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
- Scientific debates (historical illustration with CRs)
- Complexity of data analysis (illustration with AMS-02)
- Variety of detection principles, ‘research activities’, etc.

David Maurin
(LPSC)
dmaurin@lpsc.in2p3.fr

GRASPA
Annecy-le-Vieux
22 July 2019

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

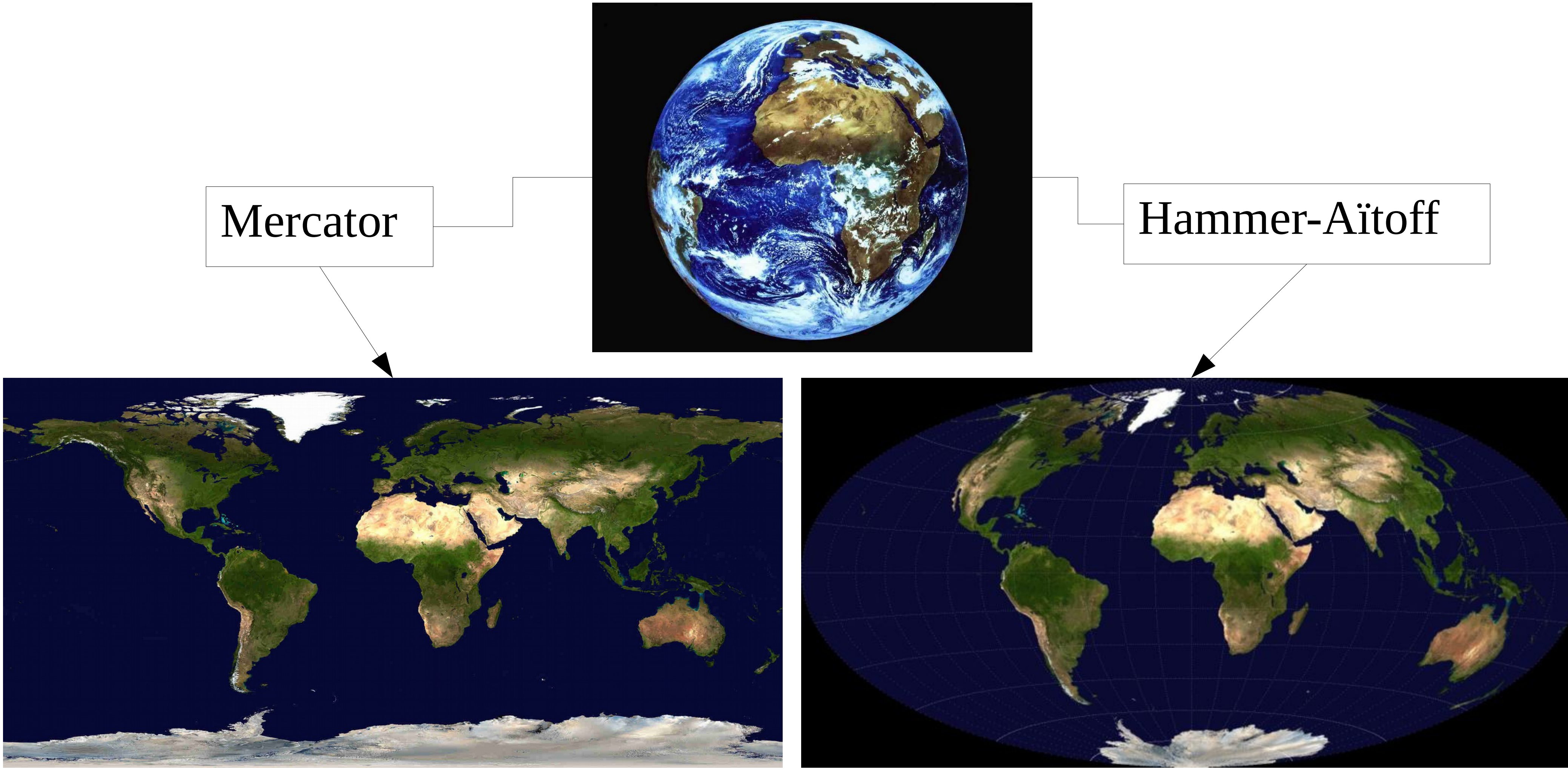
LPSC Grenoble

David Maurin
(LPSC)
dmaurin@lpsc.in2p3.fr

CNRS IN2P3 Les deux infinis
Université Grenoble Alpes

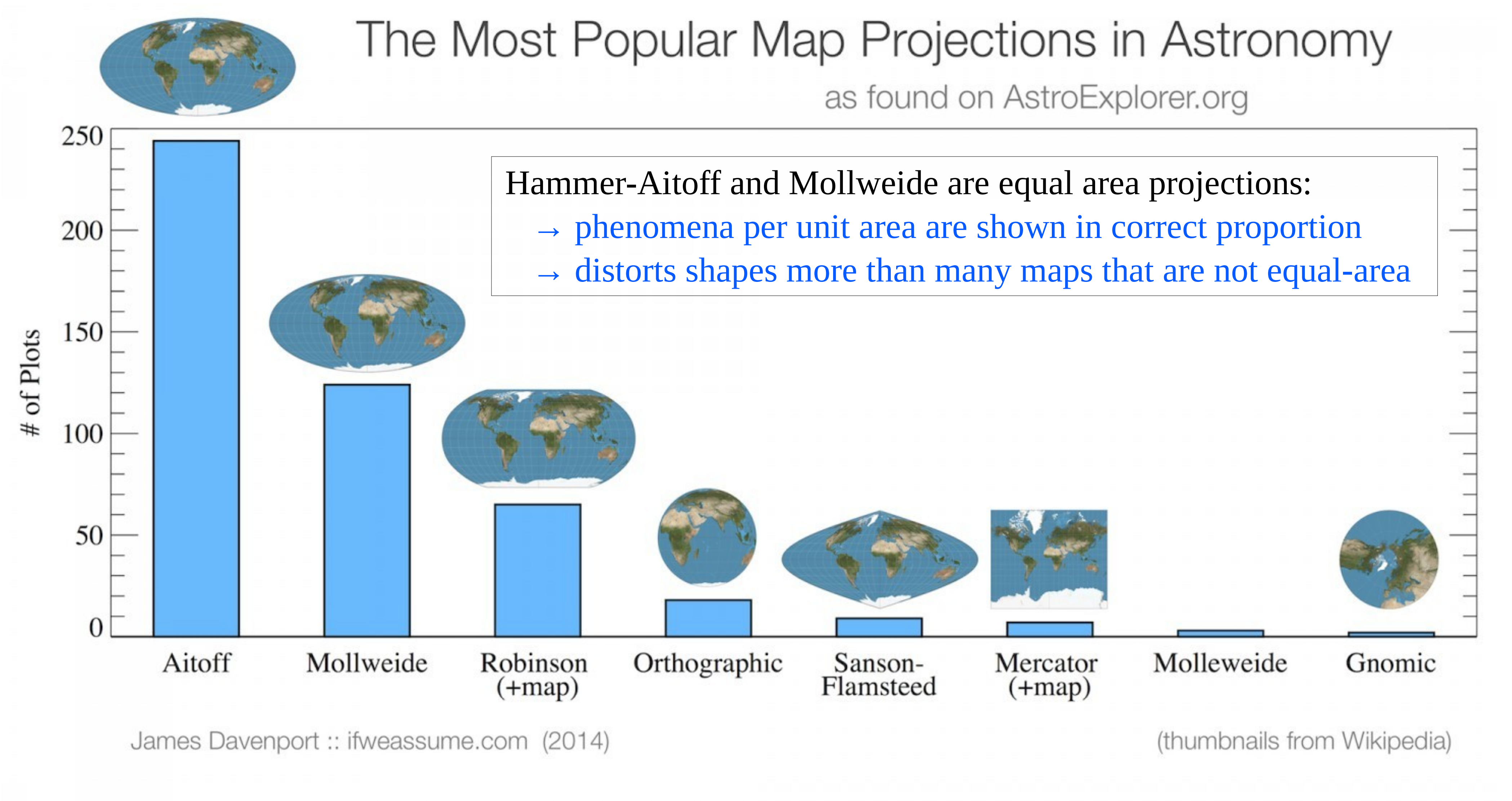
GRASPA
Annecy-le-Vieux
22 July 2019

Mapping the sphere to 2D view



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

Mapping the sphere to 2D view



Hammer-Aitoff and Mollweide are equal area projections:

→ phenomena per unit area are shown in correct proportion

→ distorts shapes more than many maps that are not equal-area

Representations of celestial coordinates in FITS

Calabretta & Greisen, A&A 395, 1077 (2002)

Galactic coordinates: the Milky Way

Unit conversion

<u>Mass</u>

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

$\sim 2.10^{30}$ kg

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

<u>Distance</u>

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

$\sim 2.10^{5}$ AU

~ 3.26 ly

Milky Way ID

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

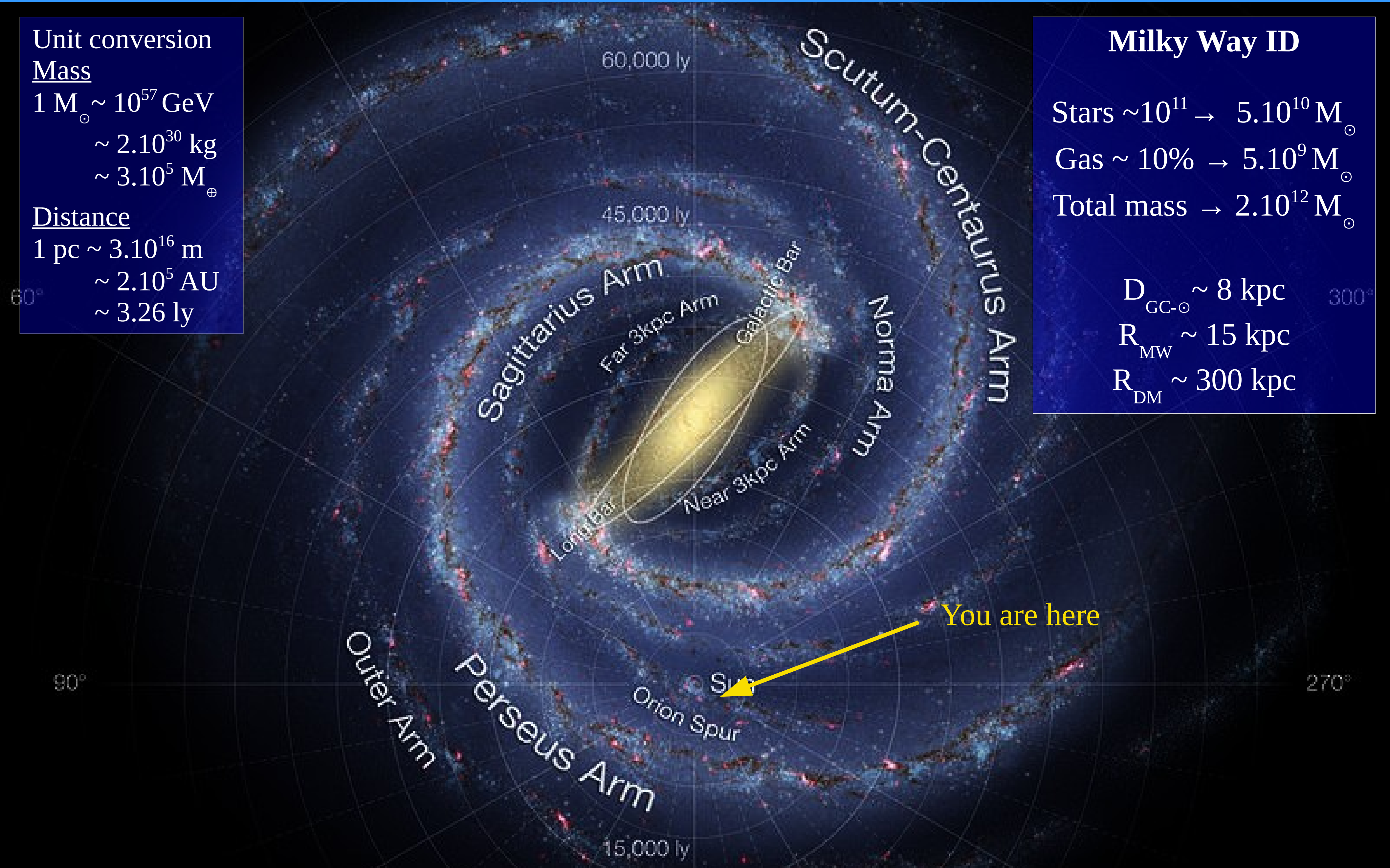
Gas $\sim 10\% \rightarrow 5.10^{9}\ M_\odot$

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

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

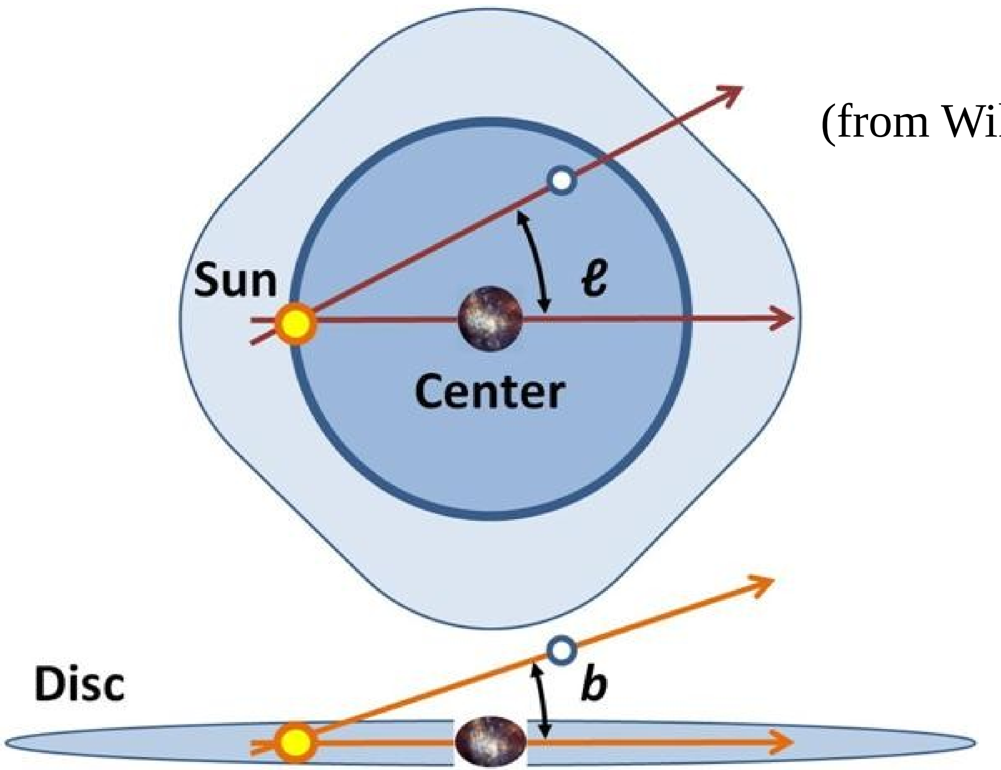
$R_{MW} \sim 15$ kpc

$R_{DM} \sim 300$ kpc

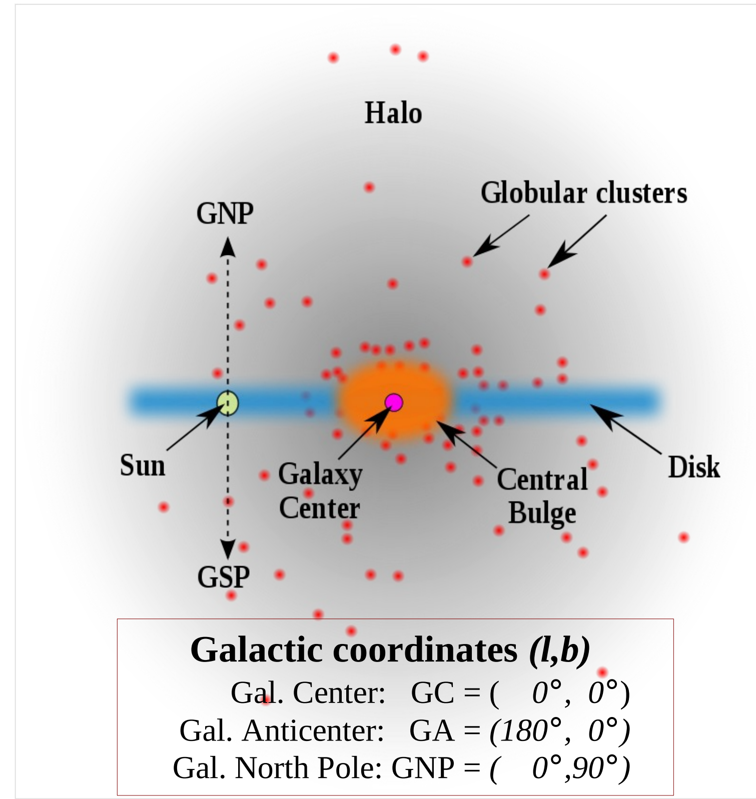


Artist's view of the Milky Way – NASA/JPL-Caltech/R. Hurt

Galactic coordinates: ‘d’, l (longitude), b (latitude)



(from Wikipedia)



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 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

