Astroparticle experiment

1) Charged cosmic rays (CRs) and AMS-02 experiment

2) High-energy gamma rays: H.E.S.S. and Fermi-LAT

Goal of the lectures

- Selected topics and instruments in astroparticle physics
- Complexity of data analysis (illustration with AMS-02)
- Variety of detection principles, ‘research activities’, etc.

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GRASPA
Annecy-le-Vieux
25 July 2022

Astroparticle experiment 2

High-energy gamma rays, H.E.S.S and Fermi-LAT

1) Introduction: projections and coordinates
2) The gamma-ray sky tour
3) Air showers and detection techniques (CRs)
4) Fermi-LAT, H.E.S.S., and exp. activities
5) Constraints on dark matter from γ-rays

Main questions in the field
→ Sources of cosmic rays
→ Origin of non-thermal emissions
→ Dark matter indirect detection

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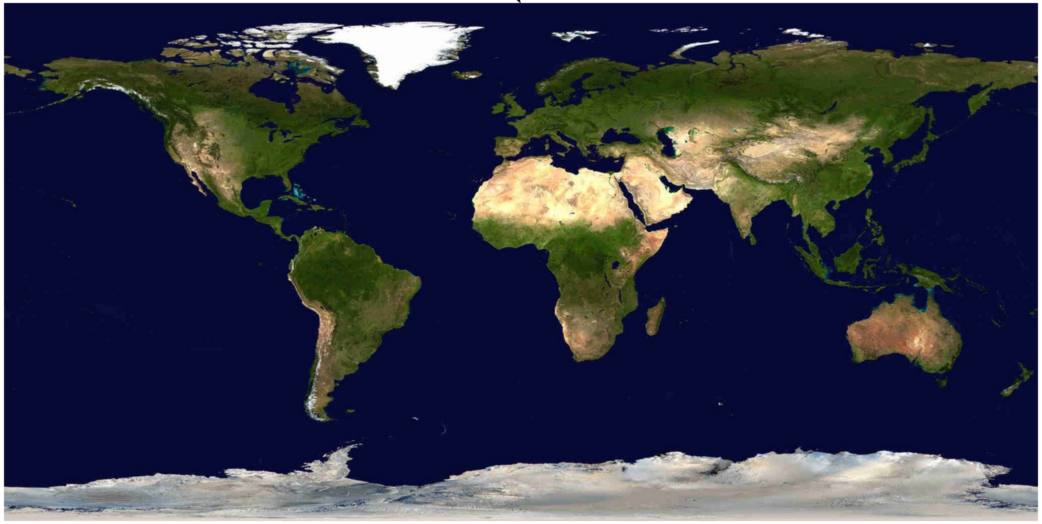
Mapping the sphere to 2D view

To go further: *representations of celestial coordinates in FITS,* Calabretta & Greisen, A&A 395, 1077 (2002)

Mercator

Hammer-Aïtoff



Hammer-Aitoff (and Mollweide) are equal area projections:
→ phenomena per unit area are shown in correct proportion
N.B.: no projection can be both equal-area and conformal (distorts angles, hence shapes)

Galactic coordinates: the Milky Way

Unit conversion

Mass

$1\ M_\odot \sim 10^{57}$ GeV

$\sim 2.10^{30}$ kg

$\sim 3.10^{5}\ M_\oplus$

Distance

1 pc $\sim 3.10^{16}$ m

$\sim 2.10^{5}$ AU

~ 3.26 ly

Milky Way ID

Stars $\sim 10^{11} \rightarrow 5.10^{10}\ M_\odot$

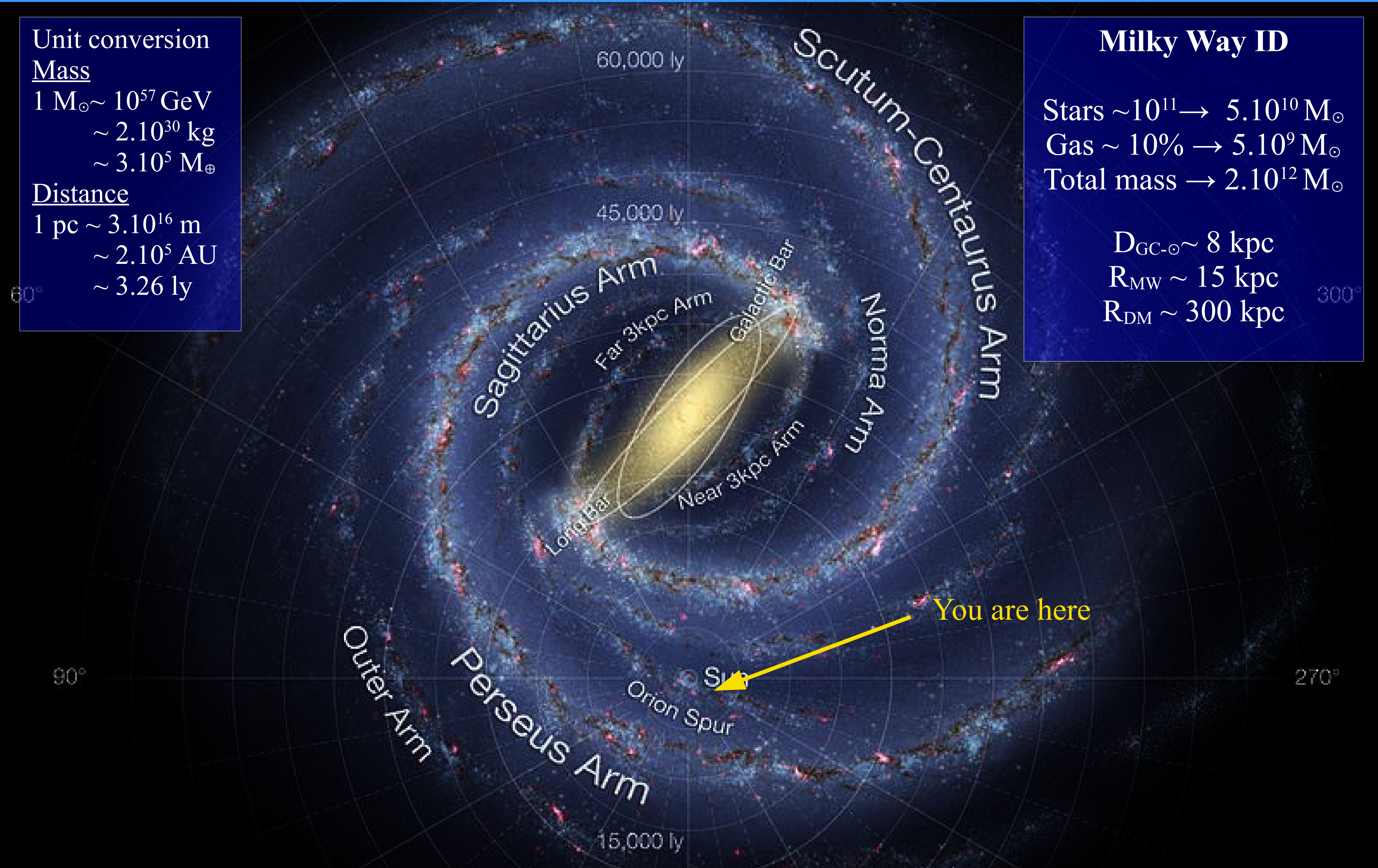
Gas $\sim 10\% \rightarrow 5.10^{9}\ M_\odot$

Total mass $\rightarrow 2.10^{12}\ M_\odot$

$D_{GC-\odot} \sim 8$ kpc

$R_{MW} \sim 15$ kpc

$R_{DM} \sim 300$ kpc



Artist's view of the Milky Way – NASA/JPL-Caltech/R. Hurt

1) Introduction: projections and coordinates
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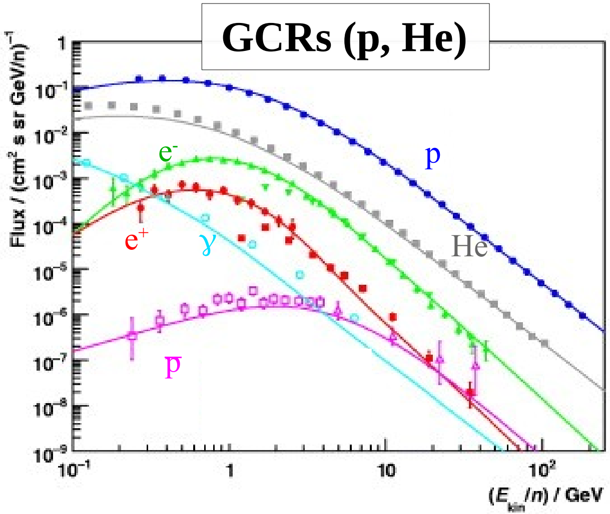
Motivation
→ Diffuse emission and origin
→ Sources of non-thermal emissions
→ GeV vs TeV sky

Diffuse emission: hadronic origin

GCRs (p, He)



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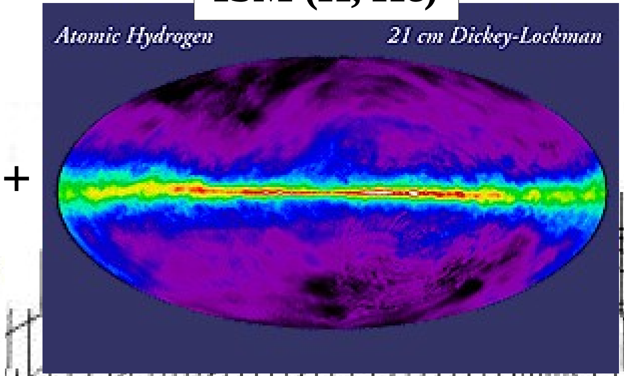
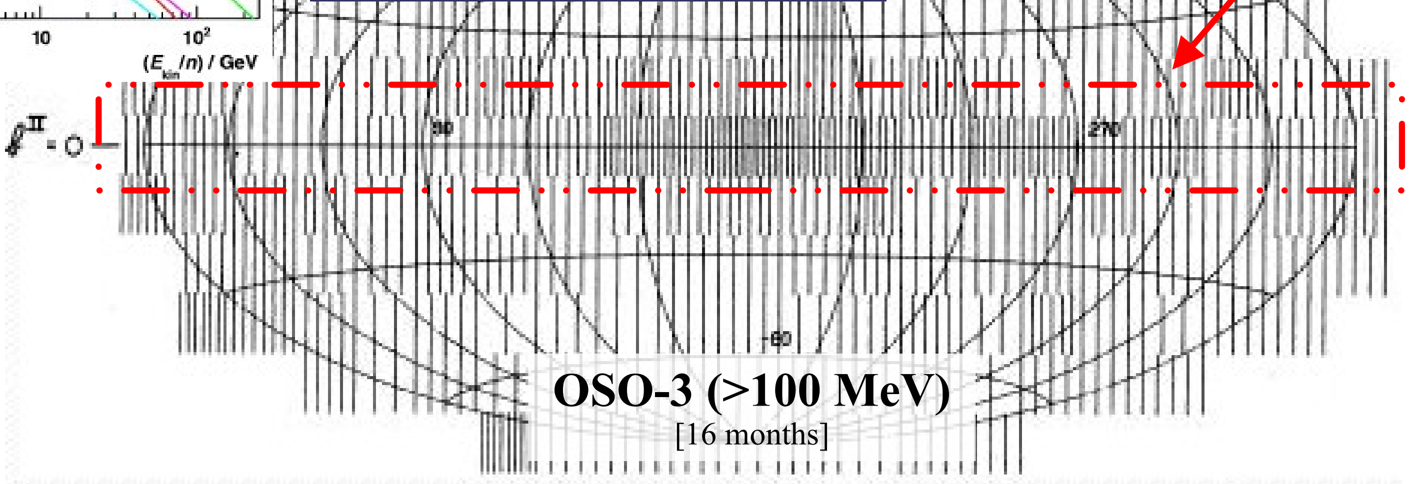
ISM (H, He)



Diffuse emission in disc = galactic
→ prop. to H_I column density (21 cm)
→ Total intensity ~ π^0 production

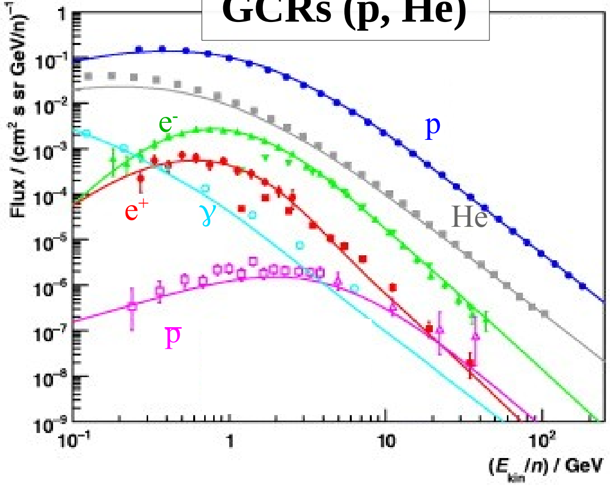


OSO-3 (>100 MeV)
[16 months]

Diffuse emission: spatial dependence (1)

Diffuse hadronic emission

GCRs (p, He)



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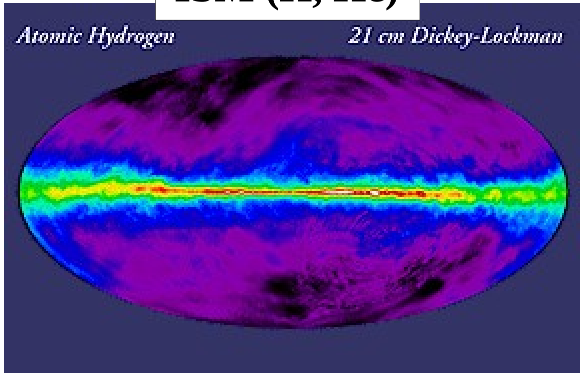
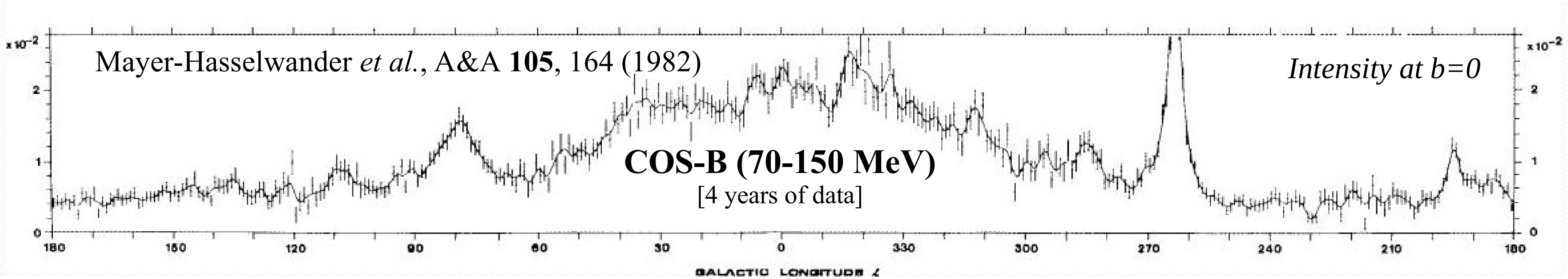
ISM (H, He)



Diffuse emission in disc = galactic
→ prop. to H_I column density (21 cm)
→ Total intensity ~ π^0 production

Signal in the disc (b=0):
origin of the different intensity peaks?



