

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 2024

March 5, 2024

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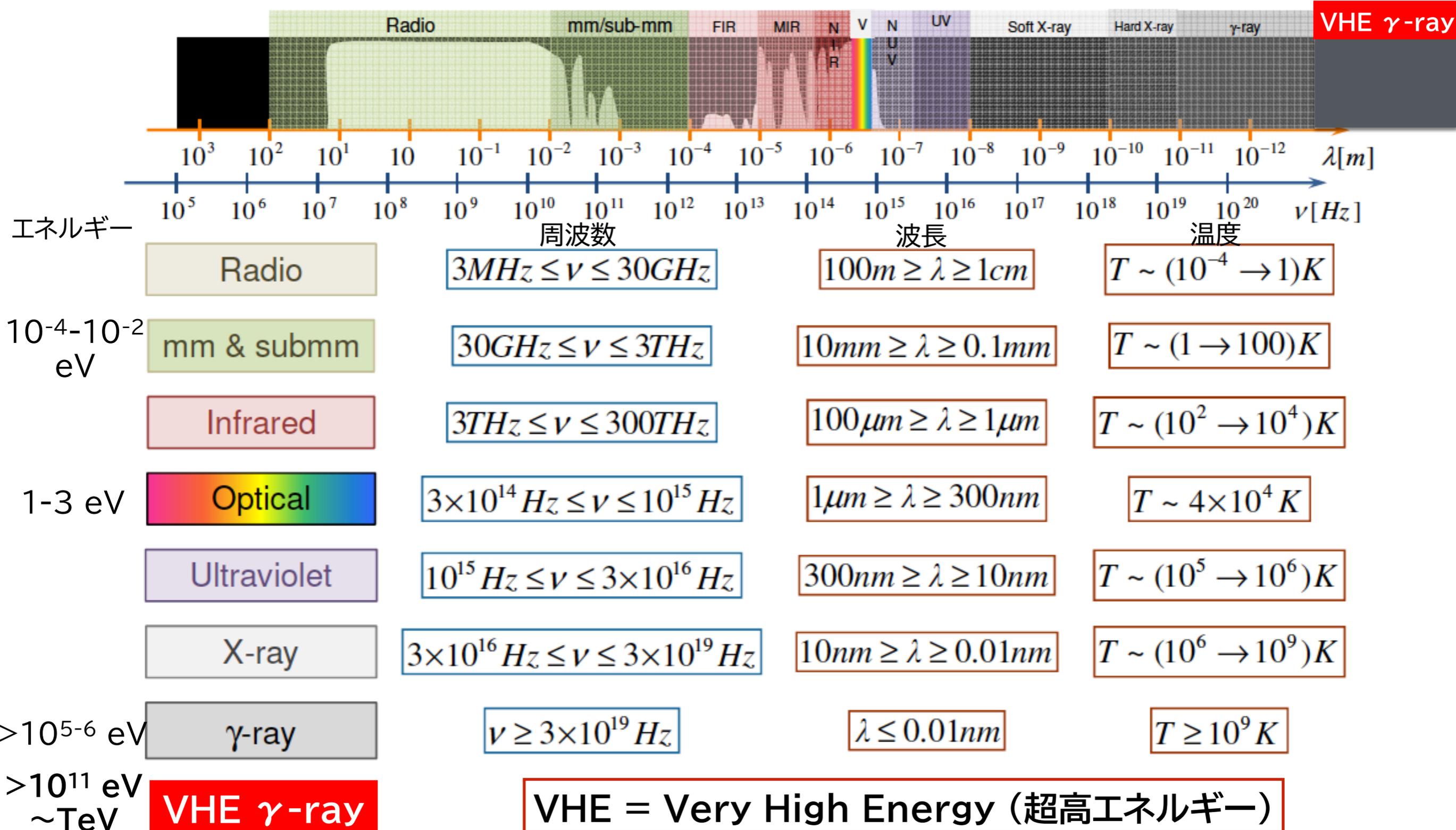
1. **ガンマ線観測の意義**
2. **多波長観測と高エネルギーガンマ線**
3. **宇宙におけるガンマ線の生成機構**
4. **ガンマ線の検出手法**
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6. **次世代ガンマ線天文台CTA**

ガンマ線による天体観測の意義

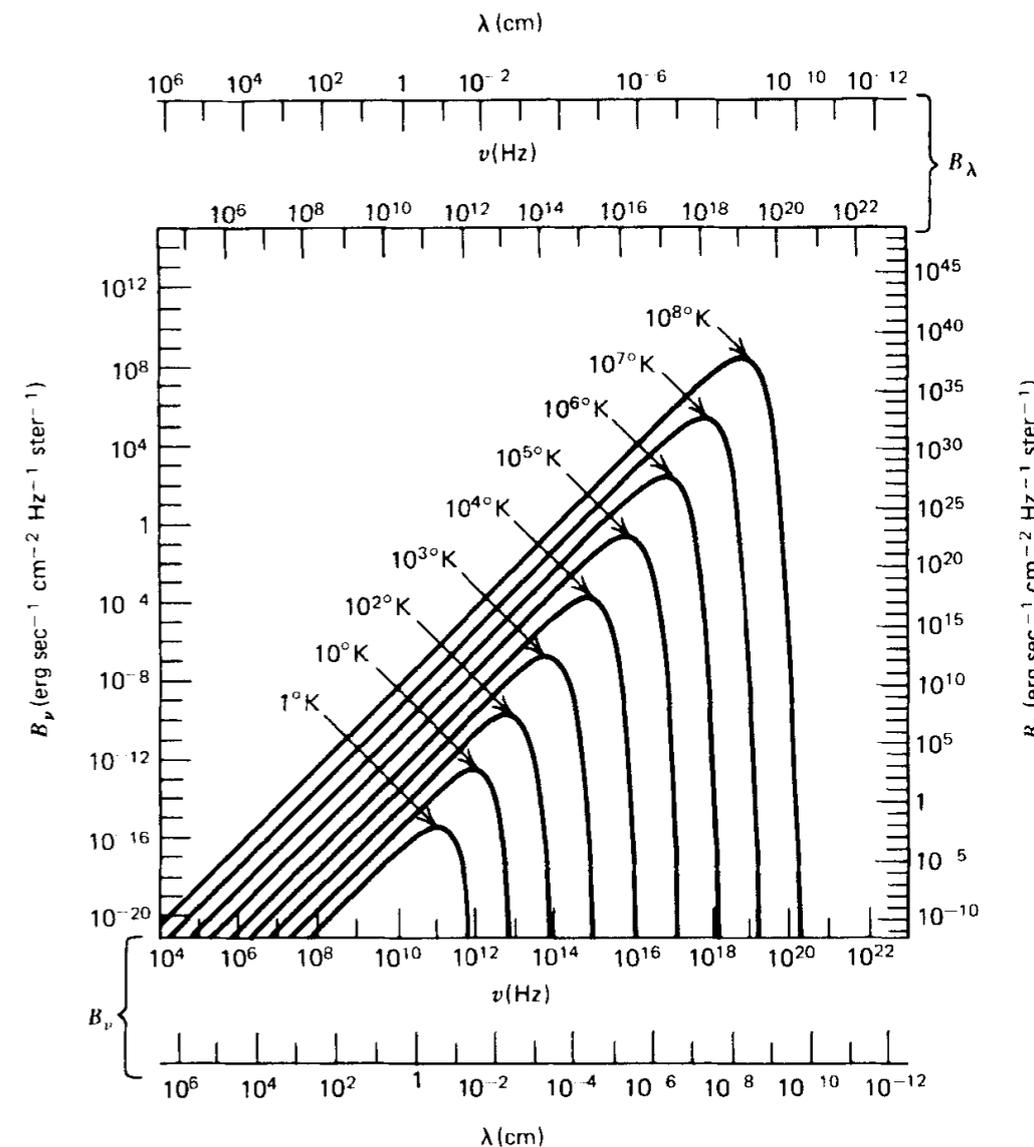
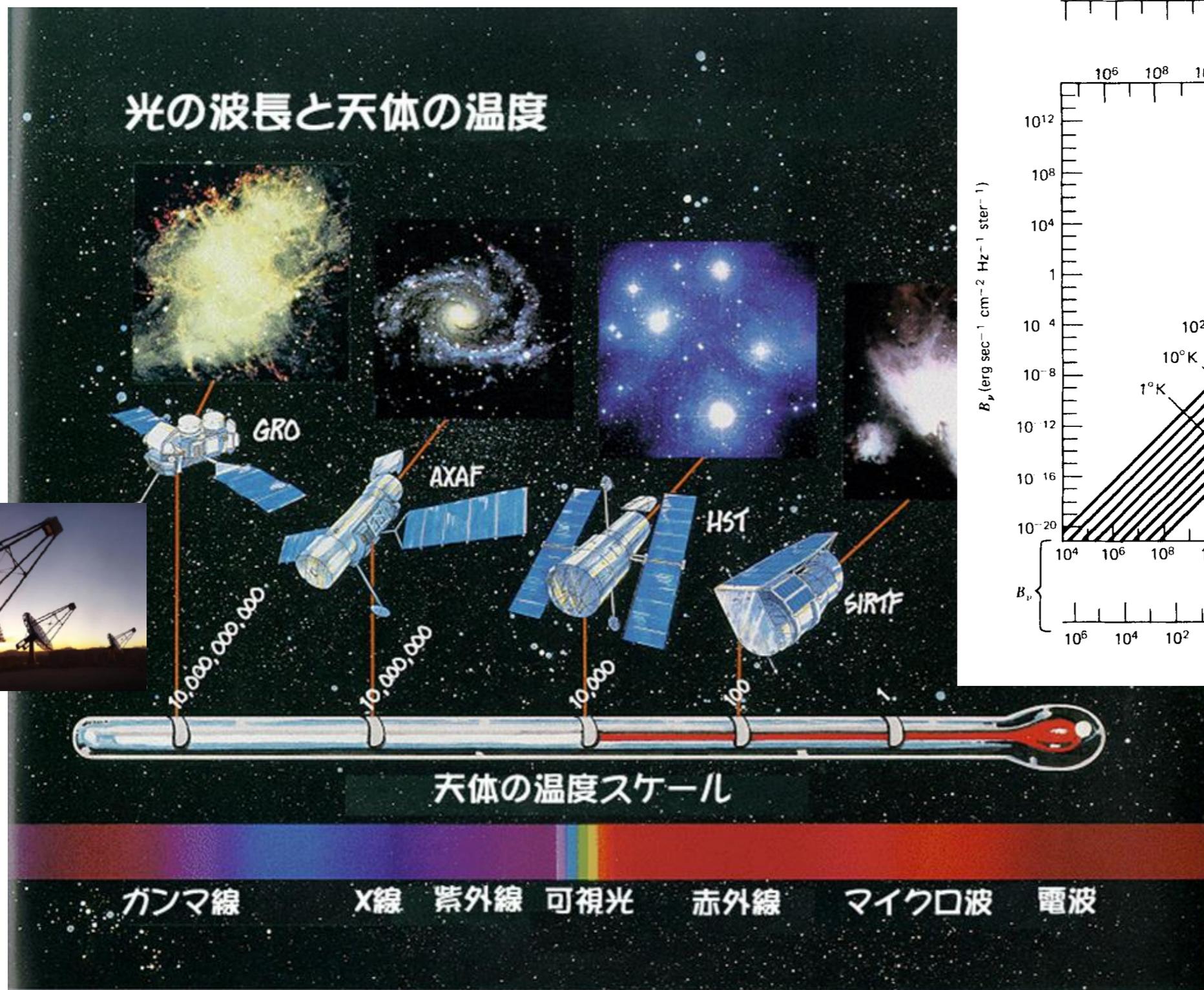


- **意義1: ガンマ線 = 最高エネルギーの光**
 - 純粋な「非熱的」放射 → 極限宇宙の姿
 - 多波長の観測から天体の放射機構が明らかになる
- **意義2: 放射線(素粒子)としてのガンマ線**
 - 天体における物理素過程の研究に好都合
 - 宇宙線の起源、暗黒物質の探索、など

多波長観測とガンマ線



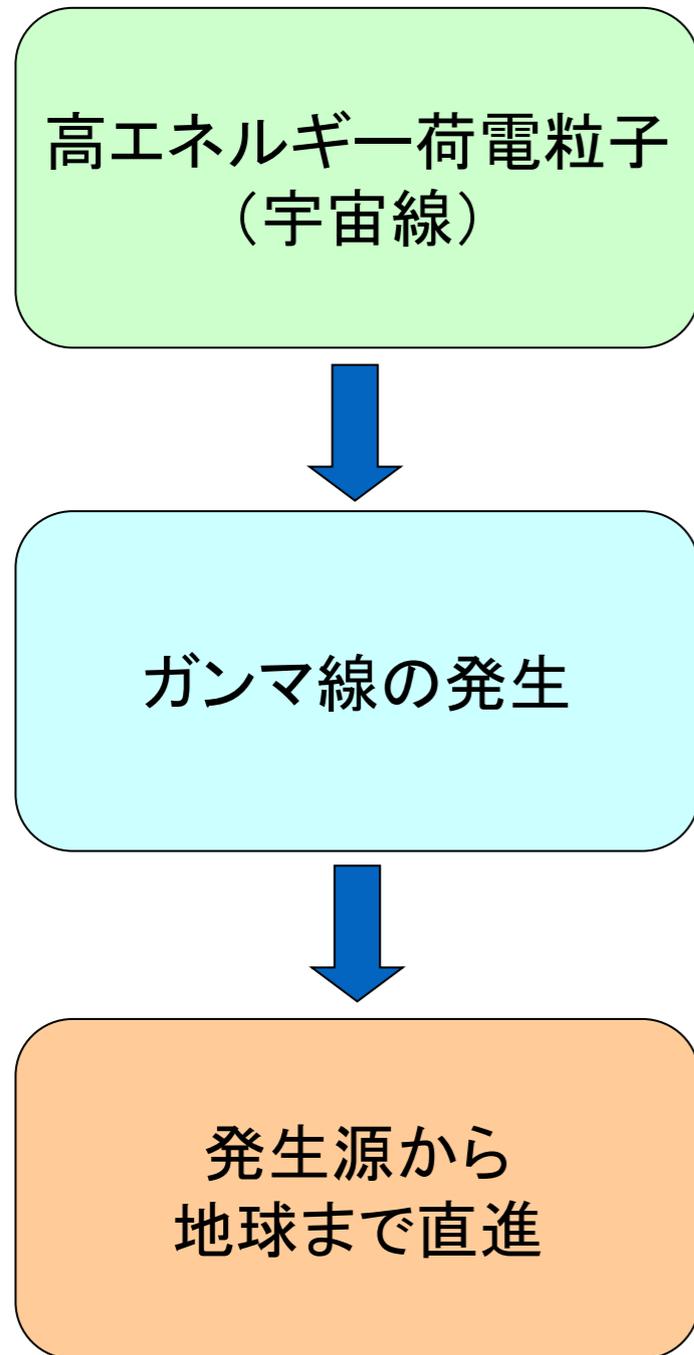
非熱的放射？



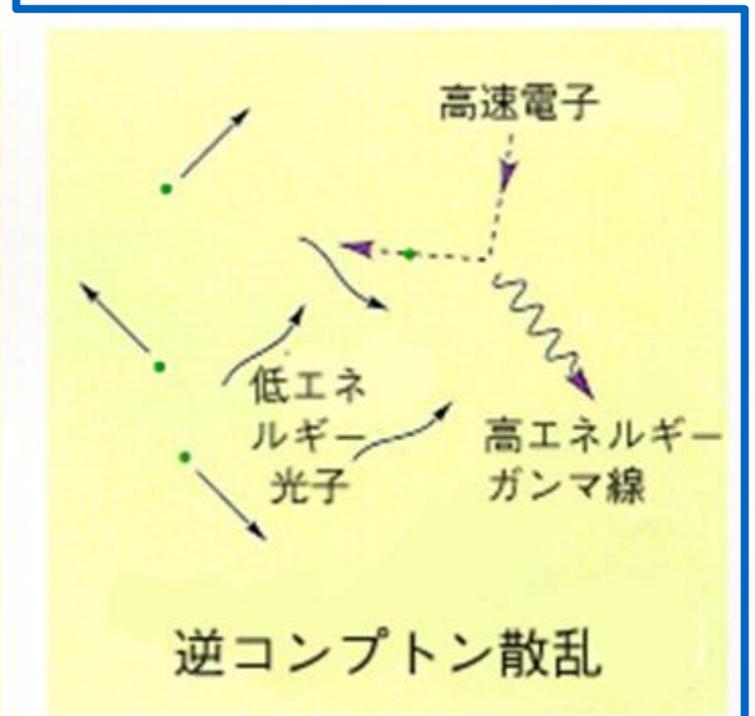
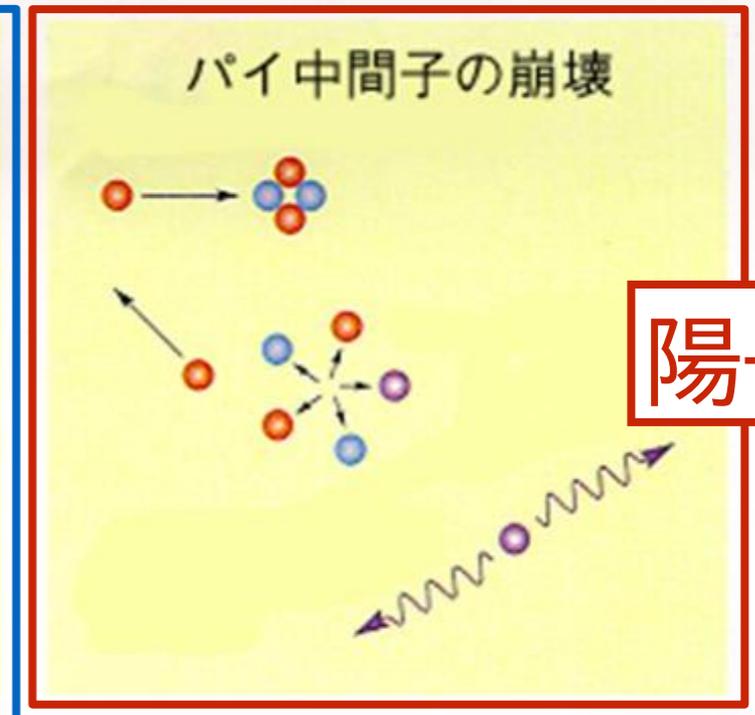
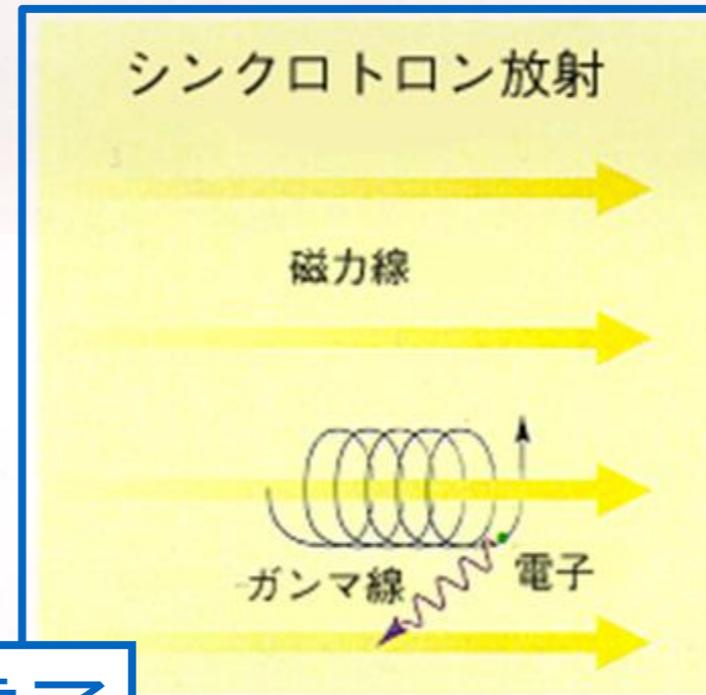
黒体放射

VHE

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

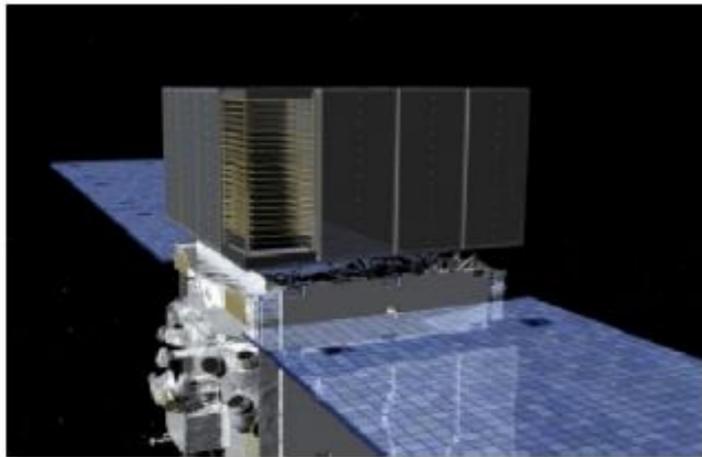
	親粒子	標的／環境
中性パイオン崩壊	陽子	物質
逆コンプトン散乱	電子	光子場
制動放射	電子	物質
シンクロトロン放射	電子	磁場
曲率放射	電子	強磁場
対消滅？	暗黒物質	質量集中
ホーキング放射？	—	PBH

