High energy gamma-ray astronomy

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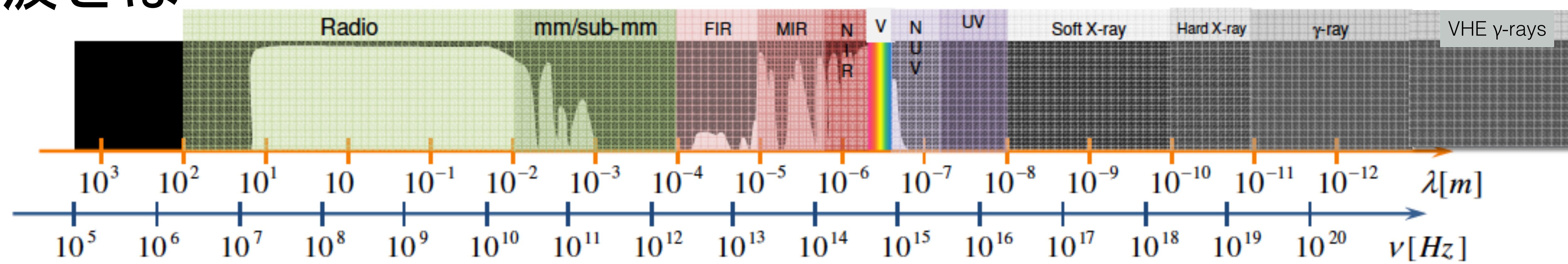
    2. Source Physics
    3. Observational Cosmology
    4. Fundamental physics
5. **Future of gamma-ray astrophysics: CTA!**

1. Multiwavelength sky

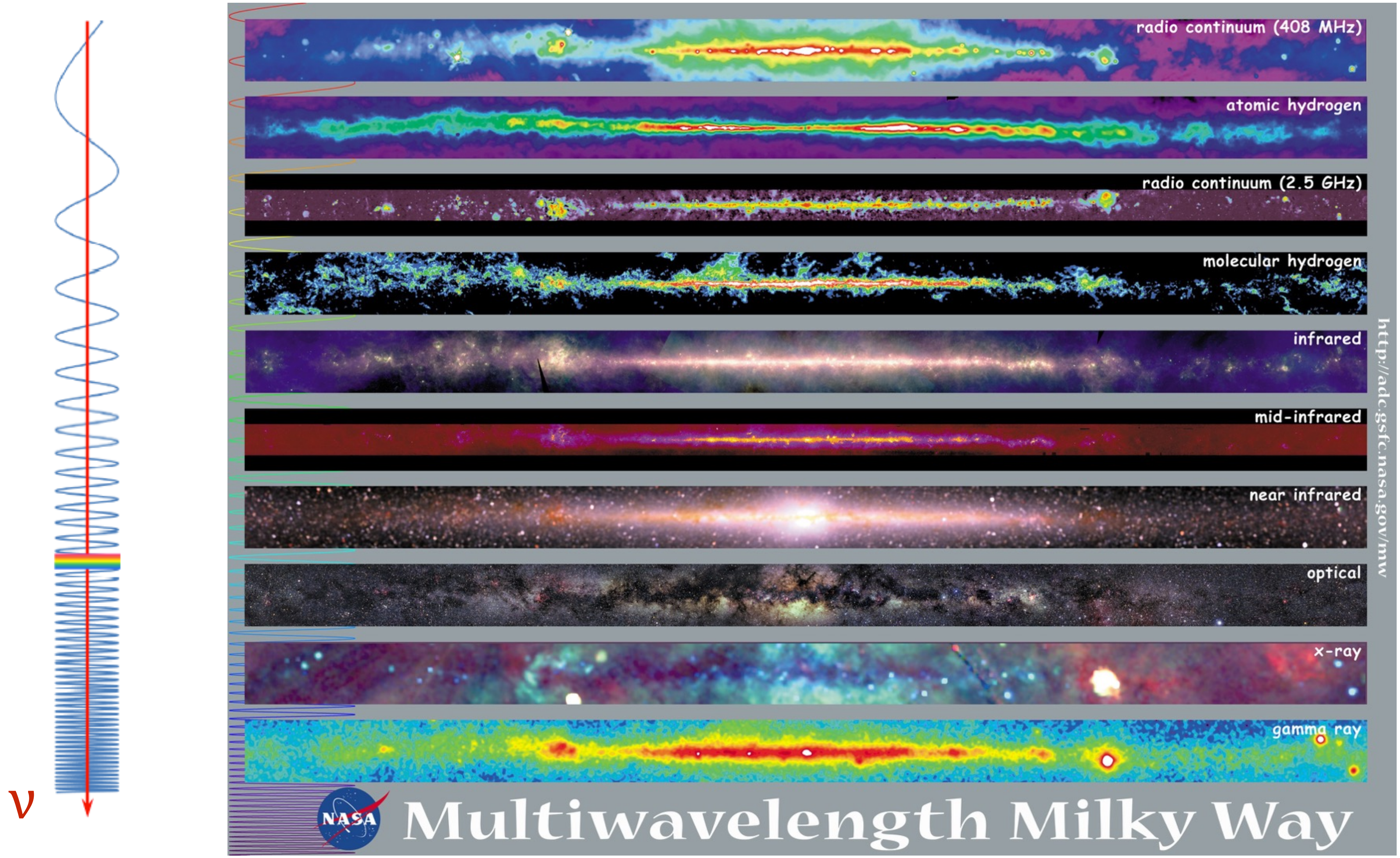
電磁波とは



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

1. Multiwavelength sky

様々な波長で宇宙をみる



Major part of what we observe is high energy astrophysics

1. Multiwavelength sky

様々な波長で宇宙をみる

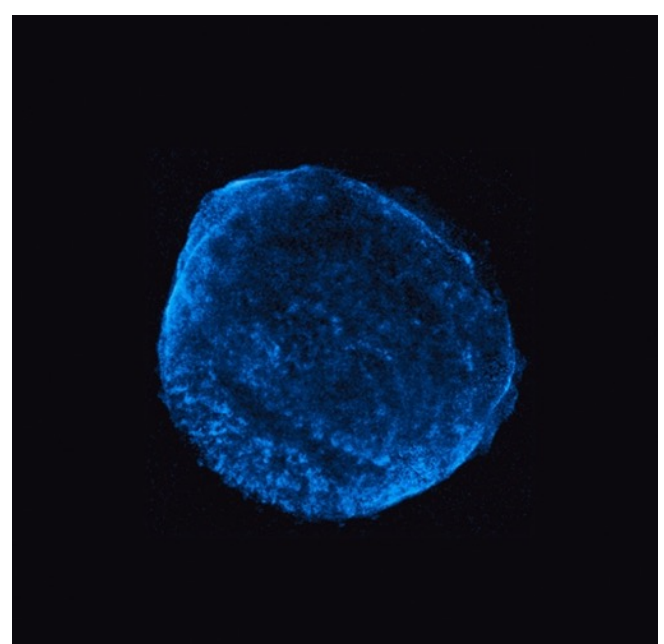
手

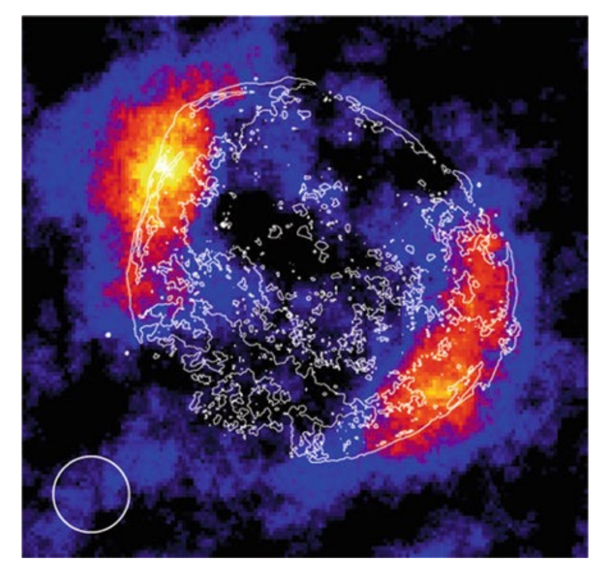
可視光

X線

超高エネルギーガンマ線

超新星残骸
SN1006





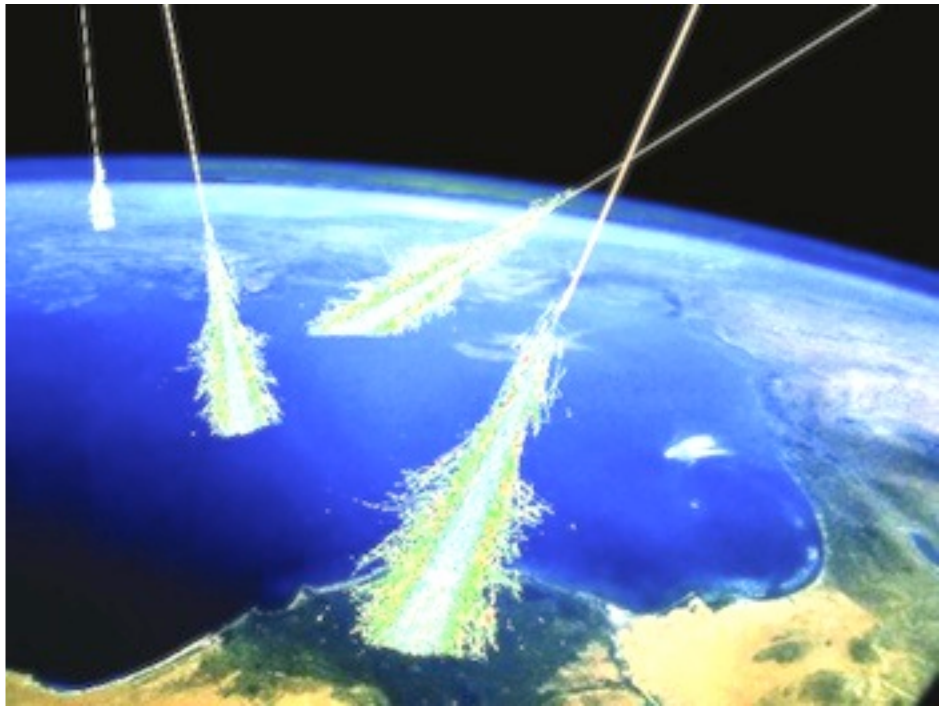
1. Multiwavelength sky

超高エネルギーガンマ線観測の目的は大きく３つ

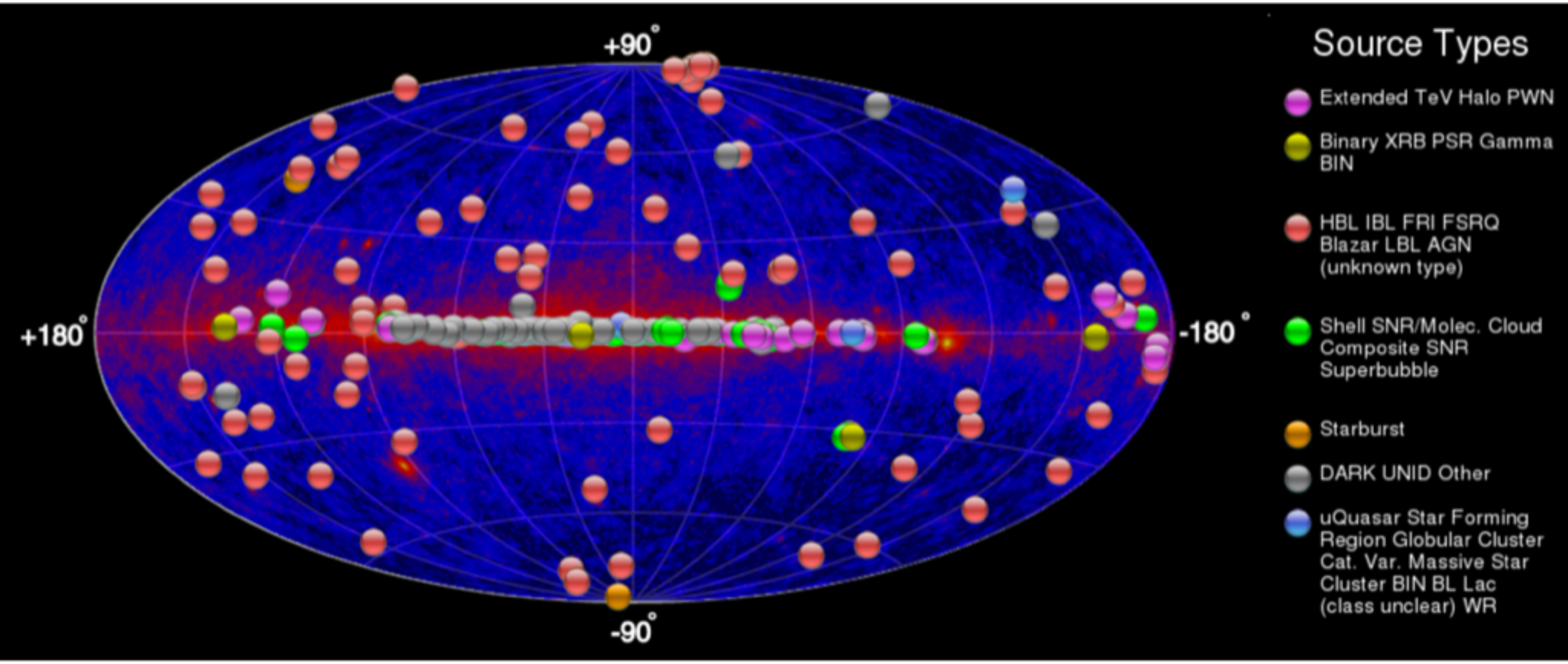
1. 宇宙線の起源と生成機構の解明

2. ブラックホール、中性子星のそばの物理現象
   - 超強重力
   - 超強磁場

3. 最先端基礎物理への貢献
   - 暗黒物質の探索
   - 量子重力理論の検証



1. Multiwavelength sky

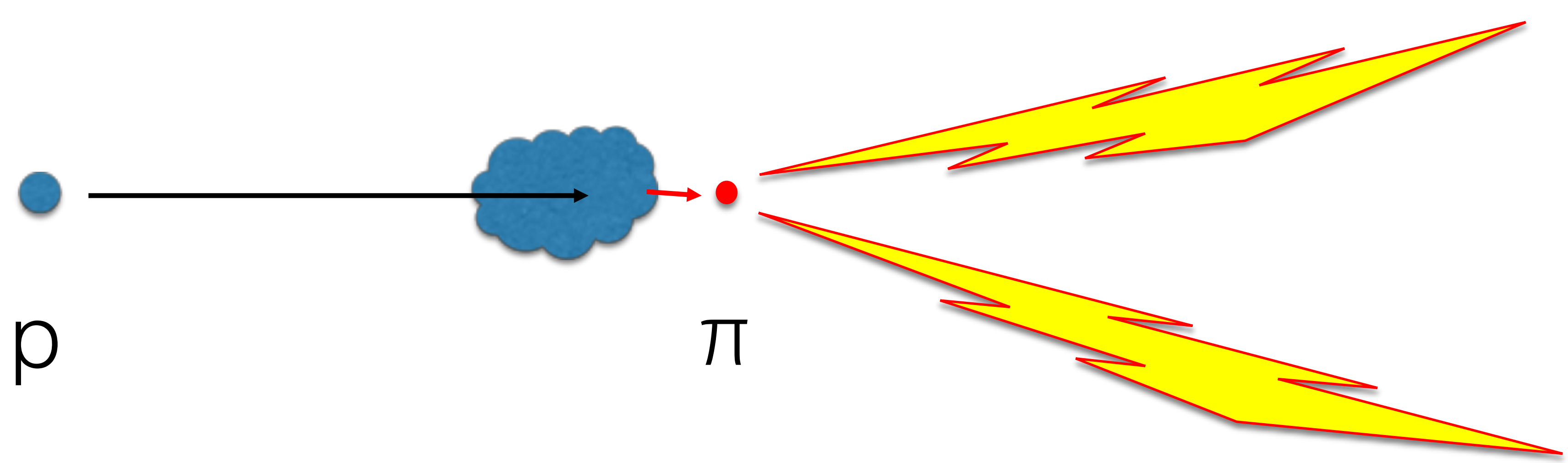


- Nominally 222 sources as of March 1, 2019
- Dominated by HESS, MAGIC and VERITAS
- Contains already 20 HAWC sources

2. How to produce gamma rays?

From protons

- **Pion decay**
  - Accelerated protons (p) interact with matter
  - $p \ p \rightarrow X + \pi_0 \rightarrow \gamma \ \gamma$



2. How to produce gamma rays?

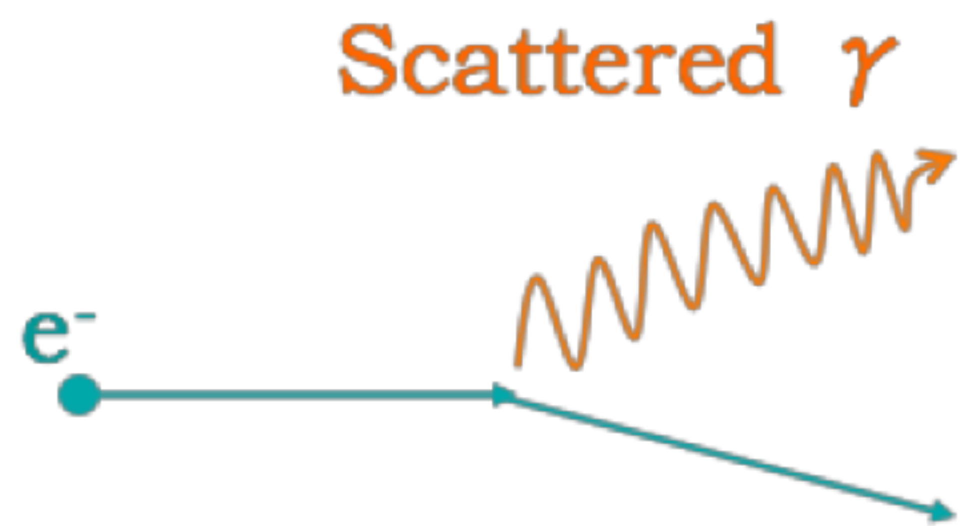
From electrons

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

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

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

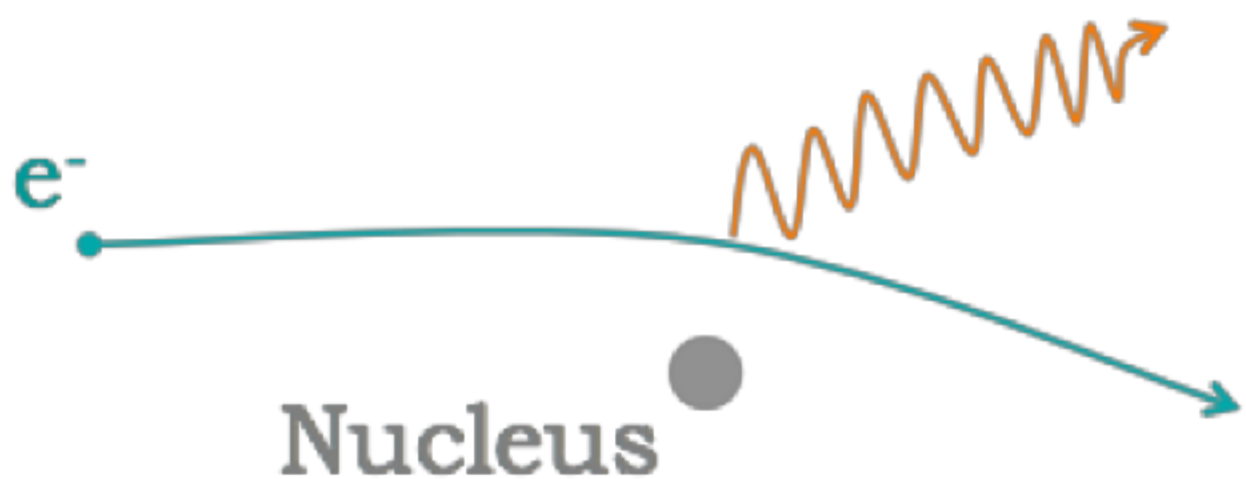
$$\gamma_{\text{Lorentz}} = 1/\sqrt{(1 - v_e^2/c^2)}$$



2. How to produce gamma rays?

From electrons

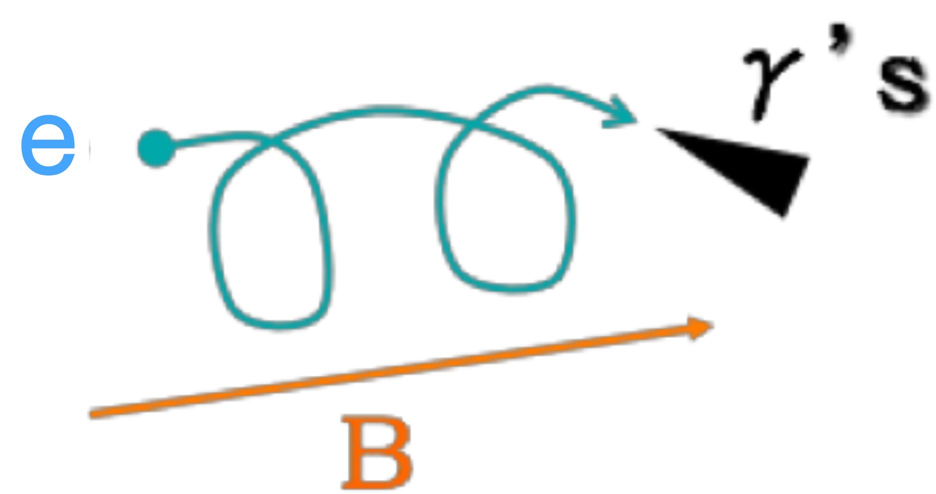
- **Bremsstrahlung**
  - Electron deceleration by a nucleus
  - Highly relativistic electrons emit gamma rays in atomic or molecular material
  - $Energy_{\gamma} \sim Energy_{e}$



2. How to produce gamma rays?

From electrons

- **Synchrotron Radiation**
  - Electron deceleration by magnetic field
  - Energy$_\gamma \sim \frac{\hbar c}{\lambda}\Gamma^2$

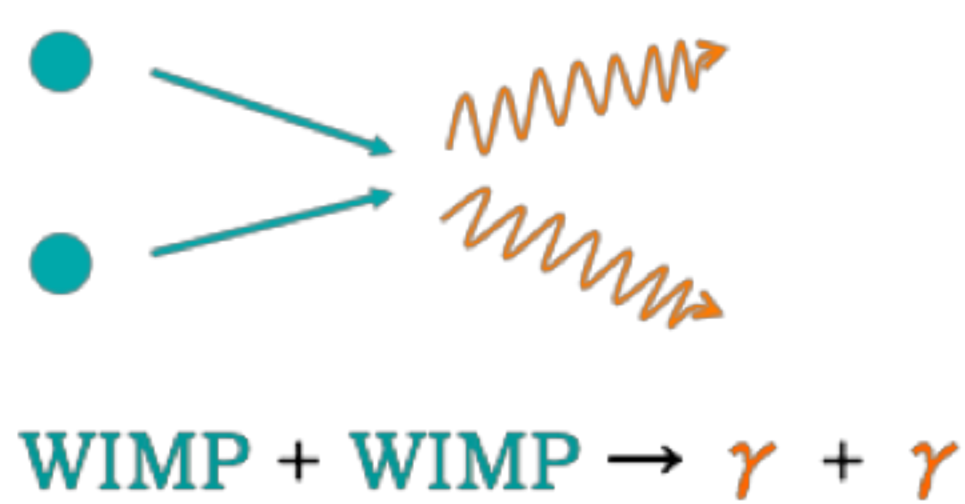


2. How to produce gamma rays?

Other ways to produce gamma rays

- Topological defects left over from the Big Bang
- Evaporation of Primadial 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 → X+ γ

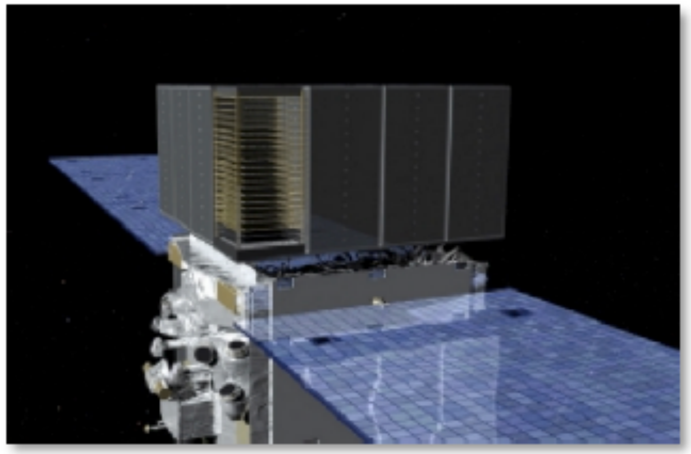


3. How to detect gamma rays?

3. How to detect gamma rays?

GAMMA RAY TELESCOPES

Space-based pair production telescopes



0.1 – 100 GeV
Small area
Background-free
Large field of view
High duty cycle

Imaging Atmospheric Cherenkov Telescopes

50 GeV – 100 TeV
Large area
Excellent bg rejection
Small field of view
Low duty cycle

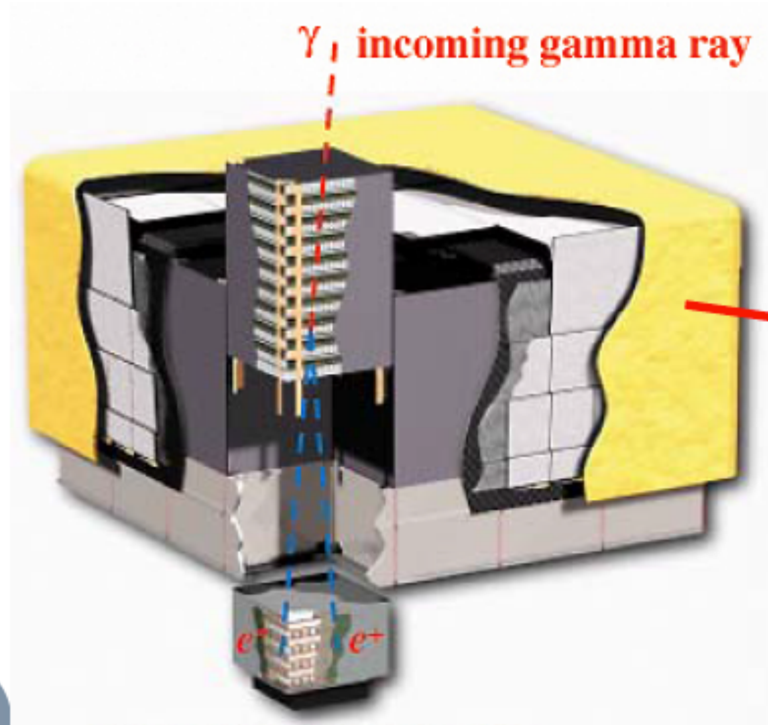
Air shower Arrays

100 GeV – 100 TeV
Large area
Good bg rejection
Large field of view
Large duty cycle

3. How to detect gamma rays?

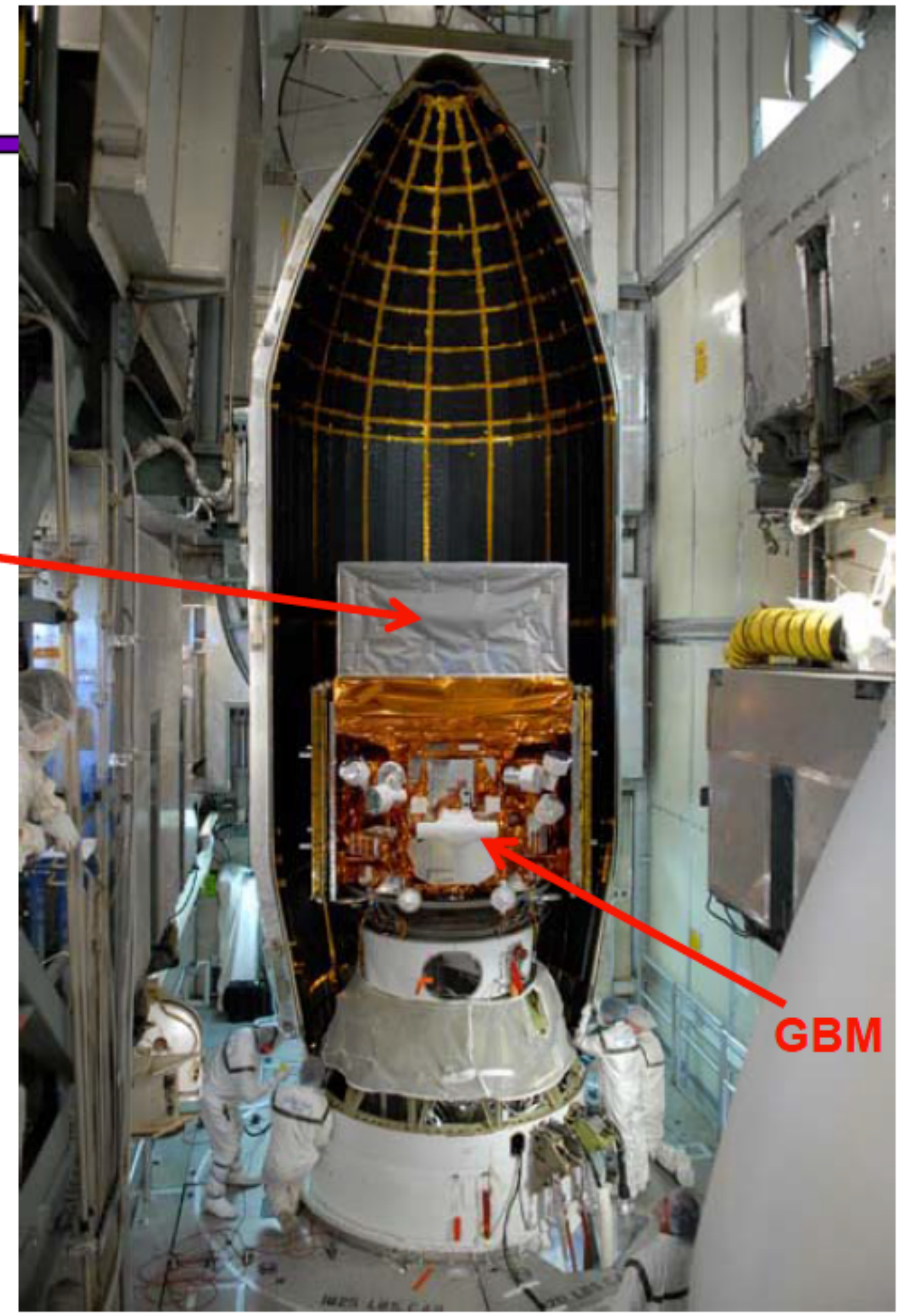
Fermi GST

Large Area Telescope (LAT)

