New Search for Monochromatic Neutrinos from Dark Matter Decay

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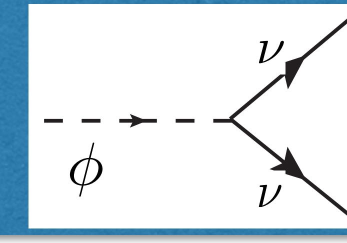
[Based on: Chaïmae El Aisati, MG & Thomas Hambye, arXiv:1506.02657]

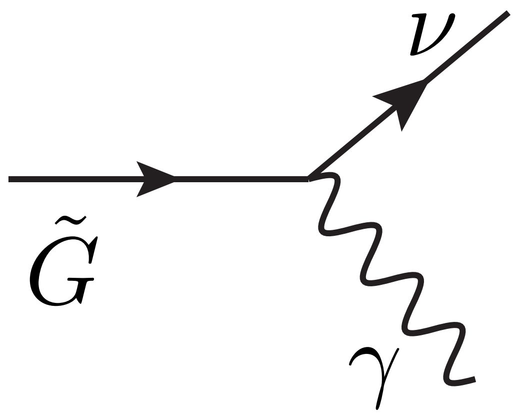
inVisibles
neutrinos, dark matter & dark energy physics
Madrid, June 23th 2015

Motivations for $\boldsymbol{\nu}$-line search

1. A monochromatic spectral line (in cosmic γ or ν) is a smoking-gun evidence for dark matter particles
2. Use latest improvements of IceCube in taking data — large eff. A, good E resolution and atm. bkg rejection
3. Explore a new analysis strategy to improve signal sensitivity — by an order of magnitude for decaying DM
4. Neutrino line searches overtake gamma-ray line sensitivities at multi-TeV energies!

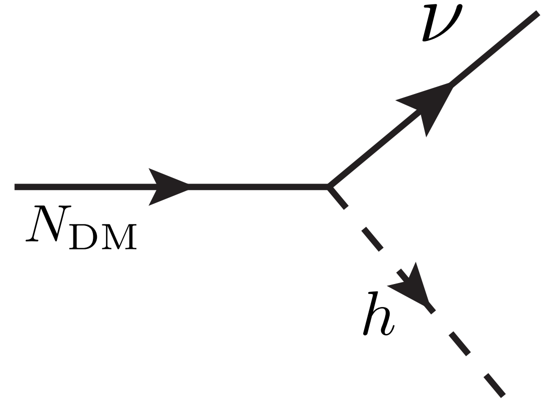
Theoretical model examples





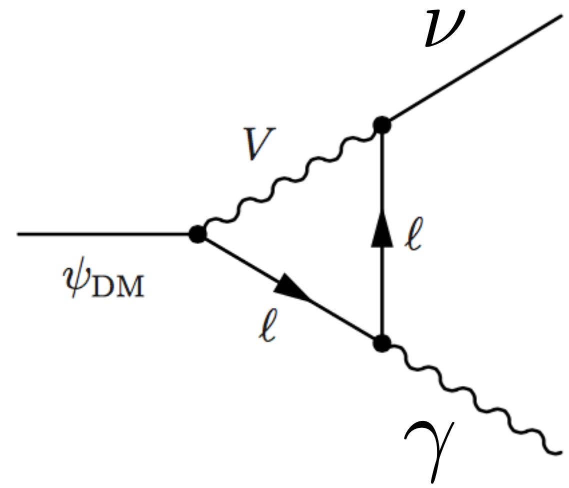
Gravitino $\not{R}$

Takayama Yamaguchi,
Phys. Lett. B 485, 388 (2000)

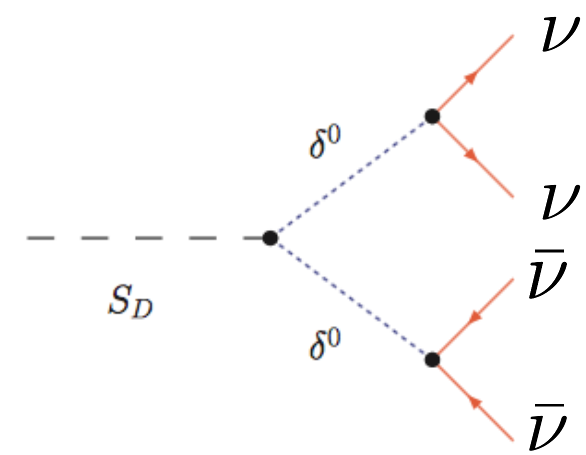


Neutrino see-saw

Rott, Kohri, Park [arXiv:1408.4575]
Higaki, Kitano & Sato, JHEP 1407



'loop of heavy states'



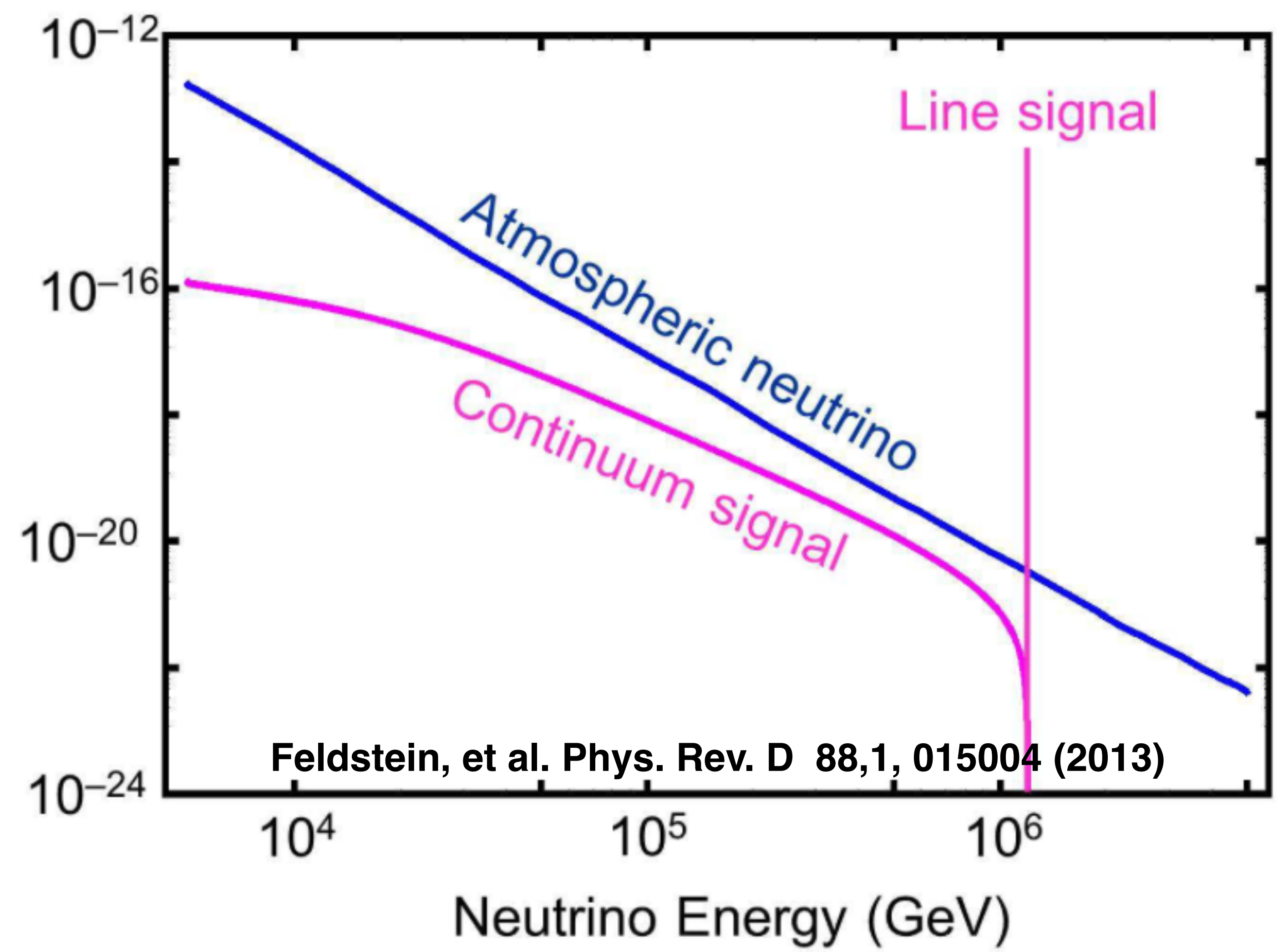
line-like

Guo, Wu Zhou,
PRD 81, 075014 (2010)

→ **Energy spectrum**

$$\frac{\mathrm{d}N}{\mathrm{d}E} \rightarrow$$

$$\simeq \delta(E_\nu - \frac{m_{\rm DM}}{2})$$



The DM induced neutrino intensity

flux from dark matter decay at energy E_ν in direction Ω

Extragalactic — isotropic

$$\frac{\mathrm{d}\phi_{\mathrm{eg}}}{\mathrm{d}E_\nu d\Omega} = \frac{\Omega_{\mathrm{DM}}\rho_{\mathrm{c}}}{4\pi}\int_0^\infty \mathrm{d}z \frac{c}{H_0\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m}}(1+z)^3}} \frac{1}{m_{\mathrm{DM}}\tau_{\mathrm{DM}}}\frac{\mathrm{d}N}{\mathrm{d}E}\bigg|_{E=E_\nu(1+z)}$$

