INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

PAMELA/ATIC cosmic-ray anomalies and new physics

1. Apr. 2009
@実験理論共同研究会
「LHC が切り拓く新しい物理」

Fuminobu Takahashi
(IPMU, Univ. of Tokyo)

Collaborators: Chen, Hamaguchi, Komatsu, Nojiri, Shirai, Torii, Yanagida

arXiv:0809.0792, 0810.4110, 0811.0477, 0811.3357, 0812.4200, 0901.1915, 0901.2168, 0902.4770

Plan of talk

- 1.Introduction
- 2.PAMELA and ATIC/PPB-BETS anomalies
- 3.Dark Matter Models
  - Annihilation and decay of dark matter
  - Hidden gauge boson
- 4.Conclusion

Introduction

Dark Matter

How can we know the presence of “dark” matter?

Gravity

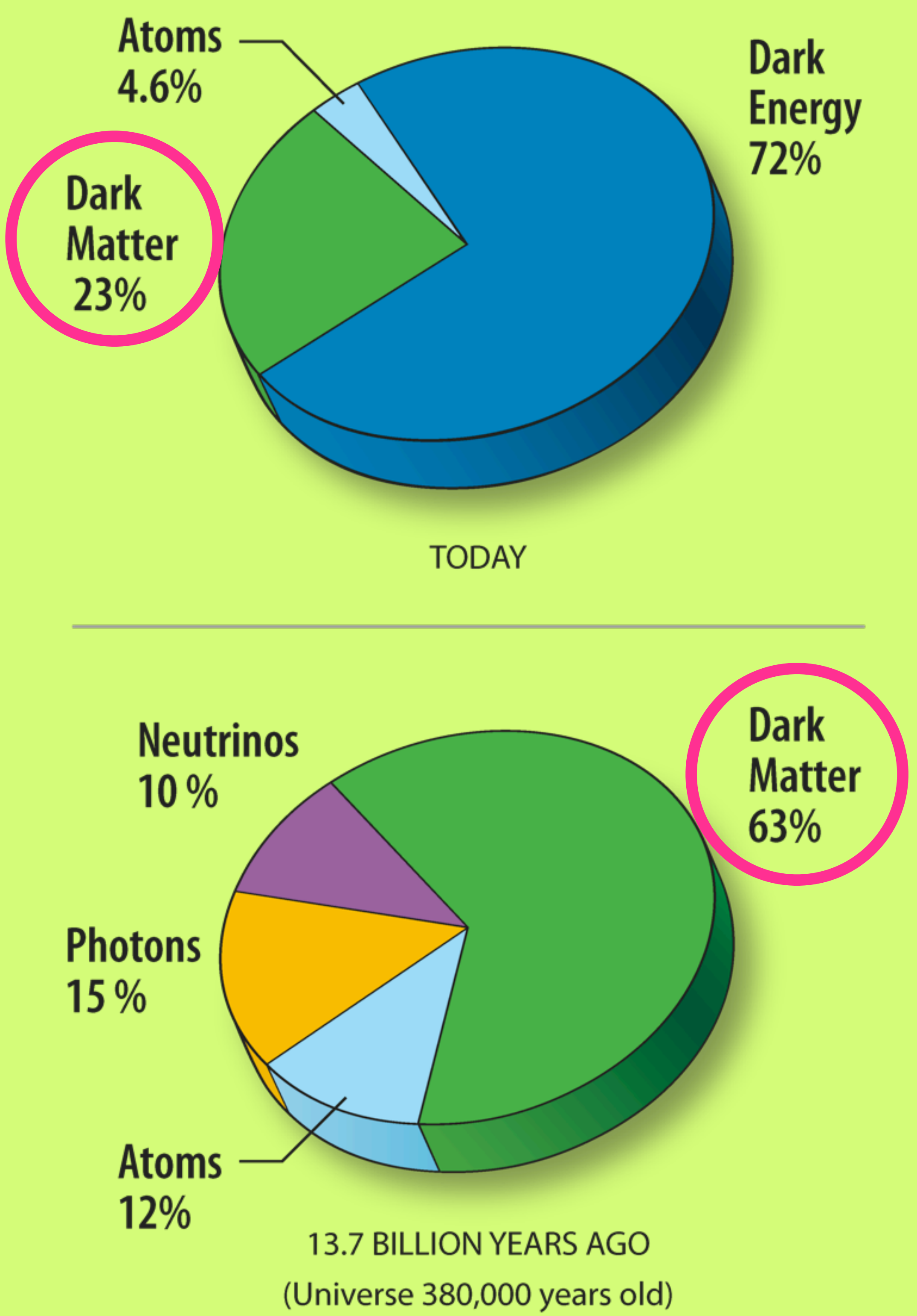
It's not just a good idea.
It's the law!

Dark Matter

The presence of DM has been firmly established.

$$\Omega_{DM} \sim 0.2$$

- CMB observation
- Rotation curves
- Structure formation
- Big bang nucleosynthesis



(taken from WMAP webpage)

Dark Matter Candidates

Many

Must be electrically neutral, long-lived and cold.

No DM candidates in SM.

- SUSY

  LSP is long-lived if R-parity is a good symmetry.

  e.g.) neutralino, gravitino, right-handed sneutrino, axino, etc..

- Little Higgs, UED, etc.

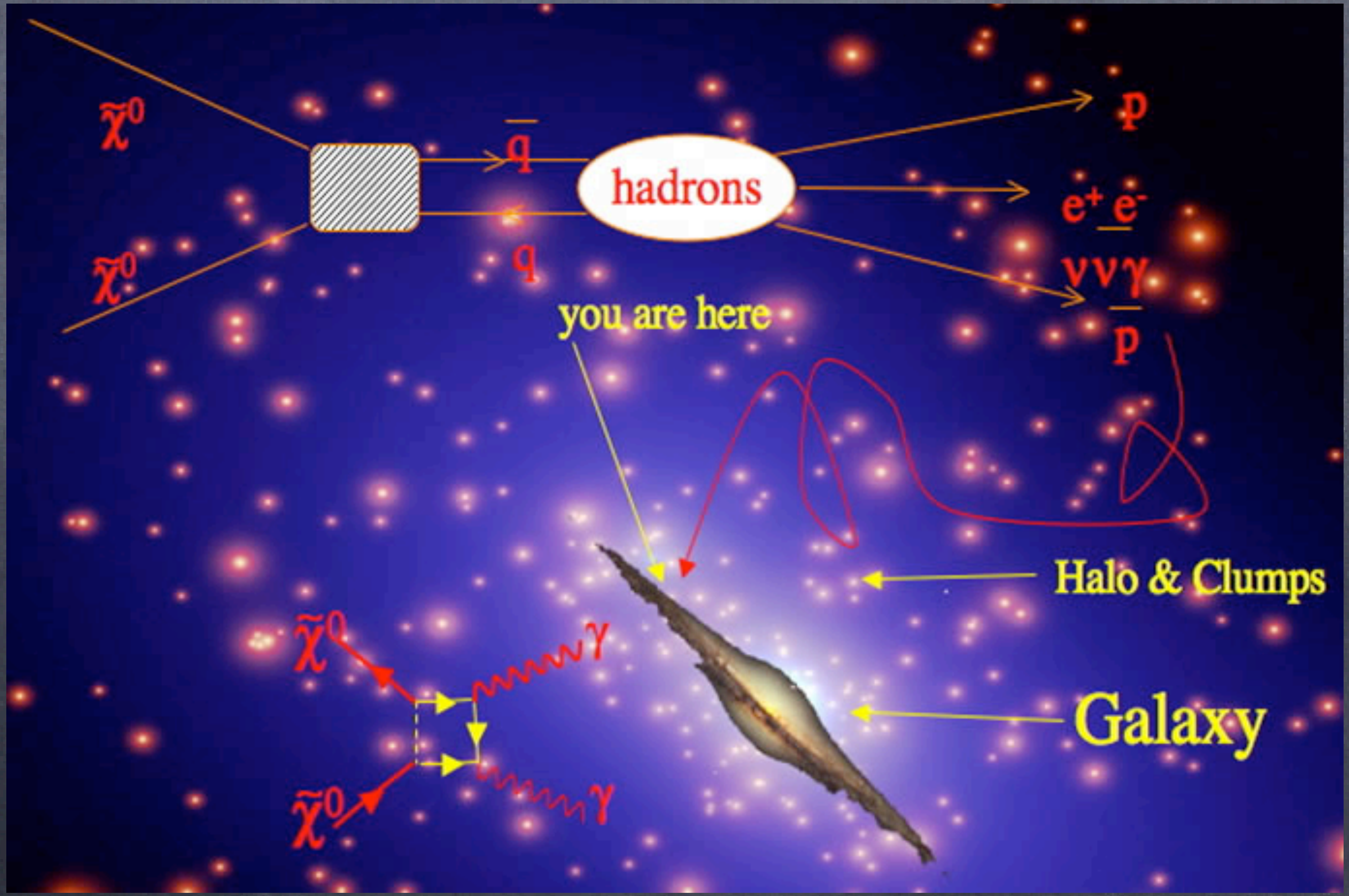
  The lightest T-parity/KK-parity particles

- Others

  Q-ball, saxion, moduli, sterile ν, etc...

Dark matter may not be completely dark.

- Collider
- Direct detection
- Indirect search:
  annihilation/decay of dark matter



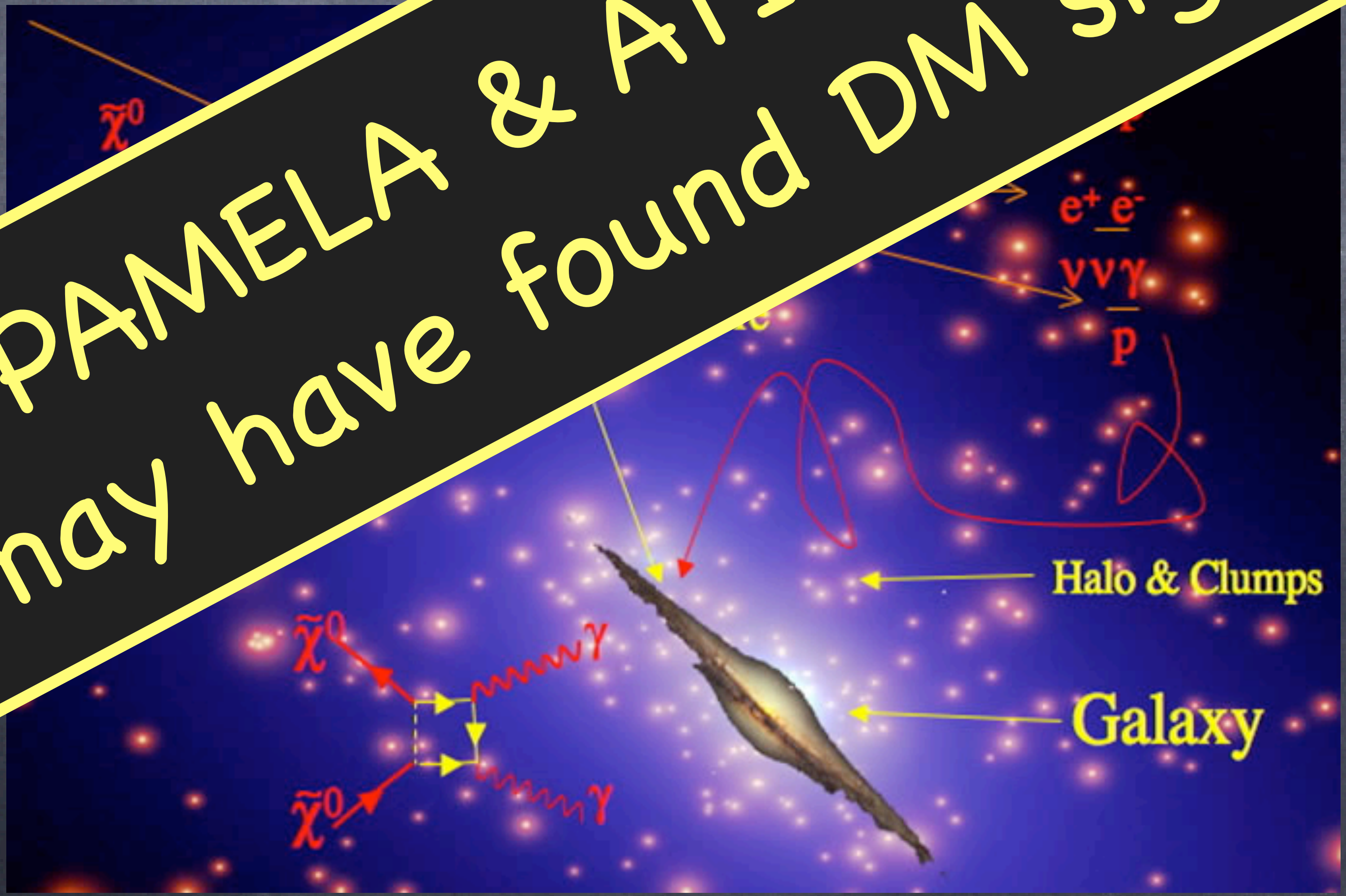
Uncertainty in propagation/ clumpiness.

(http://pamela.roma2.infn.it/index.php)

Dark matter may not be completely dark.

- Collider
- Direct detection
- Indirect search: annihilation/decay of

PAMELA & ATIC/PPB-BETS may have found DM signature?!



Uncertainty in propagation/ clumpiness.

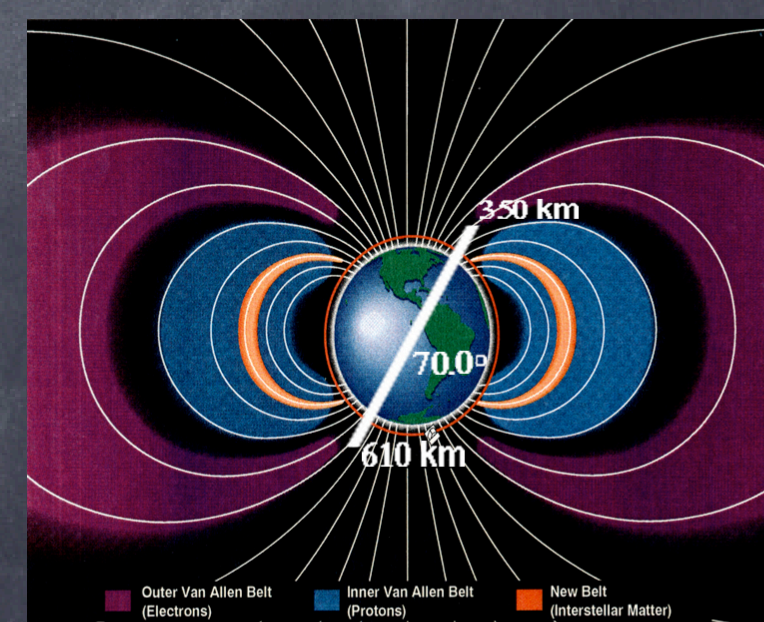
(http://pamela.roma2.infn.it/index.php)

PAMELA and ATIC/PPB-BETS

PaMeLa

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

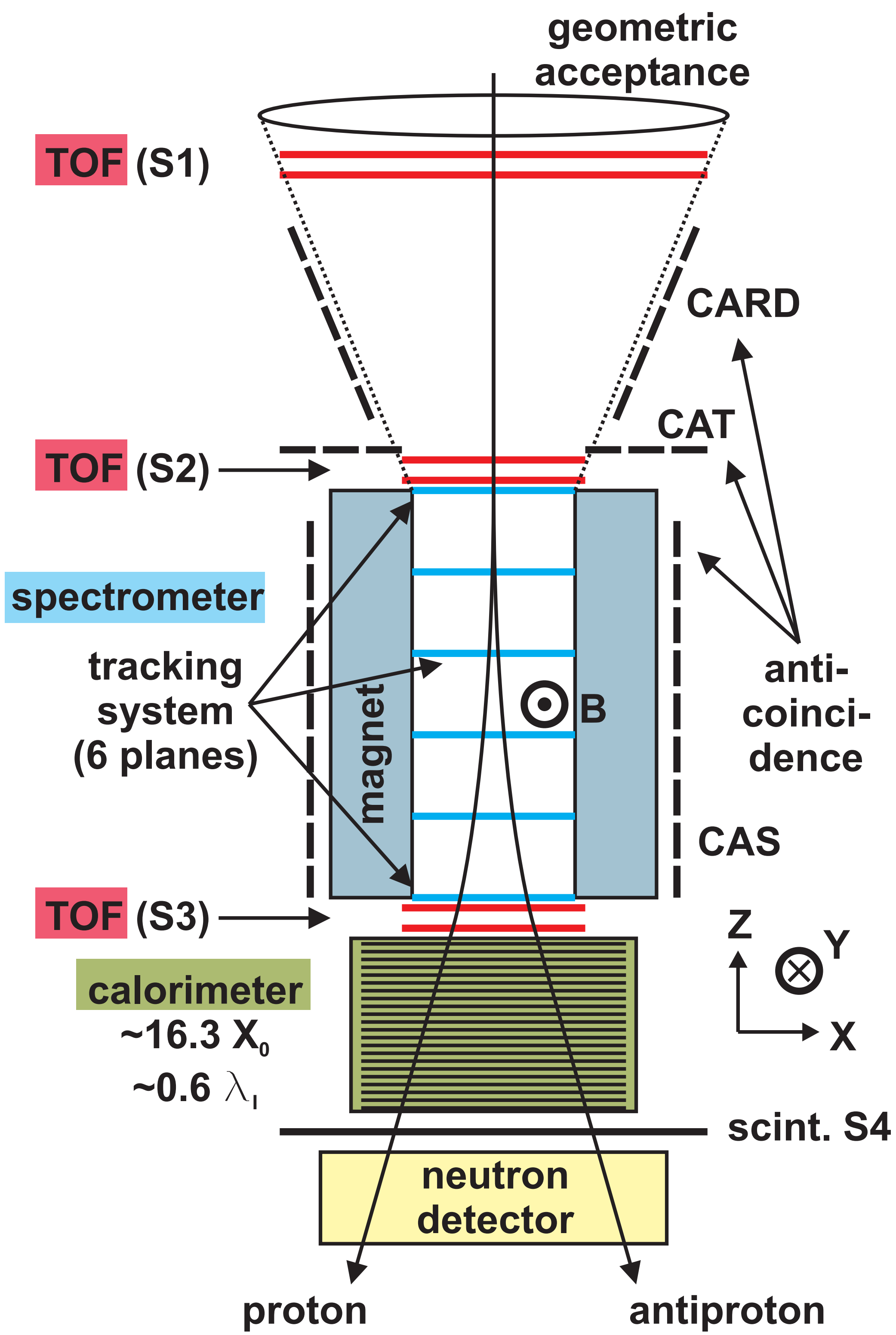
- Launched on the 15th of June 2006.
- An altitude between 350 and 610 Km with an inclination of 70°.
- Expected to operate at least by Dec. 2009 (3 years).