→ Diffuse emission and origin

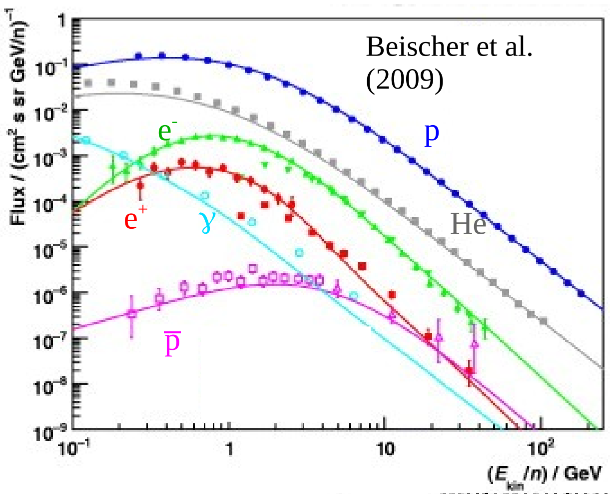
→ Sources of non-thermal emissions

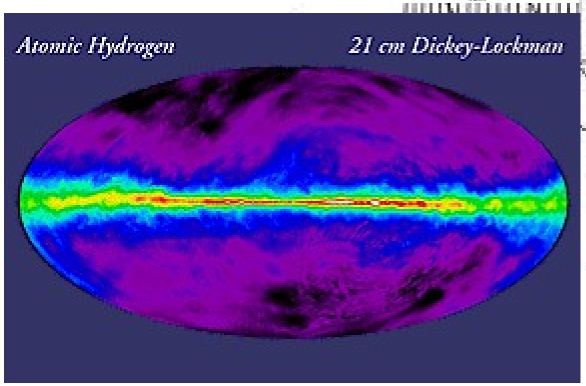
→ GeV vs TeV sky

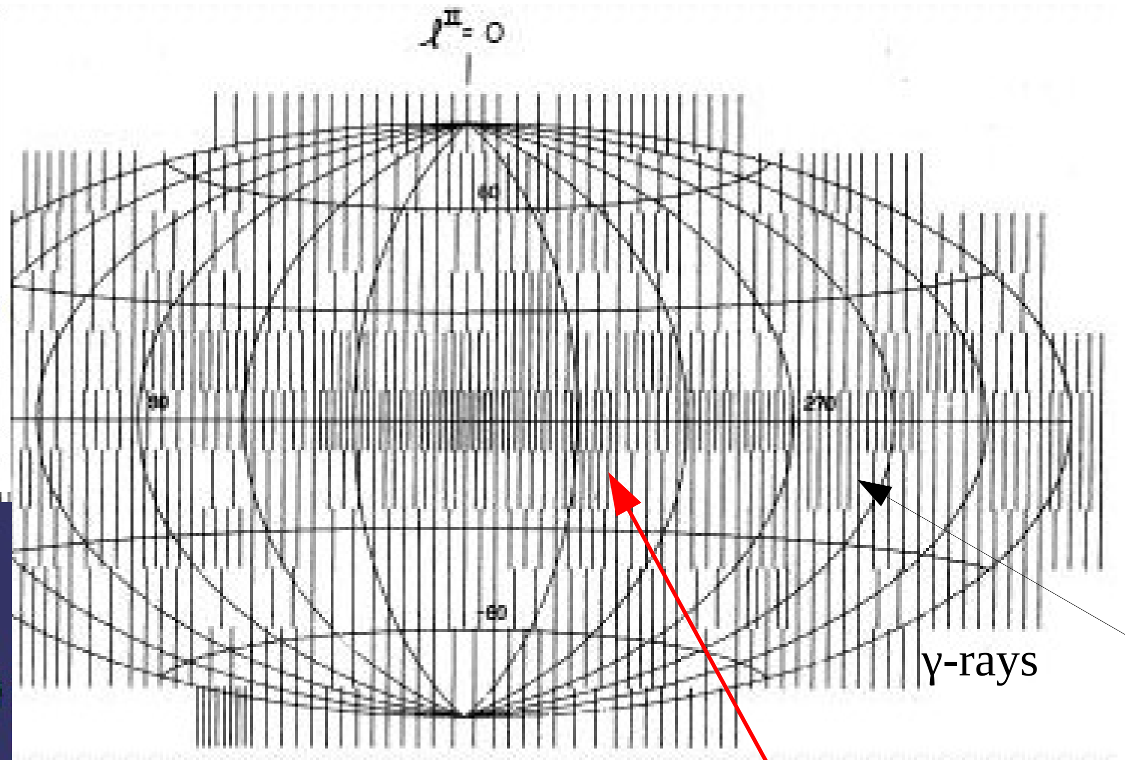
Diffuse emission: first detection >100 MeV

OSO-3 (>100 MeV)

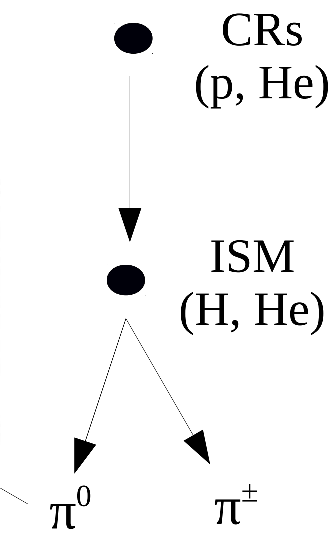
[16 months, then failure of the 2nd spacecraft tape recorder]







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



Diffuse emission in the disk = galactic origin

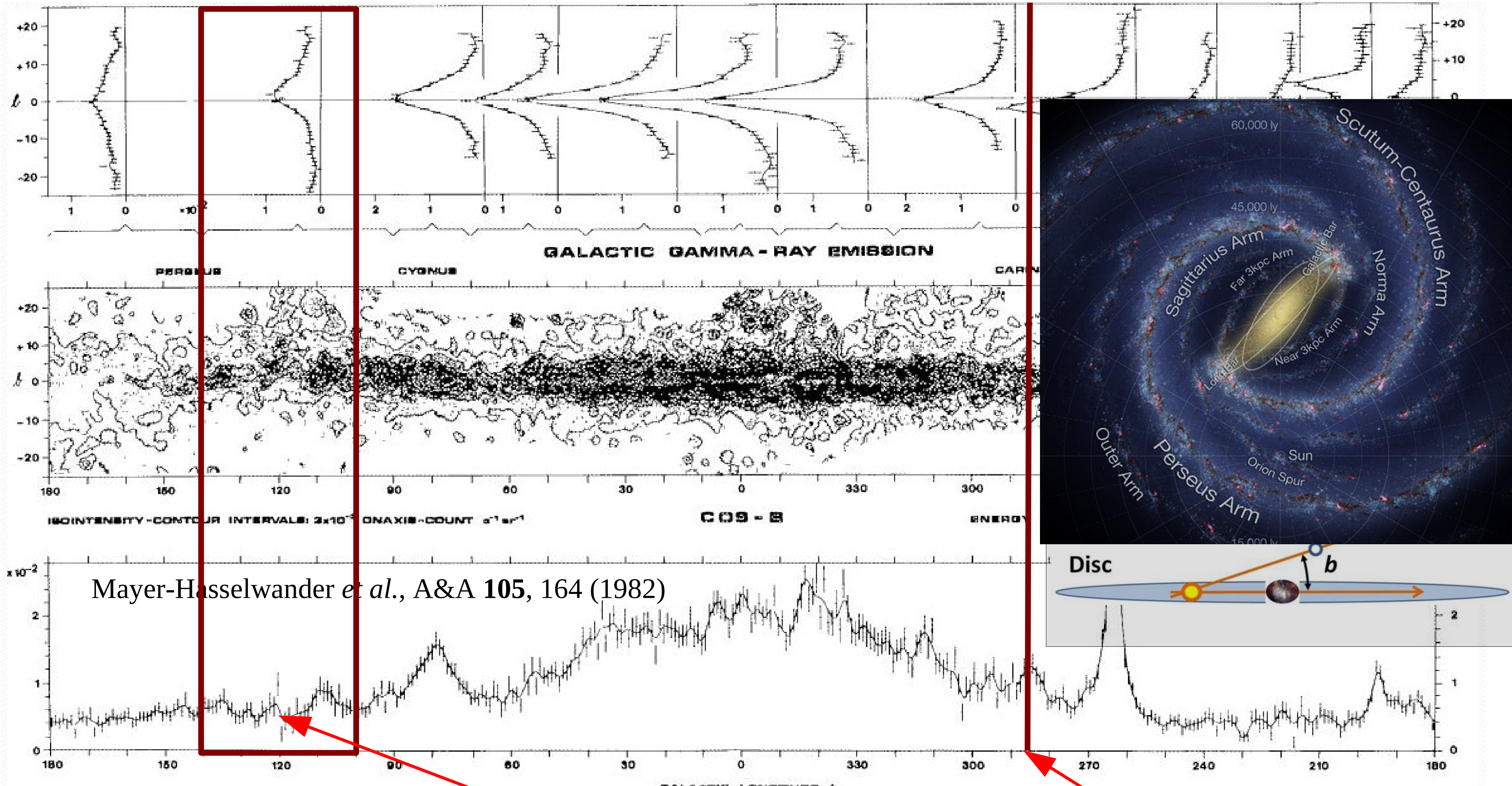
→ Distribution proportional to column density at 21cm (H_I)

→ Absolute intensity accounted for by π^0 production

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

Diffuse emission: a closer look

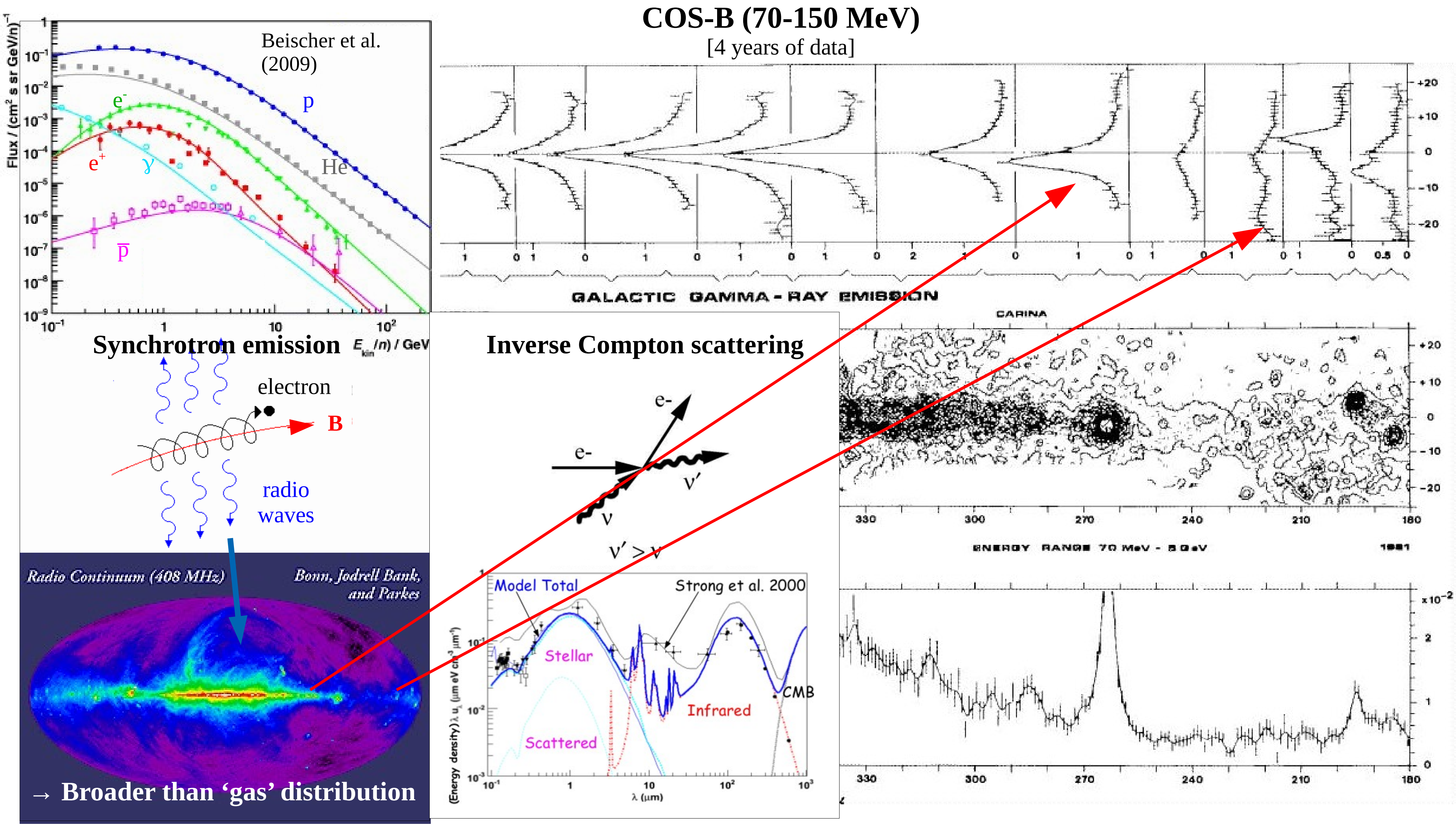
COS-B (70-150 MeV)
[4 years of data]



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

→ New correlations found: Perseus arm (*l=100°-140°*), spiral arm in Carina *(l=285°)*

Diffuse emission: a closer look



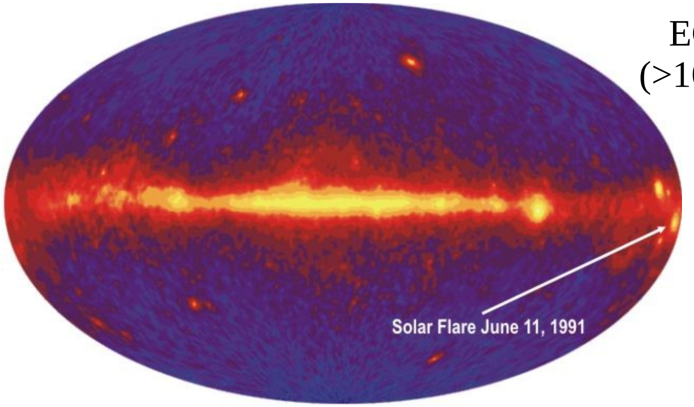
→ New correlations found: Perseus arm (*l=100°-140°*), spiral arm in Carina *(l=285°)*

→ Require additional leptonic emission (inverse Compton mostly, and synchrotron)

By the way: how to get the diffuse emission?

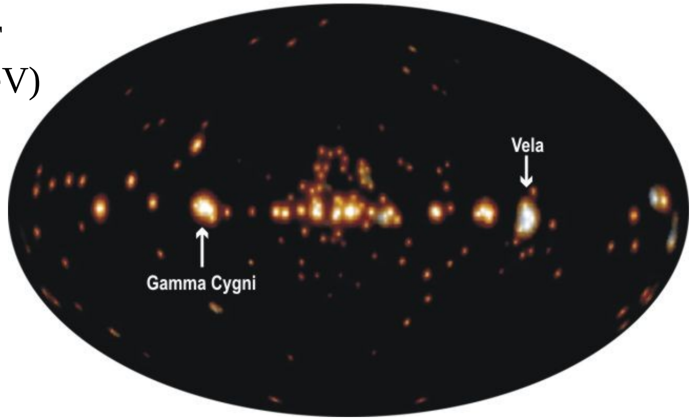
(1) Count the number of photons
(photons-instrument background)

(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 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

Morphology *and* spectral information

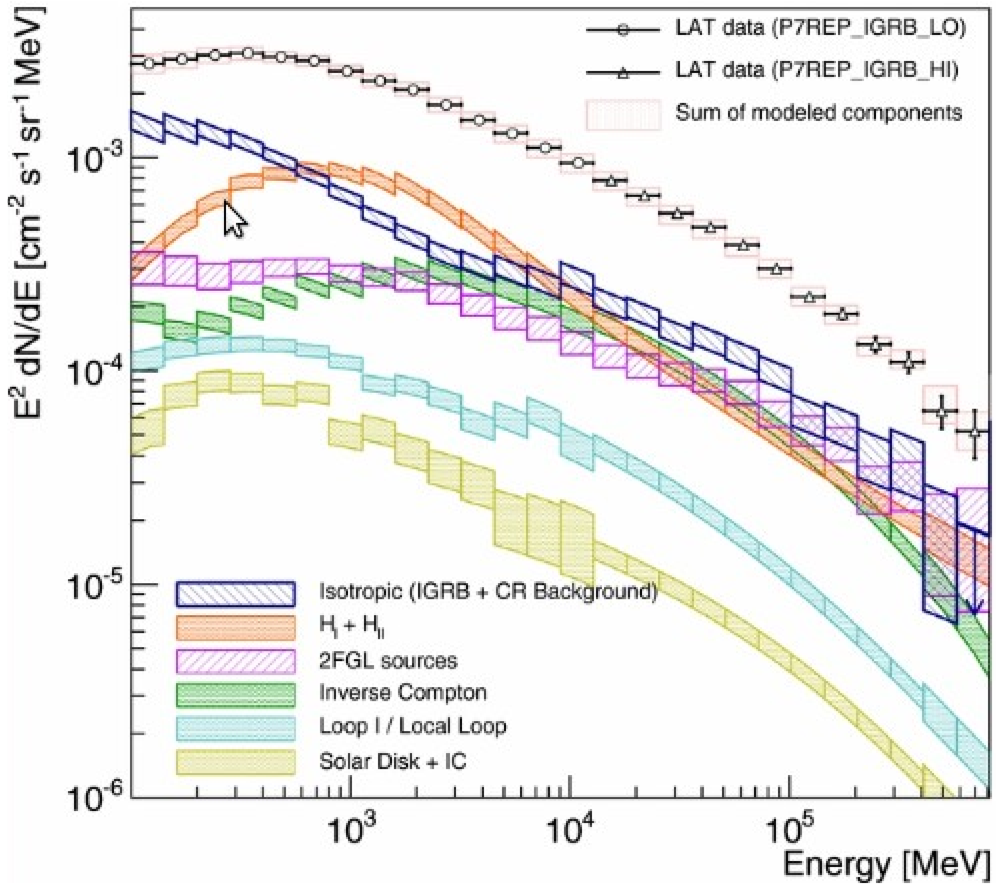
Photon Intensity ***(E,l,b)***

- Morphology (2D) → skymap for each energy
- Spectrum (1D) → spectrum in each direction

Modelling

- Gas, magnetic field: 3D
- CRs: 3D + spectrum + time (HE leptons)

