

# Astroparticle experiment 2

## [high-energy astronomy]

### **Main questions in the field**

- Source of cosmic rays
- Origin of non-thermal emissions
- Dark matter indirect detection



David Maurin  
(LPSC)

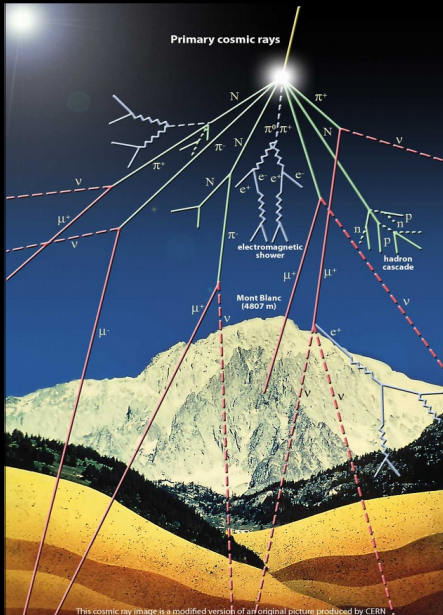
dmaurin@lpsc.in2p3.fr



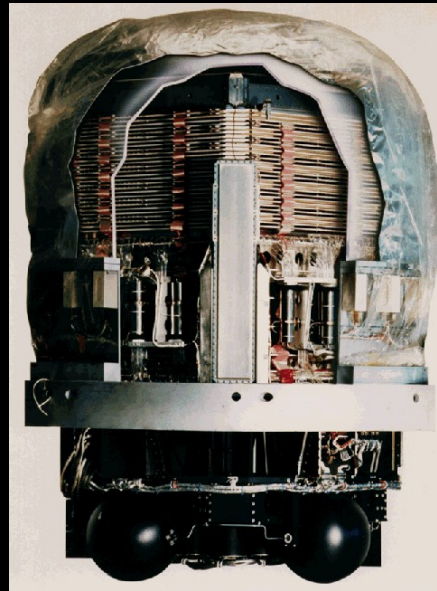
GRASPA  
Annecy-le-Vieux  
24 July 2017

# Cosmic ray physics milestones

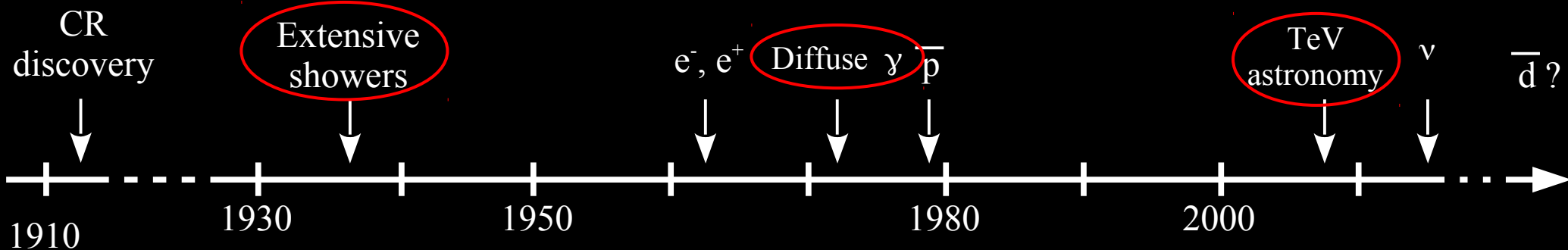
Mountain altitude < 5 km



EGRET onboard CGRO



H.E.S.S. telescopes



Cosmic rays  
= Particle physics

Particle physics  
Astrophysics

+ astroparticle physics

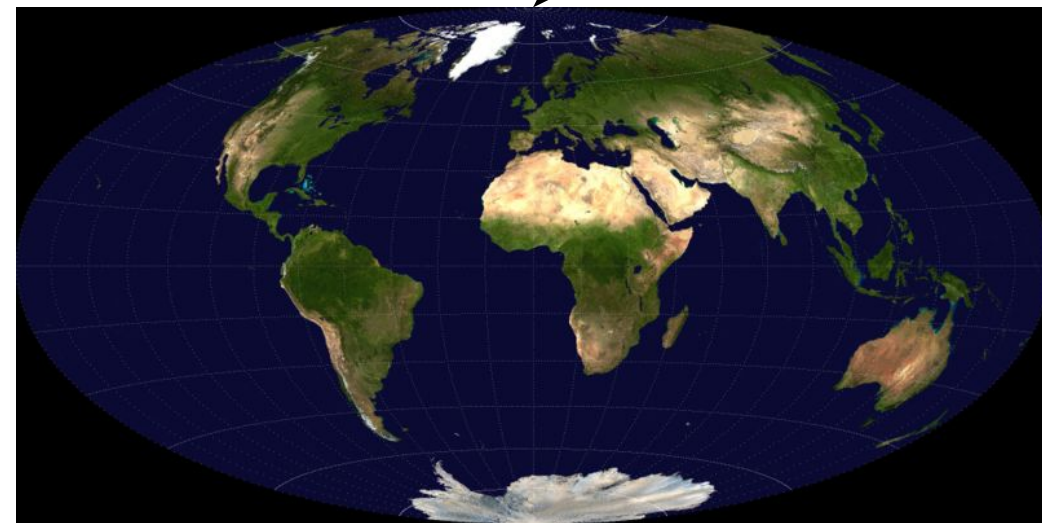
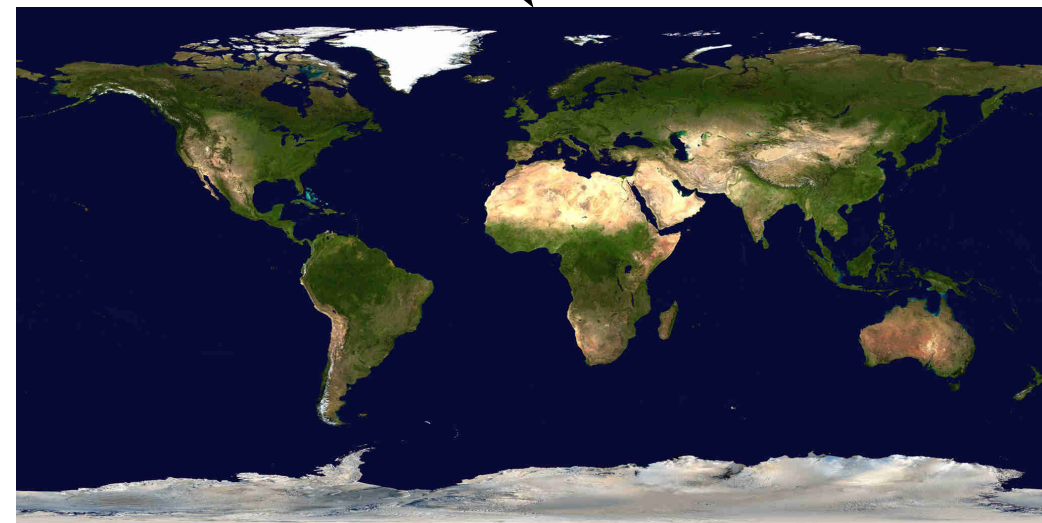
- 1) Introduction: projections and coordinates
- 2) The gamma-ray sky
- 3) Interactions in the atmosphere and showers
- 4) Fermi-LAT and H.E.S.S.
- 5) Constraints on dark matter from  $\gamma$ -rays

# Mapping the 2D sphere to the Euclidian space

Mercator



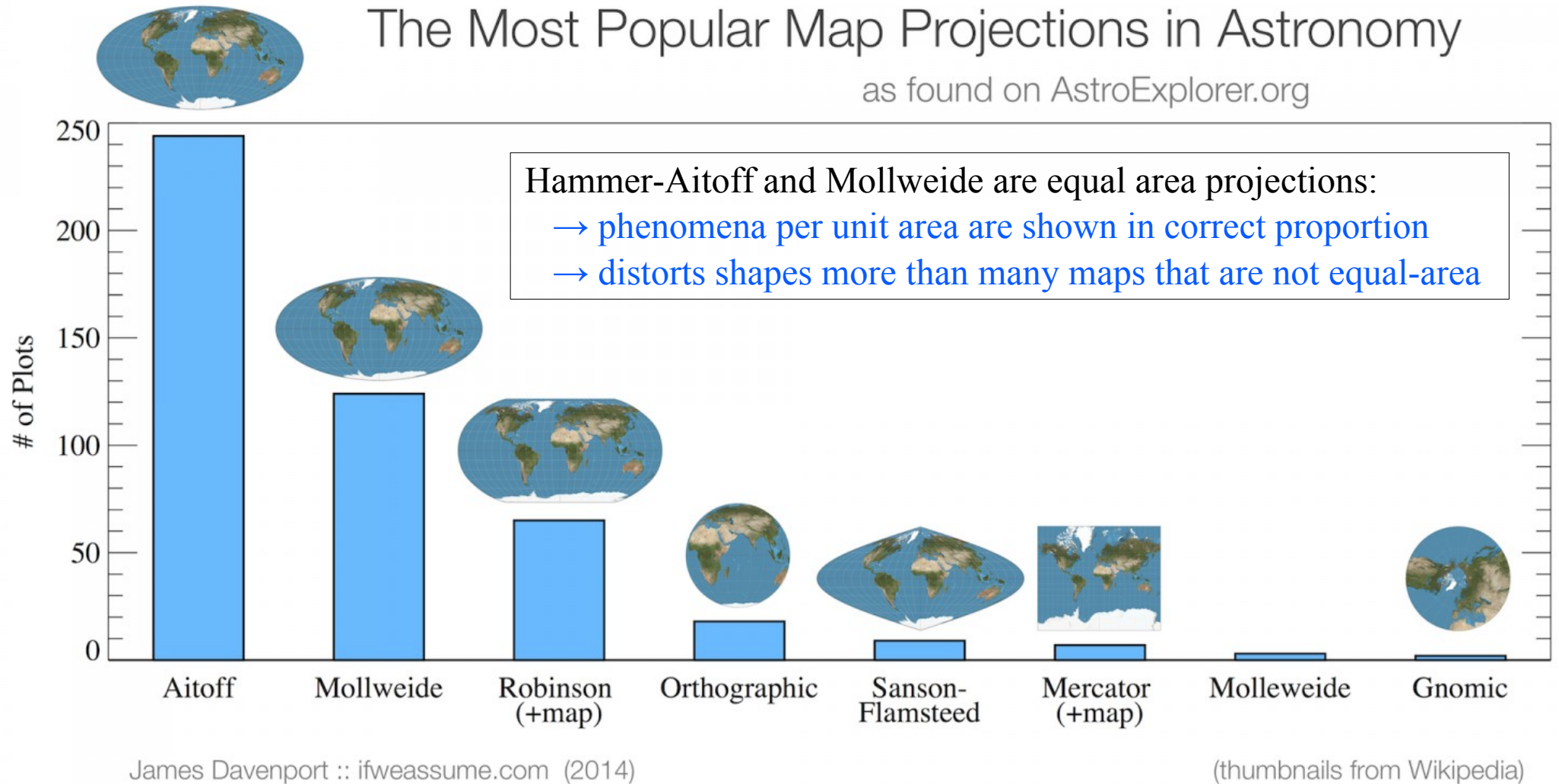
Hammer-Aitoff



Question: what projection is best for astronomical use and why?



# Mapping the 2D sphere to the Euclidian space



*Representations of celestial coordinates in FITS*  
Calabretta & Greisen, [A&A 395, 1077 \(2002\)](#)

# Galactic coordinates: the Milky Way

## Unit conversion

### Mass

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

$$\sim 2 \cdot 10^{30} \text{ kg}$$

$$\sim 3 \cdot 10^5 M_{\oplus}$$

### Distance

$$1 \text{ pc} \sim 3 \cdot 10^{16} \text{ m}$$

$$\sim 2 \cdot 10^5 \text{ AU}$$

$$\sim 3.26 \text{ ly}$$

## Milky Way ID

$$\text{Stars} \sim 10^{11} \rightarrow 5 \cdot 10^{10} M_{\odot}$$

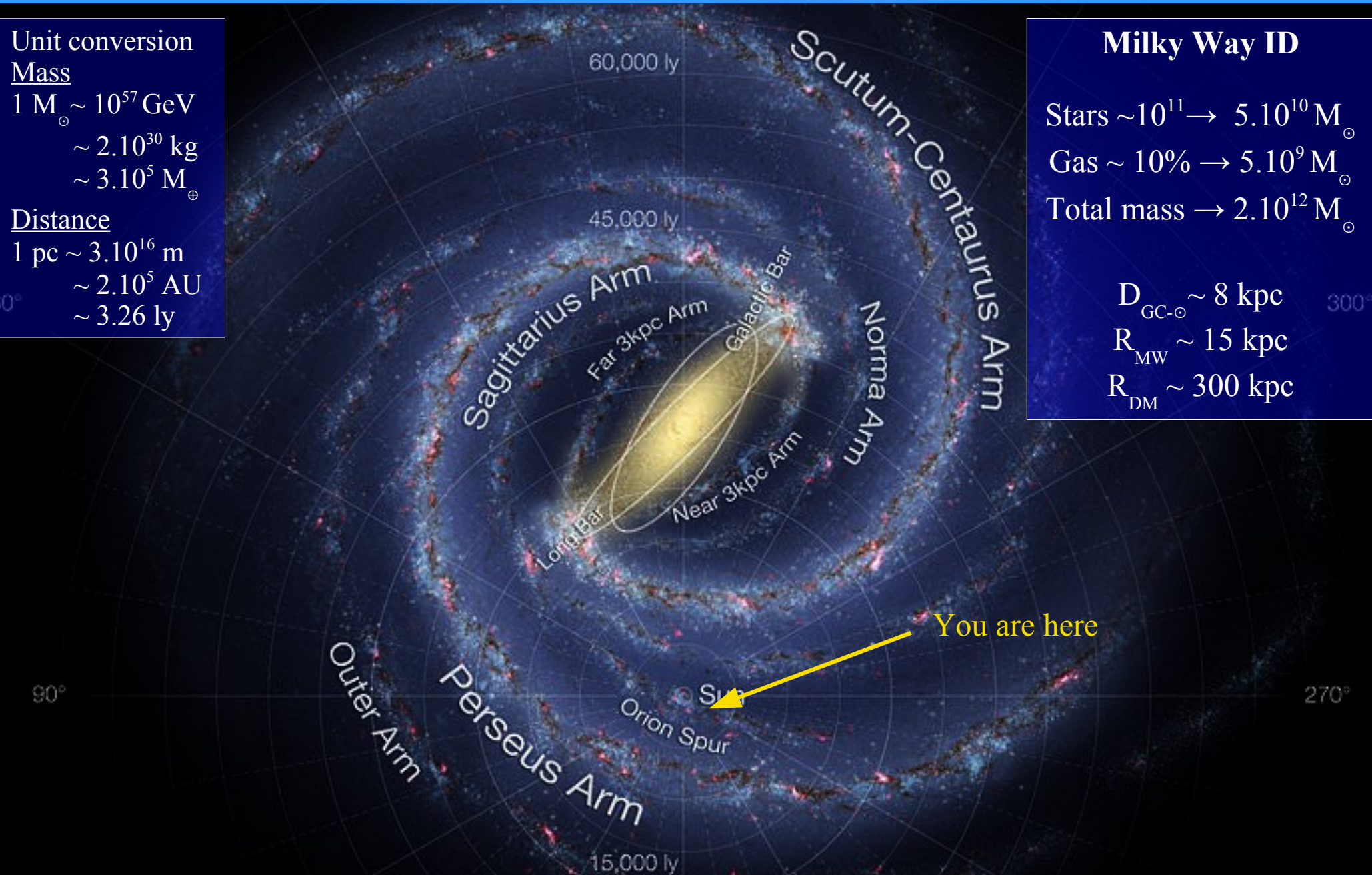
$$\text{Gas} \sim 10\% \rightarrow 5 \cdot 10^9 M_{\odot}$$

$$\text{Total mass} \rightarrow 2 \cdot 10^{12} M_{\odot}$$

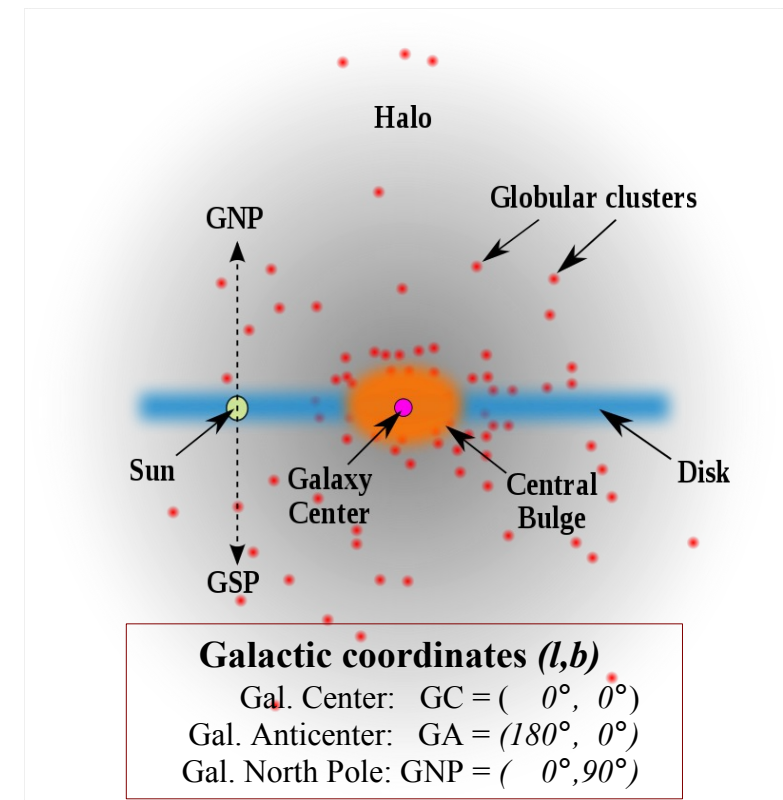
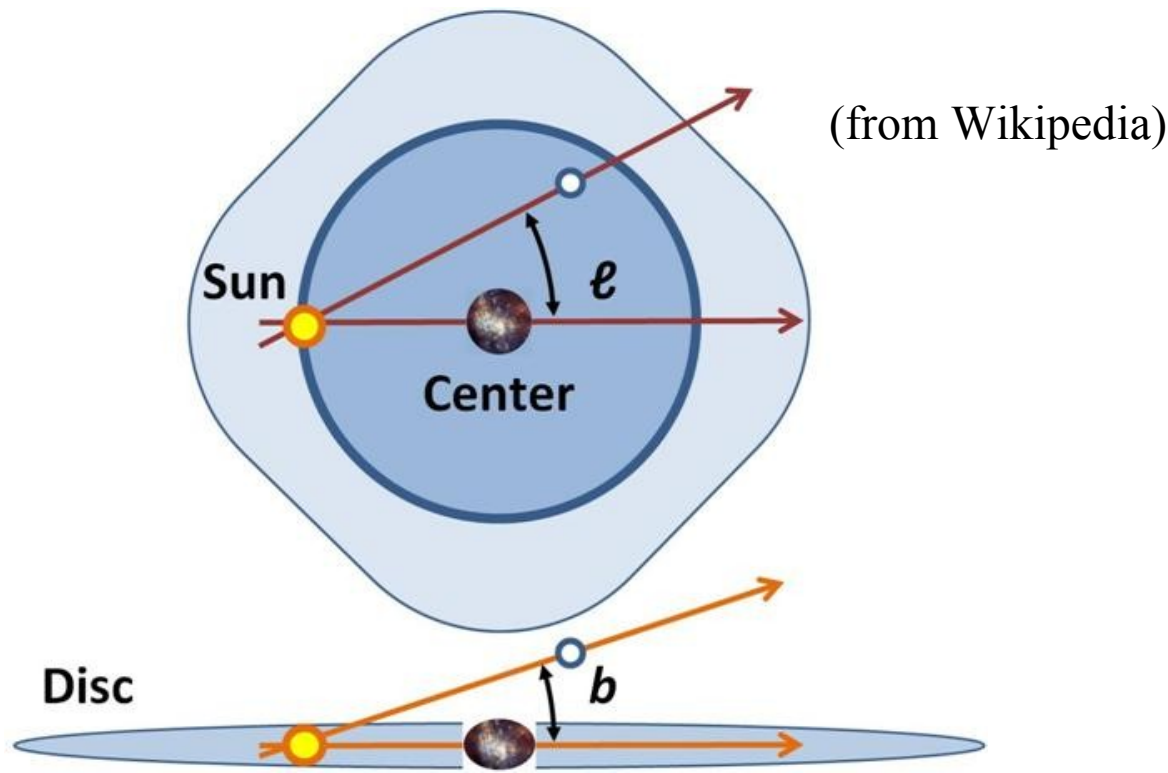
$$D_{\text{GC-}\odot} \sim 8 \text{ kpc}$$