Energy range:

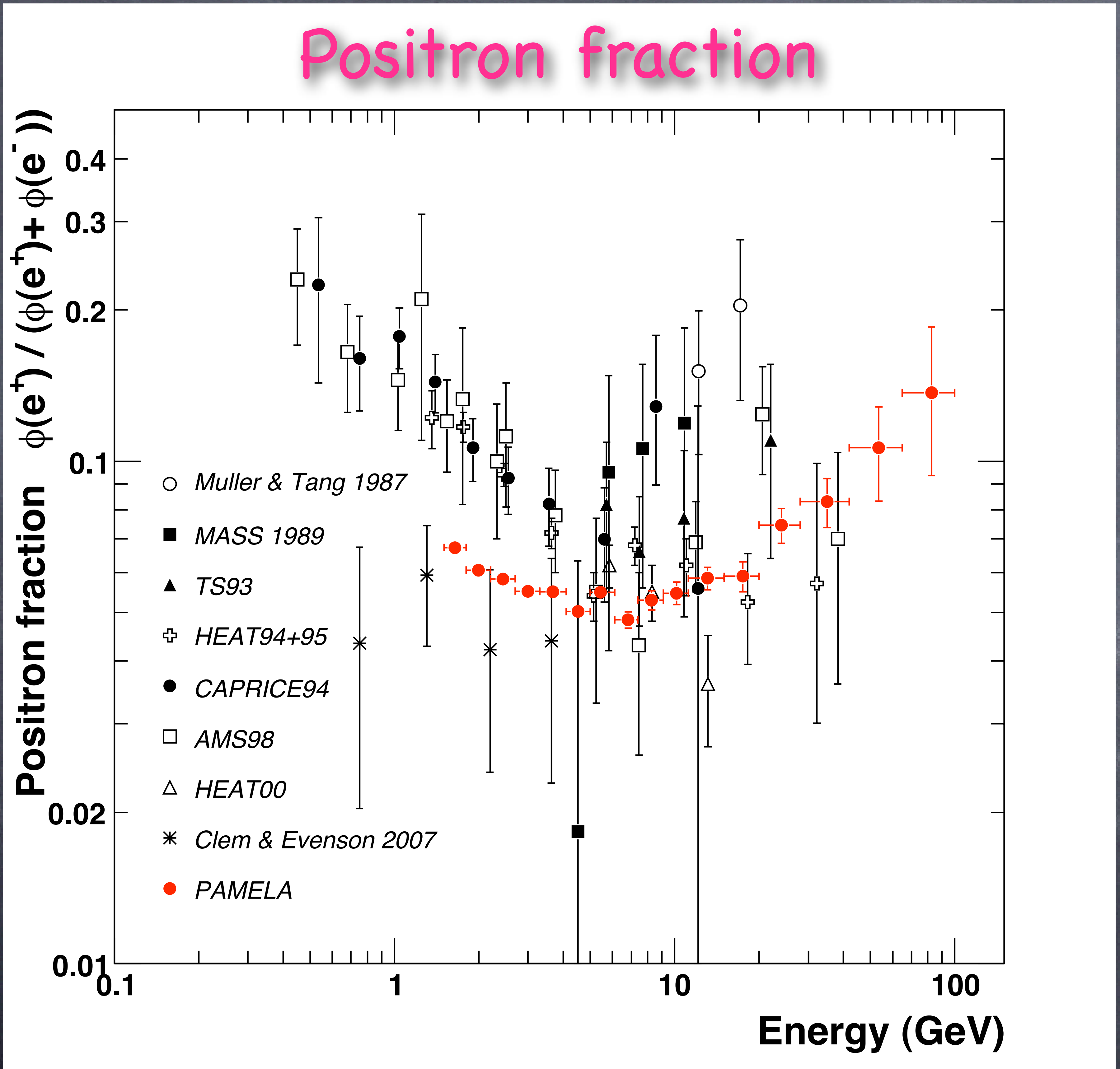
Positron: 50 MeV - 270 GeV

Antiproton: 80 MeV - 190 GeV



geometric acceptance
TOF (S1)
CARD
CAT
TOF (S2)
spectrometer
tracking system (6 planes)
magnet
B
anti-coinci-dence
CAS
TOF (S3)
Z
Y
X
calorimeter
~16.3 X_0
~0.6 λ_I
scint. S4
neutron detector
proton
antiproton

This is what PAMELA observed.



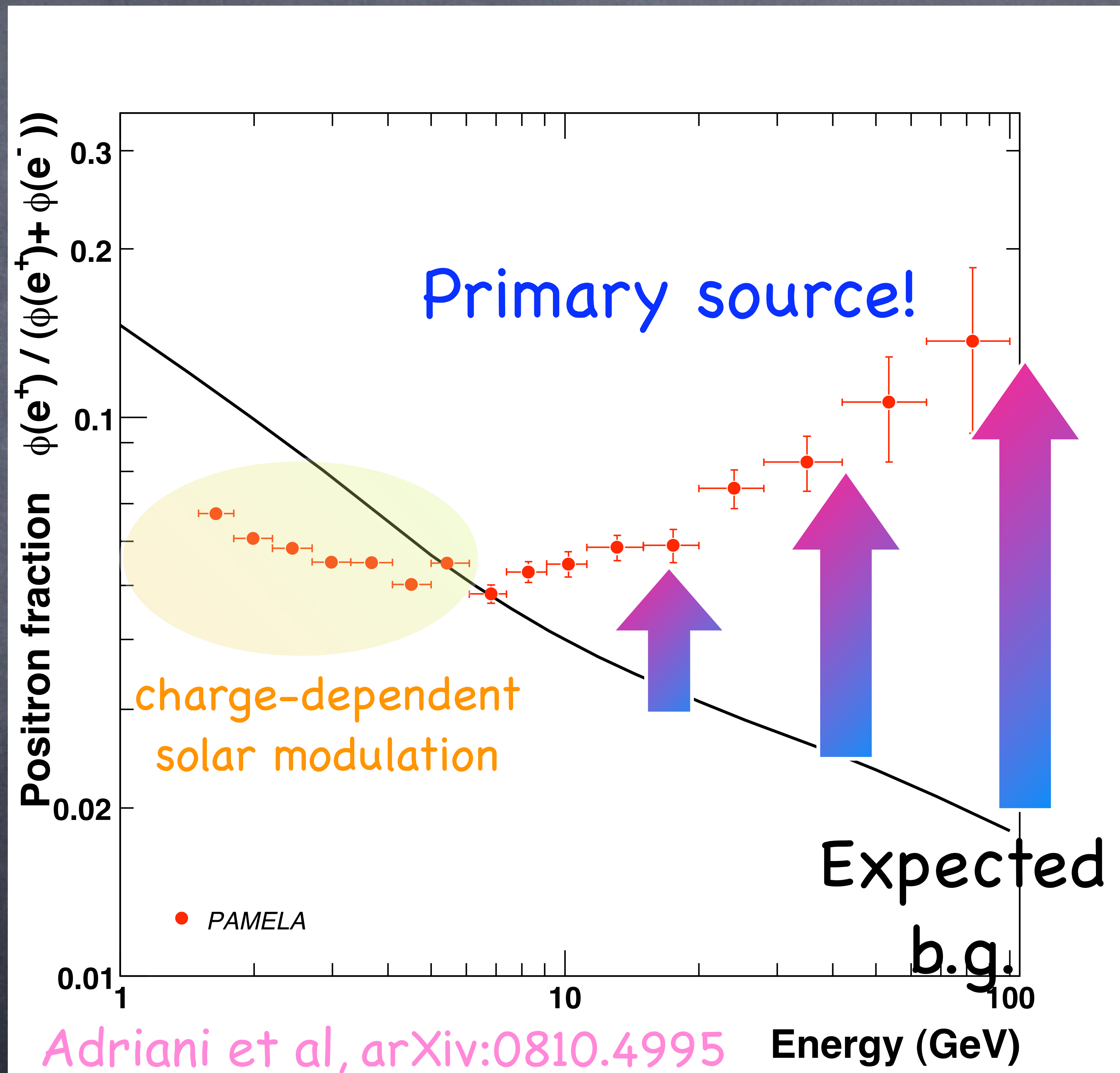
July2006-
Feb. 2008

151,672 e-
9,430 e+
in 1.5-100GeV

To appear tomorrow in Nature

Adriani et al, arXiv:0810.4995

PAMELA found an excess in the positron fraction!



Adriani et al, arXiv:0810.4995

Polar Patrol Balloon (PPB)

Advanced Thin Ionization Calorimeter (ATIC)

PPB-BETS: 2004

http://ppb.nipr.ac.jp/

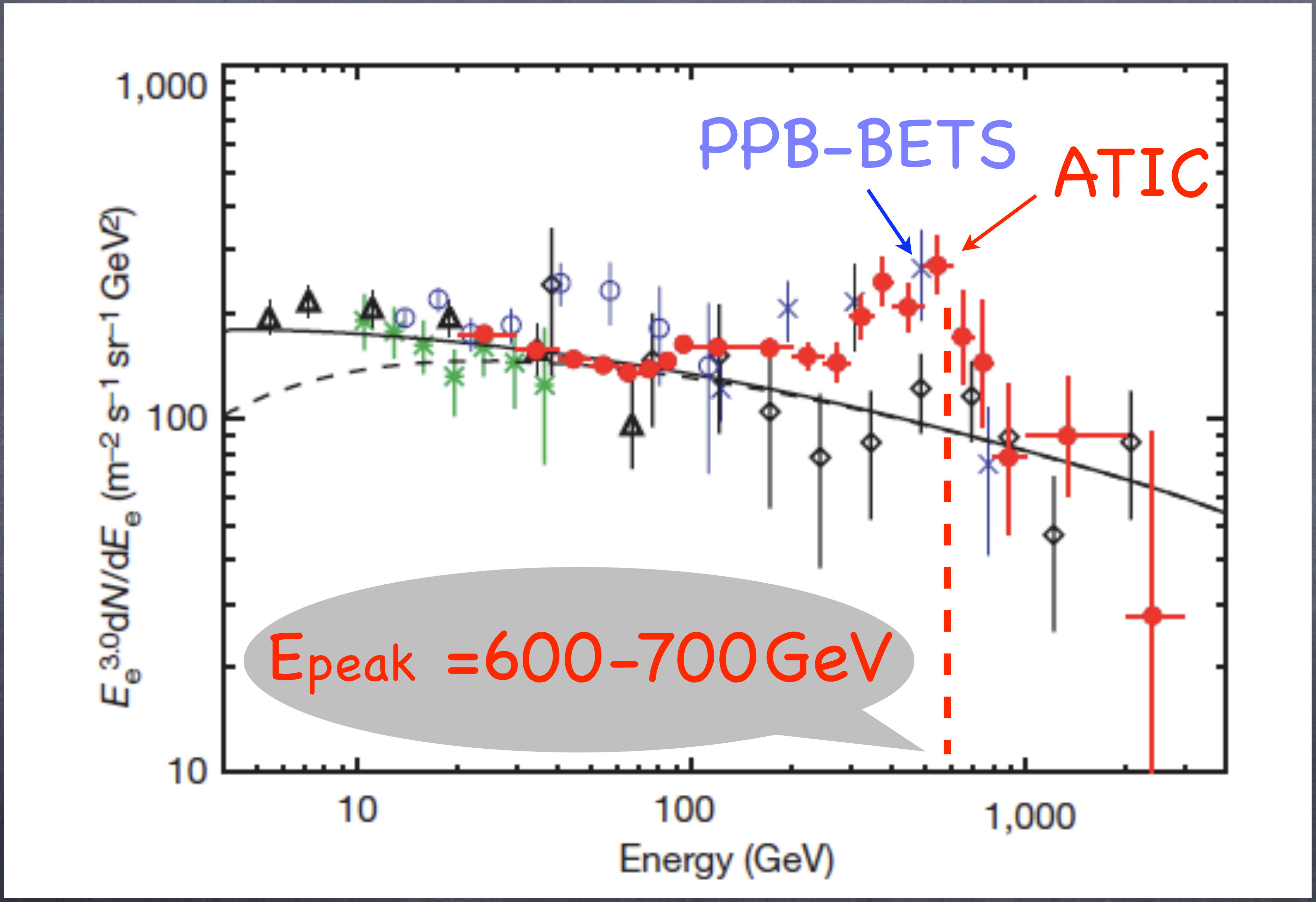
ATIC-1: 2001

ATIC-2: 2003

ATIC-4: 2008

http://atic.phys.lsu.edu/aticweb/index.html

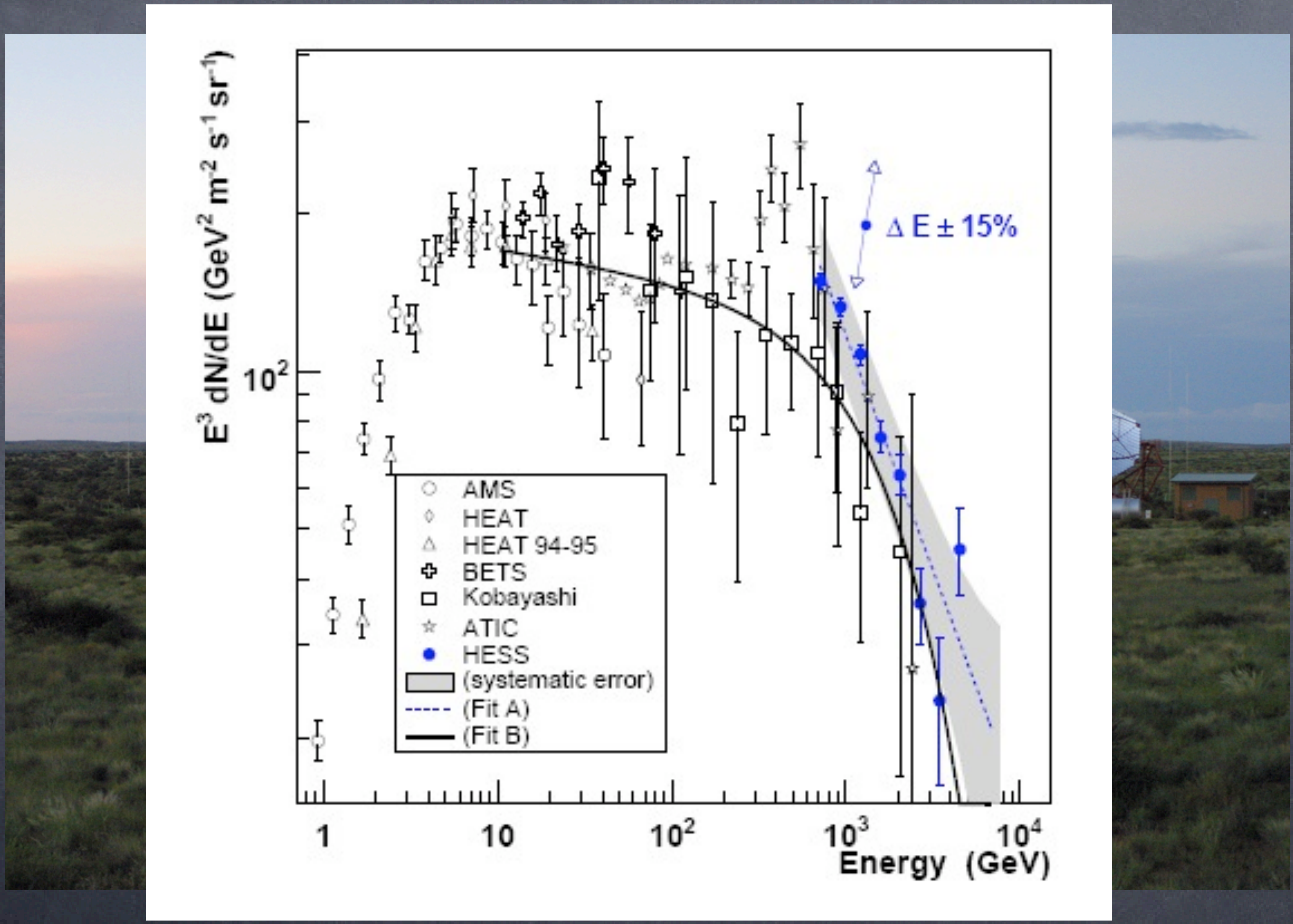
ATIC found excess in the (e^- + e^+) spectrum



Chang et al, Nature Vol.456 362 2008 [ATIC]
Torii et al, arXiv:0809.0760 [PPB-BETS]

HESS

HESS



E^3 dN/dE (GeV^2 m^2 s^{-1} sr^{-1})
10^2
1
10
10^2
10^3
10^4
Energy (GeV)
Δ E ± 15%
AMS
HEAT
HEAT 94-95
BETS
Kobayashi
ATIC
HESS
(systematic error)
(Fit A)
(Fit B)

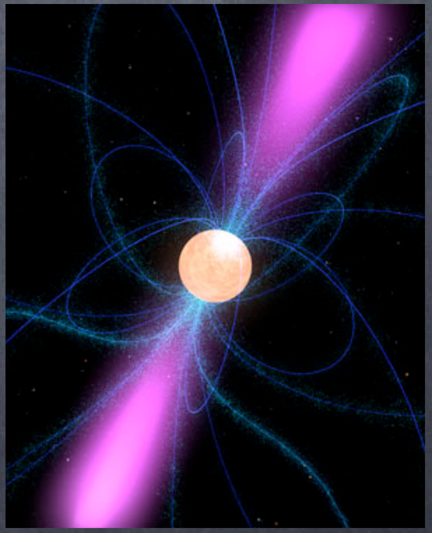
- The PAMELA data suggests that there is a local primary source for positrons.
- The positron spectrum needs to be a very hard one.
- Then, we should expect that the electron spectrum may be also significantly modified at E > 100GeV.

