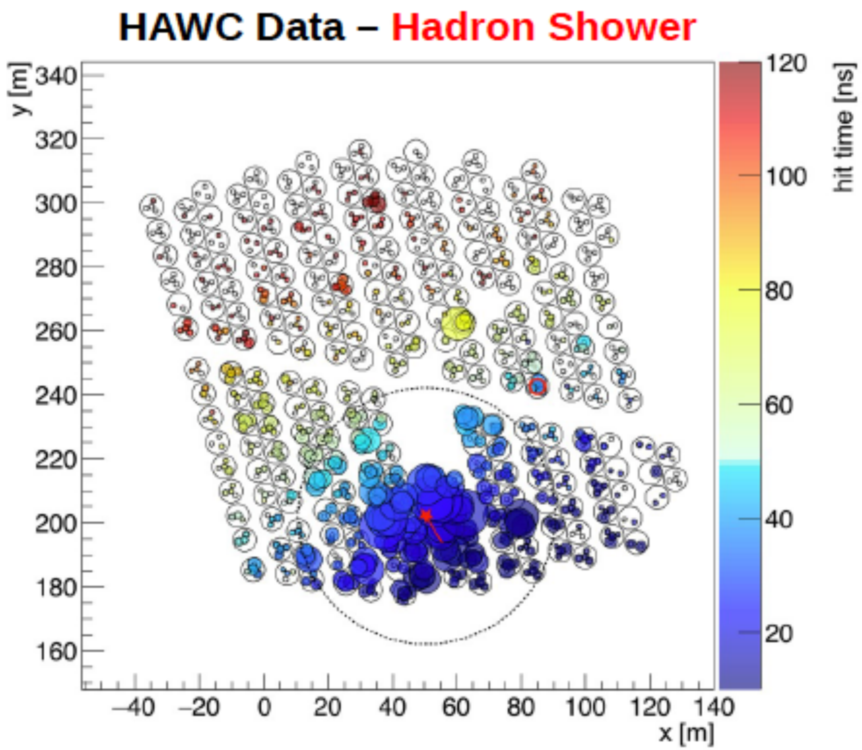


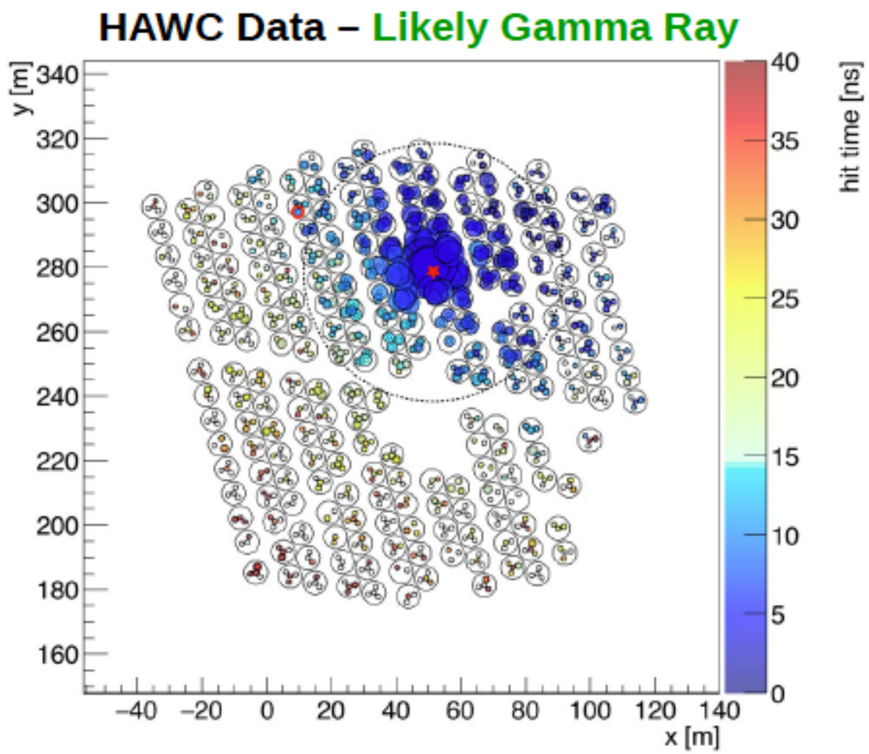


- The particle detectors can be tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- Gamma/hadron can be discriminated based on the event footprint on the detector. Although is one of the challenges of this kind of detectors.

Gamma/Hadron Separation

- Main background is hadronic CR, e.g. 400 γ/day from the Crab vs 15k CR/s.
- In gamma-ray showers, most of the signal at ground level is located near the shower axis.
- In charged cosmic rays tend to "break apart", much messier signals at ground level.



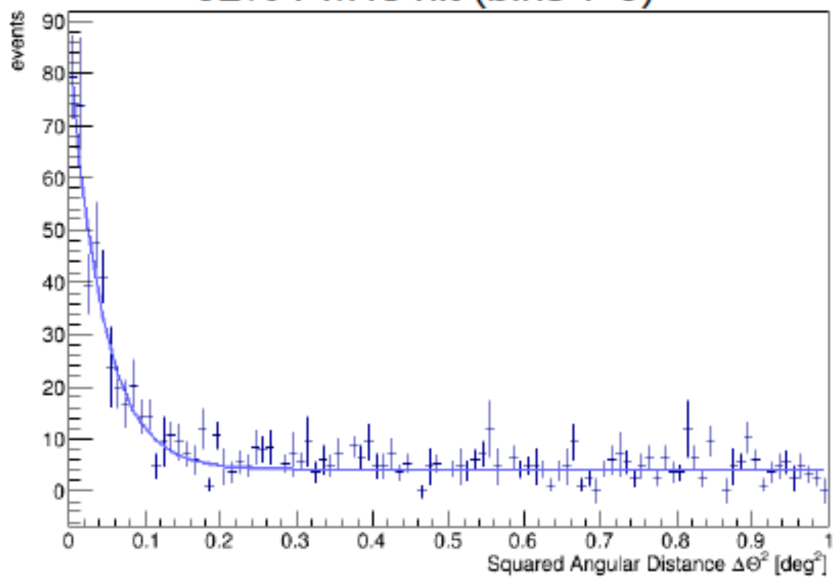


Pass 4 Preview: Crab Data

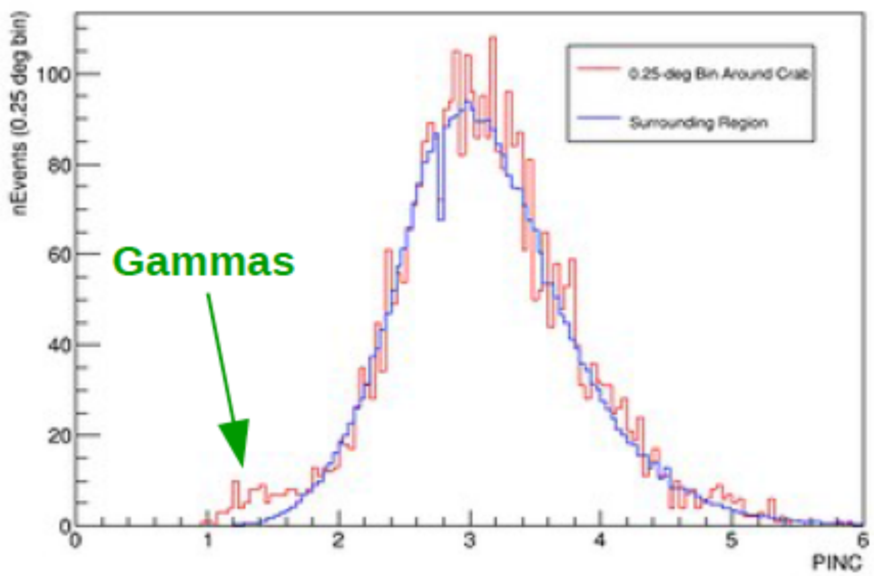
- Reconstruction and calibration improvements.

PRELIMINARY

> 62% PMTs hit (bins 7-9)



>85% PMTs Hit (bin 9)

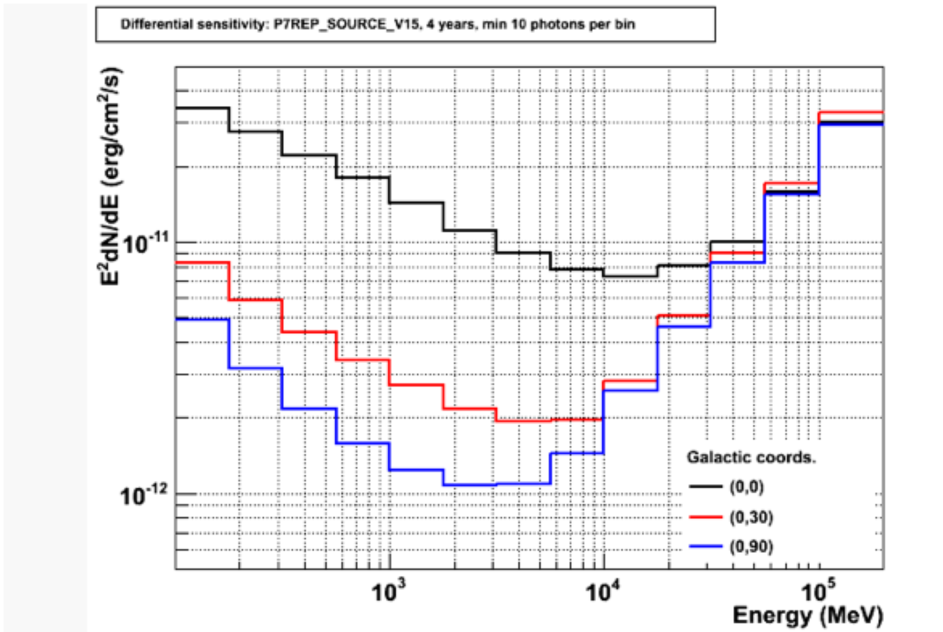


Angular resolution (68% containment): 0.24º for large event, achieving proposed resolution.

Gamma/Hadron separation:
Reject >99.9% of hadronic background for large events while retaining >50% of gamma rays.

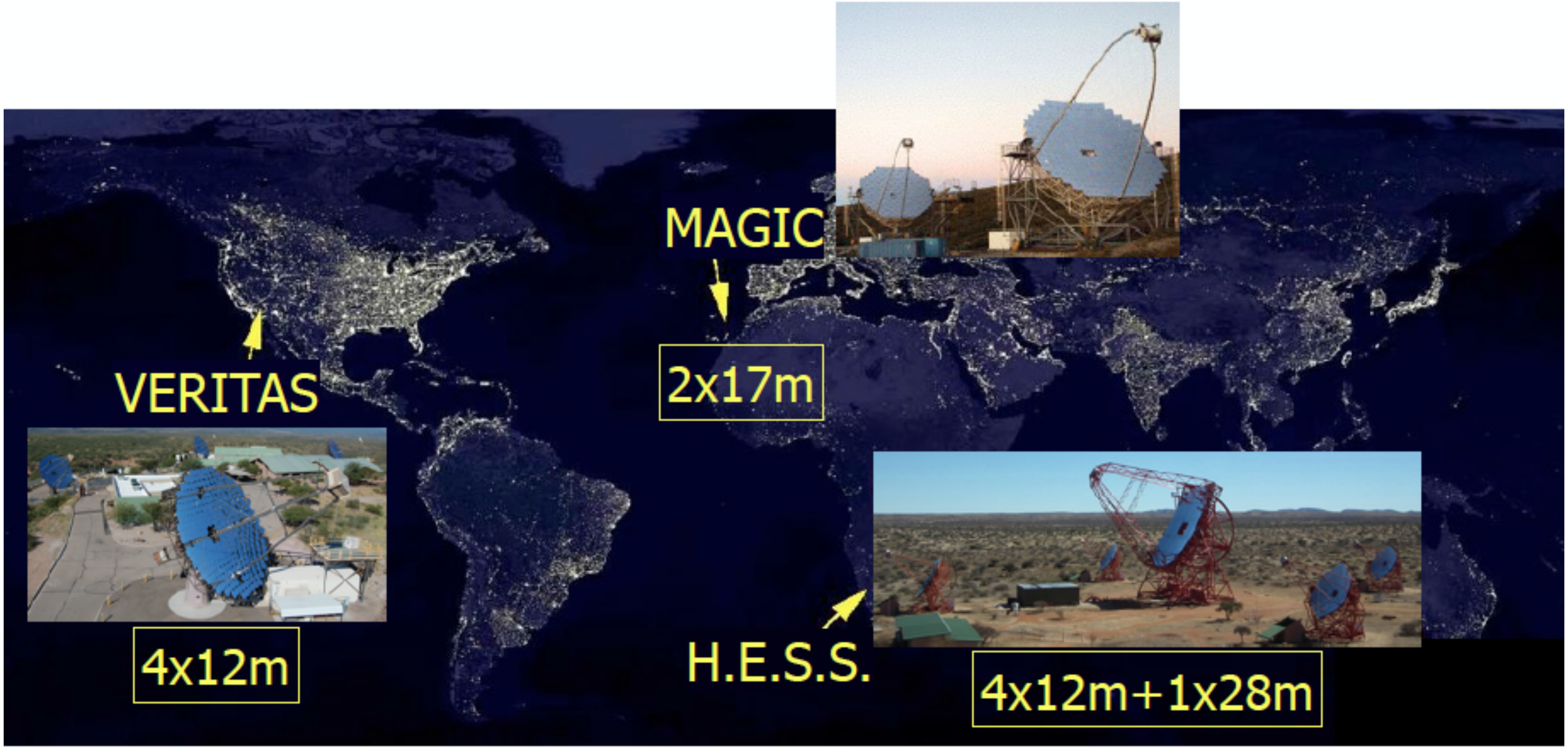
Fermi LAT gamma-rays 20 MeV-300 GeV

Fermi LAT


Differential sensitivity: P7REP_SOURCE_V15, 4 years, min 10 photons per bin
E²dN/dE (erg/cm²/s)
10⁻¹¹
10⁻¹²
10³
10⁴
10⁵
Energy (MeV)
Galactic coords.
(0,0)
(0,30)
(0,90)

TeV telescopes
50 GeV-20 TeV

Cherenkov telescopes today

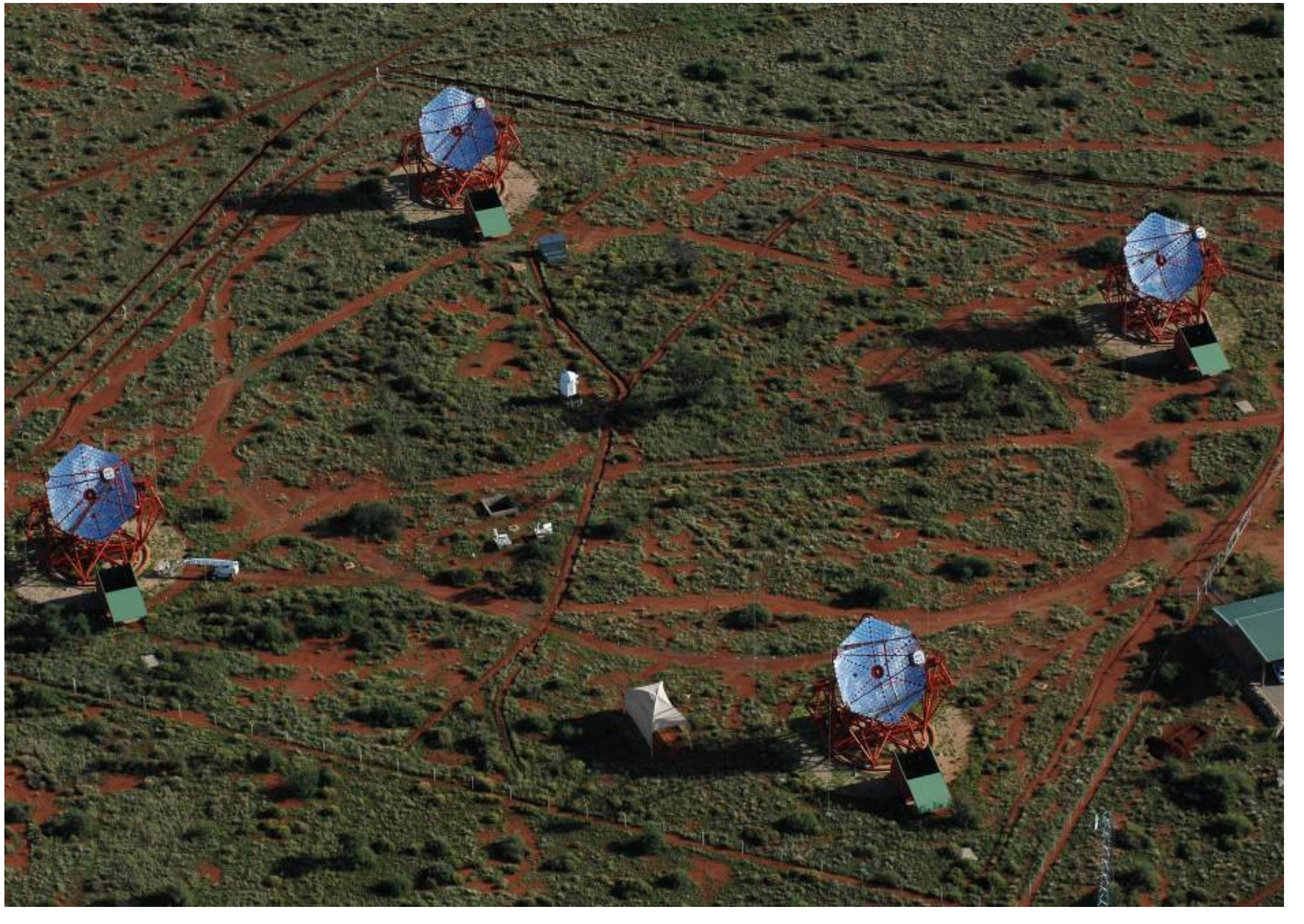


•HESS

•European Collaboration; M.P.I (Heidelberg)

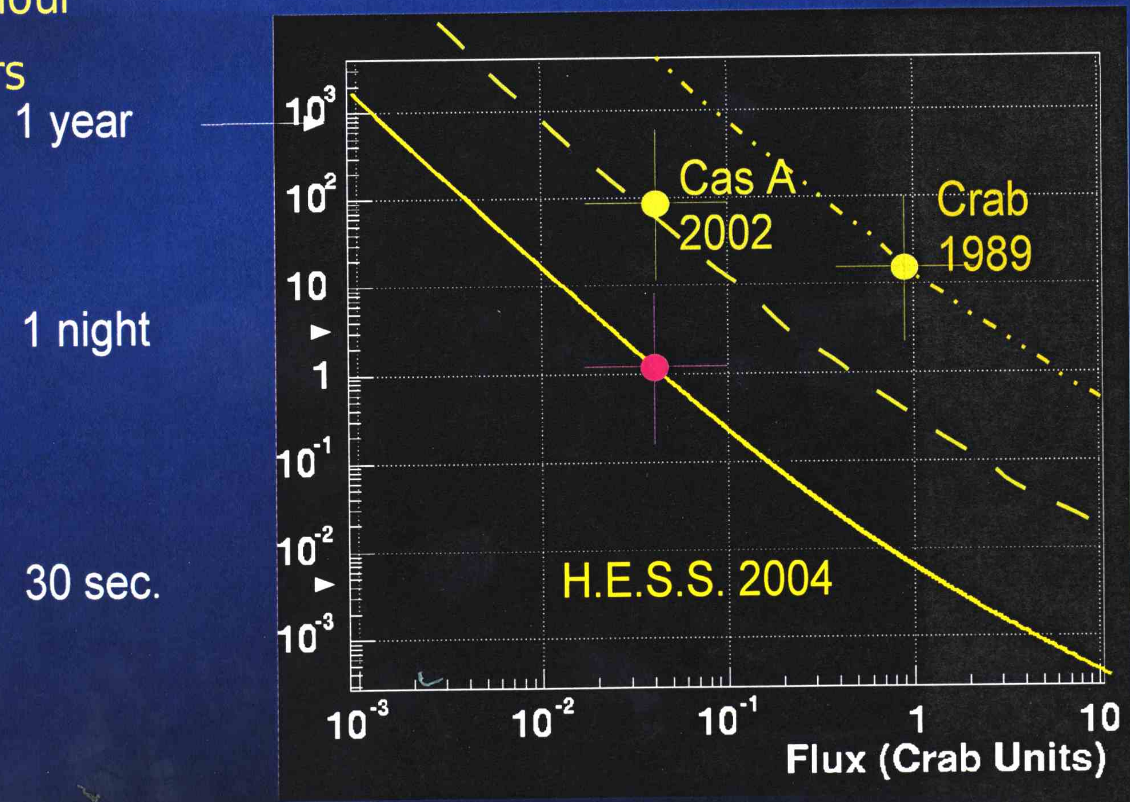
•4 x 12 m Telescopes

•Completed in Dec. 2003; located in NAMIBIA



H.E.S.S. Sensitivity

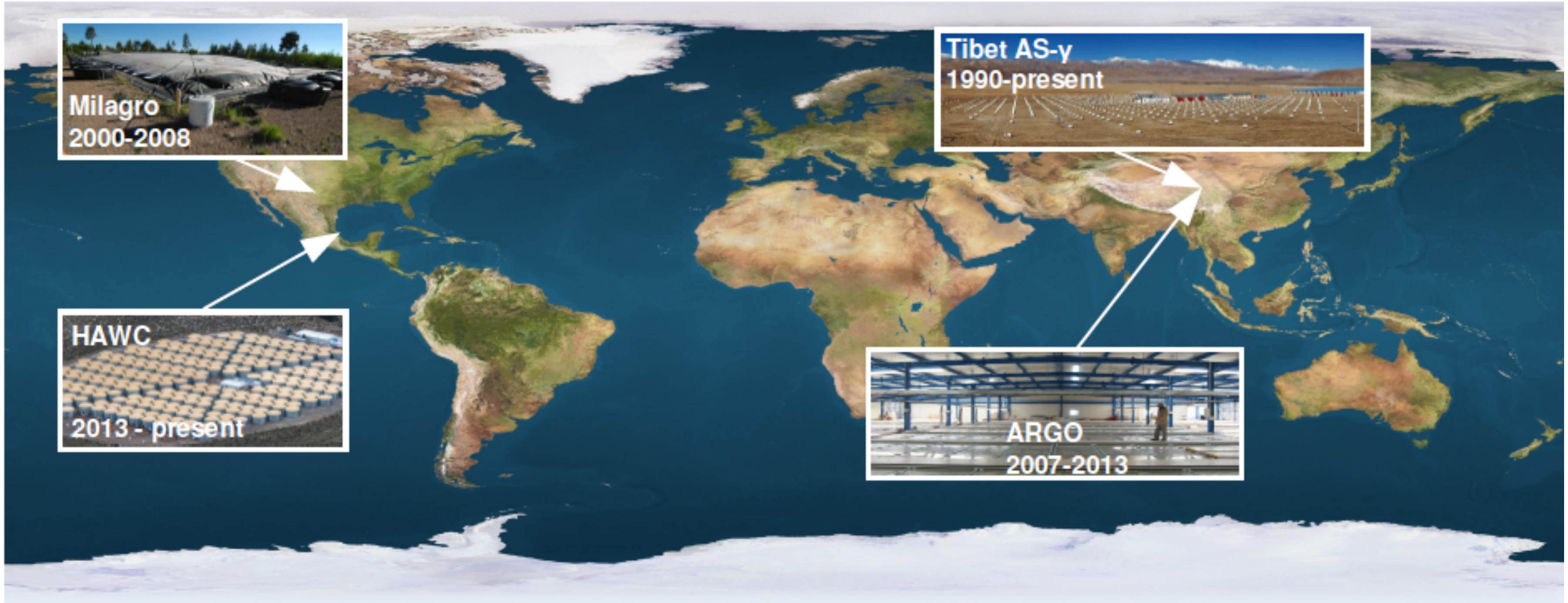
- HEGRA
  - 5% of Crab flux in 100 hours
- H.E.S.S.
  - 5% of Crab in 1 hour
  - 0.5% in 100 hours



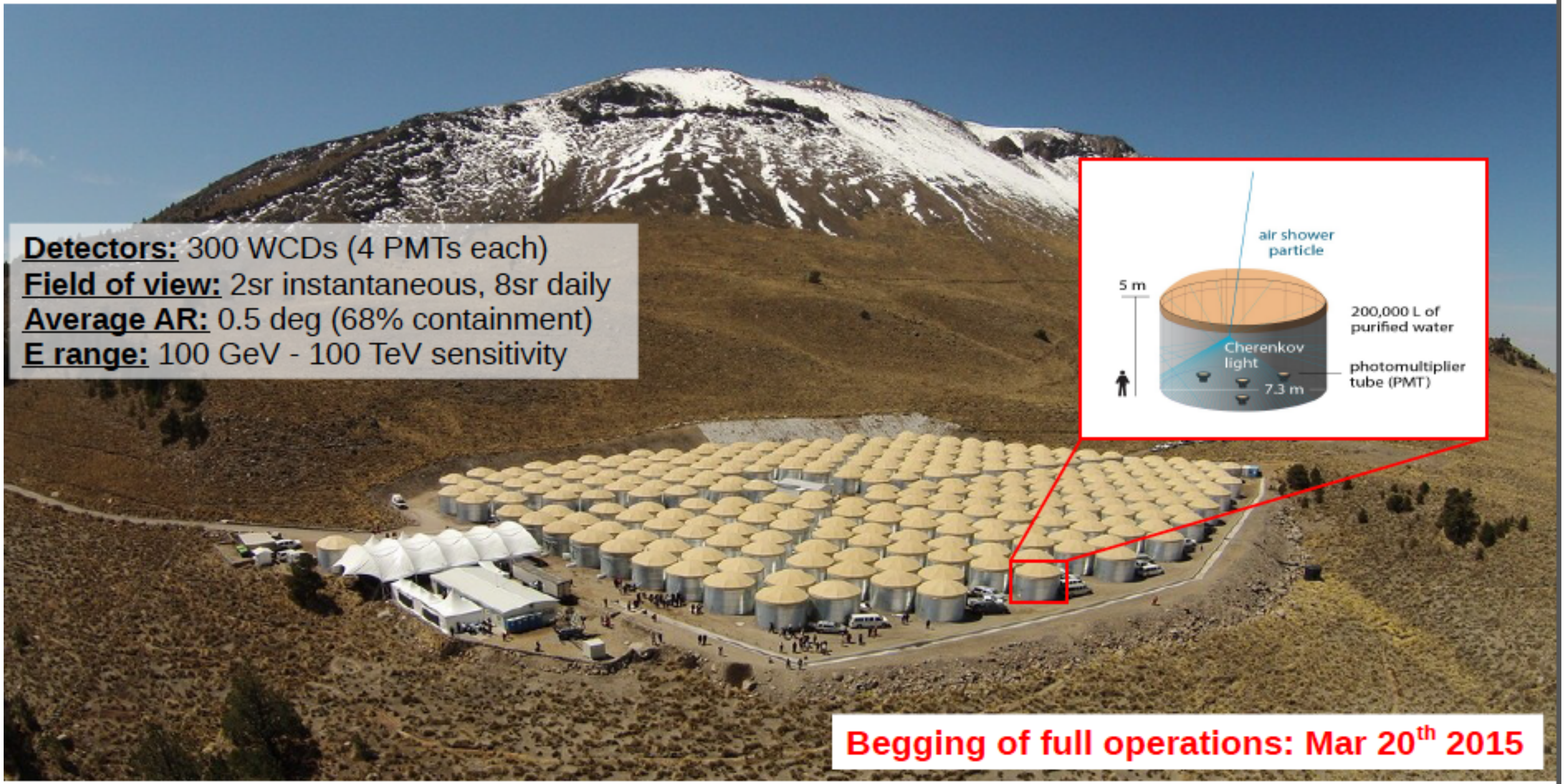
LAST
UCLA

EAS Detectors

- Several EAS arrays have been operational using different detection techniques.
- It is time for second generation experiments like HAWC.



HAWC Inauguration



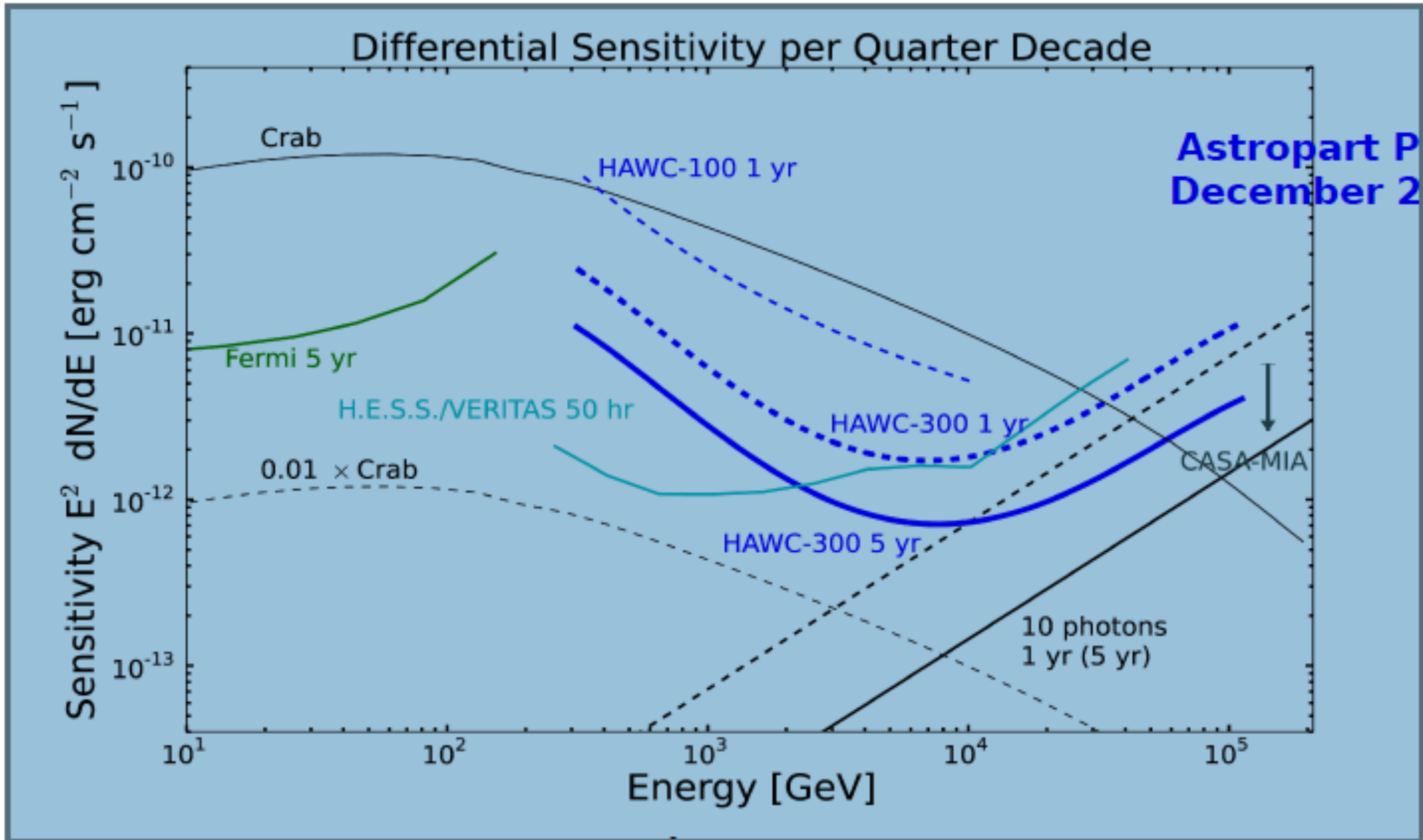
Detectors: 300 WCDs (4 PMTs each)
Field of view: 2sr instantaneous, 8sr daily
Average AR: 0.5 deg (68% containment)
E range: 100 GeV - 100 TeV sensitivity

Begging of full operations: Mar 20th 2015

HAWC Designed Sensitivity

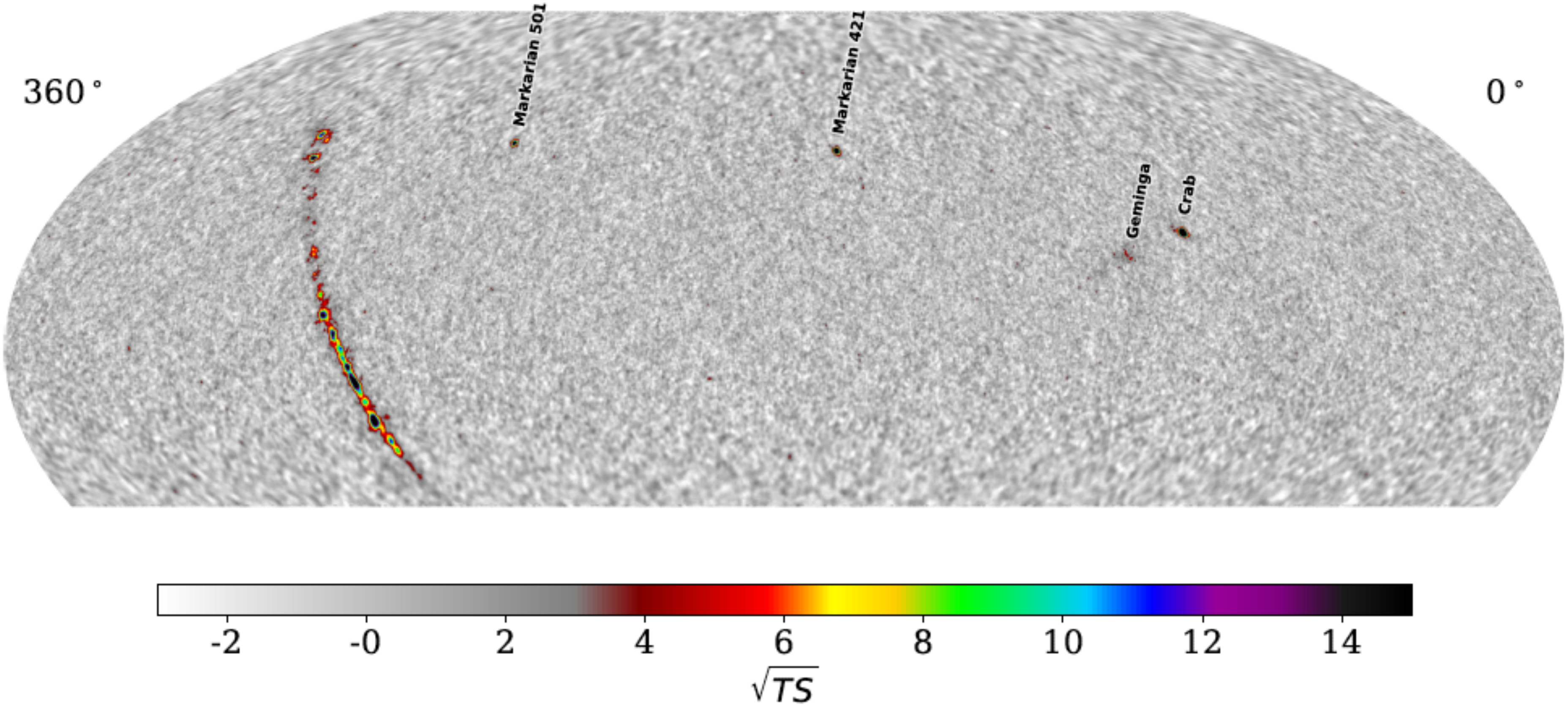
- Instantaneous sensitivity 15-20x less than IACTs.
- Exposure (sr/yr) is 2000-4000x higher than IACTs.

Survey > half the sky to:
40 mCrab [5σ] (1yr)
<20 mCrab [5σ] (5yr)

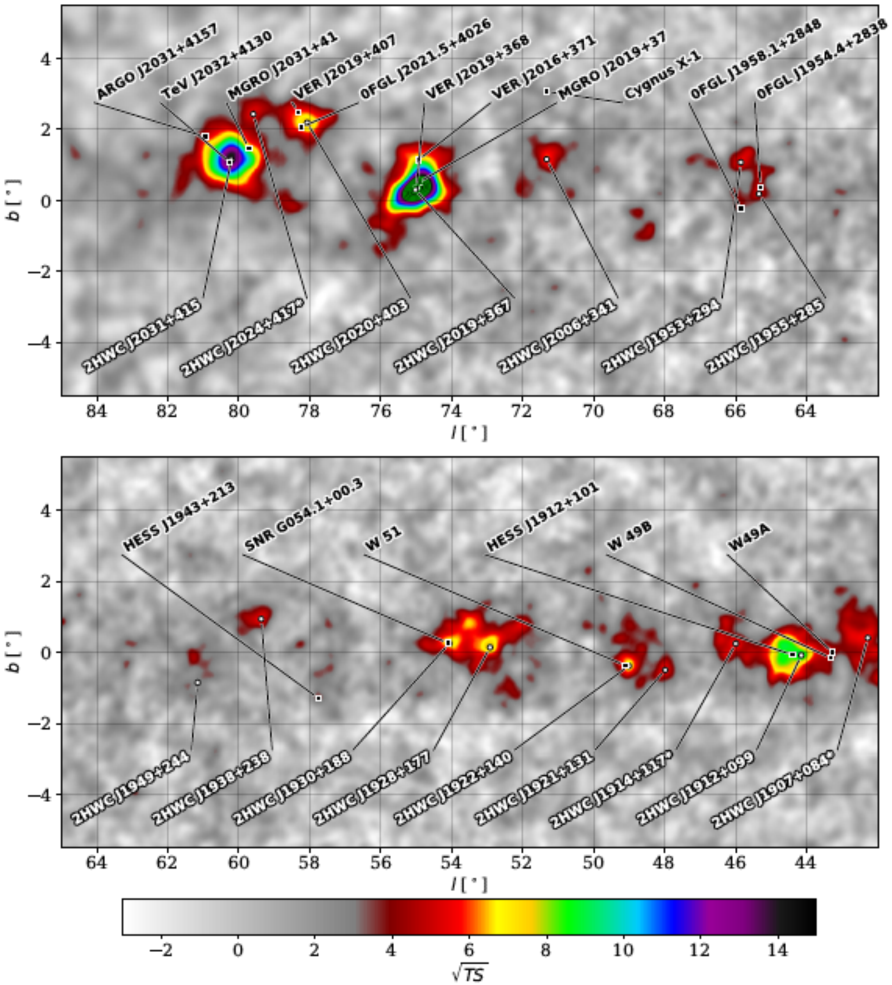


Astropart Phys 50-52, December 2013, 26-32

HAWC sky map


360°
0°
Markarian 501
Markarian 421
Geminga
Crab
-2
-0
2
4
6
8
10
12
14
$\sqrt{TS}$

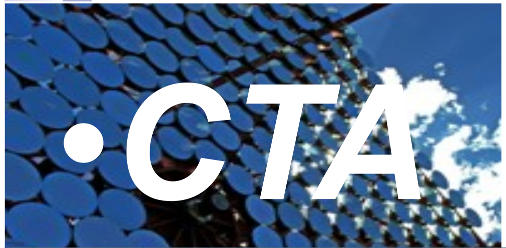
HAWC galactic plane



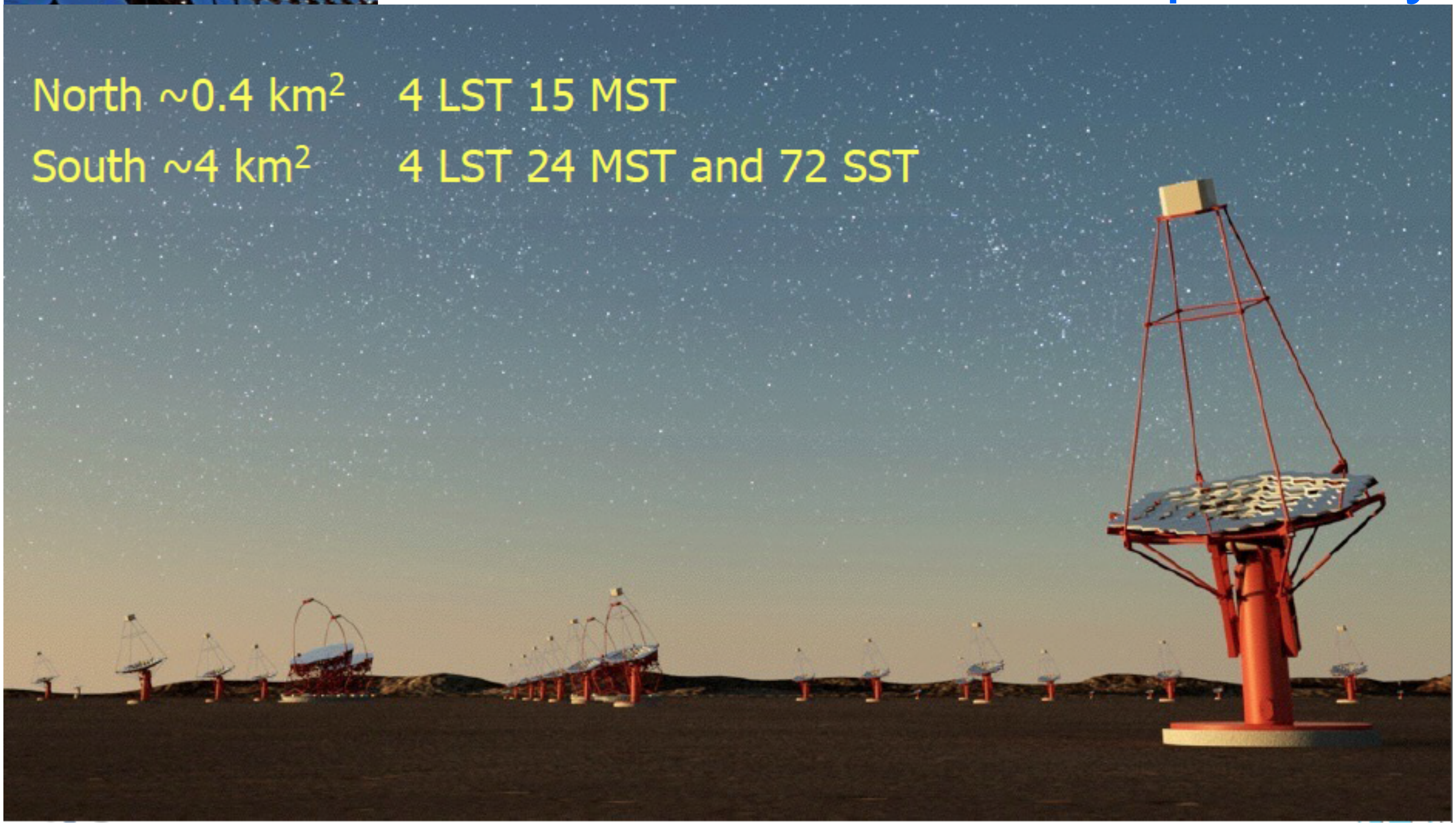
Future TeV telescopes

Wish list

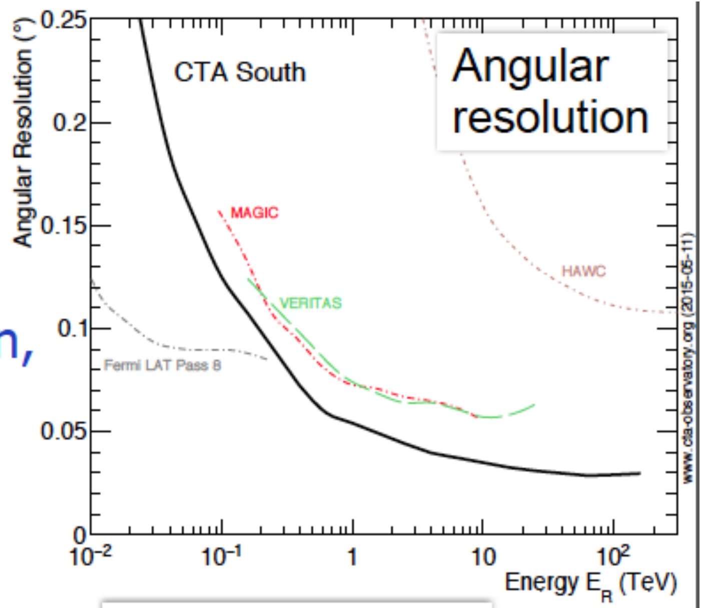
- Higher sensitivity at TeV energies (x 10)
  - more sources
- Lower threshold (some 10 GeV)
  - pulsars, distant AGN, source mechanisms
- Higher energy reach (PeV and beyond)
  - cutoff region of Galactic accelerators
- Wide field of view
  - extended sources, surveys
- Improved angular resolution
  - structure of extended sources
- Higher detection rates
  - transient phenomena



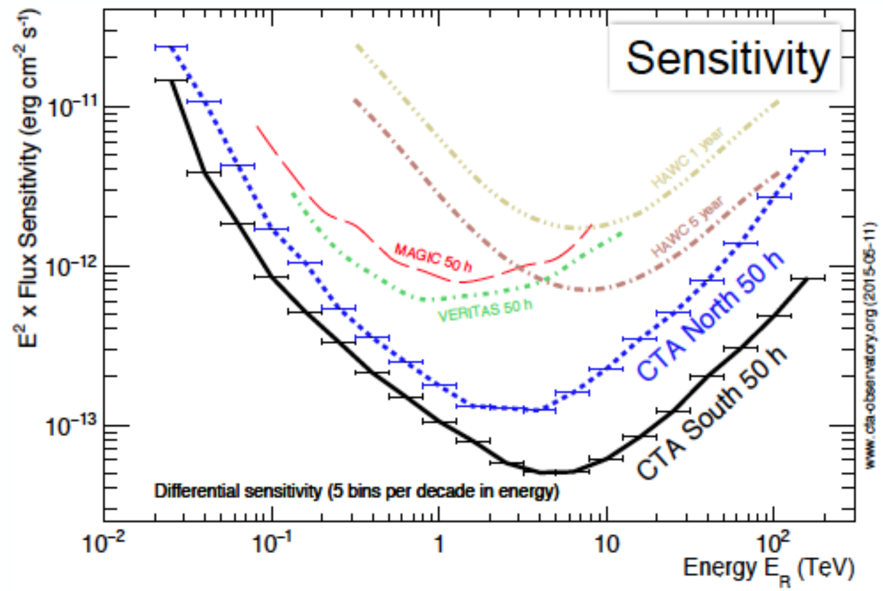
The Next Generation: The Cherenkov Telescope Array



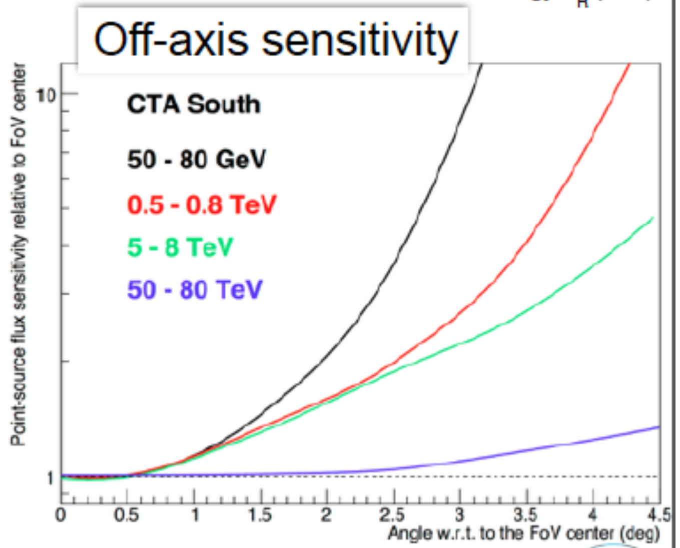
CTA Performance



> Result of large-scale simulations (900 telescopes for layout optimisation, CTA-GRID) and analysis



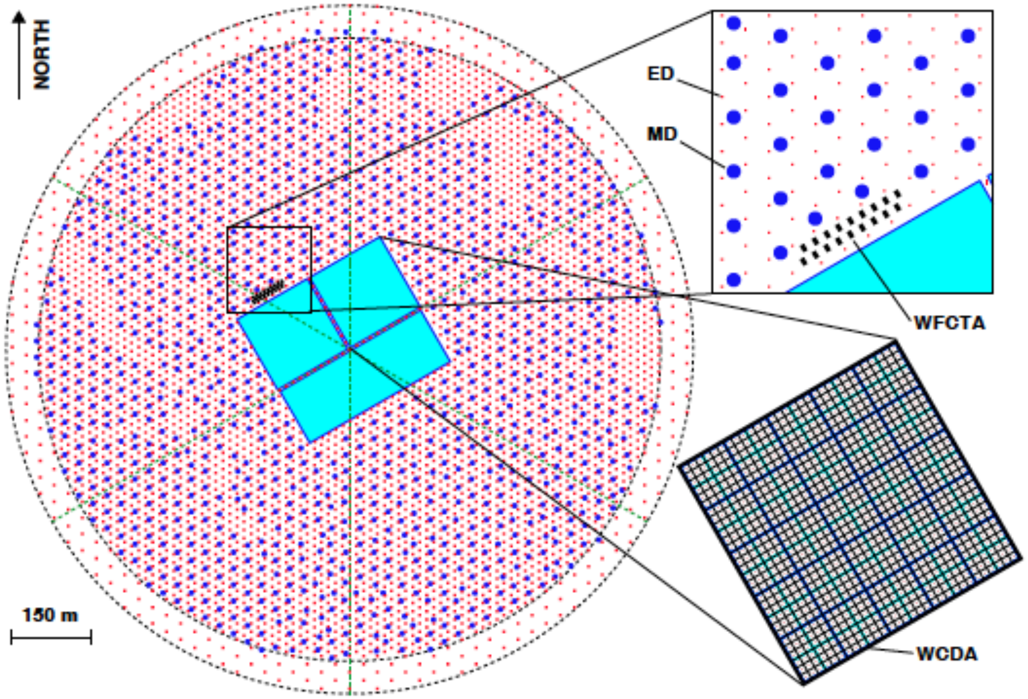
https://portal.cta-observatory.org/CTA_Observatory/performance/SitePages/Home.aspx



> MC Prod3 started recently – more realistic estimation of CTA performance

The LHAASO experiment

- 1 km^2 array, including 4941 scintillator detectors 1 m^2 each, with 15 m spacing.
- An overlapping 1 km^2 array of 1146, underground water Cherenkov tanks 36 m^2 each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m^2).



- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m^2.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.

Status of LHAASO

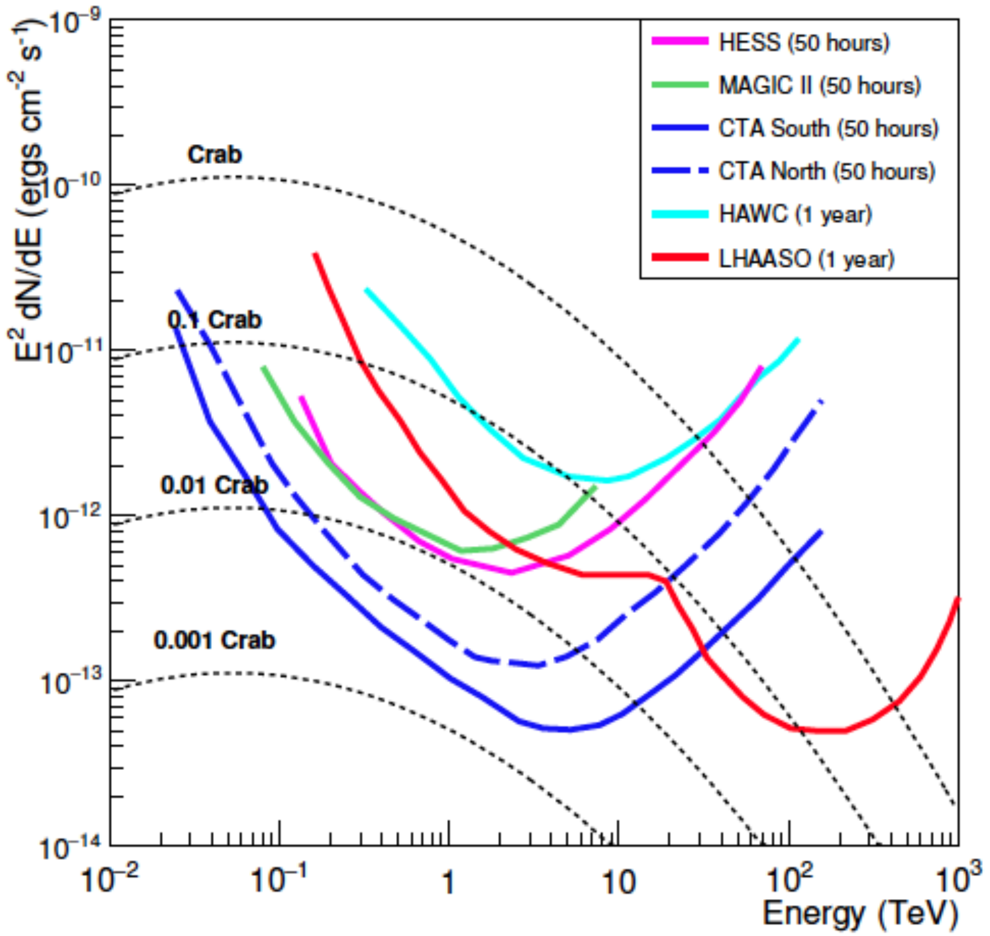
- LHAASO is finally approved and funded for detectors and infrastructures
- Construction of infrastructures started in July 2015.
- Installation of detectors started in September 2015 for tests.
- Spring 2016: Start of construction of the first water pond.

★ 2018: commissioning first pond and the first 25% of KM2A.

★ 2021: conclusion of installation of main components.

Construction of muon detectors

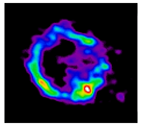
Sensitivity future detectors



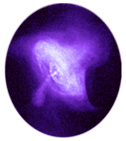
Overview of TeV gamma-ray Science

I. Astronomy and Astrophysics

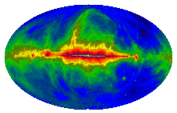
A. Galactic sources



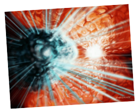
- **Shell-type Supernova Remnants**



- **Pulsar wind nebula**
- **Binary systems**
- **Microquasars**
- **Central black hole**



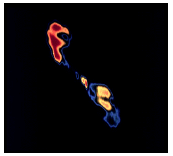
- **Galactic Diffuse Emission**



- **Galactic Cosmic Ray Origin**
- **Dark sources**

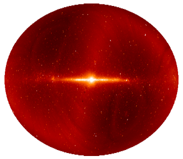
Overview of gamma-ray Science

B. Extra Galactic sources

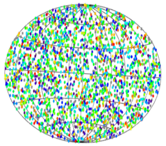


Radio galaxies

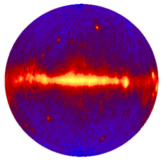
- **Blazars**



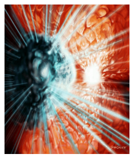
- **Extragalactic Background Light**



- **Gamma Ray Bursts**



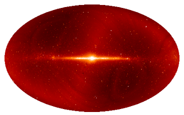
- **Unidentified Sources**



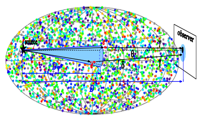
- **Ultra-High Energy Cosmic Ray Origin**

Overview of gamma-ray Science

Cosmology

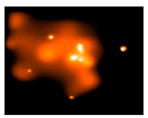


- **Extragalactic Background Light**
- **Primordial magnetic field**

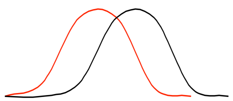


- **Distant Gamma Ray Bursts (GeV)**

Particle physics



- **Dark Matter**

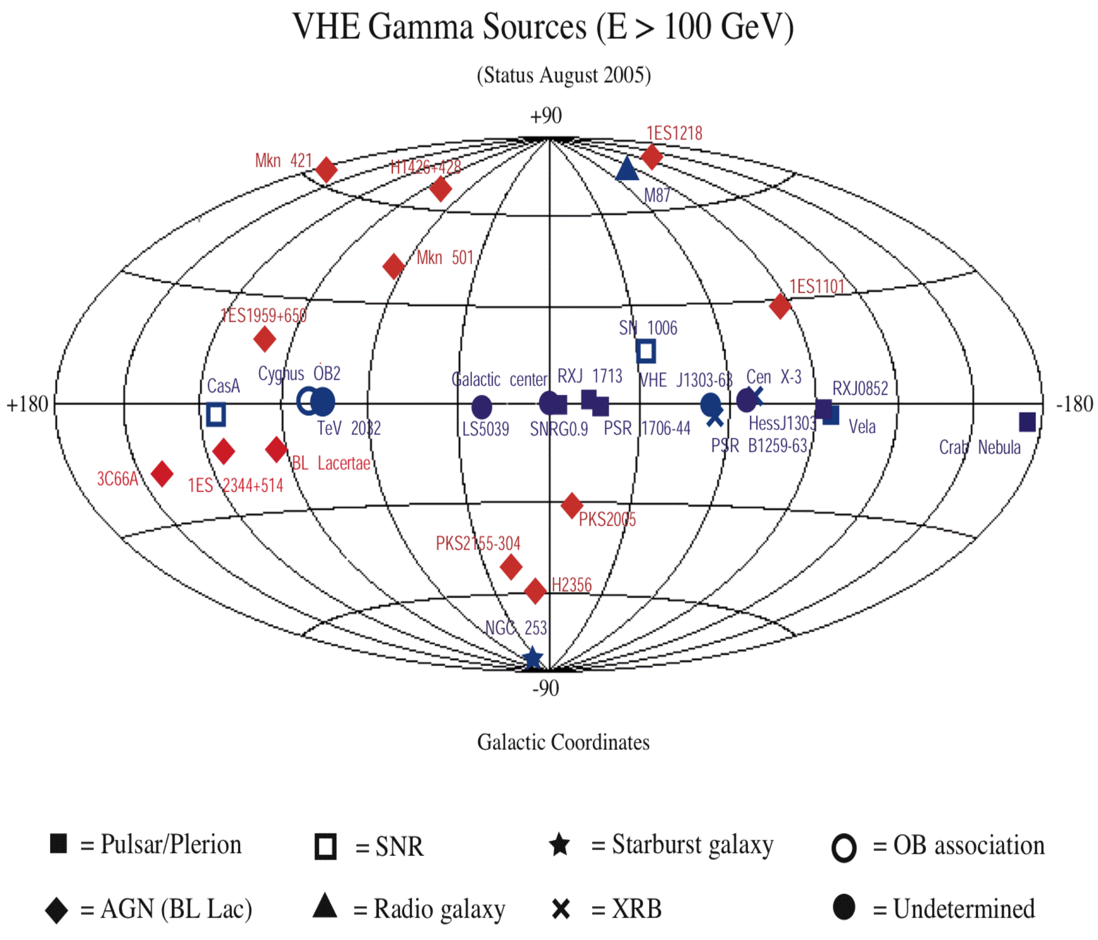


- **Lorentz symmetry violation**

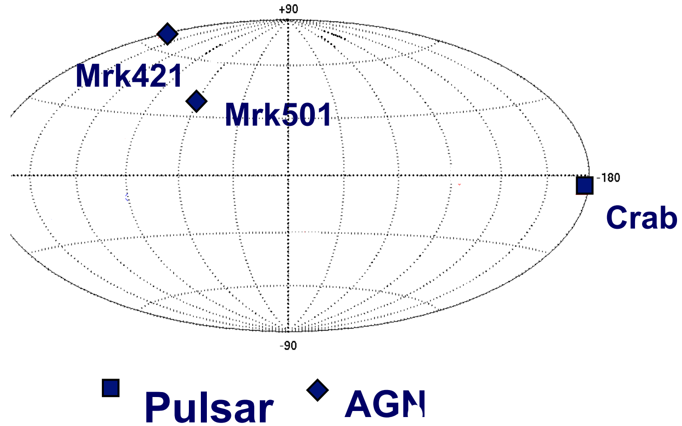
Gamma-ray sky

The VHE γ ray sky

2005

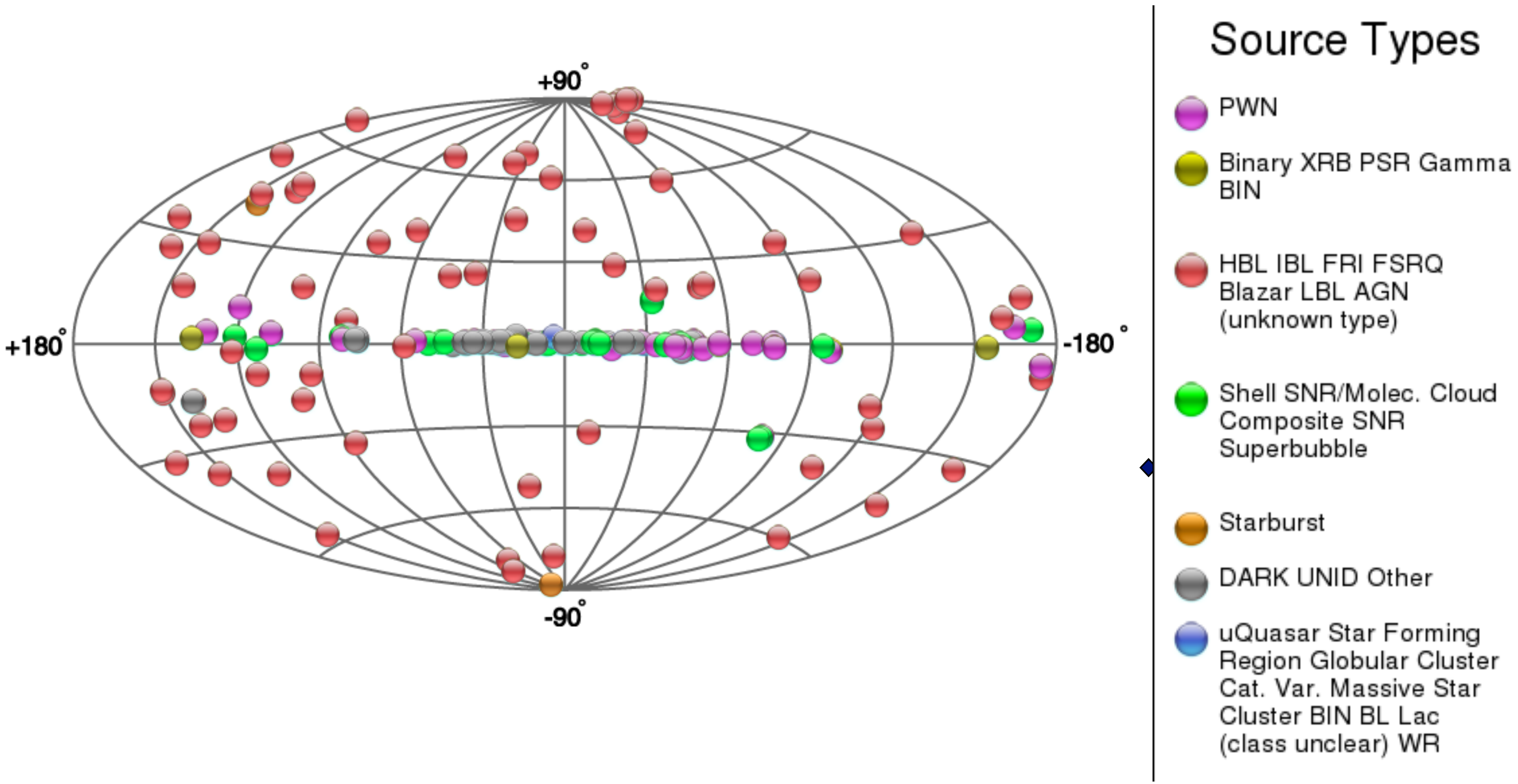


1995



The VHE γ ray sky Dec 2015

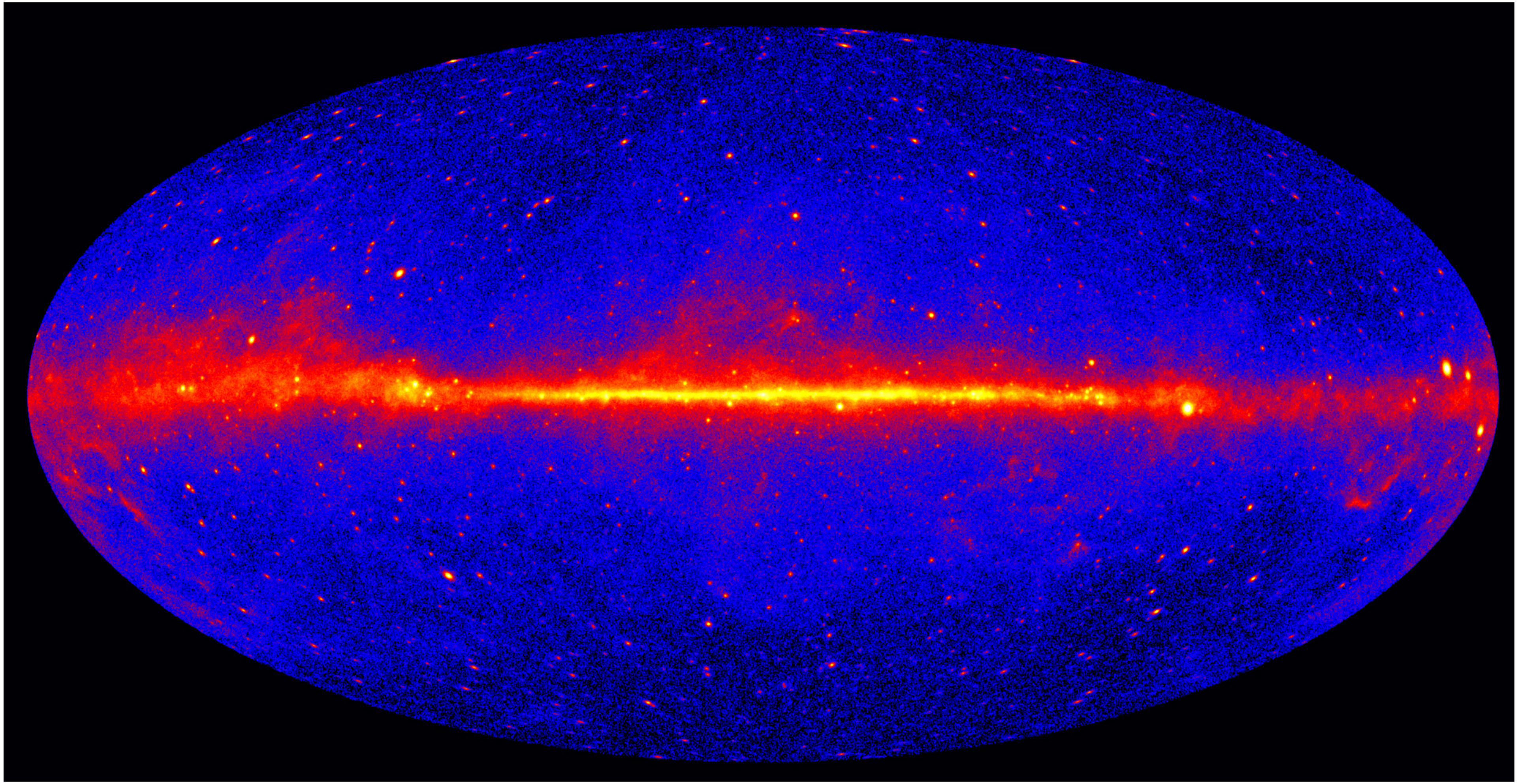
176 sources



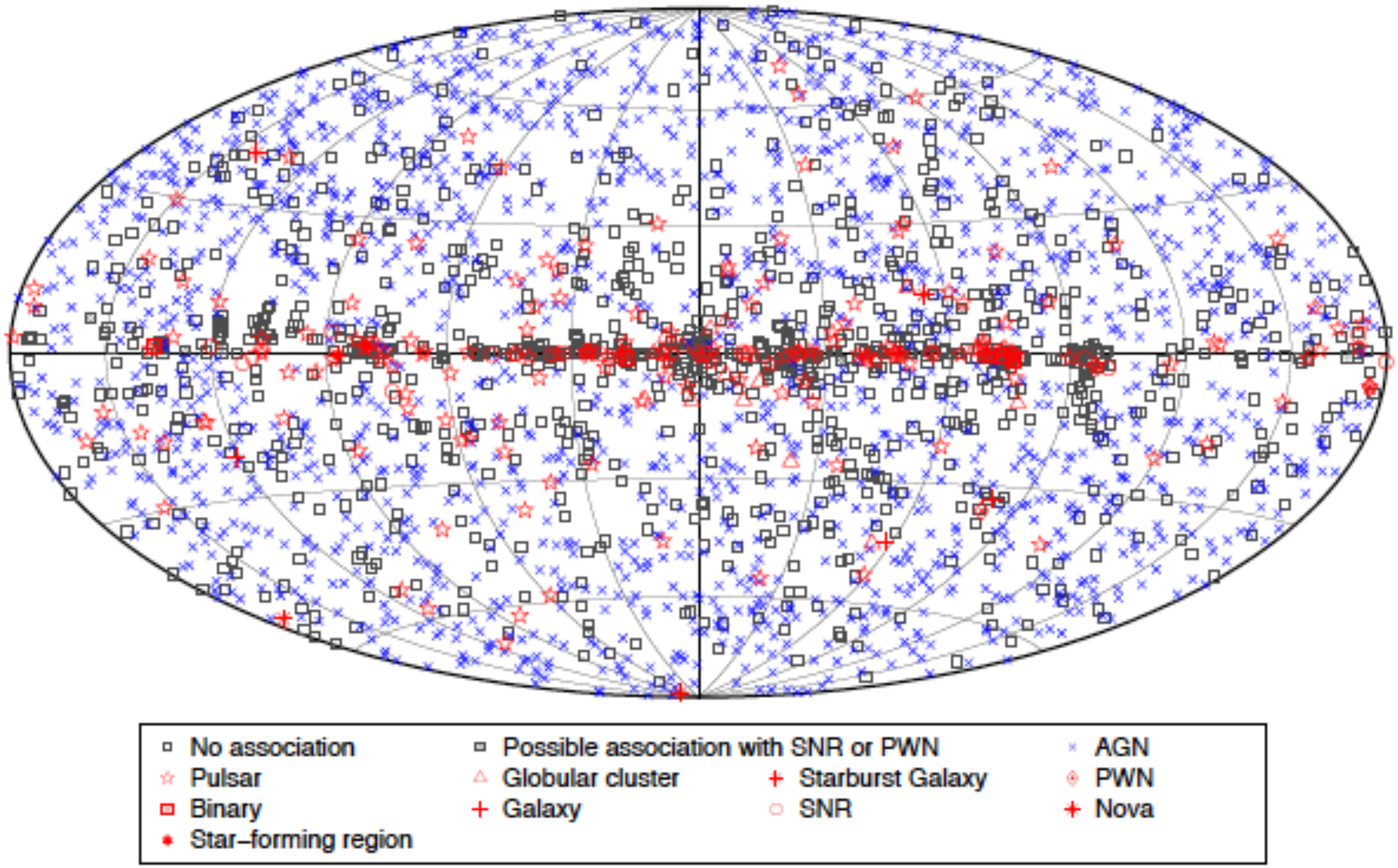
Source Counts

Source Type*	1995	2005	2015
Pulsar Wind Nebula (e.g. Crab, MSH 15-52 …)	1	5	37
Supernova Remnants (e.g. Cas-A, RXJ 1713 …)	0	4	15
Binary systems (B1259-63 etc)	0	1	6
X-ray binary	0	0	4
Galactic Center	0	1	1
Superbubble	0	1	2
Star clusters	0	0	4
Molecular clouds	0	0	2
BL LACs (e.g. Mkn 421, PKS 2155 …)	2	9	55
FSRQ	0	0	5
AGNs (M87, Cen A	0	1	4
Unidentified	0	6	42
TOTAL	[illegible]	[illegible]	[illegible]

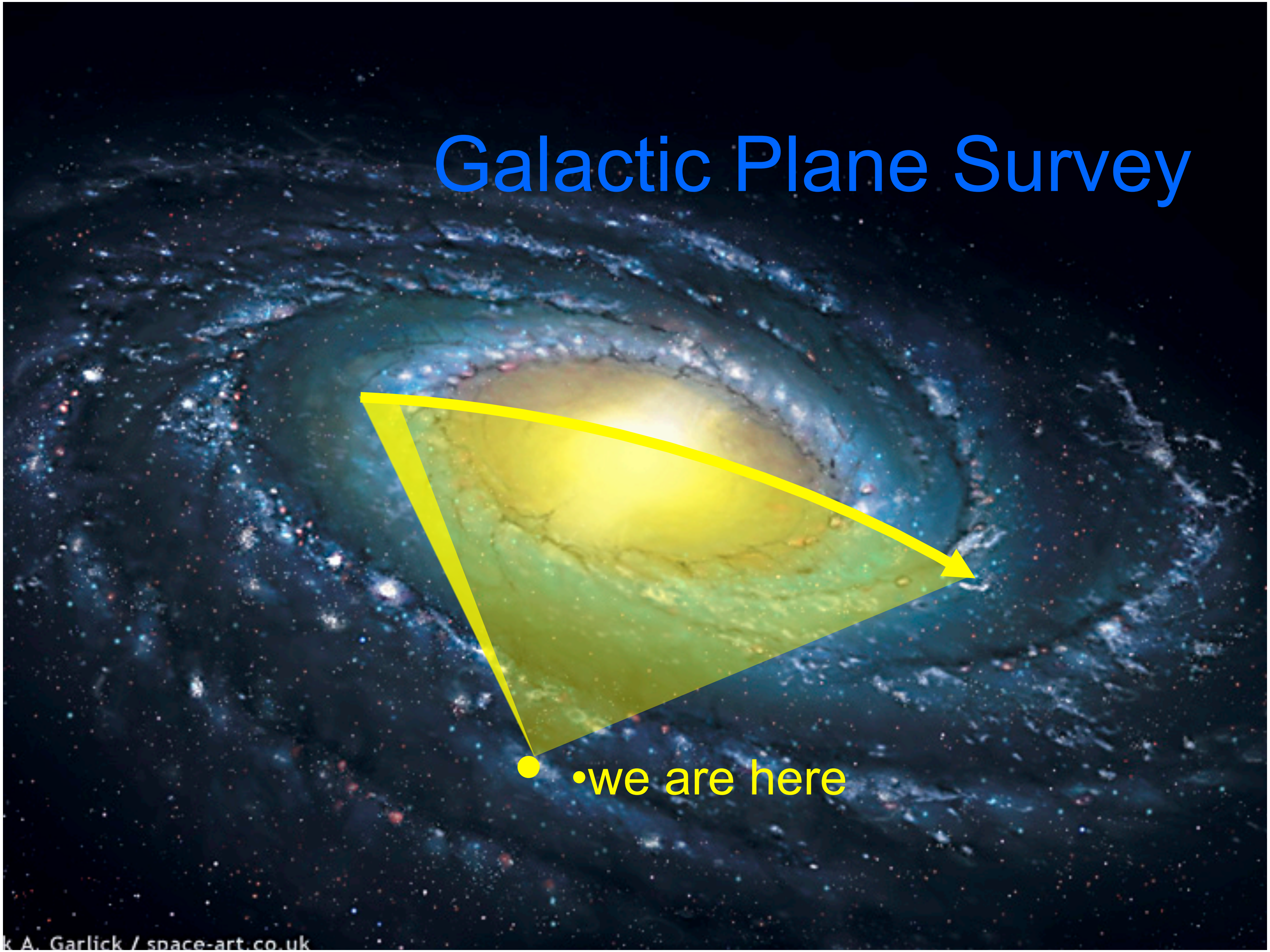
Fermi LAT 5 years all sky 1GeV



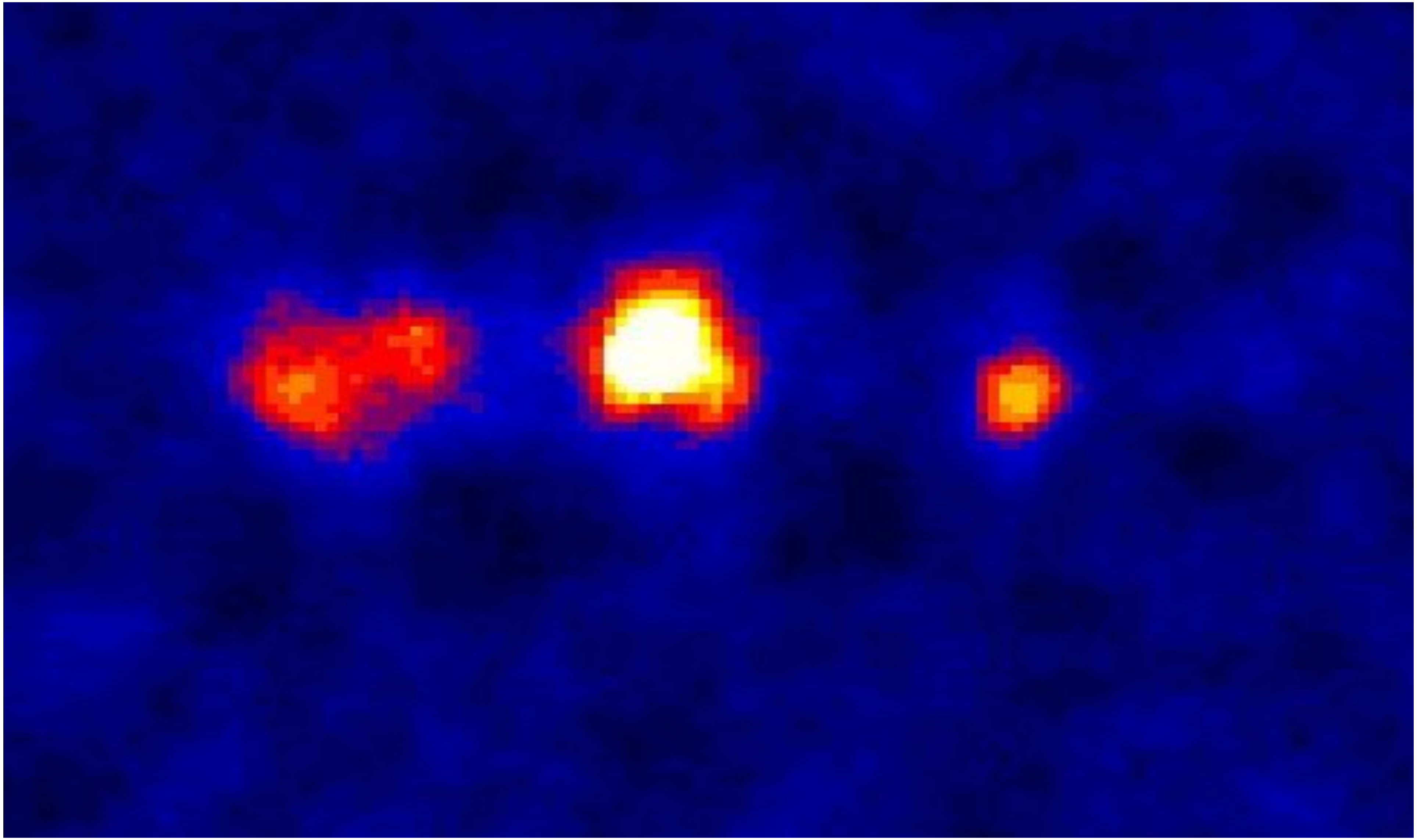
Fermi LAT source catalog: 3000 sources



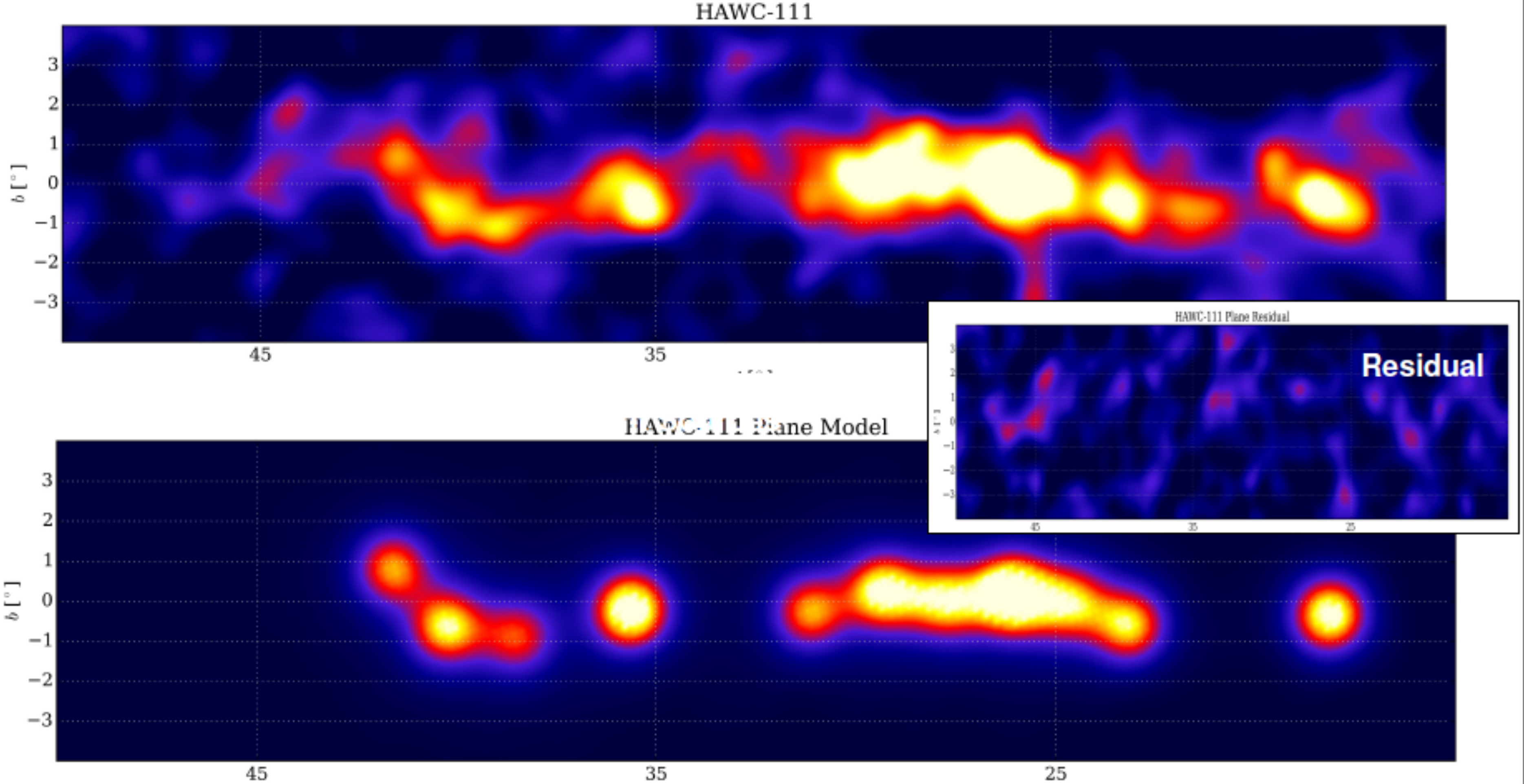
Galactic sources


Galactic Plane Survey
•we are here
k A. Garlick / space-art.co.uk

H.E.S.S Galactic Plane Survey

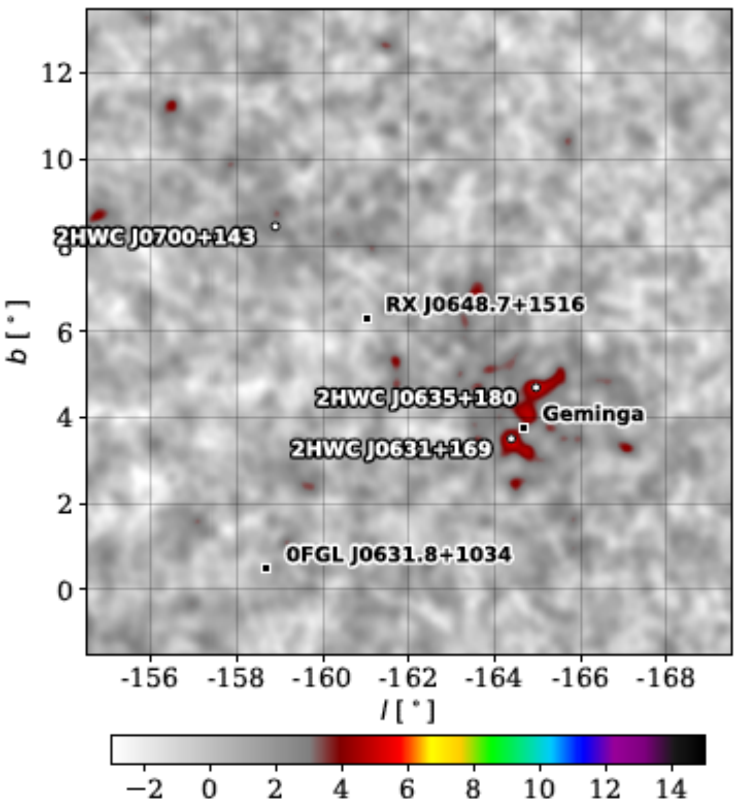


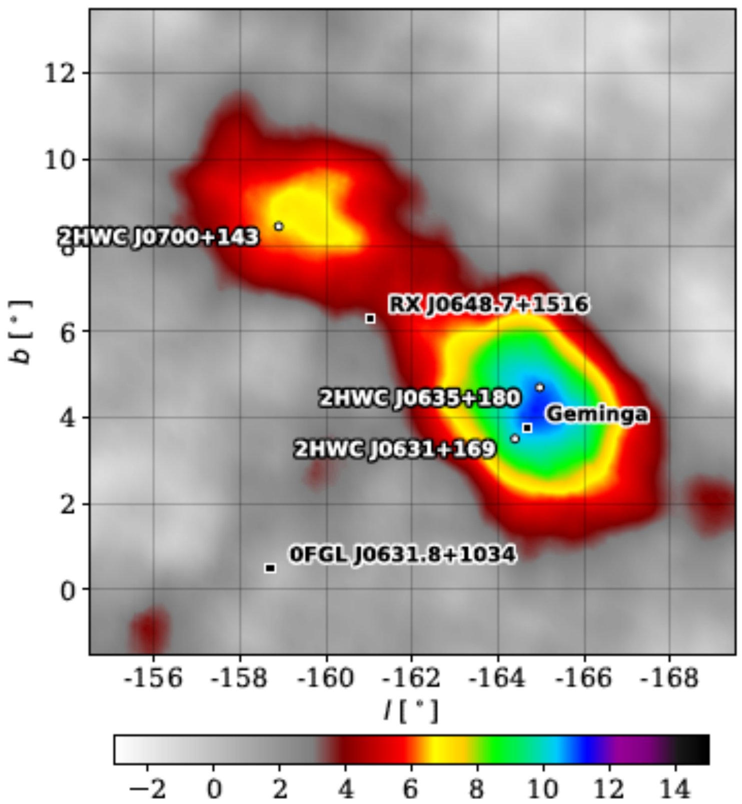
HAWC GP Survey



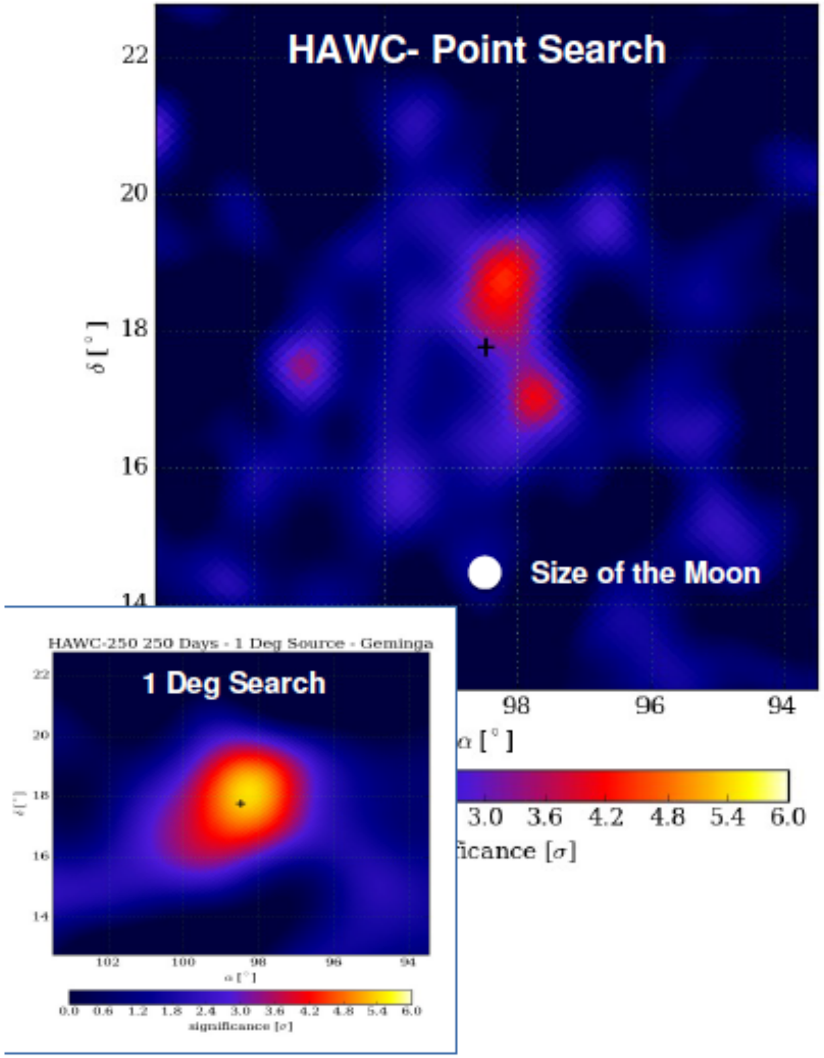
- 10 sources/candidates are >3σ post-trial: 3 firm detections (>5σ) and 7 candidates (<5σ).

