Neutrino Portal Dark Matter: From Dwarf Galaxies to IceCube

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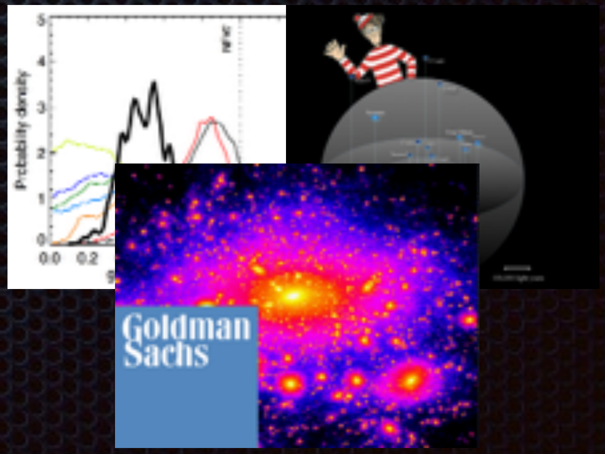
arXiv:1411.1071

T-2 Seminar, LANL, November 2014

Really this is a Neutrino Portal to the Dark Sector

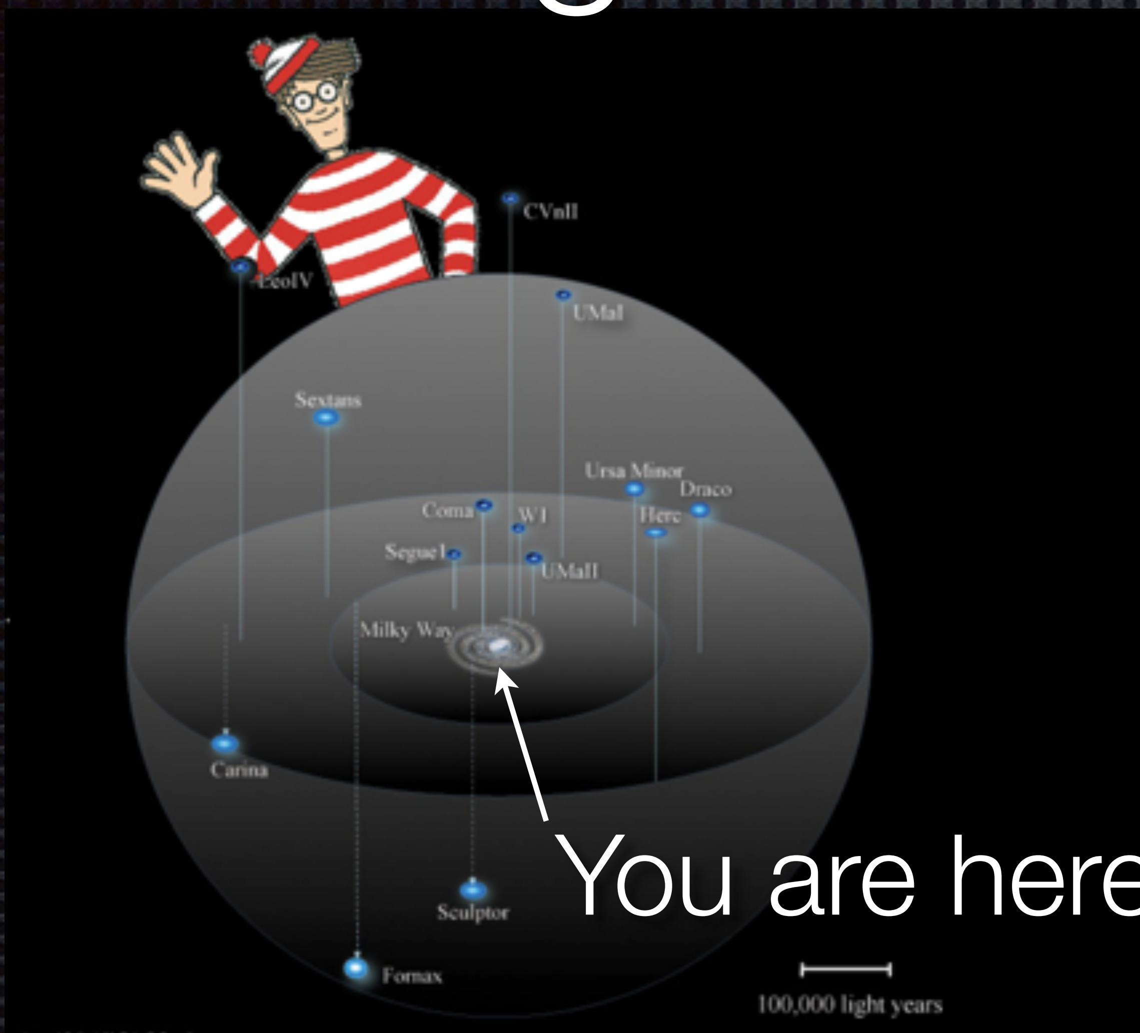
- Dark matter is definitely there, but it seems to be misbehaving.
- Experiments like LUX are ruling out large swathes of the WIMP parameter space. Akerib, et al., PRL **112**, (2014)

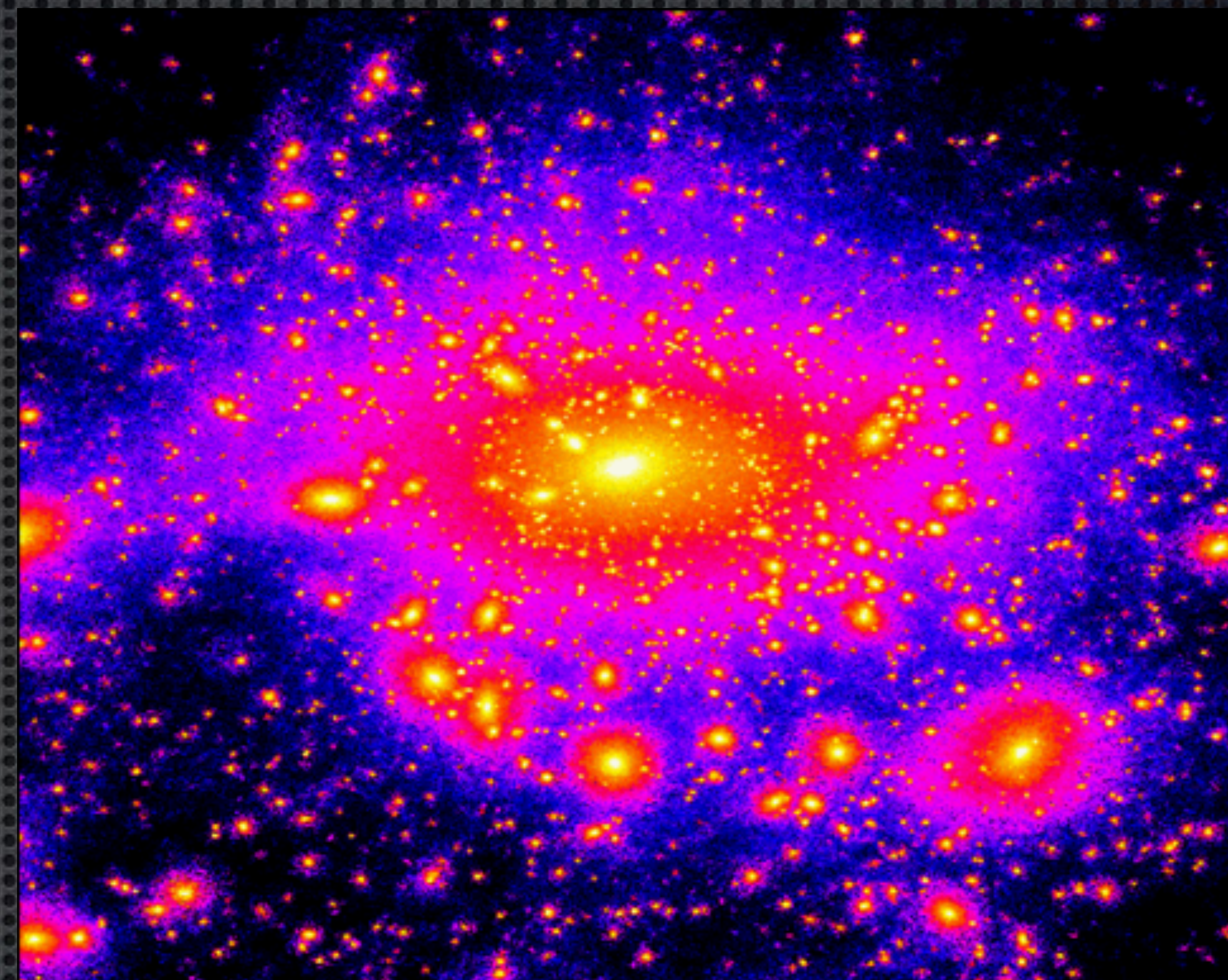
- A number of dark matter structure problems persistently appear in observations.



Feng, Kaplinghat, Huitzu, Yu, JCAP **07**, (2009)
Spergel, Steinhardt, PRL **84**, (2000)
Boylan-Kolchin, Bullock, Kaplinghat, MNRAS **415**, (2011)

Missing Satellites





$$\Omega = 1$$

$$\Omega_b = .04 \quad \Omega_\Lambda = .68 \quad \Omega_r = 8.24 \times 10^{-5}$$

Spaaaaace!!!

Simulation image courtesy of Stelios Kazantzidis

The Universe also has lots of Entropy

- There are a great many light relativistic particles left over from the Big Bang: $S/b \sim 10^{10}\, k_b/b$
- Mostly photons: $n_\gamma = 411\,\mathrm{cm}^{-3}$
- Also neutrinos: $n_\nu = 336\,\mathrm{cm}^{-3}$

$$\mathcal{L} \supset g_\nu \phi^\mu \bar{\nu}\gamma_\mu \nu$$

Missing Satellites? Maybe not so much...

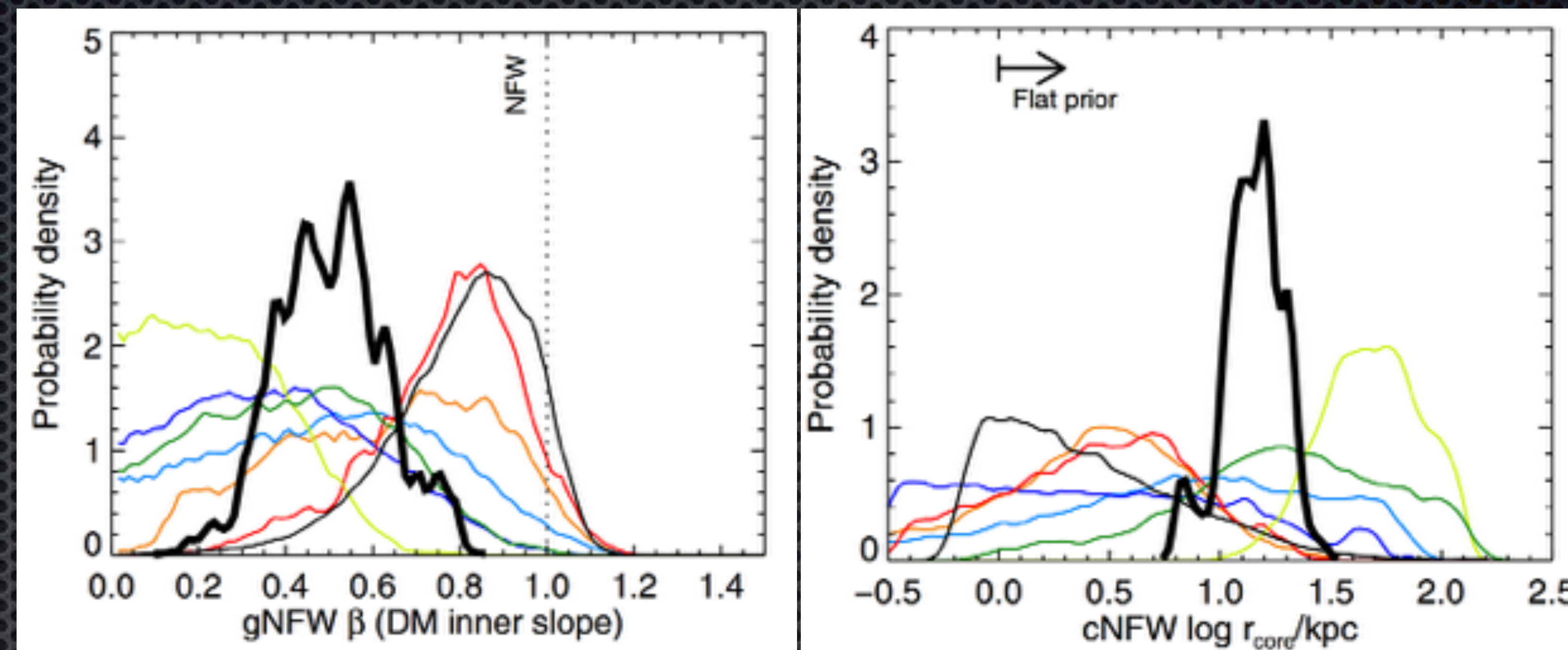
- Kinetic decoupling of dark matter and neutrinos sets the cutoff mass for small scale structure:

$$M_{\rm cut} = 1.7 \times 10^8 \, (T_{\rm kd}/{\rm keV})^{-3} \, M_\odot$$

$$T_{\rm kd} = \frac{0.062\,{\rm keV}}{N_\nu^{1/4} \, (g_X g_\nu)^{1/2}} \left(\frac{T}{T_\nu}\right)_{\rm kd}^{1/2} \left(\frac{m_X}{TeV}\right)^{1/4} \left(\frac{m_\phi}{MeV}\right)$$

$$M_{\rm cut} = 10^7 - 10^9 \, M_\odot$$

Dark Matter self interaction

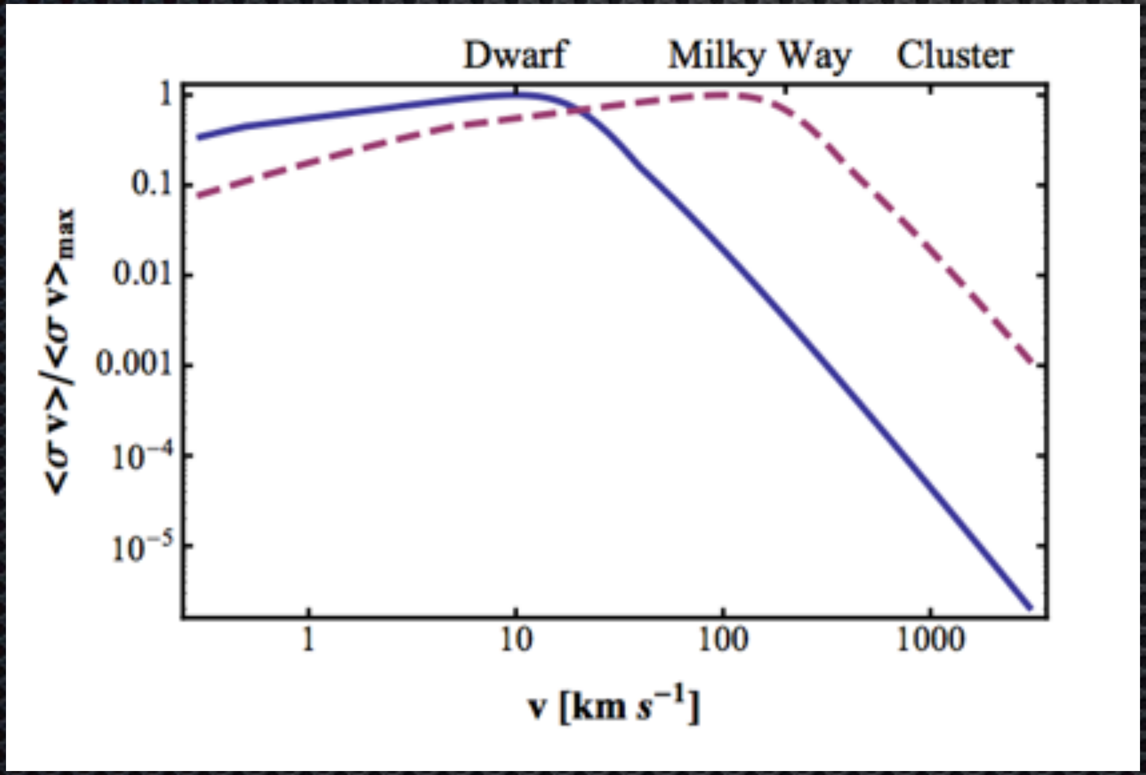


- “Cusp vs. Core” and “To Big To Fail” seem to be related.
- DM self interaction can independently solve either problem.

