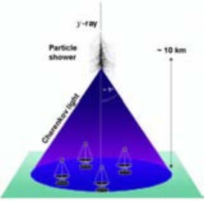
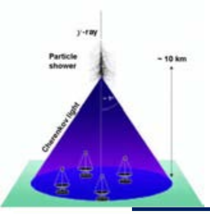
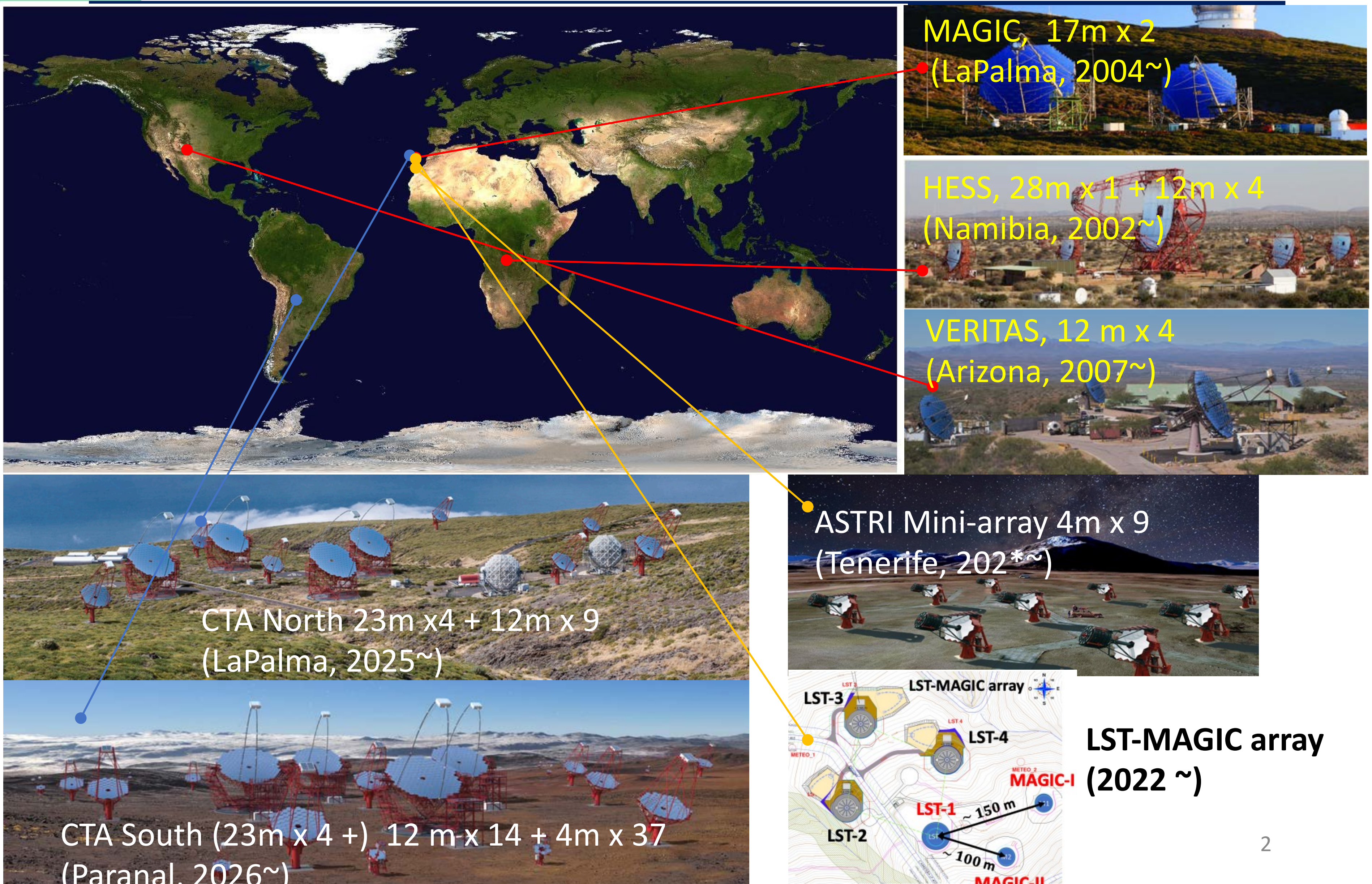


IACTによる ガンマ線観測と 宇宙線加速

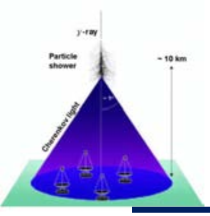
齋藤隆之
(ICRR)



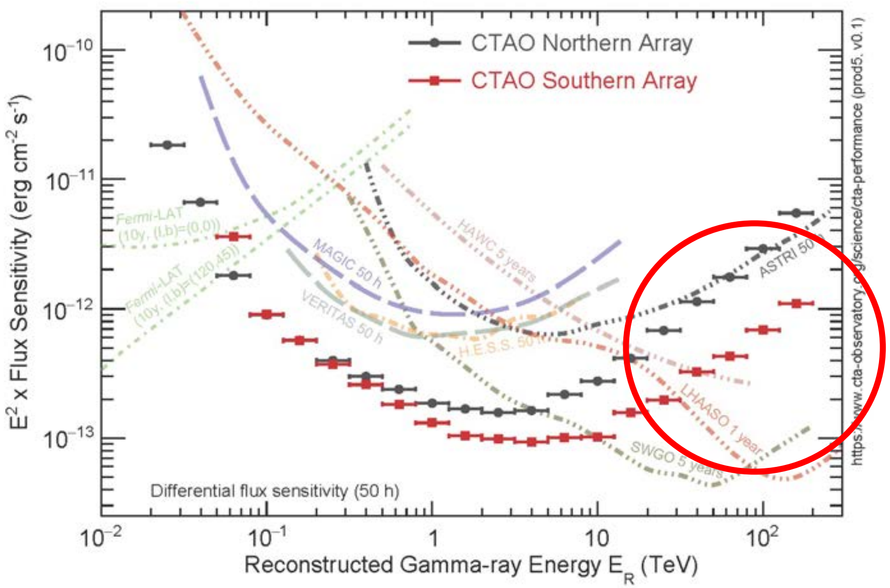
IACT

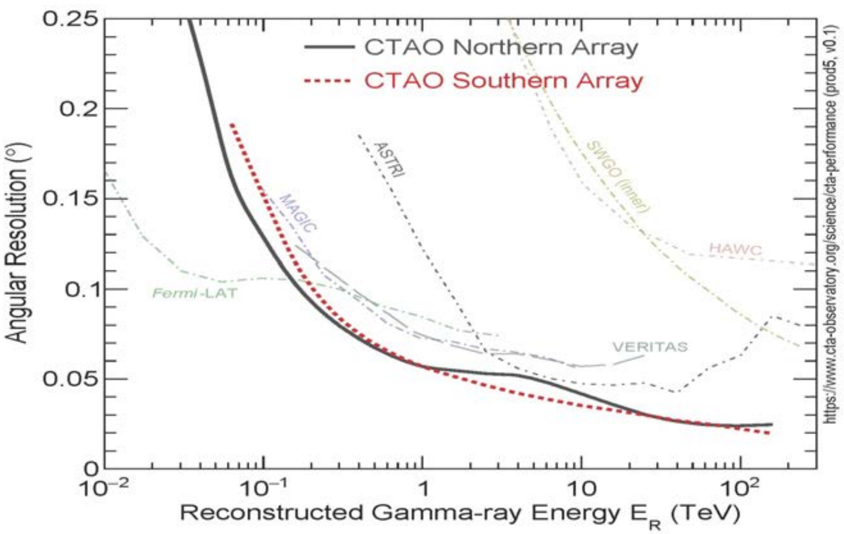


MAGIC, 17m x 2
(LaPalma, 2004~)
HESS, 28m x 1 + 12m x 4
(Namibia, 2002~)
VERITAS, 12 m x 4
(Arizona, 2007~)
ASTRI Mini-array 4m x 9
(Tenerife, 202*~)
CTA North 23m x4 + 12m x 9
(LaPalma, 2025~)
CTA South (23m x 4 +) 12 m x 14 + 4m x 37
(Paranal, 2026~)
LST-MAGIC array
LST-3
LST-4
LST-1
LST-2
MAGIC-I
MAGIC-II
~ 150 m
~ 100 m
LST-MAGIC array
(2022 ~)



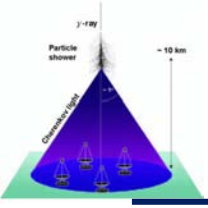
TeVガンマ線検出器の感度





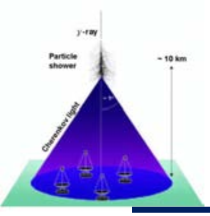
今回の勉強会のトピックスは
「銀河系内外のトランジション領域」

	IACT	Partice Detector Array
視野	~ 数度	~60度
Duty Cycle	~ 1000 hours/yr	~ 8000 hours/yr
角度分解能	~0.05 度	~ 0.2 度
ハドロン除去能力 at 1 TeV	99%, Q値5-10	50%, Q値1-3
突発事象感度	高い	低い



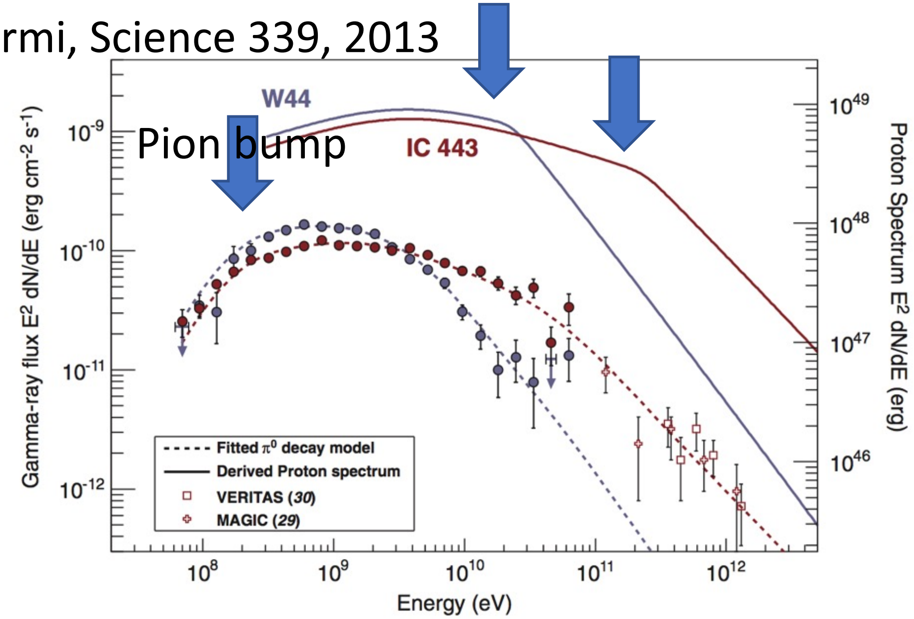
今回の勉強会のトピックスは「銀河系内外のトランジション領域」

- SNR
- PWN
- その他（銀河中心、Cygnus Cocoon)
- 銀河系外
- まとめ



ハドロン加速のSNR: IC443, W44

Fermi, Science 339, 2013



IC443 (10000 歳）
W44 (20000 歳)

ハドロン加速の証拠

PeVまでは無理

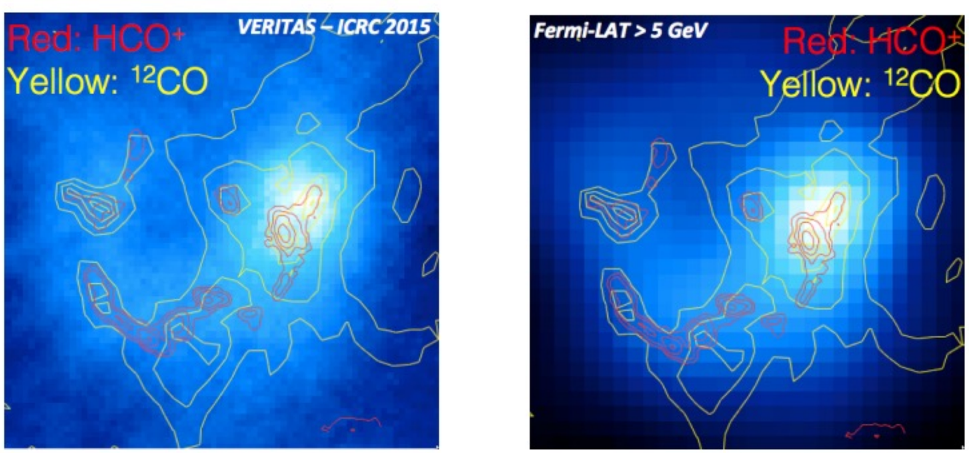
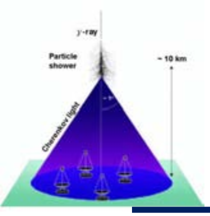


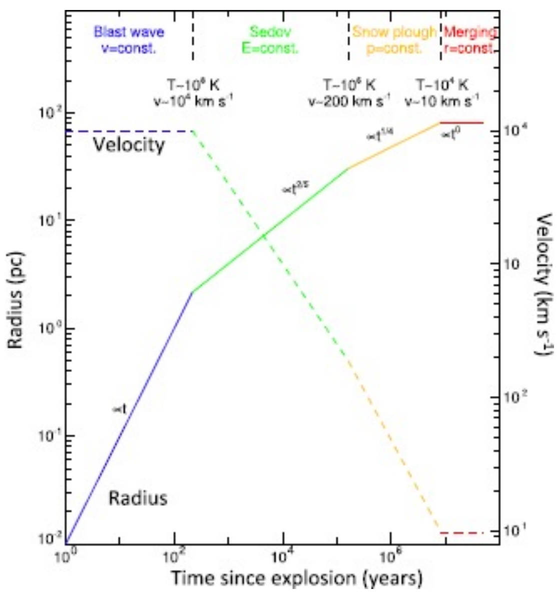
Figure 5: (left) VERITAS excess map with contours of two tracers of shocked gas, HCO^+ (red) and ^{12}CO (yellow) overlaid. (right) The *Fermi*-LAT counts map, with the same contours overlaid.