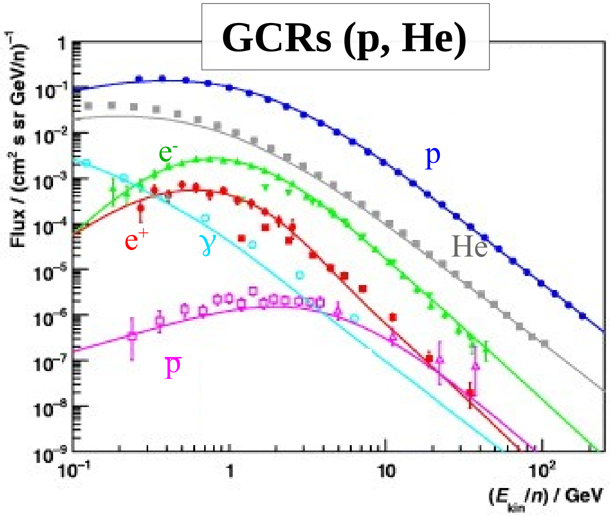
Mayer-Hasselwander *et al.*, A&A **105**, 164 (1982)

Intensity at b=0

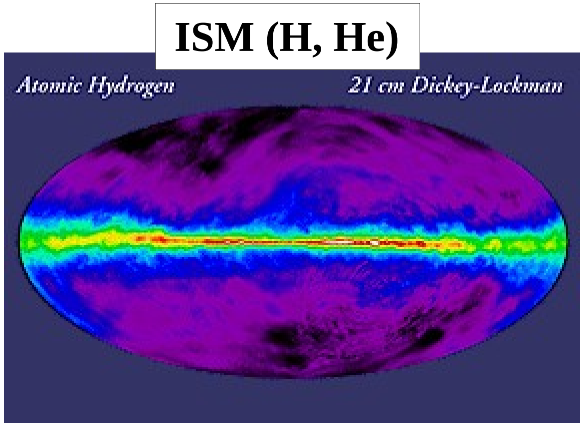
COS-B (70-150 MeV)
[4 years of data]

Diffuse emission: spatial dependence (1)

Diffuse hadronic emission

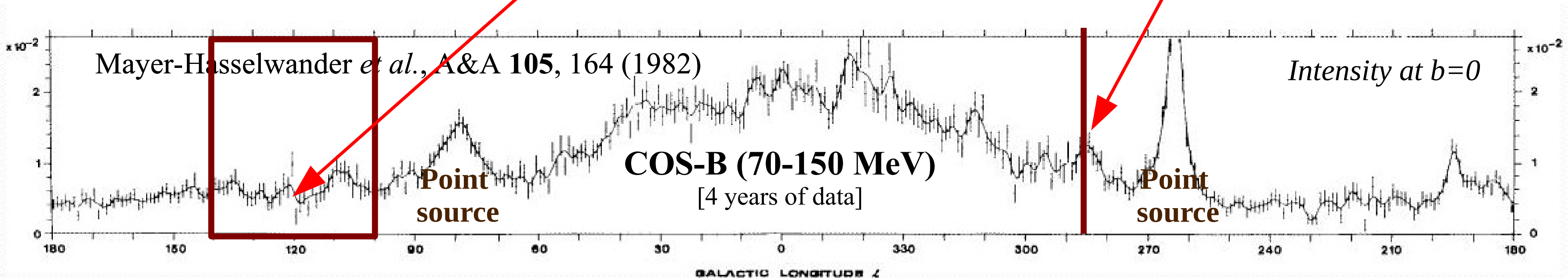

GCRs (p, He)

+


ISM (H, He)

Diffuse emission in disk = galactic
→ prop. to H_I column density (21 cm)
→ Total intensity ~ π^0 production

→ Correlations with Perseus arm (*l=100°-140°*), spiral arm in Carina *(l=285°)*


Mayer-Hasselwander *et al.*, A&A **105**, 164 (1982)

Intensity at b=0

COS-B (70-150 MeV)
[4 years of data]

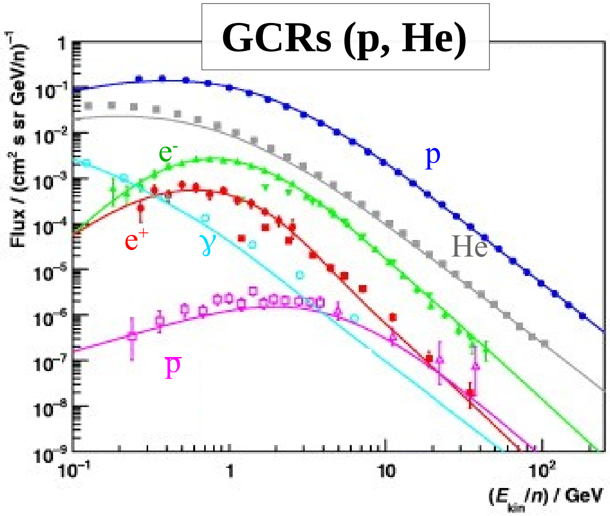
Point source

Point source

Diffuse emission: spatial dependence (2)

Diffuse hadronic emission

GCRs (p, He)



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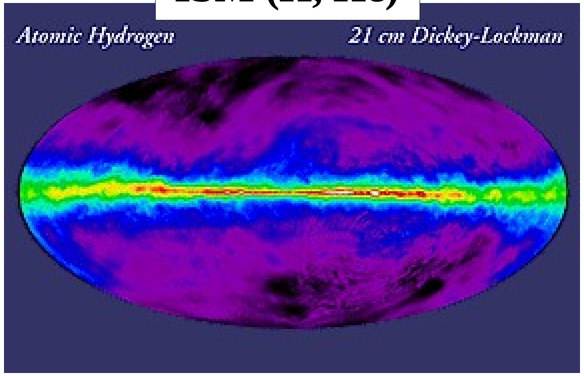
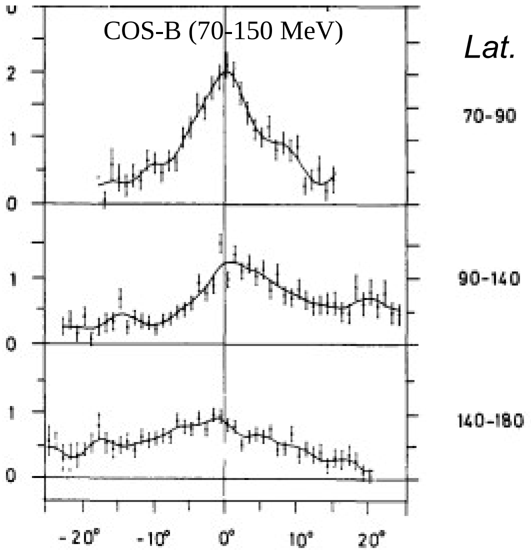
ISM (H, He)



Diffuse emission in disk = galactic
→ prop. to H_I column density (21 cm)
→ Total intensity ~ π^0 production

Point-source subtracted

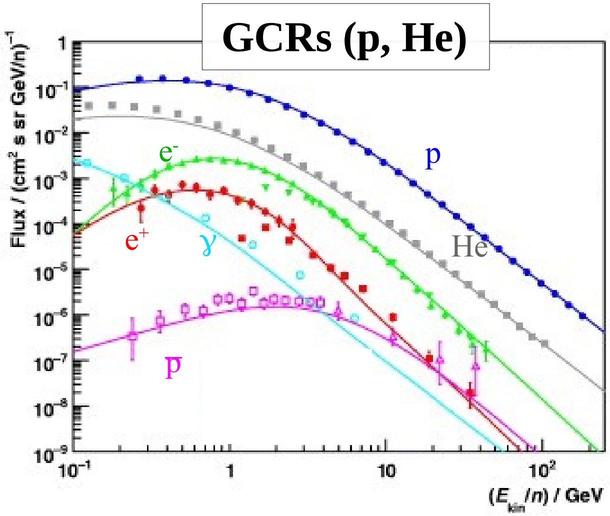
Signal perpendicular to the disc:
origin of extended emission?



Diffuse emission: spatial dependence (2)

Diffuse hadronic emission

GCRs (p, He)



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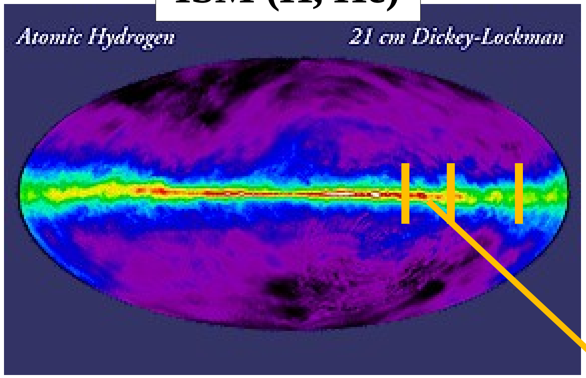
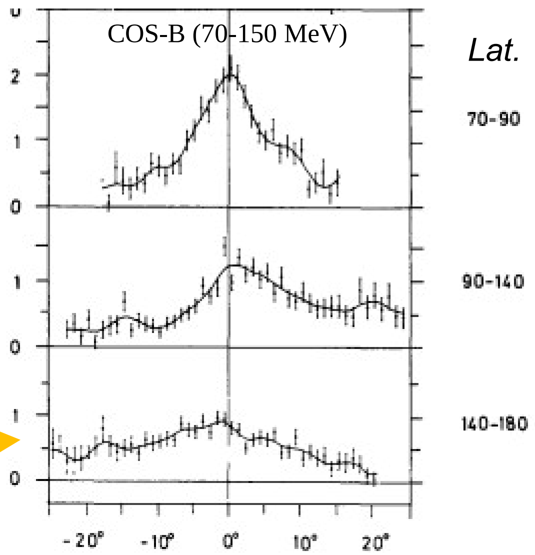
ISM (H, He)



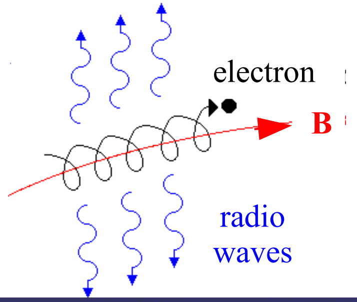
Diffuse emission in disk = galactic
→ prop. to H$_{\text{I}}$ column density (21 cm)
→ Total intensity ~ π^0 production
+ additional leptonic emission (mostly IC, synchrotron)

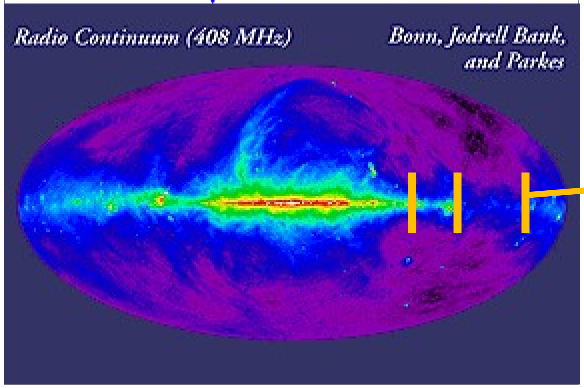
+ leptonic emission!

Point-source subtracted

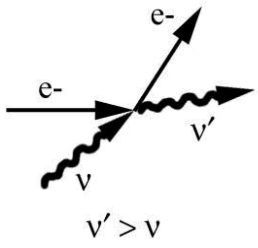


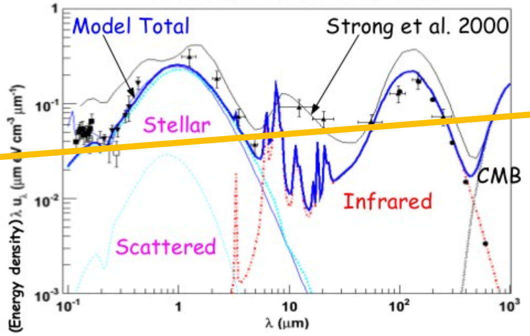
Synchrotron emission





Inverse Compton scattering



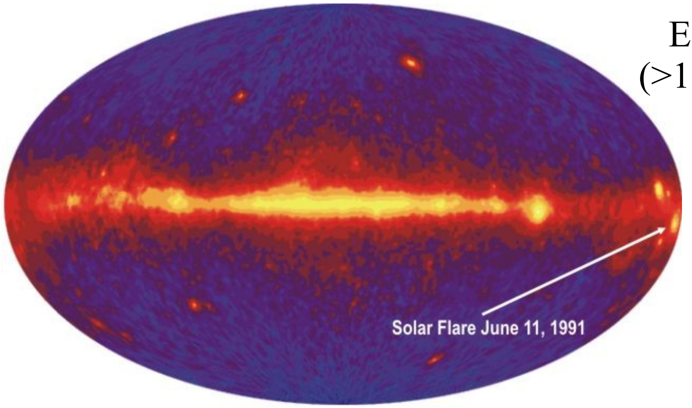


By the way: how to get the diffuse emission?

(1) Count the number of photons
(photons-instrument background)

(2) Subtract point sources

EGRET
(>100 MeV)



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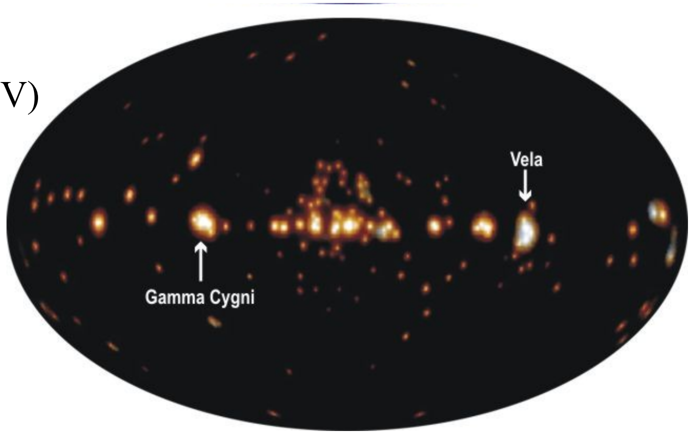


=

What remains should be the diffuse emission

In real life

(i) Source intrinsic properties

- point-like sources (e.g., SN remnants, AGN...)
- extended emission (e.g. plerions, GMC in the vicinity of a source...)
- diffuse-like emission (DE from the galactic disk, ridge, extragalactic DE...)