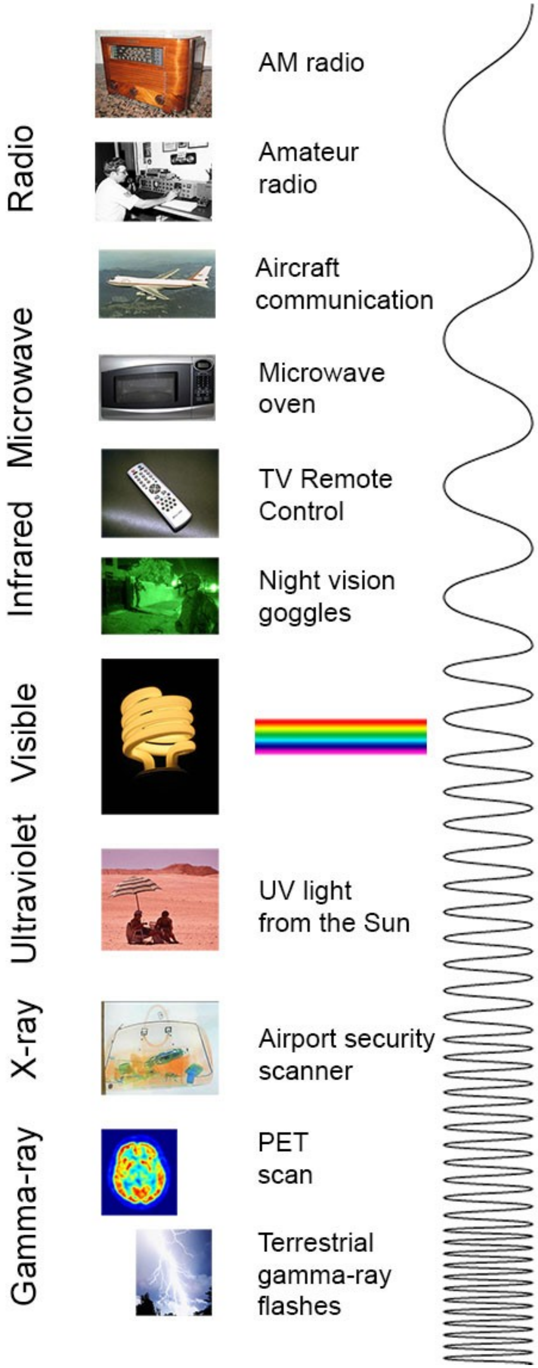
Models from the Fermi-LAT collaboration

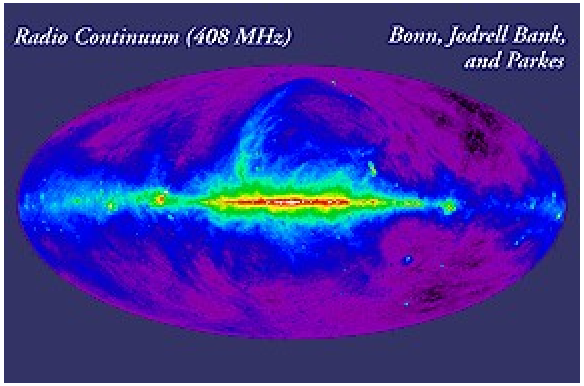


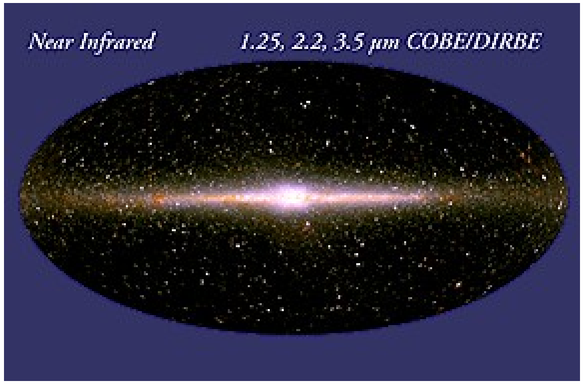
Ackermann *et al.*, ApJ 799, 86 (2015)

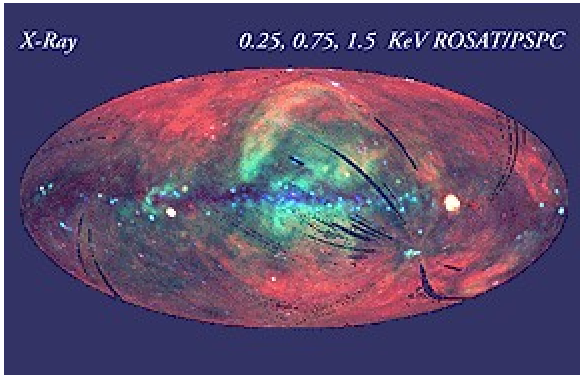
Work with the multi-wavelength sky!

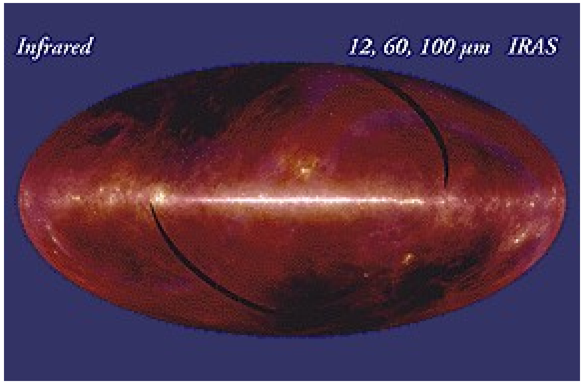
https://mwmw.gsfc.nasa.gov

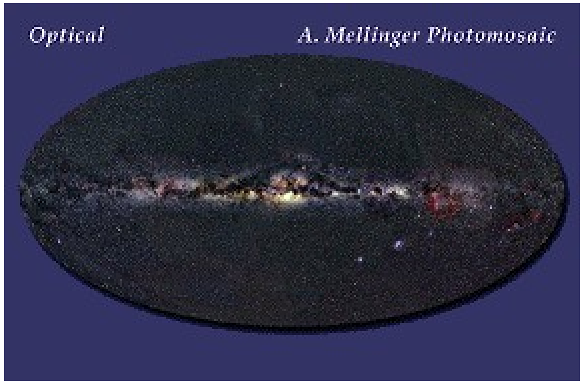


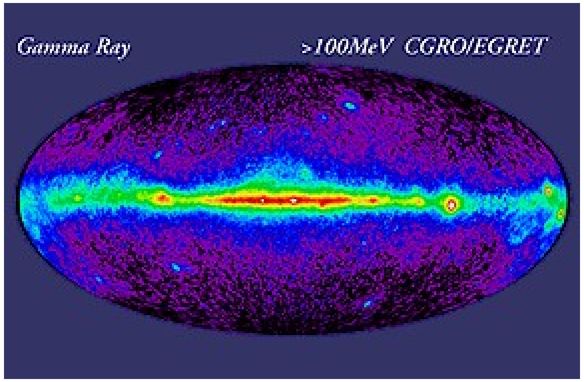






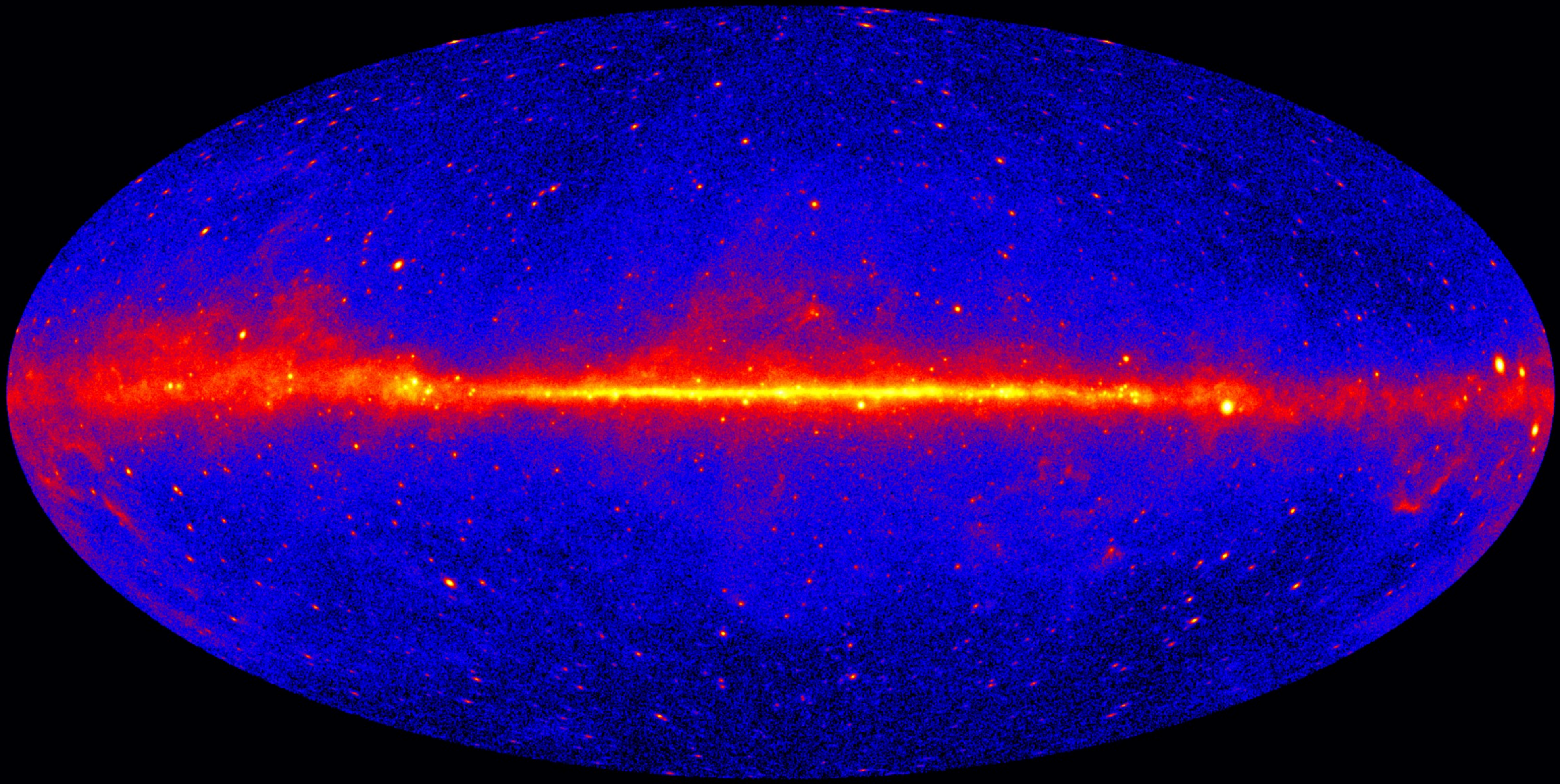






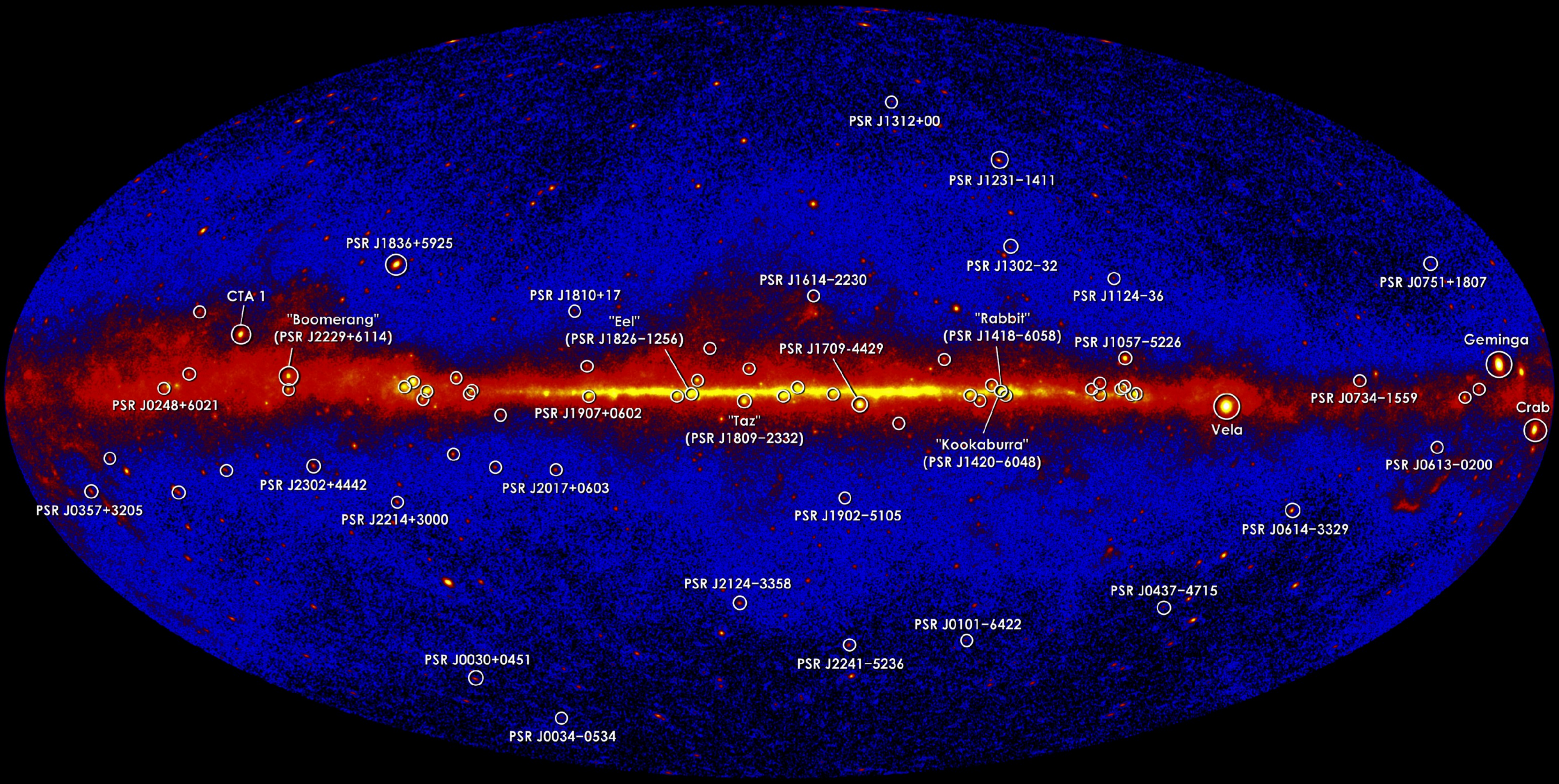
2. The γ-ray sky

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



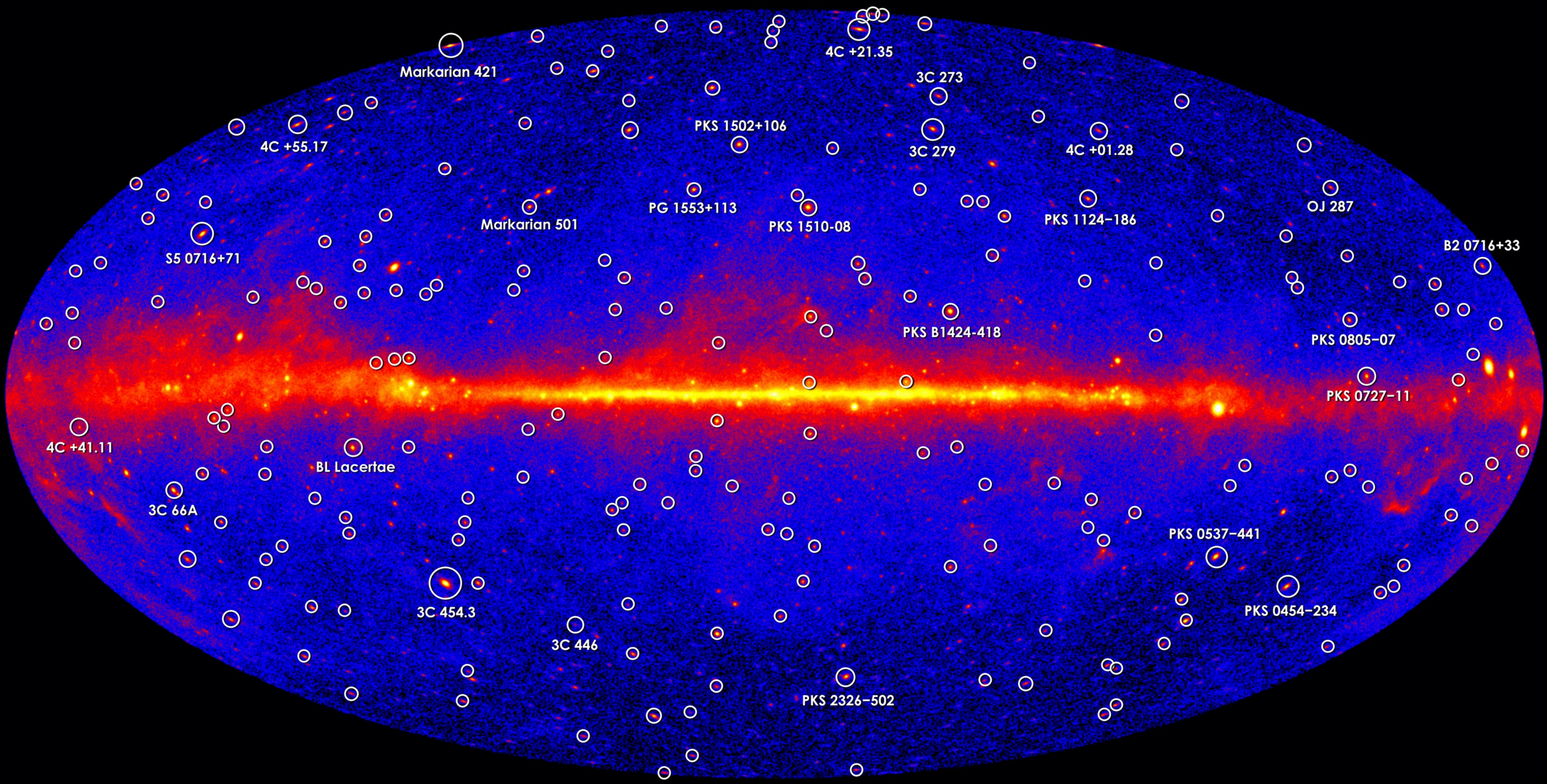
Indirect dark matter detection =
search for dark matter signature in this (astrophysical) mess

