

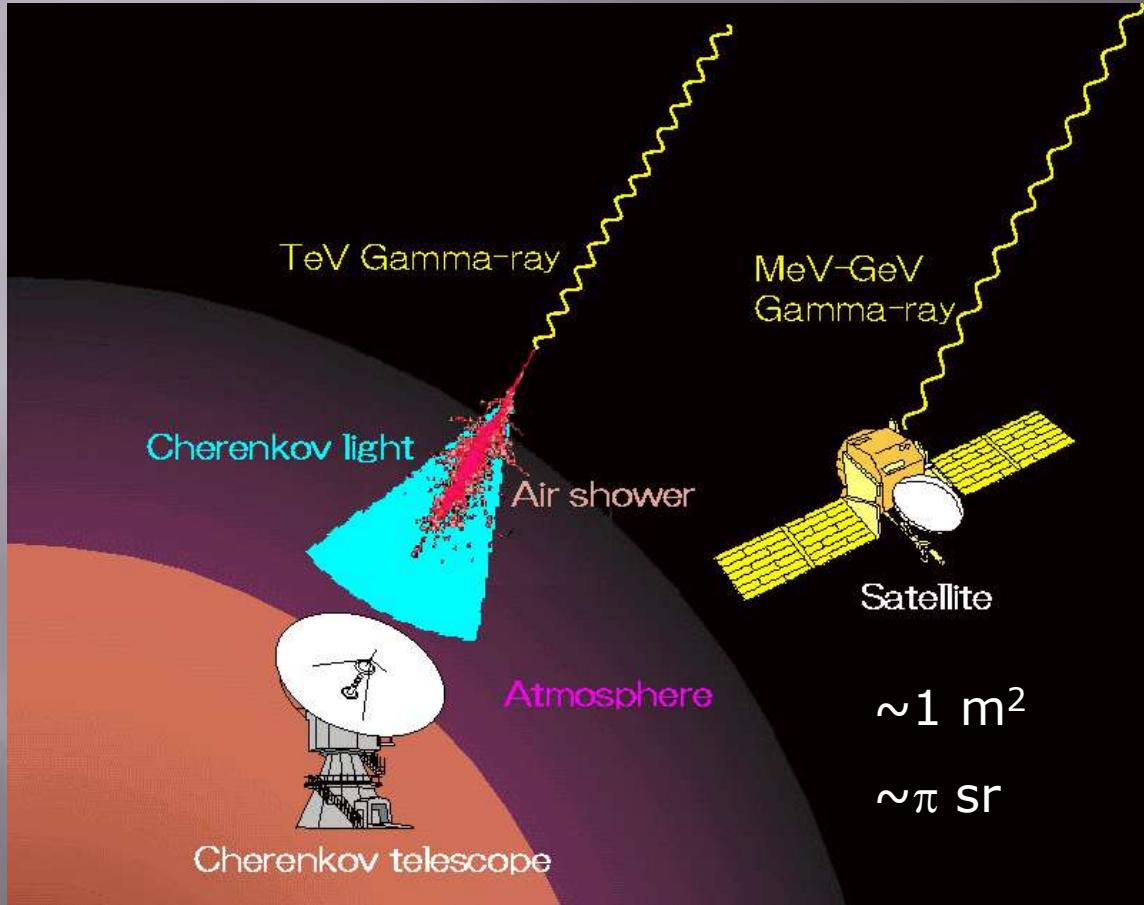
# 超高エネルギー天体ガンマ線

森 正樹

東京大学宇宙線研究所

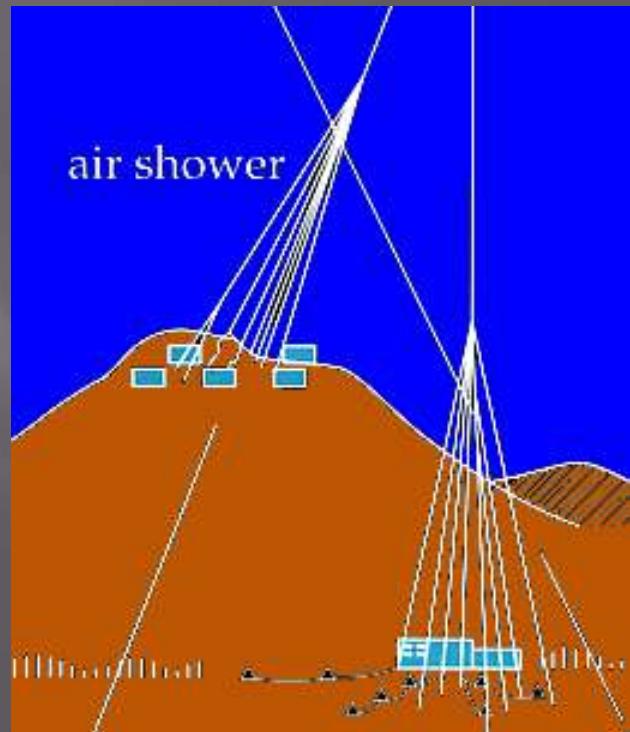
研究会「マクロでミクロな銀河団」2007年10月24–26日、たかみや瑠璃俱楽リゾート

# ガンマ線の検出



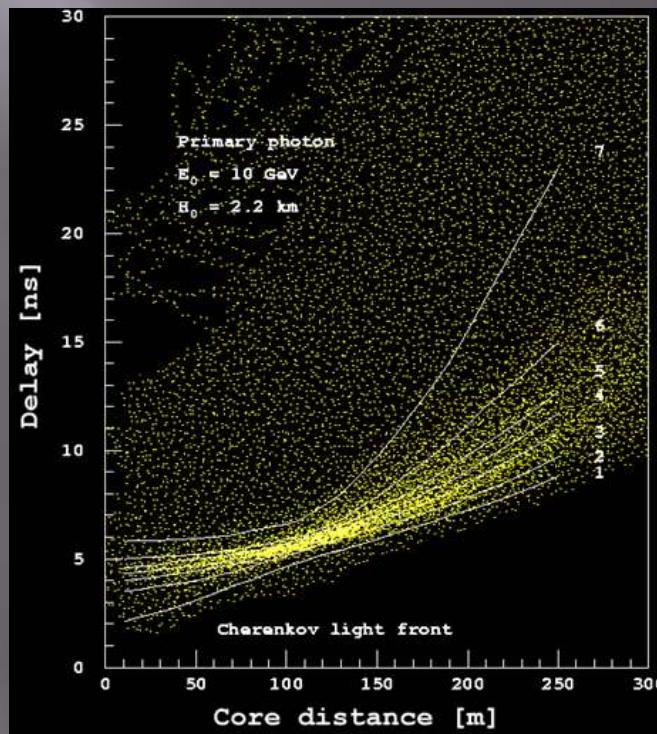
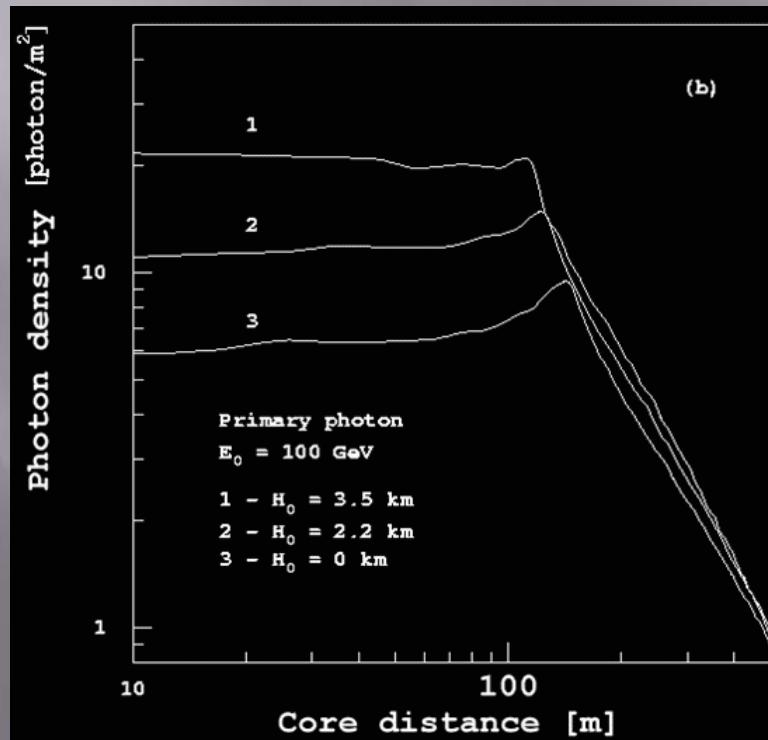
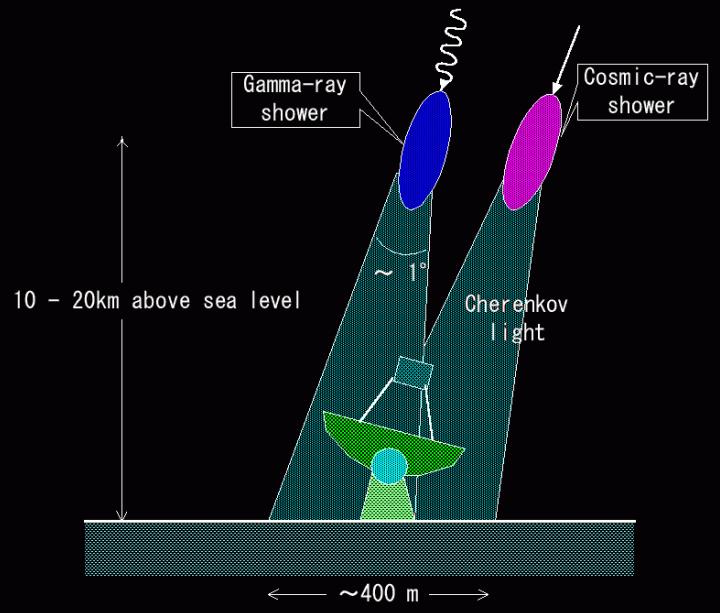
$$A \sim 10^4 \text{ m}^2$$

$$\Omega \sim 10^{-2} \text{ sr}$$



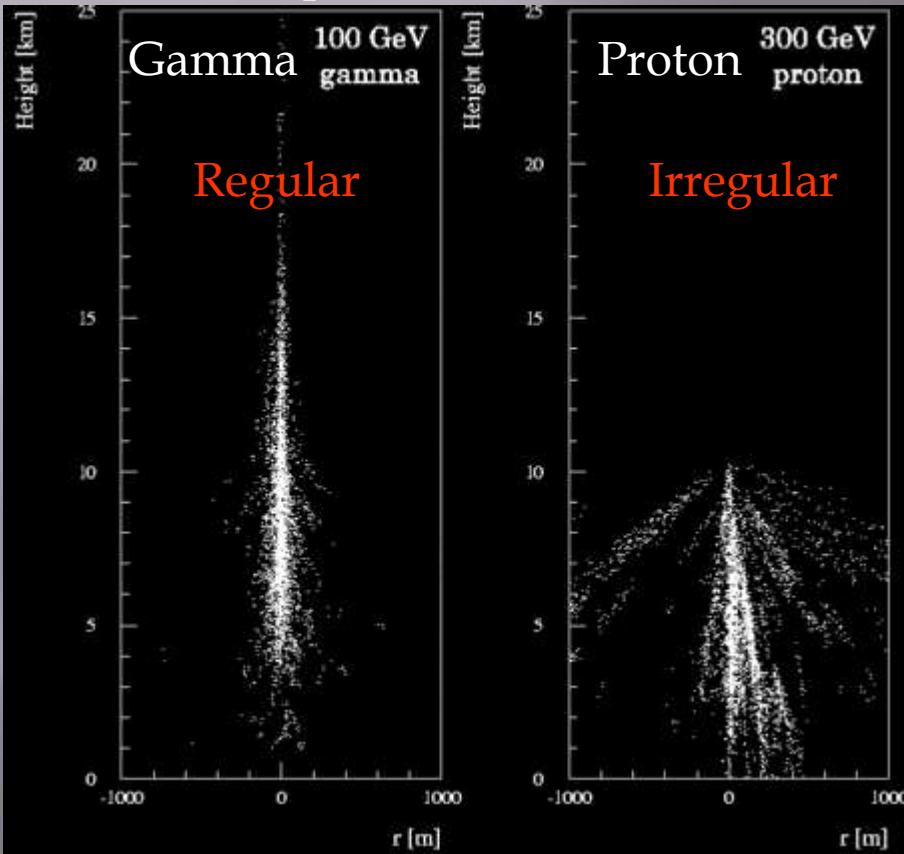
# 大気チエレンコフ 望遠鏡

Cherenkov light from gamma-ray showers  
*Lateral distribution & Timing distribution*

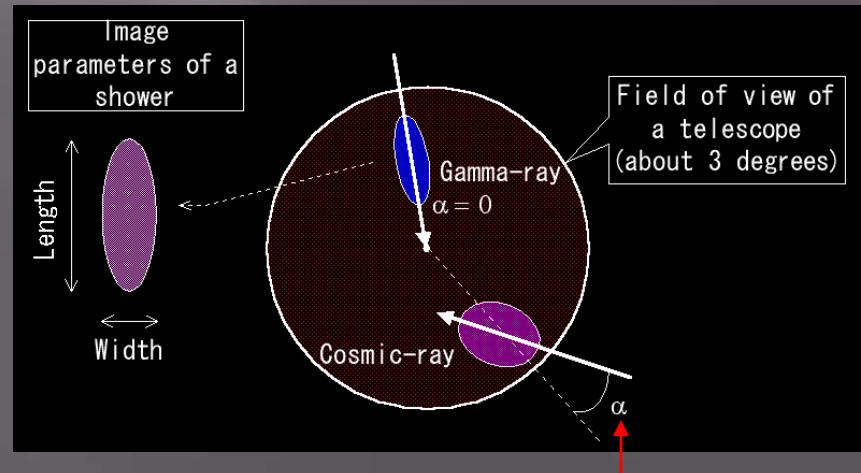
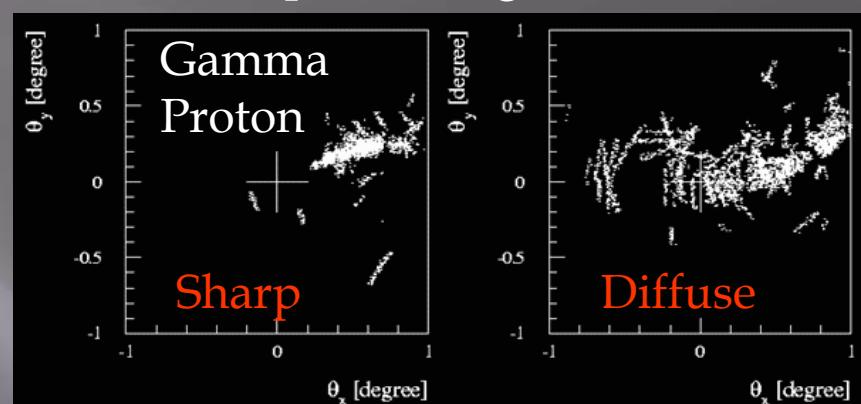


# 解像型チエレンコフ望遠鏡

Shower profile



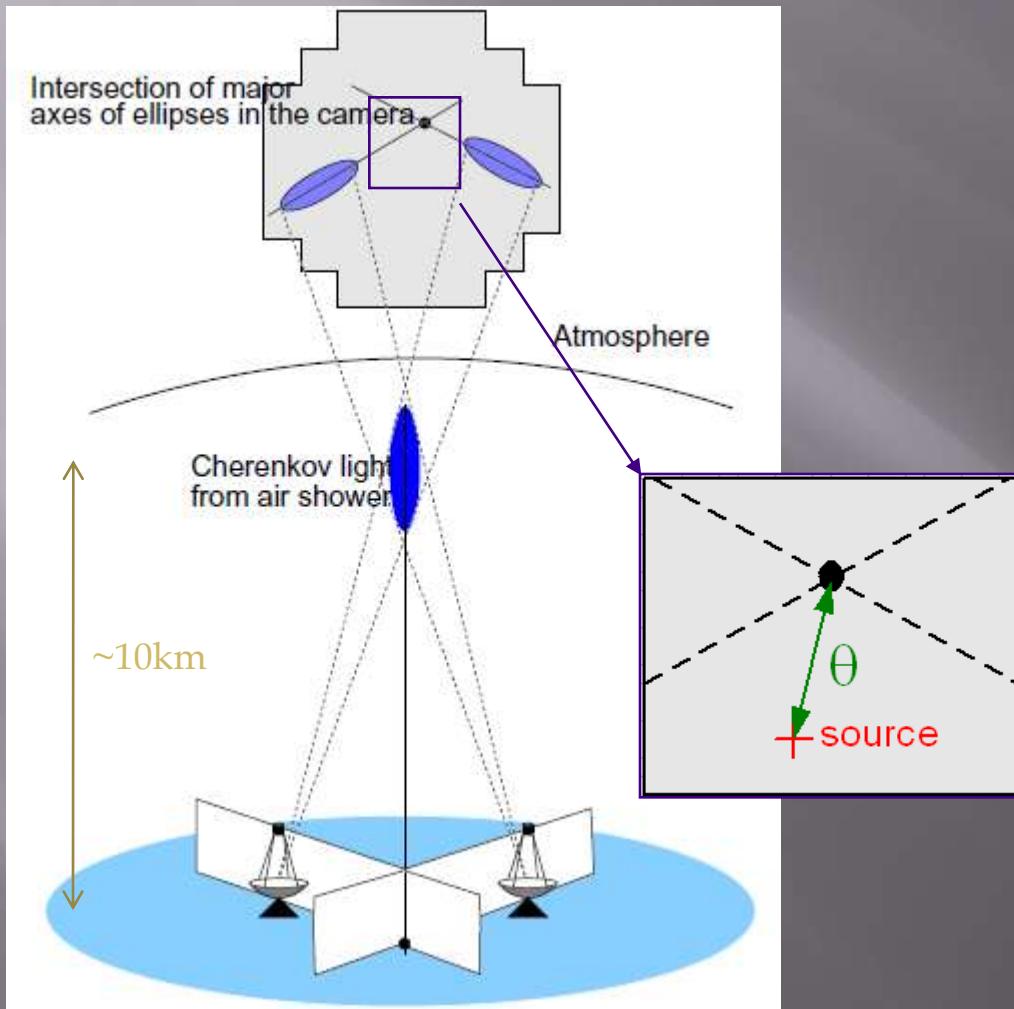
Focal plane image



⇒ 荷電宇宙線とガンマ線の識別

$\alpha$  (image orientation angle)

