高エネルギーガンマ線天文学

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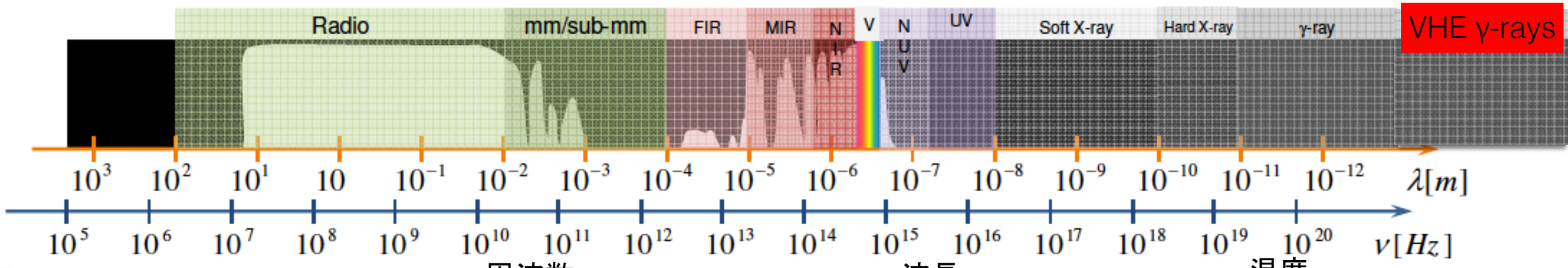
5. 次世代ガンマ線天文台CTA

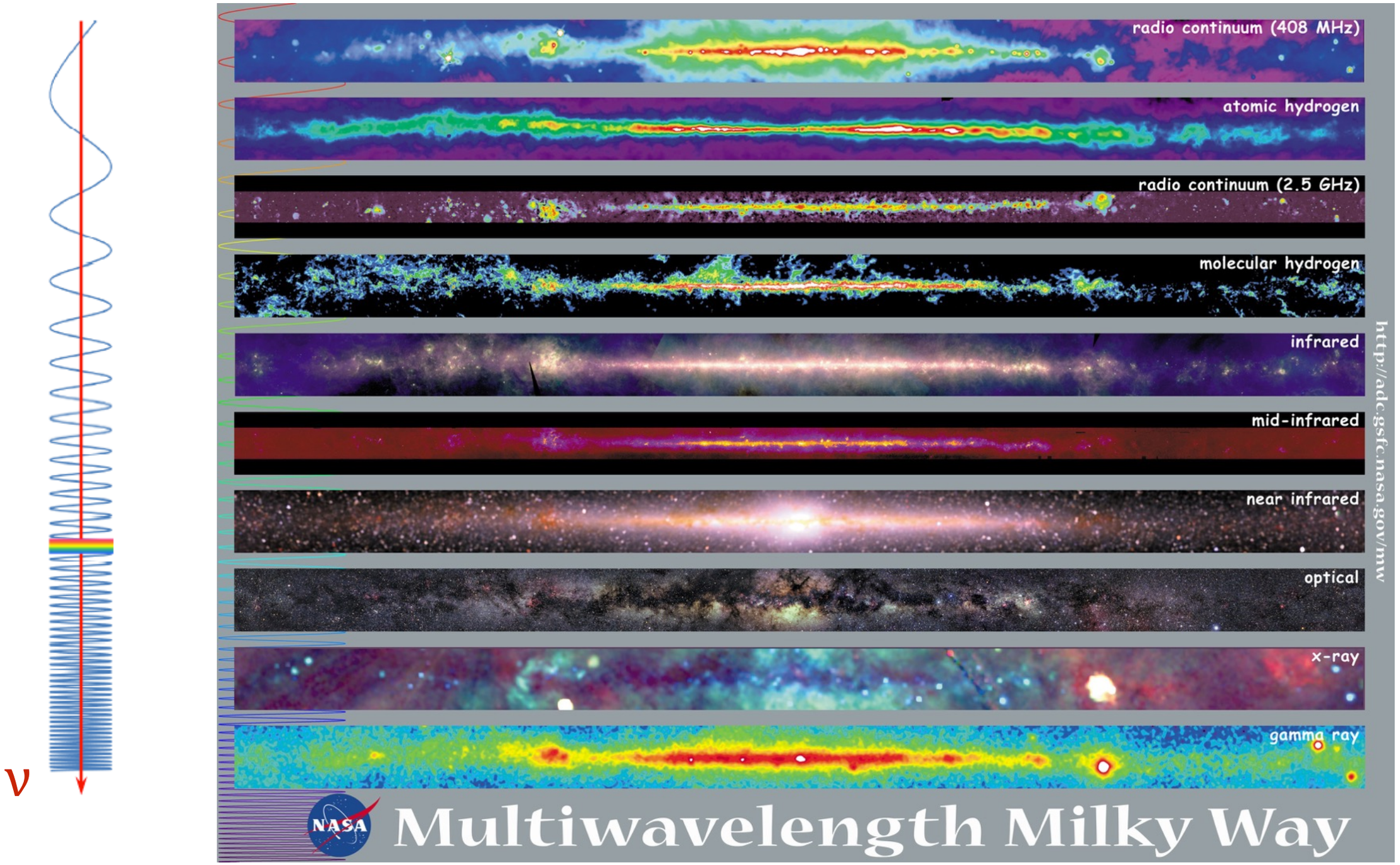
1. 多波長観測



エネルギー		周波数	波長	温度
	Radio	$3MHz \le \nu \le 30GHz$	$100m \ge \lambda \ge 1cm$	$T \sim (10^{-4} \rightarrow 1)K$
10^{-4} - 10^{-2} eV	mm & submm	$30GHz \le \nu \le 3THz$	$10mm \ge \lambda \ge 0.1mm$	$T \sim (1 \rightarrow 100)K$
	Infrared	$3THz \le \nu \le 300THz$	$100\mu m \ge \lambda \ge 1\mu m$	$T \sim (10^{2} \rightarrow 10^{4})K$
1-3 eV	Optical	$3\times10^{14}\,Hz \le \nu \le 10^{15}\,Hz$	$1\mu m \ge \lambda \ge 300nm$	$T \sim 4\times10^{4}\,K$
	Ultraviolet	$10^{15}\,Hz \le \nu \le 3\times10^{16}\,Hz$	$300nm \ge \lambda \ge 10nm$	$T \sim (10^{5} \rightarrow 10^{6})K$
	X-ray	$3\times10^{16}\,Hz \le \nu \le 3\times10^{19}\,Hz$	$10nm \ge \lambda \ge 0.01nm$	$T \sim (10^{6} \rightarrow 10^{9})K$
$>10^{5\text{-}6}$ eV	γ-ray	$\nu \ge 3\times10^{19}\,Hz$	$\lambda \le 0.01nm$	$T \ge 10^{9}\,K$
$>10^{11\text{-}12}$ eV	VHE γ-rays	> 100 GeV		

VHE=Very high energy (超高エネルギー)

1. 多波長観測


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way
ν

1. 多波長観測

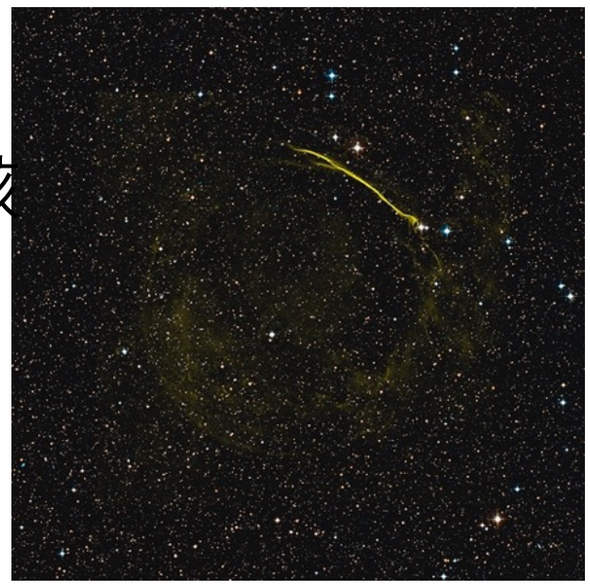
手

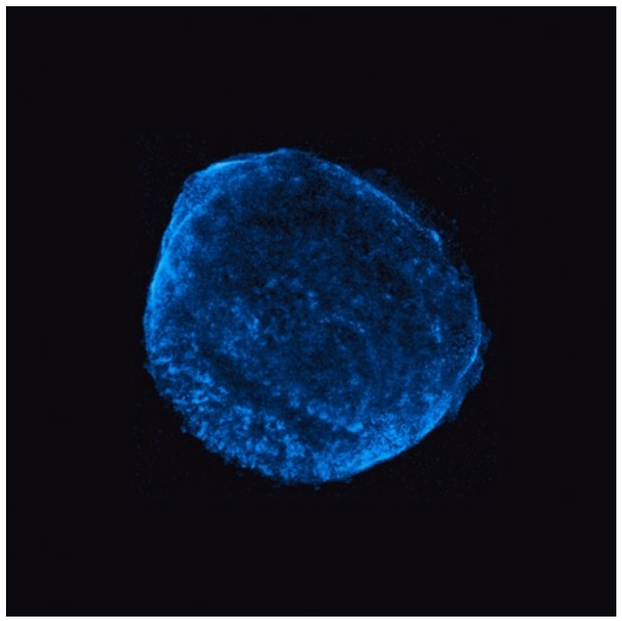
可視光

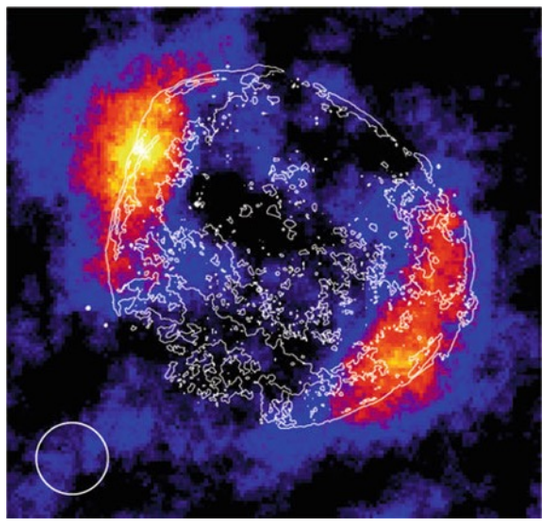
X線

超高エネルギーガンマ線

超新星残骸
SN1006

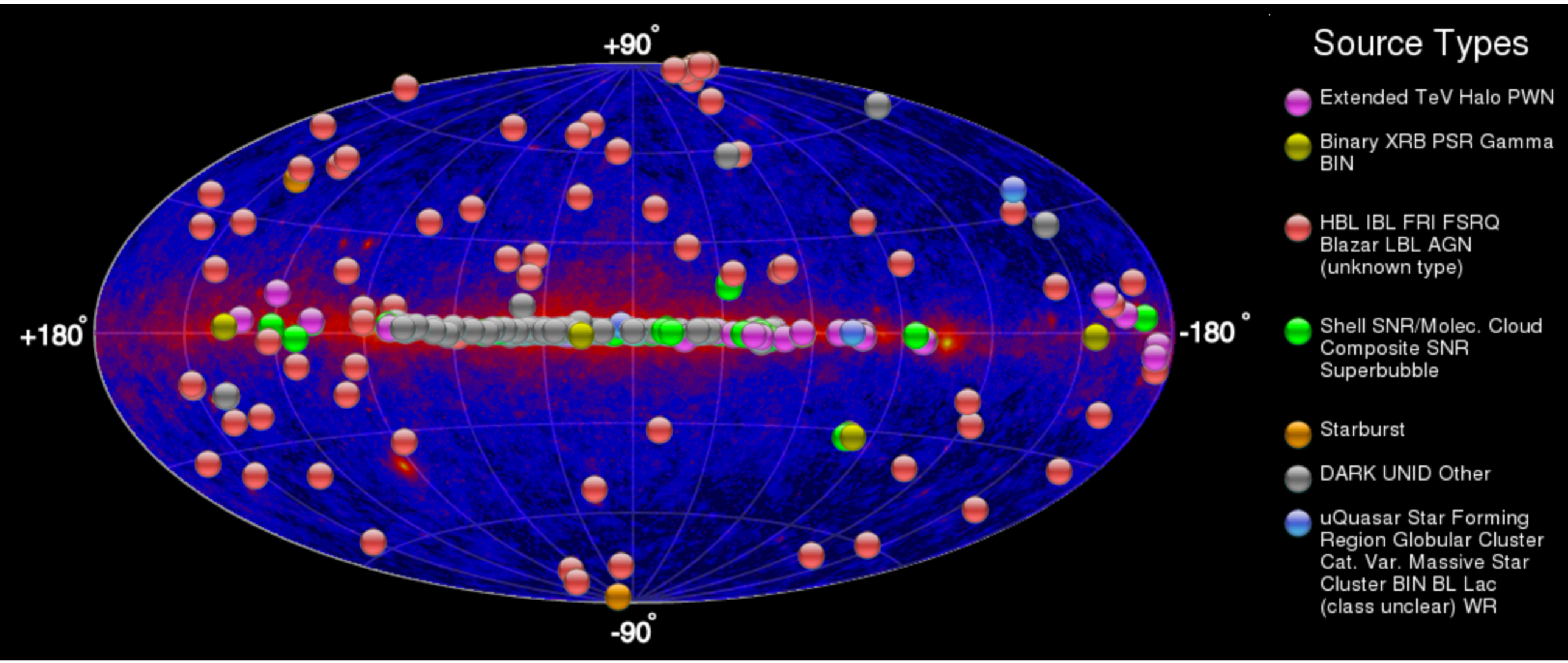






VHEガンマ線天体

VHE gamma-ray sources　(>100 GeV)

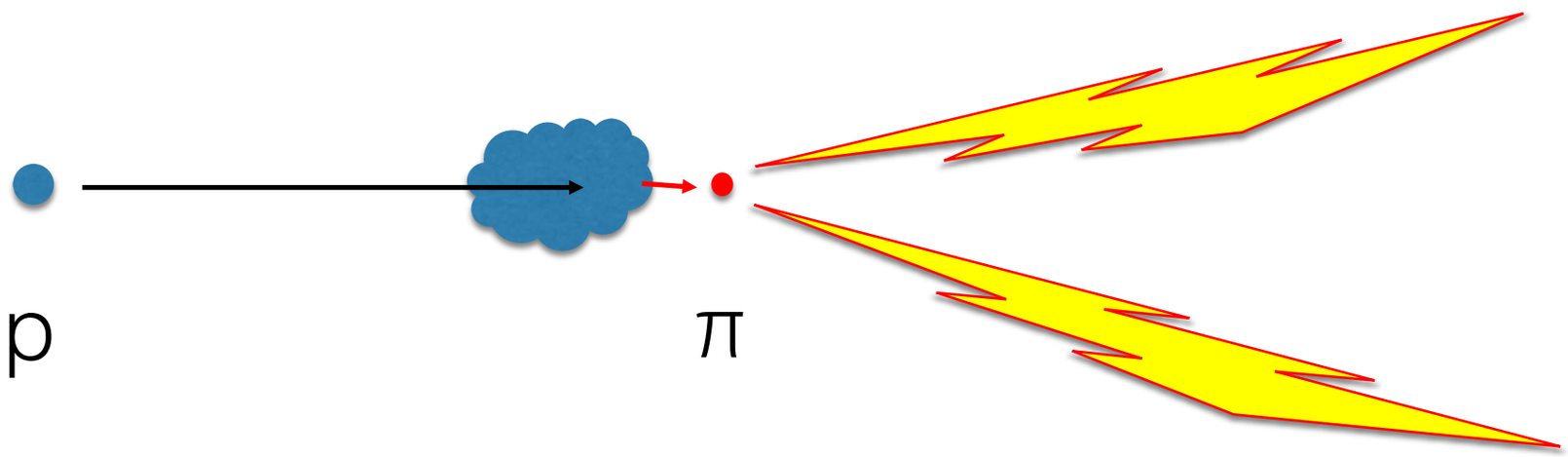


- 約230 天体
- 大部分が、チェレンコフ望遠鏡(MAGIC, HESS, VERITAS)による発見

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。それが直ちに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

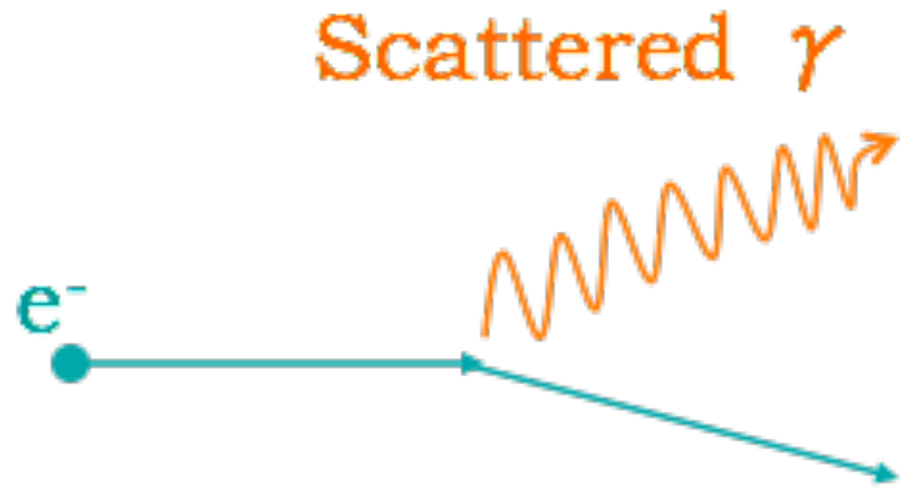
電子による生成

- 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

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

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

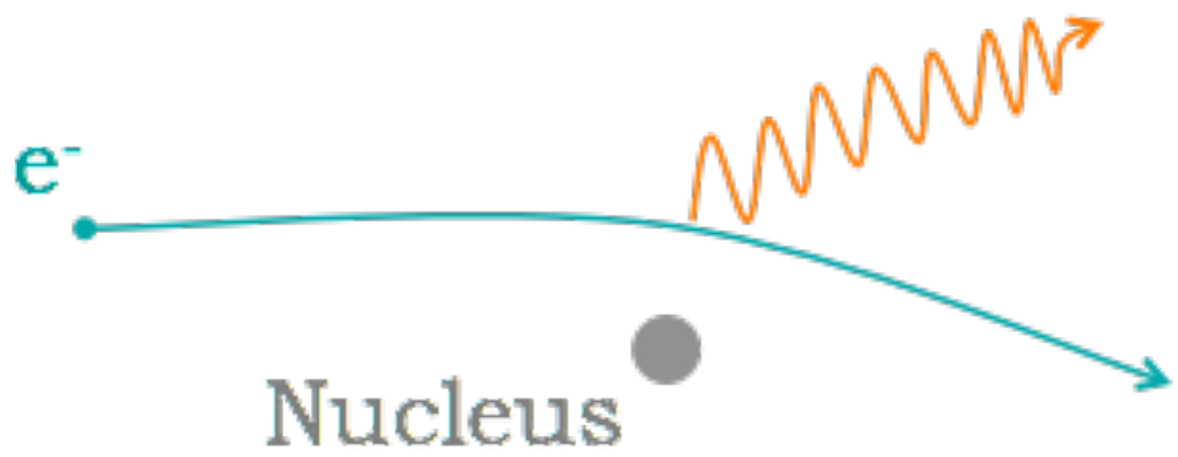
$$\gamma_{\text{Lorentz}} = 1/\sqrt{(1 - v_e^2/c^2)}$$



宇宙におけるガンマ線の生成

電子による生成

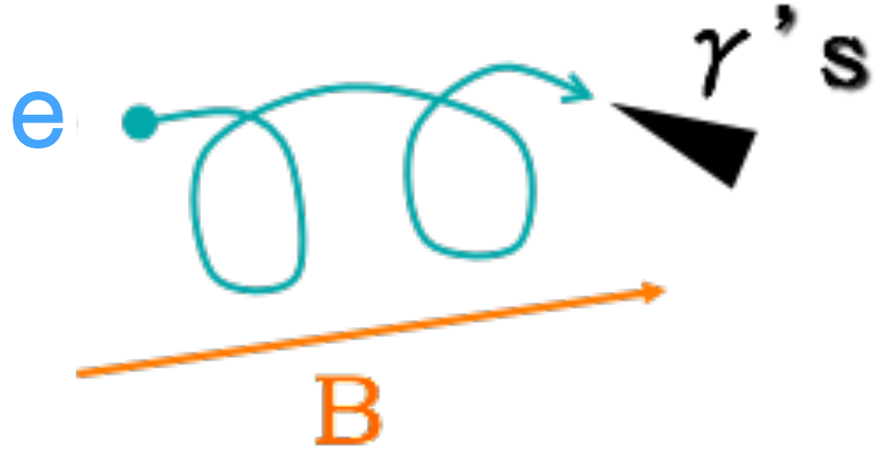
- **制動放射**
  - 加速された電子が原子核と衝突し、加速度をうけ、放射する。
  - 濃い分子雲などに宇宙線電子が衝突すると起こる
  - Energy$_\gamma$ ~ Energy$_e$



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
  - Energy $_{\gamma} \sim \frac{\hbar c}{\lambda}\Gamma^2$

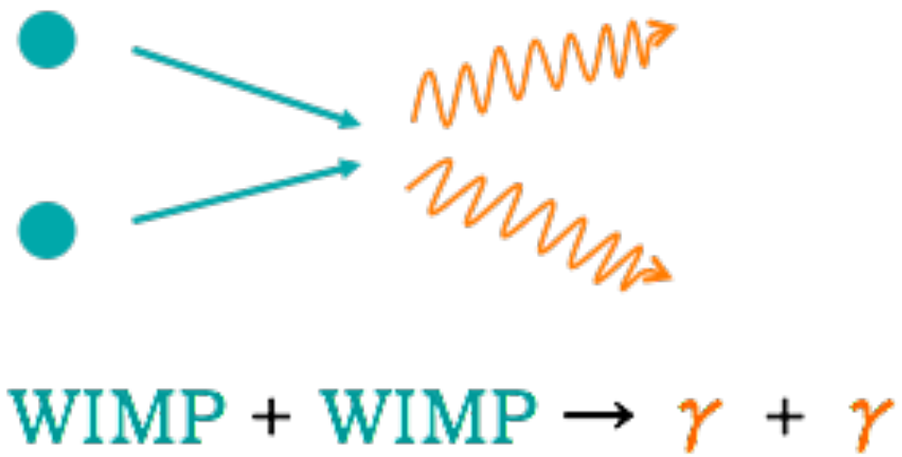


宇宙におけるガンマ線の生成

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
  DM + DM → X+ γ

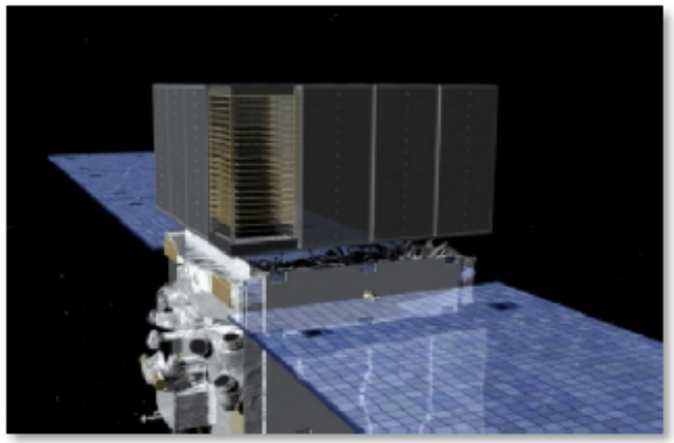


ガンマ線の検出手法

ガンマ線の検出手法

GAMMA RAY TELESCOPES

Space-based pair production telescopes

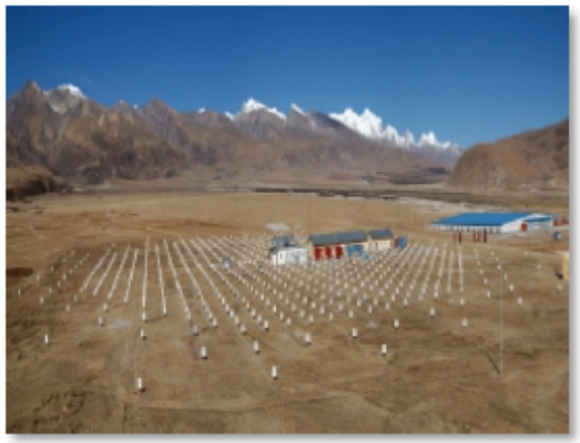


0.1 – 100 GeV
Small area
Background-free
Large field of view
High duty cycle

Imaging Atmospheric Cherenkov Telescopes

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

Air shower Arrays

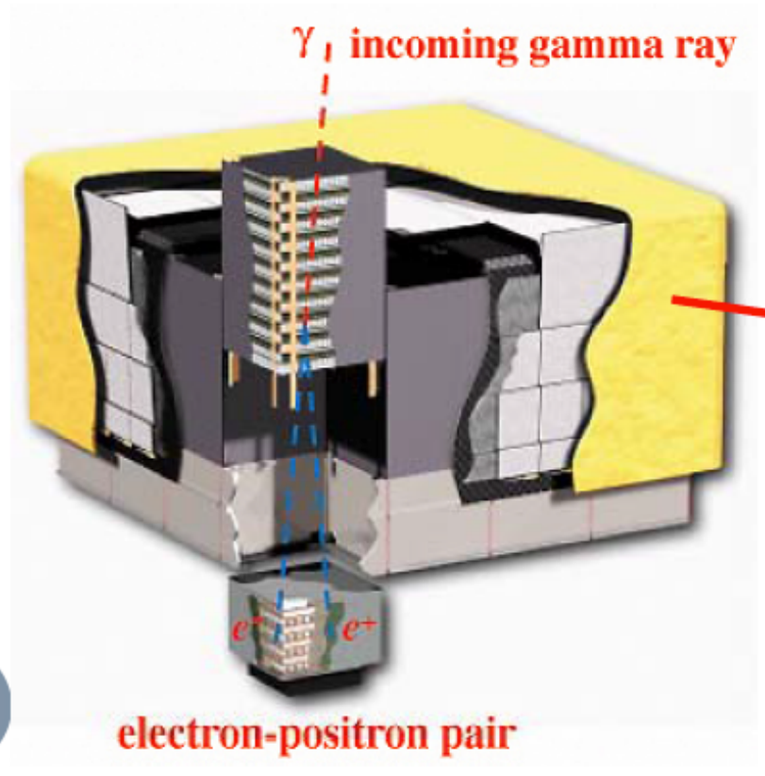


100 GeV – 100 TeV
Large area
Good bg rejection
Large field of view
Large duty cycle

ガンマ線の検出手法(GeV)