$$R_{\text{MW}} \sim 15 \text{ kpc}$$

$$R_{\text{DM}} \sim 300 \text{ kpc}$$



# Galactic coordinates: 'd', l (longitude), b (latitude)

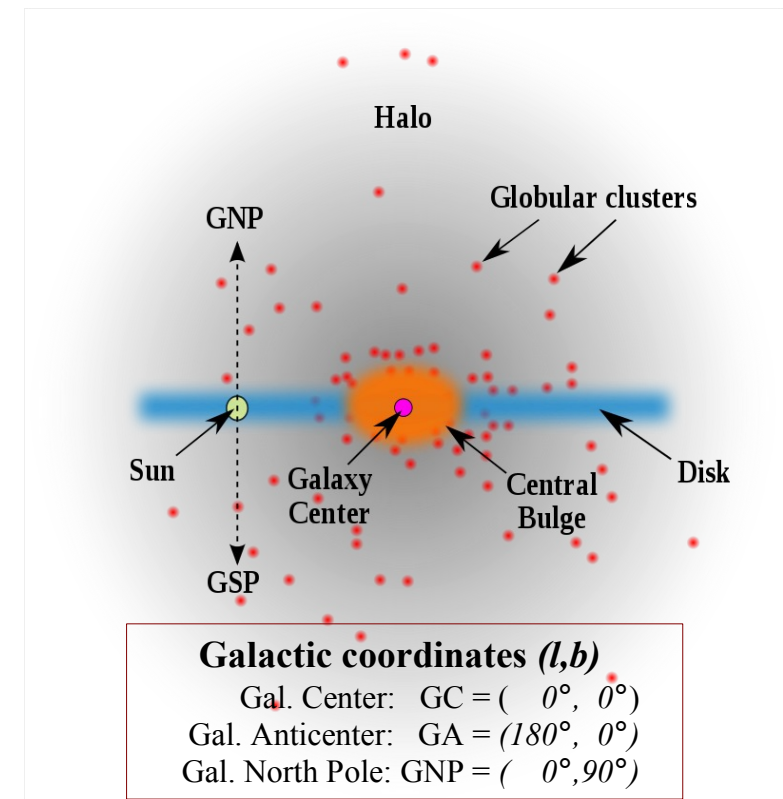
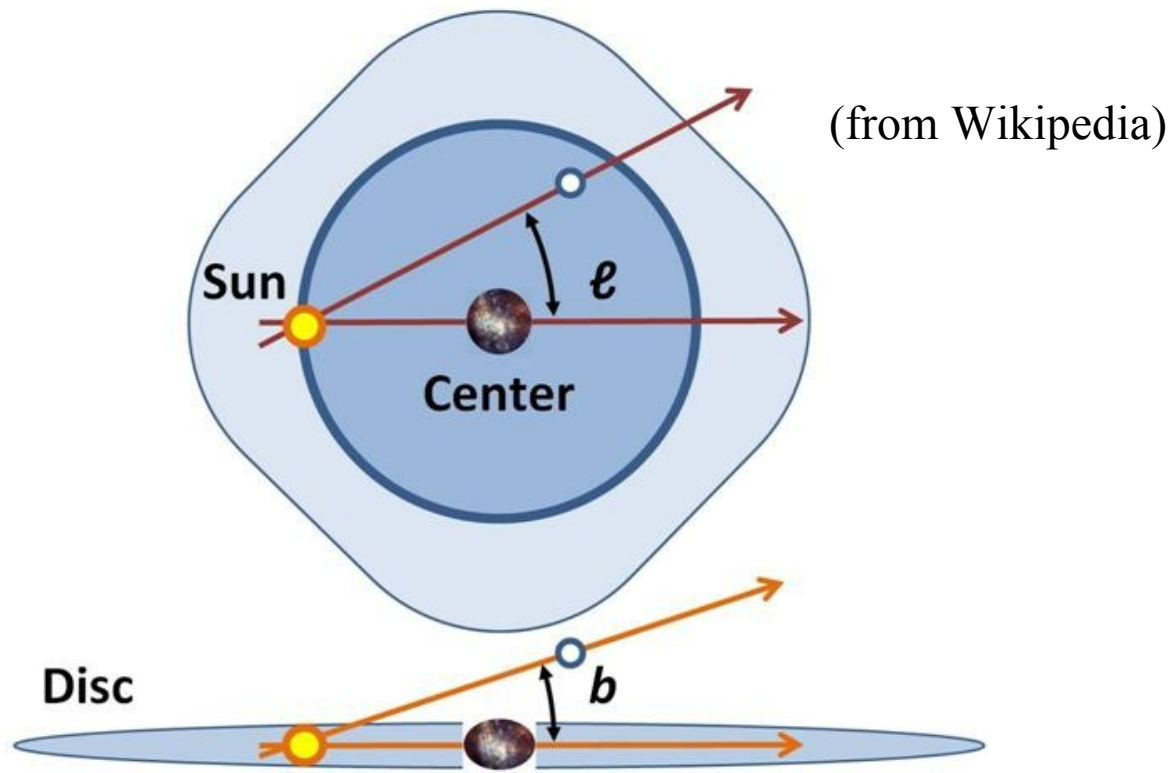


## Questions

- how would you define the galactic centre?
- at what precision do you think  $D_{GC-\odot}$  is known?



# Galactic coordinates: 'd', l (longitude), b (latitude)



## Remarks:

- still a challenge to define accurately MW properties
- coordinate system *changes* with time!

- IAU (International Astronomical Union) standards for coordinates systems
- FITS (Flexible Image Transport System) standards for archival storage

- 1) Introduction: projections and coordinates
- 2) The gamma-ray sky
- 3) Interactions in the atmosphere and showers
- 4) Fermi-LAT and H.E.S.S.
- 5) Constraints on dark matter from  $\gamma$ -rays

### **Motivation**

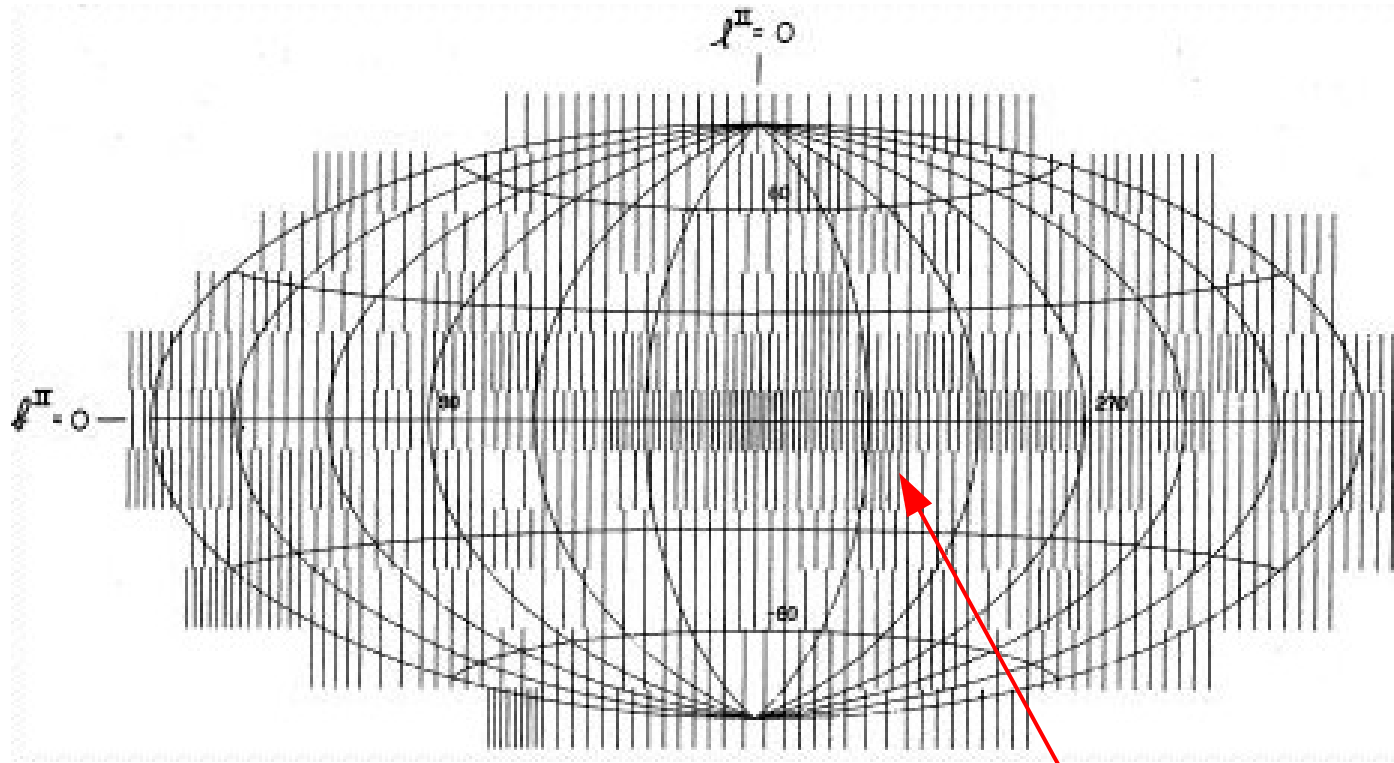
- Diffuse emission and origin
- Sources of non-thermal emissions
  - GeV vs TeV sky



# Diffuse emission: first detection $>100$ MeV

## OSO-3 ( $>100$ MeV)

[16 months, then failure of the 2<sup>nd</sup> spacecraft tape recorder]



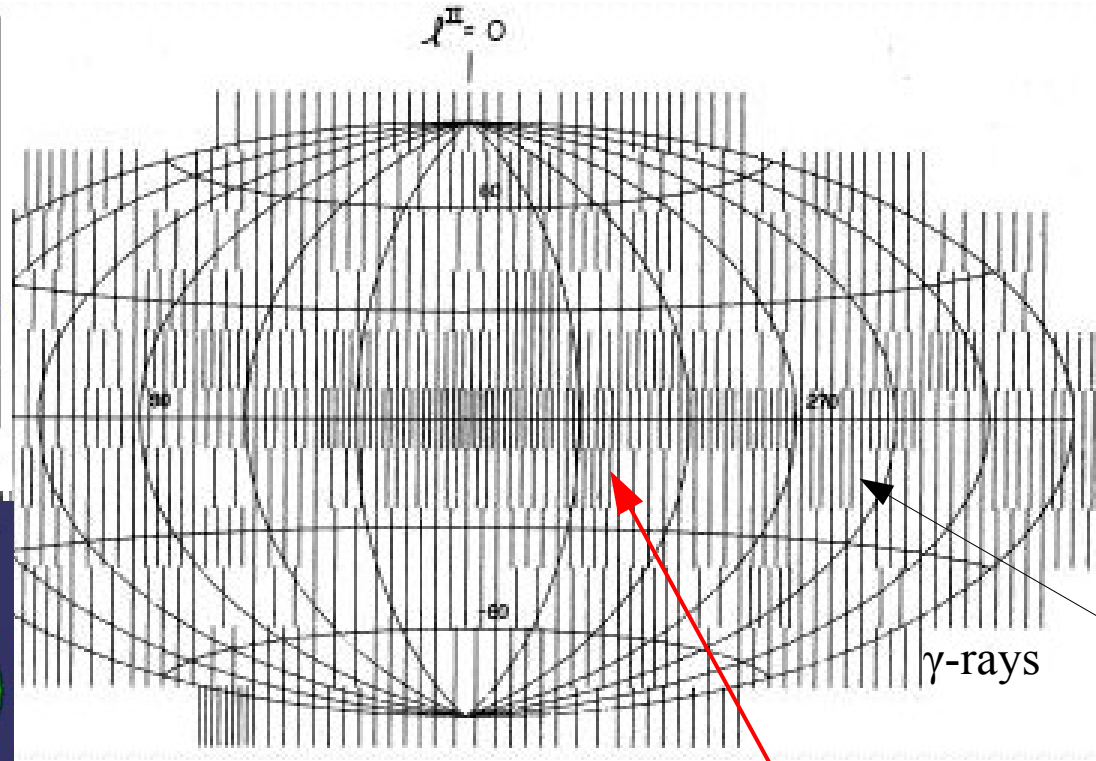
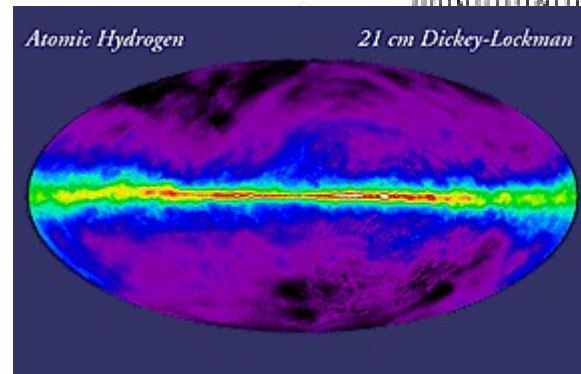
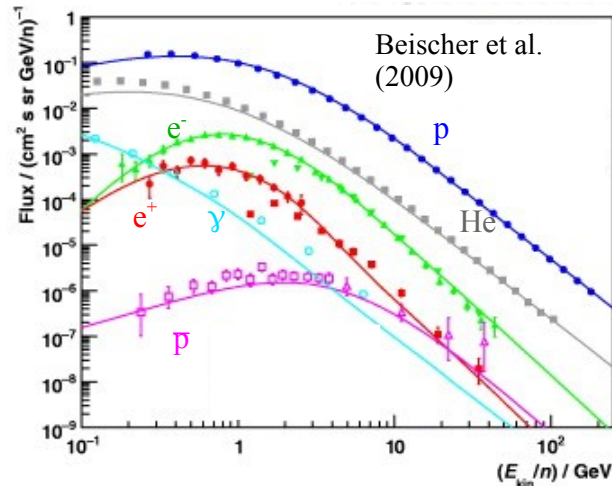
Kraushaar *et al.*, ApJ **177**, 341 (1972)

Question: can you guess what is the origin of the emission?

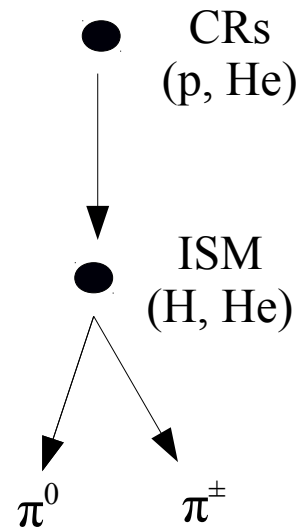
# Diffuse emission: first detection $>100$ MeV

## OSO-3 ( $>100$ MeV)

[16 months, then failure of the 2<sup>nd</sup> spacecraft tape recorder]



Kraushaar *et al.*, ApJ **177**, 341 (1972)

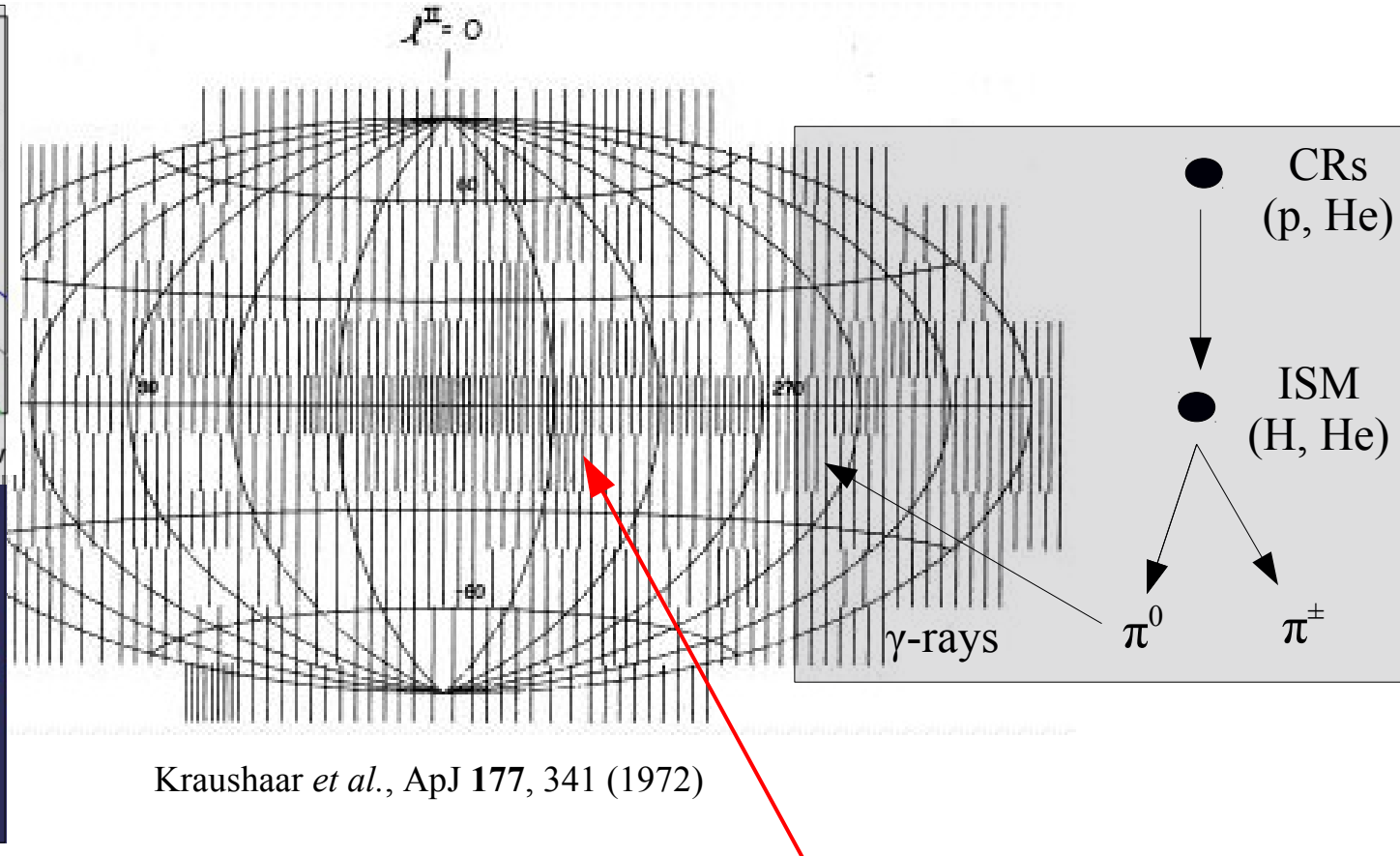
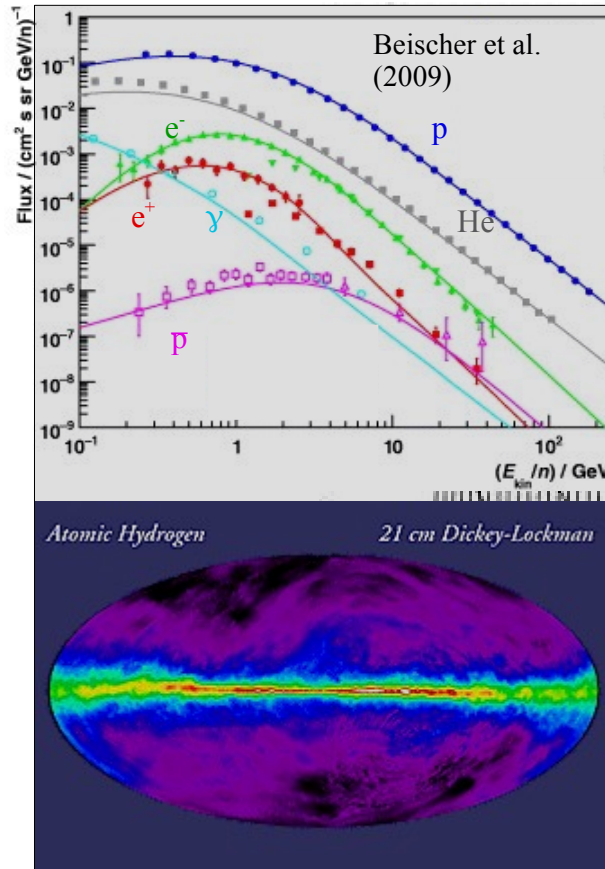


Question: can you guess what is the origin of the emission?

# Diffuse emission: first detection $>100$ MeV

## OSO-3 ( $>100$ MeV)

[16 months, then failure of the 2<sup>nd</sup> spacecraft tape recorder]



Question: can you guess what is the origin of the emission?

**Diffuse emission in the disk = galactic origin**

→ Distribution proportional to column density at 21cm (H<sub>I</sub>)

→ Absolute intensity accounted for by  $\pi^0$  production

(N.B.: there also exists an isotropic extragalactic diffuse emission)

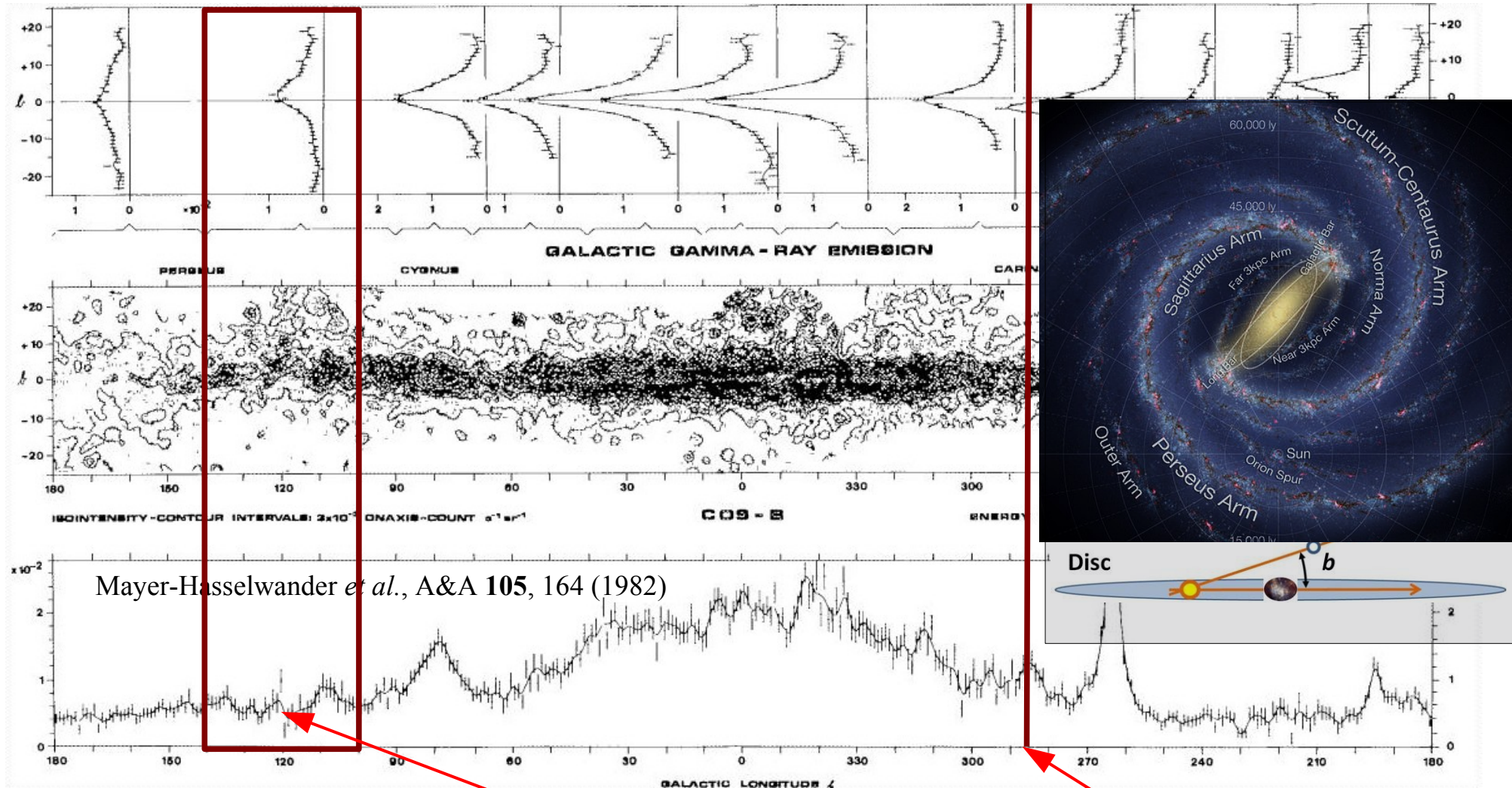




# Diffuse emission: a closer look

COS-B (70-150 MeV)

[4 years of data]



Question: Why do we have peaks? Origin of broadened latitudinal emission?