# チエレンコフ光のステレオ観測



© S.Funk, 2005

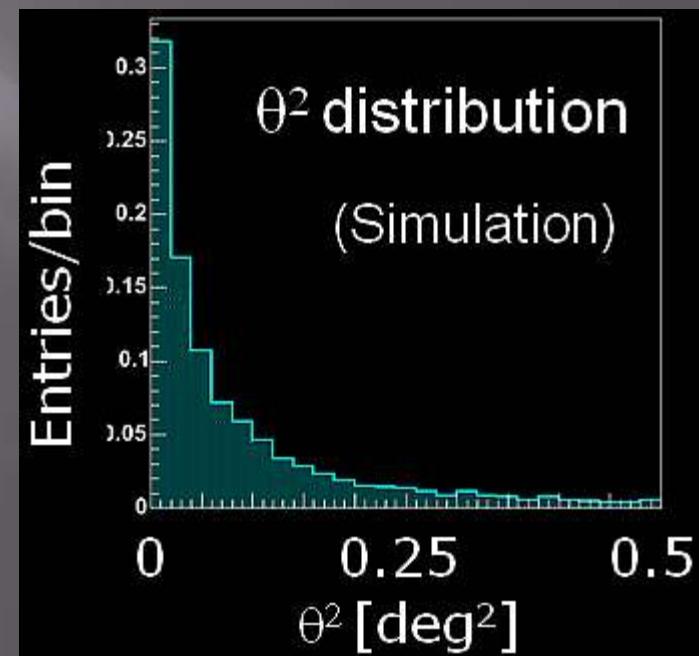
Angular resolution

$0.25\text{deg} \rightarrow 0.1\text{ deg}$

Energy resolution

$30\% \rightarrow 15\%$

Better S/N (no local muons)



# ガンマ線の検出法の比較

Base	Satellite	Ground	Ground
Gamma-ray detection	Direct (pair creation)	Indirect (atmospheric Cherenkov)	Indirect (shower array)
Energy	< 30 GeV $\rightarrow$ 100 GeV	>100 GeV $\rightarrow$ 50 GeV	>3 TeV $\rightarrow$ 1 TeV
Pros	High S/N Large FOV	Large area Good $\Delta\theta$	24hr operation Large FOV
Cons	Small area High cost	Low S/N (CR bkgd.) <i>(but imaging overcomes this!)</i> Small FOV	Low S/N (CR bkgd.) Moderate $\Delta\theta$

