JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA Cluster of Excellence

Boosted Dark Matter in IceCube and at the Galactic Center

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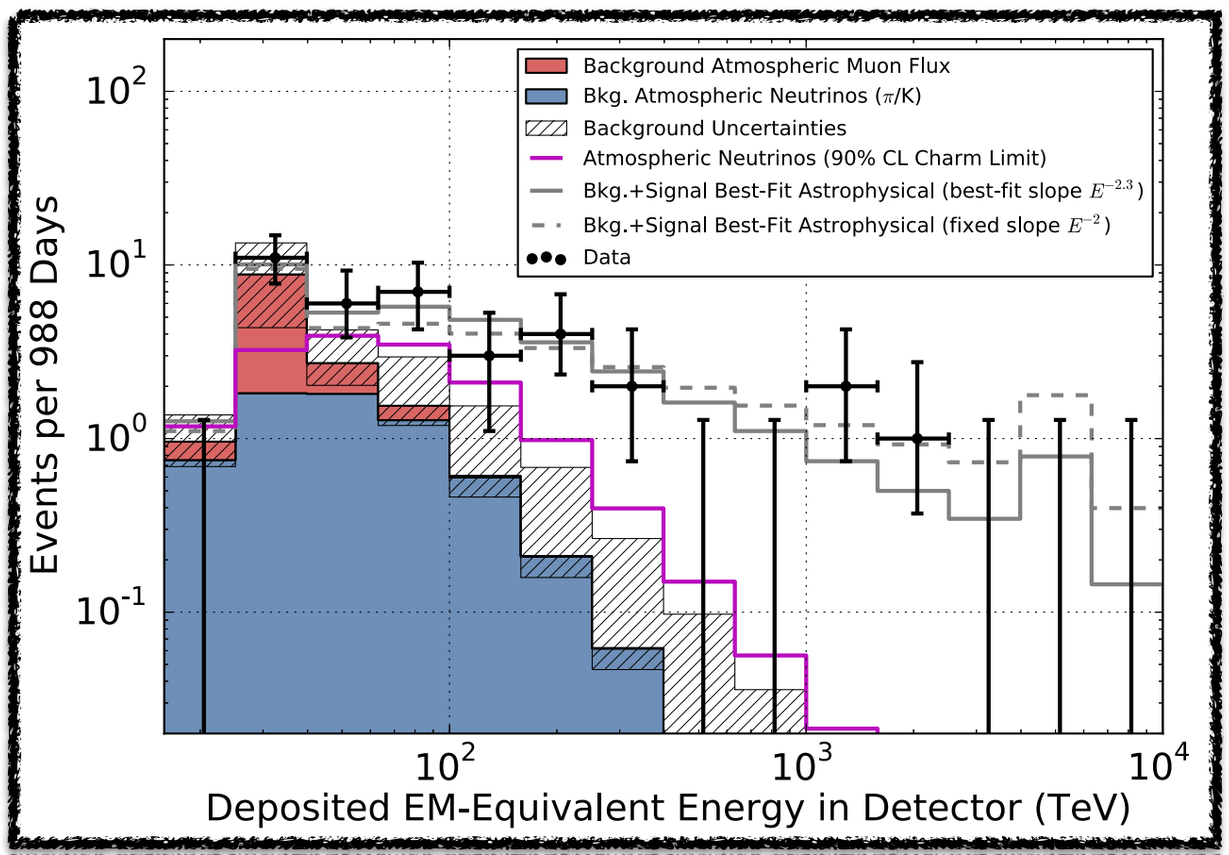
Collaborated with Joachim Kopp and Jia Liu

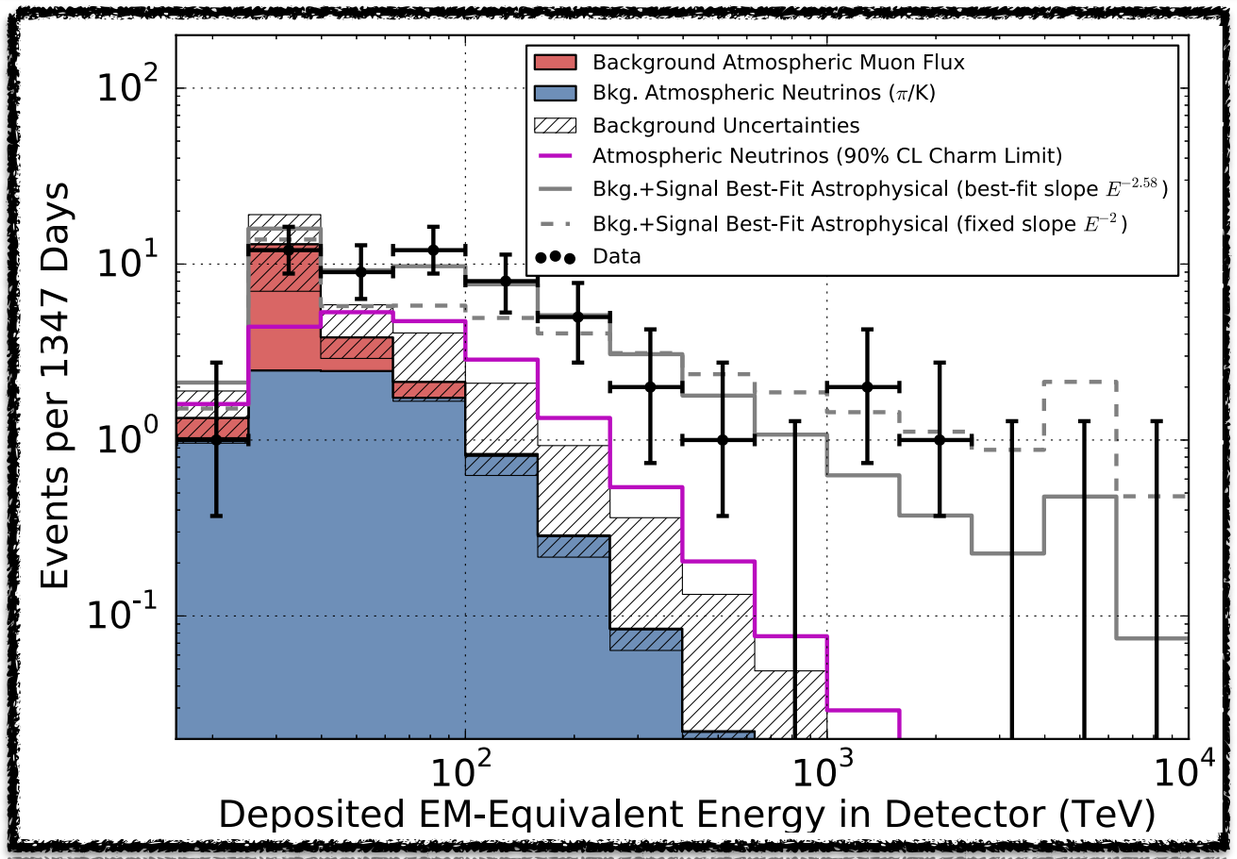
Outline

- **Introduction**
- **Framework of Boosted Dark Matter**
- **IceCube and Fermi-LAT Results analysis**
- **Constraints on Boosted Dark Matter**
- **Summary**