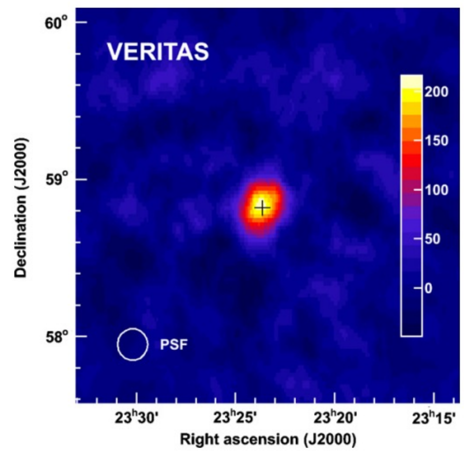
若いSNR: Tycho, Cas A

- PeV まで加速 -> 高速衝撃波->セドフ初期

$$E_{max} \propto B\, v_{sh}^2\, t_{age}$$



Cas A (340歳)



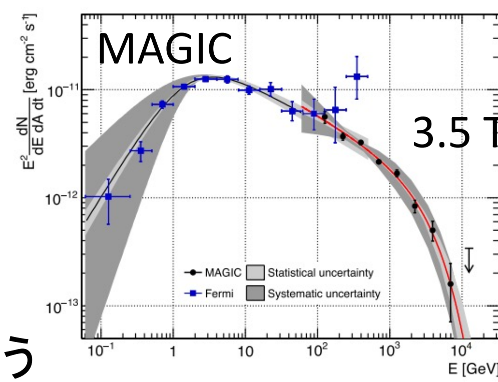
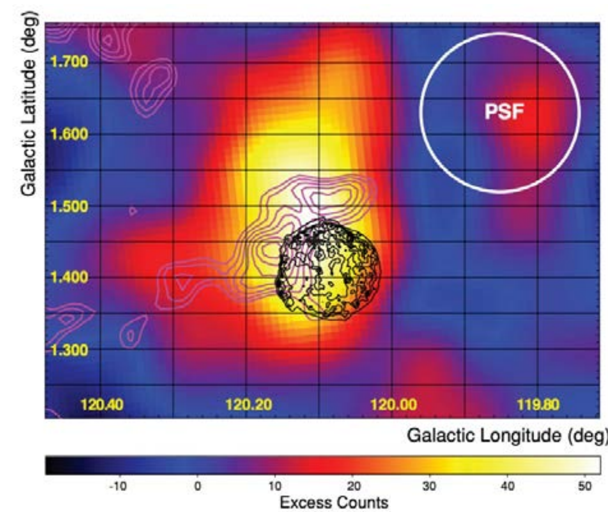


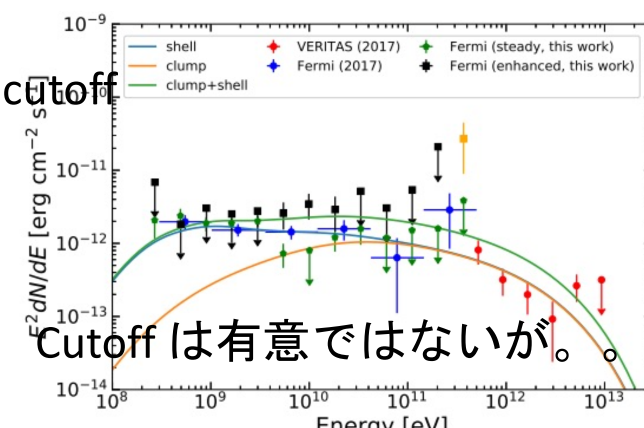
Figure 1. Spectral energy distribution measured by the MAGIC telescopes (black dots) and *Fermi* (blue squares). The red solid line shows the result of fitting the MAGIC spectrum with equation (1). The black solid line is the broken power-law fit applied to the *Fermi* spectrum.

3.5 TeV cutoff

300歳ではもう
古すぎる？

Tycho (450歳)

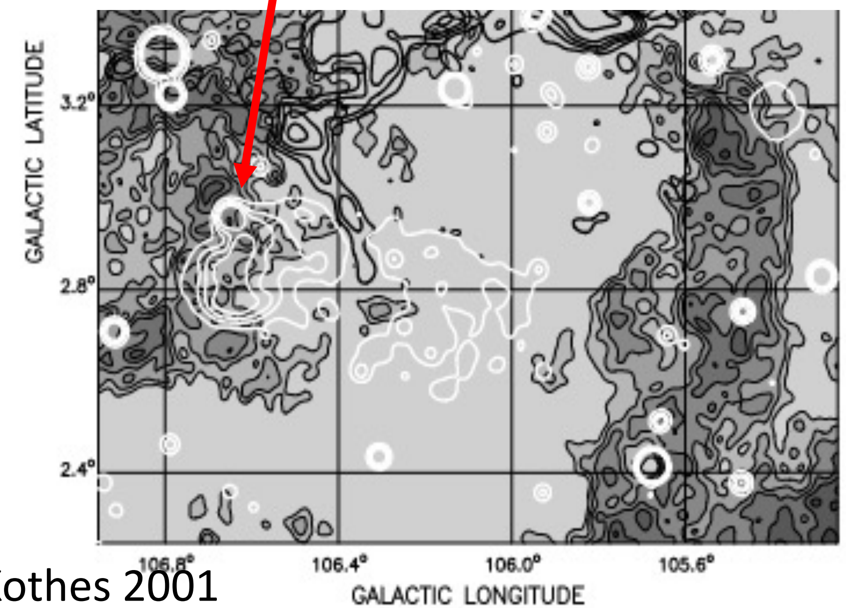




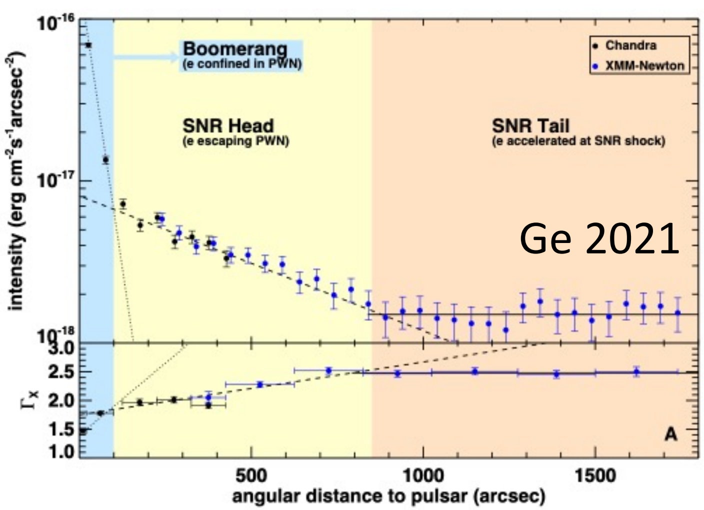
Cutoff は有意ではないが。。。

SNR G106.3 / Boomerang

Boomerang PSR



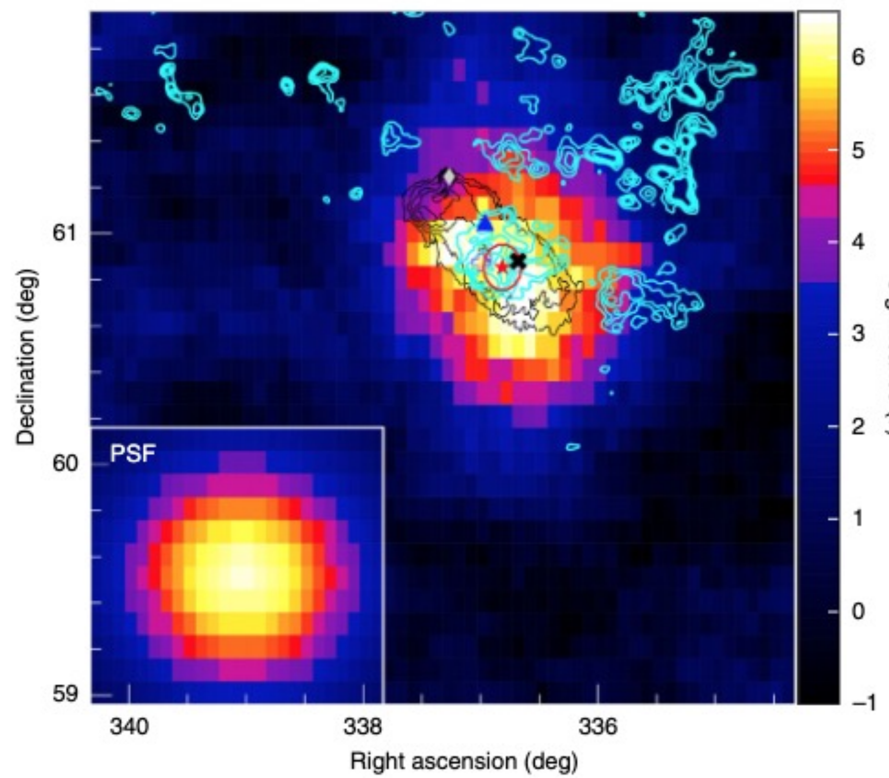
Kothes 2001



Ge 2021

(4000 - 10000歳）

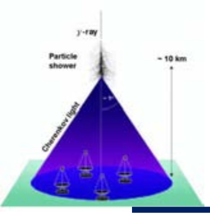
濃い分子雲に当たって非対称なSNR



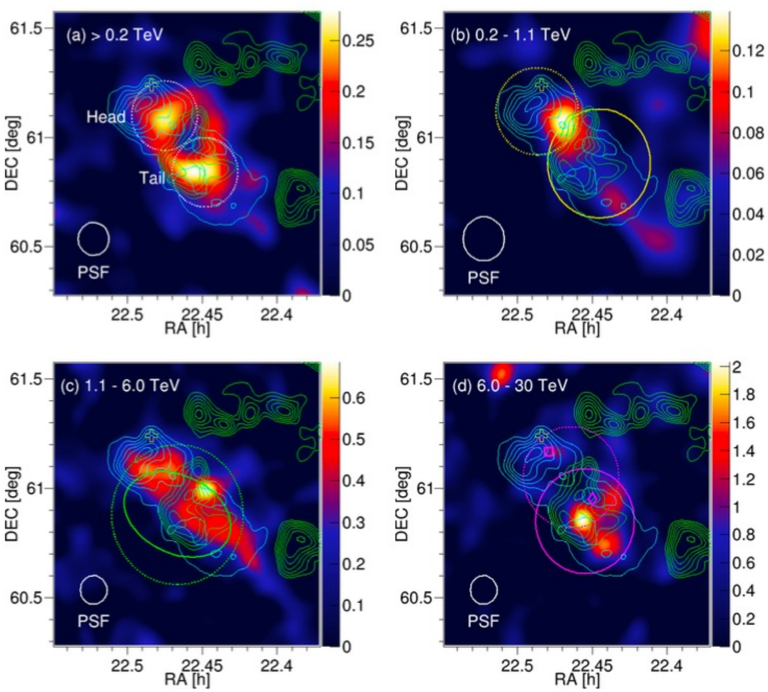
Tibet As Gamma, 10 - 100TeV (Nature Astr. 2020)

歳とってるのに衝撃波の速度が早い？？

(~ 5000 km/s, Ge et al.)

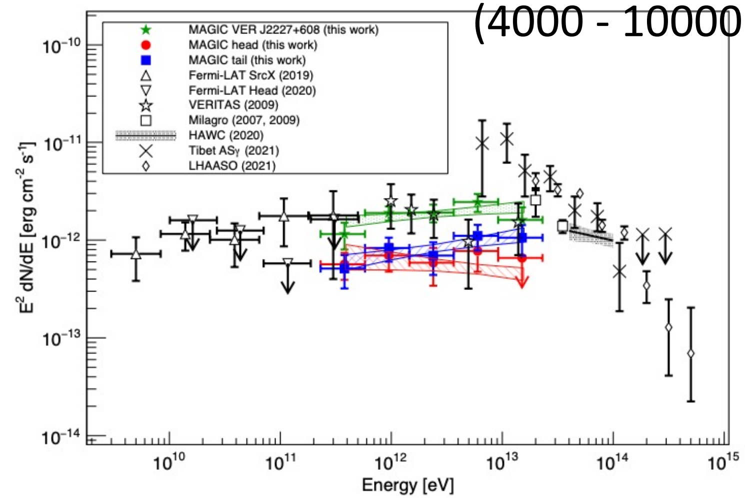


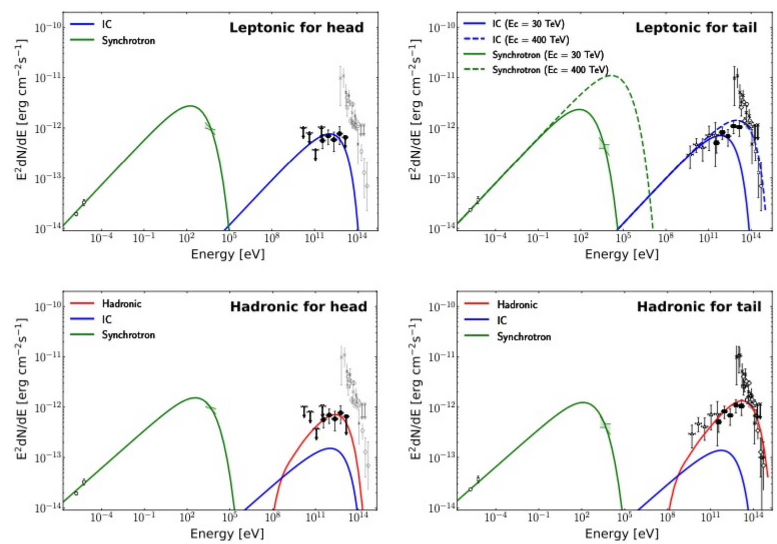
SNR G106.3 / Boomerang



MAGIC Observation (京大・岡くん)

(4000 - 10000歳）



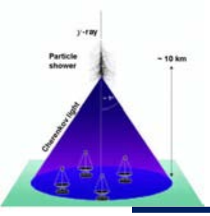


Source	α_e	$E_{c,e}$ [TeV]	$W_e > 1$ GeV [erg]	B [μG]	α_p	$E_{c,p}$ [TeV]	$W_p > 1$ GeV [erg]	N_{gas}[cm^{-3}]
Head (leptonic)	2.4	45	4.9×10^{46}	6	-	-	-	-
Tail (leptonic)	2.4	30/400†	$5.3 \times 10^{46}/5.4 \times 10^{46}$†	6	-	-	-	-
Head (hadronic)	2.5	60	1.9×10^{46}	10	1.7	150	1.0×10^{46}	100
Tail (hadronic)	2.5	35	2.0×10^{46}	10	1.7	1000	8.7×10^{45}	200

† In the top-right panel of Fig. 4, the former case and the latter case are shown with the solid and dashed lines, respectively.

