High energy gamma-ray astronomy

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Thanks to material from R. Ong, W. Hofmann, L. Stawarz, J. Holder, K. Bechtol, and the MAGIC collaboration

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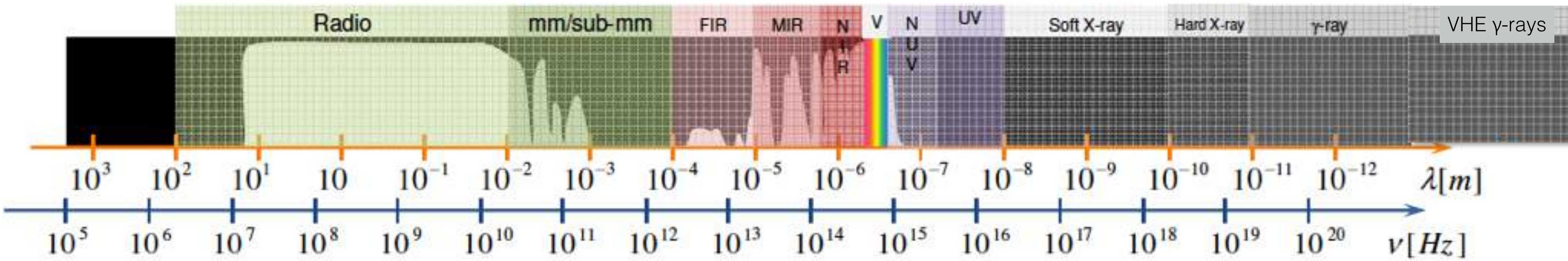
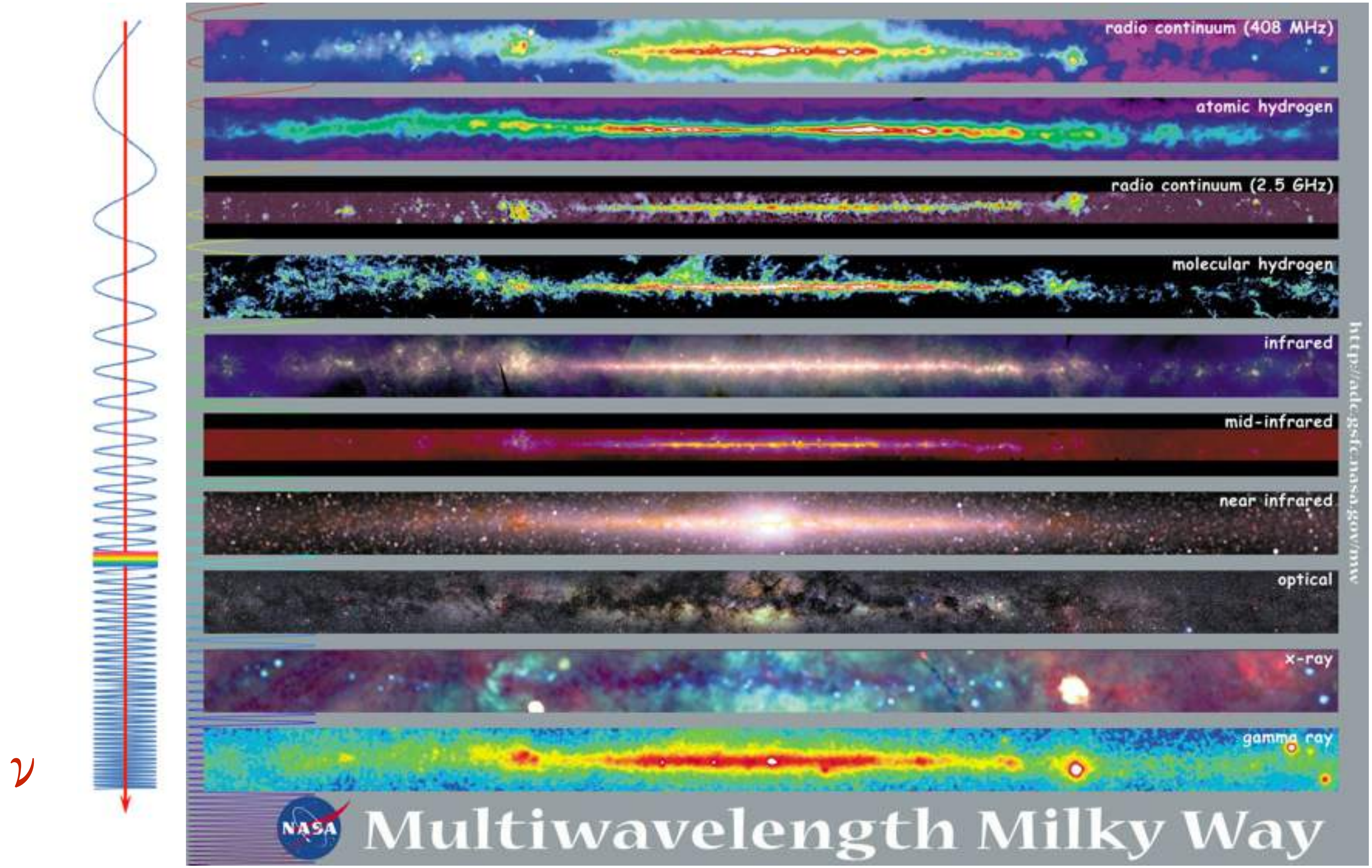
1. Multiwavelength sky

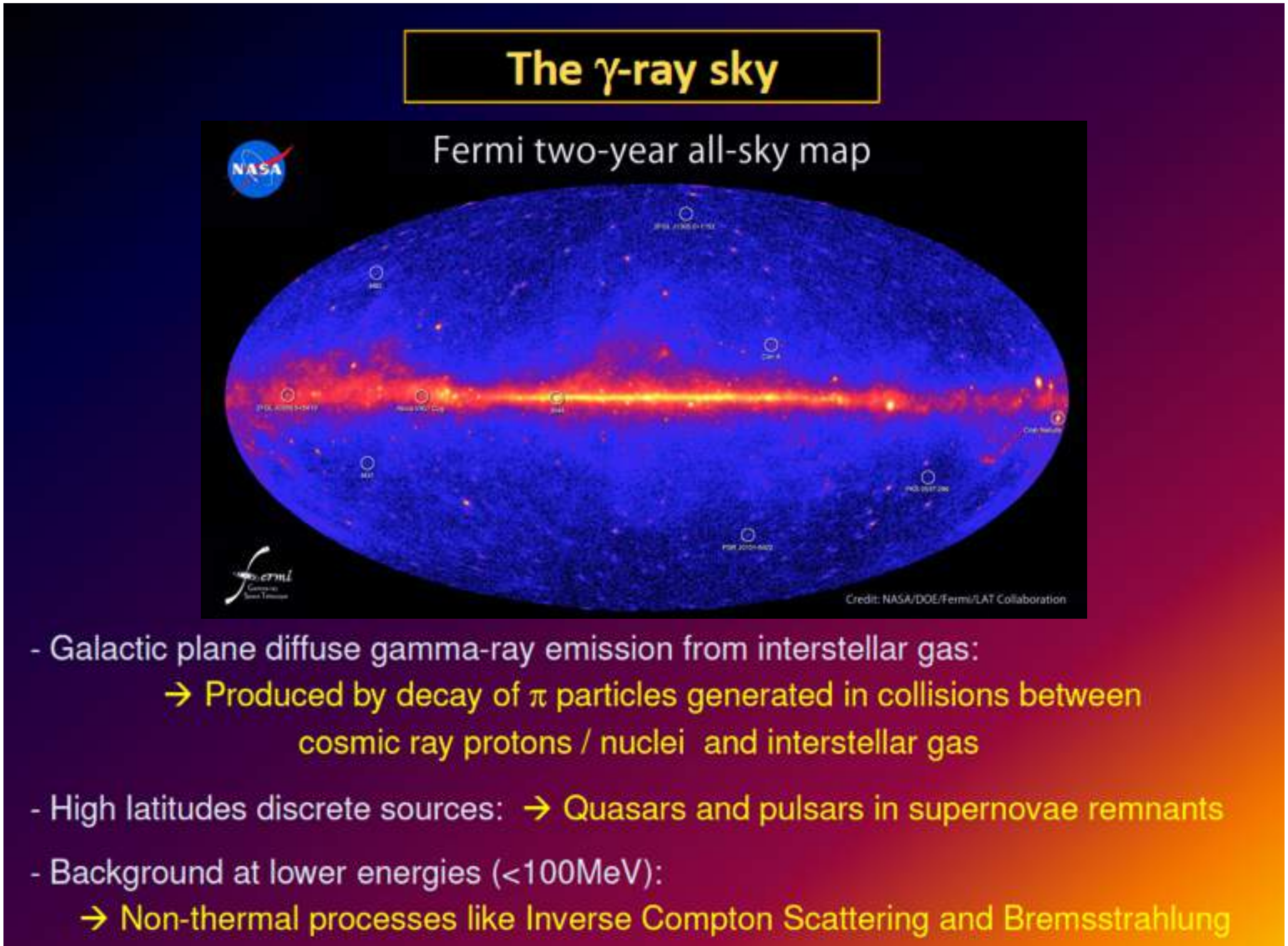


Radio	$3MHz \le \nu \le 30GHz$	$100m \ge \lambda \ge 1cm$	$T \sim (10^{-4} \rightarrow 1)K$
mm & submm	$30GHz \le \nu \le 3THz$	$10mm \ge \lambda \ge 0.1mm$	$T \sim (1 \rightarrow 100)K$
Infrared	$3THz \le \nu \le 300THz$	$100\mu m \ge \lambda \ge 1\mu m$	$T \sim (10^{2} \rightarrow 10^{4})K$
Optical	$3\times10^{14}\,Hz \le \nu \le 10^{15}\,Hz$	$1\mu m \ge \lambda \ge 300nm$	$T \sim 4\times10^{4}\,K$
Ultraviolet	$10^{15}\,Hz \le \nu \le 3\times10^{16}\,Hz$	$300nm \ge \lambda \ge 10nm$	$T \sim (10^{5} \rightarrow 10^{6})K$
X-ray	$3\times10^{16}\,Hz \le \nu \le 3\times10^{19}\,Hz$	$10nm \ge \lambda \ge 0.01nm$	$T \sim (10^{6} \rightarrow 10^{9})K$
γ-ray	$\nu \ge 3\times10^{19}\,Hz$	$\lambda \le 0.01nm$	$T \ge 10^{9}\,K$

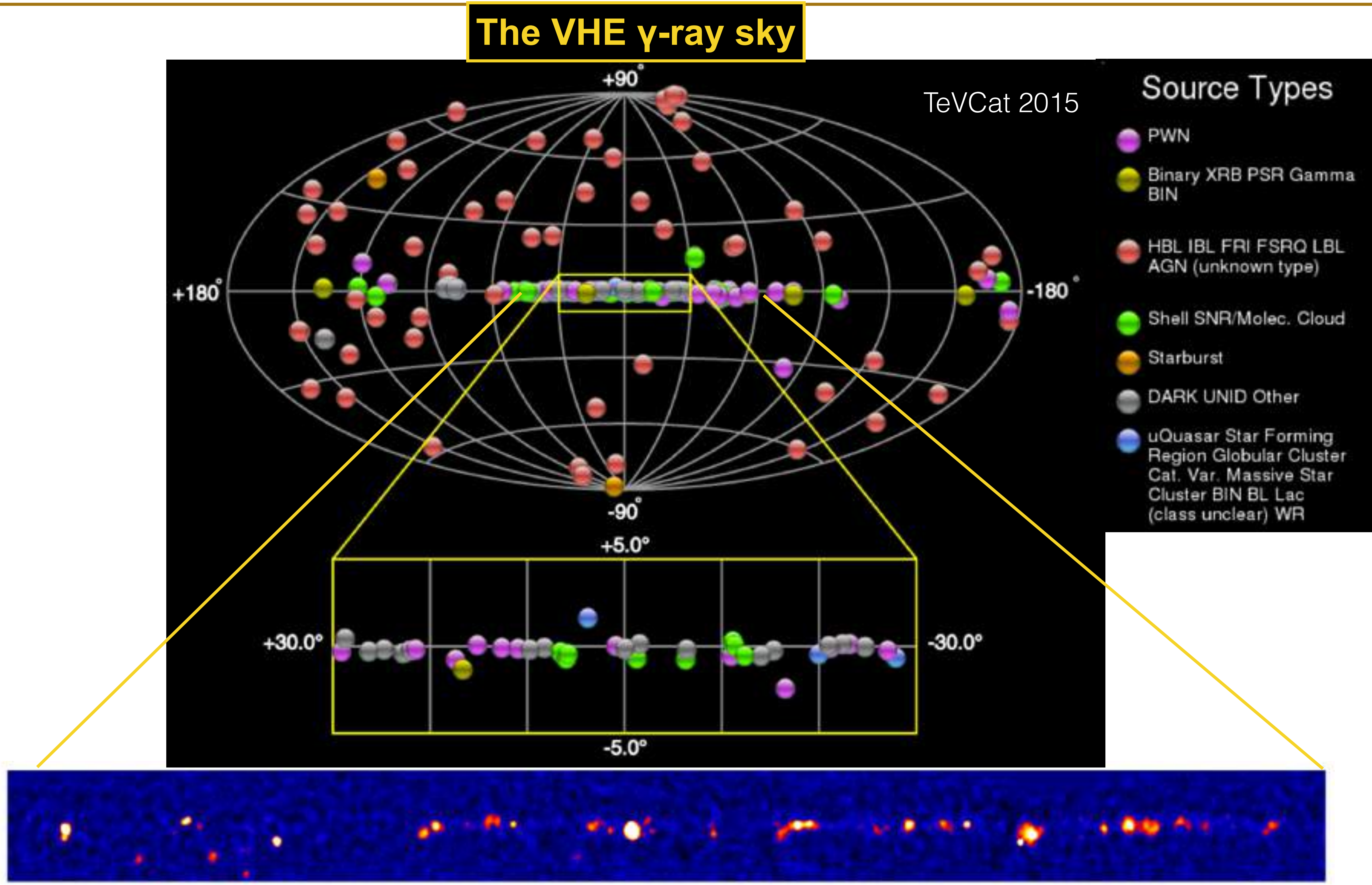
1. Multiwavelength sky



1. Multiwavelength sky



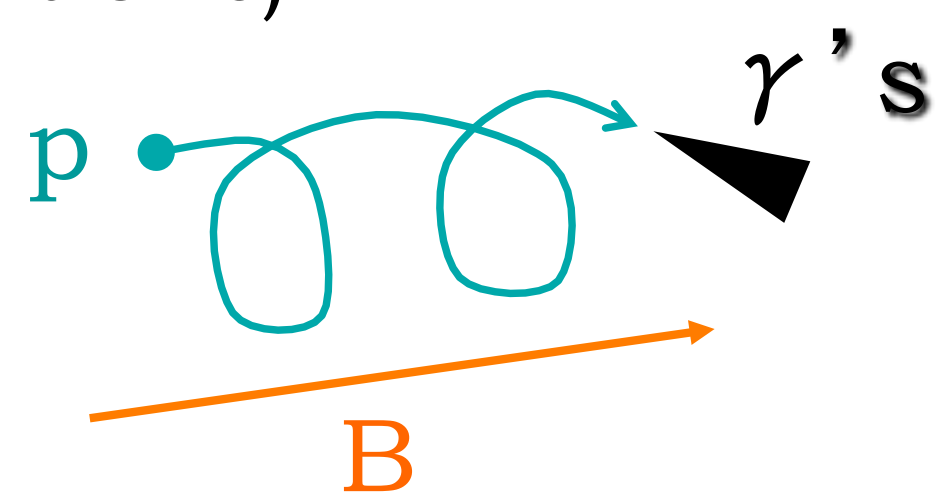
1. Multiwavelength sky



2. How to produce gamma rays?

From protons

- **Pion decay**
  - Accelerated protons (p) interact with matter
  - $p\ \ p \rightarrow X + \pi_0 \rightarrow \gamma\ \ \gamma$
- **Proton Synchrotron Emission**
  - Depends on magnetic field strength (not dominant under typical conditions)



2. How to produce gamma rays?

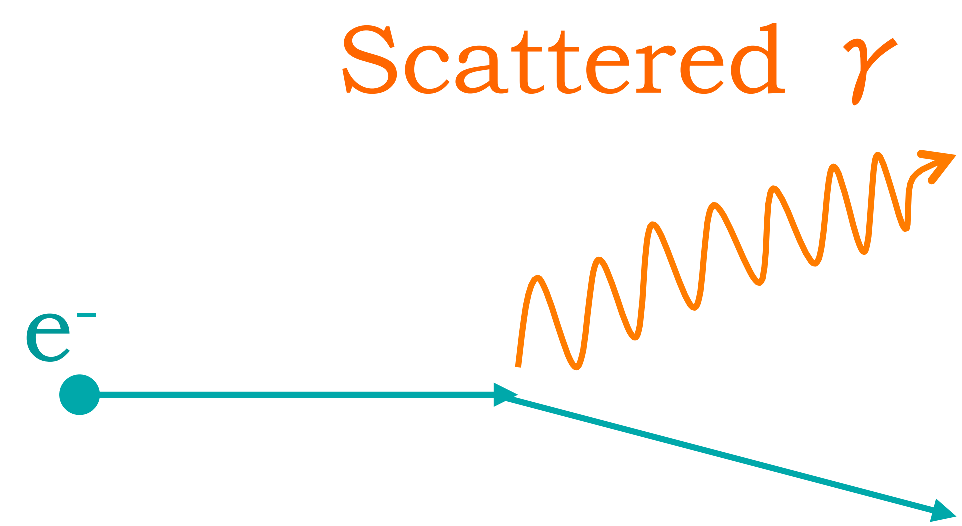
From electrons

- **Inverse Compton Scattering**
  - Collide highly relativistic electrons with photons from stars or the microwave background

$$e^- + \gamma_{\text{Low E}} \rightarrow e^- + \gamma$$

$$E_\gamma \propto (\gamma_{\text{Lorentz}})^2 \, E_{\gamma \text{ low E}}$$

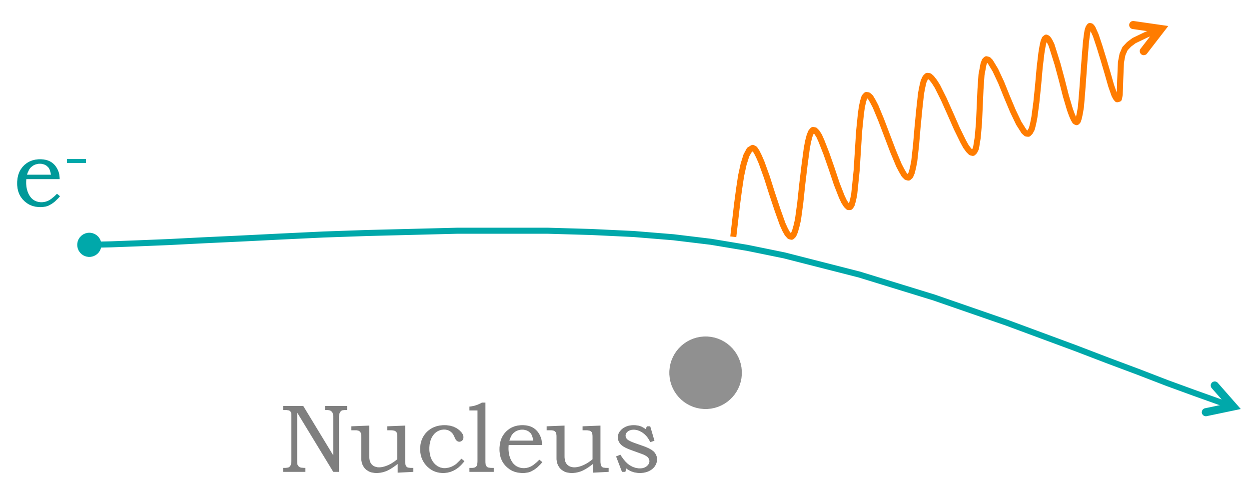
$$\gamma_{\text{Lorentz}} = 1/\sqrt{(1 - v_e^2/c^2)}$$



2. How to produce gamma rays?

From electrons

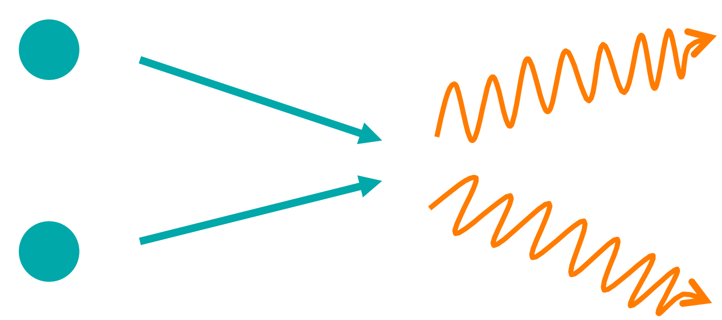
- **Bremsstrahlung** (free-free emission)
  - Electron deceleration by a nucleus
  - Highly relativistic electrons emit gamma rays in atomic or molecular material
  - $\text{Energy}_{\gamma} \sim \text{Energy}_{e}$



2. How to produce gamma rays?

Other ways to produce gamma rays

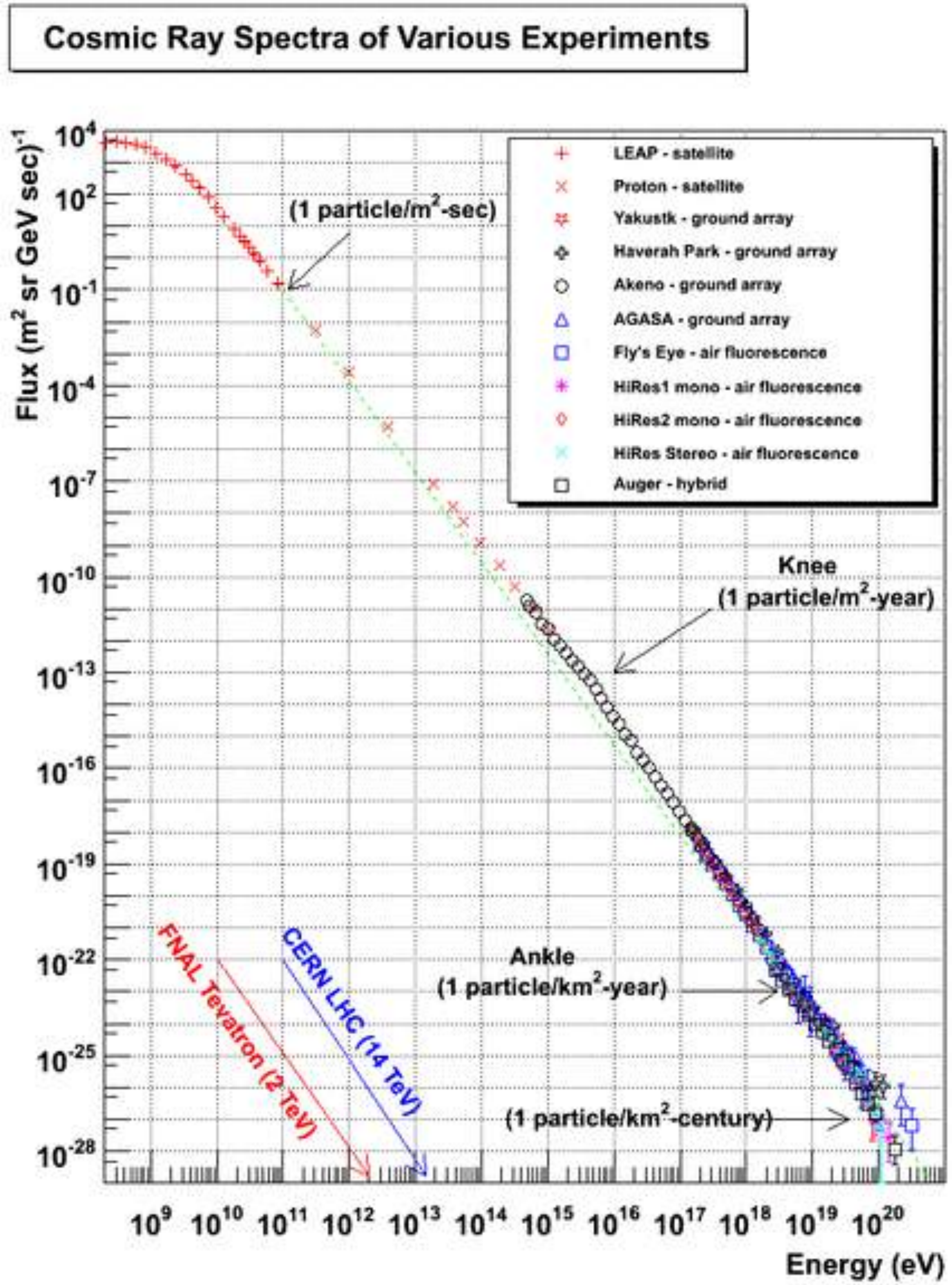
- Topological defects left over from the Big Bang?
  - Hypothesis: Black holes formed with the early Universe decay
- By-product of dark matter interactions?
  - Hypothesis: weakly interacting massive particles (WIMPs) interact to produce gamma rays: DM + DM → $\gamma\ \gamma$



WIMP + WIMP → γ + γ

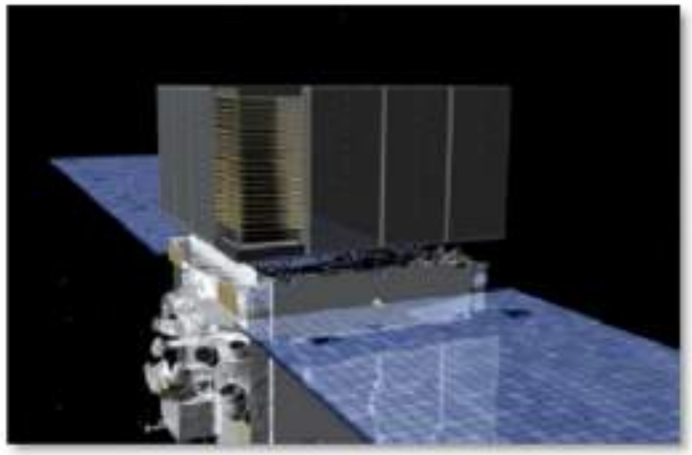
3. How to detect gamma rays?

Victor Hess and his “Flight Ops Team”, 1912

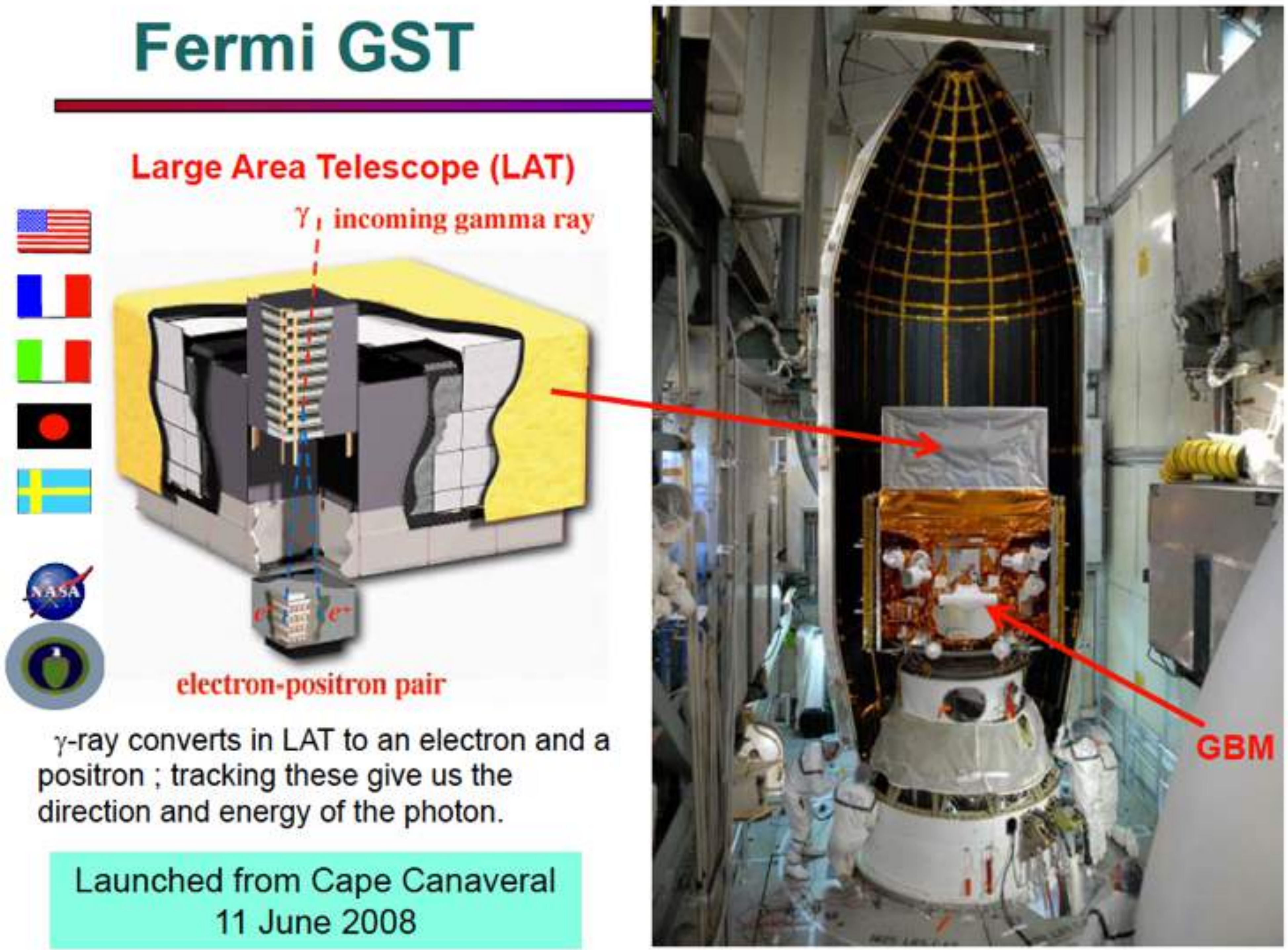


3. How to detect gamma rays?

GAMMA RAY TELESCOPES

Space-based pair production telescopes	Imaging Atmospheric Cherenkov Telescopes	Air shower Arrays
		
0.1 – 100 GeV	50 GeV – 100 TeV	100 GeV – 100 TeV
Small area	Large area	Large area
Background-free	Excellent bg rejection	Good bg rejection
Large field of view	Small field of view	Large field of view
High duty cycle	Low duty cycle	Large duty cycle