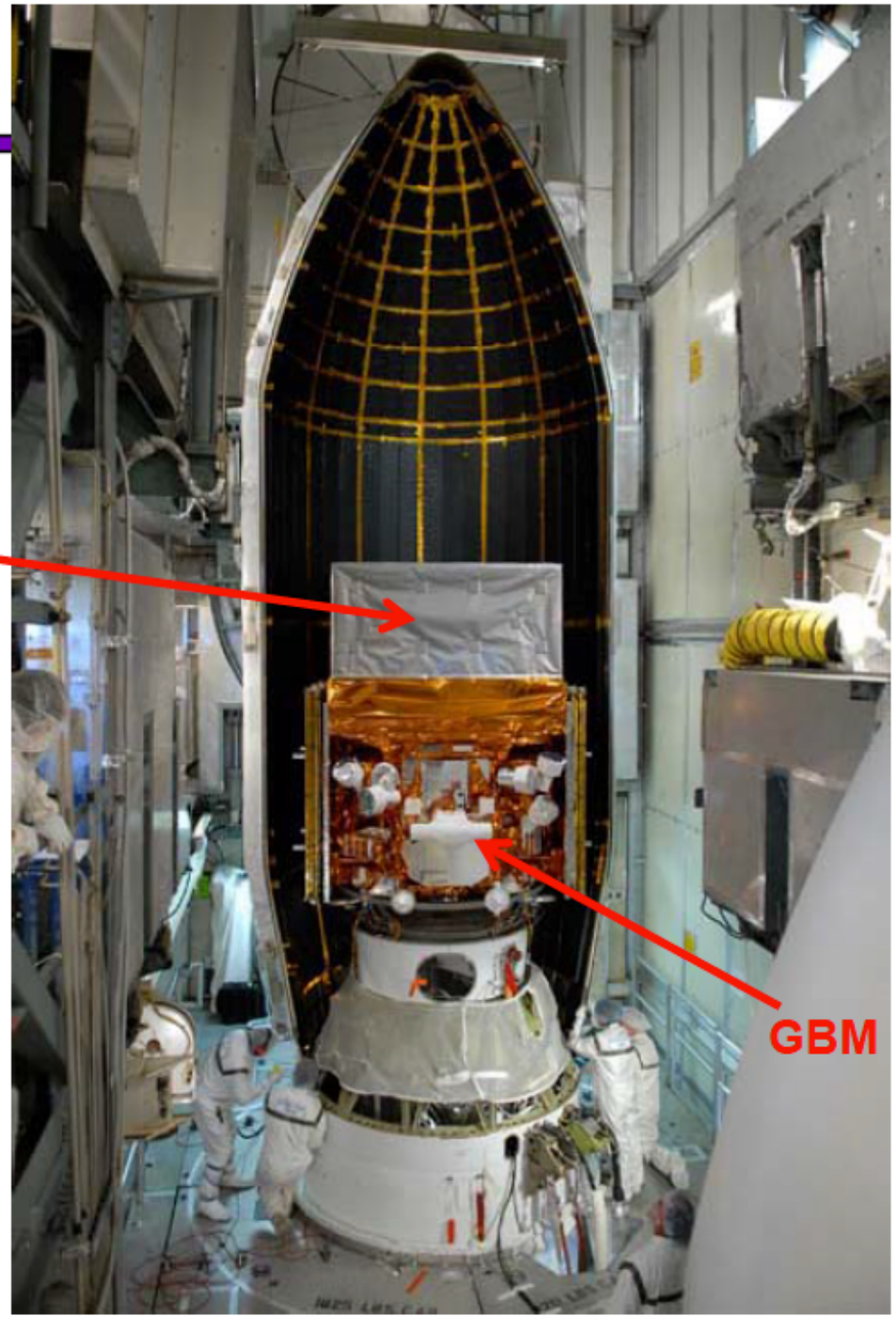
Fermi GST

Large Area Telescope (LAT)

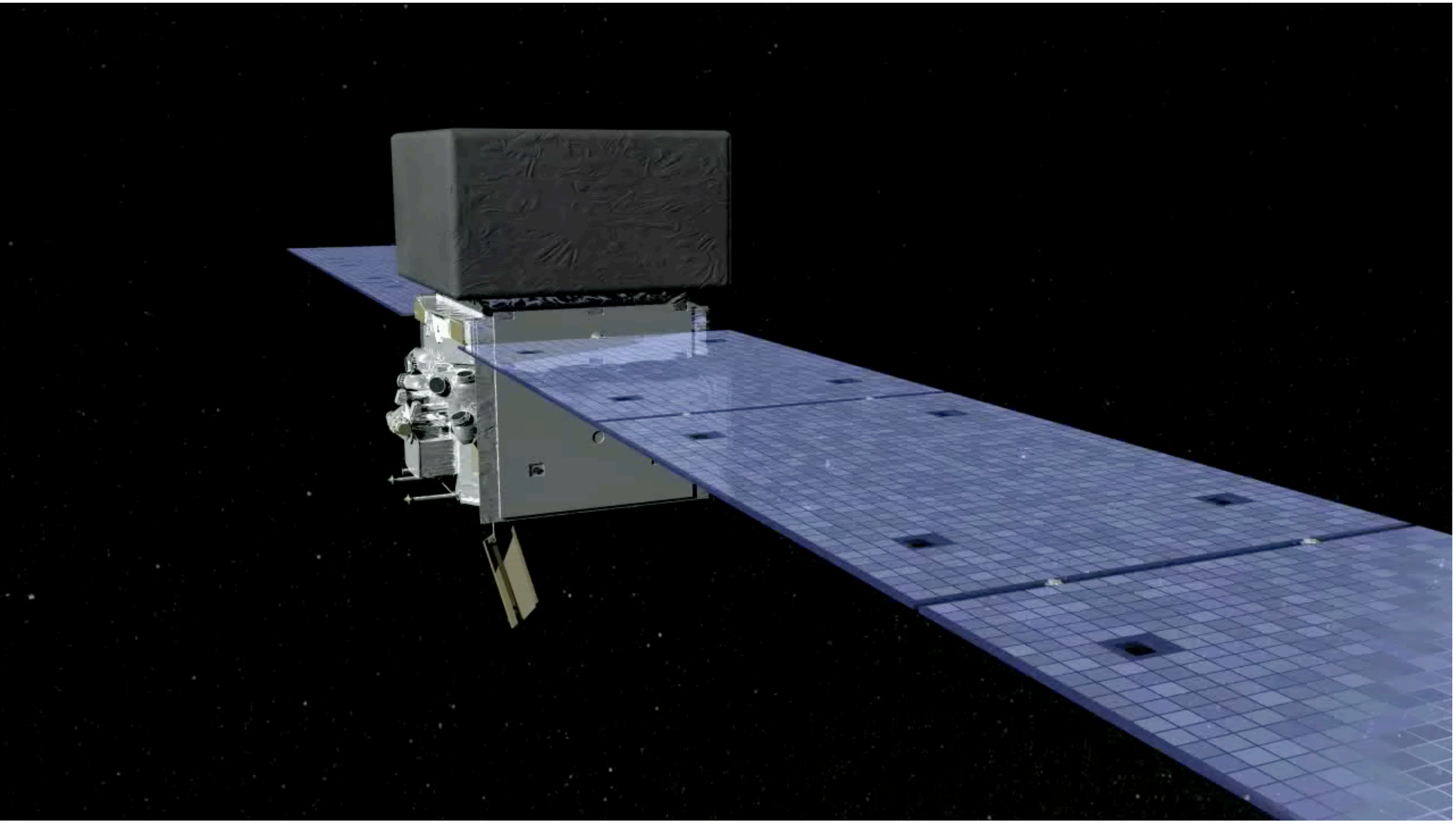


γ-ray converts in LAT to an electron and a positron ; tracking these give us the direction and energy of the photon.

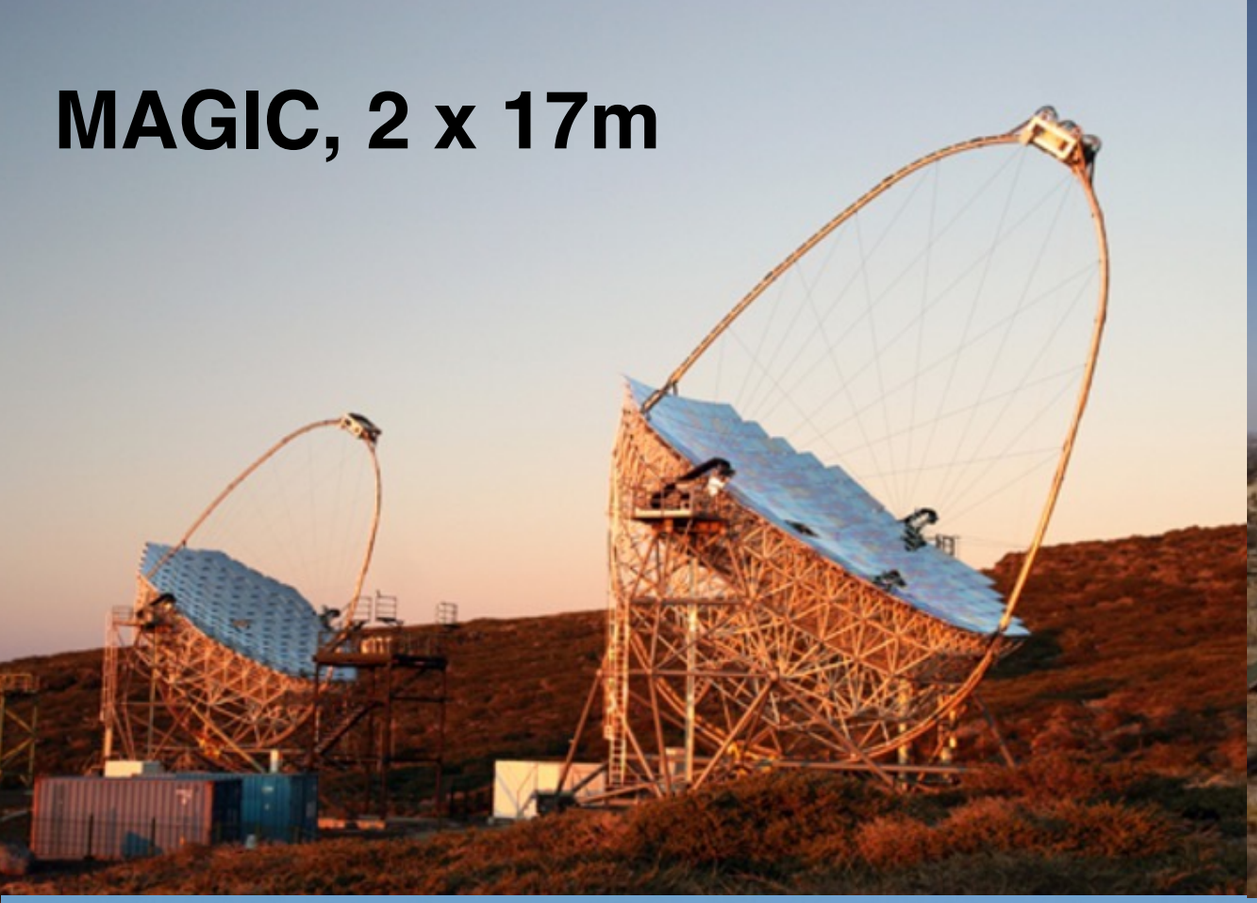
Launched from Cape Canaveral
11 June 2008



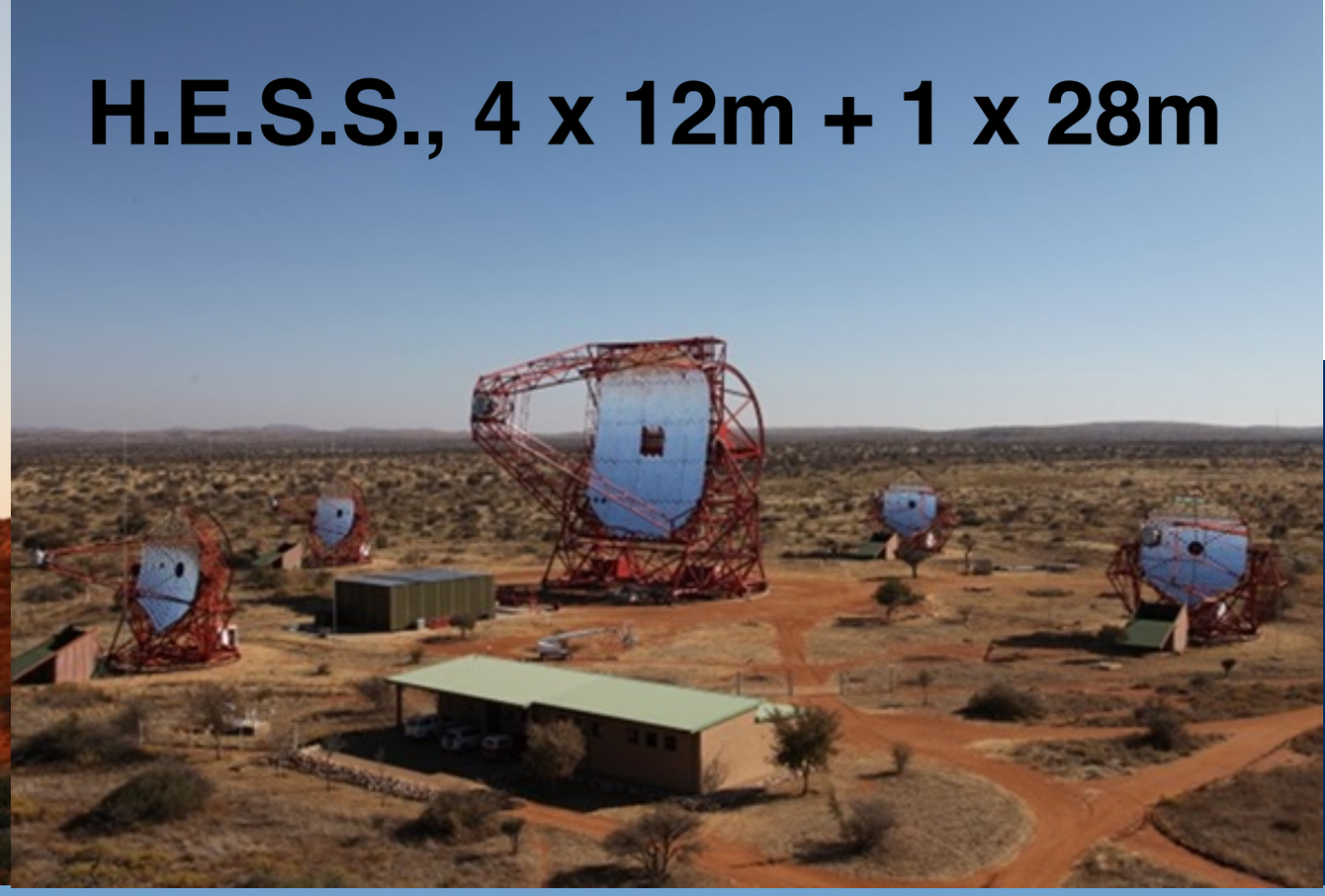
ガンマ線の検出手法(GeV)



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)

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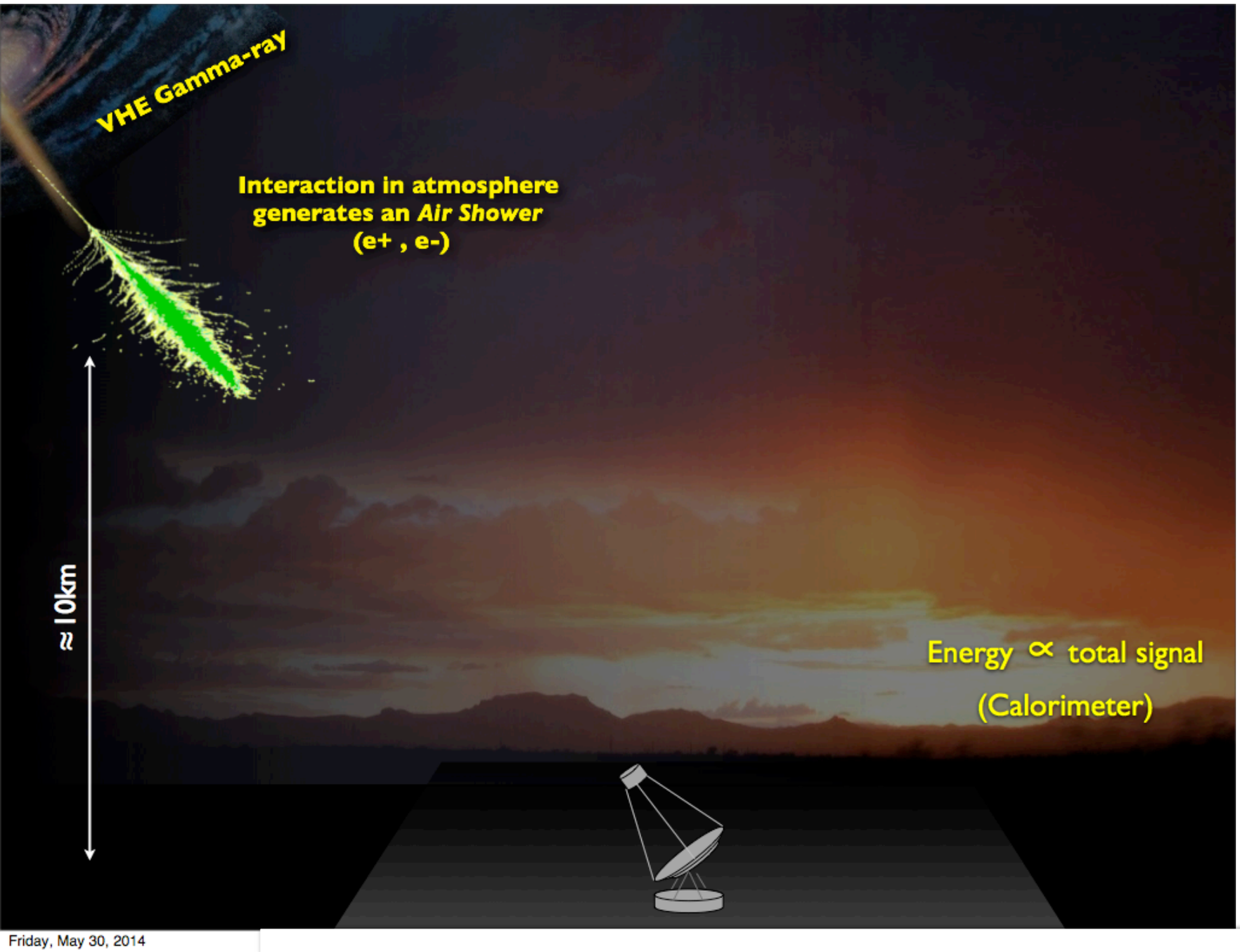
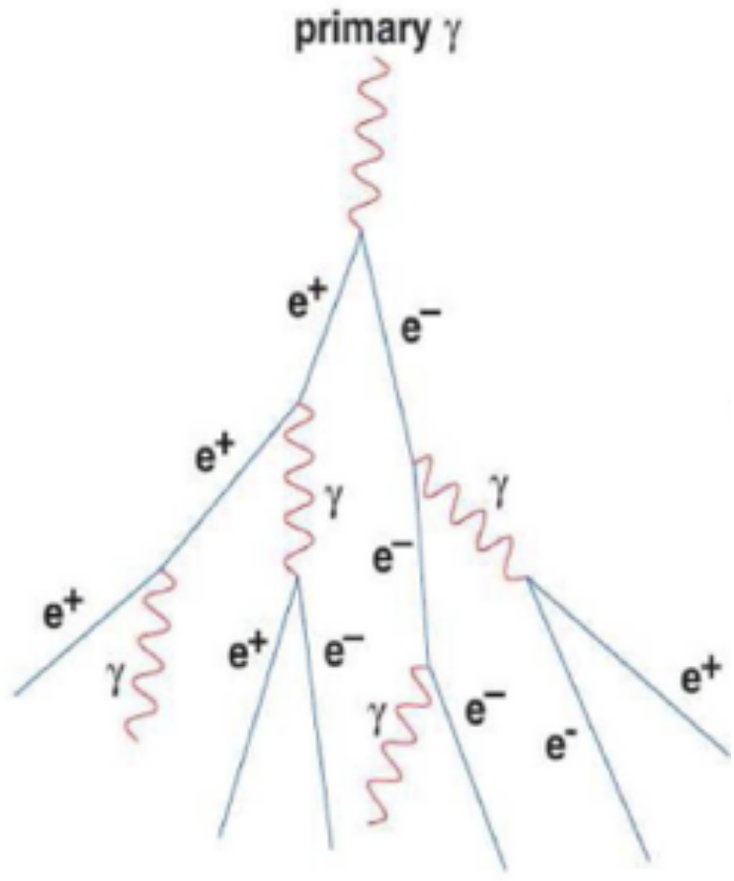
Imaging Atmospheric Cherenkov Telescope