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



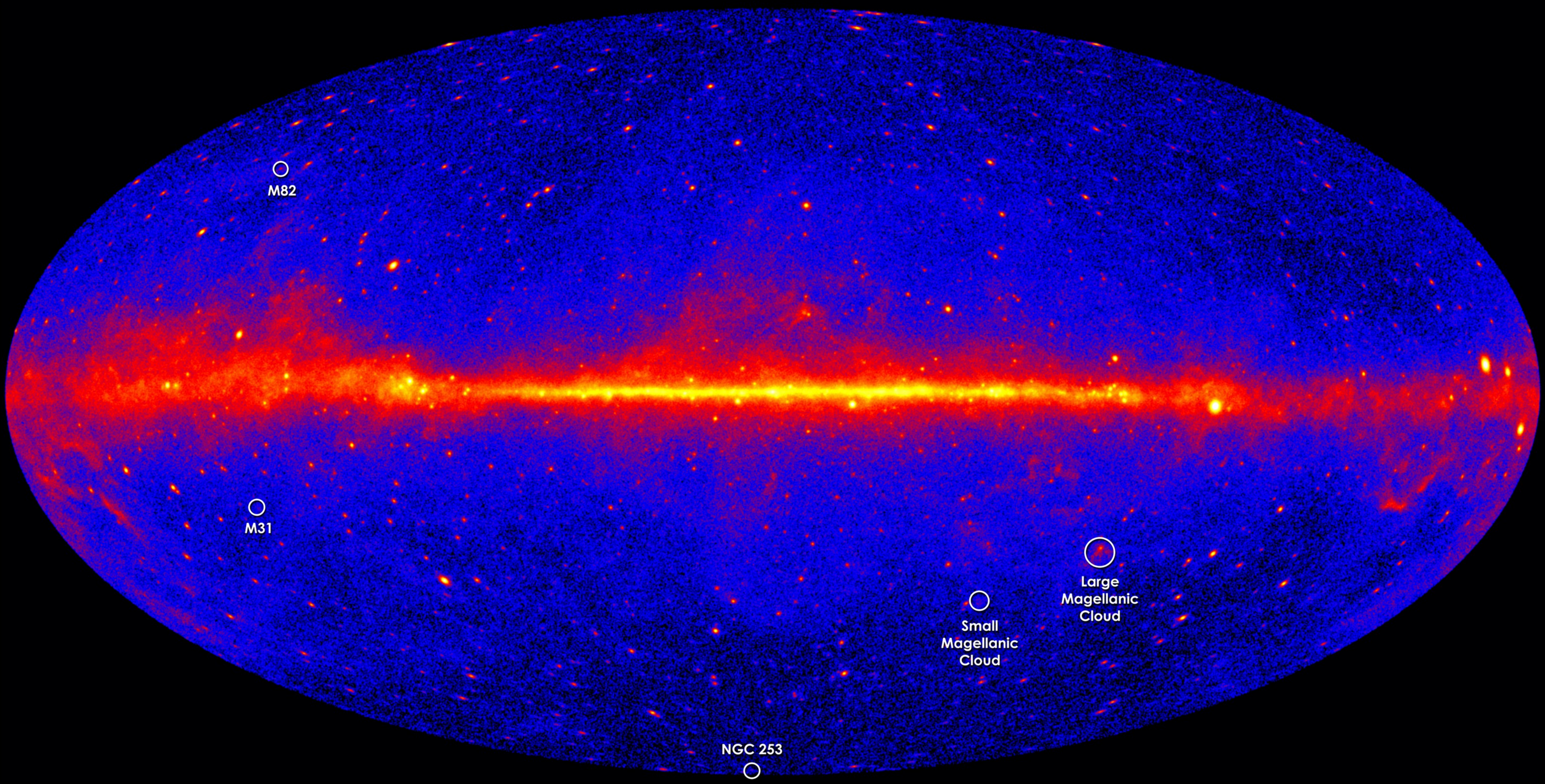
Pulsars
[rapidly rotating neutron stars]

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



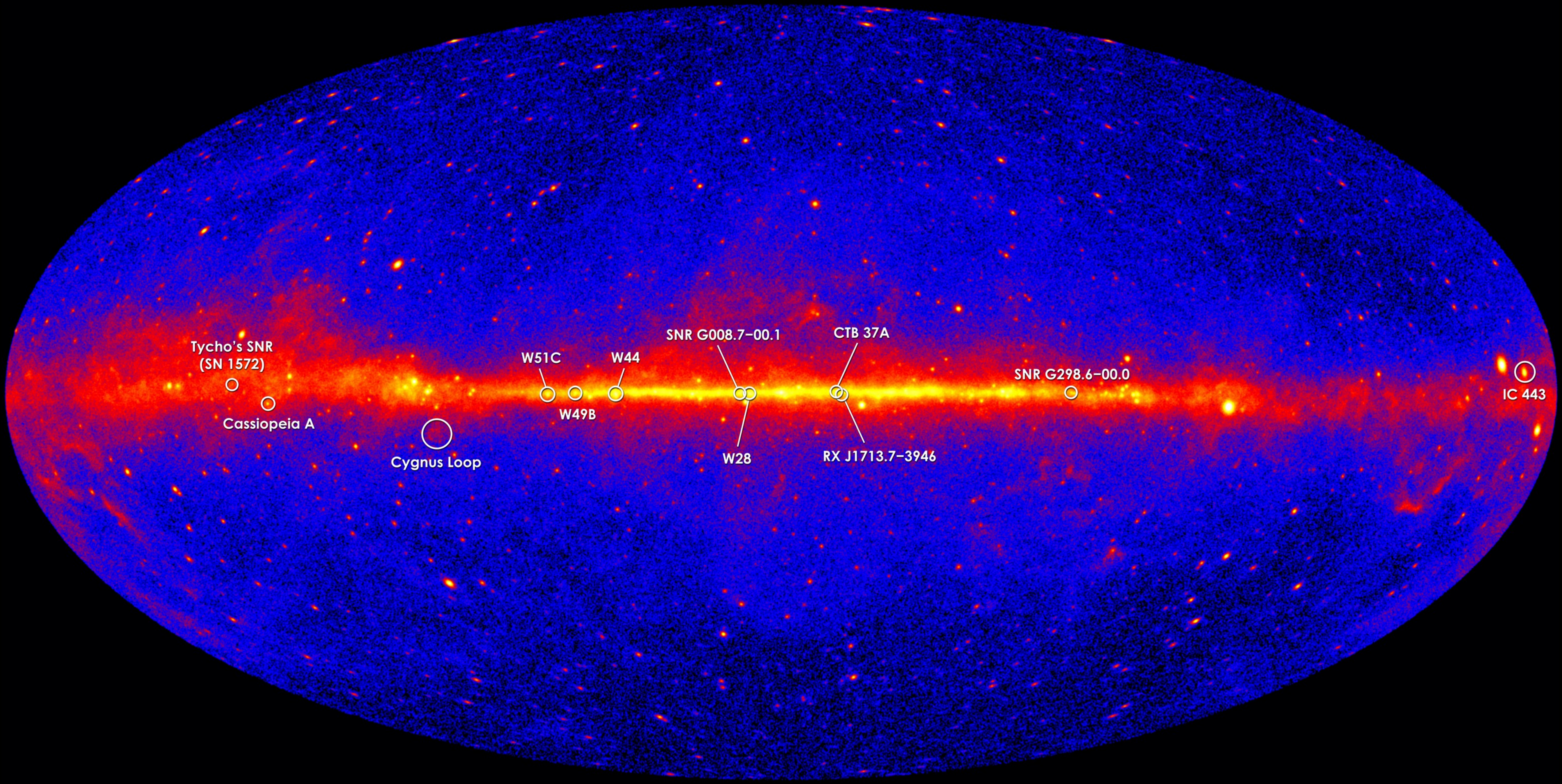
Active galaxies and blazars
[powered by $10^6 M_\odot$ black holes]

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



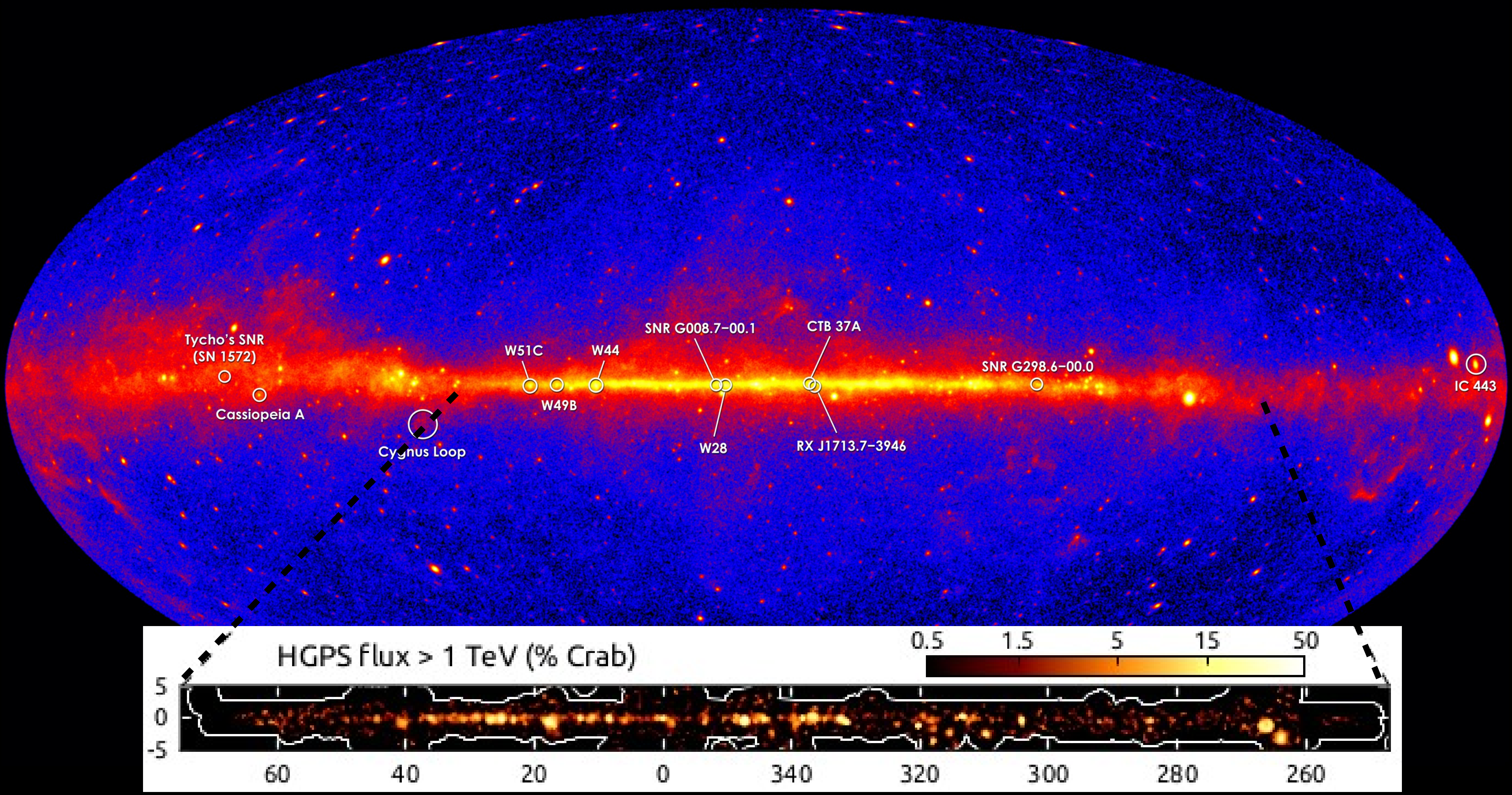
Normal and starburst galaxies

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(?)

1) Introduction: projections and coordinates

2) The gamma-ray sky tour

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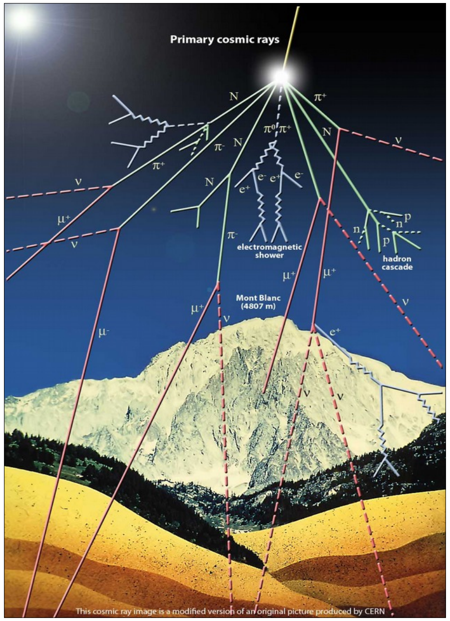
5) Constraints on dark matter from γ-rays



Motivation

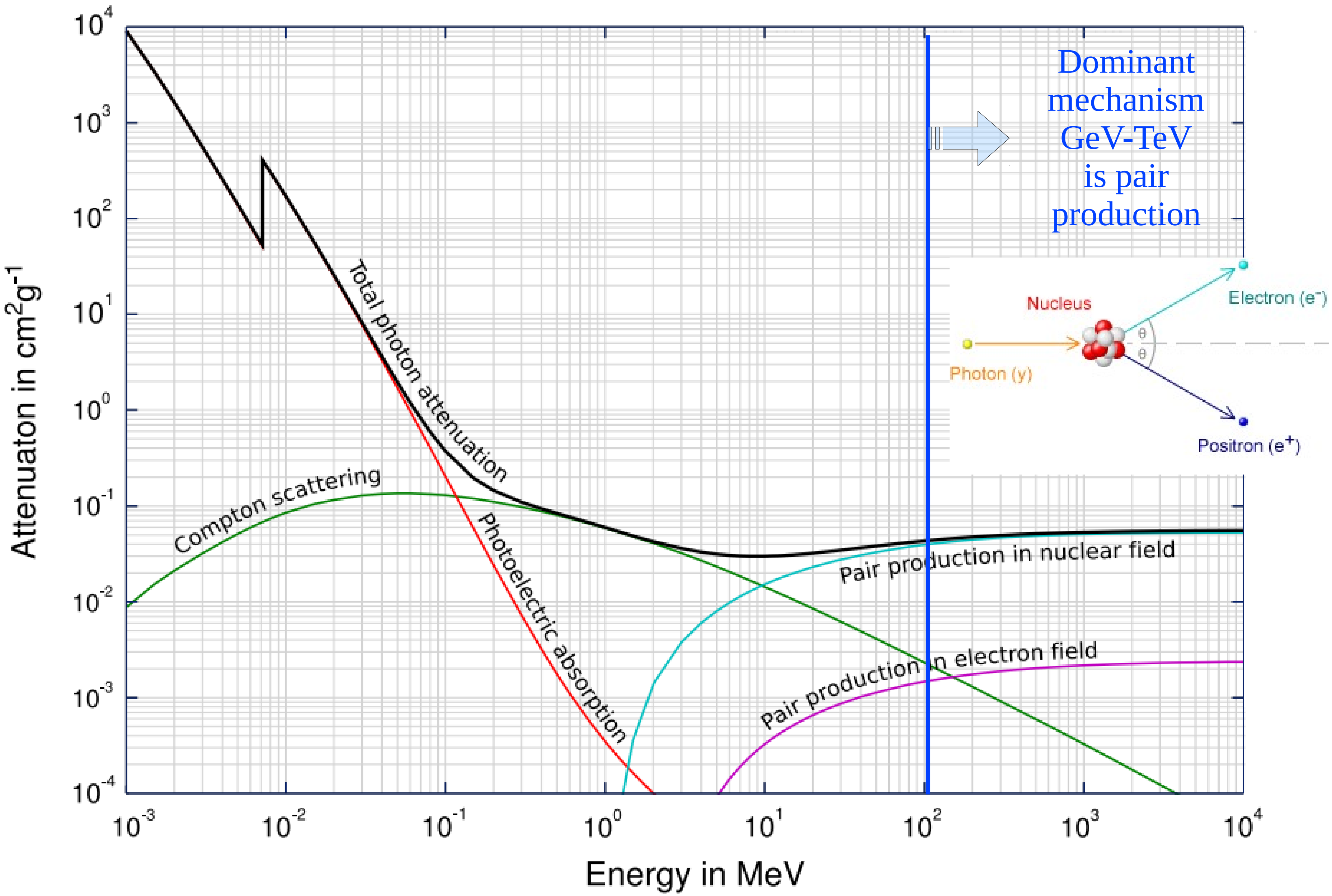
→ Take advantage of atmosphere as a calorimeter

→ Electromagnetic vs hadronic showers

→ Detector types using atmospheric showers

→ Rejection and calibration

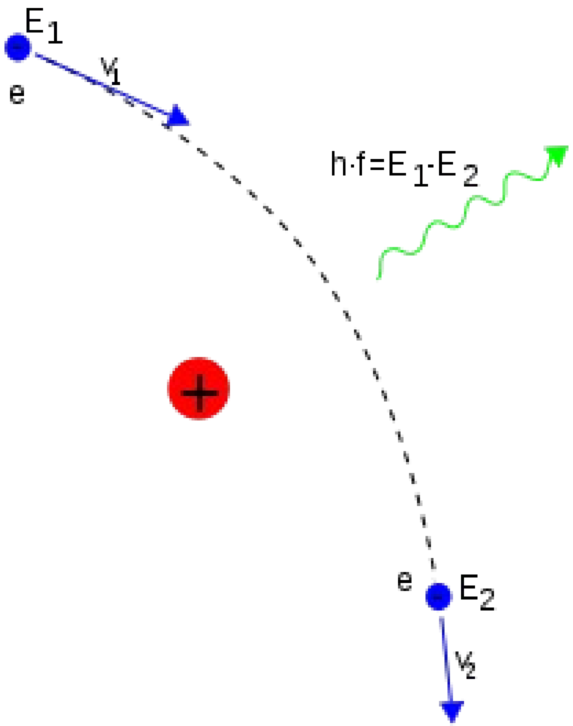
High-energy photon interaction



Dominant mechanism GeV-TeV is pair production

High energy lepton interaction

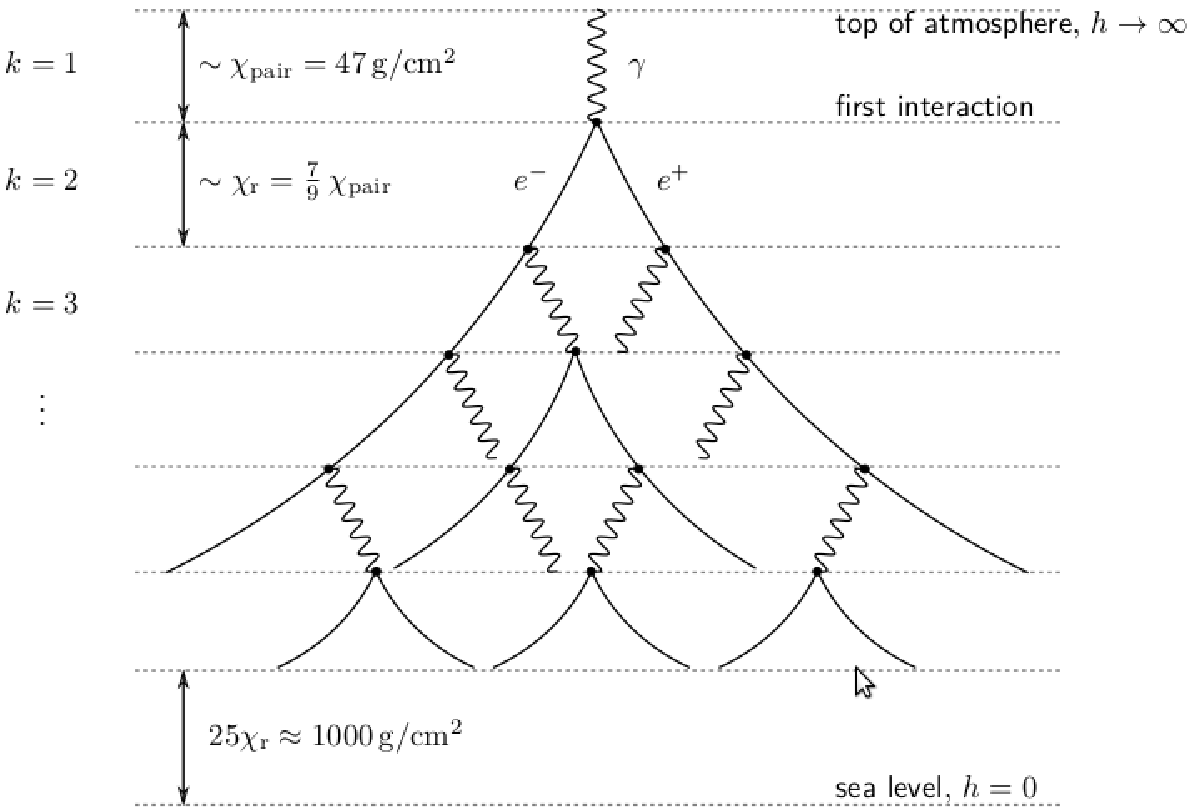
Bremsstrahlung emission
(in Coulomb field of the nucleus)