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



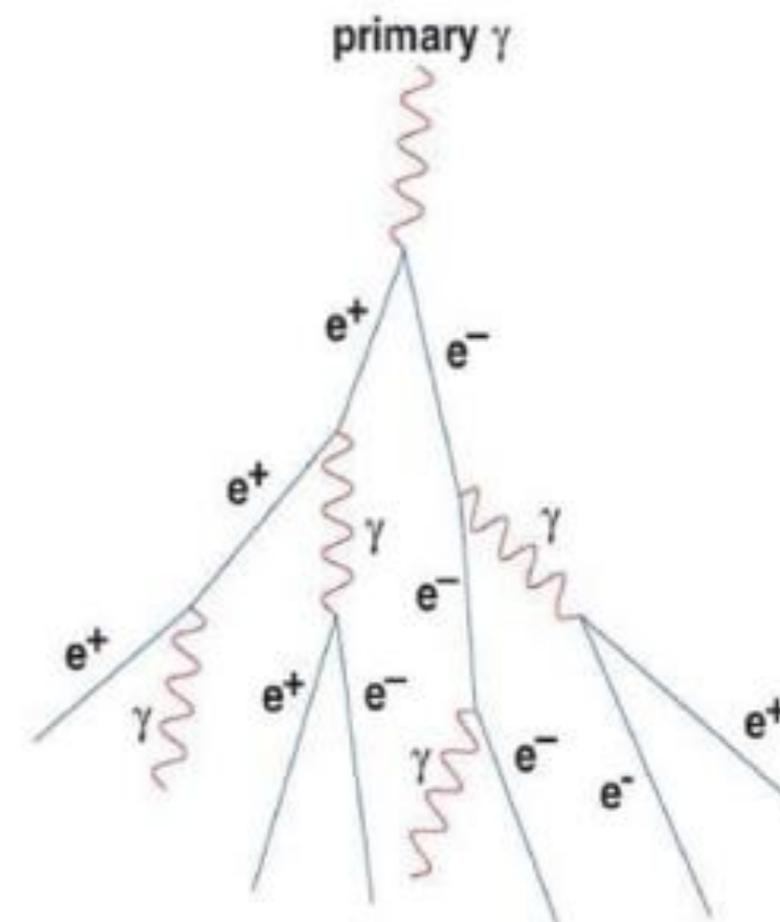
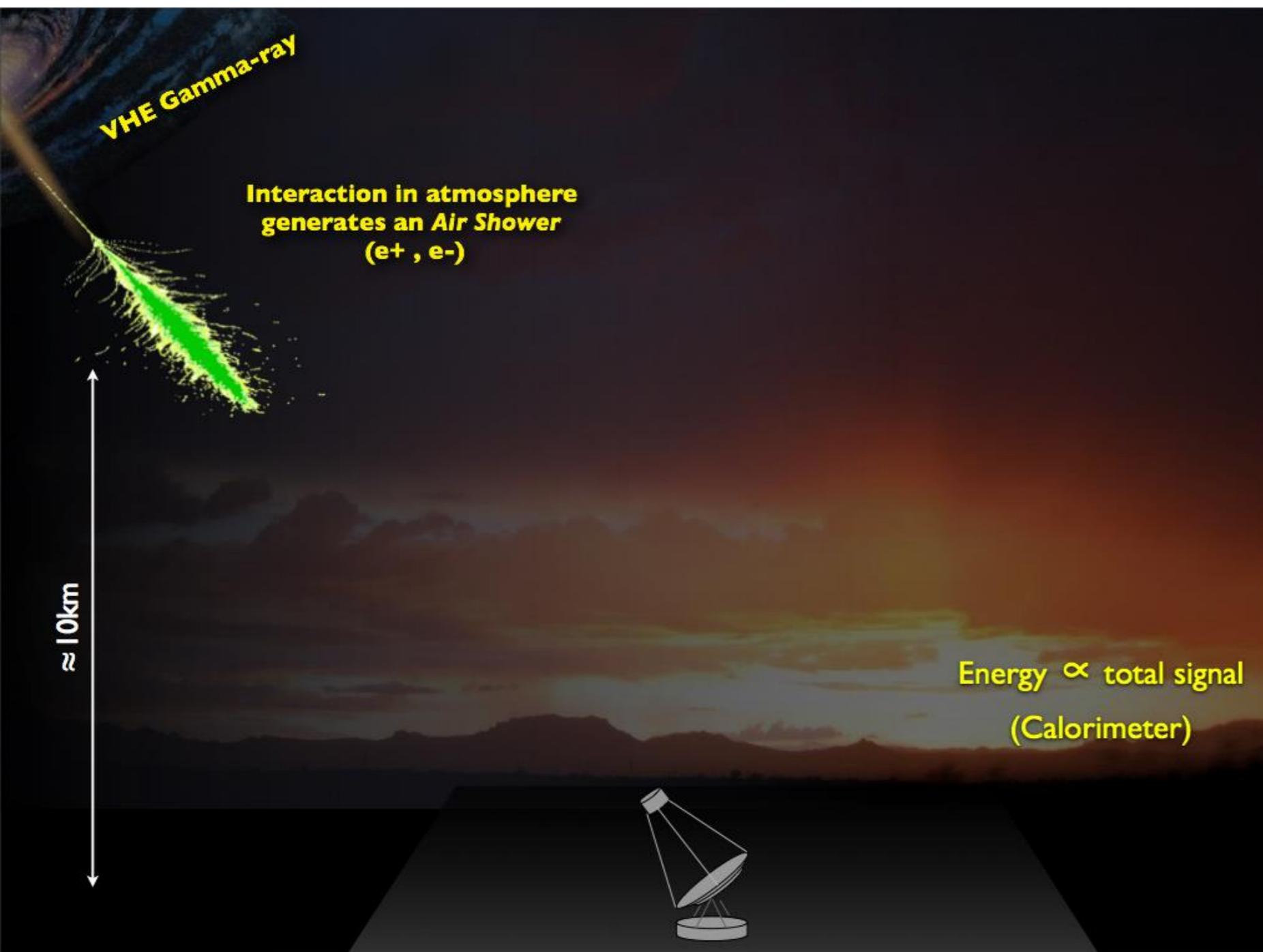
稼働中の大気チェレンコフ望遠鏡

VERITAS, 4 x 12m



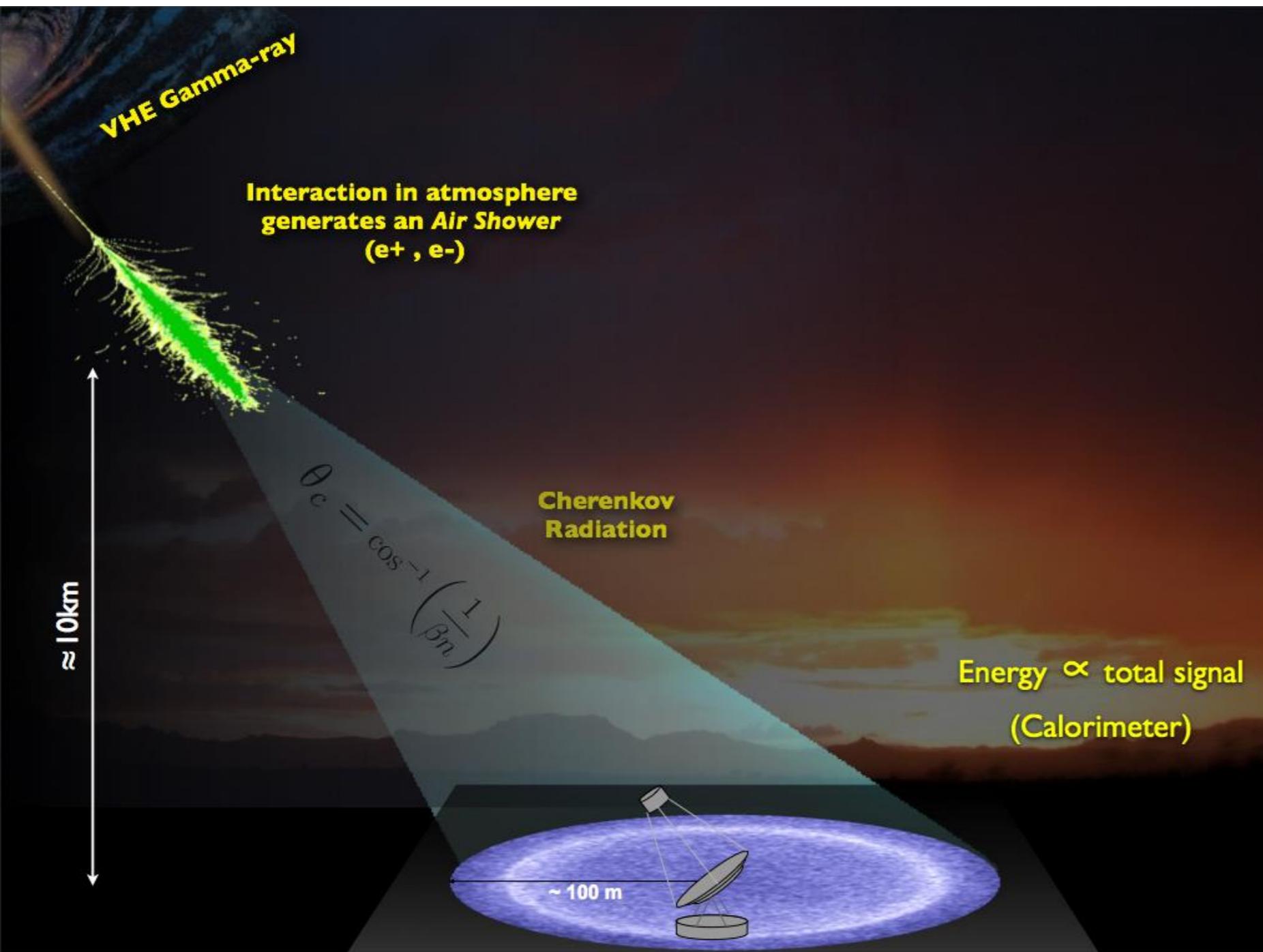
ガンマ線の検出手法(VHE)

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)

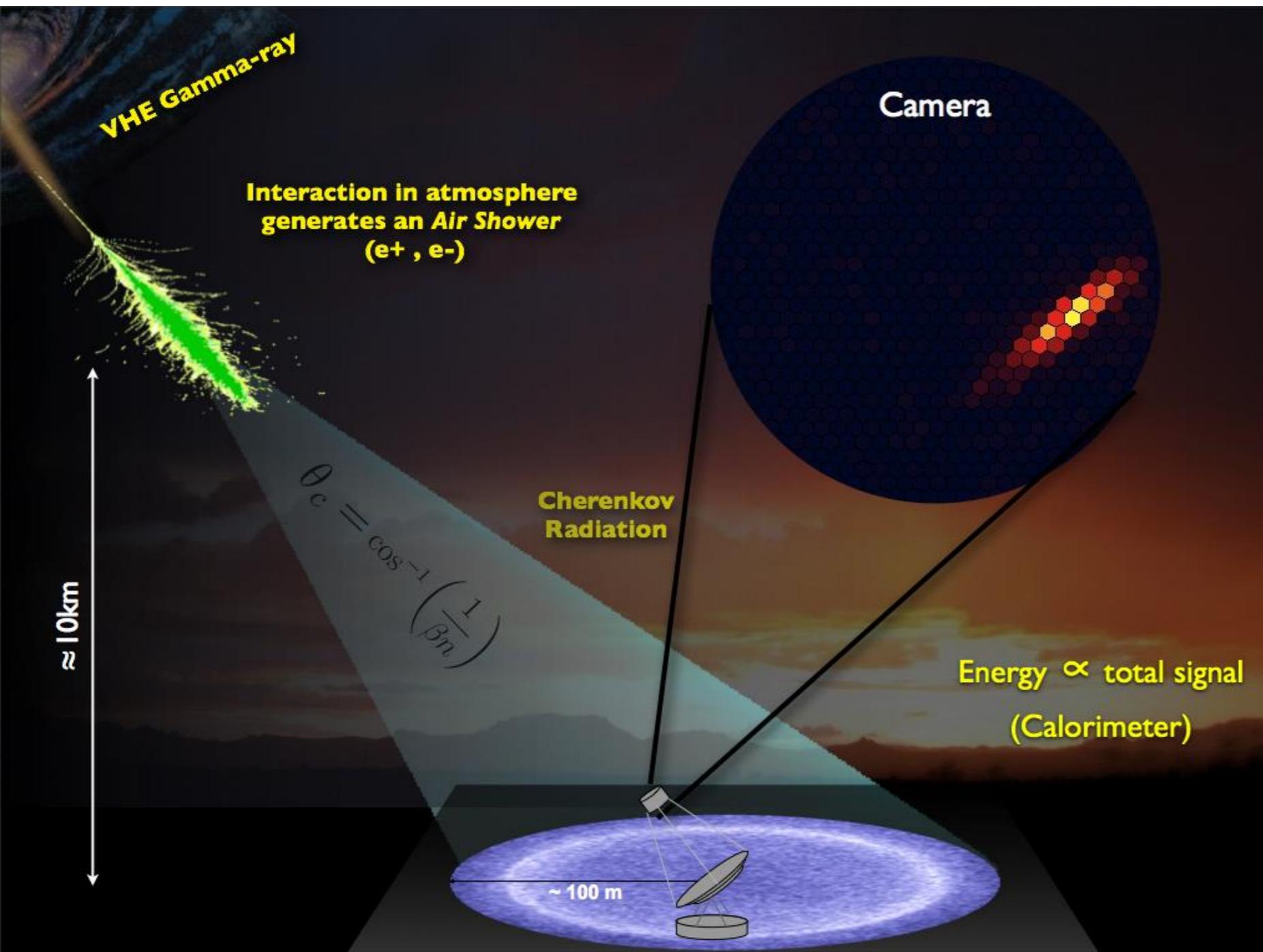


大気チェレンコフ光
(青い光)

θ_c (チェレンコフ角)
 $\sim 1^\circ$

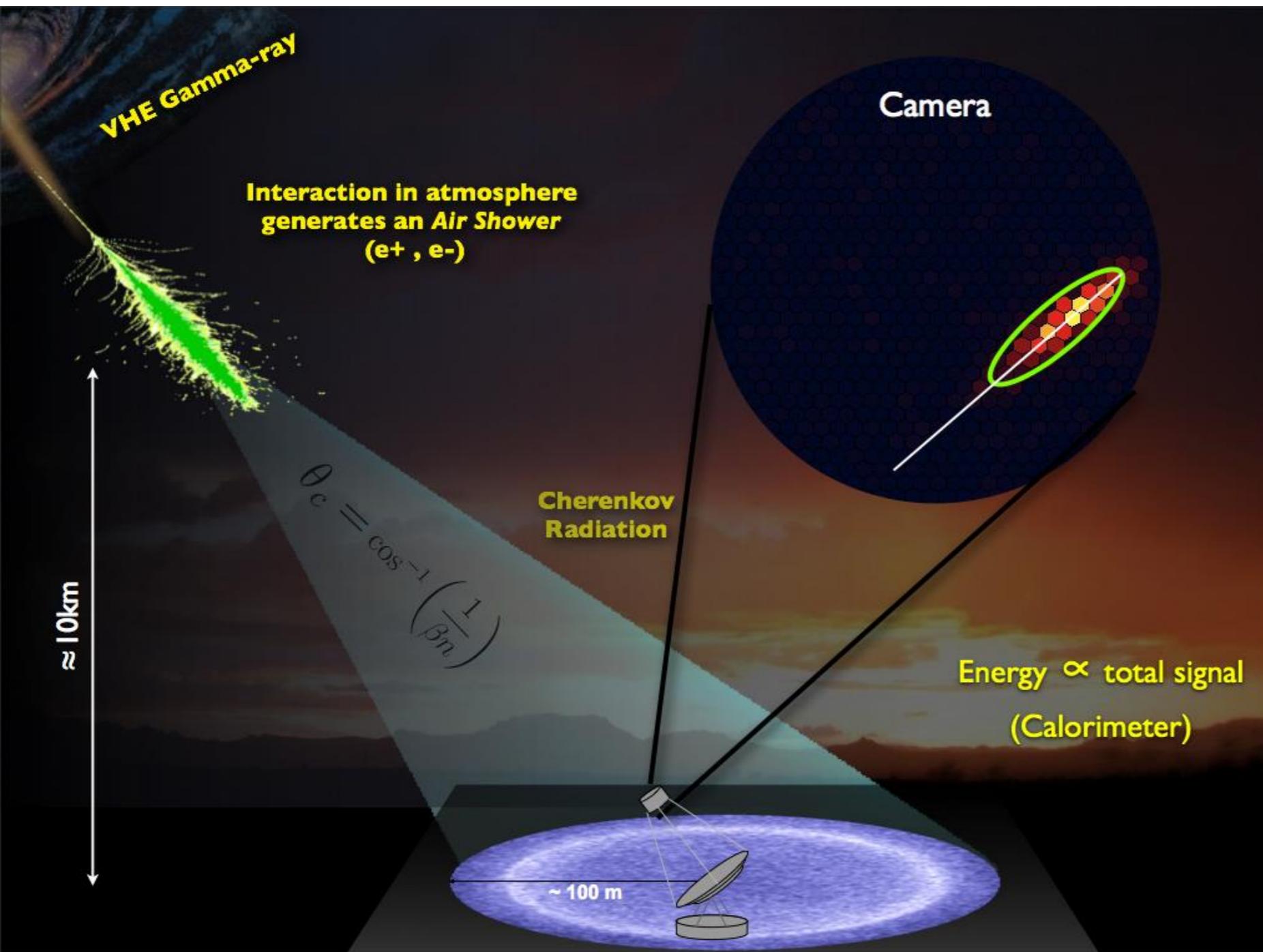
地上で $\sim 5\text{ ns}$ の
微弱な閃光
 $\sim 50\text{ 光子}/\text{m}^2$
@ $1\text{ TeV } \gamma$

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)

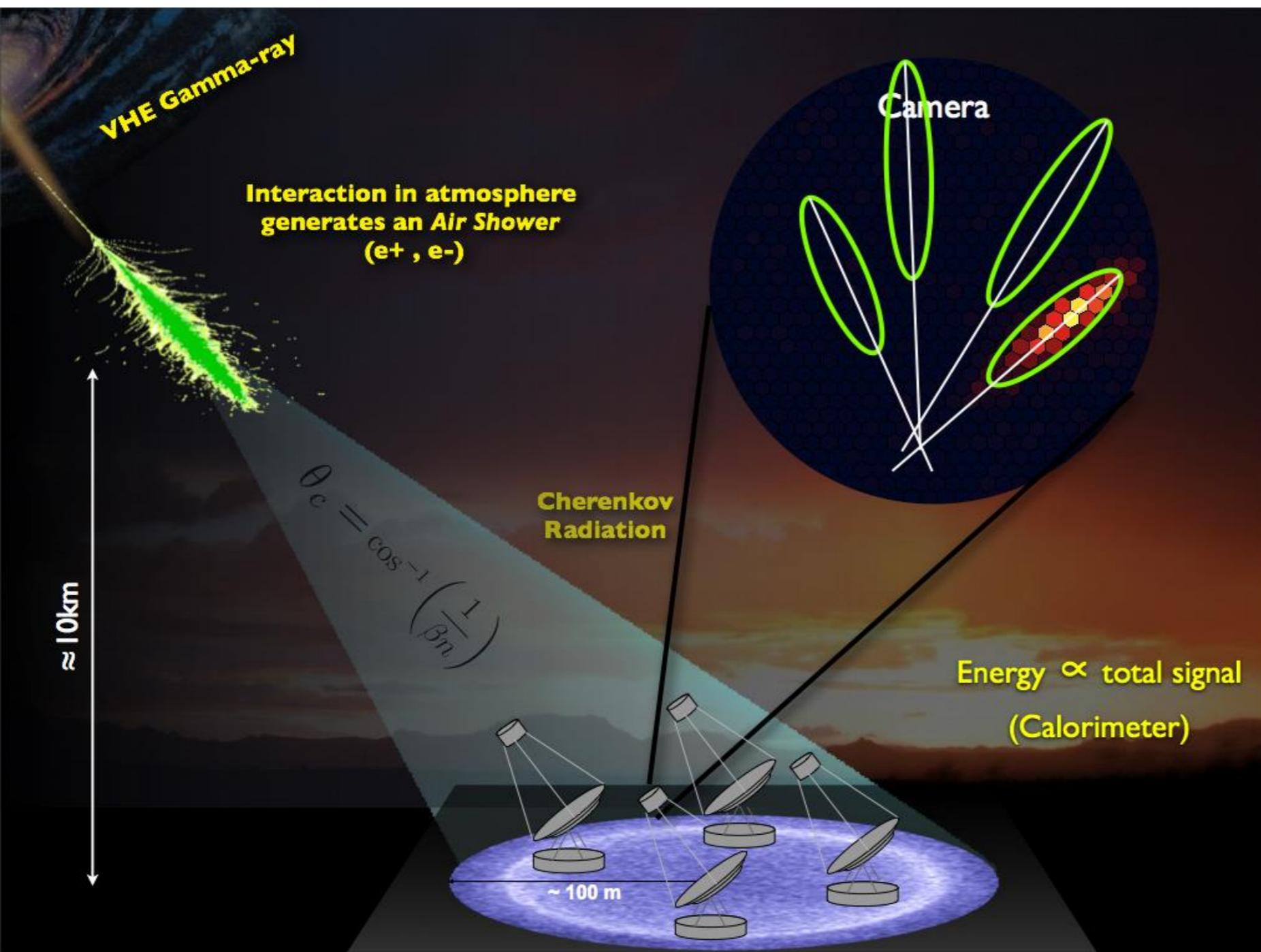


画像解析

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

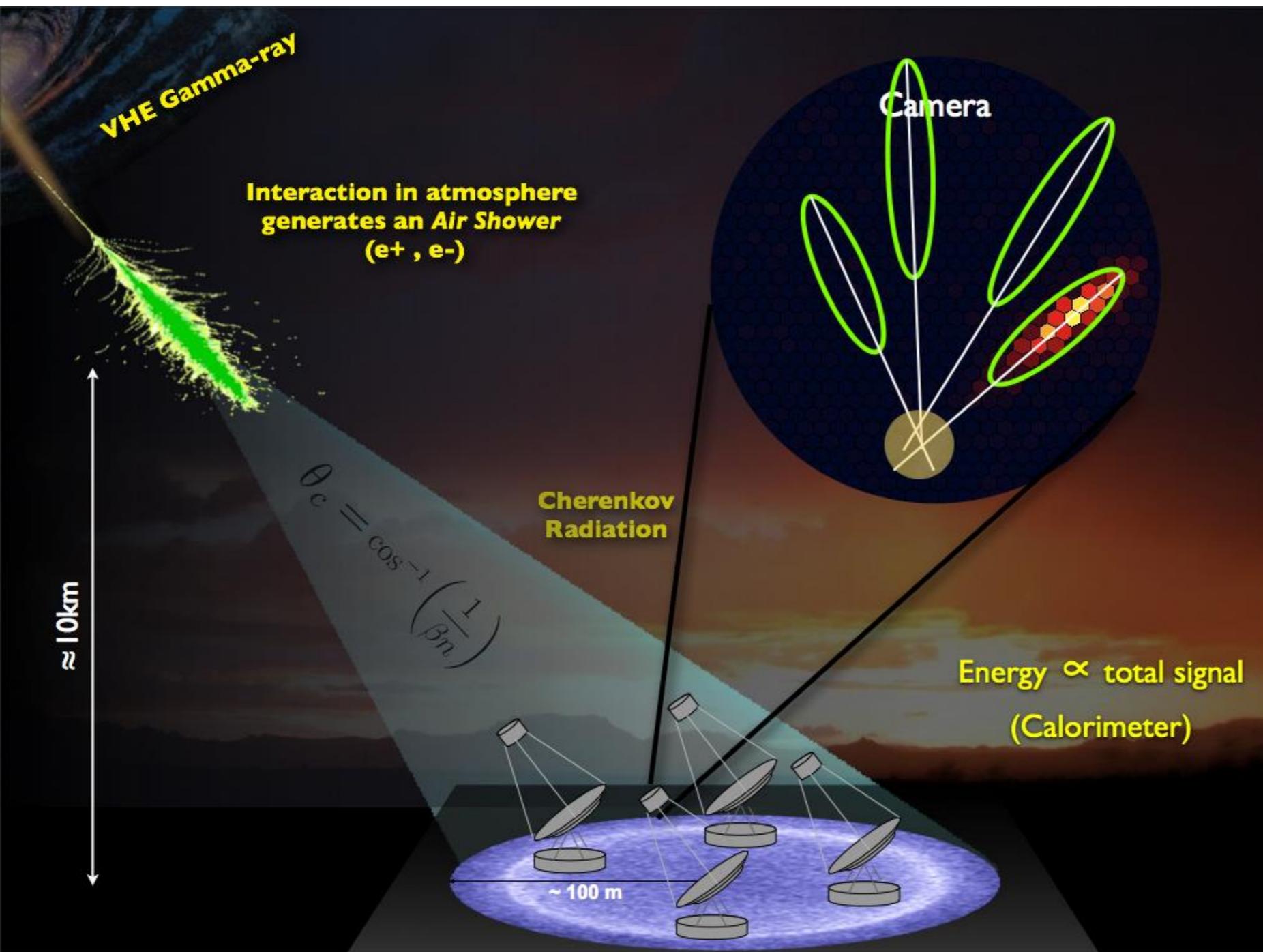
ガンマ線の検出手法(VHE)