Maybe, the PAMELA and ATIC/PPB-BETS excesses arise from the same origin.

Possible candidates

- Dark Matter decay or annihilation
- Nearby pulsars, gamma-ray burst, microquasars, or unknown astro. source.

Profumo 0812.4457, Ioka 0812.4851
Kawanaka,Ioka,Nojiri 0903.3782



DM or pulsars?

- The annihilation/decay of DM is often accompanied with anti-protons, gamma-rays, neutrinos. The observation on those particles will be complementary check.
- If the positron/electron excess is dominated by a few nearby pulsars, we may be able to observe directional anisotropy of O(0.1-1)%.

Need more data!!

Dark Matter Models

Dark matter must account for

Dark matter must account for

1) the observed electron + positron flux with a hard spectrum,

Dark matter must account for

1) the observed electron + positron flux with a hard spectrum,

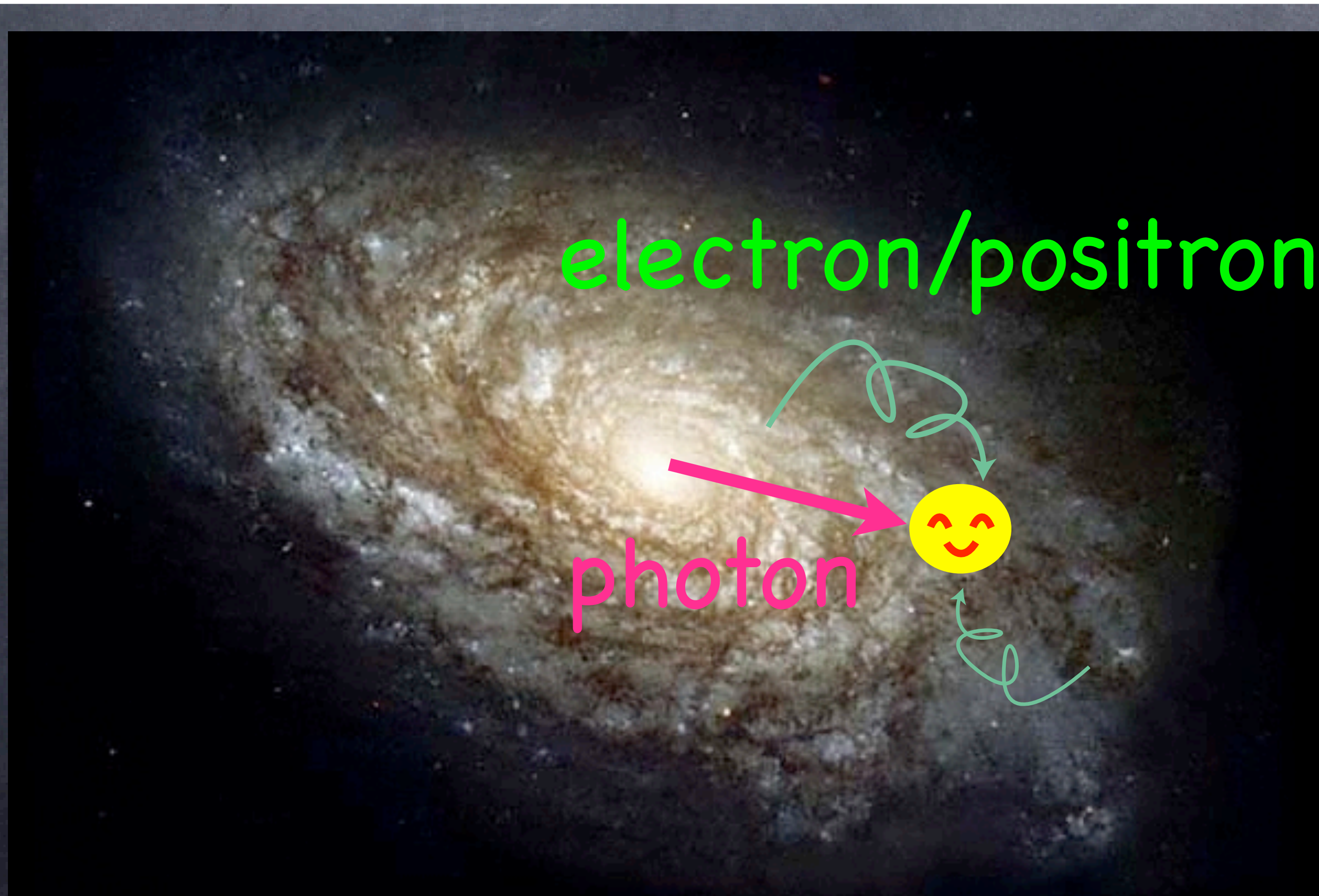
2) while avoiding anti-proton (neutrino, gamma) overproduction.

Electron + Positron flux:

Propagation through the galactic magnetic field is described by a diffusion equation

$$\frac{\partial f_e}{\partial t} = K(E)\nabla^2 f_e(E,x) + \frac{\partial}{\partial E}[b(E) f_e(E,x)] + Q(E,x)$$

diffusion — energy loss — source



Dark Matter

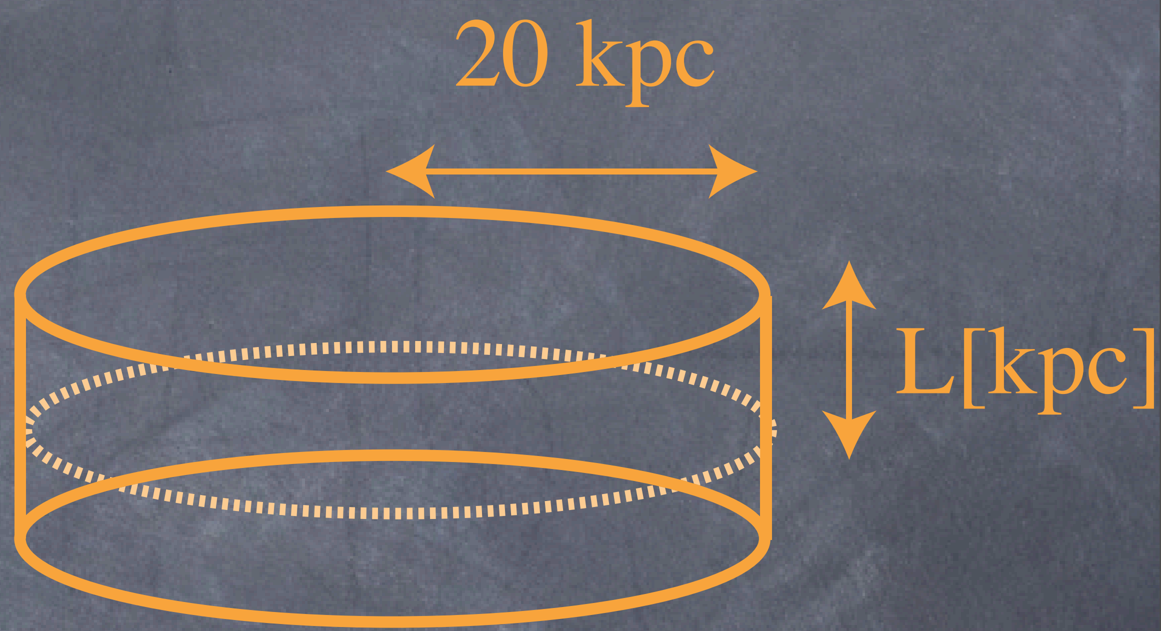
Cross-section,
Decay rate

$$\underbrace{\nabla \cdot [K(E,\vec{r})\nabla f_e]}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial E}[b(E,\vec{r}) f_e]}_{\text{energy loss}} + \underbrace{Q(E,\vec{r})}_{\text{source}} = 0$$

diffusion $K(E) = K_0 \left(\frac{E}{E_0}\right)^{\delta},$

energy loss $b(E) = \frac{E^2}{E_0 \tau_E},$

$E_0 = 1\,\mathrm{GeV} \quad \tau_E = 10^{16}\mathrm{sec}$



source $Q(E,\vec{r}) = q \cdot (\rho(\vec{r}))^p \cdot \frac{dN_e(E)}{dE}$

$$q = \begin{cases} \frac{1}{m_X \tau_X} & \text{for decay} \\ \frac{\langle \sigma v \rangle}{2m_X^2} & \text{for annihilation} \end{cases}$$

Models	δ	K_0 [kpc^2/Myr]	L [kpc]
M2	0.55	0.00595	1
MED	0.70	0.0112	4
M1	0.46	0.0765	15

Annihilating DM scenario

$$\langle \sigma v \rangle = \mathcal{O}(10^{-23})\,\mathrm{cm}^3/\mathrm{sec}$$

$m \sim 600 - 800\,\mathrm{GeV}$

(for unit boost factor)

Decaying DM scenario

Lifetime: $\tau \sim 10^{26}\mathrm{sec}$

$m \sim 1.2 - 1.6\,\mathrm{TeV}$

Annihilating DM scenario

The mass should be (600-800)GeV.

The needed annihilating cross section is

$$\langle \sigma v \rangle = \mathcal{O}(10^{-23})\,\mathrm{cm}^3/\mathrm{sec}$$

$$\gg \langle \sigma v \rangle_{\mathrm{thermal}} \simeq 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$$

cf. thermal relic abundance:

$$\Omega_{dm} h^2 \sim 0.1 \left(\frac{\langle \sigma v \rangle_{fo}}{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}} \right)^{-1}$$

In the thermal case, some enhancement is necessary.

Or DM may be non-thermally produced.

Annihilating DM scenario

The mass should be (600-800)GeV.

The needed annihilating cross section is

$$\langle \sigma v \rangle = \mathcal{O}(10^{-23}) \ \mathrm{cm}^3/\mathrm{sec}$$

$$\gg \langle \sigma v \rangle_{\mathrm{thermal}} \simeq 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

cf. thermal relic abundance:

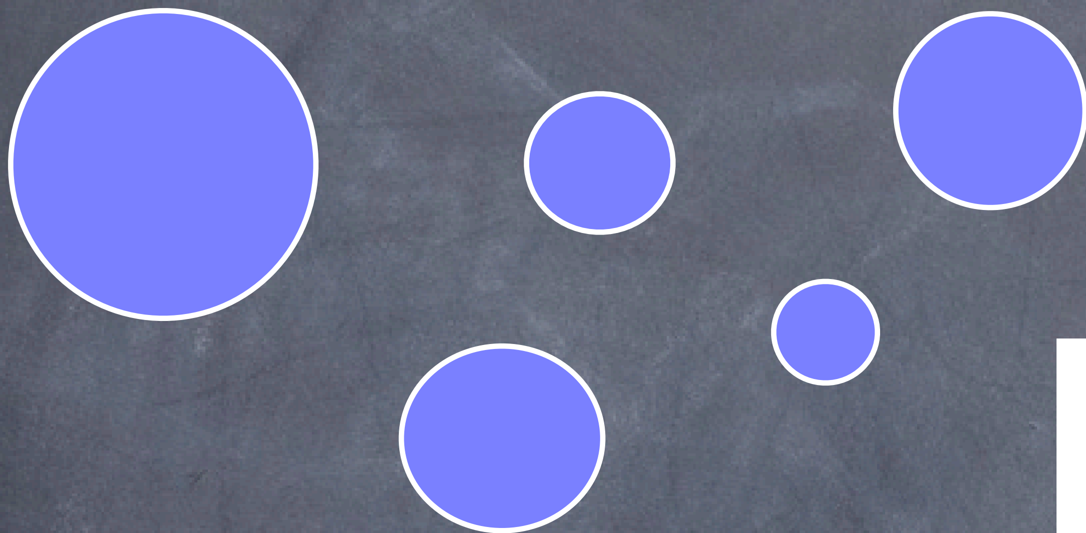
$$\Omega_{dm} h^2 \sim 0.1 \left(\frac{\langle \sigma v \rangle_{fo}}{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}} \right)^{-1}$$

In the thermal case, some enhancement is necessary.

Or DM may be non-thermally produced.

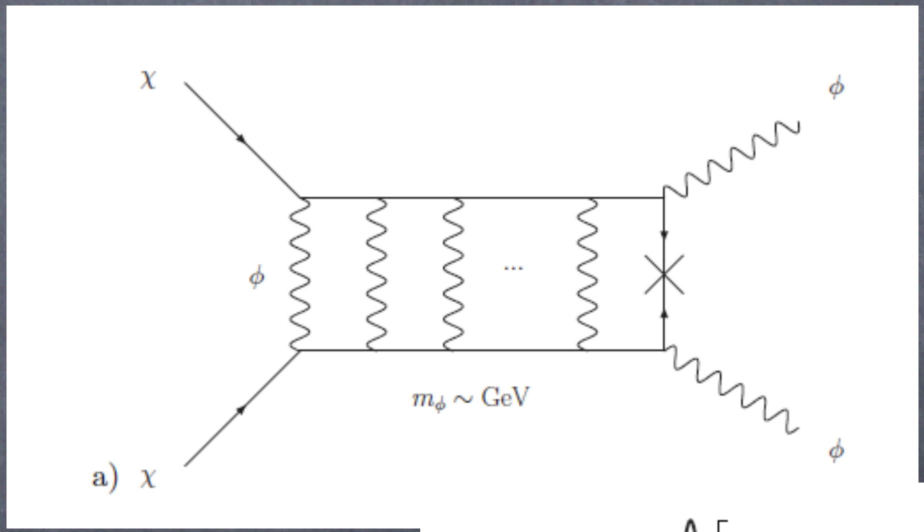
Boost factor:

The DM distribution may be clumpy, according to the N-body simulation.



$$\Gamma = \langle \sigma v \rangle n_{\rm DM}^2$$

can be enhanced.

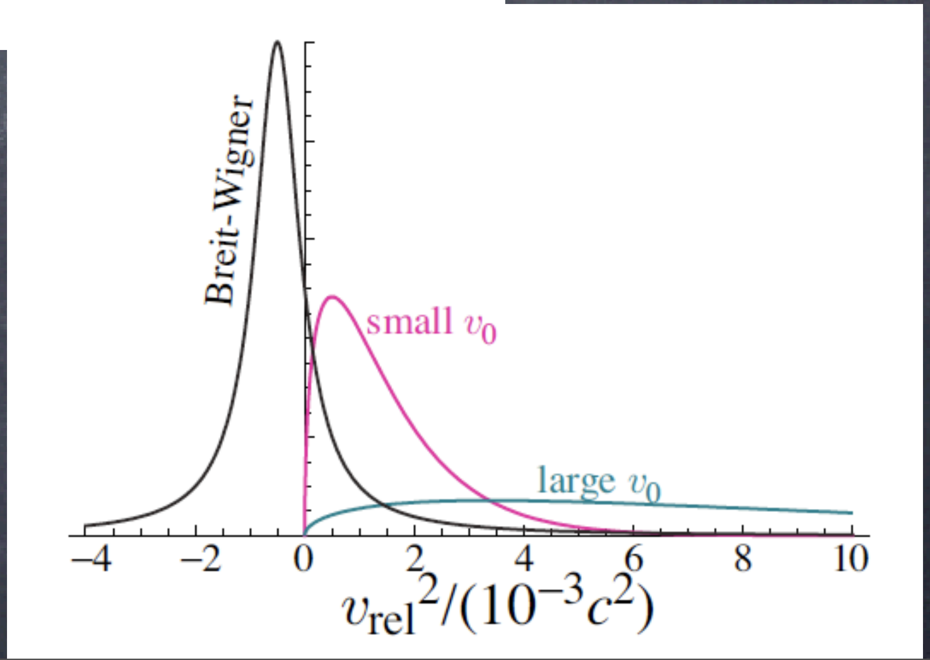


Sommerfeld effect:

Arkani-Hamed et al, 0810.0713

Breit-Wigner tail

Ibe, Murayama, Yanagida, 0812.0072



Decaying DM scenario

Dark matter particle with

Mass: $m \sim 1.2 - 1.6\,\mathrm{TeV}$

Lifetime: $\tau \sim 10^{26}\mathrm{sec}$

Independent of the boost factor.

