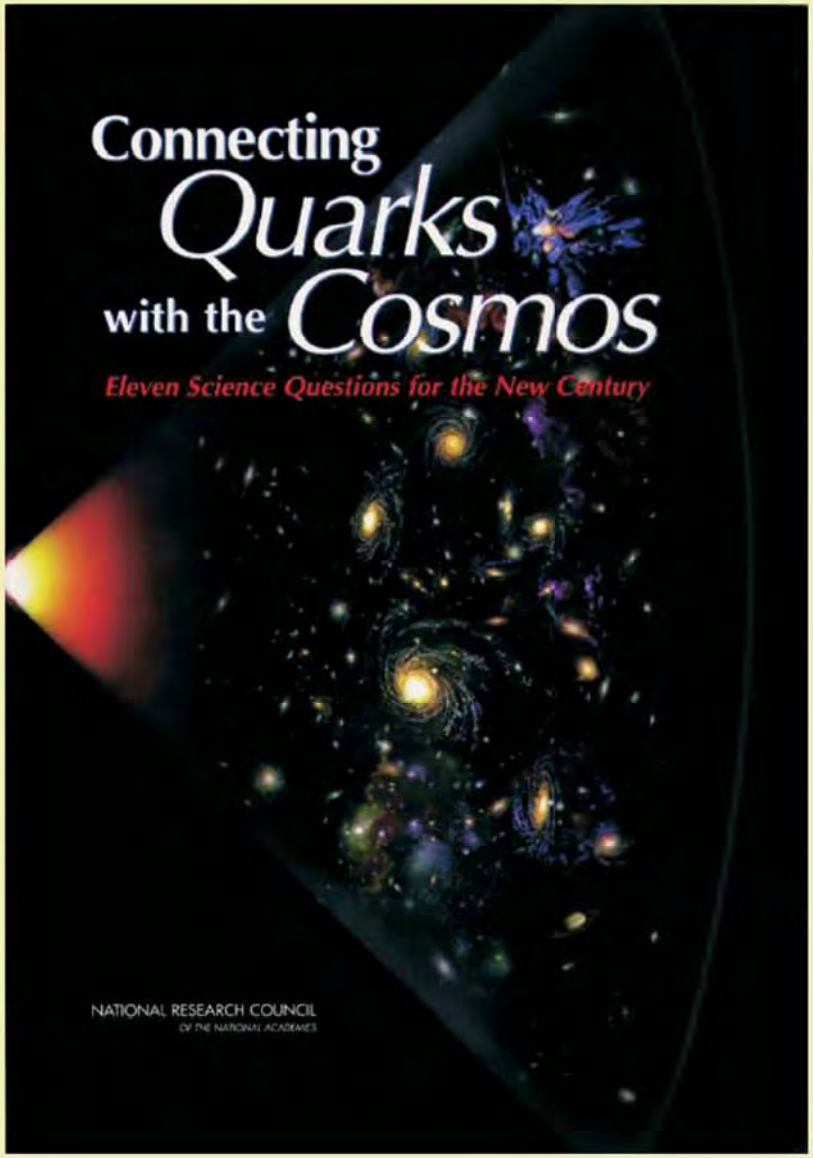
# 宇宙线起源、加速和传播问题的一些新进展

1. 简介
2. 带电宇宙线研究起源和加速
3. 中性伽玛射线研究起源
4. 带电宇宙线各向异性研究传播
5. 宇宙线和宇宙学

# 简介

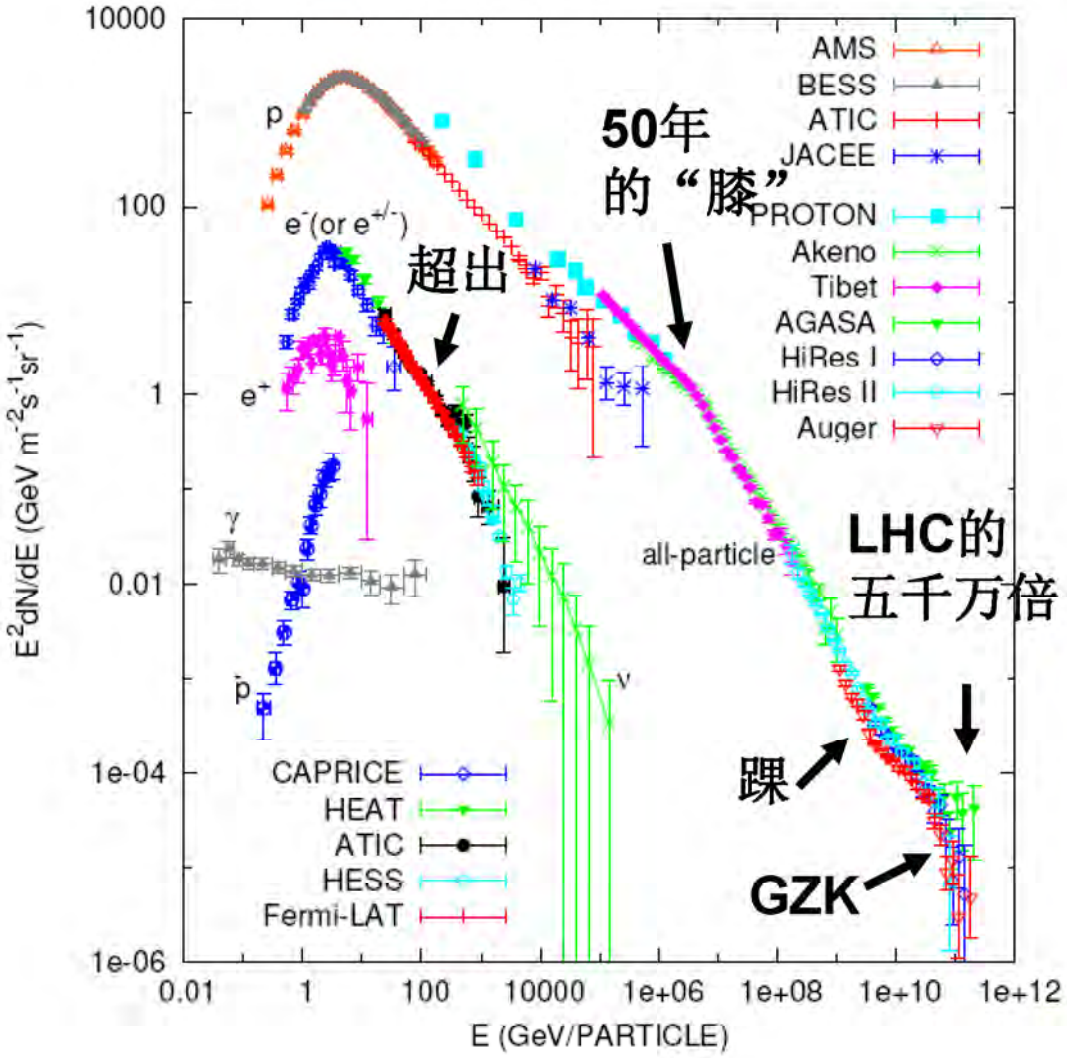
# 2002年美国国家研究委员会确定的研究前沿：
# 《联结夸克和宇宙：新世纪11个科学问题》

The Eleven Questions Identified by the *Connecting Quarks with the Cosmos* Report




1. What is Dark Matter?
2. What is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What are the Masses of the Neutrinos and How Have They Shaped the Evolution of the Universe?
6. How do Cosmic Accelerators Work and What are They Accelerating?
7. Are Protons Unstable?
8. What Are the New States of Matter at Exceedingly High Density and Temperature?
9. Are There Additional Space-Time Dimensions?
10. How Were the Elements from Iron to Uranium Made?
11. Is a New Theory of Light and Matter Needed at the Highest Energies?

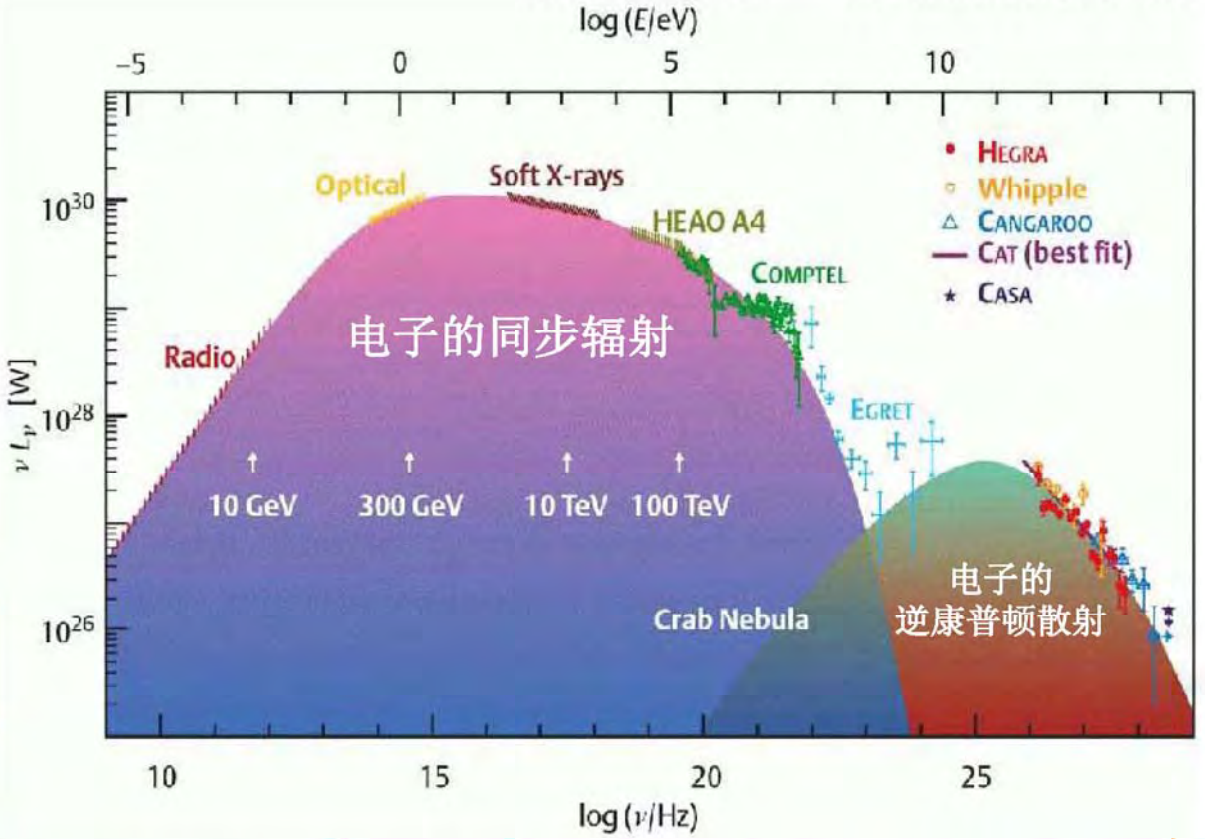
# 宇宙线的成份和能谱

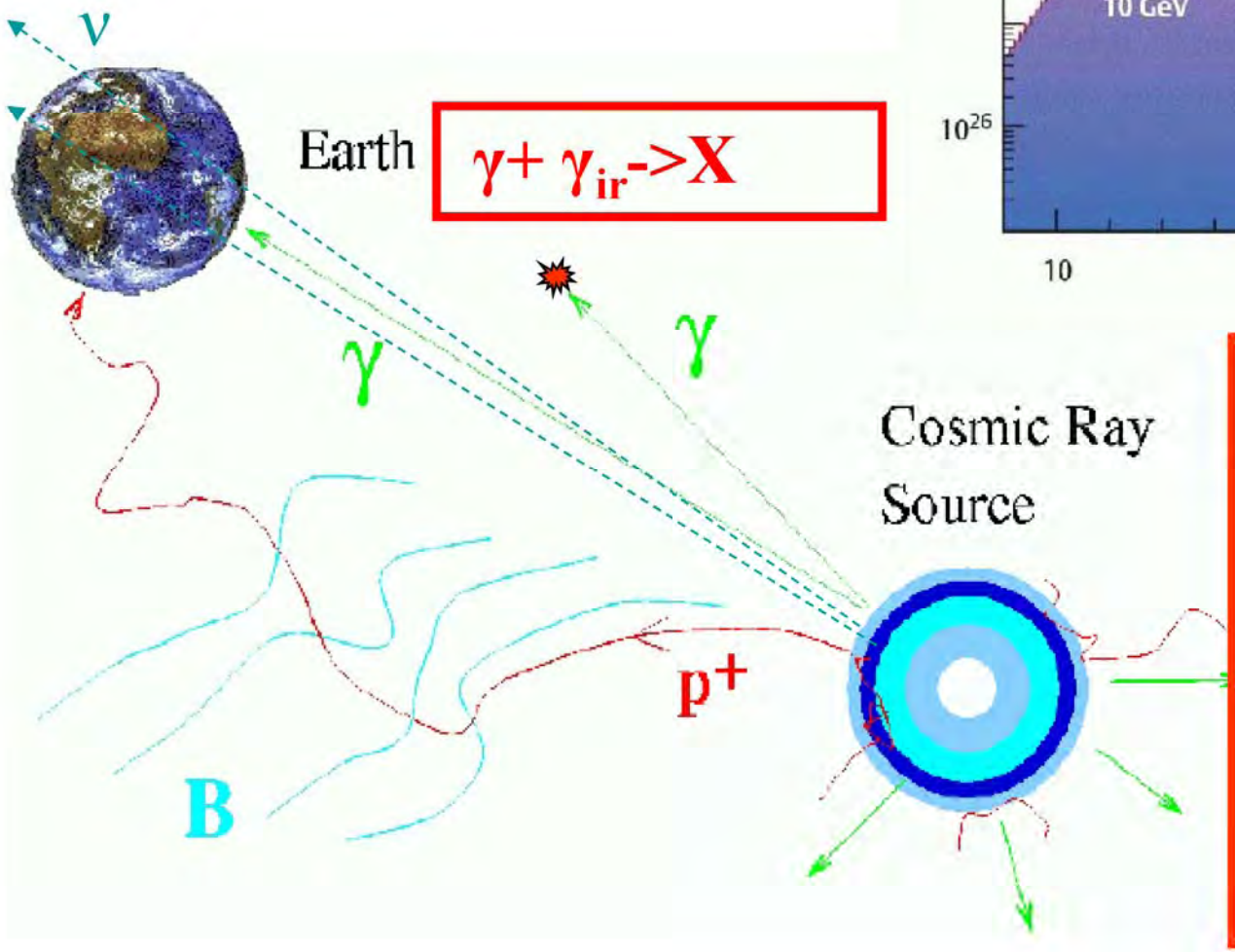



- 宇宙线主要由原子核构成；
- 年龄：$10^7$年；
- 能量密度：1eV/cm$^3$；
- 功率：~$10^{41}$尔格/秒；
- 最高宇宙线粒子的能量达到$3\times10^{20}$eV，约50焦耳。已知物理学基本规律在此能量下是否还成立？
- 宇宙线$e^{\pm}$，©，{对宇宙线起源，加速，对暗物质粒子寻找，对量子引力、天文学和宇宙学研究有重要意义。
- 宇宙线基本上呈幂率谱，~200GeV处谱变硬；4PeV有拐折，被称为“膝”，小于此能量被认为是银河内起源，大于则河外；
- 极高能有“踝”和GZK截断；

“标准烛光”蟹状星云是一个典型的电子源

# 宇宙线的起源，加速和传播




1.标准的起源和加速理论：剧烈天体演化所产生的激波；

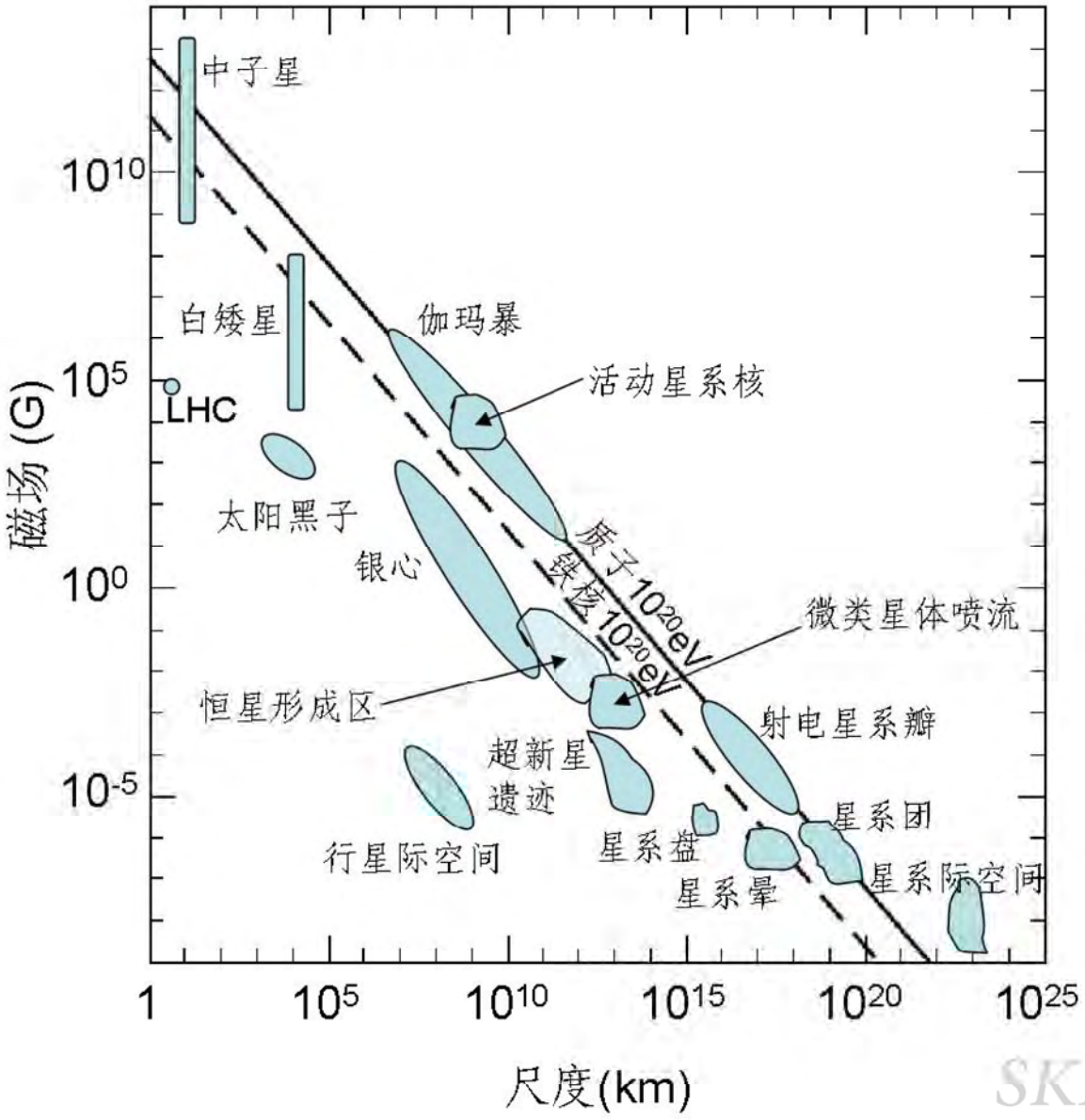
1.正在加速的源以观测γ最为有效，迄今成百上千个γ源都是电子源，核子源没找到。极高能和中微子天文；

2.古老源（>百万年）需要观测宇宙线自身（遗迹）；

2.传播：各向异性等研究。

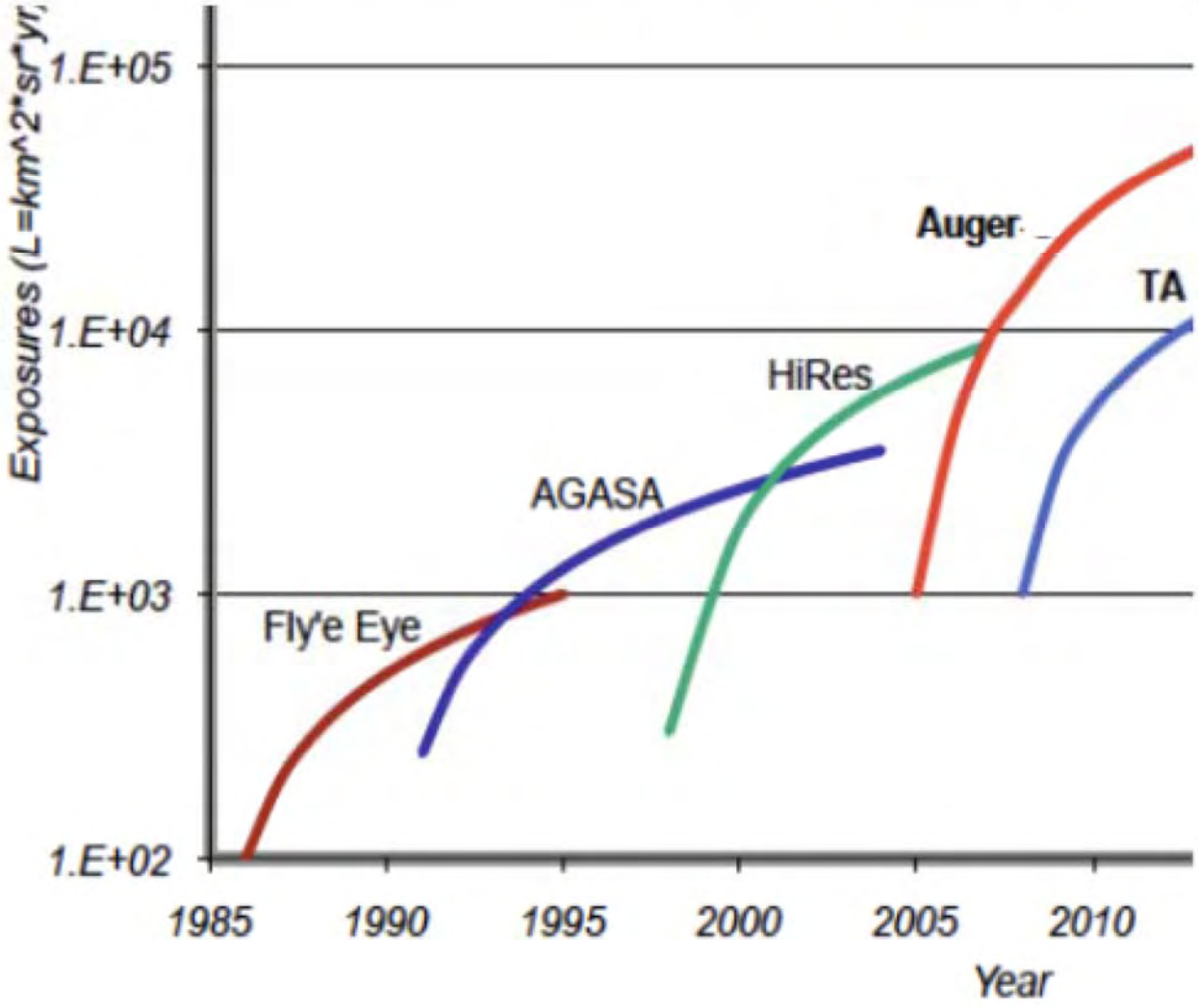
# Hillas图:$E_{max}$~β• z •B • L

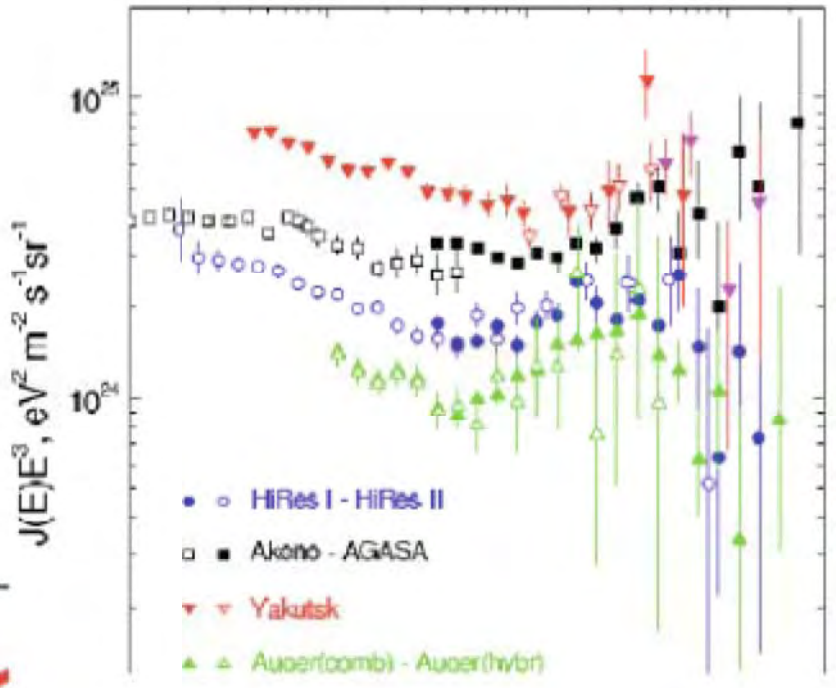
- 河内(<10**18eV)
  - 超新星遗迹;
  - 脉冲星;
  - 恒星风;
  - 微类星体;
  - OB星协;
  - 银心;
- 河外(>10**18eV)
  - 活动星系核;
  - GRB;

