Dark Matter, Dark Energy & Neutrino Mass
暗物质，暗能量和中微子质量

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理论物理前沿暑期讲习班——暗物质，中微子与粒子物理前沿

中山大学广州校区南校园 *2017*年*7*月*3-28*日

中山大學
SUN YAT-SEN UNIVERSITY

Lecture 1: Introduction to Particle Physics and Cosmology

Lecture 2: Some Basic Backgrounds of the Standard Model of Particle Physics

Lecture 3: Neutrino Mass Generation

Lecture 4: Theoretical Understanding of Dark Matter Detections

Lecture 5: Dark Energy and Gravitational Waves

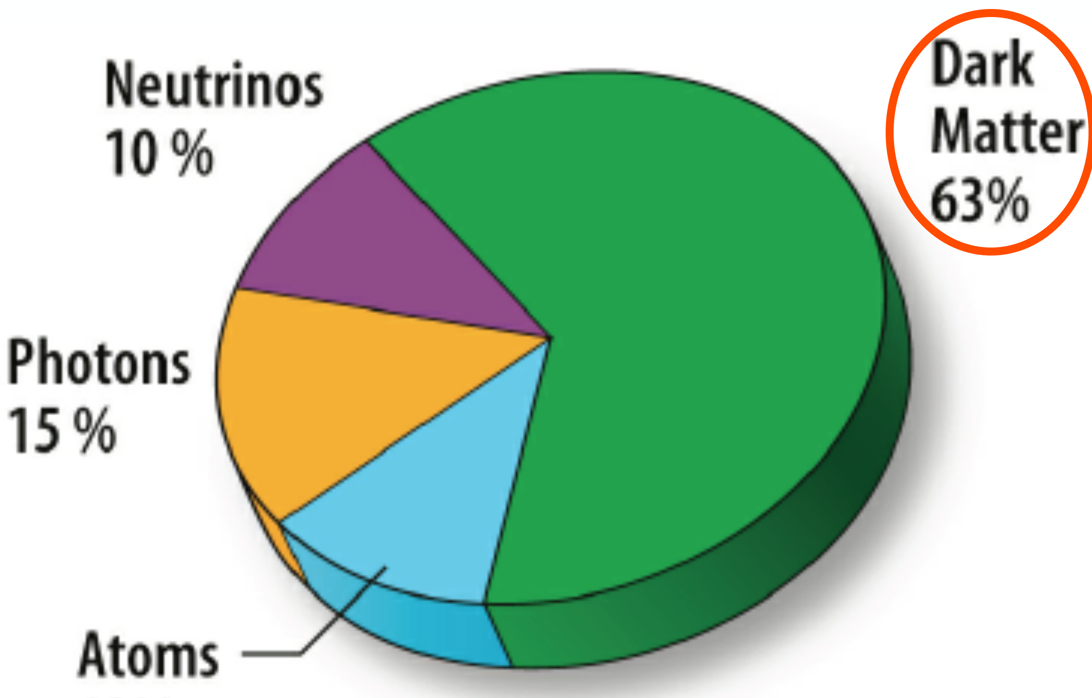
Lecture 4: Theoretical Understanding of Dark Matter Detections

Outline

- Introduction
- ***Indirect Searches for Dark Matter***
- ***Direct Detections for Dark Matter***
- ***Conclusions***

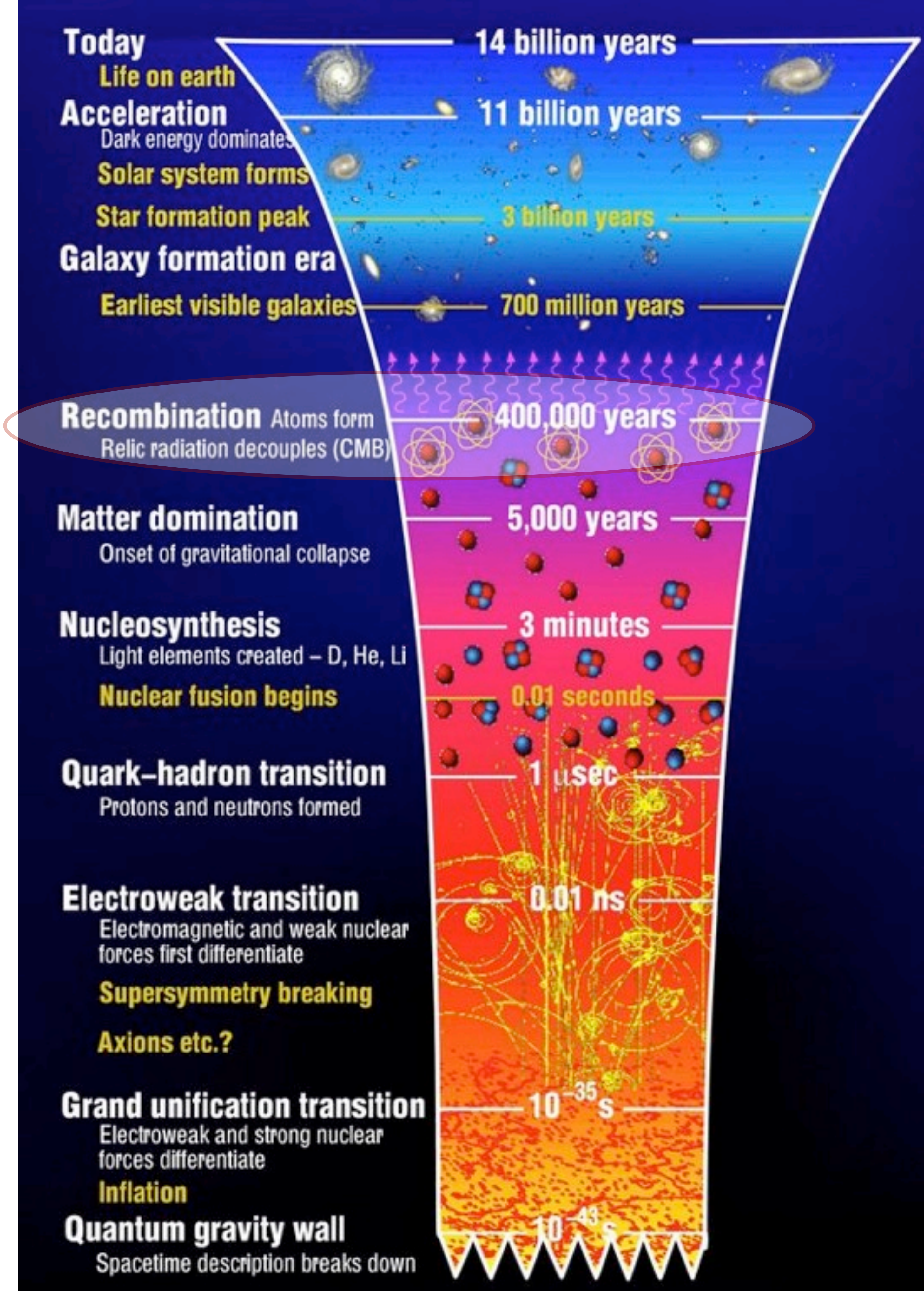
- Introduction

THE UNIVERSE, THEN

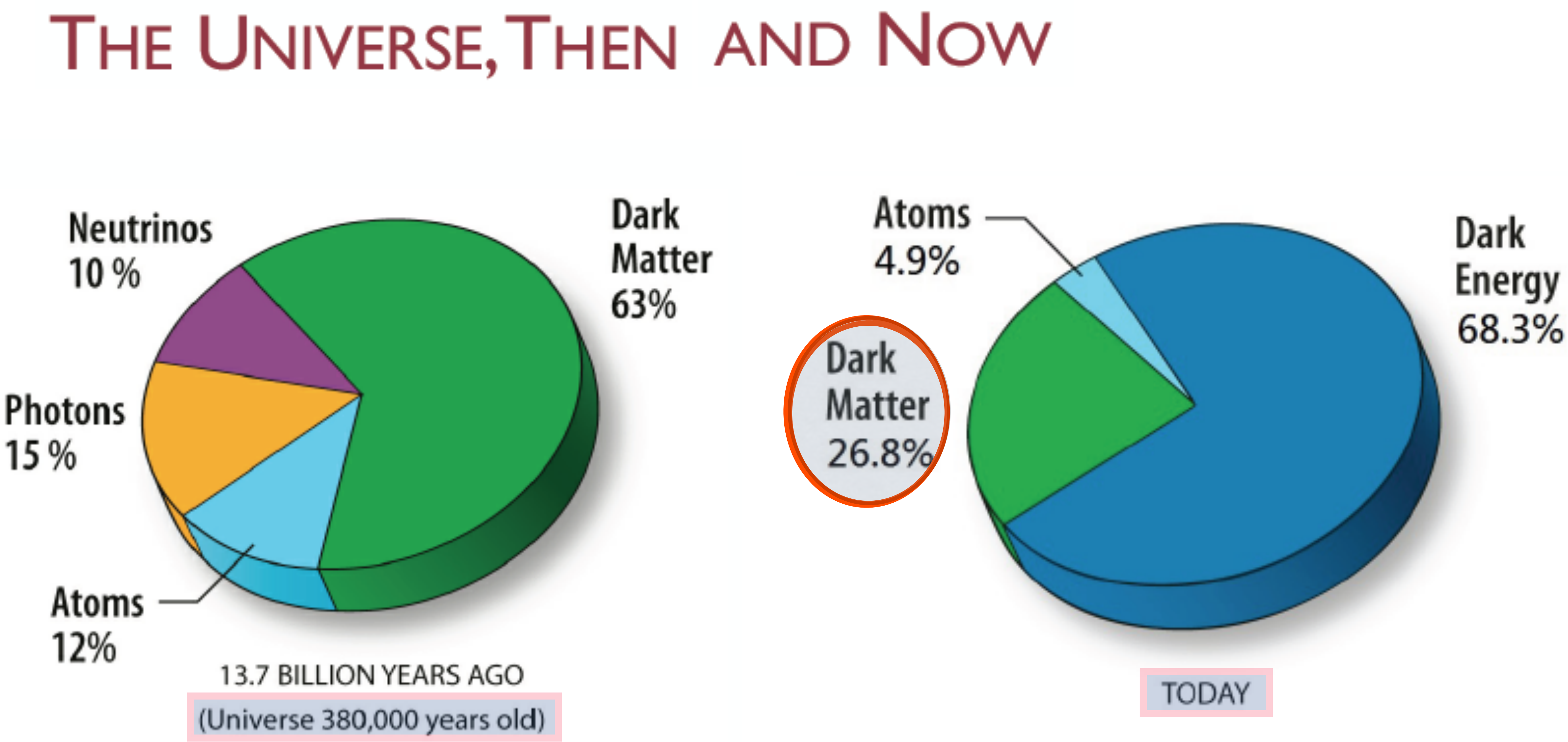


13.7 BILLION YEARS AGO

(Universe 380,000 years old)



- Introduction



Have we seen Dark Matter yet?

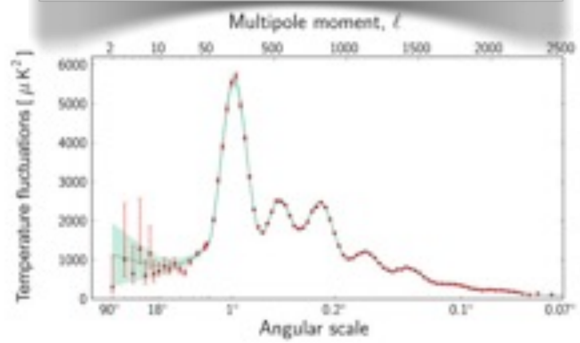
95% of the cosmic matter/energy is a mystery.

An Odyssey of Searching for Dark Matter (DM)

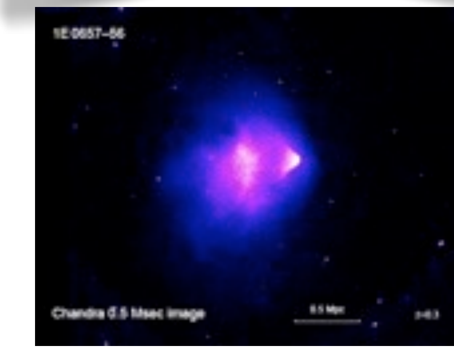
1783	J. Michell	light can be affected by gravity
1844	F. Bessel	the observed motion of Sirius and Procyon ~ dark stars
1846	U. L. Verrier	the anomalous precession of the perihelion of Mercury ~ dark planet
1877	A. Secchi	research on a nebulae ~ unseen matter scattered in space ~ dark clouds
End of 19th century	Lord Kelvin	estimated the quantity of unseen matter in the galaxy & presented the upper limit on the density of matter
	H. Poincare	"*matiere obscure* (French)"
1922	J. Kapteyn	a quantitative model to address the possible existence of dark matter
1932	J. Oort	analyzed and derived the value of the unseen matter's local density
1933	F. Zwicky	Studied the Coma cluster ~ high mass density needed to maintain the velocity dispersion of the galaxies ~ "dark matter"
1970	V. Rubin & K. Ford	The rotational velocities of the spiral galaxies are independent of the distance away from galactic center ~ no "Keplerian decline"

Observations support Dark Matter at

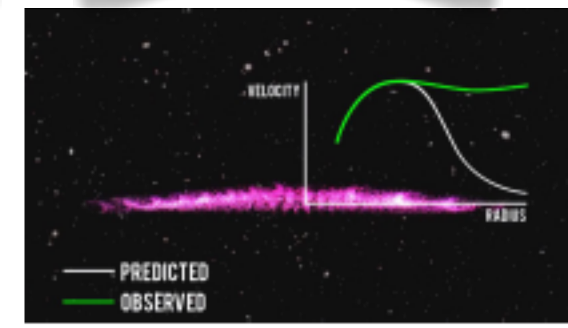
Cosmological scale



Galaxy cluster scale

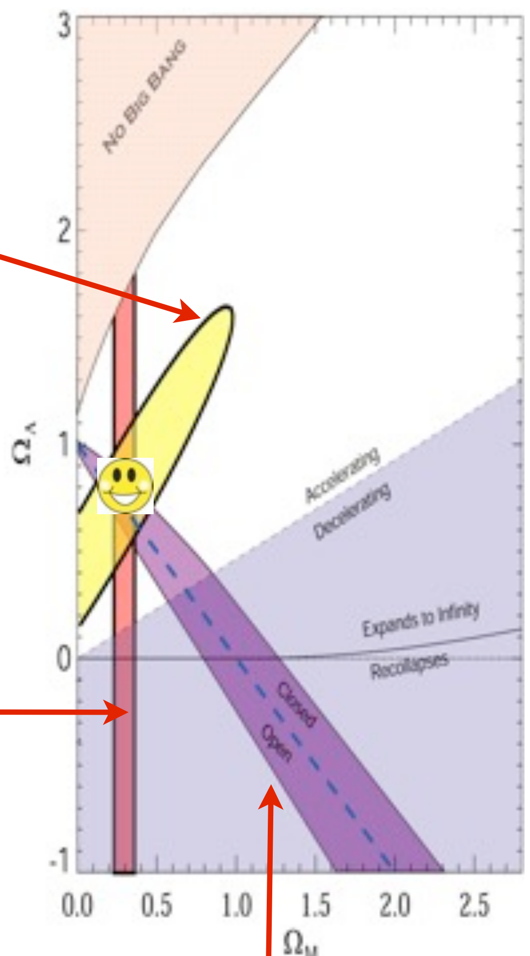


Galactic scale

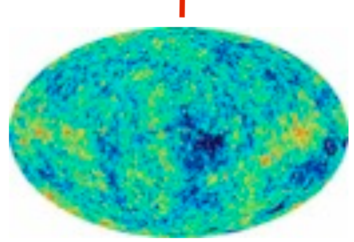


SNe Ia

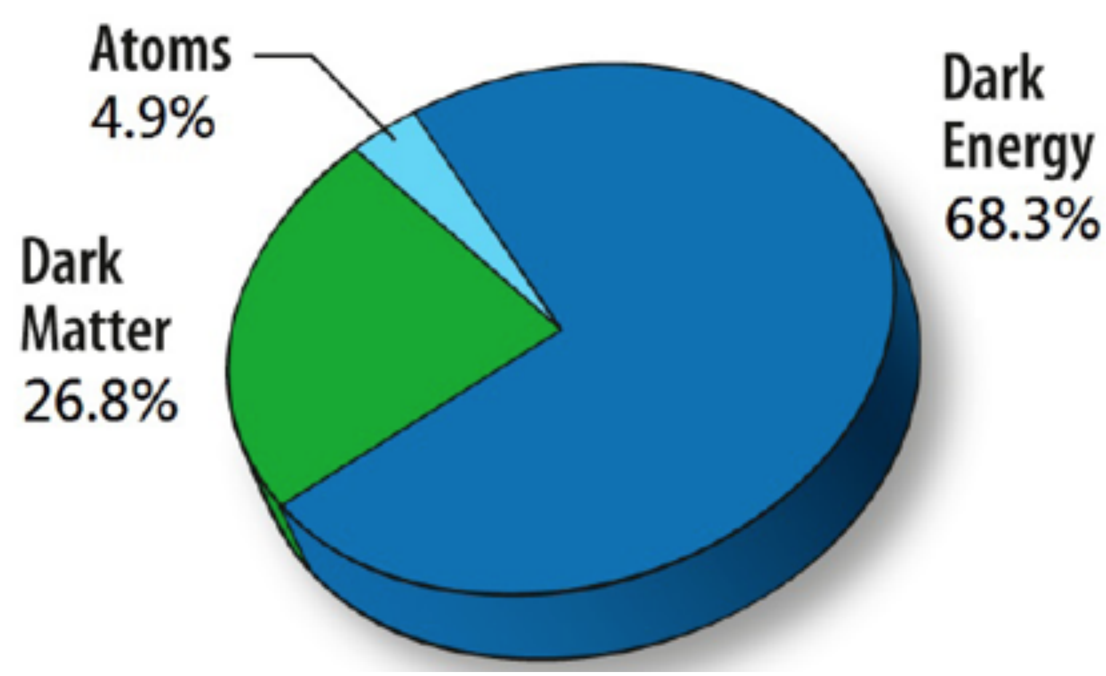
LSS



CMB



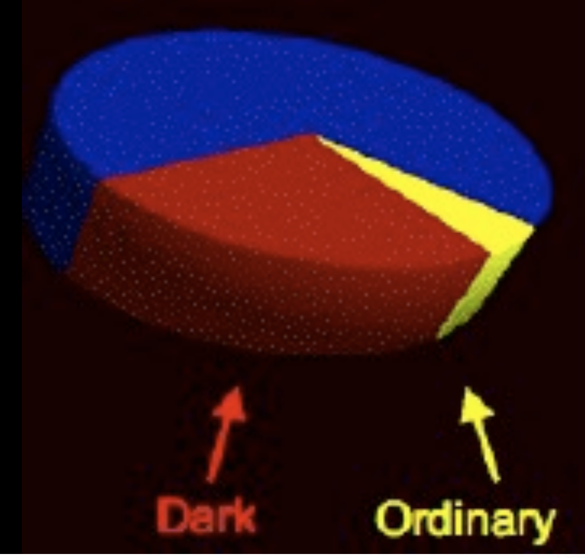
Concordance region:



$$\Omega_{\rm DM}h^2 = 0.1196 \pm 0.0031$$

Dark Matter: 26.8%

Independent methods (using primordial nucleosynthesis & the microwave background) convince us that the dark matter is a completely new kind of particle.



Dark matter cannot be the particle in the standard model, which has to be:

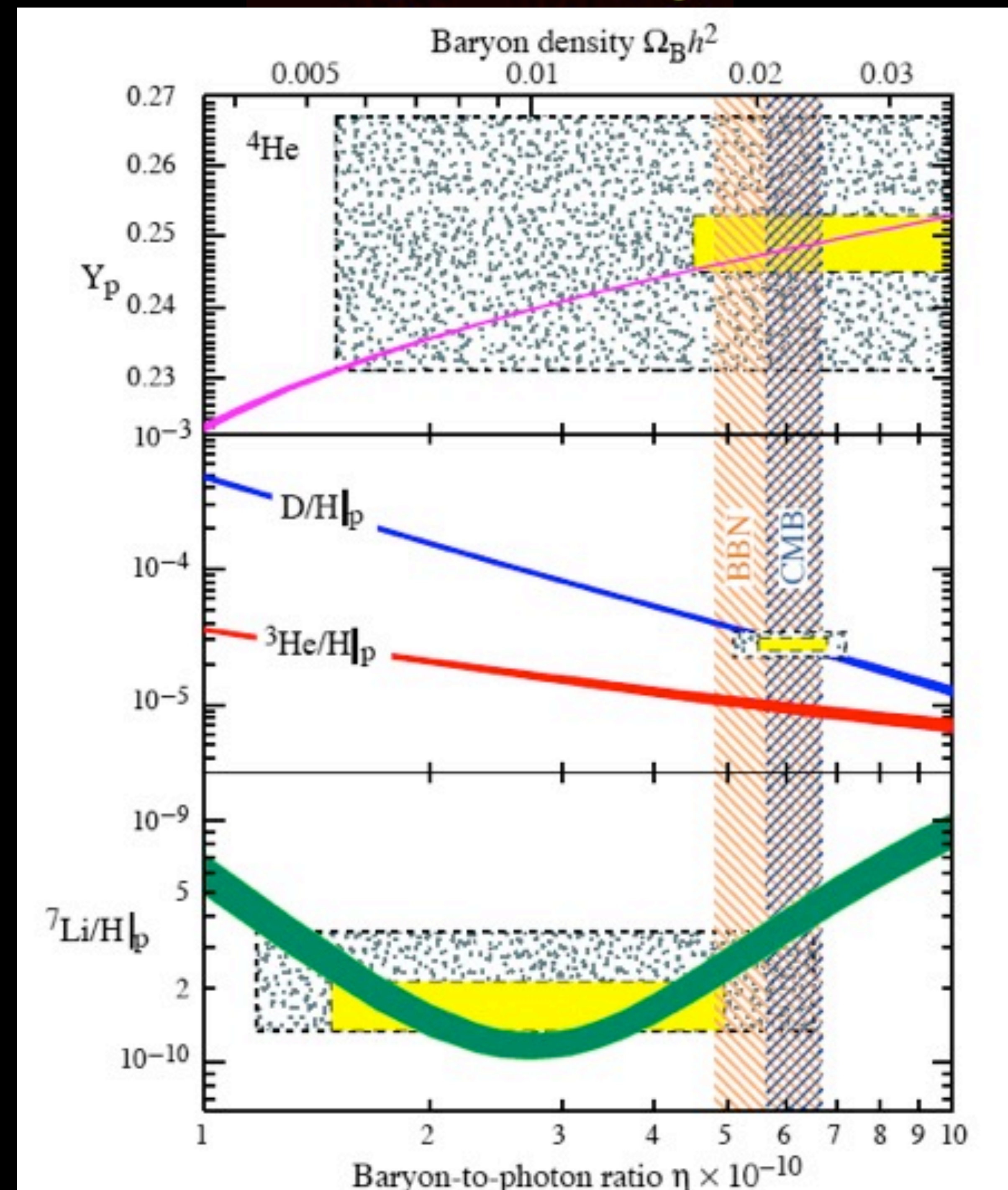
- Massive
- Non baryonic
- No charge (electric or color)
- Stable ($\tau > 10^{26}$ s, $\tau_{universe} \sim 10^{17}$ s)

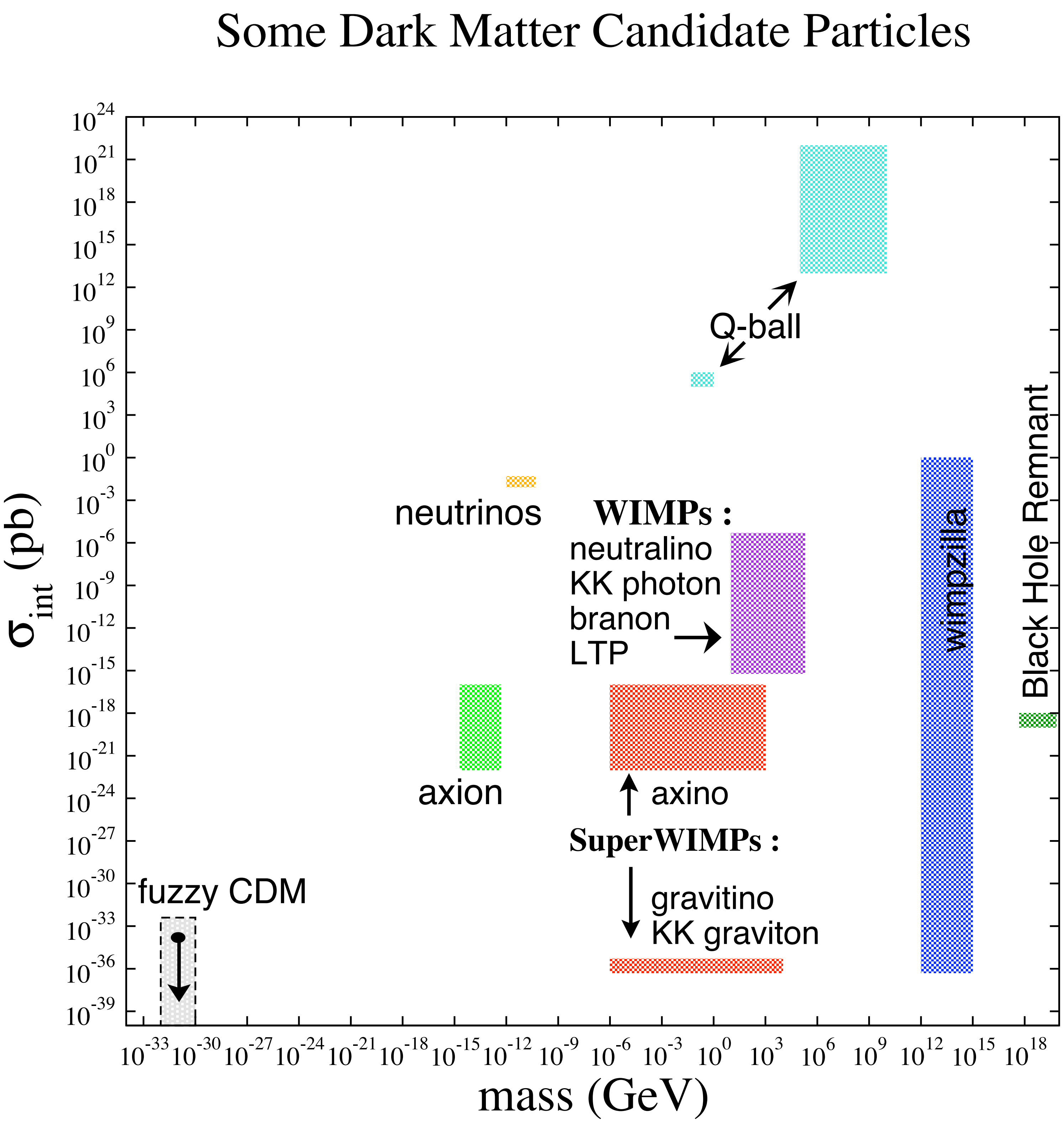
WIMP ← Weakly Interacting Massive Particles

Axion

Sterile neutrino

. . . . . .

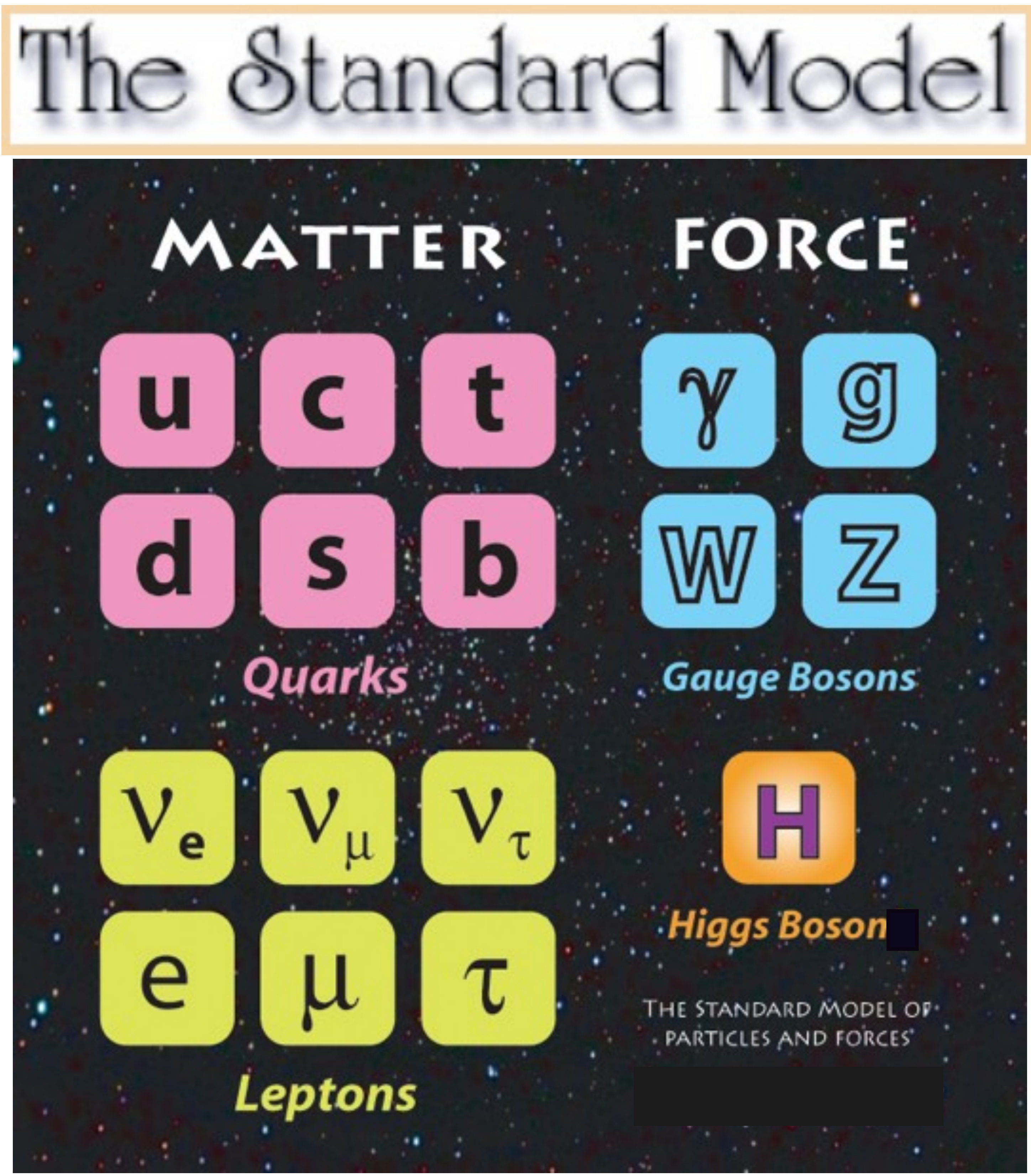




- neutrino ν – hot DM
- neutralino χ
- "generic" WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- wimpzilla,. . .

How to observe dark matter?

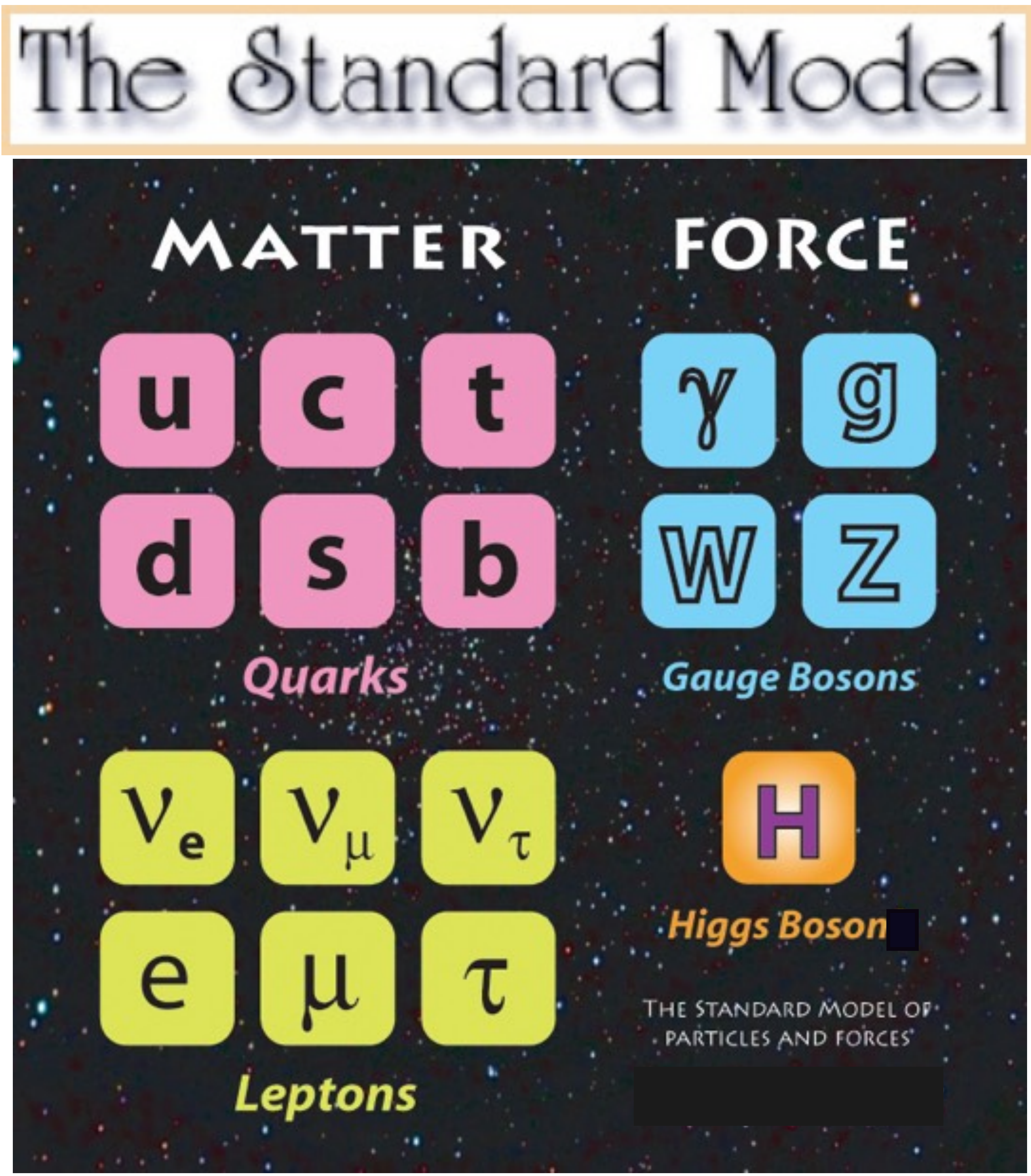
What is the real nature of Dark Matter ?



Beyond the SM

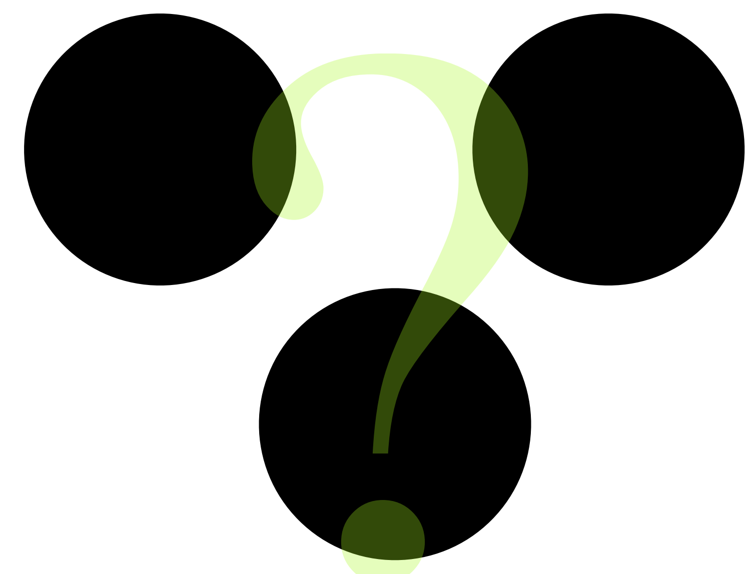
DARK MATTER

What is the real nature of Dark Matter ?

