Gamma Ray Constraints on New Physics Interpretations of IceCube Data

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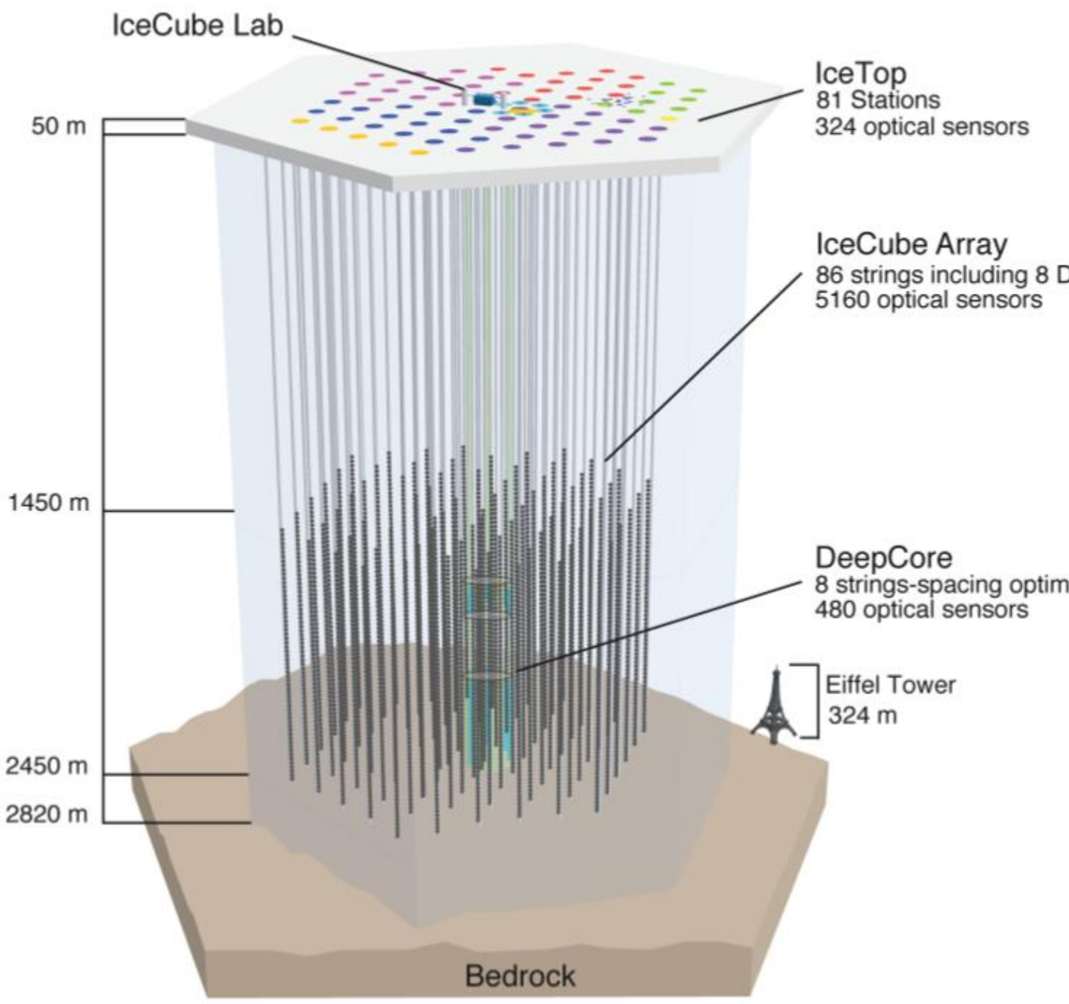
Outline

- Motivation:
  - PeV bump in IceCube data
- Astrophysical explanation:
  - Multi messenger method (Gamma Ray Constraint)
- Particle explanation:
  - Dark Matter Decay
- Other Application of the Gamma Ray Constraint:
  - Z' model
- Conclusion

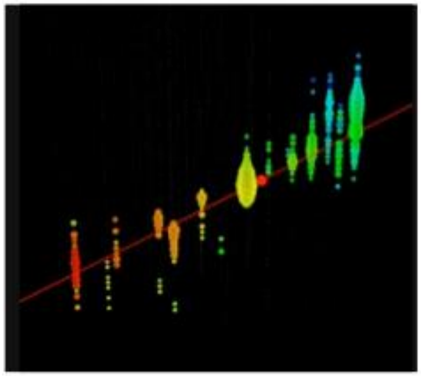
Brief Introduction of IceCube Experiment



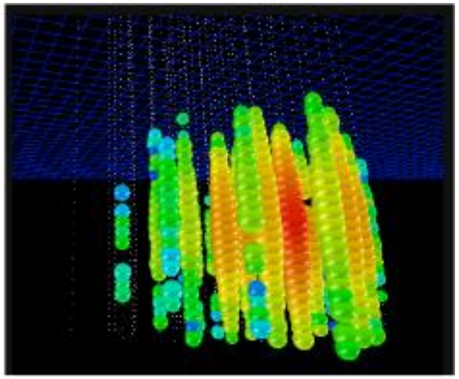
Mechanism:

$$\nu_l + N \to \begin{cases} l + X \ (CC) \\ \nu_l + X \ (NC) \end{cases}$$

Cherenkov radiation from interaction products: leptons and hadrons



track



cascade

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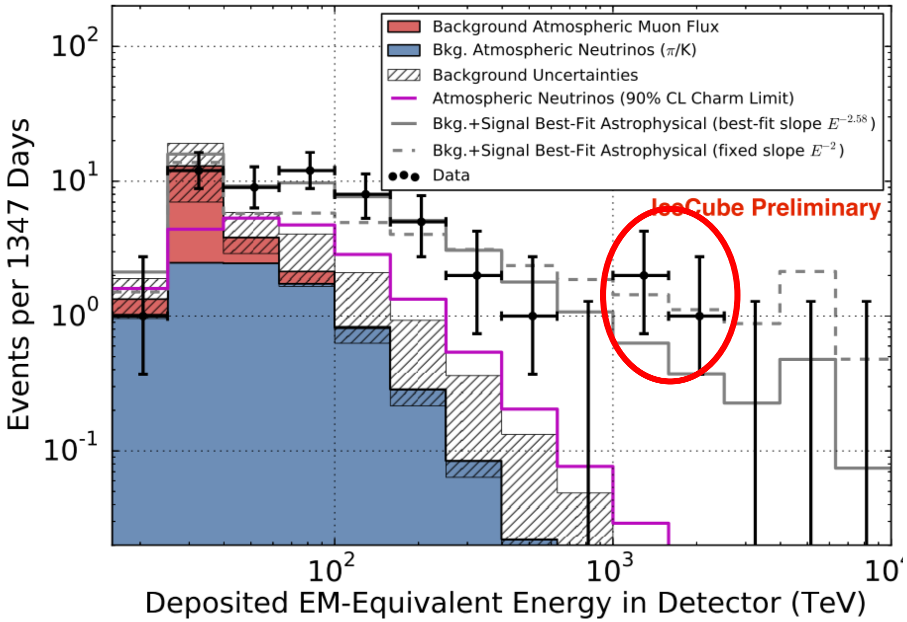
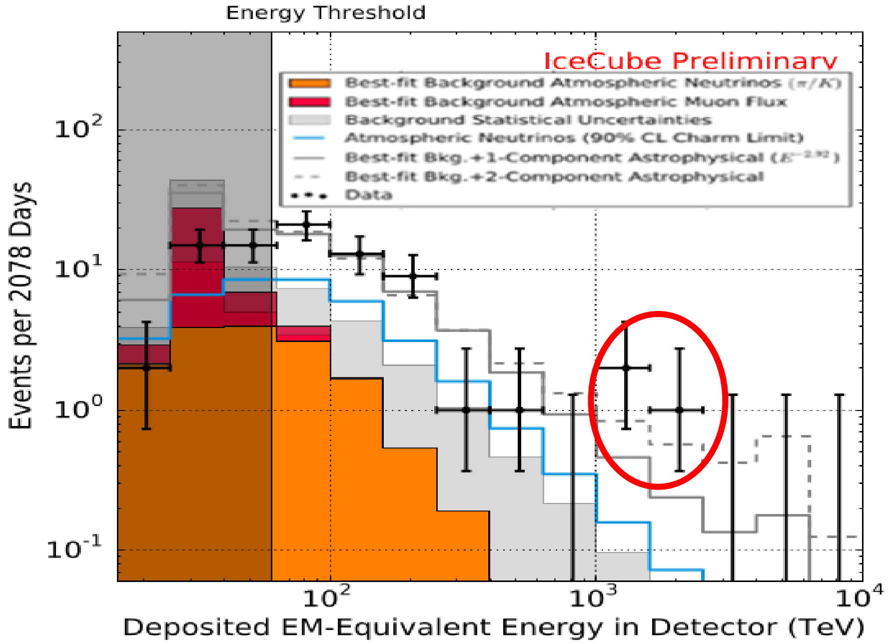
Motivation



IceCube 4 years data



IceCube 6 years data

How to explain this PeV Bump?

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Astrophysical Explanation:Multi Messenger Method

- Astrophysical source

typical source of astrophysical neutrinos and gamma photons

$$p+\gamma \to \Delta^+ \to \begin{cases} p+\pi^0 \to p+\gamma+\gamma & 2/3 \\ n+\pi^+ \to n+e^+ +\nu_e+\nu_\mu+\bar{\nu_\mu} & 1/3 \end{cases}$$

1 : 1 : 1

- $p+p \to p+p+\pi^0+\pi^+ +\pi^-$

$\pi^0 \to \gamma+\gamma$ $\pi^\pm \to e^\pm + \nu_\mu(\bar{\nu_\mu}) + \bar{\nu_\mu}(\nu_\mu) + \nu_e(\bar{\nu_e})$

- $$E_\gamma^2\Phi_\gamma \approx \frac{4}{K}(E_\nu^2\Phi_{\nu_i}) \mid_{E_\nu=0.5E_\gamma}$$

K=1 for p γ case

K=2 for p p case

$$\Phi \doteq \frac{dN}{dE\,d\Omega\,dS\,dt}$$

$\Phi_{\nu i}$ is the flux for only one flavor. Aassuming at earth, we have $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ then, this is could be think of as the flux averaged over flavor

K. Murase arXiv:1410.3680

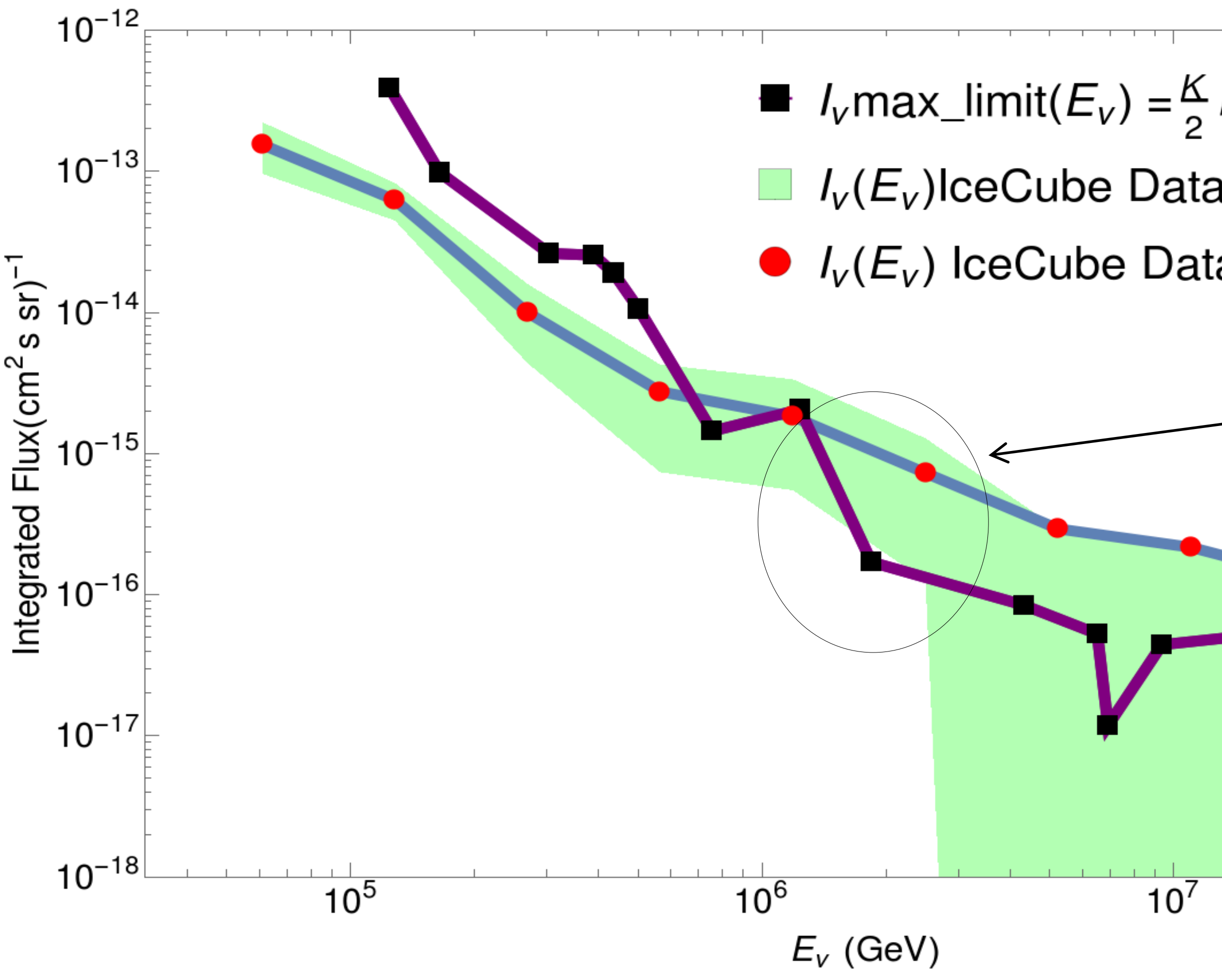
$$I_\gamma(E_\gamma) \approx \frac{2}{K} I_{\nu_i}(E_{\nu_i}) \mid_{E_\nu=0.5E_\gamma}$$