ステレオ観測

100 m程度離れた
IACT間で
視差を検出

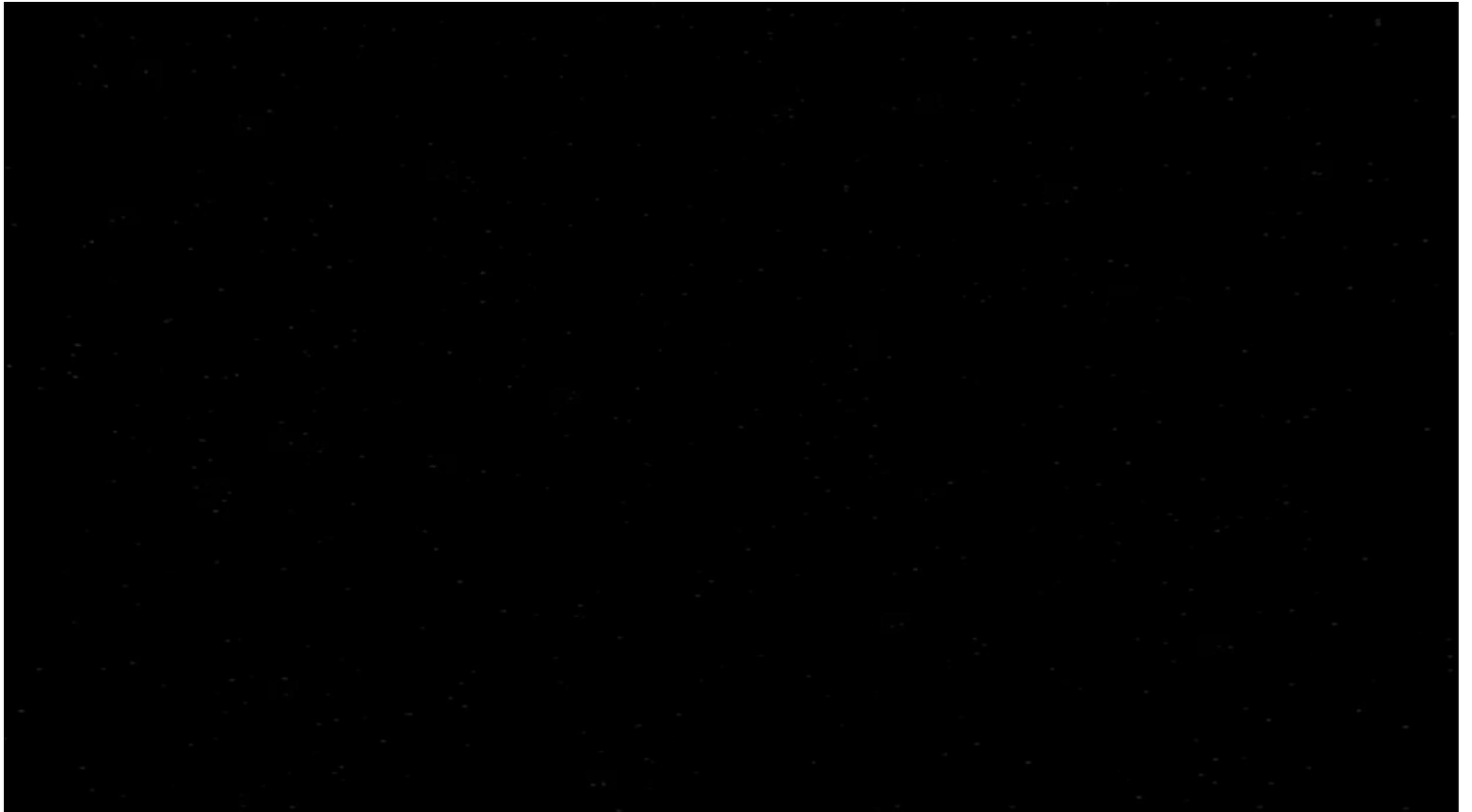
ガンマ線の検出手法(VHE)



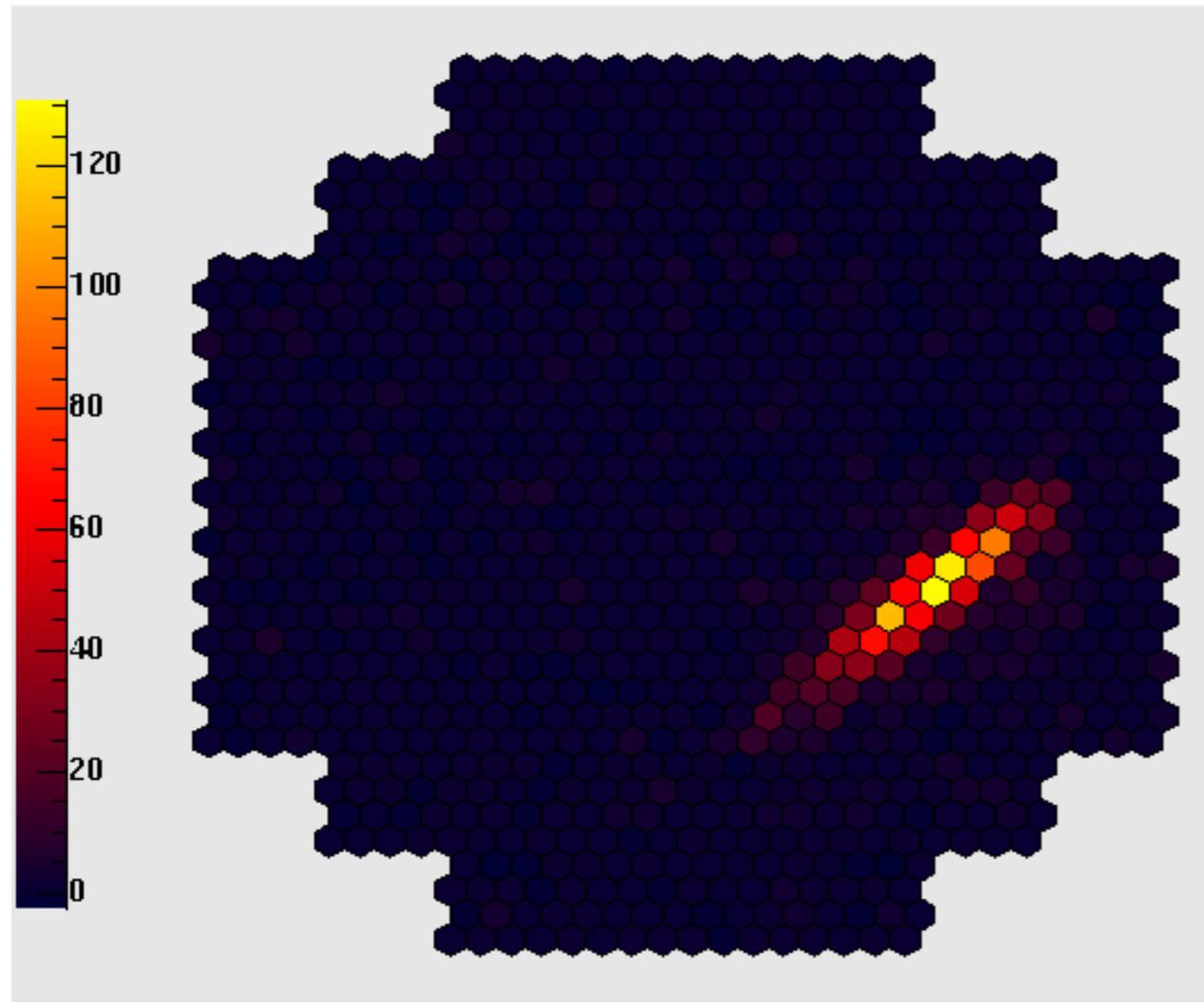
到来方向の推定

ガンマ線の検出手法(VHE)

Atmospheric showers and Cherenkov radiation

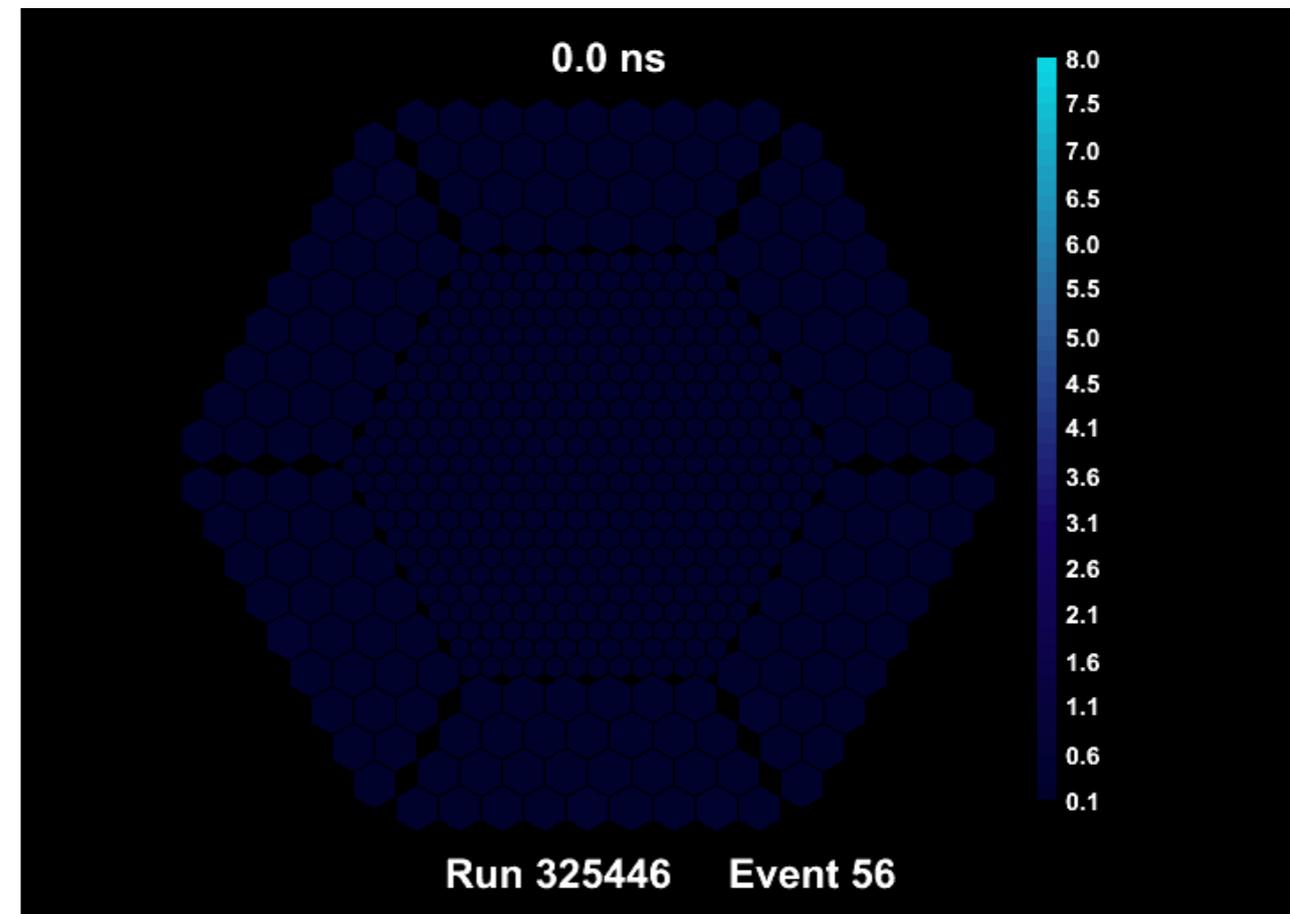


空気シャワー画像



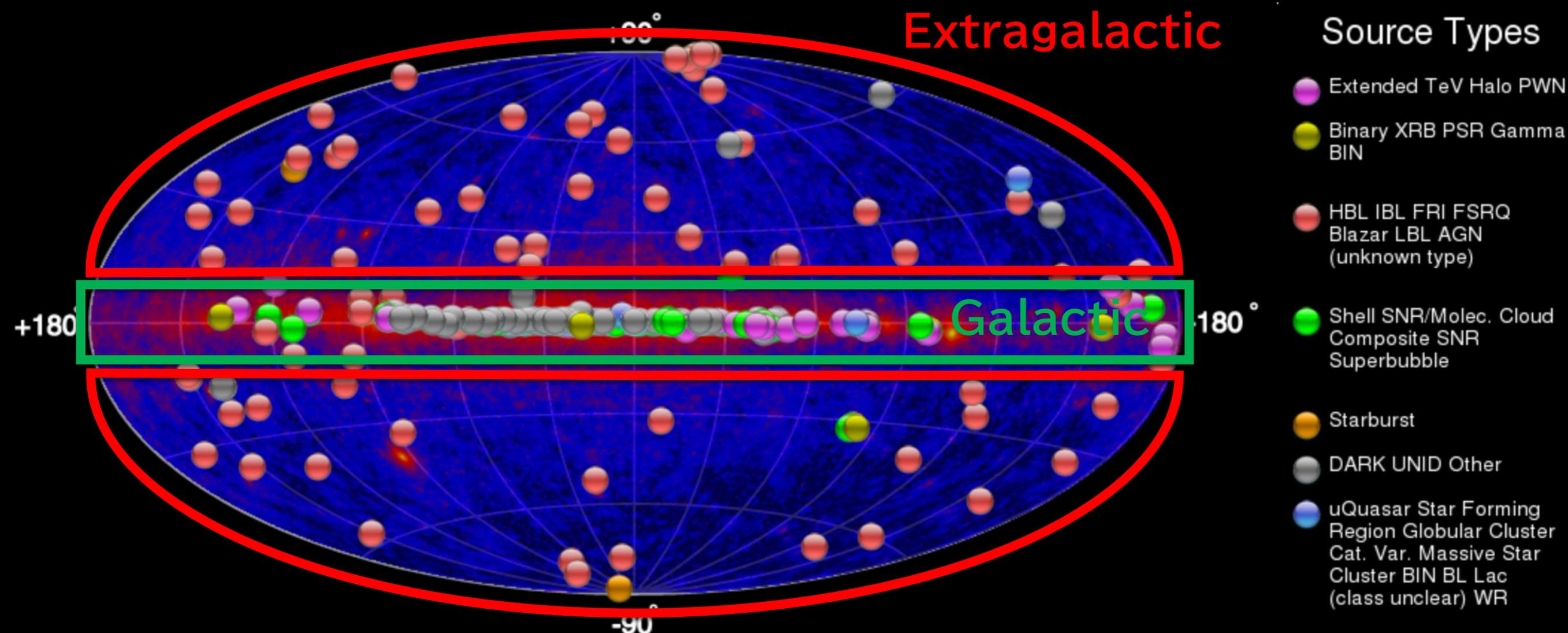
H.E.S.S.

MAGIC



VHEガンマ線天体

VHE gamma-ray sources (>100 GeV)