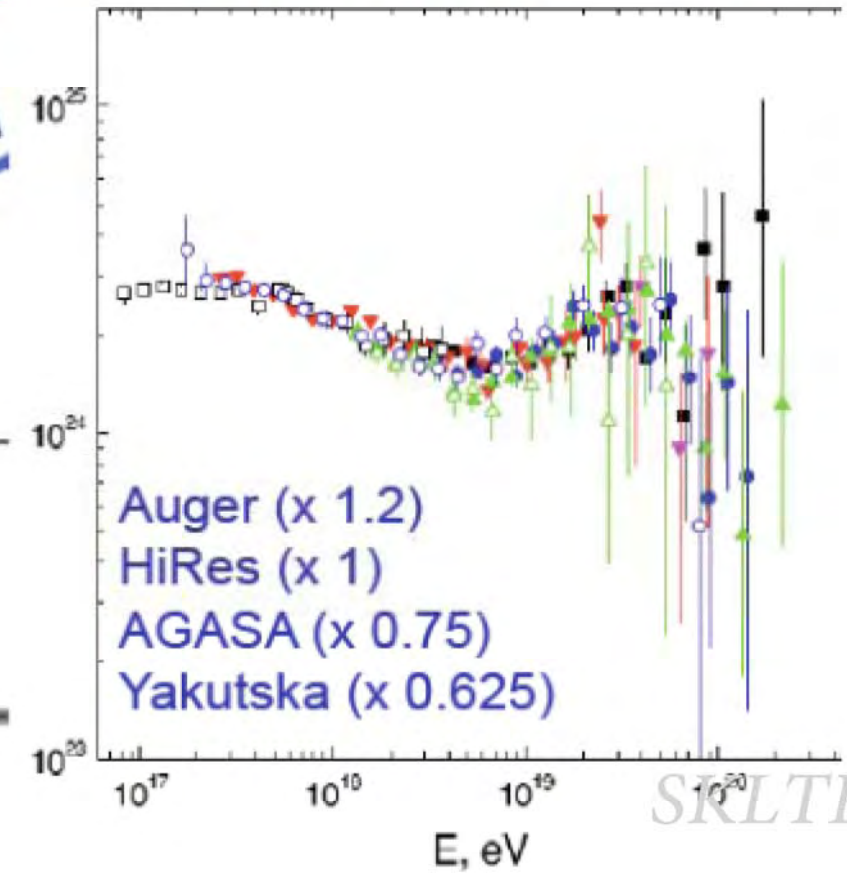


# 带电宇宙线研究起源和加速

# Last Century's question: GZK or No GZK? Observed Spectra are Consistent with GZK effect



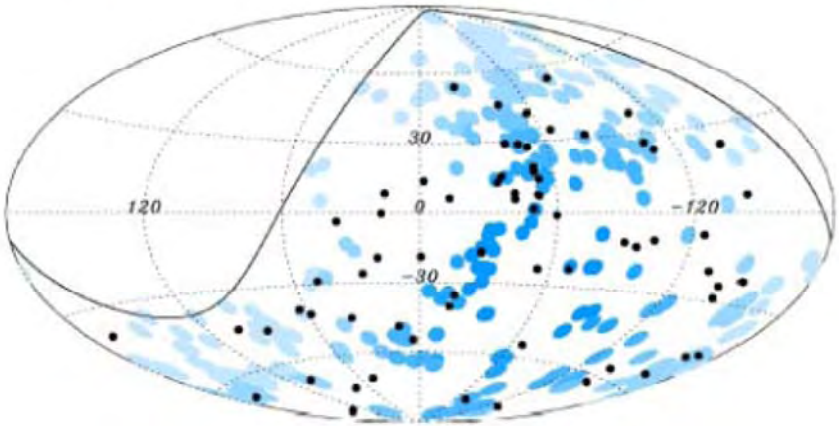



# UHE Correlation with AGNs within GZK-sphere?

Within ~75Mpc

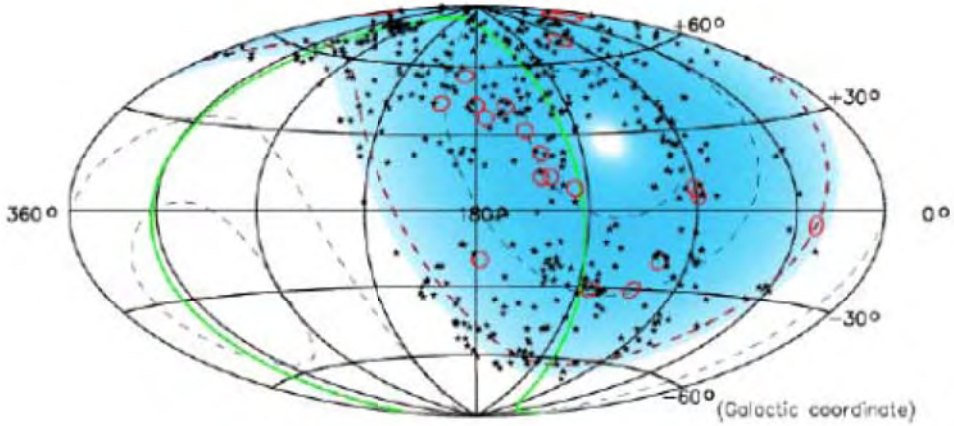
VCV catalogue, E> 57 EeV, z<0.018, distance < 3.1 deg.

**Auger**




28 out of 84 correlate

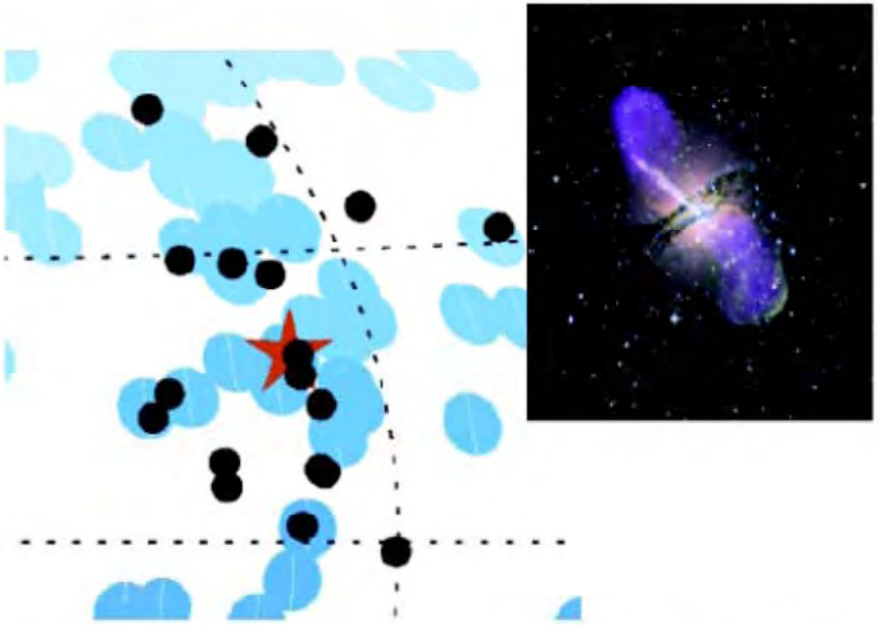
**TA**

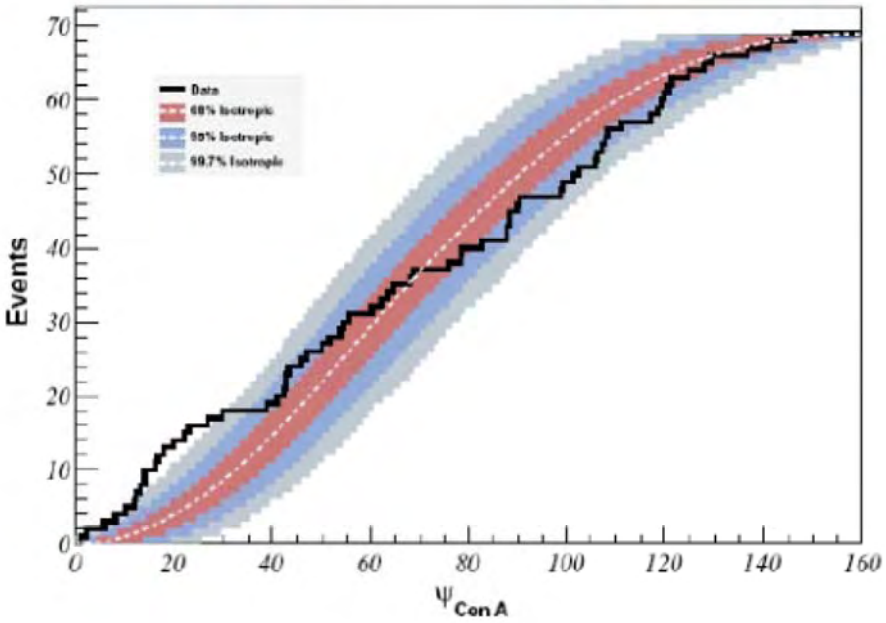



8 out of 20 correlate

**2007年：AUGER发表文章称27个最高能事例中关联的有19个，而预期的仅5个。**
**2011年：与各向同性的预期逐渐接近。**

# UHERs from CenA?





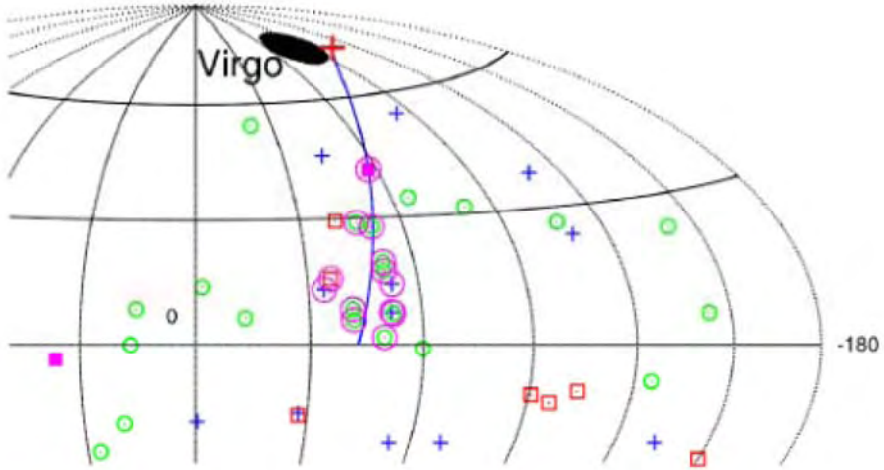

Nearest radio loud (~4Mpc) AGN

13/62 within 18 deg., expect 3.2

limits on source composition?

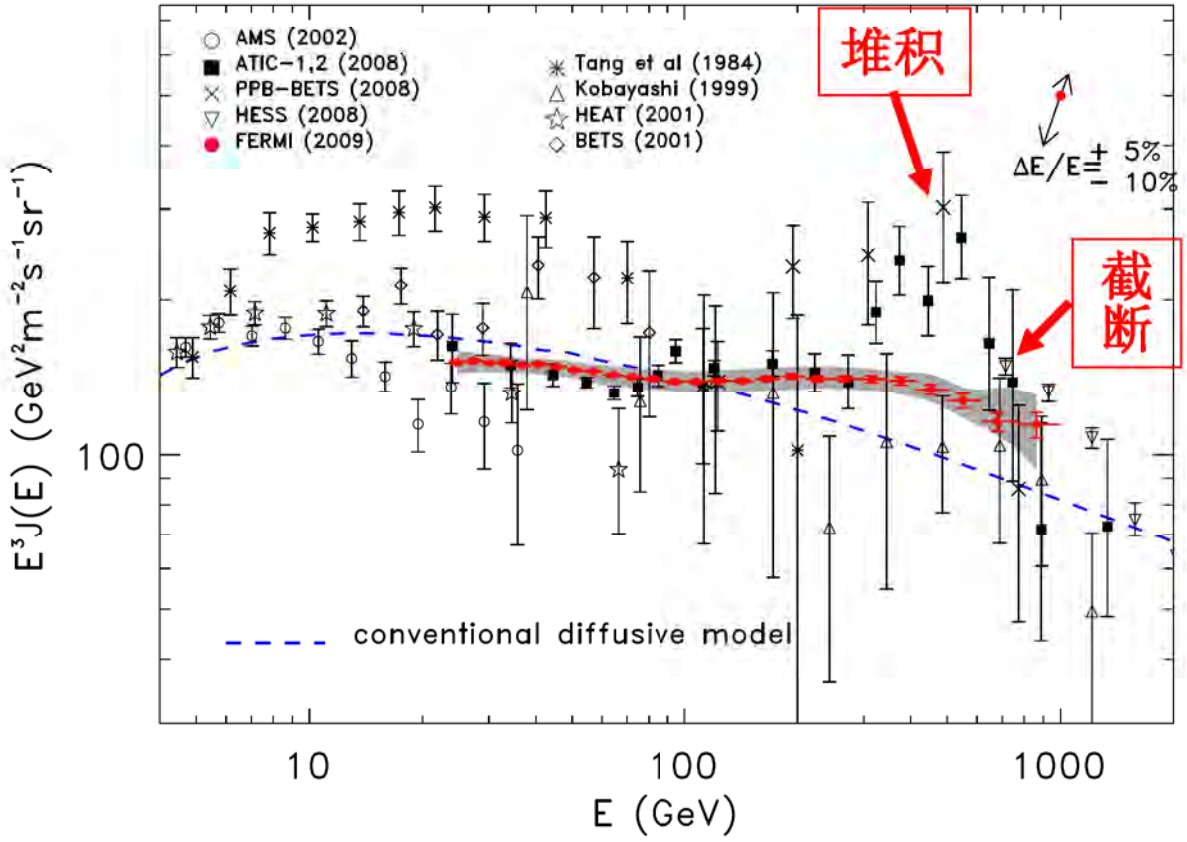
E.M. Santos [Auger Coll.], icrc868

... or Virgo? Nearest (~20Mpc) Cluster




Giacinti&Semikoz, icrc171

# ATIC/HESS/FERMI实验观测到的正负电子的超出

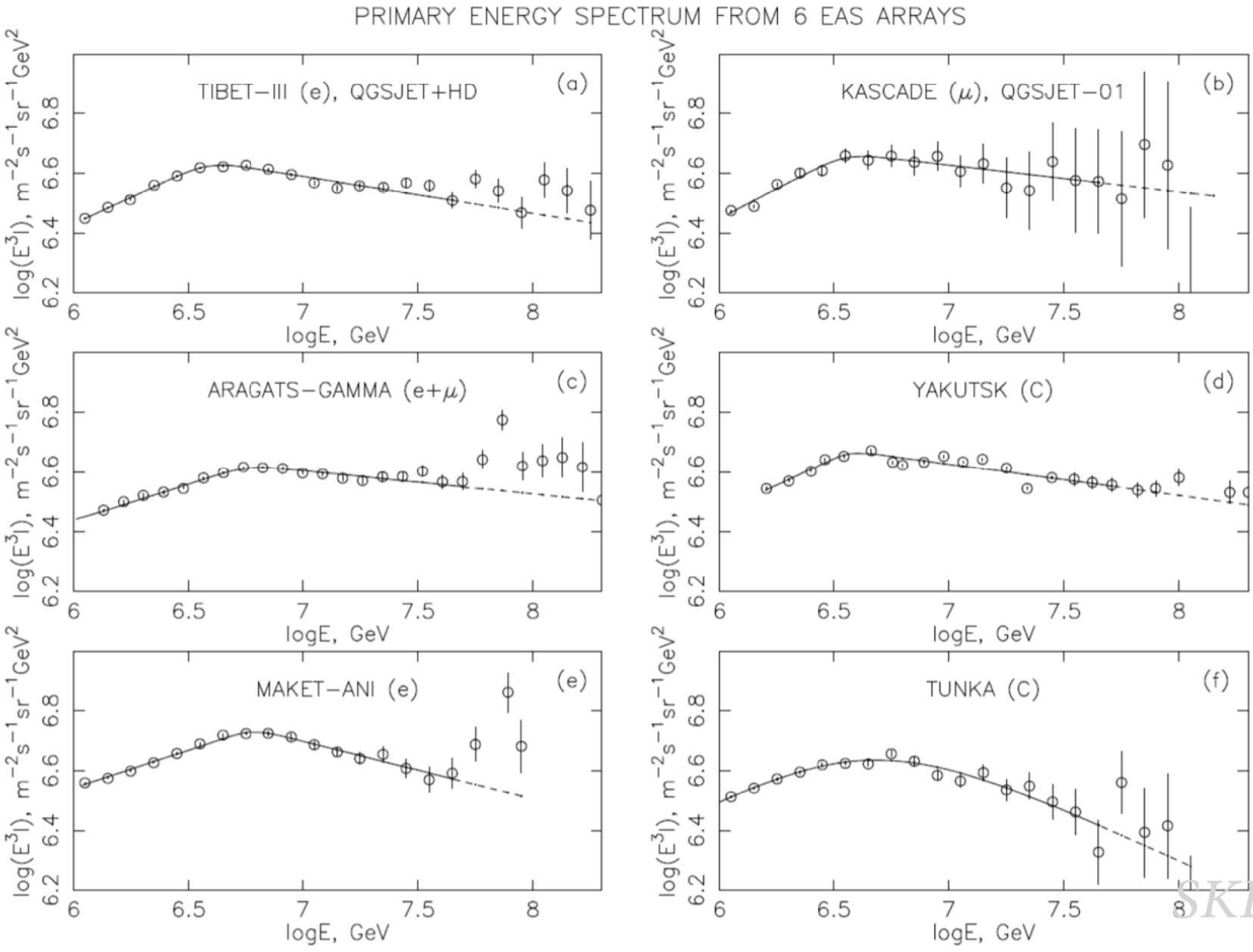



- **ATIC 等观测到的超出可能来自暗物质粒子的湮灭或衰变,但也有可能来自天体过程,携带宇宙线源的信息.**

- 这些超出在有明显的堆积和截断的特点,和具有阈能的反应的特点相符;

# More recent measurements: sharp knee and irregularity spectrum

Erlykin & Wolfendale, icrc0301



# single source vs the fine CRs spetrum and the electron spectrum

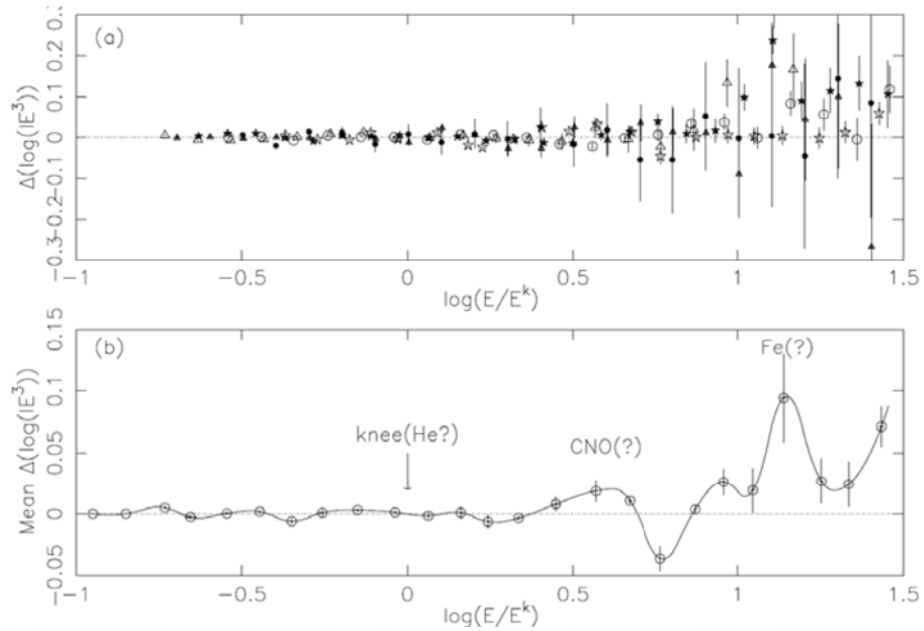
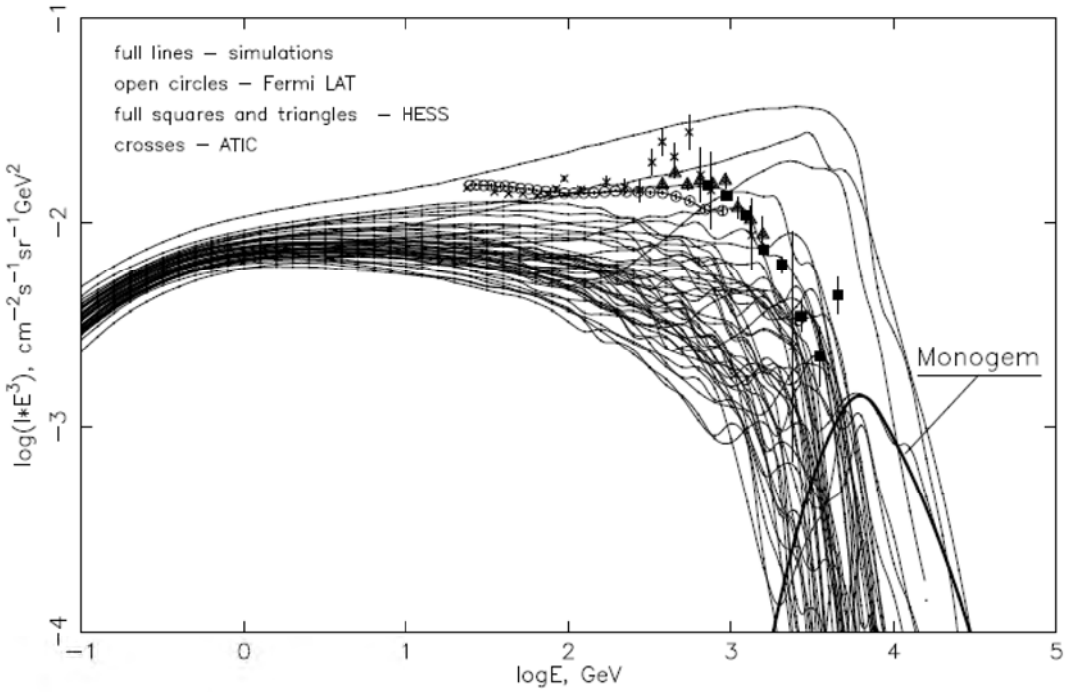


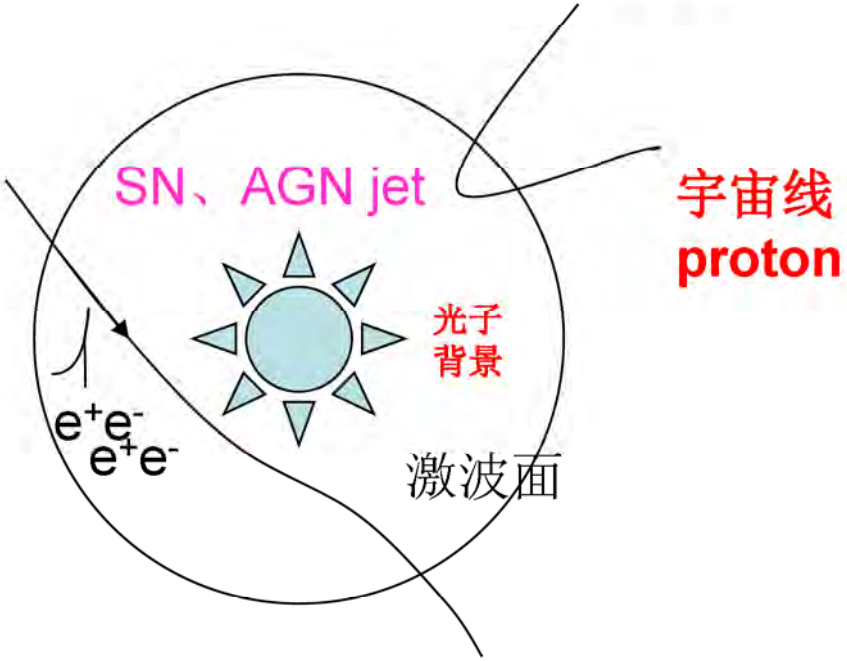

Fig. 2. Fine structure of the PCR energy spectrum. The irregularity at the position of the knee, $log(E/E^k) = 0$, is not seen since the expression (2) gives a good fi t of the spectrum in the knee region.



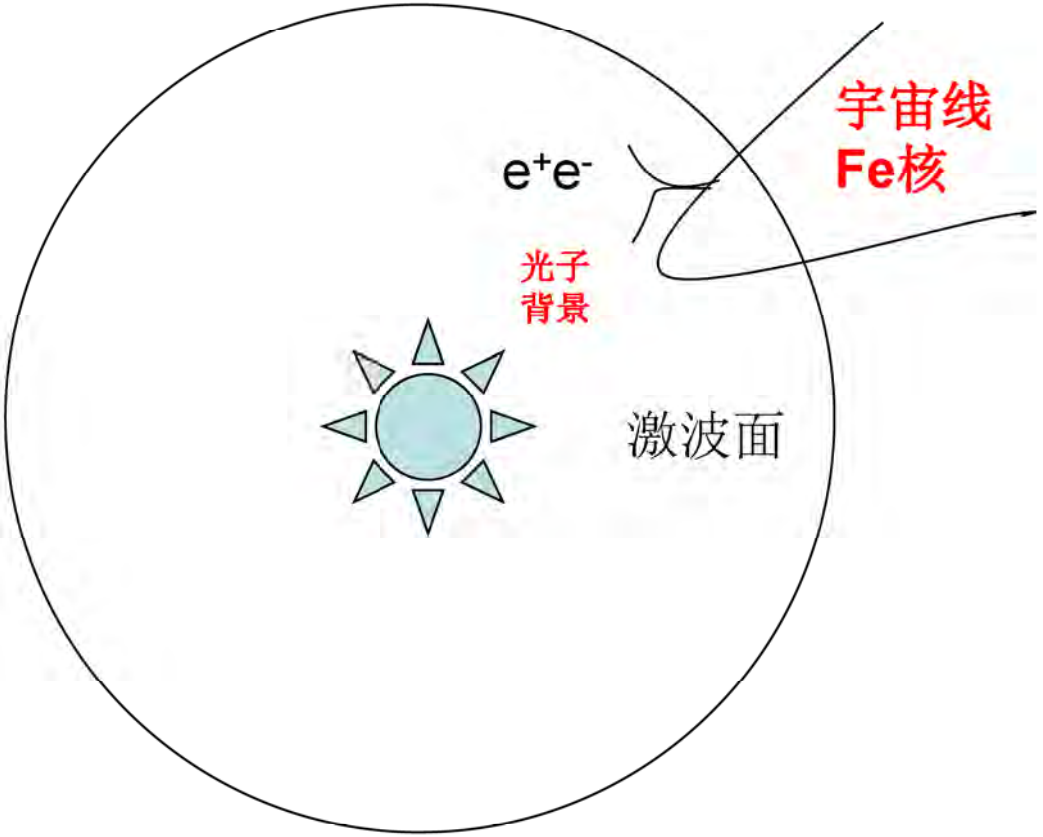

Where is the single source?