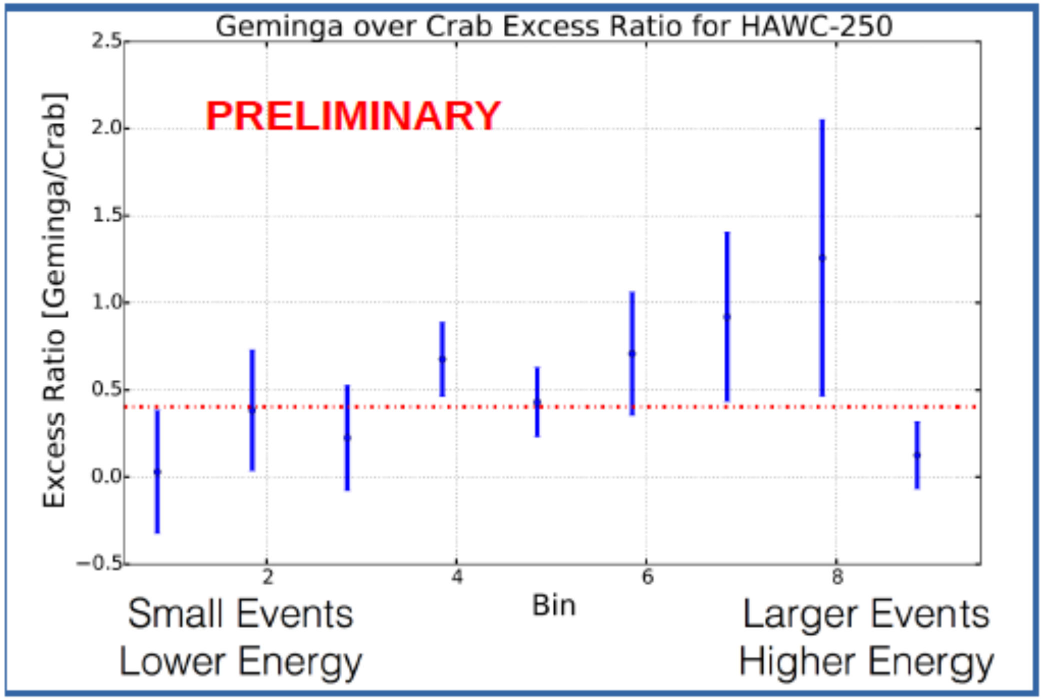
HAWC Geminga SN





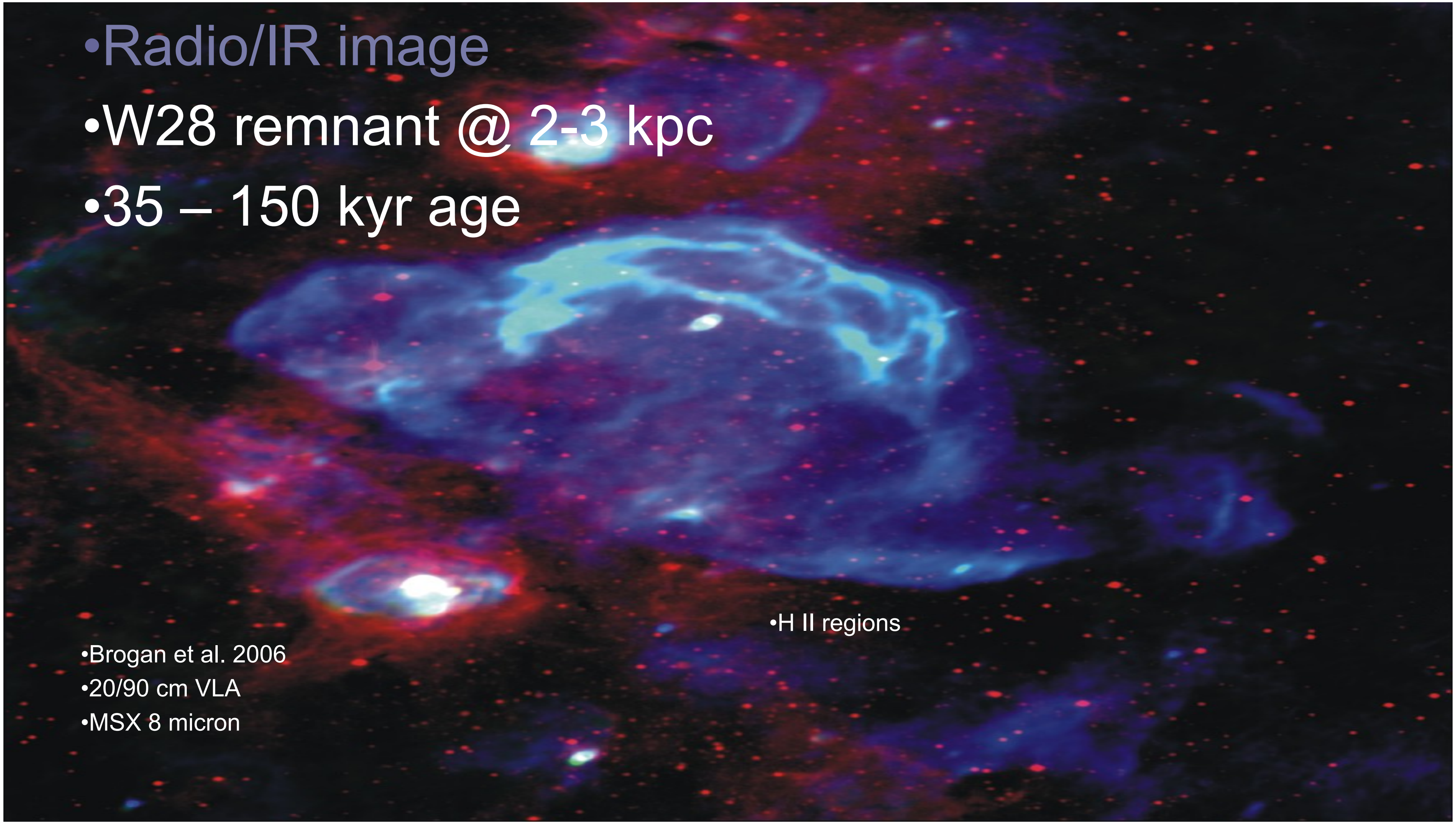
Geminga

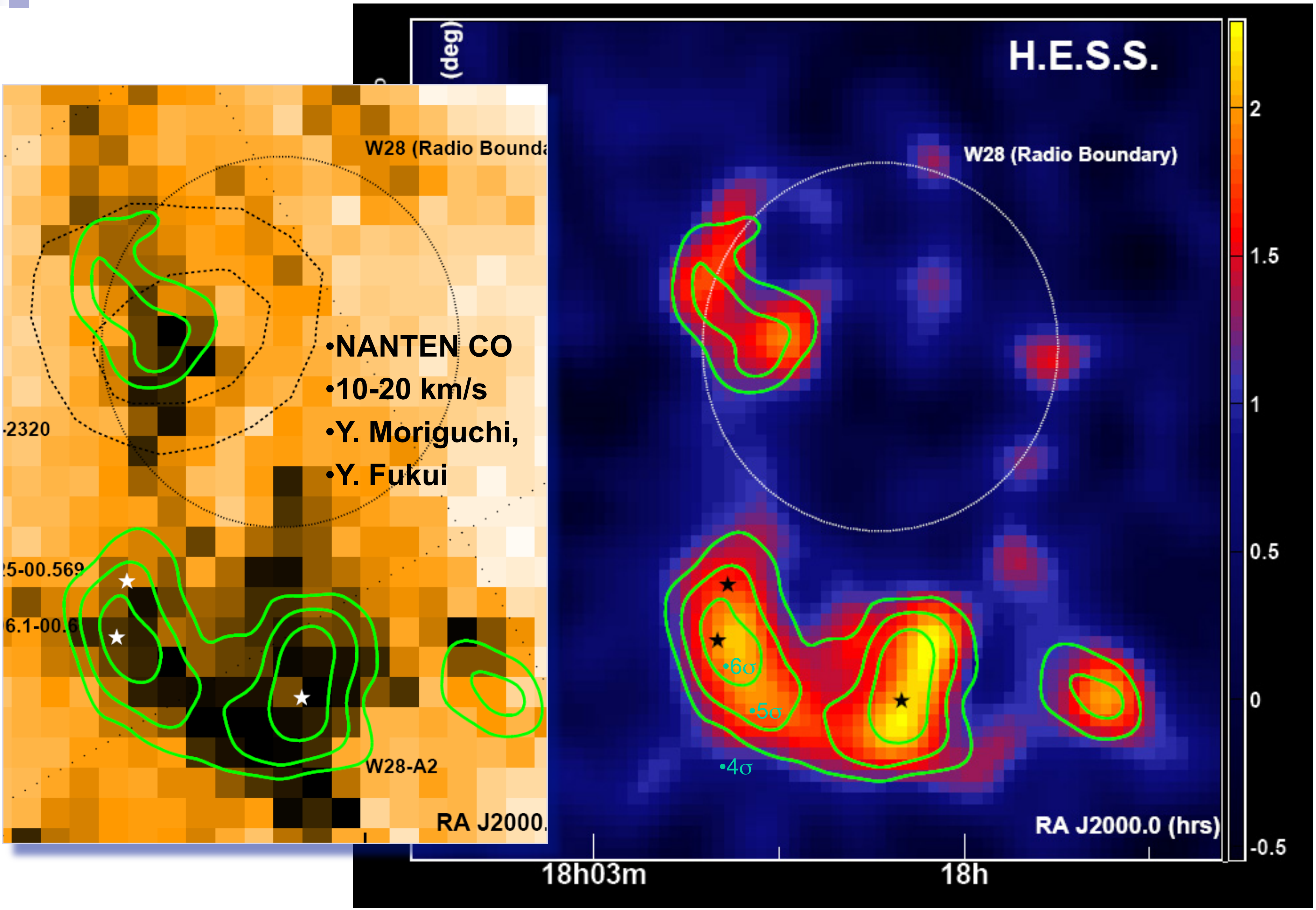




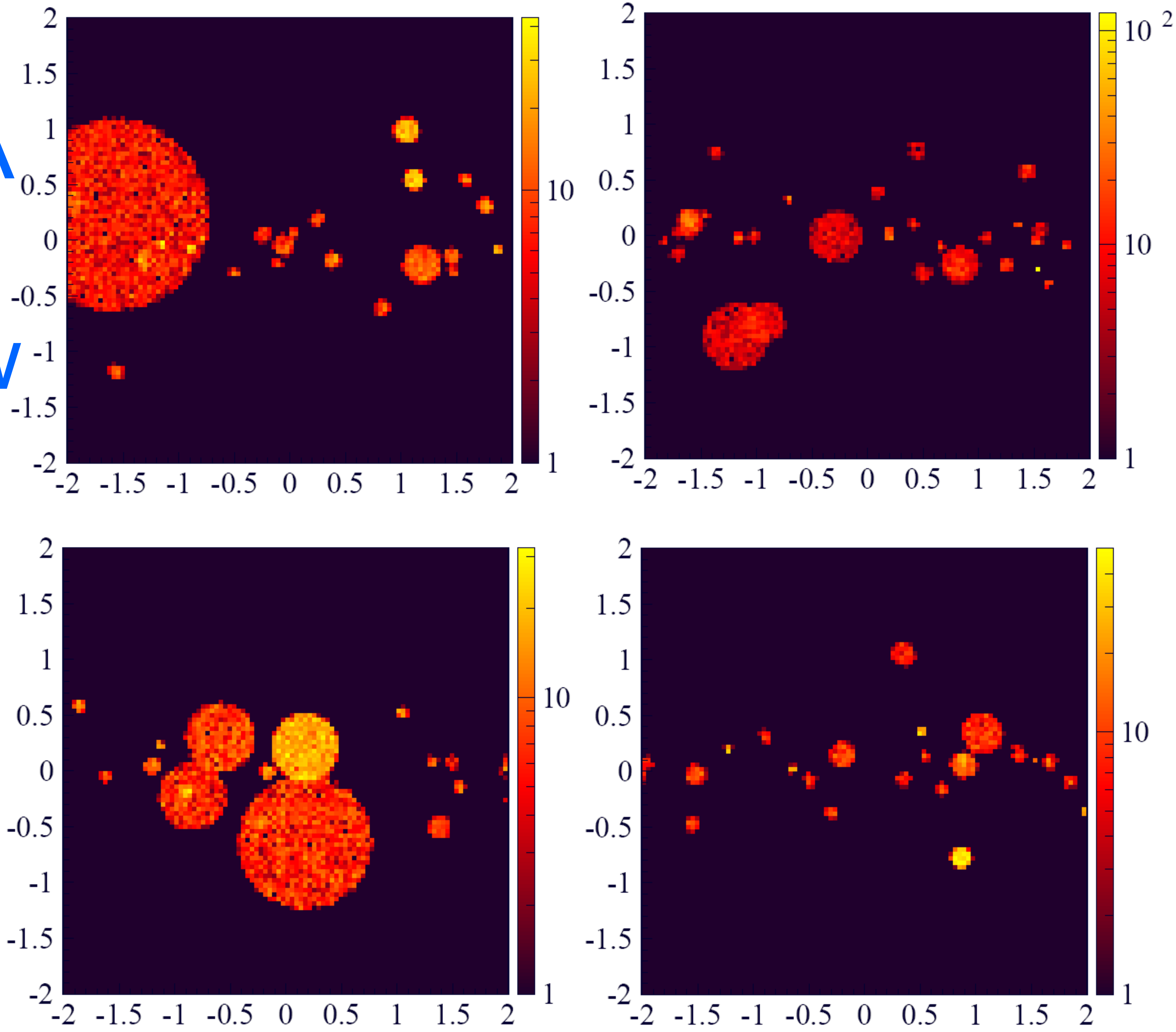
- Detected in HAWC (Pass 3) at ~6σ using a 3 deg search.
- Looks harder than the Crab.
- Analysis in progress.

Old SNRs & interacting SNRs




•NANTEN CO
•10-20 km/s
•Y. Moriguchi,
•Y. Fukui
W28 (Radio Bounda
-2320
5-00.569
6.1-00.6
W28-A2
RA J2000.
H.E.S.S.
W28 (Radio Boundary)
•6σ
•5σ
•4σ
RA J2000.0 (hrs)
18h03m
18h
2
1.5
1
0.5
0
-0.5

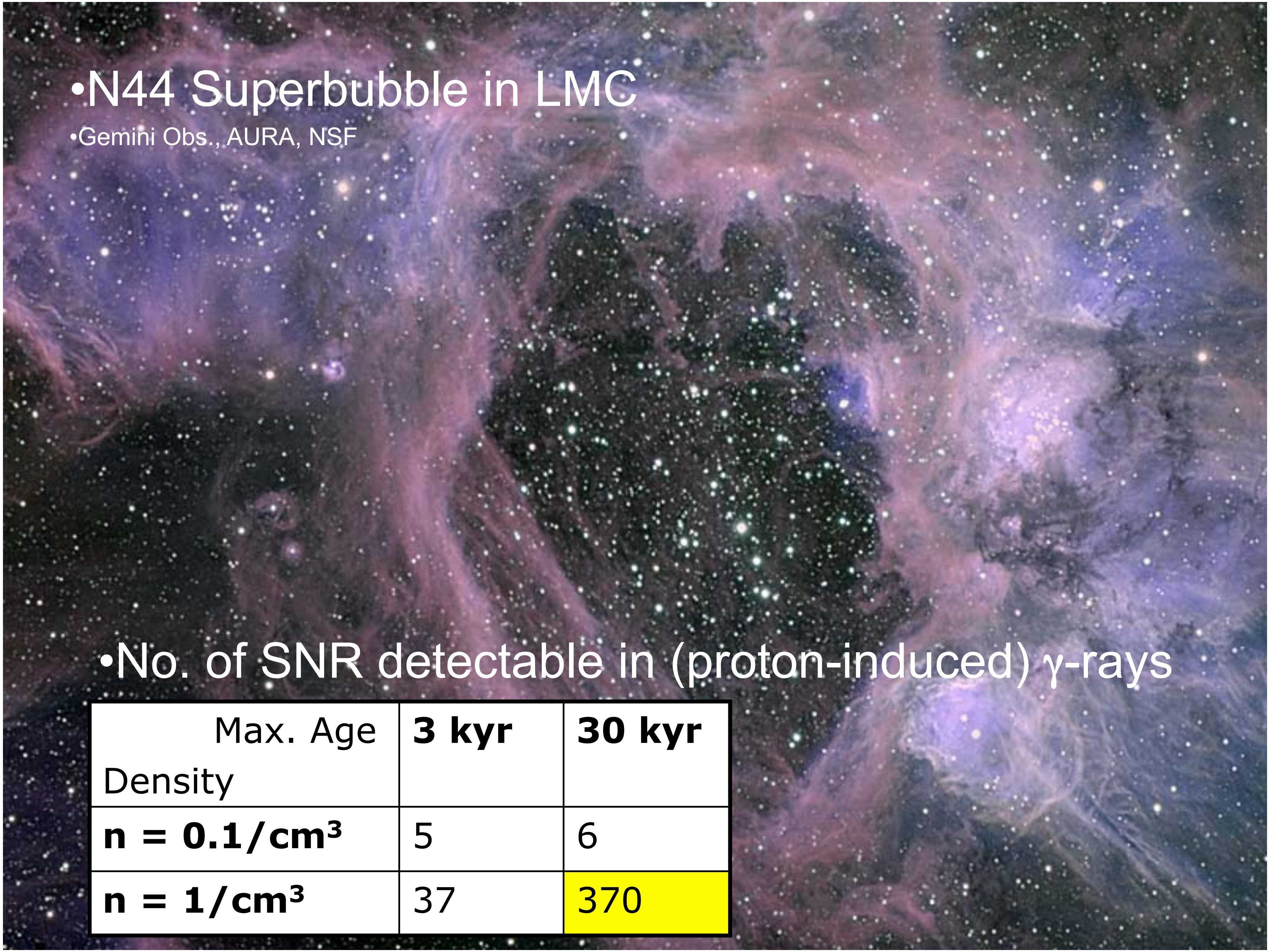
A CTA field of view



- SNR models
- using DAV 9
- n = 1
- ε = 0.1

- (consistent
- with HESS
- plane scan)

- assuming
- 1 mCrab

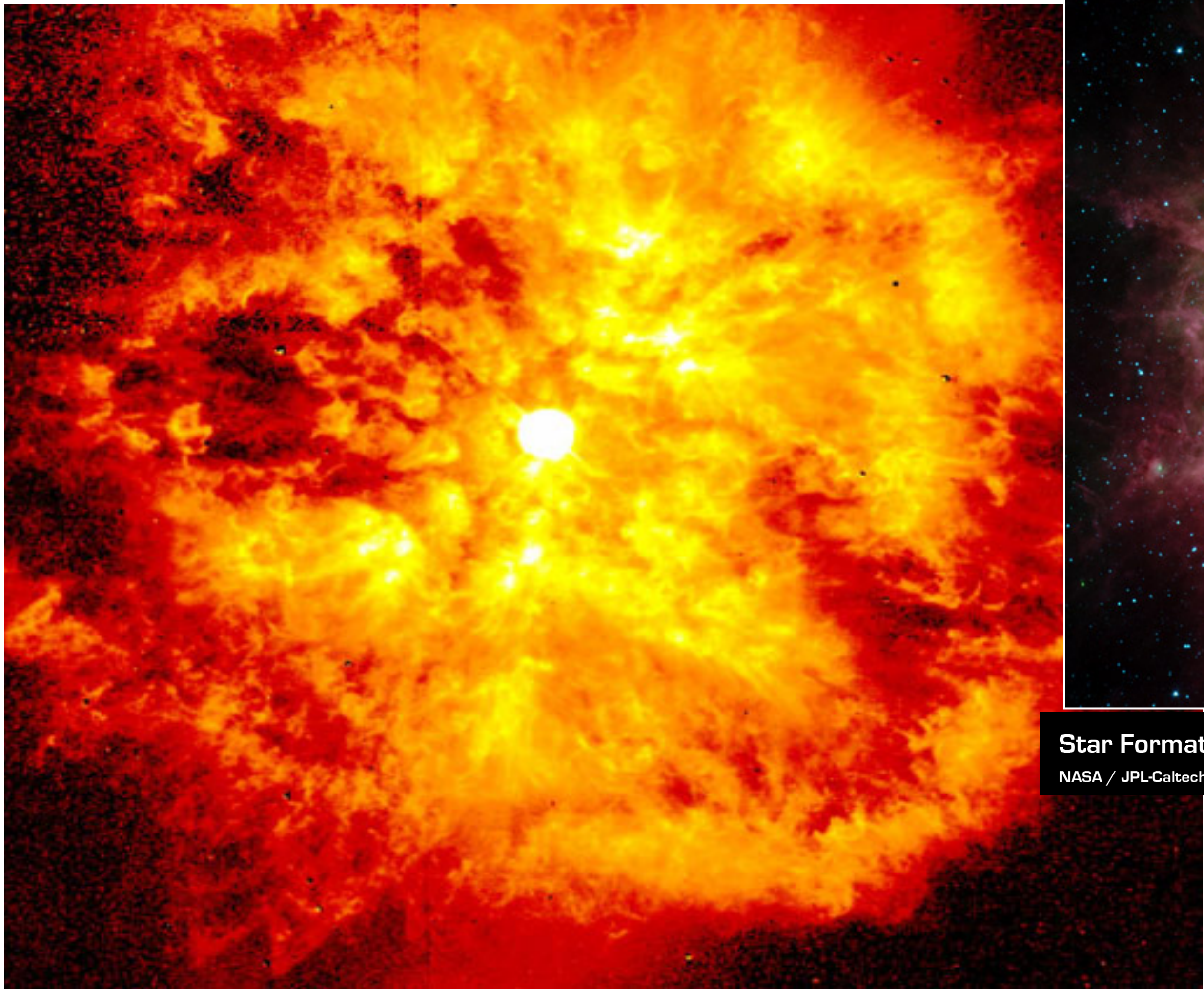


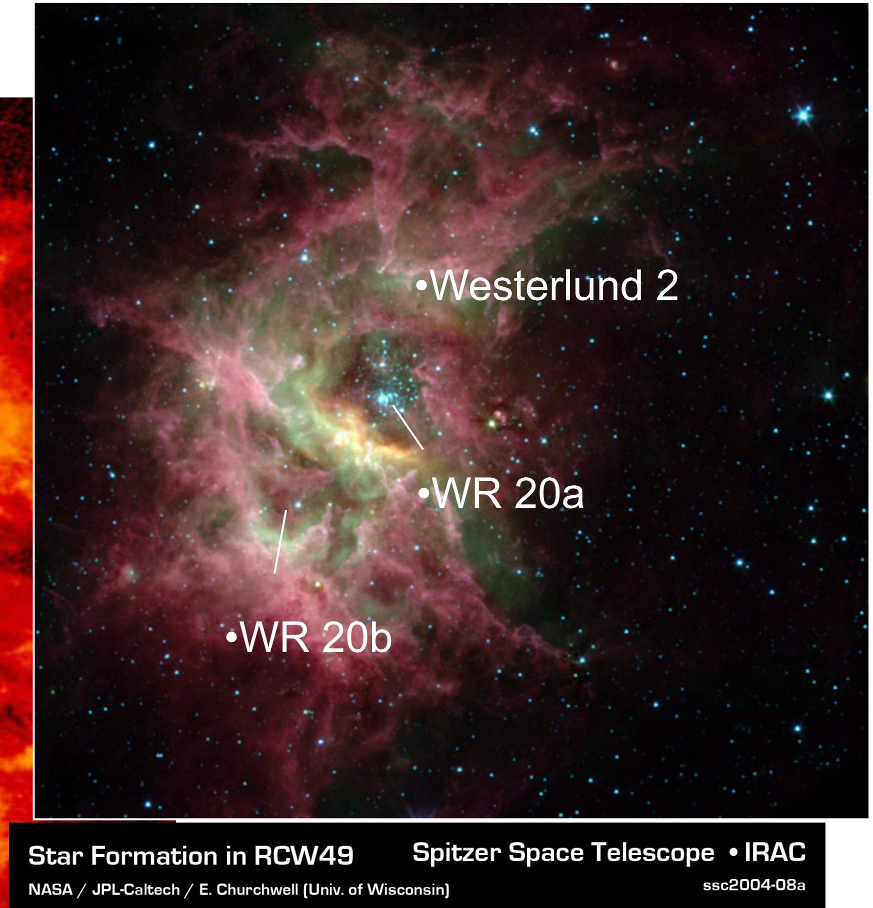
- N44 Superbubble in LMC
  - Gemini Obs., AURA, NSF

- No. of SNR detectable in (proton-induced) γ-rays

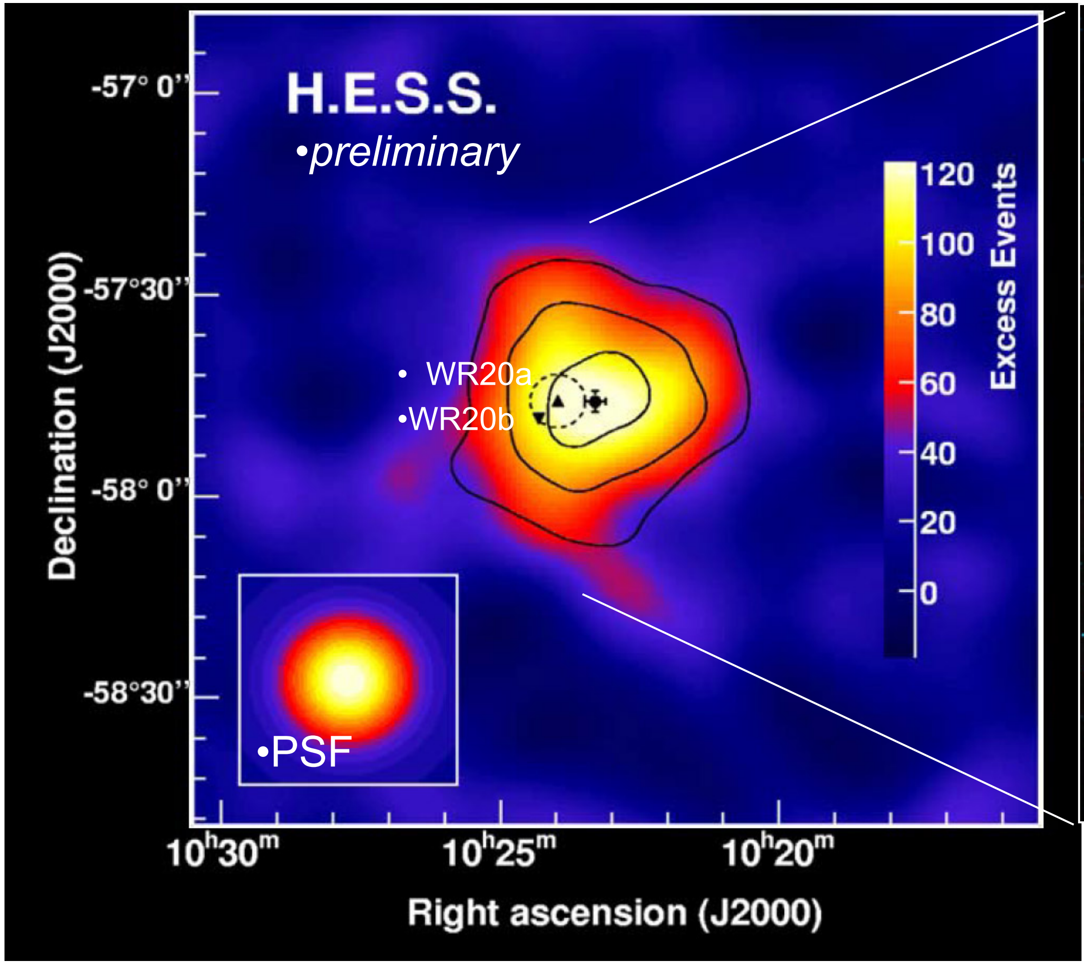
Max. Age / Density	**3 kyr**	**30 kyr**
n = 0.1/cm³	5	6
n = 1/cm³	37	370

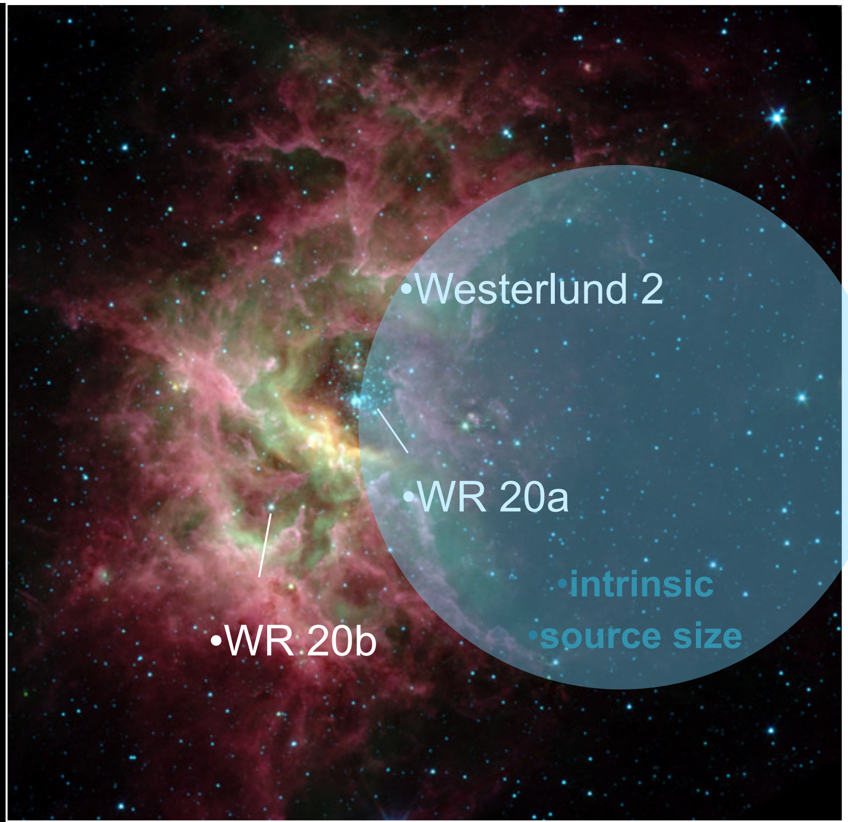
RCW 49:
Stellar Winds as Cosmic Accelerators





HESS J1023-575

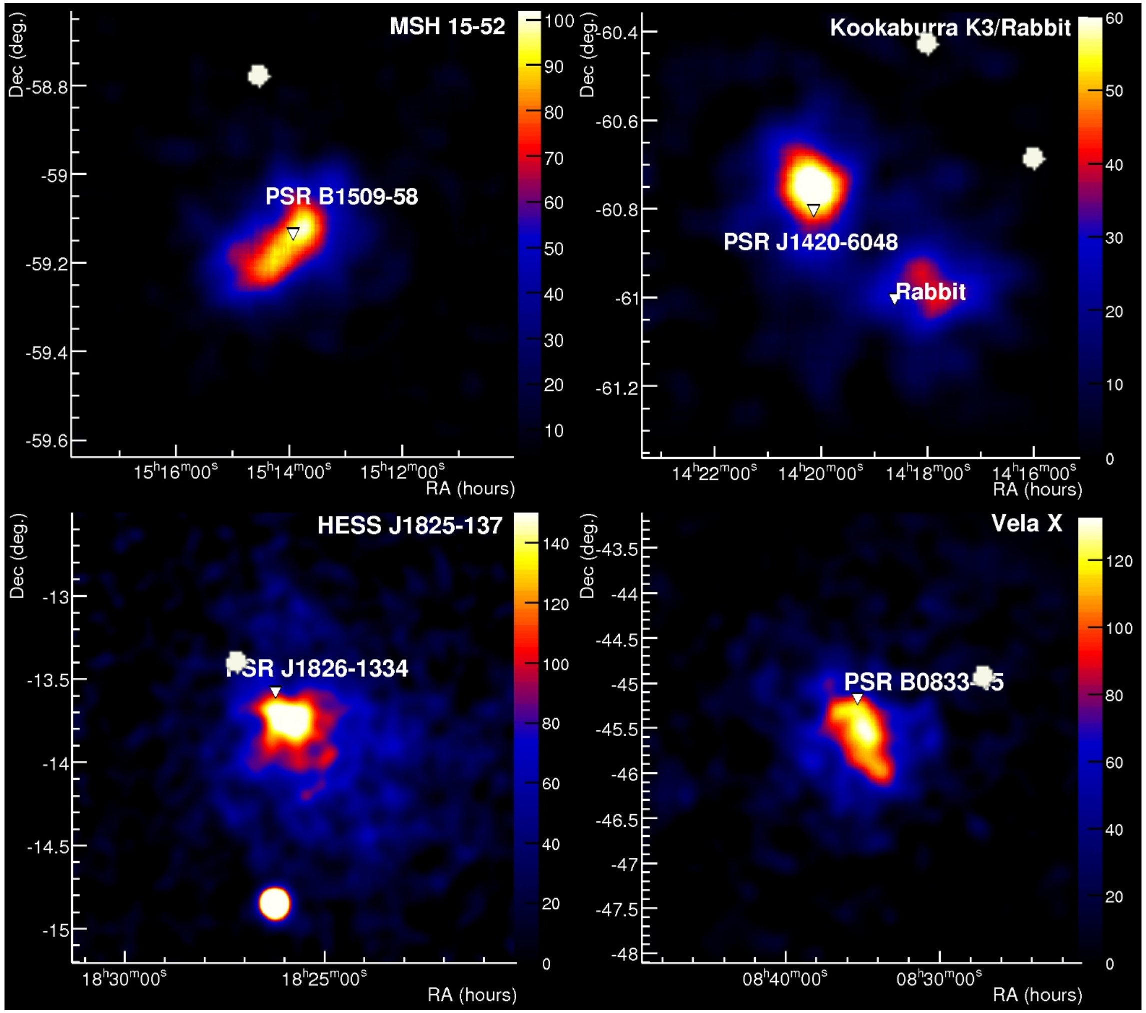




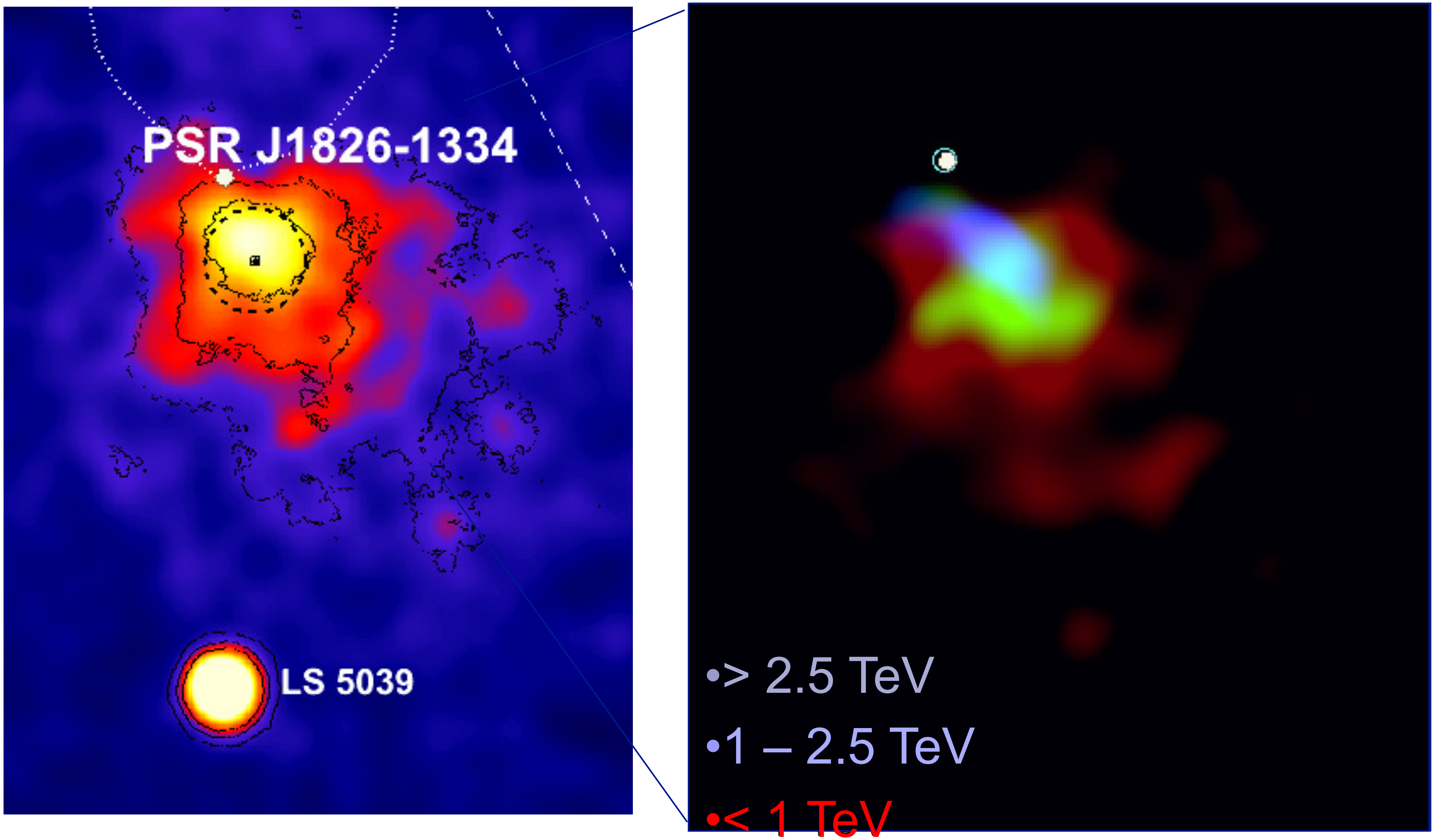
Pulsar Wind Nebulae

Extended

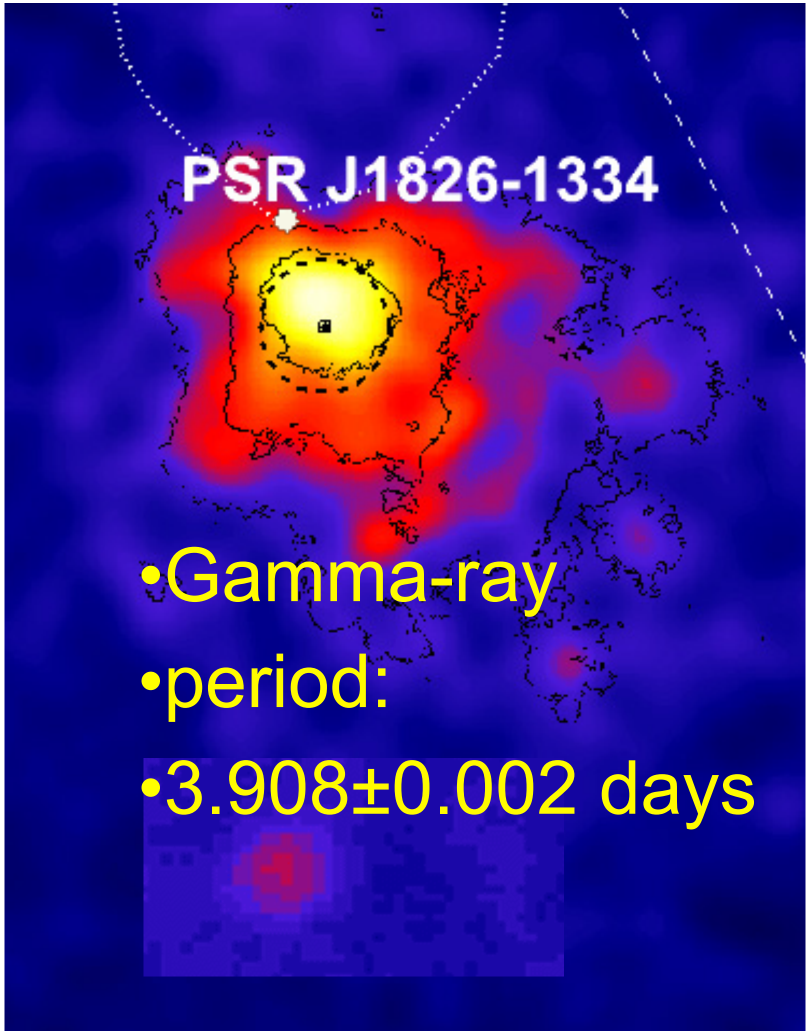
γ-ray sources



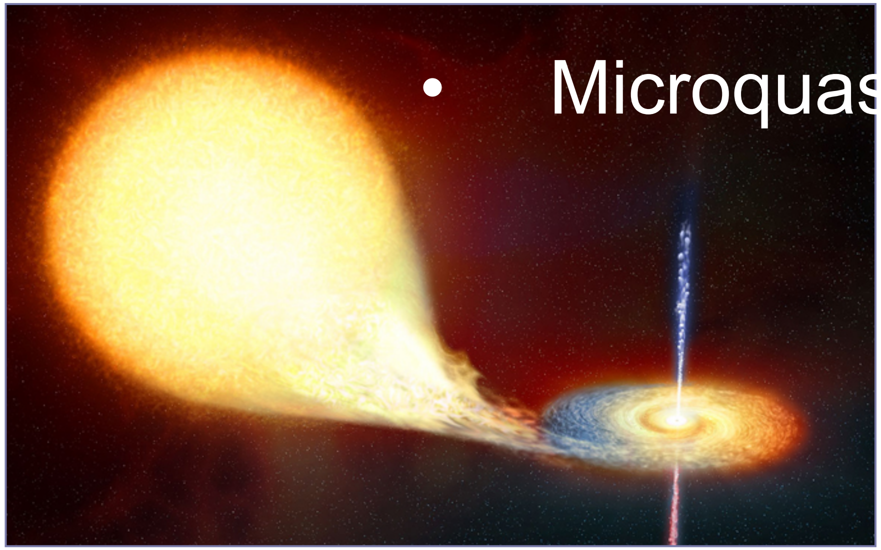
Morphology of PWN: HESS J1825-137



Binaries

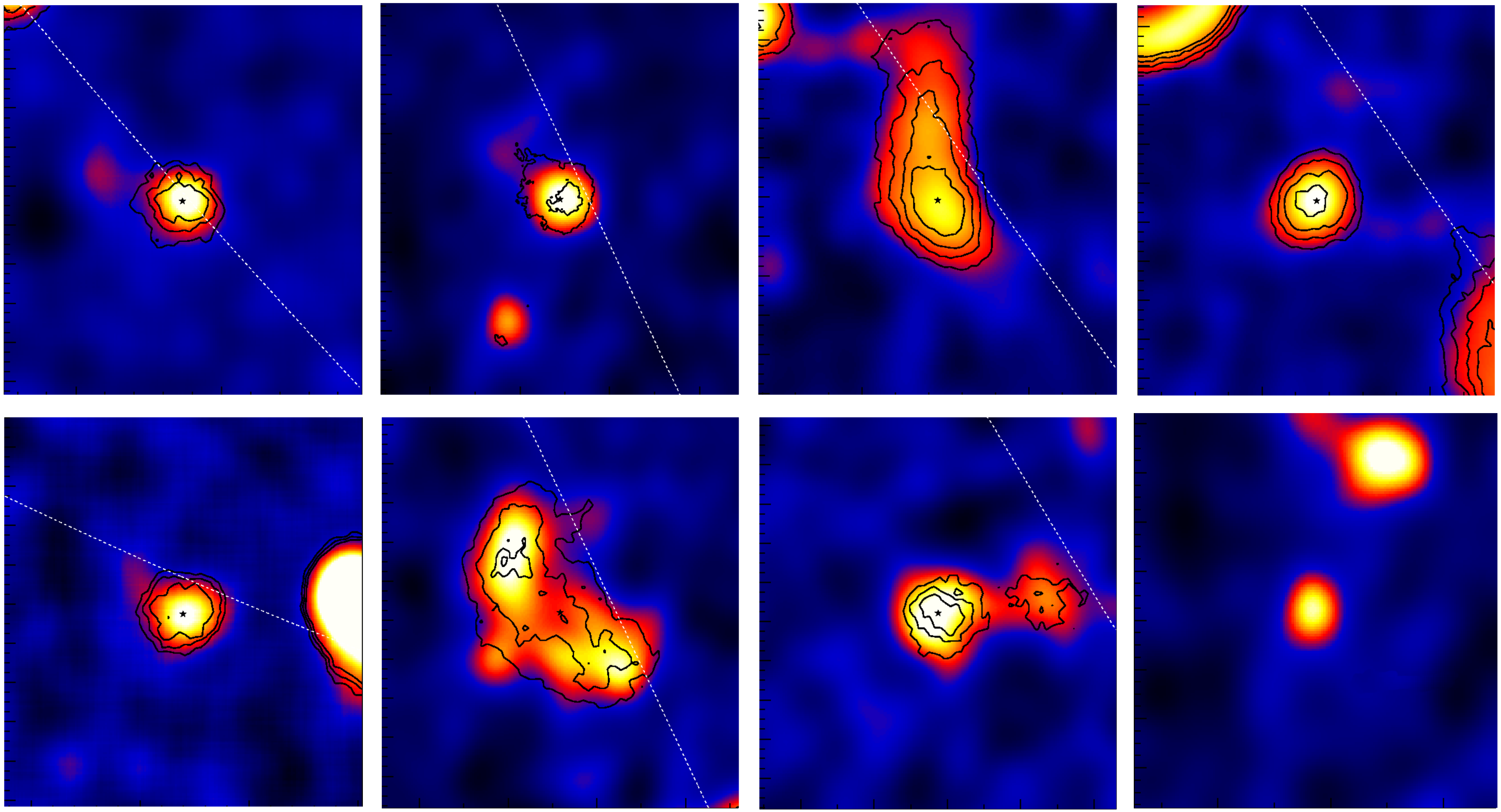


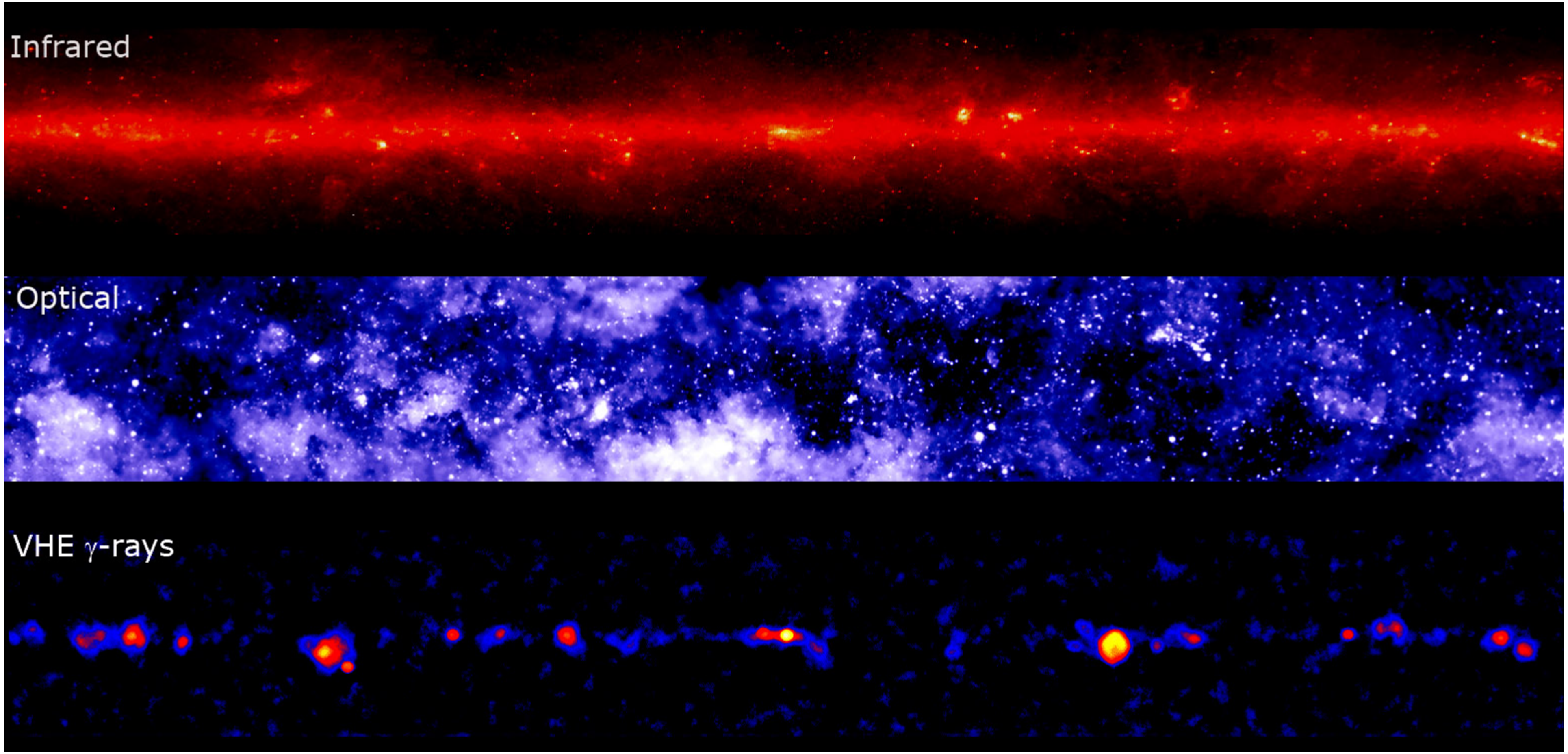
- Gamma-ray
- period:
- 3.908±0.002 days



- Microquas

"Dark" sources: Objects which only shine in gamma rays !

