宇宙線観測と天体物理学
Astrophysics and Cosmic Ray Observation

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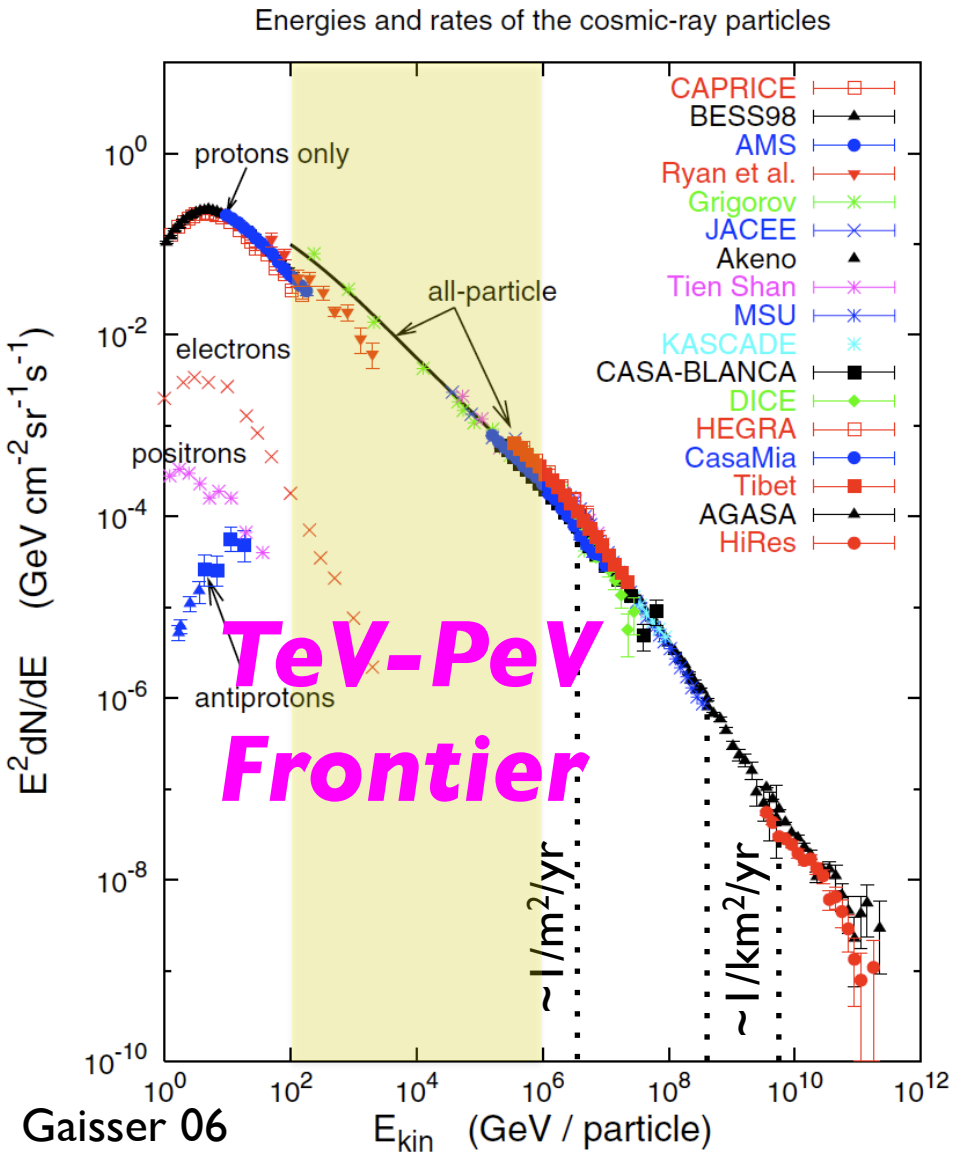
(Center for Gravitational Physics, YITP, Kyoto U.)

Not a complete review
but my biased view

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

KYOTO UNIVERSITY FOUNDED 1897
KYOTO JAPAN

Cosmic Rays



0th: Power law

$E<3\times10^{15}$eV (Knee)

$F\propto E^{-2.7}$

Supernova remnant

$L_{CR}\sim10^{41}$erg/s$\sim0.1E_{SN}/t_{SN}$

$<E<5\times10^{18}$eV (Ankle)

$F\propto E^{-3\text{-}3.2}$

Galactic origin?

$<10^{14\text{-}15}$eV by SNR?

$<E<4\times10^{19}$eV (GZK cutoff?)

$F\propto E^{-2.7}$

Extra-Galactic: AGN? GRB?

Contents

- ***$e^{\pm}$ excess: Astrophysical***
  - ✓ TeV spec., Anisotropy, … ***CALET***
- ***$\bar{p}$: No excess or pp?***
  - ✓ B/C ⇔ Li? ^{10}Be ***AMS-02***
- ***He, C, O : Superbubble?***
  - ✓ Ne, Mg, Si, Fe hardening?

Anti-^{3}He?

To date we have observed

a few events

with Z = -2 and

with mass around ^{3}He.

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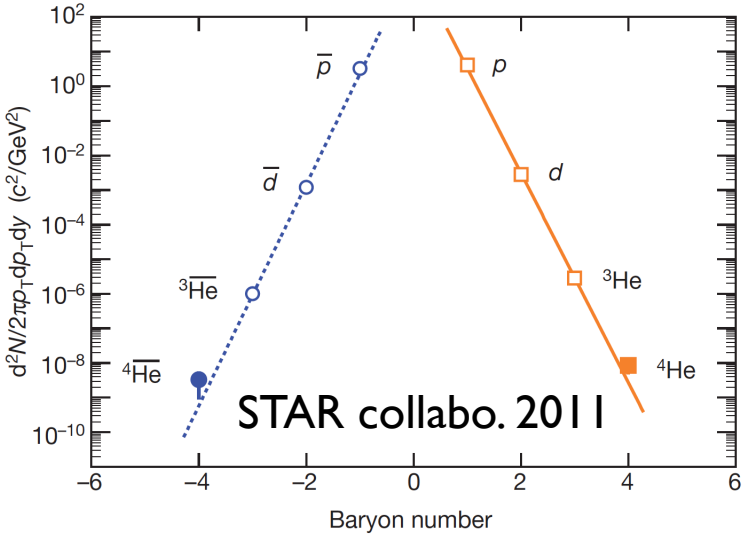
68

~anti-^{3}He/10^9 He

~anti-^{3}He/10^{10} p

~anti-^{3}He/10^6 anti-p

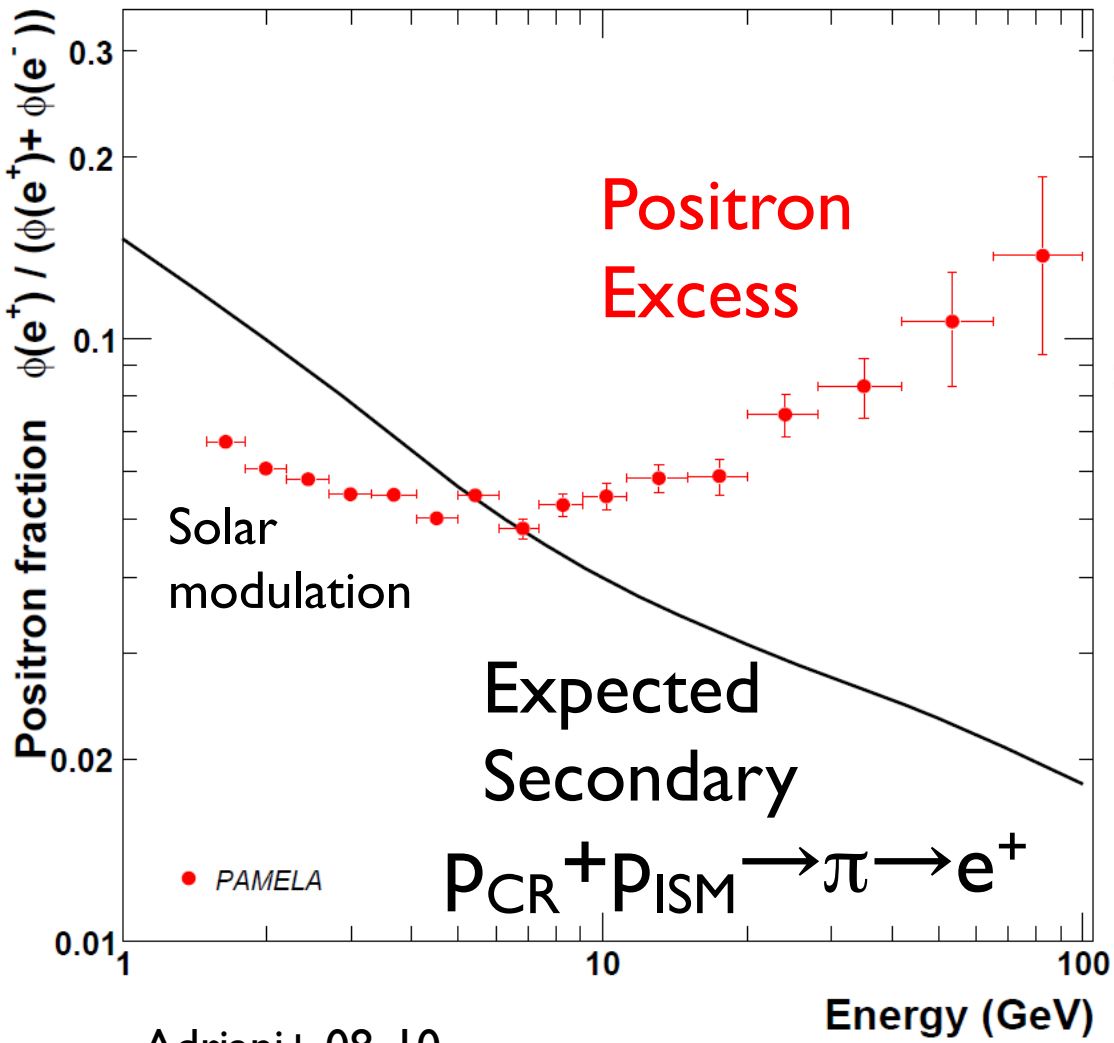


Differential invariant yields in central 200GeV Au+Au

Astrophysically POSSIBLE?

PAMELA

Positron excess above the predicted secondary



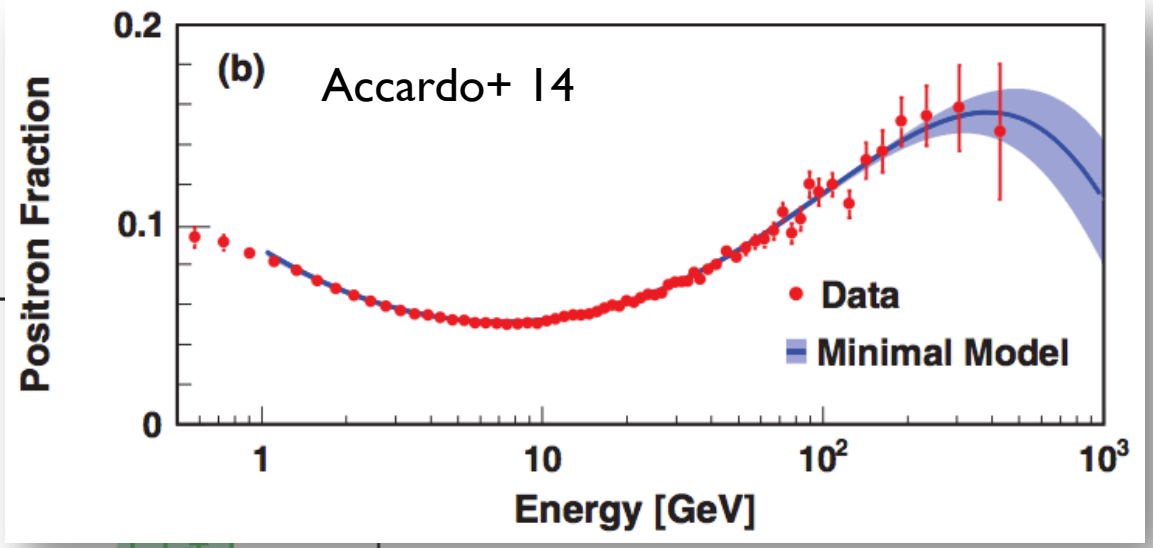
Adriani+ 08, 10

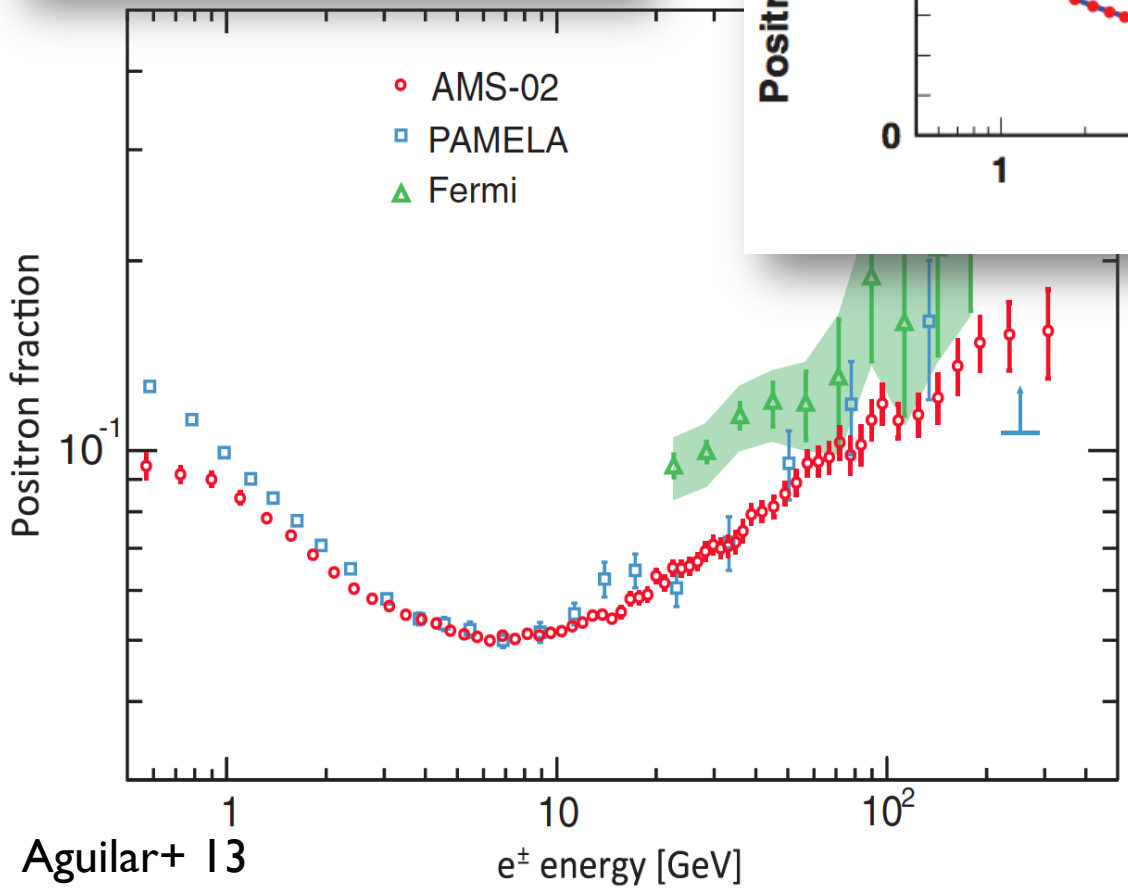
⇒ New sources
– Dark Matter?
– Astrophysical?

⇒ Many papers >10^3

Jul 06 - Feb 08
151672 e-, 9430 e+

AMS-02

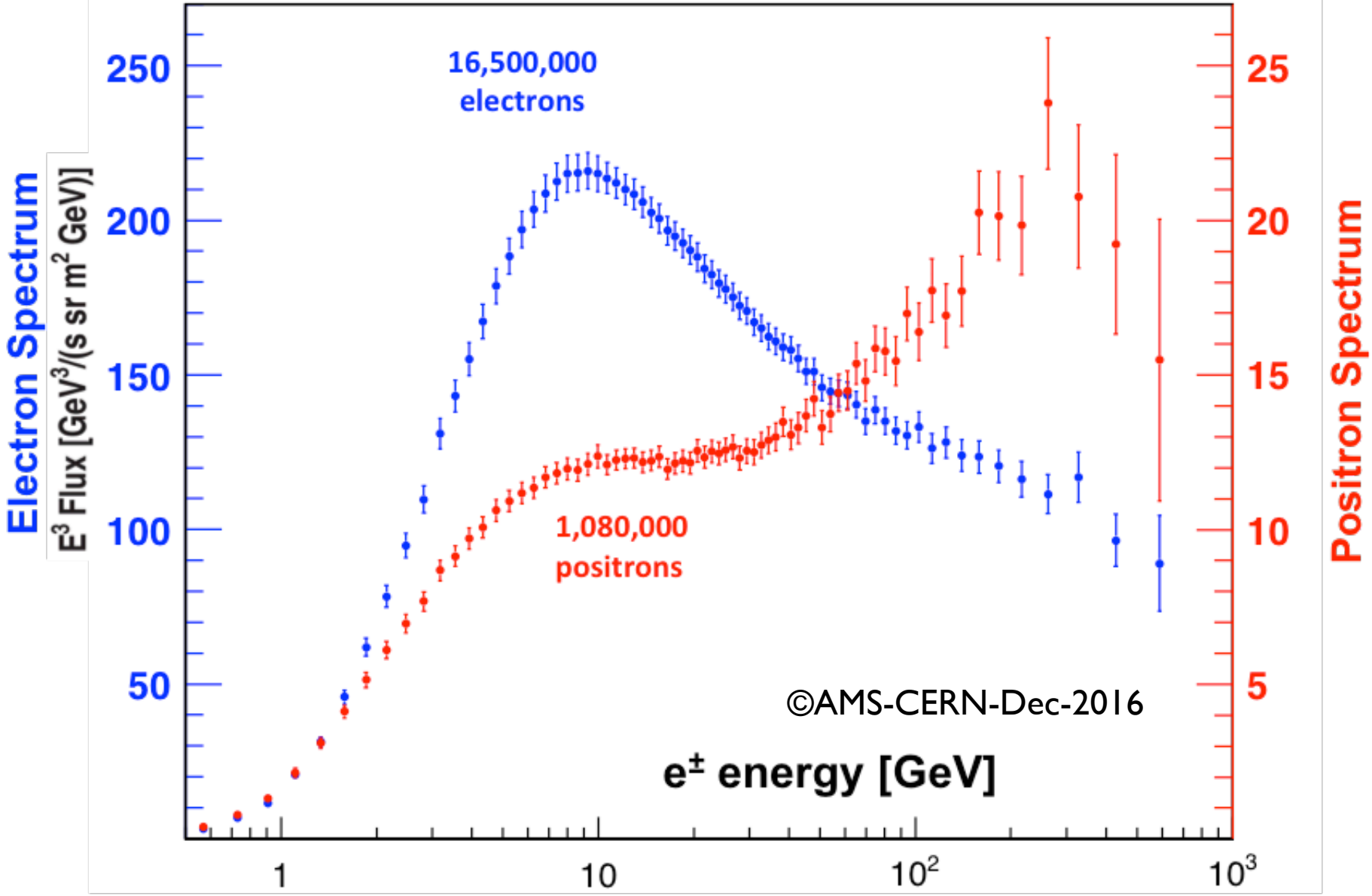




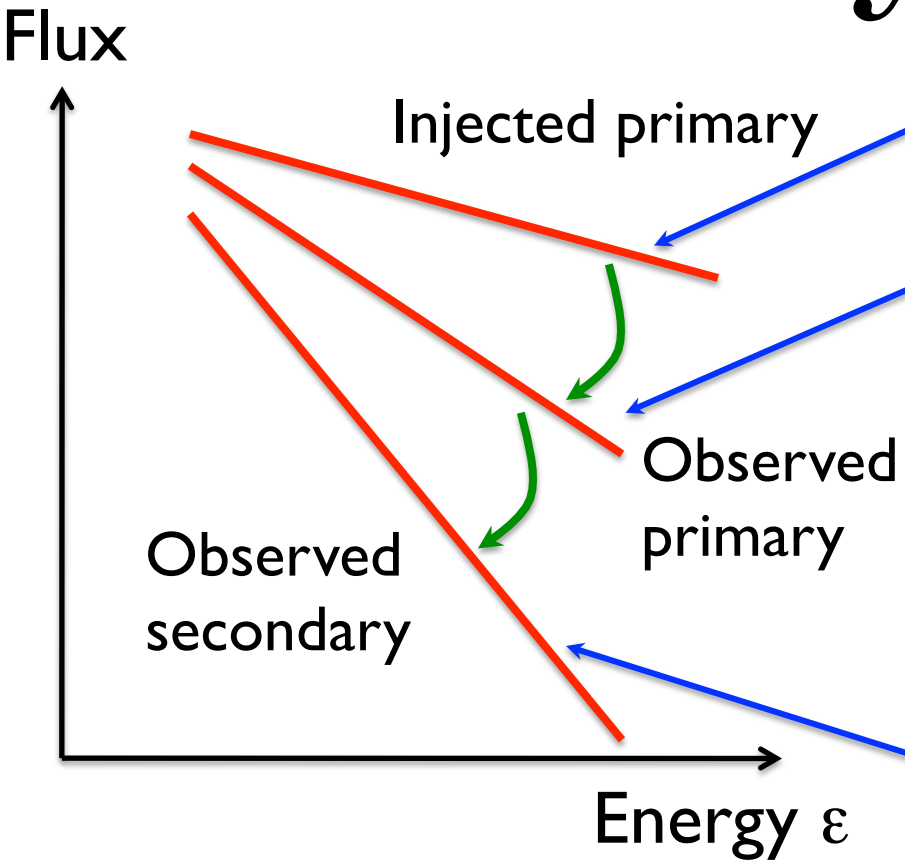
Aguilar+ 13

1. High precision
2. Up to ~500 GeV
3. No fine structure
4. Slope declines
5. No anisotropy
   δ<0.036 (95%CL)

AMS-02 $e^{\pm}$


16,500,000
electrons
1,080,000
positrons
©AMS-CERN-Dec-2016
e± energy [GeV]
Electron Spectrum
E³ Flux [GeV³/(s sr m² GeV)]
Positron Spectrum
250
200
150
100
50
25
20
15
10
5
1
10
10²
10³

Secondary Positrons



$$\Phi_1 \sim \tau_{\rm esc}(\varepsilon) \bullet Q_1(\varepsilon)$$

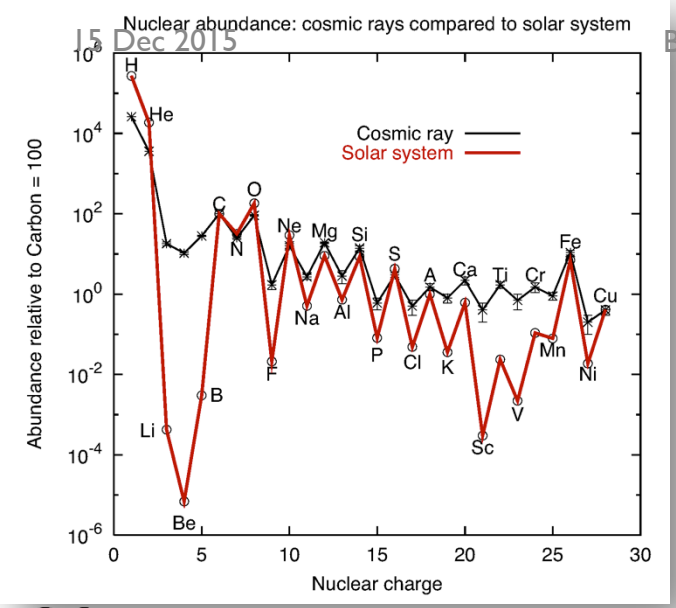
$$\propto \varepsilon^{-\delta} \bullet \varepsilon^{-\gamma}$$

$$Q_2(\varepsilon) \propto \sigma \bullet \Phi_1(\varepsilon)$$

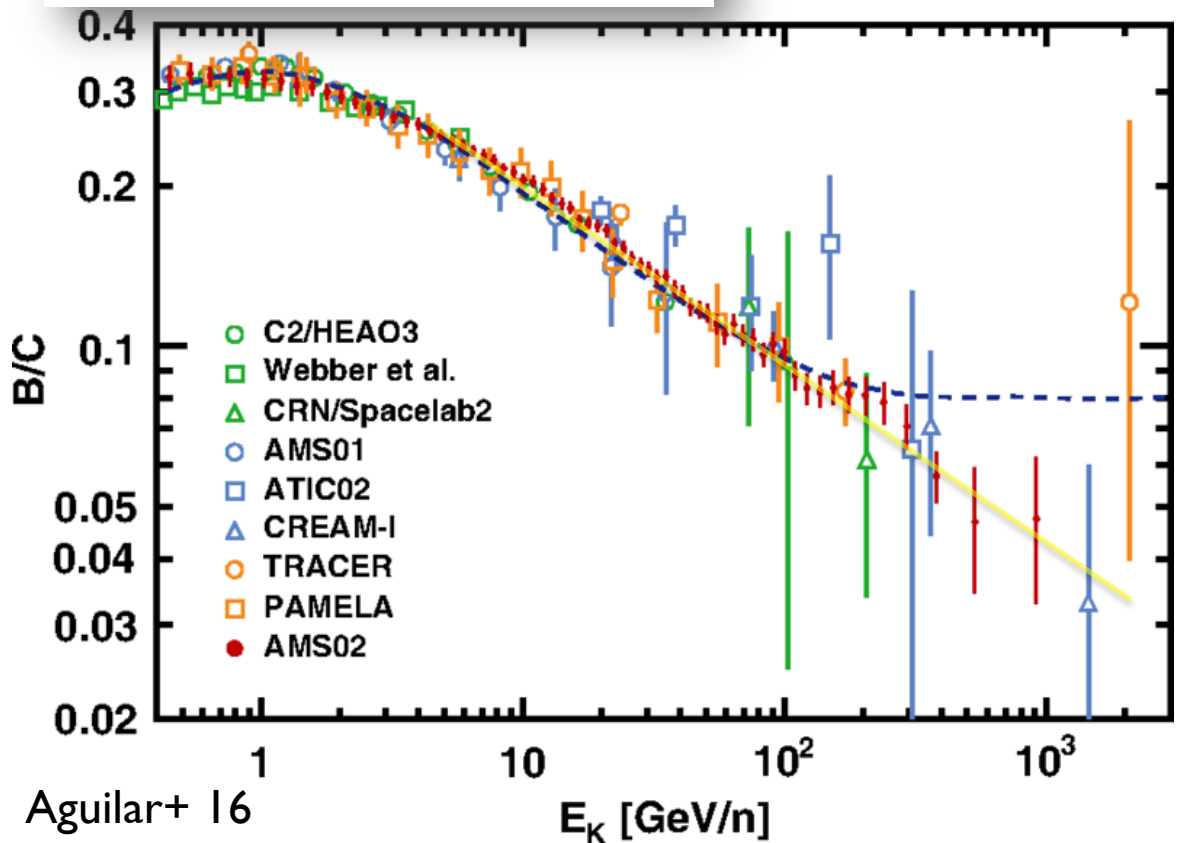
$$\Phi_2 \sim \tau_{\rm esc}(\varepsilon) \bullet Q_2(\varepsilon)$$

$$\propto \varepsilon^{-\delta} \bullet \varepsilon^{-\delta} \varepsilon^{-\gamma}$$

This is robust if escape/cooling is faster for higher energy



B/C



Aguilar+ 16

Boron is 2ndary of Carbon

$D_{diff} \sim D_0 (\varepsilon/\varepsilon_0)^{-\delta}$

$\delta \sim 0.333 \pm 0.015$

(Kolmogorov)

$D_0 \sim 2 \times 10^{28}$ cm^2/s

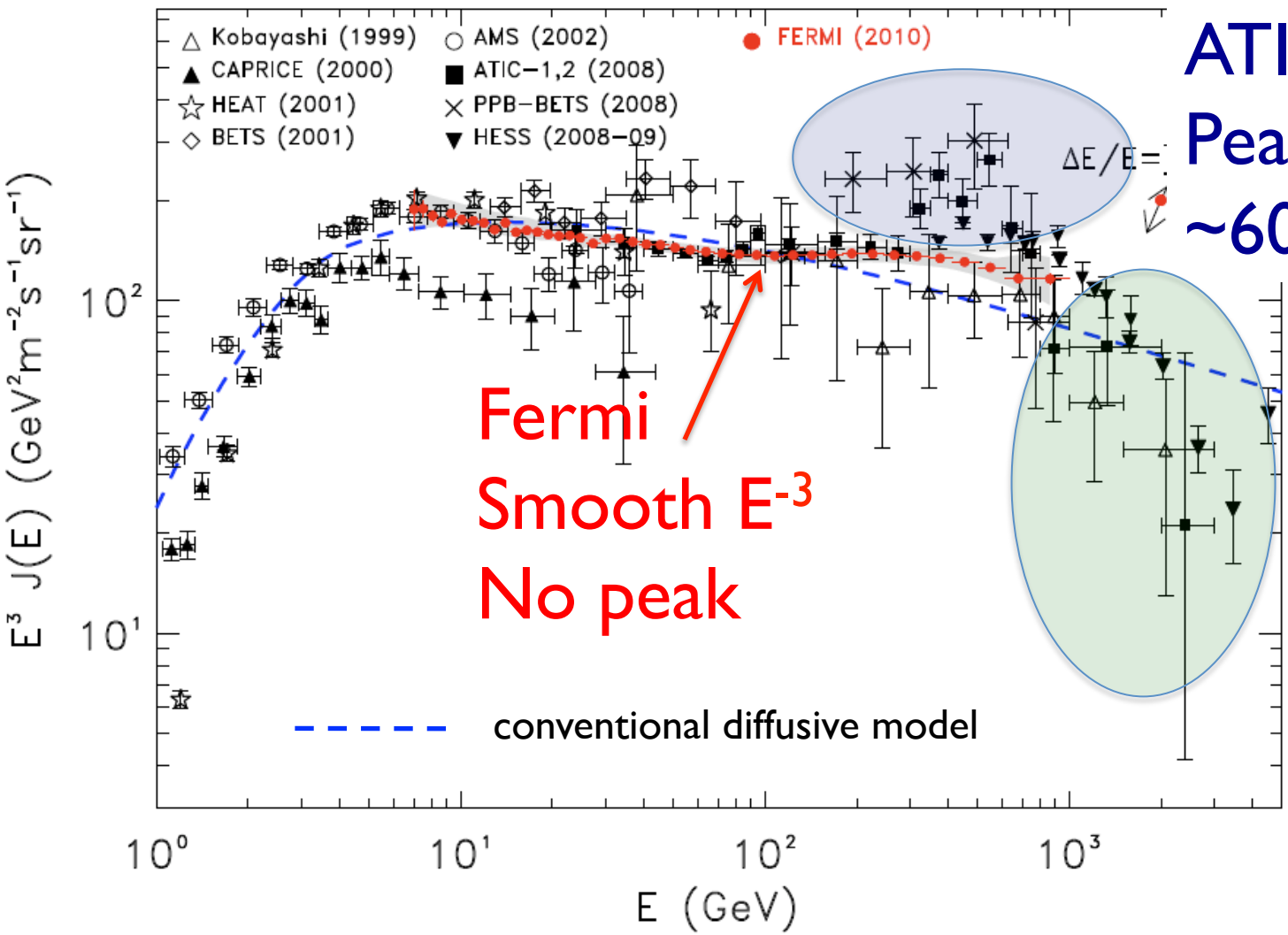
Subject to change by

- Disk & halo
- Wind convection
- Turbulent diffusion
- Reacceleration

Isotope ratio: ^{10}Be/^{9}Be

Cosmic-Ray Electron

An Excess also in (e^++e^-) Spectrum

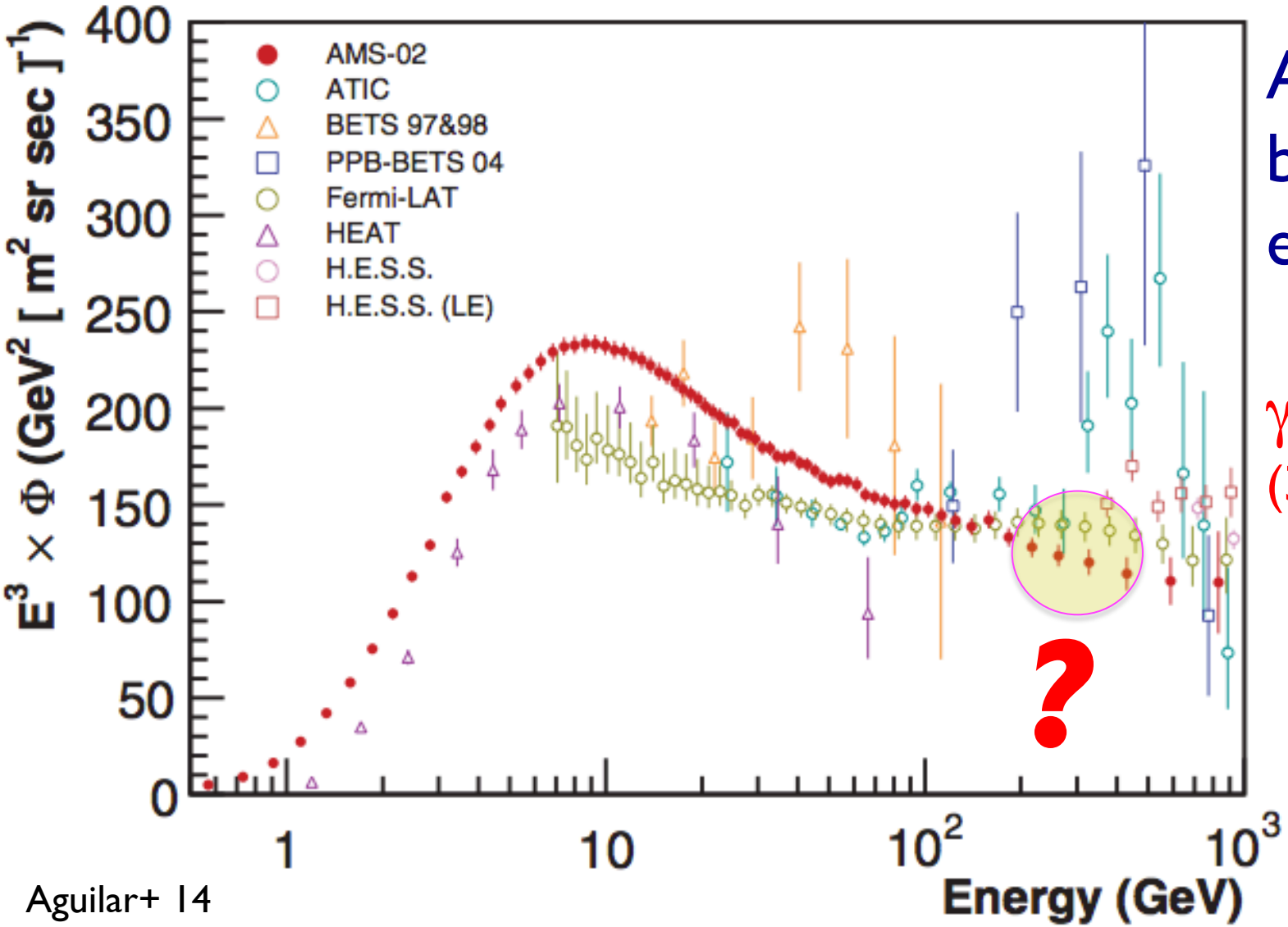


ATIC/PPB-BETS
Peak + Cutoff
~600GeV DM?