# 年轻超新星、银心的喷流等激波加速宇宙线及其和背景光子的反应

1) 在加速的早期，背景光子场的温度较高，光子能量和密度都较高，被加速的质子最先达到反应所需要的能量。产生正负电子对，质子能谱的“膝”开始形成；




2) 稍晚些时候，背景场温度下降，光子能量和密度都下降，这时重元素也被加速到需要的能量，重核的“膝”稍高；




3) 所产生的正负电子也会通过辐射及和背景光子相互作用损失能量，只有TeV以下能量的电子有较大的机会跑出来被观测到。

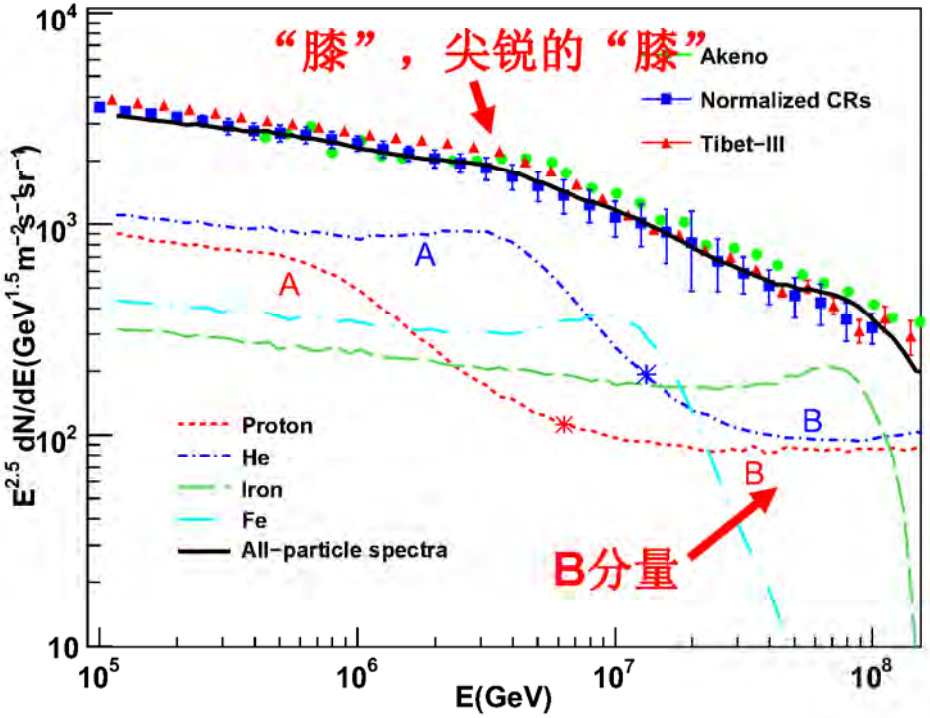
# “膝”、尖锐“膝”、B分量、能谱精细结构

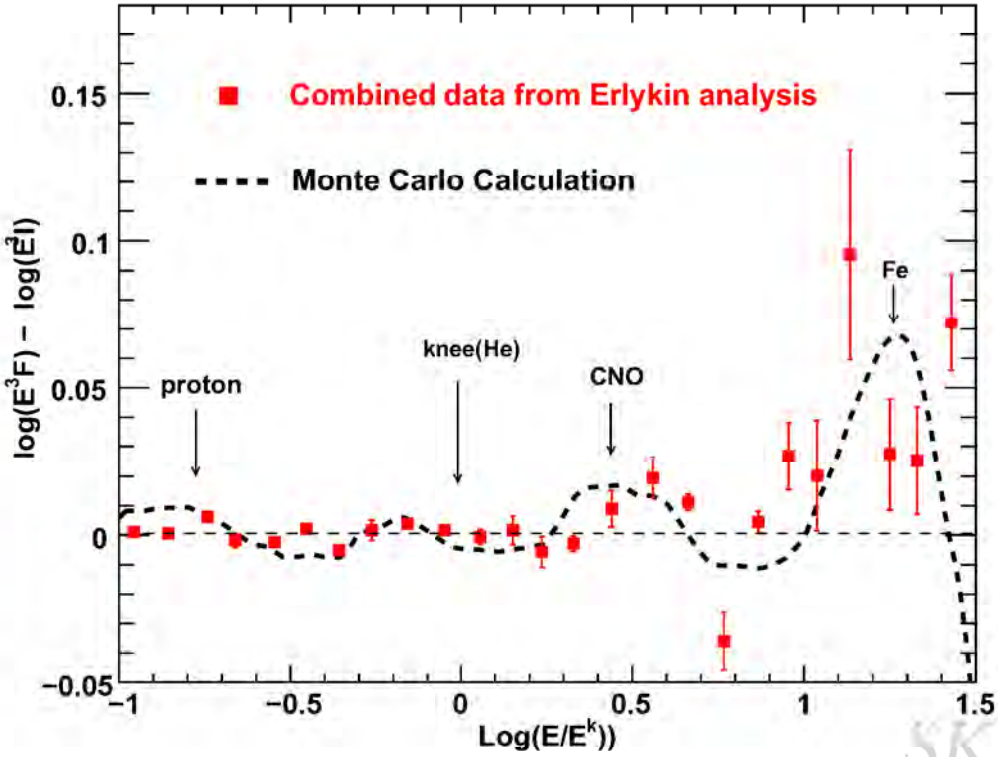
1.Hu et al., ApJ 700:L170–L173, 2009

2.B.Wang et al,Sci. China G53:842-847,2010

堆积效应自然的解释“膝”，尖锐的“膝”；
截面随能量的变化自然解释宇宙线的B分量；
反过来，这将作为模型的预言有待检验！

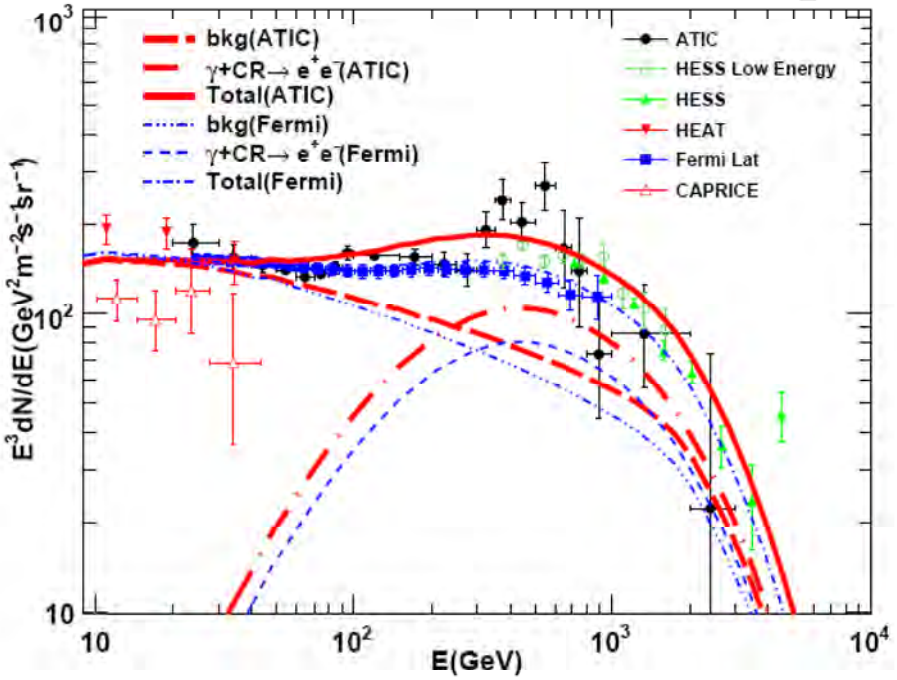
可以解释“膝”附近能谱的精细结构

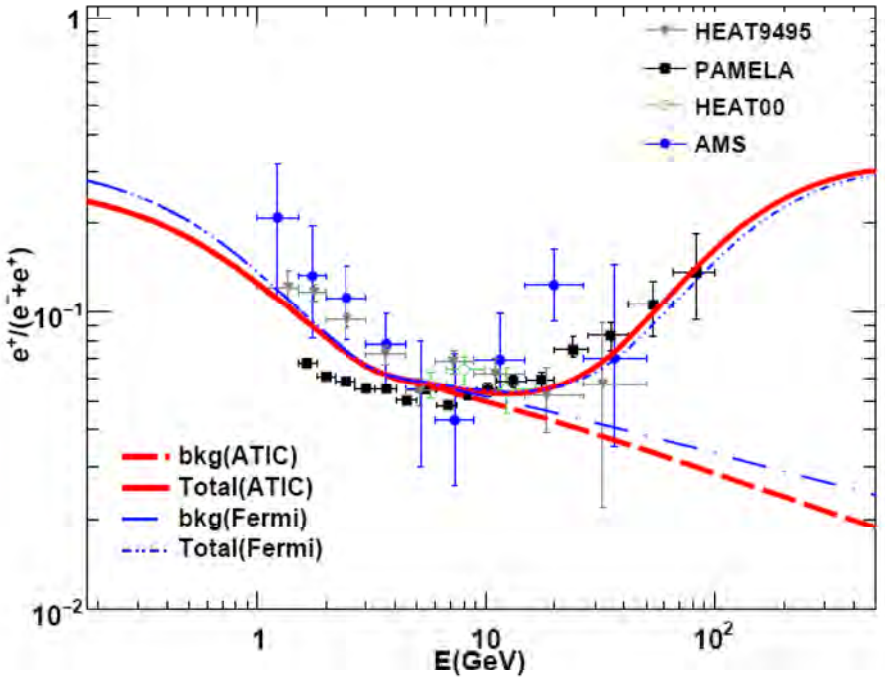


# 很好解释正负电子的超出

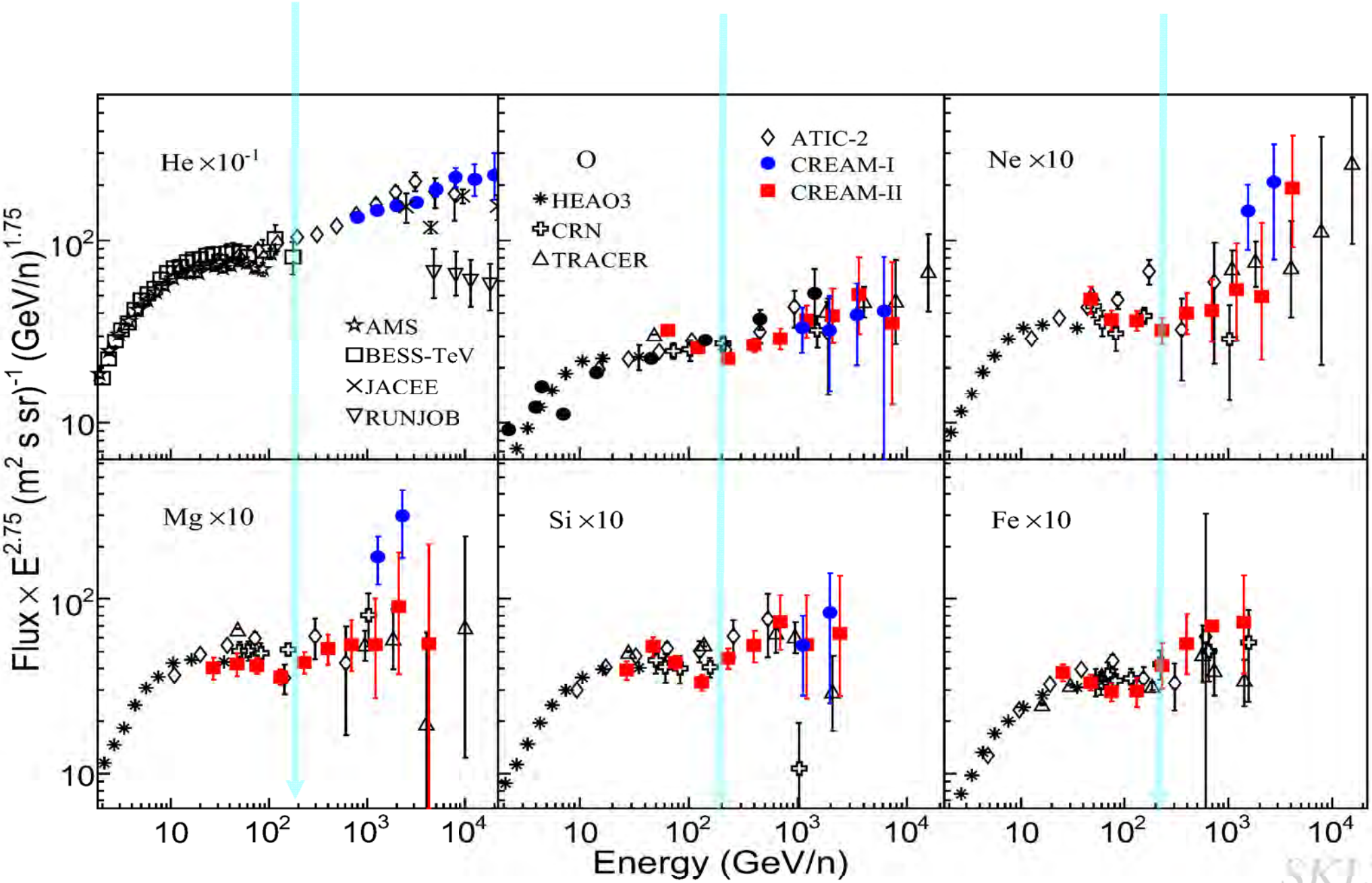
Hu et al., ApJ 700:L170–L173, 2009



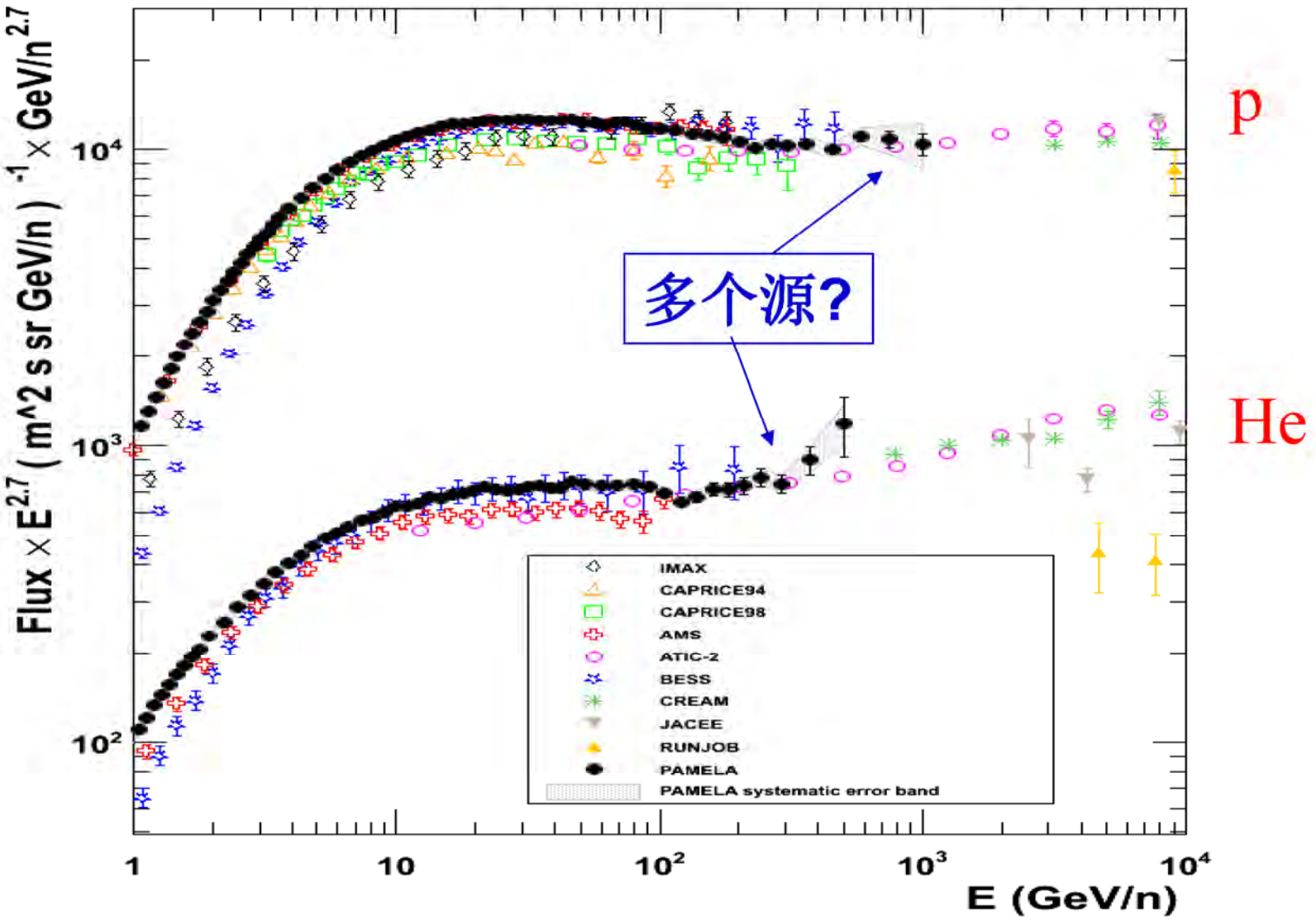




模型仅需要一组参数，单一加速源（近出的某个？银心？）

# Discrepant hardening



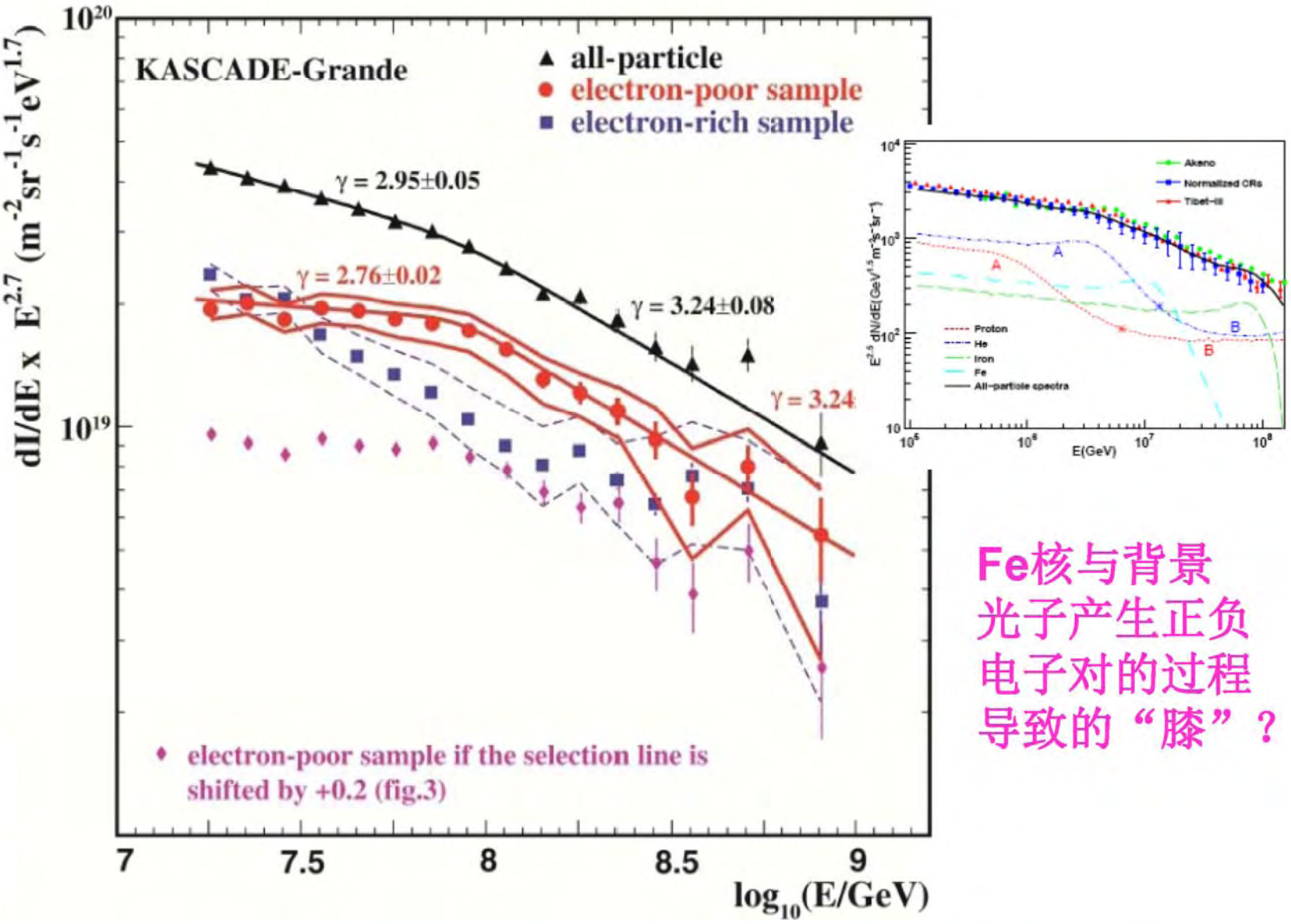
# Proton and Helium fluxes




Science 332,69 (2011)

SKLTP

# Evidence for a 'heavy knee' by KASCADE-Grande




Fe核与背景光子产生正负电子对的过程导致的“膝”？

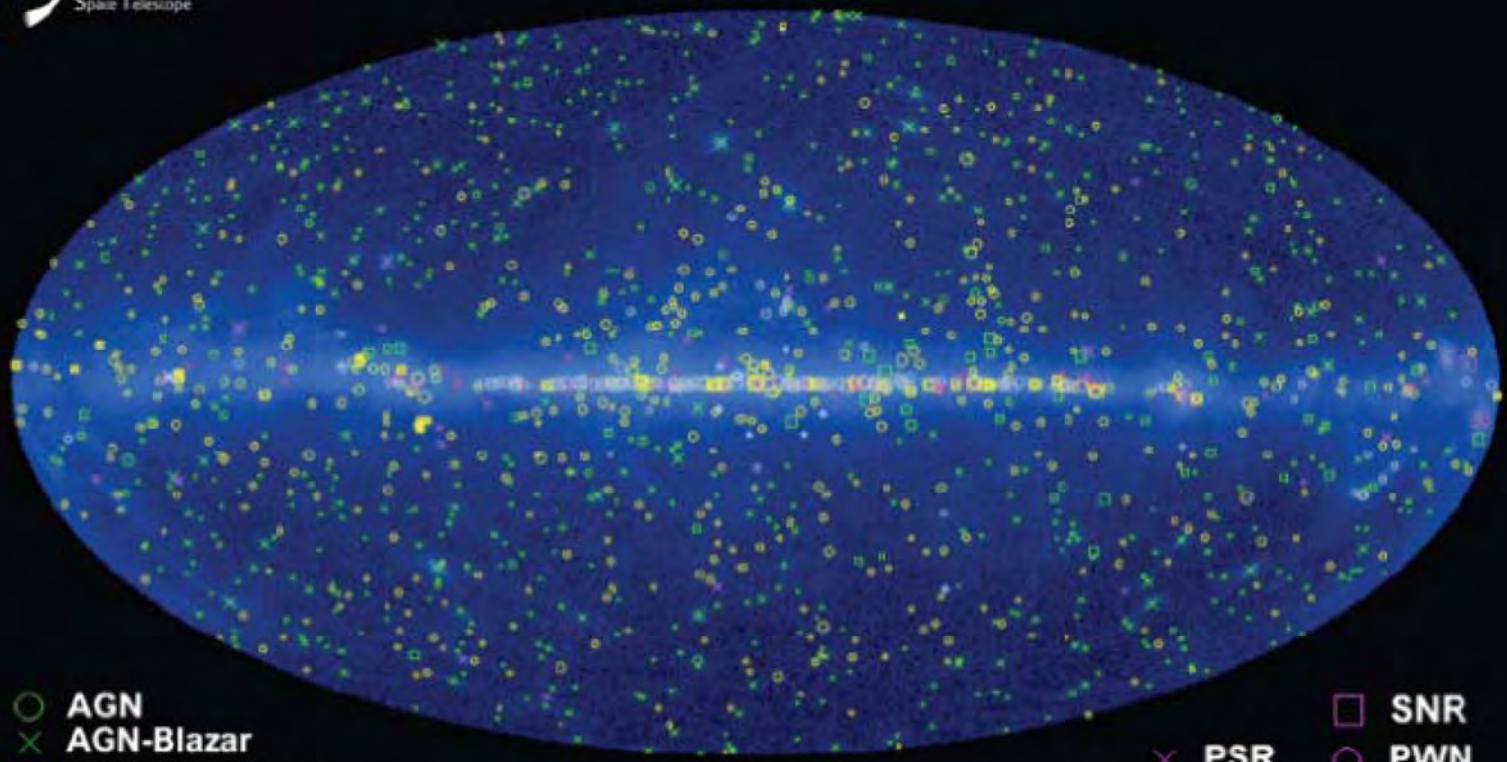
A. Haungs [KASCADE-Grande Coll.], icrc677

# 中性伽玛射线研究起源

*Fermi LAT*: good sensitivity, reasonable angular resolution, large FoV
thousand of sources - diffuse structures - monitoring transient GeV phenomena