3. How to detect gamma rays?



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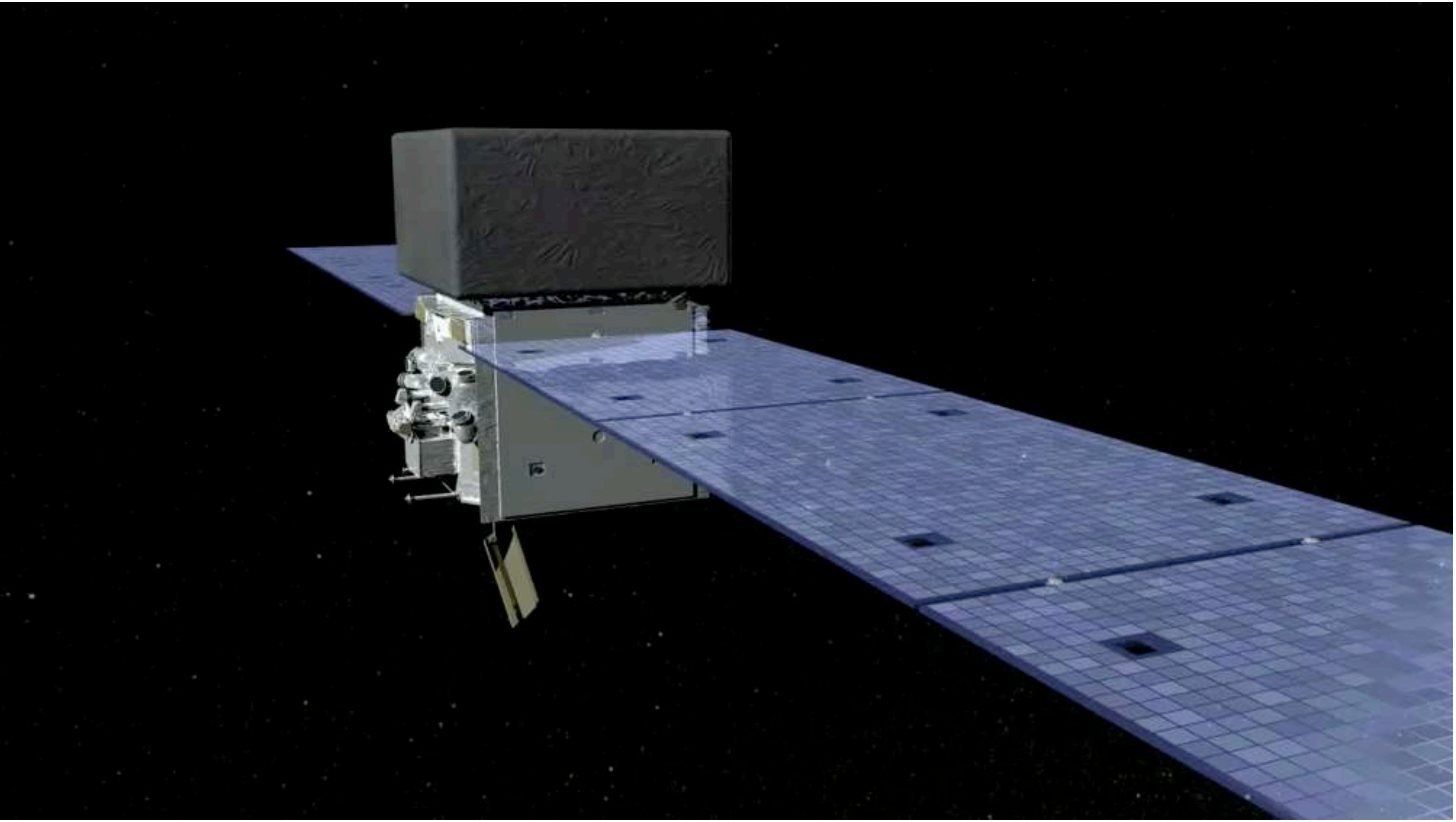

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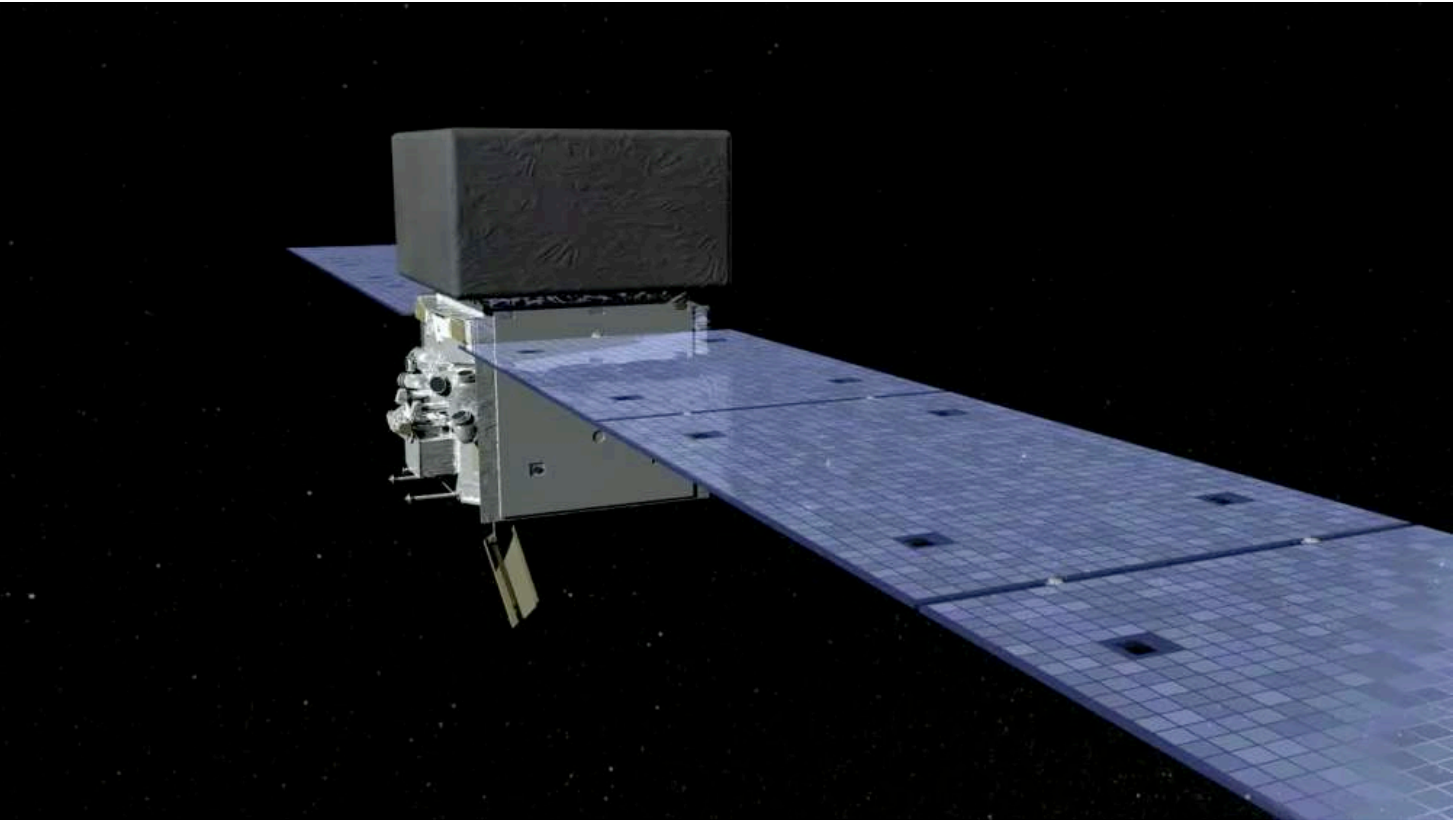
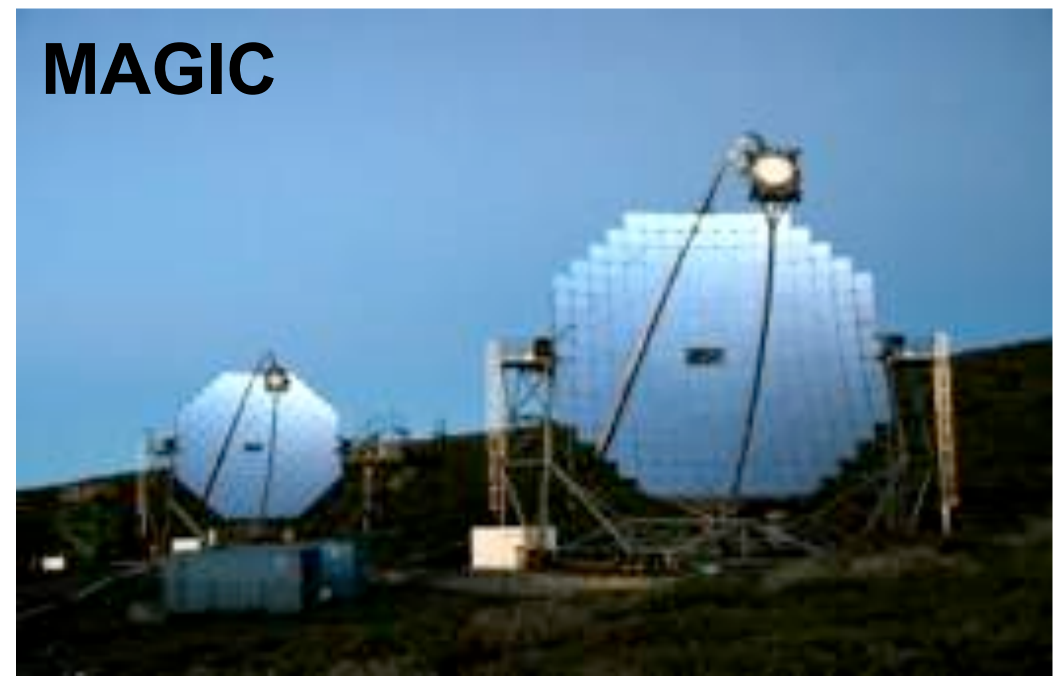


3. How to detect gamma rays?

Imaging Atmospheric Cherenkov Telescopes: The Big Three

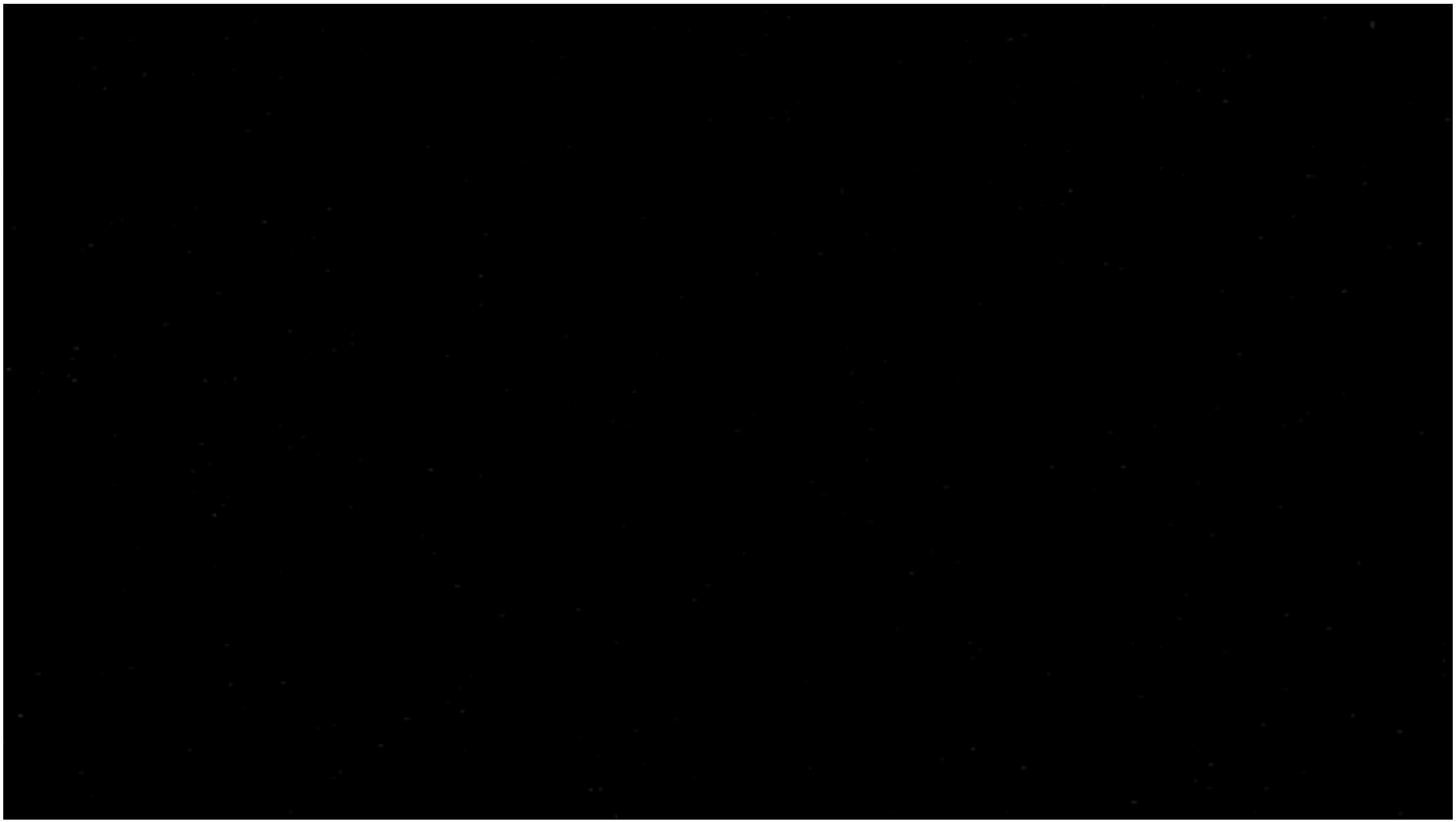


Characteristics of current generation of IACT arrays:

- Energy threshold E = 25 to 100 GeV
- Point-source integral flux sensitivity: 0.5 to 1.0 % of the Crab Nebula flux in 50 h (above 200 GeV, >100 times more sensitive than Fermi-LAT in 1 year)
- Angular resolution < 0.1º
- Energy resolution ≈ 15%

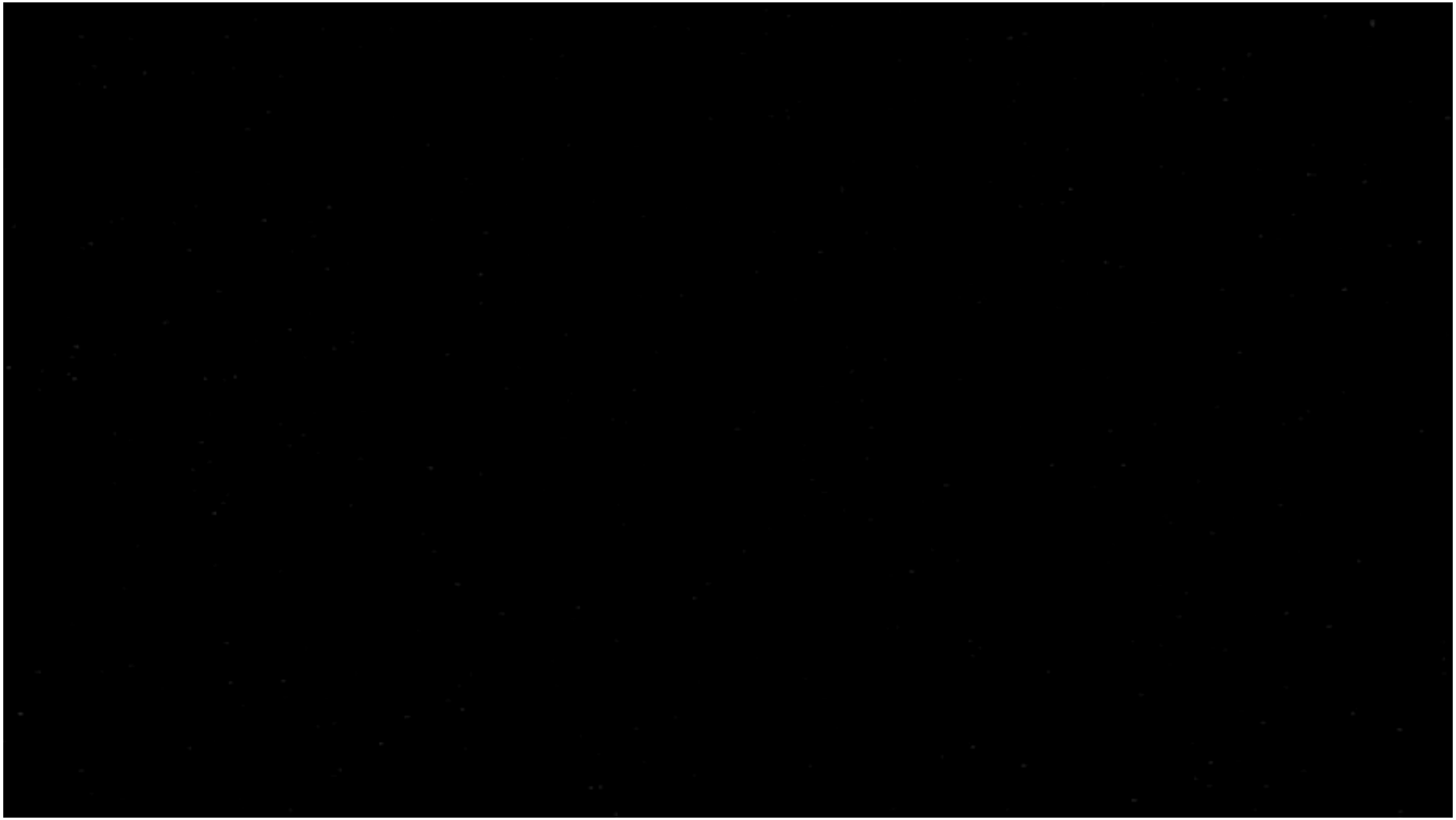
3. How to detect gamma rays?

Atmospheric showers and Cherenkov radiation



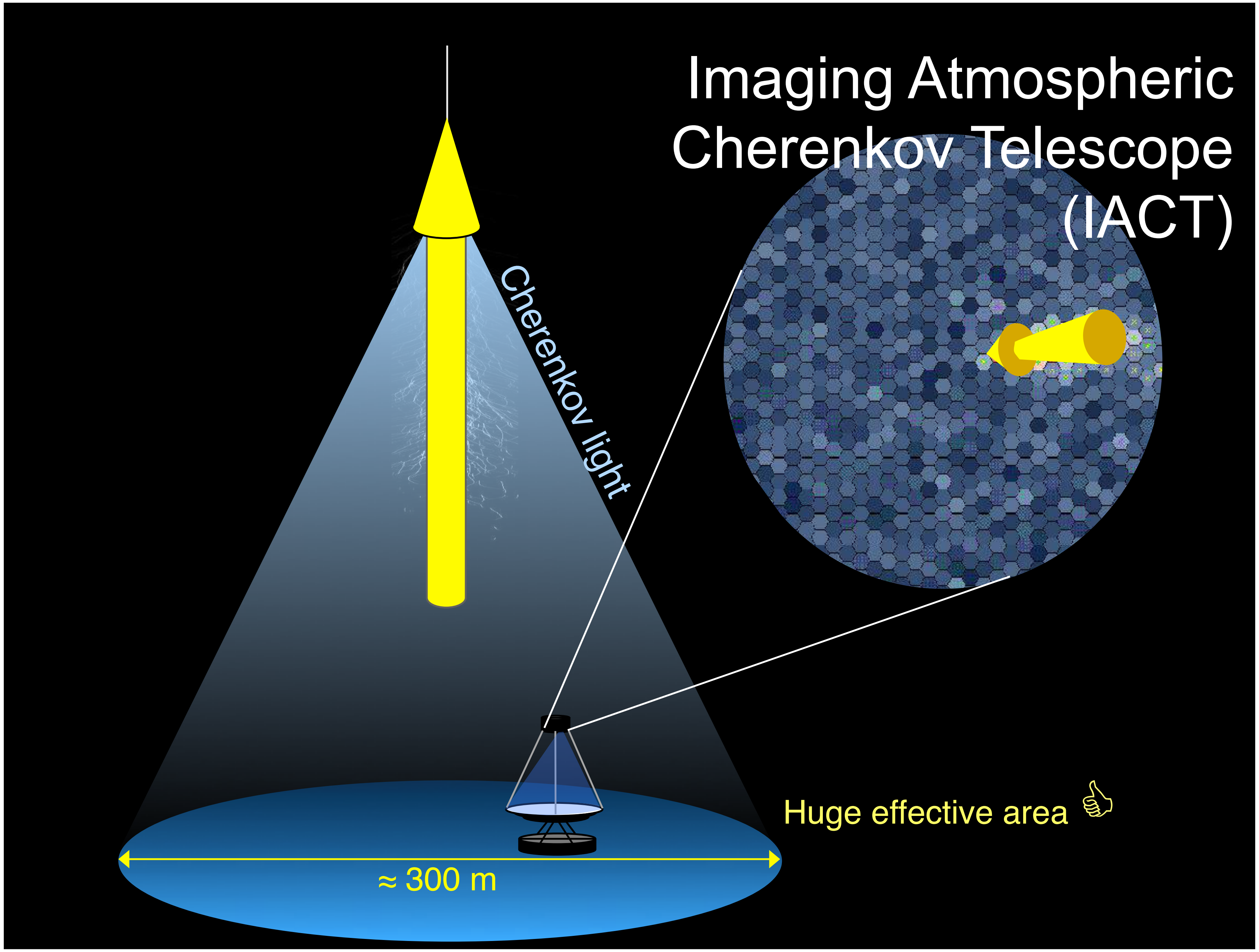
3. How to detect gamma rays?

Atmospheric showers and Cherenkov radiation



3. How to detect gamma rays?

Imaging Atmospheric Cherenkov Telescopes: Detection technique



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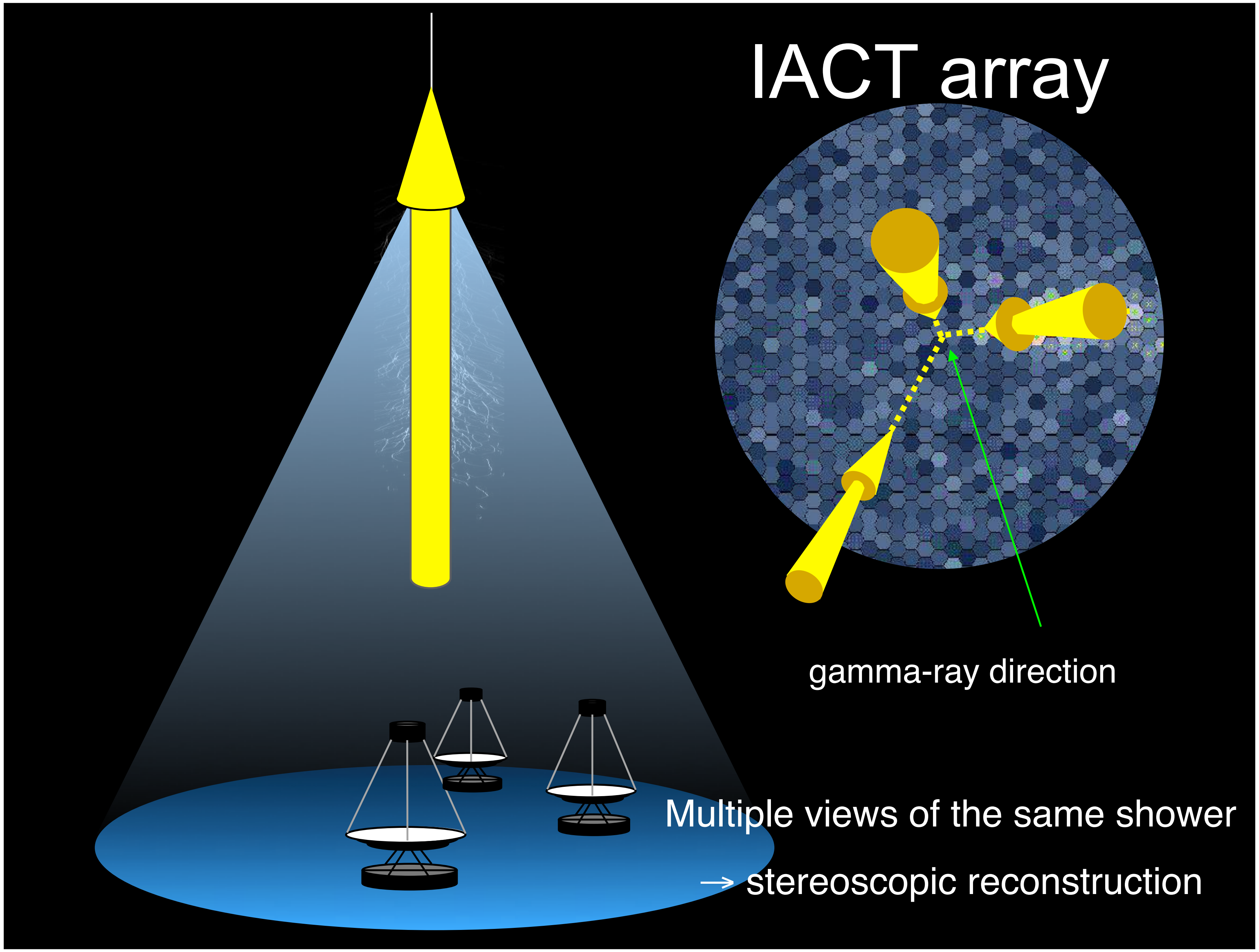
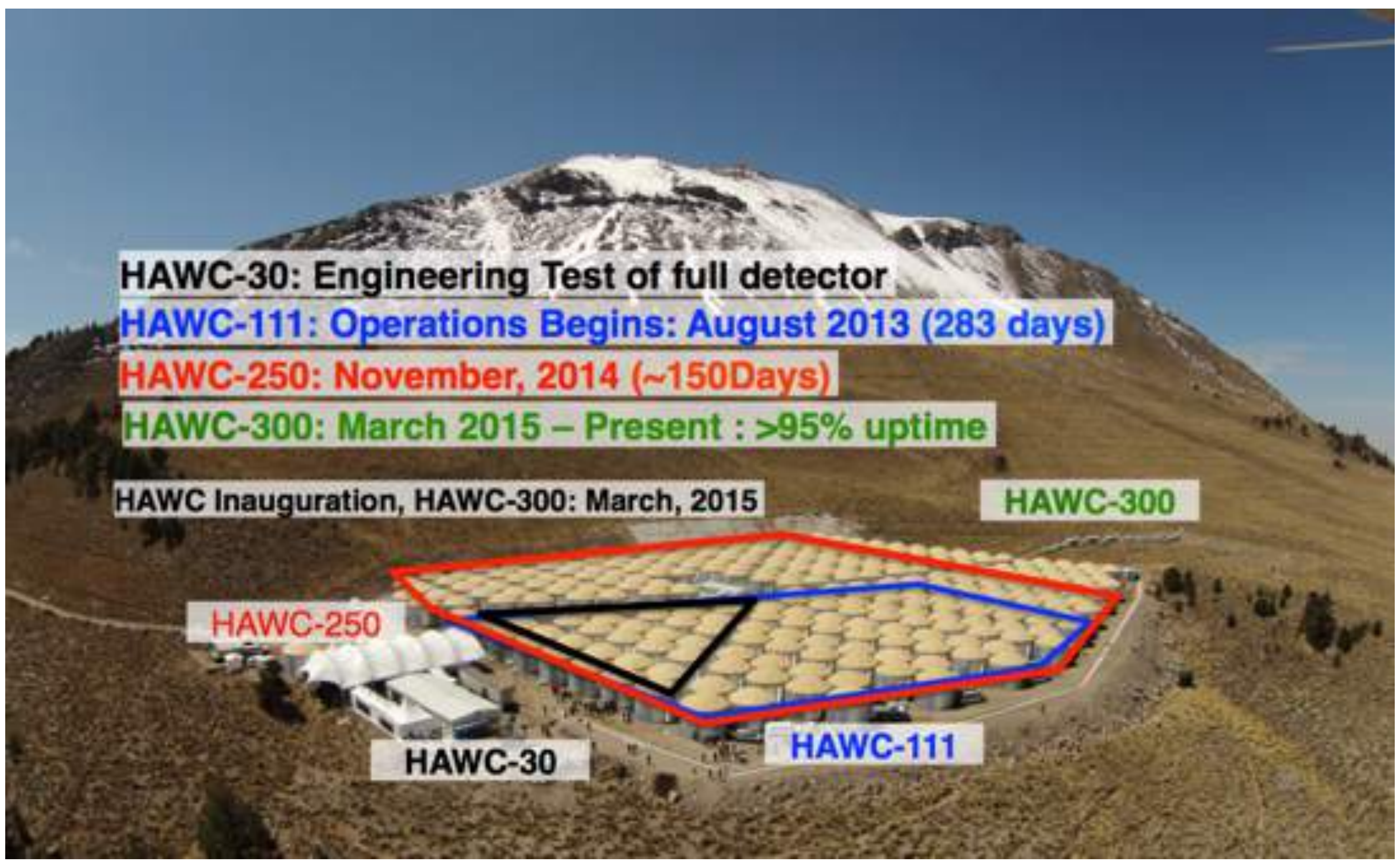
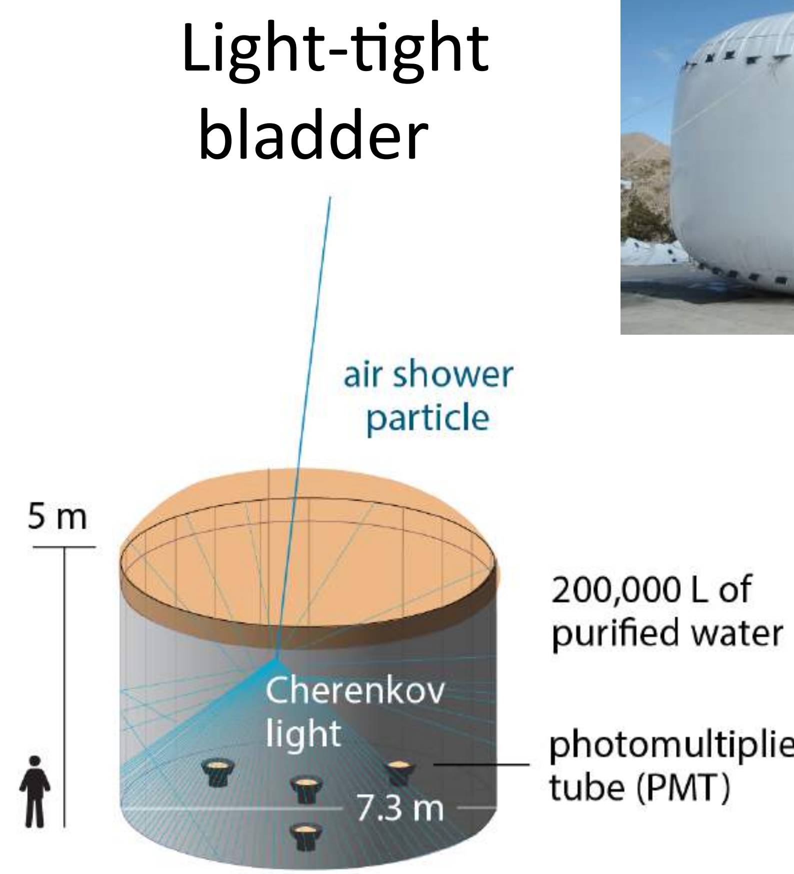
Imaging Atmospheric Cherenkov Telescopes: Detection technique



