

# Boosted Dark Matter in IceCube and at the Galactic Center

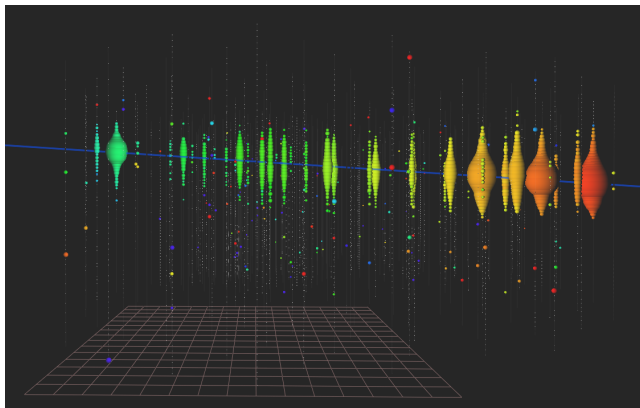
(based on JHEP 1504, 105 (2015) [arXiv:1503.02669] )  
collaborated with Joachim Kopp, Xiao-ping Wang

Jia Liu

MITP, Johannes Gutenberg University Mainz

TAUP 2015 September, Torino

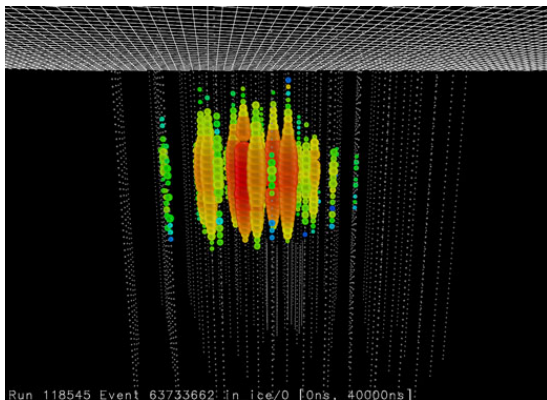
# IceCube: neutrino track event



Credit: IceCube Collaboration

- muons from charge current interaction
- Charged Current:  $\nu_{\mu}/\bar{\nu}_{\mu} + N \rightarrow \mu^{-}/\mu^{+} + N'$

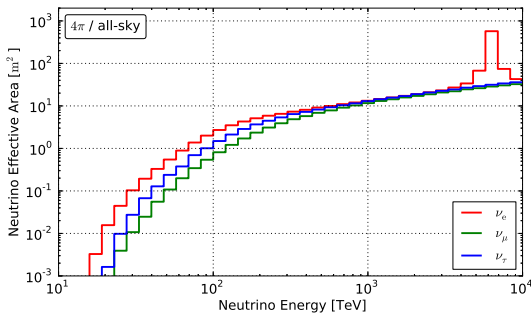
## IceCube: neutrino shower event



Credit: IceCube Collaboration

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

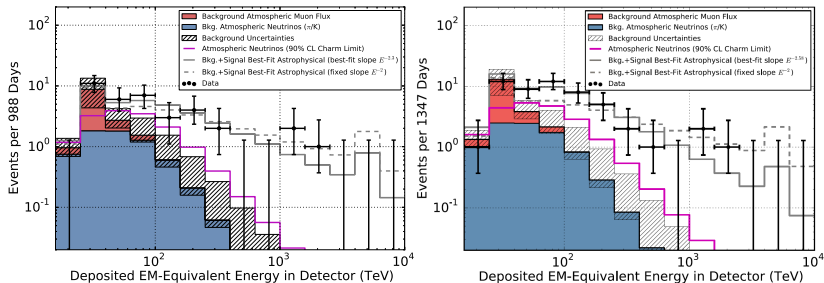
# IceCube: highest energy neutrino in history



Science 342, 1242856 (2013)

- Glashow resonance in  $\nu_e$  flavor:  $e^- + \bar{\nu}_e \rightarrow W^-$
- roughly same effective area for each flavor at high energy

# IceCube: highest energy neutrino in history



- neutrino source:  $p + p \rightarrow \pi, K \rightarrow \mu + \nu_\mu \rightarrow e + 2\nu_\mu + 1\nu_e$
- $\pi, K$  source leads flavor ratio  $(1 : 1 : 1)_\oplus$  at Earth
- best fit flavor  $(0 : 0.2 : 0.8)_\oplus$ ;  $\gamma \sim -2.5$  (from 1507.03991)