A. Newman, T. Treu, R. Ellis, D. Sand, APJ **765:25** (2013)

SIDM needs a rich phenomenology for scattering: $L \supset g_X \phi^\mu X \gamma_\mu \bar{X}$

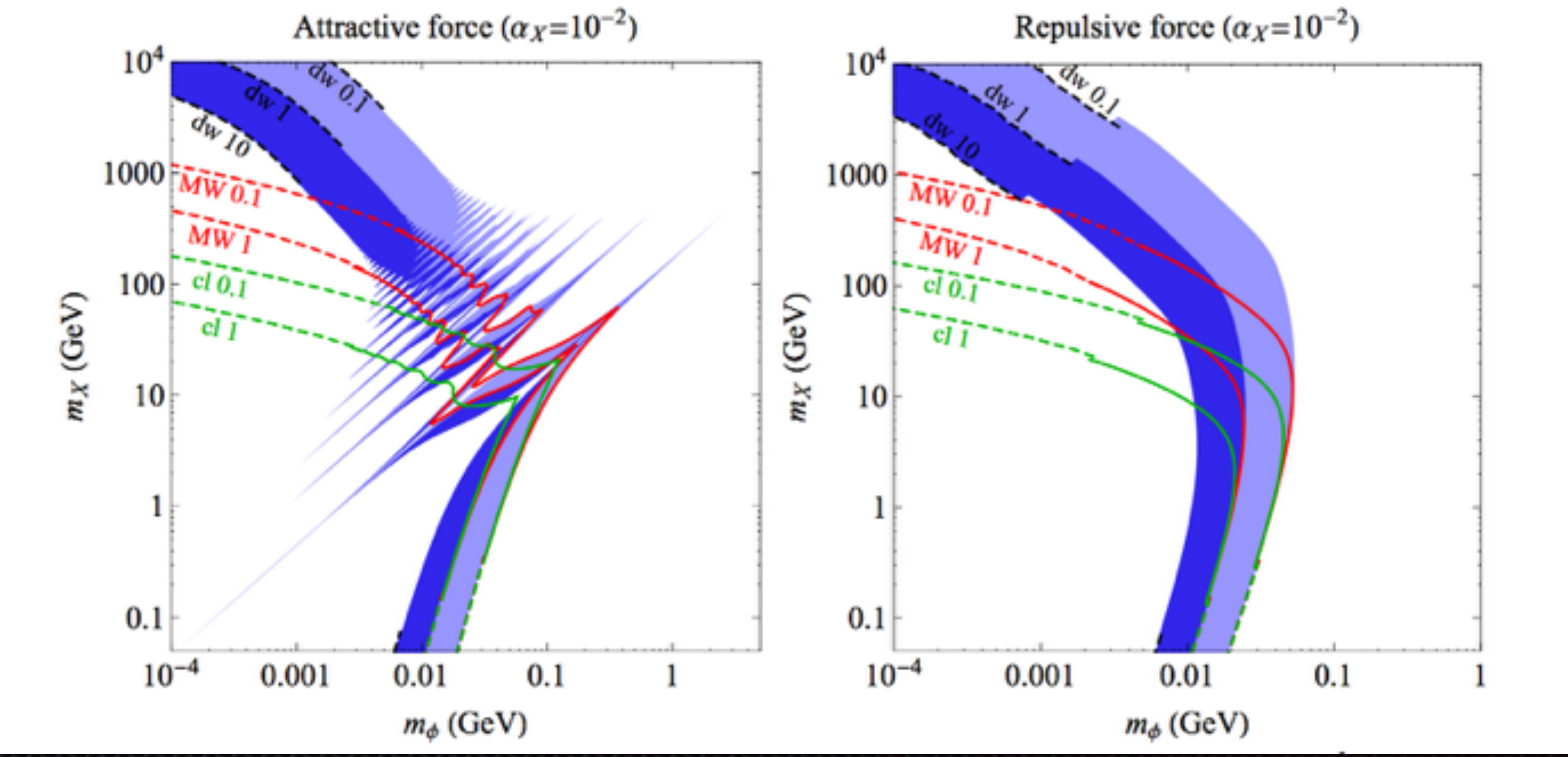
- A massive scalar or vector exchange particle is equivalent to Yukawa-potential scattering. This introduces velocity dependence to the overall cross section.



A. Loeb, N. Weiner, PRL **106** 171302 (2011)

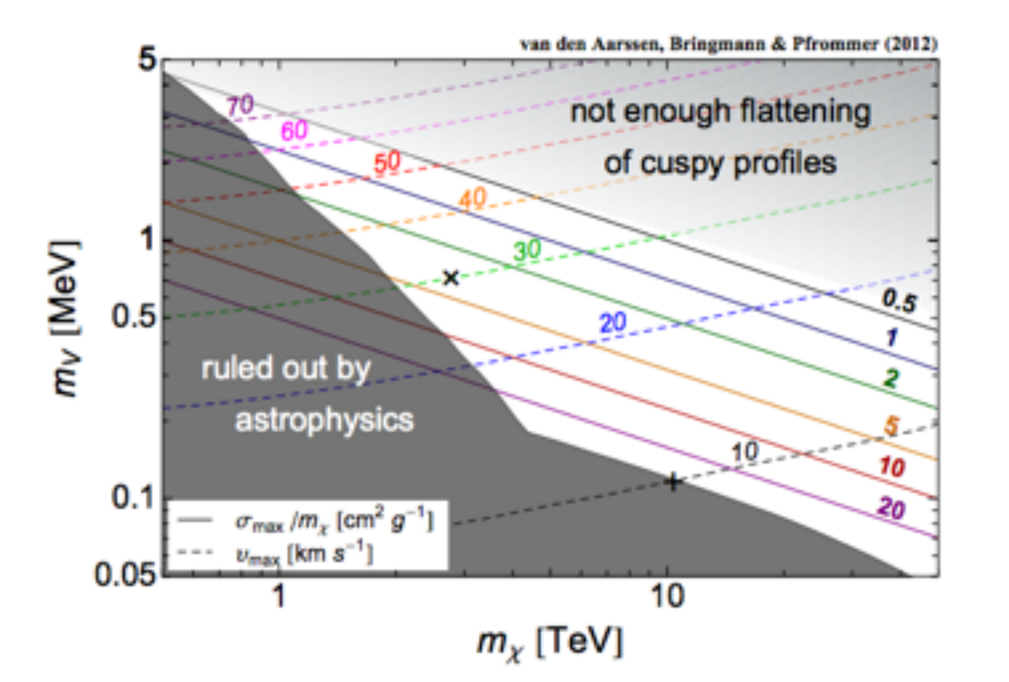
Different scattering regimes lead to rich phenomenology

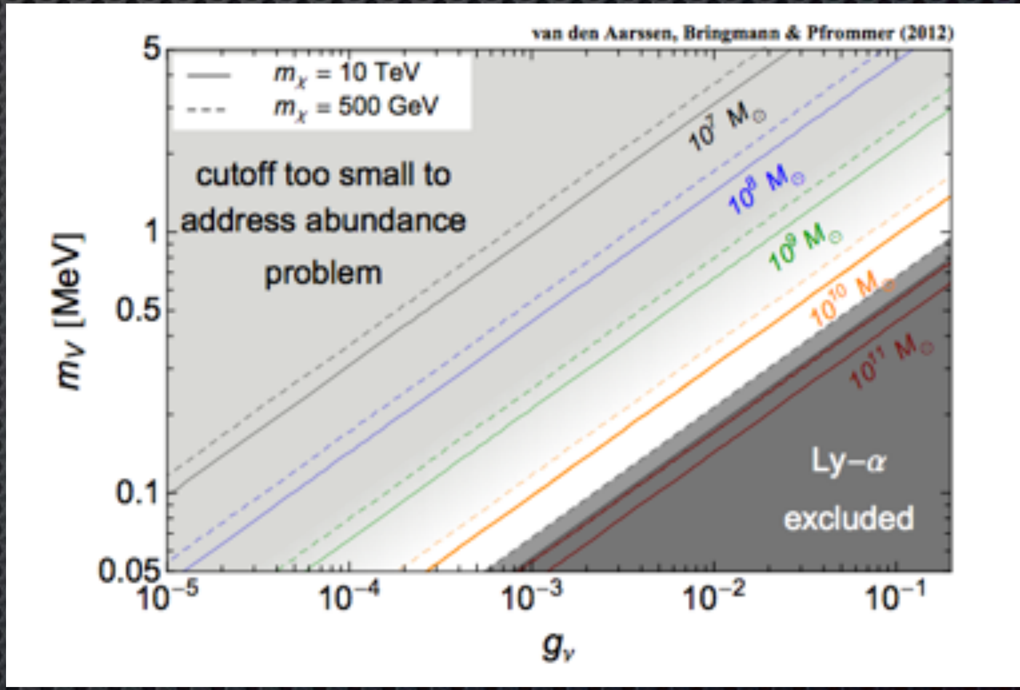
- Tulin, Yu, Zurek, PRD **87**, 116007 2013: SIDM does both simultaneously:



All three structure problems be solved at once?

- L. Aarssen, T. Bringmann, C. Pfrommer, PRL **109**, 231301 (2012): Yes they can.





- J. Cherry, A. Friedland, I. Shoemaker, arXiv:1411.1071: More parameter space is a solution for all three problems if DM is not a thermal ν relic.

Let’s not be cavalier

- Strong bounds on hidden neutrino interactions come from LEP, supernova neutrinos, rare Kaon decay, DM annihilation or contact interactions, BBN, cosmology.
- Neutrinos might still acquire hidden interactions through their mixing with a sterile state.

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix} = U \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \vdots \end{pmatrix}$$

$$L \supset g_s \phi^\mu \bar{\nu}_s \gamma_\mu \nu_s$$

$$\langle \nu_s | \nu_{e,\,\mu,\,\tau} \rangle \equiv 0$$

For relatively small mixing angles:

$$g_\nu \sim \theta_{\rm s} g_s$$

Mixing Portal Prescription

$$\mathcal{L} \supset \frac{g_a(LH)g_h(\nu_h H')}{\Lambda}$$

Basic seesaw type operator

Similar to M. Pospelov, Phys. Rev. D **84**, 085008 (2011)

$\nu_s,\ \theta_s \qquad \langle \nu_s | \nu_{e,\mu,\tau} \rangle \equiv 0$

$\phi^\mu,\ m_\phi$

Goldstone Boson associated with ν_h acquires mass when H' symmetry is broken

$$\mathcal{L} \supset g_s \phi^\mu \bar{\nu}_s \gamma_\mu \nu_s$$

An explicit vector boson example

- Our Lagrangian: $L \supset g_s \phi^\mu \bar{\nu}_s \gamma_\mu \nu_s$
- Basic tree level scattering contributions:

$$\frac{d\sigma\left(\bar{\nu}\nu \to \bar{\nu}\nu\right)}{d\cos\theta}$$

$$\frac{d\sigma\left(\nu\nu \to \nu\nu\right)}{d\cos\theta}$$

$$\frac{d\sigma\left(\bar{\nu}\nu \to \phi\phi\right)}{d\cos\theta}$$

The IceCube Detector

- Want to probe neutrino self interactions with a neutrino collider.
- Astrophysical neutrino sources are fantastic accelerators.

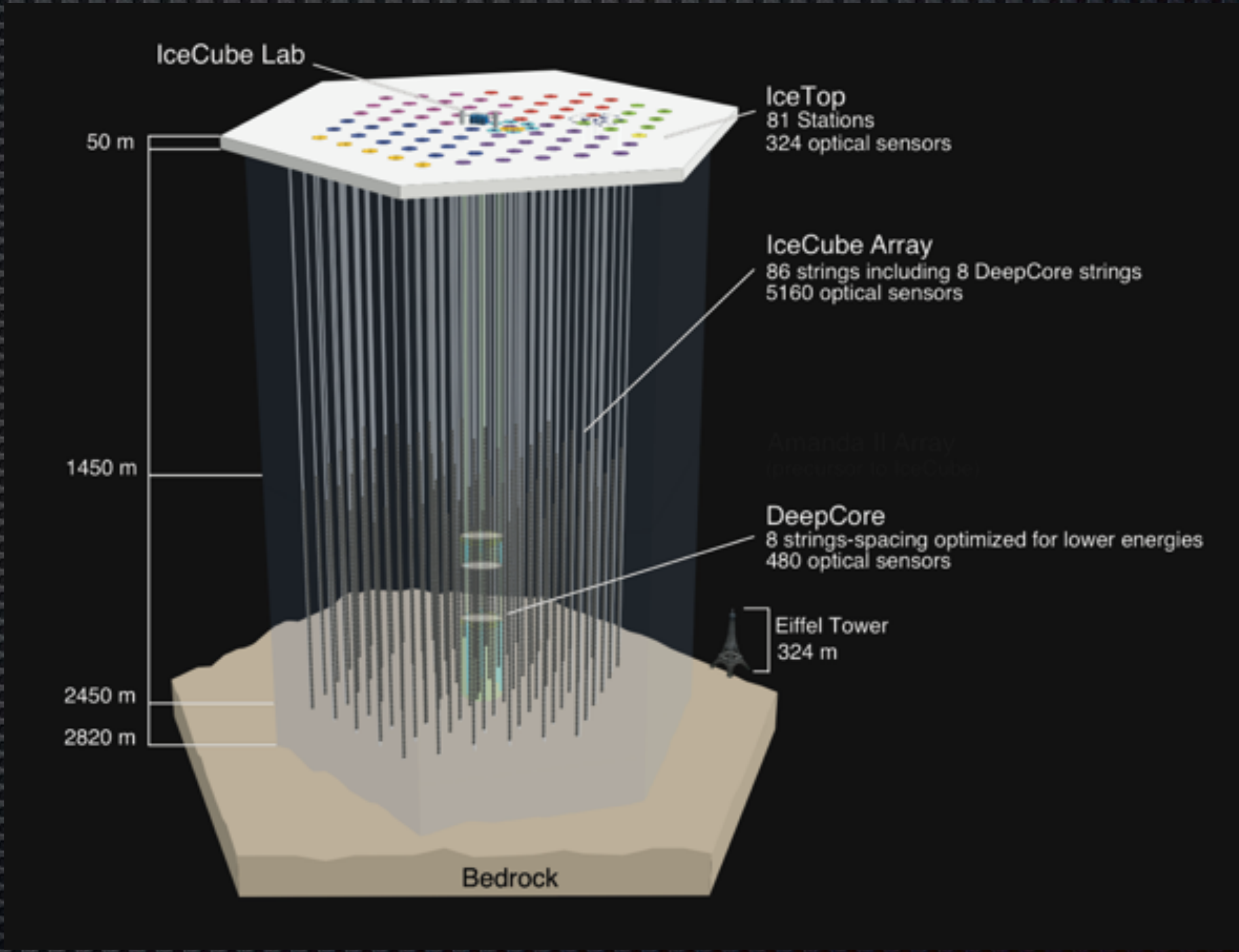


Image: C. Kopper, IceCube collaboration

High energy protons and the Cosmic Ray limit

$$p^+ + \gamma \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

- CR flux limit comes from ~1:1 correlation between observed CR protons and the above process.

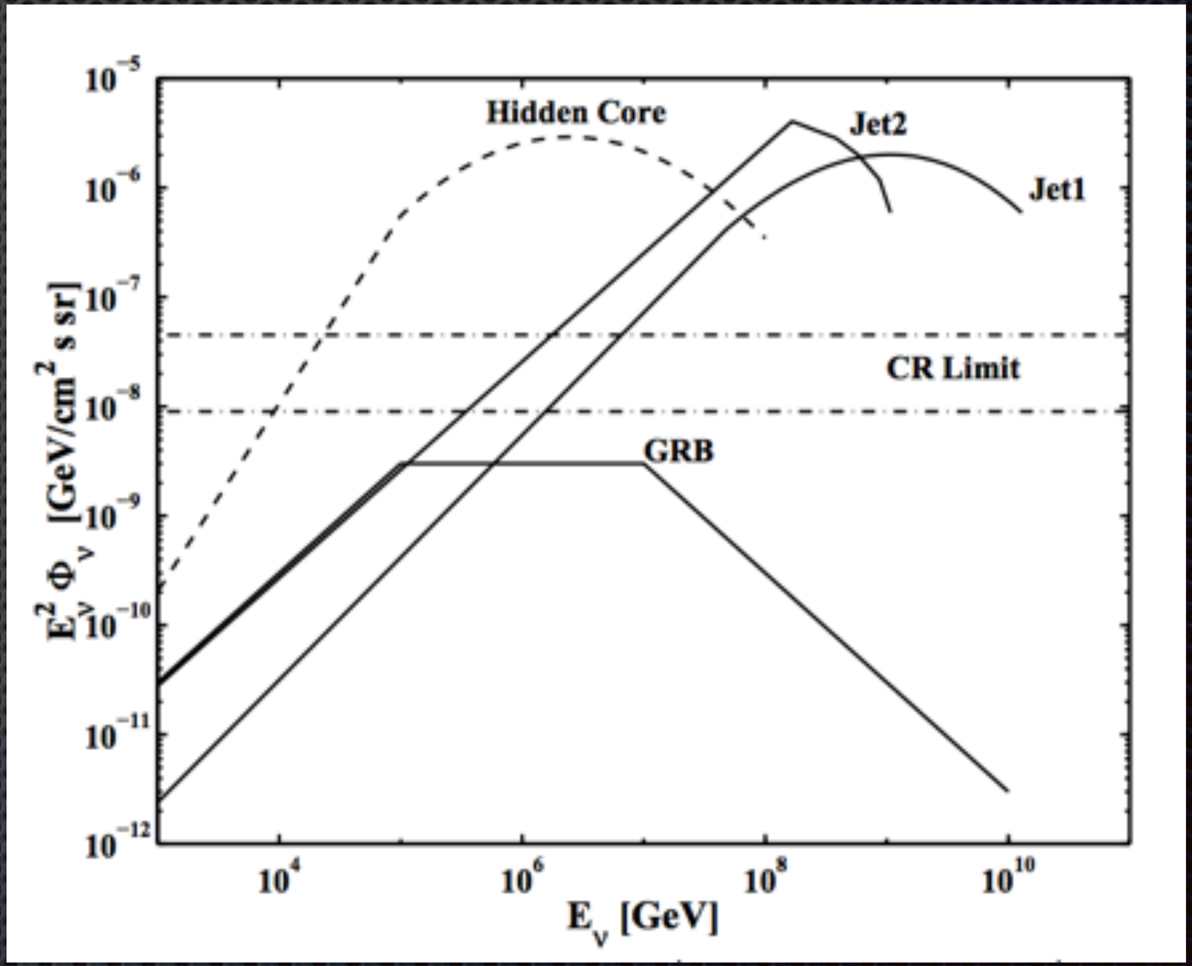
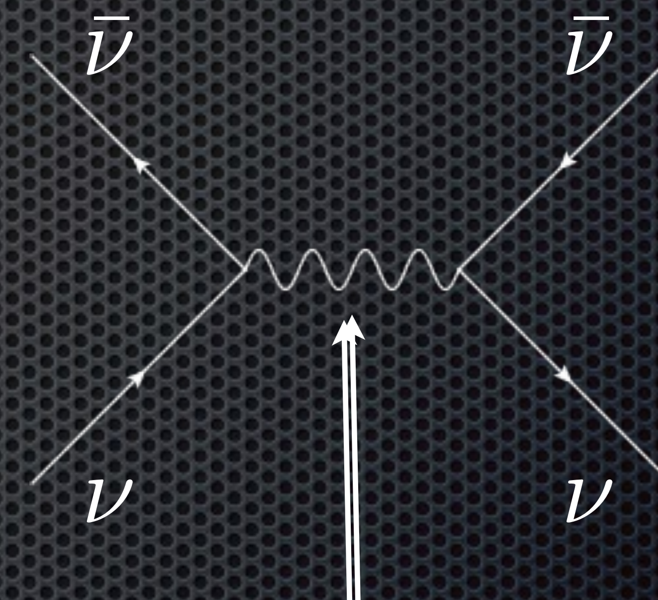
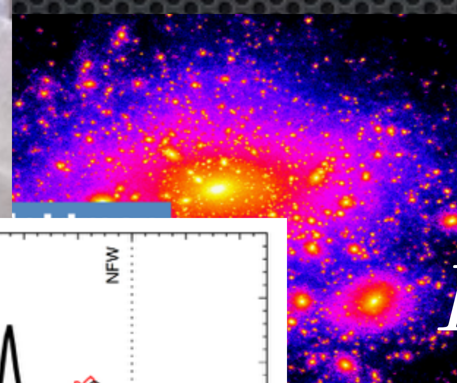


