Neutrino Portal to the Dark Sector: From Dwarf Galaxies to IceCube

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Cosmology & Particle Physics

arXiv:1411.1071

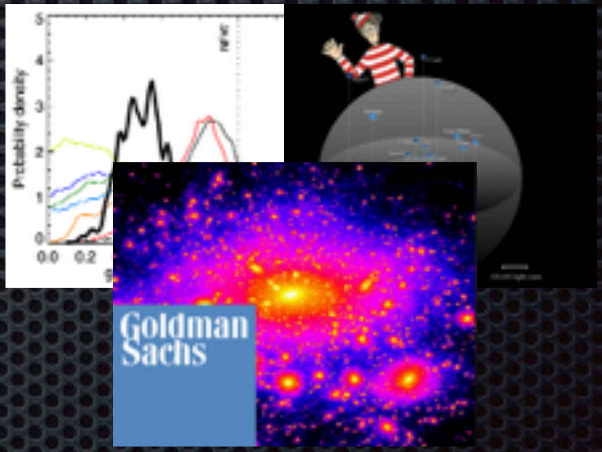
Implications of Neutrino Flavor Oscillations Workshop, Santa Fe, July 2015

Really this is a Neutrino Portal to the Dark Sector

- 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)



- Planck results seem to favor additional radiation energy density, which also resolves tension with Lensing, Clustering, and H_0 measurements.

Wyman, Rudd, Vanderveld, and Hu, Phys. Rev. Lett. **112** (2014)

Dark Matter Self Interaction

- The lack of cold cores in observed dark matter halos can be explained by brining them into contact with hotter DM particles in the halo. (Spergel, Steinhardt, PRL **84**, (2000))
- Need ~1 interaction per Hubble time:

$$\frac{\sigma_{XX}}{m_X} \sim 100\,\mathrm{fm}^2\,\mathrm{GeV}^{-1}$$

- This picks out a natural energy scale:

$$100\,\mathrm{fm}^2 \sim g^4/m_\phi^2\,,\ \text{with}\ g \sim \mathcal{O}(1) \implies m_\phi \sim \mathcal{O}(\mathrm{MeV})$$

Secluded Sector

- Whatever this MeV scale mediator is, it must be well isolated from the SM.
- A number of possibilities have been proposed for finding a “portal” which would allow us to observe this new interaction, e.g. kinetic mixing (dark photons) or Higgs mixing.
- We are going to investigate a Neutrino mixing portal. We will suppose that the secluded sector contains a fermion which couples to the SIDM mediator. Further, this fermion will mix with SM neutrinos.

Mixing Portal Prescription

$$\mathcal{L} \supset LH\nu_R + \nu_s H'\nu_R + \Lambda\nu_R\nu_R$$

$$\mathcal{L} \supset \frac{(LH)\underbrace{(\nu_s H')}}{\Lambda}$$

Basic seesaw type operator

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

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

Goldstone Boson associated with ν_s acquires mass when H’ symmetry is broken

$$\phi^\mu,\ m_\phi \quad \Big\downarrow$$

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

Missing Satellites?

- Dark Matter will couple to the secluded neutrinos through ϕ^{μ}
- Kinetic decoupling of dark matter and neutrinos sets the cutoff mass for small scale structure:

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

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

$$M_{\rm cut} = 10^{7} - 10^{9}\;M_{\odot} \quad \Longrightarrow \quad \sigma_{X\nu} \sim 100\,{\rm fm}^{2}$$

Unified SIDM solutions exist

- Possible SIDM schemes break down into different analytic limits

- The classical limit, where $m_X v \gg m_\phi$

$$\sigma_T \approx \begin{cases} \frac{2\pi}{m_\phi^2} \quad \beta^2 \ln(1+\beta^{-2}), \beta < 1, \\ \frac{\pi}{m_\phi^2} \quad \left(\ln 2\beta - \ln\ln 2\beta\right)^2, \beta > 1, \end{cases} \qquad \text{where } \beta \equiv 2\alpha_X m_\phi/(m_\chi v_{\rm rel}^2).$$