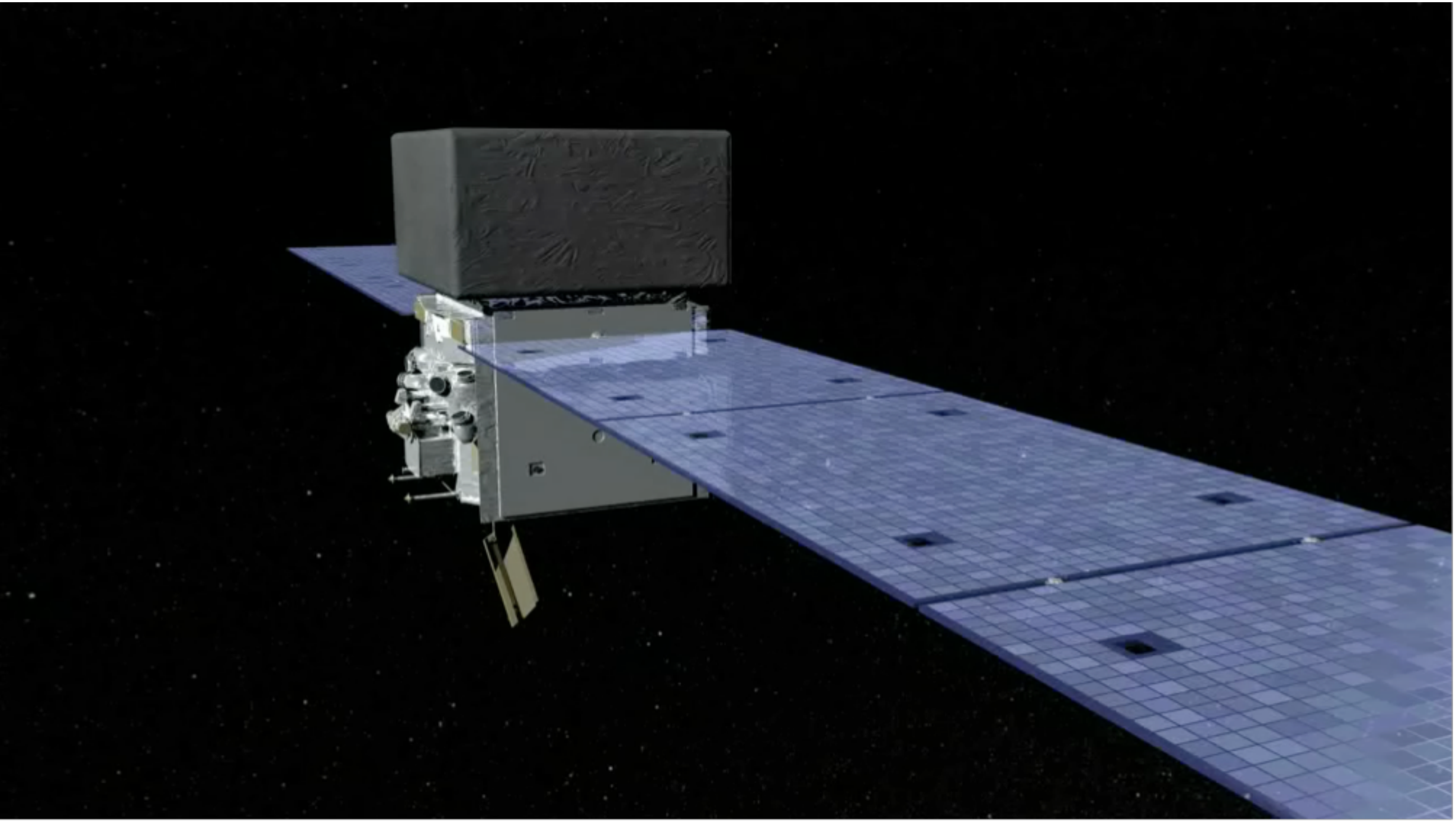


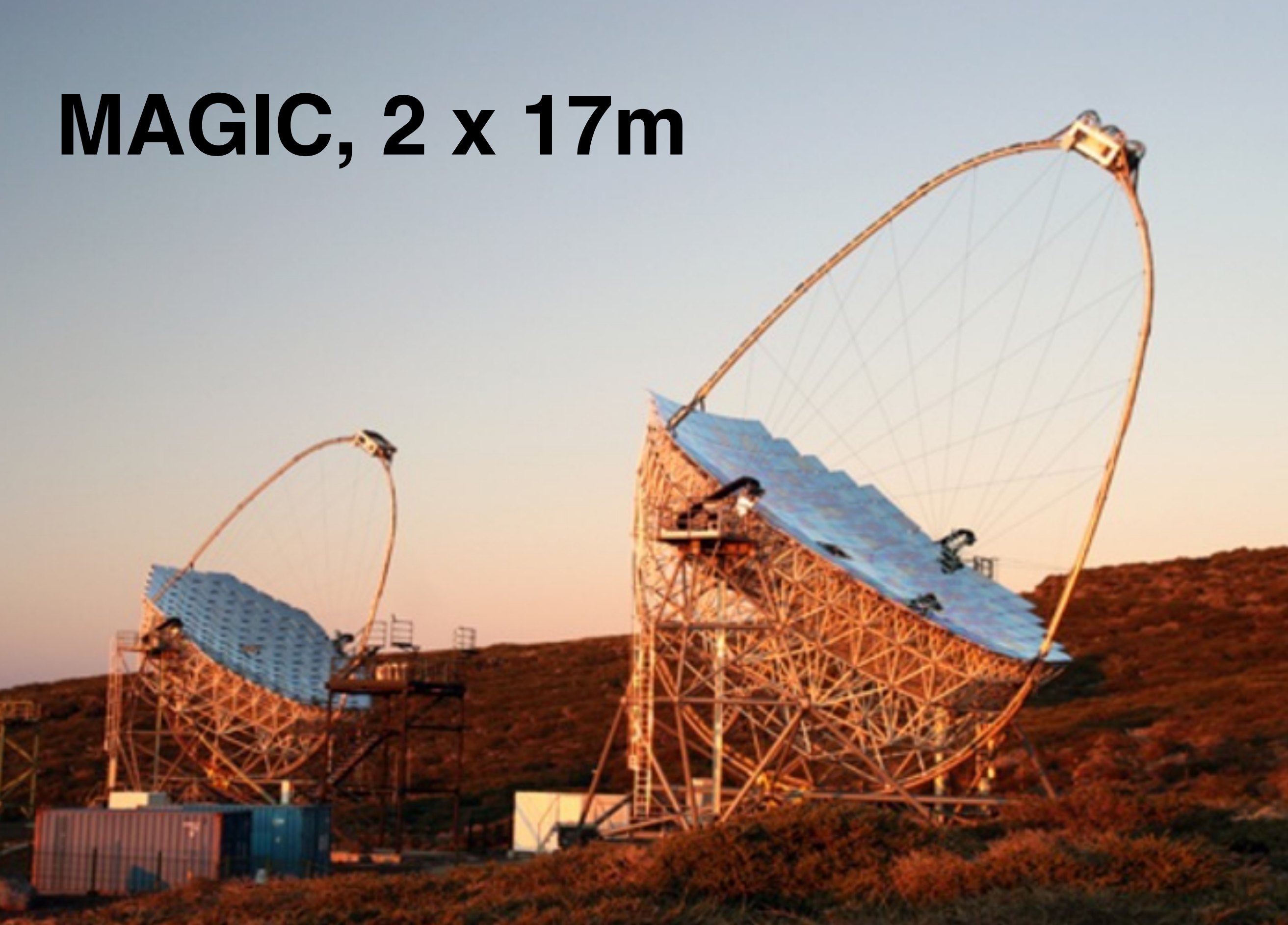
γ-ray converts in LAT to an electron and a positron ; tracking these give us the direction and energy of the photon.

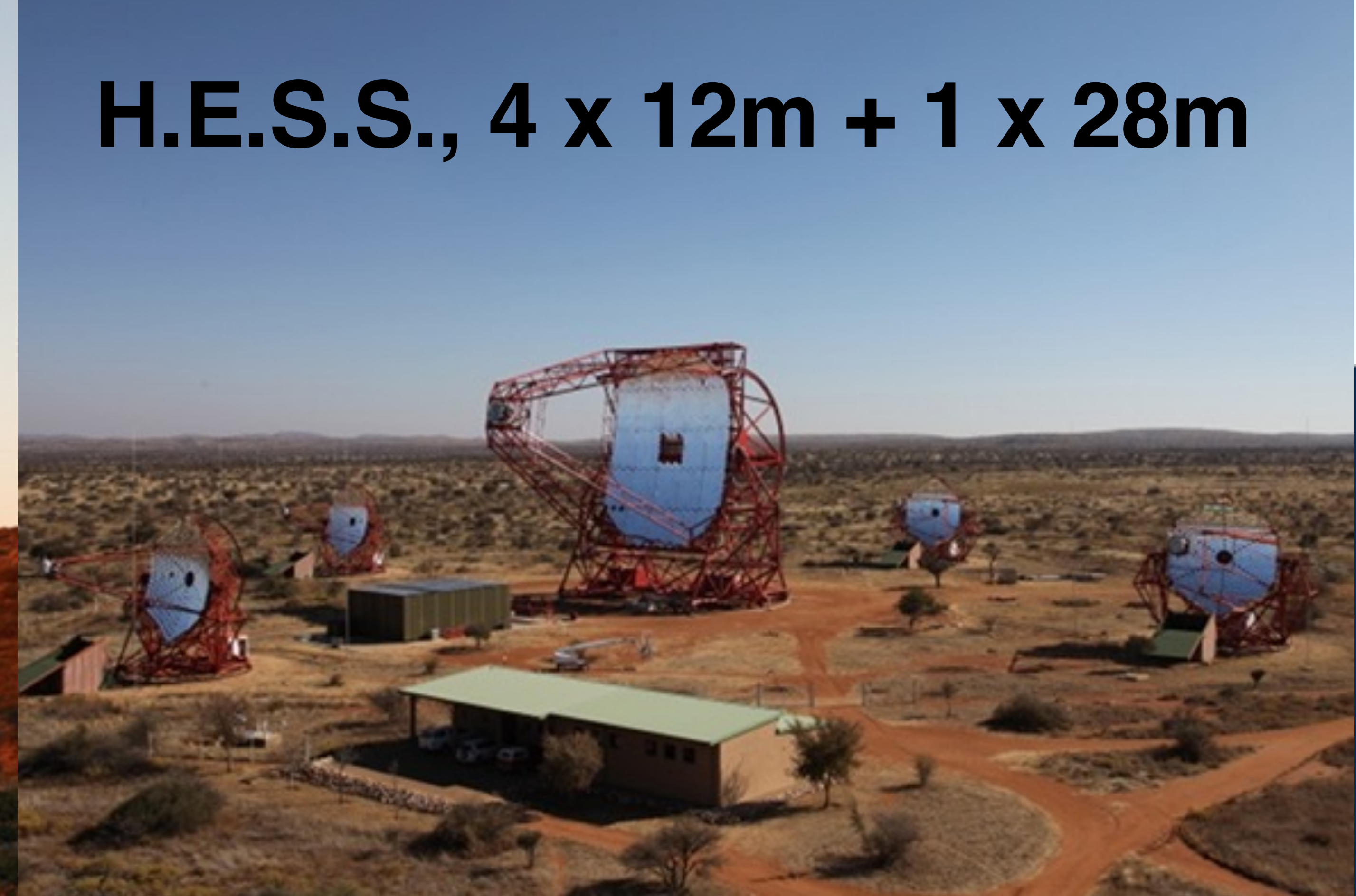
Launched from Cape Canaveral
11 June 2008



3. How to detect gamma rays?



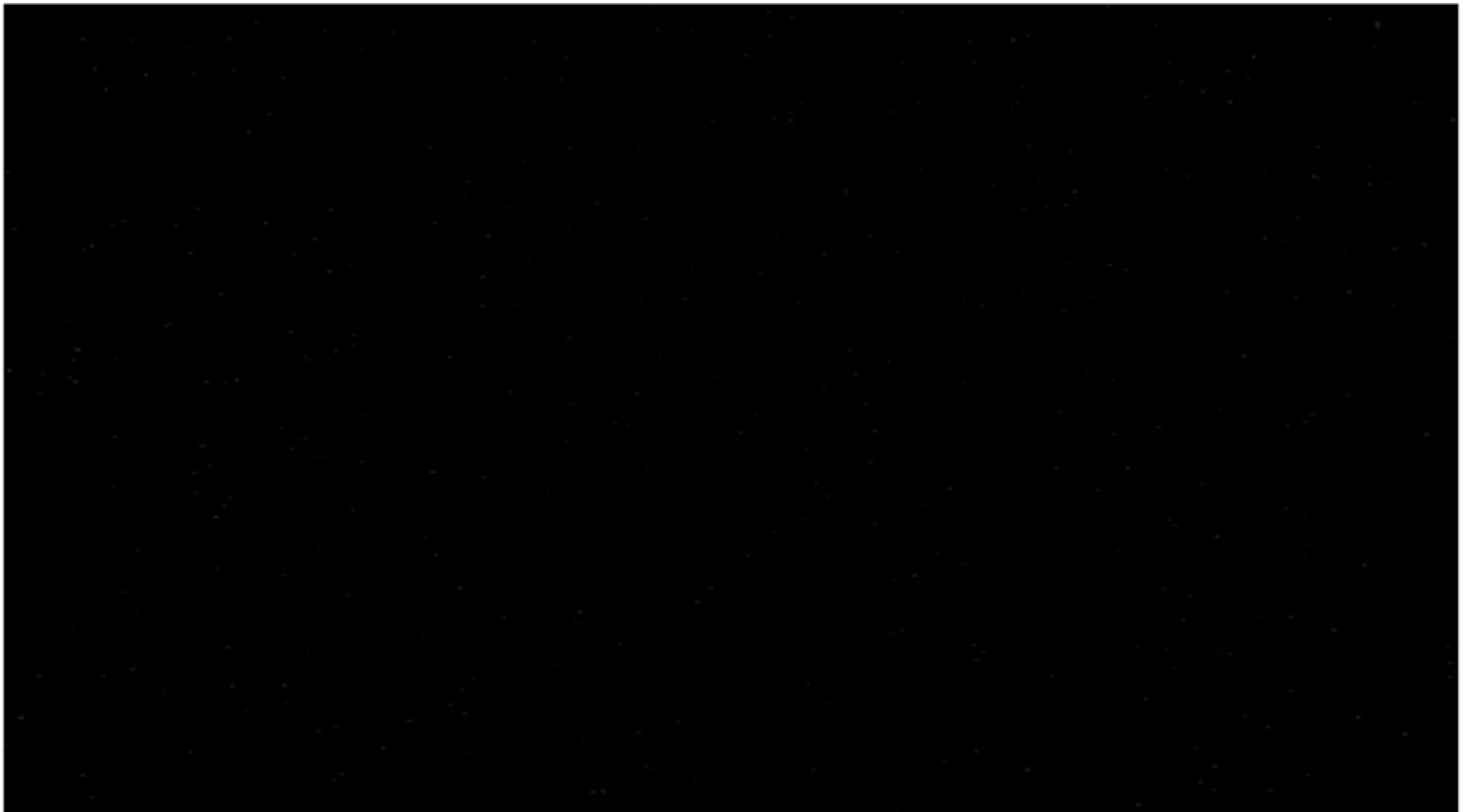

MAGIC, 2 x 17m


H.E.S.S., 4 x 12m + 1 x 28m


VERITAS, 4 x 12m

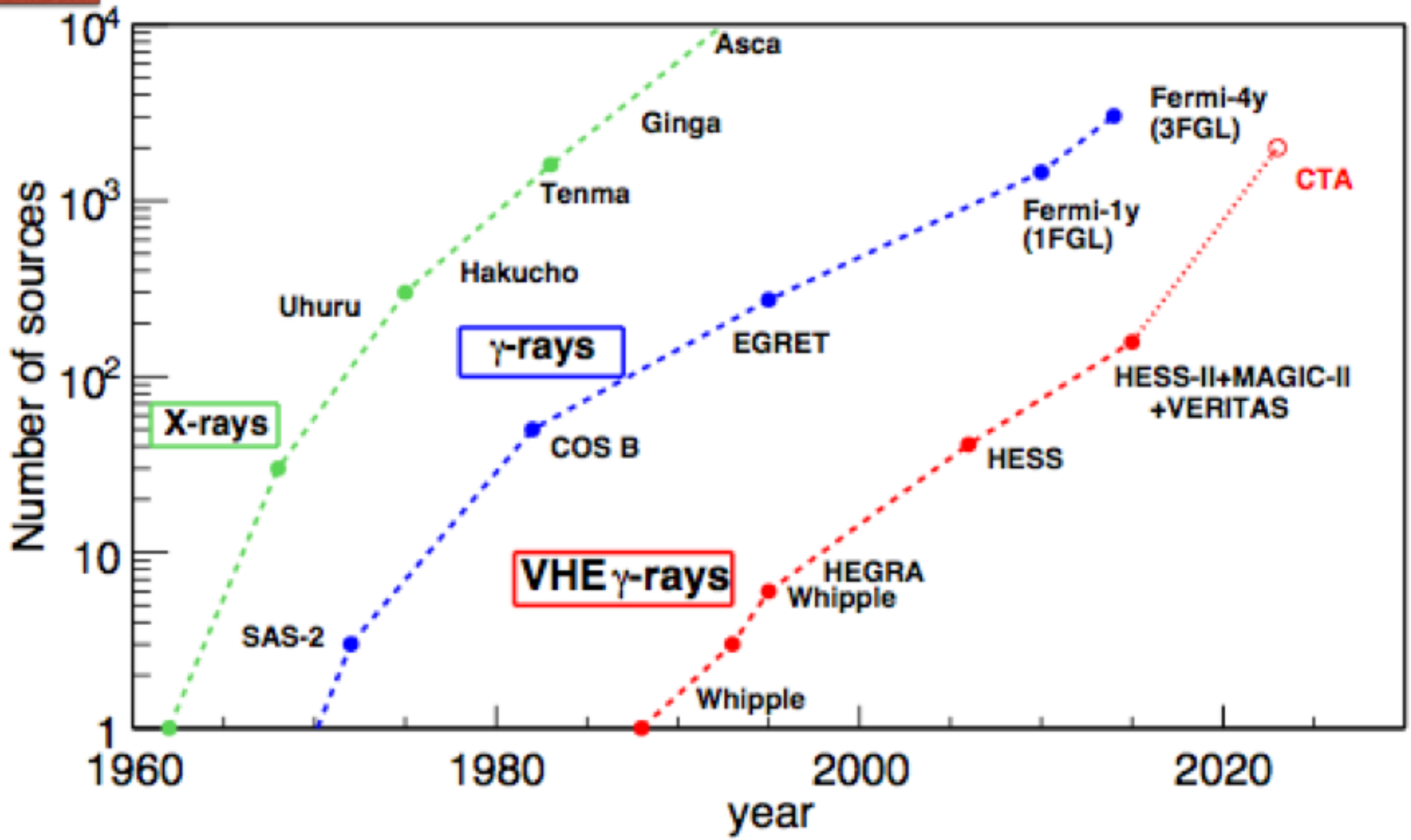
3. How to detect gamma rays?

Atmospheric showers and Cherenkov radiation



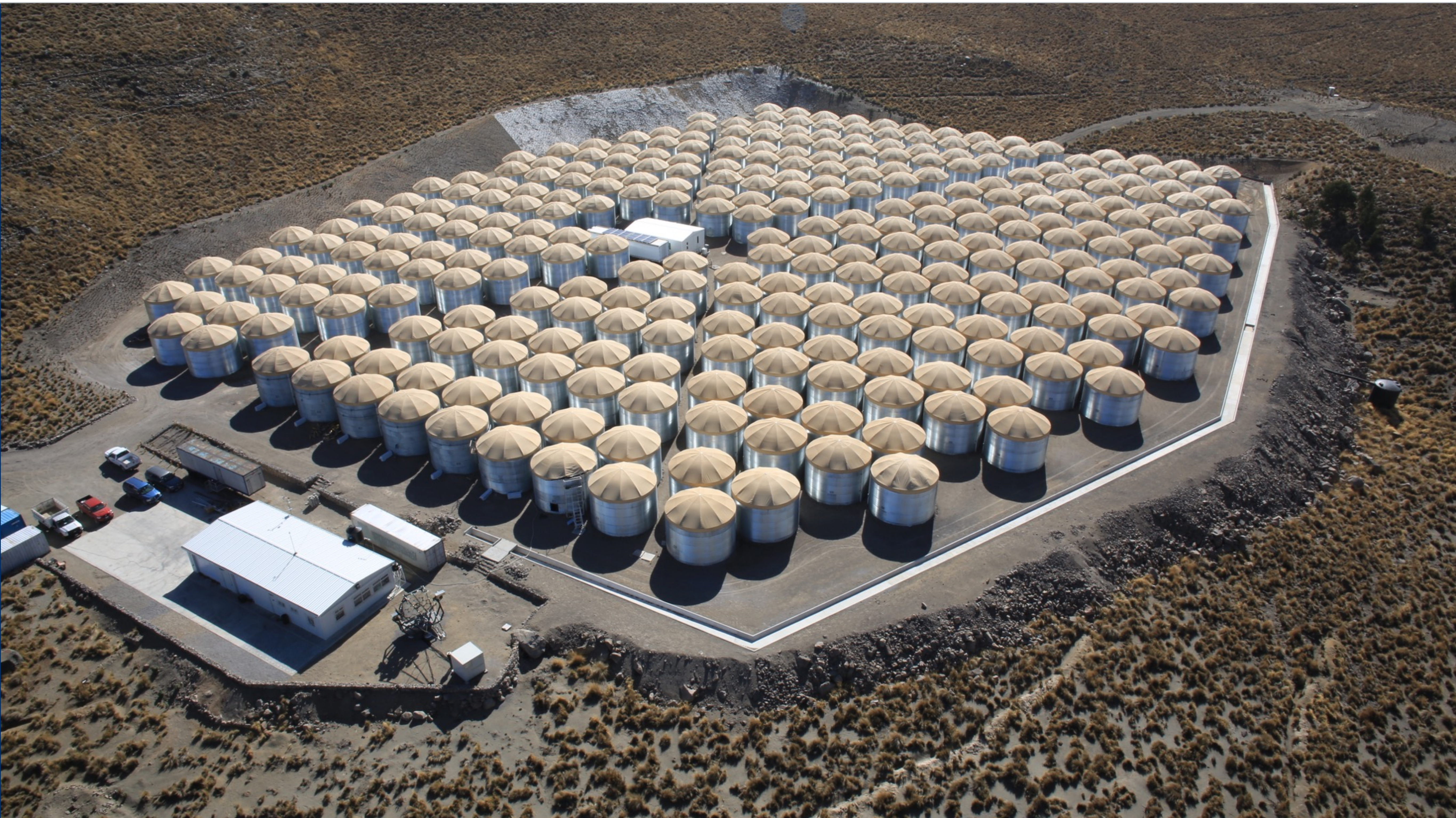
3. How to detect gamma rays?