3. How to detect gamma rays?

Air Shower Arrays. State of the Art is HAWC



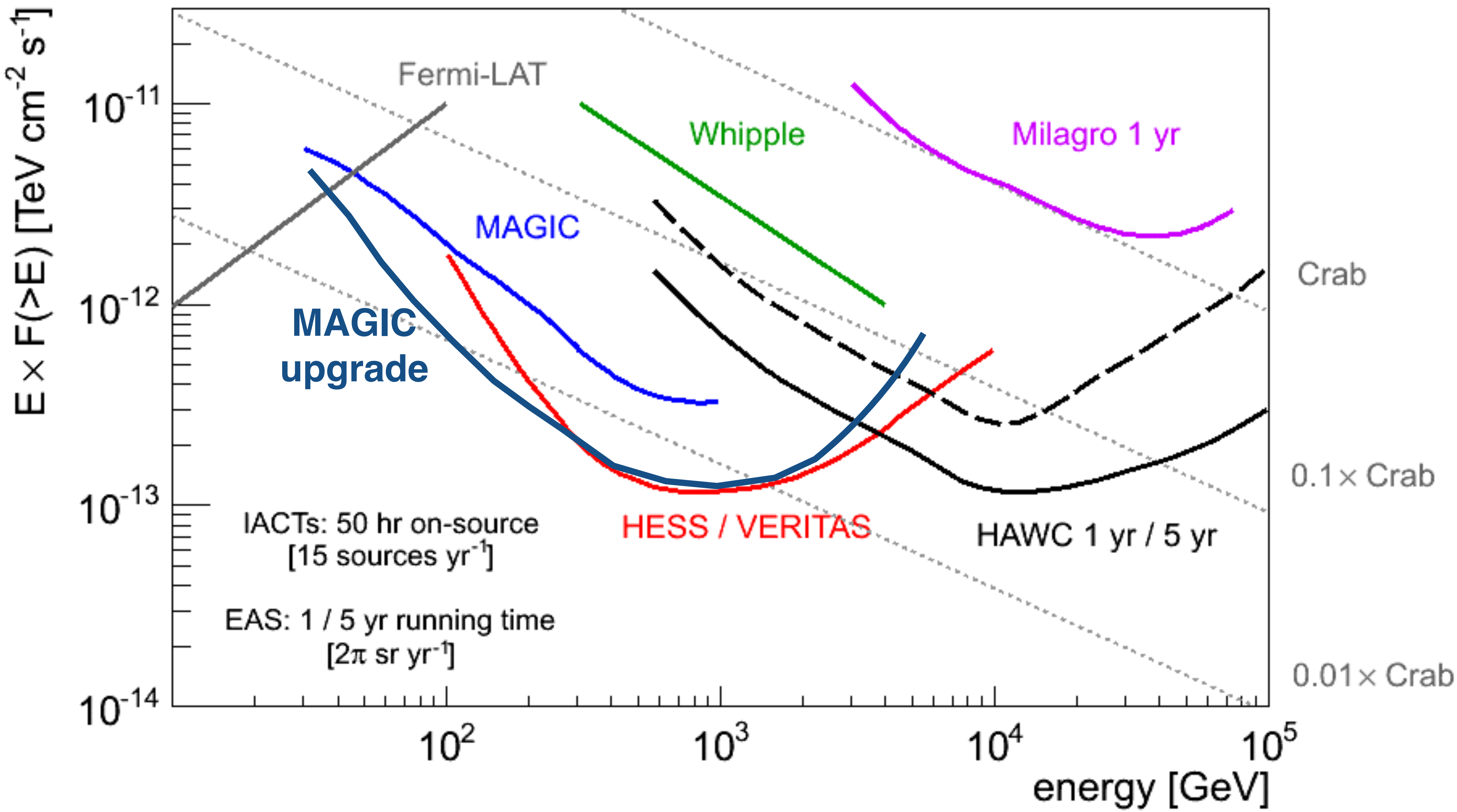


3 Hamamatsu R5912
+1 Hamamatsu R7081

Gamma and Cosmic rays interact with water in tanks or pools and produce Cherenkov radiation that is then detected by PMTs

3. How to detect gamma rays?

Sensitivities



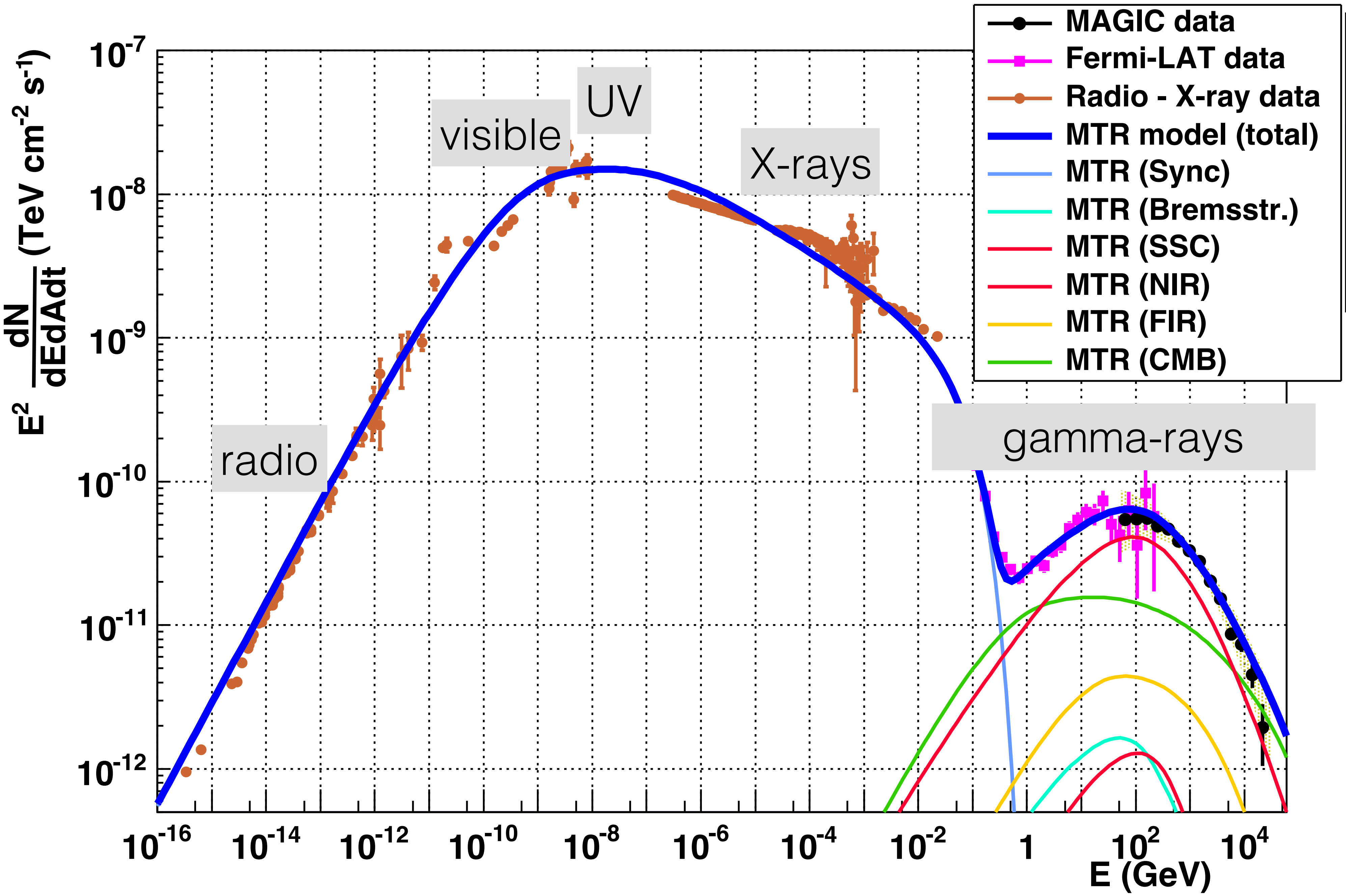
4. What do we learn from gamma rays?

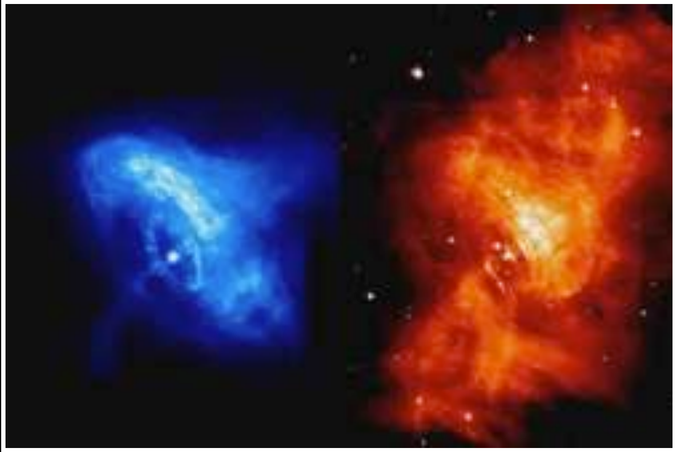
- **Origin of cosmic rays**
  - gamma rays are not deflected by intergalactic and galactic magnetic fields, they point directly to their origin
  - gamma rays can travel cosmological distances without absorption (caution: not true for E>100GeV)
- **Source Physics**: learn about environment (objects) that emit such gamma rays
- **Observational Cosmology**: use gamma ray sources as beacons to probe the star formation history and Hubble parameter
- **Fundamental physics**: dark matter searches, Lorentz invariance violation, axion like particles

4. What do we learn from gamma rays?

Crab Nebula

a non-thermal astrophysical object seen over 20 decades in energy





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Crab Nebula

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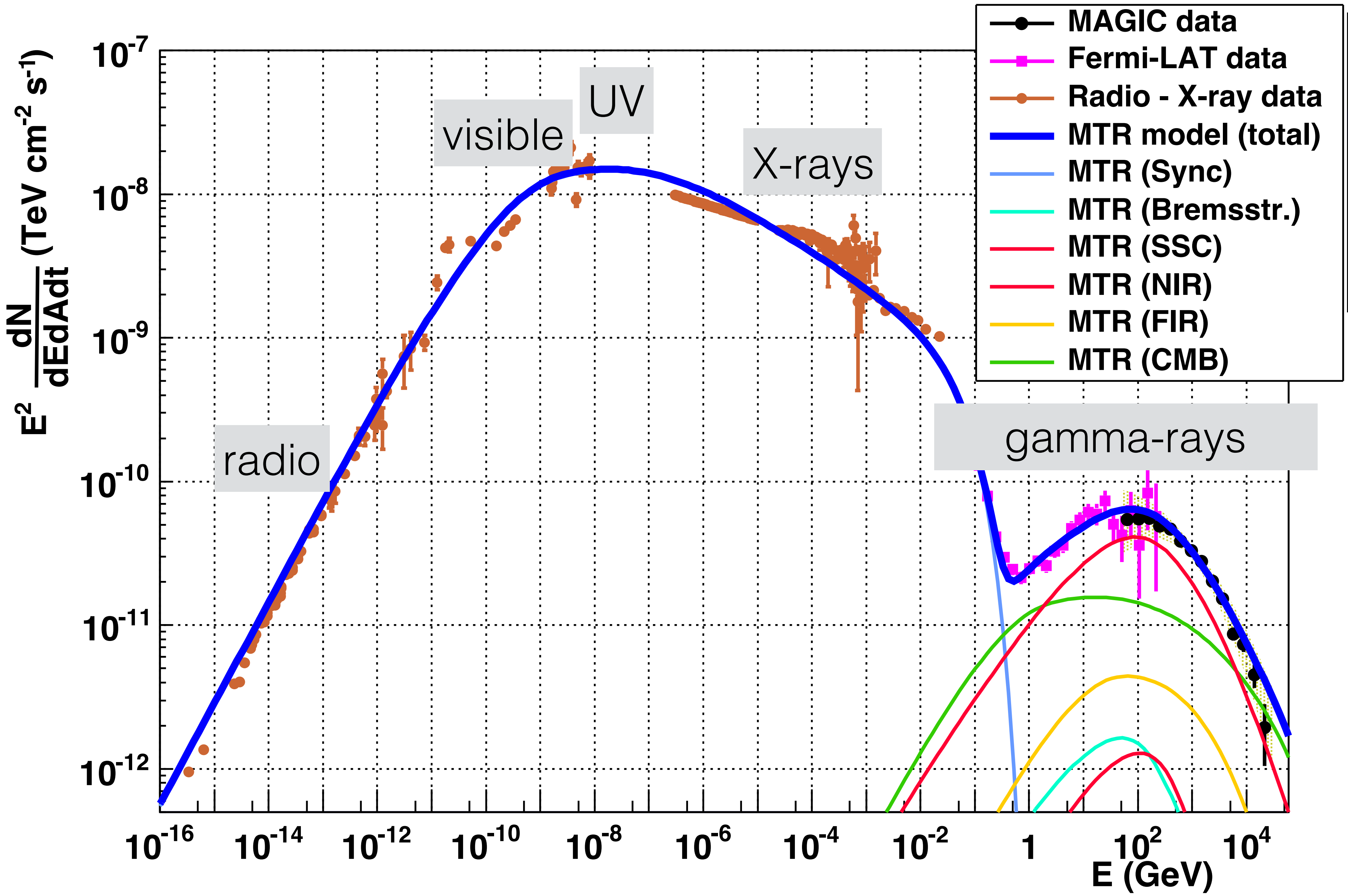
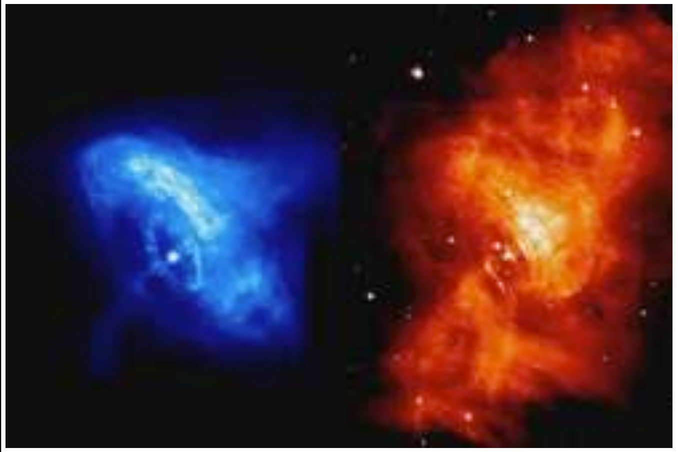
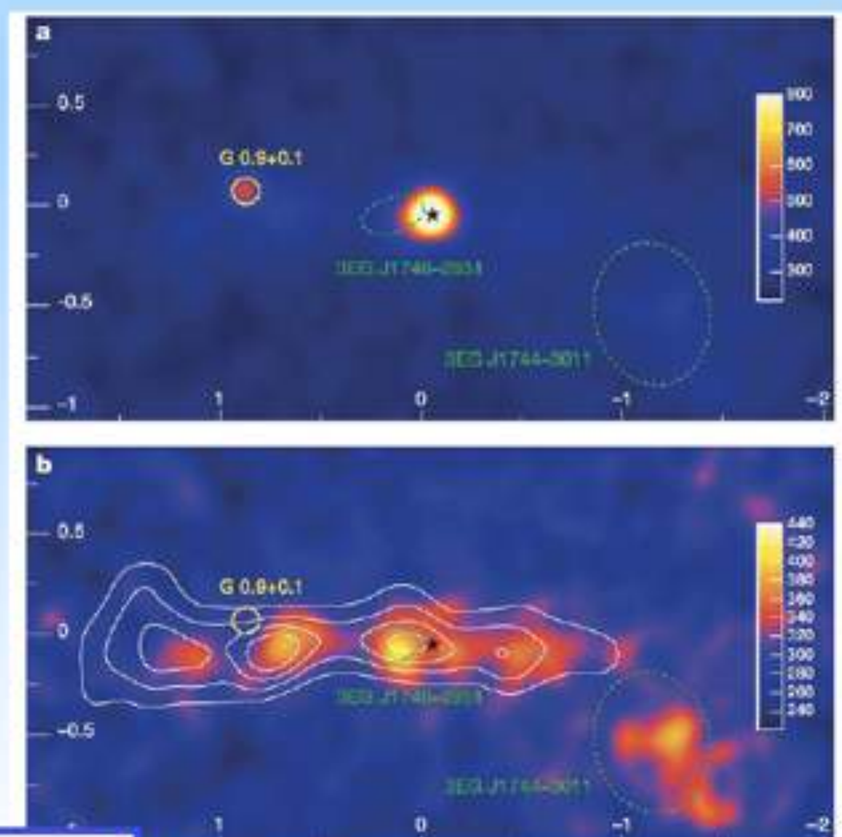


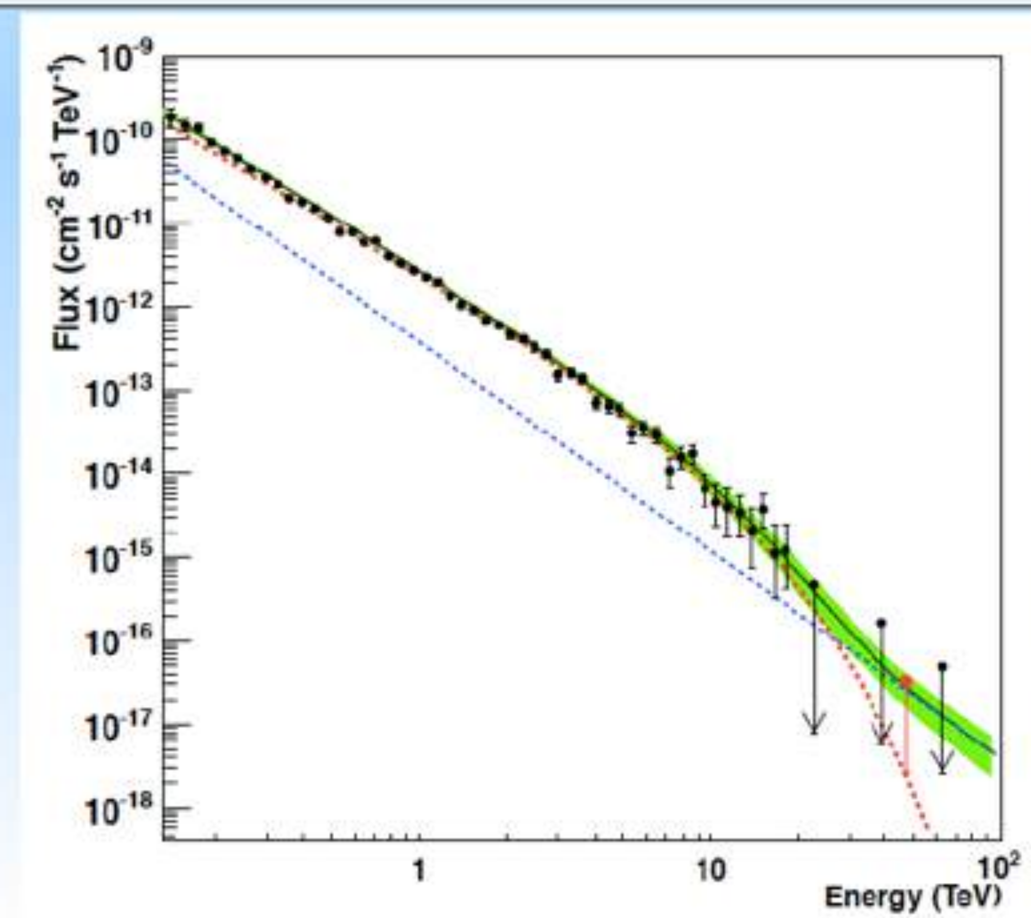


4. What do we learn from gamma rays?

Galactic Center

- H.E.S.S. I observations now comprise 220 hours (>100σ)
- Point source at SgrA*, plus a diffuse component correlated with Molecular Clouds
- Diffuse component contributes ~20% at SgrA*, and shows no cut-off
- Subtracting it allows a measurement of the intrinsic point source spectrum
  - Cut-off shifts from 11 TeV to 7 TeV

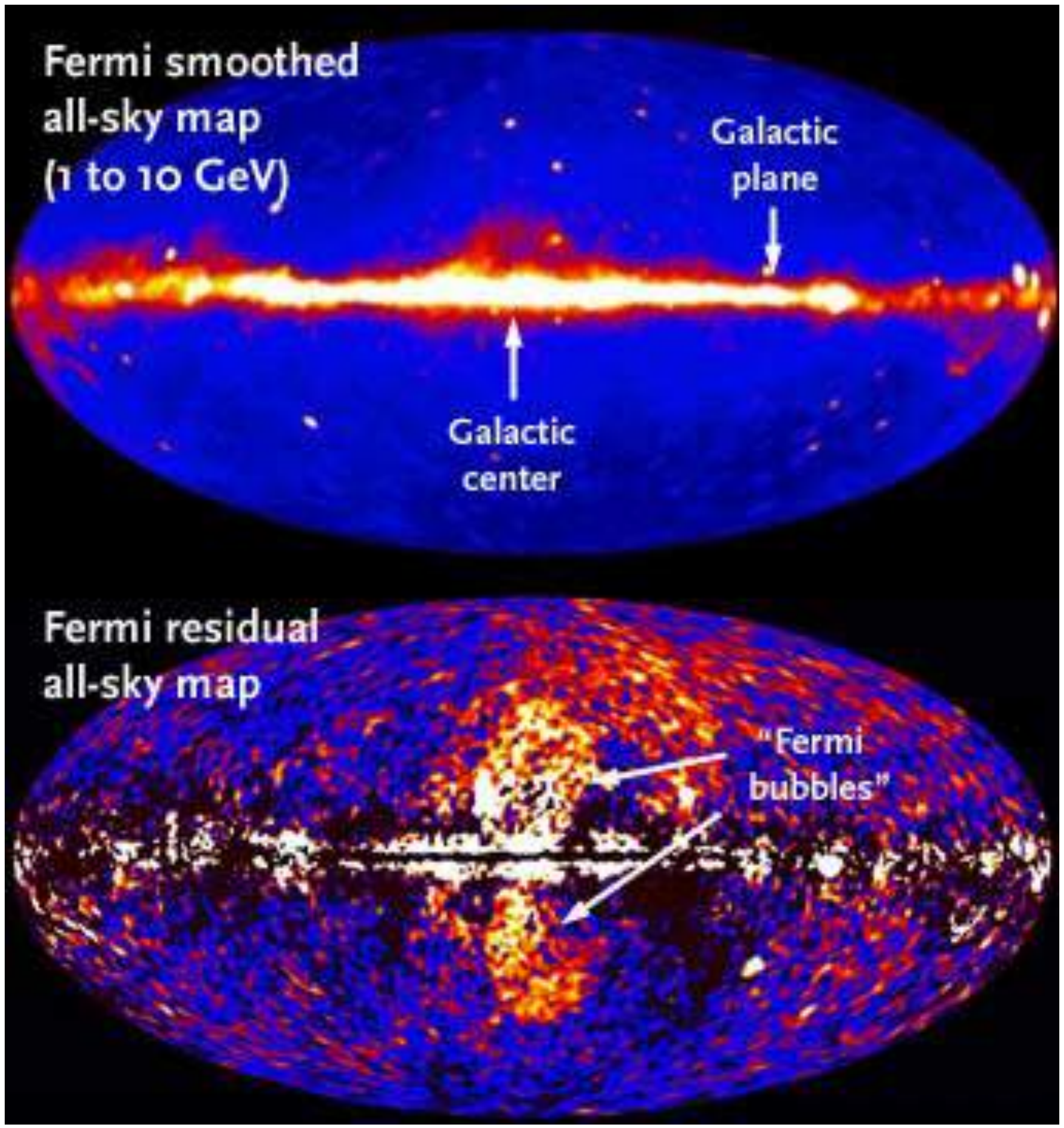


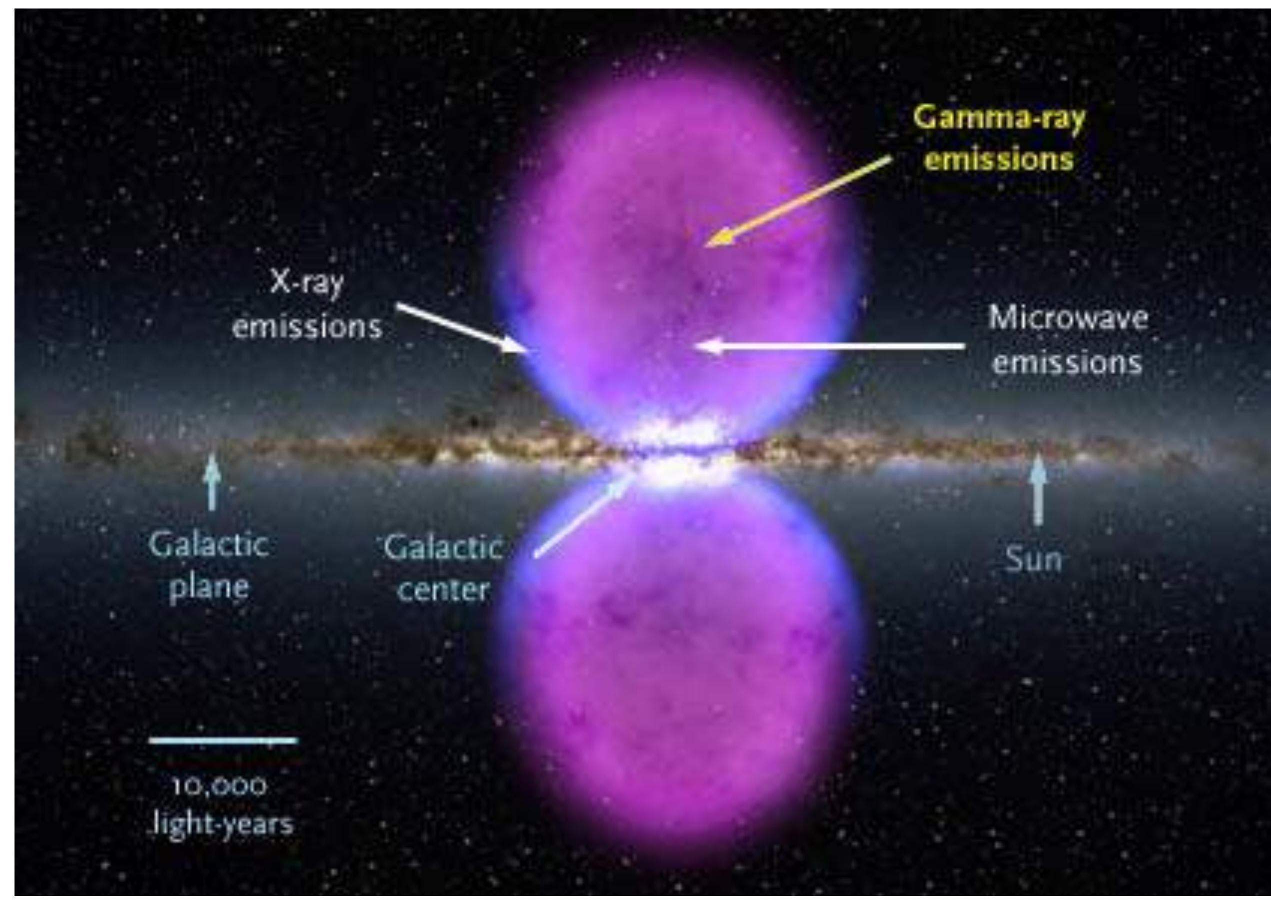


GA-EX 901

4. What do we learn from gamma rays?

Galactic Center: Fermi Bubbles



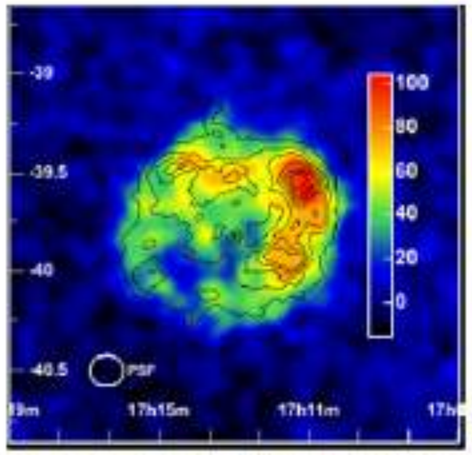


4. What do we learn from gamma rays?

Origin of Cosmic Rays = SNRs ?

Why (VHE) gamma rays?

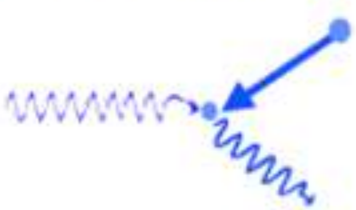
- Unlike cosmic rays, *not deflected* by interstellar magnetic fields.
- *Tracers* of parent particle populations – those particles accelerated by shocks.