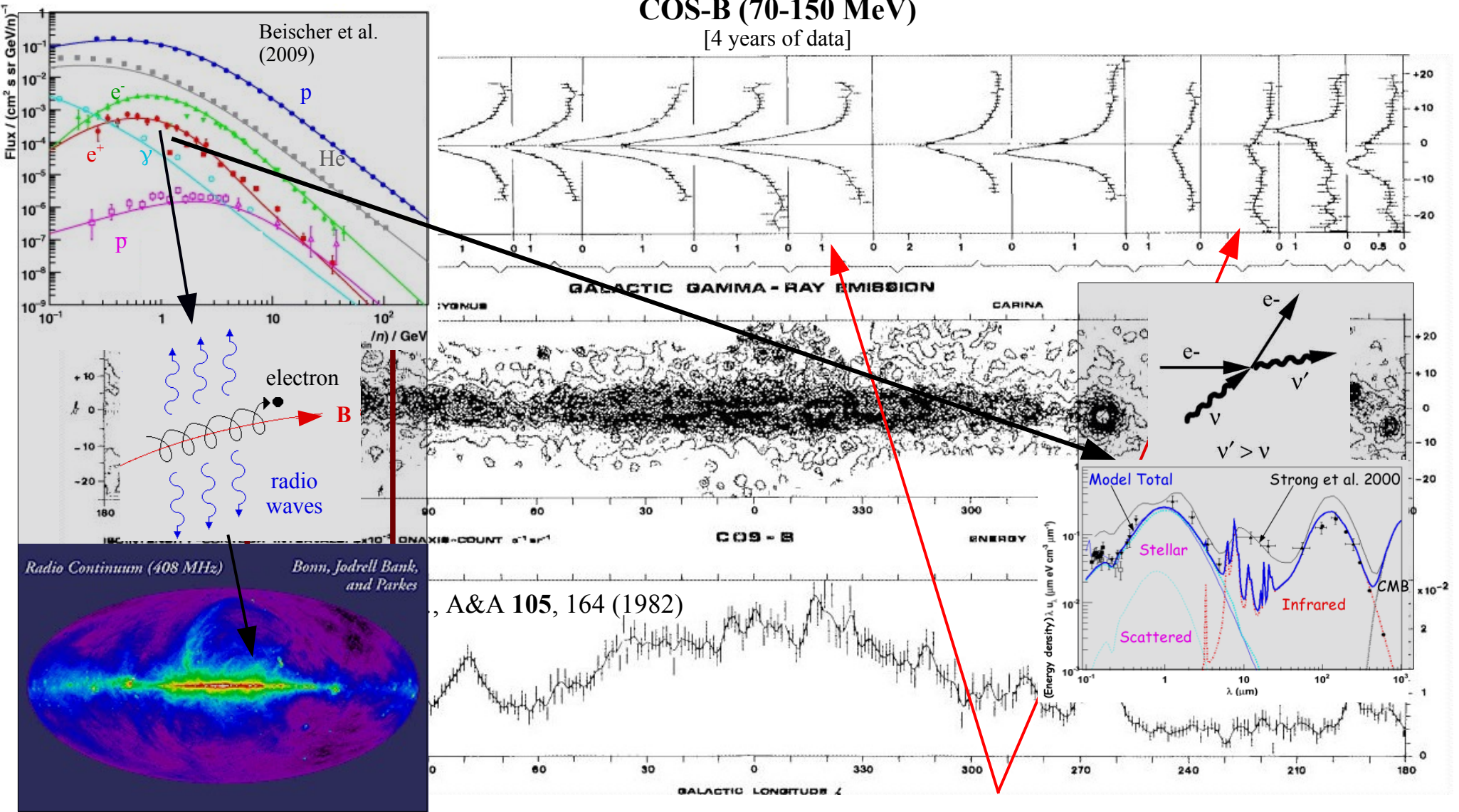
→ New correlations found: Perseus arm ( $l=100^\circ-140^\circ$ ), spiral arm in Carina ( $l=285^\circ$ )



# Diffuse emission: a closer look

## COS-B (70-150 MeV)

[4 years of data]

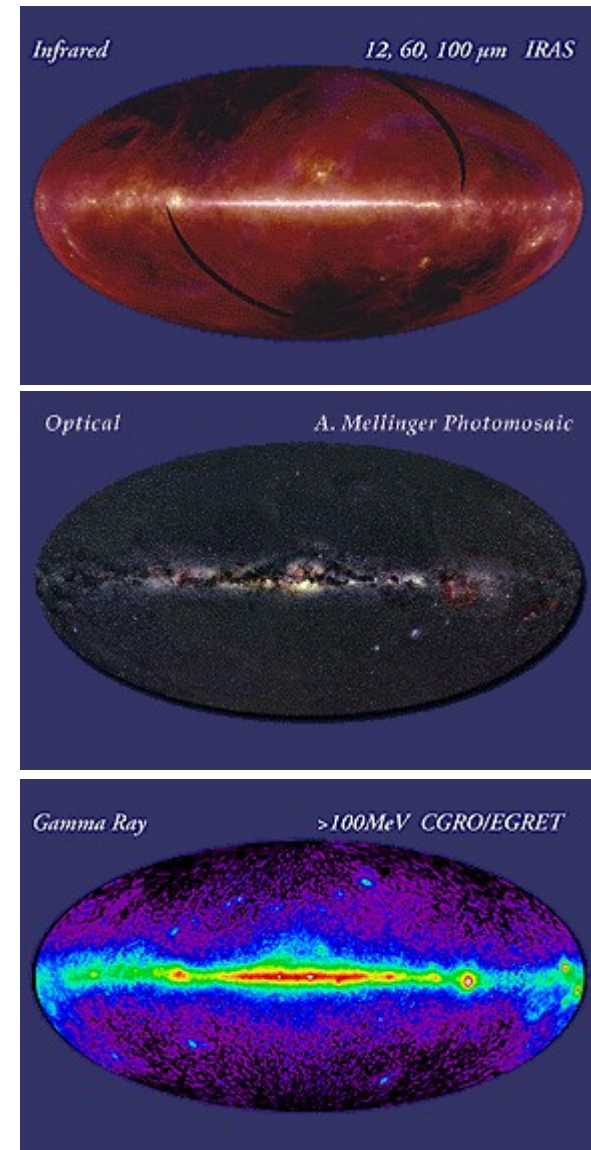
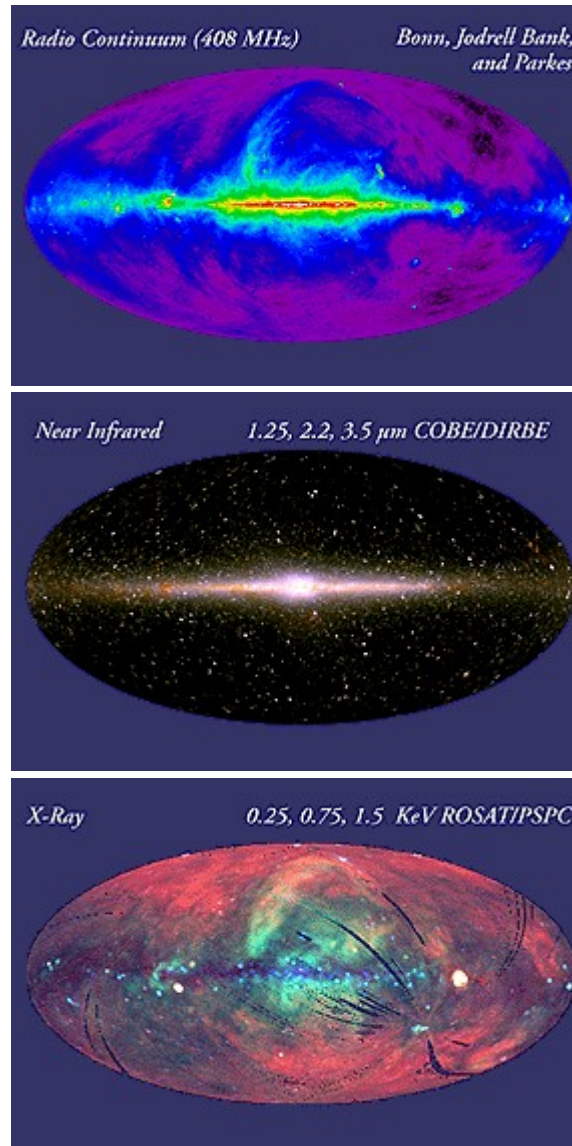
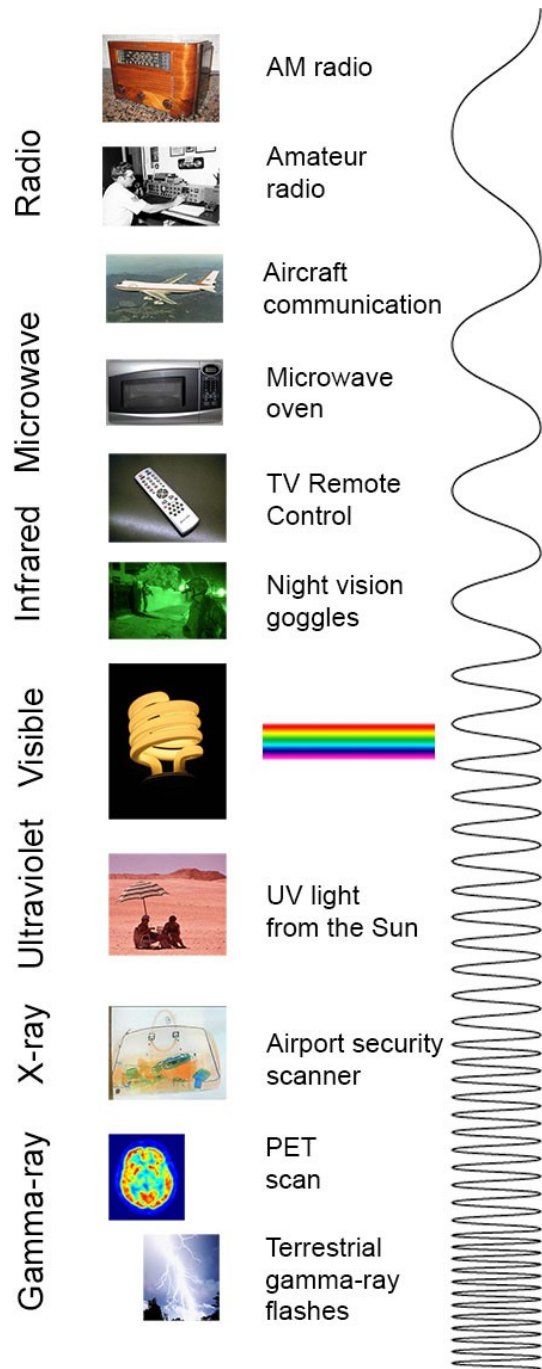


Question: Why do we have peaks? Origin of broadened latitudinal emission?

- New correlations found: Perseus arm ( $l=100^\circ-140^\circ$ ), spiral arm in Carina ( $l=285^\circ$ )
- Require additional leptonic emission (inverse Compton mostly, and synchrotron)

# Work with the multi-wavelength sky!

<https://mwmw.gsfc.nasa.gov>

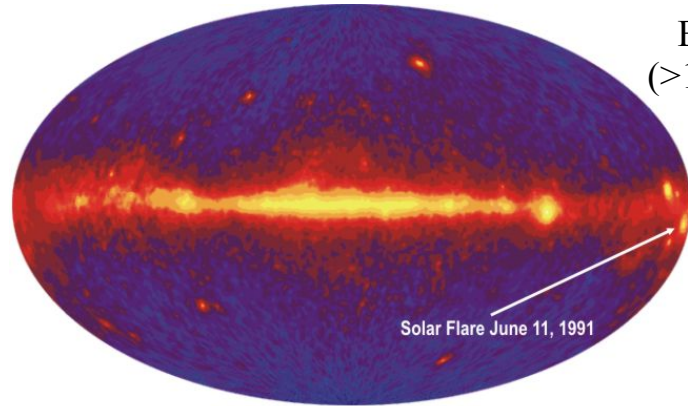




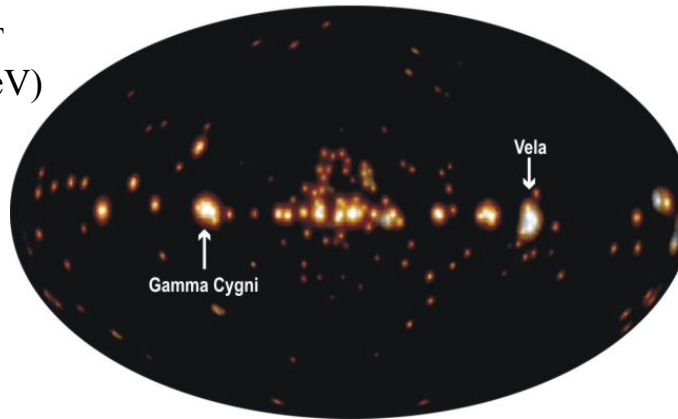
# By the way: how to get the diffuse emission?

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

(2) Subtract point sources



EGRET  
( $>100$  MeV)



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

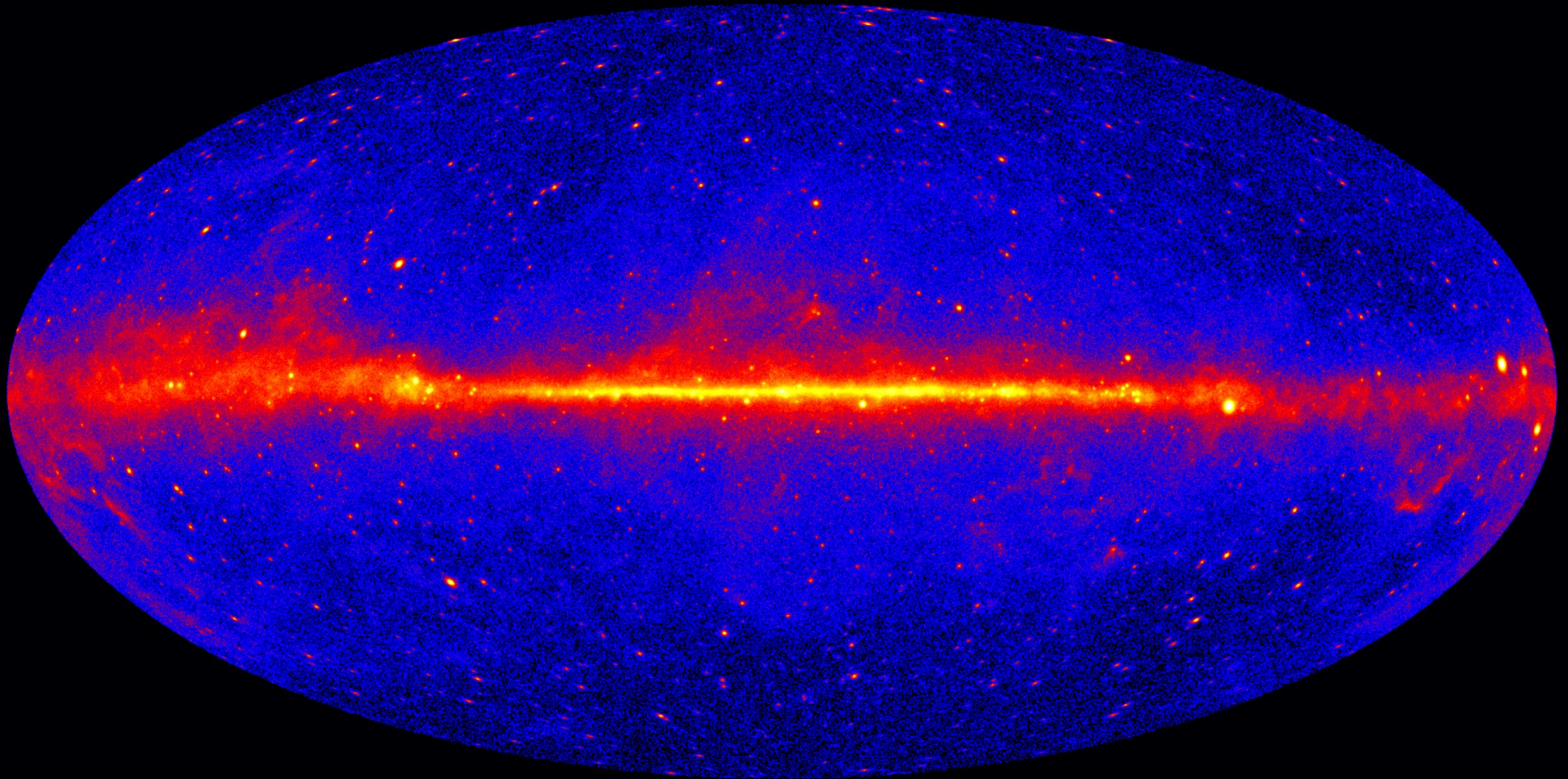
1999: OSSE find that 50% DE for soft  $\gamma$ -ray ( $<300$  keV) [Kinzer *et al.*, ApJ **515**, 215]

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

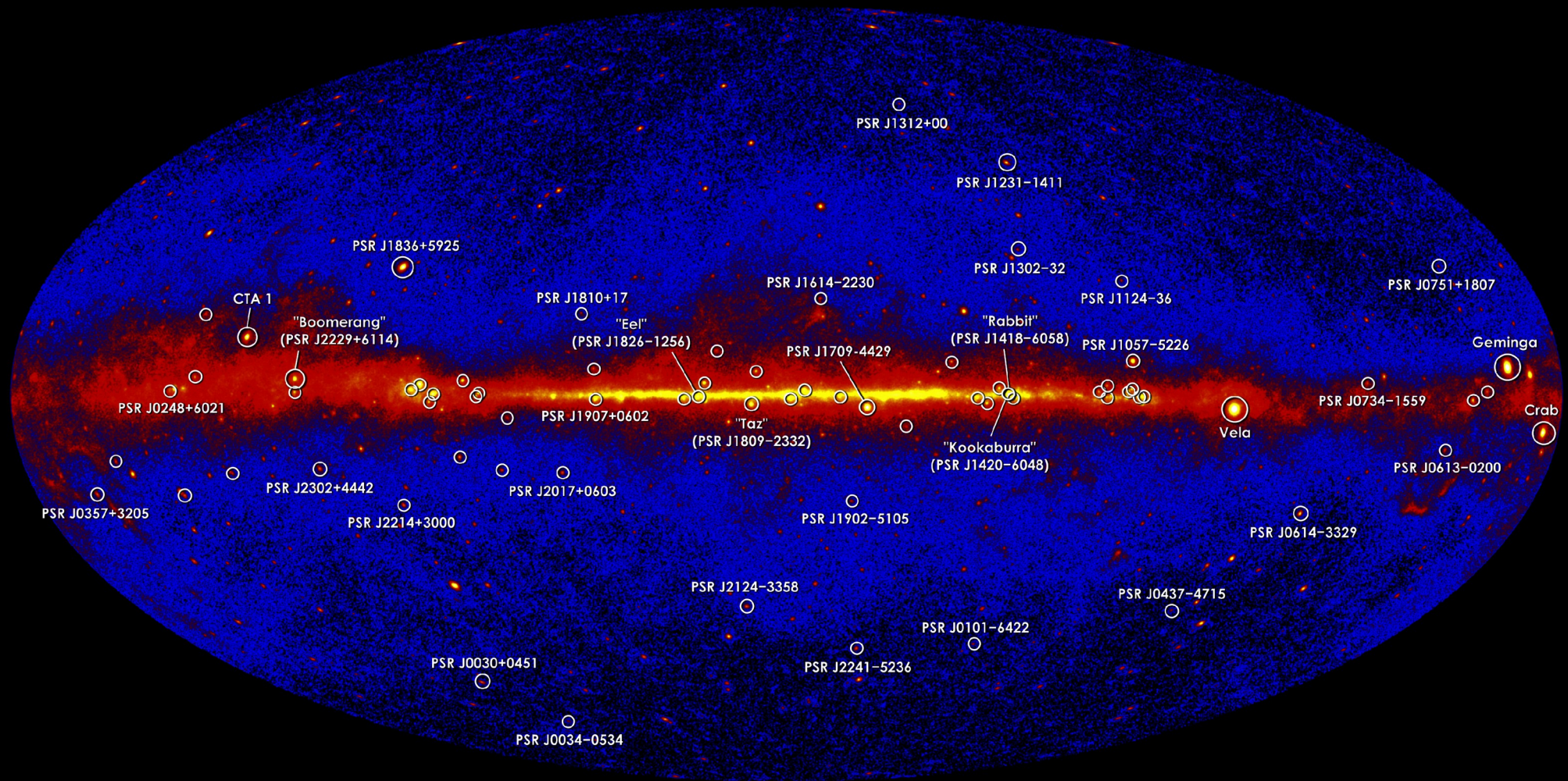
# Fermi-LAT ( $> 1$ GeV, 60 month results)