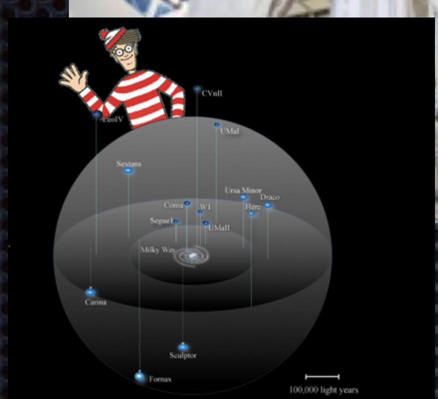
Image: Waxman and Bahcall, PRL **59**, 023002 (1999)

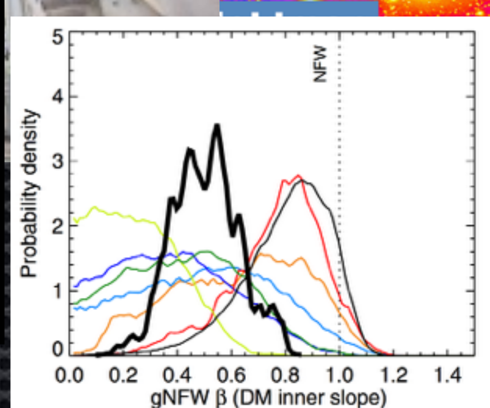
What needs to happen to create a signal in IceCube?

- Largest potential cross section comes from resonant scattering.





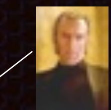




$$E^2_{\mathrm{CM}} = 2m_\nu E_\nu = m^2_{Z} \Leftarrow Z_0 \quad / \quad m^2_{\phi} \Leftarrow \phi \text{ or } \phi^\mu$$

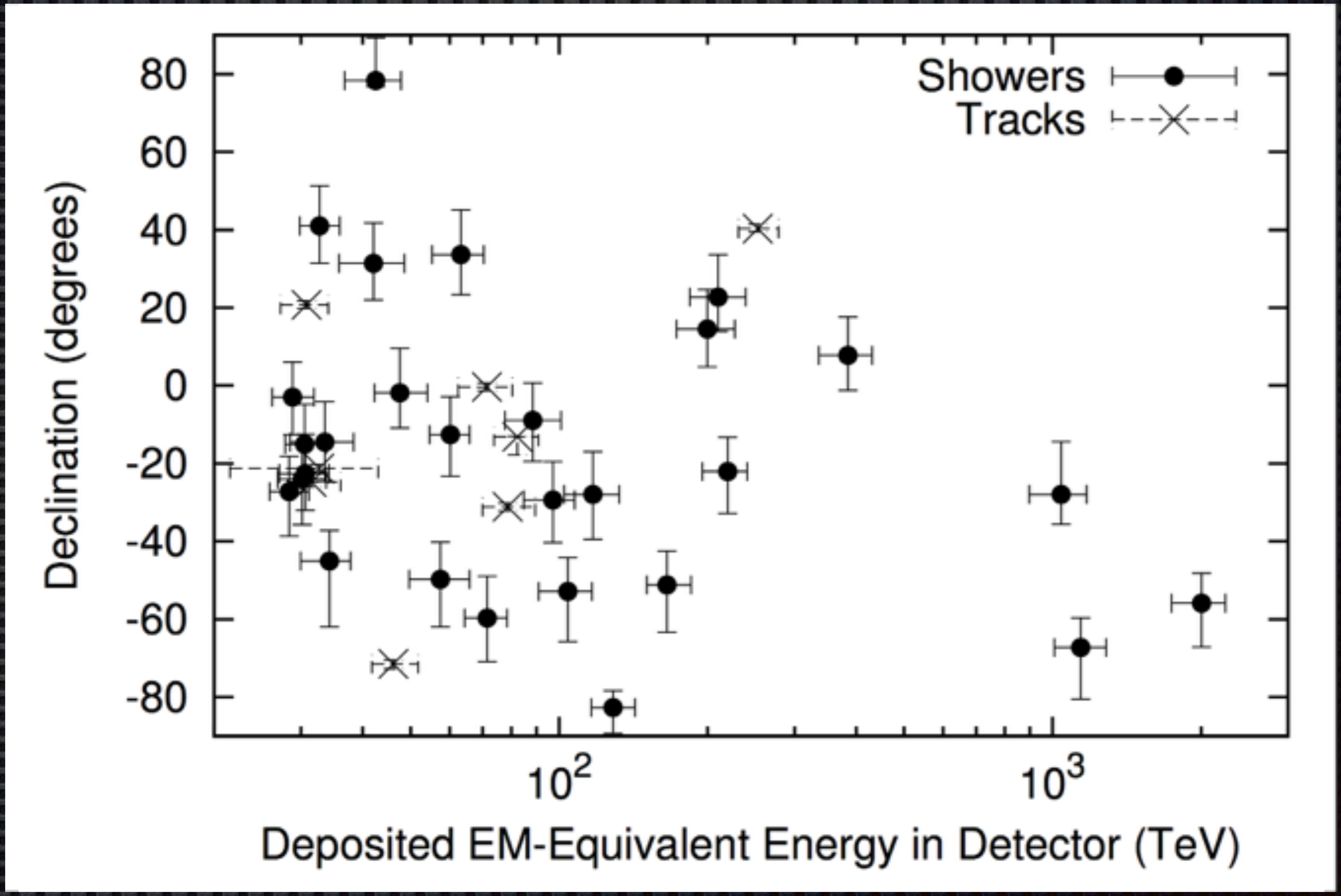
$$E_\nu \sim 1\,\mathrm{PeV} \qquad m_\nu \sim 50\,\mathrm{meV} \quad \Rightarrow m_\phi \sim 10\,\mathrm{MeV}$$

When life gives you lemons, don't make lemonade. Make life take the lemons back! I don't want your damn lemons!



IceCube found a signal!

- $5.5\,\sigma$ above expected background.
- Distribution consistent with extra-galactic sources.



IceCube collaboration: Aartsen, et al., arXiv:1405.5303

The IceCube signal and the Cosmic Ray limit

$$p^+ + \gamma \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

- CR flux limit comes from ~1:1 correlation between observed CR protons and the above process.
- The IceCube flux is nearly saturated!

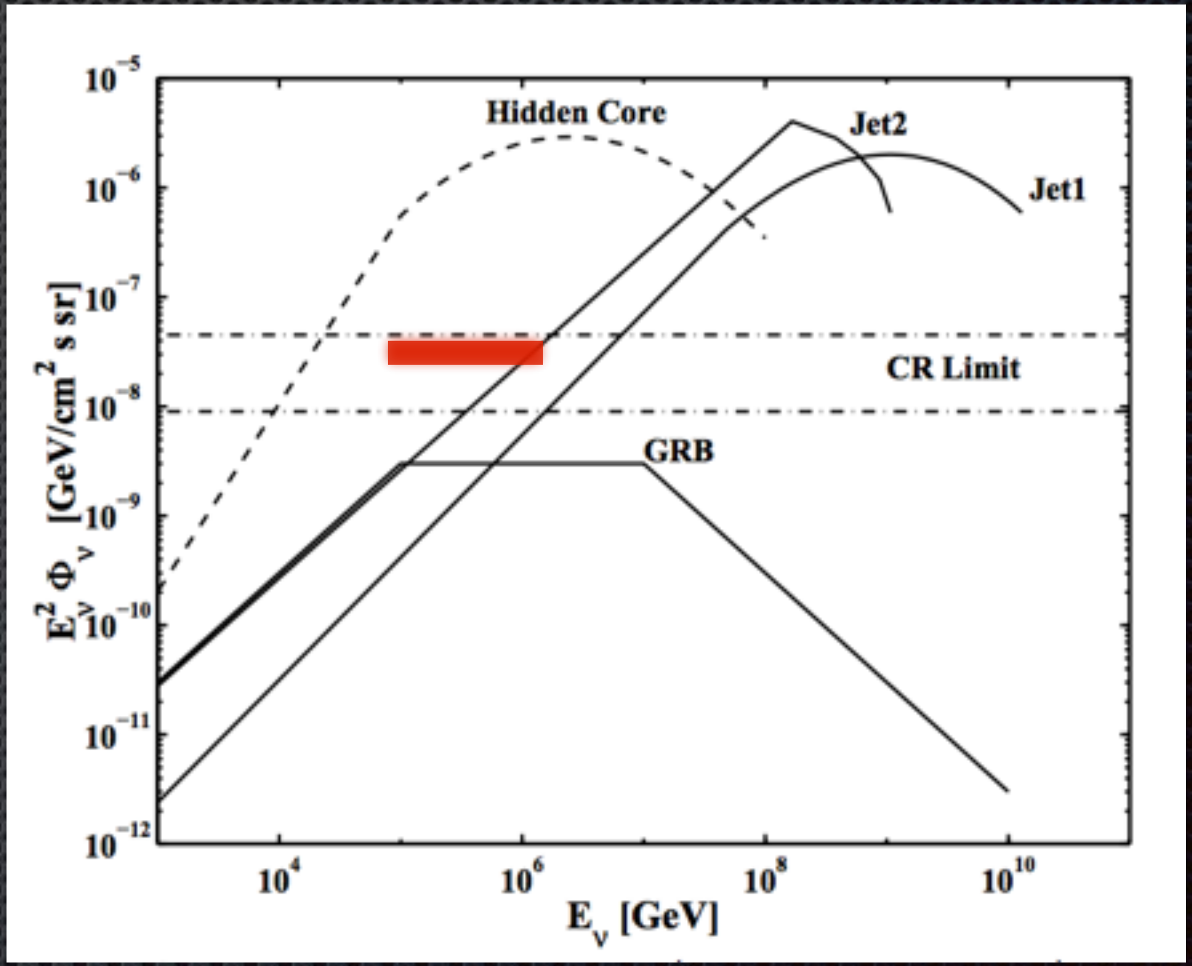
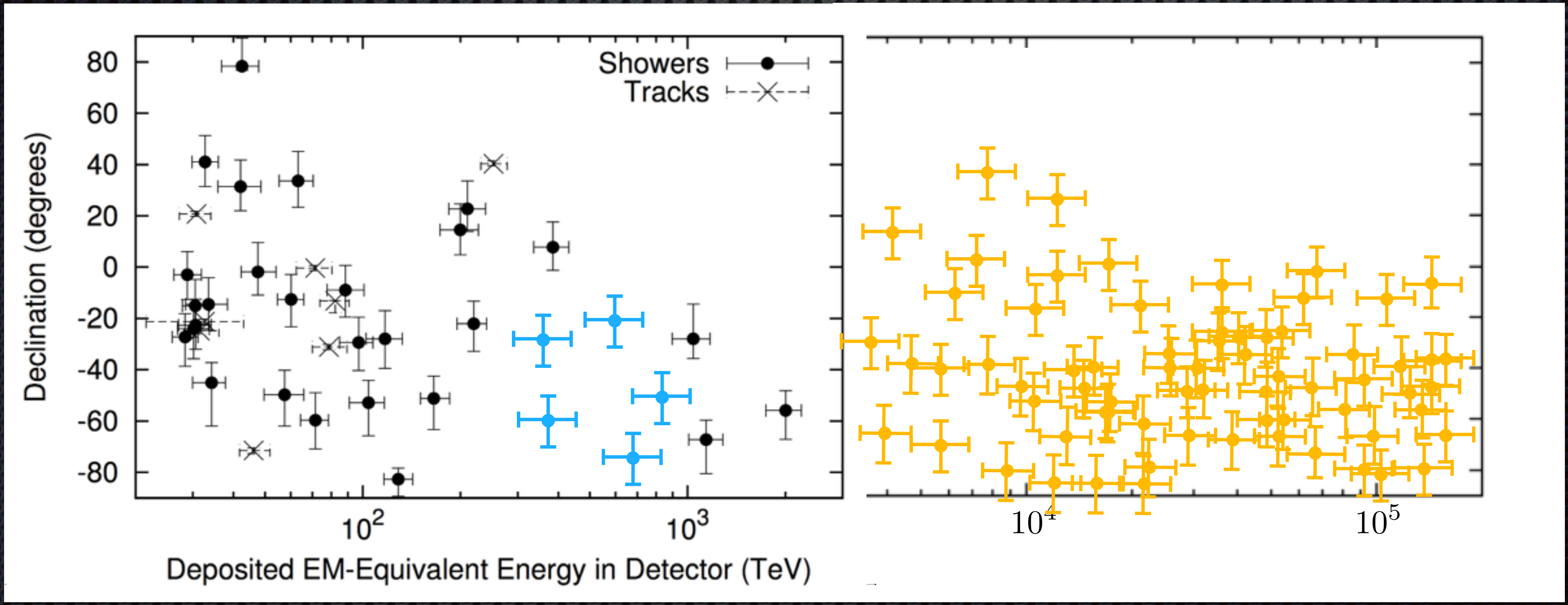


Image: Waxman and Bahcall, PRL **59**, 023002 (1999)

The Signal is Weird (in a good way)

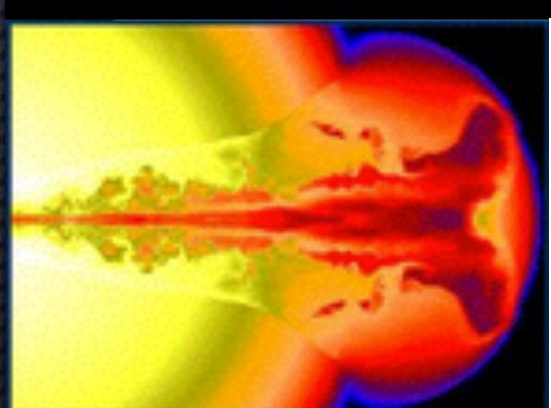
- There is a conspicuous absence of some events.

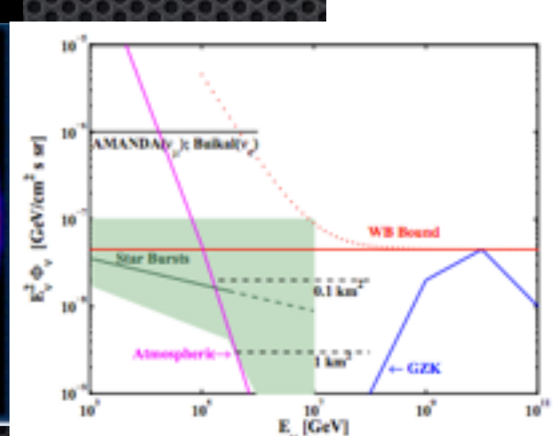


IceCube collaboration: Aartsen, et al., arXiv:1405.5303

Popular explanation

- Source effects: Source emission not understood.