IceCube Results



Phys. Rev. Lett. 113, 101101



Caudio Kopper's talk

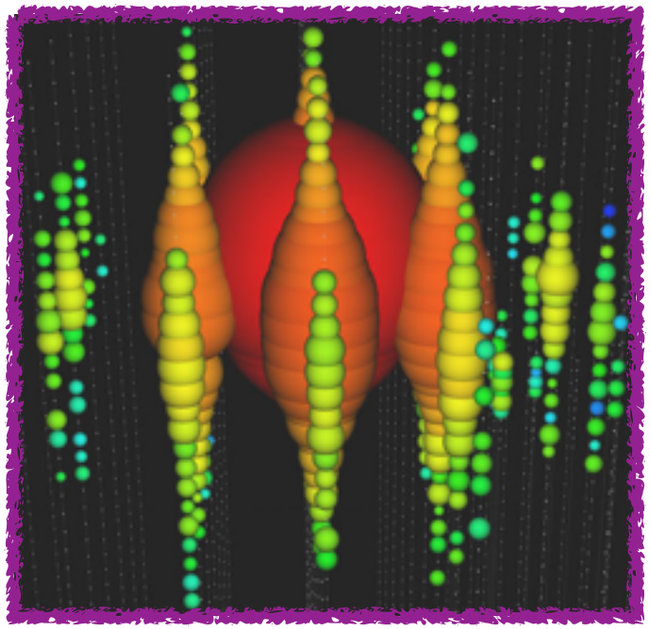
✤**Neutrino flavor ratio from Source at Earth:** $(\nu_e : \nu_\mu : \nu_\tau)_E = (1:1:1)_E$

$$p + p \rightarrow \pi, K \rightarrow \mu + \nu_\mu \rightarrow e + 2\nu_\mu + \nu_e$$

✤**Neutrino flavor ratio needed for IceCube:** $(\nu_e : \nu_\mu : \nu_\tau)_E = (0:0.2:0.8)_E$

$$\gamma \sim -2.5$$

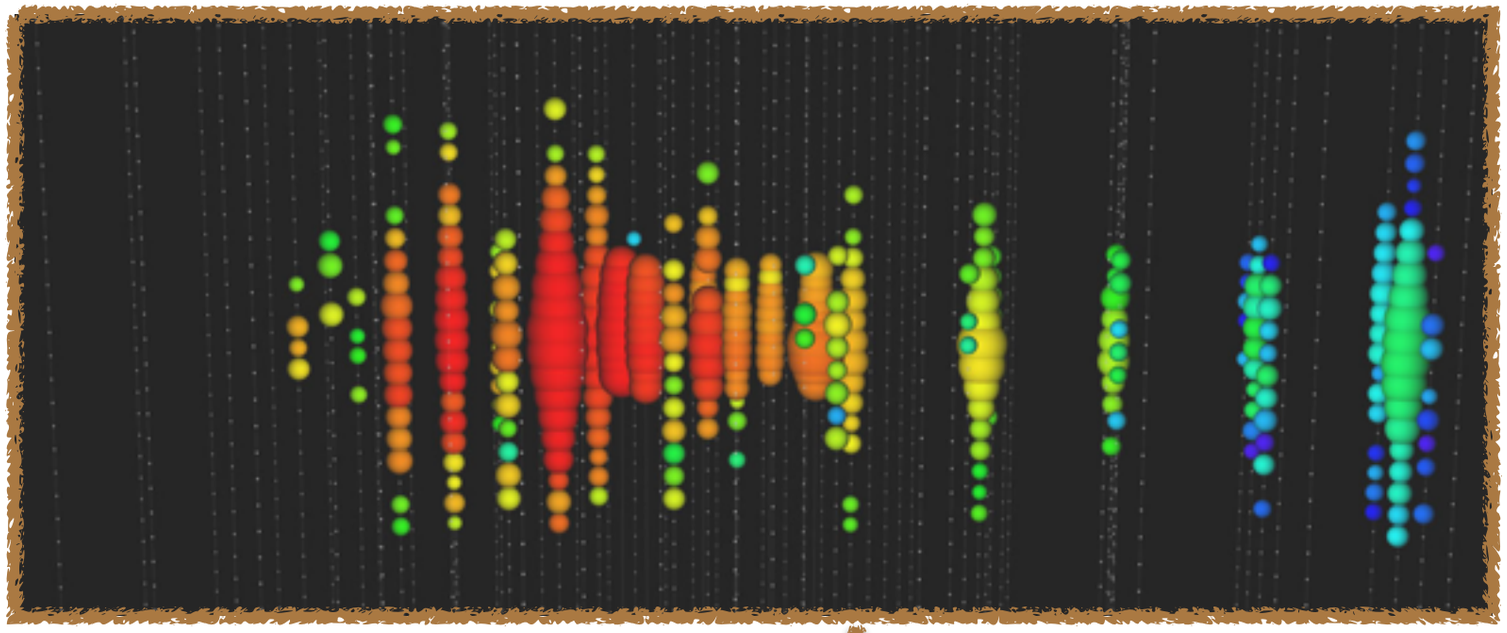
Track vs Shower event



NC and CC interaction:

$\nu_{e,\tau}/\bar{\nu}_{e,\tau} + N \rightarrow (e^-, \tau^-)/(e^+, \tau^+) + N'$

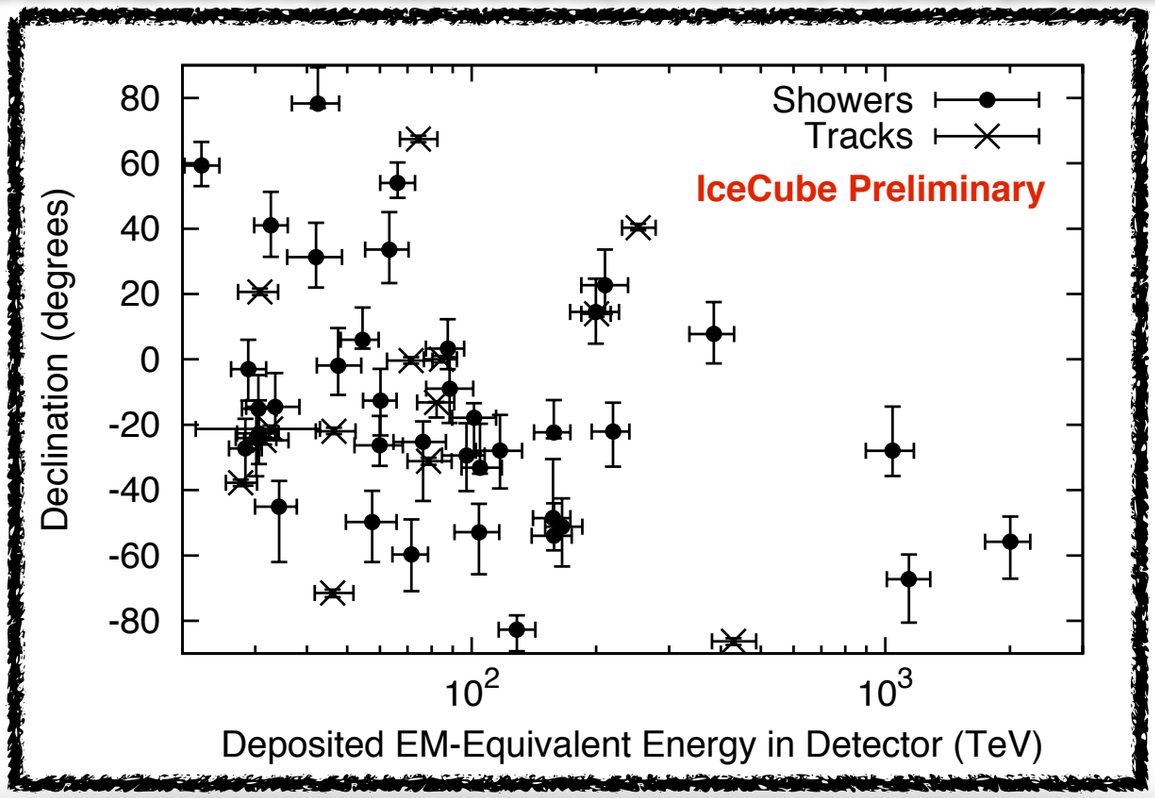
$\nu_l/\bar{\nu}_l + N \rightarrow \nu_l/\bar{\nu}_l + N$