$$I(E_0) \doteq \int_{E_0}^{\infty} \Phi(E)dE$$ I is the integrated flux

- **Gamma ray Bound → uHE neutrino bound**

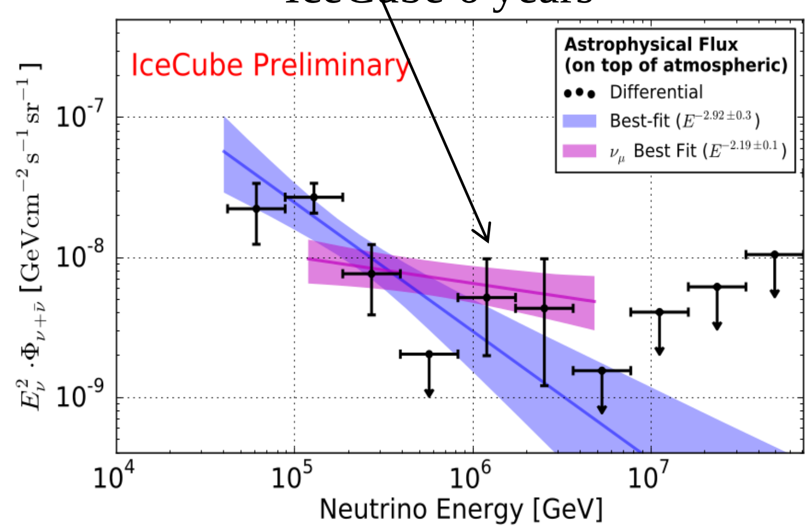
Typical astrophysics explanation fails to explain the bump

Neutrino limit is derived from a combined Gamma Ray bound (CASAMIA+HAWC+milargo+ARGO+Fermi-LAT)



PeV events dominant, causing excess

IceCube 6 years



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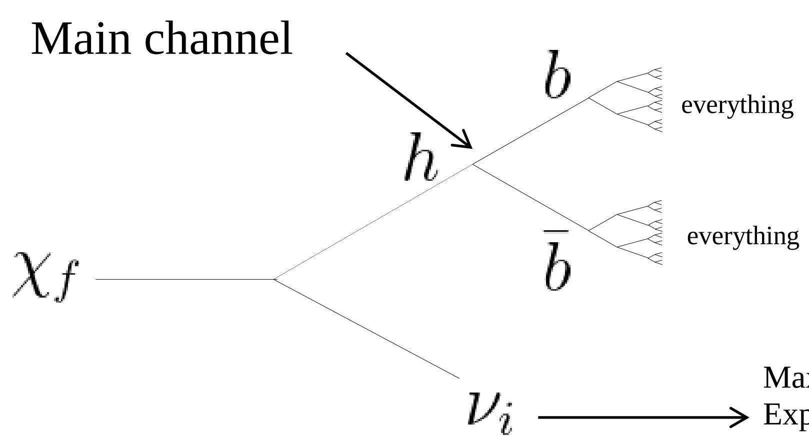
New Physics Model

- Dark Matter <u>3 Body Final State</u> Decay



Maximum Energy neutrino
Explaining the high energy bump

$$\Phi_{\nu_{total}} = \Phi_{\nu_{DM}} + \Phi_{\nu_{Astro}}$$

Always have high energy neutrino yields for this model: $E_{\nu max} \approx \frac{M_{dm}}{2}$

Effective Lagrangian of DM model:

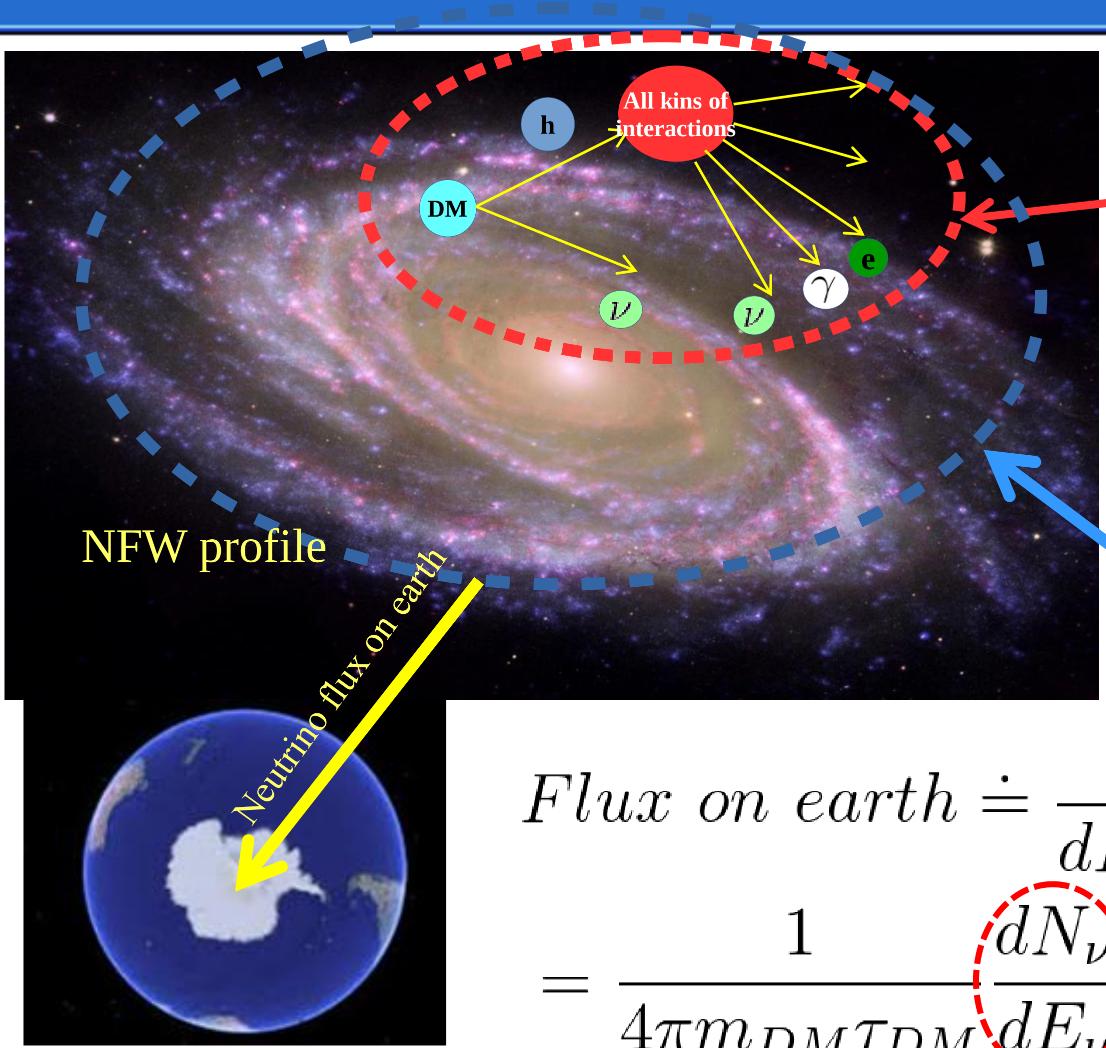
A model independent Decay Process with M_{dm} and (τ_{dm}) λ being free parameters.