Kifune plot

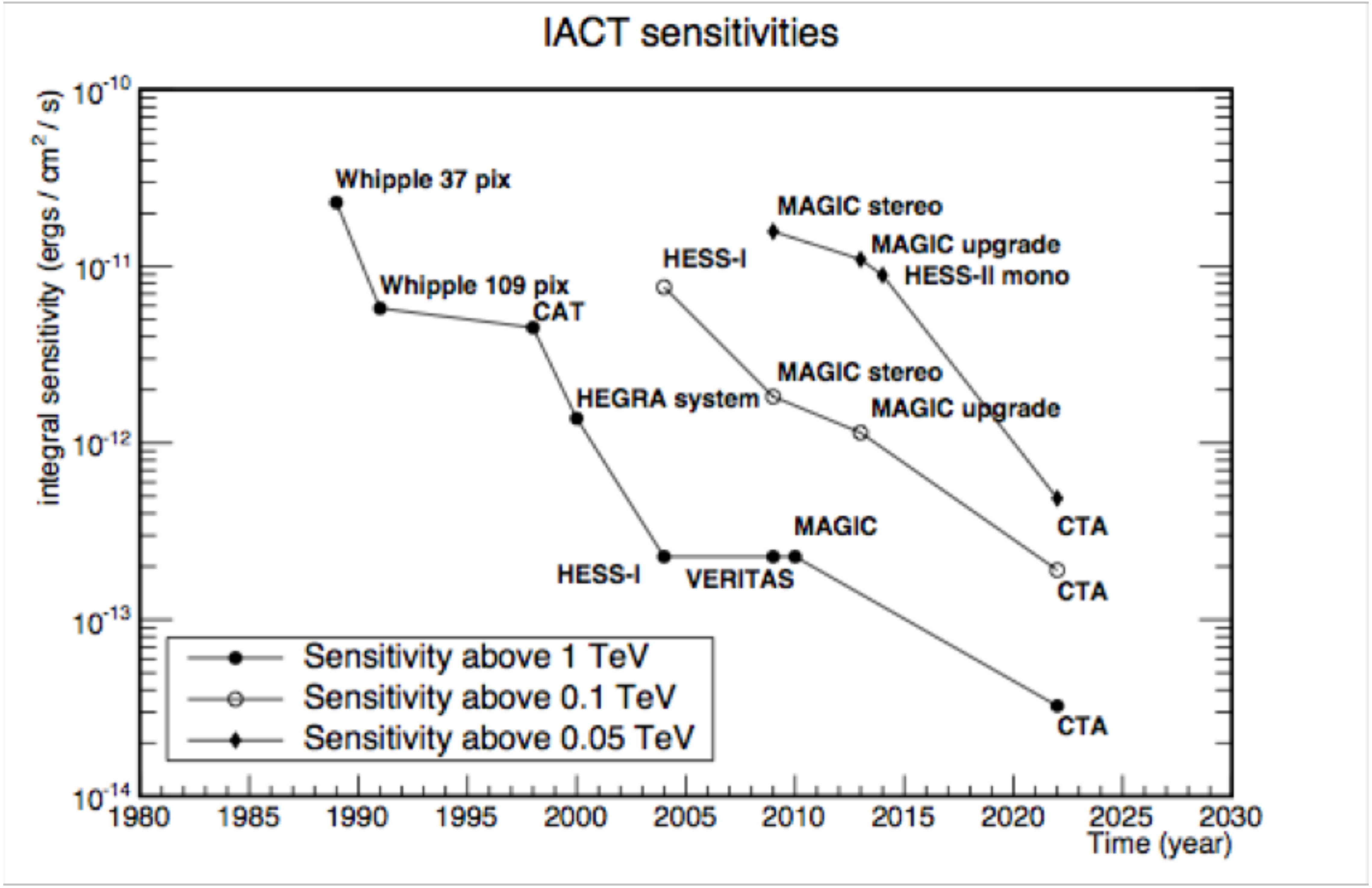


HAWC, 300 water tanks at 4100m asl

cta cherenkov telescope array

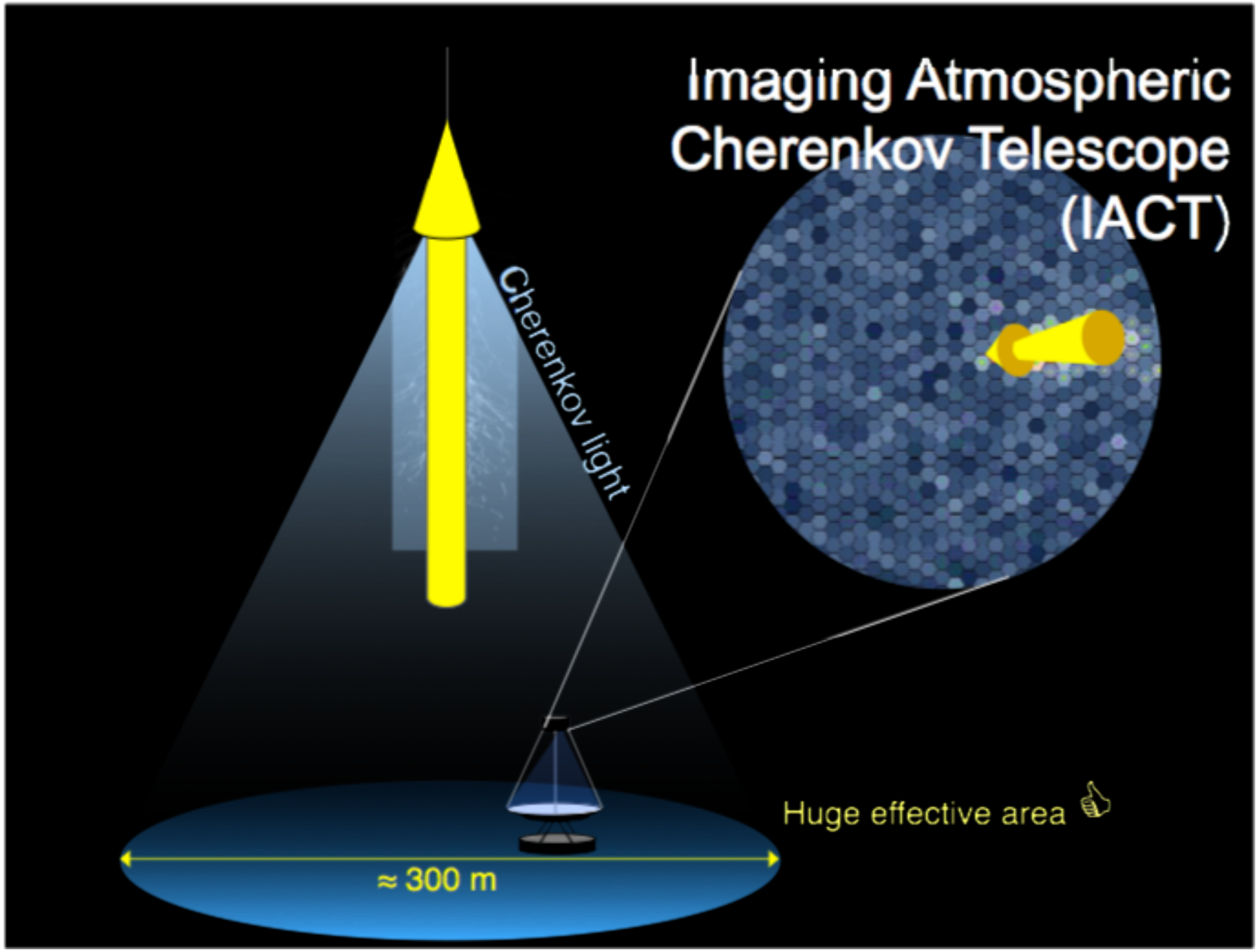


Due to the boost in flux sensitivity



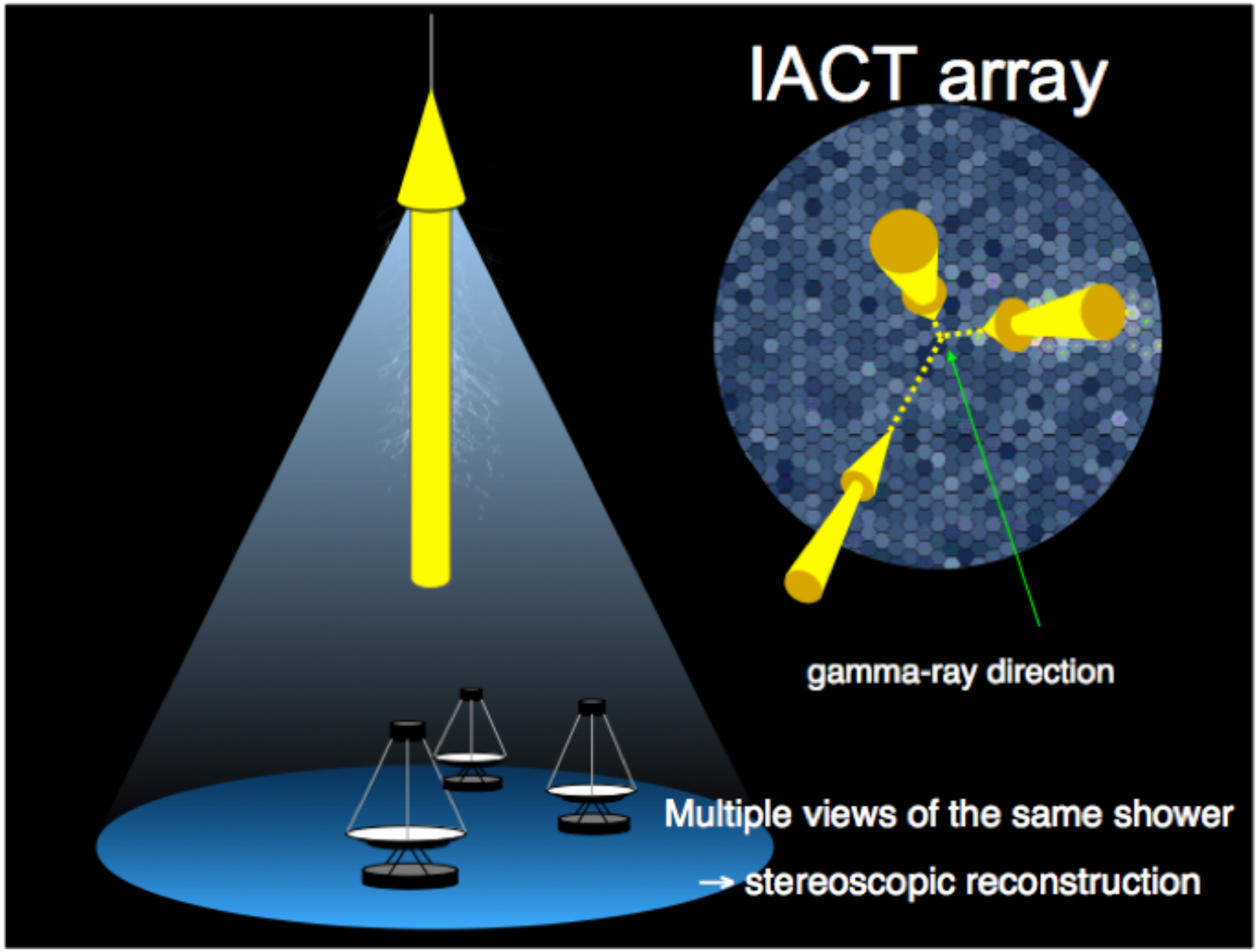
3. How to detect gamma rays?

Imaging Atmospheric Cherenkov Telescopes: Detection technique



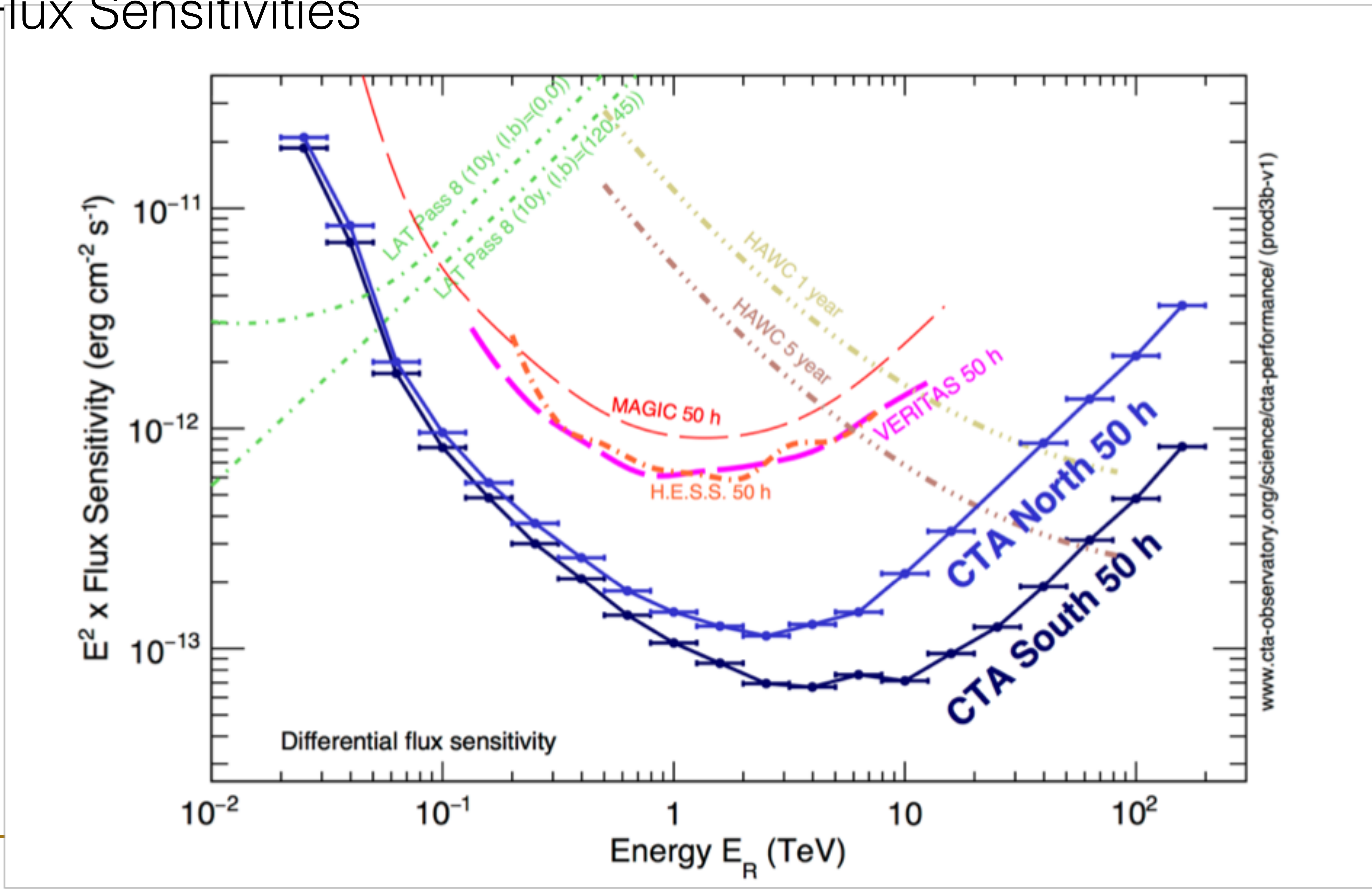
3. How to detect gamma rays?

Imaging Atmospheric Cherenkov Telescopes: Detection technique



3. How to detect gamma rays?

Flux Sensitivities

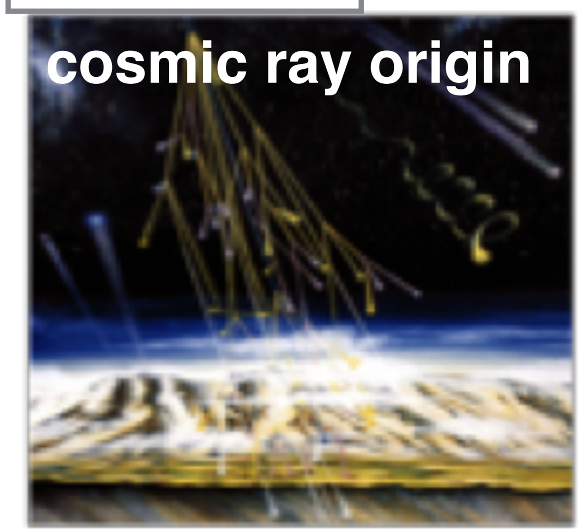


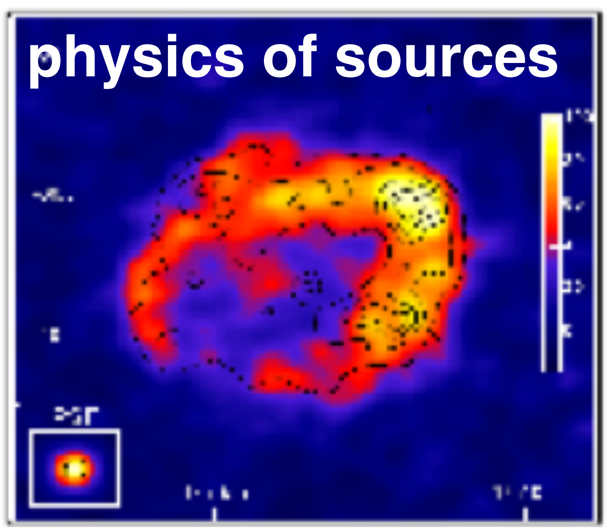
4. What do we learn from gamma rays?

- **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

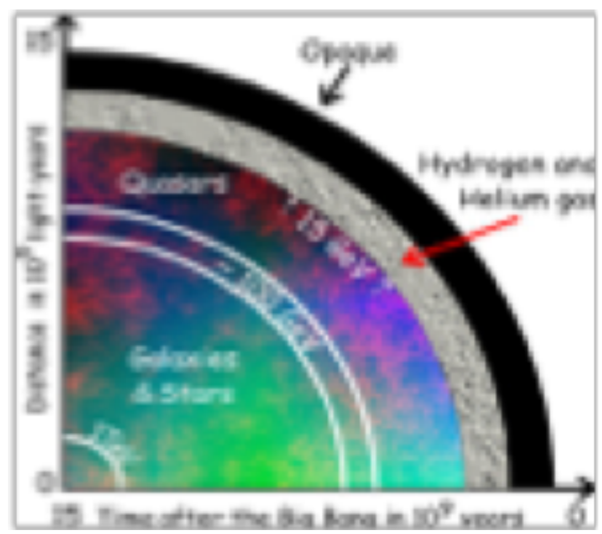
4. What do we learn from gamma rays?

Objectives

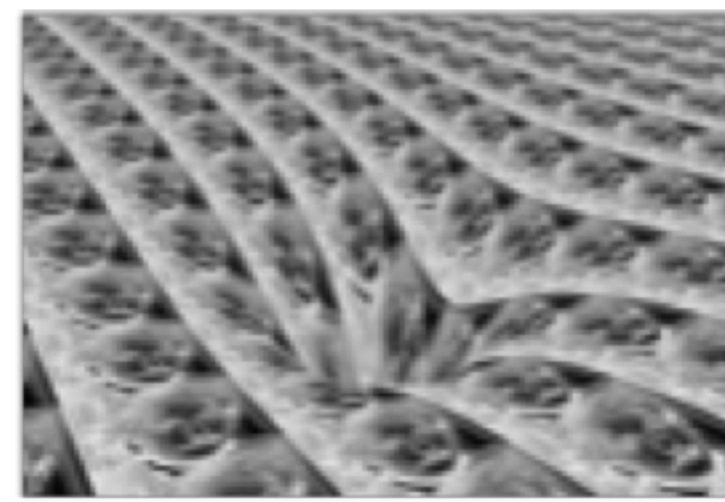


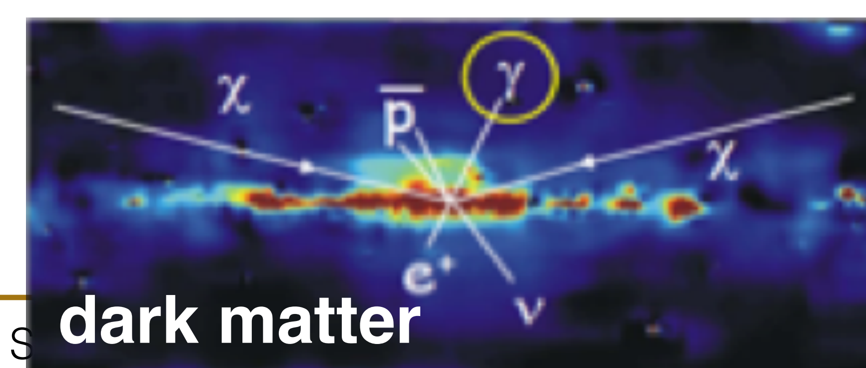


cosmology



space and time





4. What do we learn from gamma rays?

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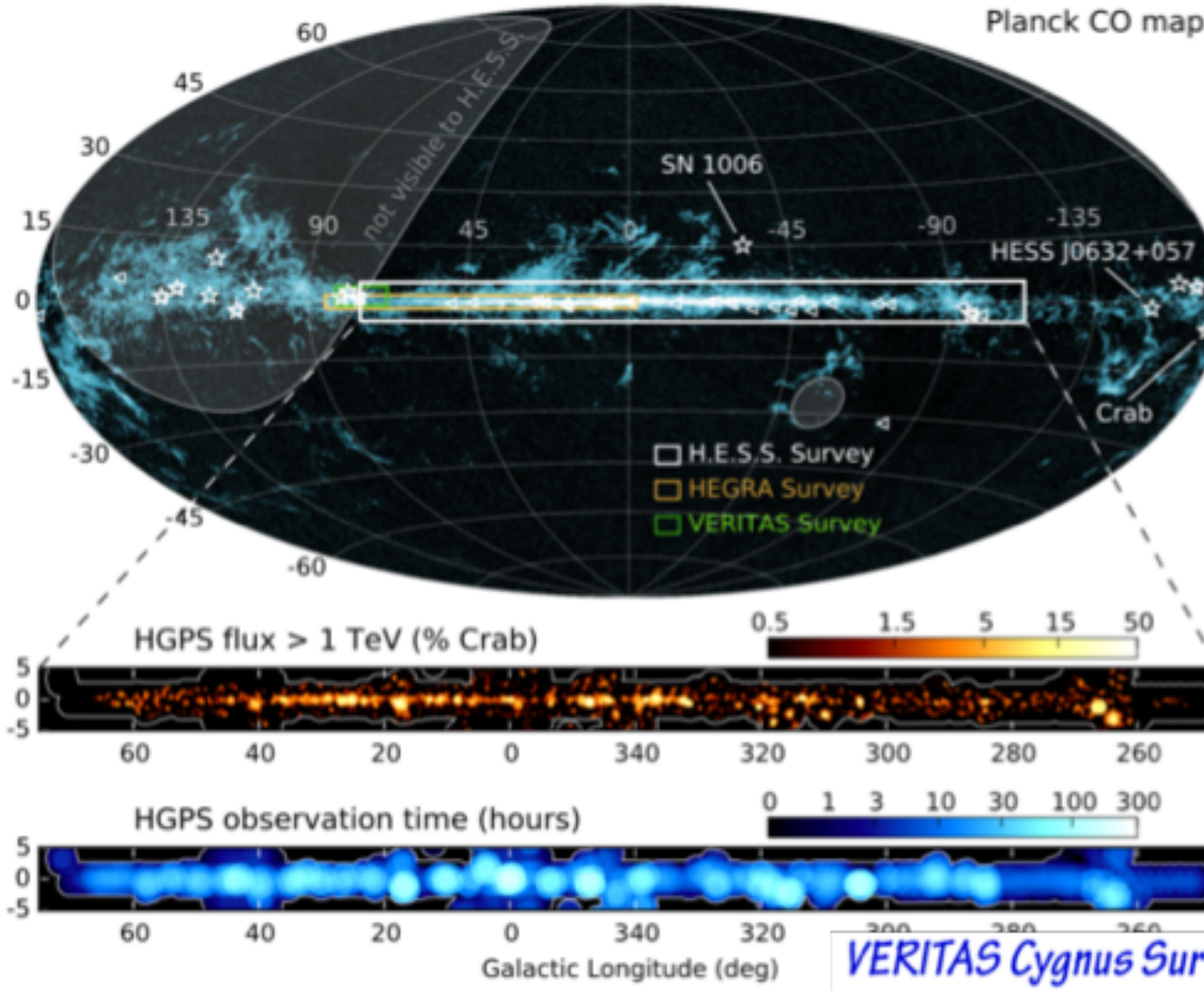
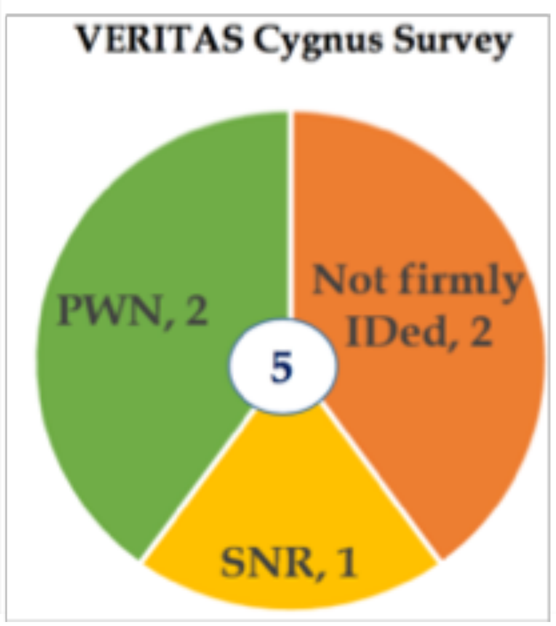
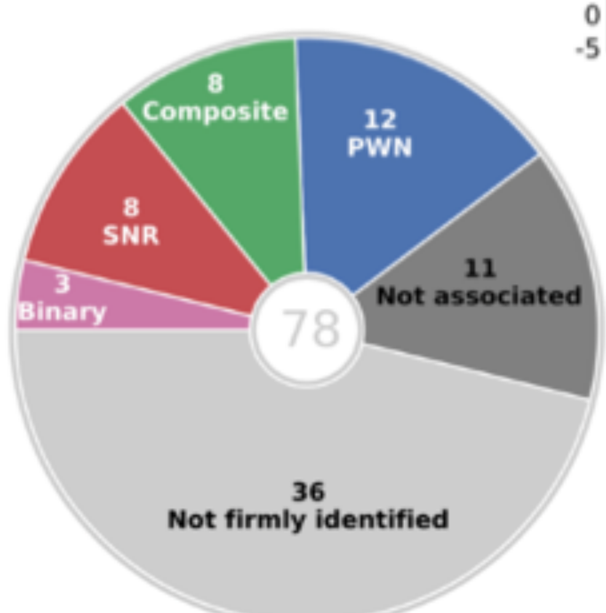
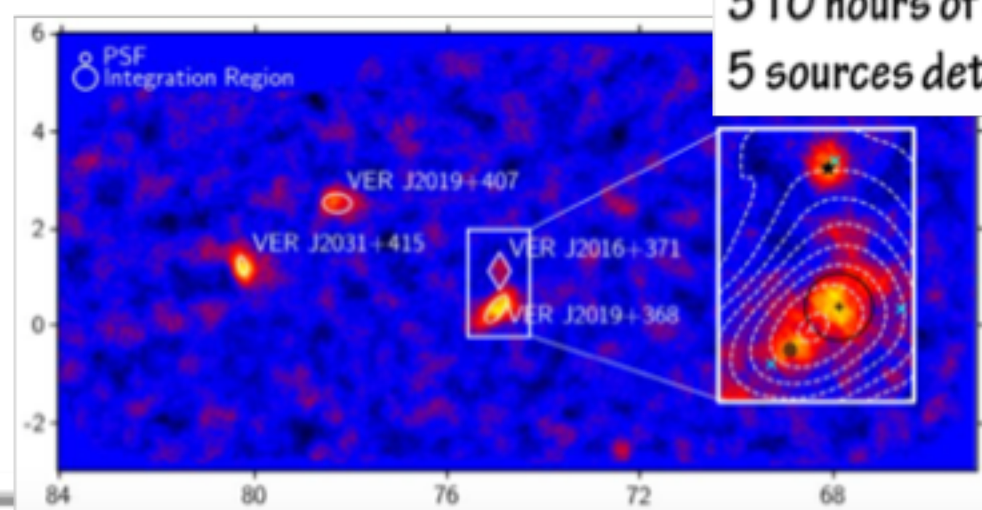
H.E.S.S. Galactic Plane Survey

- ~ 3000 hours of observations on the Galactic plane conducted
- Used to compile a survey in gamma-rays
- 78 sources included in the upcoming paper

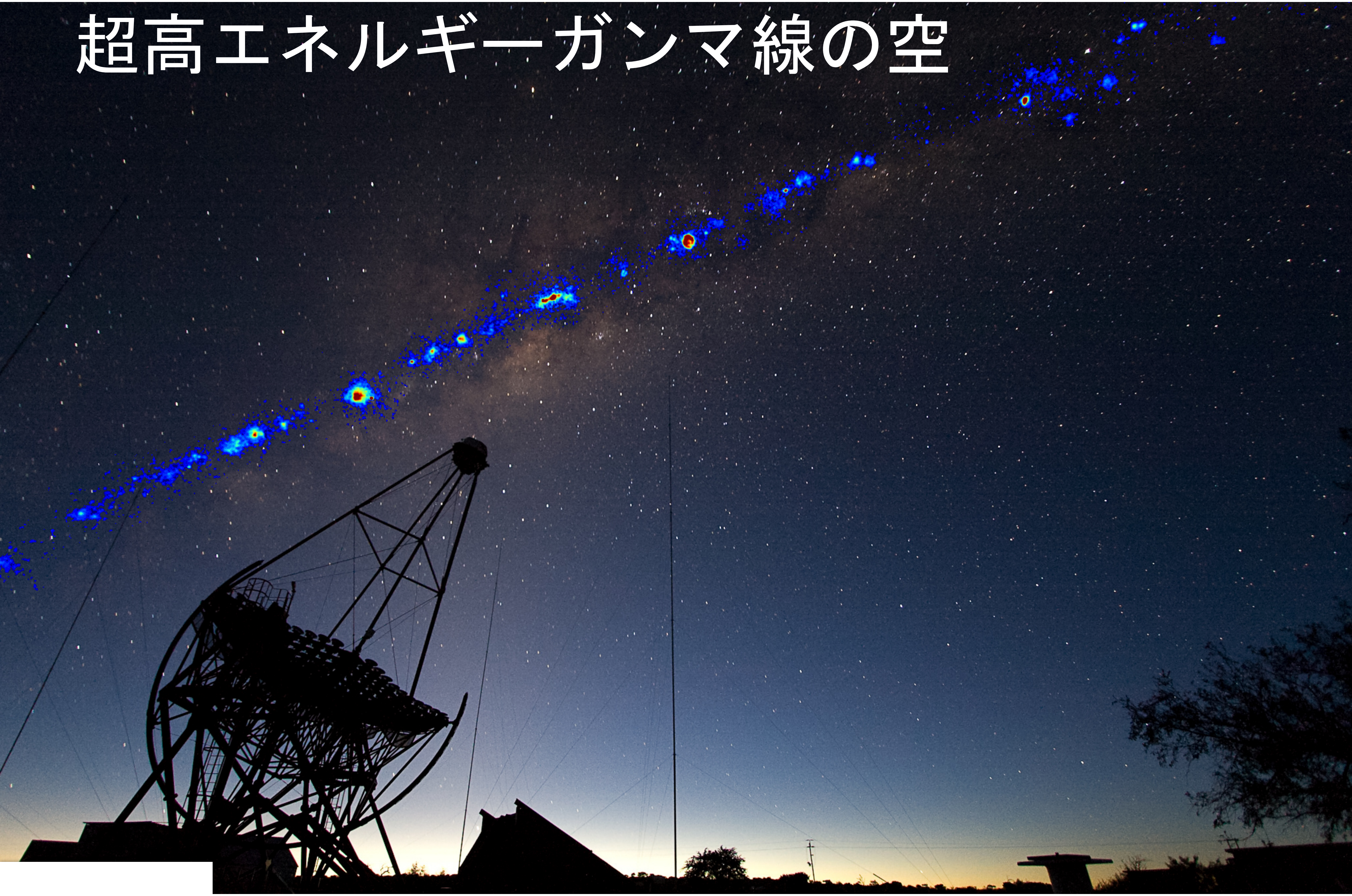








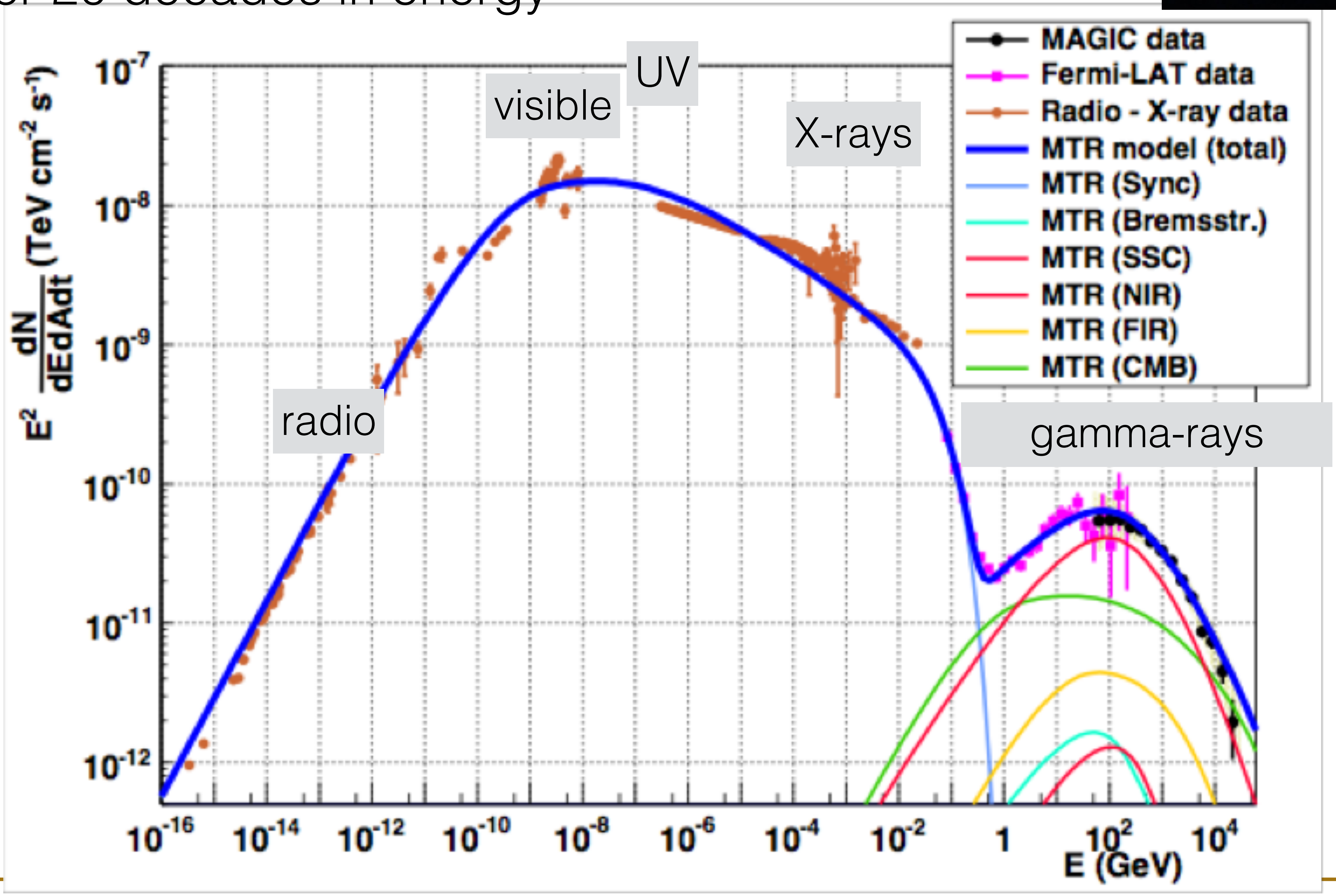
VERITAS Cygnus Survey
310 hours of observation,
5 sources detected