CC interaction:

$\nu_\mu/\bar{\nu}_\mu + N \rightarrow \mu^-/\mu^+ + N'$

Track vs Shower event



✤Mild lack of μ neutrino suggested by:

- C.-Y. Chen, P. Bhupal Dev, and A. Soni
- O. Mena, S. Palomares-Ruiz, and A. C. Vincent

✤However, The event (J2000.0)

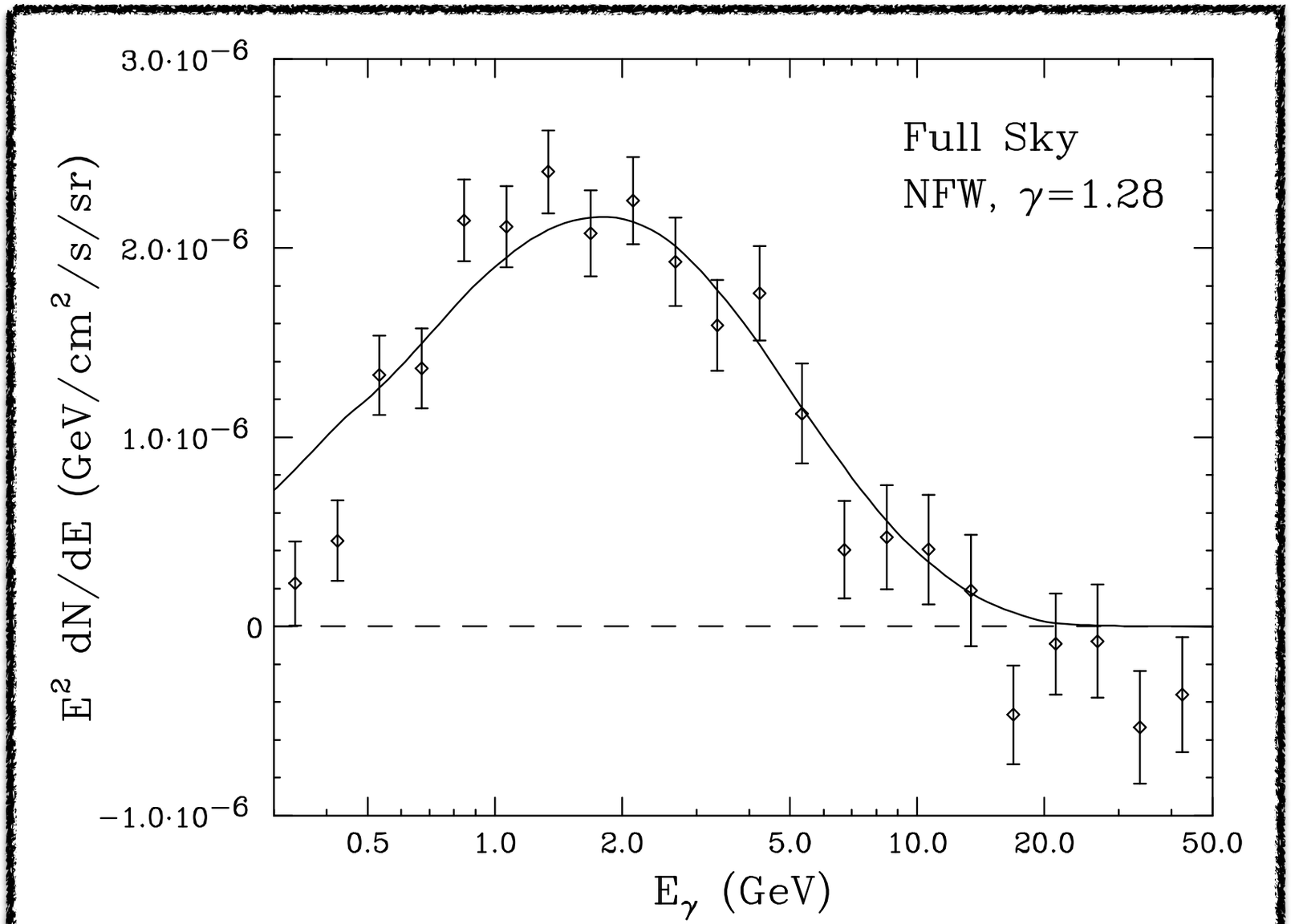
- multi-PeV neutrino-induced muon event
- a total energy of 2.6 ± 0.3 PeV within the instrumented volume of IceCube
- Need astrophysical component or DM-induced charged current (e.g. sneutrino DM)

Fermi-LAT Result

$$\chi\bar{\chi} \to b\bar{b}$$

$$m_\chi \in [30, 50]\mathrm{GeV}$$

$$\langle\sigma v\rangle \sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$$



FERMILAB-PUB-14-032-A

The Framework

- **Dark Matter Part**

$$\mathcal{L}_{\rm DS} \equiv \frac{1}{2}(\partial^\mu \phi)(\partial_\mu \phi) - \frac{1}{2} m_\phi^2 \phi^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi \bar{\chi}\chi - y_{\phi\chi}\phi\bar{\chi}\chi$$

Kinetic Terms

Mass Terms

Interaction Term

- **Interaction between DM and SM**

$$\mathcal{L}_{\rm int} \equiv i g_\chi a \bar{\chi}\gamma_5\chi + i\sum_f g_{Y_f}\frac{\sqrt{2}m_f}{v}\, a\, \bar{f}\gamma_5 f$$

Interaction to DM

Interaction to SM

The Framework

—UV completion models

✤MSSM-like model

$$iaH_1^\dagger H_2 + h.c.$$

$$g_{Y_d} = g_{Y_\ell} = -\tan\beta \sin\theta/\sqrt{2}$$
$$g_{Y_u} = -\cot\beta \sin\theta/\sqrt{2},$$

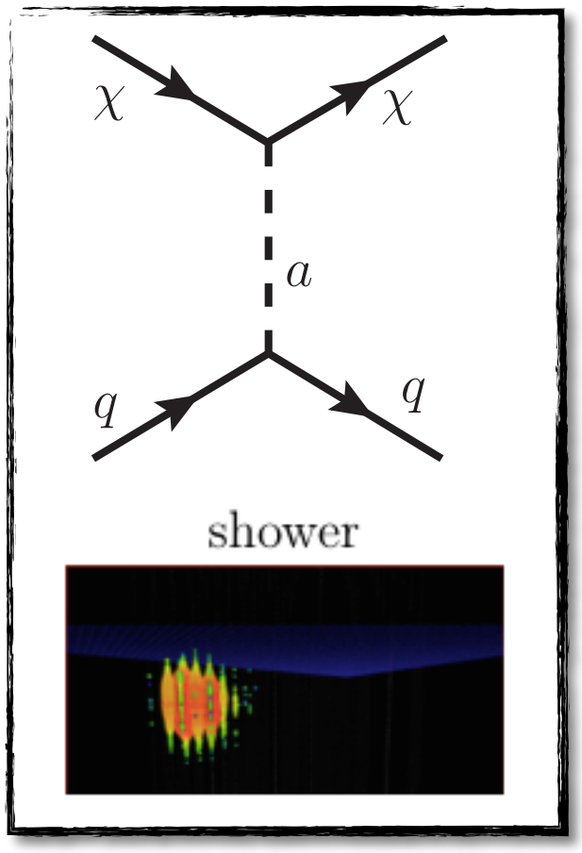
✤Flipped model

$$g_{Y_d} = -\tan\beta \sin\theta/\sqrt{2}$$
$$g_{Y_u} = g_{Y_l} = -\cot\beta \sin\theta/\sqrt{2}$$