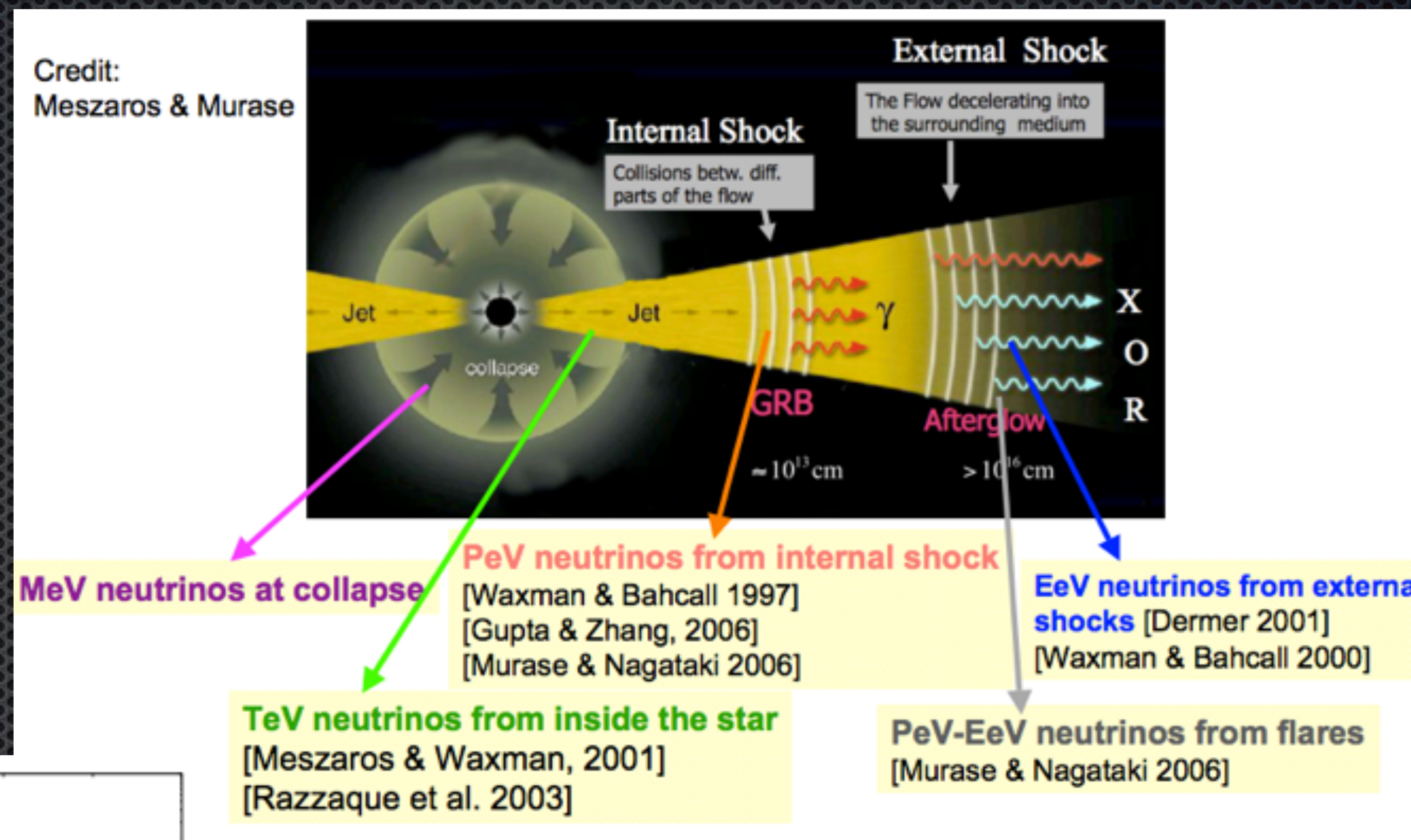
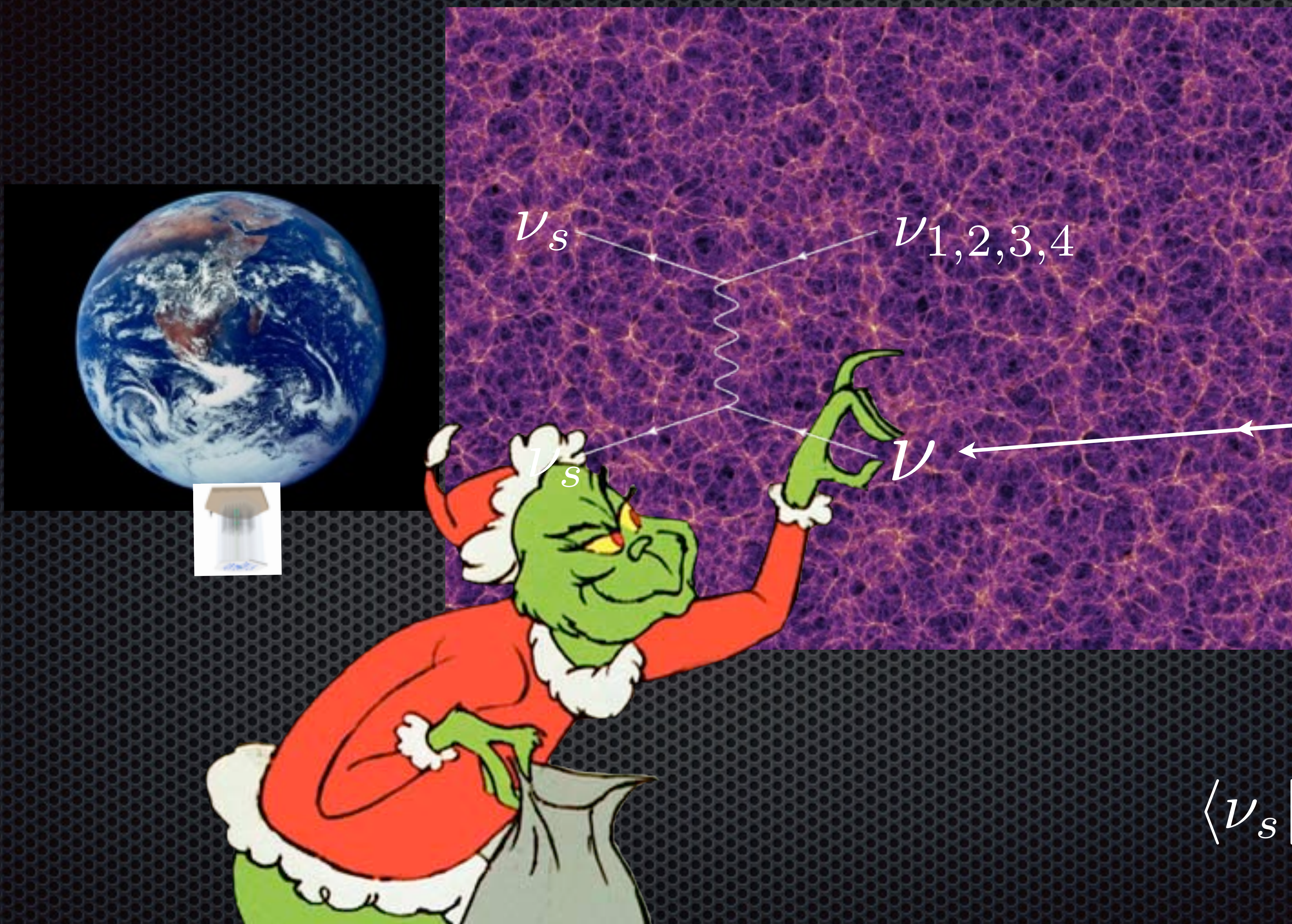
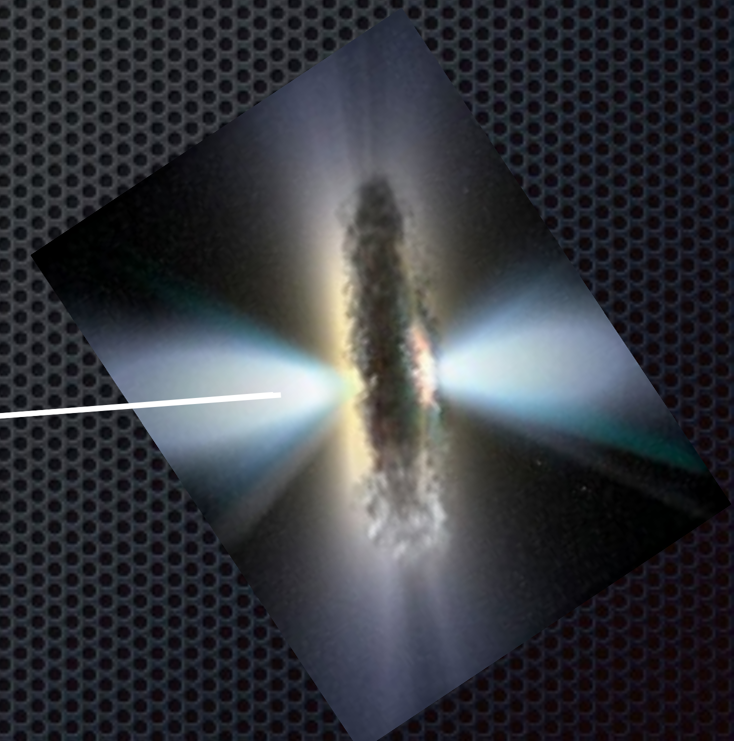


Image: Kowalski, E., MPA talk (2007)

Image: Loeb, A., Waxman, E., JCAP **5**, (2006)

Scattering = Measurement





$$\langle \nu_s | \nu_{e,\,\mu,\,\tau} \rangle \equiv 0$$

We can put our differences behind us. For Science.
You monster.

Neutrino Mixing

$$\left(\frac{\delta m^2_{\text{eff}}}{2E_\nu}\right)^2 = \left(\frac{\delta m^2_V}{2E_\nu}\cos 2\theta_V + A\right)^2 + \left(\frac{\delta m^2_V}{2E_\nu}\sin 2\theta_V\right)^2$$

$$\sin 2\theta_{\text{eff}} = \frac{\frac{\delta m^2_V}{2E_\nu}\sin 2\theta_V}{\sqrt{\left(\frac{\delta m^2_V}{2E_\nu}\cos 2\theta_V + A\right)^2 + \left(\frac{\delta m^2_V}{2E_\nu}\sin 2\theta_V\right)^2}}$$

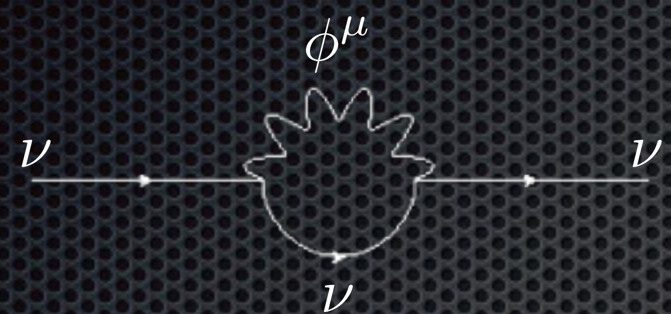
↑

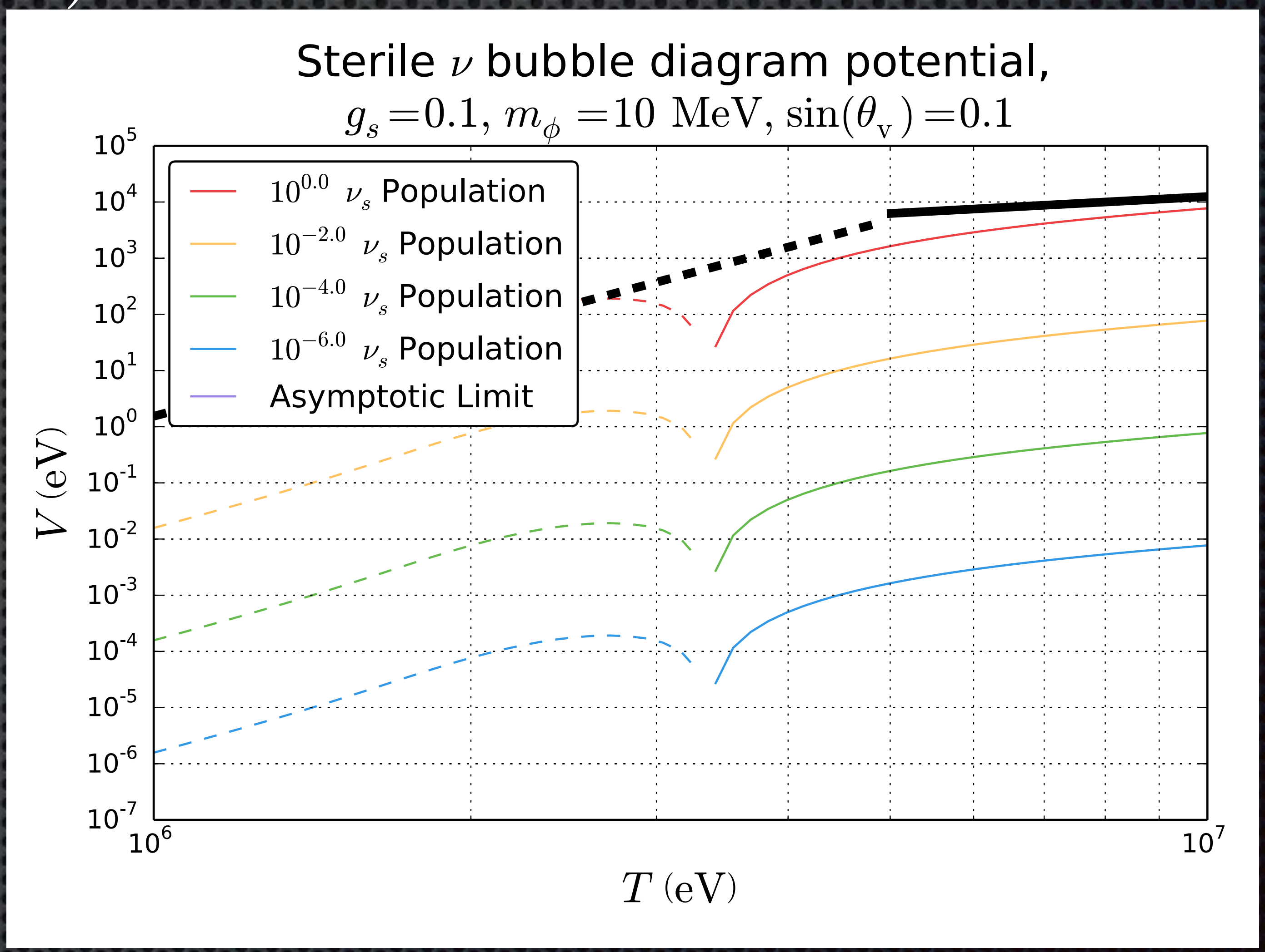
Effective mass term

Relic Sterile Abundance

B. Dasgupta and J. Kopp, PRL **112**, 031803 (2014)
S. Hannestad, R. S. Hansen, and T. Tram, PRL **112**, 031802 (2014)

$$\Sigma_{bubble}\left(k\right) = -i\frac{g_s^2}{4\pi}\int\frac{d^4p}{\left(2\pi\right)^4}\gamma^{\mu}P_L iS\left(p+k\right)\gamma^{\nu}iD_{\mu\nu}\left(p\right)$$





$$\Gamma_{f,b}\left(p\right) = 2\pi\delta\left(p^2 - m^2\right) f_{f,b}\left(p\right)$$

$$S\left(p\right) = \left(\not{p} + m\right)\left[\frac{1}{p^2 - m^2} + i\Gamma_f\left(p\right)\right]$$

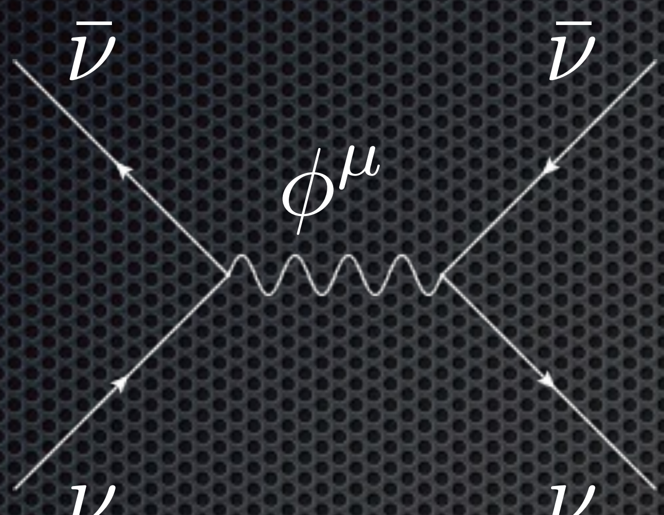
$$D^{\mu\nu}\left(p\right) = \left(-g^{\mu\nu} + p^{\mu}p^{\nu}/m_\phi^2\right)\left[\frac{1}{p^2 - M^2} + i\Gamma_b\left(p\right)\right]$$

$$V^{bubble} \simeq \begin{cases} \dfrac{7g_s^2\pi^2 E_\nu T_s^4}{45m_\phi^4} & \text{for} \quad T_s, E_s >> m_\phi \\ -\dfrac{g_s^2 T_s^2}{2E_\nu} & \text{for} \quad T_s, E_s \ll m_\phi \end{cases}$$