超高エネルギーガンマ線の空

4. What do we learn from gamma rays?

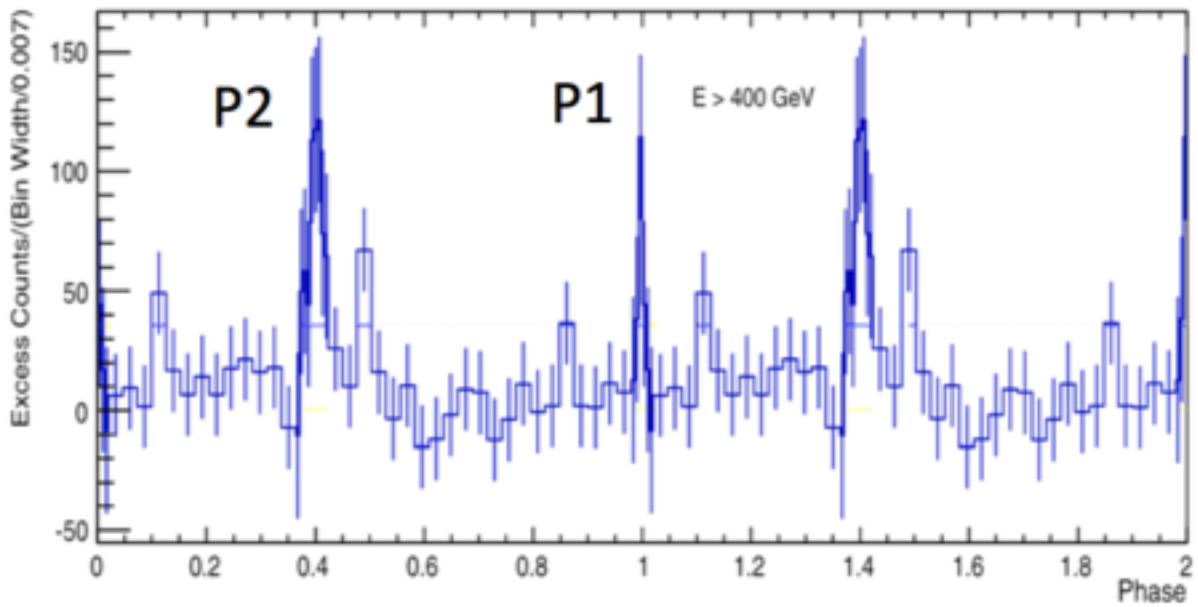
Crab Nebula

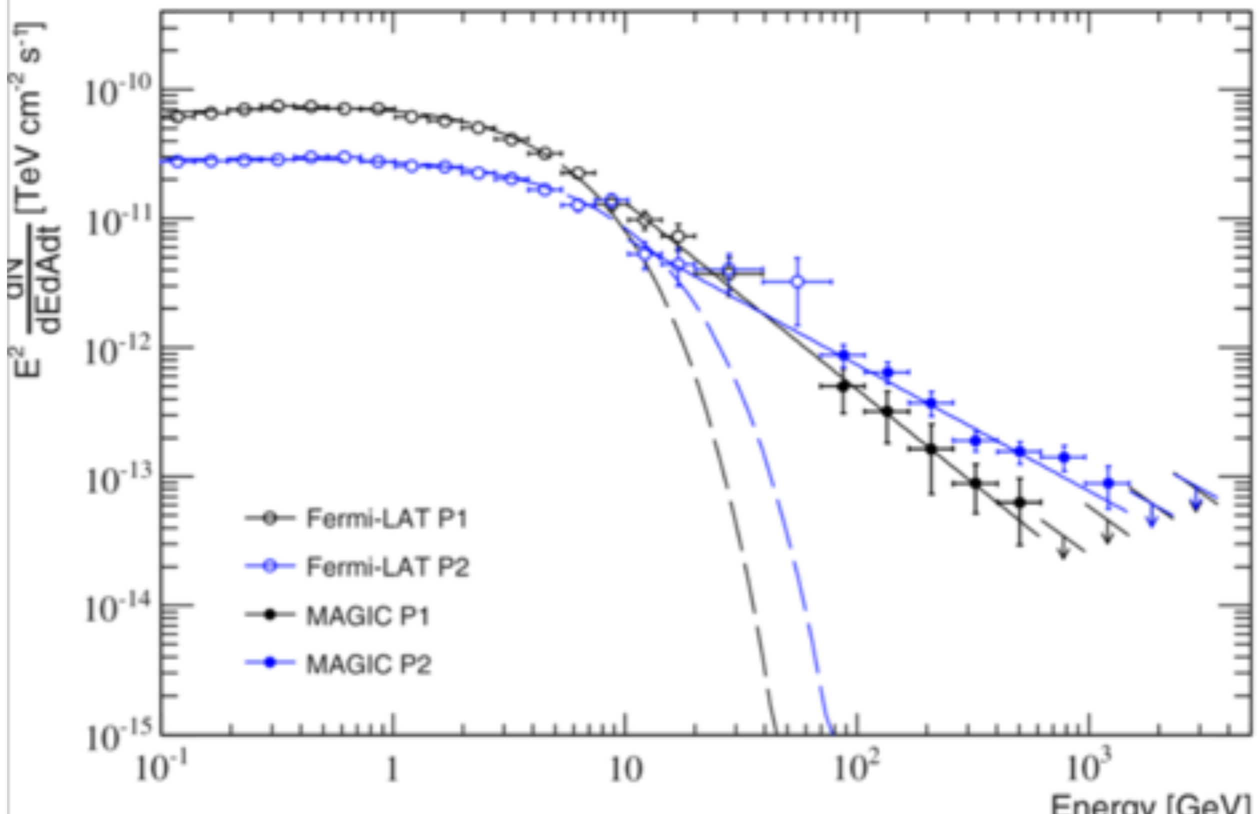
a non-thermal astrophysical object seen over 20 decades in energy



Pulsars: Crab

MAGIC, 2016, A&A, 585, A33





- MAGIC dataset: 320 h (2007-2014)
- Discovered pulsed emission from Crab spectrum extending up to 1.5 TeV
- Spectra of both peaks extending as power- laws far beyond the expected cutoffs:
  - P1 detected up to 0.6 TeV (Γ=3.5 ± 0.1)
  - P2 detected up to 1.5 TeV (Γ=3.0 ± 0.1)

4. What do we learn from gamma rays?

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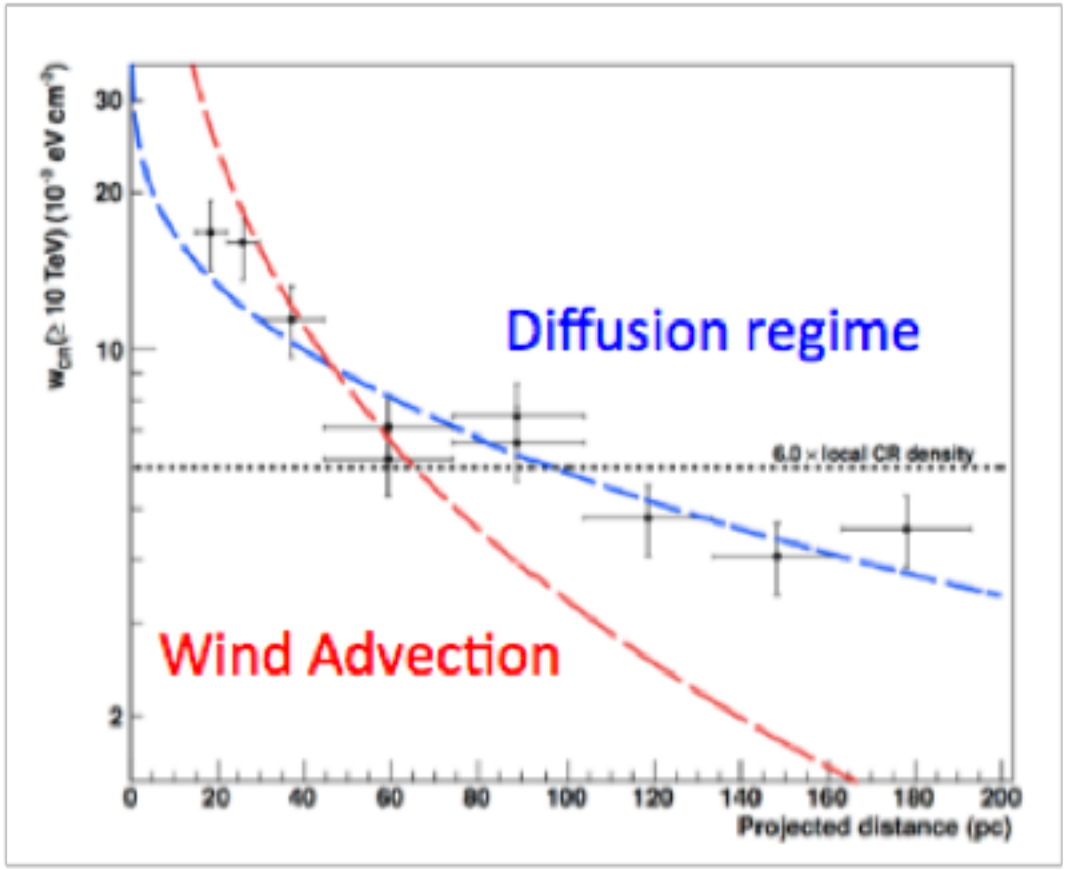
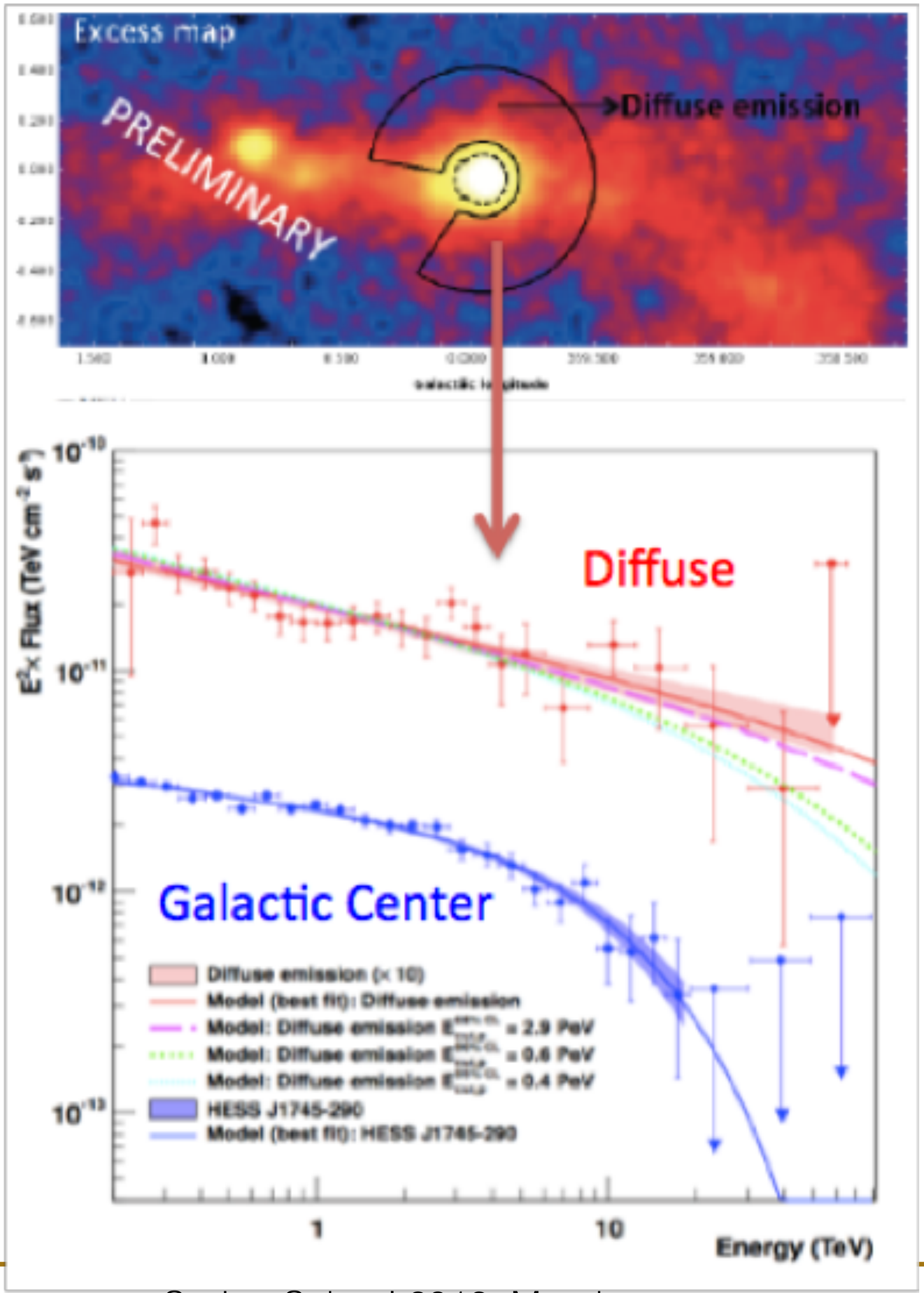
Galactic Center

HESS Deep Observation of 250hrs

Spectrum:
Parent proton could be 1PeV ➔ PeVATRON?

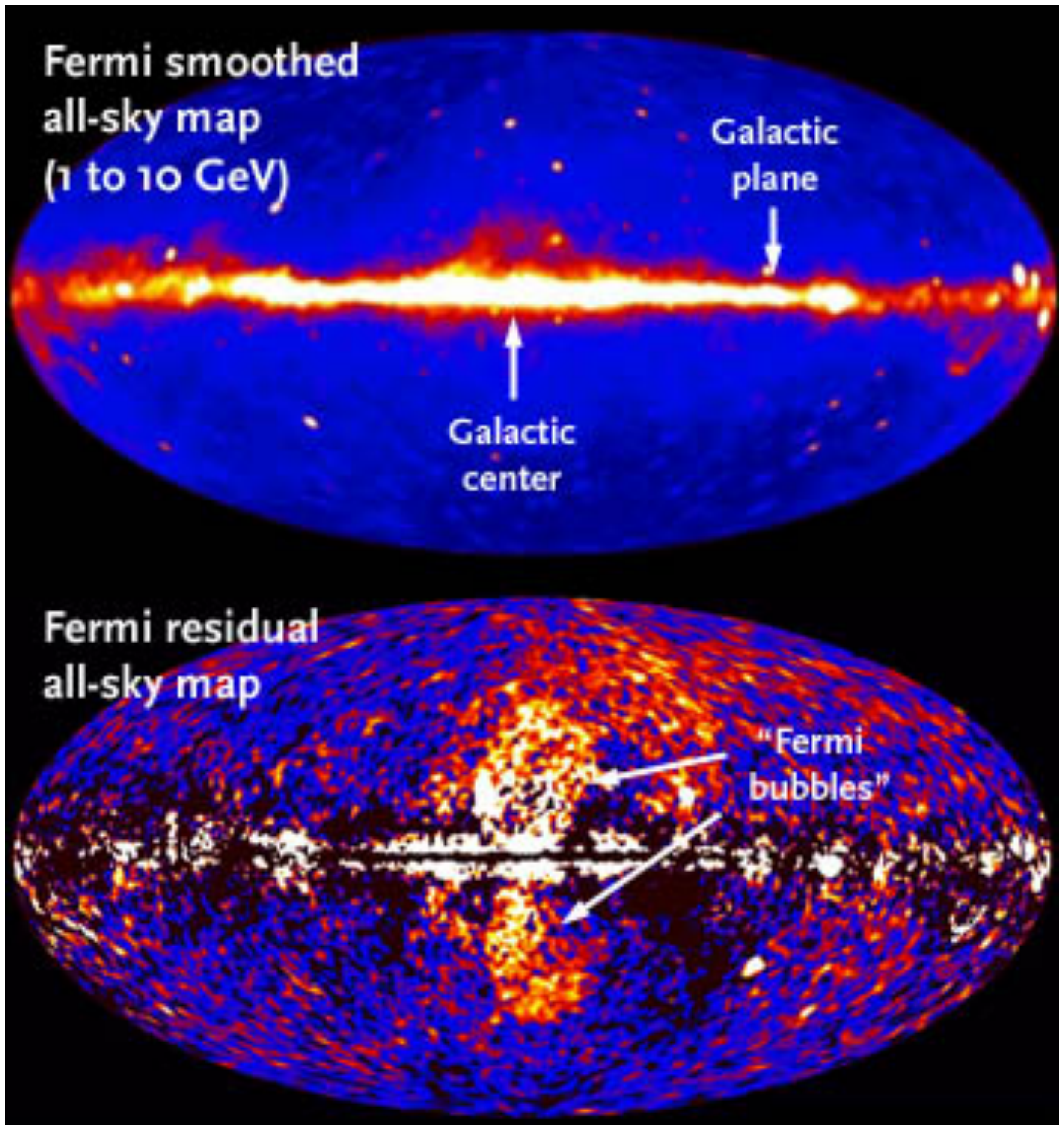
Radial distribution 1/r:
Consistent with the diffusion from the central BH

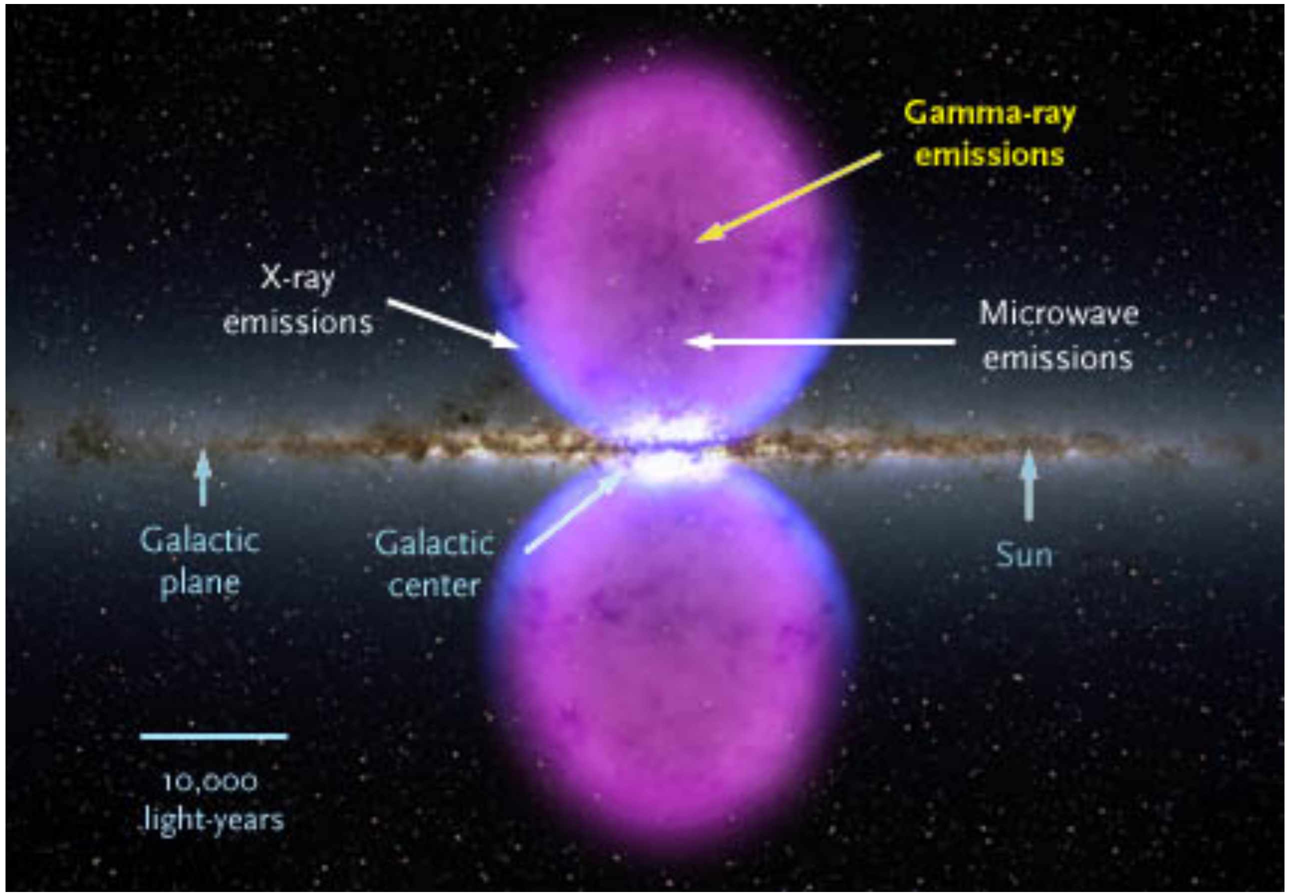




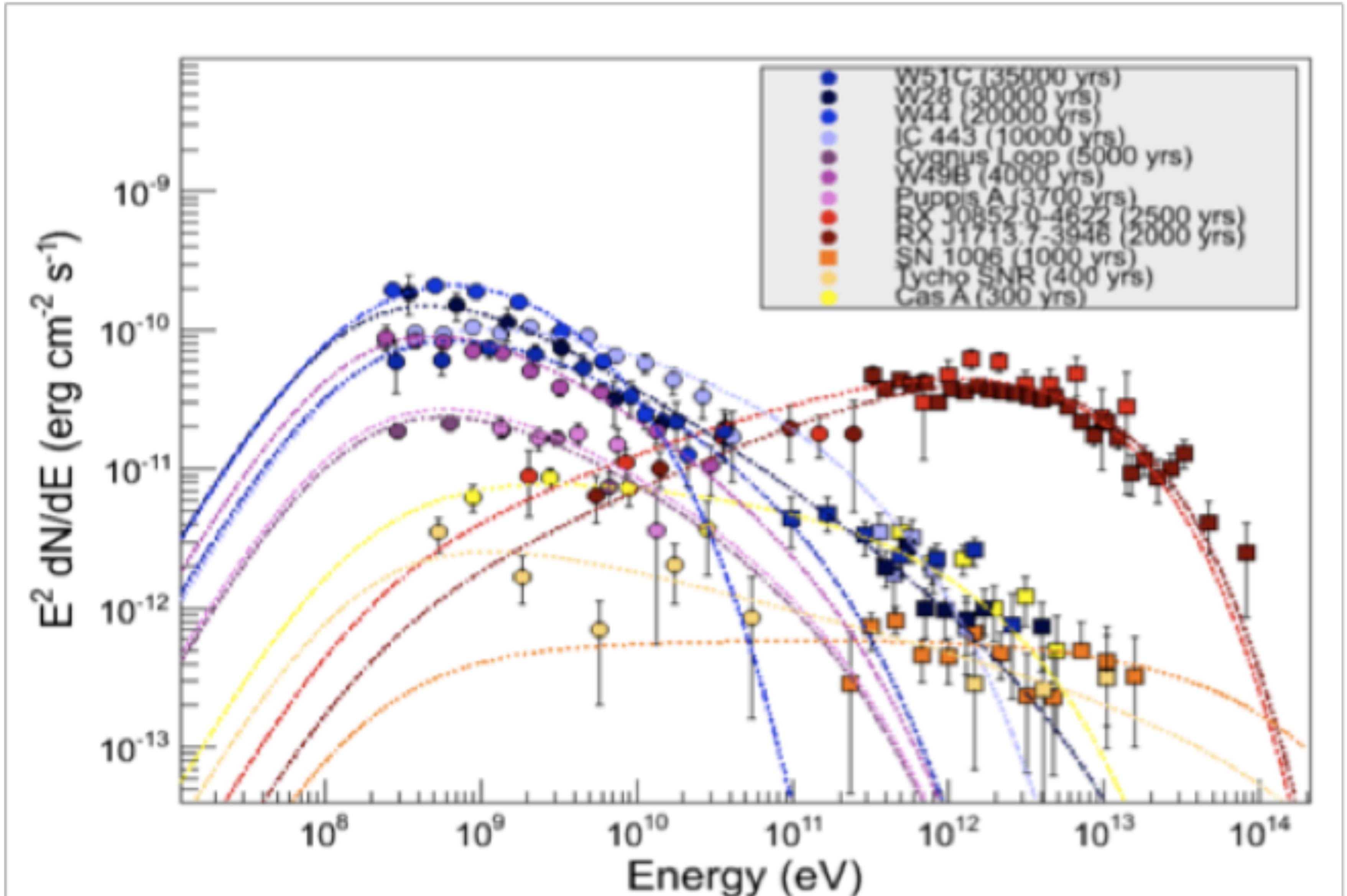
4. What do we learn from gamma rays?