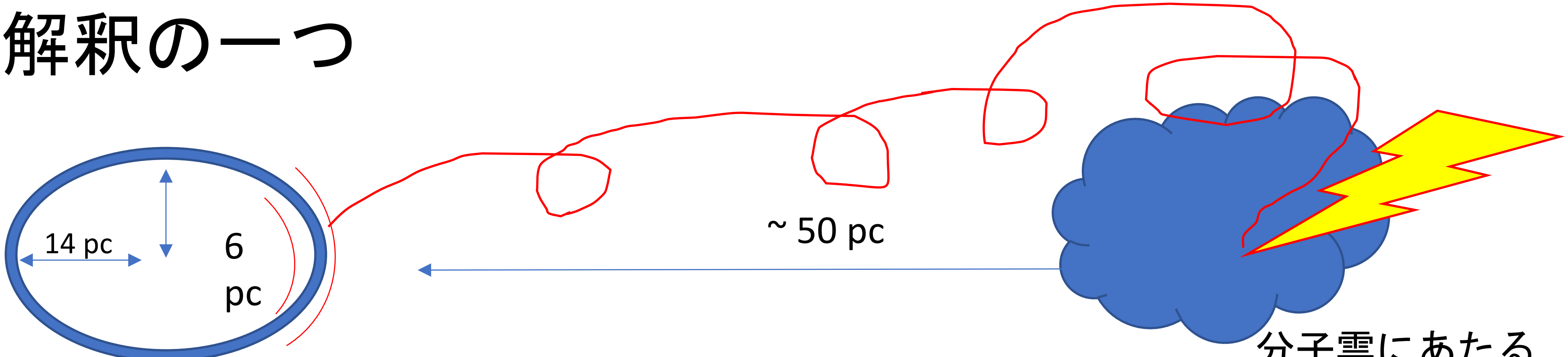
Head とTail で異なる放射機構？

Tail がLeptonicということはなさそう



Boomerang

解釈の一つ



分子雲にあたる

若い頃加速
(<300？)

数千年かけて伝播

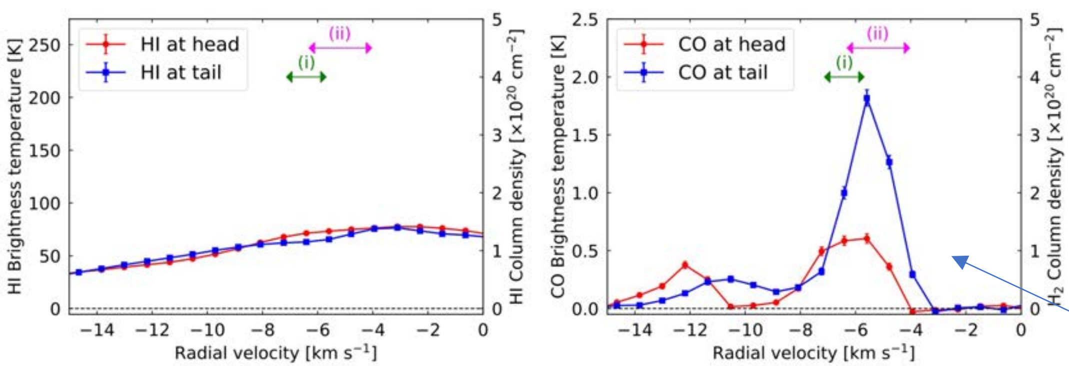
- Diffusion のスケールOK
  - 40-60 pc

$$D(E) = 10^{28}\chi\left(\frac{E}{10\ \mathrm{GeV}}\right)^{\delta}\left(\frac{B}{3\ \mu\mathrm{G}}\right)^{-\delta}\ \mathrm{cm^2\ s^{-1}}, \quad (5)$$

(Fujita et al. 2021)

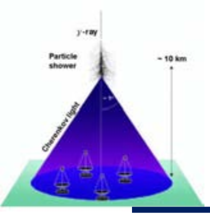
D(100 TeV) ~10^{30} cm^2 c^{-1}

- クーリングも問題なし
  - 電子はダメ(0.9 kyr)
- <2 の硬いべきも同時に説明



COのclump

Fig. B.1: The HI (left) and ^{12}CO ($J = 1-0$) (right) radial profile at the head and tail region. In both panel, red and blue data represent the profile of the head and tail regions. The green arrow labeled (i) and magenta arrow labeled (ii) show the velocity ranges pointed out by Kothes et al. (2001) and Acciari et al. (2009); Albert et al. (2020), respectively.



SNR G40.5 /VER J1907

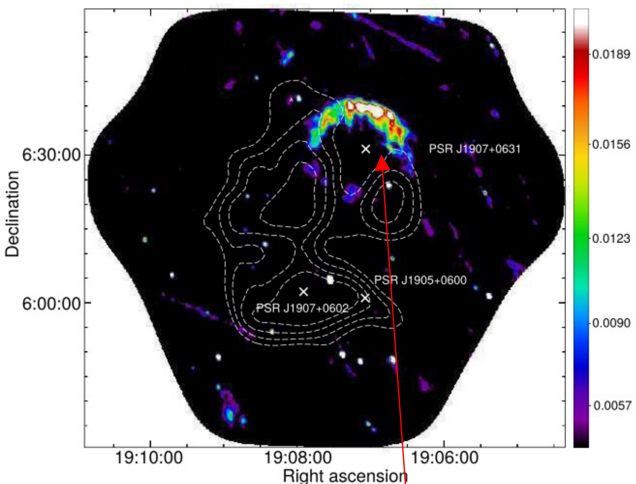
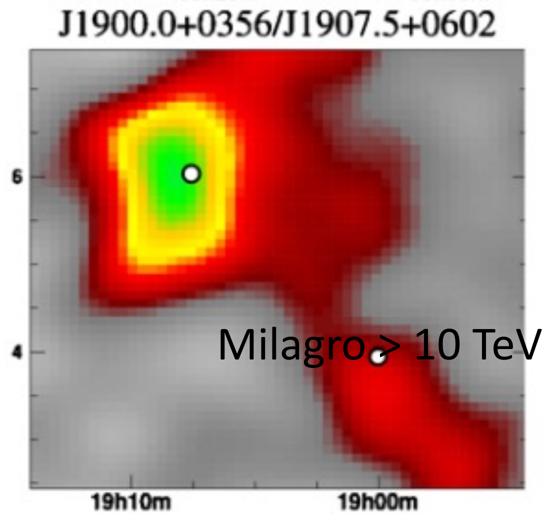
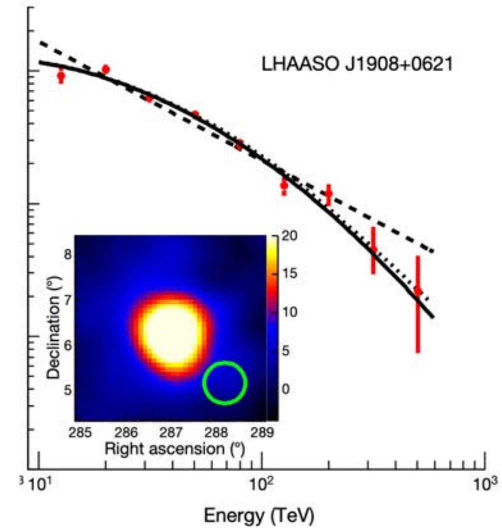


Figure 1. Radio continuum image at 1.5 GHz covering the whole extension of the TeV source VER J1907+062. This image was obtained from a combination of 12 different pointings observed with the VLA in the D configuration. The angular resolution is 51.″1 × 39.″5, PA = 21.°9 and the rms noise is 1 mJy beam^{-1}. The colour scale to the right of the image is expressed in Jy beam^{-1}. The cross signs indicate the position of the pulsars PSR J1907+0631, PSR J1907+0602, and PSR J1905+0600. The dotted contours represent the TeV emission from VERITAS extracted from Aliu et al. (2014).





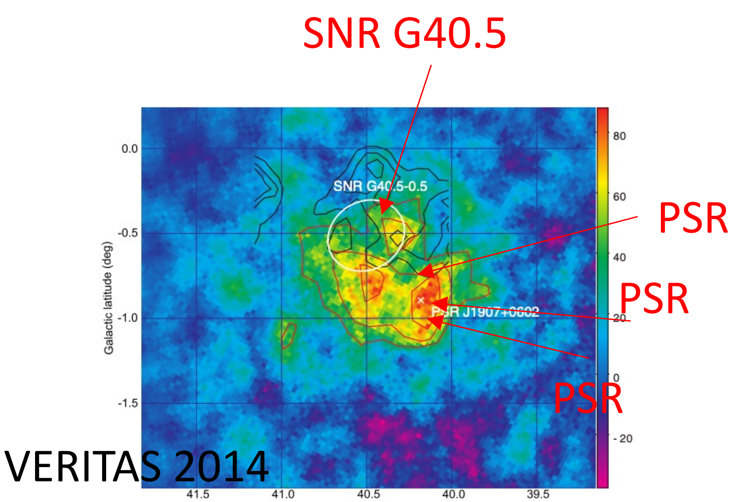
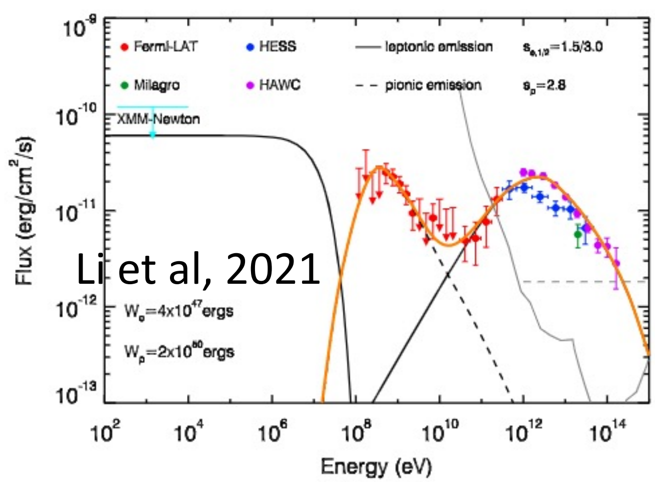
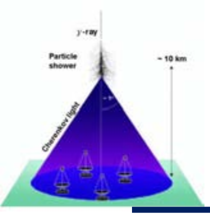


Figure 4. VERITAS map with CO emission contours overlaid. The black contours show the CO emission and are truncated at the boundaries of the available CO map. The color scale shows the excess counts and the red contours are at levels of 35, 50, and 65 counts. These approximately correspond to significance levels of 3σ, 4σ, and 5σ. The white ellipse shows the extent of SNR G40.5–0.5. The white "×" shows the location of PSR J1907+0602.
(A color version of this figure is available in the online journal.)