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



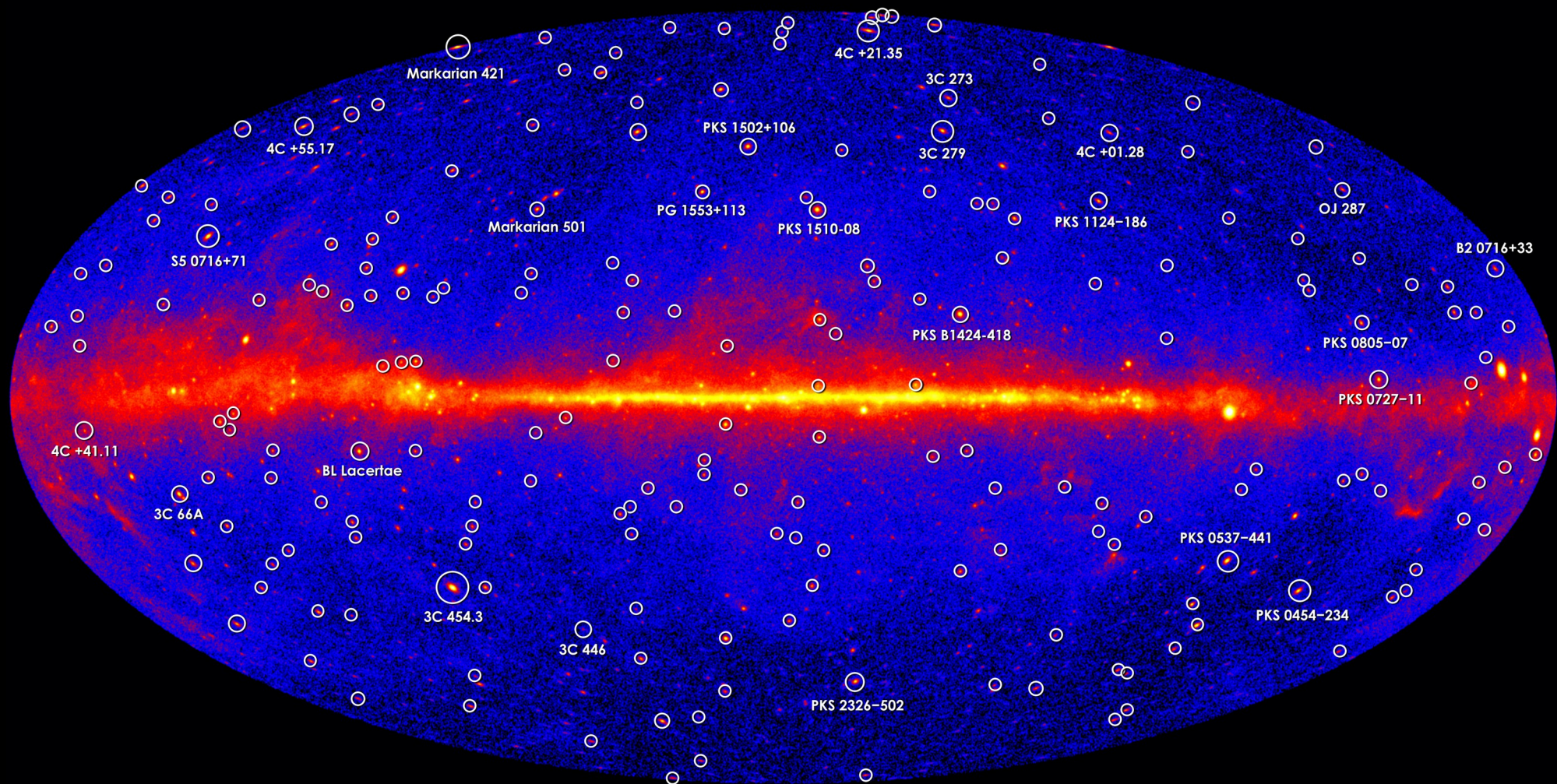
# Fermi-LAT ( $> 1$ GeV, 60 month results)



**Pulsars**  
[rapidly rotating neutron stars]



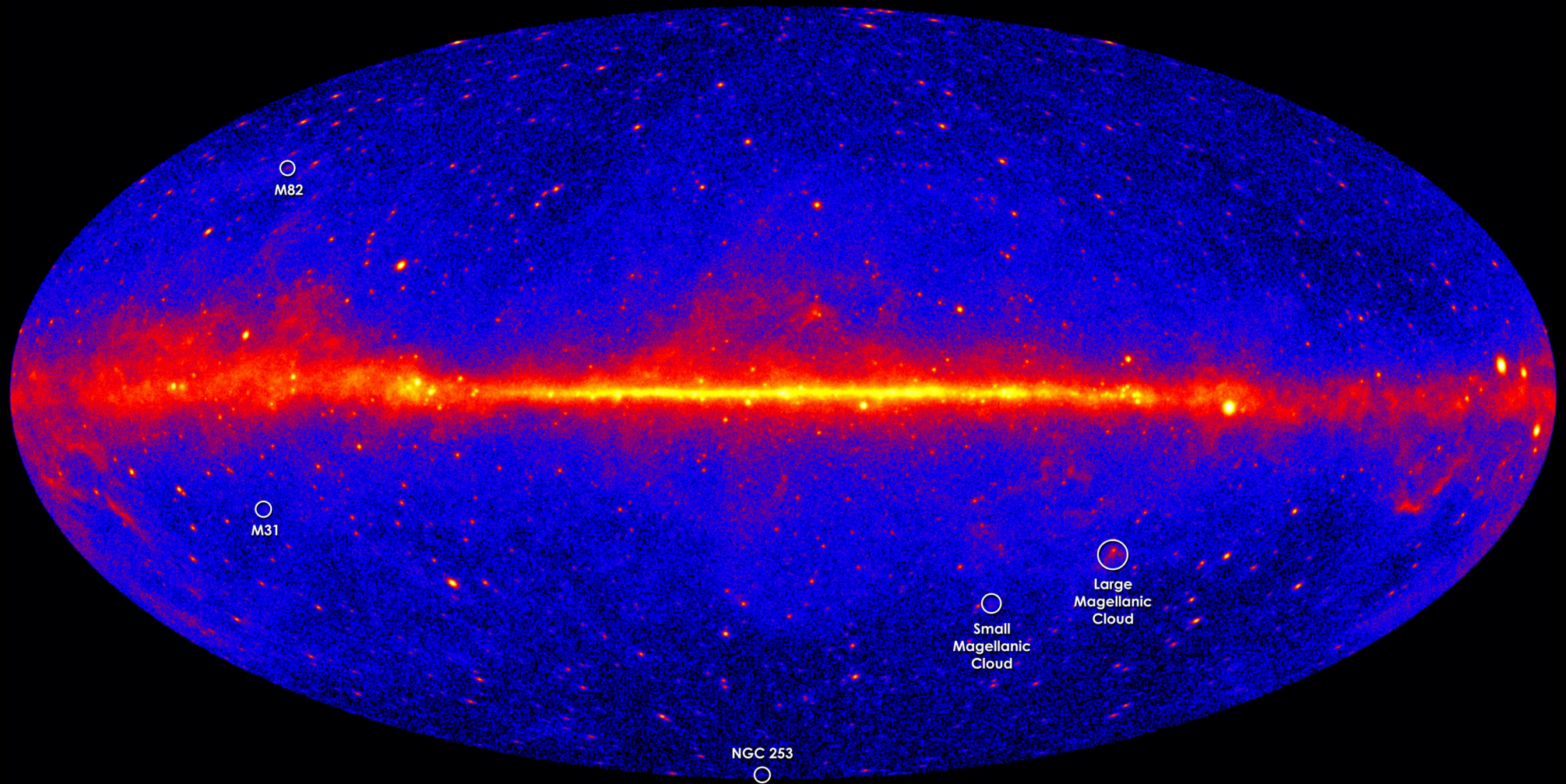
# Fermi-LAT ( $> 1$ GeV, 60 month results)



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



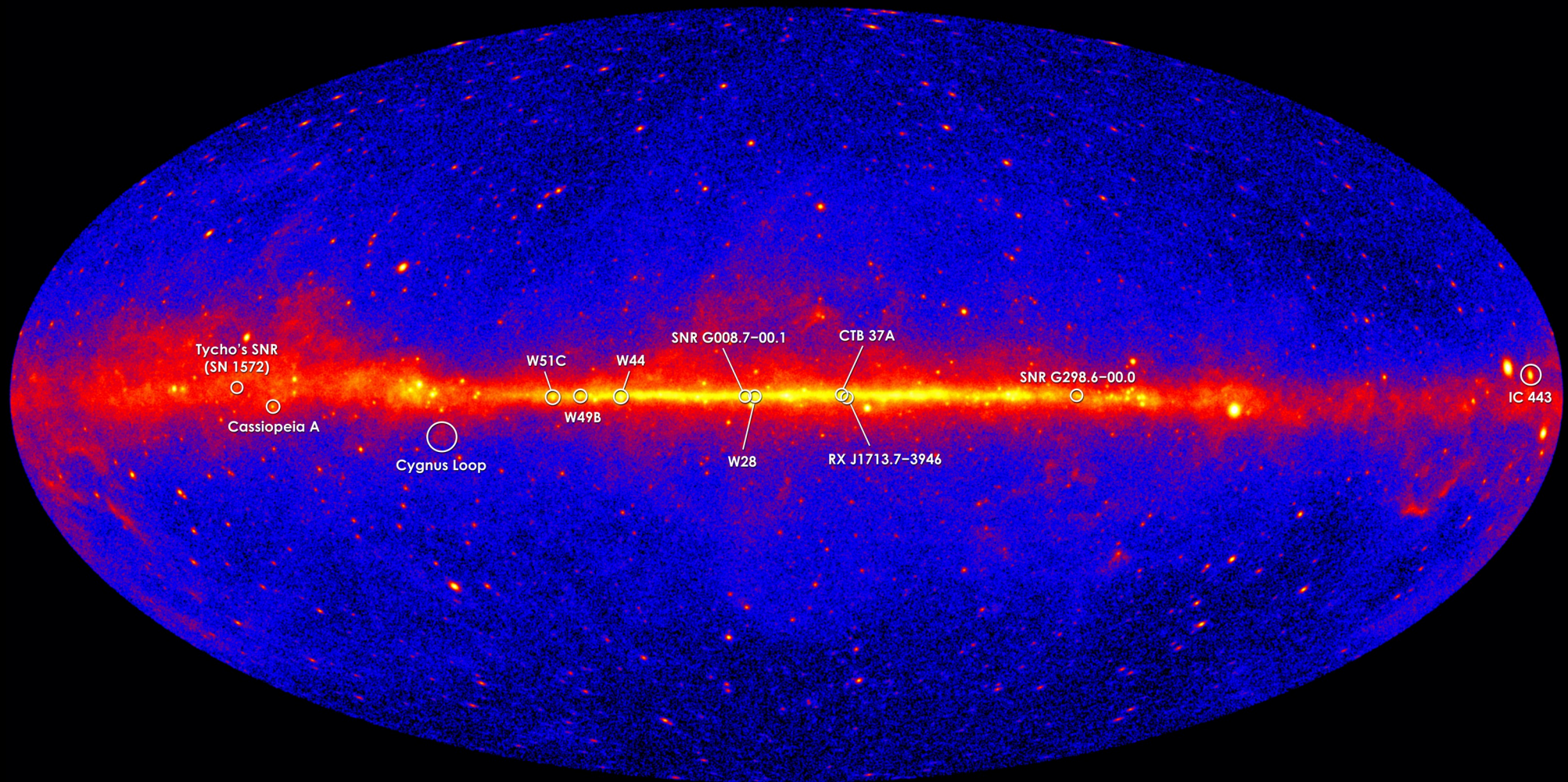
# Fermi-LAT ( $> 1$ GeV, 60 month results)



**Normal and  
starburst galaxies**



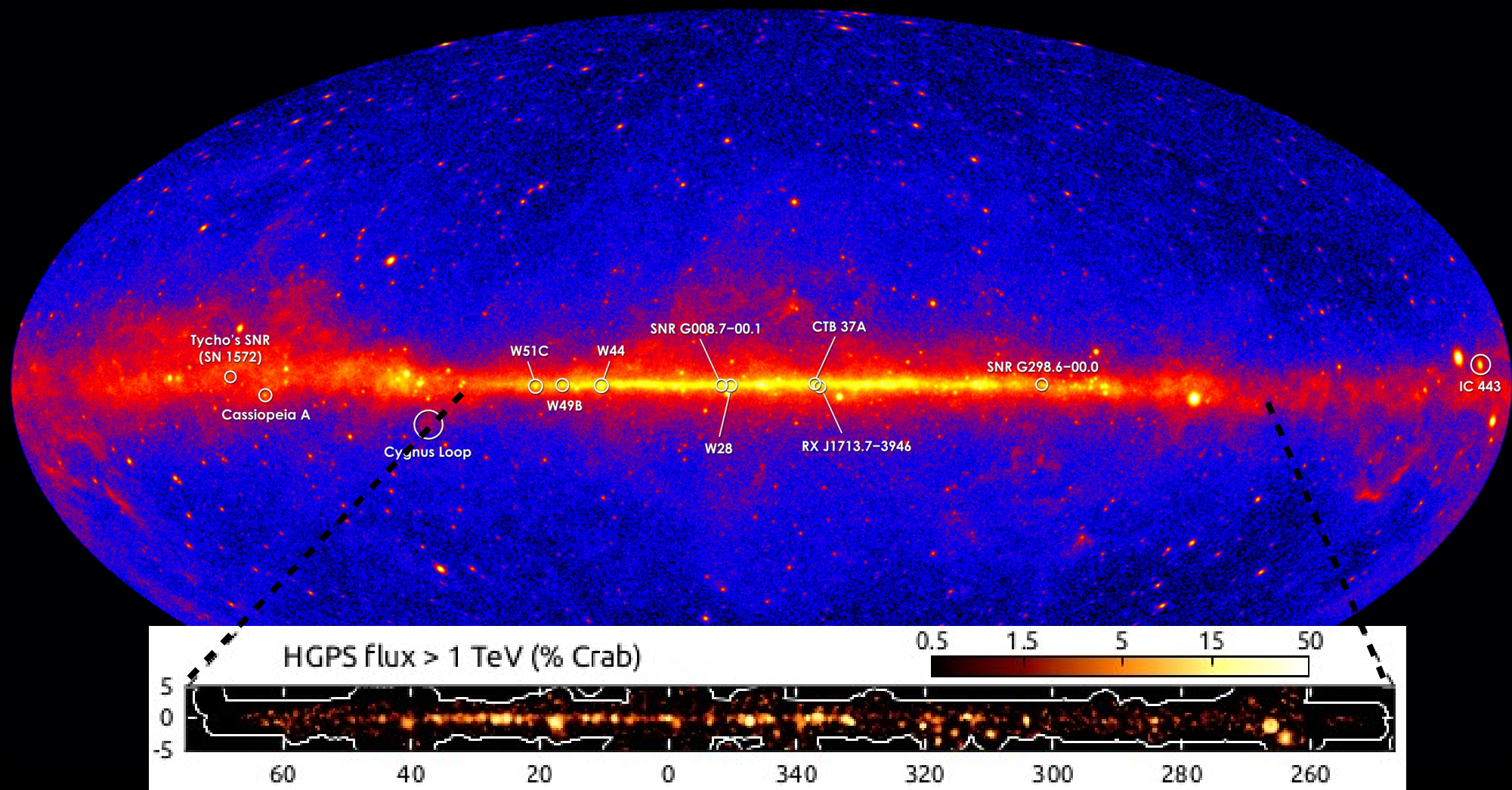
# Fermi-LAT ( $> 1$ GeV, 60 month results)



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



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



TeV sky  $\neq$  GeV sky  
 $\rightarrow$  less diffuse emission(?)

# Morphology *and* spectral information

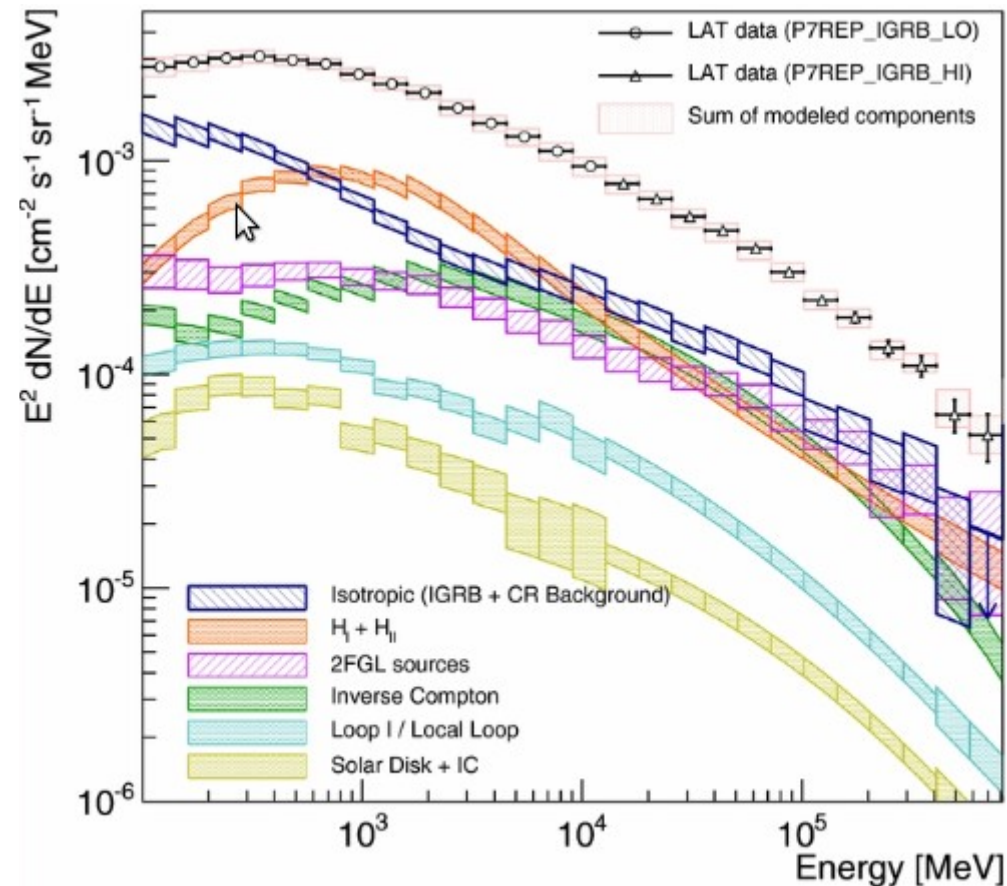
## Photon Intensity ( $E, l, b$ )

- Morphology (2D)  $\rightarrow$  skymap for each energy
- Spectrum (1D)  $\rightarrow$  spectrum in each direction

## Modelling

- 3D+1: need gas, CR, B distributions
- 3D+2: and sometimes need  $t$  in models

## Models from the Fermi-LAT collaboration



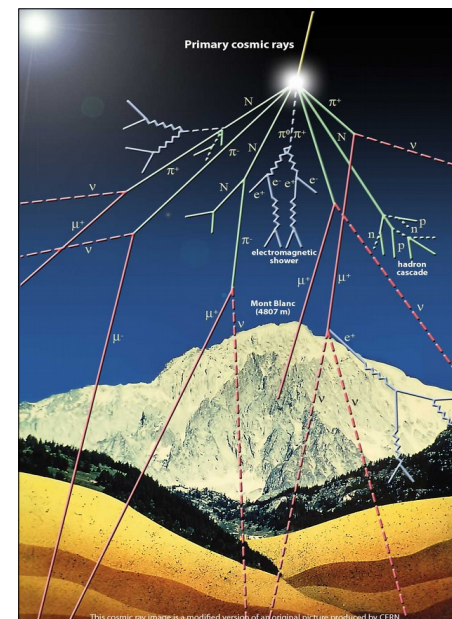
Ackermann *et al.*, [ApJ 799, 86 \(2015\)](#)



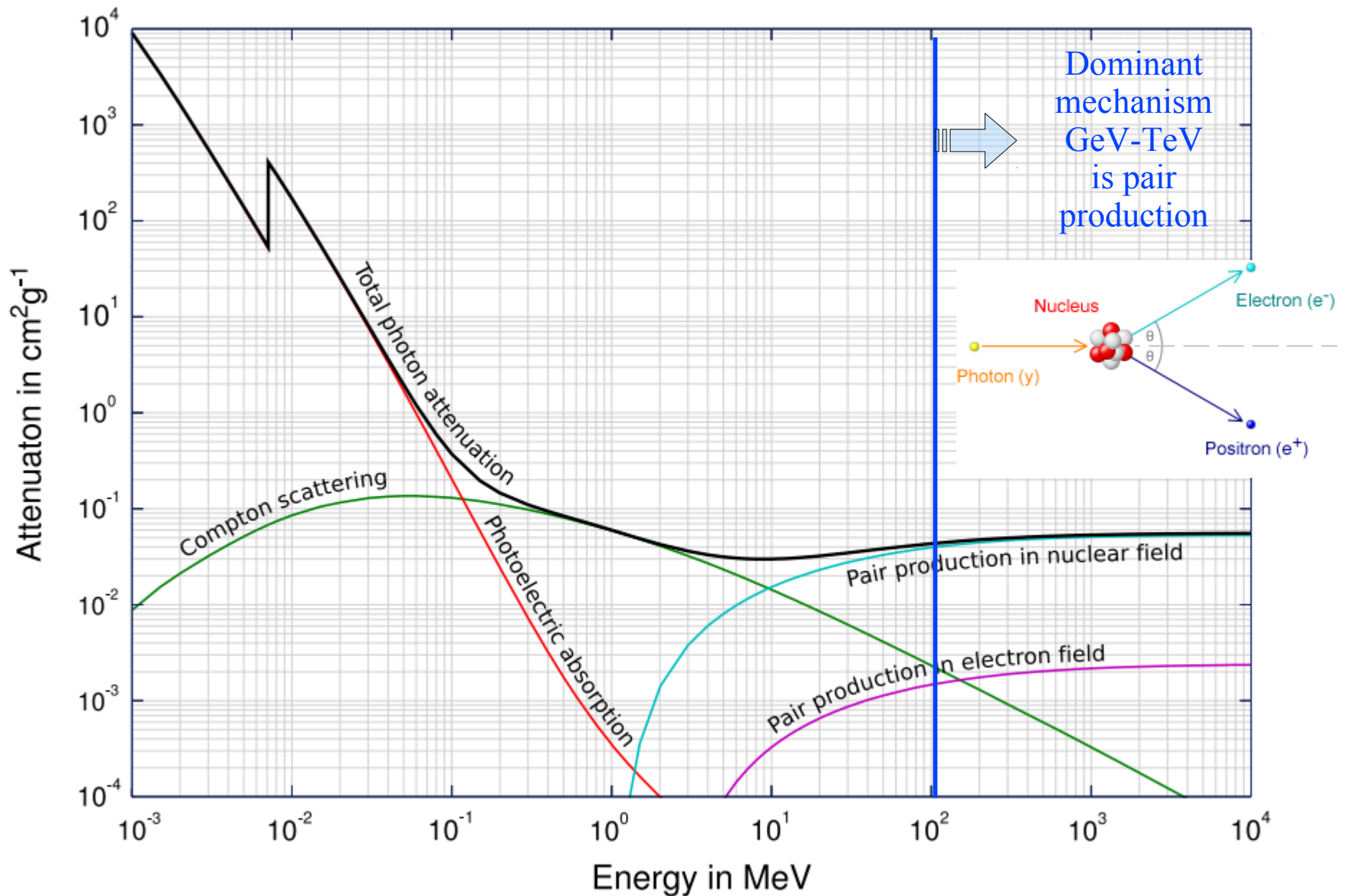
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### Motivation