The longevity of DM is a puzzle,
especially if the mass is above 1TeV.

- The lightest particle charged under an approximate discrete symmetry (LSP, LKP) Gravitino, sneutrino, neutralino

  Takayama-Yamaguchi 00
  Ibarra-Tran 08,
  Ishiwata-Matsumoto-Moroi 08,09
  Hamaguchi FT, Yanagida 09

  Chen, FT 08

- A hidden-sector particle

  Chen, FT, Yanagida 0809.0792
  Feldman et al, 0810.5762
  FT, Komatsu, 0901.1915

- A composite particle

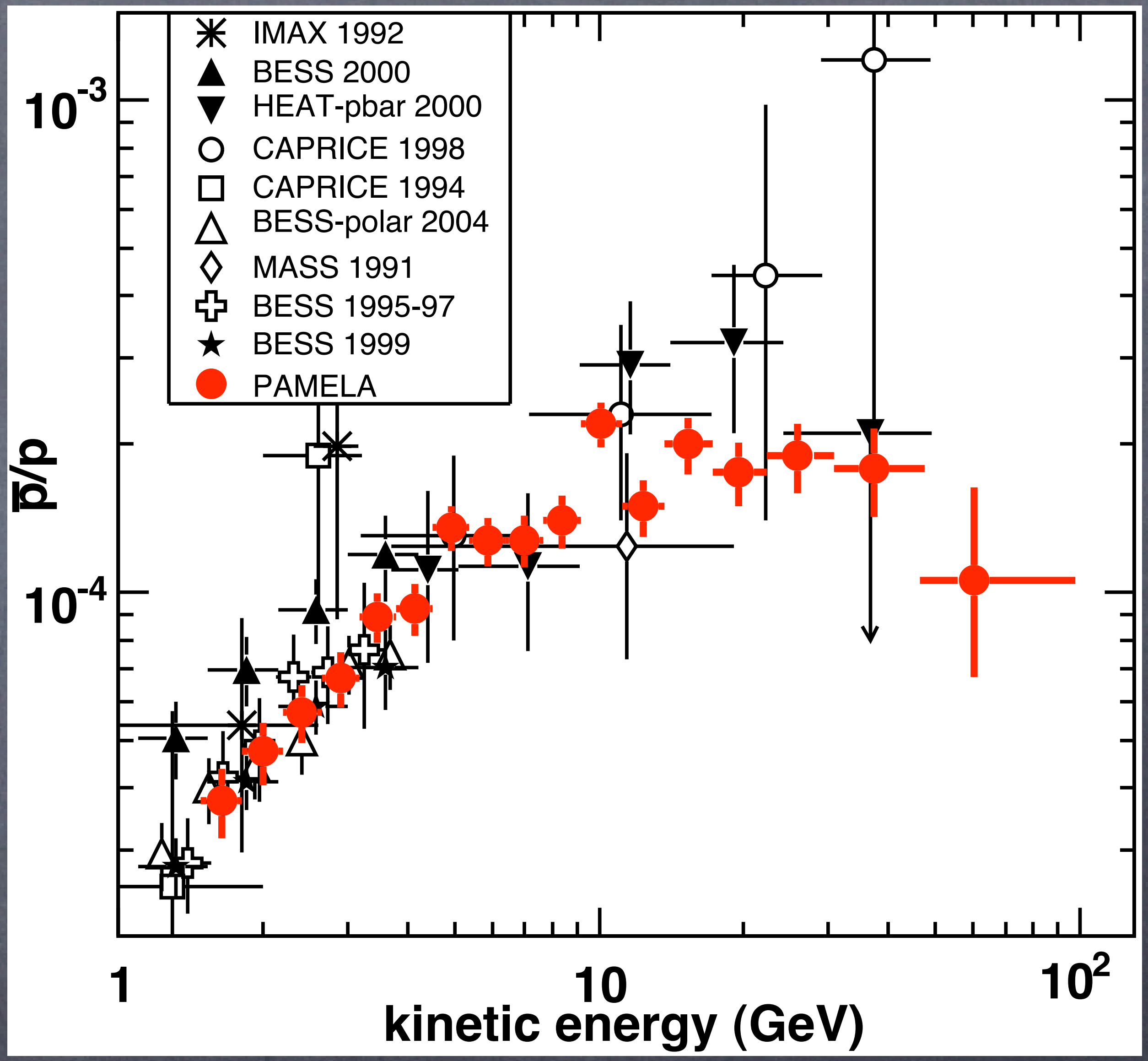
  Hamaguchi, Nakamura, Shirai, Yanagida 0811.0737
  Hamaguchi, Shirai, Yanagida 0812.2374

Why is lifetime O(10^26) sec?
Why does DM mainly decay into leptons?

Constraints on Dark Matter Models

No excess in antiprotons

- Quark, W, Z, Higgs productions tend to lead to too many antiprotons.
- Should mainly annihilate/ decay into leptons.



Most of the observed antiprotons are considered to be secondaries.

Adriani et al, arXiv:0810.4994

How to avoid the anti-proton constraint ?

- The dark matter particle decays or annihilates mainly into leptons (e.g. due to a symmetry).

  e.g.) a hidden U(1) gauge boson, leptophilic dark matter

- Maybe the dark matter particle has a lepton number.

  e.g.) right-handed sneutrino.

- The lepton number as well as a discrete symmetry responsible for the longevity of dark matter are explicitly broken altogether.

  e.g.) gravitino LSP w/ R-parity violation

- Dark matter particle first decays into lighter particle, which is prevented kinematically from decaying into hadrons.

  Arkani-Hamed et al, 0810.0713
  Pospelov et al, 0810.1502

- The solar system may be very close to a DM clump.

  Hooper et al, 0812.3202

- How to avoid the anti-proton constraint ?

Symmetry

- dark matter particle decays or annihilates mainly into leptons (e.g. due to a symmetry).

  e.g.) a hidden U(1) gauge boson, leptophilic dark matter

- Maybe the dark matter particle has a lepton number.

  e.g.) right-handed sneutrino.

- The lepton number as well as a discrete symmetry responsible for the longevity of dark matter are explicitly broken altogether.

  e.g.) gravitino LSP w/ R-parity violation

- Dark matter particle first decays into lighter particle, which is prevented kinematically from decaying into hadrons.

  Arkani-Hamed et al, 0810.0713
  Pospelov et al, 0810.1502

- The solar system may be very close to a DM clump.

  Hooper et al, 0812.3202

How to avoid the anti-proton constraint ?

Symmetry

Leptonic DM

- dark matter particle decays or annihilates mainly ...o leptons (e.g. due to a symmetry).

  e.g.) a hidden U(1) gauge boson, leptophilic dark matter

- ...e the dark matter particle has a lepton number.

  e.g.) right-handed sneutrino.

- The lepton number as well as a discrete symmetry responsible for the longevity of dark matter are explicitly broken altogether.

  e.g.) gravitino LSP w/ R-parity violation

- Dark matter particle first decays into lighter particle, which is prevented kinematically from decaying into hadrons.

  Arkani-Hamed et al, 0810.0713
  Pospelov et al, 0810.1502

- The solar system may be very close to a DM clump.

  Hooper et al, 0812.3202

How to avoid the anti-proton constraint ?

Symmetry

dark matter particle decays or annihilates mainly into leptons (e.g. due to a symmetry).

e.g.) a hidden U(1) gauge boson,
leptophilic dark matter

Leptonic DM

e the dark matter particle has a lepton number.

e.g.) right-handed sneutrino.

~~$L + Z_2$~~

- The lepton number as well as a discrete symmetry responsible for the longevity of dark matter are explicitly broken altogether.

e.g.) gravitino LSP w/ R-parity violation

- Dark matter particle first decays into lighter particle, which is prevented kinematically from decaying into hadrons.

Arkani-Hamed et al, 0810.0713
Pospelov et al, 0810.1502

- The solar system may be very close to a DM clump.

Hooper et al, 0812.3202

- How to avoid the anti-proton constraint ?

Symmetry

dark matter particle decays or annihilates mainly
...o leptons (e.g. due to a symmetry).

e.g.) a hidden U(1) gauge boson,
leptophilic dark matter

Leptonic DM

...e the dark matter particle has a lepton number.

e.g.) right-handed sneutrino.

- The lepton number as well as a discrete symmetry
...sponsible for the longevity of dark matter are
...xplicitly broken altogether.

~~$L + Z_2$~~

e.g.) gravitino LSP w/ R-parity violation

Kinematic supp.

...k matter particle first decays into lighter
particle, which is prevented kinematically from
decaying into hadrons.

Arkani-Hamed et al, 0810.0713
Pospelov et al, 0810.1502

- The solar system may be very close to a DM clump.

Hooper et al, 0812.3202

How to avoid the anti-proton constraint ?

Symmetry

dark matter particle decays or annihilates mainly
...o leptons (e.g. due to a symmetry).

e.g.) a hidden U(1) gauge boson,
leptophilic dark matter

Leptonic DM

...e the dark matter particle has a lepton number.

e.g.) right-handed sneutrino.

- The lepton number as well as a discrete symmetry
...sponsible for the longevity of dark matter are
...xplicitly broken altogether.

~~$L + Z_2$~~

e.g.) gravitino LSP w/ R-parity violation

Kinematic supp.

...k matter particle first decays into lighter
particle, which is prevented kinematically from
...ying into hadrons.

Arkani-Hamed et al, 0810.0713
Pospelov et al, 0810.1502

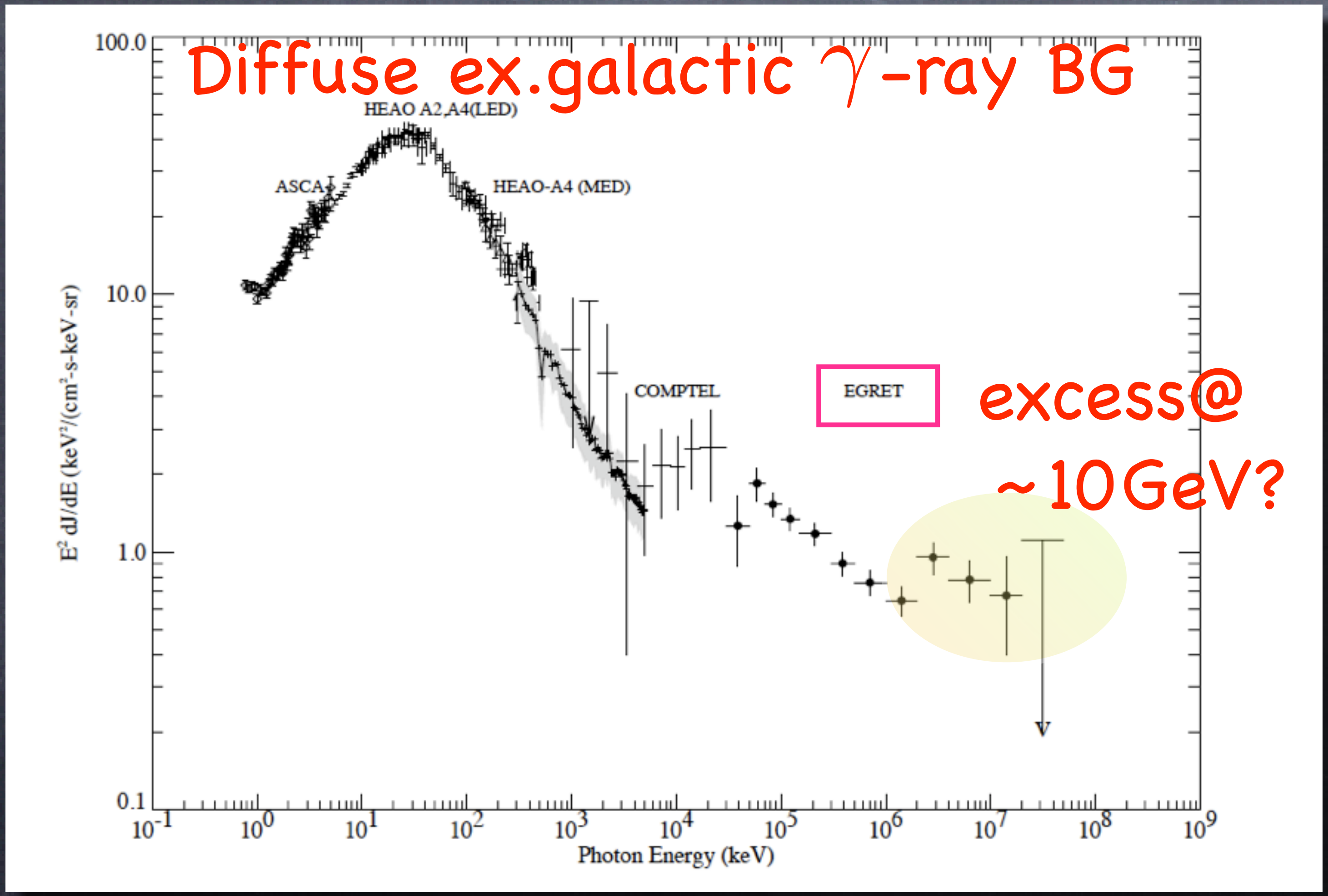
Clumpy DM

...he solar system may be very close to a DM clump.

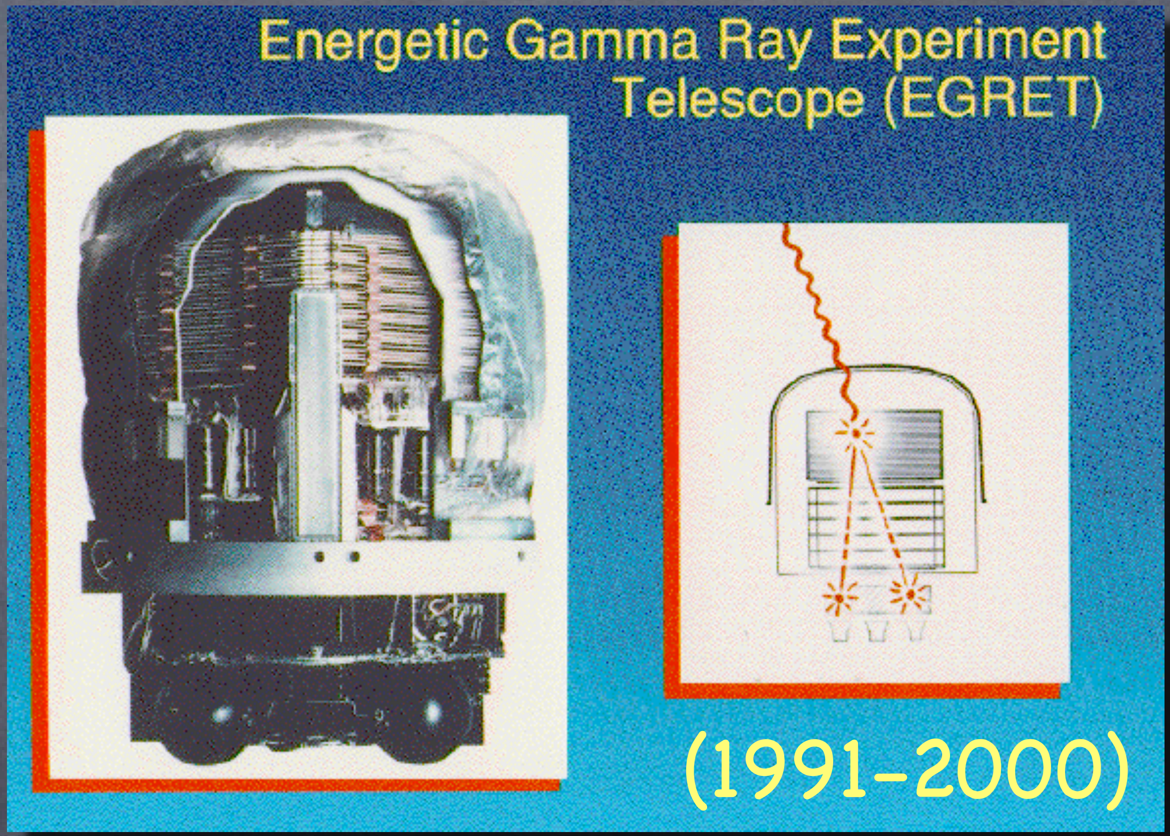
Hooper et al, 0812.3202

Gamma-rays

EGRET on CGRO(Compton Gamma Ray Observatory) satellite detected the gamma rays in the 20MeV-30GeV range.