# IceCube neutrino: possible interpretations

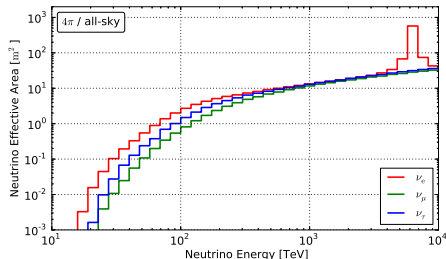
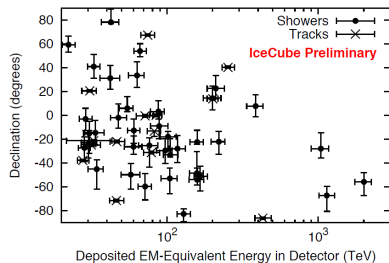
- Astrophysical neutrinos with spectrum  $\sim E^{-2.5}$
- Neutrino from dark matter (energy cutoff)
  - Decaying dark matter
  - Annihilating dark matter
  - ultra-massive long-lived particle
- Non-standard neutrino interaction (e.g. absorption from resonance)

Track event and shower event ratio problem

A shower event preferred model?

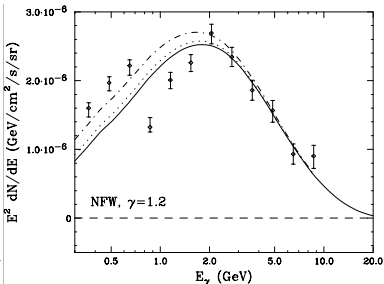
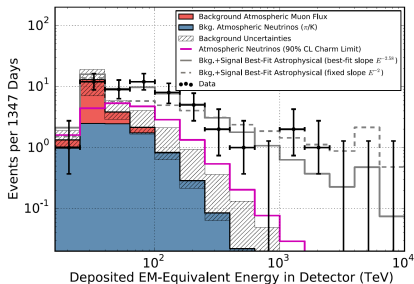
A DM induced collision? (Bhattacharya et al)

# IceCube: track event and shower event ratio



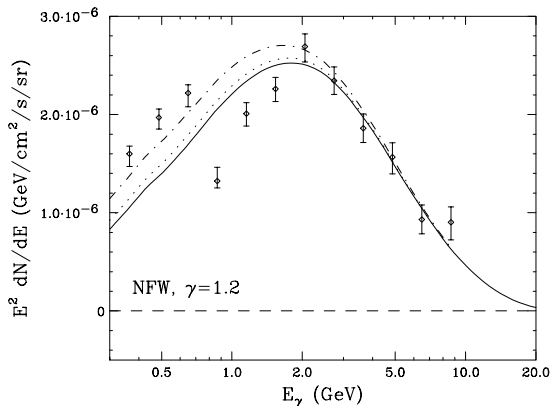
- Mild lack of  $\nu_\mu$  neutrino suggested by
  - C.-Y. Chen, P. Bhupal Dev, and A. Soni;
  - O. Mena, S. Palomares-Ruiz, and A. C. Vincent
- However, The event (J2000.0)
  - multi-PeV neutrino-induced muon event
  - a total energy of  $2.6 \pm 0.3$  PeV within the instrumented volume of IceCube
  - Need astrophysical component or DM-induced charged current (e.g. sneutrino DM)

# Summary of motivations



- IceCube
  - a model with shower events preference at high energy
- Fermi-LAT
  - gamma-ray excess at  $\sim 2\text{GeV}$  at GC

# Fermi-LAT: Galactic Center Excess



- Excess of gamma-ray at GC, peak around 2GeV
- Dark matter annihilation  $\bar{\chi}\chi \rightarrow \bar{b}b$ ,  $f_\chi^2 \langle \sigma v_{\text{rel}} \rangle_{b\bar{b}} \sim 10^{-26} \text{cm}^3/\text{s}$
- Dark matter mass 30GeV  $\sim$  50GeV (1402.6703)