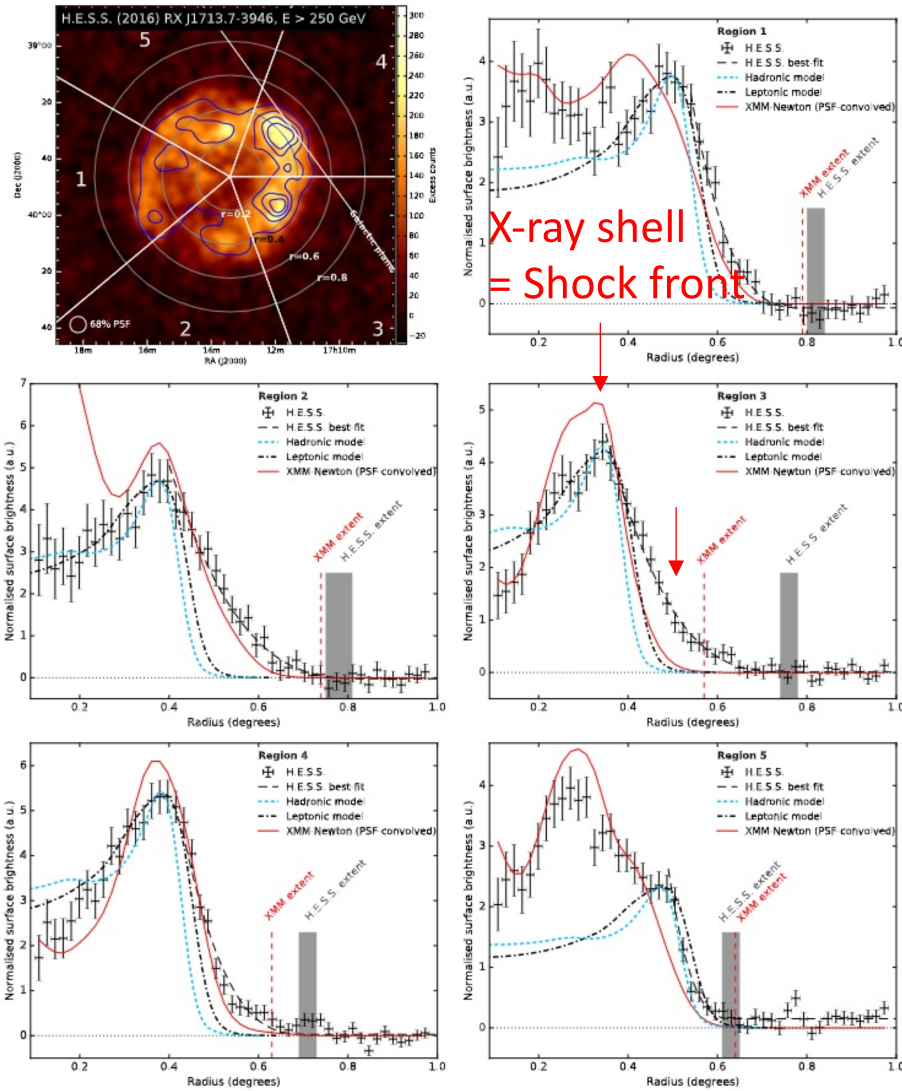


全体のスペクトラムは
Leptonic と
Hadronic
ごちゃ混ぜ

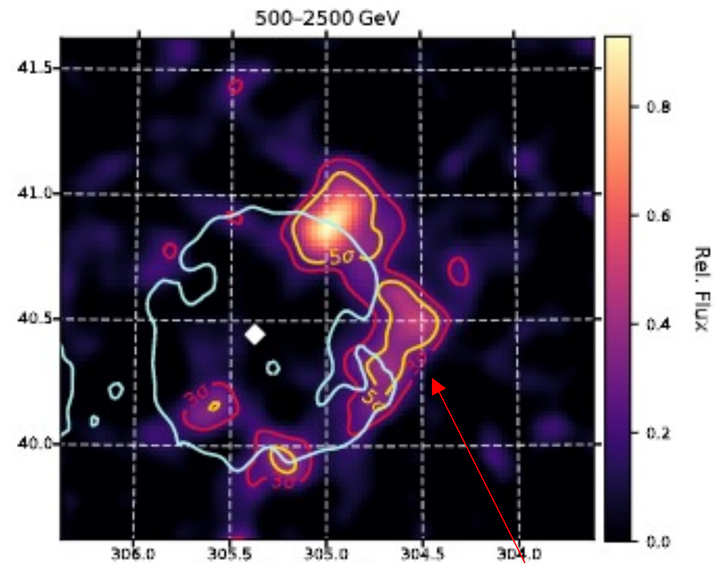
IACTで解像必要

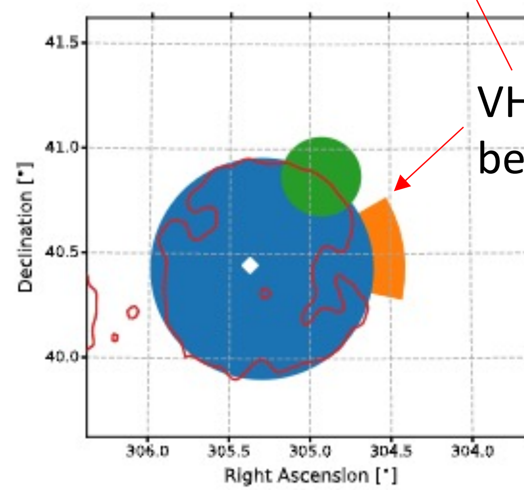


宇宙線のEscape



X-ray shell
= Shock front





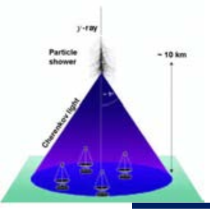
VHE emission
beyound the shell

~7000歳

2000歳

RXJ1713 by HESS
(A&A 2018)

Gamma Cygni by MAGIC
(A&A 2020)



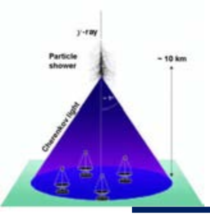
PeVatronってSNRなのか？

Table 1. List of known Galactic pevatrons as of May 2021. This list is likely to be lengthened soon due to active ongoing detection campaigns.

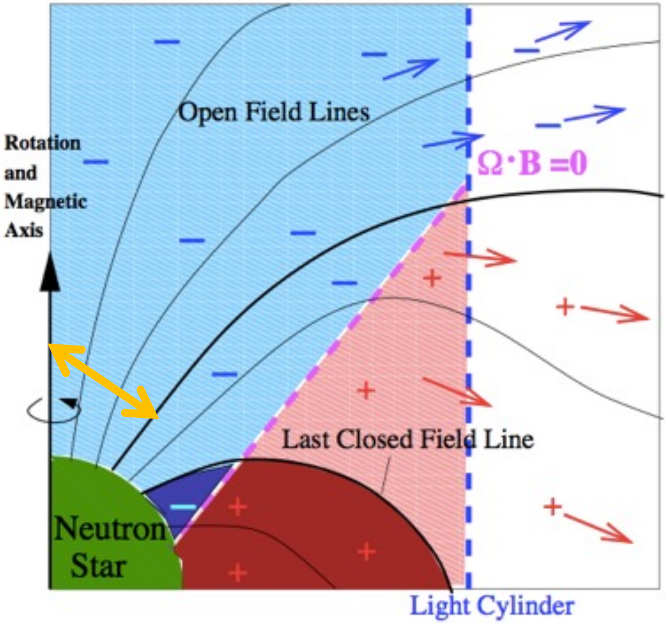
Source	Possible Association	Reference
HESS J1745-290	Sagittarius A*/Galactic center	[39]
Crab/LHAASO J0534+2202	PSR J0534+2200	[26,28,41,107]
LHAASO J1825-1326/2HWC J1825-134	PSR J1826-1334/PSR J1826-1256	[28,134]
LHAASO J1839-0545/2HWC 1837-065	PSR J1837-0034/PSRJ1838-0537	[28,40]
LHAASO J1843-0338/2HWC J1844-032	SNR G.28.6-0.1	[28,40]
LHAASO J1849-0003	PSR J1849-0001/W43	[28]
LHAASO J1908+0621/MGRO 1908+06/ 2HWC 1908+063	SNR G40.5-0.5/PSR 1907+0602/PSR 1907+0631	[28,40]
LHAASO J1929+1745	PSR J1928+1746/PSR1930+1852/SNR G54.1+0.3	[28]
LHAASO J1956+2845	PSR J1958+2846/SNR G66.0-0.0	[28]
LHAASO J2018+3651	PSR J2021+3651/Sh 2-104 (HII/YMC)	[28]
HWC J2019+368		[40]
LHAASO J2032+4102/2HWC J2031+415	Cygnus OB2/PSR 2032+4127/SNR G79.8+1.2	[28,135]
LHAASO J2108+5157		[28]
LHAASO J2226+6057	SNR G106.3+2.7/PSR J2229+6114	[28,69]
HESS J1702-420A	SNR G344.7-0.1/PSR J1702-4128	[136,137]

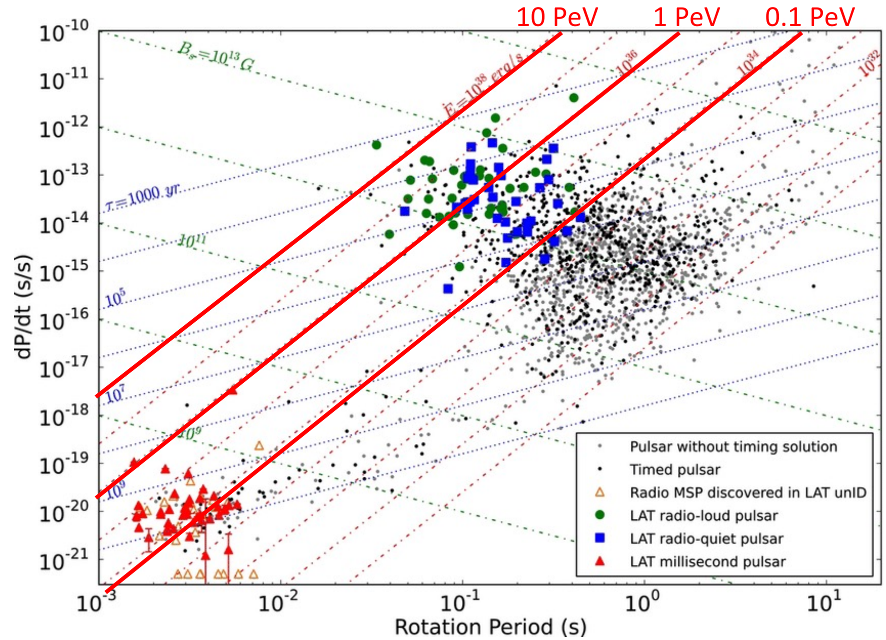
ArXiv 2110.07956, P. Cristofari

“PSR” が目に付く



パルサーの電位



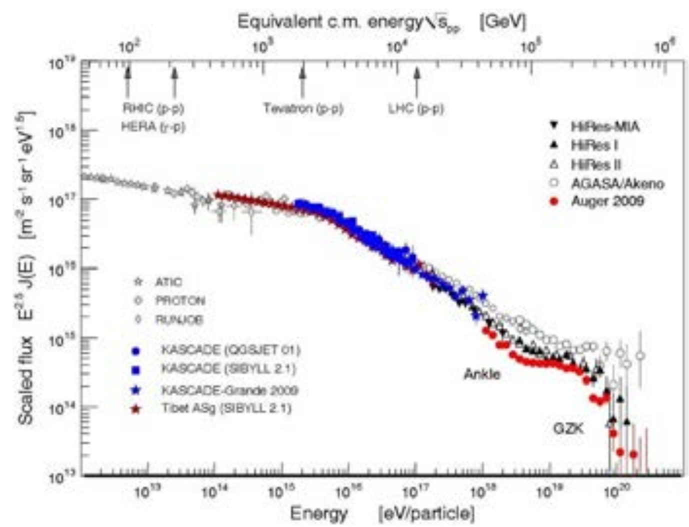


$$\mathbf{E}^{\rm in} + \frac{\mathbf{\Omega}\times\mathbf{r}}{c}\times\mathbf{B}^{\rm in} = 0$$

$$\mathbf{B}^{\rm out} = B_0 R_0^3\left(\frac{\cos\theta}{r^3}\mathbf{e}_r + \frac{\sin\theta}{2r^3}\mathbf{e}_\theta\right)$$

$$\phi^{\rm out} = -\frac{B_0\Omega R_0^5}{3cr^2}P_2(cos\theta) = -\frac{B_0\Omega R_0^5}{3cr^3}\frac{3\cos^2\theta - 1}{2}$$

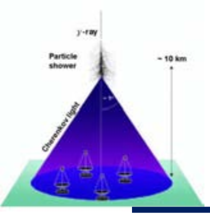
$$\Delta\phi \sim 1\times10^{18}P^{-3/2}\dot{P}^{1/2} \;\; \text{statV}$$
$$\sim 4\times10^{20}P^{-3/2}\dot{P}^{1/2} \;\; \text{V}$$

