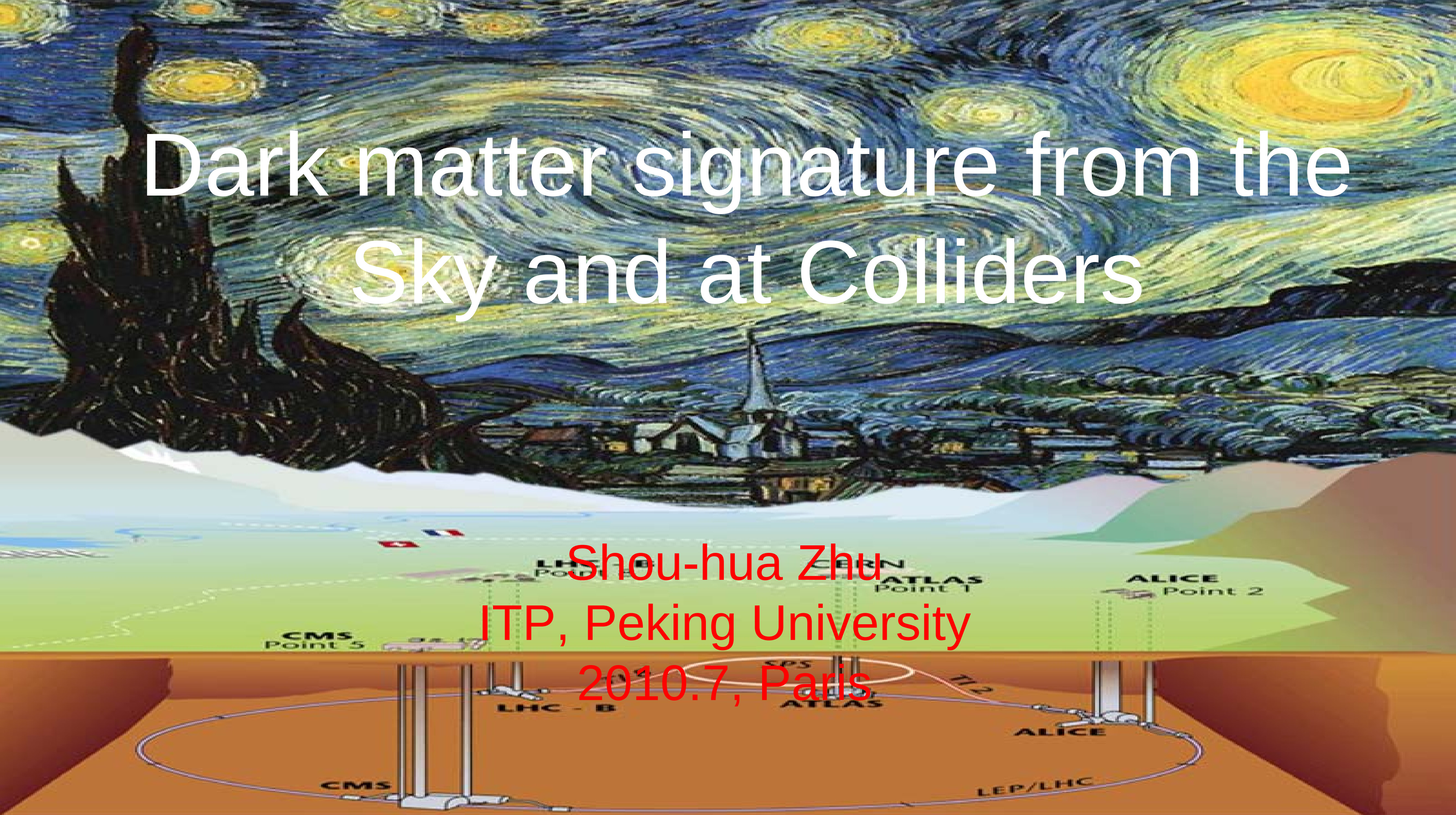


Dark matter signature from the Sky and at Colliders

Shou-hua Zhu
ITP, Peking University

2010.7, Paris

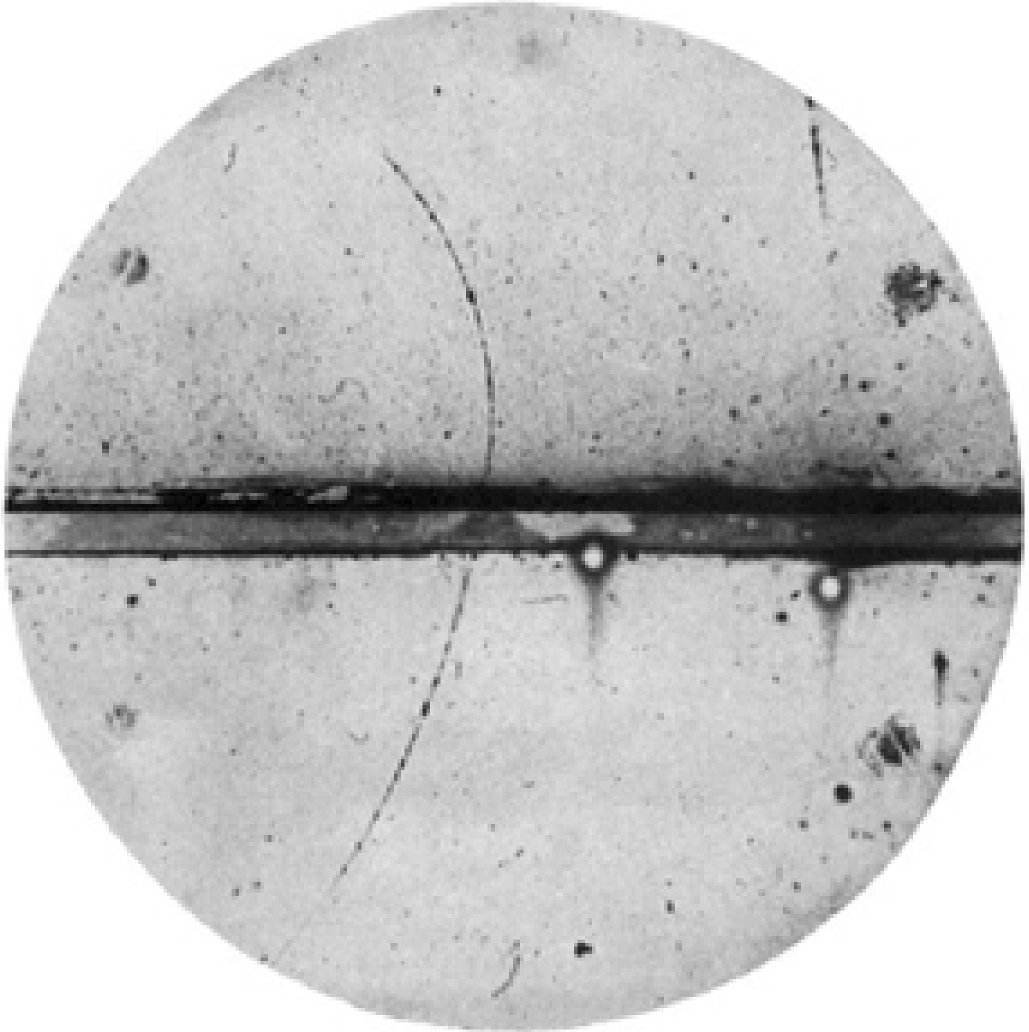
This talk is mainly based on

- Pamela data and leptonically decaying dark matter, P.F. Yin et.al., Phys. Rev. D 79, 023512 (2009), arXiv:0811.0176.
- Prospects on neutrino signals *from* Annihilating/Decaying Dark Matter to Account for the PAMELA and ATIC results, J. Liu et.al., Phys. Rev. D 79, 063522 (2009）
- Discriminate different DM scenarios *to account for the cosmic e + /- excess by synchrotron and inverse Compton radiation,* J. Zhang et.al., Phys. Rev. D 80, 023007 (2009）
- *Detecting light leptophilic gauge boson at BESIII detector,* P. f. Yin, J. Liu and S. h. Zhu, Phys. Lett. B 679, 362 (2009)
- *Detecting light long-lived particle produced by cosmic ray*, P. f. Yin, S. h. Zhu, Phys. Lett. B 685, 128 (2010)

Content

1. Brief history on synergy between accelerator/non-accelerator experiments
2. Pamela/Atic observations and possible (dark matter) explanations
3. Light boson/neutrino/photon/signals to distinguish different DM scenarios
4. V-particle(light boson) agagin?
5. Conclusions and discussions

1: Brief history



1932, Anderson

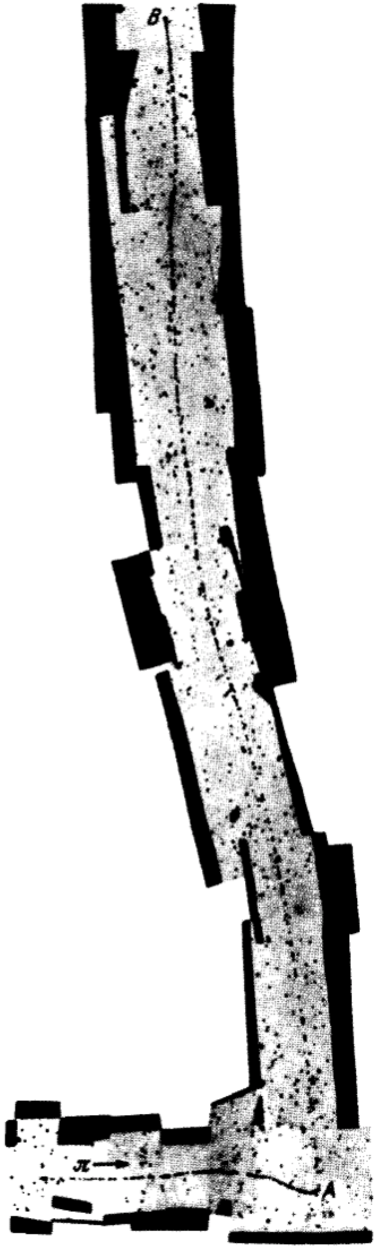
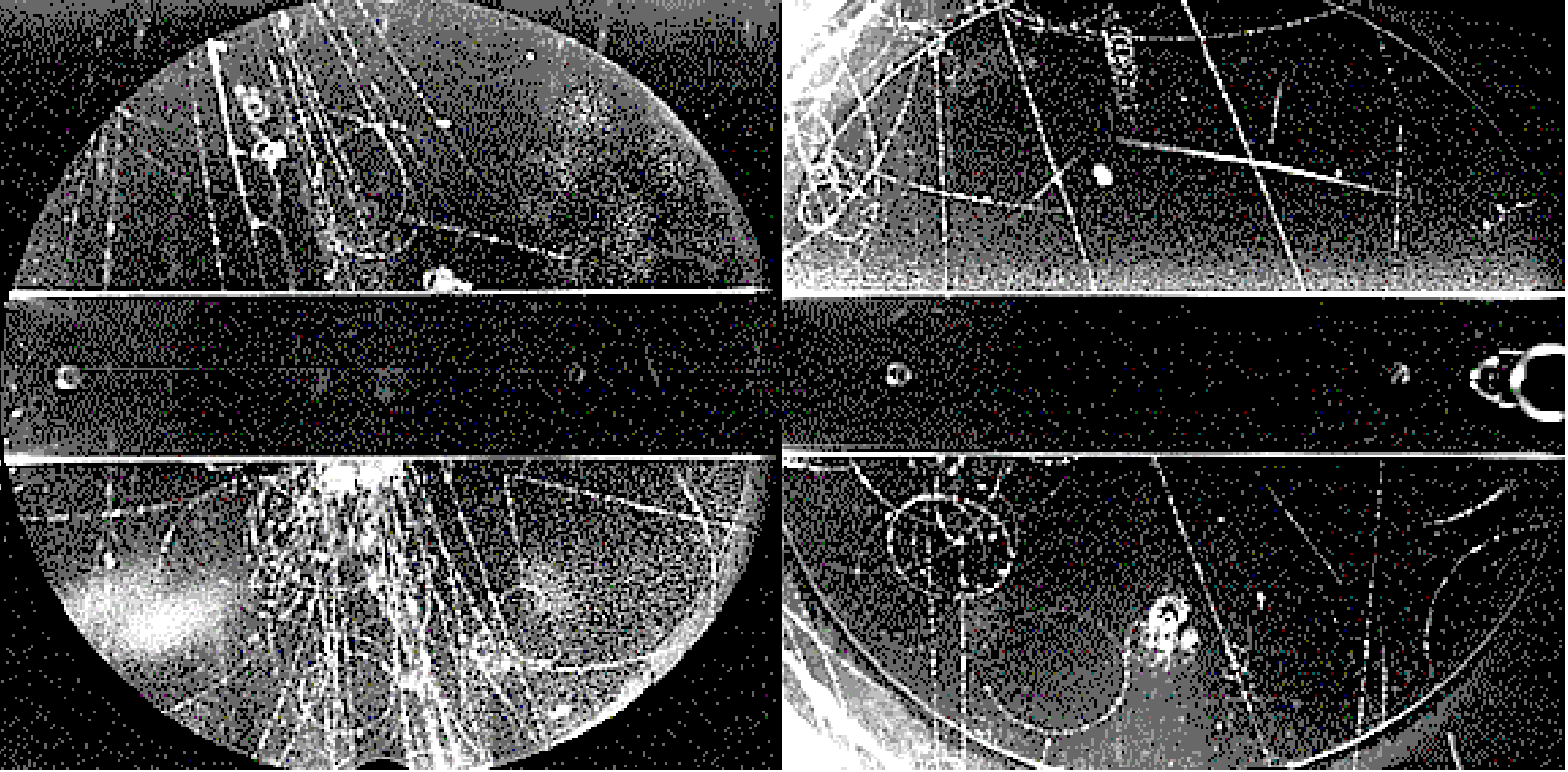


Figure 1.4 One of Powell's earliest pictures showing the track of a pion in a photographic emulsion exposed to cosmic rays at high altitude. The pion (entering from the left) decays into a muon and a neutrino (the latter is electrically neutral, and leaves no track). Reprinted by permission from C. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (New York: Pergamon, 1959). First published in *Nature* **159,** 694 (1947).

