



高エネルギーガンマ線天文学  
Very High Energy  
Gamma-Ray Astronomy

吉越貴紀

ICRR, University of Tokyo

ICRR Spring School 2026

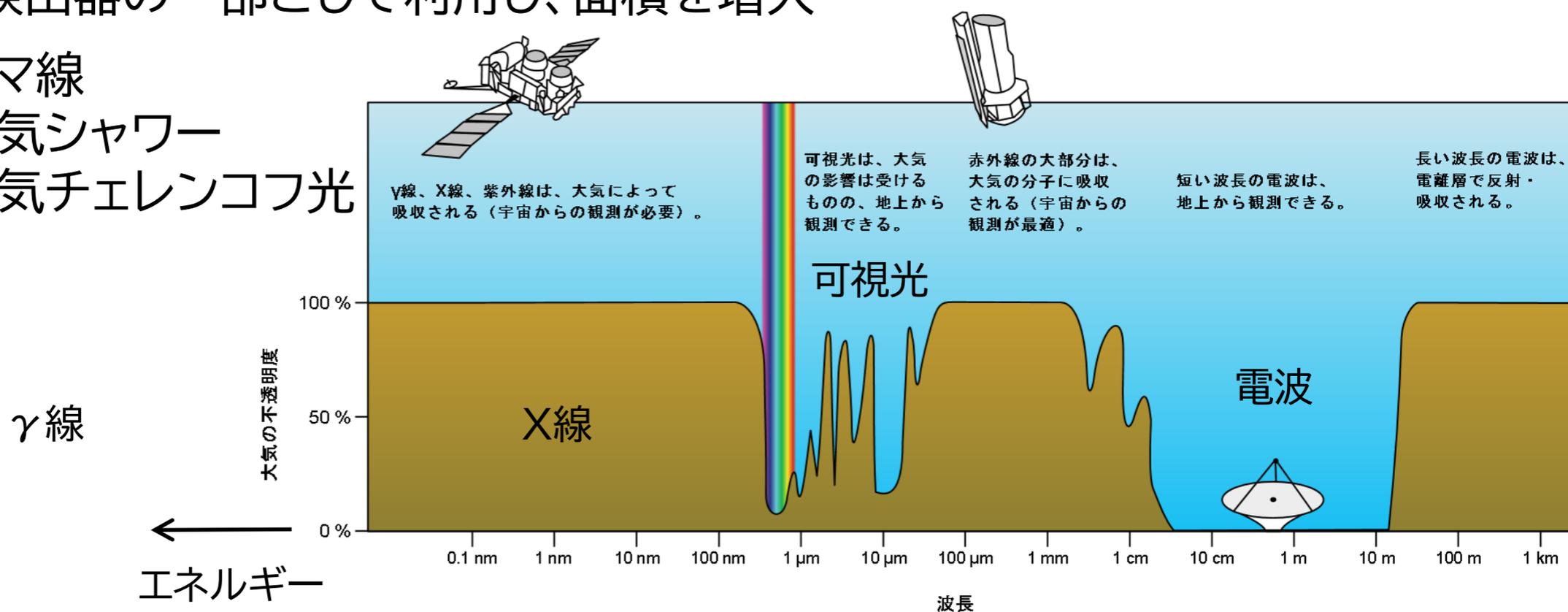
March 11, 2026

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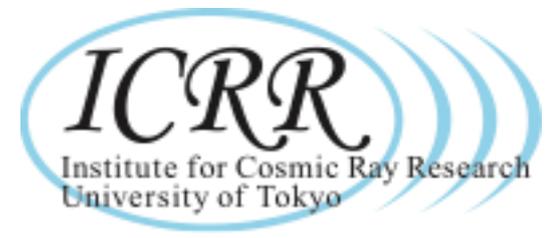
1. VHEガンマ線天文学とは？
2. ガンマ線観測の意義
3. 宇宙におけるガンマ線の生成機構
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6. 次世代ガンマ線天文台CTAO

# VHEガンマ線天文学とは？

- Very High Energy Gamma-Ray Astronomy / (超)高エネルギーガンマ線天文学
  - ガンマ線エネルギー: テラ電子ボルト帯 ( $\sim \text{TeV} = 10^{12} \text{eV}$ )
- 観測方法: 大気チェレンコフ望遠鏡 (地上天文台)
  - 地球大気はガンマ線にとって不透明  $\rightarrow$  人工衛星 ( $\sim \text{GeV} = 10^9 \text{eV}$ )
  - しかし、TeV領域ではフラックスが低く、人工衛星では面積が足りない
  - 大気を検出器の一部として利用し、面積を増大
    - ガンマ線
      - $\rightarrow$  空気シャワー
      - $\rightarrow$  大気チェレンコフ光



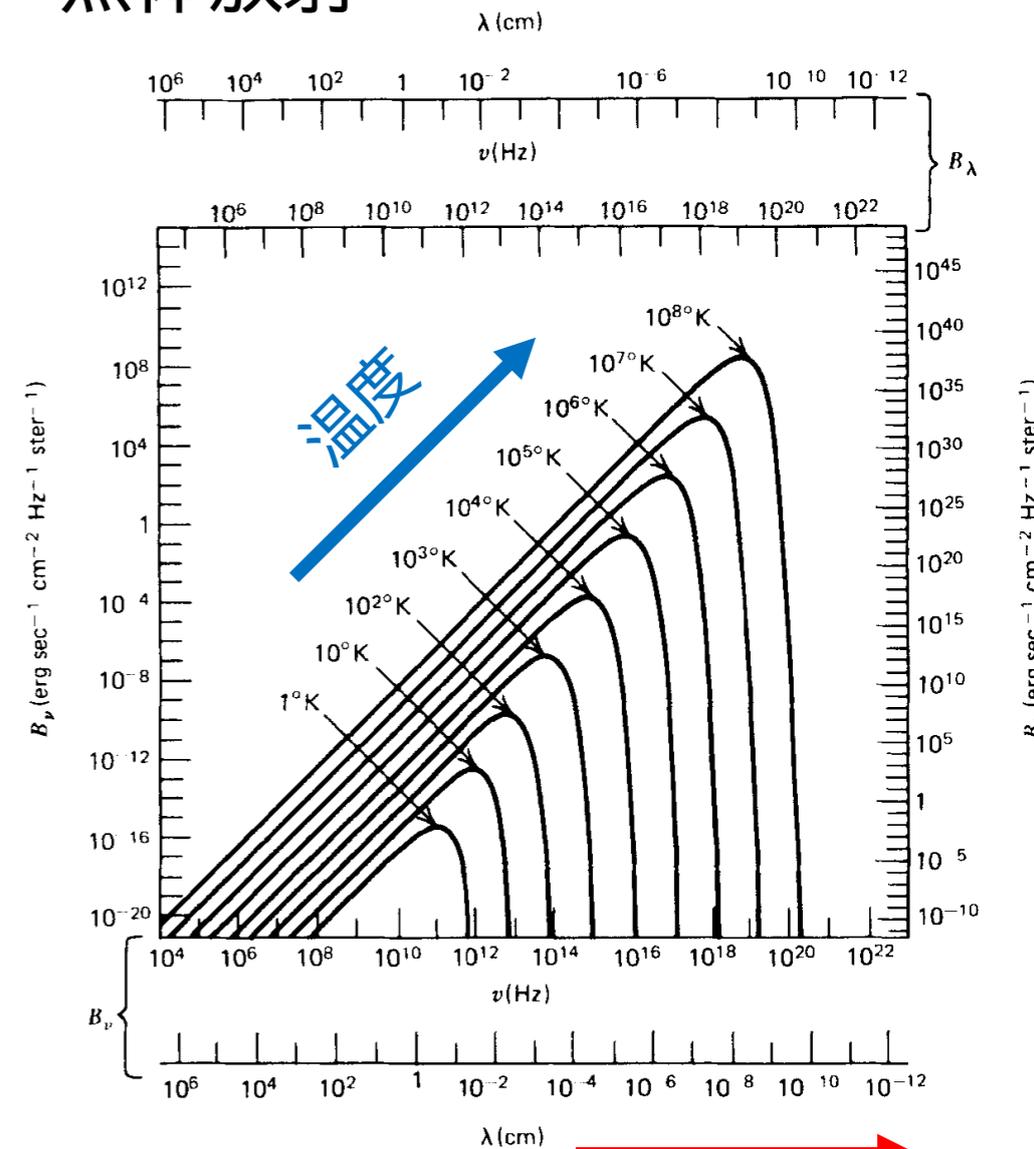
# ガンマ線による天体観測の意義



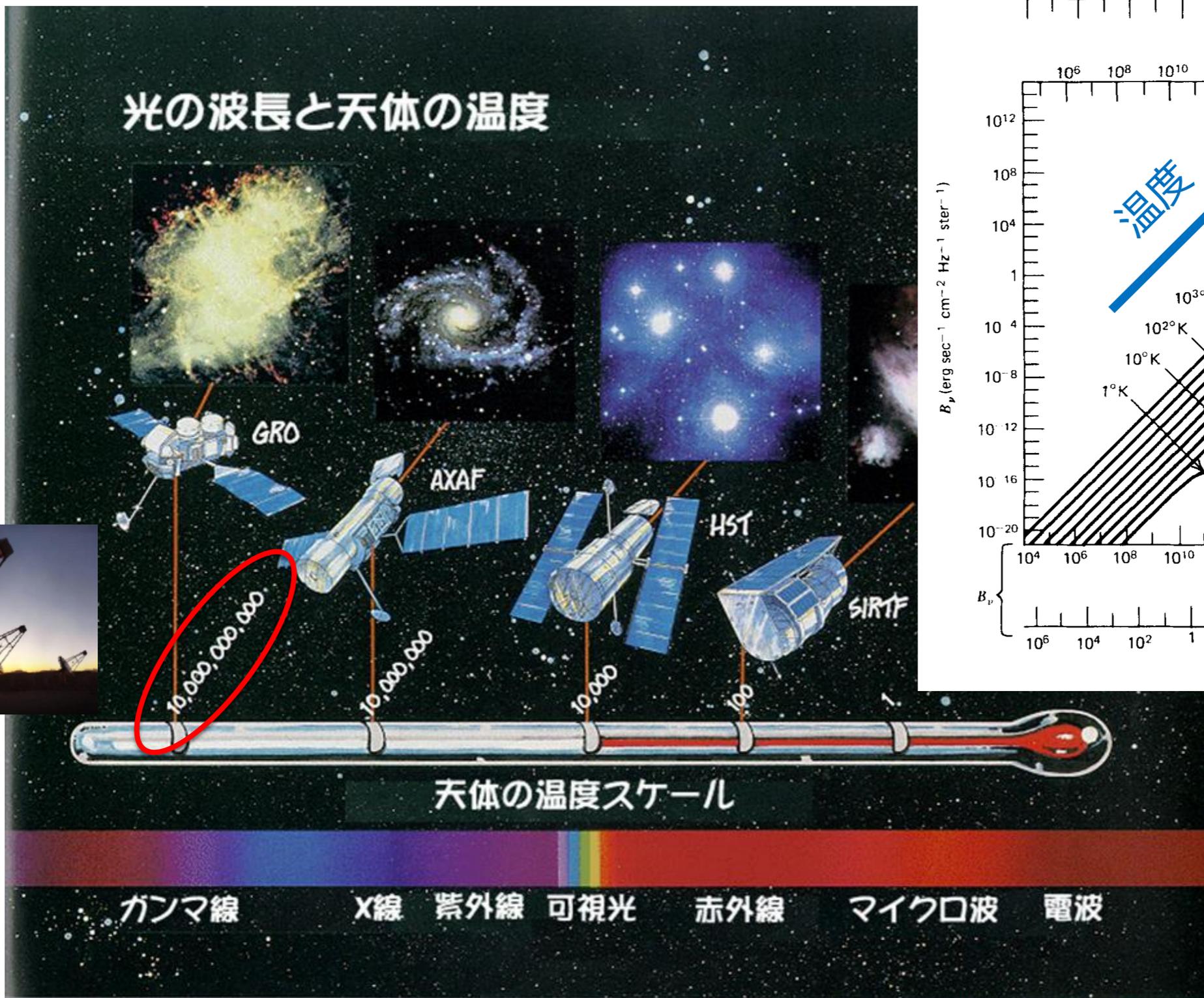
- **意義1:ガンマ線=最高エネルギーの「光」**
  - 高エネルギー／非熱的放射→宇宙の極限環境の物理
  - 多波長／マルチメッセンジャー天文学の一翼
- **意義2:放射線(素粒子)としてのガンマ線**
  - 天体における物理素過程の研究に好都合
  - 宇宙線の起源、暗黒物質の探索、など

# 非熱的放射？

## 黒体放射

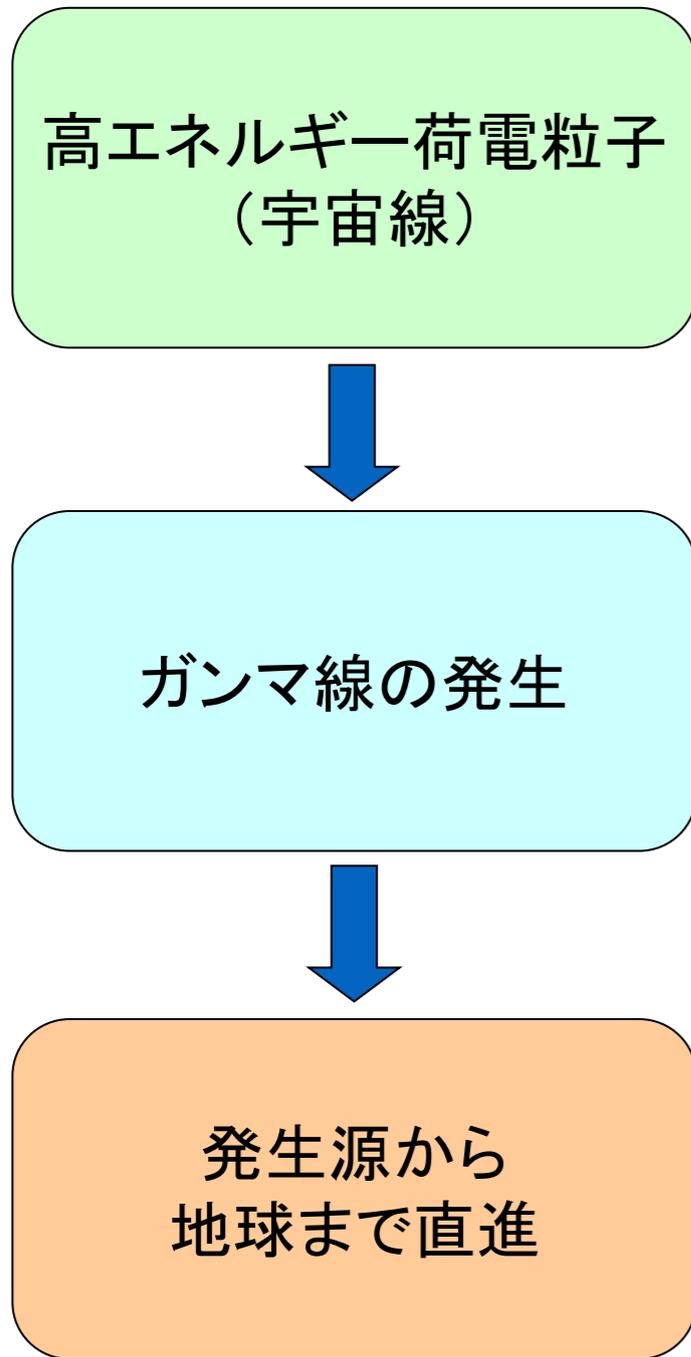


エネルギー →

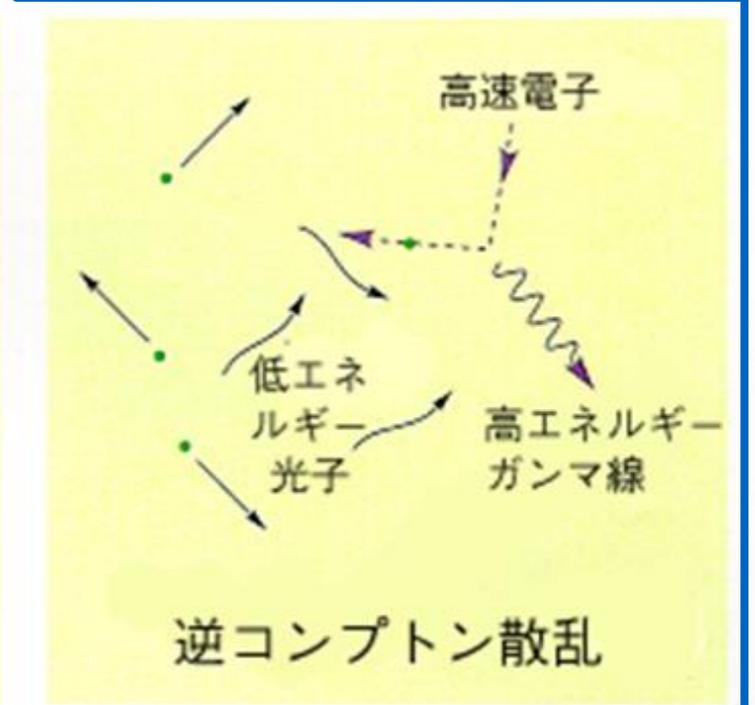
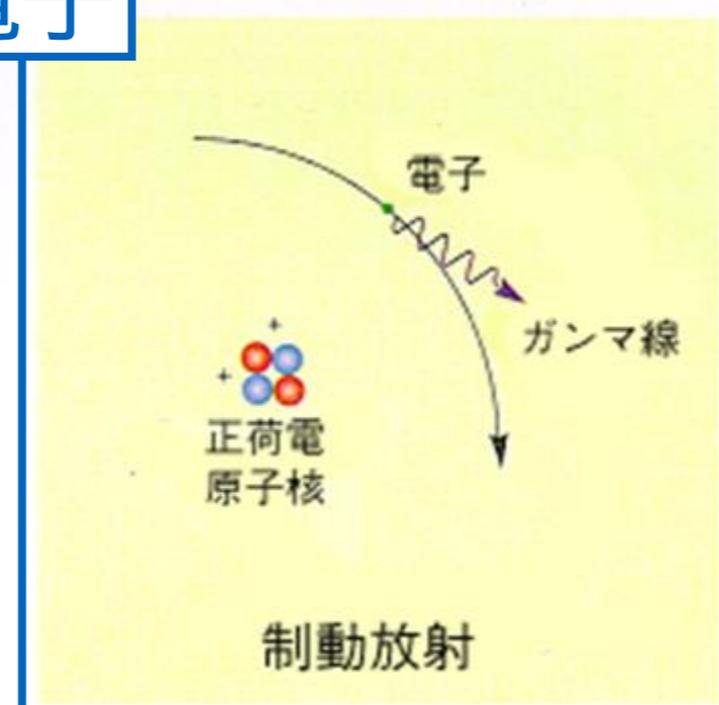
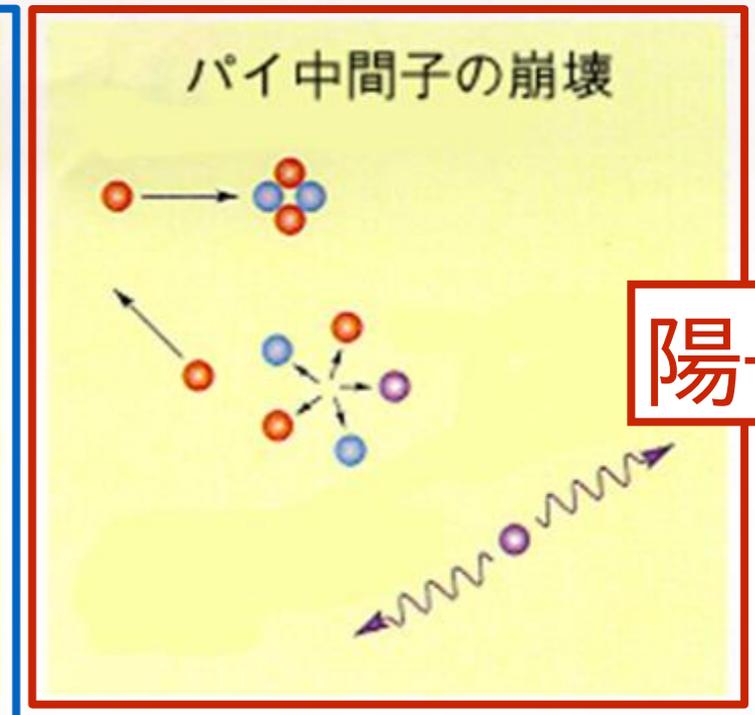
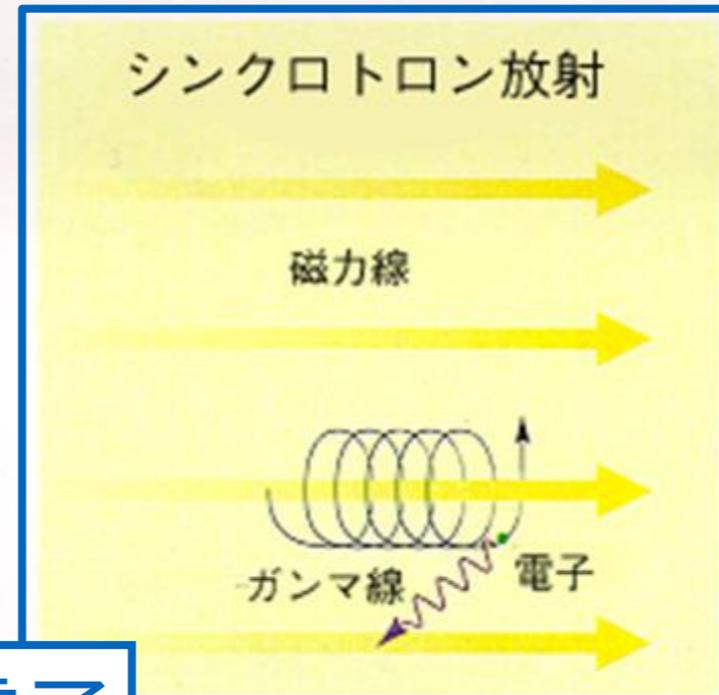