# Lagrangians

- Two dark matter  $\phi$ ,  $\chi$  in dark sector
- $\chi$  has boosted component and thermal component (see also Lina Necib, Monday)

$$\mathcal{L}_{\text{DS}} \equiv \frac{1}{2}(\partial^\mu \phi)(\partial_\mu \phi) - \frac{1}{2}m_\phi^2 \phi^2 + i\bar{\chi}\not{\partial}\chi - m_\chi \bar{\chi}\chi - y_{\phi\chi} \phi \bar{\chi}\chi \quad (1)$$

- One pseudoscalar  $a$  connect dark sector and SM

$$\mathcal{L}_{\text{int}} \equiv ig_\chi a \bar{\chi} \gamma_5 \chi + i \sum_f g_{Y_f} \frac{\sqrt{2}m_f}{v} a \bar{f} \gamma_5 f \quad (2)$$

- 6 free parameters  $m_a$ ,  $m_\phi$ ,  $m_\chi$ ,  $y_{\phi\chi}$ ,  $g_\chi$ ,  $g_Y$

## UV complete models

- MSSM-like model

$iaH_1^\dagger H_2 + h.c.$  leads to pseudoscalar  $a$  and  $A^0$  mixing

$$g_{Y_d} = g_{Y_\ell} = -\tan \beta \sin \theta / \sqrt{2} \quad (3)$$

$$g_{Y_u} = -\cot \beta \sin \theta / \sqrt{2} \quad (4)$$

- Flipped model

$iaH_1^\dagger H_2 + h.c.$  leads to pseudoscalar  $a$  and  $A^0$  mixing

$$g_{Y_d} = -\tan \beta \sin \theta / \sqrt{2} \quad (5)$$

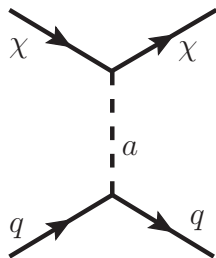
$$g_{Y_u} = g_{Y_\ell} = -\cot \beta \sin \theta / \sqrt{2} \quad (6)$$

- Vector-like quark model

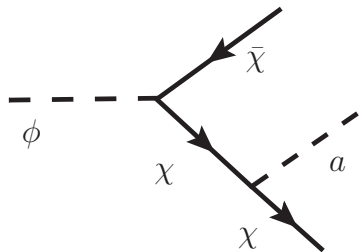
Integrating out heavy vector-like quark which mixes with SM quark

$$y_\Psi a \bar{Q} \gamma^5 \Psi + y_{mix} \bar{\Psi} H d_R + y_Q \bar{Q} H d_R \Rightarrow \bar{d} \gamma^5 d_R a \quad (7)$$

## IceCube spectrum fitting



(Primary signal)  
DM scattering  
shower events only

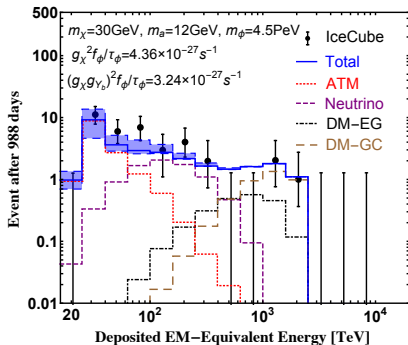


(Secondary signal)  
neutrinos from  $a$  decay  
both shower and track events

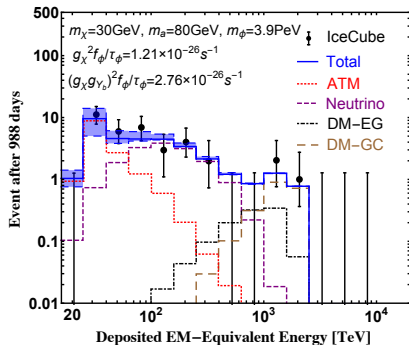
- Primary:  $\phi \rightarrow \bar{\chi}\chi$ ,  $\chi$  scatters with quark
- Secondary:  $\phi \rightarrow \bar{\chi}\chi + a$ ,  $a$  decays to b quark, producing neutrinos