HESS
~TeV cutoff

Abdo+ 09
Ackermann+ 10
Chang+ 08, Torii+ 08
Aharonian+ 08, 09
Adriani+ 11

AMS-02 ($e^- + e^+$)



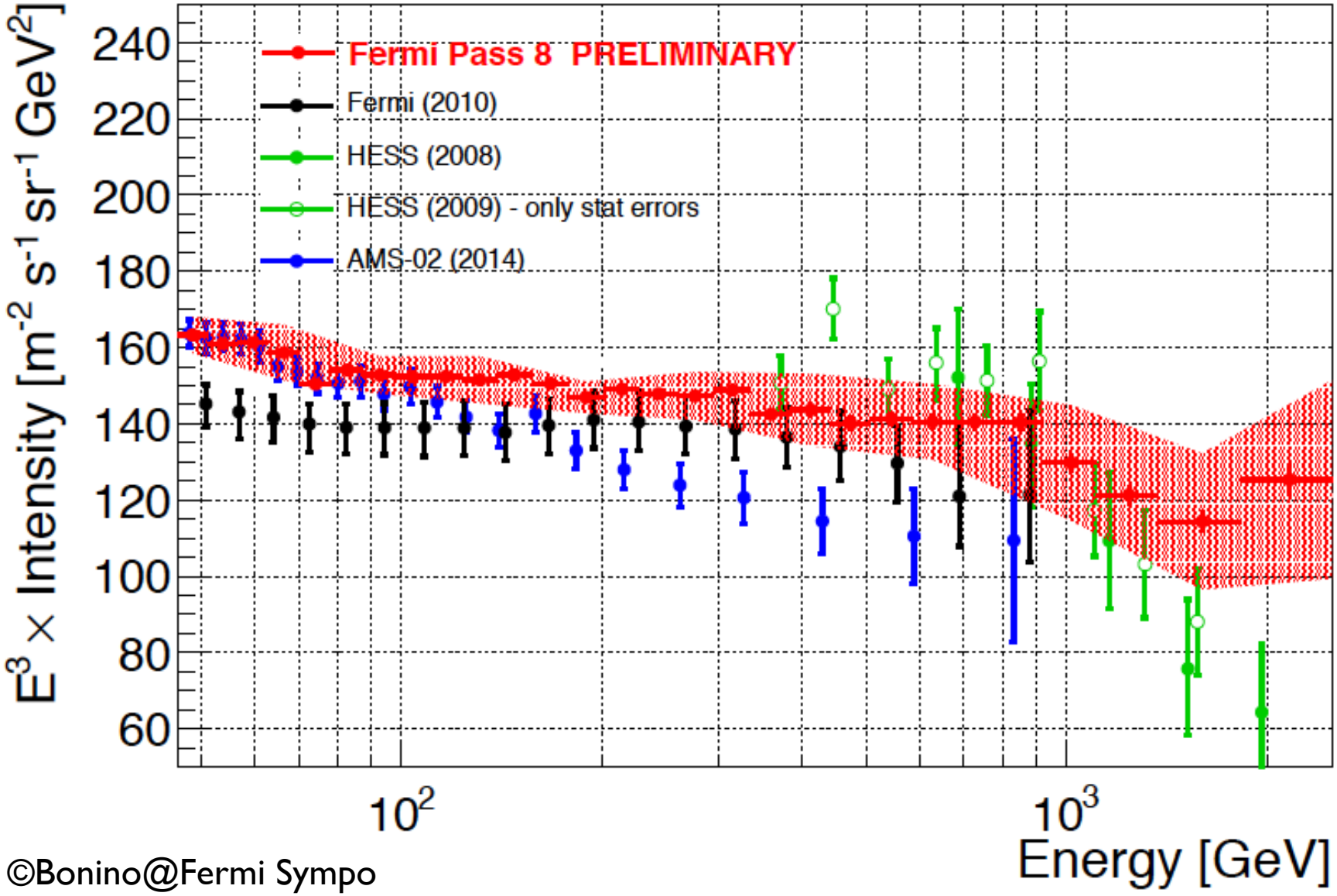
ATIC bump is excluded

γ=-3.17 (30GeV-1TeV)

⇔ Torii-san's talk

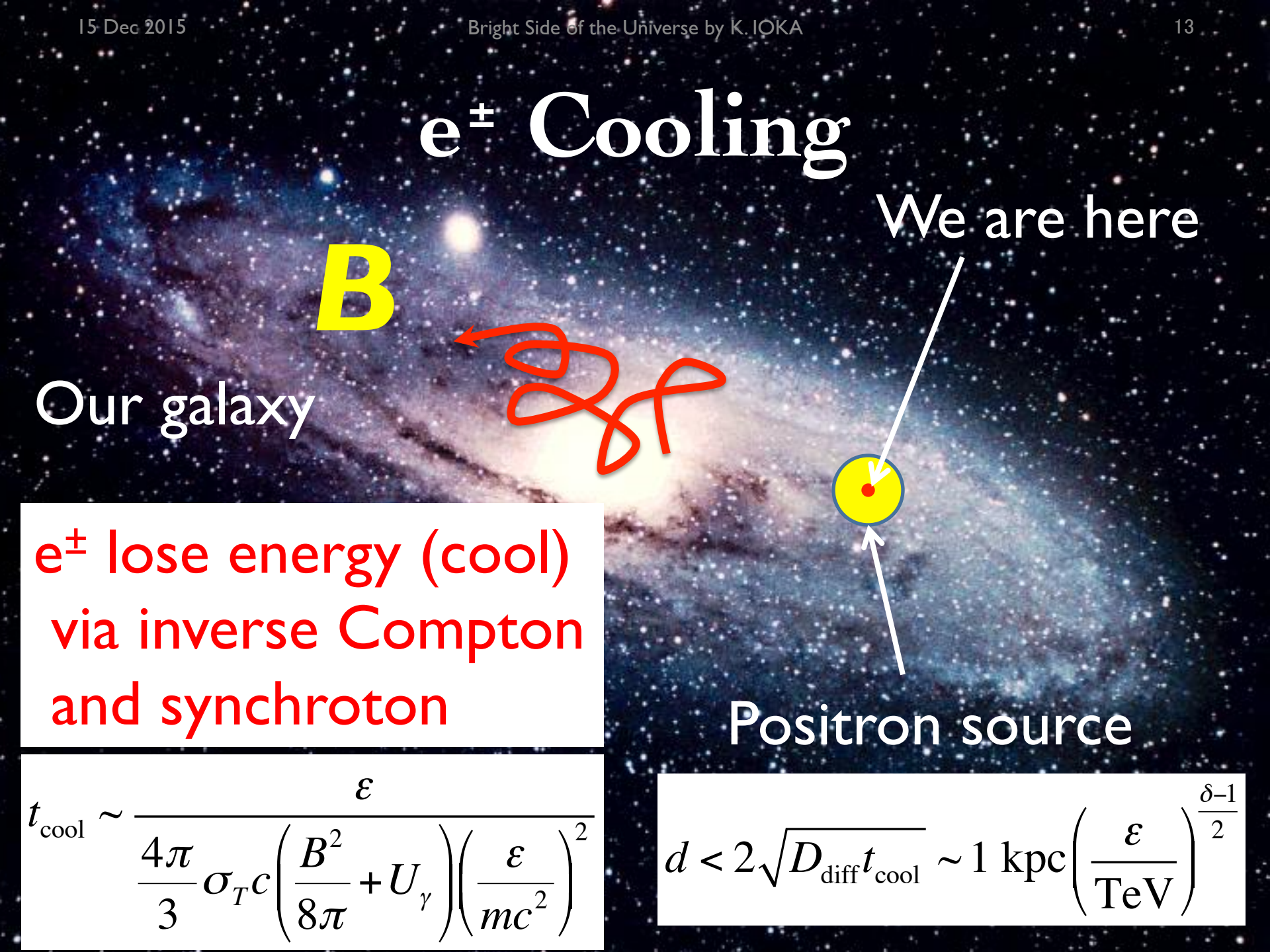
Aguilar+ 14

CRE inclusive spectrum



©Bonino@Fermi Sympo

$e^{\pm}$ Cooling

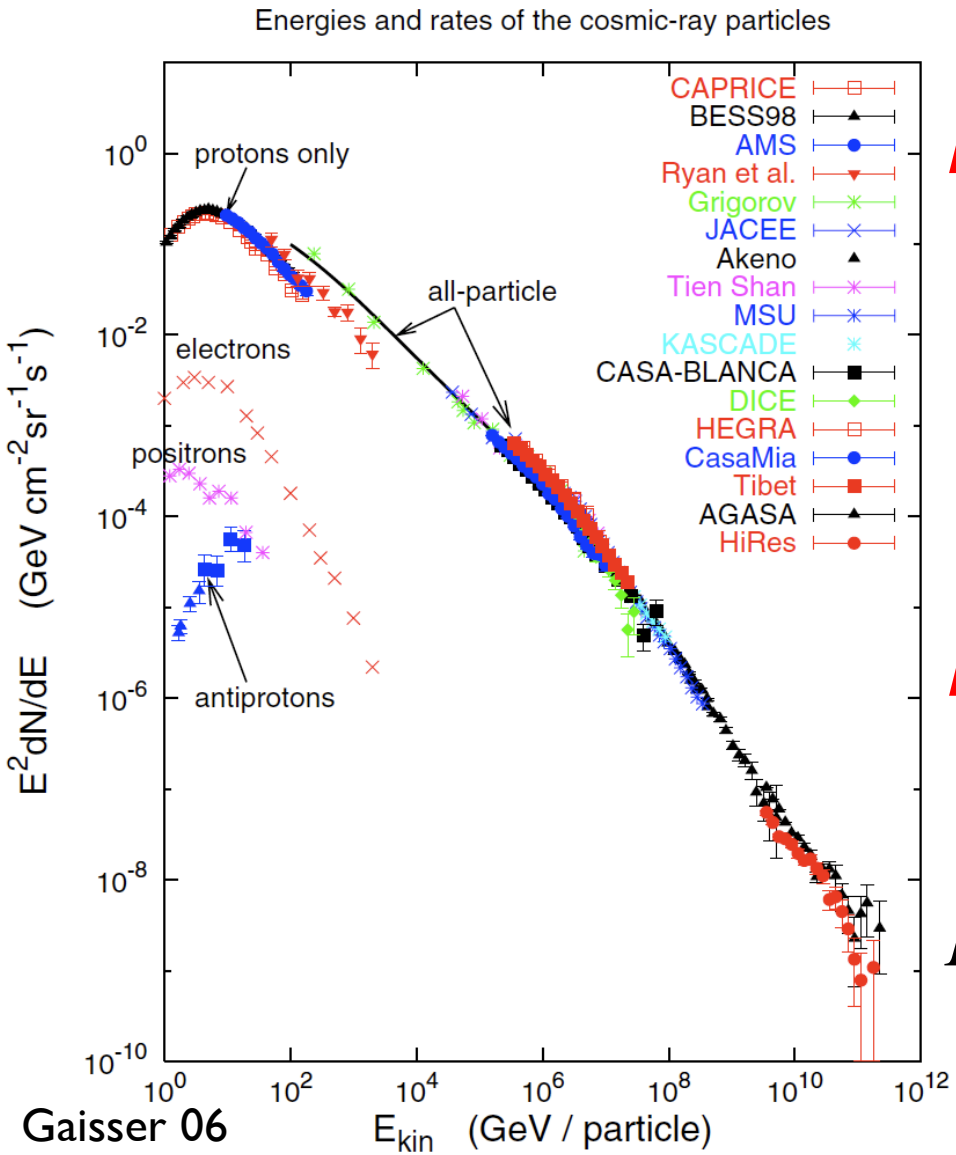


$e^{\pm}$ lose energy (cool) via inverse Compton and synchroton

$$t_{\rm cool} \sim \frac{\varepsilon}{\frac{4\pi}{3}\sigma_T c\left(\frac{B^2}{8\pi}+U_\gamma\right)\left(\frac{\varepsilon}{mc^2}\right)^2}$$

$$d < 2\sqrt{D_{\rm diff} t_{\rm cool}} \sim 1\ {\rm kpc}\left(\frac{\varepsilon}{\rm TeV}\right)^{\frac{\delta-1}{2}}$$

Energetics



Gaisser 06

$\rho_{proton} \sim 1\,\mathrm{eV/cm^3}$

Supernova

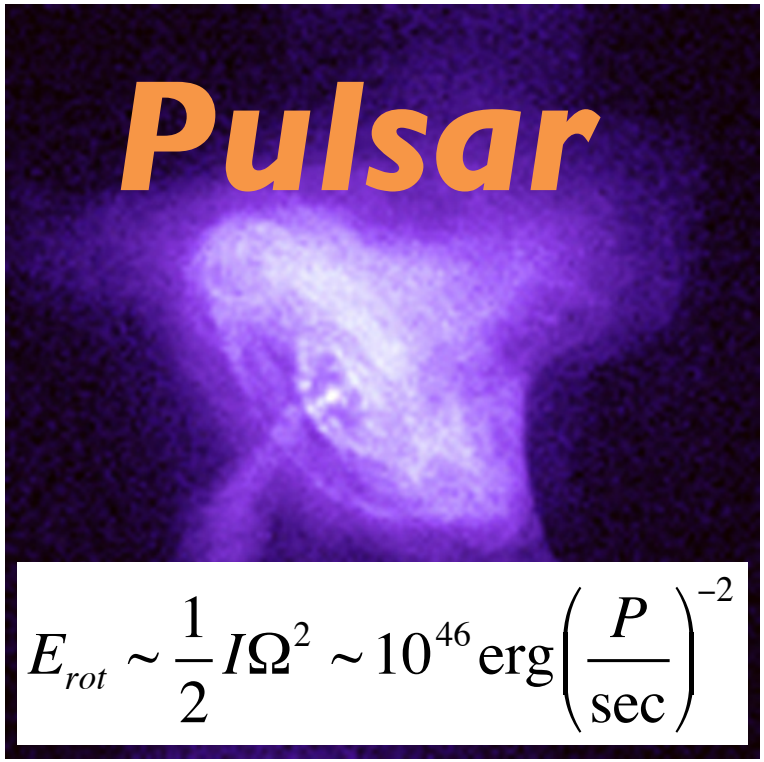
$$R_p \sim \frac{10^{50}\,\mathrm{erg}}{100\,\mathrm{yr}}$$

$\rho_{e+} \sim 10^{-4}\,\mathrm{eV/cm^3}$

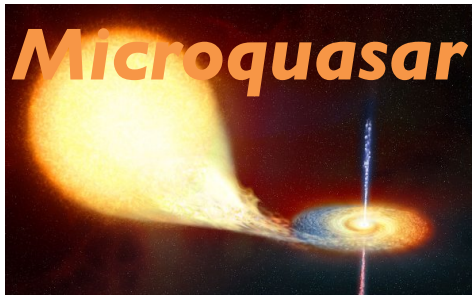
@10GeV

$$R_{e^+} \sim \frac{\rho_{e^+}}{\rho_p}\frac{t_{\mathrm{esc}}}{t_{\mathrm{cool}}} R_p \sim \frac{10^{46}\,\mathrm{erg}}{100\,\mathrm{yr}}$$

Astrophysical Models



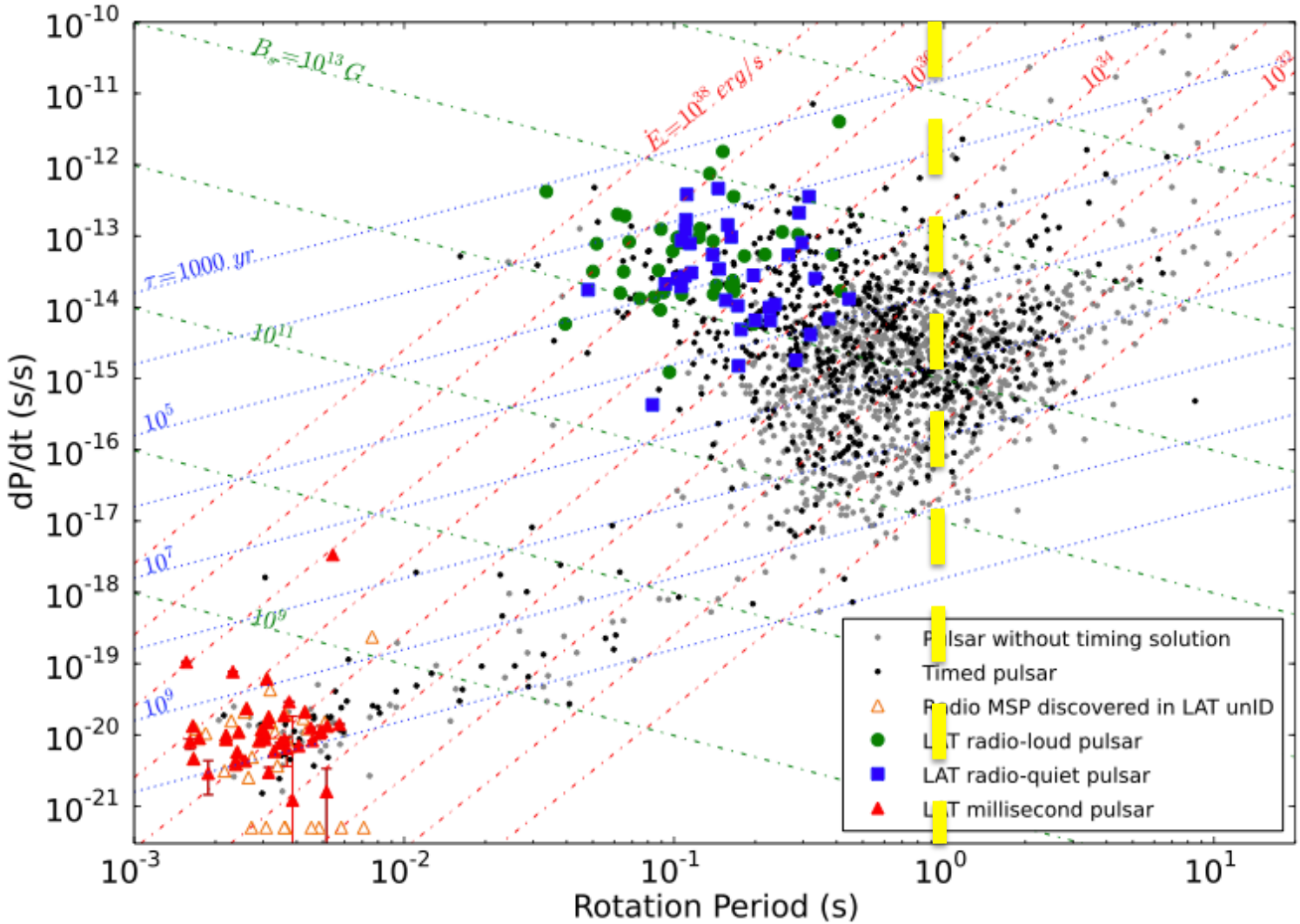
$$E_{rot} \sim \frac{1}{2} I\Omega^2 \sim 10^{46}\,\mathrm{erg}\left(\frac{P}{\mathrm{sec}}\right)^{-2}$$



Energy required for $e^{\pm}$ excess

$$R_{e^+} \sim \frac{\rho_{e^+}}{\rho_p}\frac{t_{\mathrm{esc}}}{t_{\mathrm{cool}}} R_p \sim \frac{10^{46}\,\mathrm{erg}}{100\,\mathrm{yr}}$$

Pulsars



Fermi:

γ-ray PSRs

6 → >160

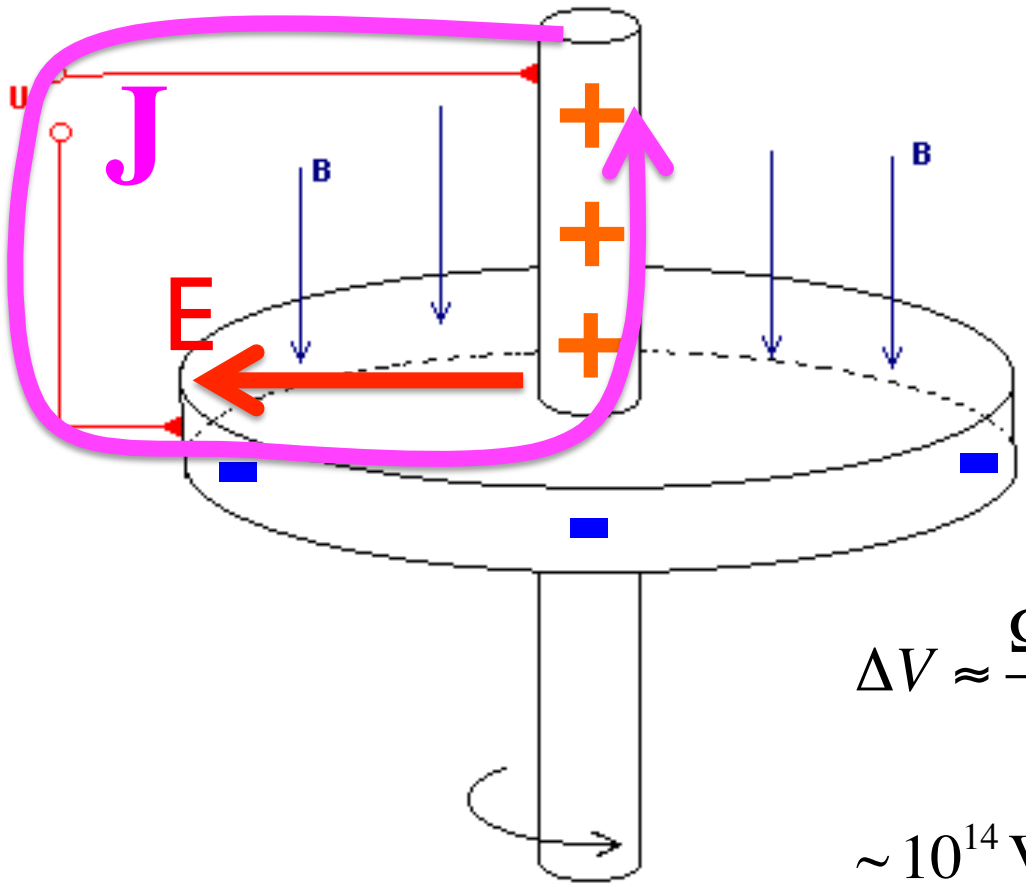
γ-ray MSPs

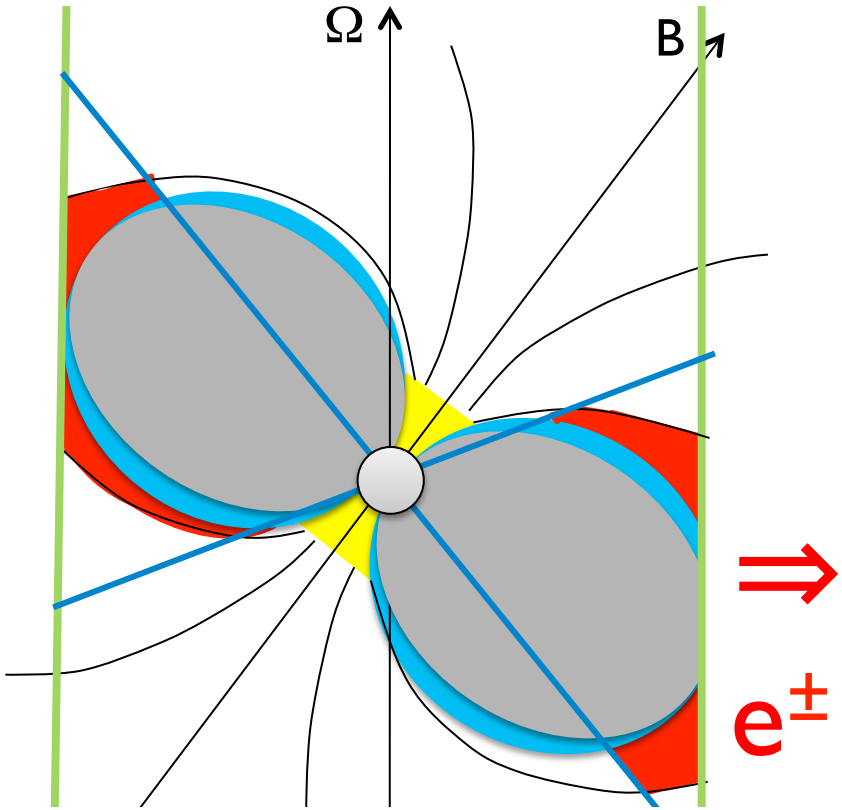
0 → >60

Abdo+ 13

Pulsars = $e^{\pm}$ Accelerators

Unipolar induction





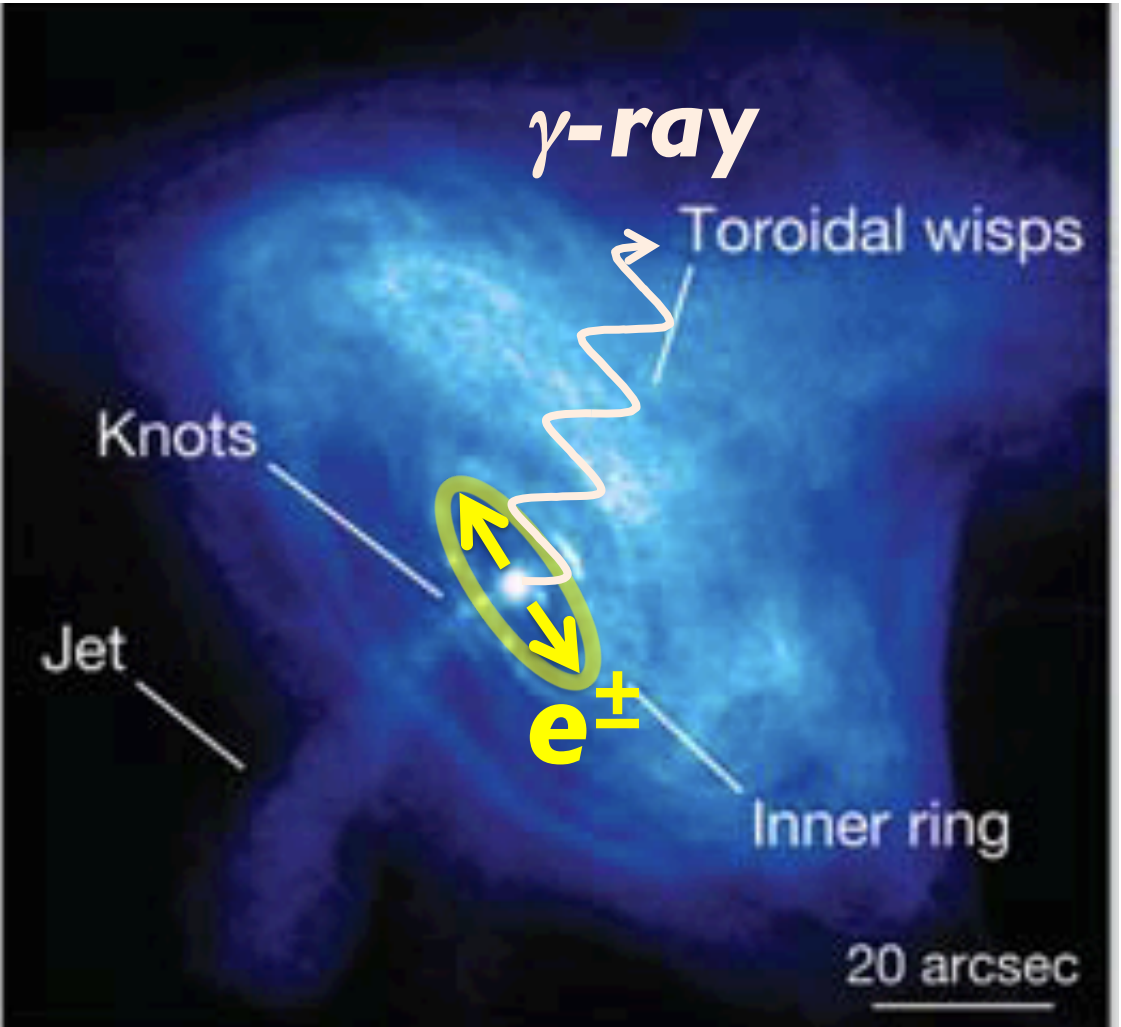
$$\Delta V \approx \frac{\Omega^2 B R^3}{2c^2}$$

$$\sim 10^{14}\,\mathrm{V}\left(\frac{\Omega}{1\ \mathrm{s}^{-1}}\right)^2\left(\frac{B}{10^{12}\,\mathrm{G}}\right)\left(\frac{R}{10^6\,\mathrm{cm}}\right)^3$$

Goldreich & Julian 69

Pulsar Wind Nebula

Most spin-down energy ⇒ Pulsar wind



(Relativistic plasma of magnetized $e^{\pm}$)

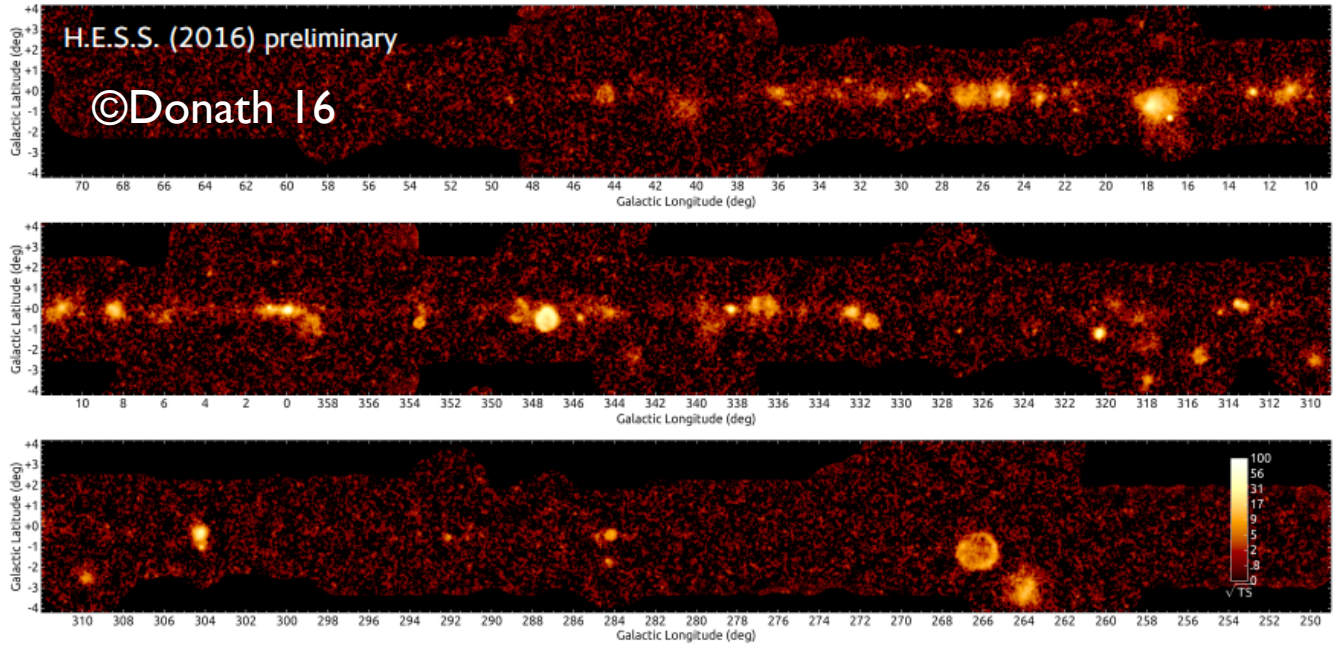
$$L_{e^{\pm}} \sim 10 L_{\gamma}$$

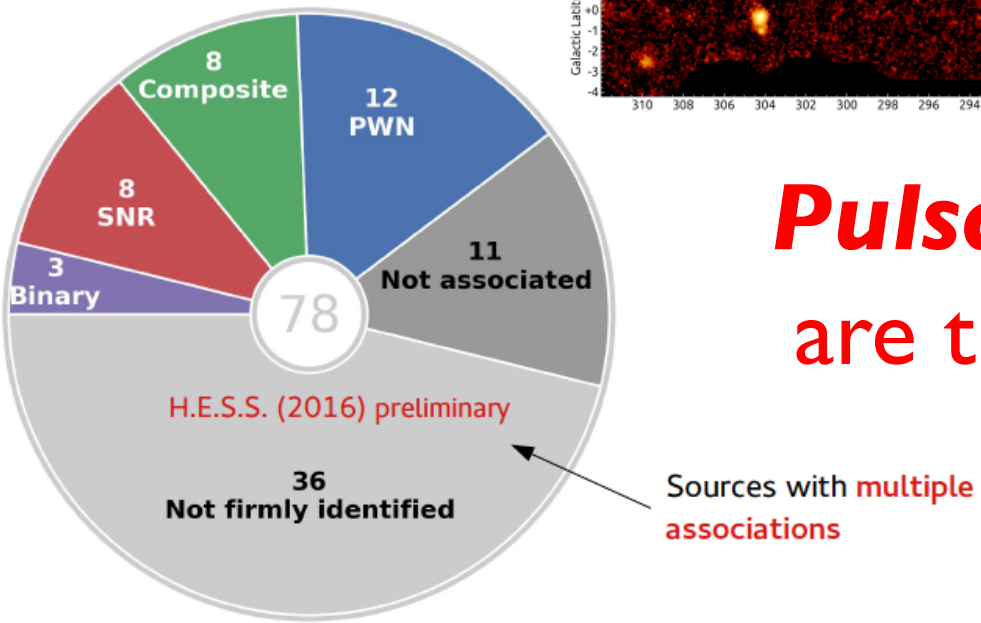
Termination shock
⇒ $e^{\pm}$ acceleration
⇒ Power law spec.