Very High Energy  
ガンマ線

# 宇宙におけるガンマ線の生成



電子



# 天体ガンマ線生成機構まとめ

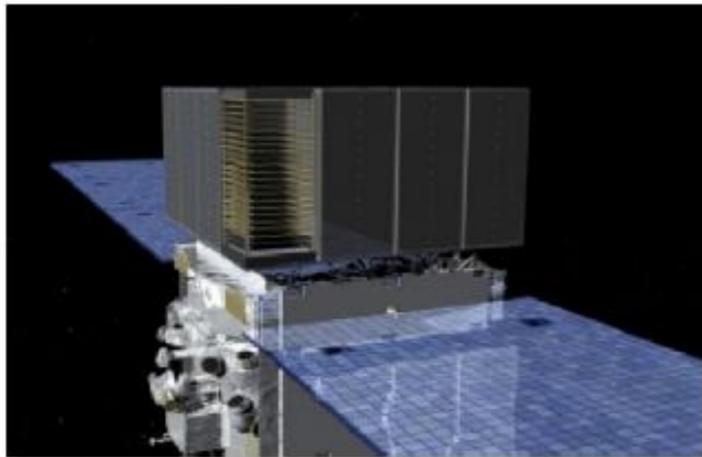
	親粒子	標的／環境
中性パイオン崩壊	陽子	物質
逆コンプトン散乱	電子	光子場
制動放射	電子	物質
シンクロトロン放射	電子	磁場
曲率放射	電子	強磁場
対消滅？	暗黒物質	質量集中
ホーキング放射？	—	PBH

# 天体ガンマ線の検出手法

## GAMMA RAY TELESCOPES

### 大気チェレンコフ望遠鏡

Space-based  
pair production  
telescopes



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

Imaging Atmospheric  
Cherenkov Telescopes

### IACTs



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

**MAGIC, 2 x 17m**



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



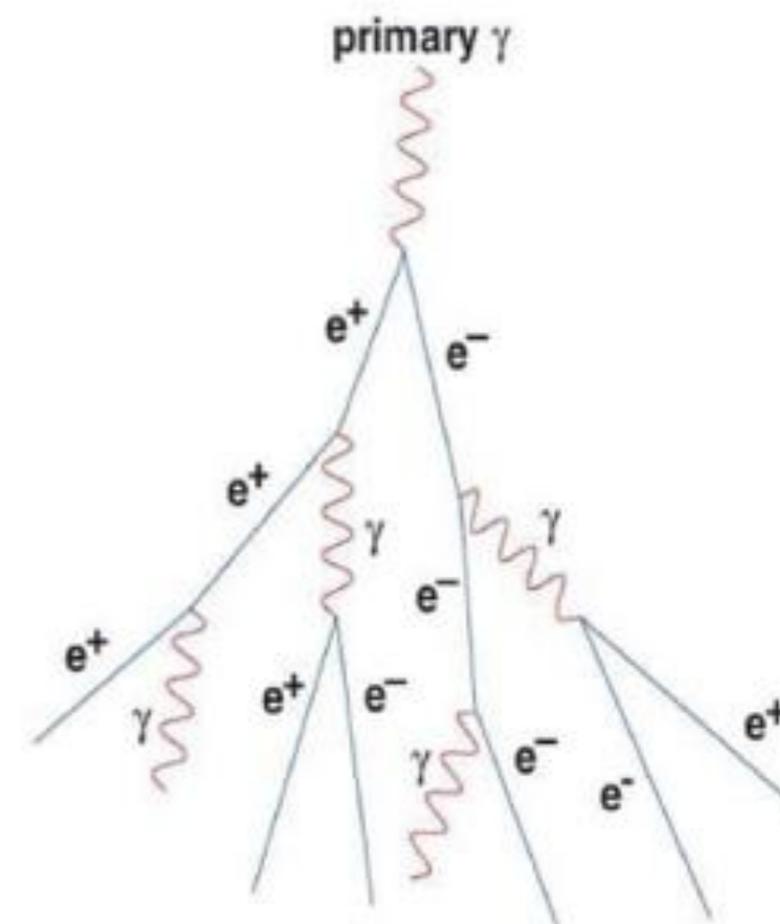
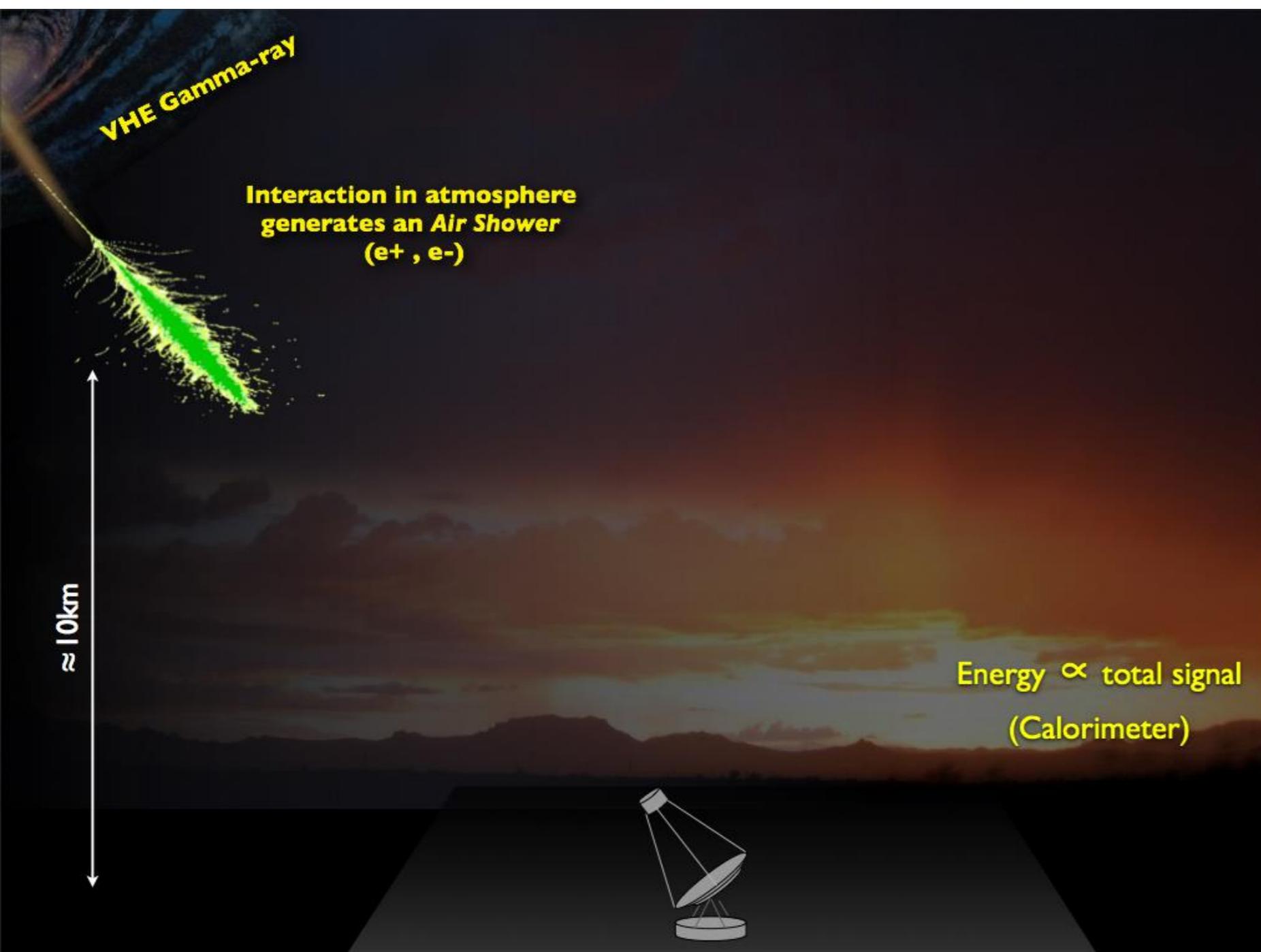
稼働中の大気チェレンコフ望遠鏡

**VERITAS, 4 x 12m**



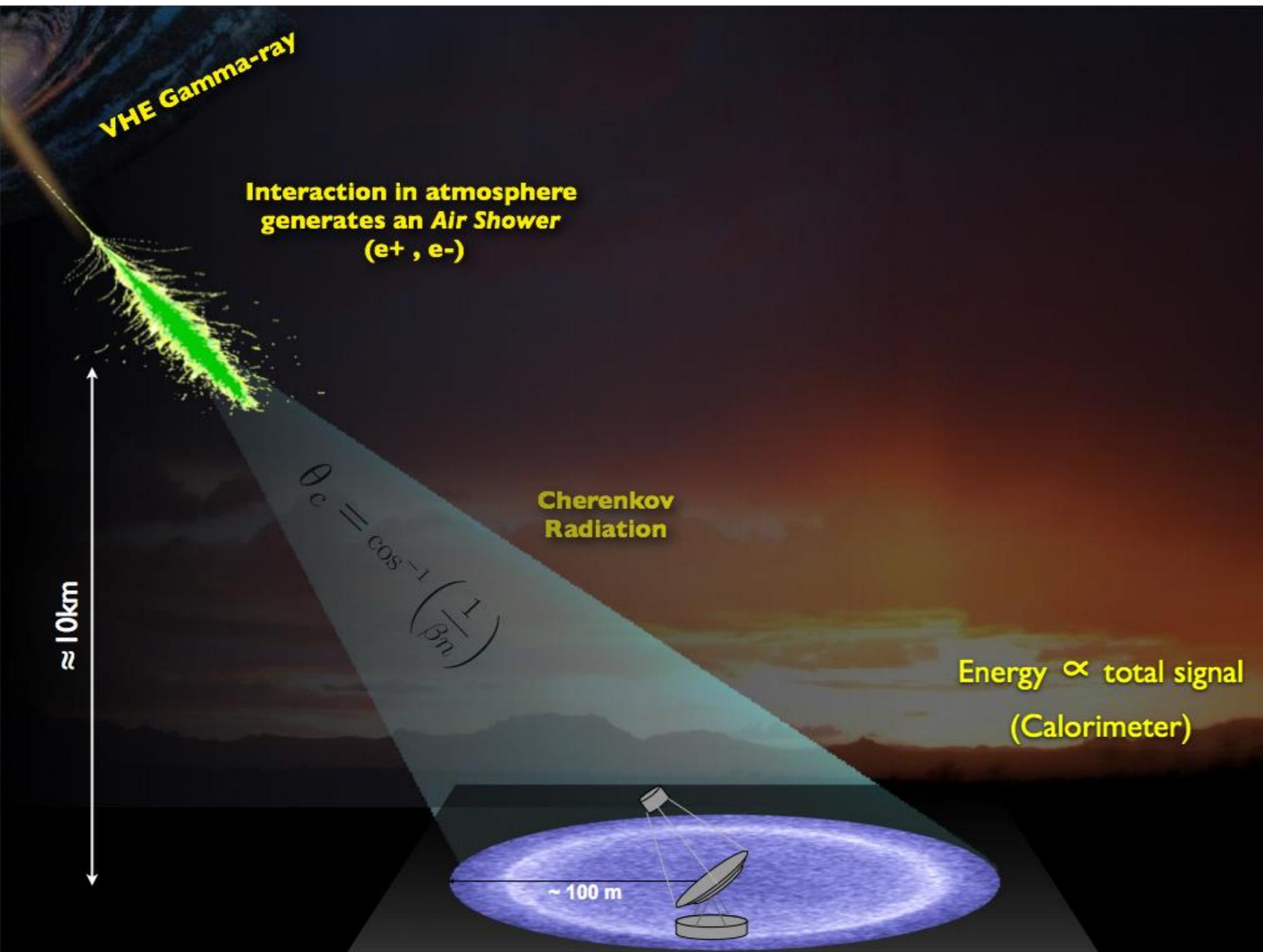
# ガンマ線の検出手法(VHE)

## Atmospheric Cherenkov Imaging Technique



電磁カスケード  
(空気シャワー)

# ガンマ線の検出手法(VHE)

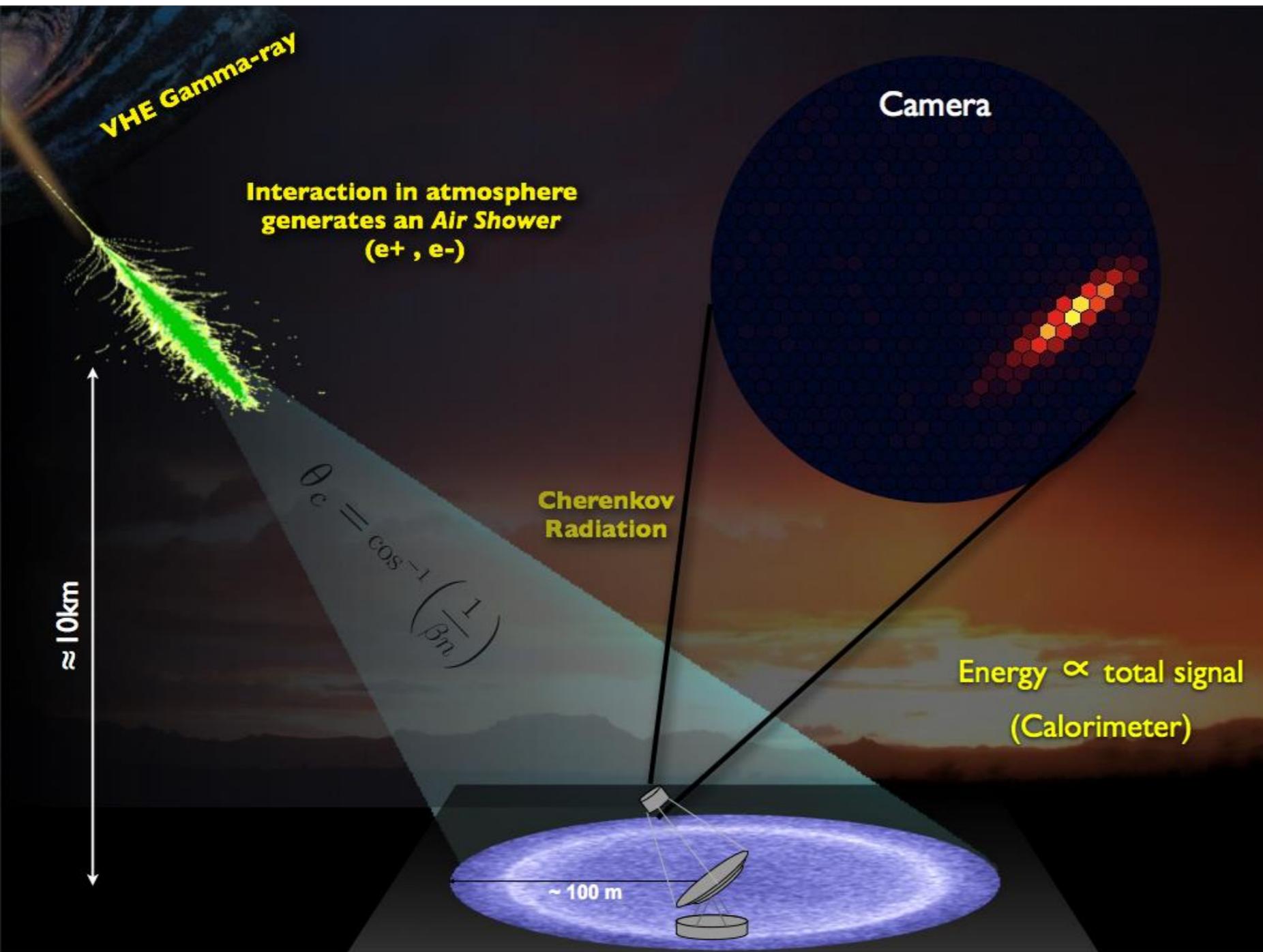


大気チェレンコフ光  
(青い光)