Fermi
Gamma-ray
Space Telescope

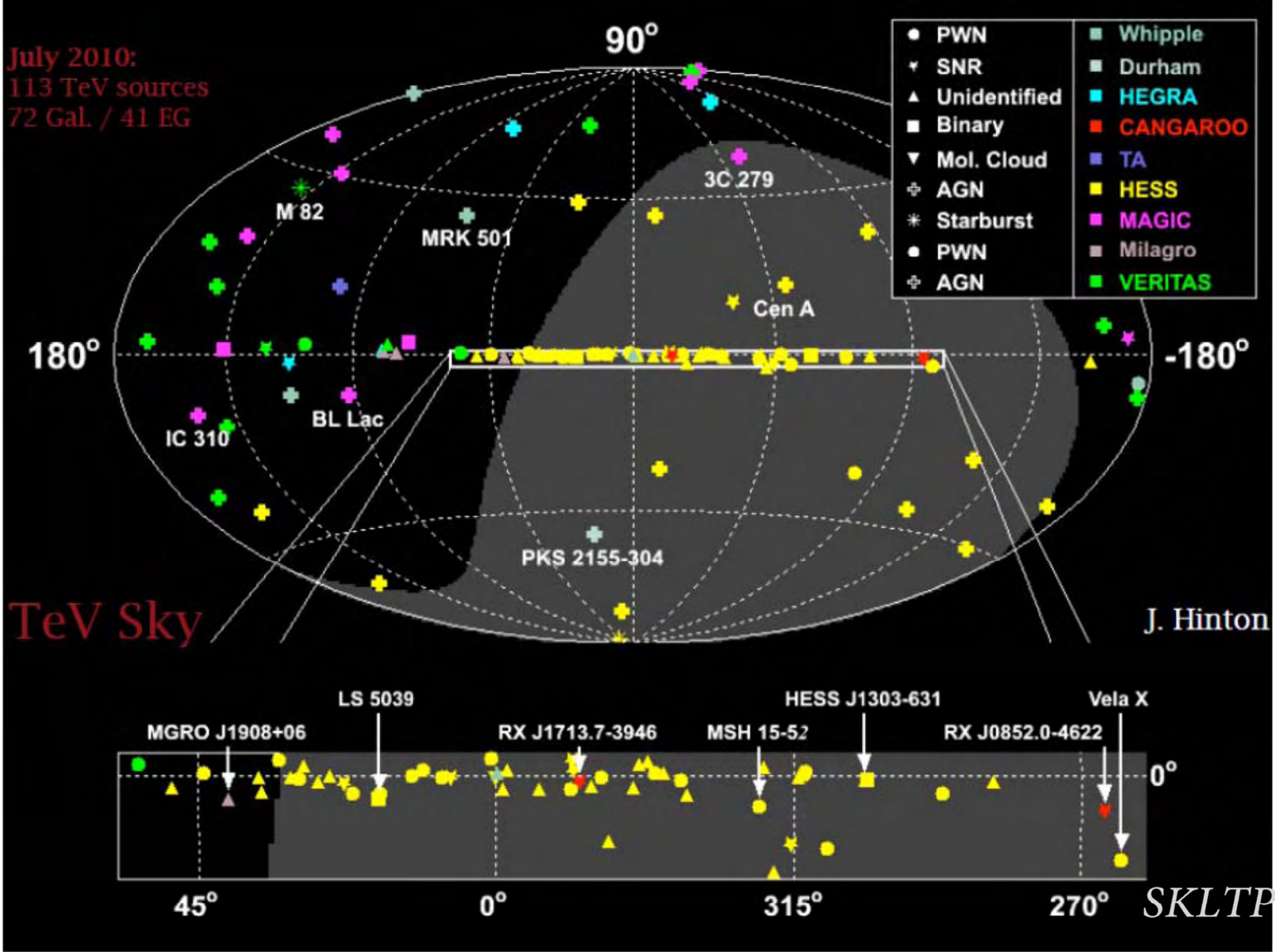
## Continuous watch of the GeV Sky



- AGN
- AGN-Blazar
- AGN-Non Blazar
- No Association
- Possible Association with SNR and PWN
- Possible confusion with Galactic diffuse emission
- Starburst Galaxy
- Galaxy
- SNR
- PSR
- PWN
- PSR w/PWN
- Globular Cluster
- HXB or MQO

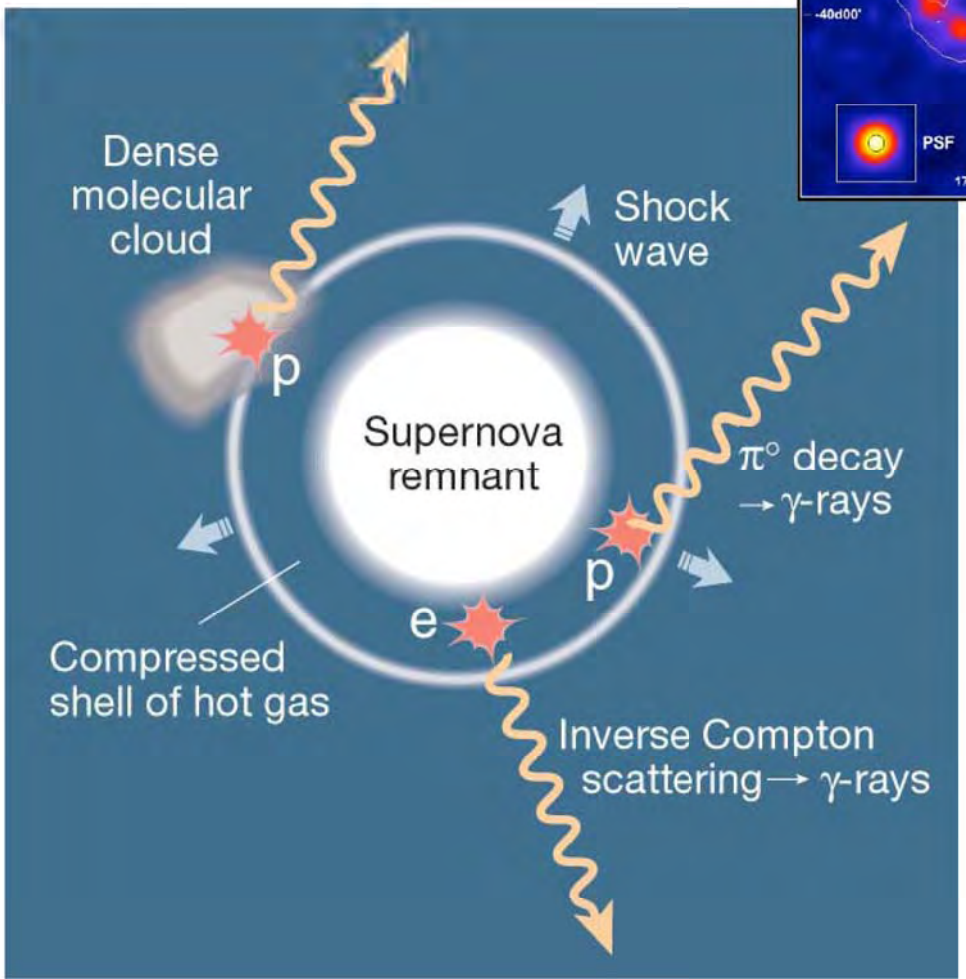
Credit: *Fermi* Large Area Telescope Collaboration

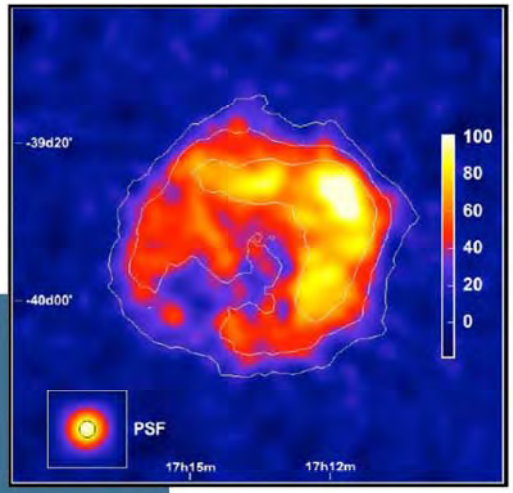
SKLTP

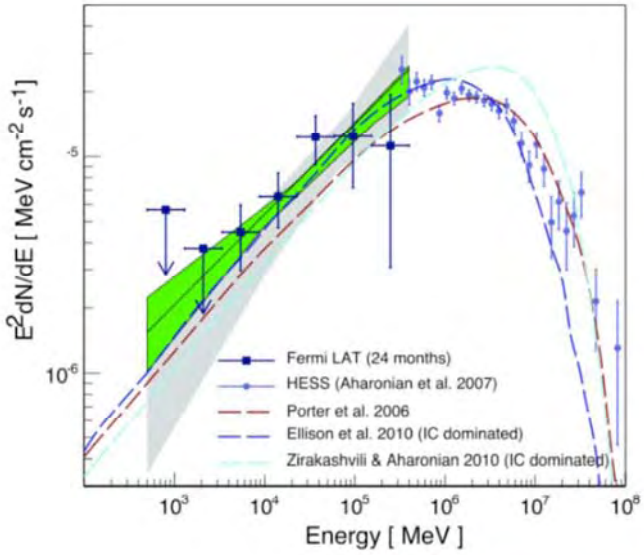

July 2010:
113 TeV sources
72 Gal. / 41 EG
90°
180°
-180°
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Starburst
PWN
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
M 82
MRK 501
3C 279
Cen A
IC 310
BL Lac
PKS 2155-304
TeV Sky
J. Hinton
MGRO J1908+06
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
0°
45°
0°
315°
270°
SKLTP

# 多波段观测壳型超新星遗迹RXJ1713.7-3946

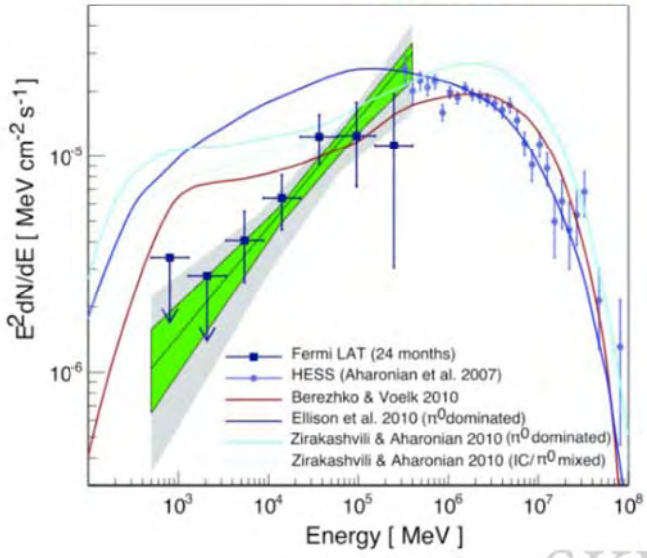
年轻(A.D.393)
距离地球:1kpc;
附近有分子云;




leptonic models

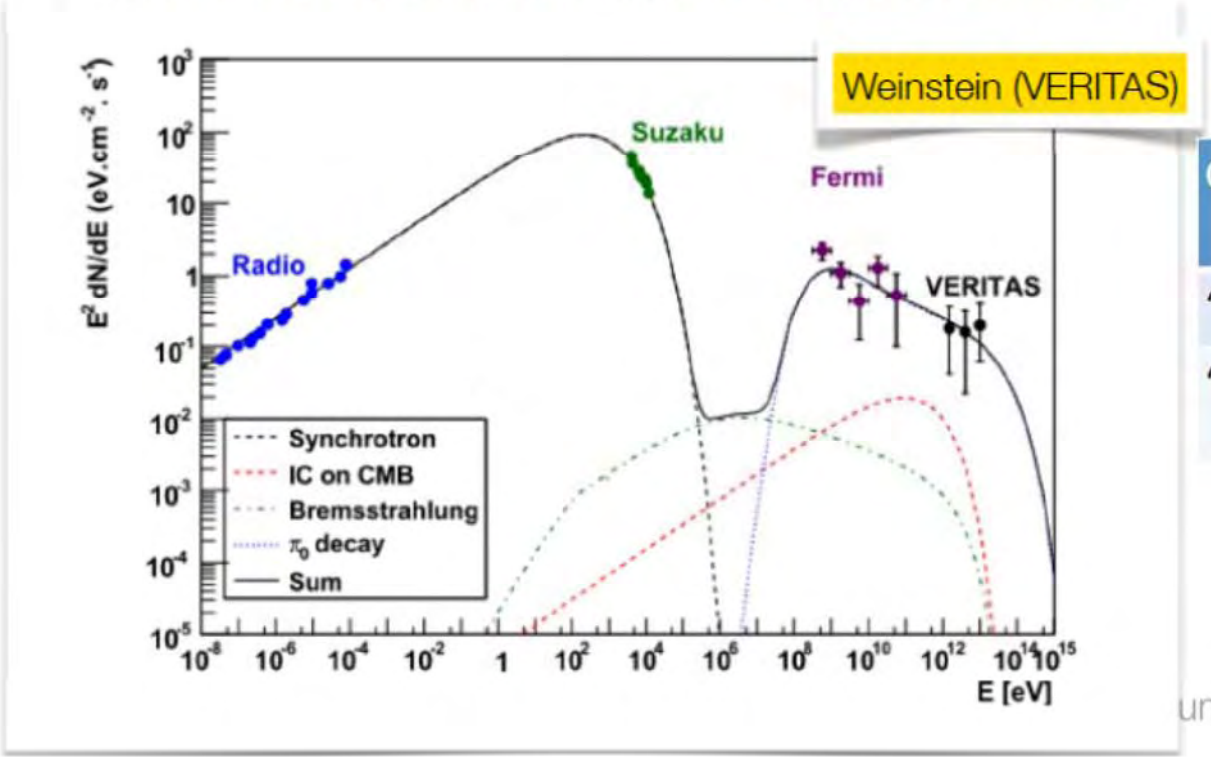





hadronic models

# Tycho SNR might now be the best case

- Tycho detected with both Fermi-LAT and VERITAS
- Leptonic model strongly disfavored
- No cutoff in VERITAS →acc time = SNR age → max proton energy > 300 TeV
- But beware drawing strong conclusion from spectral modeling. Also very weak source, both in Fermi-LAT and in VERITAS

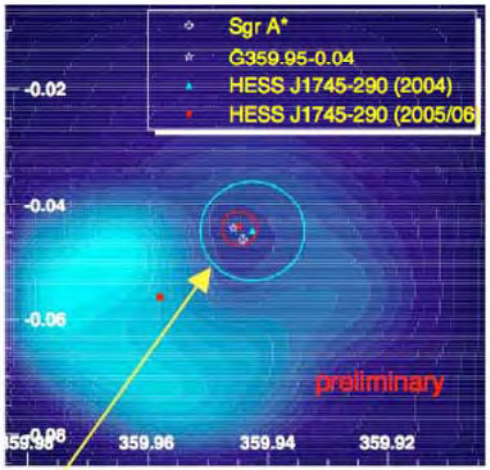



| Case | $E_{p,max}$ (TeV) | Distance (kpc) | $E_{SNR}$ (erg) |
|---|---|---|---|
| "near" | 340 | 2.78 | $10^{51}$ |
| "far" | 540 | 3.58 | $2x10^{51}$ |

Half a pevatron?

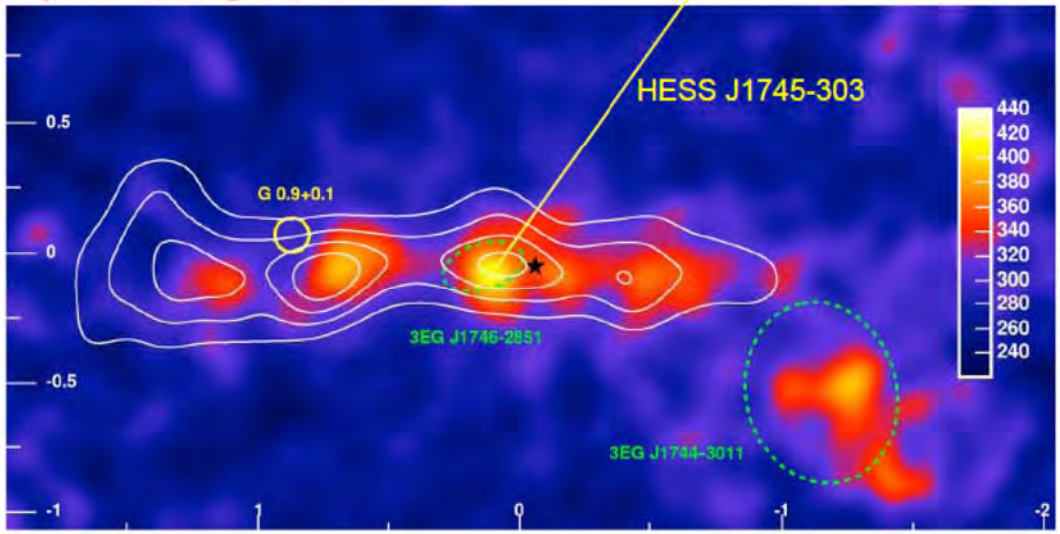
# *Galactic Center*

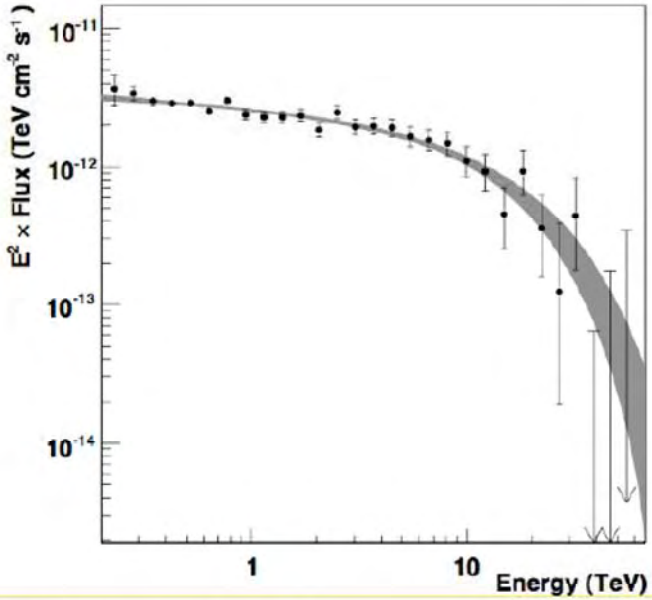
90 cm VLA radio image




Sgr A* or the central diffuse < 10pc region or a plerion? [no indication for variation]

γ-ray emitting clouds




Energy spectrum:

$dN/dE = AE^{-\Gamma} \exp[(-E/E_{0})^{\beta}]$

$\beta=1$ $\Gamma=2.1$; $E_0=15.7$ TeV

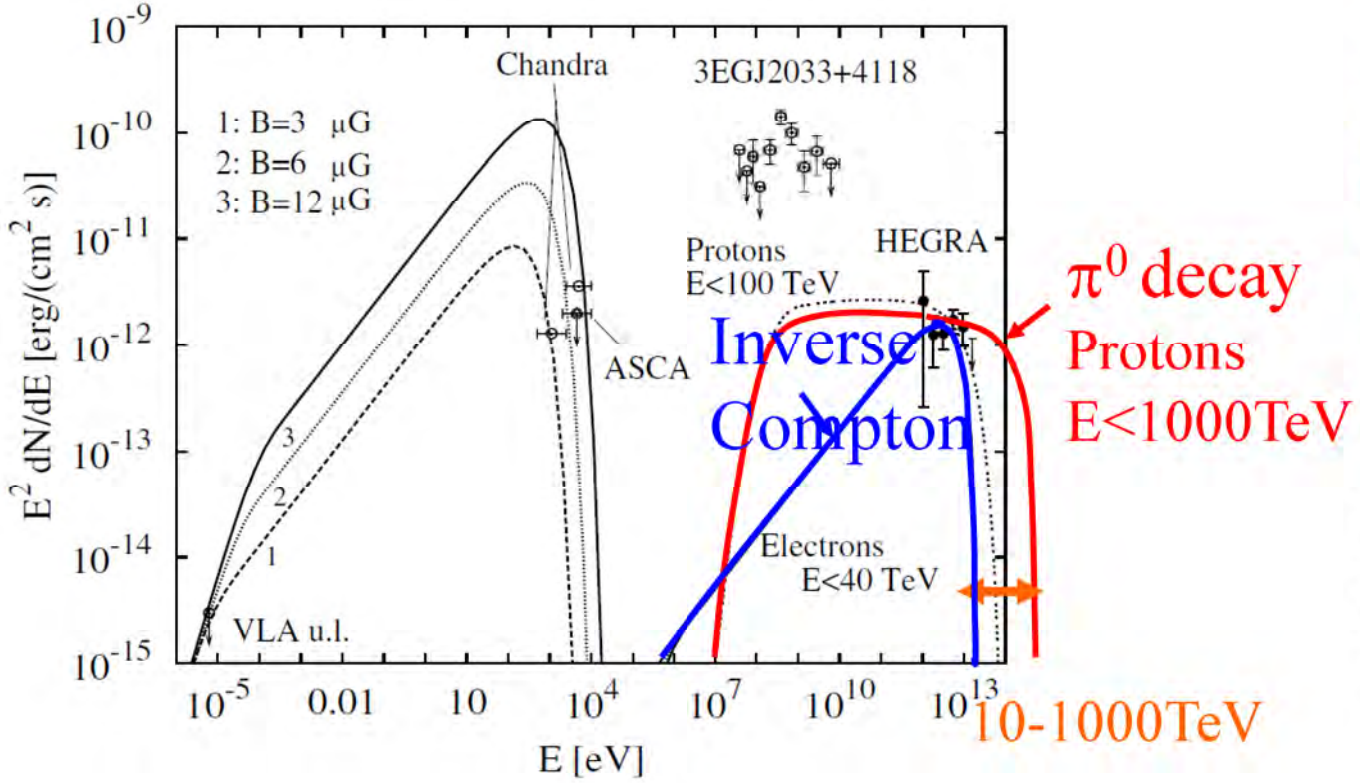
$\beta=1/2$ $\Gamma=1.9$ E0=4.0 TeV

γ-rays from GMCs in GC: a result of an active phase in Sgr A* with acceleration of CRs some $10^4$yr ago?

# 宇宙线轻子起源与强子起源，多波段联合观察

## 100TeV能区伽玛射线的观测

**TeV J2032+4130**




*Aharonian et al, A&A, 431, 197 (2005)*

- **synchrotron radiation and Klein-Nishima effect greatly suppress the 100TeV gamma ray radiation of electron by IC process.**
- **100 TeV Gamma Ray: the decay of secondary $\pi^0$ from interaction of the VHE CRs with the ambient gas**

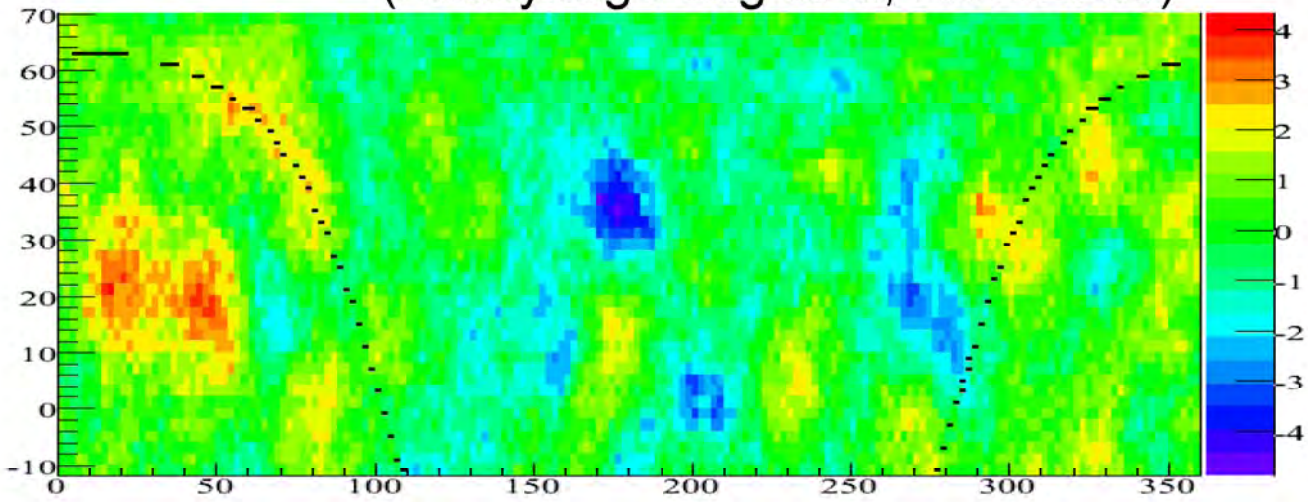
# ASγ在100TeV能区的*初步*观测

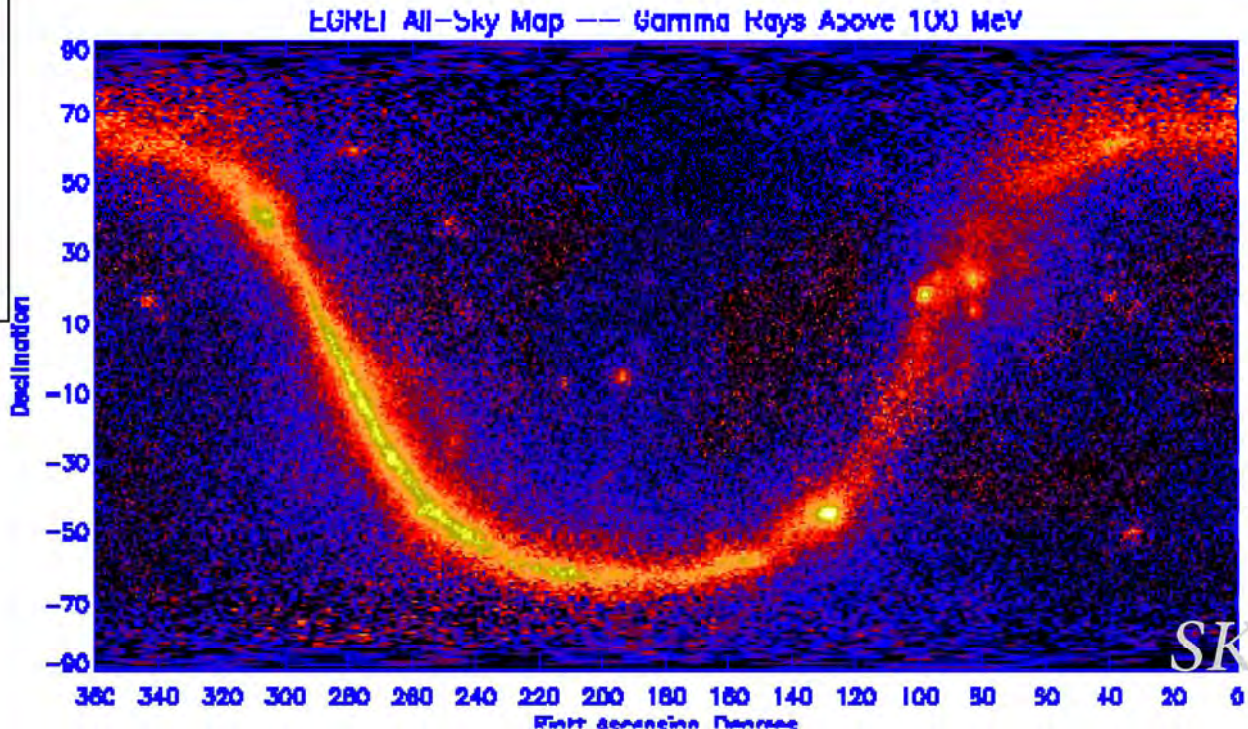
(Zhaoyang Feng et al, ICRC2009)