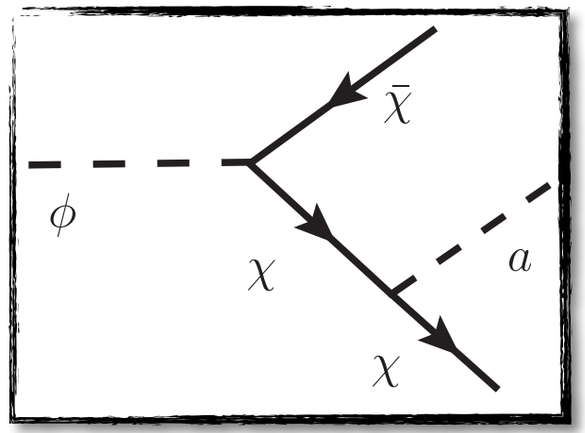
✤Vector-like quark model

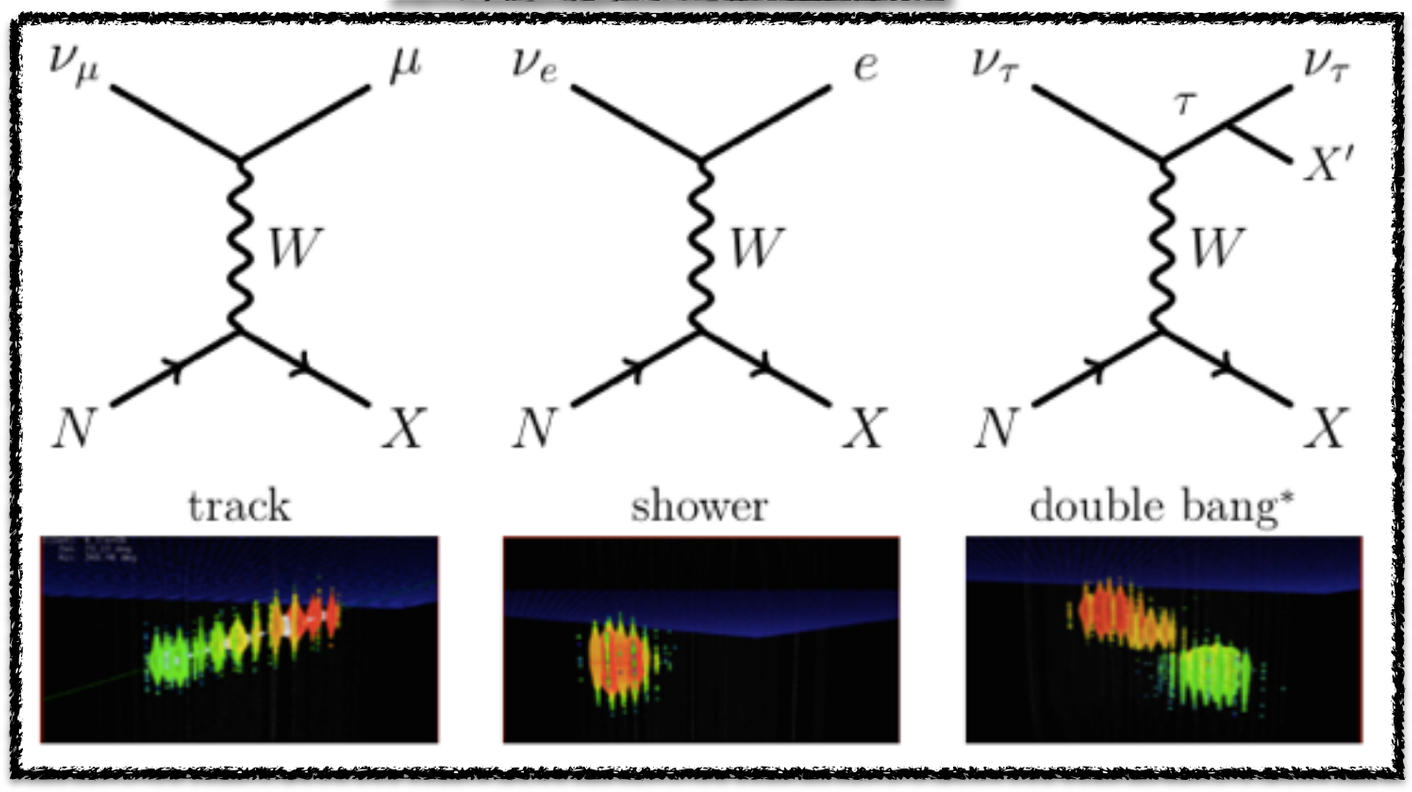
Boosted DM in IceCube

- Primary



- Secondary

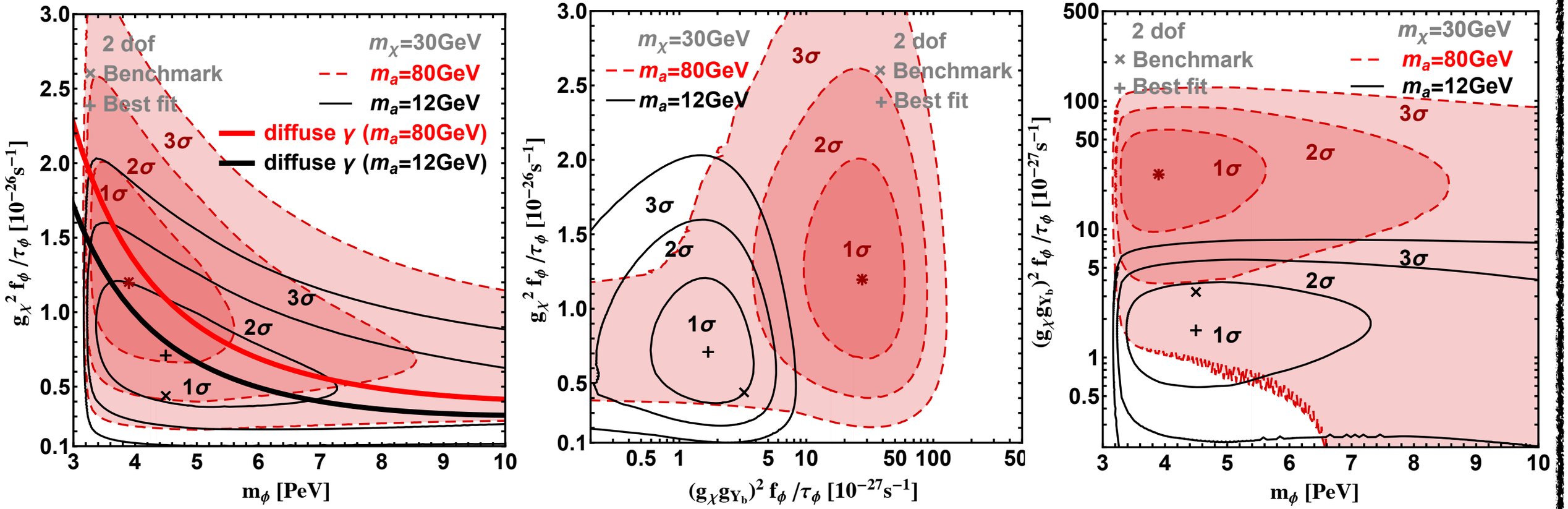




Boosted DM in IceCube

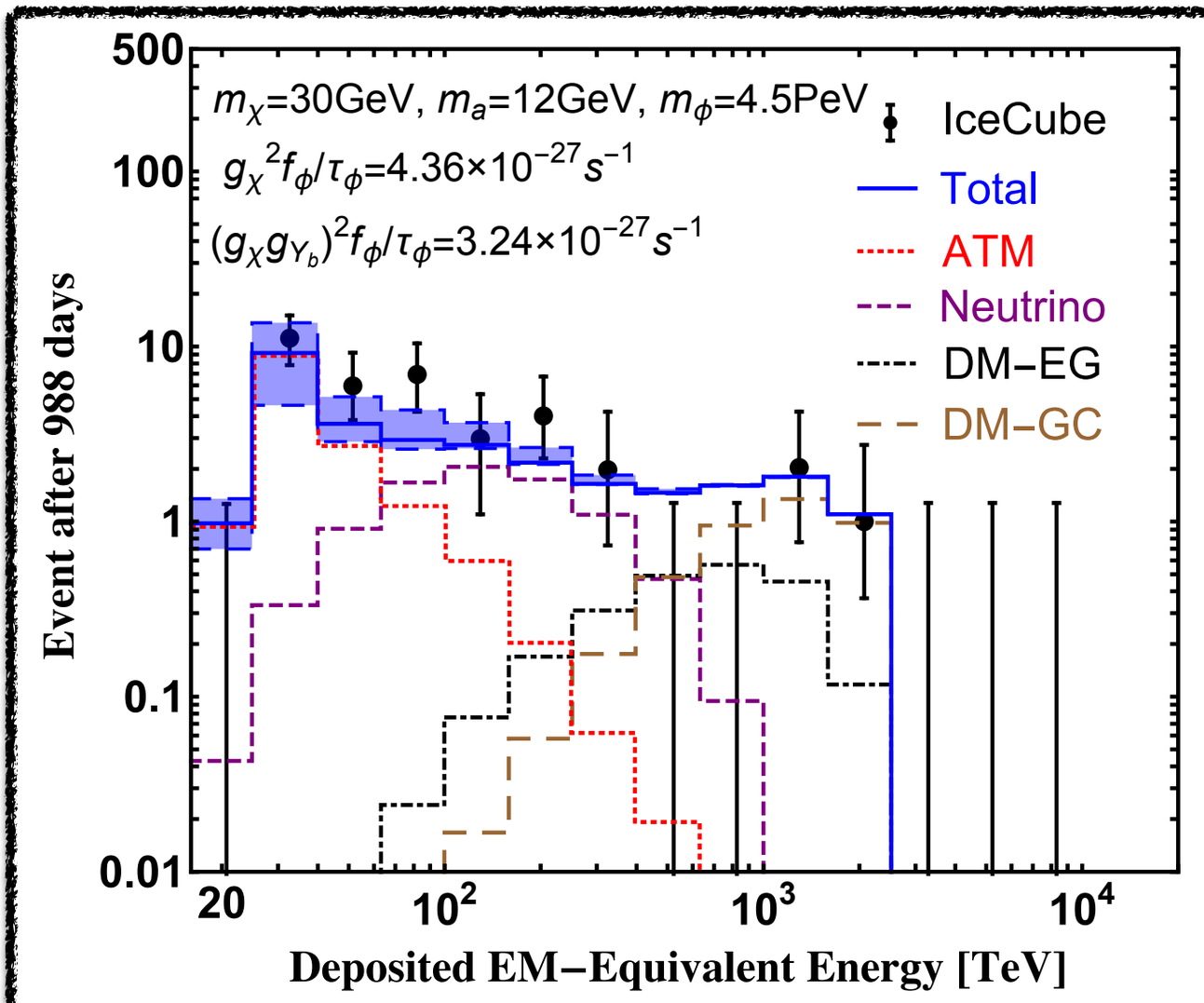
—Fitting procedure

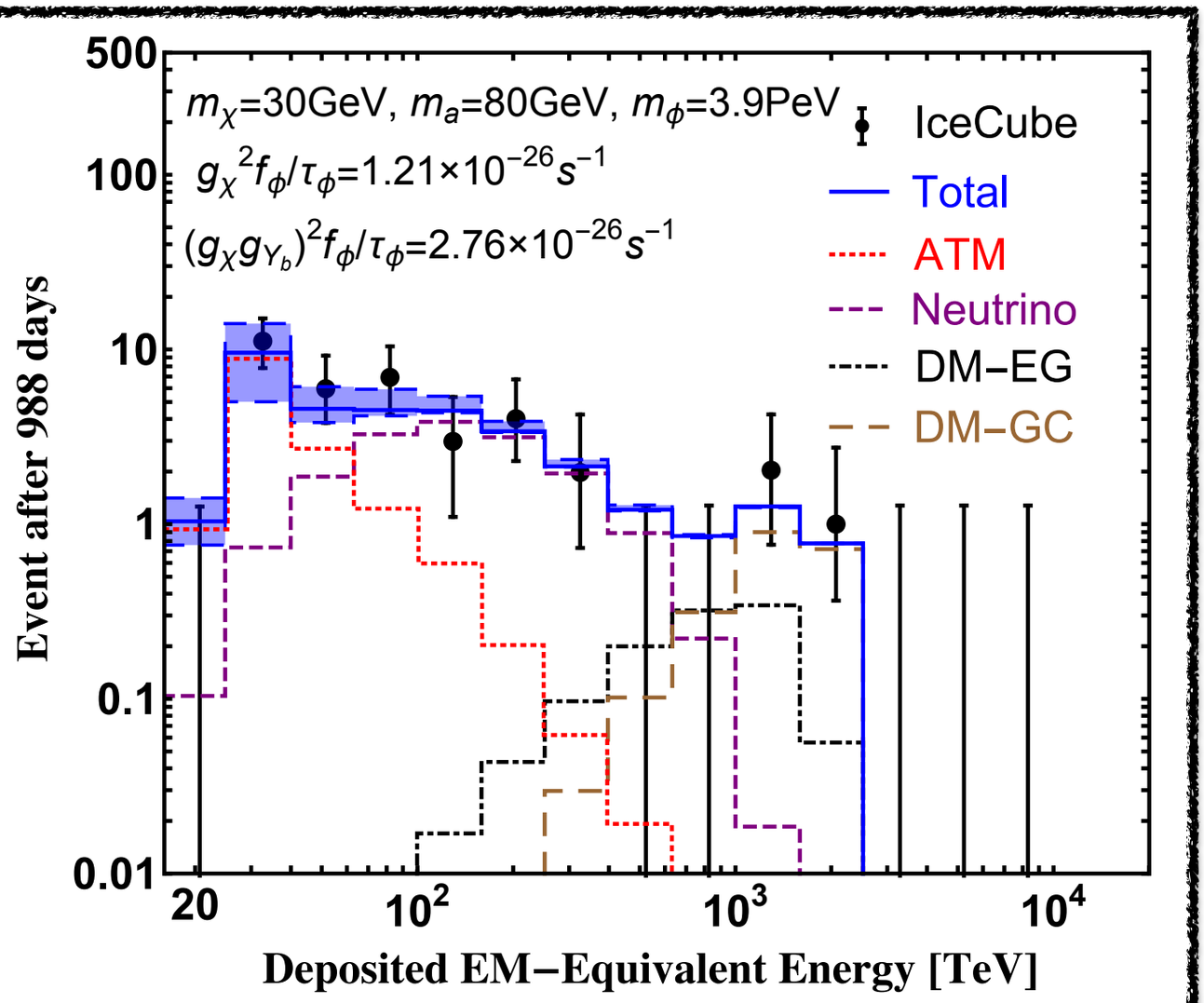
$$\mathrm{LLR}\left(m_\phi, \frac{g_{Y_b}^2 g_\chi^2 f_\phi}{\tau_\phi}, \frac{g_\chi^2 f_\phi}{\tau_\phi}\right) = \log\left(\frac{\underset{x\in[-\infty,\infty]}{\mathrm{Max}}\left[f_{\mathrm{Gauss}}(x)\ \prod_i f_{\mathrm{Poisson}}\left(S_i\left(m_\phi, \frac{g_{Y_b}^2 g_\chi^2 f_\phi}{\tau_\phi}, \frac{g_\chi^2 f_\phi}{\tau_\phi}\right) + B_i + x\,\Delta B_i \,\middle|\, O_i\right)\right]}{\underset{x'\in[-\infty,\infty]}{\mathrm{Max}}\left[f_{\mathrm{Gauss}}(x')\ \prod_i f_{\mathrm{Poisson}}\left(B_i + x'\,\Delta B_i \middle| O_i\right)\right]}\right)$$