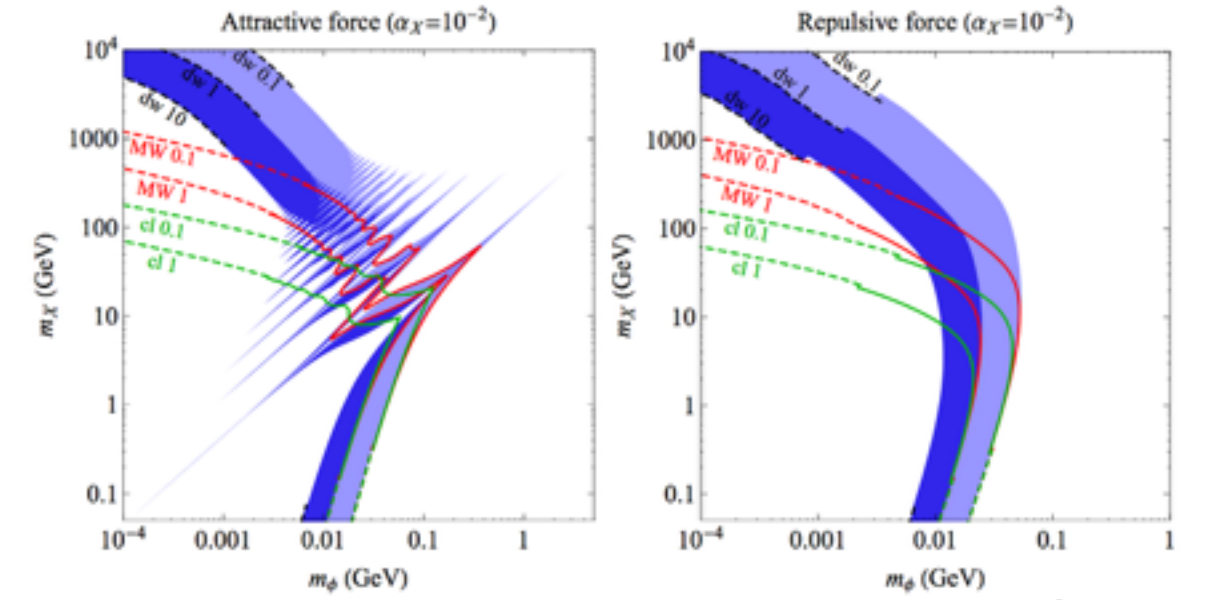
- The Born Approximation, where $\alpha_X m_X \ll m_\phi$

$$\sigma_T = \frac{g_X^4}{2\pi m_X^2 v^4}\left[\ln\left(1+\frac{m_X^2 v^2}{m_\phi^2}\right) - \frac{m_X^2 v^2}{m_\phi^2 + m_X^2 v^2}\right]$$