(ii) Analysis method and/or assumptions

2008: new EGRET analysis, 188 sources instead of 271! [Casandjian & Grenier, A&A **489**, 849]

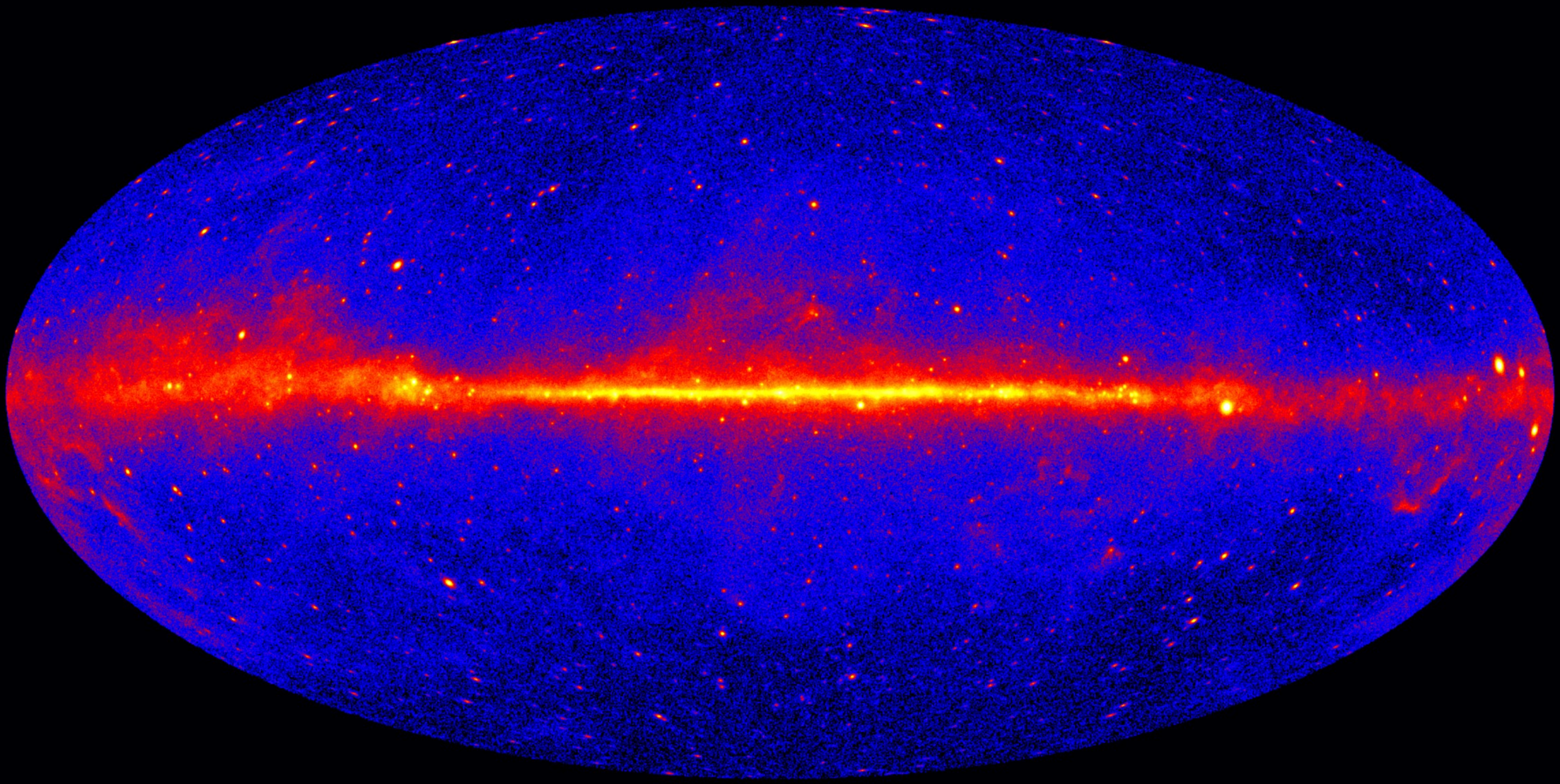
(iii) Angular resolution and/or sensitivity of the instrument

1999: OSSE find that 50% DE for soft γ-ray (<300 keV) [Kinzer *et al.*, ApJ **515**, 215]

2000: Hint at unresolved point sources HIREGS [Boggs *et al.*] + OSSE&RXTE [Valinia *et al.*]
2004: INTEGRAL find almost no diffuse emission [Lebrun, Terrier *et al.*, Nature **428**, 293]

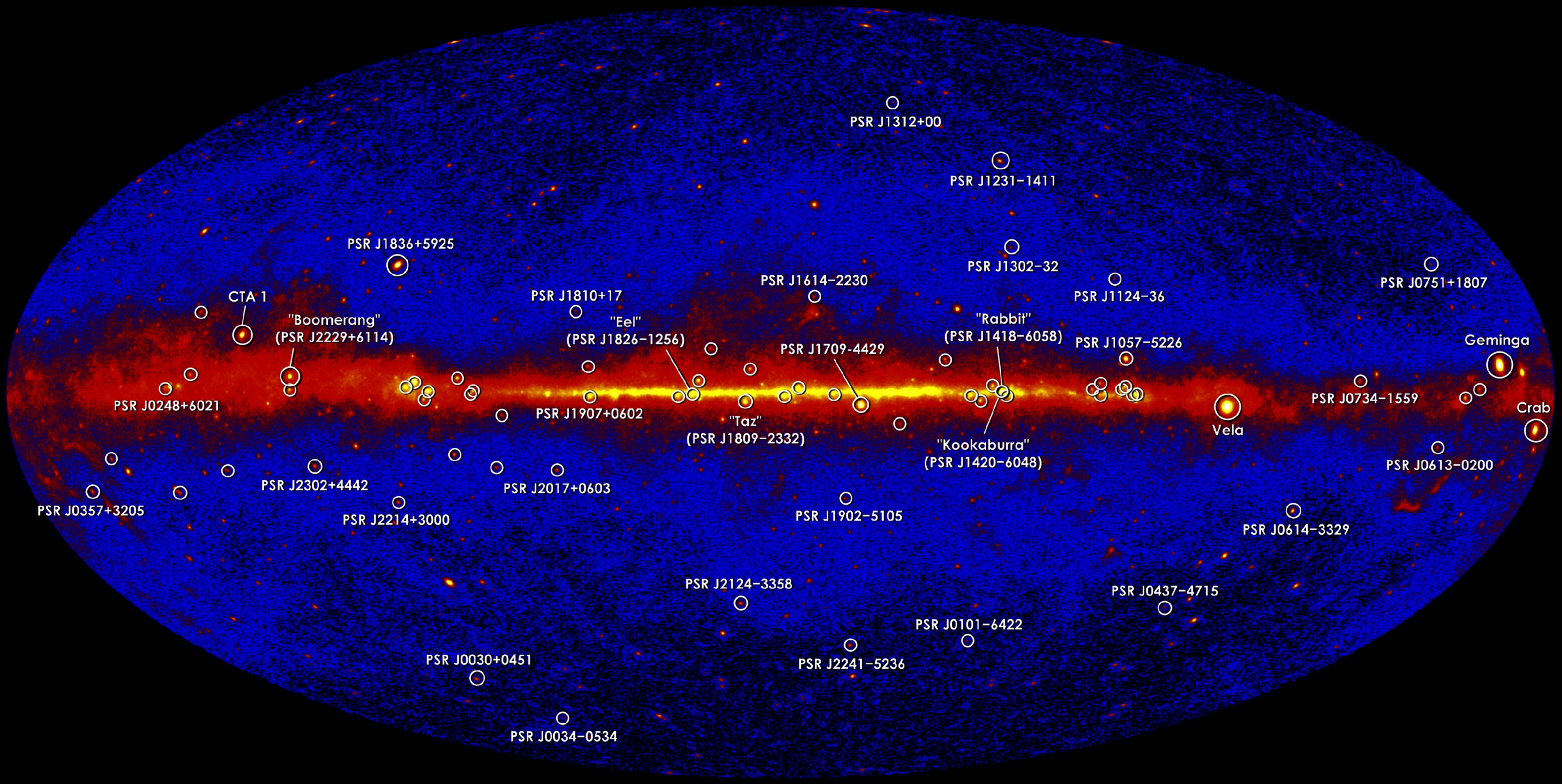
→ Identifying the truly diffuse emission is always a very difficult task

Fermi-LAT (> 1 GeV, 60 month results)



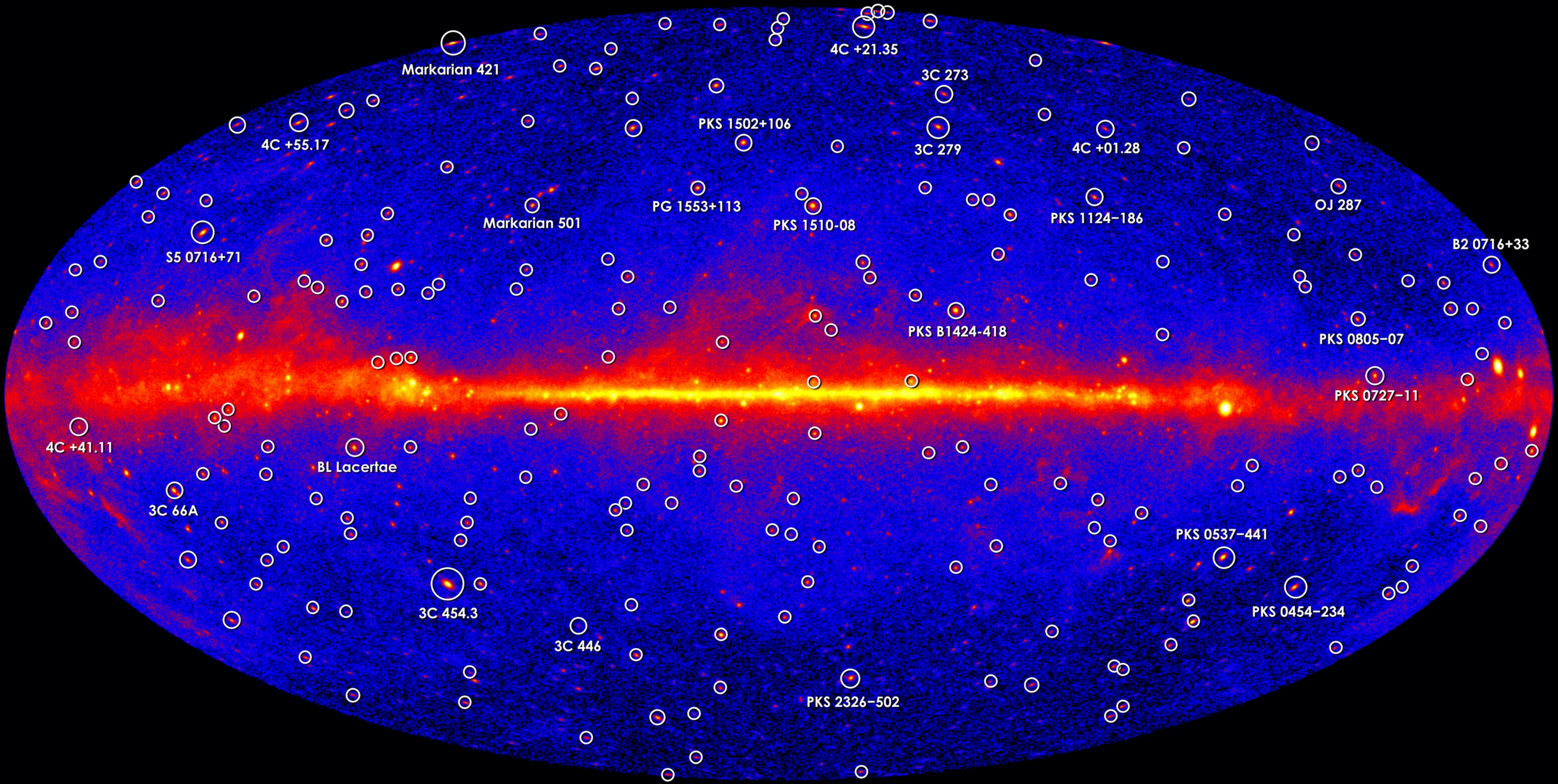
Indirect dark matter detection =
search for dark matter signature in this (astrophysical) mess

Fermi-LAT (> 1 GeV, 60 month results)



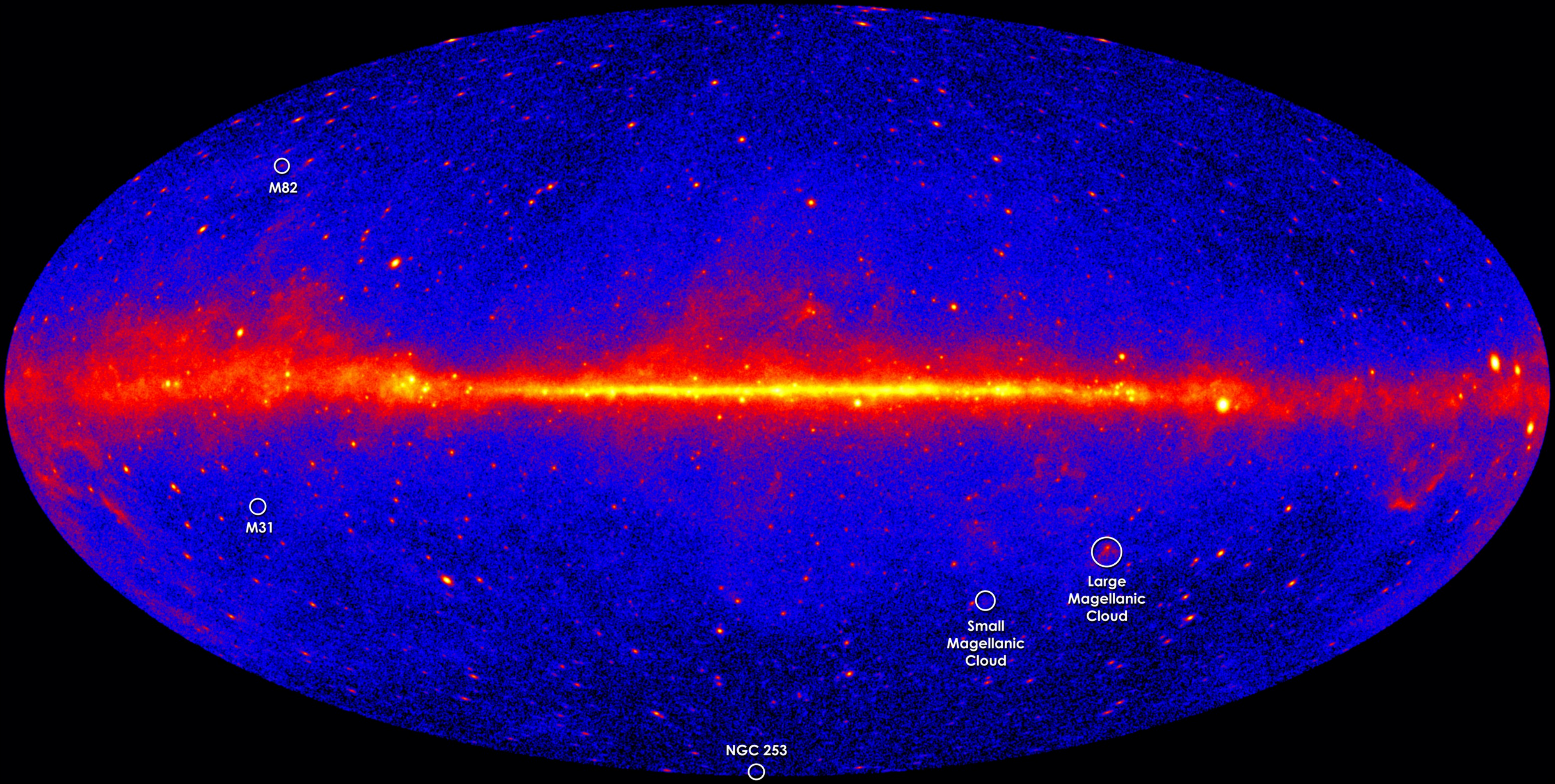
Pulsars
[rapidly rotating neutron stars]