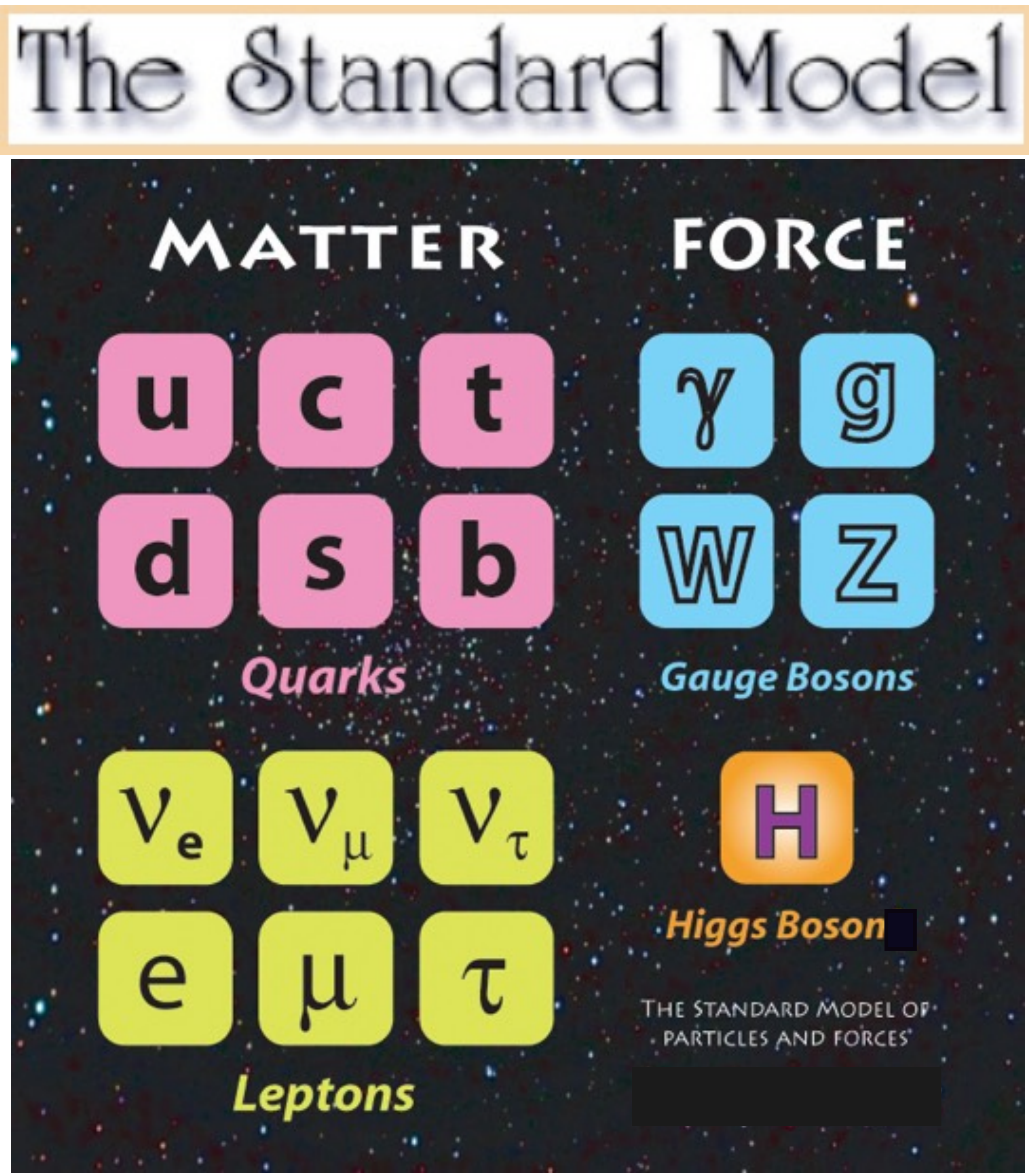


Beyond the SM

DARK MATTER

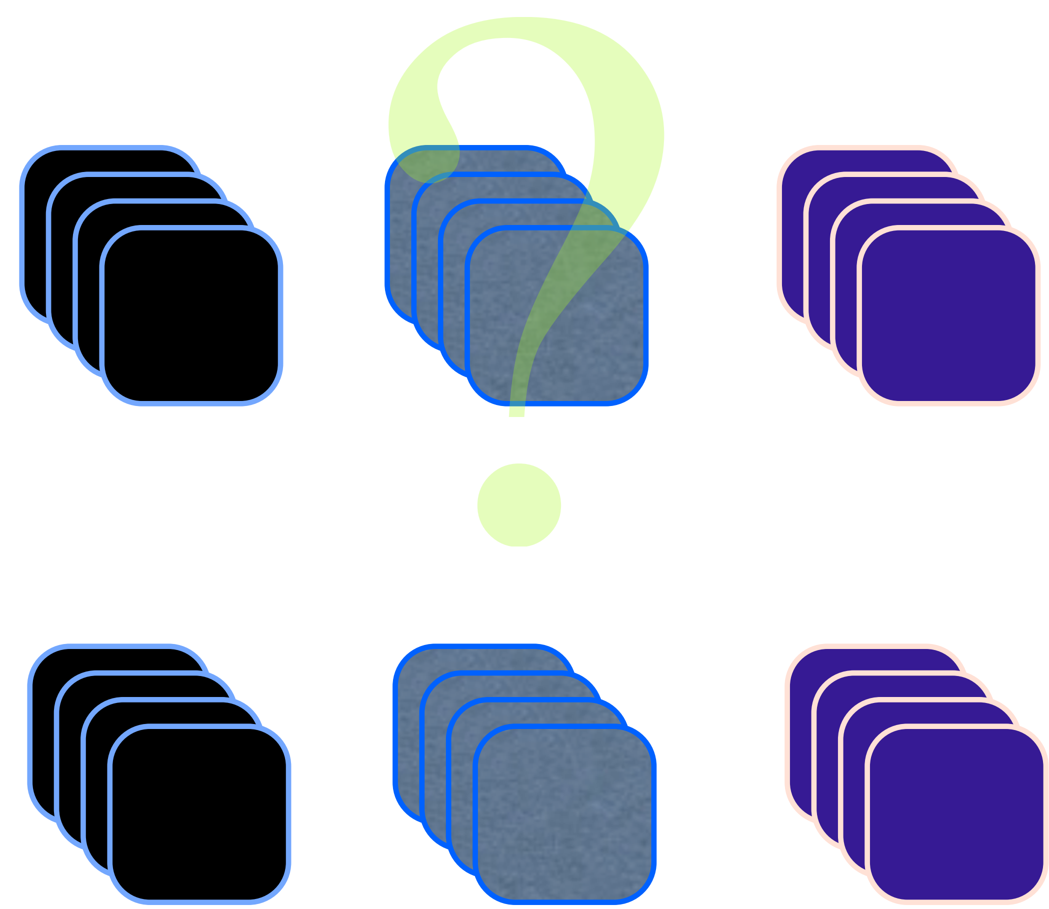


What is the real nature of Dark Matter ?



Beyond the SM

DARK MATTER

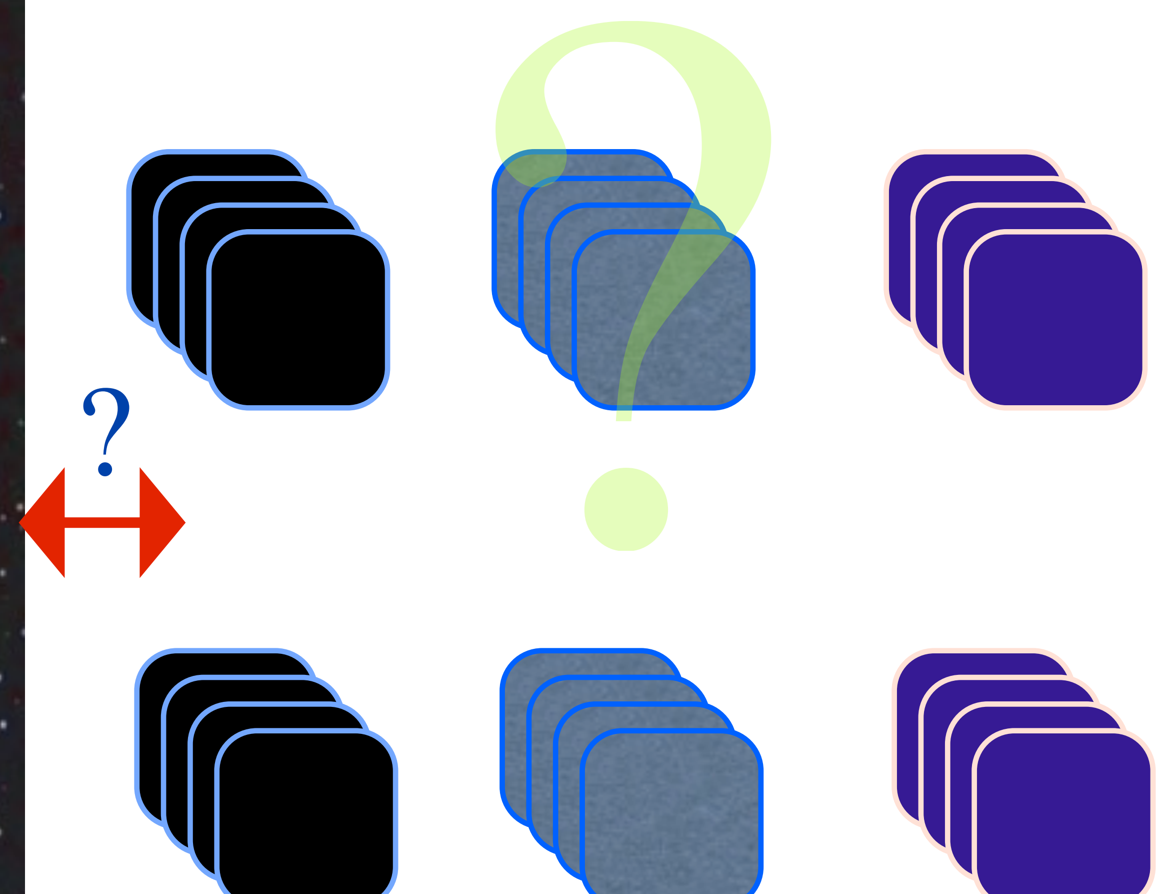


What is the real nature of Dark Matter ?

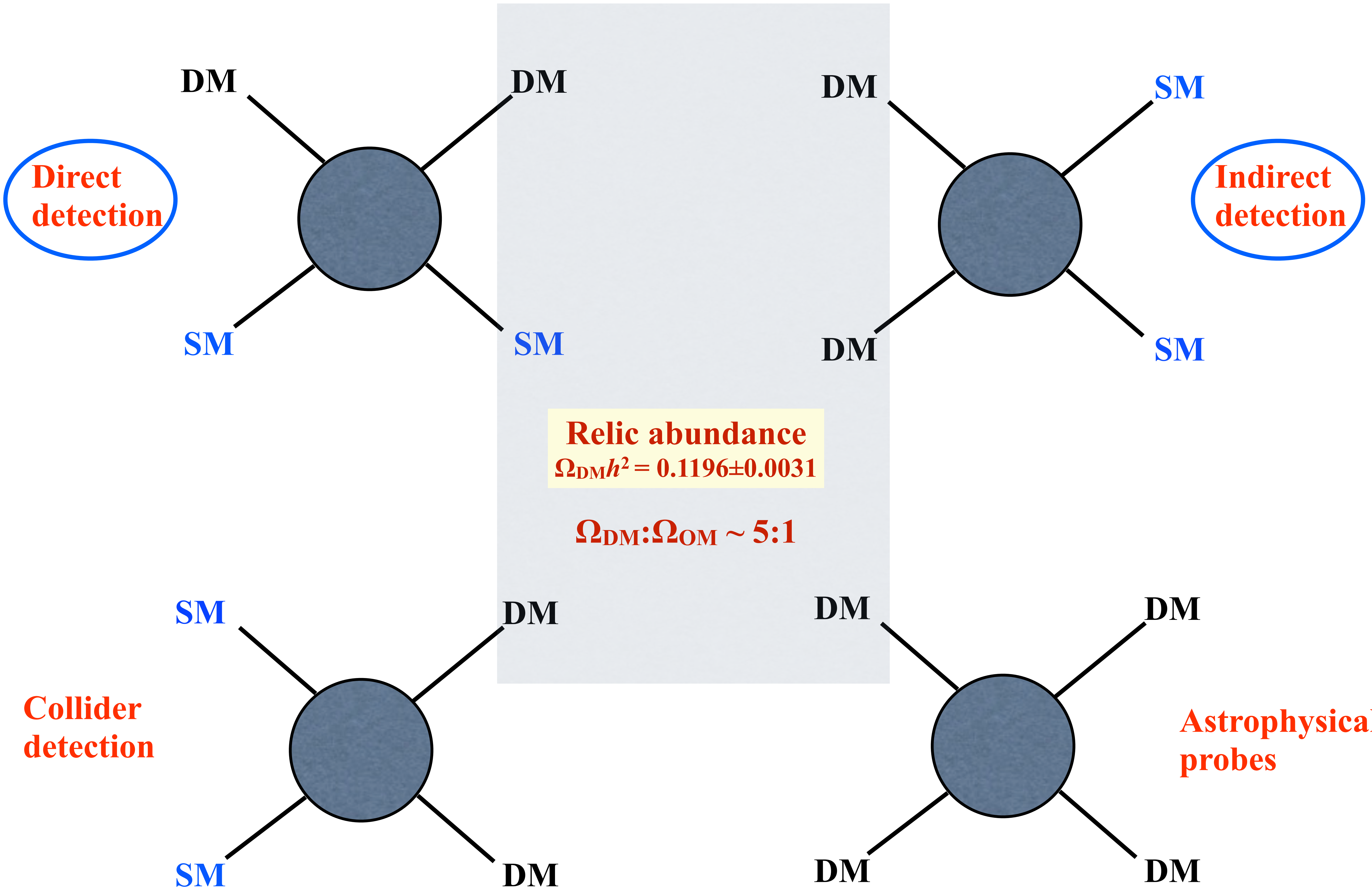
The Standard Model

Beyond the SM

DARK MATTER

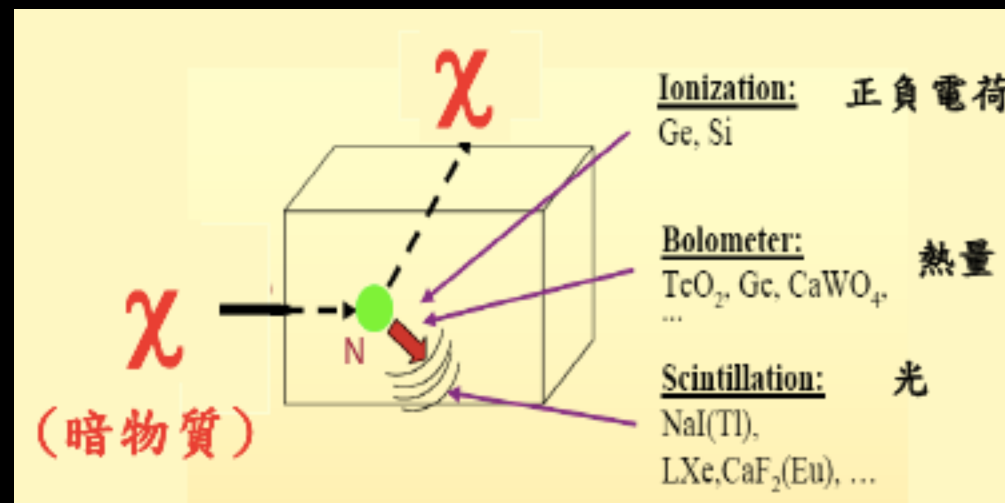


Search for Dark Matter: Some interaction beyond gravitation

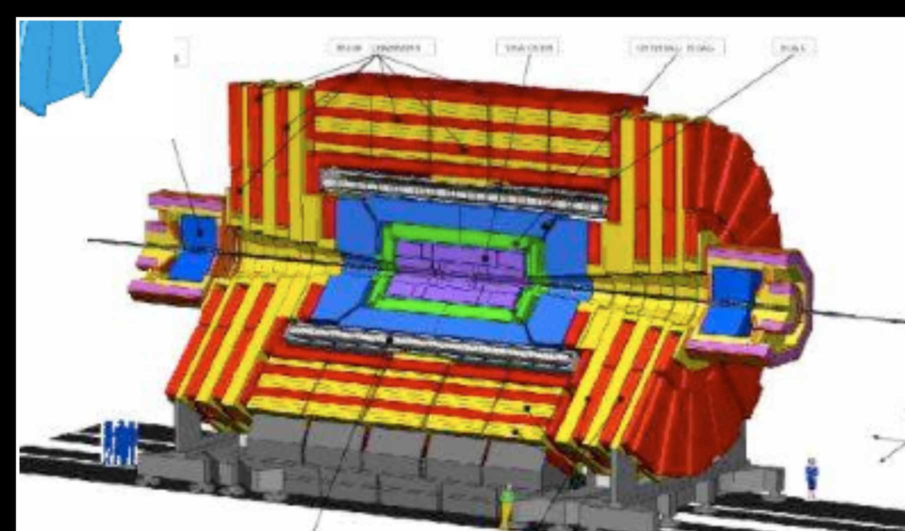


Search for Dark Matter:

Direct detection:
(underground experiments)

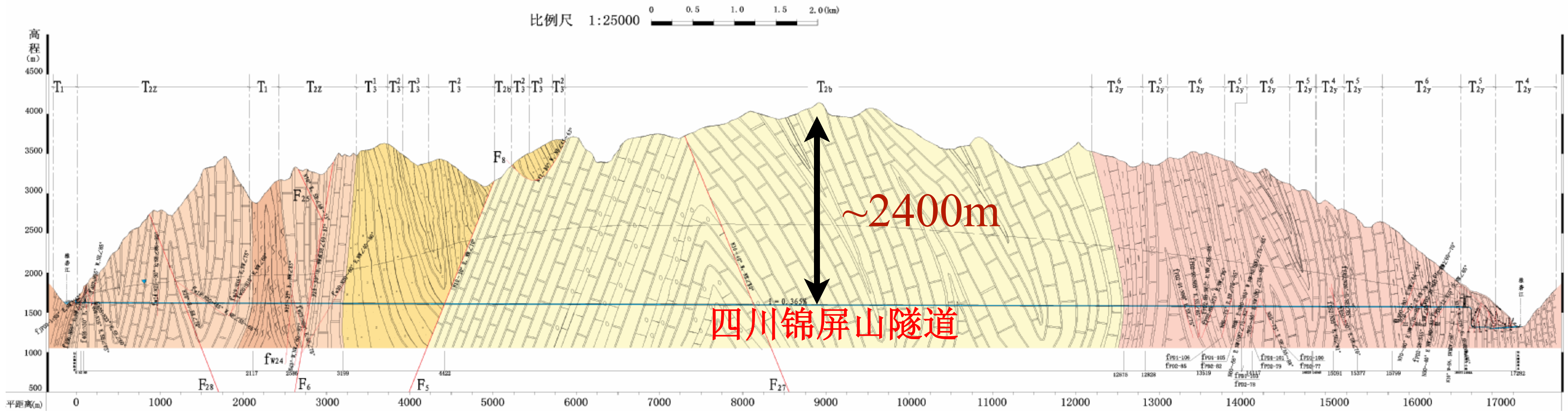


Collider searches: (LHC)

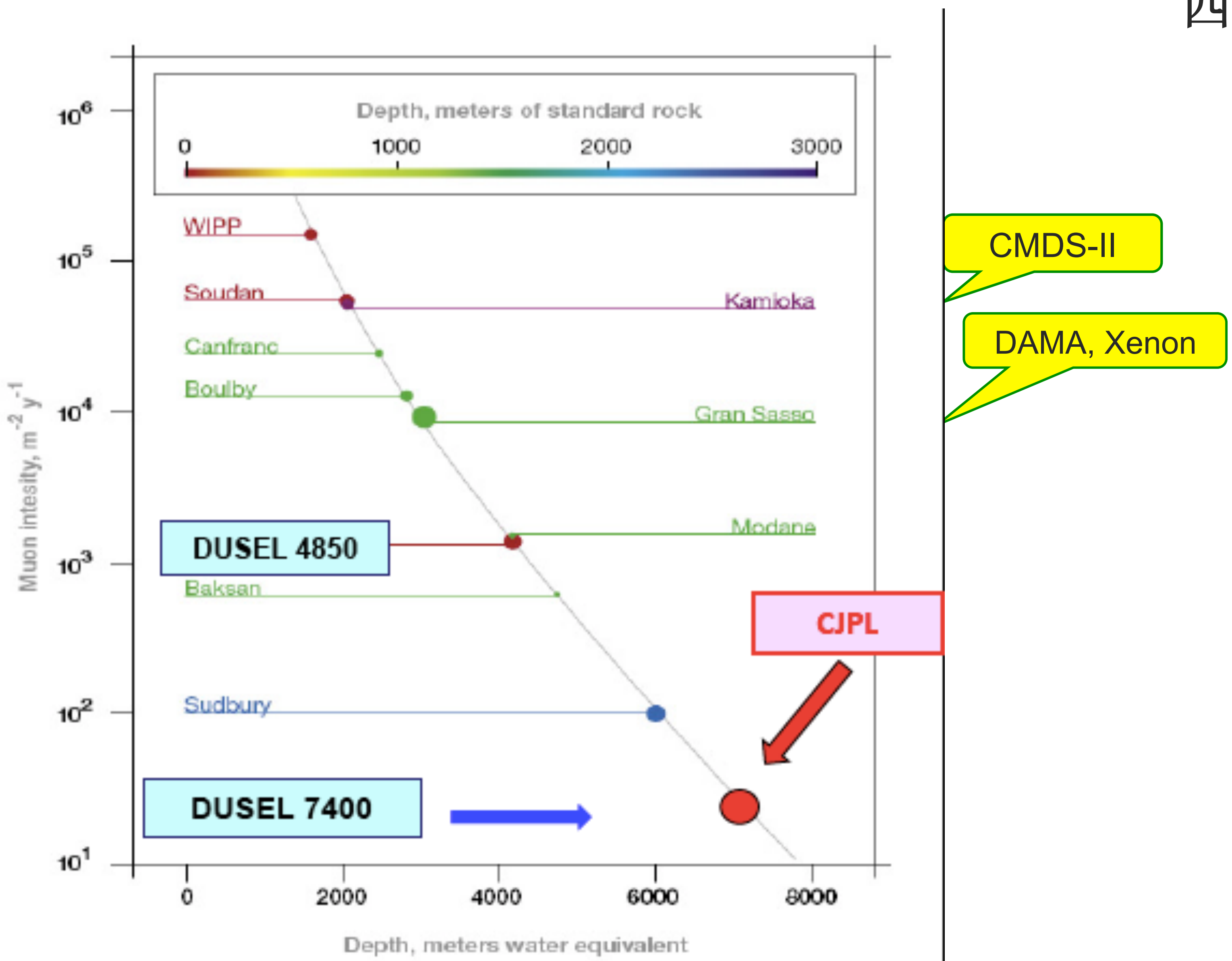


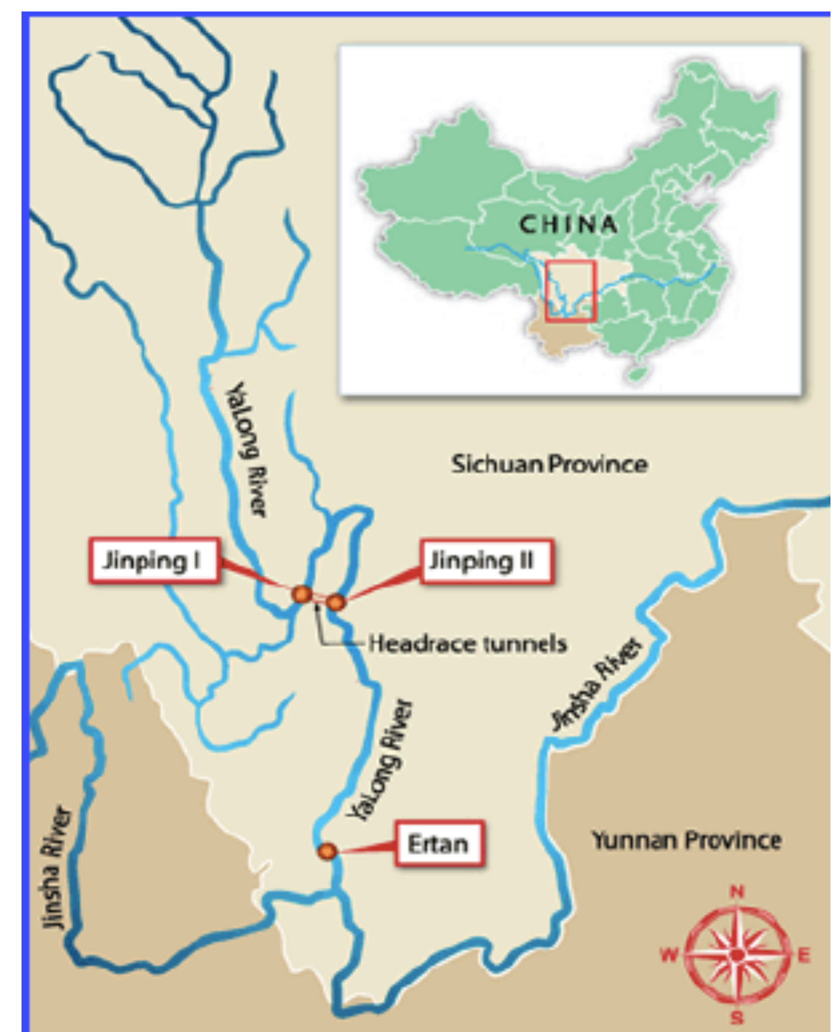
Indirect detection:
(cosmic-ray experiments)

錦屏地下實驗室(CJPL): 中國首個、世界最深的地下實驗室

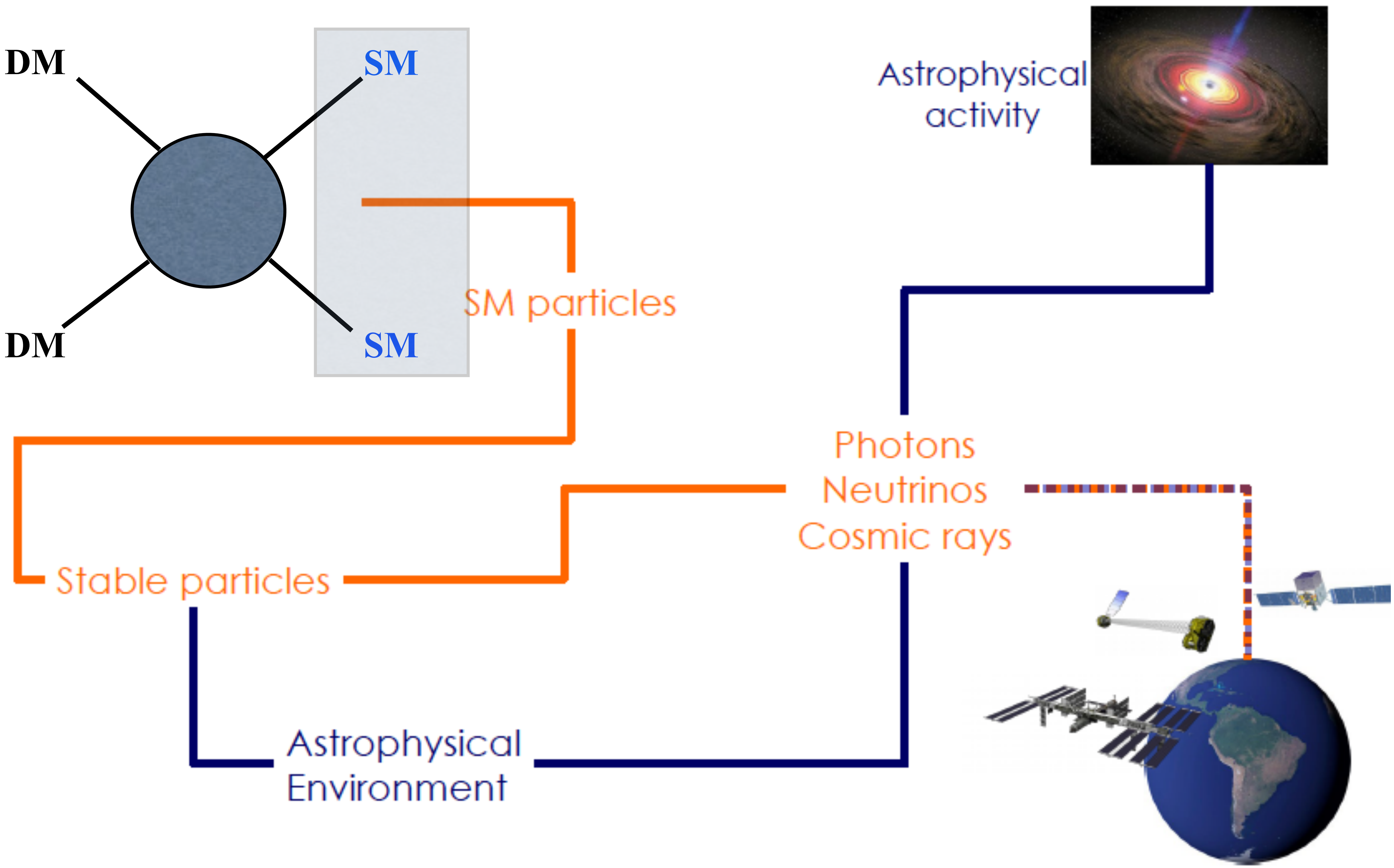


四川省锦屏山地形示意图





- ## *Indirect Searches for Dark Matter*

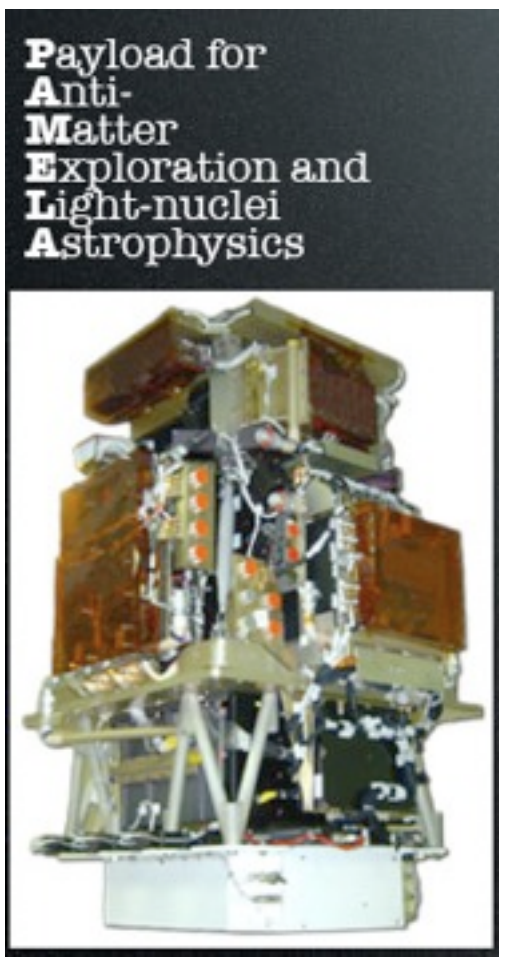


Cosmic Ray Experiments

Space Station AMS-02

Satellite

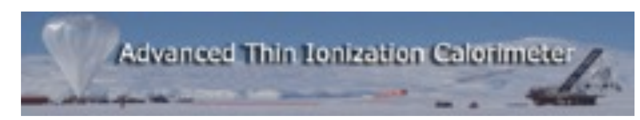
PAMELA



Fermi

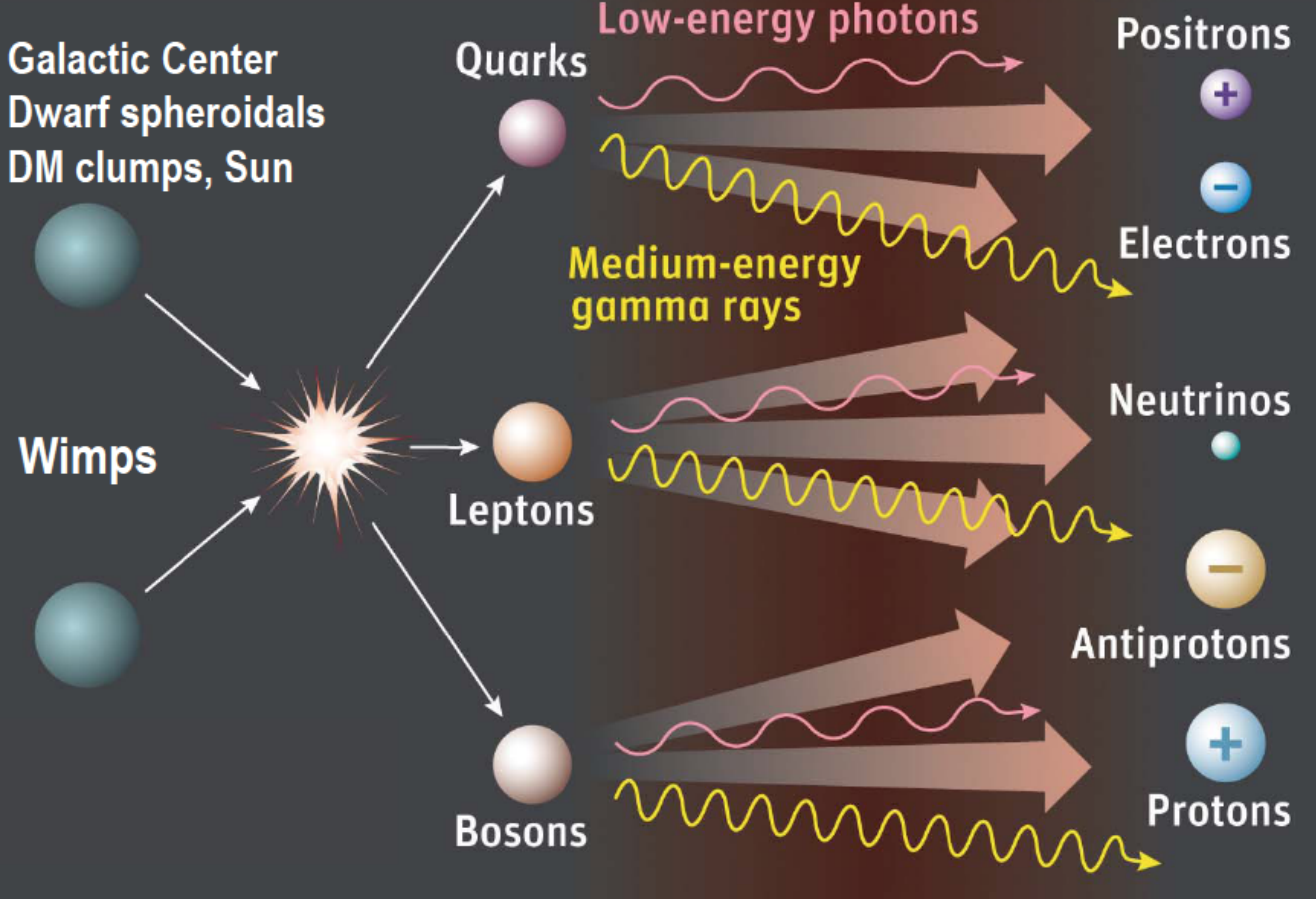
Balloon →

ATIC



ATIC (Usa + Germany, Russia, China)

Indirect Detection



Cosmic Ray Anomalies

e^+ and e^++e^- excesses

12/8/2016

Fermi: Phys.Rev.Lett. 102 (2009) 181101
Online on May 4, 2009
arXiv:0905.0025 [astro-ph.HE]

ATIC: Nature 456 (2008) 362

PAMELA: Nature 458 (2009) 607
arXiv:0810.4995 [astro-ph]

Anomalies → Pulsars ...? / Dark Matter ?

New theory of DM on arXiv every day!