$\theta_c$  (チェレンコフ角)  
 $\sim 1^\circ$

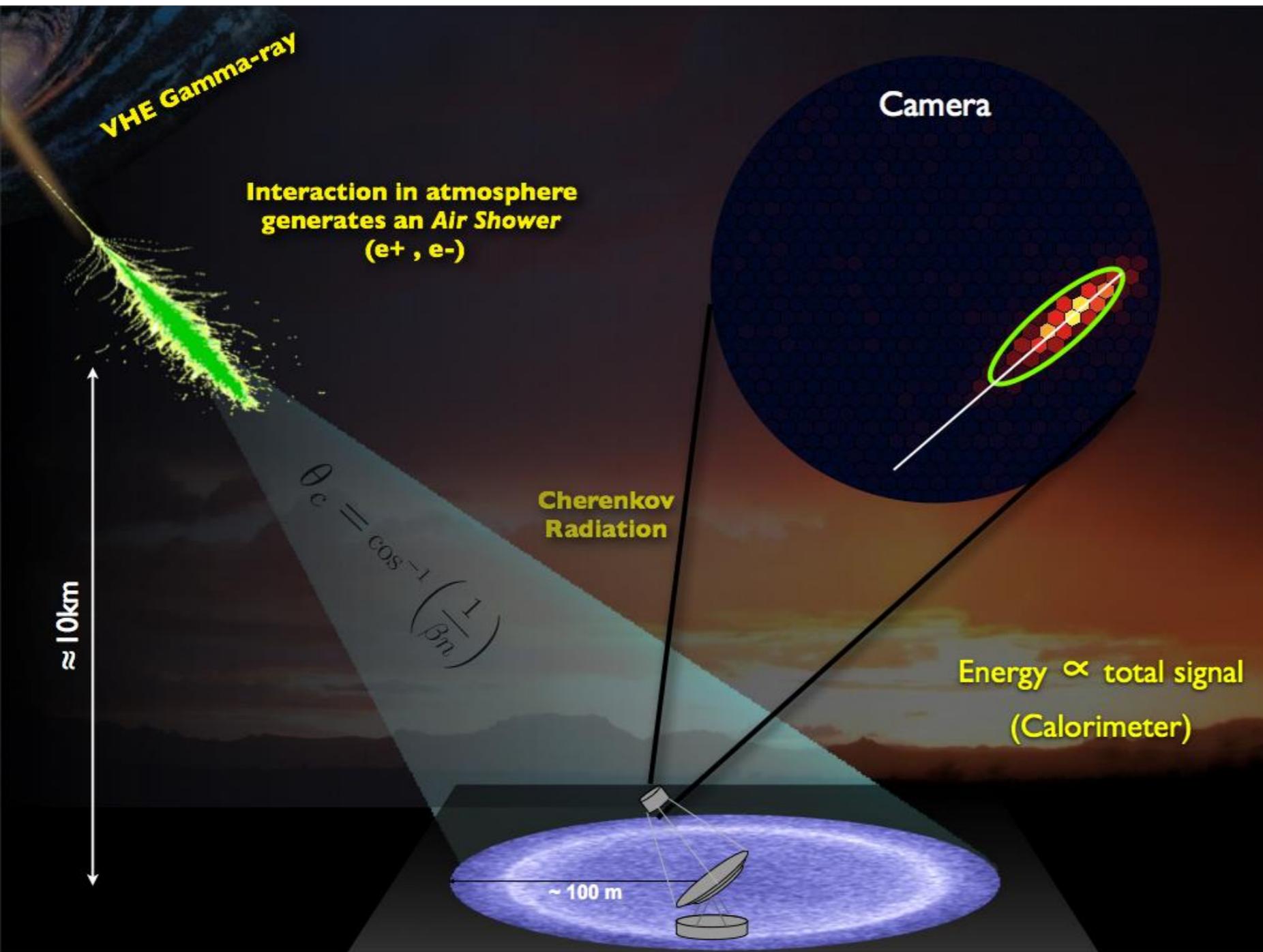
地上で $\sim 5\text{ ns}$ の  
微弱な閃光  
半径 $\sim 100\text{ m}$ の  
広がり  
 $\sim 50\text{ 光子}/\text{m}^2$   
@  $1\text{ TeV } \gamma$

# ガンマ線の検出手法(VHE)



多画素カメラで撮像

# ガンマ線の検出手法(VHE)

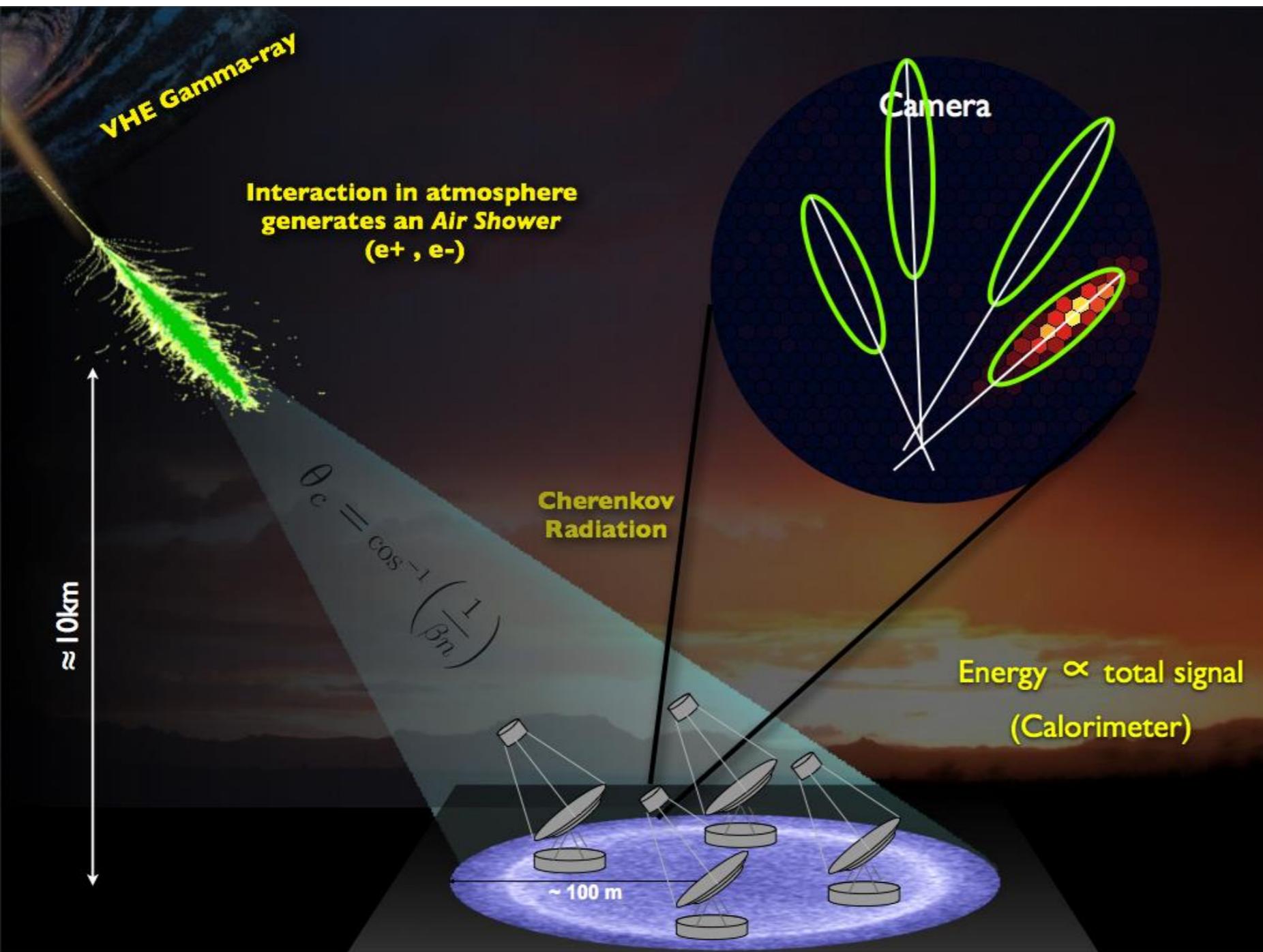


画像解析

形状から  
シャワー軸の推定  
一次粒子の推定

光量から  
エネルギーの推定

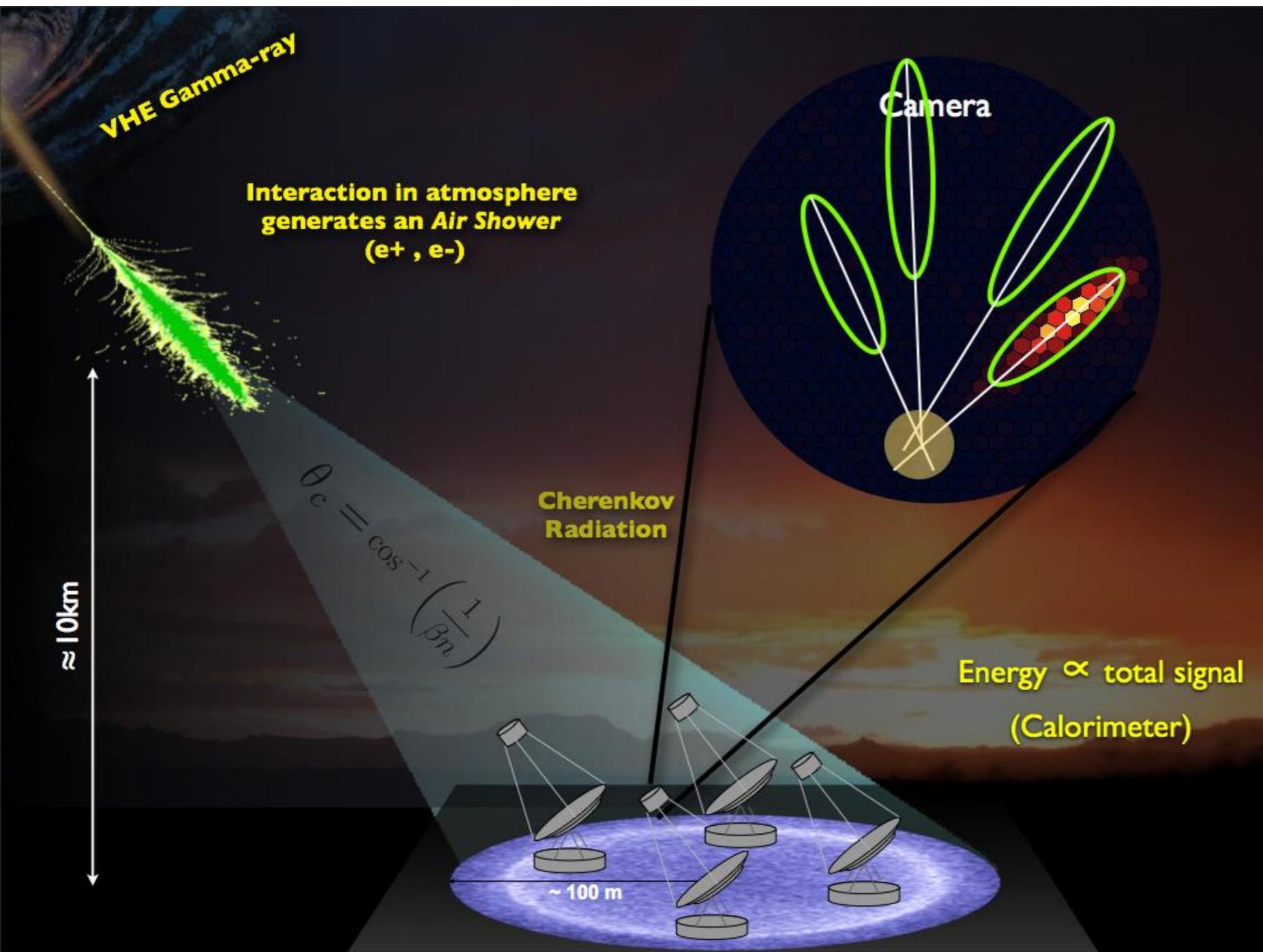
# ガンマ線の検出手法(VHE)



ステレオ観測

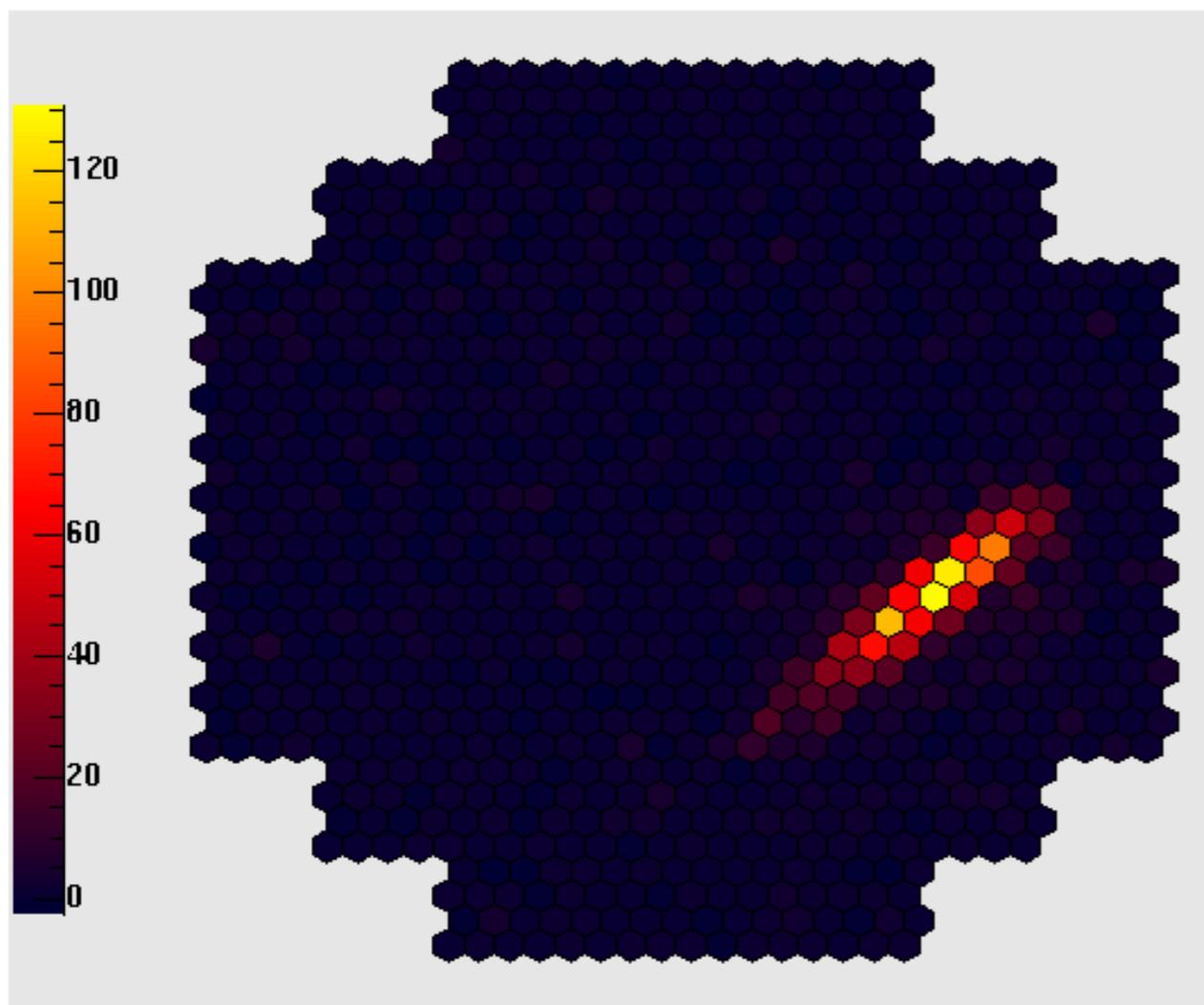
100 m程度離れた  
IACT間で  
視差を検出

# ガンマ線の検出手法(VHE)



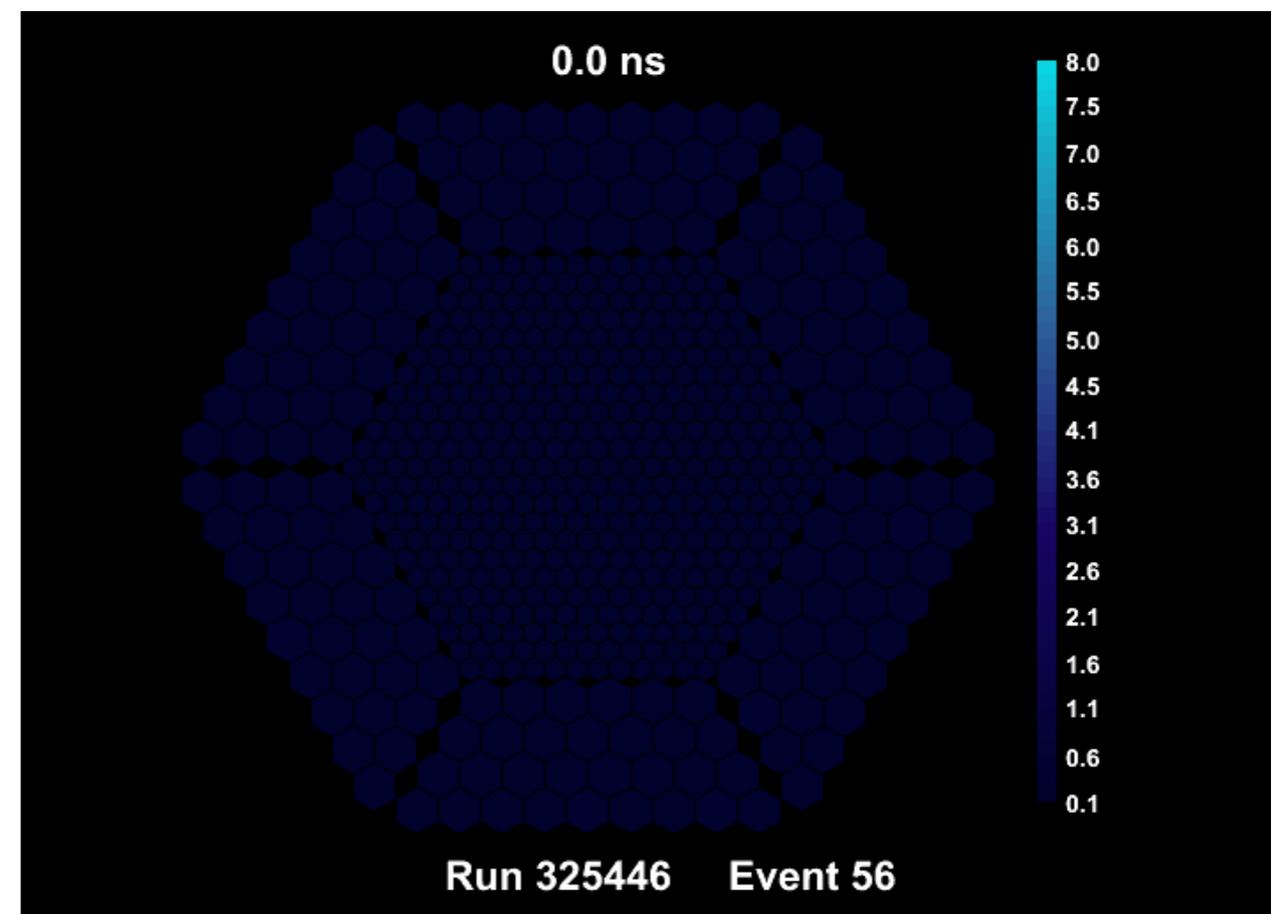
到来方向の推定

# 大気チェレンコフ光画像



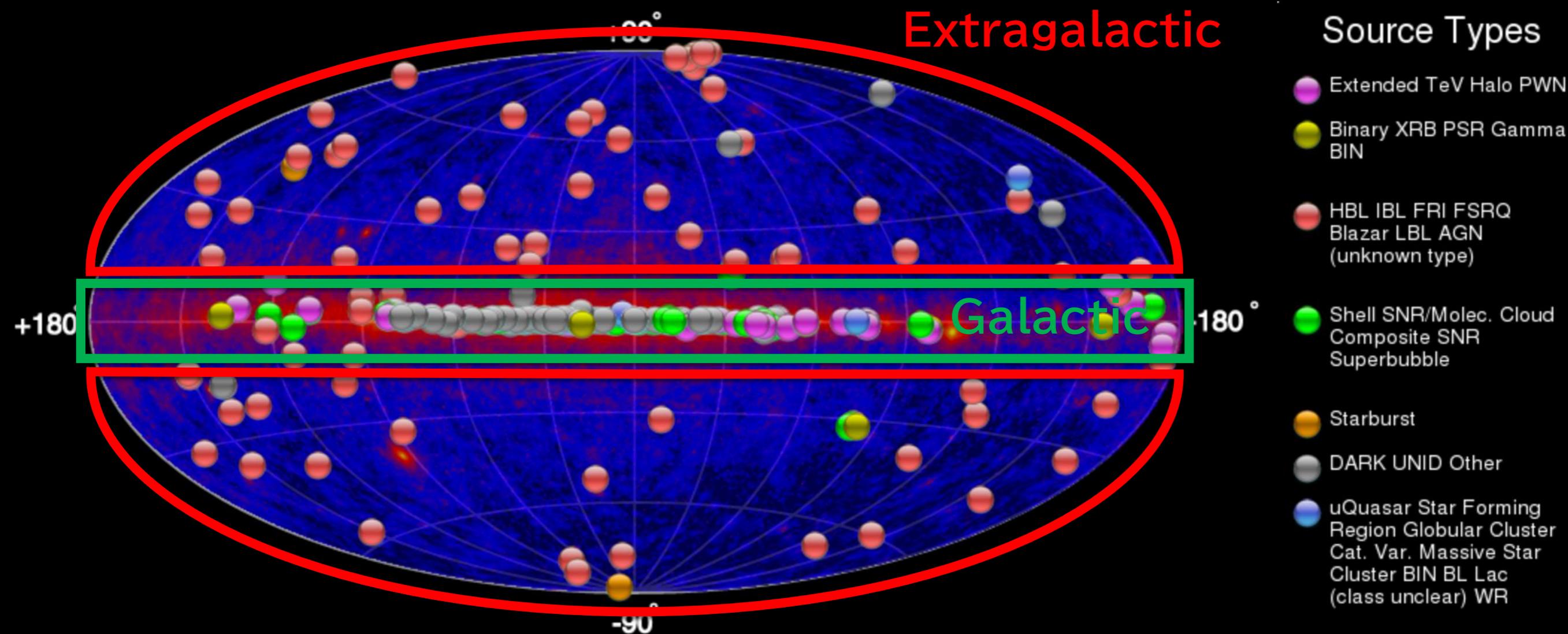
H.E.S.S.