Fermi-LAT (> 1 GeV, 60 month results)



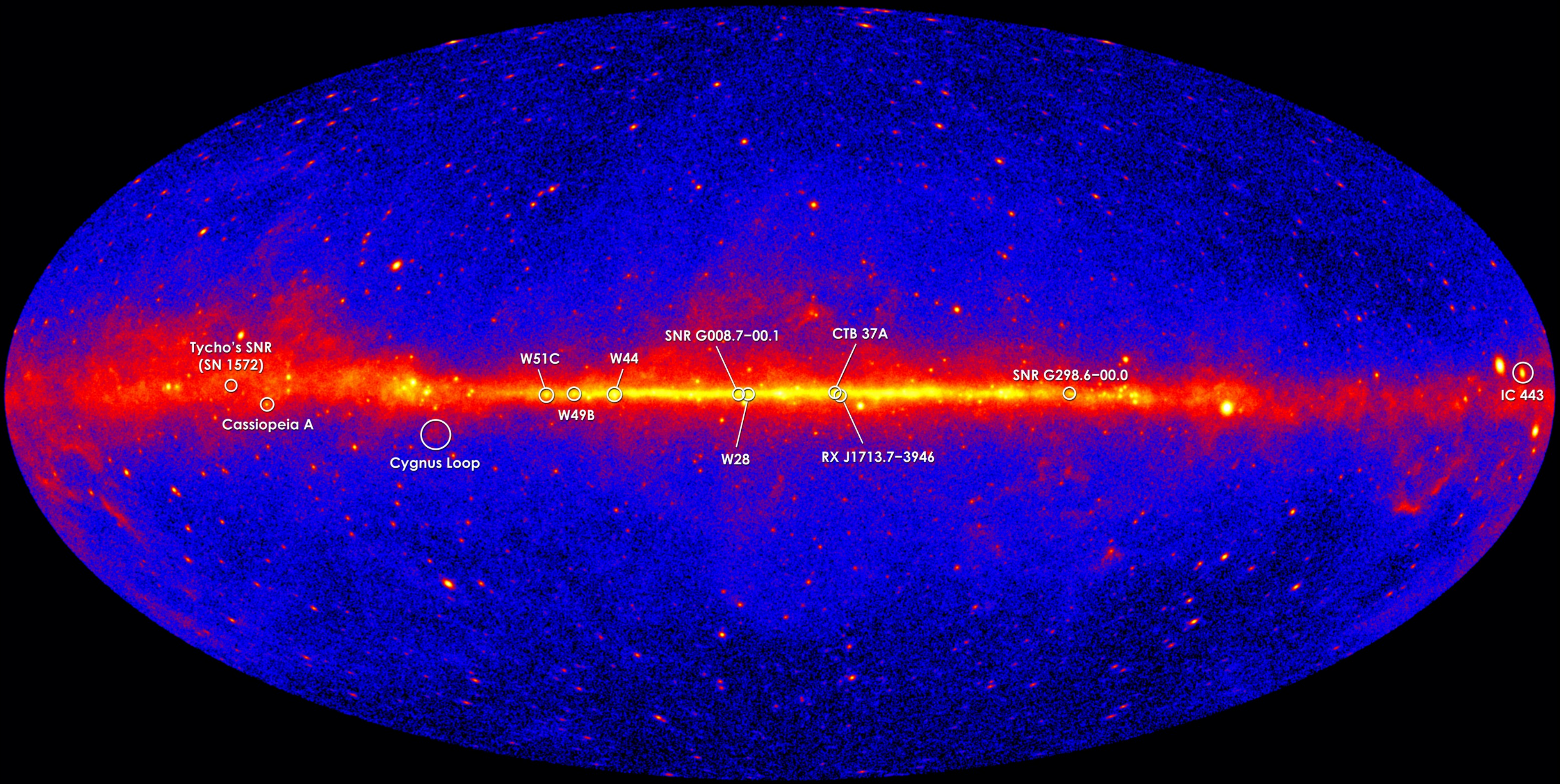
Active galaxies and blazars
[powered by $10^6 M_\odot$ black holes]

Fermi-LAT (> 1 GeV, 60 month results)



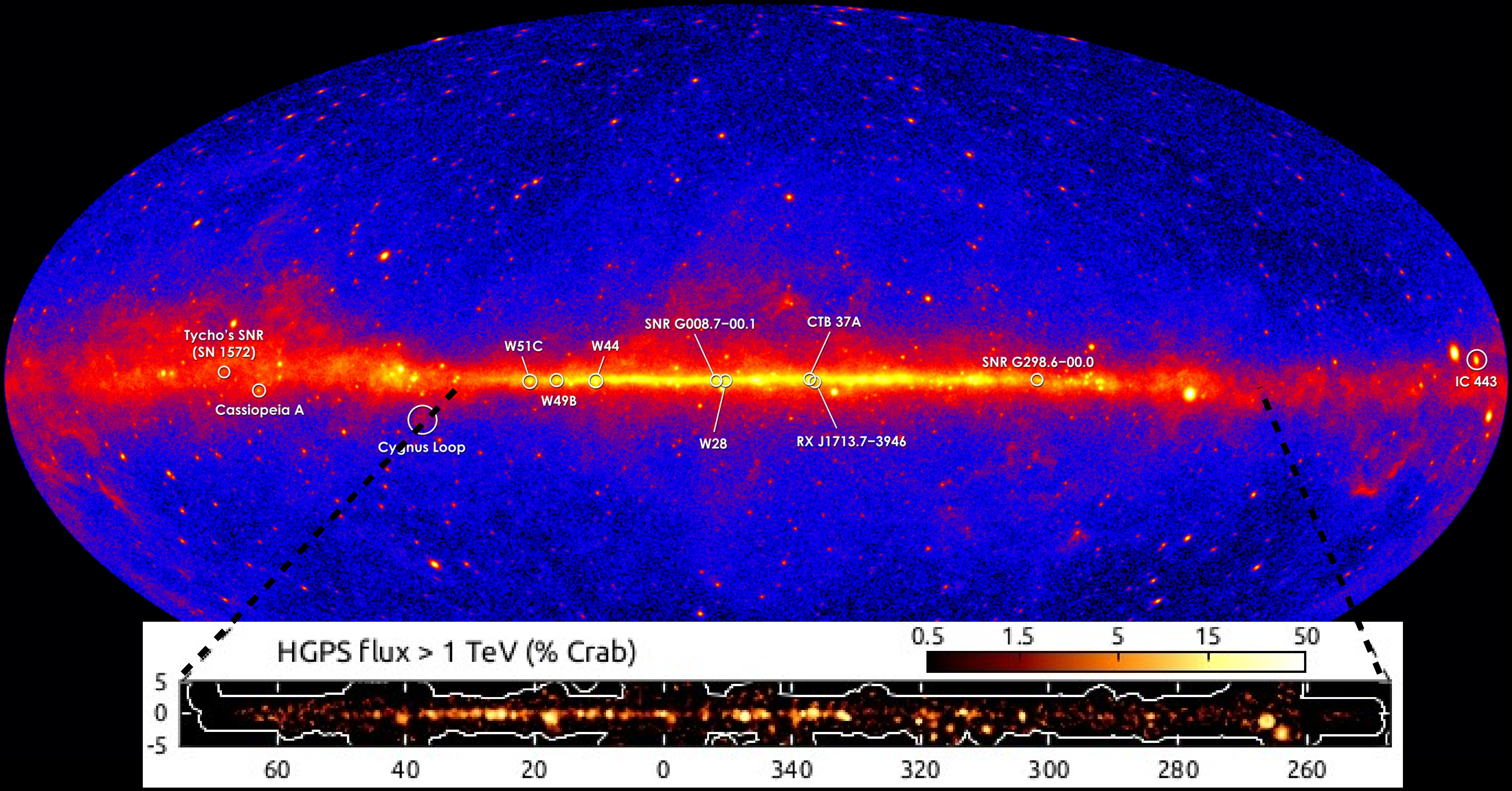
Normal and starburst galaxies

Fermi-LAT (> 1 GeV, 60 month results)



Supernova remnants
(and high mass binary systems,
globular clusters...)

Comparison with H.E.S.S. survey (> 1 TeV, 10 years)



TeV sky ≠ GeV sky

→ less diffuse emission(?)

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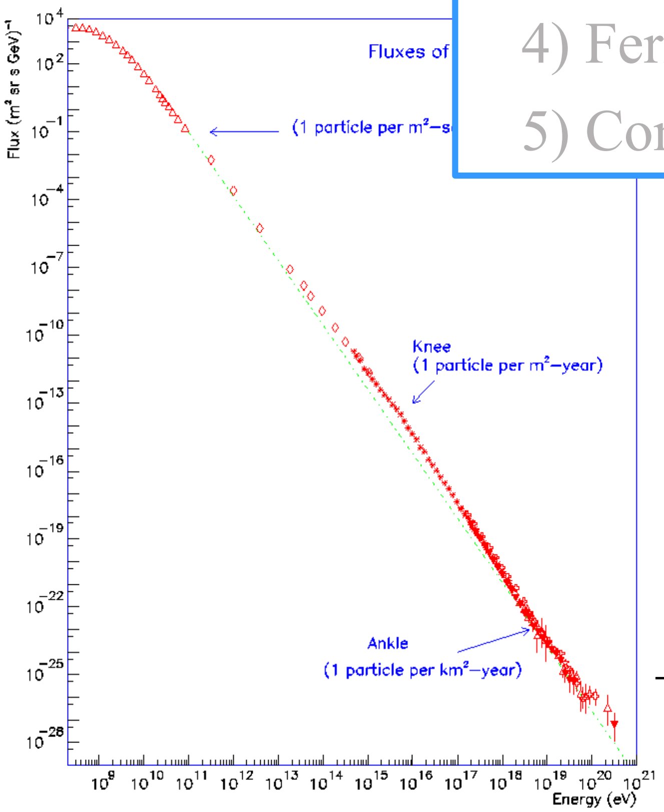


Reminder

Fluxes too small to be measured by instruments above the atmosphere

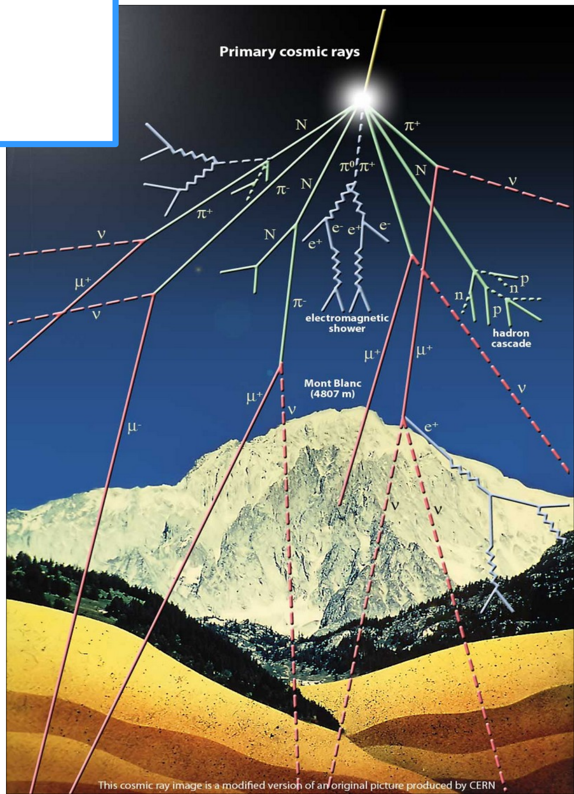
→ Use atmosphere as a “detector”

Notions covered here

→ Electromagnetic vs hadronic showers

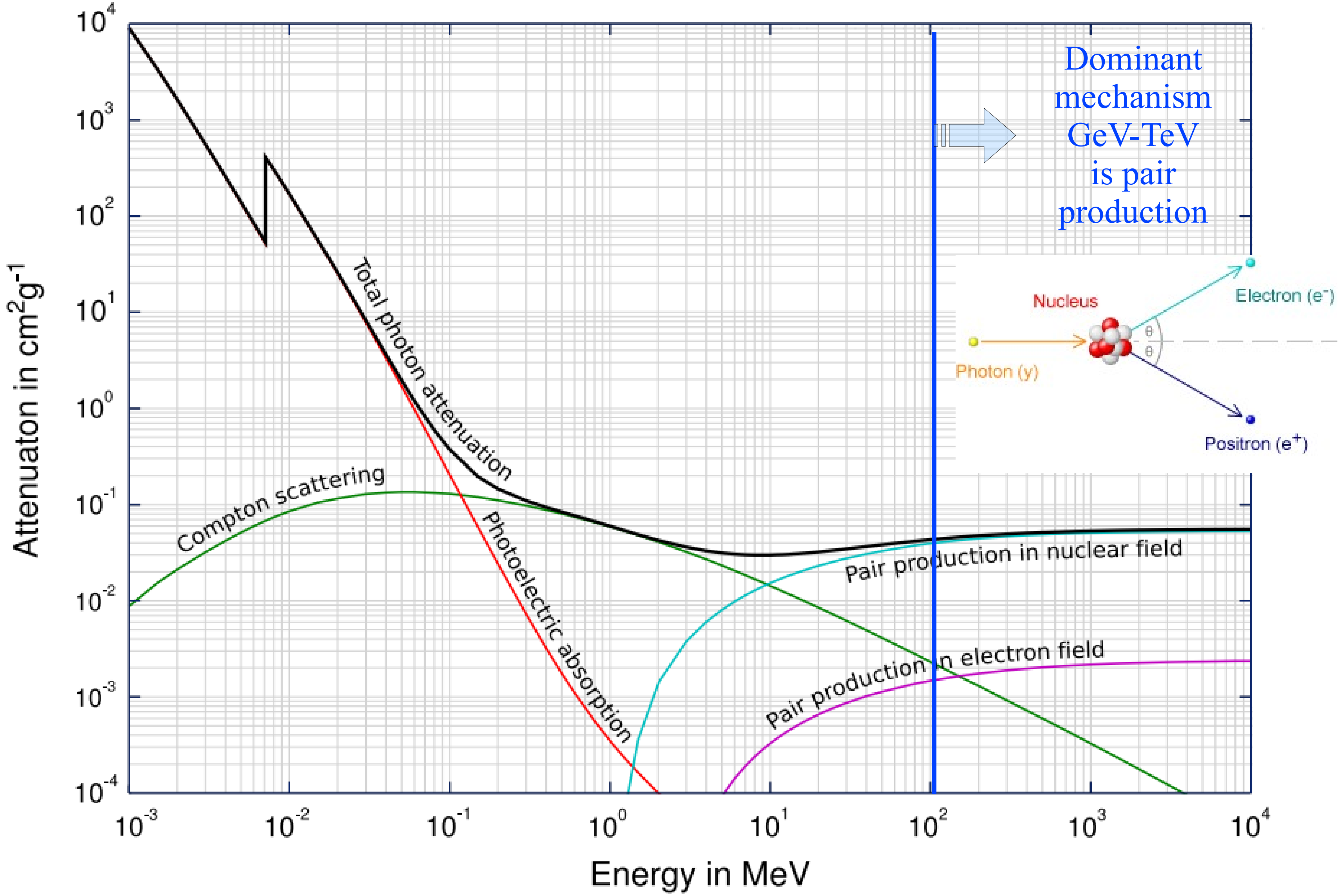
→ Detector types using atmospheric showers