1947, Powell

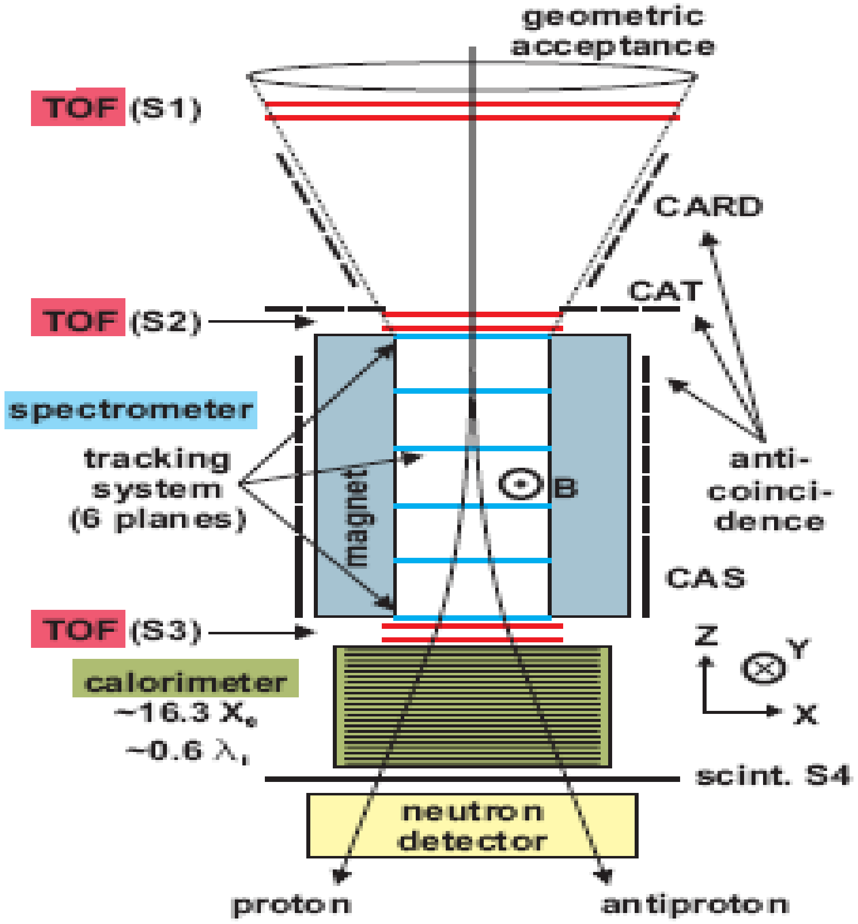


1947 by Butler and Rochester and V-particle (strange matter)

Synergy between accelerator and non-accelerator experiments

- New signature was noticed at non-accelerator expts
- Man-made accelerator-based expts pinned down the true physics behind it.
- Recently Pamela/Atic noticed some novel signatures…

2:PAMELA satellite



- **Magnetic field can distinguish charges by direction of deflexion**

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

- **Calorimeter can distinguish**

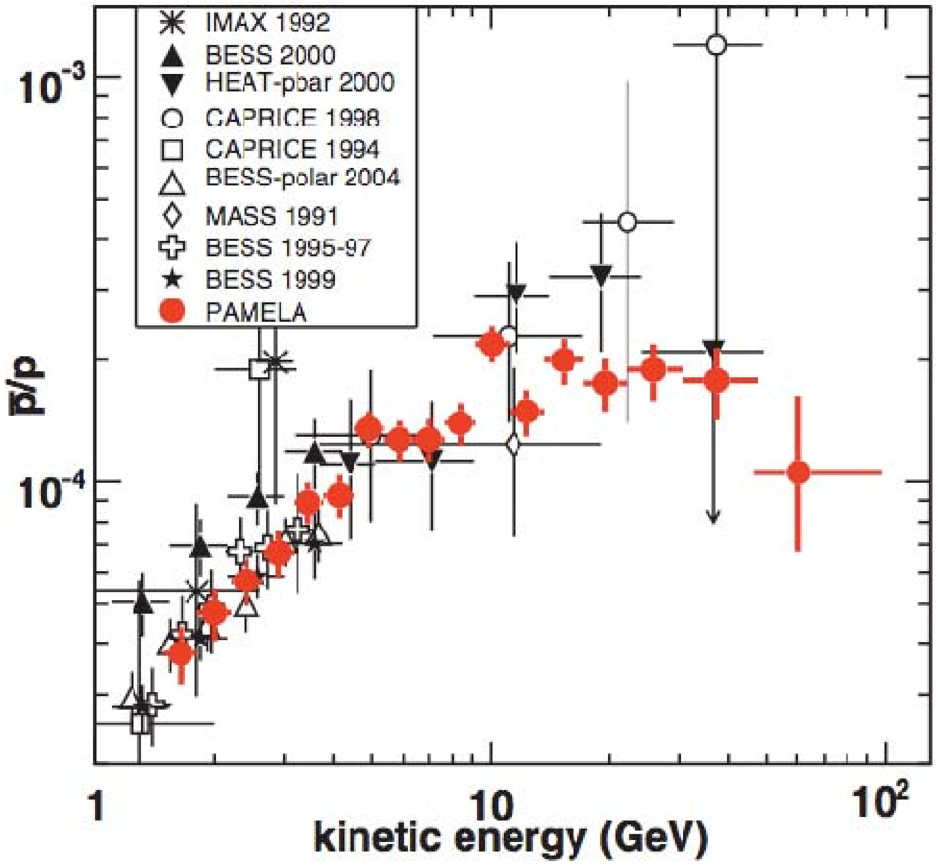
e^+, e^- $\qquad$ $\bar{p}, p$

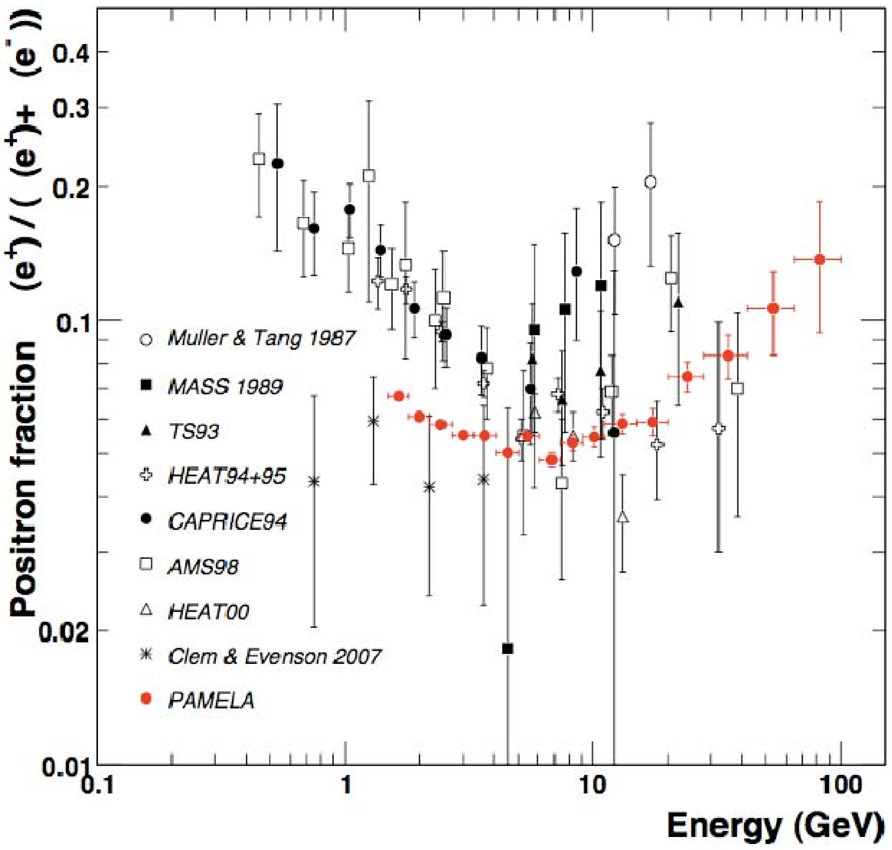
- **Detecting ability**

$$50MeV < e^+ < 270GeV$$
$$e^- < 400GeV$$
$$80MeV < \bar{p} < 190GeV$$
$$p < 700GeV$$
$$e^{\pm} < 2TeV(Cal)$$

Pamela

Pamela, 0810.4995

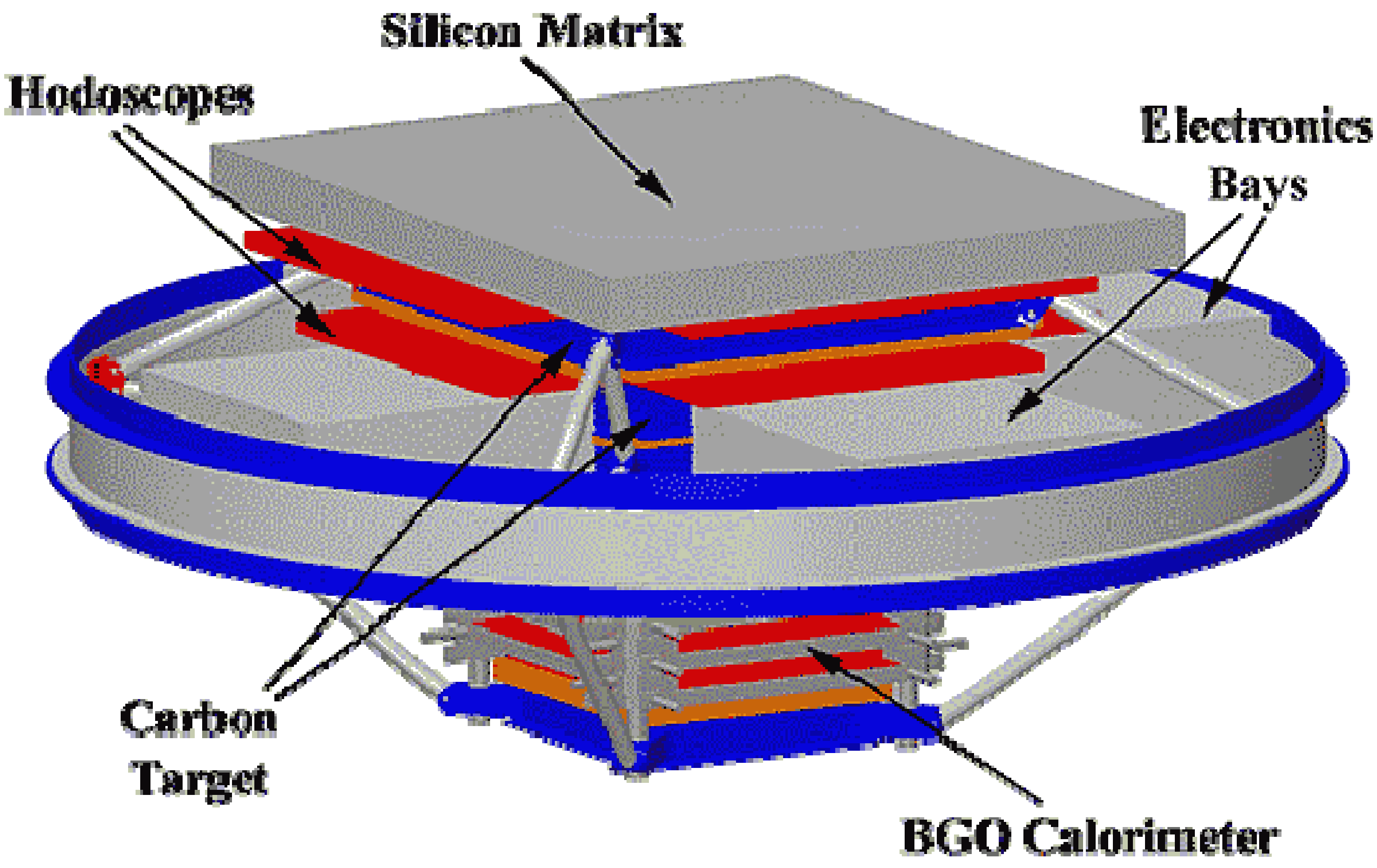




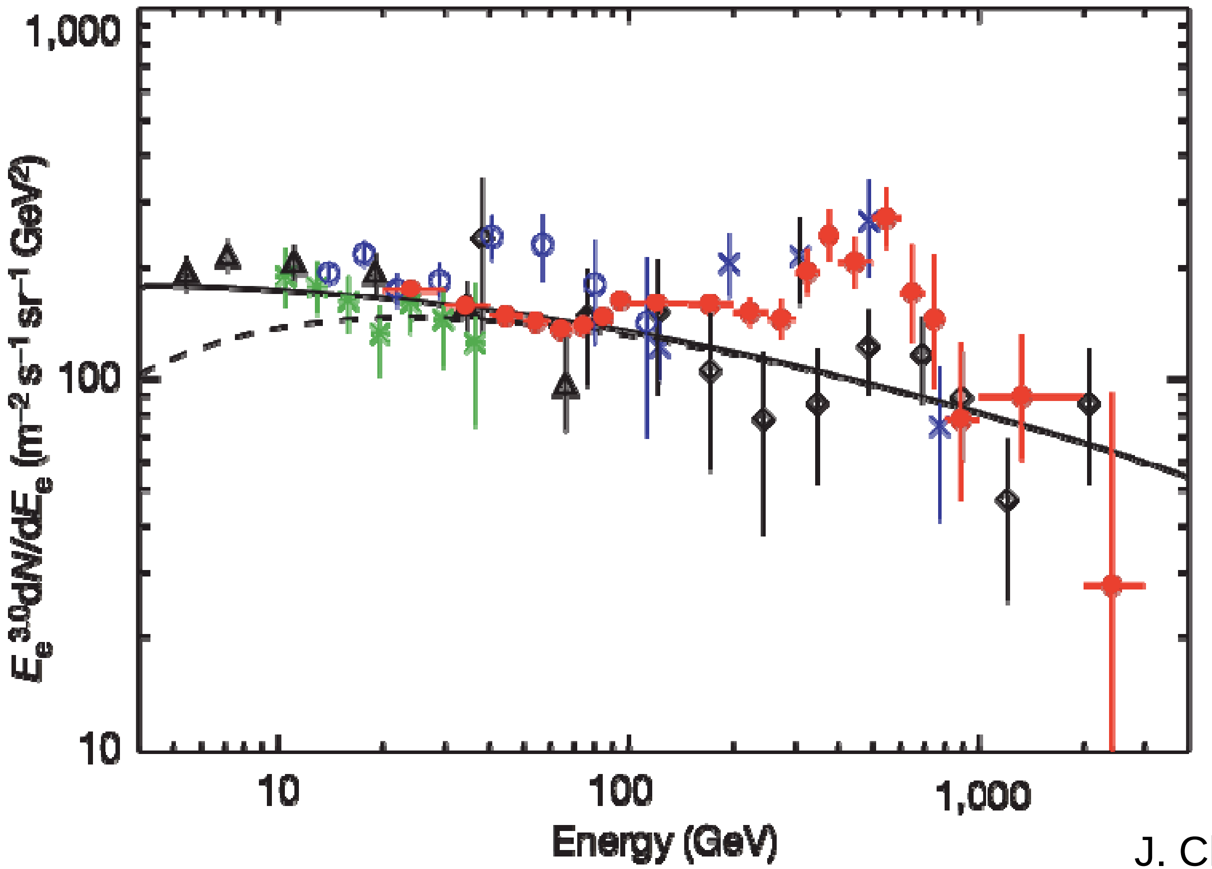
Positron and anti-proton are due to…

Pamela, PRL(2009)

Atic

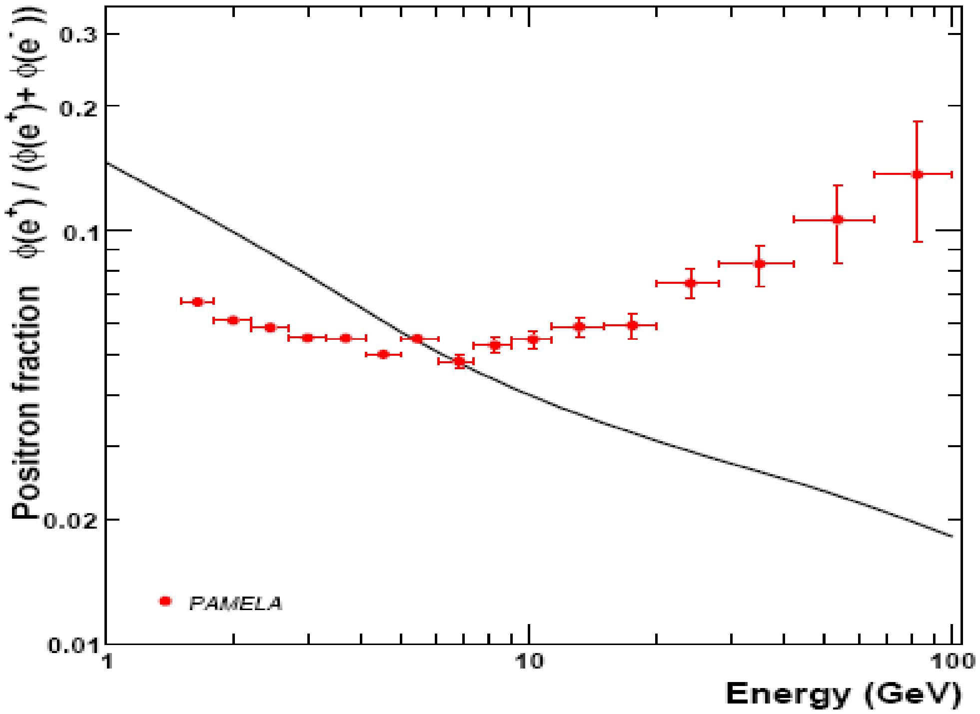

Silicon Matrix
Hodoscopes
Electronics
Bays
Carbon
Target
BGO Calorimeter

Atic



J. Chang et.al., Naure 456,362 (2008)

Implication of PAMELA data



- Need primary source of positron to provide enough flux
- The energy of such positron is up to at least 100GeV
- Not produce anti-proton
- In what energy the rise stops, ~ 800 GeV implied by Atic observation?