MAGIC



# VHEガンマ線天体

VHE gamma-ray sources (>100 GeV)

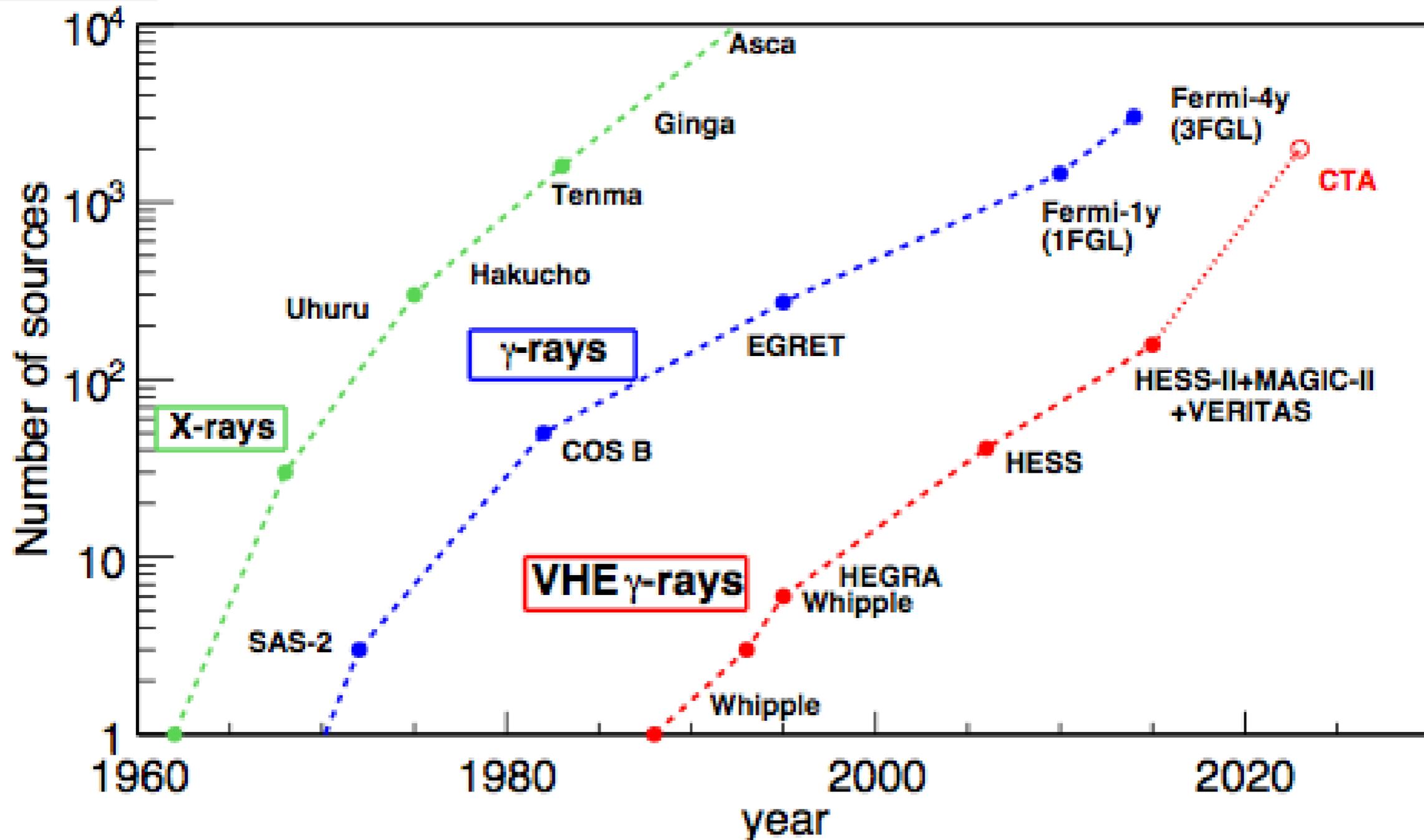


- ・ 約300天体(2026年時点)
- ・ 大部分が大気チェレンコフ望遠鏡による発見

**Fundamental:**  
基礎物理・宇宙論

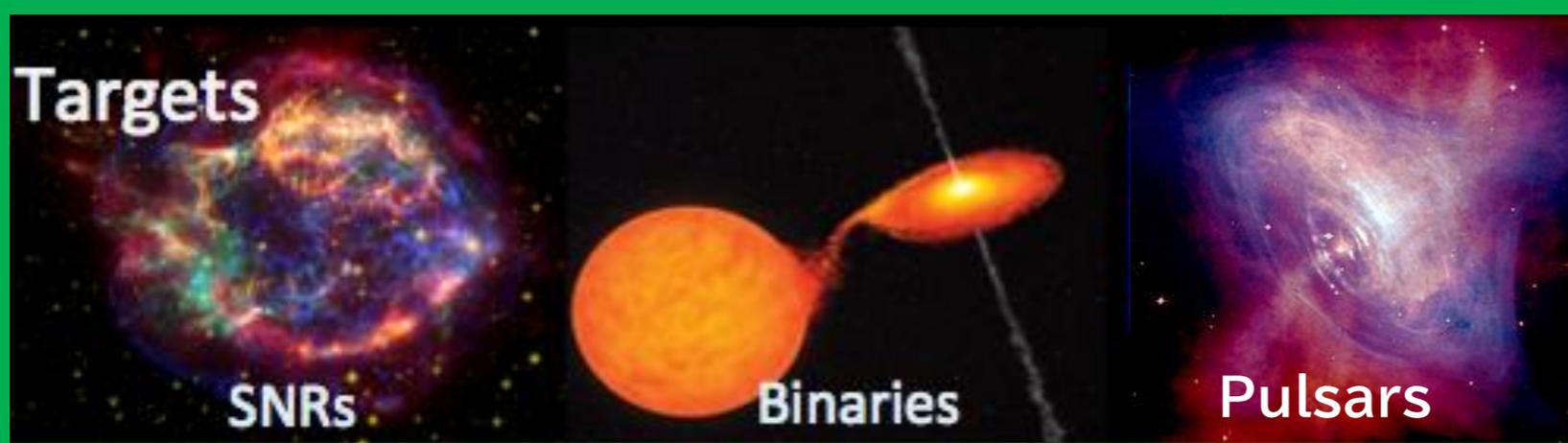
# 検出天体数の推移

Kifune plot



# ガンマ線観測で何がわかるか

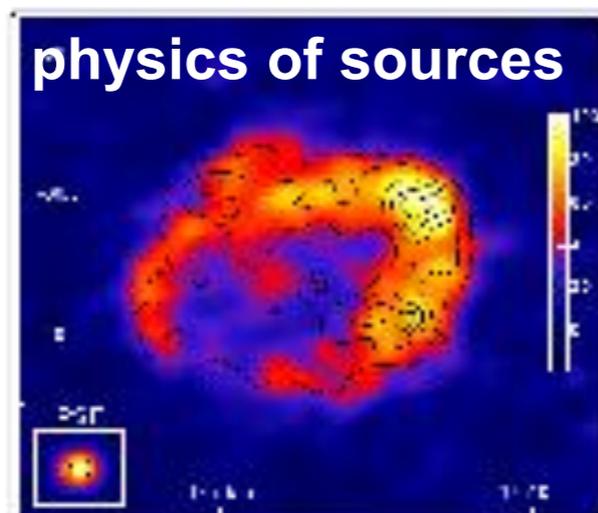
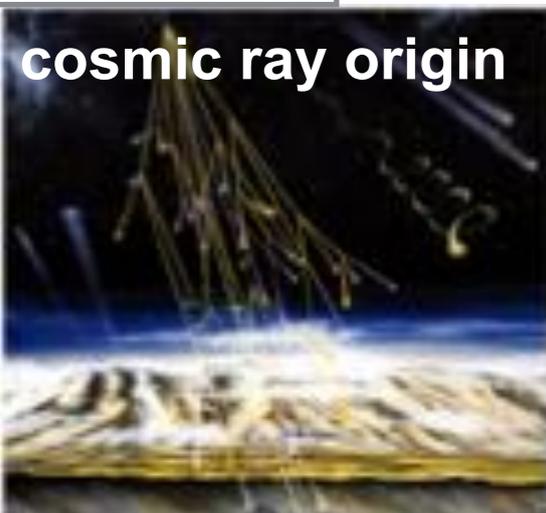
## Galactic



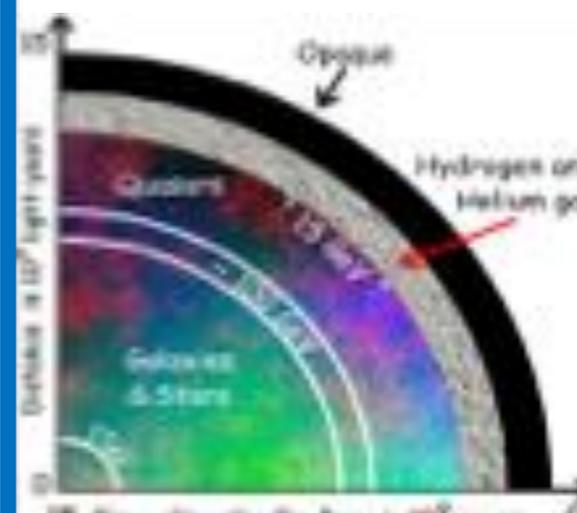
## Extragalactic



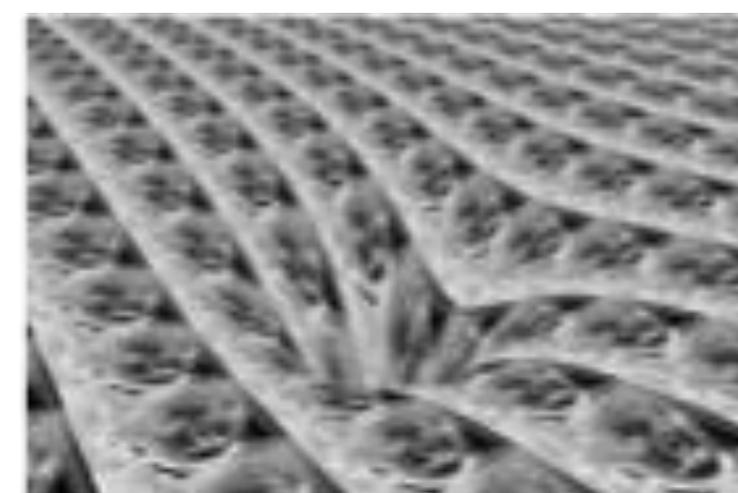
## Objectives



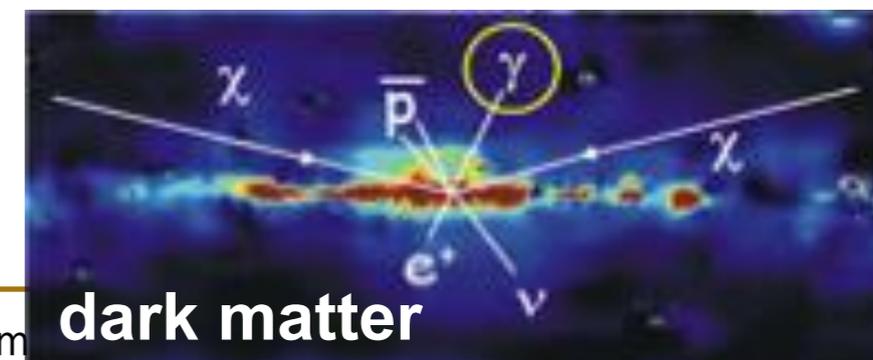
## cosmology



## space and time



## Fundamental

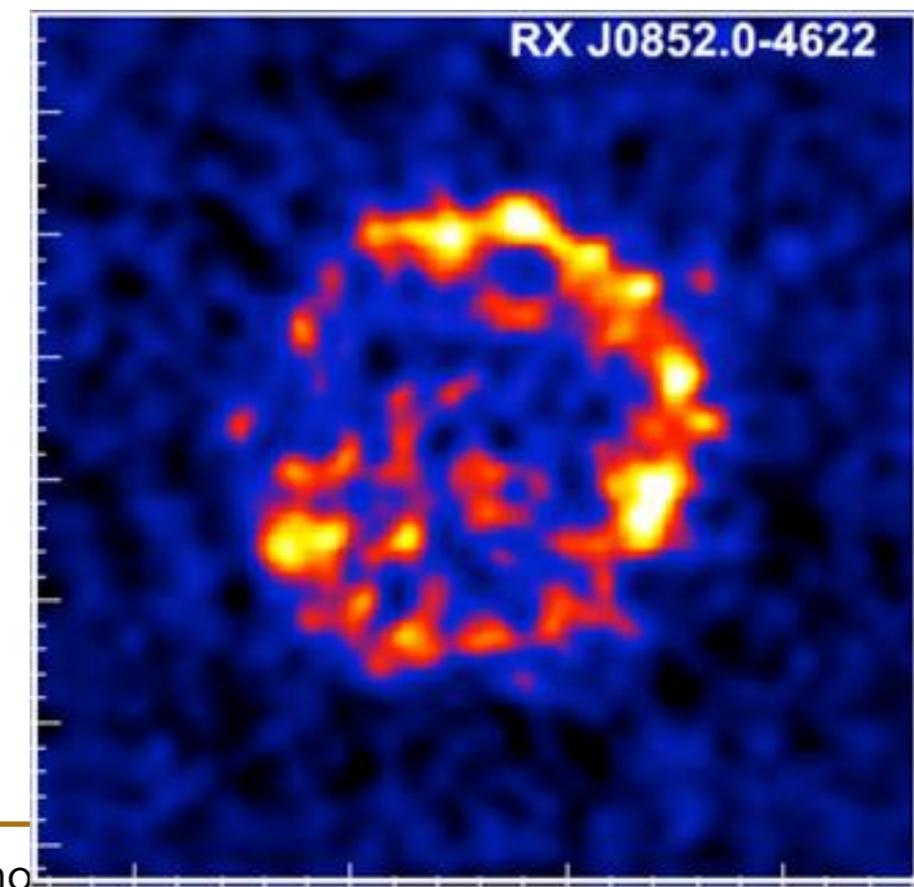
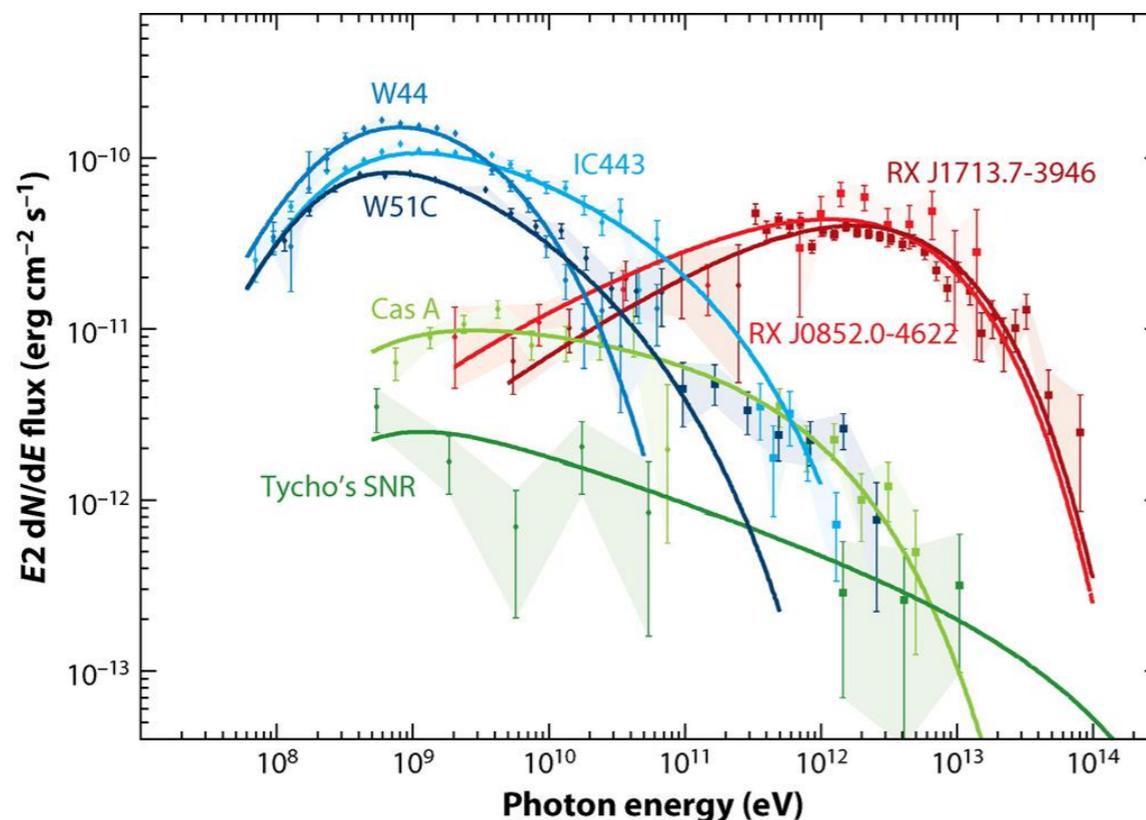
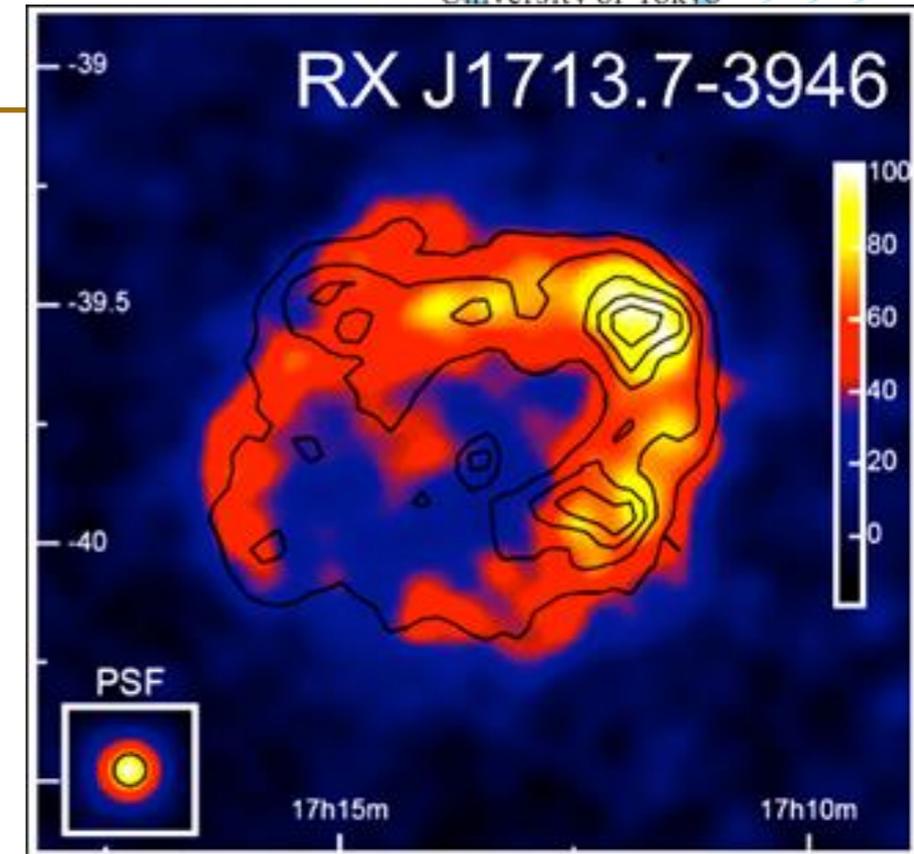