→ Rejection and calibration



This cosmic ray image is a modified version of an original picture produced by CERN

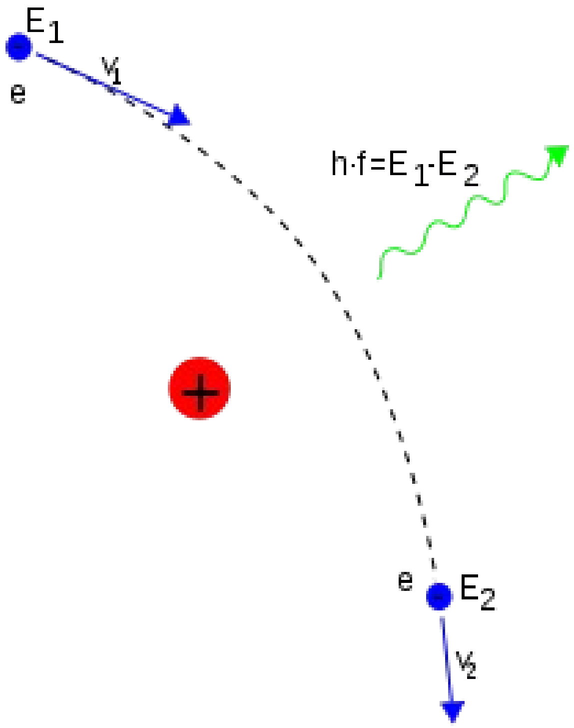
High-energy photon interaction



Dominant
mechanism
GeV-TeV
is pair
production

High energy lepton interaction

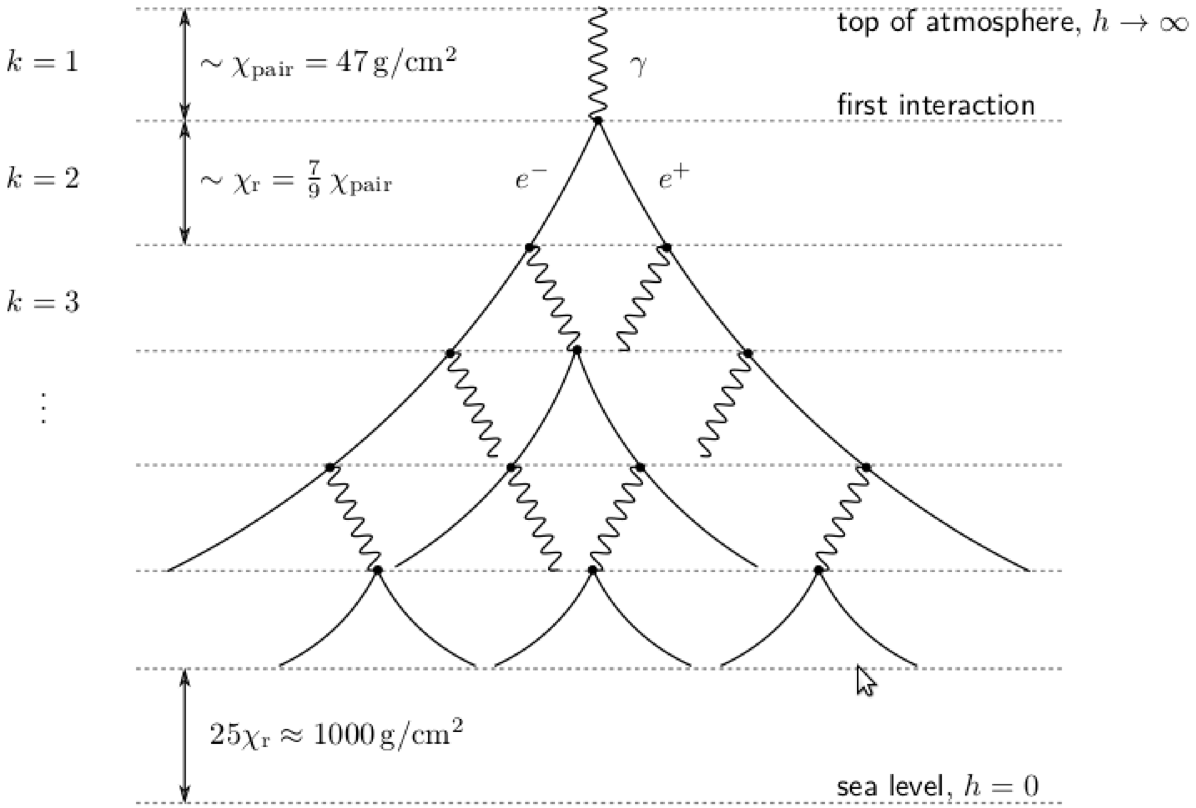
Bremsstrahlung emission
(in Coulomb field of the nucleus)



→ About same interaction length as pair production

Electromagnetic air shower

Hütten, PhD thesis (2016)

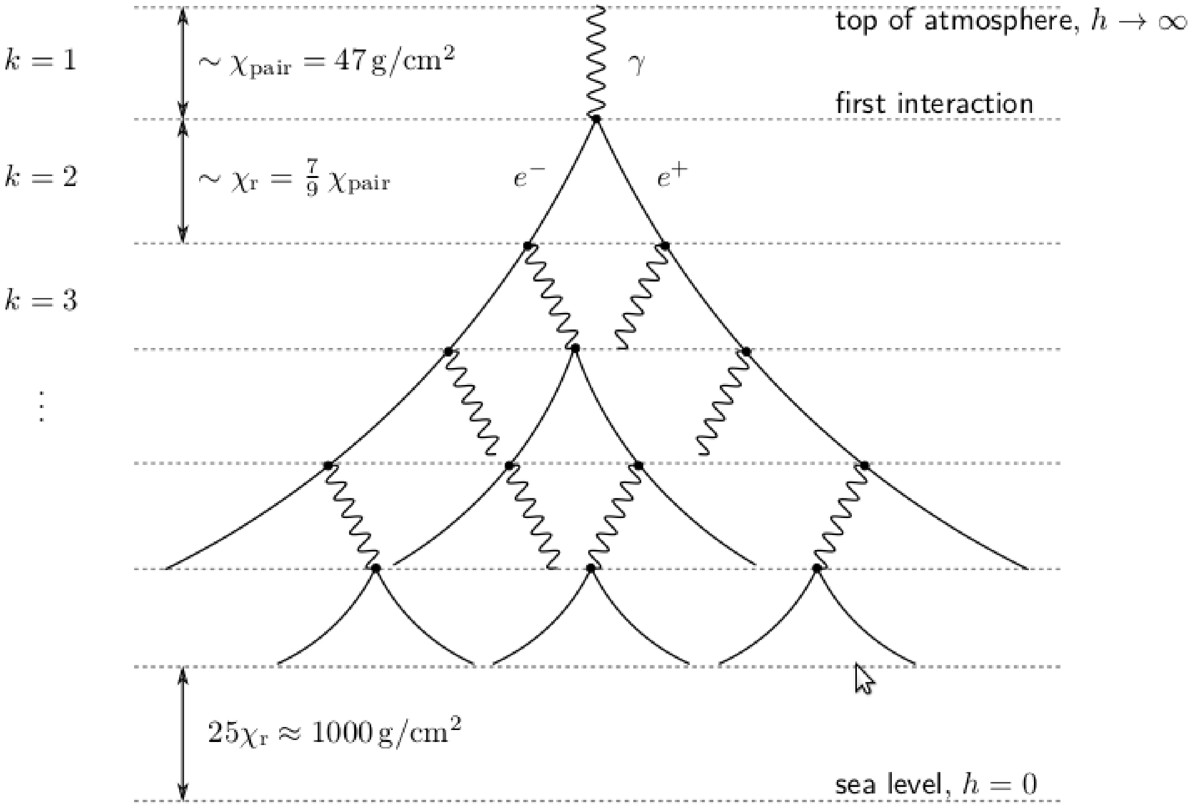


Electromagnetic radiation length X_0
~ 40 g/cm^2 in dry air

Calorimeter thicknesses
Particle physics @ LHC: ~25 X_0
γ-ray satellites: ~10 X_0
Atmosphere: ~27 X_0

Depth of shower maximum z_{max}
Homogeneous calorimeter $\propto$ log(E_0)
Atmosphere: ~ 9 km – 8.4 km × log
(log (E_0/1 TeV)

Electromagnetic air shower



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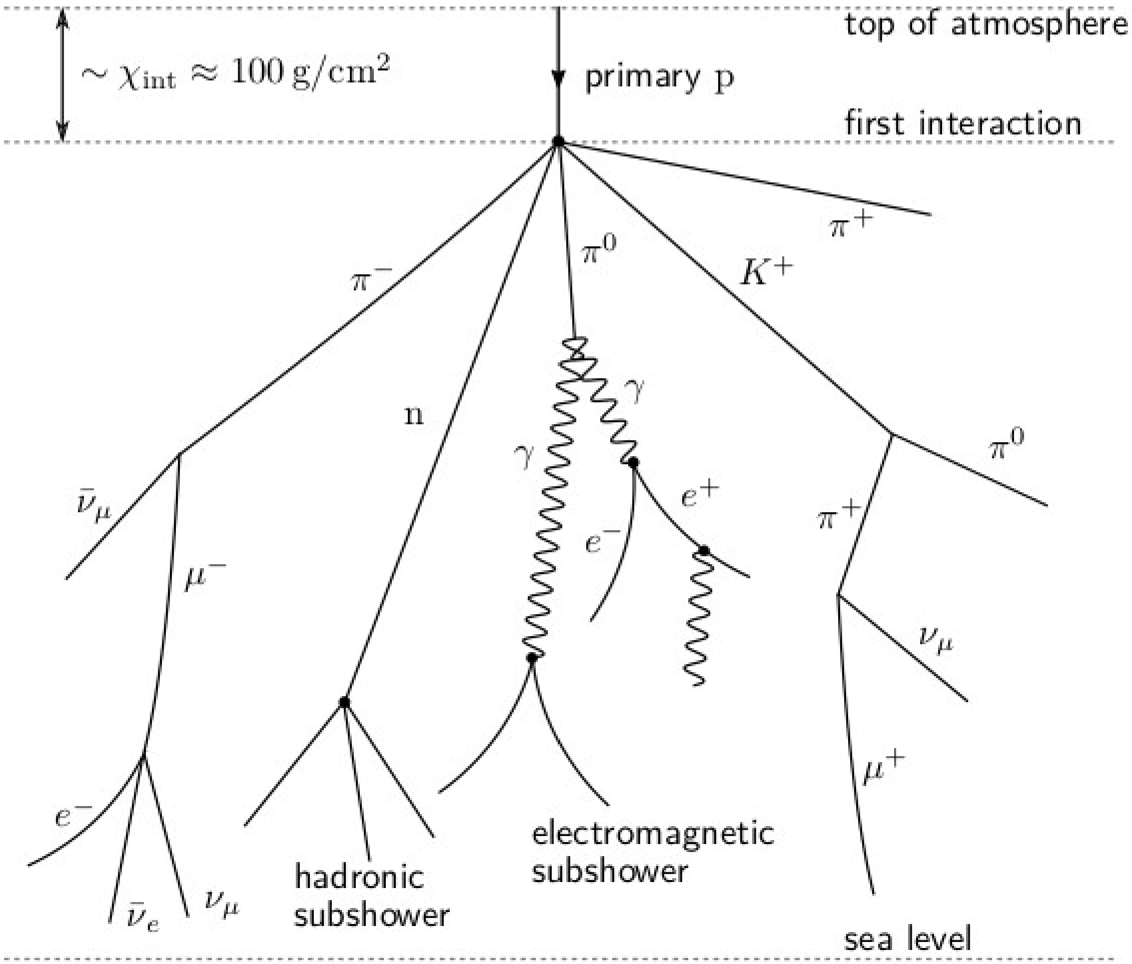
Depth of shower maximum z_{max}
Homogeneous calorimeter $\propto \log(E_0)$
Atmosphere: ~ 9 km – 8.4 km × log (log $(E_0/1\ \text{TeV})$)

And additional processes, mainly at low energy

- multiple scattering off charged particles (shower broadening)
- E losses (ionisation and atomic excitation) → shower extinction below 83 MeV)
- Electron scattering and positron annihilation (10% electron excess → **radio signal**)
- Earth's magnetic field (shower broadening in the East-West direction)
- …

Hadronic air shower

Hütten, PhD thesis (2016)



No simple description:

- nuclear interaction length
- decay lengths for unstable particles
- radiation length

→ **no universal scaling**

Sub-showers:

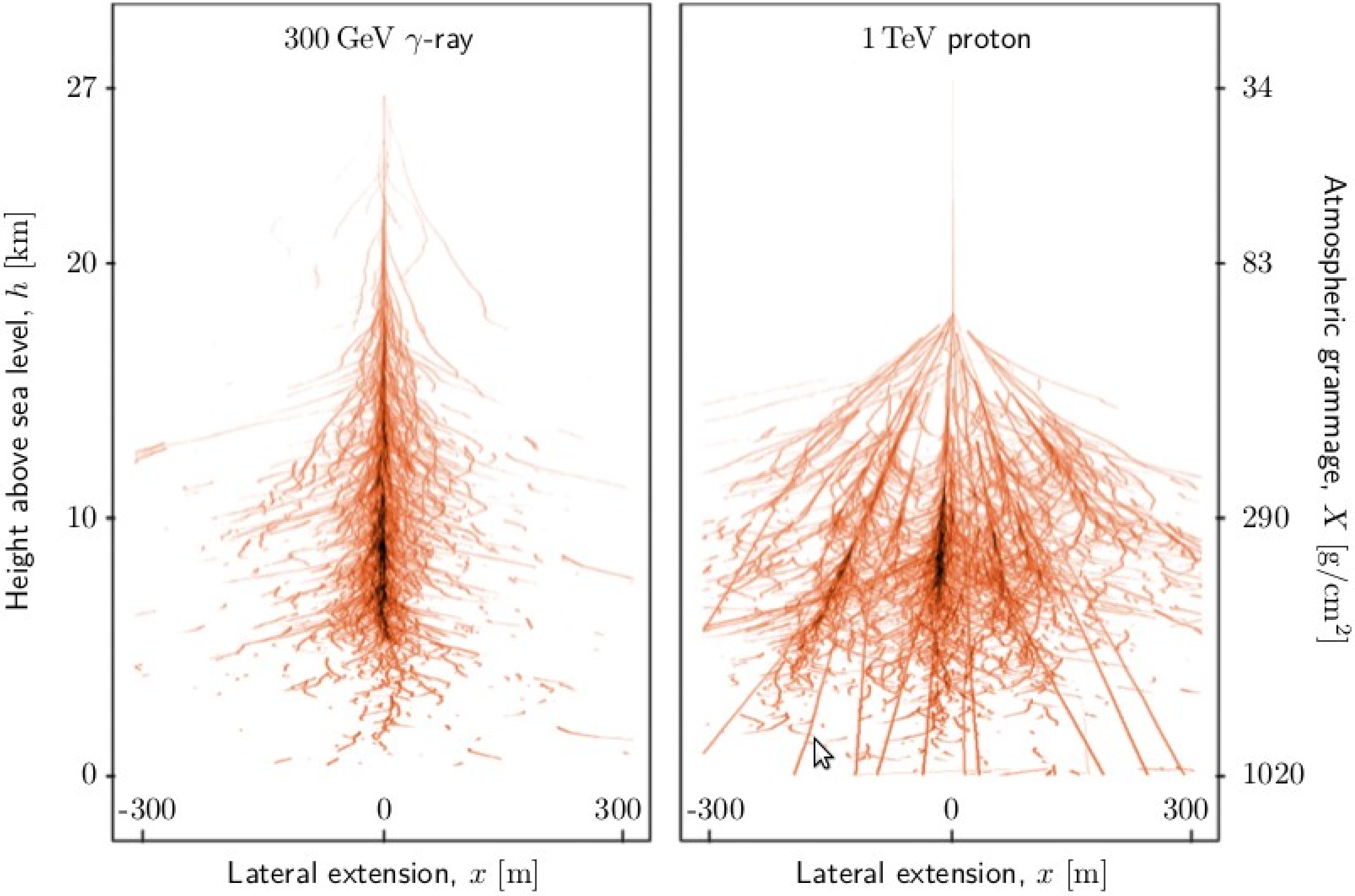
- Hadronic (n, π and K mesons)
- Electromagnetic (π^0 decay)

and particles:

- High energy μ ($\pi^\pm$ and $K^\pm$ decay)
- Atmospheric ν ($\pi^\pm$, $K^\pm$ and $\mu^\pm$ decay)

Leptonic vs hadronic shower: Monte Carlo simulation

Aharonian et al. (2008)



Geometry and variability (shower to shower)

→ Leptonic shower: simple geometry, small variability

→ Hadronic shower: complicated geometry, large variability

Main detection techniques (using Earth’s atmosphere)

Ideally, we would like to know

- Energy of the primary particle
- Direction of the primary particle
- Primary particle nature

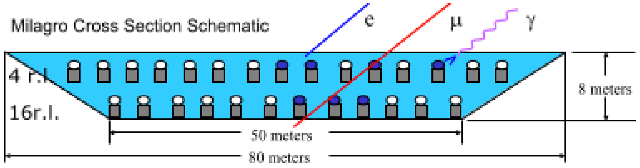
Identification capability depends on

- Particle nature
- Particle energy
- Background for the particle

Water pond

[MILAGRO, HAWC]

→ Target: PeV charged cosmic rays
→ Signal: Cerenkov light (pond)

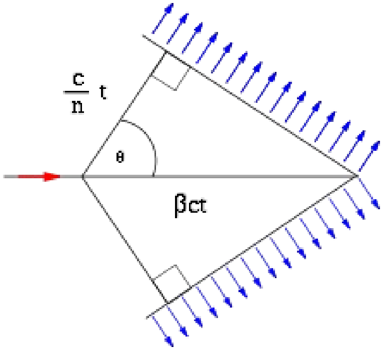


- *Direction*: timing information
- *E*: deposited E in pound
- *Identity*: muon content of shower

Cerenkov detectors

[H.E.S.S., CTA]

→ Target: TeV-PeV γ-rays
→ Signal: Cerenkov light (atmosphere)



- *Direction*: stereoscopy
- *E*: EM shower properties
- *Identity*: bkd reject. + cut on position

Hybrid detectors

[Pierre Auger obs.]

→ Target: UHECRs
→ Signal: fluorescence light (atmosphere) / surface water detectors

- *Direction*: timing+stereoscopy
- *E*: E in SD or light (cross-calib.)
- *Identity*: shower content

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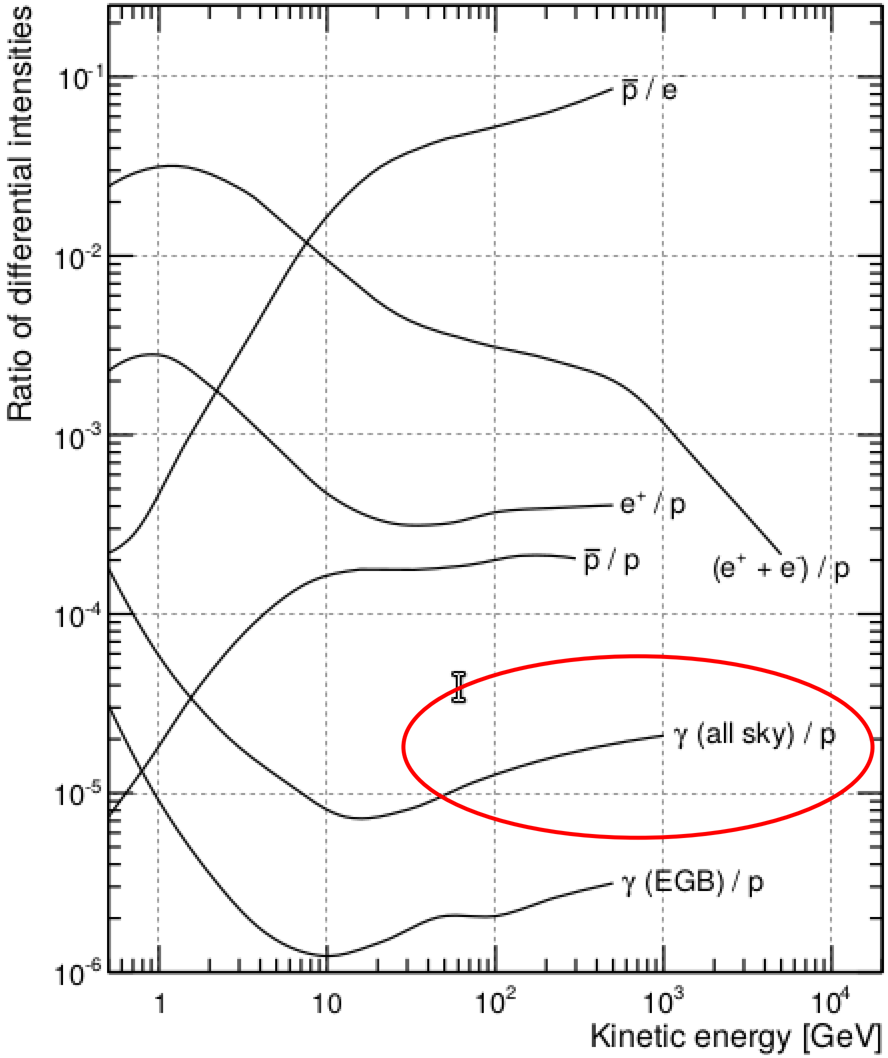
Motivation

→ Ground and satellite γ-ray detectors

→ Important experimental aspects to keep in mind

→ Research activities in a collaboration

Rejection factor is crucial for gamma-rays

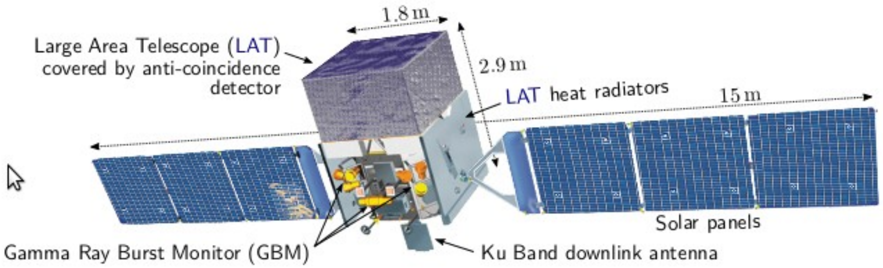


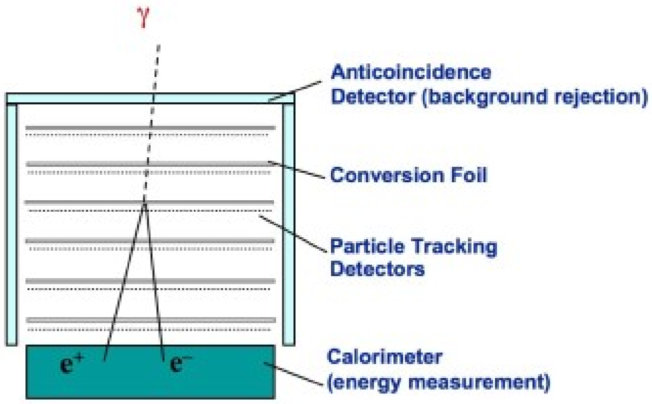
Question: How can you reduce the background in space/ground detector?

Fermi-LAT vs Cerenkov detectors

Fermi-LAT

~ 12 countries, 90 institutes, 400 researchers





Segmented electromagnetic calorimeter

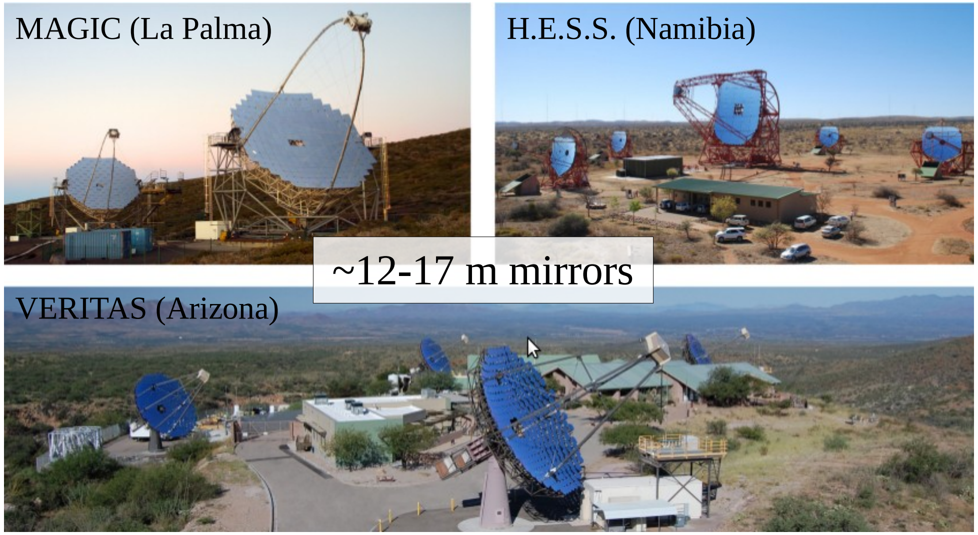
→ charged CRs vetoed by anticoincidence

→ e^- and e^+ direction in tracker

→ E from calorimeter

H.E.S.S.

~ 13 countries, 45 institutes, 250 researchers

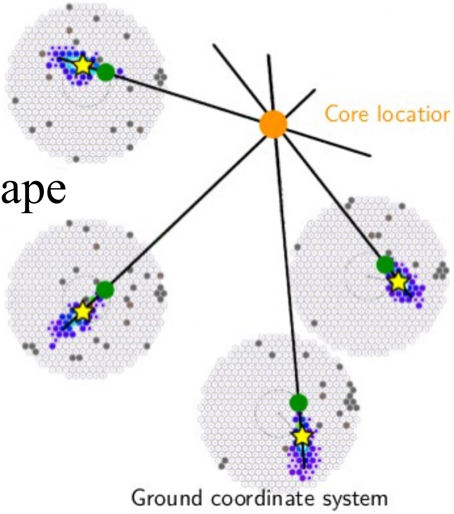


Cerenkov light

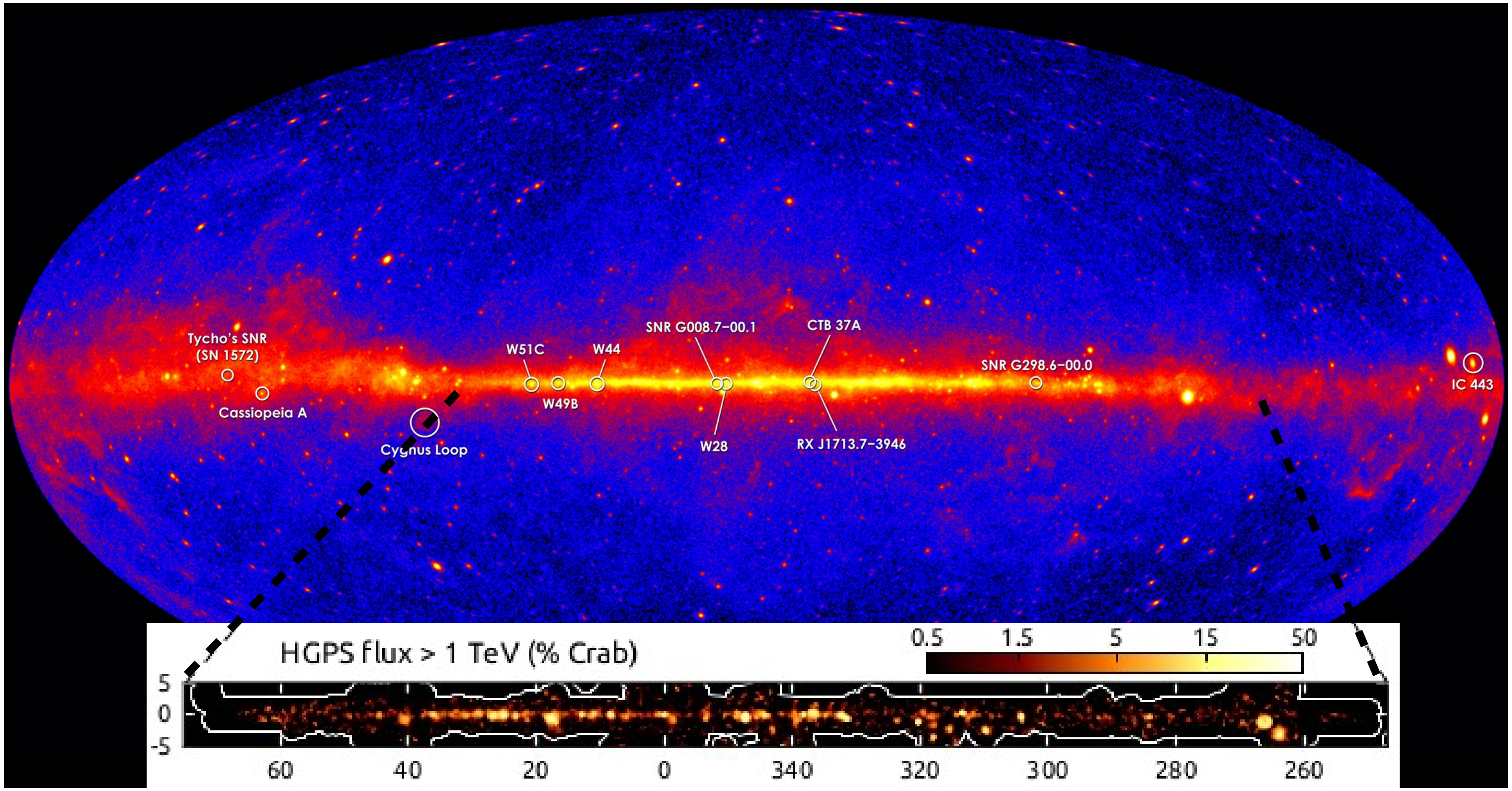
→ hadrons vetoed by image shape

→ direction from stereoscopy

→ E from shower shape



Many crucial notions not covered...