Possible interpretations

- Over 200 papers
- Pulsars
- Unnoticed QED process
- Dark Matter (DM) (focus in this talk)
- Not settled yet!

How to do full investigation?

- Adding primary positron/electron source
- Cosmic ray propagates to the Earth

Cosmic ray propagation

$$\frac{\partial \psi}{\partial t} = Q(\mathbf{x}, p) + \nabla \cdot (D_{xx} \nabla \psi - \mathbf{V}_c \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\nabla \cdot \mathbf{V}_c \psi) \right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r},$$

source term

diffusion coefficient
in the impulse space

fragmentation loss

diffusion coefficient

Convection velocity field that corresponds to
galactic wind

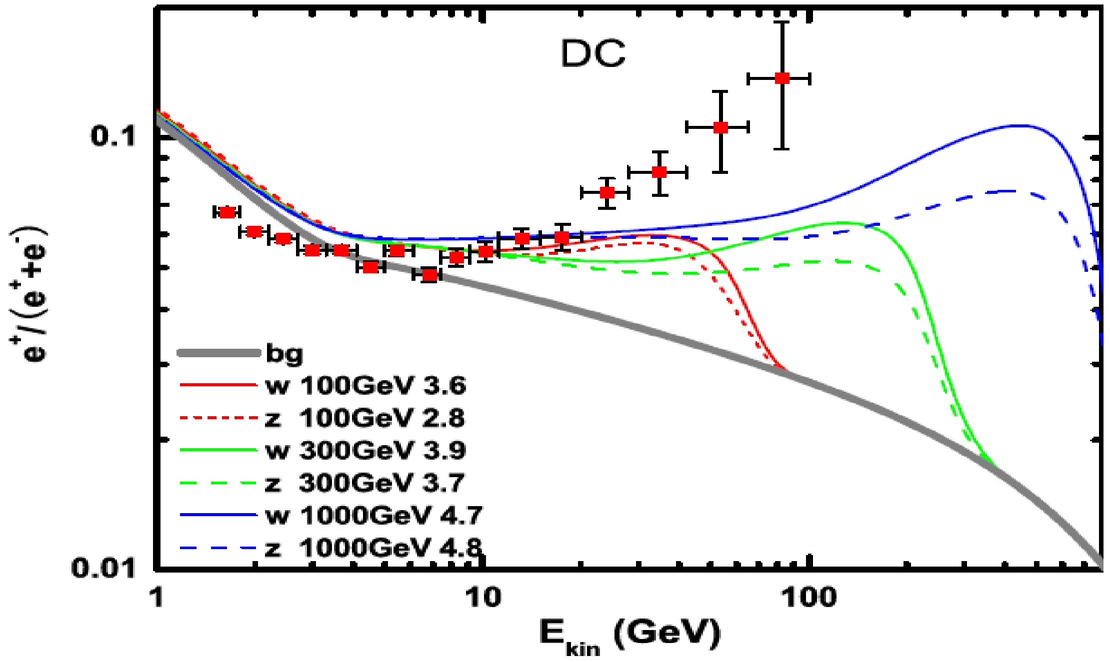
radioactive decay loss

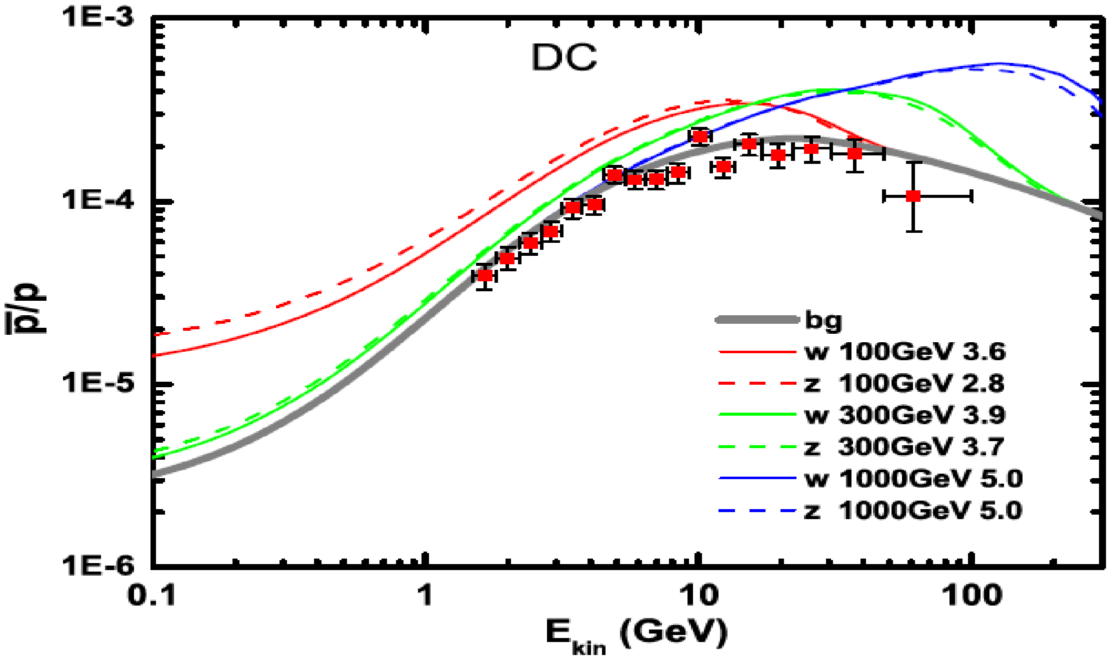
- **Propagation equation**
  http://galprop.stanford.edu/web_galprop/galprop_home.html
- **Solved by GALPROP**

Two propagation models of GALPROP

- Diffuse+ Convection (DC)
  Diffuse+ Reacceleration (DR)
- Considering constraint from B/C and 10Be/9Be
- Analysis both on positron and anti-proton
- Many authors use analytic formula to give positron fraction, and no anti-proton analysis

Positron arising from mono-energetic gauge boson

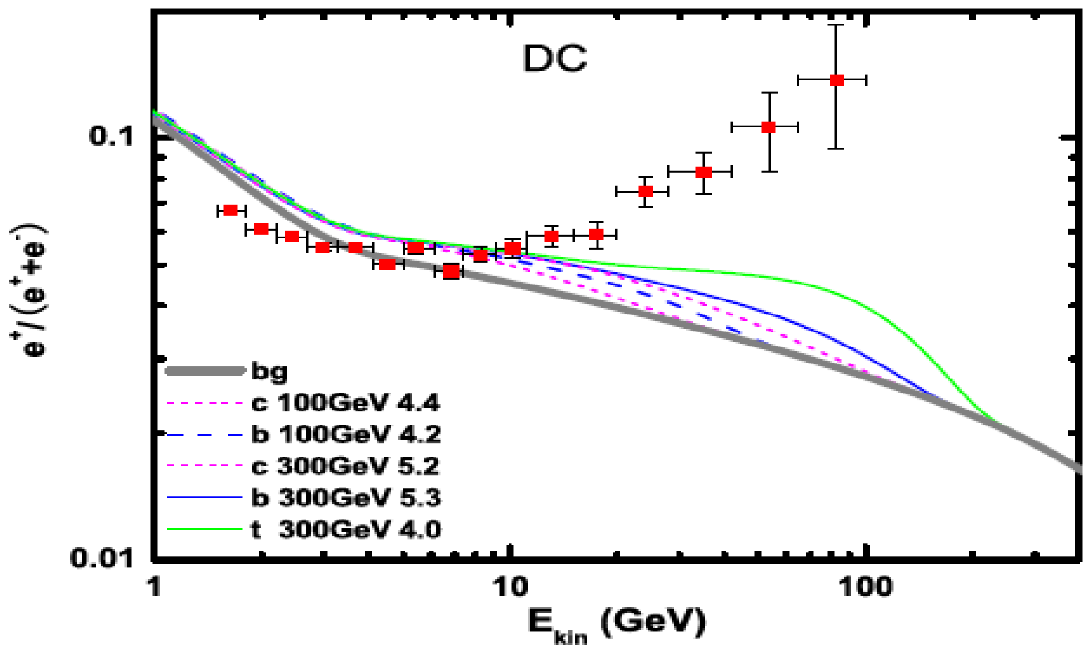


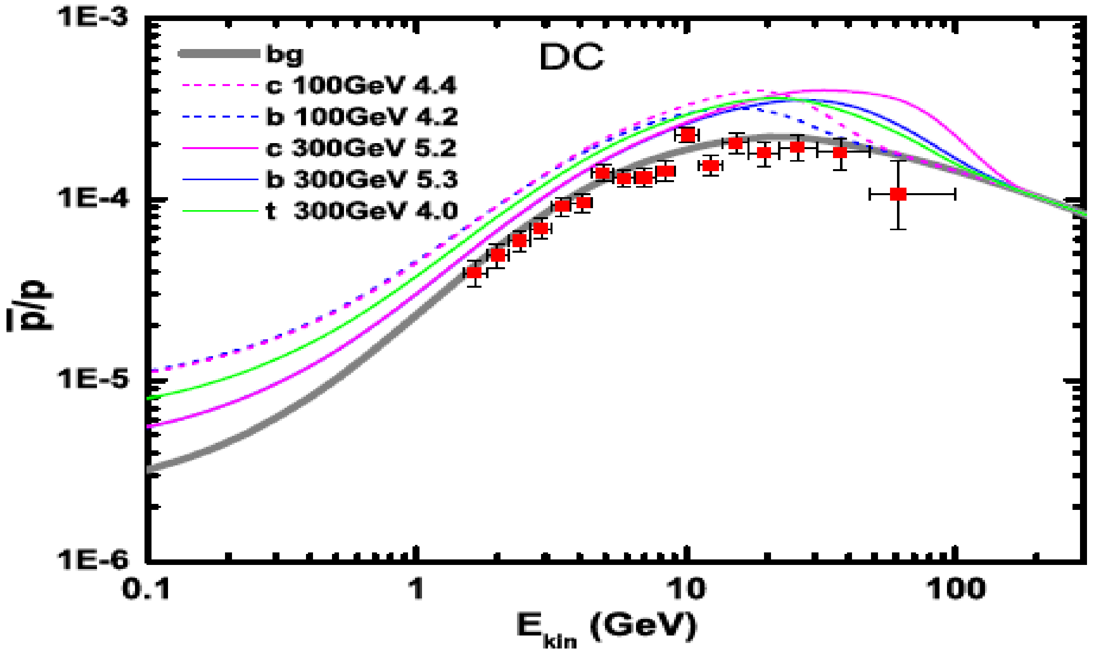


Positrons from gauge bosons are disfavored

- Examples for gauge boson as the final products of DM
- J. Hisano et al (wino)
- G. Kane et al (wino 200GeV)
- A. Ibarra et al (gravitino decay)

Positron from mono-energetic quark

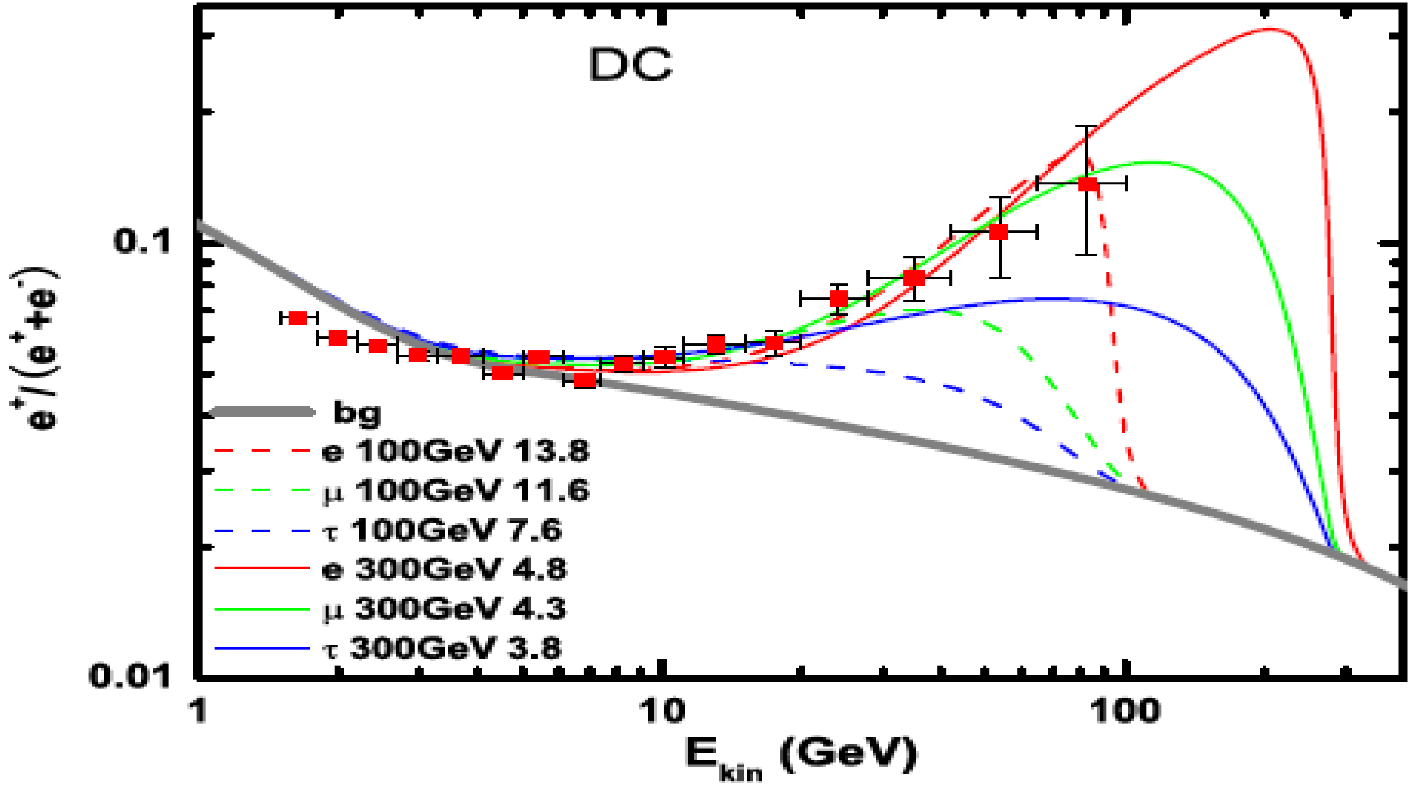




Positrons from quarks are disfavored

- b quark (~50GeV) is favored to interpret EGRET gamma ray excess
- In mSUGRA, bino and higgsino mixture.
  Now, disfavored by PAMELA data
- KK DM in universal extra dimension (UED) model has problem in explaining the anti-proton flux.