Cosmological factor

Particle Physics factor

Galactic — spatial dependence (b,l)

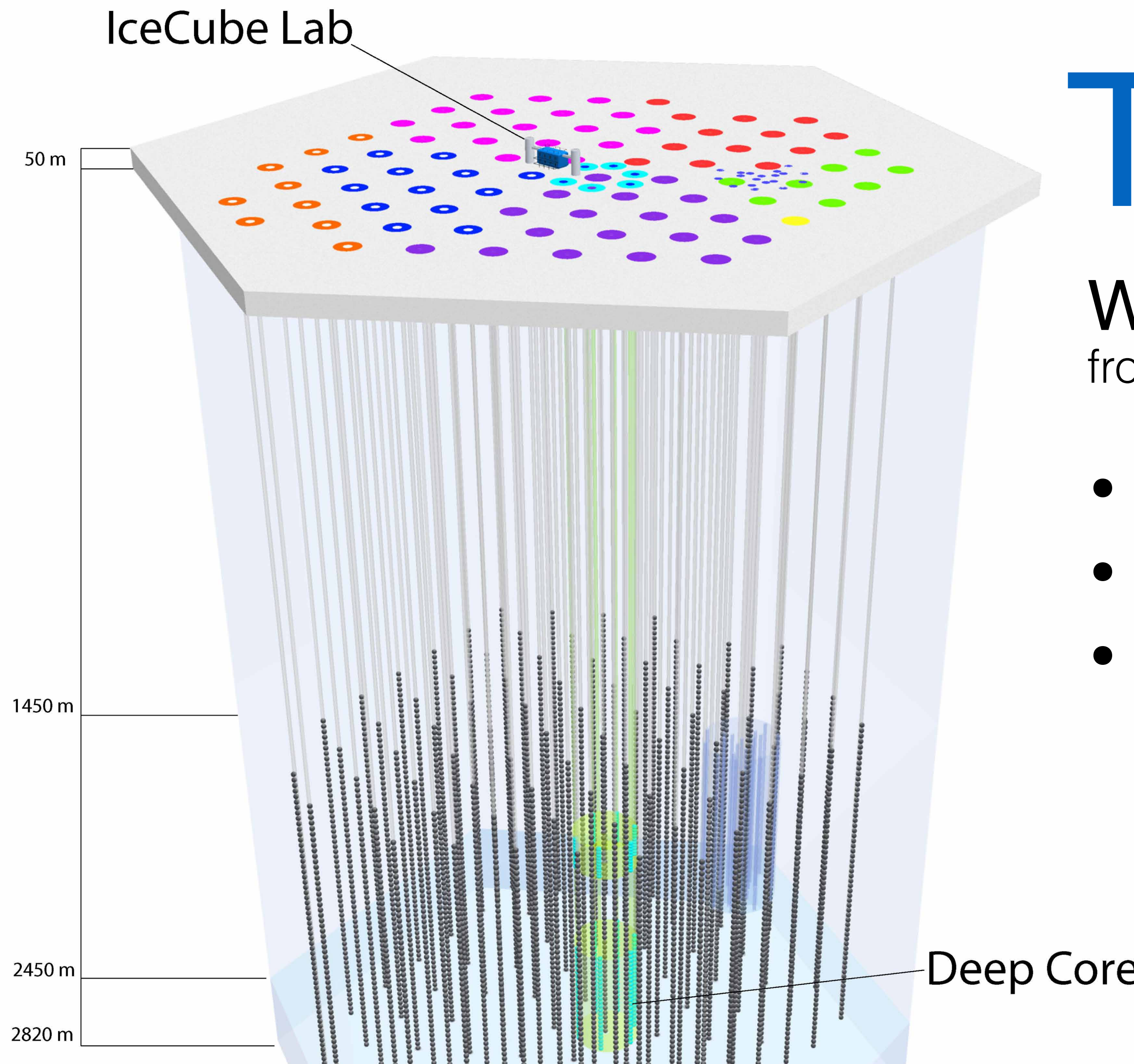
$$\frac{\mathrm{d}\phi_{\mathrm{h}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}(b,l) = \frac{1}{4\pi\, m_{\mathrm{DM}}\,\tau_{\mathrm{DM}}}\frac{\mathrm{d}N}{\mathrm{d}E_\nu}\int_{\mathrm{l.o.s.}} \mathrm{d}s\ \rho_{\mathrm{h}}[r(s,b,l)].$$

Galactic DM factor

NFW profile, $\rho_h(r) = \frac{r_\odot}{r}\left(\frac{a+r_\odot}{a+r}\right)^2 \rho_\odot,$

$$\rho_\odot = 0.39\ \mathrm{GeV/cm^3},\ r_\odot = 8.33\ \mathrm{kpc\ and}\ a = 24\ \mathrm{kpc}$$

The IceCube



We use public data
from Aartsen+ PRD 91, 022001 (2015)

- T = 641 days, from 2010 to 2012
- 78 strings + 8 Deep Core strings w/ 60 DOMs
- Detailed information on the Instrument

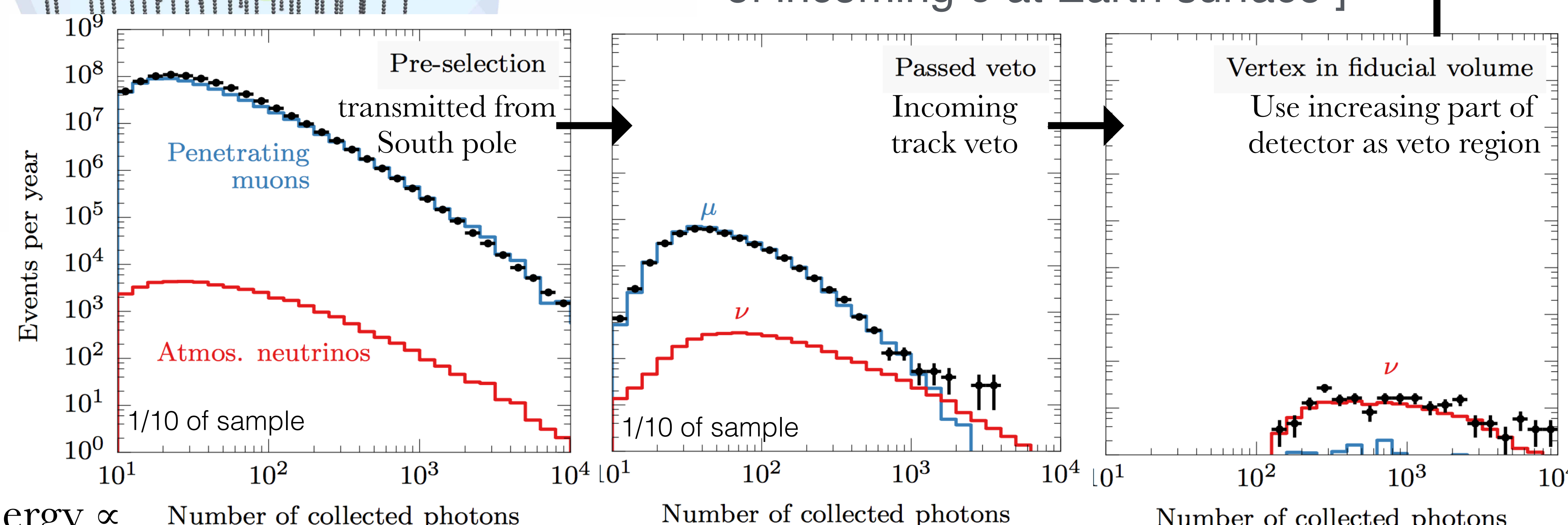
Response is provided for this data set:

★ Effective area $A_{\mathrm{eff},\alpha}(E_\nu, \theta, \phi)$

★ Energy dispersion $D^{\alpha}_{\mathrm{eff}}(E', \theta', \phi'; E_\nu, \theta, \phi)$

[Based on Monte Carlo simulation of incoming υ at Earth surface]

Data cuts →



υ energy ∝ Number of collected photons

Instrument Response

The DM signal is multiplied with the exposure $\mathcal{E}_\alpha = A_{\mathrm{eff},\alpha}(E_\nu, \theta) \times T$
and folded with the dispersion function $D^\alpha_{\mathrm{eff}}(E', \theta', \phi'; E_\nu, \theta, \phi)$