- Take advantage of atmosphere as a calorimeter
  - Electromagnetic vs hadronic showers
  - Detector types using atmospheric showers
  - Rejection and calibration

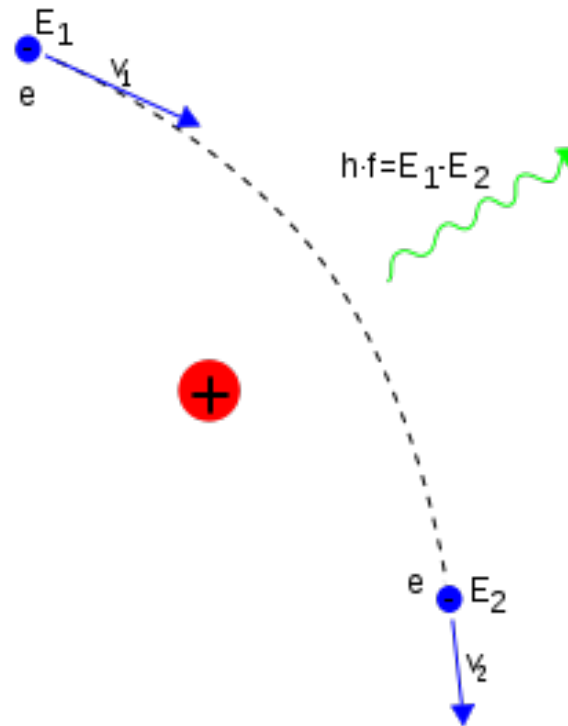


# High-energy photon interaction



# High energy lepton interaction

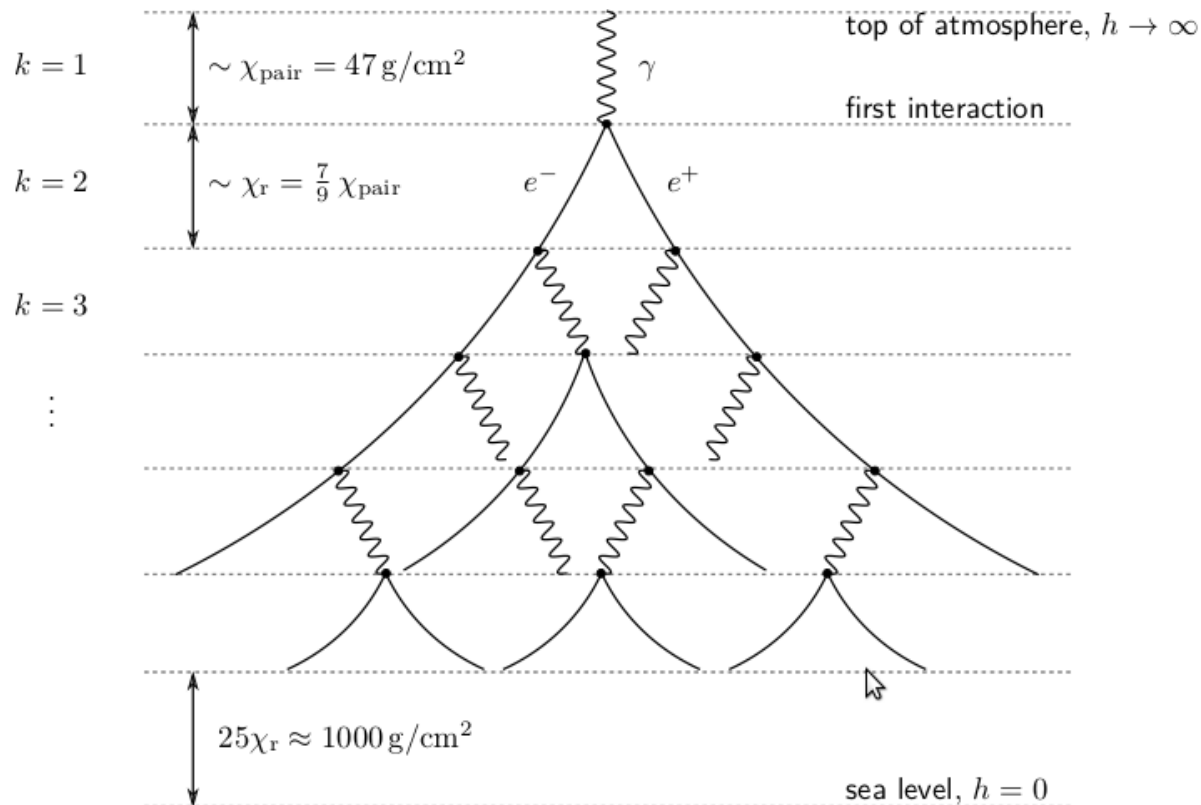
Bremsstrahlung emission  
(in Coulomb field of the nucleus)



→ About same interaction length as pair production

# Electromagnetic air shower

Hütten, PhD thesis (2016)



**Electromagnetic radiation length  $X_0$**   
 $\sim 40 \text{ g/cm}^2$  in dry air

## Calorimeter thicknesses

Particle physics @ LHC:  $\sim 25 X_0$

$\gamma$ -ray satellites:  $\sim 10 X_0$

Atmosphere:  $\sim 27 X_0$

## Depth of shower maximum $z_{\text{max}}$

Homogeneous calorimeter  $\propto \log(E_0)$

Atmosphere:  $\sim 9 \text{ km} - 8.4 \text{ km} \times \log(\log(E_0/1 \text{ TeV}))$

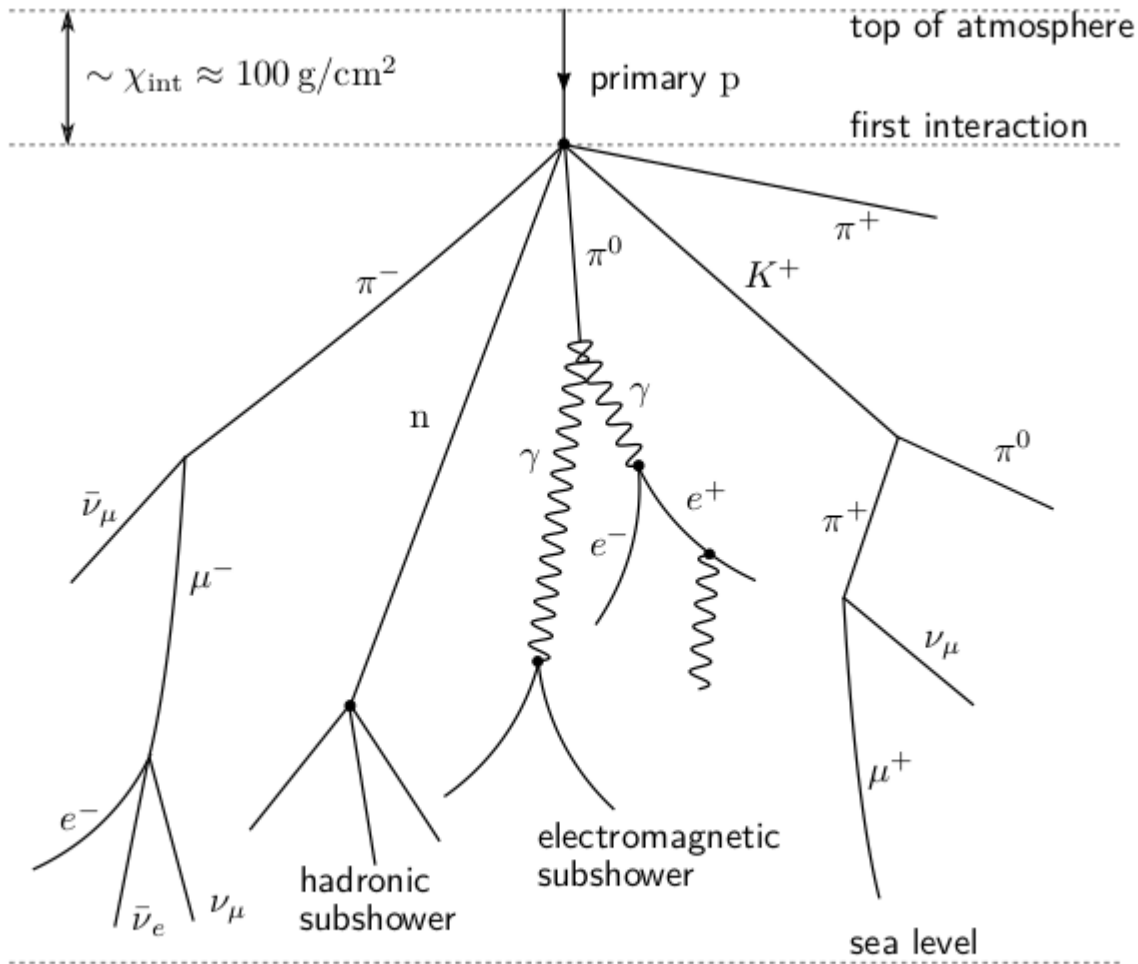
## And additional processes, mainly at low energy

- multiple scattering off charged particles (shower broadening)
- E losses by ionisation and atomic excitation (shower extinction below 83 MeV in the air)
- 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**

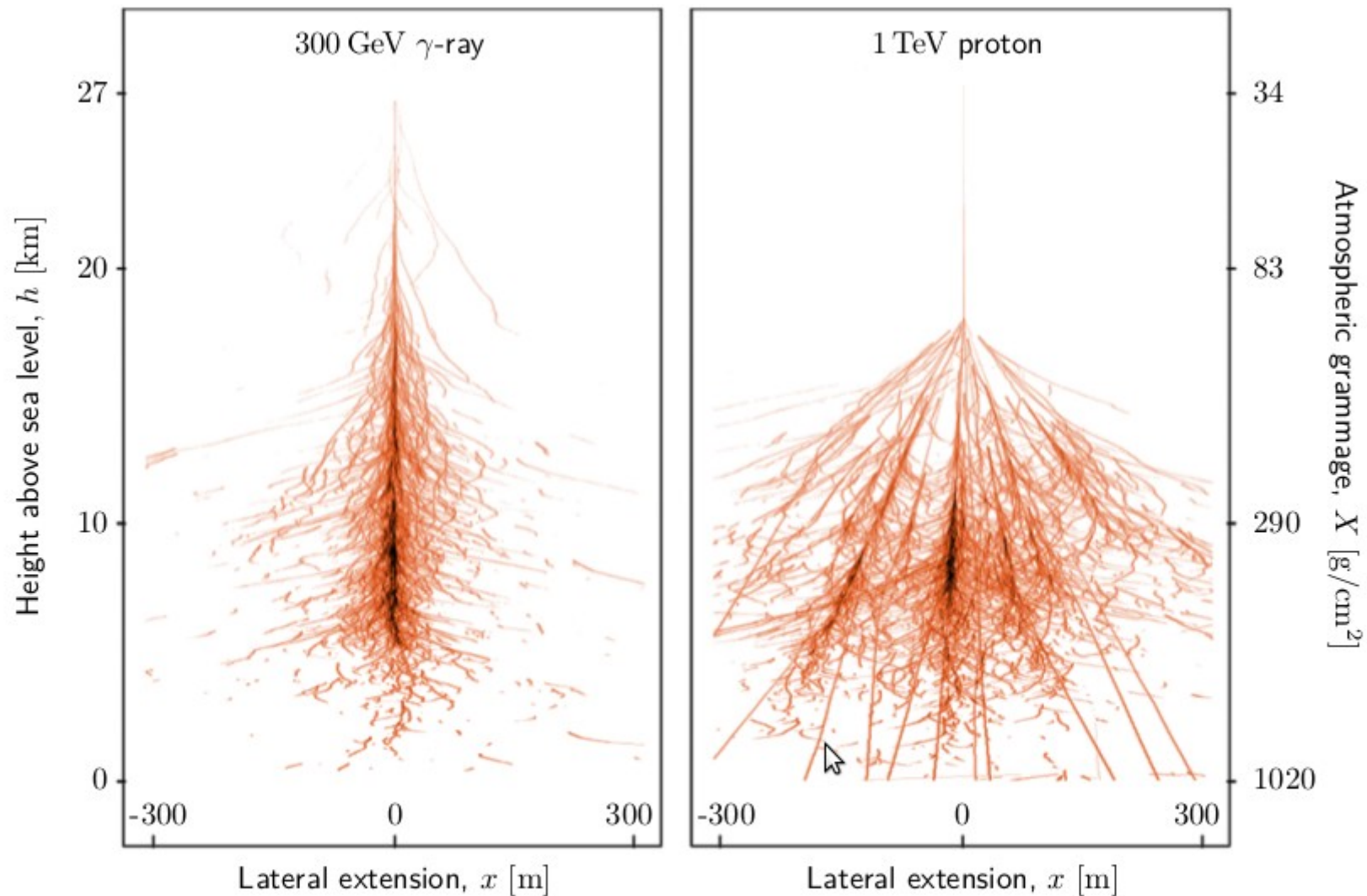
Sub-showers:

- Hadronic (n,  $\pi$  and K mesons)
- Electromagnetic ( $\pi^0$  decay)

and particles:

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

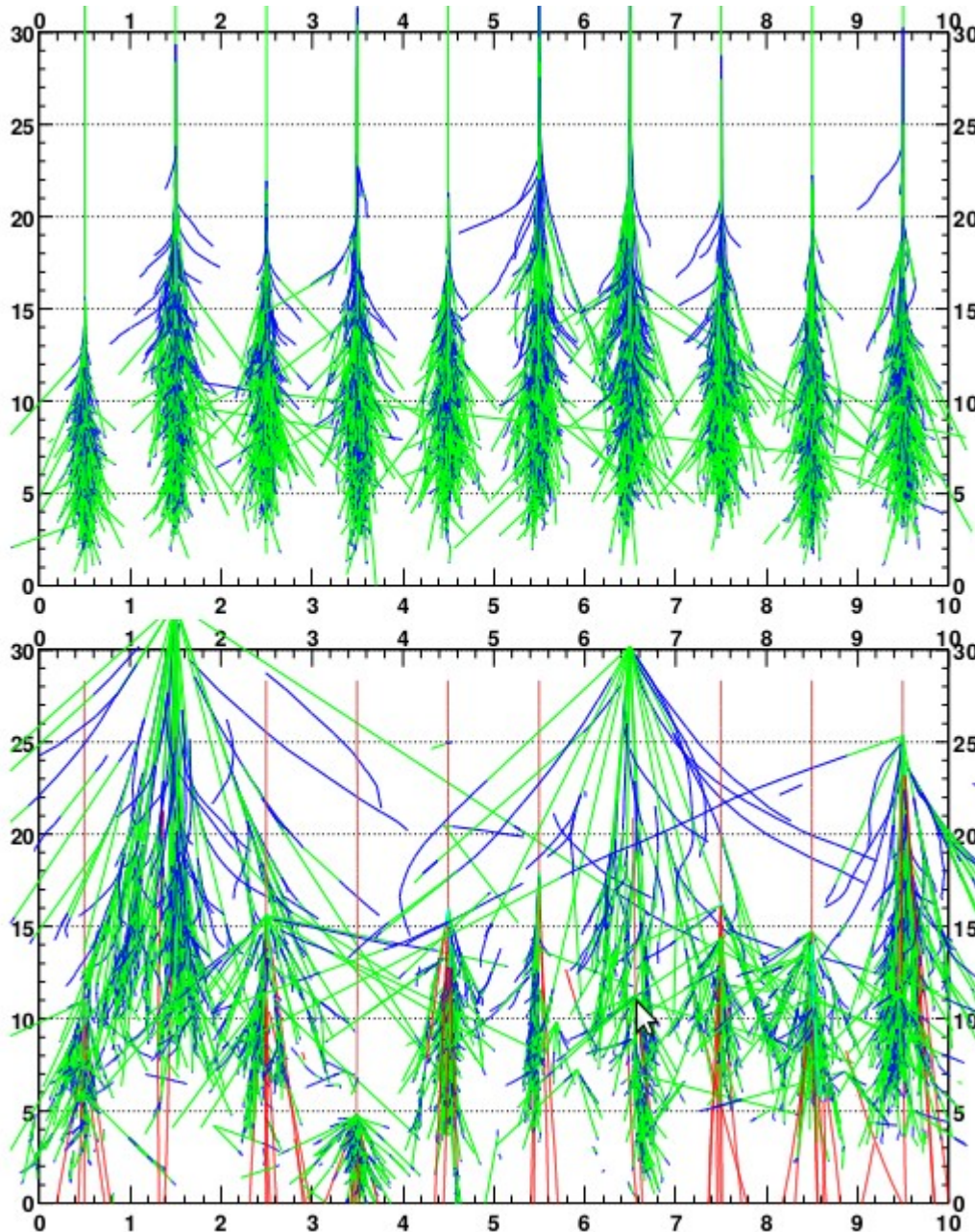
# Leptonic vs hadronic shower (1)



**Figure 3.4.:** Comparison between an electromagnetic air shower (triggered by a 300 GeV primary  $\gamma$ -ray) and a hadronic air shower (initiated by a 1 TeV proton). The figure shows the secondary particles projected onto a plane in  $(x, h)$  direction. Figure taken from [Aharonian et al. \(2008b\)](#).<sup>9</sup>

# Leptonic vs hadronic shower (2)

De Naurois & Mazin, [arXiv:1511.00463](https://arxiv.org/abs/1511.00463)



**Illustration of the intrinsic variability of shower development.**

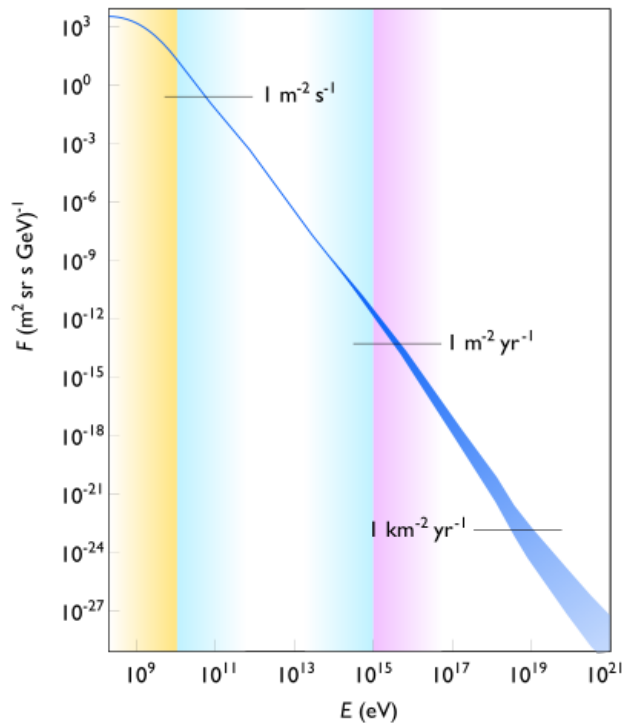
Simulation of 10 showers (300 GeV  $\gamma$ -rays)

Simulation of 10 showers (300 GeV protons)

→ larger transverse momentum transfers,  
larger fluctuations



# Detection techniques (using Earth's atmosphere)

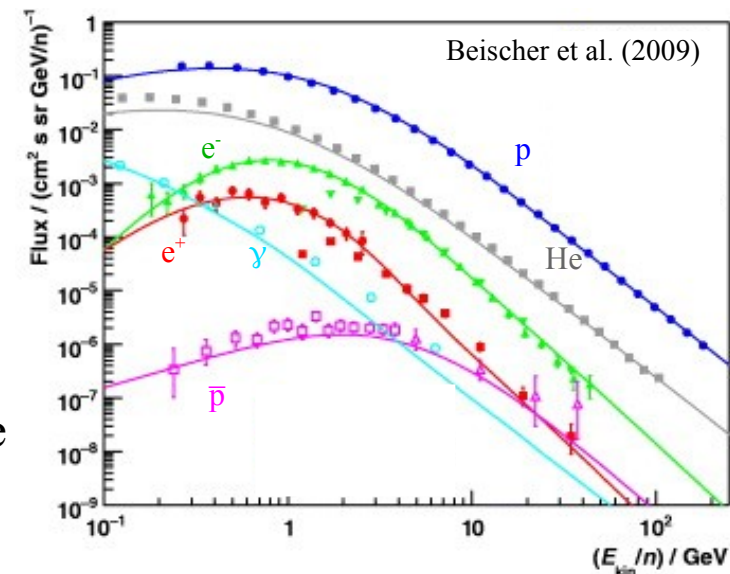


**Obviously, depends on**

- Particle nature
- Particle flux (hence E)