$$L_{new} = i\bar{\chi}_f \gamma^\mu D_\mu \chi_f - M_{dm} \bar{\chi}_f \chi_f + (\lambda \cdot \bar{\chi}_f \; h \; \nu_l + H.C.)$$

Feldstein et al (PRD '13); Esmaili, Serpico (JCAP '13); Murase et al (PRL '15); Boucenna et al (JCAP '15); Dev et al (JCAP '16); di Bari et al (JCAP '16); Cohen et al (PRL '17)

Inspired by neutrino Dirac mass model

Simulation Process to get Flux at Earth



Monte Carlo :
Madgraph5 + pyhtia 8
Deal with
decay of one DM particle

Spectrum at Production

Average over all directions for fluxes at production;
Integration of contributing DM in the whole galaxy;
……

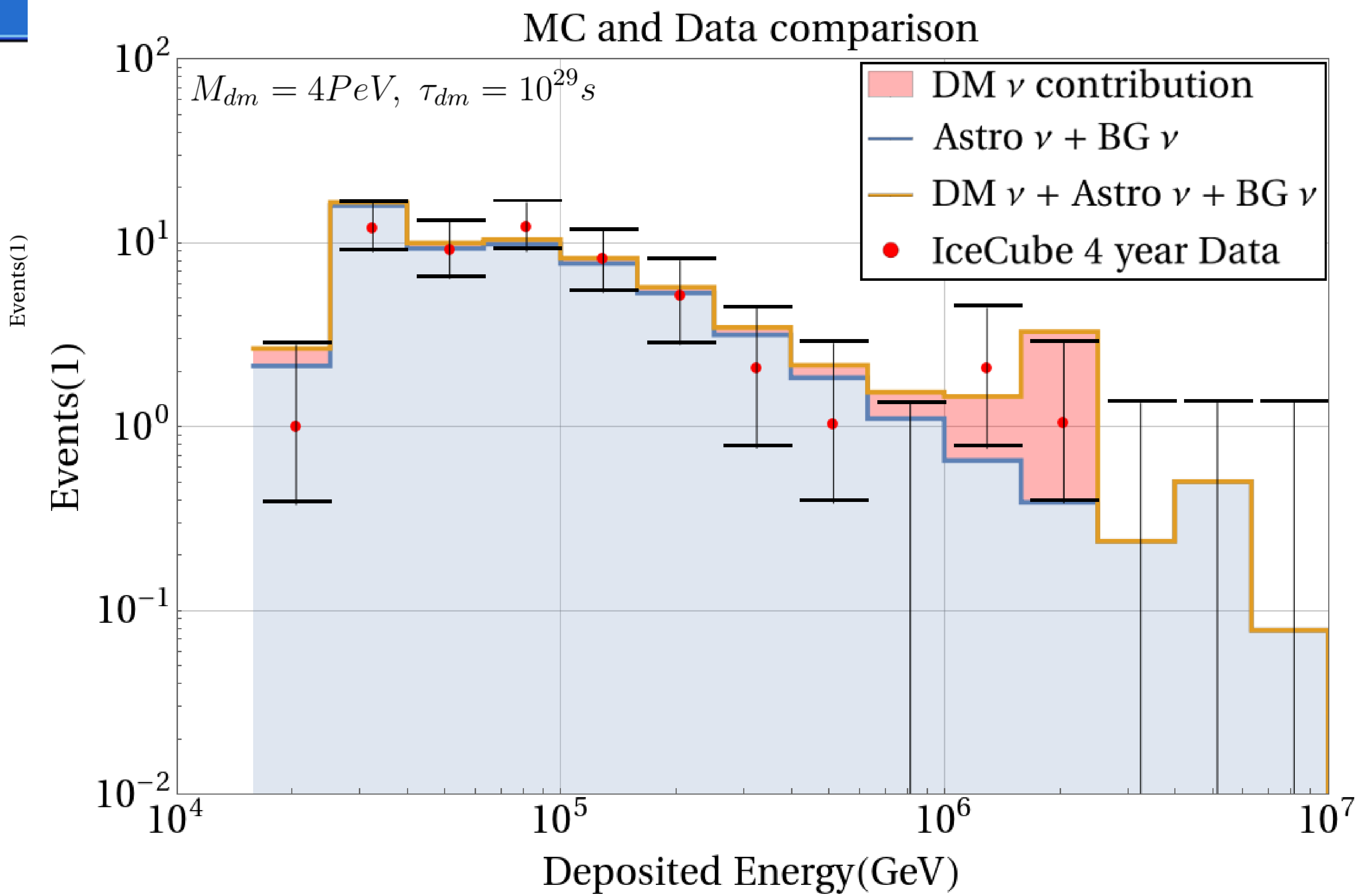
J factor or D factor

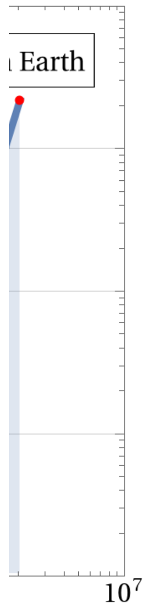
$$Flux\ on\ earth \doteq \frac{dN_\nu}{dE_\nu d\Omega dS dt}$$

$$= \frac{1}{4\pi m_{DM}\tau_{DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty ds \int d\Omega \rho_h[r(s,l,b)]$$