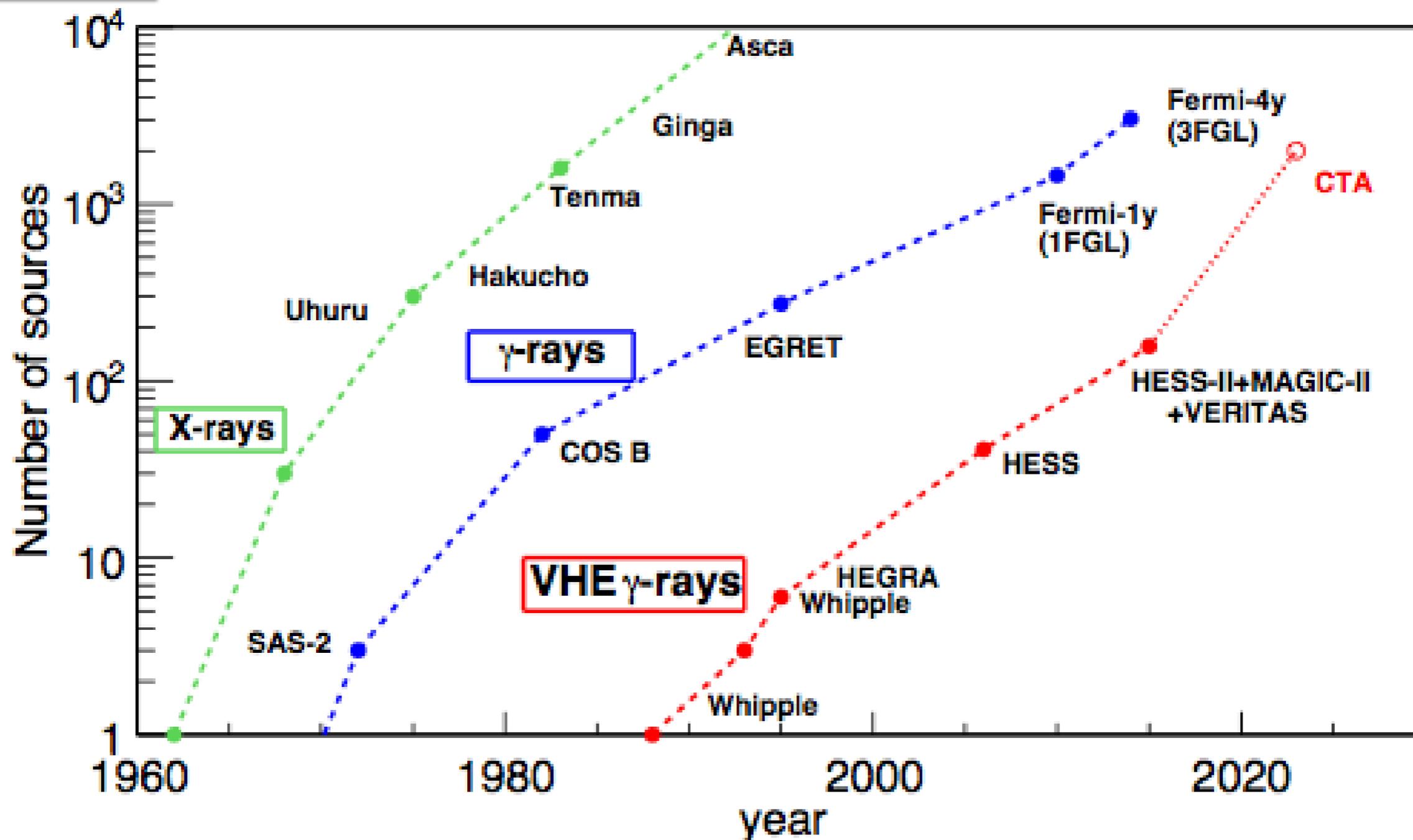


- 約270天体(2024年時点)
- 大部分が大気チェレンコフ望遠鏡による発見

Fundamental:
基礎物理・宇宙論

検出天体数の推移

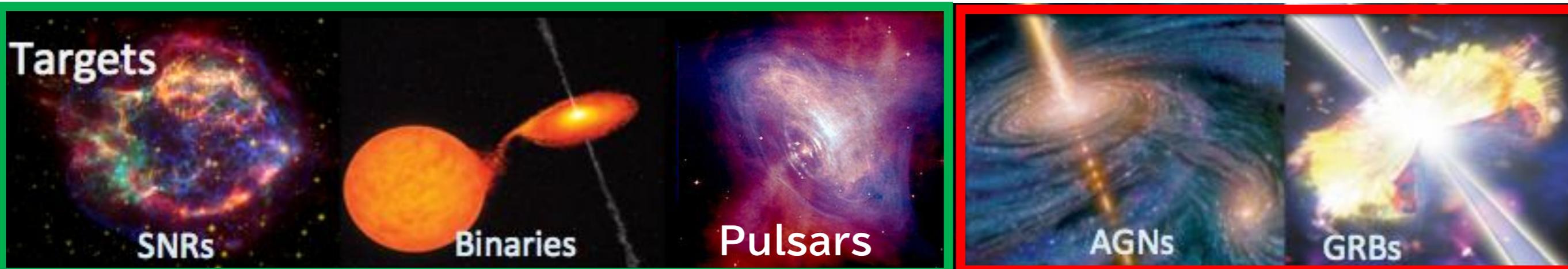
Kifune plot



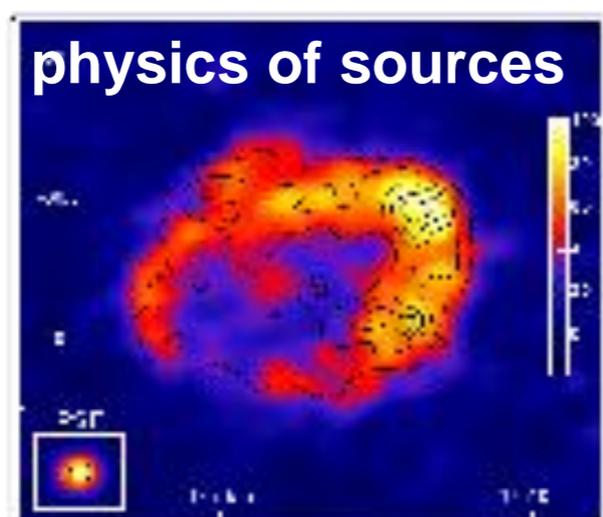
ガンマ線観測で何がわかるか

G

E



Objectives



cosmology

space and time

F

dark matter

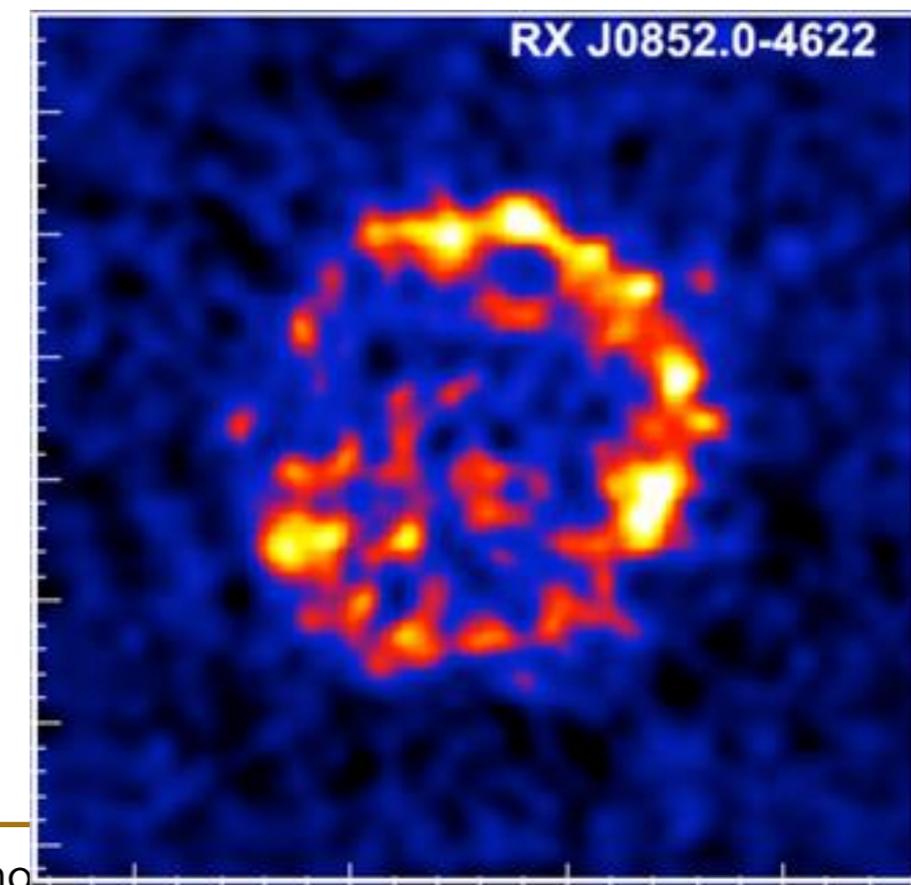
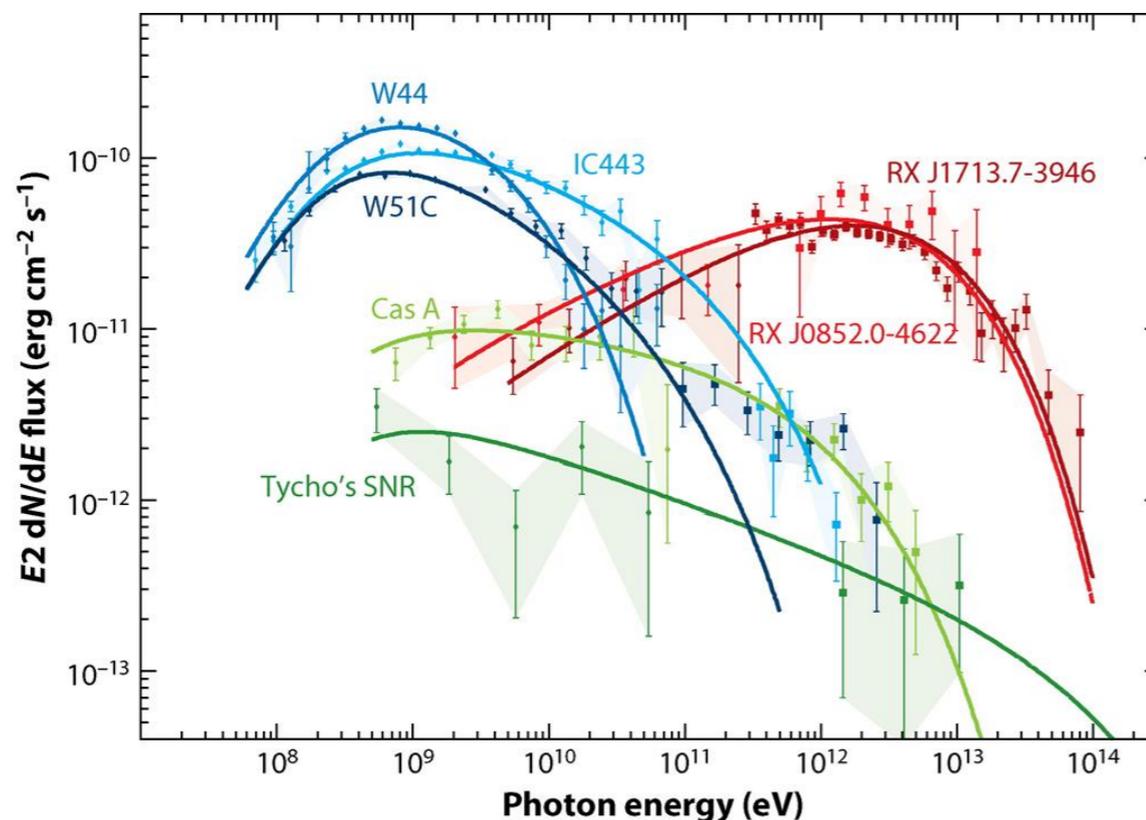
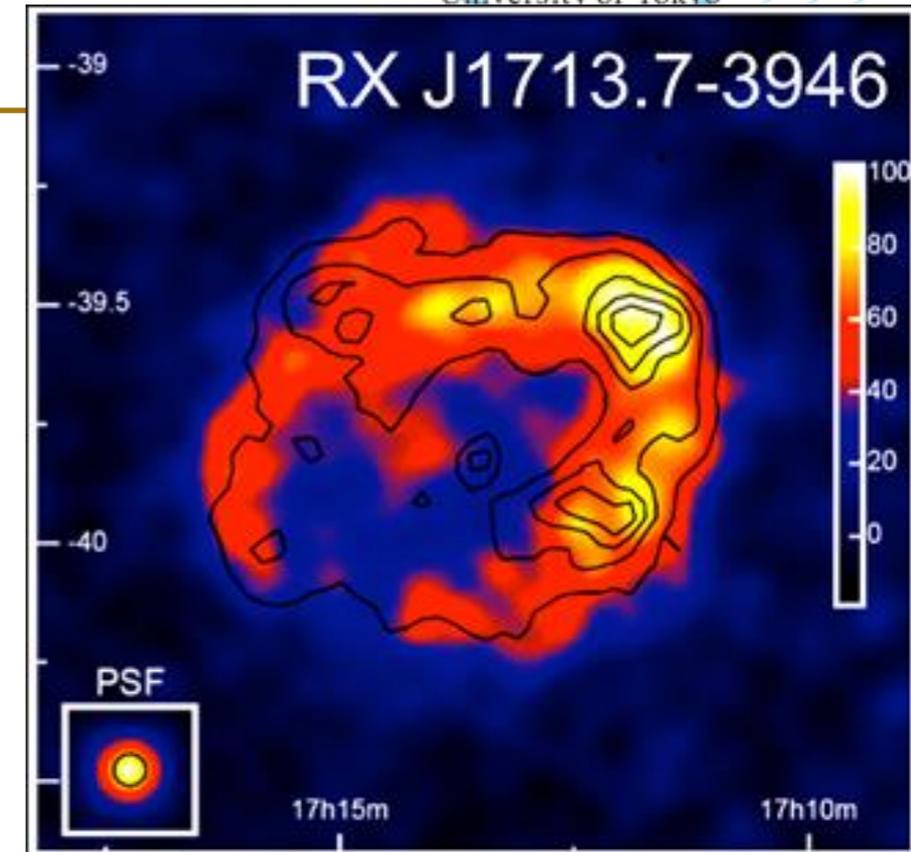
ガンマ線観測で何がわかるか



- **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。生成場所が特定できる。
- **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。

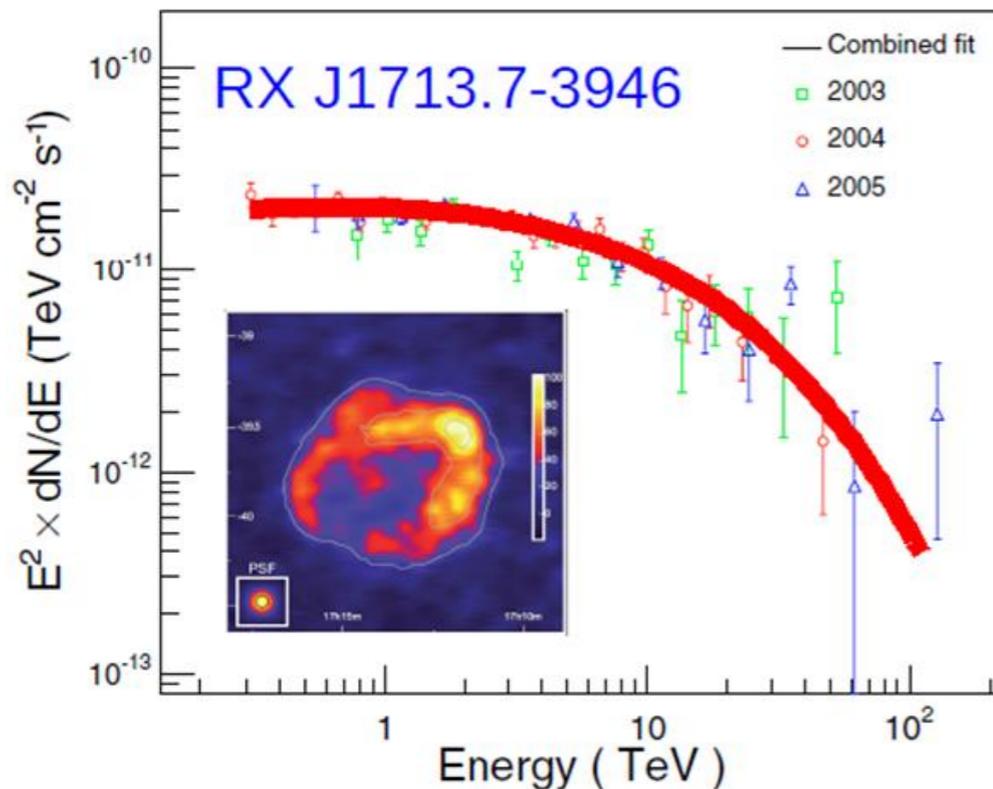
超新星残骸：宇宙線の起源？ G

- 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

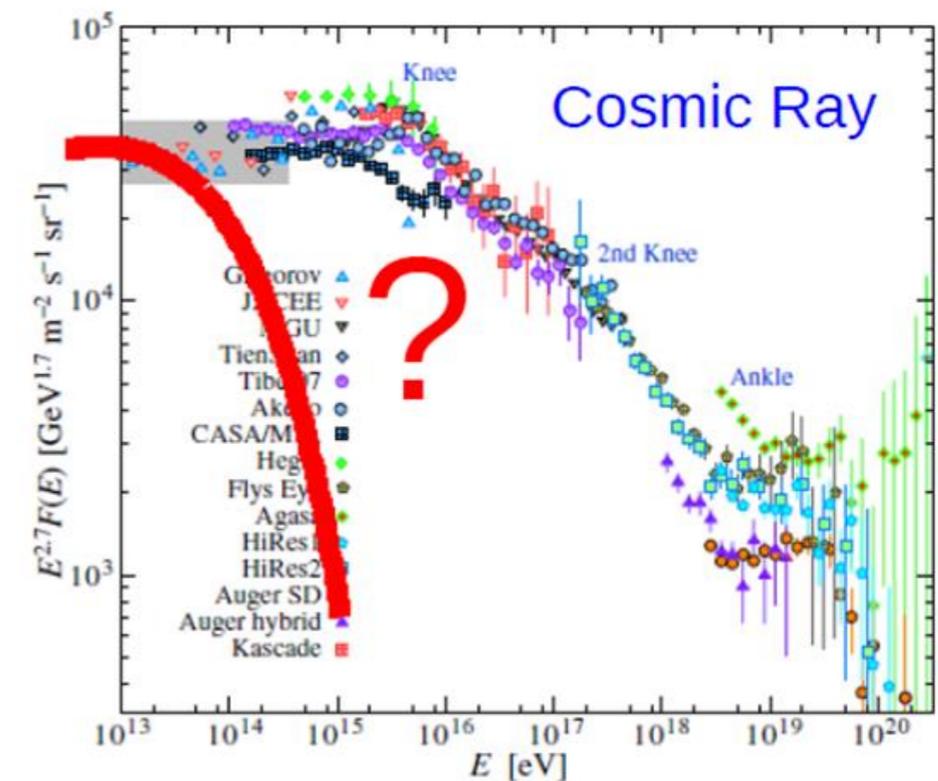
- 残された課題：
 - 100 TeV以上まで陽子起源なのか？
 - “Knee”まで説明できる天体(PeVatron)は存在するのか？
- さらに高精度な観測が必要



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



$$E' = E \times 10$$

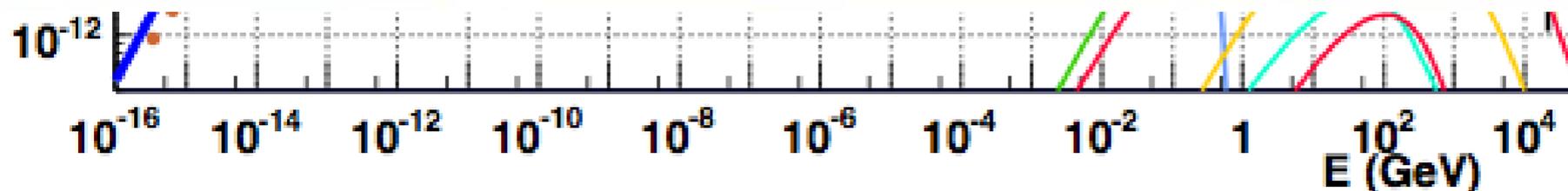
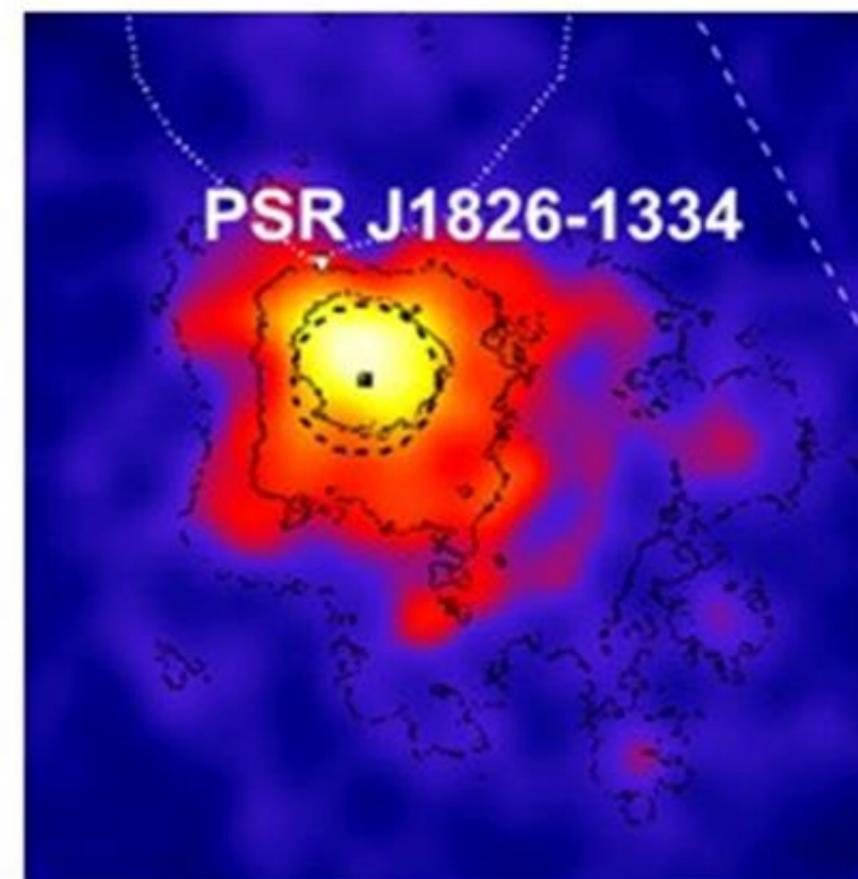
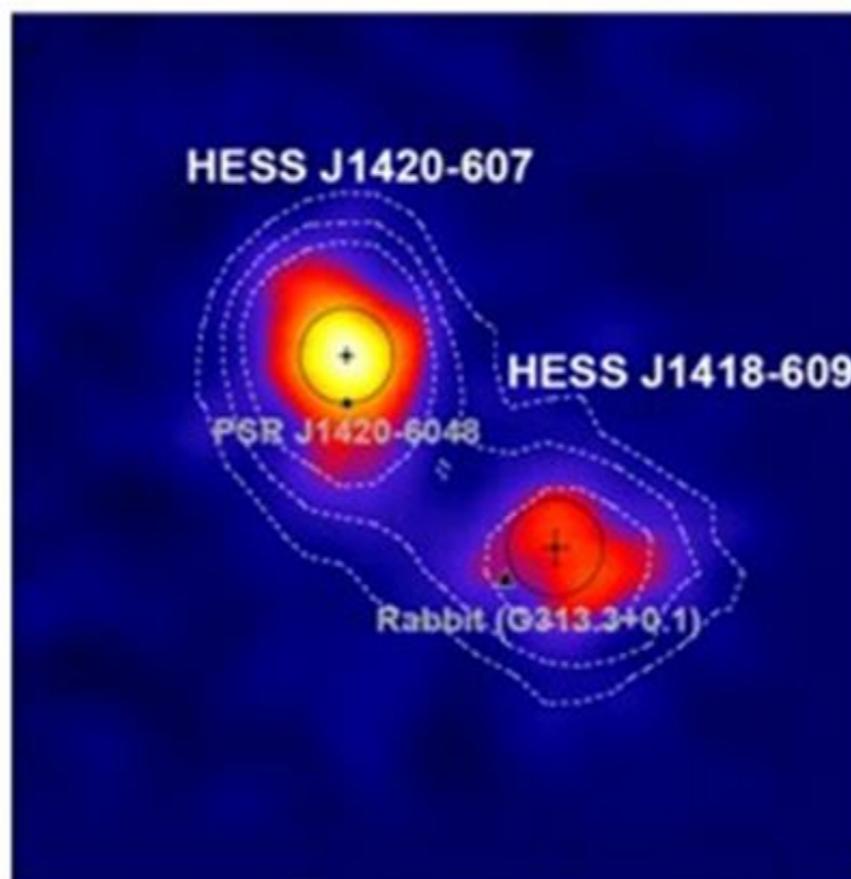
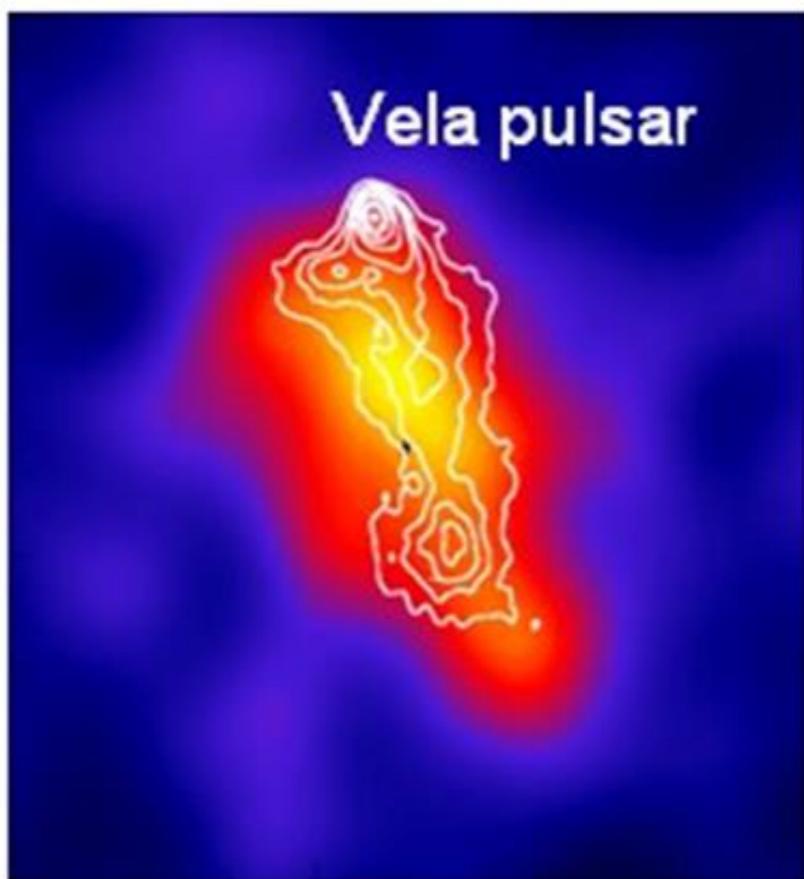
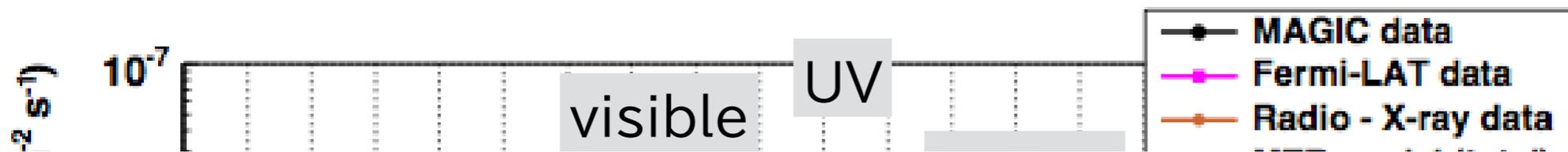