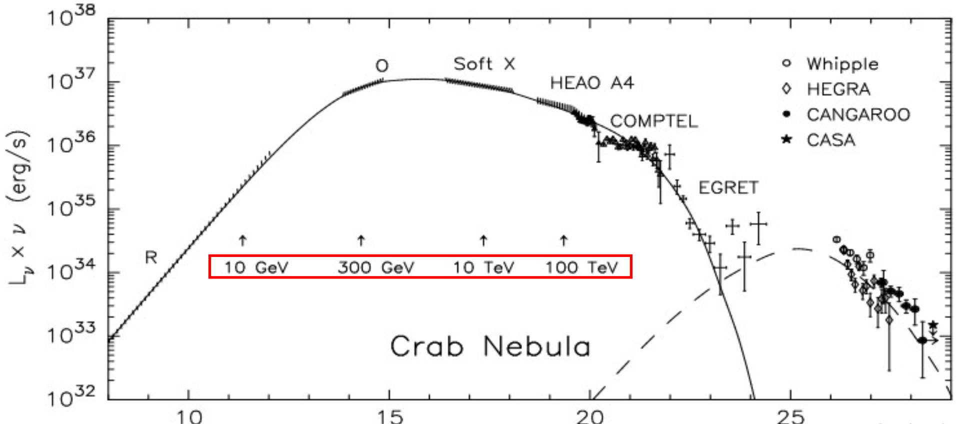


Crab の電位　40 PeV

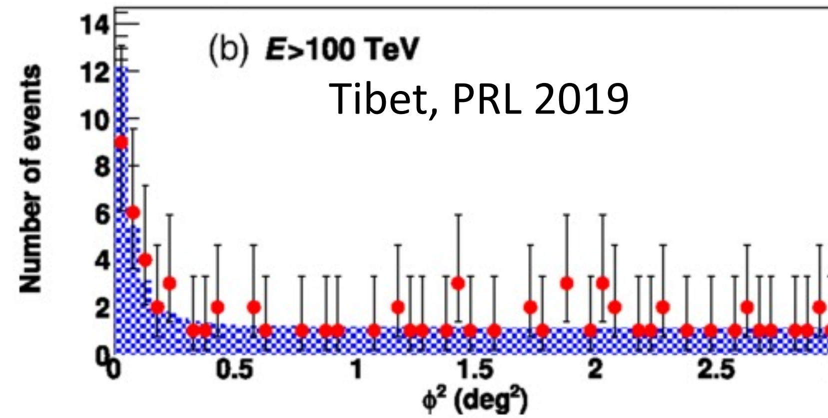
電位は$L_{spindown}^{1/2}$に比例

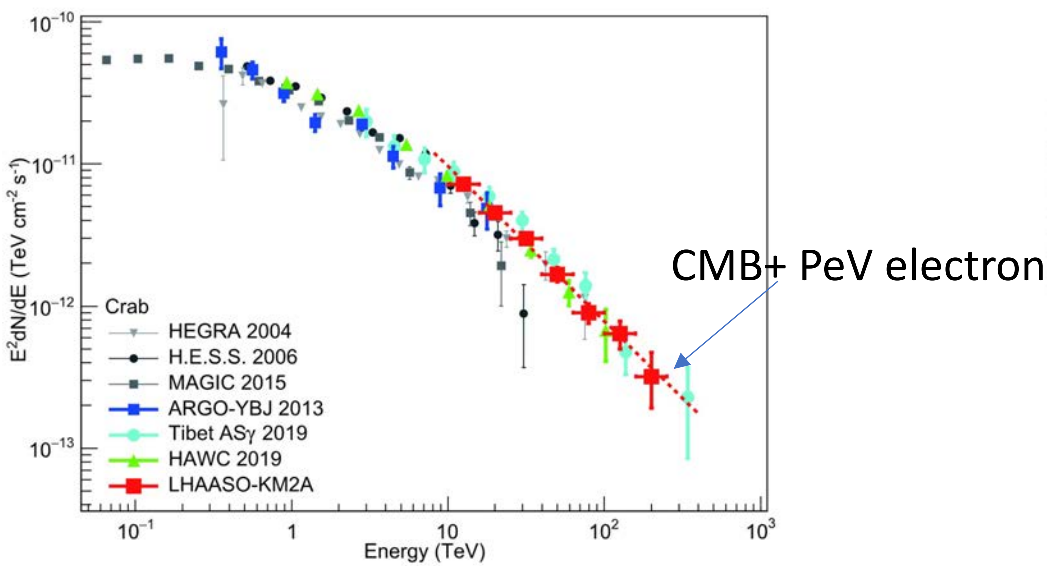
Leptonic PeVatron: Crab Nebula

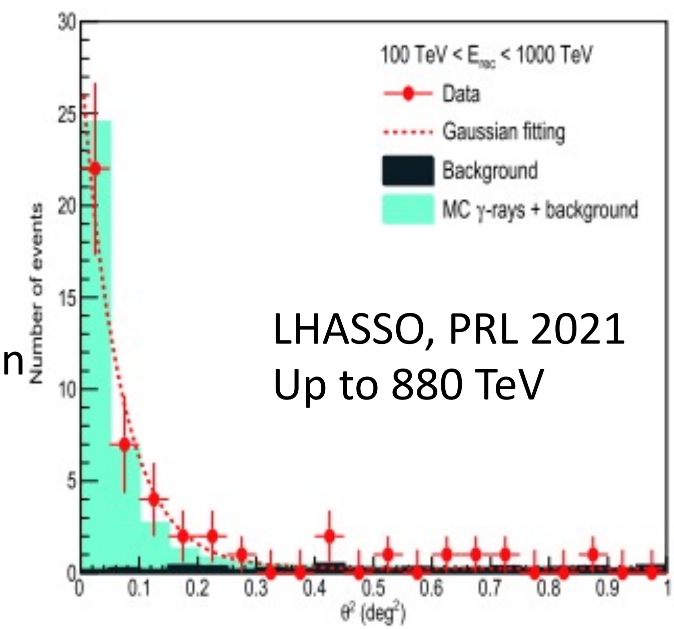


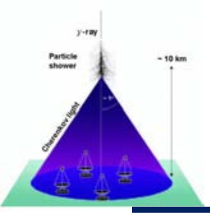


Aharonian and Atoyan 1998

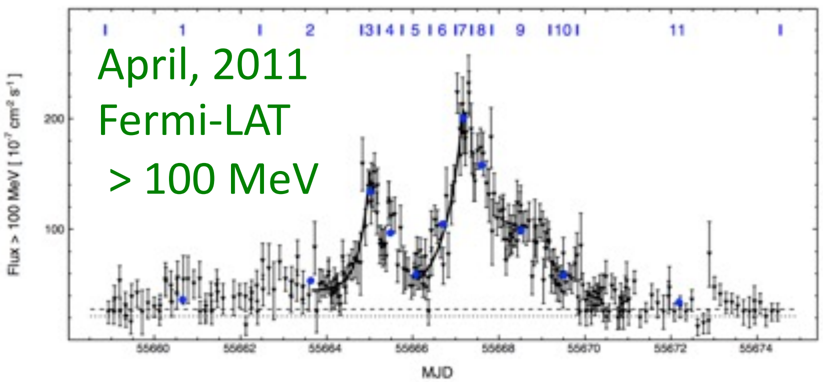


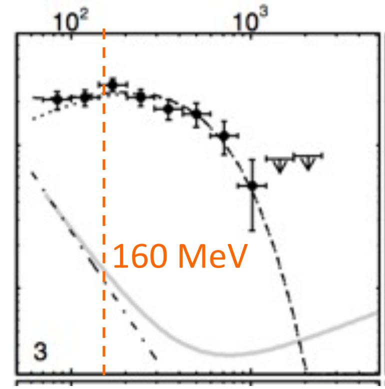






Crab Flare





シンクロトロンLimit
を大きく超える

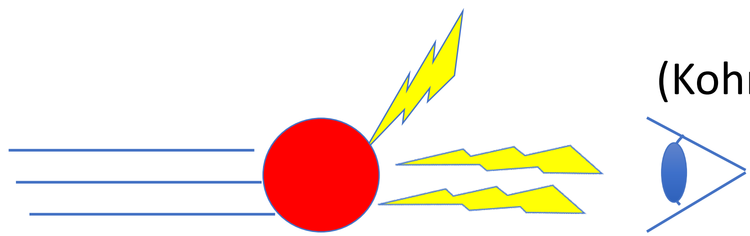
(e.g. de. Jager et al. 1996)

$$\eta eBc = 2\sigma_T c\gamma^2 U_B$$

$$E_{sync} = \frac{3}{2}\hbar\varpi_B\gamma^2 \le \frac{9}{4}\frac{mc^2}{\alpha} \cong 160\,MeV$$

Relativistic Radiative Blob?

(Kohri, Ohira, Ioka et al., (2012)



Magnetic Reconnection?
Cerruti (2013)

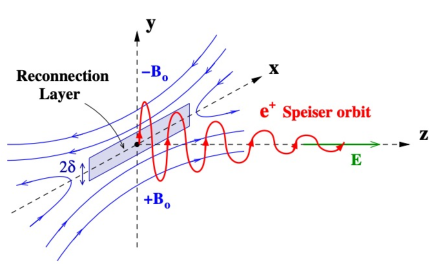
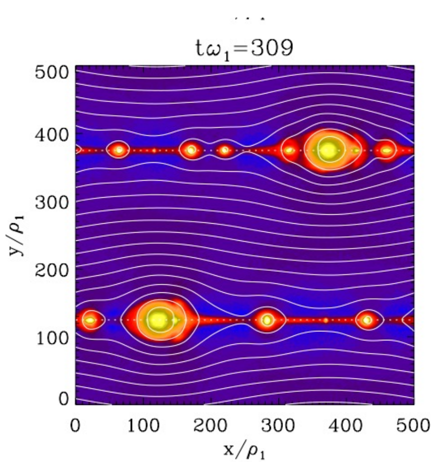
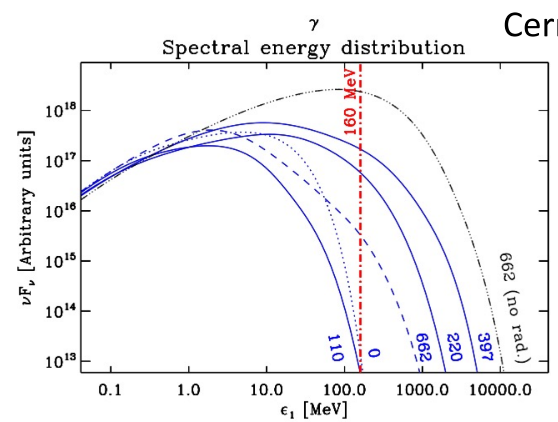
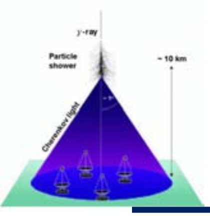


Figure 1. This diagram represents a relativistic Speiser orbit, i.e., the trajectory of a charged particle (here a positron) moving back and forth across the reconnection layer of some thickness 2δ. The particle is accelerated along the z-direction by the reconnection electric field, E. The initial reconnecting magnetic field is along the $\pm x$-directions ($\pm B_0$) and reverses across the $y = 0$ plane.
(A color version of this figure is available in the online journal.)

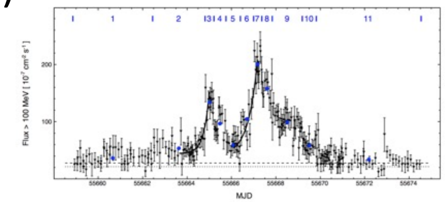




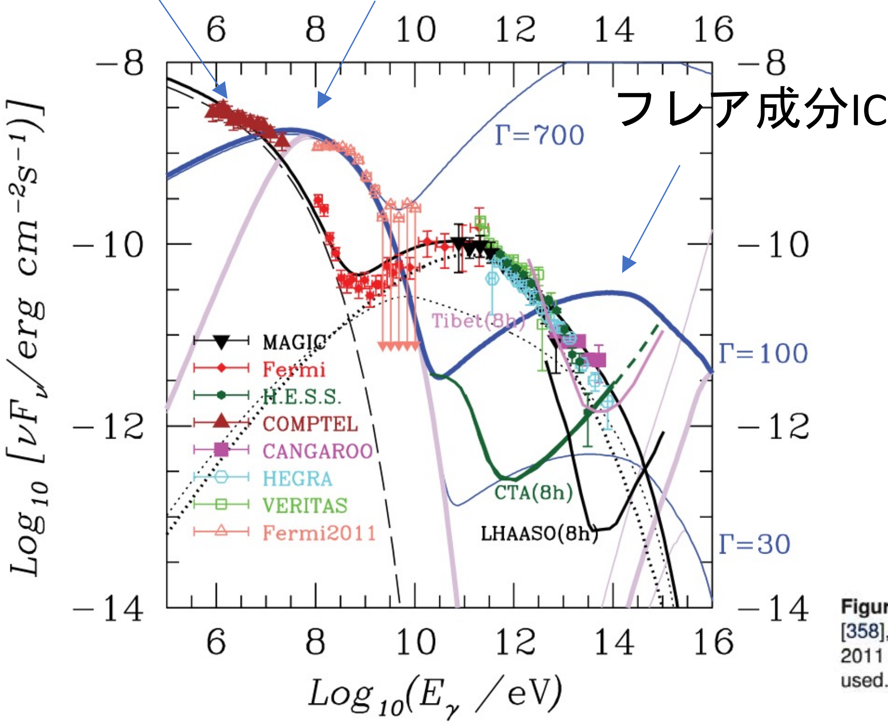


Crab Flare in PeV

Relativistic Radiative Blobならば　(Kohri, Ohira, Ioka et al., (2012)



定常成分　　フレア成分Sync



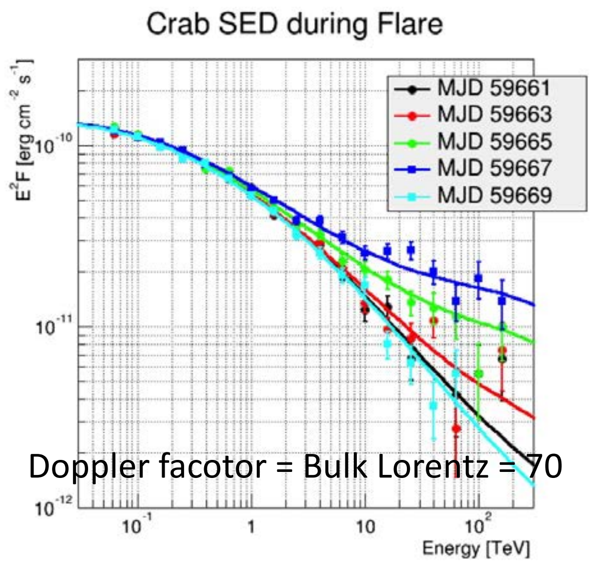
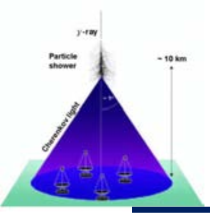


Figure 9.3 – Simulated energy spectra of a Crab nebula flare observed with CTA. The model presented in [358], assuming a Lorentz factor Γ of 70, has been used to simulate the inverse-Compton component of the 2011 April flare observed with Fermi-LAT. A total of ten pointings of 4 h each separated by one day have been used. The variable tail from 10 to 100 TeV is clearly detectable.

CTAで観測していたら

変動の強度からdoppler factorが決まり, blob size, total electyron energyなど求まる

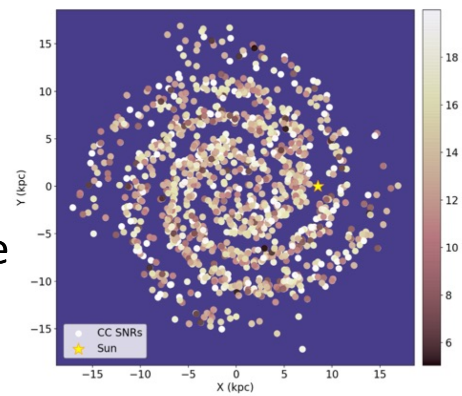


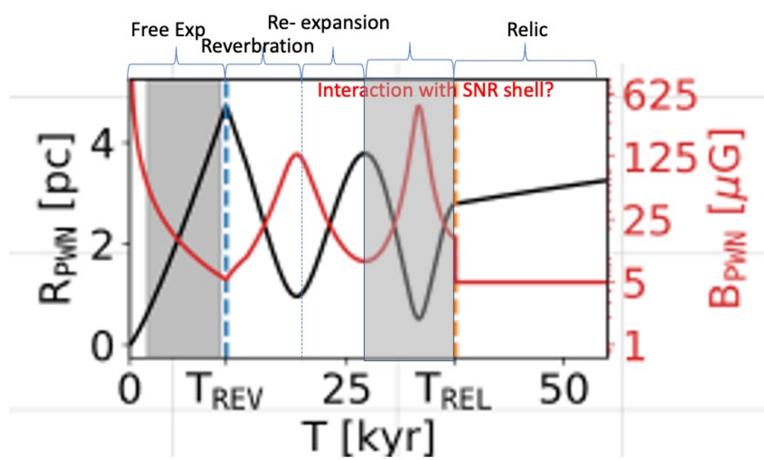
PWN– SNR shell interaction

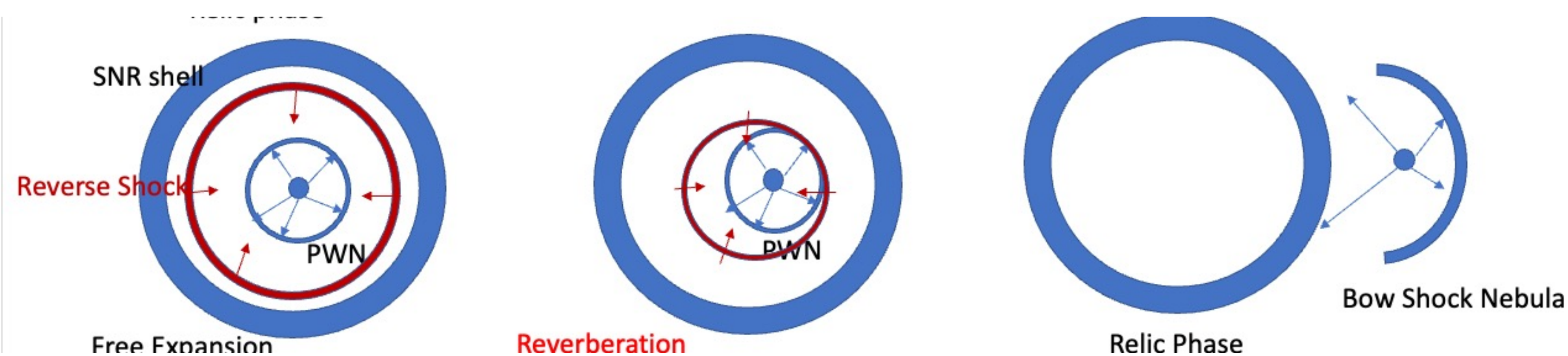
Modeling the γ–ray Pulsar Wind Nebulae population in our Galaxy MNRAS 2022

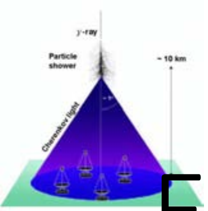
M. Fiori[1,2],* B. Olmi[3,4],† E. Amato[4,5], R. Bandiera[4], N. Bucciantini[4,5,6], L. Zampieri[2], A. Burtovoi[4]

- Simulate the time evolution of all PWNe in our Galaxy (for 100 kyear
- One zone model.
- 3 phses
  - Free Expansion phase
  - Reverberation phase
  - Relic phase









Example of Spectral Evolution

Table 1. Parameters of the source illustrated in Fig. 3.