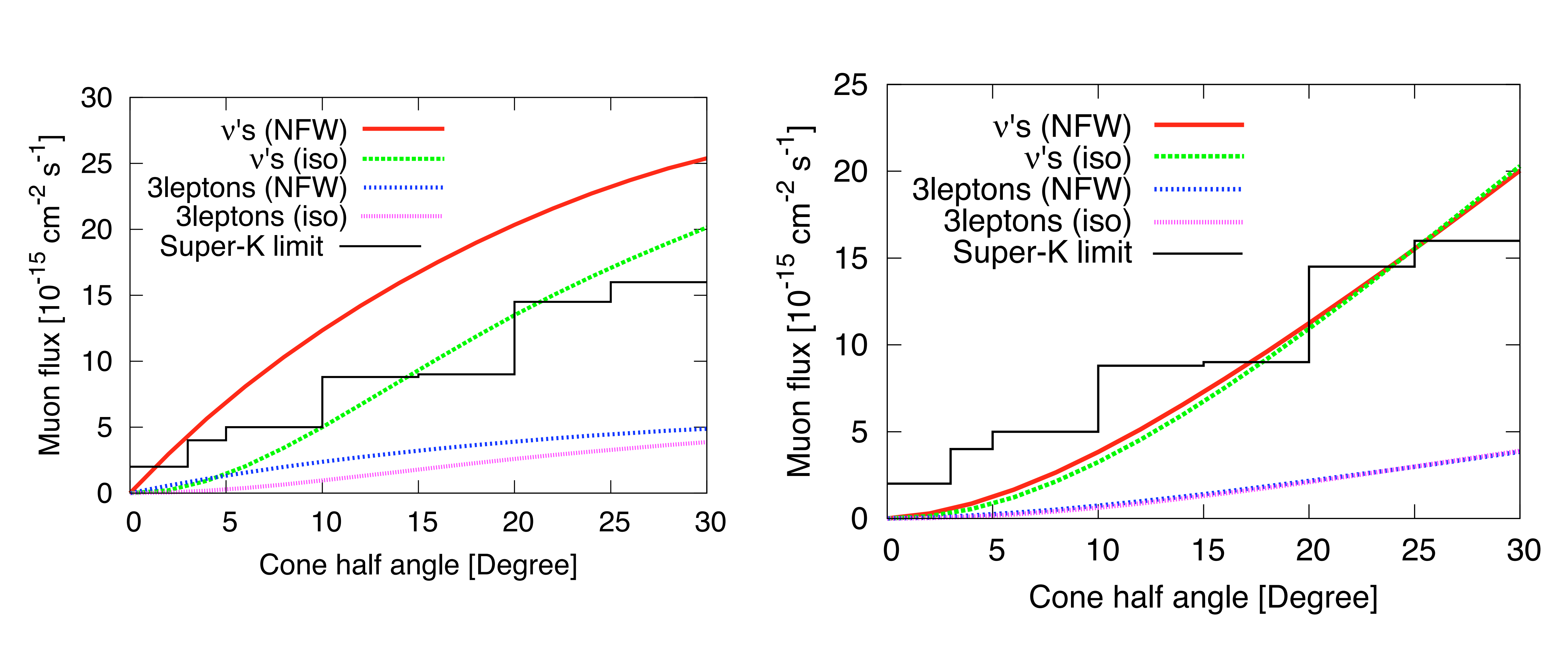
Strong, Moskalenko and Reimer (`04)



Contributions from unID point sources?

No excess in neutrinos from Galactic Center

Hisano, Kawasaki, Kohri, Nakayama,0812.0219



Tighter constraints on the annihilating DM scenario.

- Synchrotron radiation from Galactic center

  Ishiwata, Matsumoto, Moroi, 0811.4492

- Big bang nucleosynthesis

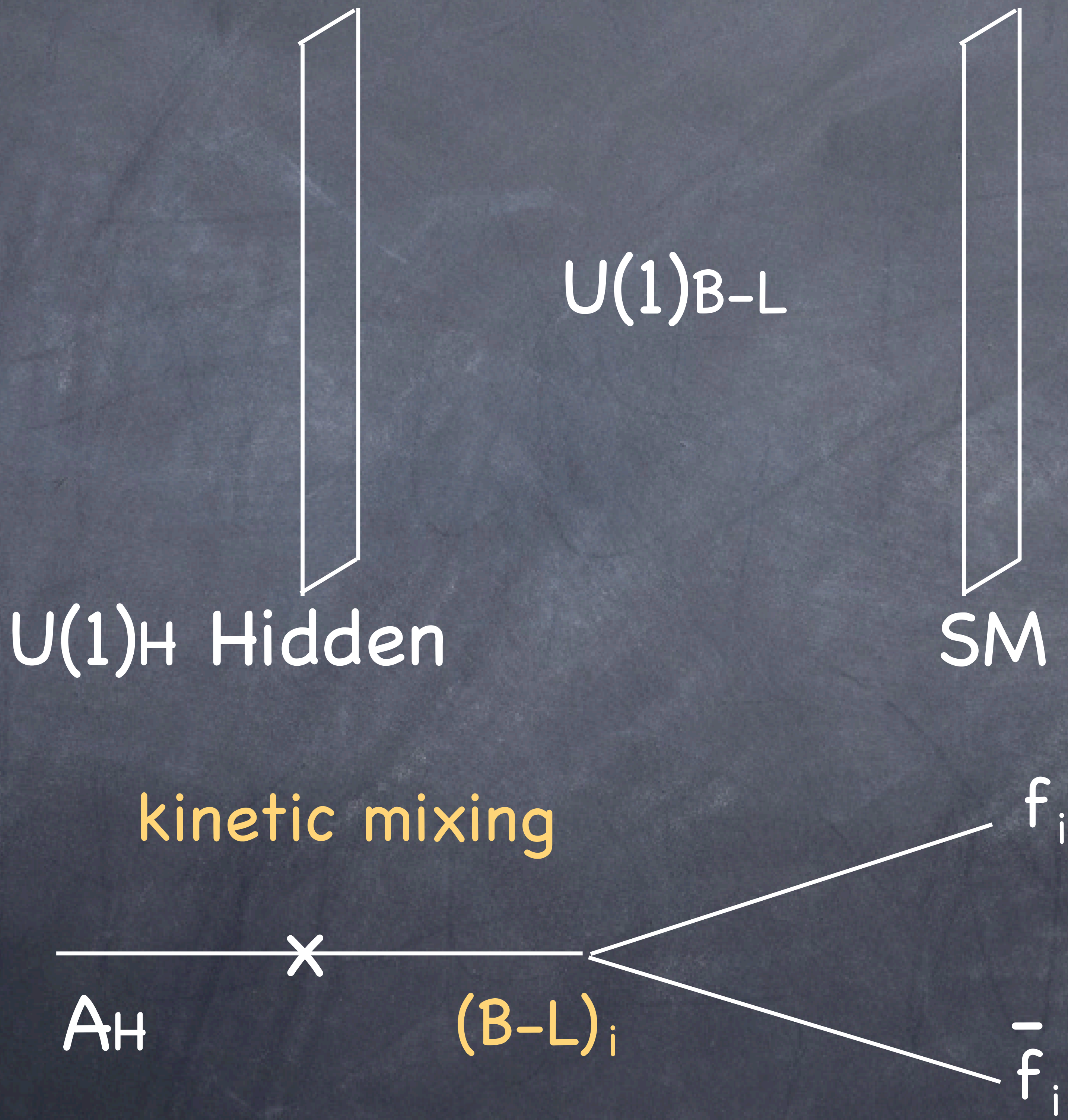
  Hisano, Kawasaki, Kohri, Nakayama,0810.1892

  Hisano, Kawasaki, Kohri, Moroi, Nakayama, 0901.3582

Hidden U(1) Gauge Boson

Hidden-gauge-boson DM

Chen, Takahashi, Yanagida (2008)
arXiv:0809.0792, 0811.0477



Lifetime OK

$$\mathcal{L}_{(4D)} = -\frac{1}{4}F^{(H)}_{\mu\nu}F^{(H)\mu\nu} - \frac{1}{4}F^{(B)}_{\mu\nu}F^{(B)\mu\nu} + \frac{\lambda}{2}F^{(H)}_{\mu\nu}F^{(B)\mu\nu}$$

$$+ \frac{1}{2}m^2 A_{H\mu}A^{\mu}_{H} + \frac{1}{2}M^2 A_{B\mu}A^{\mu}_{B},$$

kinetic mixing

We can make A's canonical and express them in terms of the mass-eigenstates:

$$A_B \simeq A'_B - \lambda \frac{m^2}{M^2} A'_H,$$

- Coupling to SM fermions:

$$\mathcal{L}_{\rm int} = q_i A^{\mu}_{B}\, \bar{\psi}_i \gamma_\mu \psi_i \supset -\lambda\, q_i \frac{m^2}{M^2} A'^{\mu}_{H}\, \bar{\psi}_i \gamma_\mu \psi_i,$$

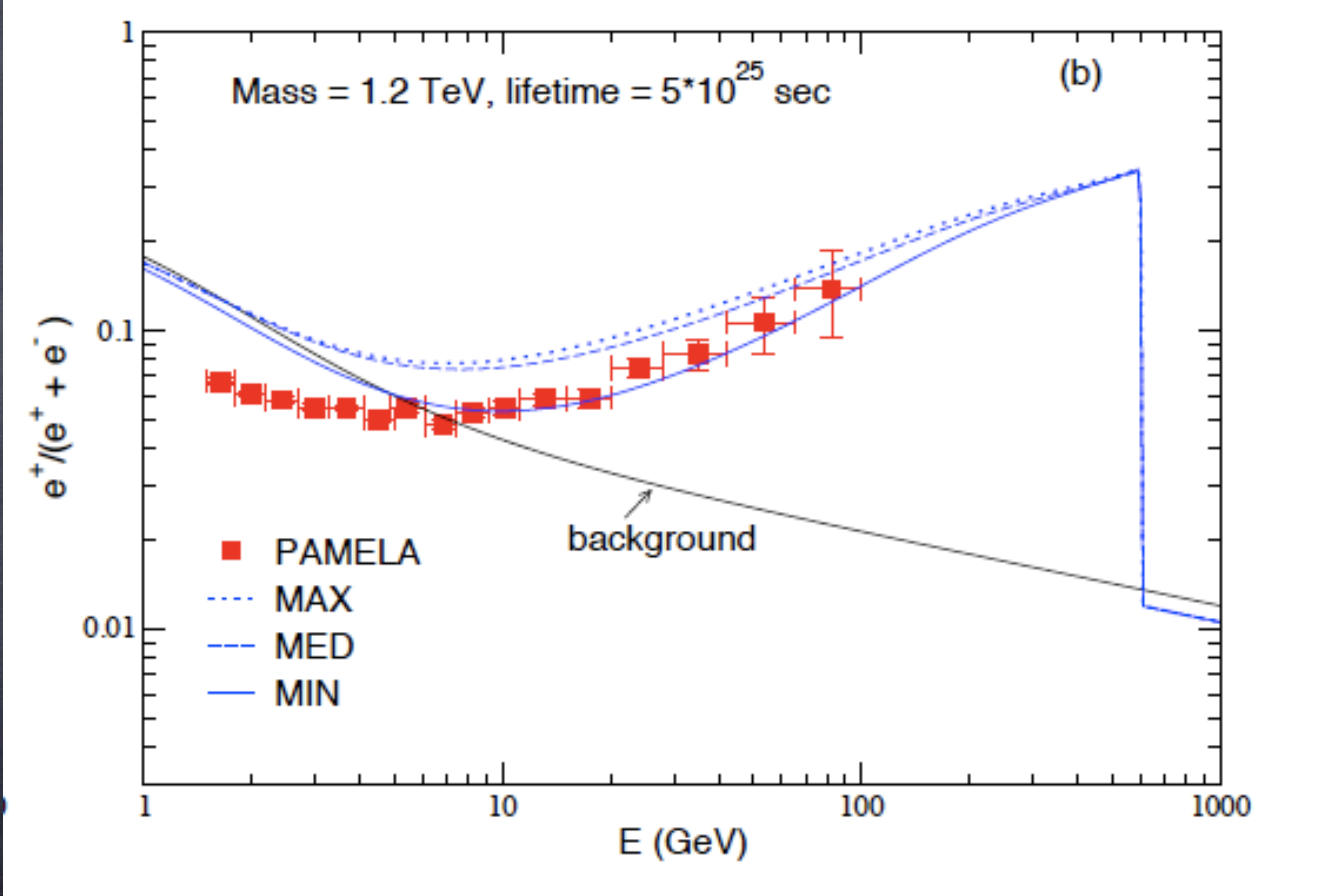
B-L charge

$$\tau \simeq 1 \times 10^{26}\,{\rm sec} \left(\sum_i N_i q_i^2\right)^{-1} \left(\frac{\lambda}{0.01}\right)^{-2} \left(\frac{m}{1.2\,{\rm TeV}}\right)^{-5} \left(\frac{M}{10^{15}{\rm GeV}}\right)^{4},$$

Lepton dominated decay modes!