Boosted DM in IceCube

—Fitting result

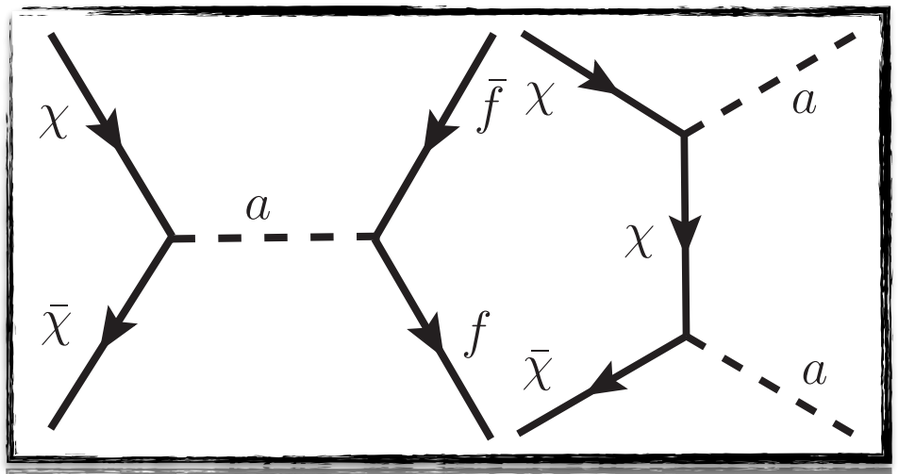




Dark Matter Relic Density

- Relic Density
  - Non-thermal production mechanisms for PeV DM
  - Thermal production for ~(30) GeV DM

$$f_\phi + f_\chi = 1 \qquad \Omega_{\phi/\chi} = f_{\phi/\chi} \times \Omega_{\rm DM}$$



- Annihilation Cross Section

$$\langle \sigma v_{\rm rel} \rangle_{f\bar{f}} \simeq \sum_f \frac{N_c^f}{2\pi} \frac{2 g_\chi^2 g_{Y_f}^2 m_\chi^2 m_f^2 / v^2}{(4m_\chi^2 - m_a^2)^2 + m_a^2 \Gamma_a^2} \sqrt{1 - m_f^2/m_\chi^2}$$

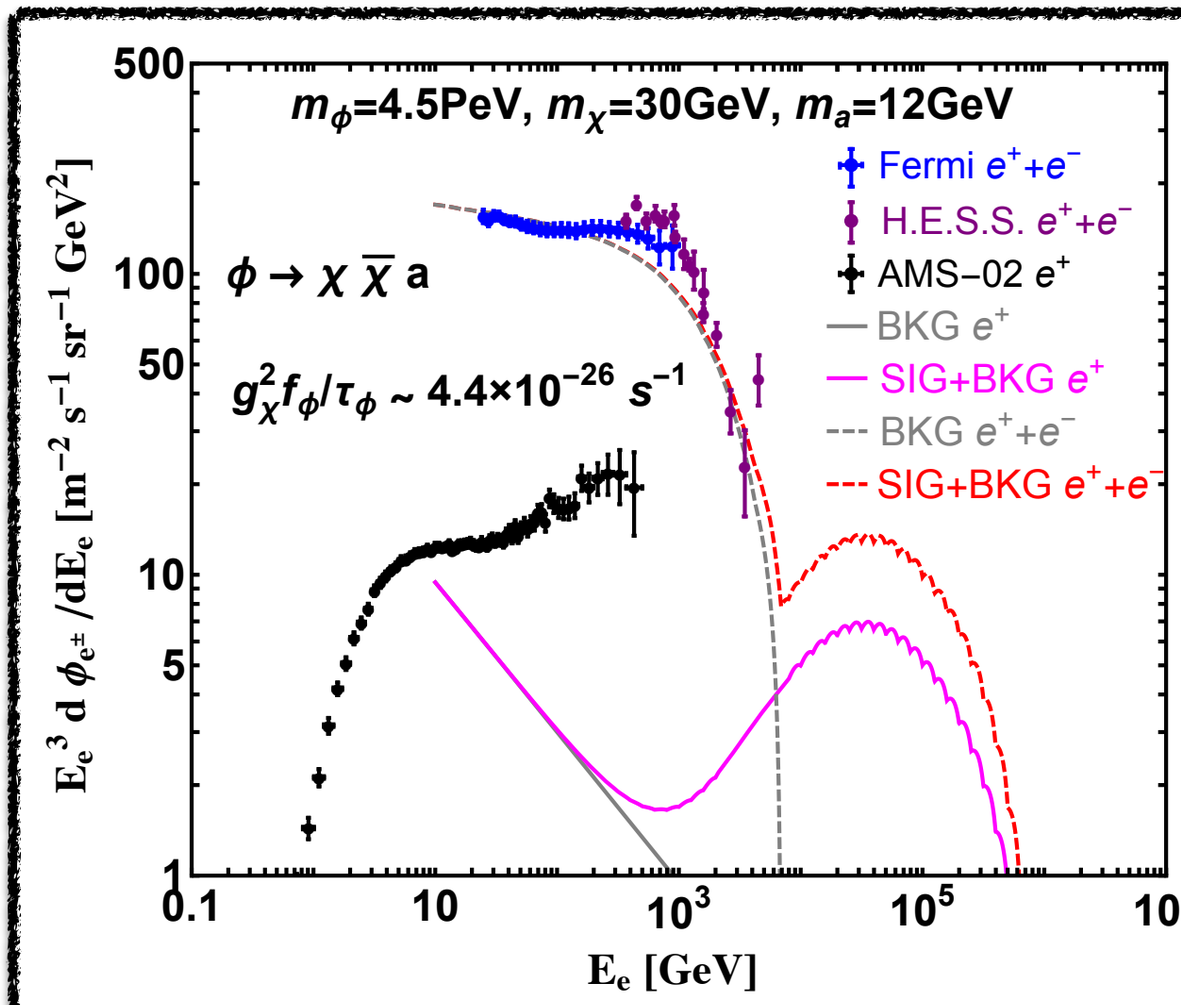
$$\langle \sigma v_{\rm rel} \rangle_{aa} \simeq \frac{g_\chi^4 m_\chi}{24\pi} \frac{(m_\chi^2 - m_a^2)^{5/2}}{(2m_\chi^2 - m_a^2)^4} \frac{6T}{m_\chi}$$