2011/5/19 (Endeavour) Physics Result published on April 3, 2013

AMS-2: Phys.Rev.Lett. 110 (2013) 141102

AMS-02: Two new PRLs published on Sept. 19, 2014

AMS days at CERN: $\bar{p}/p$ on April 15-17, 2015 (S. Ting)

AMS-02: PRL117 (2016) 091103 (Aug. 26, 2016)

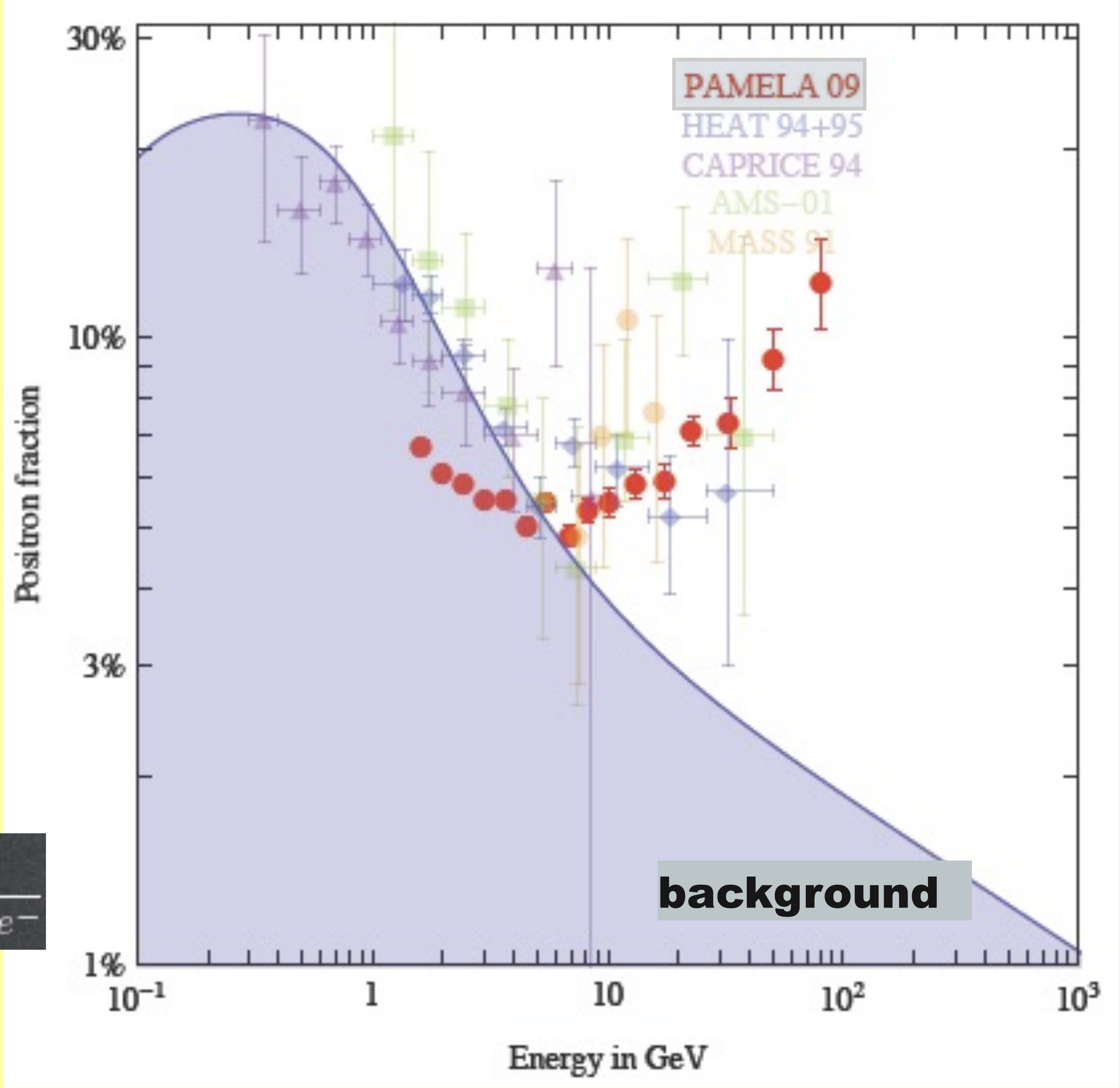
	Cited 11/16/2009	7/31/2010	4/19/2013	9/26/2014	2/2/2015	5/2/2015	7/7/2015	9/26/2016	12/8/2016
Fermi	181 →	323	642	744	769	793	802	900	909
ATIC	258 →	345	556	627	657	692	701	807	822
PAMELA	386 →	564	1040	1298	1372	1452	1481	1721	1748
New theory of DM	>200 →	300	500	550	570	590	600	630	635
AMS-2: PRL 110 (2013) 141102			→	12	240	316	366	393	598	618
AMS-02: Two new PRLs (Sept. 19, 2014)				→	0 / 0	35 / 22	58 / 38	74 / 47	208 / 152	233 / 169
AMS days at CERN (April 15-17, 2015)						→	6	15	30	--
AMS-02: PRL117 (2016) 091103								→	0	12

Positrons from PAMELA:

It can discriminate

$e^+, e^-, p, \bar{p}, \ldots$

(9430 e^+ collected)



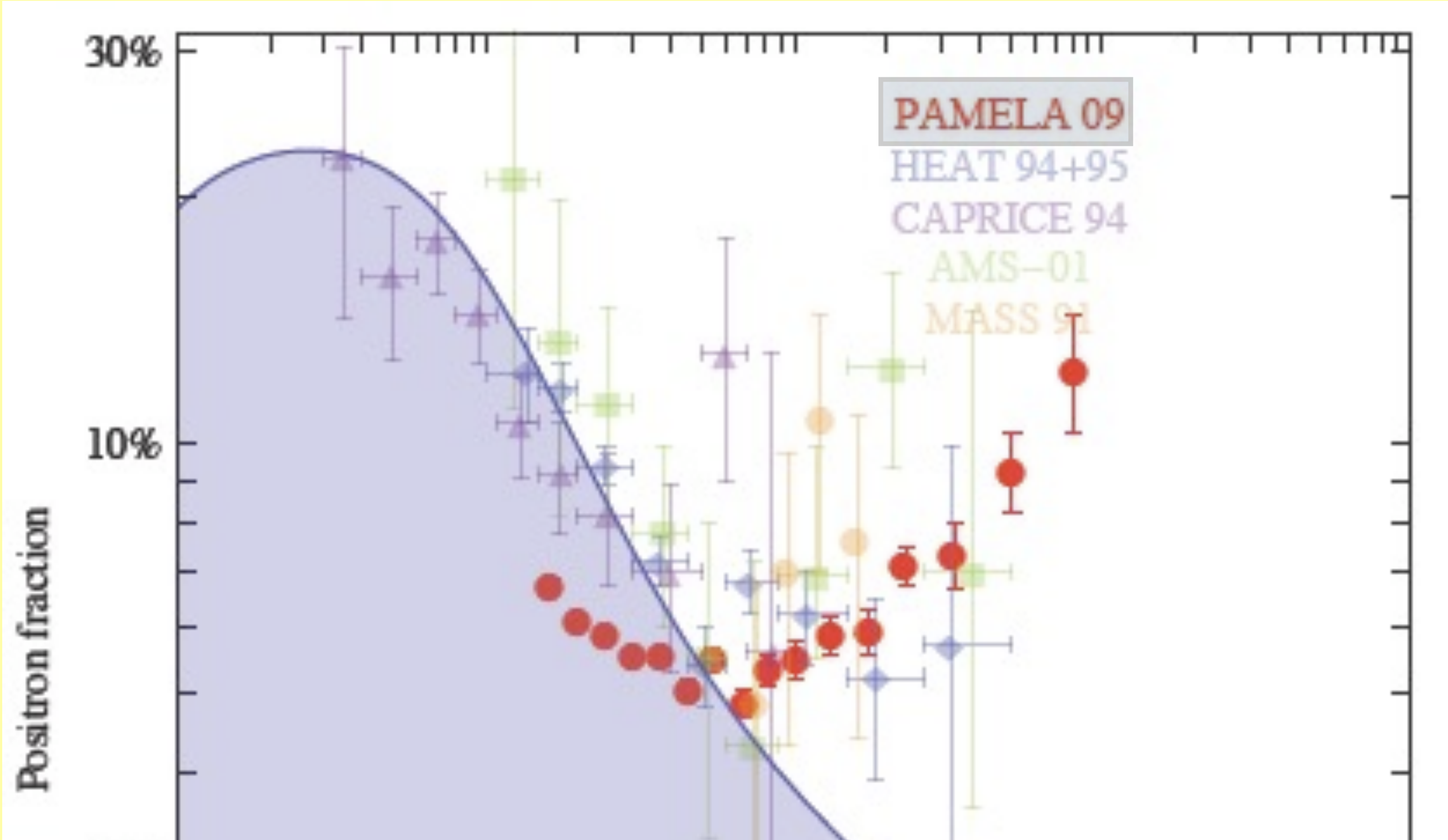
$\frac{e^+}{e^+ + e^-}$

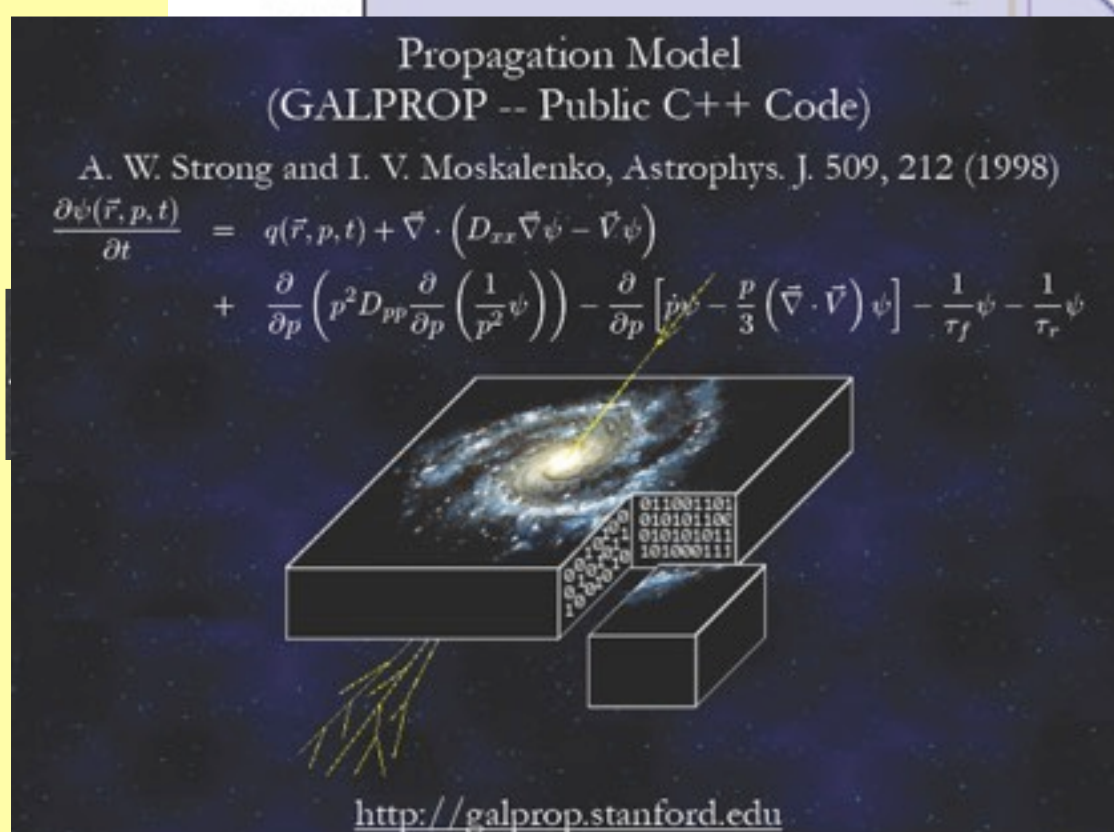
Positrons from PAMELA:

It can discriminate

$e^+, e^-, p, \bar{p}, \ldots$

(9430 e^+ collected)





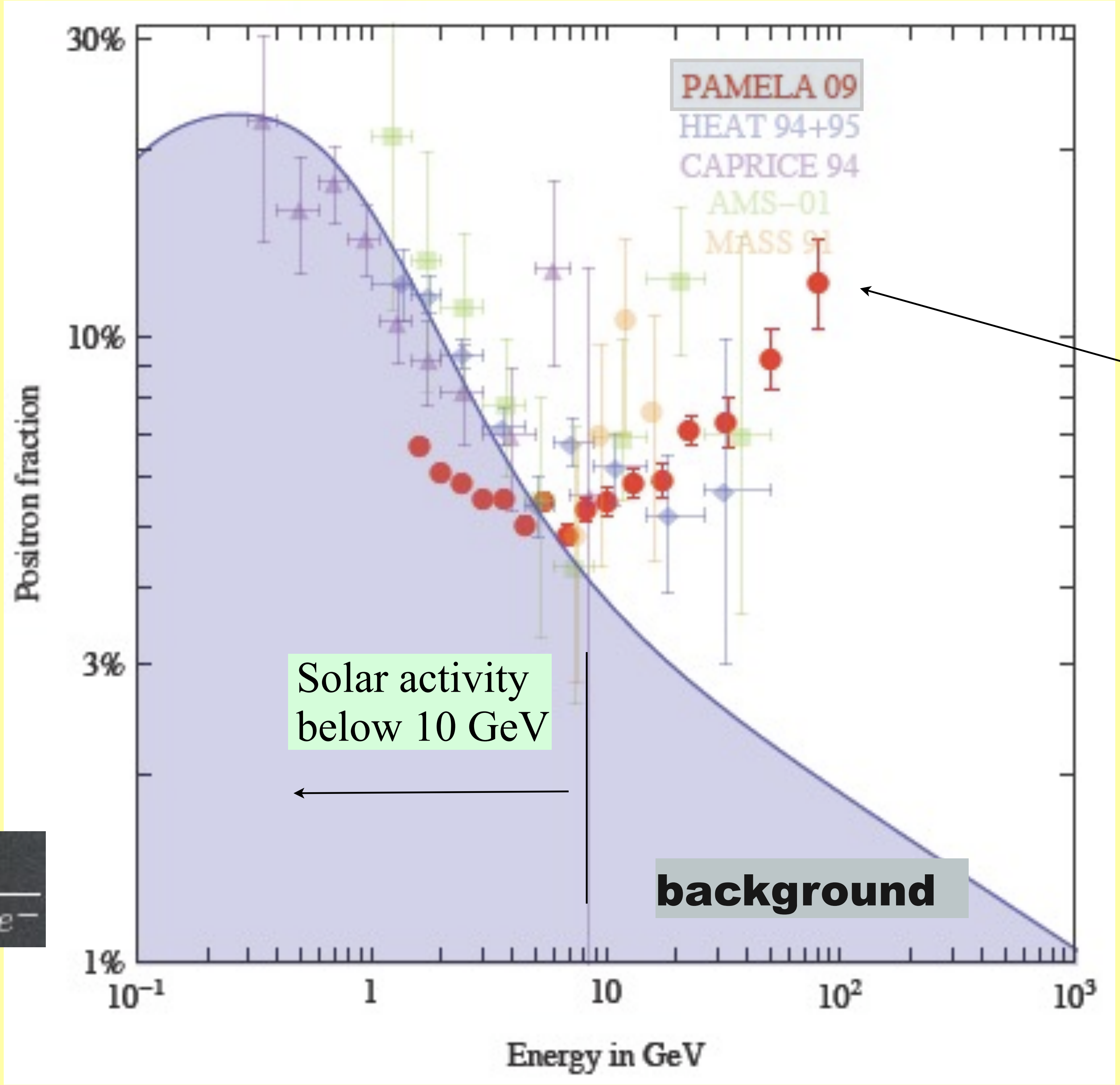
Positrons from PAMELA:

It can discriminate

$e^+, e^-, p, \bar{p}, \ldots$

(9430 e^+ collected)

$$\frac{e^+}{e^+ + e^-}$$



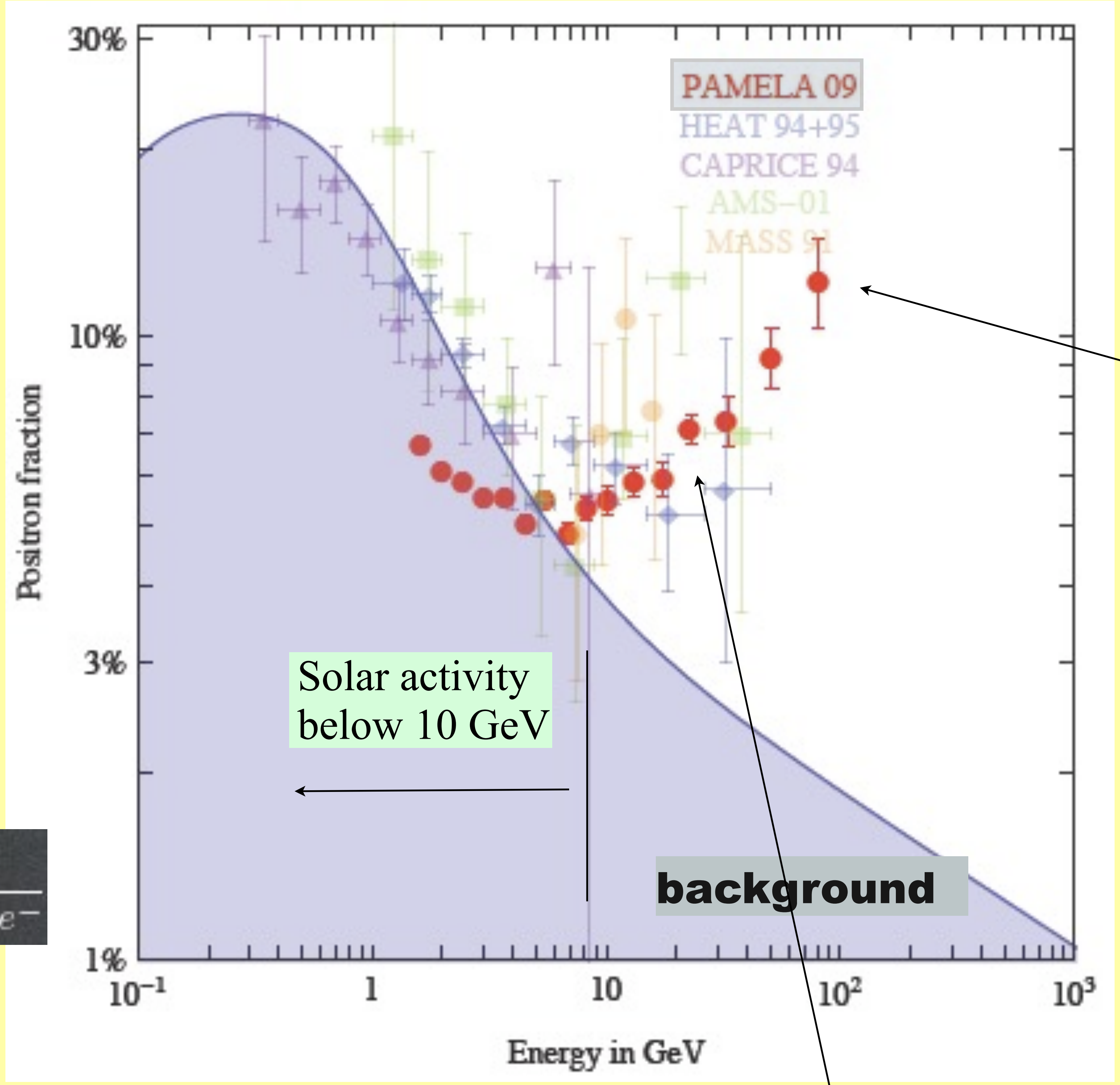
(errors statistical only, larger at high energy)

Positrons from PAMELA:

It can discriminate

$e^+, e^-, p, \bar{p}, \ldots$

(9430 e^+ collected)

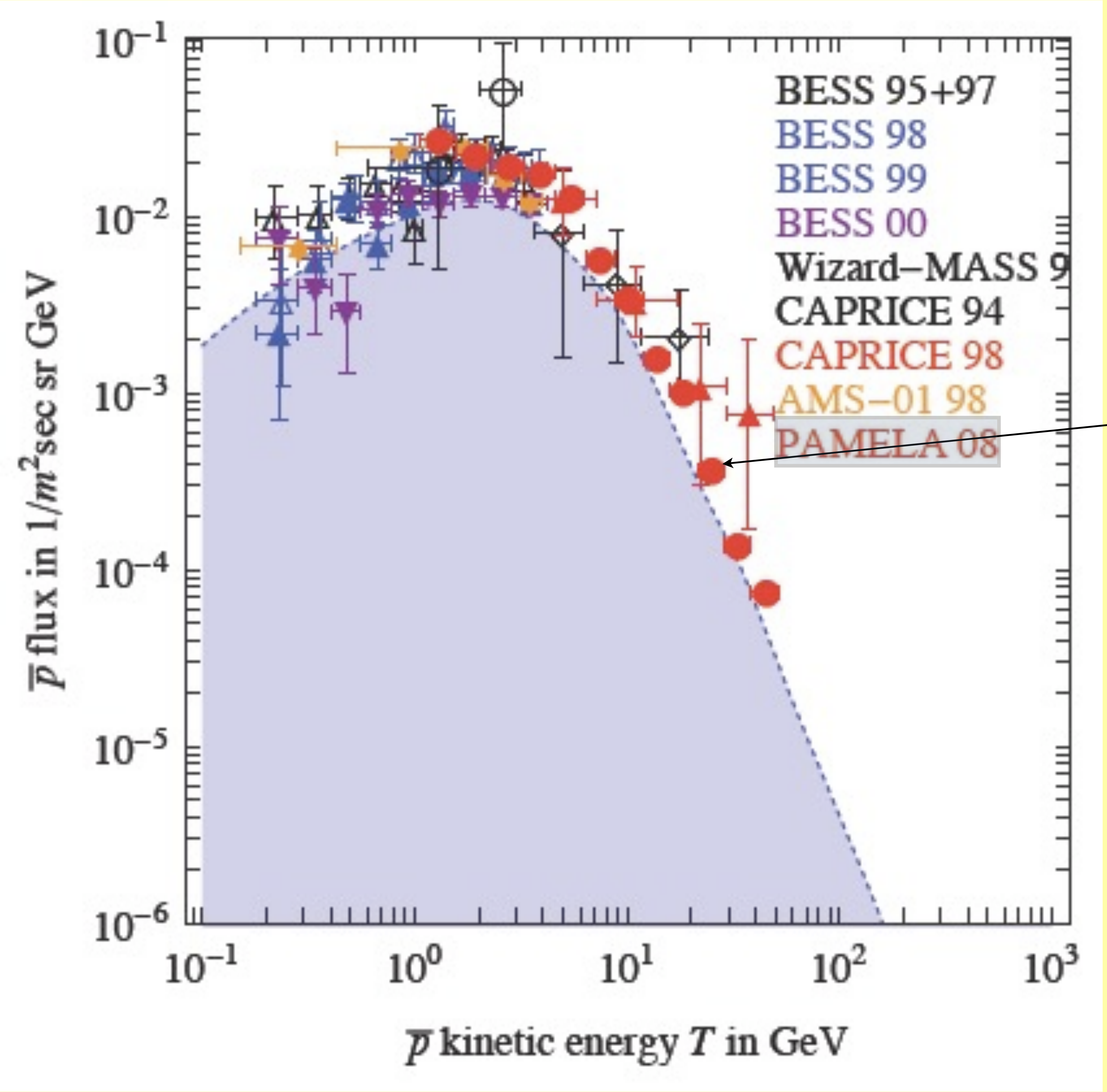


$$\frac{e^+}{e^+ + e^-}$$

(errors statistical only, larger at high energy)

☞ Steep e+ excess above 10 GeV with very large flux

Antiprotons from PAMELA:

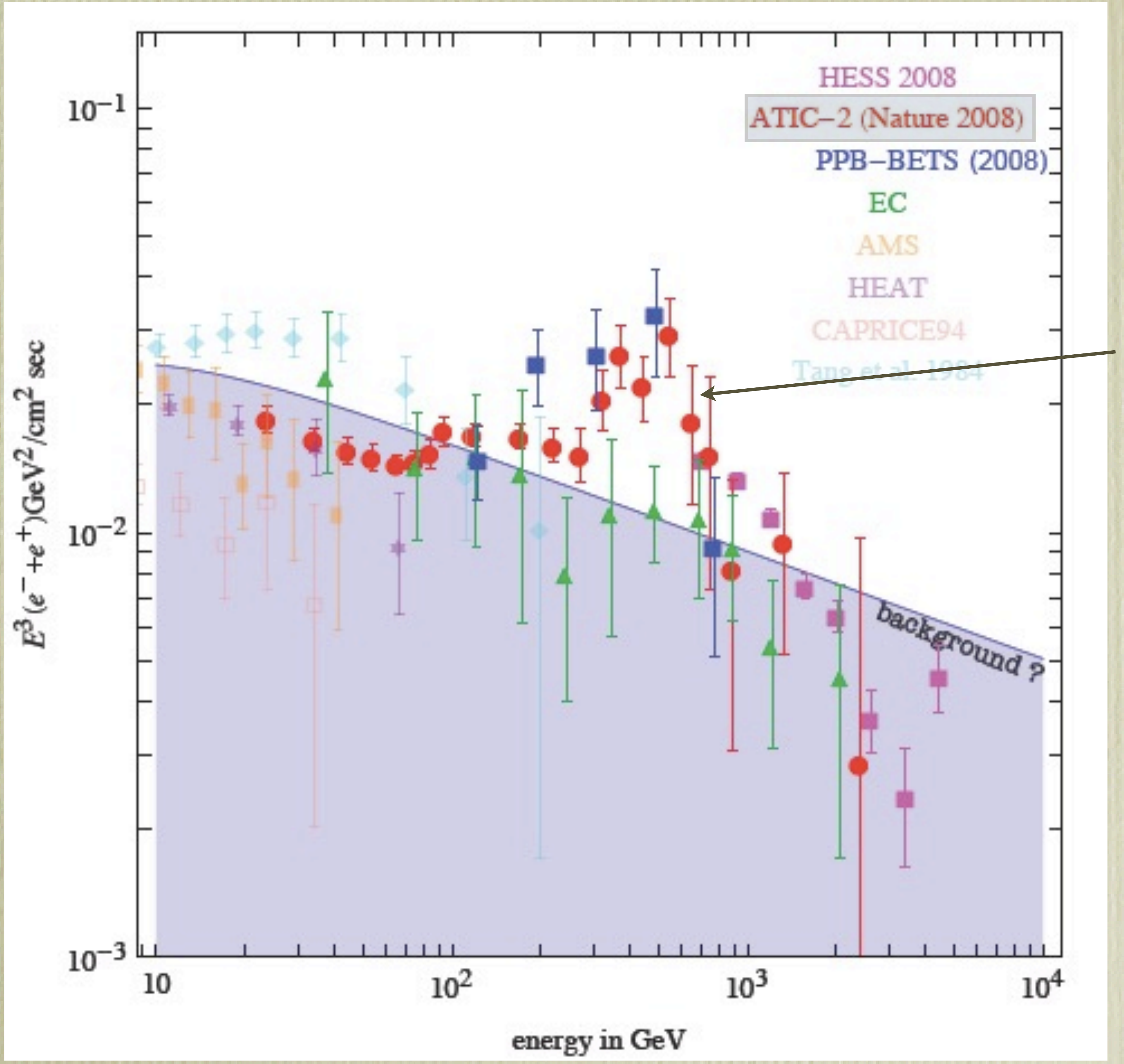


Consistent with the background

(about 1000 $\bar{p}$ collected)

Electrons + positrons from ATIC

It cannot discriminate e^+ and e^-

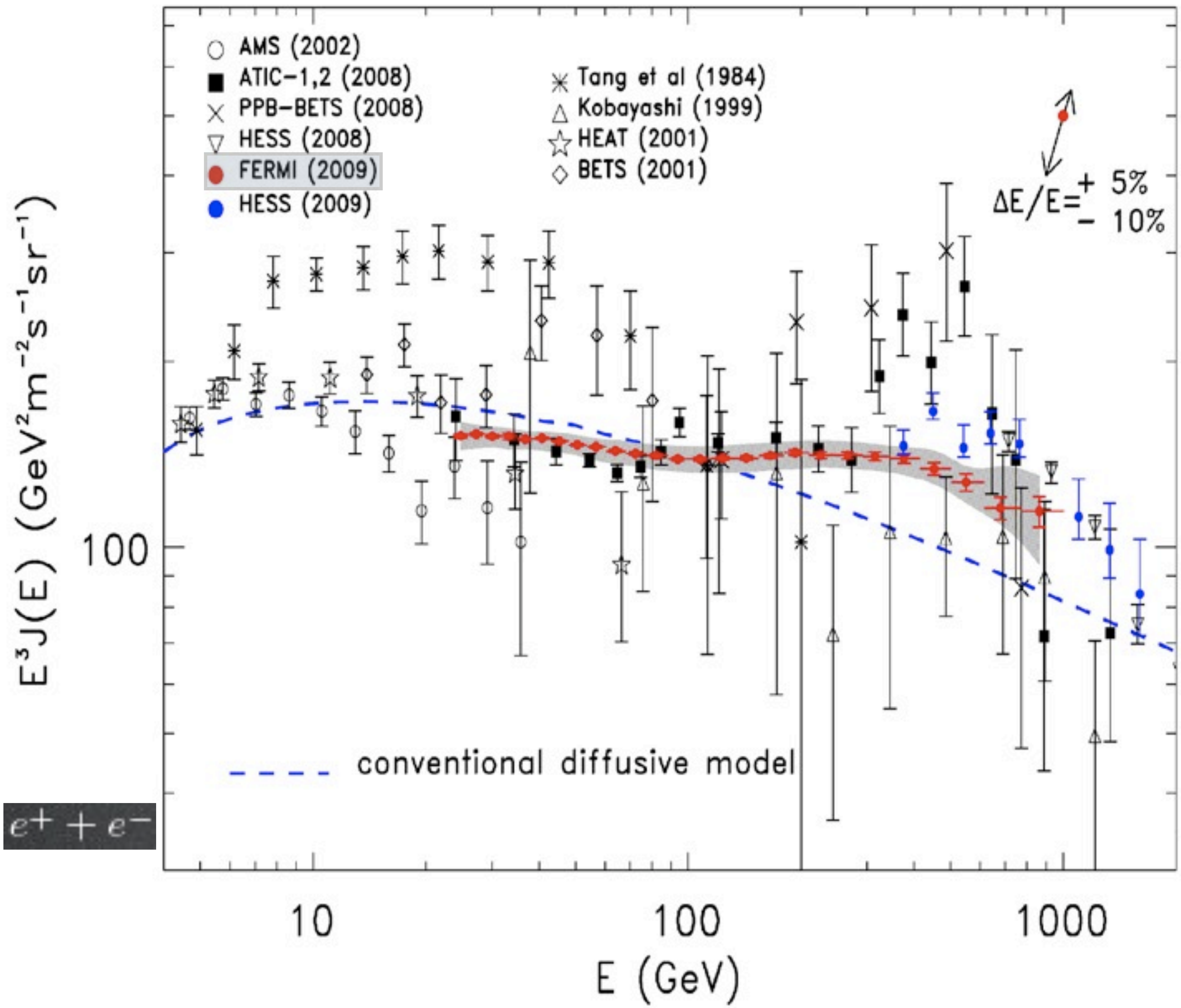


An e^++e^- excess 300-800 GeV

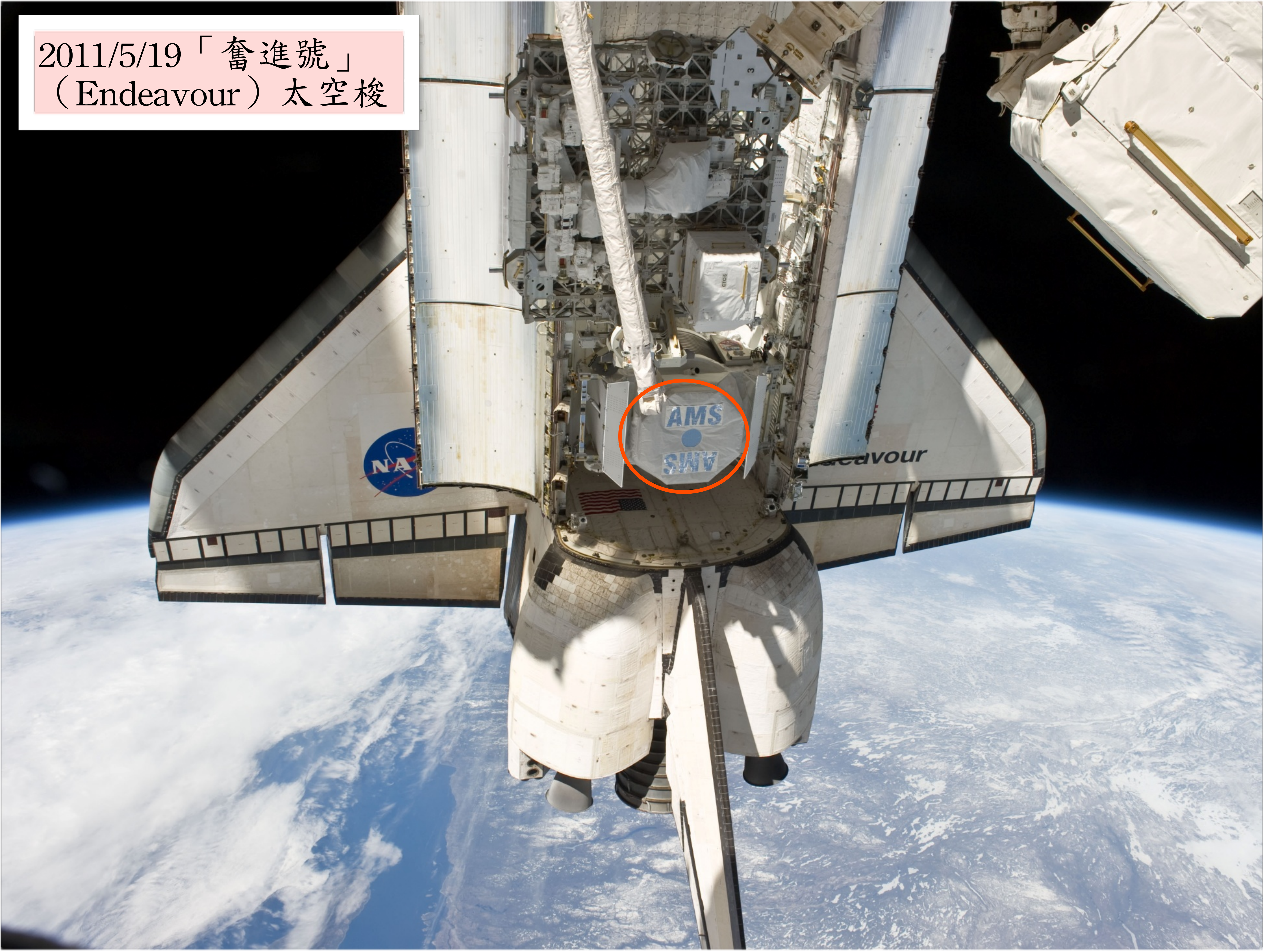
Fermi's result: PRL102(09)181101

It cannot discriminate
e^+ and e^-

arXiv:0905.0025 [astro-ph.HE]



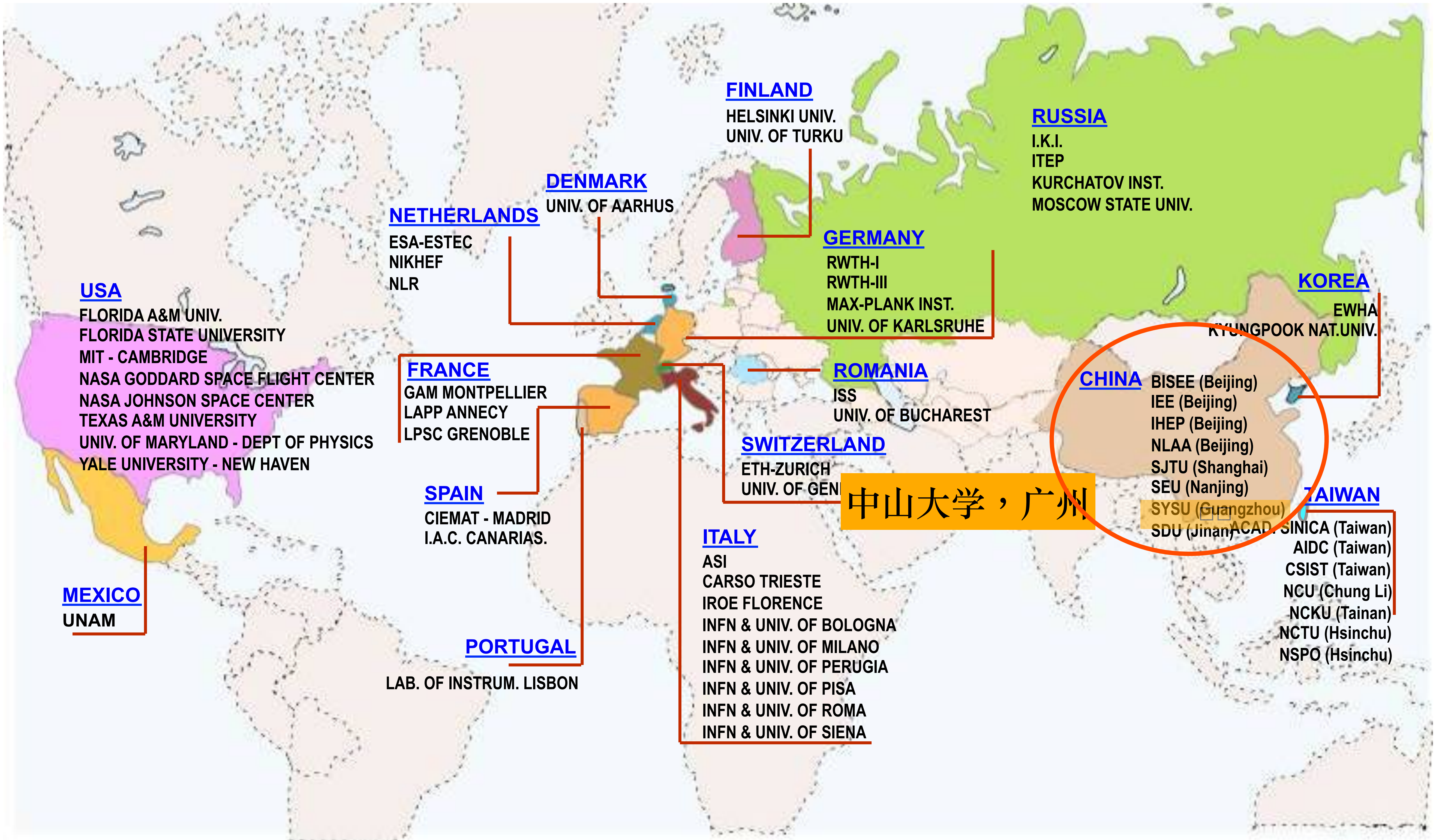
Fermi Data
4 million events
conflict with
ATIC



2011/5/19「奮進號」（Endeavour）太空梭

AMS is an International Collaboration

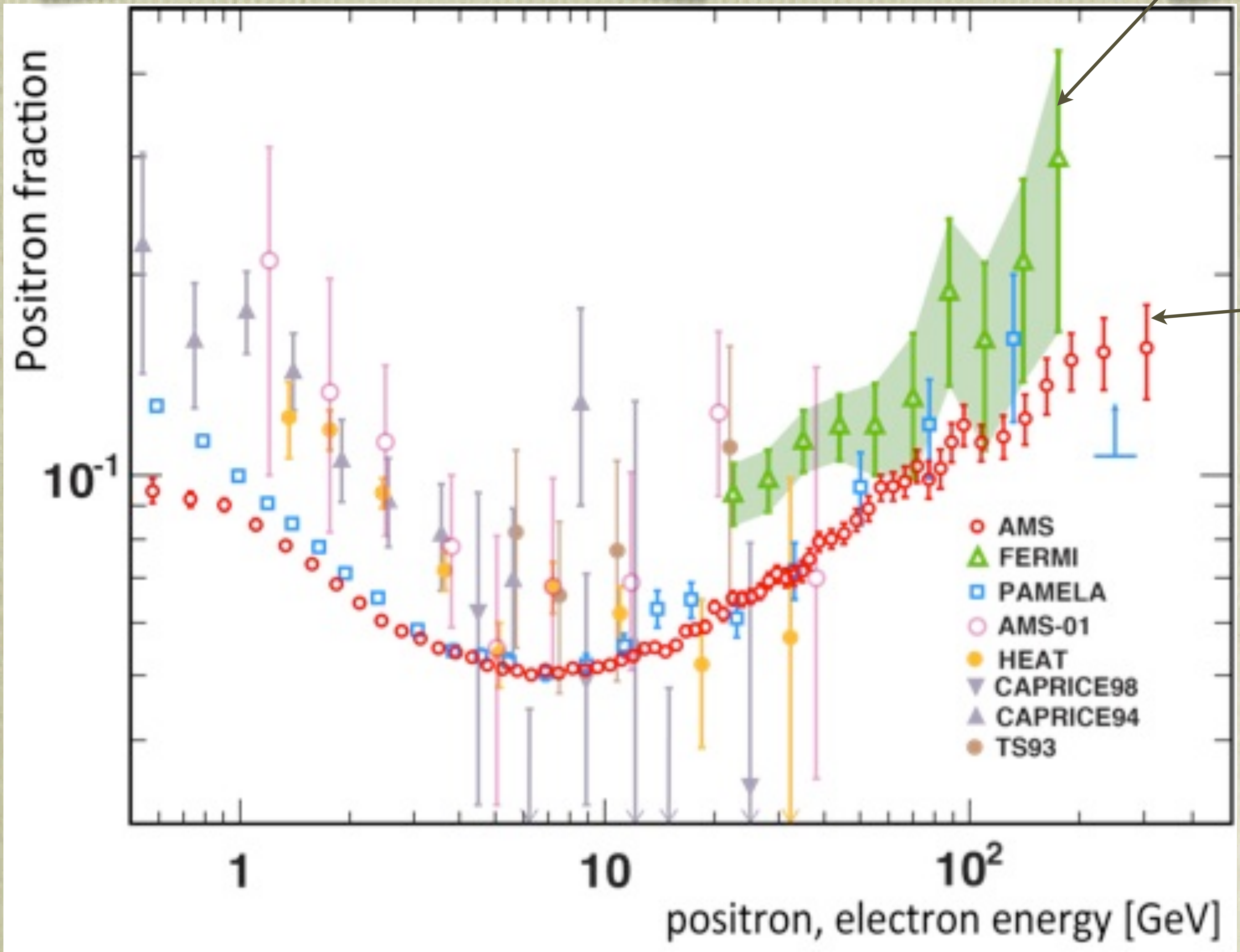
16 Countries, 60 Institutes and 600 Physicists, 17 years