Positron from mono-energetic charged lepton



	Gauge boson	Quarks	Leptons
Positron	$\surd$	$\times$	$\surd$
anti-Proton	$\times$	$\times$	$\surd$

Annihilating DM and the "dark secret"

$$Q_A(\mathrm{r}, E) = BF \frac{\langle \sigma v \rangle_A \rho^2(r)}{2\, m_{DM}^2} \left. \frac{dN(E)}{dE} \right|_A$$

- WIMP DM was in chemical equilibrium with usual matter at relatively higher temperature in the early Universe; however DM is annihilating now at lower temperature to produce flux of observed SM particles.
- If interpreting Pamela/Atic, a mysterious mismatch exists, namely Boost Factor (BF) is introduced!

Proposed physical solutions to BF

- DM Sub-halo
- Non-thermal DM production — **T. Moroi et al, hep-ph/9906527 ……**
- Sommerfeld enhancement — **J. Hisano et al, hep-ph/0412403 ……**
- Breit- Wigner enhancement — **M. Ibe et al, arXiv:0812.0072…**
- ……
- Not settled yet and need more data! For example, the light (GeV or less) particle should be confirmed/excluded by BES and/or other low energy colliders.

Why decaying DM

$$Q_D(\mathrm{r}, E) = \frac{1}{\tau_{DM}} \frac{\rho(r)}{m_{DM}} \left. \frac{dN}{dE} \right|_D$$

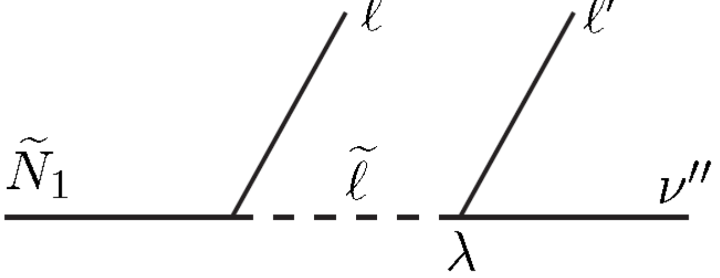
- In this scenario, the lifetime of DM is an extra parameters
- In order to solve the long-standing cold DM problem on the number of stars within galaxy

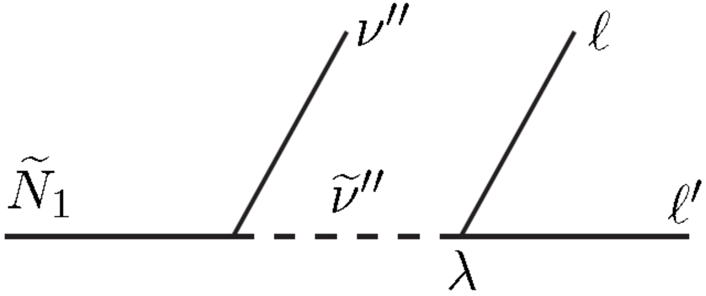
Decaying DM

- Neutralino 3-body decay — **P.F. Yin et al,** arXiv:0811.0176
- right-handed sneutrino — **C. R. Chen et al, arXiv: 0810.4110**
- gravitino — **W. Buchmuller et al, hep-ph/0702184; G. Bertone, arXiv:0709.2299; A. Ibarra et al, arXiv:0709.4593; A. Ibarra et al, arXiv:0804.4596; K. Ishiwata et al, arXiv:0805.1133; L. Covi, arXiv: 0809.5030**
- new gauge boson — **C. R. Chen et al, arXiv: 0809.0792**

Neutralino with R-parity violation

$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \overline{E}_k$$



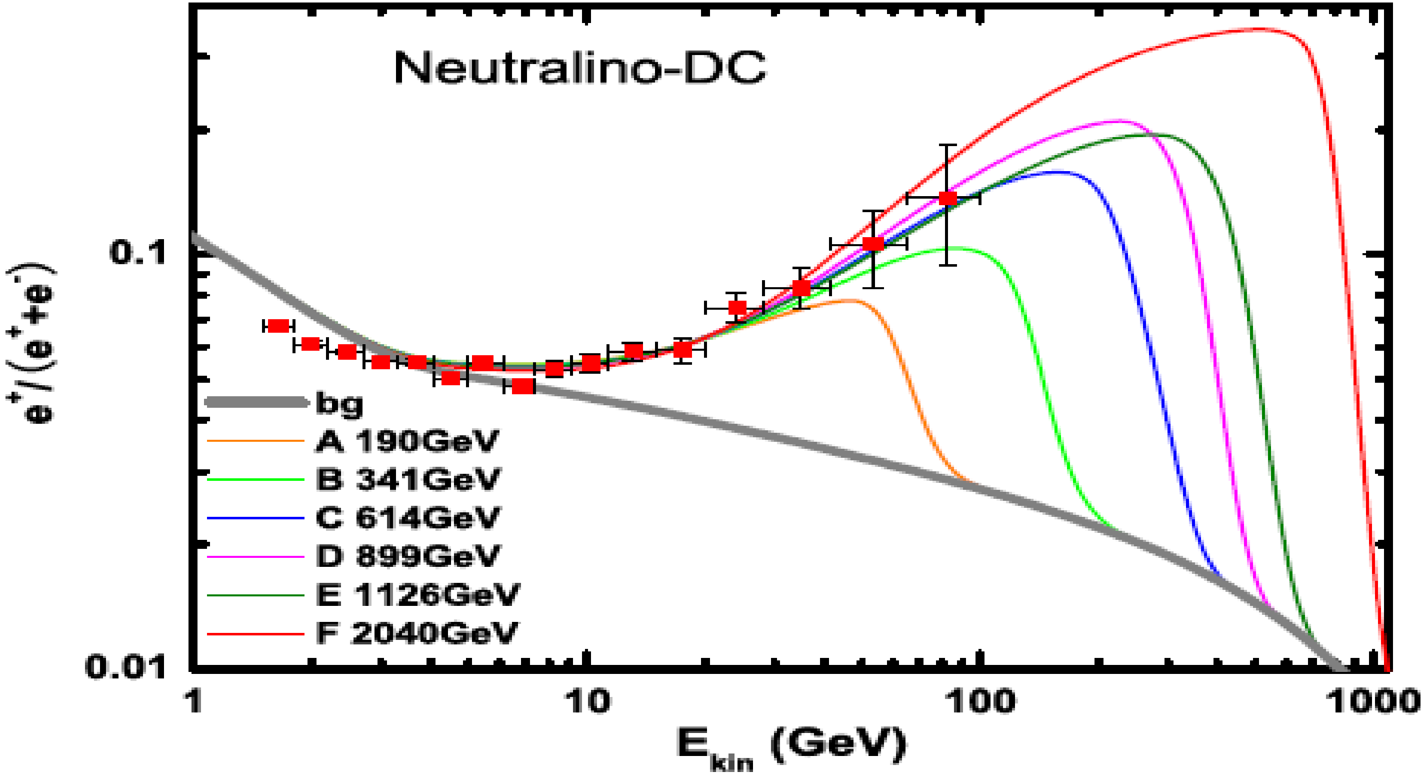


Benchmark points

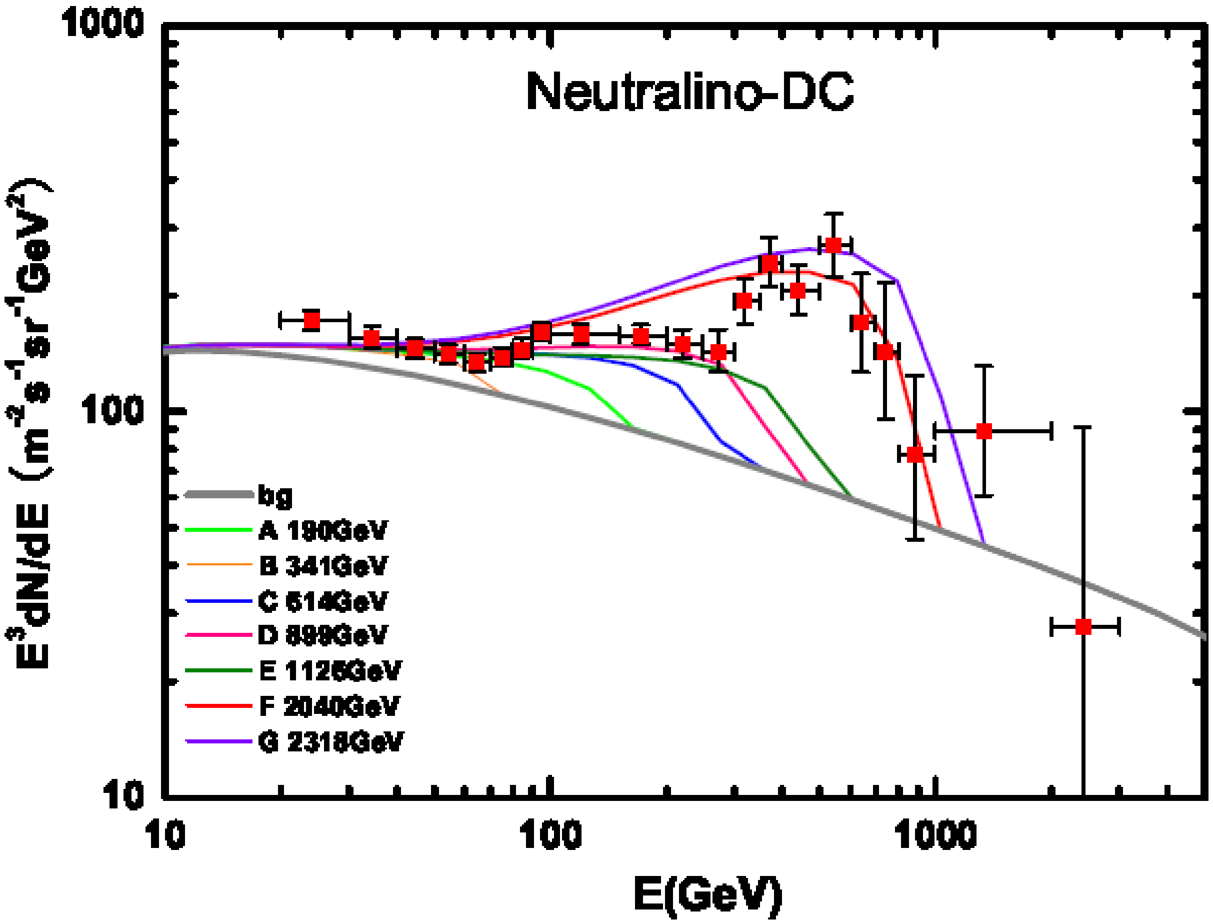
	SUSY	MC	Mass(GeV)	$m_0(GeV)$
A	SPS6	bino	190	150
	SUSY	MC	Mass(GeV)	$m_0(GeV)$
B	mSUGRA	bino	341	900
C	mSUGRA	bino	614	1750
D	mSUGRA	bino	899	5000
E	mSUGRA	higgsino	1126	9100
	SUSY	MC	Mass(GeV)	$m_0(GeV)$
F	AMSB	wino	2040	18000

DC	$\tau(10^{26}s)$	$\lambda'(10^{-25})$	DR	$\tau(10^{26}s)$	$\lambda'(10^{-25})$
A	9.1	2.2	A	7.3	2.5
B	5.3	10.3	B	4.3	11.3
C	3.4	11.5	C	2.8	12.4
D	2.5	41.5	D	2.0	46.4
E	2.0	180.1	E	1.7	195.1
F	1.2	113.7	F	1.0	122.8

Benchmark points



Benchmark points



Comments on Pamela/Atic interpretations

- Only one R-violating term in super potential can fit the PAMELA well for neutralino mass from 600GeV~2TeV, and other collider signature unchanged

- Currently 3 ways for interpreting PAMELA
  pulsars
  annihilating DM
  decaying DM
  they can both fit ATIC (which implies heavy DM)

- How to distinguish these different scenarios?

3: How to distinguish different scenarios?

Detecting light leptophilic gauge boson at BESIII

- We adopt an extra U(1) group as $L_e - L_\mu$, $L_e - L_\tau$ or $L_\mu - L_\tau$
- Lagrangian

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4}F'^{\,2}_{\mu\nu} + \frac{\kappa}{2}F'_{\mu\nu}F^{\mu\nu} + \sum_l \bar{l}(i\not{D} - m_\psi)l \\ &+ |D_\mu S|^2 - V(S) + \lambda_{SH}(S^\dagger S)(H^\dagger H) + \mathcal{L}_{DM} \end{aligned}$$

