

高エネルギー ガンマ線 天文学

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ICRR, University of Tokyo

ICRR Spring School 2022

March 1, 2022

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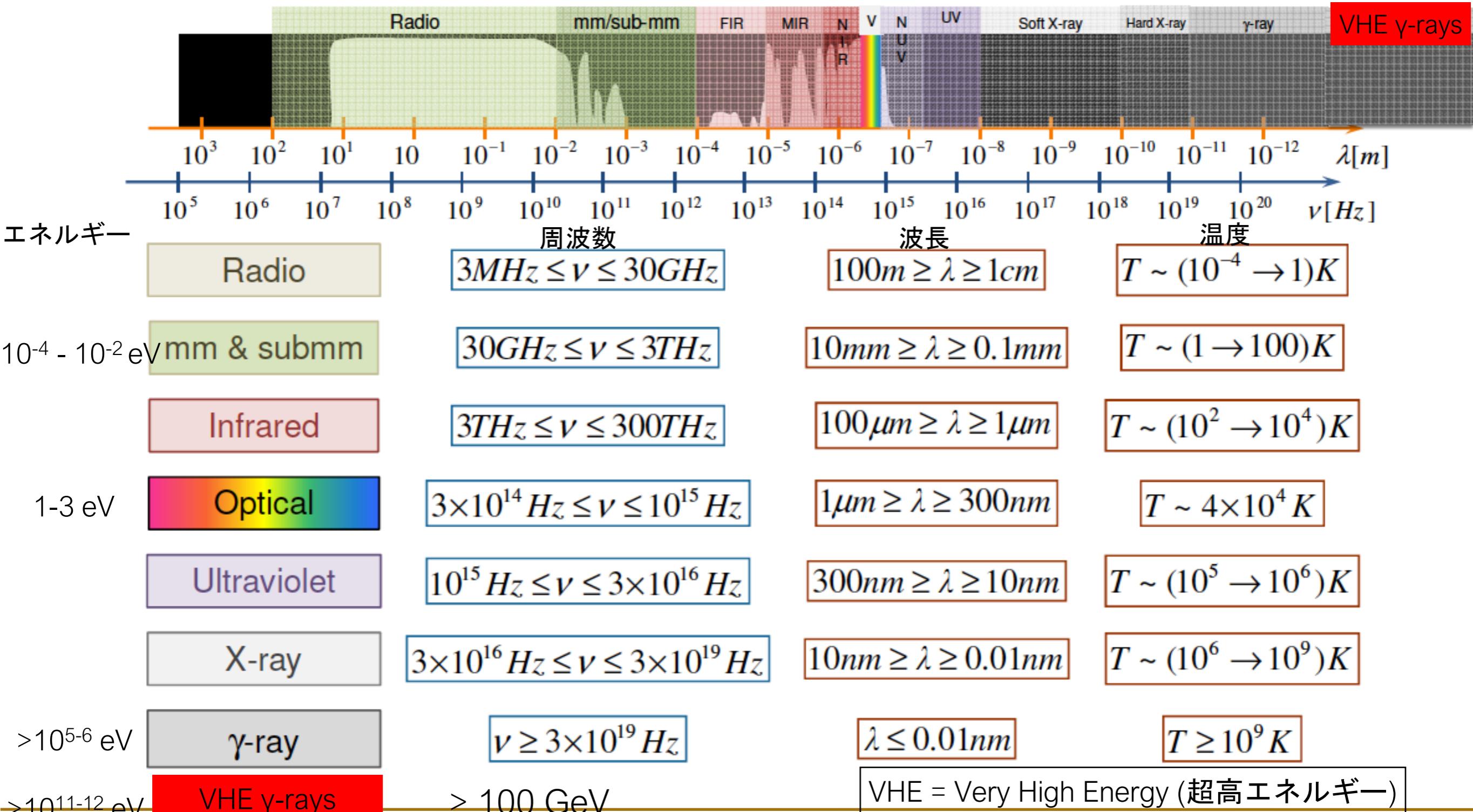
-
1. ガンマ線観測の意義
 2. 多波長観測と高エネルギーガンマ線
 3. 宇宙におけるガンマ線の生成機構
 4. ガンマ線の検出手法
 5. ガンマ線観測で何がわかるか
 6. 次世代ガンマ線天文台CTA

ガンマ線による天体観測の意義

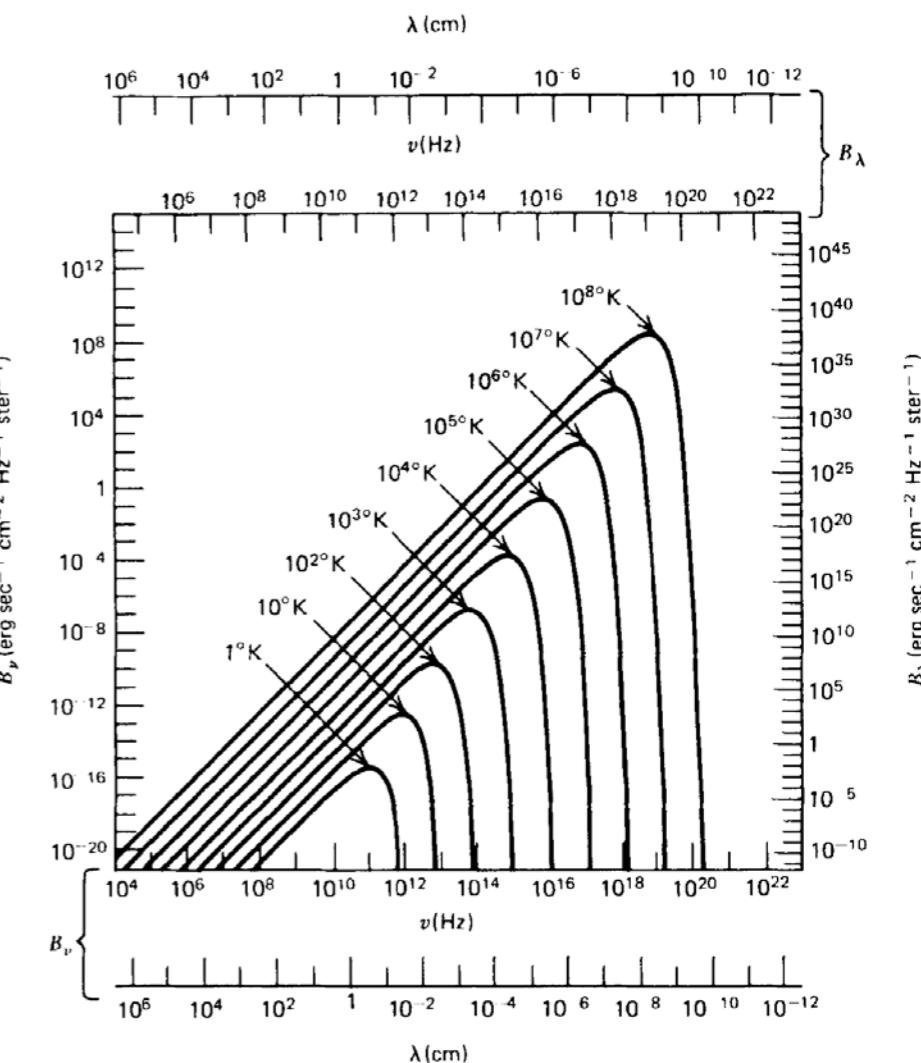


- **意義 1：ガンマ線＝高エネルギーの光**
 - 多波長の観測から天体の放射機構が明らかになる
 - 純粋な「非熱的」放射
- **意義 2：放射線（素粒子）としてのガンマ線**
 - 天体における物理素過程の研究に好都合
 - 宇宙線の起源、暗黒物質の探索、など

多波長観測とガンマ線



非熱的放射？



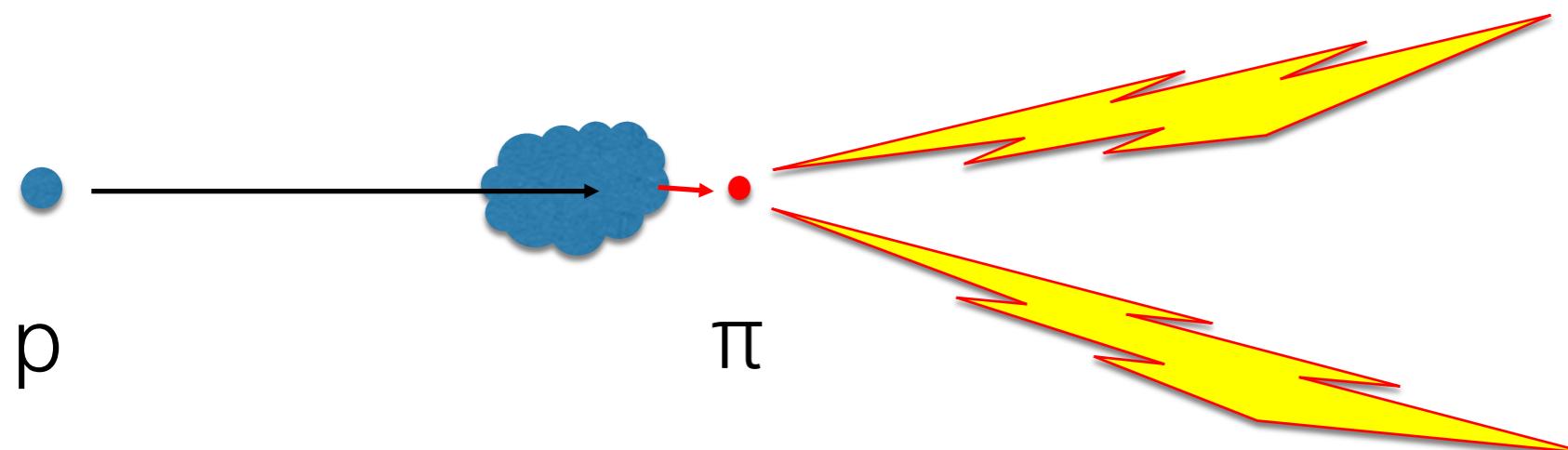
宇宙におけるガンマ線の生成

陽子による生成

- **中性パイ中間子崩壊**

- 加速された陽子が星間物質と衝突し、パイ中間子が生成される。中性のものが直ちに2つの γ 線に崩壊

- $p \ p \rightarrow X + \pi_0 \rightarrow \gamma \ \gamma$
- $Energy_{\gamma} \sim 0.1 * Energy_p$

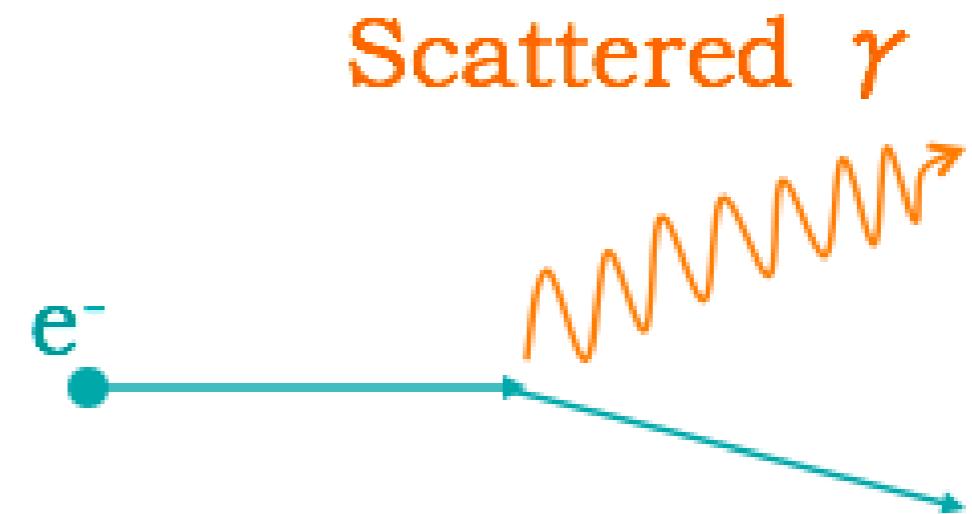


宇宙におけるガンマ線の生成

電子による生成

- 逆コンプトン散乱
 - 加速された電子が星の光など低エネルギー光子と衝突し、エネルギーを与える

$$e^- + \gamma_{\text{Low E}} \rightarrow e^- + \gamma$$
$$E_\gamma \propto (\gamma_{\text{Lorentz}})^2 E_{\gamma \text{ Low E}}$$
$$\gamma_{\text{Lorentz}} = 1/\sqrt{1 - v_e^2/c^2}$$

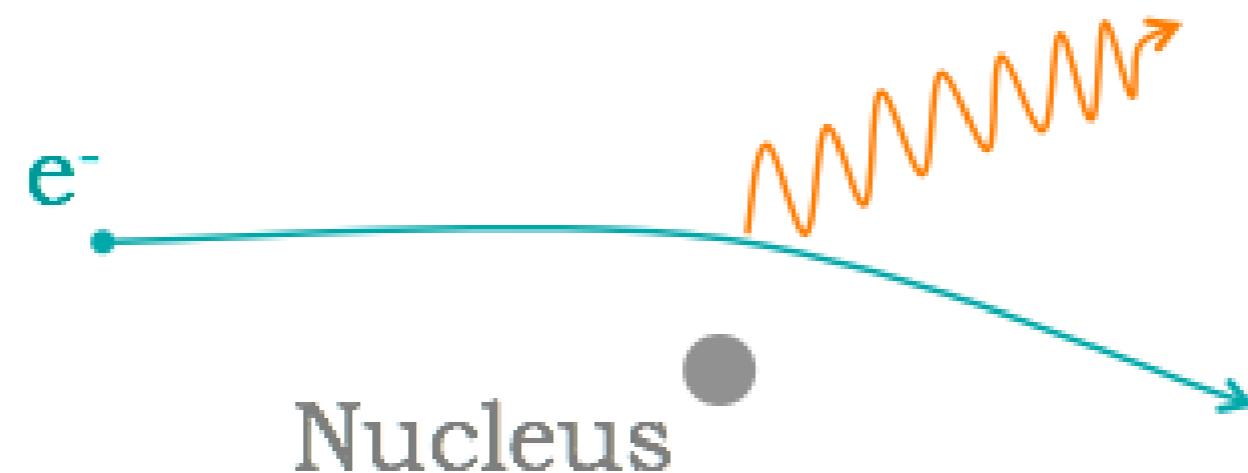


宇宙におけるガンマ線の生成

電子による生成

- **制動放射**

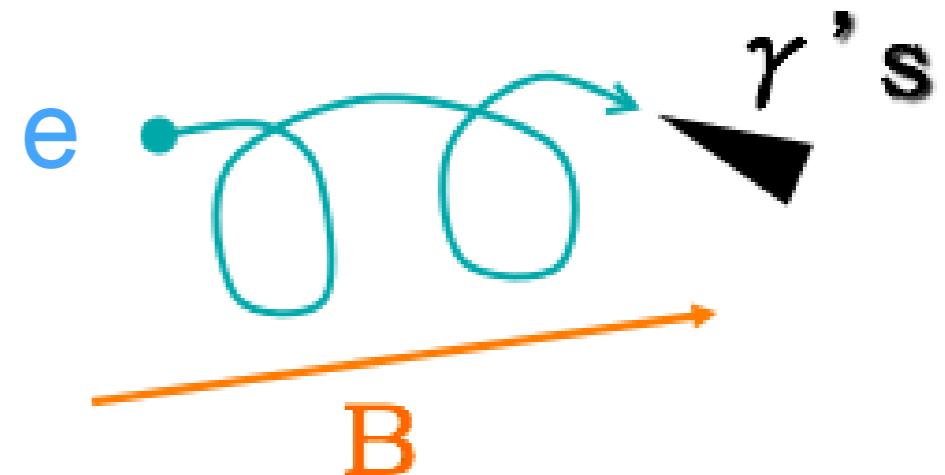
- 加速された電子が原子核と衝突し、加速度をうけ、放射する。
- 濃い分子雲などに宇宙線電子が衝突すると起こる
- $\text{Energy}_\gamma \sim \text{Energy}_e$



宇宙におけるガンマ線の生成

電子による生成

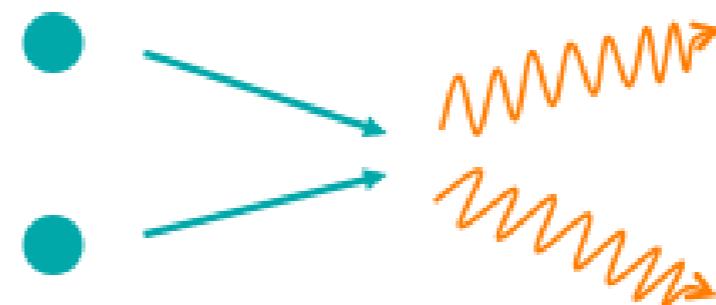
- ・ **シンクロトロン放射**
- ・ 電子が磁場により加速度を受け放射
- ・ $\text{Energy } \gamma \sim \gamma^2 B_{\perp} \text{ MHz}$
- ・ 強磁場（パルサー）→曲率放射



宇宙におけるガンマ線の生成

その他のガンマ線生成機構

- 原始ブラックホールの蒸発
 - 暗黒物質 (WIMPs) の対消滅
- $$\text{DM} + \text{DM} \rightarrow X + \gamma$$



天体ガンマ線生成機構まとめ



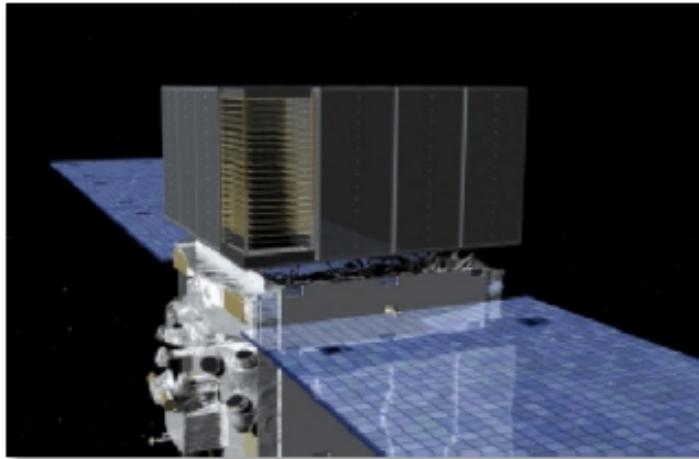
親粒子	標的／環境
中性パイオニ崩壊	陽子
逆コンプトン散乱	電子
制動放射	電子
シンクロトロン放射	電子
曲率放射	電子
対消滅	暗黒物質

天体ガンマ線の検出手法



GAMMA RAY TELESCOPES

Space-based
pair production
telescopes



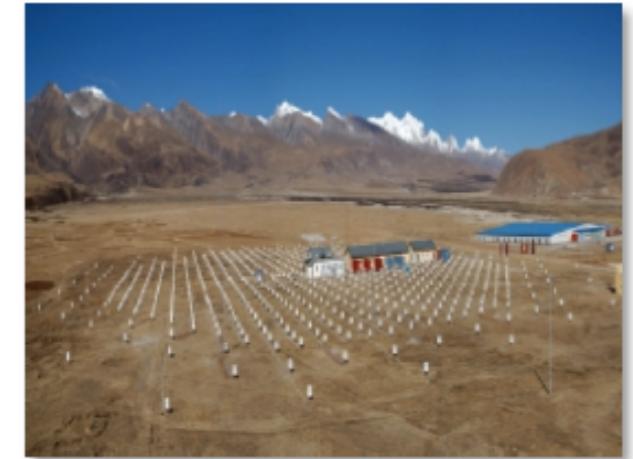
0.1 – 100 GeV
Small area
Background-free
Large field of view
High duty cycle

Imaging Atmospheric
Cherenkov Telescopes



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

Air shower
Arrays

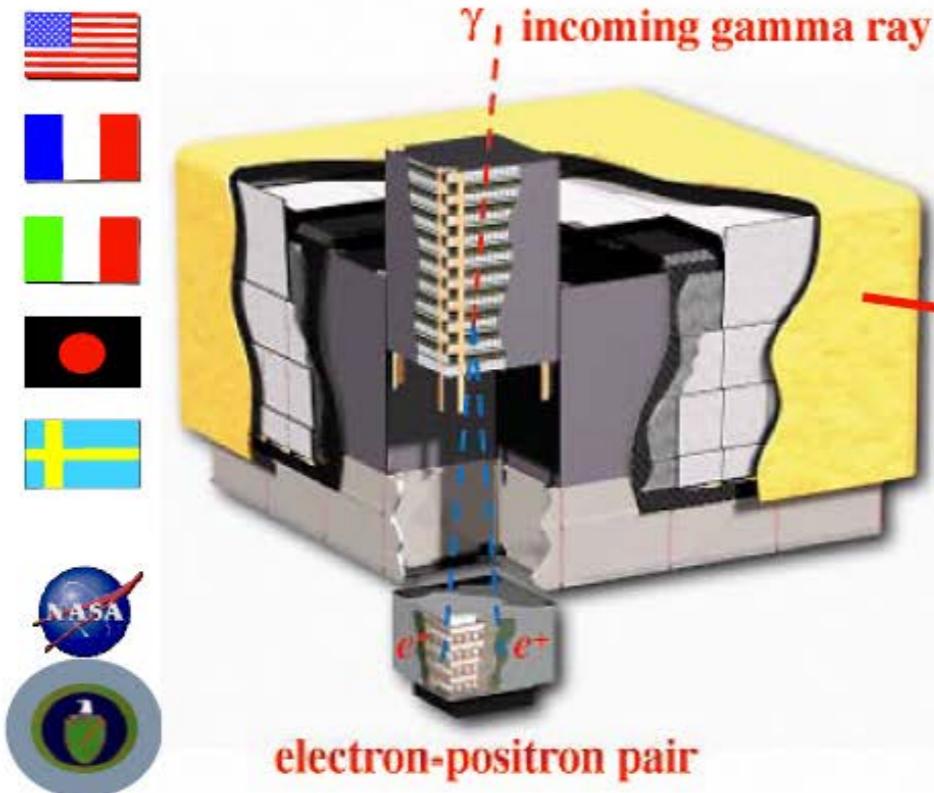


100 GeV – 100 TeV
Large area
Good bg rejection
Large field of view
Large duty cycle

ガンマ線の検出手法(GeV)