The detectors were built all over the world and assembled at CERN, near Geneva, Switzerland

AMS-02:PRL110,141102(2013)

Fermi with earth Mag.F.
PRL108,011103(2002)



AMS02
4/3/2013

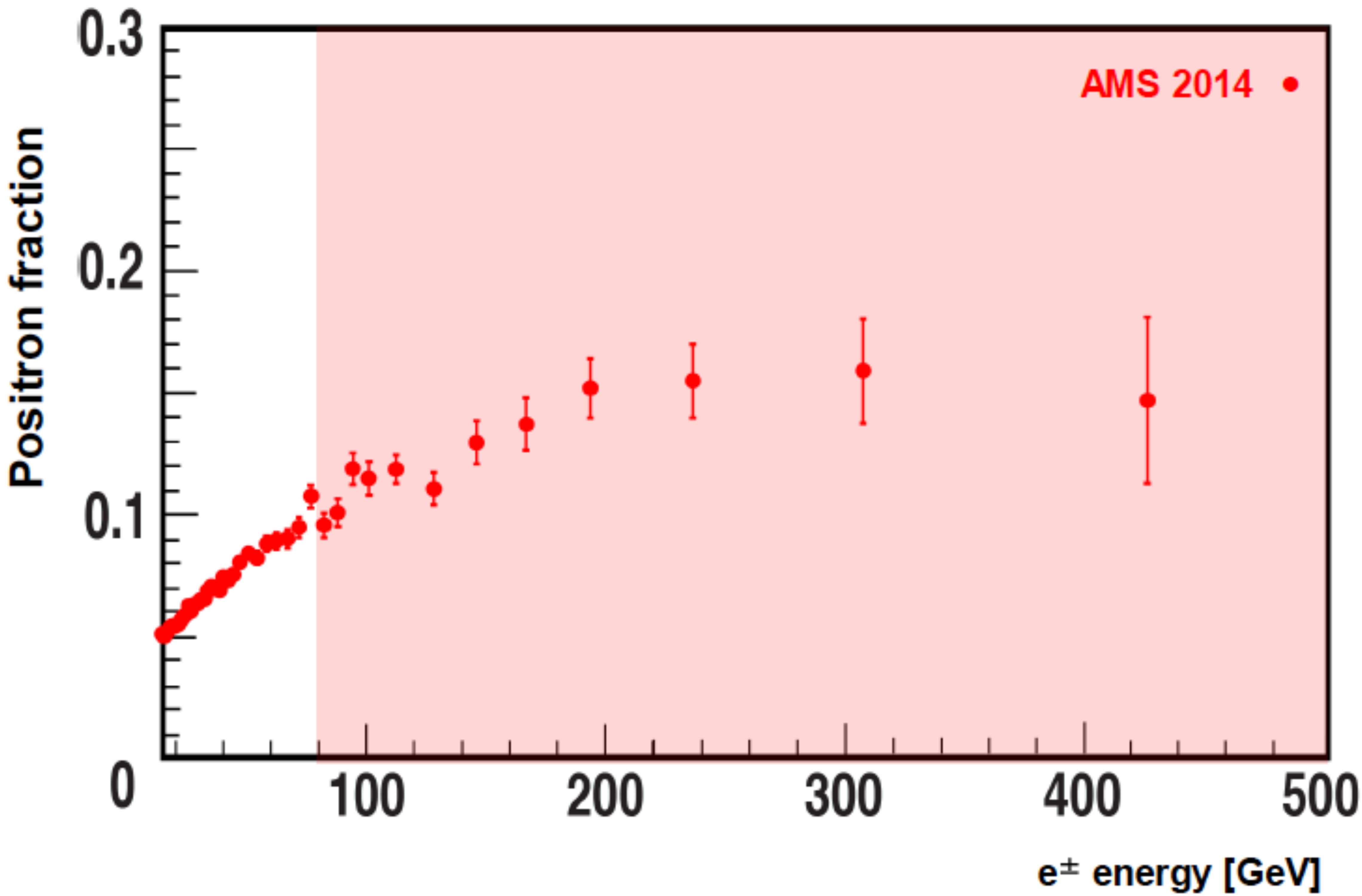
4×10^5 e^+ collected

AMS02 consistent with PAMELA but not Fermi

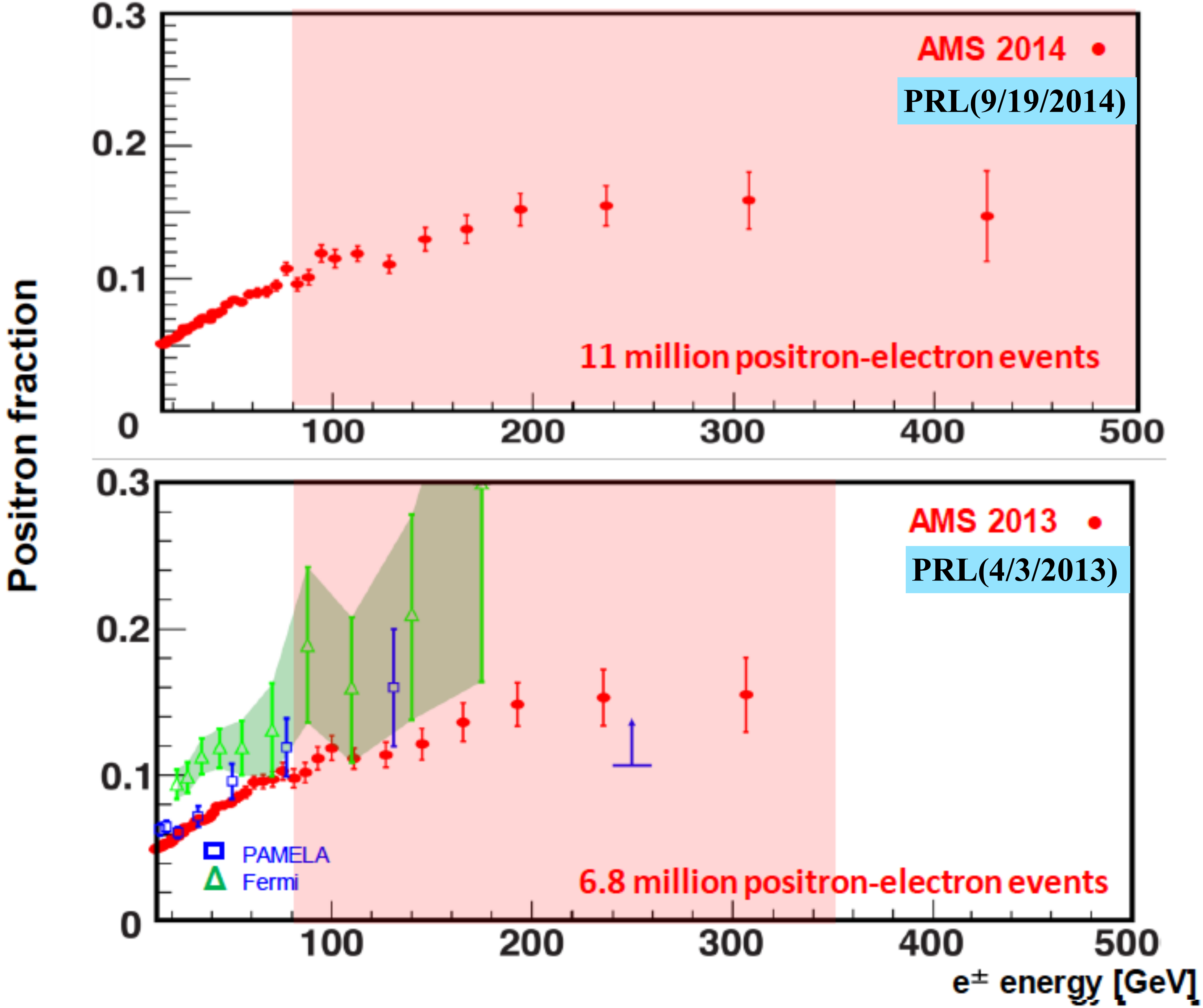
PRL(9/19/2014)

New Results on Positron Fraction

1. At much higher energy (up to 500 GeV)

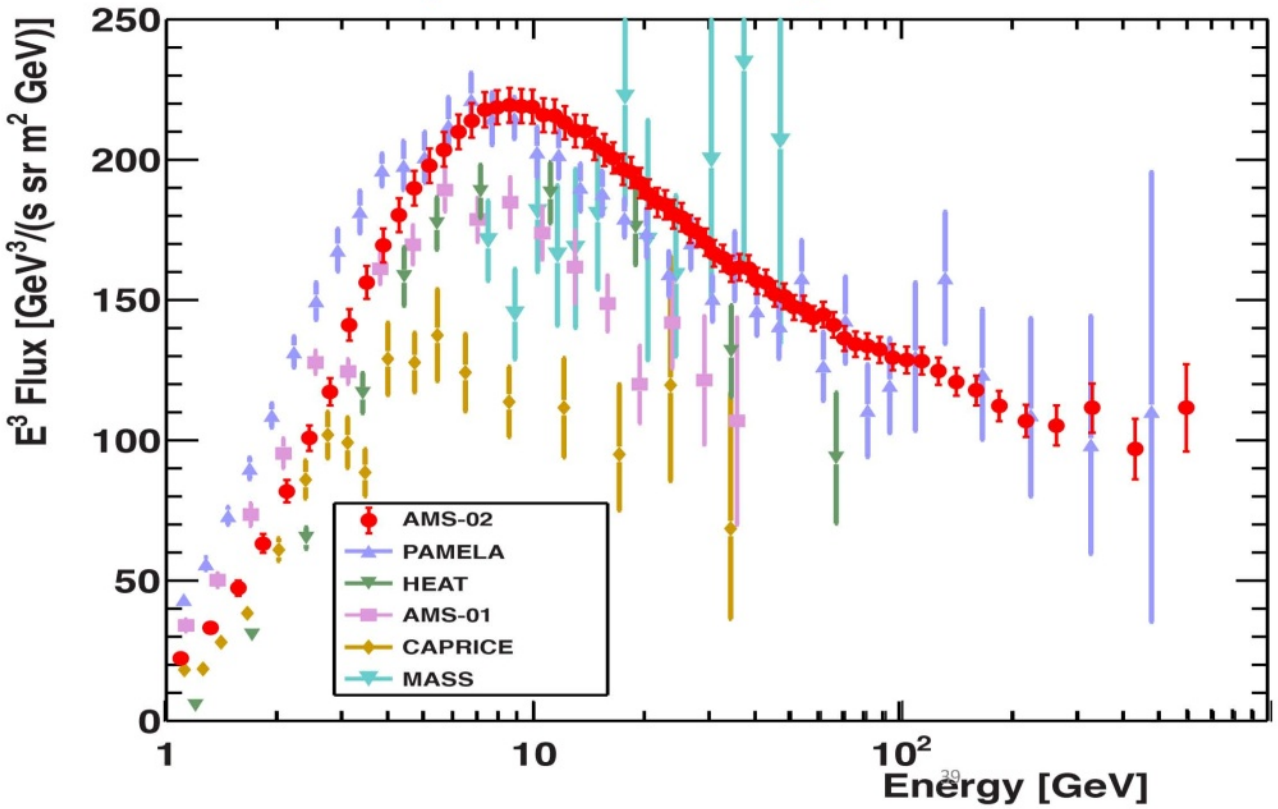


2. With much higher statistics

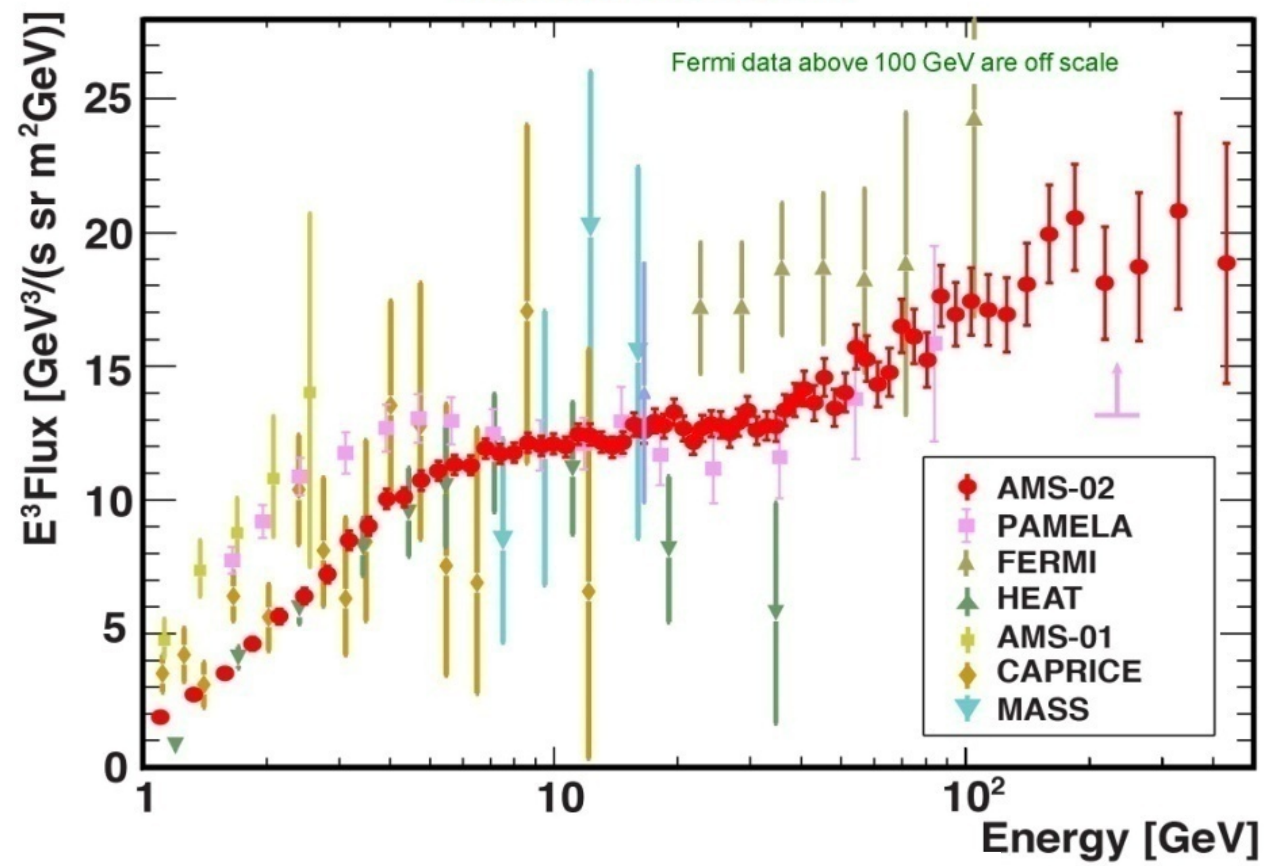


PRL(9/19/2014)

AMS Electron flux measurement
compared with early work



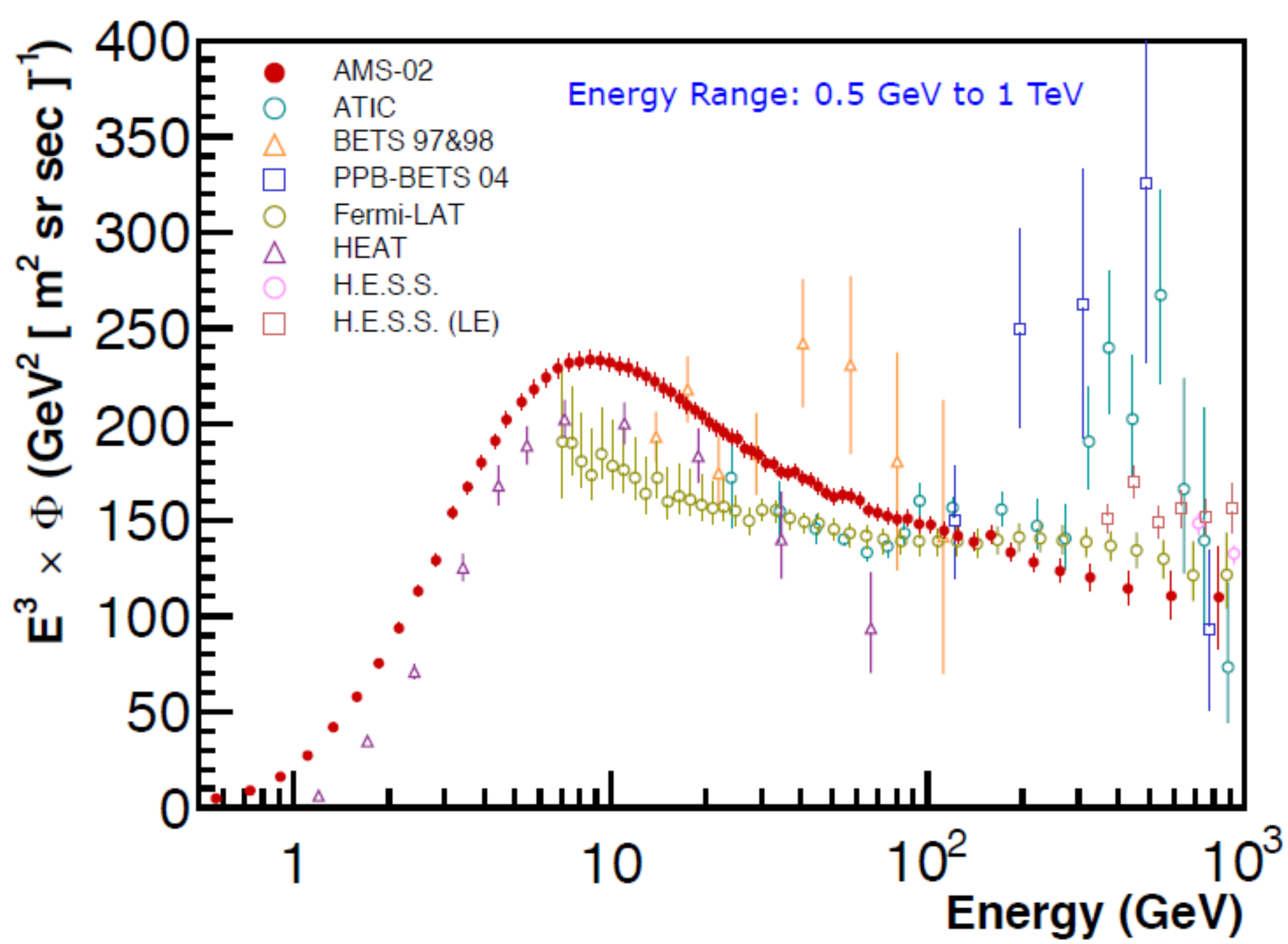
AMS Positron Flux Data
Comparison with early work



Recent Development

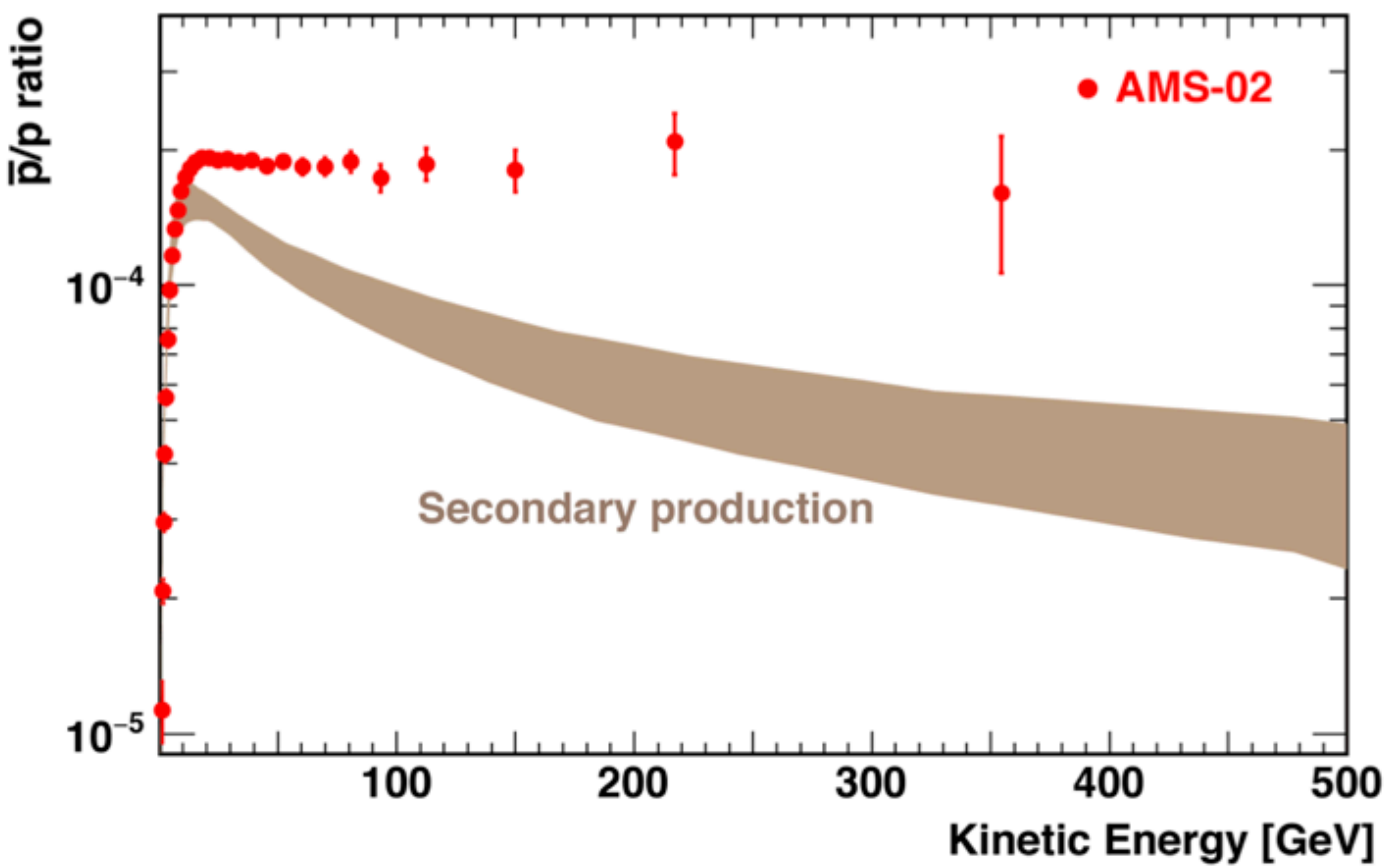
PRL113, 221102 (2014)
Nov. 28, 2014

AMS Results: ($e^+ + e^-$) flux



AMS days at CERN: anti-proton on April 15-17, 2015 (S. Ting)

(AMS-02: 290,000 antiprotons selected)

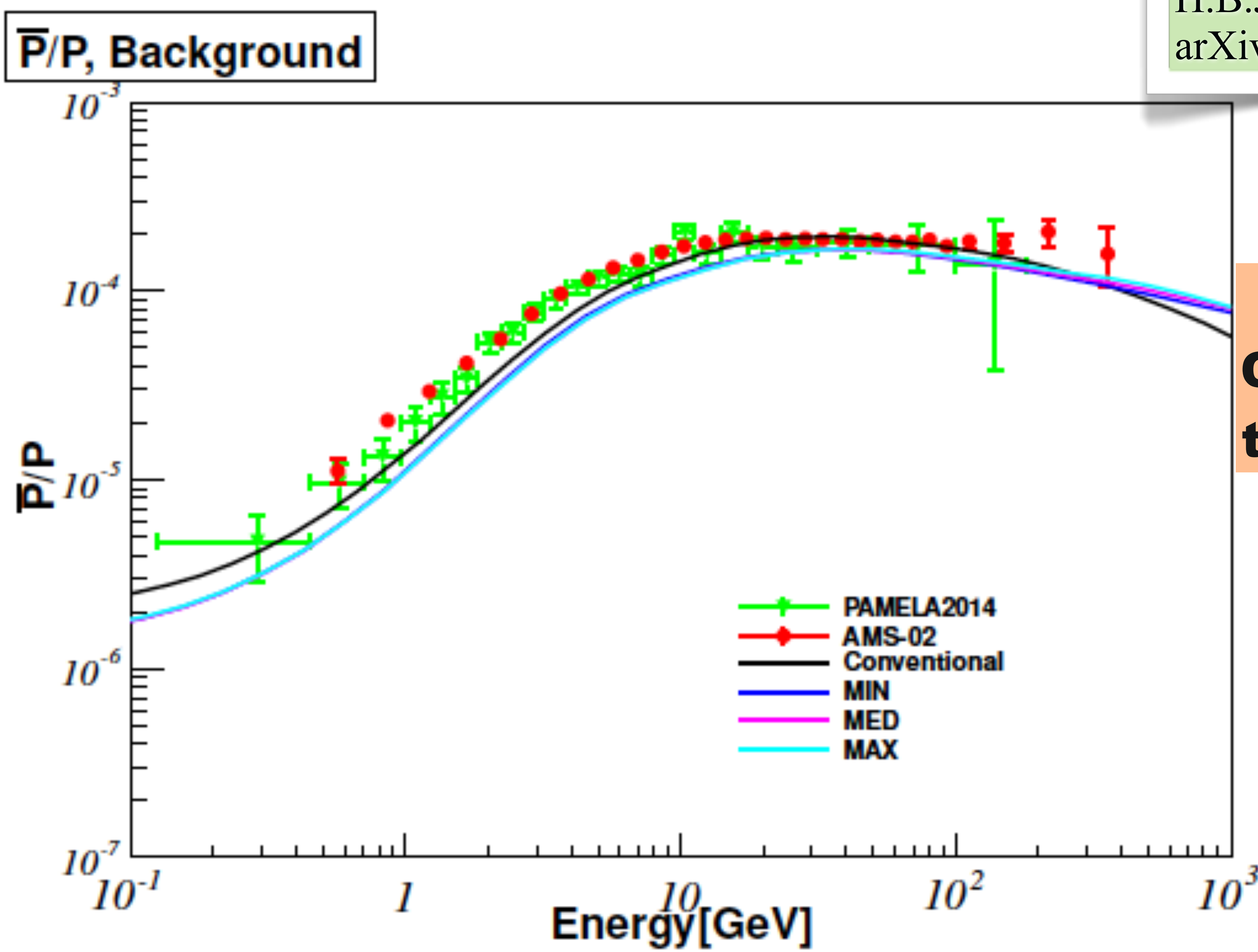


PRL117 (2016) 091103 (Aug. 26, 2016)

AMS days at CERN: anti-proton on April 15-17, 2015 (S. Ting)

(AMS-02: 290,000 antiprotons selected)

H.B.Jin, Y.L.Wu, Y.F.Zhou
arXiv:1404.04604 [hep-ph]

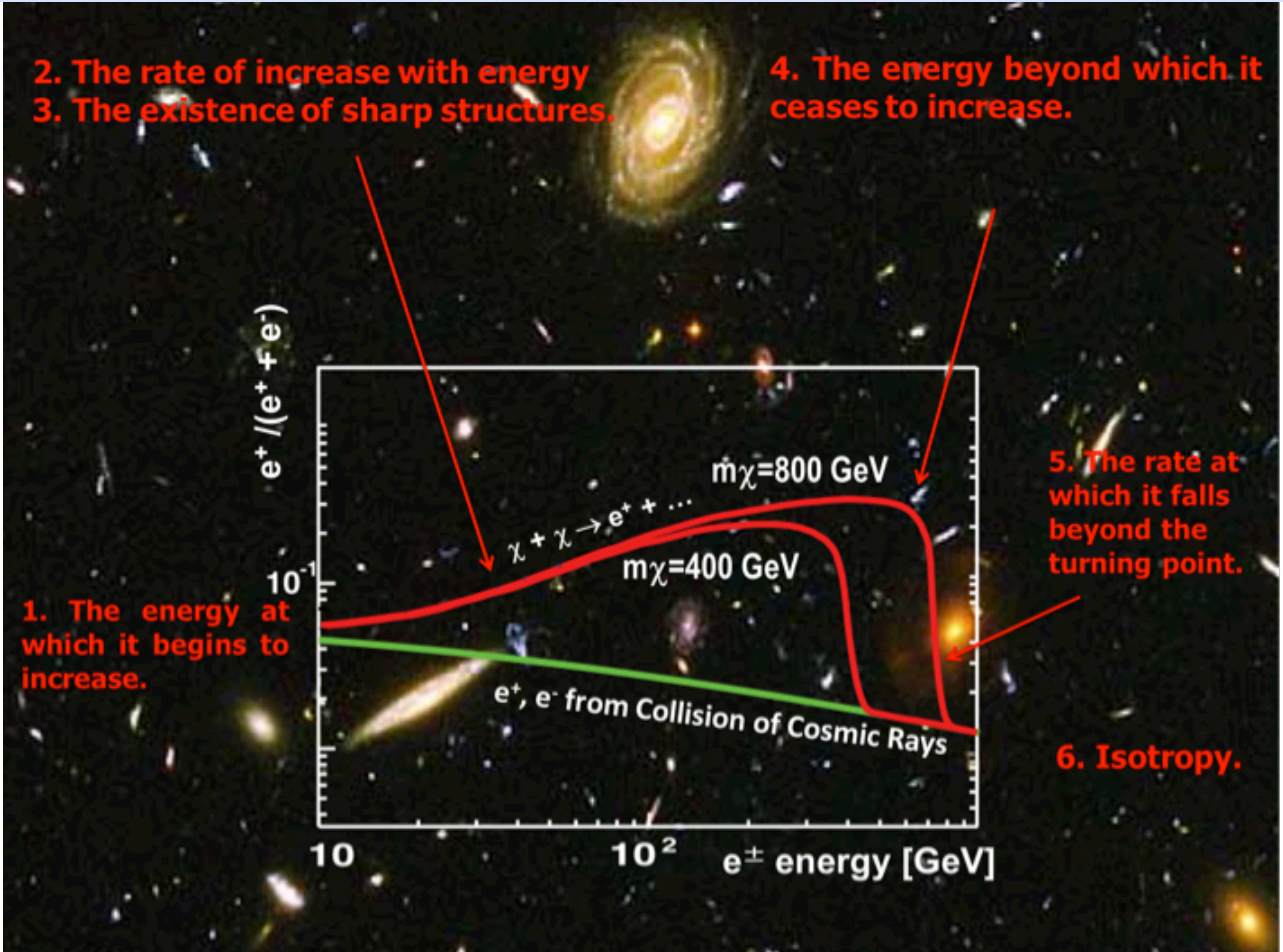


AMS-02 data Consistent with the background

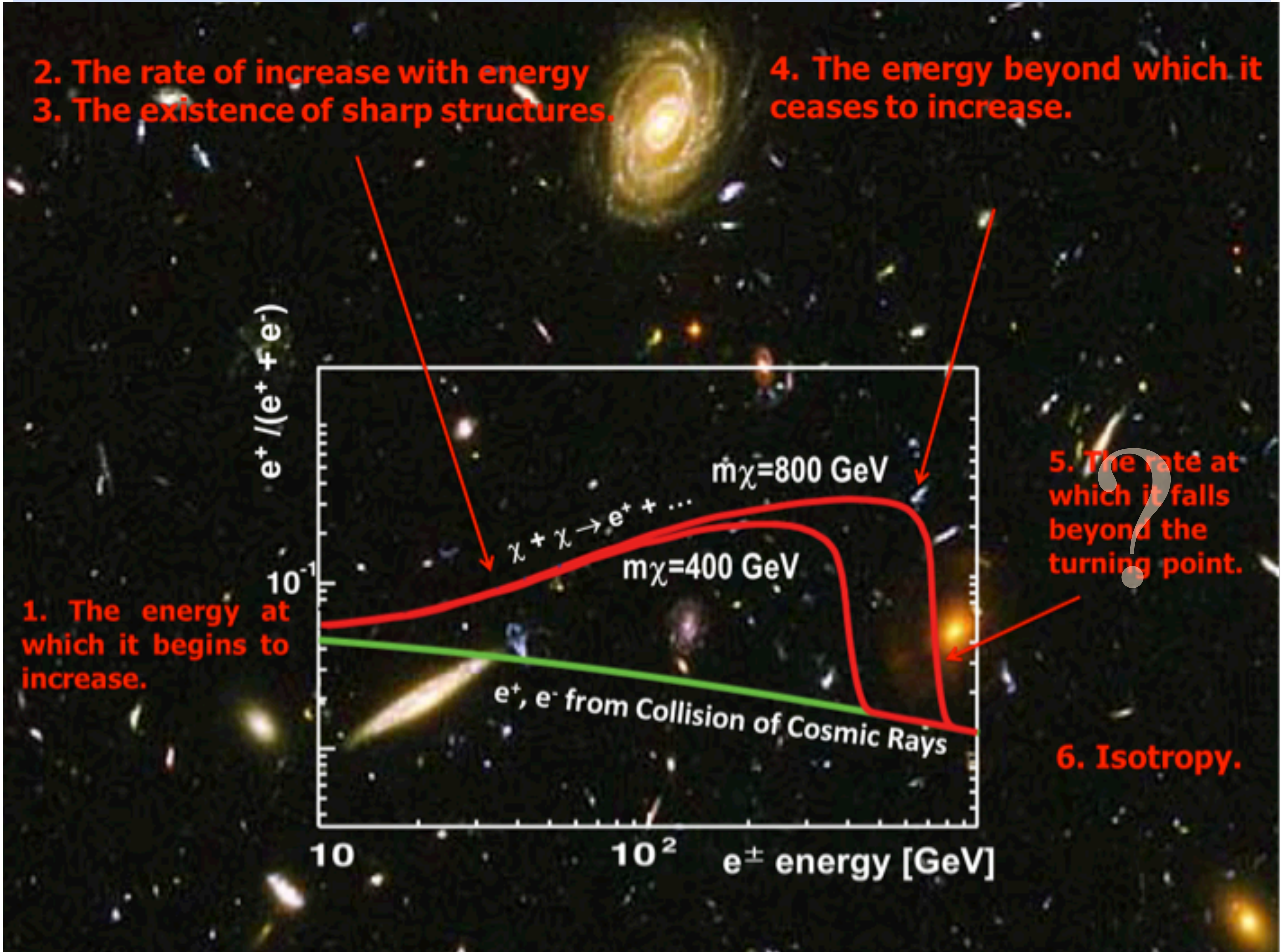
-

PRL117 (2016) 091103 (Aug. 26, 2016)

Six conditions for the evidence of Dark Matter! (S.Ting)

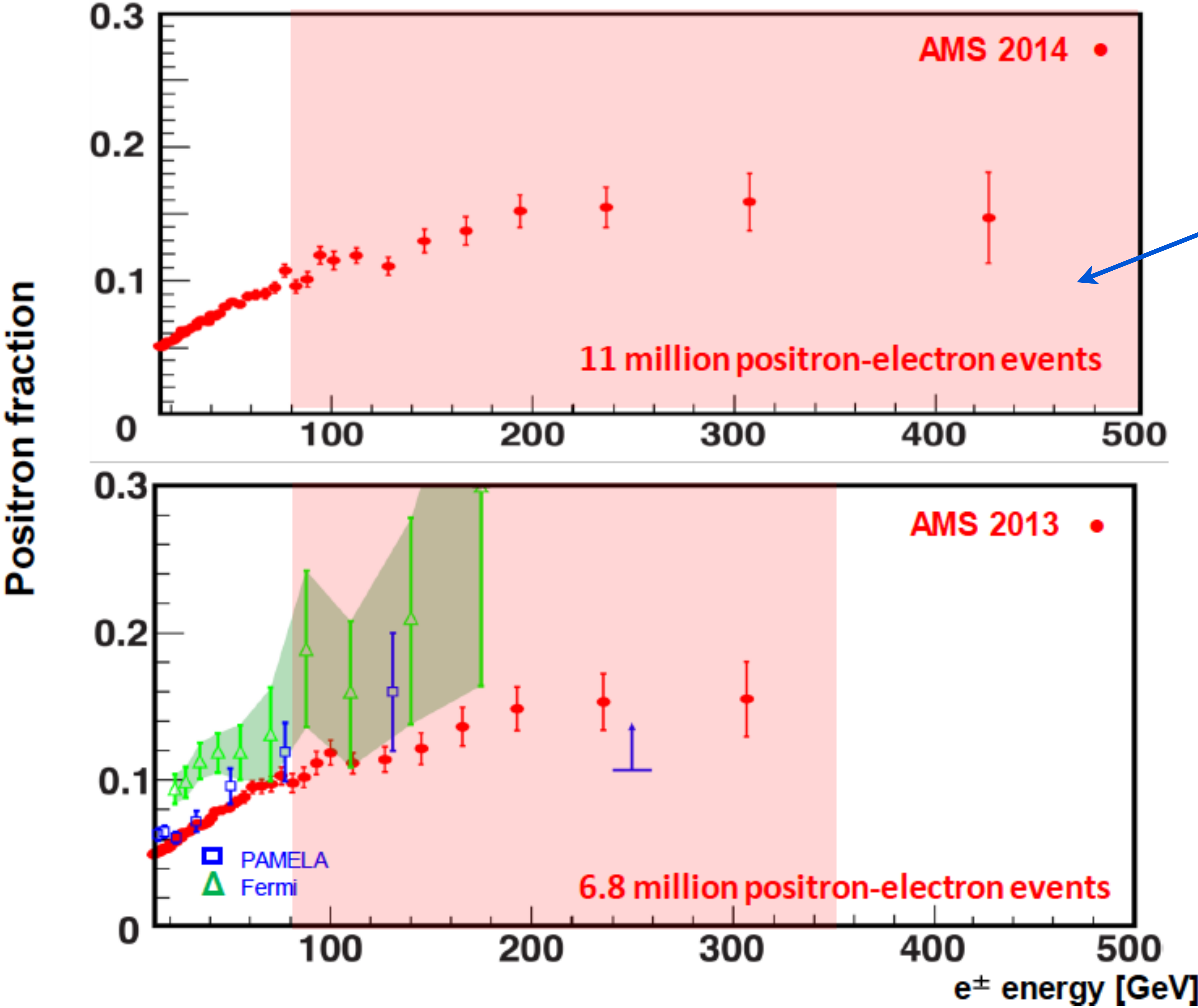


AMS-2: six conditions for Dark Matter *with five seen!*



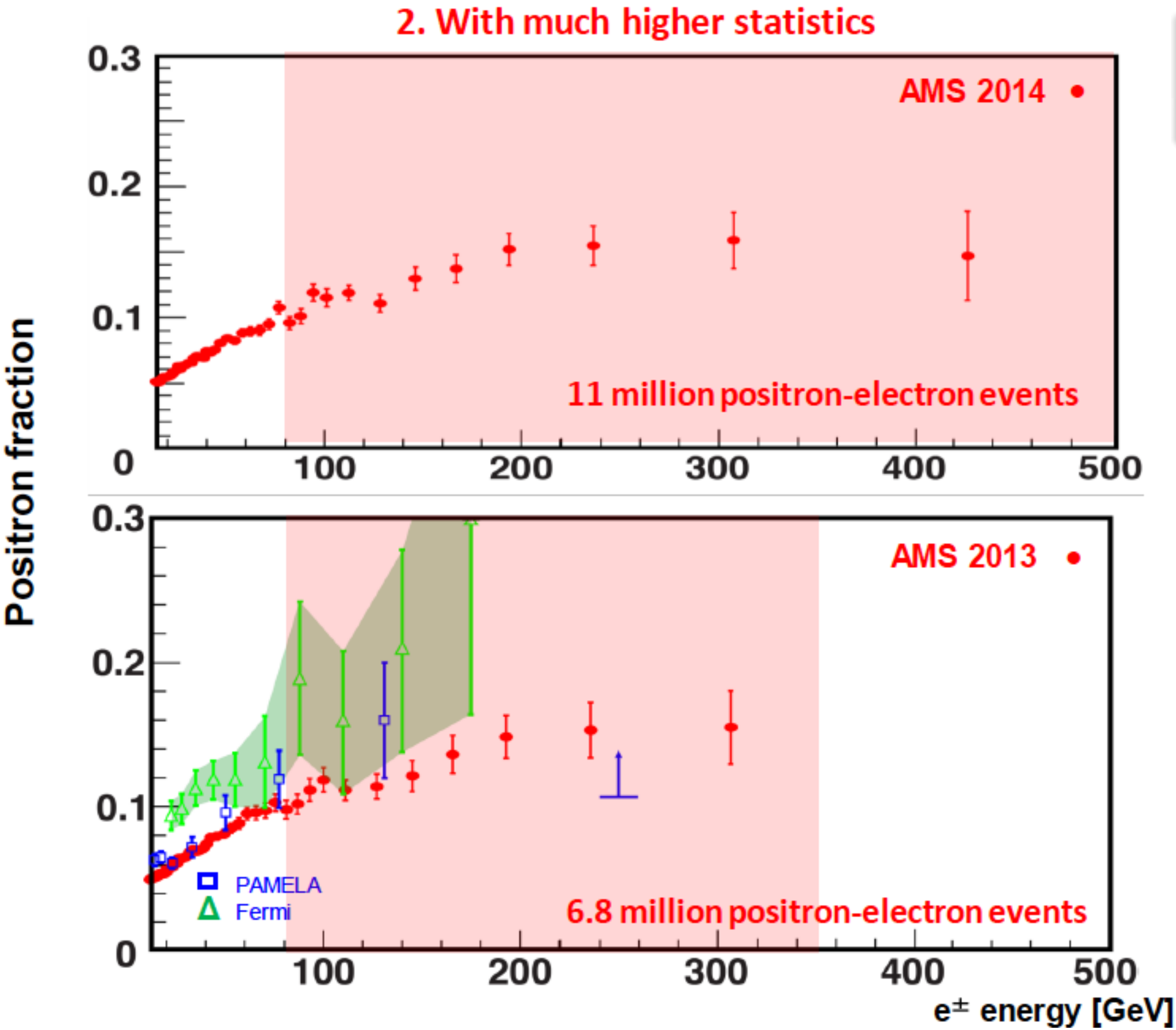
AMS-2: six conditions for Dark Matter with five seen!