	Quarks	Leptons
Nc (B-L)^2	1/3	1

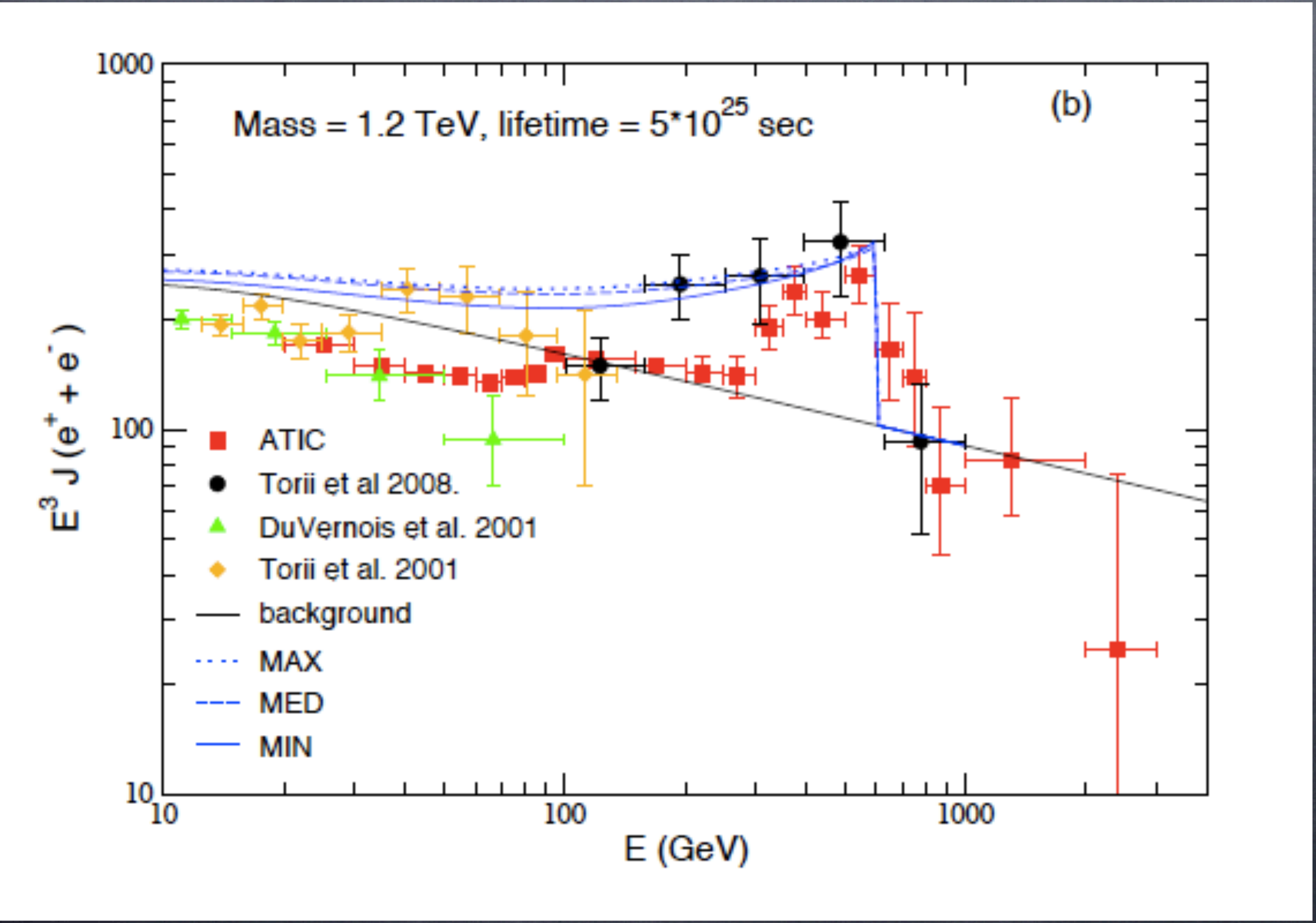
Positron Fraction



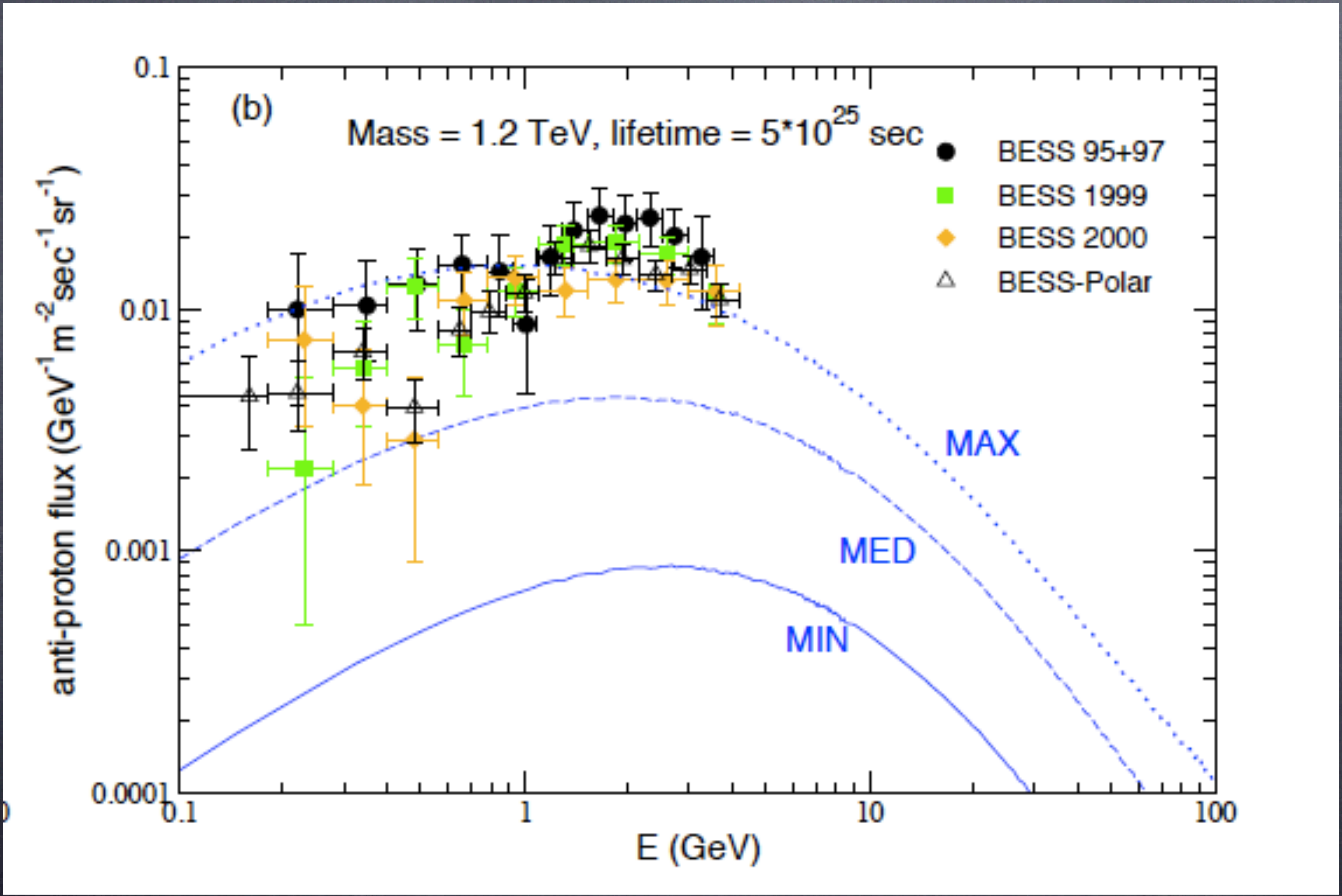
Chen, Nojiri, Takahashi, Yanagida (2008)

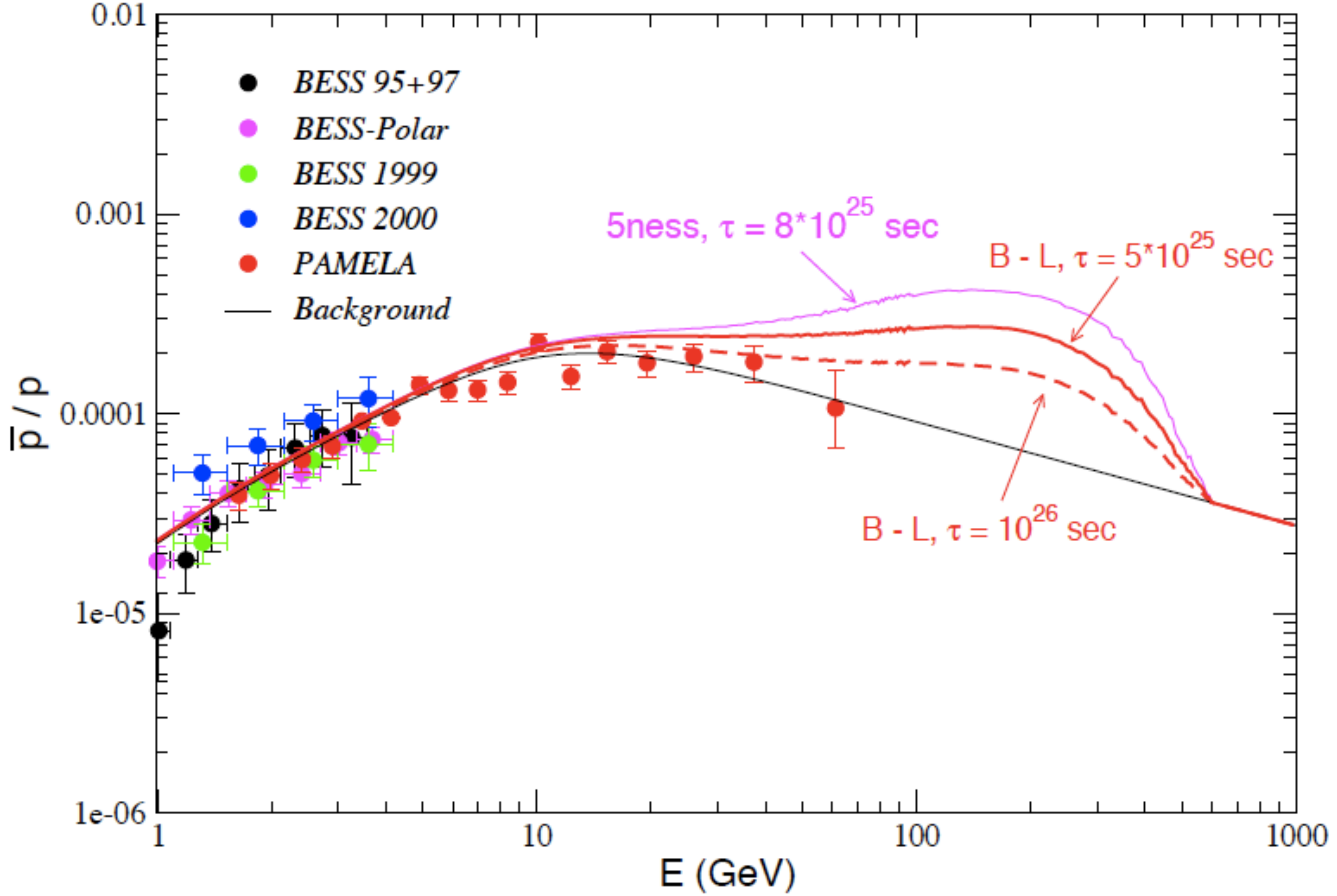
- Electron + positron spectrum:

Chen, Nojiri, Takahashi, Yanagida (2008)



Hidden-gauge-boson DM





0.01
0.001
0.0001
1e-05
1e-06
1
10
100
1000
E (GeV)
p̄ / p
BESS 95+97
BESS-Polar
BESS 1999
BESS 2000
PAMELA
Background
5ness, τ = 8*10^25 sec
B - L, τ = 5*10^25 sec
B - L, τ = 10^26 sec

Hidden U(1) Gauge Boson

- High predictivity on the branching ratios.
- Correct lifetime is naturally derived.
- Lepton dominated decay modes with suppressed antiproton flux!

The anti-proton production can be avoided if we consider the hidden U(1) gaugino!

Shirai, Takahashi, Yanagida (2009)

Conclusion

Conclusions

- The origin of PAMELA and ATIC/PPB-BETS signals may be DM decay or annihilation.

Annihilation: $$\langle \sigma v \rangle = \mathcal{O}(10^{-23})\,\mathrm{cm}^3/\mathrm{sec}$$

Enhancement of 100 - 1000 is needed for the thermal relic DM.

Or DM may be produced non-thermally.

Decay: $$\tau = \mathcal{O}(10^{26}\mathrm{sec})$$

Conclusions

- Cross-check in the gamma-rays and antiprotons will be important.
- One plausible candidate is a hidden U(1) gauge boson/ gaugino that mixes with U(1)B-L.

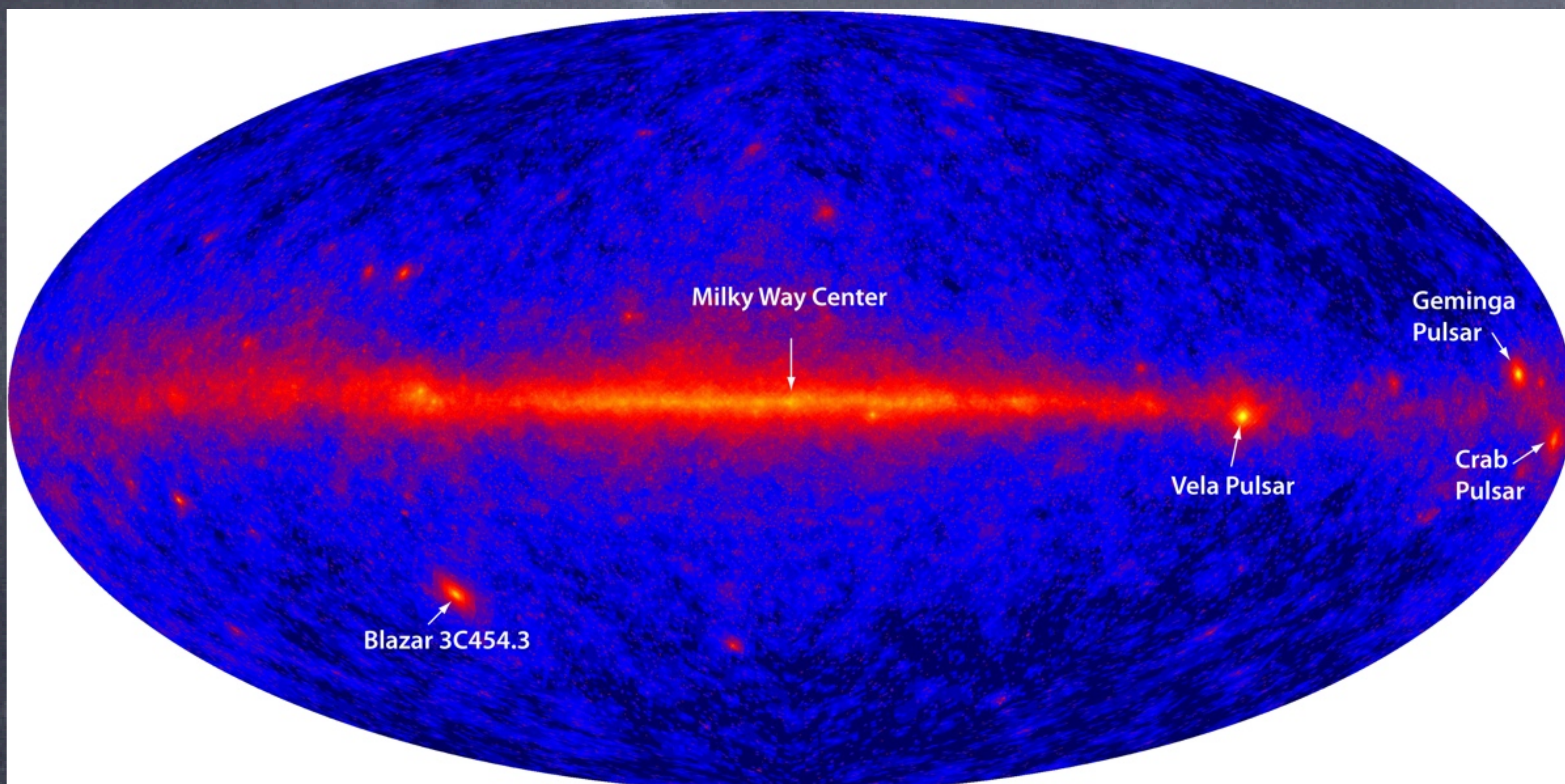
Preliminary Fermi Data

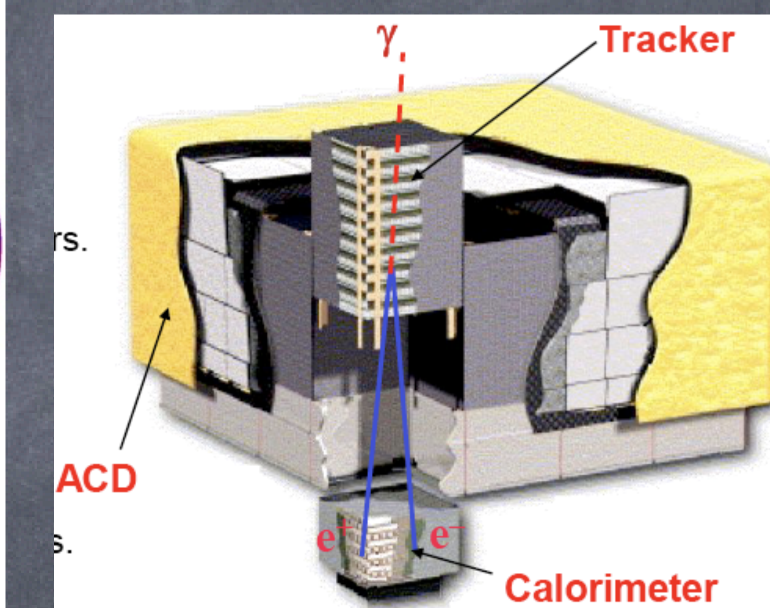
Fermi (formerly GLAST)

Launched on 11th of June, 2008.

20MeV-300GeV

First-Light sky map with 95 hrs (4 days).





Equivalent to EGRET's 1st year!!

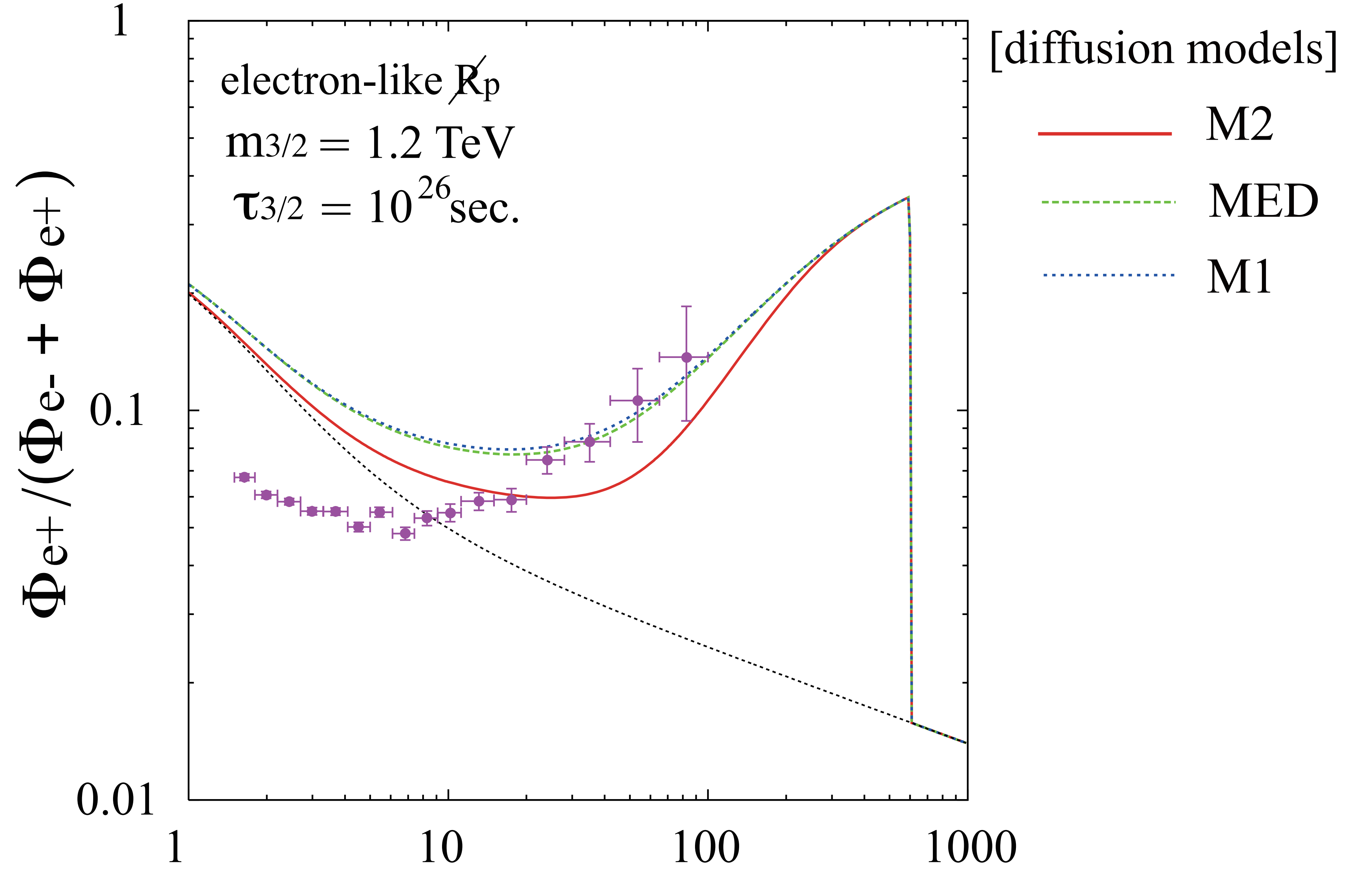
Many point sources will be identified,
all the data will be released in next August.