→ 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

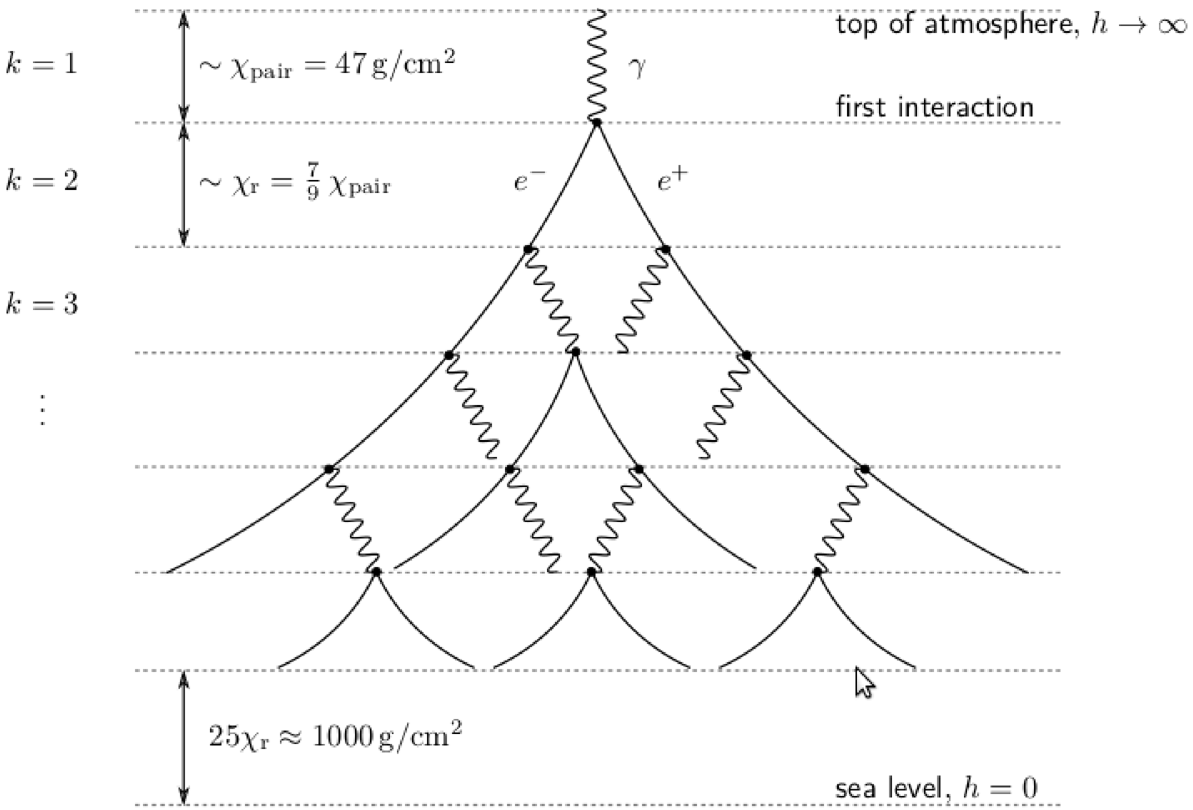
Depth of shower maximum z_{max}

Homogeneous calorimeter $\propto$ log(E_0)

Atmosphere: ~ 9 km – 8.4 km × log (log (E_0/1 TeV)

Electromagnetic air shower

Hütten, PhD thesis (2016)



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γ-ray satellites: ~10 X_0

Atmosphere: ~27 X_0

Depth of shower maximum z_{max}

Homogeneous calorimeter $\propto \log(E_0)$

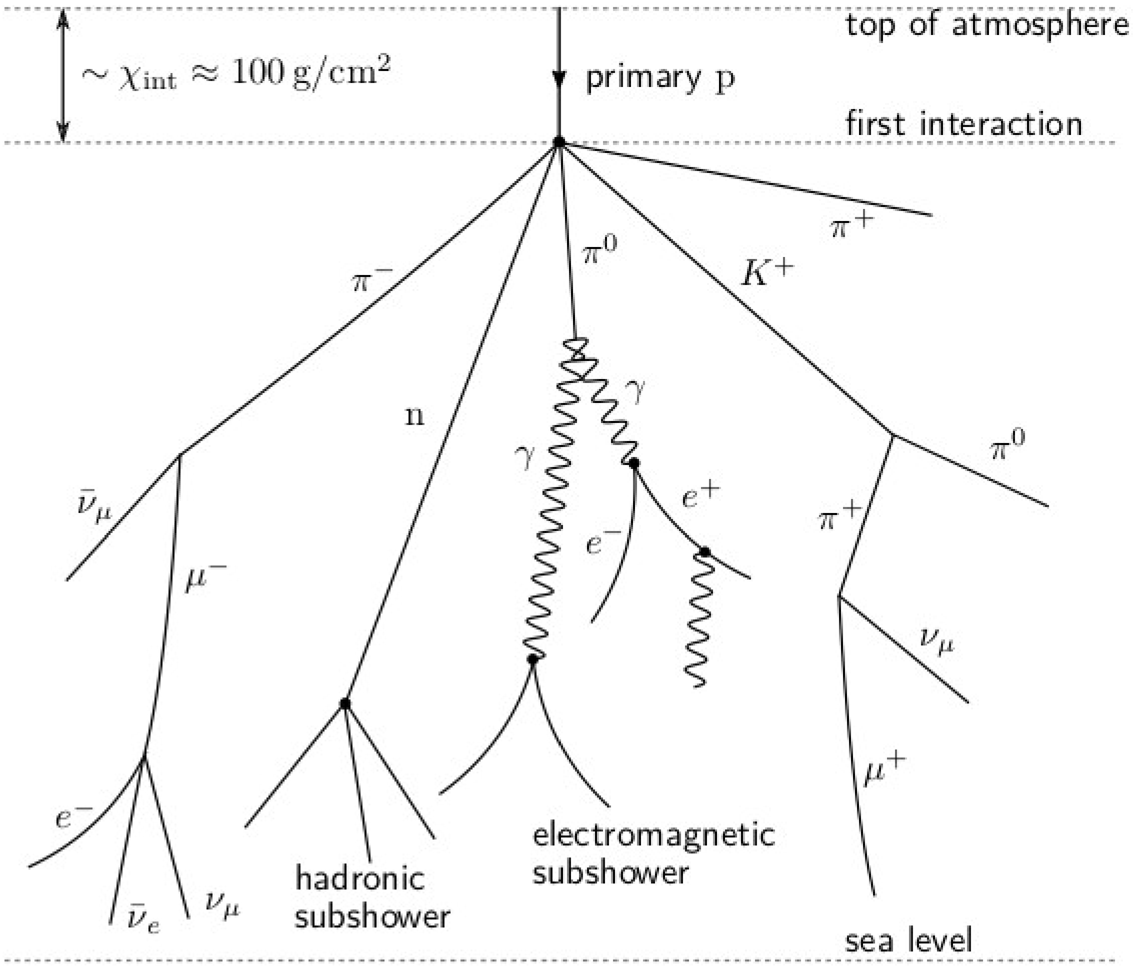
Atmosphere: ~ 9 km – 8.4 km × log (log (E_0/1 TeV)

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, 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 (1)

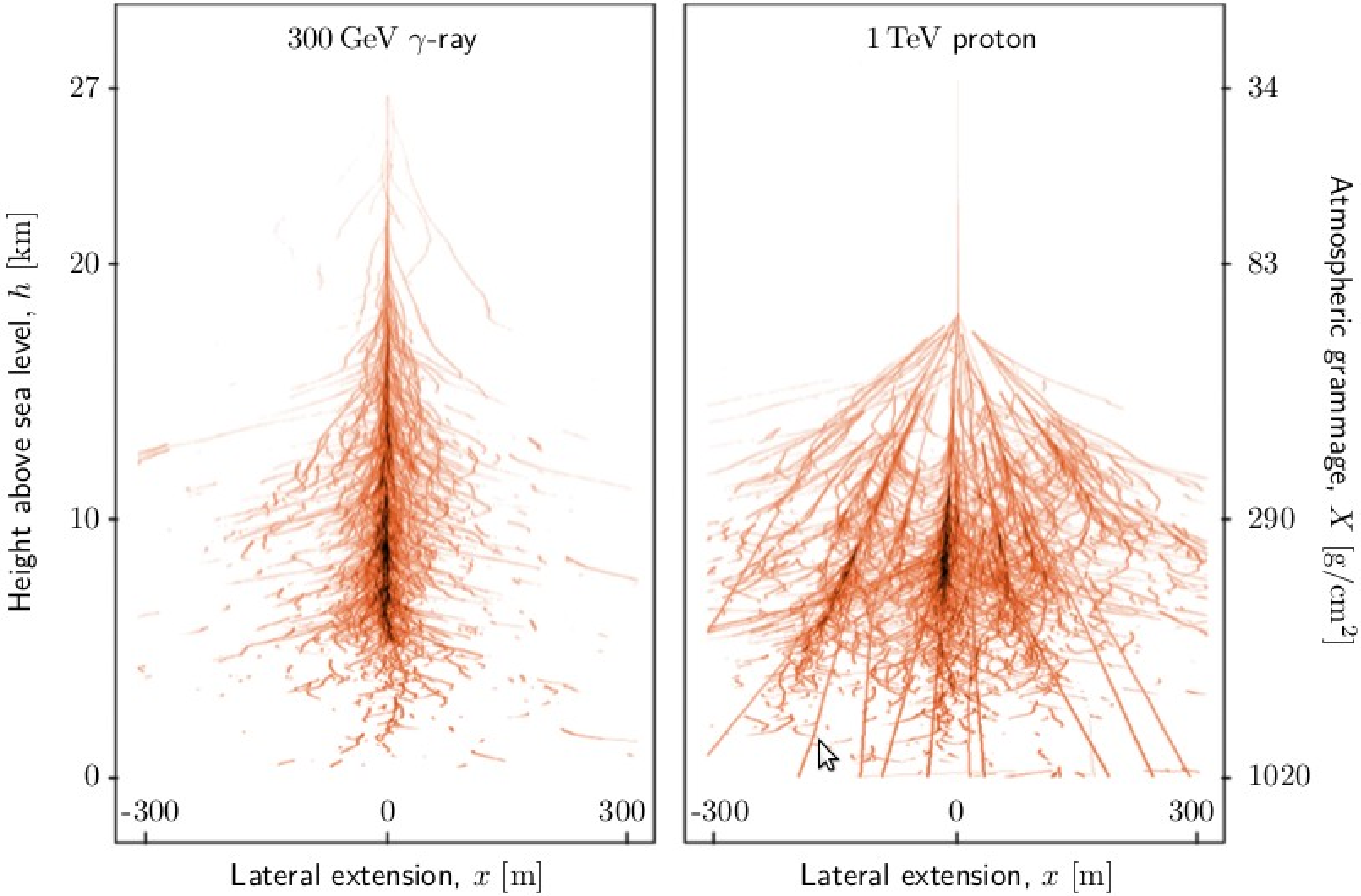


Figure 3.4.: Comparison between an electromagnetic air shower (triggered by a 300 GeV primary γ-ray) and a hadronic air shower (initiated by a 1 TeV proton). The figure shows the secondary particles projected onto a plane in (x, h) direction. Figure taken from Aharonian et al. (2008b).[9]

Leptonic vs hadronic shower (2)

De Naurois & Mazin, arXiv:1511.00463

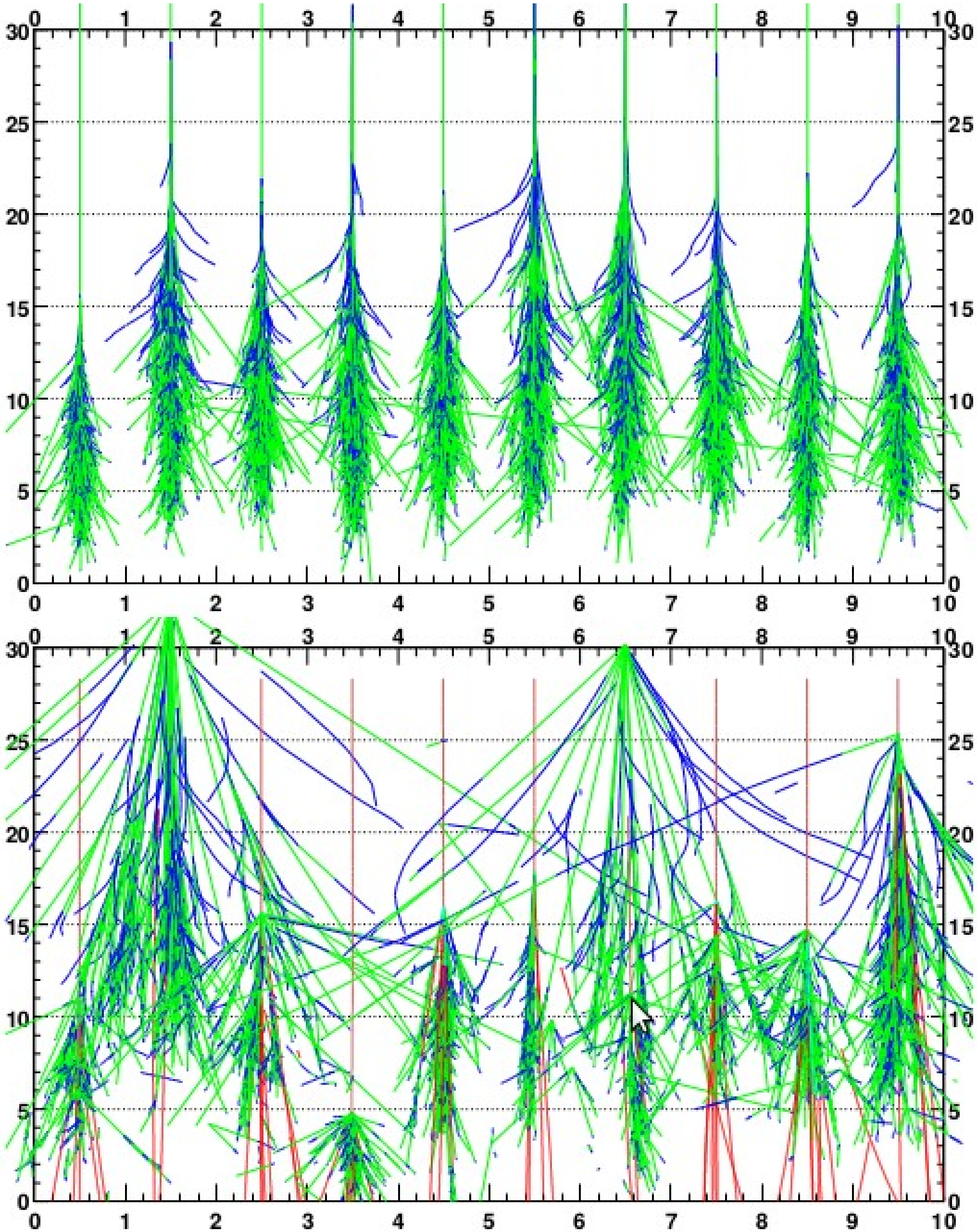


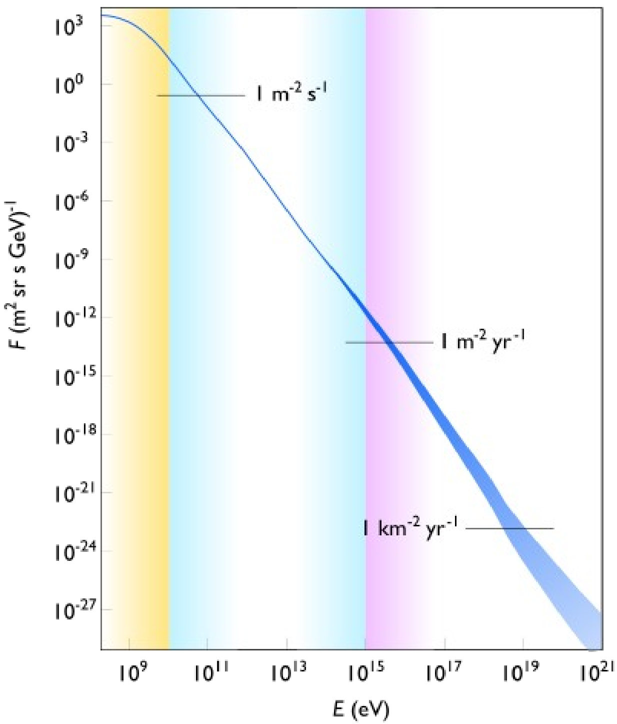
Illustration of the intrinsic variability of shower development.