- Tied together by the “quantum” regime,

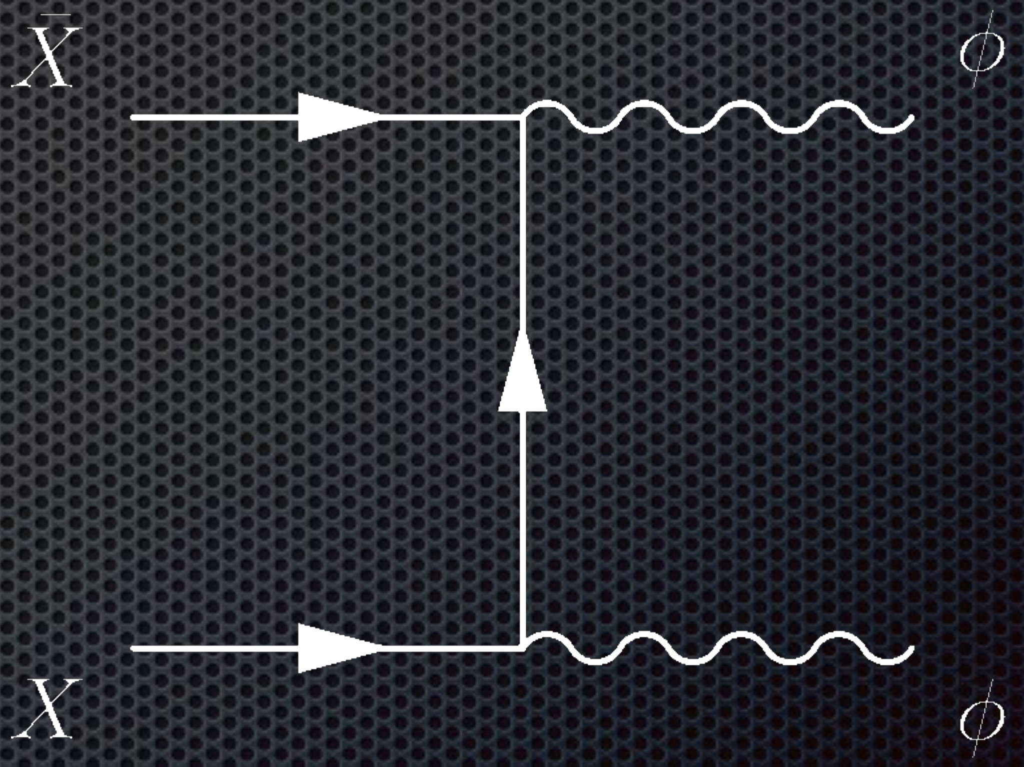
Tulin, Yu, Zurek,

PRD 87, 116007 2013



Dark Matter Annihilation

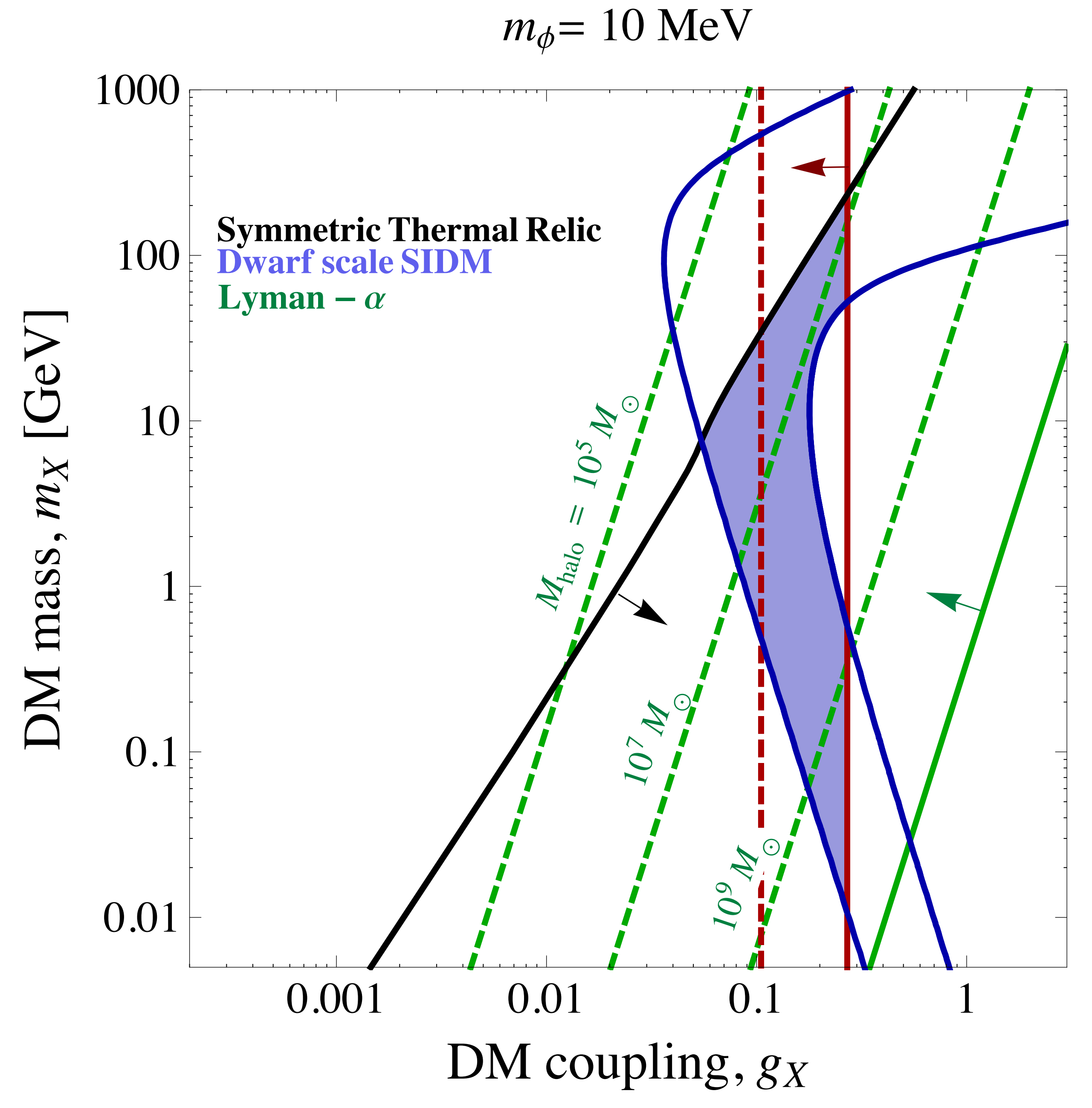
- DM can annihilate through the new interaction.
- Coupling must be large enough not to over-close the Universe.
- Coupling can also be quite strong if DM is asymmetric.