Parameter	Symbol	Our Source
Braking index	n	3
Initial spin-down age (yr)	τ_0	19971
Initial spin-down luminosity (erg s^{-1})	L_0	2.26×10^{36}
SNR ejected mass ($M_\odot$)	M_{ej}	18.60
Energy break (TeV)	E_b	0.23
Low energy index	α_1	1.25
High energy index	α_2	2.49
Magnetic fraction	η	0.08
ISM density (cm^{-3})	n_{ISM}	0.68

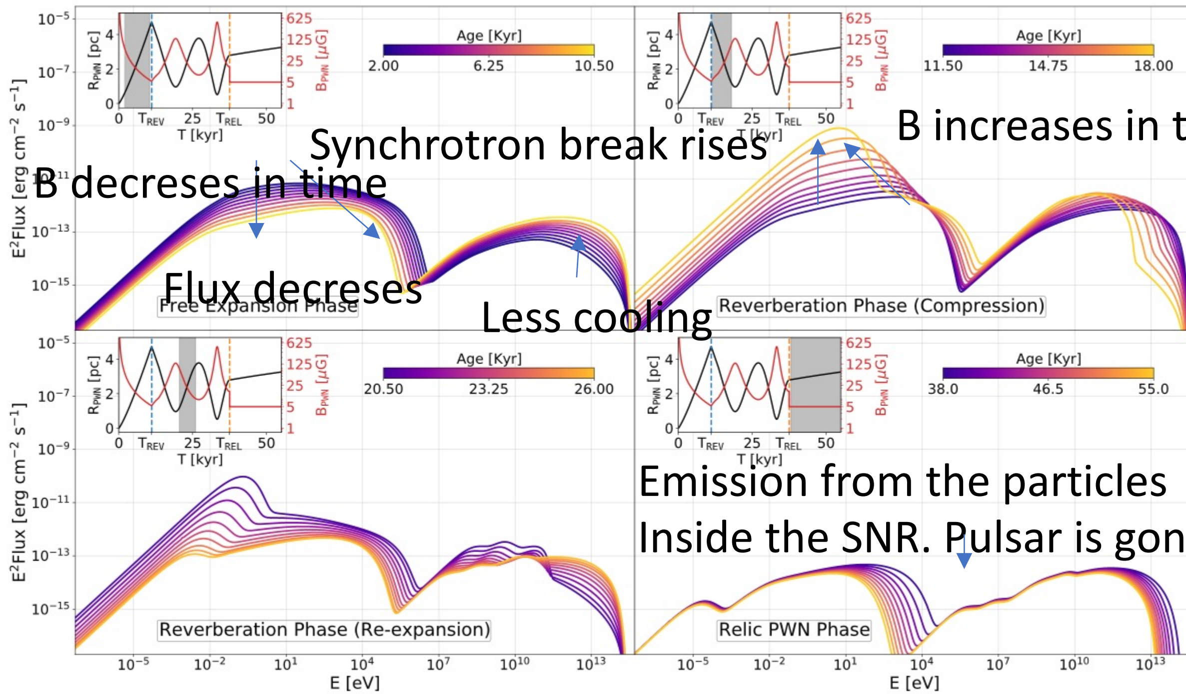
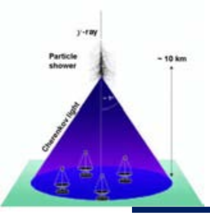


Figure 3. Spectral evolution of a (randomly extracted) source in the modeled population during different evolutionary phases. In all panels a sub-panel illustrates the evolution of the radius (in black) and of the magnetic field (in red) with time, from 0 to the time at which the PSR eventually escapes from the SNR bubble (T_{REL}). Notice that the magnetic field in the relic stage is not zero but fixed to 5 μG. The grey area in the sub-panels highlights the stage at which the spectra in each panel are extracted. The exact time to which each of the plotted spectra corresponds can be read from the color bar.



PWN– SNR shell interaction

After 100 kyears of simulation

- 11% (132 sources) are in free expansion phase
- 76% (948 sources) are in Reverberation phase
- 13% (174 sources) are in Relic phase

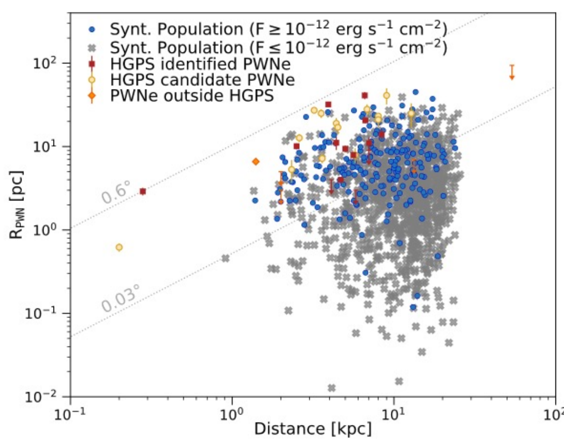


Figure 4. The TeV sizes of our synthetic population of PWNe and of those discussed within the HGPS context are reported, versus distance of the system. For the synthetic population the system extension is taken to coincide with the nebular radius at given age. Different symbols are for different subclasses as specified in the plot legend. The flux threshold at $F = 10^{-12}$erg s^{-1} cm^{-2} is taken from Abdalla et al. 2018c. Dotted lines refer to the minimum (0.03°) and maximum (0.6°) angular extension estimated by Abdalla et al. 2018b from PWNe detected in the HGPS.

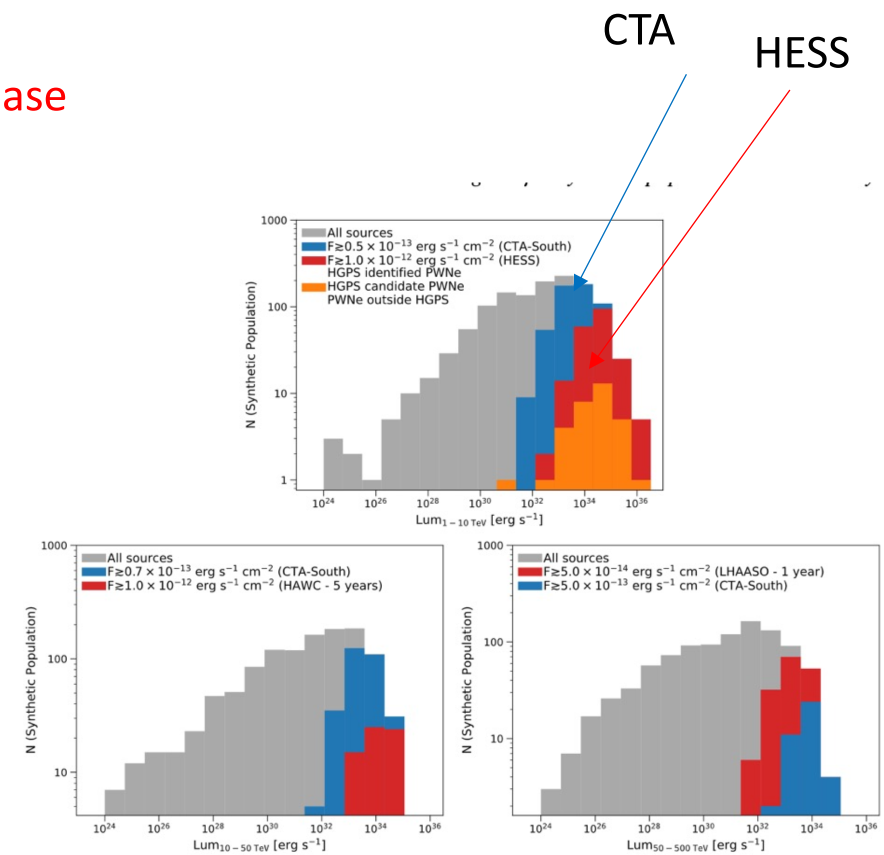
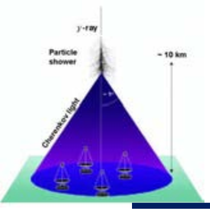


Figure 7. Total number of synthetic PWNe per luminosity beam in different γ-ray luminosity ranges (grey) and number of detectable sources by current and upcoming γ-ray instruments. *Upper panel:* sources above the H. E. S. S. threshold (red) are compared with the actual detected ones (orange) and with those above the estimated CTA threshold (from Remy et al. 2021, blue) for the 1-10 TeV range. *Bottom left panel:* expected detections by HAWC (red) and CTA (blue) in the 10-50 TeV range, with detection thresholds estimated from HAWC Collaboration et al. (2013) and Remy et al. (2021), respectively. *Bottom right panel:* LHAASO (red) vs CTA (blue) in the 50-500 TeV range, with the LHAASO detection threshold estimated from Vernetto (2016).

現在の観測とよく合う

CTA はPWNを200 天体くらい検出可能

PWN TeV Halo



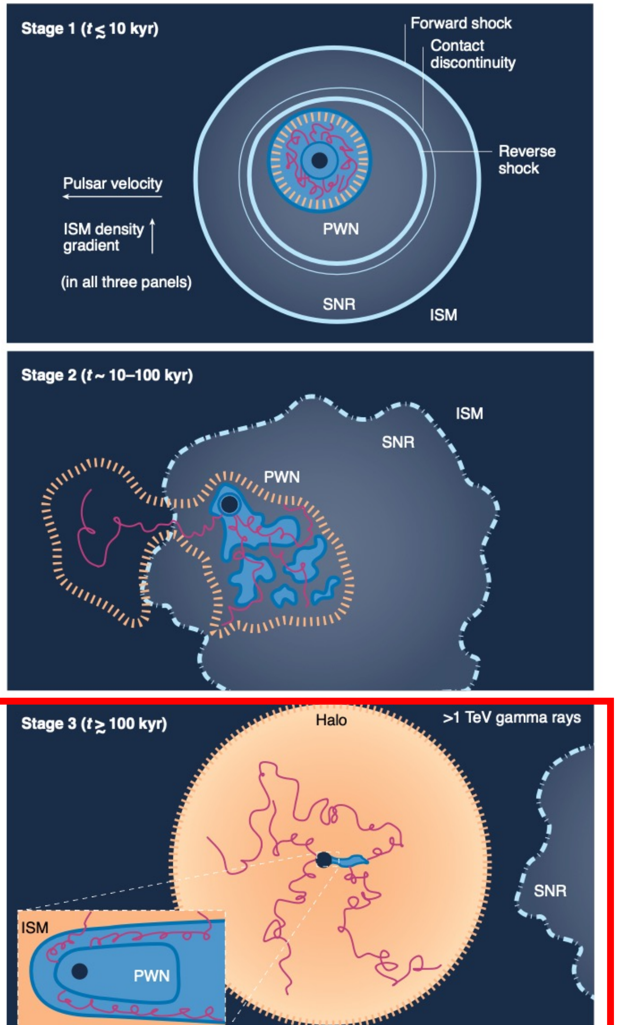
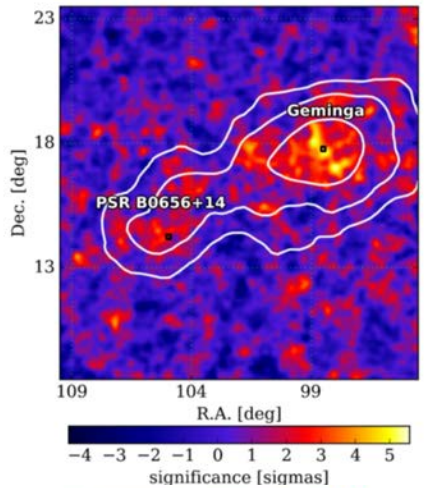
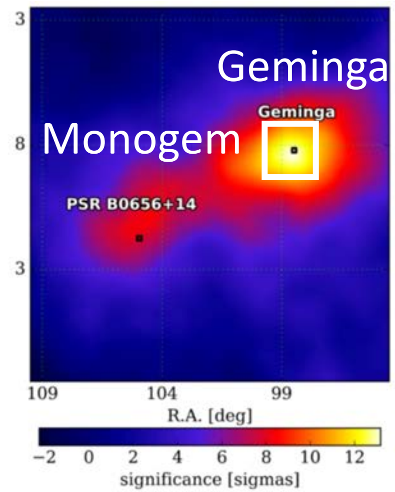
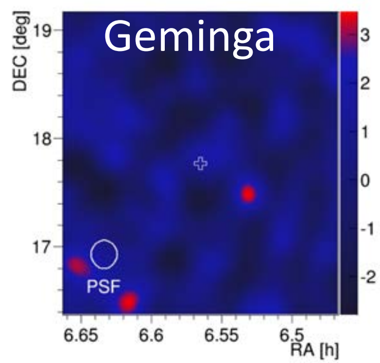


Fig. 1 | Evolutionary stages in the life of a PWN. The early confinement of particles and the later escape of (at least) the higher-energy relativistic particles to form a halo visible in teraelectronvolt gamma rays is illustrated. Figure adapted from ref. [28] under Creative Commons license CC BY 4.0.