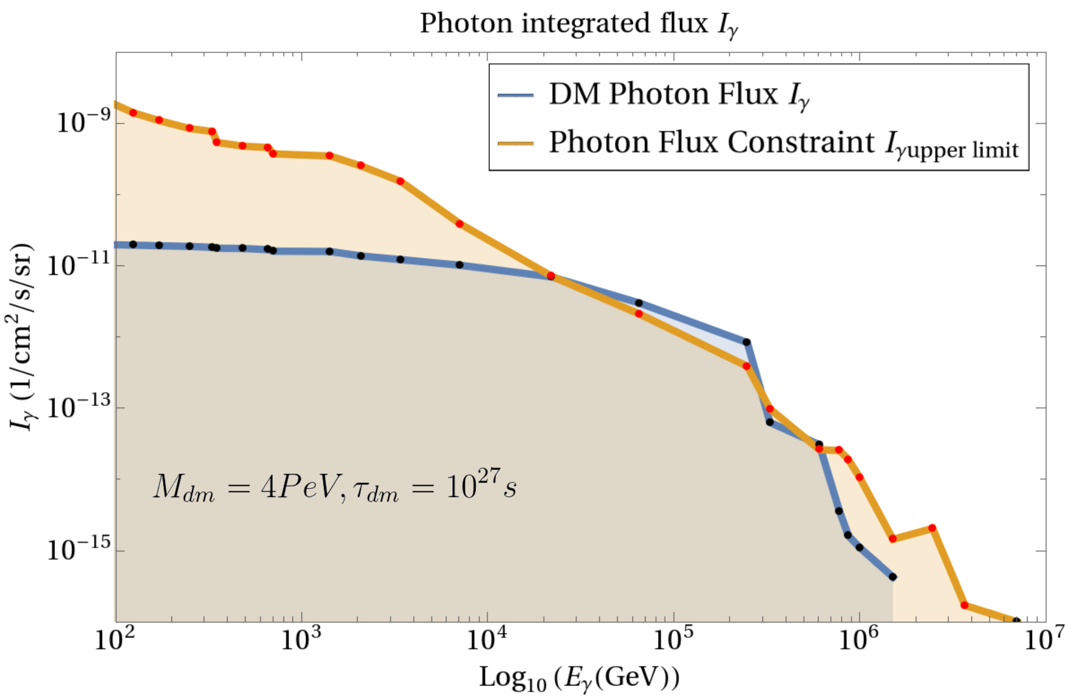
This page is an example float chart for galactic flux, similar for extragalactic

Monte Carlo of DM model

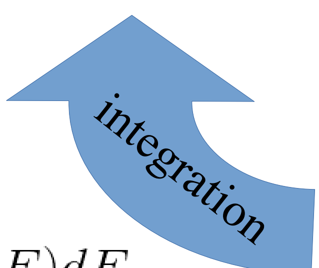




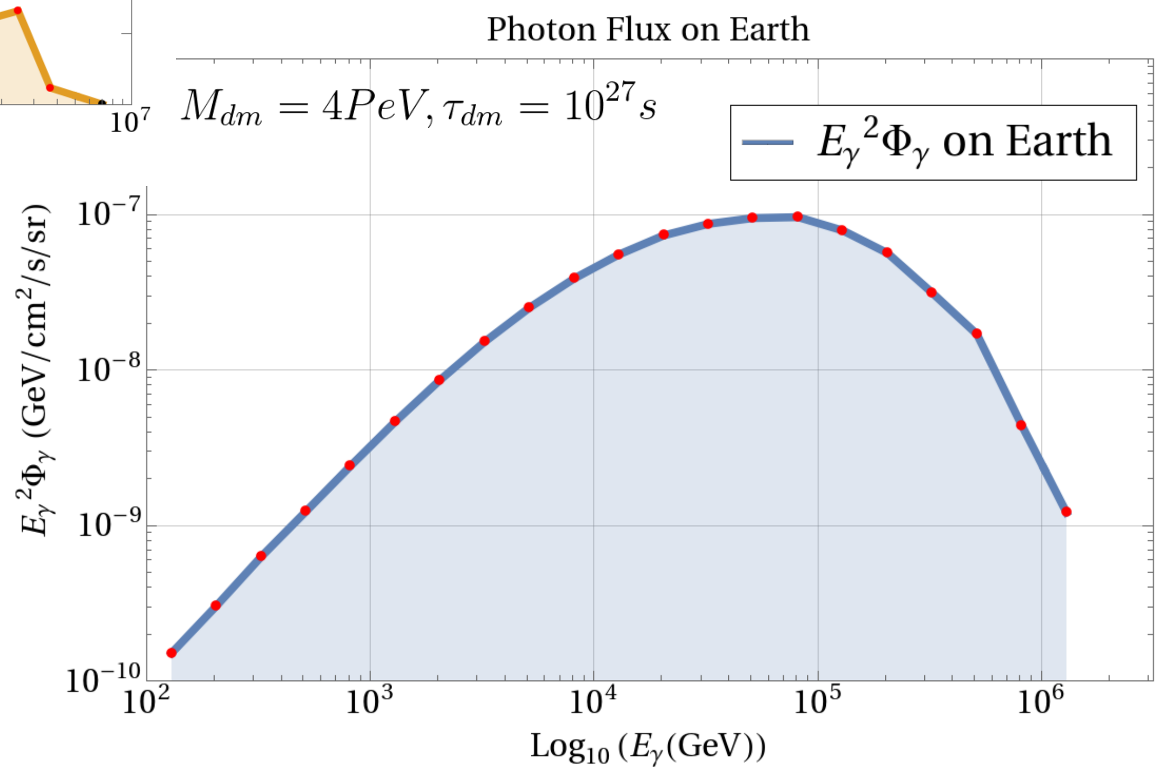
Photon flux graph



Photon Flux Constraint is the combined result of CASAMIA+HAWC+milargo+ARGO+Fermi-LAT



$$I(E_0) \doteq \int_{E_0}^{\infty} \Phi(E)dE$$



Constraining the DM parameters

- goodness of fit test:

$$L(\theta) = f_P(n;\theta) = \prod_{i=1}^{n} \frac{\mu_i^{n_i}}{n_i!} e^{-\mu_i} \qquad \theta = (M_{dm}, \tau_{dm})$$

The likelihood ratio is: $\lambda(\theta) = \dfrac{f_P(n;\theta)}{f(n;\hat{\mu})}$ where $\hat{\mu} = (n_1, n_2, \ldots, n_N)$

$$TS = -2ln(\lambda(\theta)) = 2\sum_{i=1}^{N}[\mu_i(\theta) - n_i + n_i ln\frac{n_i}{\mu_i(\theta)}]$$