上图：中日实验在100TeV能区看到有来自银道面（黑点指示的位置上）的高能伽玛射线发射的迹象（红色意味做有发射）。

该观测如被证实，将成为该领域的重要发现，为回答银河系宇宙线的起源和加速问题作出重要贡献。

中日增建的底下MUON探测器将有助于澄清问题。

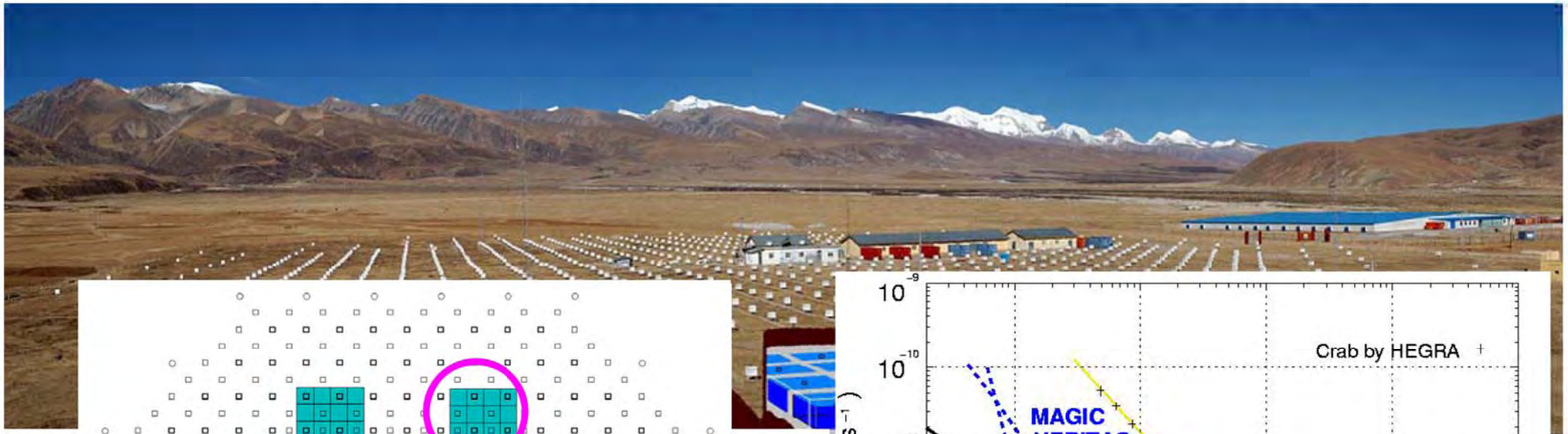


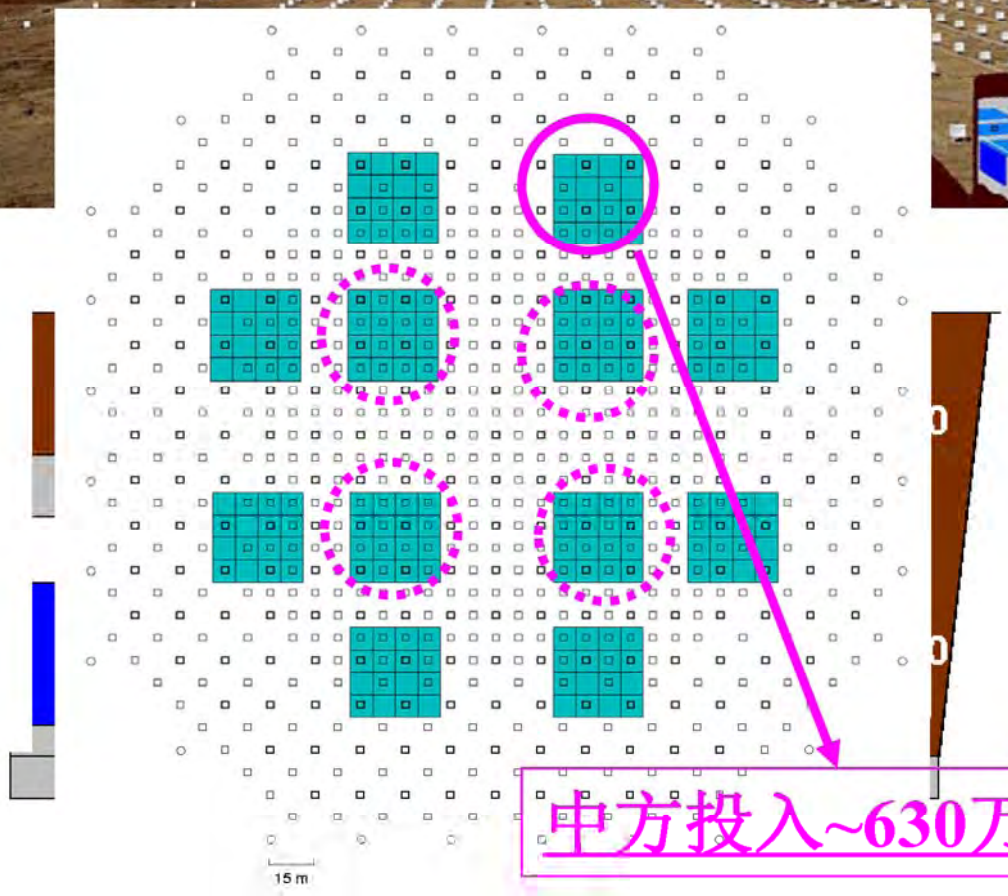



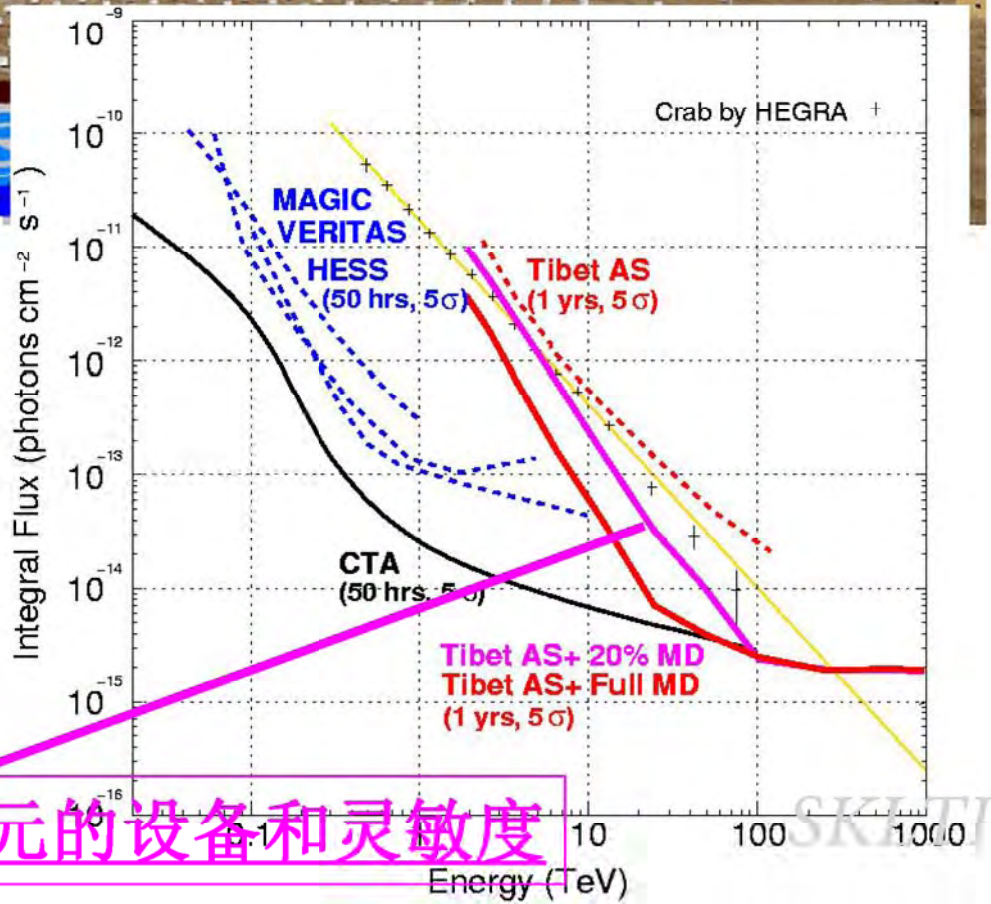

下图：EGRET观测的100MeV能区的低能伽玛射线的发射。

# 中日实验增建地下MUON探测器

## ——10TeV以上能区国际最灵敏的γ和电子探测器！



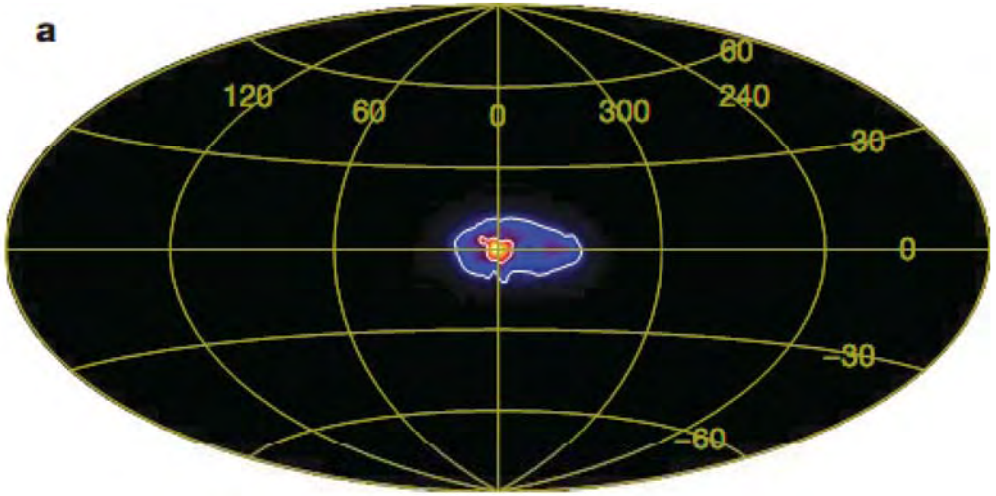



中方投入~630万元的设备和灵敏度

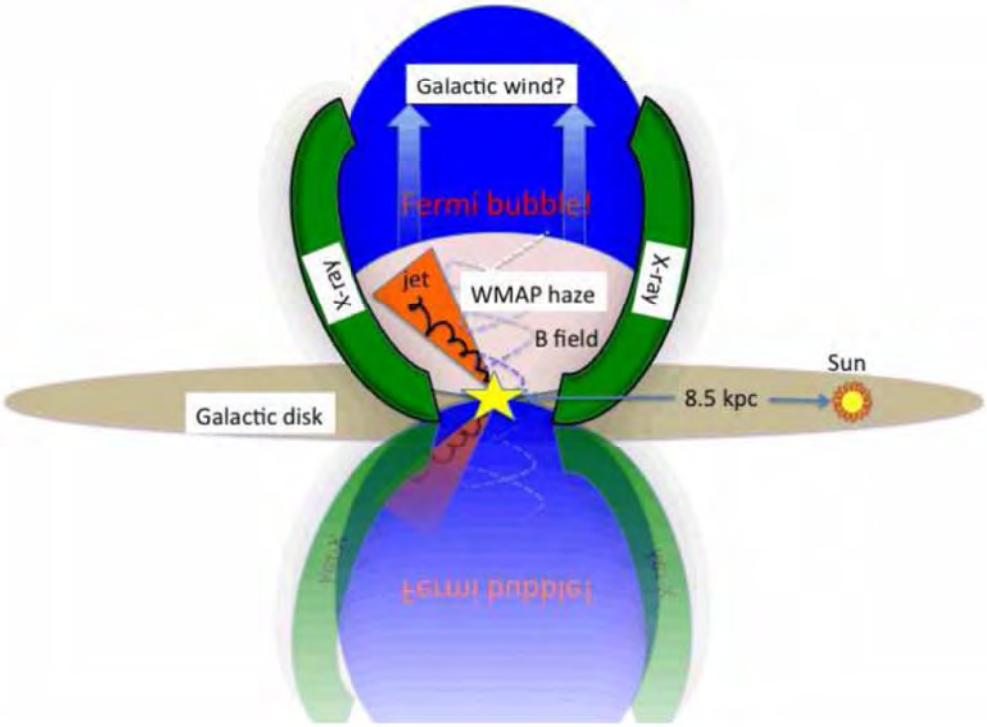
# 511keV line,Fermi Bubbles, WMAP haze and X rays etc.

~3000光年尺度



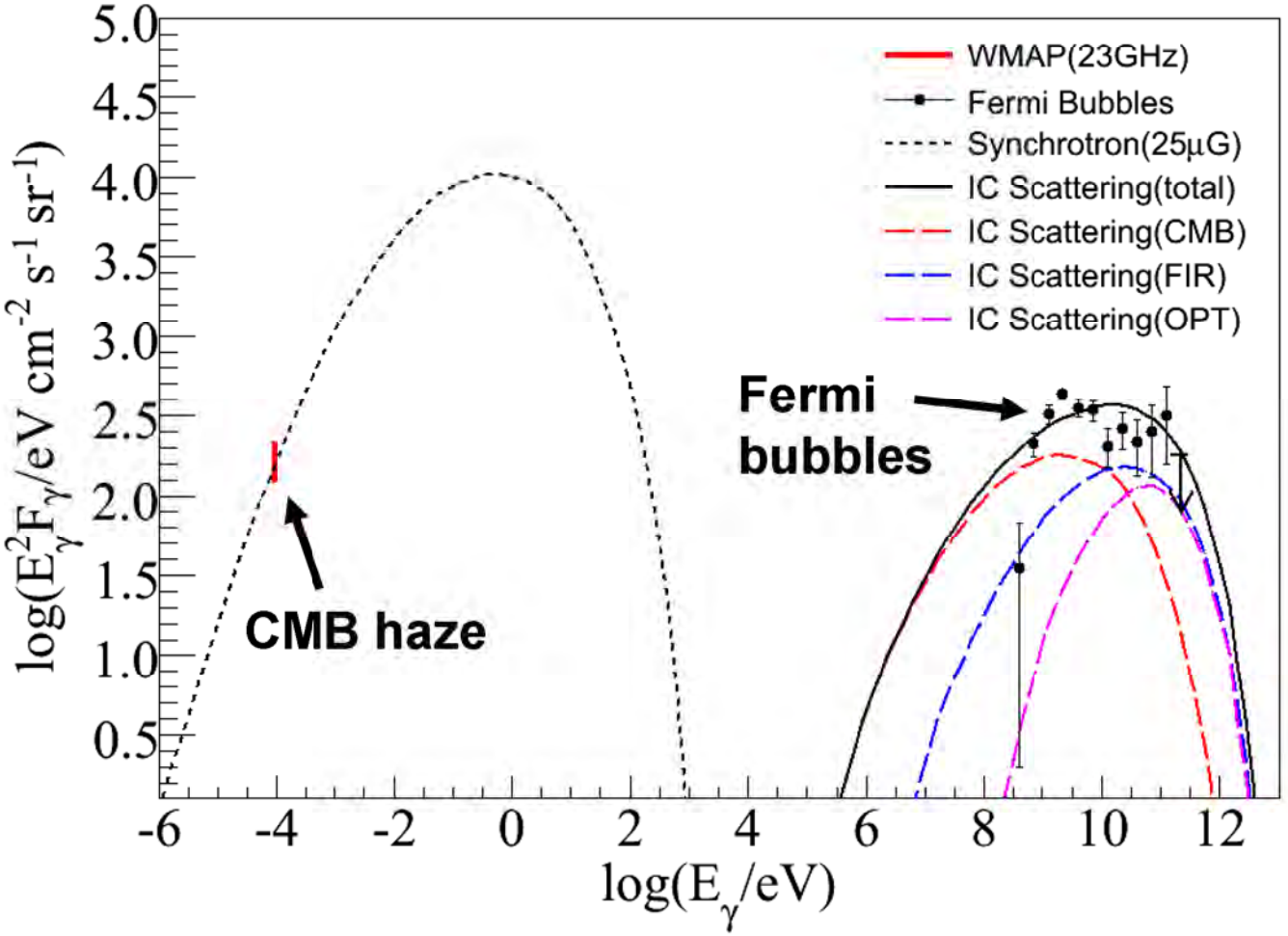

已经冷却的正电子和电子结合成电子偶数，再湮灭成两个511keV的γ。
正电子是加速源上的遗迹？

~15000光年尺度




TeV-PeV的正/负电子，和ATIC的电子能谱及流强是一致的。加速源的另一遗迹？

# 如果银心是银河宇宙线的主要源:
# 如何加速?如何反应?如何传播?




Y.Guo et al.,
arXiv:1101.5192

**511keV伽玛发射线的强度也正好能够被解释;**
**尖锐的“膝”，银心处气体的膨胀等**

Fermi Bubbles - result of pp interactions of CRs produced in the GC and accumulated in R ~10 kpc regions over 10Gyr comparable to the age of the Galaxy? (Crocker&FA 2011)

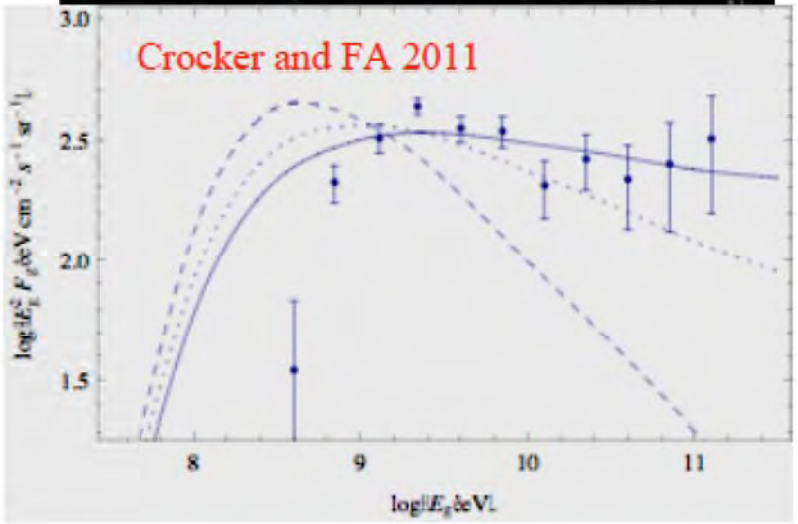
*Size - because of slow diffusion in turbulent environment (10 times slower than in the Galactic Disk)*

plasma density: $n \sim 0.01$ cm$^{-3}$ timescale: $t_{pp} \sim 5$ Gyr $< t_{Galaxy}$

saturation (calorimetric) regime can explains:

*generally homogeneous distribution of gamma-rays (local γ-ray production rate does not depend on density), unless possible gradients in the CR spatial distribution, e.g. due to propagation effects ; if the sharp edges tentatively found in the Fermi images is a real effect, they can be naturally explained by higher turbulence introduced by shocks => slower diffusion => accumulation of CRs close to the edges*

modest requirements to CR rate : $Lp \sim 10^{39}$ erg/s

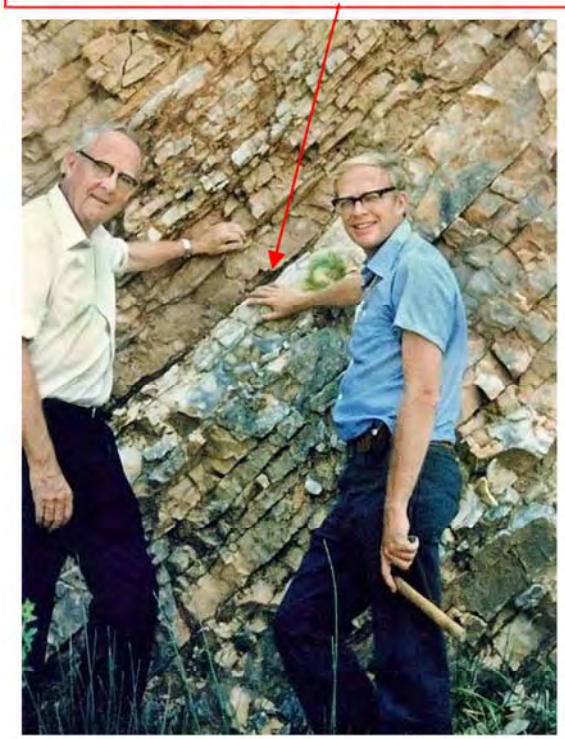


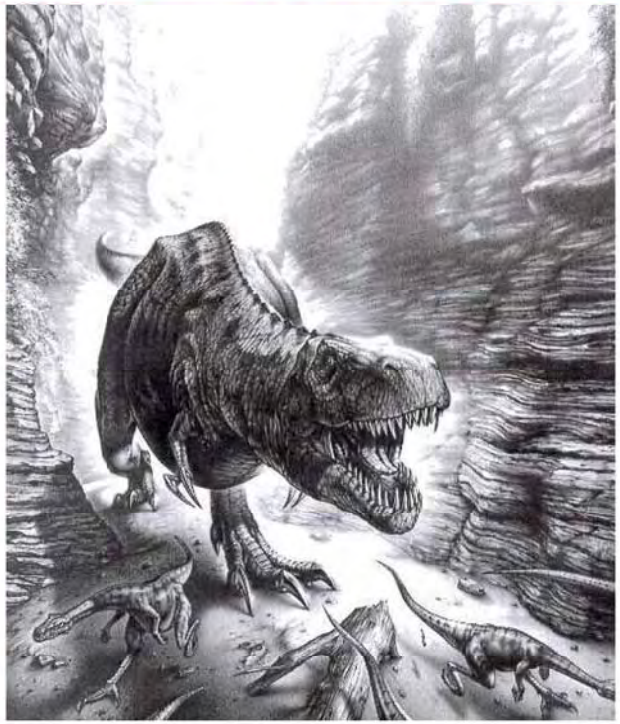

Fermi Bubbles as a ν-source ?
if γ-ray spectrum extends to 100 TeV, Km3NeT should be able to detect neutrinos after few years of operation (P Sapienza and R.Coniglione 2011)