H. A. Weldon, Phys. Rev. **D26**, 2789 (1982)
D. Notzold, G. Raffelt, Nucl. Phys. **B307**, 924 (1988);

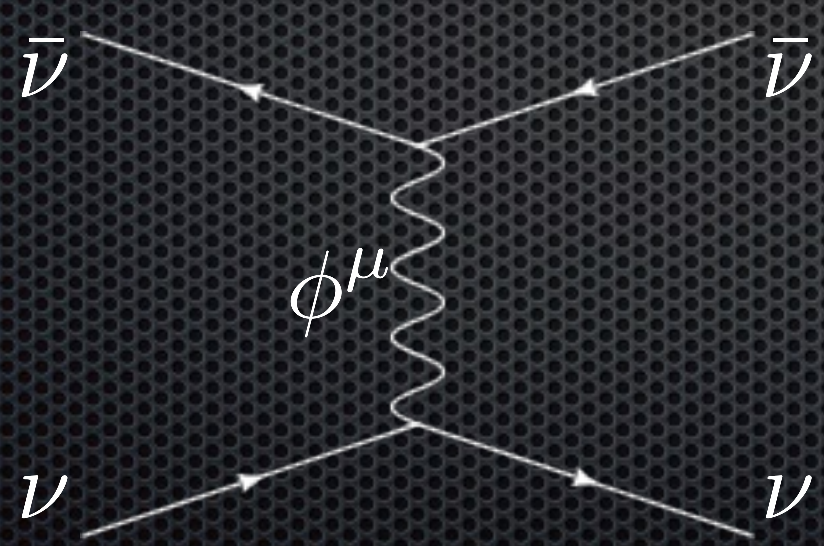
Size of the mixing angle is critical

$$g_\nu \sim \theta_\mathrm{s} g_s$$



$$\nu_a \leftrightarrow \nu_s$$

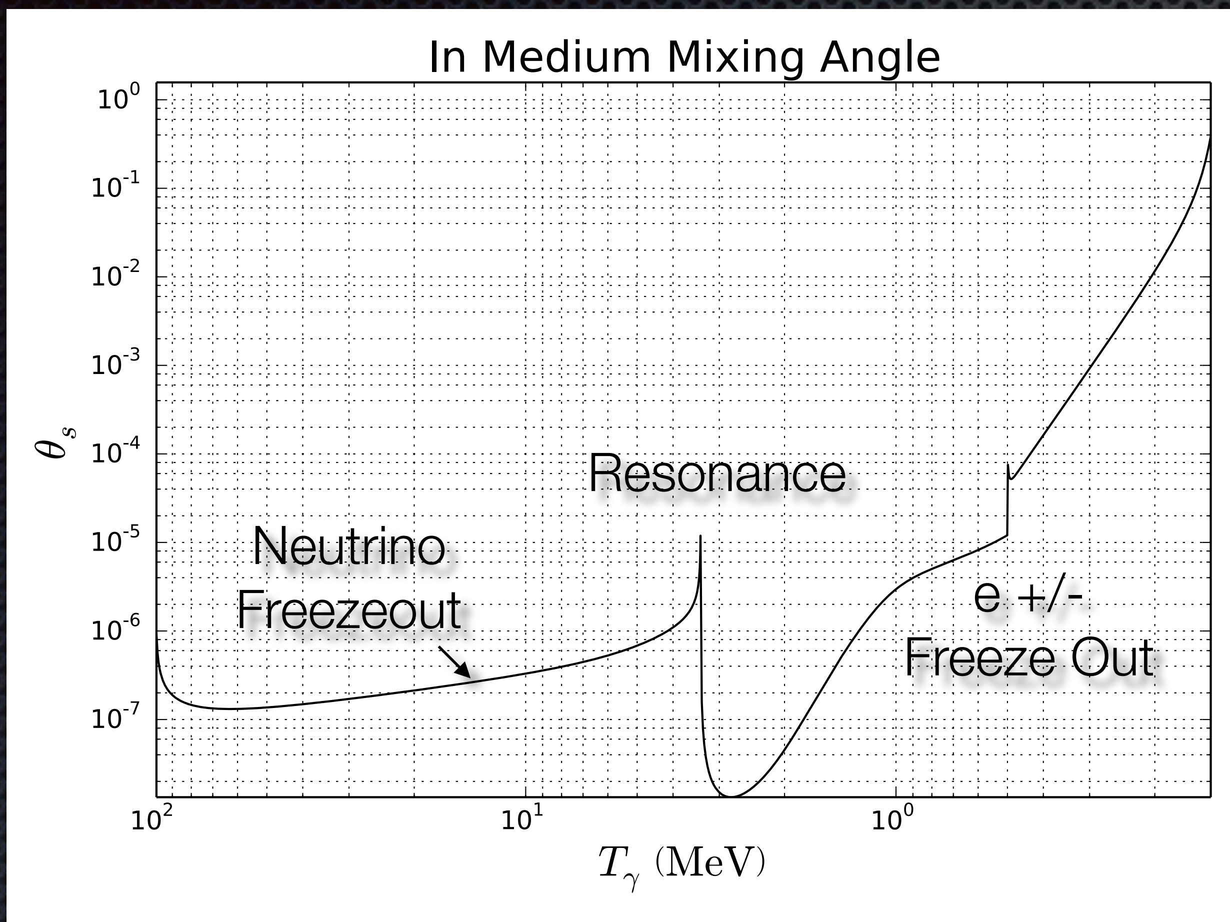
$$\sigma_{\nu\nu} \propto \theta_\mathrm{eff}^2, \theta_\mathrm{eff}^4, \theta_\mathrm{eff}^6$$

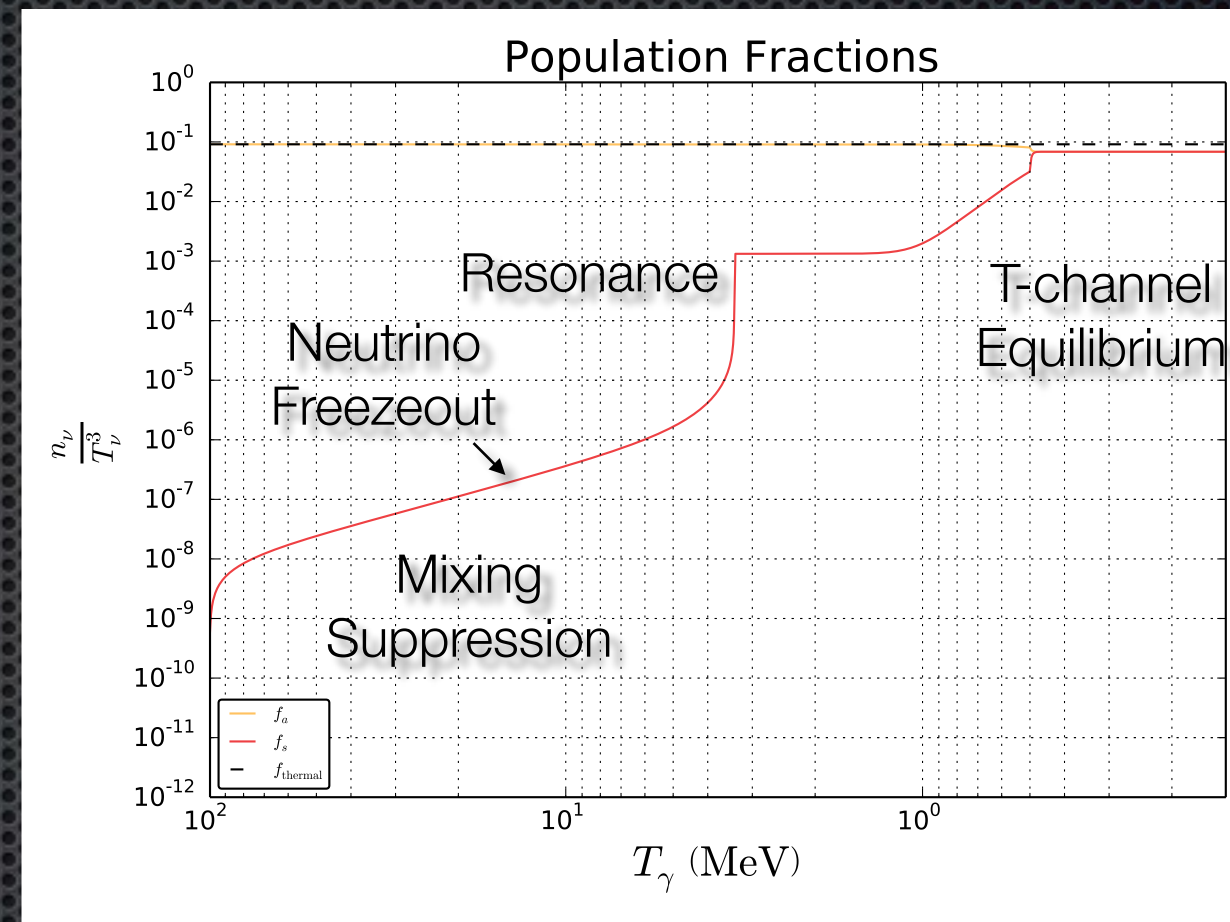


Oscillations much faster than expansion

$$\frac{\delta m^2}{2E_\nu} \gg \frac{\sqrt{g_*}T^2}{m_{pl}}$$

Relic Sterile Abundance





$$\Delta N_{\mathrm{eff,\,min}} = N_s \times 2 \times 10^{-7}$$

$$n_{\nu_s} = \frac{N_s}{3+N_s} n_{\nu,\,BBN} = \left[\frac{N_s}{3+N_s} \times 336\,\mathrm{cm}^{-3}\right]_{\mathrm{now}}$$

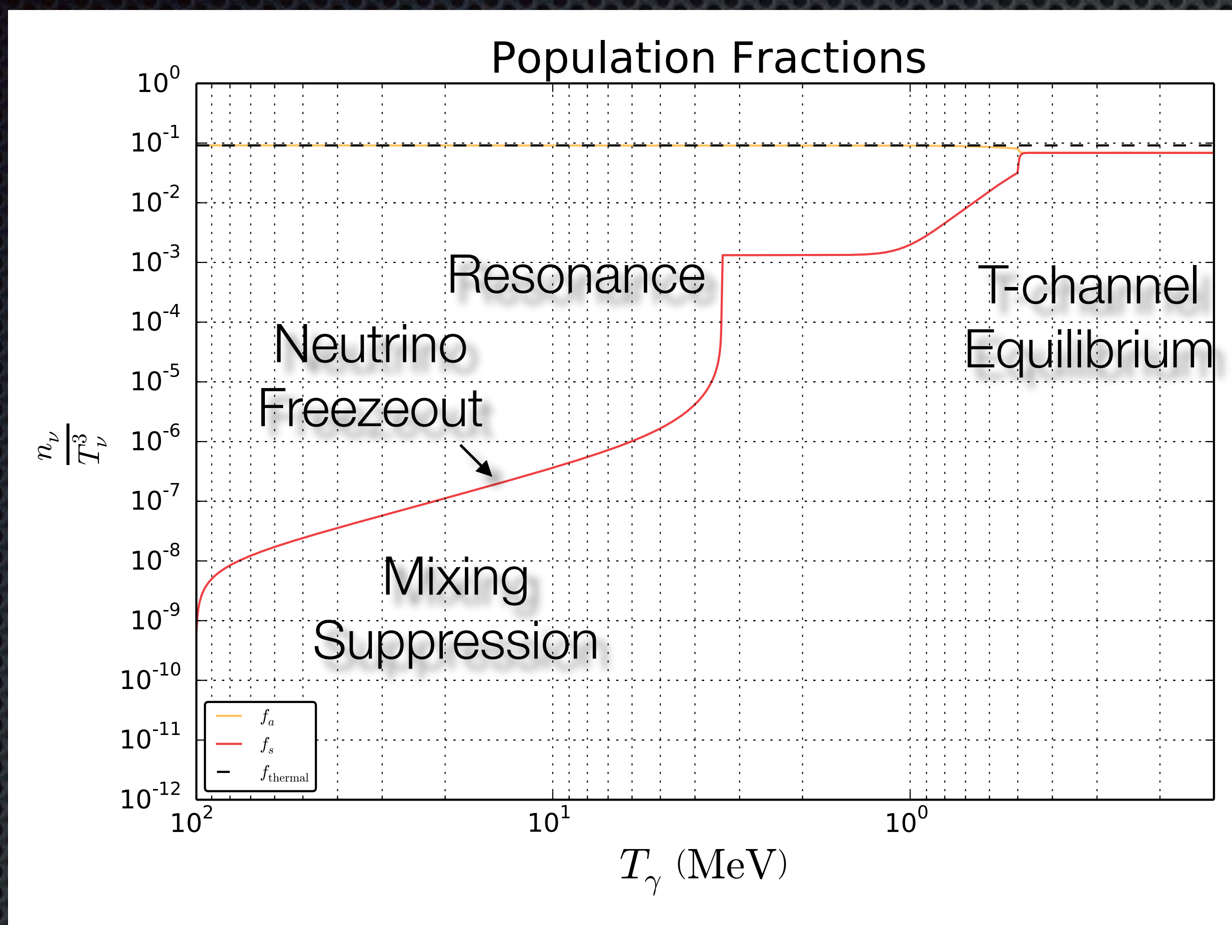
More ordinary decoupling scenario: $T_d = 1\,\mathrm{TeV}$

$$\left.\frac{T_s}{T_\gamma}\right|_{T_{KD}} = \left[\frac{g_{*,s}(T_d)\;\; g_{*,SM}(T_{KD})}{g_{*,SM}(T_d)\;\; g_{*,s}(T_{KD})}\right]^{1/3}$$