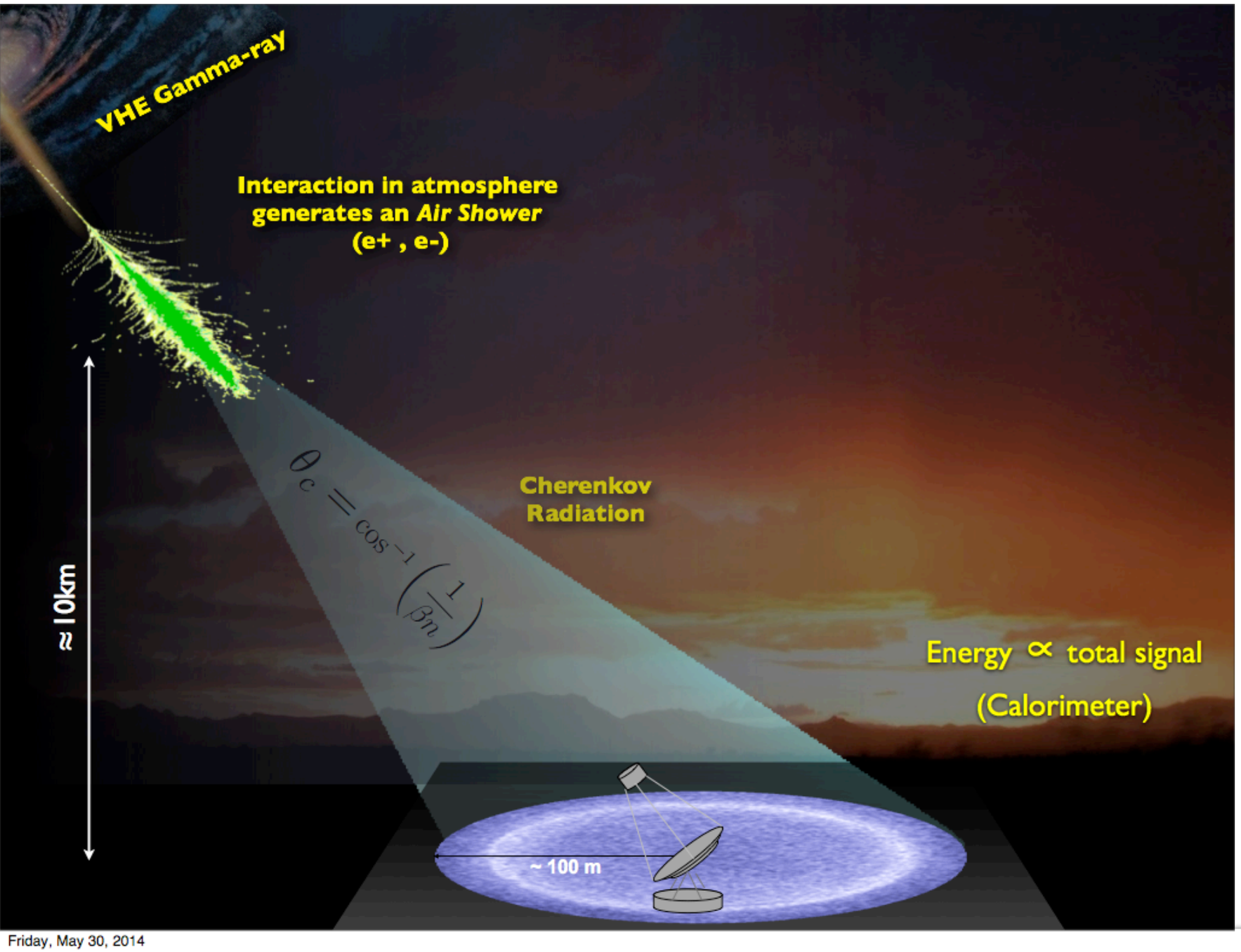




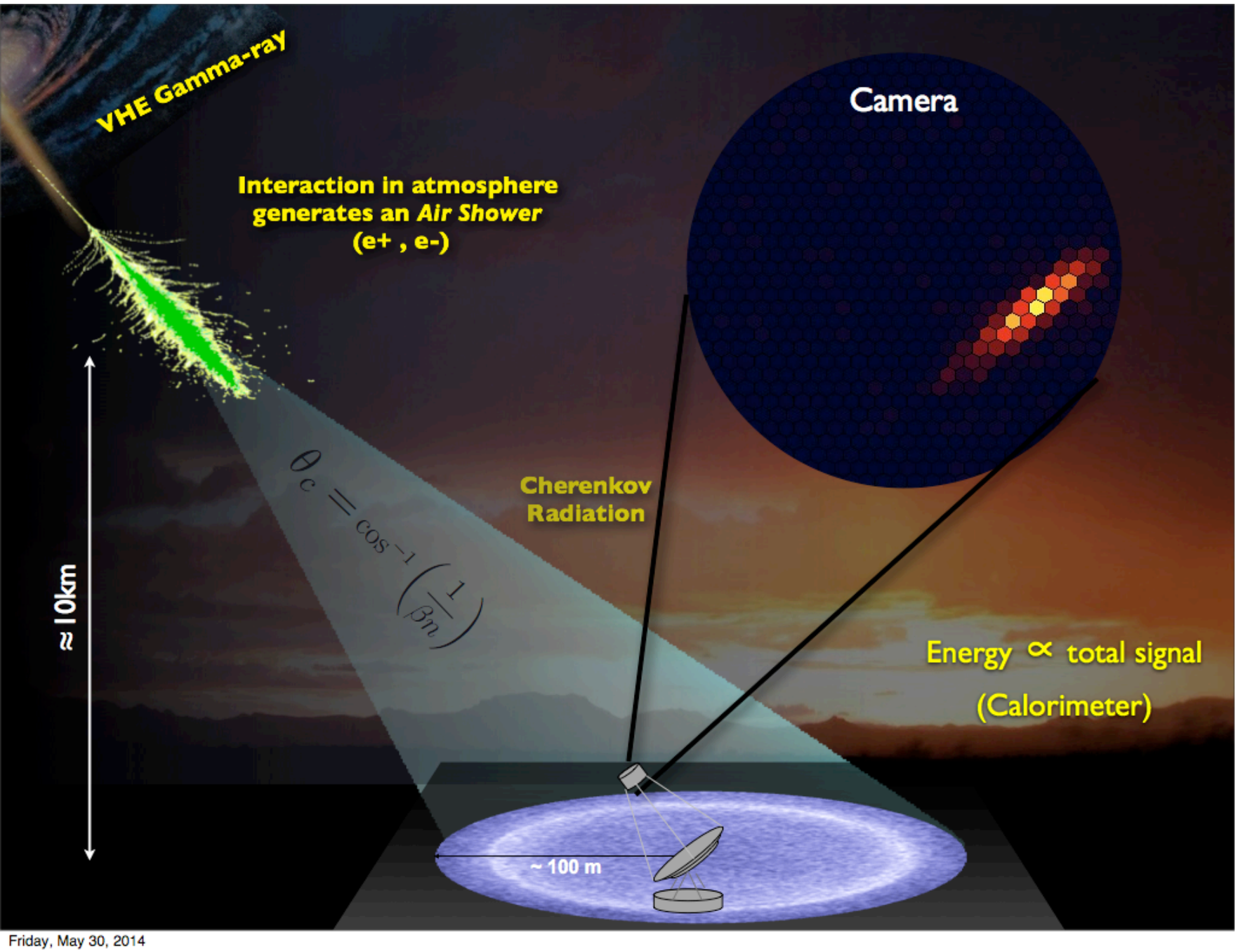
電磁カスケード
（空気シャワー）

Friday, May 30, 2014

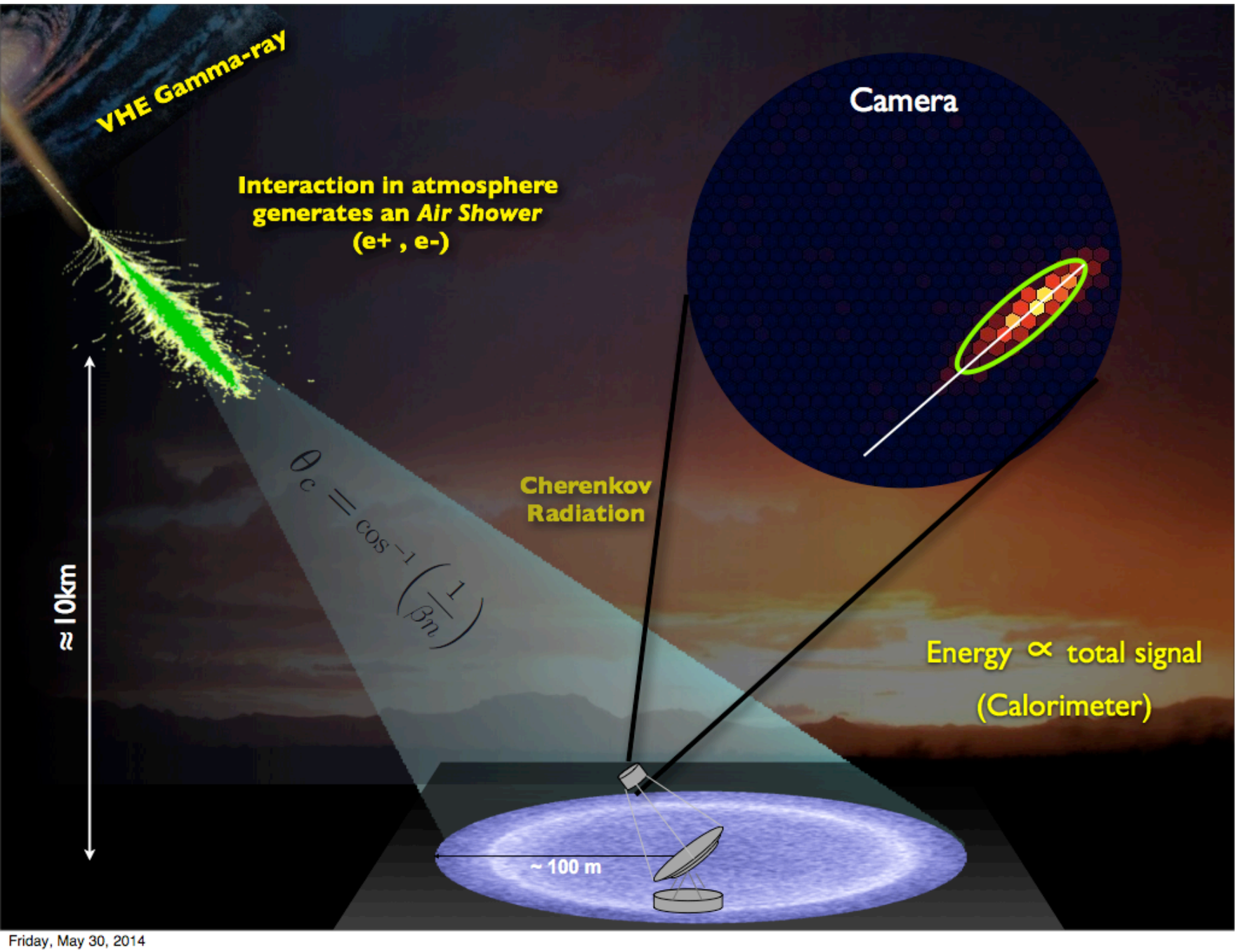
ガンマ線の検出手法(TeV)



ガンマ線の検出手法(TeV)

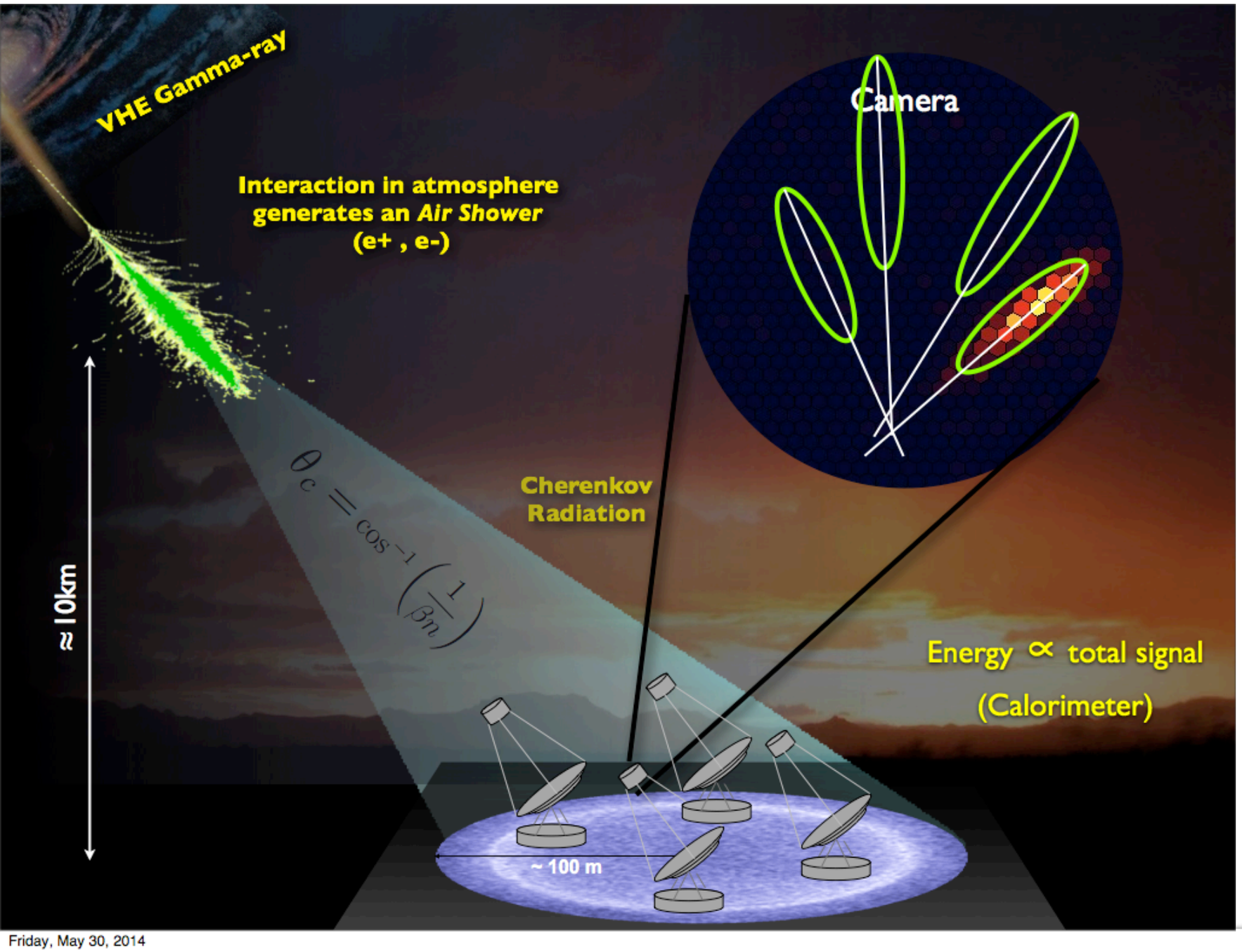


ガンマ線の検出手法(TeV)

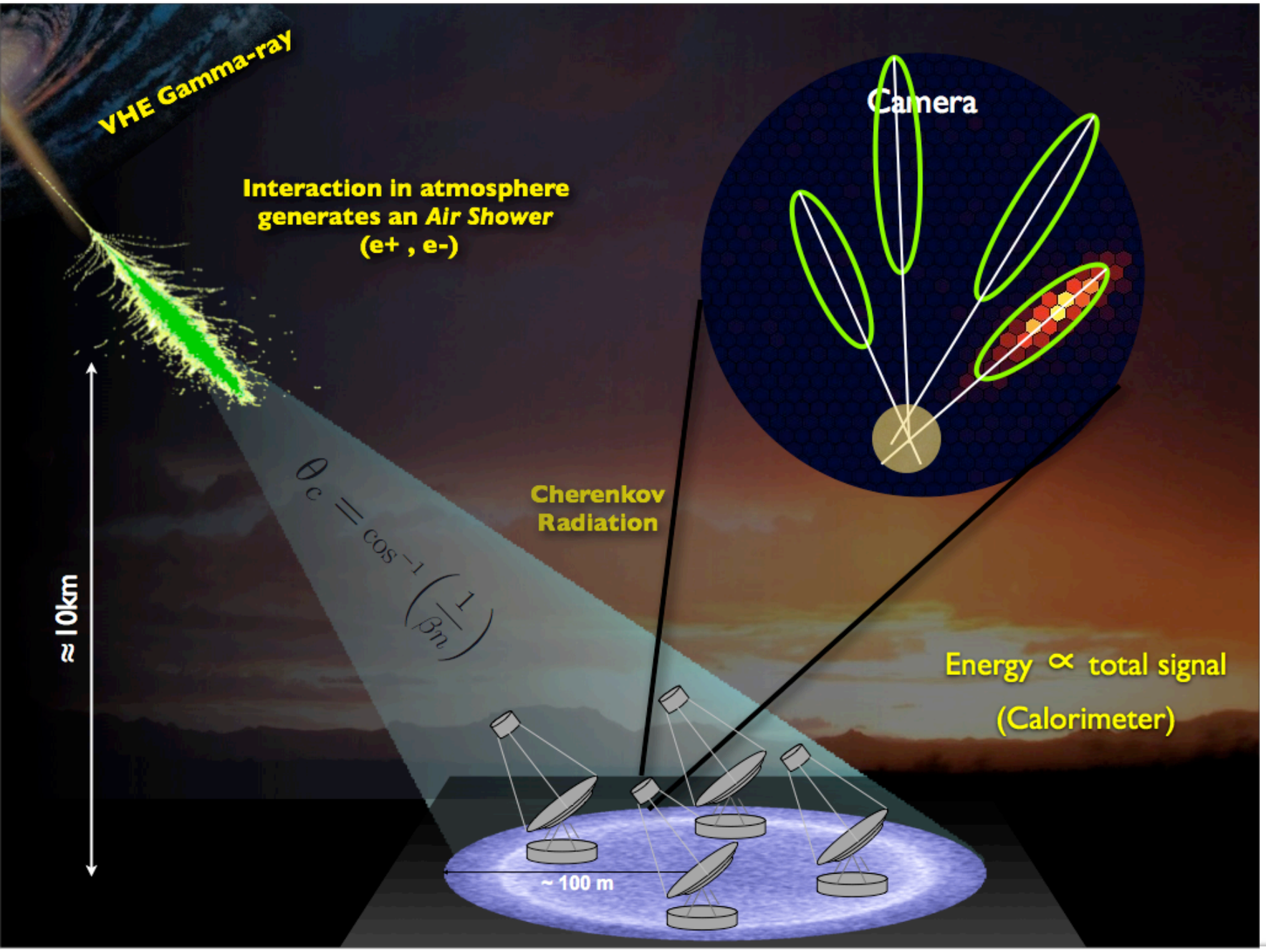


Friday, May 30, 2014

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)

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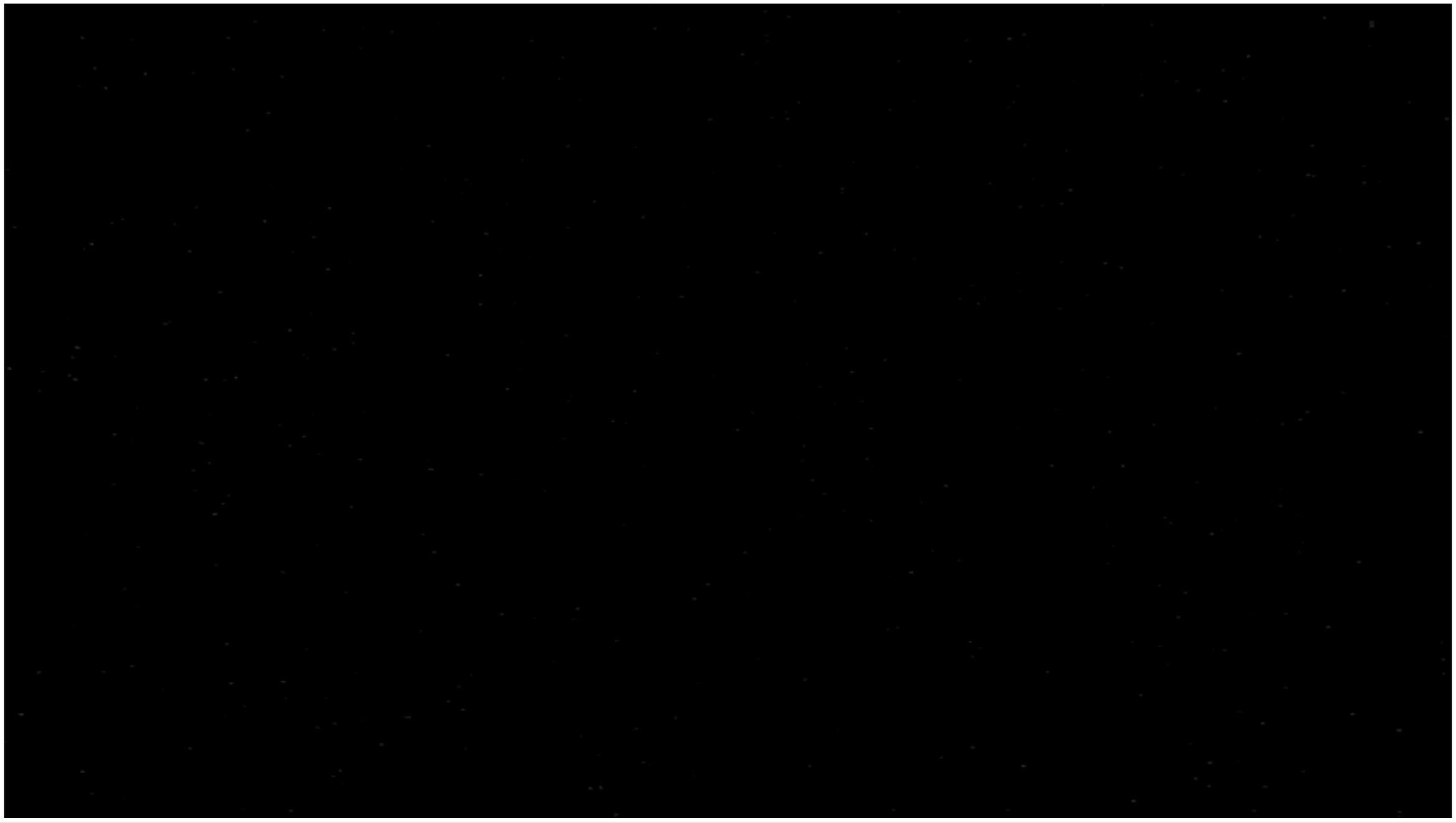
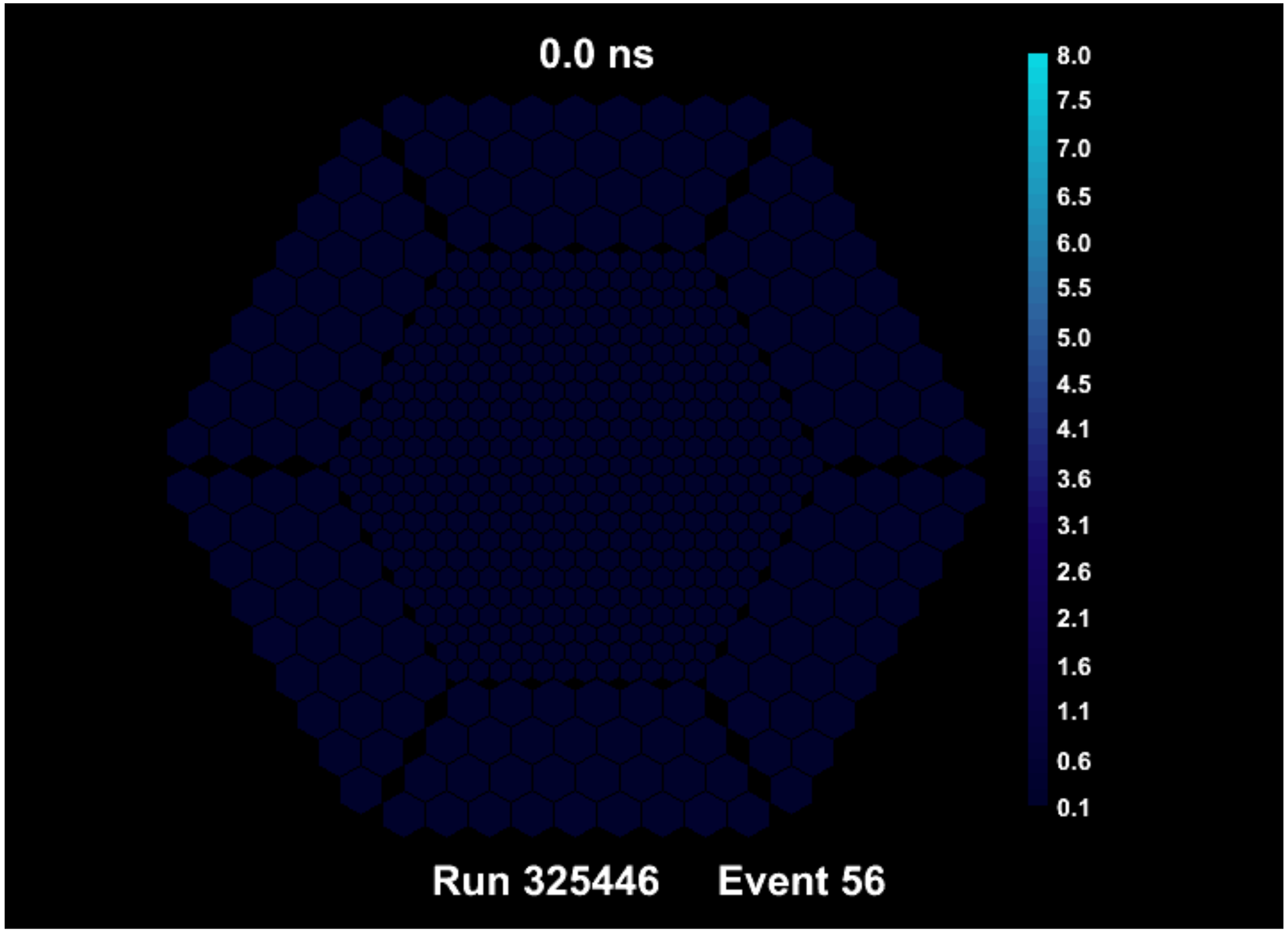
Atmospheric showers and Cherenkov radiation