PWN→SNR→ISM

TeV Gamma-Ray Sky

TeV γ-ray sources in the Milky Way (Galactic disk)

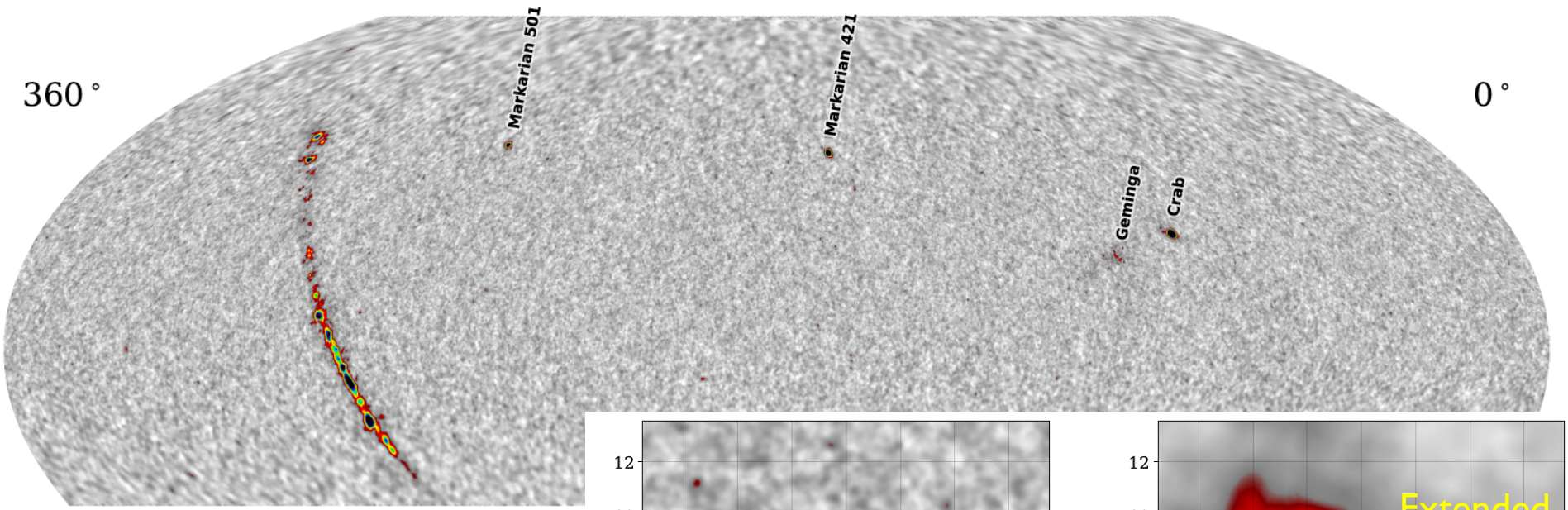


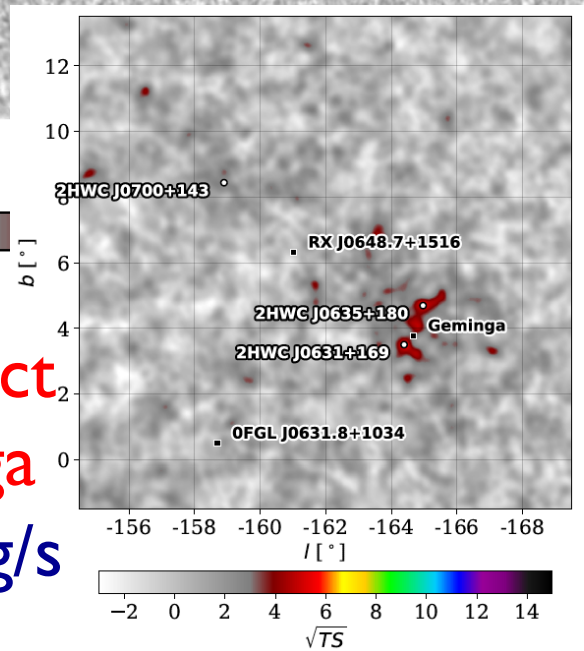


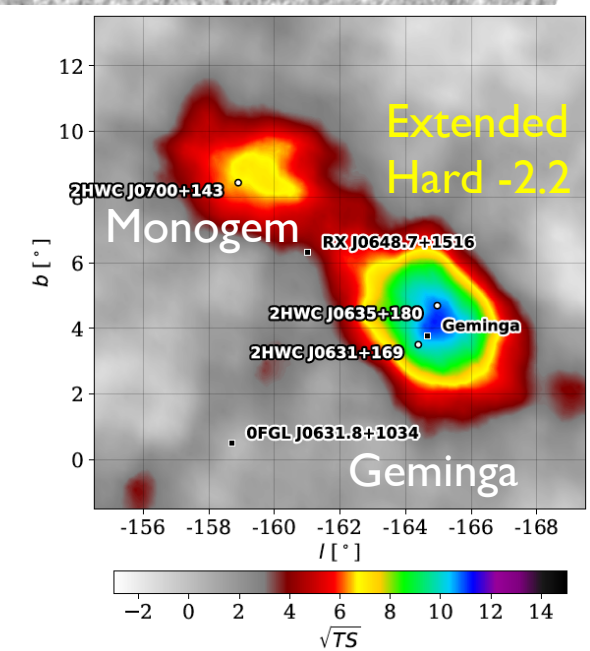
Pulsar Wind Nebula are the dominant class

Caveat: Most are unidentified

HAWC







HAWC & Milagro detect TeV γ-ray from Geminga

250pc, 342kyr, 3e34 erg/s

$e^{\pm}$ Propagation

$$\frac{\partial}{\partial t} f\left(t,\varepsilon_e,\vec{x}\right) = \boxed{K(\varepsilon_e)\nabla^2 f} + \boxed{\frac{\partial}{\partial \varepsilon_e}\left[b\varepsilon_e^2 f\right]} + \boxed{q\left(t,\varepsilon_e,\vec{x}\right)}$$

Diffusion

Energy loss by IC & synchro.

Injection

$$b \sim 10^{-16}\mathrm{GeV}^{-1}\mathrm{s}^{-1}$$

$$K(\varepsilon_e) \sim 5.8\times 10^{28}\mathrm{cm}^2\mathrm{s}^{-1}\left(1+\frac{\varepsilon_e}{4\mathrm{GeV}}\right)^{1/3}$$ ← B/C ratio

For a single burst with $q \propto \varepsilon_e^{-\alpha}$ Power law spectrum

$$f = \frac{q_0 \varepsilon_e^{-\alpha}}{\pi^{3/2} d_{diff}^3}\left(1-bt\varepsilon_e\right)^{\alpha-2} e^{-\left(d/d_{diff}\right)^2}$$

Atoyan+ 95, Shen 70

Spatially uniform over

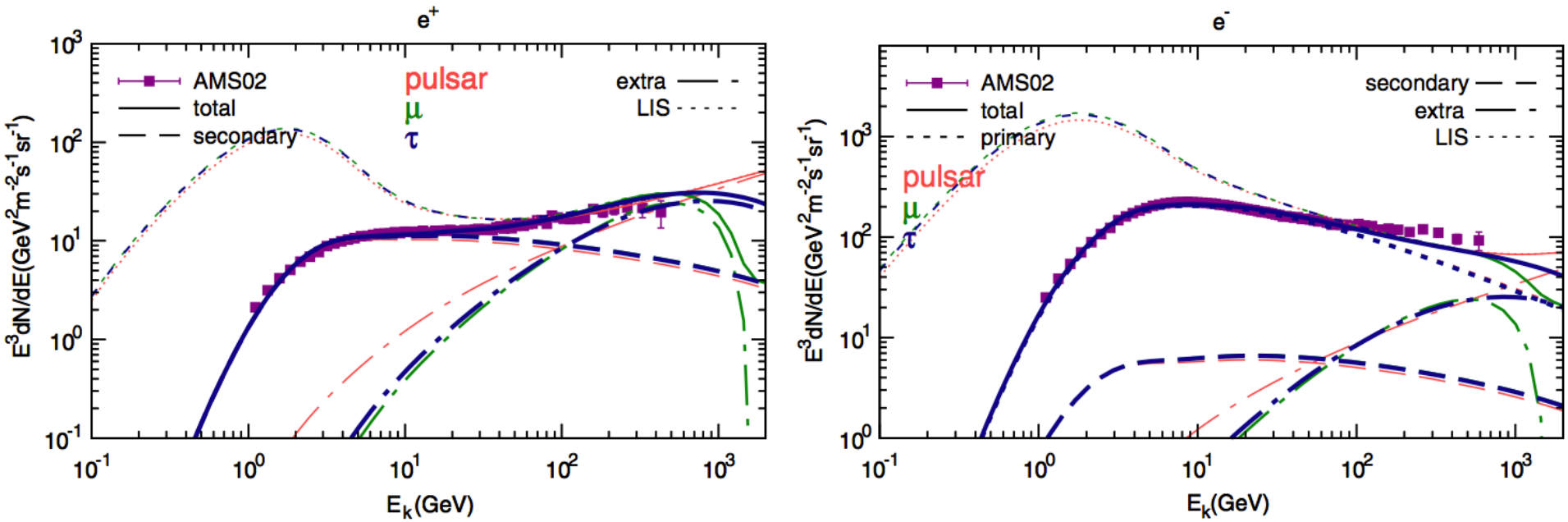
$$d_{diff}\left(t,\varepsilon_e\right) \sim 2\left[K(\varepsilon_e)t\right]^{1/2}$$

Spectral cutoff

$$\varepsilon_{\mathrm{cut}} \sim \frac{1}{bt}$$

Spectral Fitting

Astrophysical models reproduce e^+ & e^- spectra



Lin+ 15 and many others

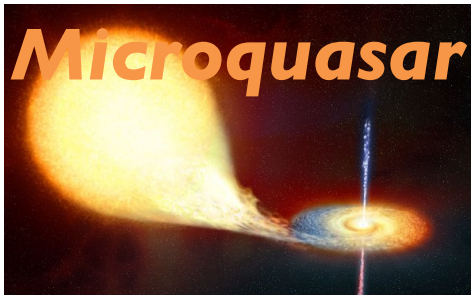
Supported by astrophysical observations

Consistent with a charge symmetric source term

Primary e^- spectrum may have hardening

Astrophysical Models

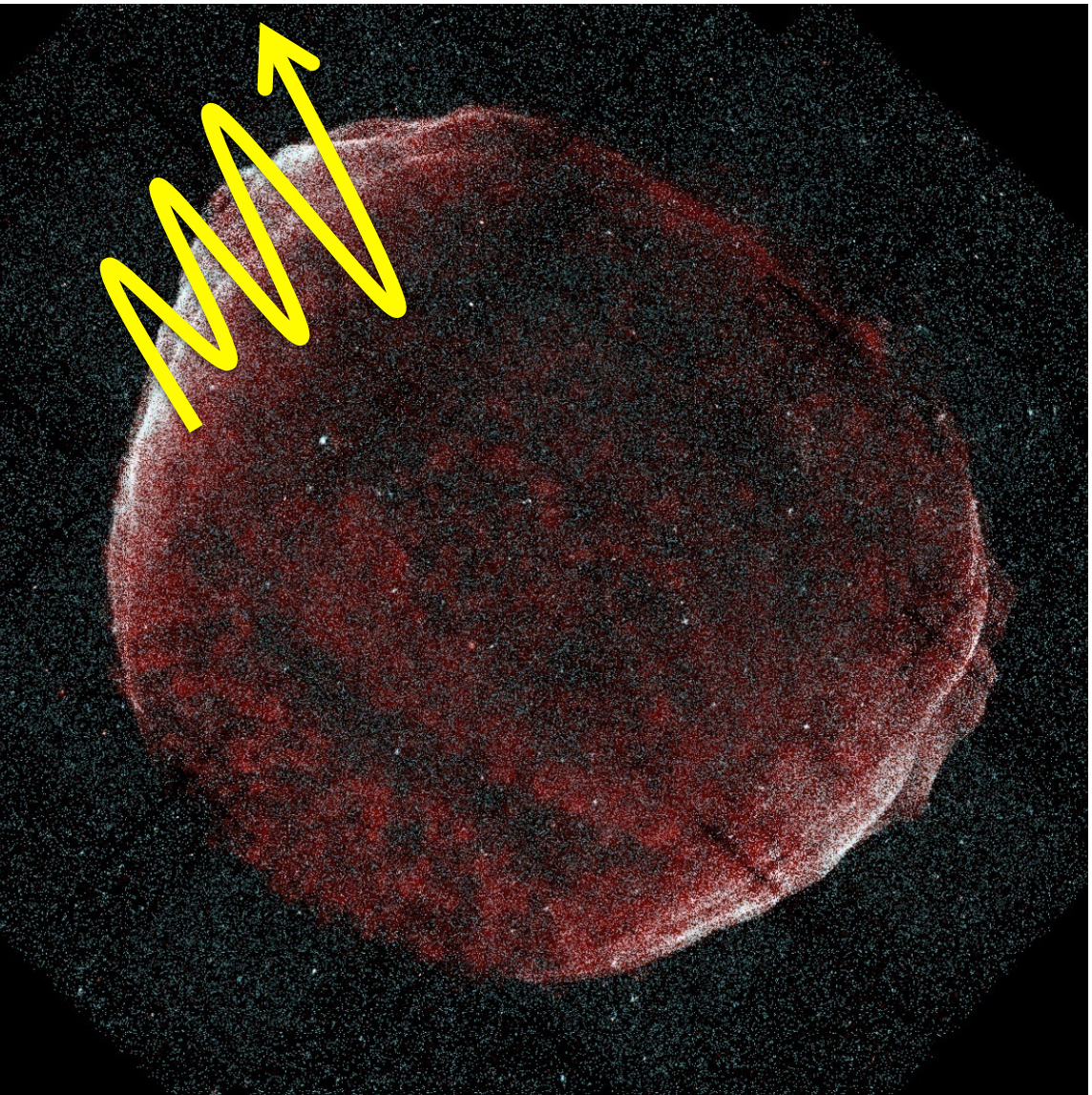
$$E_{rot} \sim \frac{1}{2} I\Omega^2 \sim 10^{46}\,\mathrm{erg}\left(\frac{P}{\mathrm{sec}}\right)^{-2}$$



Energy required for $e^{\pm}$ excess

$$R_{e^+} \sim \frac{\rho_{e^+}}{\rho_p}\frac{t_{\mathrm{esc}}}{t_{\mathrm{cool}}} R_p \sim \frac{10^{46}\,\mathrm{erg}}{100\,\mathrm{yr}}$$

Supernova Remnant



Major CR sources

$p_{CR} + p_{surrounding} \rightarrow \pi \rightarrow e^+e^-$

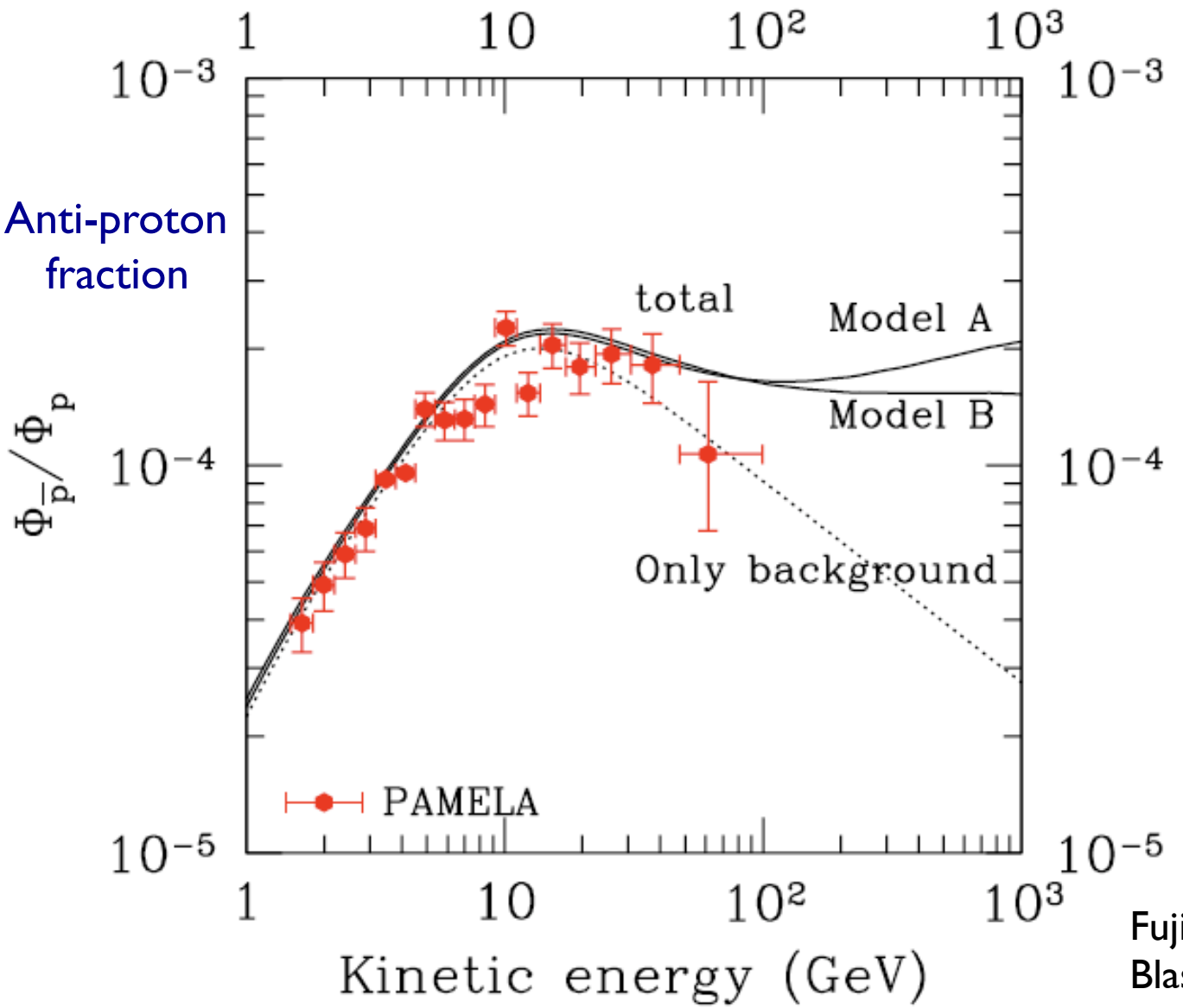
Hadronic origin

Typical τ_{pp} is small

- Dense matter (molecular cloud)
- Reacceleration

Fujita, Kohri, Yamazaki & KI 09
Blasi & Serpico 09

Anti-Proton



SNR model:

$pp \rightarrow \pi \rightarrow e^+e^-$

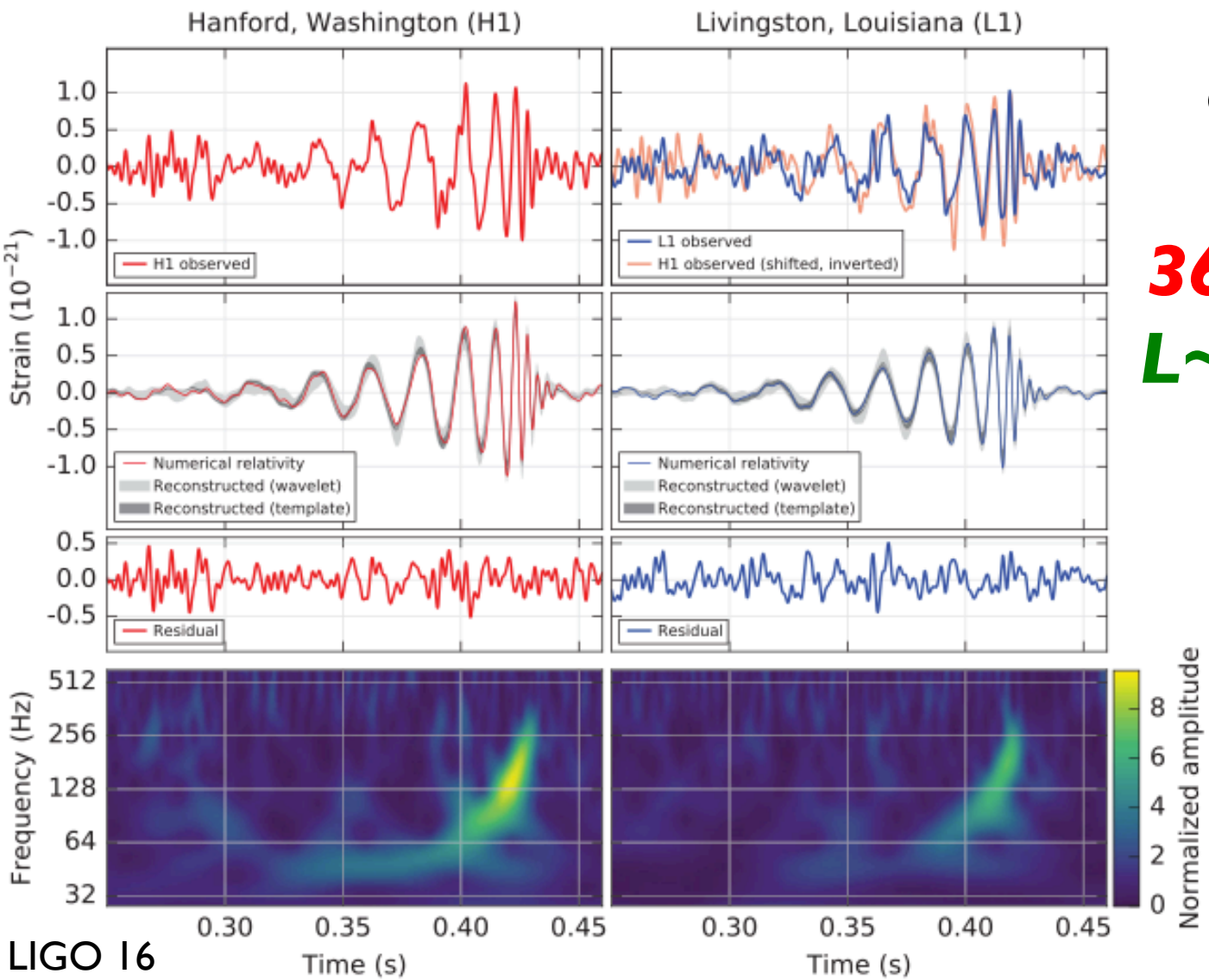
(w/ surrounding)

⇒ Inevitably anti-proton excess above ~100 GeV

⇒ AMS-02

Fujita, Kohri, Yamazaki, KI 09
Blasi & Serpico 09

GW150914



LIGO 16

1st direct detection

BH-BH

$36M_\odot+29M_\odot$

$L\sim200M_\odot c^2/s$

$\sim10^{-3}\ c^5/G$

GW151226

LVT151012

$R_{GW}\sim9\text{-}240$ events $Gpc^{-3}\ yr^{-1}$

Many BHs in Our Galaxy

KI, Matsumoto, Teraki, Kashiyama & Murase 16

70 Gpc^{-3} yr^{-1} ÷ 0.01 galaxy Mpc^{-3} × 10^{10} yr

~ 70000 Merged BHs/galaxy

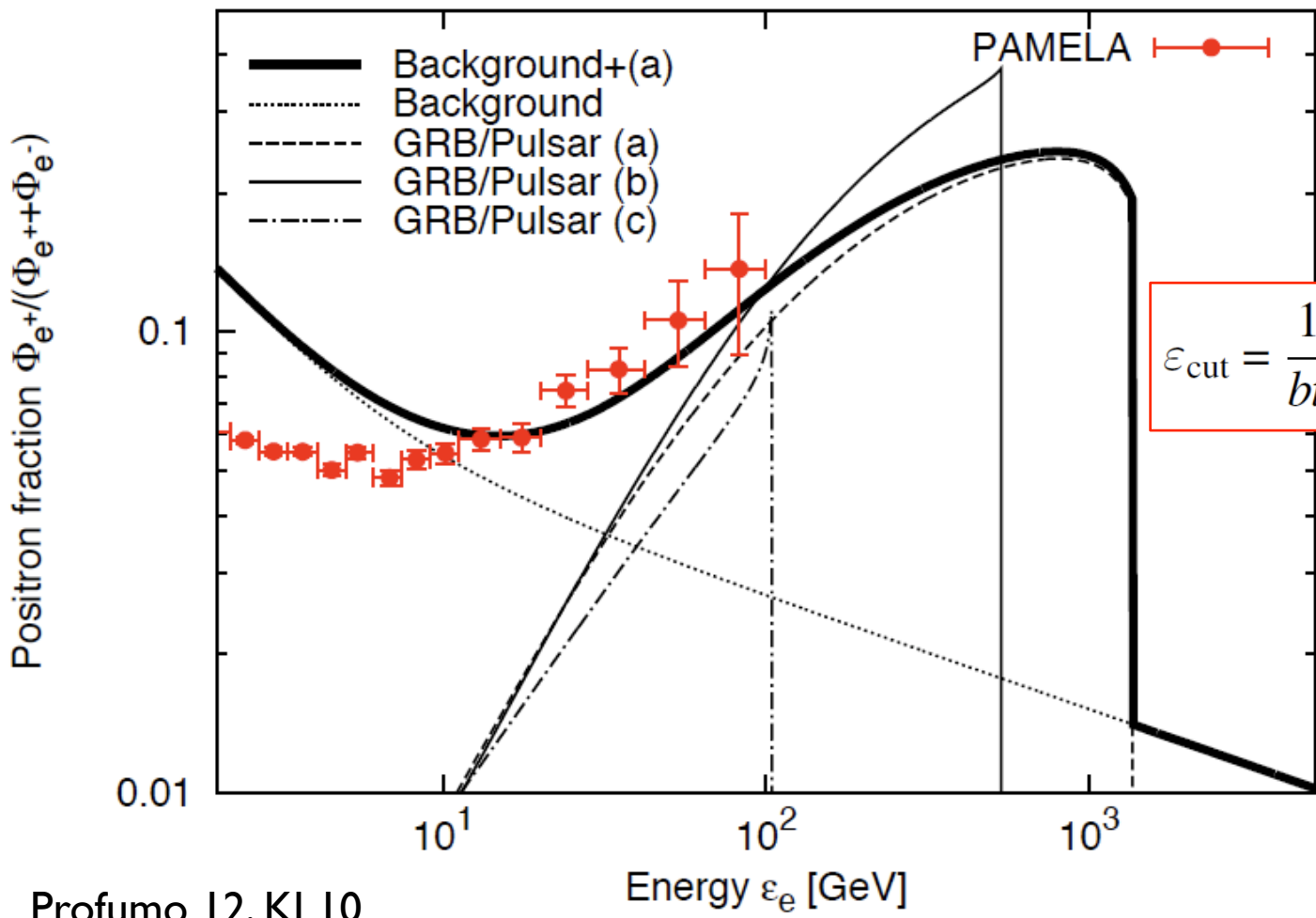
E_{spin}~10^8 Supernovae

Clues?