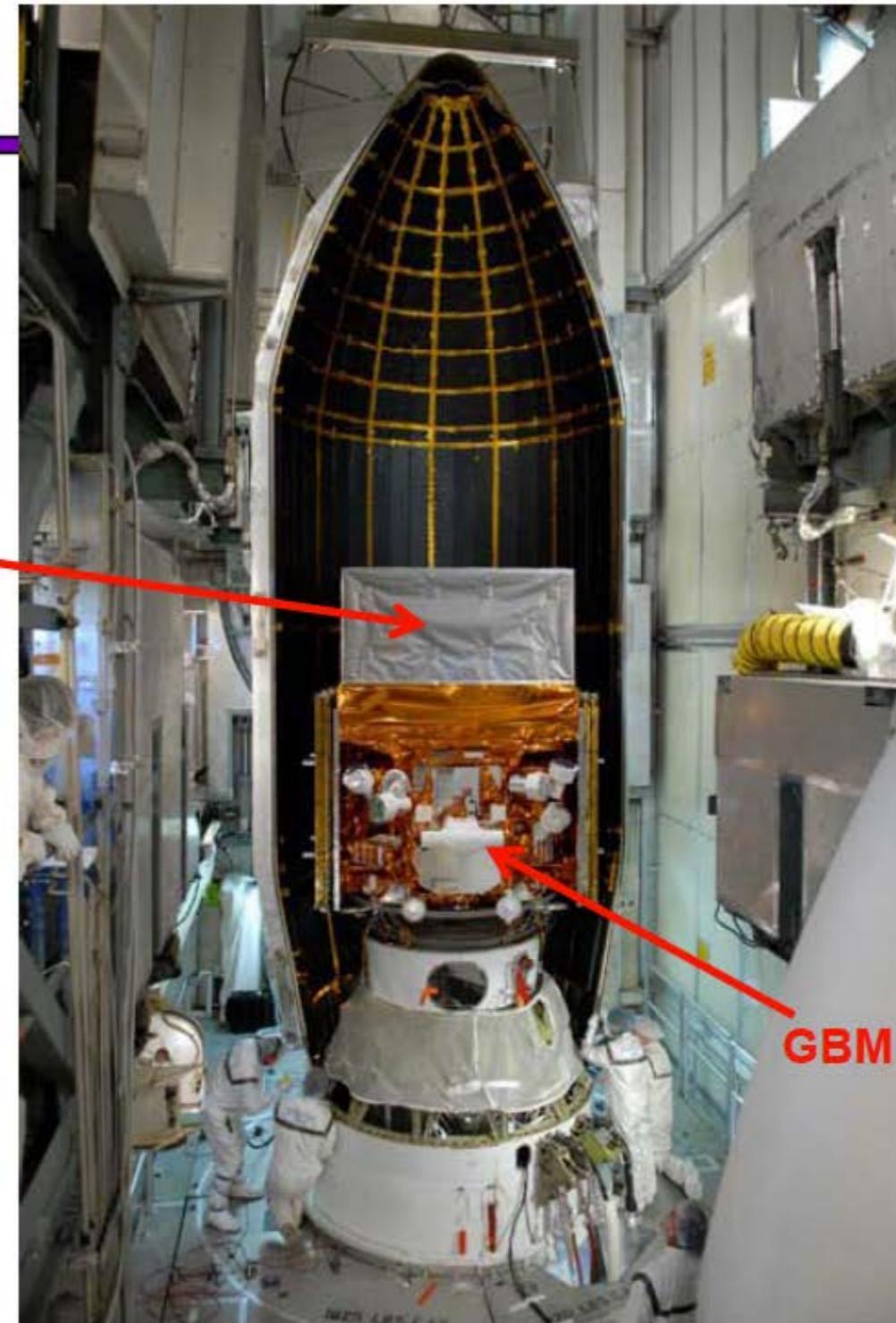
Fermi GST

Large Area Telescope (LAT)

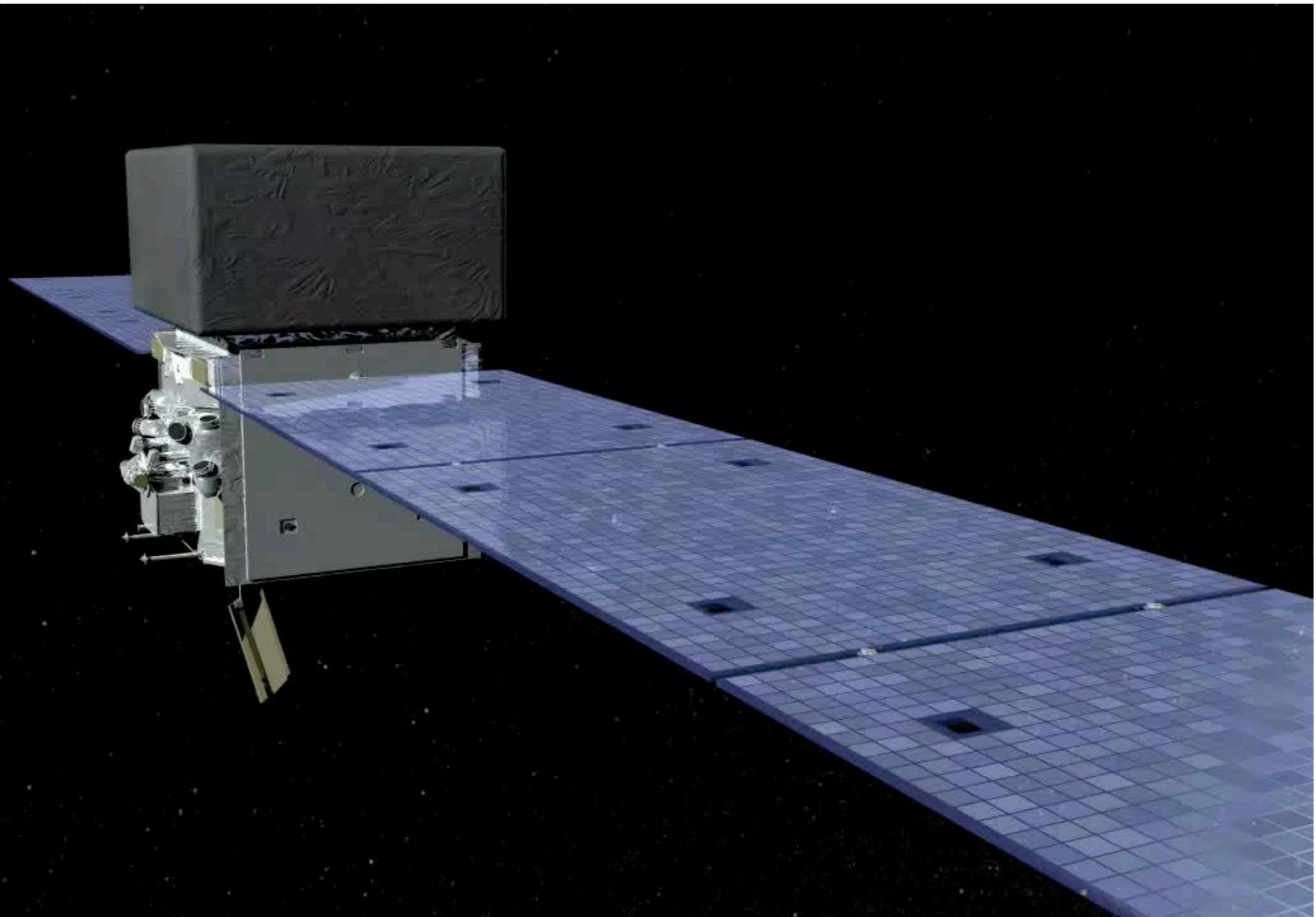


γ -ray converts in LAT to an electron and a positron ; tracking these give us the direction and energy of the photon.

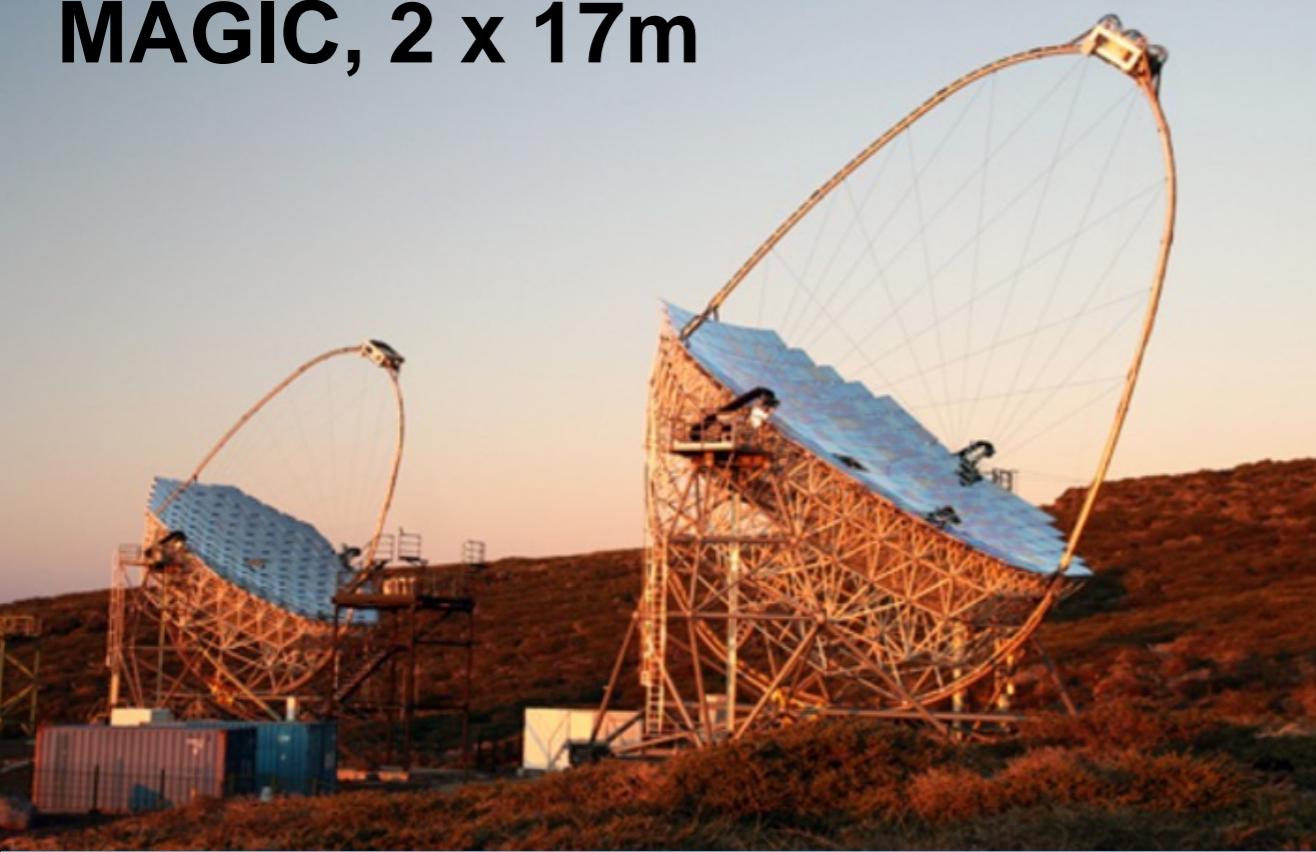
Launched from Cape Canaveral
11 June 2008



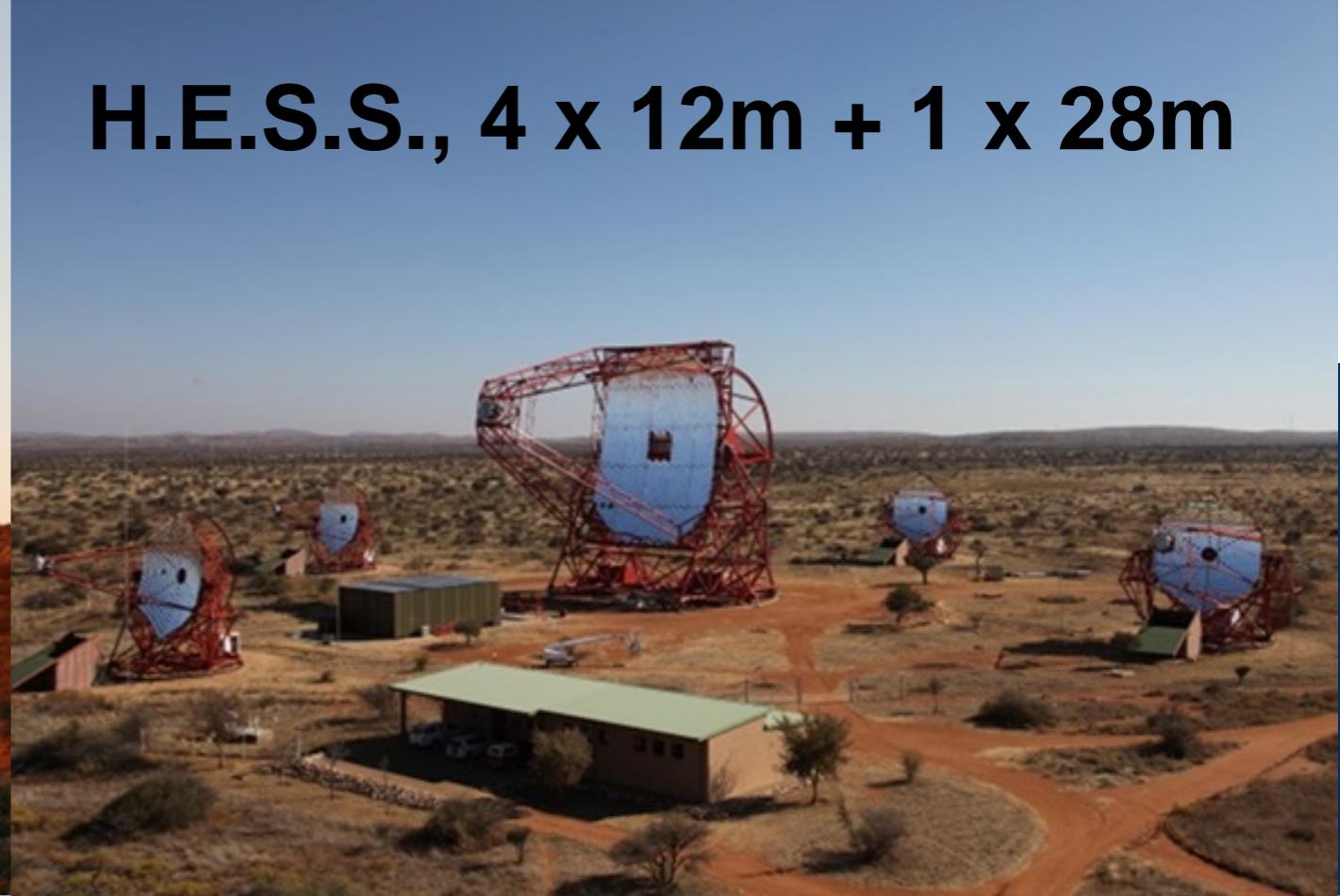
ガンマ線の検出手法(GeV)



MAGIC, 2 x 17m



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

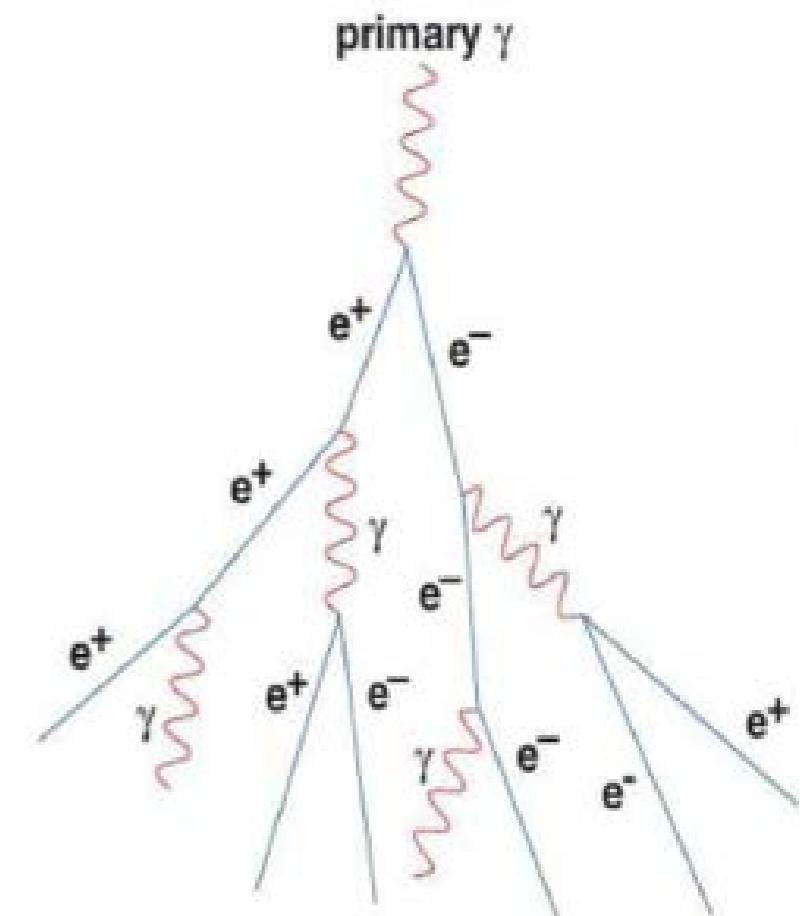
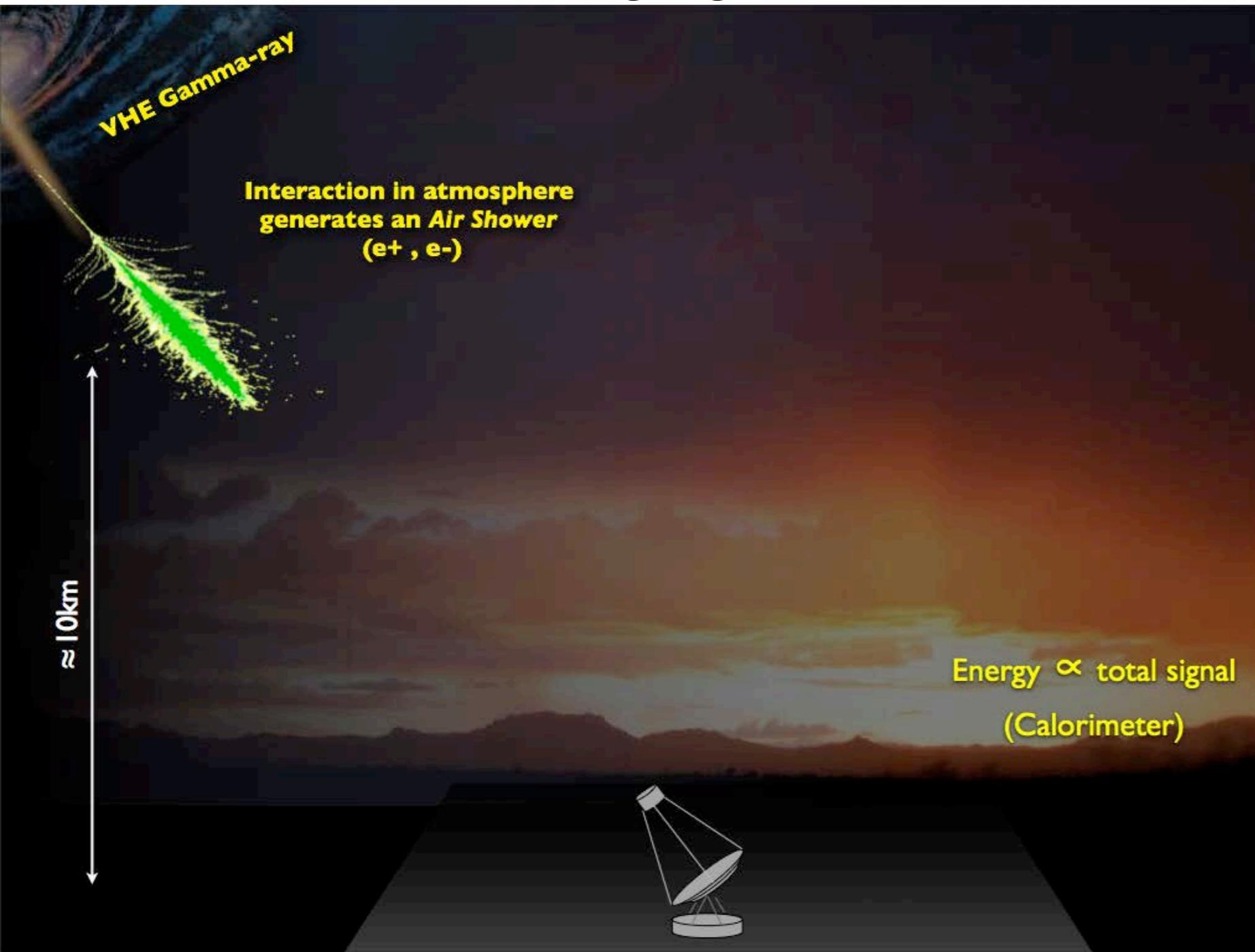


VERITAS, 4 x 12m



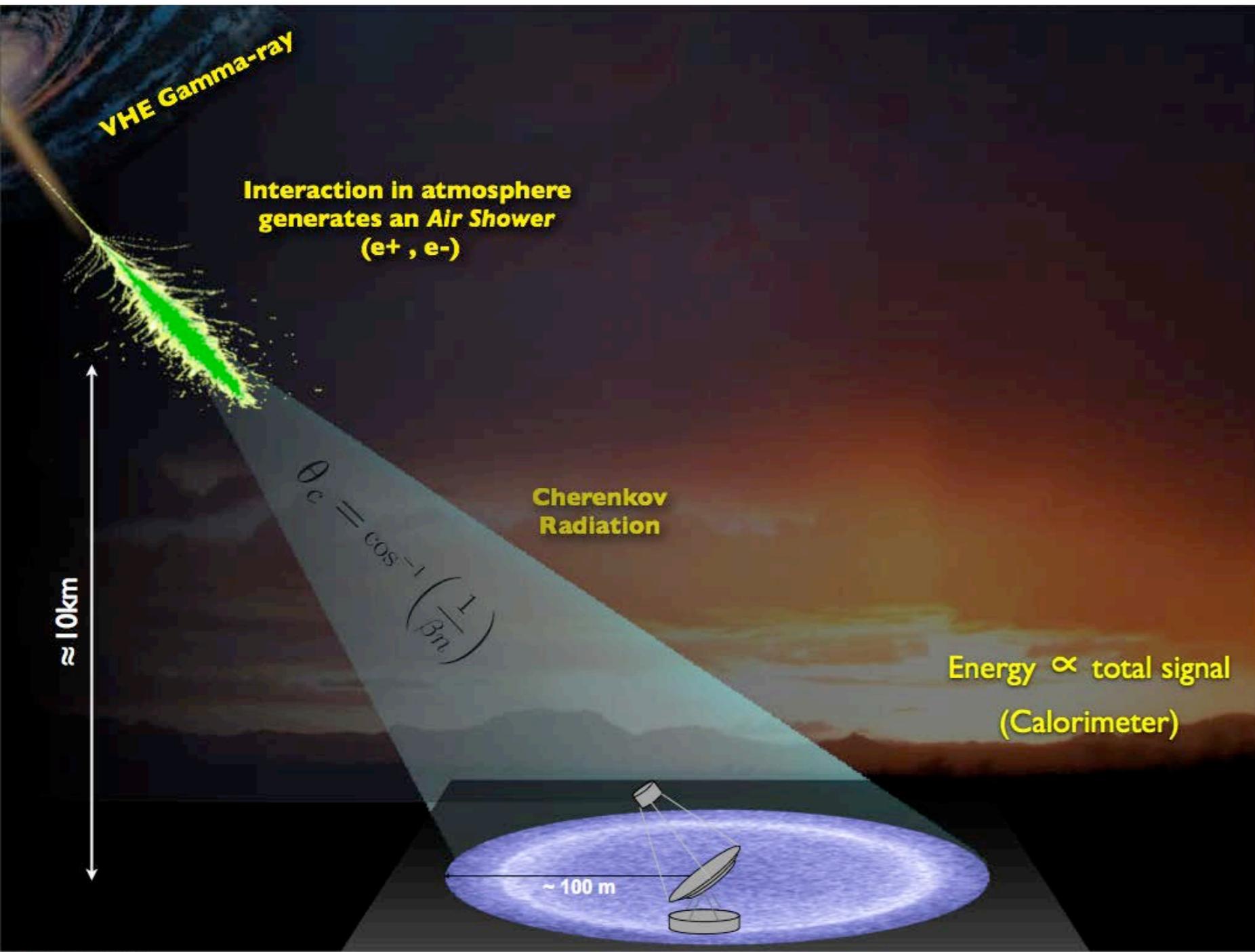
ガンマ線の検出手法(TeV)