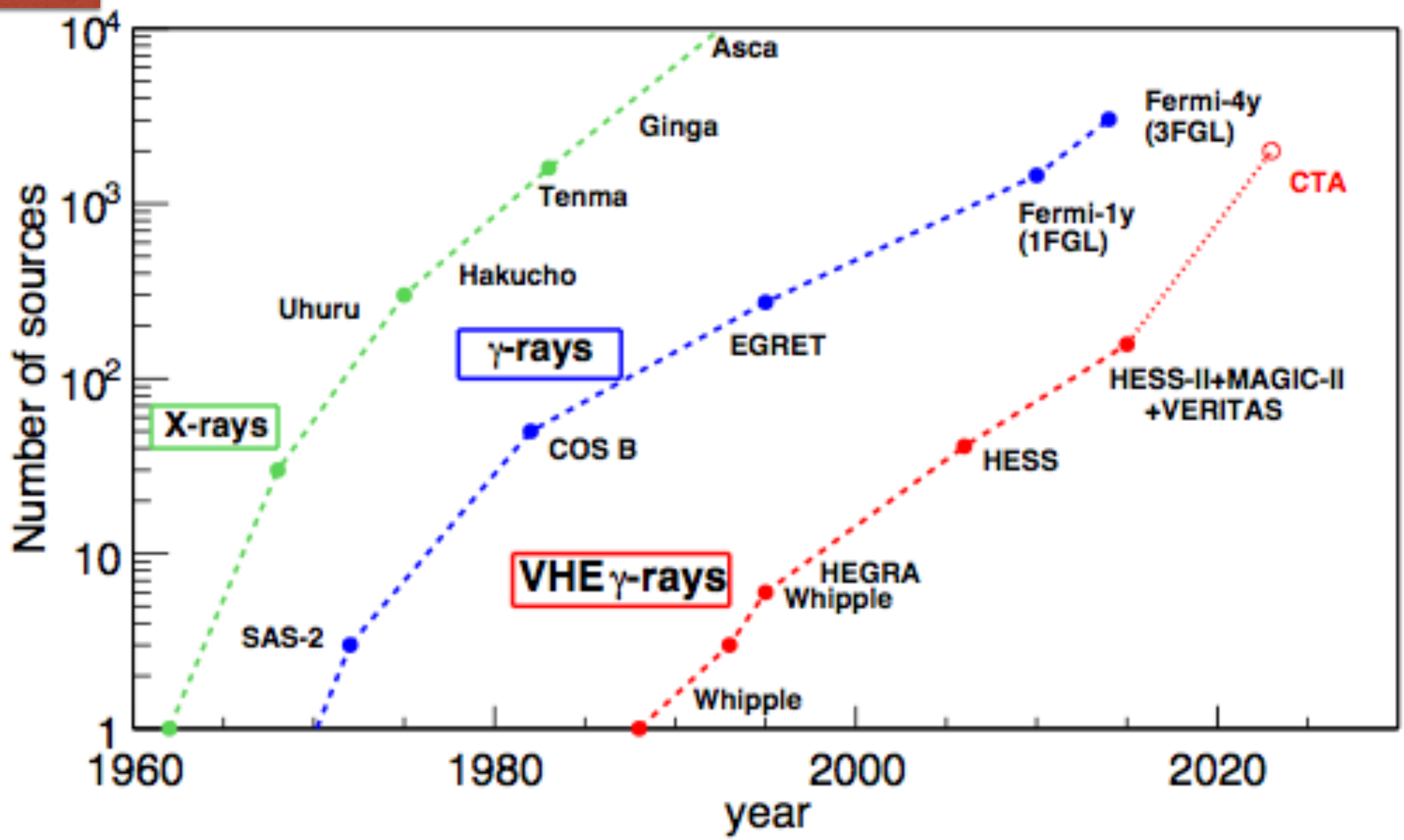


空気シャワー画像


0.0 ns
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.1
3.6
3.1
2.6
2.1
1.6
1.1
0.6
0.1
Run 325446 Event 56

検出天体数の推移

Kifune plot



ガンマ線観測でなにがわかるか

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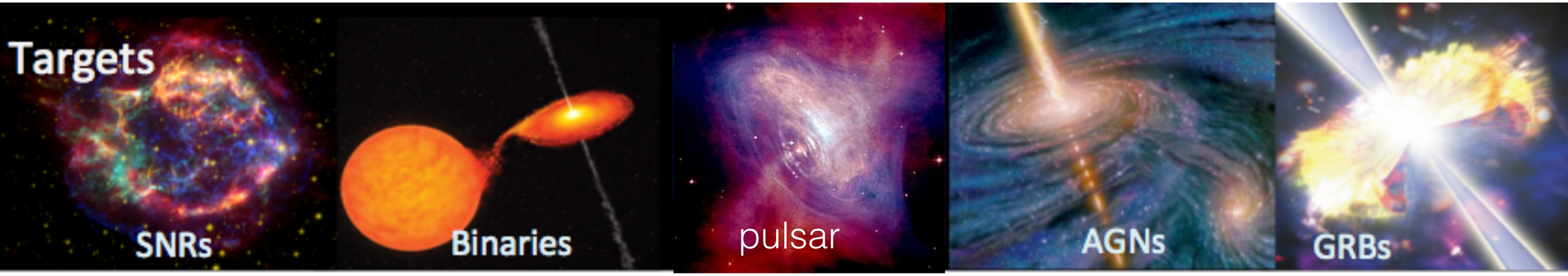
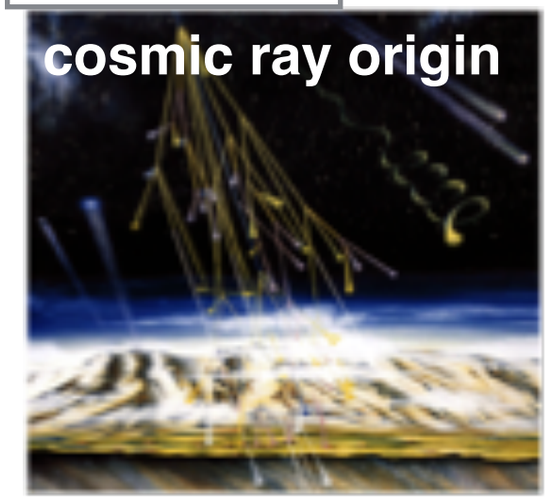
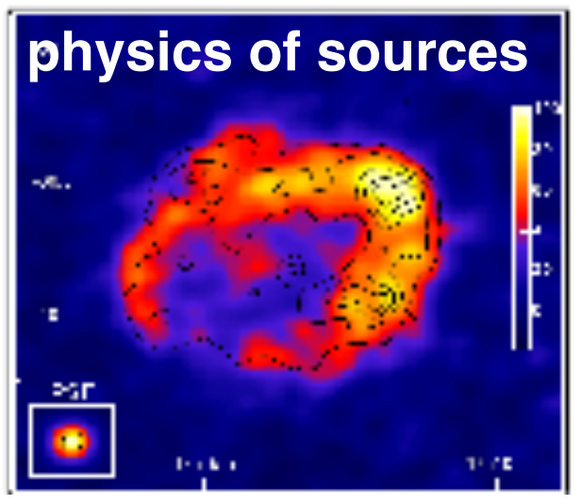


Objectives

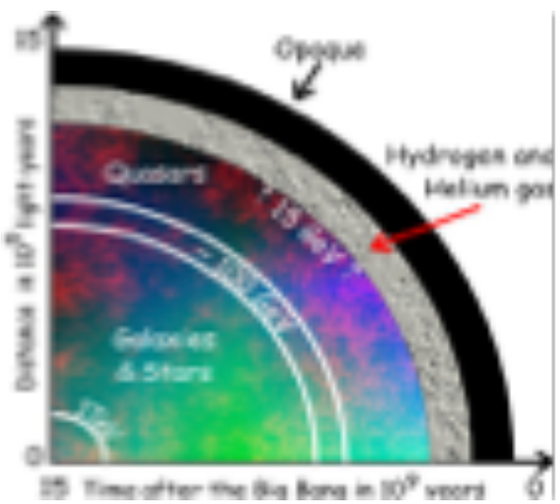
cosmic ray origin



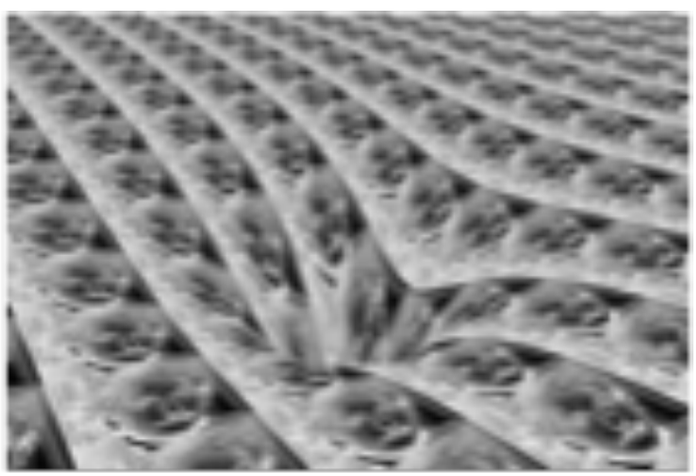
physics of sources



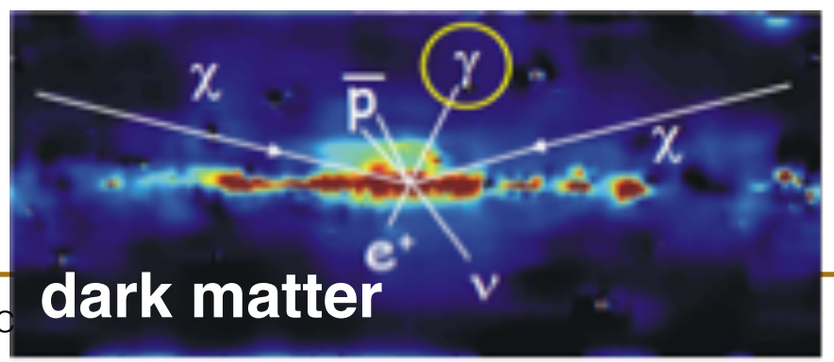
cosmology



space and time



dark matter

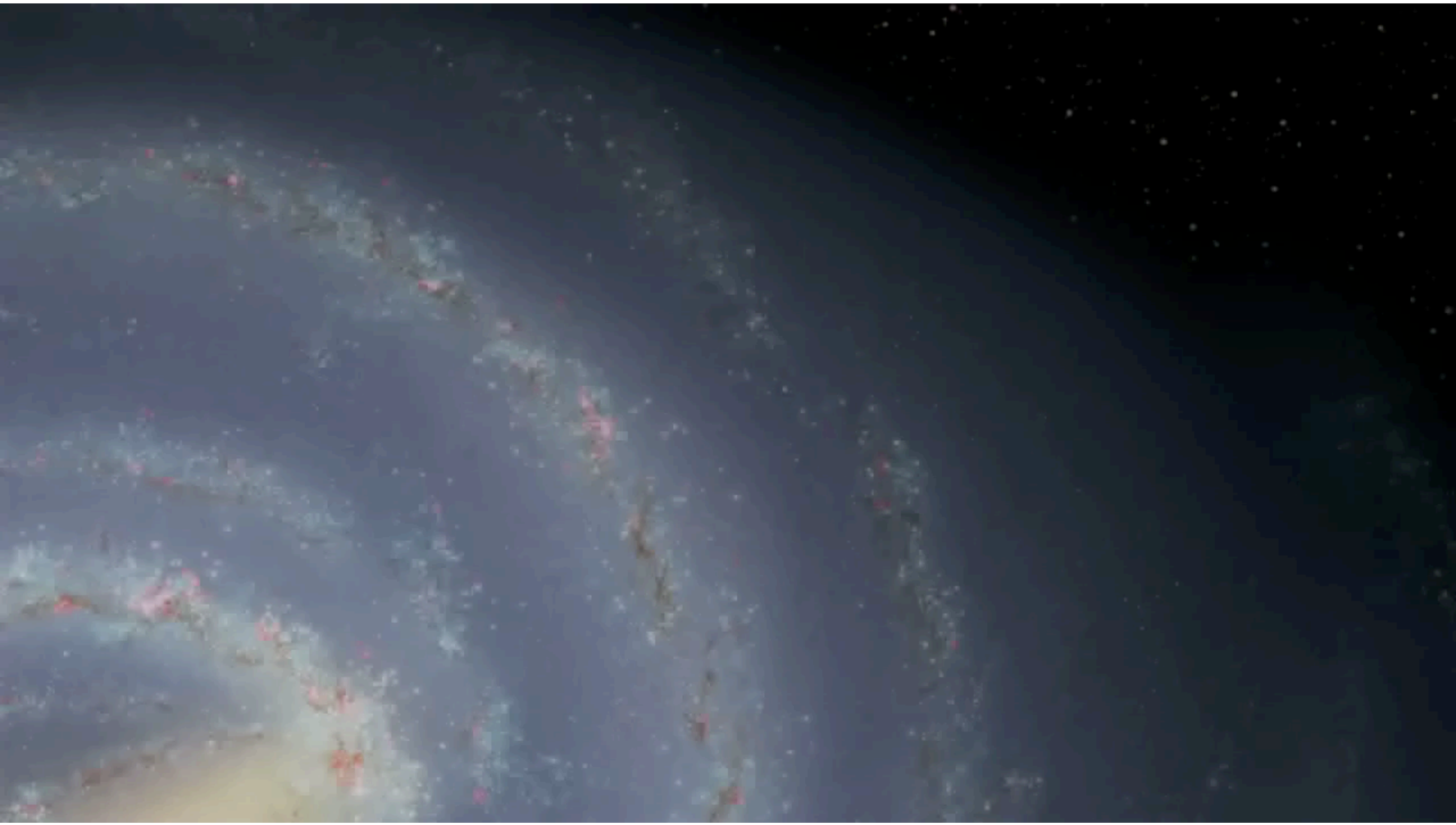


ガンマ線観測でなにがわかるか

- **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たりする。
- **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