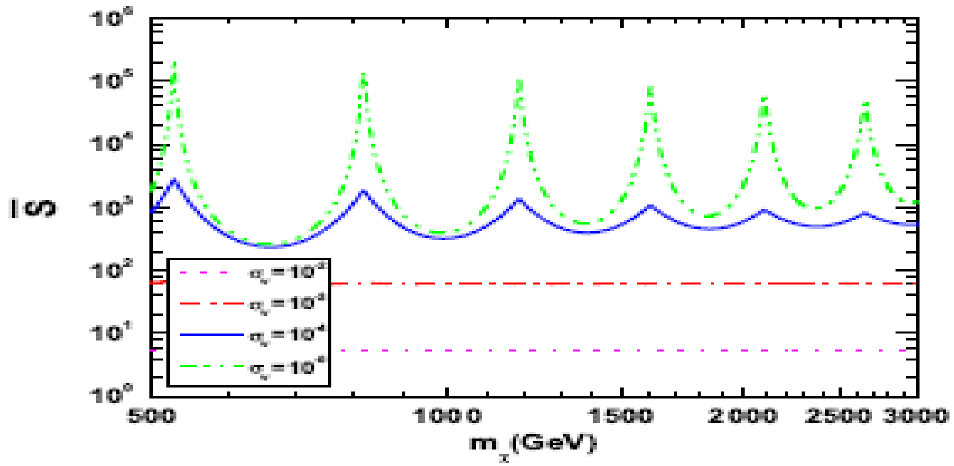
$$D_\mu = \partial_\mu + i g_A U_\mu$$

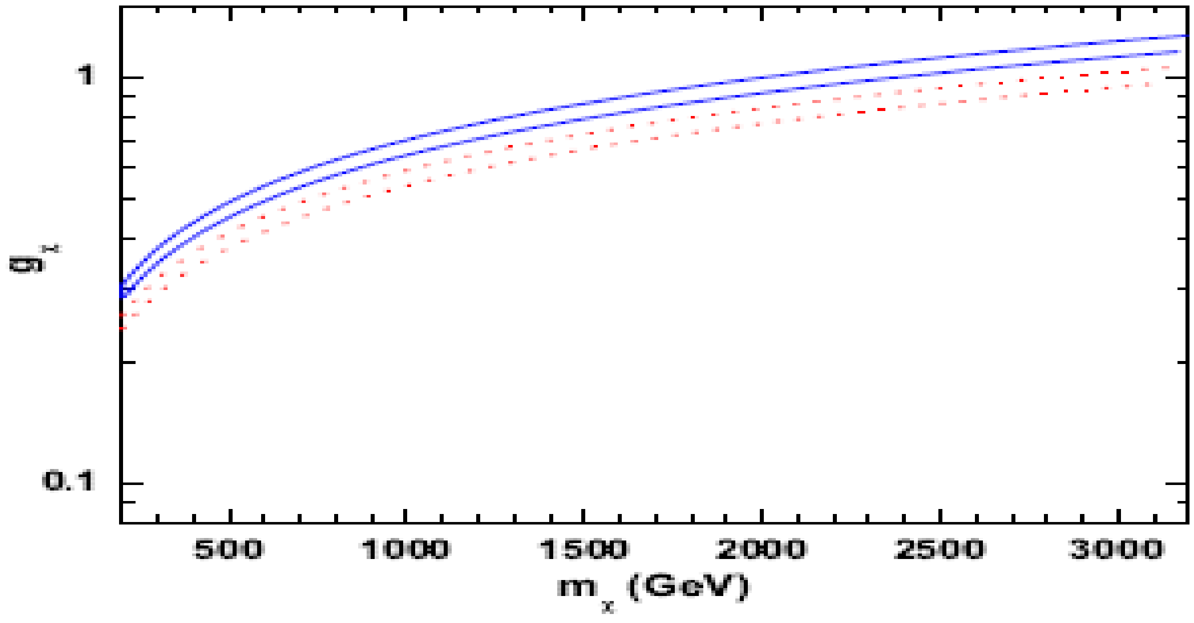
$$g_A = g'' \cdot C_A$$

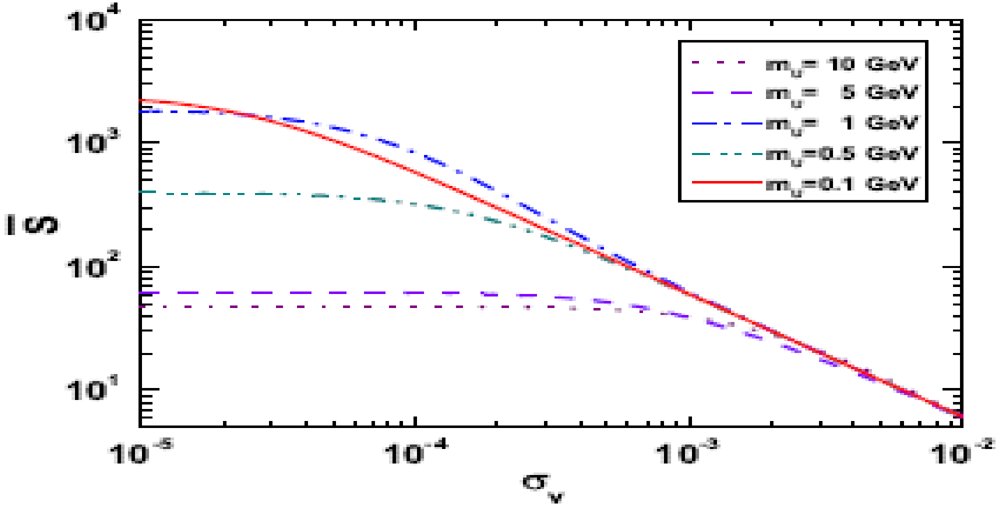
Yin, Zhu, PLB,2009

- Constrained by low-energy experiments, such as anomalous magnetic moments g-2, ν-e scattering, *etc*

- Account for relic density and boost factor







BESIII

- Mainly produced via the process $e^+e^- \rightarrow U\gamma$
- At the **BESIII**, luminosity $10^{33}cm^{-2}s^{-1}$ at $\sqrt{s} = 3.097GeV$
- Integrated luminosity as $20fb^{-1}$
- Energy resolution $2.3\%/\sqrt{E(GeV)} \oplus 1\%$, for **20MeV** to **2GeV.**
- Only consider extra gauge boson decay to neutrino, electron/positron, moun.

- Invisible decay $e^+e^- \rightarrow U\gamma \rightarrow \nu\bar{\nu}\gamma.$

  cut conditions $|\cos\theta_\gamma| < 0.9$

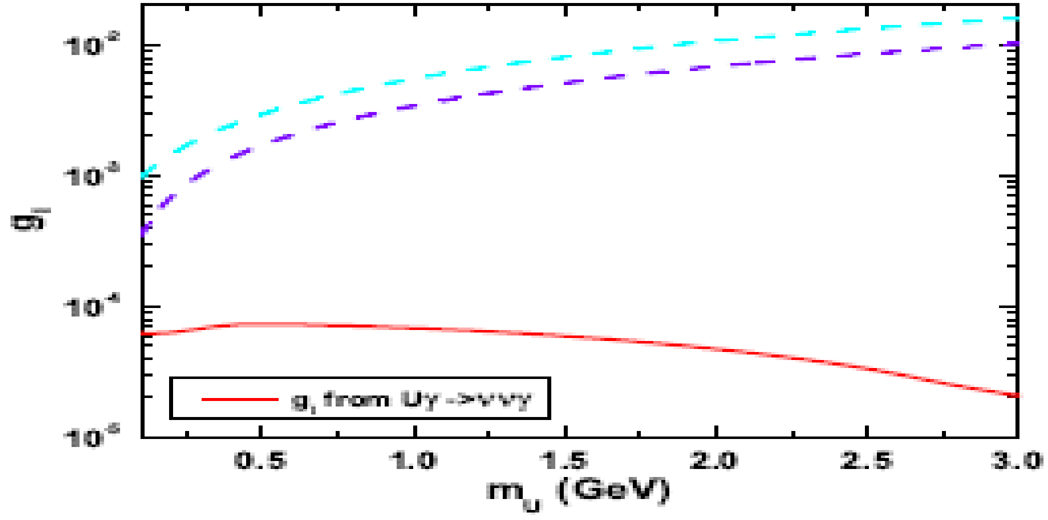
  $E_\gamma > (s - m_U^2)/(2\sqrt{s}) - 0.2GeV$

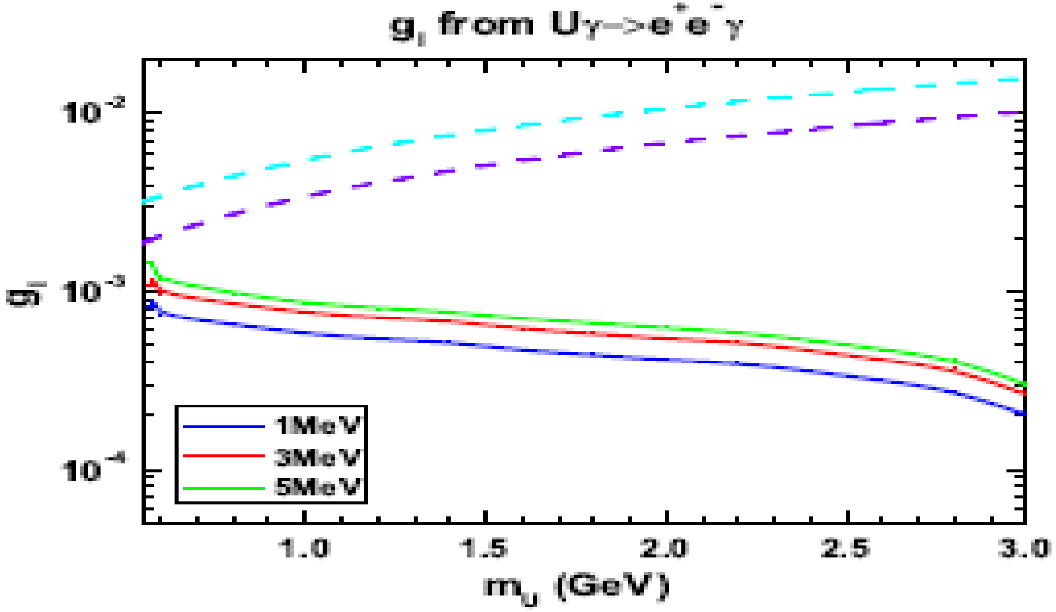
- Visible decay $e^+e^- \rightarrow U\gamma \rightarrow l\bar{l}\gamma$

  cut conditions $| m_{l\bar{l}} - m_U |< 1, 3 \; or \; 5MeV,$

  $\cos(\theta_{l\gamma}) < 0.94$

  $\cos(\theta_l) < 0.9.$





5 sigma sensitivity: 10^{-4}-10^{-5} for Invisible decay mode due to low SM backgounds, 10^{-3}-10^{-4} for visible decay mode!

4: Long-lived light boson

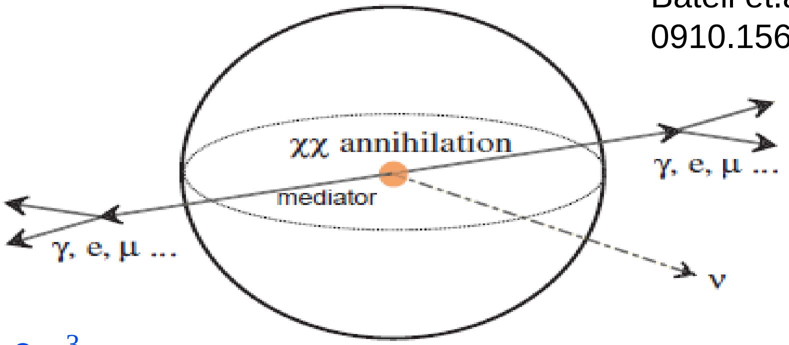
- In general, the lifetime of light boson is a free parameter,

  limited only by BBN t<1s , may be long-lived particle (LLP)

- Hidden sector with vector and Higgs portal

$$\mathcal{L} = -\frac{1}{4}F'^{2}_{\mu\nu} + \frac{\kappa}{2}F'_{\mu\nu}F^{\mu\nu} + |D_\mu h'|^2 - V(h') + \lambda_{h'H}(h'^\dagger h')(H^\dagger H) + \mathcal{L}_{DM} + \mathcal{L}_{SM}.$$

Batell et.al., 0910.1567



- **Abelian U(1) group**

  Hidden gauge boson $\gamma c\tau_{A'} \propto 1/\kappa^2 \ll 1cm$ $\kappa \sim 10^{-3}$

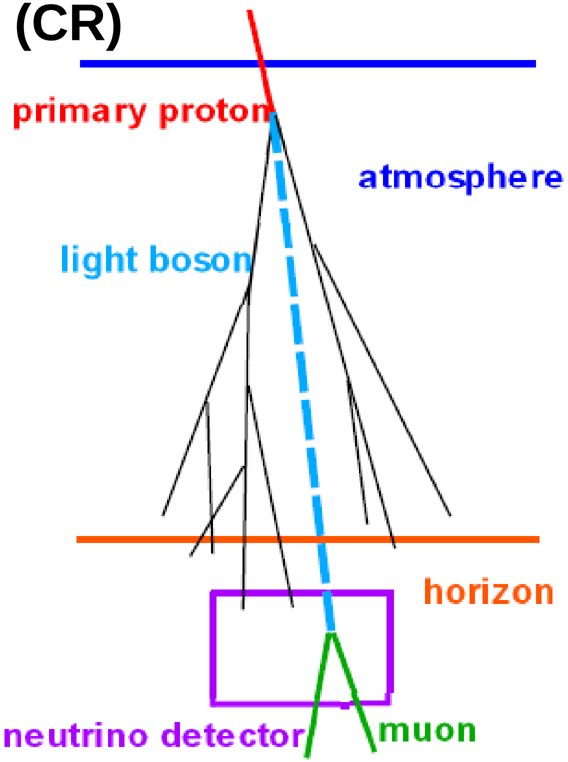
  Hidden Higgs boson if $m_{A'} > m_{h'}$ h' decay through a triangle loop

$$\gamma c\tau_{h'} \propto 1/(\kappa^4 \cdot loop\_factor) > O(10^5)km$$

- **Non-Abelian gauge group** contains an array of Hidden light bosons, some lighter particles might be LLPs

V-particle at neutrino telescope

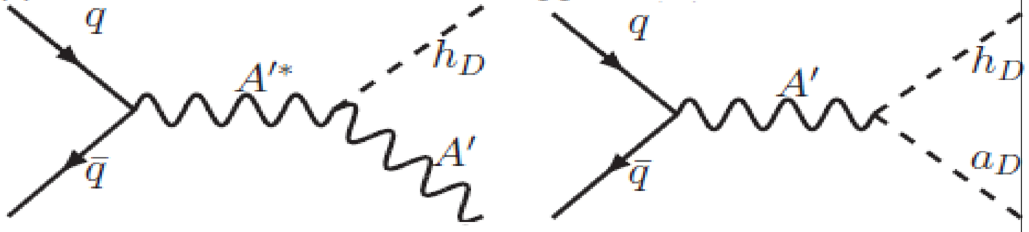
- **Detecting LLP produced by cosmic ray (CR)**



Yin, Zhu, PLB,2010

- **Two production processes**

$pp \to A'^{*} + X \to A'h' + X$ $\quad$ $pp \to A' + X \to h'a' + X$

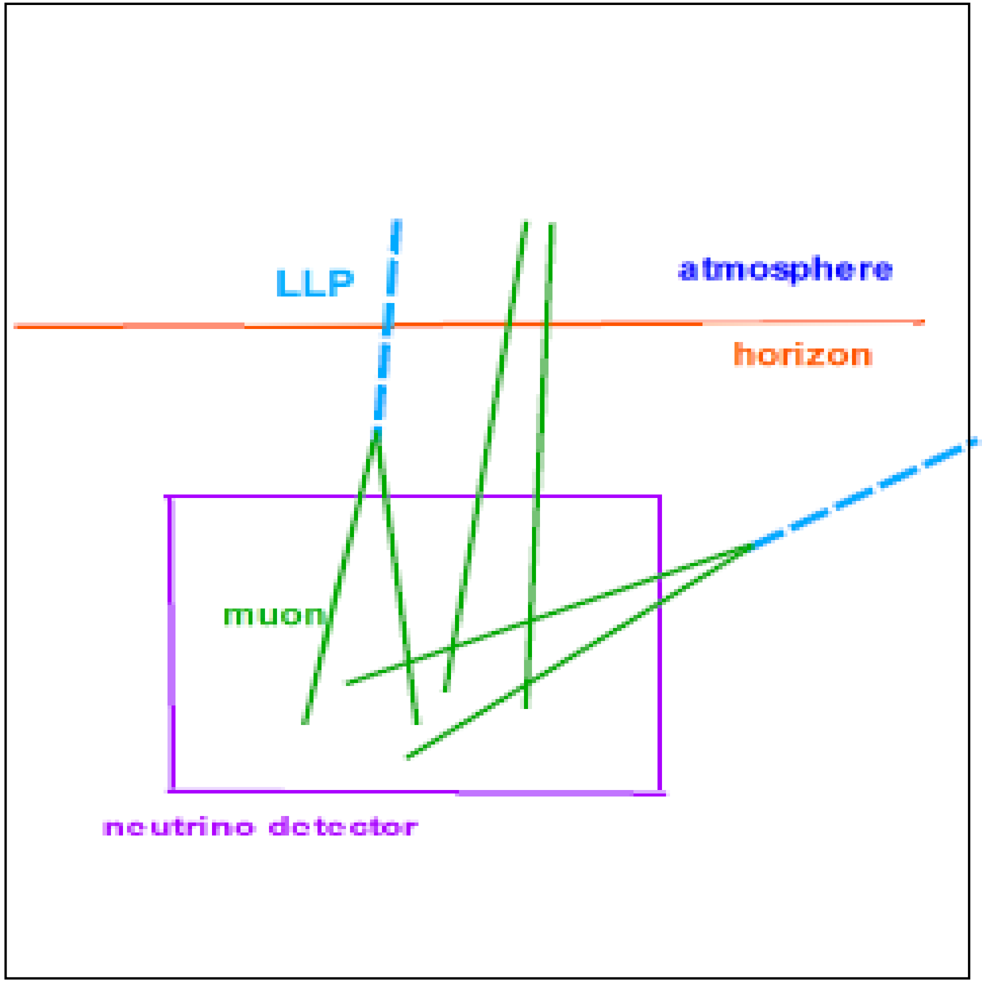


- The flux of primary nucleons in the cosmic rays $\Phi_N(E) \approx 1.8 (E/GeV)^{-\alpha} \frac{nucleons}{cm^2\ s\ sr\ GeV}$