**Goal**

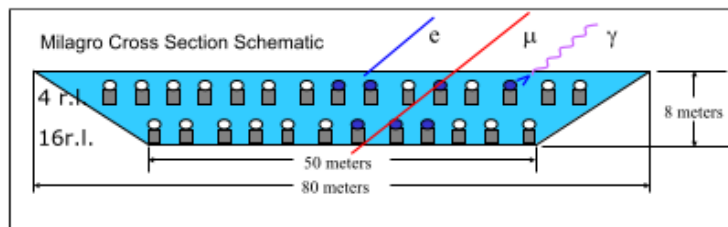
- Energy of the primary particle
- Direction of the primary particle
- Primary particle nature



## Water pond

[MILAGRO, HAWC]

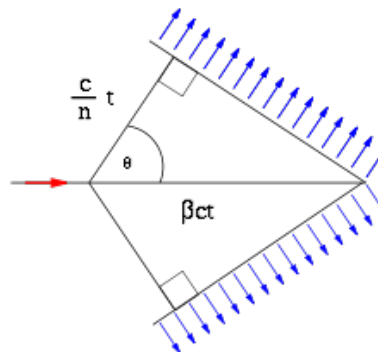
- timing information (direction)
- EM and hadronic showers (energy)



## Cerenkov detectors

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

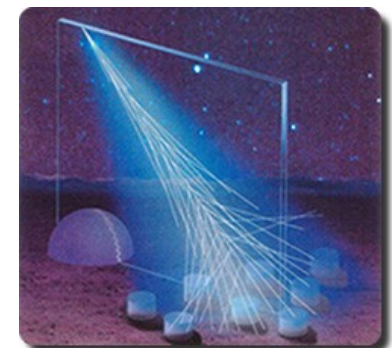
- Cerenkov light (energy)
- stereoscopy (direction)



## Hybrid detectors

[AUGER]

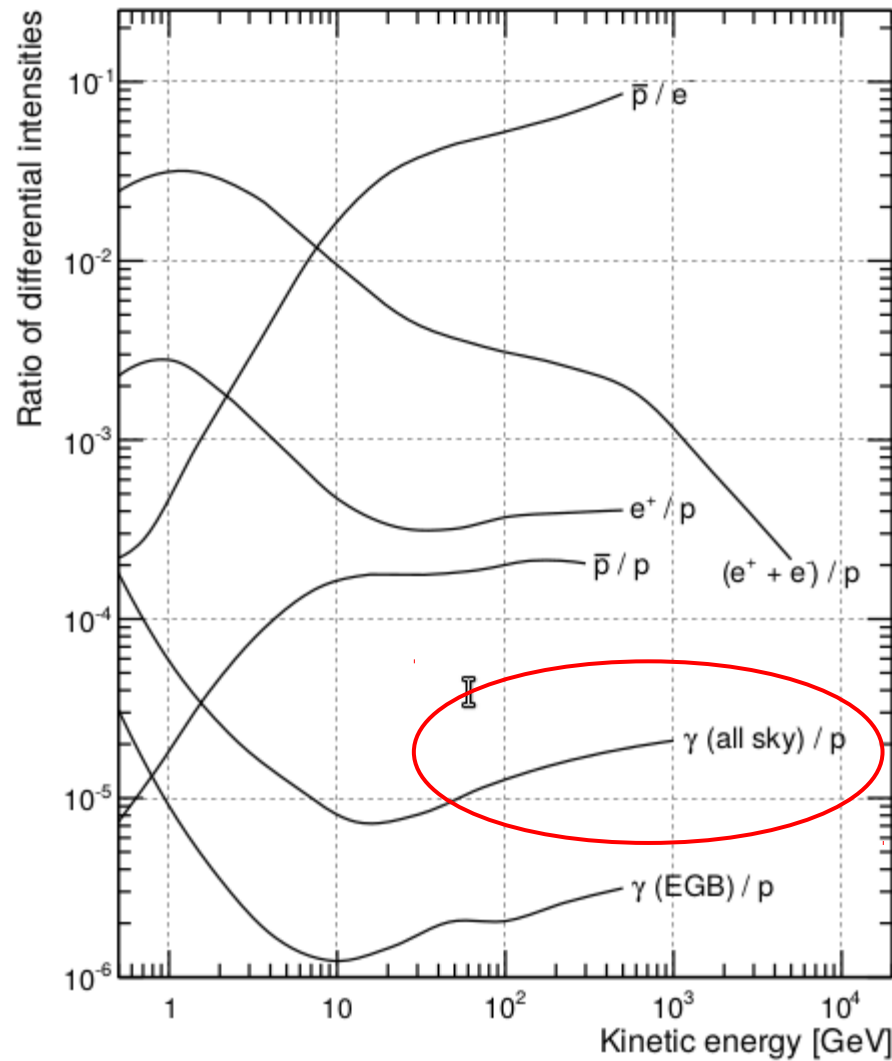
- 4 fluorescence telescopes
- 1660 surface detectors



3. Interactions/showers



# Rejection factor



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

# Energy and position calibration

Question: what generic procedures can you think of to ensure

$$\rightarrow E_{\text{measured}} = E_{\text{true}} ?$$

$\rightarrow$  correct source reconstruction

- Pre-flight calibration
  - $\rightarrow$  Test beams (e.g., @ CERN)
  - $\rightarrow$  Monte Carlo simulation
- In-flight (on-line) calibration
  - $\rightarrow$  Use specific data samples with known properties
  - $\rightarrow$  Use reference source (Crab nebula)
  - $\rightarrow$  Calibrate position from bright sources
- Inter-calibration
  - $\rightarrow$  Internal calibration system (e.g., diodes)
  - $\rightarrow$  Hybrid detectors (e.g., AUGER)

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### **Motivation**

- Ground and satellite  $\gamma$ -ray detectors
- Important experimental aspects to keep in mind
  - Research activities in a collaboration



# Cerenkov telescopes

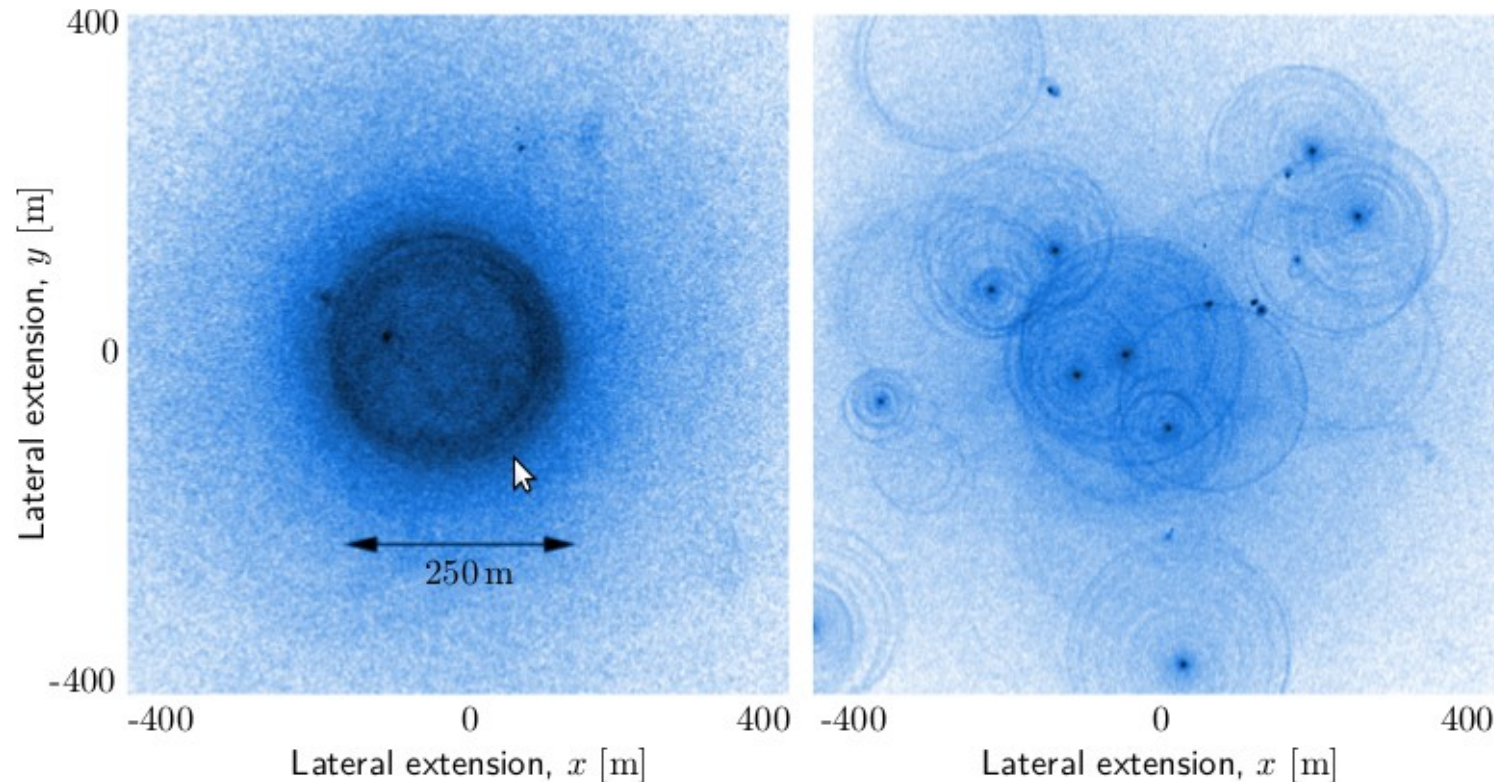
H.E.S.S.: ~ 13 countries, 45 institutes, 250 researchers



**Figure 3.5.:** Currently operating third generation IACT arrays: The **MAGIC** telescopes on La Palma, Canarian Islands (*upper left*, mirror diameters 17 m), the four **H.E.S.S.** telescopes (mirror diameters 12 m) and the large **H.E.S.S. II** telescope (average mirror diameter 28 m) on the Khomas Highland in Namibia (*upper right*), and the **VERITAS** array near Tucson, Arizona, USA (*bottom*, mirror diameters 12 m). Image credits by the **MAGIC/H.E.S.S.** & **VERITAS** collaborations.

# Cerenkov light pool

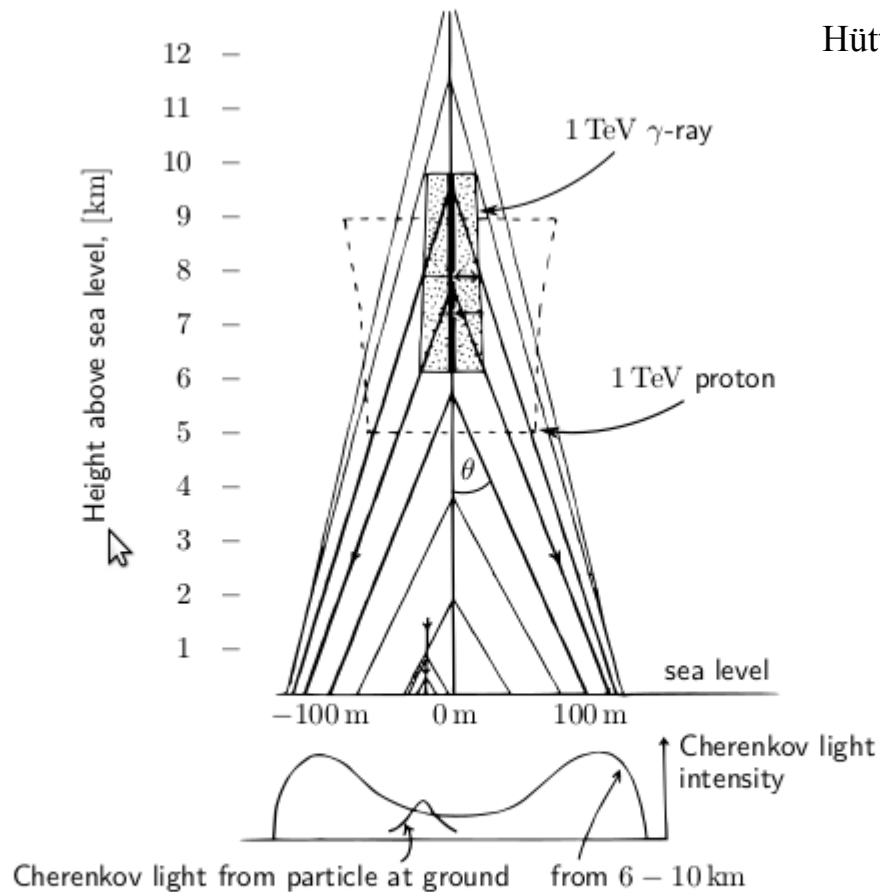
N.B.: Cerenkov flash  $\lesssim 10$  ns (beware of NSB)  
→ ultrafast PMTs and electronic readout



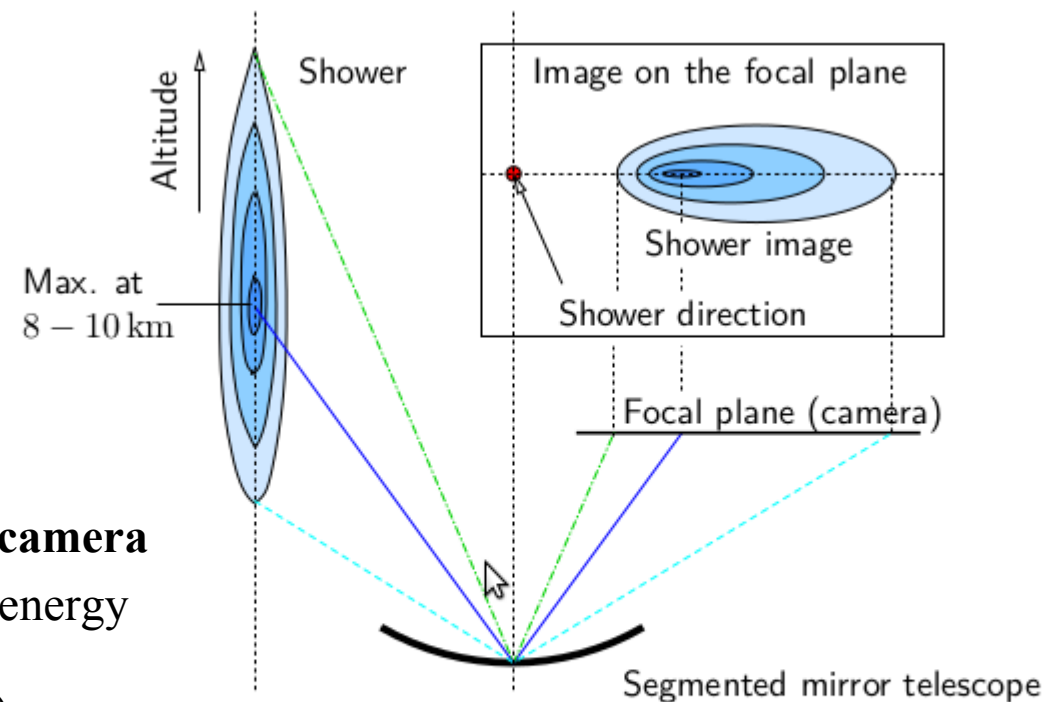
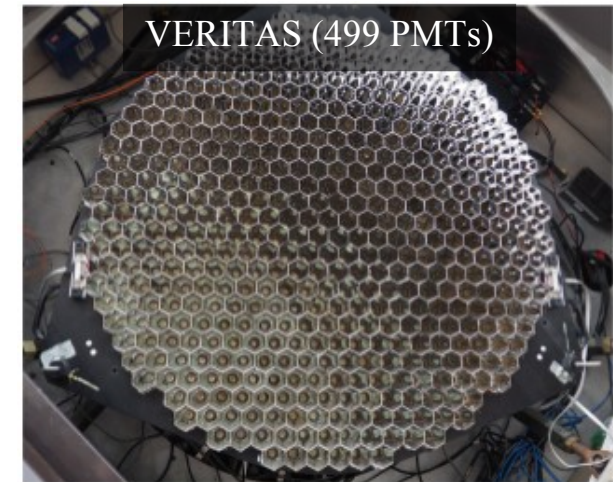
**Figure 3.6.:** Comparison between the time-integrated Cerenkov light pool at ground level of an electromagnetic air shower (*left*; triggered by a 300 GeV primary  $\gamma$ -ray, like in [Figure 3.4](#)) and a hadronic air shower (*right*; initiated by a 1 TeV proton, like in [Figure 3.4](#)). Both showers approximately produce the same amount of Cerenkov light (see text). The figures are obtained by Monte-Carlo (MC) simulations of the showers and the showers' Cerenkov light emission. On the right figure, the intense dots originate from muons reaching the ground and most of the rings originate from the various electromagnetic subshowers. Figure taken from [Aharonian et al. \(2008b\)](#).



# Shower image on the camera



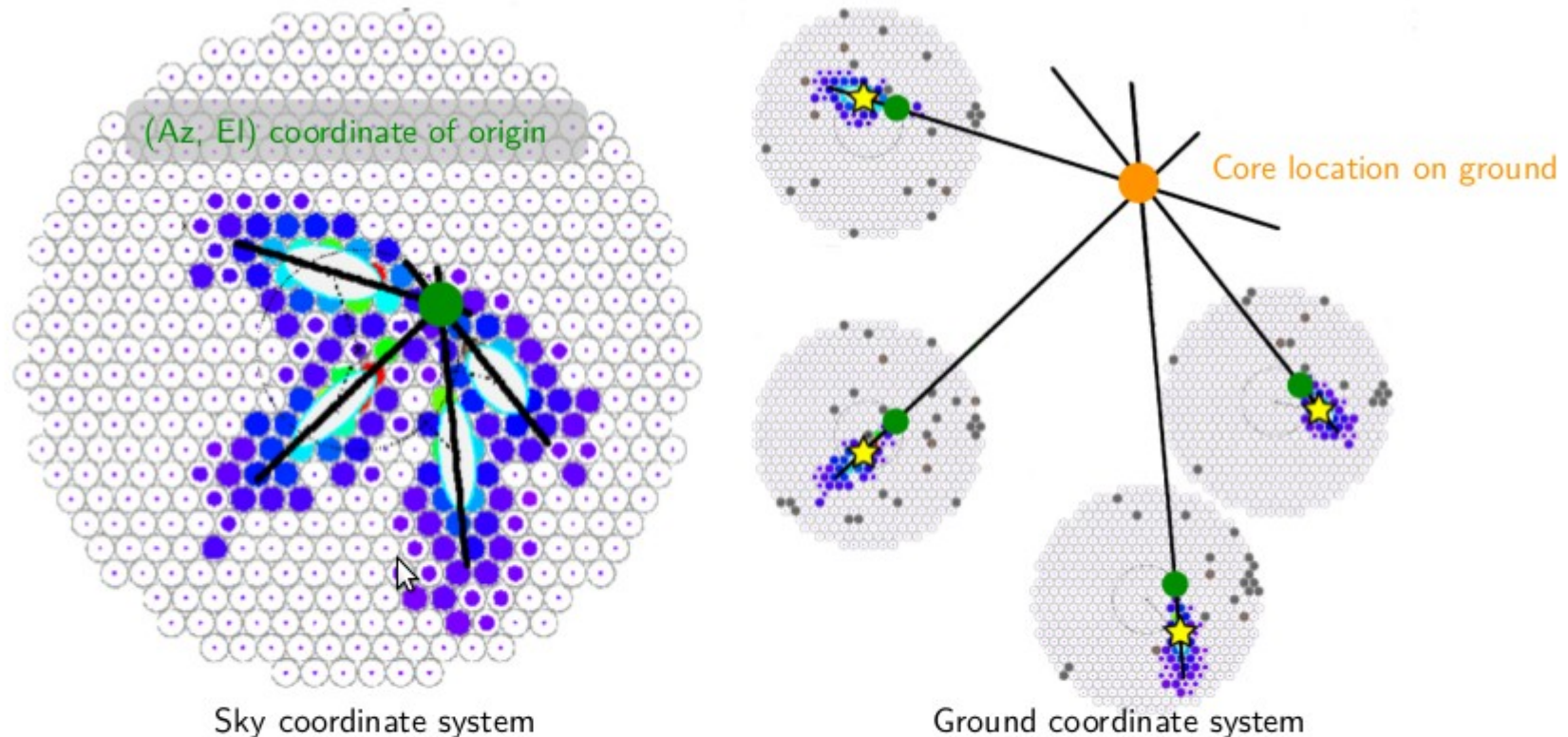
Hütten, PhD thesis (2016)



**Ellipse in the shower gives ellipse on the camera**

- Image shape parameters to reconstruct energy
- Image shape to veto hadrons (require good granularity of camera)

# Stereoscopic observation: principle



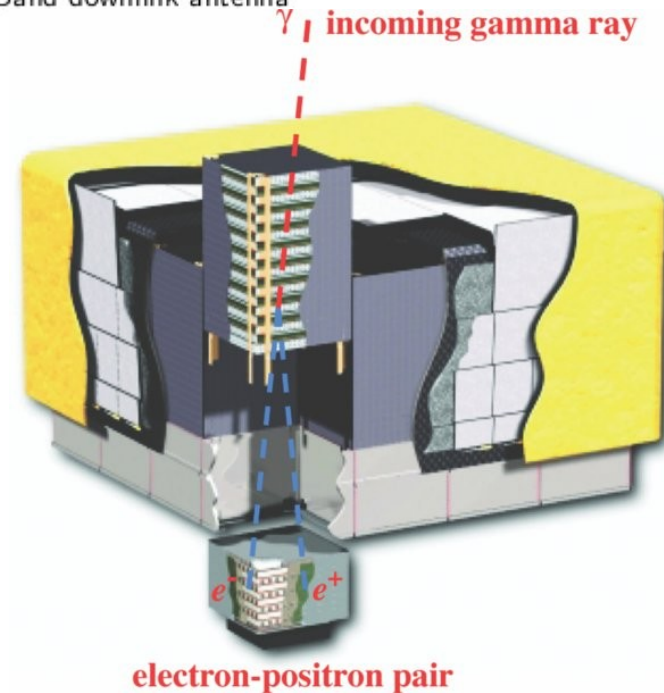
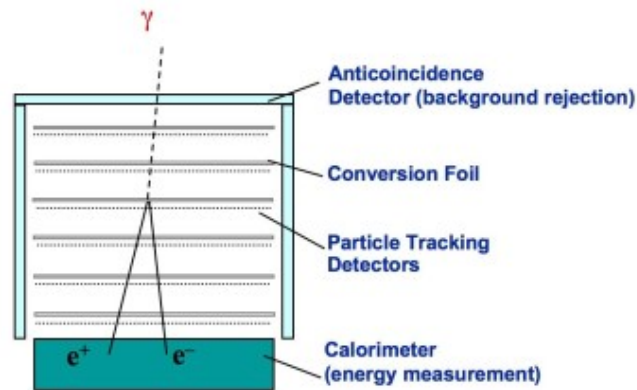
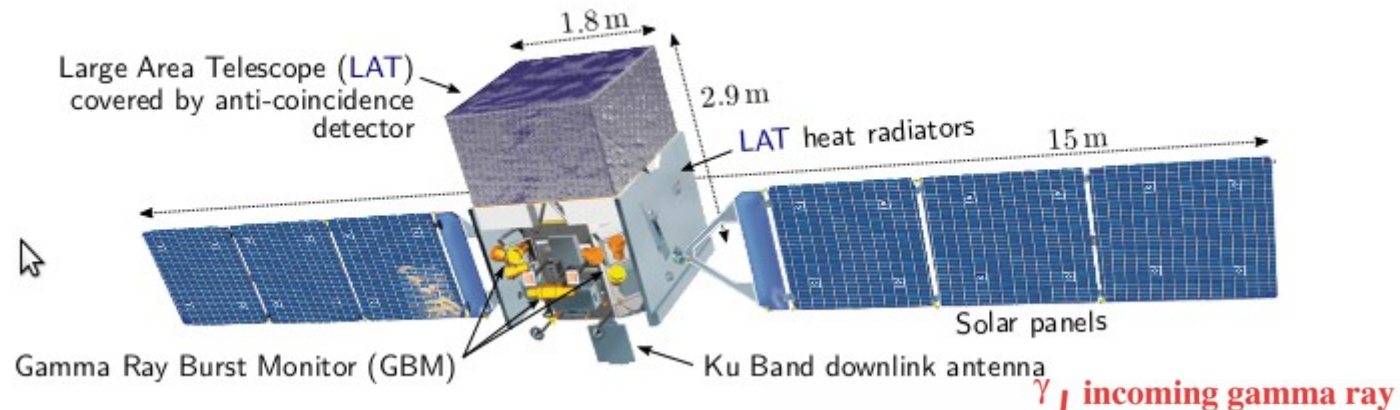
**Figure 3.10.:** Stereoscopic reconstruction of the air shower origin in the sky (*left*) and the impact point of the shower axis on the ground (*right*). The shower direction (green point on the left) is obtained as intersection of the major semiaxes of the shower ellipses of all images in the same camera coordinate system. On the right, the shower axis intersection point at ground is obtained as intersection of the lines connecting the center of gravity (yellow star) of each shower image, and the shower direction (green point) in the camera images located in the ground coordinate system of the telescopes. The figure illustrates a real, most likely electromagnetic event recorded by the **VERITAS** array. Figure courtesy of S. Vincent.