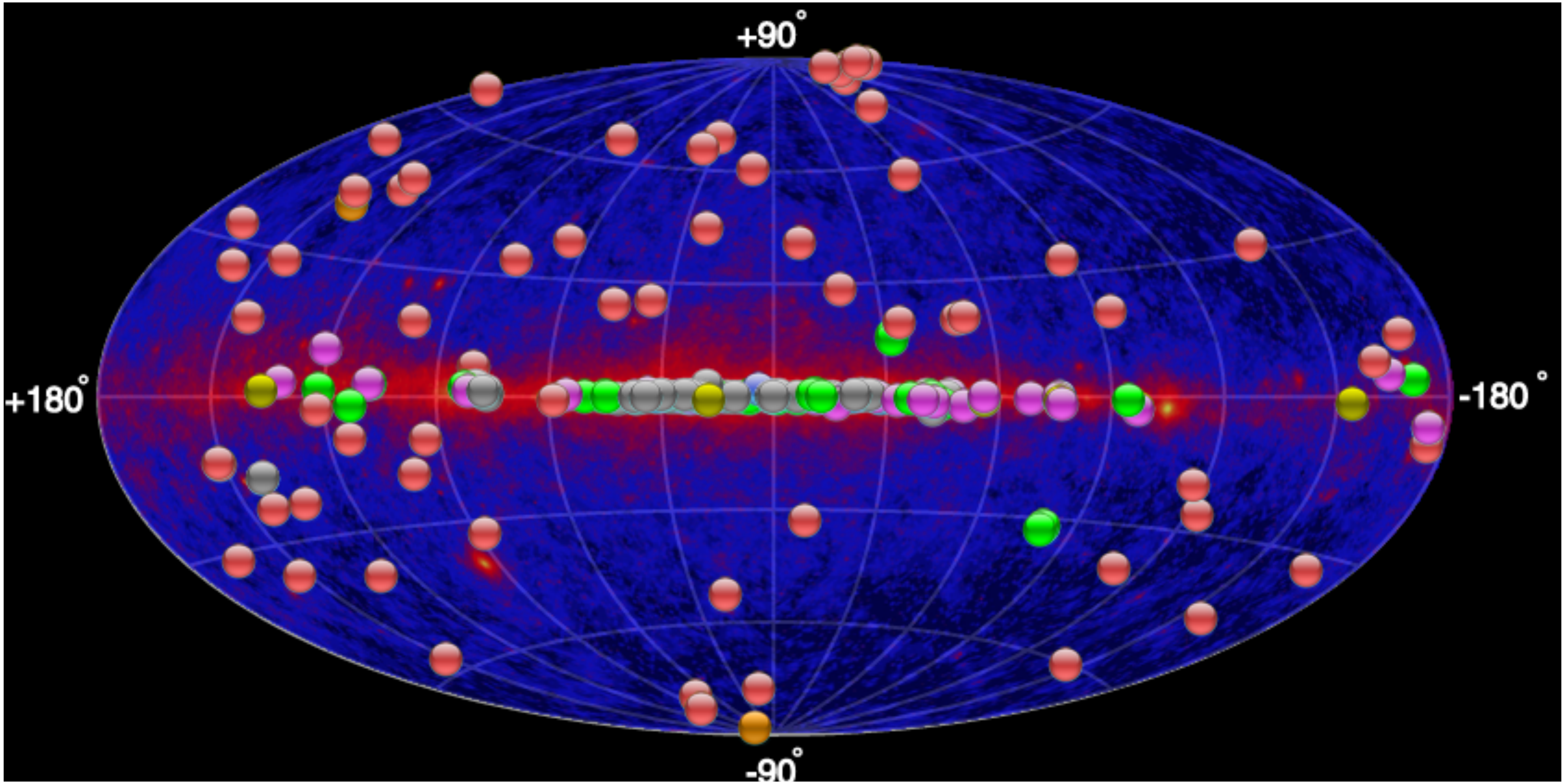




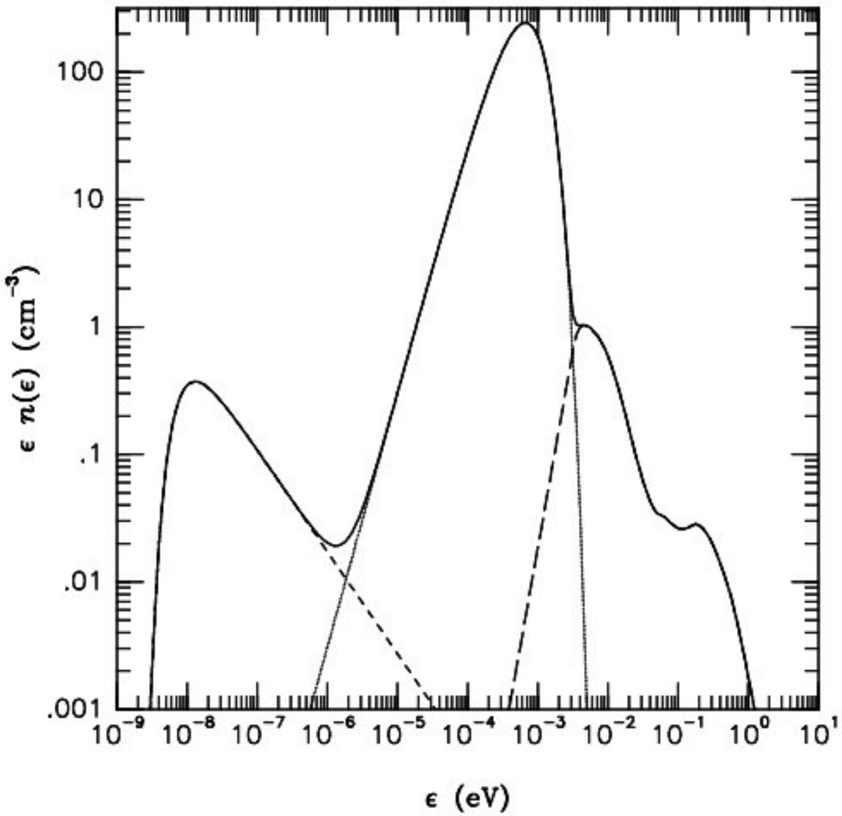
•The age of real VHE gamma ray astronomy has started

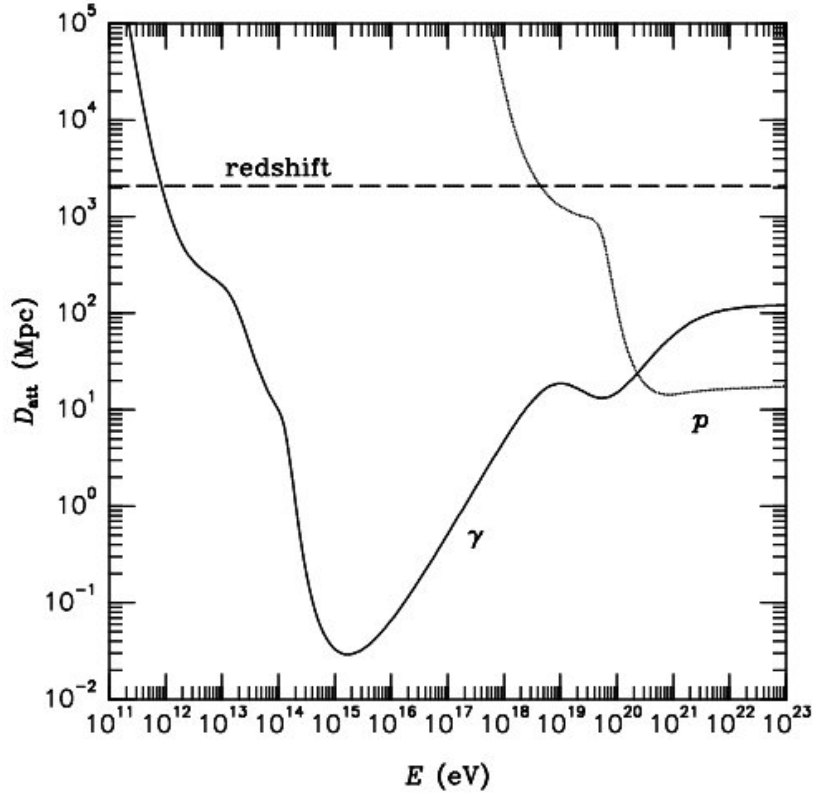
Extra-galactic gamma-ray sources and extragalactic background light

1000 sources in GeV and 60 in TeV



Diffuse backgrounds



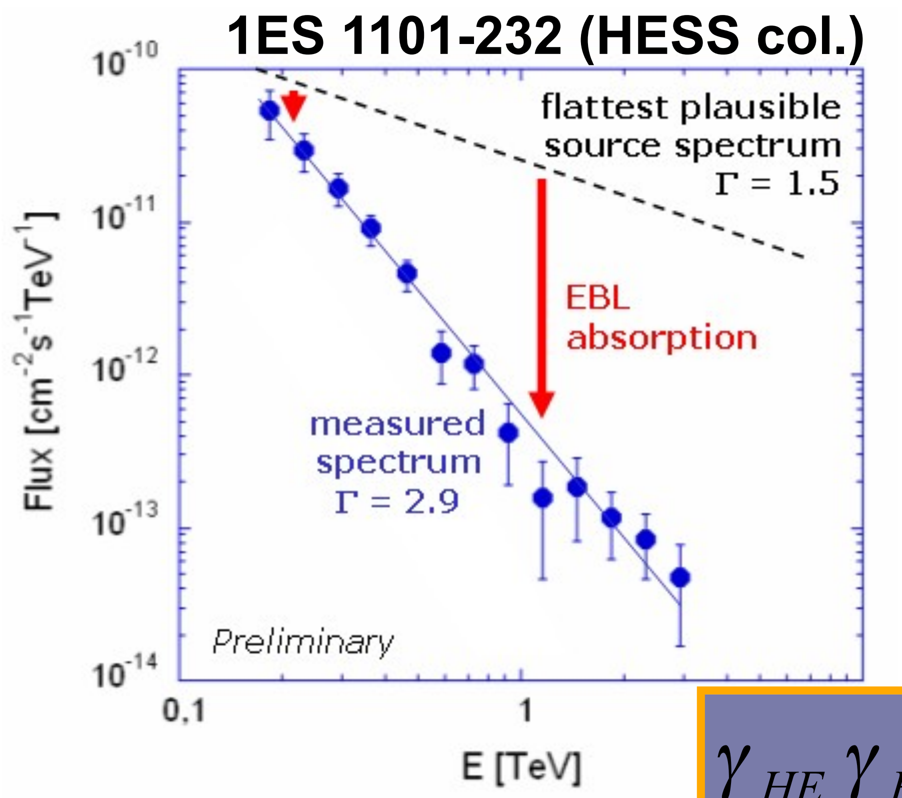


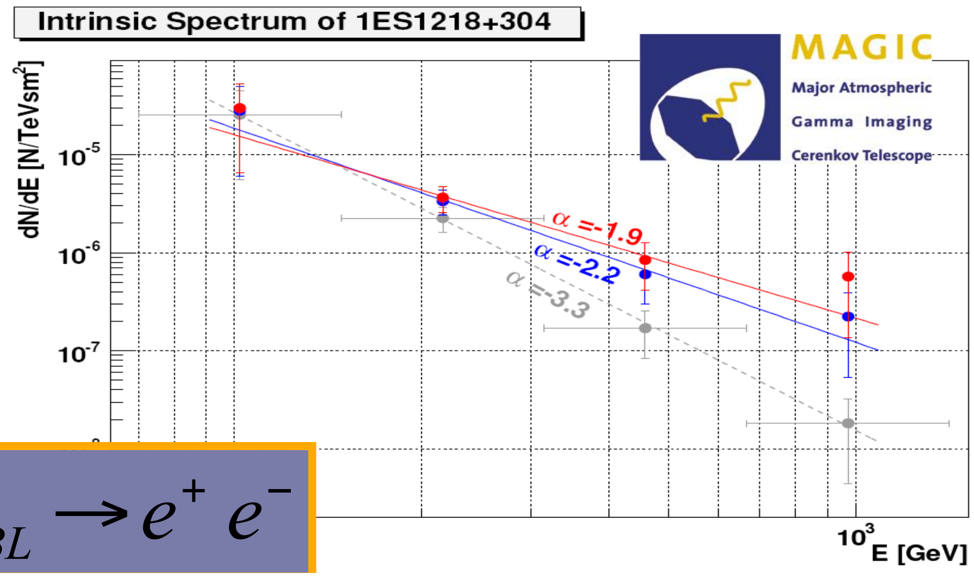
Extrag. Background Light

Cosmological radiation from star formation and evolution.

Spectral signature from gg absorption for Eg ~ 50-2000 GeV.

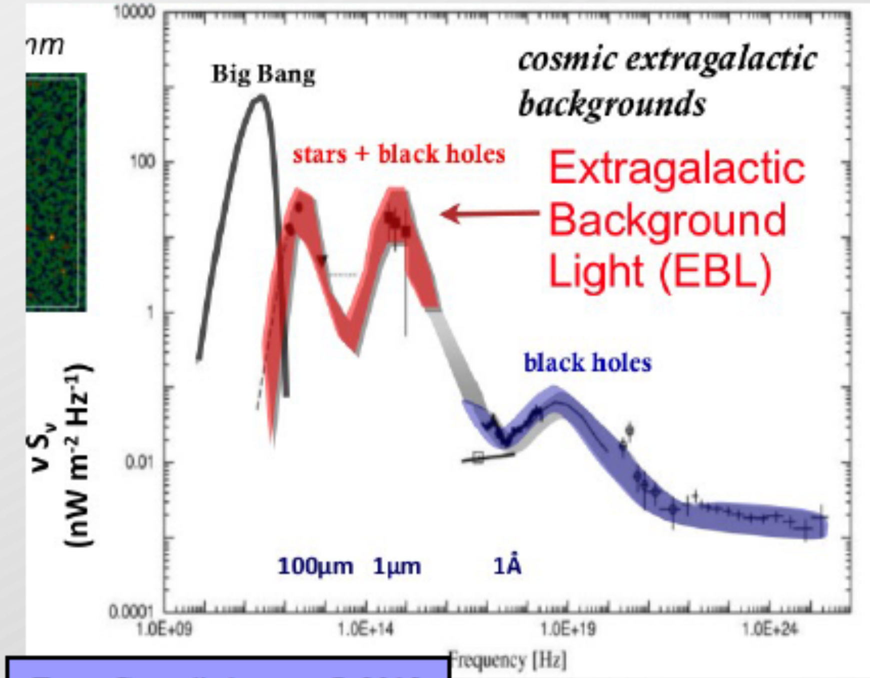
Use measured AGN spectra to constrain EBL.





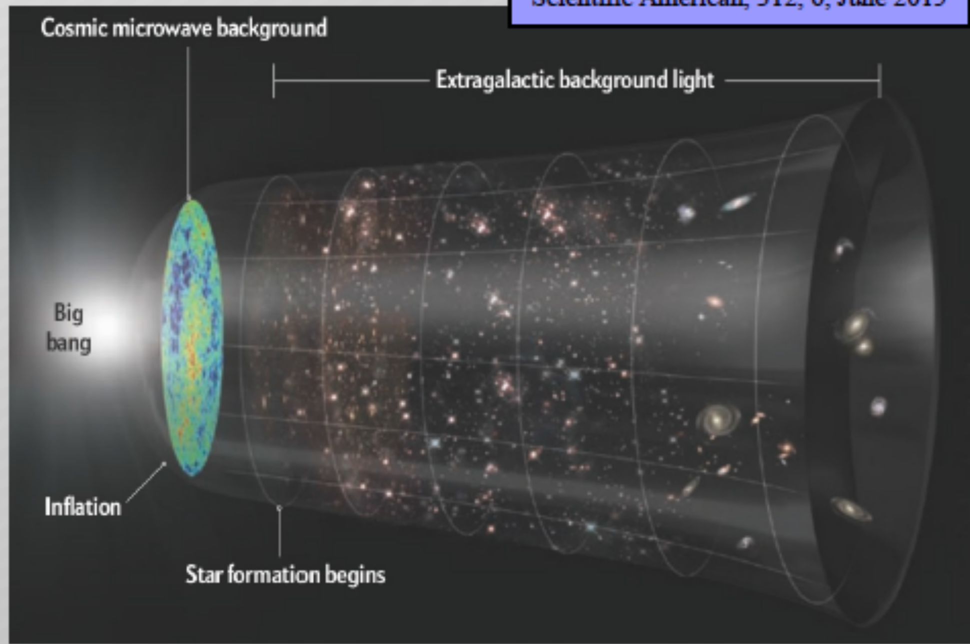
$$\gamma_{HE}\,\gamma_{EBL} \rightarrow e^+ e^-$$

Diffuse extragalactic backgrounds



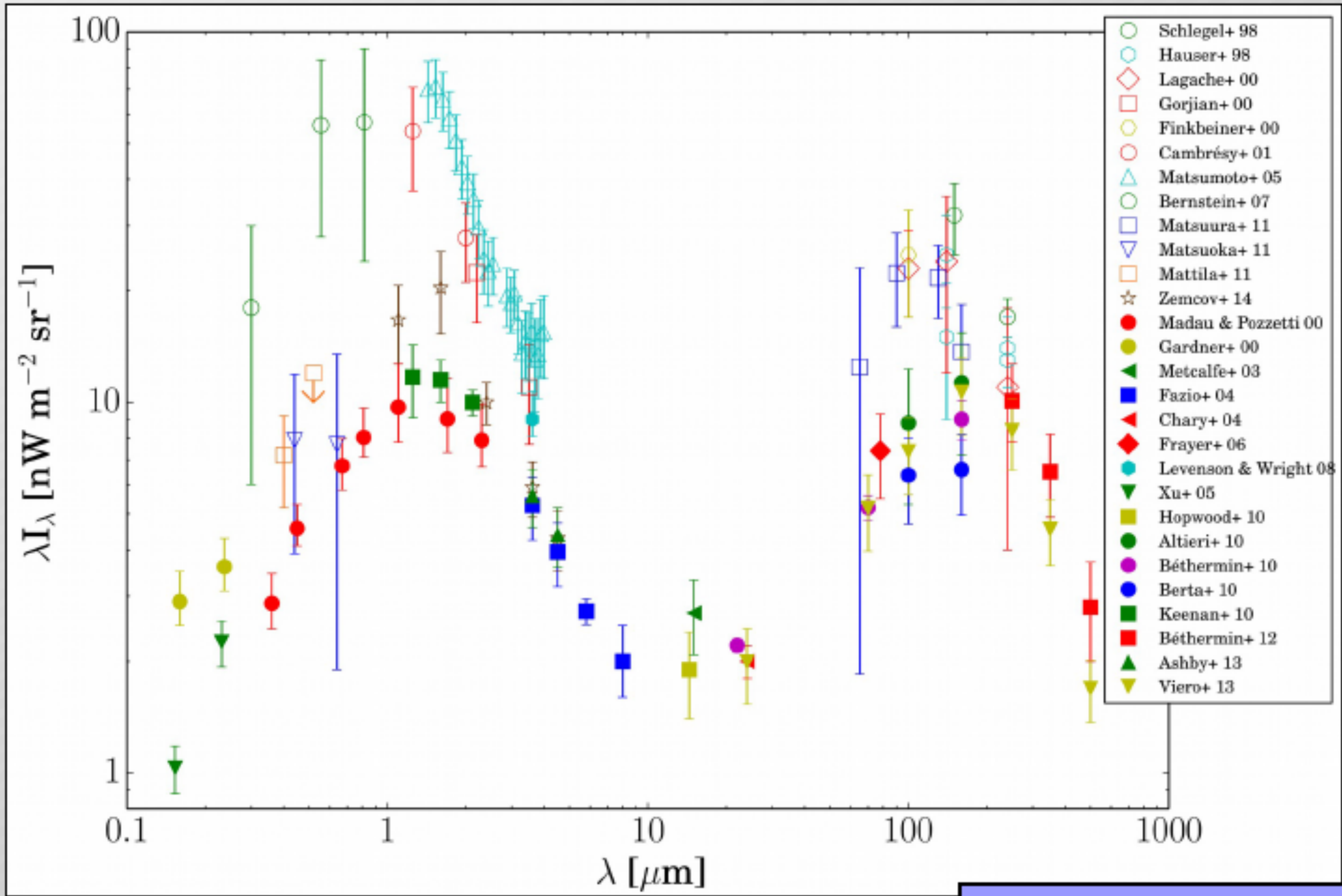
From Genzel's lecture @ 2013 Jerusalem Winter School

Scientific American, 312, 6, June 2015



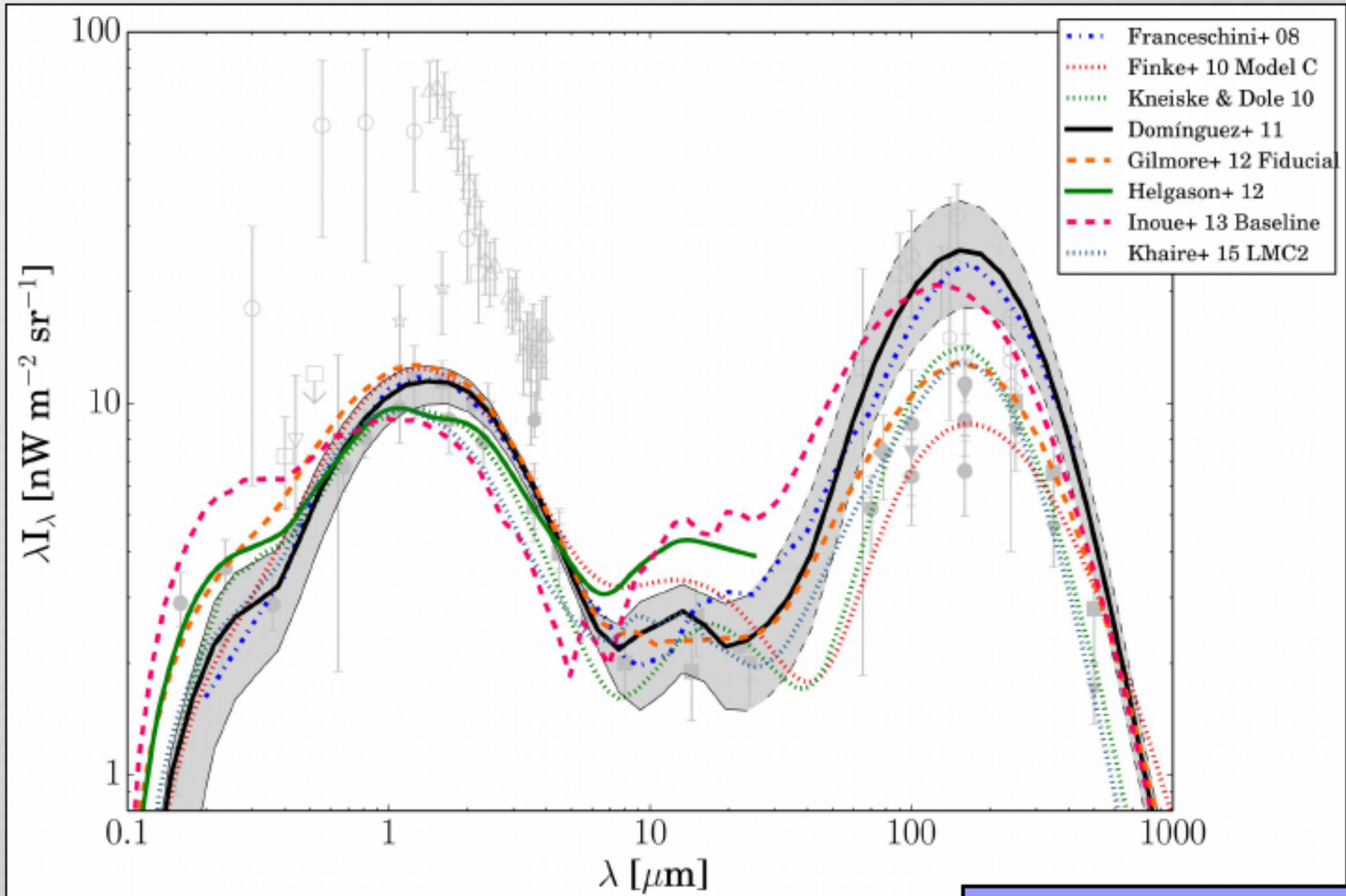
- The EBL is the accumulated diffuse light produced by star formation processes and accreting black holes over the history of the Univere from the UV to the far-IR.
- It contains fundamental information about galaxy evolution, cosmology, and it is essential for the full energy balance of the Universe.

Local EBL: Data and Models



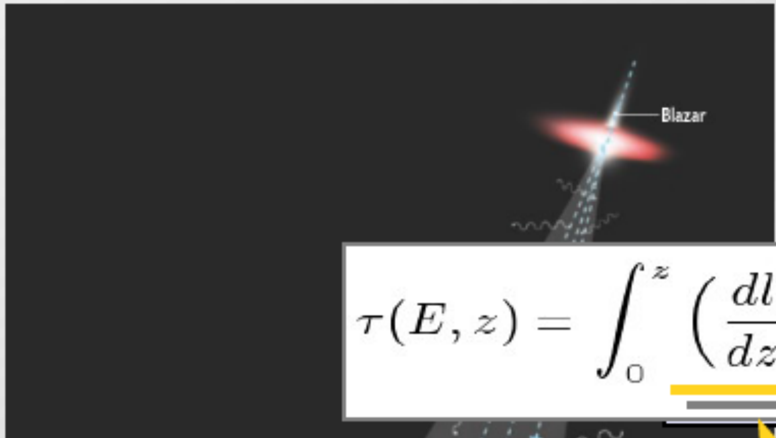
Domínguez & Primack, 15 in prep.

Local EBL: Data and Models



Domínguez & Primack, 15 in prep.

Gamma-Ray Attenuation



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

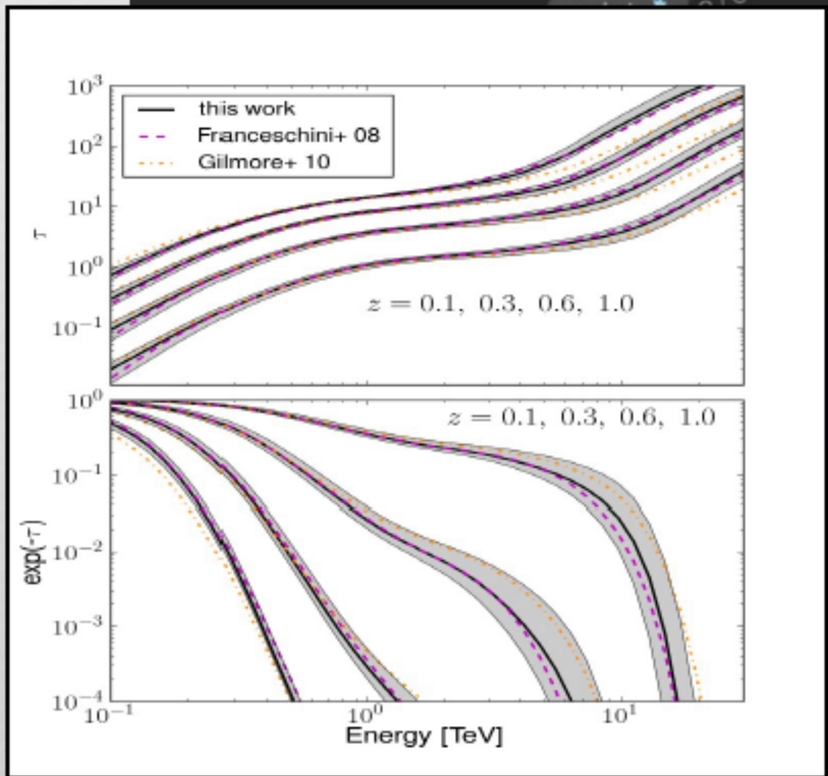
$$\tau(E,z) = \int_0^z \left(\frac{dl'}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{min}}^{\infty} d\varepsilon' \, \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$

Distance (cosmology)

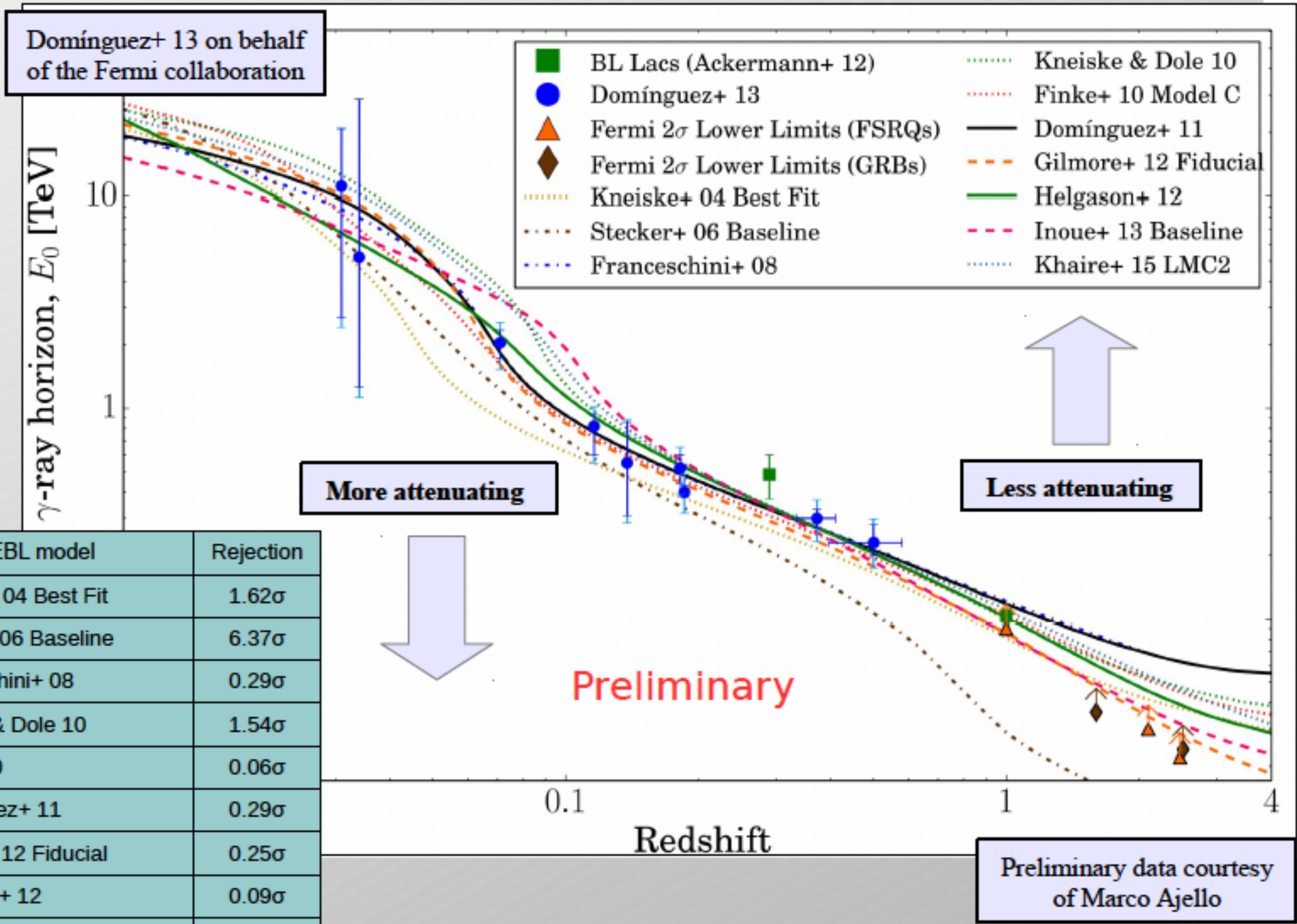
Interaction angle

Cross section

EBL photon density evolution (cosmology)

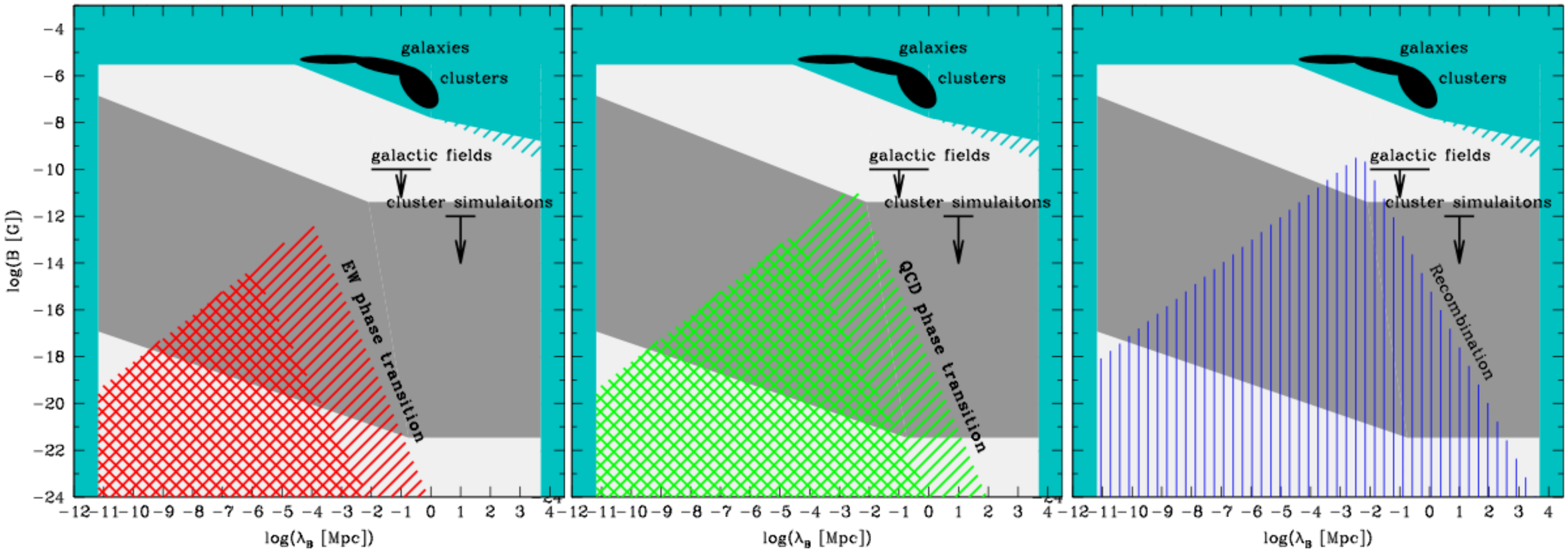


Cosmic γ-ray Horizon: Results



EBL model	Rejection
Kneiske+ 04 Best Fit	1.62σ
Stecker+ 06 Baseline	6.37σ
Franceschini+ 08	0.29σ
Kneiske & Dole 10	1.54σ
Finke+ 10	0.06σ
Domínguez+ 11	0.29σ
Gilmore+ 12 Fiducial	0.25σ
Helgason+ 12	0.09σ
Inoue+ 13 Baseline	2.12σ
Khaire+ 15 LMC2	1.27σ

Extra-galactic sources and determination of magnetic field



A.Neronov, D.S., PRD 2009, arXiv:**0910.1920**

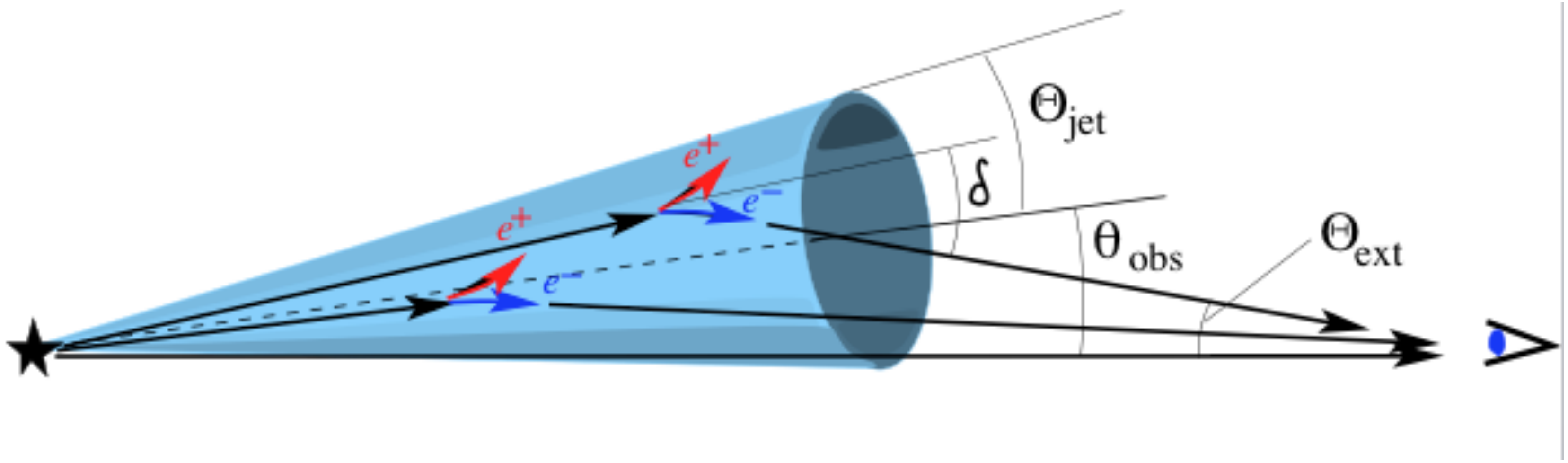
•Magnetic fields might be generated via "battery" effects during phase transitions in the Early Universe.

•In principle, the initial magnetic field energy density might provide non-negligible contribution to the overall energy density of the Universe.

•Magnetic field correlation length could not exceed the size of cosmological horizon; strength of magnetic field averaged over large distance scales could not exceed the "causality" limit

•Damping processes remove small-scale magnetic fields in the course of cosmological evolution.

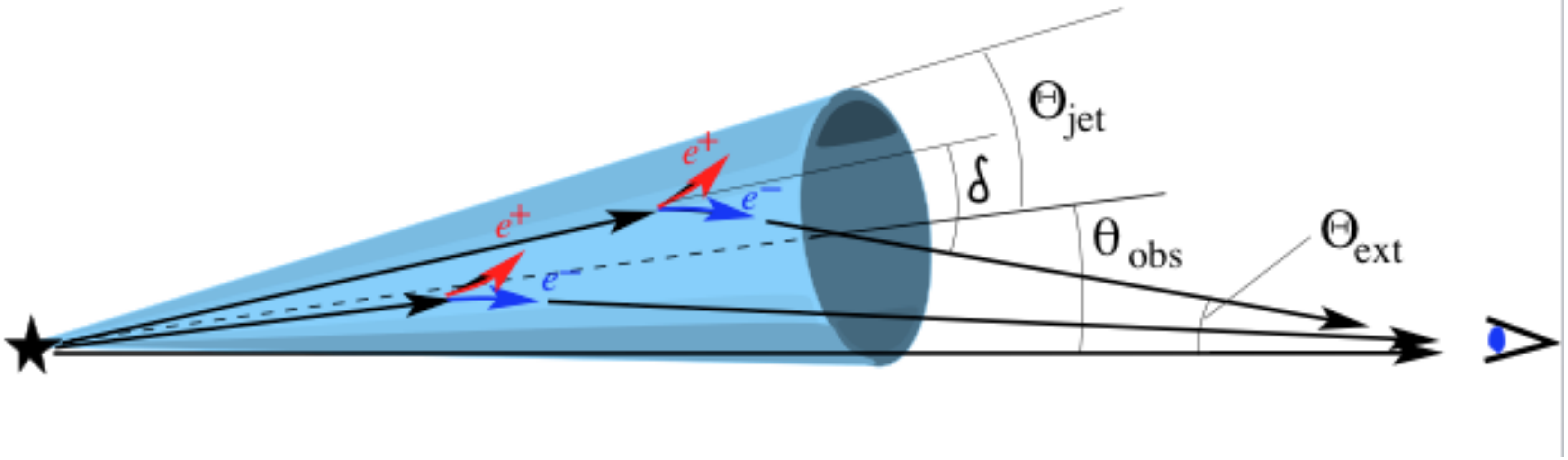
•Imaging of cascade: 3-d cascade needed



•3-d cascade in turbulent EGMF

•A.Neronov, D.S., M.Kachelriess, S.Ostapchenko and A.Elyev , 2009

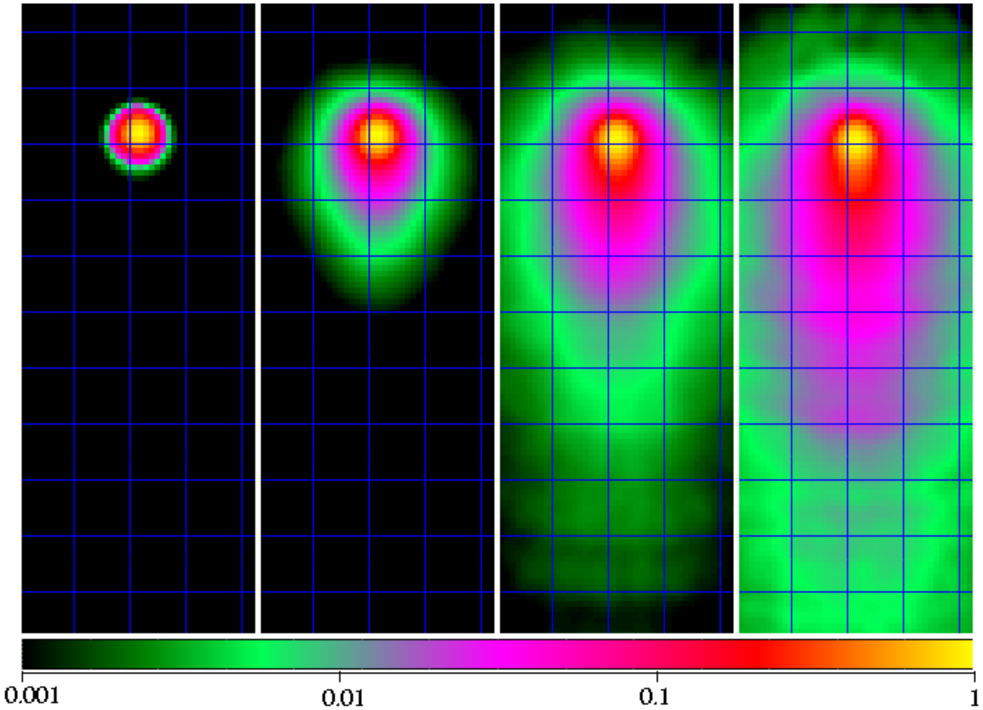
•Imaging of cascade: EGMF



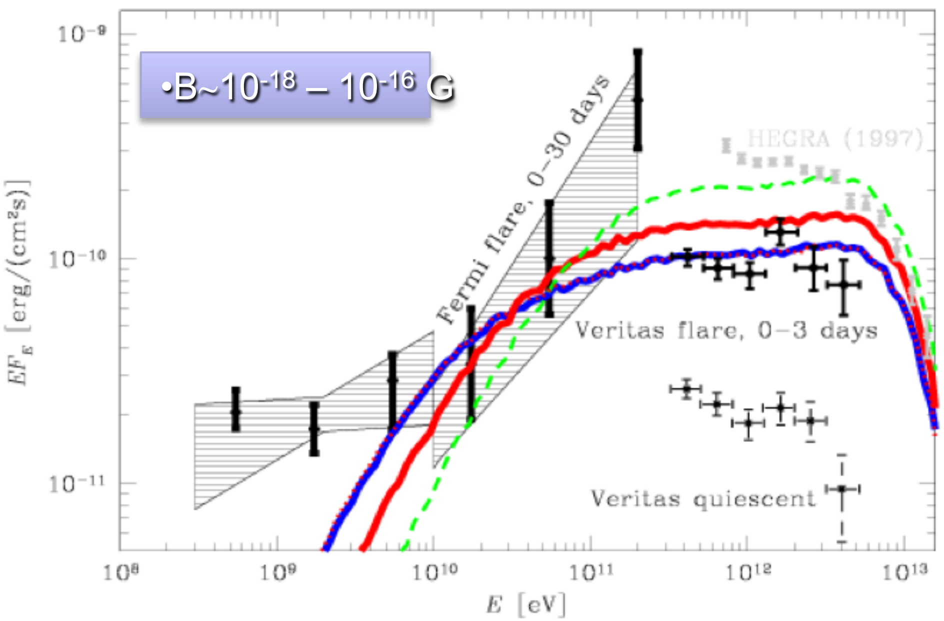
•**Imaging**: cascade component forms an extended emission around initially point source.