Gravitino DM

Gravitino DM with broken R-parity can fit PAMELA

Ishiwata, Matsumoto, Moroi `08

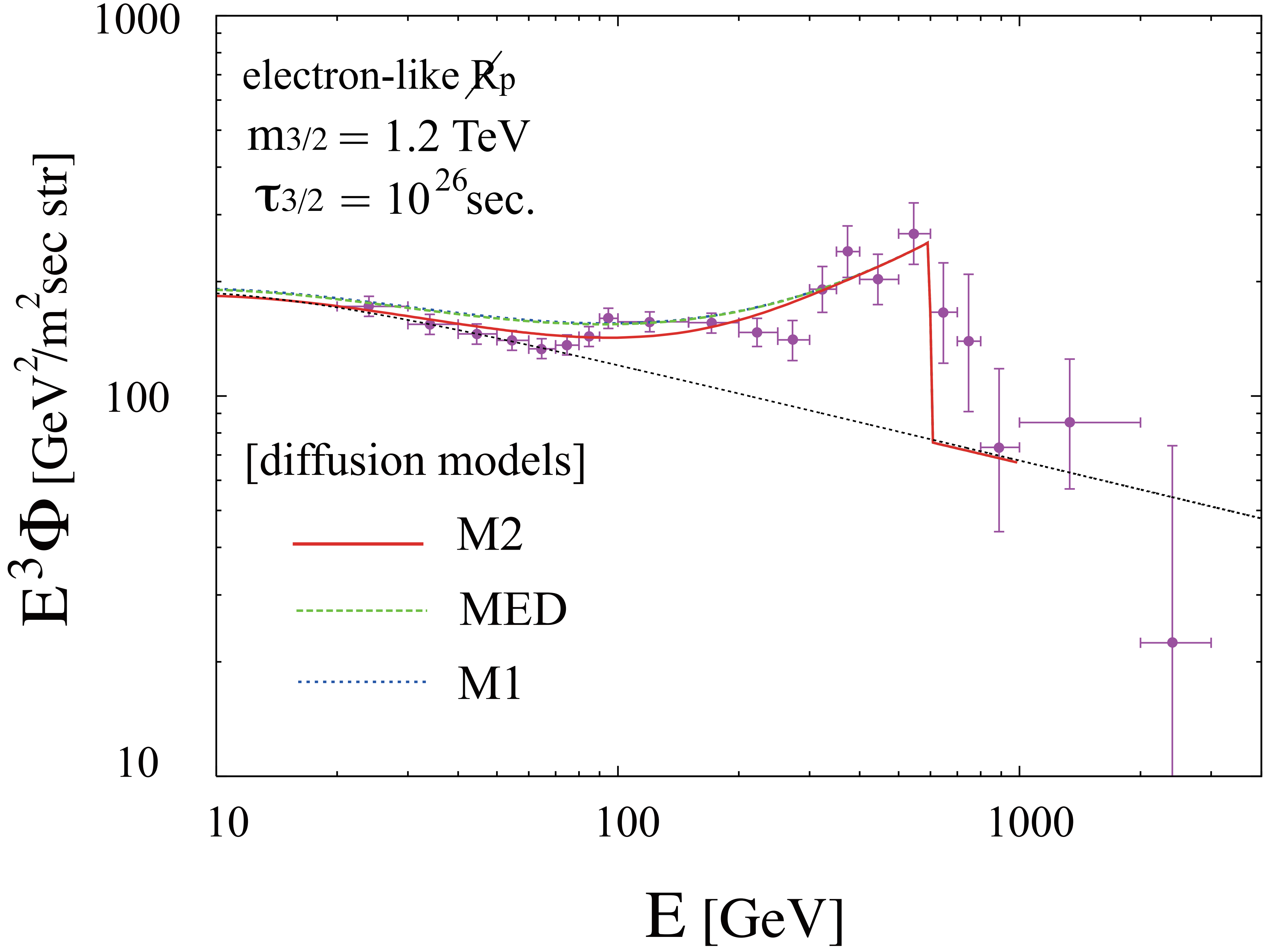
[see also Ibarra and Tran`08]



Hamaguchi, FT, Yanagida, `09

The gravitino DM can also explain the ATIC data:

Hamaguchi, FT, Yanagida, `09



Gravitational Dark Matter Decay

FT, Eiichiro Komatsu: arXiv:0901.1915

Dark matter particle with

Mass: $m \sim 1.2 - 1.6\,\mathrm{TeV}$

Lifetime: $\tau \sim 10^{26}\mathrm{sec}$

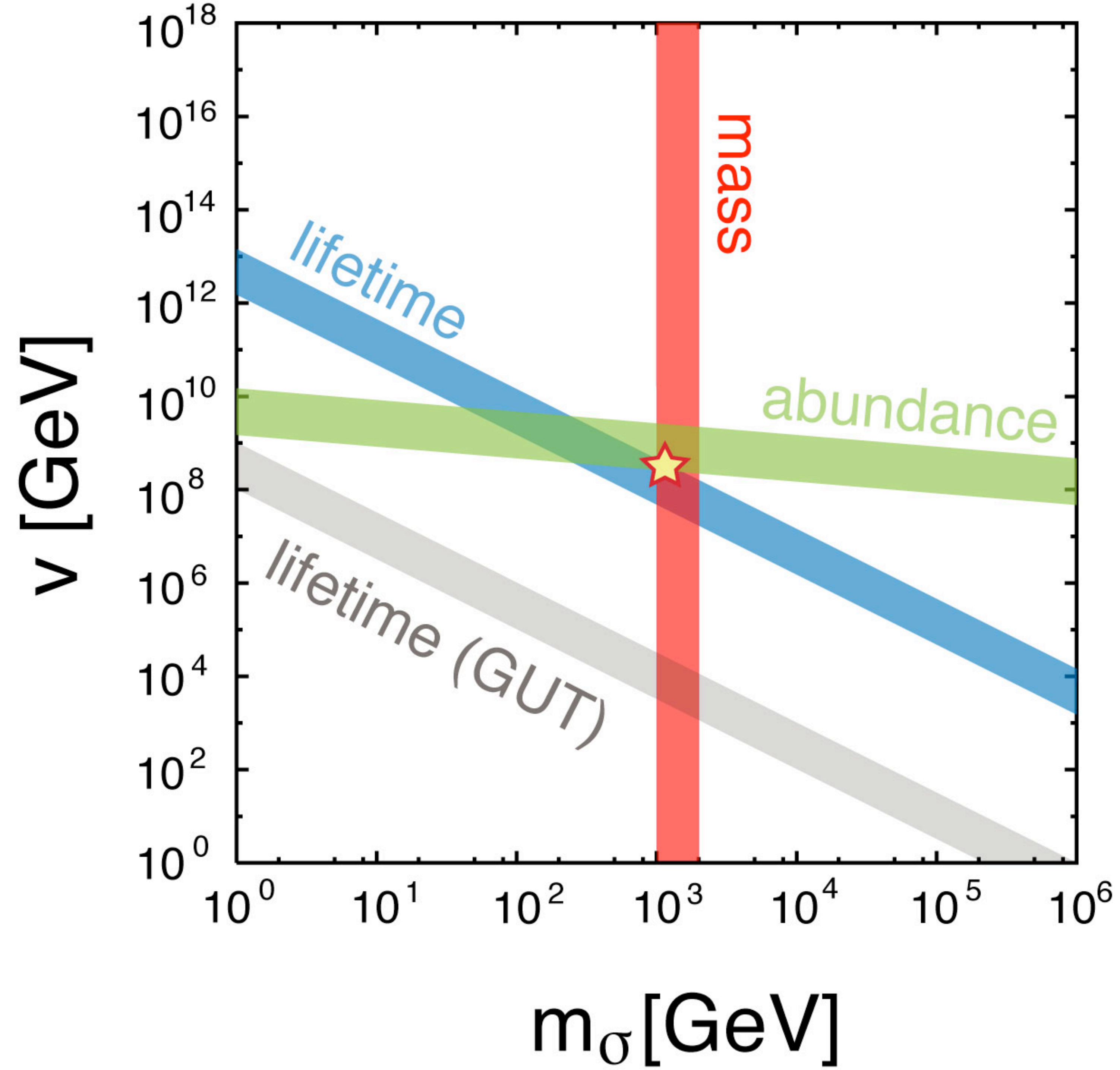
$$\Gamma \sim \frac{1}{32\pi}\left(\frac{v}{M_P}\right)^2 \frac{m_\sigma^3}{M_P^2},$$

$$\Rightarrow \quad m \sim 1.2\,\mathrm{TeV} \qquad v \sim 10^9\,\mathrm{GeV}$$

Then, the abundance is naturally explained by the coherent oscillations.

$$\Omega_\phi h^2 = 0.2A\left(\frac{g_*}{100}\right)^{-\frac{1}{4}}\left(\frac{v}{10^9\,\mathrm{GeV}}\right)^2\left(\frac{m_\sigma}{1\,\mathrm{TeV}}\right)^{\frac{1}{2}}.$$

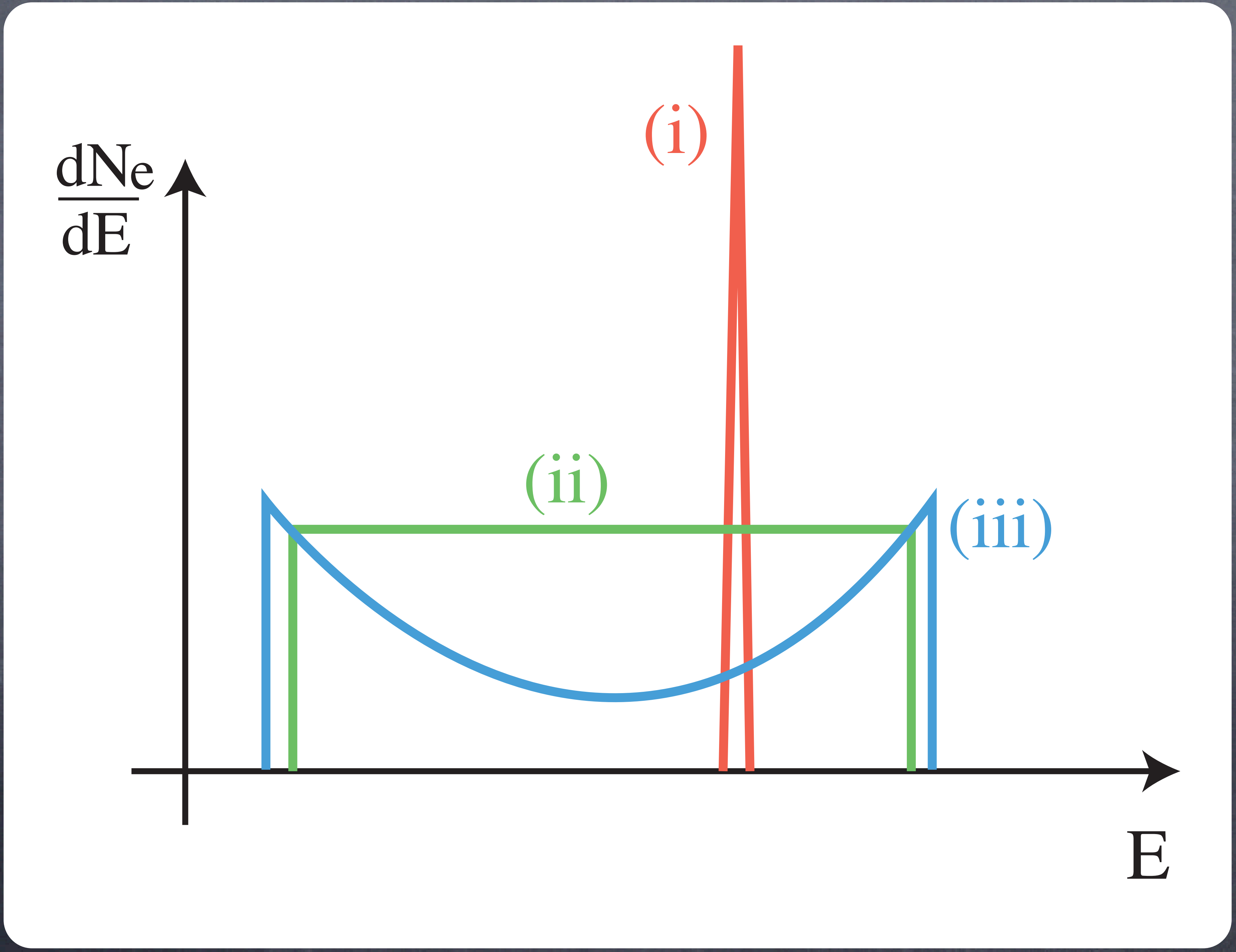
Three lines meet at one point!!!