- Spectrum at >TeV
- Anisotropy
- Anti-proton
- …

Cooling Cutoff

High-energy $e^{\pm}$ lose energy by synch. & inv. Compton



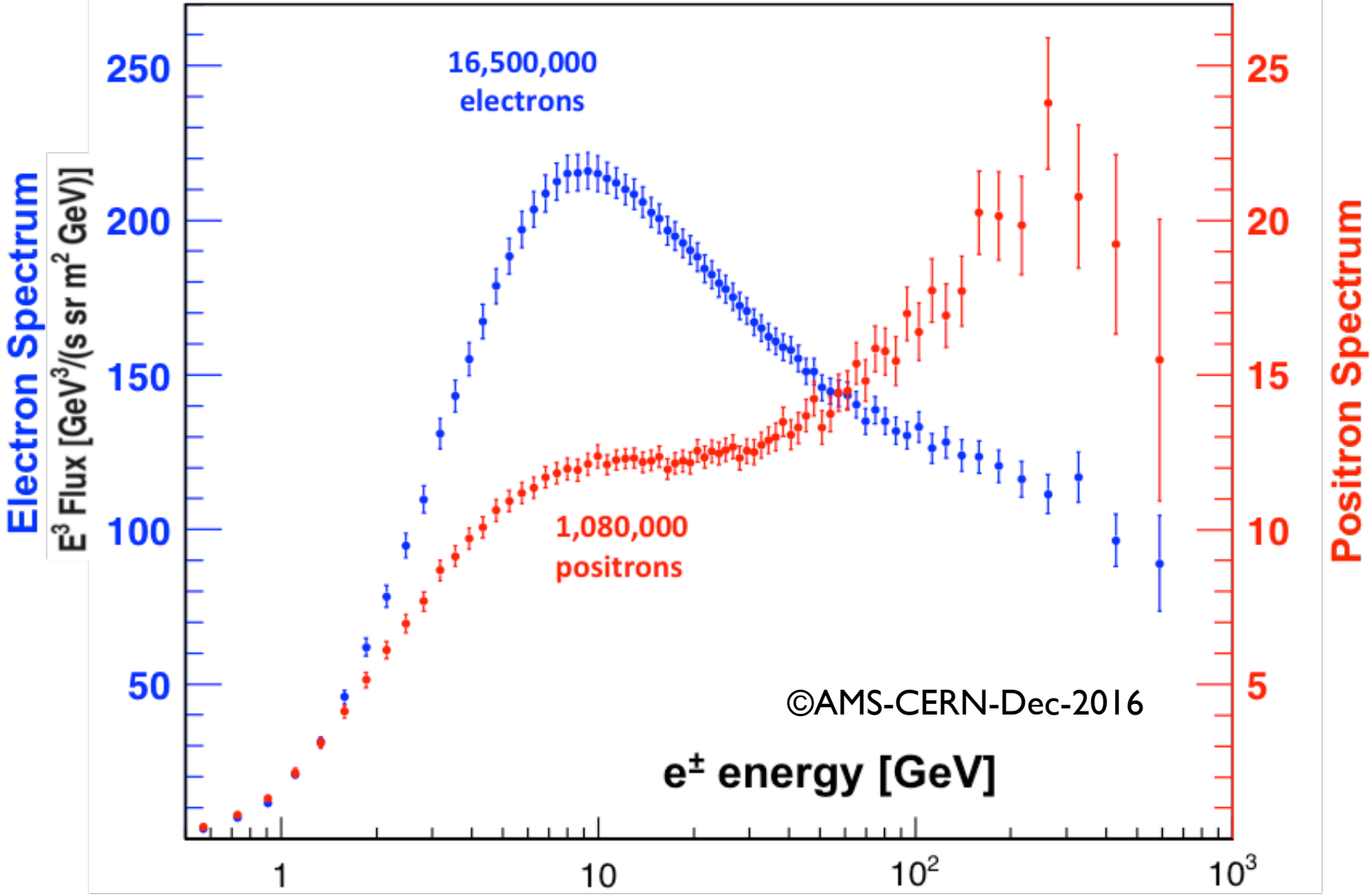
$$t_{cool} \propto \varepsilon_e^{-1}$$

$$\varepsilon_{\rm cut} = \frac{1}{bt} \simeq 300 \left(\frac{10^6 {\rm yr}}{t_{\rm age}}\right) {\rm GeV}$$

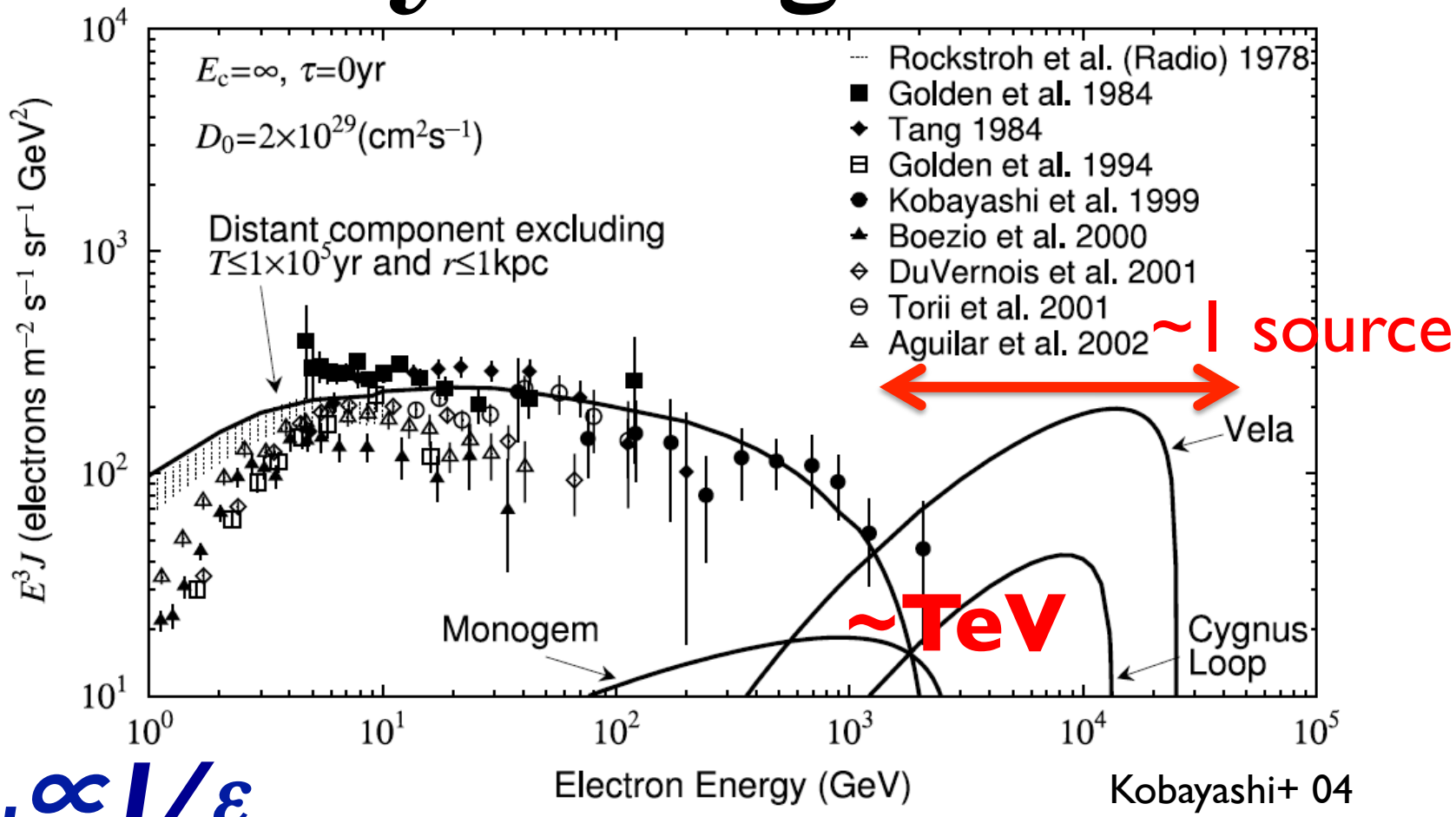
Cooling cutoff mimics DM cutoff

Profumo 12, KI 10

AMS-02 $e^{\pm}$


16,500,000
electrons
1,080,000
positrons
©AMS-CERN-Dec-2016
e± energy [GeV]
Electron Spectrum
E³ Flux [GeV³/(s sr m² GeV)]
Positron Spectrum
250
200
150
100
50
25
20
15
10
5
1
10
10²
10³

Nearby Young Source

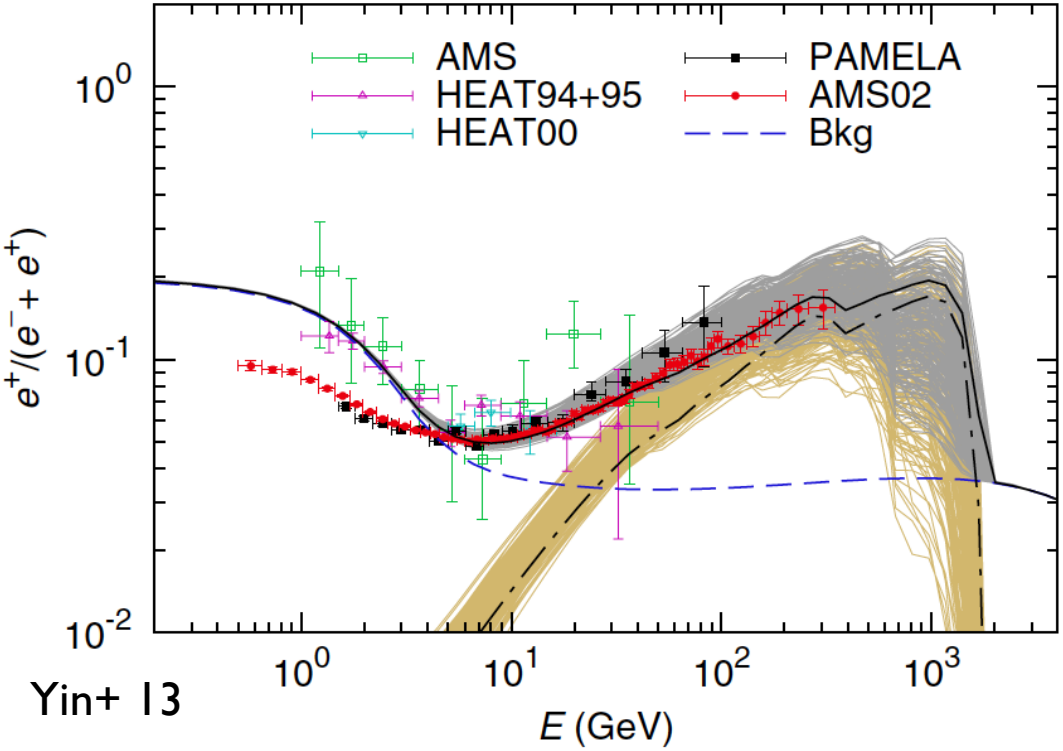


Kobayashi+ 04

$t_{cool} \propto 1/\varepsilon_e$

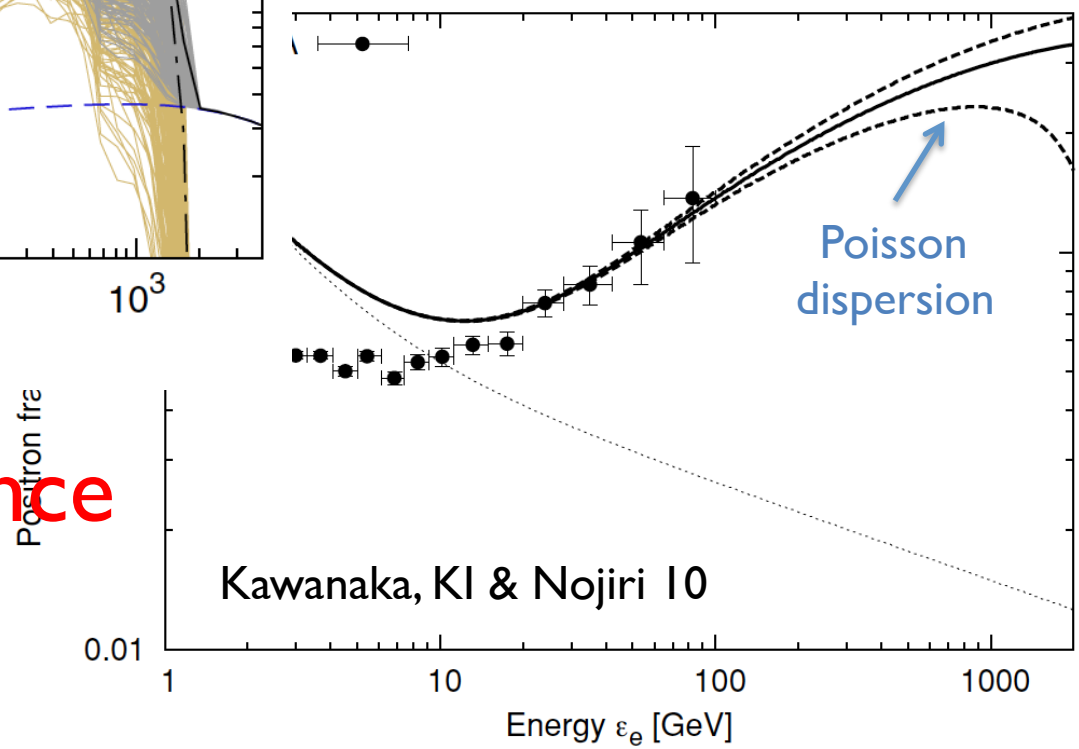
$$N_{\rm PSR}(\varepsilon_e) \sim 6\left(\frac{\varepsilon_e}{\rm TeV}\right)^{-5/3}\left(\frac{R}{0.7\times10^{-5}\,{\rm yr}^{-1}\,{\rm kpc}^{-2}}\right)$$

Spectrum: Fine Structure



Yin+ 13

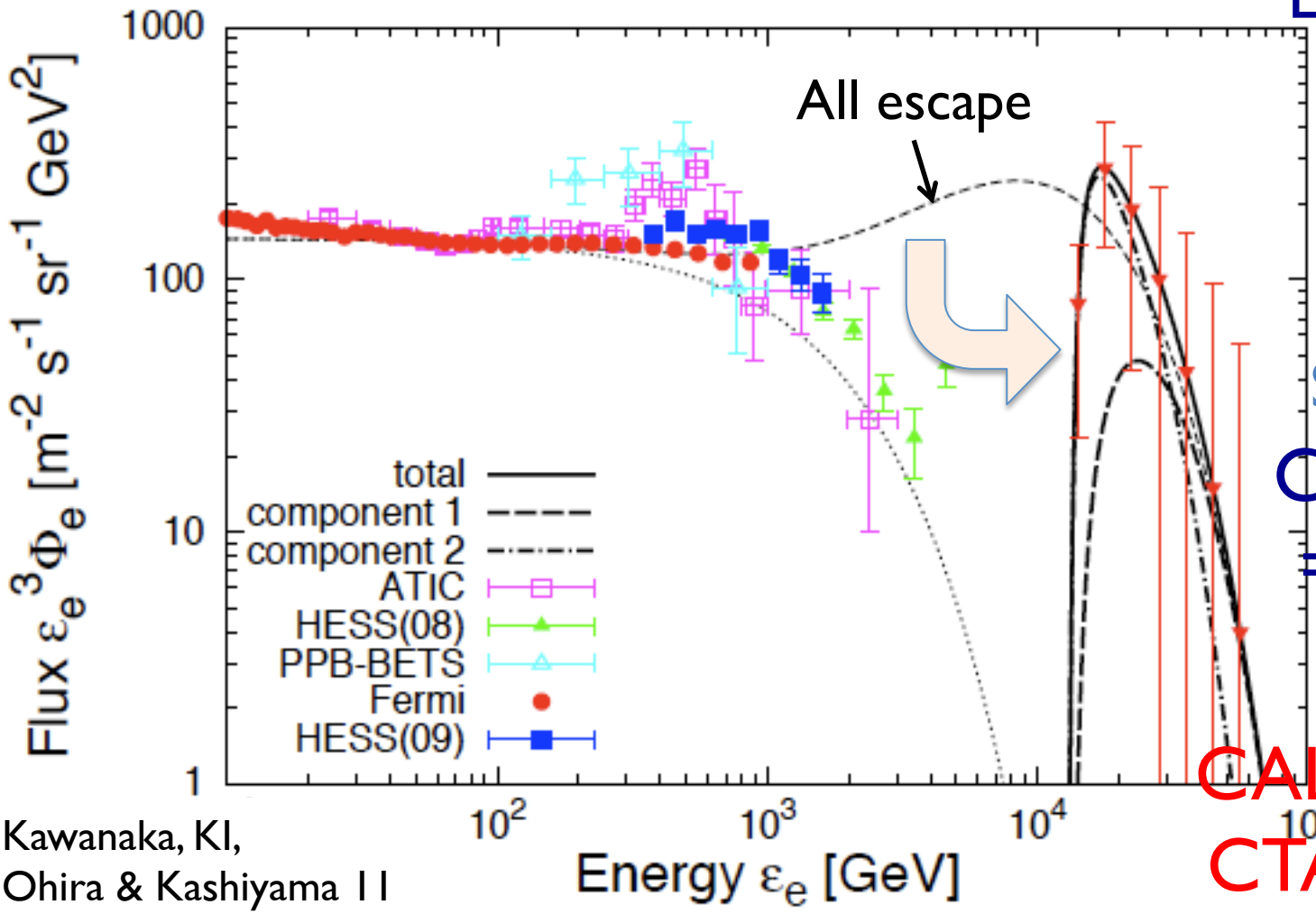
Multiple pulsars make fine structure

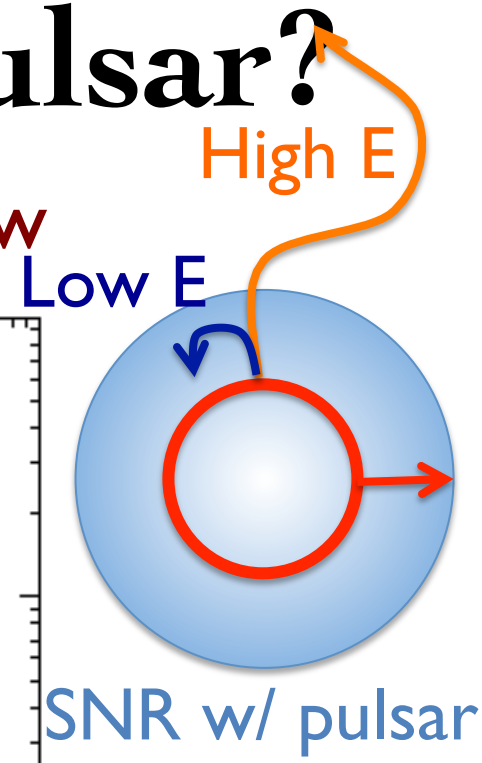


Large cosmic variance at high energy

Line Spectrum by Pulsar?

Nearby source (e.g., Vela) in TeV e window





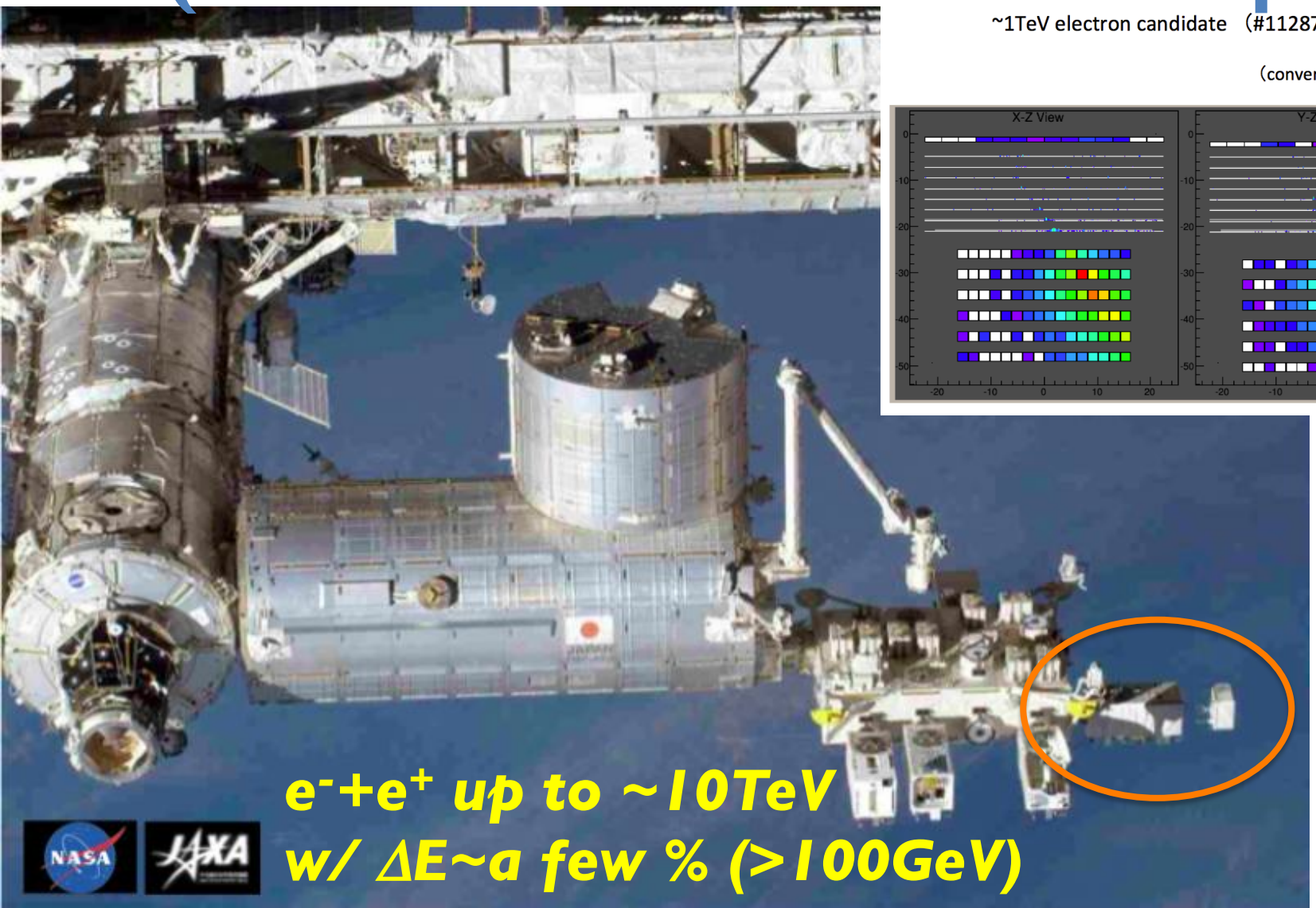
Confinement
⇒Low Ene. cutoff

CALET, DAMPE
CTA, LHAASO

Kawanaka, KI,
Ohira & Kashiyama 11

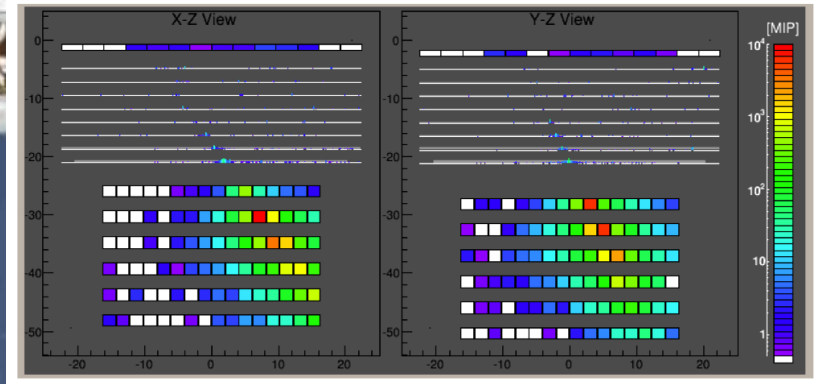
CALET

(CALorimetric Electron Telescope)



~1TeV electron candidate (#1128791625_17544)

(converted to MIP by calibration)



e^-+e^+ up to ~10TeV
w/ ΔE~a few % (>100GeV)

Set on Aug. 25

>TeV data is taking!

Wukong (悟空; DAMPE)

DArk Matter Particle Explore

China, Swiss, Italy

17 Dec 2015~

Total: 33 rad length

e, γ: 5GeV-10TeV

ΔE=1%@800GeV

0.3 m^2

p: 100GeV-100TeV

ΔE=40%@800GeV

0.2 m^2

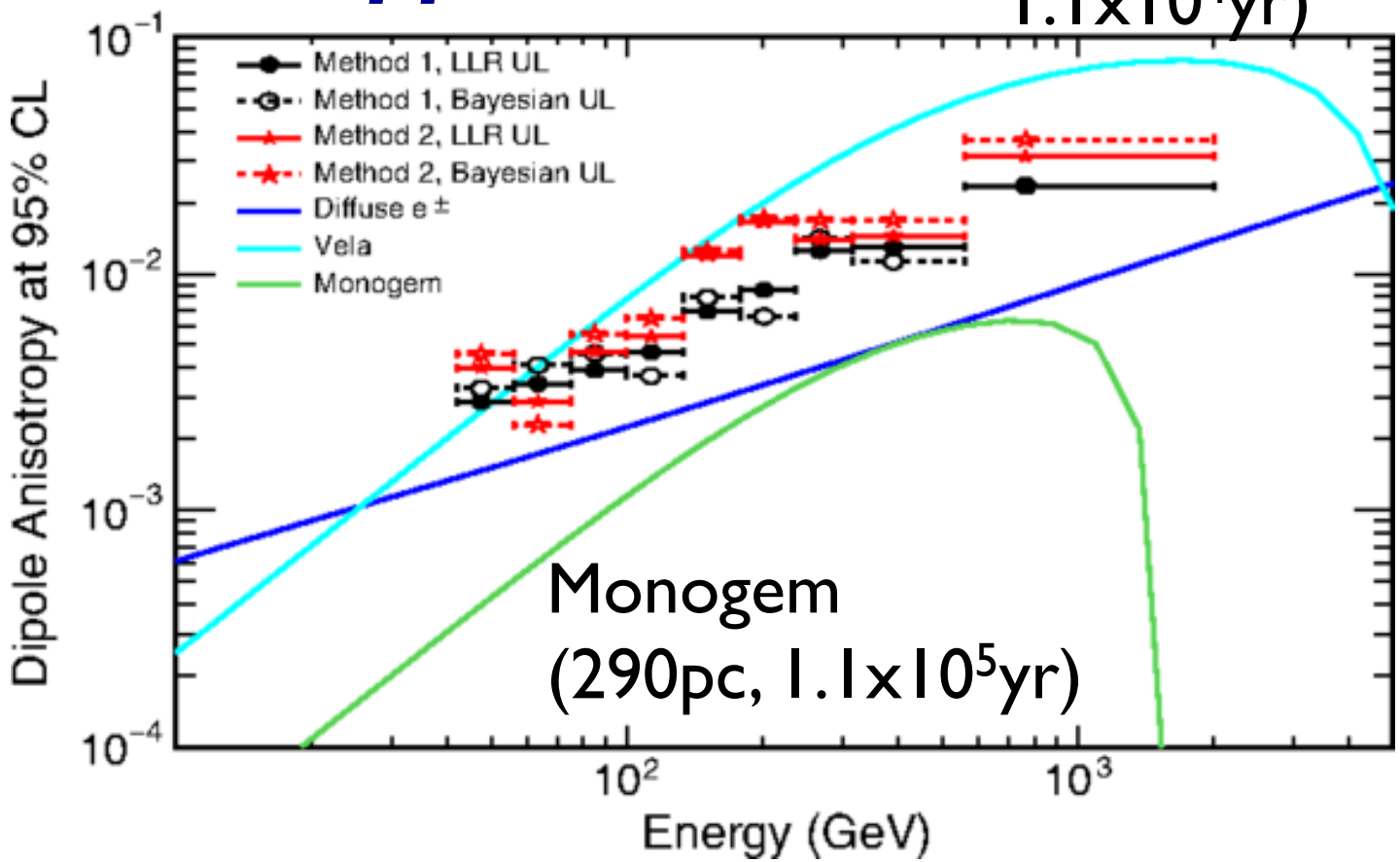
$\Delta\theta$=0.1°@100GeV

Also Motz's talk

e^- Anisotropy

Fermi upper limits

Vela (290pc, 1.1×10^4yr)



Monogem (290pc, 1.1×10^5yr)

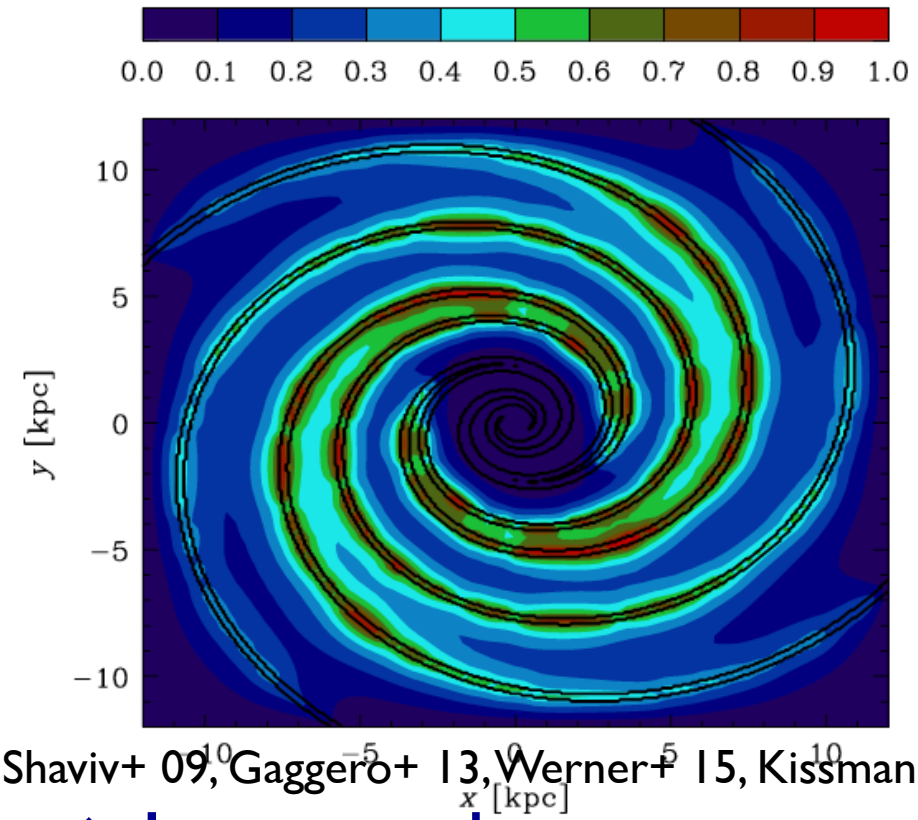
$$\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{3K|\nabla f|}{cf} \sim \frac{3d}{2ct}$$

$\delta<3\times10^{-3}$ (95%CL; 42GeV<E)