# VHE Experimental World

MILAGRO



STACEE



MAGIC



TIBET



MILAGRO

STACEE

VERITAS

MAGIC

TACTIC

TIBET  
ARGO-YBJ

PACT

GRAPES

TACTIC

VERITAS

HESS

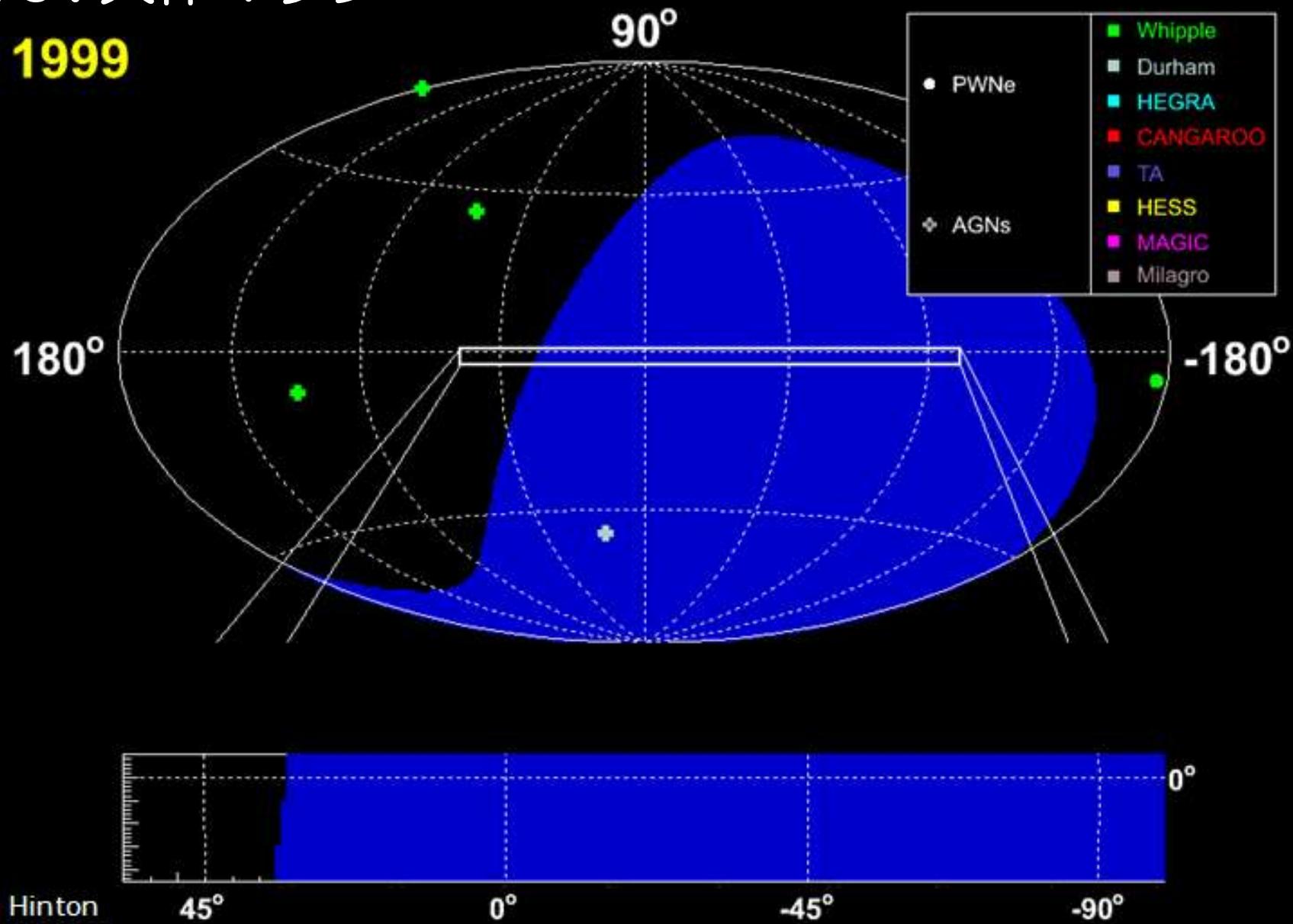
CANGAROO III

HESS

CANGAROO

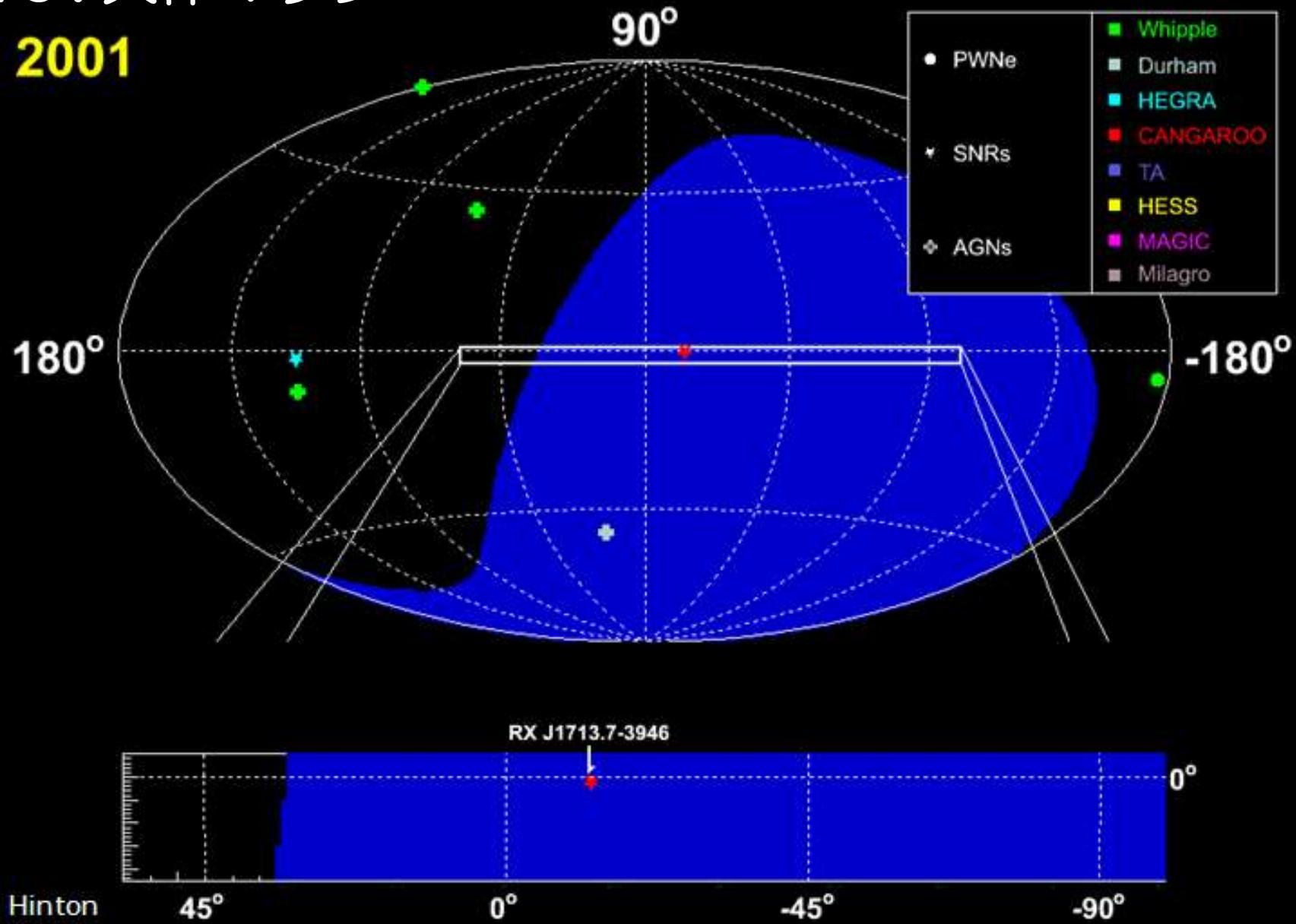
# TeV天体マップ

1999



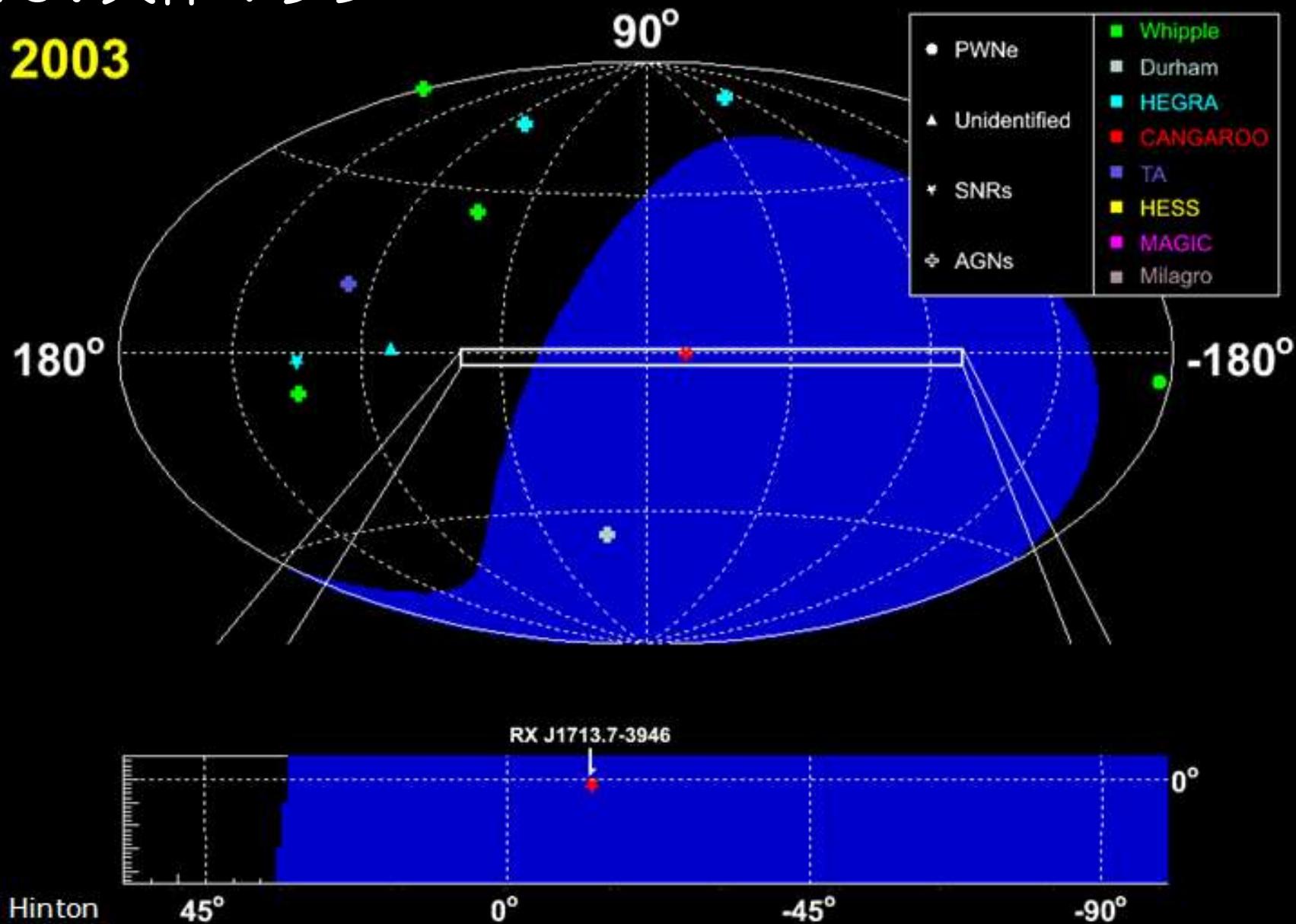
# TeV天体マップ

2001



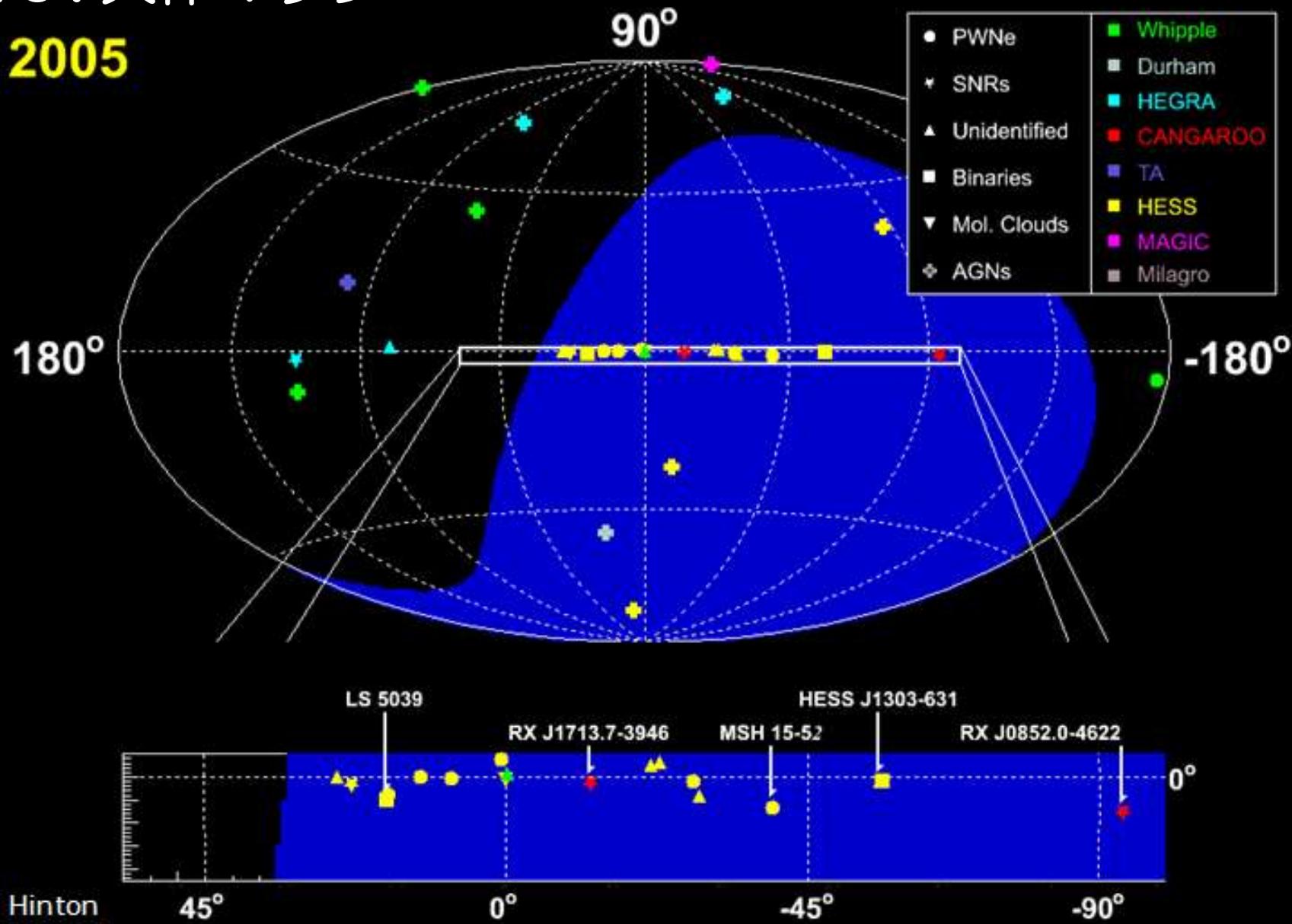
# TeV天体マップ

2003



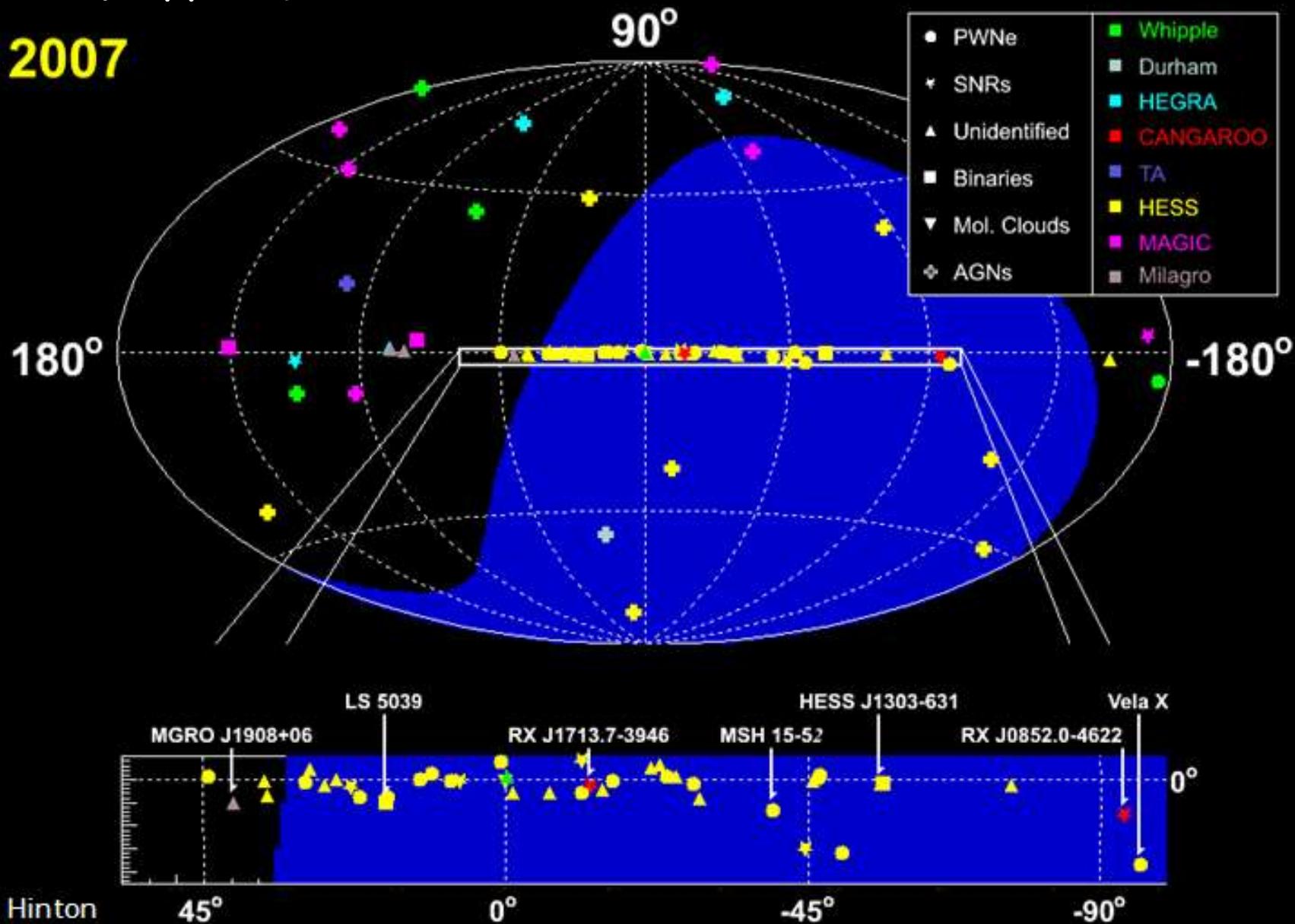
# TeV天体マップ

2005



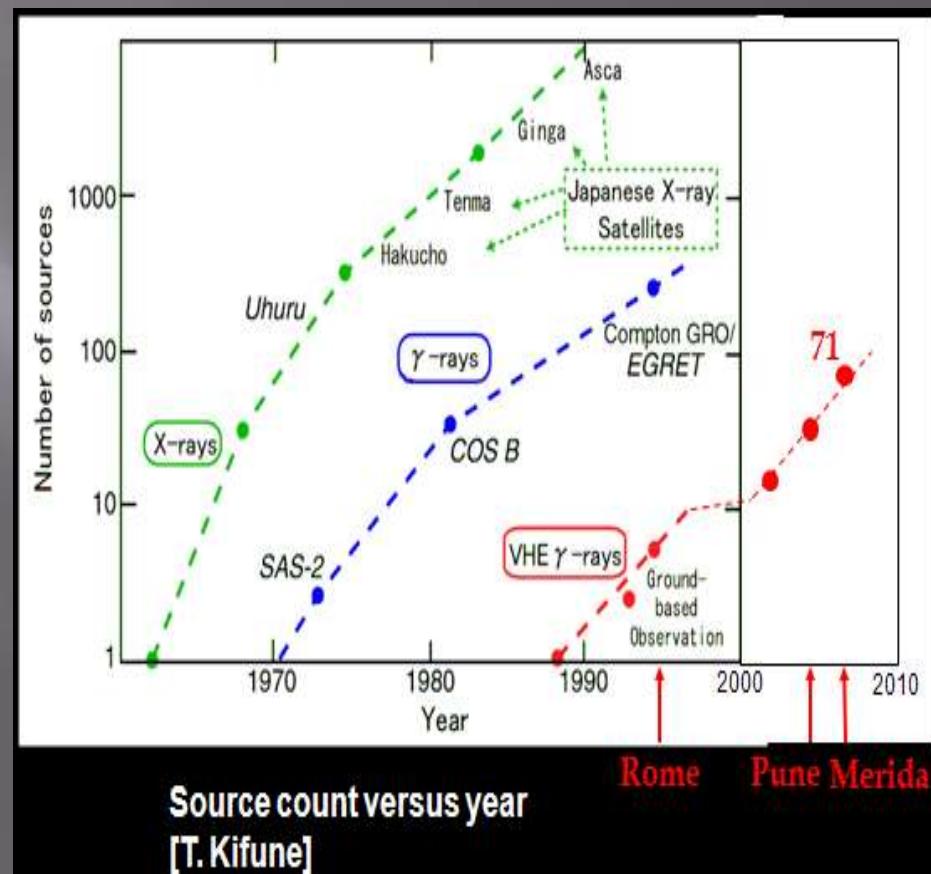
# TeV天体マップ

2007



# TeV天体の増殖

Class	2003	2005	2007
PWN	1	6	18
SNR	2	3	7
Binary	0	2	4
Diffuse	0	2	2
AGN	7	11	19
UnId	2	6	21
Total	12	33	71!

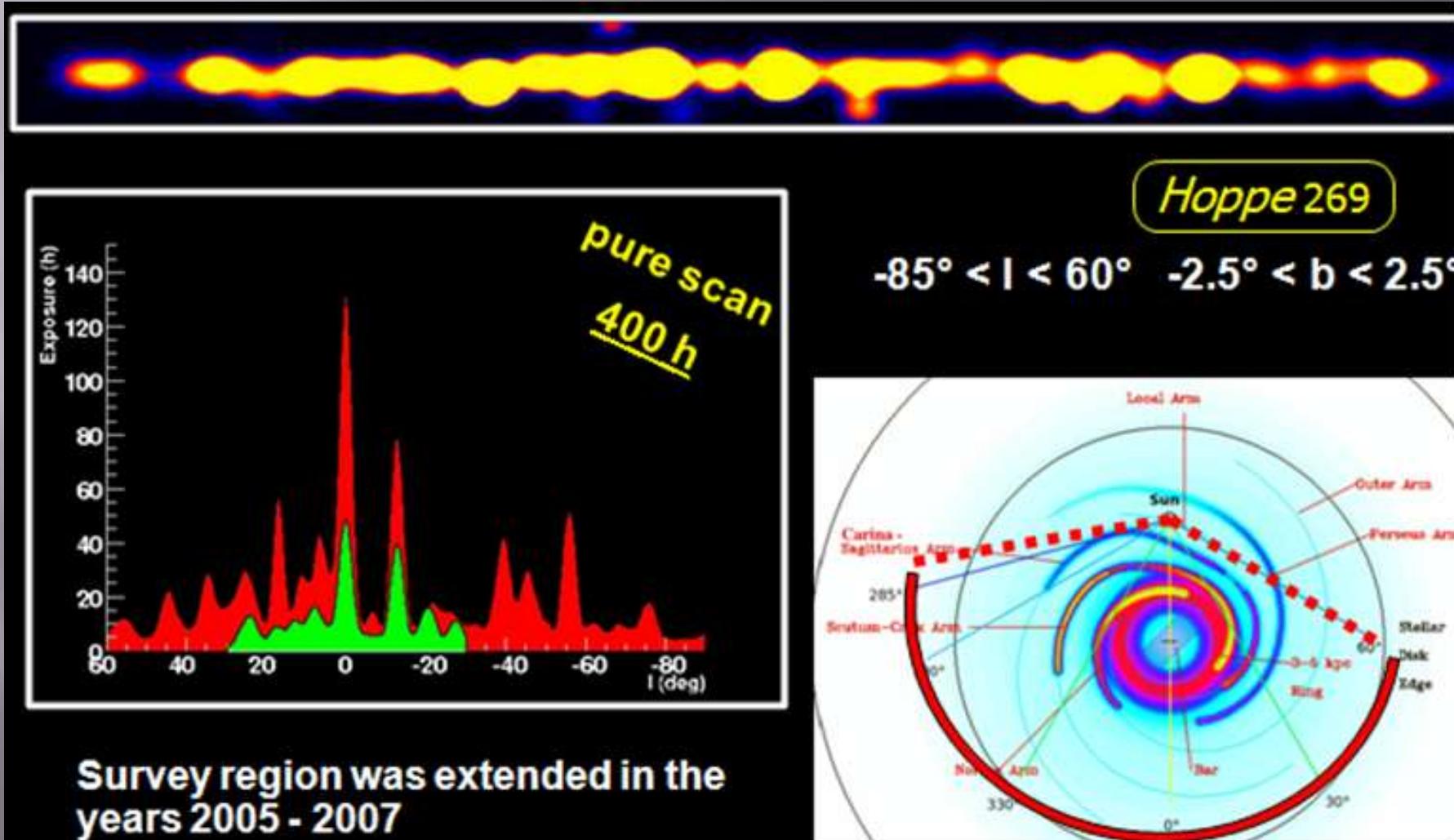


"Kifune plot"

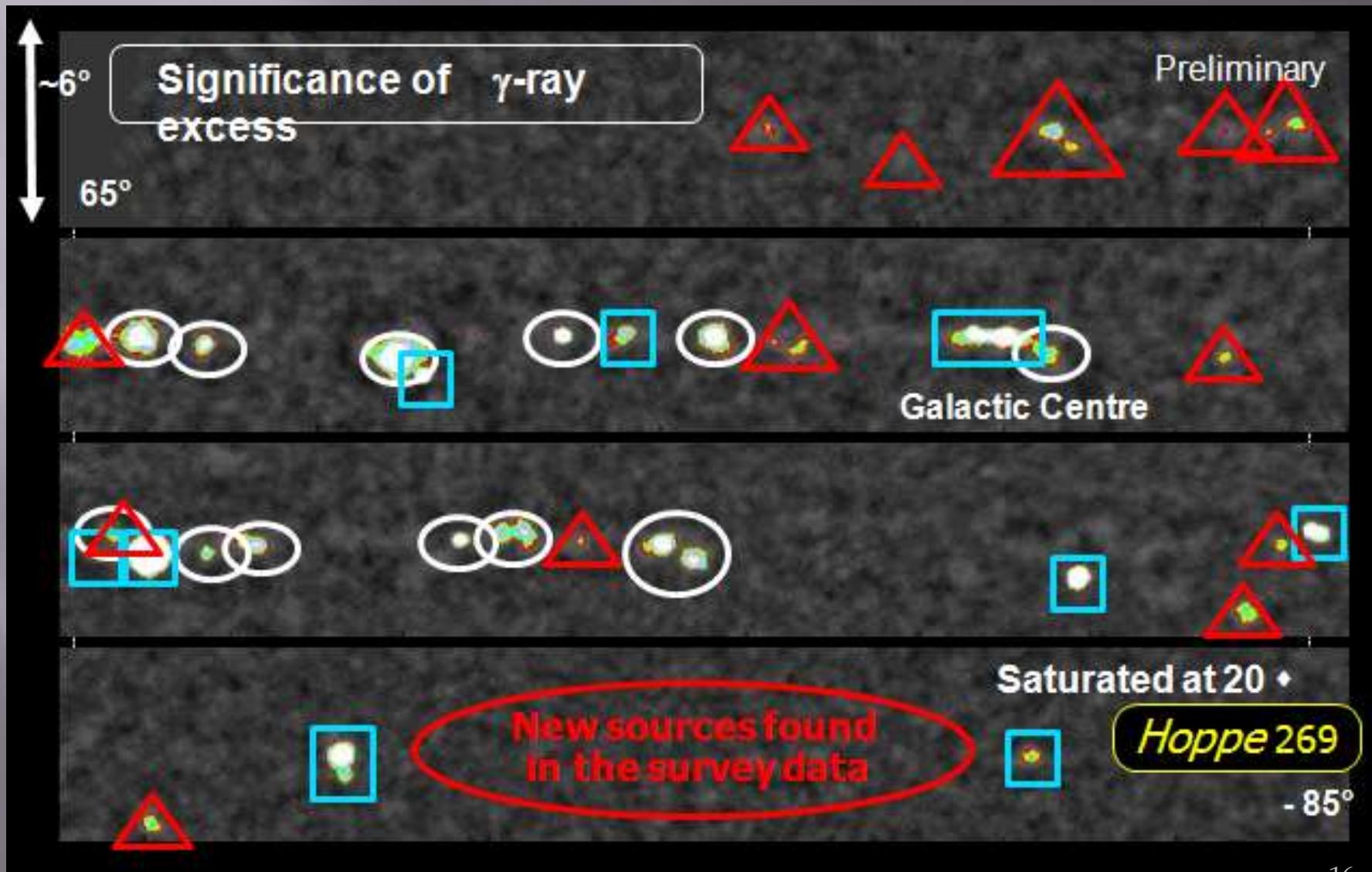
# TeV天体（候補）の多様性

銀河系内天体	超新星残骸	7個
	パルサー星雲	18個
	連星系・マイクロクエーサー	4個
	銀河中心	1個
	diffuse成分	2個
	分子雲	未発見
銀河系外天体	活動銀河	19個
	近傍銀河	未発見
	スターバースト銀河	未発見
	銀河群・銀河団	未発見
未同定天体		21個
ガンマ線バースト		未発見
ダークマター		未発見
量子重力		未発見

# H.E.S.S.銀河面サーベイ

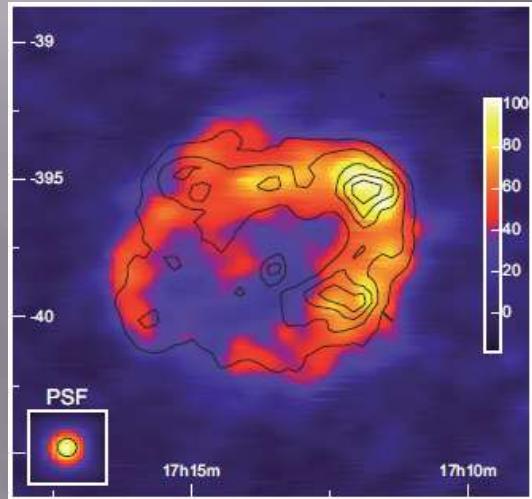


# H.E.S.S.銀河面サーベイ

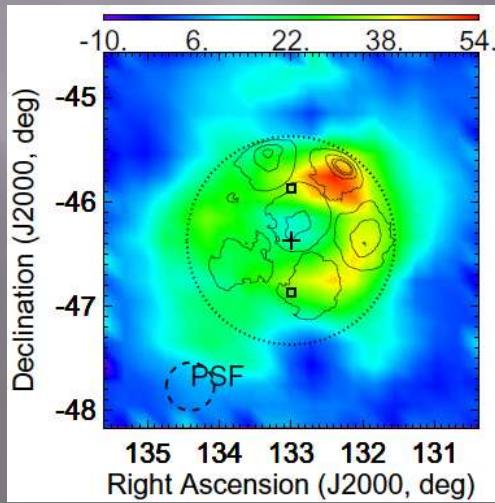
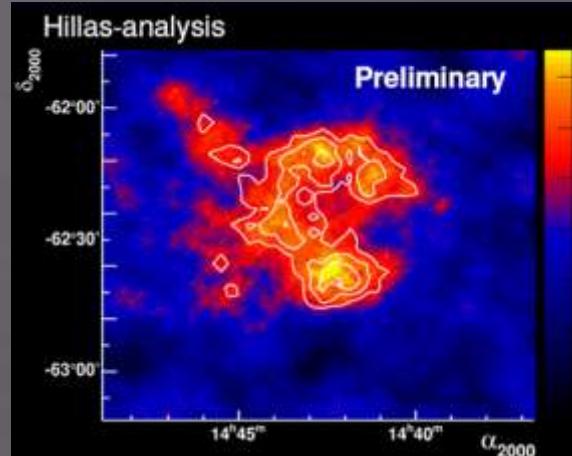


# 超新星残骸＝宇宙線の起源？

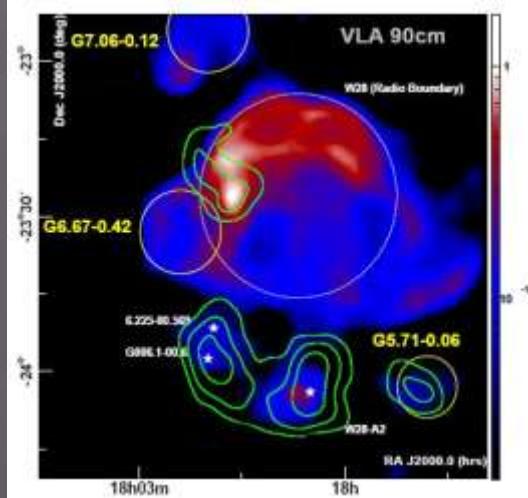
RXJ 1713.7-3946  
[H.E.S.S.,  
Aharonian et al.  
2006]



RCW86  
[H.E.S.S.,  
ICRC2007]

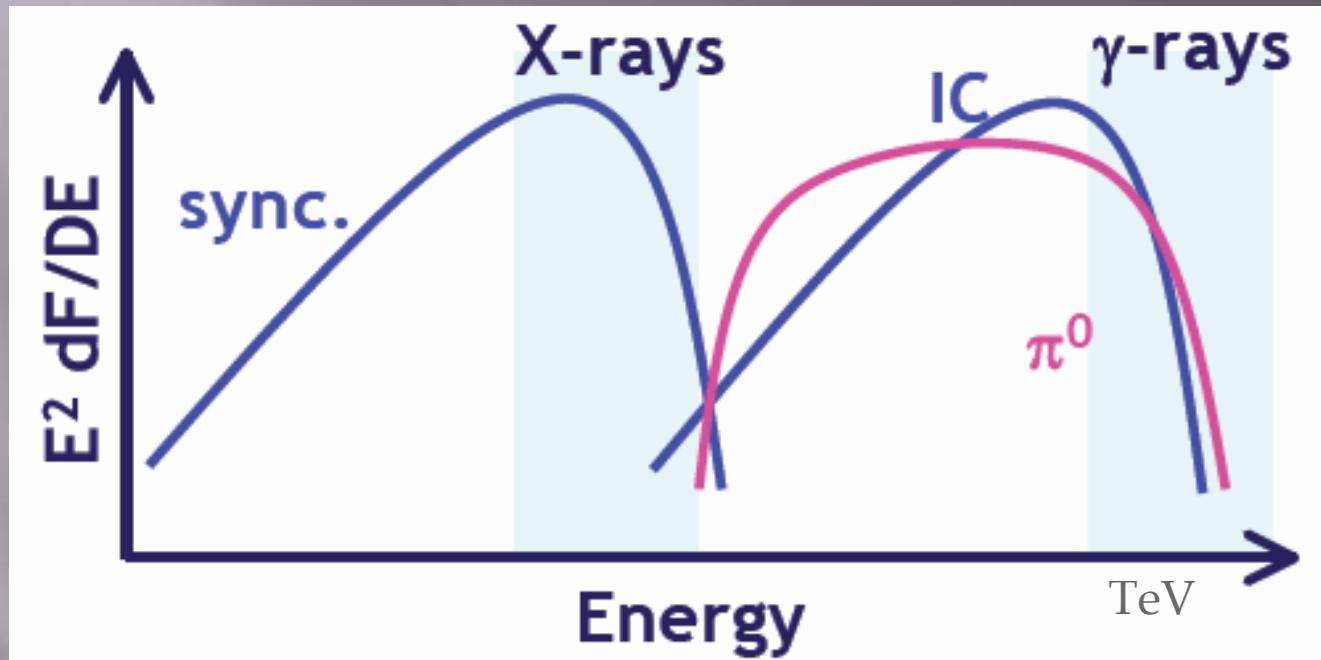


RXJ 0852-04622  
[CANGAROO-III,  
Enomoto et al.  
2006]