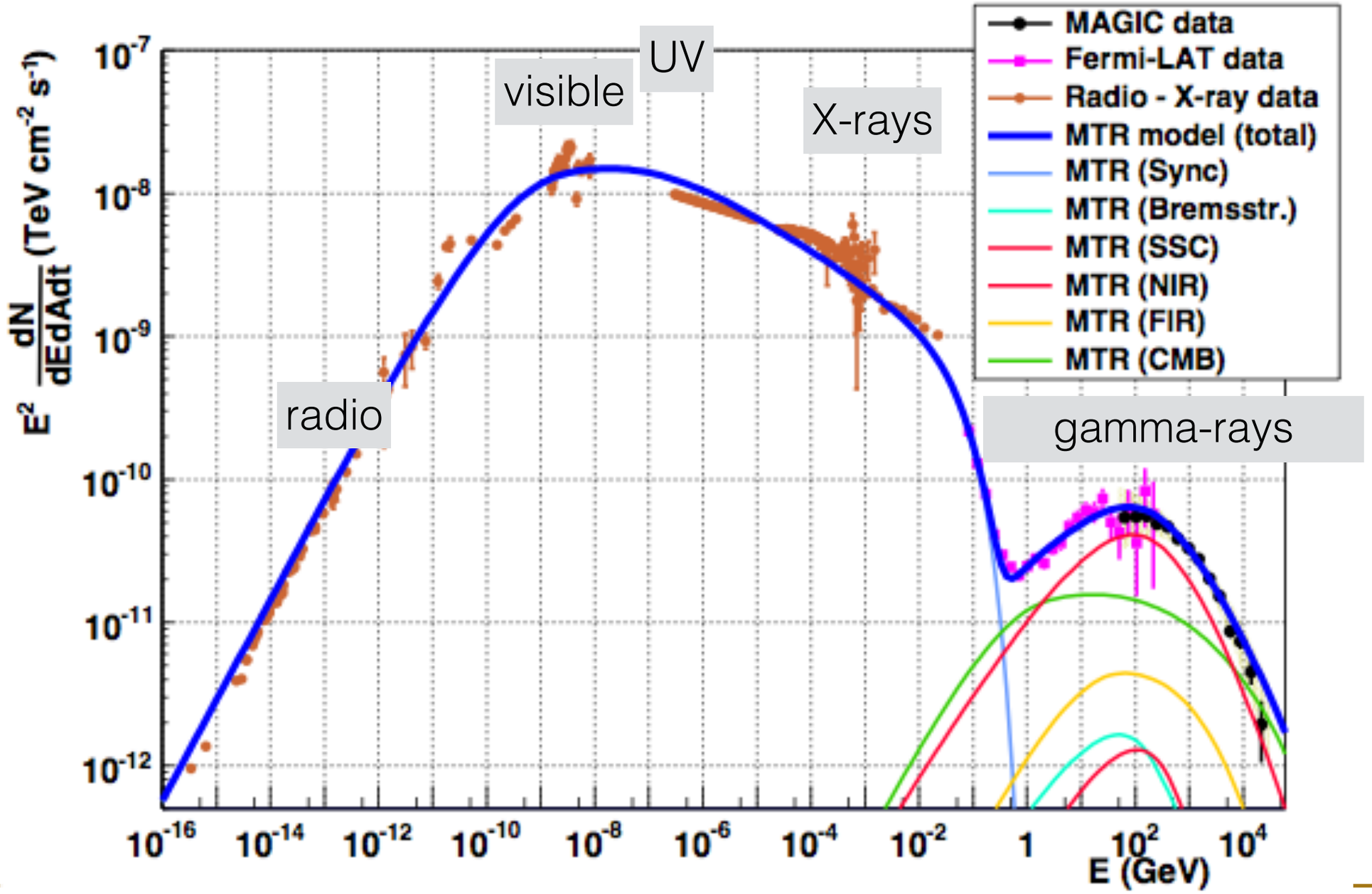
宇宙線の加速とガンマ線の放射



パルサー風星雲

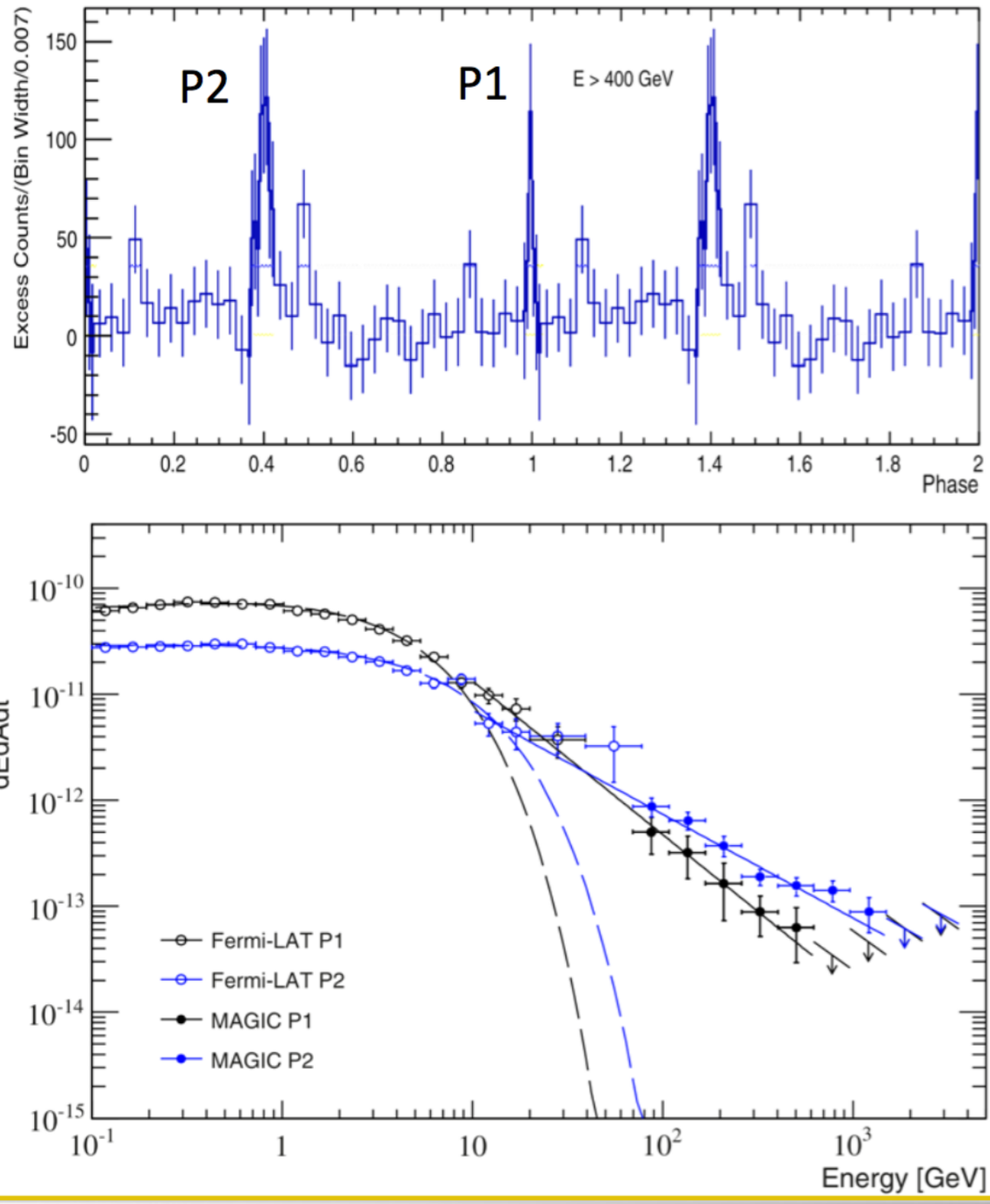
Crab Nebula

非熱的な放射で、２０桁にもわたる帯域で放射



Pulsars: Crab

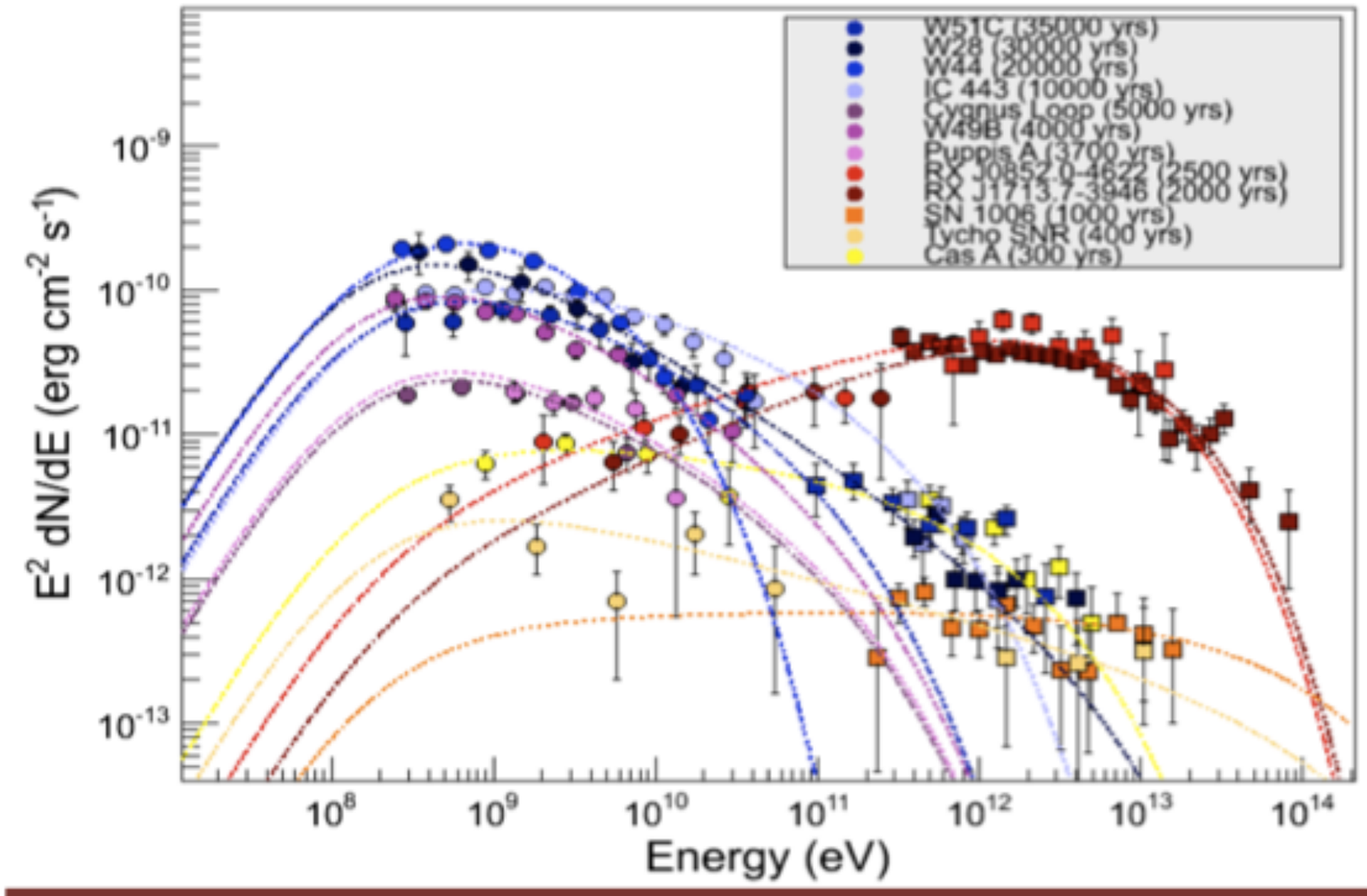
MAGIC, 2016, A&A, 585, A33



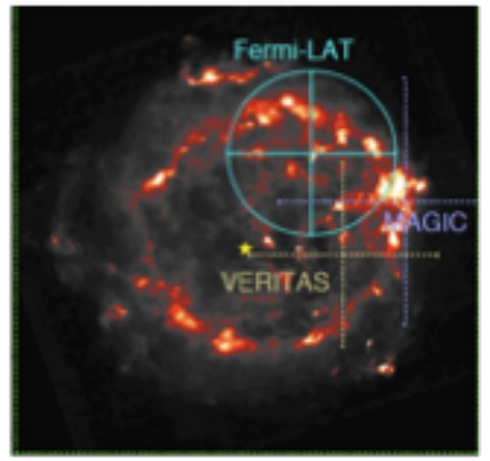
MAGIC

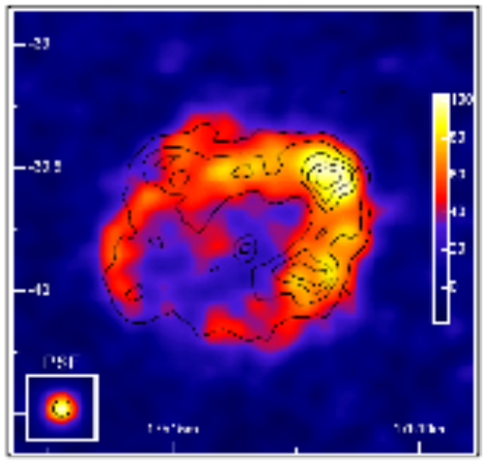
- MAGIC dataset: 320 h (2007-2014)
- Discovered pulsed emission from Crab spectrum extending up to 1.5 TeV
- Spectra of both peaks extending as power- laws far beyond the expected cutoffs:
  - P1 detected up to 0.6 TeV (Γ=3.5 ± 0.1)
  - P2 detected up to 1.5 TeV (Γ=3.0 ± 0.1)

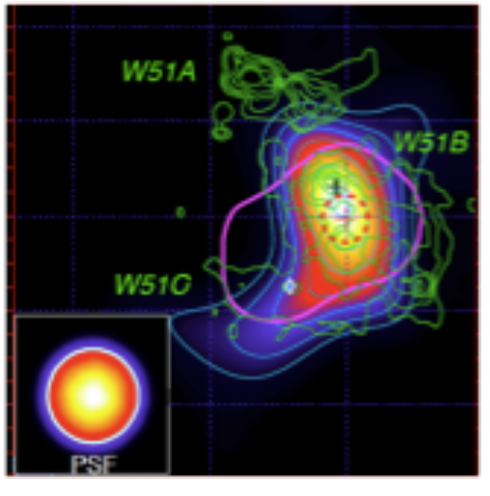
超新星残骸



- 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

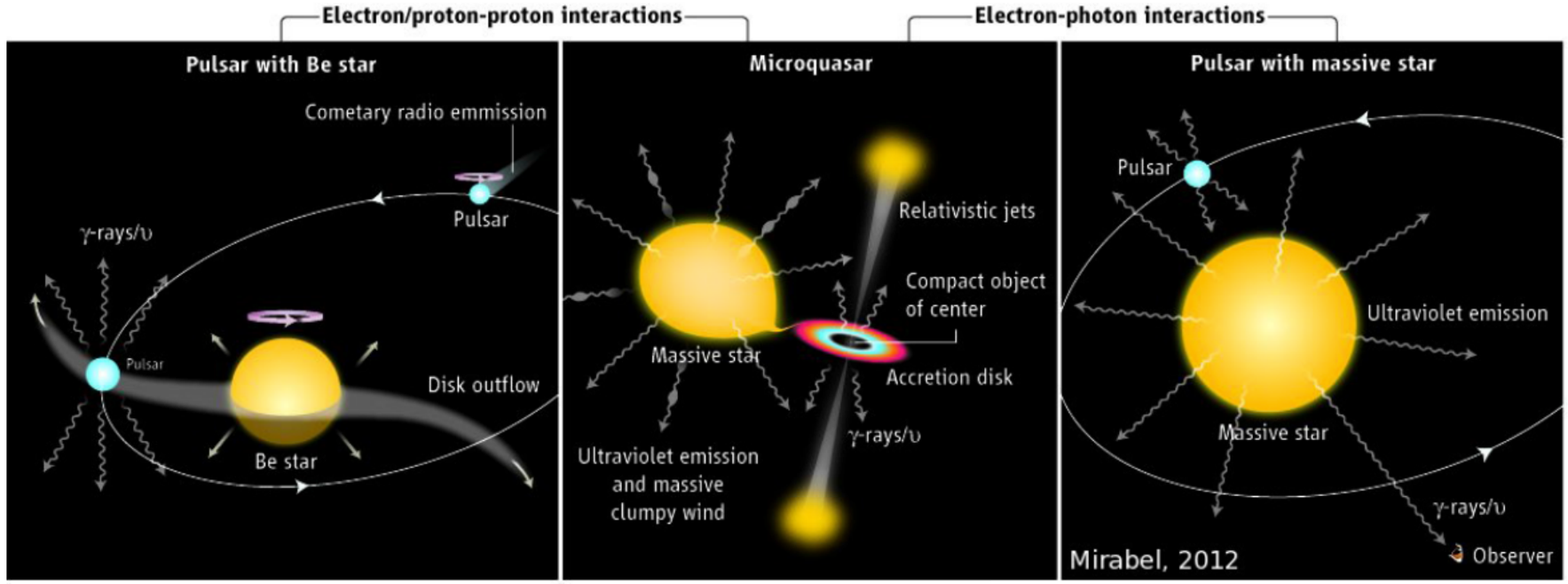


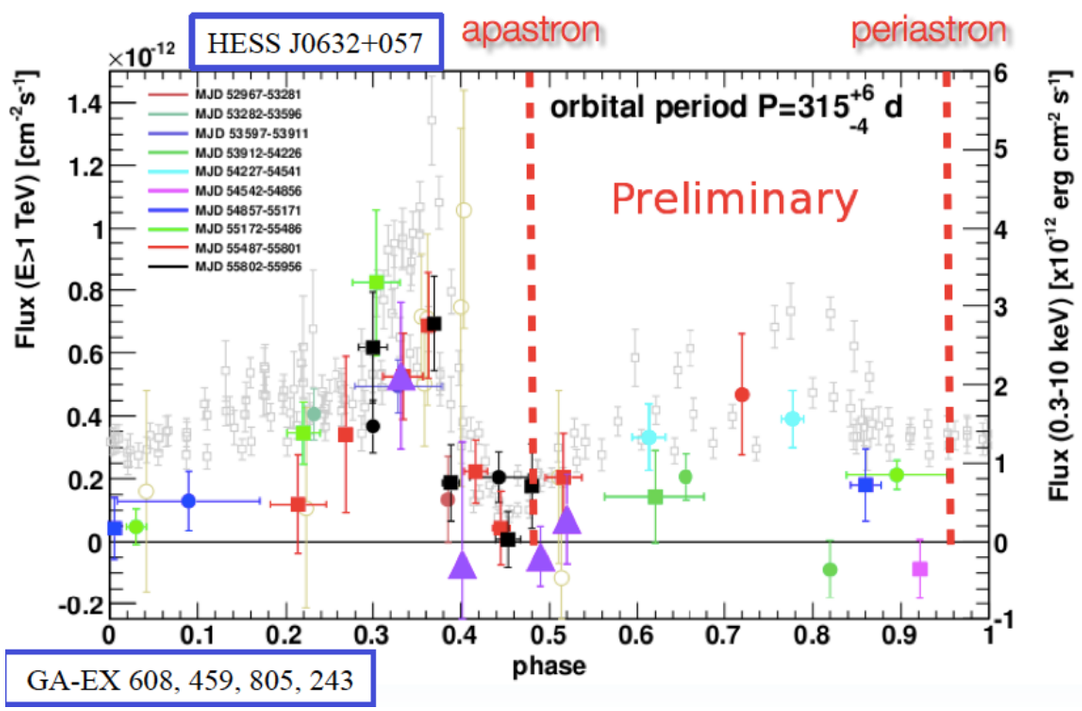




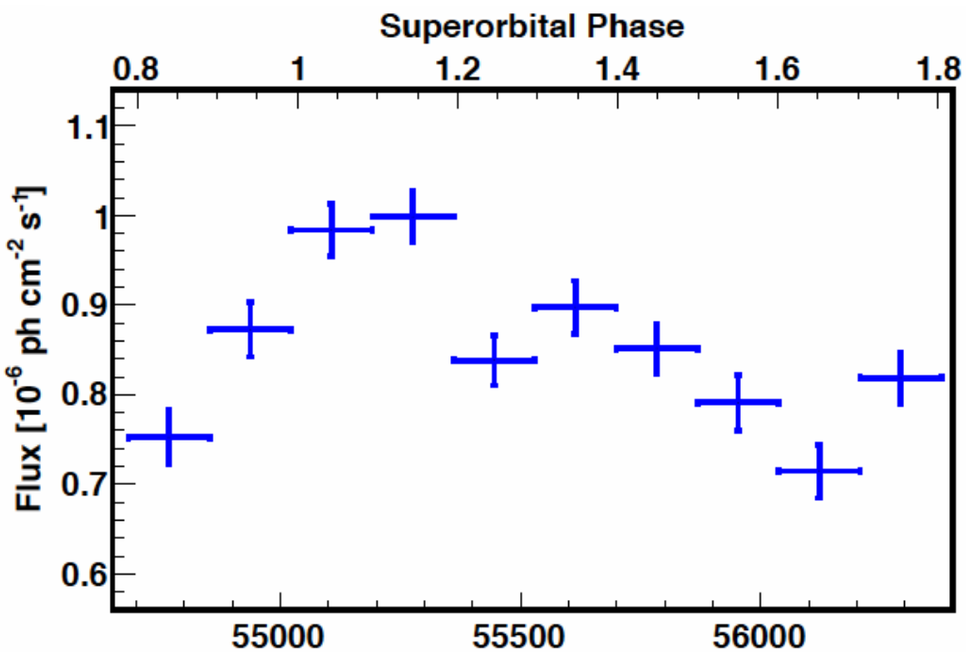
ガンマ線連星

Gamma-ray Binary systems





LSI +61 303 Superorbital Modulation!



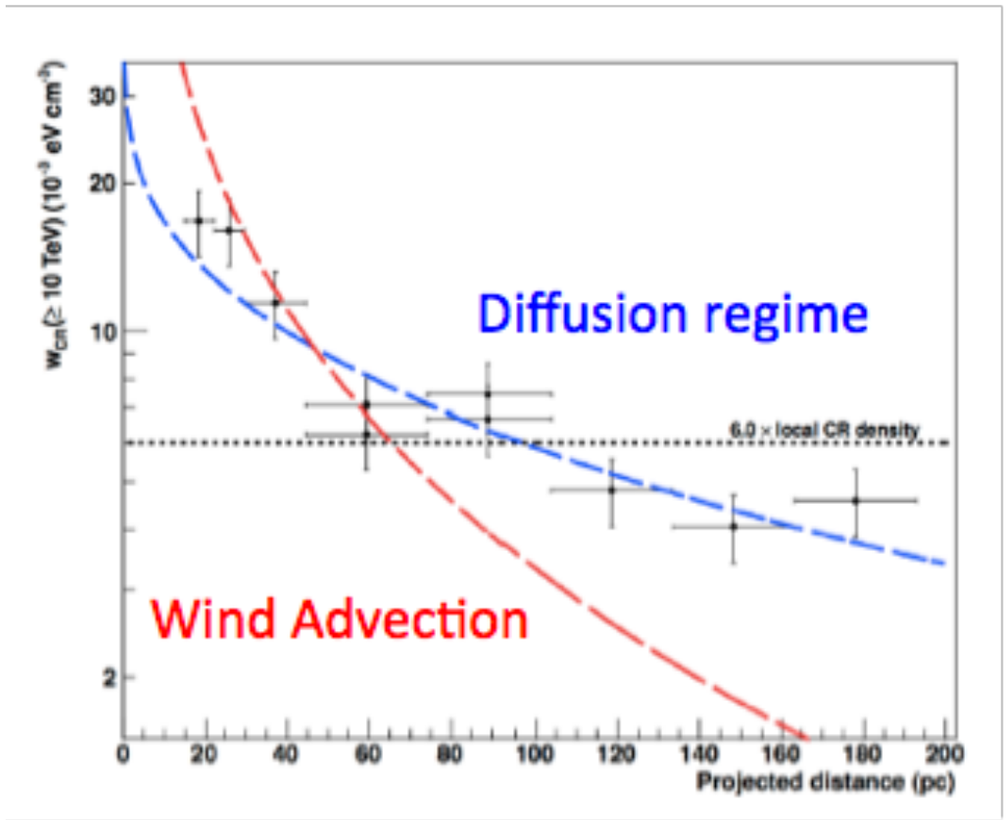
銀河中心

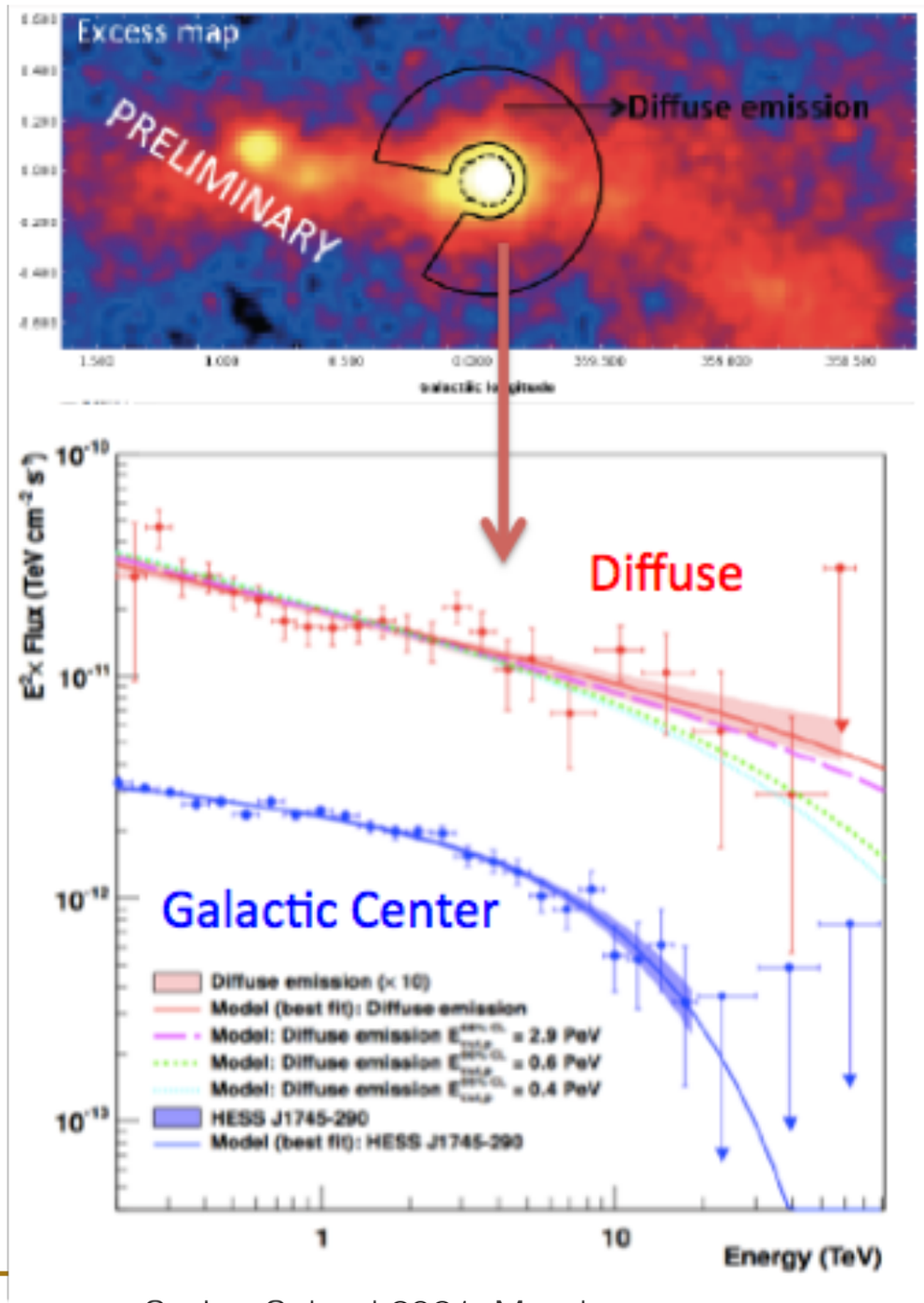
Galactic Center

HESS Deep Observation of 250hrs

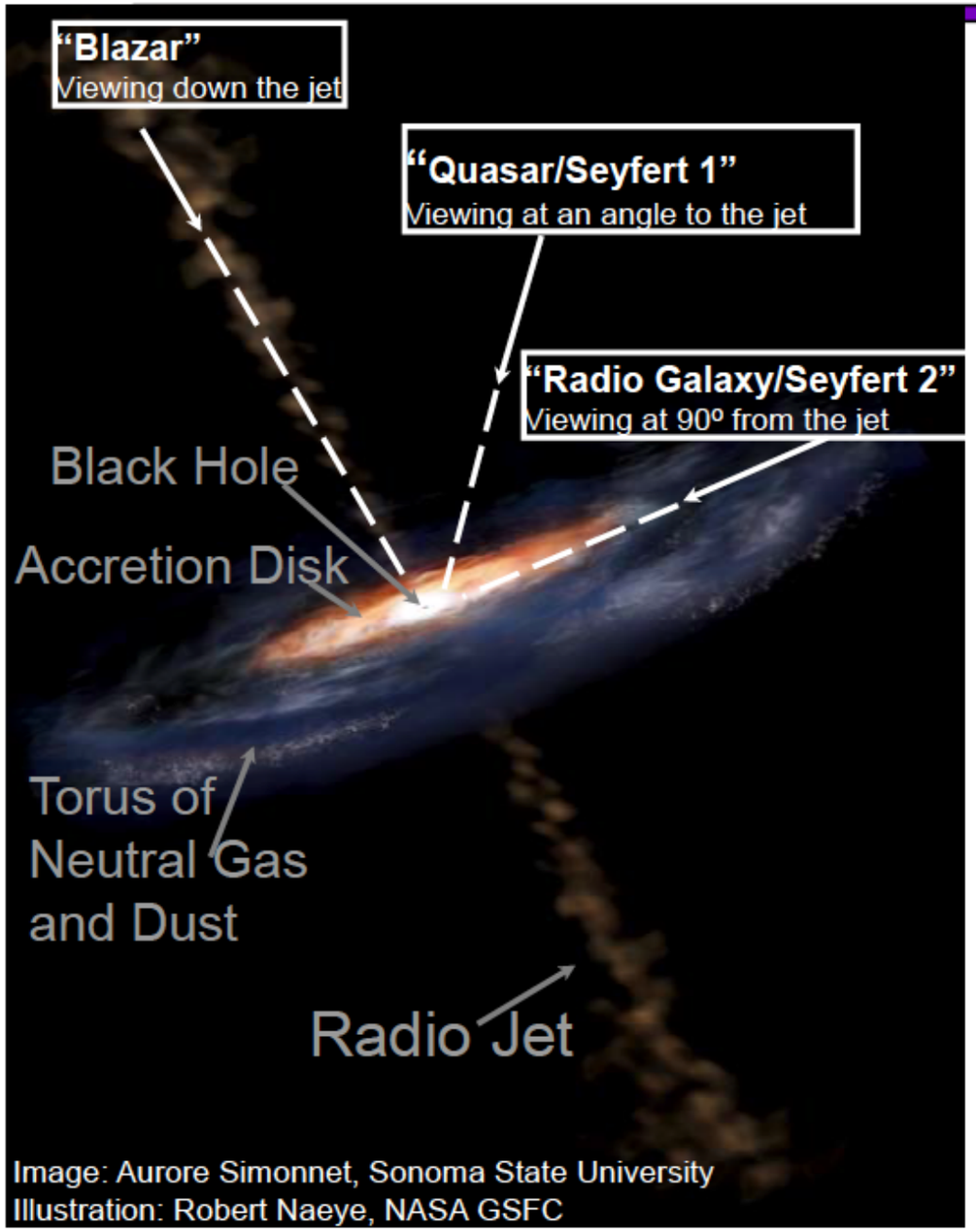
Spectrum:
Parent proton could be 1PeV ➔ PeVATRON?