Limit $\propto t^{-1/2}$; For multiple sources, anisotropy ↓

Local Structures

Spiral distribution

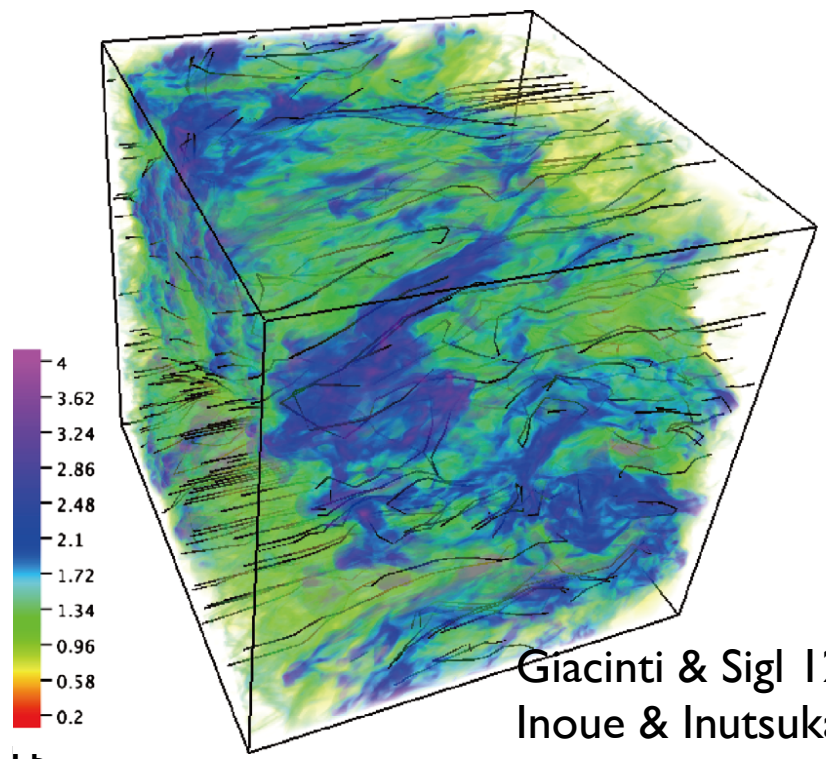


Shaviv+ 09, Gaggero+ 13, Werner+ 15, Kissmann+ 15

⇒ Less nearby sources

⇒ Less anisotropy

Local B Structure

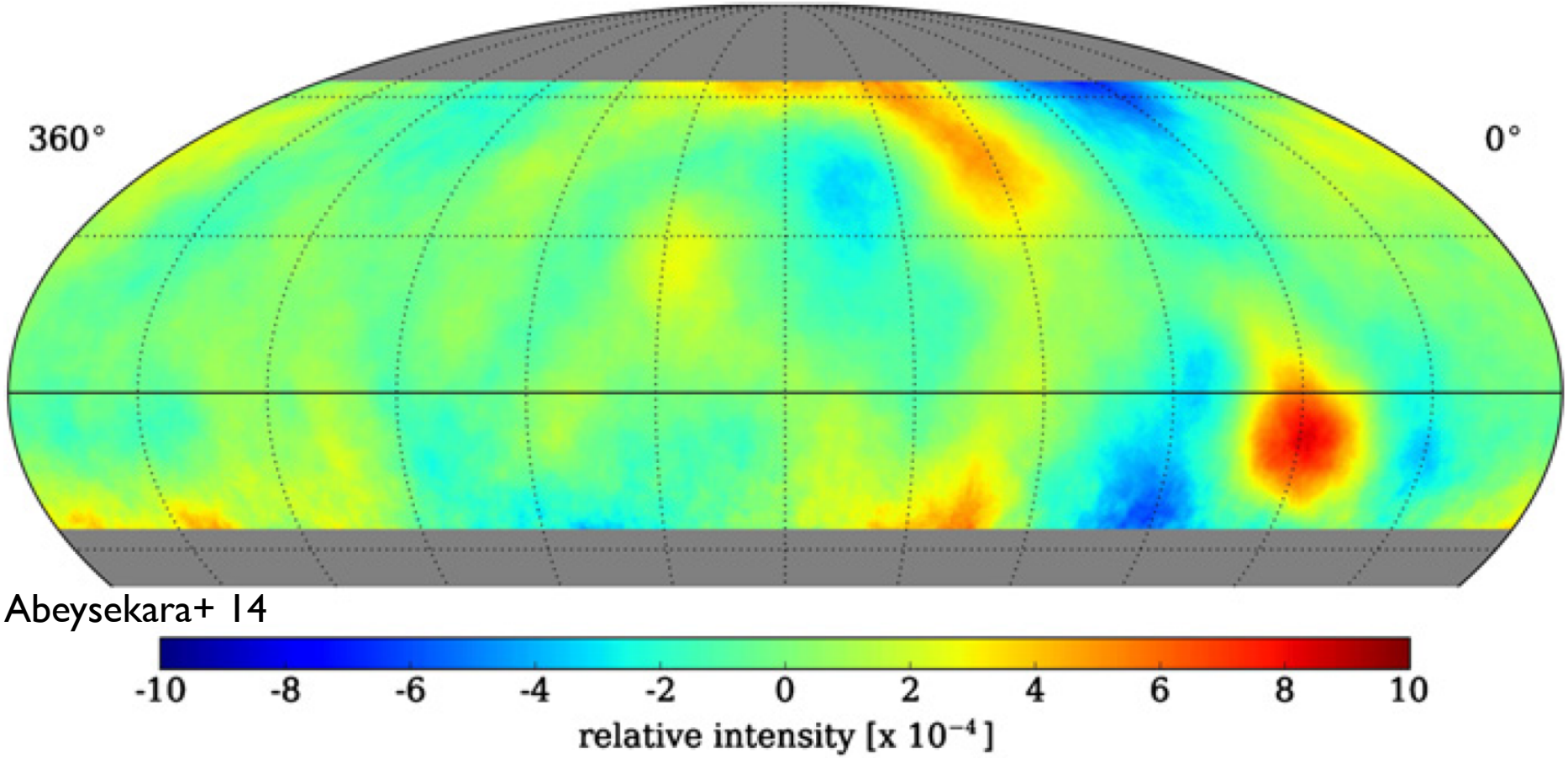


Giacinti & Sigl 12
Inoue & Inutsuka 12
Harding+ 16

$$r_g(p) \approx \frac{p}{eZB} \approx 10^{-3}\,\mathrm{pc}\left(\frac{p/Z}{\mathrm{TeV}}\right)\left(\frac{B}{\mu G}\right)^{-1}$$

p Anisotropy

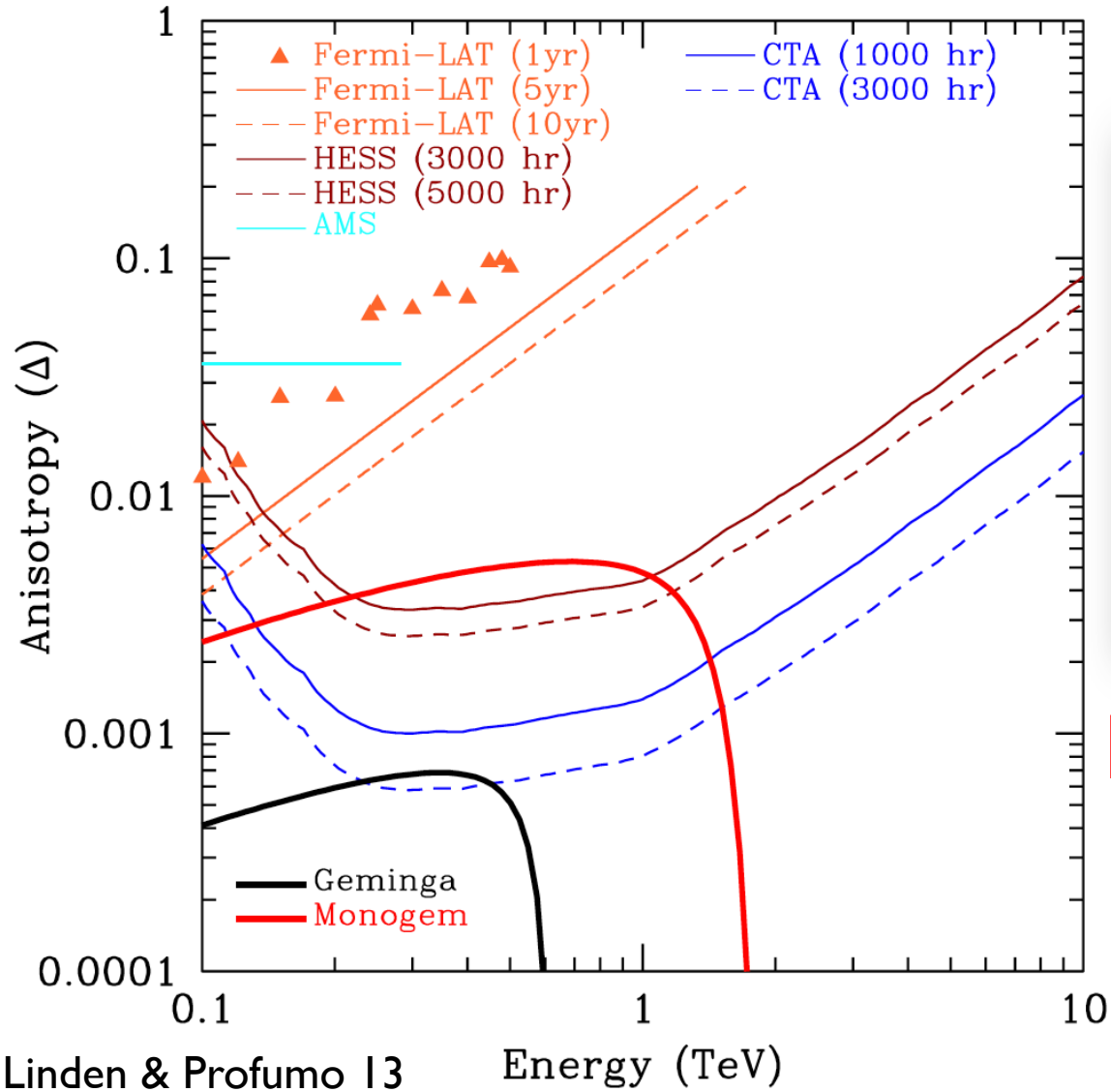
HAWK observe small-scale anisotropy of TeV CRs



Abeysekara+ 14

$\delta > 3\times10^{-4}$ but Coherent B field (non-diffusive)?

CTA



Linden & Profumo 13

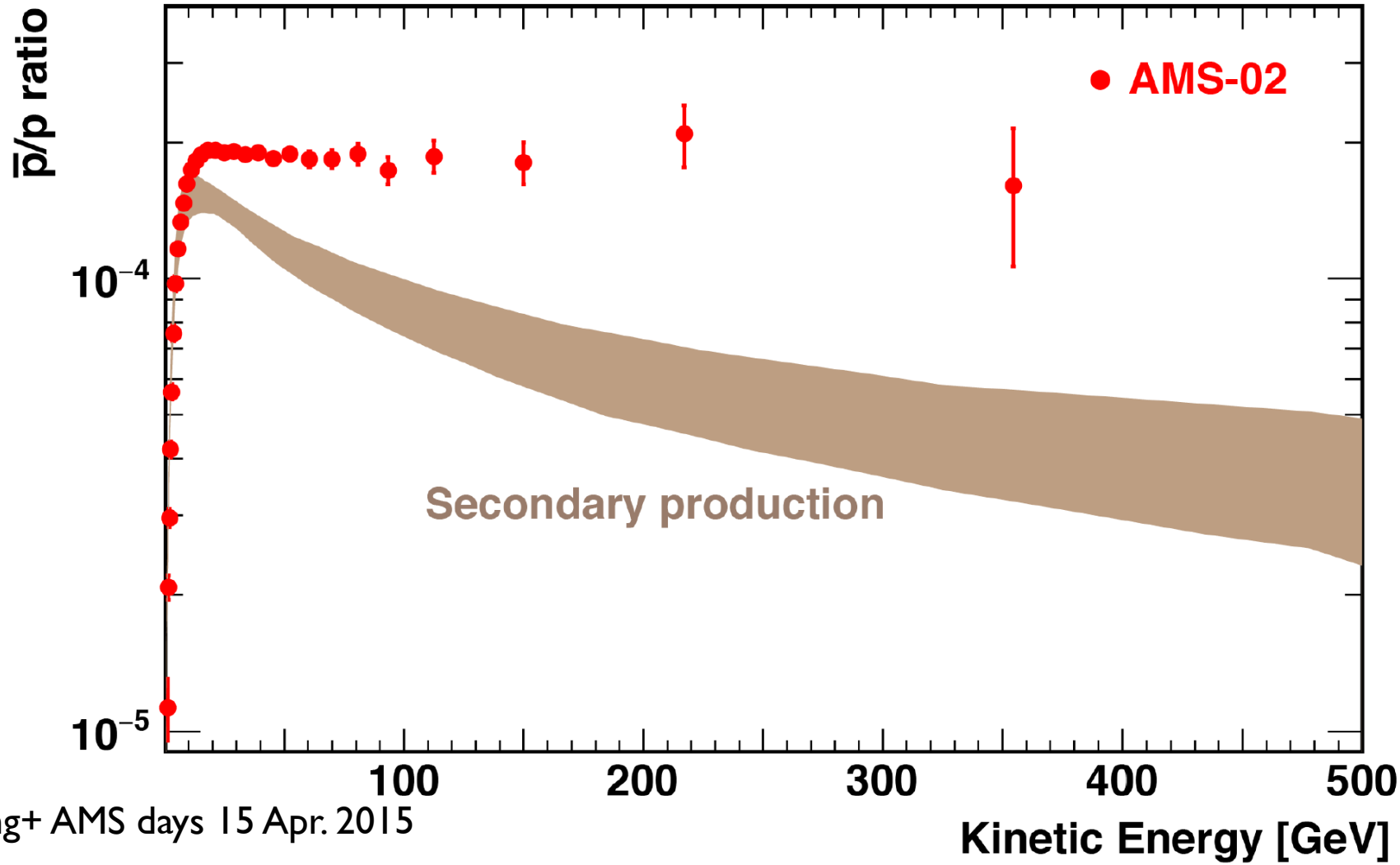
Huge effective area

It may be difficult to control the systematics

Contents

- ***$e^{\pm}$ excess: Astrophysical***
  - ✓ TeV spec., Anisotropy, … ***CALET***
- ***$\bar{p}$: No excess or pp?***
  - ✓ B/C ⇔ Li? ^{10}Be ***AMS-02***
- ***He, C, O : Superbubble?***
  - ✓ Ne, Mg, Si, Fe hardening?

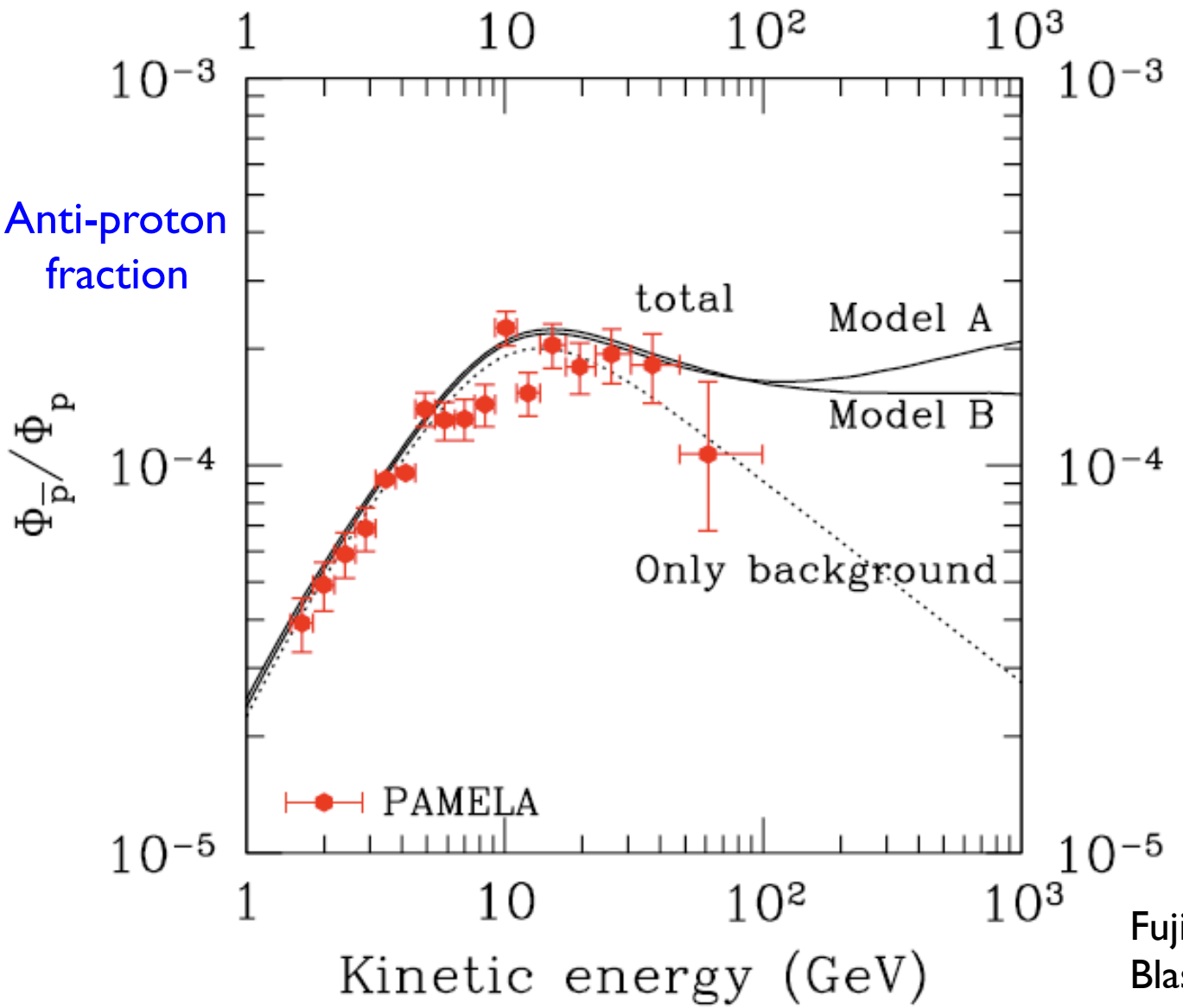
AMS-02 Anti-Proton



Ting+ AMS days 15 Apr. 2015

Figure 1. Antiproton to proton ratio measured by AMS. As seen, the measured ratio cannot be explained by existing models of secondary production.

Anti-Proton



SNR model:

$pp \rightarrow \pi \rightarrow e^+e^-$

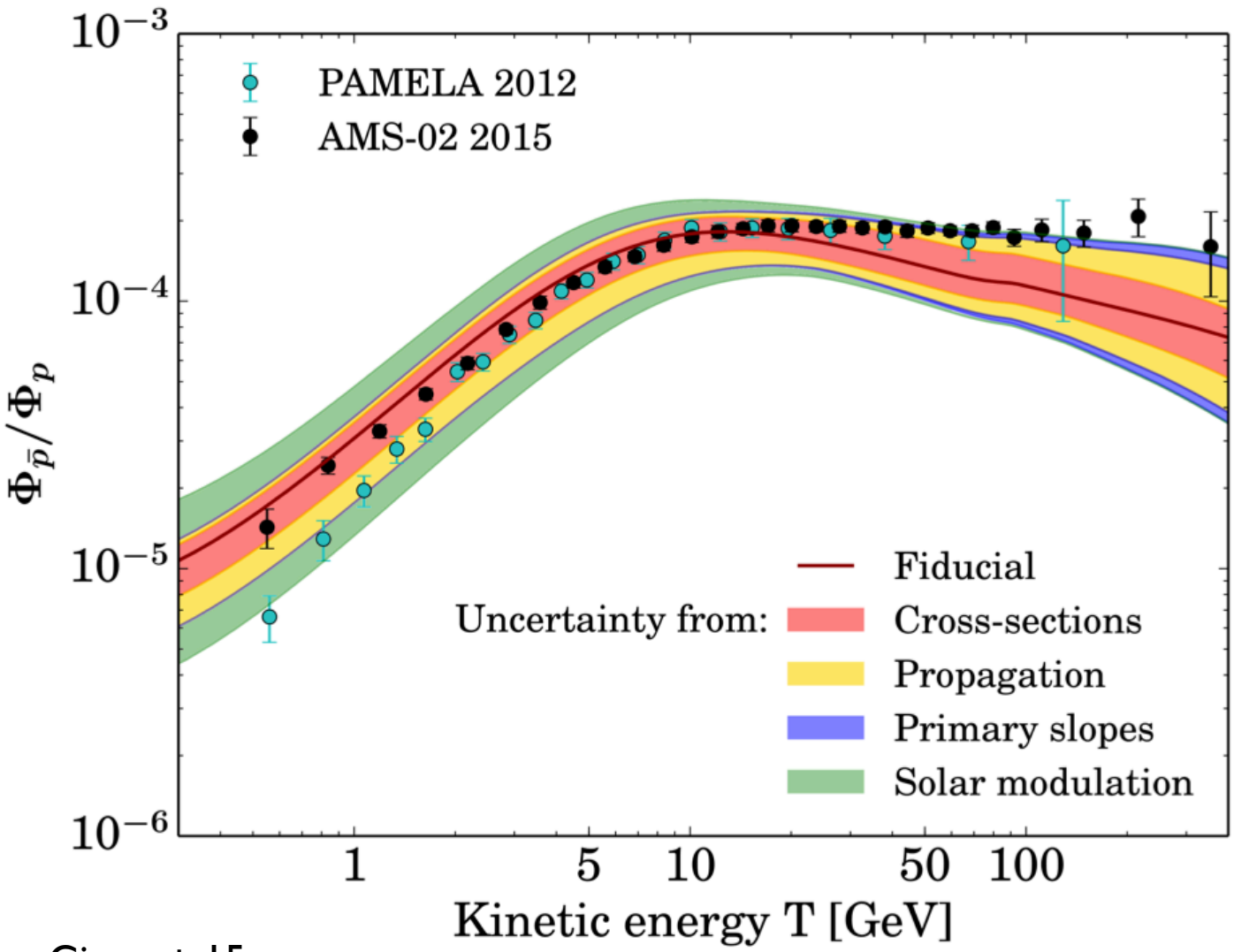
(w/ surrounding)

⇒ Inevitably anti-proton excess above ~100 GeV

⇒ AMS-02

Fujita, Kohri, Yamazaki, KI 09
Blasi & Serpico 09

Just 2ndary Anti-proton?



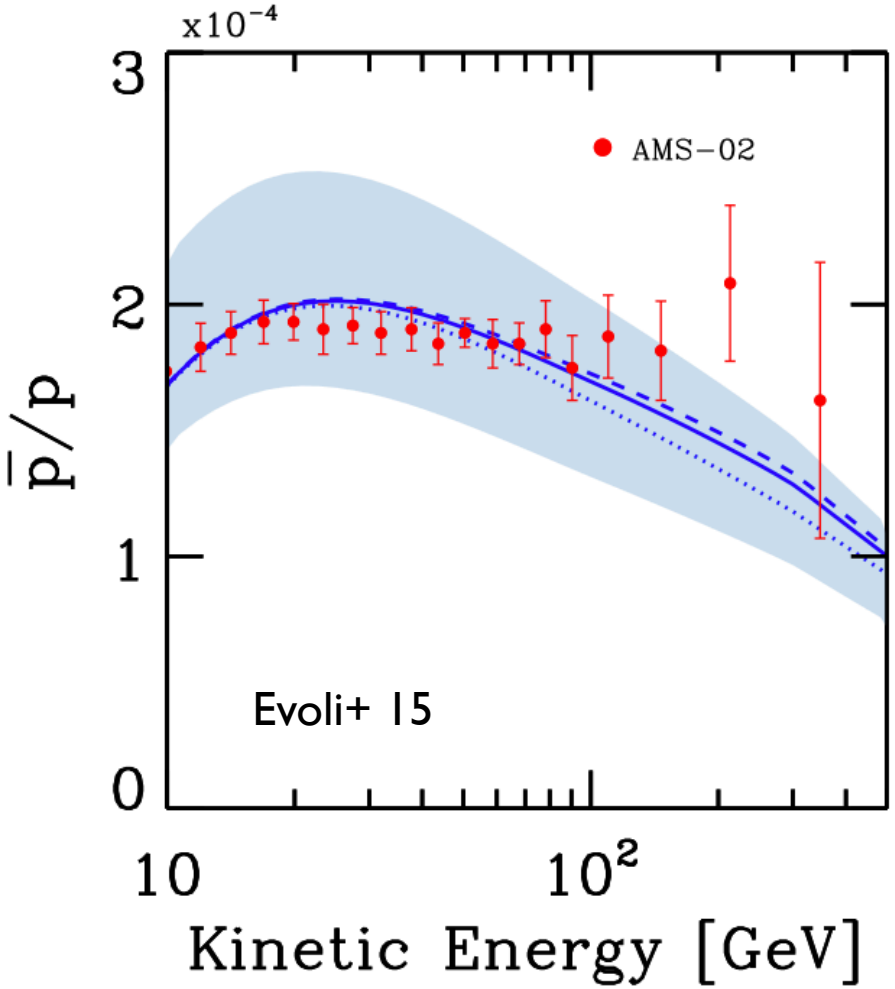
Giesen+ 15

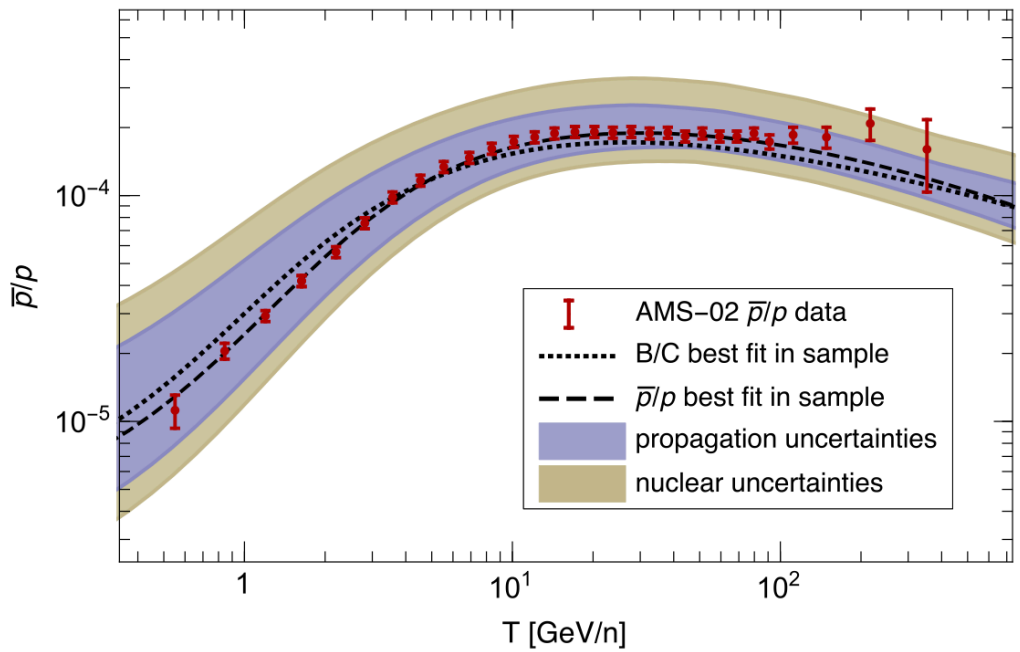
Excess is marginal?

- Small $|\delta|$ ($D_{diff} \sim \varepsilon^{-\delta}$)
- N49 exp. @CERN
- Hard p, He

Just 2ndary Anti-proton?

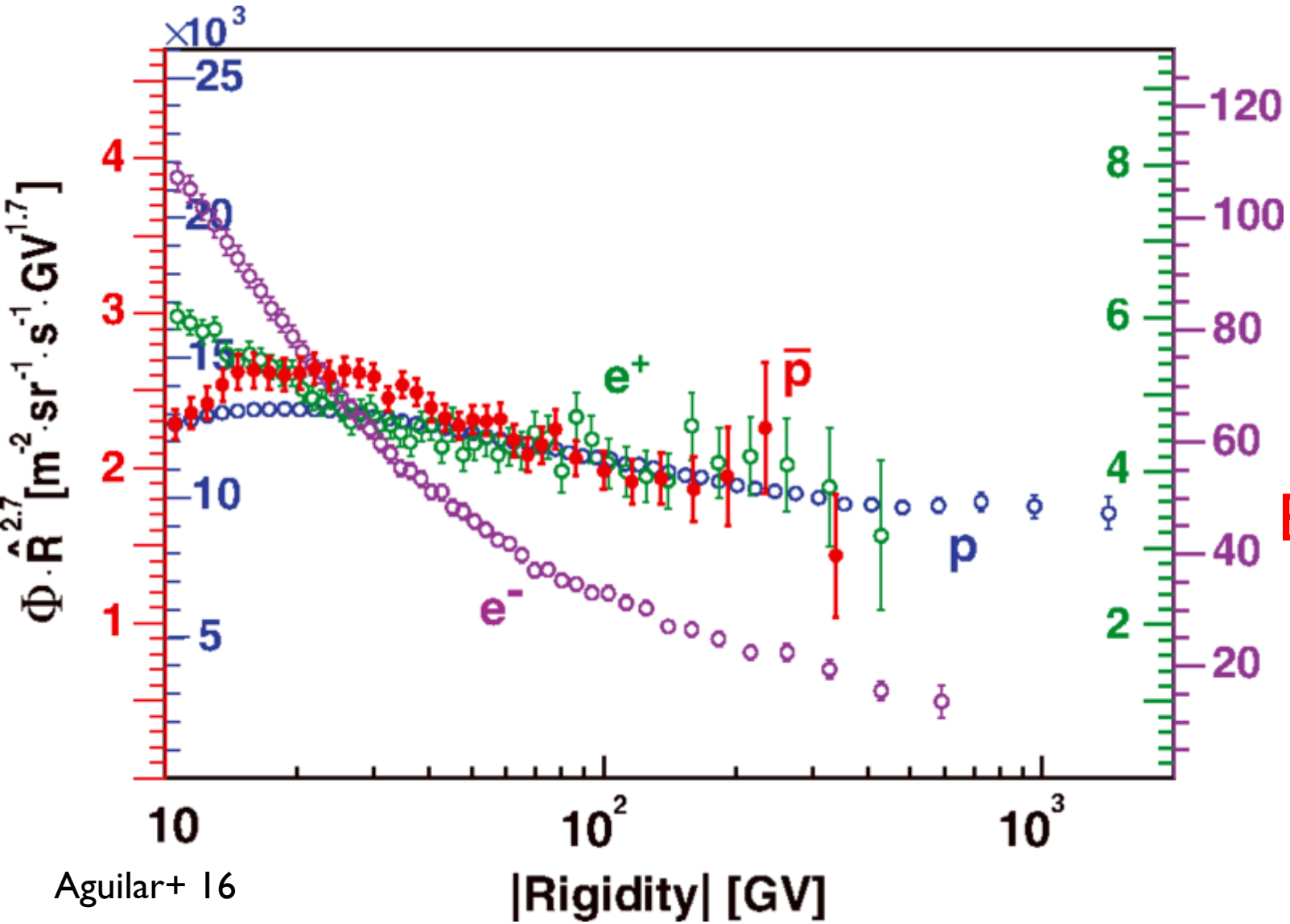
Similar results on anti-proton uncertainties





Kappl+ 15

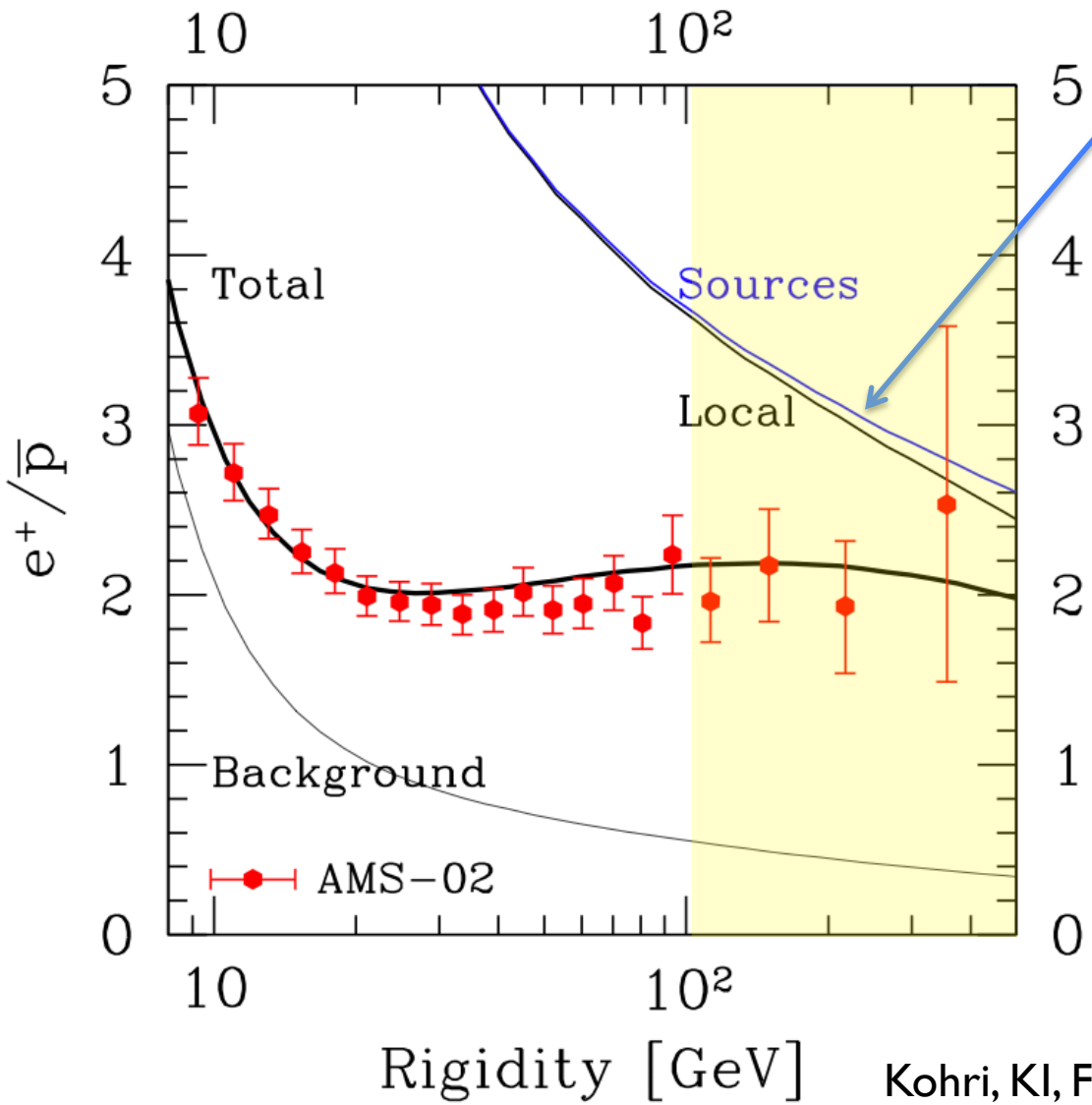
AMS-02: e^+ & p



Identical spectral shape @ E>60GeV

Aguilar+ 16

Right Branching Fraction



Branching ratio of $pp \rightarrow e^+$ & $\bar{p}$ within a factor 2 at >100 GeV!

pp or coincidence?