**1) 全银河宇宙线能量的千分之一被量能器型全吸收;**
**2)几乎是星系的时间里扩散了5kpc,但不到全银河系;**

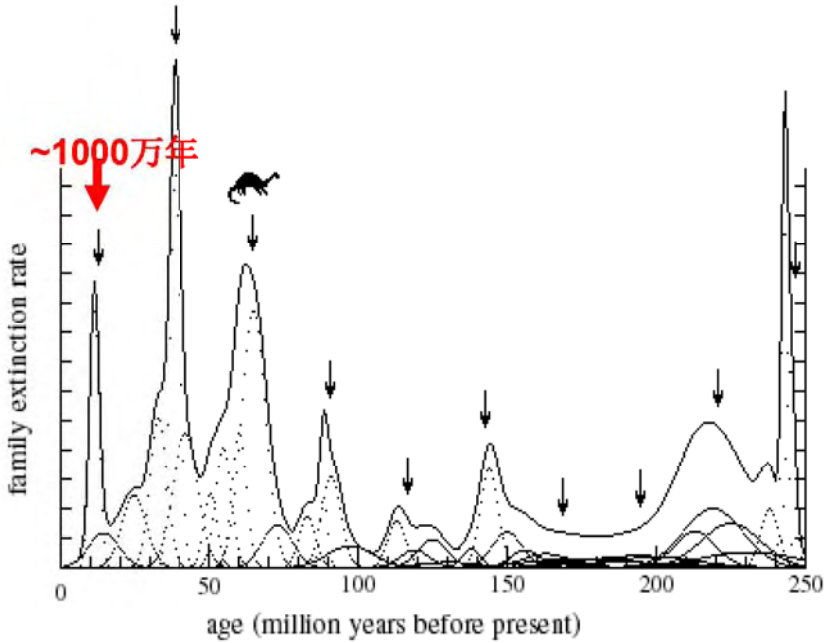
# 恐龙的陨石灭绝理论
# 和2600万年的物种大灭绝周期

恐龙灭绝年代的1厘米地层含大量来自外太空的铱





Luis and Walter Alvarez at the K-T Boundary in Gubbio, Italy 1981




D.Raup and J.Sepkoski, *PNAS*, 81, (1984) 801-805

是尚未发现的太阳伴星“复仇女神”？还是“银心”的爆炸？

# 带电宇宙线各向异性研究传播

# ASγ实验观测到高能的2D宇宙线强度

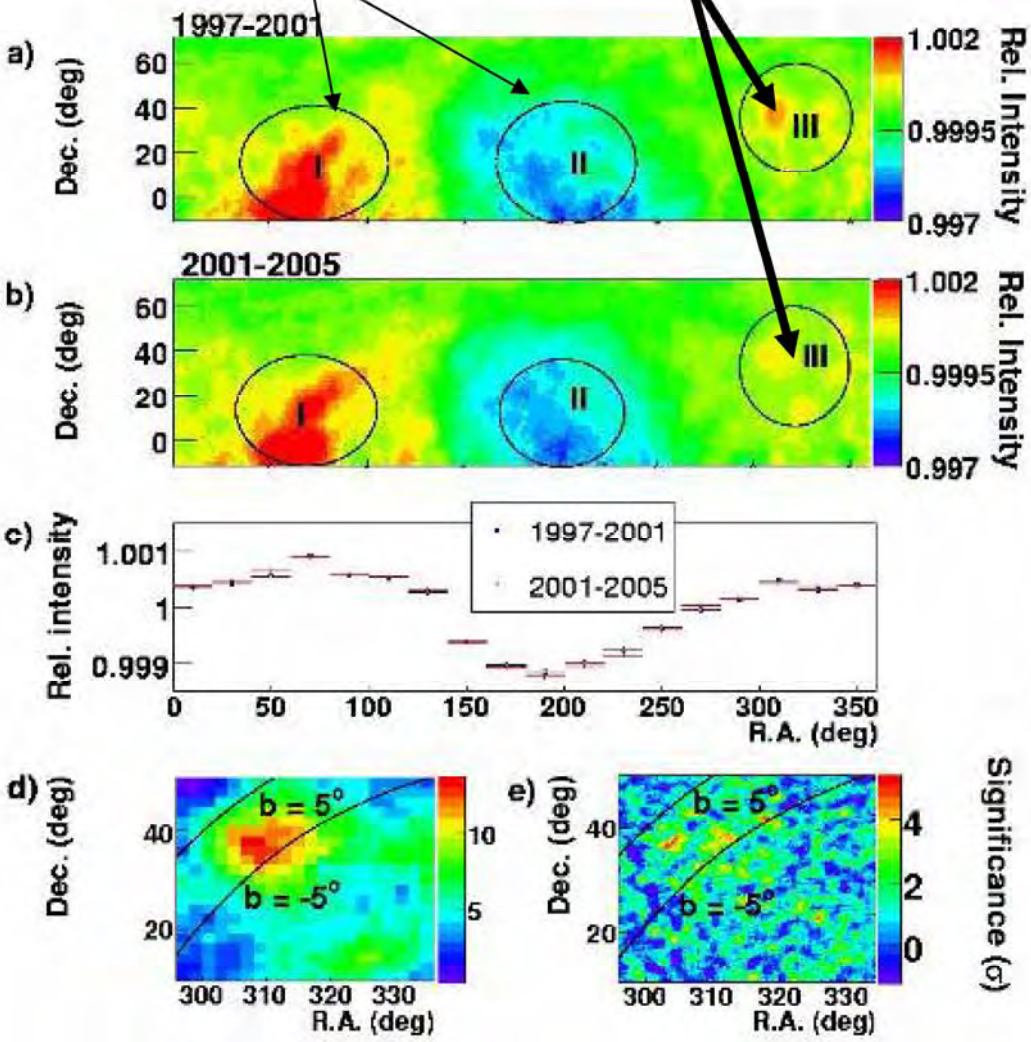
## 《科学》314(2006)439-443

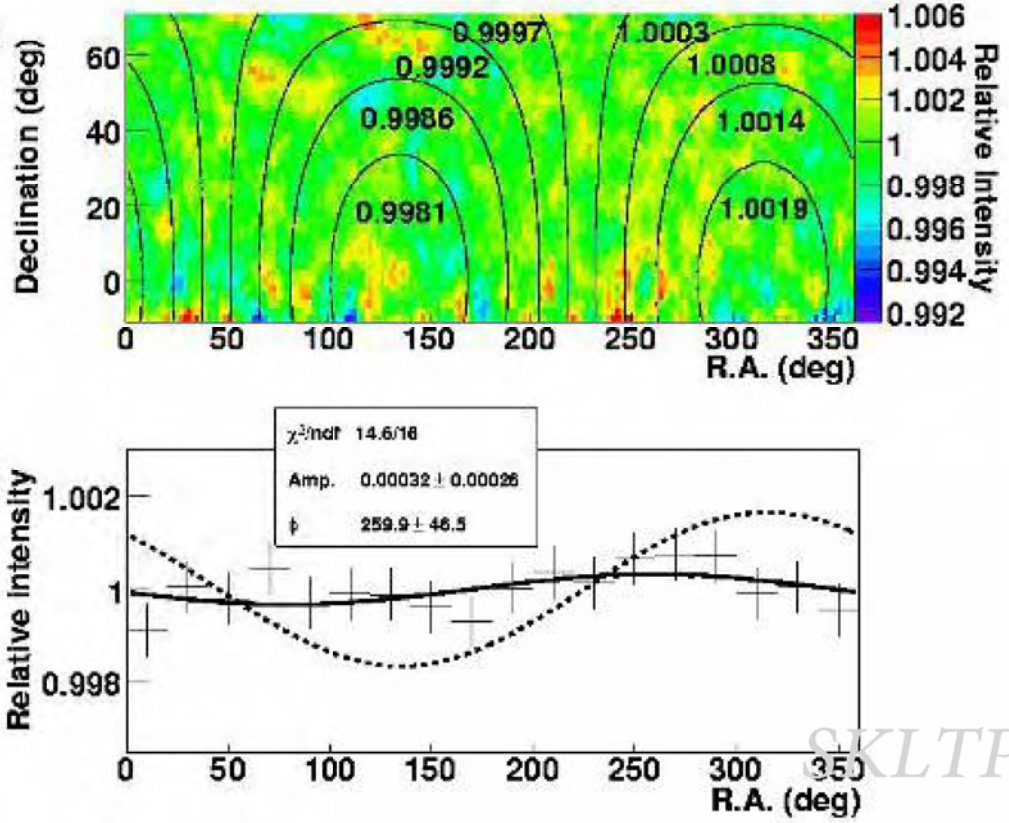
2006年度中国科学院十大创新成果 之一；
2007年《科学发展报告》；
第一届“中国百篇最具影响优秀国际学术论文”
迄今已经被引用了97次。

TeV最精确
(2011√)

发现天鹅座
的新超出
(γ发射?)

大于300TeV能量，各向异性消失，
宇宙线绕银心转动。(2006√)



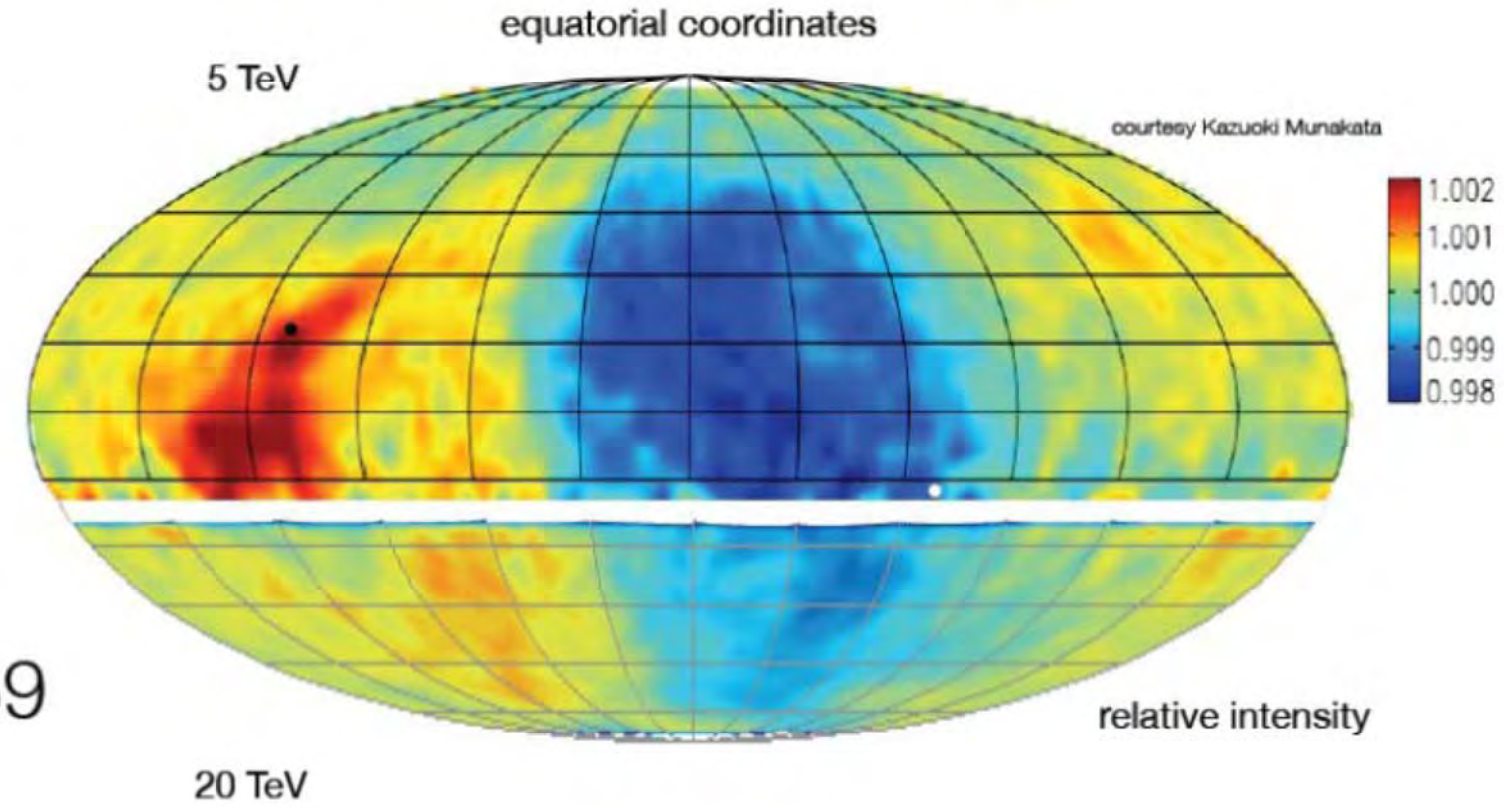



# Cosmic Ray Anisotropy

## Compared to Northern Sky

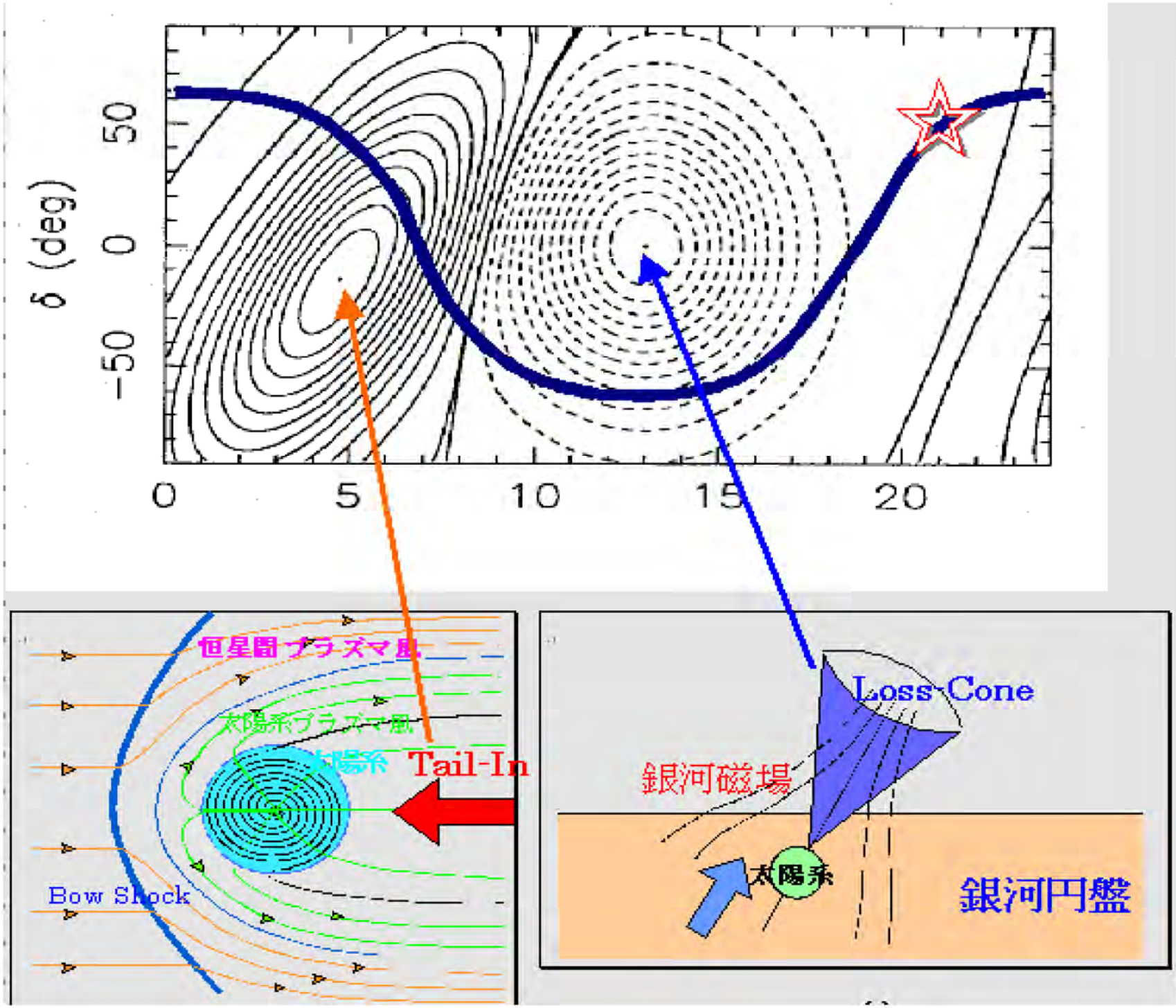
Tibet-III

IceCube-59




**ARGO-YBJ也得到了和ASγ相同的结果.**

the orientation of the dipole moment does **not** correspond to the relative motion in the Galaxy (Compton-Getting effect)


δ (deg)
50
0
−50
0
5
10
15
20
恒星間プラズマ風
太陽系プラズマ風
太陽系
Tail-In
Bow Shock
Loss-Cone
銀河磁場
太陽系
銀河円盤

# 数十至数百GeV的结果

**Nagashima, Fujimoto, Jacklyn (JGR, 103, 1998)**

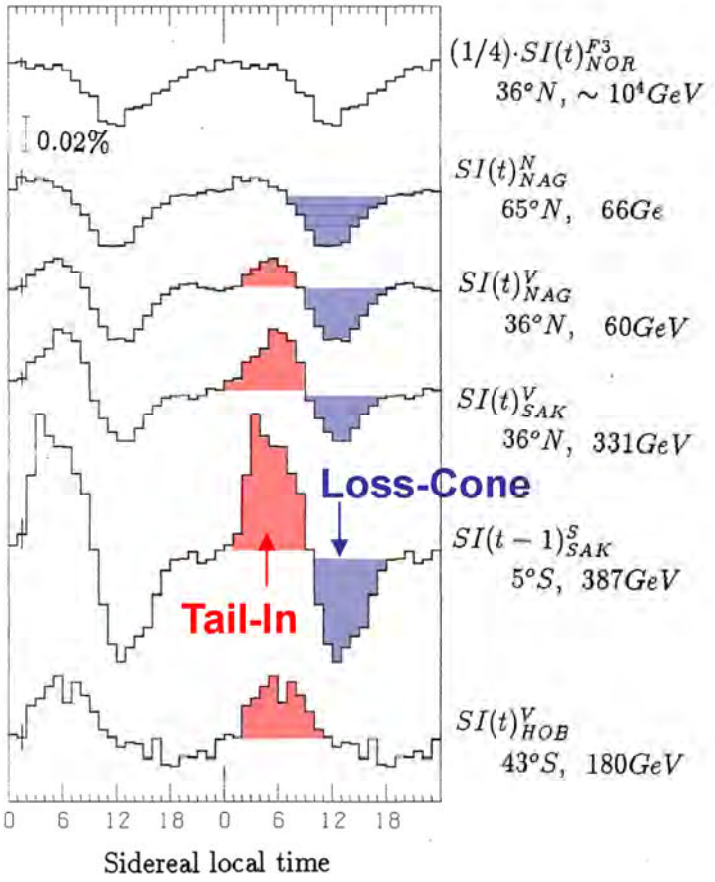



**Figure 1.** Cosmic-ray sidereal daily variation $SI(t)$ in local time corrected for the influence of solar daily variation by the method using the antisidereal daily variation $ASI(t_a)$. The superscript and subscript indicate the telescope and station, respectively. The median energy ($E_m$) and the latitude ($\lambda_C$) of the center direction of viewing of the telescope are shown on each variation. At the top, the sidereal variation $SI(t)^{F3}_{NOR}$ of the galactic origin observed by air showers ($F3$) at Mount Norikura is shown for reference [cf. *Nagashima et al.*, 1989]. The time shift by minus 1 hour in $SI(t-1)^{S}_{SAK}$ is the correction for the eastward deviation of the telescope from due south (see Table 1). The error expresses the dispersion of the hourly intensity.

**Hall et al. (JGR, 103, 1998)**

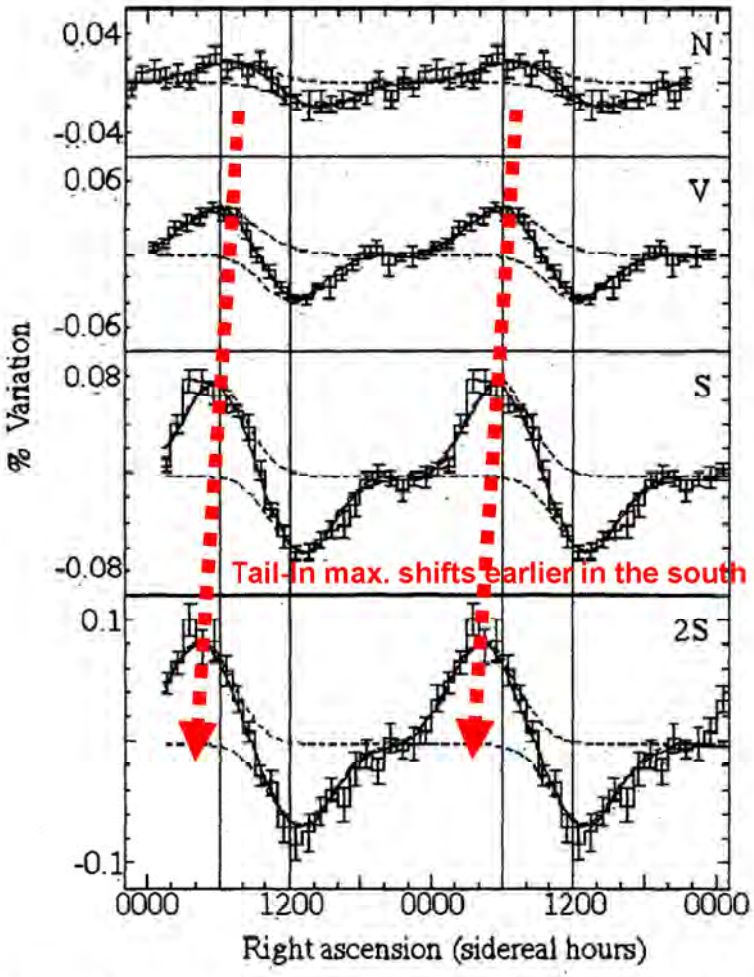



**Figure 1.** Average hourly percent deviations of the Sakashita underground muon north (N), vertical (V), and south (S and 2S) telescopes from 1978 to 1994. Vertical lines are shown at 0600 and 1200 local sidereal time. The individual best fit Gaussians superposed on the best fit constant terms are shown by the dashed lines, while the overall fit is indicated by the solid line.

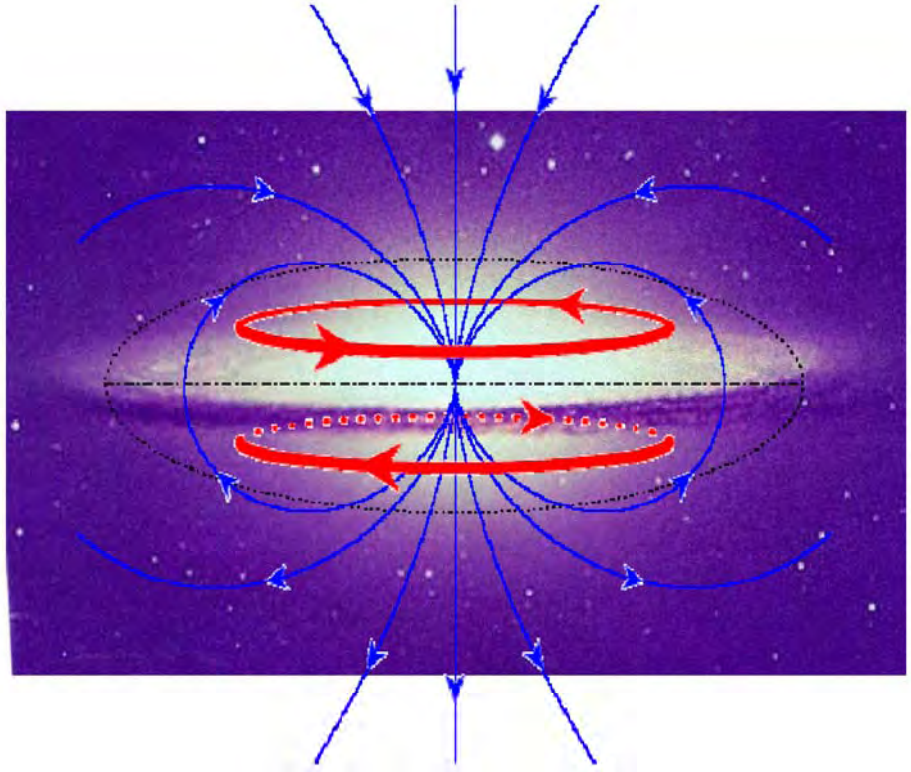
# 银道坐标系里的三个宇宙线各向异性（流动）的方向及其贡献的大尺度磁场结构


宇宙线粒子数/银河总核子数~$5\times10^{-11}$!

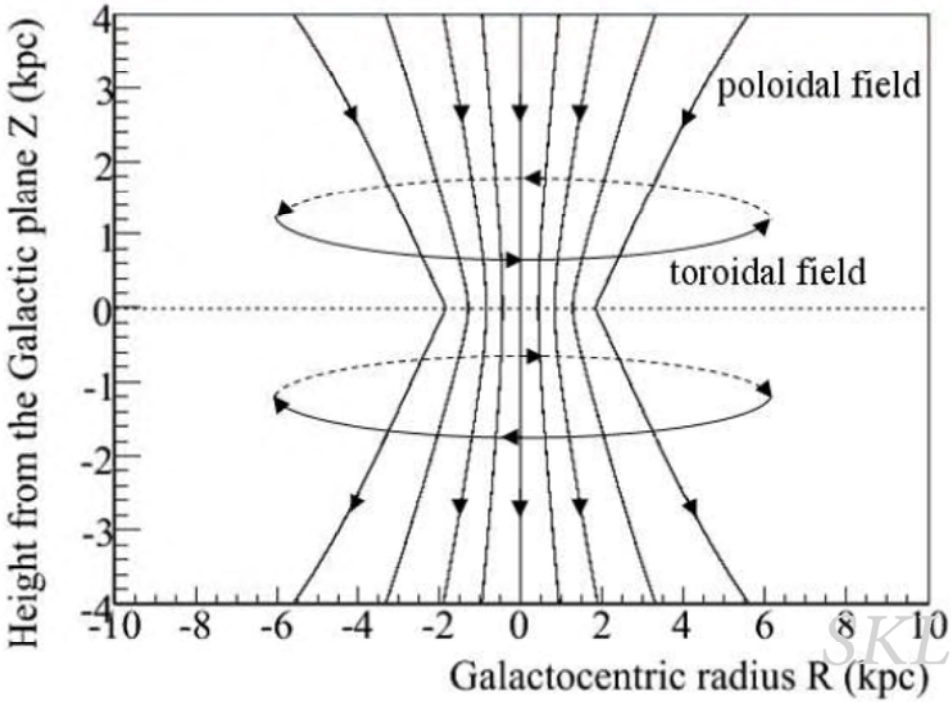
1)星系的电荷分布怎样?

2)星系间是否存在“范德瓦尔斯”力?