Imaging Atmospheric Cherenkov Telescope

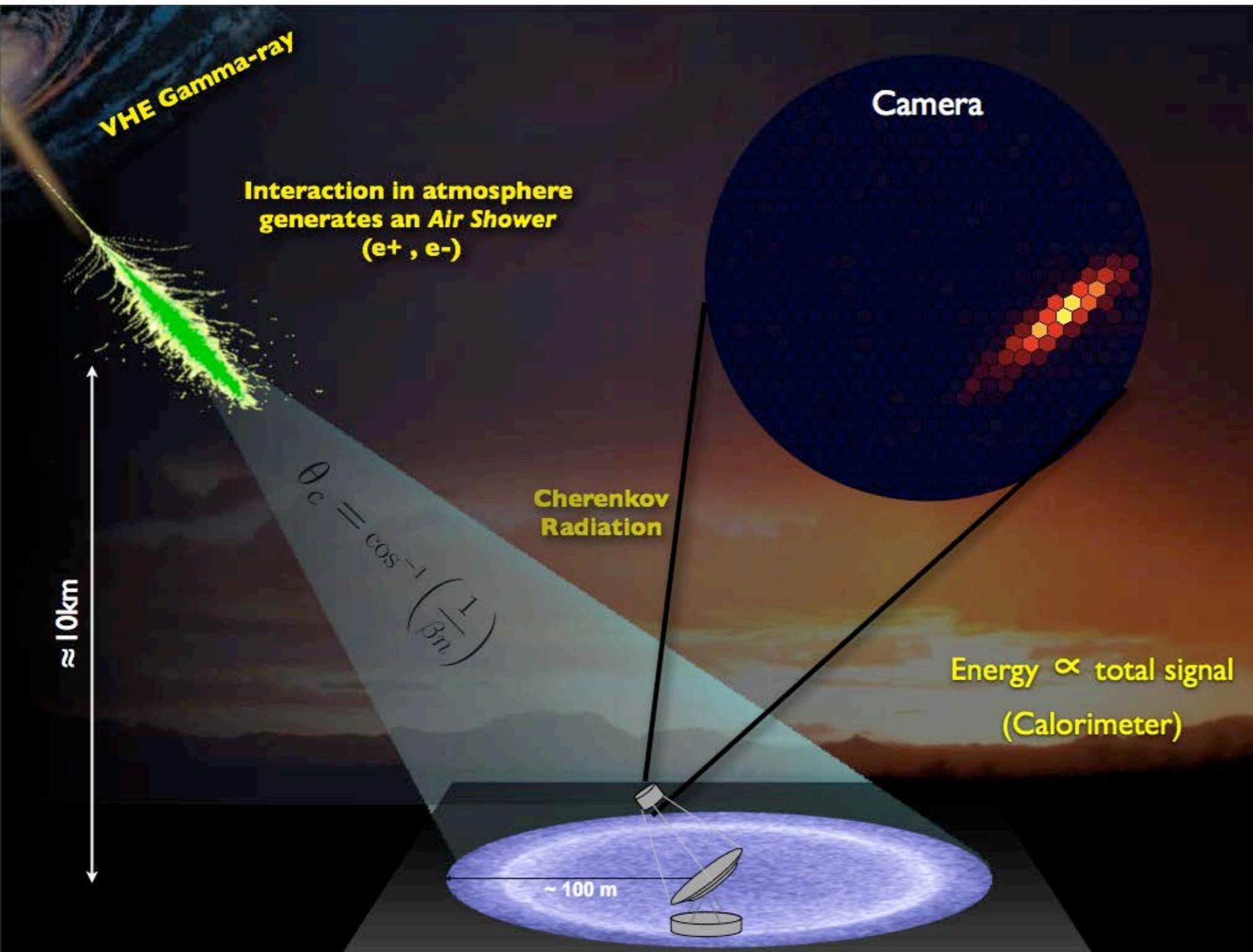


電磁カスケード
(空気シャワー)

ガンマ線の検出手法(TeV)

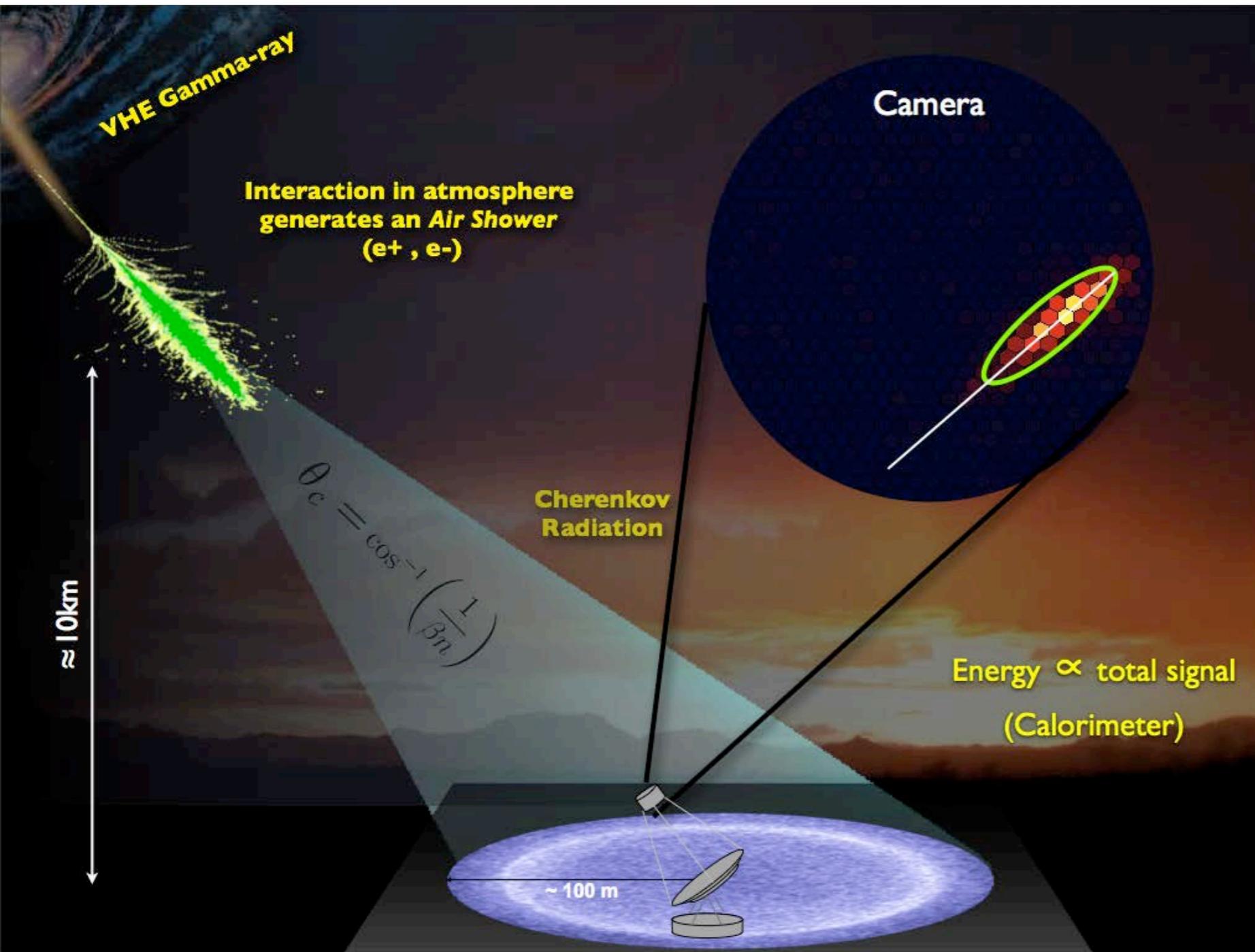


ガンマ線の検出手法(TeV)



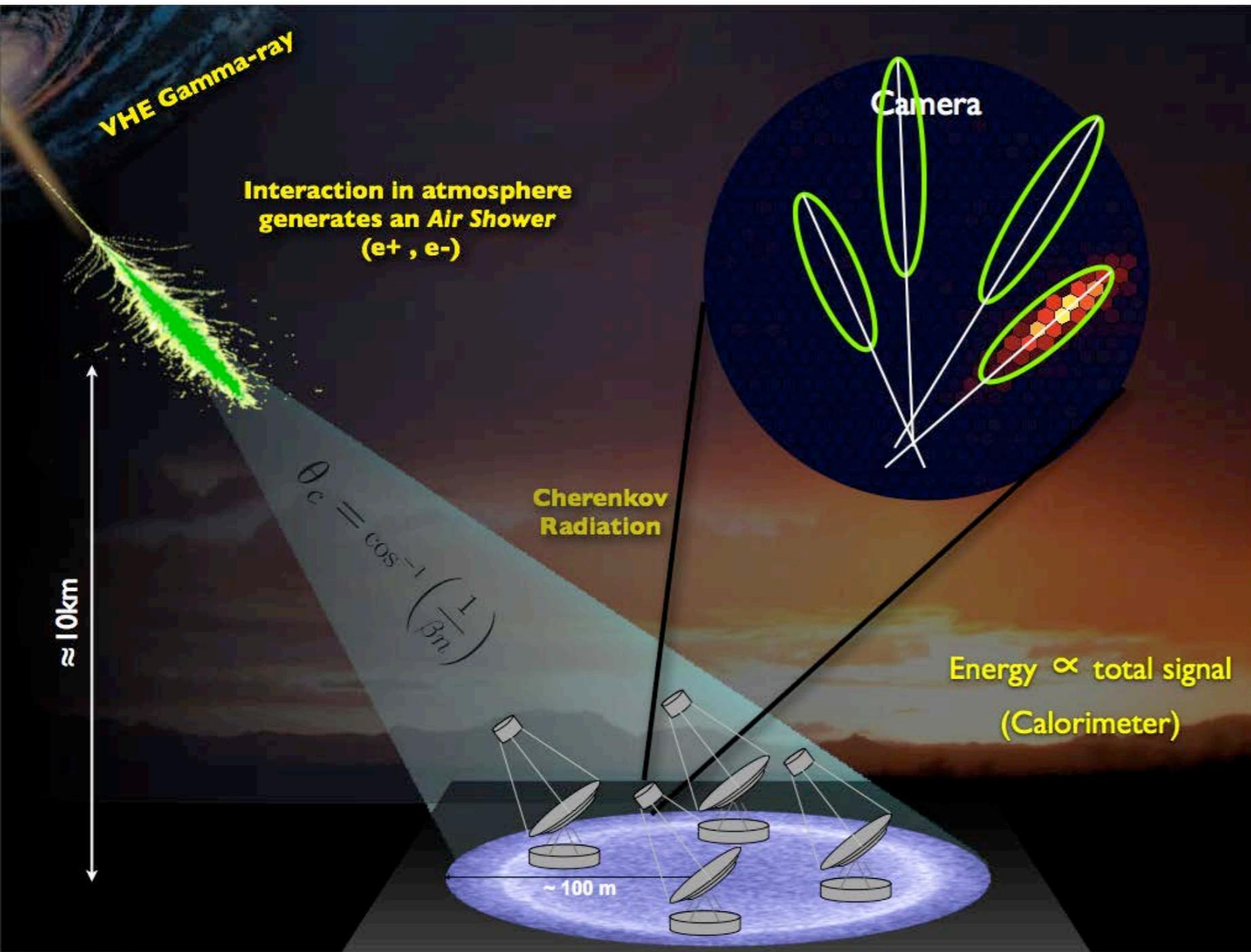
Friday, May 30, 2014

ガンマ線の検出手法(TeV)

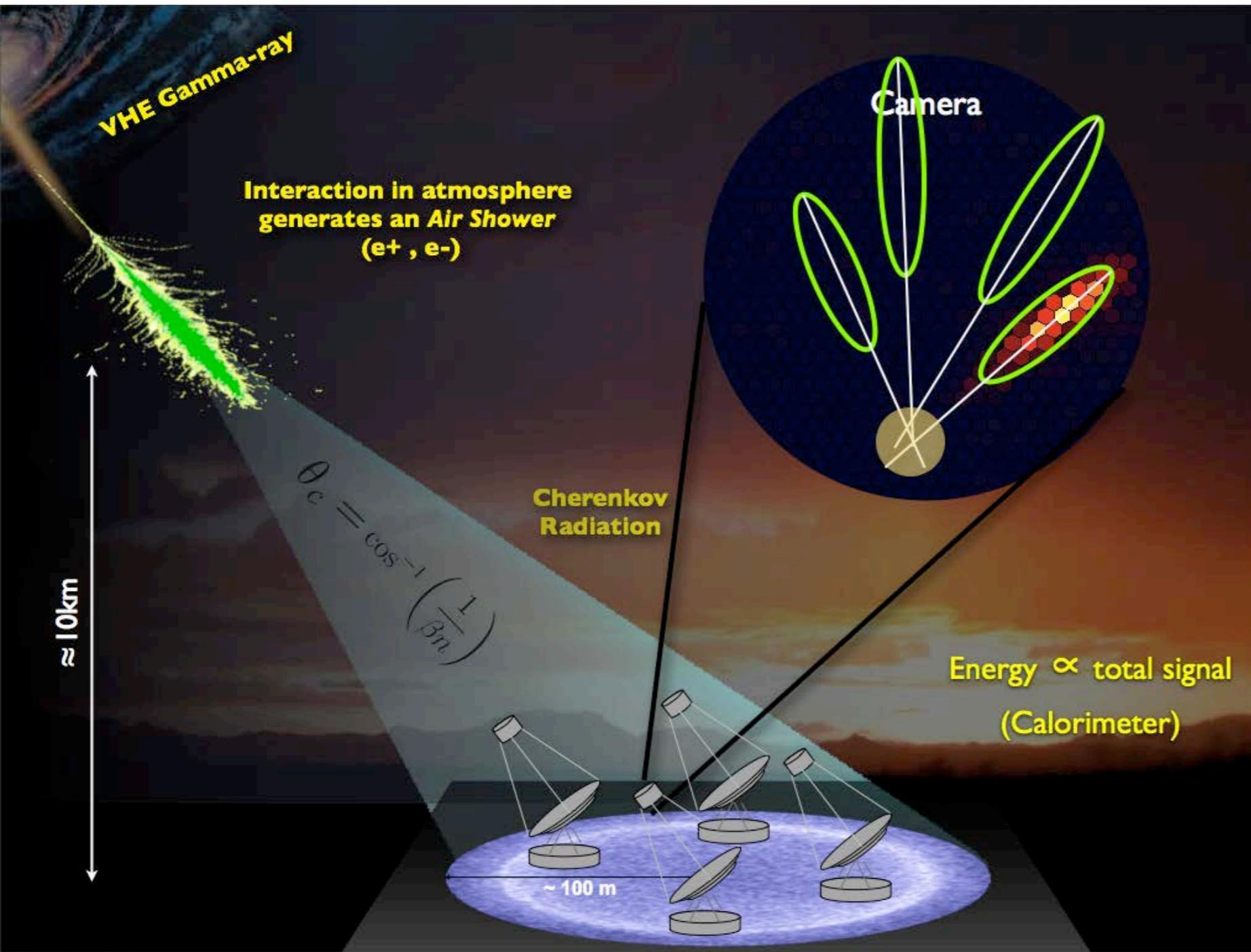


Friday, May 30, 2014

ガンマ線の検出手法(TeV)



ガンマ線の検出手法(TeV)



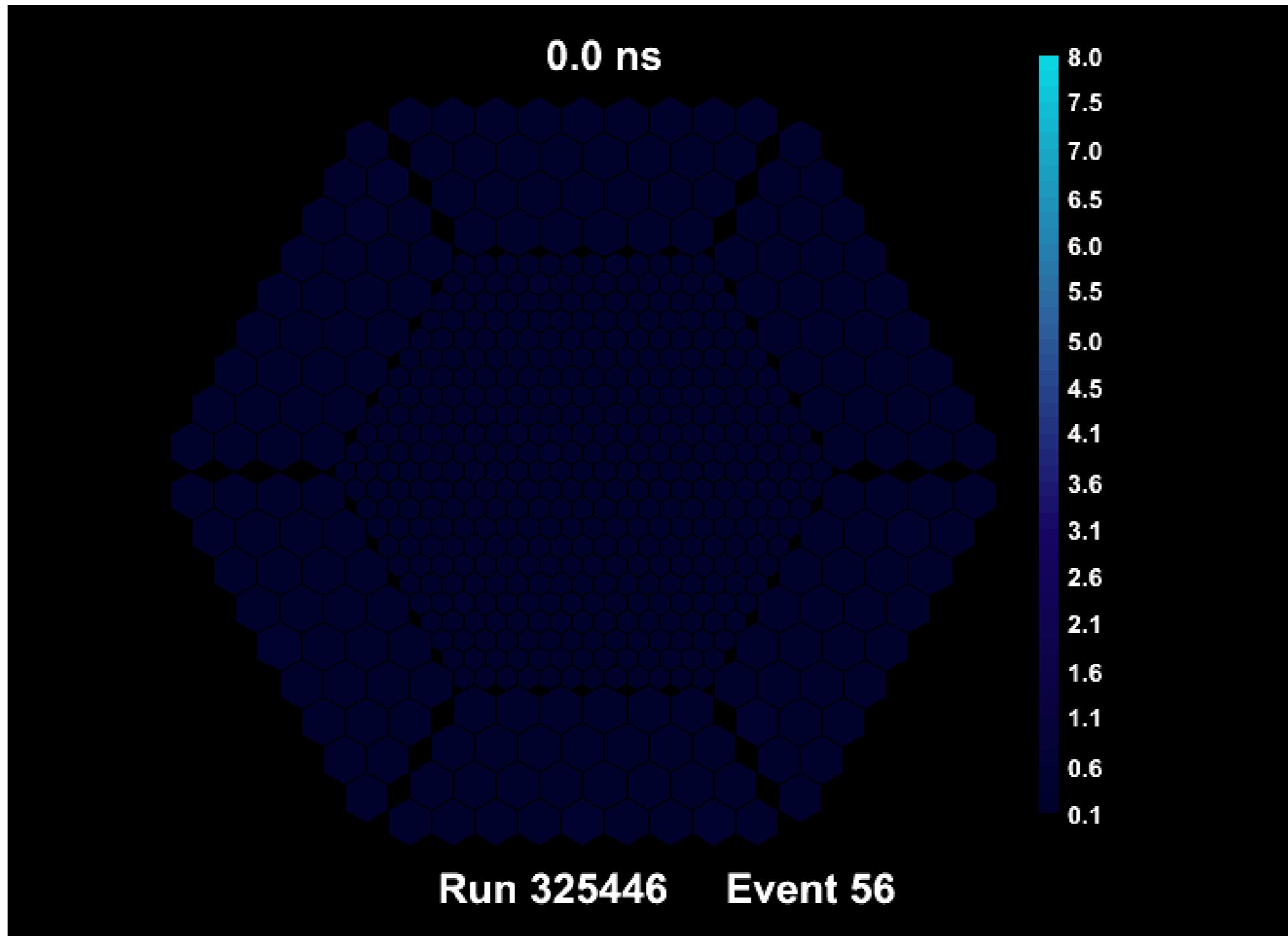
ガンマ線の検出手法(TeV)



Atmospheric showers and Cherenkov radiation

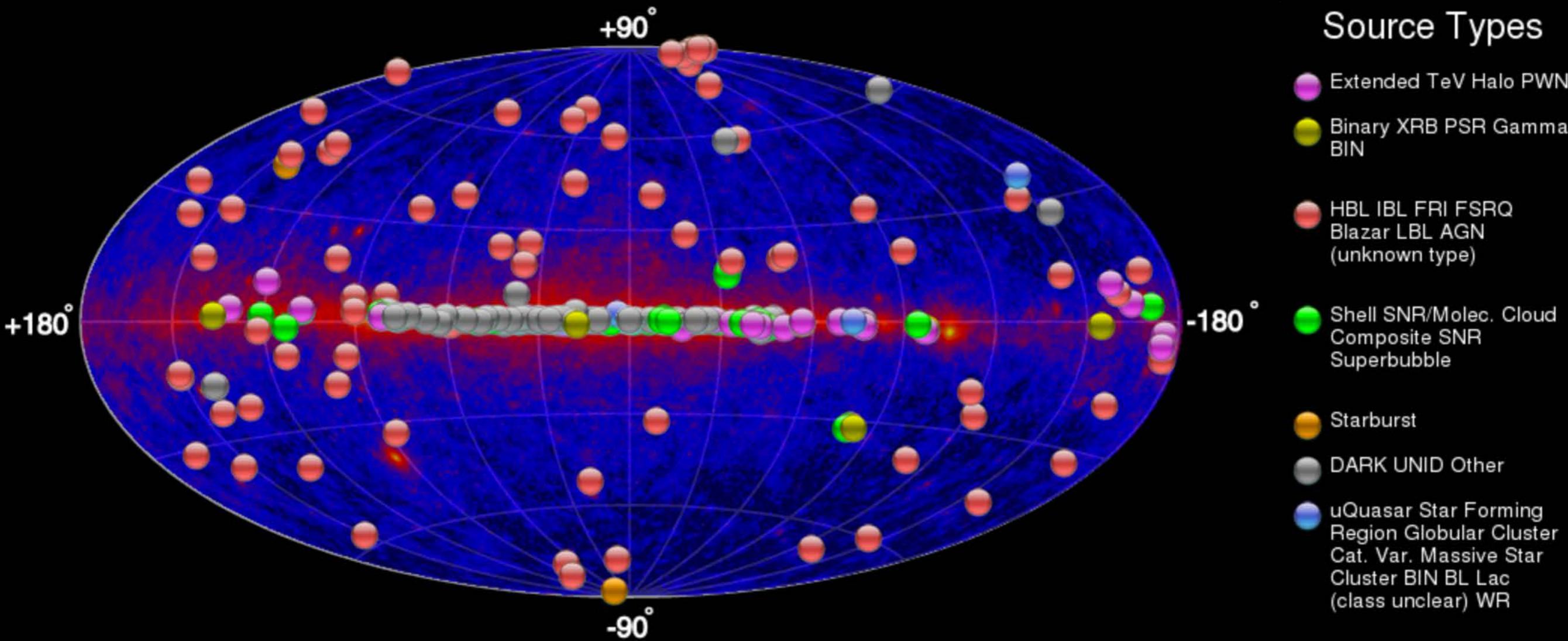


空気シャワー画像



VHE ガンマ線天体

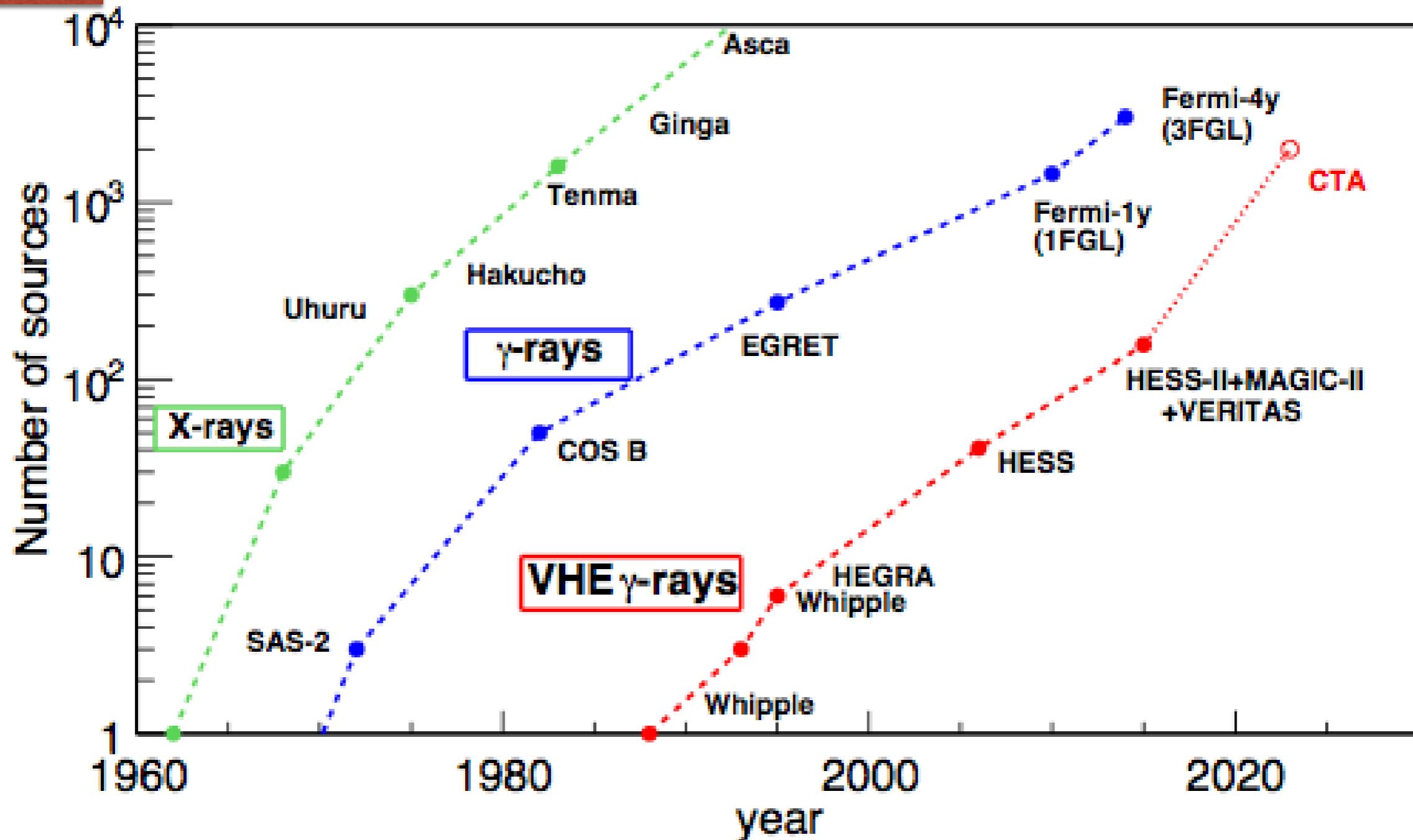
VHE gamma-ray sources (>100 GeV)