# ガンマ線観測で何がわかるか

- **宇宙線の起源:**
  - 宇宙線の加速現場近傍でガンマ線が放射。
  - ガンマ線は銀河内外の磁場によって曲げられない。生成場所を特定できる。
- **宇宙の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寄与:**
  - 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を辿れる。
  - 暗黒物質の有力候補(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。

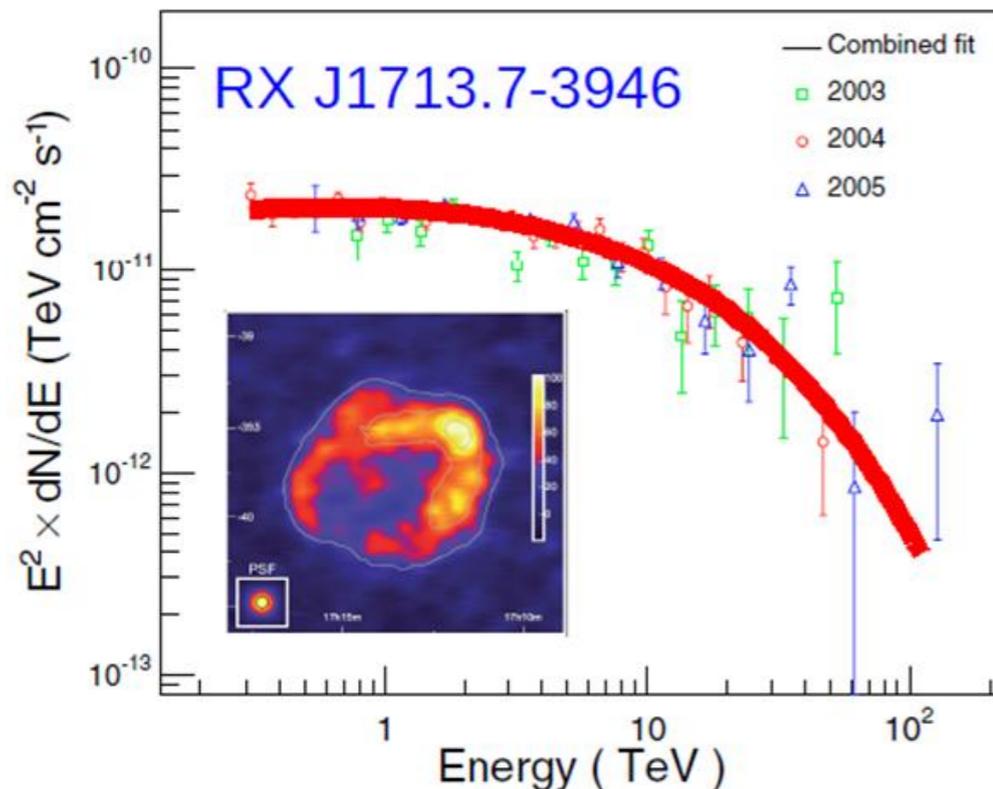
# 超新星残骸：宇宙線の起源？ G

- 宇宙線業界長年の謎
  - 宇宙線(原子核)が磁場により攪乱される
- シェルからVHEガンマ線を検出
  - SNRは粒子加速源！
- 「パイオンバンブ」の検出
  - 低エネルギーでは陽子起源らしい



# 超新星残骸：宇宙線の起源？ G

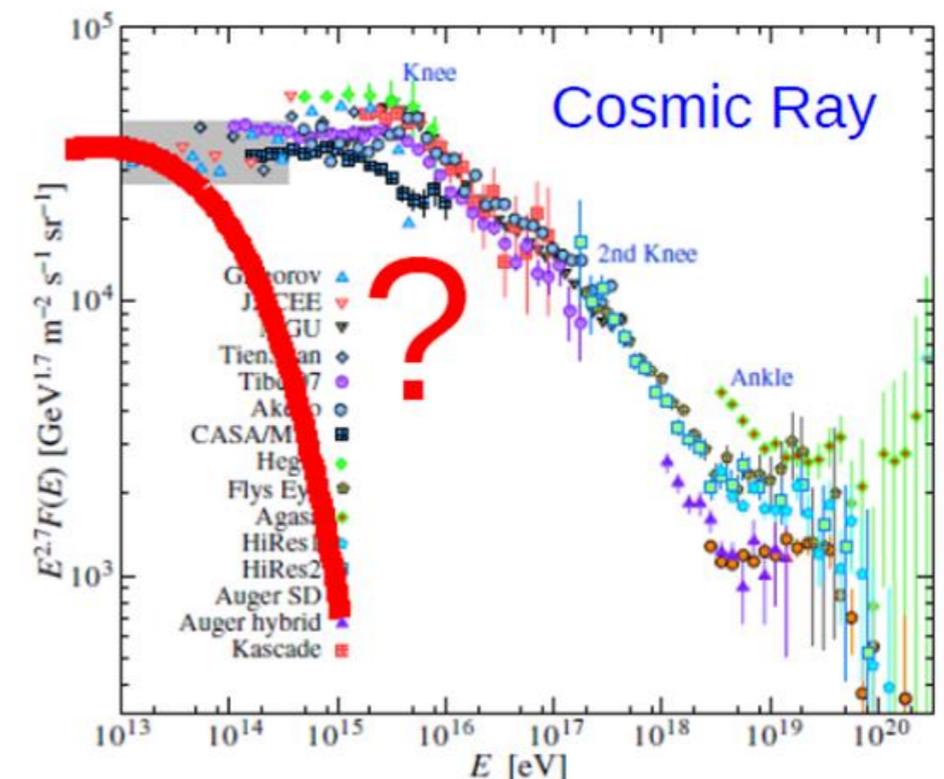
- 残された課題：
  - 100 TeV以上まで陽子起源なのか？
  - “Knee”まで説明できる天体(PeVatron)は存在するのか？
- さらに高精度な観測が必要



$$\Gamma' = \Gamma + 0.7$$



$$E' = E \times 10$$

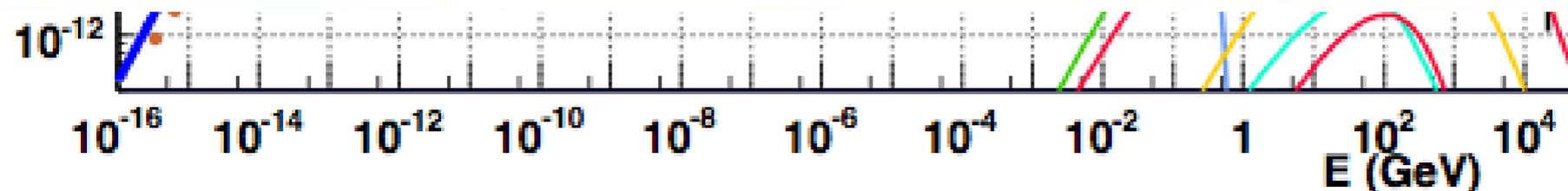
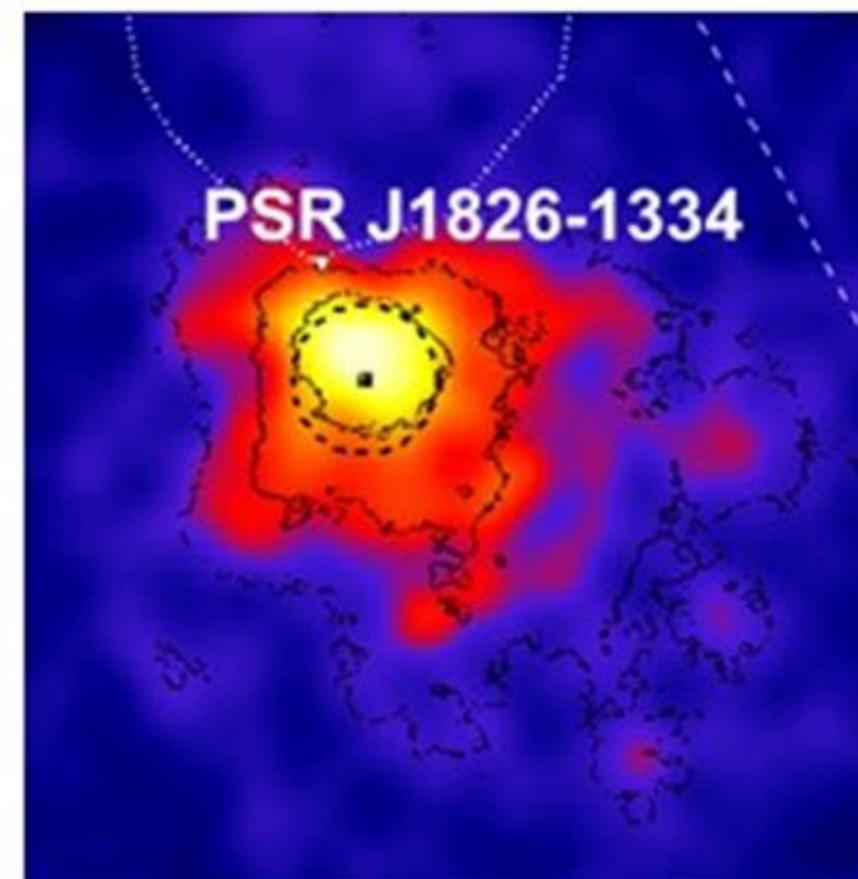
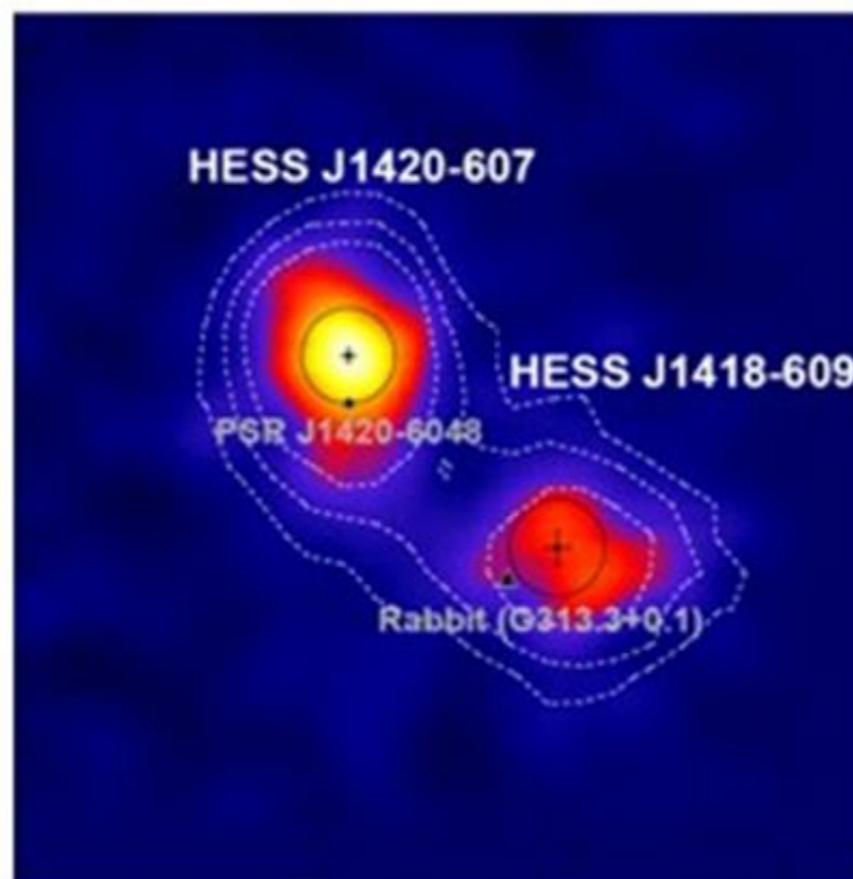
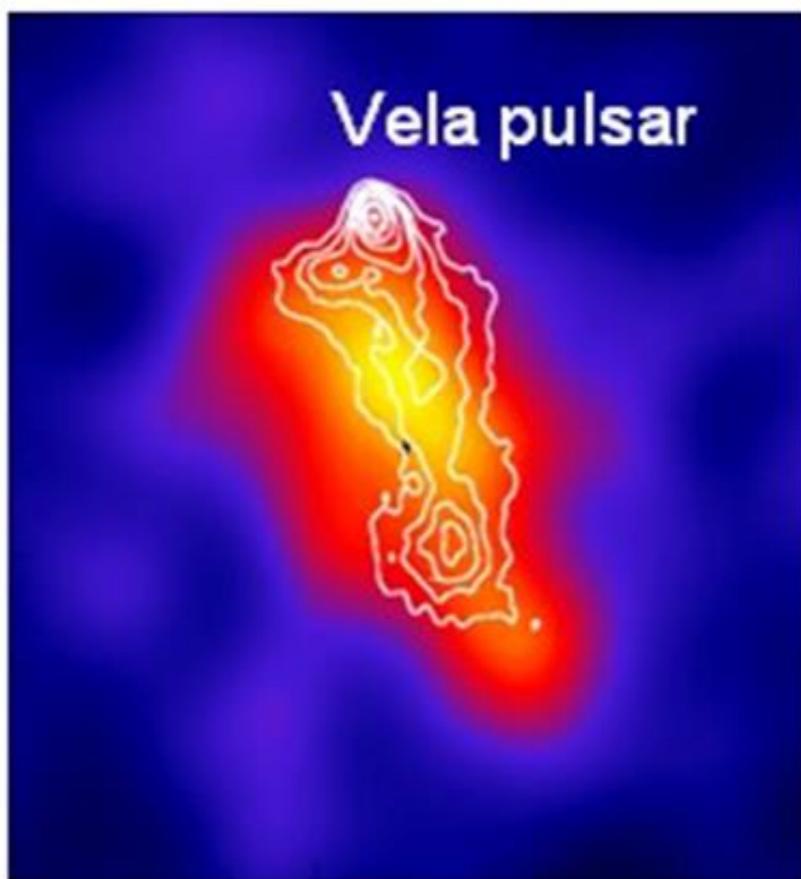
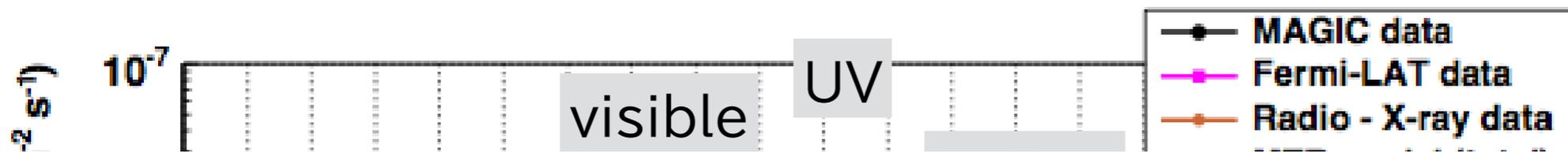