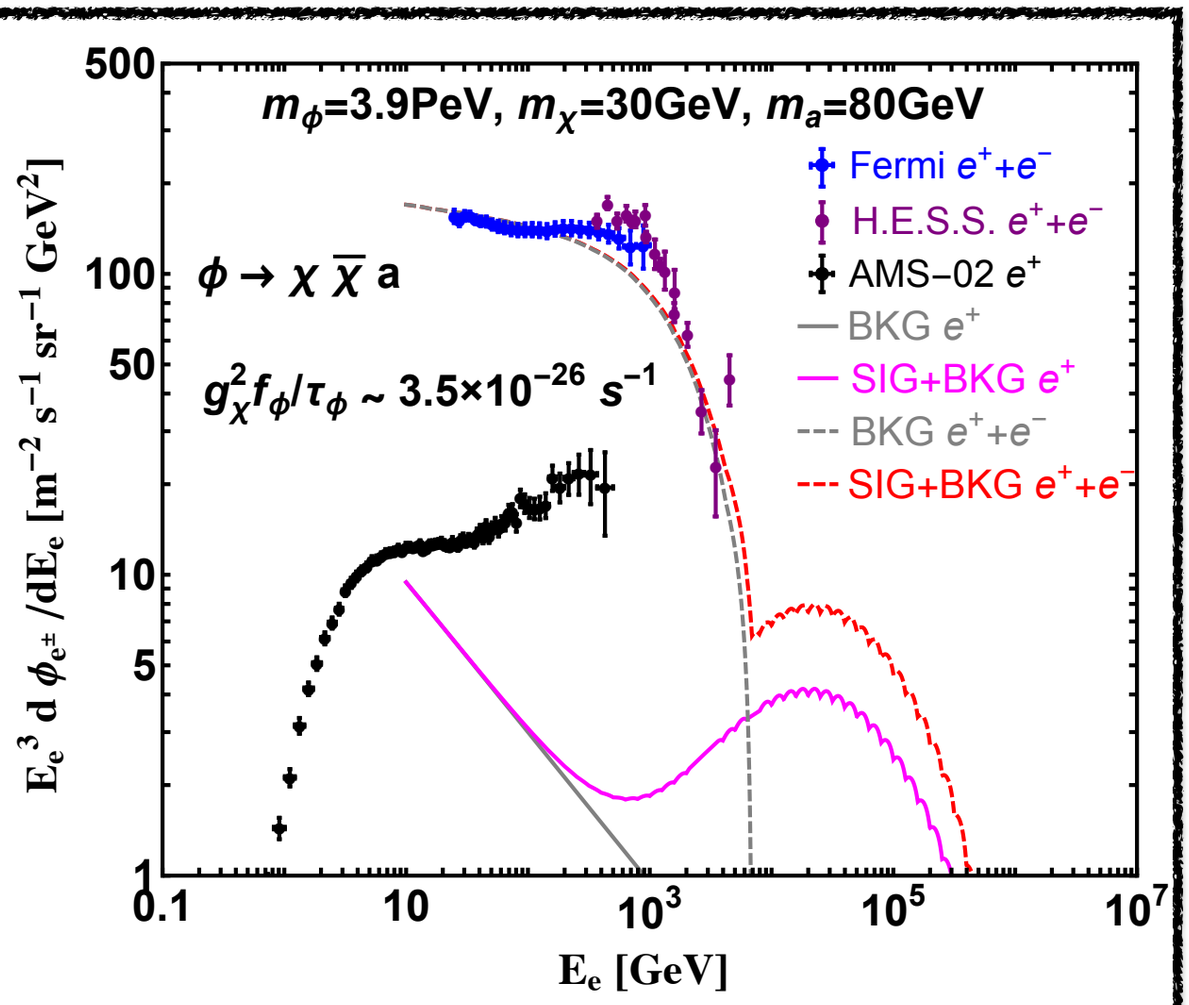
$$m_a = 12{\rm GeV} \quad f_\chi \simeq 0.6 \quad \langle \sigma v_{\rm rel} \rangle_{b\bar{b}} = 2.8 \times 10^{-26} {\rm cm}^3/{\rm s}$$
$$m_a = 80{\rm GeV} \quad f_\chi \simeq 0.33 \quad \langle \sigma v_{\rm rel} \rangle_{b\bar{b}} = 18 \times 10^{-26} {\rm cm}^3/{\rm s}$$

Constraints

—Positron flux

$$\frac{d\Phi_{e^\pm}(E_e,\vec{x})}{dE_e} \propto \Gamma_3(\phi \to \chi\bar{\chi}a) \sum_f \mathrm{BR}(a \to f\bar{f}) \int_{E_e}^{m_\phi/2} dE_e^S \frac{dN^f_{e^\pm}(E_e^S)}{dE_e^S}$$