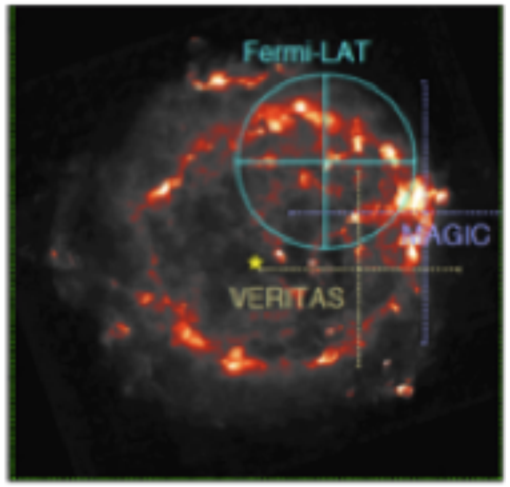
Galactic Center: Fermi Bubbles

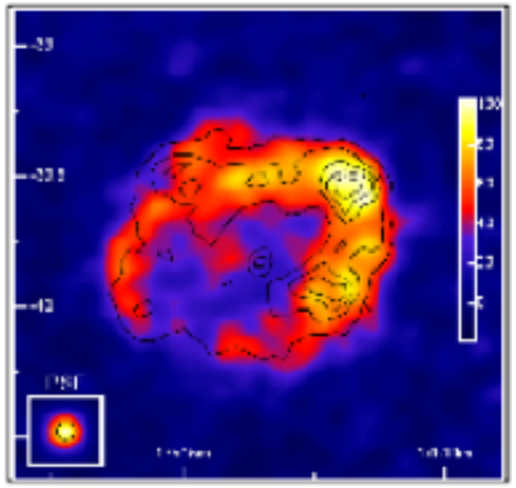


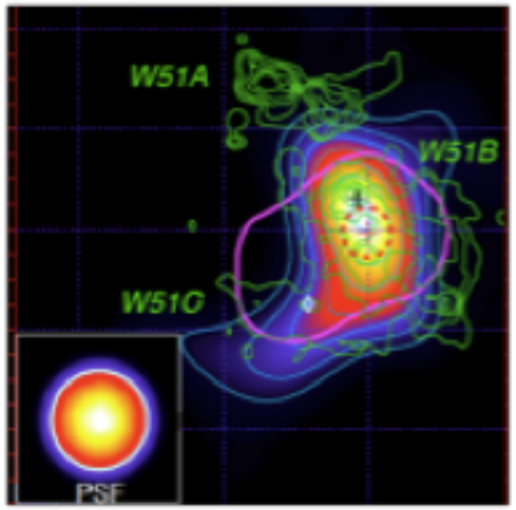


4. What do we learn from gamma rays?





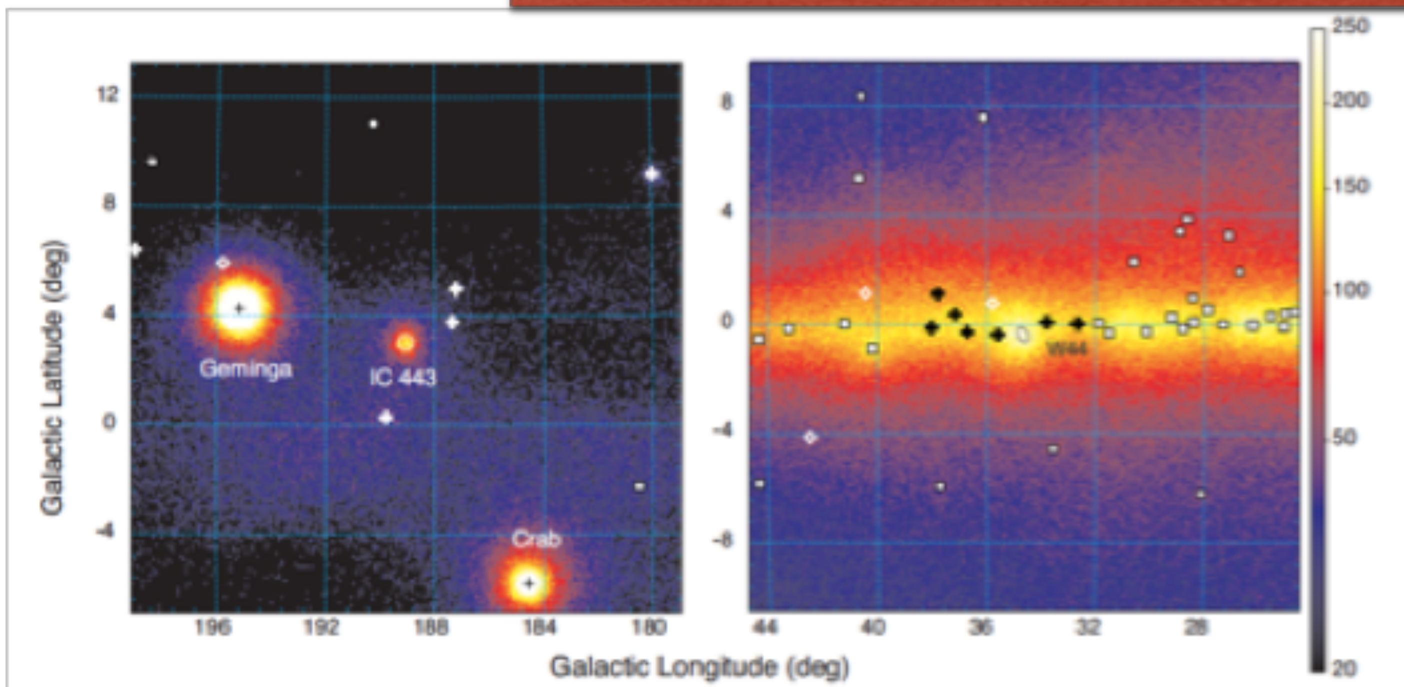


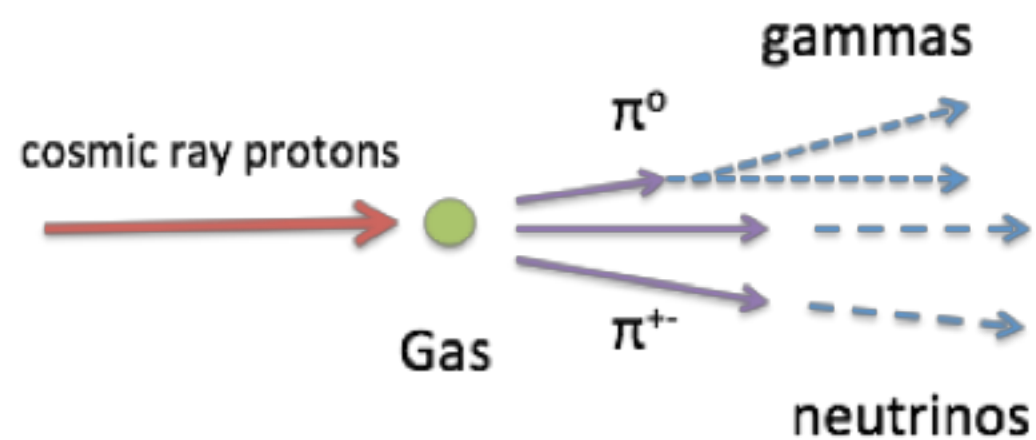


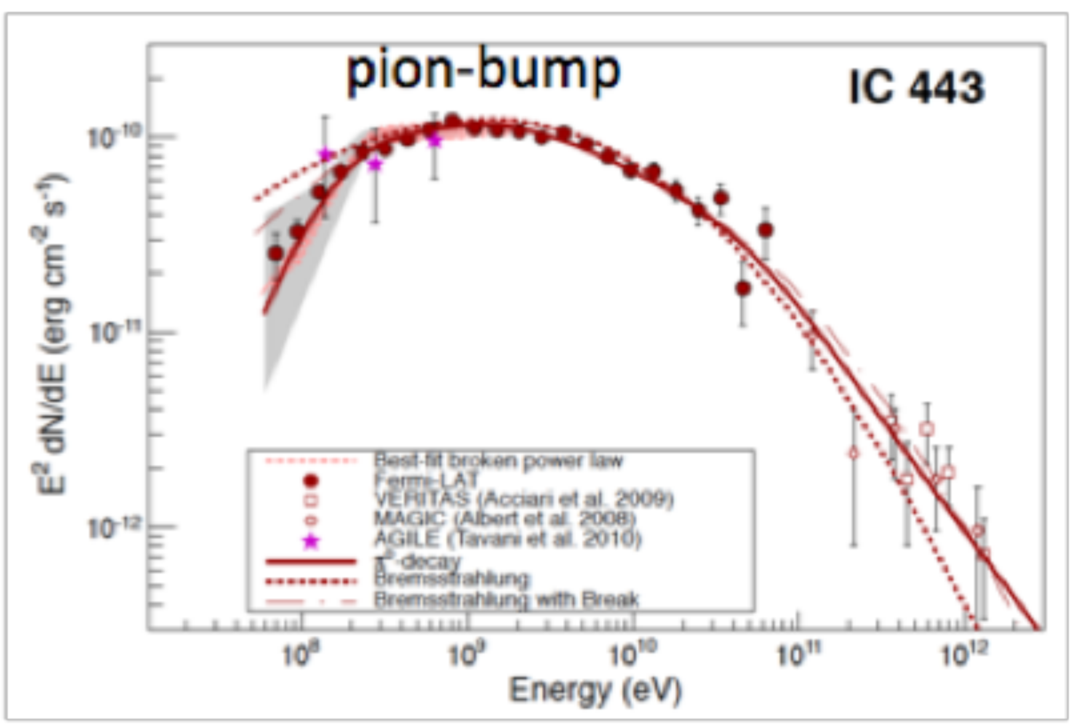
- Different stages of SNRs as cosmic ray accelerator
- CTA will deliver more information on SNRs as cosmic ray accelerators
- We can survey most of SNRs in our galaxy → C.R. energetics

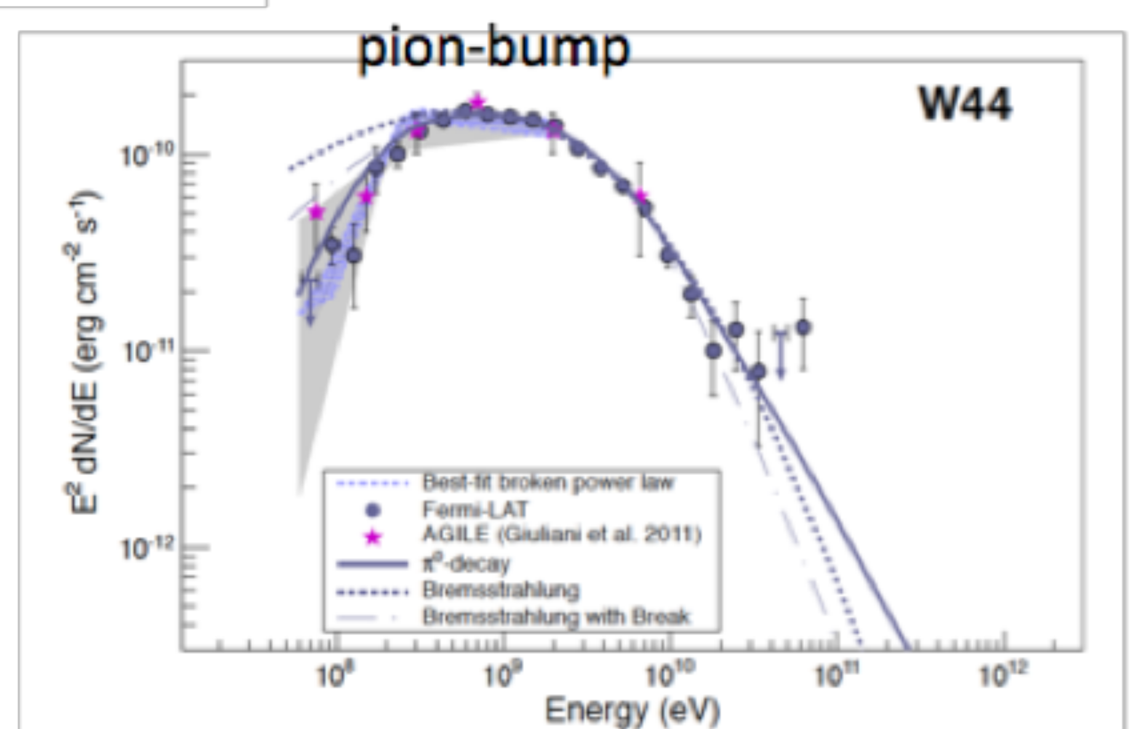
4. What do we learn from gamma rays?

Super Nova Remnants as cosmic ray accelerators
IC443 and W44, FERMI Collaboration (in Science)



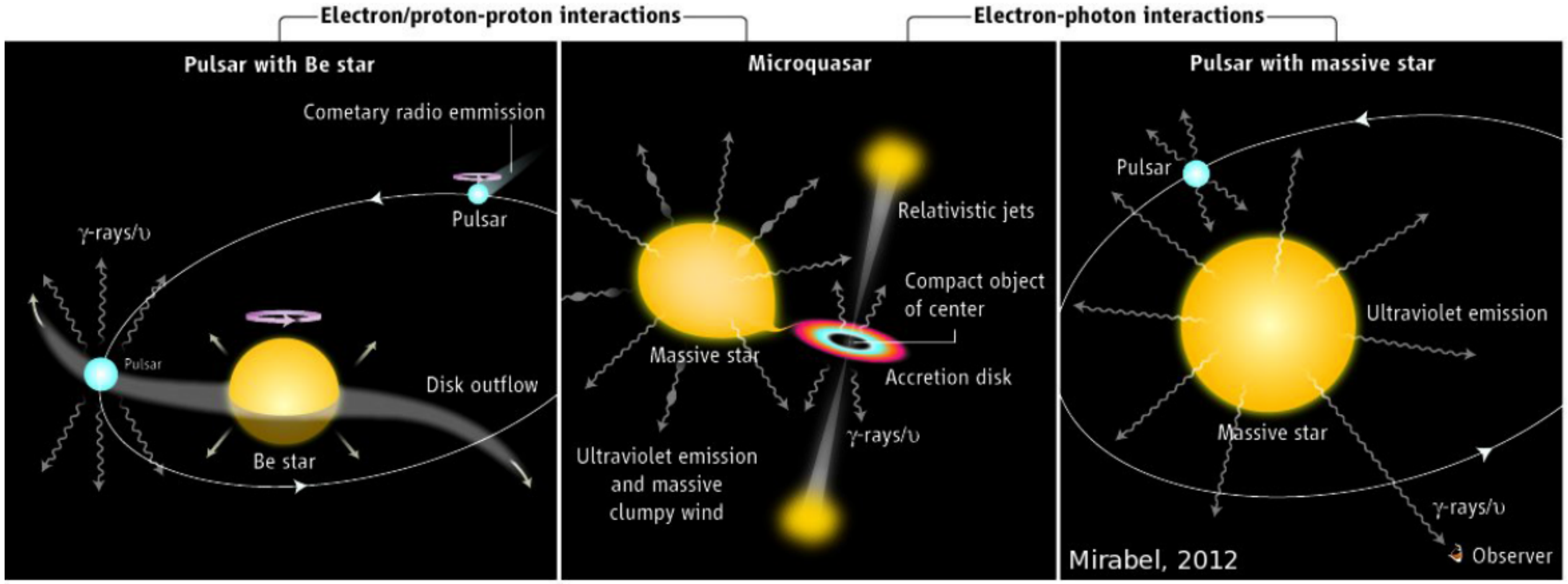


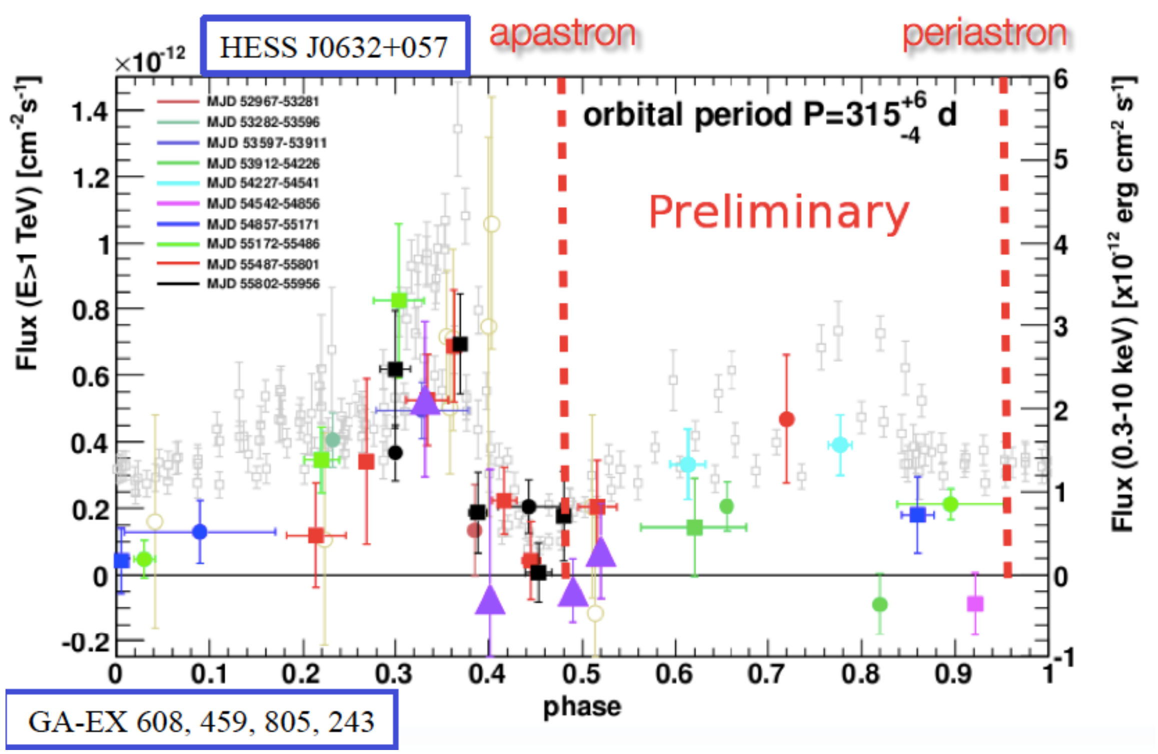




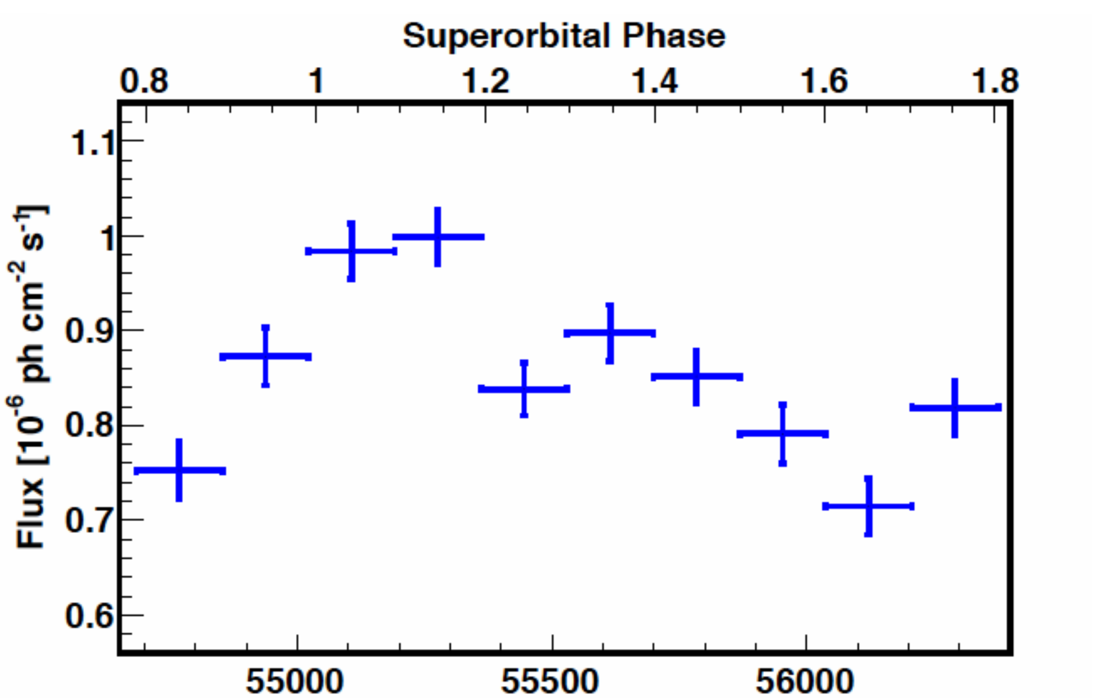
4. What do we learn from gamma rays?

Gamma-ray Binary systems



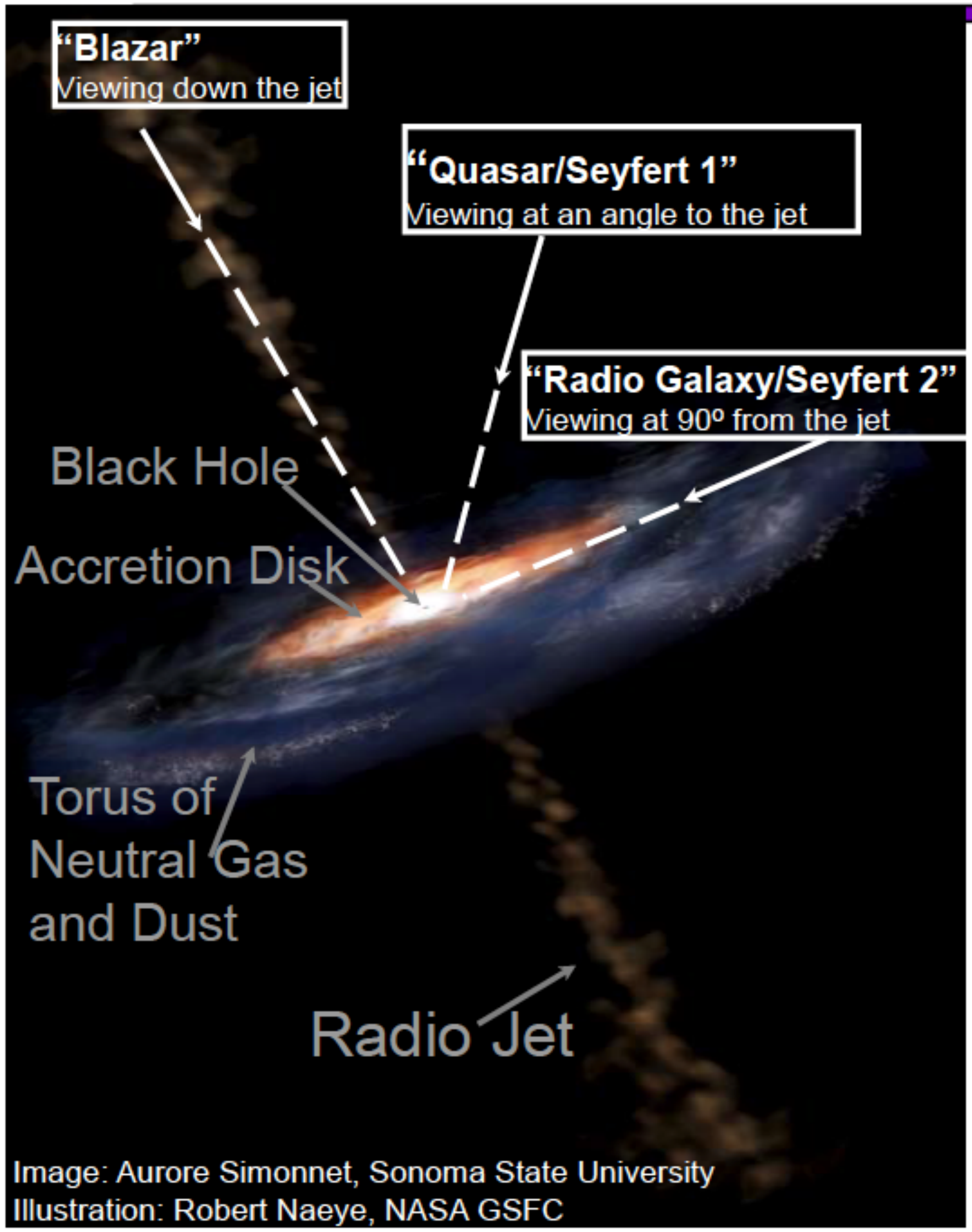


LSI +61 303 Superorbital Modulation!



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

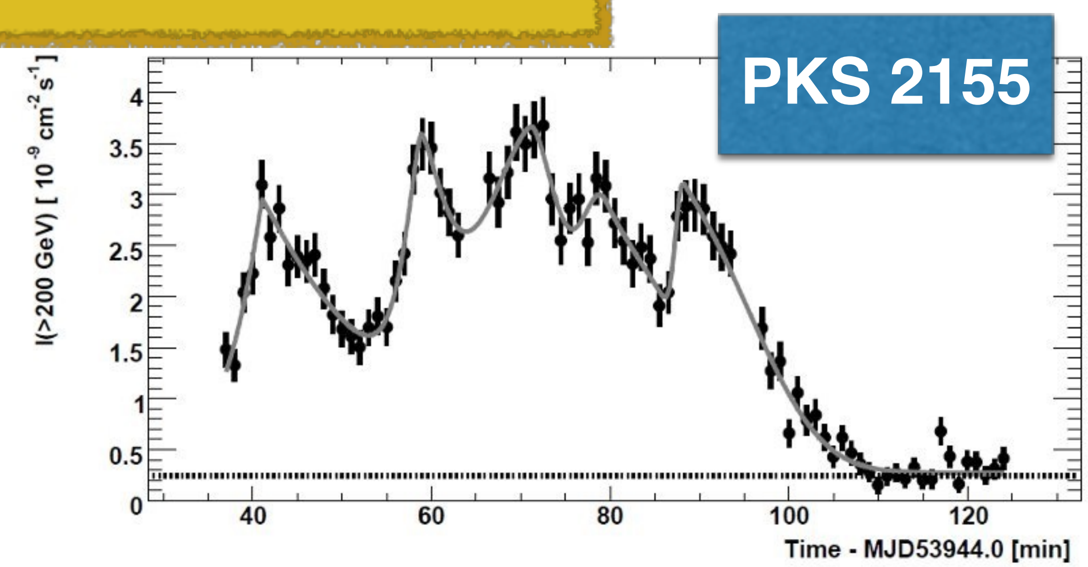
But also radio galaxies (e.g M87)

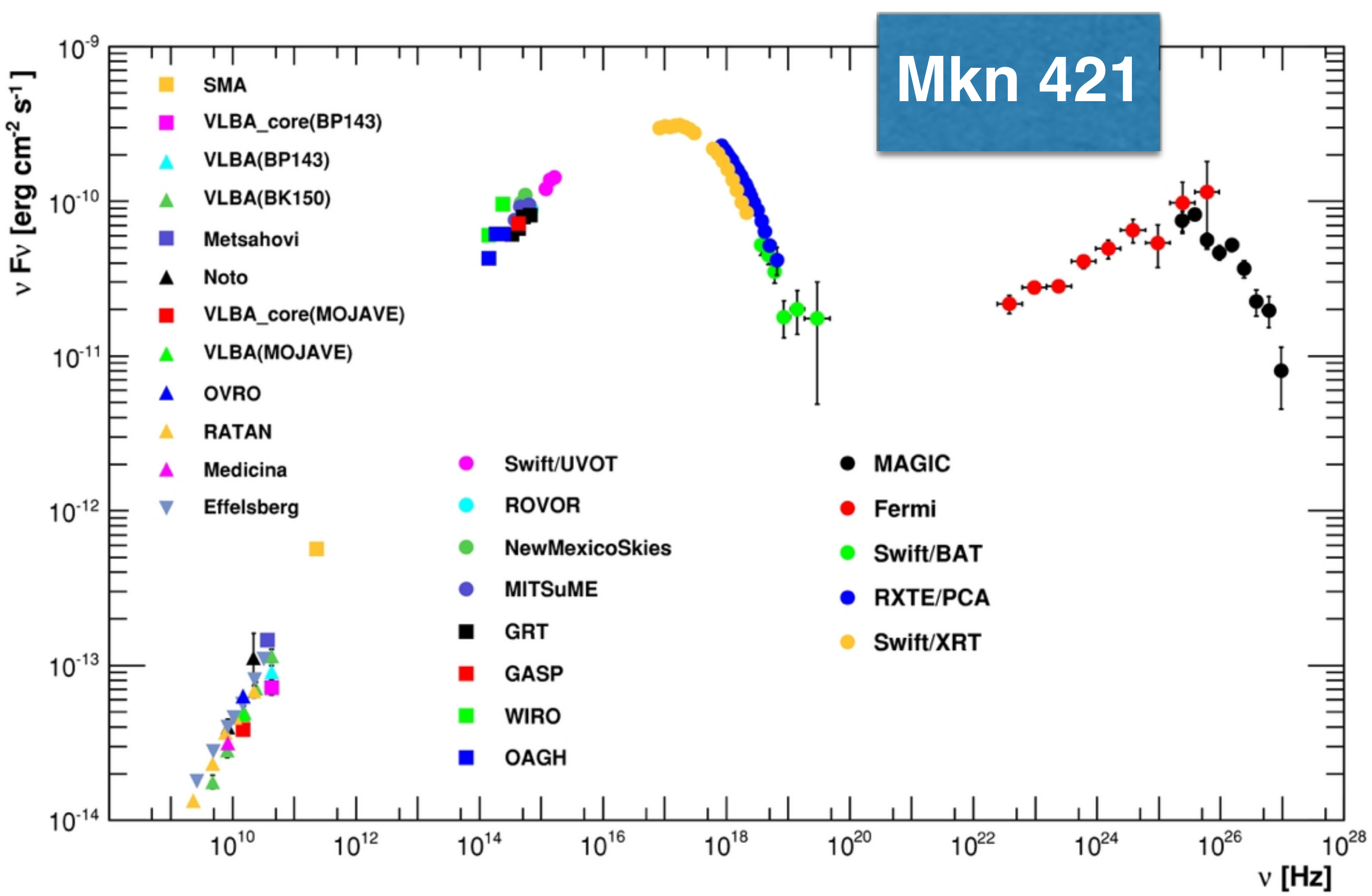
- ➔ Jet viewed from the side

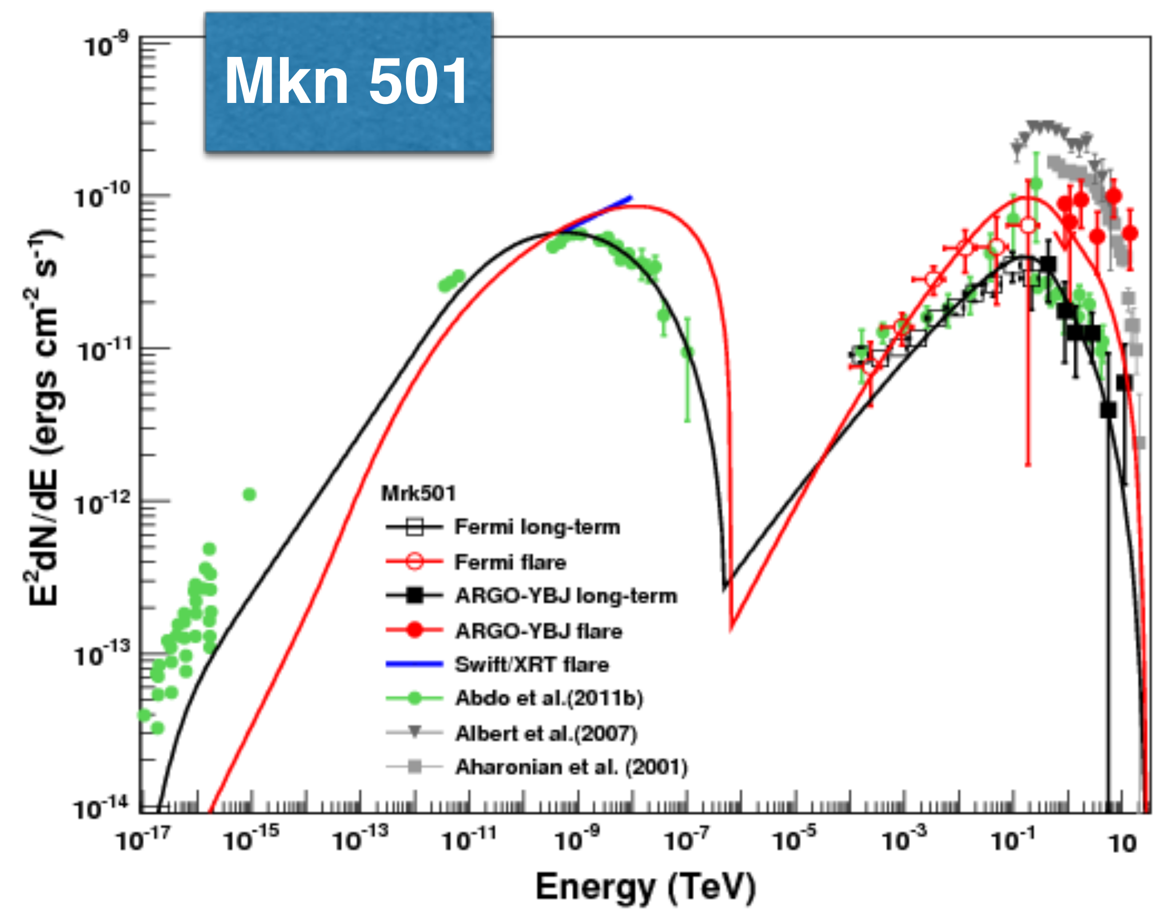
4. What do we learn from gamma rays?

BLAZARS

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







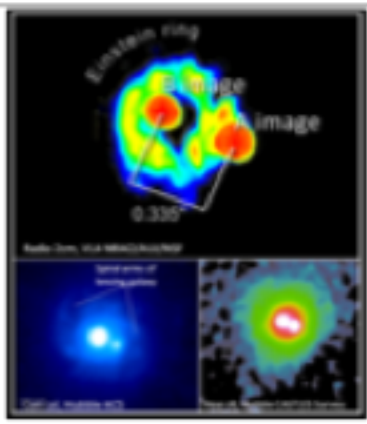
4. What do we learn from gamma rays?