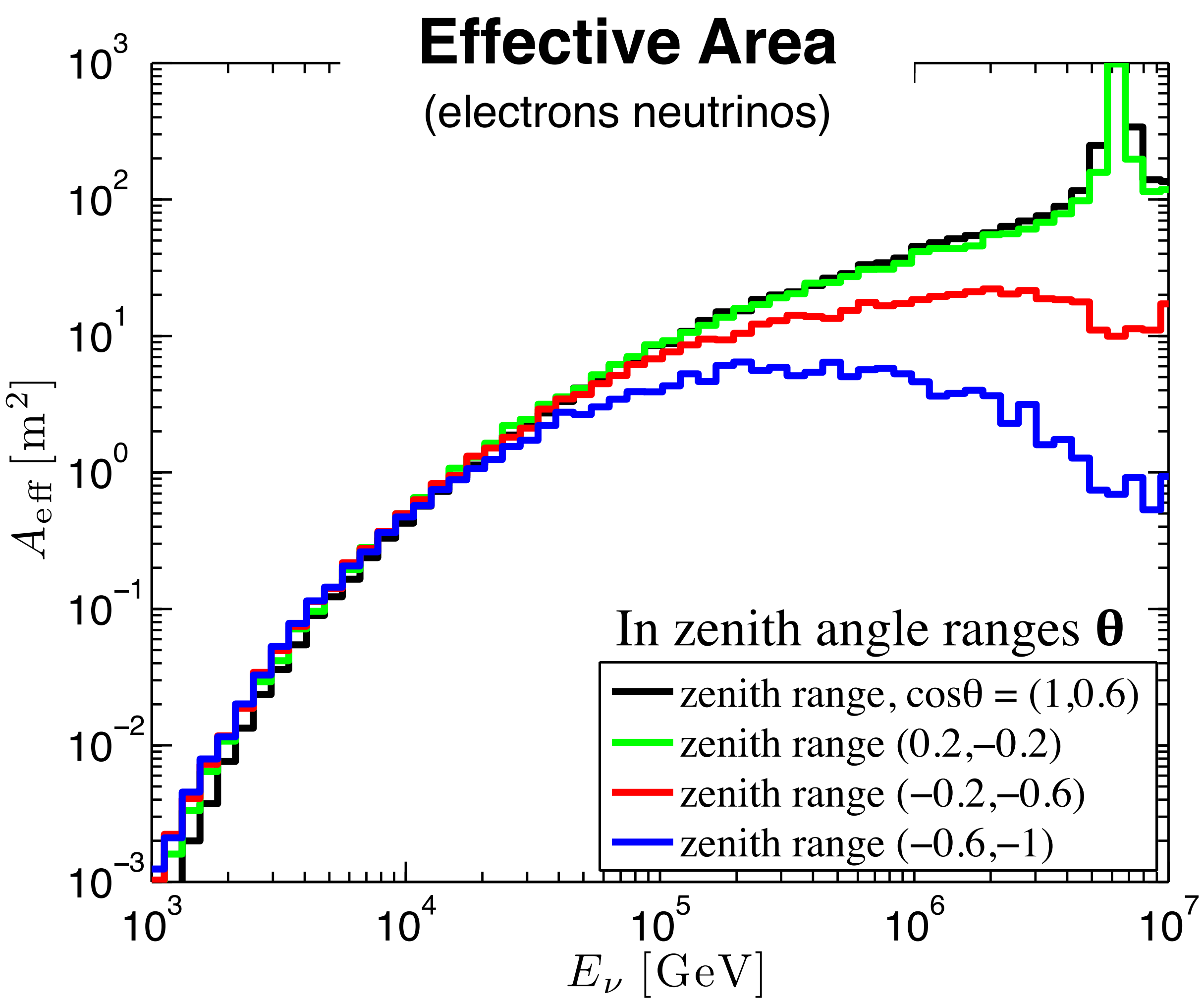
$$\frac{\mathrm{d}N_\alpha}{\mathrm{d}E_\nu \mathrm{d}\Omega \mathrm{d}E' \mathrm{d}\cos\theta' \mathrm{d}\phi'} = \frac{\mathrm{d}(\phi_\mathrm{h} + \phi_\mathrm{eg})_\alpha}{\mathrm{d}E_\nu \mathrm{d}\Omega} \mathcal{E}_\alpha D_{\mathrm{eff},\alpha}$$

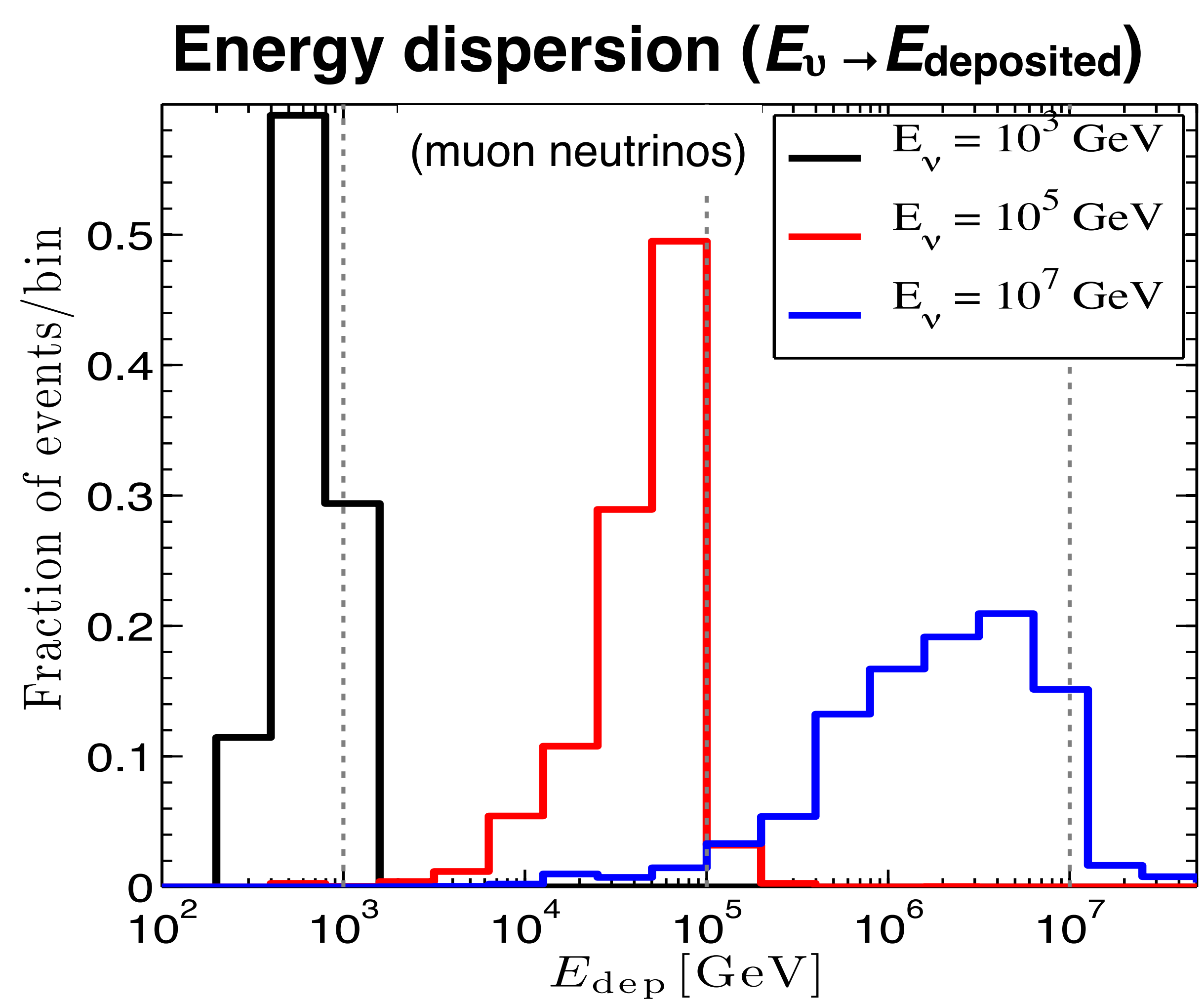
for each neutrino type $\alpha = \{e, \mu, \tau, \bar{e}, \bar{\mu}, \bar{\tau}\}$

"theory" → "observables"