# パルサー風星雲<sup>G</sup>

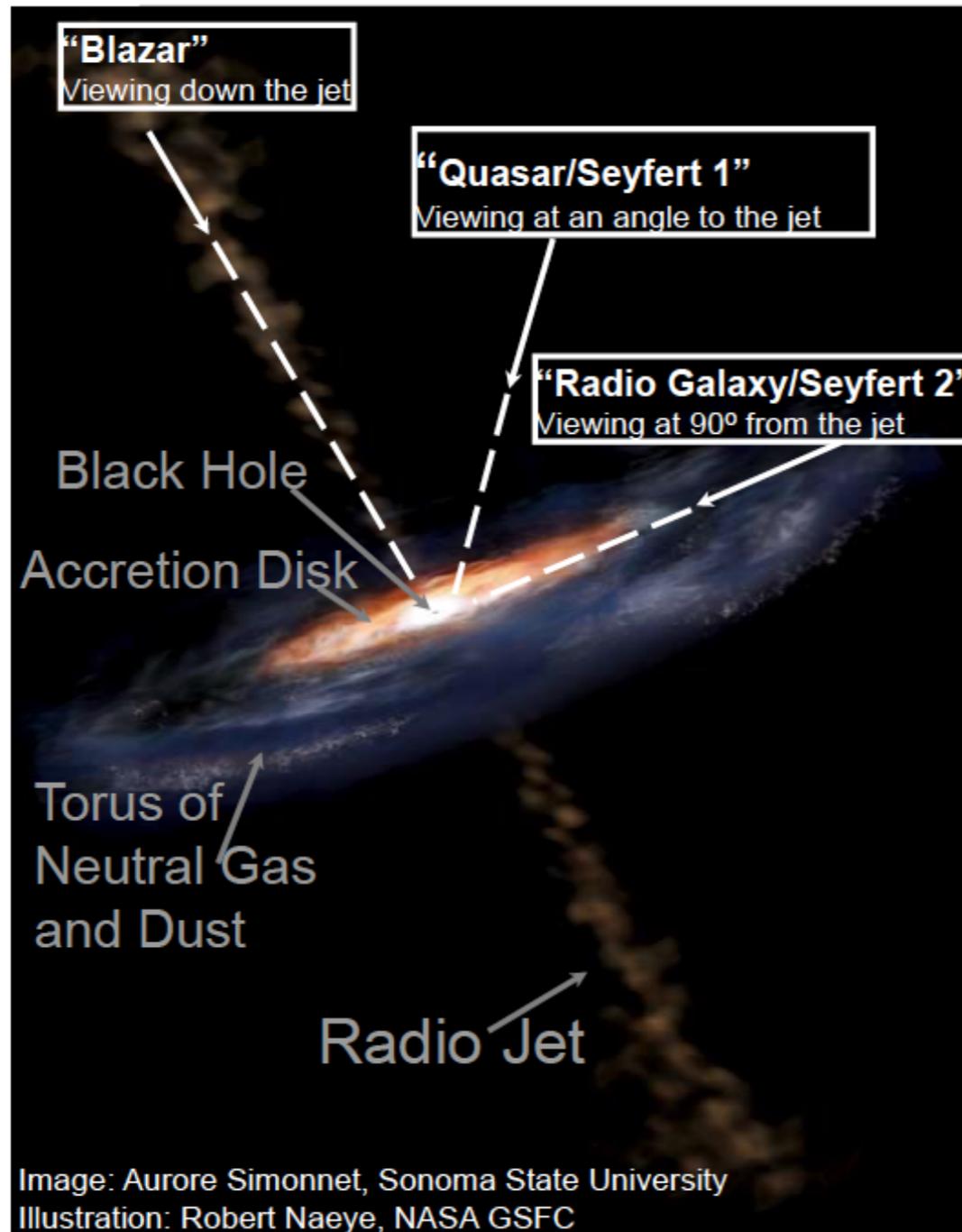
## Crab Nebula



非熱的で、20桁にもわたる帯域で放射



## 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:

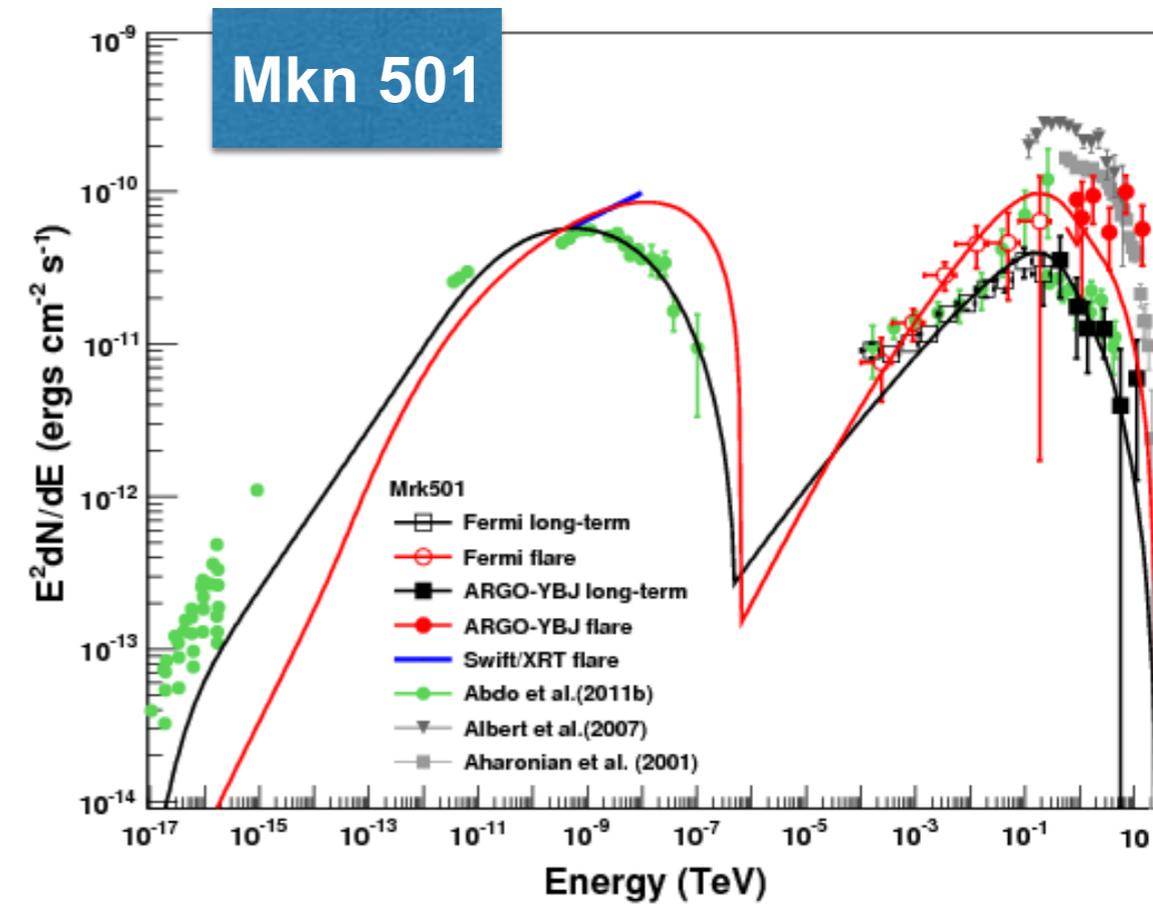
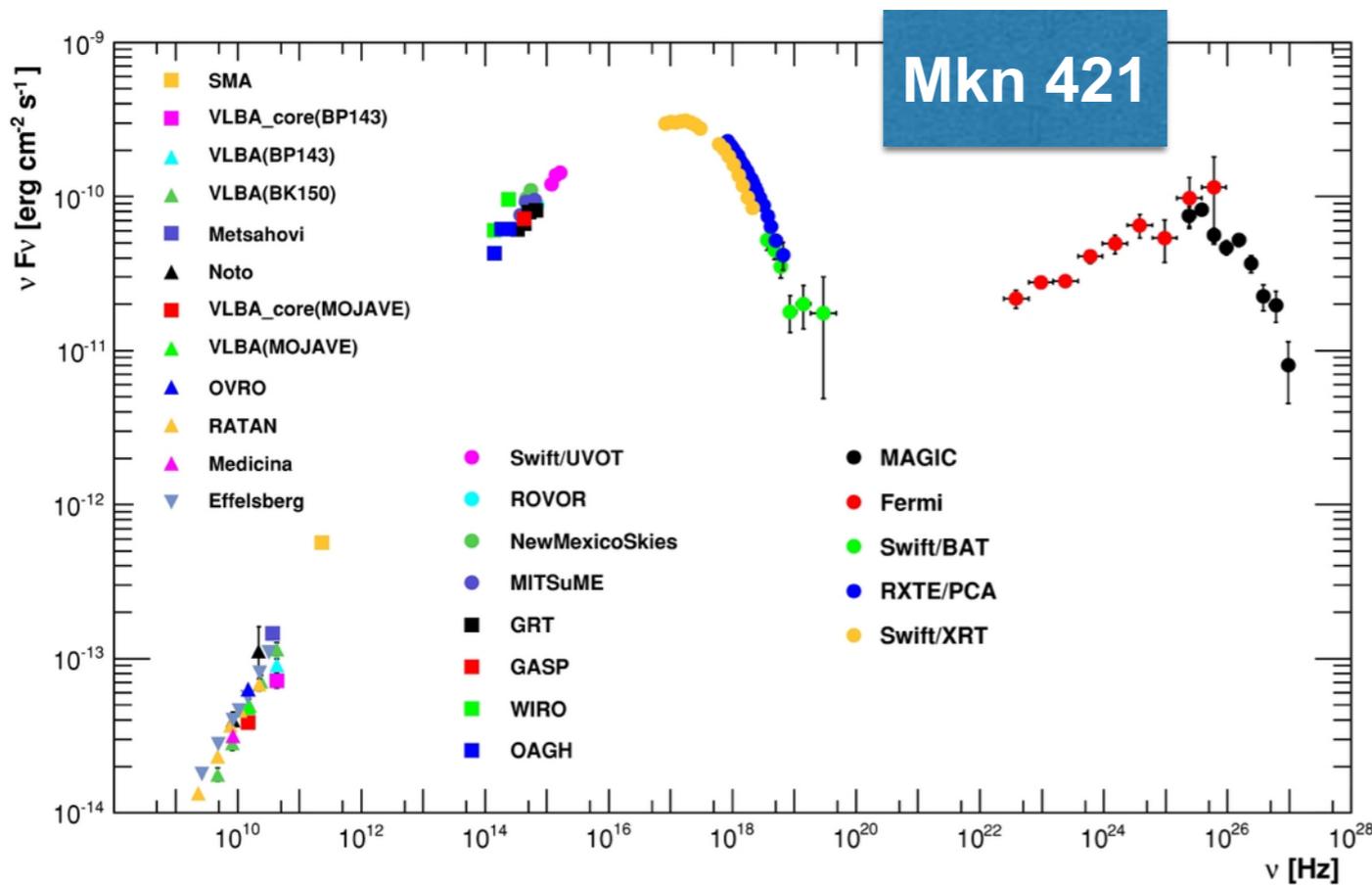
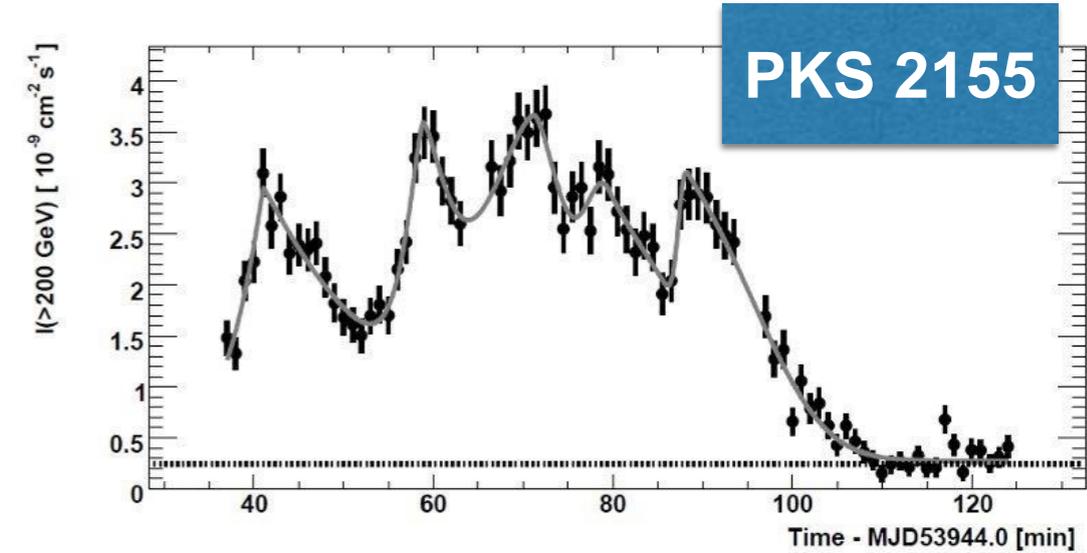
- Blazars
  - Jets aligned with line of sight

But also radio galaxies (e.g M87)

- Jet viewed from the side

# 活動銀河核(ブレイザー)E

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

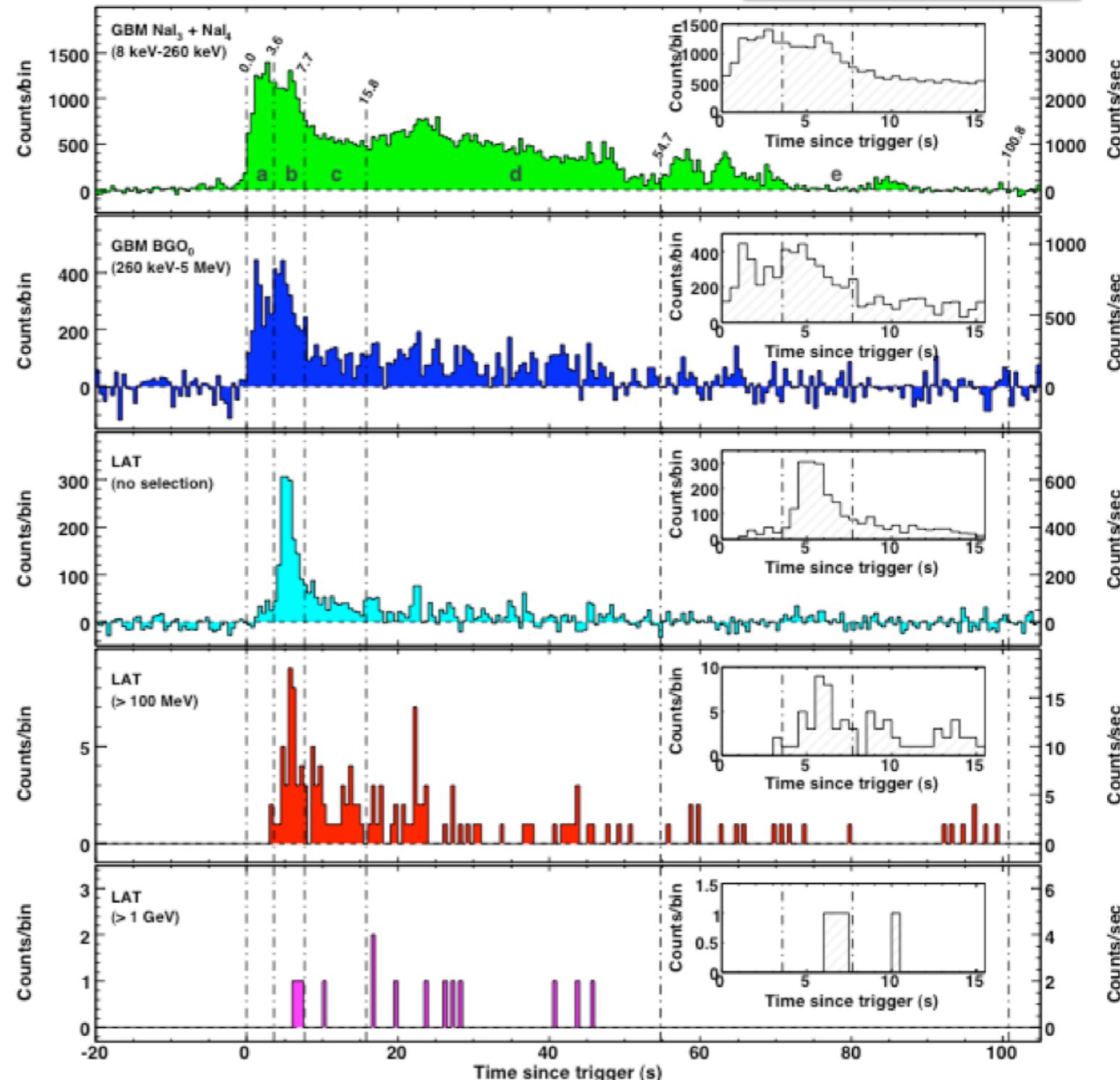


# ガンマ線バースト<sup>E</sup>

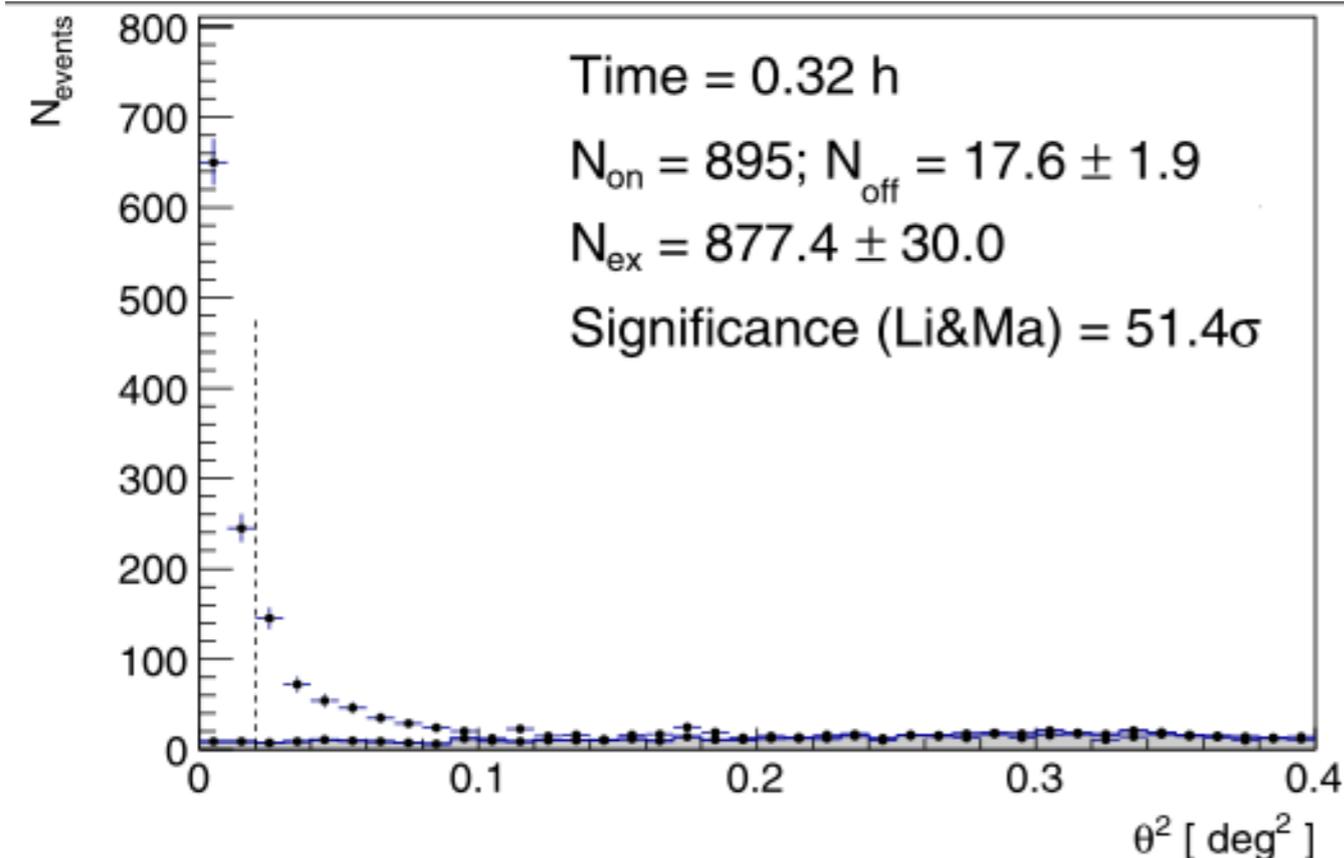
GRB 080916C

- 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.

$$z = 4.35 \pm 0.15$$



# GRB 190114C<sup>E</sup>



Extended Data Fig. 2 | Significance of the  $\gamma$ -ray signal between  $T_0 + 62$  s and  $T_0 + 1,227$  s for GRB 190114C. Distribution of the squared angular distance,  $\theta^2$ , for the MAGIC data (points) and background events (grey shaded area).  $\theta^2$  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  $\theta^2$ . This defines the signal region, where the number of events coming from the source ( $N_{\text{on}}$ ) and from the background ( $N_{\text{off}}$ ) are computed. The errors for 'on' events are derived from Poissonian statistics. From  $N_{\text{on}}$  and  $N_{\text{off}}$ , the number of excess events ( $N_{\text{ex}}$ ) is computed. The significance is calculated using the Li & Ma method<sup>12</sup>.



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

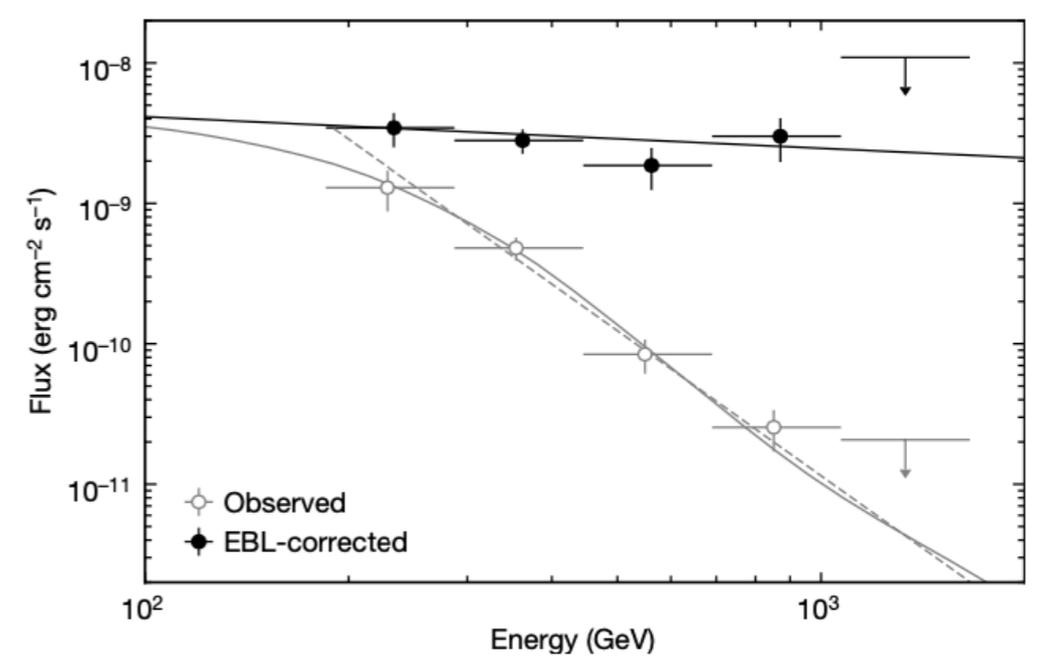


Fig. 2 | Spectrum above 0.2 TeV averaged over the period between  $T_0 + 62$  s and  $T_0 + 2,454$  s for GRB 190114C. Spectral-energy distributions for the