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

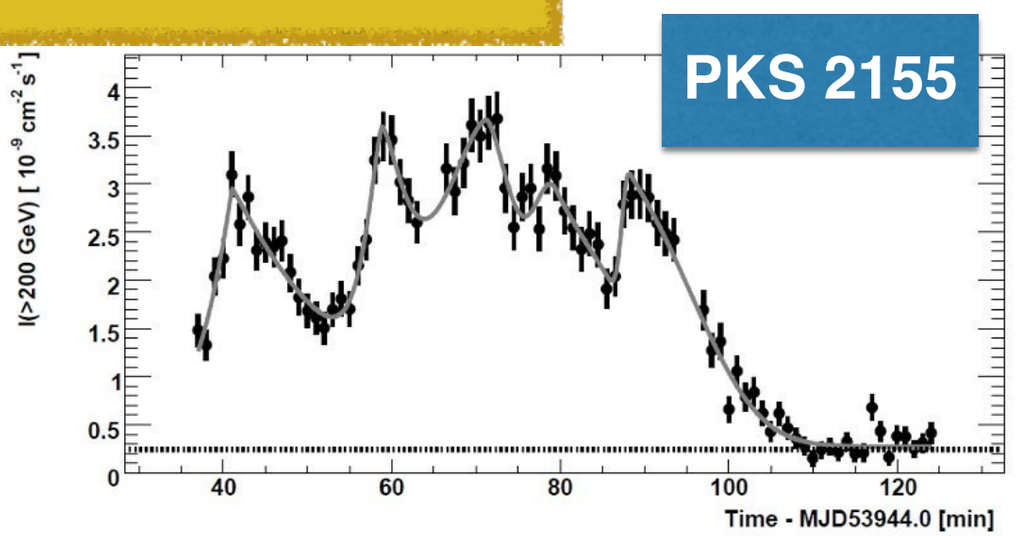
But also radio galaxies (e.g M87)

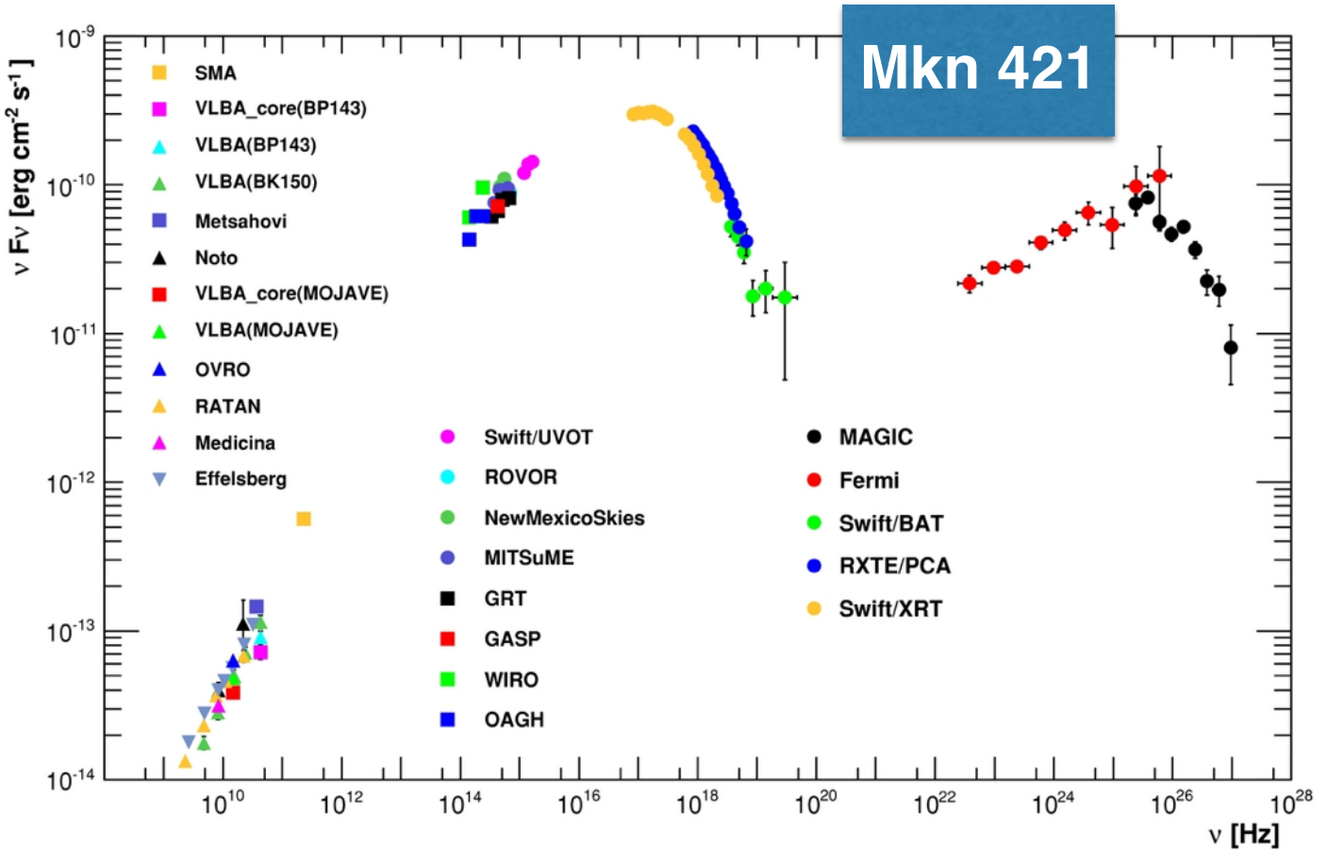
- ➔ Jet viewed from the side

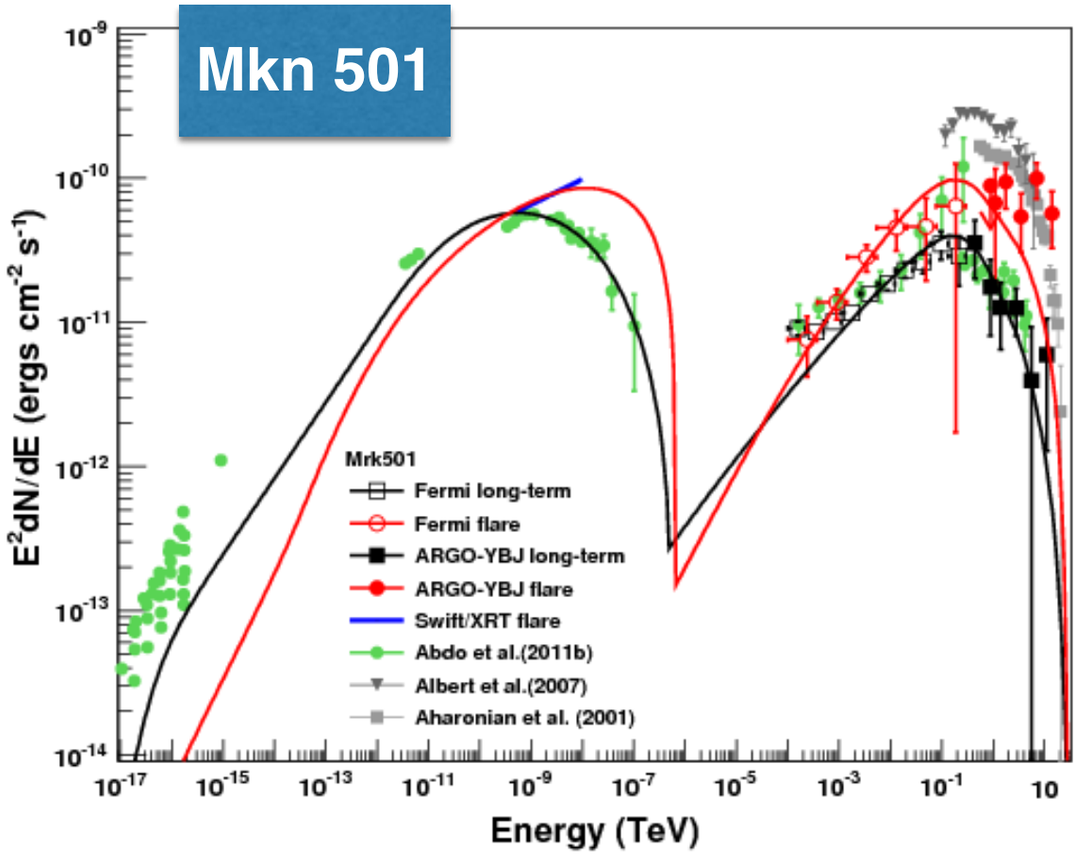
活動銀河核（ブレーザー）

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

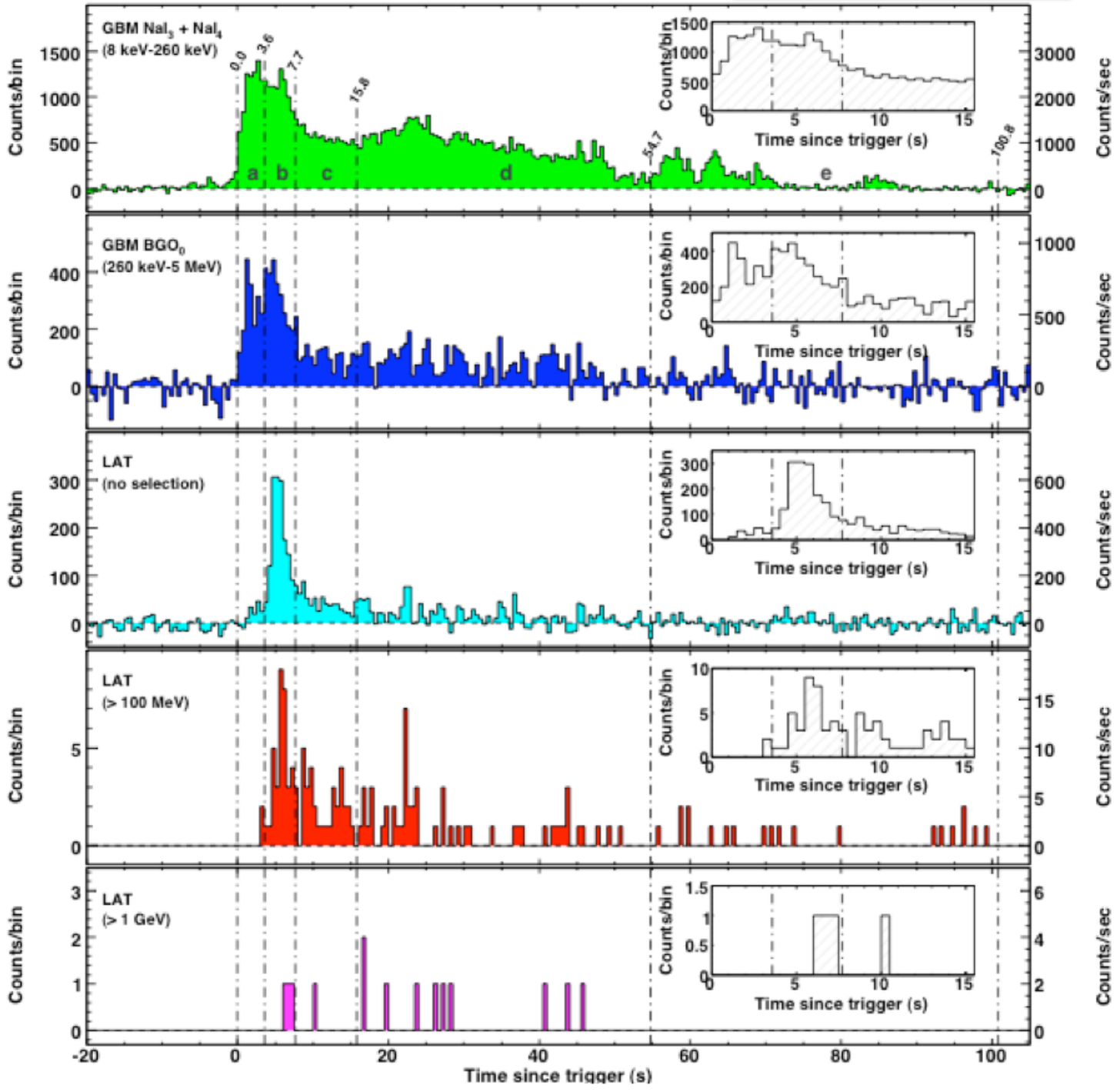
- Gamma-ray bursts (GRBs) are highly energetic explosions signaling the death of massive stars in distant galaxies.

- In September 2008, Fermi observed the exceptionally luminous GRB 080916C, with the largest apparent energy release yet measured.

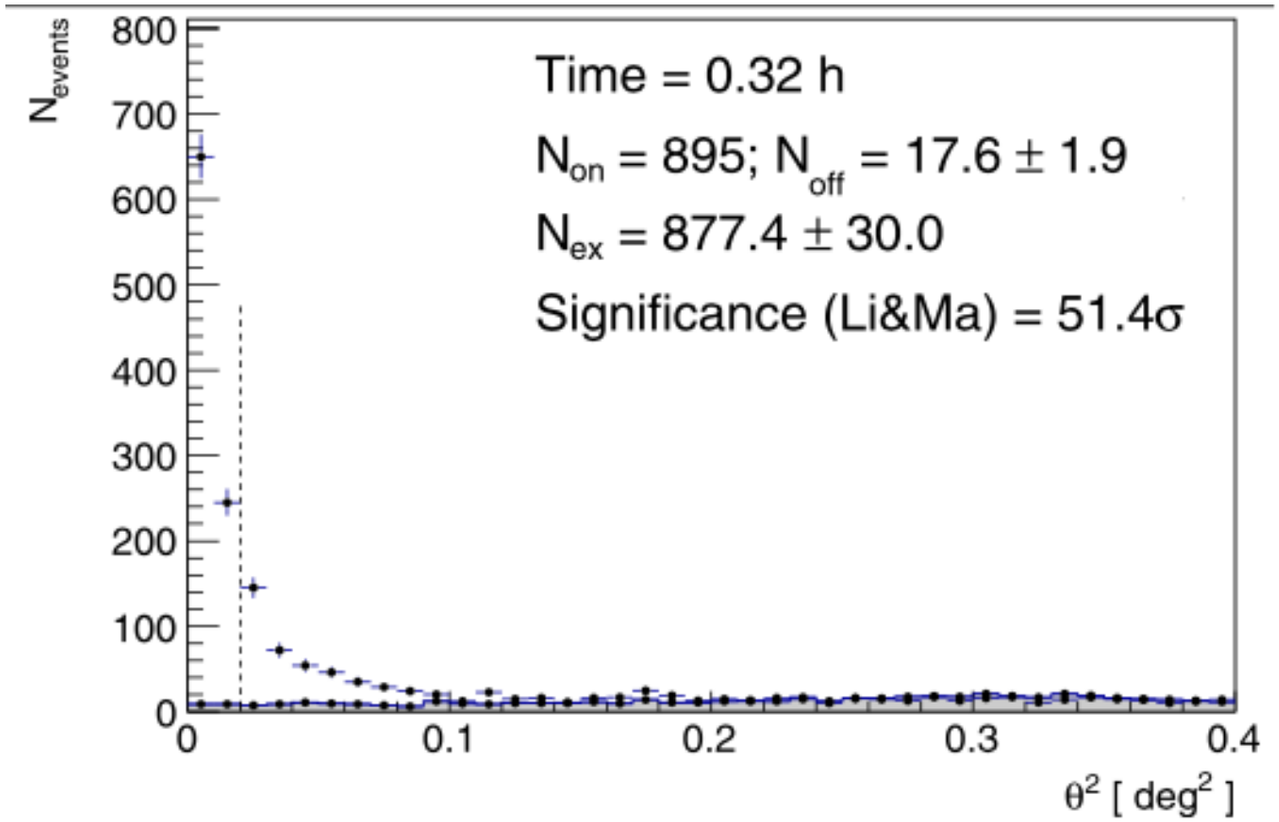
- The high-energy gamma rays are observed to start later and persist longer than the lower energy photons.

$$z = 4.35 \pm 0.15$$

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 method[42].

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

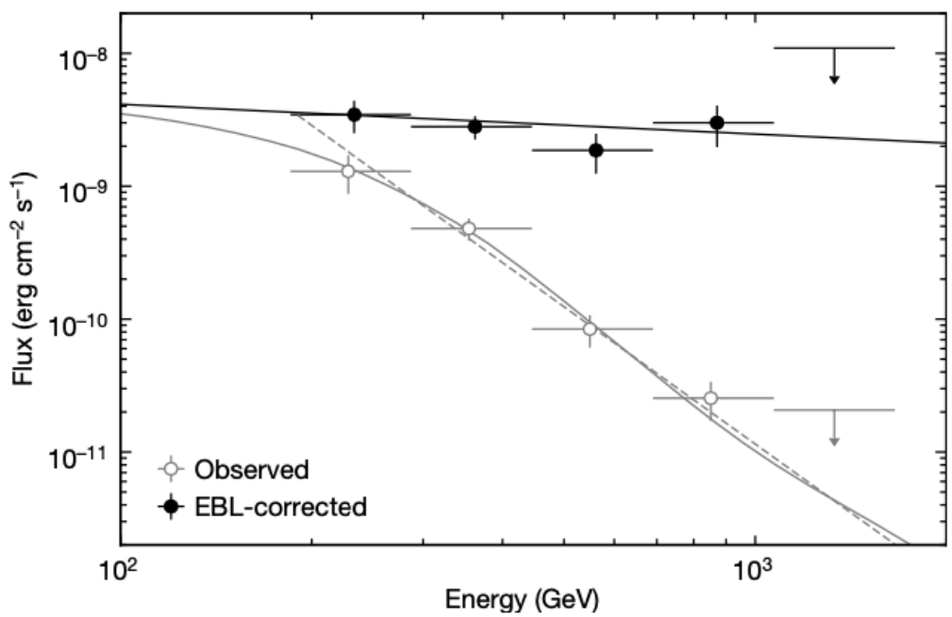
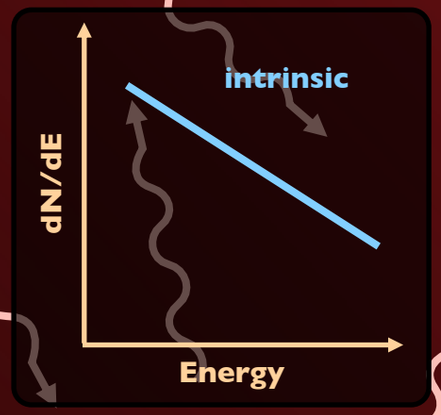


Fig. 2 | Spectrum above 0.2 TeV averaged over the period between T_0 + 62 s and T_0 + 2,454 s for GRB 190114C. Spectral-energy distributions for the

AGN

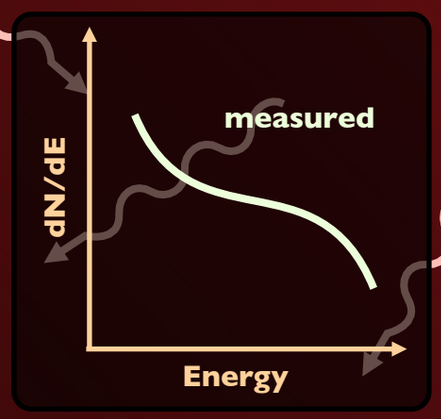


Stars and **Dust**
in Galaxies

HE/VHE Υ-Rays

UV/O/IR
Photons

e-
e+



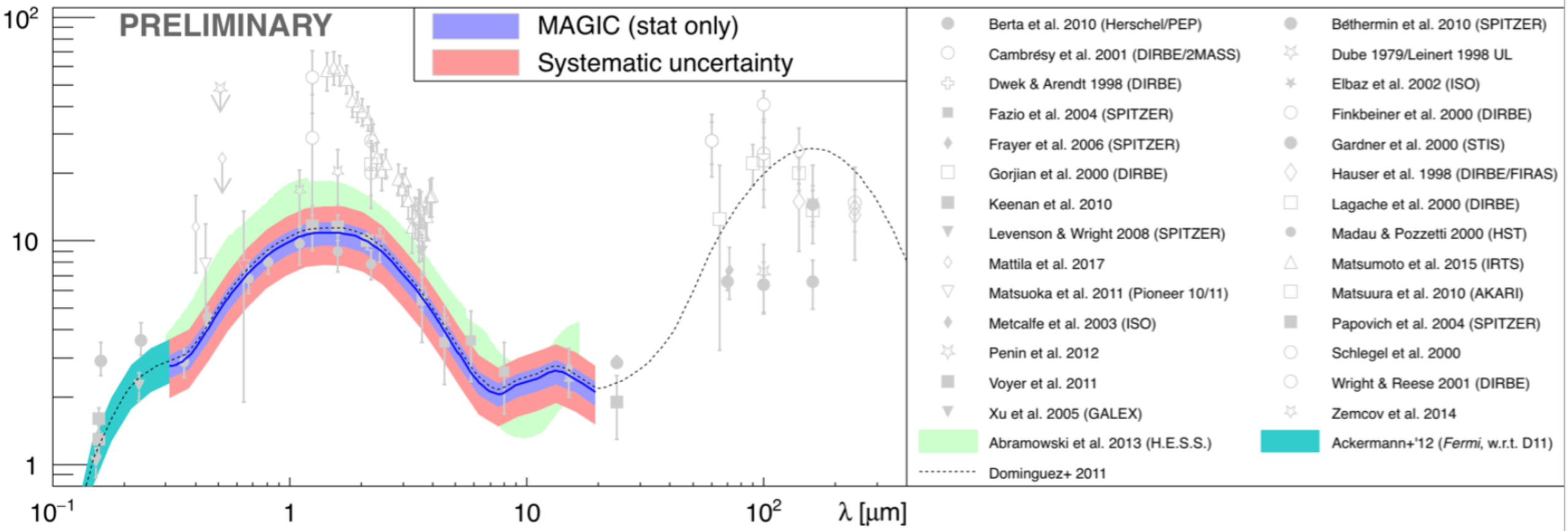
$$E_\gamma E_{\mathrm{EBL}} \approx 4(m_e c^2)^2 \approx 1\,\mathrm{MeV}^2$$
$$E_{\mathrm{EBL}} \sim \mathrm{eV} \rightarrow E_\gamma \sim \mathrm{TeV}$$

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

slide from M Raue

銀河外背景光

Extragalactic Background Light



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

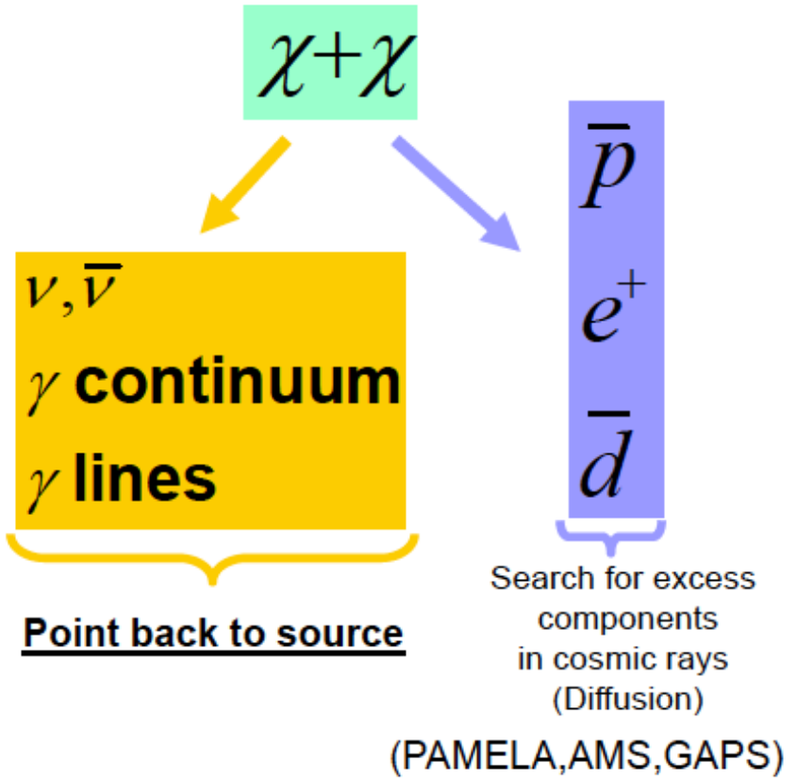
Not much more EBL than the one from the resolved galaxies

暗黒物質対消滅

Search for Cold Dark Matter

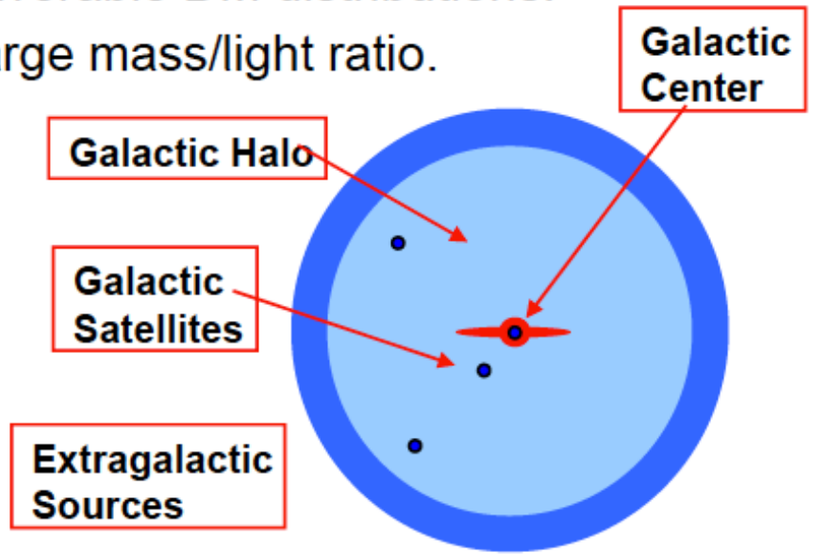
Hypothesis: DM = WIMPs

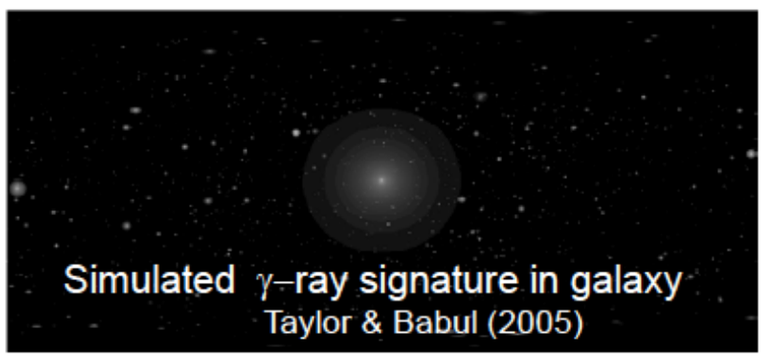
- Indirect detection of WIMP annihilation → γ, ν etc.