2. With much higher statistics



5. The rate at which it falls beyond the turning point.

AMS-2: six conditions for Dark Matter with five seen!



2016

?

It would be observed in 2024!

丁肇中
Talk at CERN on Dec. 8, 2016

中國
``悟空”衛星

Possible interpretations: e^+ and $e^+ + e^-$ excesses

Astrophysics: nearby pulsars ......

Particle physics: Dark Matter (DM)

Dark matter annihilation: DM DM $\longrightarrow$ SM SM

- $0.5\ \text{TeV} < M < 1\ \text{TeV}$
- $<\sigma v> \sim 10^{-26}\ \text{cm}^3\text{s}^{-1} \sim 10^{-9}\ \text{GeV}^{-2}$
- $\text{BF} \sim 10^2 - 10^4$

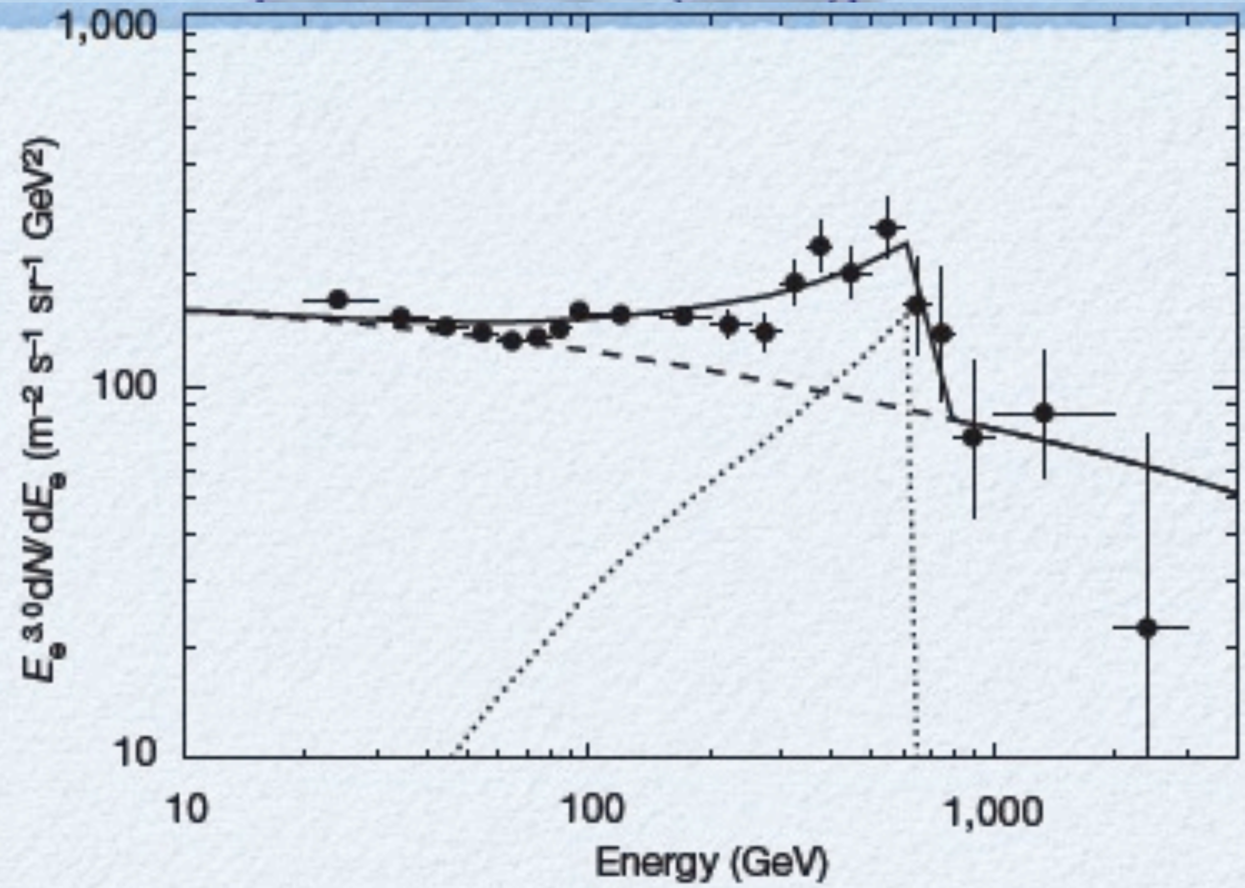
Dark matter decay: DM $\longrightarrow$ 2 or 3 SMs

$M \geq 1\ \text{TeV},\ \tau \geq 10^{26}\ \text{s}$

Note: the age of the universe (4.3×10^{17} s).

ATIC Energy Spectrum vs. KK Dark Matter

[Nature 07477 (2008)]



這篇文章的第一作者也是``悟空"衛星計畫的首席科學家

Figure 4 | Assuming an annihilation signature of Kaluza–Klein dark matter, all the data can be reproduced. The GALPROP general electron spectrum resulting from sources across the galaxy is shown as the dashed line. The dotted curve represents the propagated electrons from the annihilation of a Kaluza–Klein particle. The dotted curve assumes an isothermal dark matter halo of 4-kpc scale height, a local dark matter density of 0.3 GeV cm^{-3}, a Kaluza–Klein mass of 620 GeV, and an annihilation cross section rate of 1×10^{-25} cm^3 s^{-1}, which implies a boost factor of ~200. The sum of these signals is the solid curve. Here the spectrum is multiplied by $E^{3.0}$ for clarity. The solid curve provides a good fit to both the magnetic spectrometer data[30,31] and calorimeter data[16,32] and reproduces all of the measurements from 20 GeV to 2 TeV, including the cut-off in the observed excess. All error bars are one standard deviation.

a Kaluza-Klein mass of 620 GeV

Which DM can fit the data?

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - Yin, Yuan, Liu, Zhang, Bi, Zhu, 0811.0176: Leptonically decaying DM - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - K.Hamaguchi, E.Nakamura, S.Shirai, T.T.Yanagida, 0811.0737: Decaying DM in Composite Messenger - E.Ponton, L.Randall, 0811.1029: Singlet DM - A.Ibarra, D.Tran, 0811.1555: Decaying DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.3357: Decaying Hidden-Gauge-Boson DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - E.Nardi, F.Sannino, A.Strumia, 0811.4153: Decaying DM in TechniColor - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075: Decaying DM in GUTs - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM- S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split-UED DM - .Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - C.-H.Chen, C.-Q.Geng, D.Zhuridov, 0901.2681: Fermionic decaying DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - Goh, Hall, Kumar, 0902.0814: Leptonic Higgs - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

Which DM can fit the data?

C.-H.Chen, C.-Q.Geng, D.Zhuridov, 0901.2681: Fermionic decaying DM

Phys.Lett. B675, 77 (2009)

C.H.Chen, C.Q.Geng, D.Zhuridov, JCAP 0910, 001 (2009) [0906.1646 [hep-ph]],
Neutrino Masses, Leptogenesis and Decaying Dark Matter

C.Q.Geng, D.Huang, L.H.Tsai, PRD89, 055021 (2014) [1312.0366 [hep-ph]],
Imprint of Multicomponent Dark Matter on AMS-02

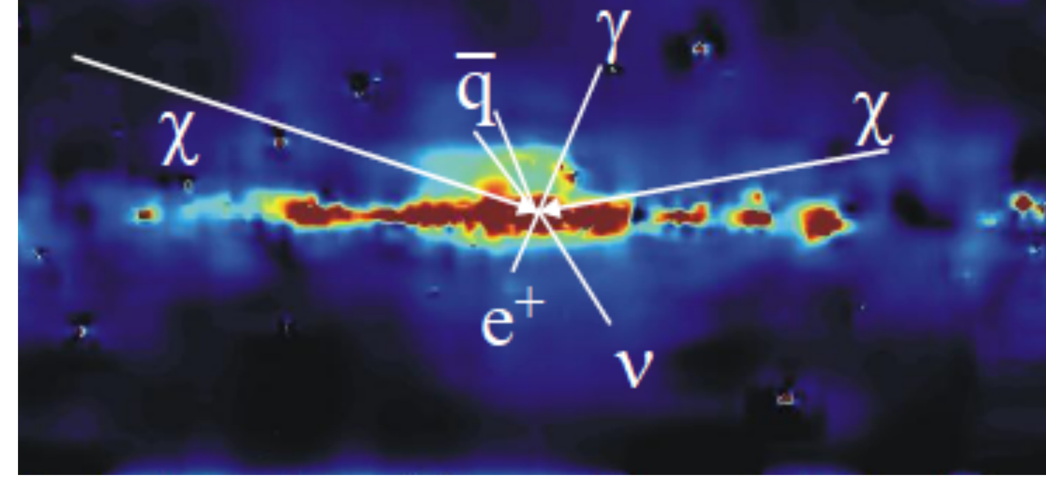
C.Q.Geng, D.Huang, C.Lai, PRD91, (2015) [1411.3813 [astro-ph]],
Revisiting Multicomponent Dark Matter with New AMS-02 Data

The total e^- and e^+ fluxes are:

$$\Phi_{e-} = \kappa\,\Phi_{e-}^{prim} + \Phi_{e-}^{DM} + \Phi_{e-}^{sec}$$

$$\Phi_{e+} = \Phi_{e+}^{DM} + \Phi_{e+}^{sec},$$

κ: the uncertainty in primary e^- normalization



Background:

Supernova shock and diffuse outward (primary)

$$\Phi_{e-}^{prim}(E) = \frac{0.16E^{-1.1}}{1 + 11E^{0.9} + 3.2E^{2.15}} \quad [\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}]$$

collisions among cosmic ray nuclei and intersellar medium (secondary)

$$\Phi_{e-}^{sec} = \Phi_{e+}^{sec}$$

Secondary $e^-(e^+)$ produced in propagation, modeled by GALPROP

Two-Component Decaying DM

DM source terms:

$$Q(\mathrm{x}) = \frac{\rho(\mathrm{x})}{2}\left[\frac{1}{\tau_1 M_1}\left(\frac{dN}{dE}\right)_1 + \frac{1}{\tau_1 M_2}\left(\frac{dN}{dE}\right)_2\right]$$

e^- (e^+) diffusion eq. and solved numerically by GALPROP

Half Density

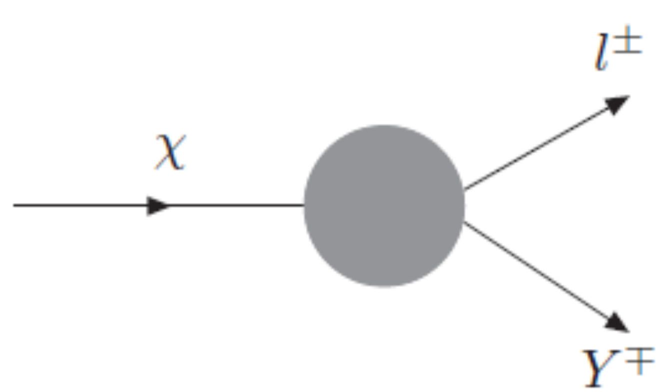
ρ(x): DM density distribution, here we use isothermal profile

τ_i: DM lifetime

M_i: DM Mass

DM decay processes:

model-dependent



Fermionic Decaying DM model:

C.H.Chen, C.Q.Geng, D.Zhuridov, PLB675(09)77 [0901.2681 [hep-ph]]

New Particles: 1 scalar doublet η; 2 neutral leptons N_k + SM ← A minimal model

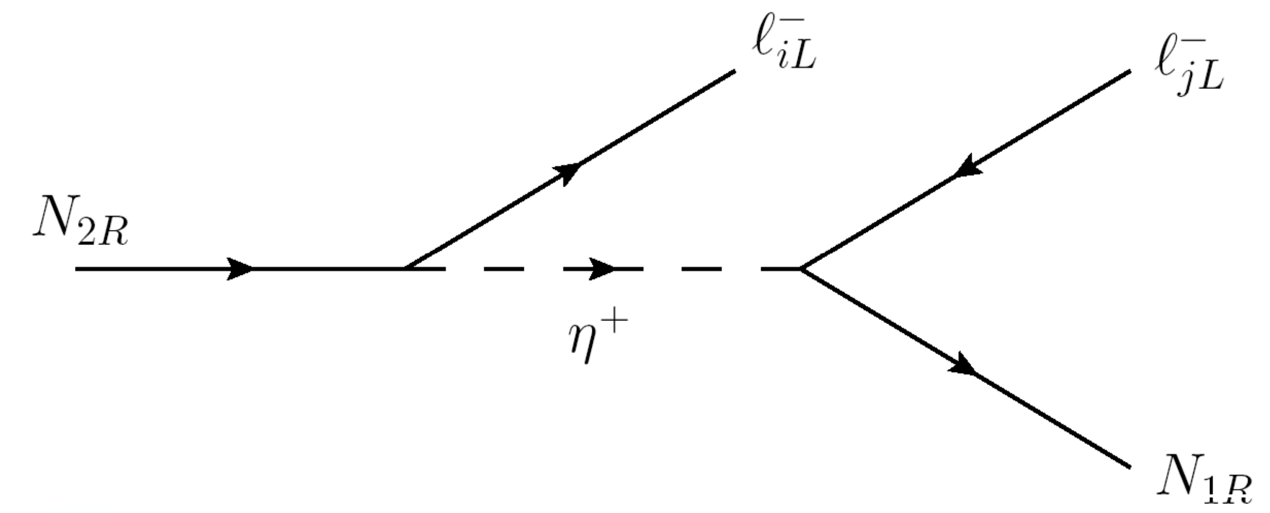
New particles are odd under Z_2 symmetry

The new Majorana mass term and Yukawa couplings can be written as

$$M_k N_k N_k + y_{ik} \bar{L}_i \eta N_k + \text{H.c.},$$

where L is the lepton doublet and i, k are the flavor indexes. We consider the mass spectrum $M_1 < M_2 < M_\eta$.

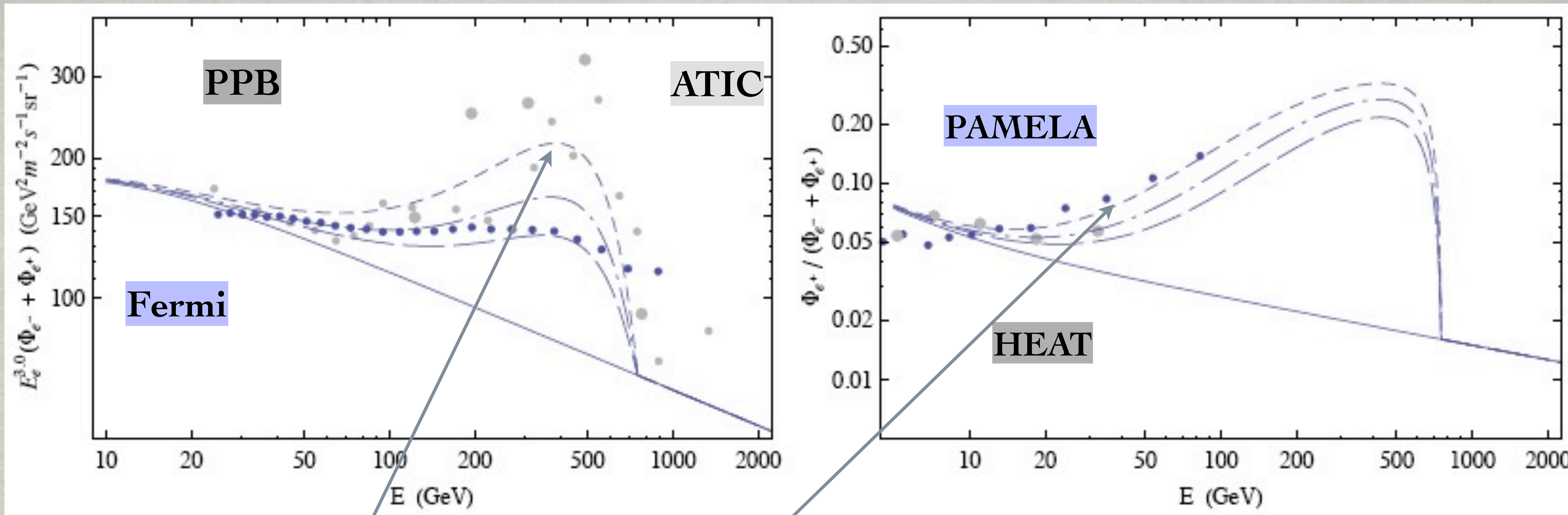
3-body DM decays:



$$\tau_{N_2} \simeq \frac{1}{\Gamma(N_2 \to N_1 \ell_i^\pm \ell_j^\mp)} = \frac{512(2\pi)^3}{5} \frac{M^4 M_2^3}{(M_{21}^2)^4},$$

where $M_{21}^2 = M_2^2 - M_1^2$ is the DM lepton mass splitting and $M \equiv M_\eta / y$ with $y \equiv |y_{ik}|$.

$$\frac{dN_e}{dE} = \frac{96 M_2^3}{(M_{21}^2)^4} \left[(M_{21}^2) E^2 - 2 M_2 E^3 \right]$$



$\tau_2 \sim 10^{26}\text{s}, \ M_1 = 10 \text{ GeV}, \ M_2 = 1.5 \text{ TeV}$

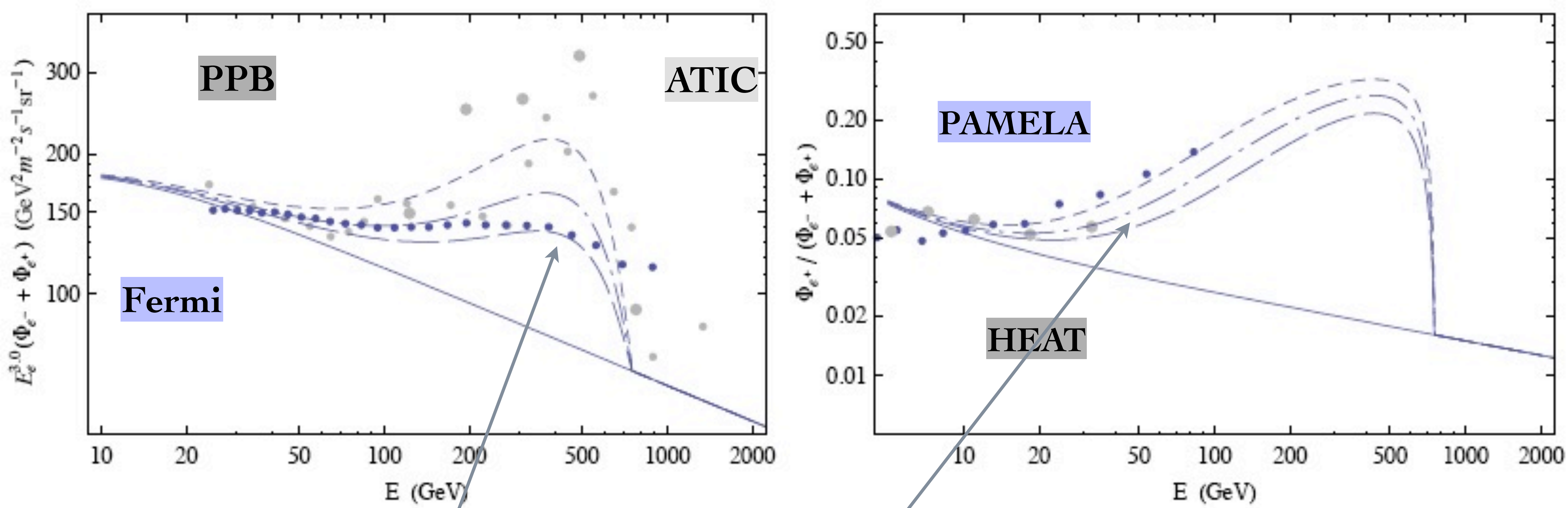
MED propagation

- - - - - - - $M = 4 \times 10^{15}$ GeV

— · — · — · — $M = 4.5 \times 10^{15}$ GeV

— — — — — — $M = 5 \times 10^{15}$ GeV

☞ **ATIC and PAMELA can be fitted well simultaneously**



$\tau_2 \sim 10^{26}\mathrm{s},\ M_1 = 10\ \mathrm{GeV},\ M_2 = 1.5\ \mathrm{TeV}$

MED propagation

- - - - - - - $M = 4 \times 10^{15}$ GeV

— · — · — · — $M = 4.5 \times 10^{15}$ GeV

— — — — — — $M = 5 \times 10^{15}$ GeV

☞ **ATIC and PAMELA can be fitted well simultaneously**

BUT Fermi and PAMELA canNOT

A dark matter model with realistic neutrino masses and leptogenesis:

Chen, CQG and Zhuridov, JCAP 10, 001 (2009)
arXiv:0906.1646 [hep-ph]

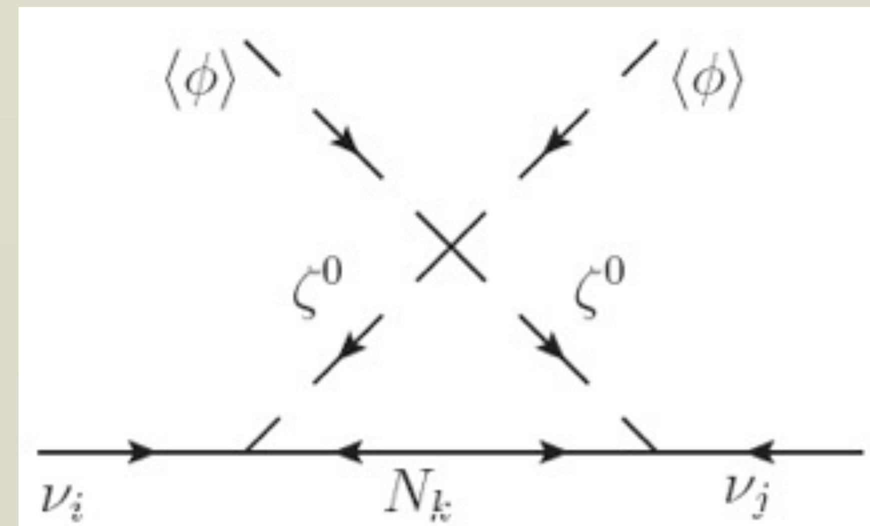
Particle	ζ	η	N_i	N
Z_2	$-$	$+$	$-$	$+$
Z_2'	$+$	$-$	$+$	$-$

+ SM

$$\frac{M_{ij}}{2} N_i^T C N_j + \frac{M}{2} N^T C N + y_{ij} \bar{L}_i \zeta N_j + y_i' \bar{L}_i \eta N + \mu^2 \eta^\dagger \zeta + \frac{\lambda}{2} (\phi^\dagger \zeta)^2 + \text{H.c.} ,$$

Neutrino masses:

$$(m_\nu)_{ij} = \frac{\mathcal{O}(\lambda)}{16\pi^2} \sum_{k=1}^{2} \frac{y_{ik} y_{jk}}{M_k} v^2$$



$$m_\nu = \mathcal{O}(0.01 - 0.1 \text{ eV}) \text{ if } \lambda = \mathcal{O}(10^{-4}),\ y_{ij} = \mathcal{O}(10^{-3})$$

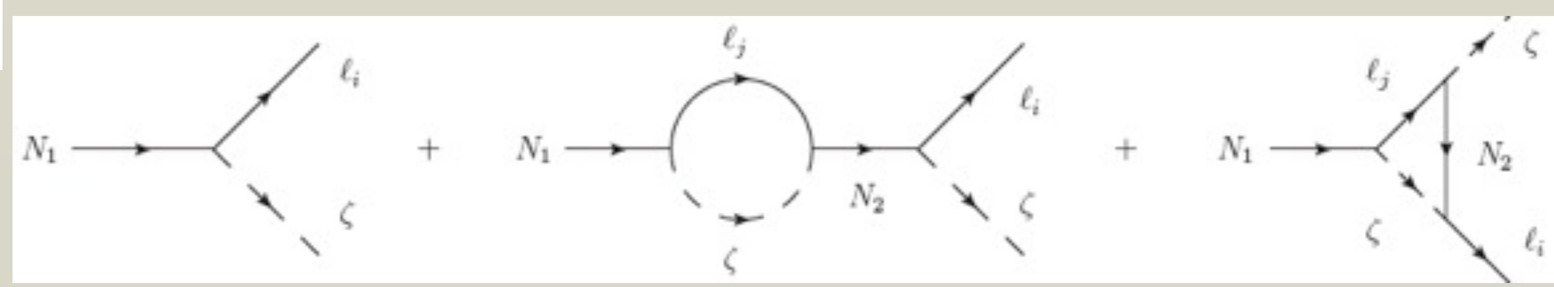
$$M_i = \mathcal{O}(100 \text{ GeV} - 10 \text{ TeV}).$$

Leptogenesis:

$$\varepsilon \simeq -\frac{3}{16\pi} \frac{1}{(y^\dagger y)_{11}} \text{Im} \left[(y^\dagger y)_{12}^2 \right] \frac{M_1}{M_2}.$$

$$\frac{n_B}{s} \simeq -\frac{1}{15} \frac{\varepsilon}{g_*} \simeq 10^{-10}$$

$$g_* \simeq 100$$



DM decays:

$$\Gamma_i = \frac{|y_i'|^2}{4\pi}\left(\frac{|\mu|}{M_\eta}\right)^4 \frac{M_-^2}{M},\qquad \tau_N = \frac{1}{4\sum_i \Gamma_i} = \frac{\pi A^4 M}{M_-^2}$$

$$A = \frac{M_\eta}{|\mu|(\sum_i |y_i'|^2)^{1/4}},\qquad M_\pm = \frac{M^2 \pm M_\zeta^2}{2M},\qquad \varepsilon = |y_\mu'|^2/|y_e'|^2$$

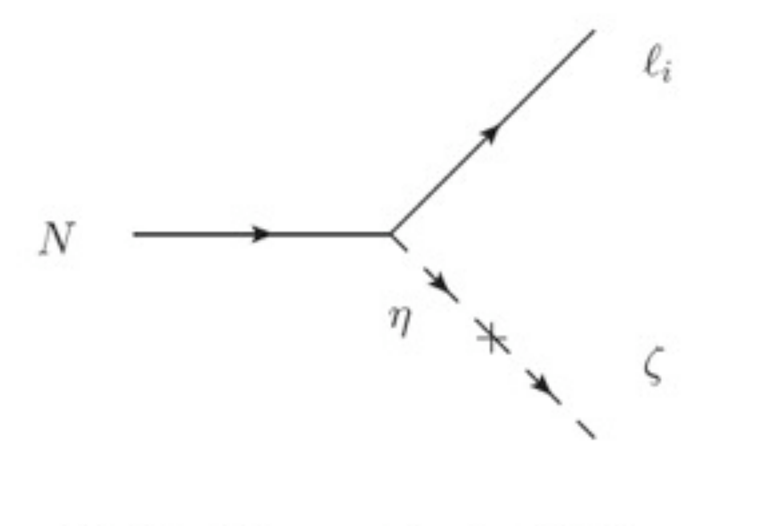
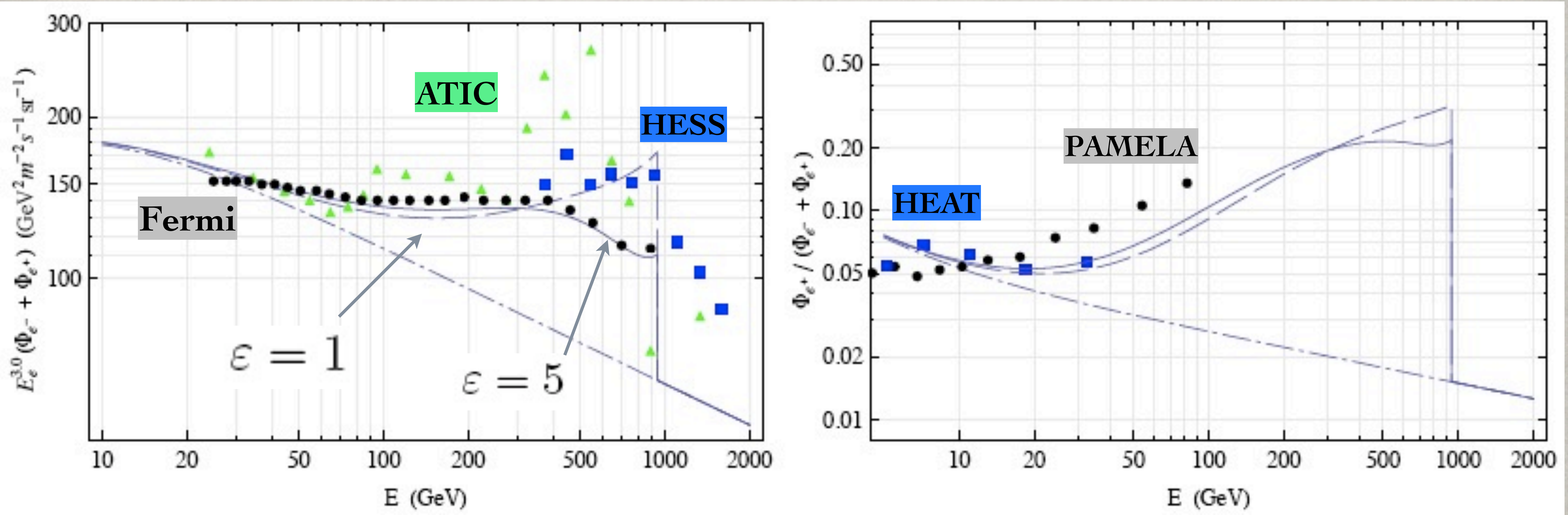


FIG. 3: Diagram for the DM decay.

$$\tau_N = 2.5\times 10^{26}\ \mathrm{s},\ M = 2\ \mathrm{TeV},\ M_\zeta = 500\ \mathrm{GeV}$$