Given a CL → Favored parameters region

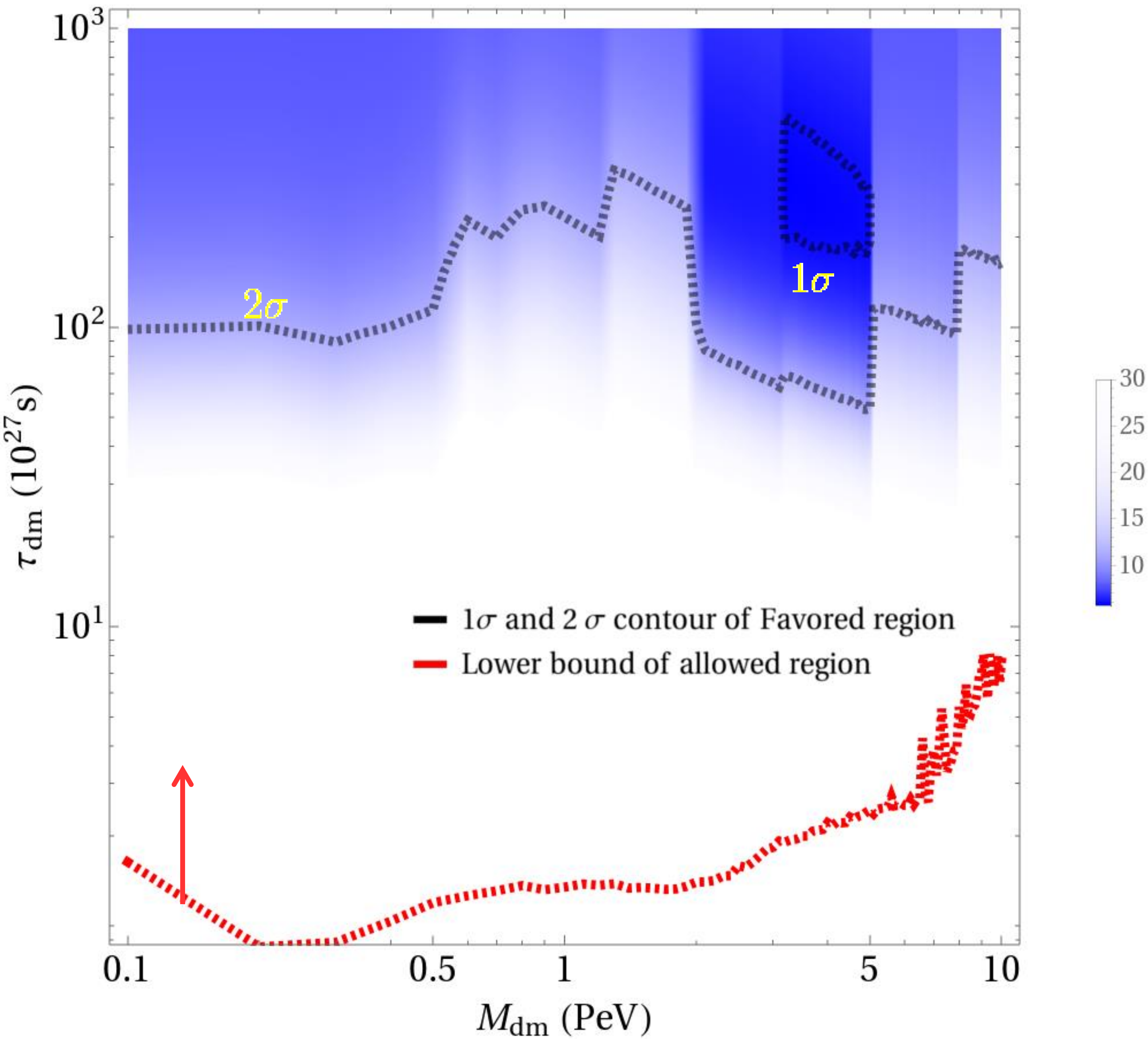
- Comparison with Gamma ray constraint:

(τ_{dm}, M_{dm}) → $I_{dm}(\tau_{dm}, M_{dm}) > I_{constraint}?$ $\xrightarrow{T}$ veto; $\xrightarrow{F}$ allow region

Favored parameters region from Goodness of fit and Gamma ray constraint

Due to less statistics, only one sigma region is closed area.

Lower bound(Red) is very conservative, so much lower than the favored region from goodness of fit.



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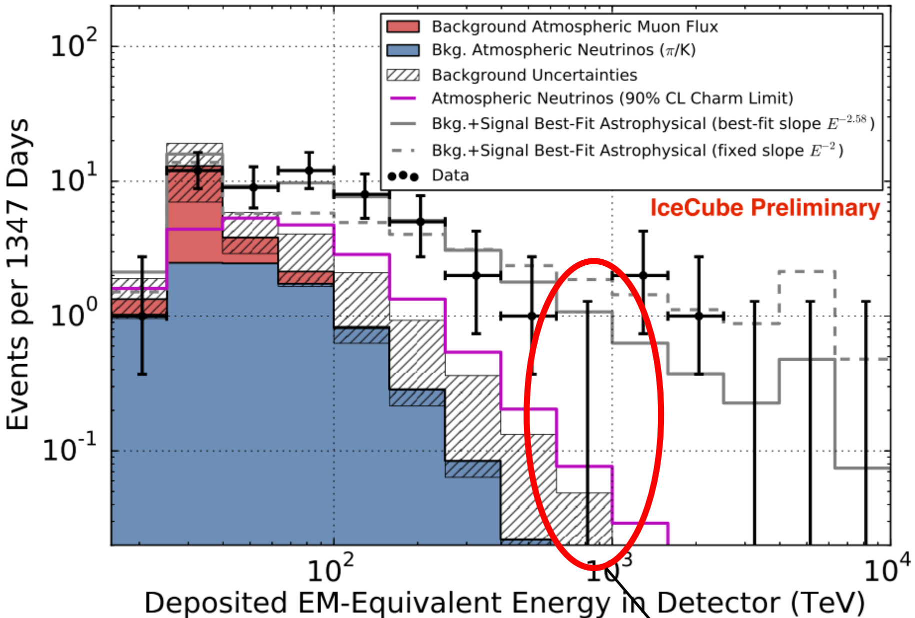
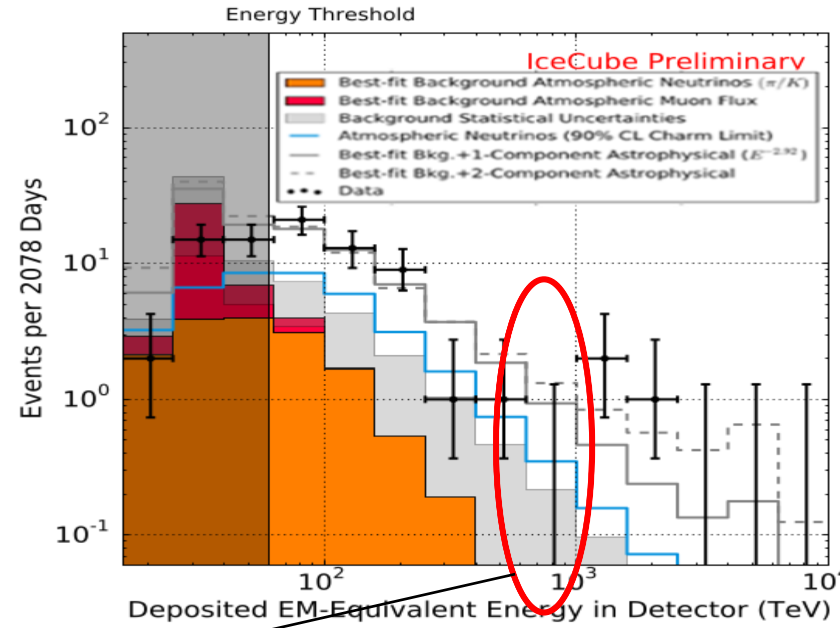
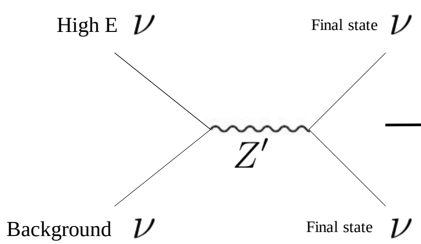
Gap of IceCube Data and Z' model