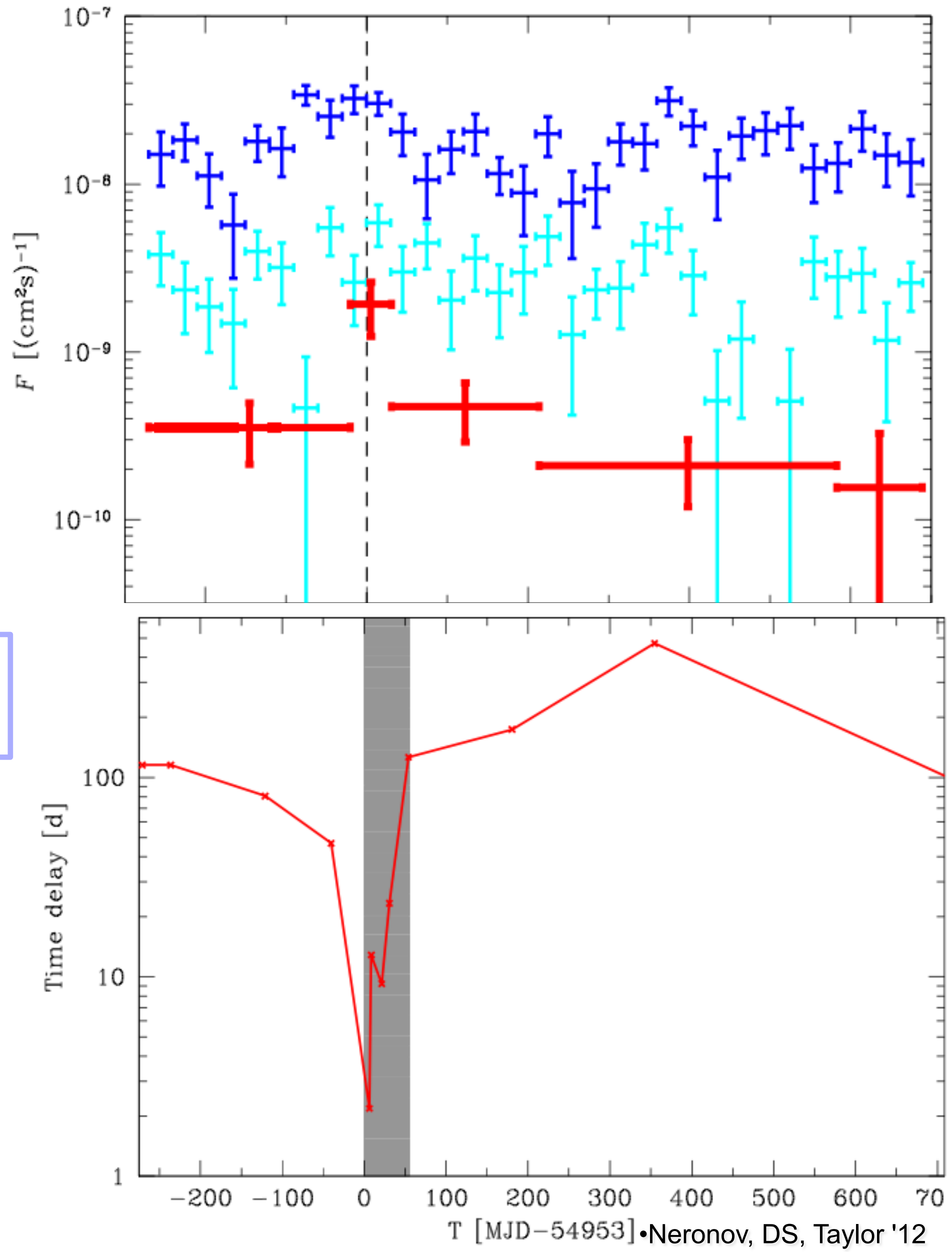
• – detectability depends on

the telesope PSF and on the scale of angular deflections of e+e- pairs **(i.e. on the strength of EGMF)**



• Search for the time-delayed cascade emission





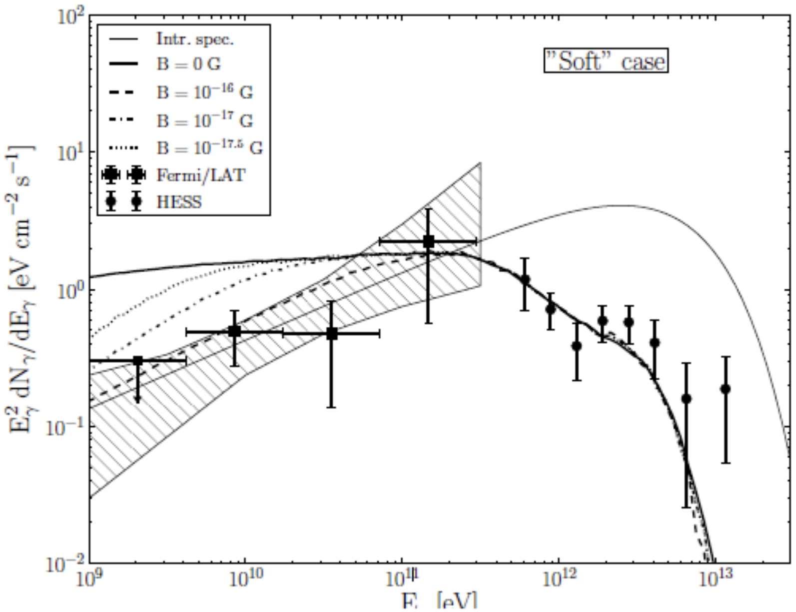
•Neronov, DS, Taylor '12

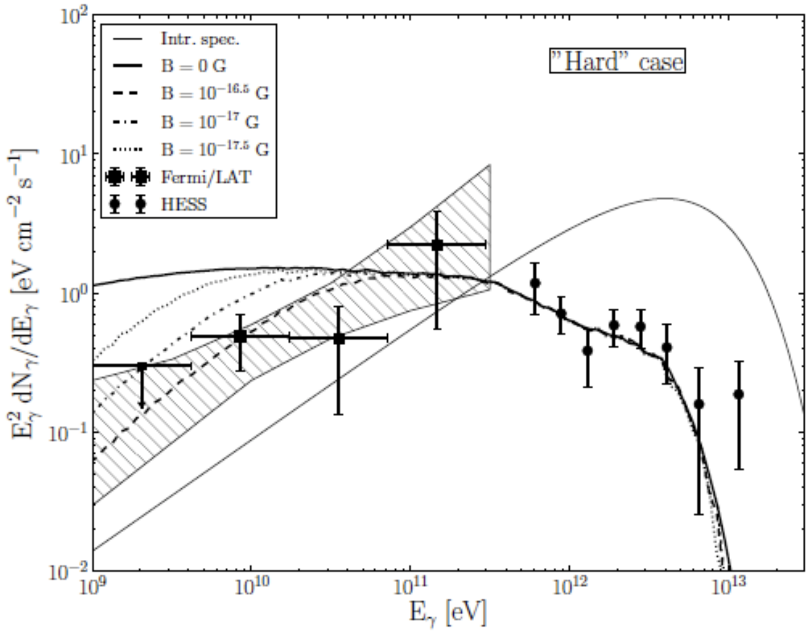
•The flare occurred during the multiwavelength campaing, including HE and VHE observations.

•Fermi data indicate that the flare lasted 30-50 days, but the VHE observations cover only the first three days of the flare.

•Fermi data indicate a peculiar hardening of the spectrum above ~10 GeV during the flare. One possibility for the explanation of the hard component is the cascade emission suppressed at low energies by too-large time delay.

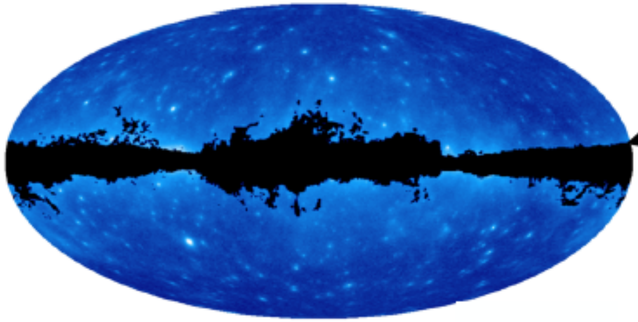
EGMF from 1ES 0229+200





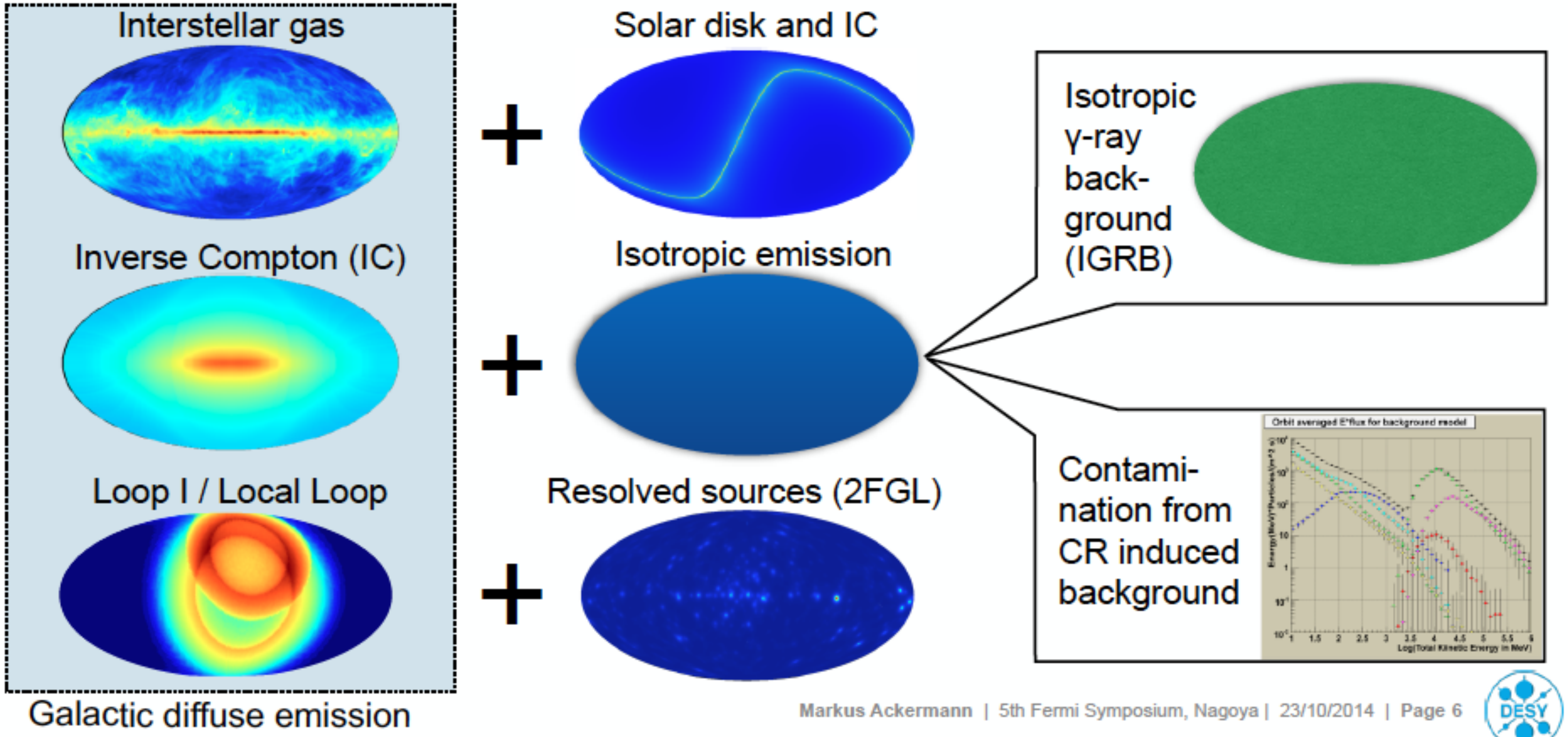
Diffuse gamma-ray background

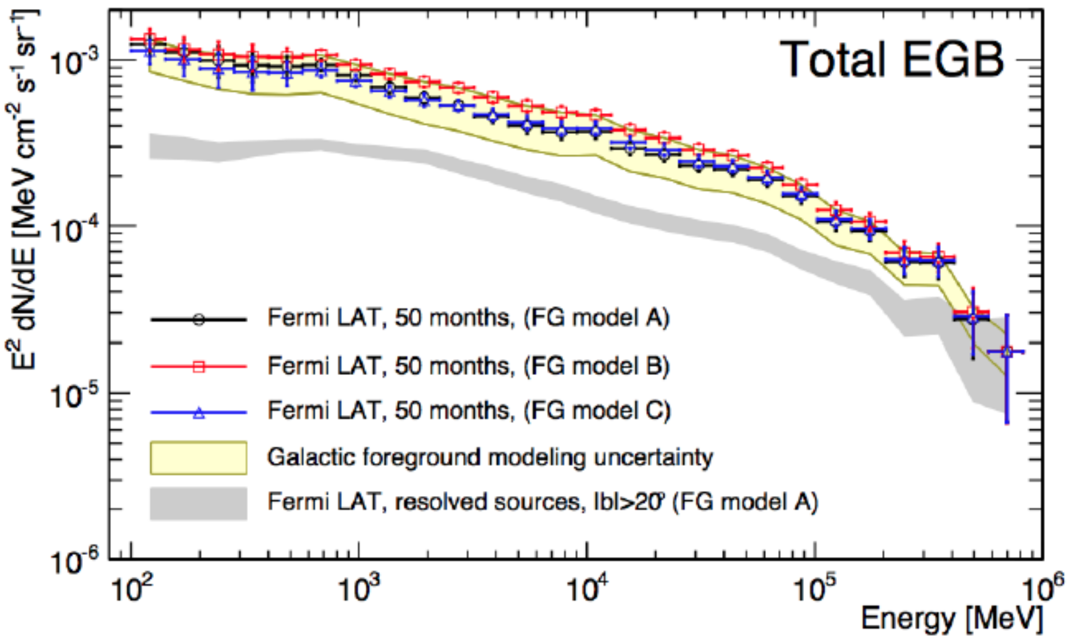
Derivation of the isotropic gamma-ray background



Not used in this analysis:
- Galactic plane
- Regions with dense molecular clouds
- Regions with non-local atomic hydrogen clouds

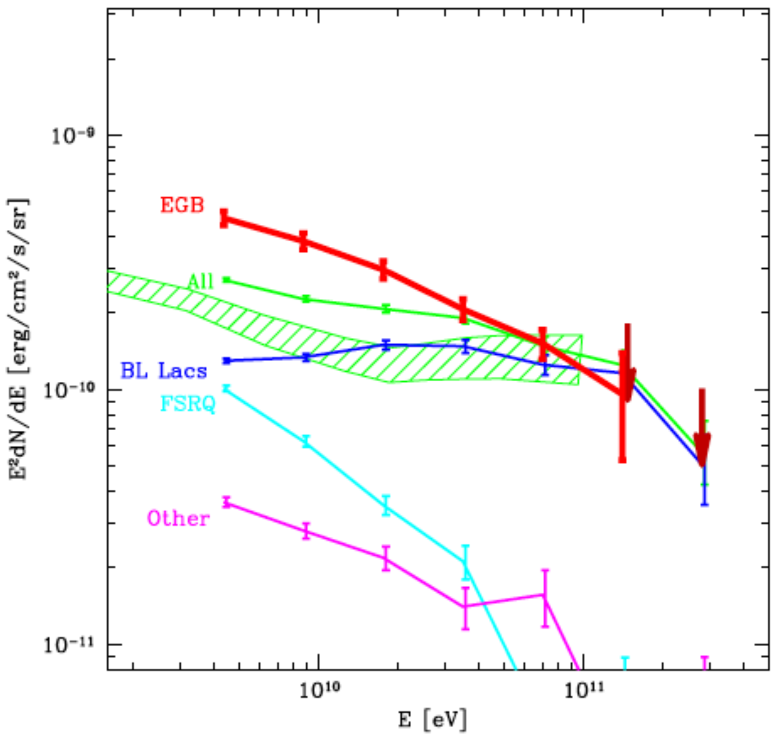
=

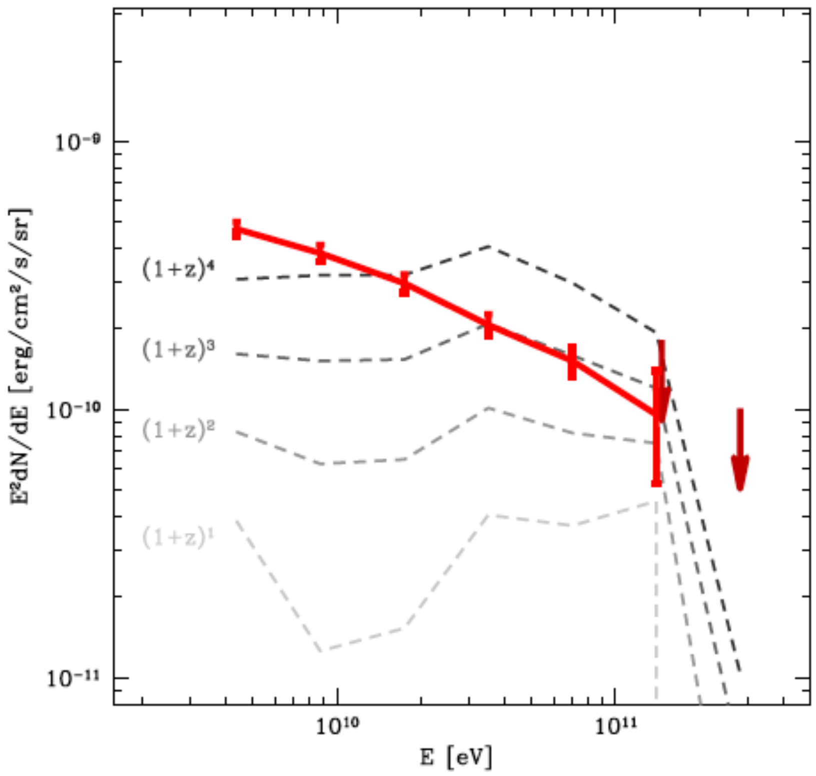




- **Sum of the intensities** of IGRB and the resolved high-latitude sources.
- Contribution of high-latitude Galactic sources **<< 5%.**
- Spectrum can be parametrized by **power-law with exponential cutoff**.
- Spectral index **~ 2.3**, cutoff energy **~ 350 GeV.**

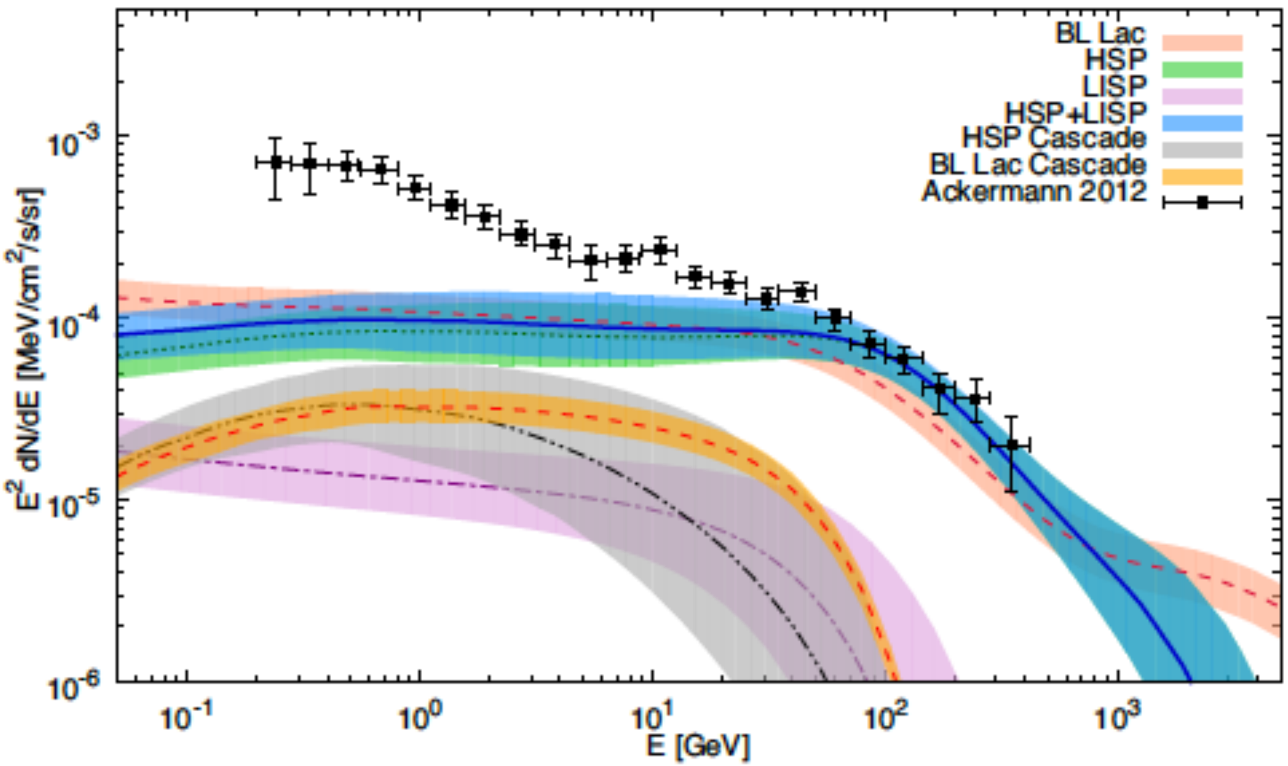
BL Lacs give main contribution to diffuse gamma-ray flux





A.Neronov, D.S. Astrophys.J. 757 (2012) 61

BL Lacs give main contribution to high energy part of diffuse gamma-ray flux



•M. Di Mauro et al, arXiv:1311.5708

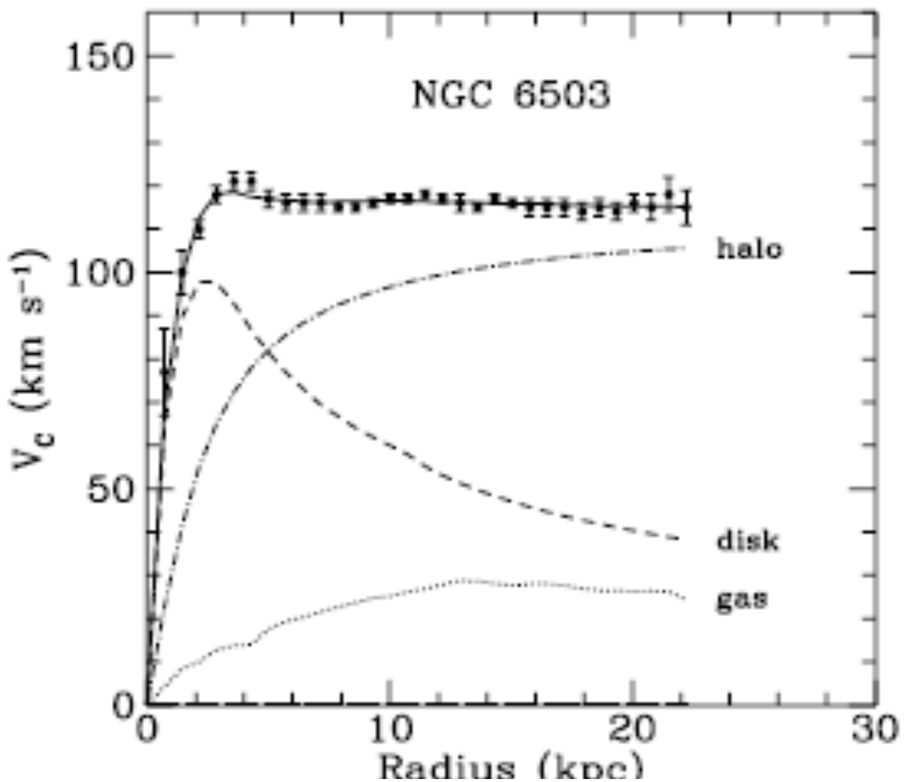
Fermi confirmed resolution of BL Lac sources above 50 GeV

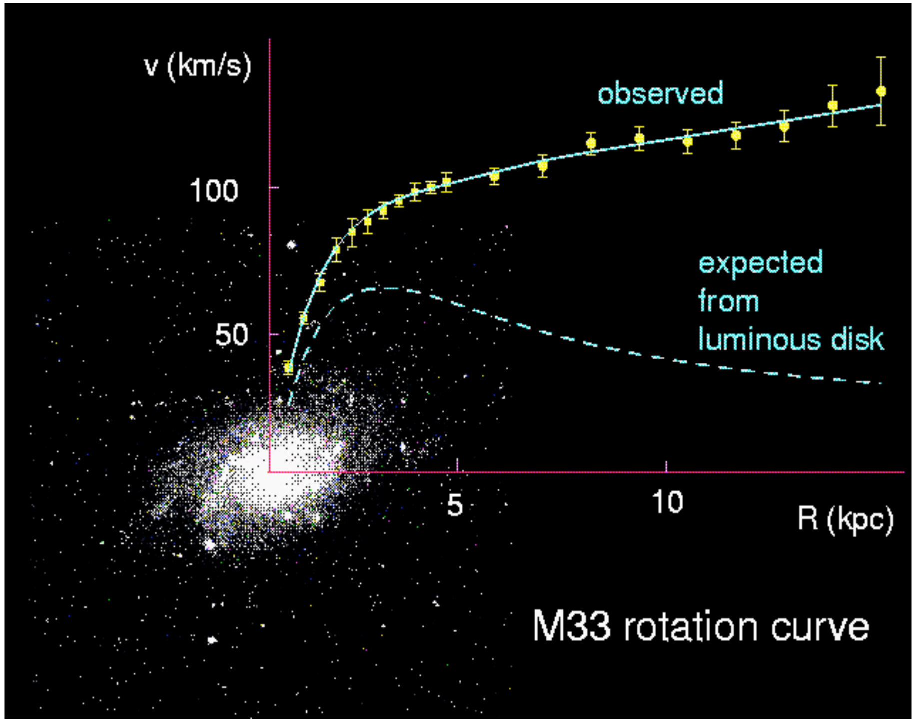
cm^{-2} s^{-1}). We employ a one-point photon fluctuation analysis to constrain the behavior of dN/dS below the source detection threshold. Overall the source count distribution is constrained over three decades in flux and found compatible with a broken power law with a break flux, S_b, in the range $[8 \times 10^{-12}, 1.5 \times 10^{-11}]$ ph cm^{-2} s^{-1} and power-law indices below and above the break of $\alpha_2 \in [1.60, 1.75]$ and $\alpha_1 = 2.49 \pm 0.12$ respectively. Integration of dN/dS shows that point sources account for at least $86^{+16}_{-14}\%$ of the total extragalactic γ-ray background. The simple form of the derived source count distribution is consistent with a single population (i.e. blazars) dominating the source counts to the minimum flux explored by this analysis. We estimate the density of sources

- **Fermi collaboration, arXiv:1511.00693**

Indirect detection of Dark Matter

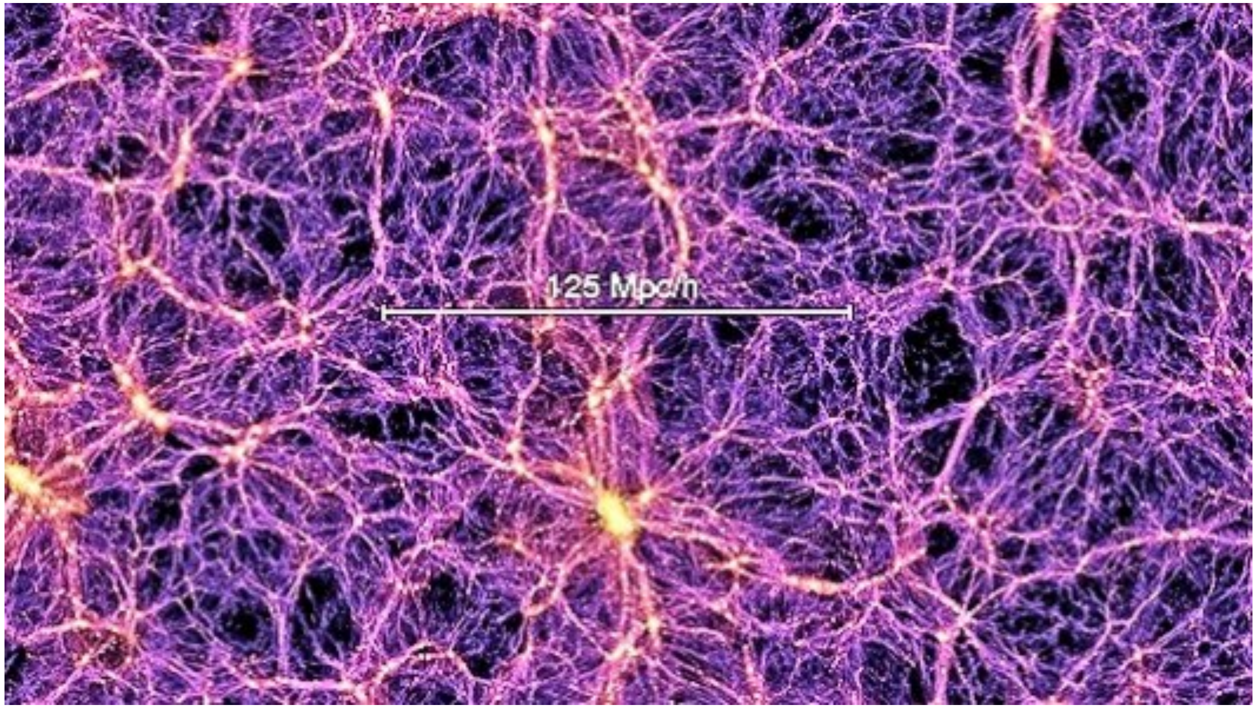
- Rotation Curves of galaxies





- Red Region: X Ray
- Blue Region: Gravitational lensing

- Large Scale Structure

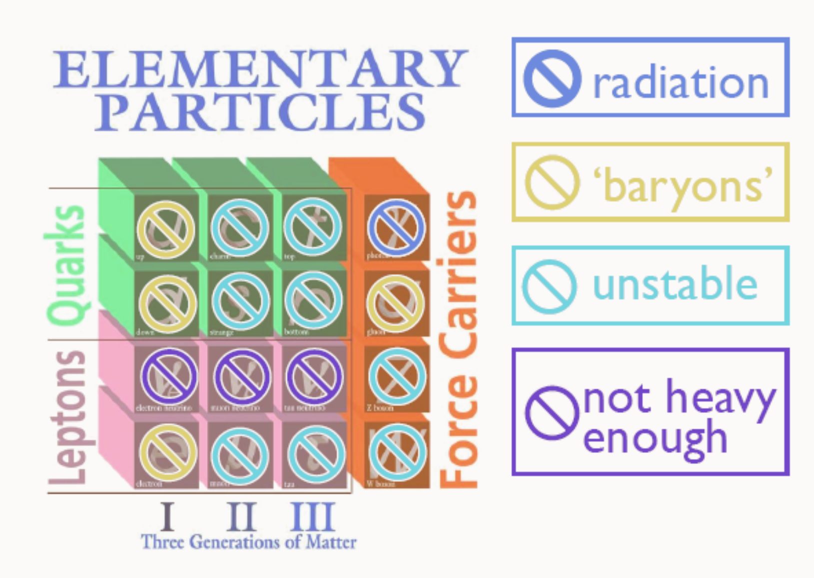


The N-body Simulation of Dark Matter Universe

Structure: Core, Filament and Cosmic Void.

•What we know about DM particles so far ?

- **neutral**



- **cold** (part of it can be warm)

- **weak interaction** (with itself and with ordinary matter) ? **Maybe!**

- **profile** (around us $\rho_{\chi} \approx 0.3 GeV/cm^3$ $V \approx 220$ km/s)

Neutrino dark matter

Neutrino seems to be a perfect dark matter candidate: neutral, stable, massive, abundantly produced in the early Universe

Cosmic neutrinos

- We know how neutrinos interact and we can compute their primordial number density $n_\nu = 112\,\mathrm{cm}^{-3}$ (per flavour)
- To give correct dark matter abundance the sum of neutrino masses, $\sum m_\nu$, should be $\sum m_\nu \sim 11\,\mathrm{eV}$

Tremaine-Gunn bound (1979)

- Such light neutrinos **cannot form small galaxies** – one would have to put too many of them and violated Pauli exclusion principle
- Minimal mass for fermion dark matter $\sim 300 - 400\,\mathrm{eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would oveclose the Universe ($\Omega \sim 3!$)

Two roads from neutrino dark matter

Dark matter cannot be **light** and **weakly interacting** at the same time

Alternatives:

Light and necessarily **super-weakly** interacting — **HNL**

Heavy and weakly interacting — **WIMP**

. . . and of course other, completely orthogonal ideas, like axions

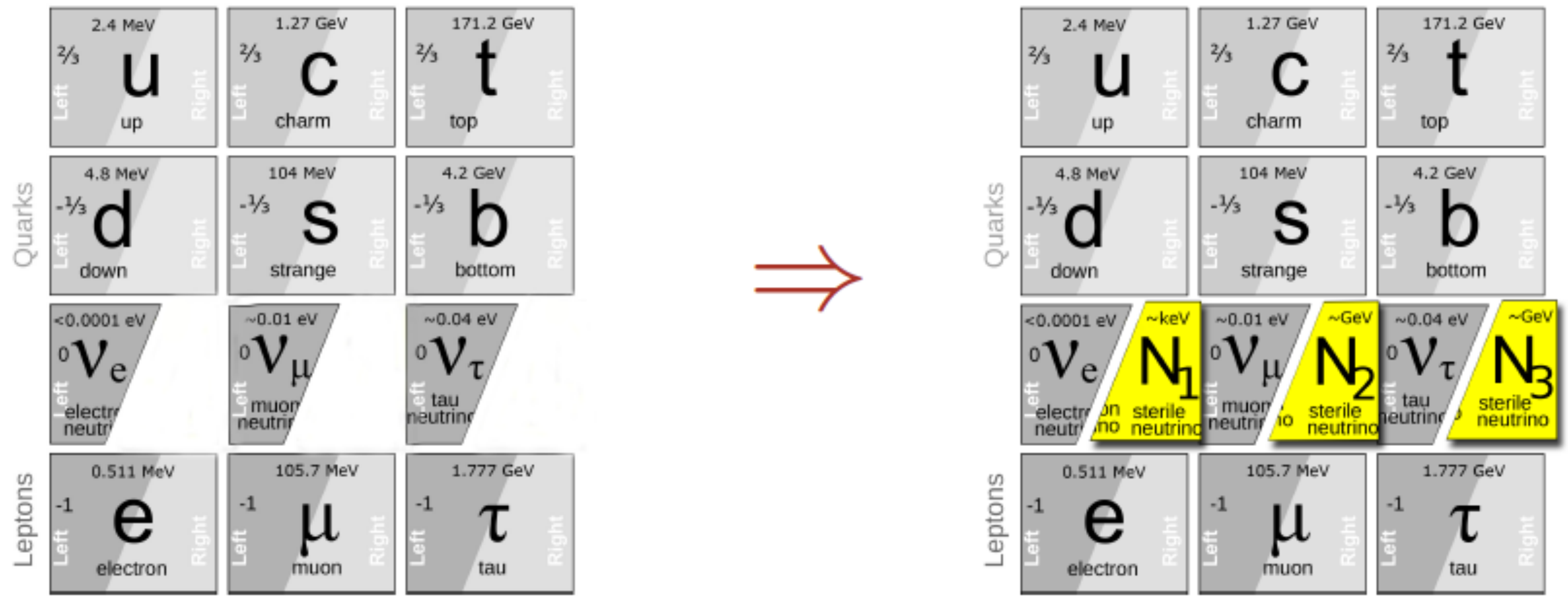
HNLs as dark matter

- Can be **light** (down to Tremaine-Gunn bound)
- Can be **warm** (born relativistic and cool down later)
- Can be **decaying** (stability is not required)
- Can be **produced** in correct amounts (via mixing with neutrinos)

Heavy neutral leptons

Extension of Standard Model with heavy neutral leptons

Asaka & Shaposhnikov'05. **Review:** Boyarsky+'09



Can this be a **unified Standard Model** of particle physics and cosmology

Sharing success of the Standard Model at accelerators and resolving major BSM problems: Neutrino masses and oscillations; Baryon asymmetry of the Universe; Dark matter

Type I seesaw model

Majorana mass term

$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial\!\!\!/ N + Y\,\bar{N}(\tilde{H}\cdot L) + \frac{1}{2}\bar{N}MN^c + \text{h.c.}$$

Dirac mass term

- Neutrinos are light because $m_{\text{Dirac}} \ll M$:

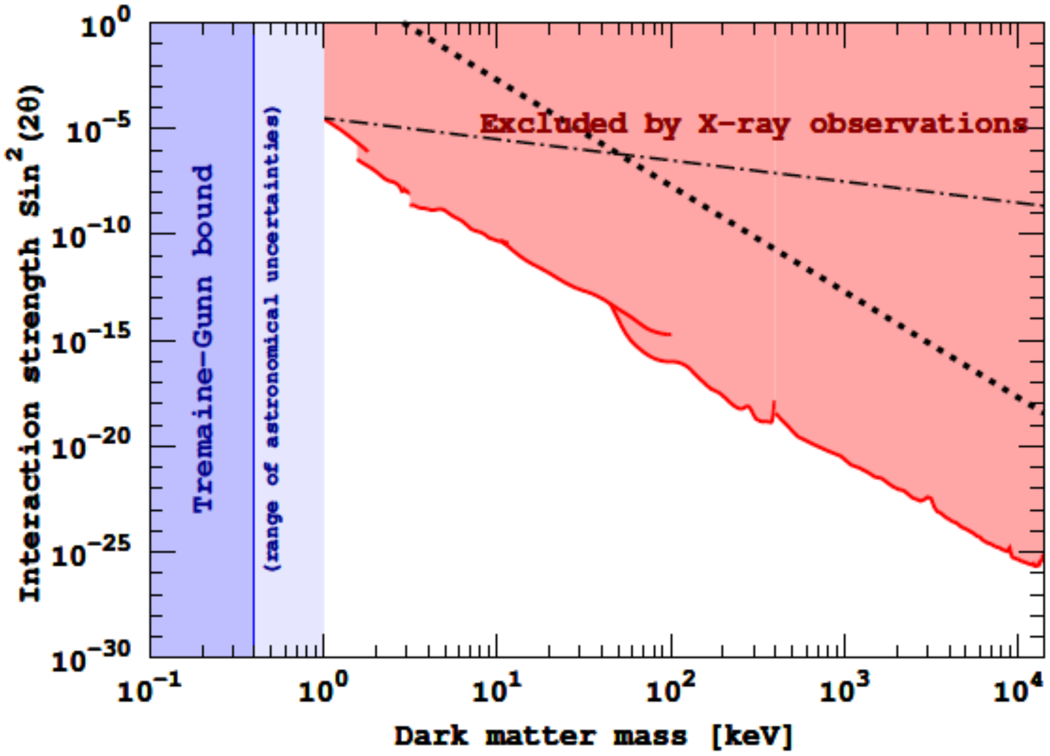
$$m_\nu \simeq \frac{(m_{\text{Dirac}})^2}{M} = U^2 M$$

- active-sterile mixing angle

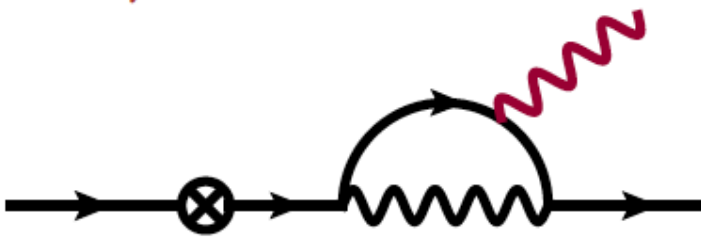
$$U = \frac{m_{\text{Dirac}}}{M} \ll 1$$

The new particle is called "Sterile neutrino" or "heavy neutral lepton" or **HNL**

Parameter space of HNL dark matter I



- Non-observation of decay line $N \to \gamma + \nu$

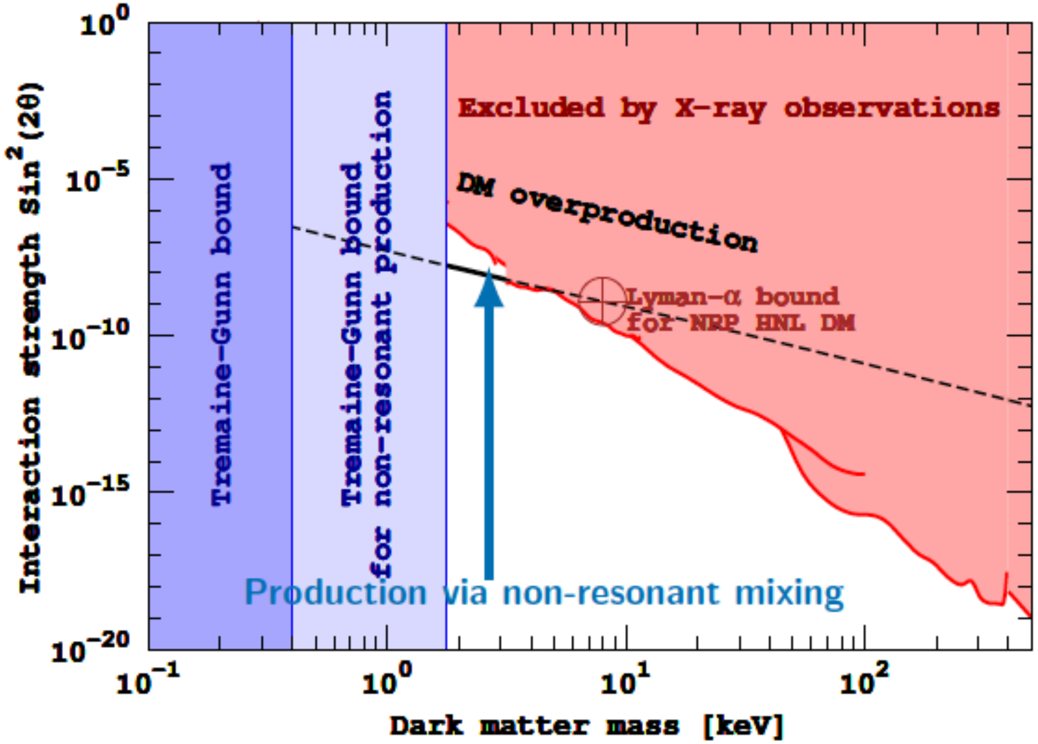


- Lifetime $\gg$ Age of the Universe (dotted line)
- Contribution to neutrino masses

$$m_{\odot} \sim U^2 M$$

[Asaka+'05; Boyarsky+'06]