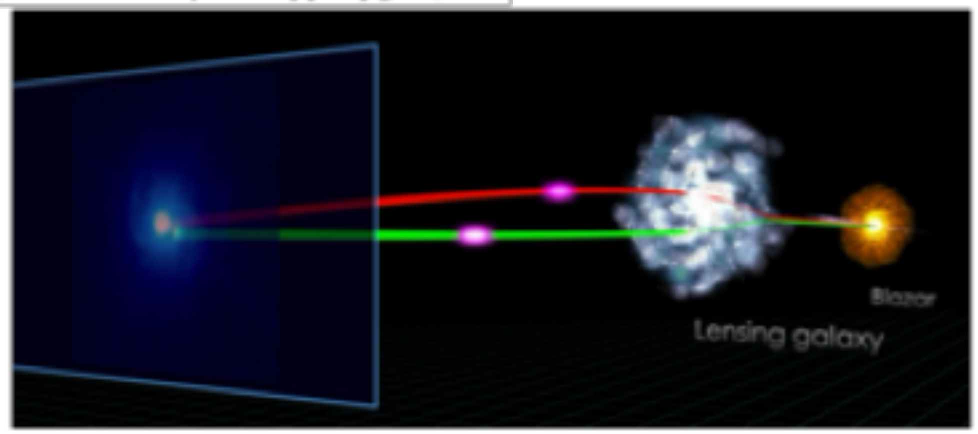
FSRQ S3 0218+357 z =0.944

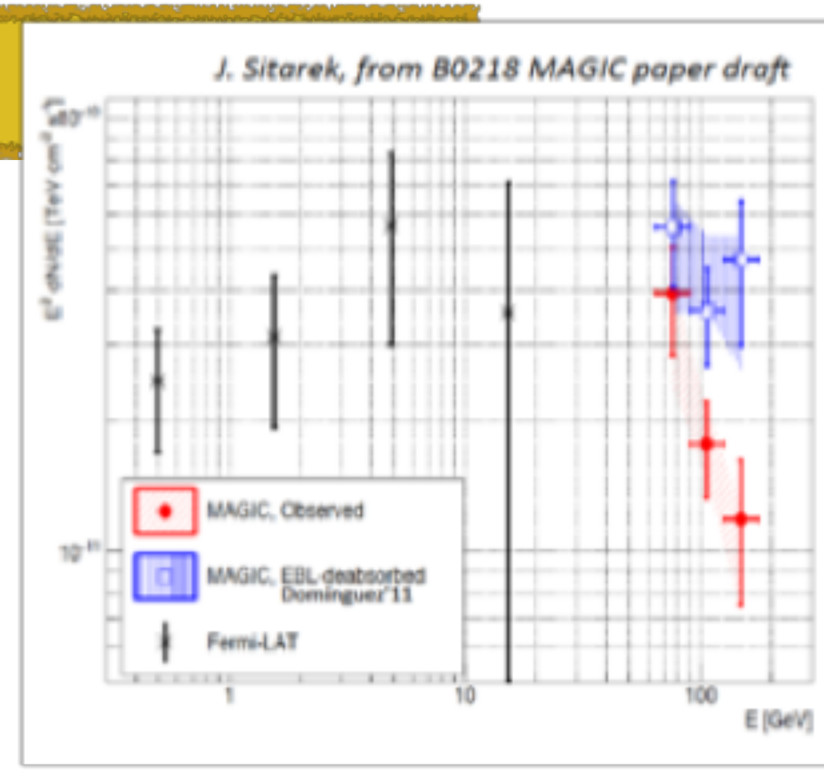
BLAZARS

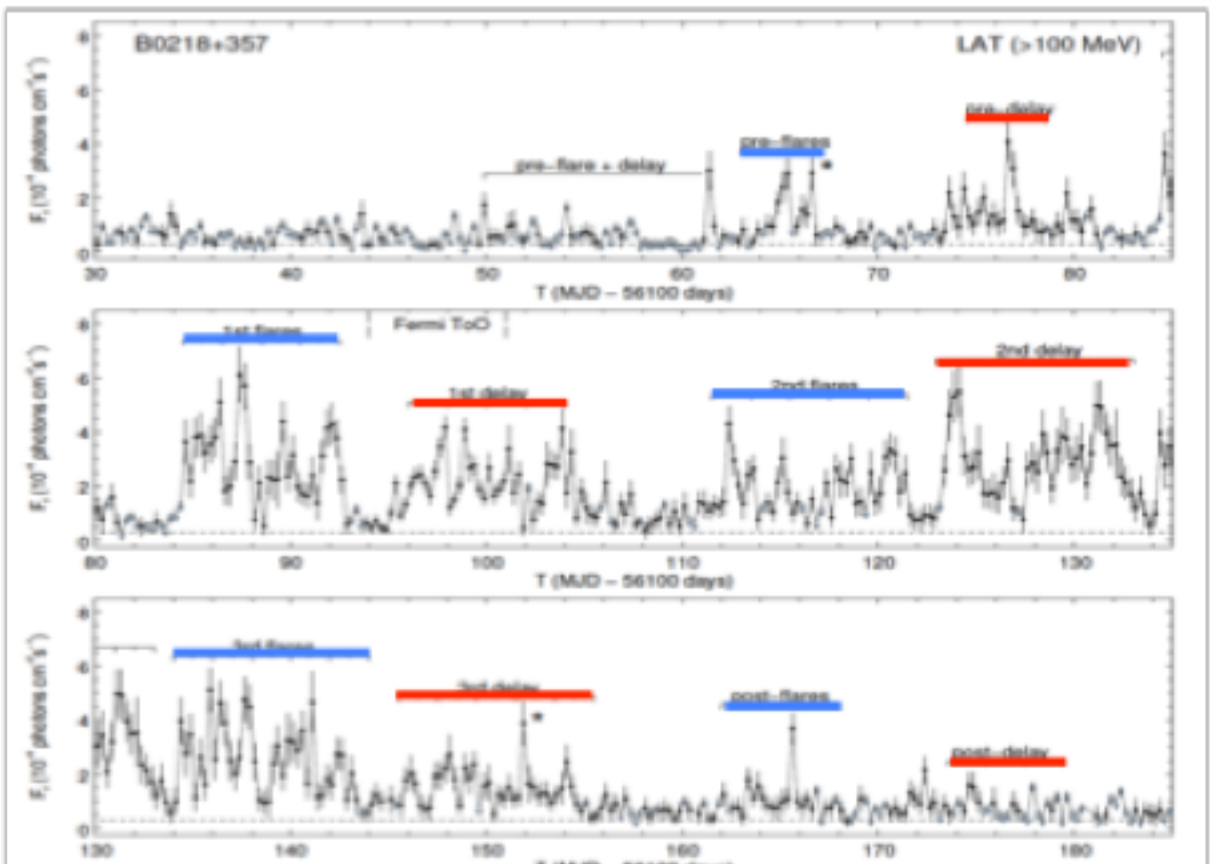
Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 With the MAGIC Telescopes

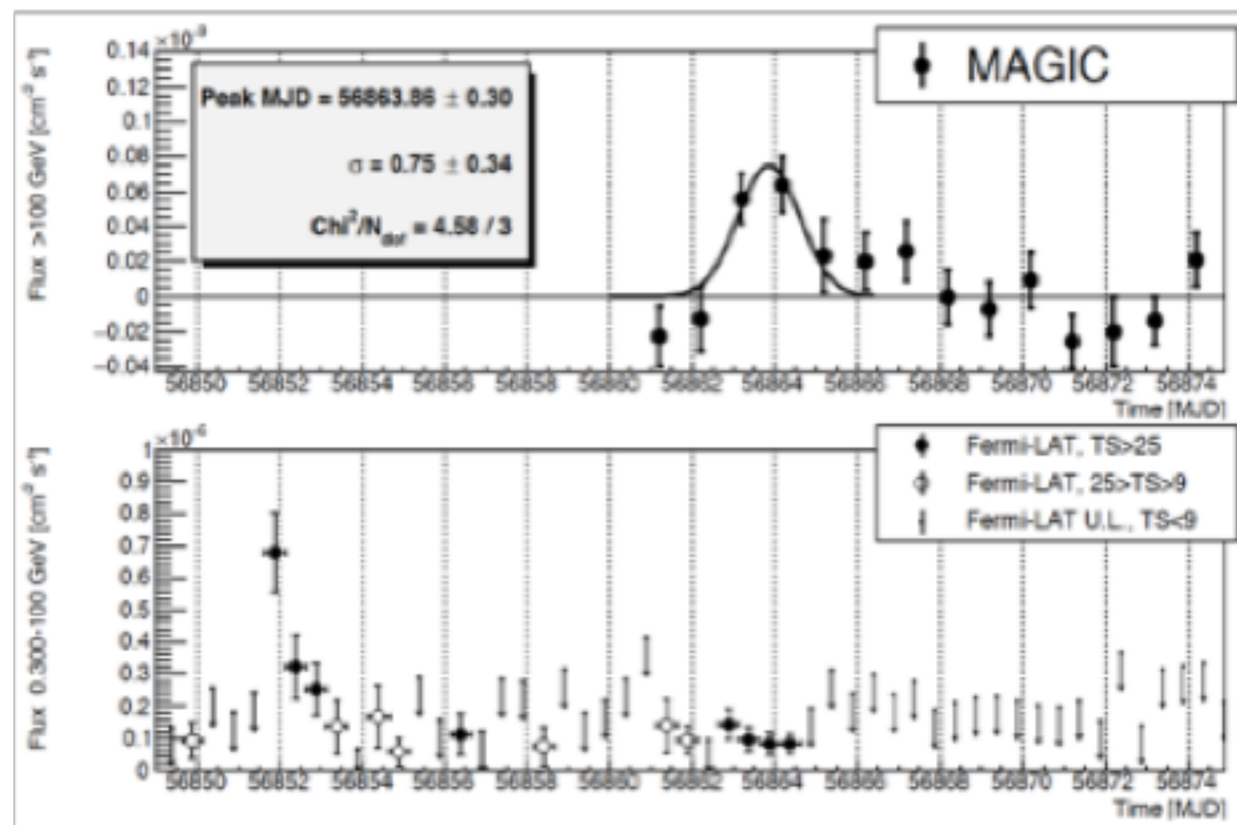
ATel #6349; *Razmik Mirzoyan (Max-Planck-Institute for Physics) On Behalf of the MAGIC Collaboration*
on 28 Jul 2014; 14:20 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)







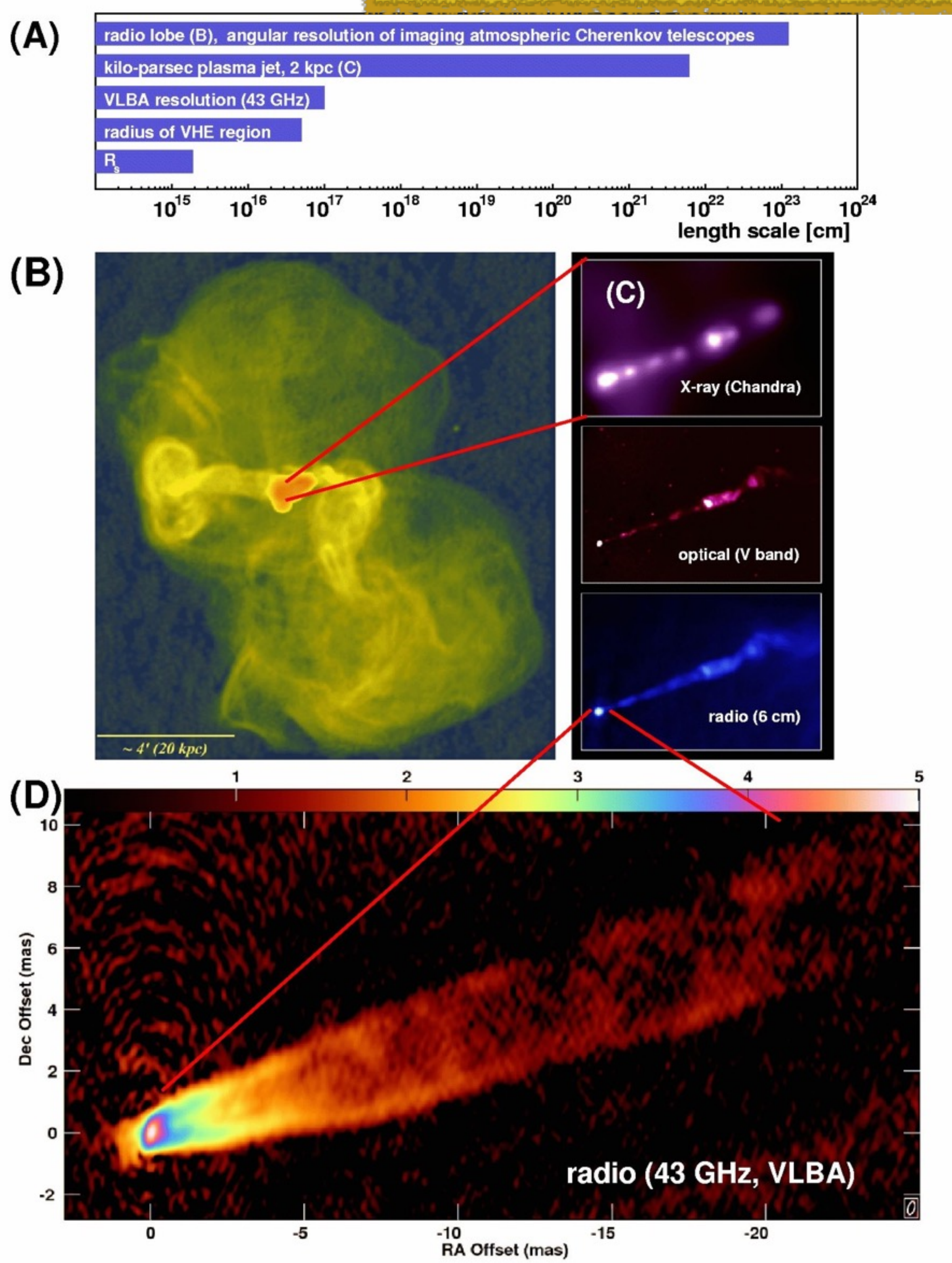


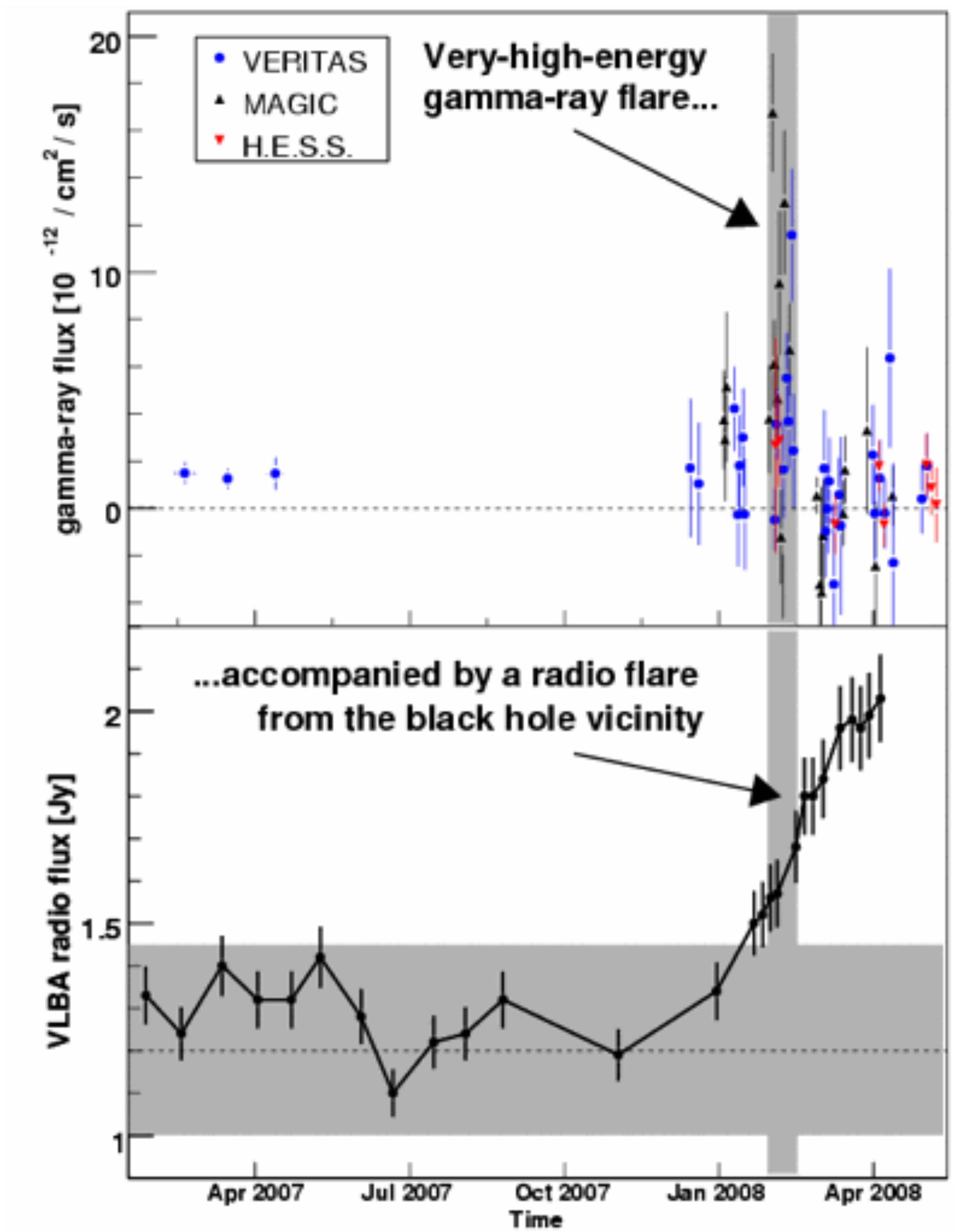


4. What do we learn from gamma rays?

Radio galaxies

- M87: best studied radio galaxy





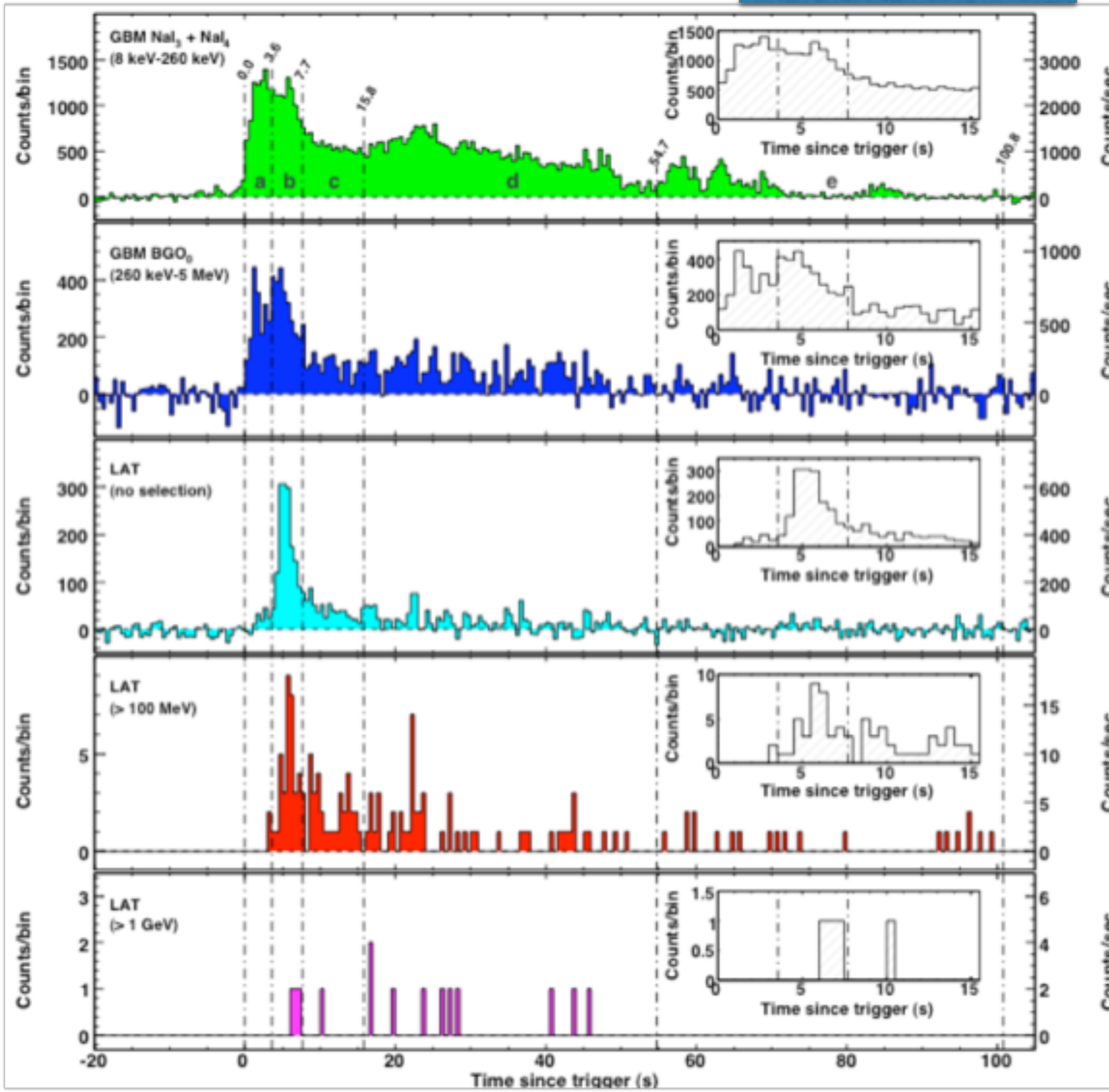
4. What do we learn from gamma rays?

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.

$z = 4.35 \pm 0.15$



4. What do we learn f

GRBs

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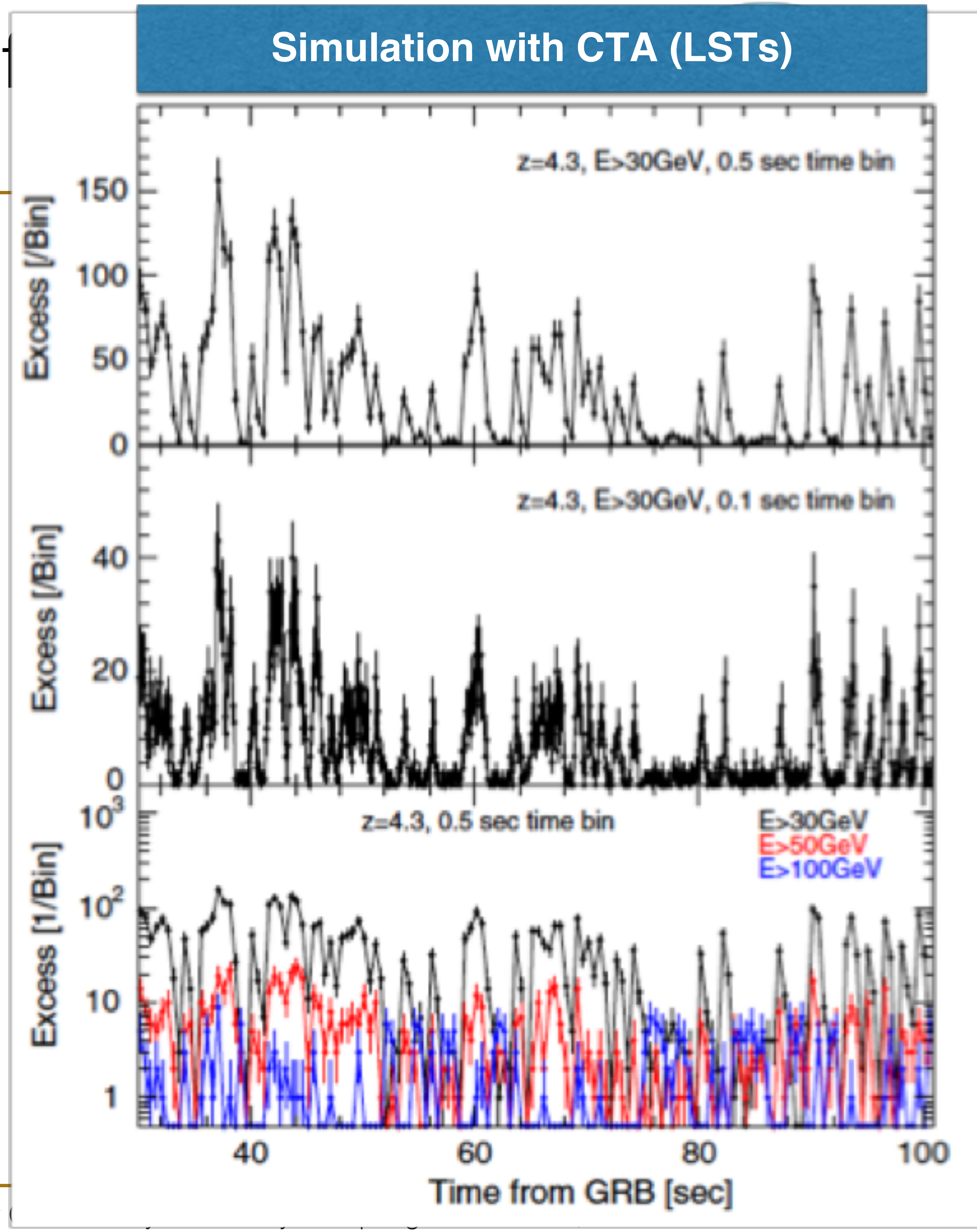
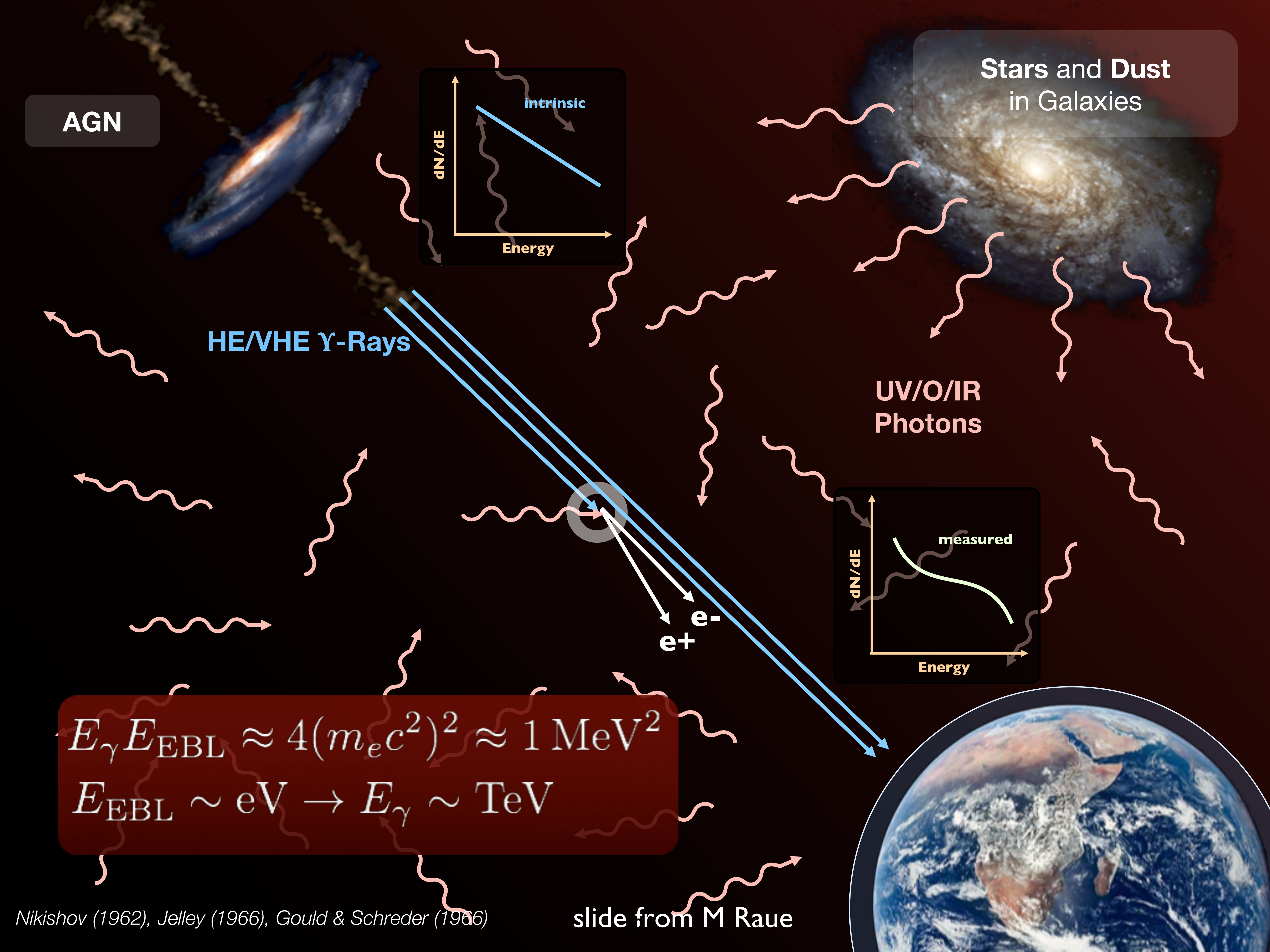
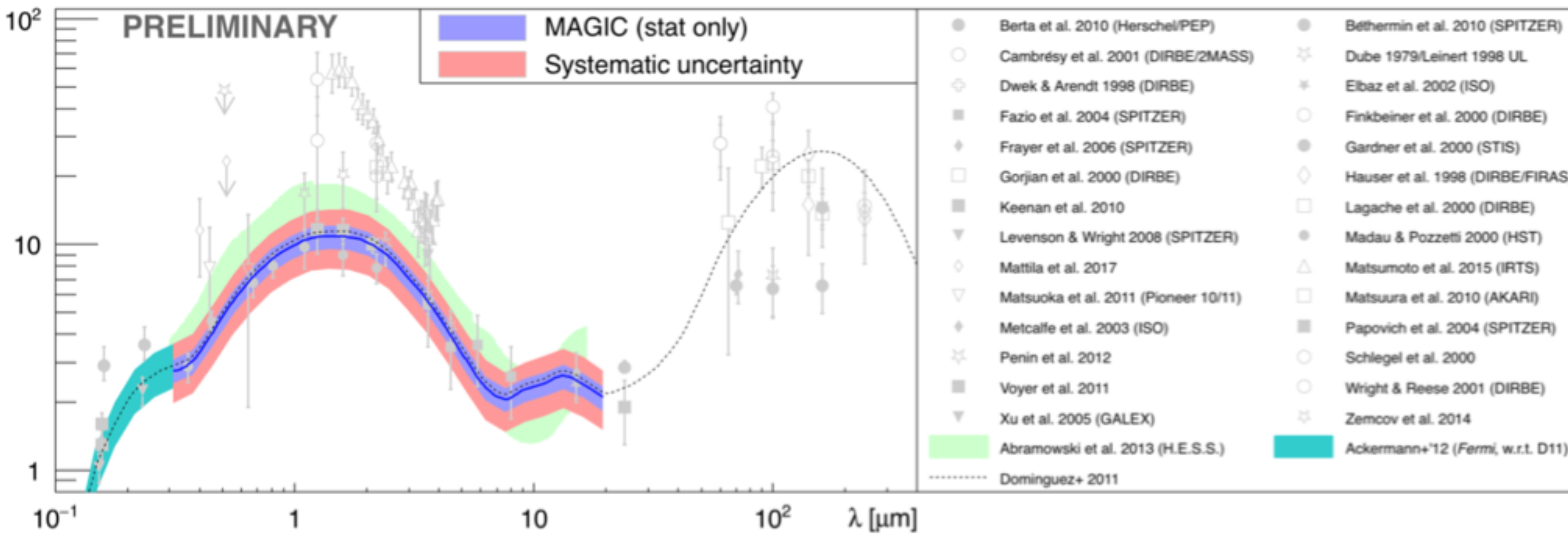