- Better accuracy for source position, energy reconstruction
- Better background rejection



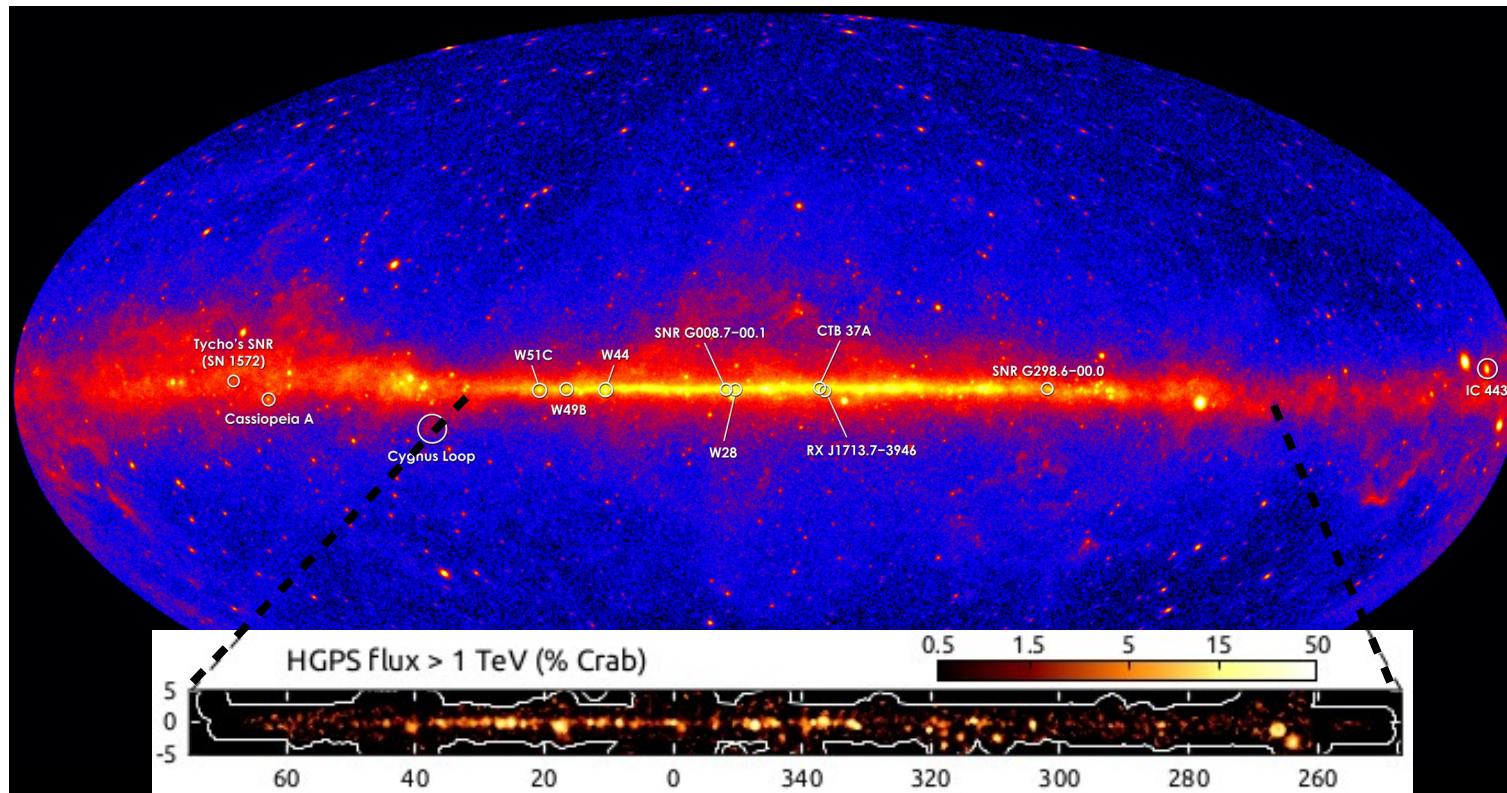
# Fermi satellite and Fermi-LAT

Fermi: ~ 12 countries, 90 institutes, 400 researchers



- Segmented electromagnetic calorimeter**
- reconstruct  $e^-$  and  $e^+$  direction in tracker
- reconstruct total energy from calorimeter
- charged particles vetoed by anticoincidence

# Many crucial notions not covered...



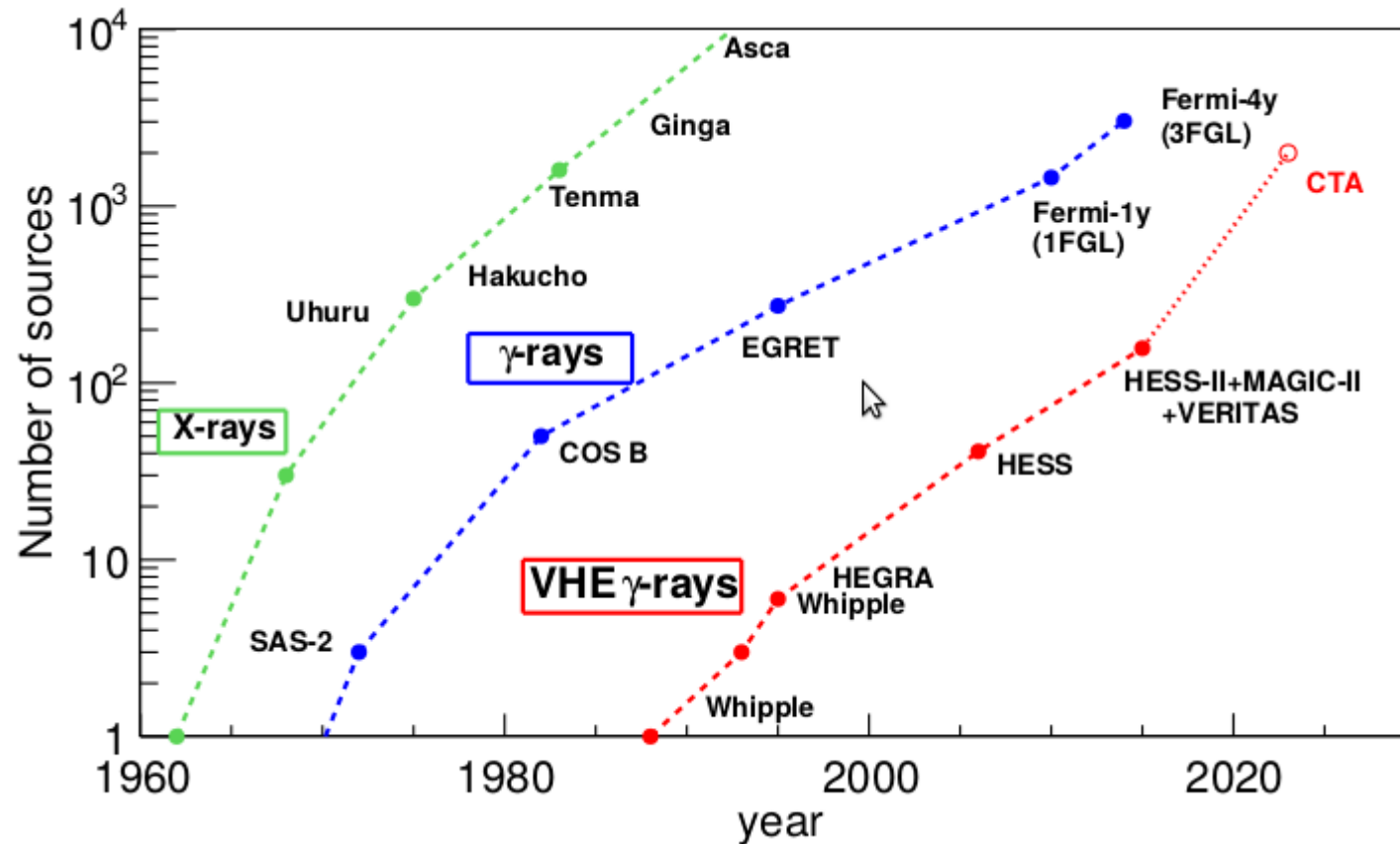
Question: how would you explain the difference between Fermi-LAT and H.E.S.S. coverages (first light  $\sim 10$  years ago for both)?

- Field of view
- Duty cycle
- Sensitivity

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

... in any case,  $\gamma$ -ray astronomy has a bright future

De Naurois & Mazin, [arXiv:1511.00463](https://arxiv.org/abs/1511.00463)



→ Field of view  
→ Duty cycle  
→ Sensitivity

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

# Associated 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
- 3) Interactions in the atmosphere and showers
- 4) Fermi-LAT and H.E.S.S.
- 5) Constraints on dark matter from  $\gamma$ -rays

### **Motivation**

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

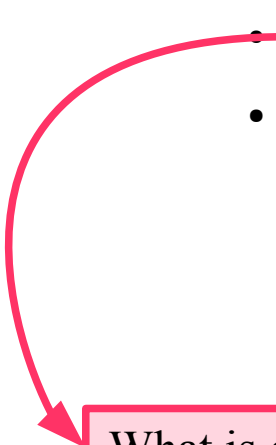
# Cosmological model: $\Lambda$ CDM

## Content of the Universe (CMB, SNe...)

- Radiation
  - Cold dark matter
  - Cosmological constant
- }  $\Lambda$ CDM

## Planck CMB results ([arXiv 1502.01589](#)): today

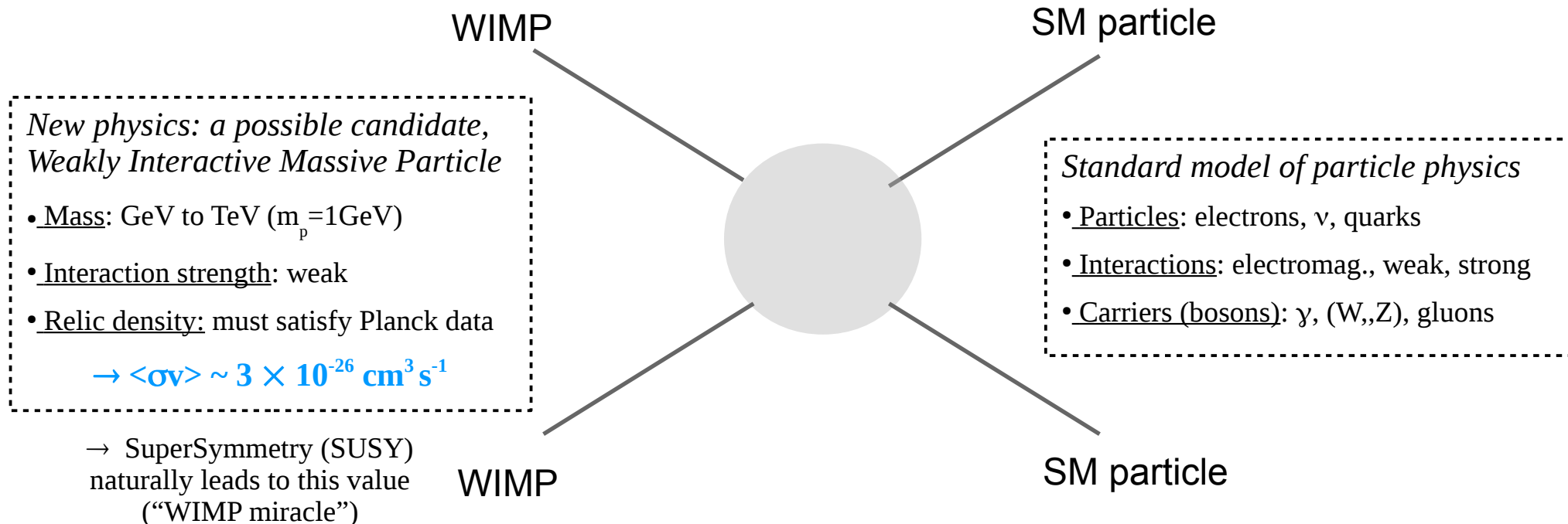
- Dark Energy  $\sim 68\%$  (accelerating expansion of the Universe)
- Dark Matter  $\sim 27\%$  (hierarchical structure formation)
- Ordinary Matter  $\sim 5\%$



What is dark matter (DM)? Can we detect it (other than gravitationally)?

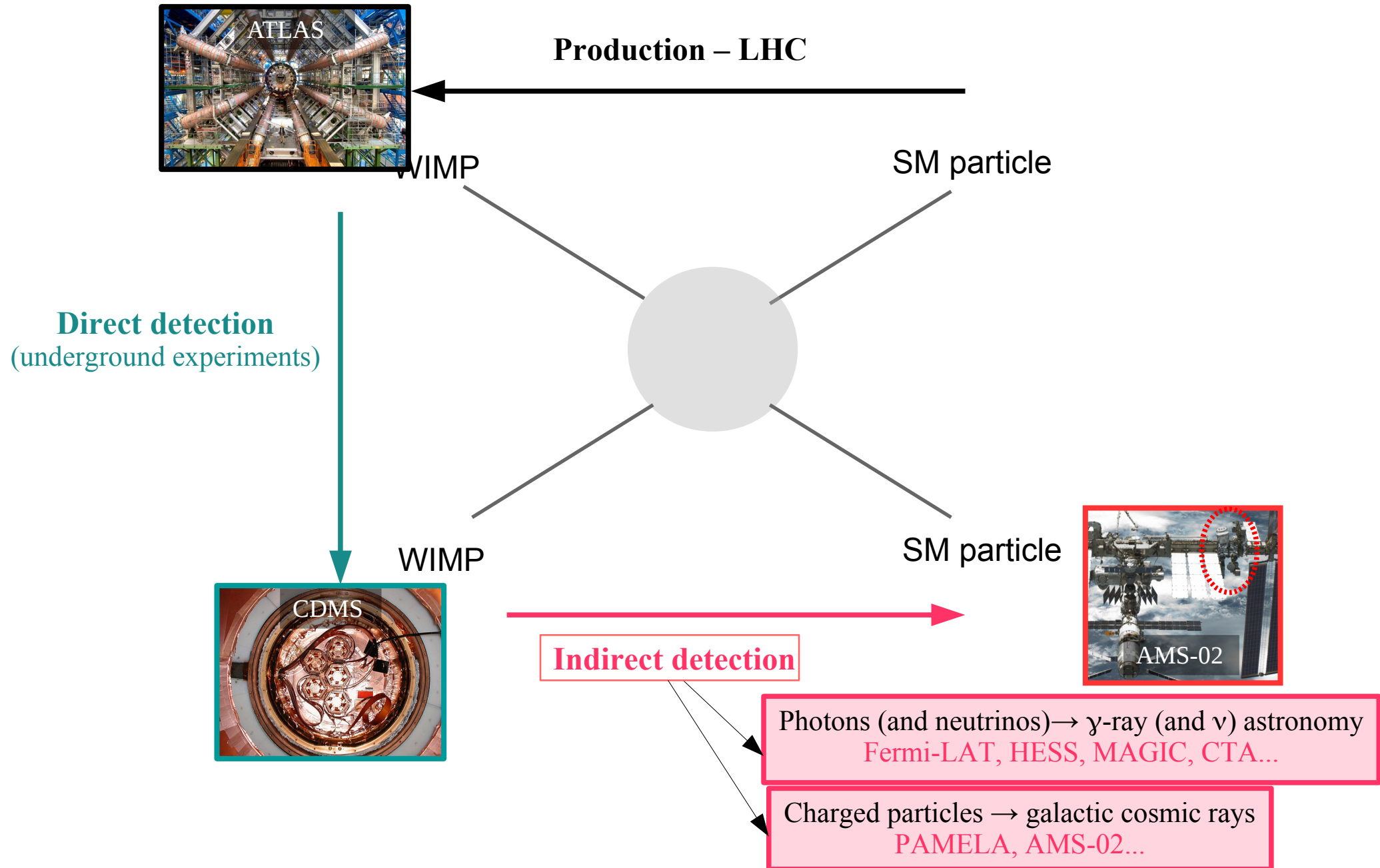
# Dark matter candidate: WIMP scenario

## Schematic view of interactions



*N.B.: many other theories, candidates at different masses (e.g., axions), etc.*

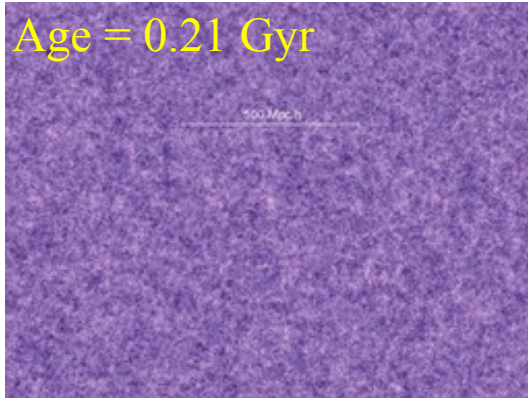
# Dark matter indirect detection



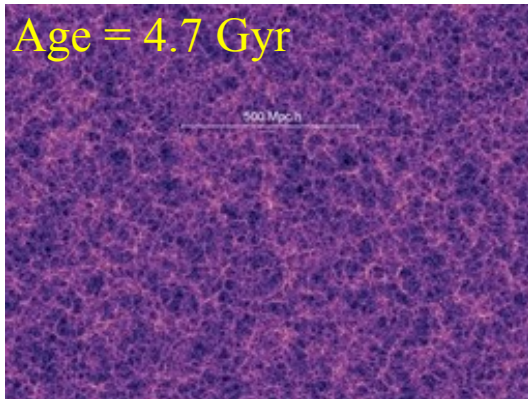


# DM distribution: hierarchical structure formation

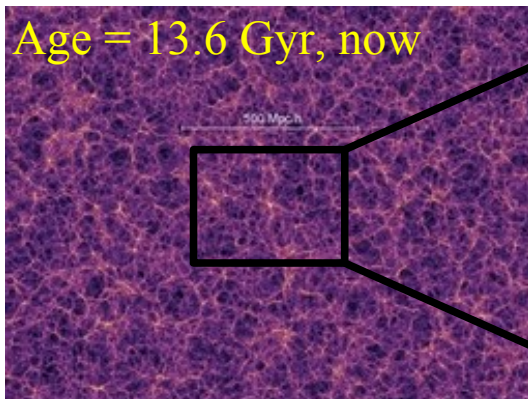
Age = 0.21 Gyr



Age = 4.7 Gyr



Age = 13.6 Gyr, now

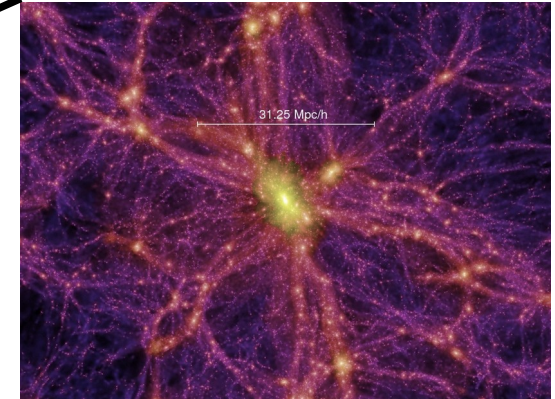
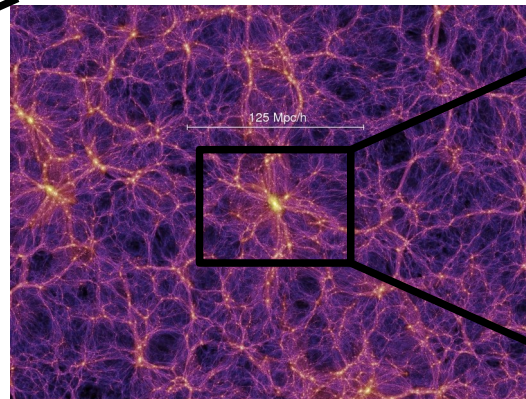