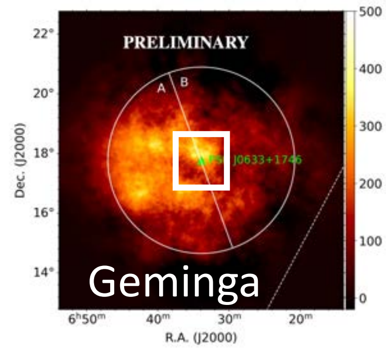




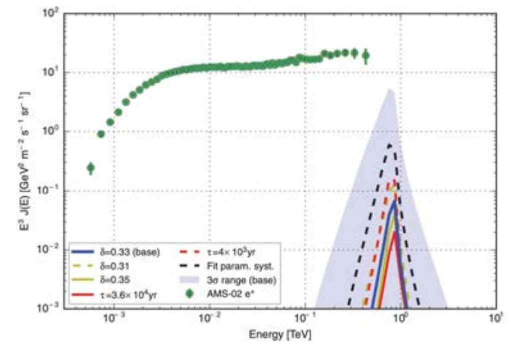
HAWK 2017



MAGIC 2016



HESS 2021

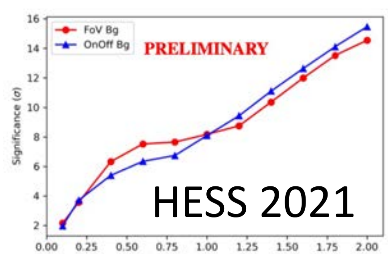


Diffusion が遅すぎる

D(100 TeV) 5 x 10^{27} cm^2 s^{-1}

なぜ？Turbulance?

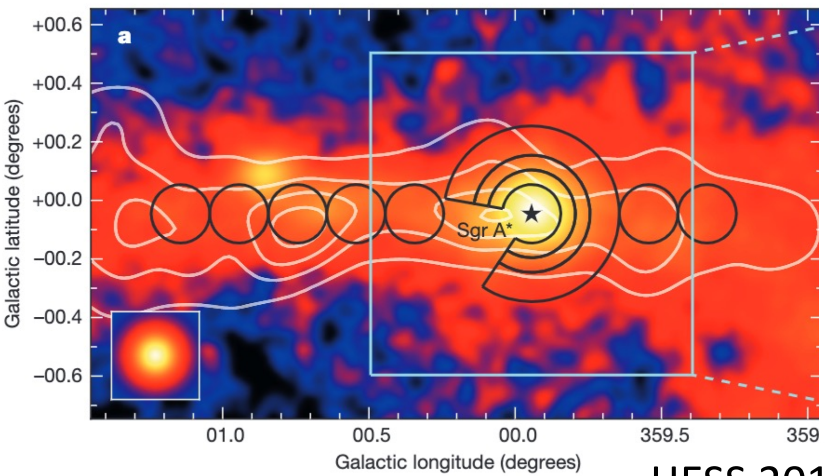
ポジトロンExcessを説明できない？

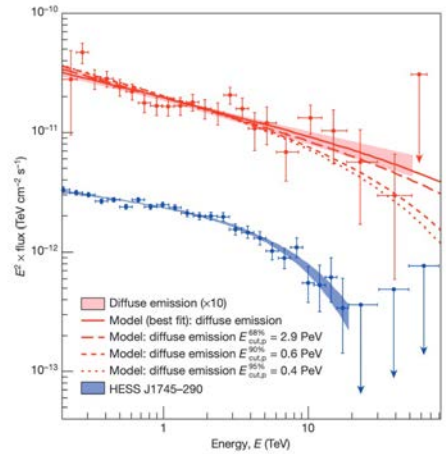


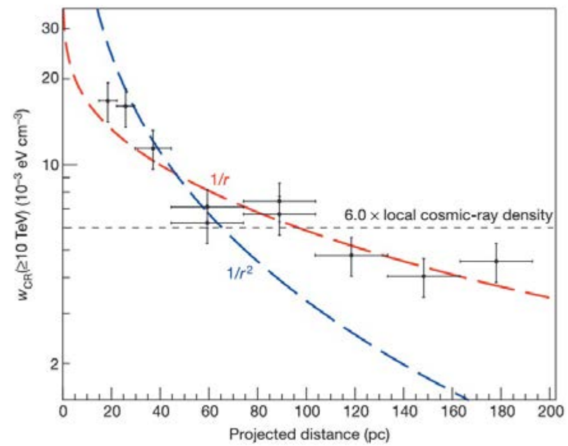
HESS 2021

IACTで、Profile, 拡散の様子きっちり測ることが、非常に重要

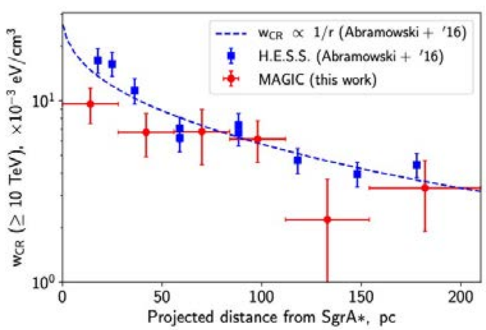
銀河中心

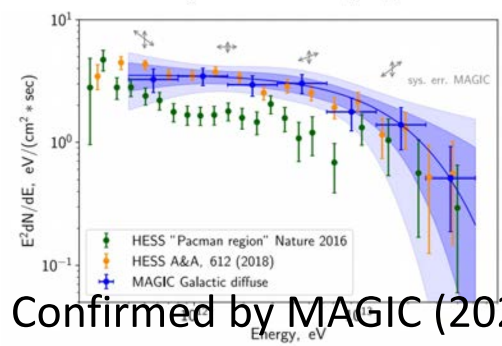






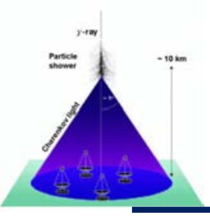
HESS 2016





Confirmed by MAGIC (2020)

- 少なくとも400 TeV までは加速していそう
- 銀河中心からの継続注入＋diffusionでプロファイルは説明できる。
  - 10 TeV以上の陽子で10^{49} erg
  - 2000年以上
  - $10^{37\text{-}38}$erg/sの注入
- SMBHで説明はつく。
- (銀河面に分布する多数のSNRでも説明できるが)

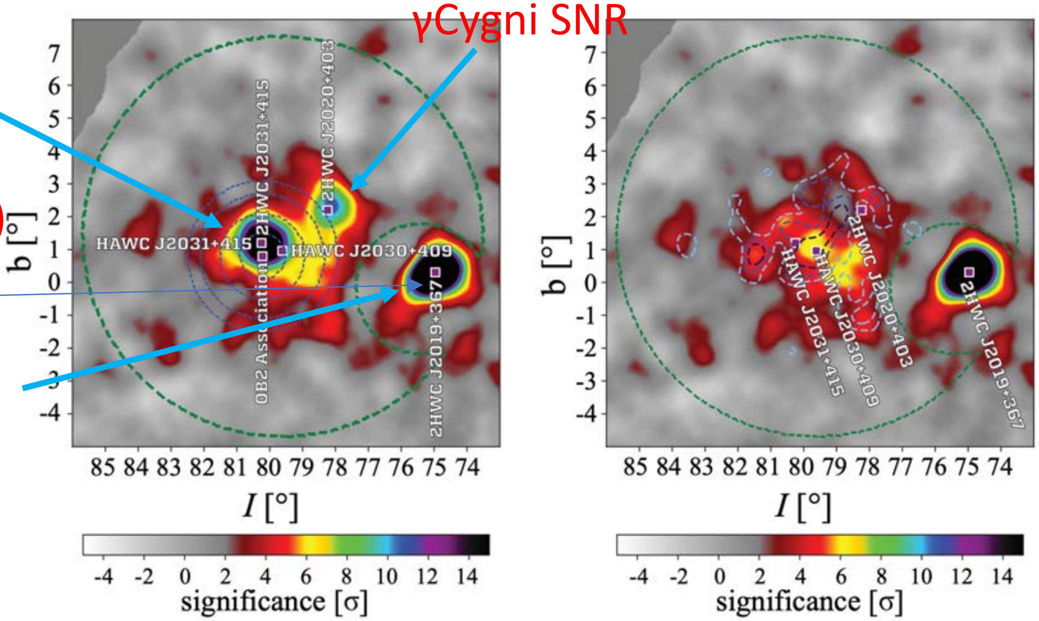


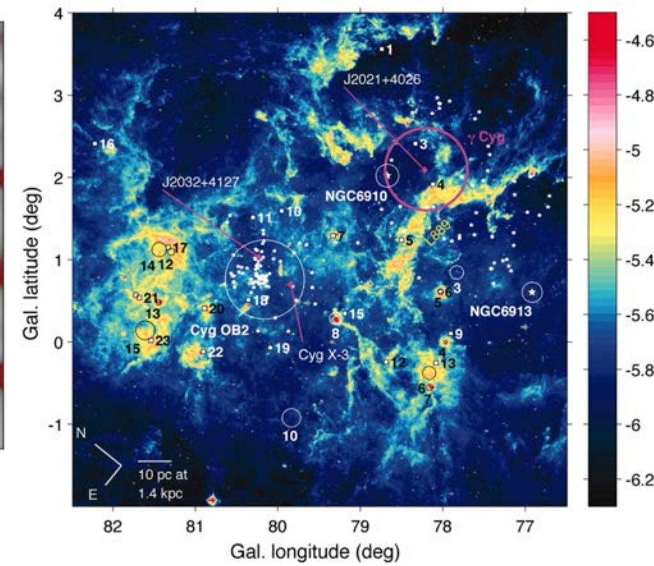
Cygnus Cocoon

Lhasso
100 TeV
天体
(TeV J2032)

Lhasso
100 TeV
天体
(Dragonfly)

γCygni SNR

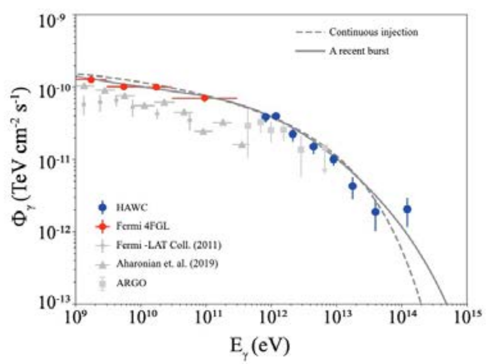




Superbubbleにある

Cygnus OB2 からのinjectionで1/rで説明可能。

ただし、SNR、PWNなどいろいろあるので、IACTによる高解像観測が必要



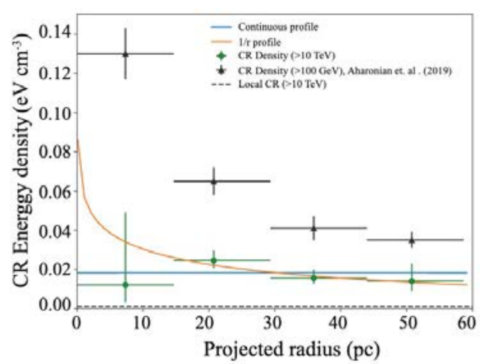
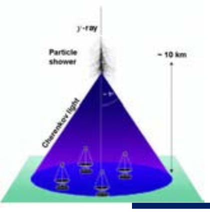
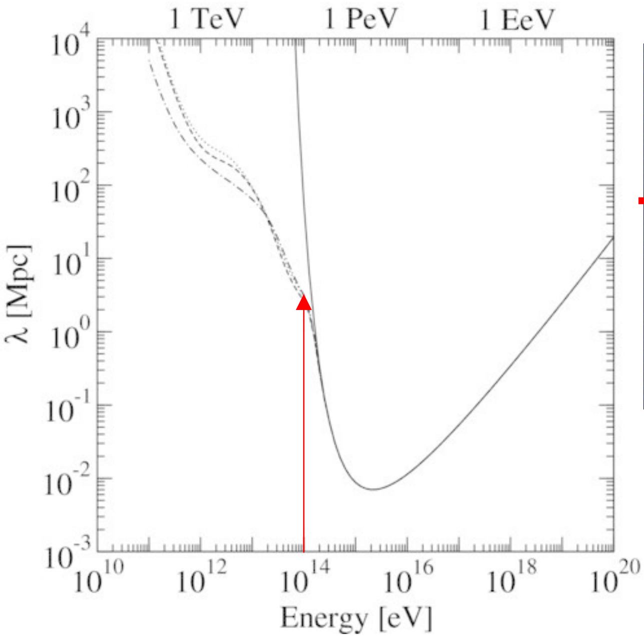


Figure 2: **Spectral energy distribution of the gamma-ray emission and cosmic ray (CR) density at the Cocoon region. Left**: Spectral energy distribution of the Cocoon measured by different γ-ray instruments.