- 約250天体（2022年時点）
- 大部分が大気チエレンコフ望遠鏡による発見

検出天体数の推移

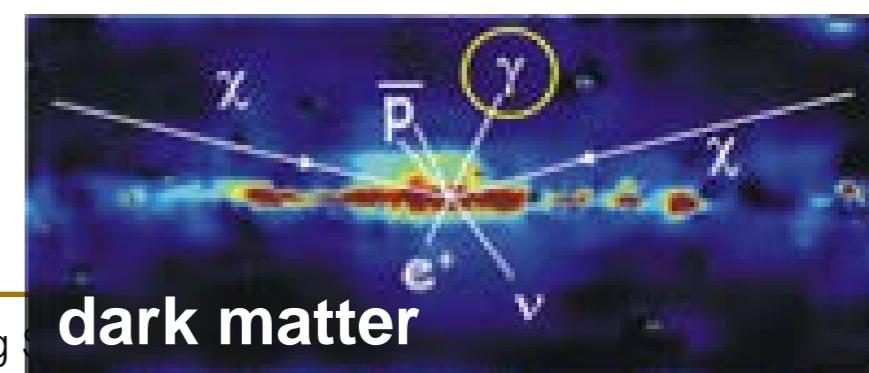
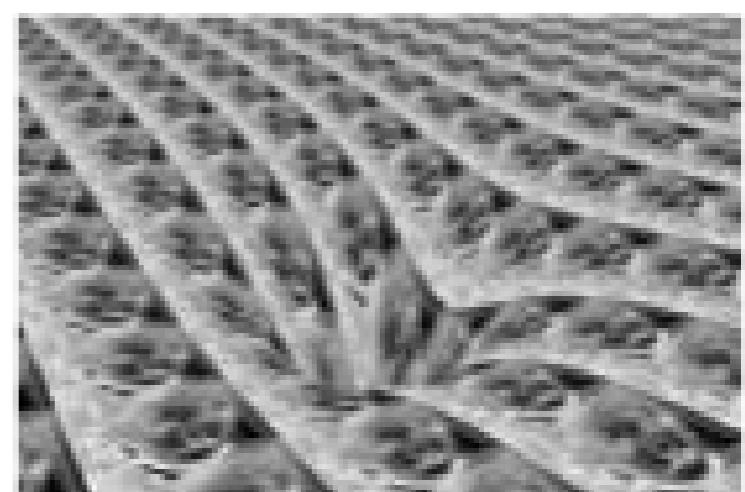
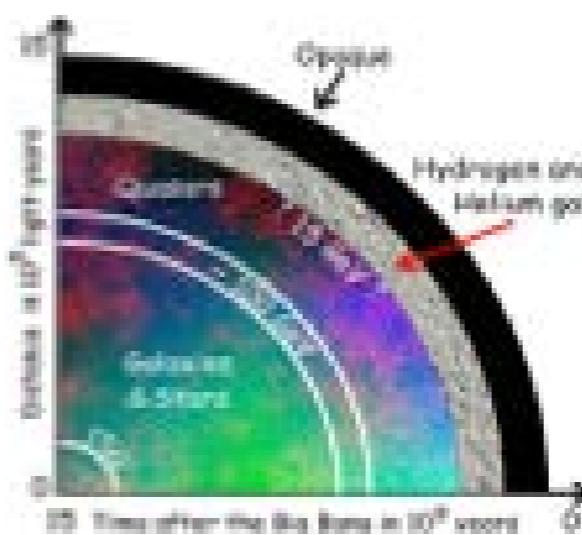
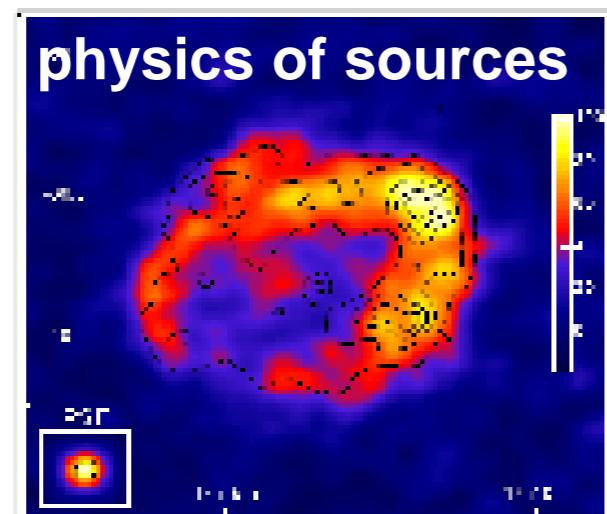
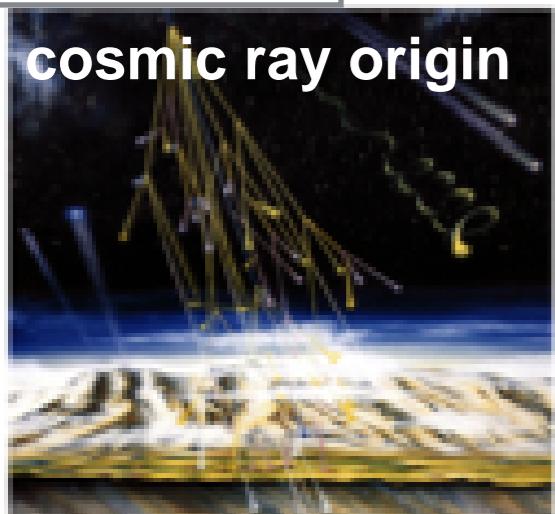
Kifune plot



ガンマ線観測で何がわかるか



Objectives



ガンマ線観測で何がわかるか

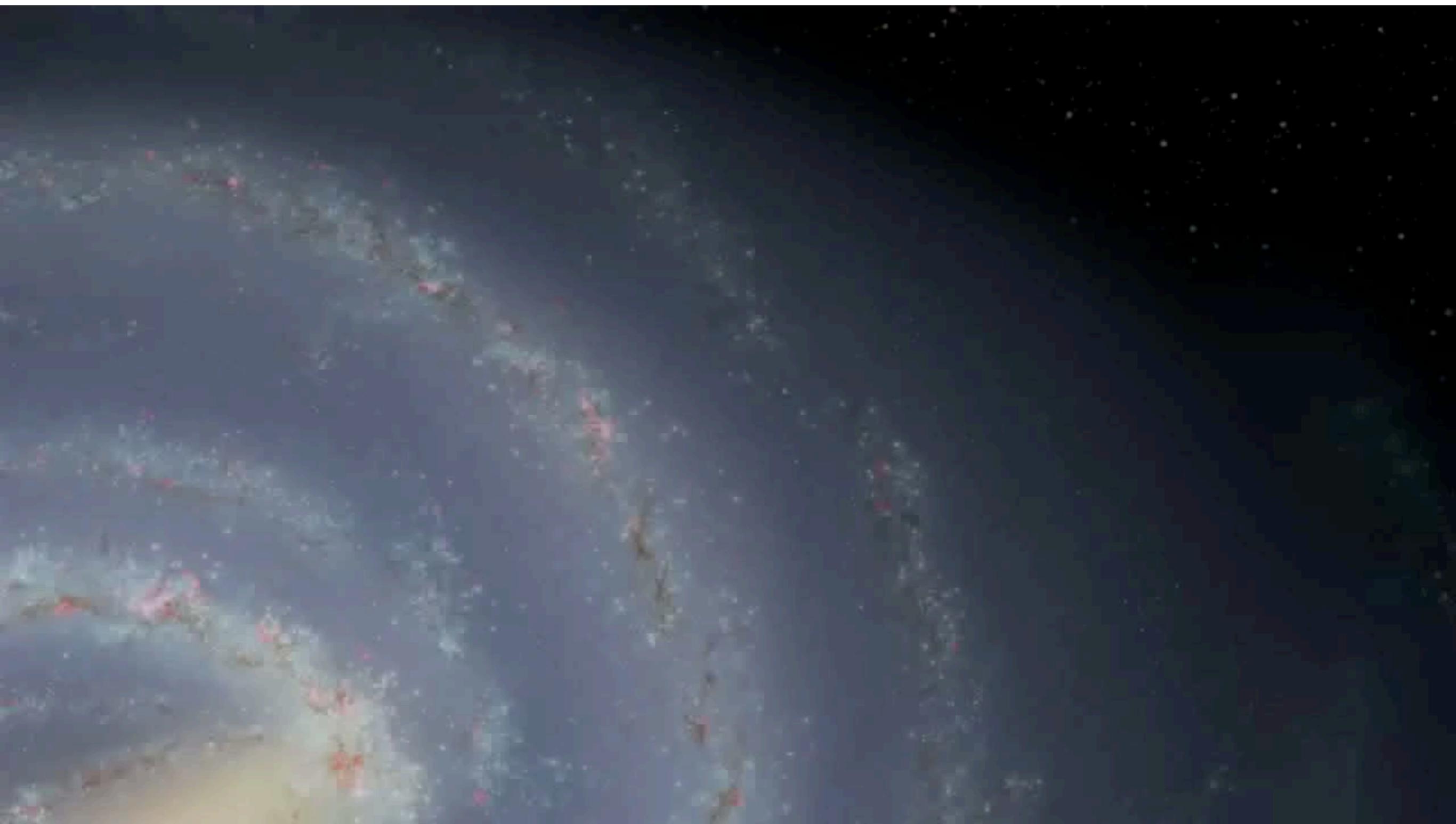


- ・ **宇宙線の起源：**
 - ・ 宇宙線の生成現場でガンマ線が放射される。
 - ・ ガンマ線は銀河内外の磁場によって曲げられない。生成場所が特定できる。
- ・ **極限環境における物理：**
 - ・ ガンマ線はブラックホールや中性子星近傍で生成され、極限環境の性質を反映する。
- ・ **宇宙論や基礎物理への貢献：**
 - ・ ガンマ線は、赤外背景放射により吸収される。吸収量で、星や銀河の進化の歴史が辿れる。
 - ・ 暗黒物質の最有力候補(WIMPs)の質量がTeVスケール。対消滅により、TeVスケールの二次ガンマ線が期待。
 - ・ TeVほどの高エネルギーにおける量子重力効果などが検証できる。

宇宙線の加速とガンマ線の放射



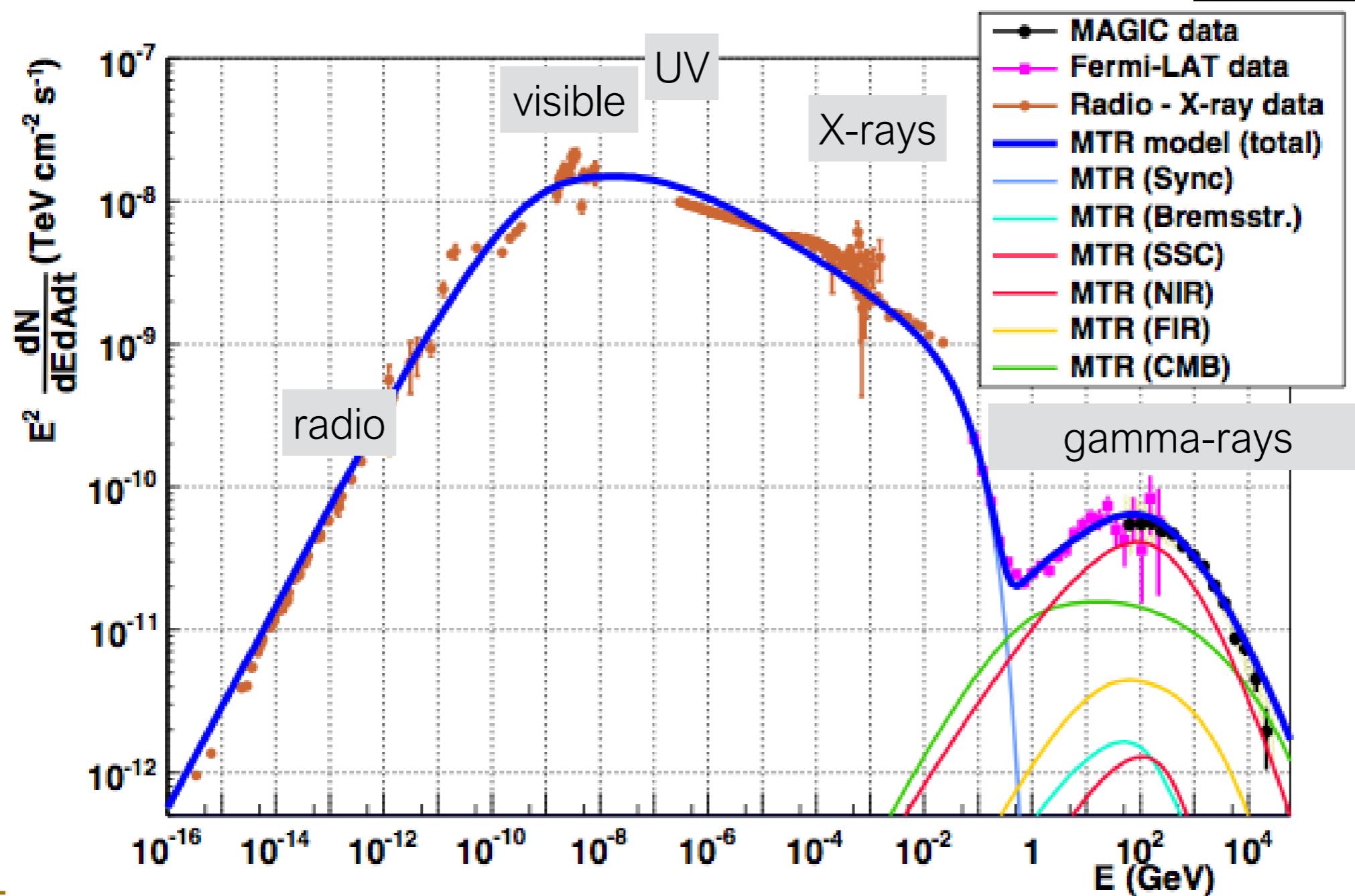
宇宙線の加速とガンマ線の放射



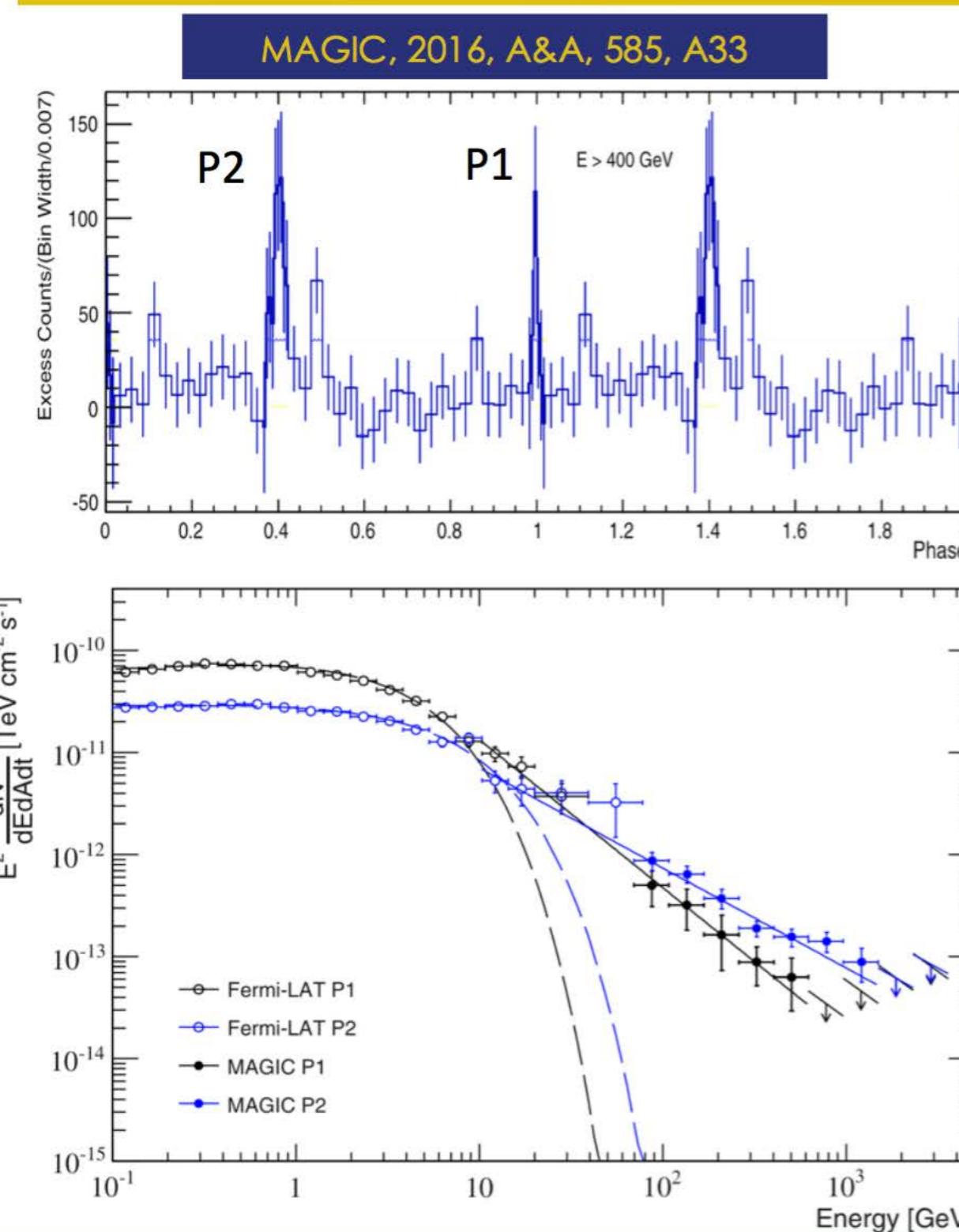
パルサー風星雲

Crab Nebula

非熱的な放射で、20桁にもわたる帯域で放射



Pulsars: Crab

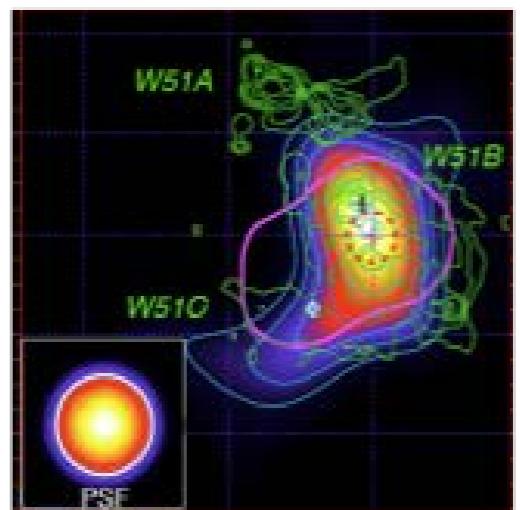
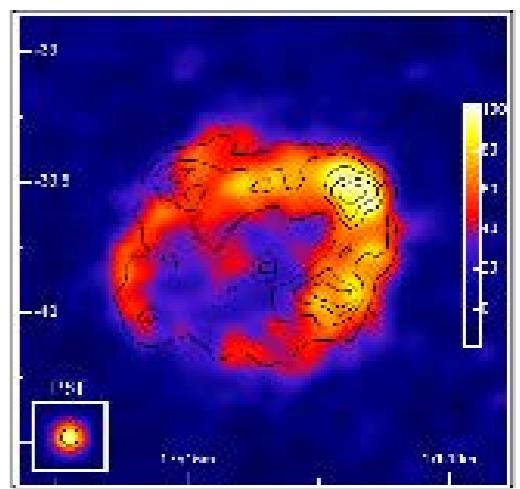
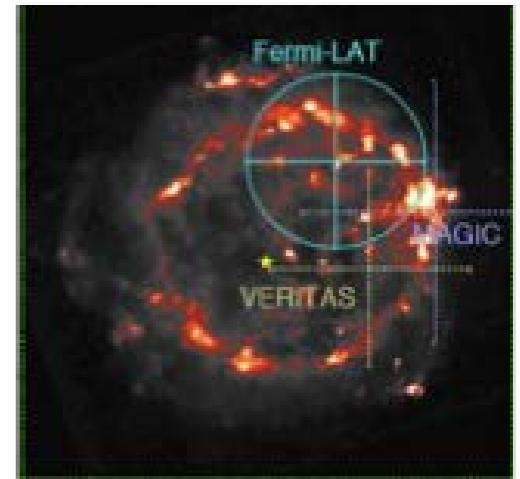
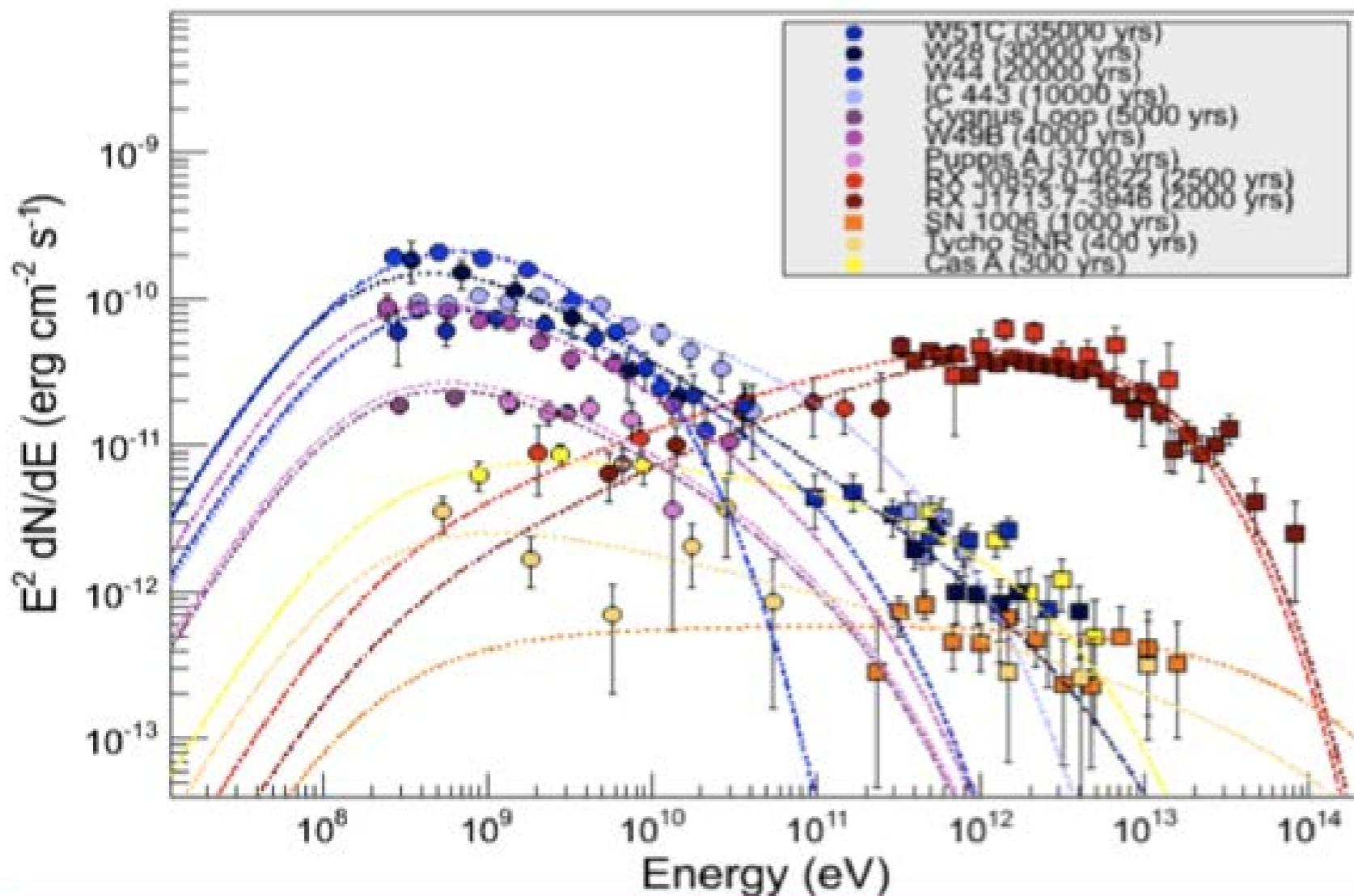