Ratio is robust because the same r_{Larmor} gives the same diffusion

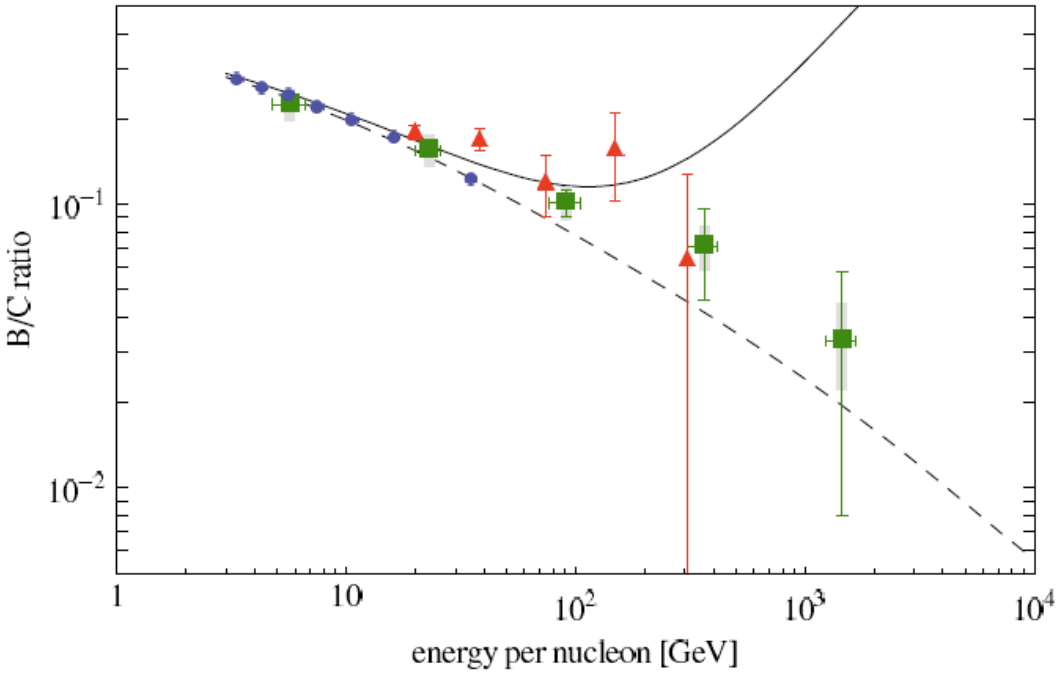
Kohri, KI, Fujita & Yamazaki 15

B/C for e± Excess

Similar B/C upturn was predicted for e± excess

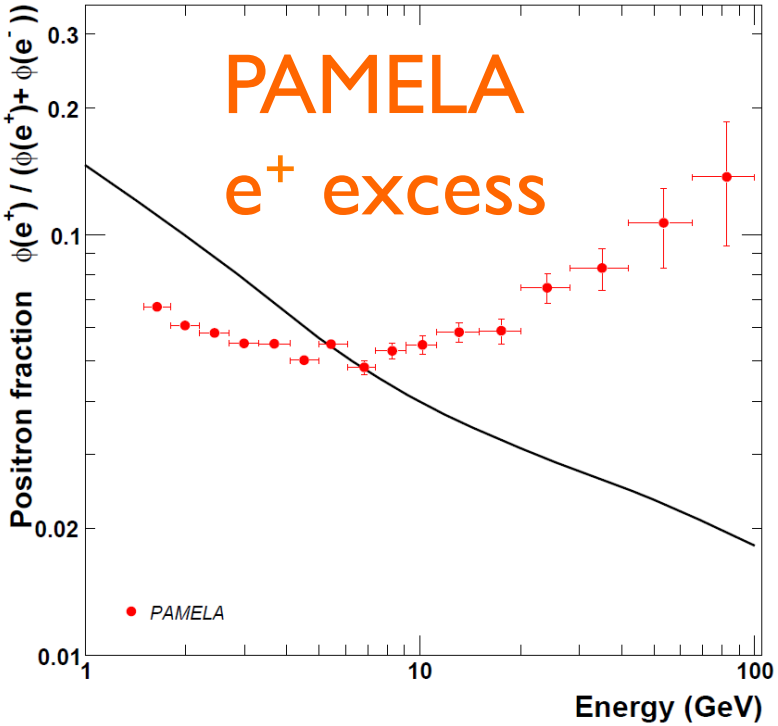
e+, anti-proton & boron are 2ndary

No B/C upturn ⇒ SN happens in low metal region?



Mertsch & Sarkar 09

Also nested-leaky box by Cowsik & Burch 09

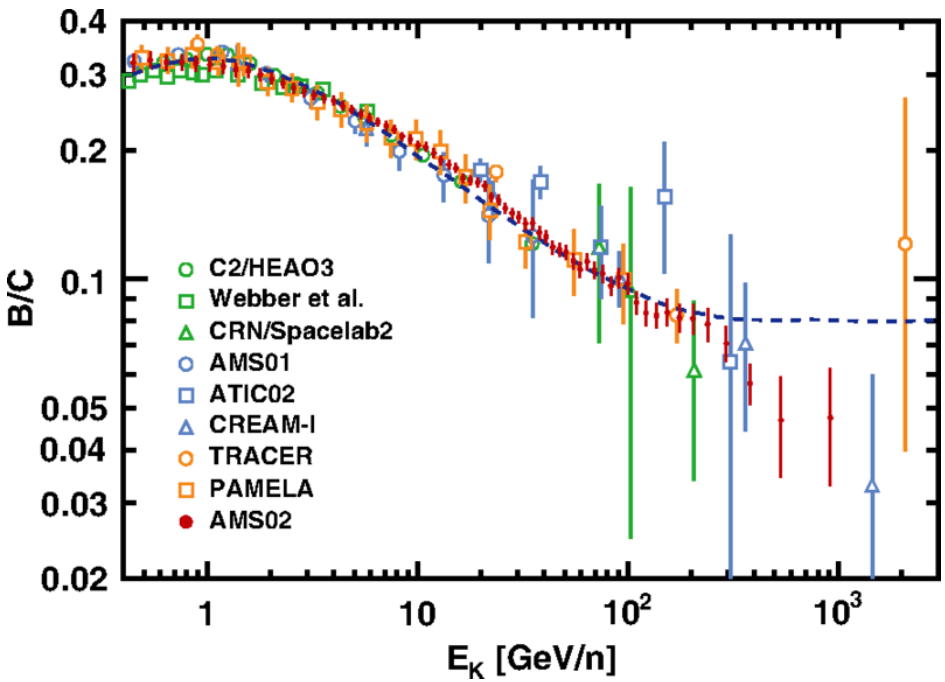


Adriani+ 08, 10

B/C v.s. Li

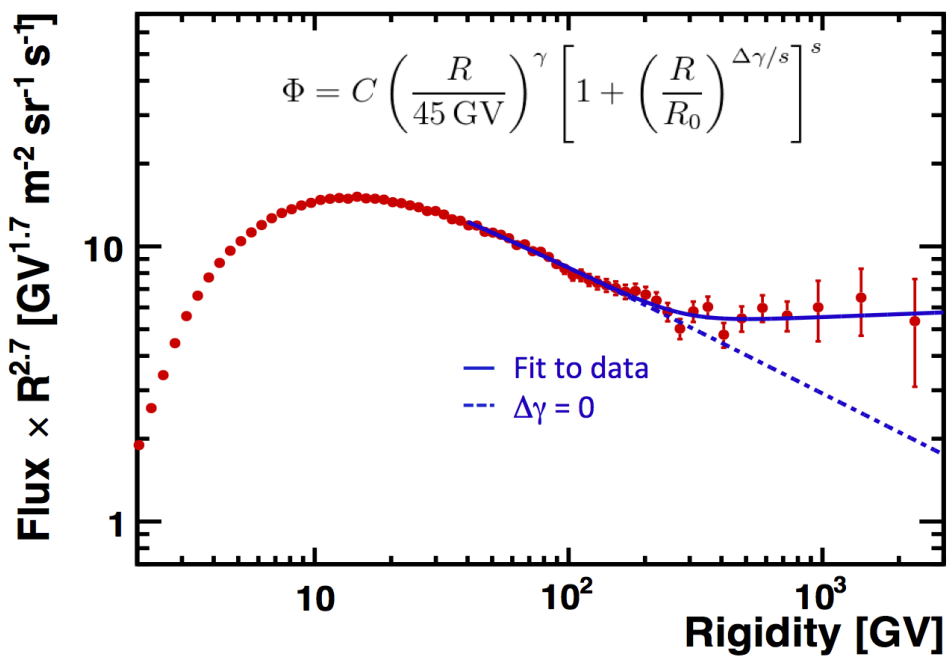
AMS-02 has internal inconsistency?

B/C



Aguilar+ 16

Li



Derome+ AMS days 15

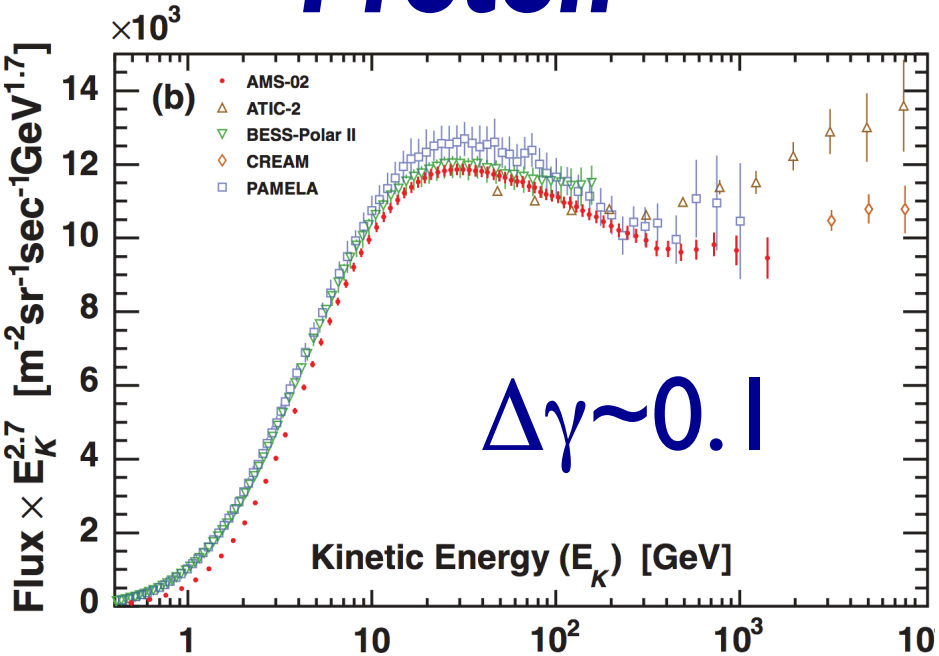
Both boron and Lithium are usually secondary

Contents

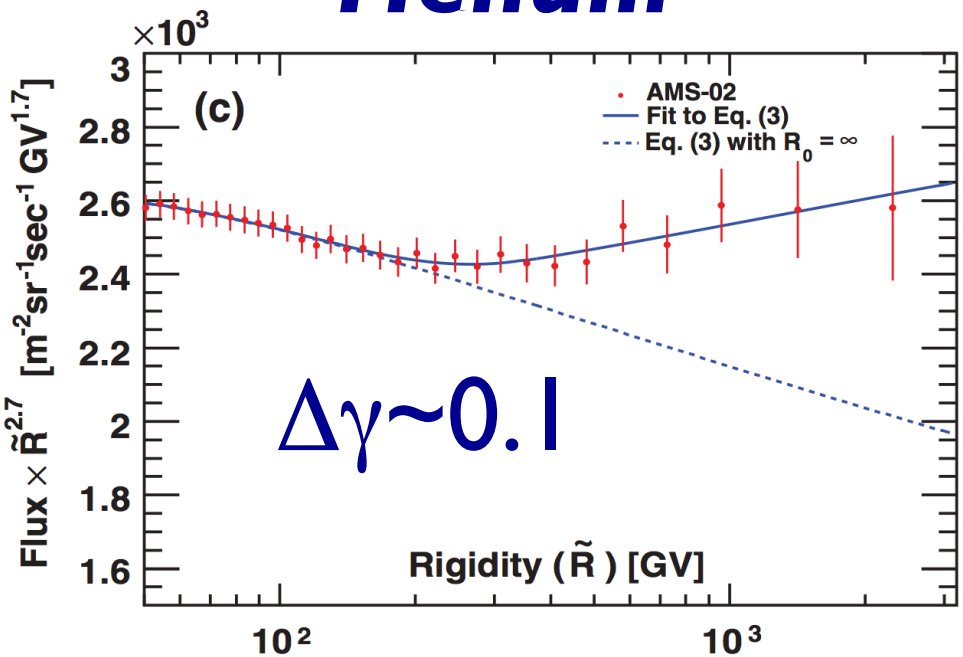
- ***$e^{\pm}$ excess: Astrophysical***
  - ✓ TeV spec., Anisotropy, … ***CALET***
- ***$\bar{p}$: No excess or pp?***
  - ✓ B/C ⇔ Li? ^{10}Be ***AMS-02***
- ***He, C, O : Superbubble?***
  - ✓ Ne, Mg, Si, Fe hardening?

Spectral Breaks

Proton



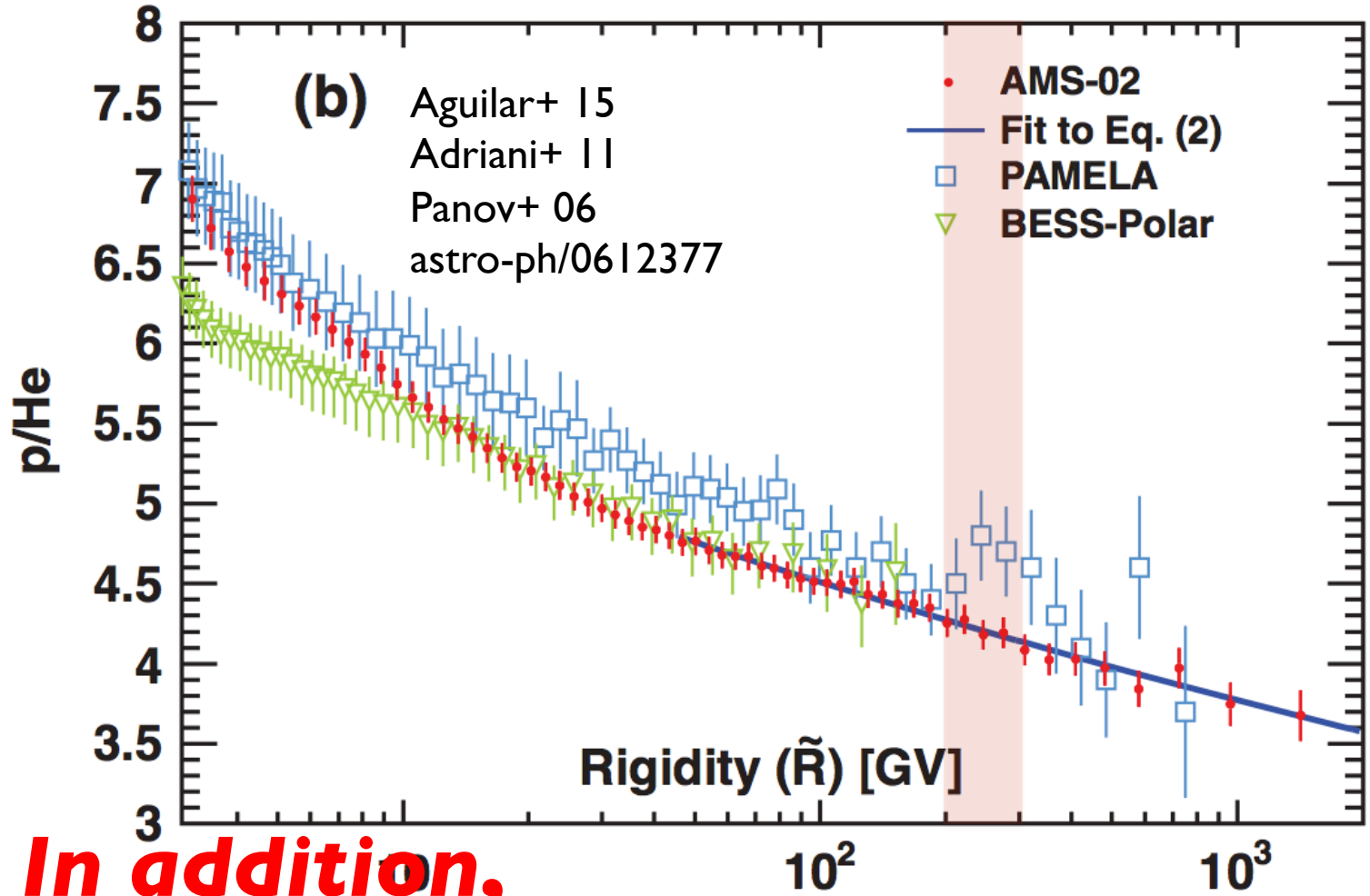
Helium



Aguilar+ 15a,b
Ahn+ 10

AMS-02 confirms that p & He spectral indices hardens at >200GV

Spectral Difference

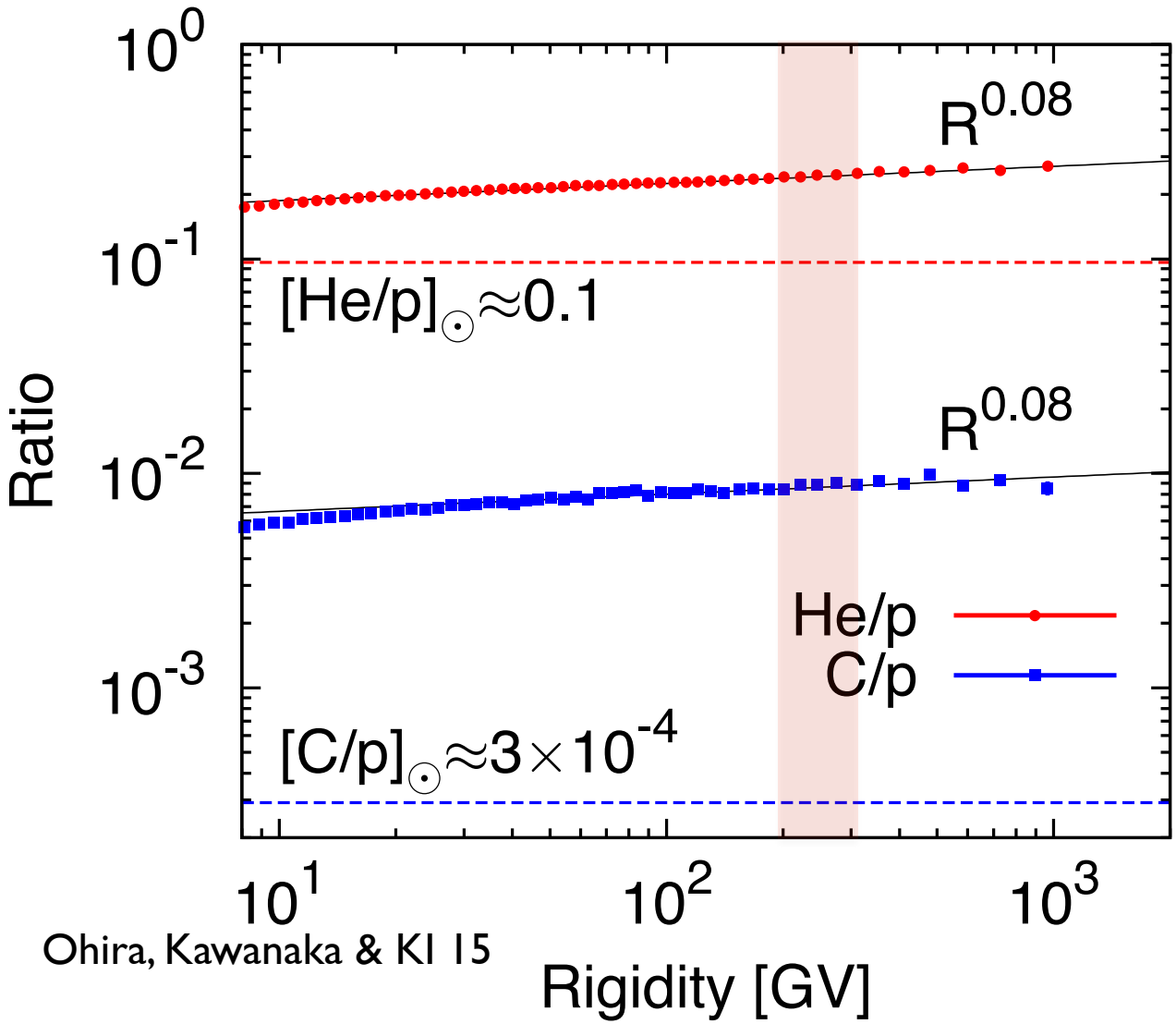


p/He has no break

In addition,

He is harder than proton by $\gamma_{p/He}$=-0.077

He/p & C/p



Ohira, Kawanaka & KI 15

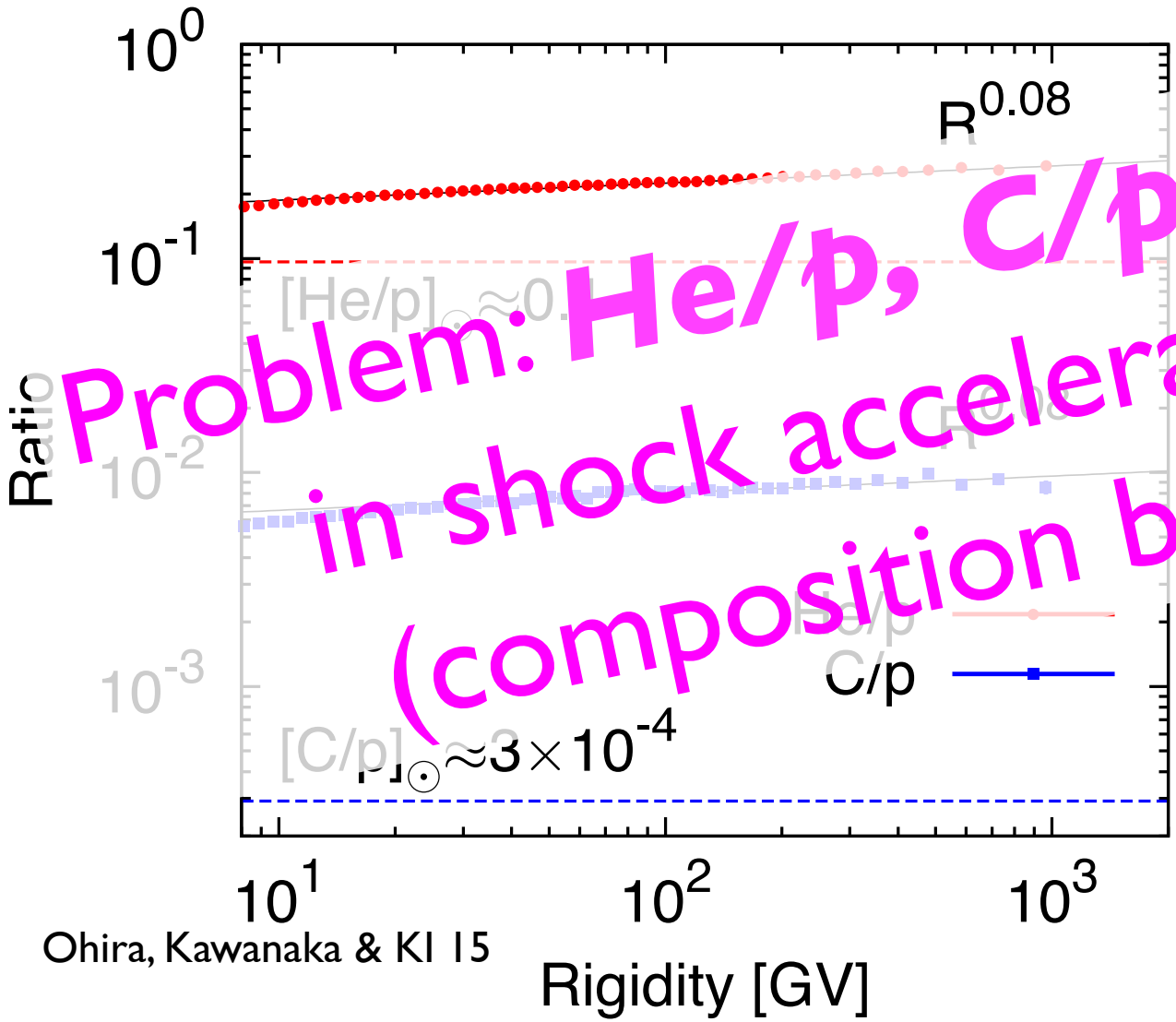
He/p ≠ const
C/p ≠ const

He/p ∝ $R^{0.08}$
C/p ∝ $R^{0.08}$

He/p>$[He/p]_\odot$
C/p>$[C/p]_\odot$

No breaks

He/p & C/p



Ohira, Kawanaka & KI 15

He/p ≠ const

C/p ≠ const

He/p ∝ C/p

∝ $R^{0.08}$

He/p>[He/p]$_\odot$

C/p>[C/p]$_\odot$

No breaks

Problem: He/p, C/p=const in shock acceleration (composition blind)

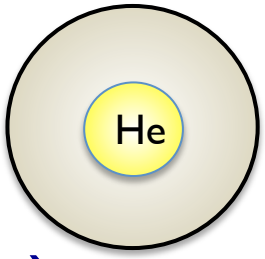
Helium is Special

- He/p ~ ***3×Y$_\odot$!*** @100TeV
- Stellar nucleosynthesis never double the mean Y (∵ Schonberg-Chandrasekhar)

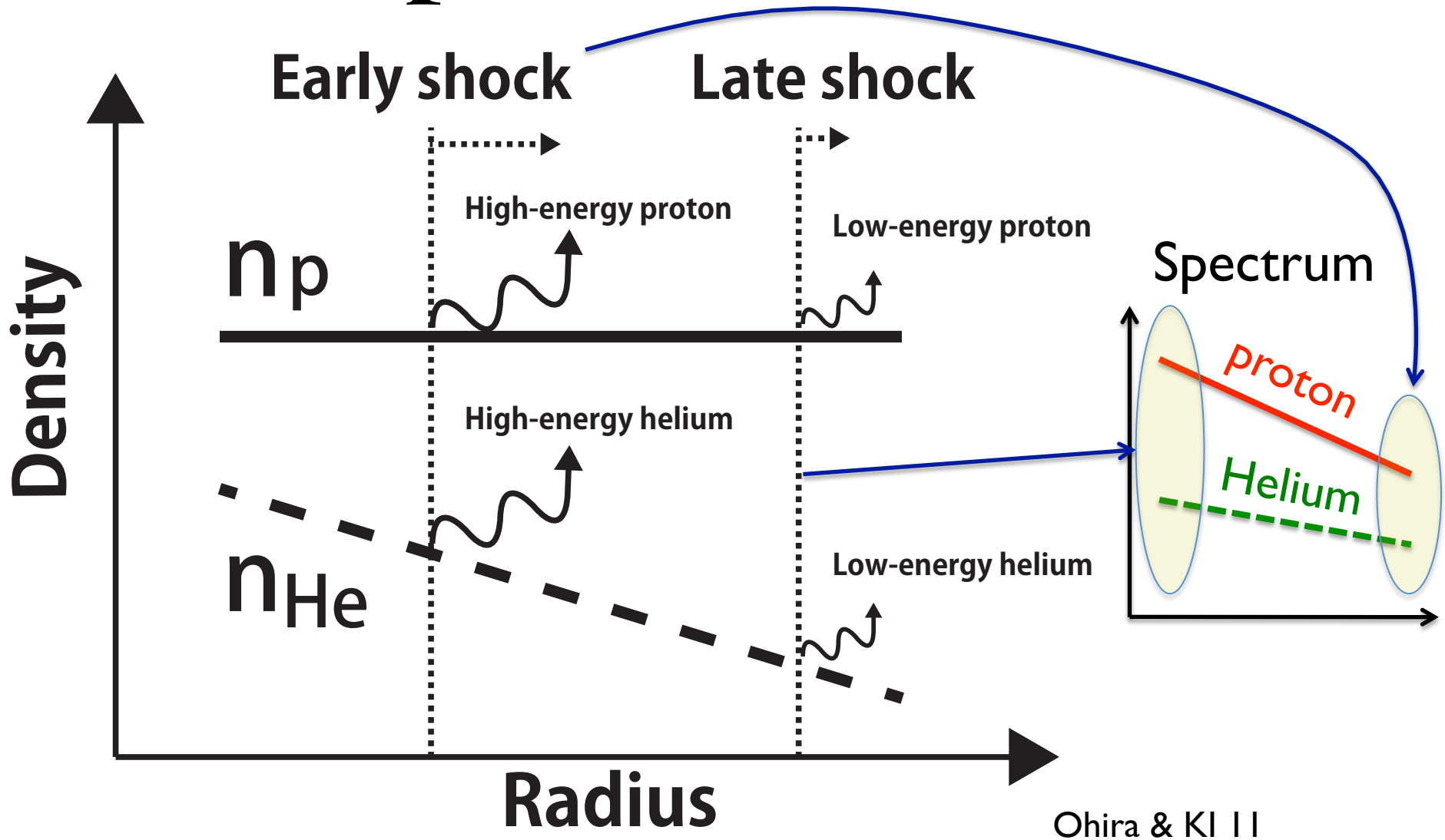
: Reason to invoke ***Big Bang***

⇒ Ejecta-enriched region

$M_{He}/M<$
q_{SC}~0.1

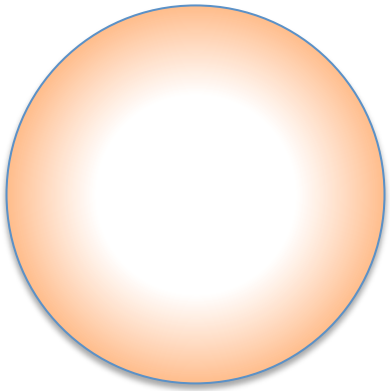


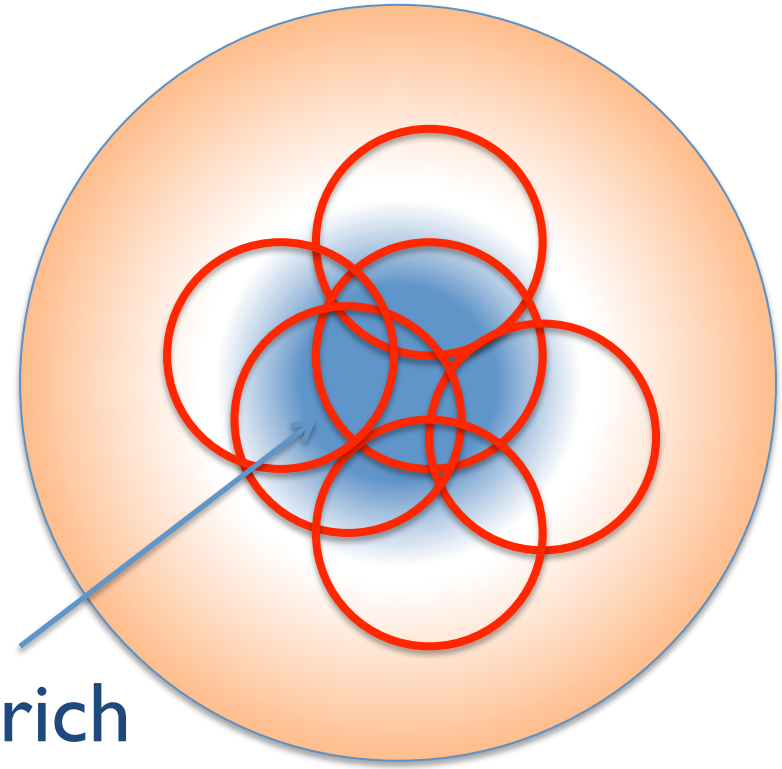
Composition Gradient



Ohira & KI 11
Ohira, Kawanaka & KI 15

CR origin ~ Superbubble?