W28  
[H.E.S.S.,  
ICRC2007]

# 加速粒子とスペクトル

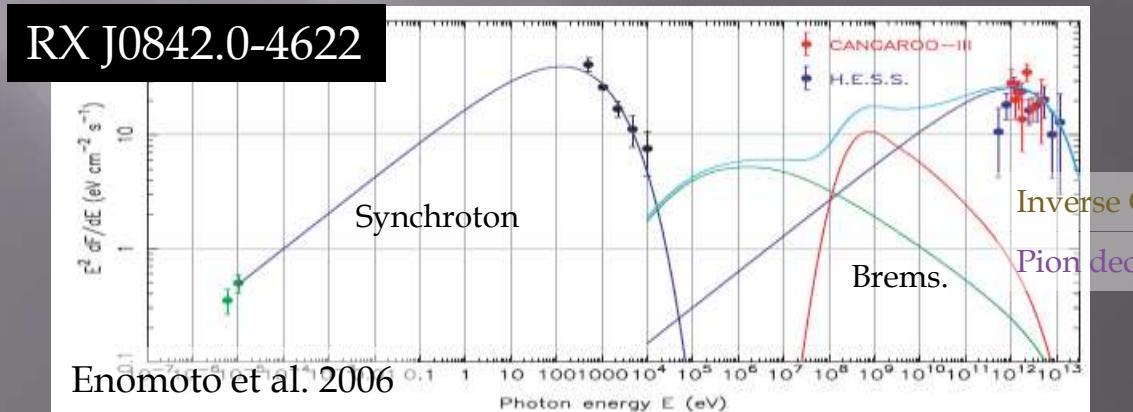
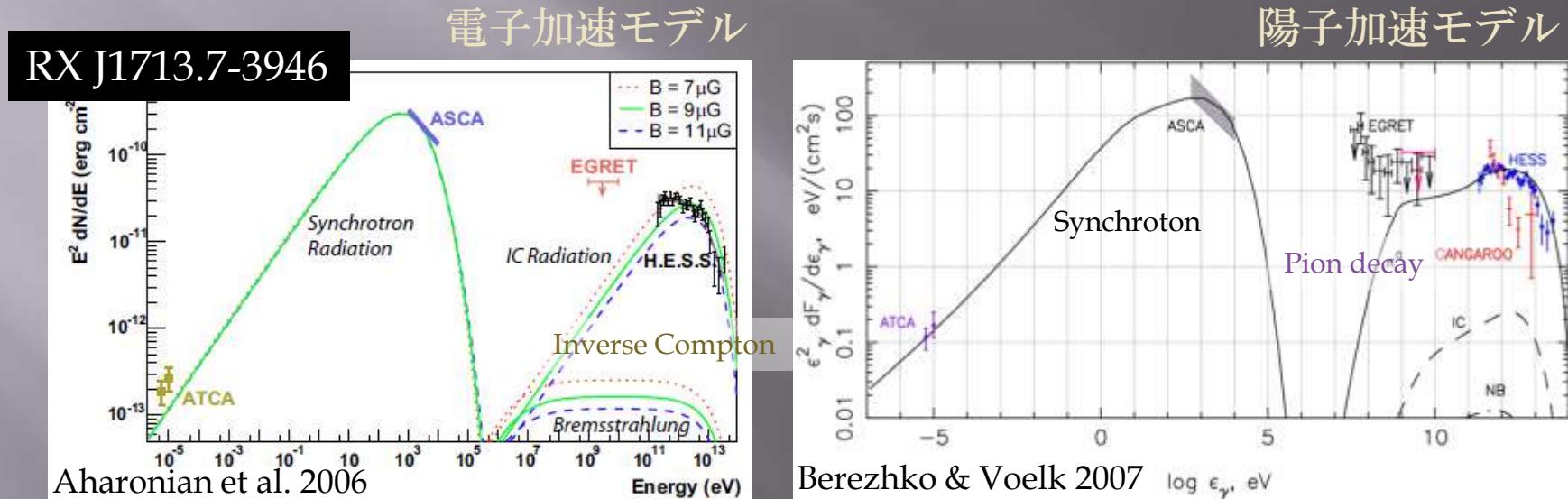


©A.Bamba



# 超新星残骸のスペクトル

ハードなスペクトル+カットオフ： $\sim E^{-2} \exp(-E/E_{\max})$



加速されている粒子の種類についてはまだ決定的証拠がない！

# 加速粒子の識別は簡単ではない？

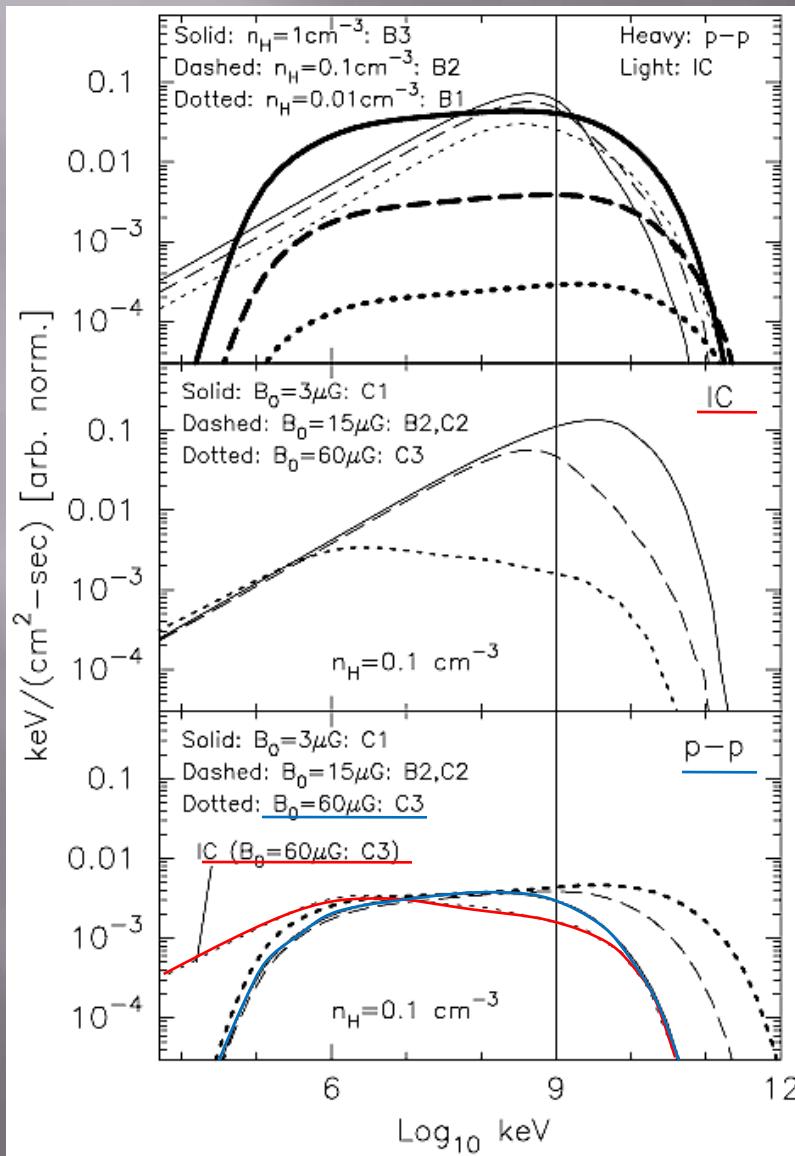
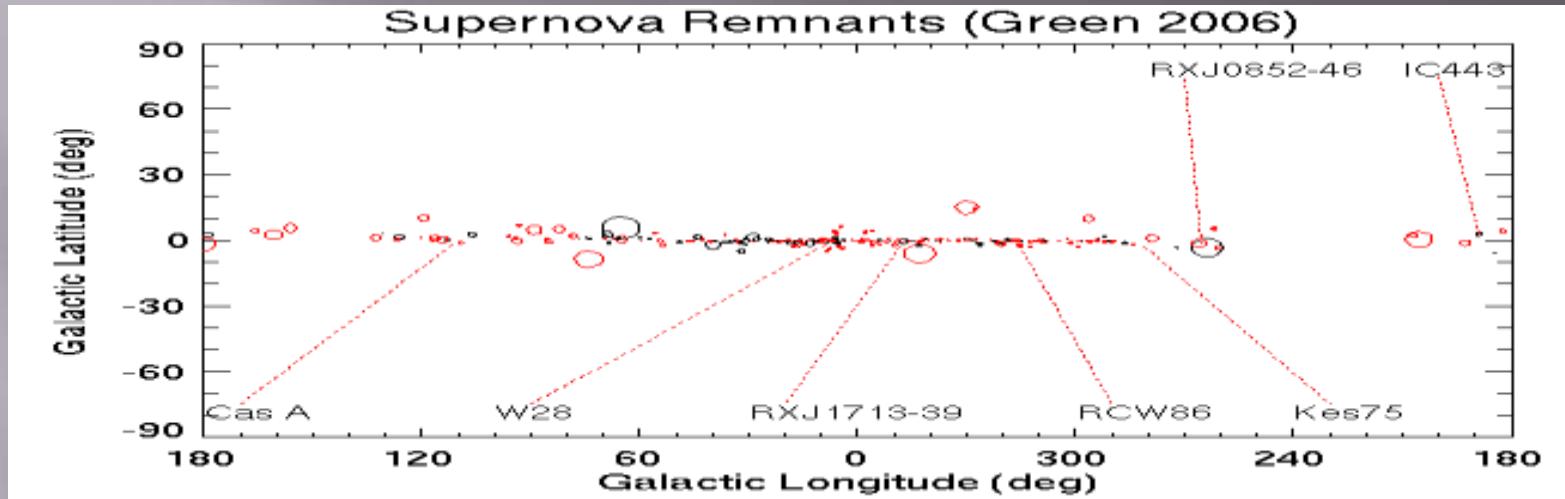


FIG. 12.—Pion-decay and IC emission for a range of  $n_{\text{H}}$  and  $B_0$ . In the top panel, the heavy curves are pion decay, the light curves are IC, and  $\epsilon_{\text{rel}} = 36\%$  and  $B_0 = 15 \mu\text{G}$  in all cases. The strong dependence of pion decay on ambient density  $n_{\text{H}}$  is evident. The middle panel shows IC, and the bottom panel shows pion decay for  $n_{\text{H}} = 0.1 \text{ cm}^{-3}$ , with  $B_0$  varying from 3  $\mu\text{G}$  (solid curves) to 15  $\mu\text{G}$  (dashed curves) to 60  $\mu\text{G}$  (dotted curves). For comparison to the  $\pi^0$ , we show in the bottom panel the IC emission for  $B_0 = 60 \mu\text{G}$  (light dotted curve). The particle distributions producing the emission in the bottom two panels are those shown in the top panel of Fig. 11.

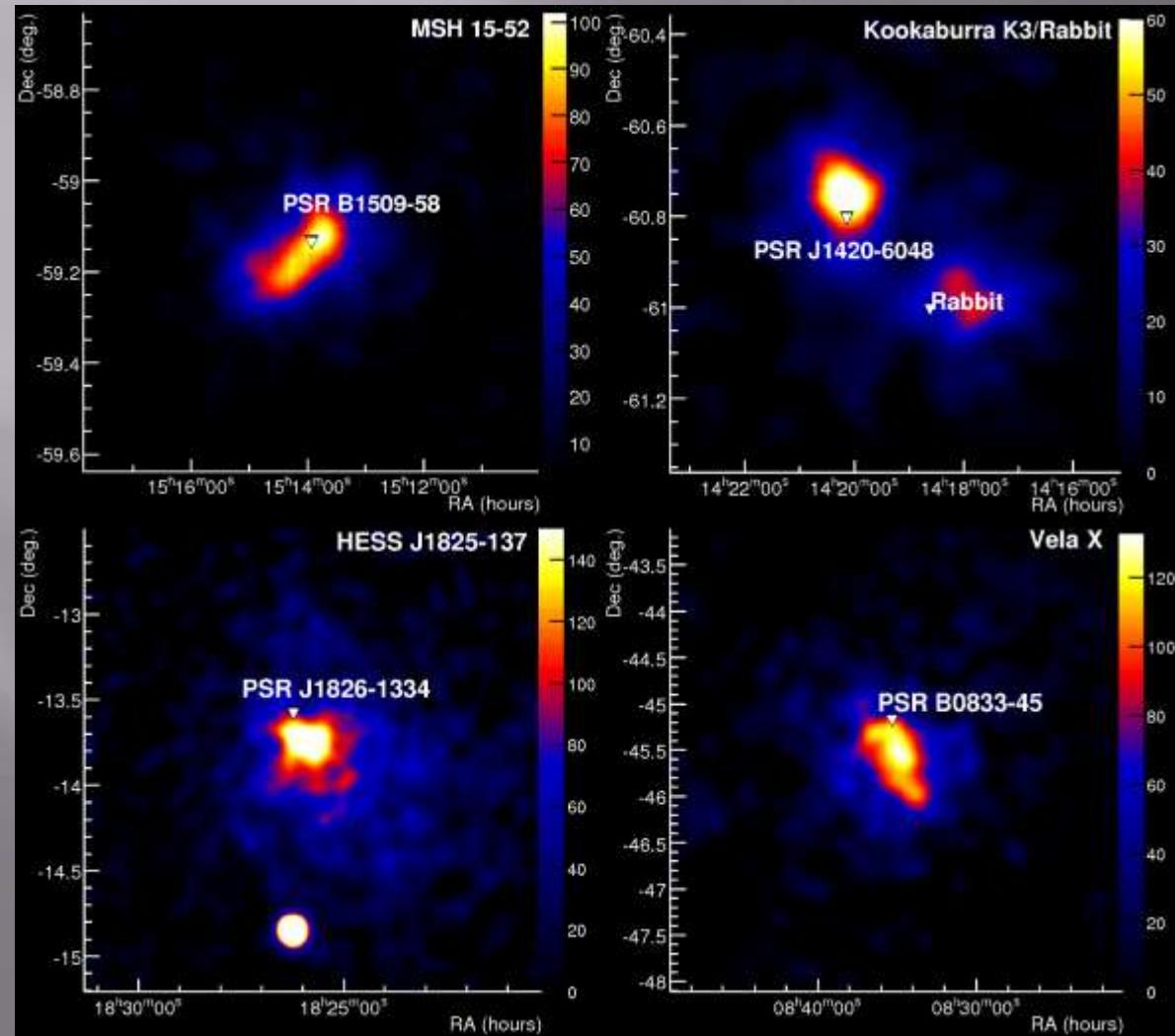
磁場が強い場合はGeV-TeVでは識別は困難！

# 超新星残骸の数と宇宙線



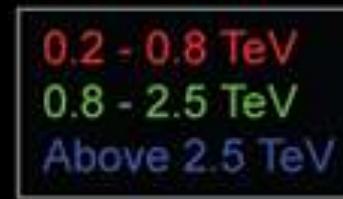
- 銀河内の超新星残骸の数
  - SN rate  $\sim 1/30$ yr, accelerating particles during  $\sim 10^4$ yr  
 $\Rightarrow \sim 300$  active SNRs  
 $\Rightarrow \sim 3$  SNRs within 1kpc (assuming Case & Battacharya distribution [A&AS 120, 437, 1996])
- $\sim 1$ Crab TeVガンマ線を出す超新星残骸 (RXJ1713, RXJ0852:ともに距離  $\sim 1$  kpc)
  - $L_\gamma \sim 6 \times 10^{35}$ erg/s ( $>$ GeV, assuming  $E^{-2.6}dE$ )
  - 300 SNRs  $\Rightarrow W_\gamma$ (Galaxy)  $\sim 2 \times 10^{38}$ erg/s
- 銀河の宇宙線光度
  - $1 \text{ eV/cm}^3, V \sim 10^{66-67} \text{cm}^3, \tau \sim 10^{14-15} \text{s} \Rightarrow W_{\text{CR}} \sim 10^{40} \text{erg/s}$
- $\therefore W_\gamma \sim 0.02 W_{\text{CR}}$ : TeVガンマ線天体は数十個?