Gap of icecube data at $E \sim 9 \cdot 10^2 TeV$



$$\longrightarrow \quad E_{\nu_f} << E_{\nu_{HE}} \qquad m_{Z'} \sim \sqrt{2 m_\nu E_{\nu_{HE}}} \sim 1MeV$$

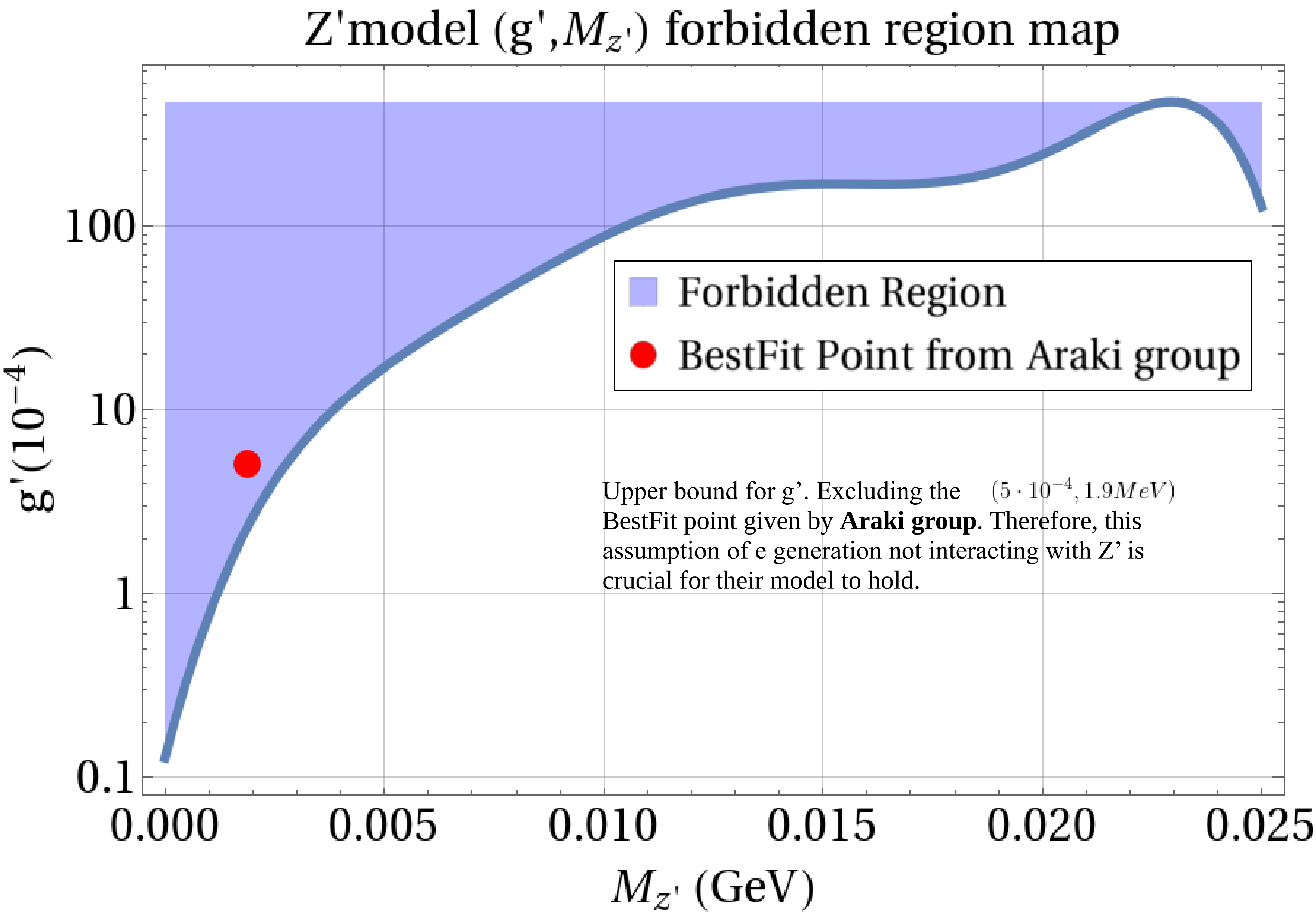
$$L_{Z'} = g_{Z'} Q_{\alpha\beta} (\bar{\nu_\alpha} \gamma^\rho P_L \nu_\beta + \bar{l_\alpha} \gamma^\rho l_\beta) Z'_\rho$$

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

Assumption: interaction only among muon and tau generation

T. Araki et al (PRD '15); Cherry, Friedland, Shoemaker '14; DiFranzo, Hooper (PRD '15); Heeck (PLB '16); Dev et al (PLB '16)

Gamma radiation for the expanded model



Upper bound for g'. Excluding the $(5 \cdot 10^{-4}, 1.9MeV)$ BestFit point given by **Araki group**. Therefore, this assumption of e generation not interacting with Z' is crucial for their model to hold.

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Conclusion

- Pure astrophysical explanation for the Icecube PeV bump is disfavored by the gamma ray constraint

- The DM decay model: DM$\rightarrow$ b b~ v could explain the bump with parameters confined in favored region

- Gamma ray constraint could also be used to test the validity of New Physics models, for example, light Z' model.

Thank you!

Back up slides, haven't done yet

- Derivation of the flux identity
- Derivation of Z' model's D factor
- Higher order cascades

Reminder of the relations between coupling constant and decay width:

$$\Gamma_{dm} \approx \frac{3}{32\pi} M_{dm} \lambda^2$$

$$for\ \ M_{dm} = 1PeV, \tau_{dm} = 10^{27}s,\ \ we\ have\ \lambda \sim 1.48 \times 10^{-28}$$

$$E_\gamma^2\Phi_\gamma \approx \frac{4}{K}(E_\nu^2\Phi_{\nu_i})\mid_{E_\nu=0.5E_\gamma}$$

Same amount of 3 pions, and they have approximately same energy:

$$p\ p \rightarrow \pi^0\ \pi^+\ \pi^-$$

$$\gamma\ \ \gamma\ \ e\ 2\nu_\mu\ \nu_e e\ 2\nu_\mu\ \nu_e$$

$$E_\gamma = 1/2E_\pi \qquad \Delta N_\pi \doteq \Delta N_{\pi^+} = \Delta N_{\pi^-} = \Delta N_{\pi^0}$$

$$E_{\pi^+} = E_{\pi^-} = E_{\pi^0} = E_\pi$$

$$E_\nu = 1/4E_\pi$$ 1 pion goes to 4 leptons,share share the E

$$\Delta N_\pi = \int_{E_{\pi1}}^{E_{\pi2}} \frac{dN_\pi}{dE_\pi}\cdot dE_\pi \quad (1)$$

$$\frac{dN_\gamma}{dE_\gamma}\mid_{E_\gamma=E_\pi/2} = 4\frac{dN_\pi}{dE_\pi}\mid_{E_\pi}$$