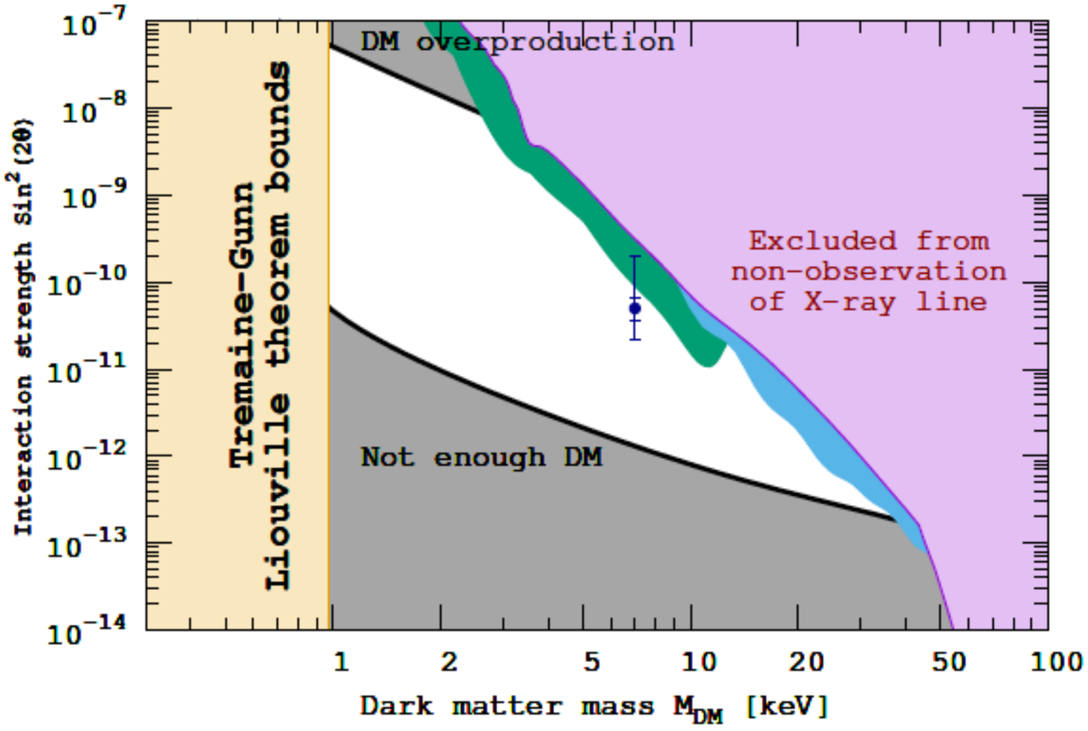
Parameter space of HNL dark matter II



- Production via non-resonant mixing
  [Dodelson & Widrow'93; Asaka, Laine, Shaposhnikov'06]
- Liouville bound (neglecting feedback from baryons)
  [Boyarsky, O.R. et al.'08; Gorbunov+'08]
- Lyman-α bound
  [Boyarsky, Lesgourgues, O.R., Viel'08]

- Production via mixing and decay signal depend on the same mixing angle U^2
- X-ray bounds grow very fast with mass (flux $\sim M_N^5$)

Parameter space of HNL dark matter III



- White region: production via **resonant** mixing [Shi & Fuller'93; Laine & Shaposhnikov'08]
- Requires: lepton asymmetry exceeding η_{baryon} by many orders of magnitude at $T \sim 100 - 500\,\mathrm{MeV}$

In summary

- HNL DM is **light** ($1 - 50$ keV) if there are no other particles
- Yukawa of HNL DM are tiny ($\mathcal{O}(10^{-10})$ or below)

Reminder: 3.5 keV line story

Two groups reported an identified feature in the X-ray spectra of dark matter-dominated objets

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10

ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

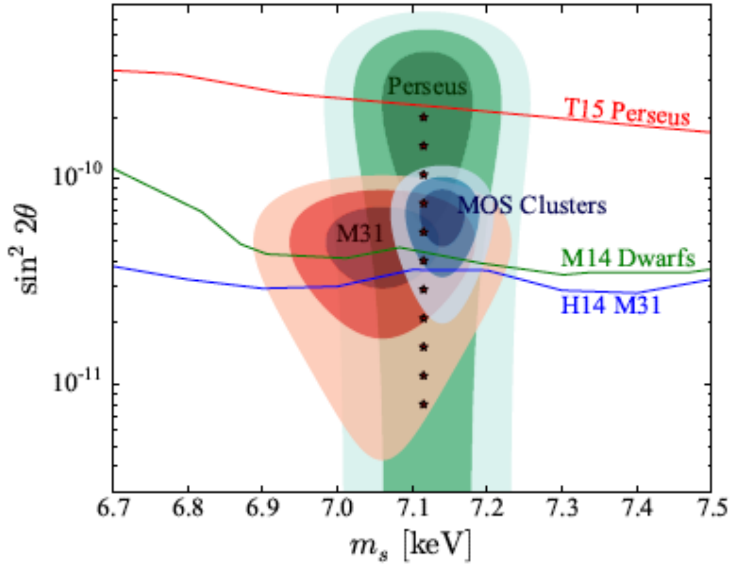
PRL (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30-50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
- **Possible origin:** decay $\mathrm{DM} \to \gamma + \nu$ (fermion) or $\mathrm{DM} \to \gamma + \gamma$ (boson)

Subsequent works

For overview see e.g. [1602.04816] "A White Paper on keV Sterile Neutrino Dark Matter"

- Subsequent works confirmed the presence of the 3.5 keV line in some of the objects
  Boyarsky O.R.+, Iakubovskyi+; Franse+; Bulbul+; Urban+; Cappelluti+
- challenged it existence in other objects
  Malyshev+; Anderson+; Tamura+; Sekiya+
- argued astrophysical origin of the line
  Gu+; Carlson+; Jeltema & Profumo; Riemer-Sørensen; Phillips+



[1507.06655]

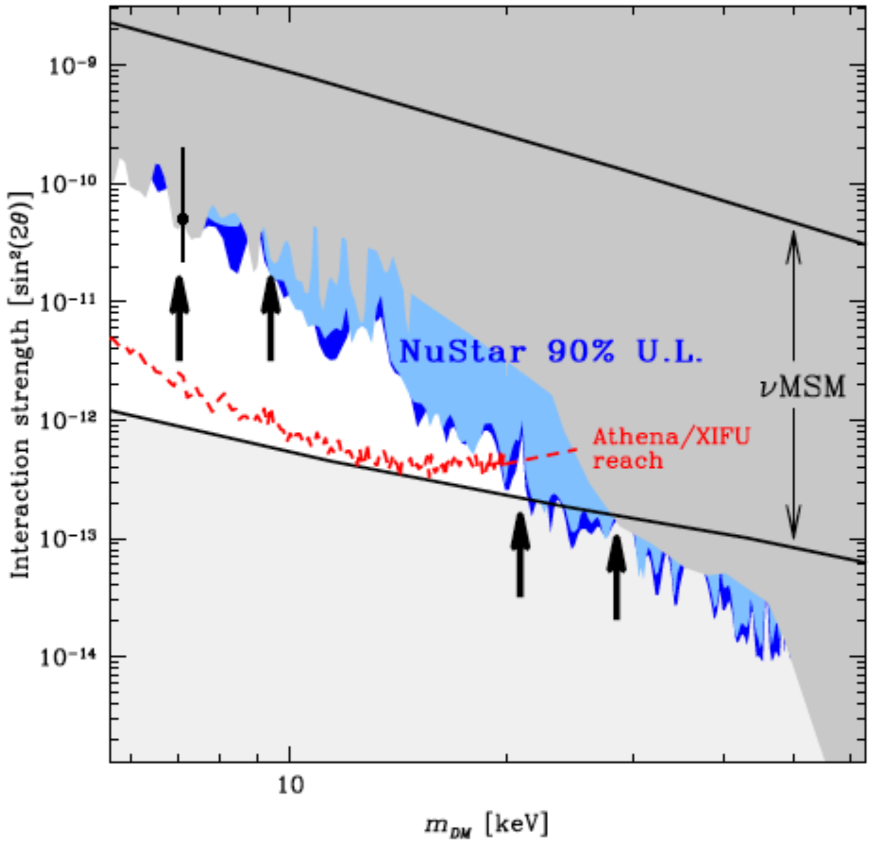
A common explanation for every detection and non-detection?

- When comparing bounds from different objects one should be careful — dark matter content in each of them uncertain by a factor $2-3$

Line in NuStar

Milky Way halo. Neronov & Malyshev [1607.07328]. Also Ng+ [1609.00667]

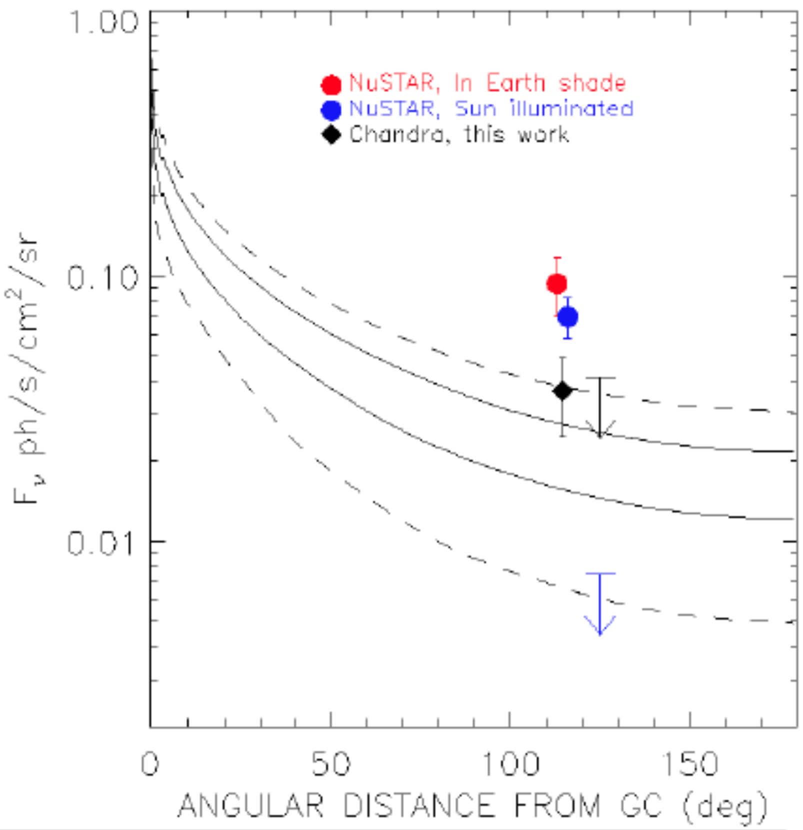
- The 3.5 keV is present in the spectrum with 11σ significance
- The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band
- The 3.5 keV line has been previously attributed to reflection of the sunlight on the telescope structure
- However, in the dataset when Earth shields satellite from the Sun the line is present with the same flux



Line in Chandra

Cappelluti+'17

- Most recently: 10 Msec of Chandra observation of Chandra Deep Fields
- 3σ detection of a line at ~ 3.5 keV
- If interpreted as dark matter decay – this is a signal from Galactic halo outskirts ($\sim 115°$ off center)
- Chandra has mirrors made of Iridium (rather than Gold as XMM or Suzaku) – absorption edge origin becomes unlikely

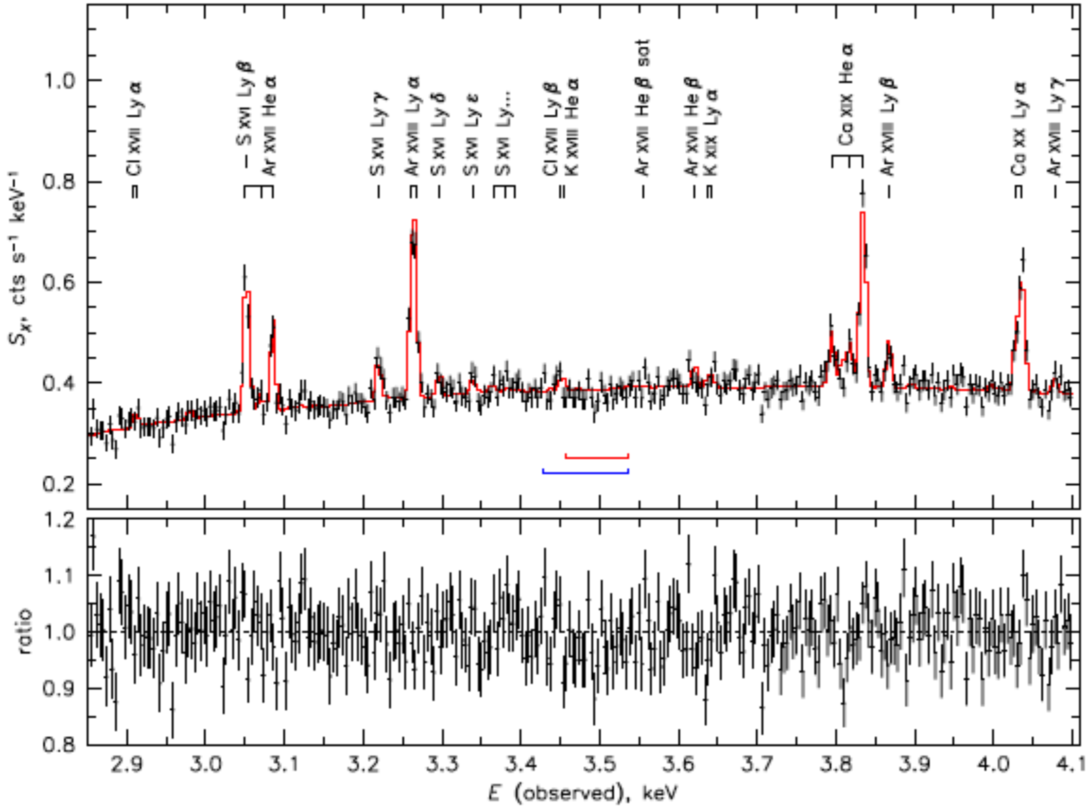


By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely

Next step for 3.5 keV line: resolve the line

- Astro-H/Hitomi – new generation X-ray spectrometer with a superb spectral resolution
- Launched February 17, 2016
- ☹ Lost few weeks later
- Before its failure observed the center of Perseus galaxy cluster
- The observations was in calibration phase (additional filters block most of X-ray below 3 keV)

Perseus center spectrum [1607.07420]



What did we learn with existing Hitomi data?

- Due to its super energy resolution, *Hitomi* can distinguish between atomic line broadening (thermal velocities $\sim 10^2\,\mathrm{km/sec}$) and decaying dark matter line broadening (virial velocity $\sim 10^3\,\mathrm{km/sec}$)
- Even the short observation of Hitomi showed that Potassium, Clorium, etc. do not have super-solar abundance in Perseus cluster $\Rightarrow$ 3.5 keV line is **not** astrophysical
- Bounds much weaker for a **broad** (dark matter) line $\Rightarrow$ not at tension with previous detections

- This does not seem to be astrophysics (Hitomi spectrum)
- This does not seem to be systematics (4 different instruments)
- ???

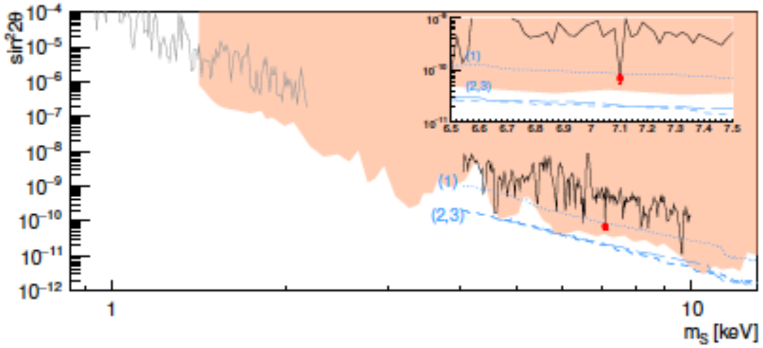
Future of decaying dark matter searches in X-rays

Another Hitomi

JAXA is planning to send a replica of Hitomi satellite (within about 2 years)

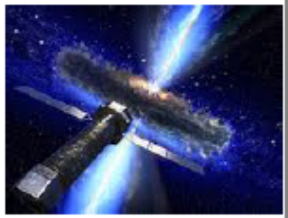
Microcalorimeter on sounding rocket (2017)

- Large field-of-view and very high spectral resolution
- Can resolve narrow lines from diffuse sources
- Flying time $\sim 10^2$ sec



Athena+

- Large ESA X-ray mission (2028) with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)



ALPs

Physics case for axions: Strong CP problem

> Most general gauge invariant Lagrangian of QCD up to dimension four:

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \overline{q} \left(i\gamma_\mu D^\mu - \mathcal{M}_q \right) q - \frac{\alpha_s}{8\pi} \, \theta \, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

- Fundamental parameters of QCD: strong coupling α_s, quark masses m_u, m_d, ..., and theta parameter

$$\overline{\theta} = \theta + \arg \det \mathcal{M}_q$$

> Theta term $\propto G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$ odd under P and T, i.e. leads to CP violation in flavor conserving interactions

> Most sensitive probe of P and T violation in flavor conserving interactions: electric dipole moment (EDM) of neutron; experimentally

$$|d_n| < 2.9 \times 10^{-26} \; e \, \mathrm{cm}$$

> Strong CP problem:

$$d_n(\overline{\theta}) \sim \frac{e \overline{\theta} m_u m_d}{(m_u + m_d) m_n^2} \sim 6 \times 10^{-17} \; \overline{\theta} \; e \, \mathrm{cm} \Rightarrow |\overline{\theta}| \lesssim 10^{-9}$$

Physics case for axions: Strong CP problem

- Peccei-Quinn solution of strong CP problem based on observation that the vacuum energy in QCD, inferred from effective chiral Lagrangian,

$$V(\bar{\theta}) = \frac{m_\pi^2 f_\pi^2}{2} \frac{m_u m_d}{(m_u + m_d)^2} \bar{\theta}^2 + \mathcal{O}(\bar{\theta}^4)$$

  has localised minimum at vanishing theta parameter:

  If theta were a dynamical field, its vacuum expectation value (vev) would dynamically relax to zero

- Introduce field a(x) as dynamical theta parameter, enjoying a shift symmetry, $a \to a + \text{const.}$, broken only by anomalous couplings to gauge fields,

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu a \, \partial^\mu a - \frac{\alpha_s}{8\pi} \left(\bar{\theta} + \frac{a}{f_a} \right) G^b_{\mu\nu} \tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \ldots$$

  - Can eliminate theta by shift $a(x) \to \bar{a}(x) \equiv a(x) + \bar{\theta} f_a$; QCD dynamics (see above) leads to vanishing vev, $\langle \bar{a} \rangle = 0$, i.e. P, T, and CP conserved
  - Elementary particle excitation of field around vev: axion (Weinberg 78; Wilczek 78)

Physics case for axions: Strong CP problem

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{\alpha_s}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma}\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

- For large decay constant f_a: prime paradigm of a WISP (Kim 79; Shifman et al 80; Zhitnitsky 80; Dine et al 81)

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(C_{a\gamma} - \frac{2}{3}\frac{m_u + 4m_d}{m_u + m_d}\right) \sim 10^{-12}\ \mathrm{GeV}^{-1}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

$$m_a = \frac{m_\pi f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\mathrm{meV} \times \left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

- Strong constraints from astrophysics (non-excessive energy loss of stars):

$$f_a \gtrsim 10^9\ \mathrm{GeV}$$

Physics case for axions and ALPs: NGBs of SSB

- In 4D field theoretic extensions of the Standard Model (SM), axion field realised as phase of a complex $SU(2)_L \times U(1)_Y$ singlet scalar field whose vev breaks a global anomalous chiral $U(1)_{\rm PQ}$ symmetry,

$$\Phi(x) = \frac{v_{\rm PQ} + \rho(x)}{\sqrt{2}}\, {\rm e}^{ia(x)/f_a}$$

  - At energies much below the symmetry breaking scale $v_{\rm PQ}$ the low-energy effective field theory is that of a (pseudo-)Nambu-Goldstone Boson (NGB) with decay constant

$$f_a = v_{\rm PQ}/C_{ag}$$

- More axion-like particles (ALPs) may arise as NGBs from the breaking of more than one anomalous $U(1)_{\rm PQ}$

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu a_i\,\partial^\mu a_i - \frac{\alpha_s}{8\pi}\left(\bar\theta + C_{ig}\frac{a_i}{f_{a_i}}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{i\gamma}\frac{a_i}{f_{a_i}}\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

Photon/axion conversions

- 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

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

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

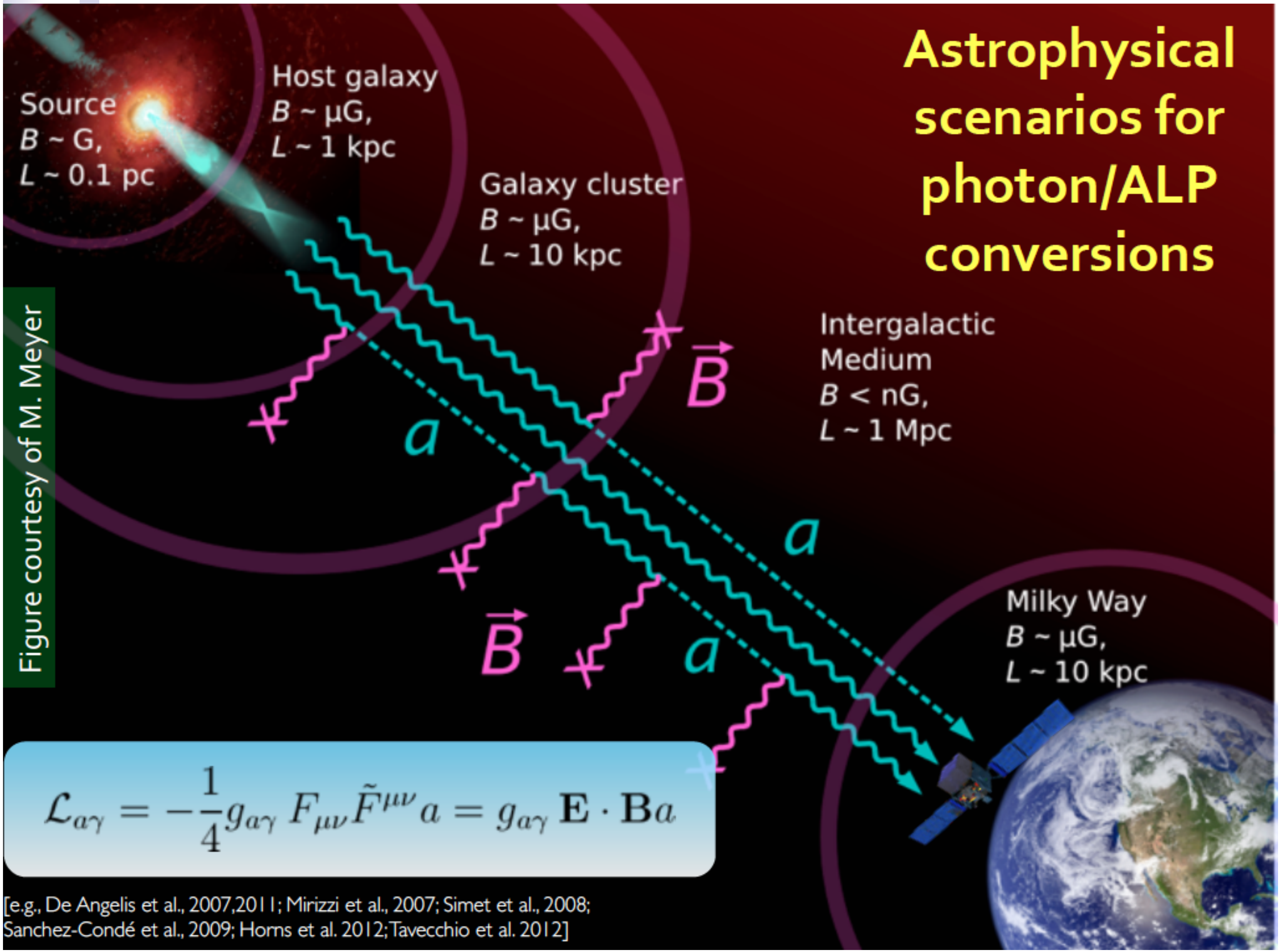
Photon/axion conversions the main vehicle used in axion searches at present (ADMX, CAST...).

Some astrophysical environments fulfill the mixing requirements

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

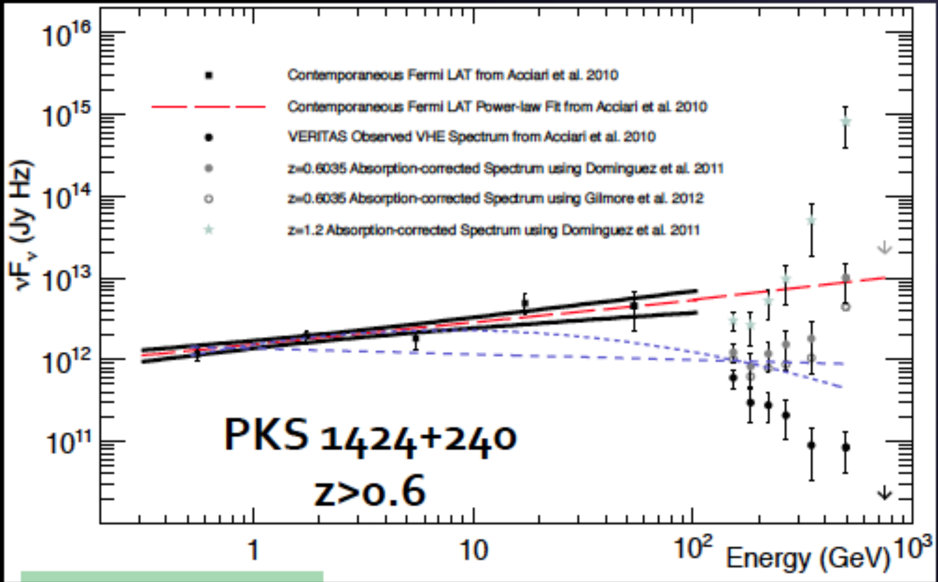
$M_{11} \geq 0.114$ GeV (CAST limit)

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

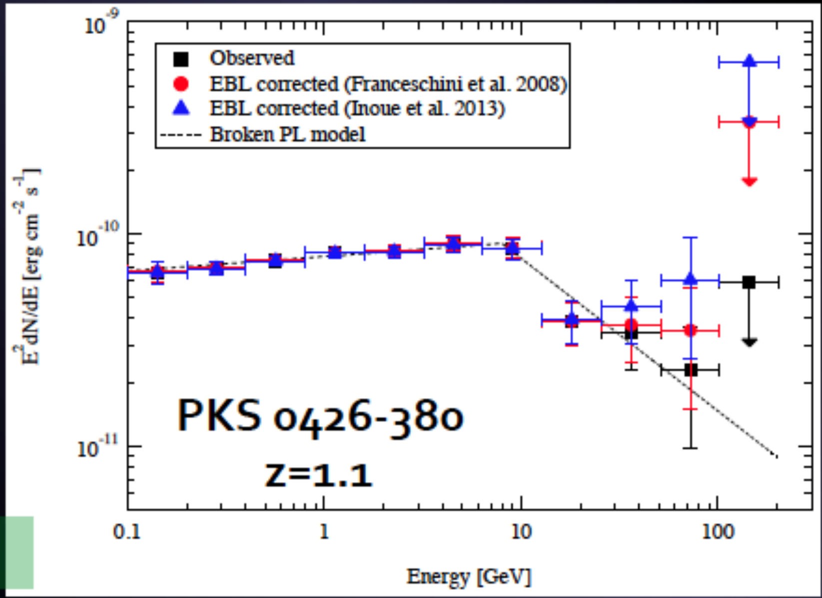

Astrophysical scenarios for photon/ALP conversions
Source
$B \sim$ G,
$L \sim 0.1$ pc
Host galaxy
$B \sim \mu$G,
$L \sim 1$ kpc
Galaxy cluster
$B \sim \mu$G,
$L \sim 10$ kpc
Intergalactic Medium
$B <$ nG,
$L \sim 1$ Mpc
Milky Way
$B \sim \mu$G,
$L \sim 10$ kpc
a
$\vec{B}$
Figure courtesy of M. Meyer
$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$
[e.g., De Angelis et al., 2007,2011; Mirizzi et al., 2007; Simet et al., 2008; Sanchez-Condé et al., 2009; Horns et al. 2012; Tavecchio et al. 2012]

Hints of new Physics in γ-ray data?
SPECTRAL "HARDENING" at high τ

Some de-absorbed, *intrinsic* AGN spectra are best described by power laws with spectral indices smaller than 1.5 – too "hard" AGN spectra



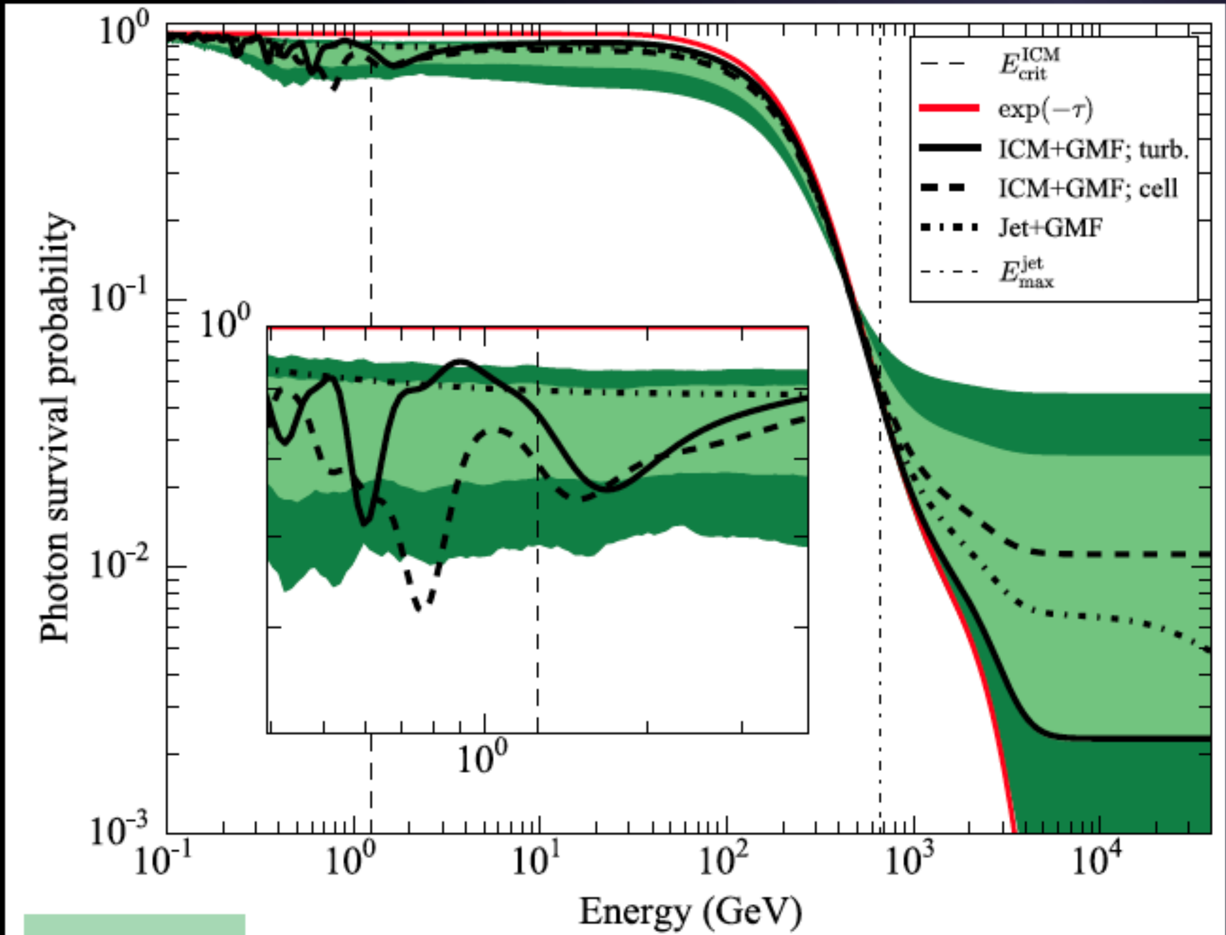
Furniss+13c



Tanaka+13

Note that the last data points give τ ~ 5 !!

ALPs modify the spectrum of AGNs



Meyer+14

PG 1553+113

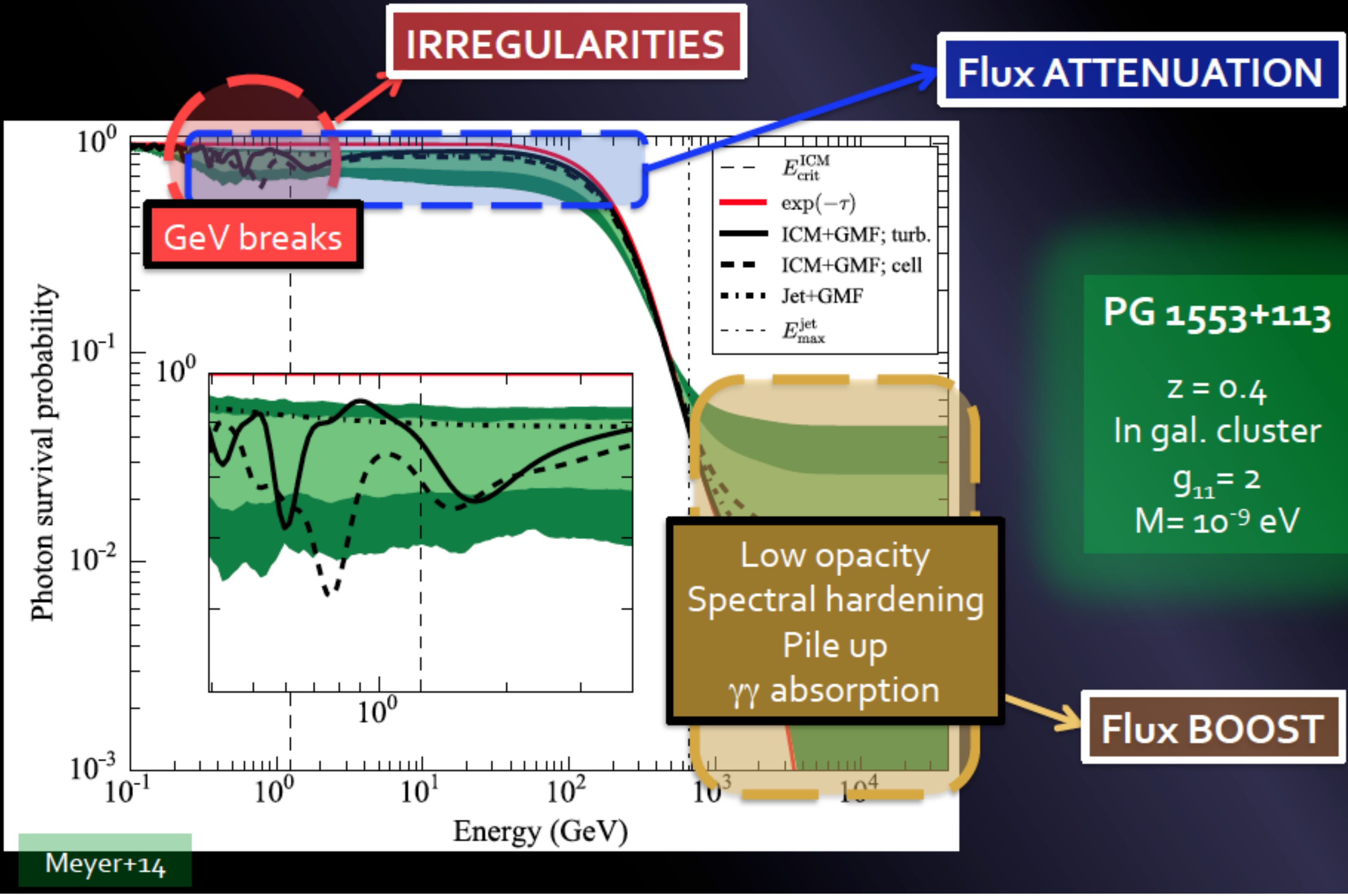
z = 0.4

In gal. cluster

$g_{11} = 2$

$M = 10^{-9}$ eV

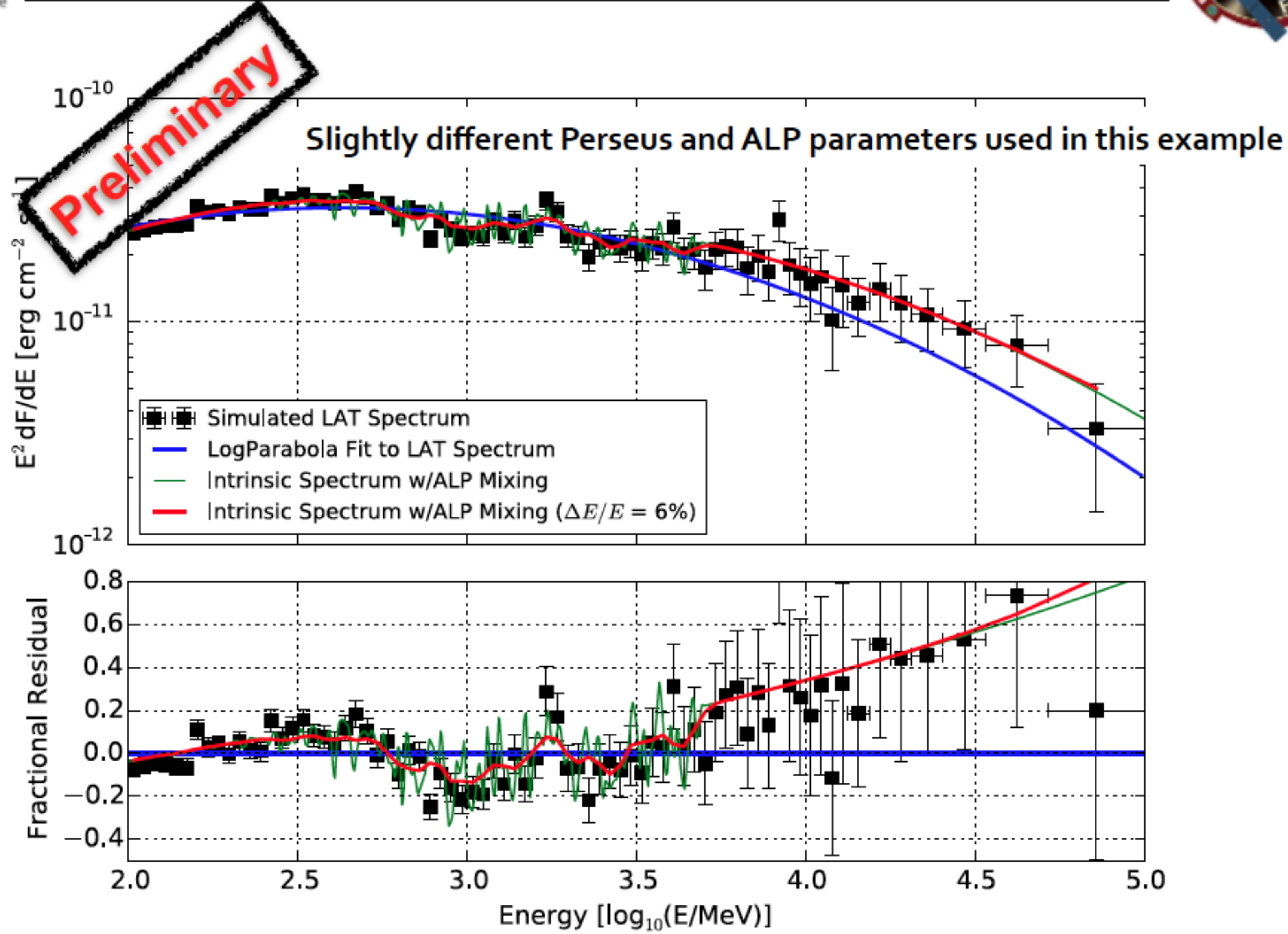
ALPs could explain these anomalies



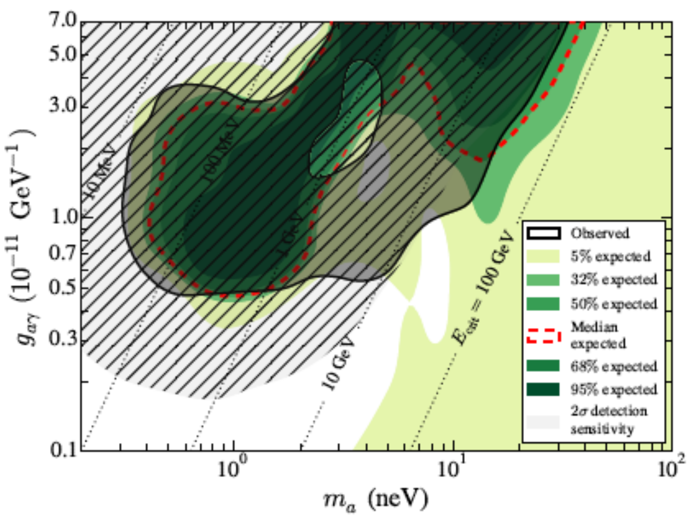
PG 1553+113

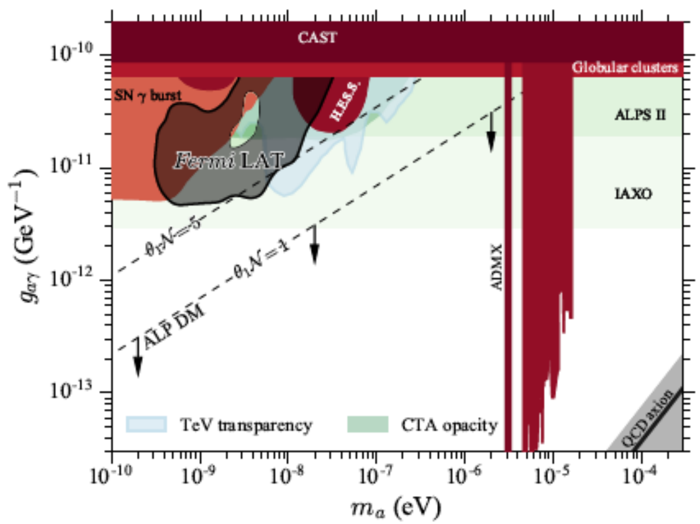
z = 0.4
In gal. cluster
g_{11}= 2
M= 10^{-9} eV

Simulated LAT spectrum of NGC1275 including Axion-like particles



Fermi search for ALPs





WIMPs

Dark Matter Abundance (WIMP)

Basic Concepts

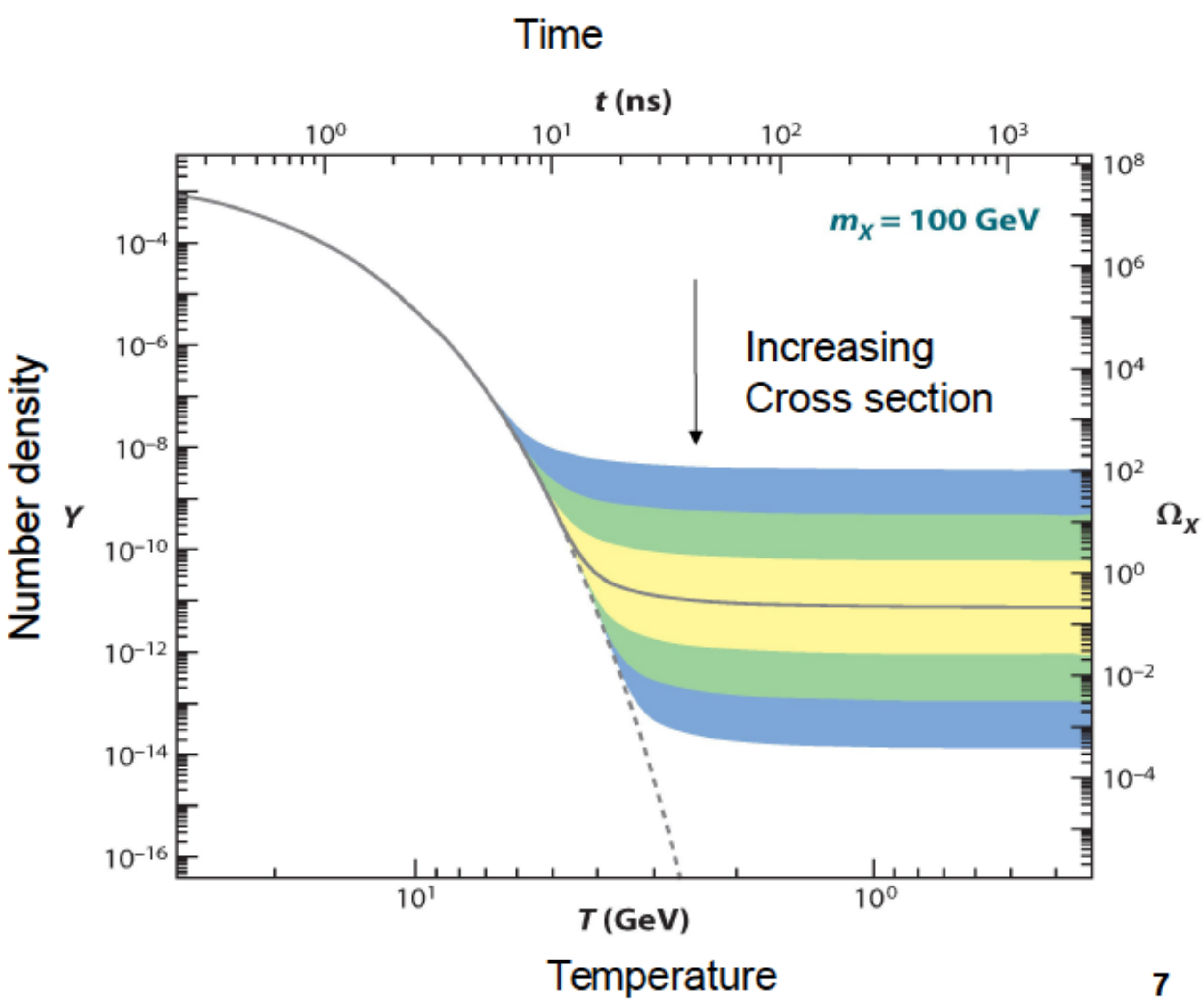
A. dark matter particles could interact with standard model particles and reach thermal equilibrium. **Non-thermal processes are also OK.**

B. After the universe cooled down and expanded, eventually the expansion rate equaled the interaction rate → freeze-out.

C. After the freeze-out the dark matter particles clustered forming the structures we observe today.

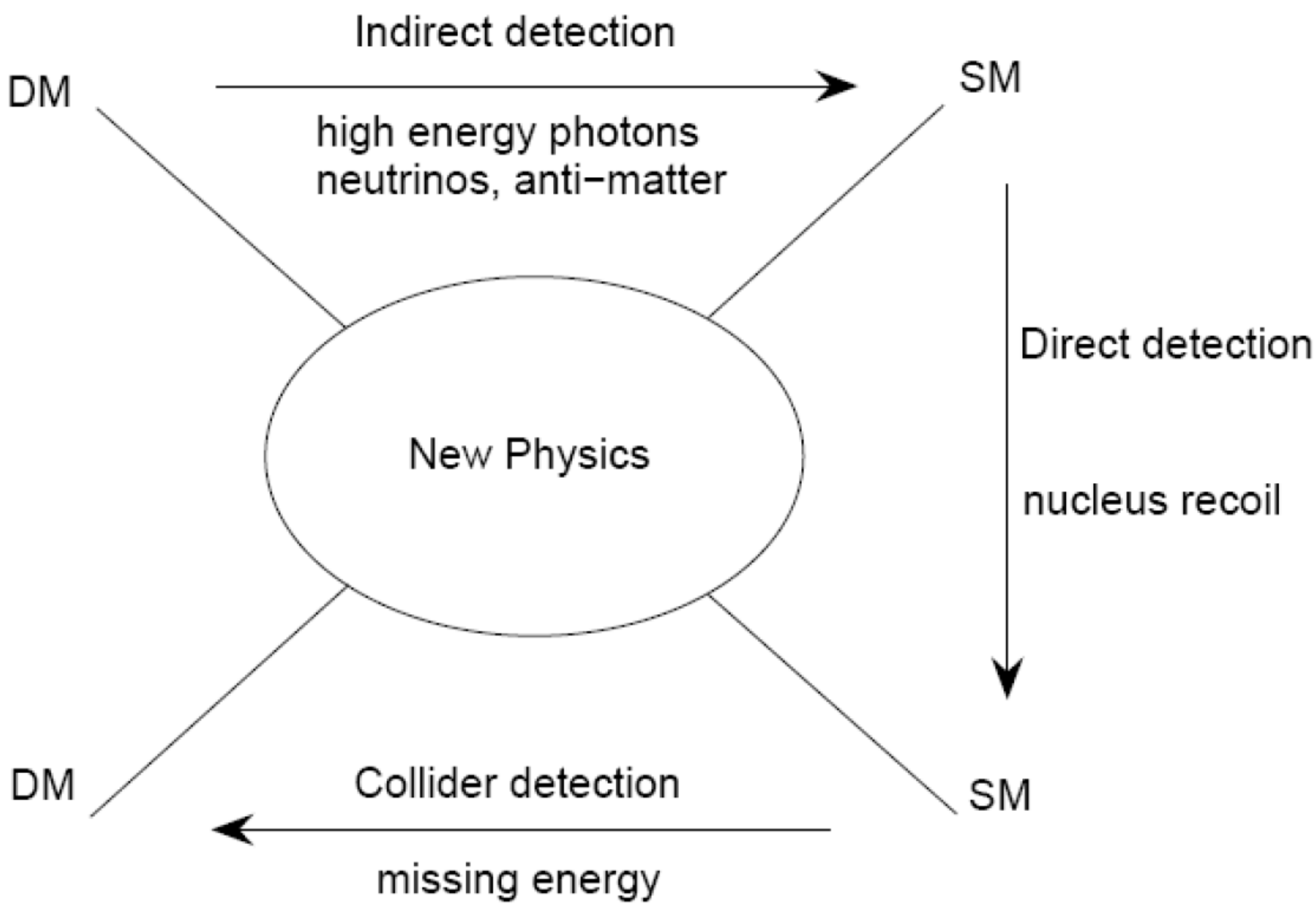
D. In the WIMP paradigm the abundance is connected to the annihilation cross section at freeze-out.