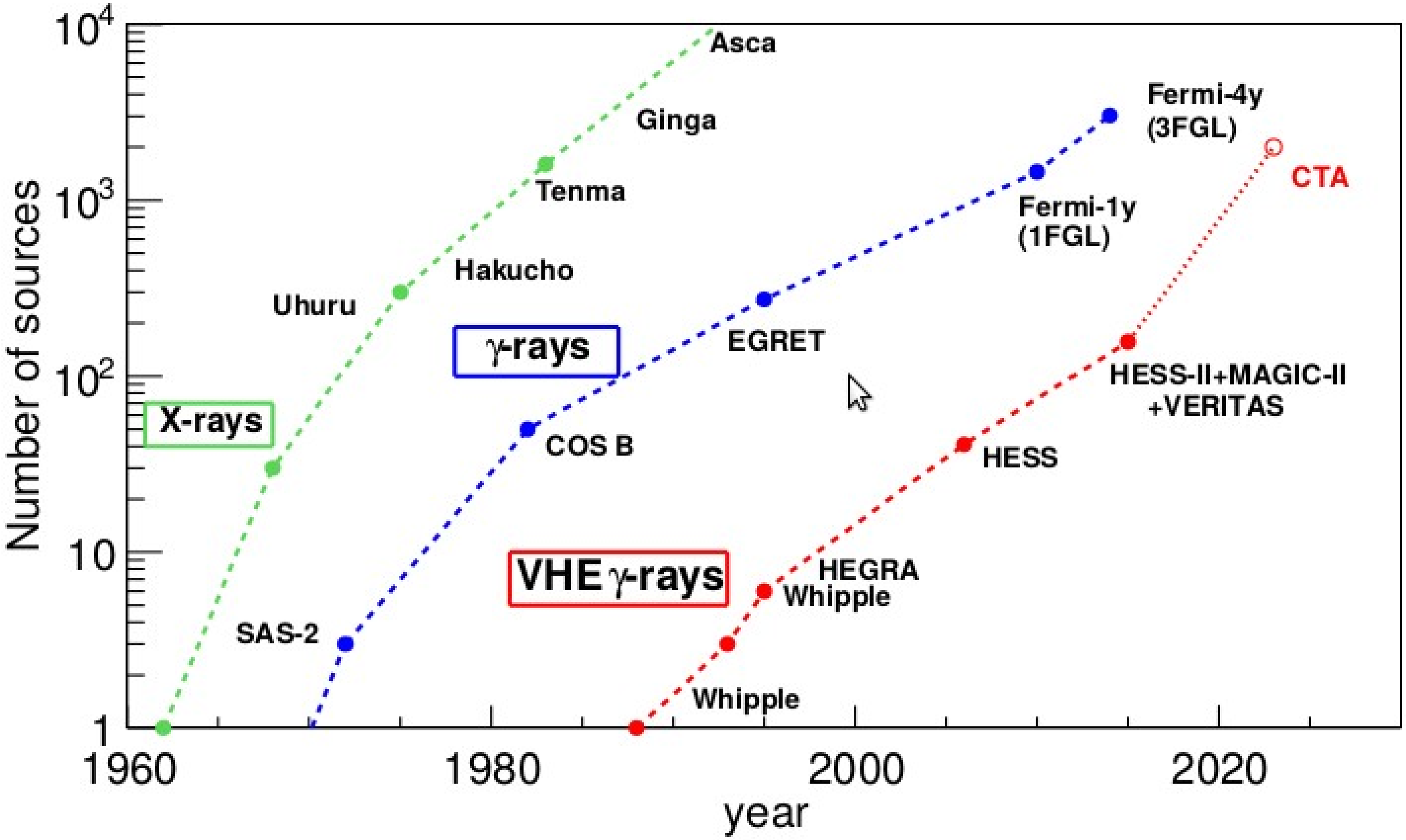
Question: how would you explain the difference between Fermi-LAT and H.E.S.S. “footprint” (first light ~10 years ago for both)?

→ Field of view
→ Duty cycle
→ γ-ray spectrum
→ Sensitivity

→ Effective area/acceptance/rejection capabilities
→ Angular/energy resolution

… in any case, γ-ray astronomy has a bright future

De Naurois & Mazin, arXiv:1511.00463



→ Field of view
→ Duty cycle
→ γ-ray spectrum
→ Sensitivity

→ Effective area/acceptance/rejection capabilities
→ Angular/energy resolution

More on energy and position calibration

Question: what generic procedures can you think of to ensure
→ $E_{measured} = E_{true}$?
→ correct source reconstruction

- Pre-flight calibration
  → Test beams (e.g., @ CERN)
  → Monte Carlo simulation

- In-flight (on-line) calibration
  → Use specific data samples with known properties
  → Use reference source (Crab nebula)
  → Calibrate position from bright sources

- Inter-calibration
  → Internal calibration system (e.g., diodes)
  → Hybrid detectors (e.g., AUGER)

More on research activities

Question: what do you think we are doing (at the various stages of experiments)?

Before starting a new project

- Scientific goal and expected return (must involve large enough community)
- Proof of concept (+validation by Monte Carlo)
- Design (mechanics, electronics…), computing resources, cost evaluation

→ *Go to funding agencies*

During construction

- Build sub-detectors, sub-systems
- Design software analysis
- Supervise integration
- ...

Starting/during exploitation

- Monitor stability of instrument
- Calibration (more Monte Carlo)
- Design analysis methods/software for your physics problem/specific source
- Collaborate/compete with your colleagues/community
- Write papers, give talks (collaboration and/or international meetings)

→ *Exciting science and fun for everyone's taste!*

1) Introduction: projections and coordinates
2) The gamma-ray sky tour
3) Air showers and detection techniques (CRs)
4) Fermi-LAT, H.E.S.S., and exp. activities
5) Constraints on dark matter from γ-rays

Motivation
→ Connect theoretical/experimental lectures
→ Dark matter distributions and targets
→ Current limits from DM indirect detection

Dark matter candidate: WIMP scenario

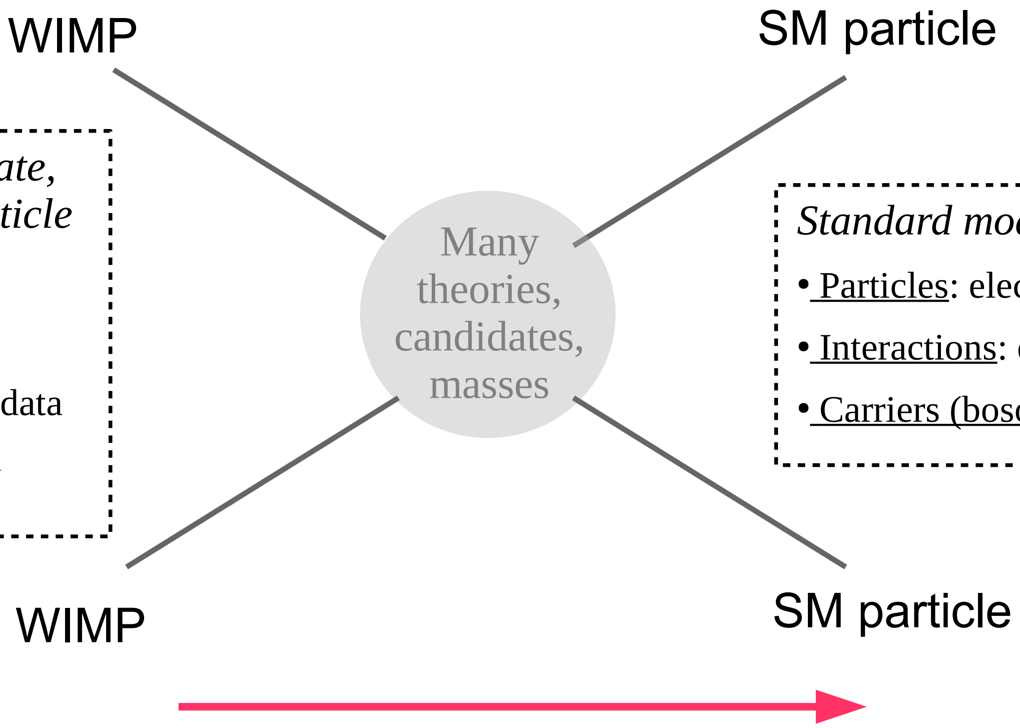
Schematic view of interactions

New physics: a possible candidate, Weakly Interactive Massive Particle

- Mass: GeV to TeV (m_p=1GeV)
- Interaction strength: weak
- Relic density: must satisfy Planck data

→ $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ cm^3 s^{-1}

→ SuperSymmetry (SUSY) naturally leads to this value ("WIMP miracle")



Standard model of particle physics

- Particles: electrons, ν, quarks
- Interactions: electromag., weak, strong
- Carriers (bosons): γ, (W,,Z), gluons

Indirect detection

Photons (and neutrinos)→ γ-ray (and ν) astronomy
Fermi-LAT, HESS, MAGIC, CTA...

Charged particles → galactic cosmic rays
PAMELA, AMS-02...

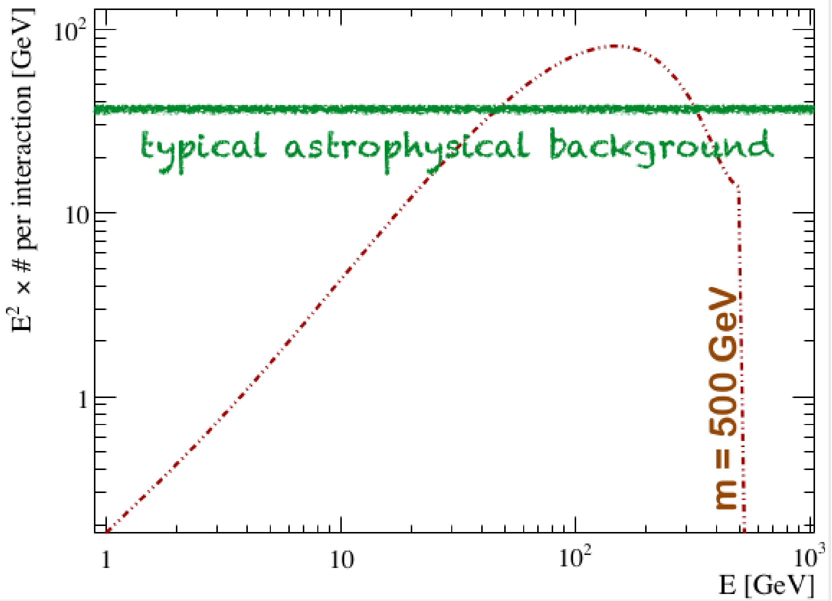
Limit on DM annihilation cross-section <σv>

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi,\theta,\Delta\Omega) = \underline{\frac{d\Phi_\gamma^{PP}}{dE_\gamma}(E_\gamma)} \times J(\psi,\theta,\Delta\Omega)$$

Particle physics

Weakly Interacting
Massive Particles
m WIMP~ 0.1 – 100 TeV

$$\frac{d\Phi_\gamma^{PP}}{dE_\gamma}(E_\gamma) \equiv \frac{1}{4\pi}\,\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\cdot\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f$$



Dark matter-induced signal strength

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi,\theta,\Delta\Omega) = \underbrace{\frac{d\Phi_\gamma^{PP}}{dE_\gamma}(E_\gamma)}_{\text{Particle physics}} \times \underbrace{J(\psi,\theta,\Delta\Omega)}_{\text{Astrophysics}}$$

Weakly Interacting
Massive Particles
m $_{\text{WIMP}}$~ 0.1 – 100 TeV

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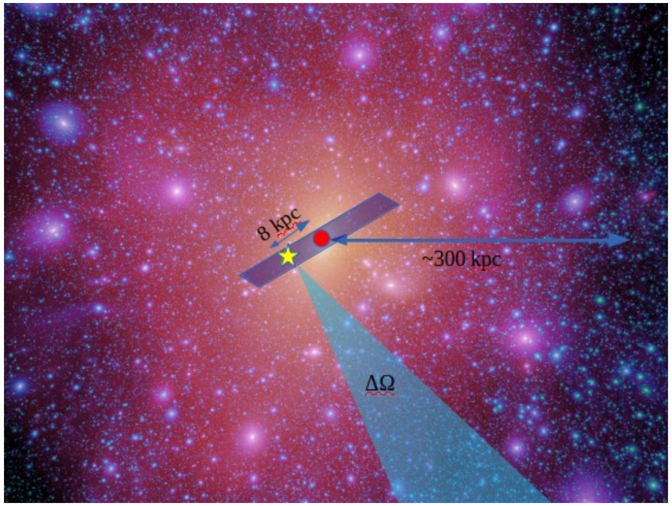
From numerical
simulations or data

$$J(\psi,\theta,\Delta\Omega) = \int_0^{\Delta\Omega}\int_{\rm l.o.s}\rho^2(l(\psi,\theta))\;dl\,d\Omega$$

Dark matter distribution *ρ*



Question: what target would you pick?