# パルサー星雲



- 系内ではメジャーなTeV天体
  - Hinton (2007ICRC)によればTeV天体71個中18個
  - 比較的若く(<10<sup>5</sup>年)スピンドownエネルギーの大きなパルサーに付随
- パルサー本体から離れたところに10pc程度の広がり
- 電子起源の逆コンプトン散乱による $\gamma$ 線？

# パルサー星雲：エネルギー別の形状



Funk389

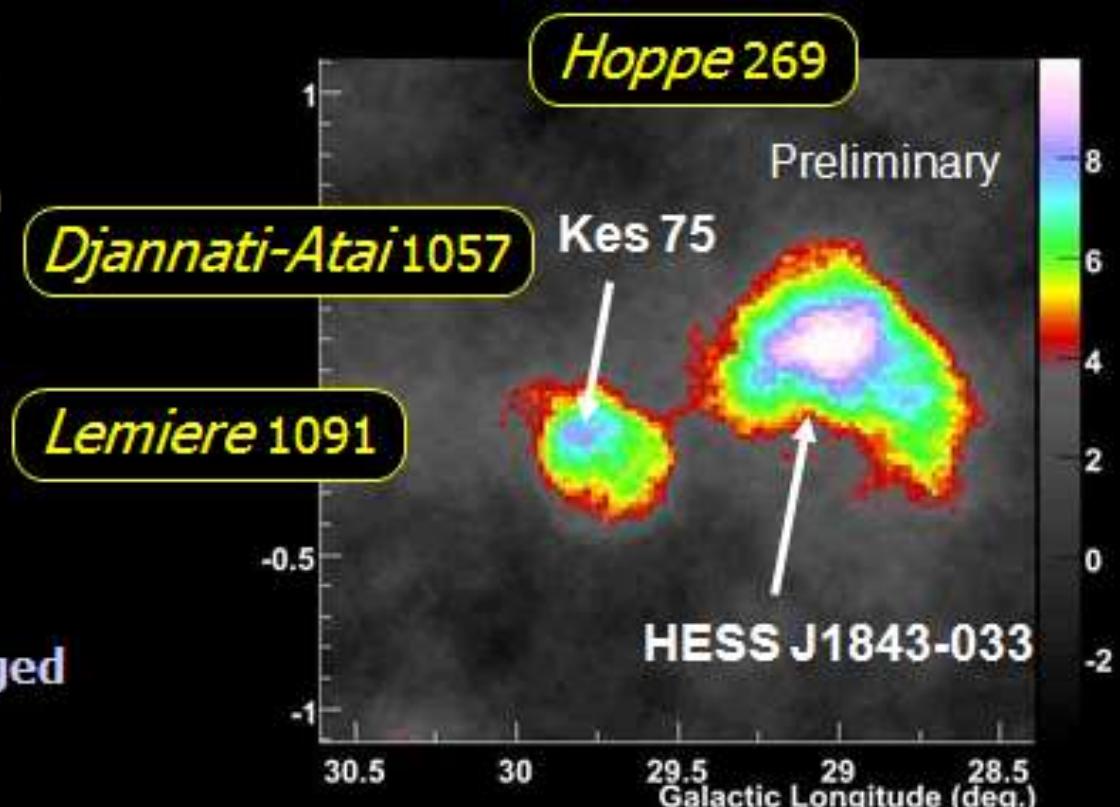
- **HESS J1825-137 associated with energetic pulsar**
- **Spectral steepening seen away from the pulsar**
- **Very likely this is evidence for cooling of electrons in the Nebula**
  - Seen in several *X-ray* PWN
- **A first in gamma-ray astronomy!**

PSR J1826-1334



# パルセー星雲 (続)

- **PSR J1846-0258 in Kes 75**
  - Youngest pulsar in our galaxy
- **G21.5-0.9**
  - Also v. young
- **HESS J1357-645, HESS J1718-385, HESS J1809-193, HESS J1912+102**
  - PWNe of middle aged pulsars
- **Geminga??**
  - C3 'hotspot' from Milagro –  $5.1 \rightarrow 2.8 \sigma$
  - 3 degrees across – almost impossible for IACTs...



# パルサー星雲とスピンドウン率

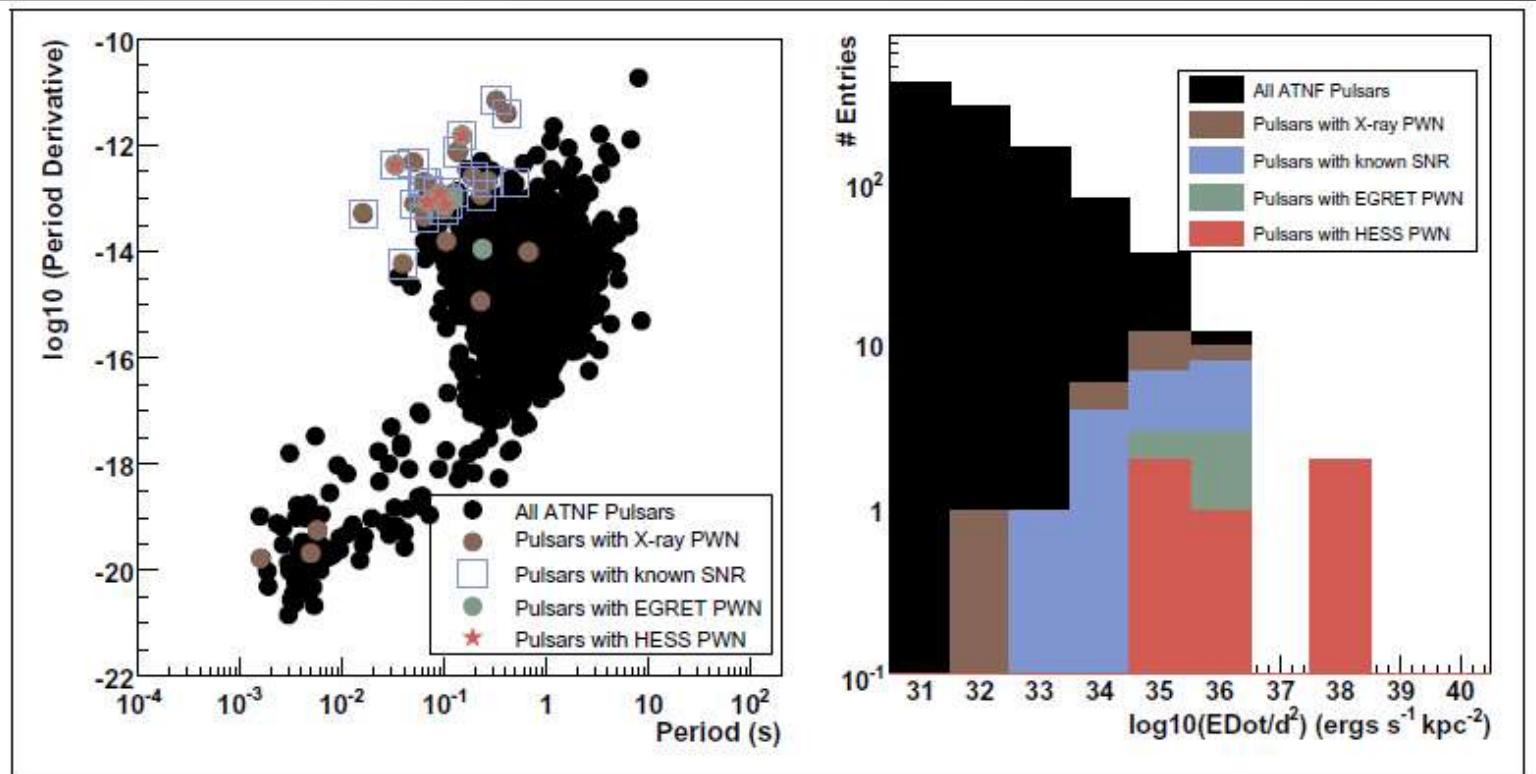
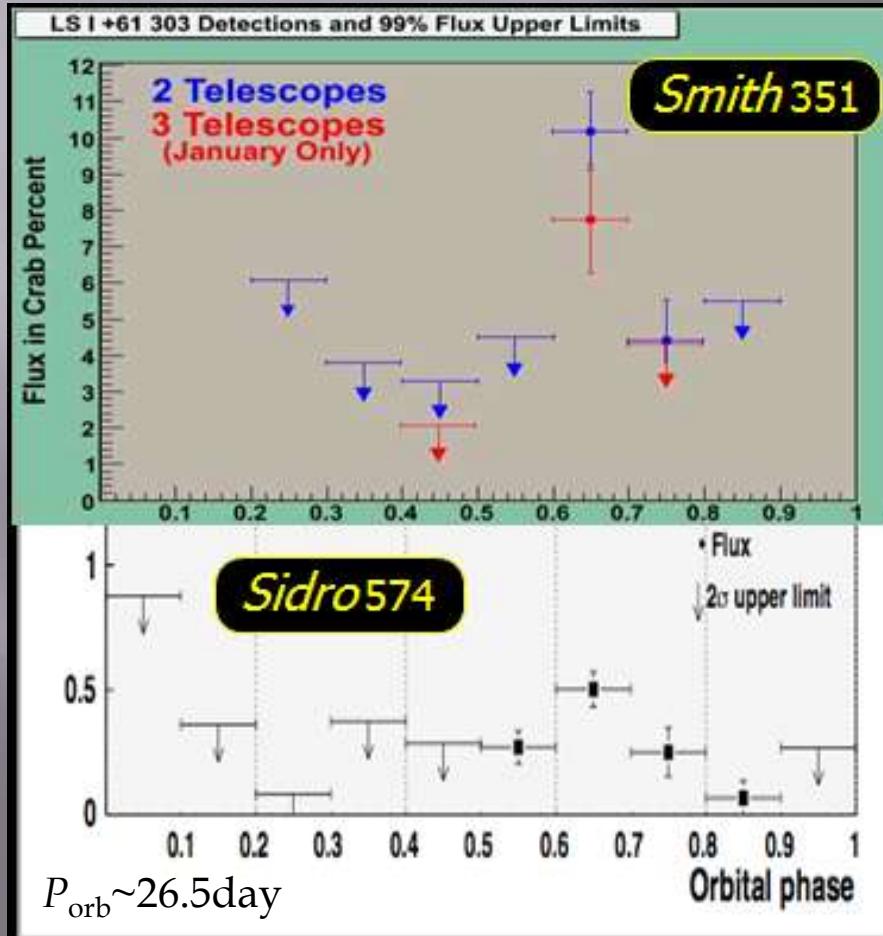


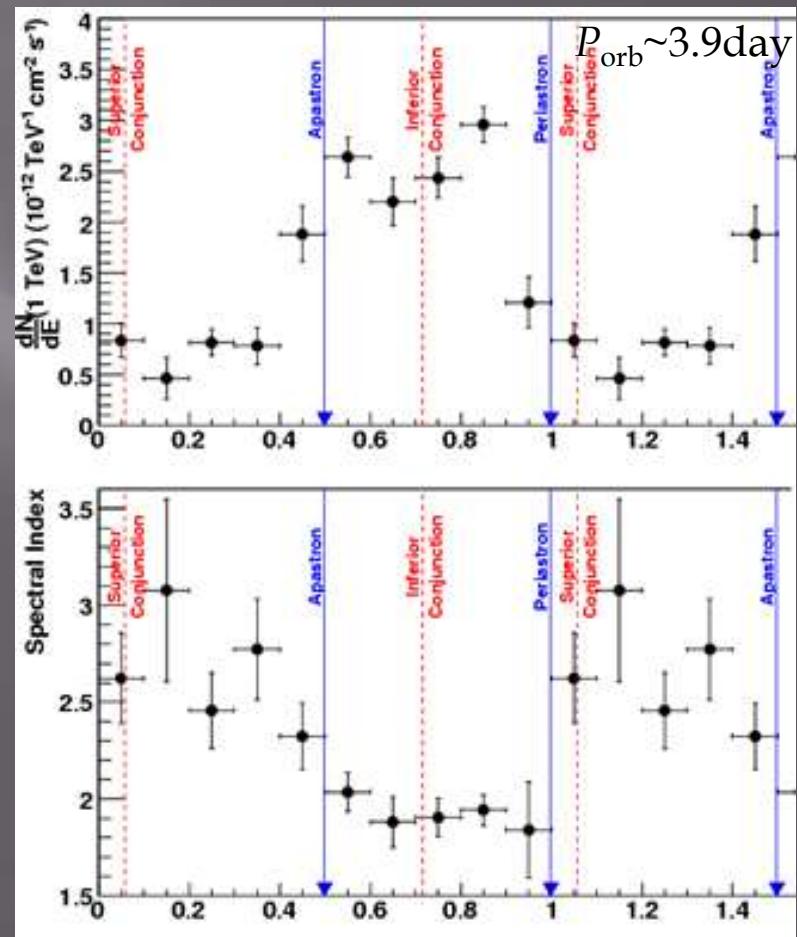
Figure 3: Top:  $P - \dot{P}$  diagram for pulsars: all ATNF pulsars (black), with detected X-ray PWN (brown), with a known corresponding SNR (blue), potentially associated to an EGRET source (green), associated to a H.E.S.S. VHE PWN (red). Bottom: Energy output for the selections used at the top.

# ガンマ線連星

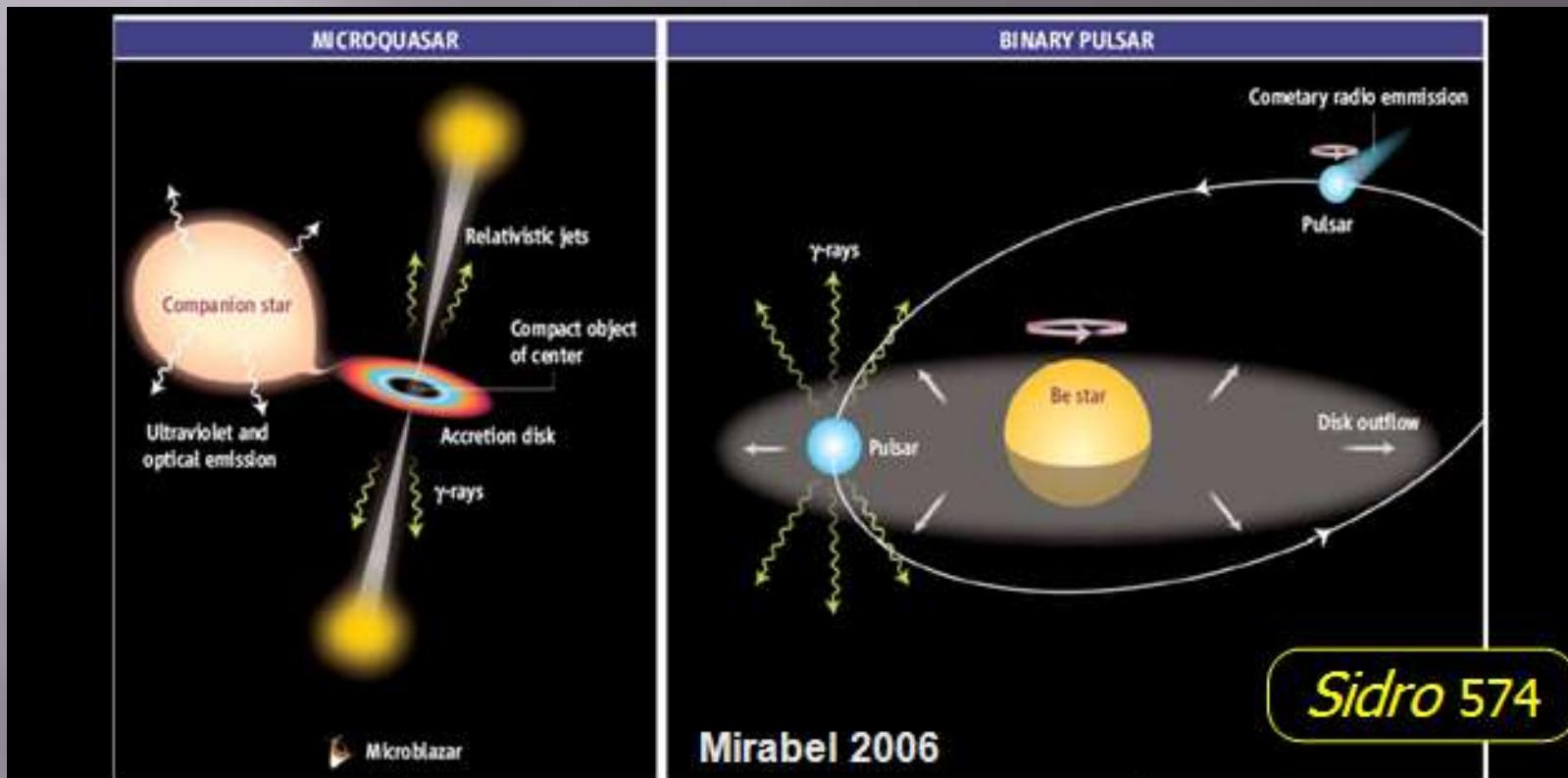
LSI +61 303 (VERITAS/MAGIC)



LS 5039 (H.E.S.S.)



# ガンマ線連星の放射

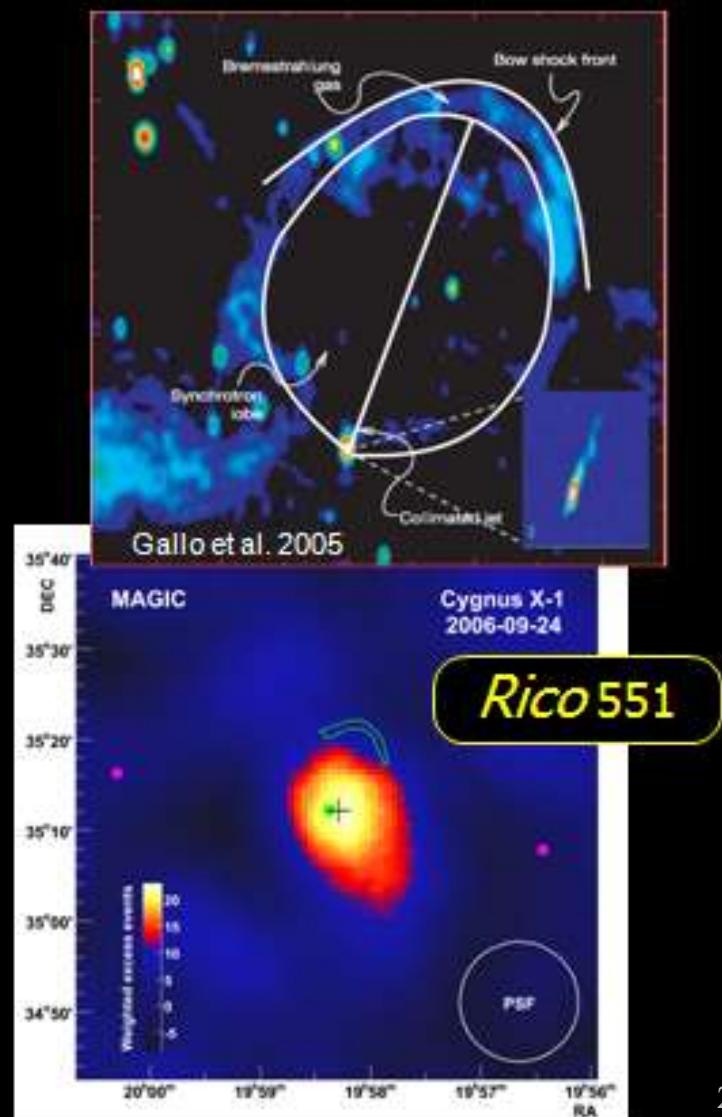


**Microquasar:** particles (electrons or hadrons) are accelerated in a jet  
Bosch-Ramon et al. (2006), Romero et al. (2007)

$\gamma$ -rays produced in the shock where the wind of the young pulsar and the wind of the Be star collide  
Dubus (2006), Dhawan et al. (2006)