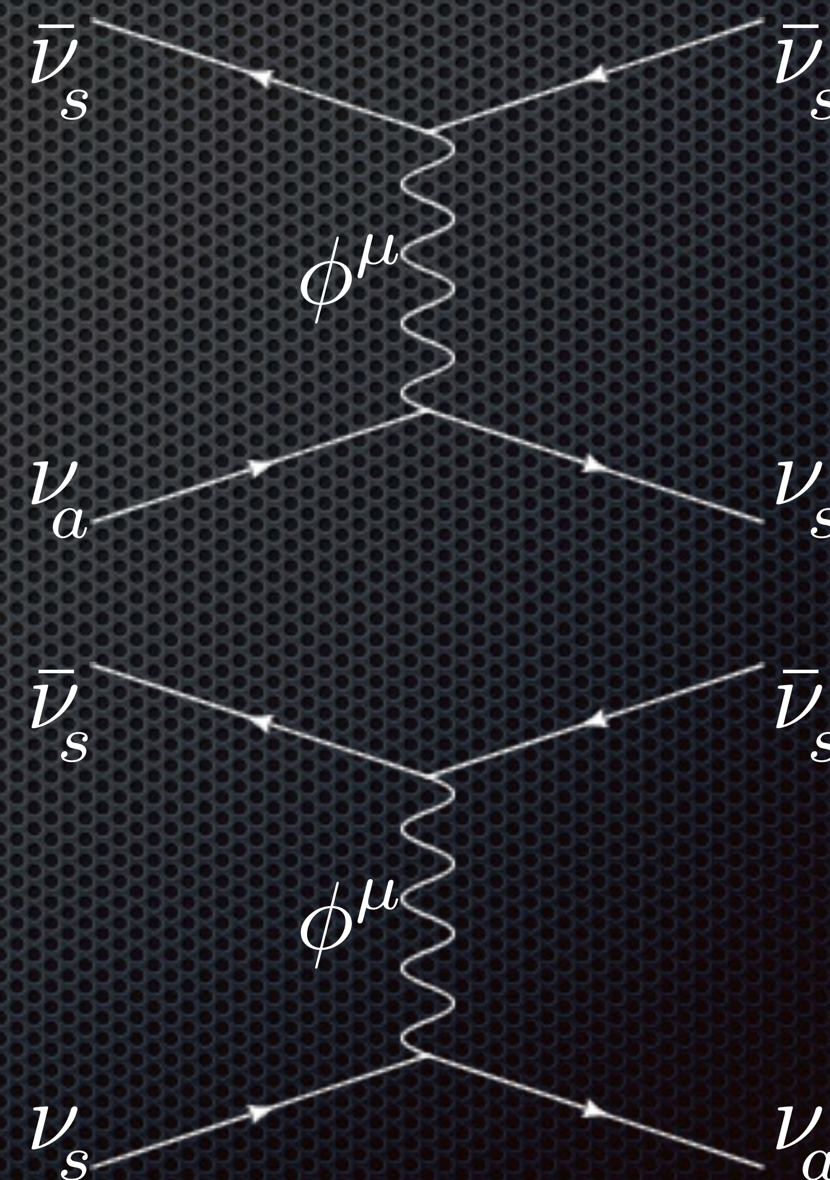
$$T_s/T_\gamma \simeq 0.47$$

$$\Delta N_{eff} \simeq 0.27$$

Relic Sterile Abundance

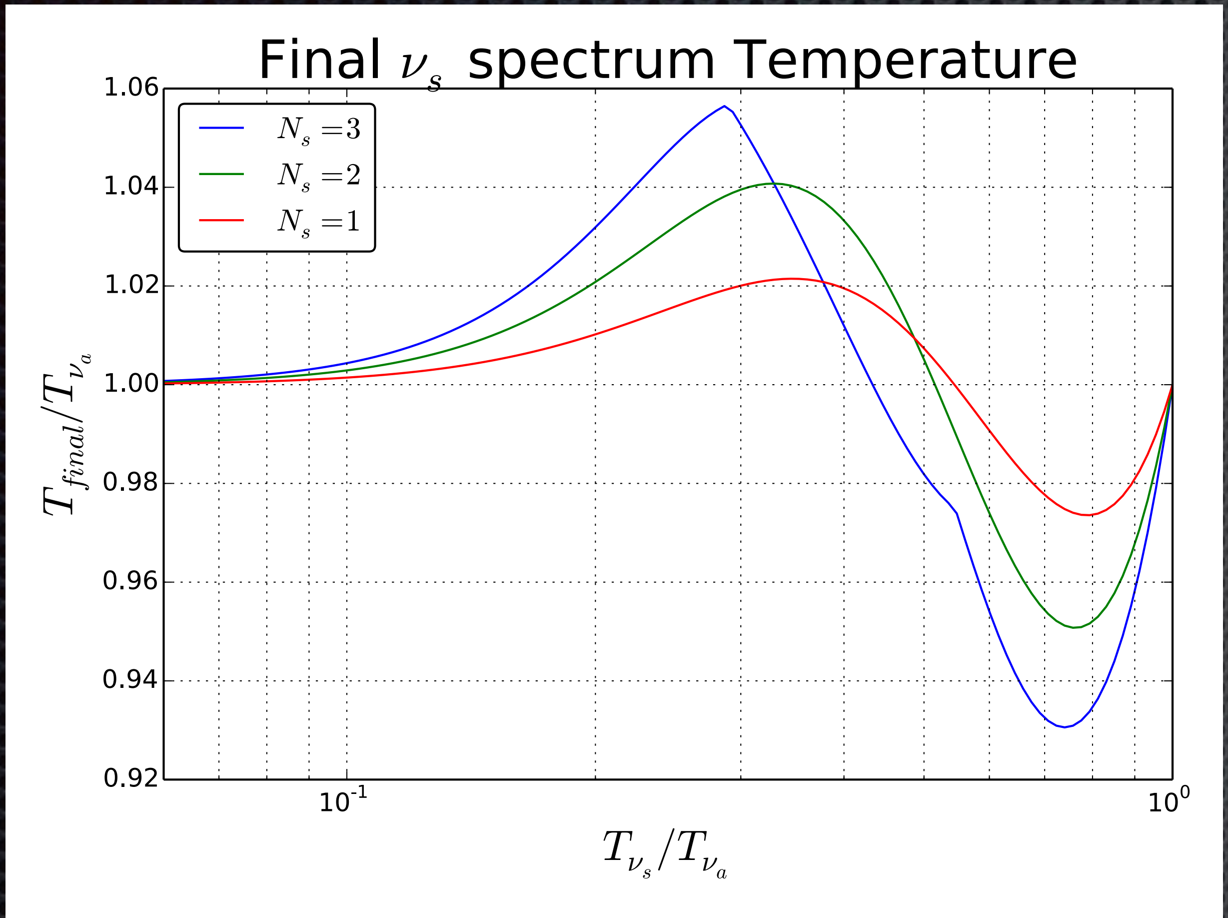


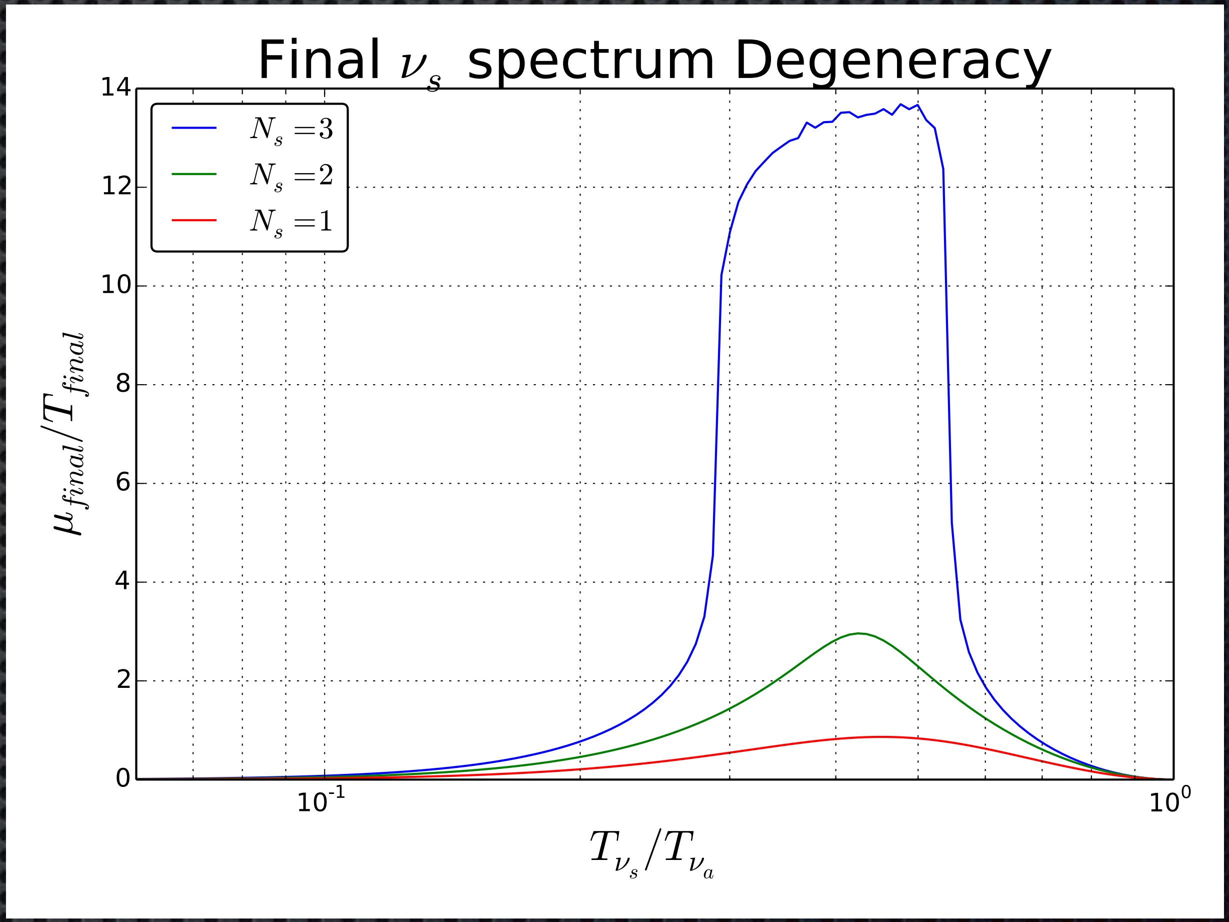
$$\sigma_{\nu\nu} \propto \theta_{eff}^2$$



$$f_\nu\left(p, T_\nu\right) \propto \frac{1}{e^{p/T_\nu} + 1}$$

This results in spectral distortions $T_{\nu_s}/T_{\nu_a} \simeq 0.66$



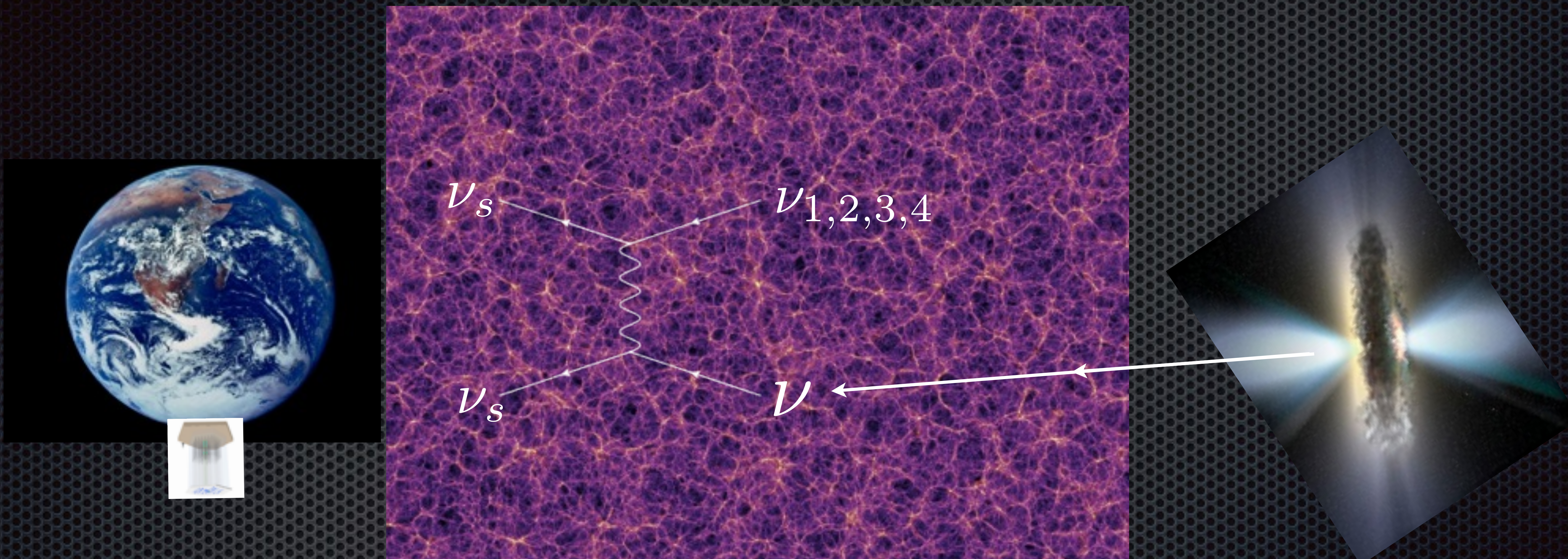


$T_{final} \simeq (4/11)^{1/3} T_\gamma$

$\eta \simeq 0.5$

$$n_\nu \simeq 0.84 \times n_{thermal}$$

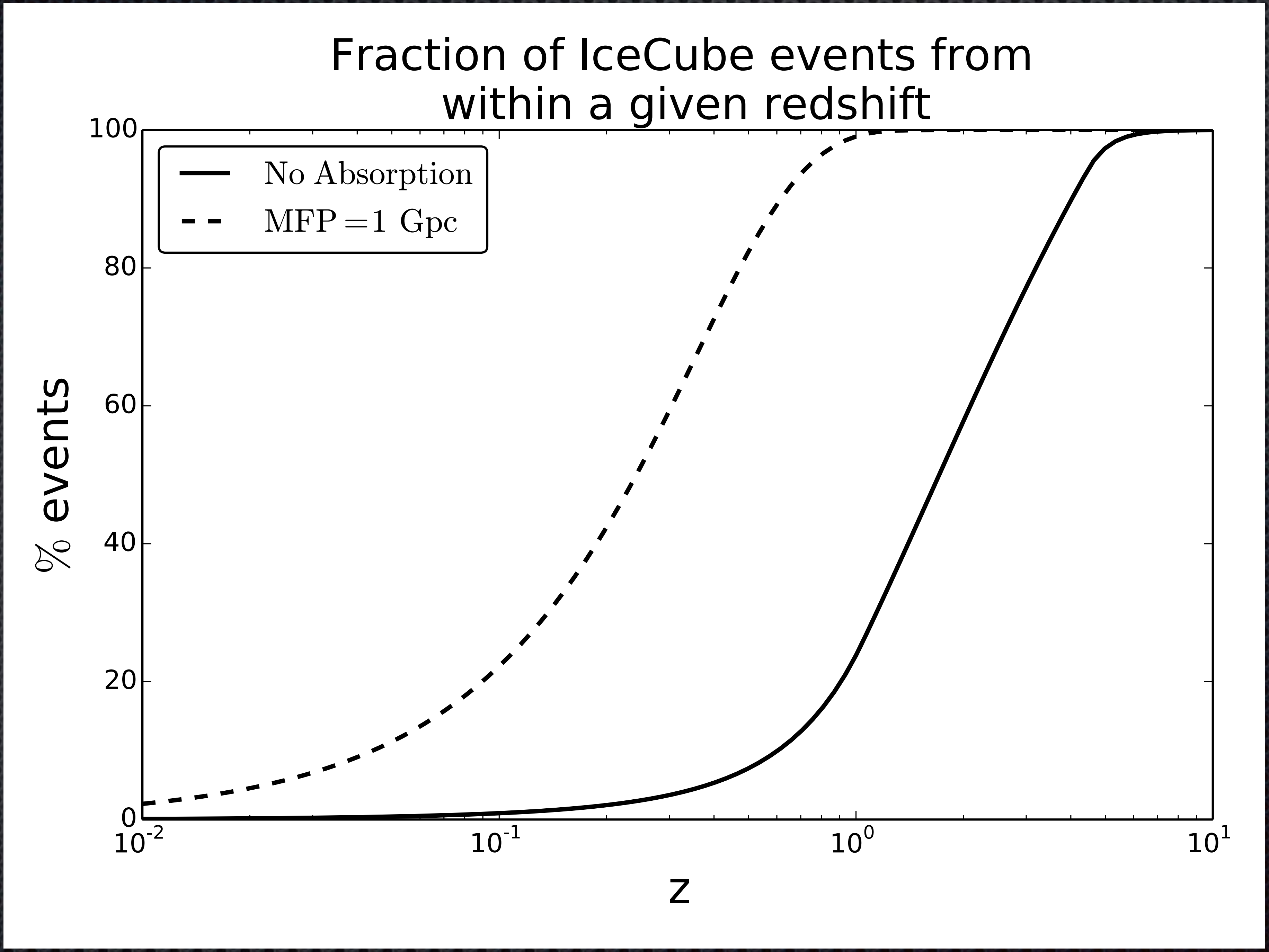
Testing the presence of ν_s



$$\sigma^t_{\nu\nu}(z) = \begin{cases} \sin^2\theta_s \frac{s g_s^4}{2\pi m_\phi^4}, & s \ll m_\phi^2\,, \\ \sin^2\theta_s \frac{3 g_s^4}{4\pi m_\phi^2}, & s \gg m_\phi^2\,. \end{cases}$$

$$\langle \nu_s | \nu_{e,\,\mu,\,\tau} \rangle \equiv 0$$

A cartoon example



Propagate neutrinos over cosmological distances

- Sources and source evolution taken from H. Yuksel, et al., APJ **683** (2008) and Hasinger, Miyaji, Schmidt, Astron. and Astrophys. **441** (2005).
- Use most recent best fit ΛCDM parameters including Planck data: $H(z)^2 = H_0^2\left[\Omega_\Lambda + \Omega_m (1+z)^3 + \Omega_{rad}(1+z)^4\right]$
- Use FRW scaling of relevant quantities:

$$n_\nu(z) = n_{\nu,0}(1+z)^3$$

$$T_\nu(z) = T_{\nu,0}(1+z)$$

$$E_\nu(z) = E_{\nu,0}(1+z)$$

$$dr_p(z) = \frac{c\,dz}{(1+z)\,H(z)}$$

This defines the optical depth

$$\tau = \int_0^{r_p} n_{\nu_s}(z)\,\sigma_{\nu\nu}(z)\,dr_p = \int_0^{z_i} \frac{c n_{\nu_s}(z)\,\sigma_{\nu\nu}(z)\,dz}{(1+z)H(z)}$$

We'll take a moment to define of a few scattering regimes:

"$MFP < 50\,\mathrm{Mpc}$", $\tau \geq 1$ for $\mathrm{r_p} = 50\,\mathrm{Mpc}$

"IceCube isotropic sources", $\tau \geq 1$ for $\mathrm{r_p} > 50\,\mathrm{Mpc}$

"$C\nu B$ optically thin", $\tau \geq 1$ for $\mathrm{z_i} = 10$

Fascinating new wrinkle:

Mon. Not. R. Astron. Soc. **000**, 1–13 (2014) Printed 11 June 2014 (MN LaTeX style file v2.2)

Are both BL Lacs and pulsar wind nebulae the astrophysical counterparts of IceCube neutrino events?

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11 June 2014

ABSTRACT
IceCube has recently reported the discovery of high-energy neutrinos of astrophysical origin, opening up the PeV (10^{15} eV) sky. Because of their large positional uncertainties, these events have not yet been associated to any astrophysical source. We have found plausible astronomical counterparts in the GeV – TeV bands by looking for sources in the available large area high-energy γ-ray catalogues within the error circles of the IceCube events. We then built the spectral energy distribution of these sources and compared it with the energy and flux of the corresponding neutrino. Likely counterparts include mostly BL Lacs and two Galactic pulsar wind nebulae. On the one hand many objects, including the starburst galaxy NGC 253 and Centaurus A, despite being spatially coincident with neutrino events, are too weak to be reconciled with the neutrino flux. On the other hand, various GeV powerful objects cannot be assessed as possible counterparts due to their lack of TeV data. The definitive association between high-energy astrophysical neutrinos and our candidates will be significantly helped by new TeV observations but will be confirmed or disproved only by further IceCube data. Either way, this will have momentous implications for blazar jets, high-energy astrophysics, and cosmic-ray and neutrino astronomy.

Key words: BL Lacertae objects: general — gamma-rays: galaxies — neutrinos — pulsars: general — radiation mechanisms: non-thermal

1 INTRODUCTION

The IceCube South Pole Neutrino Observatory[1] has reported the first evidence of high-energy astrophysical neutrinos[2] (Aartsen et al. 2013; IceCube Collaboration 2013), and more recently has confirmed and strengthened these observations by publishing a sample of 35 events with a deposited energy from 30 TeV to 2 PeV (IceCube Collaboration 2014). With this enlarged sample the null hypothesis that all events are associated with the atmospheric background can be rejected at the 5.7σ level. If the observation of ultra-high energy cosmic rays revealed the existence of extreme cosmic accelerators, the IceCube neutrinos show that hadronic particle physics is in action in astrophysical sites at an energy scale somewhat higher than any man-made accelerator. IceCube is therefore opening a new window at the high-energy frontier of particle- and astro-physics. Motivated by this discovery we investigate here plausible γ-ray counterparts of the IceCube events and discuss possible new scenarios. The detection of high-energy neutrinos up to the PeV (10^{15} eV) scale implies the existence of a class of astrophysical objects accelerating protons up to at least $10^{16} - 10^{17}$ eV, which then collide with other protons (pp collisions) or photons ($p\gamma$ collisions). High-energy γ-rays with energy and flux about a factor two higher than the neutrinos at the source, and therefore reaching the $\gtrsim 60$ TeV range for the IceCube events, are also expected as secondary products in both cases (Kelner, Aharonian, & Bugayov 2006; Kelner & Aharonian 2008). In the following we refer to these γ-rays as neutrino *twins*. The study of these twin photons would provide the most direct way to shed light on the origin of the IceCube neutrinos. The twin photons, however, cannot be at the moment investigated due to the fact that present γ-ray telescopes reach only $\sim 20 - 40$ TeV. Moreover, depending on the sources and their distance, absorption of the twin photons might dilute the direct photon-neutrino connection.

The topology of the IceCube detections are broadly classified in two types: 1. cascade-like, characterised by a compact spherical energy deposition; 2. track-like, defined by a dominant linear topology from the induced muon. A large majority of the 35 IceCube events are characterised by

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[1] http://icecube.wisc.edu
[2] In this paper neutrino means both neutrino and antineutrino.