Simulation of 10 showers (300 GeV γ-rays)

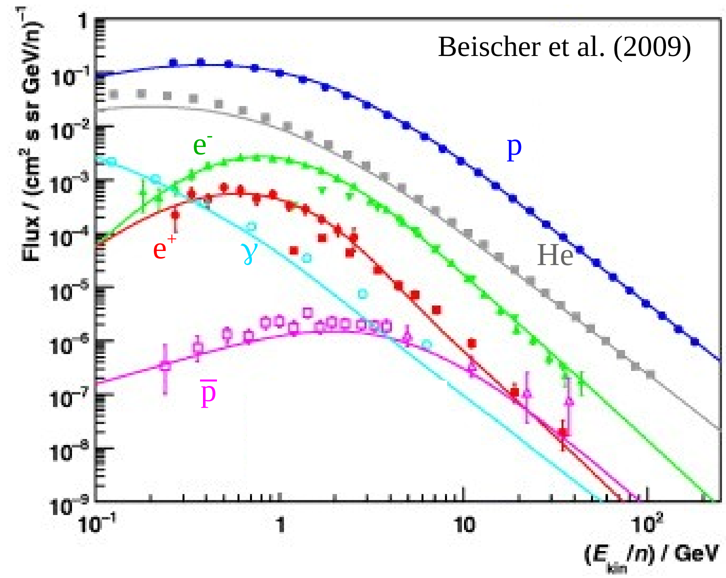
Simulation of 10 showers (300 GeV protons)

→ larger transverse momentum transfers, larger fluctuations

Detection techniques (using Earth’s atmosphere)

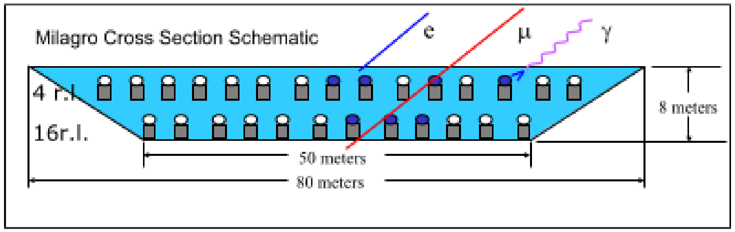


Goal
- Energy of the primary particle
- Direction of the primary particle
- Primary particle nature

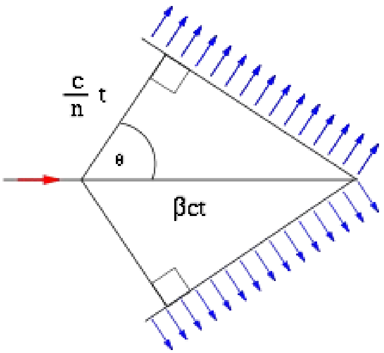


Obviously, depends on
- Particle nature
- Particle energy
- Particle spectrum

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

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

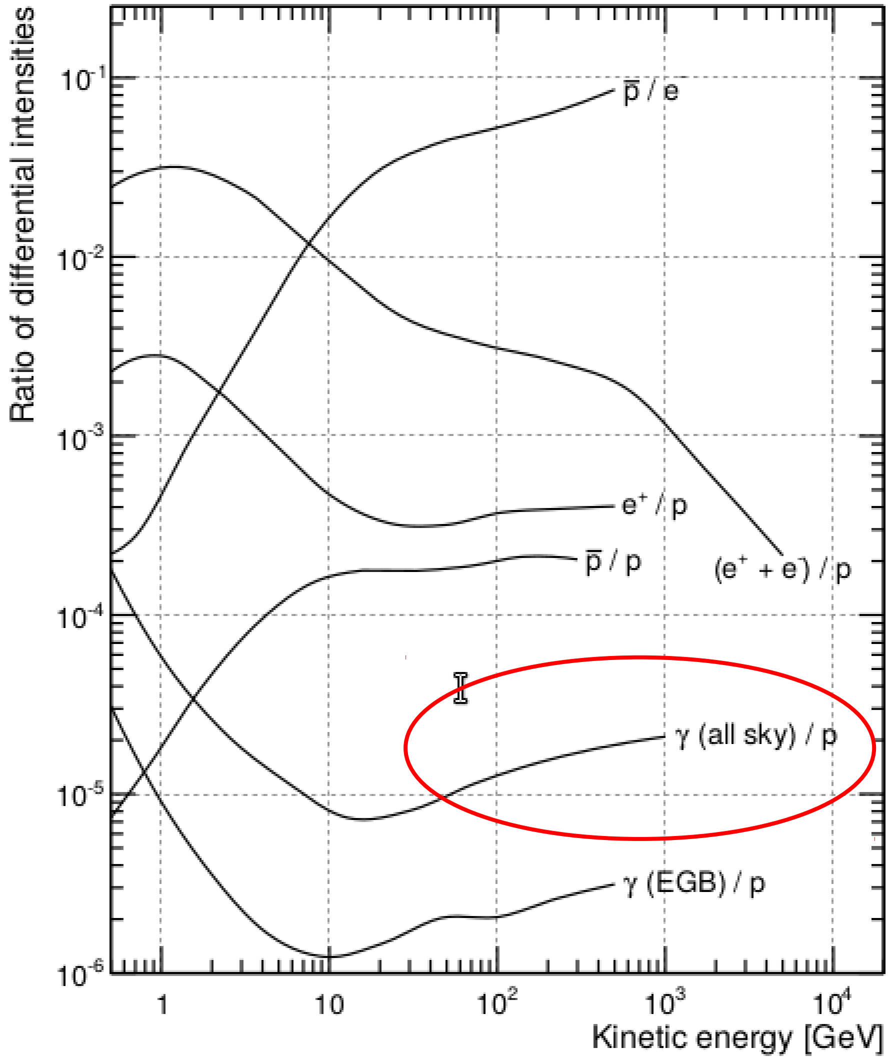
Motivation

→ Ground and satellite γ-ray detectors

→ Important experimental aspects to keep in mind

→ Research activities in a collaboration

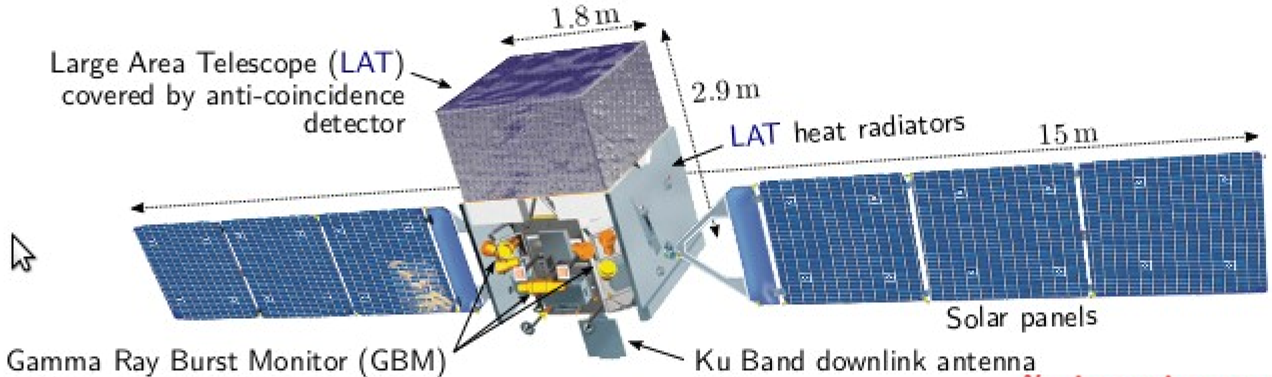
Rejection factor is crucial for gamma-rays

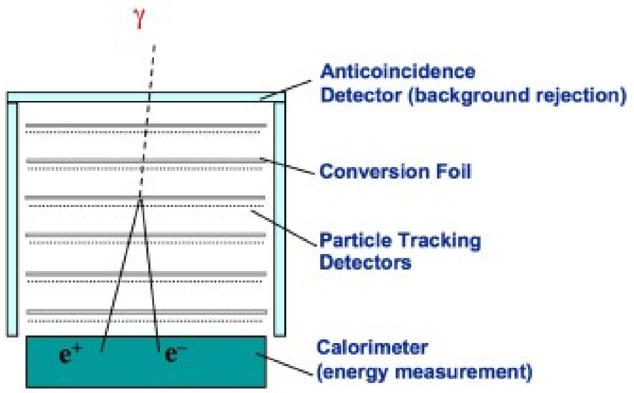


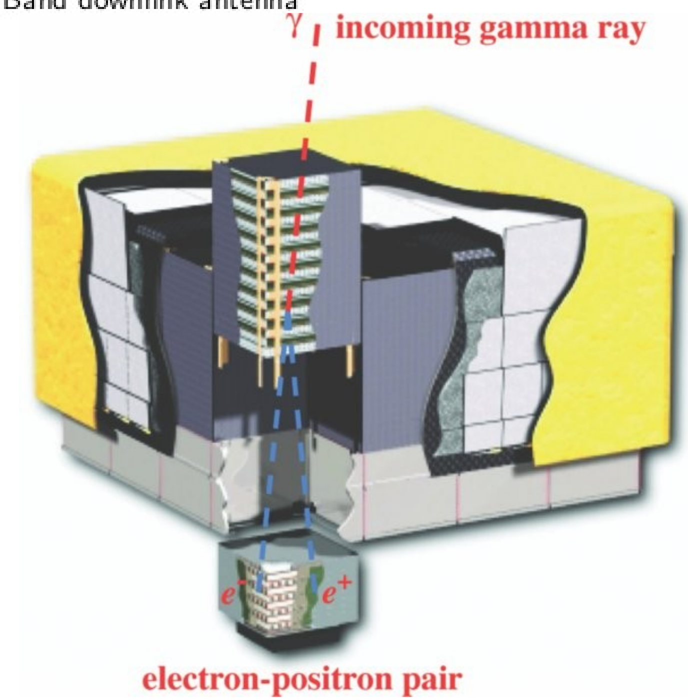
Question: How can you reduce the background in space/ground detector?

Fermi 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

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

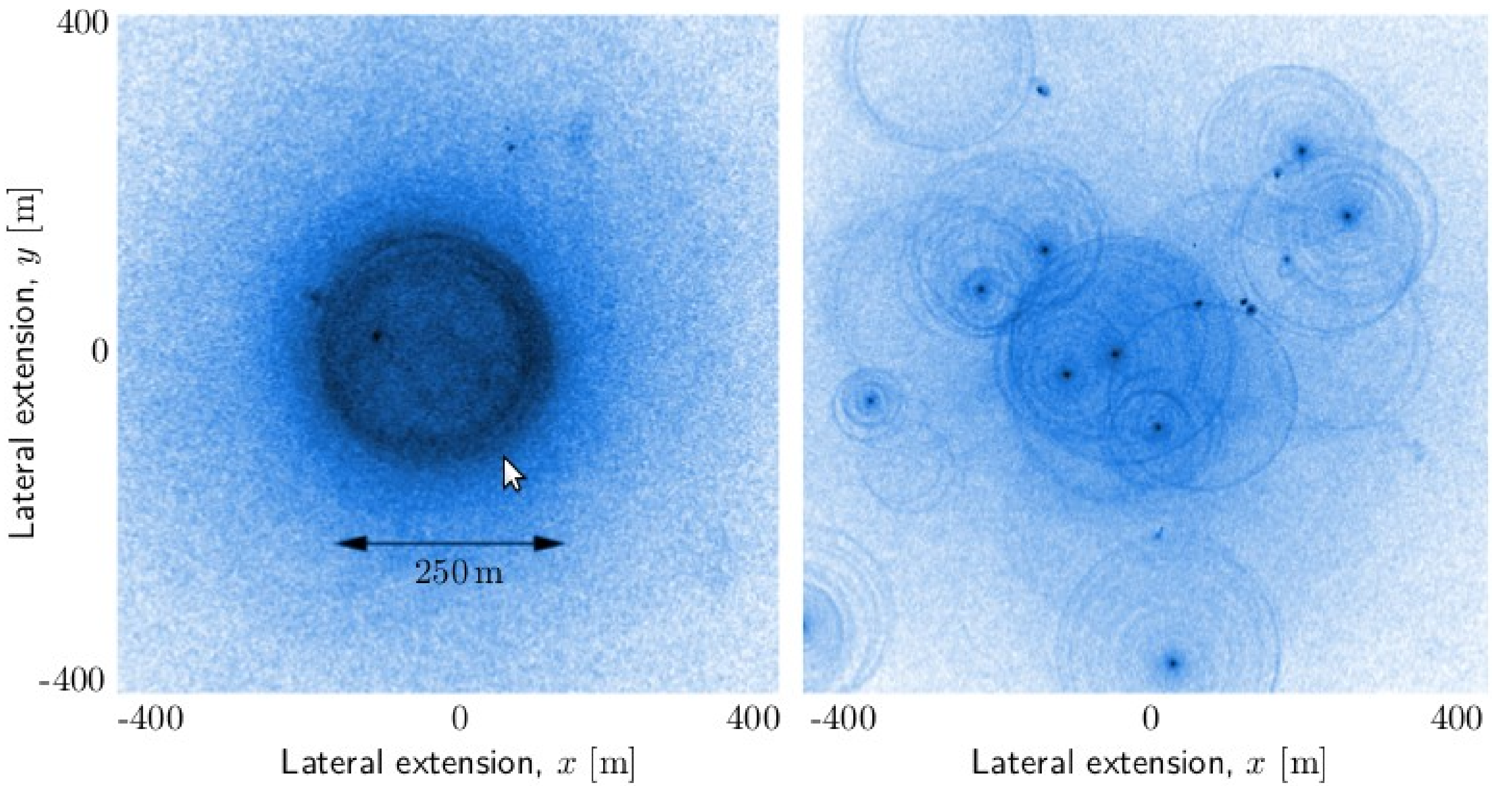
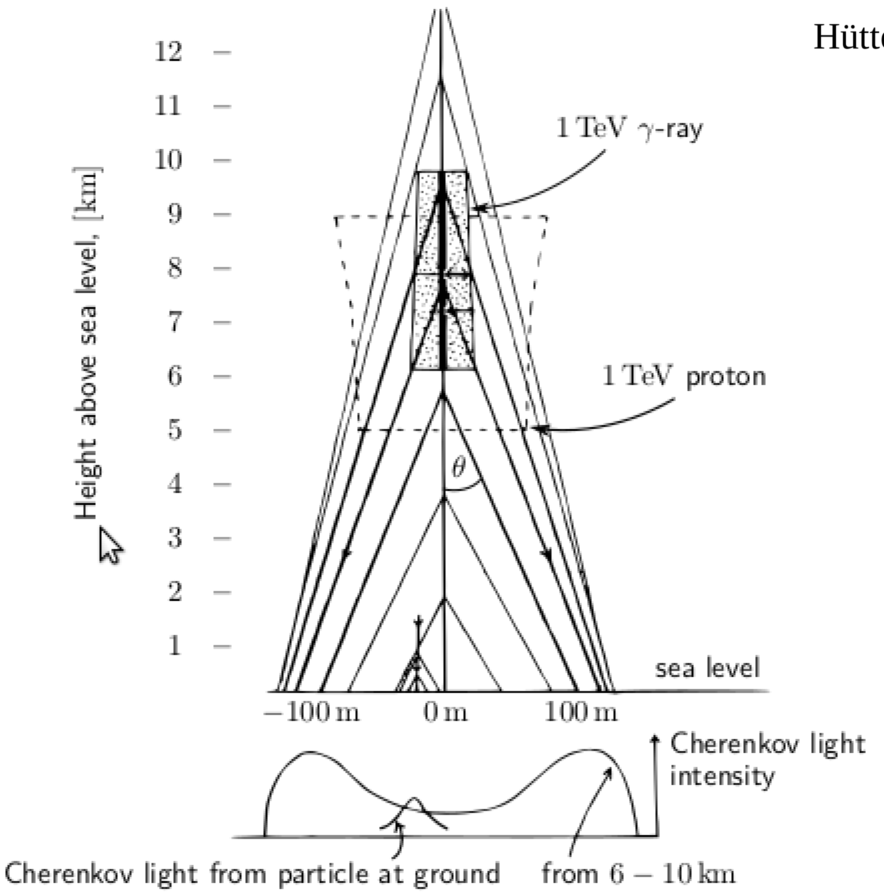
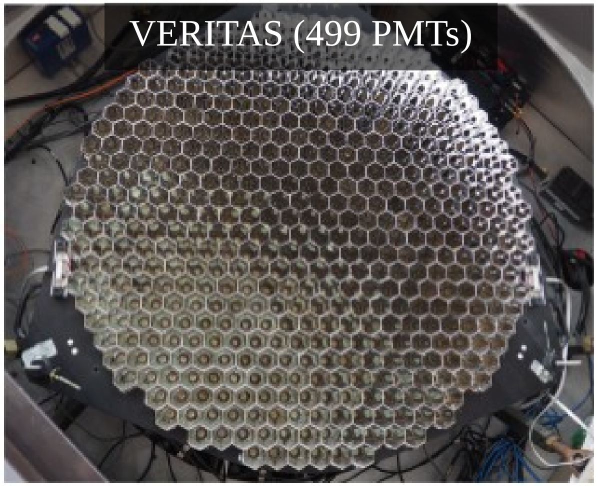


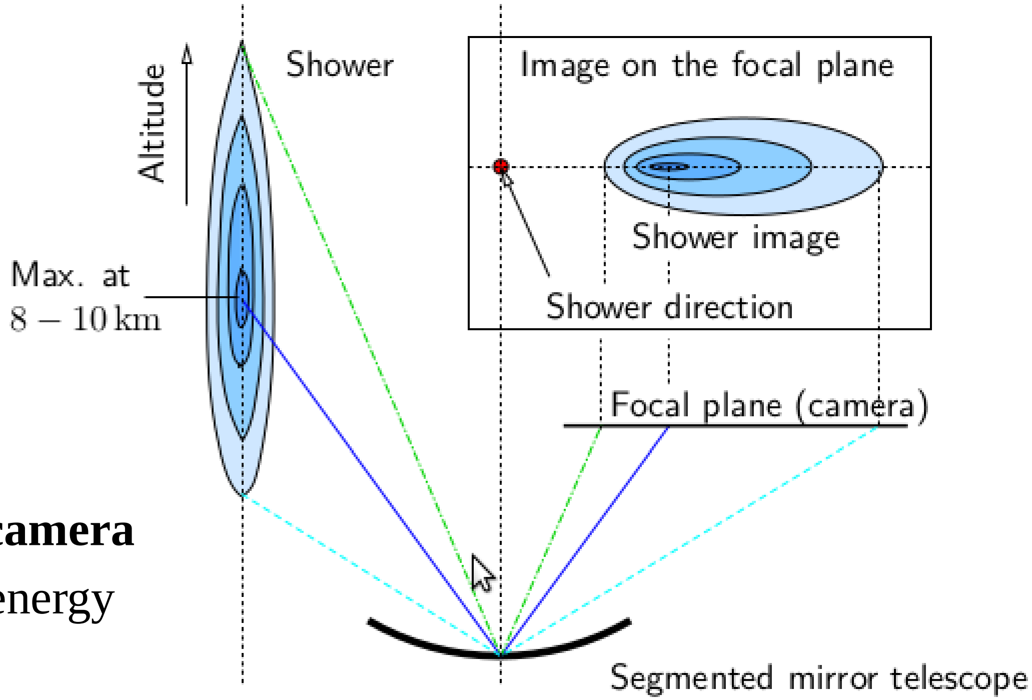
Figure 3.6.: Comparison between the time-integrated Cherenkov light pool at ground level of an electromagnetic air shower (*left*; triggered by a 300 GeV primary γ-ray, like in Figure 3.4) and a hadronic air shower (*right*; initiated by a 1 TeV proton, like in Figure 3.4). Both showers approximately produce the same amount of Cherenkov light (see text). The figures are obtained by Monte-Carlo (MC) simulations of the showers and the showers' Cherenkov 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