# 暗黒物質対消滅<sup>F</sup>

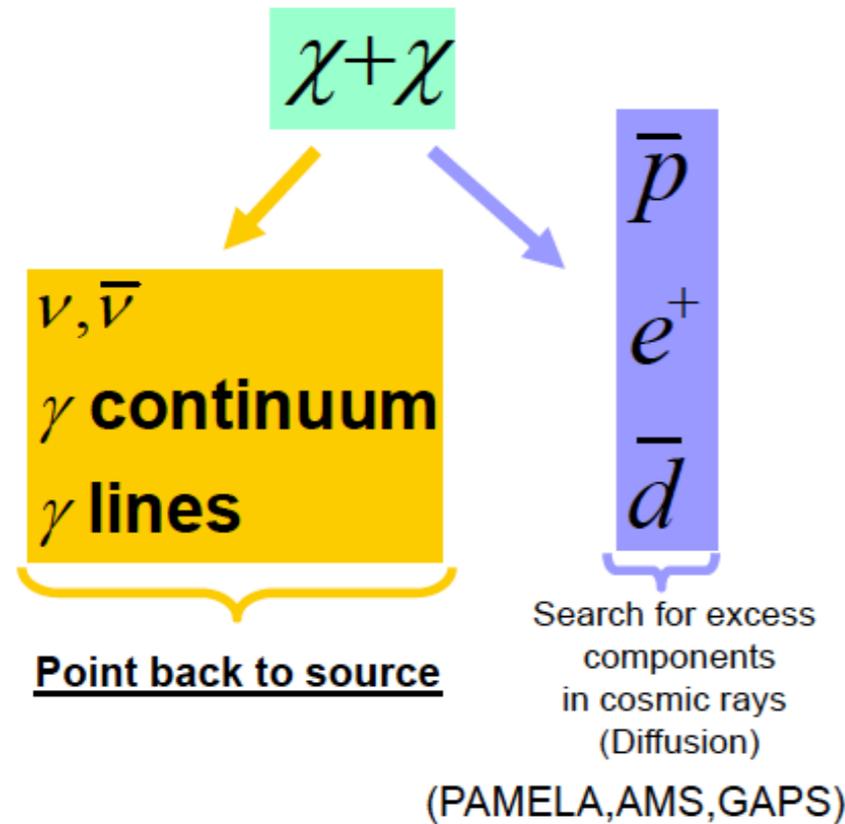
## Search for Cold Dark Matter

Hypothesis: DM = WIMPs

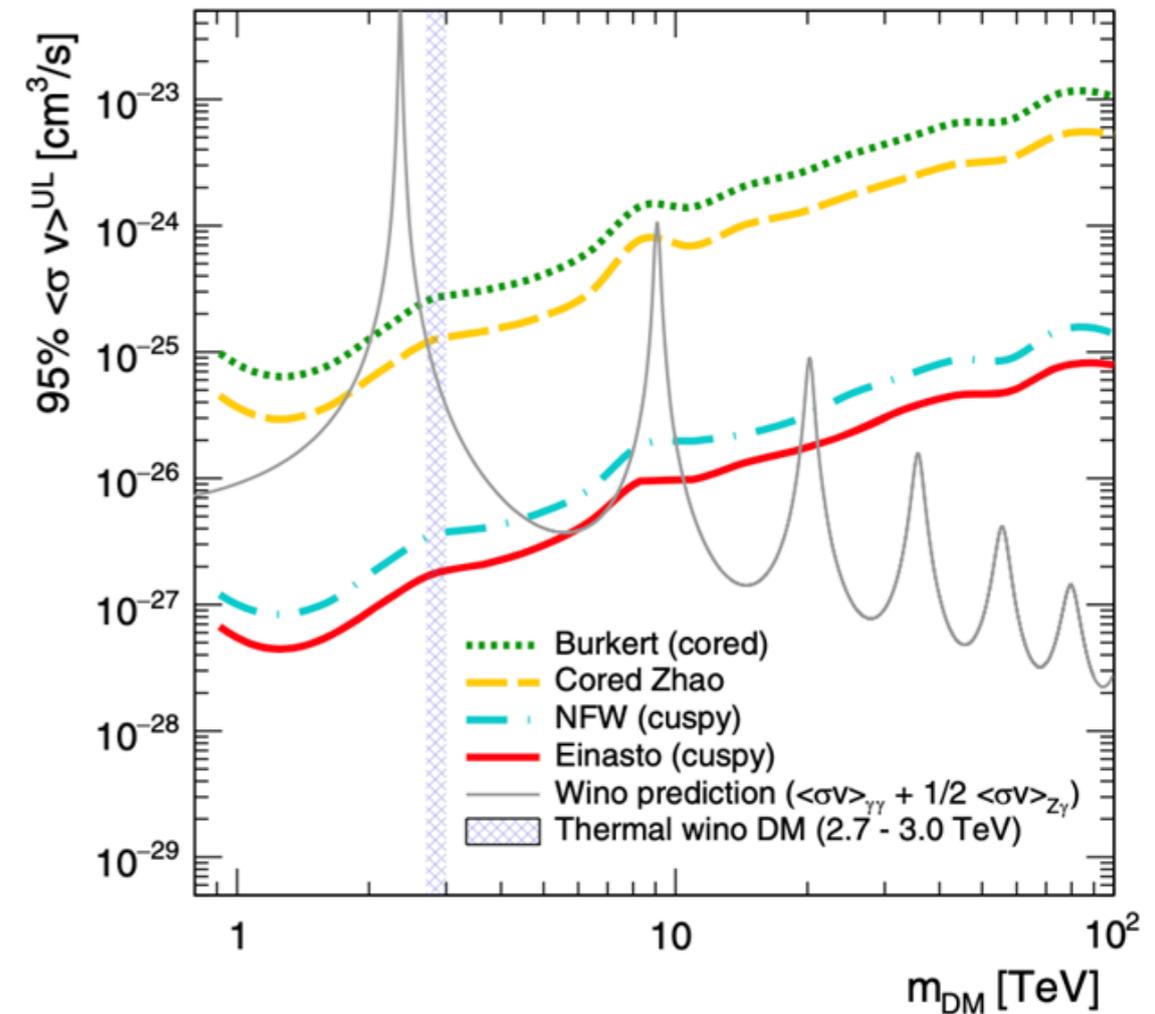
- Indirect detection of WIMP annihilation  $\rightarrow \gamma, \nu$  etc.

Target regions with:

- Favorable DM distributions
- Large mass/light ratio



MAGIC U.L. (2023)  
Line Search from G.C.



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

# Next Big Step: Cherenkov Telescope Array

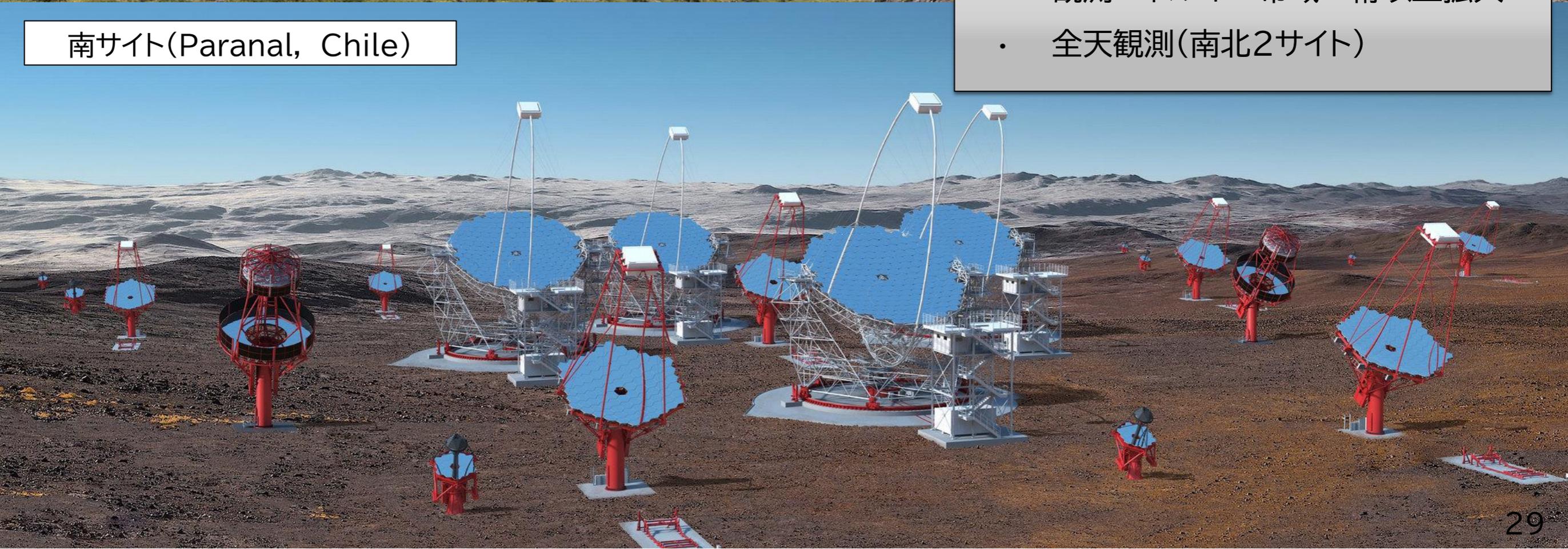


北サイト(La Palma, Spain)



- ・ 観測感度一桁向上
- ・ 観測エネルギー帯域一桁以上拡大
- ・ 全天観測(南北2サイト)

南サイト(Paranal, Chile)