Theory Signal

Detector response





Dark Matter Signal Spectrum

Full differential information into binned prediction

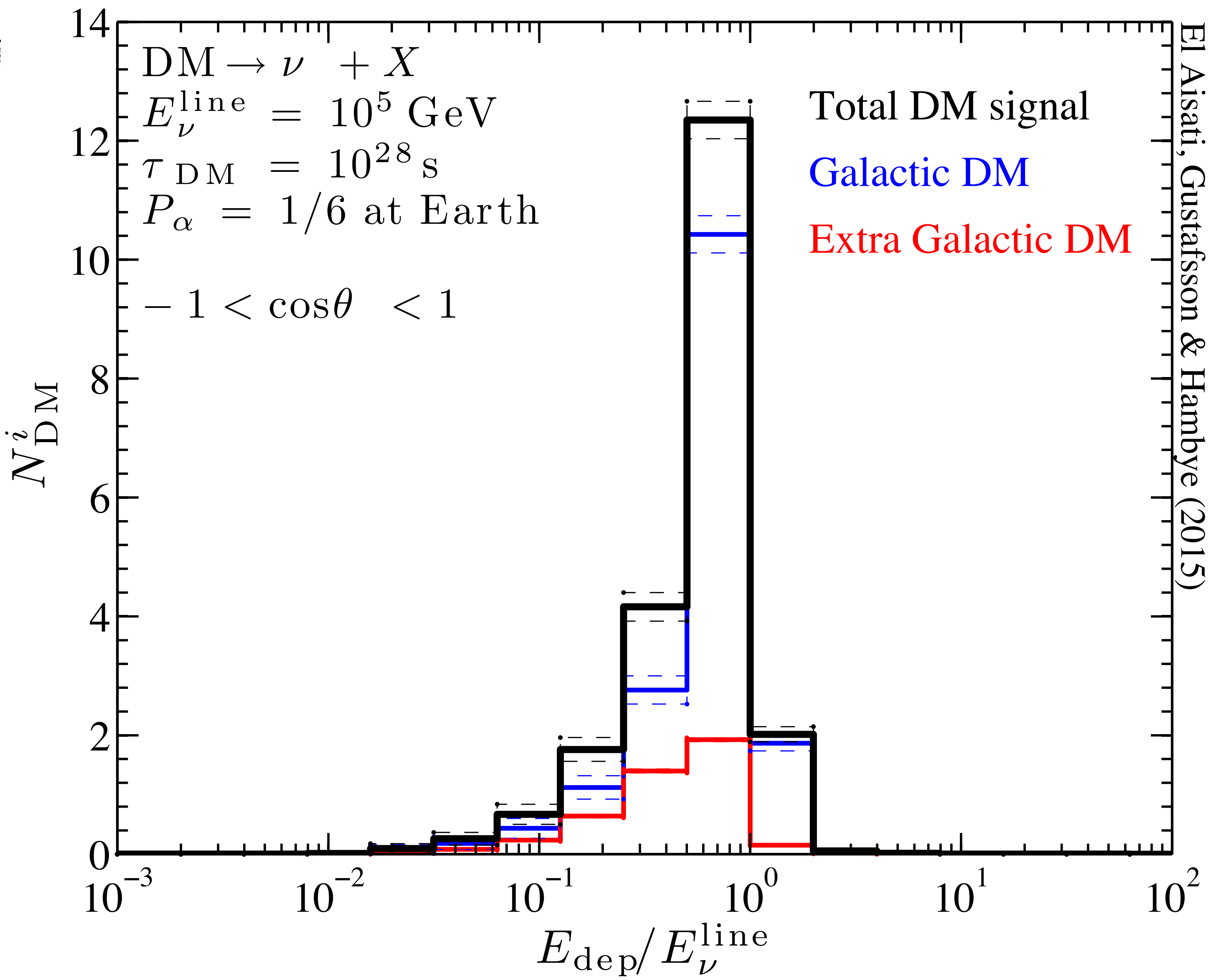
$$N^i_{\rm DM} = \int_{\Delta_i E'} \mathrm{d}E' \int_{\Delta\theta'(t)} \mathrm{d}\cos\theta' \int_{\Delta\phi'(t)} \mathrm{d}\phi' \int \mathrm{d}E \int_{4\pi} \mathrm{d}\Omega \sum_{\substack{\alpha=e,\mu,\tau,\\ \bar{e},\bar{\mu},\bar{\tau}}} P_\alpha \frac{\mathrm{d}N_\alpha}{\mathrm{d}E_\nu \mathrm{d}\Omega \mathrm{d}E' \mathrm{d}\cos\theta' \mathrm{d}\phi'}$$

Energy bin *i*

RoI (use full sky)

Integrate over all *E* and *Ω*

Signal



Neutrino flux composition @ Earth surface.

Typical assumption, flavor democratic and particle/anti-particle symmetric:

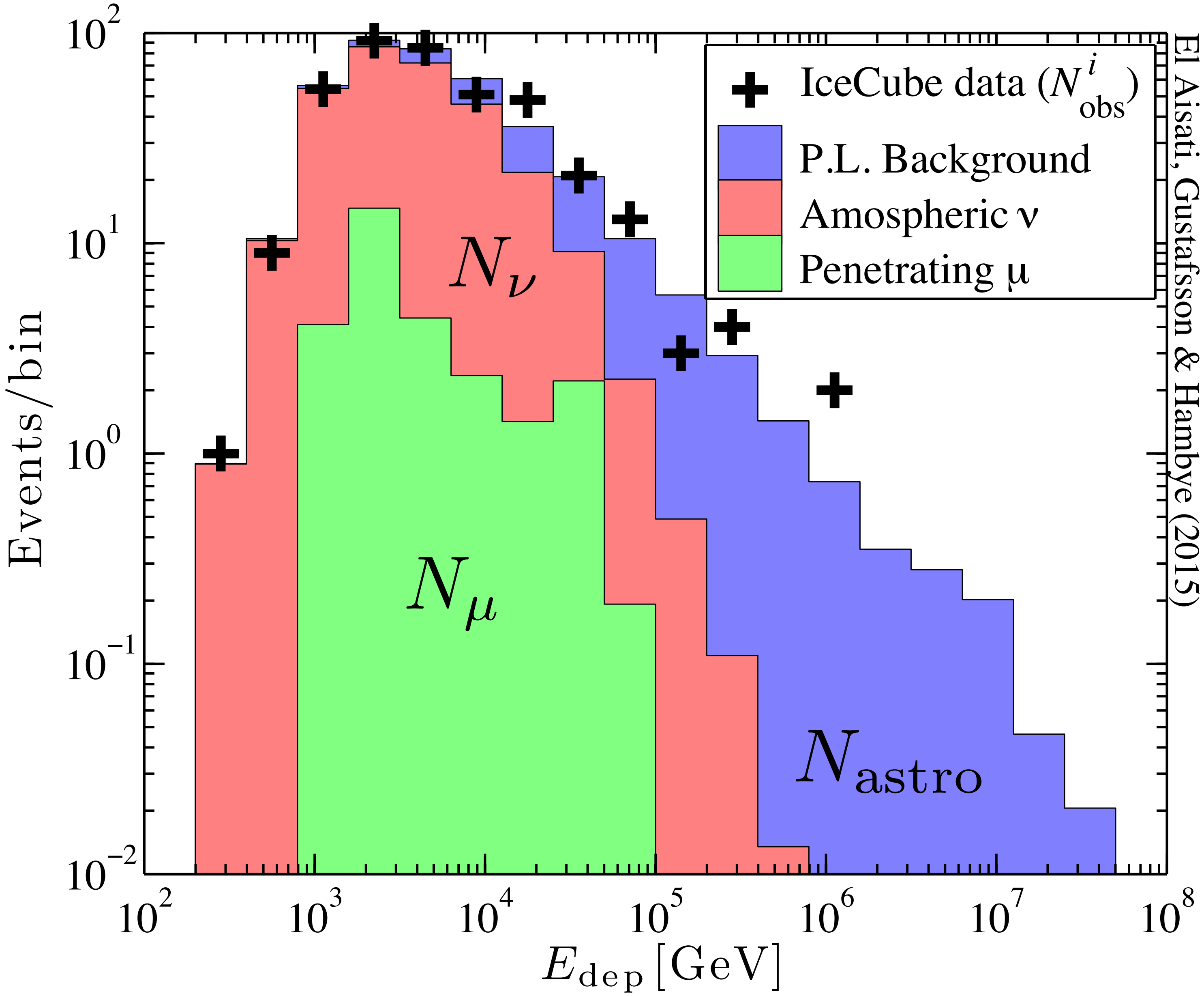
$$P_\alpha \simeq 1/6$$

(For a particular flavor at source use Long base-line oscillations:

$$P(\nu_e \leftrightarrow \nu_e) = 0.573, \quad P(\nu_e \leftrightarrow \nu_\mu) = 0.277$$
$$P(\nu_e \leftrightarrow \nu_\tau) = 0.150, \quad P(\nu_\mu \leftrightarrow \nu_\mu) = 0.348$$
$$P(\nu_\mu \leftrightarrow \nu_\tau) = 0.375, \quad P(\nu_\tau \leftrightarrow \nu_\tau) = 0.475.$$
)

Neutrino data

Aartsen+ PRD 91, 022001 (2015)



Model for the data

- Known atmospheric backgrounds: Muons (N_μ), Atmospheric **υ** (N_υ) Assumed power-law Astrophysical bkg:

M. Honda et al. PRD **75**, 043006 (2007)

$$\frac{\mathrm{d}\phi_{\mathrm{astro}}}{\mathrm{d}E_\nu \mathrm{d}\Omega} = 3\phi_0 \left(\frac{E_\nu}{E_0}\right)^{-\gamma}$$

Detector convolved model prediction:

$$N^i_{\mathrm{model}} = n_{\mathrm{sig}} N^i_{\mathrm{DM}}(m_{\mathrm{DM}}, \tau_0) + n_1 N^i_\mu + n_2 N^i_\nu + n_3 N^i_{\mathrm{astro}}(\gamma, \phi_0)$$