パルサー風星雲^G

Crab Nebula

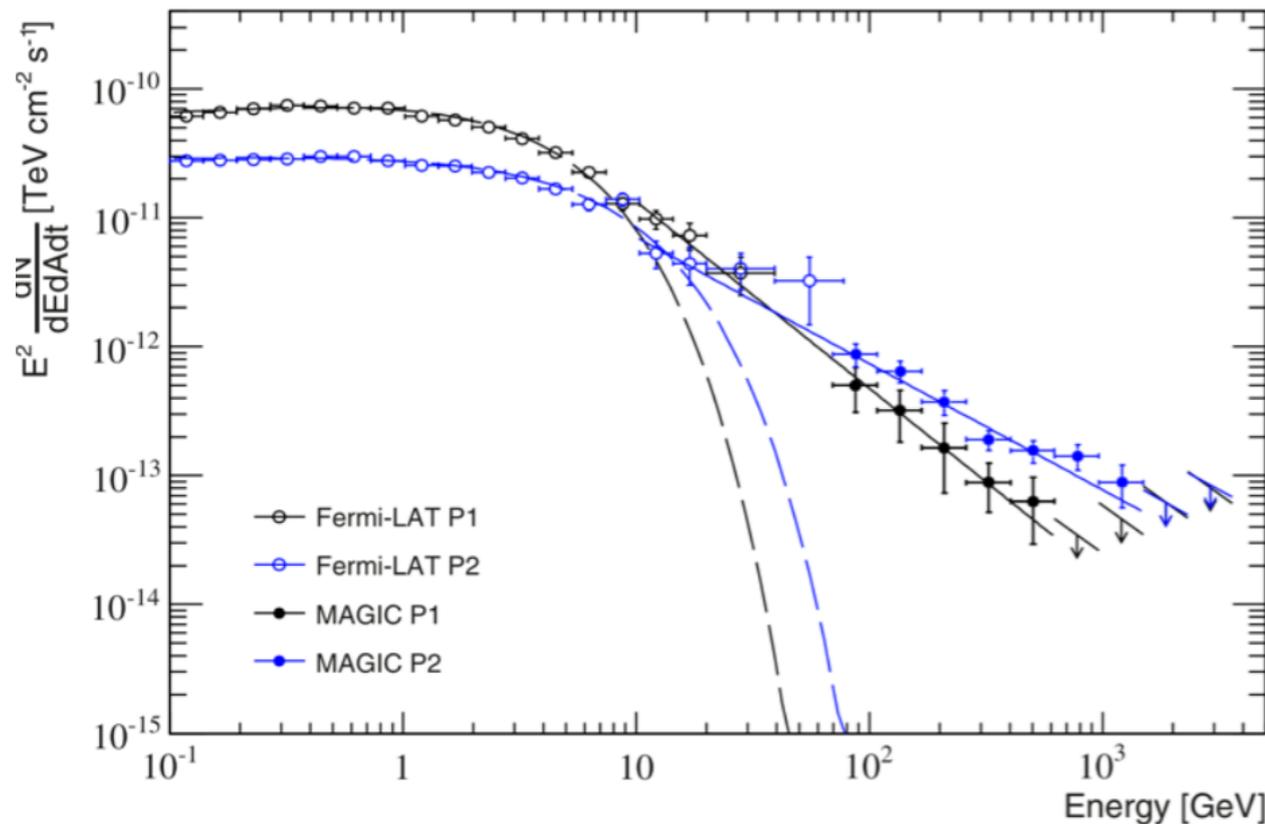
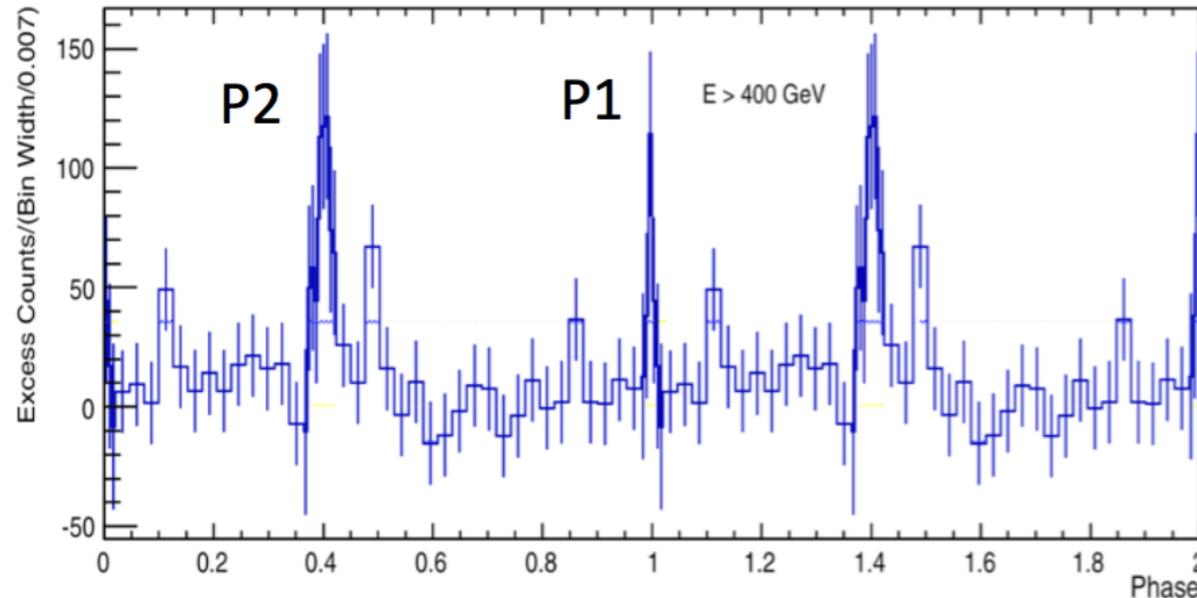


非熱的で、20桁にもわたる帯域で放射

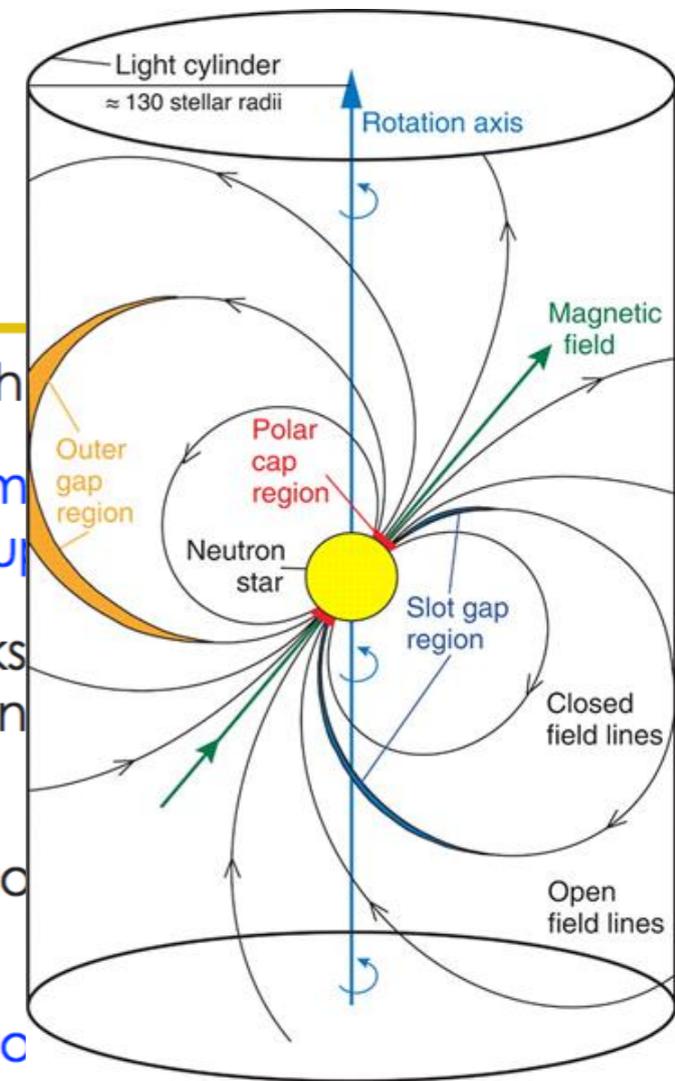


Pulsars: Crab^G

MAGIC, 2016, A&A, 585, A33



- MAGIC dataset: 320 h
- Discovered pulsed emission spectrum extending up to 10 TeV
- Spectra of both peaks are power-laws far beyond their cutoffs:
 - P1 detected up to $(\Gamma=3.5 \pm 0.1)$
 - P2 detected up to $(\Gamma=3.0 \pm 0.1)$



天の川銀河中心GF

Galactic Center

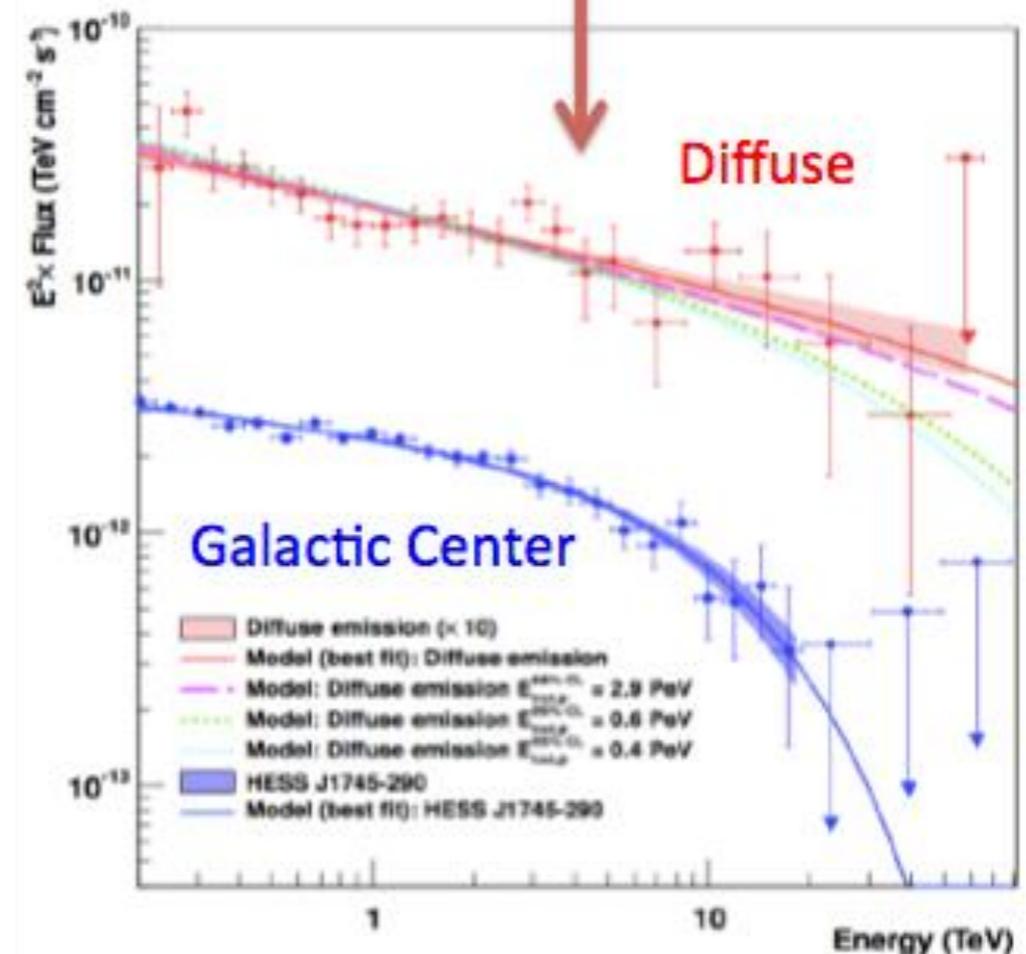
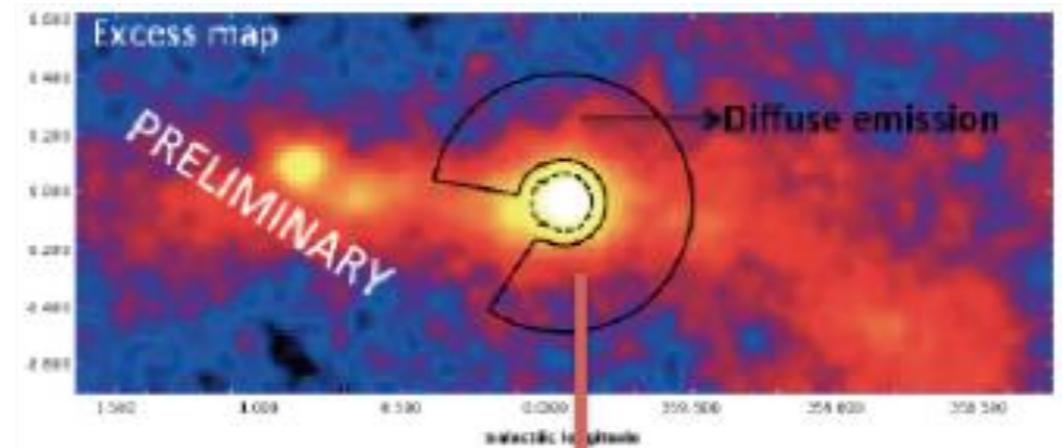
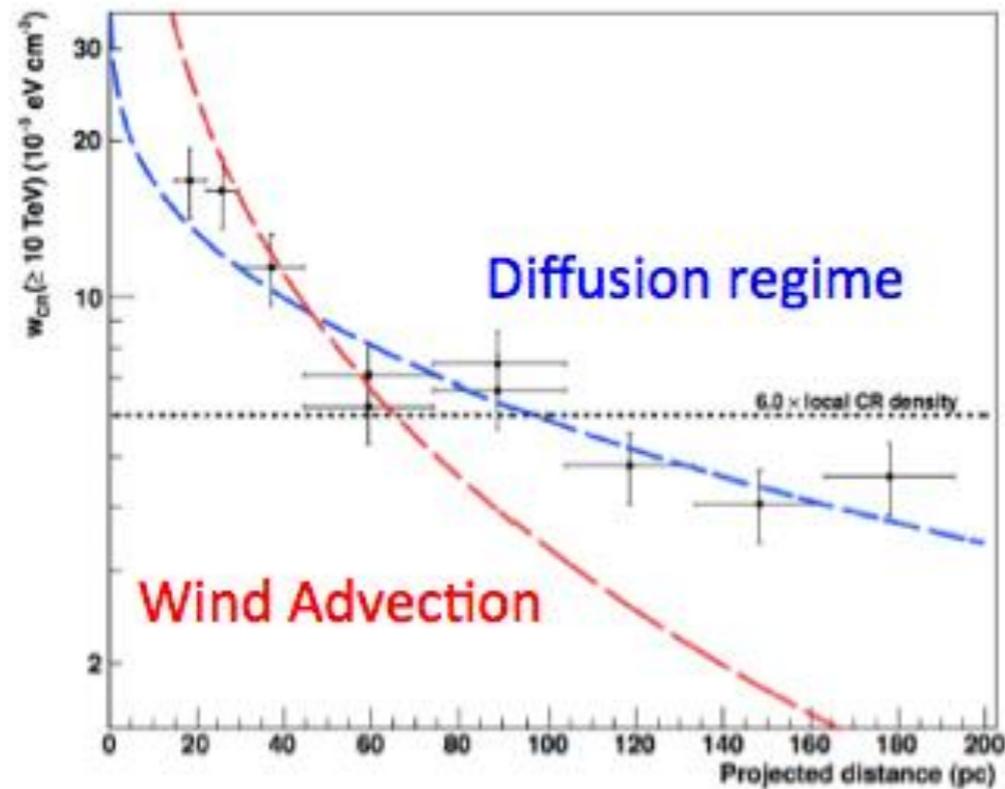
HESS Deep Observation of 250hrs

Spectrum:

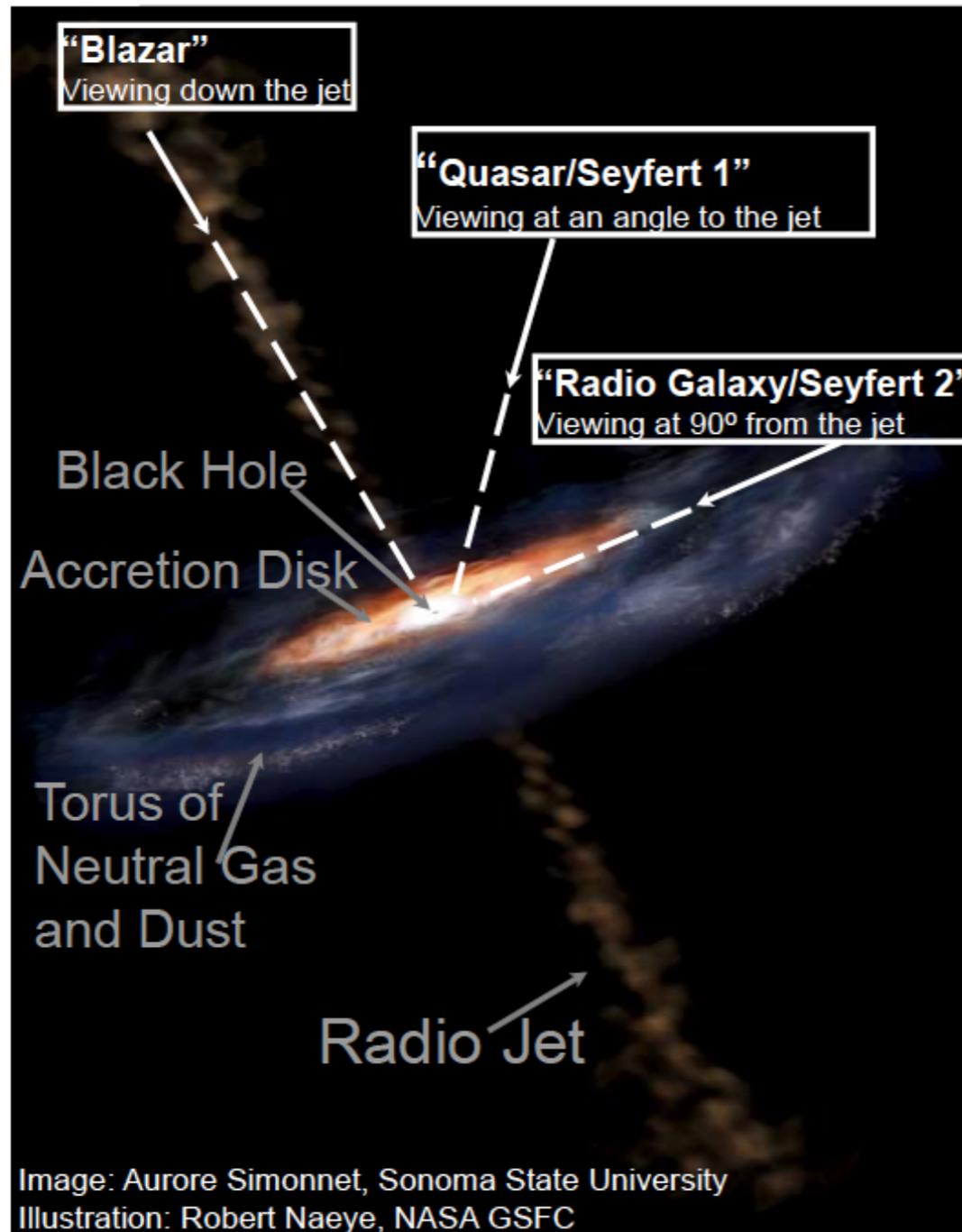
Parent proton could be 1PeV → PeVATRON?

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

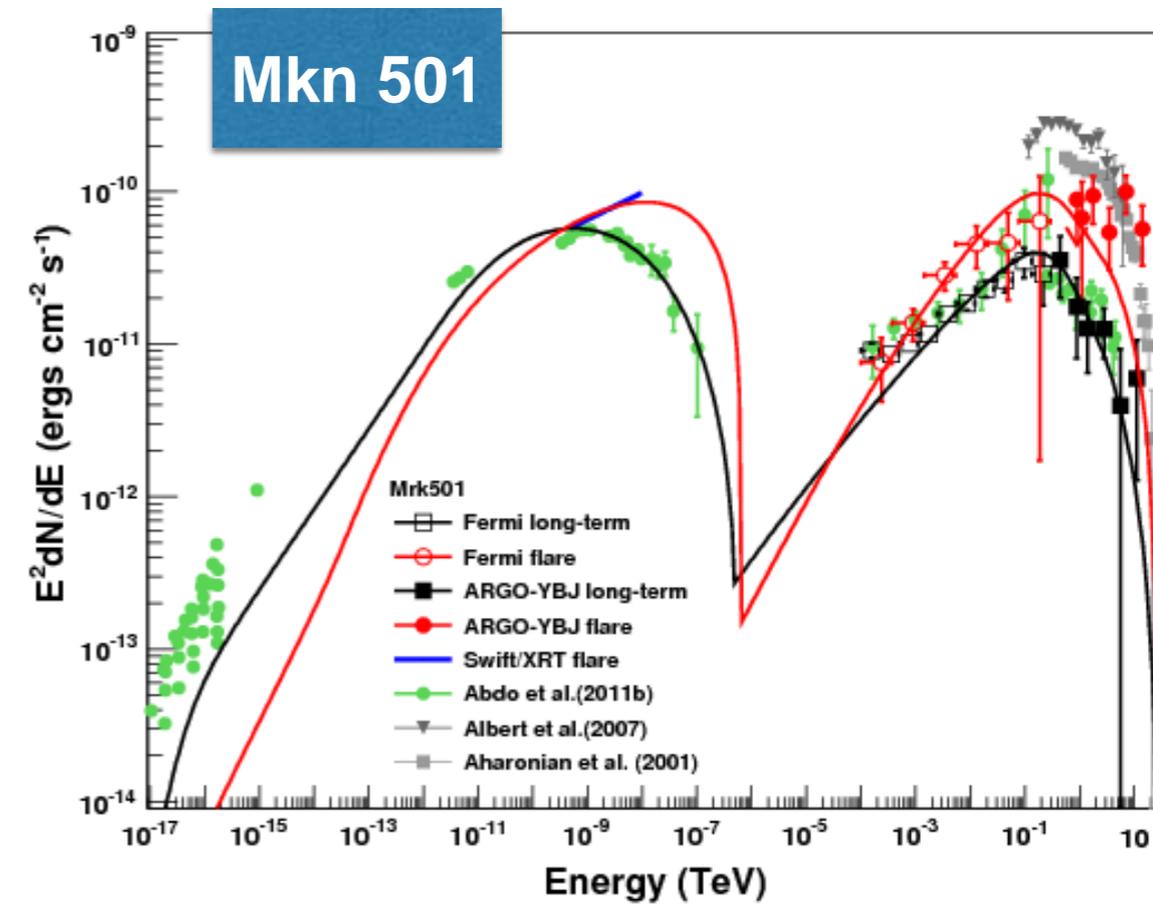
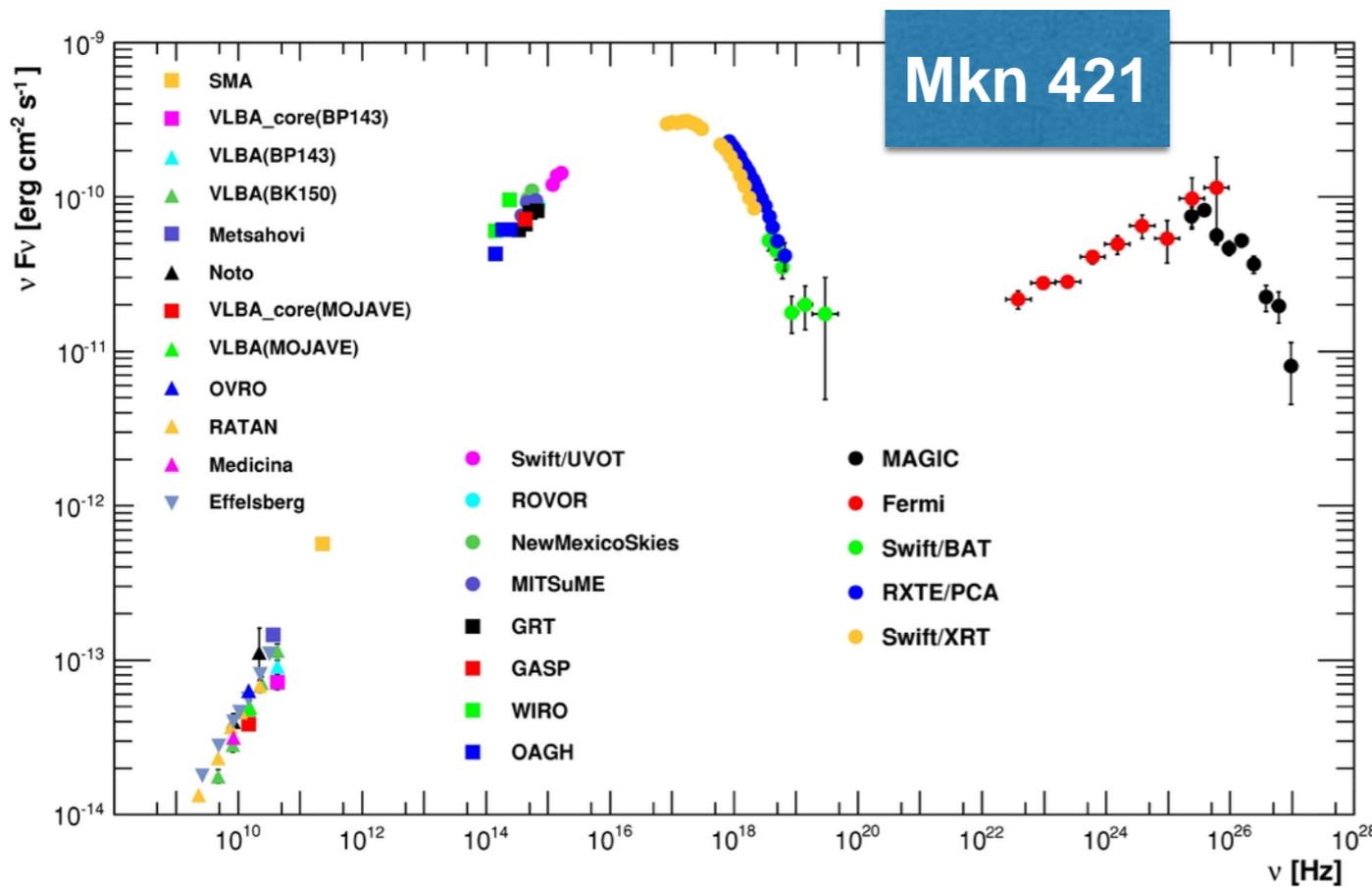
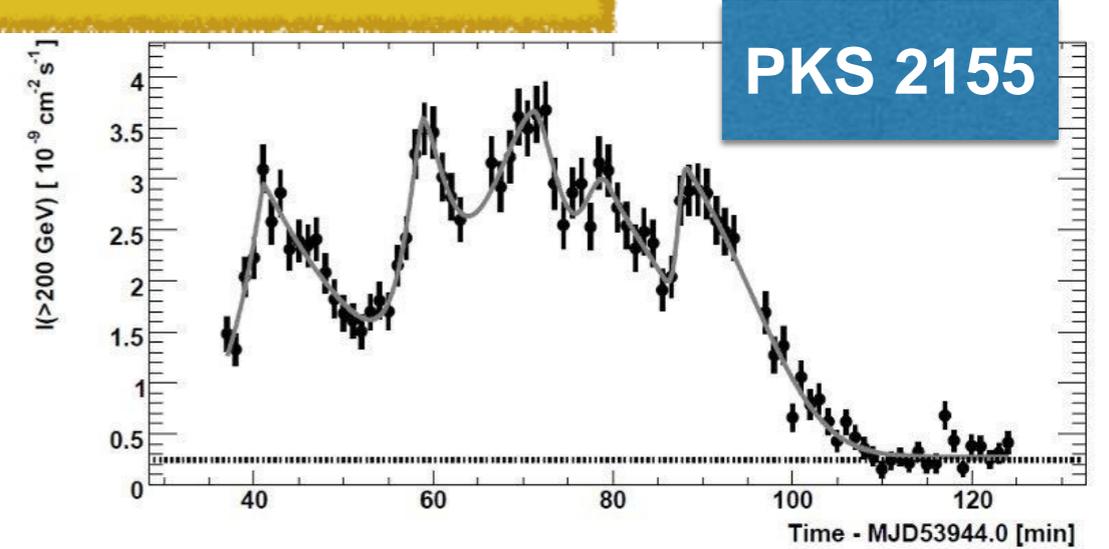
But also radio galaxies (e.g M87)