- MAGIC dataset: 320 h (2007-2014)
- Discovered pulsed emission from Crab spectrum extending up to 1.5 TeV
- Spectra of both peaks extending as power-laws far beyond the expected cutoffs:
 - P1 detected up to 0.6 TeV ($\Gamma=3.5 \pm 0.1$)
 - P2 detected up to 1.5 TeV ($\Gamma=3.0 \pm 0.1$)



5

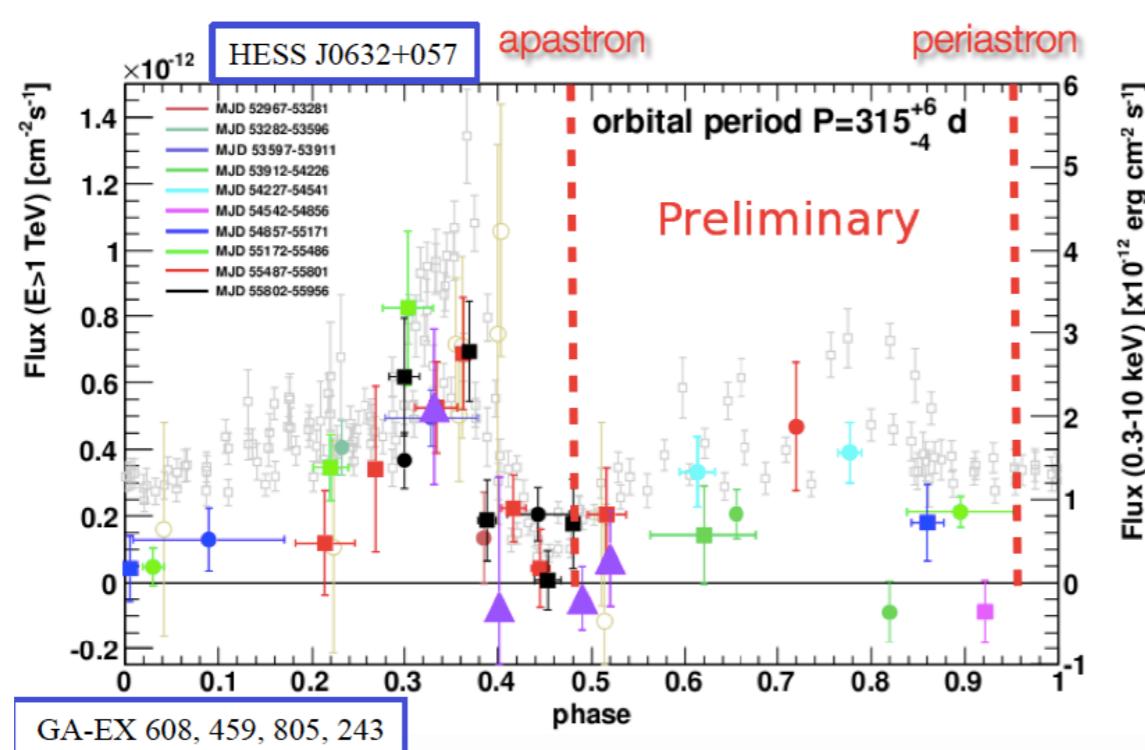
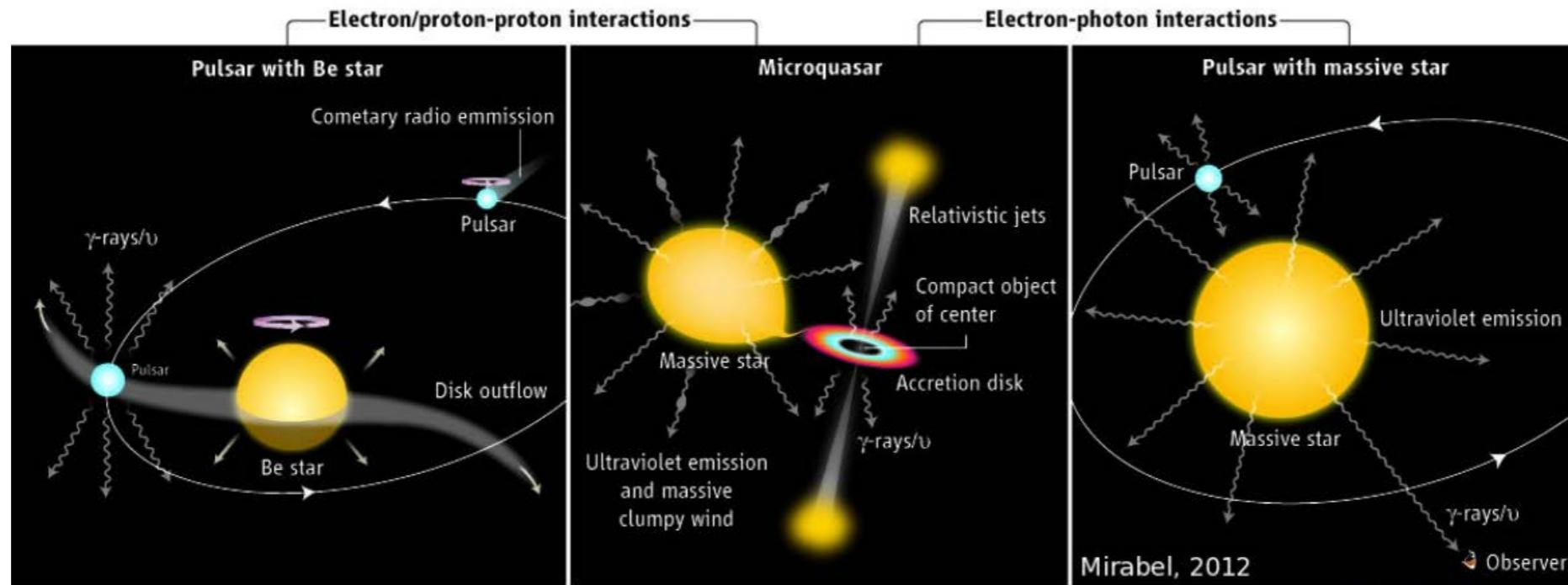
超新星残骸



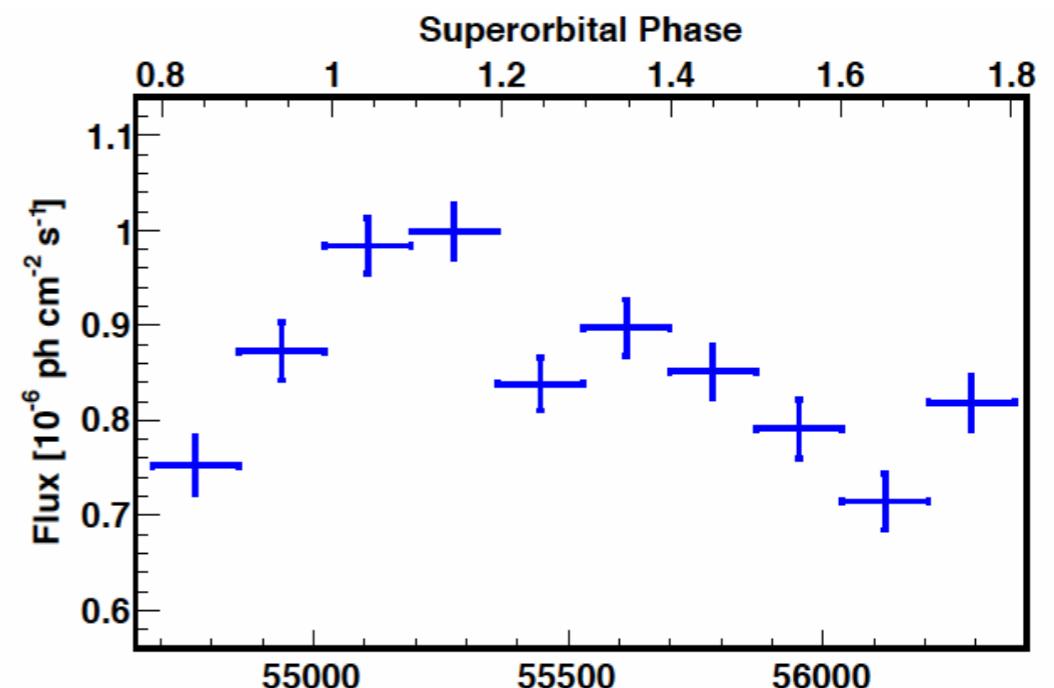
- Different stages of SNRs as cosmic ray accelerator
- CTA will deliver more information on SNRs as cosmic ray accelerators
- We can survey most of SNRs in our galaxy → C.R. energetics

ガンマ線連星

Gamma-ray Binary systems



LSI +61 303 Superorbital Modulation!



Galactic Center

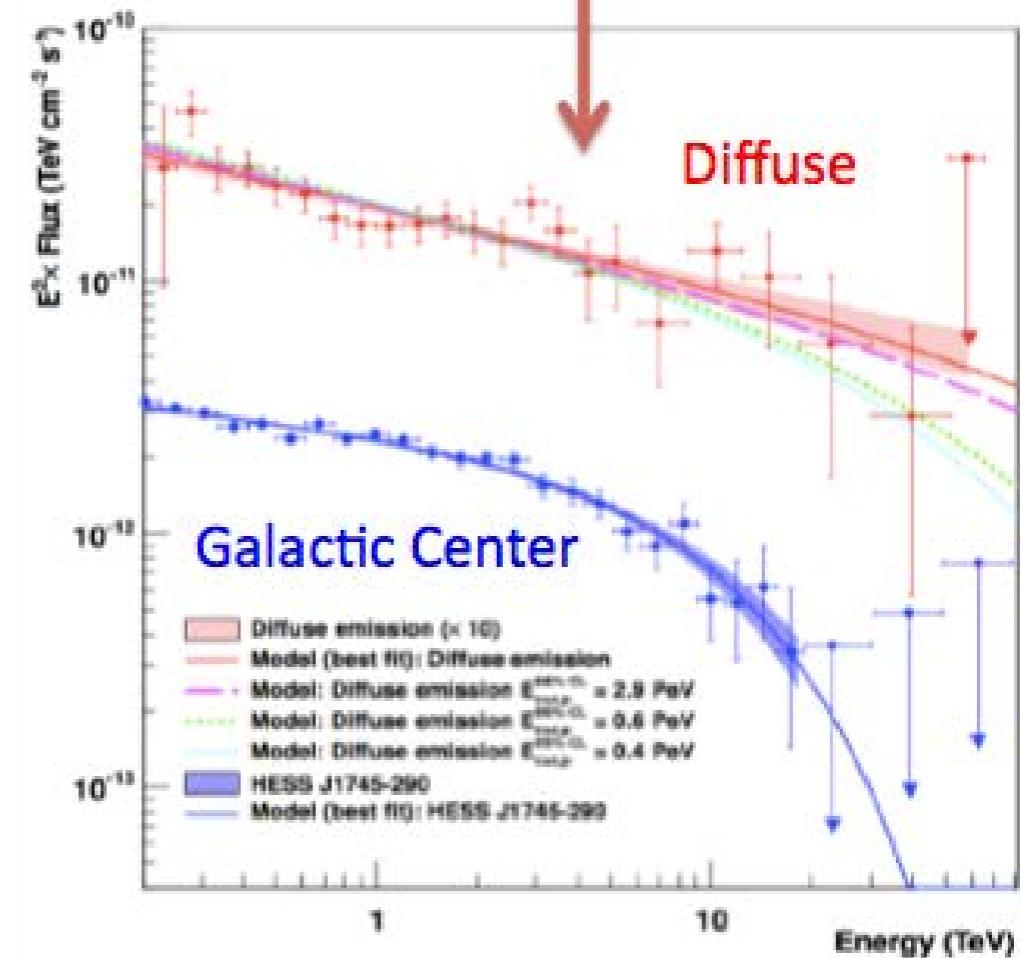
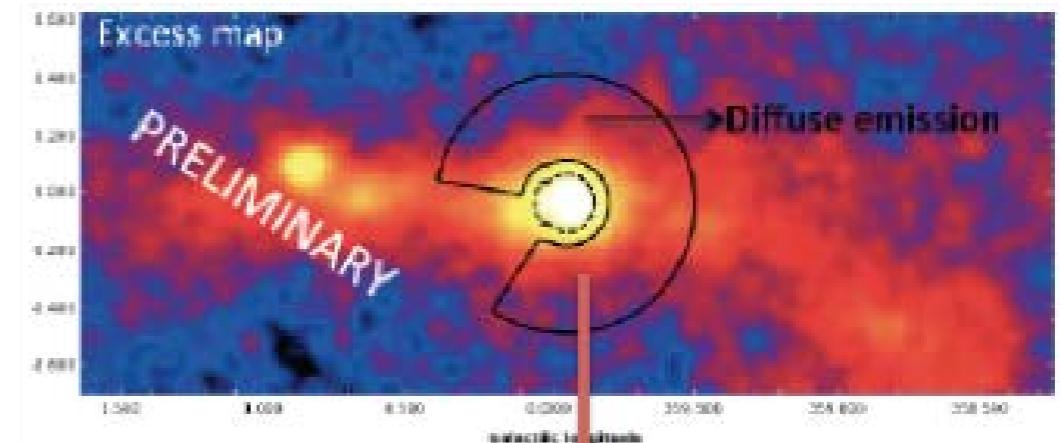
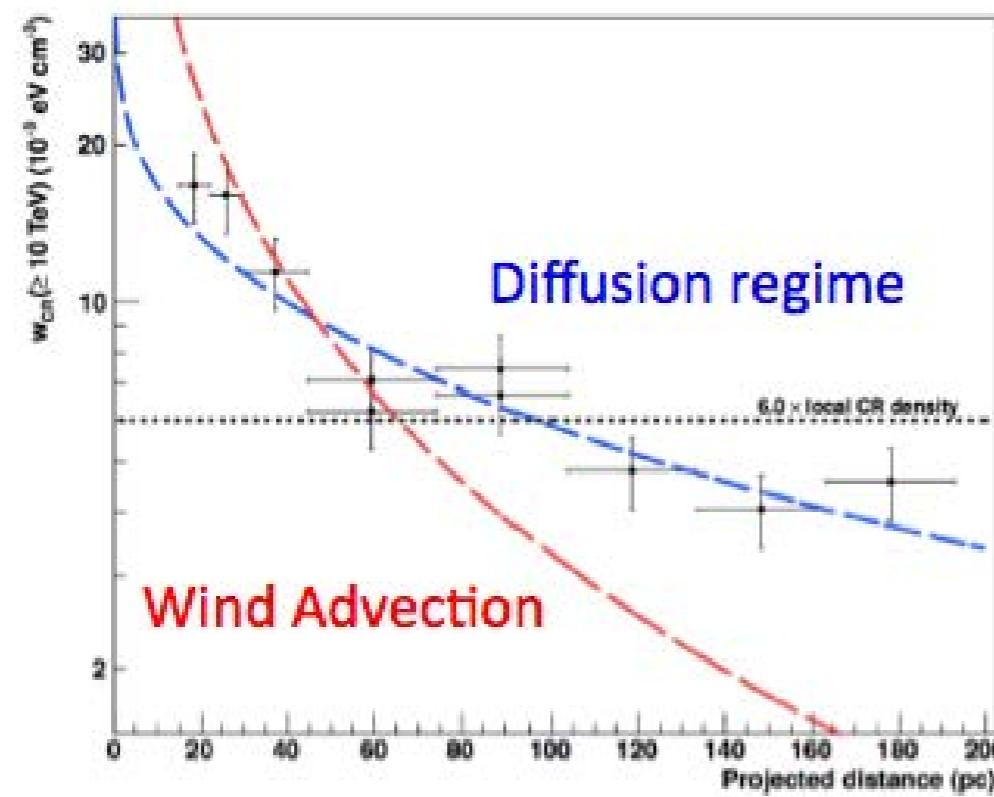
HESS Deep Observation of 250hrs

Spectrum:

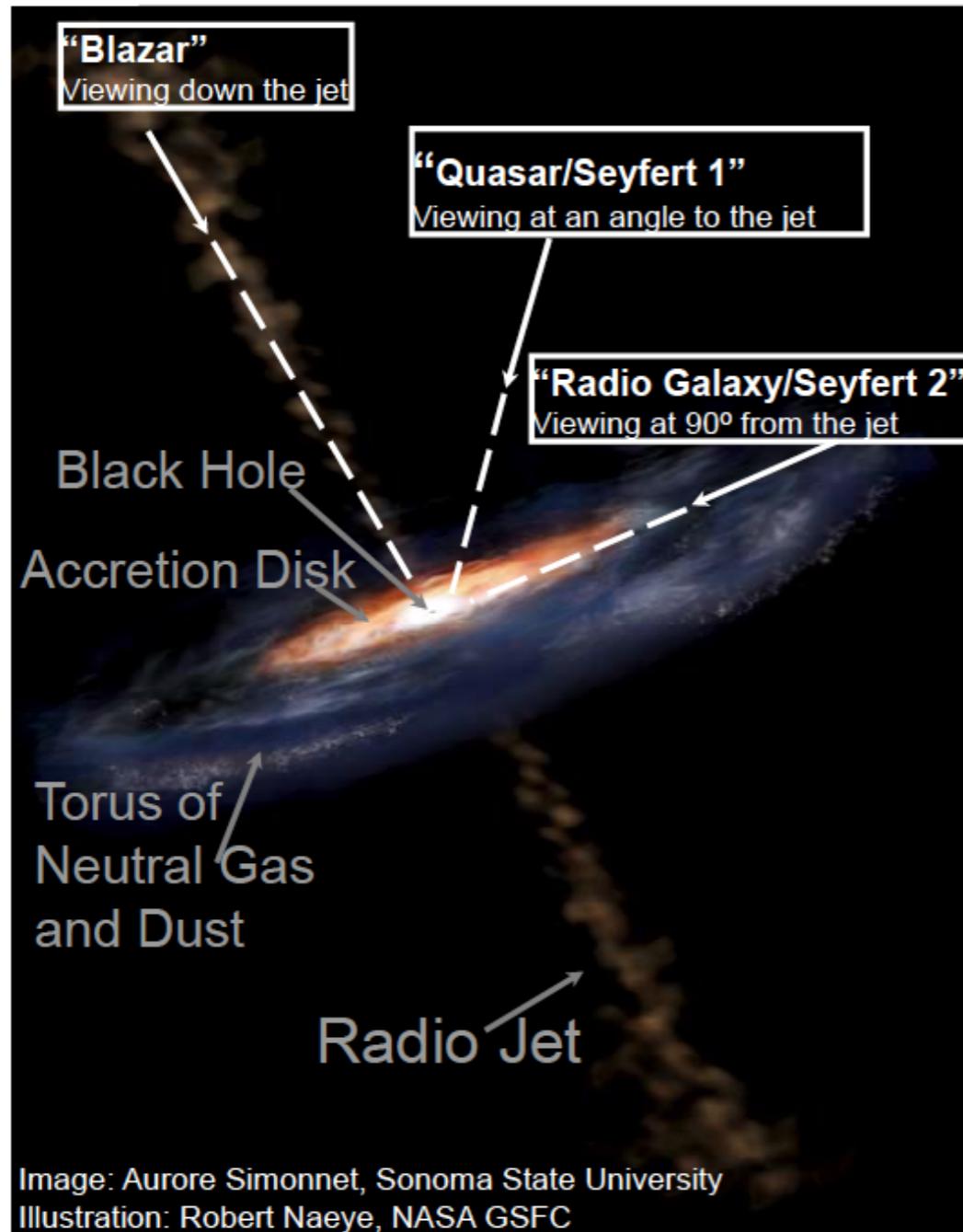
Parent proton could be 1PeV → PeVATRON?