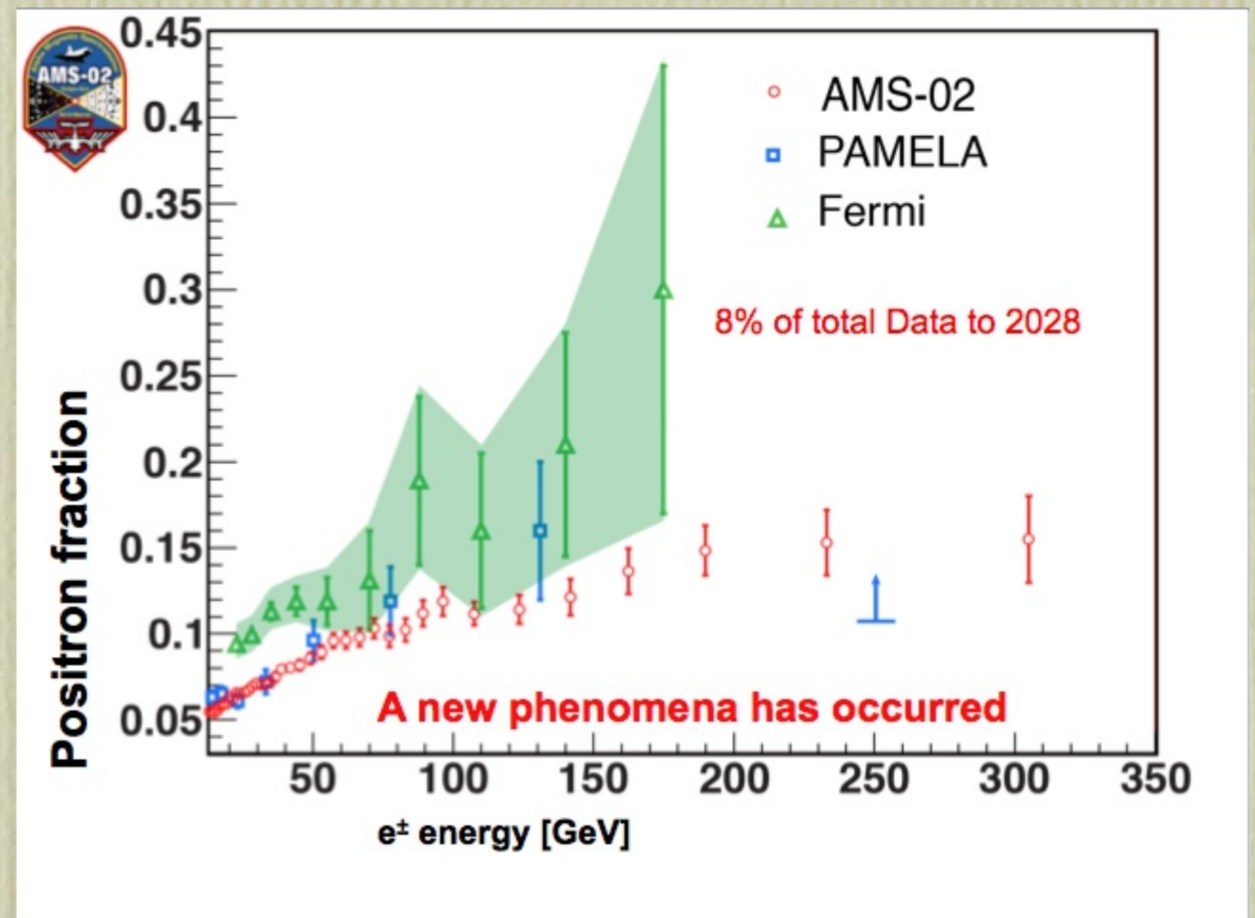


☞ **Fit Fermi and PAMELA well if the muon effect is large**

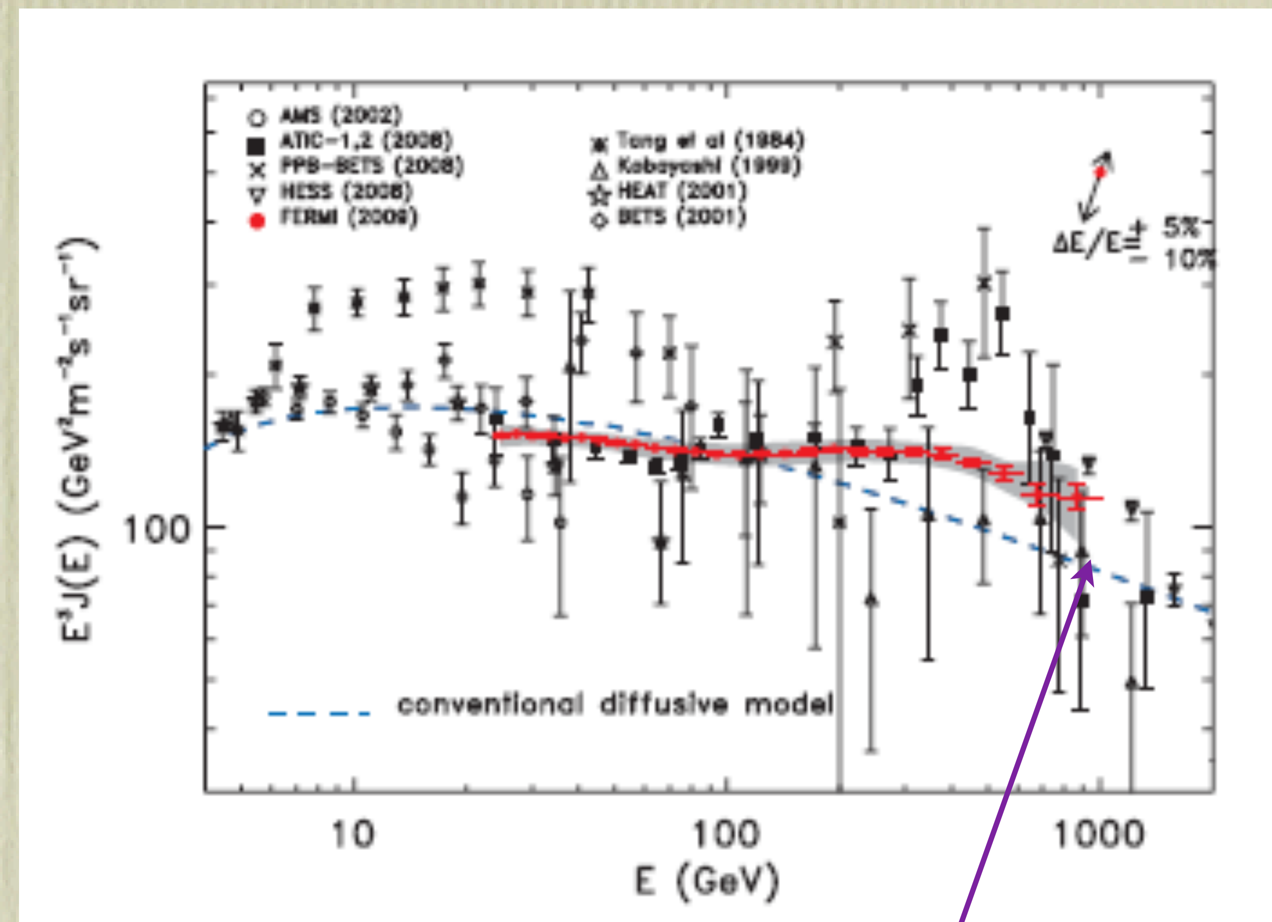
Multi-component Dark Matter

CQG,Huang,Tsai,PRD89(2014)055021
CQG,Huang,Lai, PRD91(2015)095006

AMS-02 Positron Fraction Spectrum



Femi-LAT $e^{+}+e^{-}$ Spectrum



Observations:

1. The excess of total $e^{+}+e^{-}$ flux by Fermi-LAT extends to 1 TeV, at least one DM cutoff should be larger than 1 TeV;

Multi-component Dark Matter

CQG,Huang,Tsai,PRD89(2014)055021
CQG,Huang,Lai, PRD91(2015)095006

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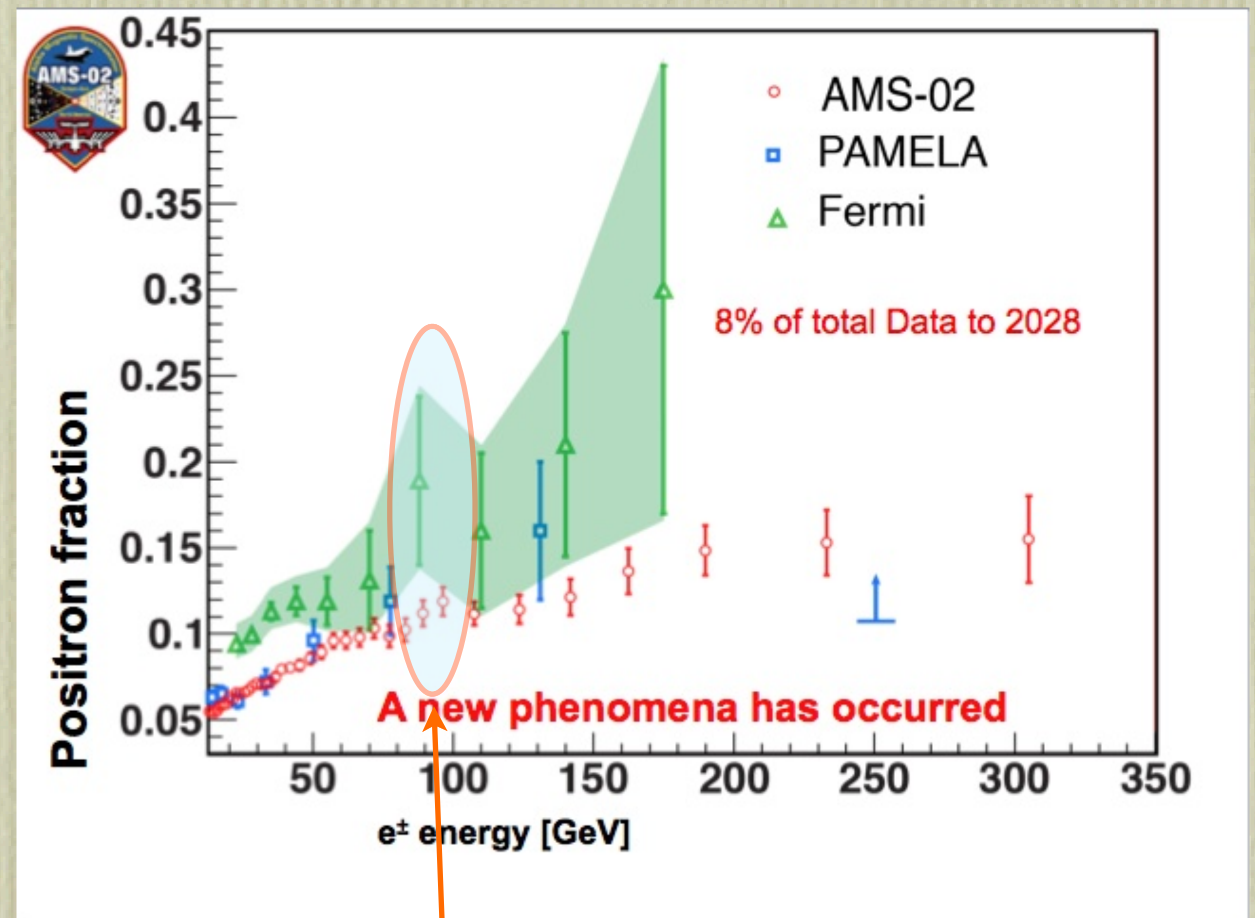
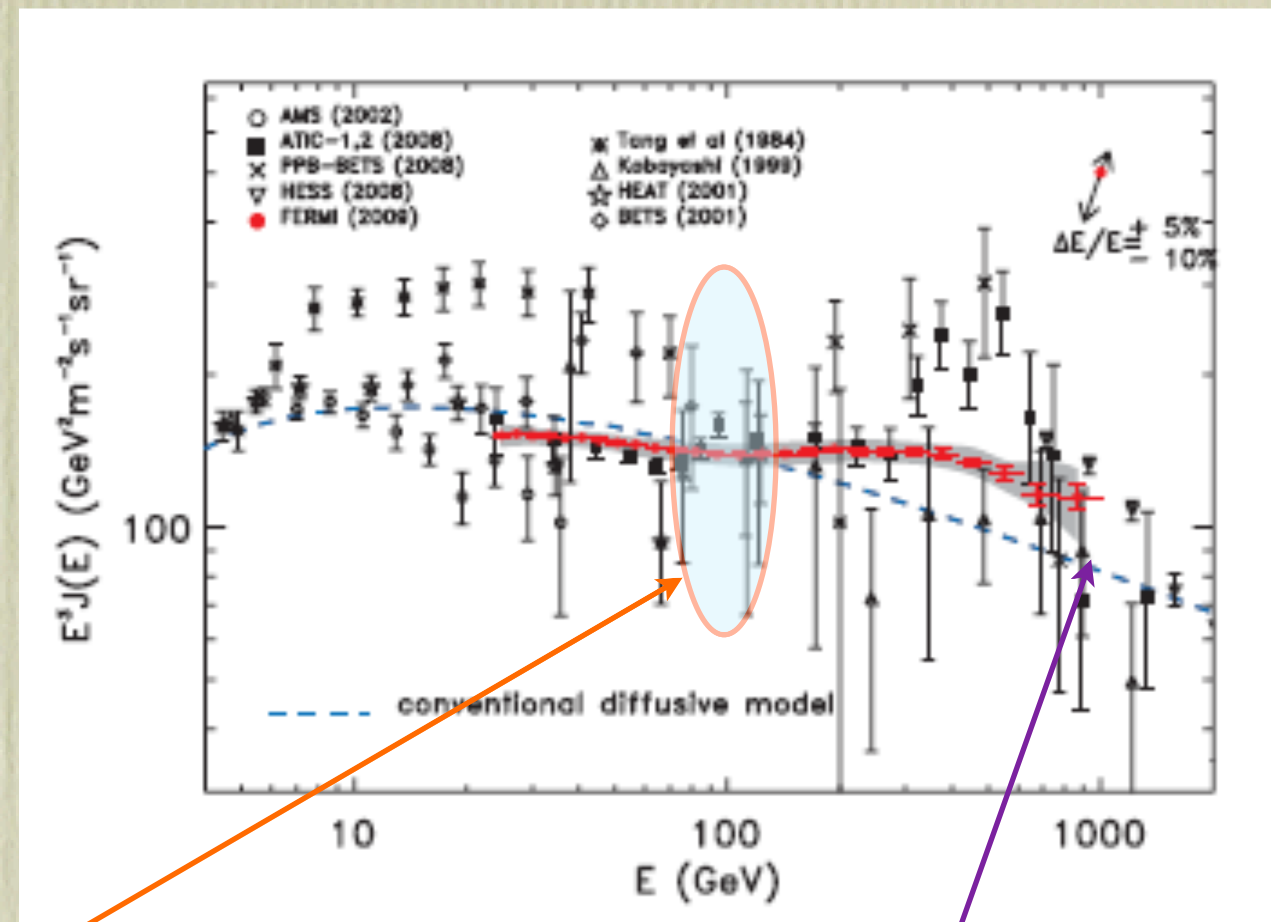


Femi-LAT $e^{+}+e^{-}$ Spectrum



Observations:

1. The excess of total $e^{+}+e^{-}$ flux by Fermi-LAT extends to 1 TeV, at least one DM cutoff should be larger than 1 TeV;

2. The substructure at around 100 GeV could result from some additional lighter DM.

DM with two-body decaying into $e^{\pm}$

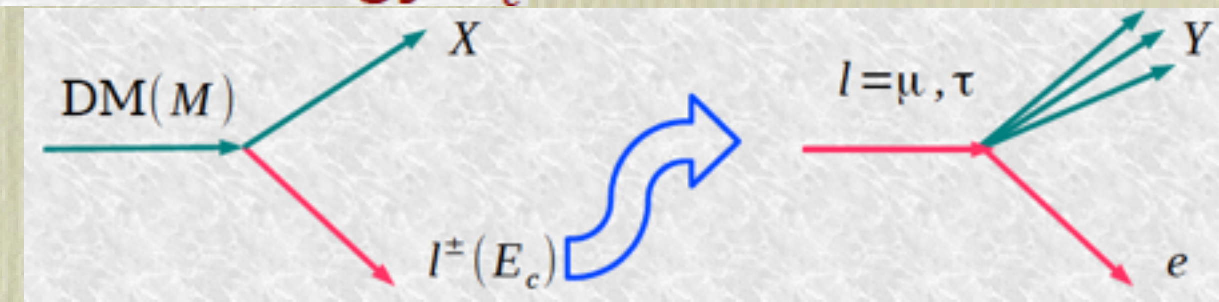
CQG,Huang,Tsai,PRD89(2014)055021

$\mathrm{DM} \rightarrow l^{-}(l^{+}) + X$ with a specific charged leton energy E_c

$$\Phi_e^{tot} = \kappa\, \Phi_e^{primary} + \Phi_e^{secondary} + \Phi_e^{DM}$$

$$\Phi_p^{tot} = \Phi_p^{secondary} + \Phi_p^{DM}$$

electron=e
positron=p



$$\left(\frac{dN_{e,p}}{dE}\right)_i = \frac{1}{2}\left[\epsilon_i^e \left(\frac{dN^e}{dE}\right)_i + \epsilon_i^\mu \left(\frac{dN^\mu}{dE}\right)_i + \epsilon_i^\tau \left(\frac{dN^\tau}{dE}\right)_i\right],$$

$$E_{ci} = \frac{M_i^2 - M_Y^2}{2M_i}$$

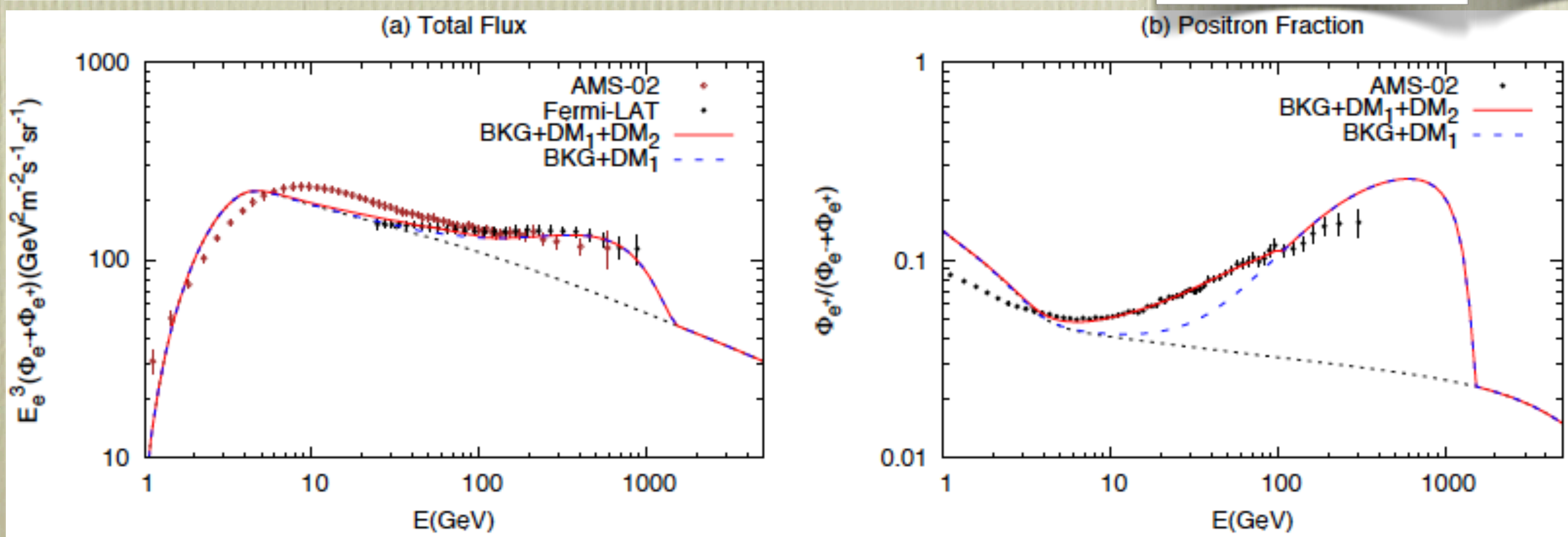
We only open the μ two-body decay for DM_1 and mainly the τ one for DM_2

M_1=3030 GeV, M_2=416 GeV (M_Y=300 GeV); E_{c1}=1500 GeV, E_{c2}=100 GeV

κ	ϵ_H^e	ϵ_H^μ	ϵ_H^τ	$\tau_H(10^{26}\mathrm{s})$	ϵ_L^e	ϵ_L^μ	ϵ_L^τ	$\tau_L(10^{26}\mathrm{s})$	$\chi^2_{\min}$	$\chi^2_{\min}/d.o.f.$
0.844	0	1	0	0.76	0.018	0	0.982	0.82	62.3	1.06

68 data points:
AMS-02: 42
Fermi-LAT: 26

(E > 10 GeV)



CQG,Huang,Tsai,PRD89(2014)055021

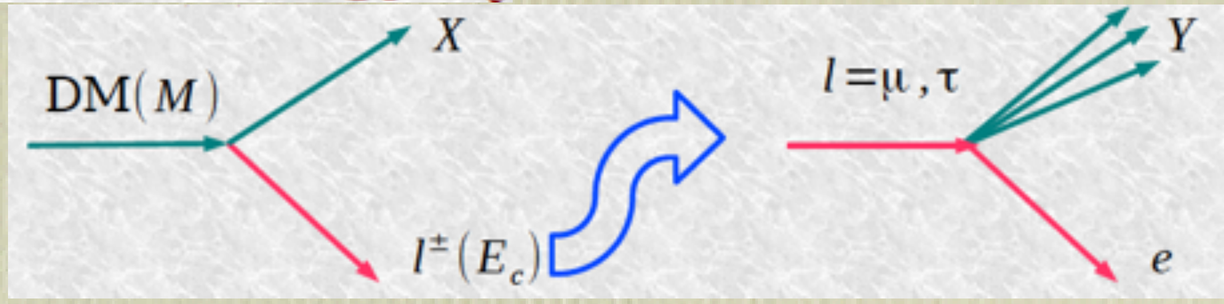
DM with two-body decaying into $e^{\pm}$

DM $\rightarrow l^-(l^+) + X$ with a specific charged leton energy E_c

$$\Phi_e^{tot} = \kappa\,\Phi_e^{primary} + \Phi_e^{secondary} + \Phi_e^{DM}$$

$$\Phi_p^{tot} = \Phi_p^{secondary} + \Phi_p^{DM}$$

electron=e
positron=p



$$\left(\frac{dN_{e,p}}{dE}\right)_i = \frac{1}{2}\left[\epsilon_i^e\left(\frac{dN^e}{dE}\right)_i + \epsilon_i^\mu\left(\frac{dN^\mu}{dE}\right)_i + \epsilon_i^\tau\left(\frac{dN^\tau}{dE}\right)_i\right],$$

$$E_{ci} = \frac{M_i^2 - M_Y^2}{2M_i}$$

We only open the μ two-body decay for DM_1 and mainly the τ one for DM_2

M_1=3030 GeV, M_2=416 GeV (M_Y=300 GeV); E_{c1}=1500 GeV, E_{c2}=100 GeV

κ	ϵ_H^e	ϵ_H^μ	ϵ_H^τ	$\tau_H(10^{26}\mathrm{s})$	ϵ_L^e	ϵ_L^μ	ϵ_L^τ	$\tau_L(10^{26}\mathrm{s})$	$\chi^2_{\min}$	$\chi^2_{\min}/d.o.f.$
0.844	0	1	0	0.76	0.018	0	0.982	0.82	62.3	1.06

68 data points:
AMS-02: 42
Fermi-LAT: 26

(E > 10 GeV)

E_c(GeV)	κ	ϵ^e	ϵ^μ	ϵ^τ	$\tau(10^{26}\mathrm{s})$	$\chi^2_{\min}$	$\chi^2_{\min}/d.o.f.$
1000	0.73	0.09	0	0.91	0.66	463	7.35
1300	0.72	0.04	0	0.96	0.71	516	8.19
1500	0.71	0.02	0	0.98	0.74	541	8.46

Only DM_1

CQG, D.Huang, C.Lai, PRD91 (2015) 095006
``Revisiting Multicomponent Dark Matter with New AMS-02 Data"

$$\Phi_e^{(\text{tot})} = \kappa_1 \Phi_e^{(\text{primary})} + \kappa_2 \Phi_e^{(\text{secondary})} + \Phi_e^{\text{DM}},$$
$$\Phi_p^{(\text{tot})} = \kappa_2 \Phi_p^{(\text{secondary})} + \Phi_p^{\text{DM}}.$$

AMS-02
PRL110, 141102 (2013)
PRL113, 121101 (2014)
PRL113, 121102 (2014)

$$\left(\frac{dN_{e,p}}{dE}\right)_i = \frac{1}{2}\left[\epsilon_i^e \left(\frac{dN^e}{dE}\right)_i + \epsilon_i^\mu \left(\frac{dN^\mu}{dE}\right)_i + \epsilon_i^\tau \left(\frac{dN^\tau}{dE}\right)_i\right],$$

140 data points:
e^+ fraction: 42+1
e^+ flux: 48
e^- flux: 49
(E > 10 GeV)

***E_{cL}* of DM_L (416 GeV) is fixed to be 100 GeV with M_Y=300 GeV**

E_{cH}(GeV)	κ_1	κ_2	$\epsilon^e_{H,L}$	$\epsilon^\mu_{H,L}$	$\epsilon^\tau_{H,L}$	$\tau_{H,L}(10^{26}\text{s})$	χ^2_{min}	χ^2_{min}/d.o.f.
600	0.94	1.49	0.18, 0.02	0.74, 0.00	0.08, 0.98	1.52, 1.34	102	0.78
800	0.94	1.49	0.05, 0.02	0.65, 0.00	0.30, 0.98	1.08, 1.39	102	0.78
1200	0.94	1.50	0.00, 0.01	0.80, 0.00	0.20, 0.99	0.62, 1.61	102	0.78
1500	0.94	1.50	0.00, 0.04	1.00, 0.17	0.00, 0.79	0.60, 1.98	105	0.81

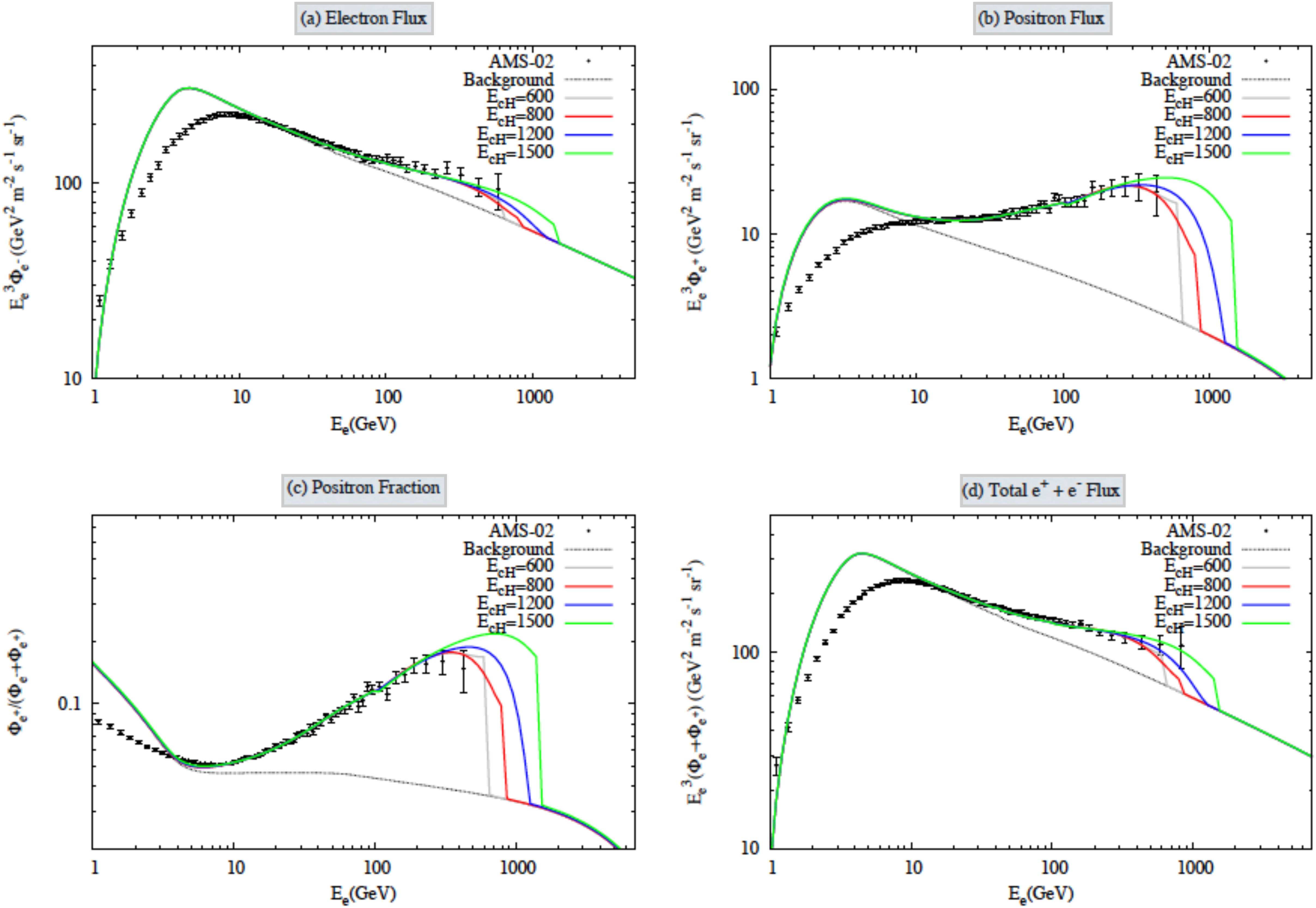


FIG. 2. (a) Electron flux, (b) positron flux, (c) positron fraction, and (d) total $e^+ + e^-$ flux from the two-component DM contributions with the best-fitting parameters given in Table III for E_{cH} =600, 800, 1200 and 1500 GeV, respectively.

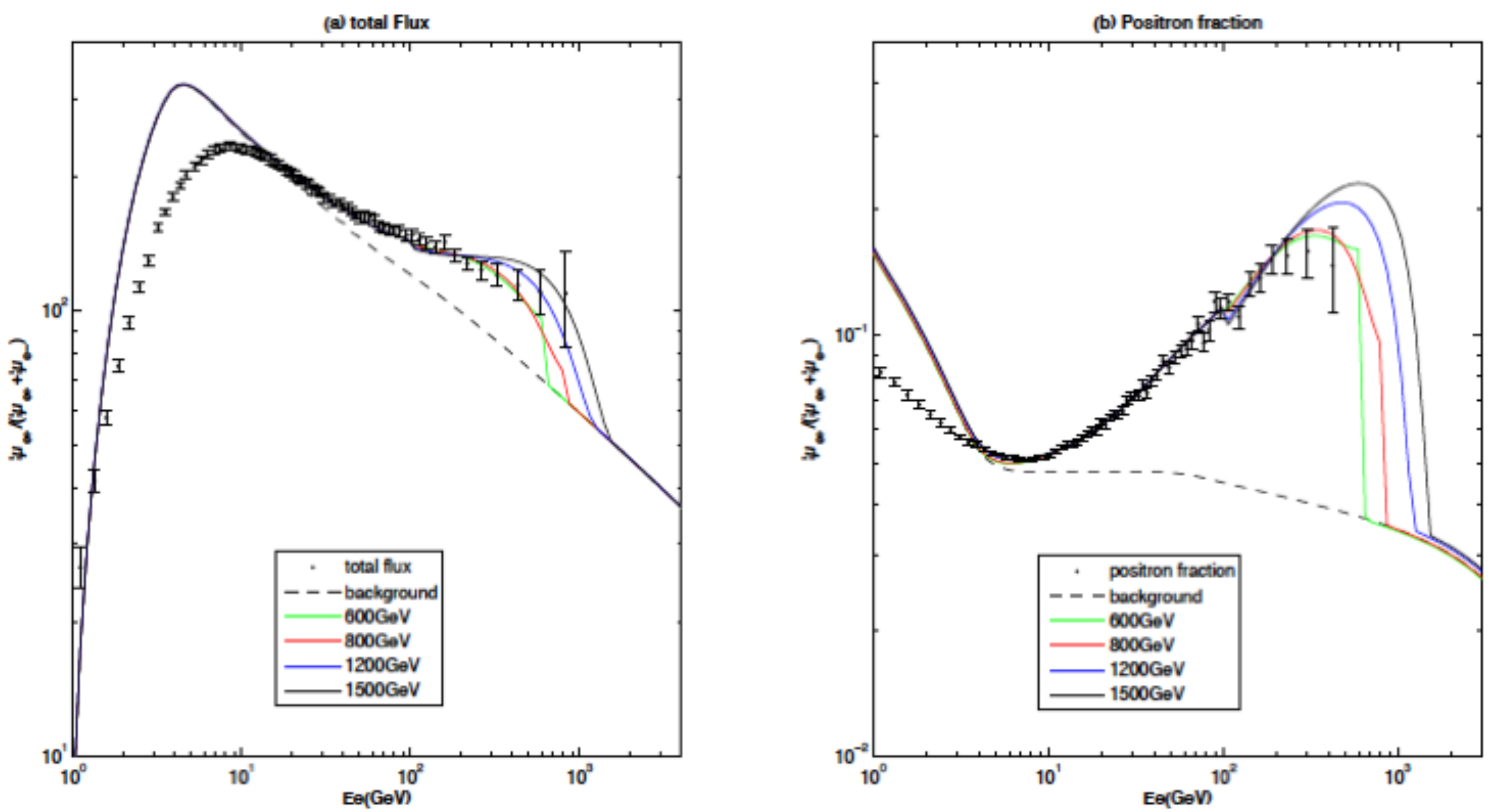
C.Lai, D.Huang, CQG, Mod. Phys. Lett. A30, 1550188 (2015)
``Multicomponent Dark Matter in the Light of New AMS-02 Data"

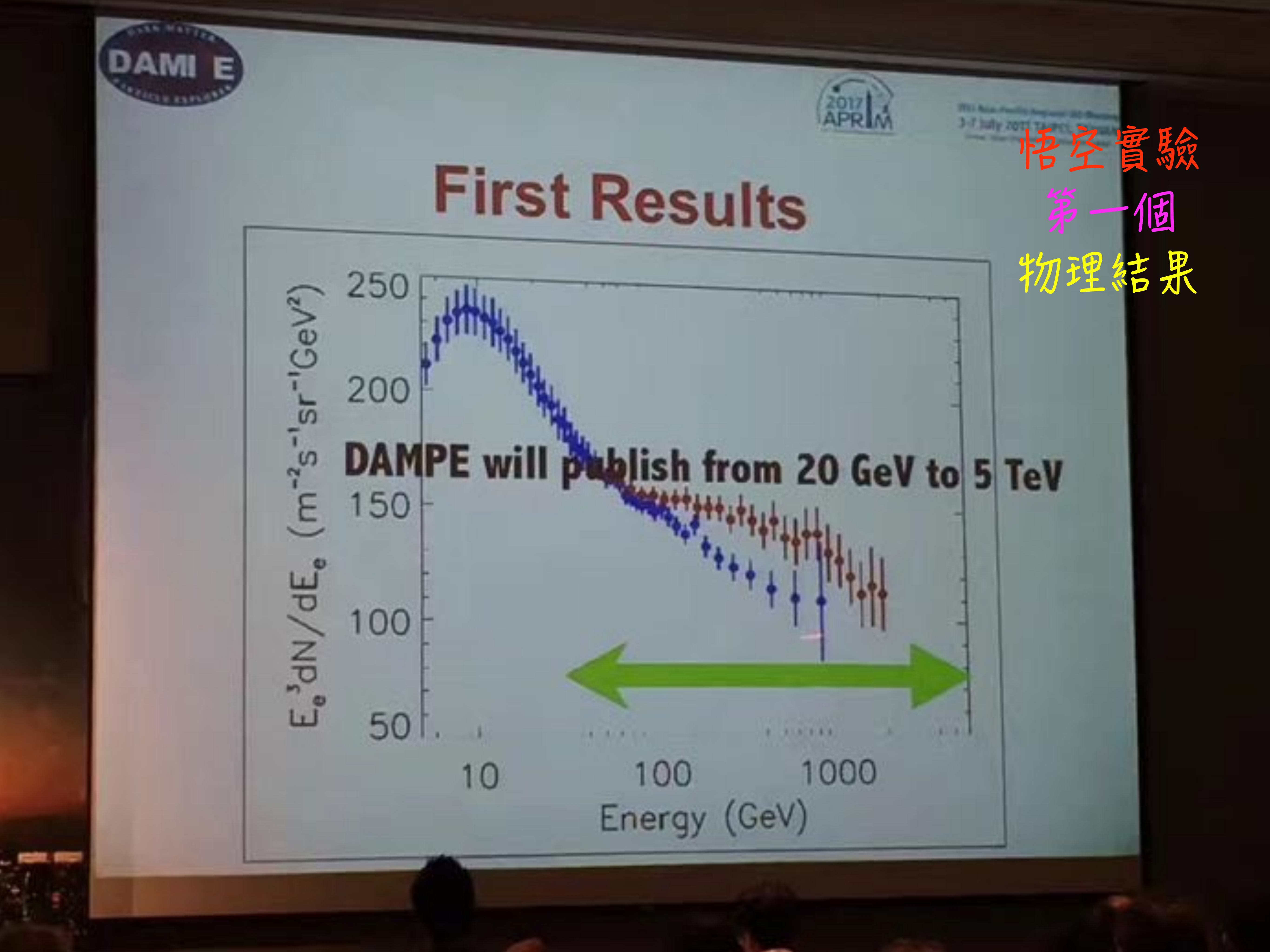
AMS-02
PRL110, 141102 (2013)
PRL113, 221102 (2014)

E_{cL} of DM_L (416 GeV) is fixed to be 100 GeV with M_Y=300 GeV

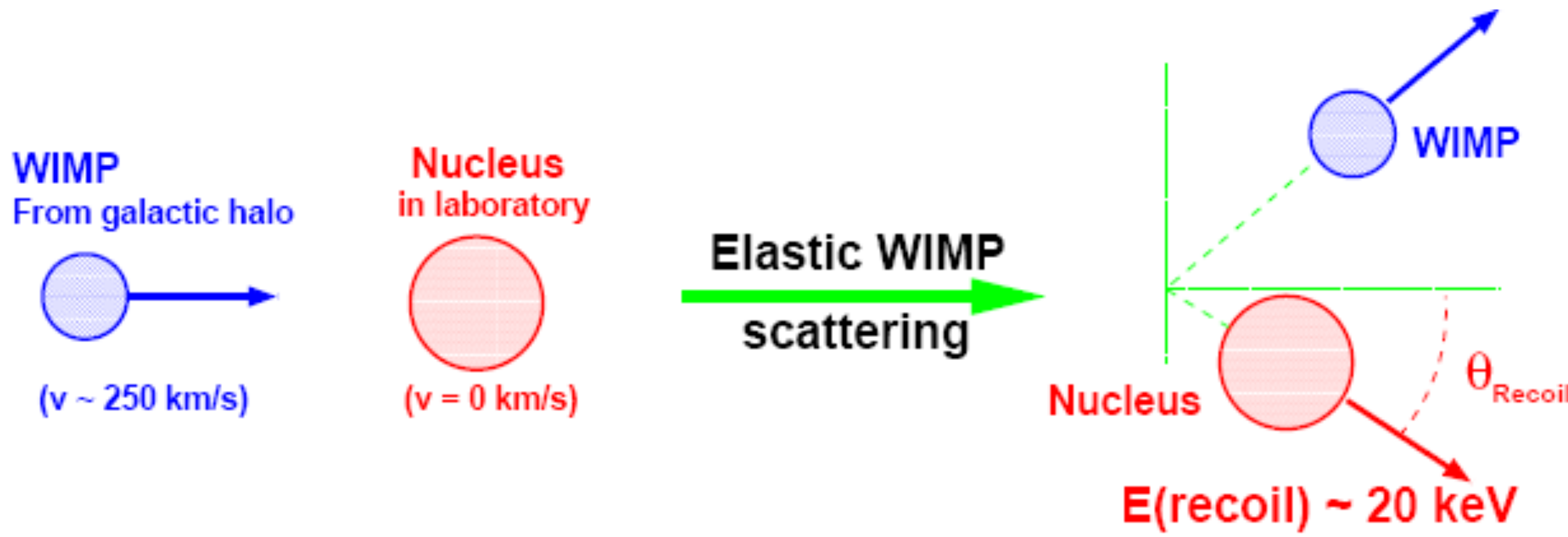
E_{cH}(GeV)	κ_1	κ_2	$\epsilon_L^{e,\mu,\tau}$	$\epsilon_H^{e,\mu}$	$\tau_L(10^{26}\text{s})$	$\tau_H(10^{26}\text{s})$	$\chi^2_{\rm min}$	$\chi^2_{\rm min}$/d.o.f.
600	0.94	1.51	0.02, 0, 0.98	0.18,0.82	1.43	1.60	94	1.09
800	0.94	1.52	0.04, 0.08, 0.88	0.05, 0.95	1.58	1.32	97	1.13
1200	0.94	1.57	0.12, 0.48, 0.40	0, 1	2.58	1.06	107	1.24
1500	0.94	1.60	0.20, 0.80, 0	0, 1	3.41	0.93	119	1.38