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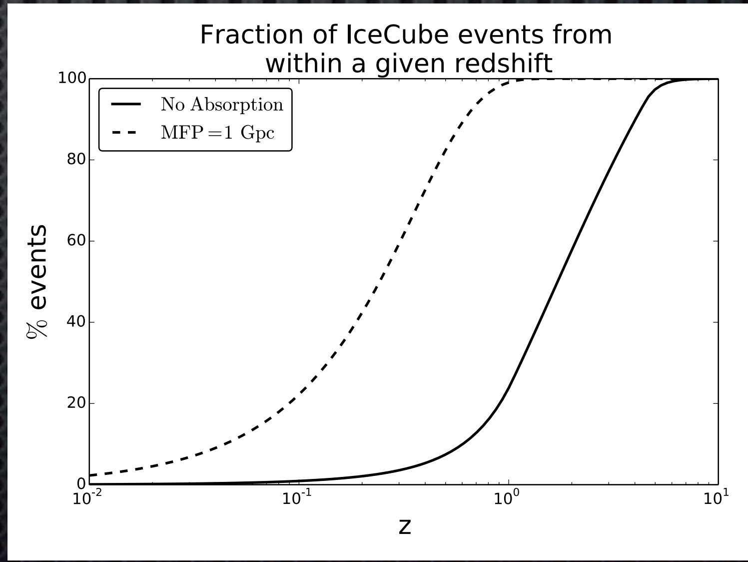
9 IceCube events found correlated with gamma ray point sources:
2 from galactic pulsar wind nebulae
7 from BL Lacs (AGN), 3 from sources less than z < 0.212

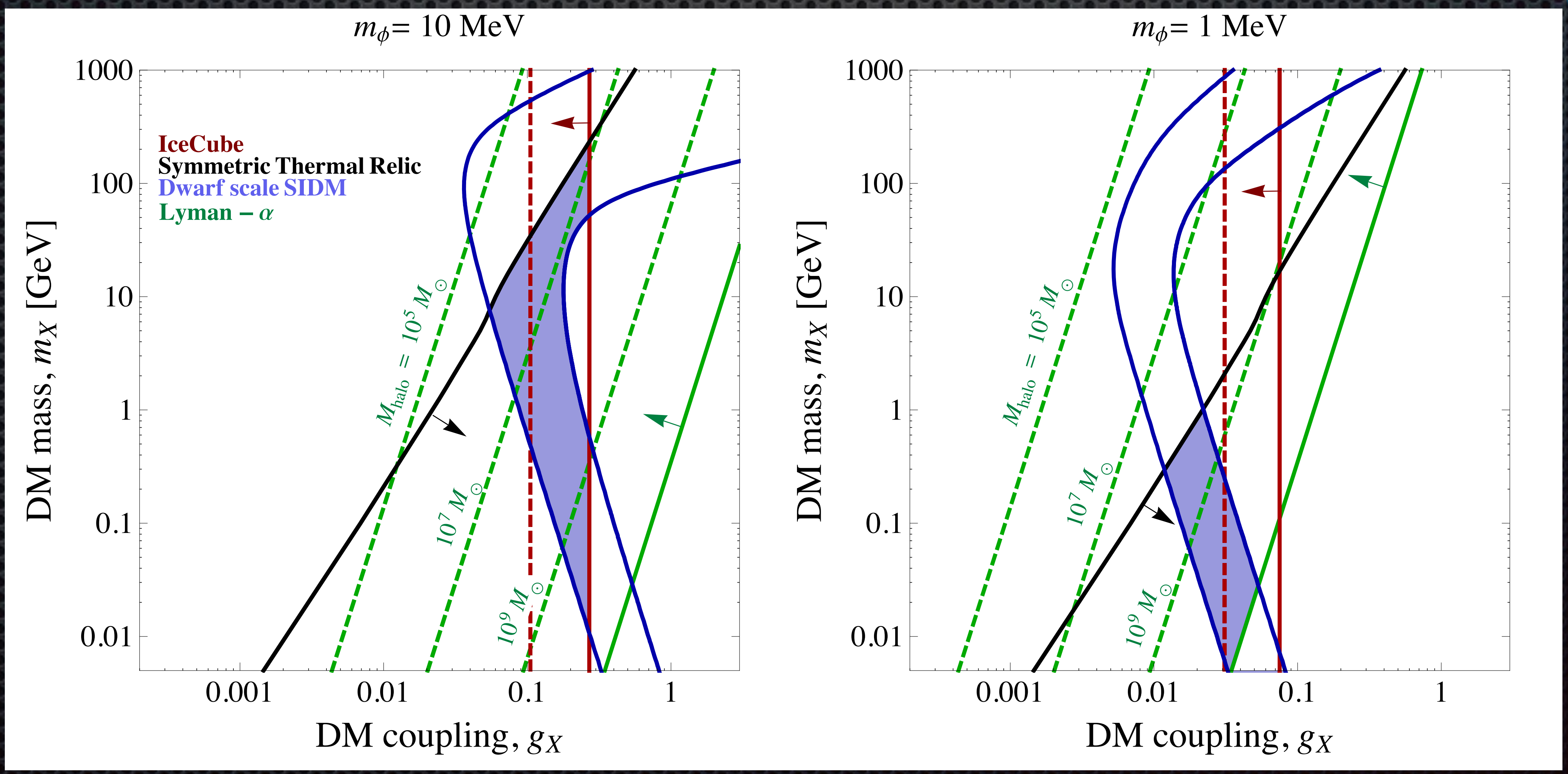


expect only 0.34 events!

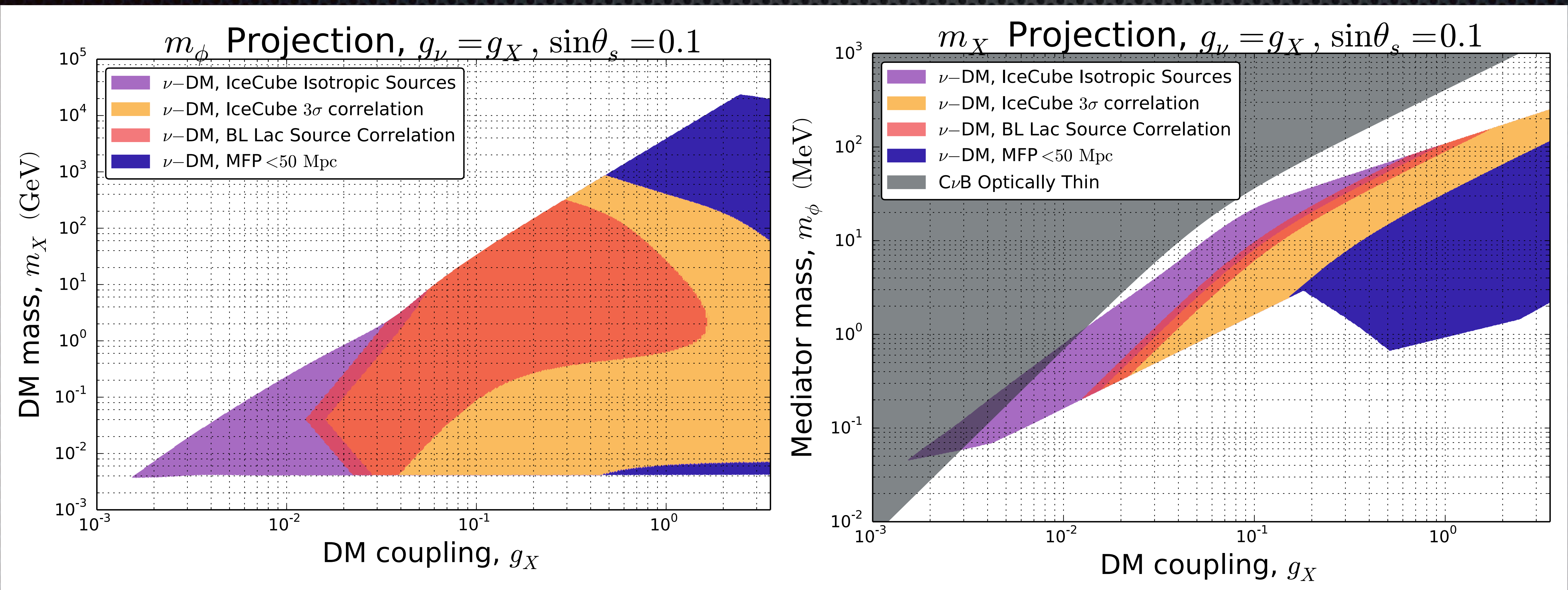
How does all of this fit with SIDM?

$$\mathcal{L} \supset g_X \phi^\mu X \gamma_\mu \bar{X} + g_s \phi^\mu \nu_s \gamma_\mu \bar{\nu}_s$$

$$g_X = g_s$$



Projecting over all m_ϕ



Nearby source correlation is significant at the 3σ level

Nearby (z<.212) event correlation is consistent with the original predictions for AGN!

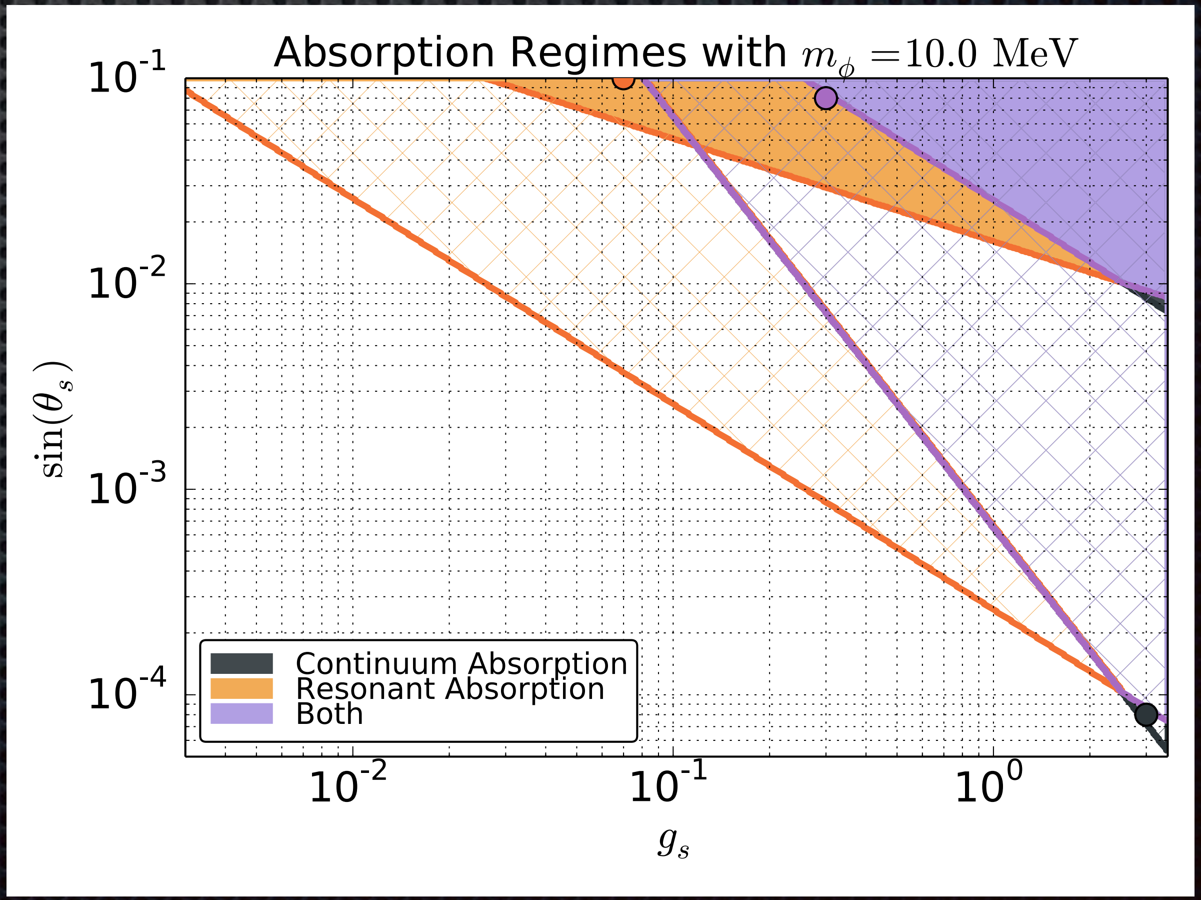
Optical Depth

$$\tau(z) = \langle \sigma_{\nu\nu} \rangle (z)\, n_\nu^{\text{eff}}(z)\, dr_p(z)$$

- Scattering probability: $Pdz = 1 - e^{-\tau}$
- Which channels absorb neutrinos depends on our choice of g_s and θ_s:

Resonant $\tau \propto P_{is} \tilde{P}_{as} \frac{36\pi g_s^2}{m_\phi^2}$

Continuum $\tau \propto P_{is} \tilde{P}_{as} \frac{3 g_s^4}{4\pi m_\phi^2}$



Scattering on a Thermal Background

- The $C\nu B$ has an effective temperature: $T_\nu = (4/11)^{1/3} T_\gamma$
- Which retains the Fermi-Dirac shape:

$$f_\nu (p, T_\nu) = \frac{1}{e^{p/T_\nu} + 1}$$

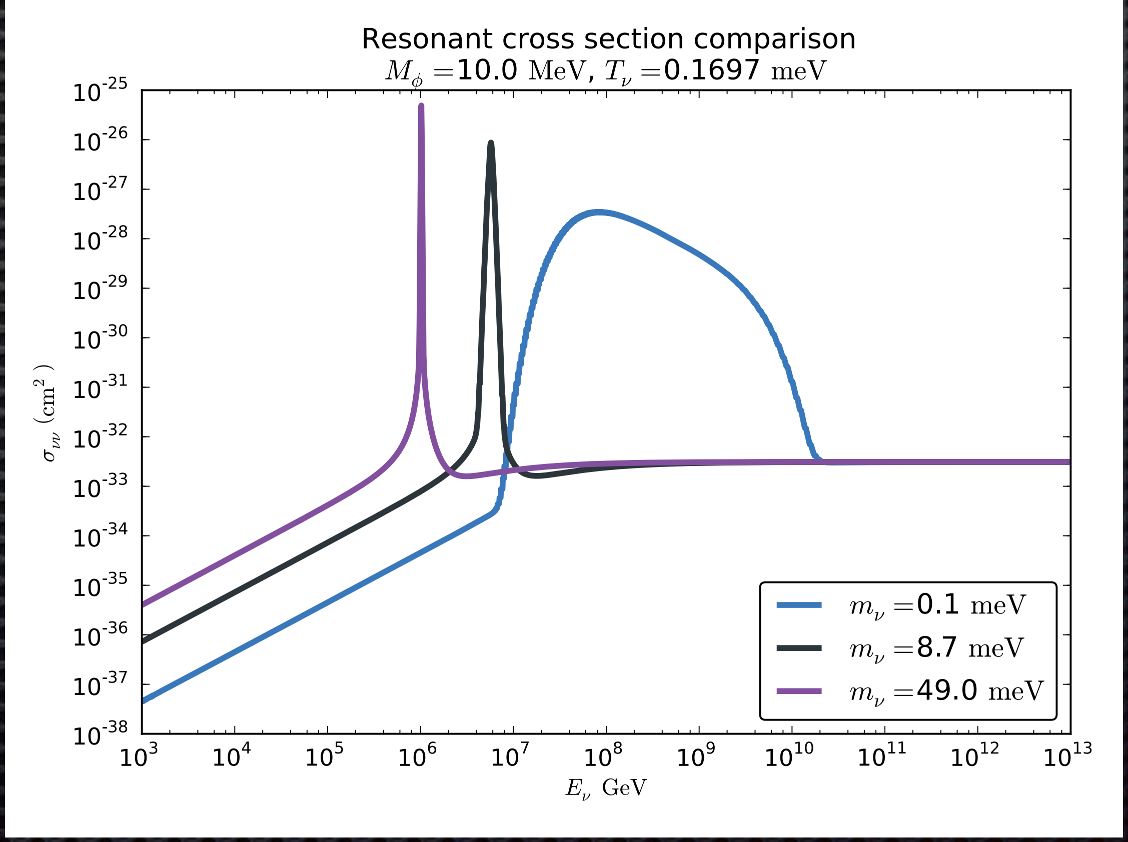
- So our cross sections must be convolved with the thermal motion of the $C\nu B$:

$$\langle \sigma_{\nu\nu} \rangle = \frac{\int d\mathbf{p}^3 \sigma_{\nu\nu} (E_\nu, \mathbf{p}, m_\nu) f_\nu (\mathbf{p}, m_\nu, T_\nu)}{\int d\mathbf{p}^3 f_\nu (\mathbf{p}, m_\nu, T_\nu)}$$