- Jet viewed from the side

活動銀河核(ブレイザー)E

BLAZARS

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



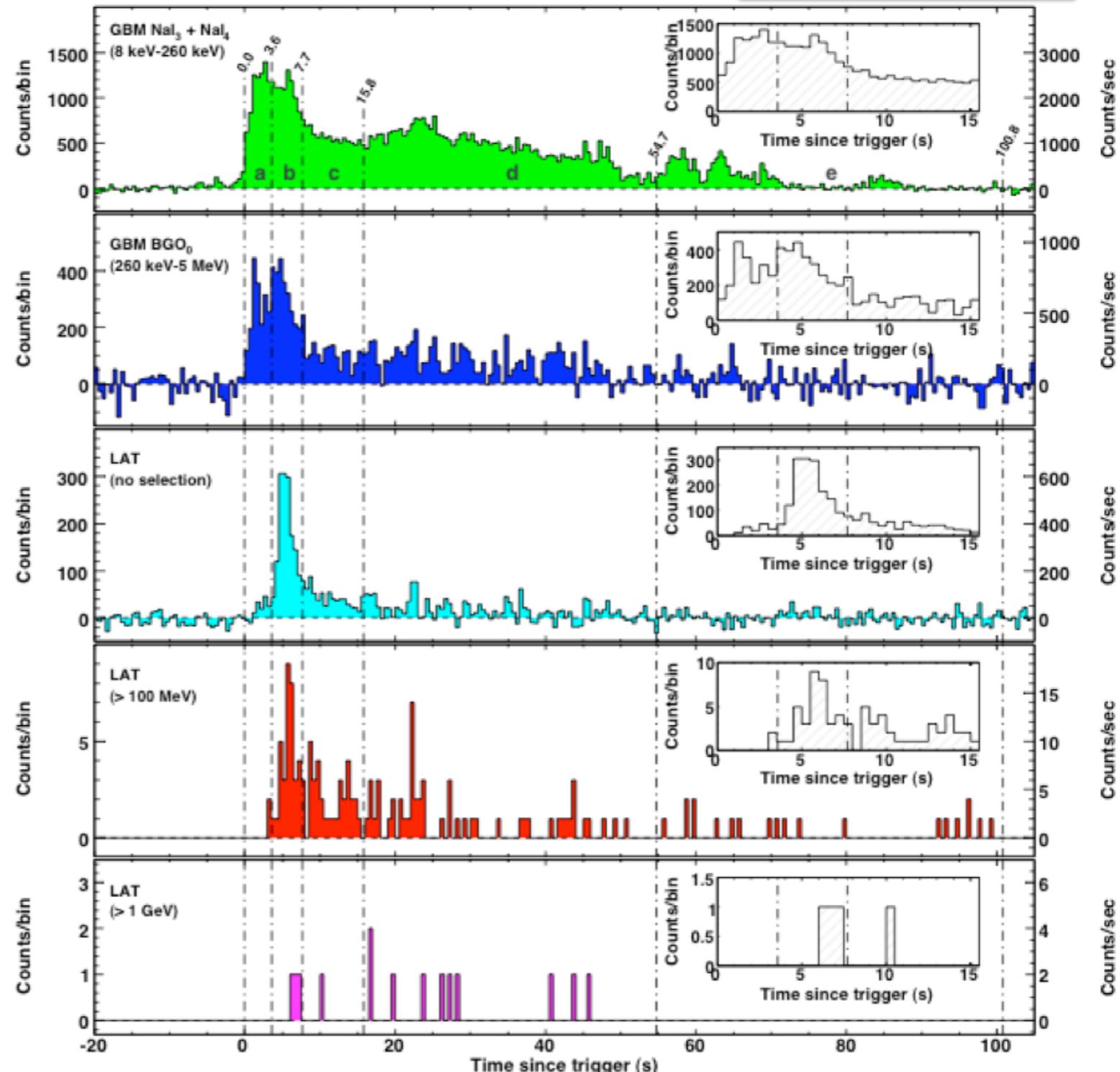
ガンマ線バースト^E

GRBs

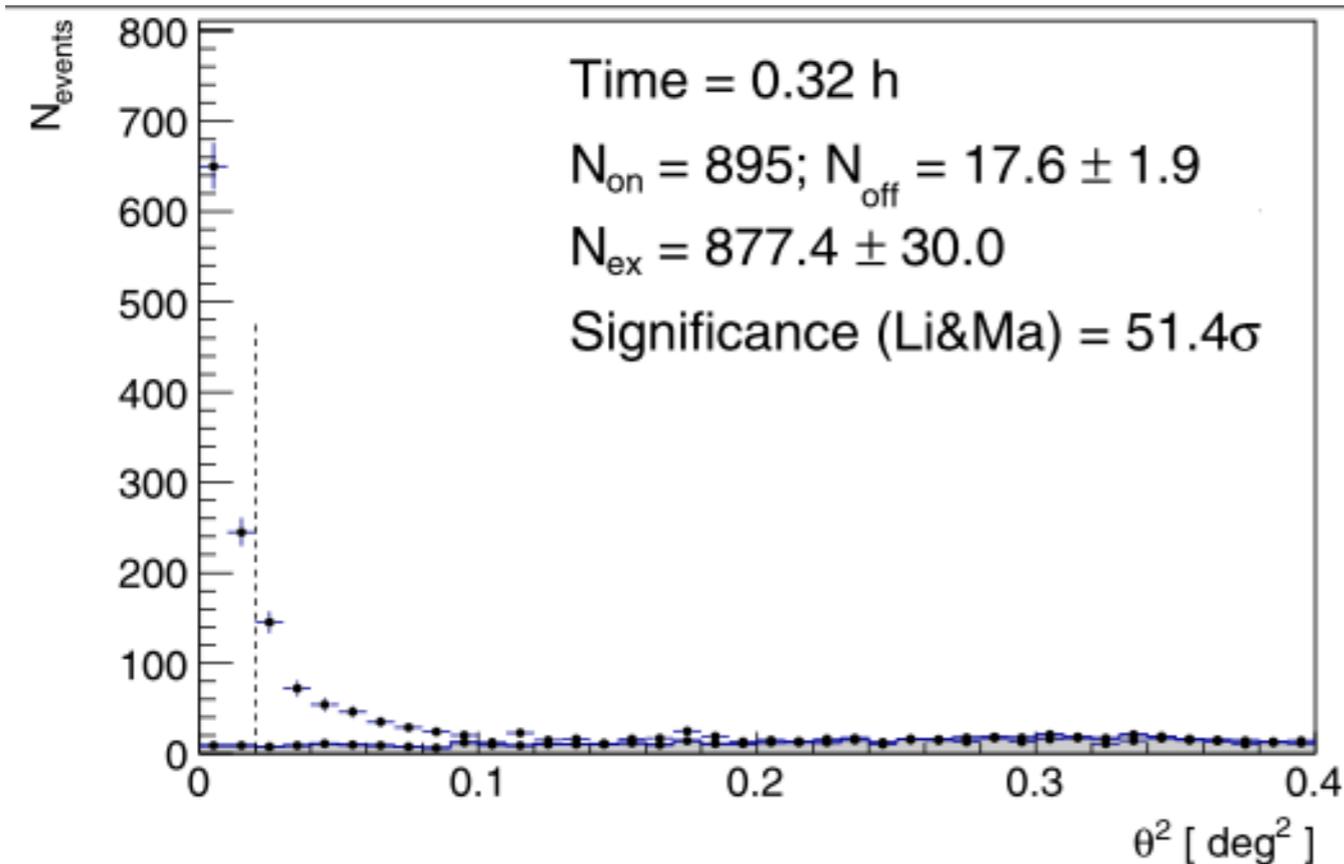
GRB 080916C

- 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.

$$z = 4.35 \pm 0.15$$



GRB 190114C^E



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 method¹².



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

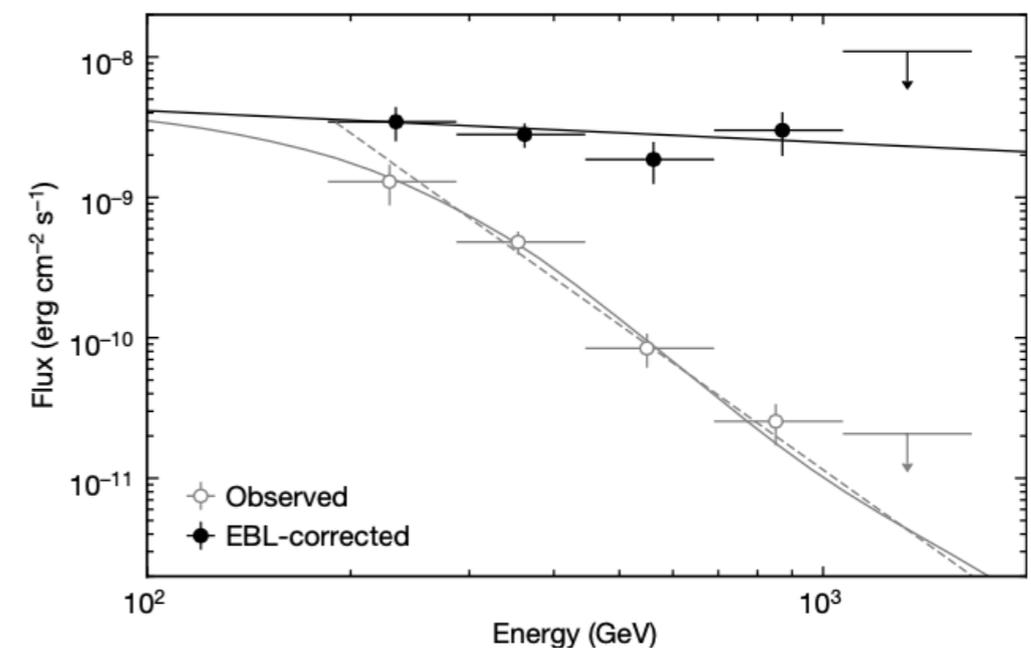


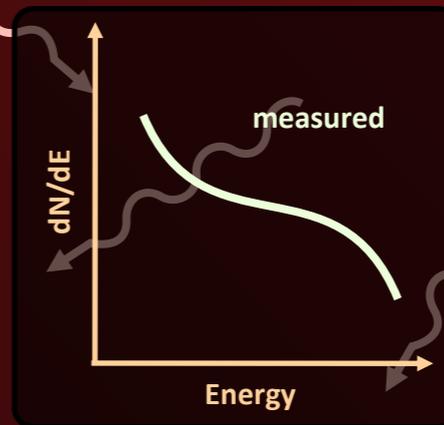
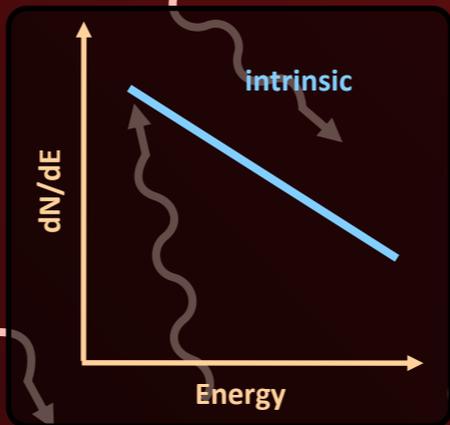
Fig. 2 | Spectrum above 0.2 TeV averaged over the period between $T_0 + 62$ s and $T_0 + 2,454$ s for GRB 190114C. Spectral-energy distributions for the

AGN

Stars and Dust in Galaxies

HE/VHE Y-Rays

UV/O/IR Photons



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

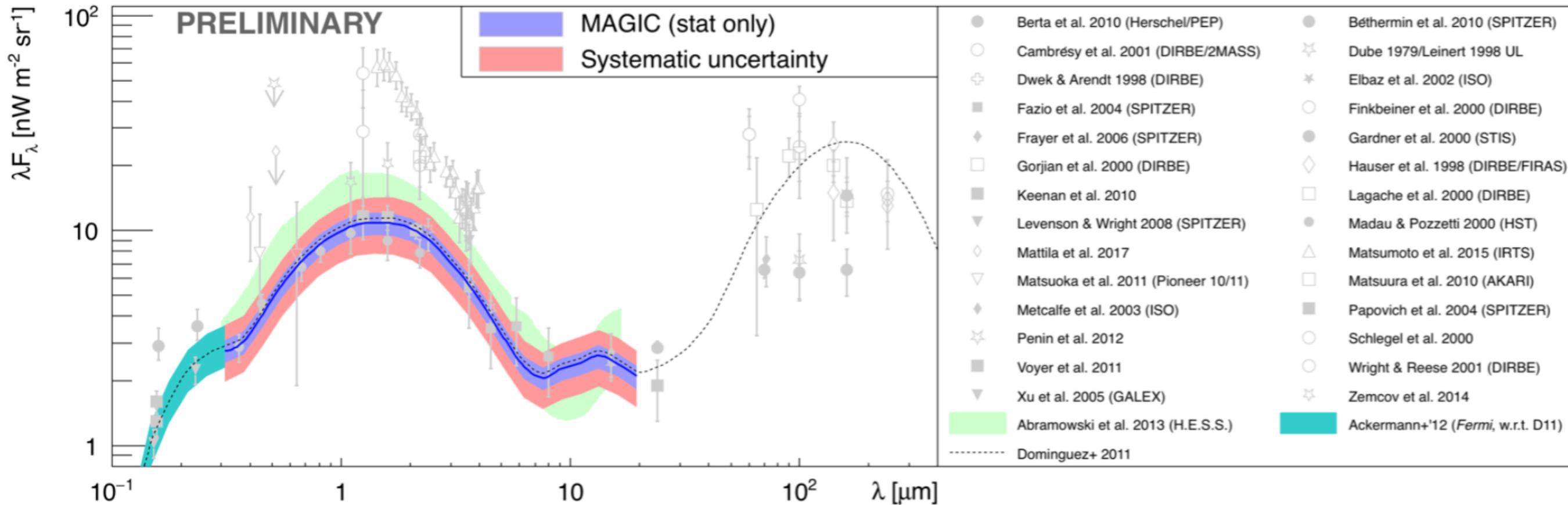
$$E_{\text{EBL}} \sim \text{eV} \rightarrow E_\gamma \sim \text{TeV}$$

e^+
 e^-



銀河外背景光^F

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^F

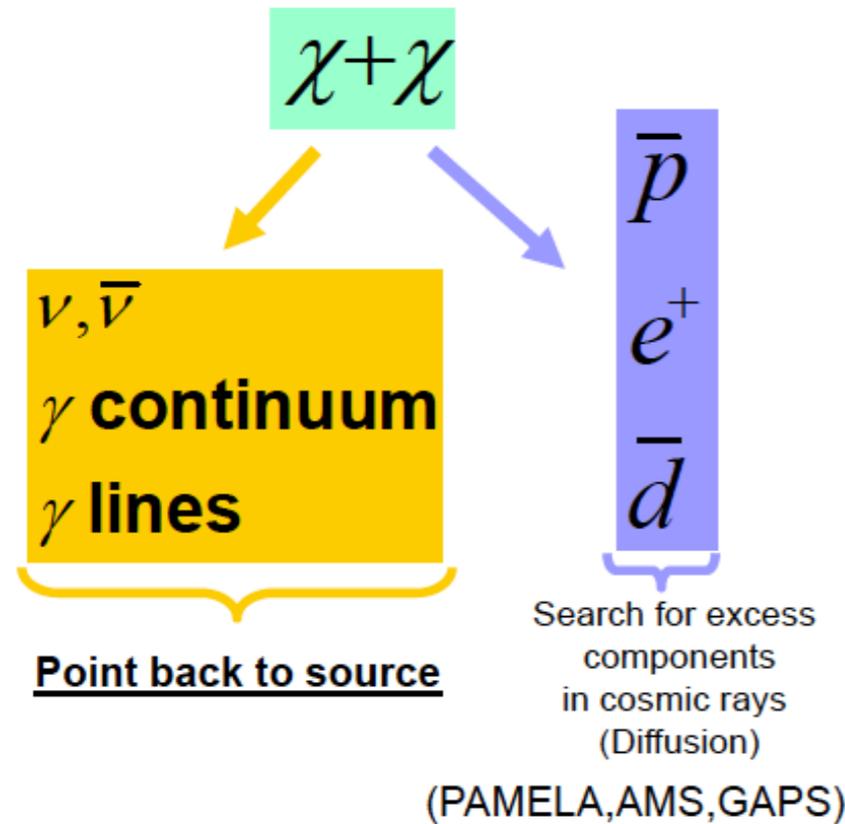
Search for Cold Dark Matter

Hypothesis: DM = WIMPs

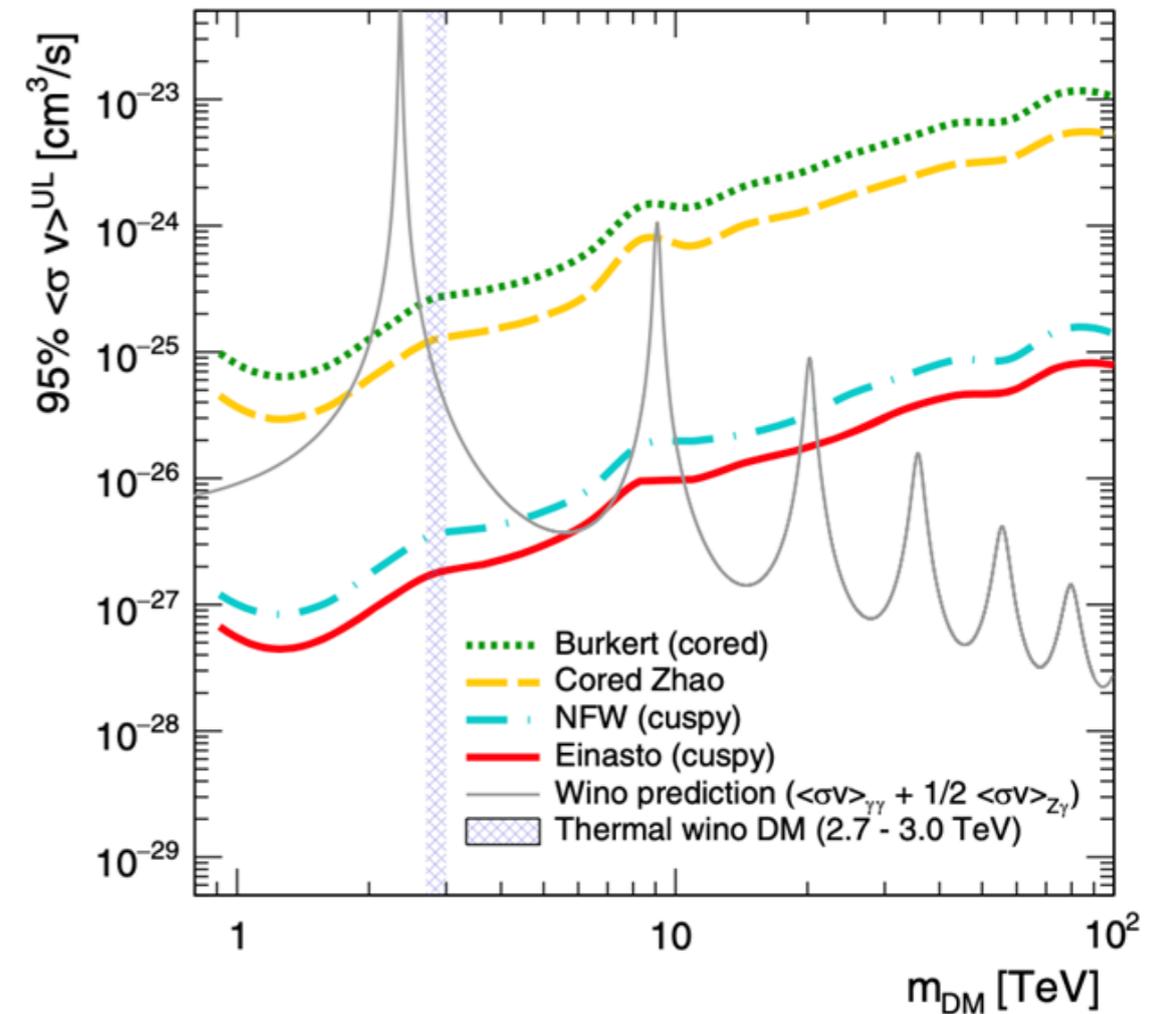
- Indirect detection of WIMP annihilation $\rightarrow \gamma, \nu$ etc.