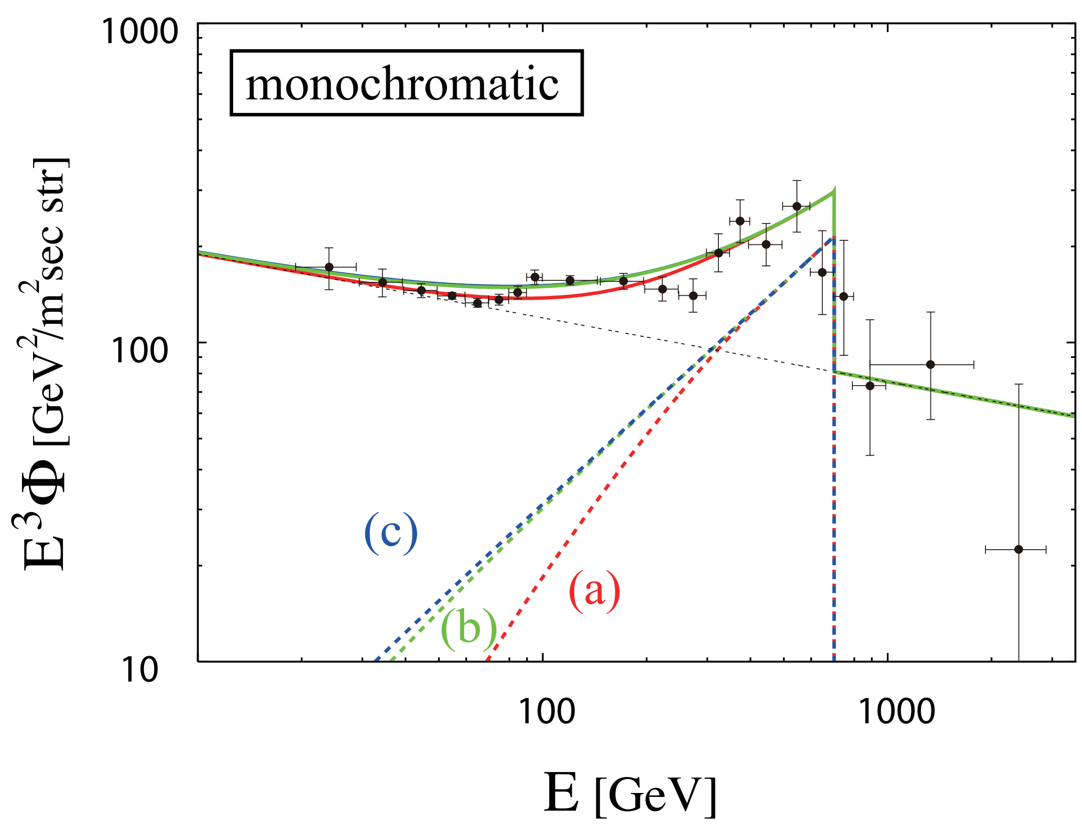


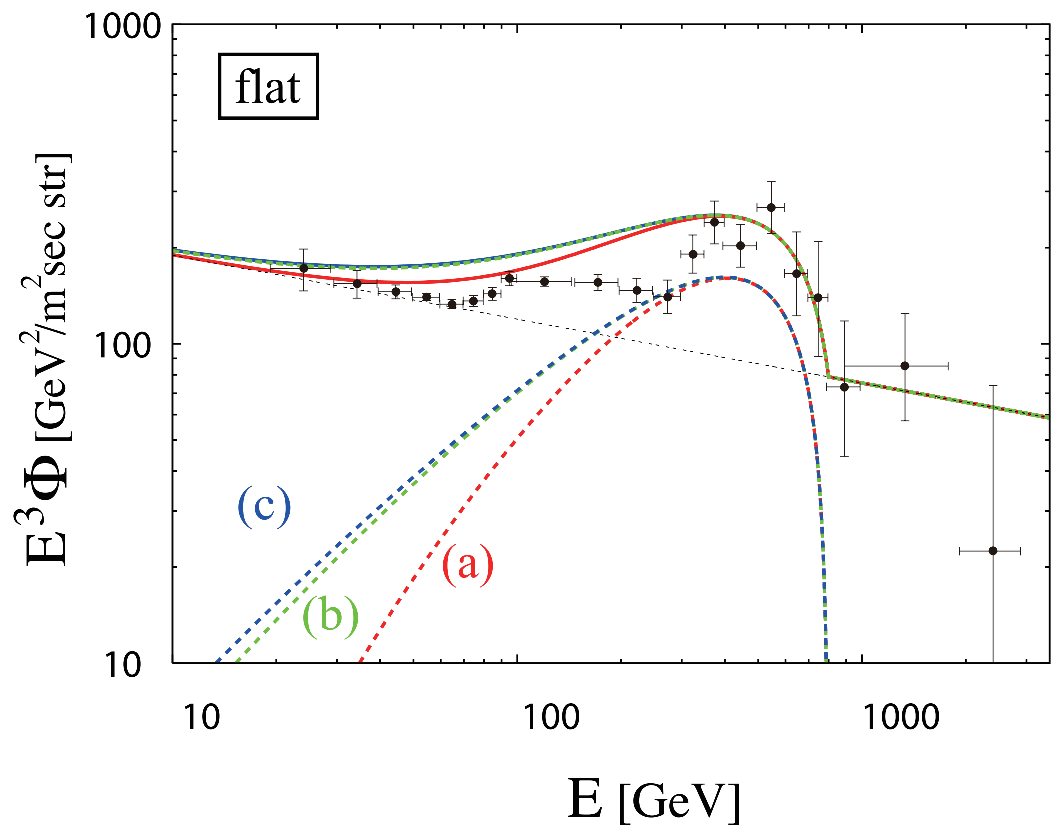
Dark Matter Model Selection

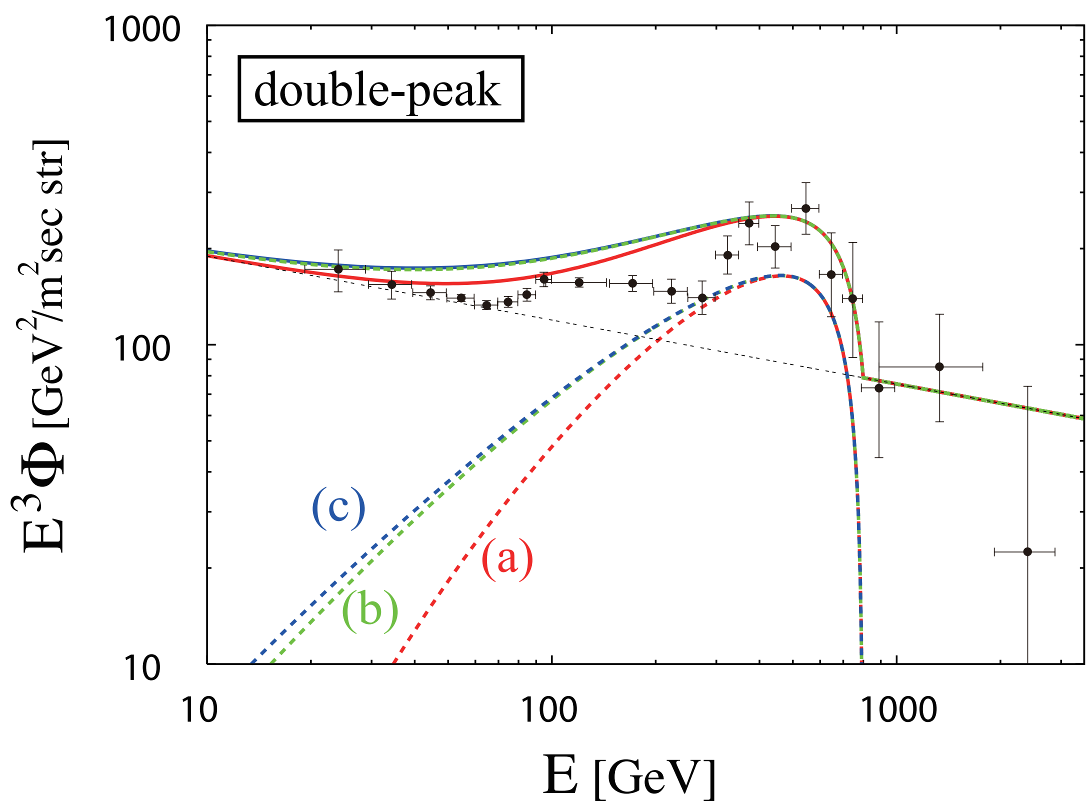
Chen, Hamaguchi, Nojiri, FT, Torii
arXiv:0812.4200

- Initial source spectrum of electrons is model-dependent:









[diffusion models]

(a) — M2

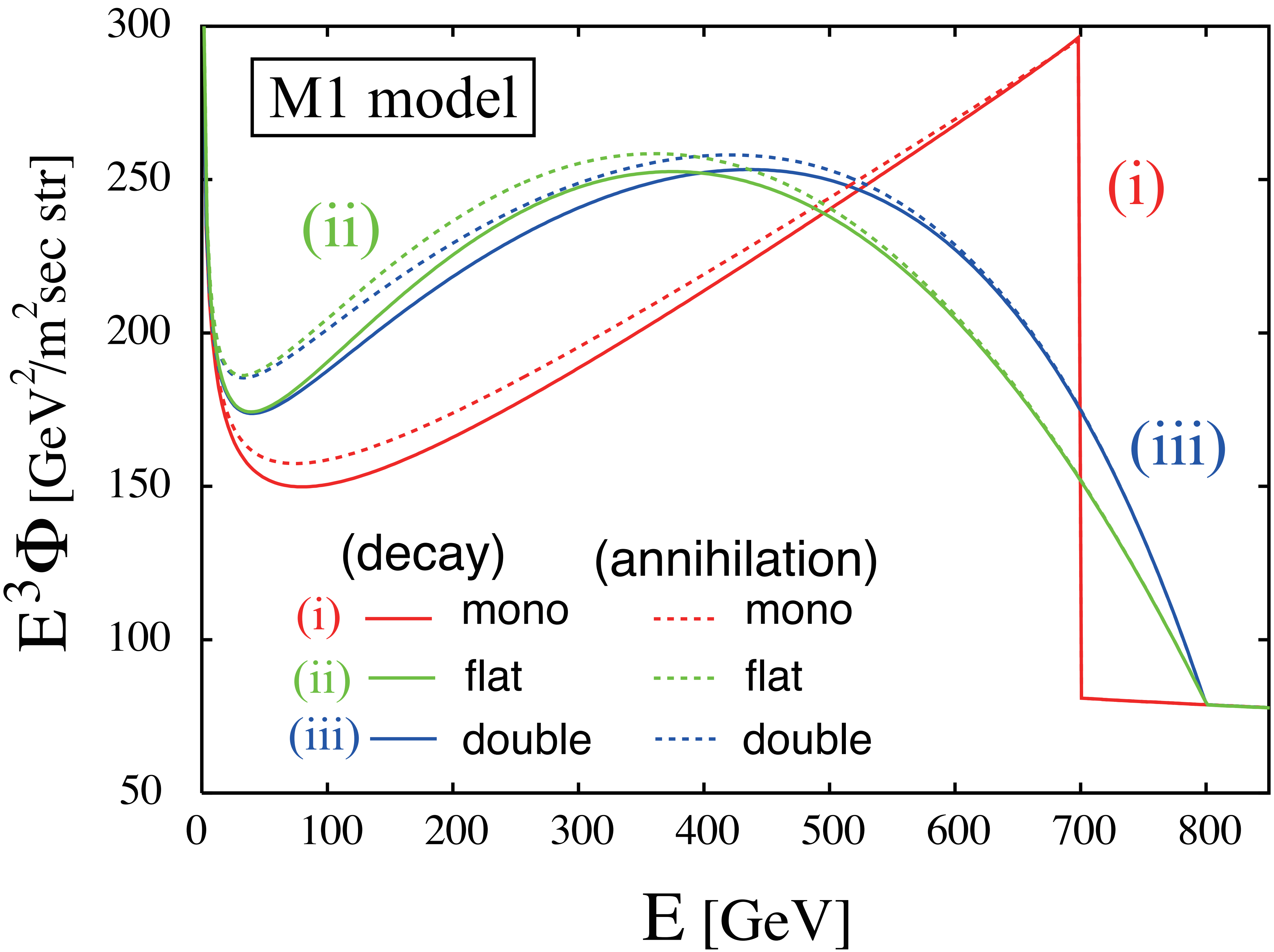
(b) — MED

(c) — M1

Decaying DM with

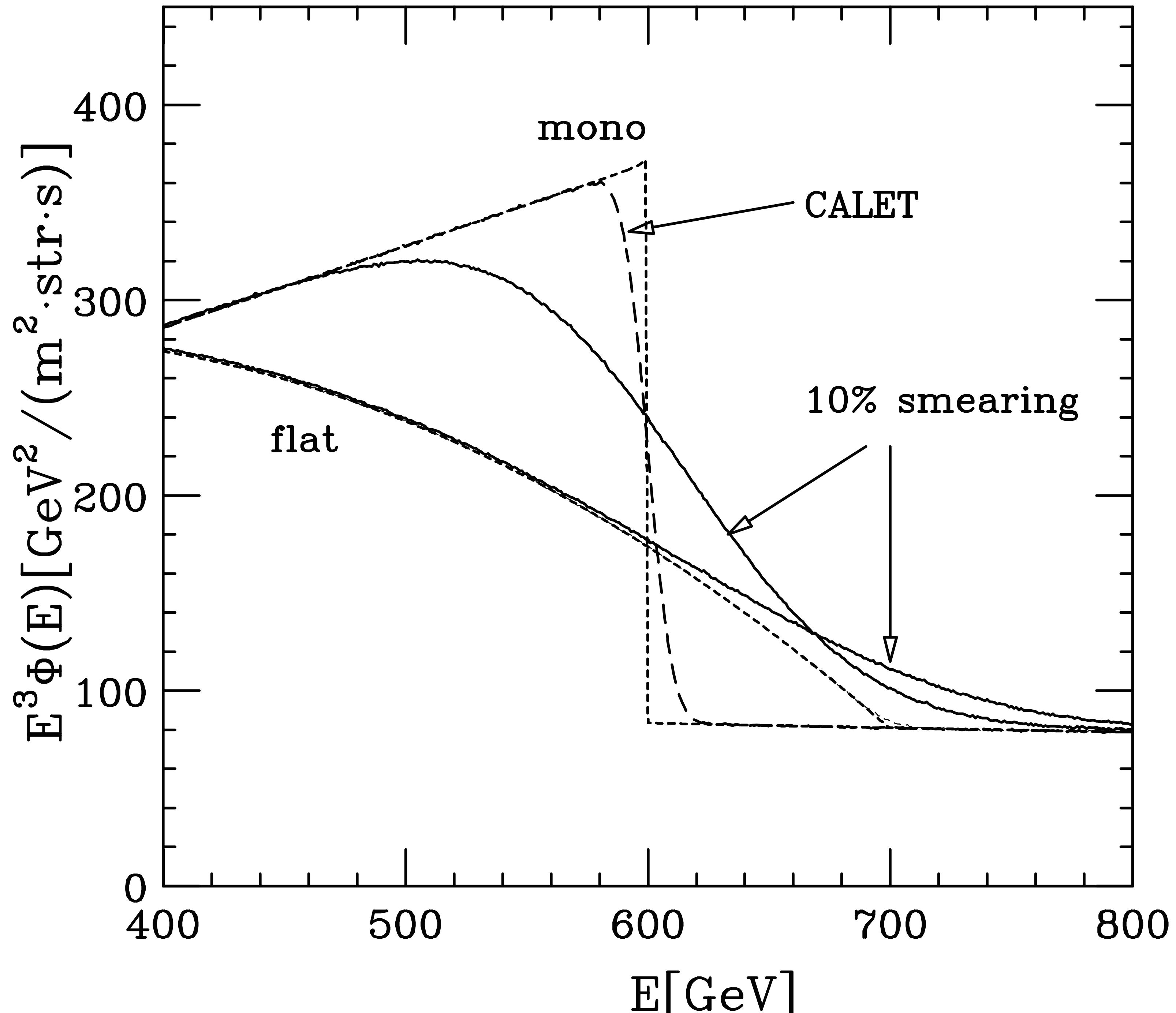
$$\tau = 3.3 \times 10^{26}\,\text{sec} \quad m = 1.4\,\text{TeV}$$

$$\tau = 1.1 \times 10^{26}\,\text{sec} \quad m = 1.6\,\text{TeV}$$



M1 model
300
250
200
150
100
50
0
100
200
300
400
500
600
700
800
E^3 Φ [GeV^2/m^2 sec str]
E [GeV]
(i)
(ii)
(iii)
(decay)
(annihilation)
(i) mono
mono
(ii) flat
flat
(iii) double
double

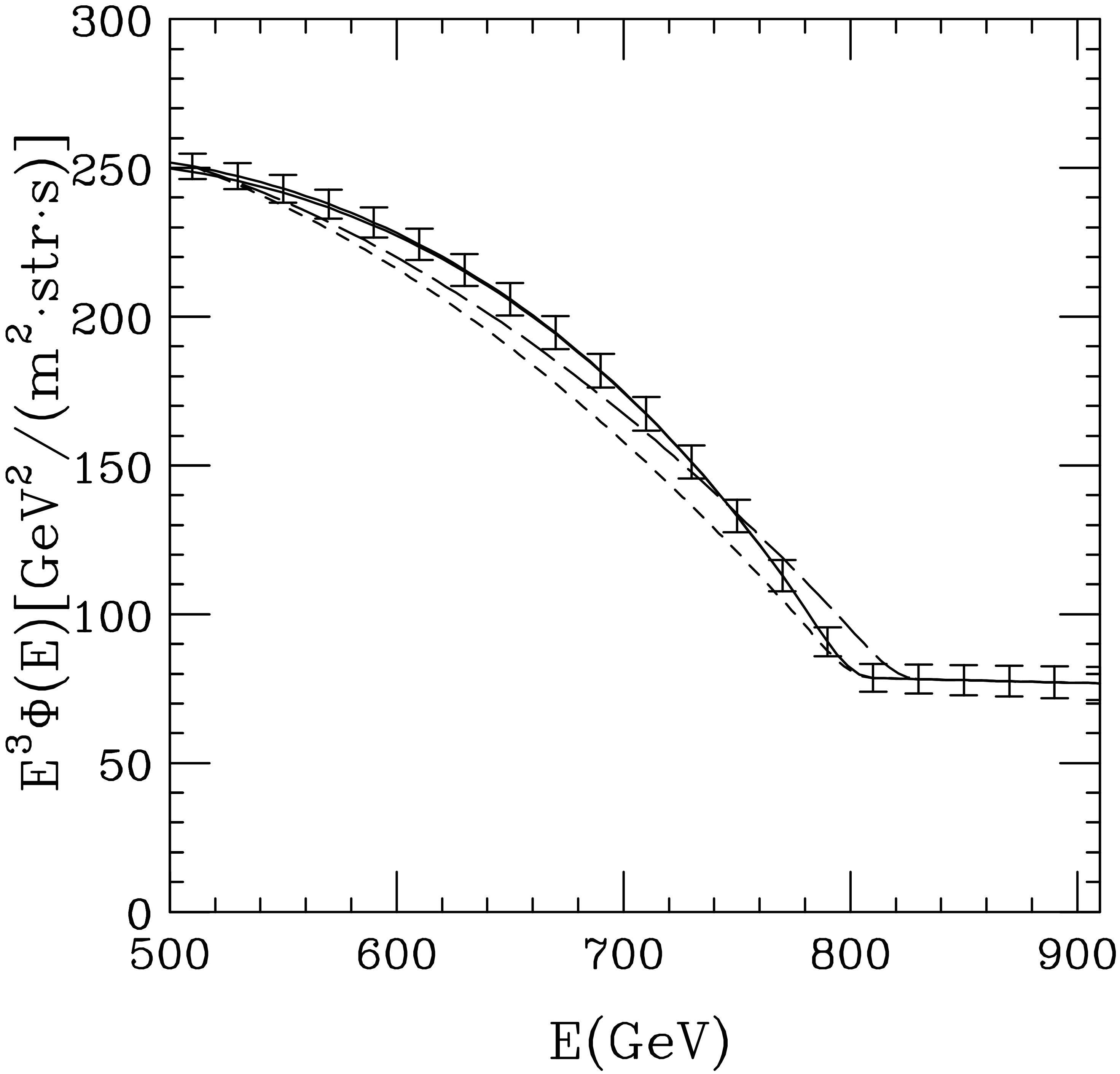
Smearing Effect



Fermi: 10% energy resolution

CALET: (7/sqrt[E/10GeV] + 1)%

CALET 5yr data may be able to tell the difference between double-peak and flat ones.



Solid: double-peak

Dotted: Flat w/ 800GeV

Dashed: Flat w/ 820GeV