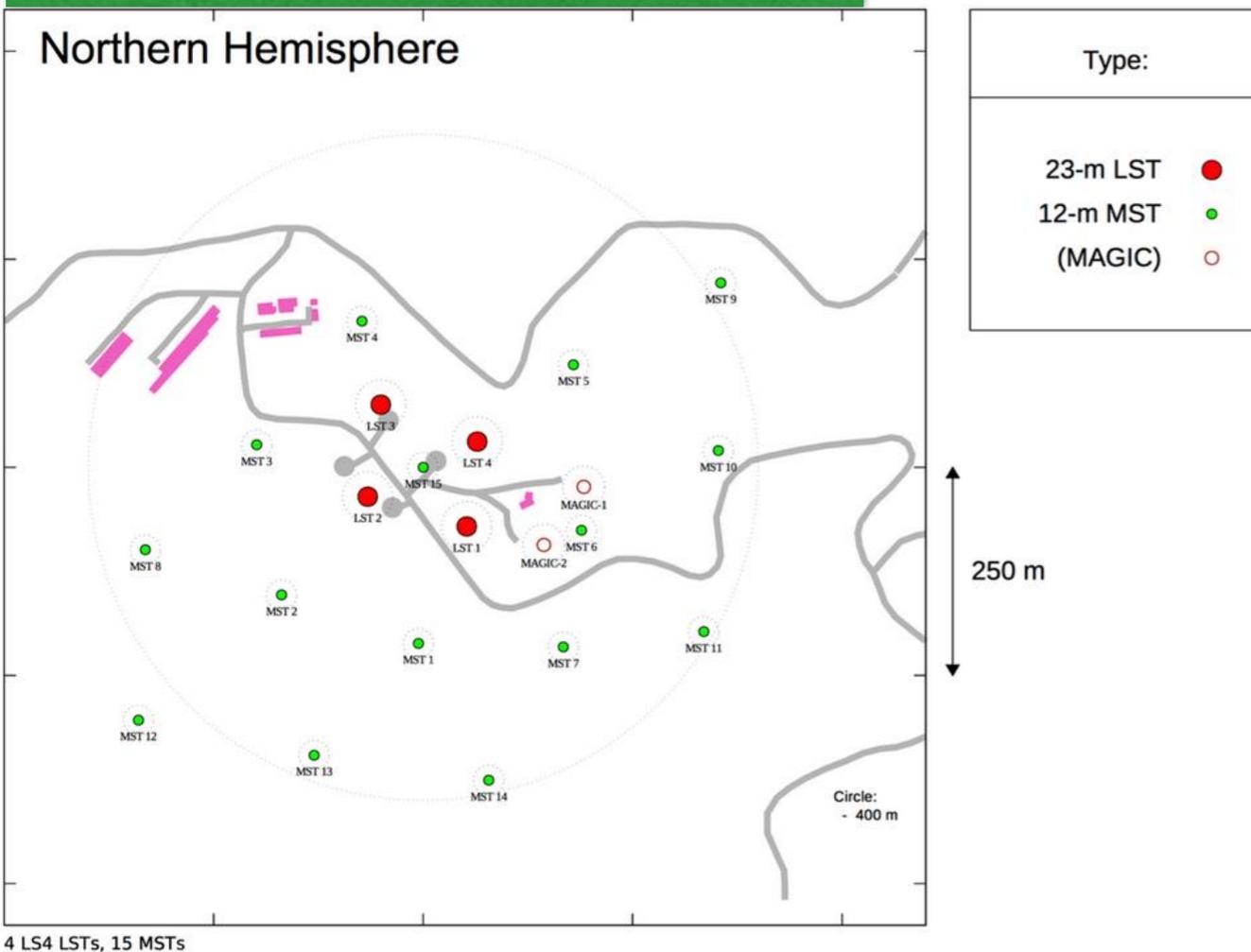


# CTAO: Array Layouts



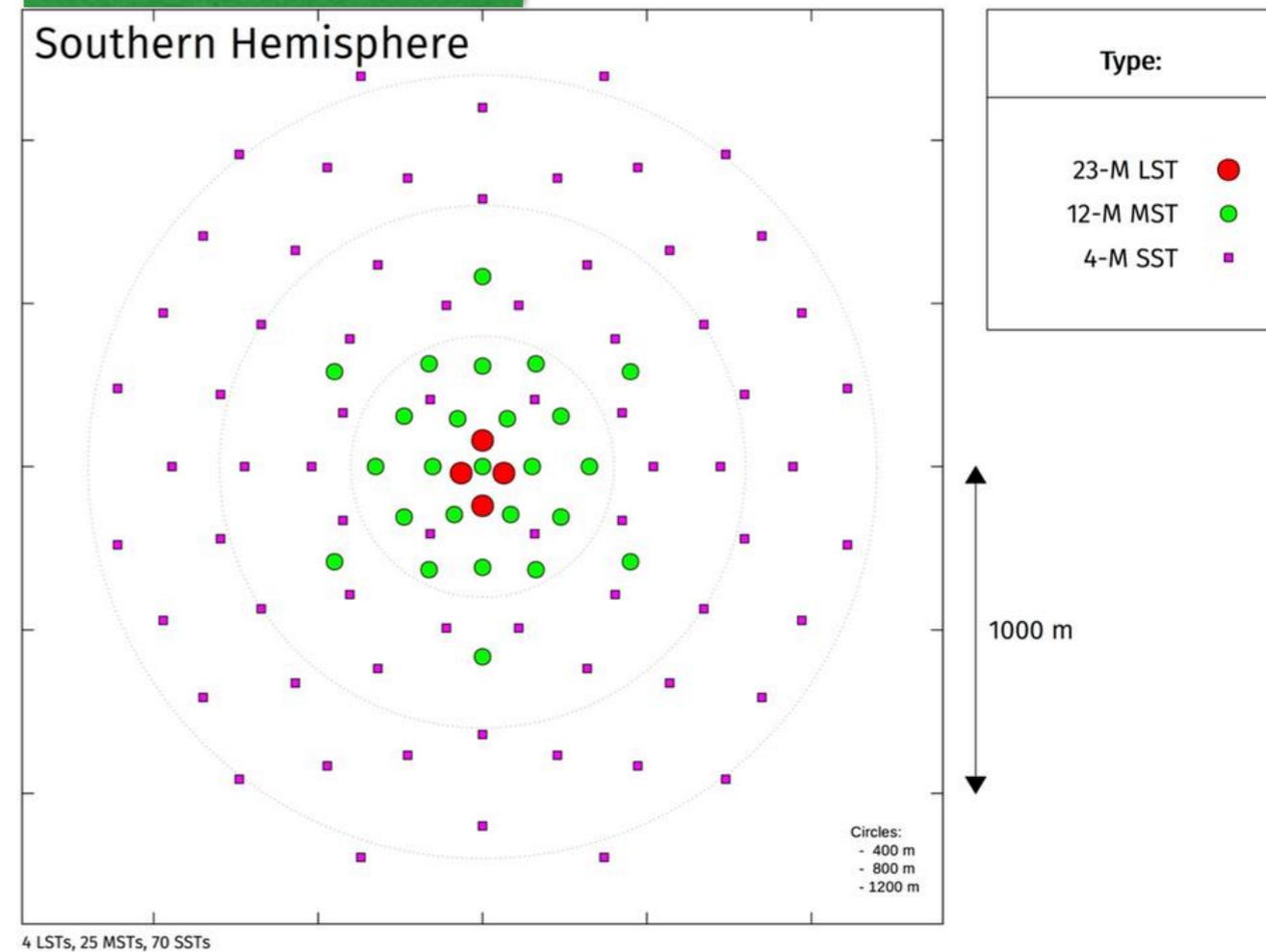
## 北サイト

### La Palma, Canary islands



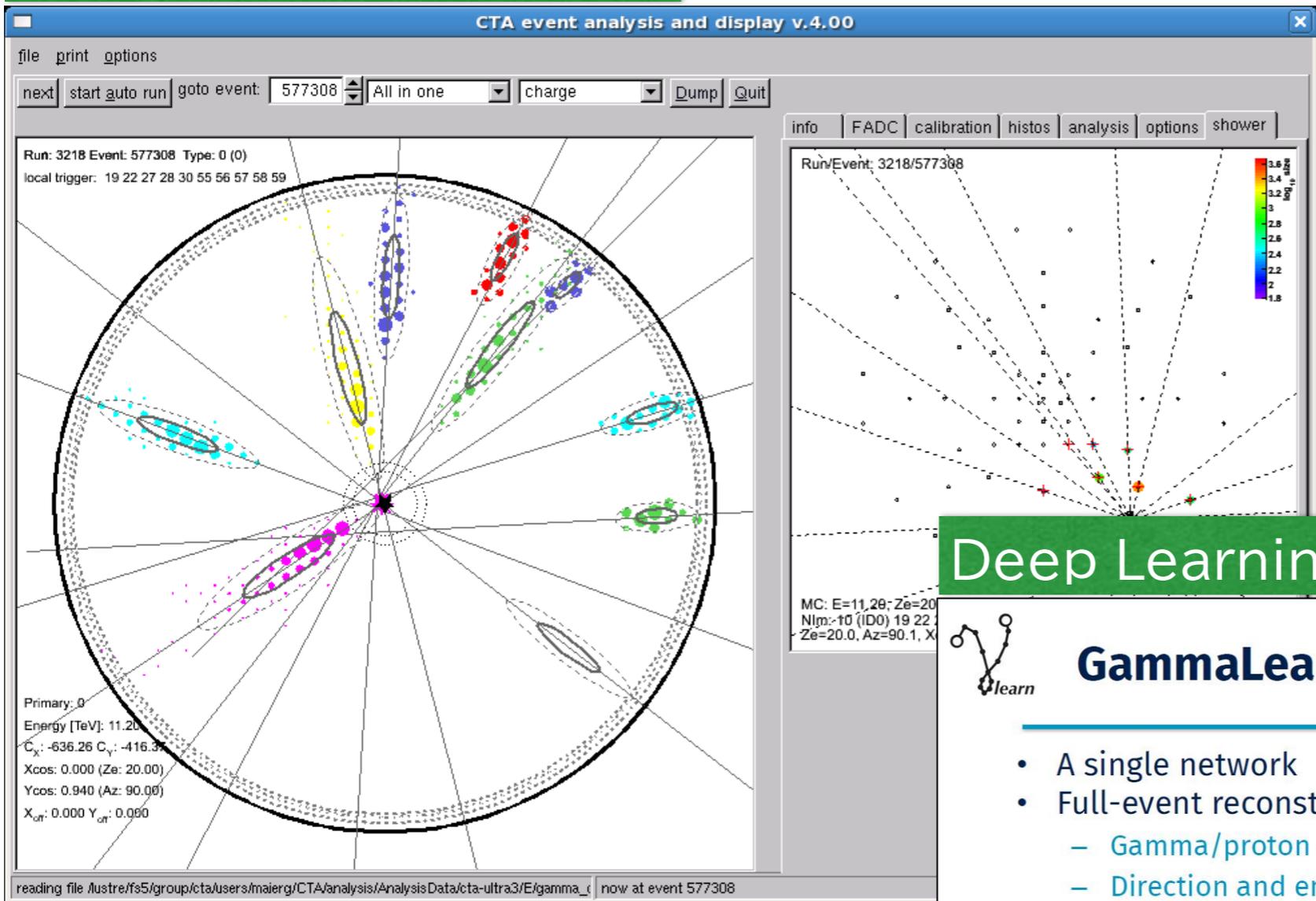
## 南サイト

### Paranal, Chile



# CTAO: Analysis Techniques

## Monte Carlo Simulation



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？

## Deep Learning

Vuillaume+ 2021

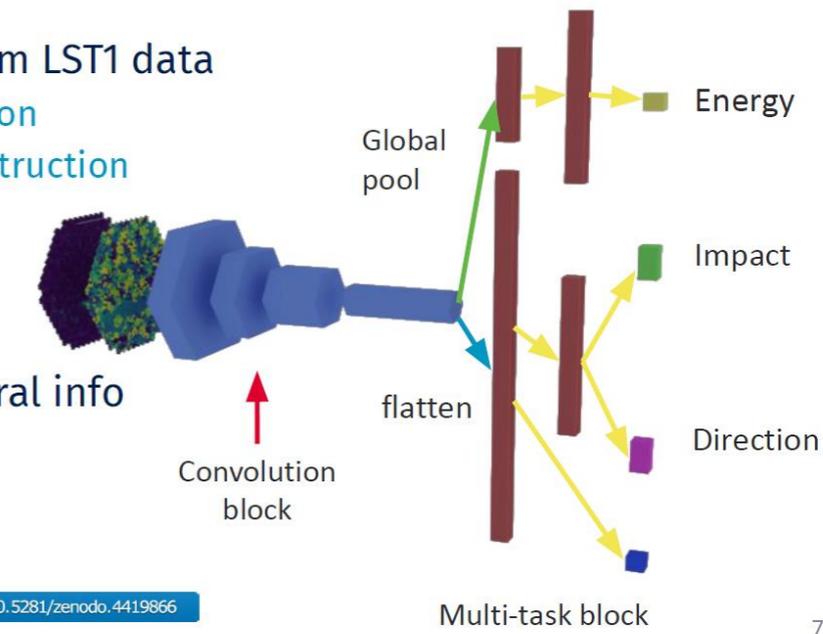


### GammaLearn : $\gamma$ -PhysNet



- 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

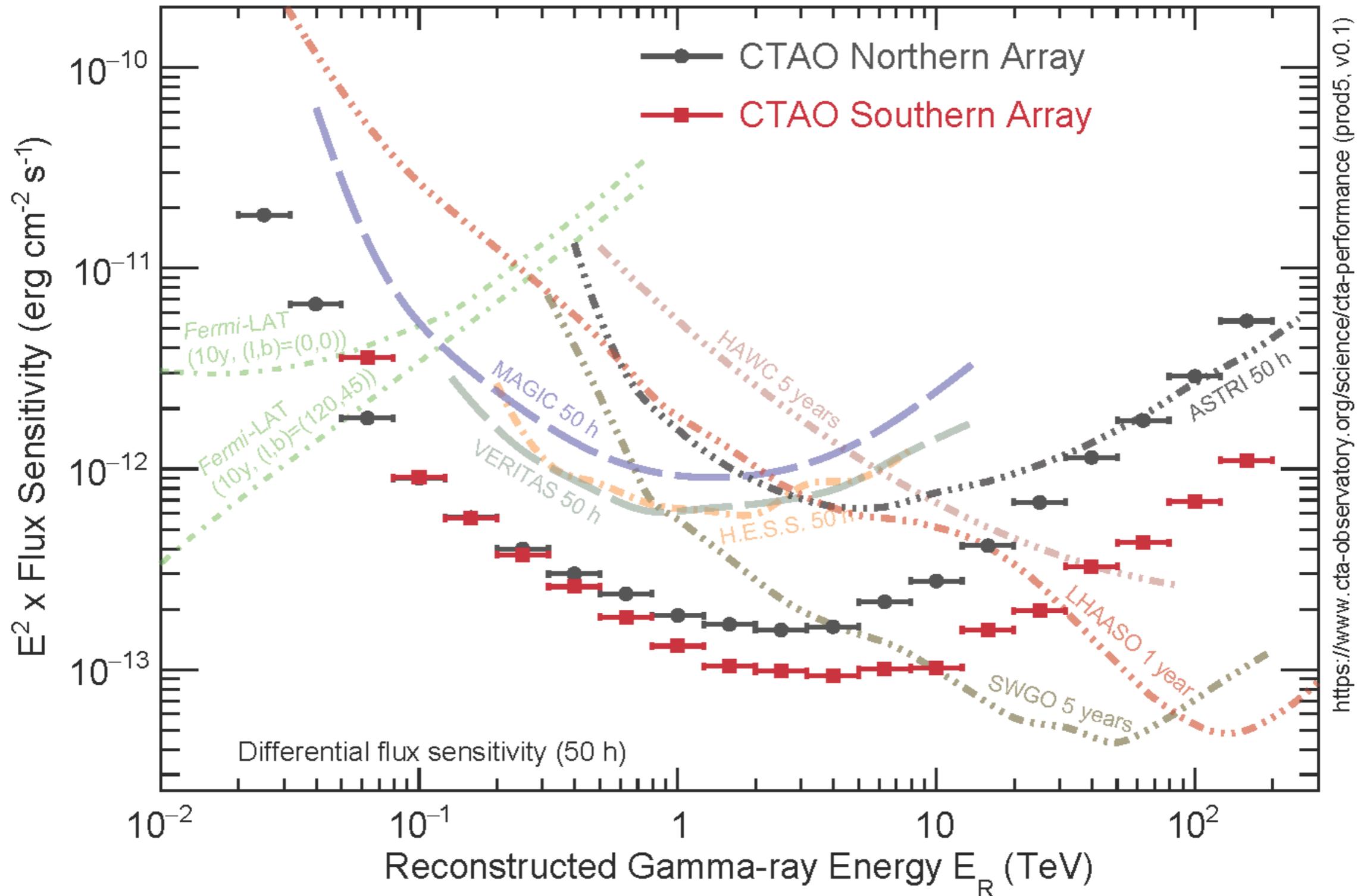


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## Maier & Holder 2017

# CTAO: Flux Sensitivities

## Flux Sensitivities



# CTAO: Large-Sized Telescopes

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



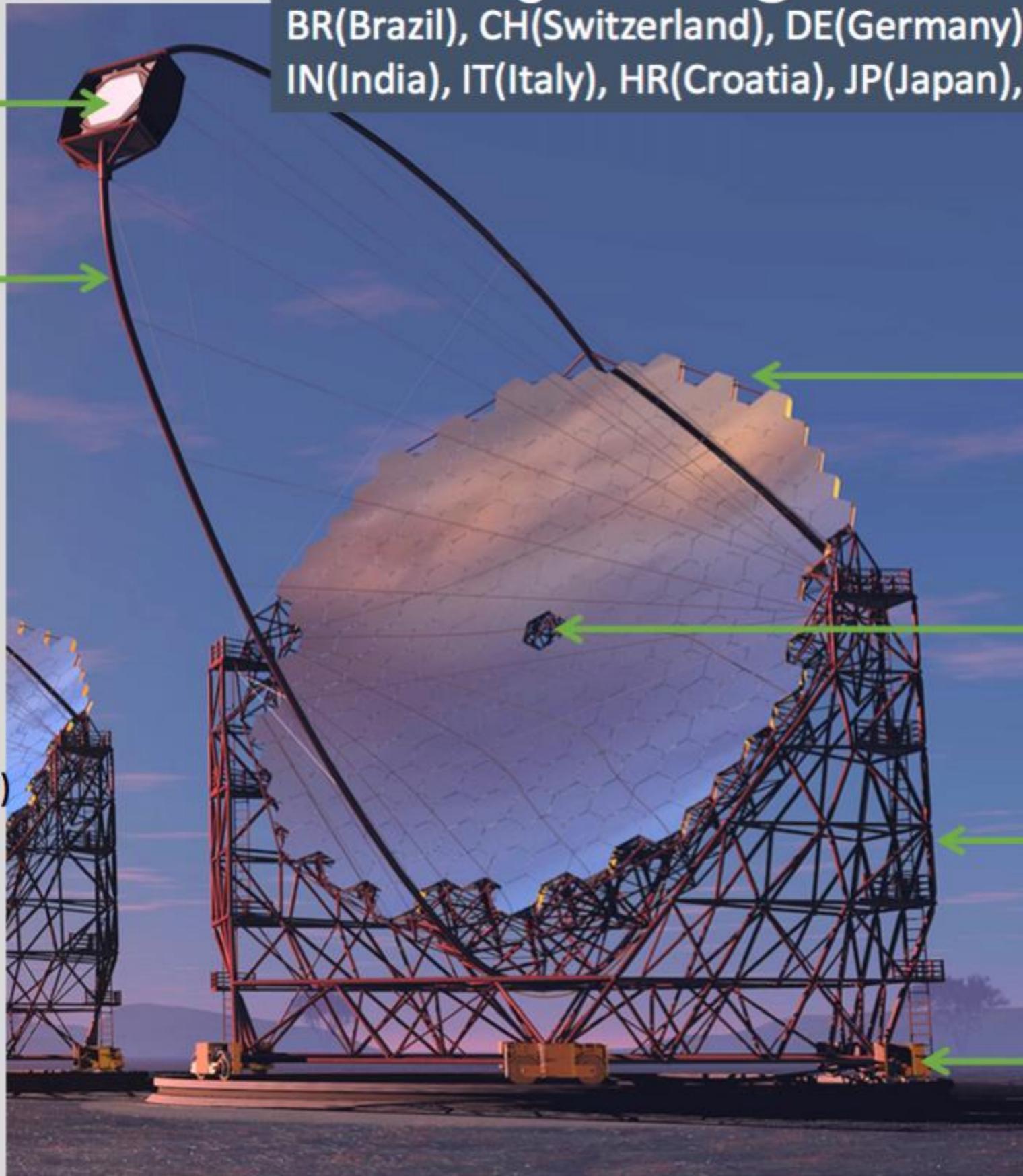
# LST Project : Big International Effort

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)

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

ICRR, Japan



Developed last 6 years

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

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

Mirca, La Palma



## 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

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



7 LGs

+



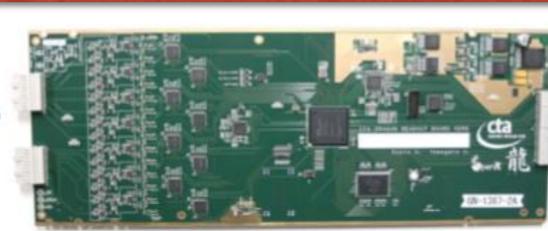
7 PMTs

+



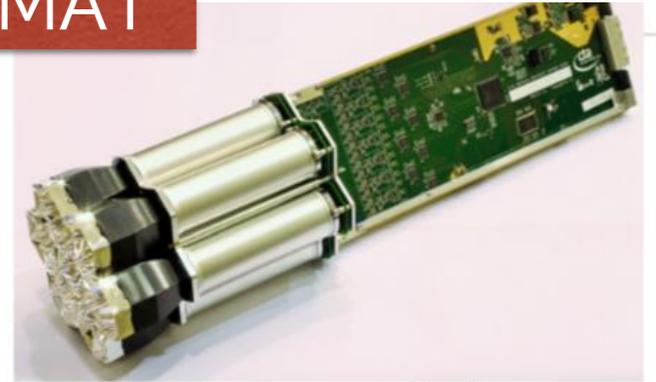
SCB

+



Dragon board

=



FPI module



Module assembly



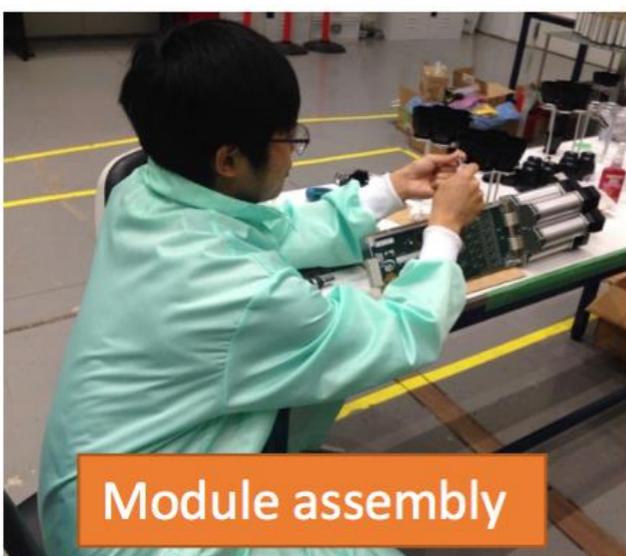
19 tested modules



Trigger back planes

265 modules/ Tel.  
needed.

270 modules are  
assembled @ IAC



Module assembly



Network switch and TIB  
(now TIBv4 available!)

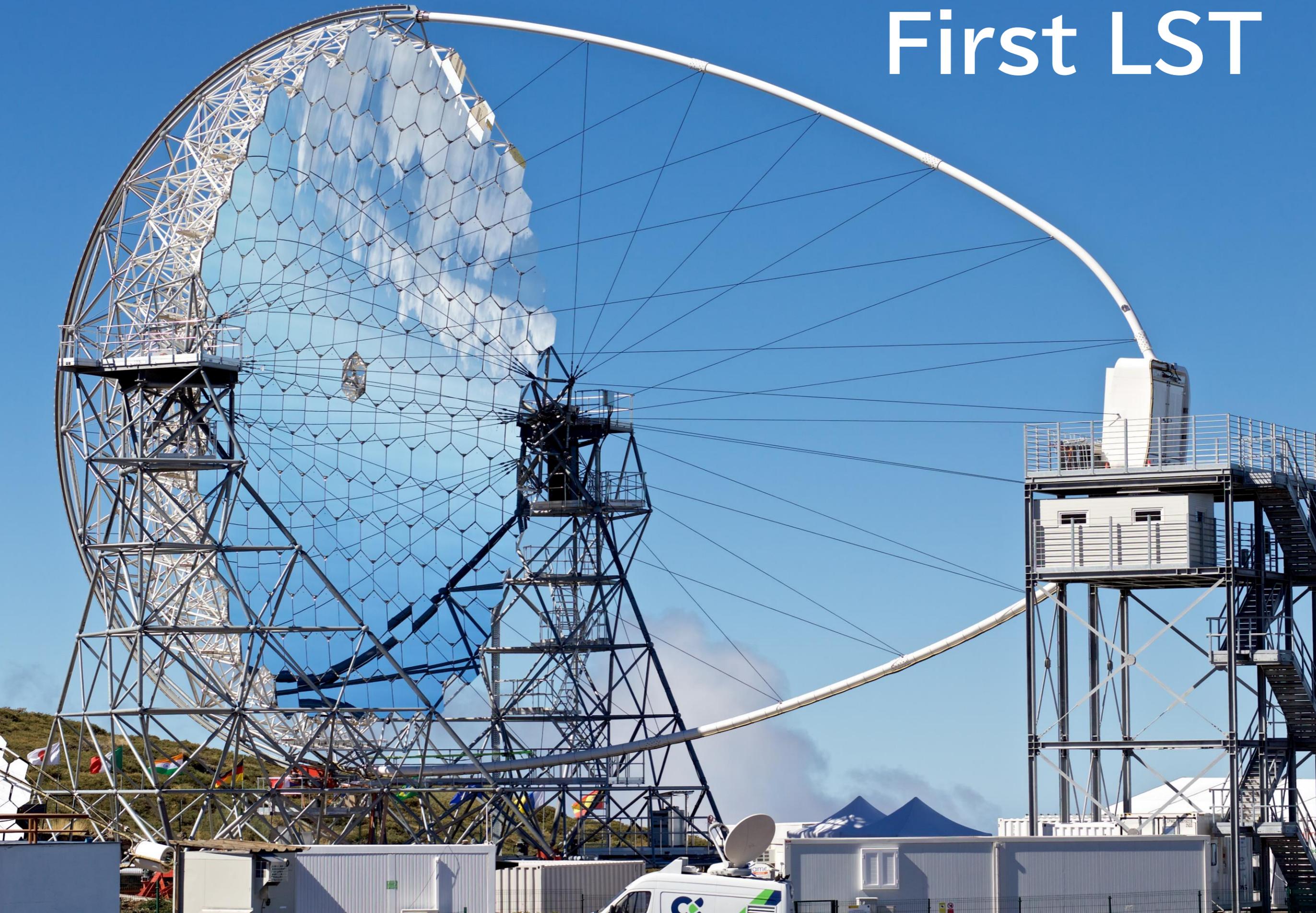


Camera server

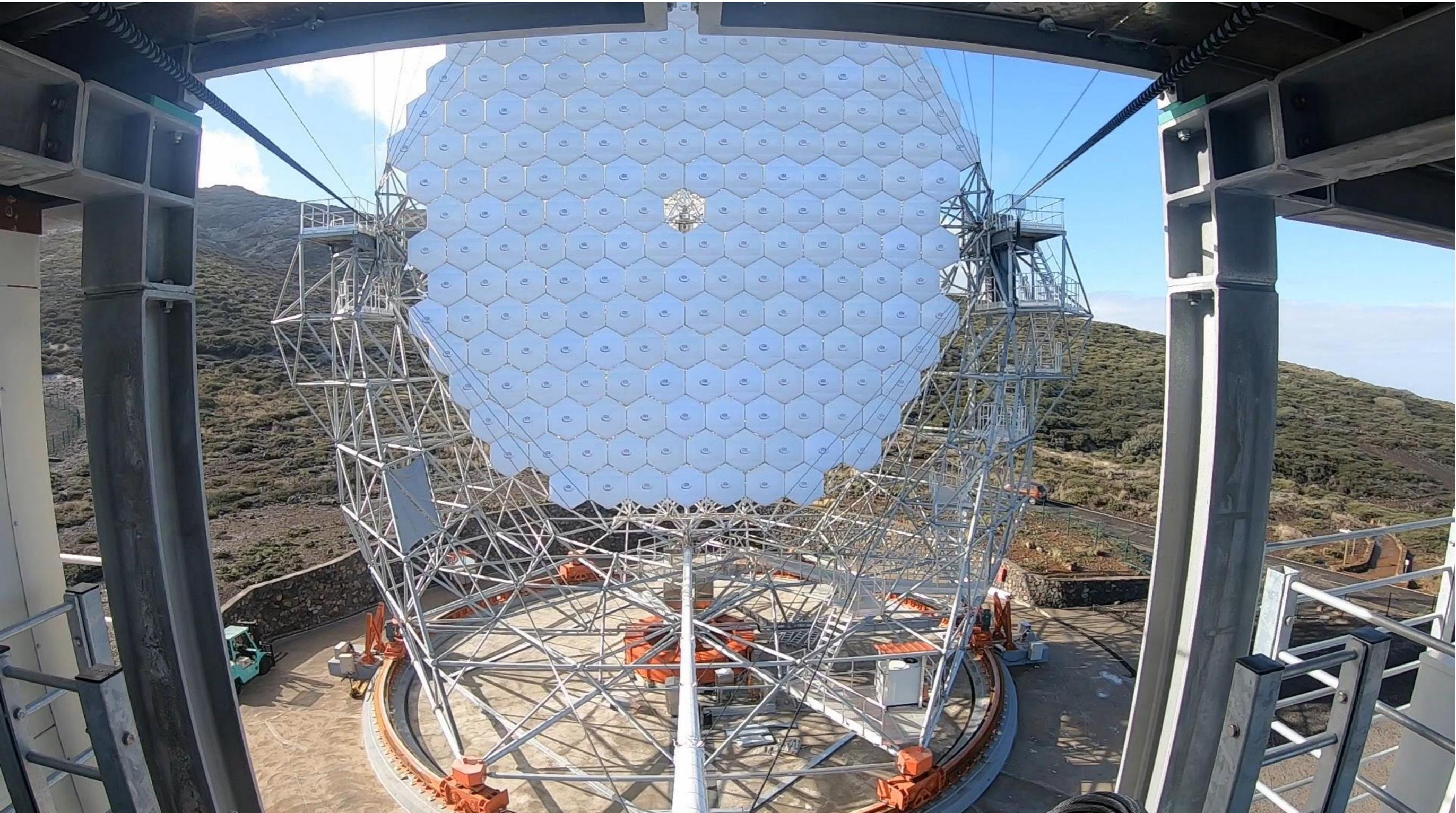
Now ready  
to ship  
to IFAE

21

# First LST



# Fast Rotation of LST



# CTAO北サイト:今後の計画

North: La Palma (Spain)

2025年11月時点



# 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
  - 大気チェ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CTAO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
  - まもなく北LSTアレイが稼働開始  
→低エネルギー帯ではフルスペックが実現！