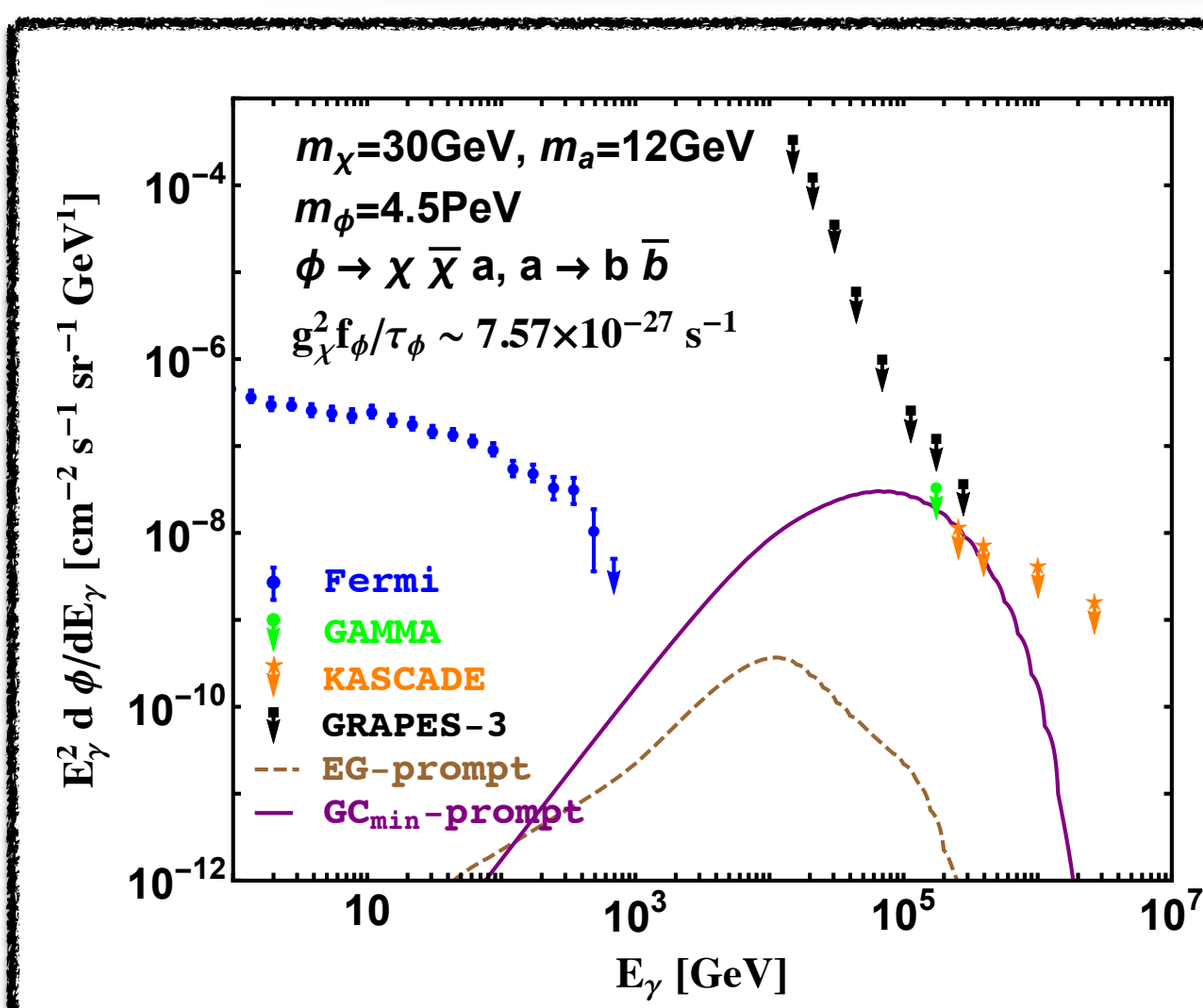


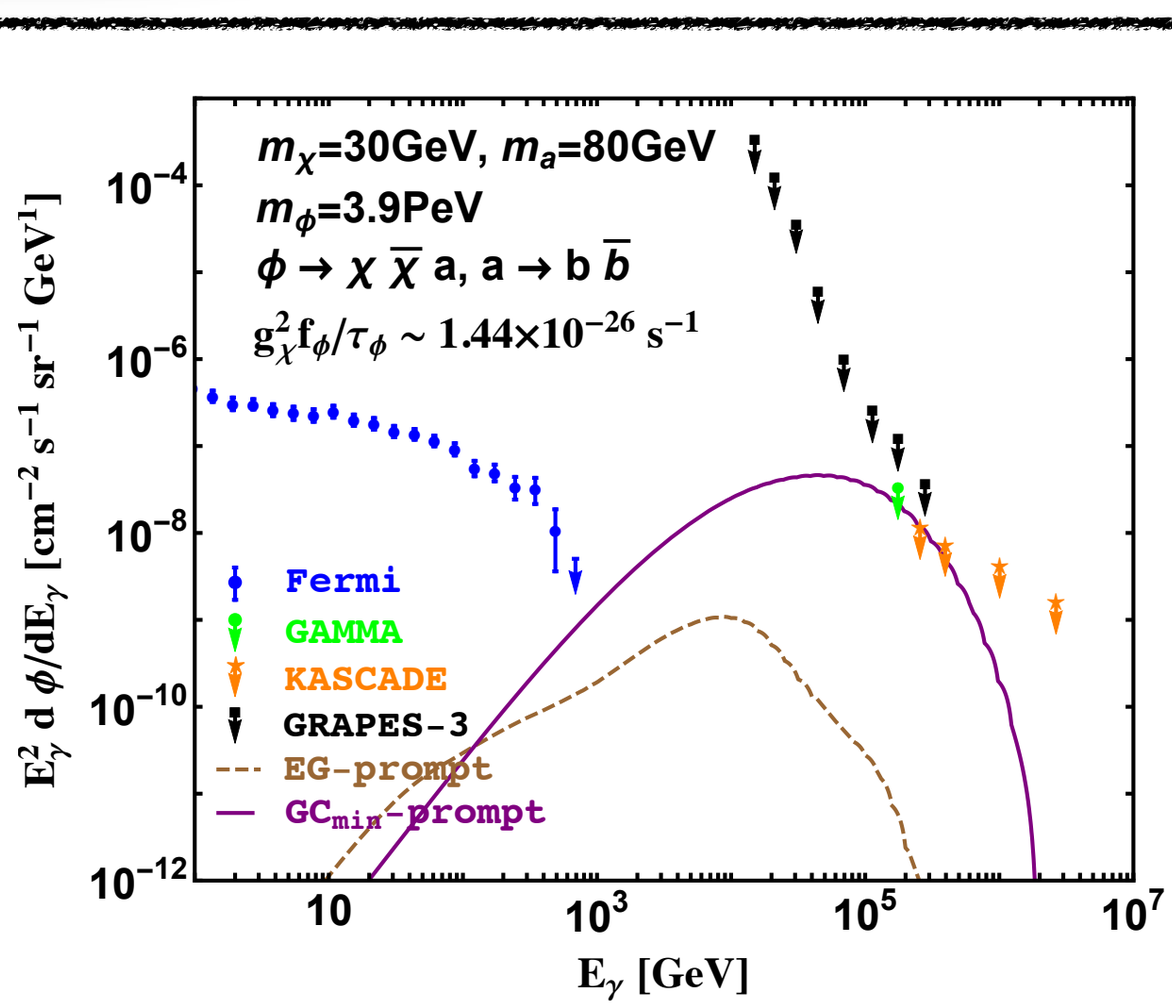


Constraints

—Gamma Ray flux

$$\frac{d\Phi_{\rm diffuse}}{dE_\gamma} = \frac{d\Phi_{\rm GC}}{dE_\gamma d\Omega}\Big|_{\rm minimum} + \frac{d\Phi_{EG}}{dE_\gamma} \quad \Leftrightarrow \quad \exp[-{\rm Abs}(E_\chi, z)]$$





Constraints —Others

- Direct Detection

$$\frac{d\sigma}{dE_r} = \frac{m_T}{32\pi}\frac{1}{v^2}\frac{g_\chi^2}{(Q^2+m_a^2)^2}\frac{(Q^2)^2}{m_N^2 m_\chi^2}\sum_{N,N'=p,n} g_N g_{N'} F_{\Sigma''}^{N,N'}$$

- Flavor Physics

MSSM-like

$$B_s \to \mu^+\mu^-$$

$$m_a \sim 10\mathrm{GeV} \quad \tan\beta\sin\theta = \sqrt{2g_{Y_d}g_{Y_u}} \lesssim 0.4$$
$$m_a \sim 80\mathrm{GeV} \quad \tan\beta\sin\theta = \sqrt{2g_{Y_d}g_{Y_u}} \lesssim 3.8$$

flipped

$$m_a \sim 10\mathrm{GeV} \quad \sin\theta = \sqrt{2g_{Y_d}g_{Y_u}} \lesssim 0.4$$

$$\mathrm{BR}(h\to aa) \simeq 0.02\left(\frac{m_A}{800\ \mathrm{GeV}}\right)^4\left(\frac{\sin\theta}{0.01}\right)^4 < 0.22$$

only MSSM-like and flipped mode

- LHC constraint

$$g_{Y_b} \lesssim 20$$

only vector-like model

Summary

- IceCube: a peaked shower event contribution around PeV.

- Fermi-LAT: gamma-ray excess at ~ 2GeV at galactic center region.

- (J2000.0) event calls for astrophysical component or DM charged current interaction (e.g. sneutrino SM)

Thank you !