Radial distribution $1/r$:

Consistent with the diffusion from the central BH



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

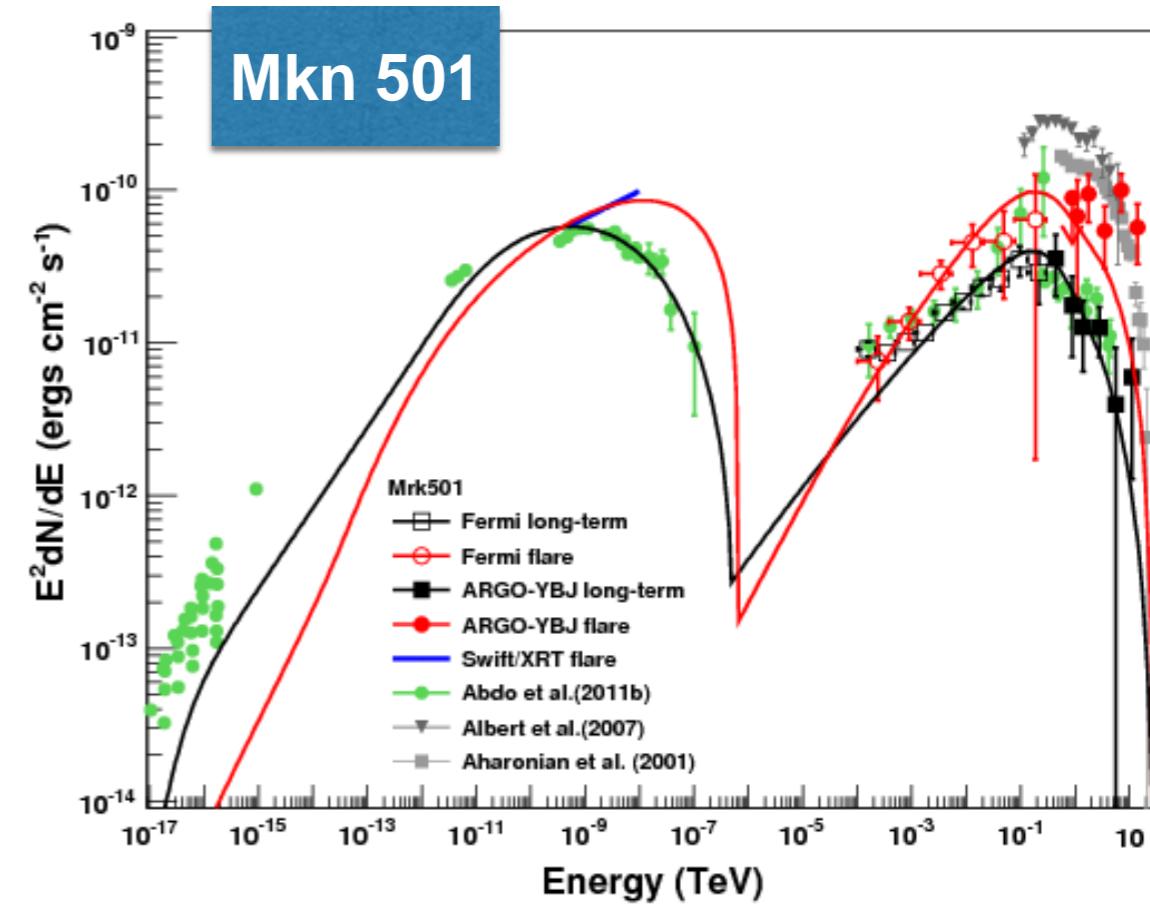
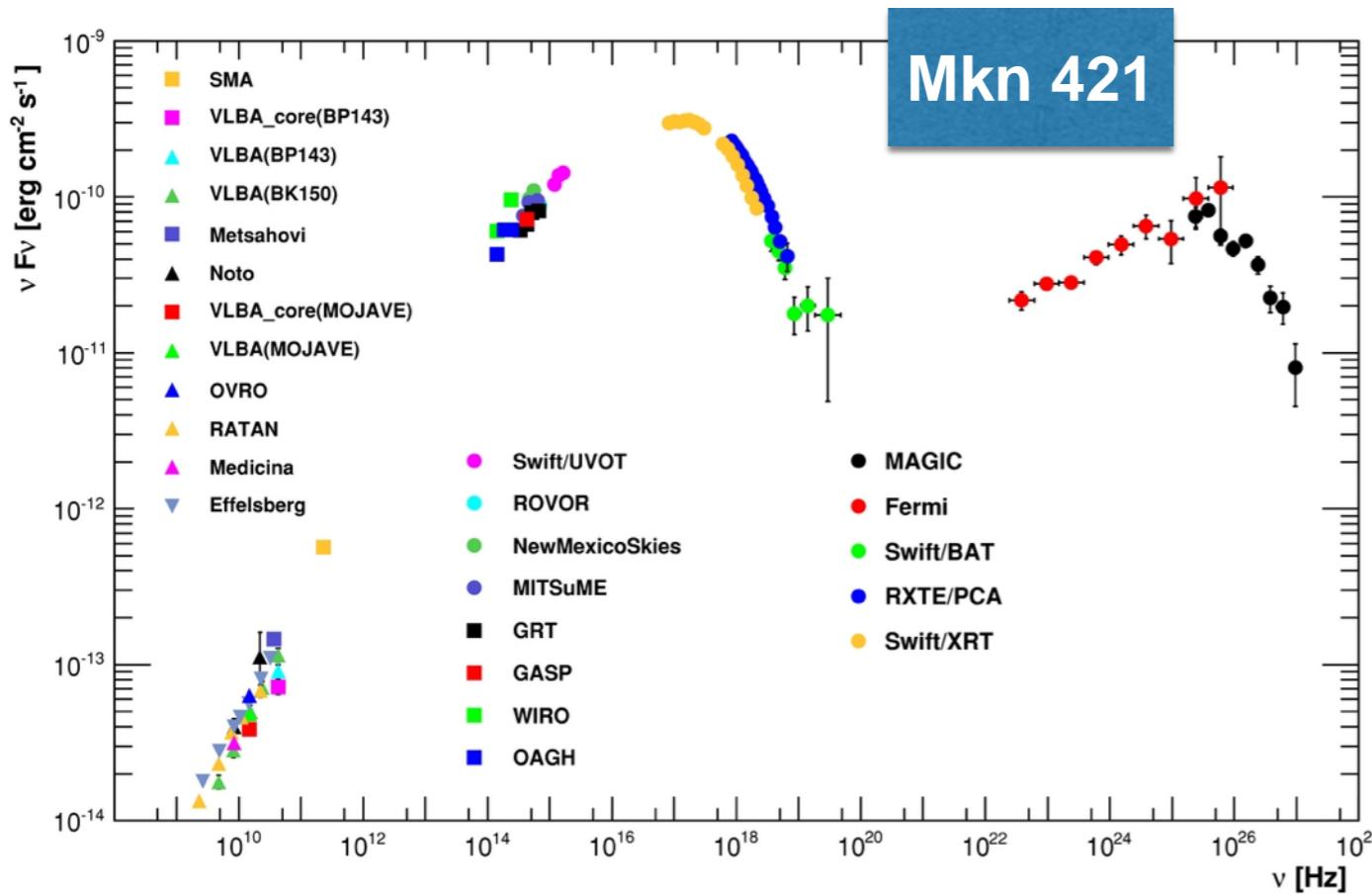
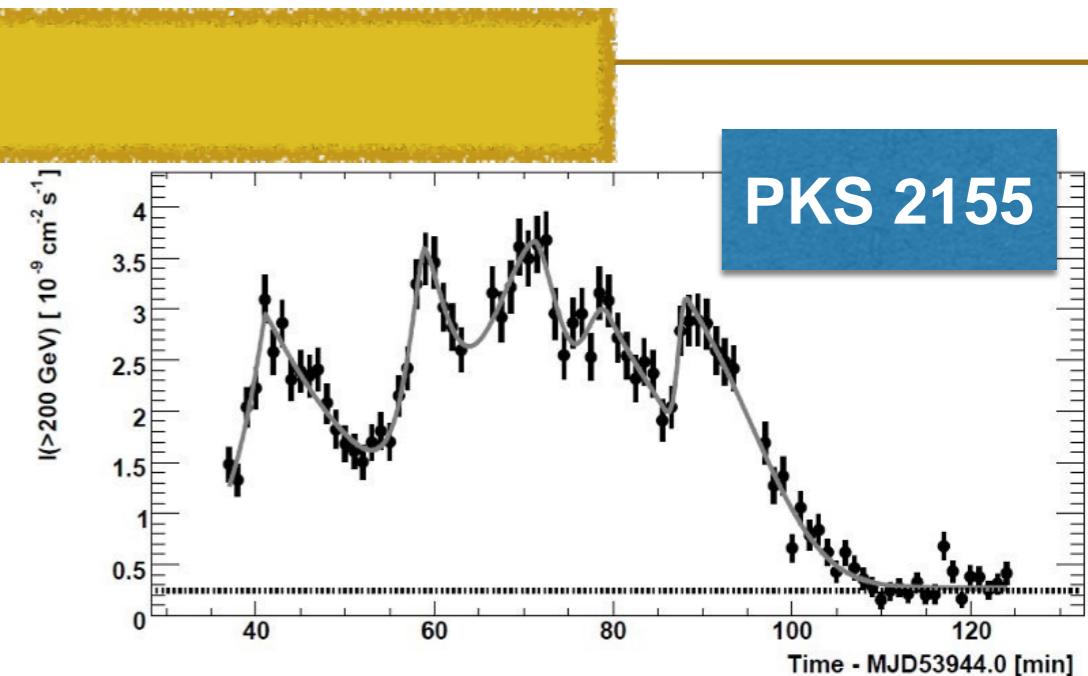
So far, AGN are generally:

- Blazars
 - Jets aligned with line of sight
- But also radio galaxies (e.g M87)
 - Jet viewed from the side

活動銀河核（ブレーザー）

BLAZARS

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



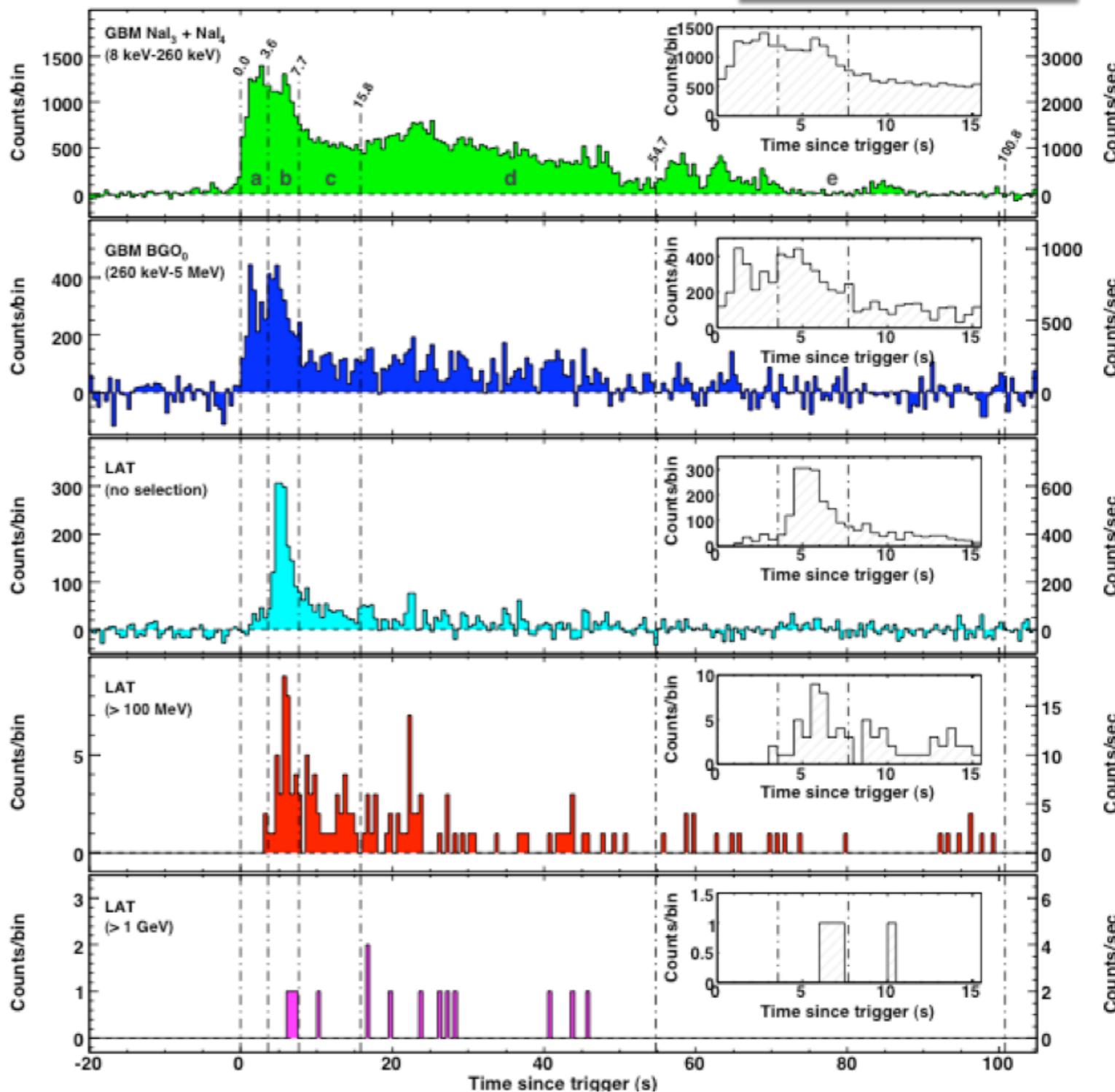
ガンマ線バースト

GRBs

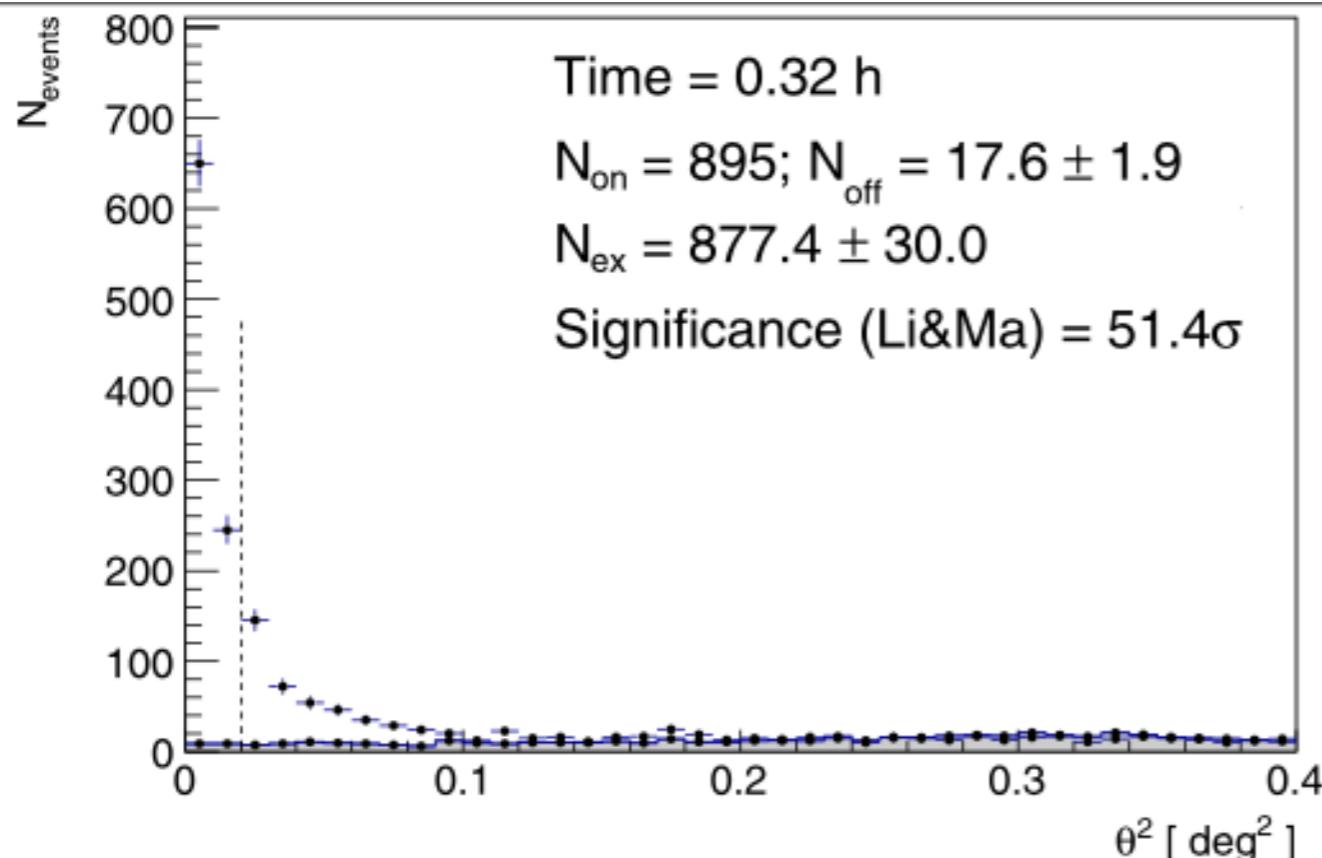
- Gamma-ray bursts (GRBs) are highly energetic explosions signaling the death of massive stars in distant galaxies.
- In September 2008, Fermi observed the exceptionally luminous GRB 080916C, with the largest apparent energy release yet measured.
- The high-energy gamma rays are observed to start later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

$$z = 4.35 \pm 0.15$$

GRB 080916C



GRB 190114C



Extended Data Fig. 2 | Significance of the γ-ray signal between $T_0 + 62$ s and $T_0 + 1,227$ s for GRB 190114C. Distribution of the squared angular distance, θ^2 , for the MAGIC data (points) and background events (grey shaded area). θ^2 is defined as the squared angular distance between the nominal position of the source and the reconstructed arrival direction of the events. The dashed

vertical line represents the value of the cut on θ^2 . This defines the signal region, where the number of events coming from the source (N_{on}) and from the background (N_{off}) are computed. The errors for 'on' events are derived from Poissonian statistics. From N_{on} and N_{off} , the number of excess events (N_{ex}) is computed. The significance is calculated using the Li & Ma method⁴².

IACTによる初めての
ガンマ線バースト検出
(2019, Jan 14th)

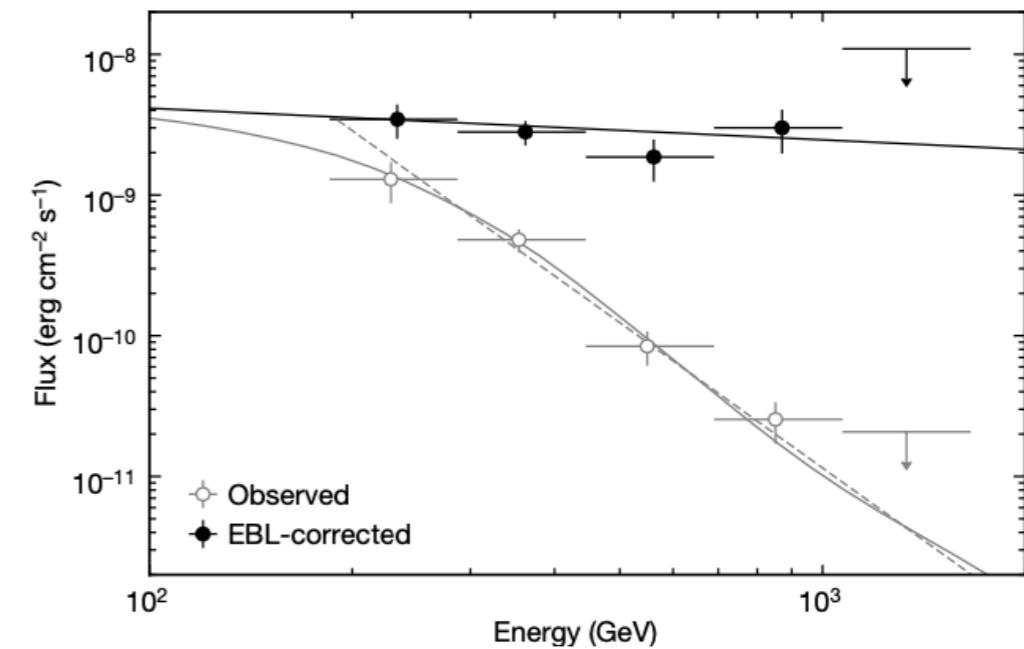
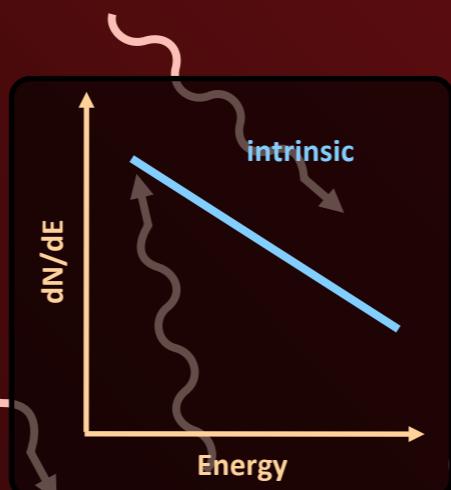


Fig. 2 | Spectrum above 0.2 TeV averaged over the period between $T_0 + 62$ s and $T_0 + 2,454$ s for GRB 190114C. Spectral-energy distributions for the

AGN

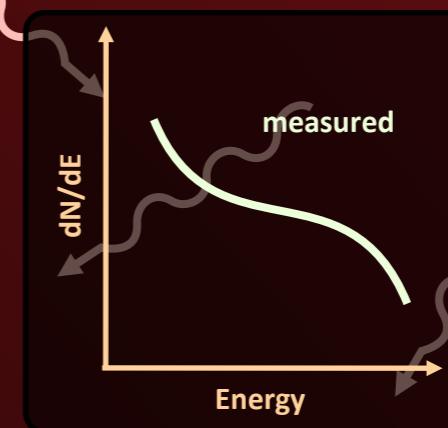


HE/VHE Y-Rays

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

Stars and Dust
in Galaxies

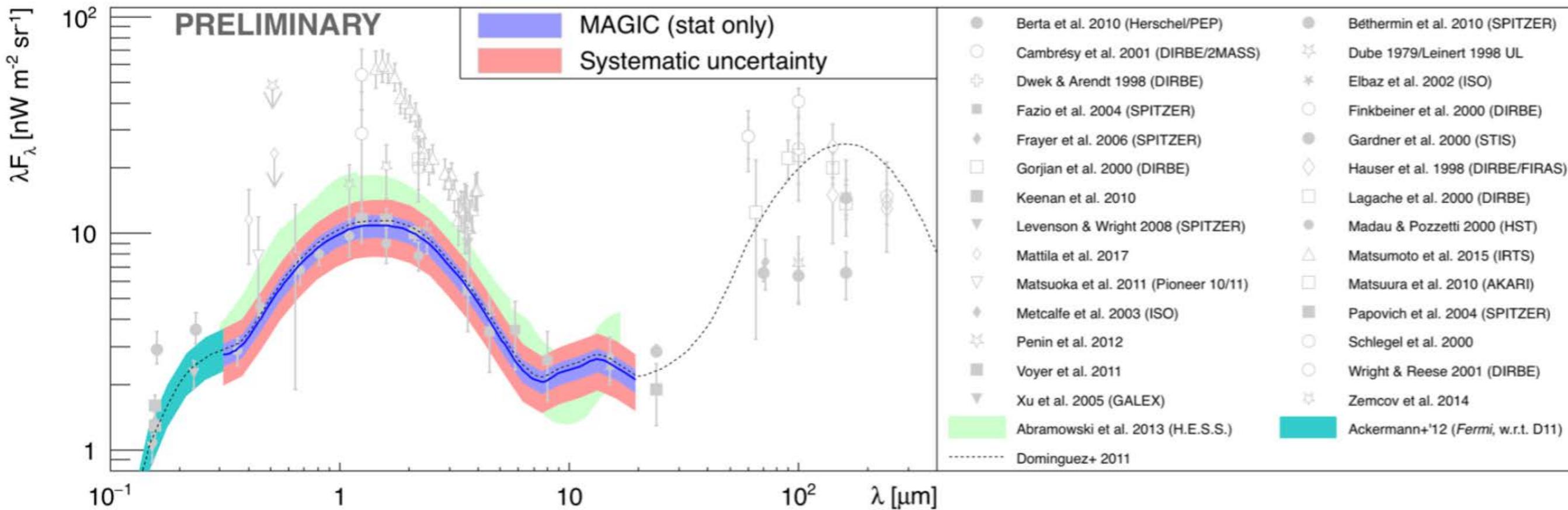
UV/O/IR
Photons



slide from M Raue



Extragalactic Background Light



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

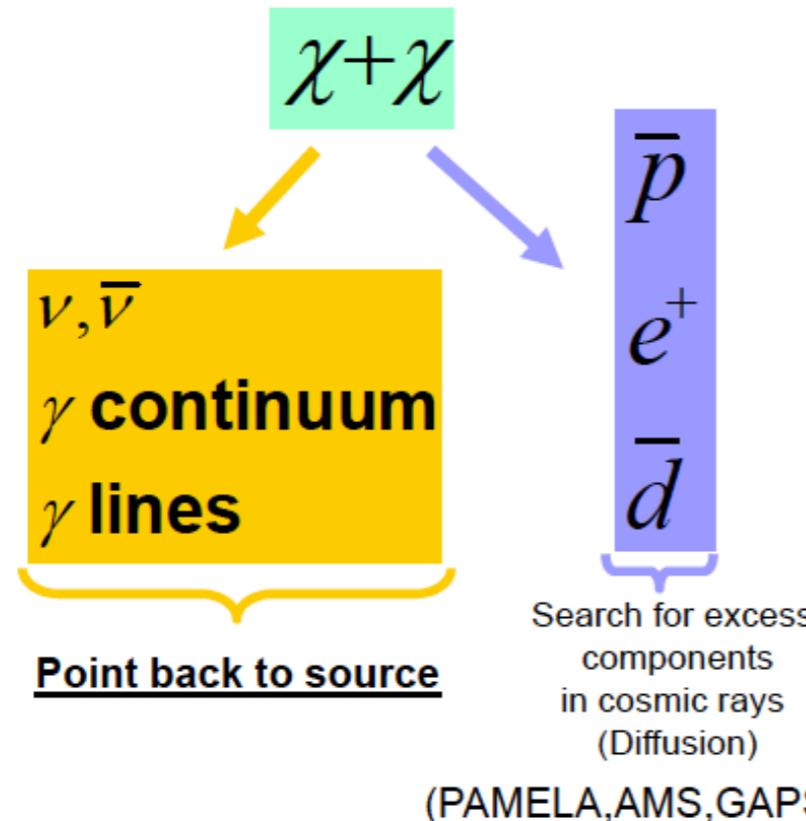
Not much more EBL than the one from the resolved galaxies