## IceCube spectrum fitting

	$m_a$ [GeV]	$m_\phi$ [PeV]	$m_\chi$ [GeV]	$g_{Y_b}$	$g_\chi$	$\tau_\phi/f_\phi$ [ $10^{25}$ s]	$\langle\sigma v_{\text{rel}}\rangle_{b\bar{b}}$ [ $10^{-26}$ cm <sup>3</sup> /s]	$f_\chi$	$\text{BR}_3(\phi\rightarrow\chi\bar{\chi}a)$	Comment
BP 1	12	4.5	30	0.86	0.396	3.6	2.8	0.6	0.022	Vector-like
BP 2	80	3.9	30	1.51	0.462	1.8	18	0.33	0.026	



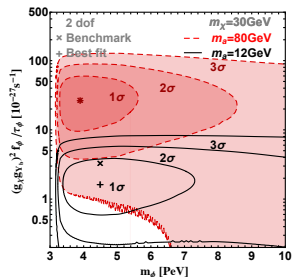
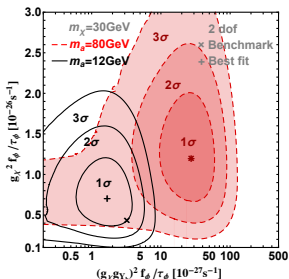
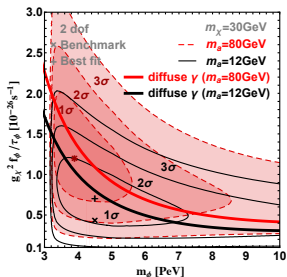
(BP 1)



(BP 2)

## IceCube spectrum fitting

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

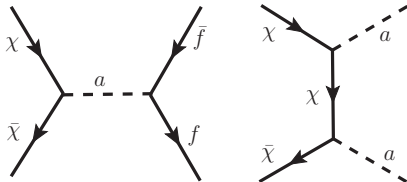


- 6 free parameters  $m_a$ ,  $m_\phi$ ,  $m_\chi$ ,  $y_{\phi\chi}$ ,  $g_\chi$ ,  $g_Y$
- $m_\chi$  fixed by Fermi-LAT,  $m_a$  chose by hand.
- 6 – 3 – 2 = 1 free parameter fixed by relic density and Fermi-LAT.

# DM relic density

- Relic density
  - Non-thermal production mechanism for PeV  $\phi$
  - Thermal production for  $\sim 30$  GeV  $\chi$
  - $f_\phi + f_\chi = 1$  and  $f_{\chi,\phi} \equiv \Omega_{\chi,\phi}/\Omega_{\text{DM}}$

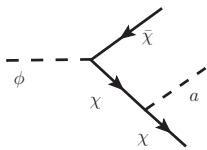
- $\chi$  annihilation channels



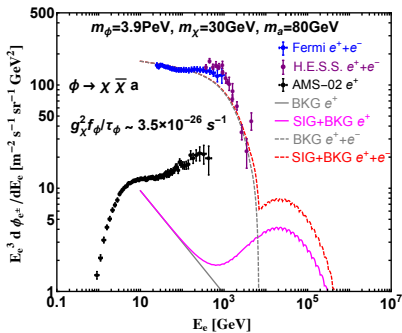
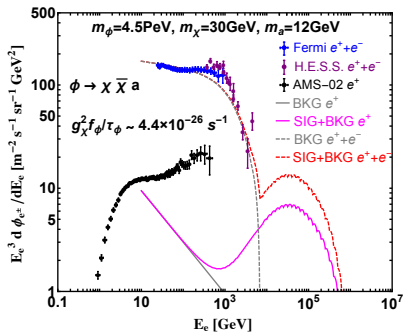
	$m_a$ [GeV]	$m_\phi$ [PeV]	$m_\chi$ [GeV]	$g_{Y_b}$	$g_\chi$	$\tau_\phi/f_\phi$ [ $10^{25}$ s]	$\langle\sigma v_{\text{rel}}\rangle_{b\bar{b}}$ [ $10^{-26}$ cm <sup>3</sup> /s]	$f_\chi$	$\text{BR}_3(\phi \rightarrow \chi\bar{\chi}a)$	Comment
BP 1	12	4.5	30	0.86	0.396	3.6	2.8	0.6	0.022	Vector-like
BP 2	80	3.9	30	1.51	0.462	1.8	18	0.33	0.026	