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

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

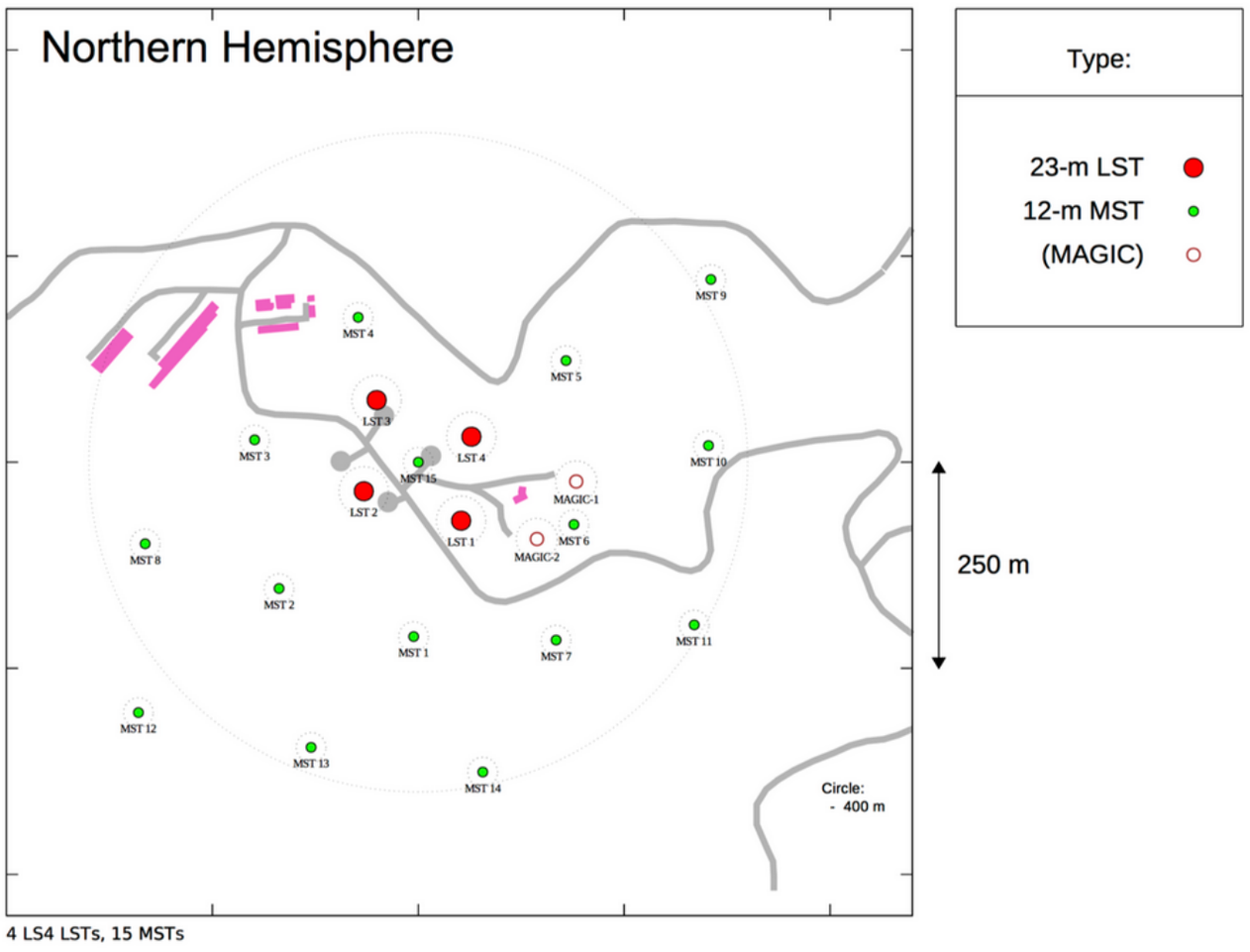
Core array expansion
with dual-mirror
telescopes

High-energy section:
30-70 x 4-6 m tel. (SST)
Davies-Cotton reflector
(or Schwarzschild-Couder)
- FOV: ~10 degrees
10 km^2 area at
multi-TeV energies

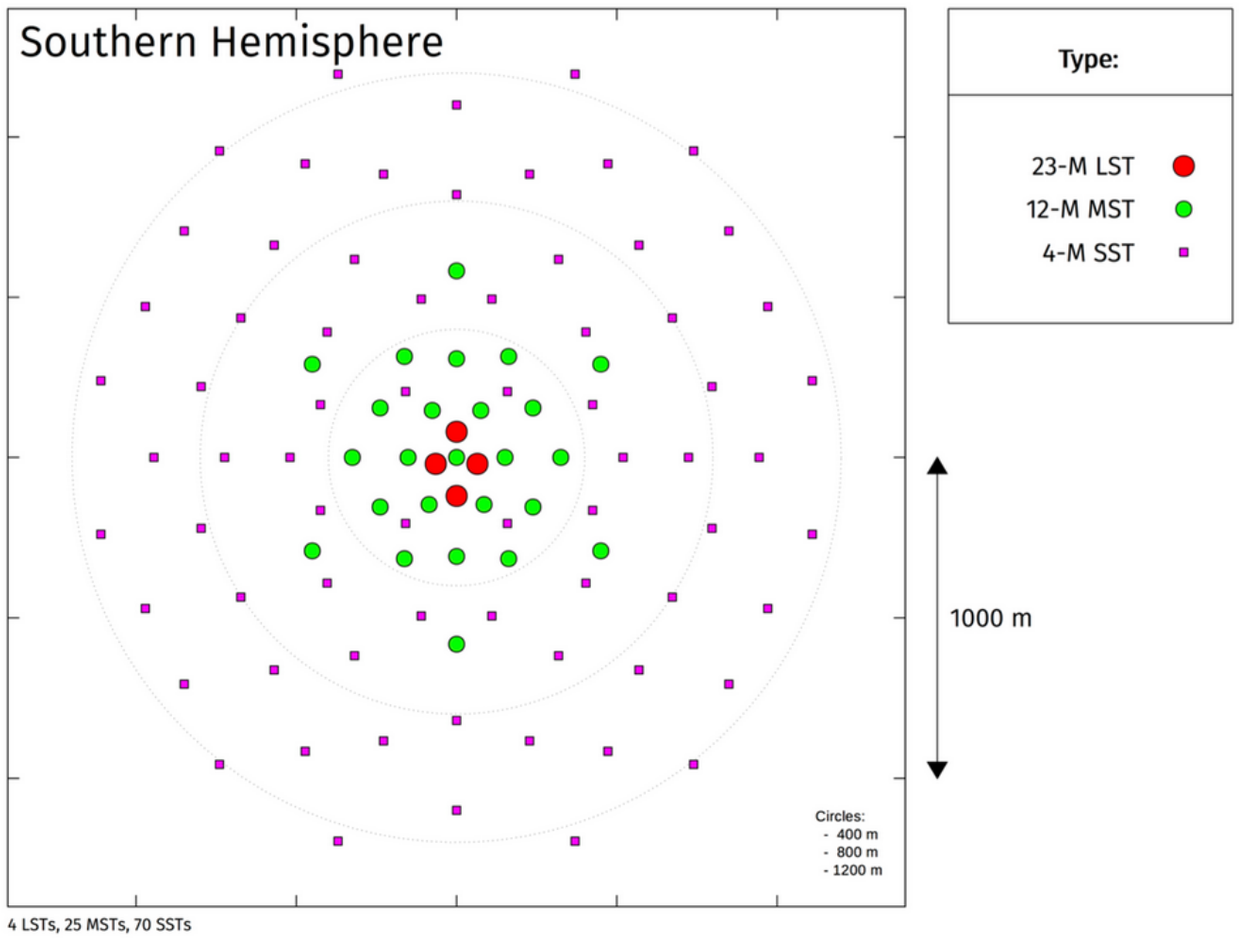
5. Future of Gamma-Ray astrophysics

ICRR
Institute for Cosmic Ray Research
University of Tokyo

La Palma, Canary islands



Paranal, Chile



5. Future of Gamma-Ray astrophysics

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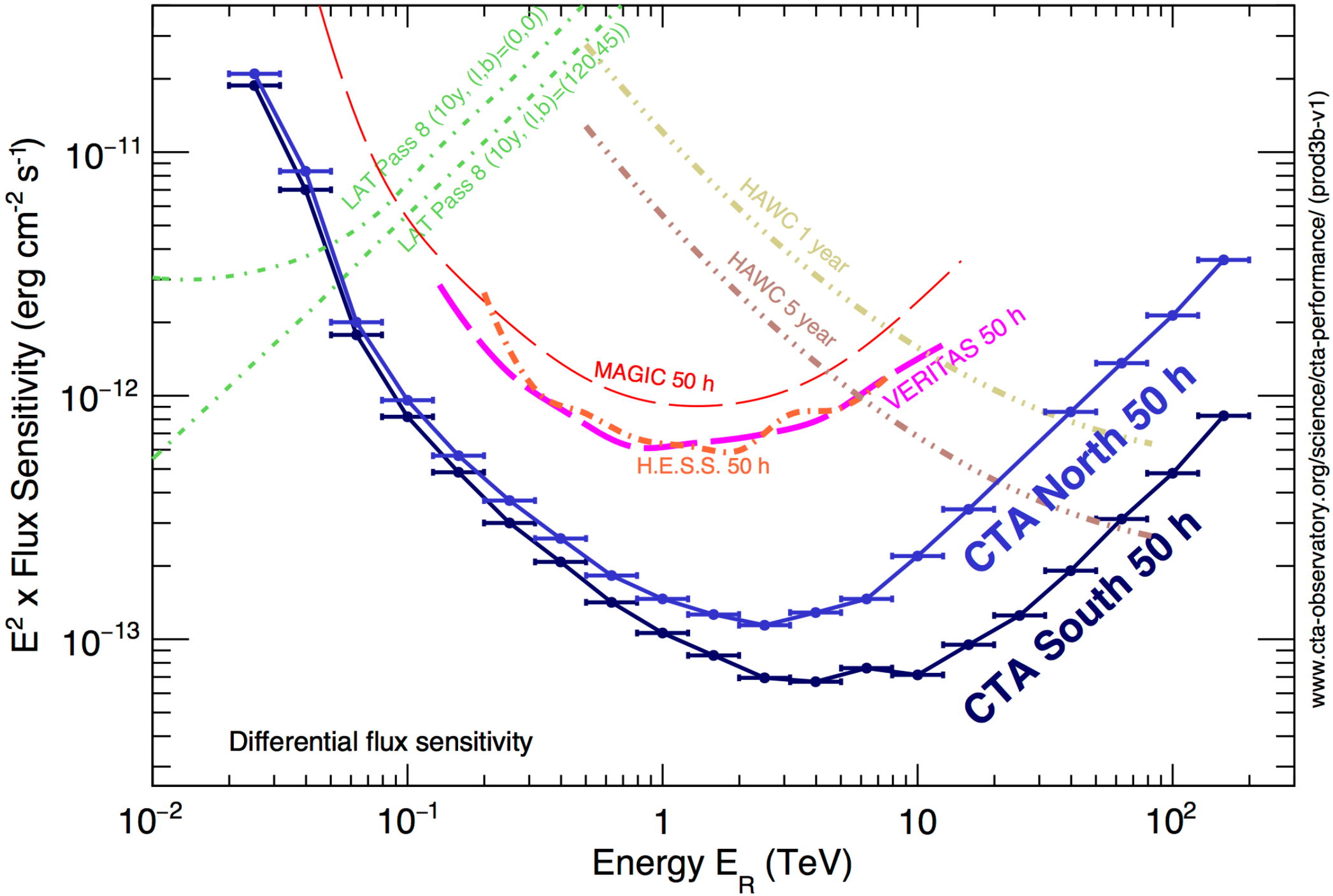
Institute for Cosmic Ray Research
University of Tokyo

Flux Sensitivities



5. Future of Gamma-Ray astrophysics

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Large Size Telescopes of CTA

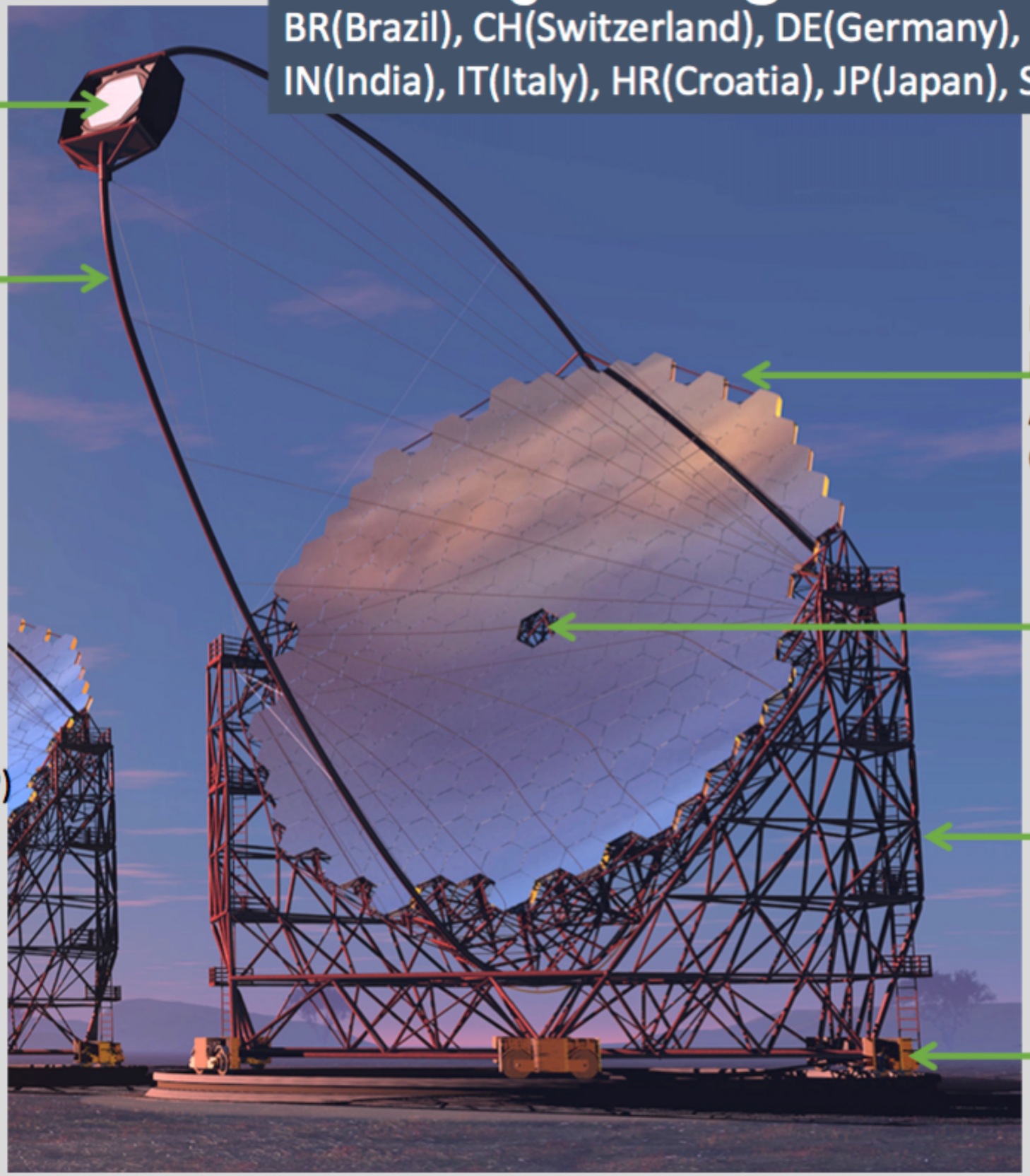
LST collaboration:
11 countries
223 members
(134 receiving emails)
73 FTEs

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)

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

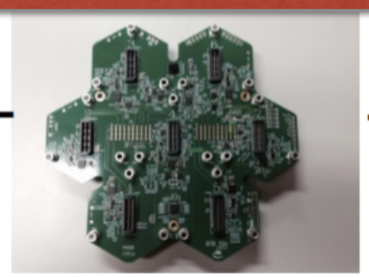
Japan + INFN-Pisa + IAC + IFAE + Complutense + CIEMAT

7 LGs

+

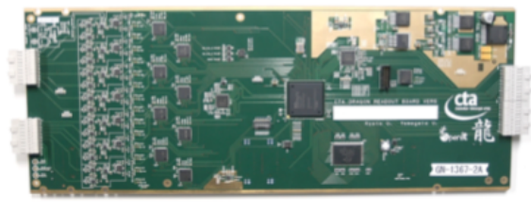
7 PMTs

+



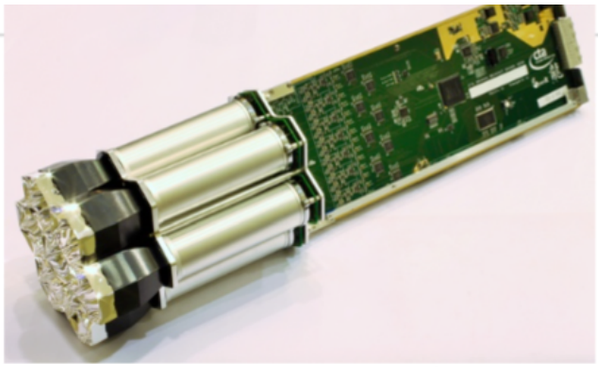
SCB

+



Dragon board

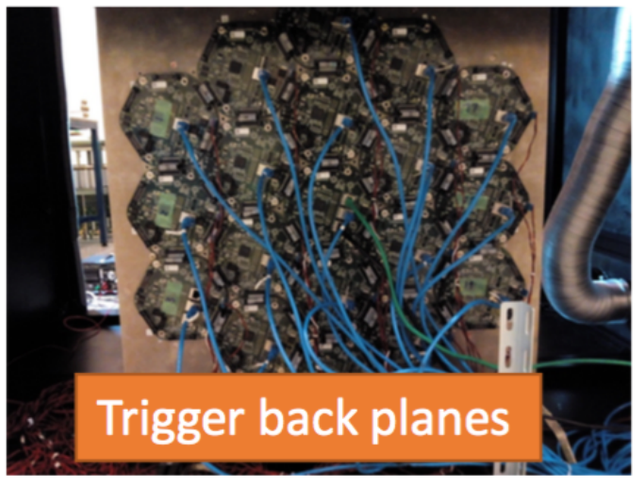
=



FPI module

Module assembly

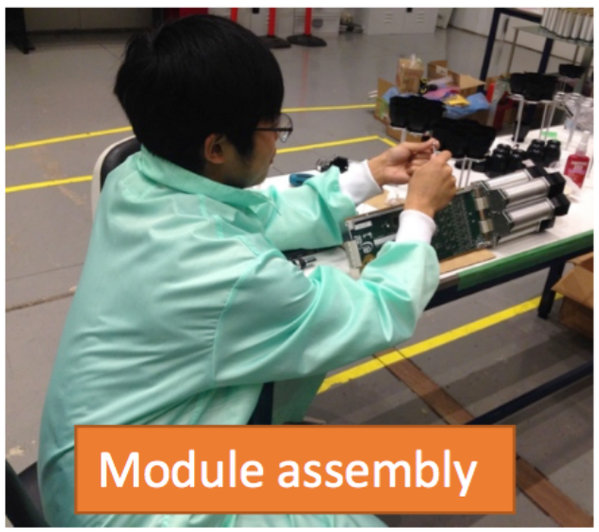
19 tested modules



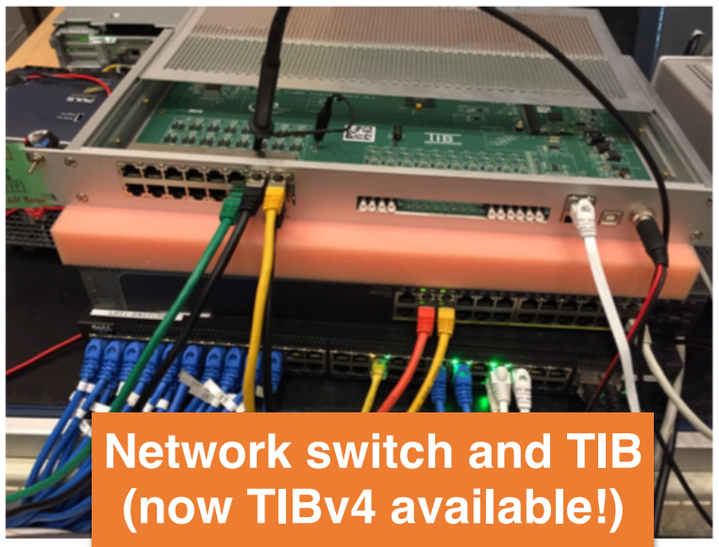
Trigger back planes

265 modules/ Tel. needed.

270 modules are assembled @ IAC



Module assembly



Network switch and TIB (now TIBv4 available!)