## Numerical simulations

- Start from primordial density fluctuations
- Let evolve under gravity
- Stop after 13.6 Gyr

→ look at resulting density map at scales of interest

Galaxy clusters  
size ~ Mpc, masse ~  $10^{15} M_{\odot}$



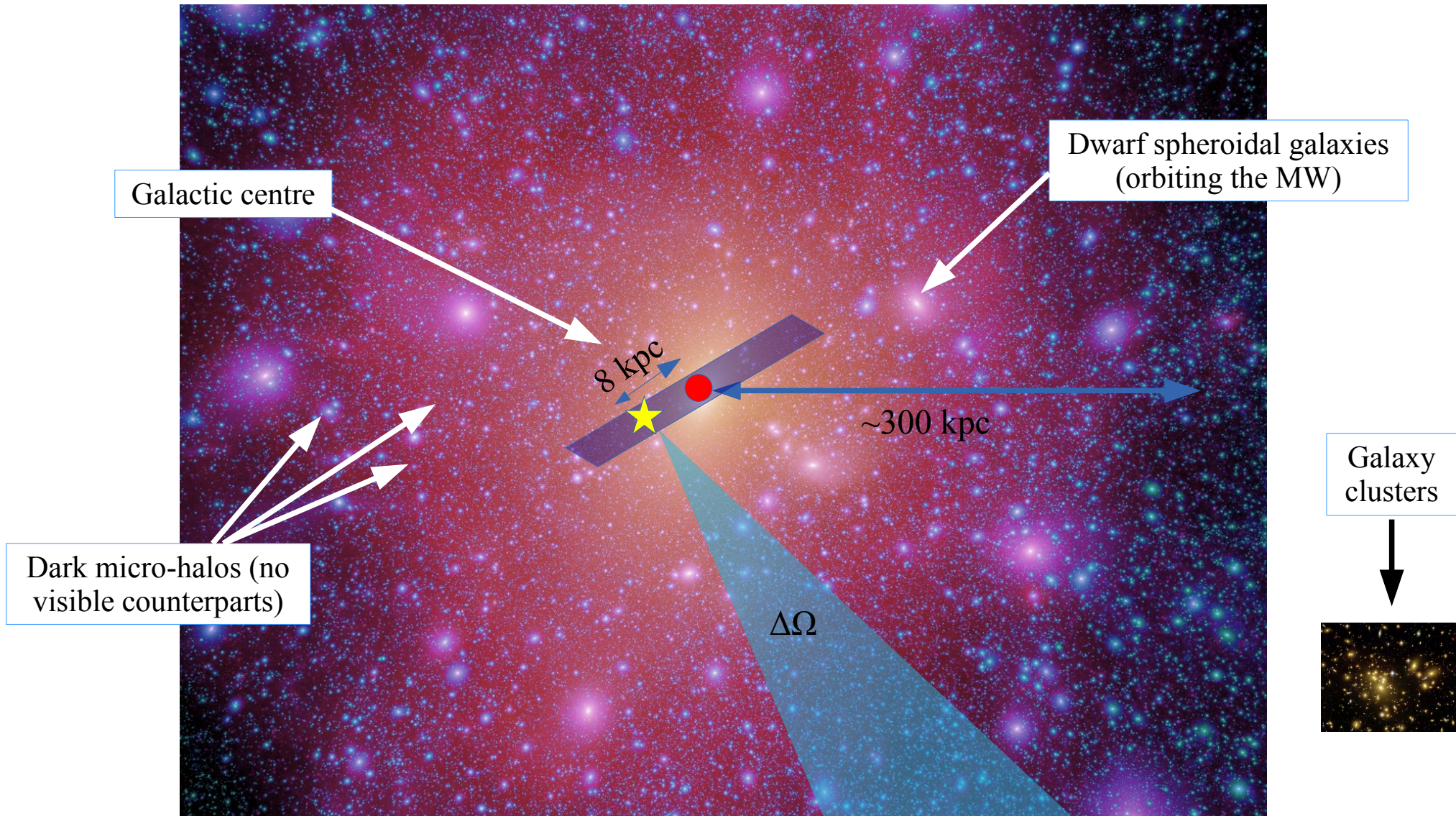
Millenium run – Springel et al. (2005)

5.  $\gamma$ -rays and dark matter



# DM distribution in the Milky Way

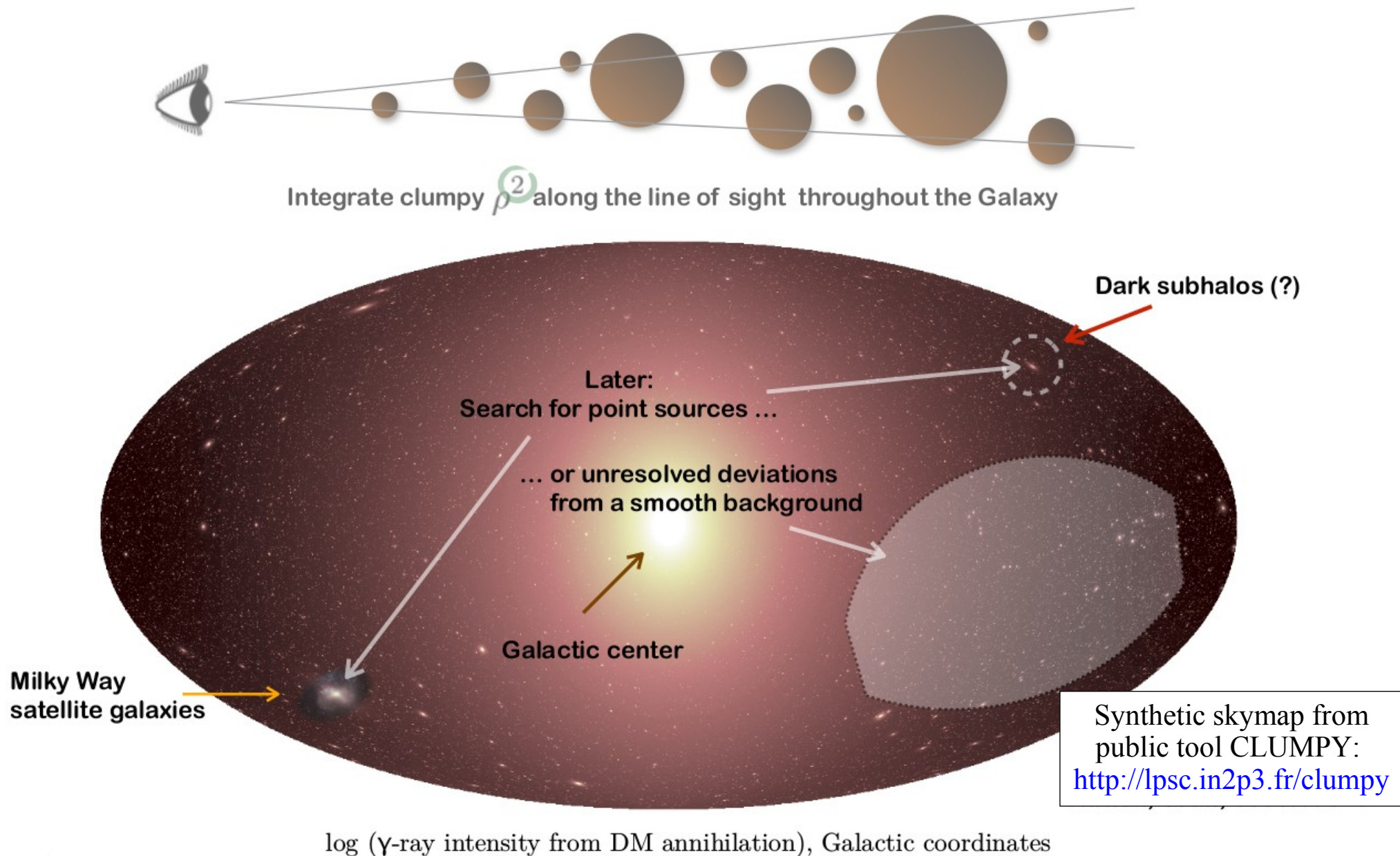
Dense ( $\sim \int \rho^2$ ) – Close ( $1/d^2$ ) – No astrophysical background



Question: what target would you pick?  
How does the signal skymap look like?



# From DM density to $\gamma$ -ray skymap





# 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  
 $m_{\text{WIMP}} \sim 0.1 - 100 \text{ TeV}$

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

From numerical  
simulations or data

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

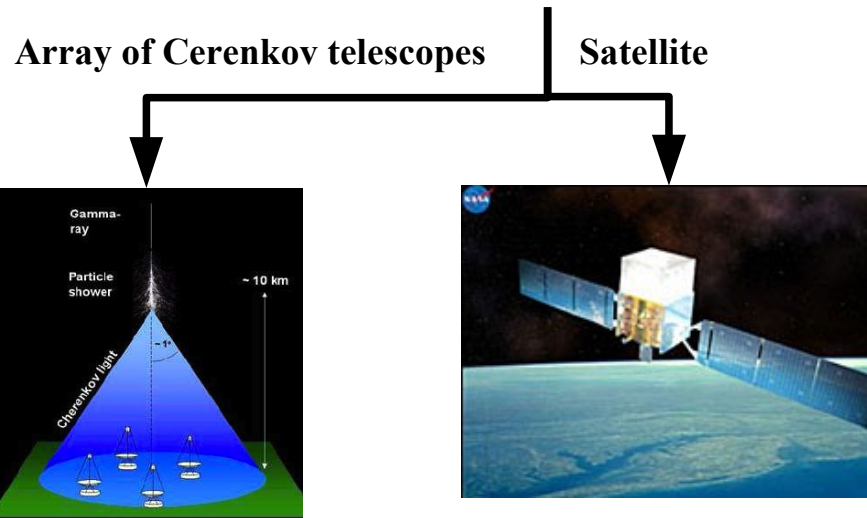
# Limit on DM annihilation cross-section $\langle\sigma v\rangle$

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

Instrumental sensitivity

Particle physics

Constrained



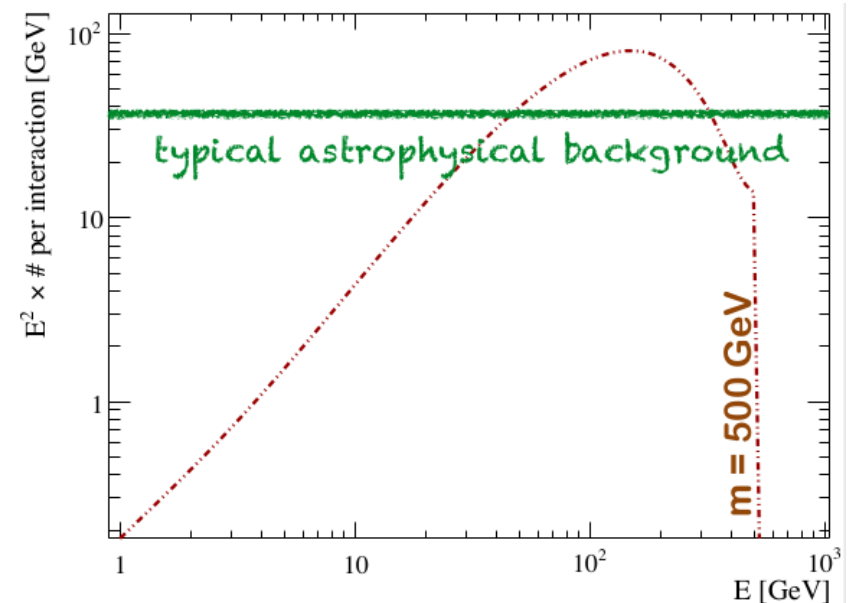
**H.E.S.S. + CTA**

**Fermi-LAT (since 2008)**

- Ground based
- 100 GeV  $\rightarrow$  100 TeV
- Resolution:  $0.2^\circ - 0.02^\circ$
- Pointed instrument
- Background limited

- Space-borne
- 30 MeV – 300 GeV
- Resolution:  $1^\circ - 0.1^\circ$
- Fullsky
- Signal limited

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

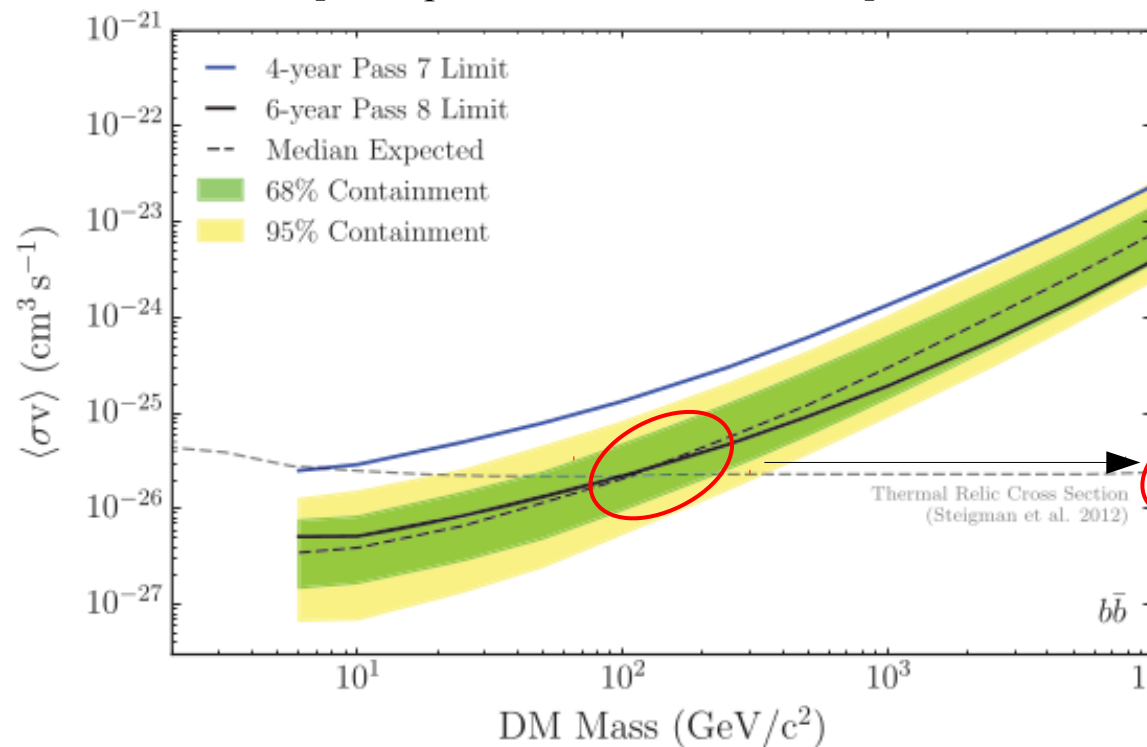


# Exclusion plots: Fermi-LAT and CTA

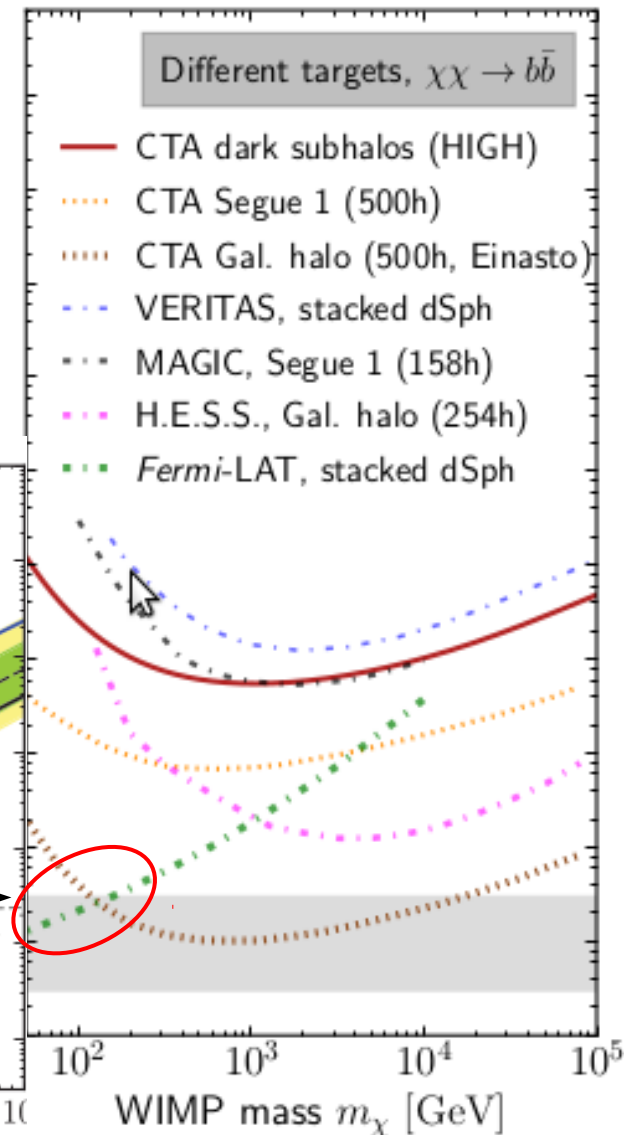
$$\langle \sigma_{\text{ann}} v \rangle \propto m_\chi^2 \times J(\alpha_{\text{int}}) \times \text{Sensitivity} \times \frac{dN^{pp}}{dE}$$

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

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

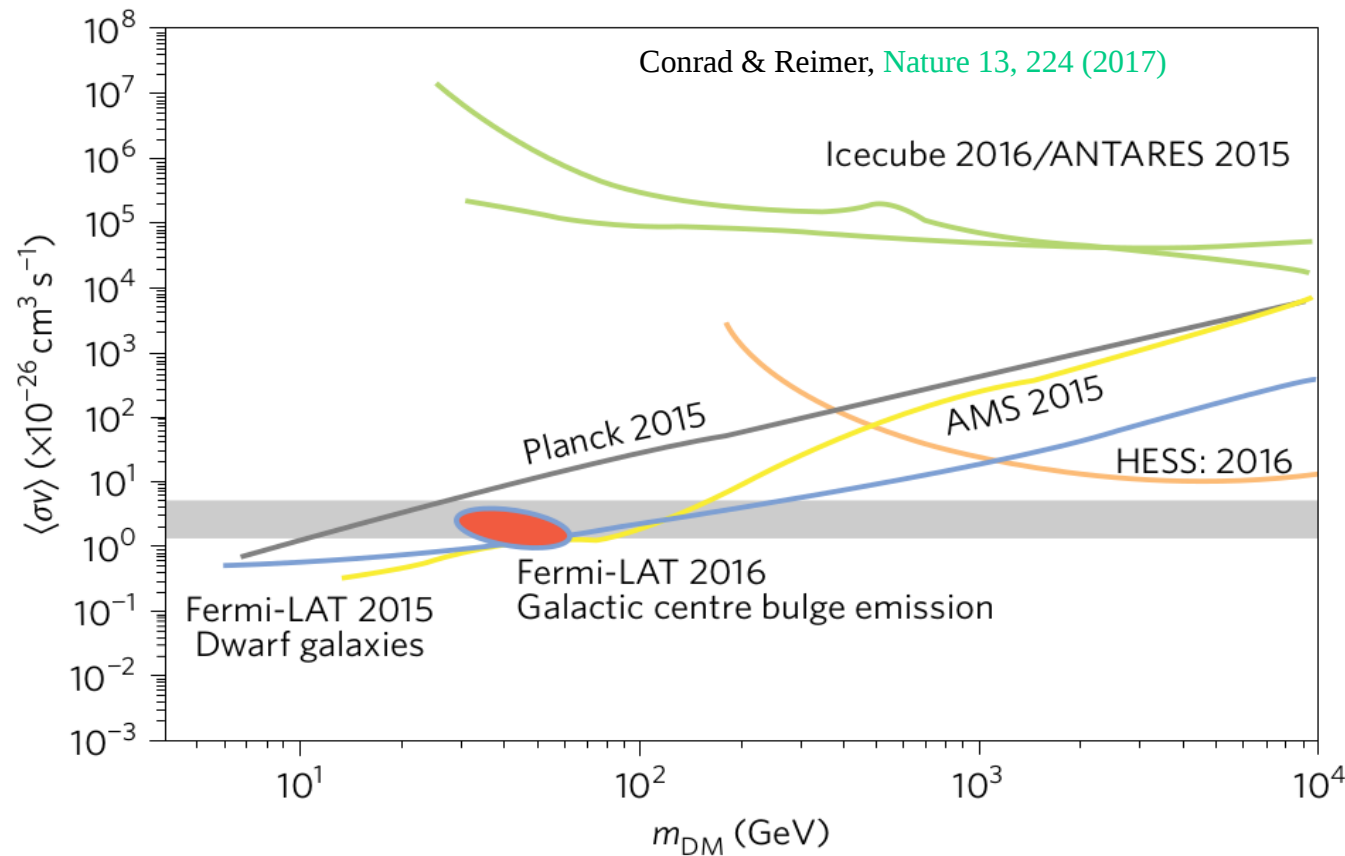


Hütten et al. (2016)  
[CTA prospects]





# Comparison/complementarity of indirect detection targets



→  $\gamma$ -rays from dSphs and antiprotons provide best targets for DM searches

# Conclusions

## **High precision era**

- Astroparticle physics lively field of research
  - New instruments online soon
  - Big questions might be solve tomorrow
- Plenty of research activities in which to have fun