SNR Image (RXJ 1713-3946)

Accelerated electrons → VHE γ-rays

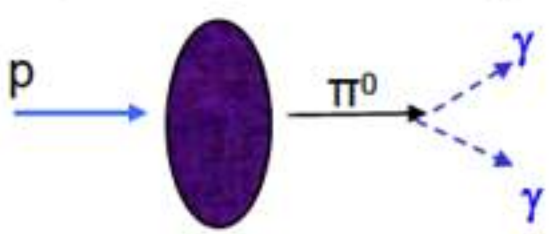
Up-scattering of soft photons



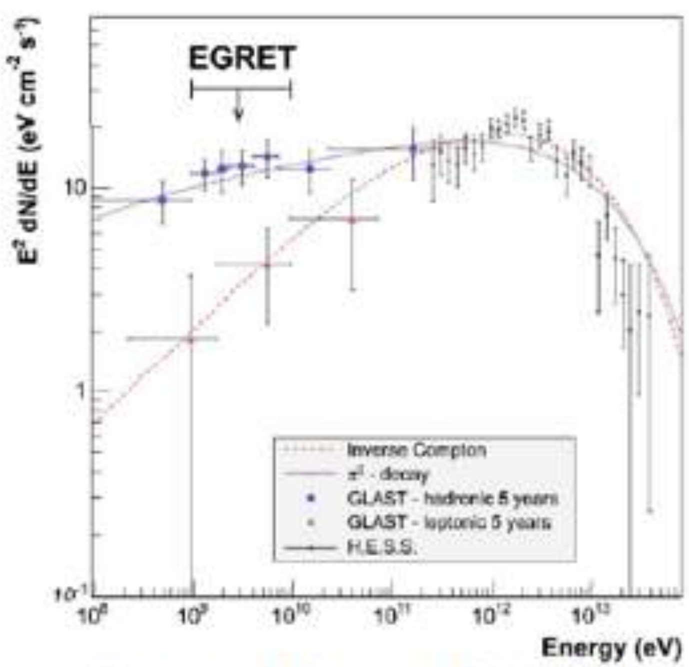
Inverse Compton Scattering

Accelerated protons → VHE γ-rays

Target interaction, π^0 decay



Target material

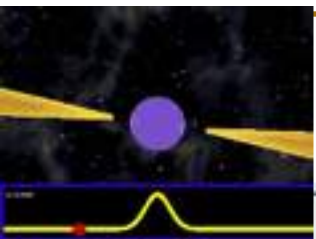


Spectral Energy Distribution

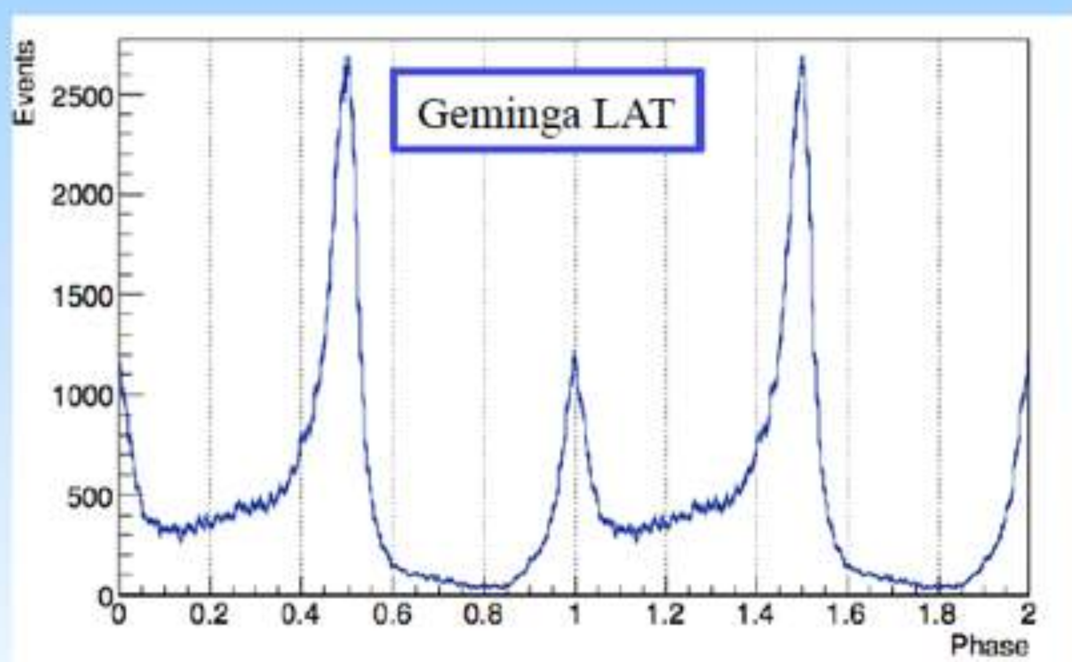
There is good evidence for SNR acceleration of CRs, but the case is far from settled.

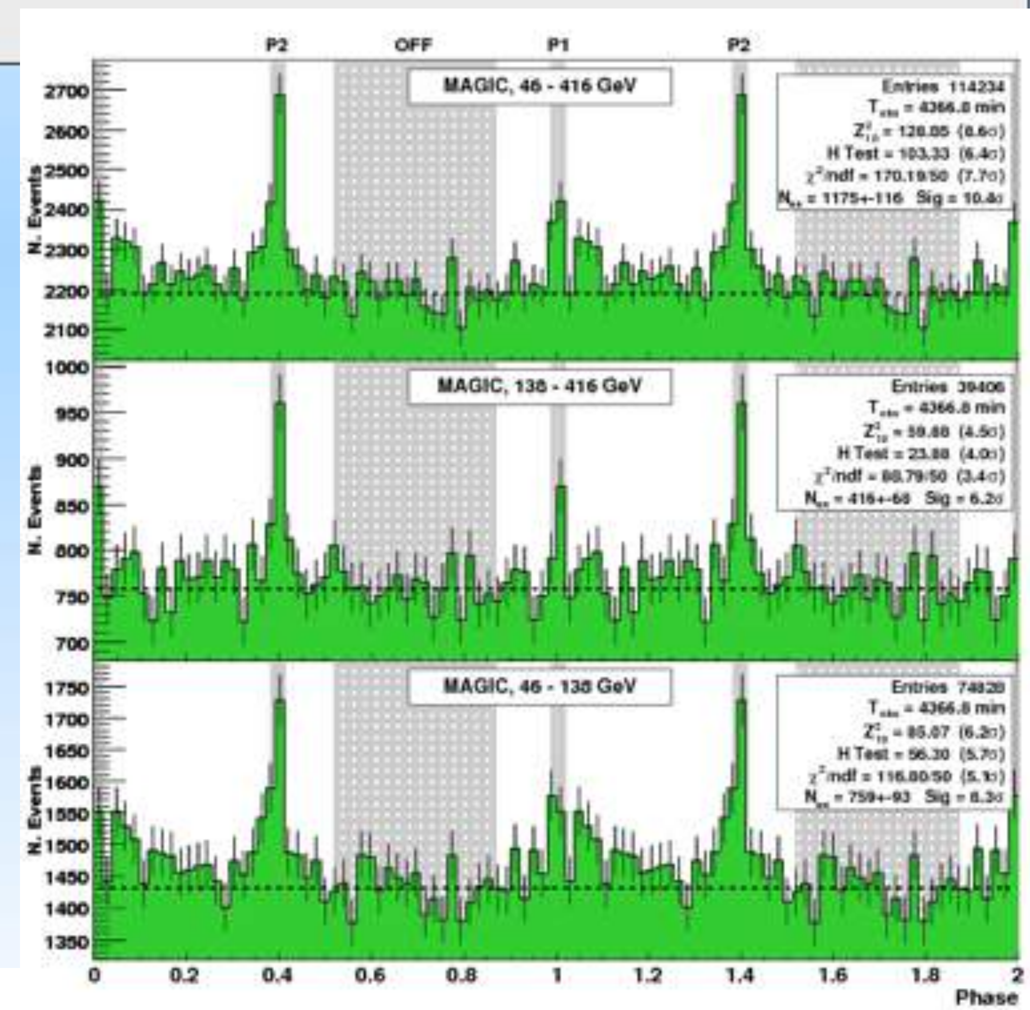
4. What do we learn from gamma rays?

Pulsars: >100 in Fermi, 2 in TeV

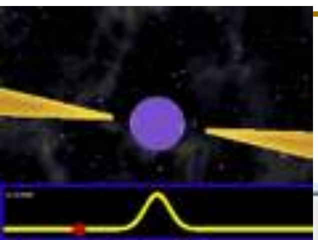


- New results for the Crab pulsar coming soon: "sharp peaks and possible bridge emission"
- MAGIC gave 75 hour upper limits to emission from Geminga >50GeV
- VERITAS uses the Crab pulsar to search for Lorentz invariance violation.
    - Limits the energy scale to 3×10^{17} GeV





4. What do we learn from gamma rays?



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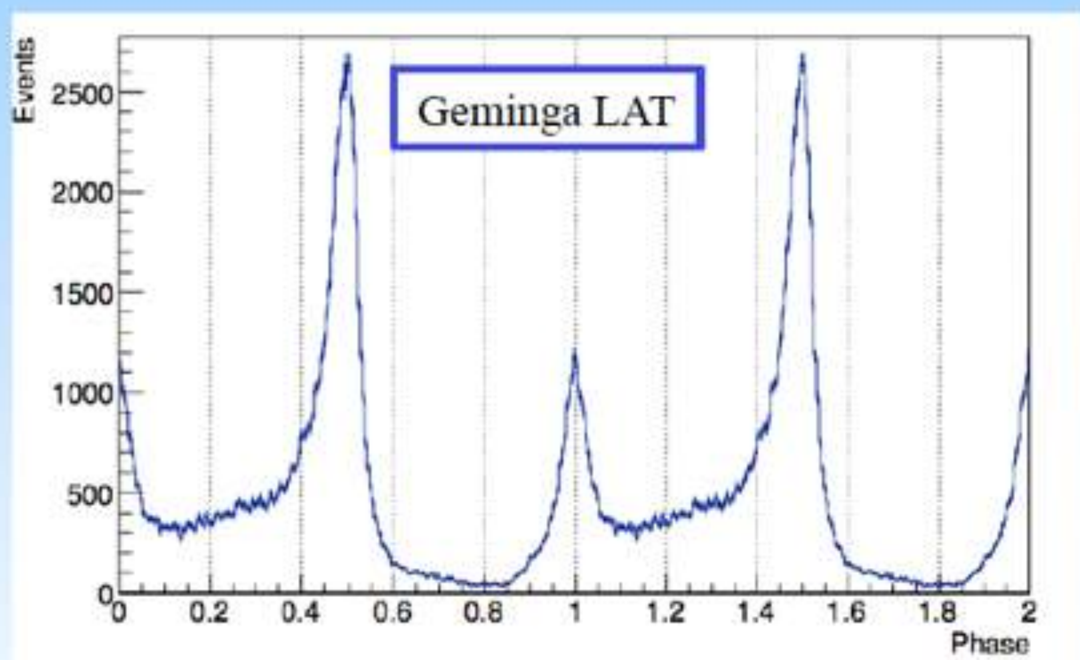
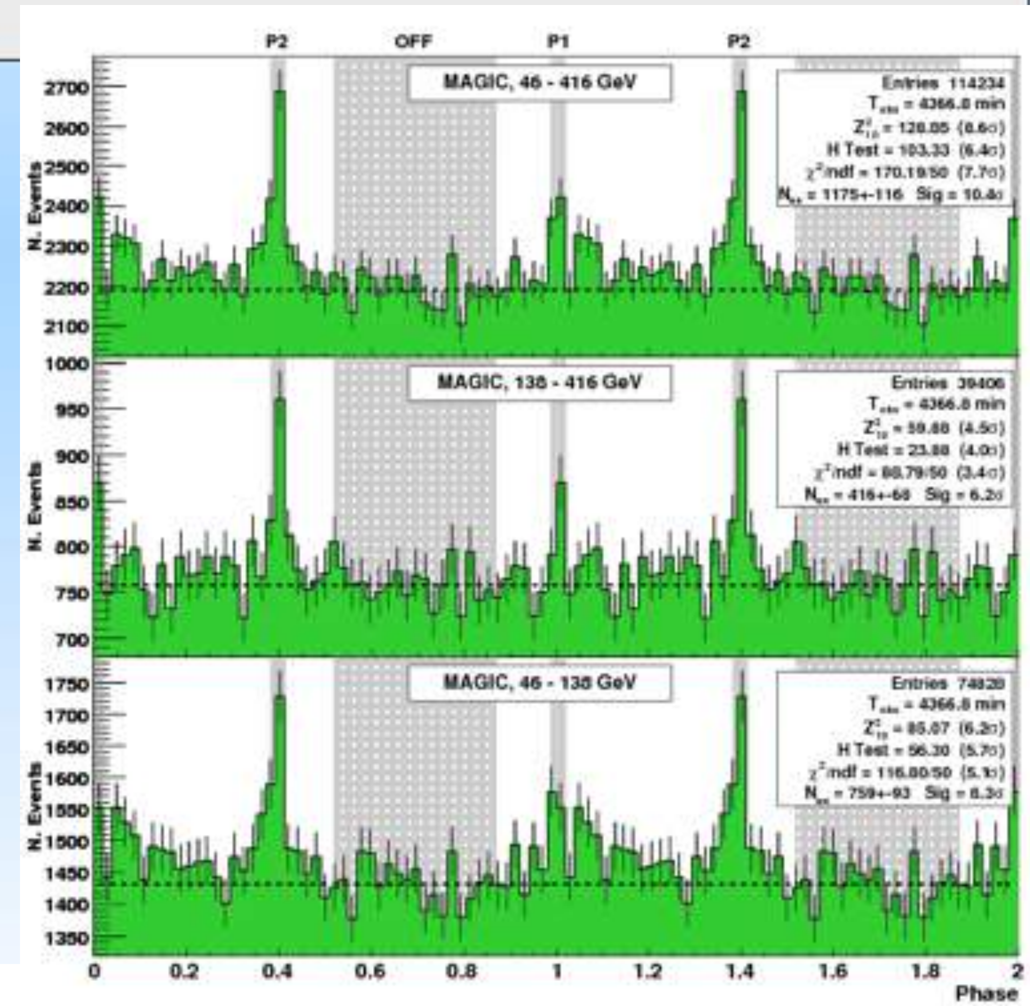
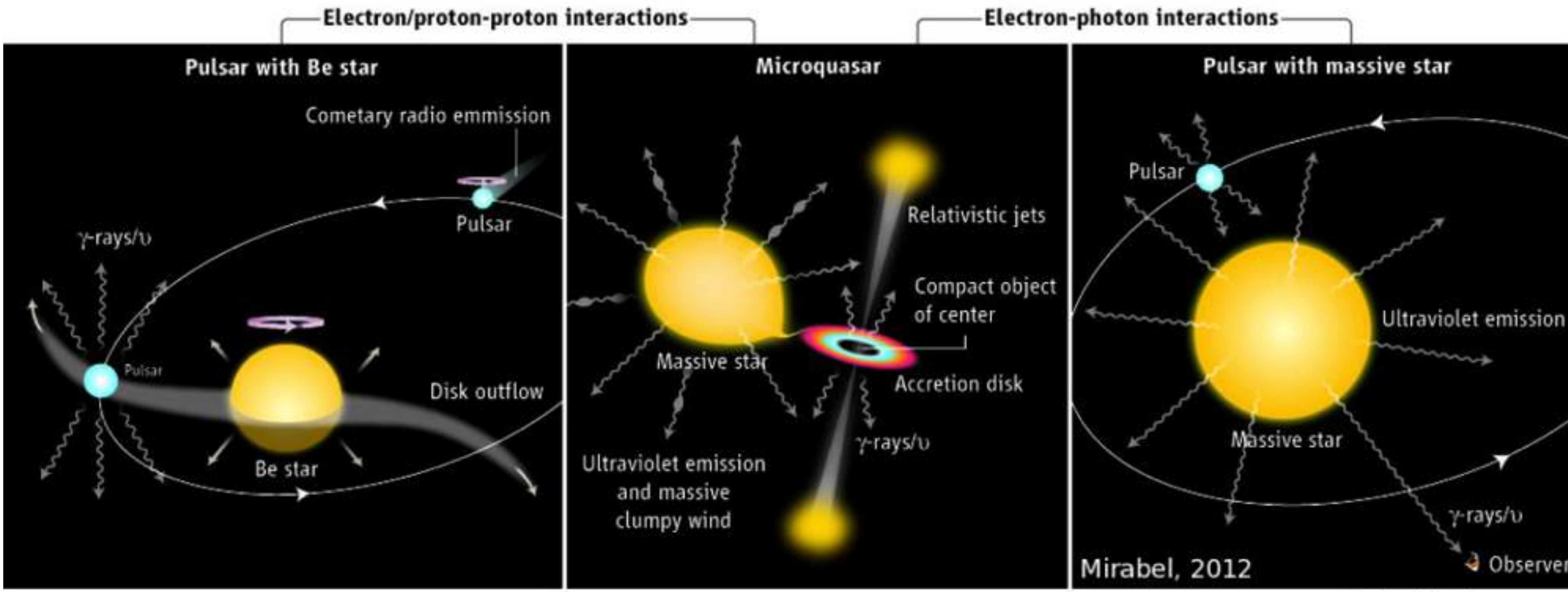




4. What do we learn from gamma rays?

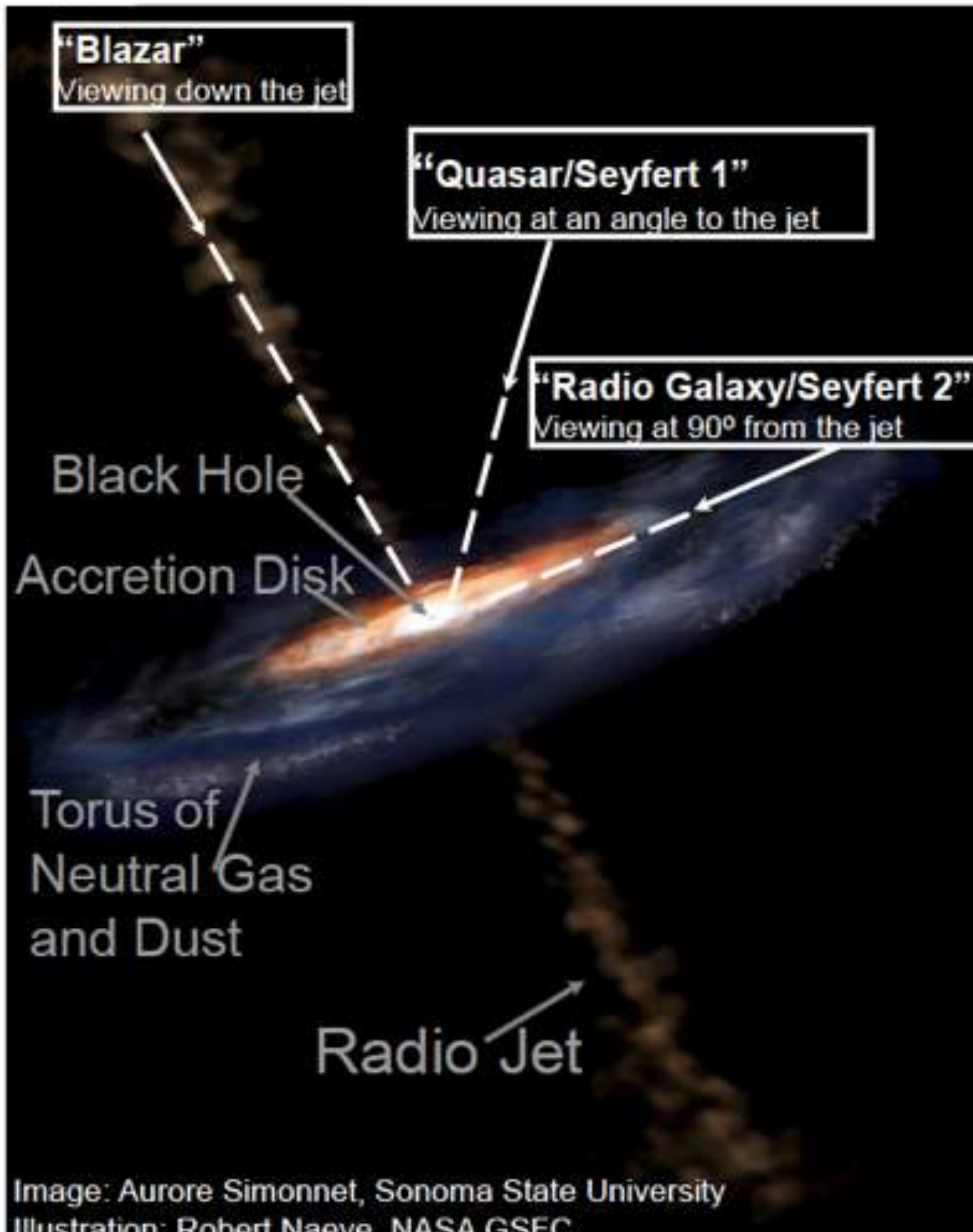
Gamma-ray Binary systems



Mirabel

4. What do we learn from gamma rays?

Active Galaxies



Active Galactic Nuclei (AGN)

- High-luminosity extragalactic objects
  - ➔ Probe properties of the universe at large distances
- Highly variable !
- Jets powered by accretion on to supermassive BH

So far, AGN are generally:

- Blazars
  - ➔ Jets aligned with line of sight

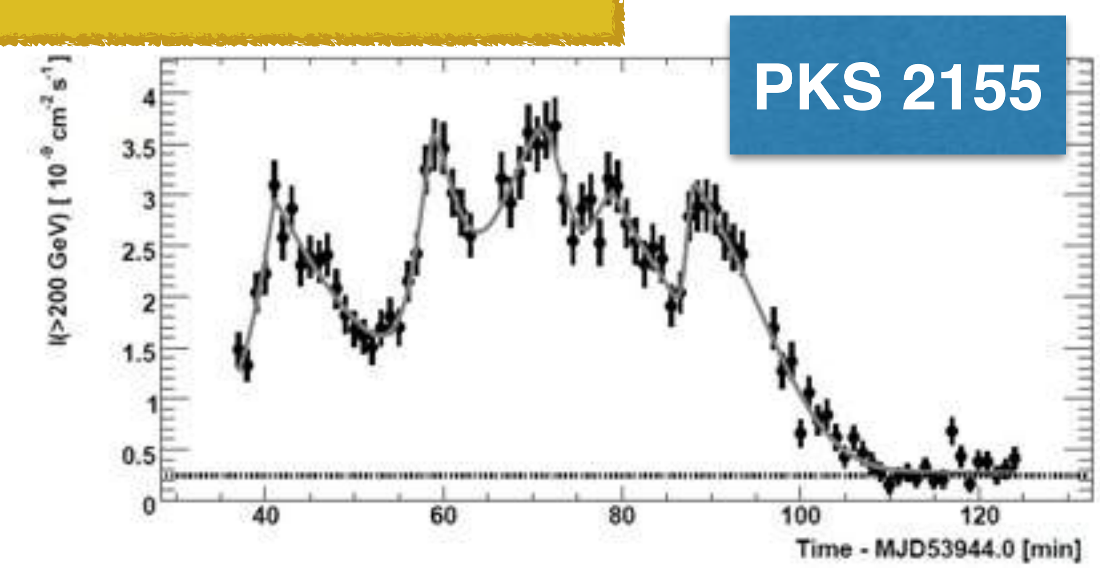
But also radio galaxies (e.g M87)

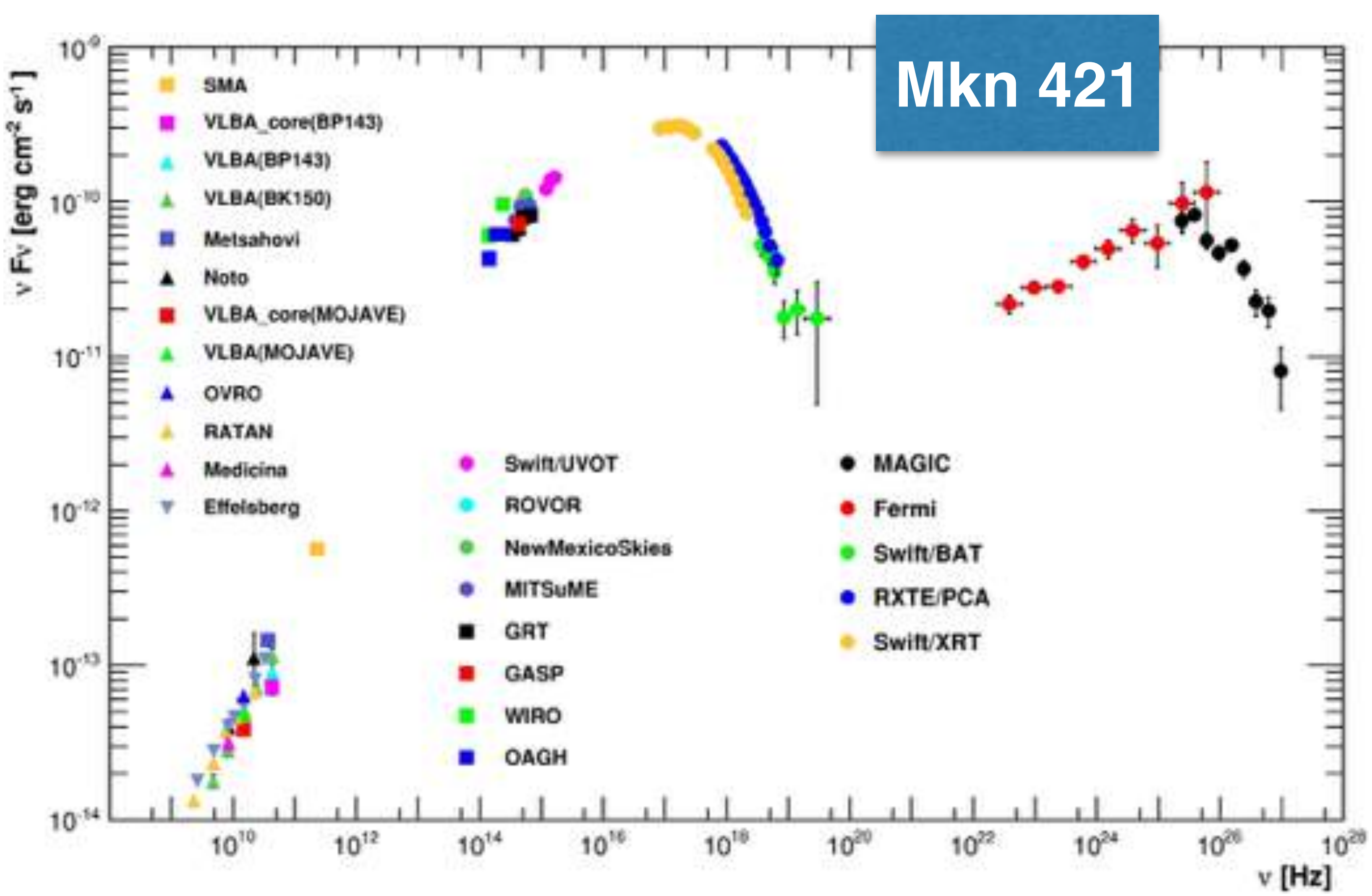
➔ Jet viewed from the side

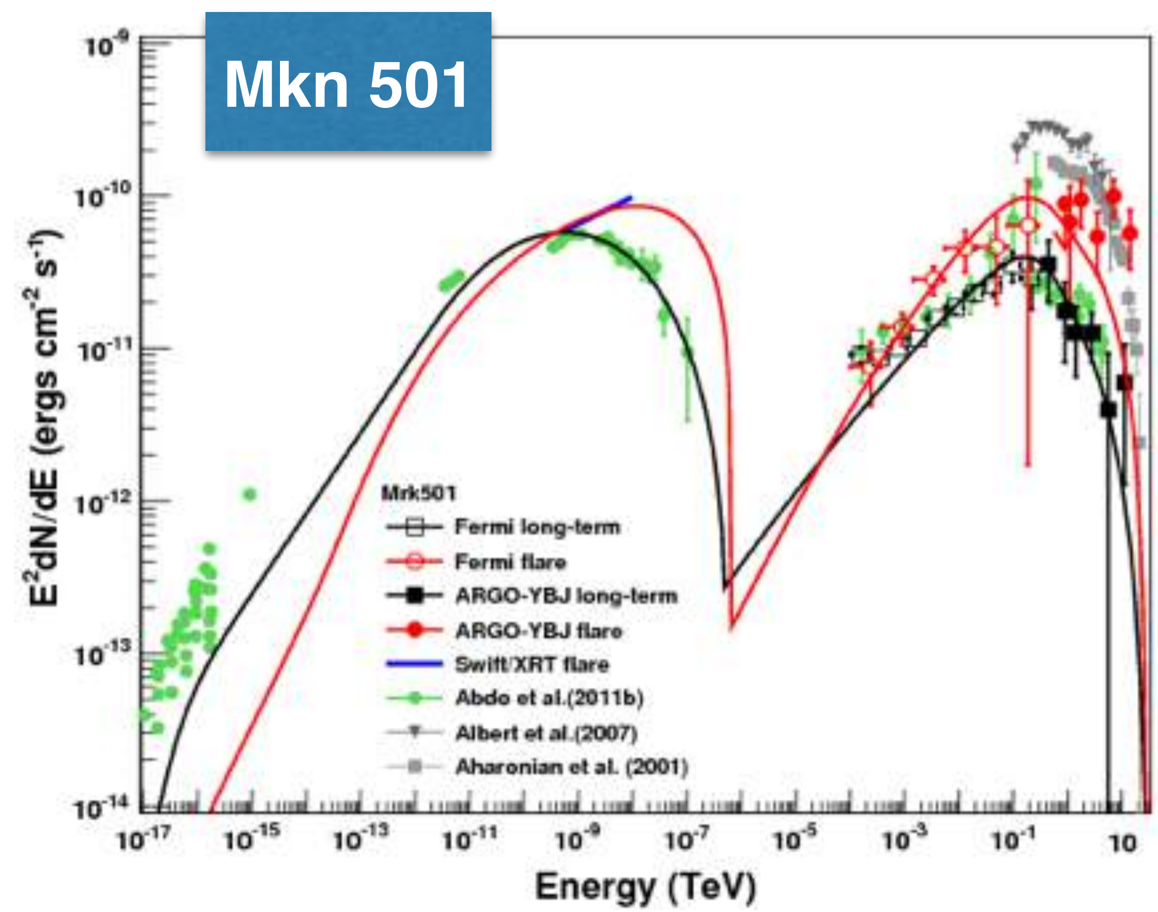
4. What do we learn from gamma rays?