DM signal strength

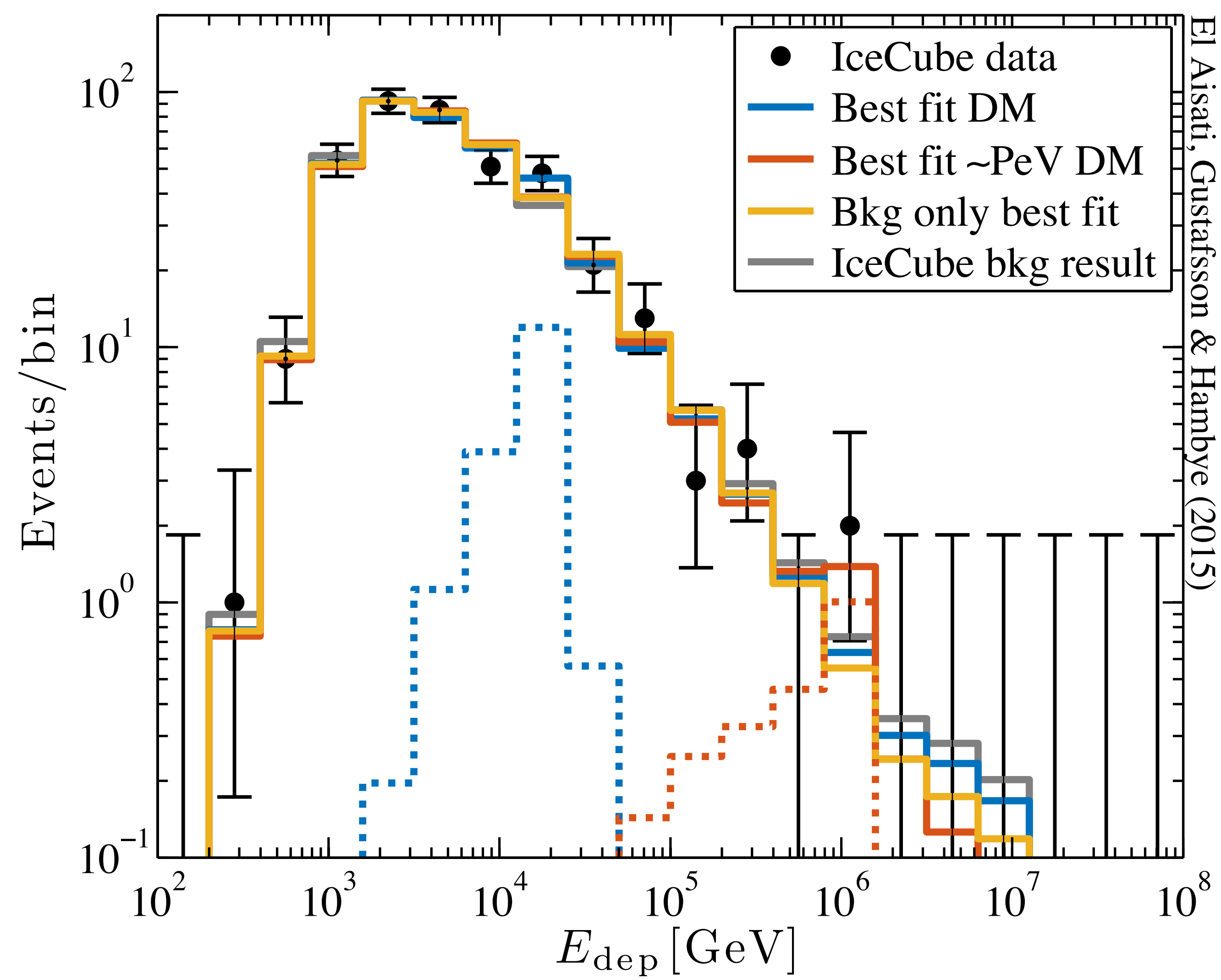
Free normalizations and free PL index

$$n_{\mathrm{sig}} \equiv \tau_0 / \tau_{\mathrm{sig}}$$

- Build Likelihood function
[20 bins from 100 GeV to 10^8 GeV]

$$\mathcal{L} = \prod_{\mathrm{bins}\ i} \frac{(N^i_{\mathrm{model}})^{N^i_{\mathrm{obs}}}}{N^i_{\mathrm{obs}}!} e^{-N^i_{\mathrm{model}}}$$

Note: bkg model gives good χ^2 fit to data, p-value = 0.42



Search

↓

Form a Test Statistics from
Profile Likelihood ratios

$$\mathrm{TS} = 2\ln\frac{\mathcal{L}(n_{\rm sig} = n_{\rm sig,best}, \hat{\theta})}{\mathcal{L}(n_{\rm sig} = 0, \hat{\hat{\theta}})}$$

nuisance param. $\theta = \{n_{1,2,3}, \gamma\}$

TS has an asymptotic distribution of:

$$\frac{1}{2}\left[\delta(TS) + \chi^2_{1-\rm dof}(TS)\right]$$

Chernoff theorem (Annals Math. Statist. 25, 573 (1938).

Search

↓

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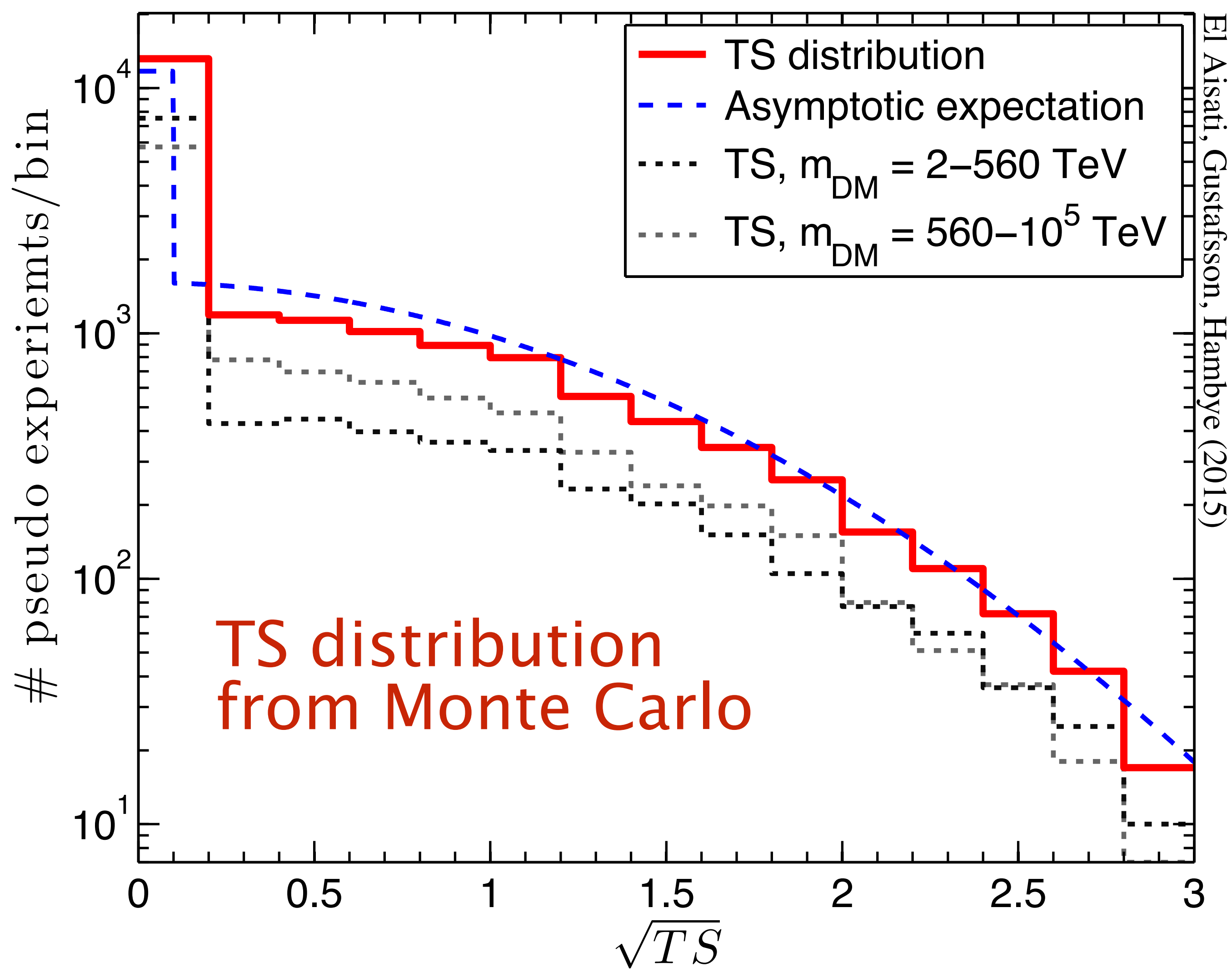

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The significance (in no. of $\boldsymbol{\sigma}$) for rejecting the bkg. model in favor of the DM signal is given by $\sqrt{\mathrm{TS}}$