Right relic abundance → Annihilation cross section at the weak scale



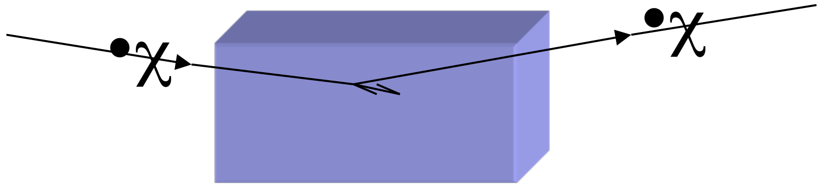
The methods of detecting Dark Matter

Detection of particle dark matter

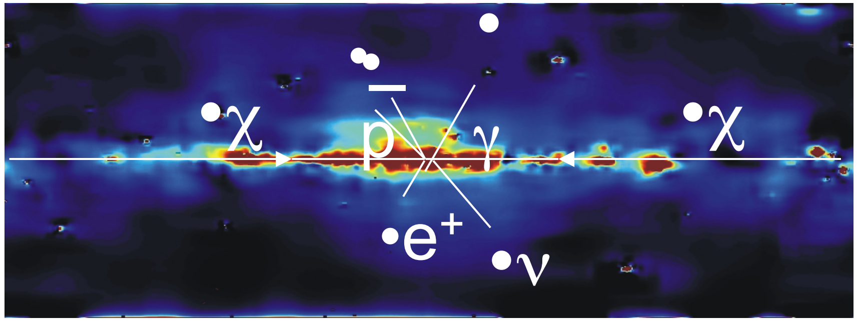


The detection of dark matter

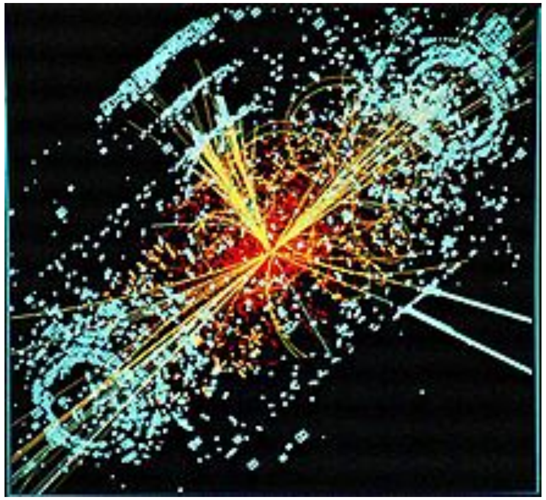
- Direct detection ：
  PandaX, CDEX, Xenon, CDMS, DAMA, COGENT and so on



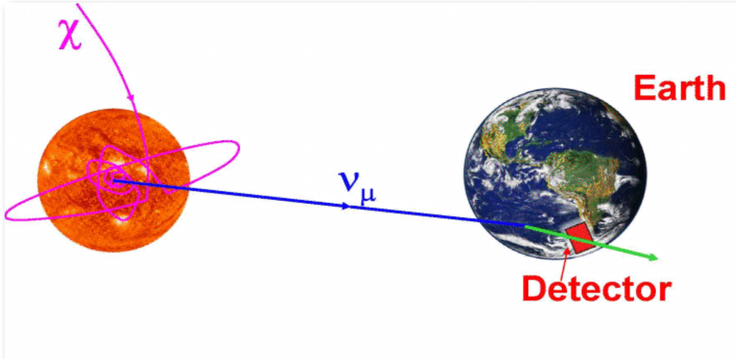
- Indirect detection ：
  Pamela ,ATIC, Fermi, HESS, AMS02, DAMPE and so on



- Collider: LHC



Indirect Detection of Dark Matter



Neutrinos
in the core of the Sun

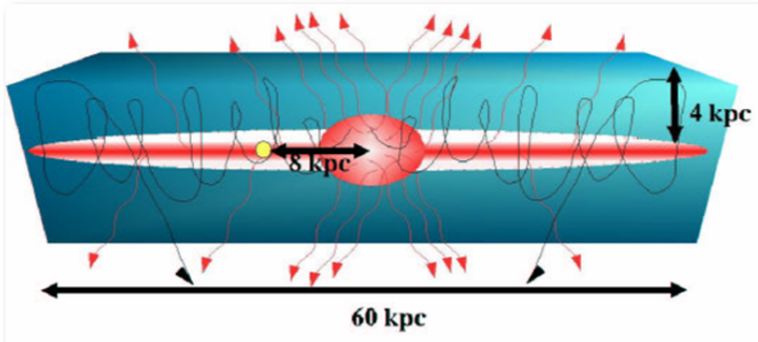
Gamma Rays from annihilations
in the galactic halo, near the

galactic center, in dwarf galaxies, etc.

Positrons/Antiprotons from annihilations
throughout the galactic halo

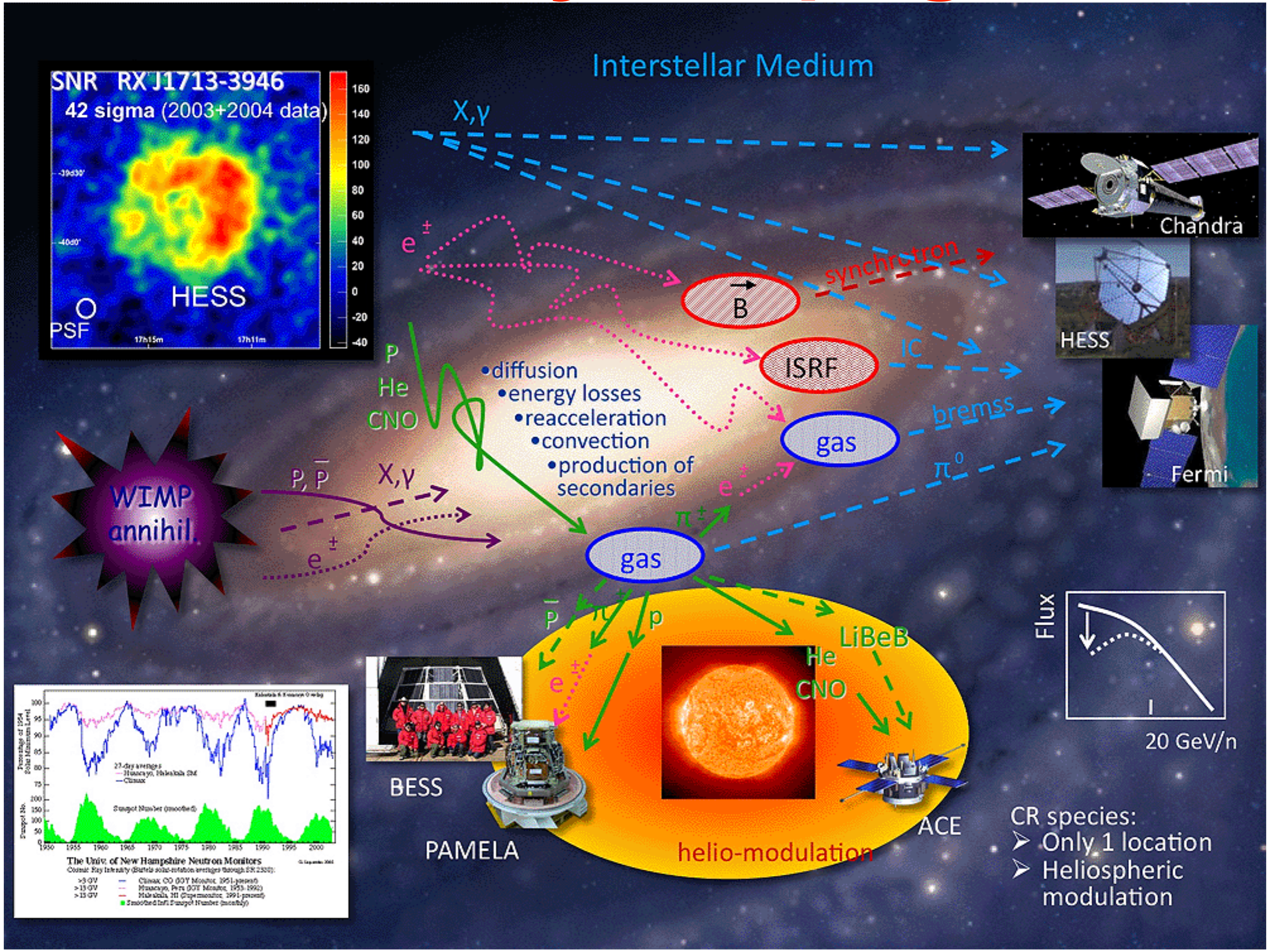
Synchrotron Radiation from electron/
positron interactions with the
magnetic fields of the inner

galaxy

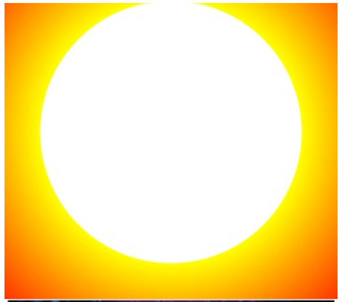


•**From Dan Hooper**

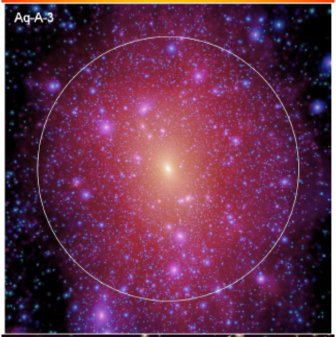
•Cosmic Ray Propagation



•Targets to detect dark matter particles

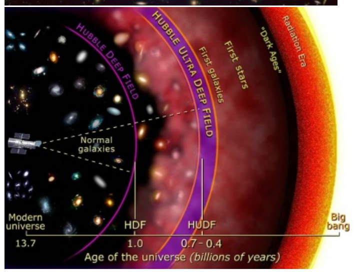


•Sun

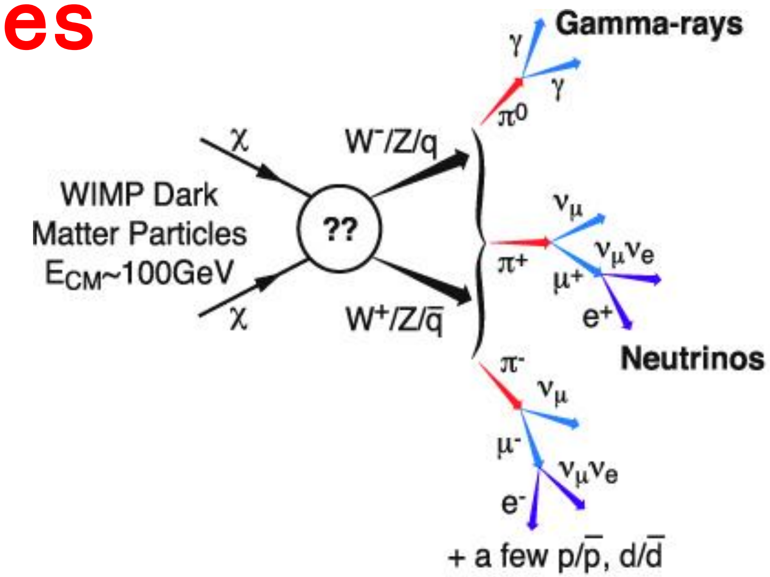


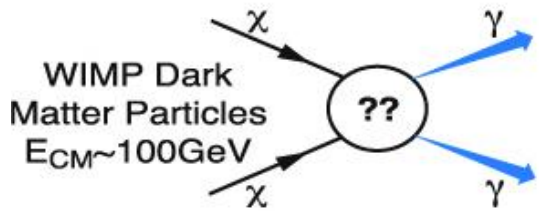
•Galaxy

•Galaxy Cluster



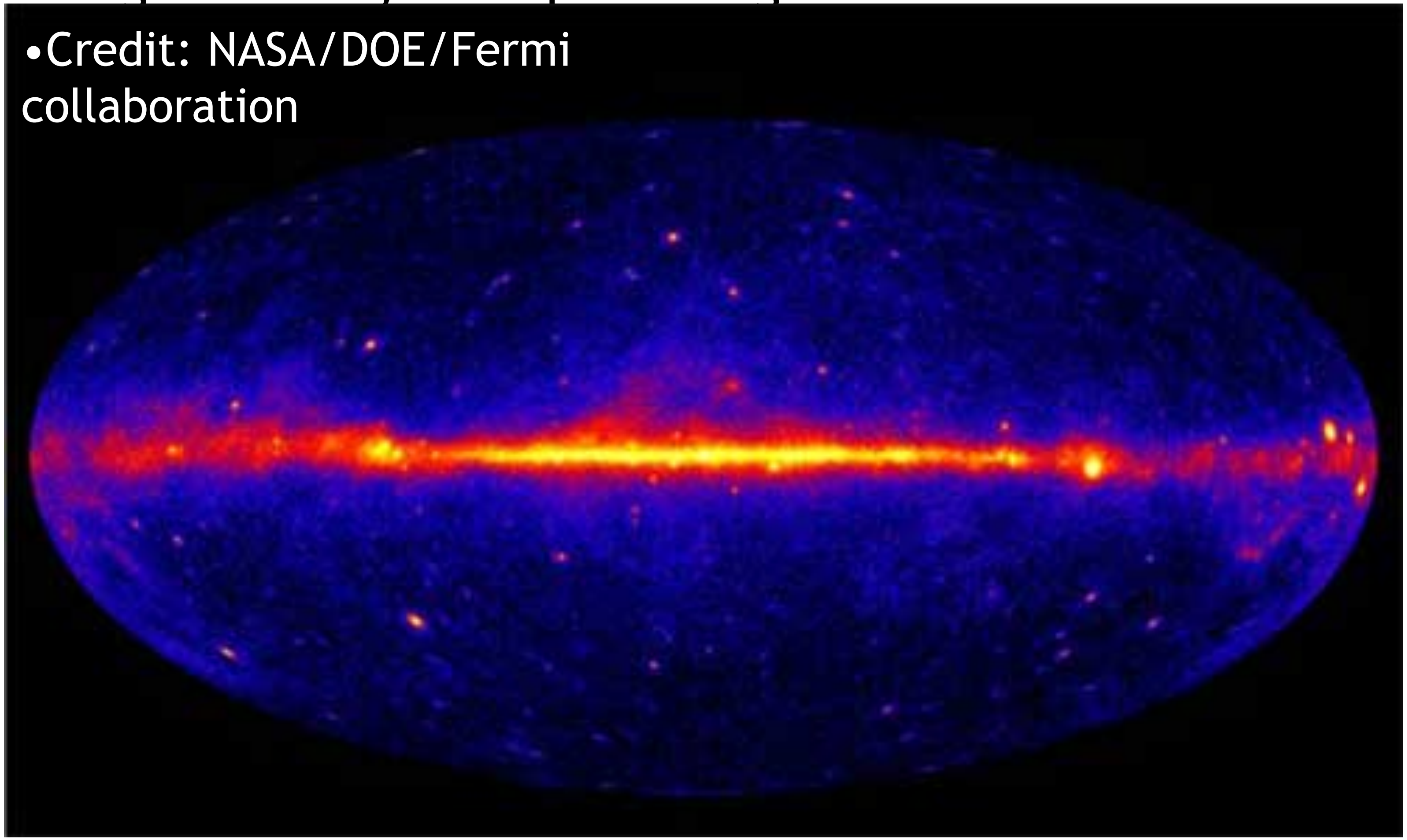
•Deep extragalactic space and early Universe





•Baltz et al. 2008

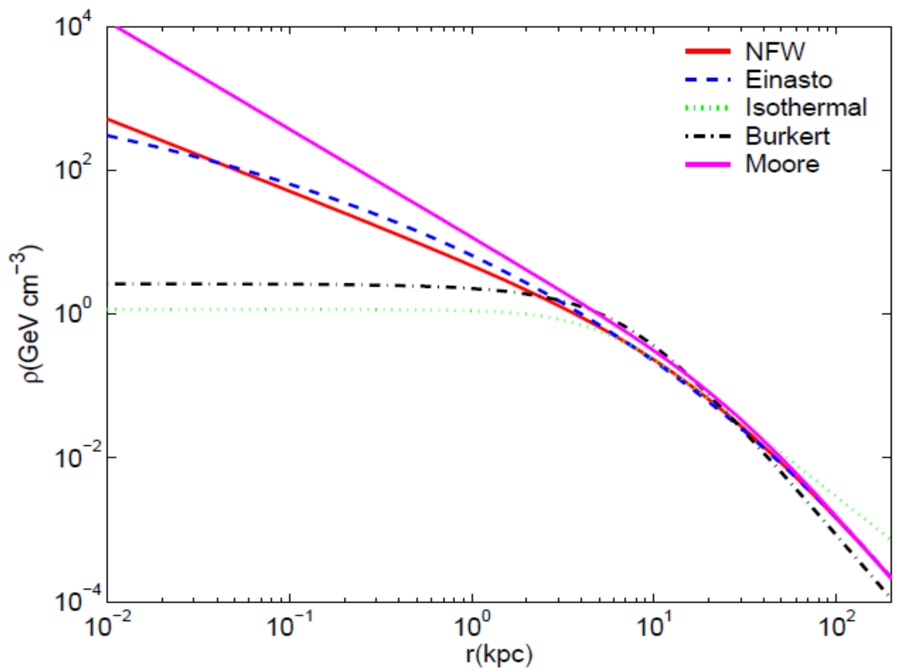
• Fermi gamma-rays can provide good test of the DM models



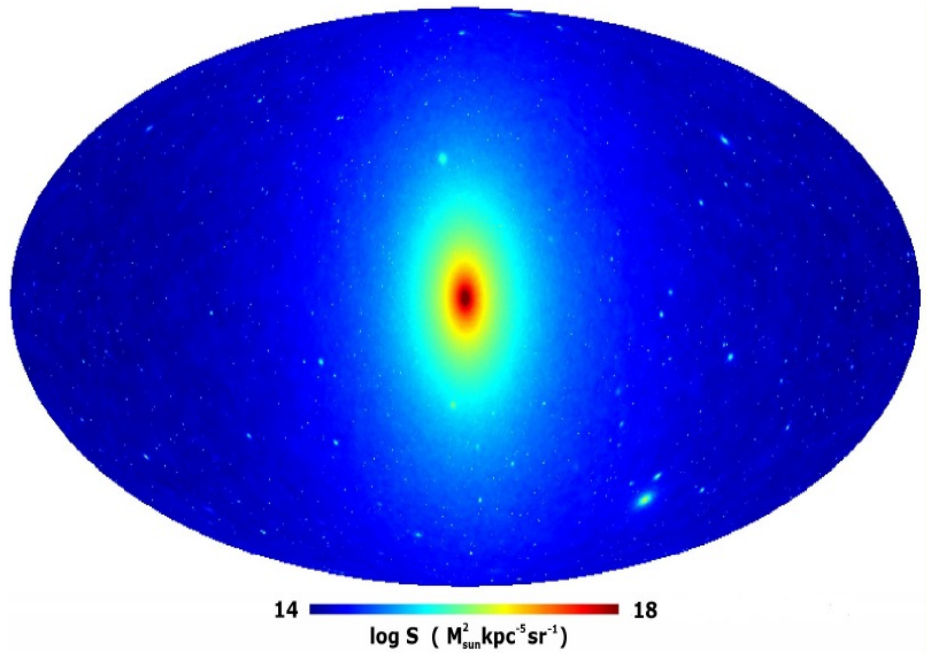
- Galactic center
- Galactic halo
- Dwarf galaxies

- Clusters
- Extra-galactic diffuse
- Line search

The gamma-ray sky map produced by dark matter annihilation in our Galaxy

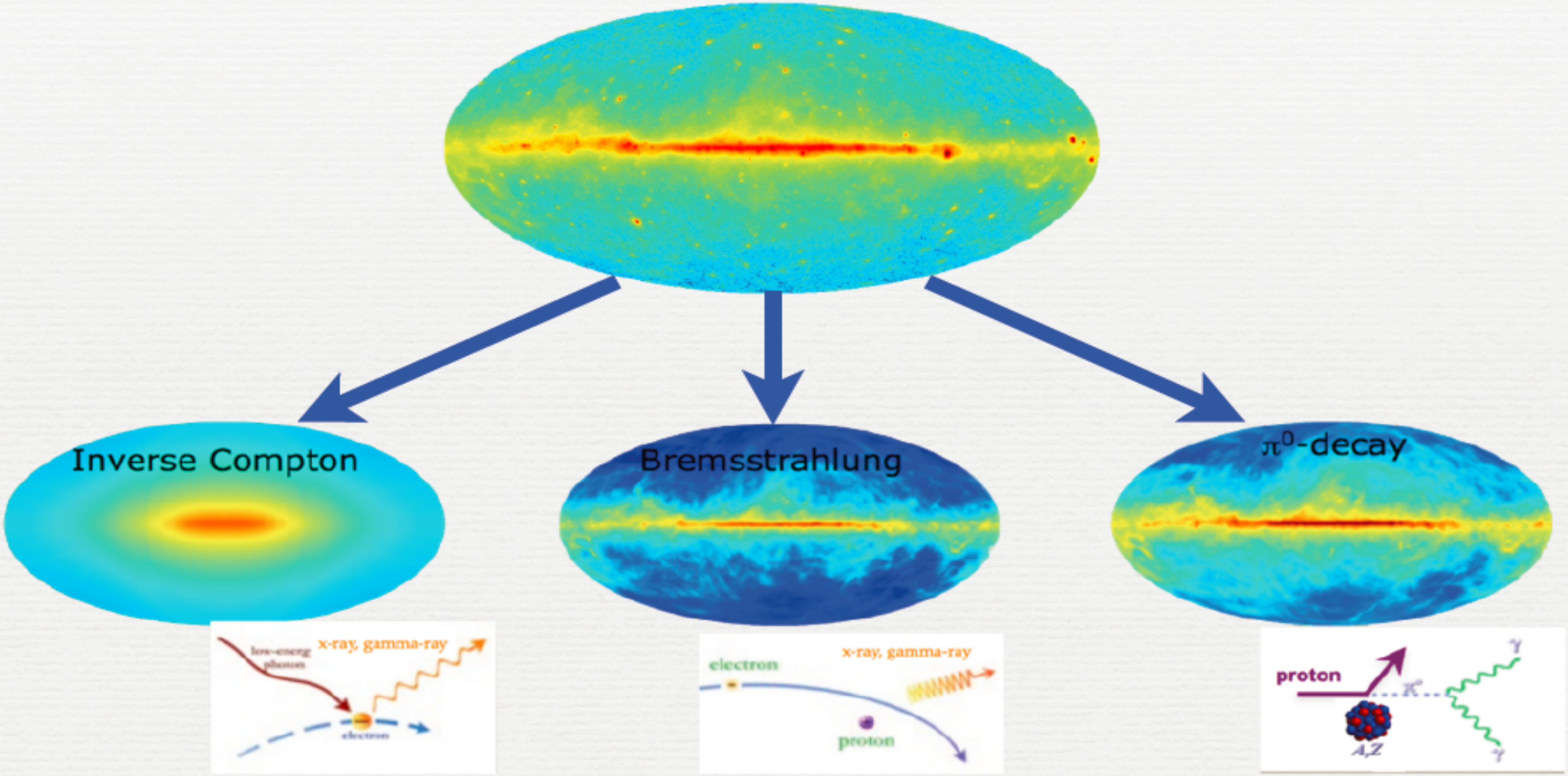


•The J-Factor of different dark matter profile models.



•The Galaxy center is the best region to detect dark matter.

Diffuse Galactic γ-ray Emission: Origin



Dark Matter Annihilation: Gamma-ray Excess at the Galactic Center

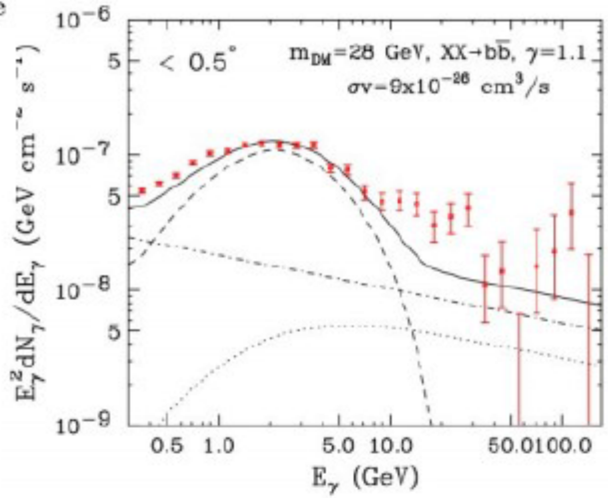
First observation (2009)

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

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[3] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm^3/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astro-



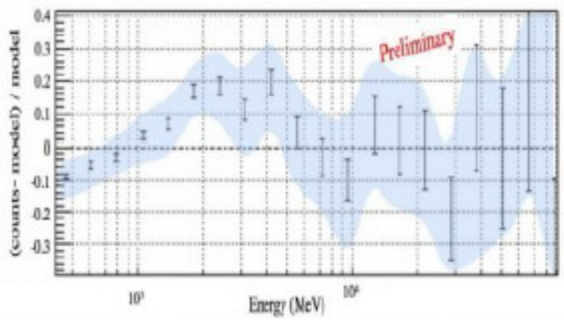
First Fermi-LAT team members – report (2009)

2009 Fermi Symposium, Washington, D.C., Nov. 2-5

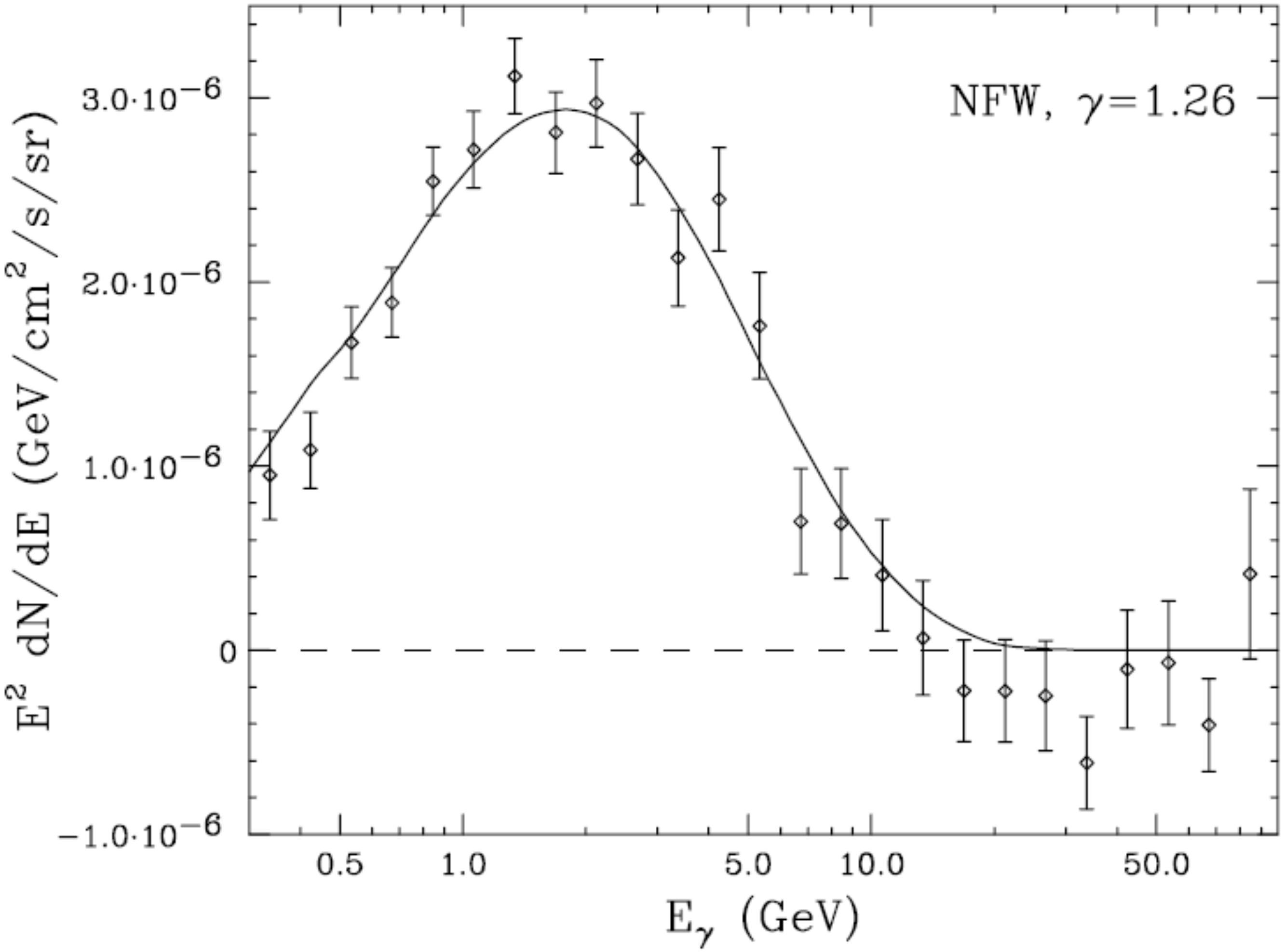
Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy

...is reported. The diffuse gamma ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models.
An improved model of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.

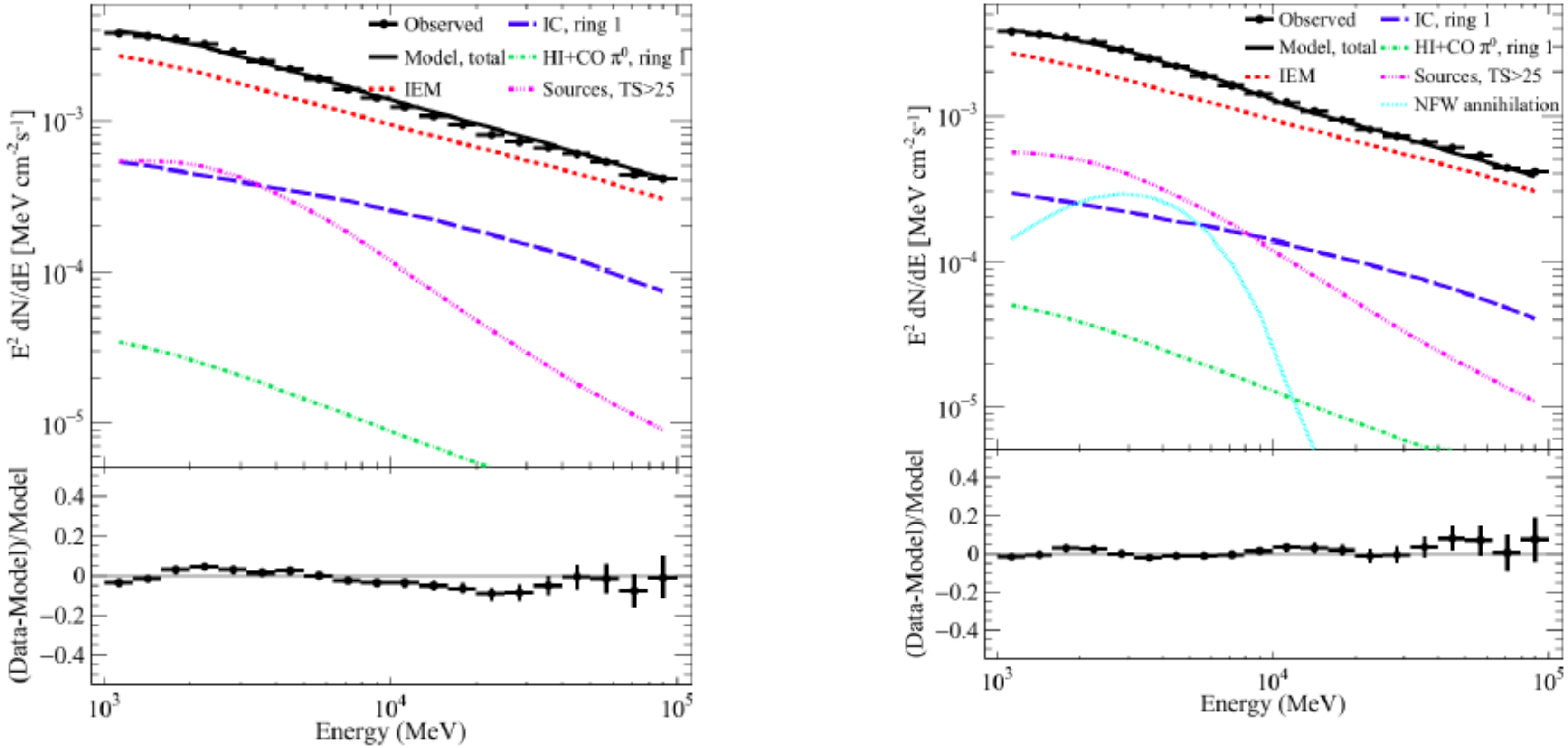


The GeV Excess



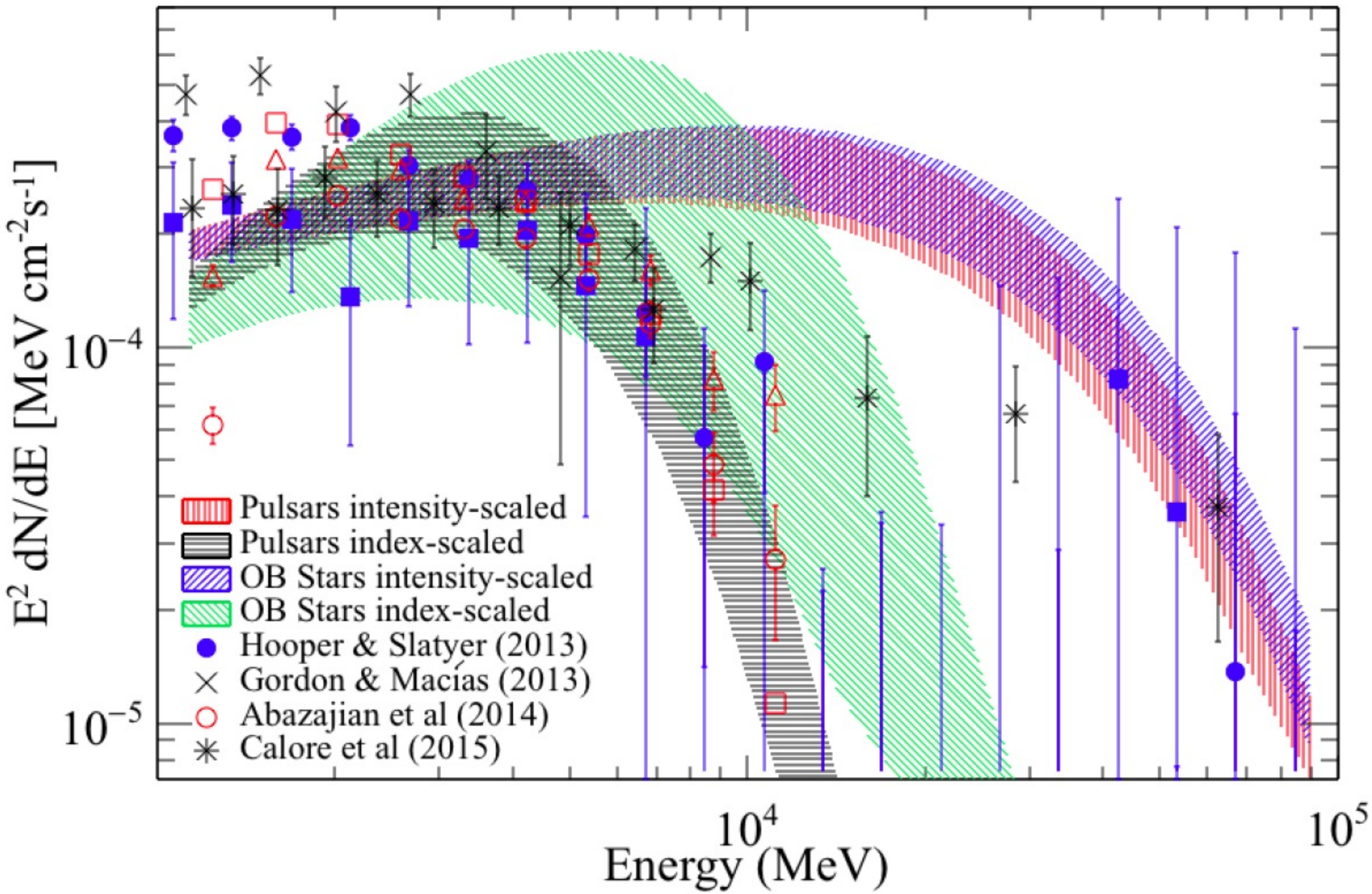
• Daylan et al. 2015

The GeV Excess



•Fermi collaboration 2015

GeV excess in Fermi Pass 8 data

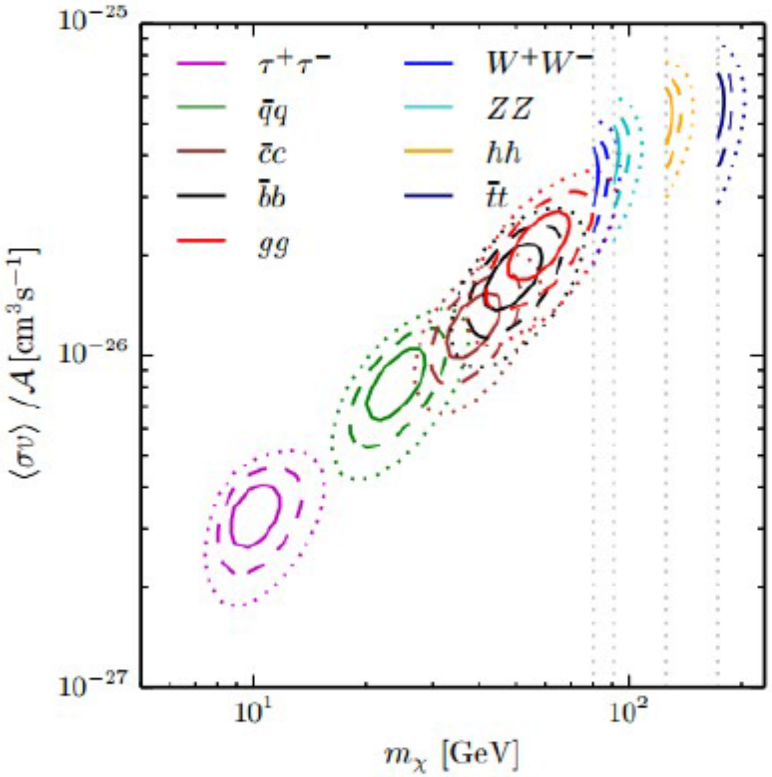


arXiv:1511.02938v1

Gamma-ray Excess in the Galactic Center

Interpretations

Dark Matter



F. Calore et al, 1411.4647

Many dark matter models fit the Galactic excess easily, but only some are consistent with direct detection and collider bounds.

Other Sources

1. Young Pulsars

   K. N. Abazajian+, 1402.4090.
   R. Bartels+, 1506.05104;
   S. Lee+,1506.05124;

2. Collisions between gas with protons accelerated by a black holes.

   T. Linden+, 1203.3539;
   O. Macias+, 1410.1678

3. Collisions between gas with cosmic-rays (e.g. non-thermal bremsstrahlung from a population of electrons scattering off neutral molecular clouds)

   F. Yusef-Zadeh+,1206.6882

4. Series of Burst-like events during an active past of our galaxy

   E. Carlson+,1405.7685
   J. Petrovic+, 1405.7928

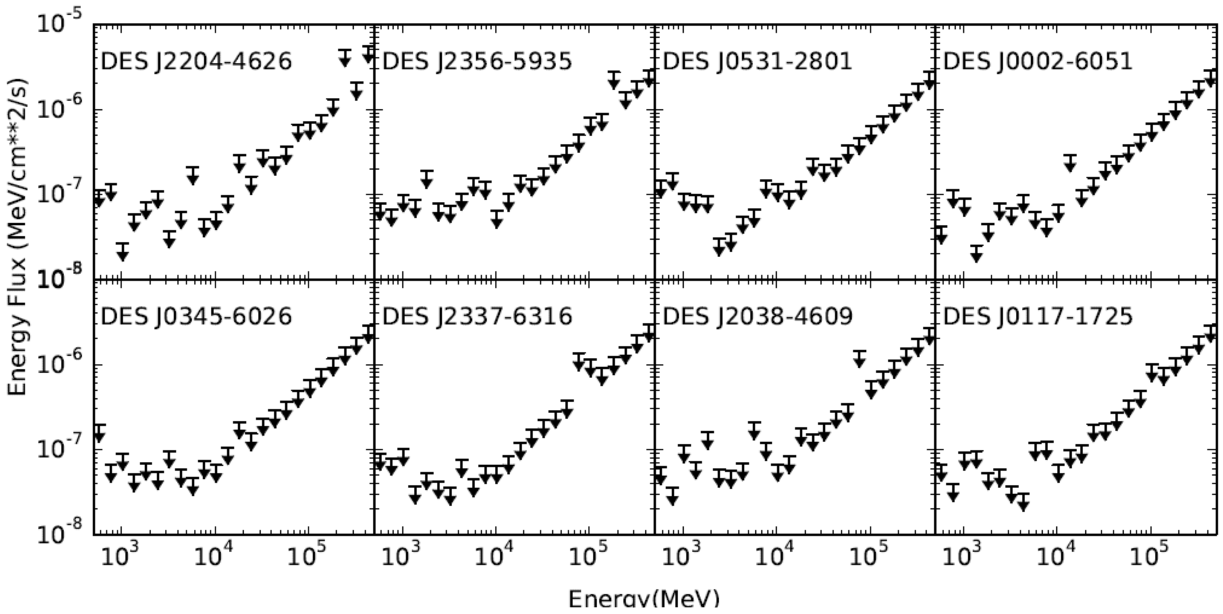
5. Different distributions of distribution cosmic-ray sources

   E. Carlson+,1510.04698
   D. Gaggero+, 1507.06129

GeV Excess in the dwarf galaxies?