BLAZARS

- Extremely variable on all time scales
- Relativistic jets with large Lorentz factors
- >1000 Fermi blazars, 60 in TeV regime



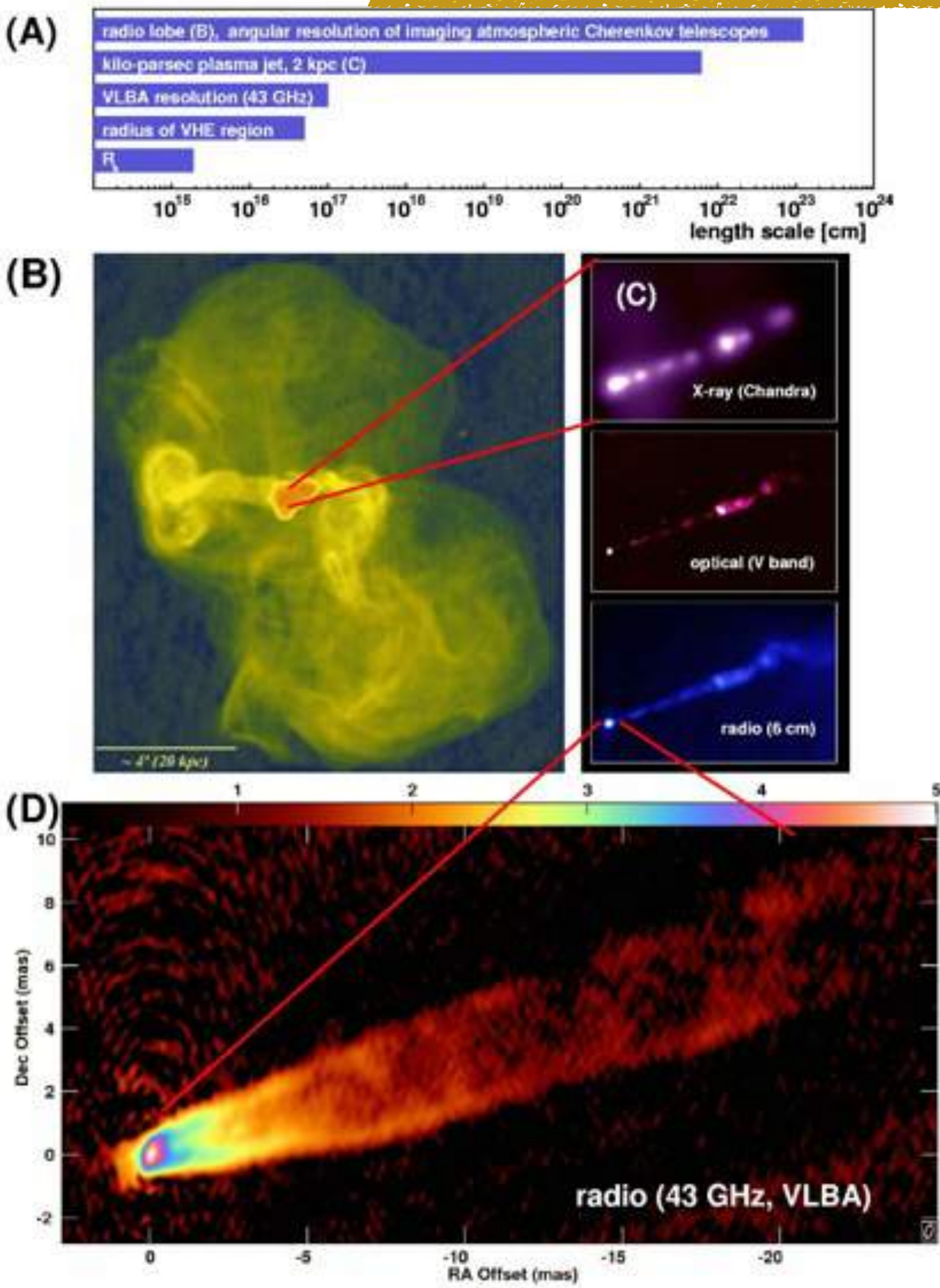


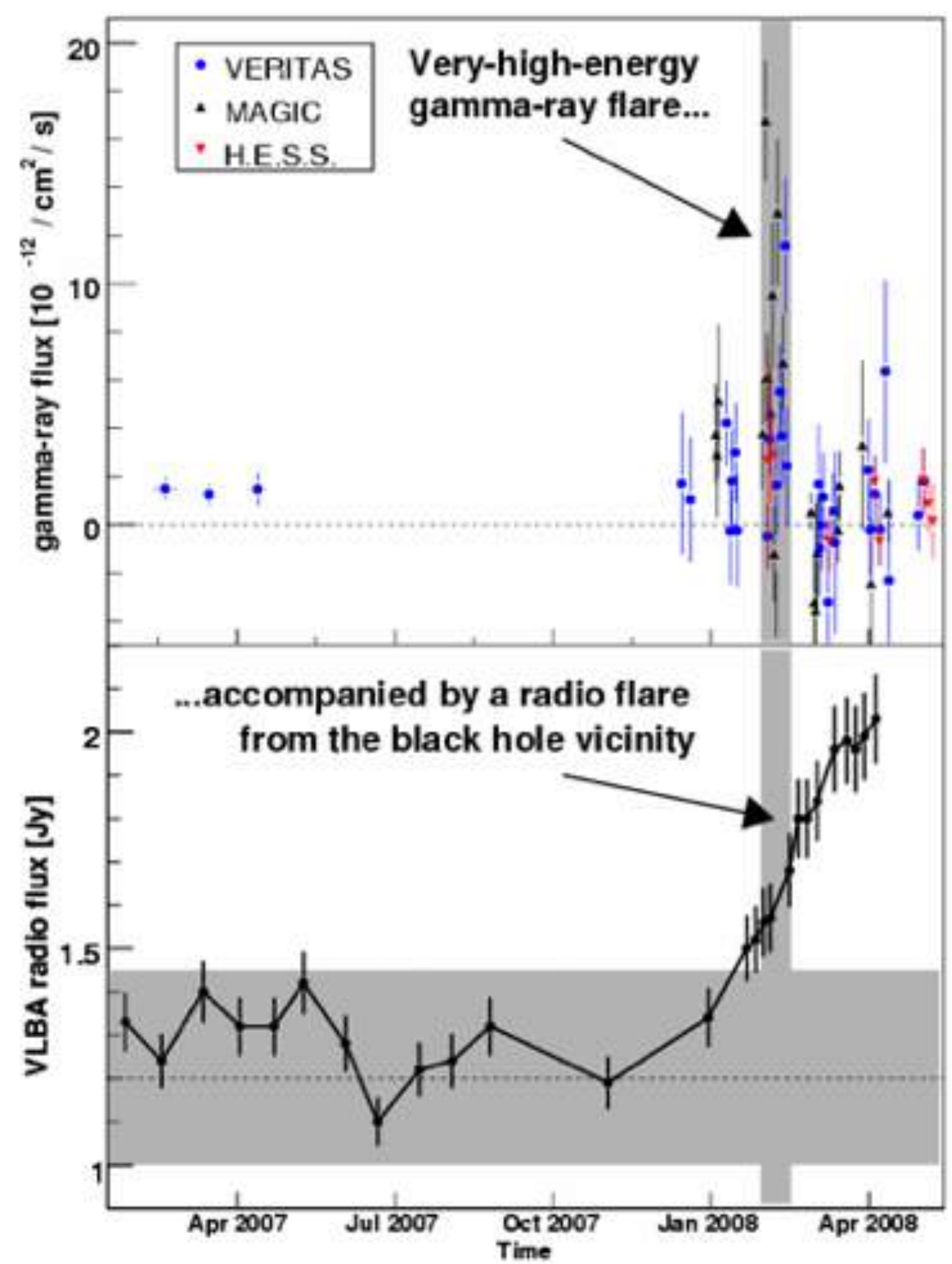


4. What do we learn from gamma rays?

Radio galaxies

- M87: best studied radio galaxy





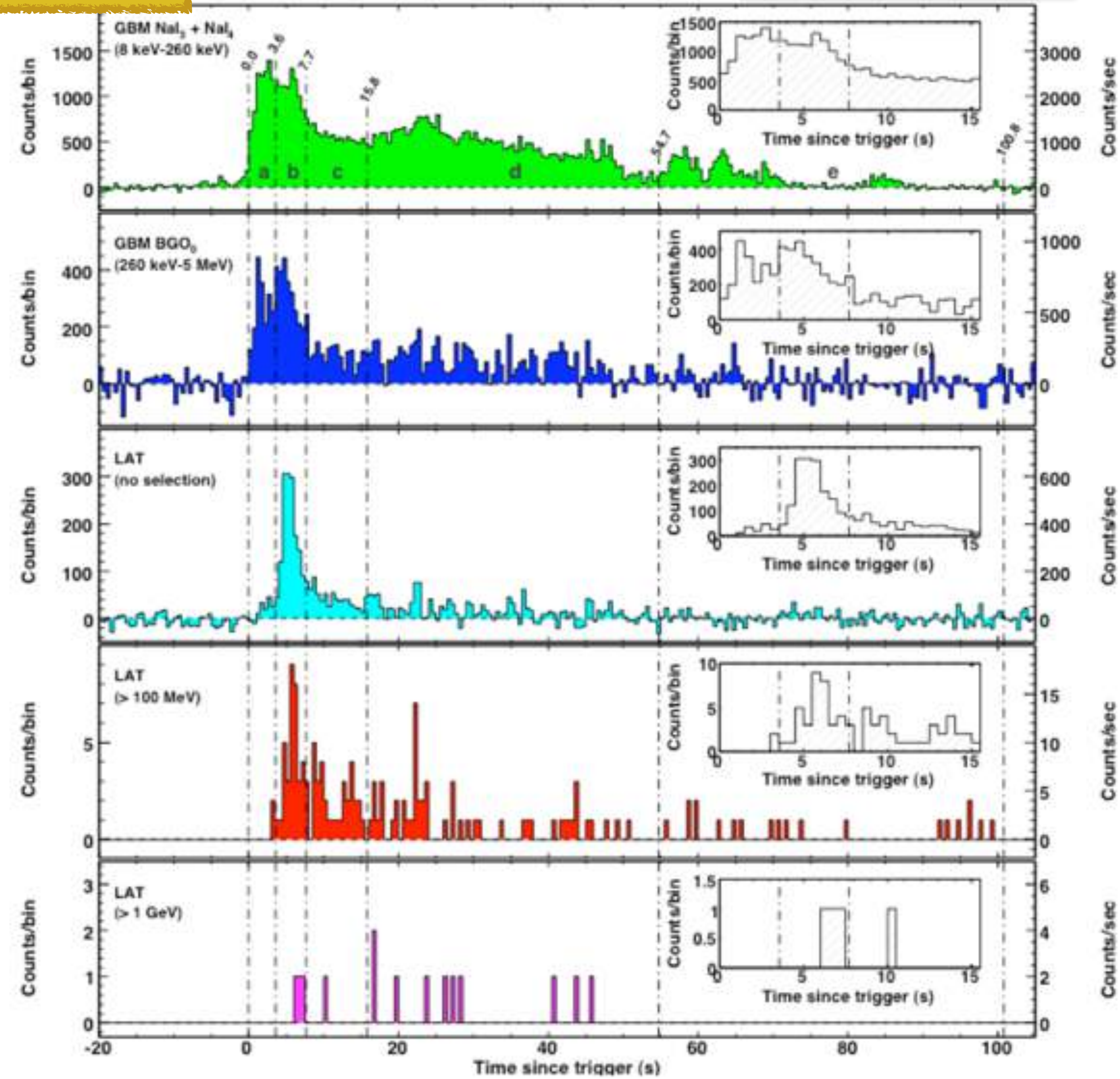
4. What do we learn from gamma rays?

GRBs

GRB 080916C

- Gamma-ray bursts (GRBs) are highly energetic explosions signaling the death of massive stars in distant galaxies.
- In September 2008, Fermi observed the exceptionally luminous GRB 080916C, with the largest apparent energy release yet measured.
- The high-energy gamma rays are observed to start later and persist longer than the lower energy photons.

$z = 4.35 \pm 0.15$

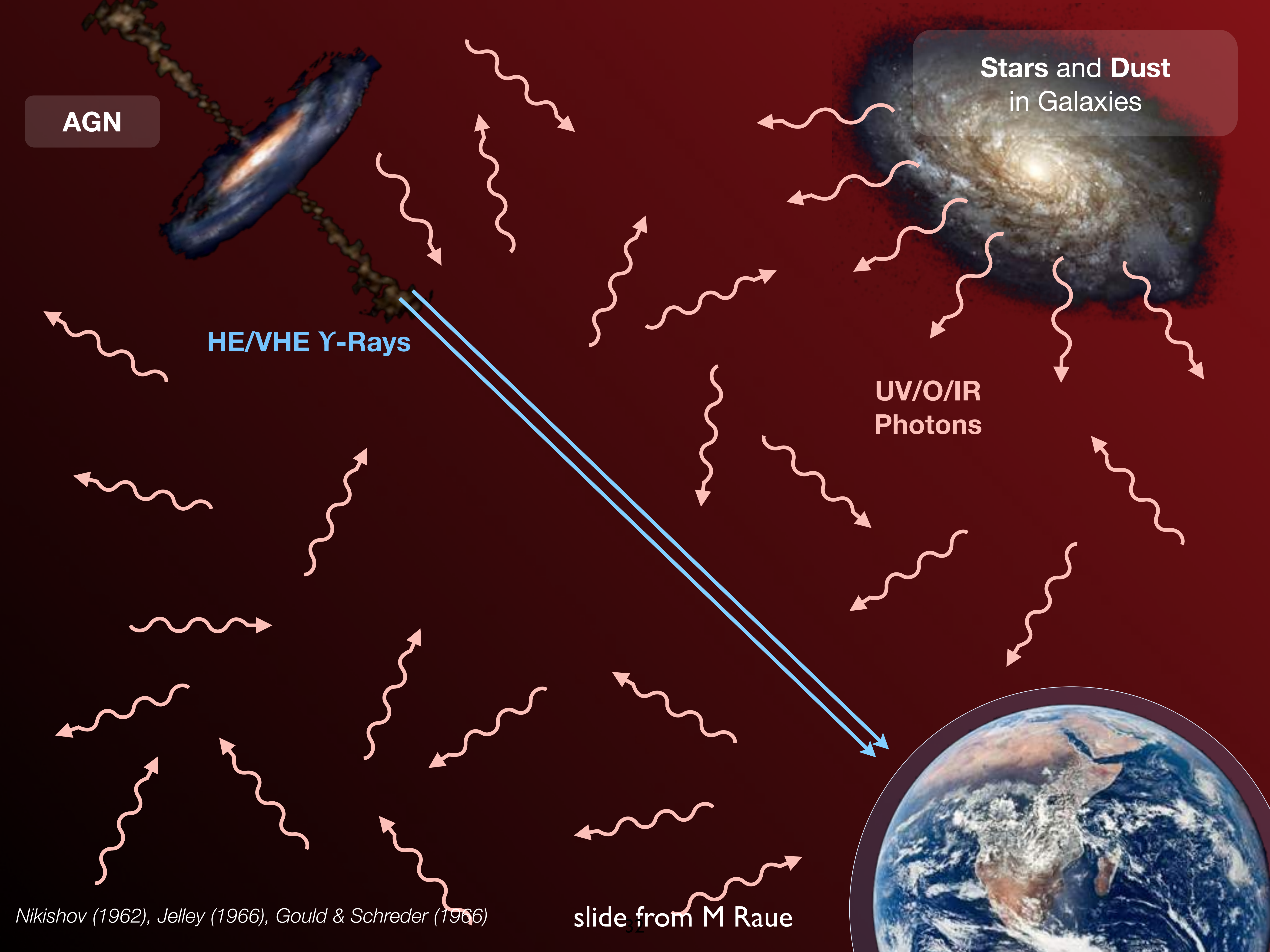


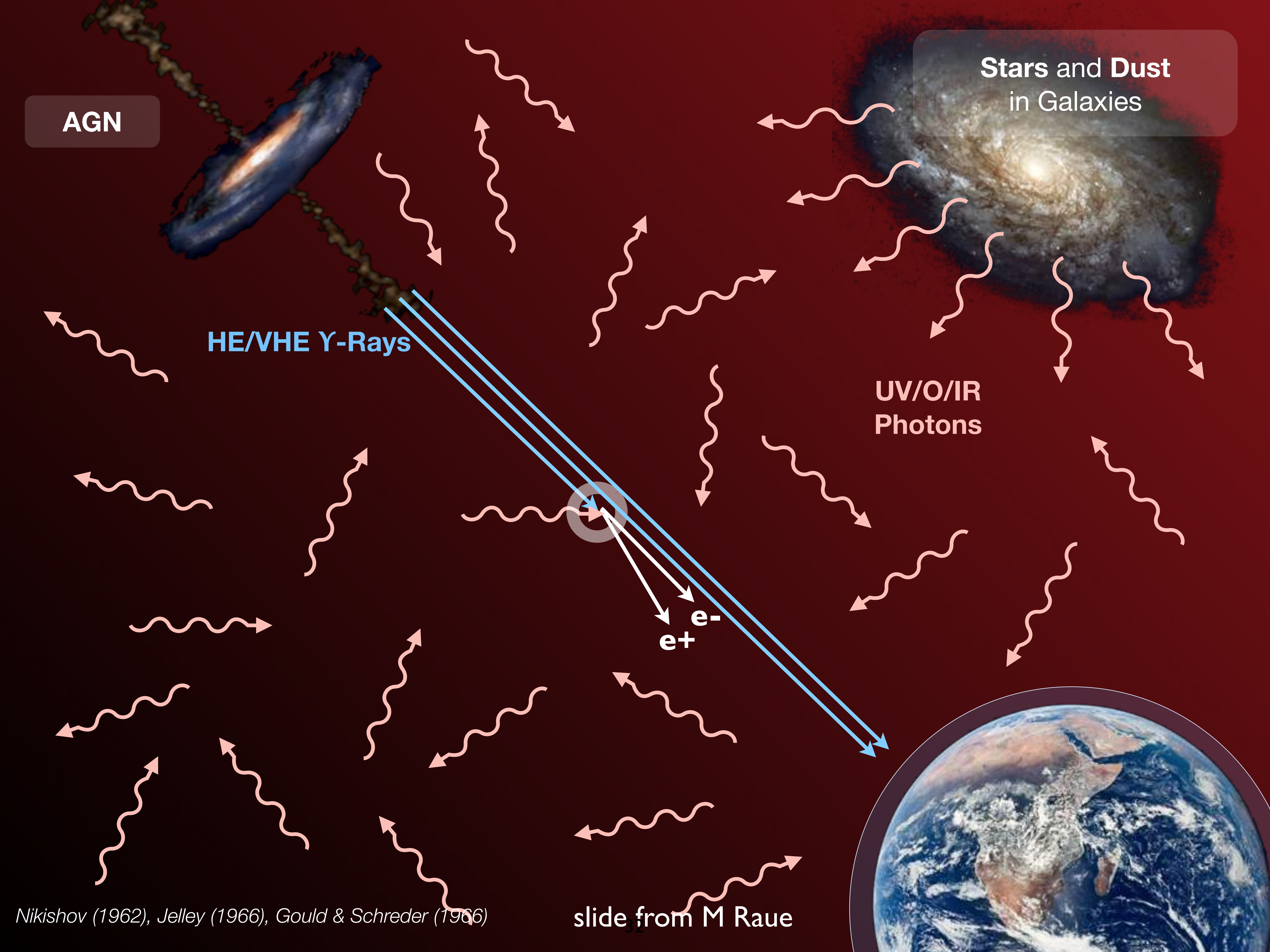
AGN

HE/VHE γ-Rays

Nikishov (1962), Jelley (1966), Gould & Schreder (1966)

slide from M Raue


AGN
Stars and Dust
in Galaxies
HE/VHE γ-Rays
UV/O/IR
Photons
Nikishov (1962), Jelley (1966), Gould & Schreder (1966)
slide from M Raue
32


AGN
Stars and Dust
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e+
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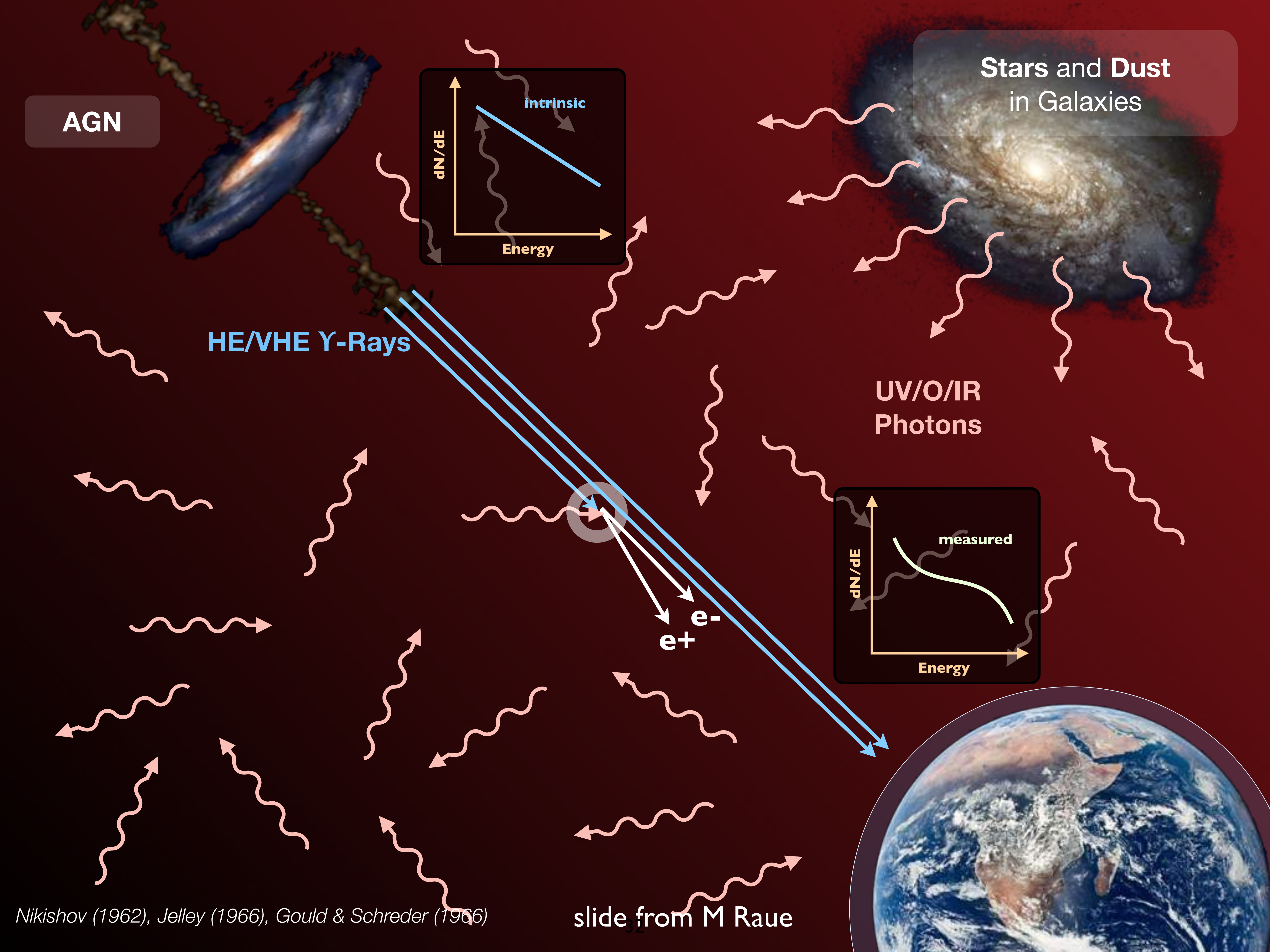
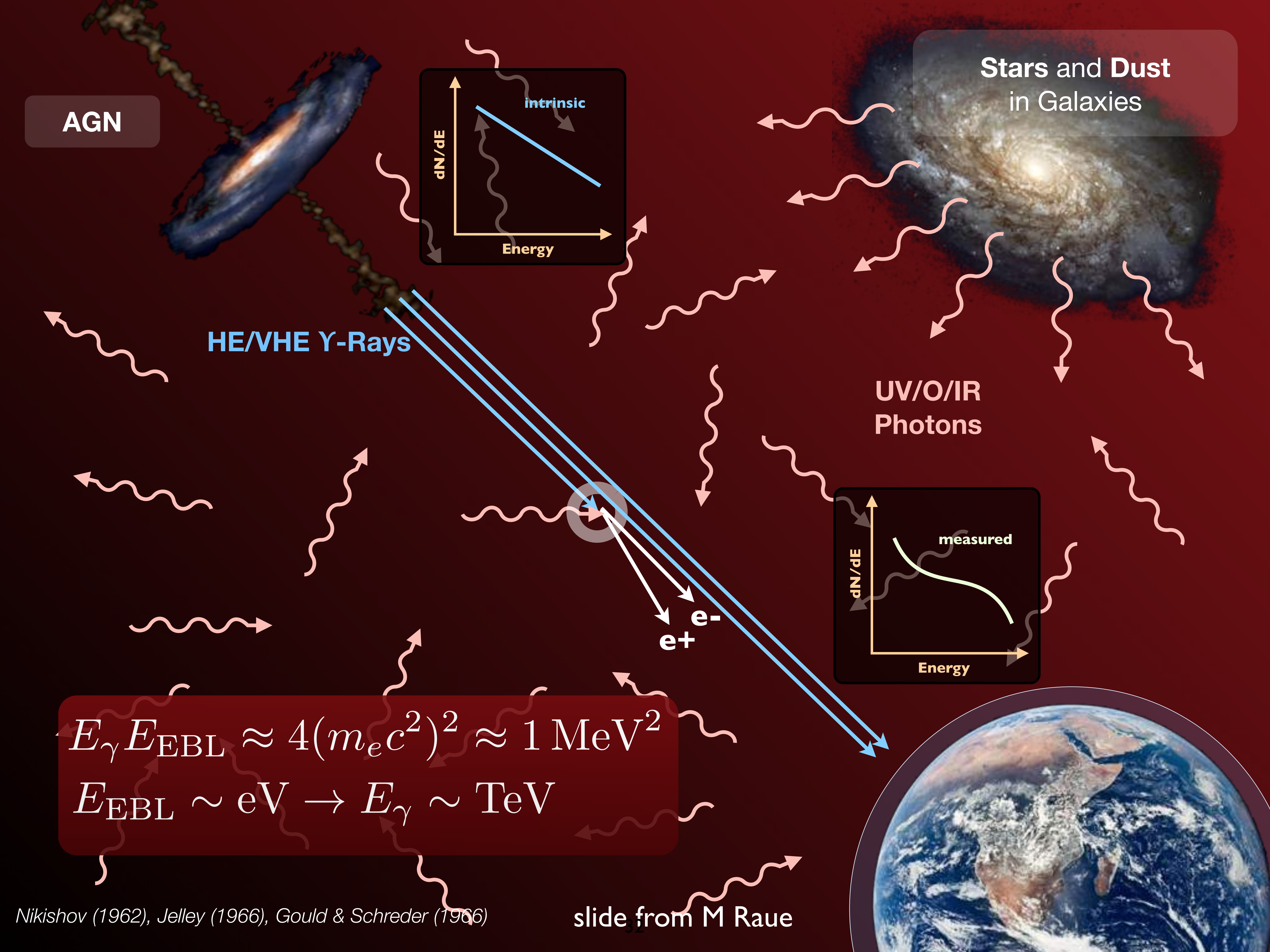


AGN
Stars and Dust in Galaxies
intrinsic
dN/dE
Energy
HE/VHE Υ-Rays
UV/O/IR Photons
measured
dN/dE
Energy
e-
e+
Nikishov (1962), Jelley (1966), Gould & Schreder (1966)
slide from M Raue



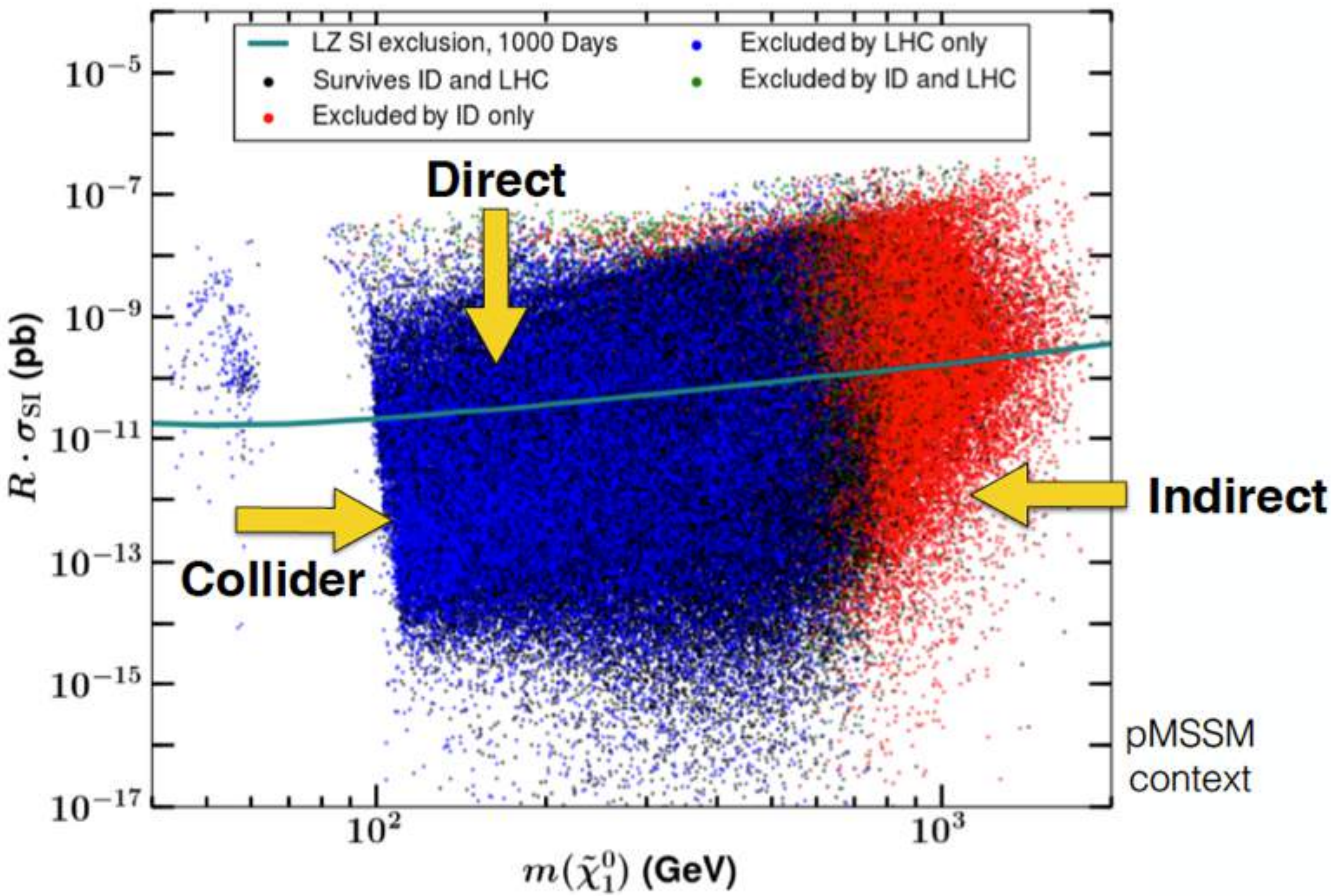
$$E_\gamma E_{\mathrm{EBL}} \approx 4(m_e c^2)^2 \approx 1\,\mathrm{MeV}^2$$
$$E_{\mathrm{EBL}} \sim \mathrm{eV} \rightarrow E_\gamma \sim \mathrm{TeV}$$