STATISTICAL ANALYIS

Search → Limits

If no DM detected

↓

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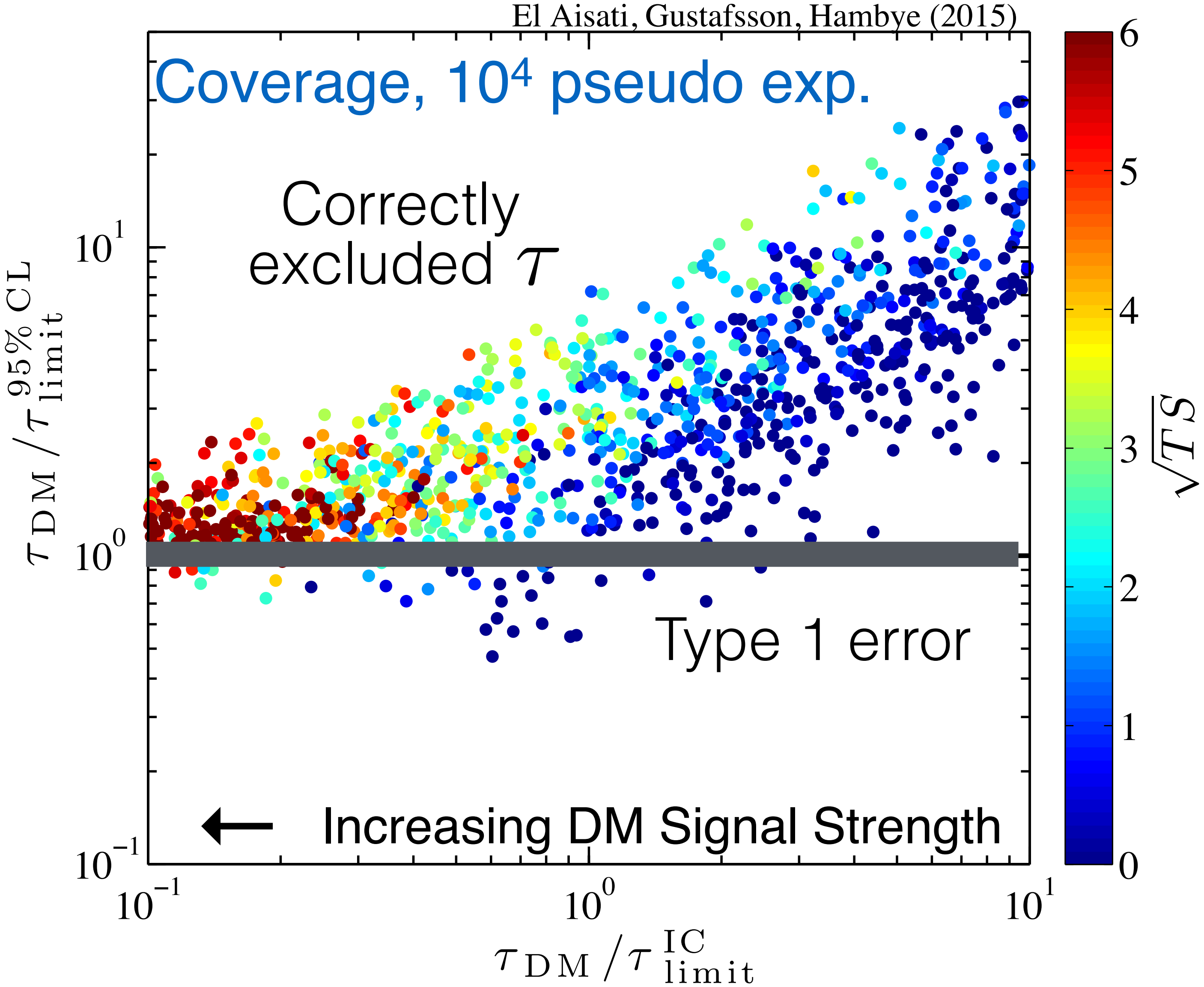
Limits

95% CL limit from maximal signal such that $n_{\rm limit}$

$$TS = 2\ln \frac{\mathcal{L}(n_{\rm sig} = n_{\rm sig,best}, \hat{\theta})}{\mathcal{L}(n_{\rm sig} = n_{\rm limit}, \hat{\hat{\theta}})} < 2.71$$

$$\tau_{\rm limit} = \tau_0 / n_{\rm limit}$$

STATISTICAL ANALYIS



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↓

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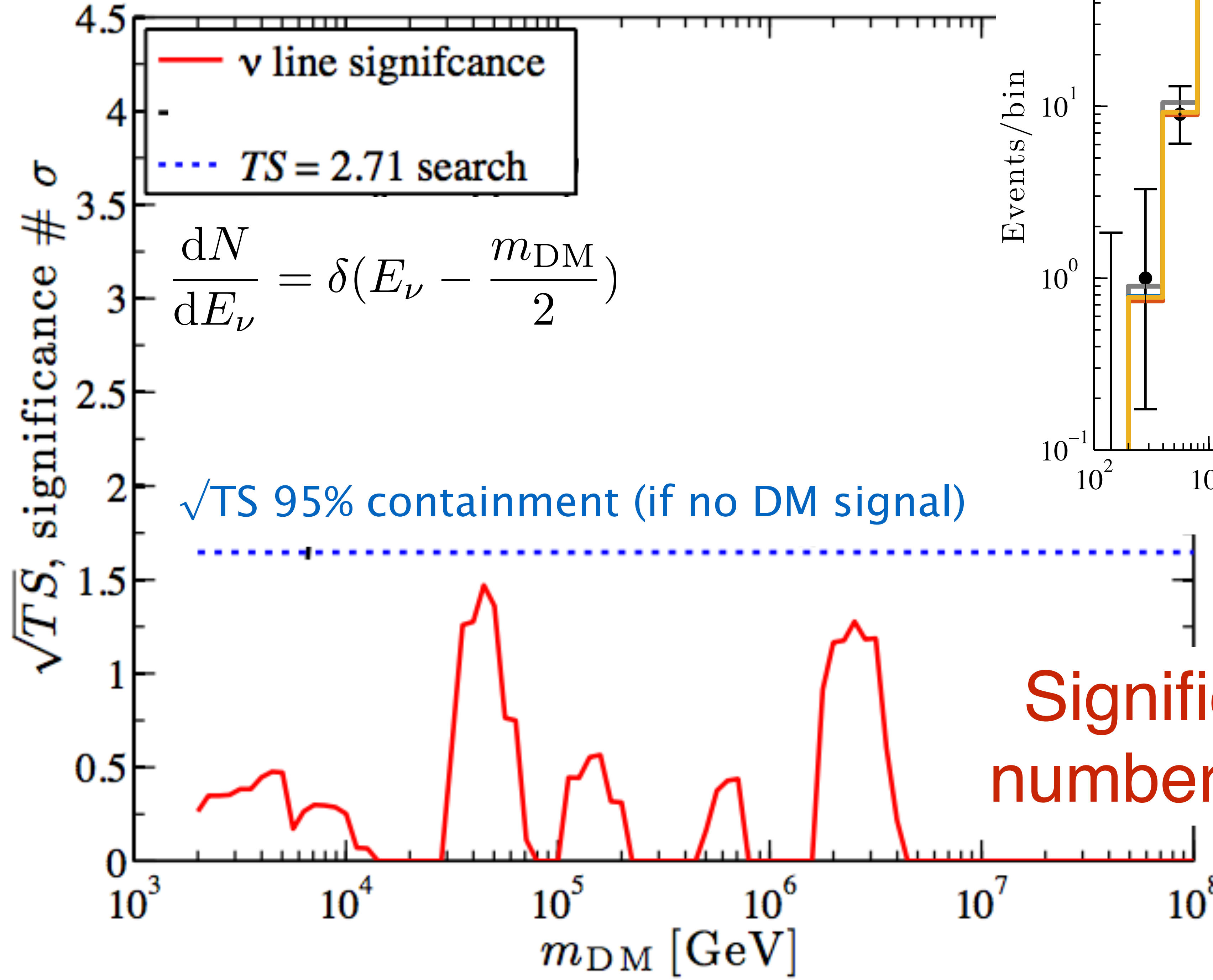
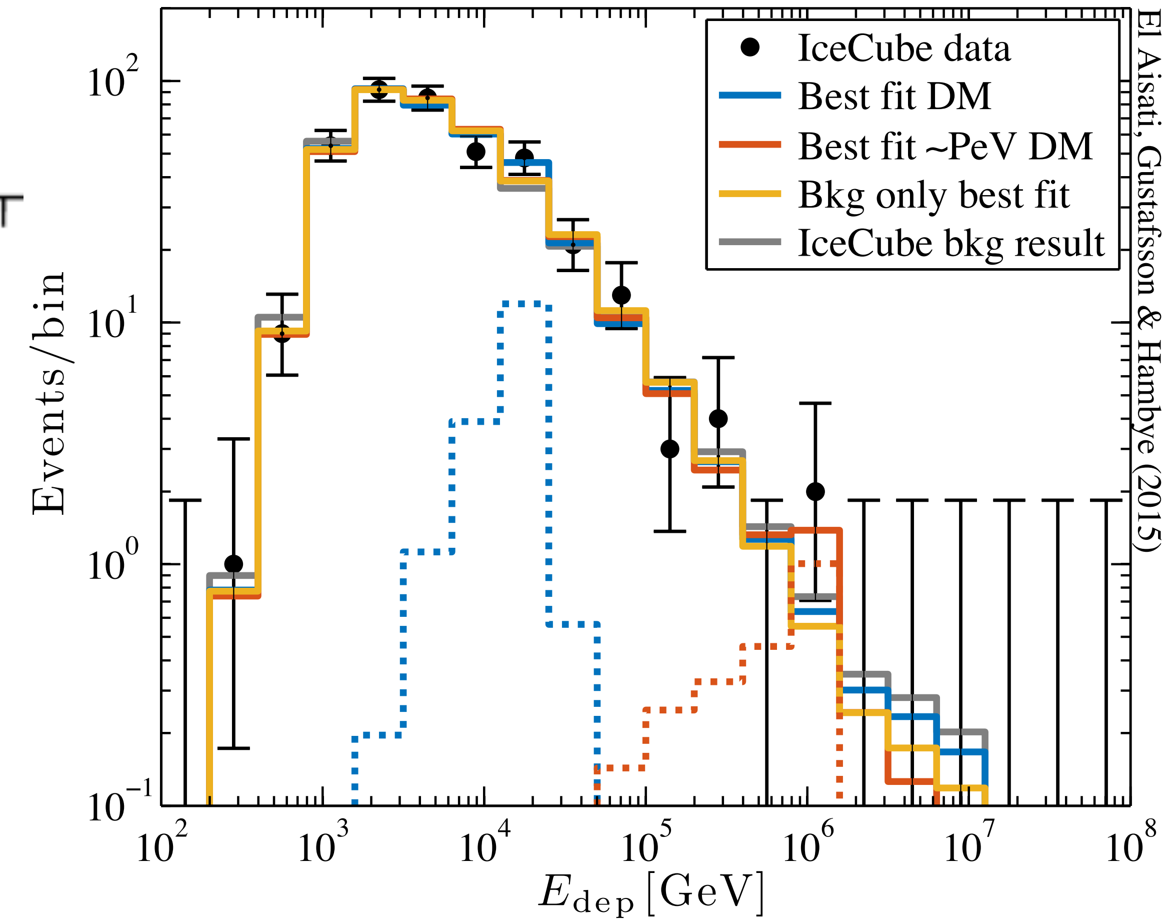
Search for ν-line from DM