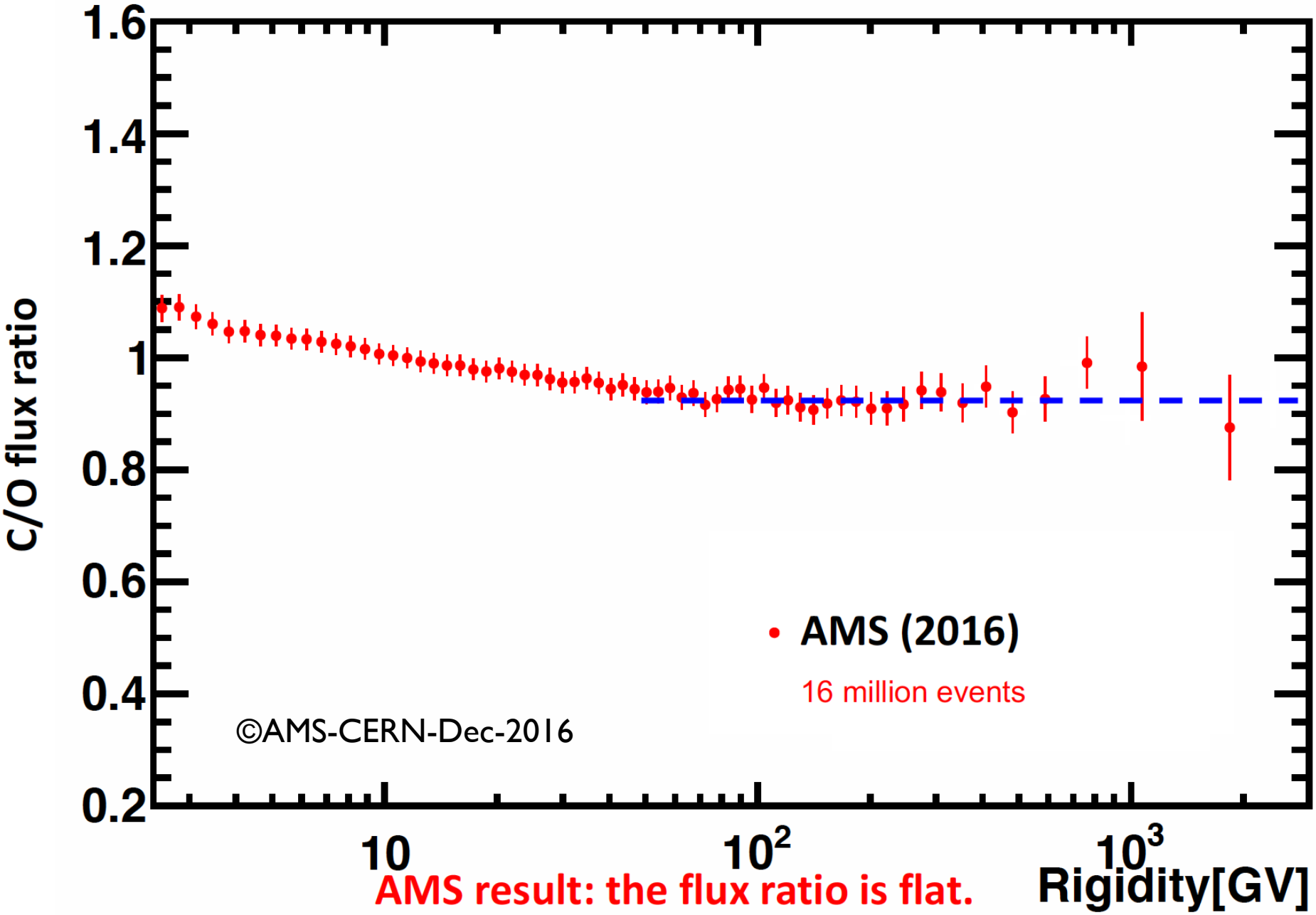
Isolated SNR
(~Fermi SNR)

not a main channel??

Multiple SNR
Superbubble

Predict hardenings of heavy elements

The AMS carbon/oxygen flux ratio



AMS result: the flux ratio is flat.

Scenarios for Different Cosmic-Ray Spectra

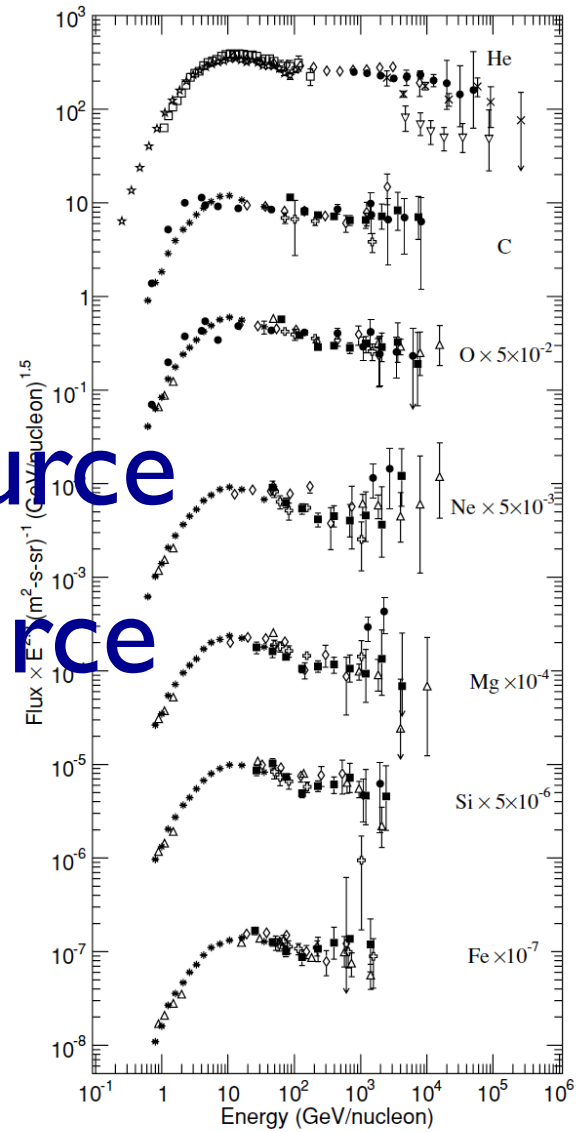
TABLE I. Score sheet for models of different cosmic-ray spectra.

Model	Mechanism	Score	Comment	Reference
Propagation	Spallation	C	Inconsistent with data of B/C	[9]
Different sources	Wind	C	Requires suppression of He (p) acceleration in the ISM (winds)	[10]
	Reverse shock	B	Requires suppression of He acceleration in the ISM	[11]
Injection	Injection	C	Inconsistent with C/He = const	[12]
Inhomogeneous environment	Ionization	C	Inconsistent with C/He = const	[13]
	Superbubble	A	Consistent with observations, and CRs originate from ejecta.	[8]

Ohira, Kawanaka & KI 15

Scenarios for Break

1. Propagation
2. Injection
3. Local high-energy source
4. Local low-energy source



Vladimirov+ 12
Khiali, Haino & Feng 17

B/C break?

Ne, Mg, Si, Fe breaks?

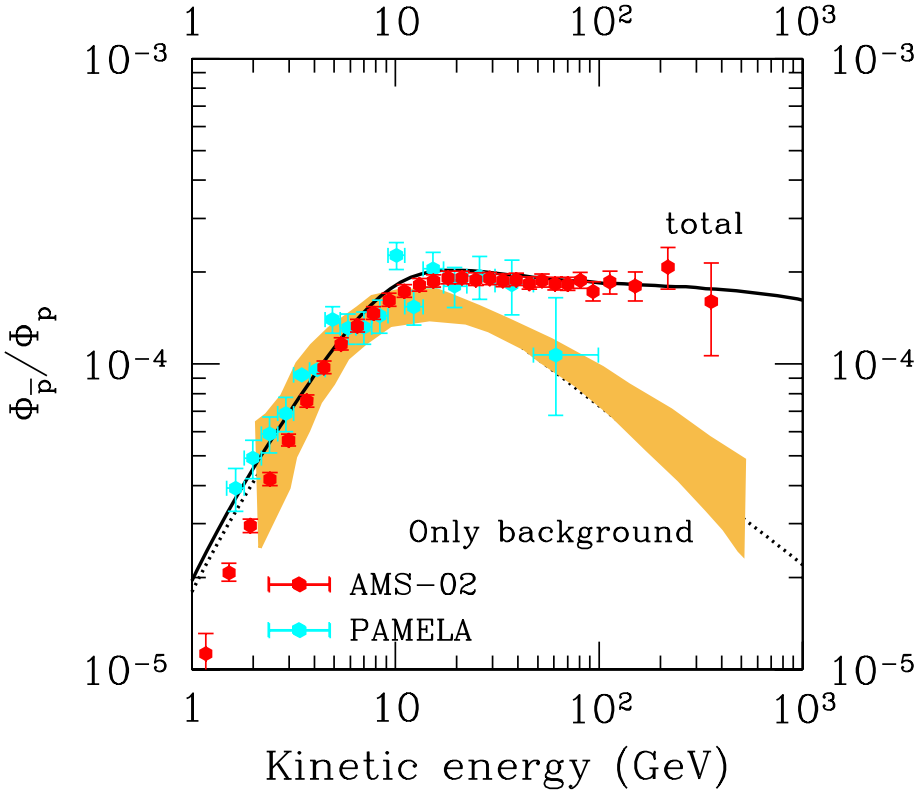
Contents

- ***$e^{\pm}$ excess: Astrophysical***
  - ✓ TeV spec., Anisotropy, … ***CALET***
- ***$\bar{p}$: No excess or pp?***
  - ✓ B/C ⇔ Li? ^{10}Be ***AMS-02***
- ***He, C, O : Superbubble?***
  - ✓ Ne, Mg, Si, Fe hardening?

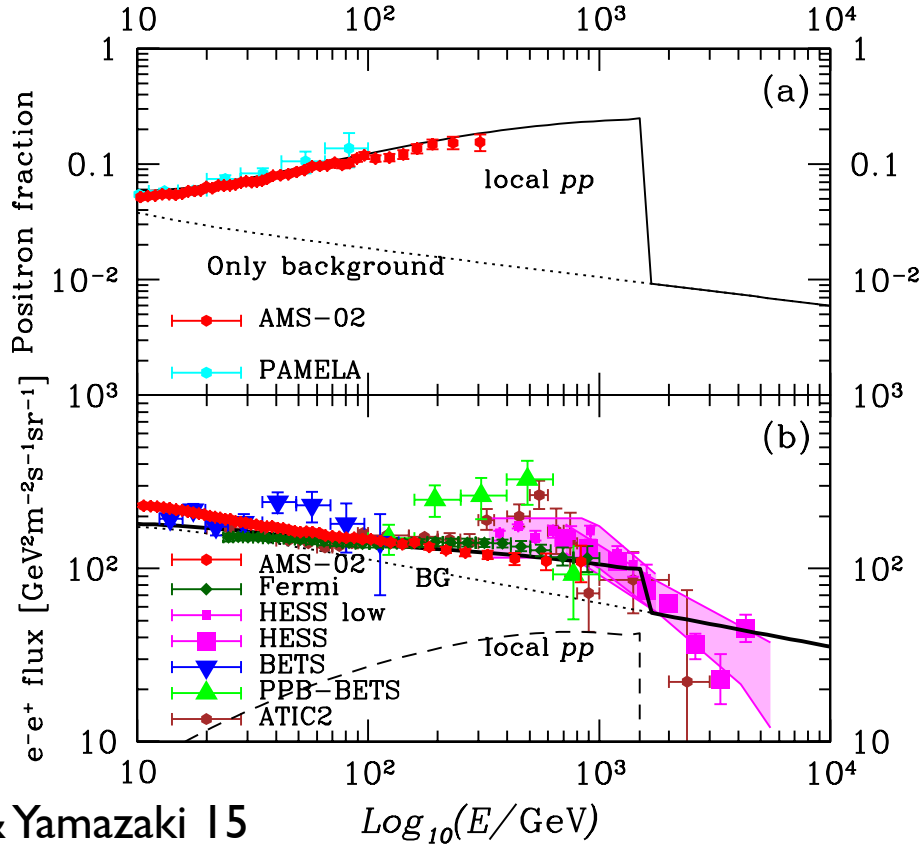
Thank You

pp in Supernova Remnant without Pulsars nor DM?

Anti-proton fraction



Positron & Electron



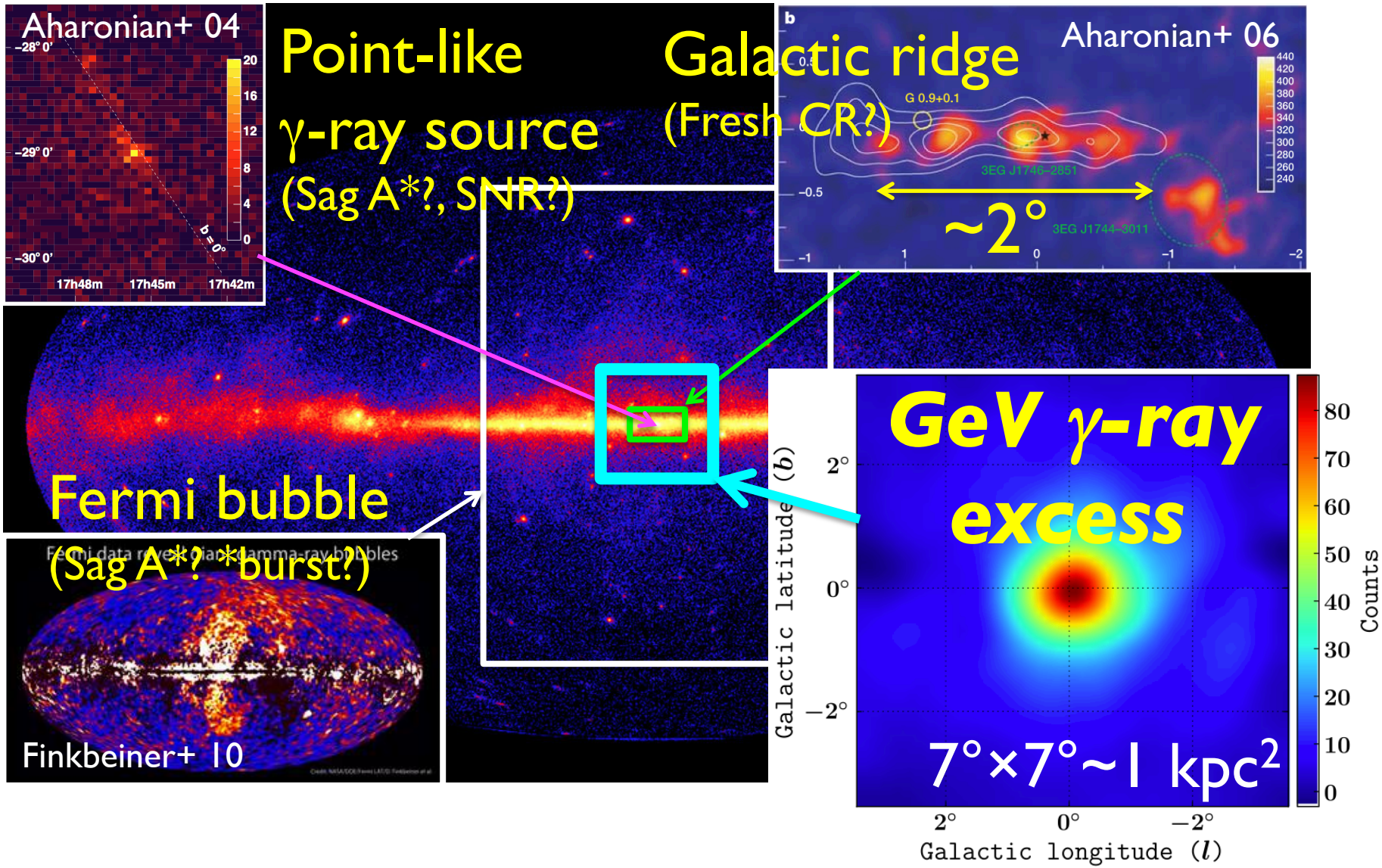
Kohri, KI, Fujita & Yamazaki 15

δ=0.42, D_0=2e28cm^2/s
Dense cloud n=50cm^{-3}, R=40pc
s=2.15, E_{max}=100TeV, E_{tot}=2.6e50erg, d=200pc

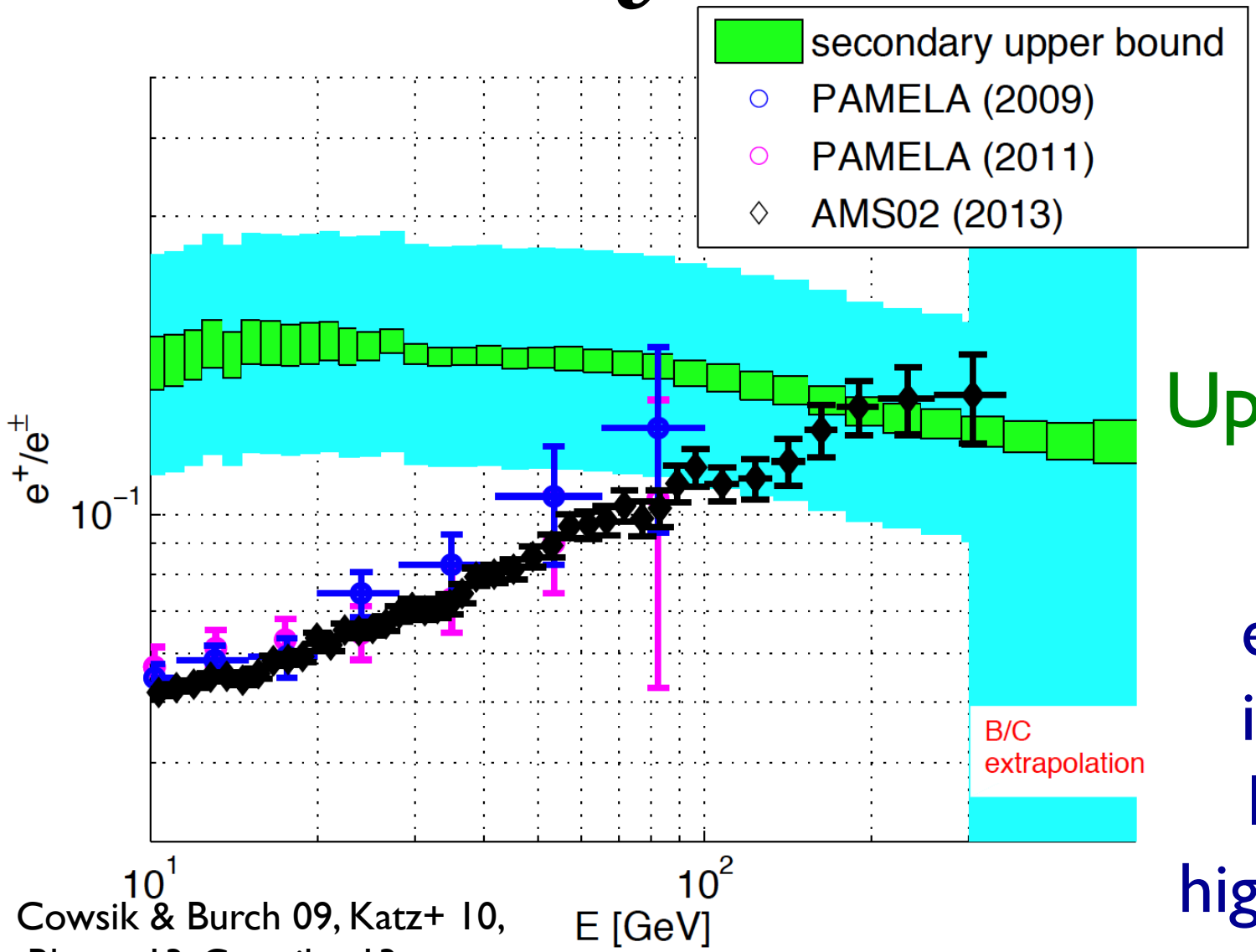
Simultaneous Fittings

Galactic Center

Morselli's talk



Secondary e^+ still Viable?

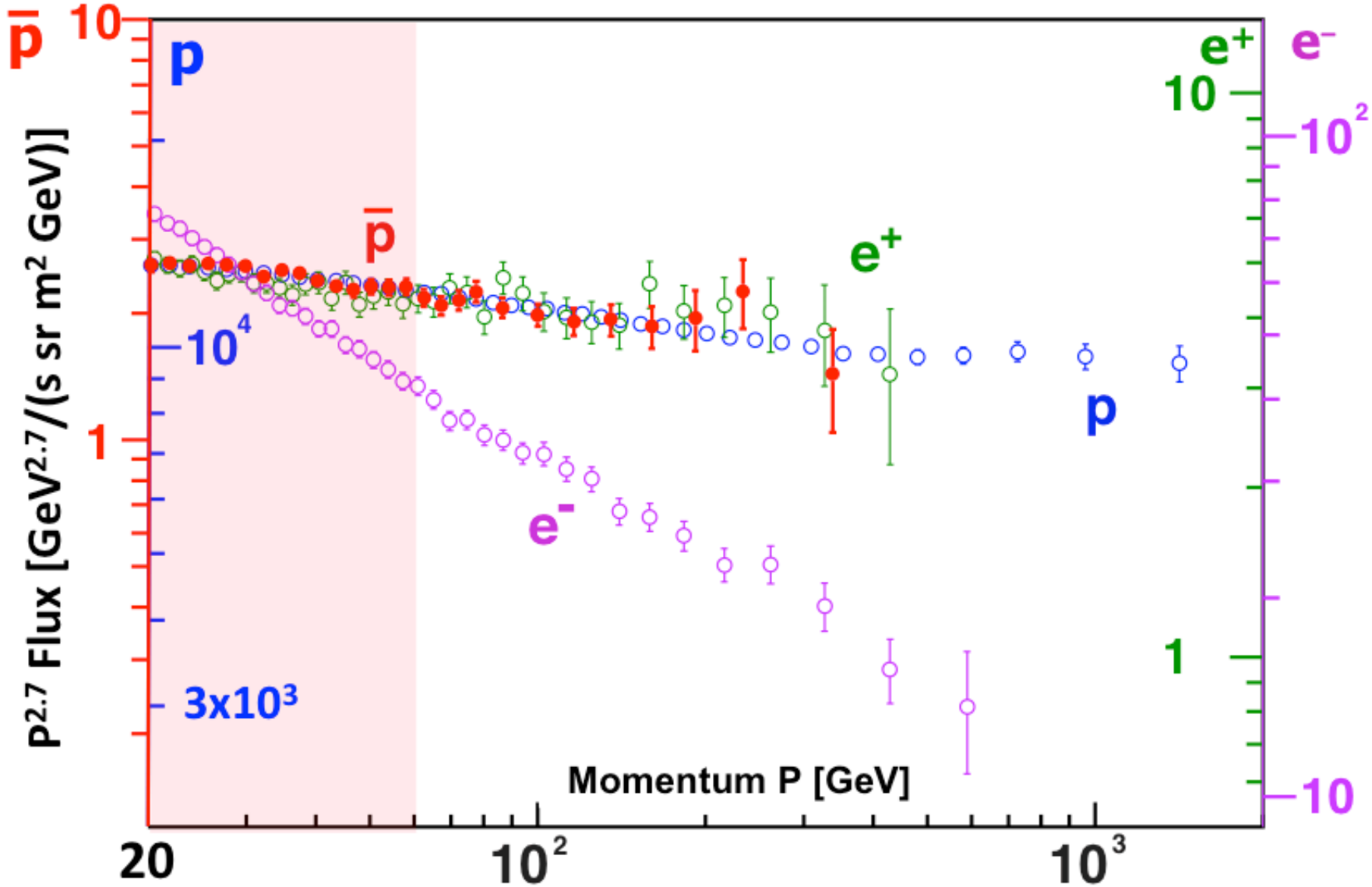


$p_{CR} + p_{ISM} \rightarrow \pi^+ \rightarrow e^+$

Upper Limits by B/C

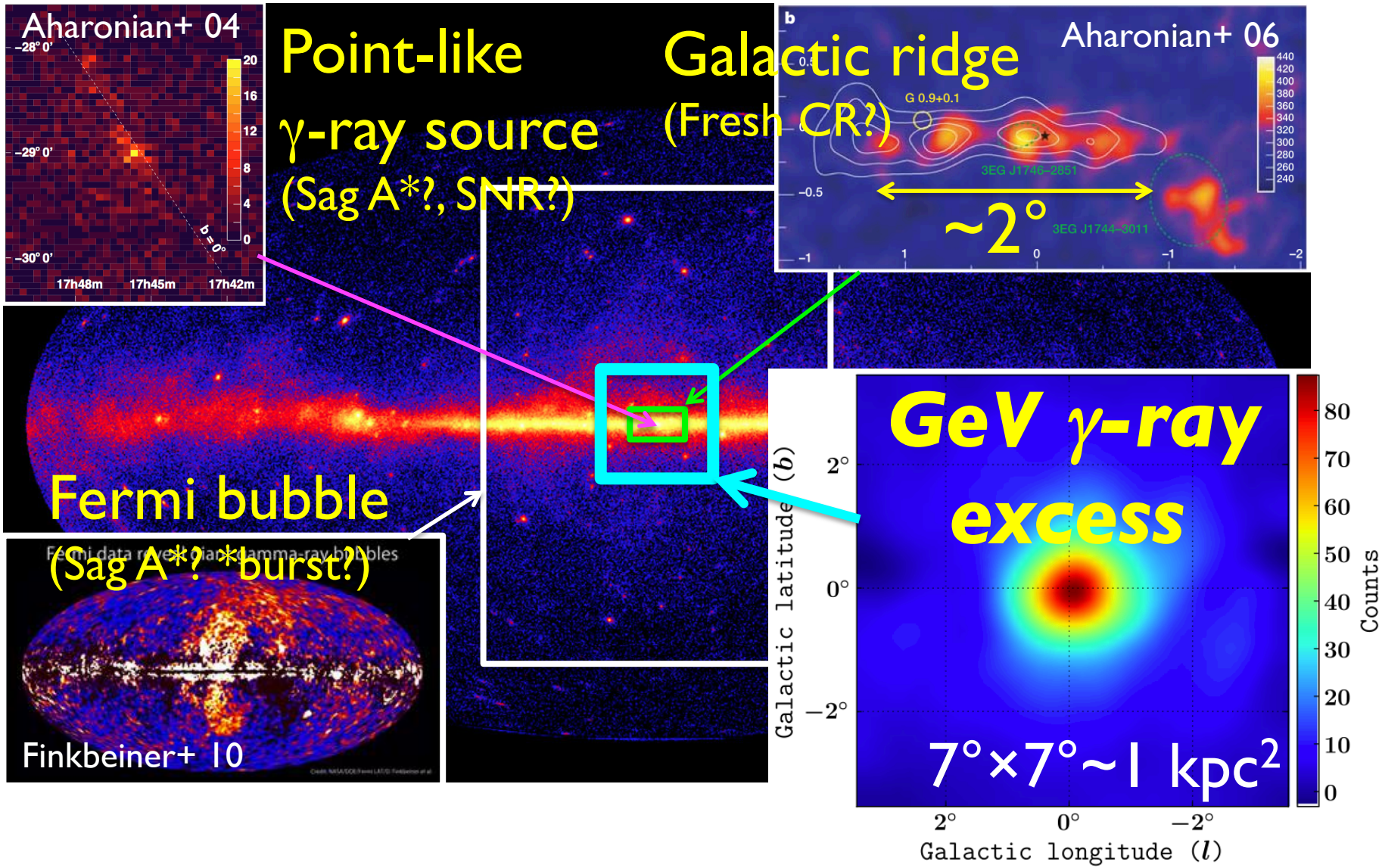
$e^+/e^\pm$ rise if t_{escape} is longer at higher energy

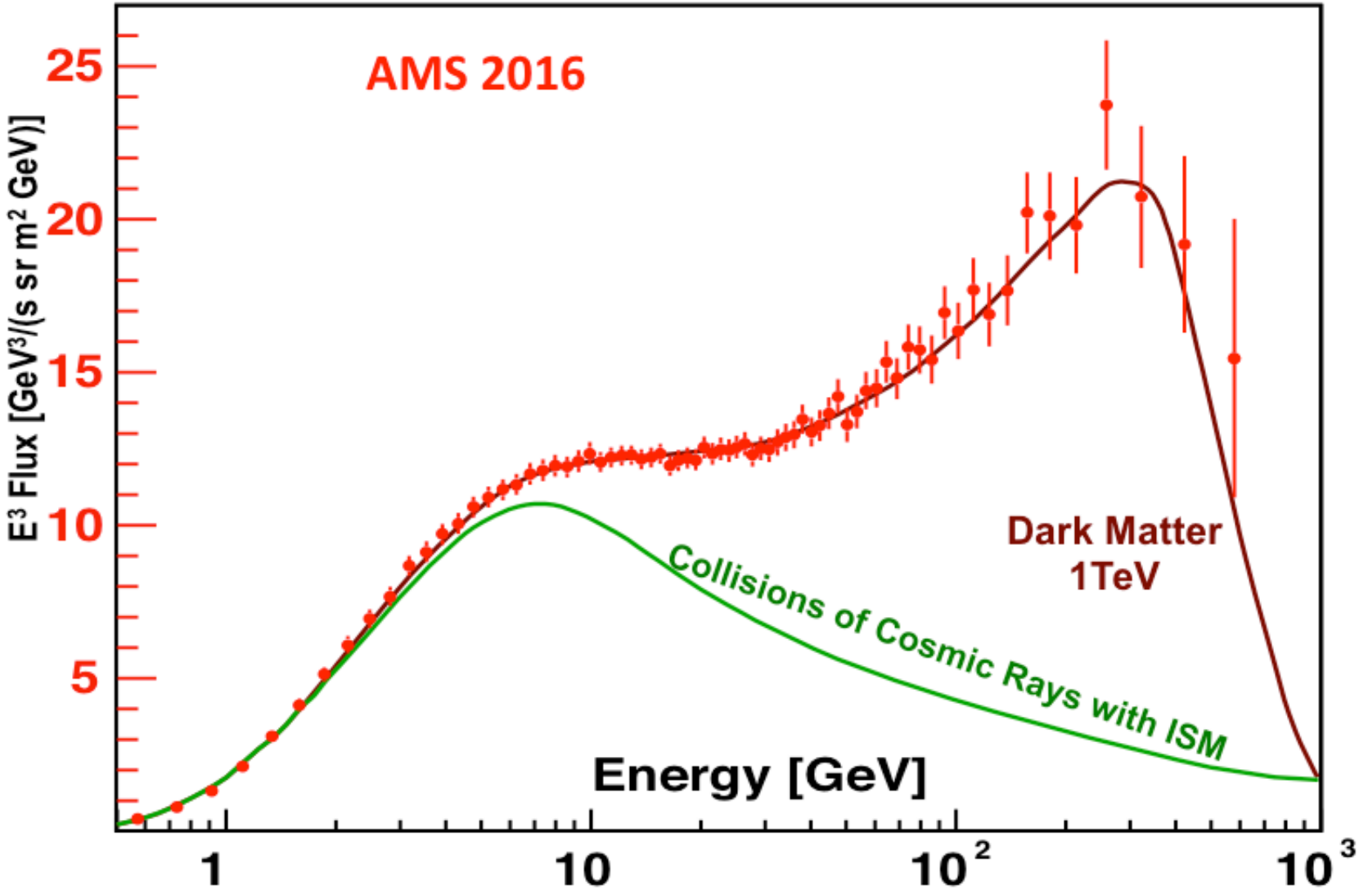
Cowsik & Burch 09, Katz+ 10, Blum+ 13, Cowsik+ 13


p̄
10
p
e+
e−
10
10²
p̄
e+
10⁴
p
1
e-
1
3x10³
Momentum P [GeV]
10
P2.7 Flux [GeV2.7/(s sr m2 GeV)]
20
10²
10³