Derivative for Epi2

$$= 1/2\Delta N_\gamma = 1/2\int_{E_{\gamma1}=1/2E_{\pi1}}^{E_{\gamma2}=1/2E_{\pi2}} \frac{dN_\gamma}{dE_\gamma}\cdot dE_\gamma \quad (2)$$

$$N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} = 1:2:0$$

oscillation

$$N_{\nu_e}\mid_{earth} : N_{\nu_\mu}\mid_{earth} : N_{\nu_\tau}\mid_{earth} = 1:1:1$$

$$N_{\nu_e}\mid_{earth} = N_{\nu_\mu}\mid_{earth} = N_{\nu_\tau}\mid_{earth} \doteq N_\nu = N_{\nu_e}$$

$$\frac{dN_\nu}{dE_\nu}\mid_{E_\nu=1/4E_\pi} = 8\frac{dN_\pi}{dE_\pi}\mid_{E_\pi}$$

Derivative for Epi2

$$2\Delta N_\pi = \Delta N_\nu$$

$$\frac{dN_\nu}{dE_\nu}\mid_{E_\nu=1/4E_\pi} = 2\frac{dN_\gamma}{dE_\gamma}\mid_{E_\gamma=1/2E_\pi} \longrightarrow 2E_\nu^2\frac{dN_\nu}{dE_\nu}\mid_{E_\nu=1/4E_\pi} = E_\gamma^2\frac{dN_\gamma}{dE_\gamma}\mid_{E_\gamma=1/2E_\pi}$$

$$E_\gamma^2 \Phi_\gamma \approx \frac{4}{K}(E_\nu^2 \Phi_{\nu_i}) \mid_{E_\nu = 0.5 E_\gamma}$$

$$p\ \gamma \rightarrow \begin{cases} \frac{2}{3}\ p\ \pi^0 \rightarrow \gamma\gamma \\ \frac{1}{3}\ n\ \pi^+ \rightarrow e\ 2\nu_\mu\ \nu_e \end{cases}$$

Same amount of 3 pions, and they have approximately same energy:

$$2\Delta N_{\pi^+} = \Delta N_{\pi^0}$$

$$E_\gamma = 1/2 E_\pi$$

$$E_{\pi^+} = E_{\pi^-} = E_{\pi^0} = E_\pi$$

$$E_\nu = 1/4 E_\pi$$ 1 pion goes to 4 leptons,share share the E

$$\Delta N_{\pi^0} = \int_{E_{\pi 1}}^{E_{\pi 2}} \frac{dN_{\pi^0}}{dE_\pi} \cdot dE_\pi \quad (1)$$

$$= 1/2 \Delta N_\gamma = 1/2 \int_{E_{\gamma 1} = 1/2 E_{\pi 1}}^{E_{\gamma 2} = 1/2 E_{\pi 2}} \frac{dN_\gamma}{dE_\gamma} \cdot dE_\gamma \quad (2)$$

pi0

$$\frac{dN_\gamma}{dE_\gamma} \mid_{E_\gamma = E_{\pi^0}/2} = 4 \frac{dN_{\pi^0}}{dE_{\pi^0}} \mid_{E_\pi}$$

Derivative for Epi2

$$2\Delta N_{\pi^+} = \Delta N_{\pi^0}$$

Due to only pi+,no pi-

$$N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} = 1 : 2 : 0$$

oscillation

$$N_{\nu_e} \mid_{earth} : N_{\nu_\mu} \mid_{earth} : N_{\nu_\tau} \mid_{earth} = 1 : 1 : 1$$

$$N_{\nu_e} \mid_{earth} = N_{\nu_\mu} \mid_{earth} = N_{\nu_\tau} \mid_{earth} \doteq N_\nu = N_{\nu_e}$$

pi+

$$\frac{dN_\nu}{dE_\nu} \mid_{E_\nu = 1/4 E_{\pi^+}} = \boxed{4} \frac{dN_{\pi^+}}{dE_{\pi^+}} \mid_{E_\pi}$$

Derivative for Epi2

$$\Delta N_{\pi^+} = \Delta N_\nu$$

$$\boxed{2} \frac{dN_\nu}{dE_\nu} \mid_{E_\nu = 1/4 E_\pi} = \boxed{} \frac{dN_\gamma}{dE_\gamma} \mid_{E_\gamma = 1/2 E_\pi} \longrightarrow \boxed{8} E_\nu^2 \frac{dN_\nu}{dE_\nu} \mid_{E_\nu = 1/4 E_\pi} = E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \mid_{E_\gamma = 1/2 E_\pi}$$

Twice more than Murase's Formula, I think he took pi0 and pi+ to have same amount

Details of goodness of fit

- goodness of fit test:

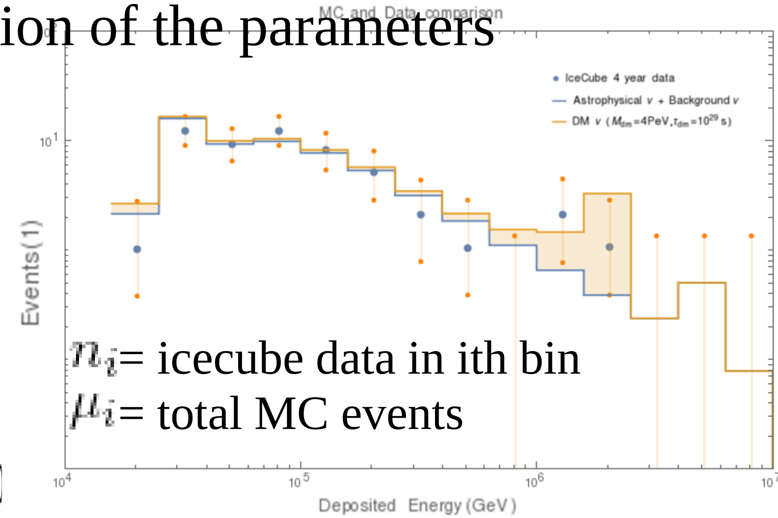
- We use this statistical method to provide favored region of the parameters

For binned data, we could take it as Poisson distribution:

$$L(\theta) = f_P(n;\theta) = \prod_{i=1}^{n} \frac{\mu_i^{n_i}}{n_i!} e^{-\mu_i} \qquad \theta = (M_{dm}, \tau_{dm})$$

The likelihood ratio is:

$$\lambda(\theta) = \frac{f_P(n;\theta)}{f(n;\hat{\mu})} \qquad \text{where} \qquad \hat{\mu} = (n_1, n_2, ..., n_N)$$



n_i= icecube data in ith bin

μ_i= total MC events

We choose the test statistic as:

$$TS = -2ln(\lambda(\theta)) = 2\sum_{i=1}^{N}[\mu_i(\theta) - n_i + n_i ln\frac{n_i}{\mu_i(\theta)}]$$

TS will be a function of theta and thus we could find out the region that is statistically favored

To acquire the TS distribution of Mdm and tdm, we perform a grid calculation:

Mdm=(0.1, 0.2,…,10)PeV

Tdm=10^(1,1.03,1.06,…,3)*10^27 s