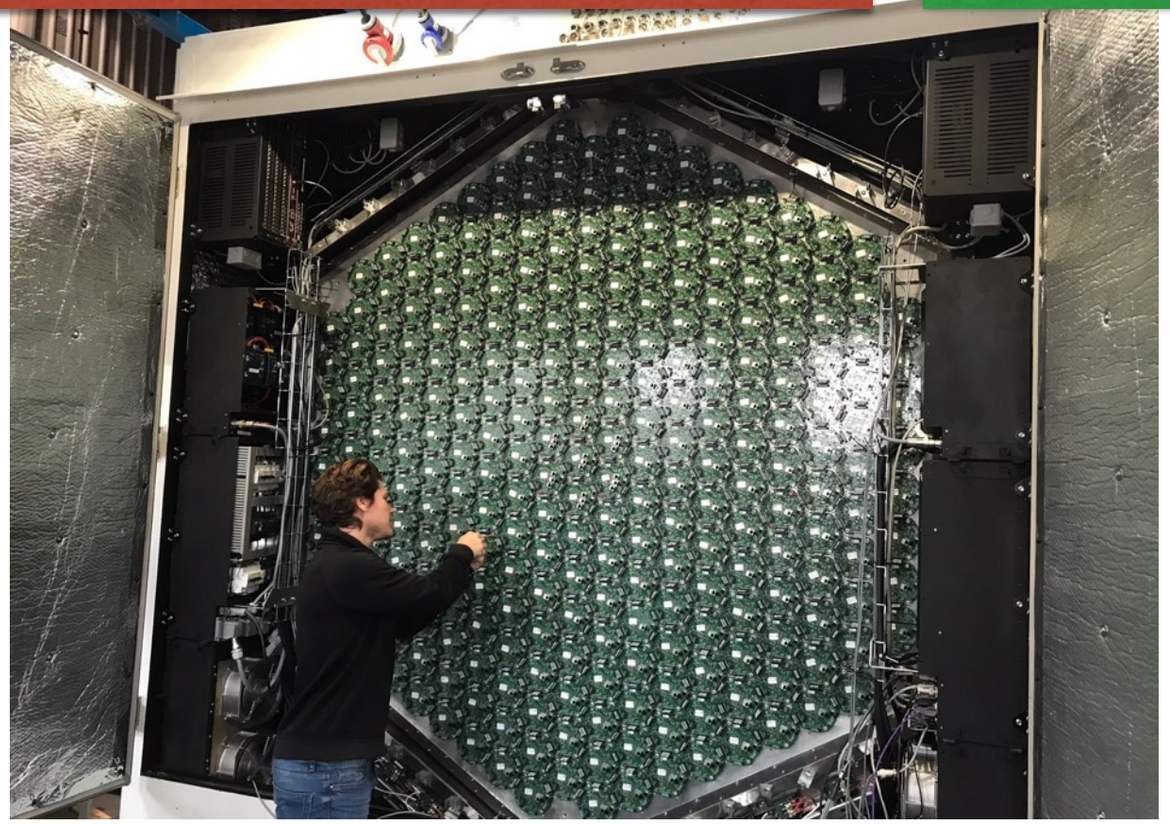
Camera server

Now ready to ship to IFAE

LST1 progress since November 2017

Backplanes of the camera installed

Jan 2018



Camera mechanics finished

Feb 2018

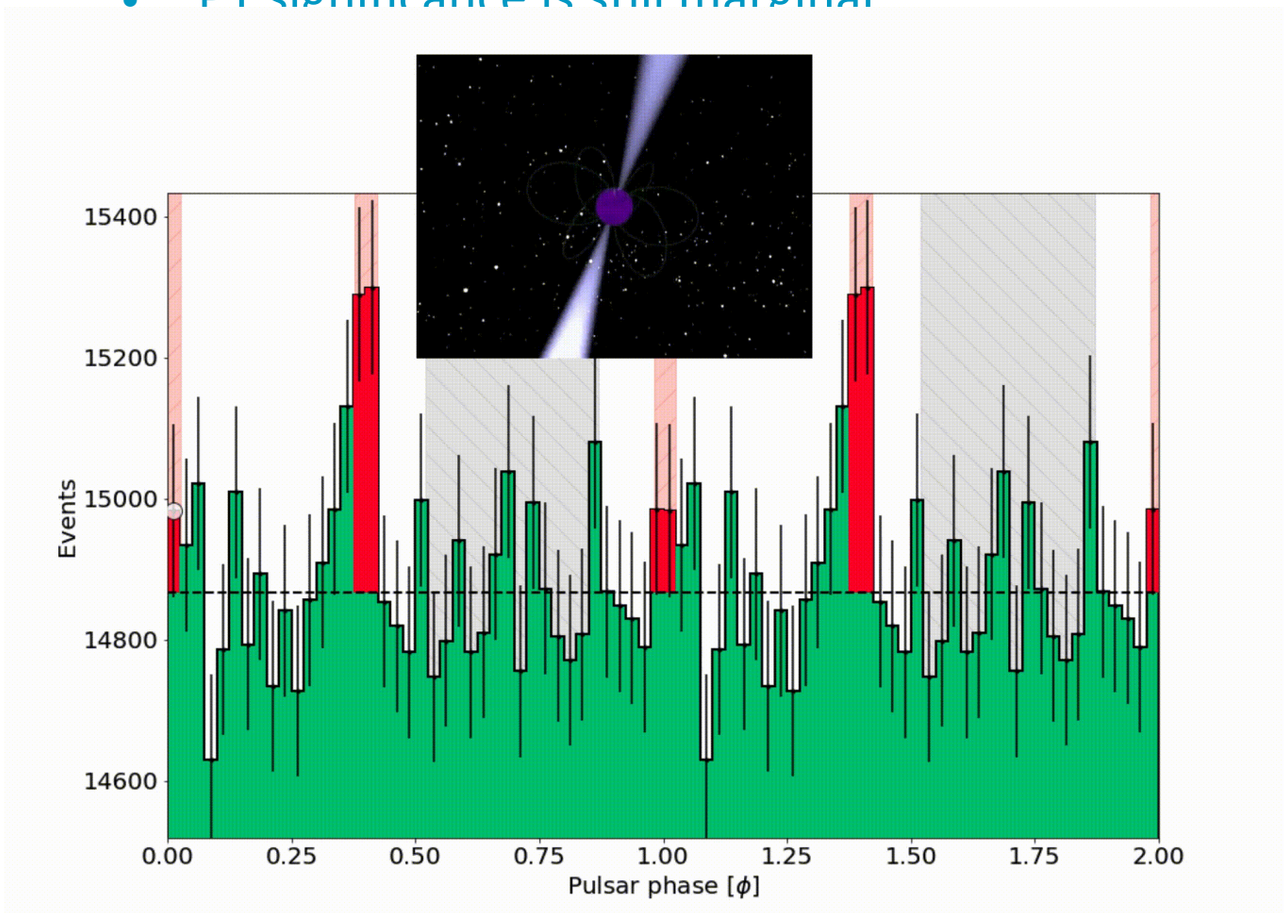
Camera Installation On the telescope

Sep 2018

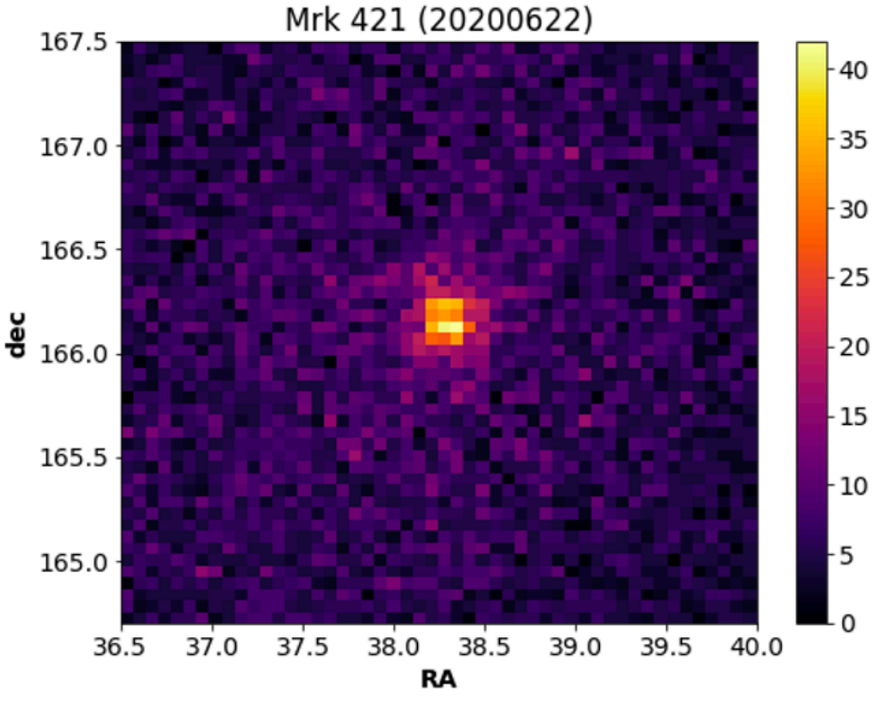
Oct 2018

Engineering runs

- Crab pulsar
  - Challenging to detect a pulsar only with commissioning data (11.4 h from early 2020)
  - P2 clearly detected with significance 5.2 σ
  - P1 significance is still marginal

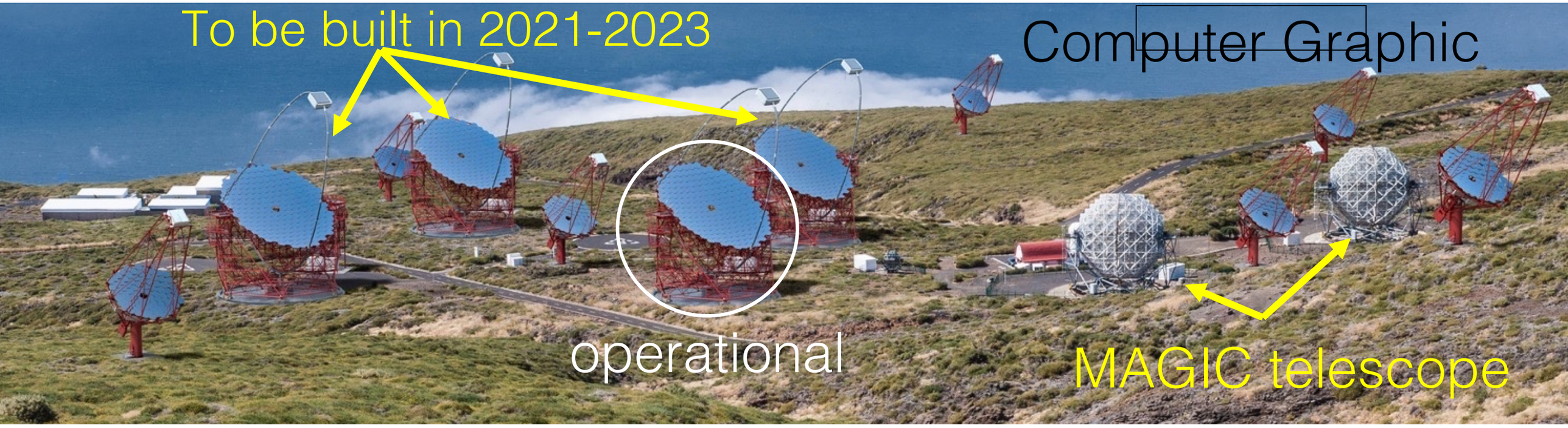


- AGNs
  - Follow-up observations of flaring sources
  - Already detected Mrk 421, Mrk 501, 1ES J1959+650, 1ES 0647+250 (likely the most distant source detected by the LST)



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

- ガンマ線観測の意義、目的は
  - 宇宙線起源の解明
  - 中性子星、ブラックホール近傍などの極限環境の研究
  - 宇宙論や基礎物理への貢献

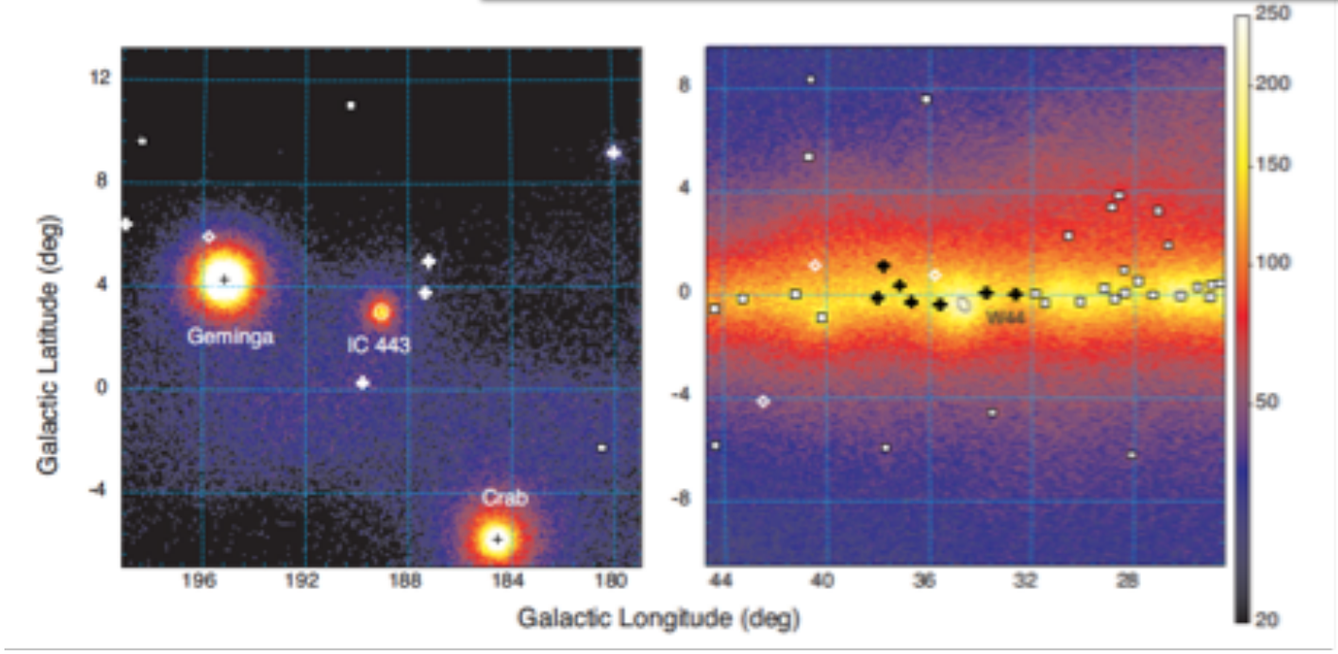
- VHEガンマ線天文学はまだ若く、CTAにより大きな発展が期待

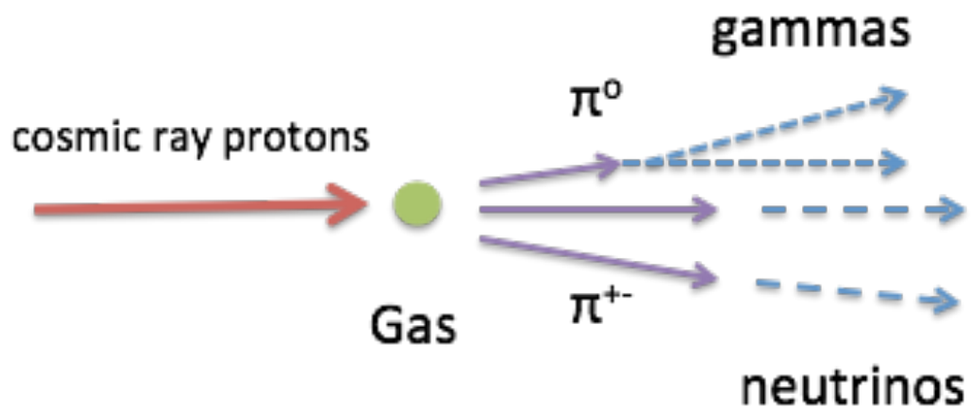
Your (possible) future

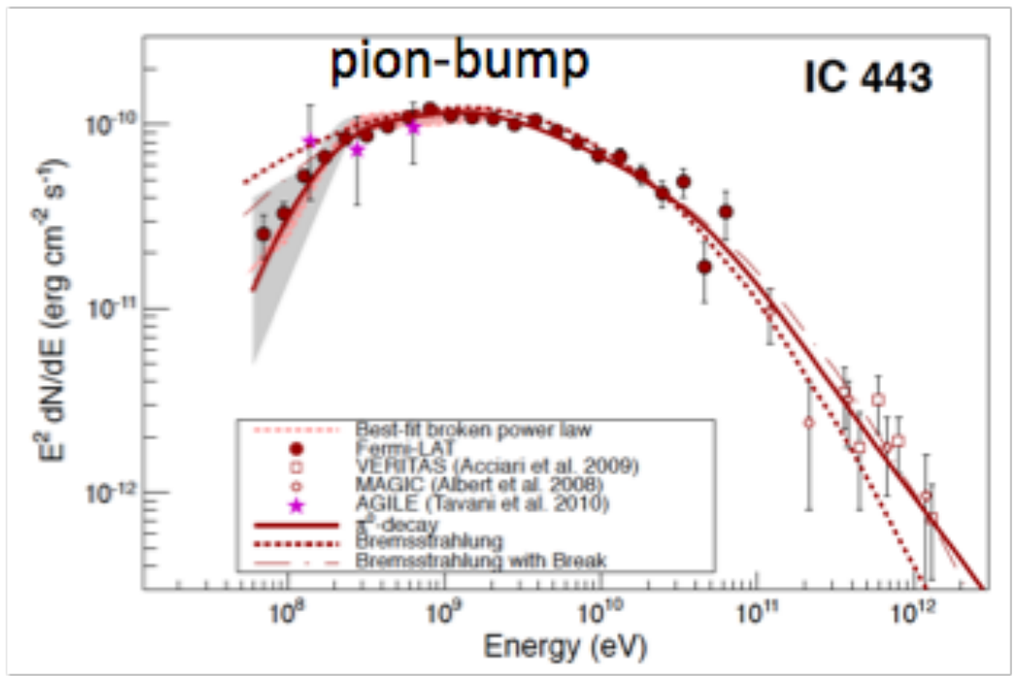
ICRR
Institute for Cosmic Ray Research
University of Tokyo

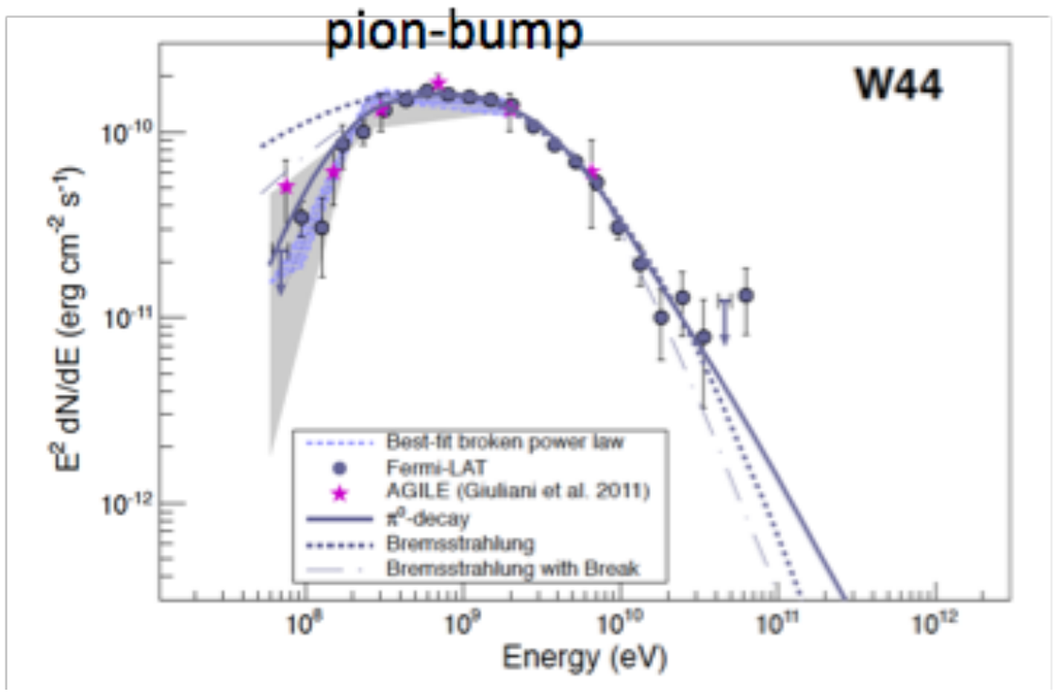
超新星残骸

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









ガンマ線観測でなにがわかるか

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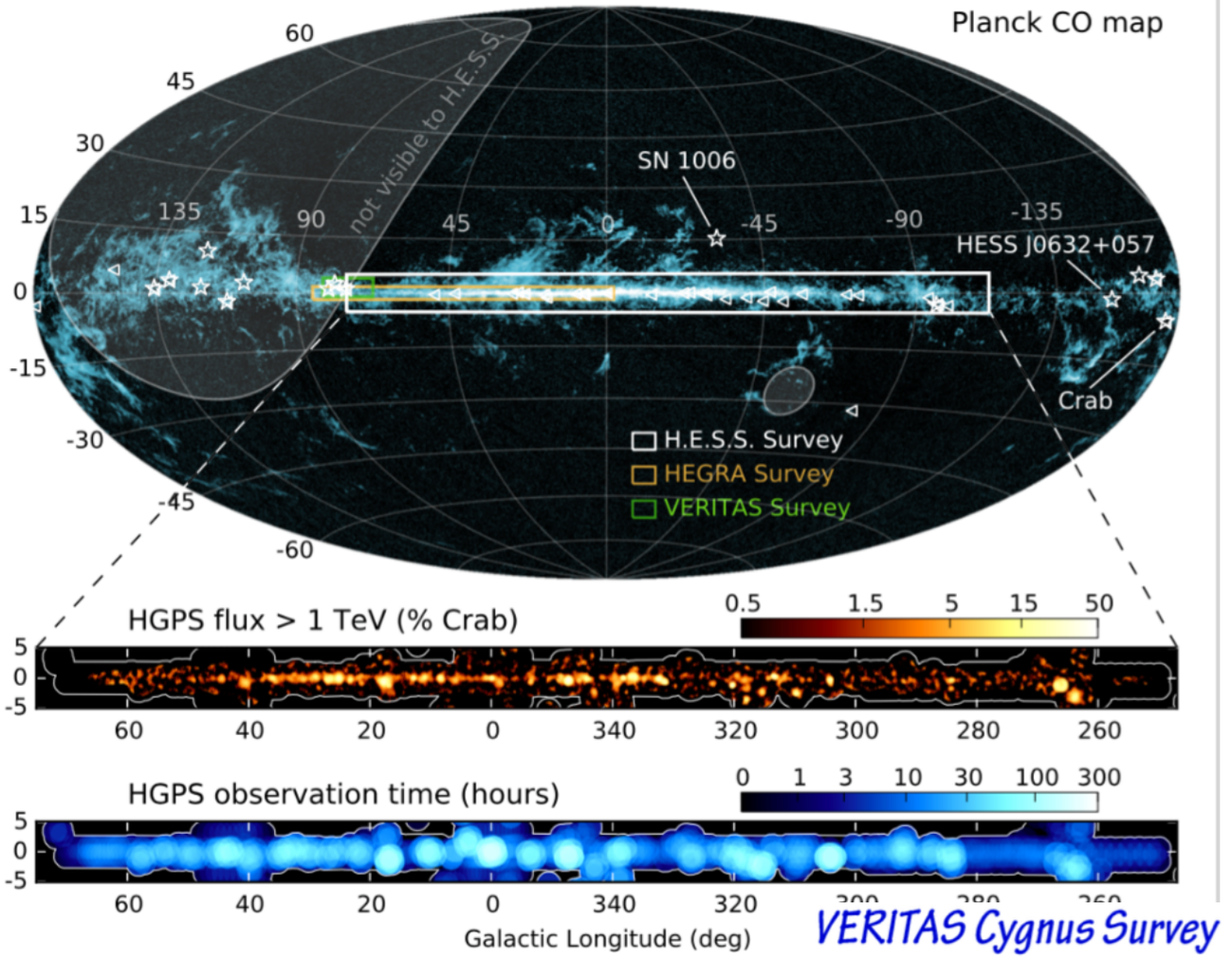
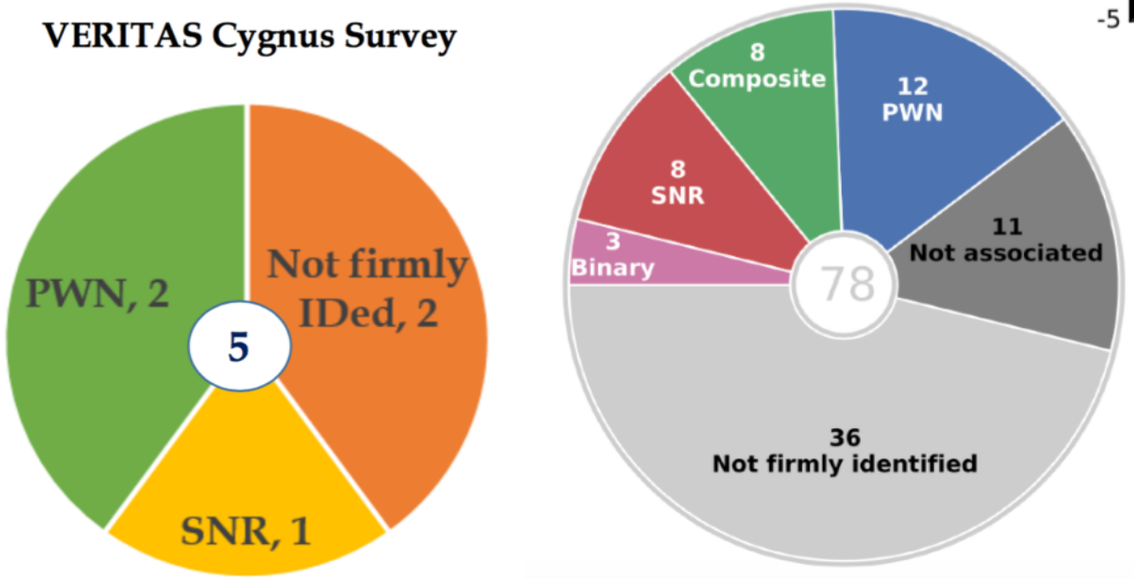
University of Tokyo

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