AGN
intrinsic
dN/dE
Energy
Stars and Dust
in Galaxies
HE/VHE ϒ-Rays
UV/O/IR
Photons
e-
e+
measured
dN/dE
Energy
$E_\gamma E_{\rm EBL} \approx 4(m_e c^2)^2 \approx 1\,{\rm MeV}^2$
$E_{\rm EBL} \sim {\rm eV} \rightarrow E_\gamma \sim {\rm TeV}$
Nikishov (1962), Jelley (1966), Gould & Schreder (1966)
slide from M Raue

4. What do we learn from gamma rays?

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Extragalactic Background Light



- Compared to other gamma-based EBL scale measurements
- Good agreement with HESS and Fermi-LAT measurements

Not much more EBL than the one from the resolved galaxies

4. What do we learn from gamma rays?

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**

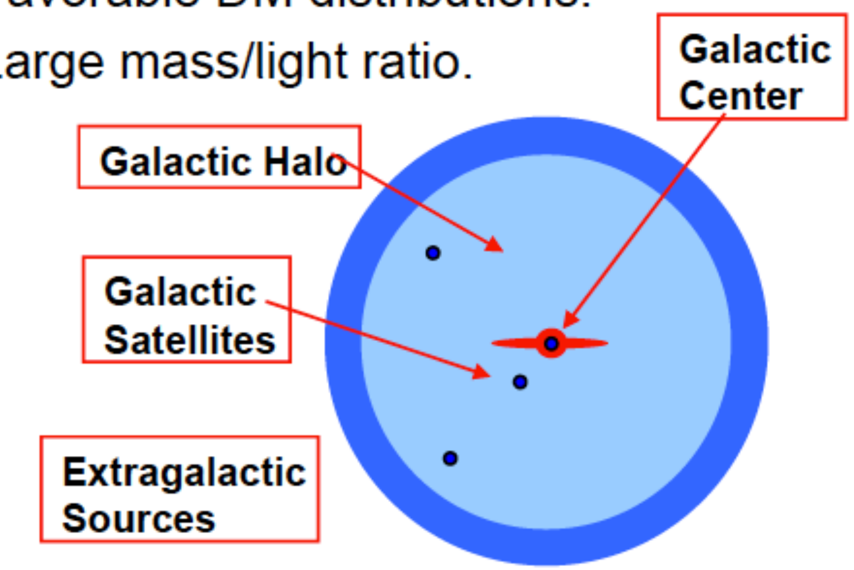
Point back to source

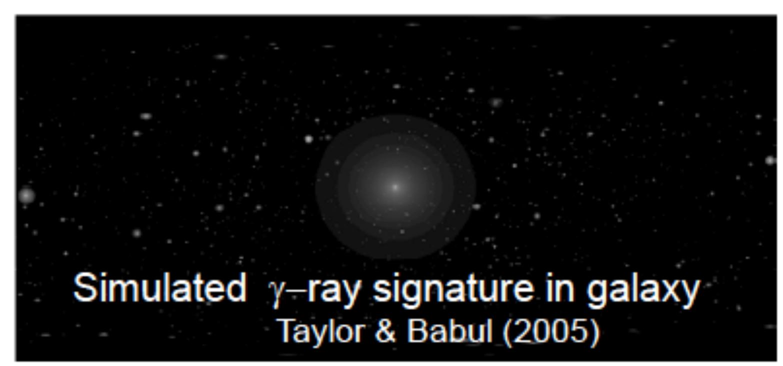
$\bar{p}$
e^+
$\bar{d}$

Search for excess components in cosmic rays (Diffusion)

(PAMELA,AMS,GAPS)

Target regions with:
- Favorable DM distributions.
- Large mass/light ratio.

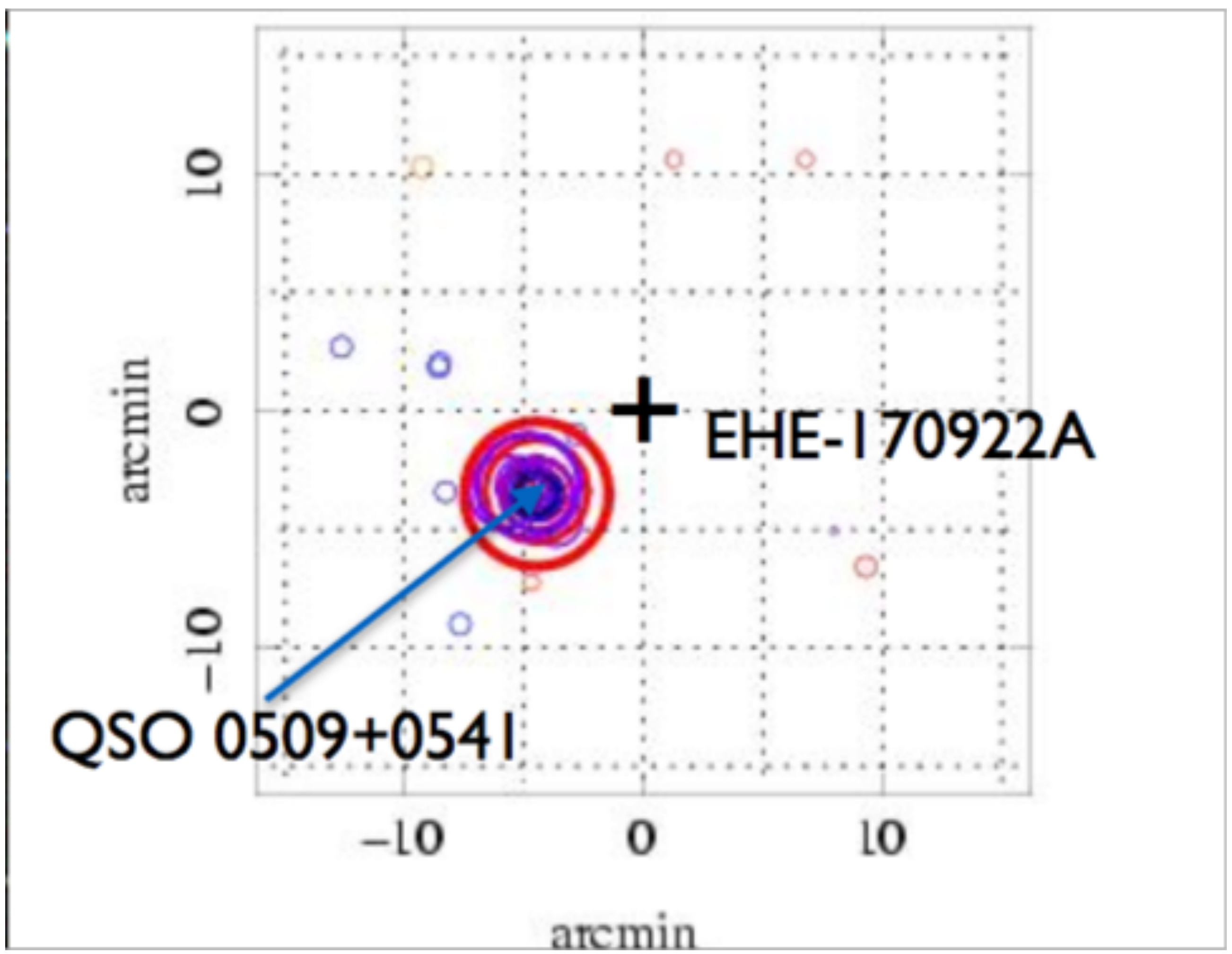


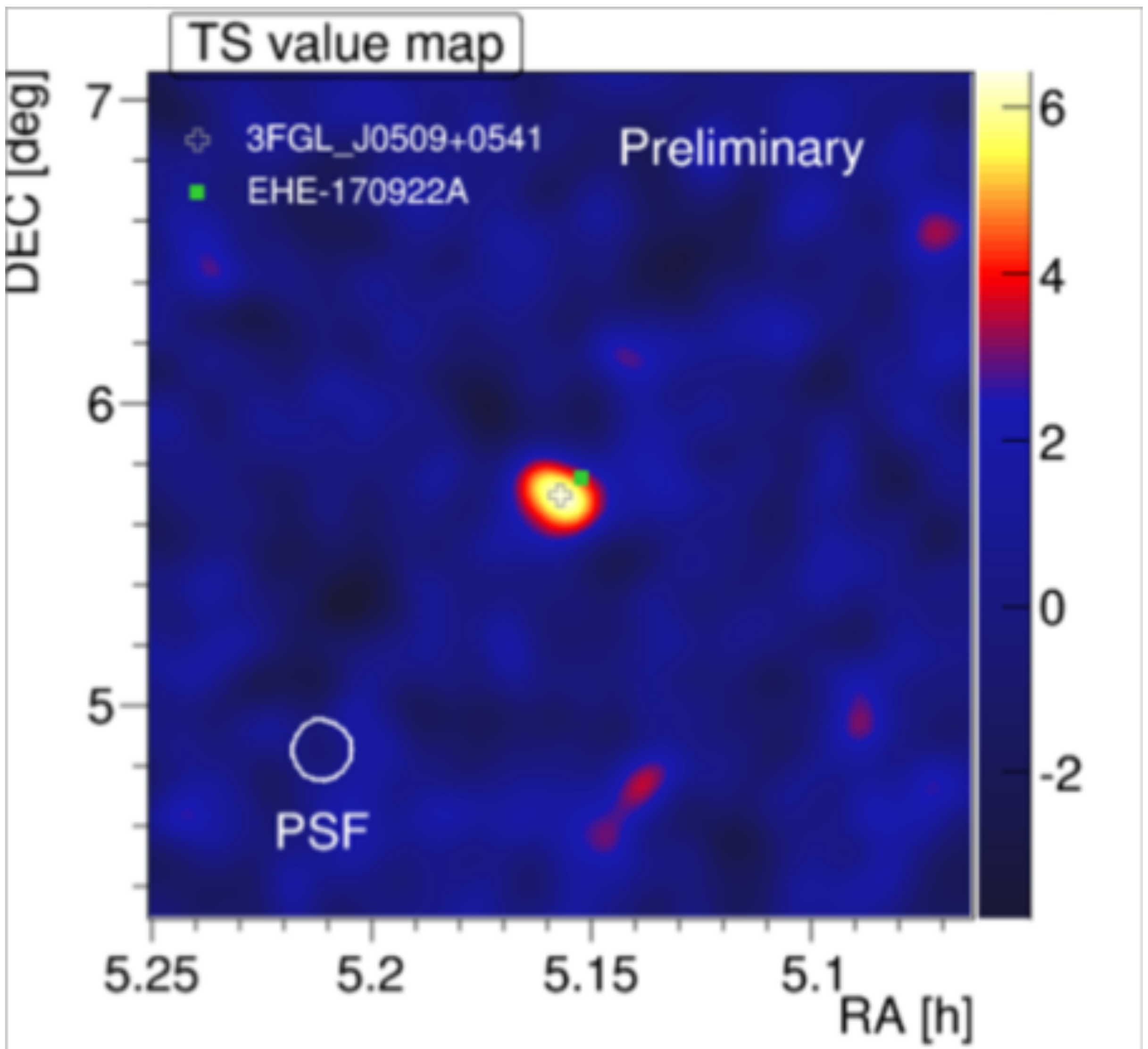


Complementary approach to direct detection & LHC
Goal is to do DM astronomy !

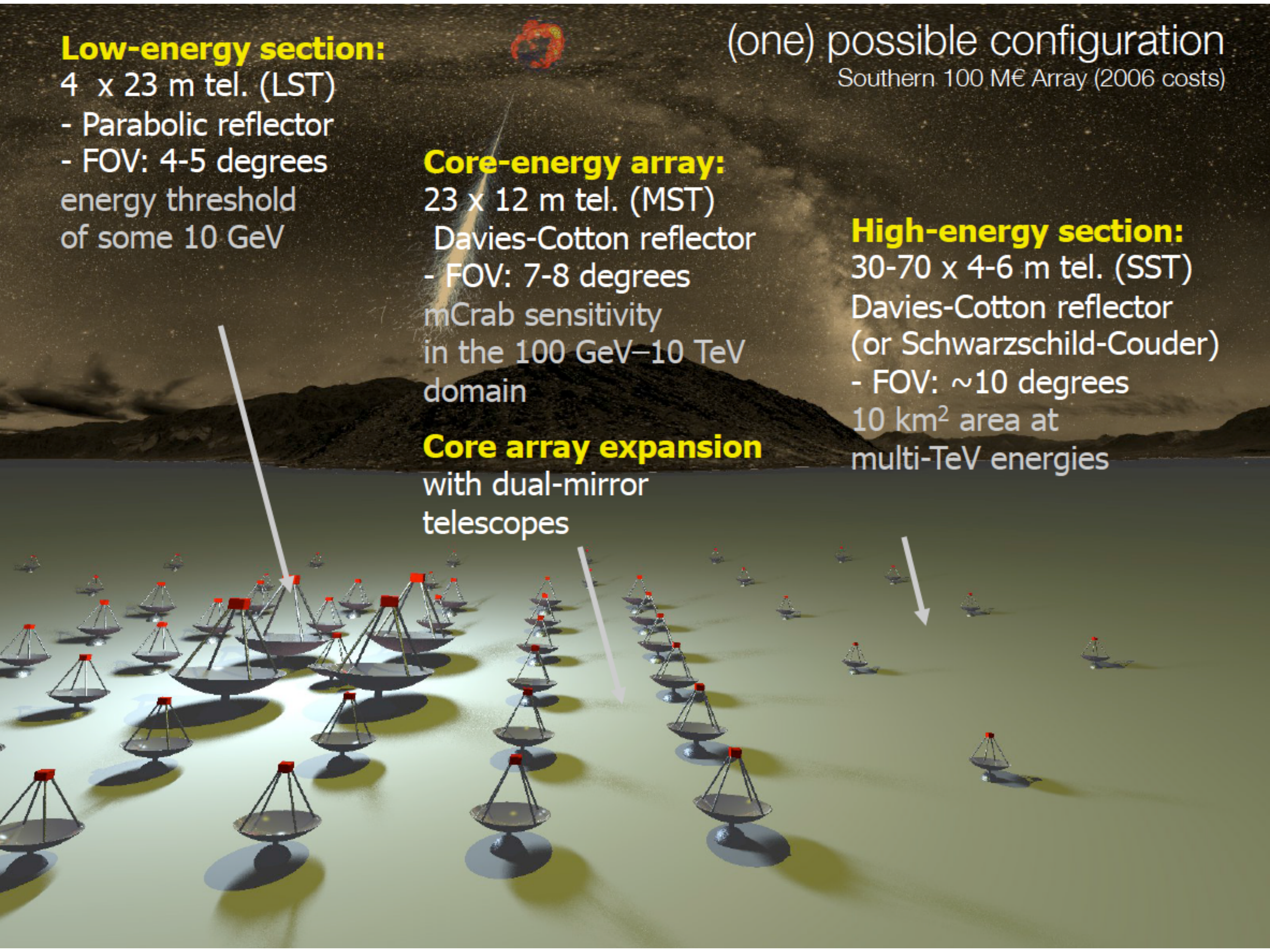
Multimessendger

- September 2017: TXS0506+056 (z=0.3365) in flaring state coinciding with Extremely High Energy (EHE, through-going track) neutrino event
- Chance coincidence or proof of hadronic emission?





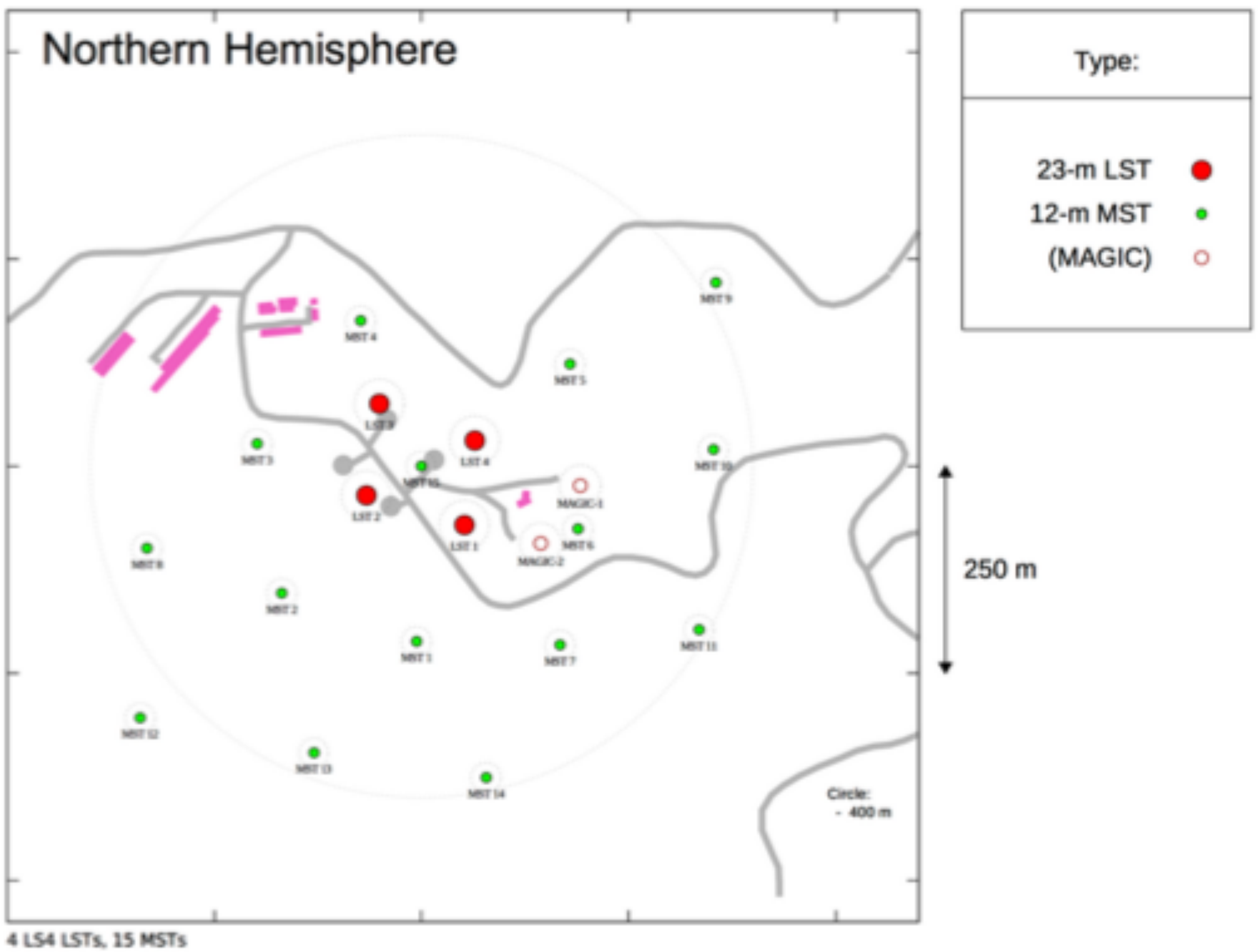

THE NEXT BIG STEP:
THE CHERENKOV TELESCOPE ARRAY
10 fold improvement in sensitivity
10 fold improvement in usable energy range
much larger field of view
strongly improved angular resolution
cta
cherenkov telescope array