→ Dense (~ ∫ ρ^2), close ($1/d^2$),
and no astrophysical background

Dark matter-induced signal strength

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi,\theta,\Delta\Omega) = \underbrace{\frac{d\Phi_\gamma^{PP}}{dE_\gamma}(E_\gamma)}_{\text{Particle physics}} \times \underbrace{J(\psi,\theta,\Delta\Omega)}_{\text{Astrophysics}}$$

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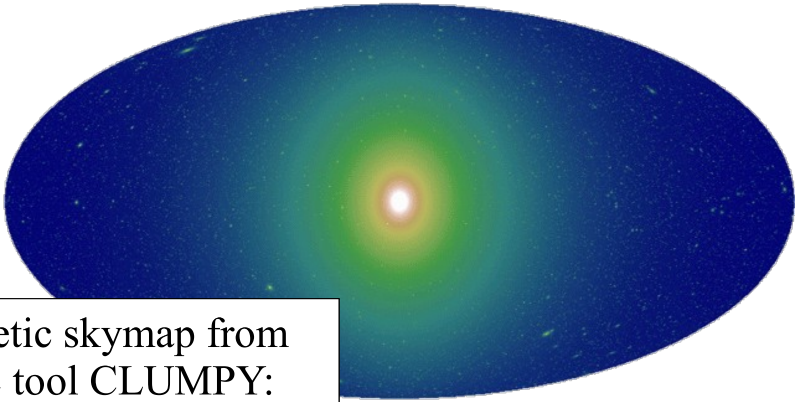
$$J(\psi,\theta,\Delta\Omega) = \int_0^{\Delta\Omega}\int_{\rm l.o.s}\rho^2(l(\psi,\theta))\;dl\,d\Omega$$

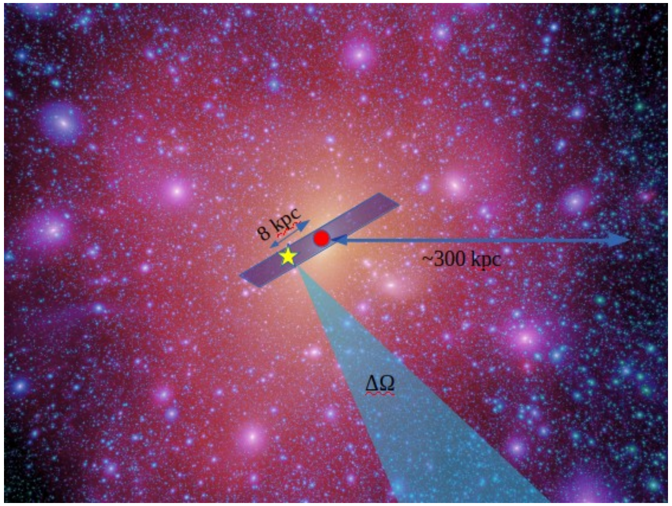
From *ρ* to J to DM-induced γ-rays

- ρ^2 integrated along the line-of-sight
- DM annihilation spectrum



Synthetic skymap from public tool CLUMPY: http://lpsc.in2p3.fr/clumpy

Dark matter distribution

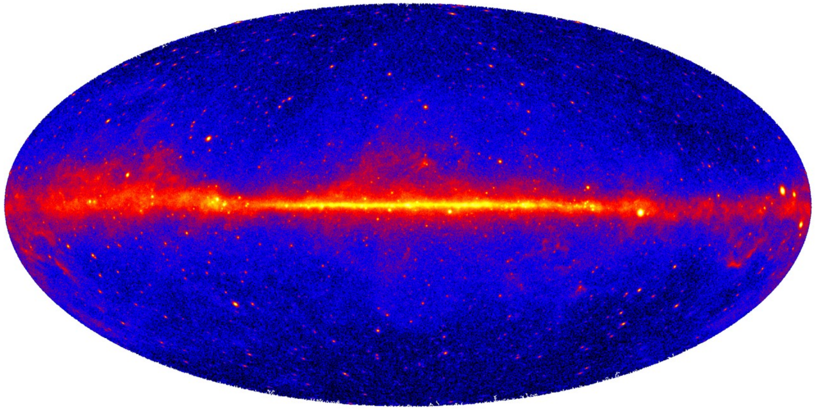


Dark matter-induced signal strength

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi,\theta,\Delta\Omega) = \underline{\frac{d\Phi_\gamma^{PP}}{dE_\gamma}(E_\gamma)} \times \underline{J(\psi,\theta,\Delta\Omega)}$$

Particle physics

Astrophysics



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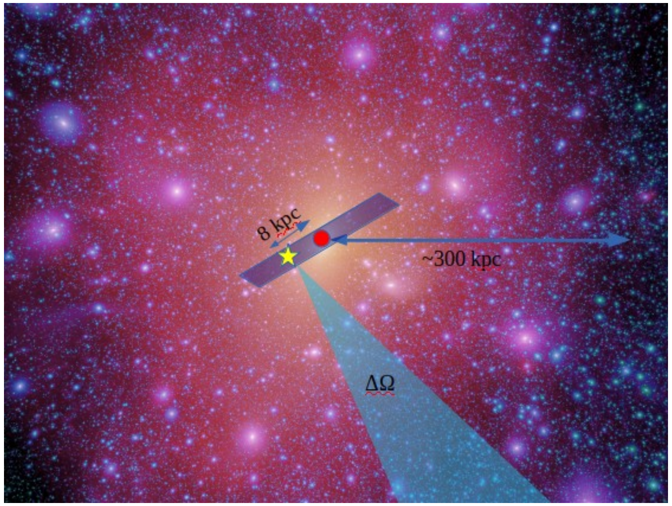
Dark matter distribution



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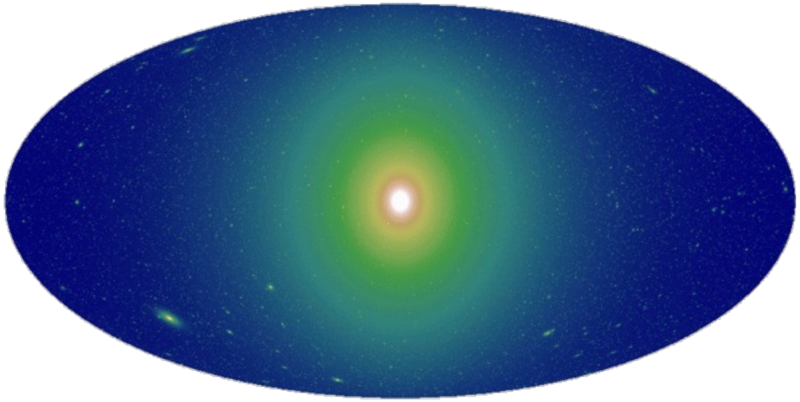


Dark matter-induced signal strength

$$\underline{\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi,\theta,\Delta\Omega)} = \underline{\frac{d\Phi^{PP}_\gamma}{dE_\gamma}(E_\gamma)} \times \underline{J(\psi,\theta,\Delta\Omega)}$$

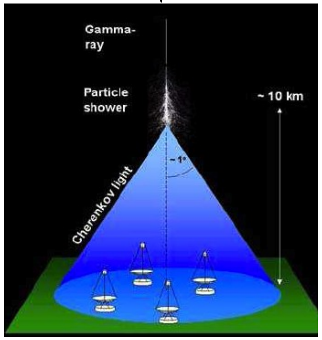
Instrumental sensitivity

Particle physics

Astrophysics

Array of Cerenkov telescopes

Satellite



H.E.S.S. + CTA

- Ground based
- 100 GeV → 100 TeV
- Resolution: 0.2° – 0.02°
- Pointed instrument
- Background limited

Fermi-LAT (since 2008)

- Space-borne
- 30 MeV – 300 GeV
- Resolution: 1° – 0.1°
- Fullsky
- Signal limited

$$\frac{d\Phi^{PP}_\gamma}{dE_\gamma}(E_\gamma) \equiv \frac{1}{4\pi}\overset{??}{\boxed{\frac{\langle\sigma_{\rm ann}v\rangle}{2m_\chi^2}}}\cdot\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$$J(\psi,\theta,\Delta\Omega) = \int_0^{\Delta\Omega}\int_{\rm l.o.s}\rho^2(l(\psi,\theta))\;dl\,d\Omega$$

Dark matter-induced signal strength

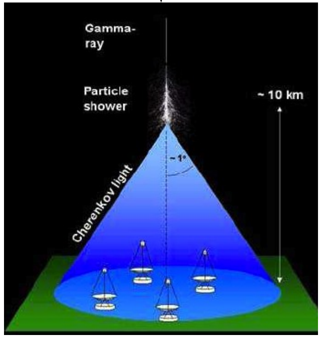
$$\underline{\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi,\theta,\Delta\Omega)} = \underline{\frac{d\Phi^{PP}_\gamma}{dE_\gamma}(E_\gamma)} \times \underline{J(\psi,\theta,\Delta\Omega)}$$

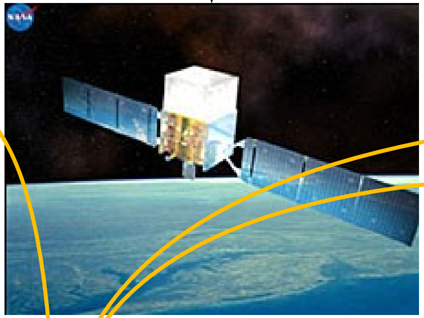
Instrumental sensitivity

Particle physics

Astrophysics

Array of Cerenkov telescopes | **Satellite**





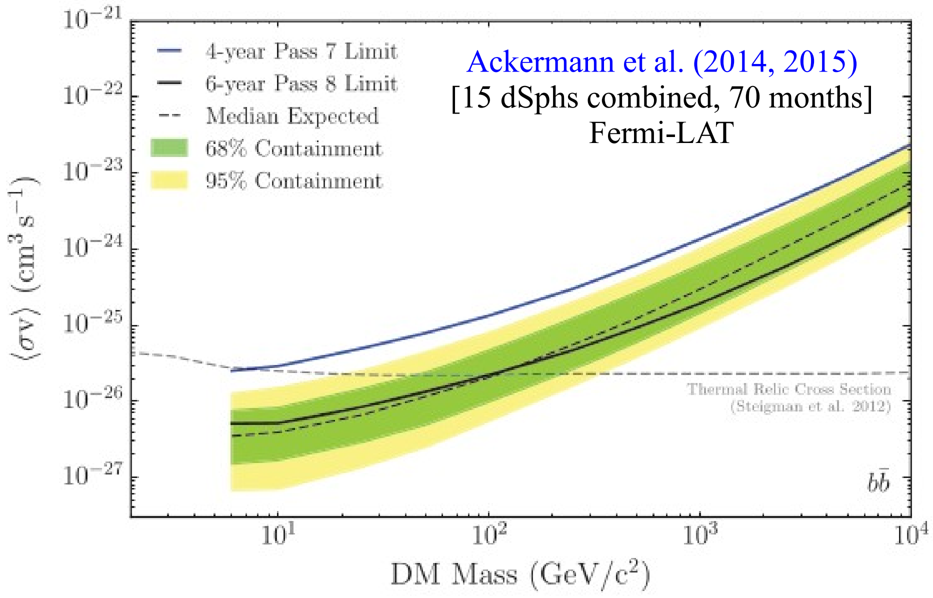
??

$$\frac{d\Phi^{PP}_\gamma}{dE_\gamma}(E_\gamma) \equiv \frac{1}{4\pi}\boxed{\frac{\langle\sigma_{\rm ann}v\rangle}{2m_\chi^2}}\cdot\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$$J(\psi,\theta,\Delta\Omega) = \int_0^{\Delta\Omega}\int_{\rm l.o.s}\rho^2(l(\psi,\theta))\;dl\,d\Omega$$

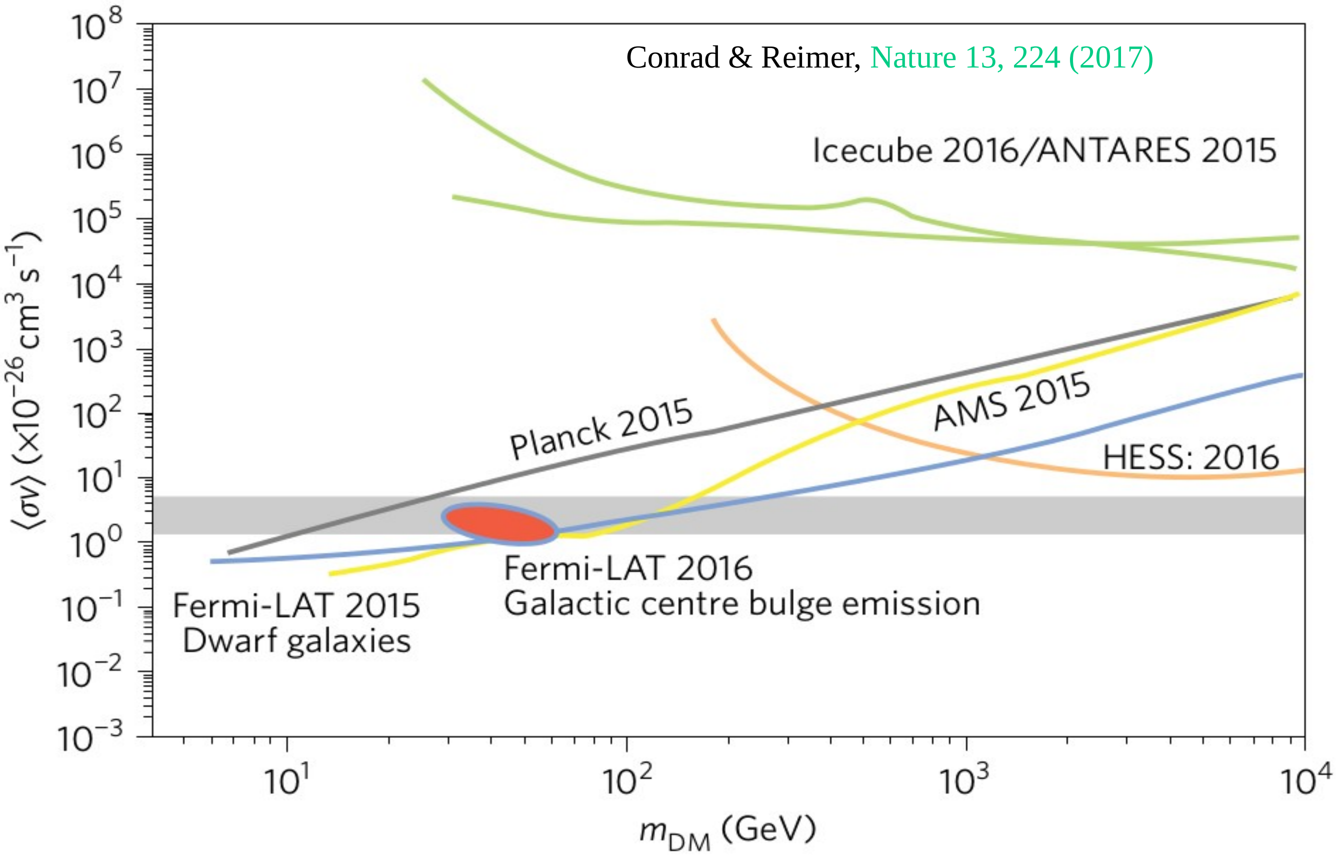
$$\boxed{\langle\sigma_{\rm ann}v\rangle \propto m_\chi^2 \times J(\alpha_{\rm int}) \times \text{Sensitivity} \times \frac{dN^{pp}}{dE}}$$

→ After ~30 years of effort,
WIMP dark matter may be within reach



Ackermann et al. (2014, 2015)
[15 dSphs combined, 70 months]
Fermi-LAT

Comparison/complementarity of indirect detection targets



→ γ-rays from dSphs and antiprotons provide best targets for DM searches