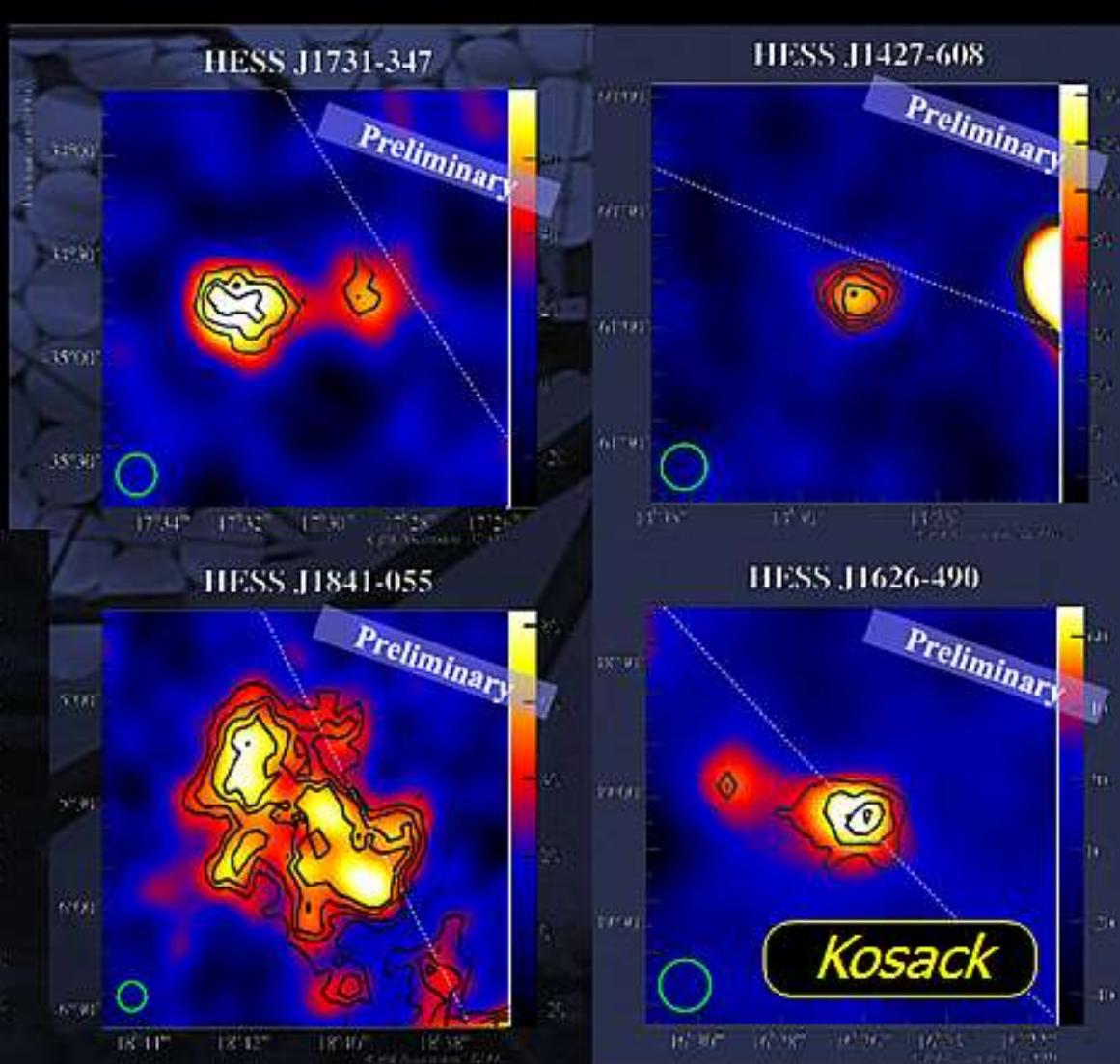
# ガンマ線連星 : Cyg X-1

- **Black hole binary**  $M_{\text{BH}} > 13M_{\odot}$ ,  
 $M_{\text{star}} \sim 30 M_{\odot}$
- **Relativistic jet**  $v > 0.6 c$
- **40 hours of MAGIC observations**
- **4.9  $\sigma$  signal seen in one 79 minute time slice**
- **Estimated significance 4.1  $\sigma$  after correction for statistical trials**
- **Very exciting but not yet firmly established as a VHE source**



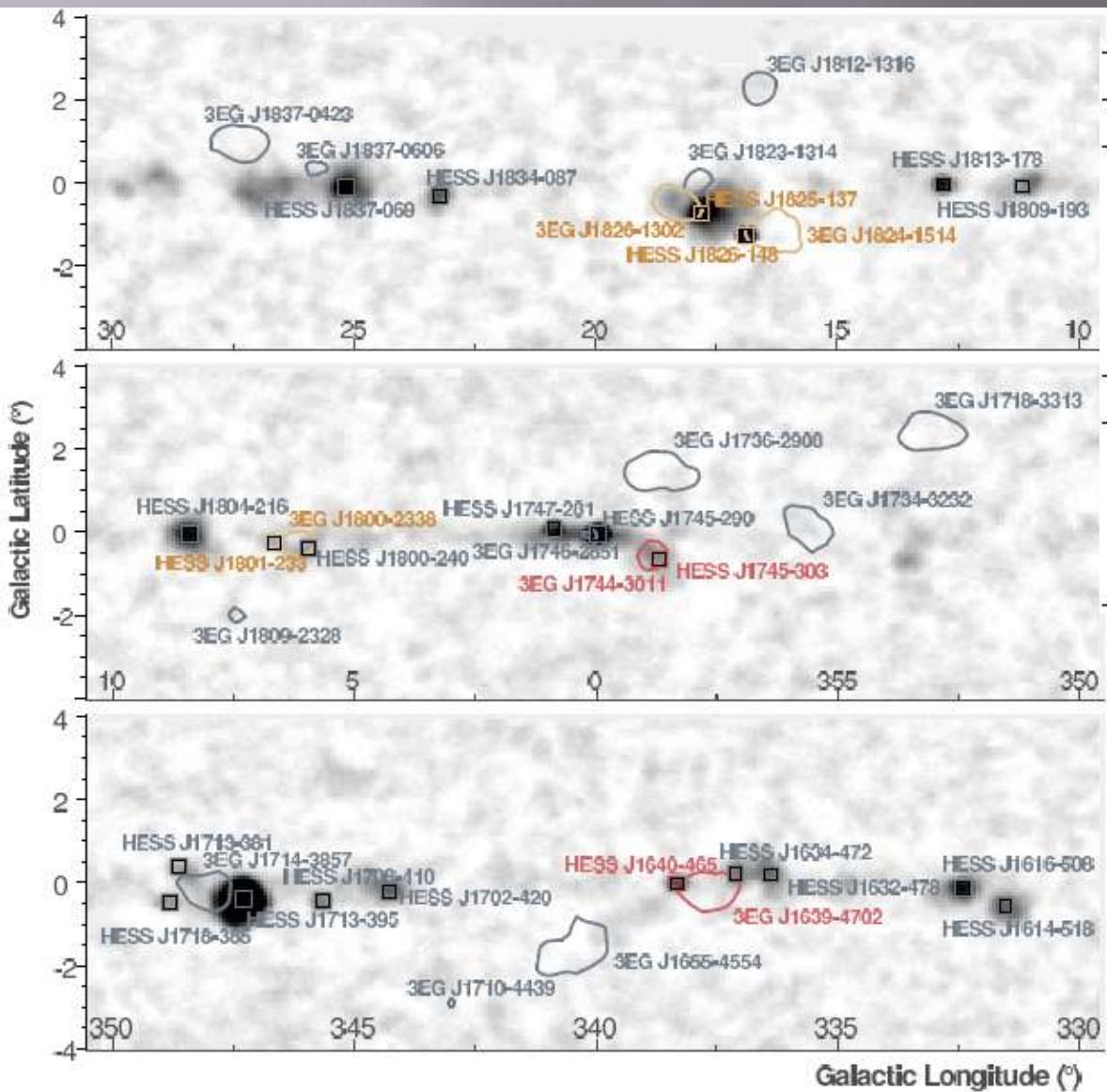
# 未同定TeV天体 ("dark" sources)

- **6 new TeV gamma-ray sources**
  - none with compelling counterpart
  - Relegated to a poster!

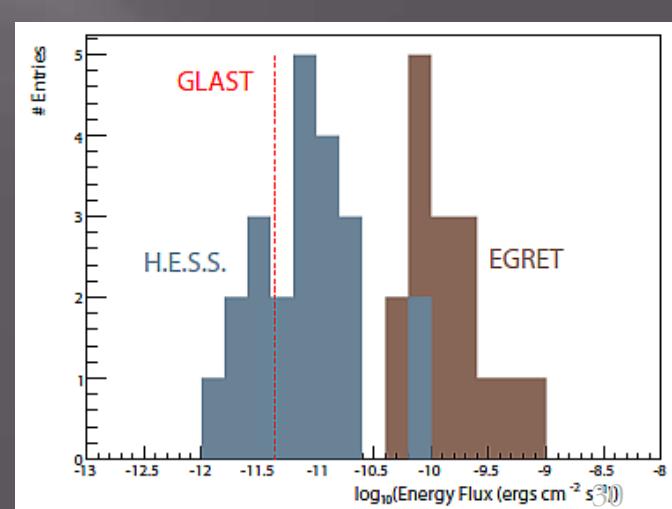


# TeV-GeV対応？

Coincident sources



EGRET source	VHE $\gamma$ -ray source	Potential Counterpart
Within the H.E.S.S. GPS		
3EG J1639-4702	HESS J1640-465	G338.3-0.0 (SNR/PWN)
3EG J1744-3011	HESS J1745-303	
3EG J1800-2338	HESS J1801-233	W28 (SNR)
3EG J1826-1302	HESS J1825-137	G18.0-0.7 (PWN)
3EG J1824-1514	HESS J1826-148	LS 5039 (Binary)
Outside the H.E.S.S. GPS		
3EG J0241+6103	MAGIC J0240+613	LSI+61 303 (Binary)
3EG J0617+2238	MAGIC J0616+225	IC443 (SNR/PWN)
3EG J0634+0521	HESS J0632+058	Monoceros
3EG J1420-6038	HESS J1420-607	Kookaburra (PWN)

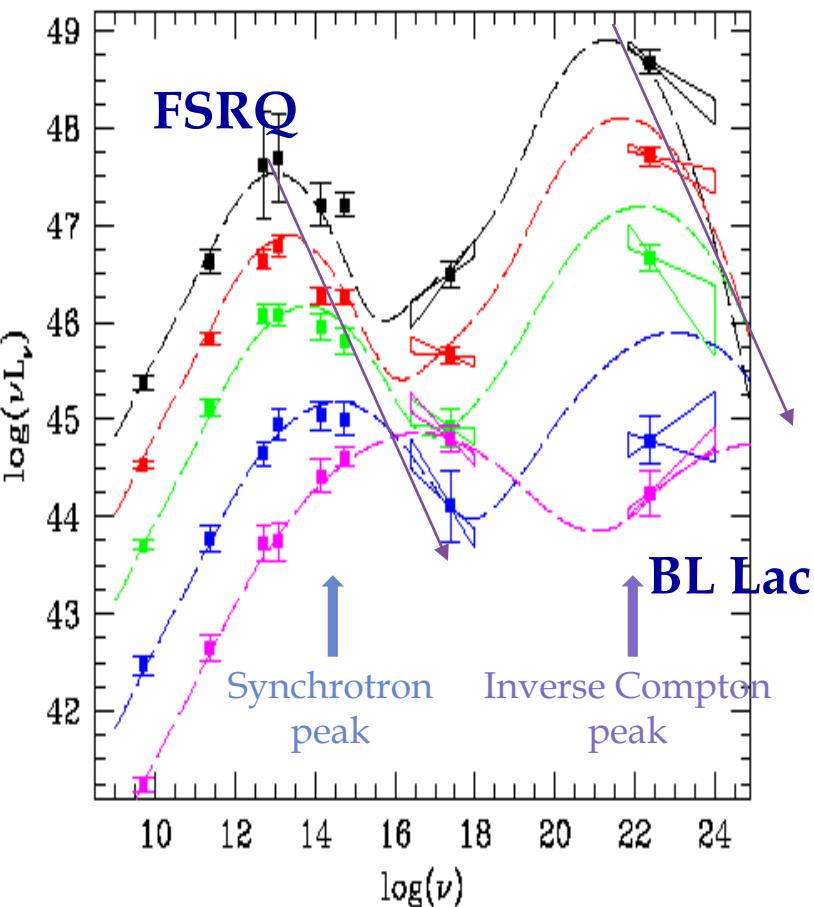


# 銀河系外TeV天体

Name	Discovered	Year	z	Contributions
M 87	HEGRA	2003	0.004	VERITAS-Colin, HESS-Beilicke, MAGIC-
Mrk 421	Whipple	1992	0.031	MILAGRO-Smith, VERITAS-Fegan, +
Mrk 501	Whipple	1996	0.034	TACTIC-Godambe, MAGIC-Paneque, +
1ES 2344+514	Whipple	1998	0.044	MAGIC-Wagner
→ Mrk 180	MAGIC	2006	0.046	MAGIC-Mazin
1ES 1959+650	TA	2002	0.047	MAGIC-Hayashida
→ BL Lac	MAGIC	2006	0.069	MAGIC-Hayashida
→ PKS 0548-322	HESS	2006	0.069	HESS-Superina
PKS 2005-489	HESS	2005	0.071	HESS-Costamante
PKS 2155-304	Durham	1999	0.116	HESS-Punch, CANGAROO-Sakamoto, +
H 1426+428	Whipple	2002	0.129	VERITAS-Krawczynski
→ 1ES 0229+200	HESS	2007	0.140	HESS-Raue
H 2356-309	HESS	2005	0.165	HESS-Costamante
1ES 1218+304	MAGIC	2005	0.182	MAGIC-Hayashida
1ES 1101-232	HESS	2005	0.186	HESS-Puelhofer
→ 1ES 0347-121	HESS	2007	0.188	HESS-Raue
→ 1ES 1011+496	MAGIC	2007	0.212	MAGIC-Mazin
→ PG 1553+113	HESS/MAGIC	2005	?	MAGIC-Wagner, HESS-Benbow
→ 3C 279	MAGIC	2007	0.536	MAGIC-Teshima