(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

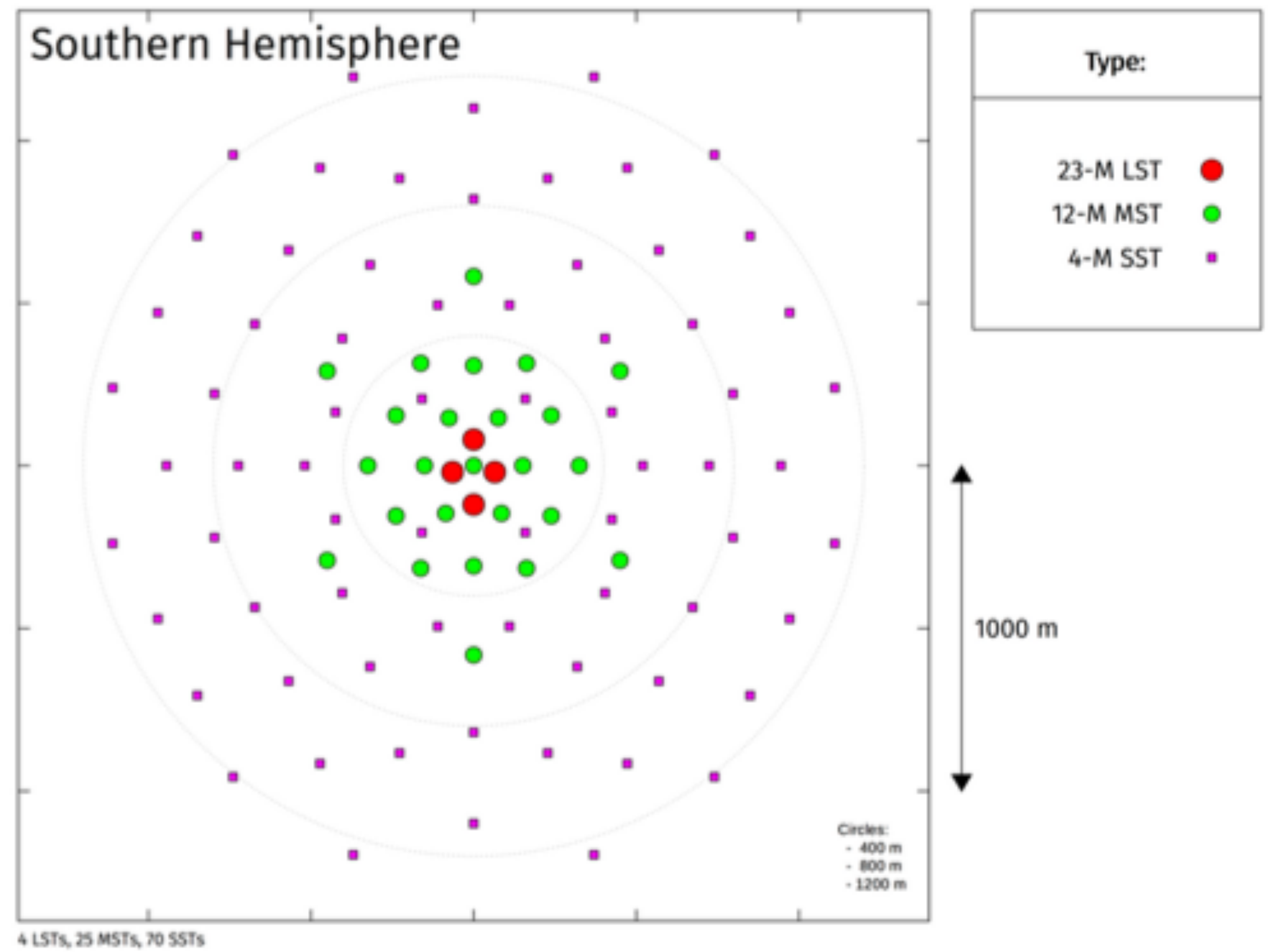
Cherenkov Telescope Array

5. Future of Gamma-Ray astrophysics

La Palma, Canary islands

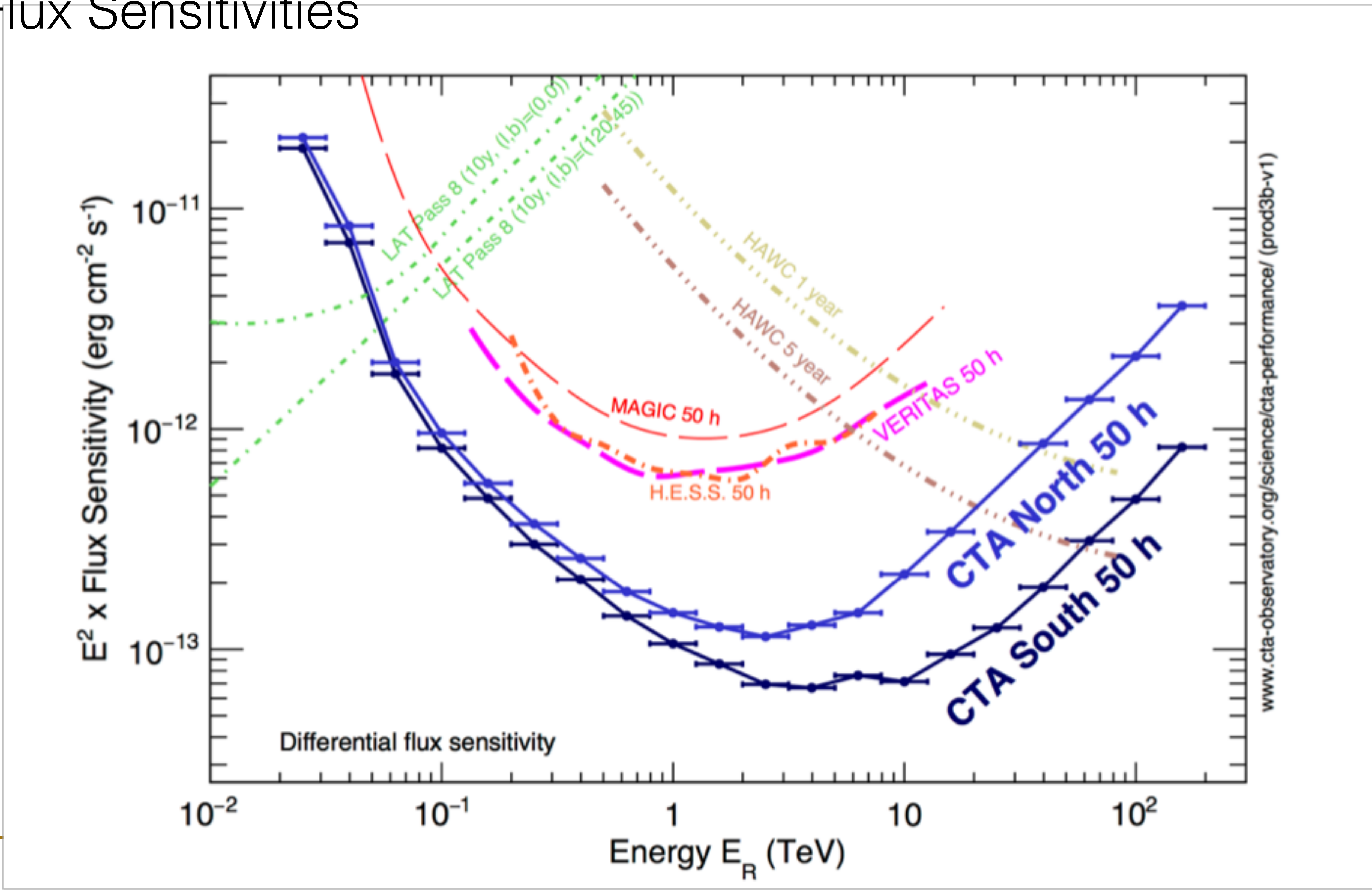


Paranal, Chile

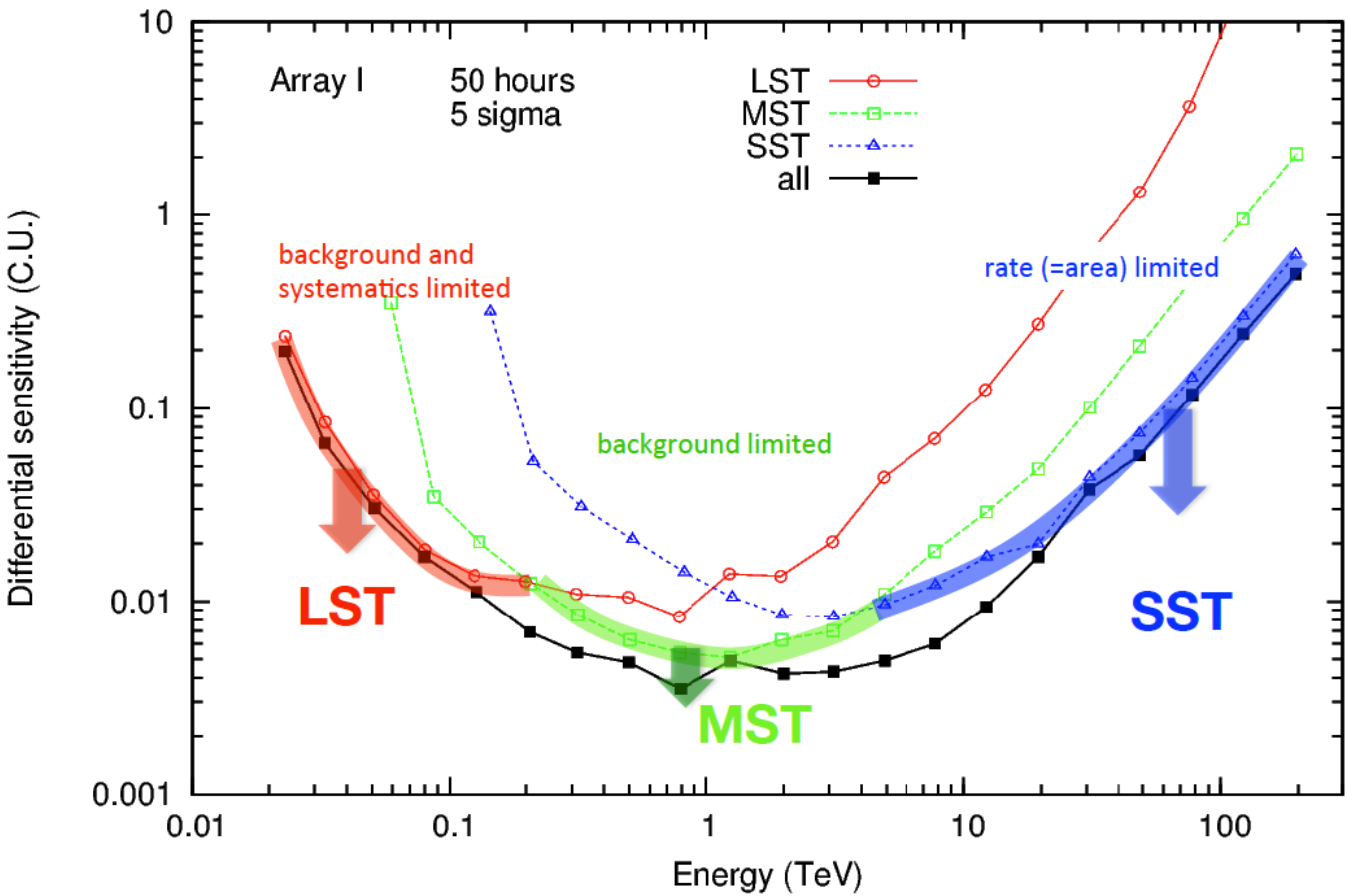


5. Future of Gamma-Ray astrophysics

Flux Sensitivities



5. Future of Gamma-Ray astrophysics



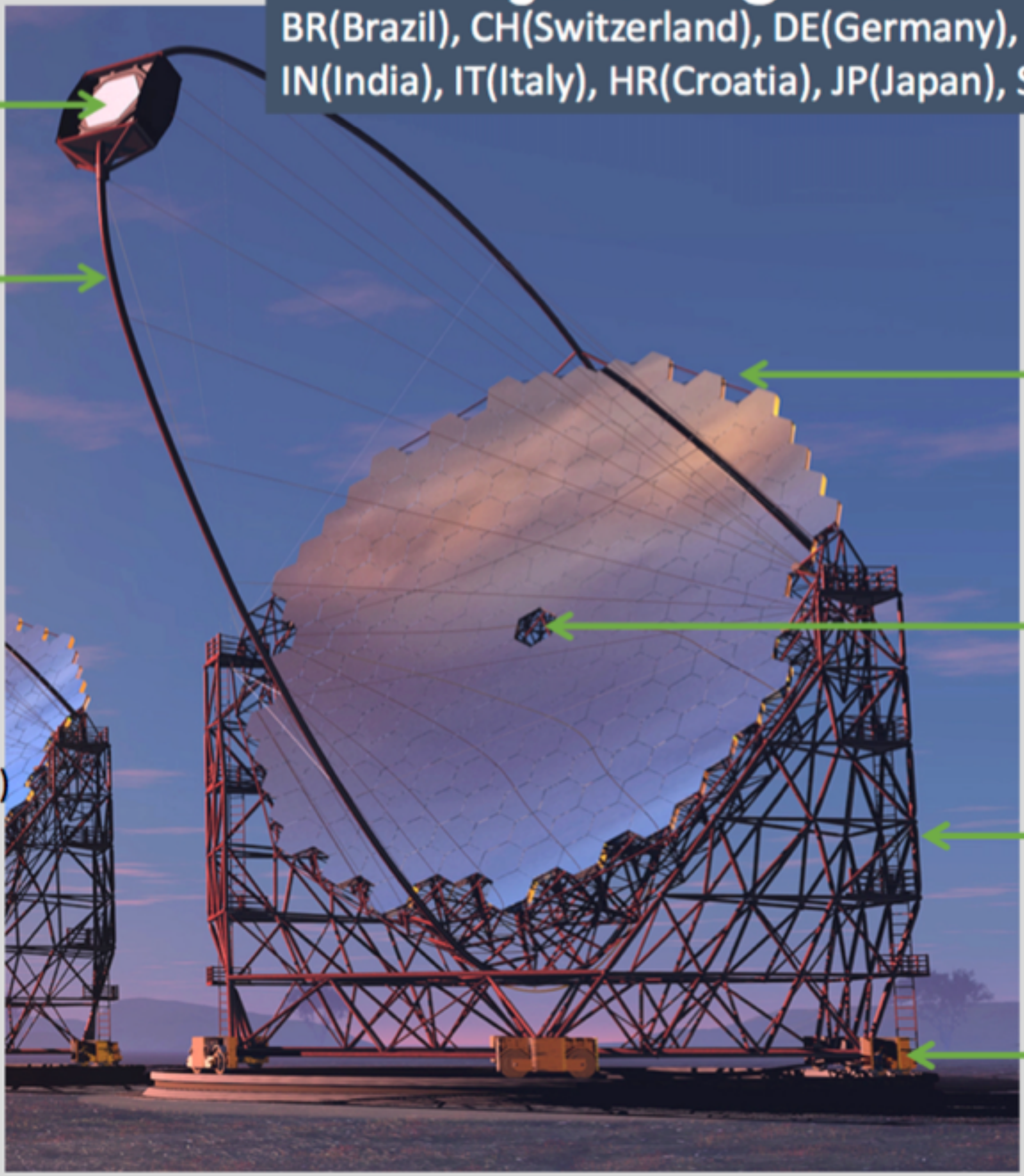
5. Future of Gamma-Ray astrophysics

Large Size Telescopes of CTA

LST collaboration:
11 countries
223 members
(134 receiving emails)
73 FTEs

LST Project : Big International Effort

BR(Brazil), CH(Switzerland), DE(Germany), ES(Spain), FR(France), IN(India), IT(Italy), HR(Croatia), JP(Japan), SE(Sweden)



Focal Plane Instr.
Electronics (JP/IT/ES)
Camera body (ES)

Camera Supporting Structure (FR/IT)

Mirror (JP)
Interface Plate(DE/BR/JP)
Actuator (JP/CH)
CMOS-Cam (JP)

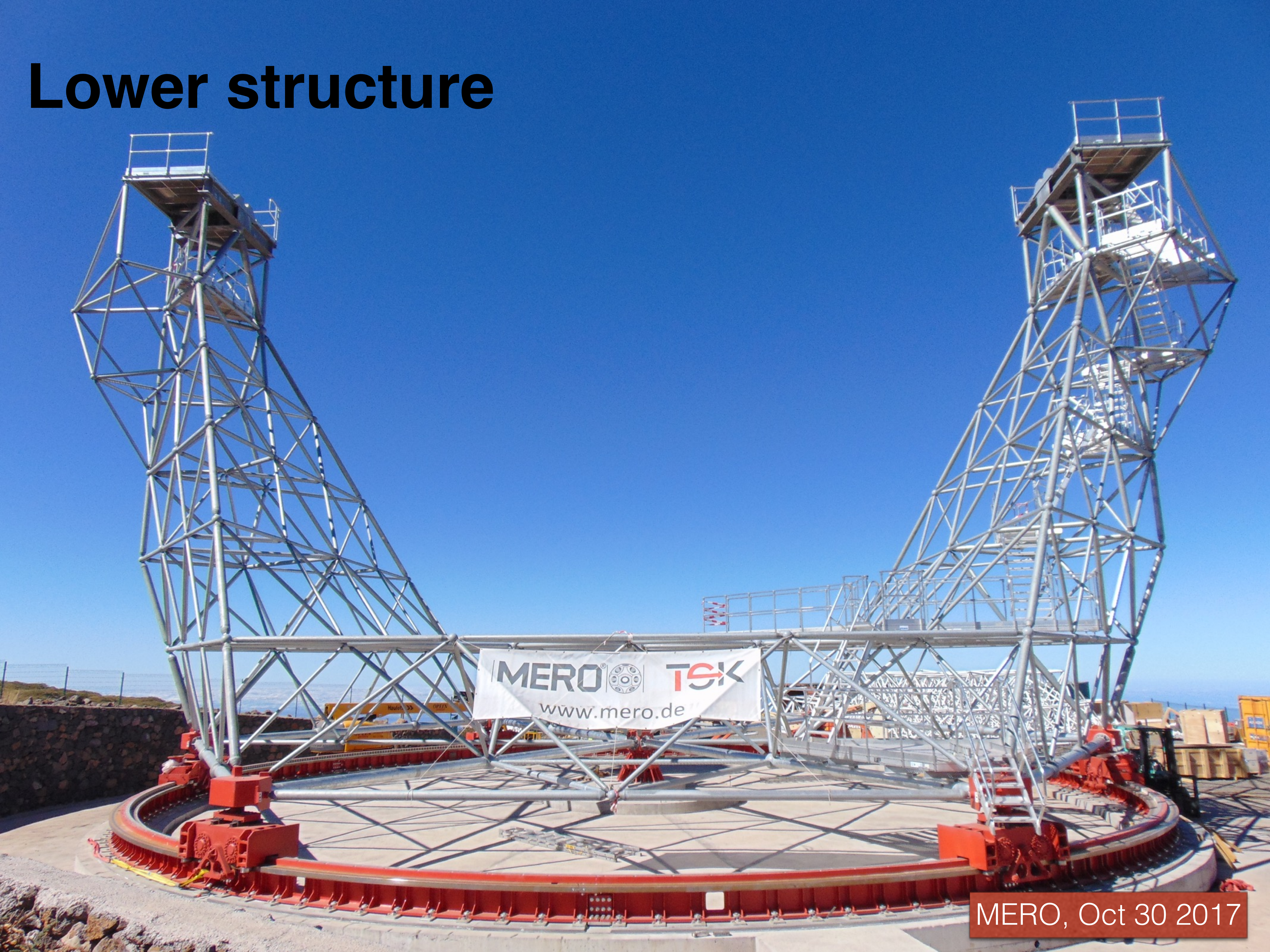
Star Guider (SE)
Calibration Box (IN/IT)

Flywheel, UPS (JP)
Computers, network (JP)

Structure (DE)
Access Tower (DE/ES)

Drive (DE/FR/ES)
Bogie (DE/ES/IT)
Rail (DE/ES)
Foundation (ES)

Lower structure



MERO, Oct 30 2017

Dish installed

December 2017


counterweight installed
dish turned
Feb 17, 2018
Inauguration of LST1: 10 Oct 2018

Mirrors

ICRR, Japan

Developed last 6 years

- Light weight 45kg
- Tolerance <10μm
- Reflectivity > 92%
- Aging ~1% /yr

Before 2016 : 100 Mirror proto.
2016 : LST1-LST2 Mirrors (400)
2017 : LST3-LST4 Mirrors (500)
produced and in production

shipped

Shipping schedule

2017 Aug : LST1-2 Mirrors (400 units) @La Palma
2017 Oct: LST3 (200 units) are shipped
2017 Dec : LST4-5 Mirrors (300 units)

Camera

cherenkov telescope array

Japan + INFN-Pisa + IAC + IFAE + Complutense + CIEMAT

7 LGs

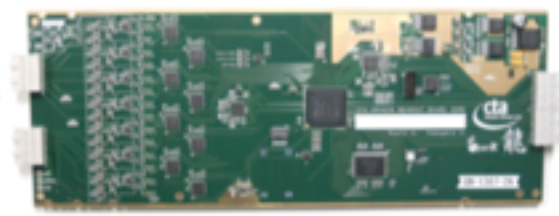
+

7 PMTs

+

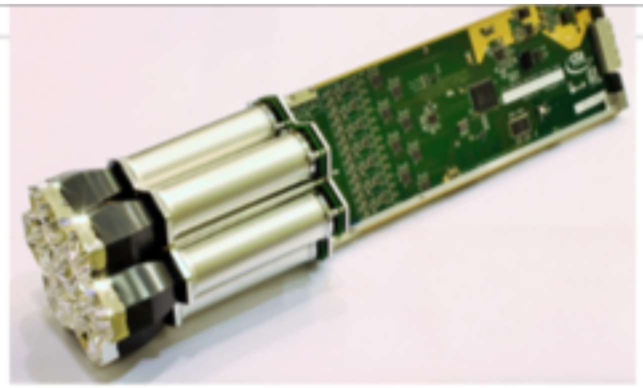
SCB

+



Dragon board

=



FPI module

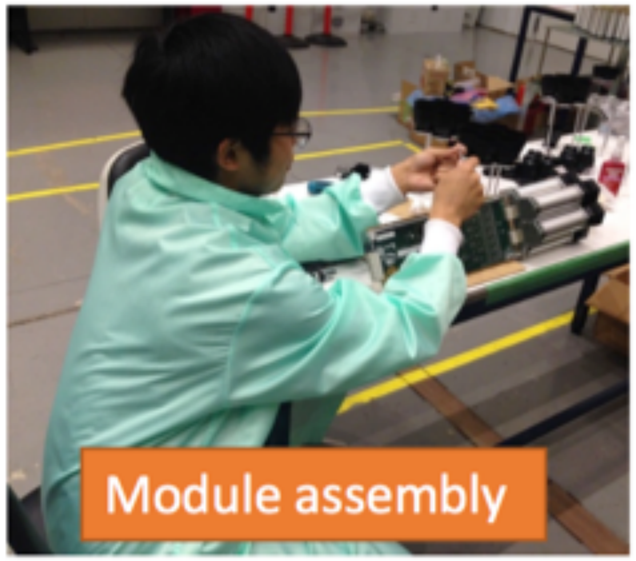
Module assembly

19 tested modules

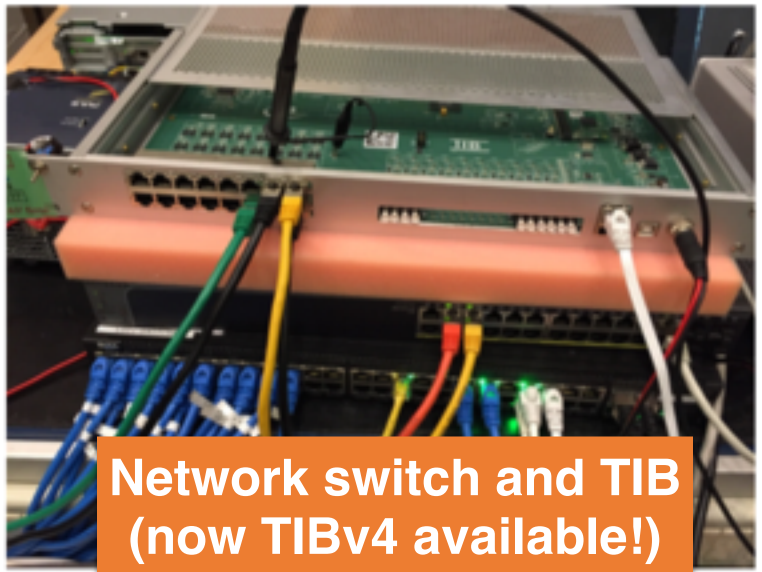
Trigger back planes

265 modules/ Tel. needed.

270 modules are assembled @ IAC



Module assembly



Network switch and TIB (now TIBv4 available!)

Camera server

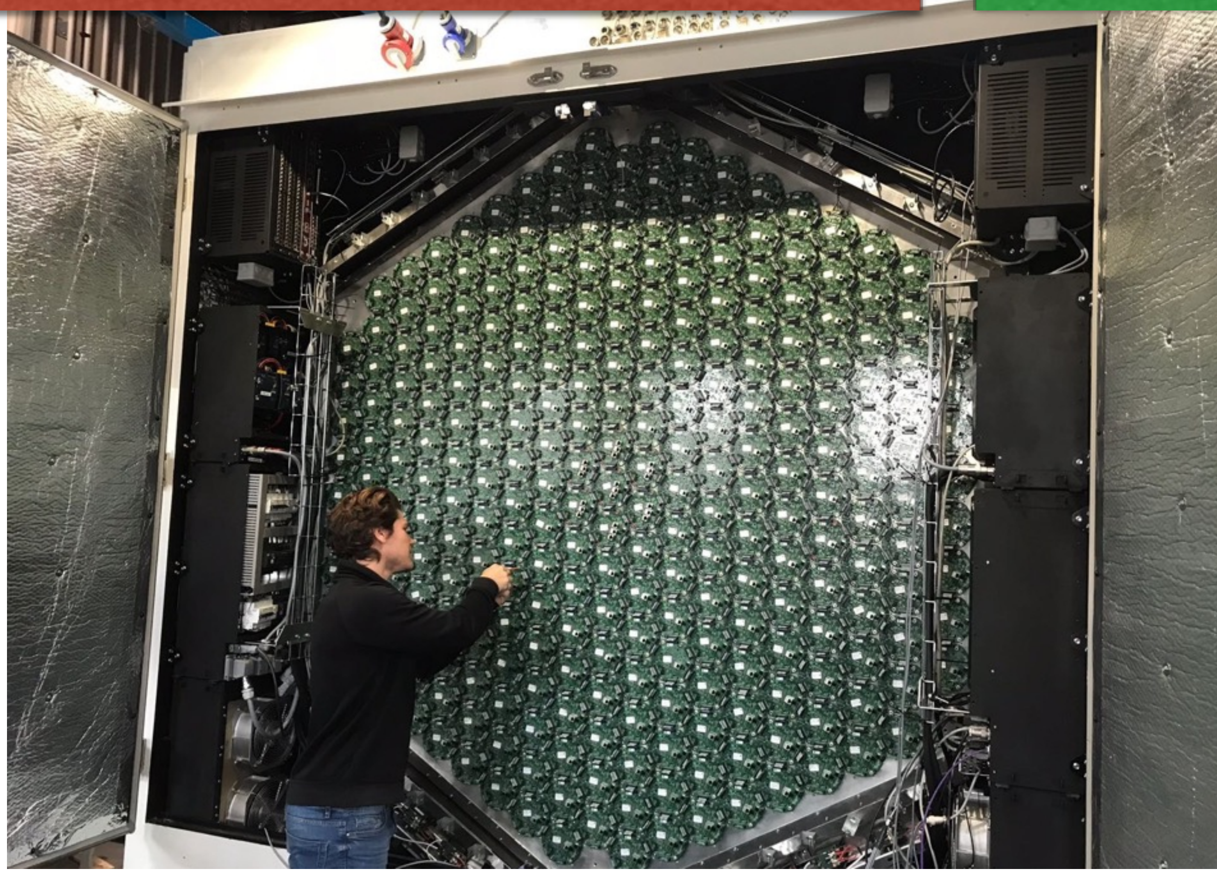
Now ready to ship to IFAE

21

LST1 progress since November 2017

Backplanes of the camera installed

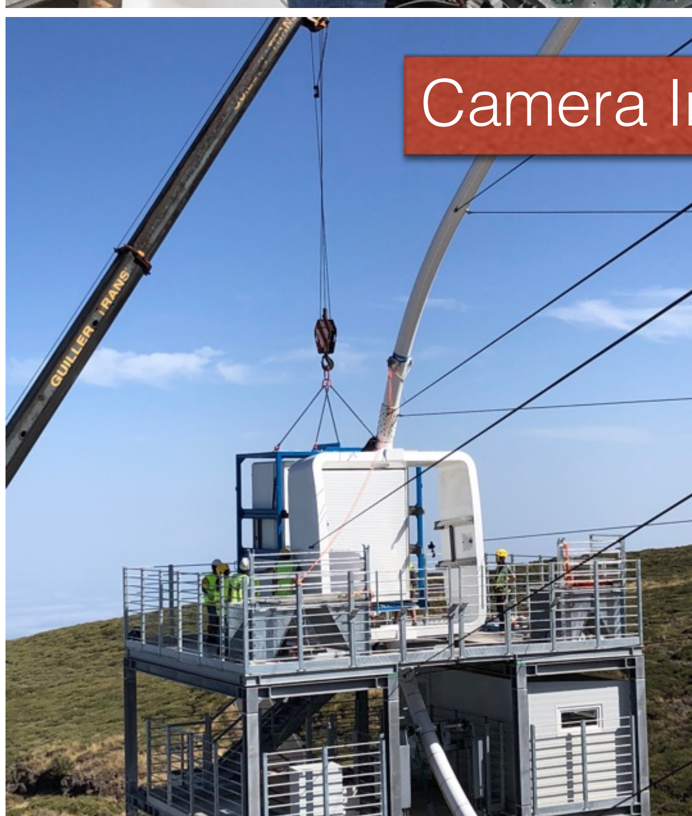
Jan 2018



Camera mechanics finished

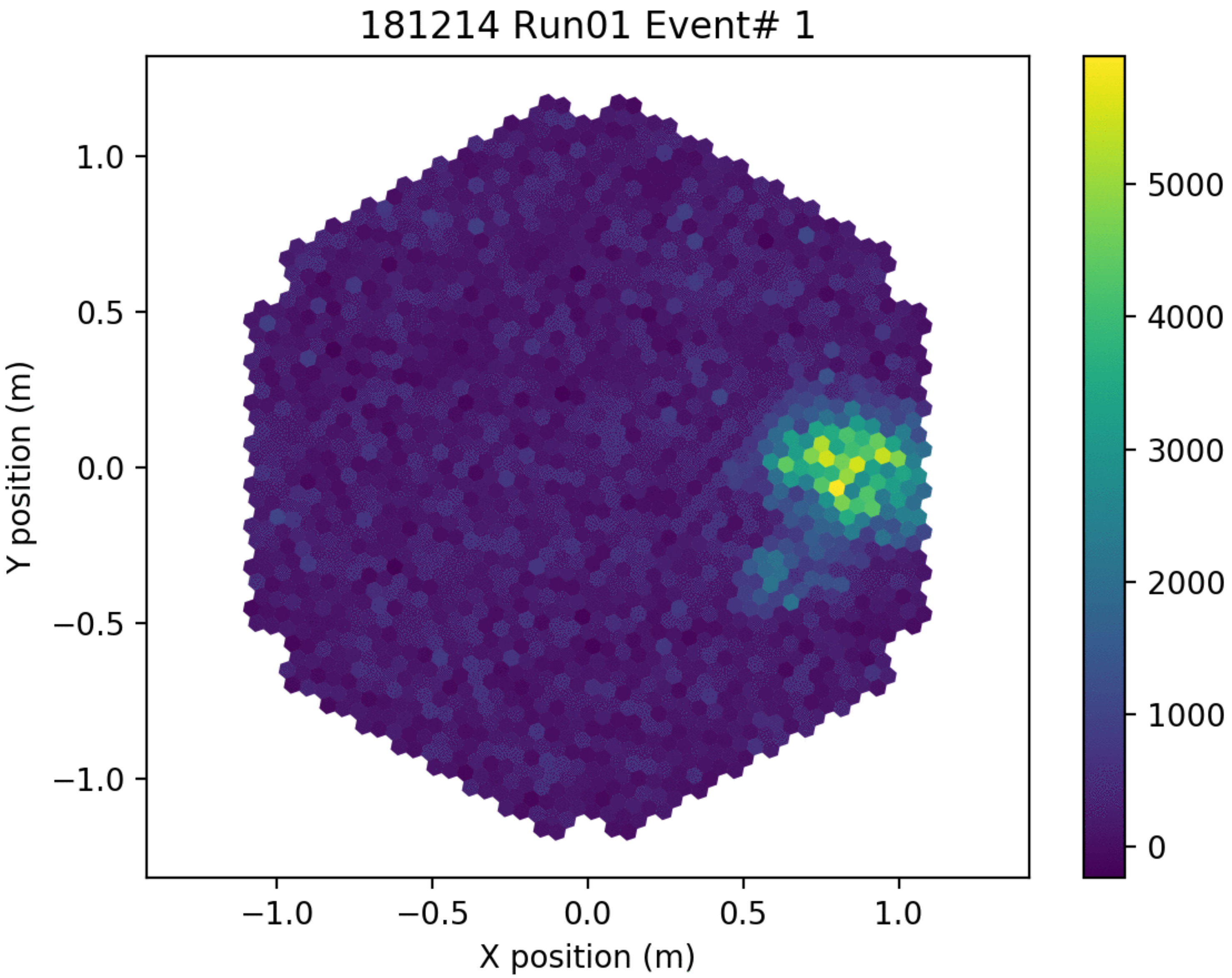
Feb 2018

Camera Installation On the telescope



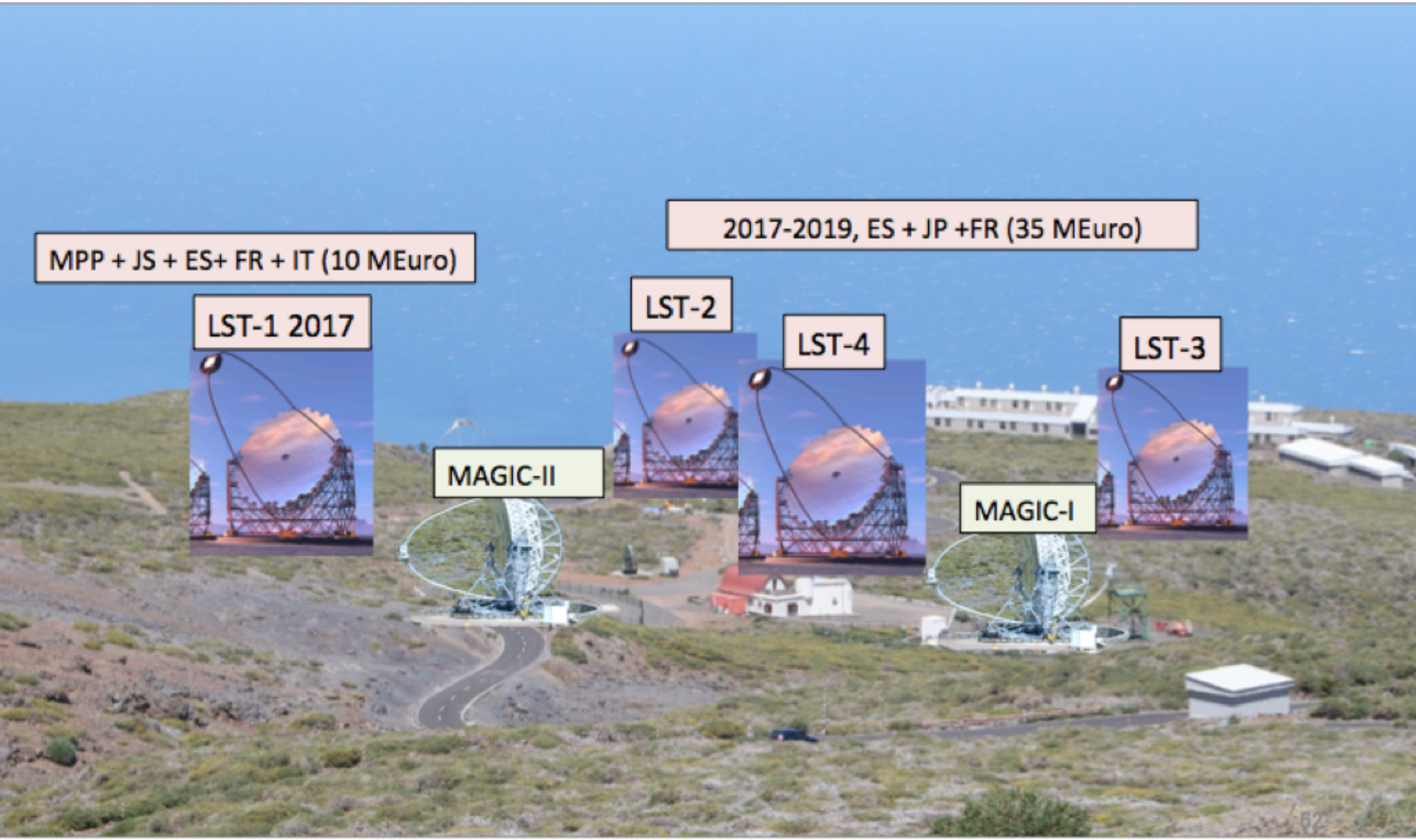
Sep 2018

Oct 2018



試験観測が始まっている

4 LSTs in La Palma




top view, 2025
CTA operations building
MST 9
MST 4
MST 5
LST 3
MST 10
MST 3
LST 4
MST 15
LST 2
MST 6
LST 1
MST 8
MST 2
MST 1
MST 7
MST 11
MST 12
MST 13
MST 14

Your (possible) future

ICRR
Institute for Cosmic Ray Research
University of Tokyo