暗黒物質対消滅

Search for Cold Dark Matter

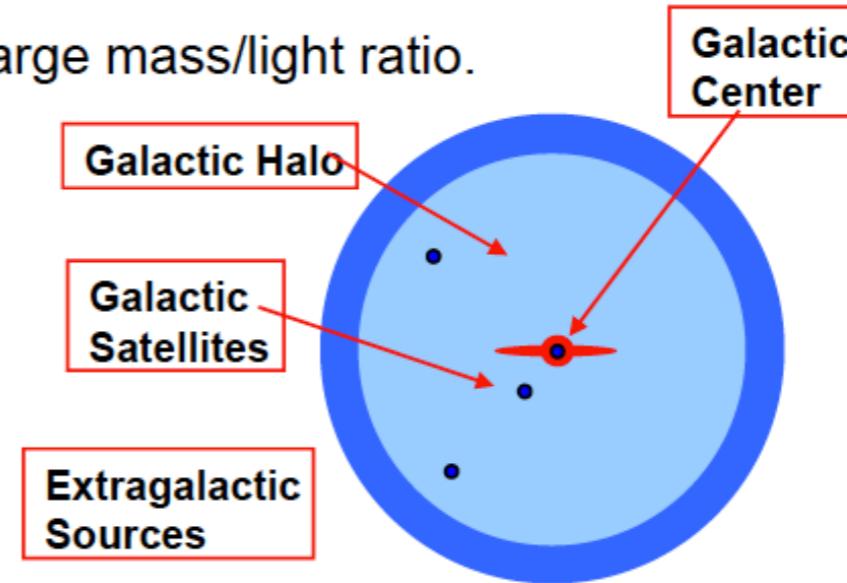
Hypothesis: DM = WIMPs

- Indirect detection of WIMP annihilation $\rightarrow \gamma, \nu$ etc.



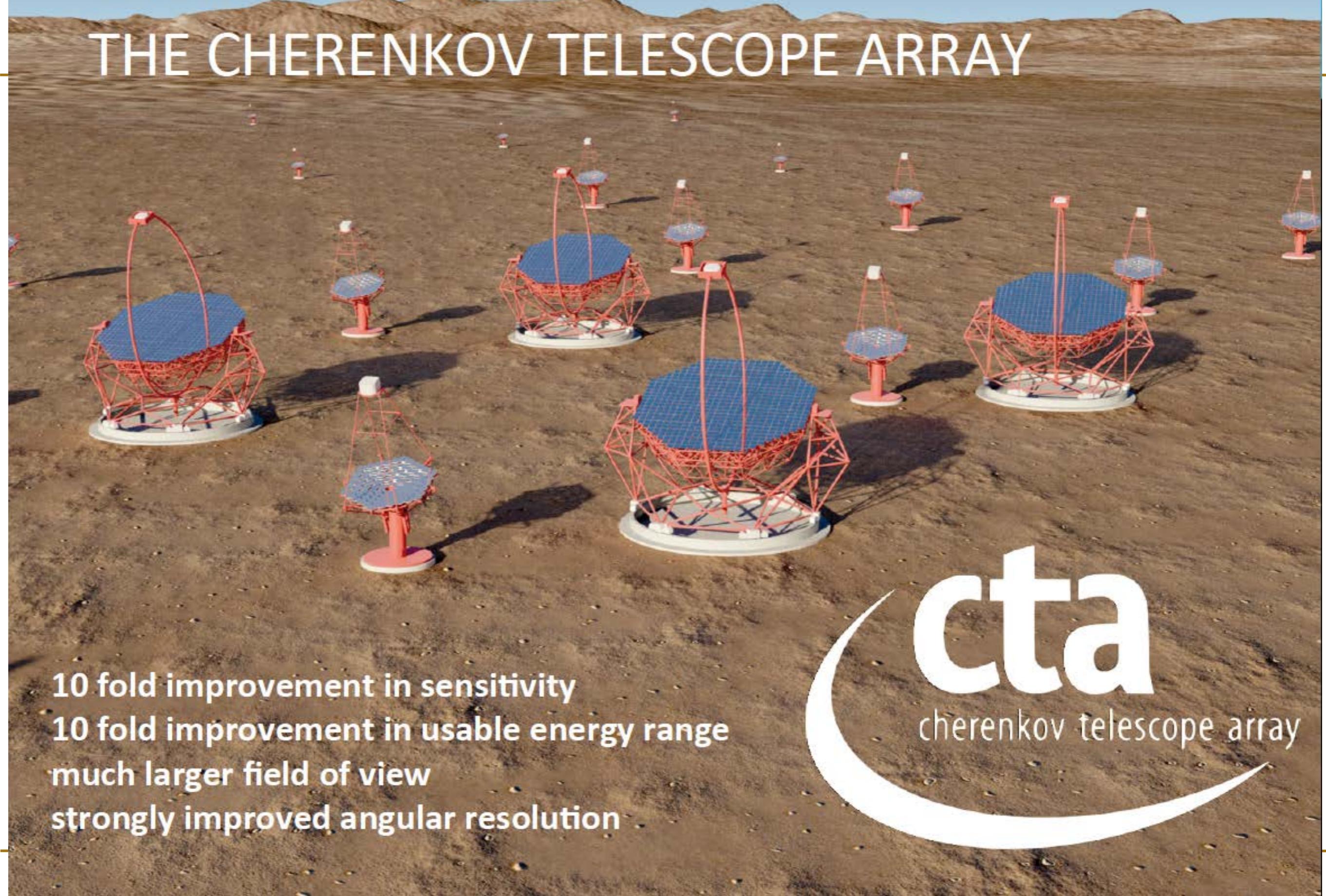
Target regions with:

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



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

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**



Low-energy section:

4 x 23 m tel. (LST)

- Parabolic reflector
- FOV: 4-5 degrees
- energy threshold
of some 10 GeV



(one) possible configuration

Southern 100 M€ Array (2006 costs)

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)

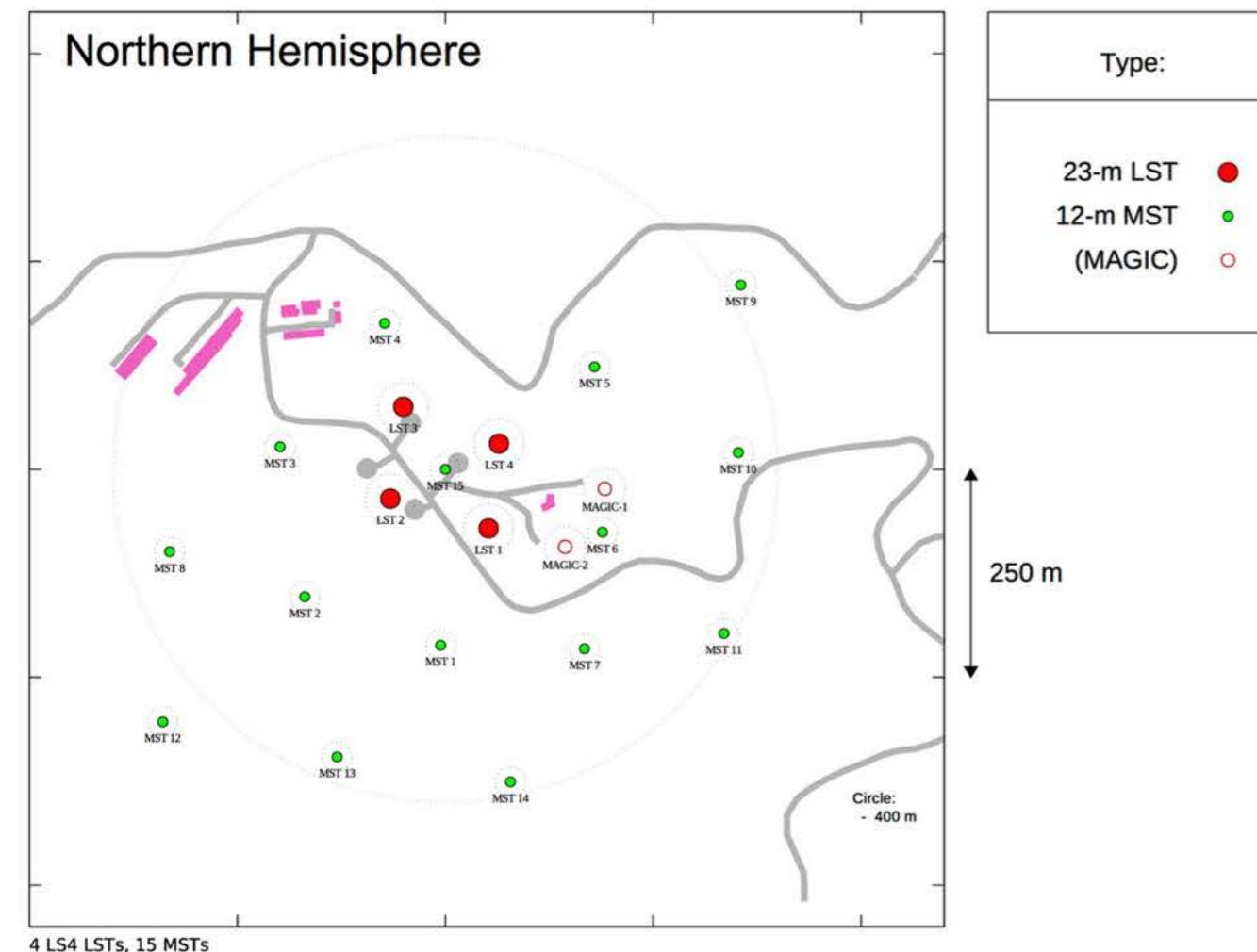
Davies-Cotton reflector
(or Schwarzschild-Couder)

- FOV: ~10 degrees

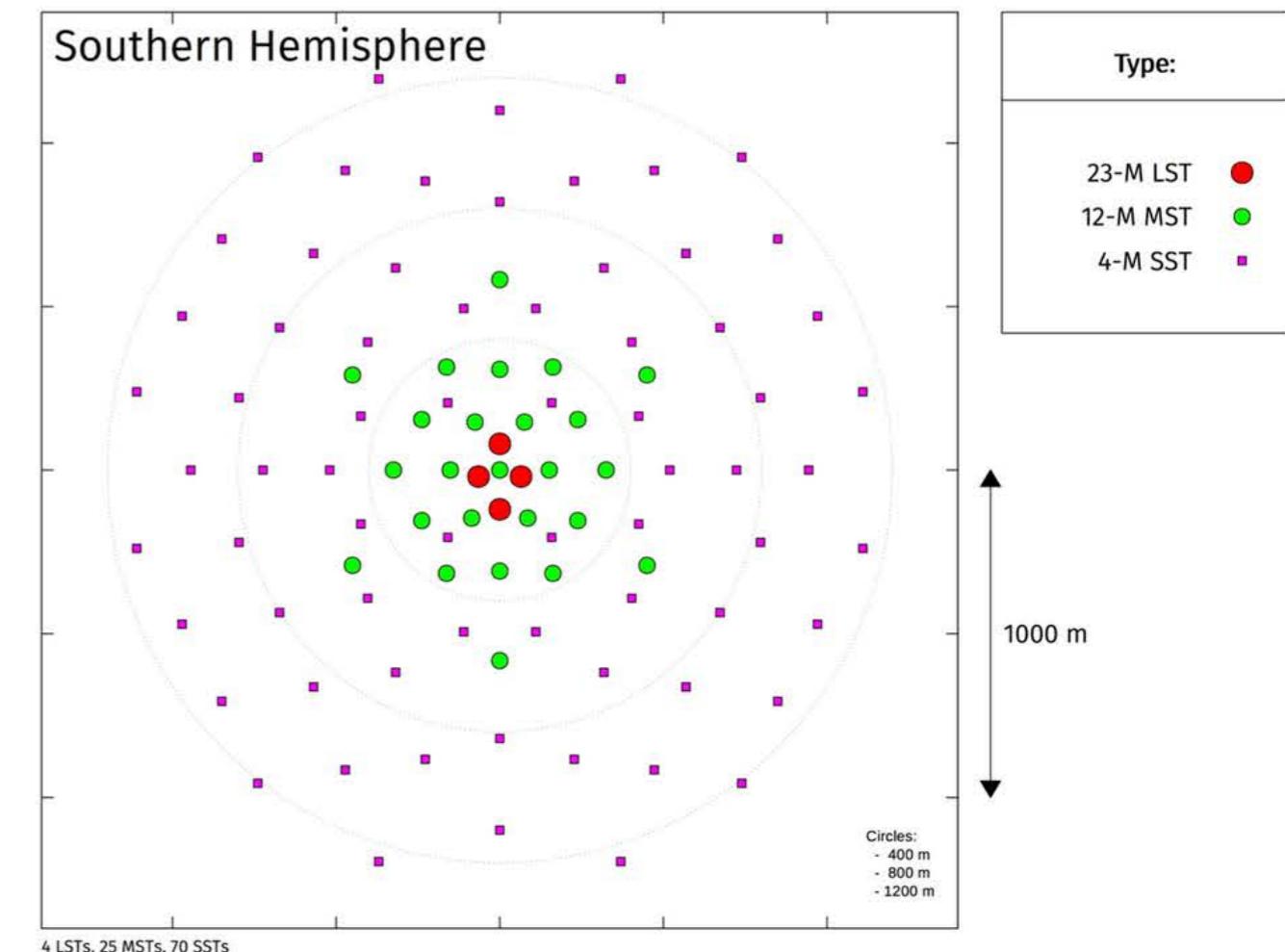
10 km² area at
multi-TeV energies

CTA: Array Layouts

La Palma, Canary islands

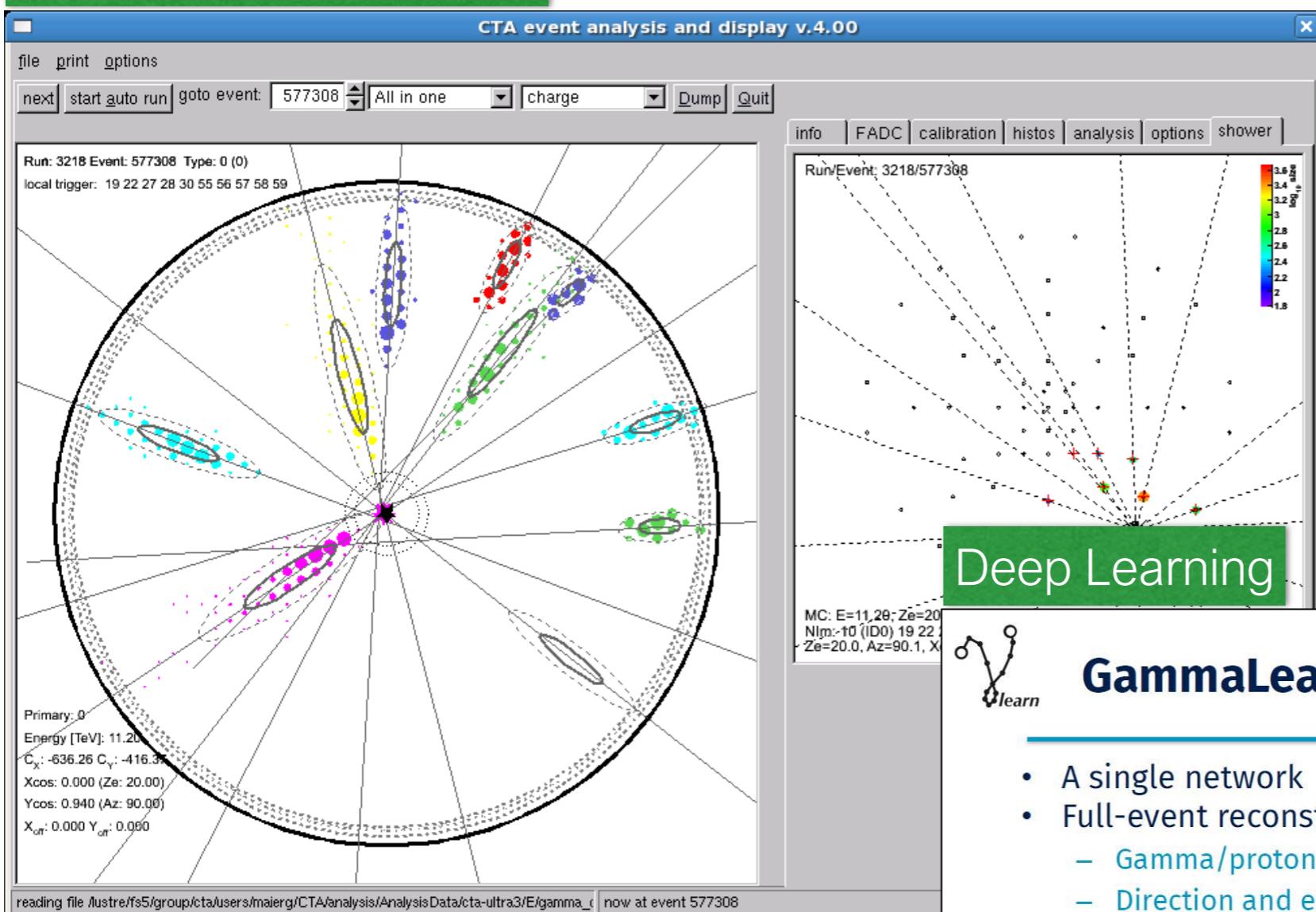


Paranal, Chile



CTA: Analysis Techniques

Monte Carlo Simulation



Deep Learning

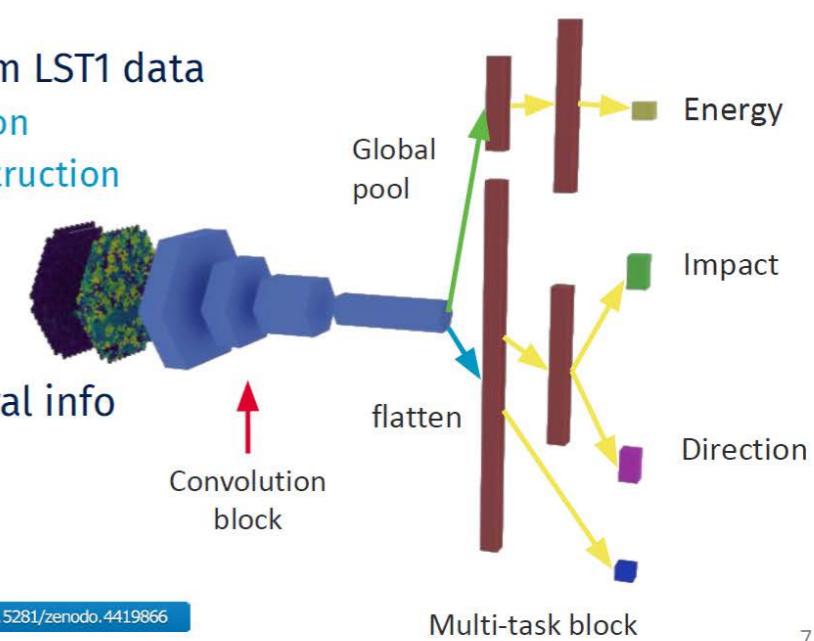
ITが得意な学生さん、
大学院でチャレンジ
してみませんか？

Vuillaume+ 2021

GammaLearn : γ -PhysNet

- A single network
- Full-event reconstruction from LST1 data
 - Gamma/proton discrimination
 - Direction and energy reconstruction