韩金林组A0；
与符合观测。

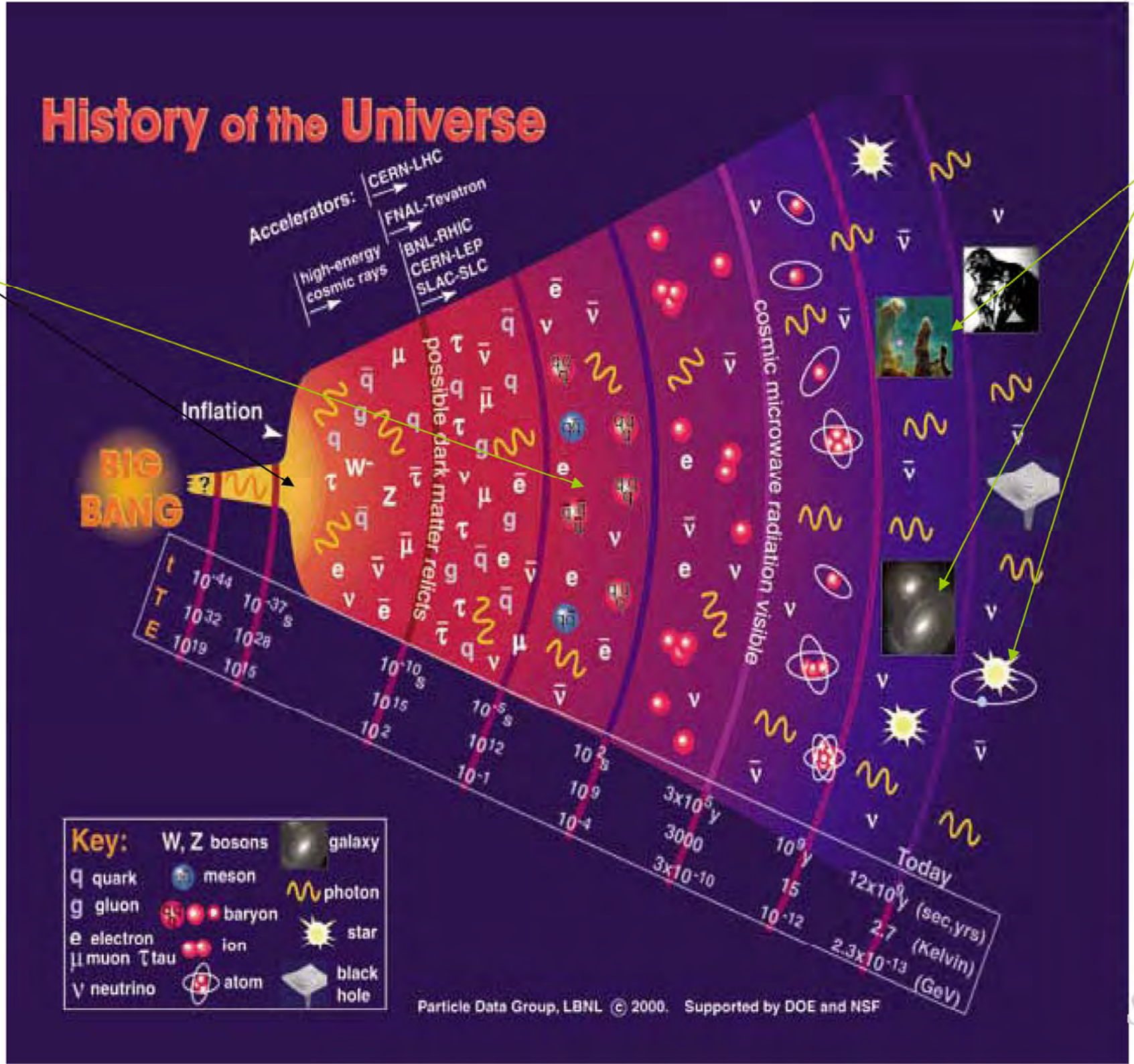


上：ASγ观测，下：我们模型计算出的磁场(X.B.Qu et al., arXiv:1101.5273)。



# 宇宙线和宇宙学

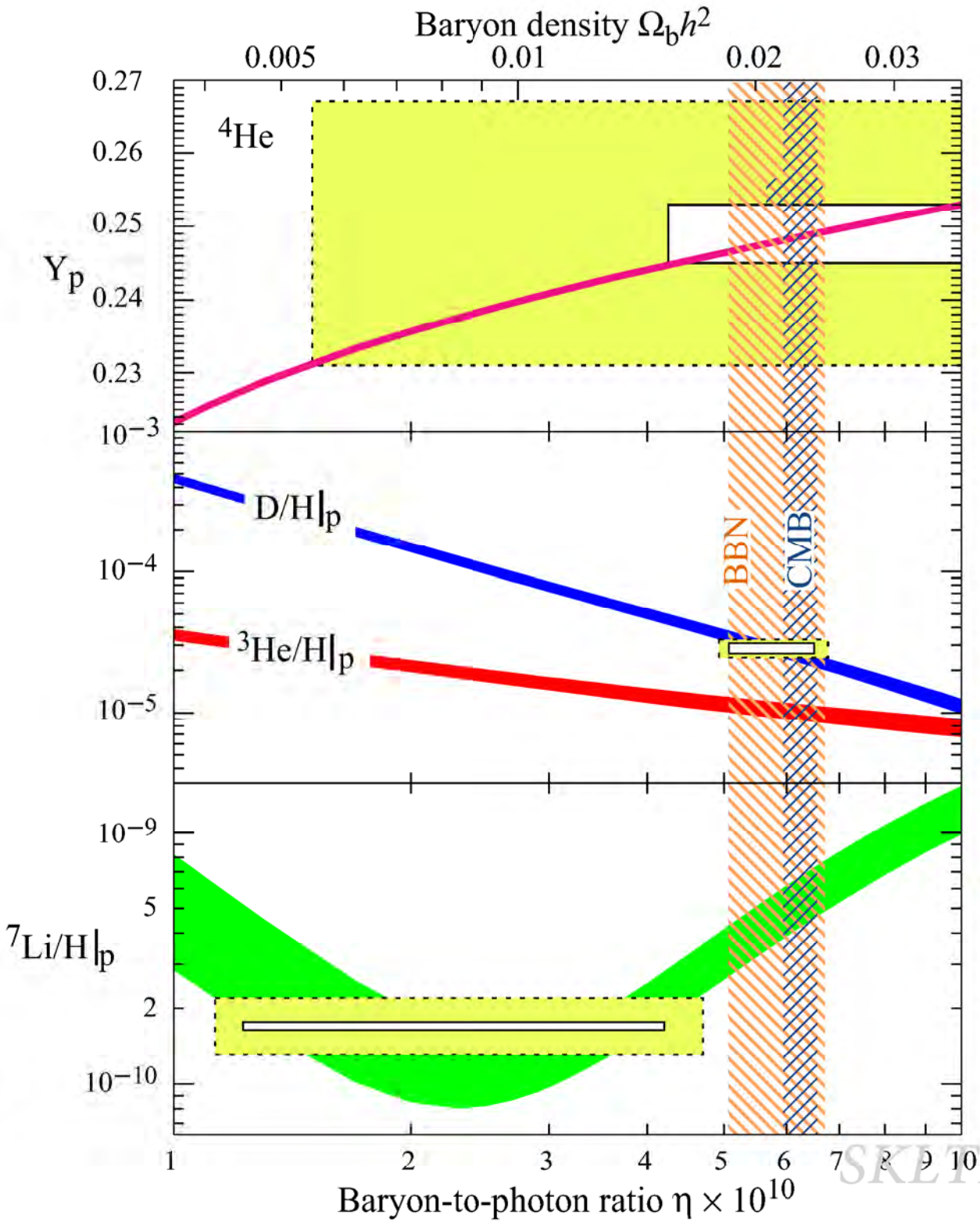
大爆炸BBN时候是否也有过宇宙线？




通常所研究的宇宙线起源于：星系，恒星等

# 宇宙大爆炸的Li丰度问题

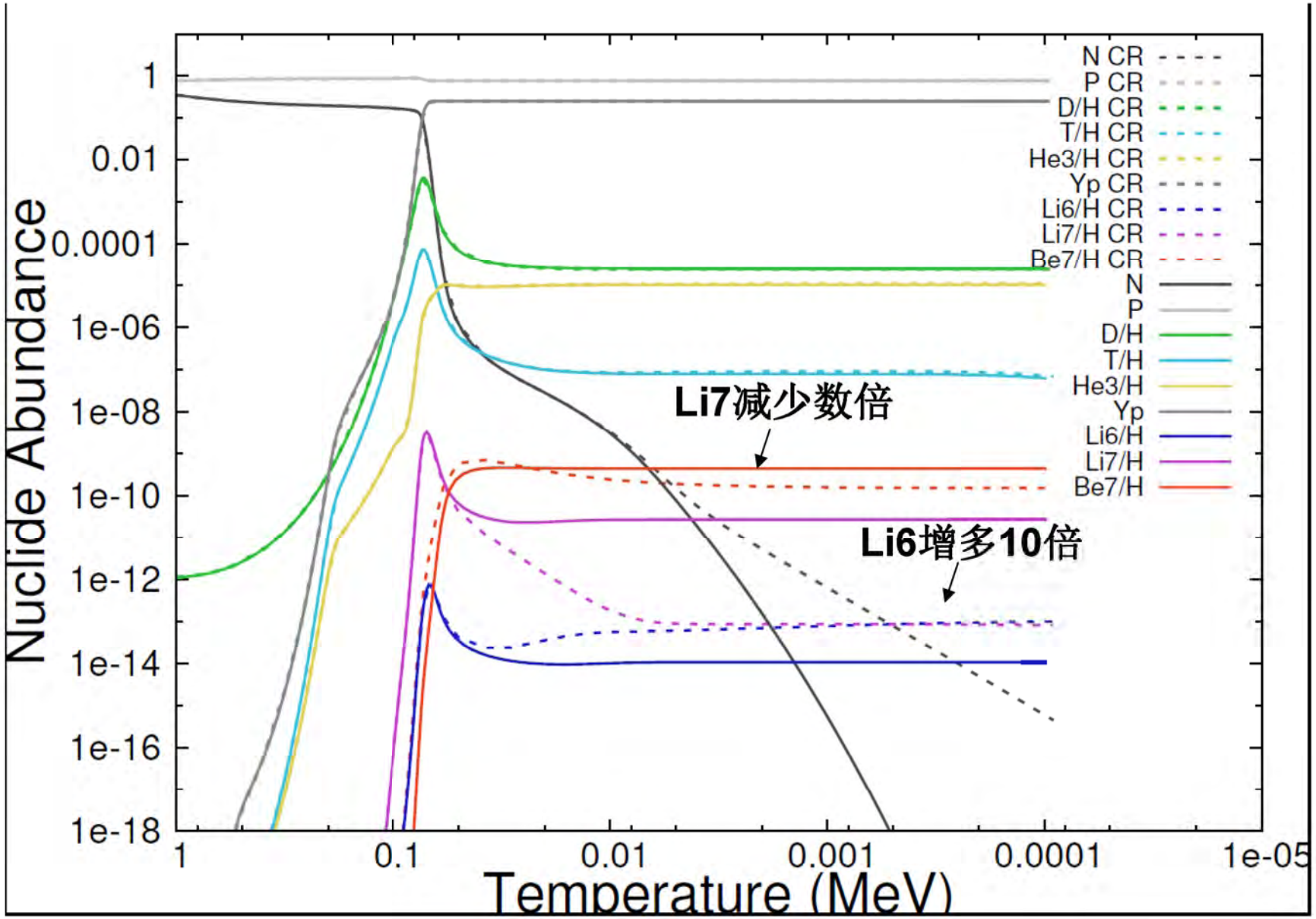
- 系统误差
- 天体起源
  - 星系早期宇宙线
  - **BBN时期宇宙线**
- 新物理
  - 时变的物理参数
  - **BBN时新粒子衰变**



# 少量的CR@BBN可解决LI丰度问题

1) Be7(p; pα)He3 (阈能1.814MeV); 2) He4(d;γ )Li6 (2MeV附近有共振峰);

预印本:**Ming-ming Kang,Yang Hu,Hong-bo Hu,Shou-hua Zhu,arXiv:1110.0163**



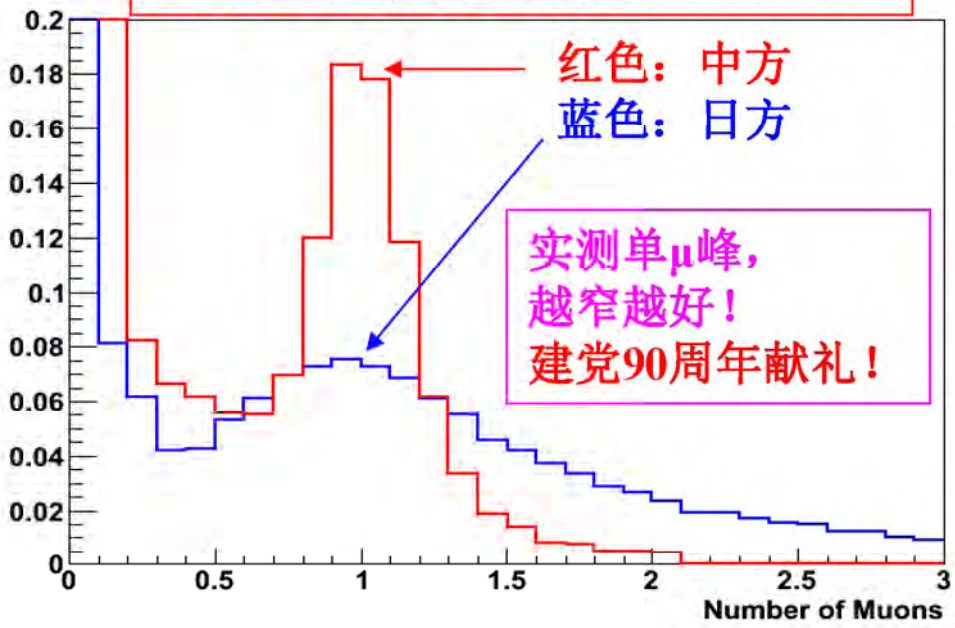
# 谢谢!

# 备用透明片

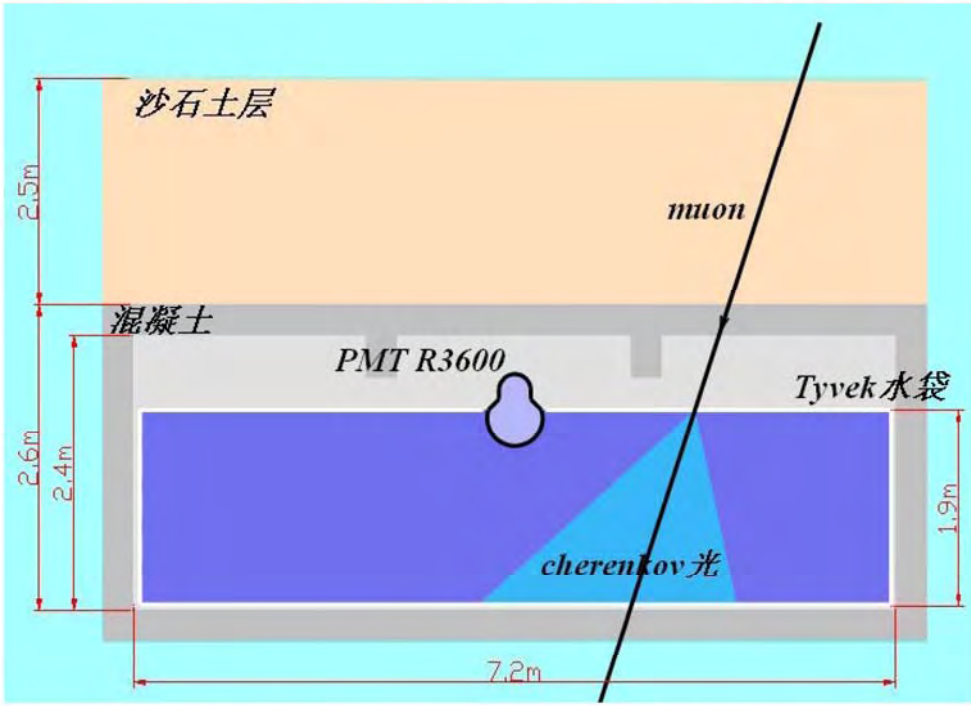
# 中方μ子探测器性能远好于日方

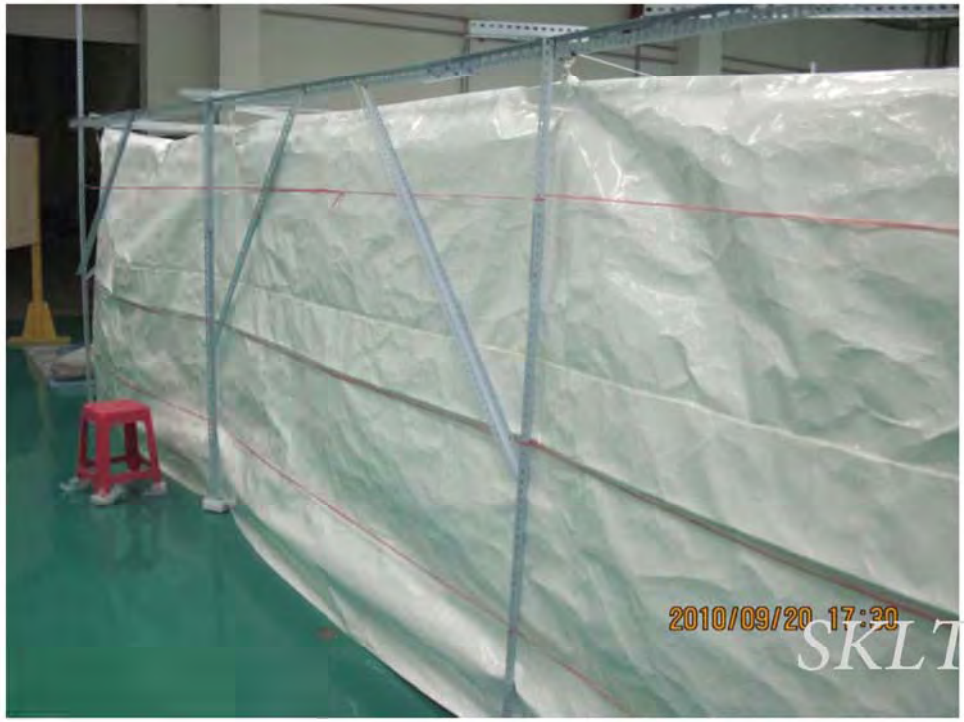
日方:水深1.5米,敞开易被污染,上方无反射

主要和山大,河北师大,藏大合作完成

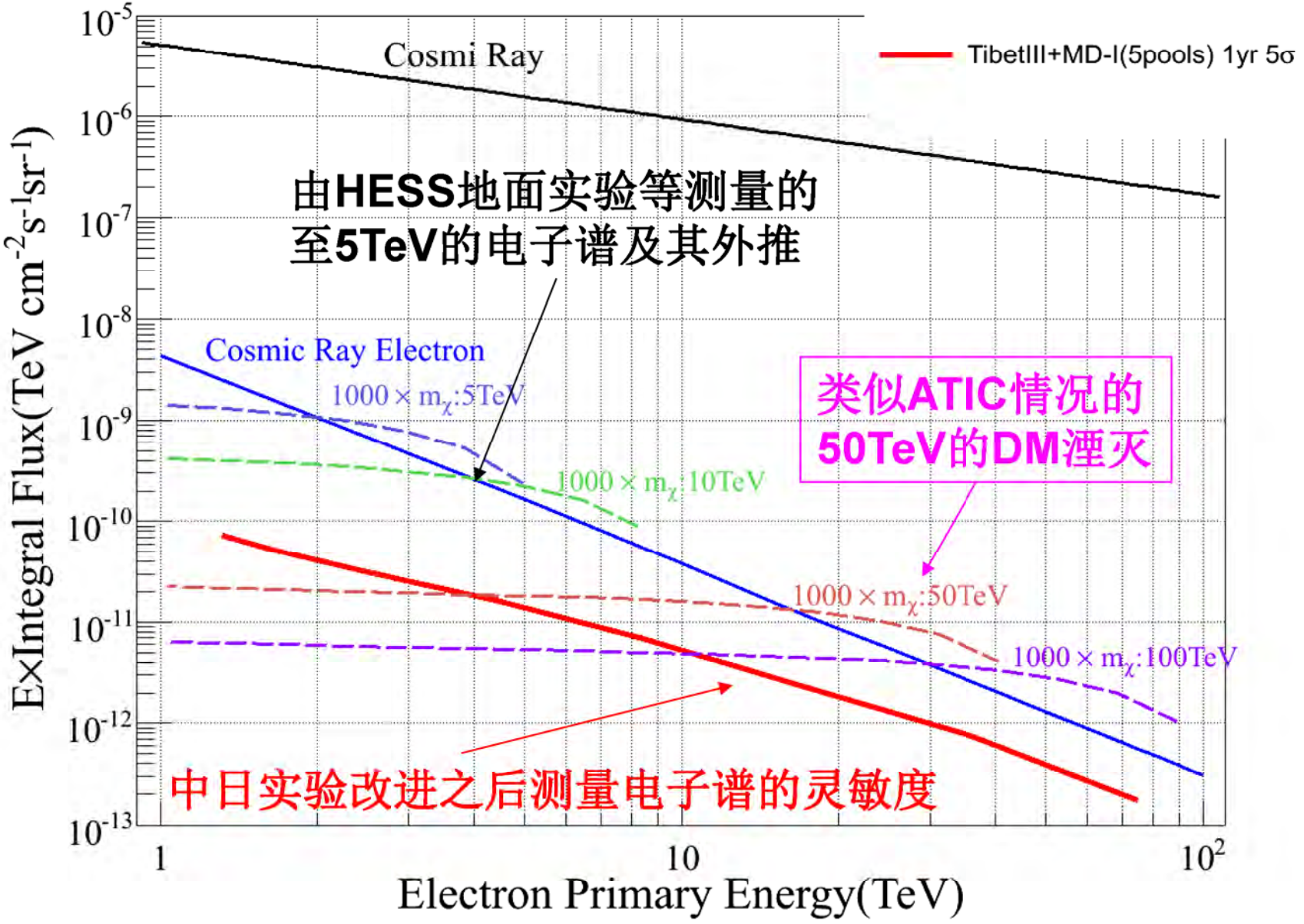



中方:水深1.9米,密封防污染,全方位反射



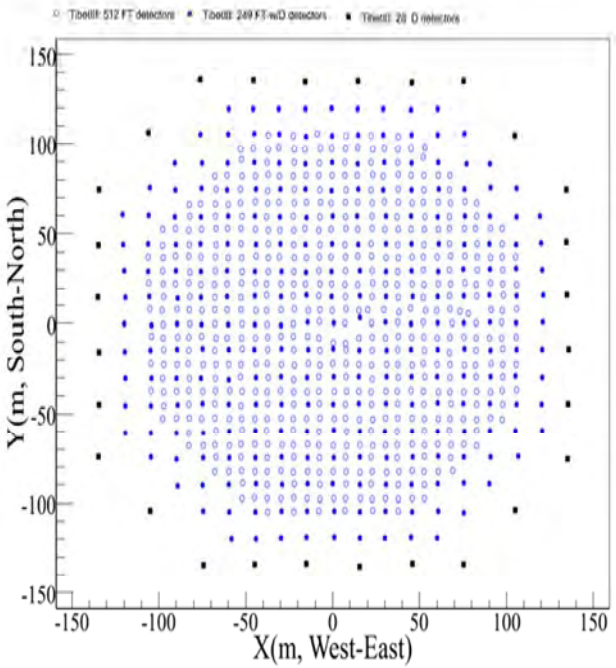
# 10TeV以上最高精度宇宙线电子谱测量及质量在10TeV以上的暗物质粒子寻找



# 表面阵列扩建(已获基金委重点项目批准)

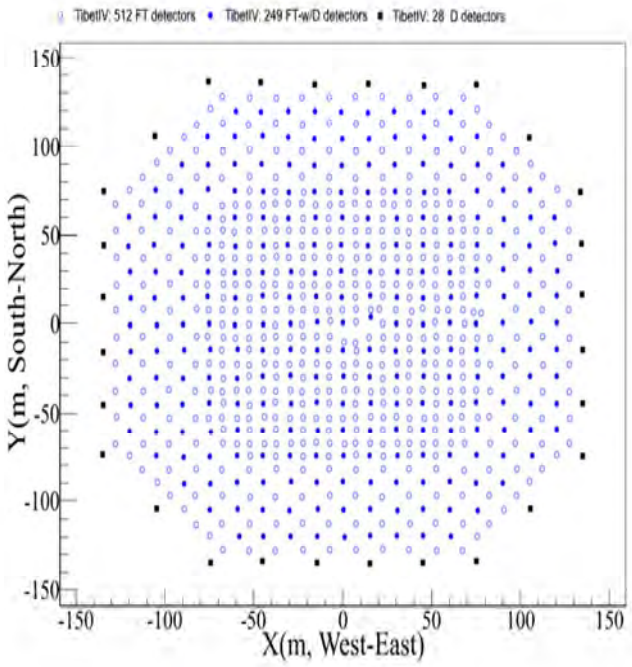
1. 继续提高100TeV能区的灵敏度对于发现性工作有重要意义；
2. 无需再增加地下μ子探测器，而需扩大表面阵列；
3. 通过此项工作,使中方也掌握性能优异的表面阵列。