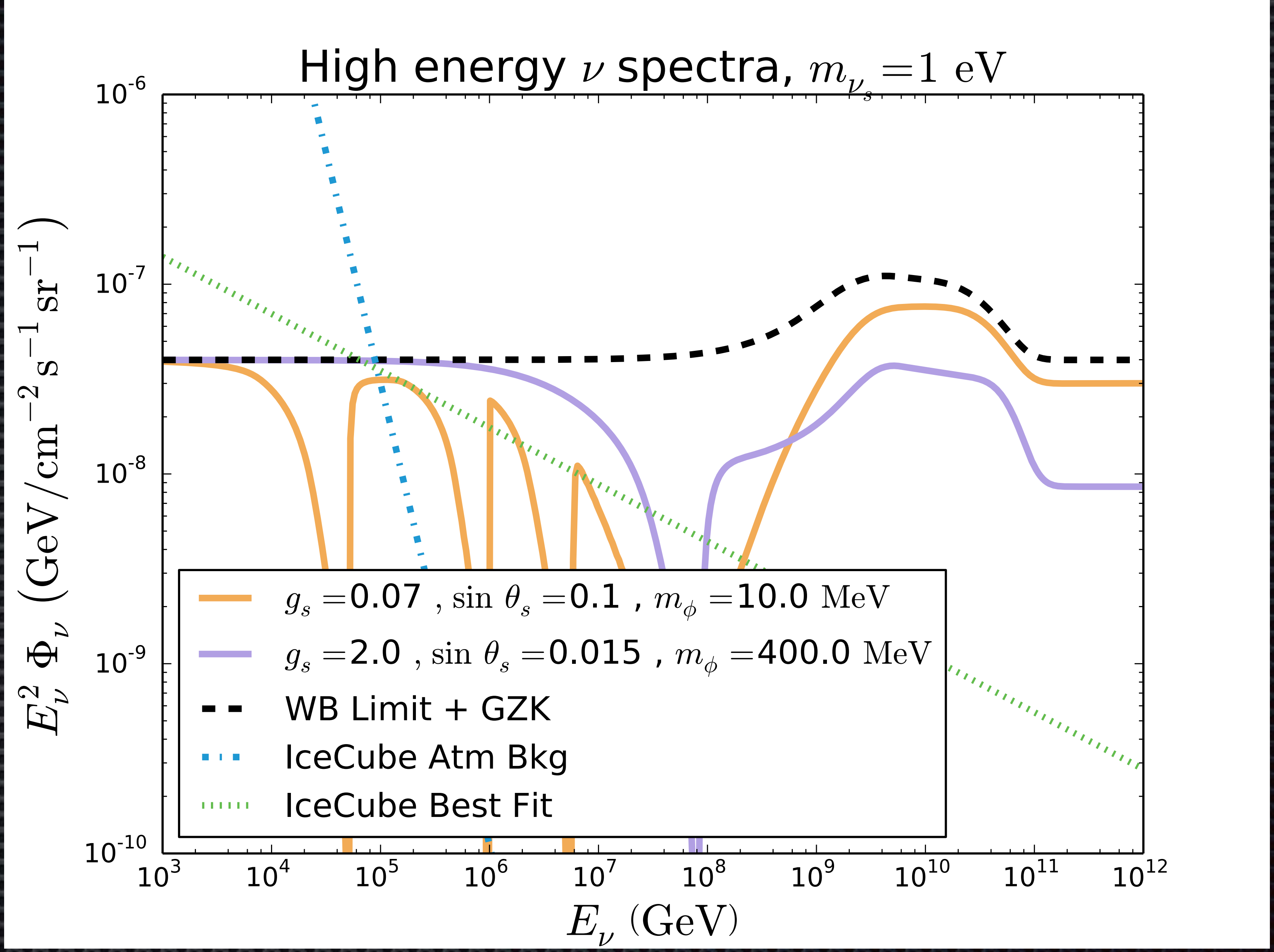
Thermal Broadening

- Non-relativistic: $s \approx 2m_\nu E_\nu$
- Relativistic: $s \approx 2E_\nu \left(\sqrt{p_\nu^2 + m_\nu^2} - p_\nu \cos\theta\right)$

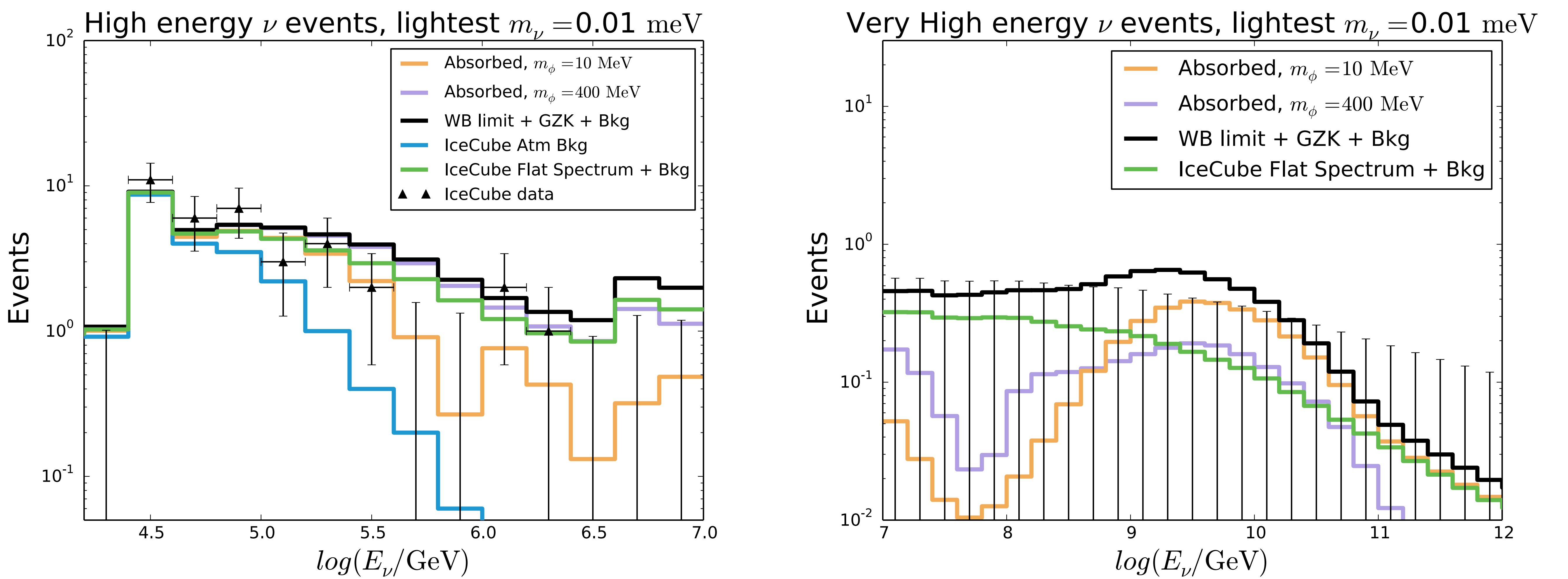
$$\sigma\left(\bar{\nu}\nu \to \bar{\nu}\nu\right) \propto \int_{-1}^{1} \frac{g_\nu^4}{16\pi s} \left[\frac{t^2 + u^2}{\left(s - m_\phi^2\right)^2 + \left(m_\phi \Gamma_\phi\right)^2}\right] d\cos\theta + \ldots$$



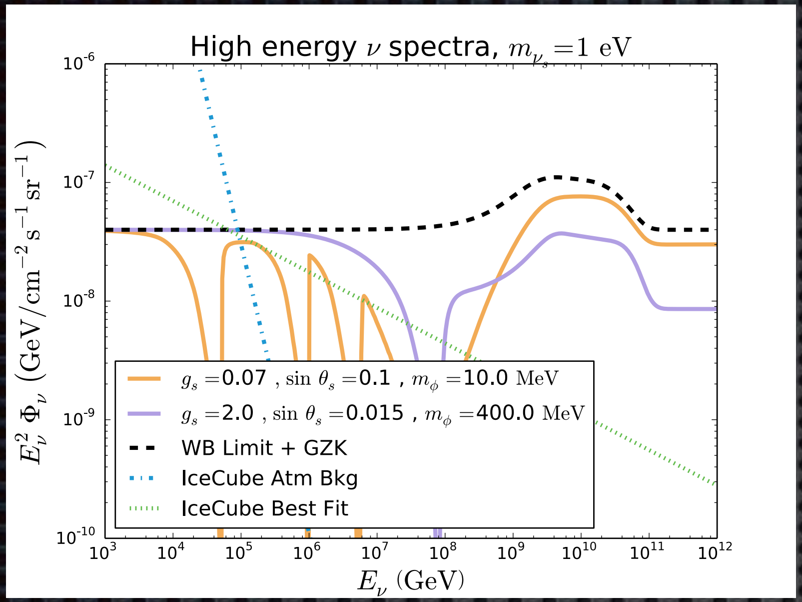
Some results:

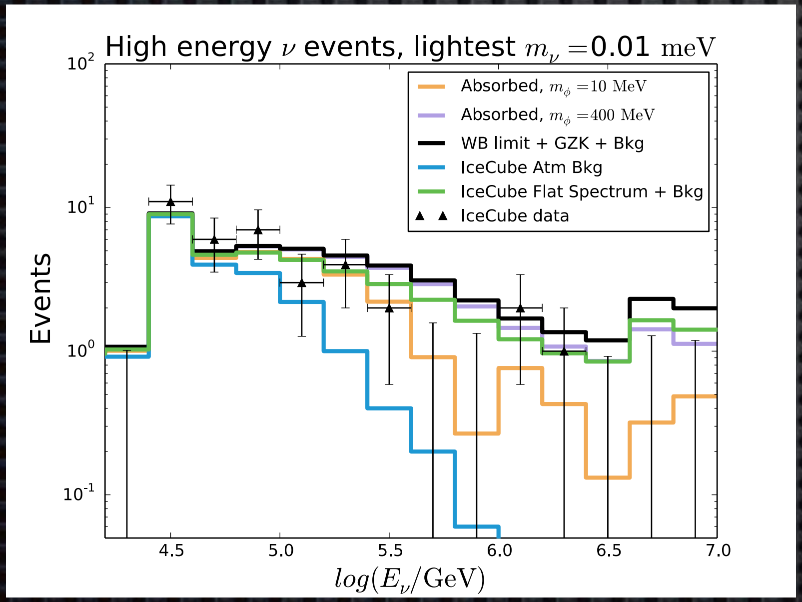


How does this fit with the observed IceCube data?

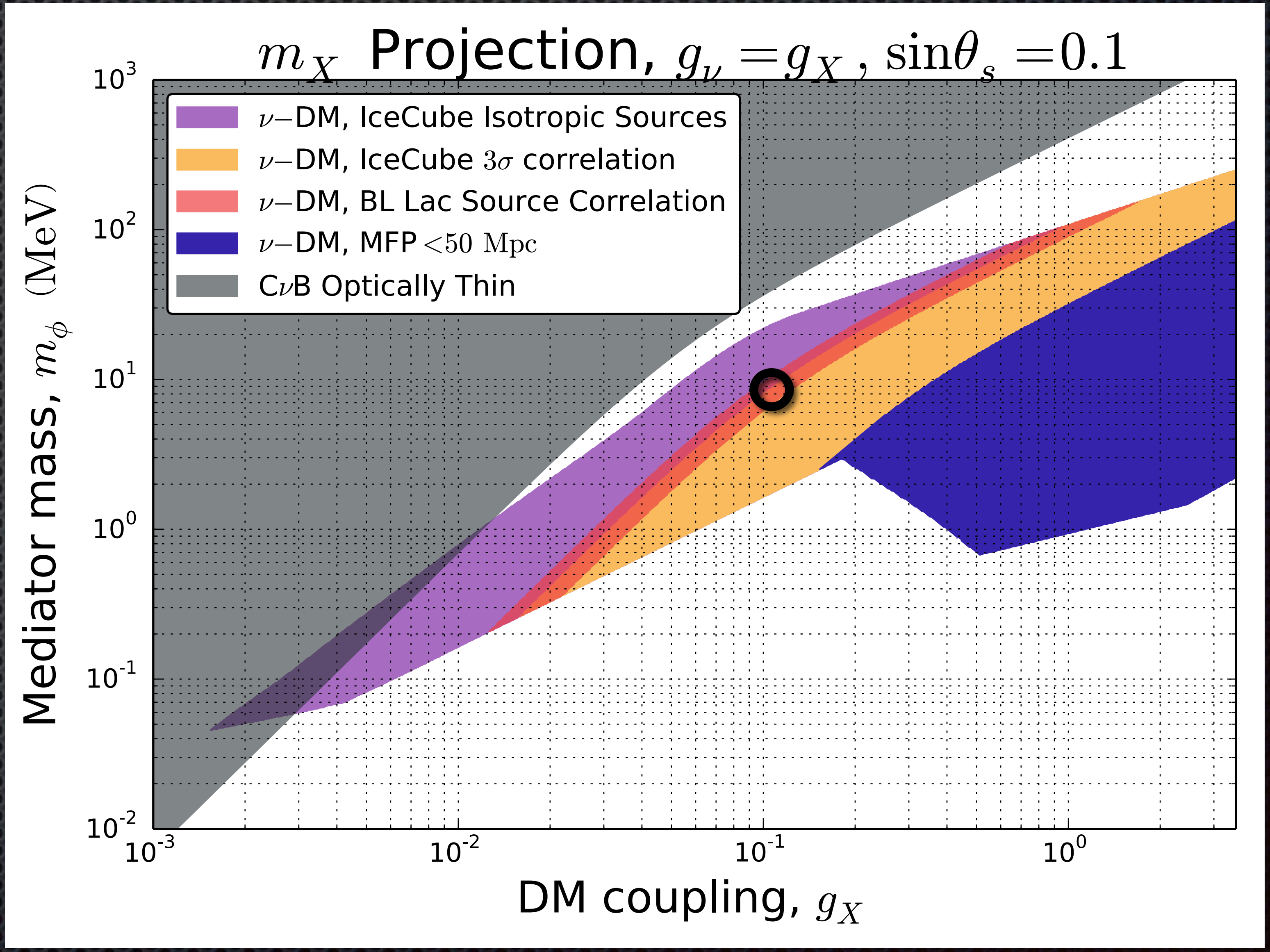


The IceCube best fit combined with correlation data





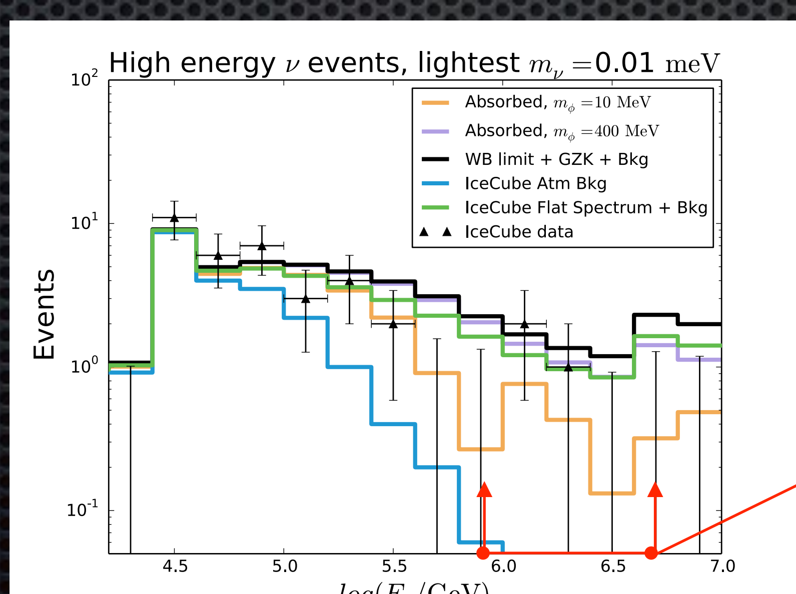
$\Rightarrow$



Side bonus: We might be able to measure the ν mass scale!

$$E_{\rm CM}^2 = m_\phi^2 = 2 m_\nu E_{\rm res}$$

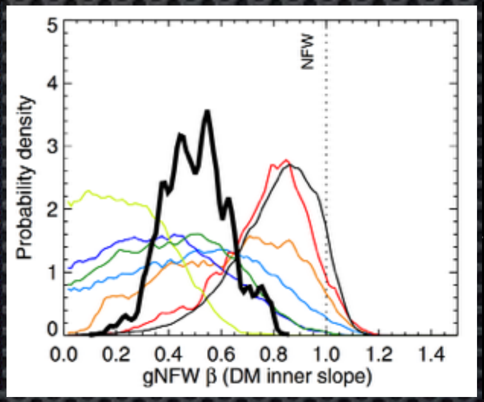
$$\Delta m^2 = m_{\nu,i}^2 - m_{\nu,j}^2 = \frac{m_\phi^4}{4}\left(\frac{1}{E_{\rm res,i}^2} - \frac{1}{E_{\rm res,j}^2}\right)$$

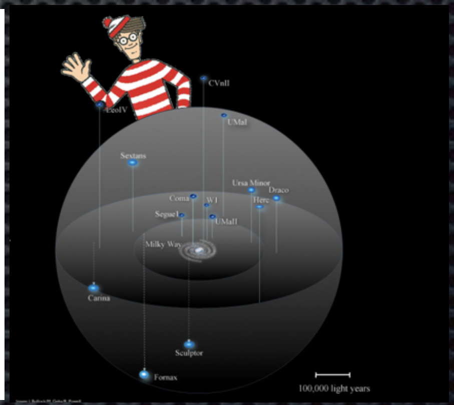


Δm^2_{atm}

Conceptual Progress:

- A neutrino portal goes a long way to tying up some the loose threads of dark sector physics.



- Further it does so in a way that is eminently testable with IceCube.

Some things need more investigation

- N effective is unchanged in our minimal model, but TeV - GeV decoupling temperatures for the dark sector will impact N effective.
- Late time re-coupling creates a good deal of neutrino rest mass. Does this violate the bounds on the sum of light neutrino masses?
- Neutrino self interactions with MeV scale mediators *will* do something in core collapse supernovae.

Conclusions:

- Hidden neutrino interactions provide a novel and surprisingly apt model of the high energy neutrino signal in IceCube
- If these hidden interactions are a byproduct of a neutrino portal to the dark sector, an astonishing chain of coincidental solutions to dark matter structure problems issue forth.
- IceCube is taking data right now, and will eventually make a definitive statement on this model!

Thank you very much!