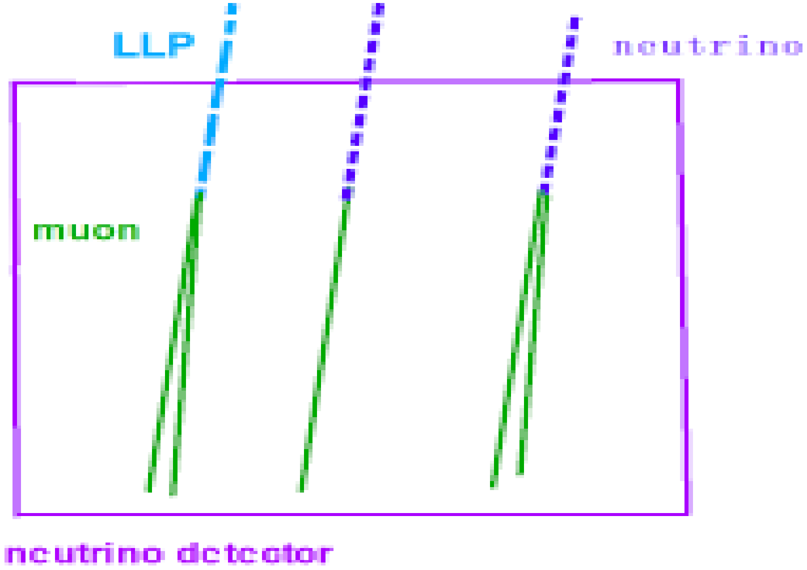
- The main component is proton

- The flux of new particles produced by CR $\mathcal{P}^h_{h'}(E) \approx A\sigma^{hN}_{h'}/\sigma_T$

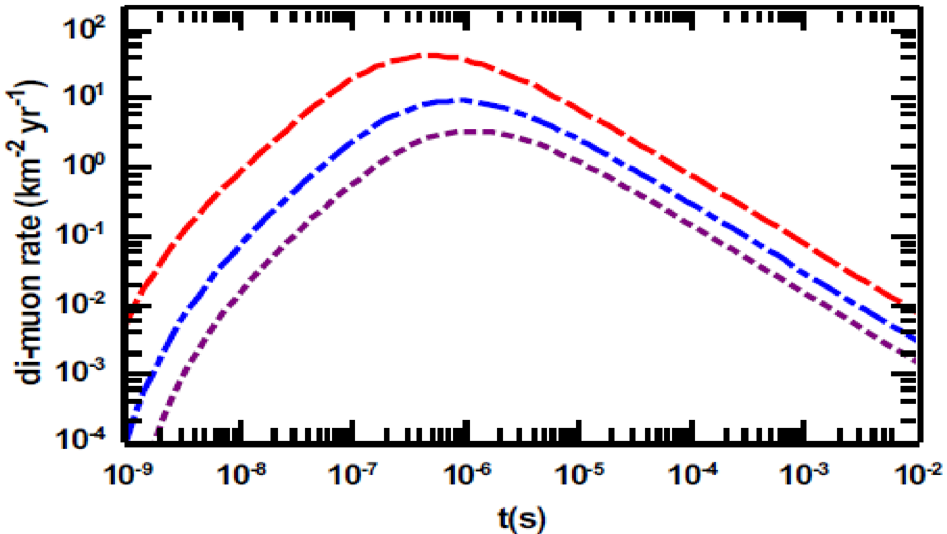
$$\Phi_{h'} = \sum_h \int_{E_{min}}^{E_{max}} dE\ \Phi_h(E)\ \mathcal{P}^h_{h'}(E)$$



- **LLPs decay near the detector**
- di-muon events entering the detector
- **Large muon background**
- **Large di-muon background**
- One shower contains many hadrons, two muons from different hadrons decays
- Electro-weak Drell-Yan processes
- Difficult to suppress



- **LLPs decay in the detector** di-muon with ‘obvious’ decay vertex
- **The angle between two muons is small**
- **Di-muon background**
- Detecting hadronic shower arising from vN interaction may be useful to reject such backgrounds



IceCube can observe O(10)events km^-2 yr^-1!

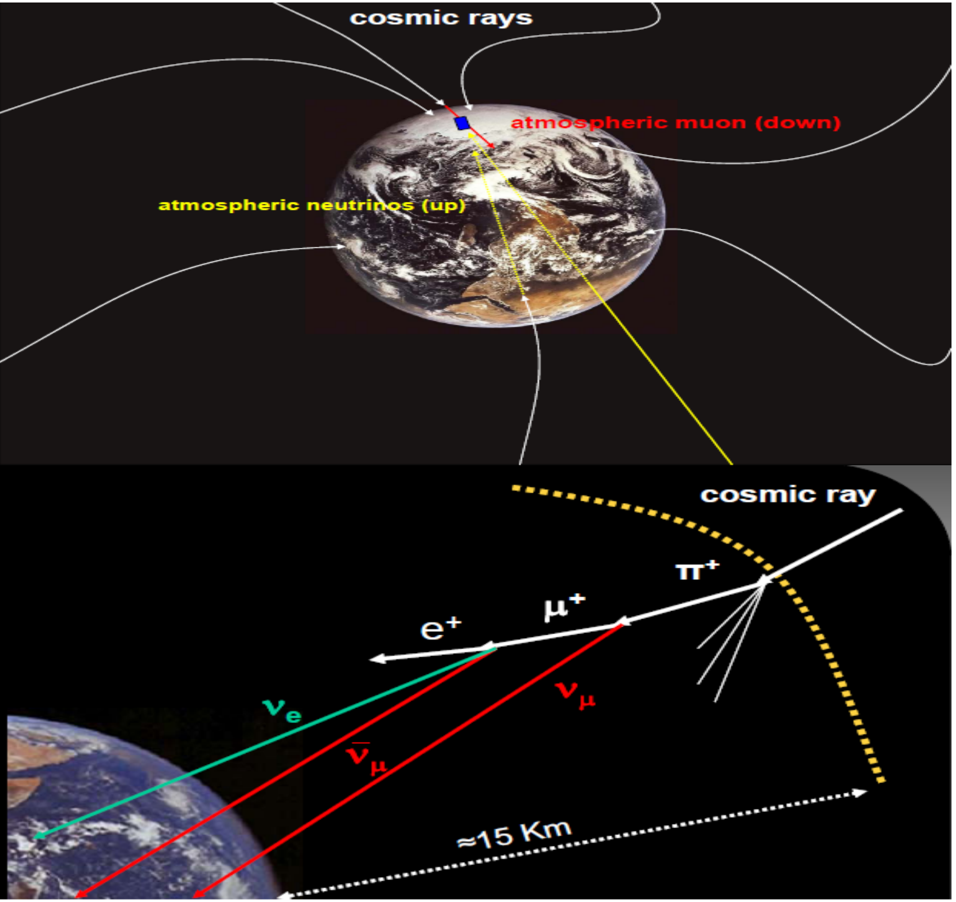
5: Conclusions and Discussions

- Pamela/Atic may have provided new insights (DM?) on particle physics.
- Neutrino telescope and other non-accelerator observations are necessarily consistent with the DM intepretation of Pamela observation.
- Colliders (BES/Babar/LEP/Tevatron/LHC) are necessary machines to pin down the whole picture.
- V-particle in cosmic ray again?
- The era of synergy between non-accelerator and accelerator experiments!

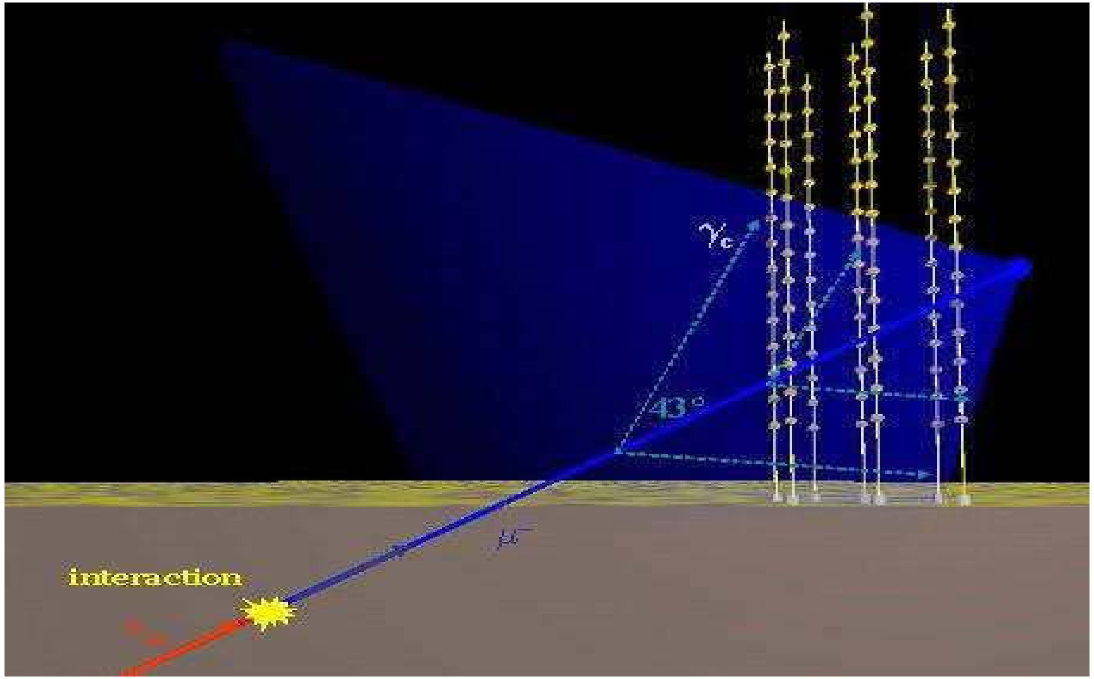
Thanks for your attention!

Backup slides

Detect neutrinos in the deep ice/water

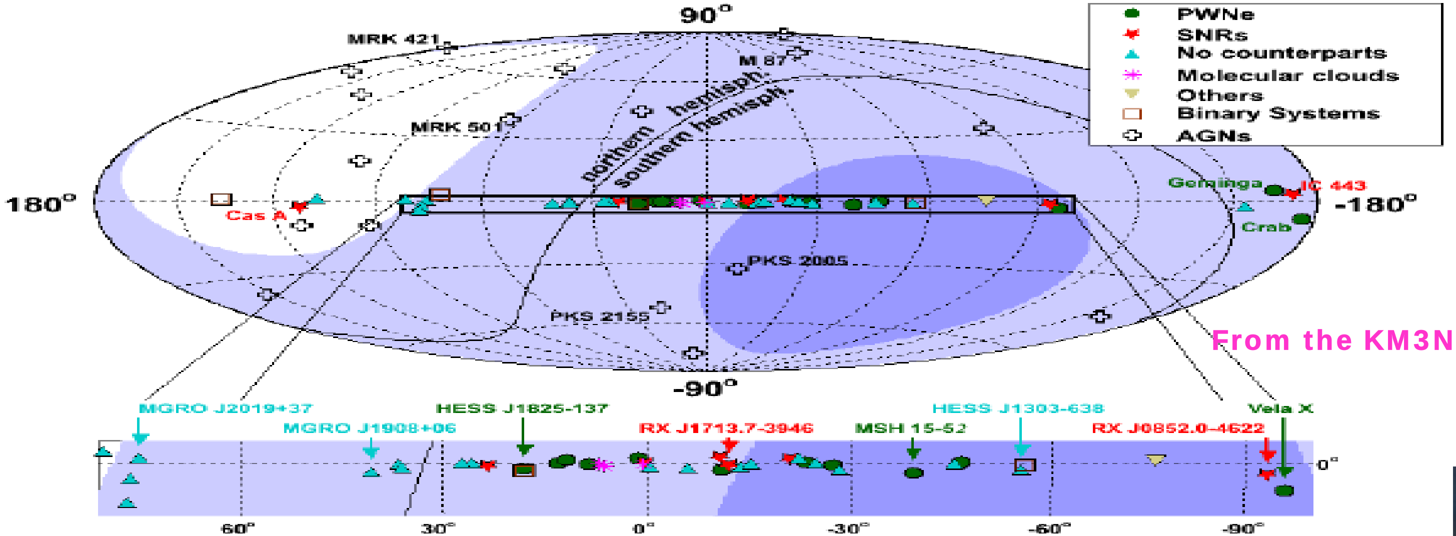


From the talk of F. Halzen, DM Workshop 07

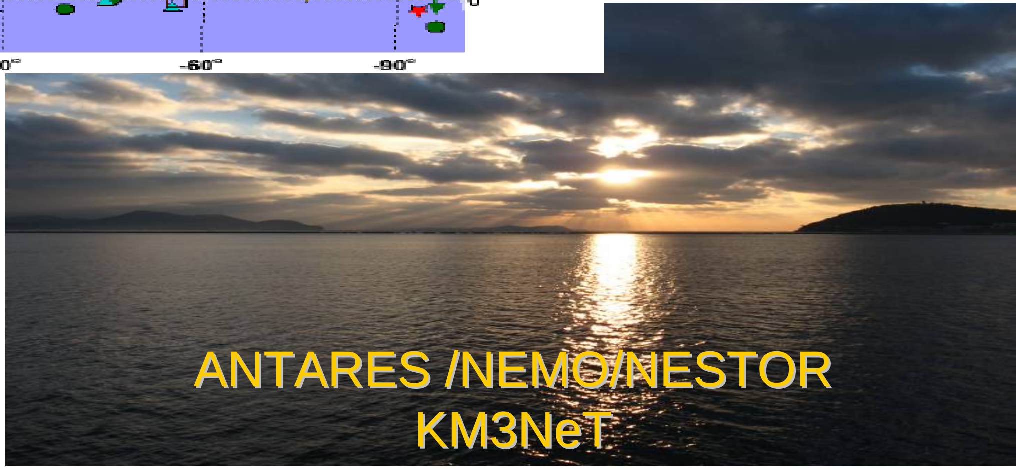


From the KM3NeT design report

IceCube and Antares



From the KM3NeT design report



From the talk of J. Carr, IHEP summer school 08

Neutrino Signals from Dark Matter in Light of PAMELA /Atic results

- Neutrino Signal
  1. neutrinos from muon/tau decay
  2. large neutrino flux associate with large positron signals
  3. high energy neutrino >600GeV or higher as signals. The background (due to …) is smaller.