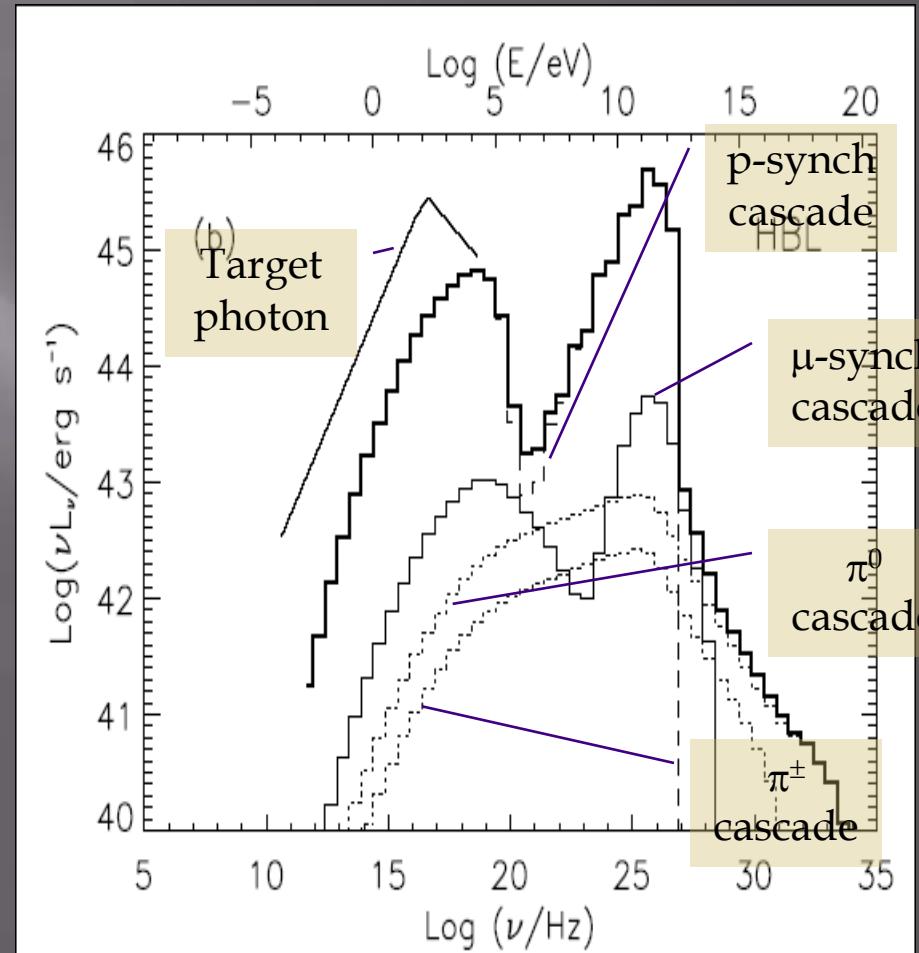
8 new AGN

# 活動銀河核の放射



電子モデル

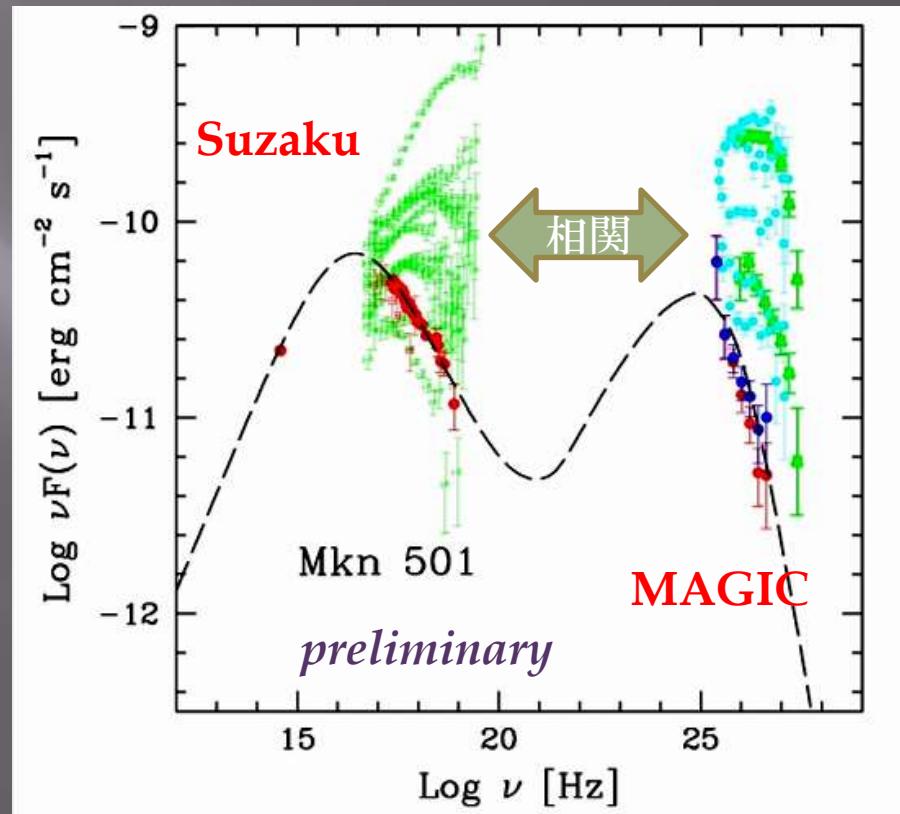
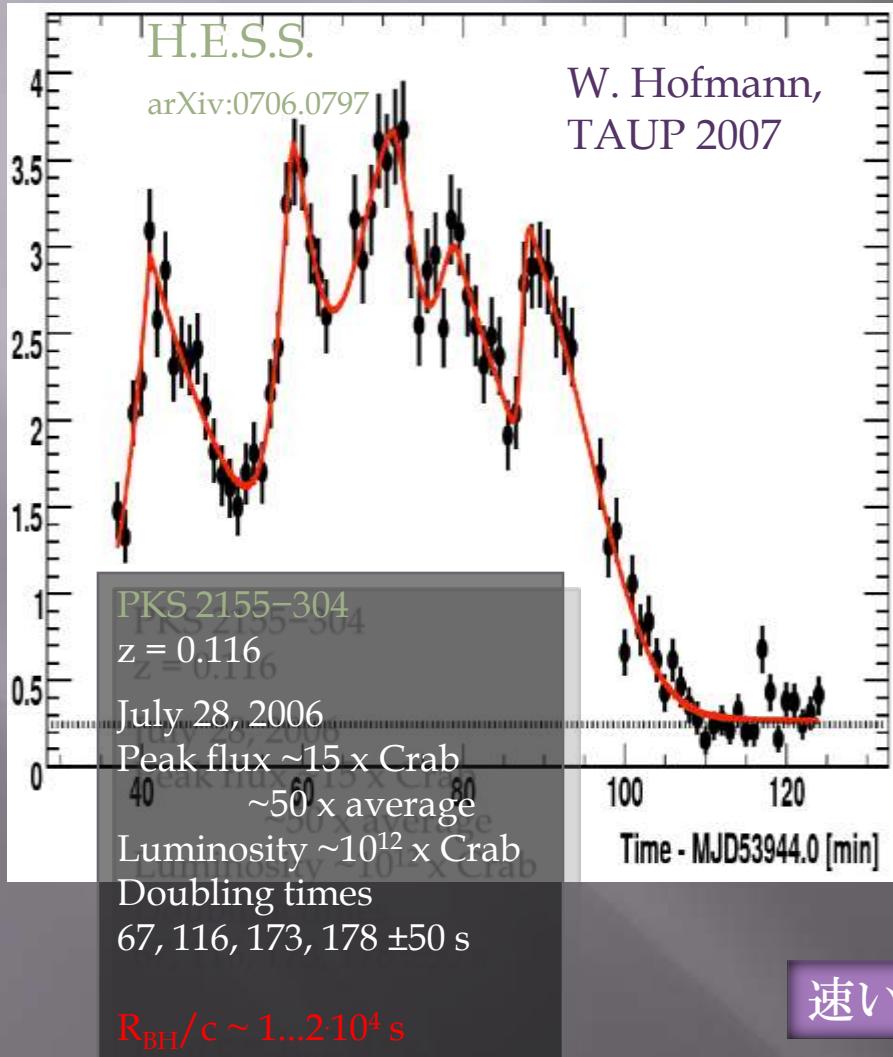
Fossati et al. 1998



陽子モデル

Muecke et al. APh 18, 32 2003

# 活動銀河核の速い時間変動



M. Hayashida, ICRC 2007

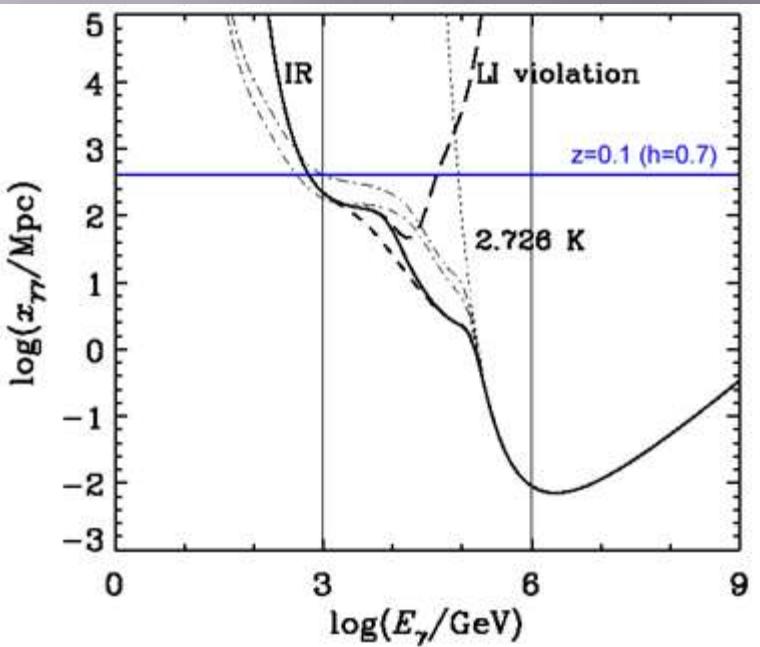
速い時間変動 ⇔ 粒子加速場所と加速機構

# 背景赤外線による吸収

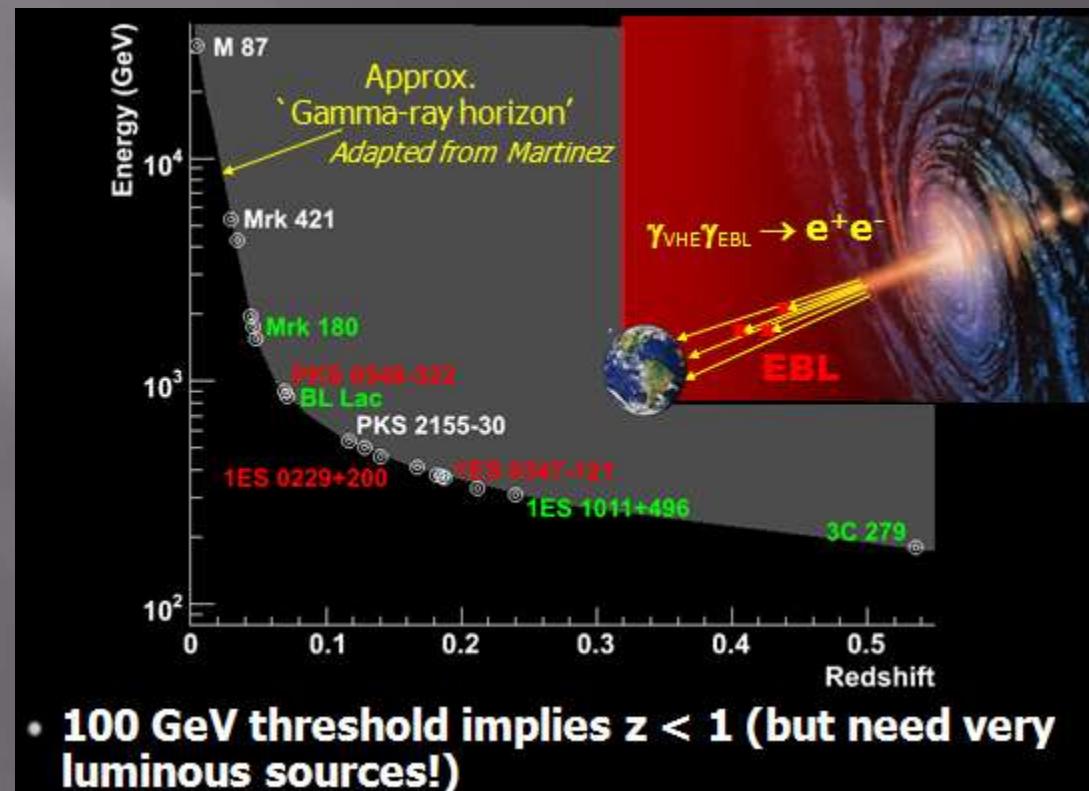
観測されるスペクトルには銀河間空間での伝播効果がかかる！



Mean free path for  $e^+e^-$  pair production



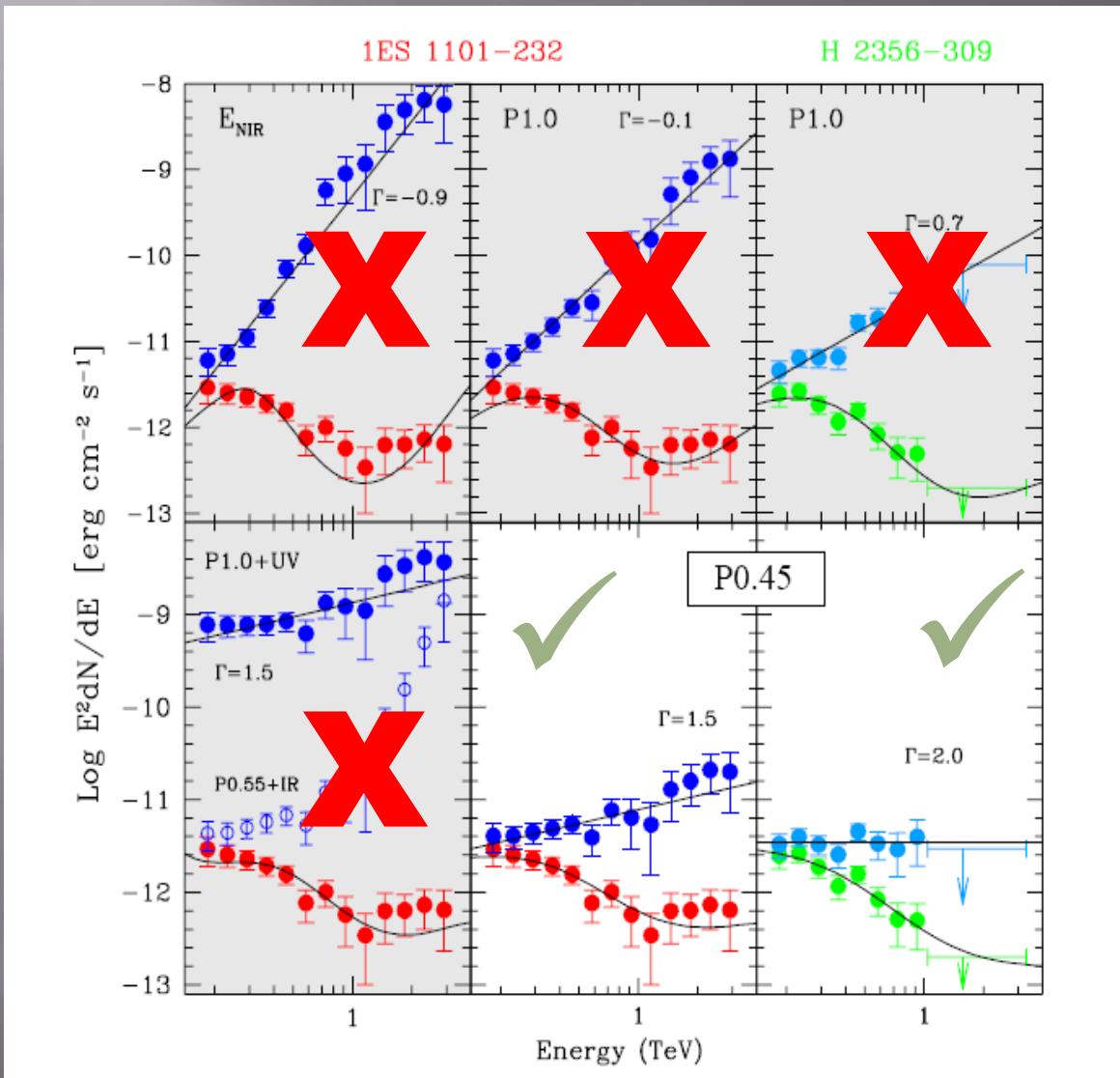
Protheroe & Meyer, Phys.Lett. B493 (2000) 1



Jim Hinton, rapporteur talk, ICRC 2007

源でのスペクトルと吸収の効果を分離できない！

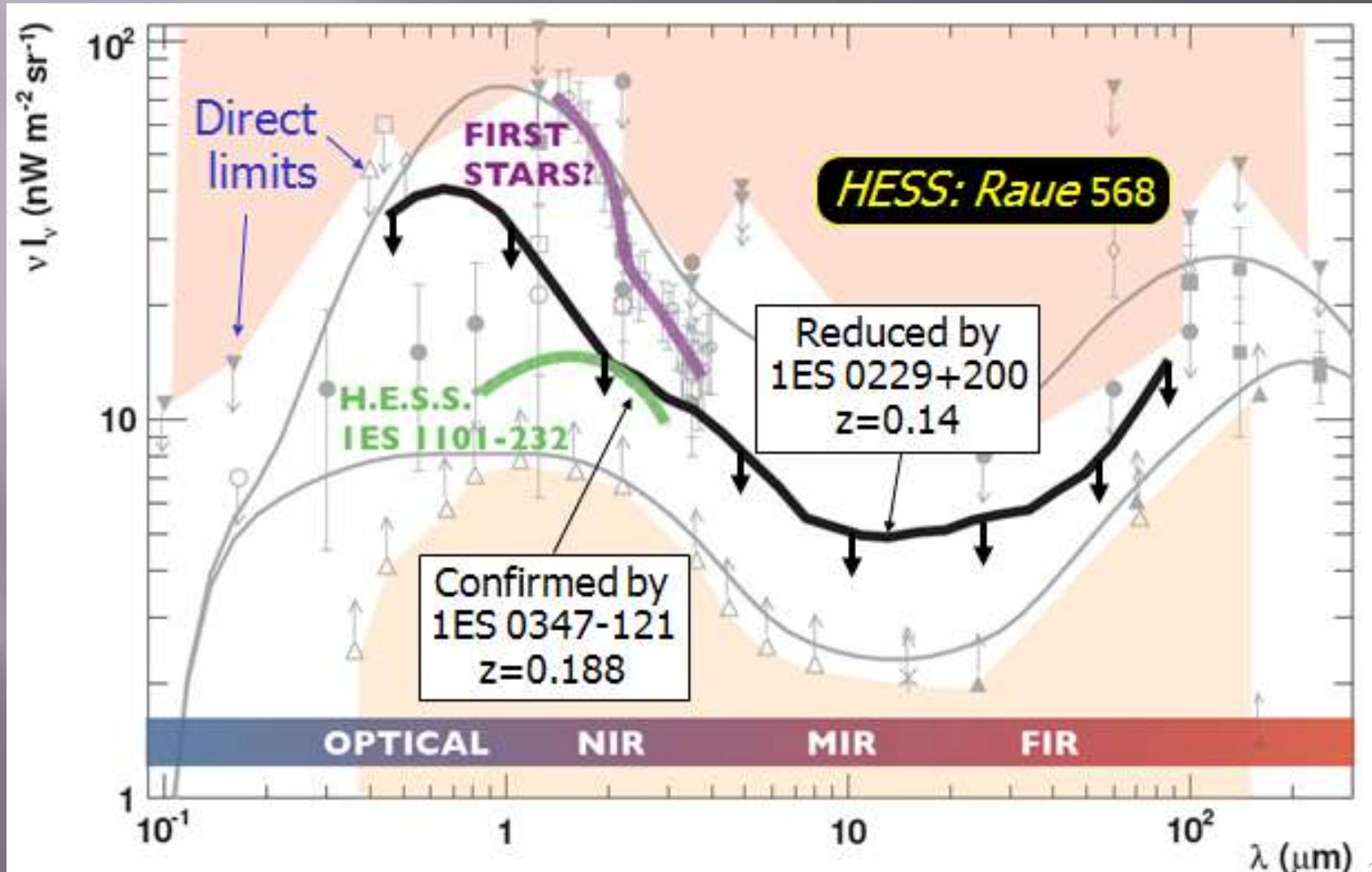
# 吸収前のスペクトルの推定



$E^{1.5}$  より  
ハードでは  
ないと仮定

ある範囲の  
モデルは  
棄却

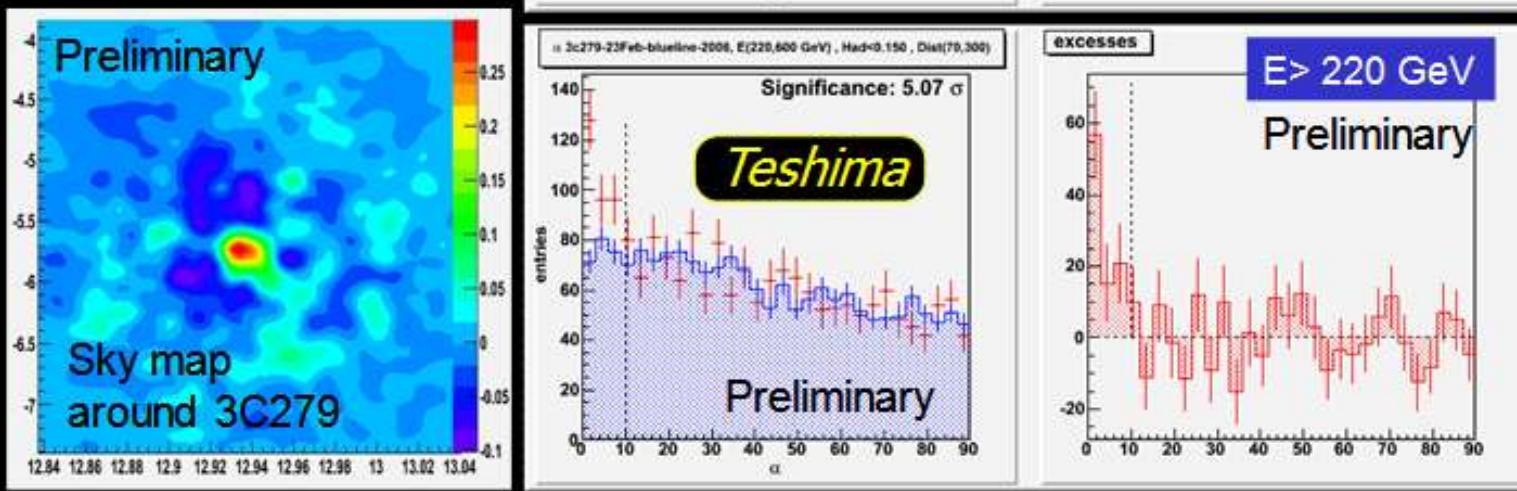
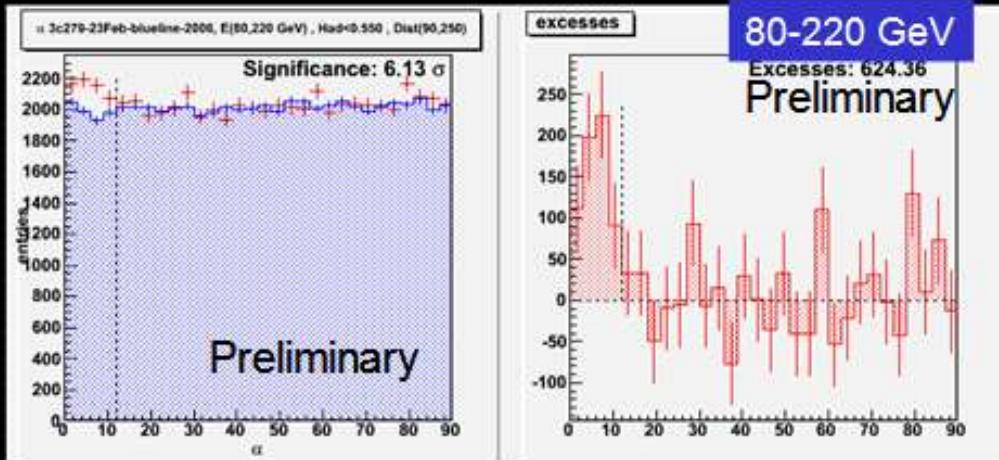
# TeV観測による背景赤外放射の制限