Target regions with:

- Favorable DM distributions
- Large mass/light ratio

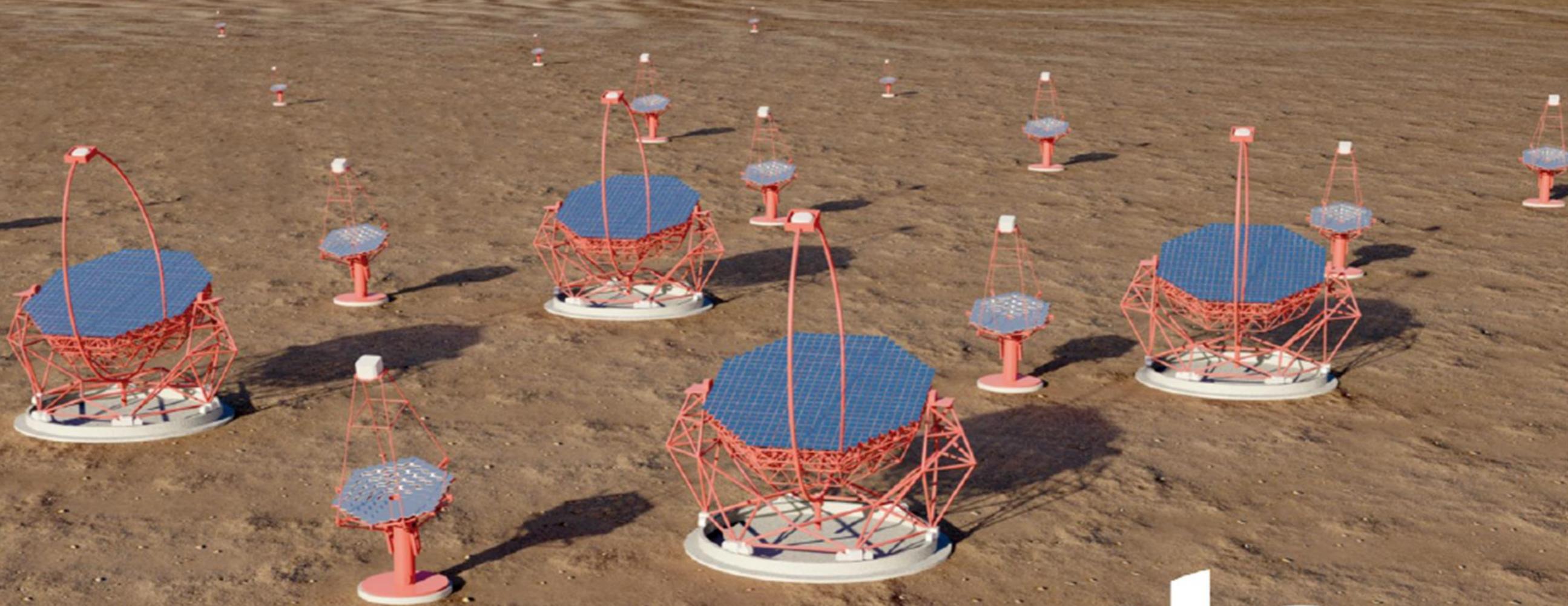


MAGIC U.L. (2023)
Line Search from G.C.



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

THE NEXT BIG STEP: THE CHERENKOV TELESCOPE ARRAY



- 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)



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

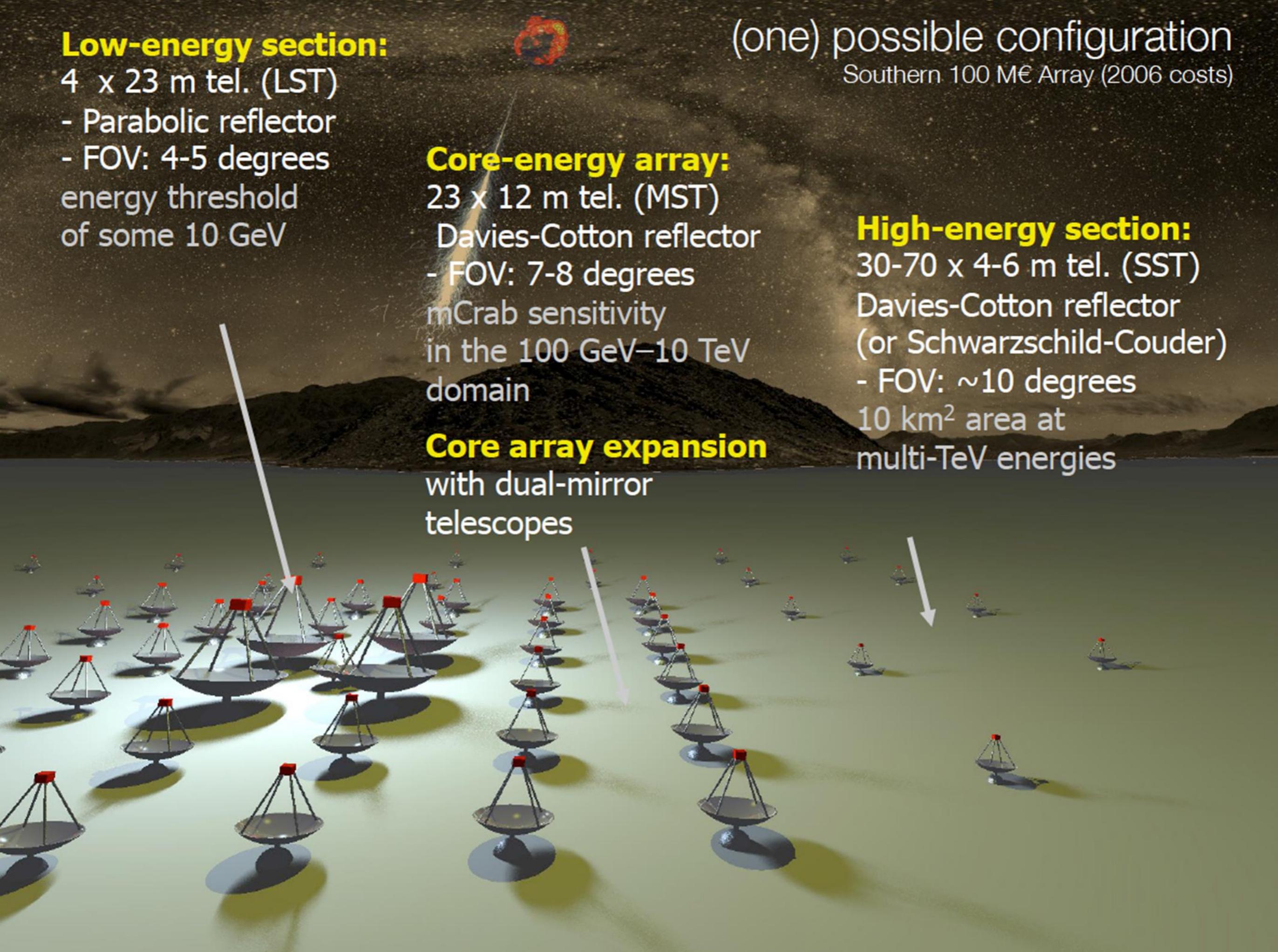
Core array expansion with dual-mirror telescopes

(one) possible configuration

Southern 100 M€ Array (2006 costs)