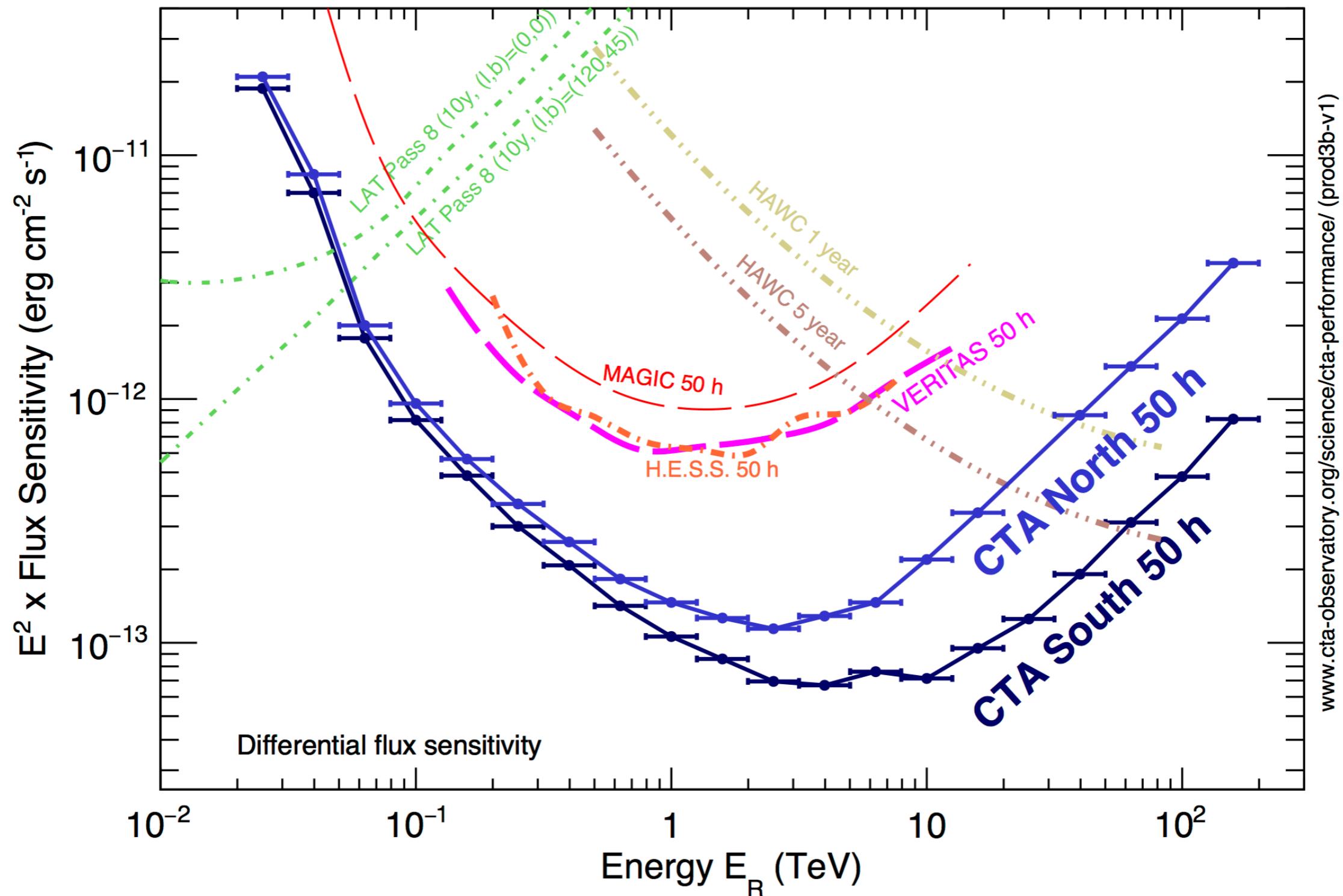
- Hard parameter sharing
- Input: Image charge + temporal info
- Convolution block:
 - ResNet-56 backbone
 - Full pre-activation
 - Indexed Convolutions



Maier & Holder 2017

CTA: Flux Sensitivities

Flux Sensitivities



CTA: Large-Sized Telescopes



Large Size Telescopes of CTA

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



A. Reale

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)

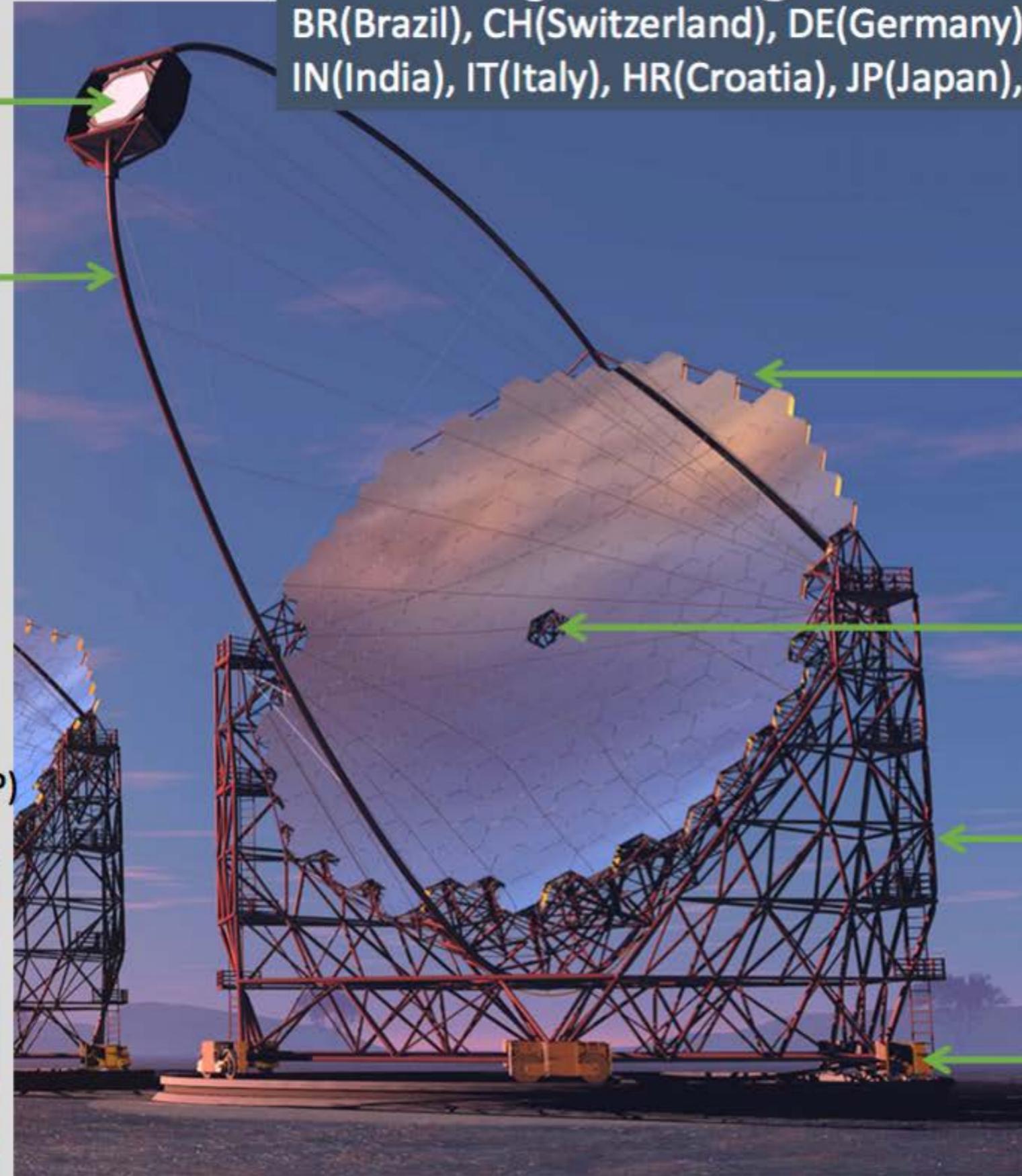
Camera body (ES)

Camera Supporting

Structure (FR/IT)

Flywheel, UPS (JP)

Computers, network (JP)



Mirror (JP)

Interface Plate(DE/BR/JP)

Actuator (JP/CH)

CMOS-Cam (JP)

Star Guider (SE)

Calibration Box (IN/IT)

Structure (DE)

Access Tower (DE/ES)

Drive (DE/FR/ES)

Bogie (DE/ES/IT)

Rail (DE/ES)

Foundation (ES)

Mirrors



cherenkov
telescope
array

ICRR, Japan



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)

Developed last 6 years

- Light weight 45kg
- Tolerance $< 10\mu\text{m}$
- Reflectivity > 92%
- Aging ~1% /yr

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



Camera

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



cherenkov
telescope
array



7 LGs



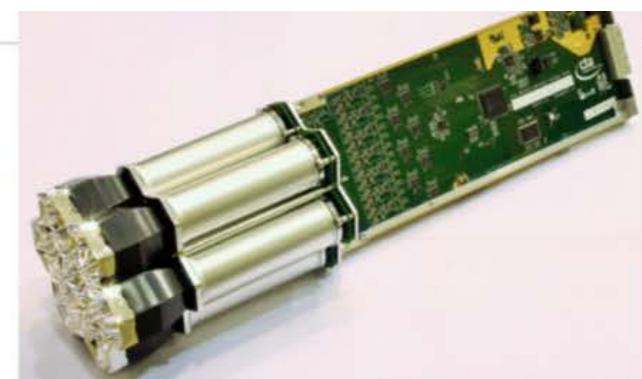
7 PMTs



SCB



Dragon board



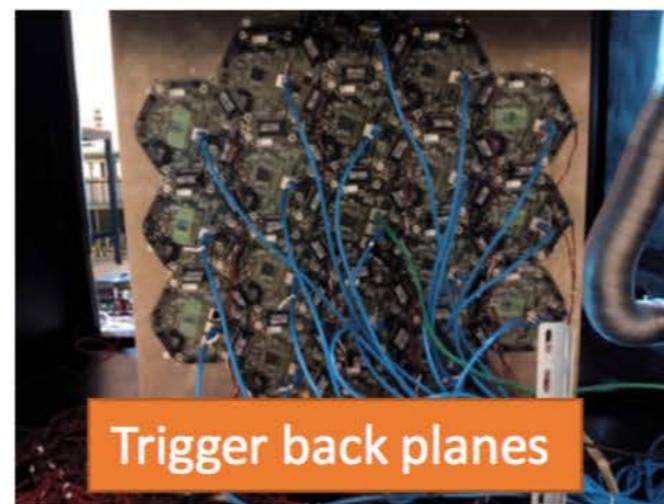
FPI module



Module assembly



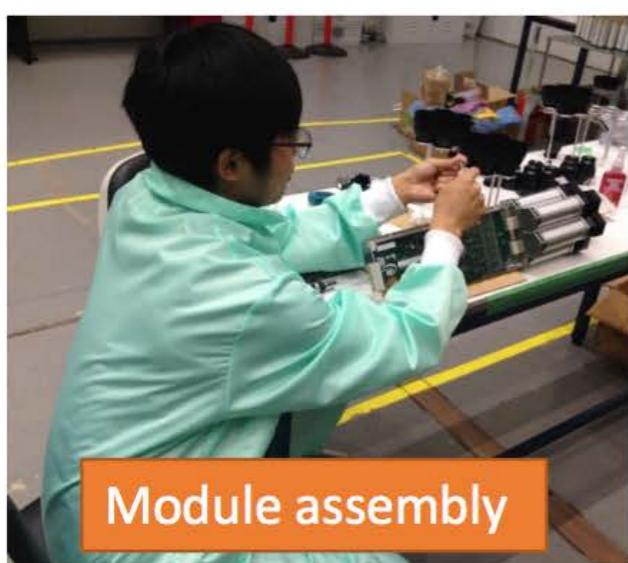
19 tested modules



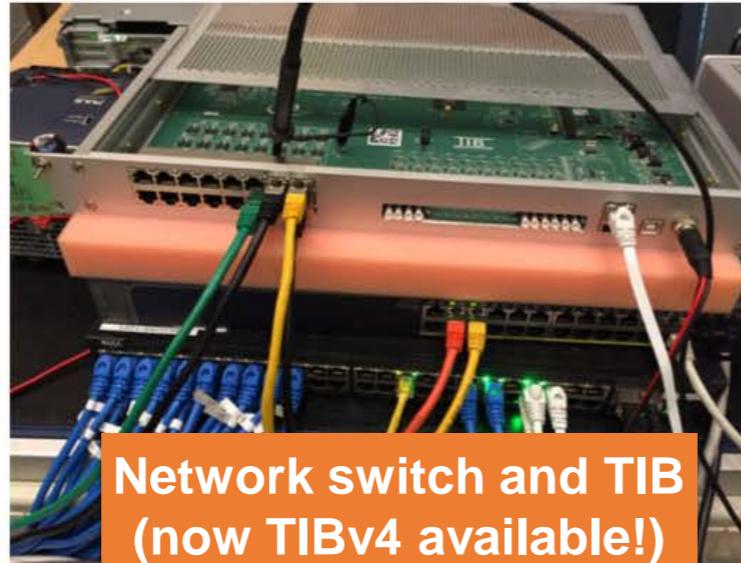
Trigger back planes

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

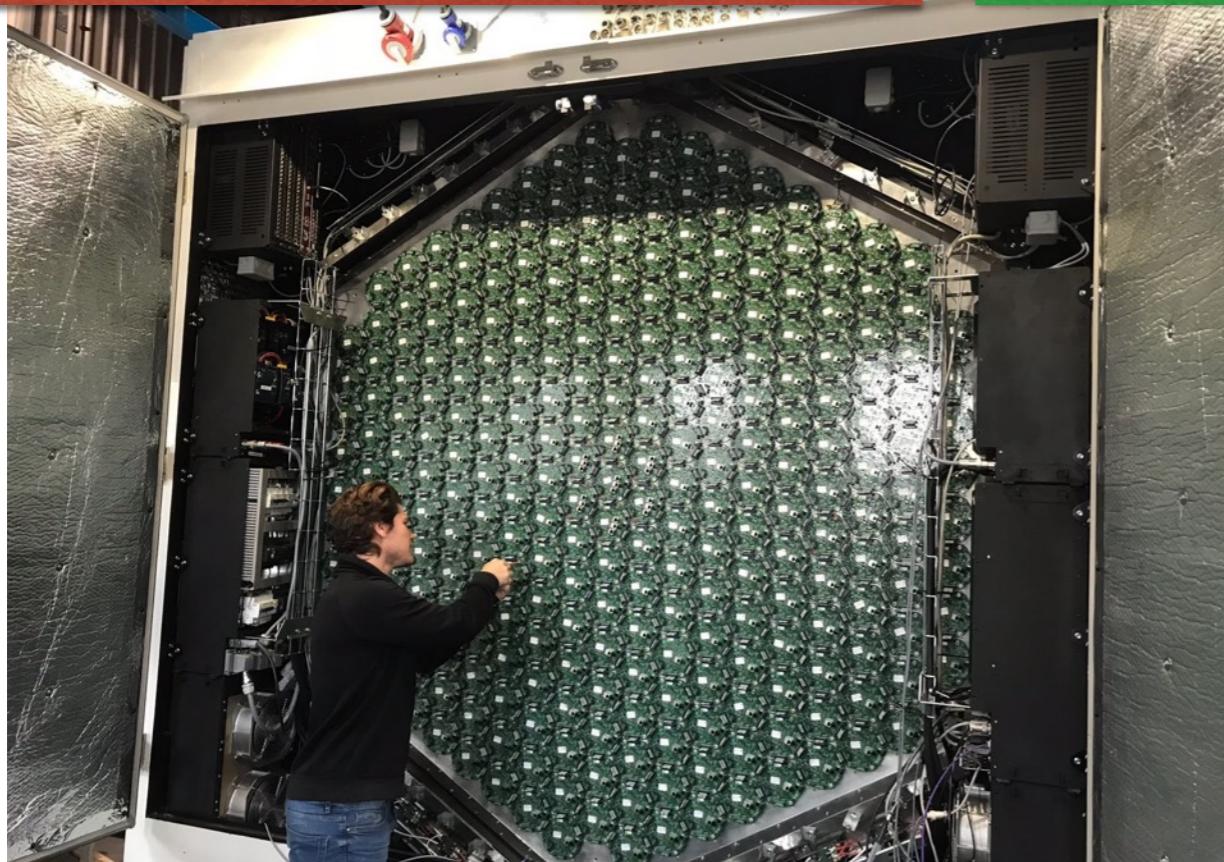
21

50

LST1 progress since November 2017

Backplanes of the camera installed

Jan 2018



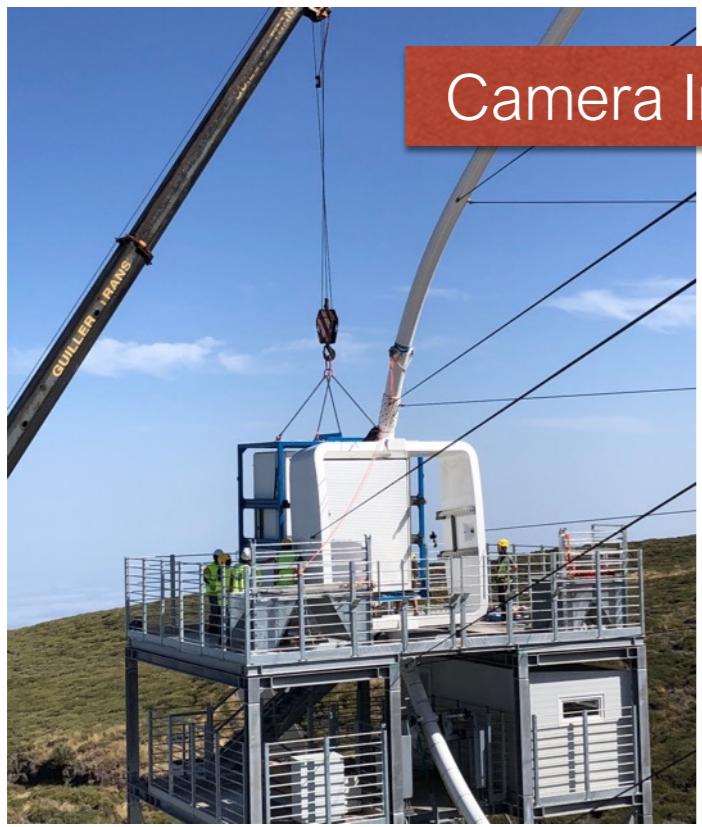
Camera mechanics finished

Feb 2018



Camera Installation On the telescope

Sep 2018

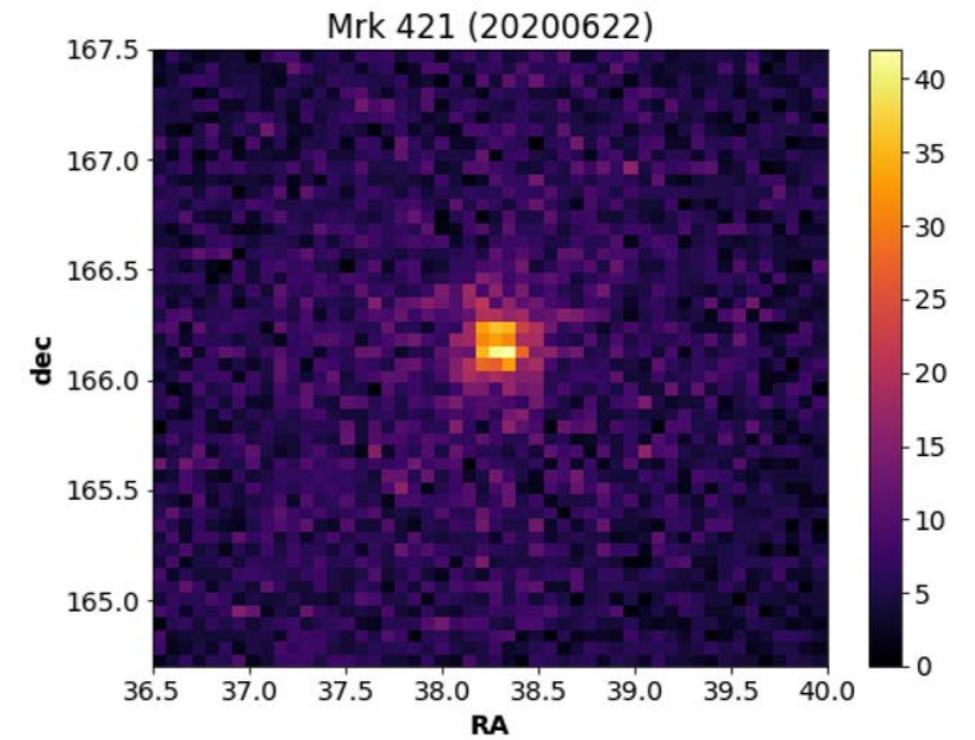
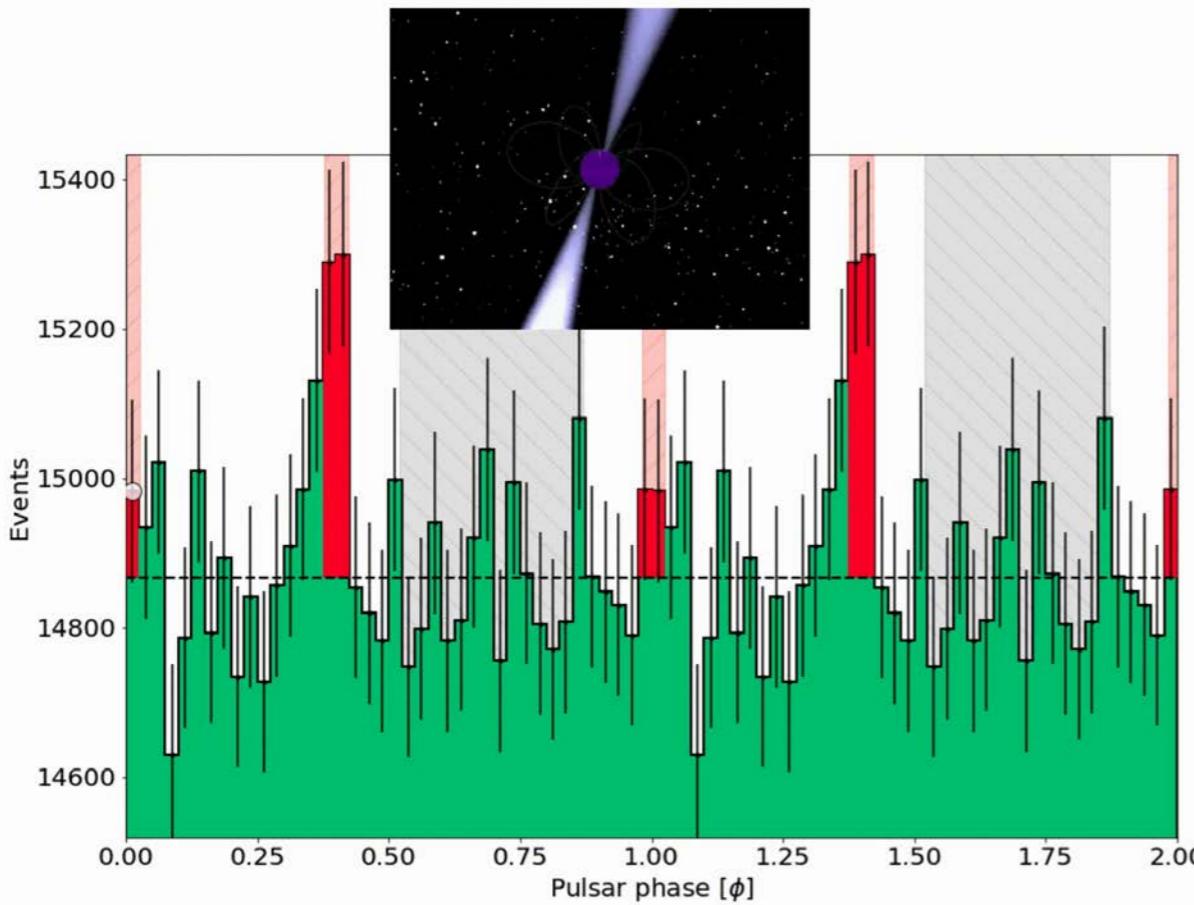


Oct 2018



Engineering runs

- Crab pulsar
 - Challenging to detect a pulsar only with commissioning data (11.4 h from early 2020)
 - P2 clearly detected with significance 5.2σ
 - P1 significance is still marginal
- AGNs
 - Follow-up observations of flaring sources
 - Already detected Mrk 421, Mrk 501, 1ES J1959+650, 1ES 0647+250 (likely the most)



CTA北サイト 今後の計画



North: LaPalma (Spain)



ぜひ一緒に世界最高の望遠鏡を作りましょう

まとめ



- VHEガンマ線天文学はまだ若いが、発展著しい
 - 宇宙線起源、BH近傍等の極限環境の物理、宇宙論、基礎物理など、研究対象が豊富
 - 大気チエレンコフ光を利用した観測手法は確立したが、さらなる高度化が進んでいる
- 次世代VHEガンマ線天文台CTAで研究はさらに発展
 - 観測感度は従来の10倍、天体数もおそらく10倍
 - 新発見を期待