- Especially, “Sommerfeld effect” enhances the signal from DM subhalo due to the lower velocity dispersion.

N. Arkani-Hamed et al. , Phys. Rev. D. 79, 015014 (2009).

Neutrino flux from DM annihilation in the galactic center (GC) and DM Subhalo

$$\phi^A(E,\theta) = \rho_\odot^2 R_\odot \times \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN}{dE} \times J^A(\theta)$$

- Neutrino flux formula

local DM density 0.34 GeV cm^-3

Distance between the GC and Sun 8.5 kpc

- Particle Physics factor

$$\langle\sigma v\rangle = \langle\sigma v\rangle_0 \times \mathrm{BF}.$$

typical cross section for DM relic density

Boost fatcor

- Astrophysical factor

$$J^A(\theta) = \frac{1}{\rho_\odot^2 R_\odot}\int_{\mathrm{LOS}} \rho^2(l)dl$$

$$\rho(r) = \frac{\rho_s}{(r/r_s)^\gamma[1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

DM mass density profile

Neutrino flux from DM decay in the GC and Subhalo

$$\phi^D(E,\theta) = \rho_\odot R_\odot \times \frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi}\frac{dN}{dE} \times J^D(\theta)$$

- Neutrino flux formula

- Particle Physics factor

lifetime of DM

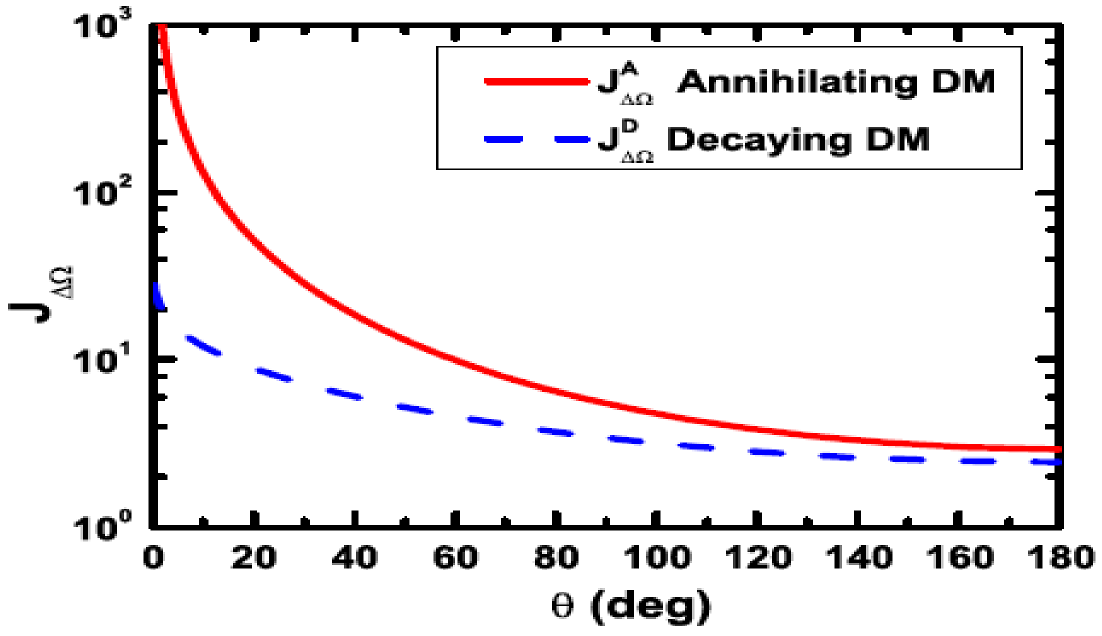
- Astrophysical factor

$$J^D(\theta) = \frac{1}{\rho_\odot R_\odot}\int_{\mathrm{LOS}} \rho(l)\,dl$$

- The solid angle average of J factor is defined as

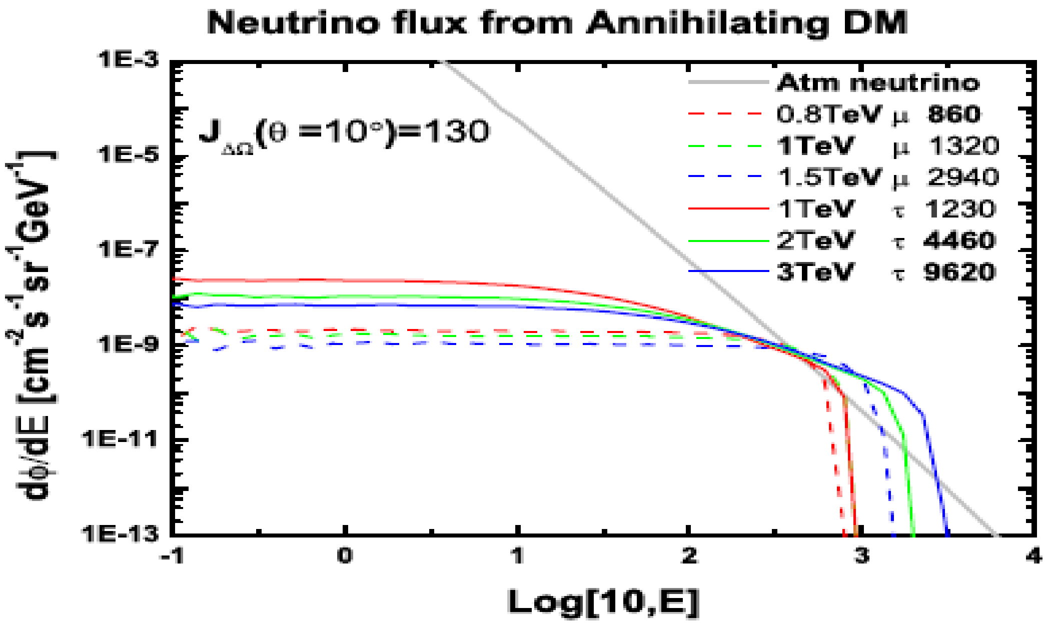
$$J^{A,D}_{\Delta\Omega} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} J^{A,D}(\theta)\,d\Omega,$$

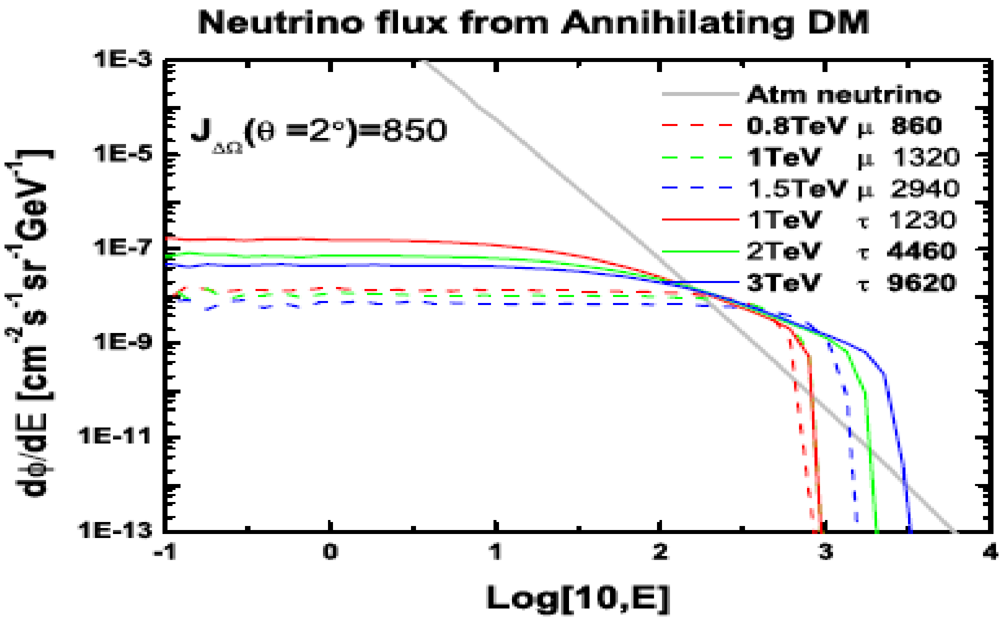
Astrophysical factor from GC



- Annihilating DM benefits from cusped DM profile
- The GC is good candidate for DM indirect detect

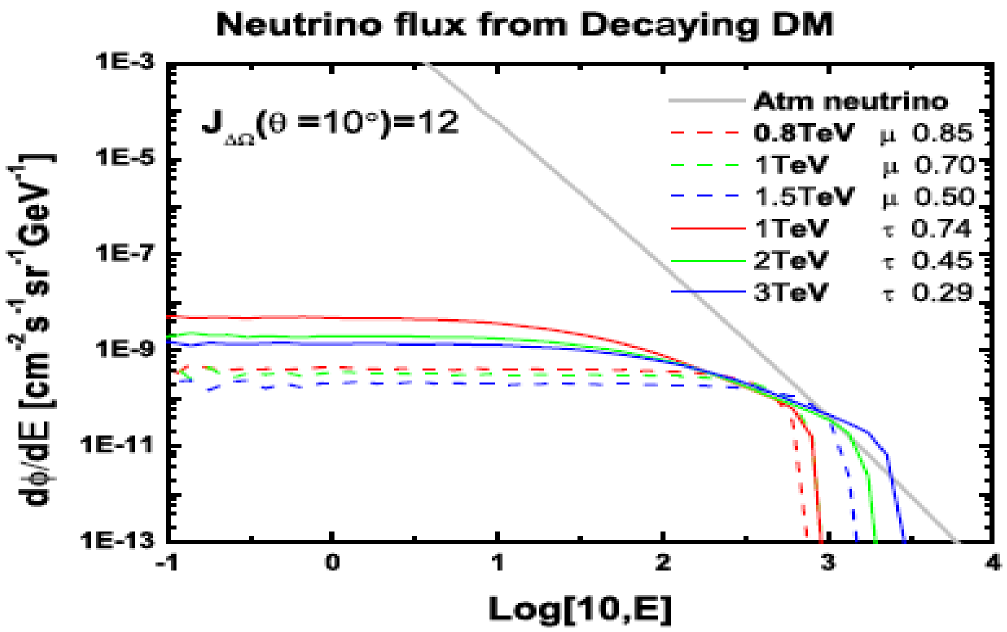
Neutrino flux from GC for annihilating DM

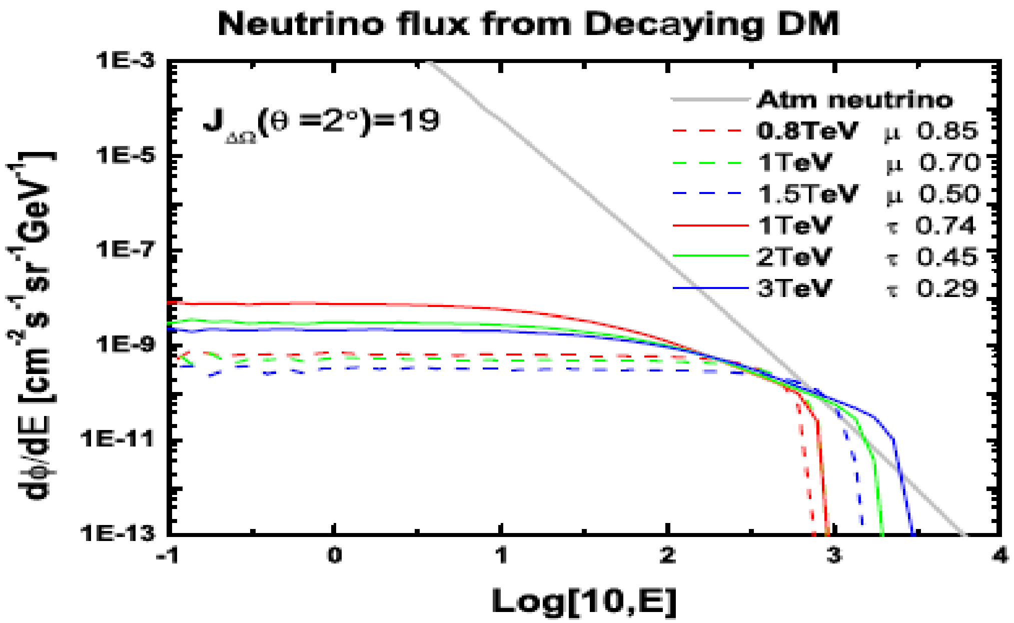




- **Heavy DM is easier to detect**
- **Tau channel produce more neutrinos**
- **Annihilating DM benefits from cusped profile**
- **High angular resolution is crucial for cut spherical atmospheric neutrino**

Neutrino flux from GC for decaying DM





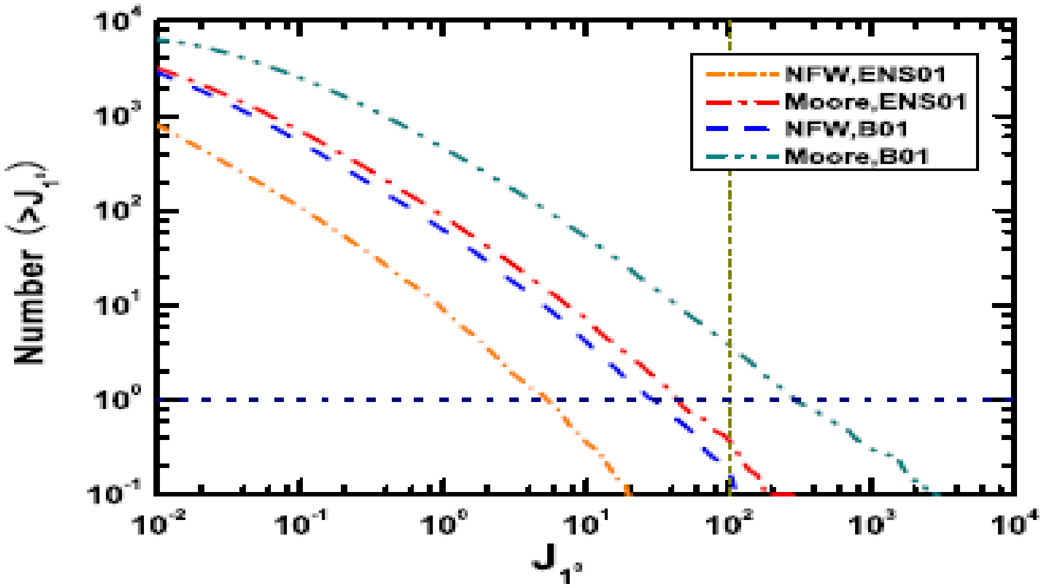
- **The neutrino signals from decaying DM is difficult to detect**

Neutrino flux from Subhalo

- **Massive DM subhalo can be point source**

$$J_{\Delta\Omega}^{Subhalo}(\theta = 1^{\circ}) \sim 100 \text{ or even larger values}$$