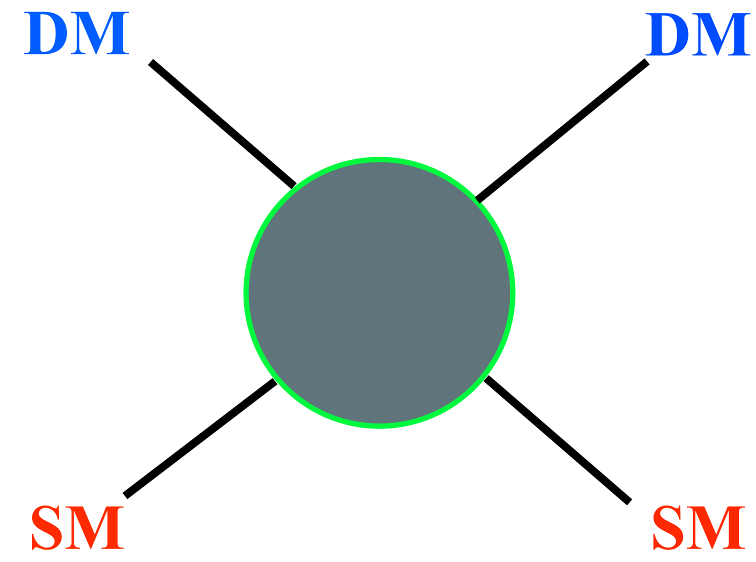
93 data points:
e^+ fraction: 43
$e^+ + e^-$ T.flux: 50
(E > 10 GeV)




2017 APRIM
First Results
悟空實驗
第一個
物理結果
250
200
150
100
50
$E_e^3 dN/dE_e$ ($m^{-2}s^{-1}sr^{-1}GeV^2$)
DAMPE will publish from 20 GeV to 5 TeV
10
100
1000
Energy (GeV)

- ***Direct Detections for Dark Matter***





Rate < 1 event/day/kg of detector

Need low background

Deep underground sites
Radio-purity of components
Active/passive shielding

Need large detector mass (kg -> ton)

Recoil energy : O(1~10) keV

Need low recoil energy threshold

Direct detection experiments:
SNOLab DEAP, CLEAN, Picasso, COUPP, DAMIC, SuperCDMS
Soudan CDMS, CoGeNT
Homestake LUX, LZ
Modane EDELWEISS
Canfranc ArDM, ANAIS
Boulby DRIFT
Gran Sasso XENON, CRESST, DAMA/LIBRA, DarkSide
YangYang KIMS
Jinping PandaX, CDEX
Kamioka XMASS, Newage
South Pole DM Ice

Accelerator searches:
CERN Atlas, CMS

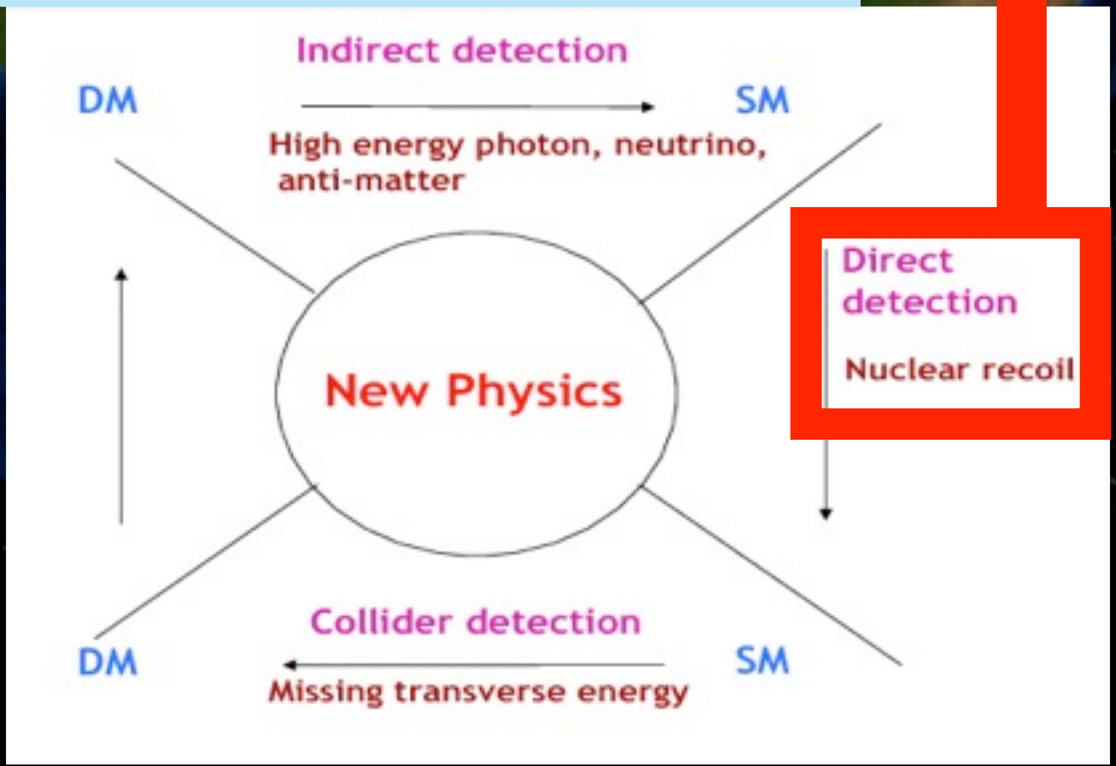
Indirect detection experiments:
Namibia HESS
La Palma MAGIC
Arizona VERITAS
South Pole IceCube
ISS AMS-02
Resurs DK-1 PAMELA
Fermi Large Area Telescope

Axion searches:
Washington ADMX

Veerle Tammer, 2015

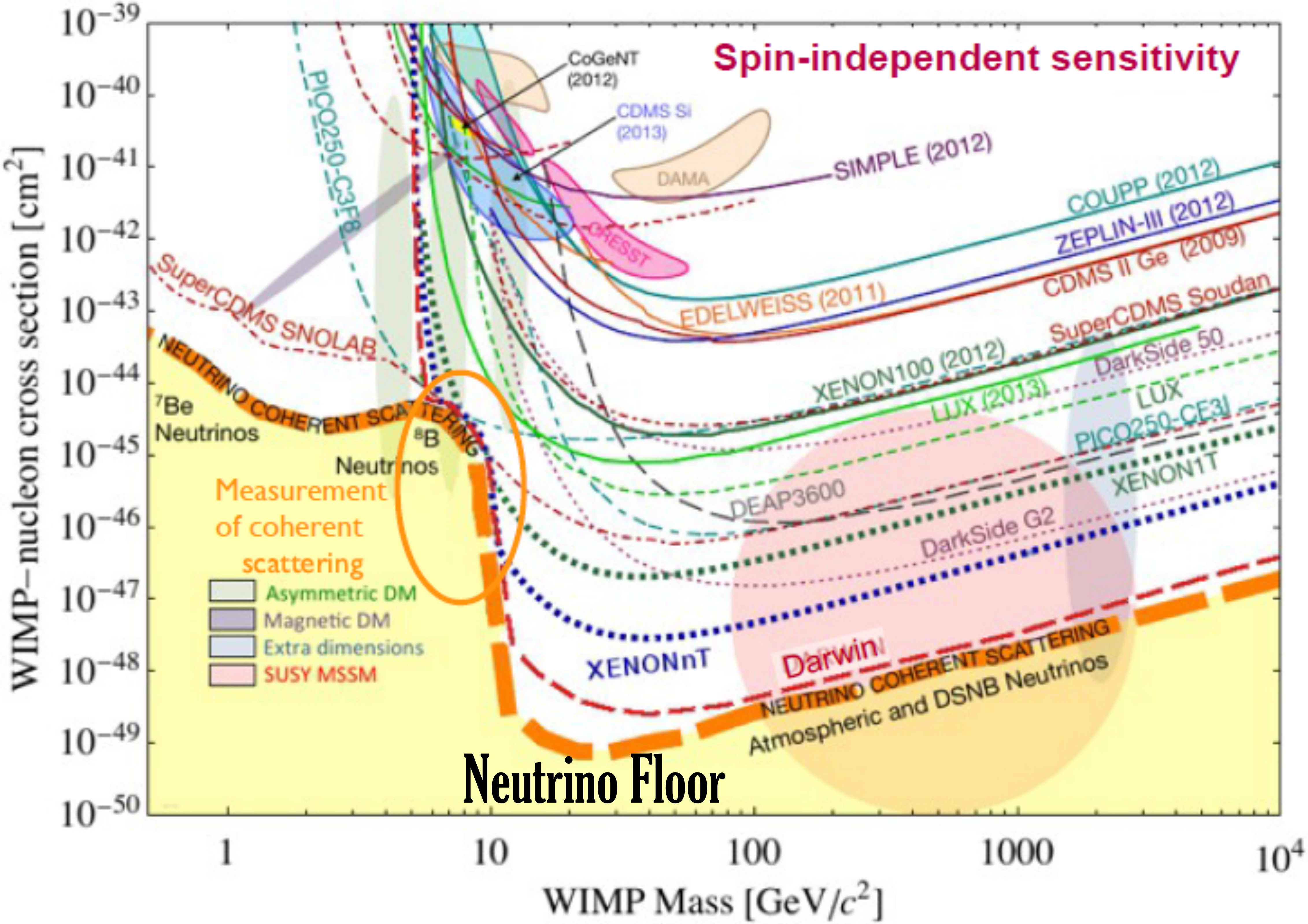
WebGL Earth • Cesium • Tiles Courtesy of MapQuest

Measure the recoil energy deposited by the interaction of a WIMP particle with a nucleus in the detector



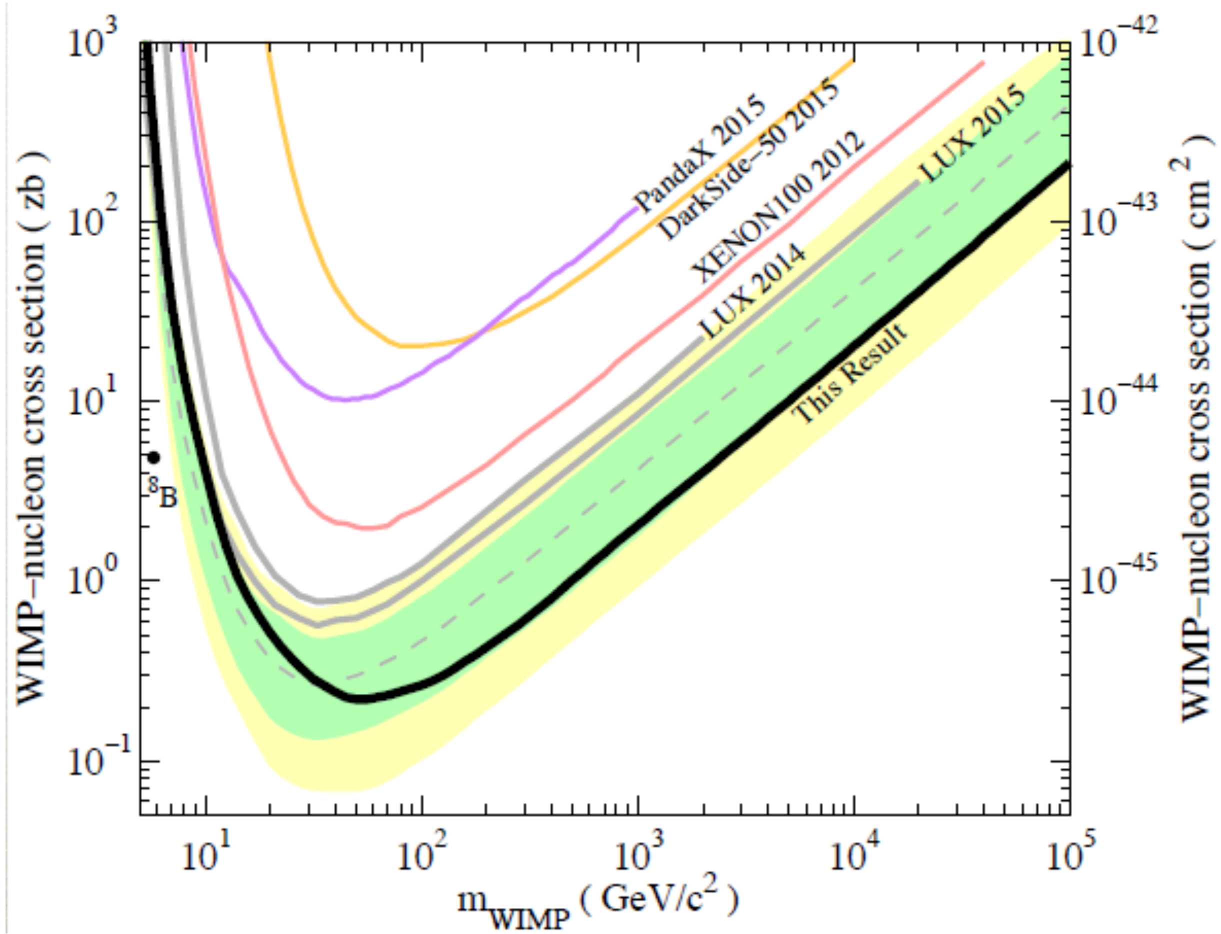
Current Status and Future Goal

Credit: Uwe Oberlack @ Darwin 2015



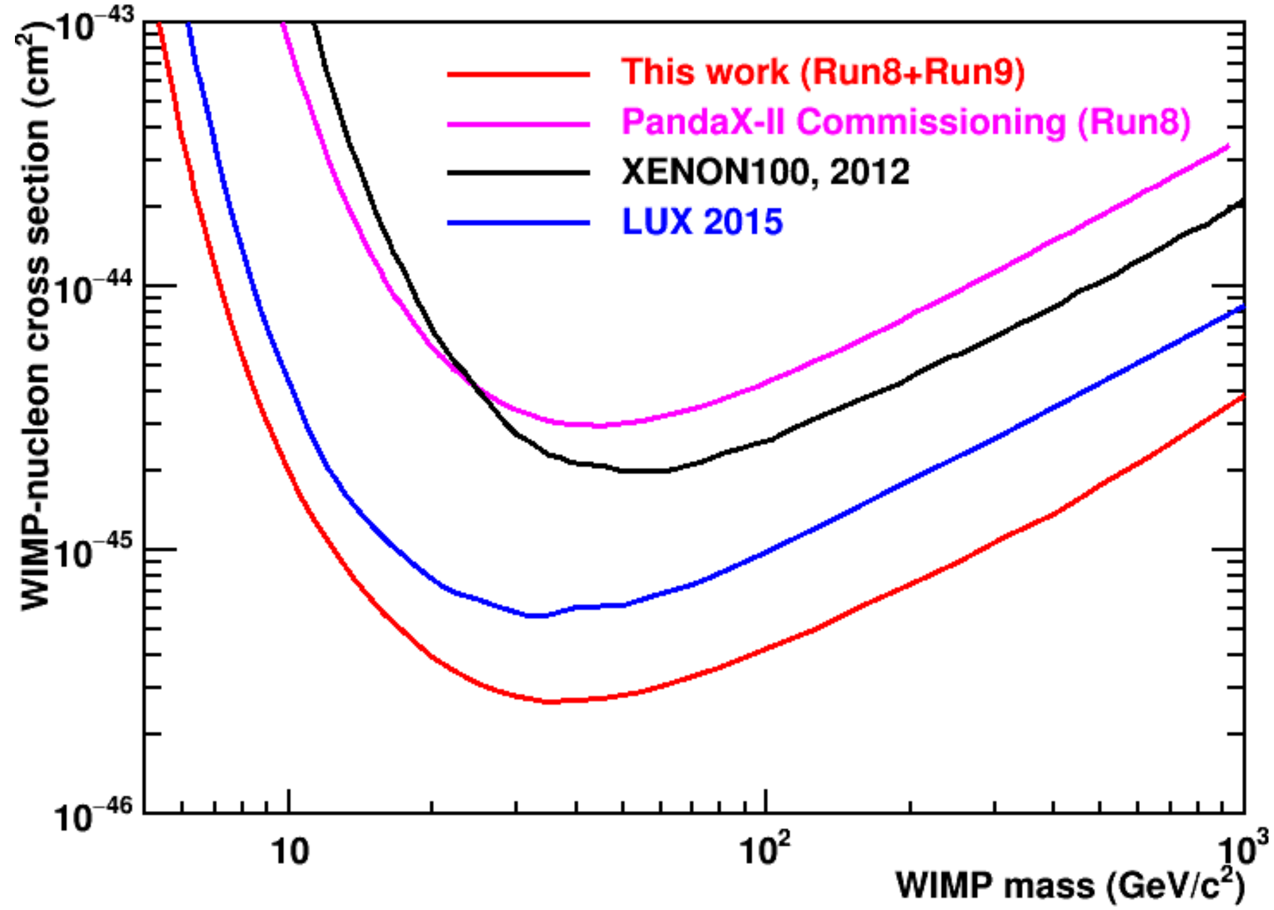
Recent Development

LUX2016



Minimum exclusion of **2.2 x 10^{-46} cm^2** at 50 GeV

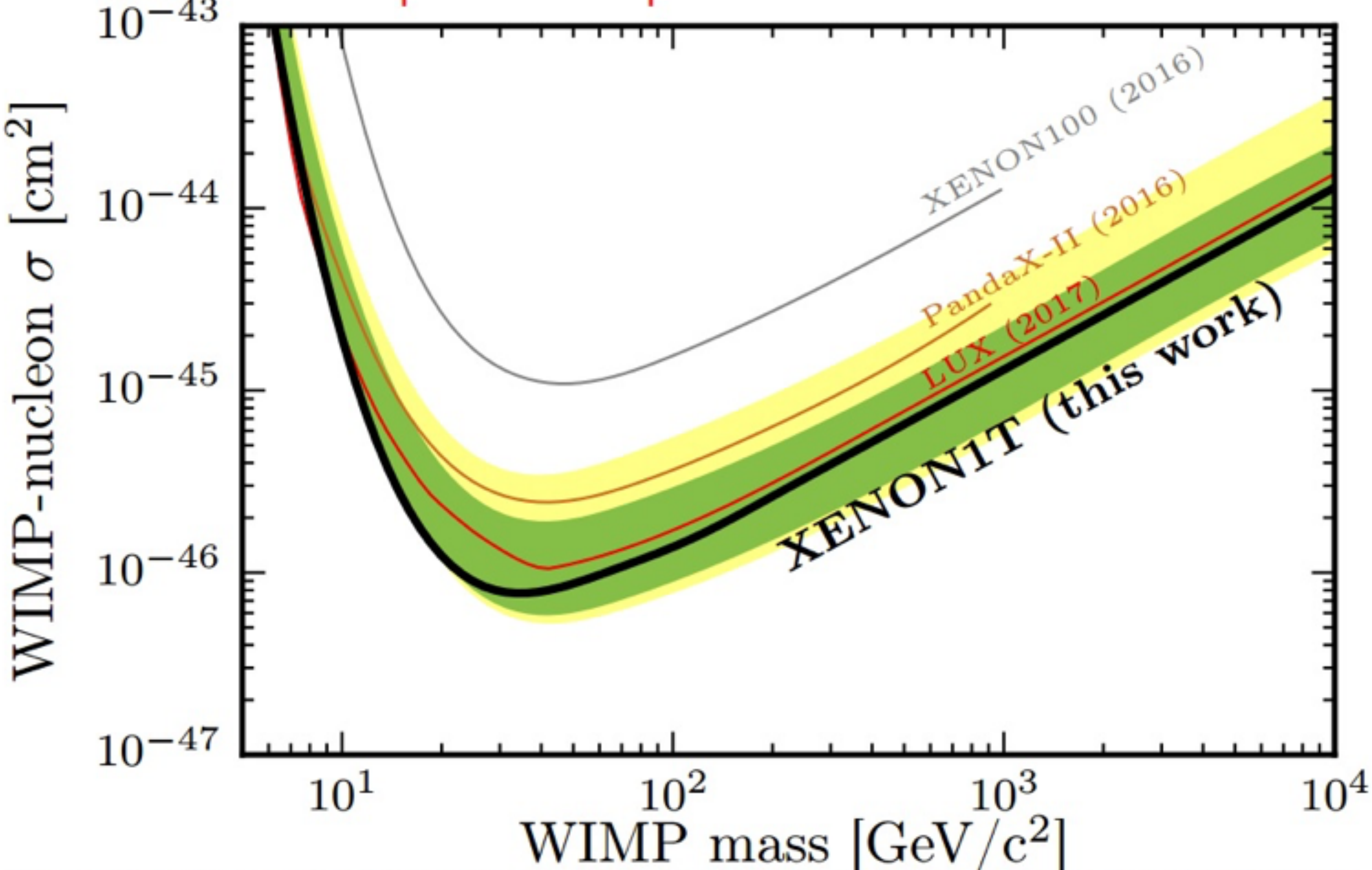
PandaX-II



Minimum upper limit

2.7x10^{-46} cm^2 @ 39.8 GeV/c^2

WIMP parameter space is further reduced



The spin-independent WIMP-nucleon cross section limits as a function of WIMP mass at 90% confidence level (black) for this run of XENON1T. In green and yellow are the 1- and 2σ sensitivity bands. Results from LUX (red), PandaX-II (brown), and XENON100 (gray) are shown for reference.

Reported by XENON1T on April 14, 2017 (See http://xenon1t.org/)

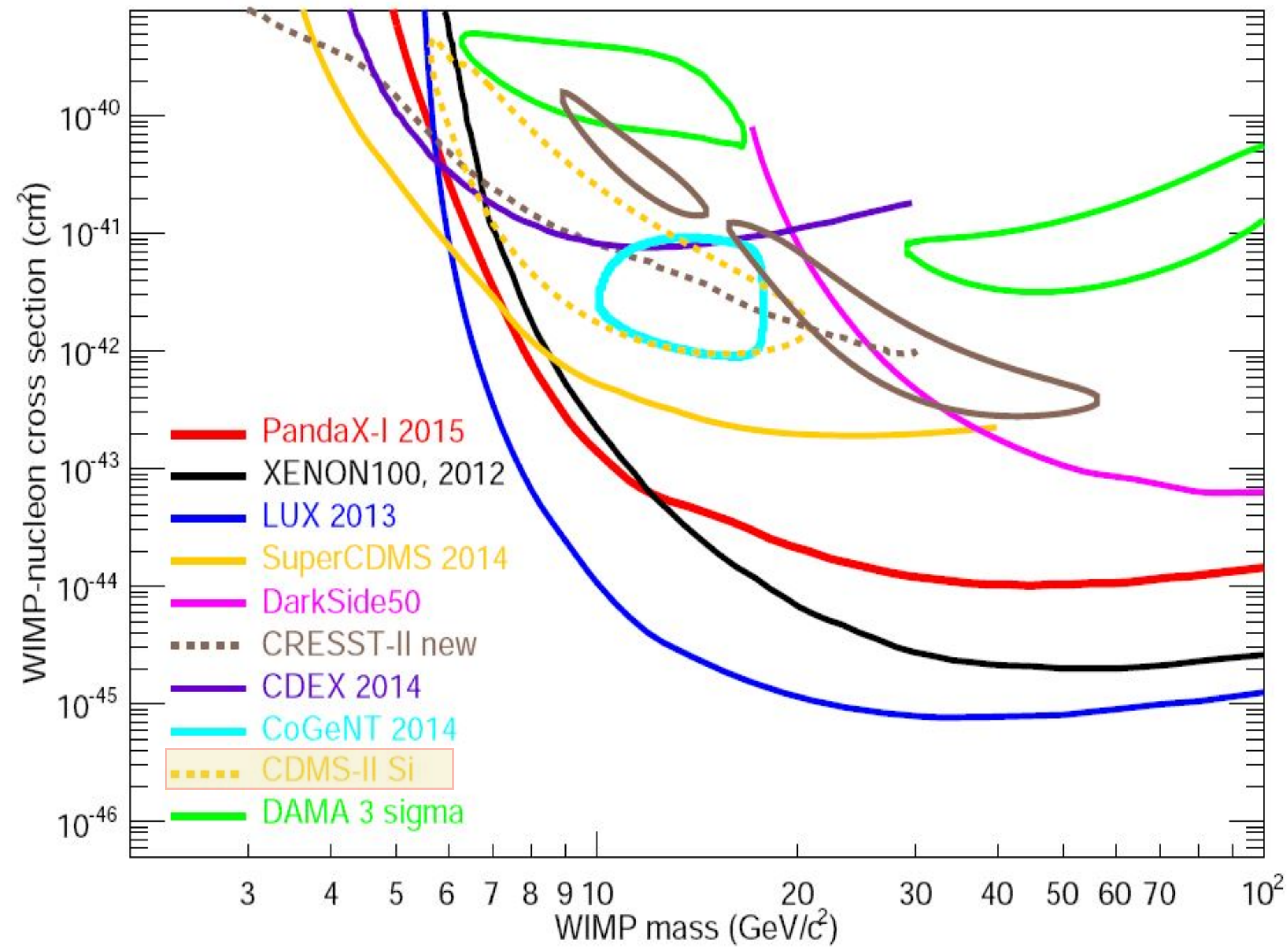
Positive signals

DAMA: Annual Modulation

CoGent, CDMS-Si: Excess in events

Negative limits

SuperCDMS, CDMSlite, Xenon10(100), CRESST-II, LUX, CDEX, PandaX



Positive signals

DAMA: Annual Modulation

CoGent, CDMS-Si: Excess in events

Negative limits

SuperCDMS, CDMSlite, Xenon10(100), CRESST-II, LUX, CDEX, PandaX

Possible Solutions (before LUX2013)

Isospin Violation: Tuning the couplings between n and p
→ **the sensitivities to Ge and Xe are maximally reduced**

Exothermic DM: Nuclear recoiling through the down-scattering
→ **the sensitivity to light nucleus is enhanced**

Light Mediator: Momentum dependent interactions,
→ **the nuclear recoil energy spectra are changed with the light nuclei favored**

After LUX2013, a single mechanism above CANNOT reconcile the CDMS-Si anomaly with other upper limits, but the combination can do the job

After new datasets from LUX2015 and SuperCDMS in 2015, we would like to know if the solutions are still valid.

Before PandaX-II LUX2016

CQG, D.Huang, C.H.Lee and Q.Wang,
``Direct Detection of Exothermic Dark Matter with Light Mediator''
JCAP 1608 (2016) 009 [arXiv: 1605.05098]

Exothermic interaction + Light Mediator
(+ Isospin Violation)

Generalized Effective Operator (spin-independent)

Two Majorana Fermionic WIMP DMs

$$\mathcal{O} = \frac{c_N}{q^2 + m_\phi^2}(\bar{\chi}_H \gamma^\mu \chi_L + \bar{\chi}_L \gamma^\mu \chi_H)(\bar{N}\gamma_\mu N)$$

Isospin Violation

Light Mediator

Down-Scattering

SI DM-nucleus Differential Cross Section

$$\frac{d\sigma_T}{dq^2} = \frac{m_T}{2\mu_{\chi p}^2 v^2}\bar{\sigma}_p [Z + \xi(A-Z)]^2 G(q^2) F_T^2(q^2) \,,$$

$$\xi \equiv c_n / c_p$$

$$G(q^2) = \frac{(1 + q_{\rm min}^2/m_\phi^2)(1 + q_{\rm ref}^2/m_\phi^2)}{(1 + q^2/m_\phi^2)^2}$$

$\mu_{\chi N}$ is the nucleon-WIMP reduced mass

$\bar{\sigma}_N$ is the reference cross section defined at $v_{\rm ref} = 200 \ {\rm km \cdot s^{-1}}$

$F_T(q^2)$ is the nuclear form factor

Differential Recoil Event Rate

$$\frac{dR}{dE_{\rm nr}} = \frac{dN}{M_T dt dE_{\rm nr}} = \frac{\rho_\chi}{m_\chi}\int_{|\mathbf{v}|>v_{\rm min}} d^3\mathbf{v} v f(\mathbf{v}) \frac{d\sigma_T}{dq^2}$$

$$= \frac{\rho_\chi}{2 m_\chi \mu_{\chi p}^2}\bar{\sigma}_p [Z + (A-Z)\xi]^2 G(E_{\rm nr}) F_A^2(E_{\rm nr}) \eta(E_{\rm nr}, t)$$

Local DM Density
$\rho_\chi = 0.3 \ {\rm GeV/cm^3}$

$$\eta(E_{\rm nr}, t) = \int_{|\mathbf{v}|>v_{\rm min}} d^3\mathbf{v} \frac{f(\mathbf{v})}{v}$$

$$v_{\rm min} = \frac{1}{\sqrt{2 E_{\rm nr} m_T}} \left| \delta + \frac{m_T E_{\rm nr}}{\mu_{\chi T}} \right|$$

$$\delta = m_L - m_H < 0$$

Exothermic Scattering

Observables

Total Rate

$$R(t) = \int_0^\infty dE_{\rm nr} \underline{\epsilon(s)} \underline{\Phi(f_s(E_{\rm nr}), s_1, s_2)} \left(\frac{dR}{dE_{\rm nr}} \right)$$

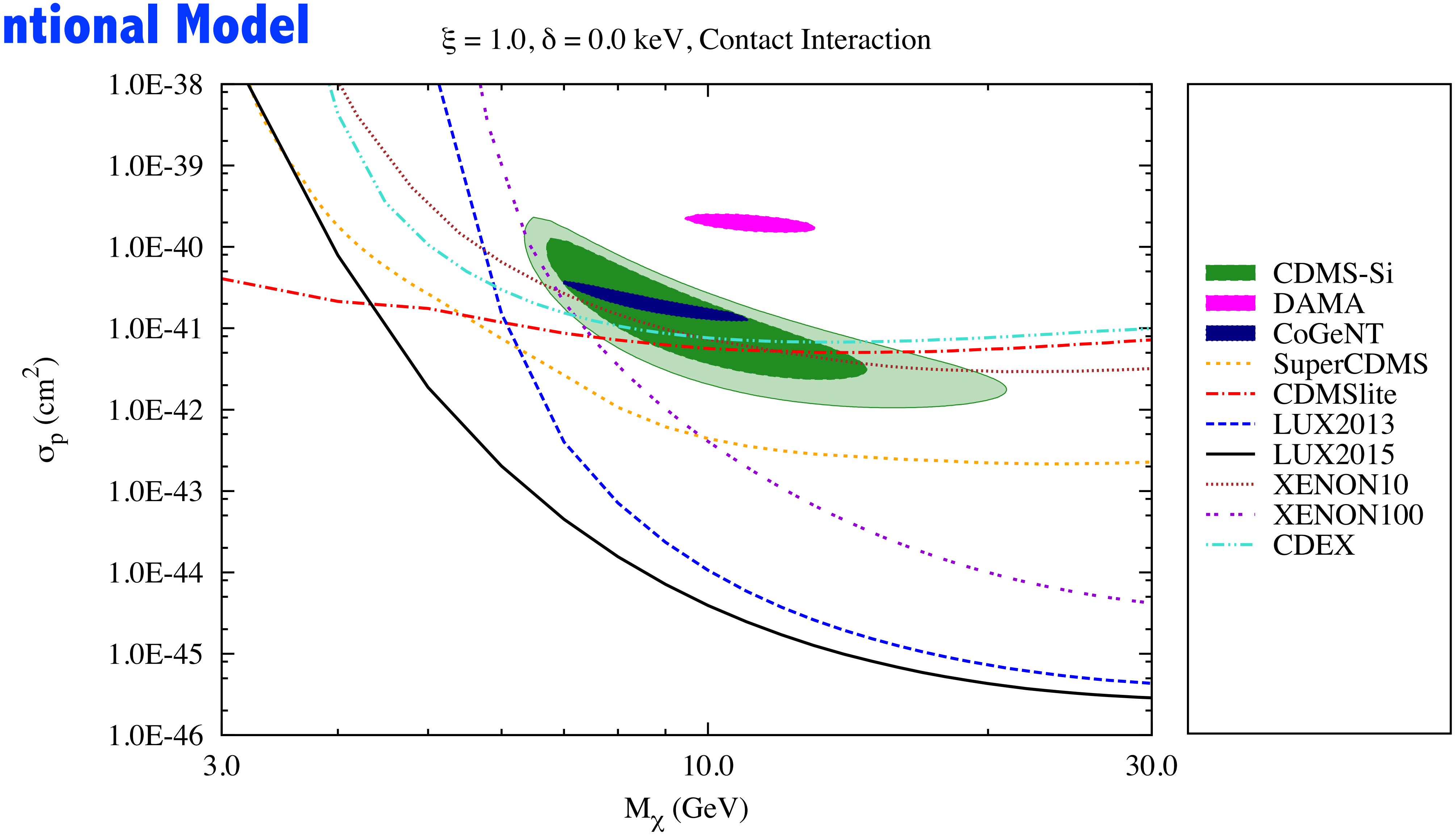
Detector Efficiency

Detector Resolution

Total Recoil Events

$$N_{\rm rec} = {\rm Ex} \cdot R_{\rm tot}(t)$$

Conventional Model

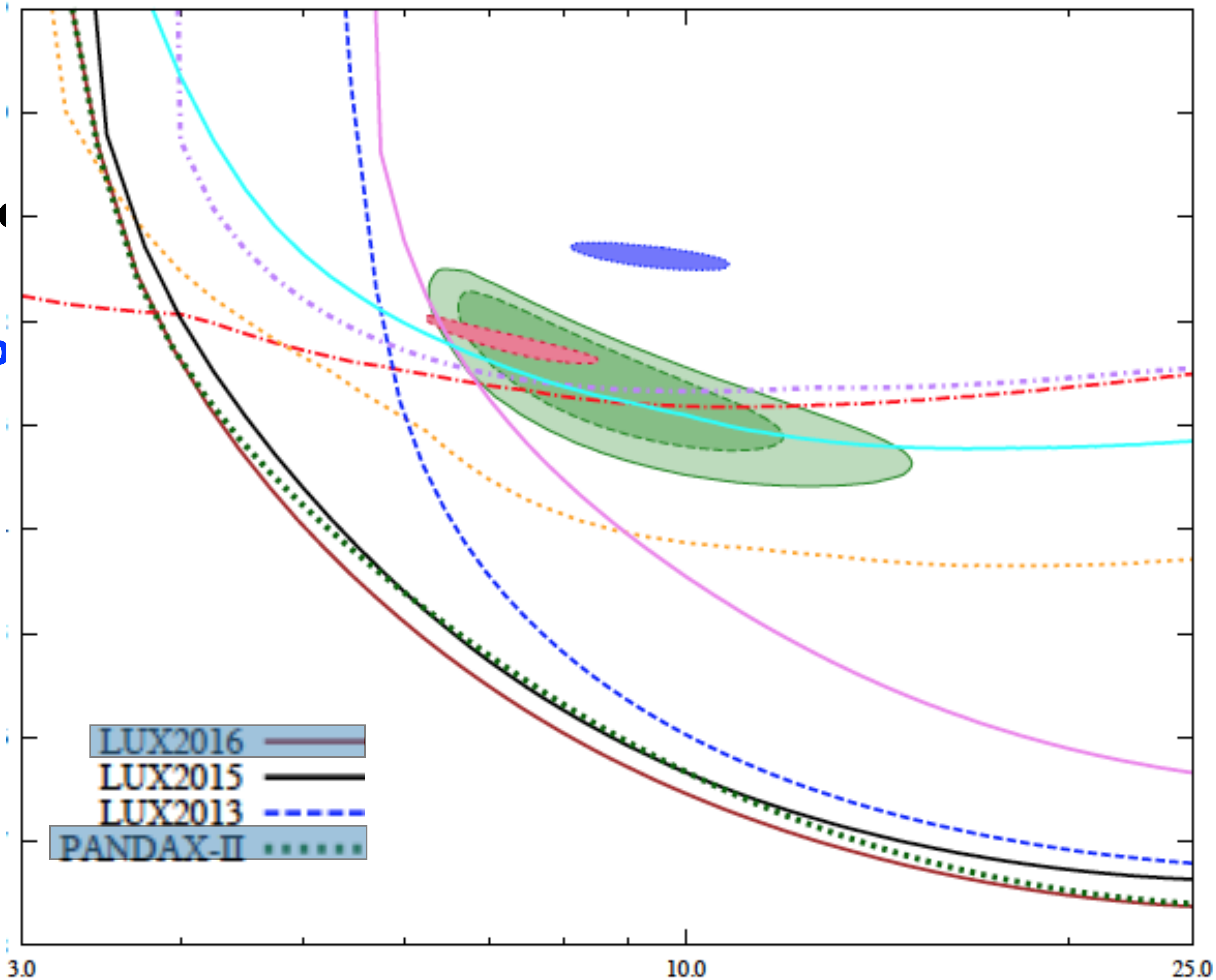


Observables

Total Rate $$R(t) = \int_0^\infty dE_{\rm nr}\epsilon(s)\Phi(f_s(E_{\rm nr}), s_1, s_2)\left(\frac{dR}{dE_{\rm nr}}\right)$$