Nikishov (1962), Jelley (1966), Gould & Schreder (1966)

slide from M Raue

4. What do we learn from gamma rays?

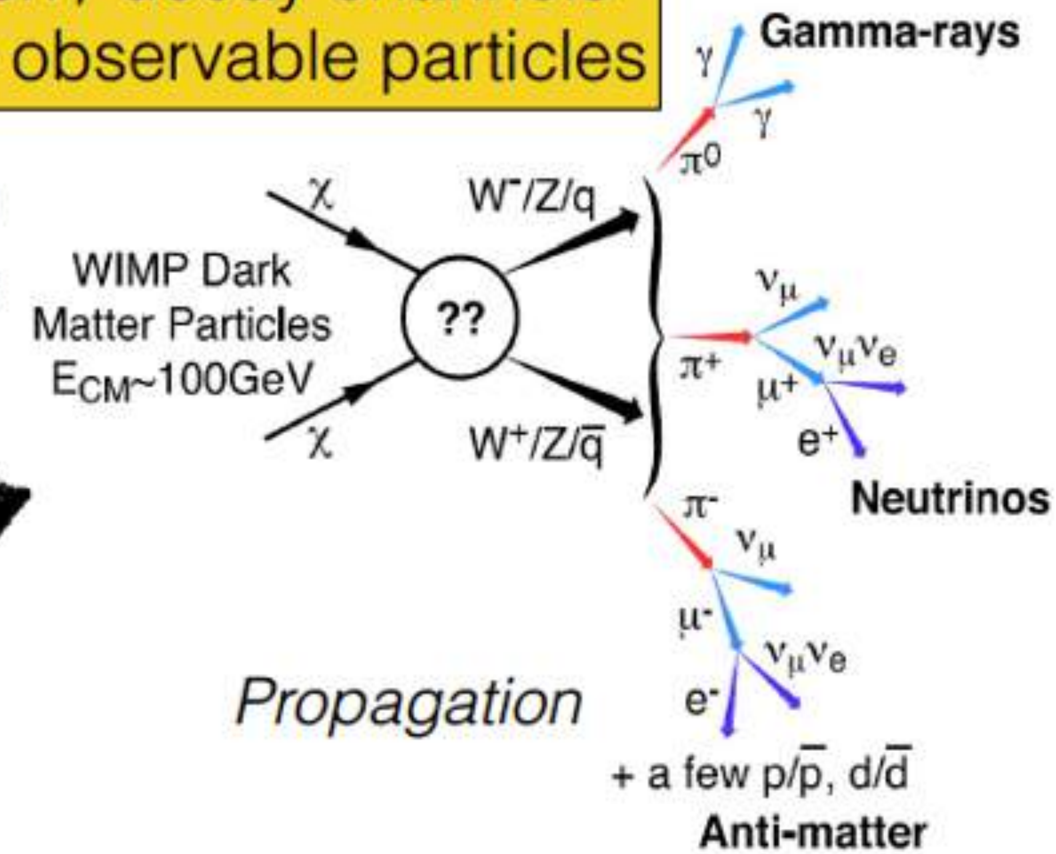
4.4 Fundamental physics: dark matter



Indirect Dark Matter Search Strategy

Annihilation / decay channels and stable observable particles

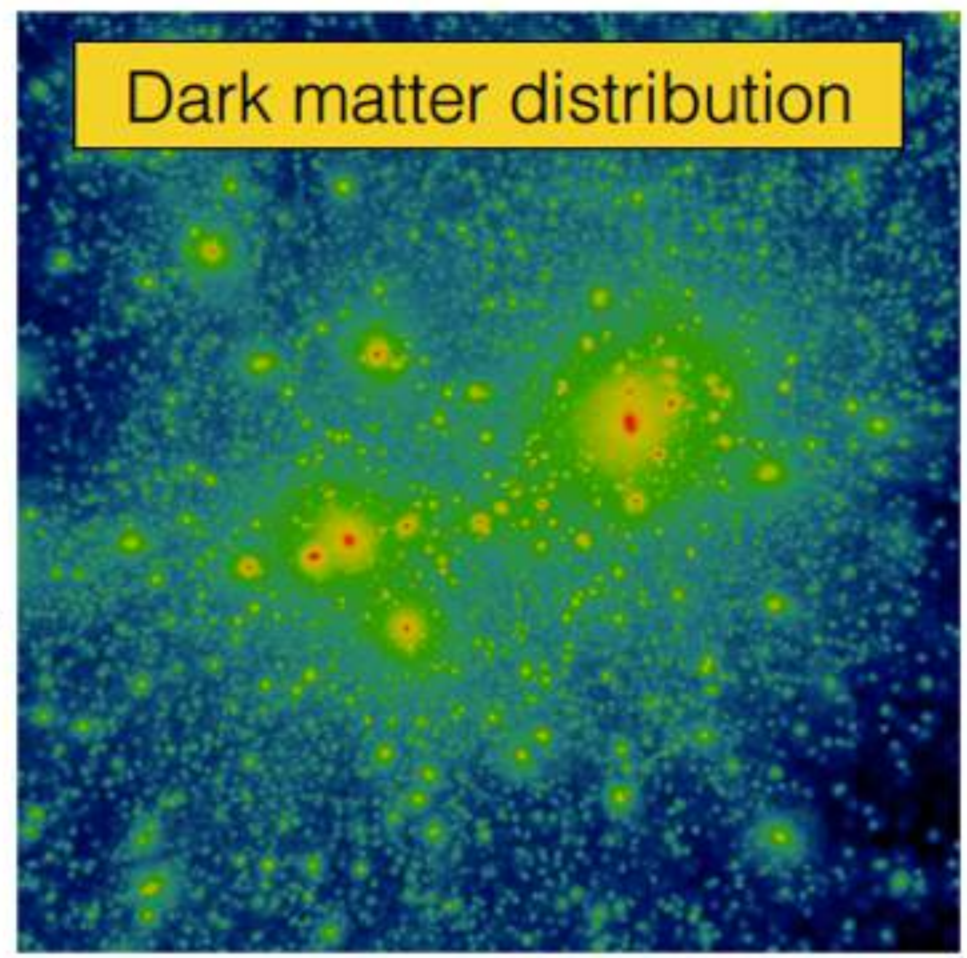
Particle Physics



Propagation

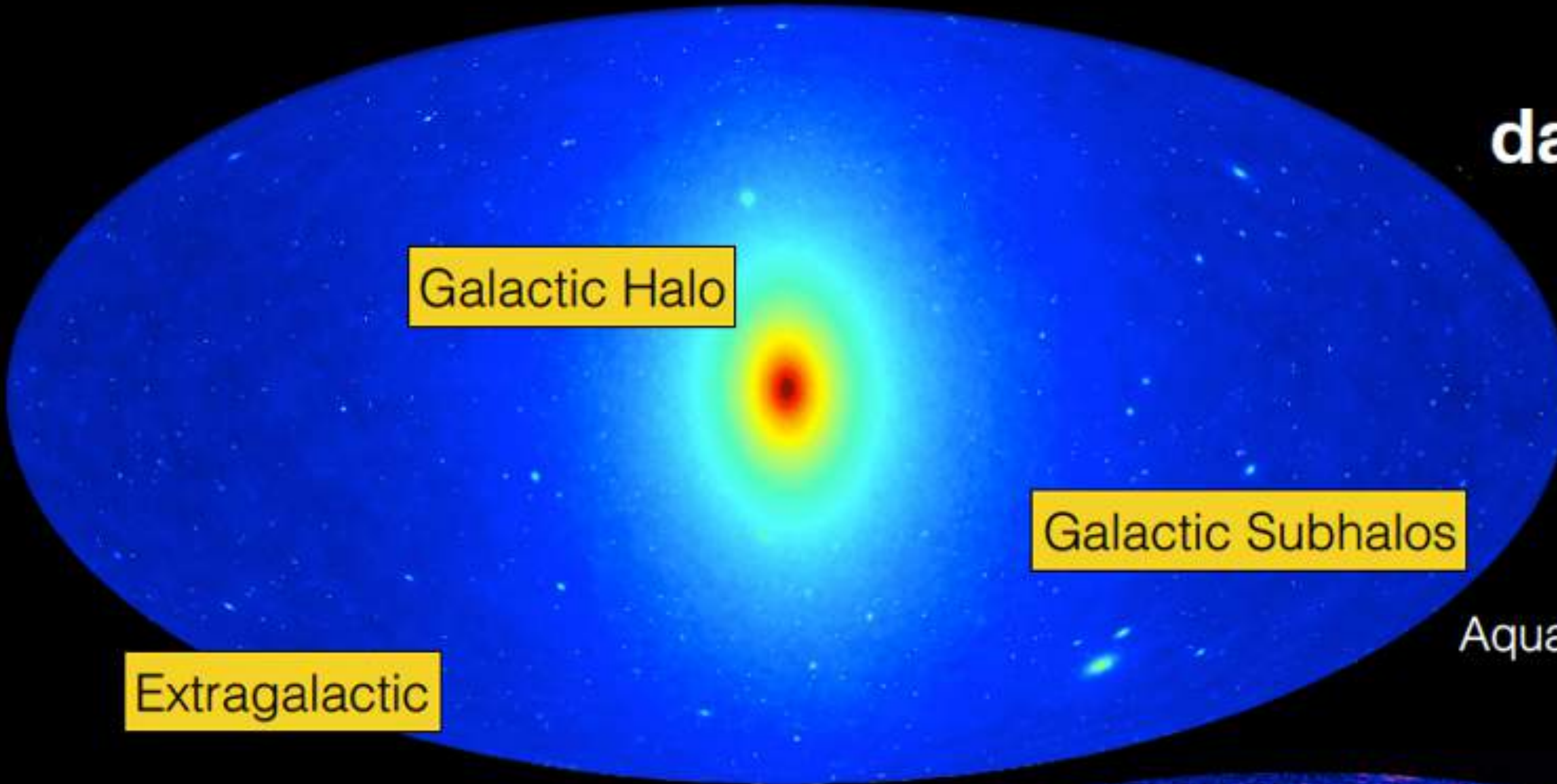
Example: Gamma-ray flux

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\text{J}-\text{factor}}$$



Numerical simulations, rotation curves, velocity dispersions, etc.

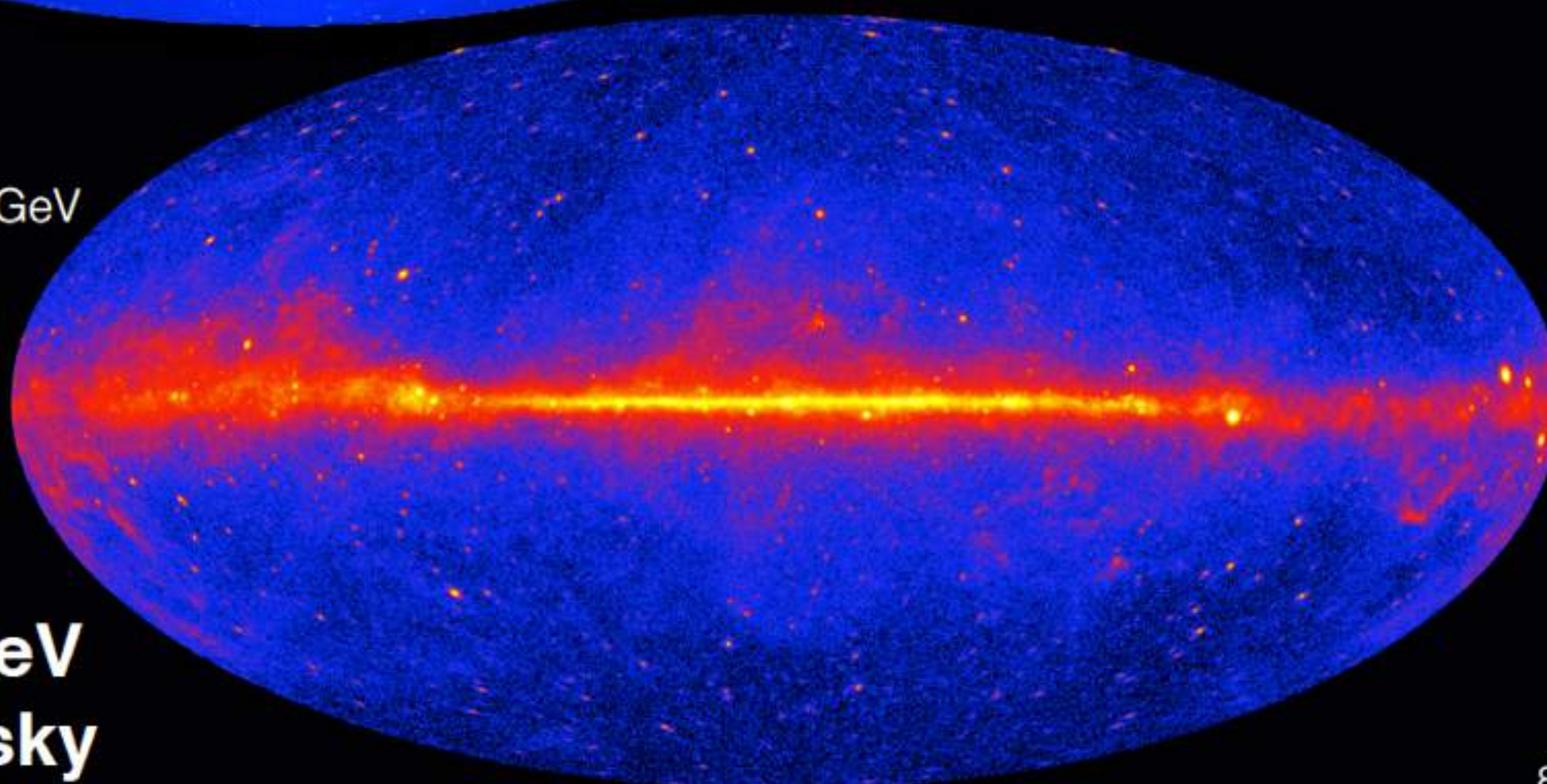
+ Model the "conventional" astrophysical emission processes



Theoretical dark matter sky
(annihilation)

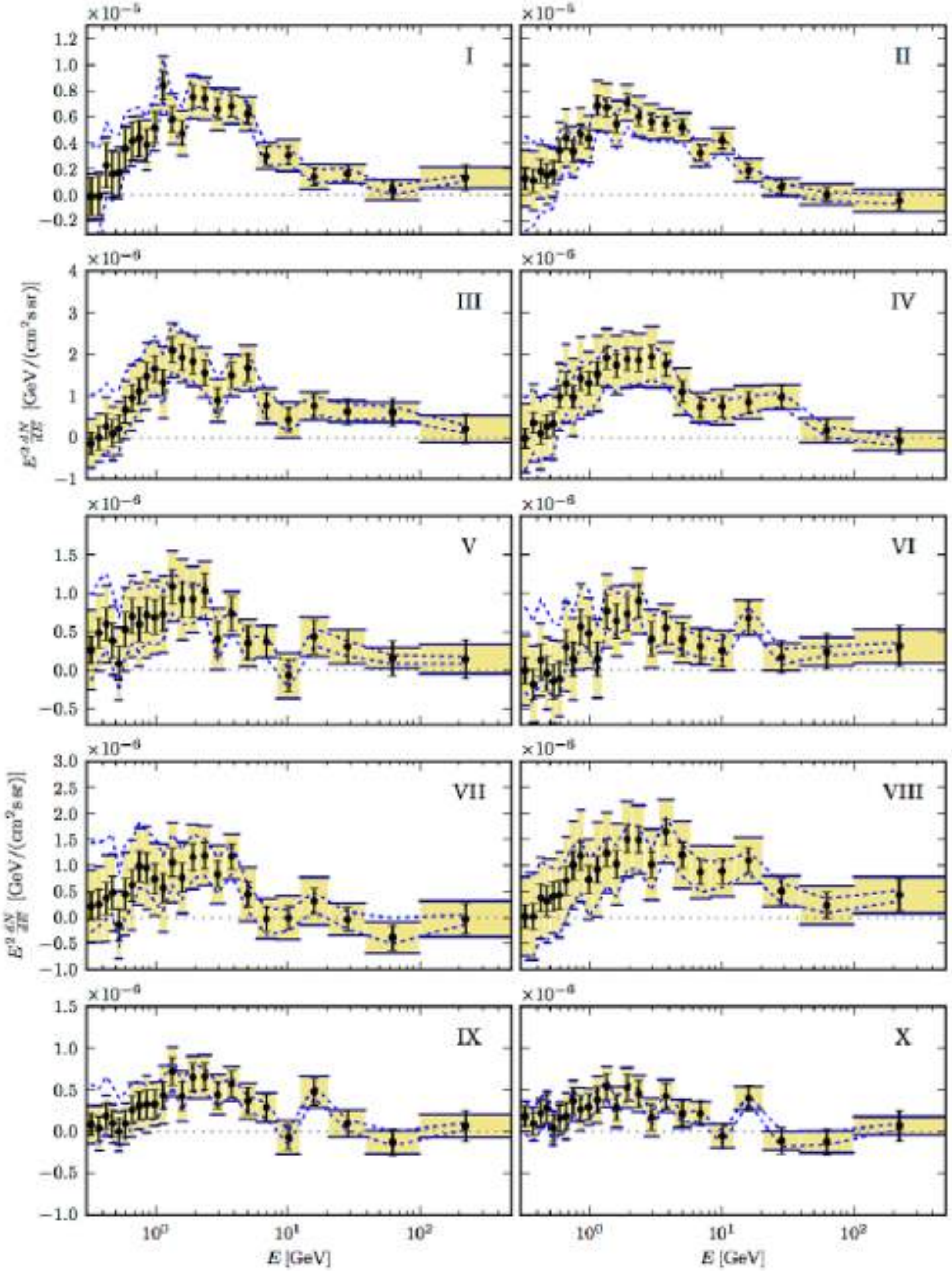
Aquarius simulation

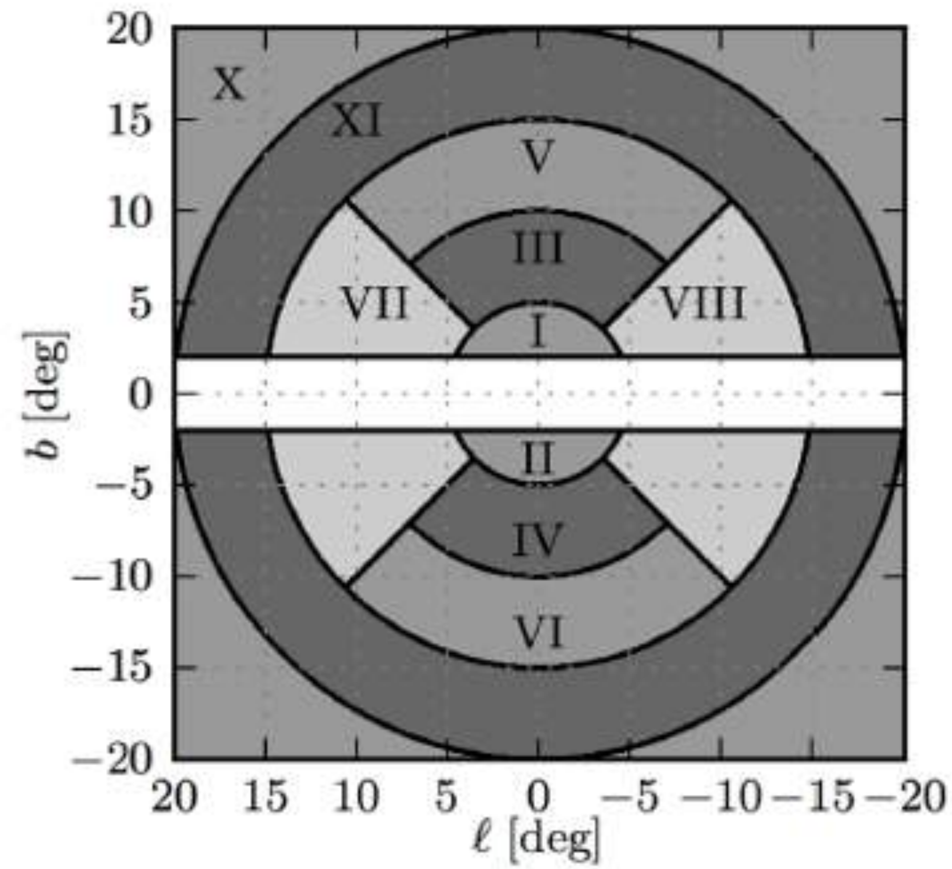
***Fermi*-LAT**, 5 years, >1 GeV



Observed GeV gamma-ray sky

Galactic Center Excess

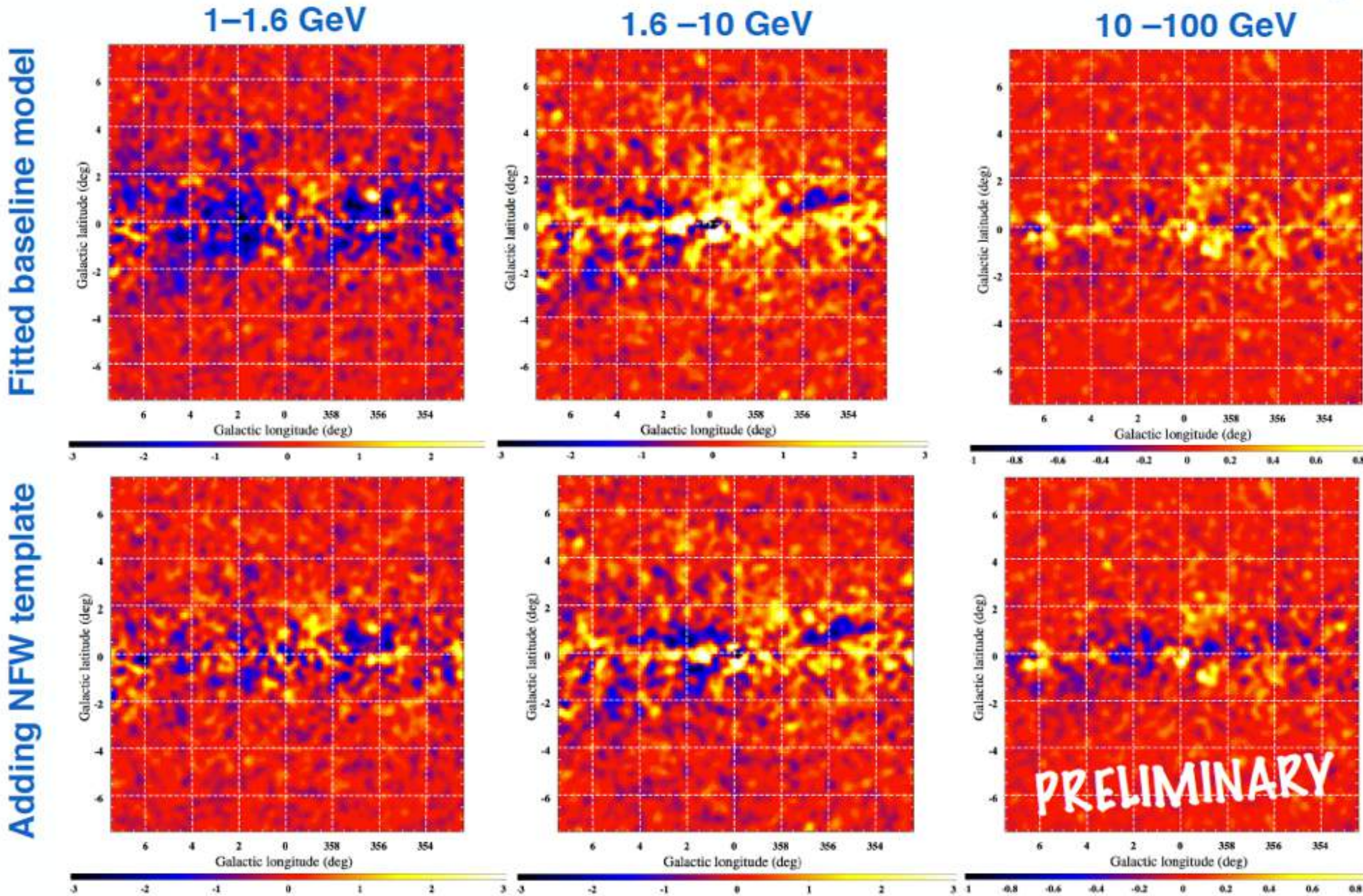




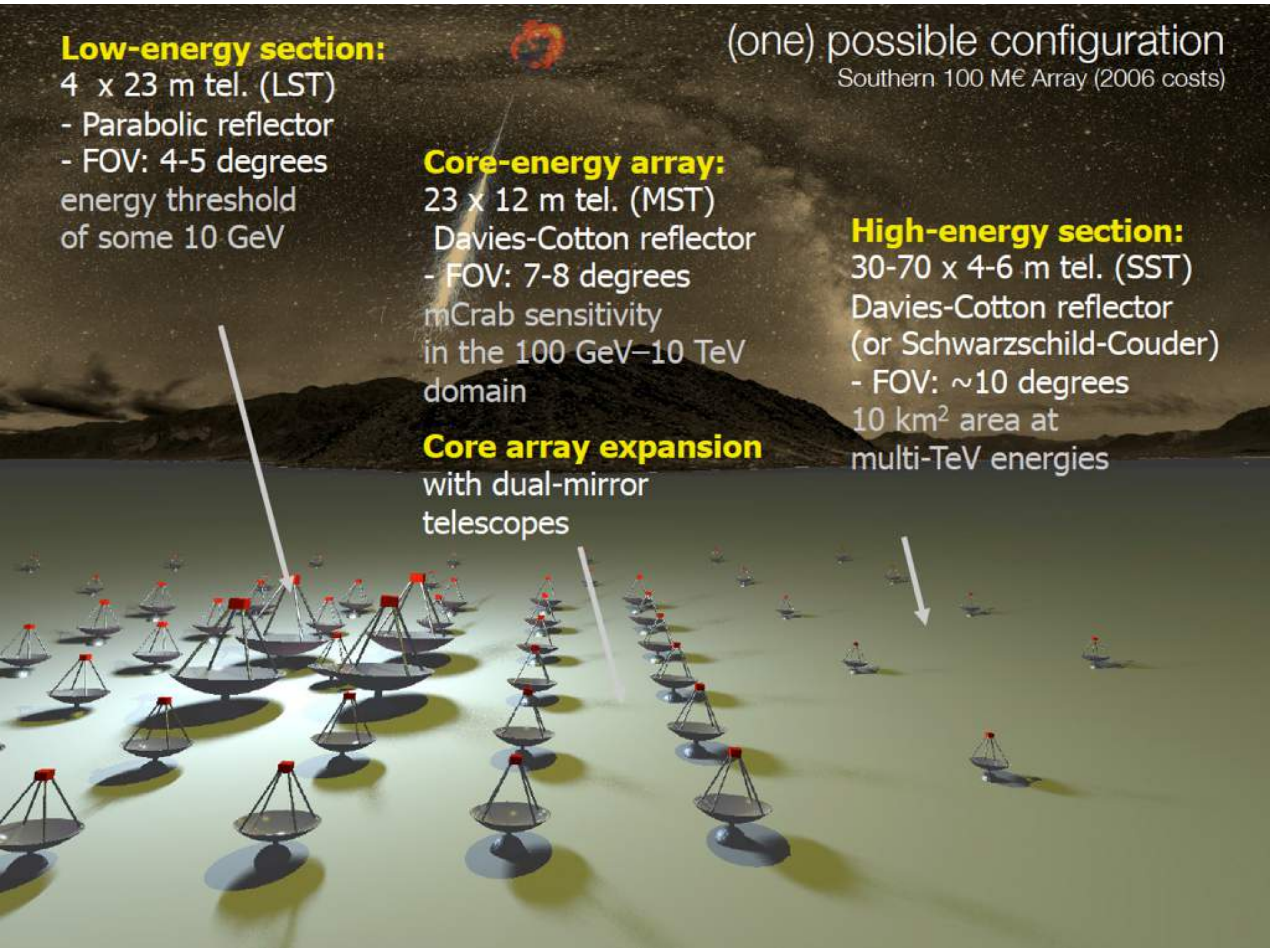
Consistent spectral form observed over much of the inner Galaxy extending at least 10° (1.5 kpc) from Galactic Center

Calore et al. 2015, JCAP, 03, 038
arXiv:1409.0042

Inner Galaxy: Residual Emission

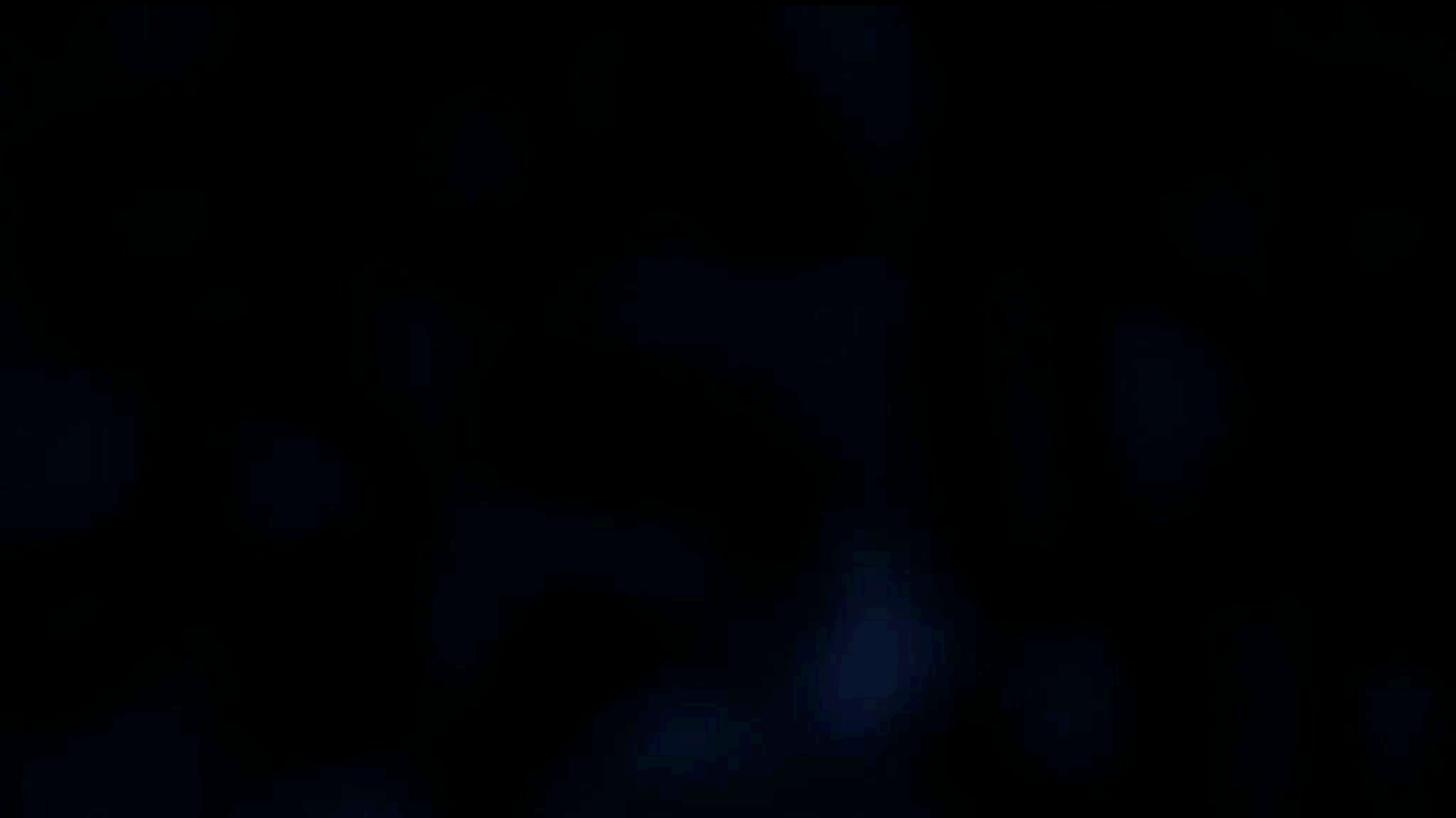


5. Future of Gamma-Ray astrophysics

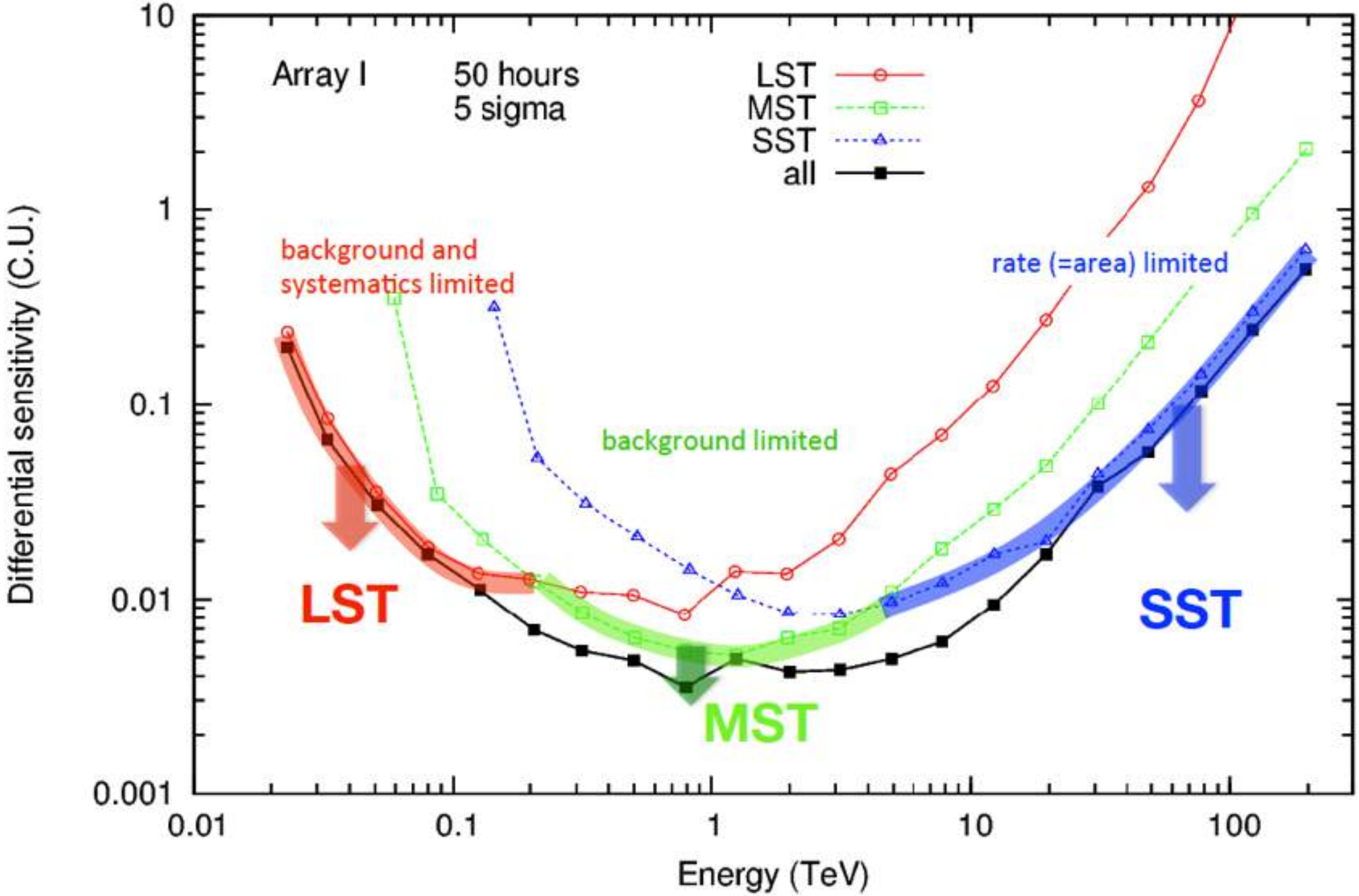

(one) possible configuration
Southern 100 M€ Array (2006 costs)
Low-energy section:
4 x 23 m tel. (LST)
- Parabolic reflector
- FOV: 4-5 degrees
energy threshold
of some 10 GeV
Core-energy array:
23 x 12 m tel. (MST)
Davies-Cotton reflector
- FOV: 7-8 degrees
mCrab sensitivity
in the 100 GeV–10 TeV
domain
Core array expansion
with dual-mirror
telescopes
High-energy section:
30-70 x 4-6 m tel. (SST)
Davies-Cotton reflector
(or Schwarzschild-Couder)
- FOV: ~10 degrees
10 km² area at
multi-TeV energies