- Fermi-LAT requirement satisfied  $f_\chi^2 \langle\sigma v_{\text{rel}}\rangle_{b\bar{b}} \sim 10^{-26}$  cm<sup>3</sup>/s

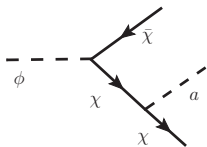
# Electron and positron constraint



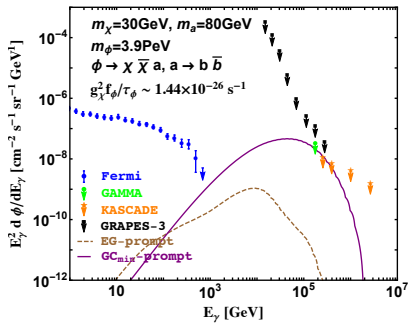
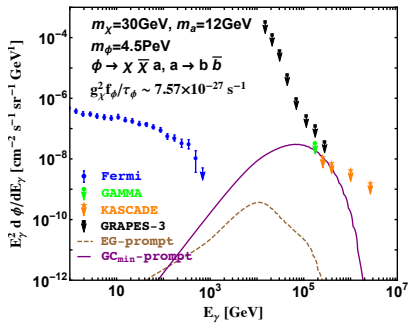
$a \rightarrow \bar{b}b$  produce secondary  $\nu$ ,  $e$  and  $\gamma$



# Gamma ray constraint



$a \rightarrow \bar{b}b$  produce secondary  $\nu$ ,  $e$  and  $\gamma$

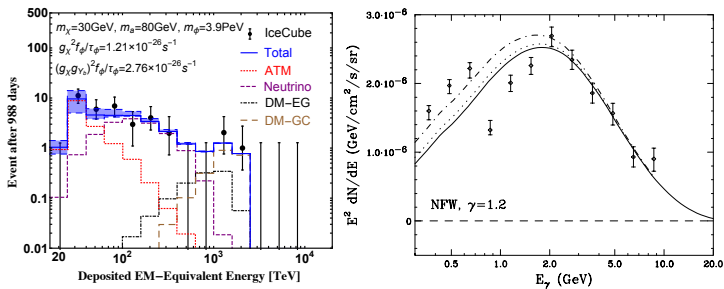


# Other constraints

- Direct detection constraint
- Flavor physics, e.g.  $B_s \rightarrow \mu^+ \mu^-$
- Collider constraint, e.g.  $h \rightarrow aa$  and heavy quark limits

$m_a$	IceCube		galactic center		$m_\chi$	$\langle \sigma v_{\text{rel}} \rangle_{b\bar{b}} f_\chi^2$	$e^\pm$	diffuse $\gamma$	Lab	Model	$g_{Y_b}$
	Boosted DM	Secondary $\nu$	$m_\chi$	$\langle \sigma v_{\text{rel}} \rangle_{b\bar{b}} f_\chi^2$							
[GeV]	$m_\phi$ [PeV]	$g_{Y_b}^2 g_\chi^2 f_\phi / \tau_\phi$ [ $10^{-26} \text{ s}^{-1}$ ]	$g_\chi^2 f_\phi / \tau_\phi$ [ $10^{-26} \text{ s}^{-1}$ ]	[GeV]	[ $10^{-26} \text{ cm}^3/\text{s}$ ]	[ $10^{-26} \text{ s}^{-1}$ ]	[ $10^{-26} \text{ s}^{-1}$ ]				
12	4.5	0.32	0.44	30	1	$\lesssim 4.4$	$\lesssim 0.76$	MSSM-like	$\lesssim 0.3$		
								Flipped	$\lesssim 0.013 \tan \beta$		
								Vector-quark	$\lesssim 20$		
80	3.9	2.8	1.2	30	2	$\lesssim 3.5$	$\lesssim 1.44$	MSSM-like	$\lesssim 3$		
								Flipped	–		
								Vector-quark	$\lesssim 20$		

# Summary



- IceCube
  - a peaked shower event contribution ( $\chi$  neutral current scattering)
- Fermi-LAT
  - gamma-ray excess at  $\sim 2\text{GeV}$  at GC ( $\bar{\chi}\chi \rightarrow \bar{b}b$ )
- (J2000.0) event calls for astrophysical component or DM with charged current interaction (e.g. sneutrino DM)