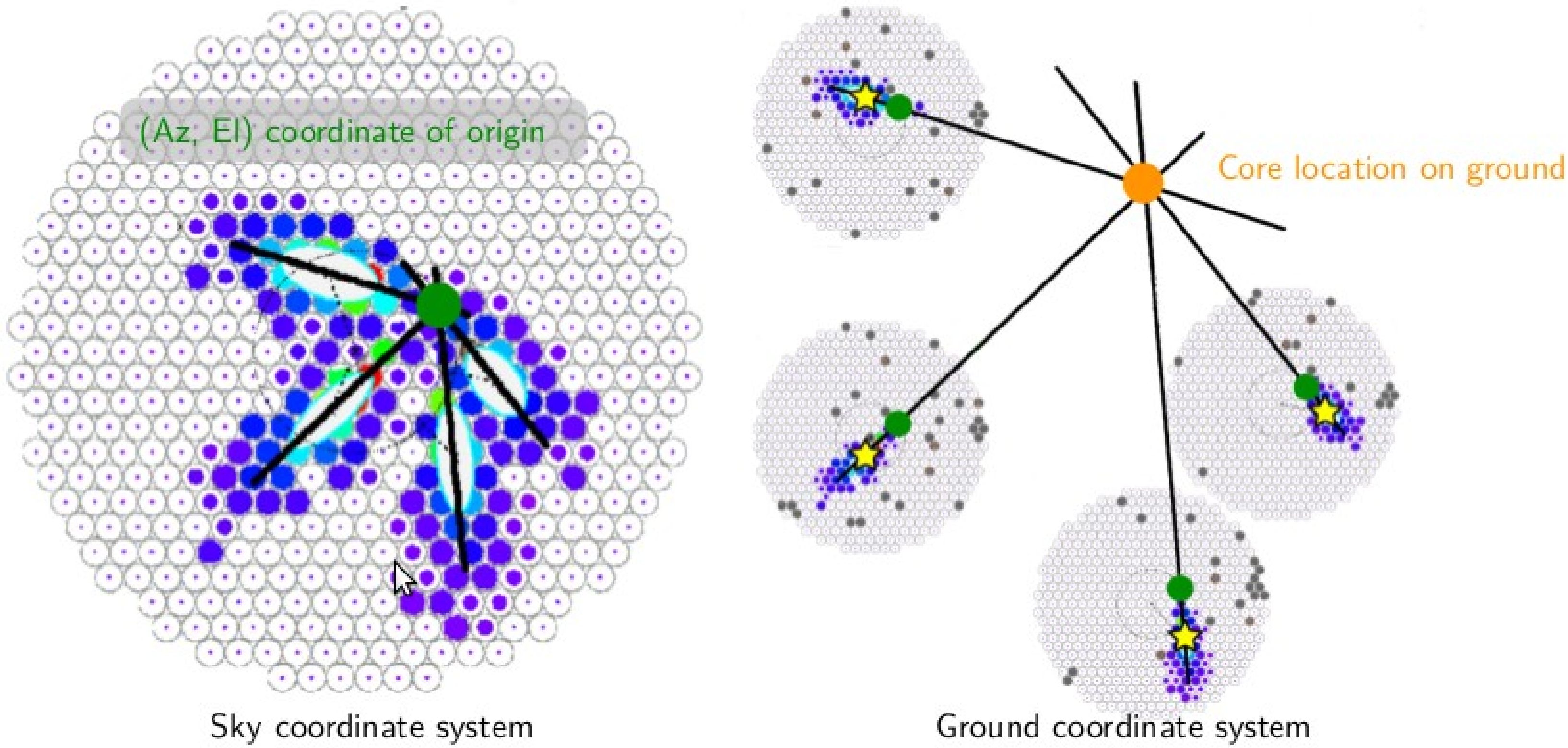
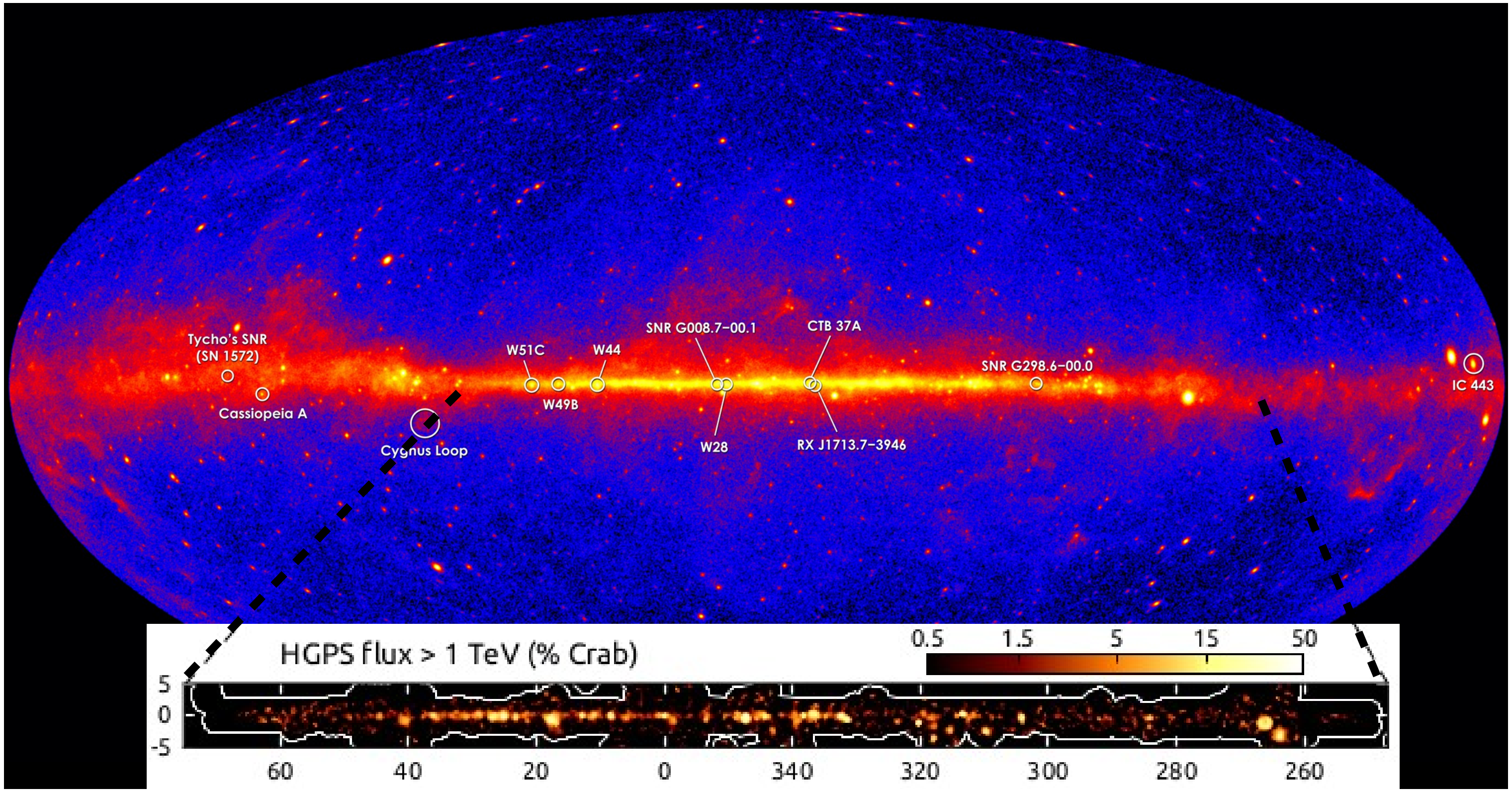


Figure 3.10.: Stereoscopic reconstruction of the air shower origin in the sky (*left*) and the impact point of the shower axis on the ground (*right*). The shower direction (green point on the left) is obtained as intersection of the major semiaxes of the shower ellipses of all images in the same camera 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

Many crucial notions not covered...



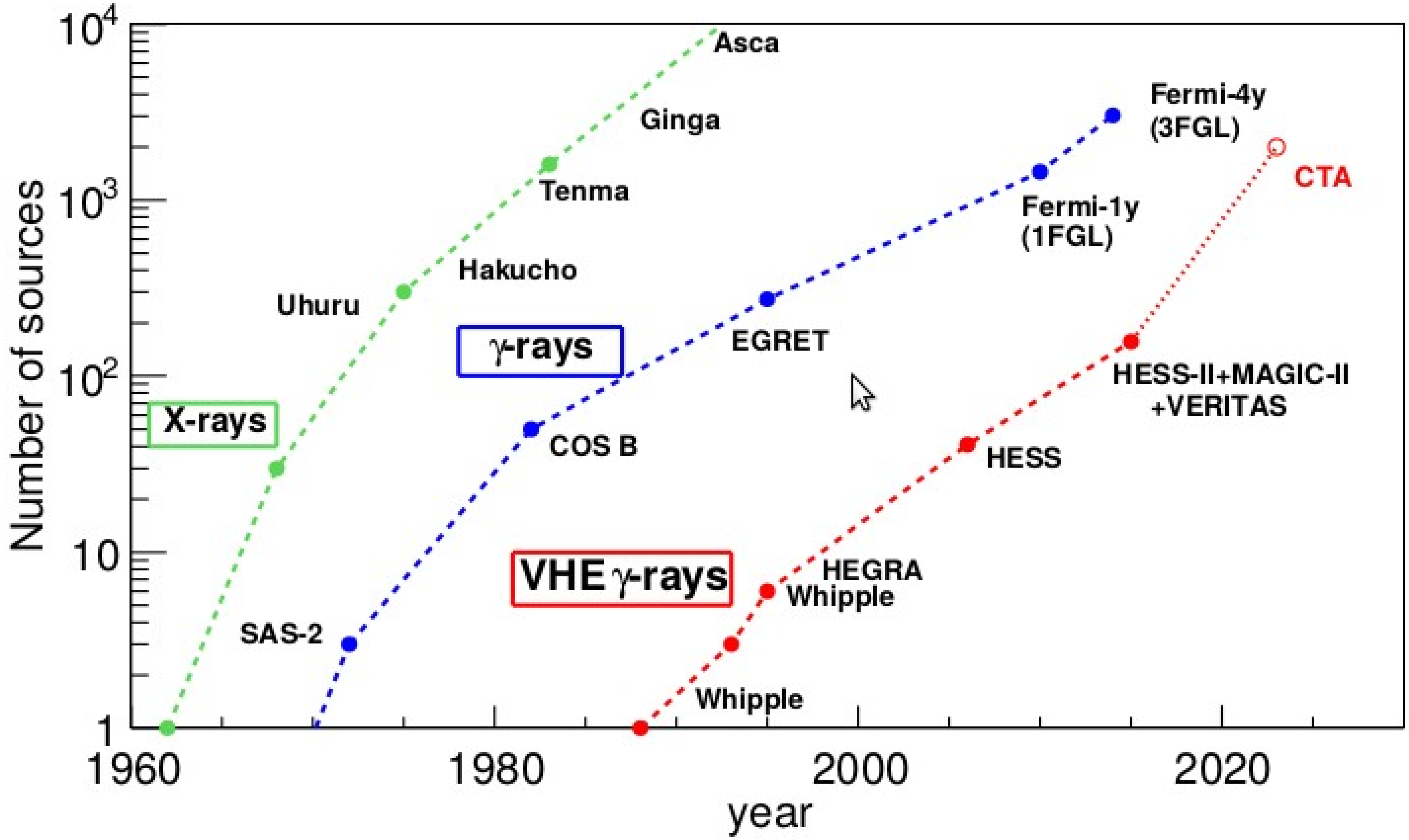
Question: how would you explain the difference between Fermi-LAT and H.E.S.S. coverages (first light ~10 years ago for both)?

→ 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

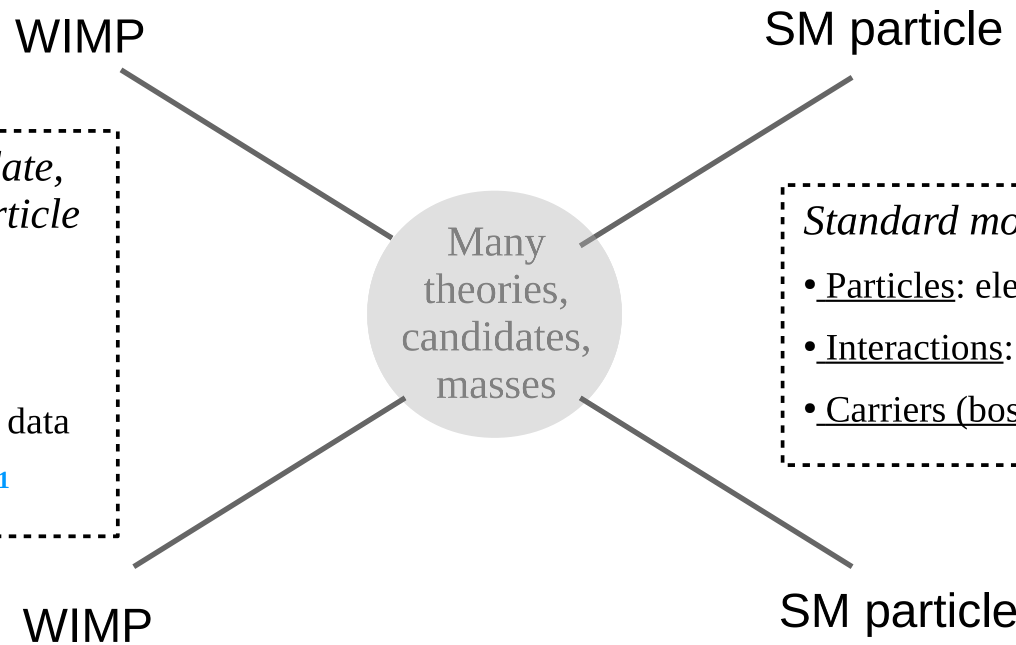
Schematic view of interactions

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

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

→ 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...

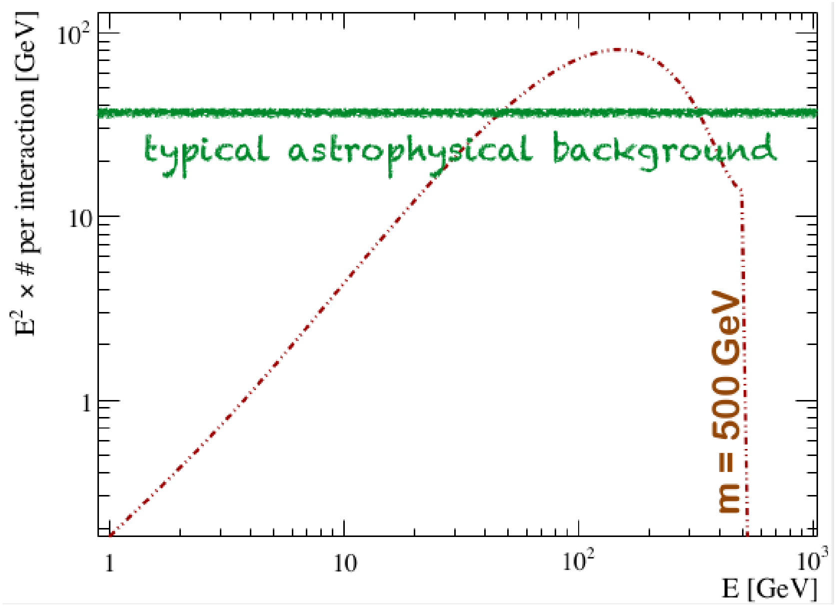
Limit on DM annihilation cross-section <σv>

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

Particle physics

Weakly Interacting
Massive Particles
$m_{WIMP} \sim 0.1 - 100$ TeV

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



Dark matter-induced signal strength

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

Particle physics

Astrophysics

Weakly Interacting
Massive Particles
$m_{WIMP} \sim 0.1 - 100$ TeV

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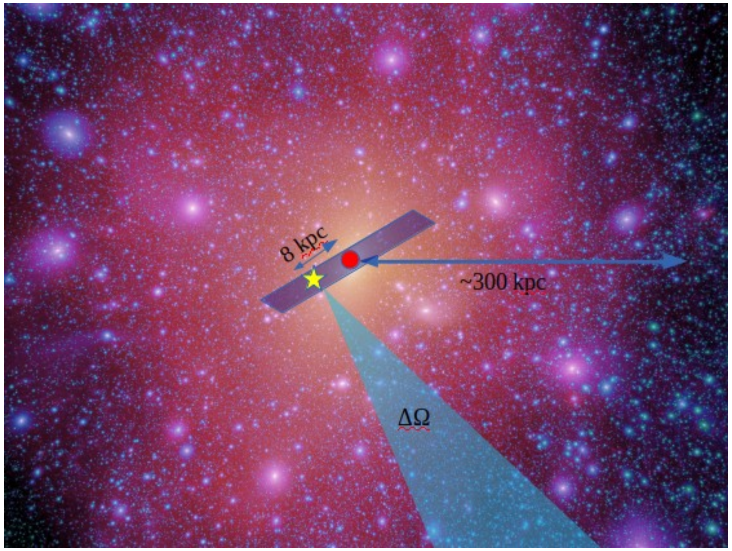
From numerical
simulations or data

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



Question: what target would you pick?

Dark matter-induced signal strength

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

Particle physics

Astrophysics

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Massive Particles
m $_{WIMP}$ ~ 0.1 – 100 TeV

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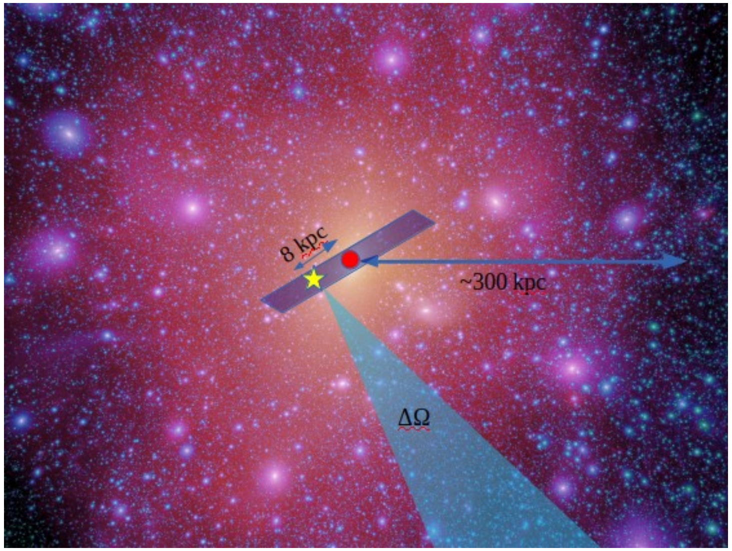

Question: what target would you pick?