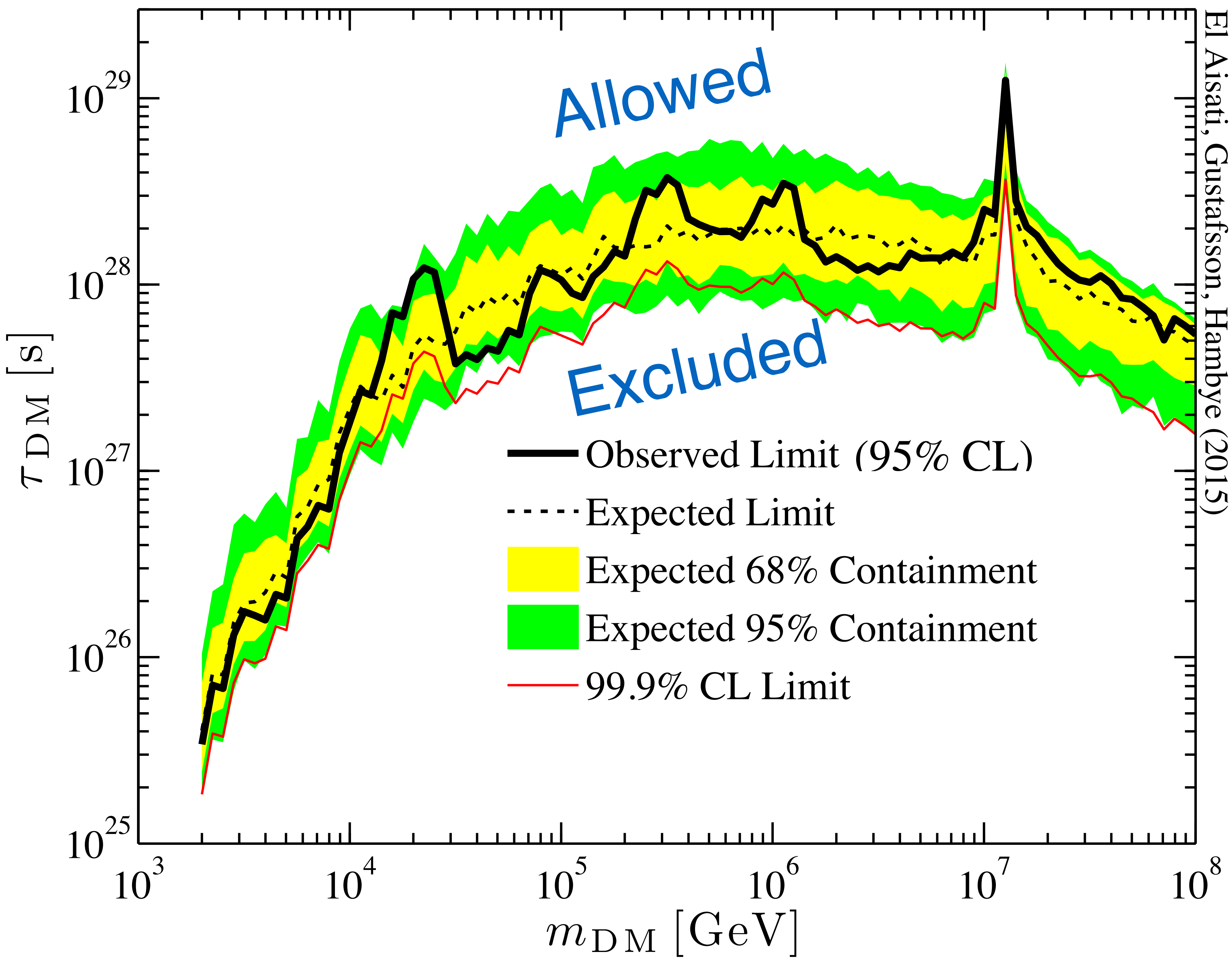




Significance in number of sigma

No line detected

Lifetime limits



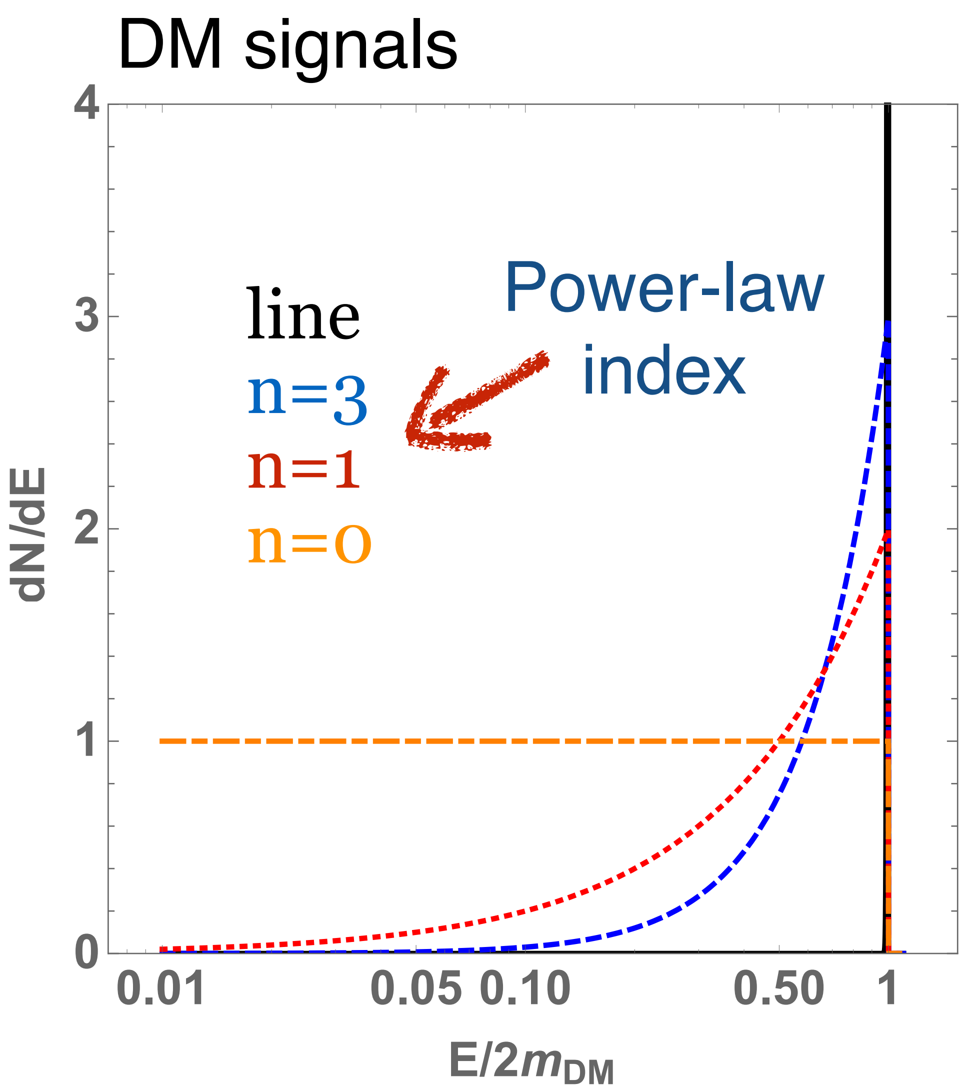
Various line-like signals

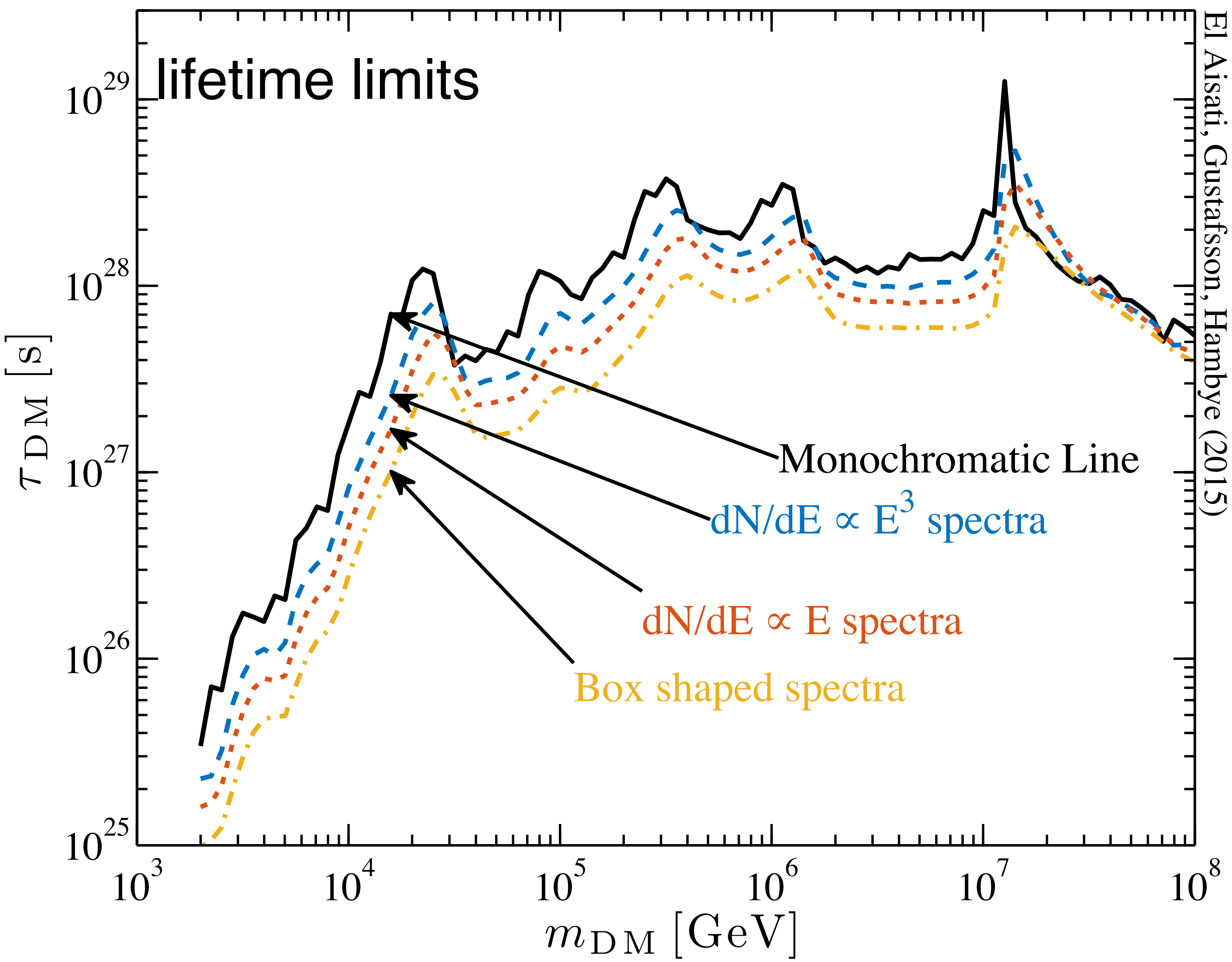
A phenomenological parametrization
(3-body decay, IB, Box shape)

$$\frac{dN}{dE} = \frac{2^{n+1}(n+1)}{m_{\rm DM}} \left(\frac{E}{m_{\rm DM}}\right)^n \Theta(m_{\rm DM} - 2E)$$

Power-law index

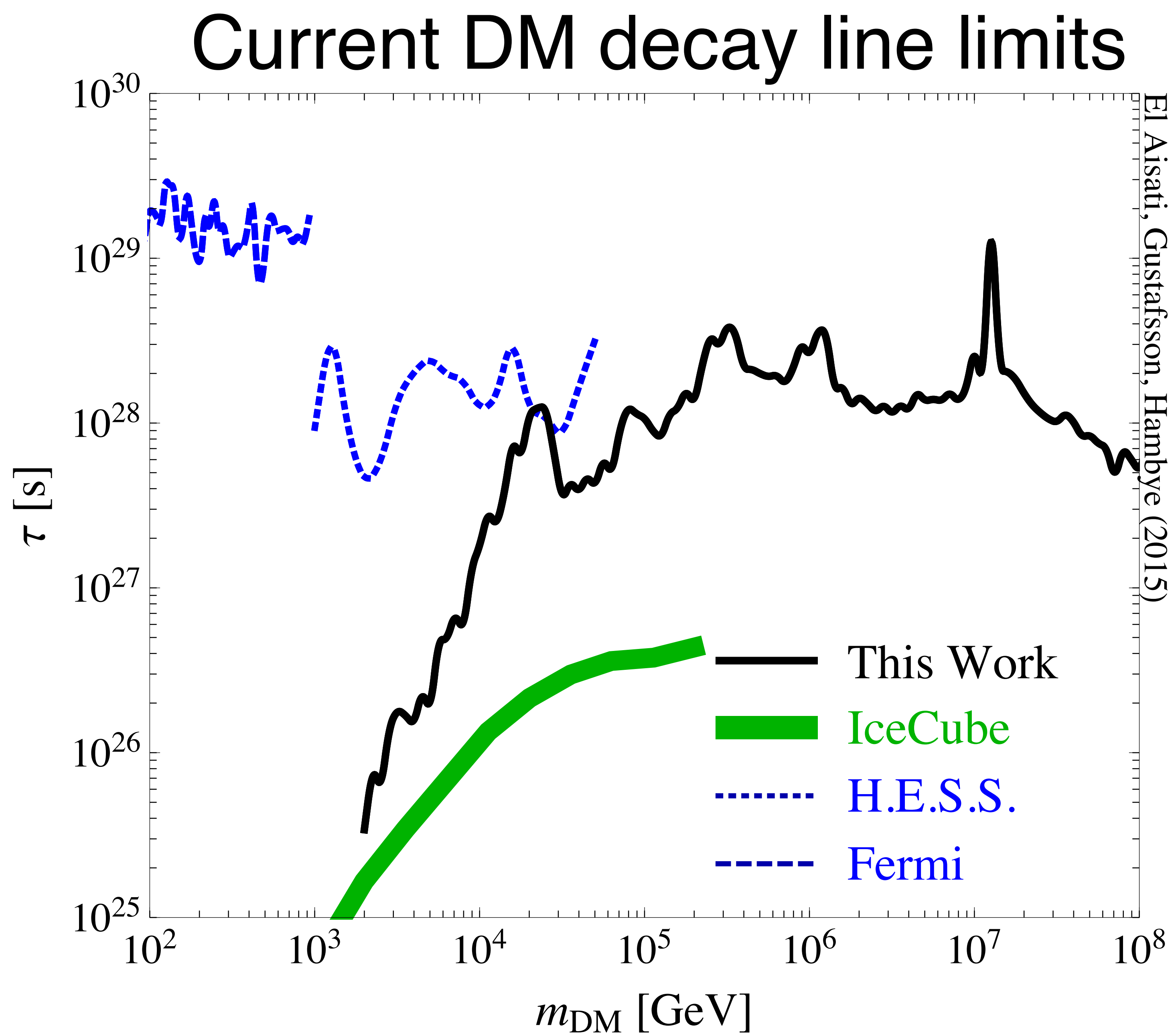
Heaviside step-function





Conclusions

- New approach to search for DM induced **υ**-line
- No significant line detected — room to increase sensitivity
- Improved current bounds on DM lifetimes by more than an order of magnitude
- Reach higher sensitivity than gamma-ray line searches for DM masses above ~ 50 TeV



IceCube PRD **84** (2011)
HESS PRL **110** (2013)
Fermi Arxiv:1506.00013

Backup Slides

A simple DM bound

Require that DM signal (+ minimal bkg) not overshoot data