Cherenkov Telescope Array

Cherenkov Telescope Array



5. Future of Gamma-Ray astrophysics



5. Future of Gamma-Ray astrophysics

Large Size Telescopes of CTA

大口径望遠鏡：国際チーム

ドイツ(40), スペイン(82), フランス(21), イタリア(28), 日本(60), ブラジル,スイス,インド, スウェーデン, クロアチア

望遠鏡主要パラメーター	
口径	23m
望遠鏡重量	100トン
高速回転	180°/20秒
追尾精度	14秒角

FPI/Elec (日、伊)
Camera body (西)

CSS (仏、伊)

MIR (日)
Interface PL (独、伯、日)
Actuator (日、瑞)
CMOS-Cam (独、日)

StarGuider (瑞典)
CalibBox (印、伊)

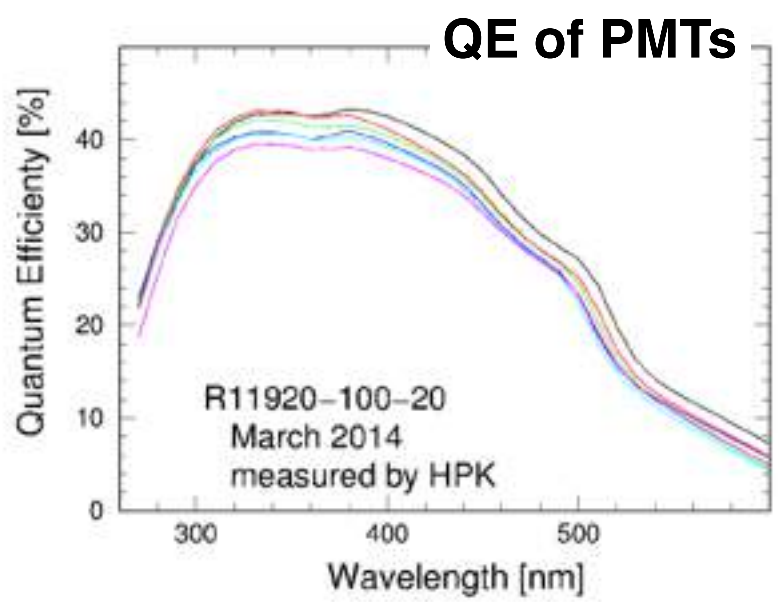
Structure (独)
Access Tower (独)

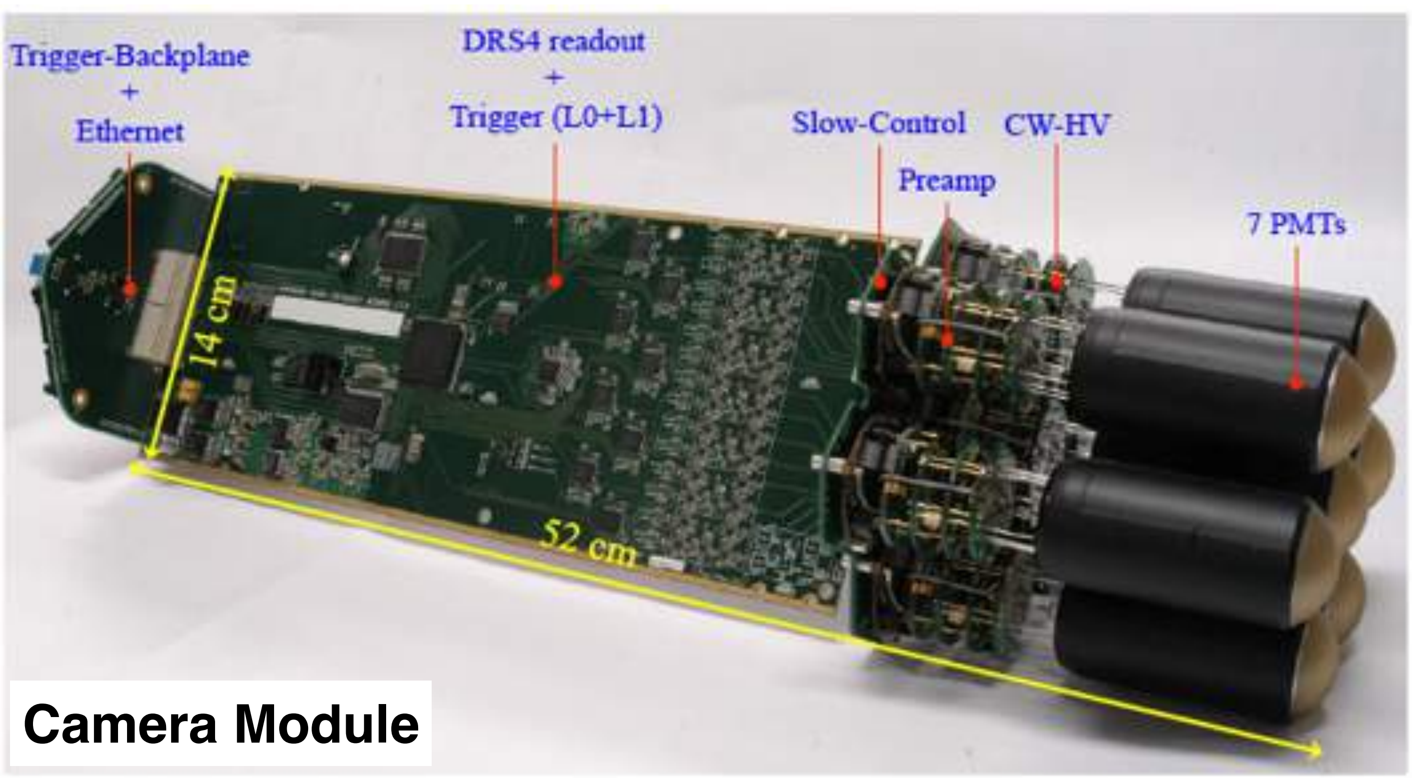
Drive (独/仏/西)
Bogie (独/西)
Rail (独/西)
Found. (独/西)

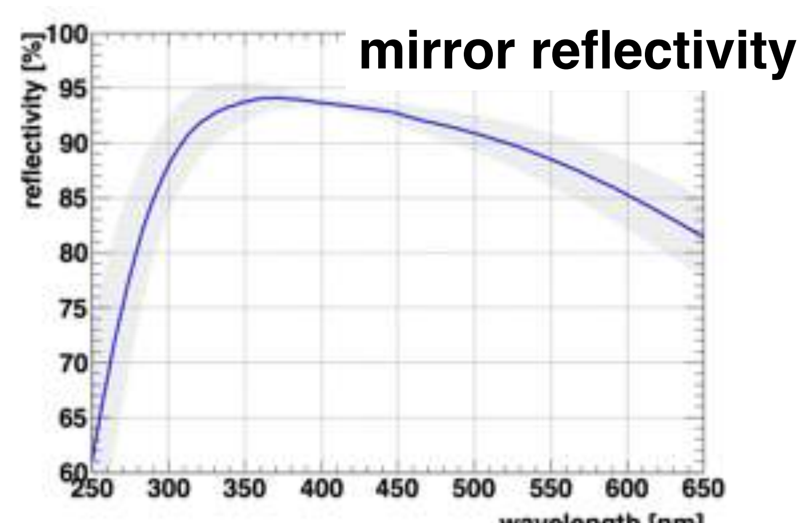
Flywheel, UPS (独、西)
Comp. (独、伊、日)

Large Size Telescope of CTA

Light Guides

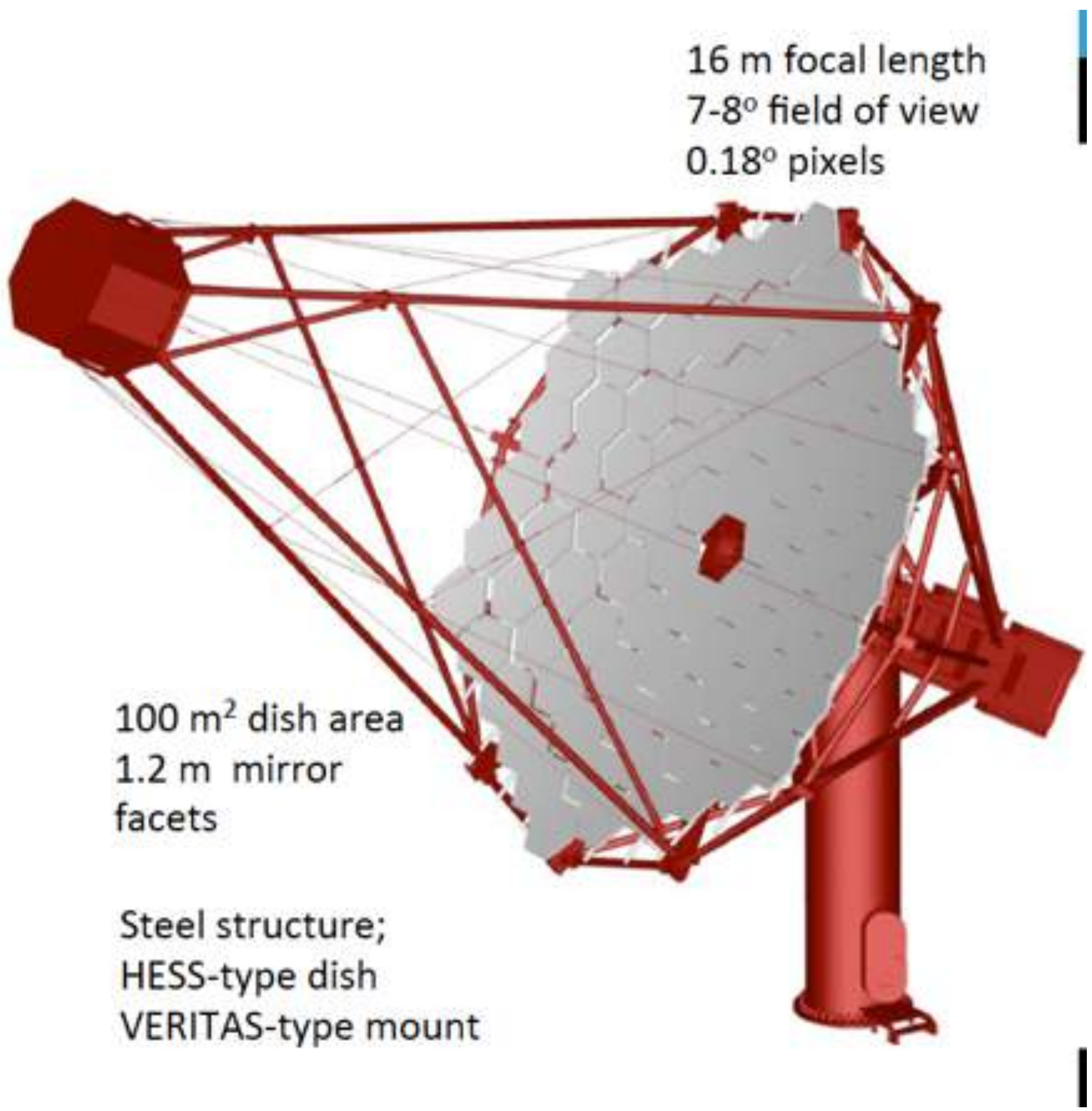




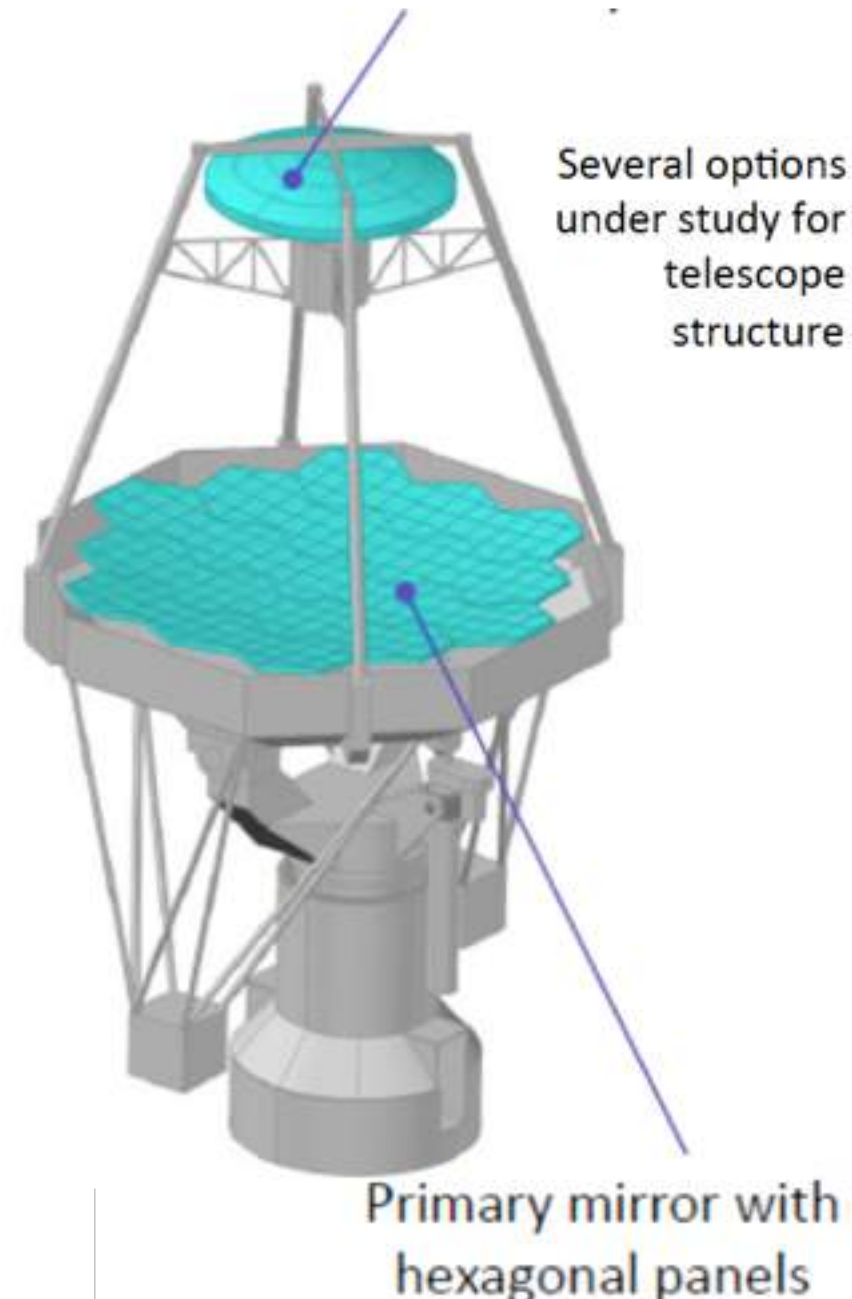


5. Future of Gamma-Ray astrophysics

Medium Size Telescope



Small Size Telescope



The corner stone ceremony at ORM La Palma 2015 Oct

Your future

BACKUP

Search for Cold Dark Matter

Hypothesis: DM = WIMPs

- Indirect detection of WIMP annihilation → γ, ν etc.

$\chi + \chi$

$\nu, \bar{\nu}$

γ **continuum**

γ **lines**

Point back to source

$\bar{p}$

e^{+}

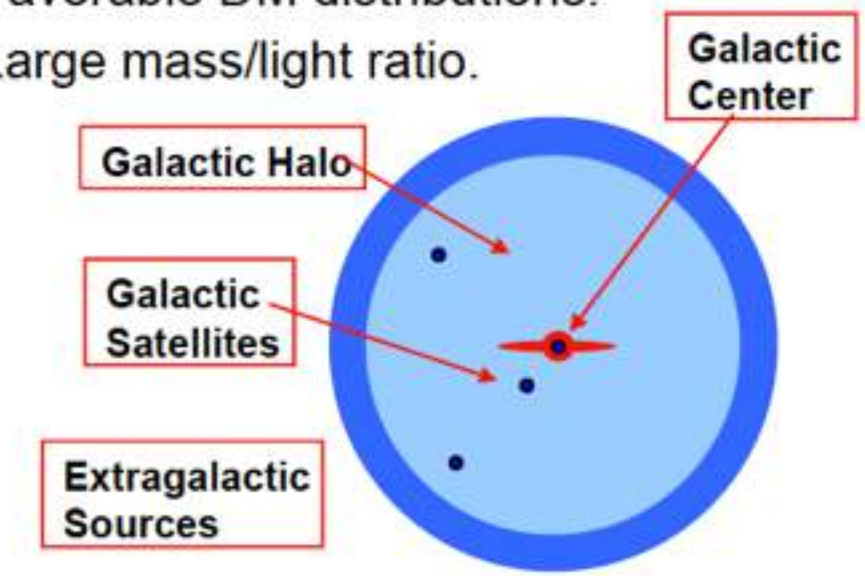
$\bar{d}$

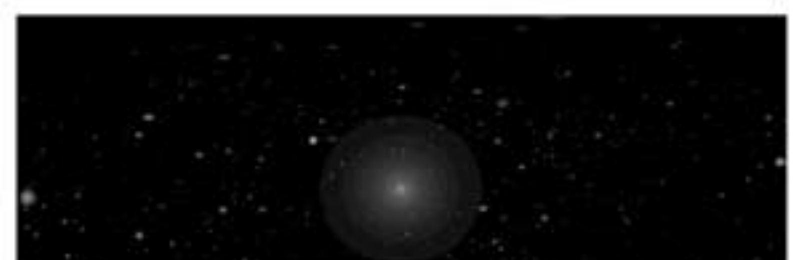
Search for excess components in cosmic rays (Diffusion)

(PAMELA,AMS,GAPS)

Target regions with:

- Favorable DM distributions.
- Large mass/light ratio.





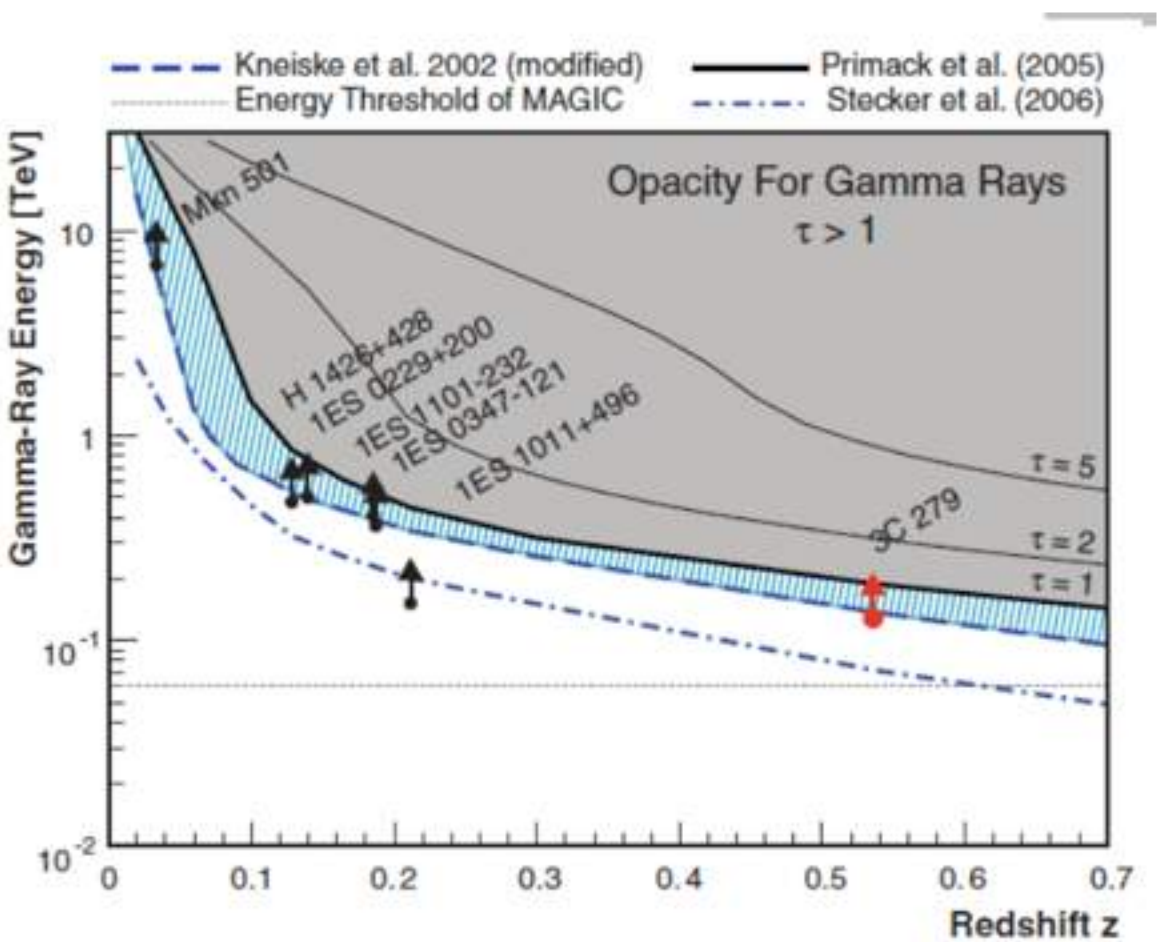
Simulated γ-ray signature in galaxy
Taylor & Babul (2005)

Complementary approach to direct detection & LHC
Goal is to do DM astronomy !

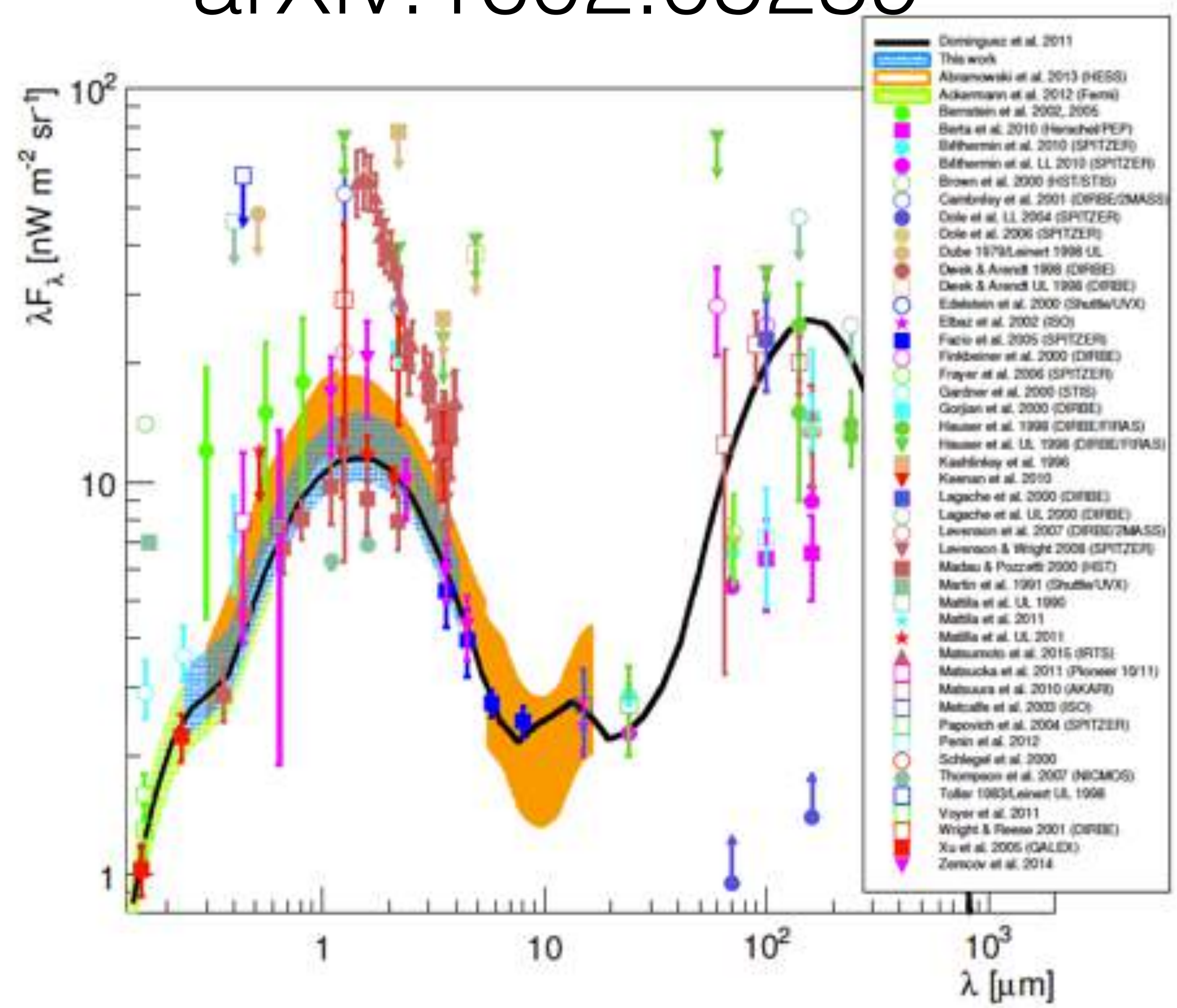
4. What do we learn from gamma rays?