ガンマ線の限界





100 TeVで ~1 Mpc

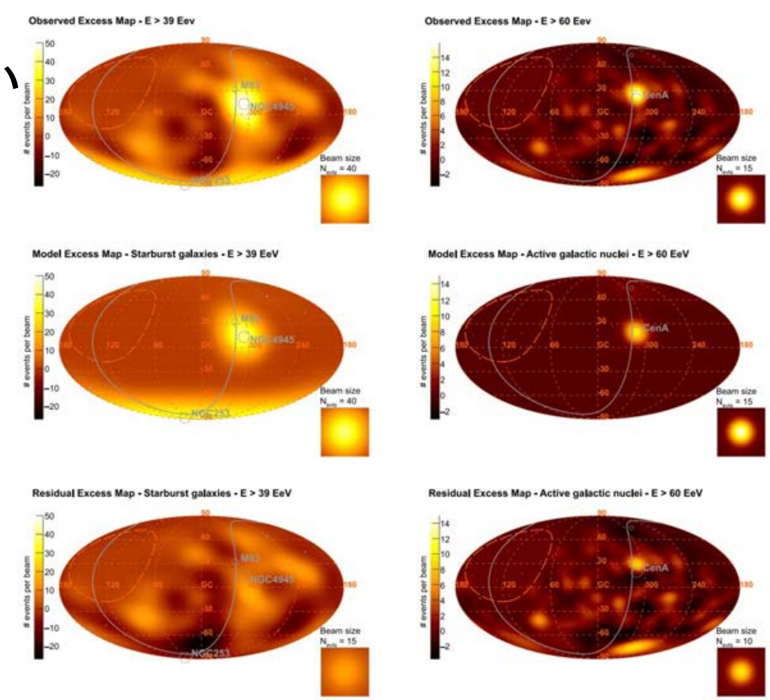
TeVCat: http://tevcat.uchicago.edu/

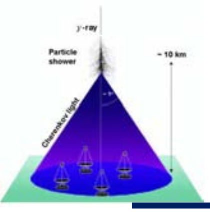
Markarian 501	16 53 52.2	+39 45 37	HBL	1996.01	z = 0.034	Default Catalog
Markarian 421	11 04 19	+38 11 41	HBL	1992.08	z = 0.031	Default Catalog
3C 264	11 45 05.0	+19 36 23	FRI	2018.03	z = 0.0217	
IC 310	03 16 43.0	+41 19 29	AGN (unknown type)	2010.03	z = 0.018	
NGC 1275	03 19 48.1	+41 30 42	FRI	2010.10	z = 0.0175	
M 87	12 30 47.2	+12 23 51	FRI	2003.05	z = 0.0044	Default Catalog
Centaurus A	13 25 30.3	-43 00 15	FRI	2009.03	z = 0.00183	Default Catalog
M 82	09 55 52.7	+69 40 46	Starburst	2009.07	3900 kpc	Default …g
NGC 253	00 47 32.54	-25 17 25.4	Starburst	2009.07	2500 kpc	Default …g
LHA 120-N 157B	05 37 44	-69 09 57	PWN	2012.01	50 kpc	Default …g
30 Dor C	05 35 55	-69 11 10	Superbubble	2014.10	50 kpc	Defa…
LMC N132D	05 24 47	-69 38 50	SNR/Molec. Cloud	2014.10	50 kpc	Default …og
CTB 37B	17 13 57.6	-38 12 00	Shell	2006.01	13.2 kpc	Default Catalog
SNR G349.7+00.2	17 17 57.8	-37 26 39.6	SNR/Molec. Cloud	2013.07	11.5 kpc	Default Catalog
W 49B	19 11 07.3	+09 09 37.0	SNR/Molec. Cloud	2010.12	11.3 kpc	Default Catalog
SNR G327.1-01.1	15 54 37	-55 05 27	PWN	2012.01	9 kpc	Default Catalog

ここまで

観測可能なのは、
Starbust Galaxy ぐらい

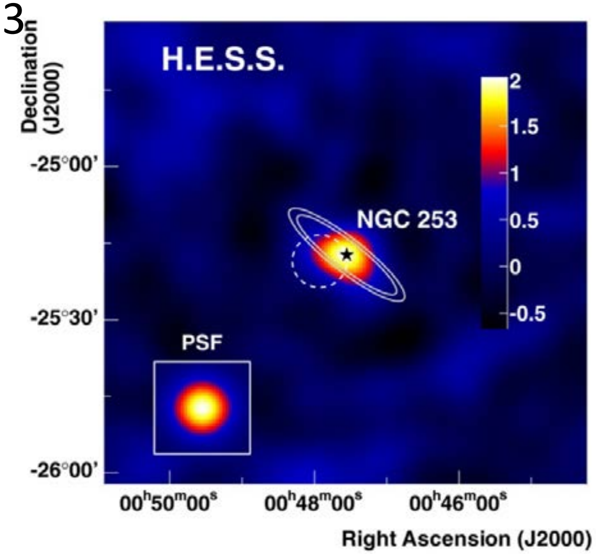
Starburst銀河は
Auger > 40 EeV
と相関？
(TAでは確認できず)



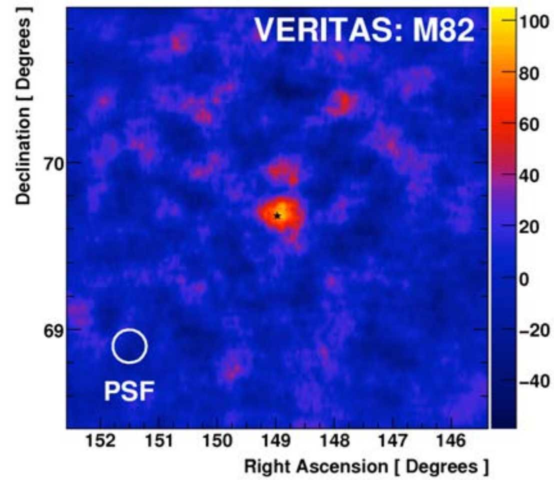


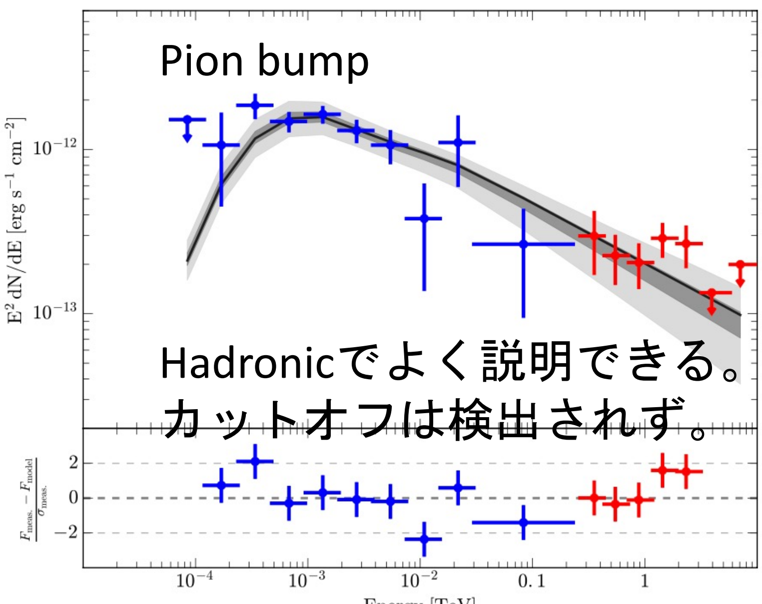
Starburst Galaxy

NGC 253



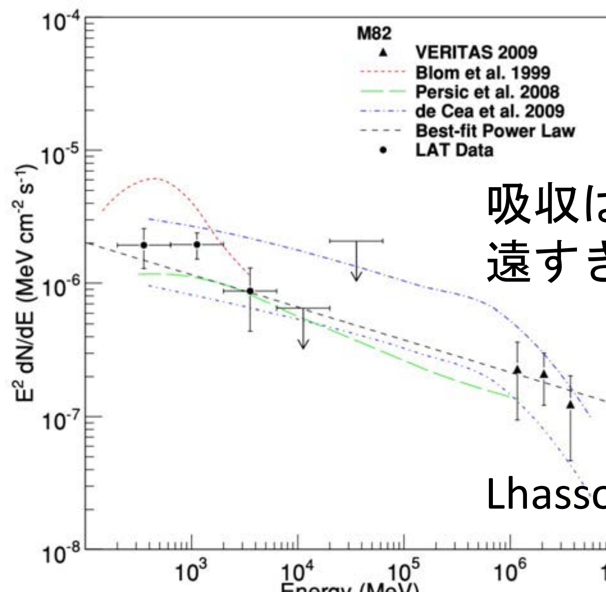
M82





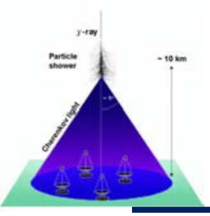
Pion bump

Hadronicでよく説明できる。
カットオフは検出されず。

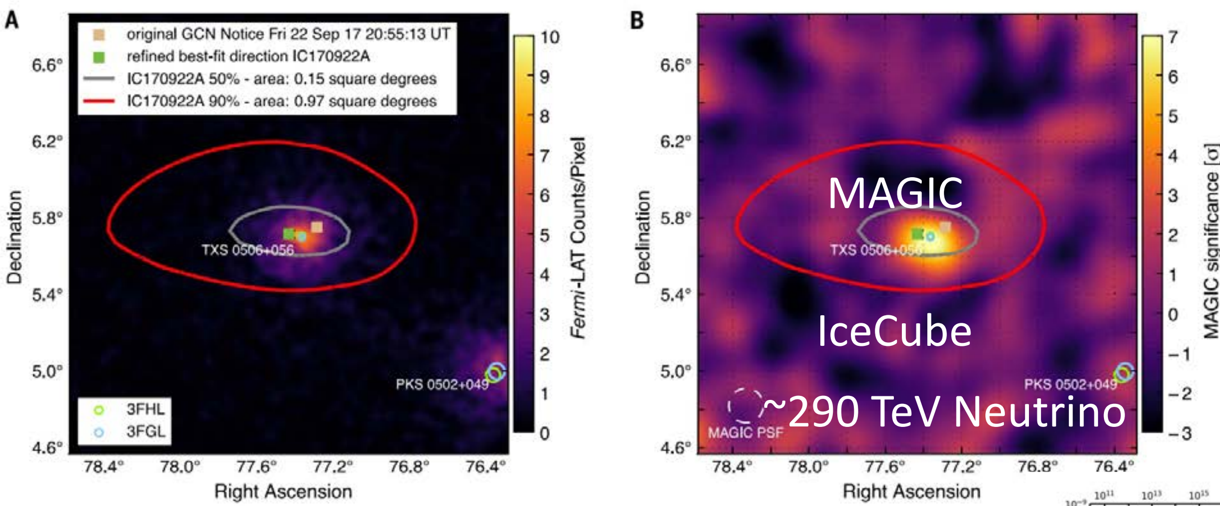


吸収はなくても
遠すぎてFluxが小さい

LhassoやCTAに期待



ニュートリノーガンマ相関

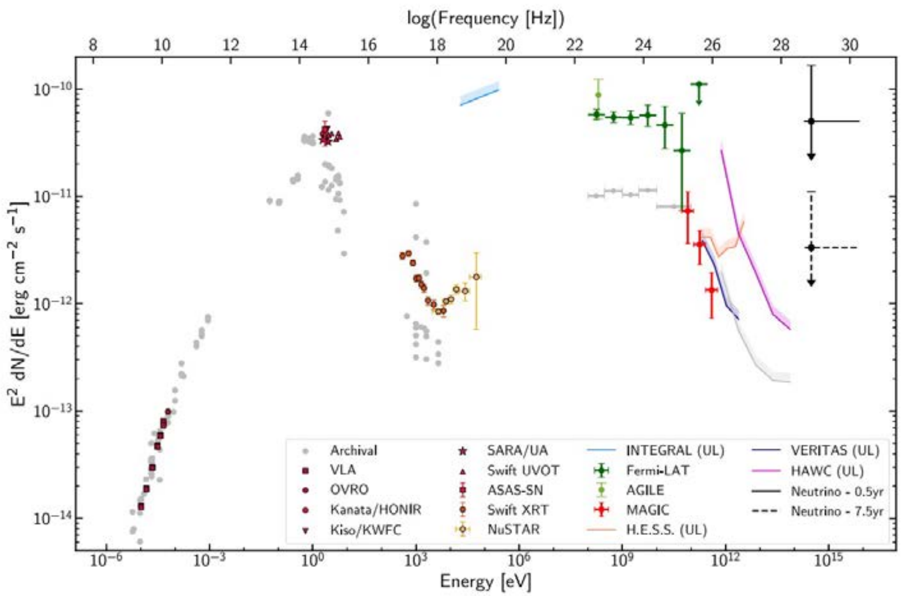


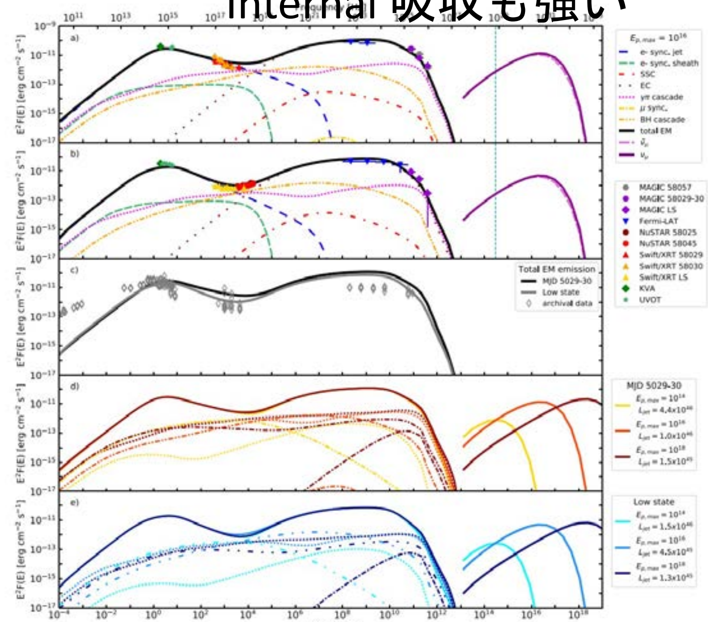
Blazer TXS0506+056
（３シグマcoincidence)

up to 10 PeV

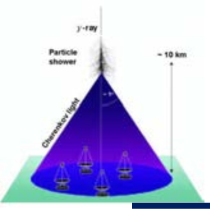
P + 光子 -> pi -> neutrino

ガンマは主にLeptonic EC
Internal 吸収も強い



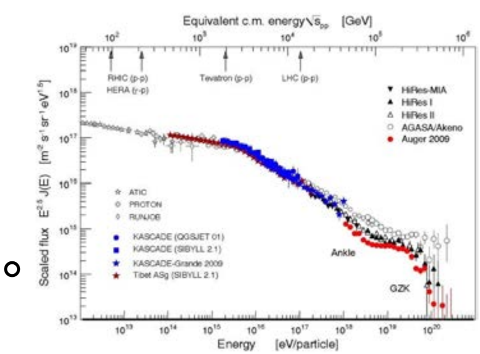


高エネルギー側の情報はニュートリノ頼み。Localizationはガンマ。



まとめ

- IACTの角度分解能が、宇宙線の加速源、Escape, 伝播のスタディに非常に重要
  - Source Confusion
  - 放射profile
  - 拡散係数
- パルサーのポテンシャルは無視できない
  - Peta Volt 電池
  - Crab Flare も面白い
- SNR shellとPWNの相互作用を考慮する必要がありそう。
  - Reverberation Phase
  - TeV Halo
  - G106
- 100 TeVガンマ線では1Mpc以上の宇宙は見えない。
  - ニュートリノとの相関が重要になってくる
  - Starburst Galaxyは一応見える



- いろいろわかってきたが、まだ宇宙線スペクトラムを説明するまでには至ってない