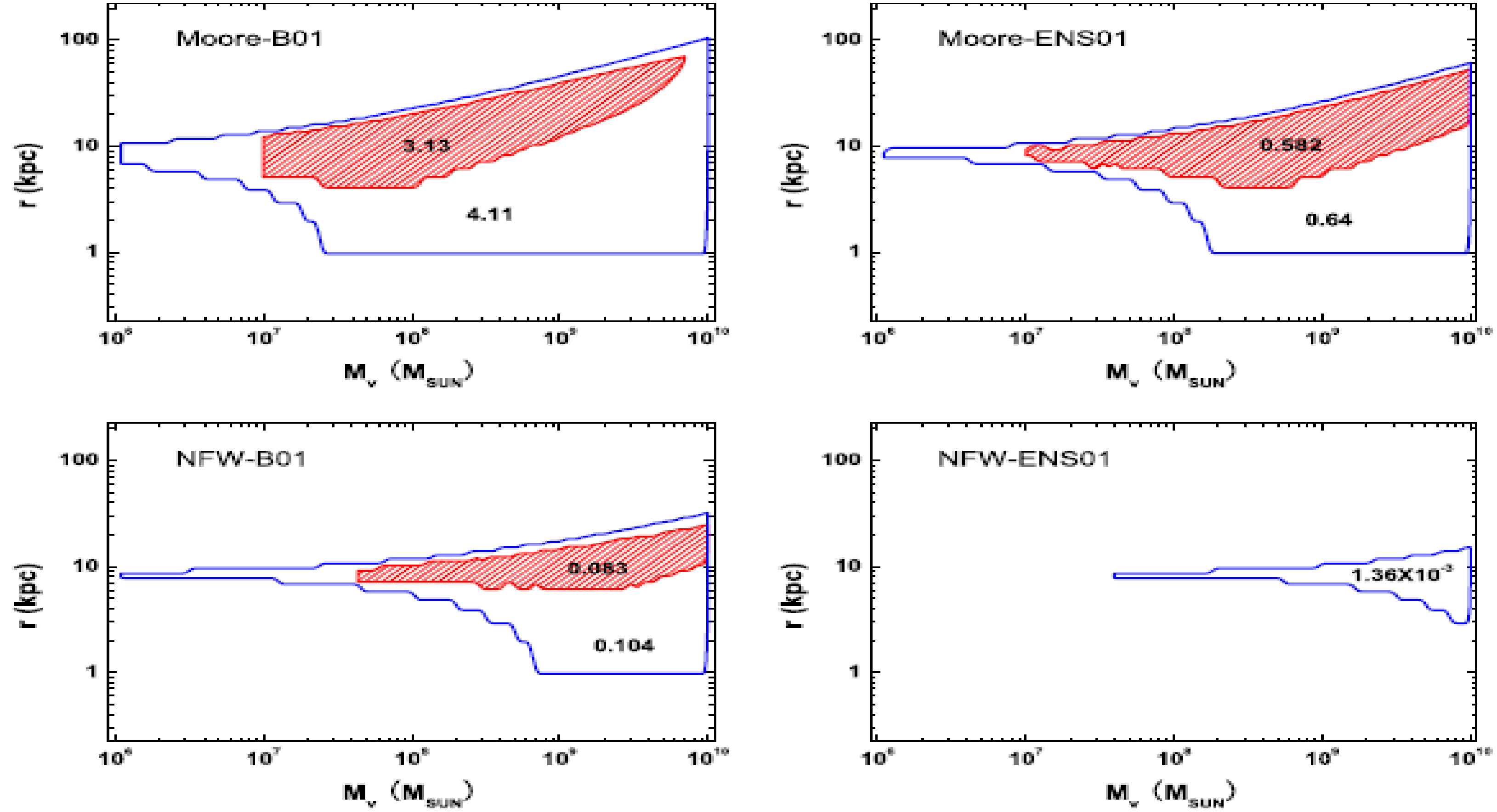
P. F. Yin et al. , Phys. Rev. D. 78, 065027 (2008).



- **Small cone can suppress background**

- **Enhancement:**
  Annihilating DM >Decaying DM

Neutrino flux from Subhalo



- **The probabilities to find such massive subhalo**

Muon flux calculation

$$\frac{dN_\mu}{dE_\mu} = \int_{E_\mu}^{\infty} \frac{d\phi_{\nu_\mu}}{dE_{\nu_\mu}} [\frac{d\sigma_\nu^p(E_{\nu_\mu}, E_\mu)}{dE_\mu}\rho_p + \frac{d\sigma_\nu^n(E_{\nu_\mu}, E_\mu)}{dE_\mu}\rho_n] R_\mu(E_\mu) A_{eff}(E_\mu) dE_{\nu_\mu} + (\nu \longrightarrow \bar{\nu})$$

- **cross section for the muon production process**

$$vp \longrightarrow lX \text{ and } vn \longrightarrow lX$$

- **muon range: the distance that**

  a muon can travel

$$\frac{dE}{dx} = -\alpha - \beta E$$

- **muon neutrino flux arrived at the telescope.**

  we assume three flavor neutrino flux are equal due to vacuum oscillation.

- **effective area of telescope**

- **Counting for both muon and anti-muons**

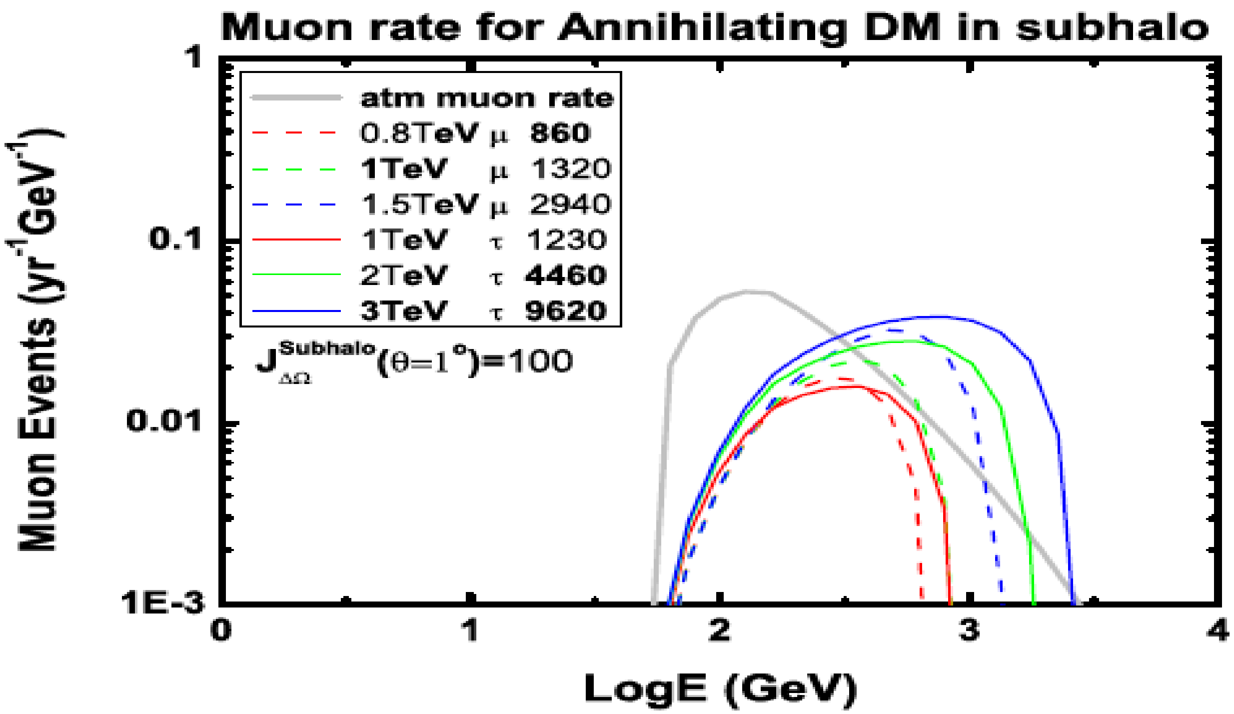
Muon rate from GC at Antares

TABLE I. The neutrino event numbers in the energy interval 500 GeV–1 TeV for eight years of Antares operation from the 2° cone in the GC direction. σ is the significance defined as $S/\sqrt{B}$.

channel	N	σ	channel	N	σ
atm	1.5	-	atm	1.5	-
0.8 TeV μ	7.7	6.2	1 TeV τ	12.2	9.9
1 TeV μ	16.5	13.4	2 TeV τ	21.2	17.2
1.5 TeV μ	29.4	23.9	3 TeV τ	23.3	18.9

Muon rate for DM in the Subhalo at IceCube

- Muon rate for annihilating DM in the Subhalo



Muon rate from Subhalo at IceCube

TABLE II. The total muon and antimuon numbers in the energy interval 500 GeV–1 TeV for ten years operation of IceCube for massive subhalo. σ is the significance defined as $S/\sqrt{B}$.

channel	N	σ	channel	N	σ
atm	57.6	-	atm	57.6	-
0.8 TeV μ	21.7	2.9	1 TeV τ	41.5	5.5
1 TeV μ	55.2	7.3	2 TeV τ	136.4	20.0
1.5 TeV μ	144.9	19.1	3 TeV τ	188.6	24.8

Comments on high energy neutrino as the discriminator

- **In annihilating DM scenario**
  Antares is promising for discovering the neutrino signal from the GC
  IceCube is promising for discovering the neutrino signal from Subhalo

- **In decaying DM scenario it is difficult.**

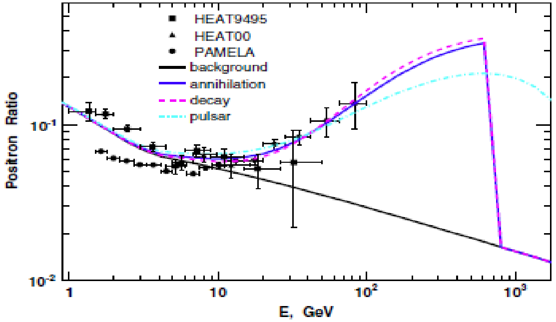
- **In pulsar scenario it is difficult too.**

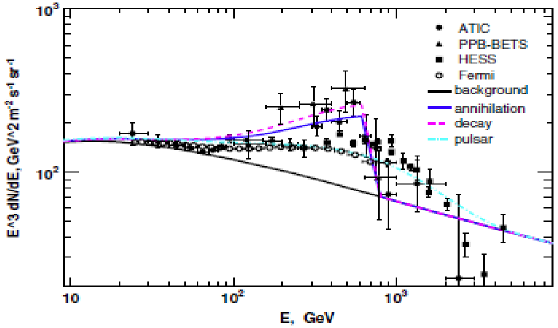
Gamma ray and synchrotron

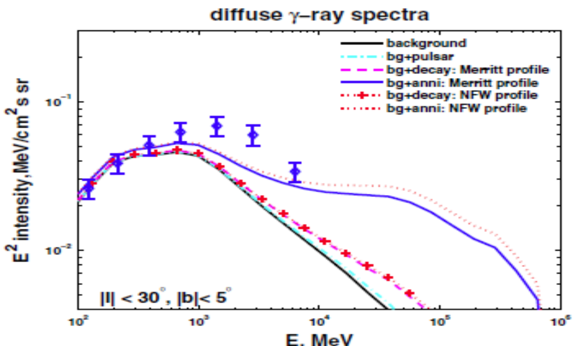
- **Inverse compton scattering,** high-energy electron/positron scatter with low energy photons, such as **starlight**, **infrared light from dust**, **CMB**, and accelerate them to high-energy

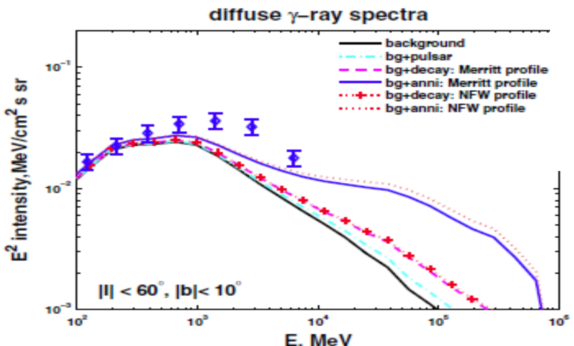
- Assume DM annihilate/decay to charged leptons

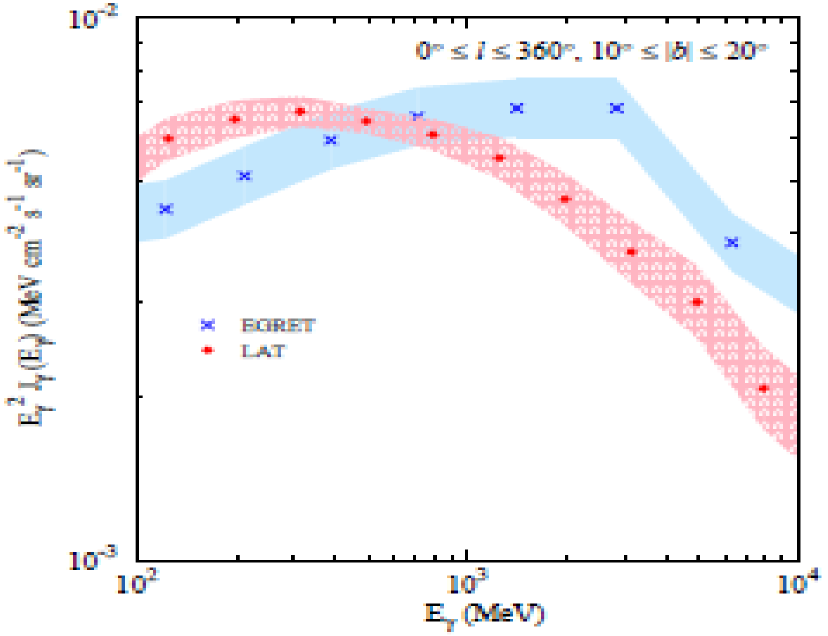
- **Fermi did not detect low energy excess reported by EGRET**









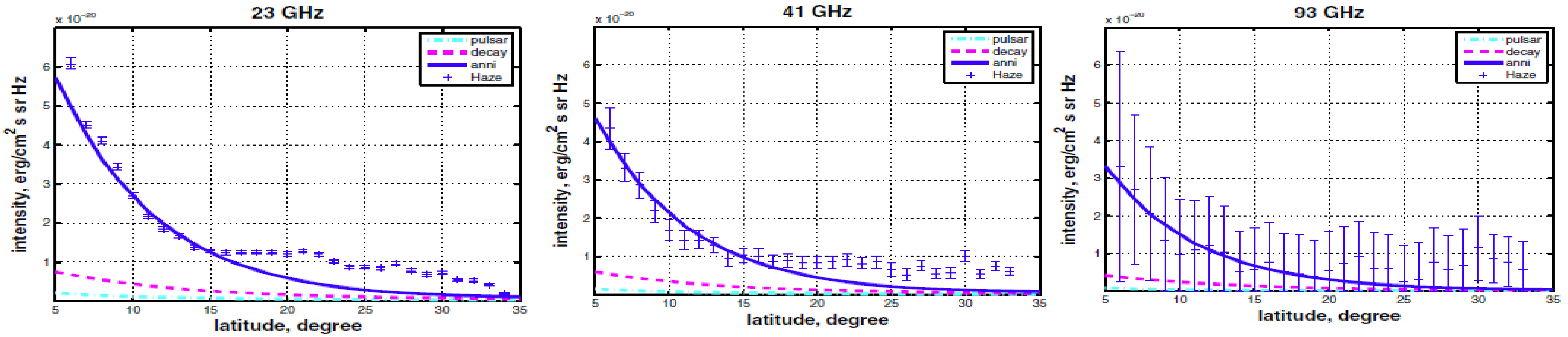


Zhang et al, PRD, 2009

Gamma ray and synchrotron

- **Synchrotron radiation**, electron/positron loss energy in the Galactic magnetic field , and emit synchrotron radiation.

- **WMAP haze**, possible synchrotron excess in the GC



- **Annihilating DM produce more photon than decaying DM and pulsar,**

  it could be tested or excluded by Fermi future results.