EBL

MAGIC, Science 320,1752 (2008)



MAGIC, accepted by A&A, arXiv:1602.05239

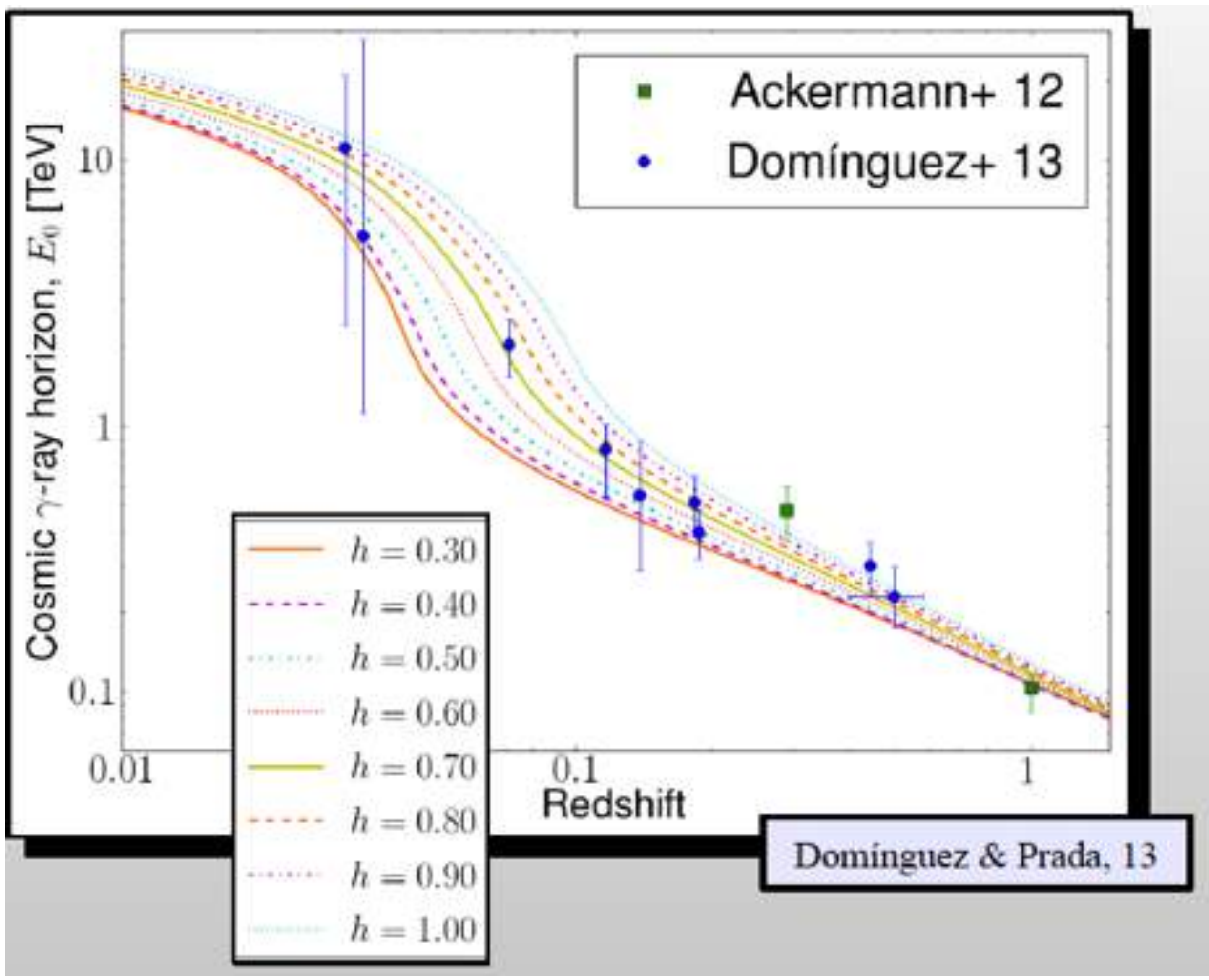


Not much more EBL than the one from the resolved galaxies

4. What do we learn from gamma rays?

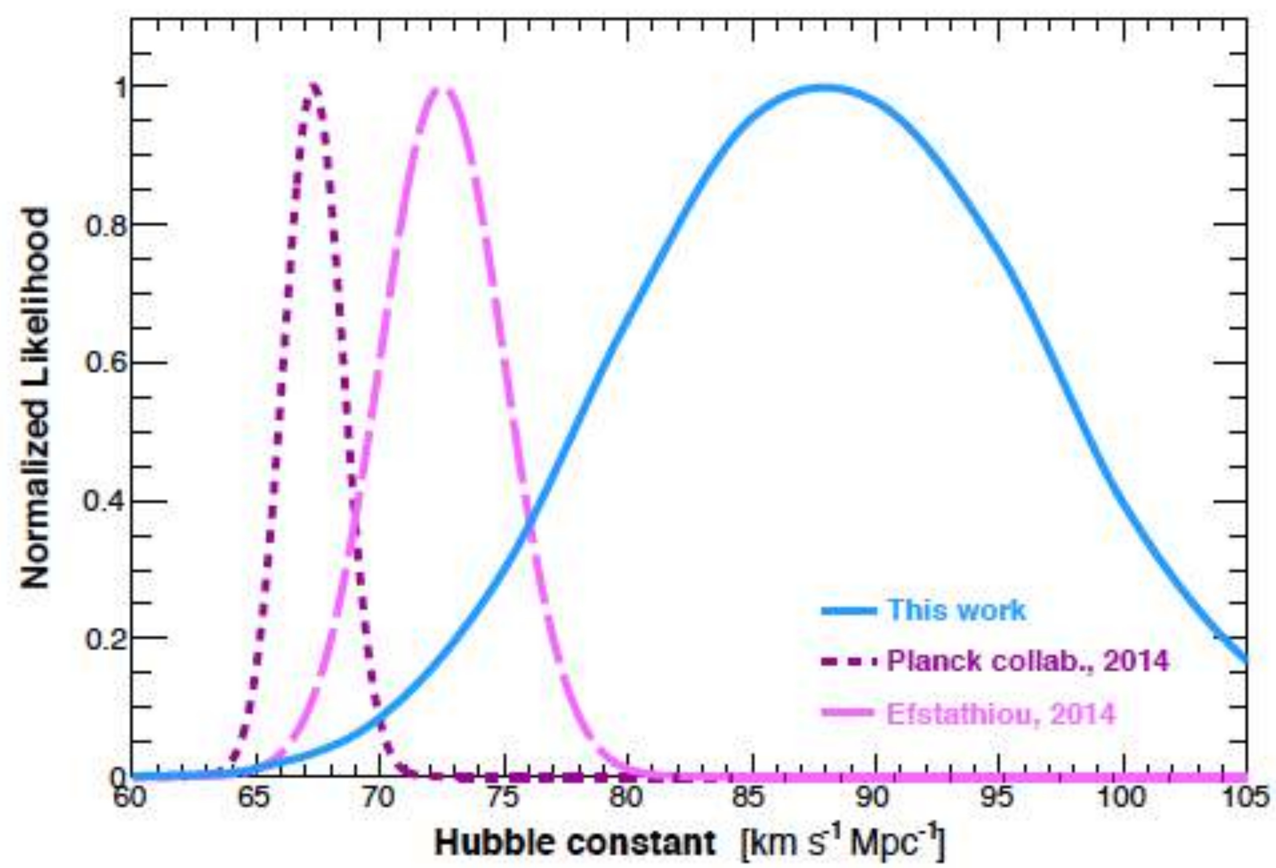
4.3 Observational cosmology: Hubble constant

Dominguez et al (2013)



$H_0 = (72 \pm 5_{stat} \pm 10_{syst})$ km/s/Mpc

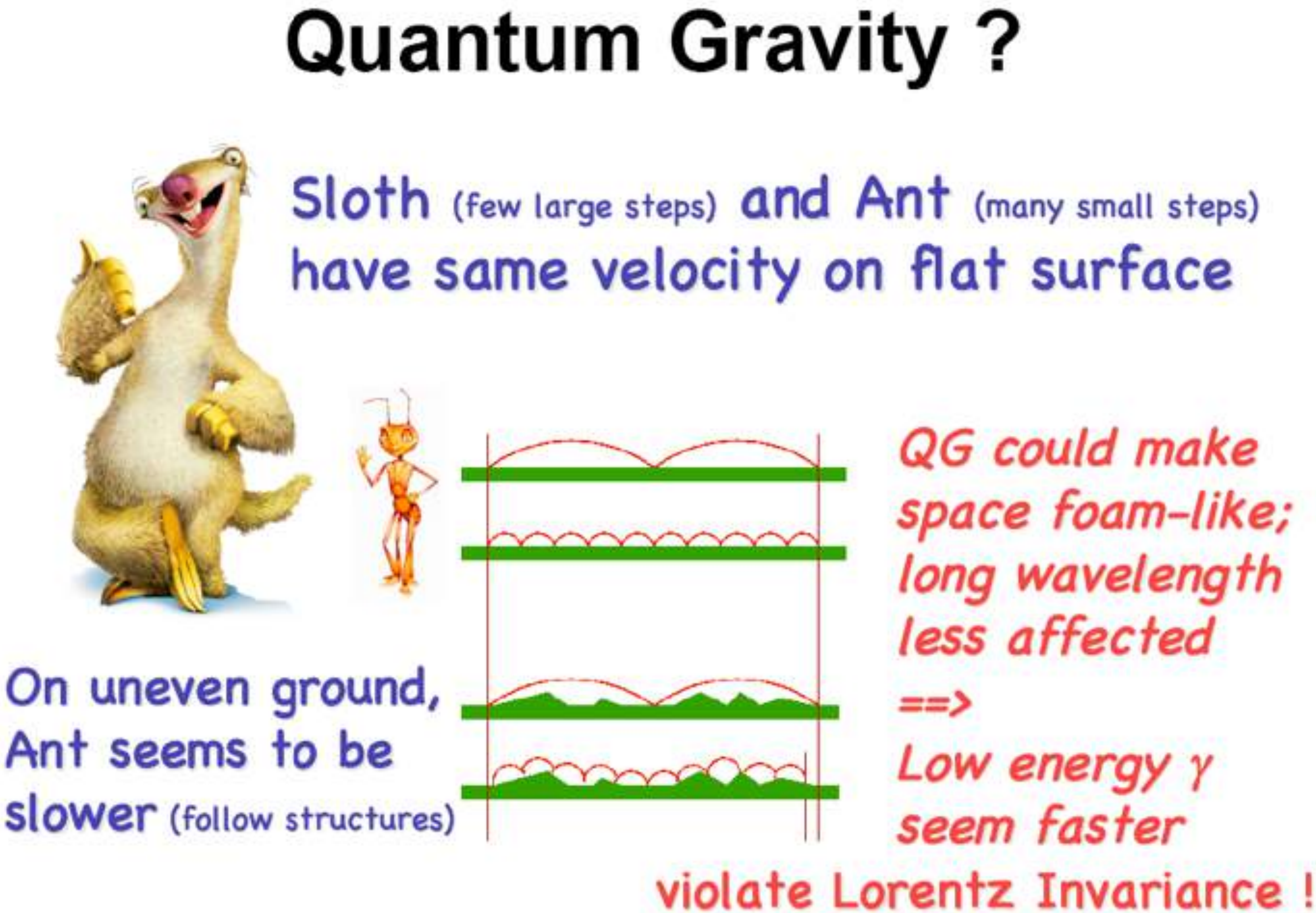
Biteau&Williams (2015)



$H_0 = (88 \pm 8_{stat} \pm 13_{syst})$ km/s/Mpc

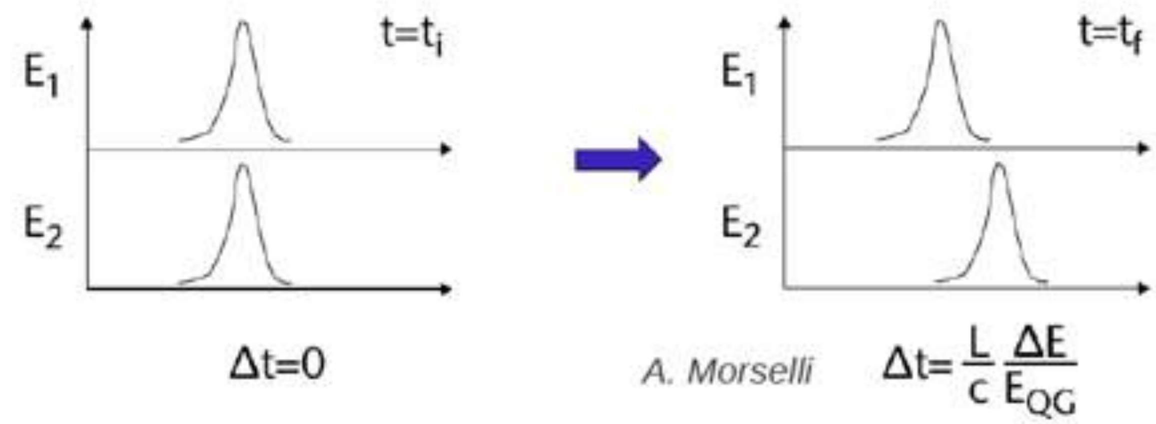
4. What do we learn from gamma rays?

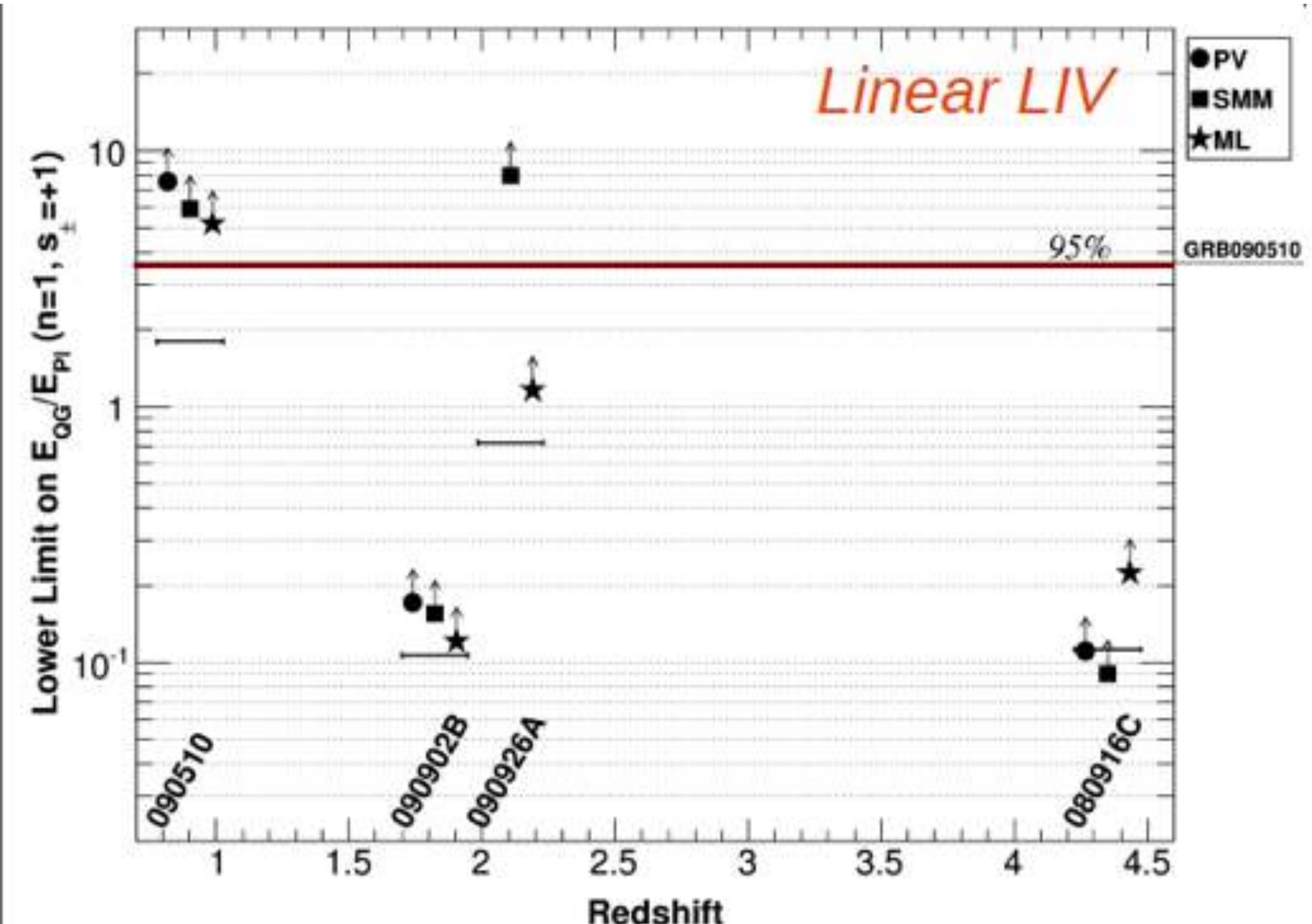
4.4 Fundamental physics: Lorentz invariance violation

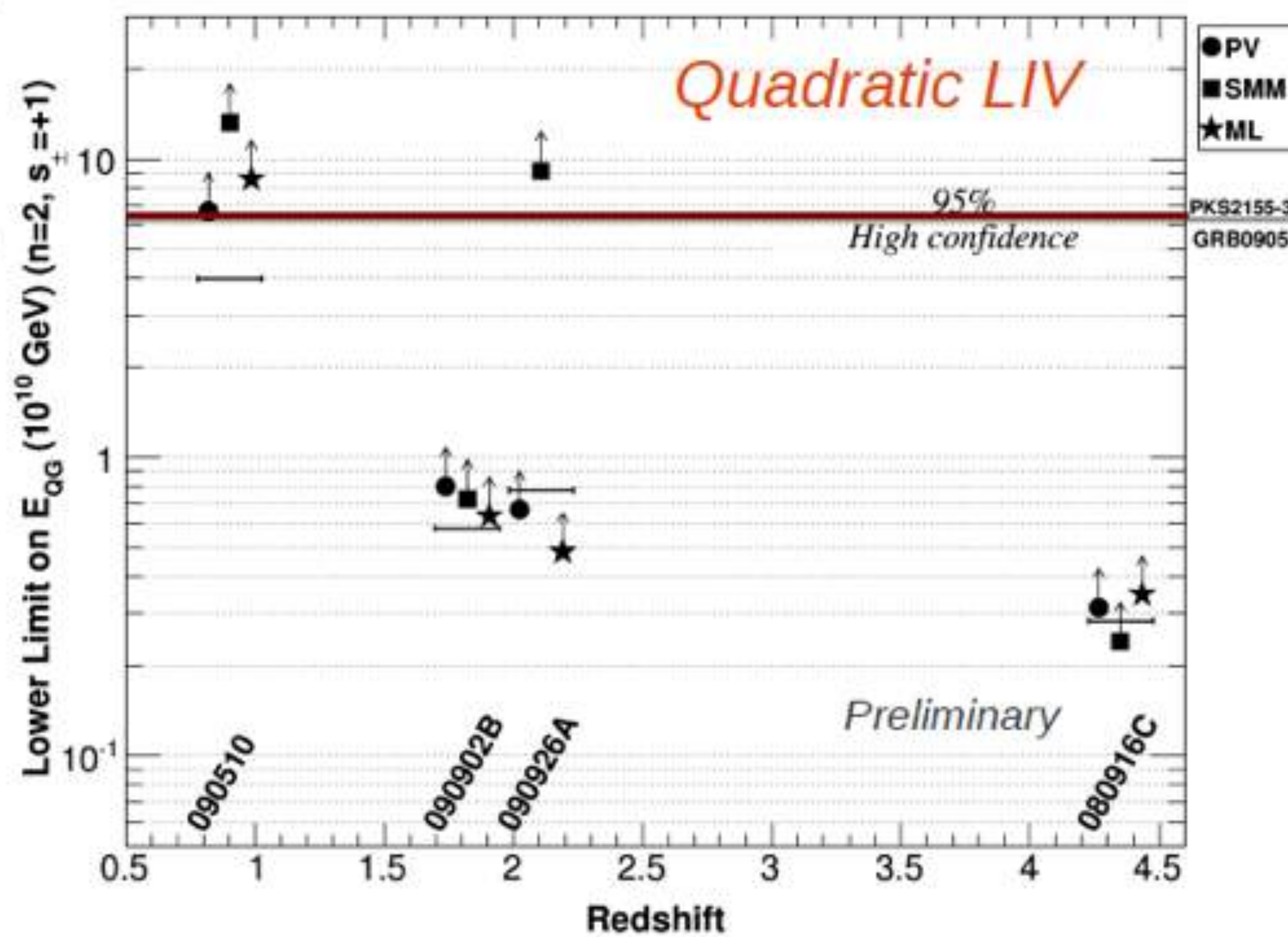


4. What do we learn from gamma rays?

- Assume that they were emitted at the same time
- Check on different sources and distances

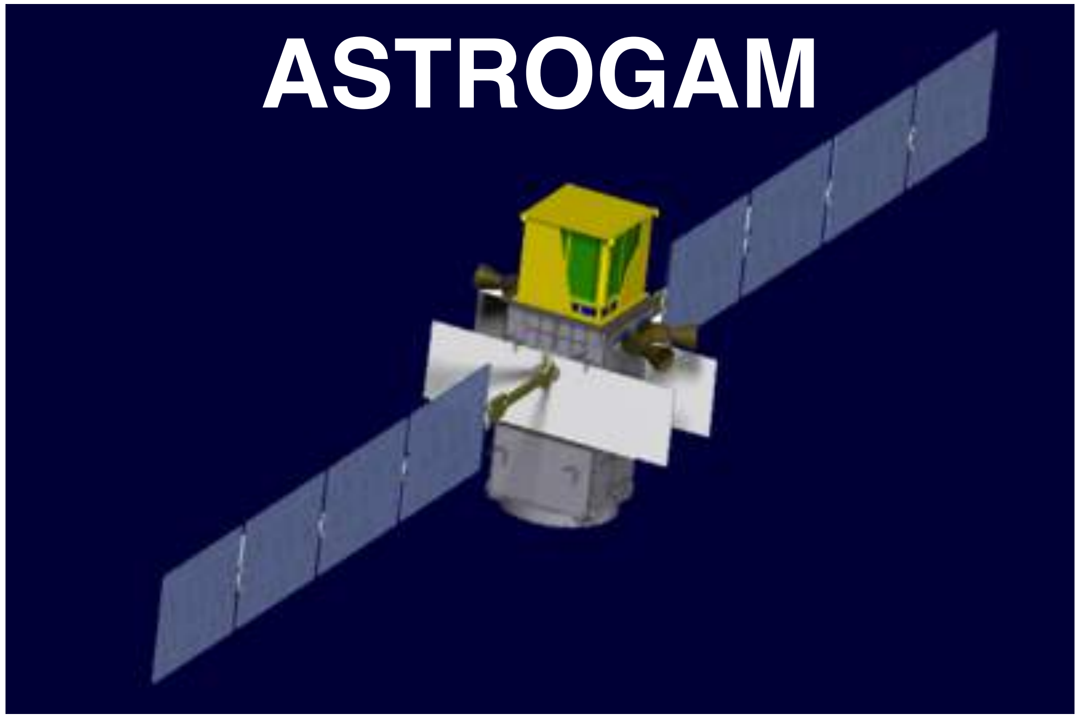


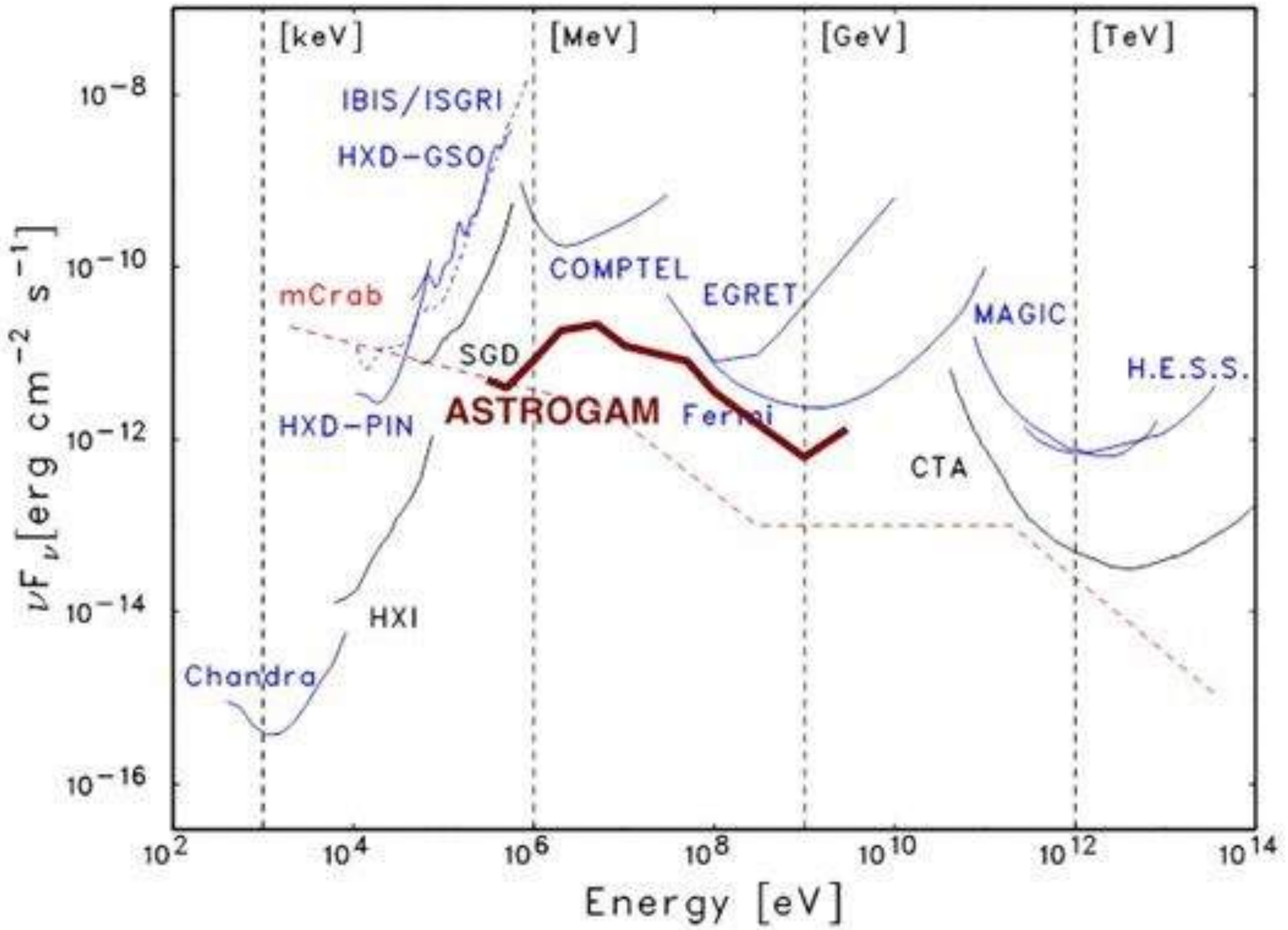


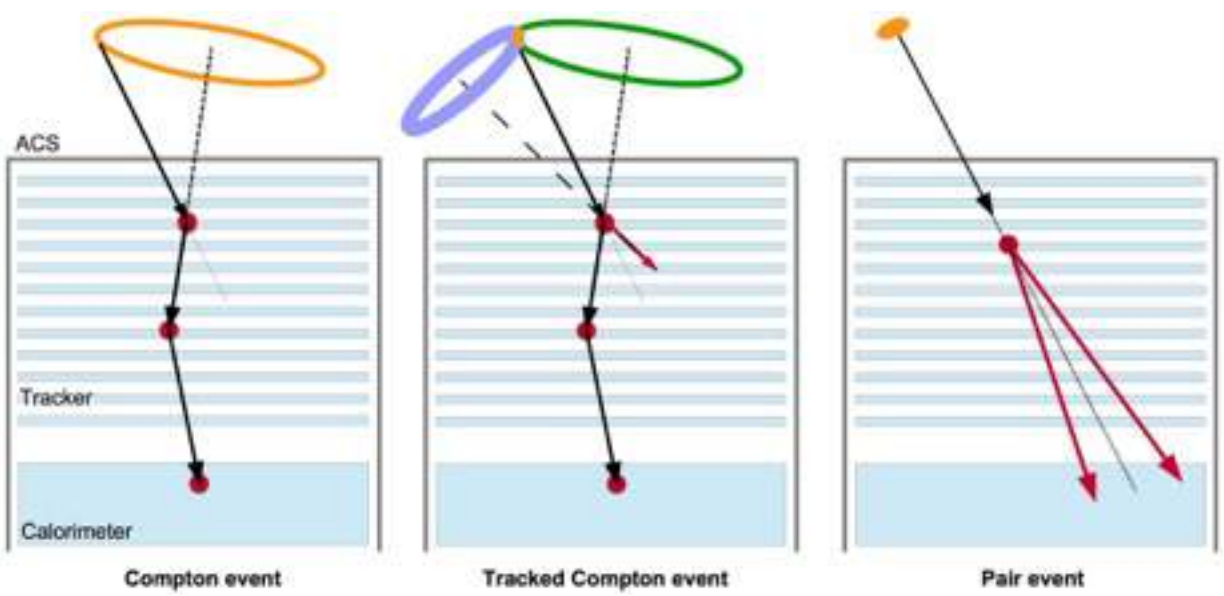


5. Future of Gamma-Ray astrophysics

- **0.3-100 MeV, extending to GeV**
- **70 planes DSSD tracker**
- **2.7 rad. length Calorimeter**
- **~1deg angular resolution**
- **~15% energy resolution**
- **2.6 sr Field Of View (21% of the sky)**



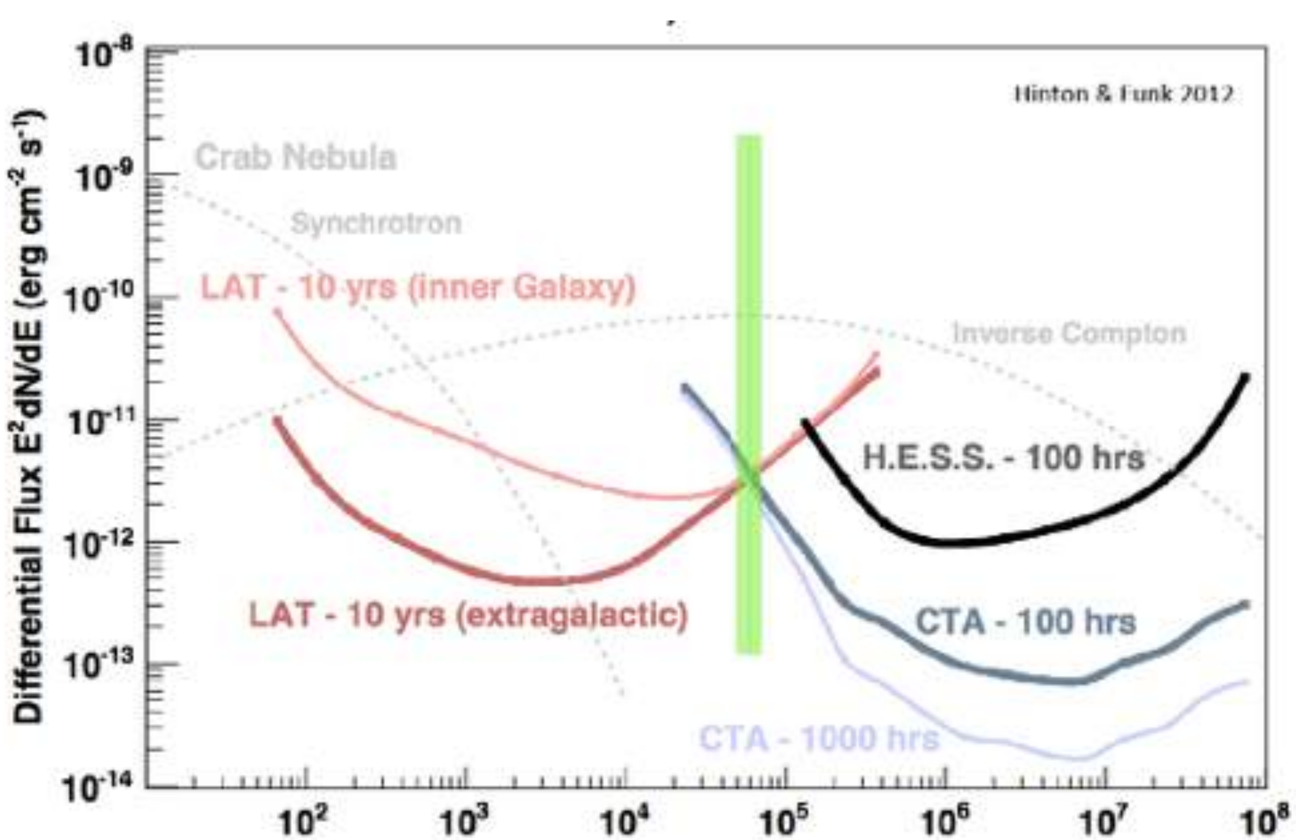




5. Future of Gamma-Ray astrophysics

CTA in MWL context

Flux sensitivity
for steady sources



Flux sensitivity
for transient sources