当前:36900M²



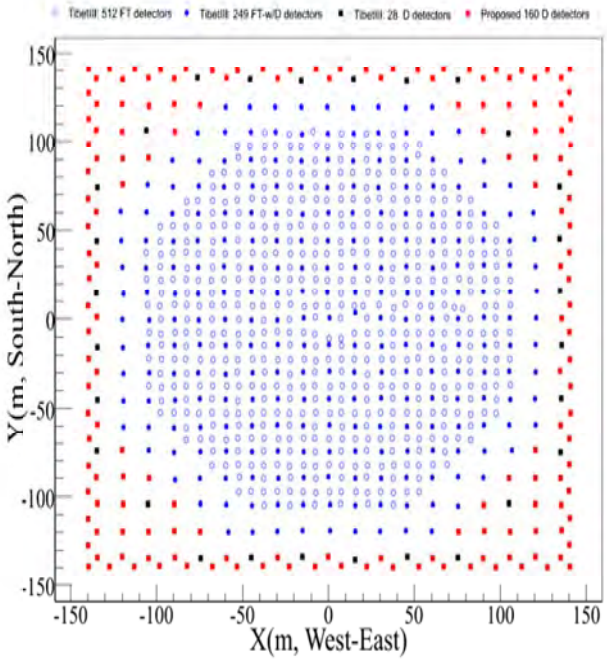

1）外缘30米间距
2）保护层15米；
3）内部7.5米间距

日方:50000M²



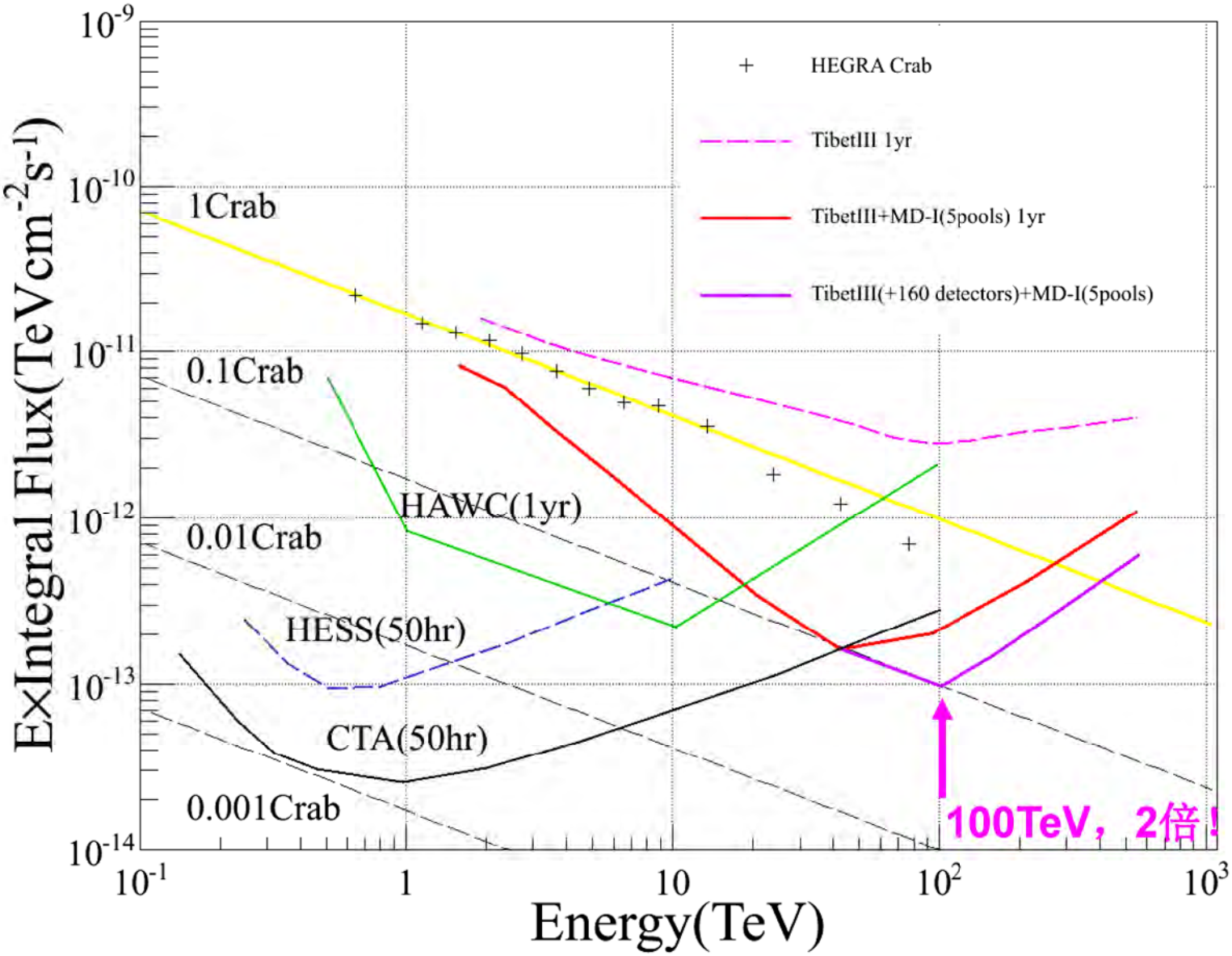

1）仅增加面积1/3；
2）牺牲TeV能区；
3）牺牲运行时间；

中方(已批准):72900M²

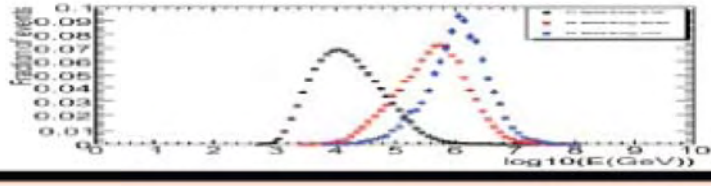



1）优化100TeV，花费少；
2）扩大面积达两倍；
3）中方有大的贡献

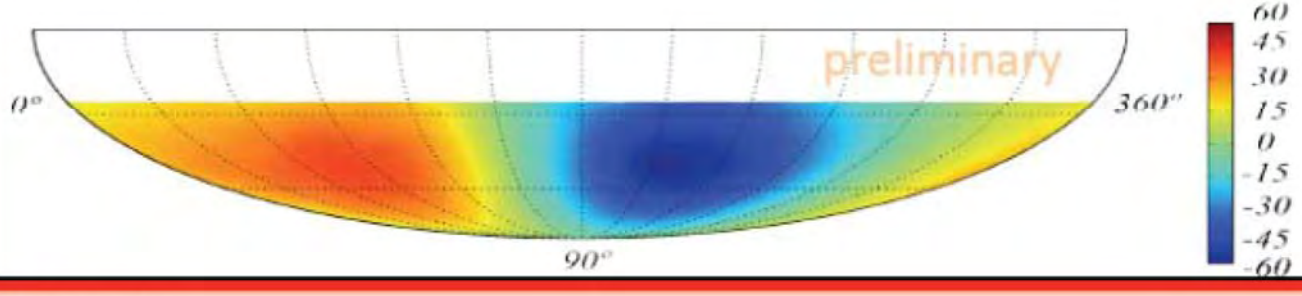
# 预计灵敏度:100TeV能区再提高2倍！



# A peak into the 1 PeV region

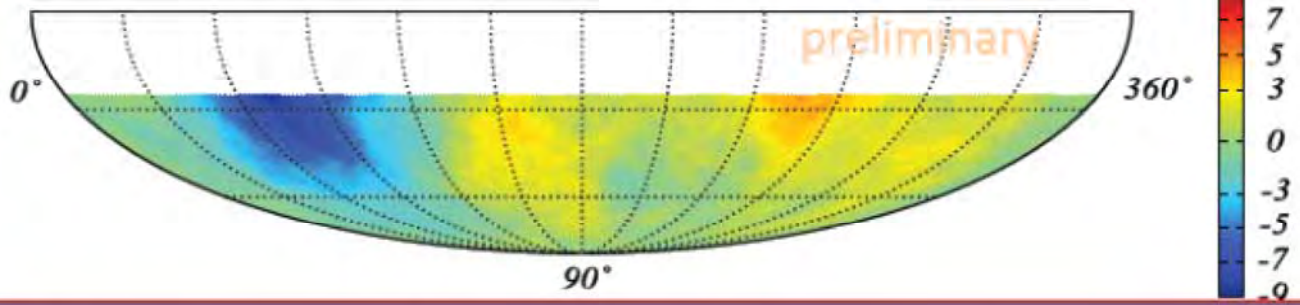



20 TeV



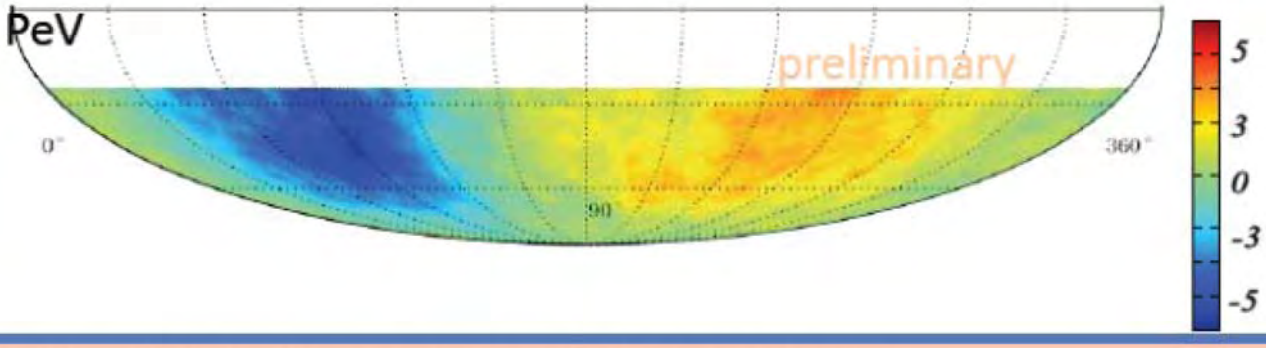

21 Billion events

400 TeV




580 Million events

1 PeV



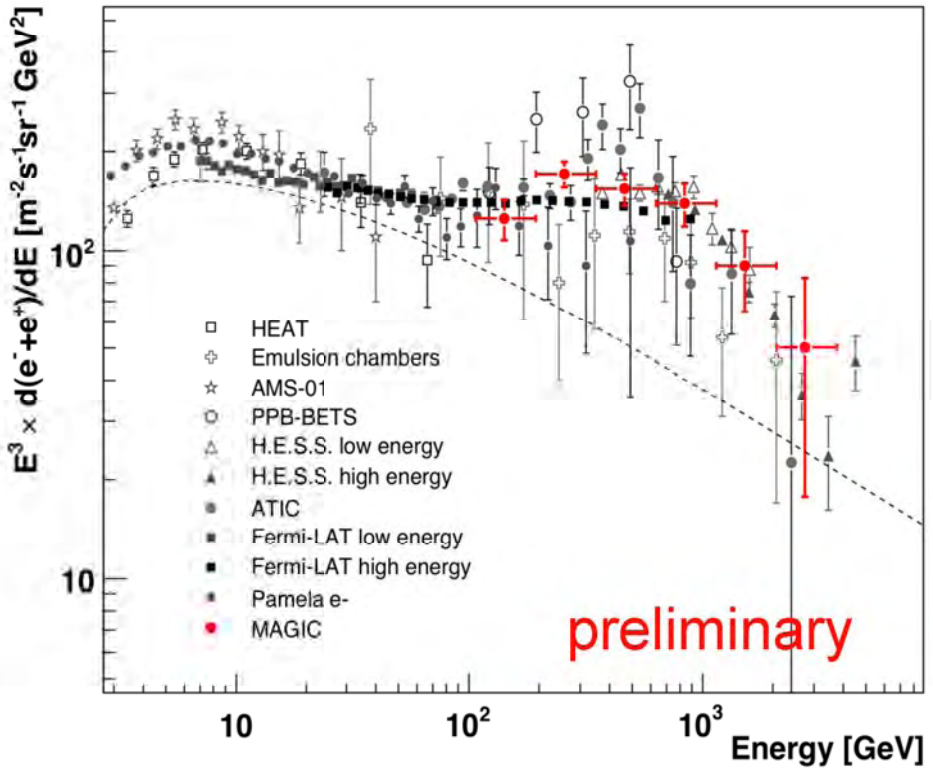

137 Million events

- *No identified significant Anisotropy in the 1 PeV skymap*
- *The anisotropy is persistent with that observed at 400 TeV*
- *IC86 will enable us to understand the energy dependence with higher statistics closer to the knee region*

SKLTP

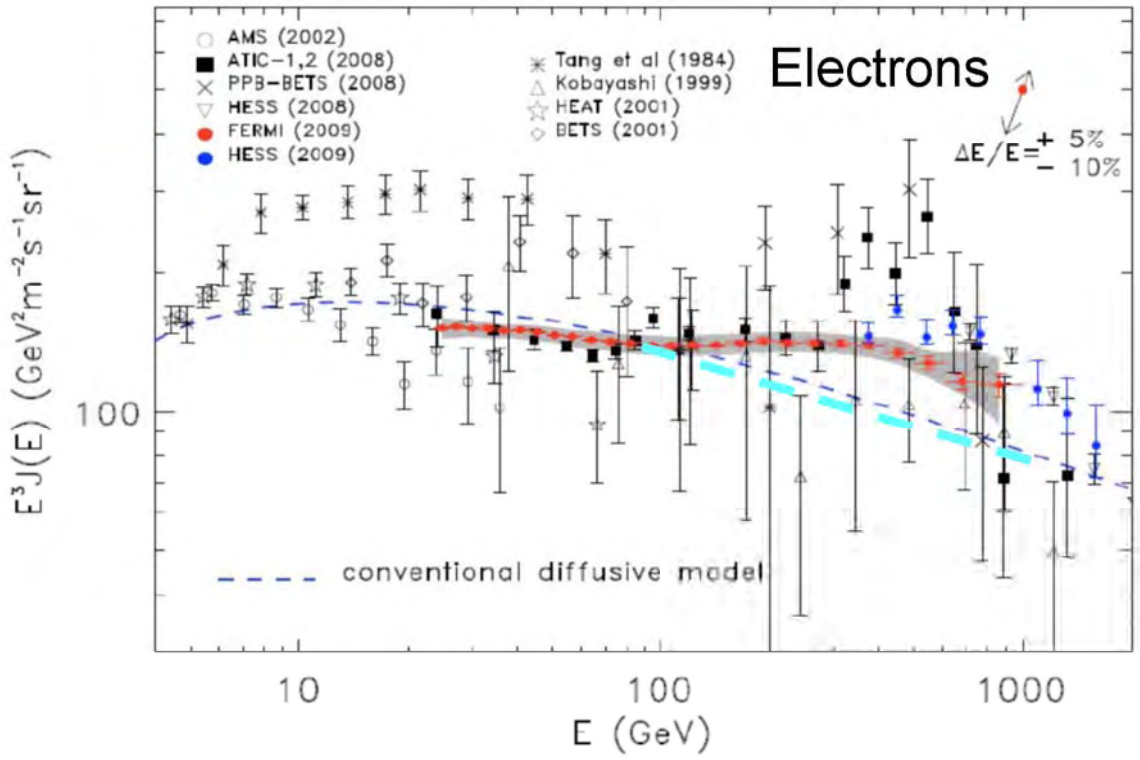
# CR $e^- + e^+$ spectrum

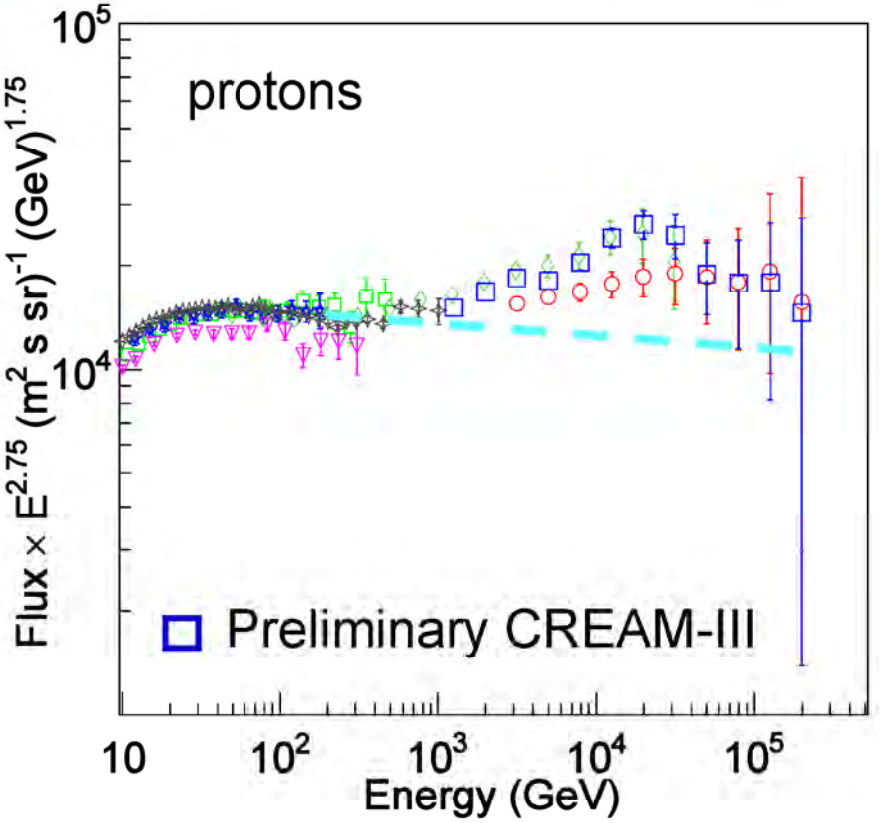
- See talk by Borla-Tridon, id680.
- First result based on only 14h of observations: measured $e^{\pm}$ spectrum in the energy range between **100 GeV and 3 TeV.**
- Preliminary results fitted by a power-law with index $\Gamma = -3.16 \pm 0.06_{stat} \pm 0.15_{sys}$.
- Spectrum in good agreement with previous measurements (bump observed by ATIC cannot be excluded or confirmed).




Related initiative: determine $e^+/e^-$ ratio by measuring the moon shadow. Observations ongoing, see talk by Colin, id1114

# Is a single mechanism/source responsible?

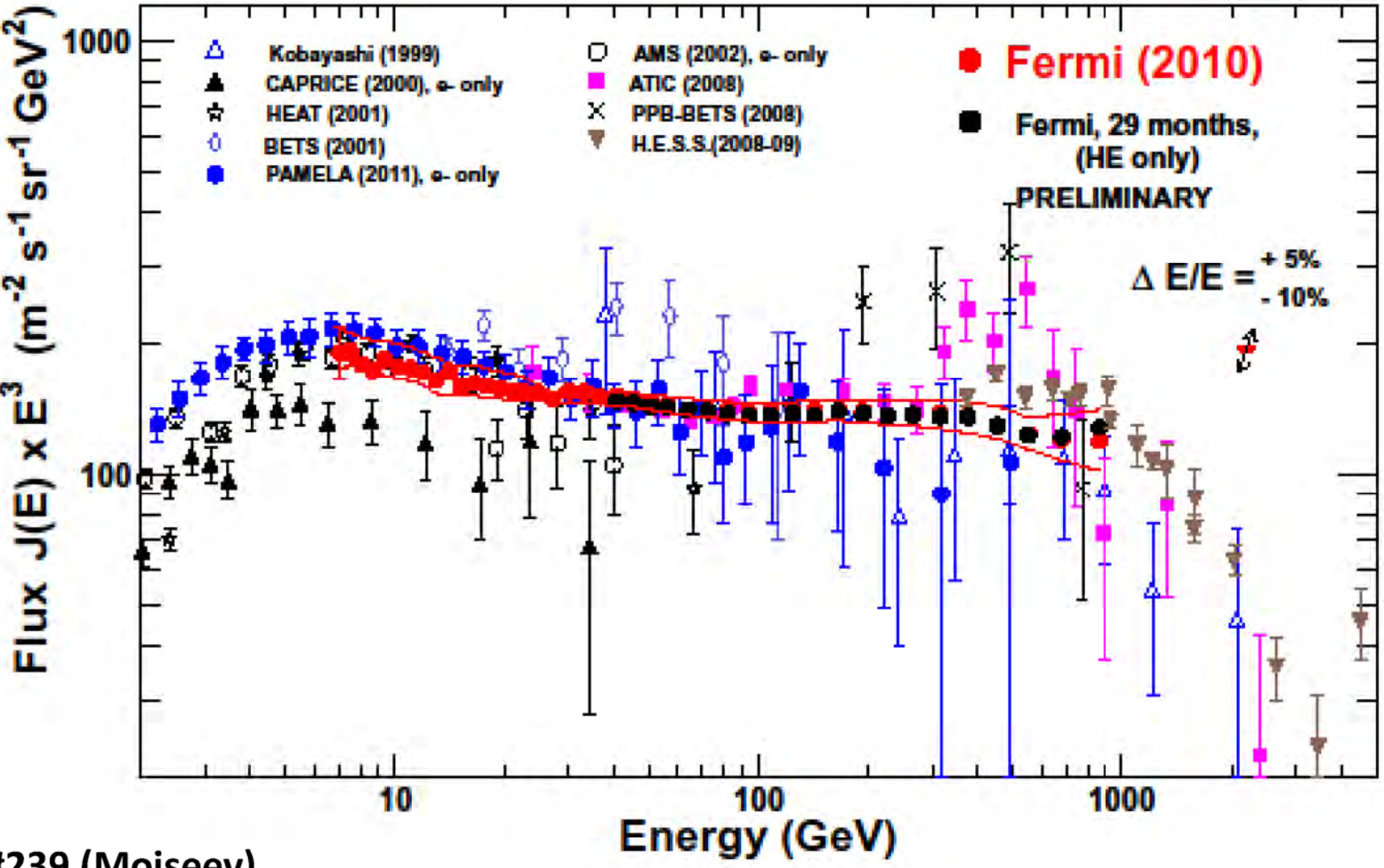



- Whatever the explanation, nuclear spectra must be accounted for in explanations of the electron anomaly and cosmic-ray "knee."
- An evidence of hadron sources within distances comparable to the range of electrons travelling through the ISM?

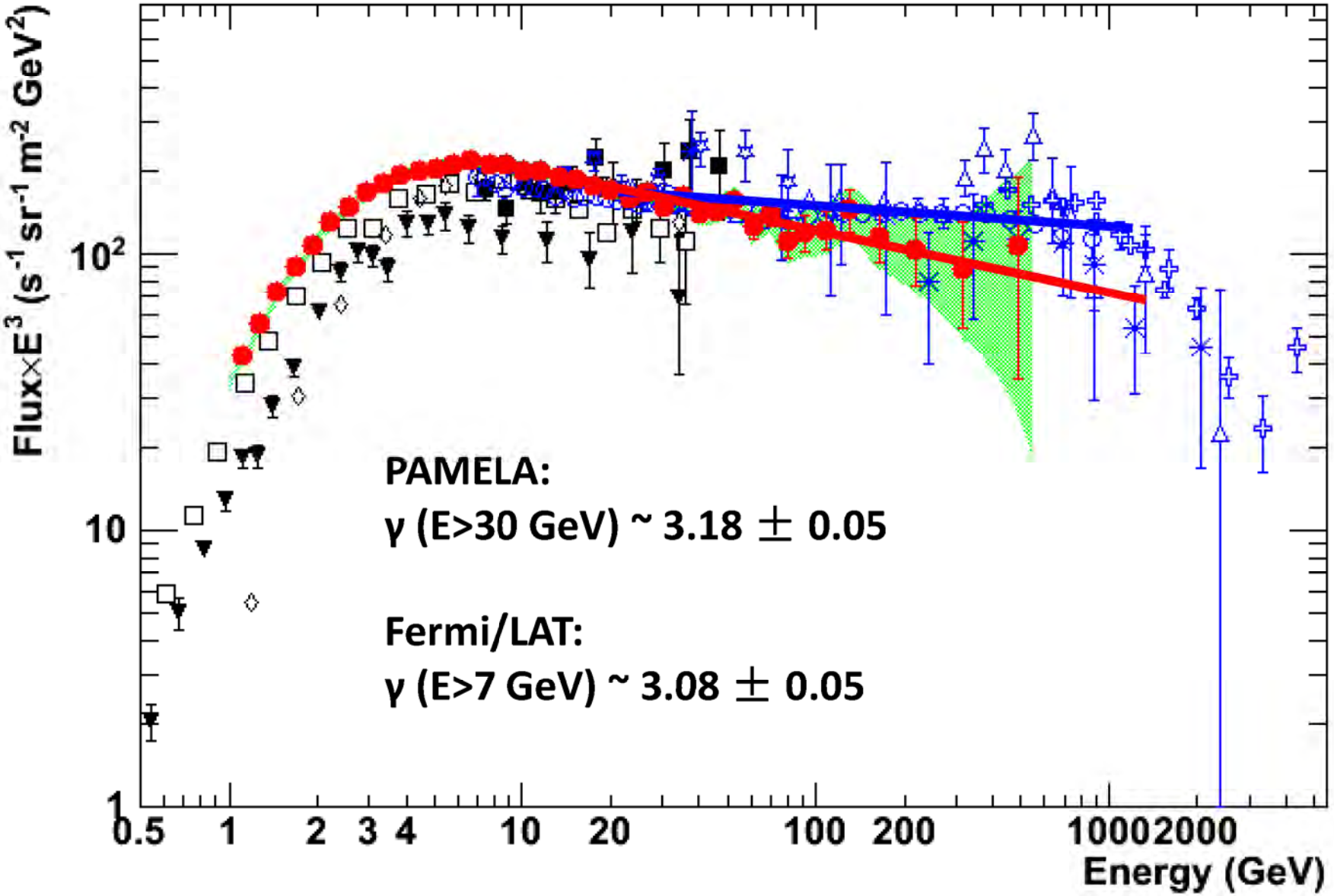
# Fermi/LAT 29month electrons

- Compatible with 2010 (1 year) measurement




#239 (Moiseev)

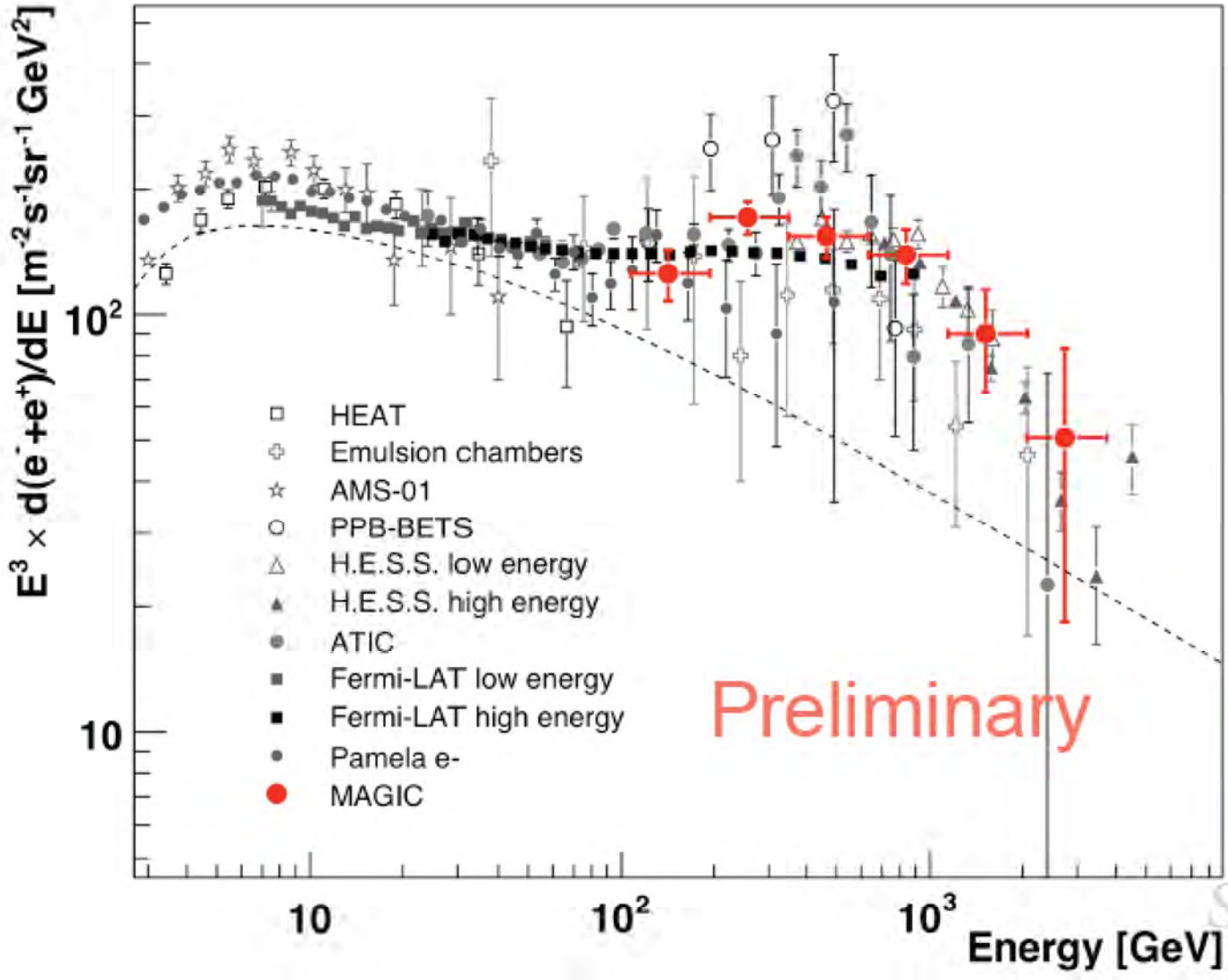
# PAMELA Spectrum (e- only)




#815 (Mocchiutti)

# MAGIC – IACT Method

- Spectrum in agreement with others – softer spectrum above ~1 TeV




**#680 - Tridon**

# A local source?