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

Dark matter-induced signal strength

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

Particle physics

Astrophysics

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Massive Particles
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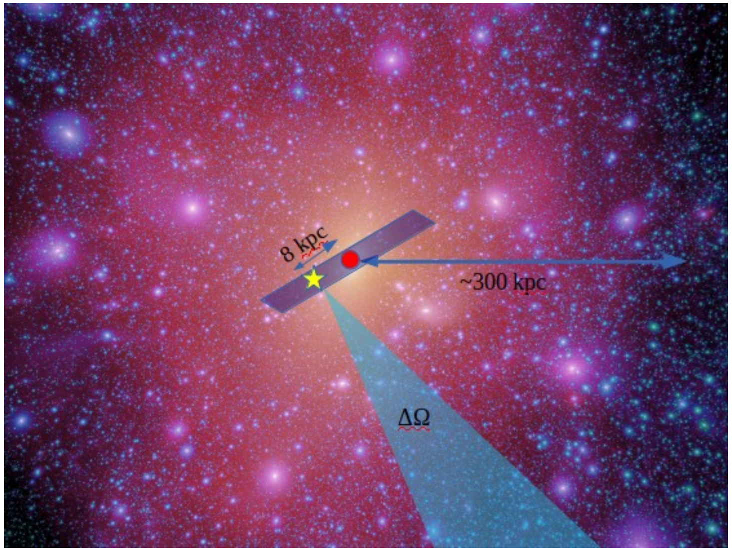
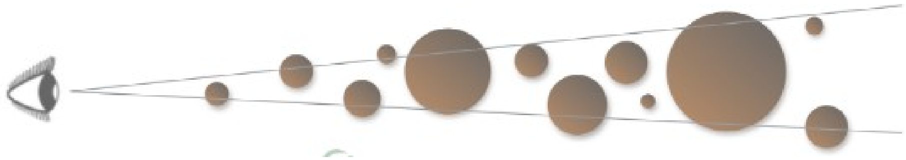


Question: how does the signal skymap look like?



Dark matter-induced signal strength

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

Particle physics

Astrophysics

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From numerical simulations or data

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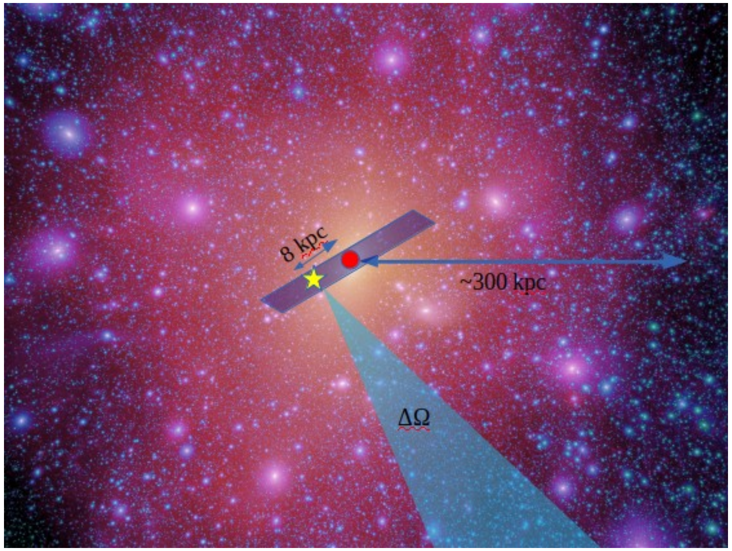
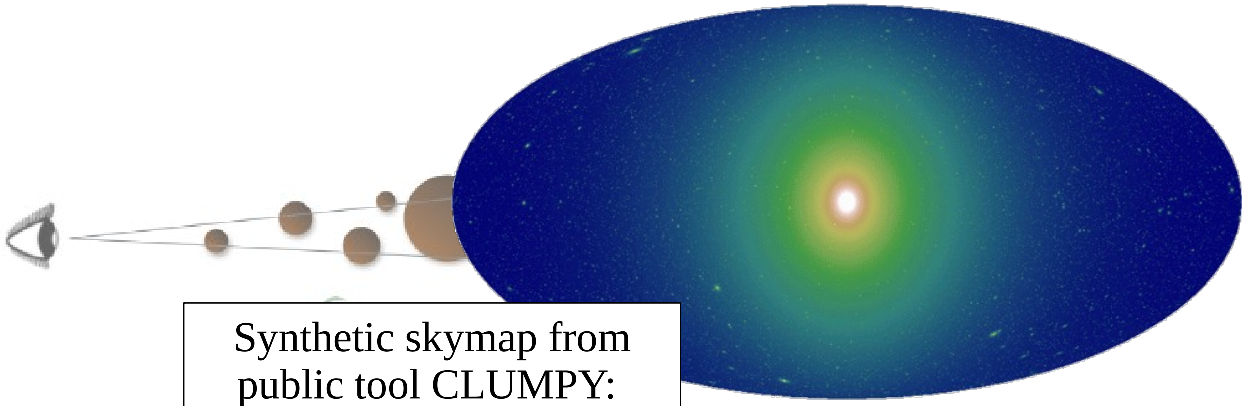
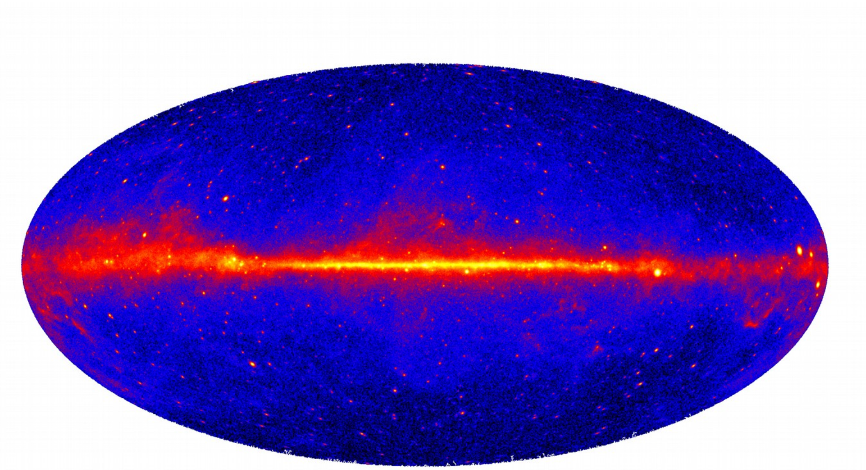




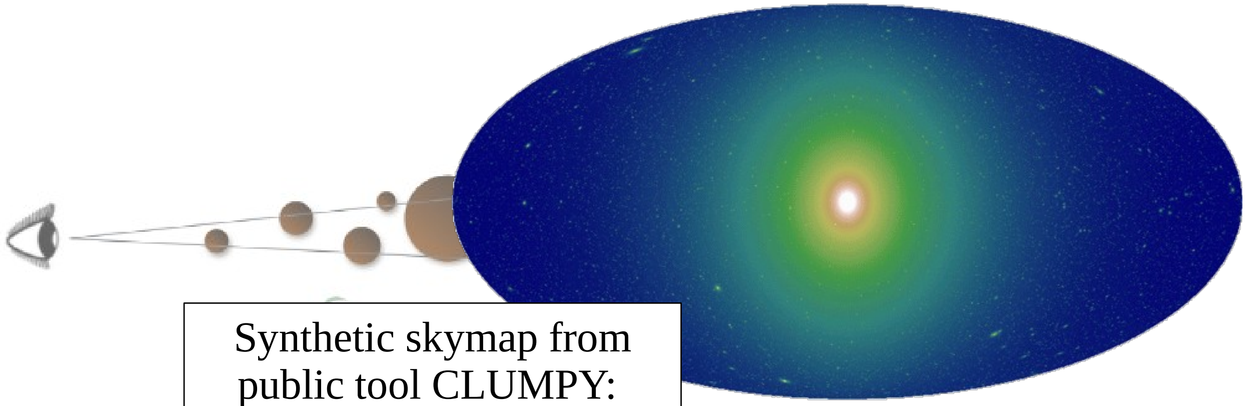
Synthetic skymap from public tool CLUMPY:
http://lpsc.in2p3.fr/clumpy

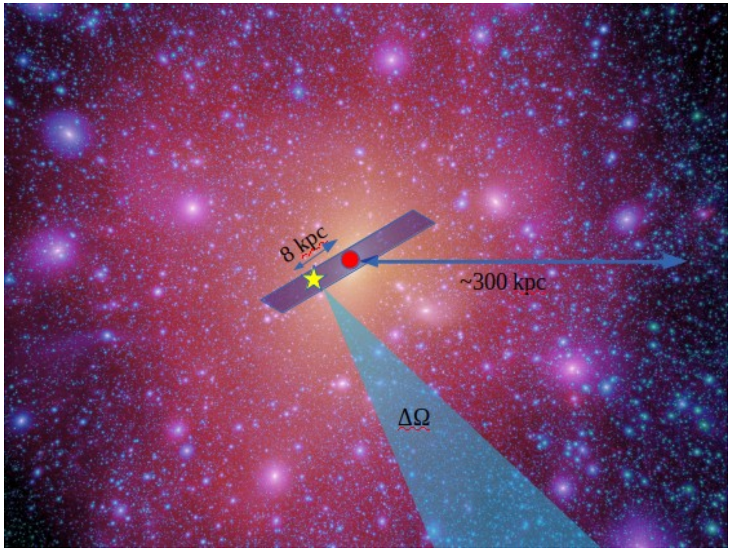
Dark matter-induced signal strength

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



vs





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Dark matter-induced signal strength

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

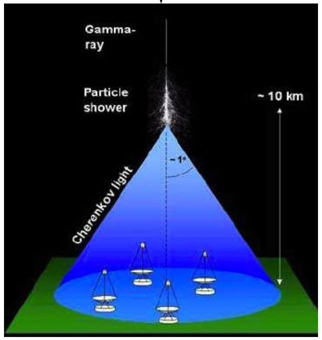
Instrumental sensitivity — Particle physics — Astrophysics

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

??

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

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

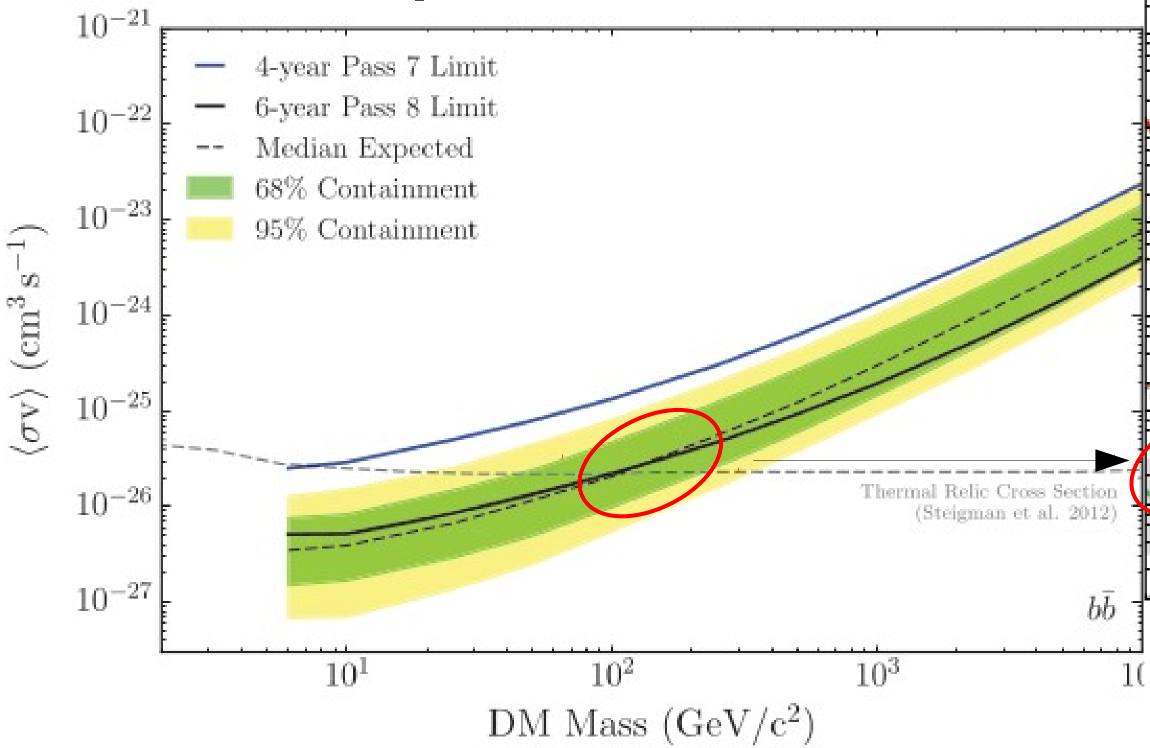
Exclusion plots: Fermi-LAT and CTA

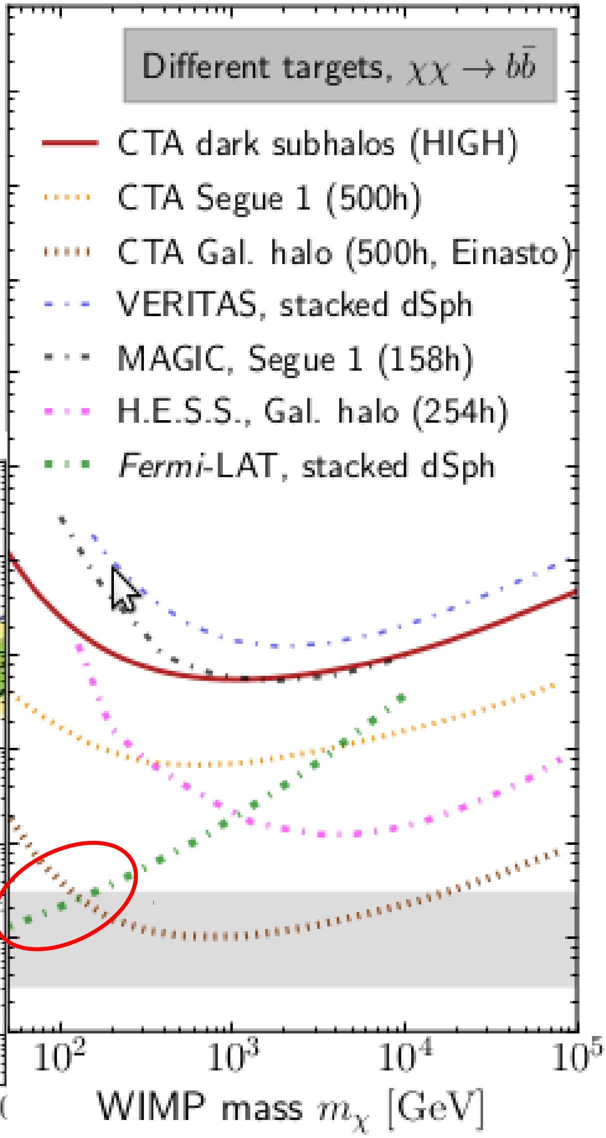
$$\langle \sigma_{\rm ann} v \rangle \propto m_\chi^2 \times J(\alpha_{\rm int}) \times \text{Sensitivity} \times \frac{dN^{pp}}{dE}$$

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

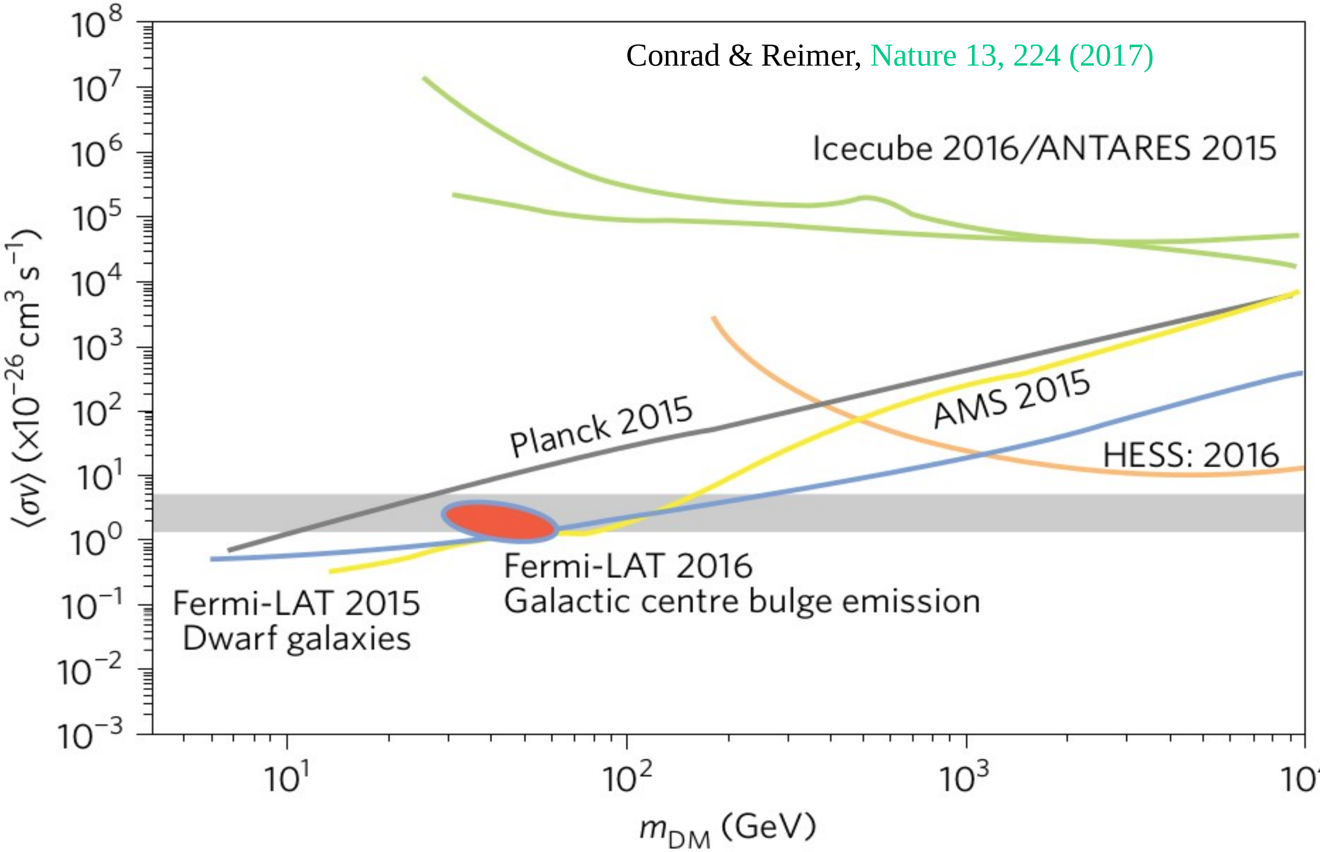
Ackermann et al. (2014, 2015)
[15 dSphs combined, 70 months]

Hütten et al. (2016)
[CTA prospects]





Comparison/complementarity of indirect detection targets



→ γ-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