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

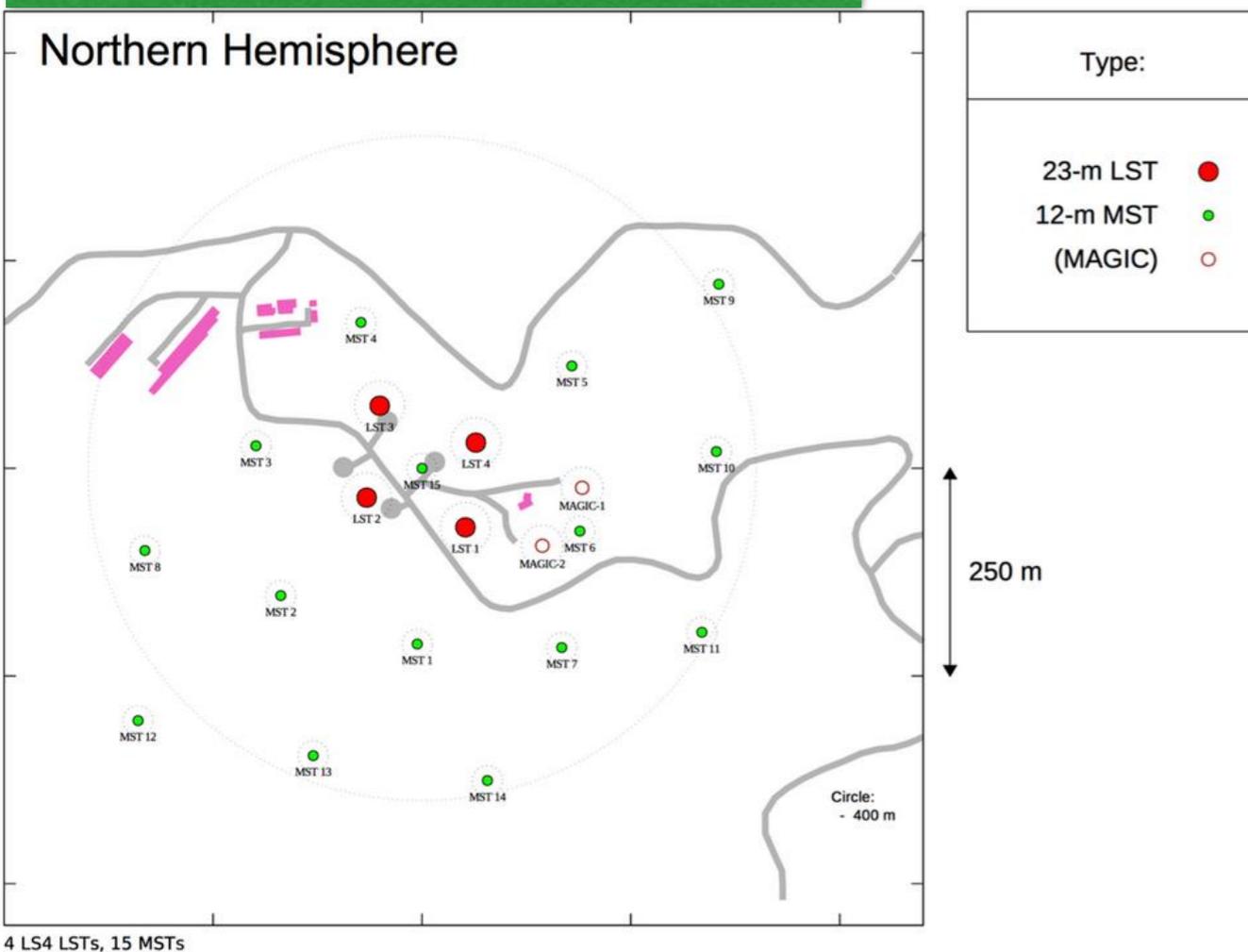


CTA: Array Layouts



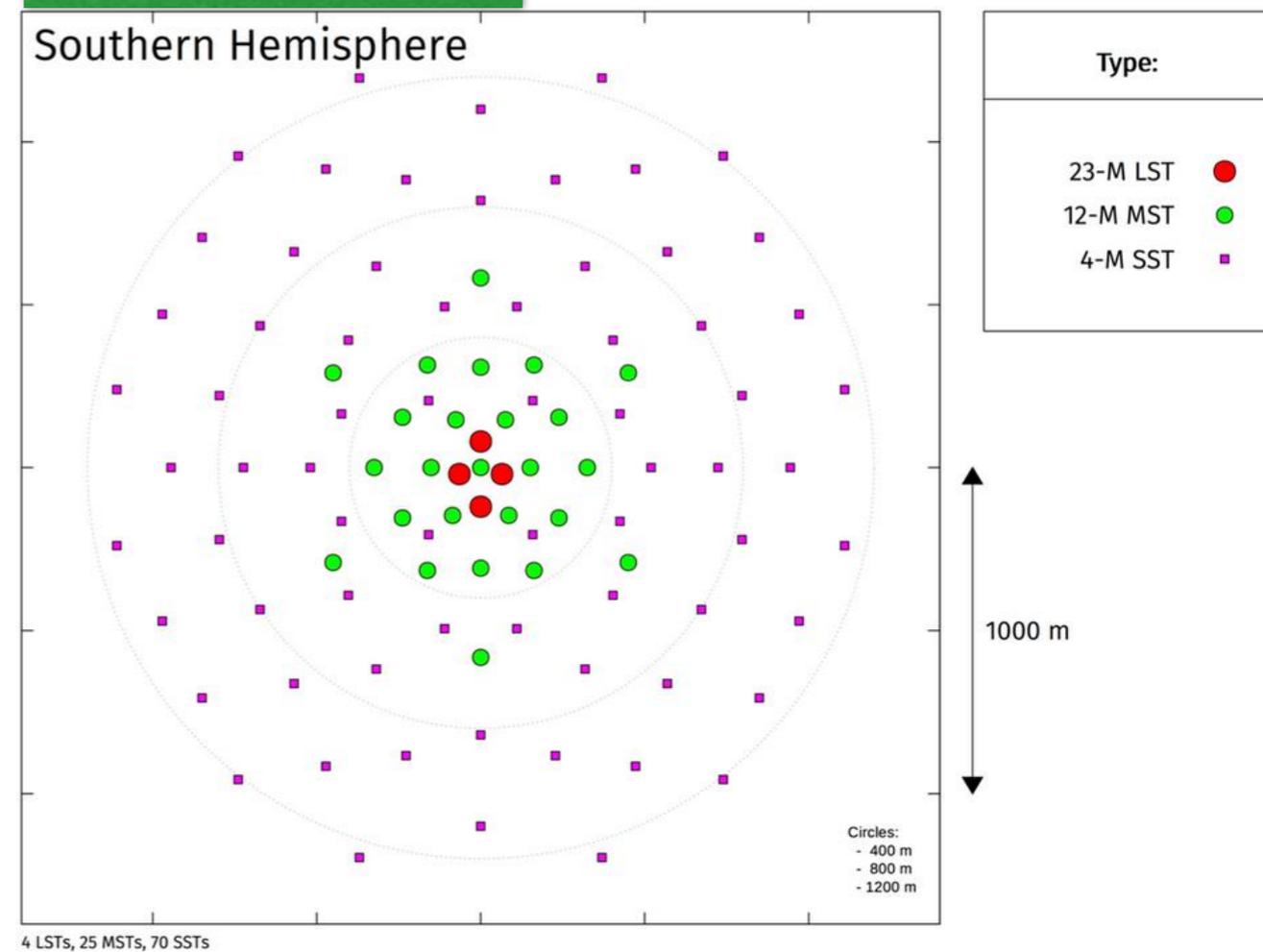
北サイト

La Palma, Canary islands



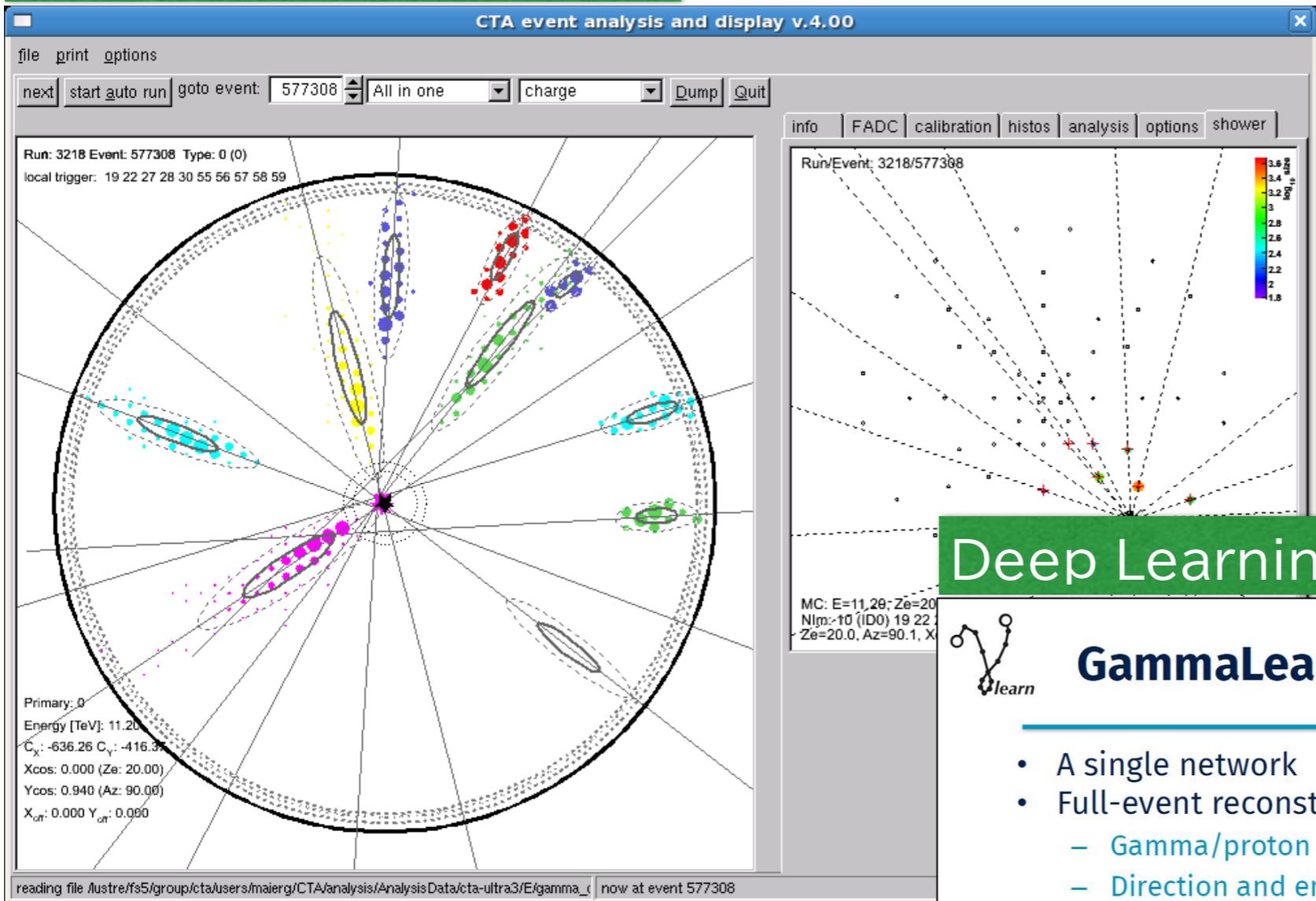
南サイト

Paranal, Chile



CTA: Analysis Techniques

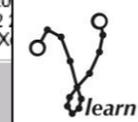
Monte Carlo Simulation



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

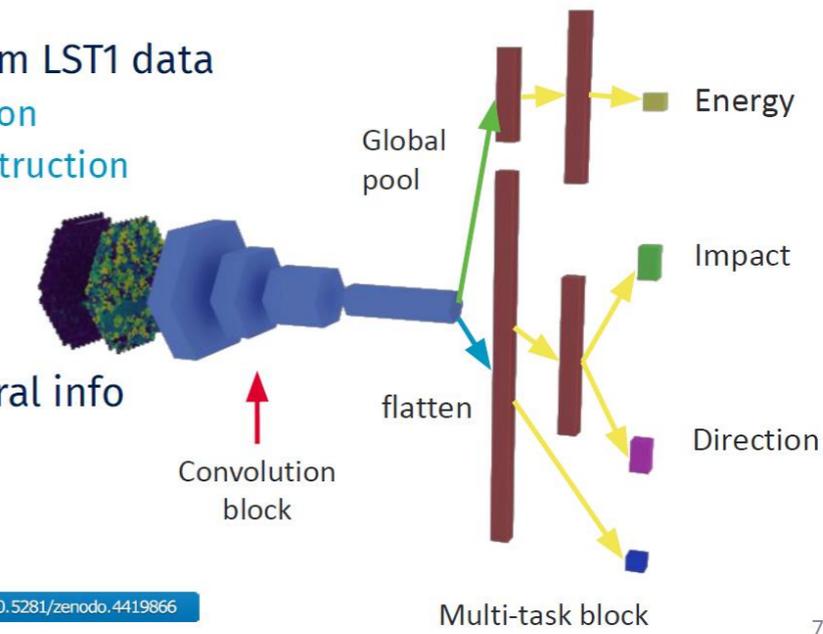


GammaLearn : γ -PhysNet



- 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

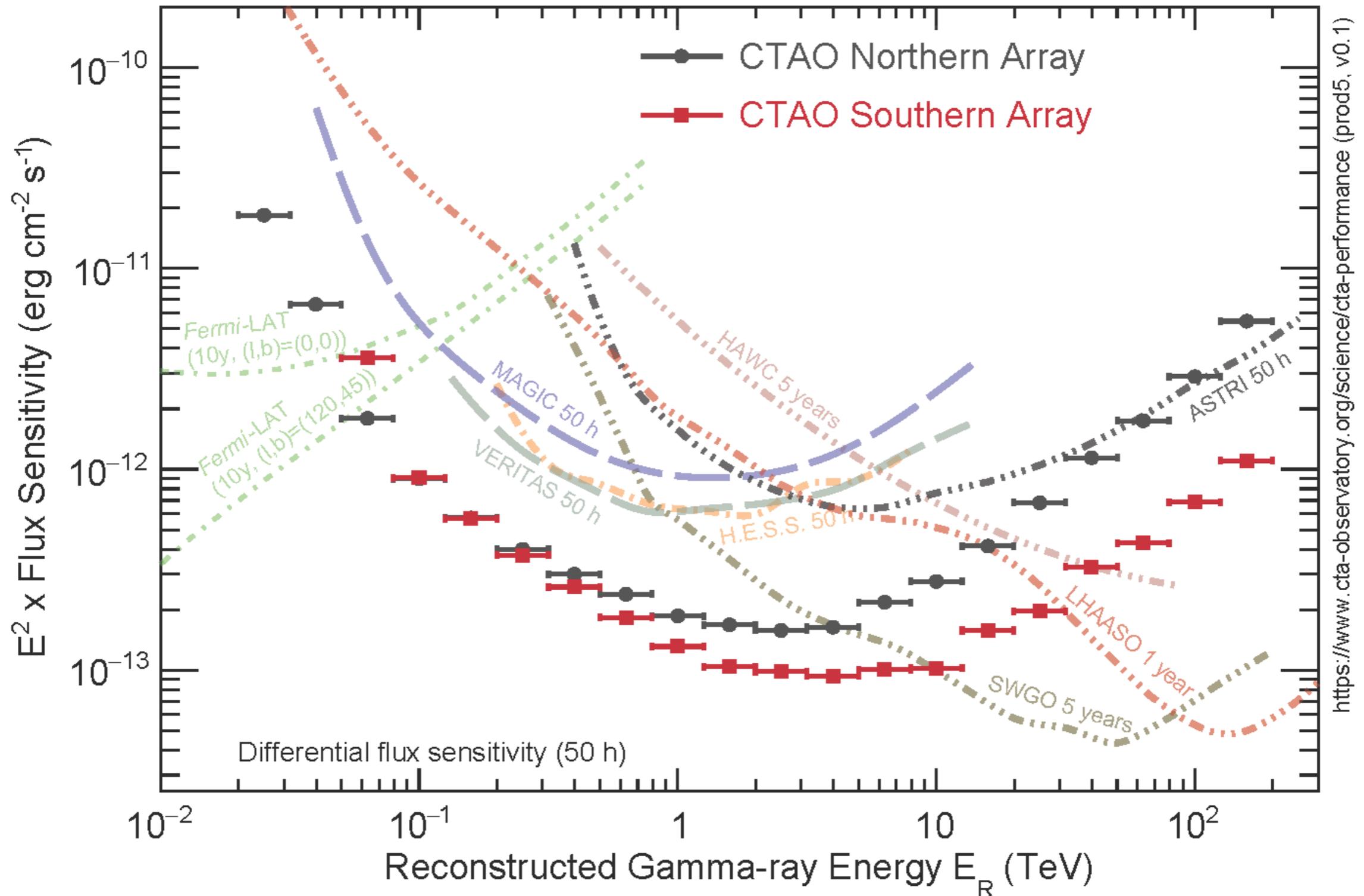


DOI: 10.5281/zenodo.4419866

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



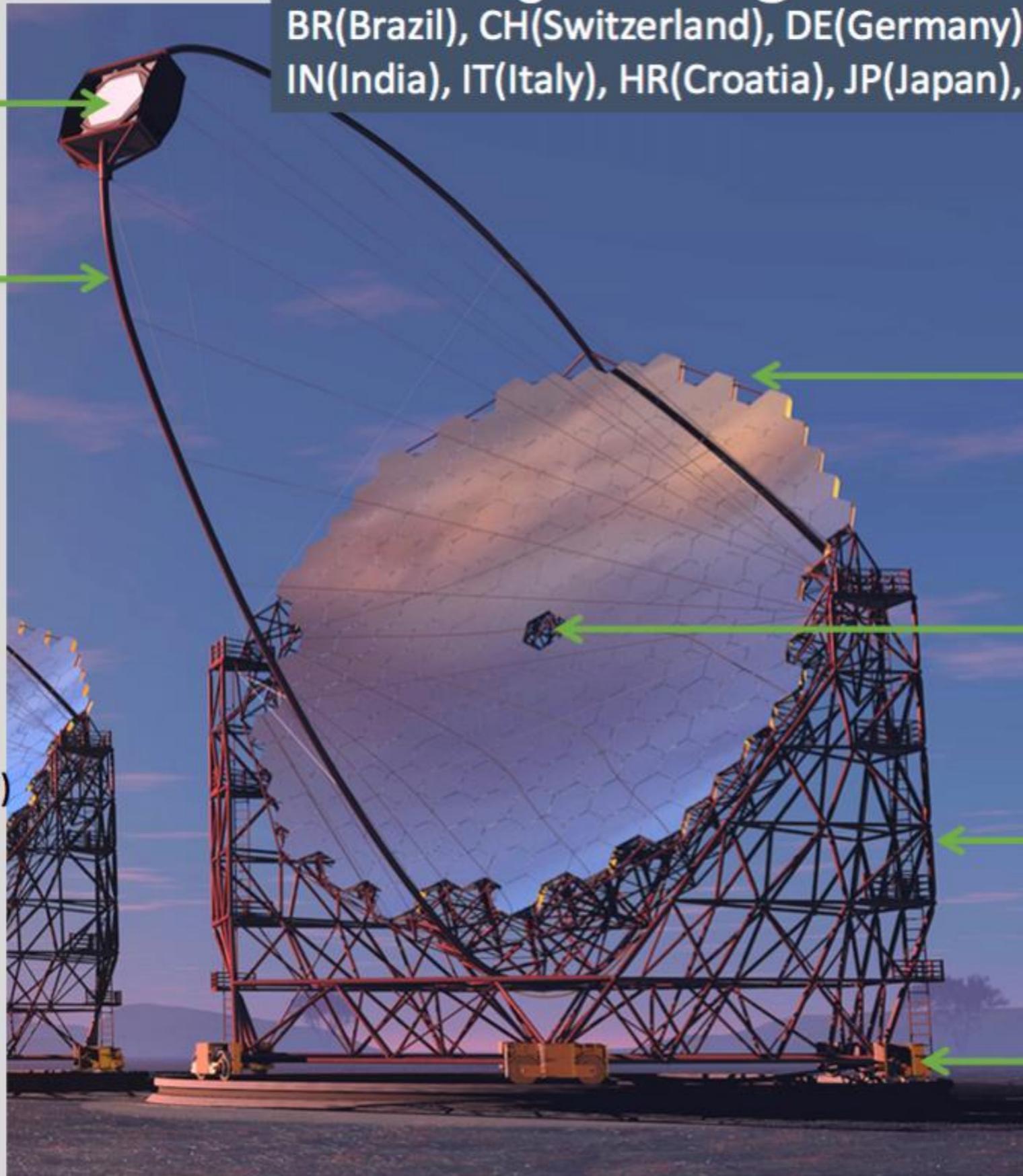
LST Project : Big International Effort

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

+



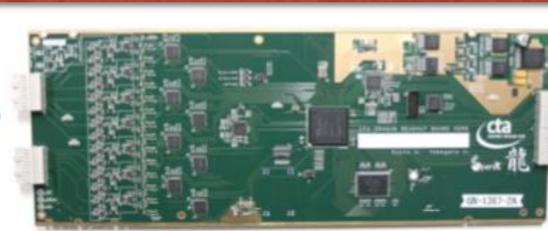
7 PMTs

+



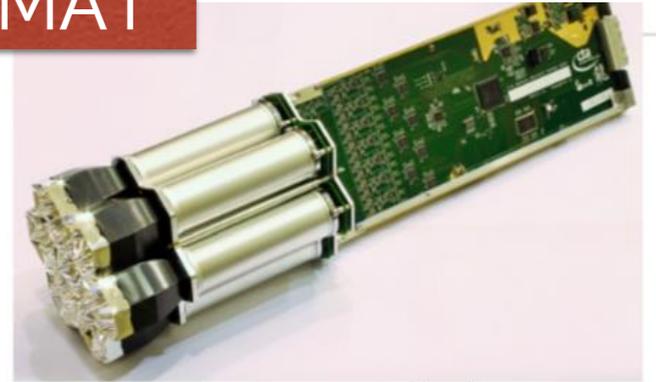
SCB

+



Dragon board

=



FPI module



Module assembly



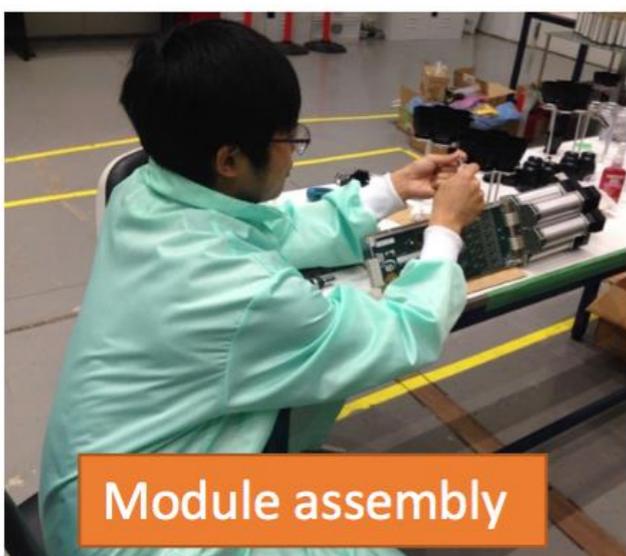
19 tested modules



Trigger back planes

265 modules/ Tel.
needed.

270 modules are
assembled @ IAC



Module assembly



Network switch and TIB
(now TIBv4 available!)



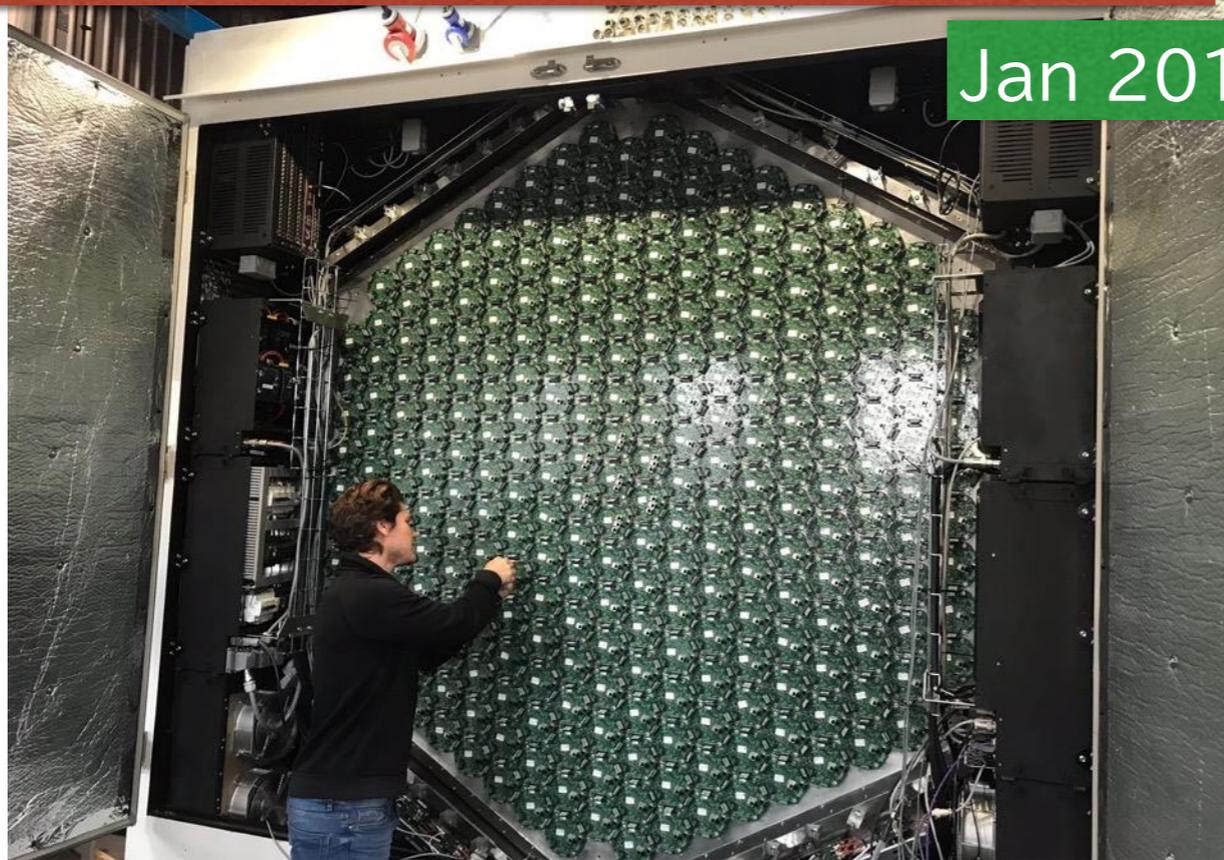
Camera server

Now ready
to ship
to IFAE

21

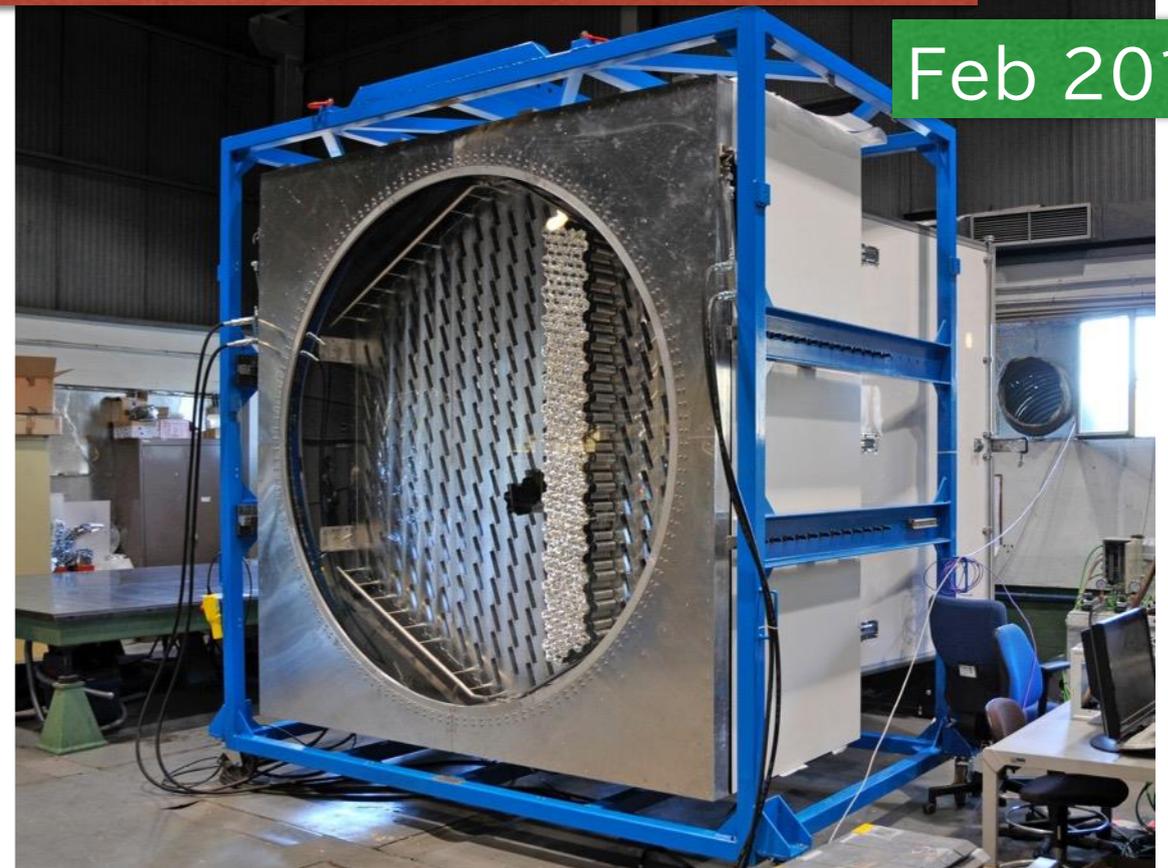
LST1 progress since November 2017

Backplanes of the camera installed



Jan 2018

Camera mechanics finished



Feb 2018

Camera Installation On the telescope

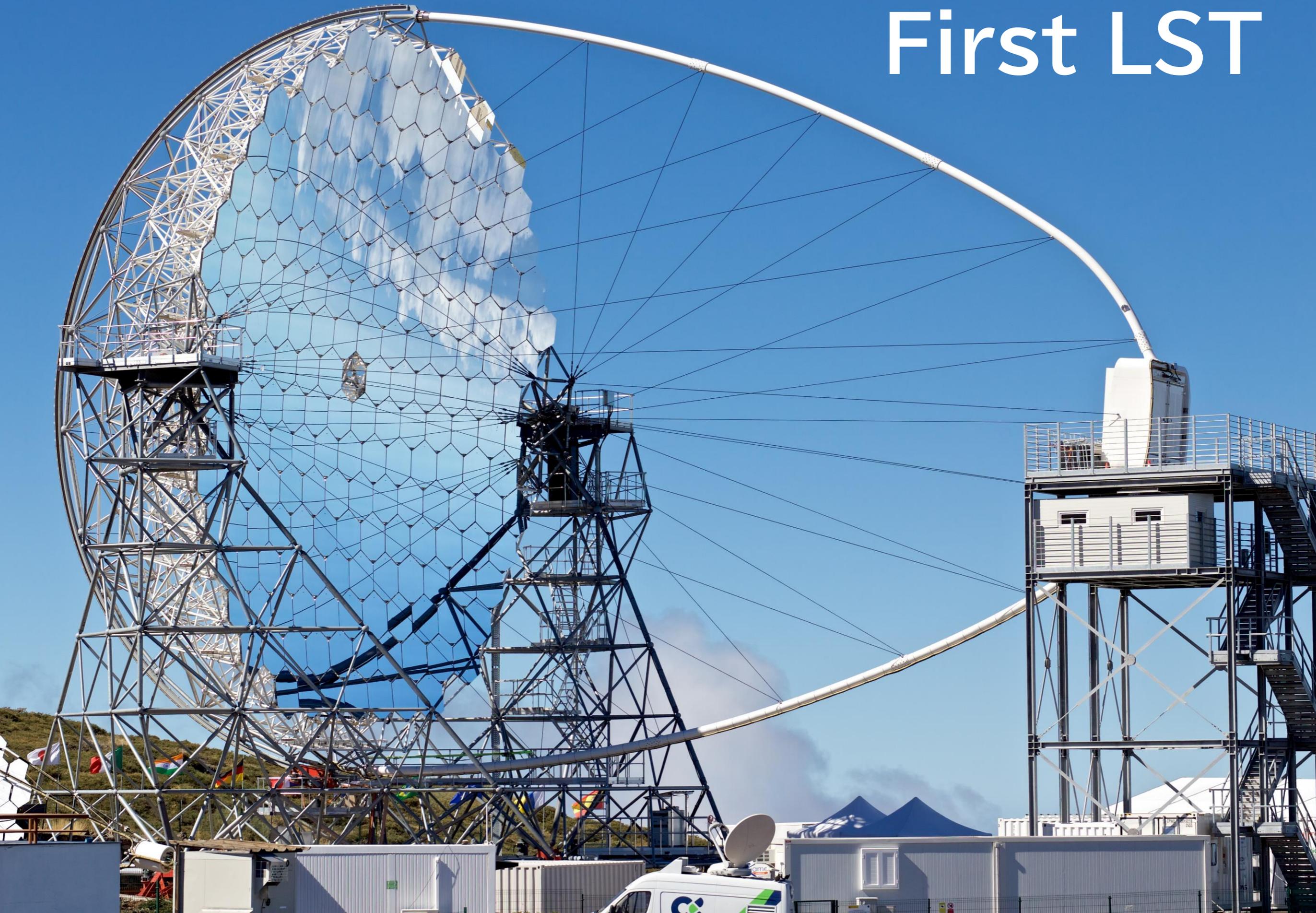


Sep 2018

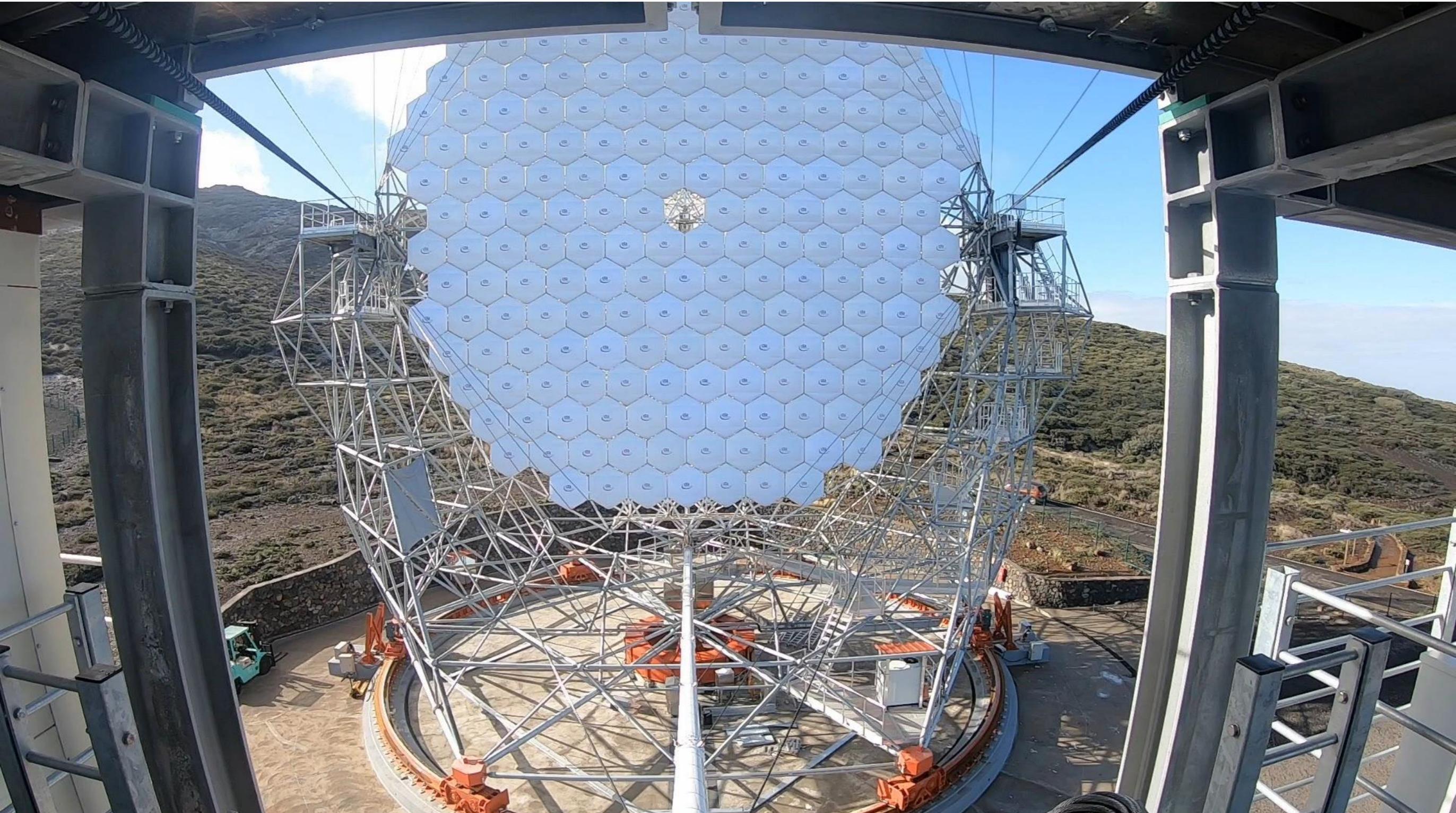


Oct 2018

First LST



Fast Rotation of LST



CTA北サイト:今後の計画

North: La Palma (Spain)



2024年2月時点

まとめ

- VHEガンマ線天文学はまだ若いですが、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