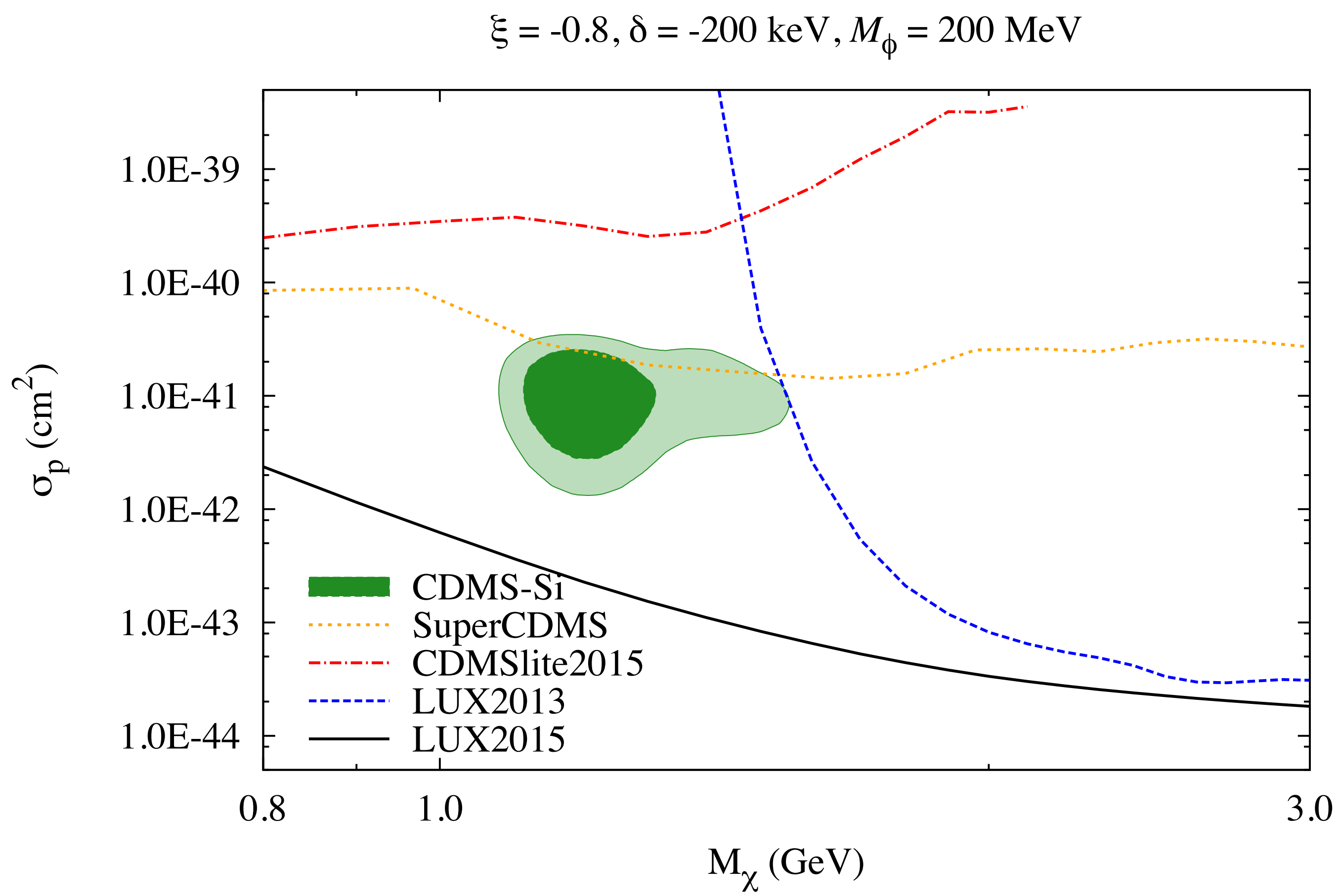
Total Re

Conventio

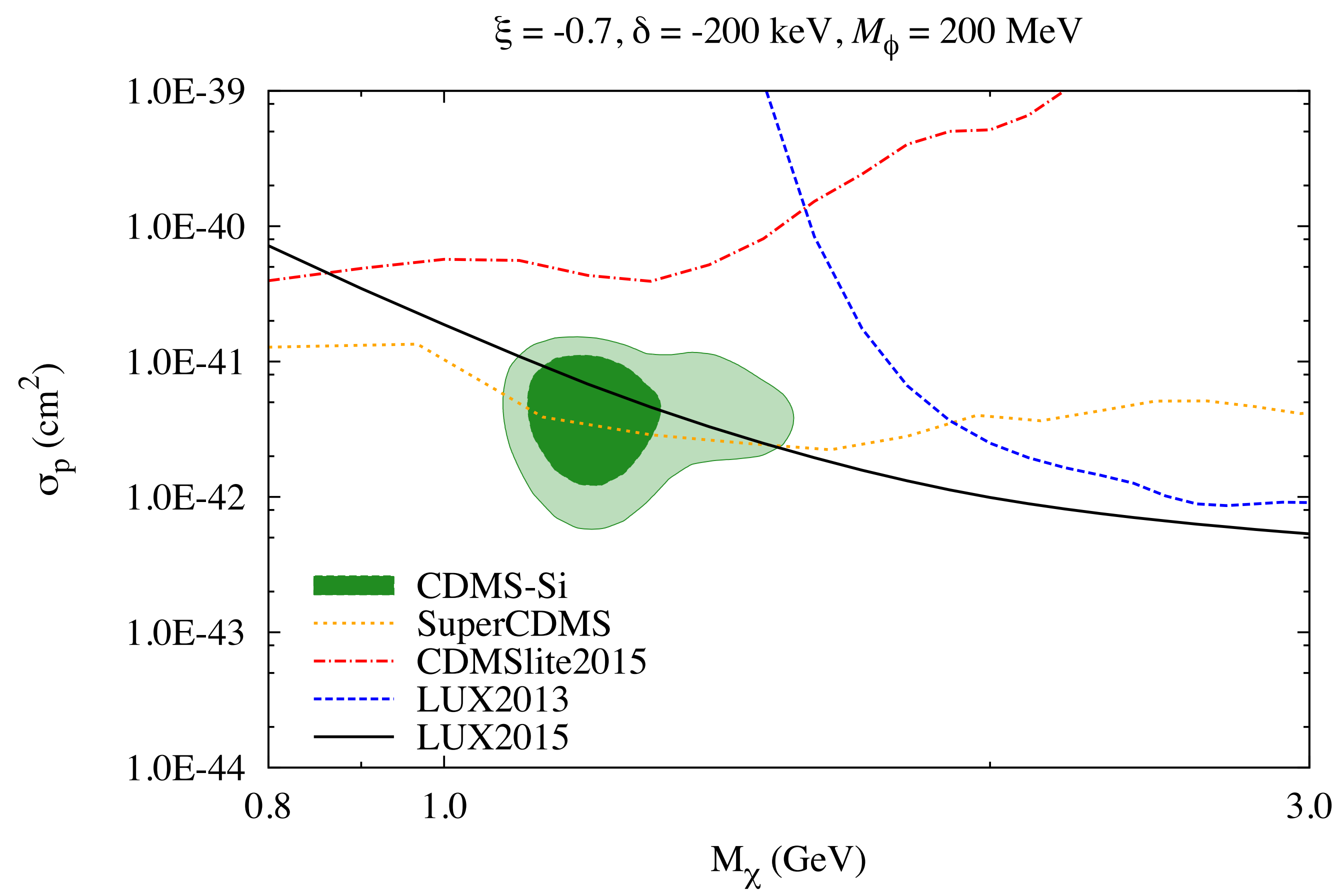


Isospin Violation + Exothermic Interaction

Ge-phobic: ξ=-0.8

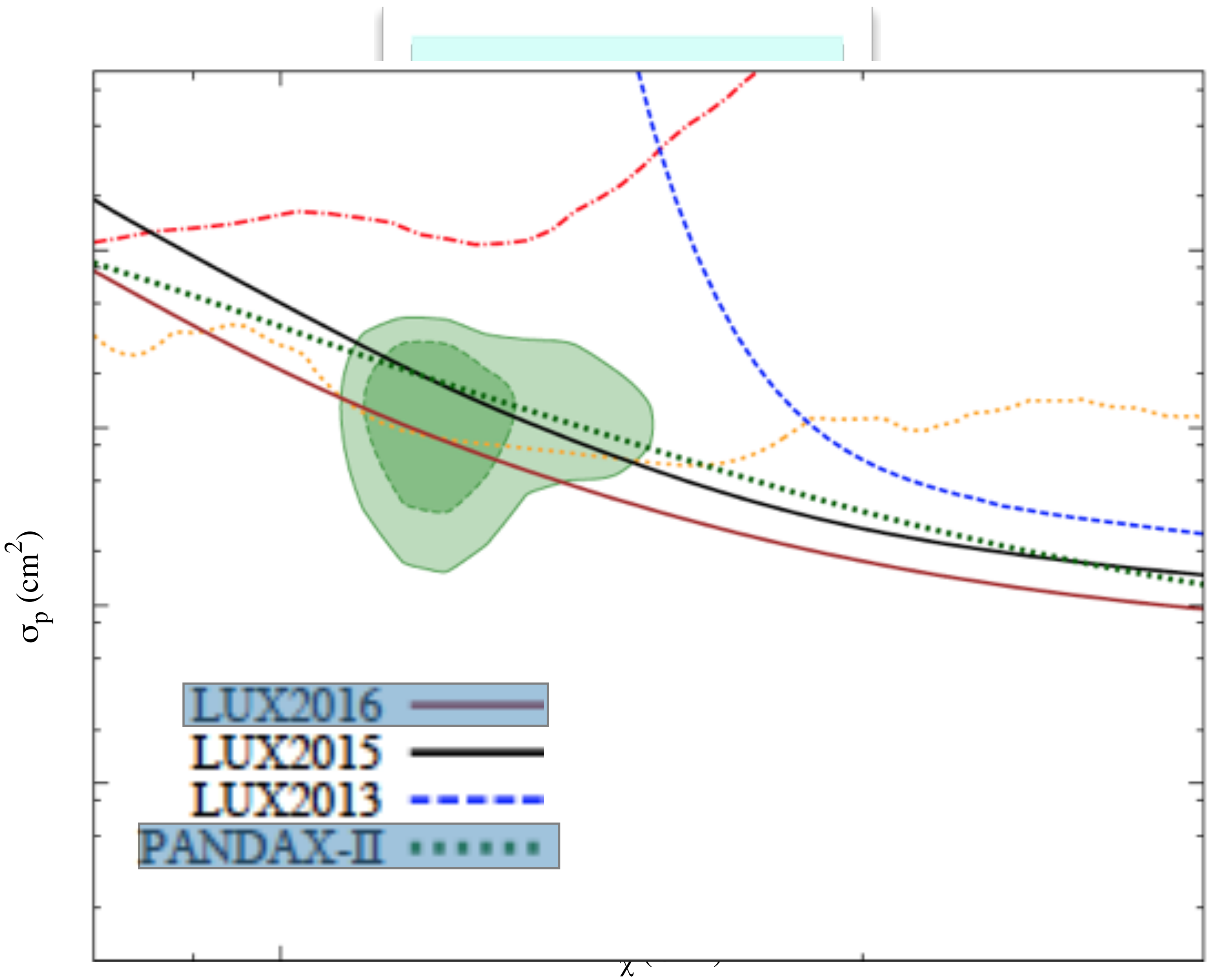


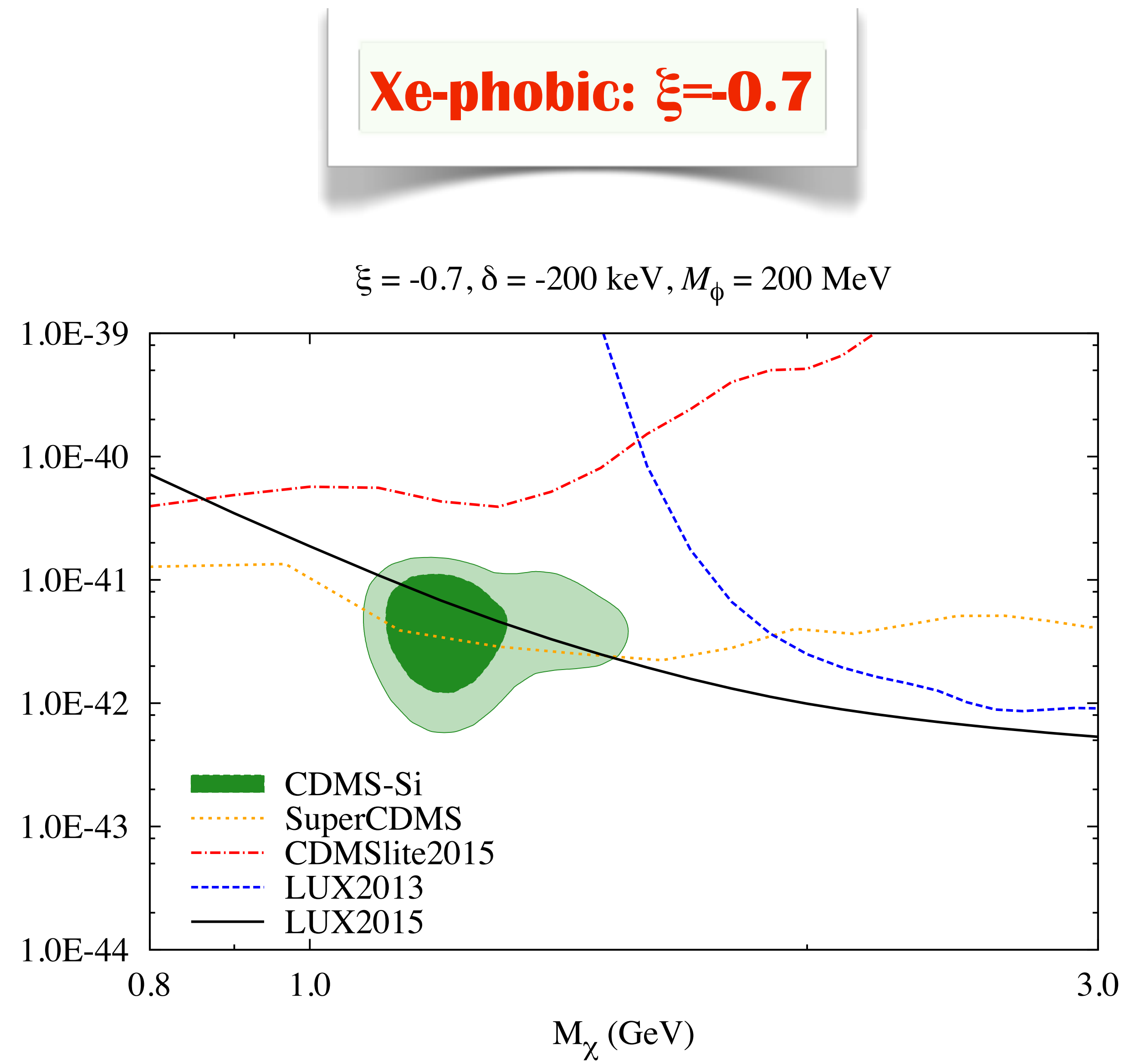
Xe-phobic: ξ=-0.7



- **Only Xe-phobic models work**
- **Gap becomes maximal at δ~-200 keV**

Isospin Violation + Exothermic Interaction

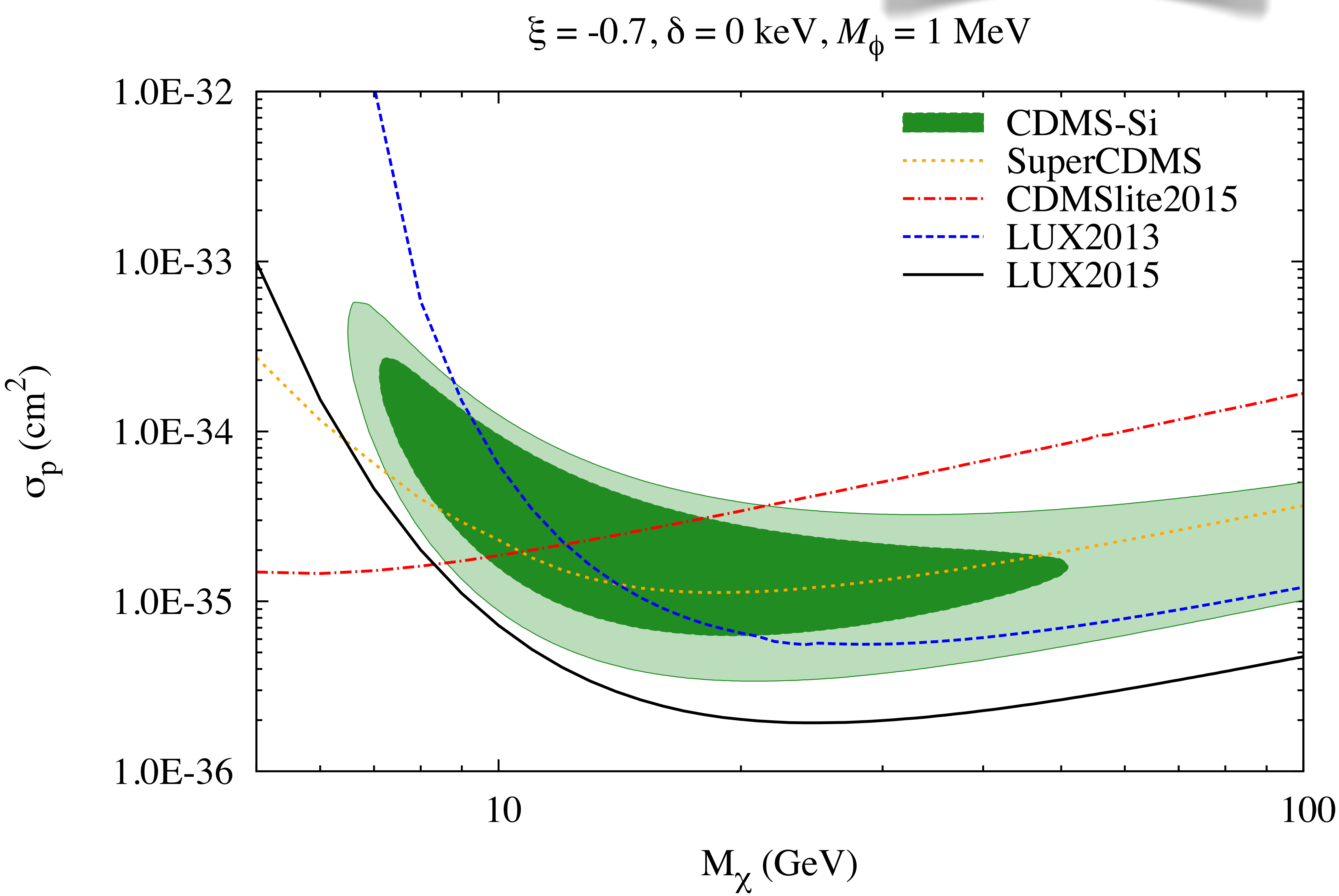




- **Only Xe-phobic models work**
- **Gap becomes maximal at $\delta \sim -200$ keV**

Isospin Violation + Light Mediator

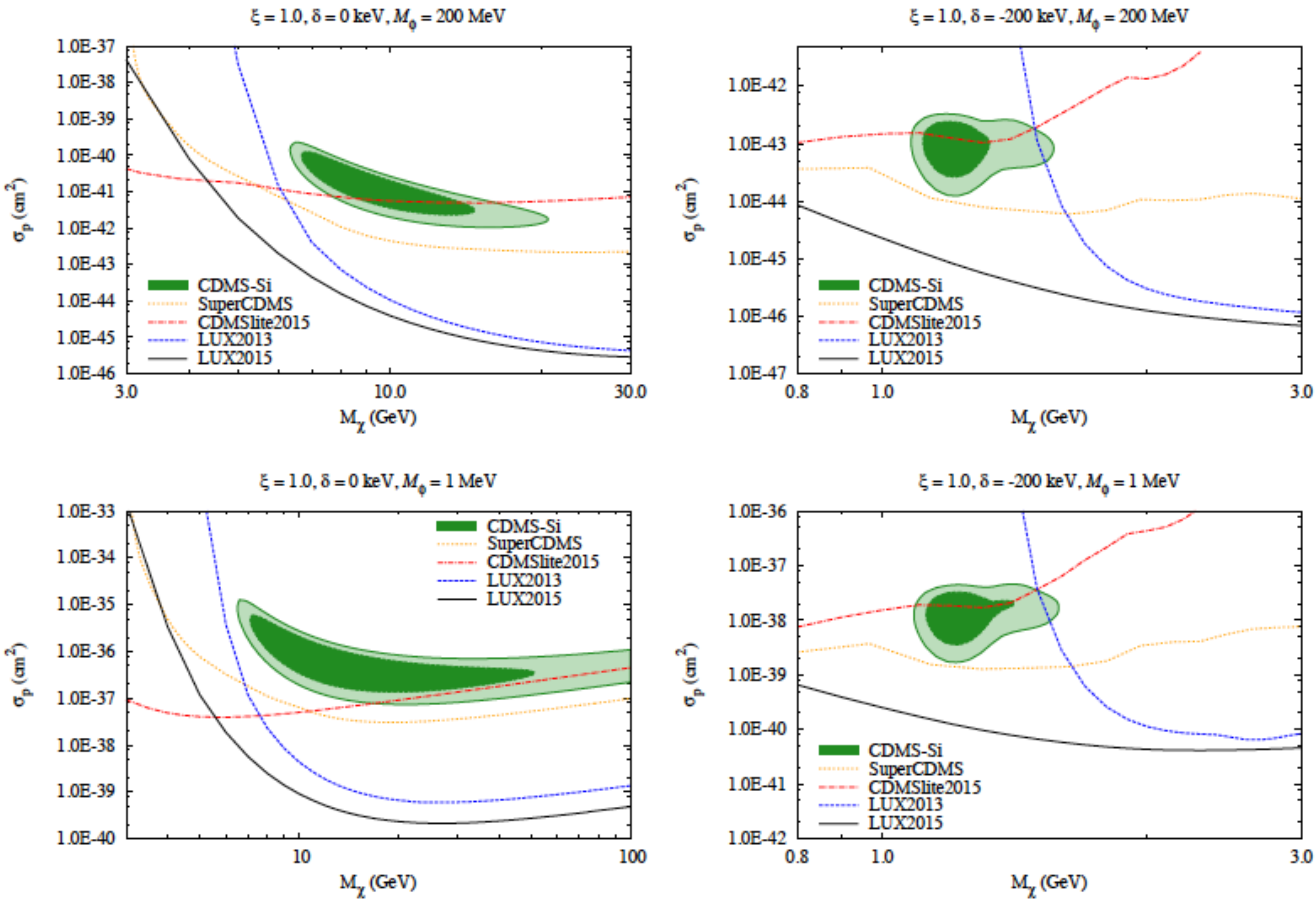
Xe-phobic: ξ=-0.7



This mechanism cannot work under LUX2015, which excludes the whole CDMS-Si 90% region of interest

Exothermic Interaction + Light Mediator

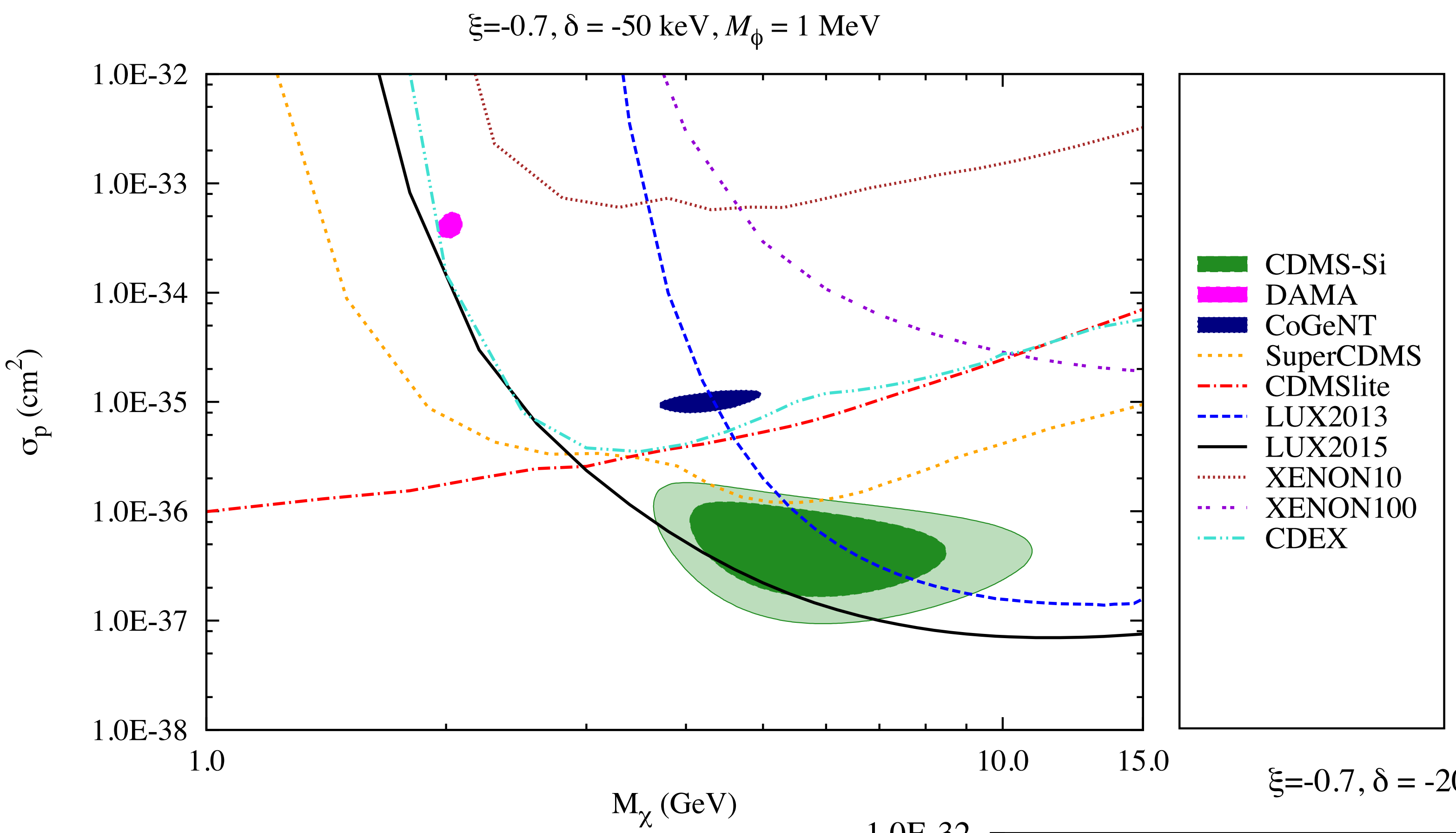
Isospin conserved: ξ=1.0

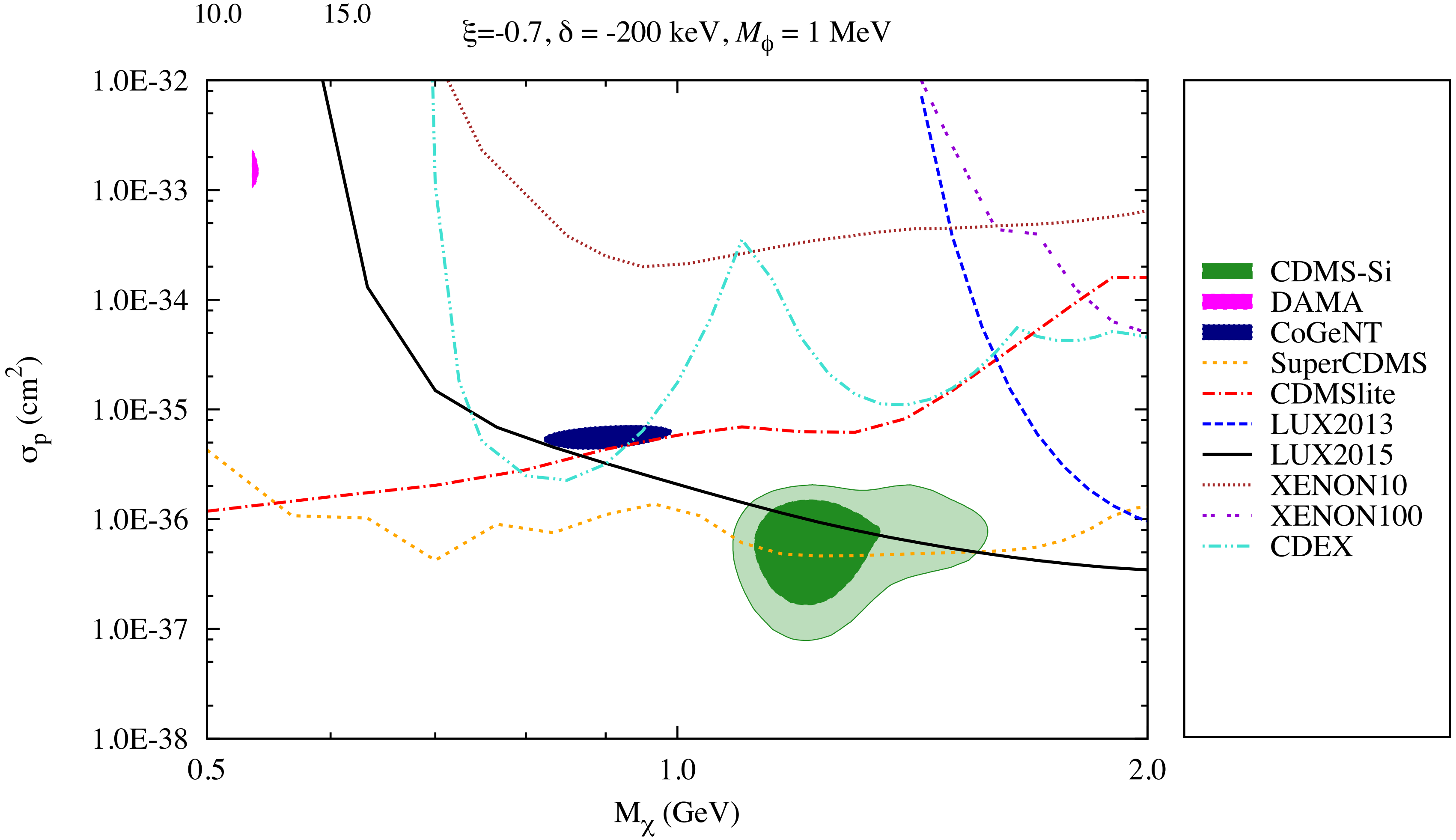


ruled out

Isospin Violation +Exothermic Interaction + Light Mediator

Xe-phobic: ξ=-0.7

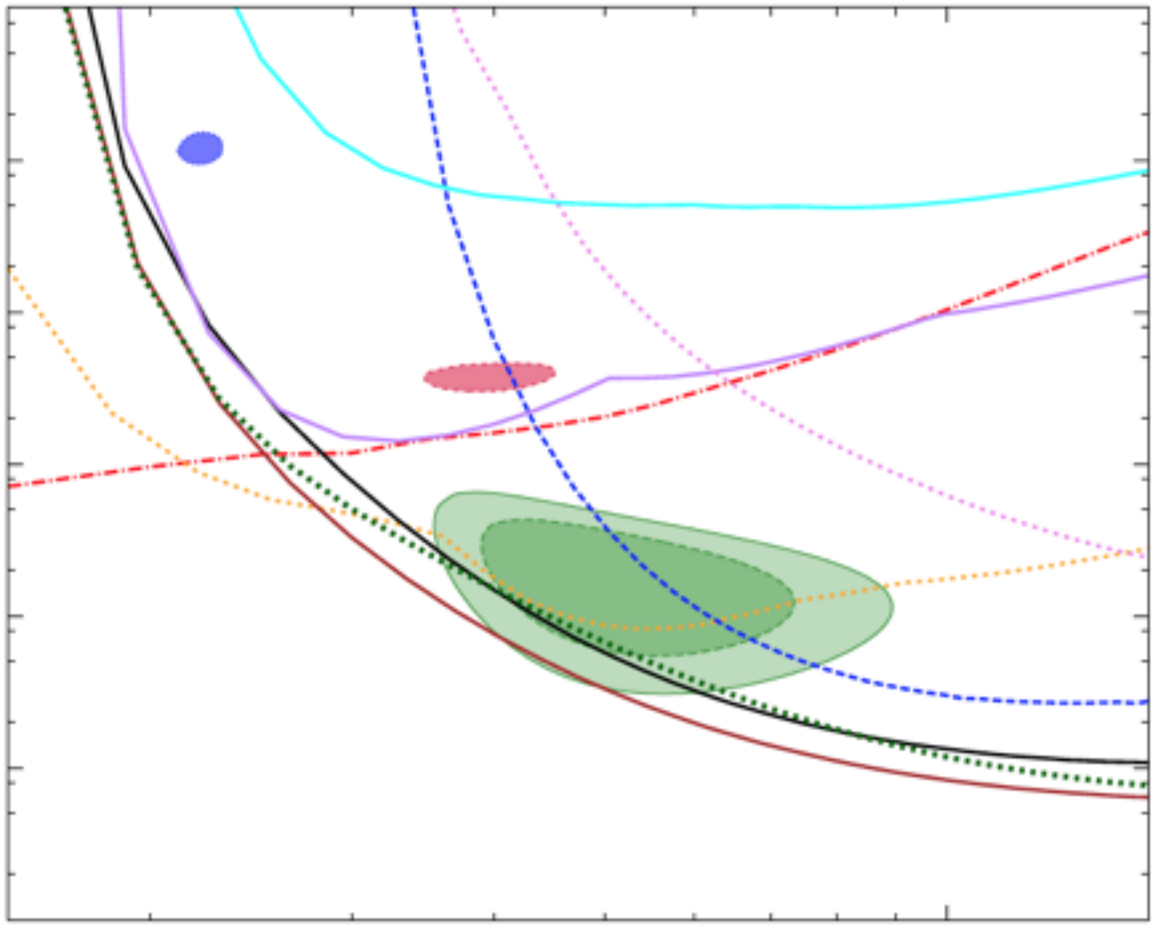


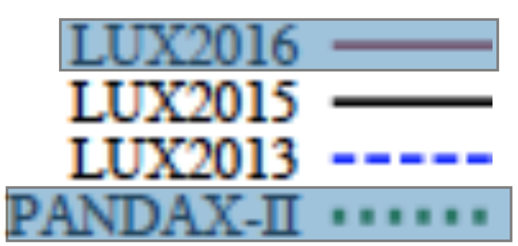


Isospin Violation +Exothermic Interaction + Light Mediator

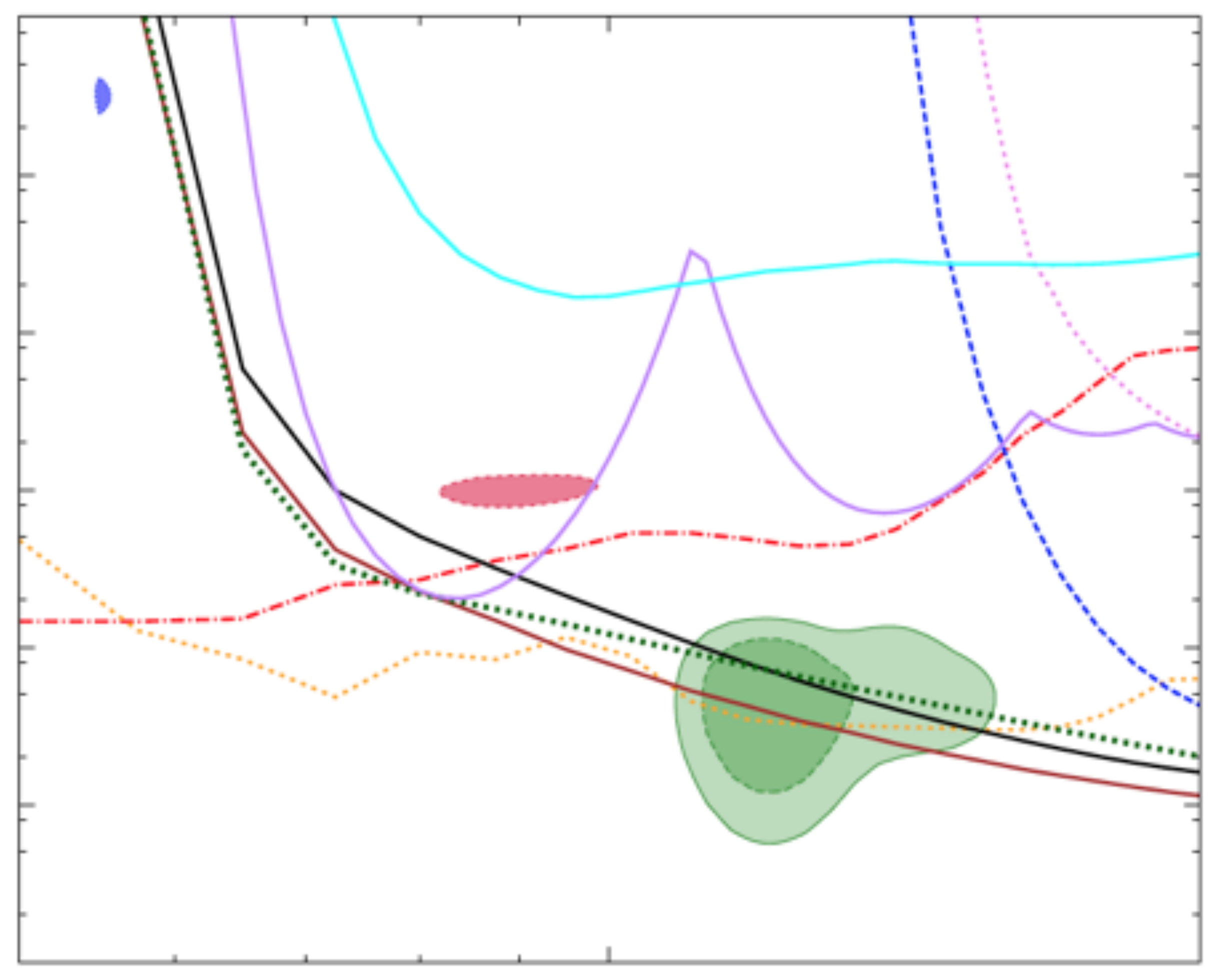
Xe-phobic: ξ=-0.7

ξ=-0.7, δ = -50 keV, M_ϕ = 1 MeV





ξ=-0.7, δ = -200 keV, M_ϕ = 1 MeV



Summary

- 26.8% of the Universe: Dark Matter, which has been only seen from large scale structures with gravitational effects.

- e^+ ($e^+ + e^-$) excesses in cosmic rays in the energy range of 10-450 (10 - 1000) GeV have been observed by PAMELA and AMS-02 (ATIC and Fermi), with a possible substructure around 100 GeV identified, which can be explained by DM with multi-components.

- There exist some controversies between positive signals (DAMA, CoGent, CDMS-Si) and negative limits (SuperCDMS, CDMSlite, Xenon, CRESST-II, LUX, CDEX, PandaX) from direct DM searches. The tension between CDMS-Si and other null experiments would be reduced for Xe-phobic exothermic interactions with isospin v. + light mediator.

- To understand the real nature of Dark Matter

☞ More future data from various direct and indirect searches are needed.

謝謝！