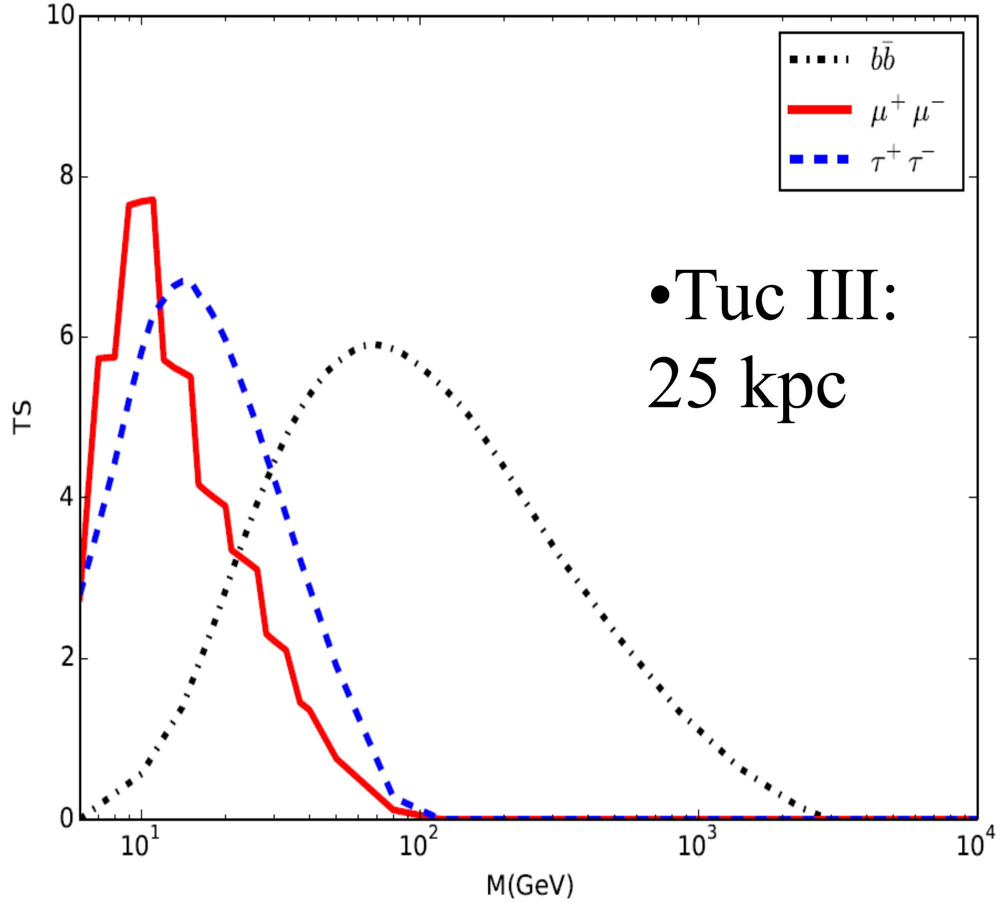
TABLE I: DES2 dSph Candidates and the Estimated J-factors

Name	$(l, b)^a$ (deg)	Distance^b (kpc)	$\log_{10}$ (Est.J)^c $\log 10(\mathrm{GeV}^2\mathrm{cm}^{-5})$
DES J2204-4626	(351.15,-51.94)	53 ± 5	18.8
DES J2356-5935	(315.38,-56.19)	25 ± 2	19.5
DES J0531-2801	(231.62,-28.88)	182 ± 18	17.8
DES J0002-6051	(313.29,-55.29)	48 ± 4	18.9
DES J0345-6026	(273.88,-45.65)	92 ± 13	18.3
DES J2337-6316	(316.31,-51.89)	55 ± 9	18.8
DES J2038-4609	(353.99,-37.40)	214 ± 16	17.6
DES J0117-1725	(156.48,-78.53)	30 ± 3	19.3



- Shang Li 1511.09252

•GeV Excess in the Dwarf Galaxies?



•(Li, S. et al. 2016)

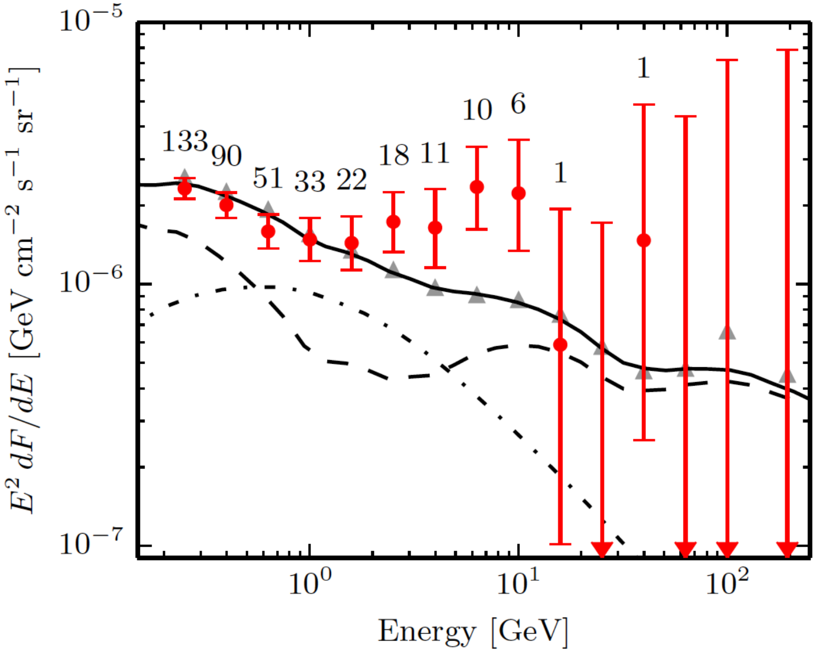
Evidence for Gamma-ray Emission from the Newly Discovered Dwarf Galaxy Reticulum 2

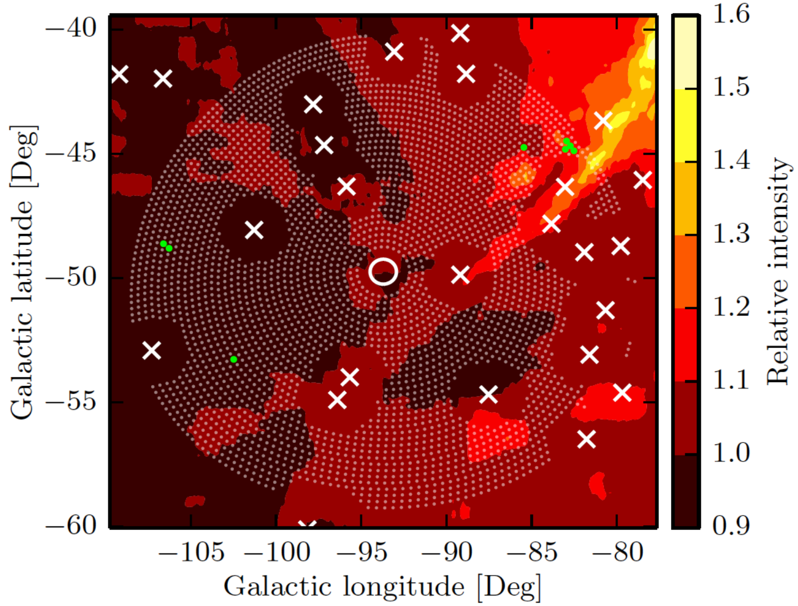
Alex Geringer-Sameth[*] and Matthew G. Walker[†]
McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Savvas M. Koushiappas[‡]
Department of Physics, Brown University, Providence, RI 02912, USA

Sergey E. Koposov, Vasily Belokurov, Gabriel Torrealba, and N. Wyn Evans
Institute of Astronomy, University of Cambridge, Cambridge, CB3 0HA, UK

(Dated: March 10, 2015)

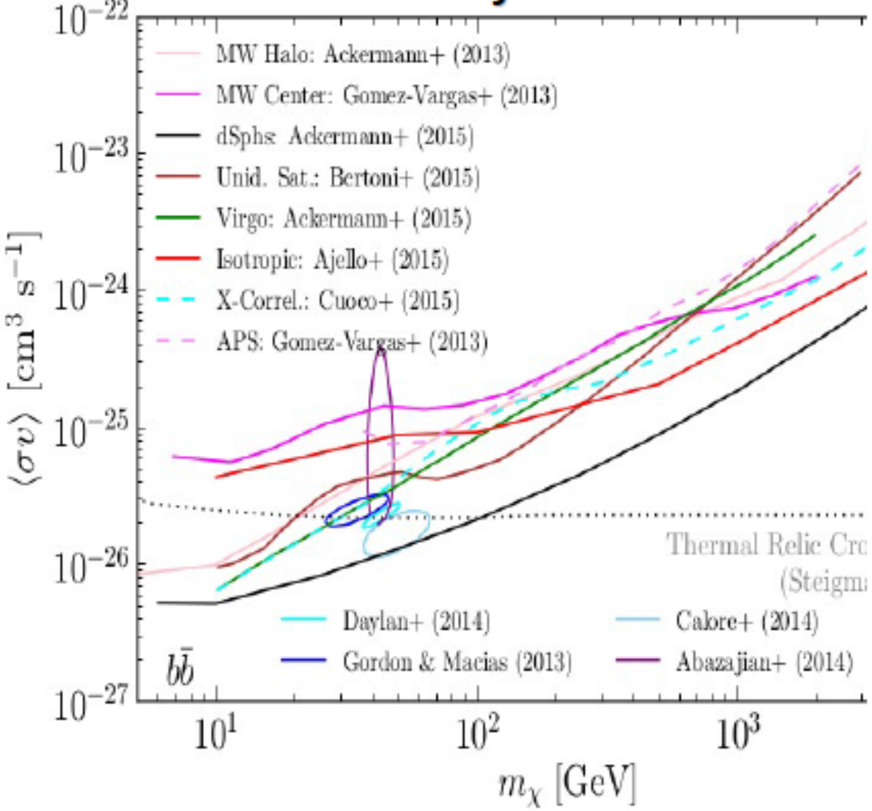




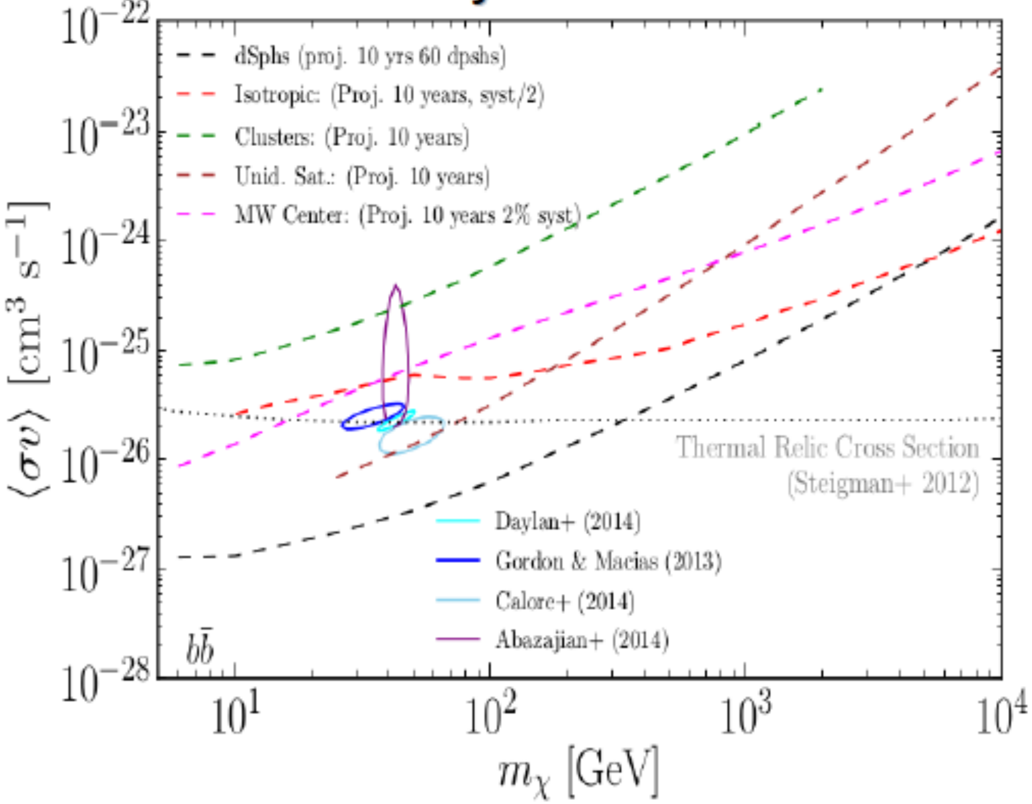
FERMI-LAT

Status of the Gamma-ray Excess in the Galactic Center

Today



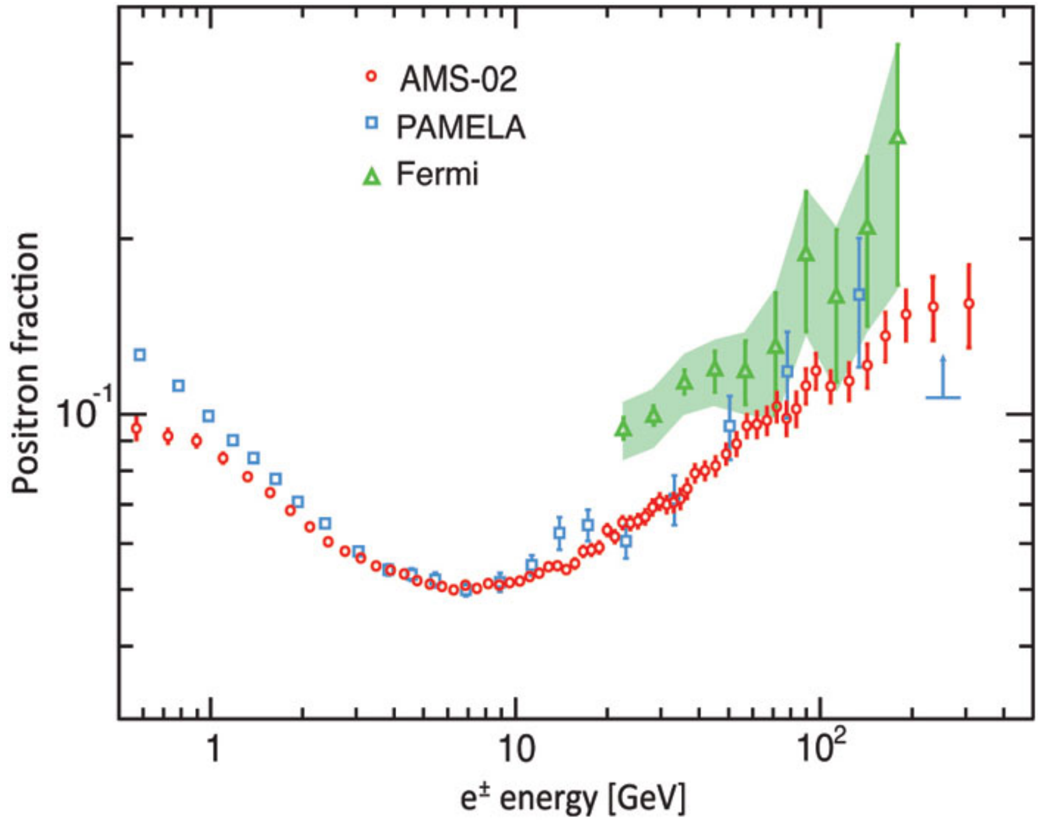
3 years from now



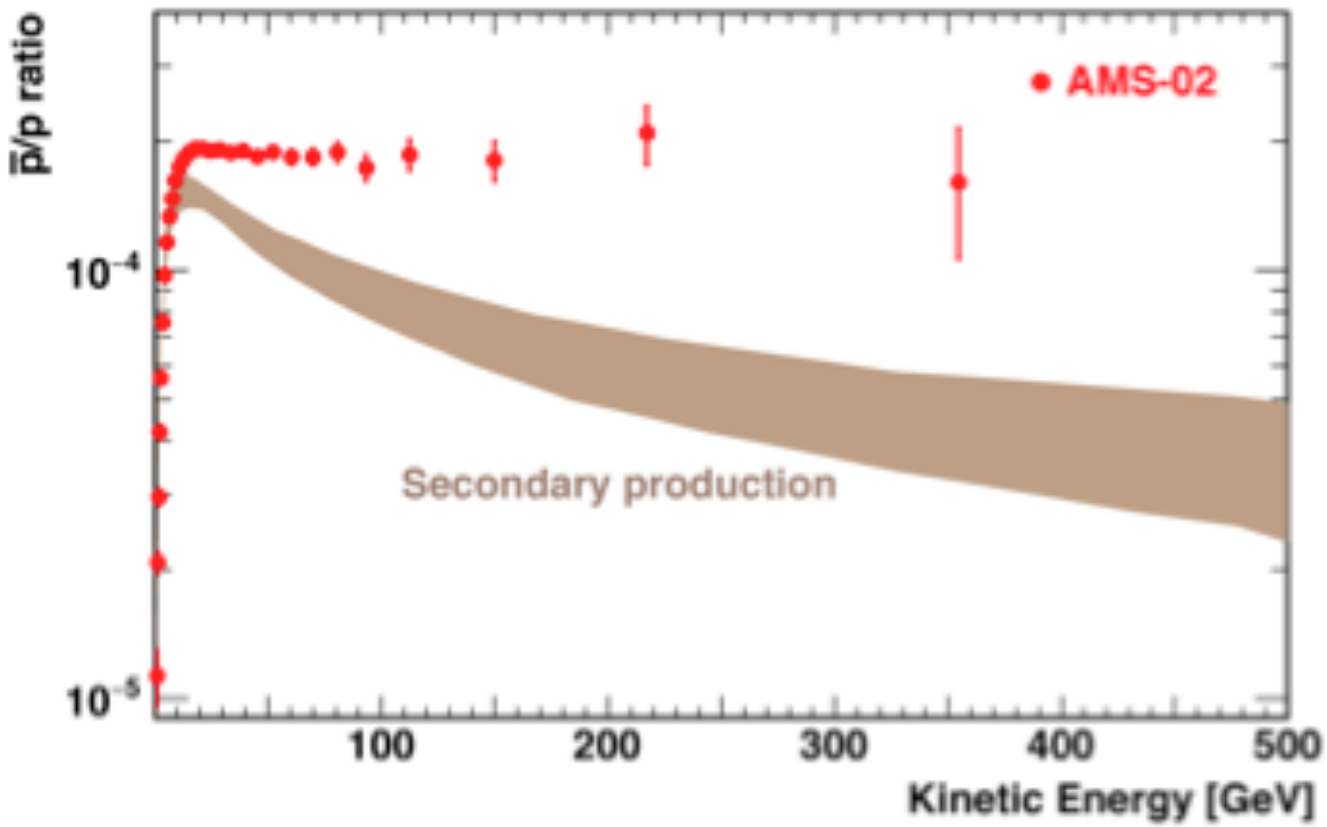
From the right panel, one could conclude that the dark matter interpretation of the galactic center excess will be decisively confirmed or ruled in the near future.

Positron and anti-proton excess

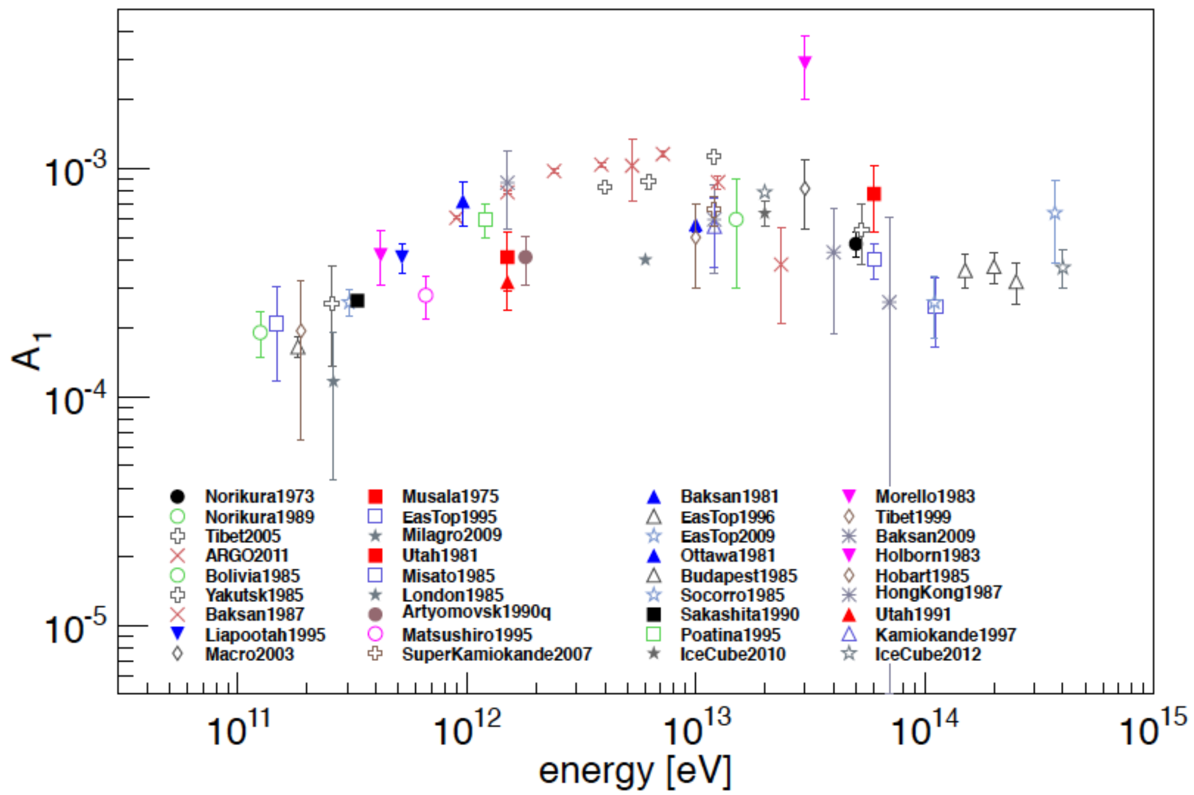
Positron to (electron + positron) ratio by PAMELA, Fermi, AMS-2



Anti-protons by AMS-2

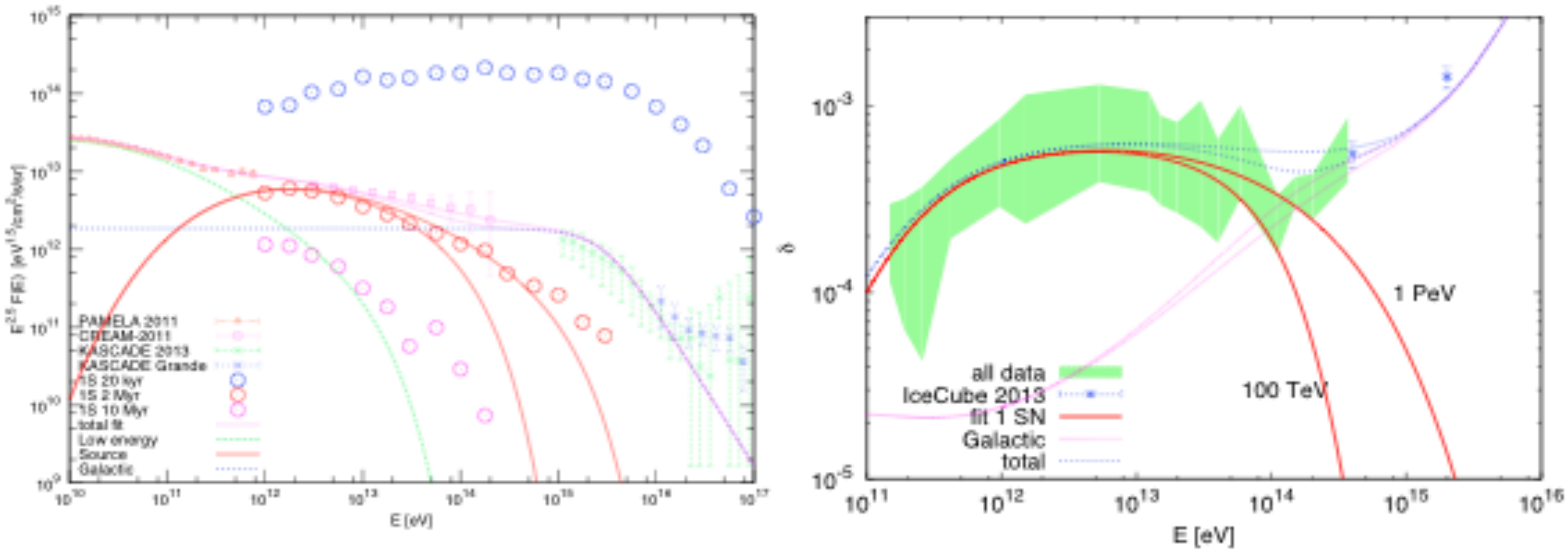


Dipole anisotropy of cosmic rays



- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

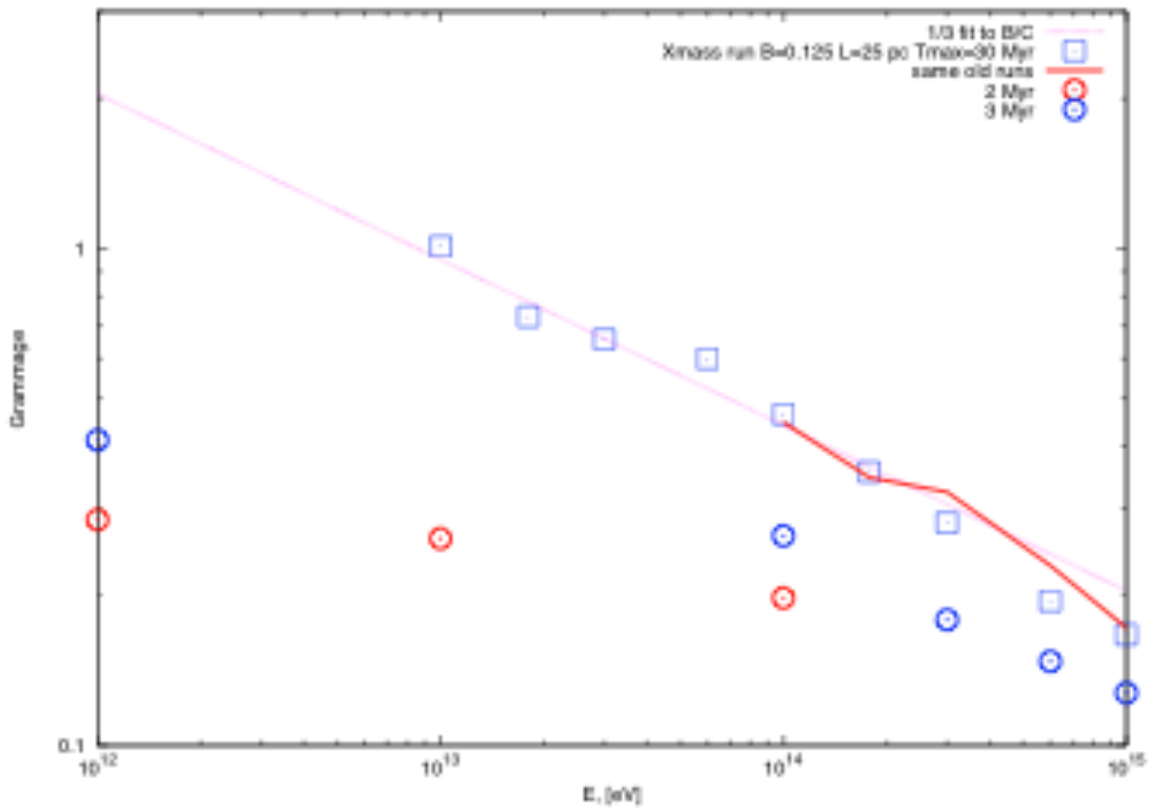
Anisotropy and flux from 2 Myr SN



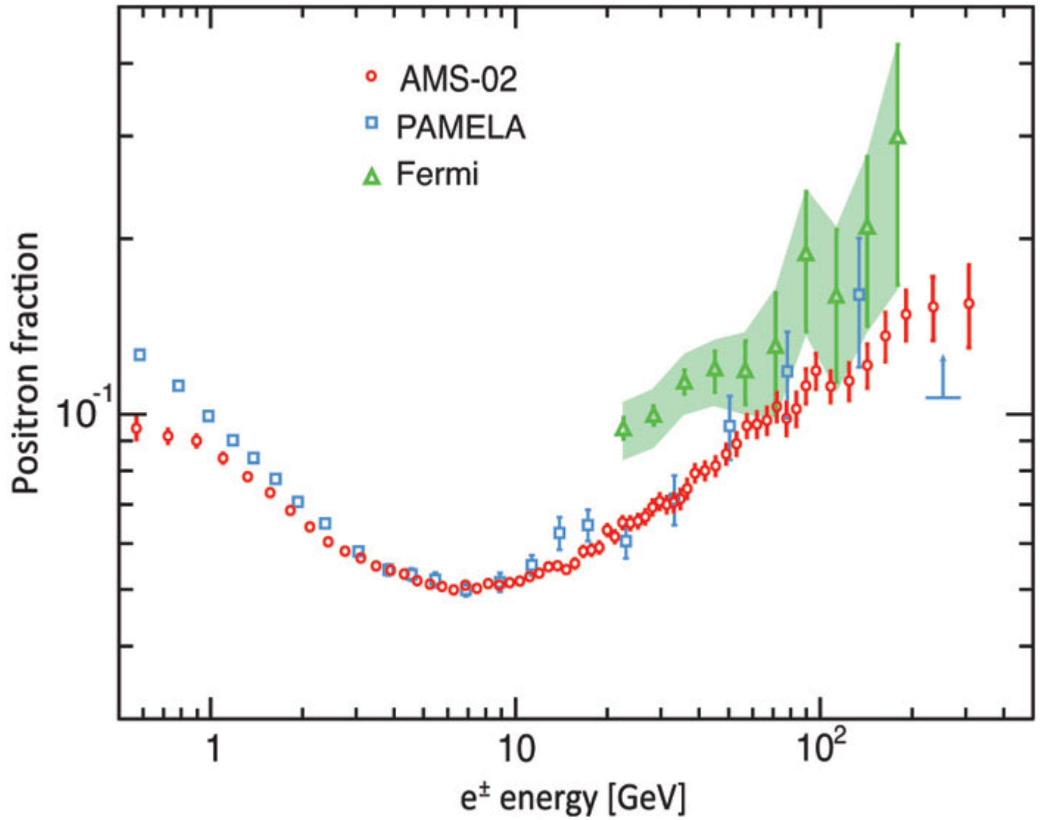
•A=3/2 R/T

- V.Savchenko, M.Kachelriess, and D.Semikoz, arXiv:1505.02720

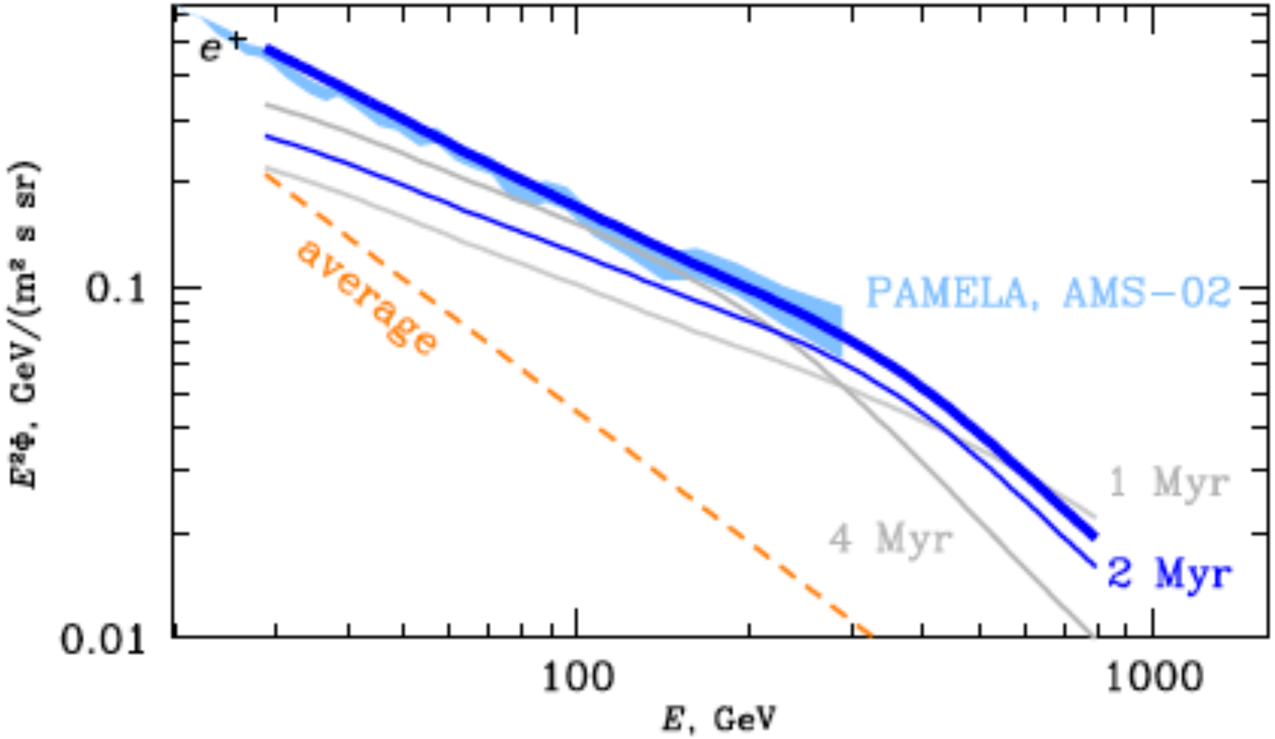
Grammage to create secondaries



Positron to (electron + positron) ratio

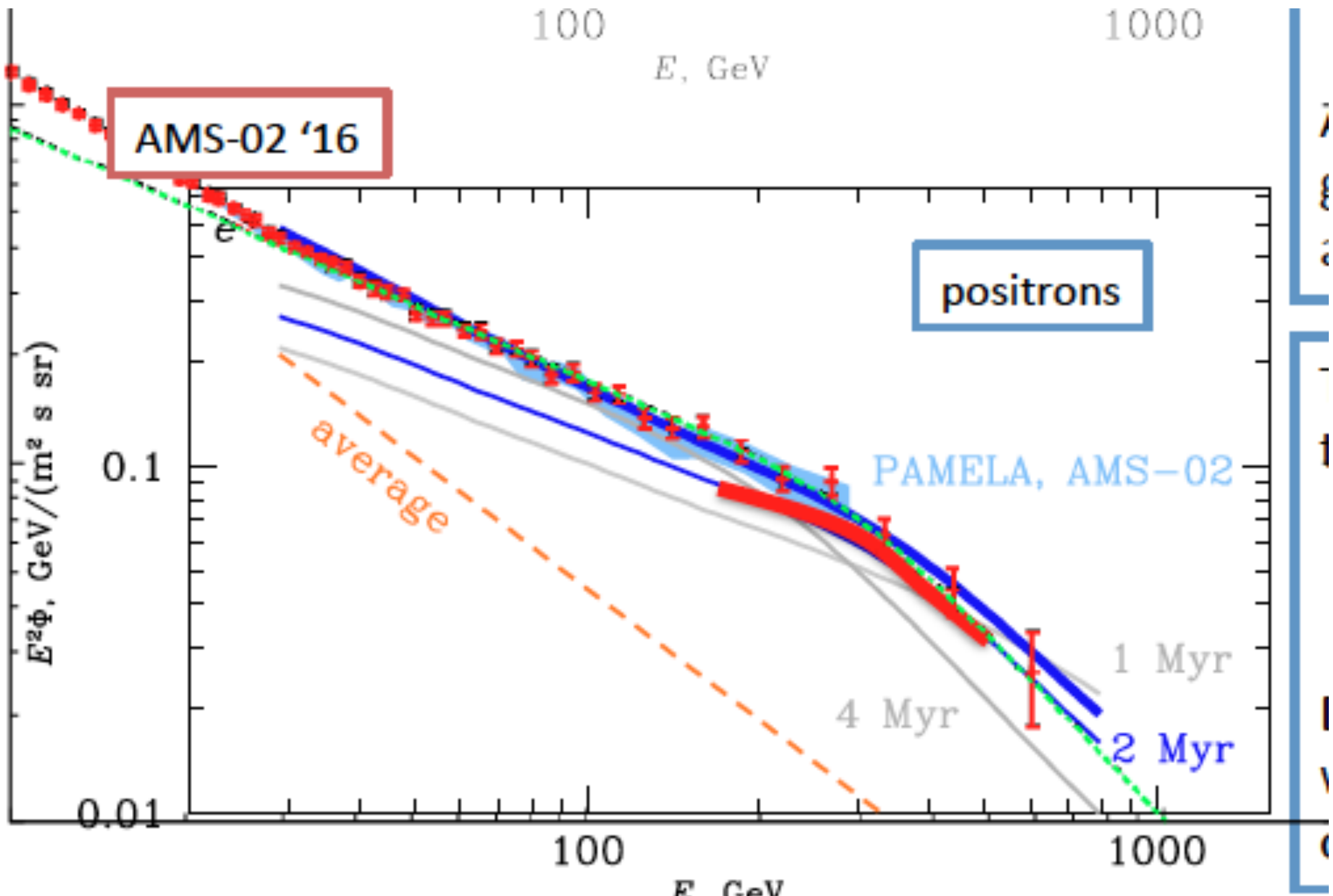


Positron flux PAMELA/AMS-II



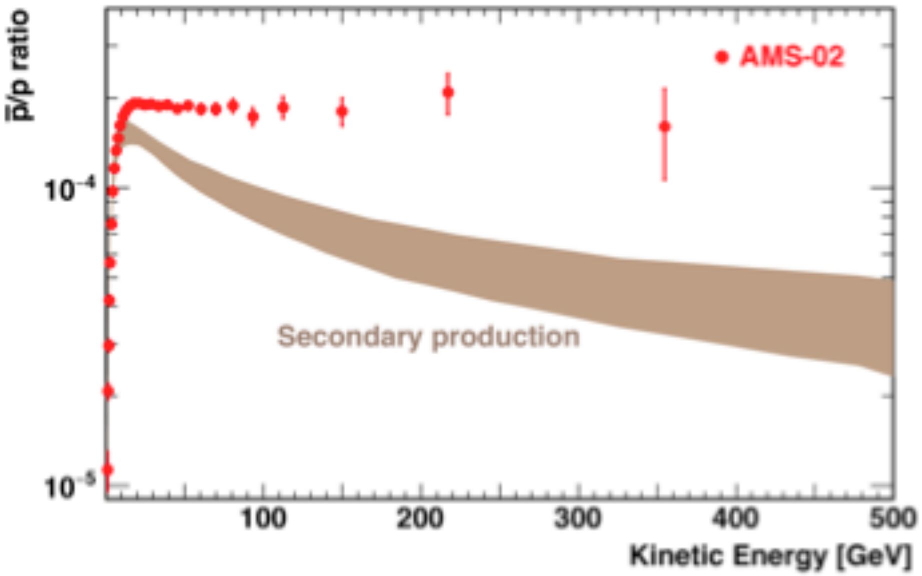
- M.Kachelriess, A. Neronov and D.Semikoz, arXiv:1504.06472

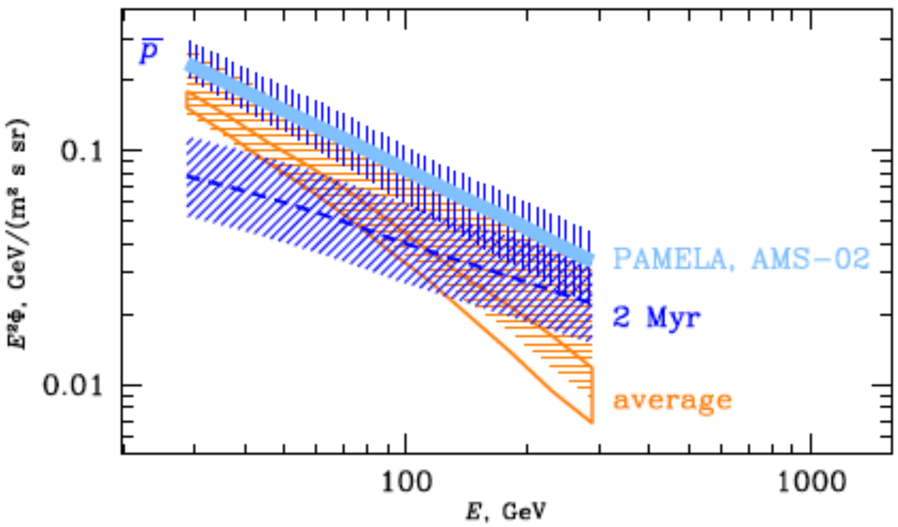
Positron flux PAMELA/AMS-II



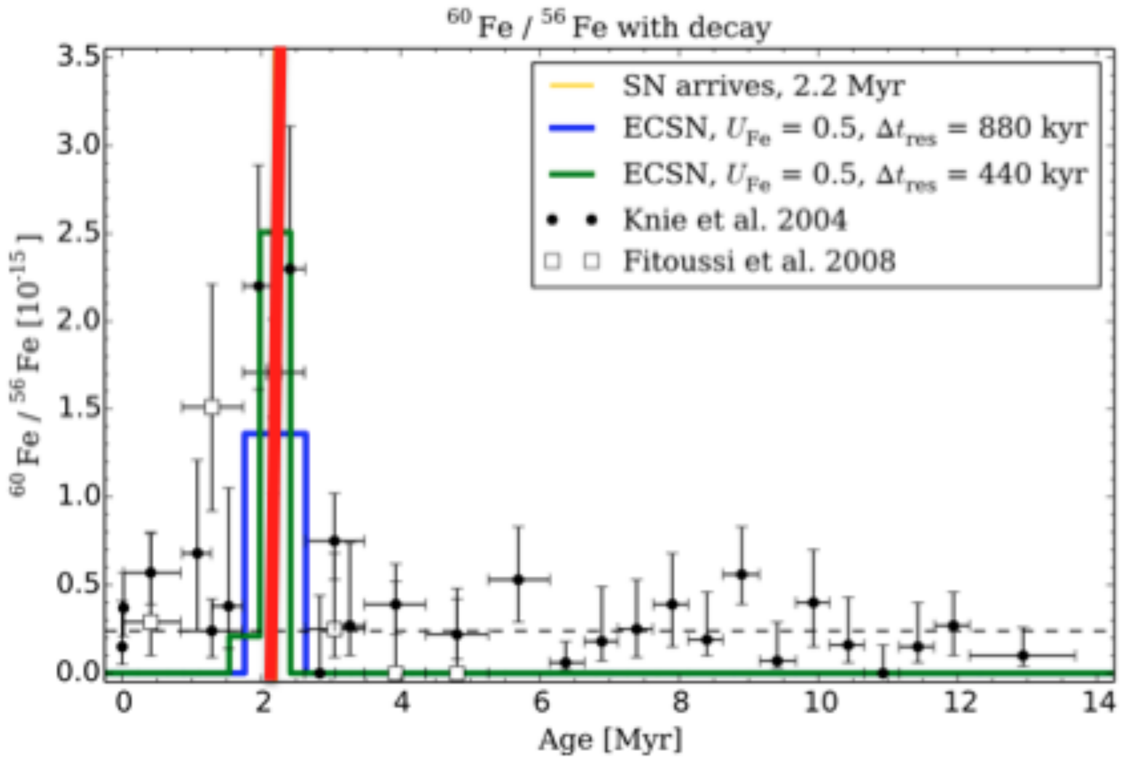
Kachelriess et al. ‘15

Antriprotons





Nearby SN from Fe60 in ocean crust



•Knie et al. '99, '04, Fry et al. '15

Conclusions:

- Gamma-ray astronomy works
- Will help to understand hadronic component in different kind of astrophysical sources
- helps to establish extragalactic IR/O backgrounds
- Diffuse gamma-ray background dominated by unresolved sources
- Will allow to study magnetic field in the voids of large scale structure: primordial magn. field!
- Give constraint/signature on Dark Matter