$$N^i_{\rm DM} + N^i_{\rm bkg} < N^i_{\rm limit}$$

DM signal as determined on last slide
(function of DM lifetime $\tau_{\rm DM}$)

N_μ
N_ν

Parameter	Best-fit value
Penetrating μ flux	$1.73 \pm 0.40\, \Phi_{\rm SIBYLL+DPMJET}$
Conventional ν flux	$0.97^{+0.10}_{-0.03}\, \Phi_{\rm HKKMS}$

Aartsen+ PRD 91, 022001 (2015)

Atmospheric backgrounds

$$N^i_{\rm bkg} = n_1 N^i_\mu + n_2 N^i_\nu$$

$n_1 \downarrow 0.54$ $n_2 \downarrow 0.94$ of nominal value 1

shifted down 2$\boldsymbol{\sigma}$

Observed events per E bin

$$\sum_{k=0}^{N^i_{\rm obs}} \frac{(N^i_{\rm limit})^k}{k!} e^{-N^i_{\rm limit}} = 1 - q.$$

Limit

($\boldsymbol{q}$ = 95% CL
Classical Neyman
band construction)

$$\tau_{\rm limit} = \min\{\tau_{\rm DM} \in \mathbb{R}^+ | \forall i : N^i_{\rm DM} + N^i_{\rm bkg} < N^i_{\rm limit}\}.$$

Conservative Limits

DM signal + minimal atmospheric background not "overshoot" data