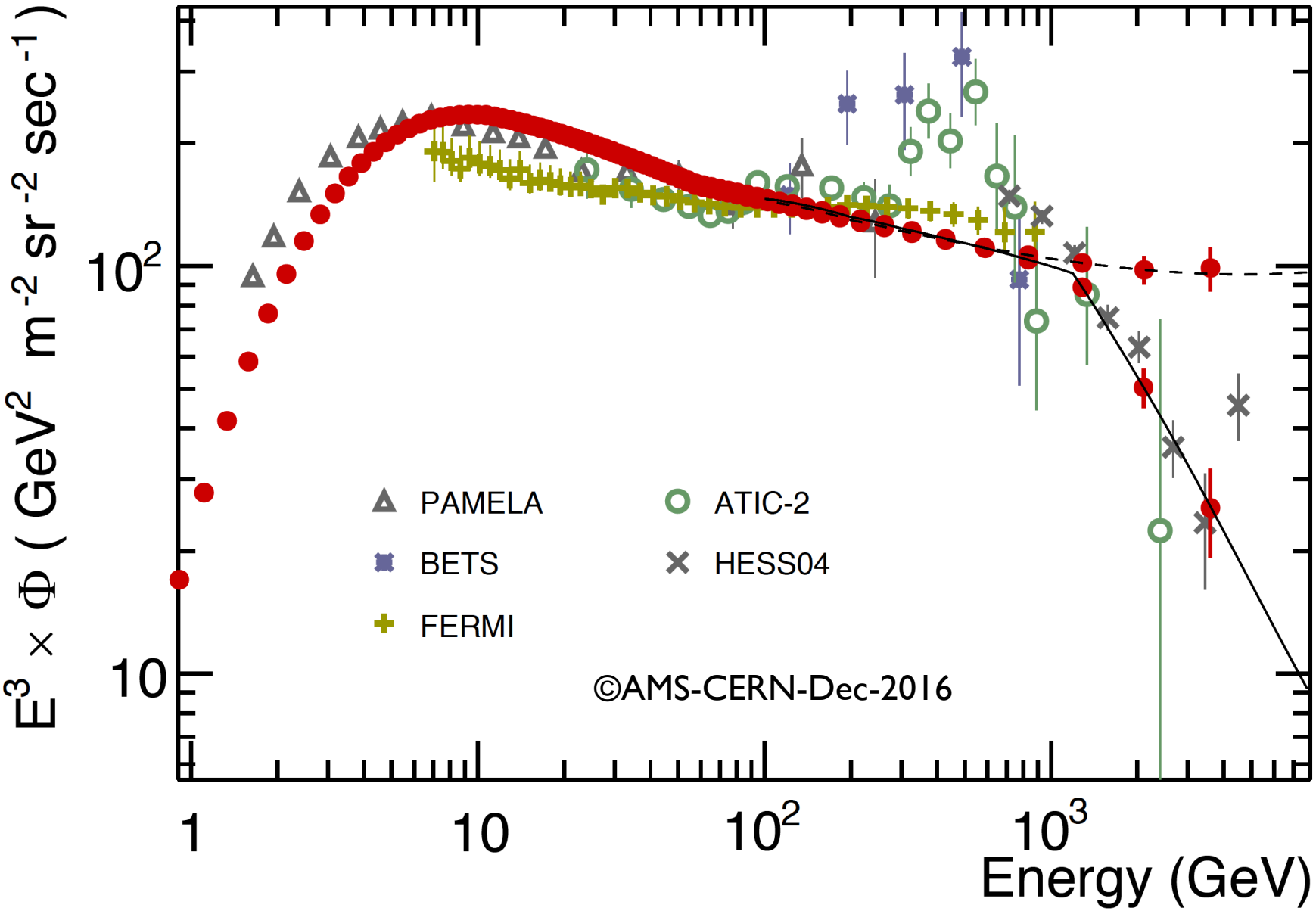
Galactic Center

Morselli's talk



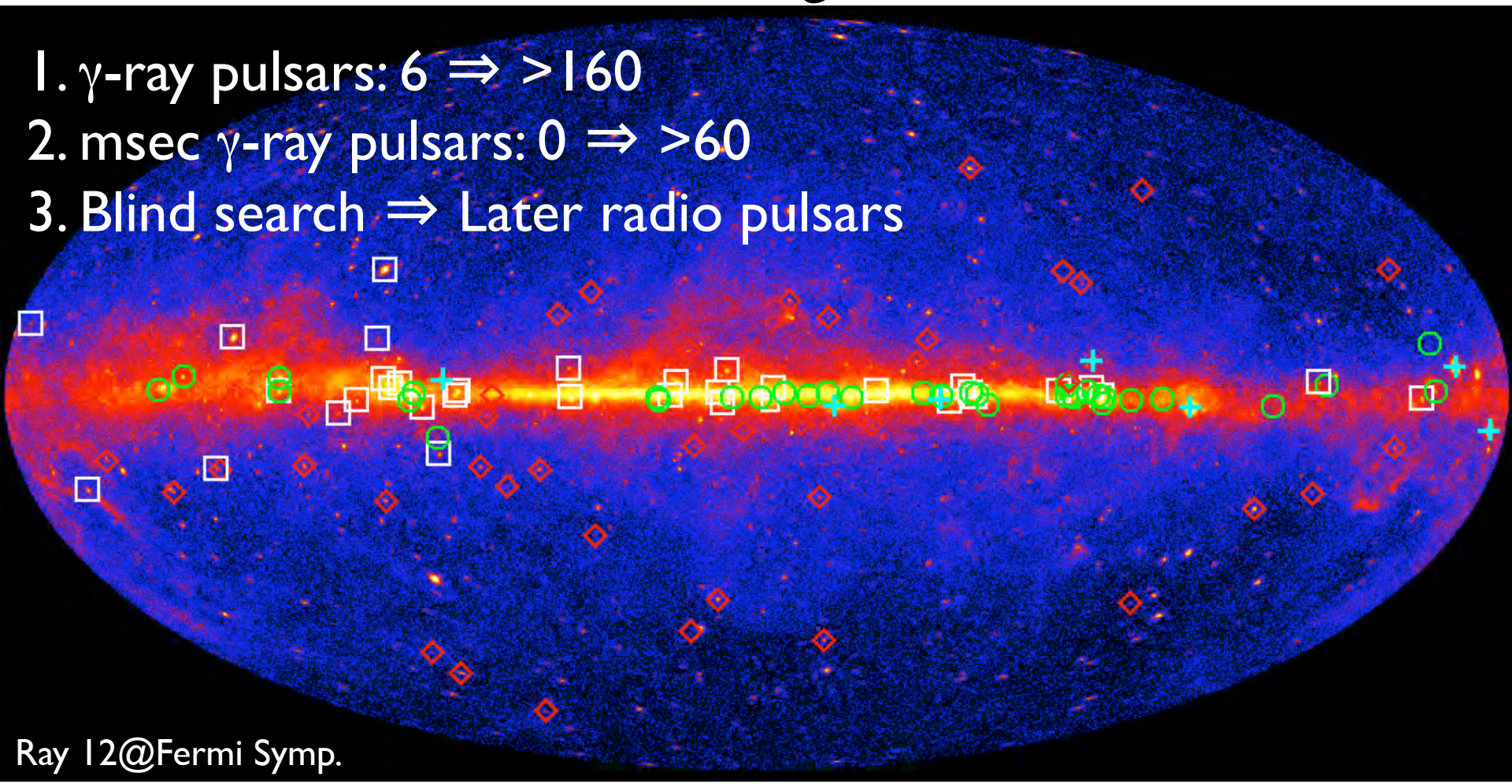

AMS 2016
E³ Flux [GeV³/(s sr m² GeV)]
25
20
15
10
5
Dark Matter
1TeV
Collisions of Cosmic Rays with ISM
Energy [GeV]
1
10
10²
10³

The AMS ($e^+ + e^-$) flux in 2024



AMS will be able to distinguish the ($e^+ + e^-$) flux behavior above 1 TeV

Gamma-Ray Pulsars

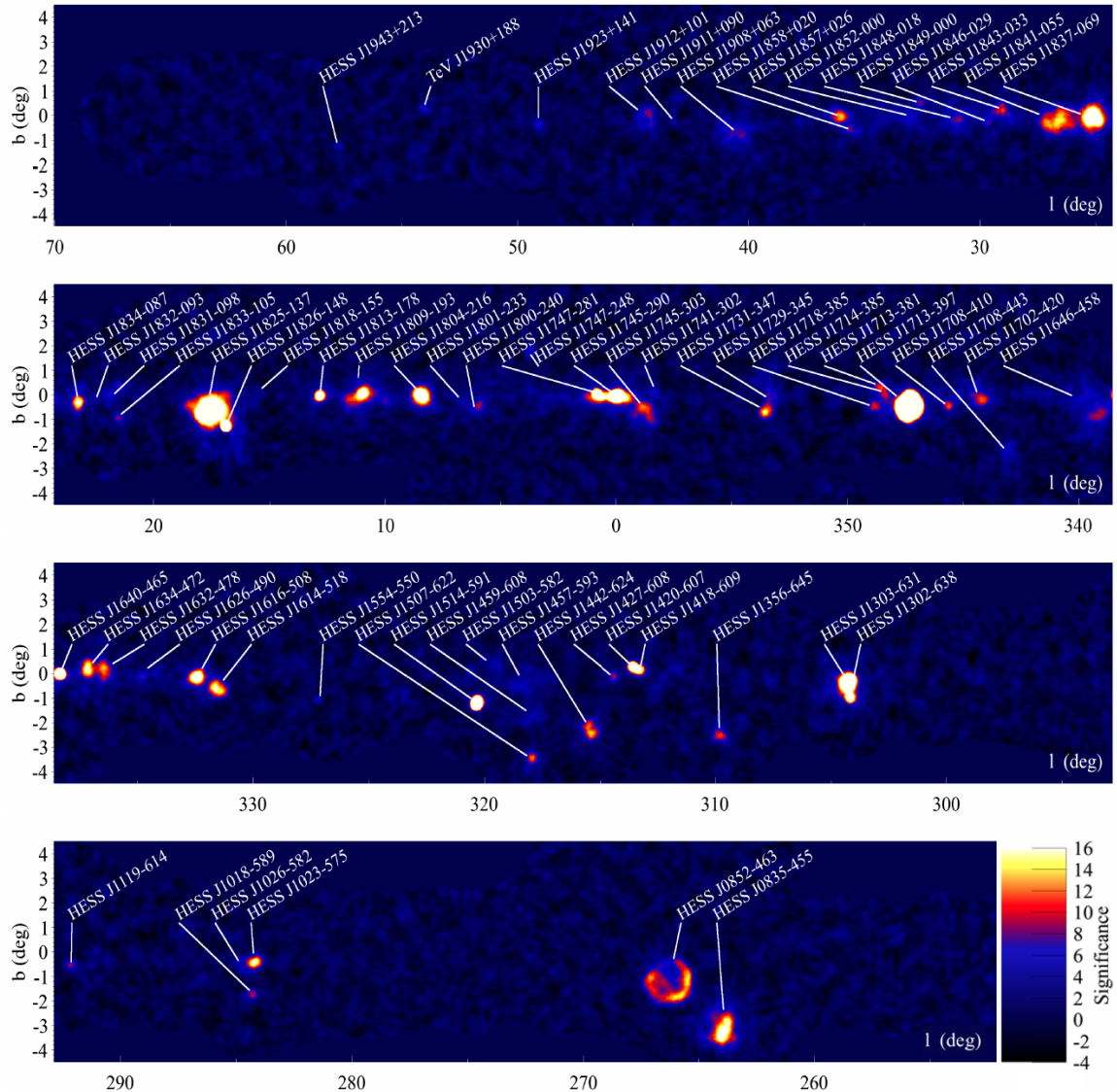


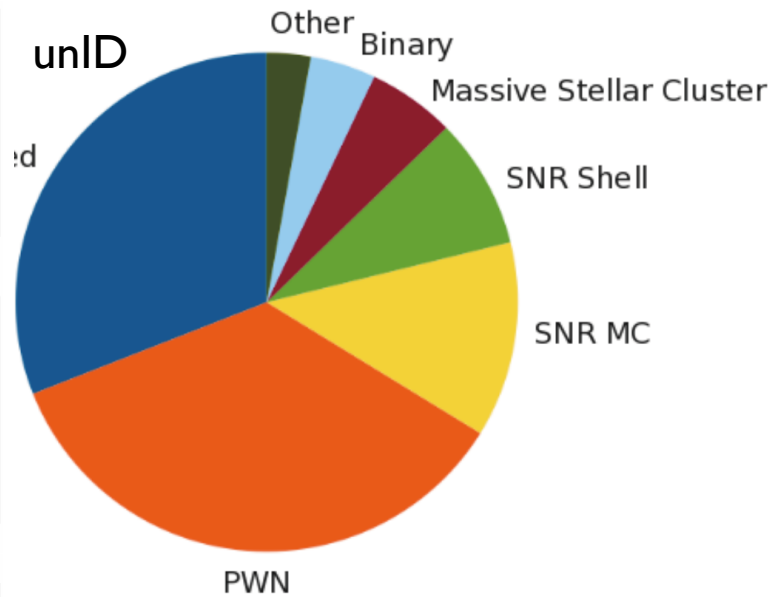
Fermi satellite (LAT) has found ***>160 γ-ray pulsars***

CGRO PSRs (+), young radio-selected (○), young gamma-selected (□), MSPs (◇)

TeV Gamma-Ray Sky

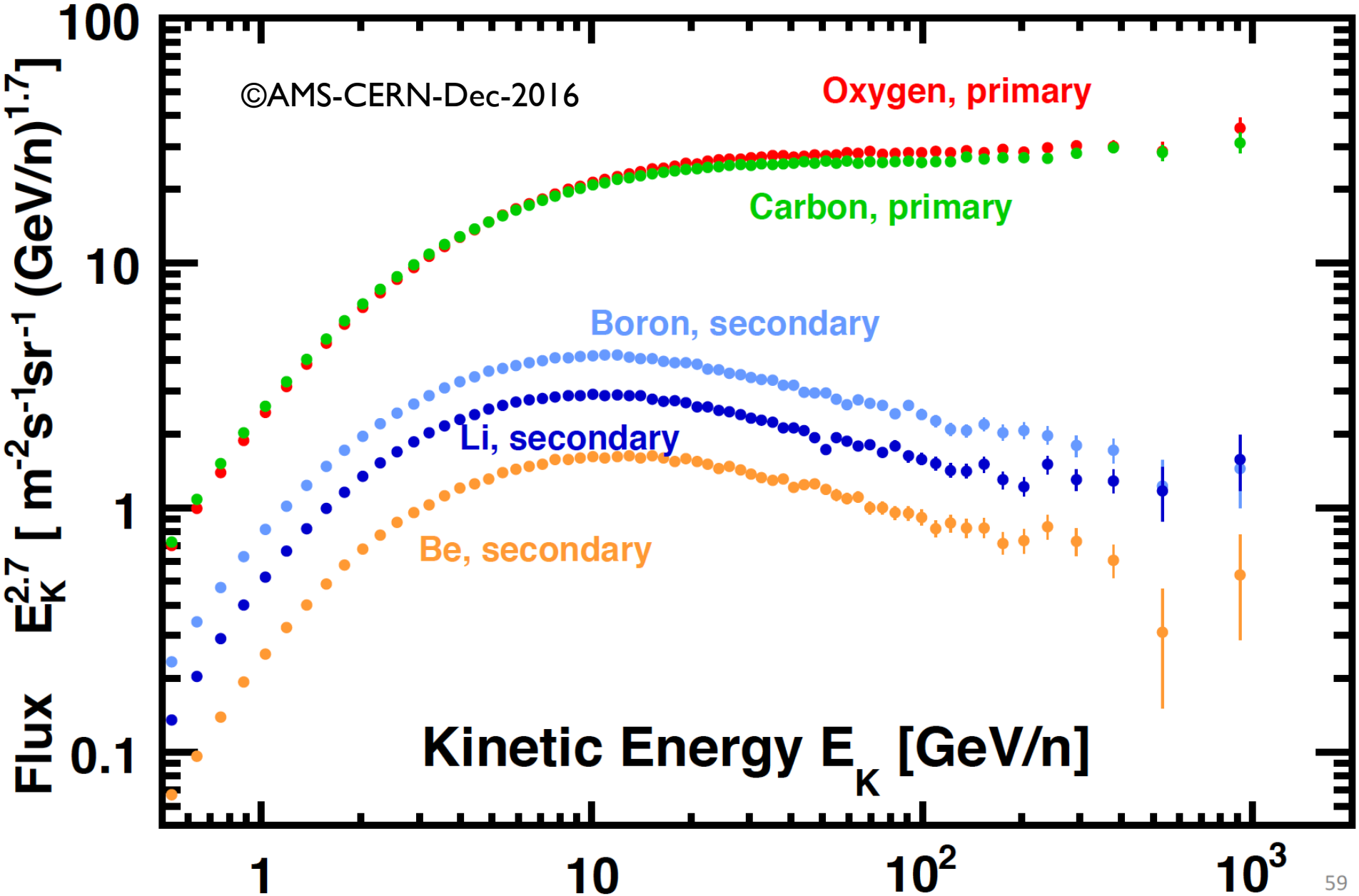
1307.4690



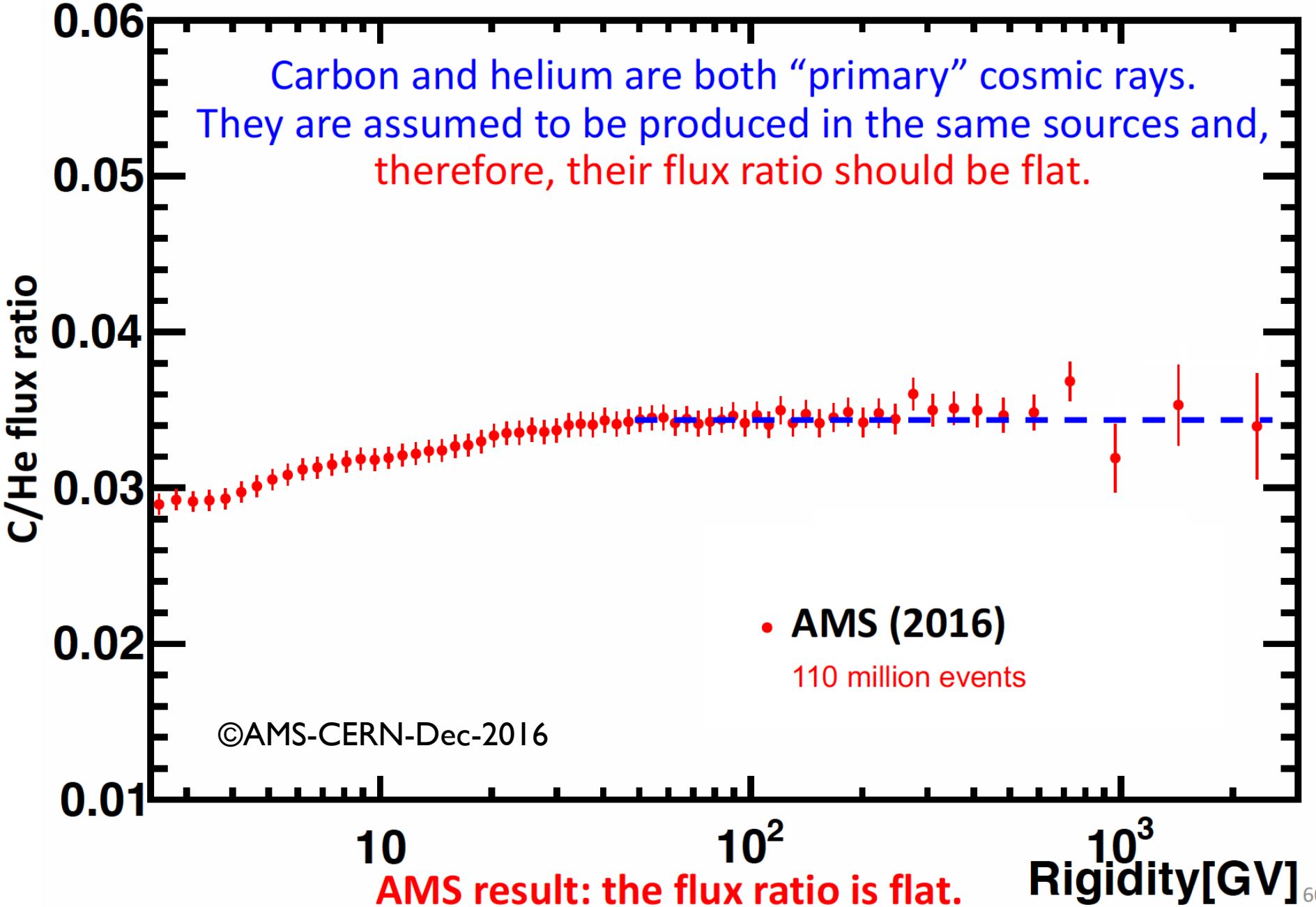


Pulsar Wind Nebula dominates TeV γ-ray sky

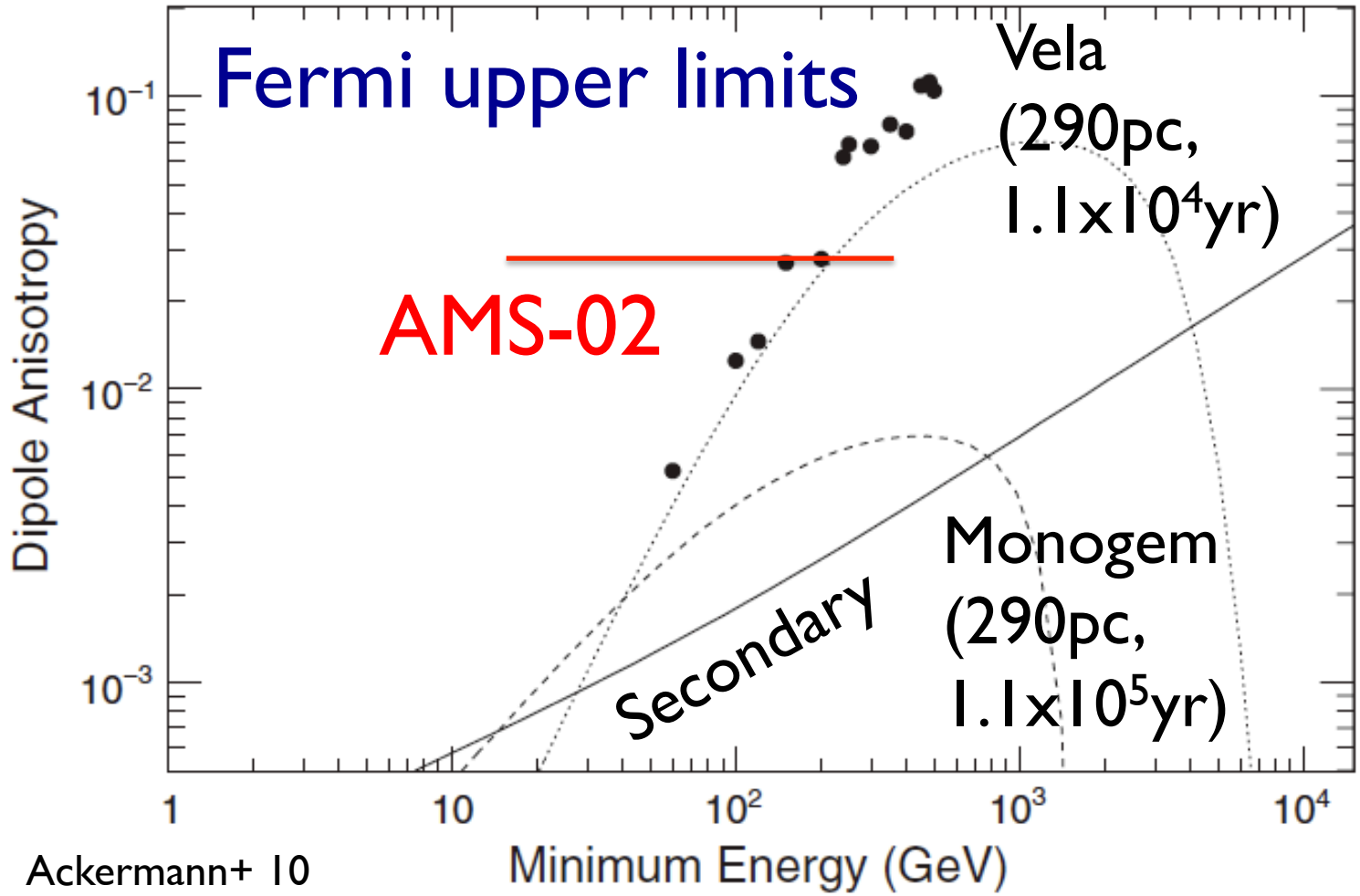
Physics Result 17: Primary and secondary Cosmic Rays have very different momentum dependence



Physics Result 18: The AMS carbon/helium flux ratio



e^- Anisotropy



Ackermann+ 10

$$\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{3K|\nabla f|}{cf} \sim \frac{3d}{2ct}$$

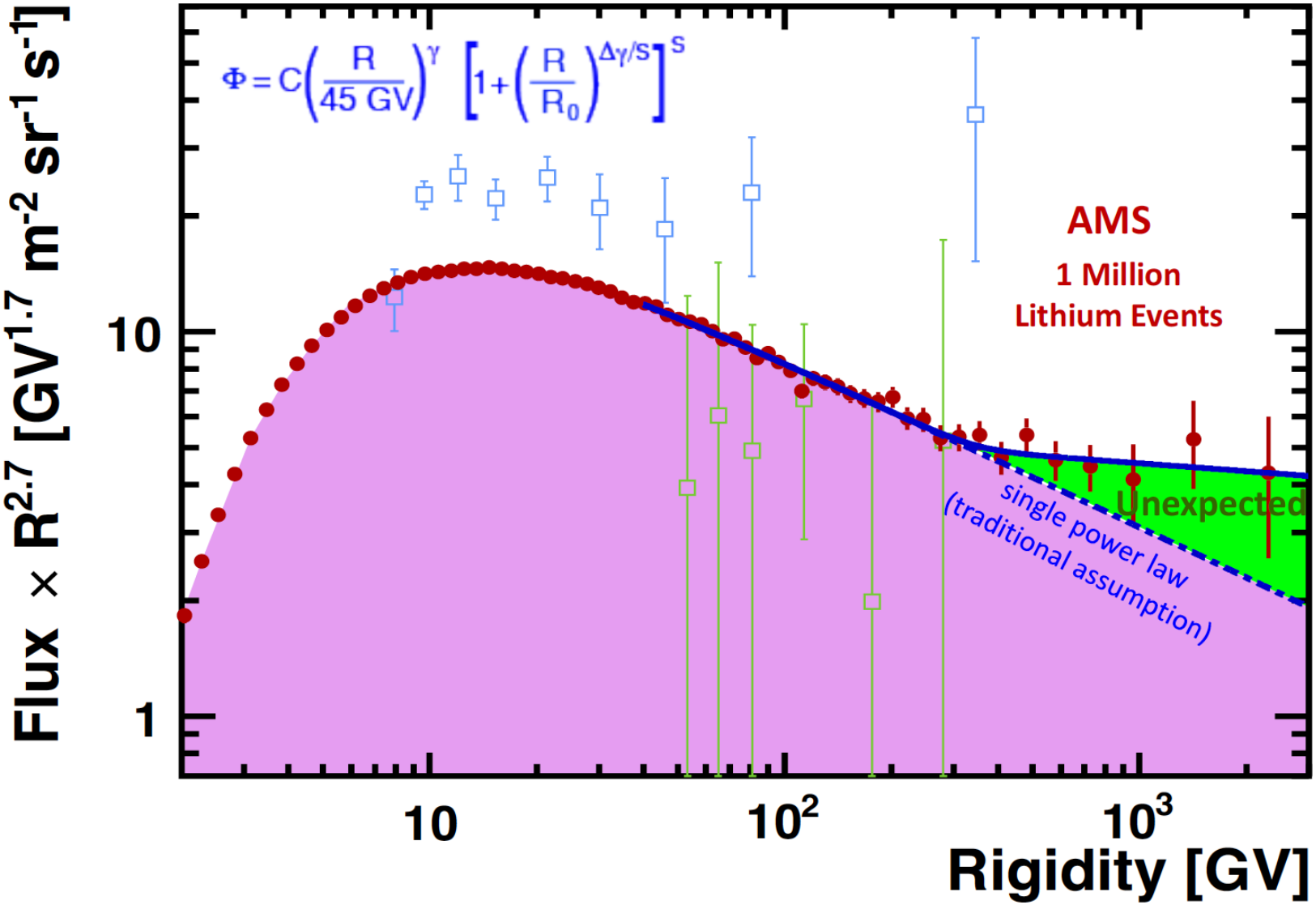
δ<0.030 (95%CL; 16-350GeV) by AMS-02

Limit $\propto t^{-1/2}$; For multiple sources, anisotropy ↓

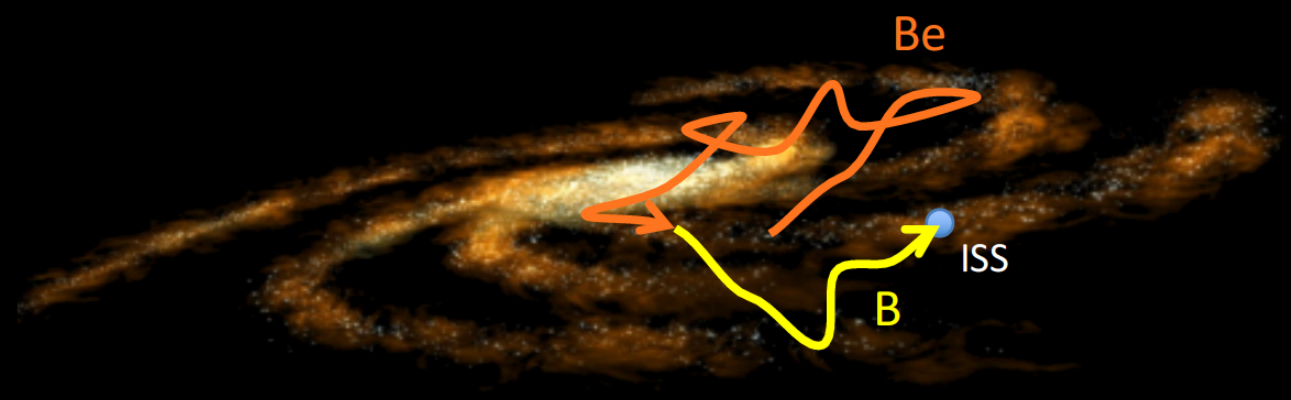
Physics Result 10: The Lithium flux

New AMS results on Secondary Cosmic Rays (Lithium)

New information: The Lithium spectrum behaves similar to protons and Helium and the Lithium flux cannot be described by a single power law.



Flux Ratios: Beryllium-to-Boron and age of cosmic rays

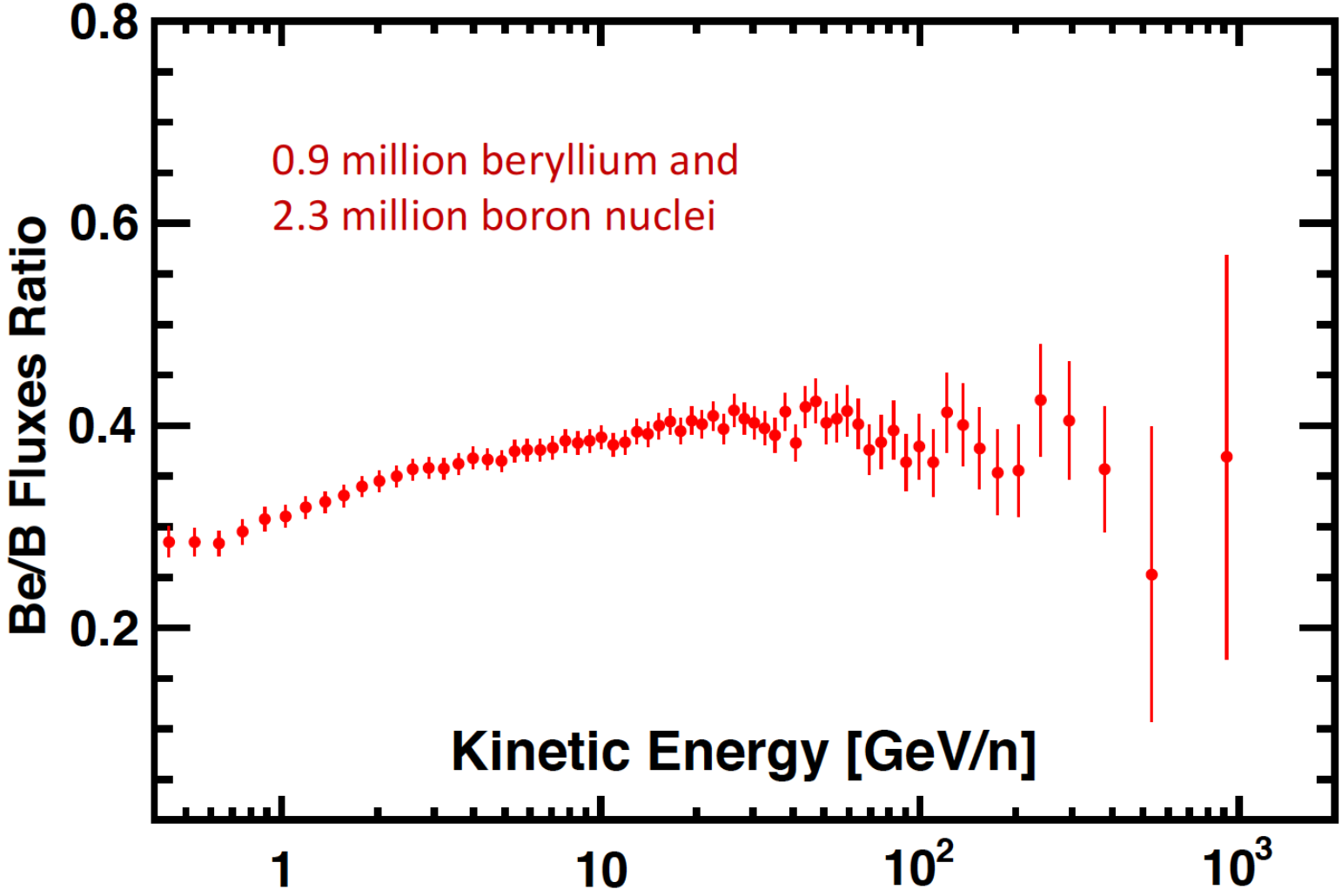


$$^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + e^{-} + \bar{\nu}_e$$

The ^{10}Be half-life is 1.5×10^{6} years.

The Be/B ratio rises with energy due to relativistic time dilation. Be/B provides information on the age of cosmic rays in the Galaxy.

Physics Result 13: The Beryllium-to-Boron flux ratio



AMS: The age of cosmic rays in the galaxy is ~12 million years.