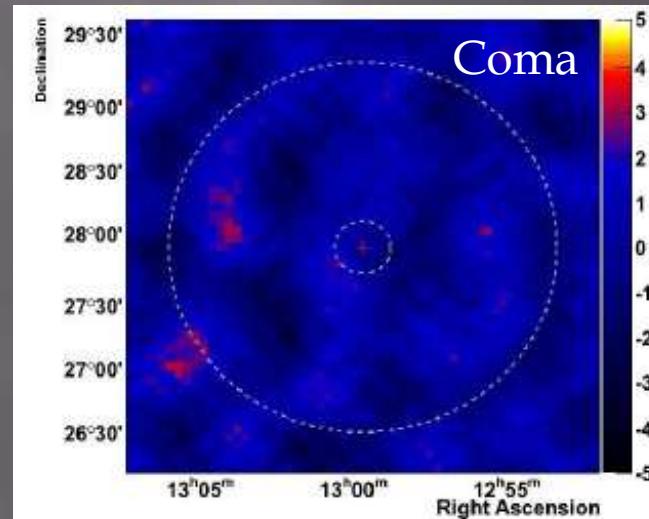
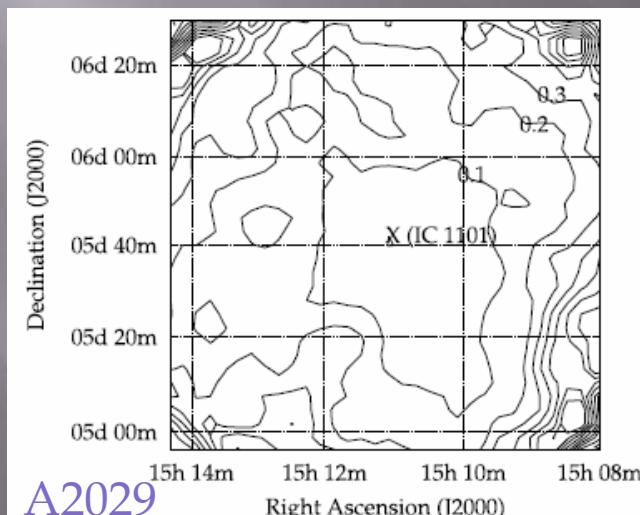
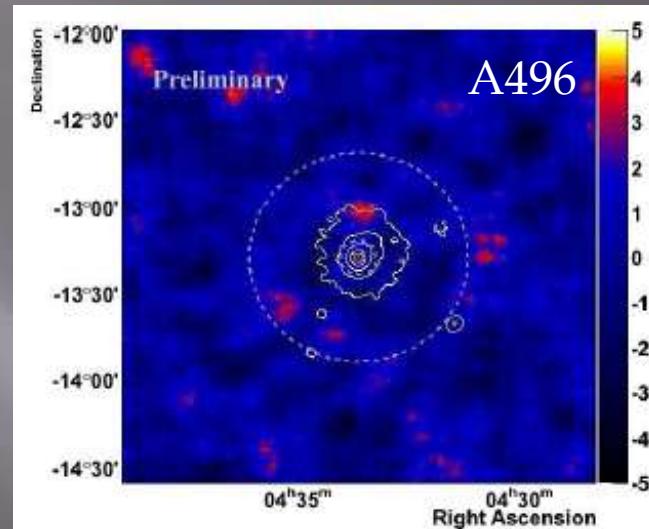
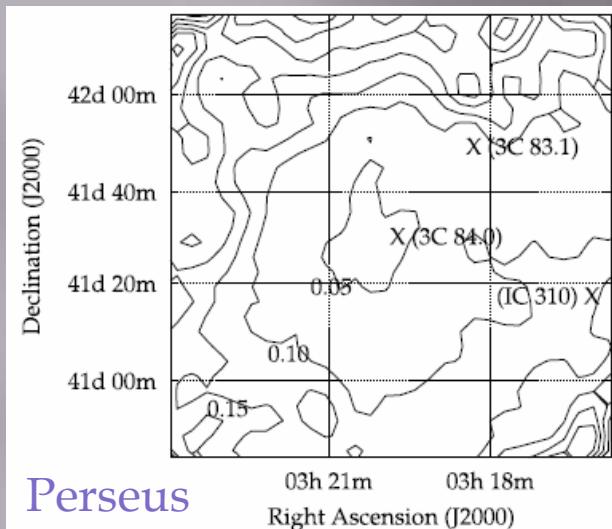
# 3C279 at $z=0.538$

**3C 279: One night, 23<sup>rd</sup> Feb 2006**

- **6.1  $\sigma$  in low Energy band**
  - Post-trails?
- **5.1  $\sigma$   $>220$  GeV**
  - Surprising!



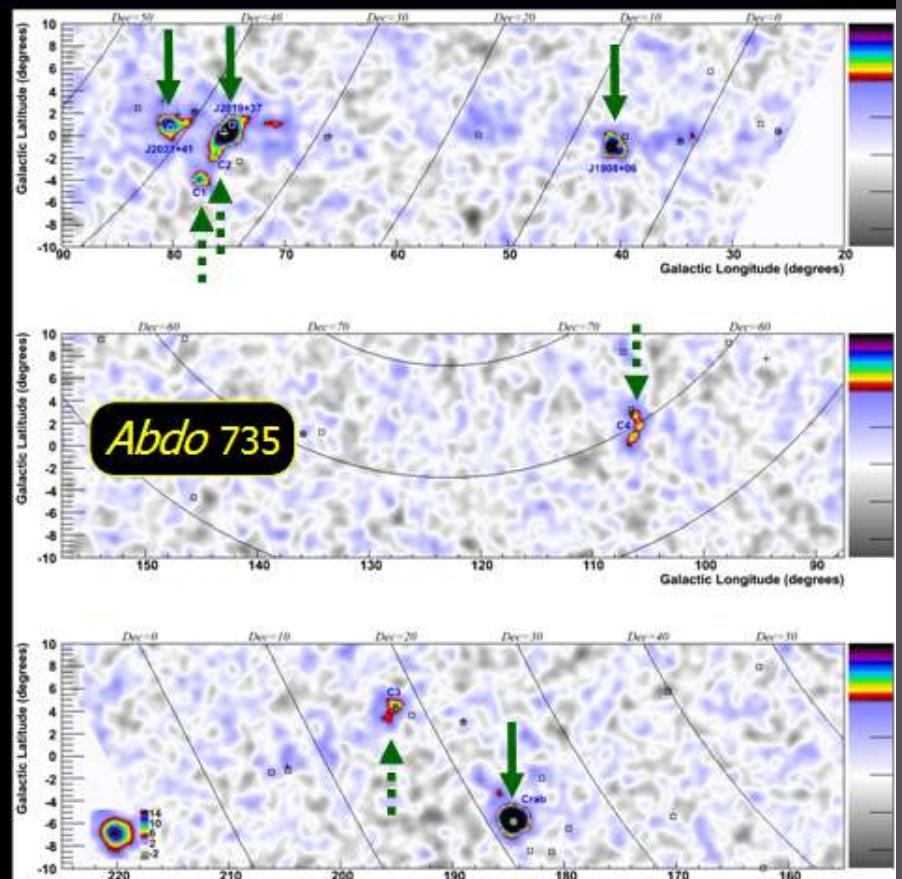
# 銀河団：上限値のみ



# 地上粒子検出器

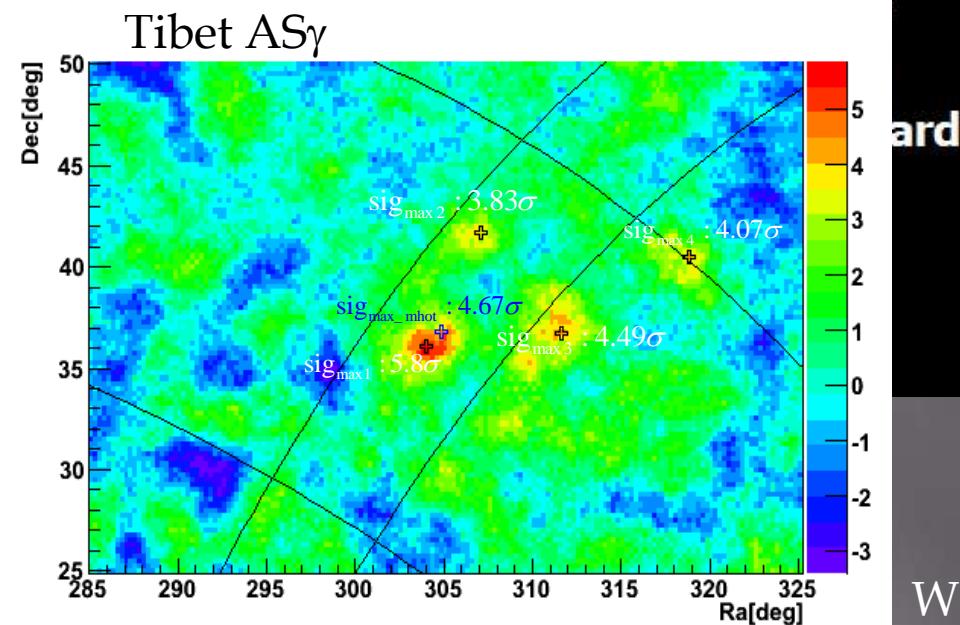
## Milagro Sources and Candidates

- 7 year map
- $\gamma$ /hadron cut raises median energy to 20 TeV
- 3 new sources significant post trials



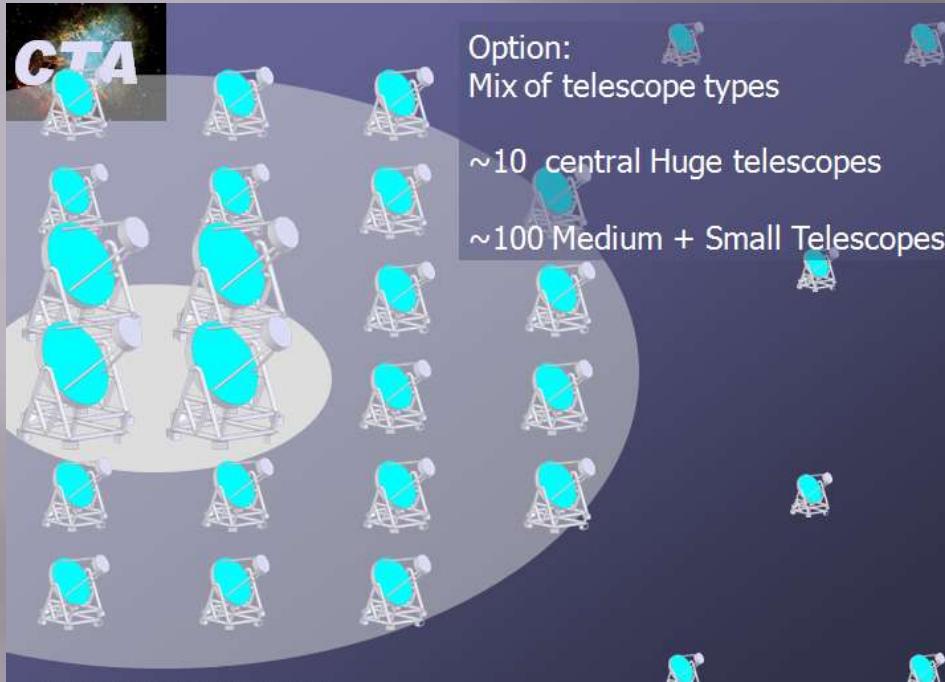
Abdo, ICRC 2007

Wang, ICRC 2007



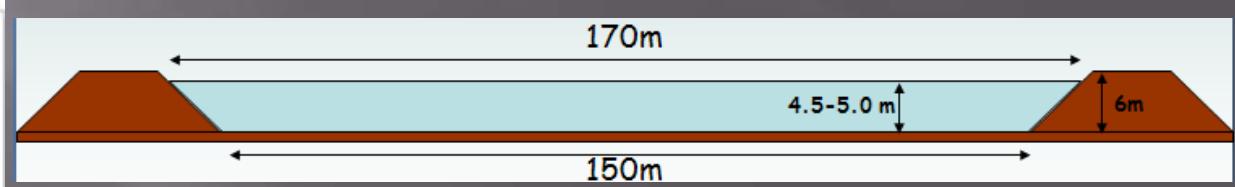
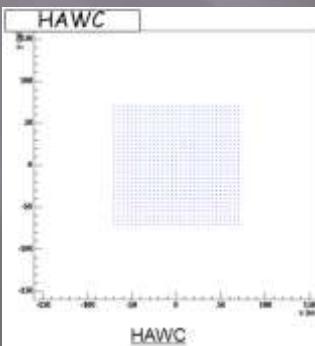
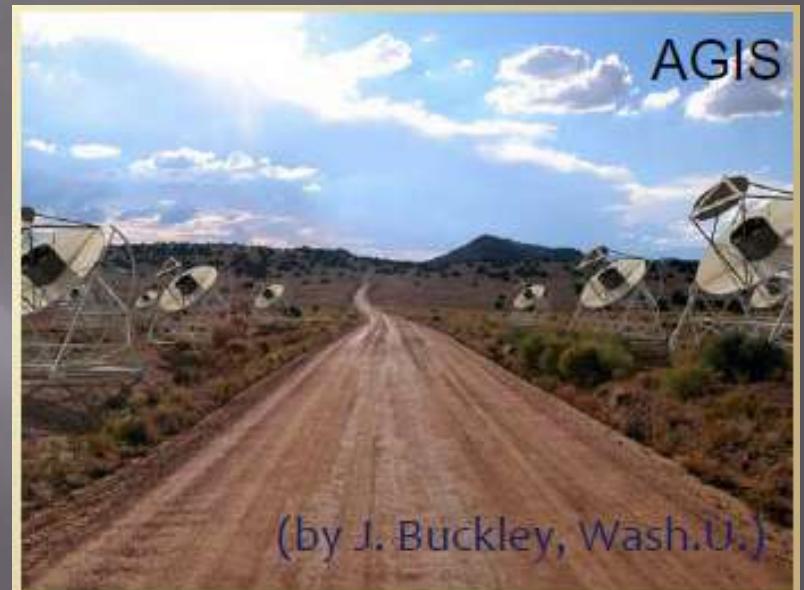
# 将来計画

CTA (Cherenkov Telescope Array): EU++



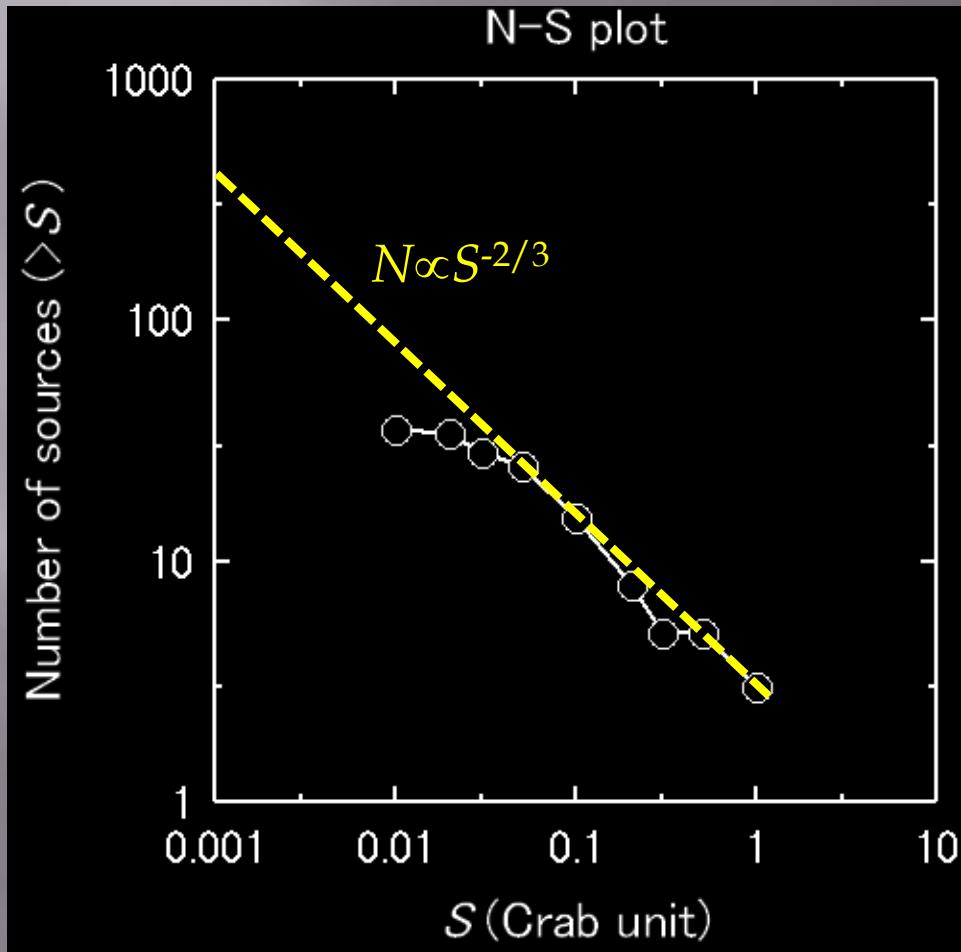
Picture: Courtesy of W.Hofmann

AGIS (Advanced Gamma-ray Imaging System): USA++



HAWC (High Altitude Water Cherenkov): USA

# Summaryに代えて：log N-log S関係



$\times 2$  (北+南)  
↓  
1000 TeV sources  
if mCrab!

Data: H.E.S.S. catalog