SIDM Parameter Space

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

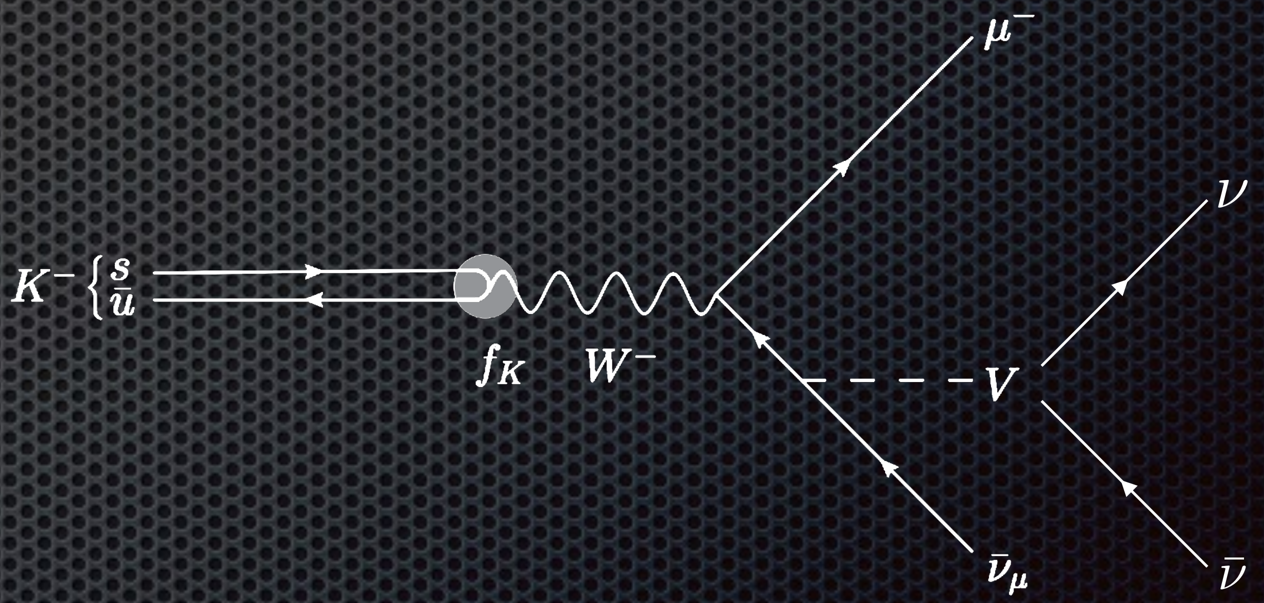
$$g_X = g_s$$



J. Cherry, A. Friedland, I. Shoemaker, arXiv:1411.1071

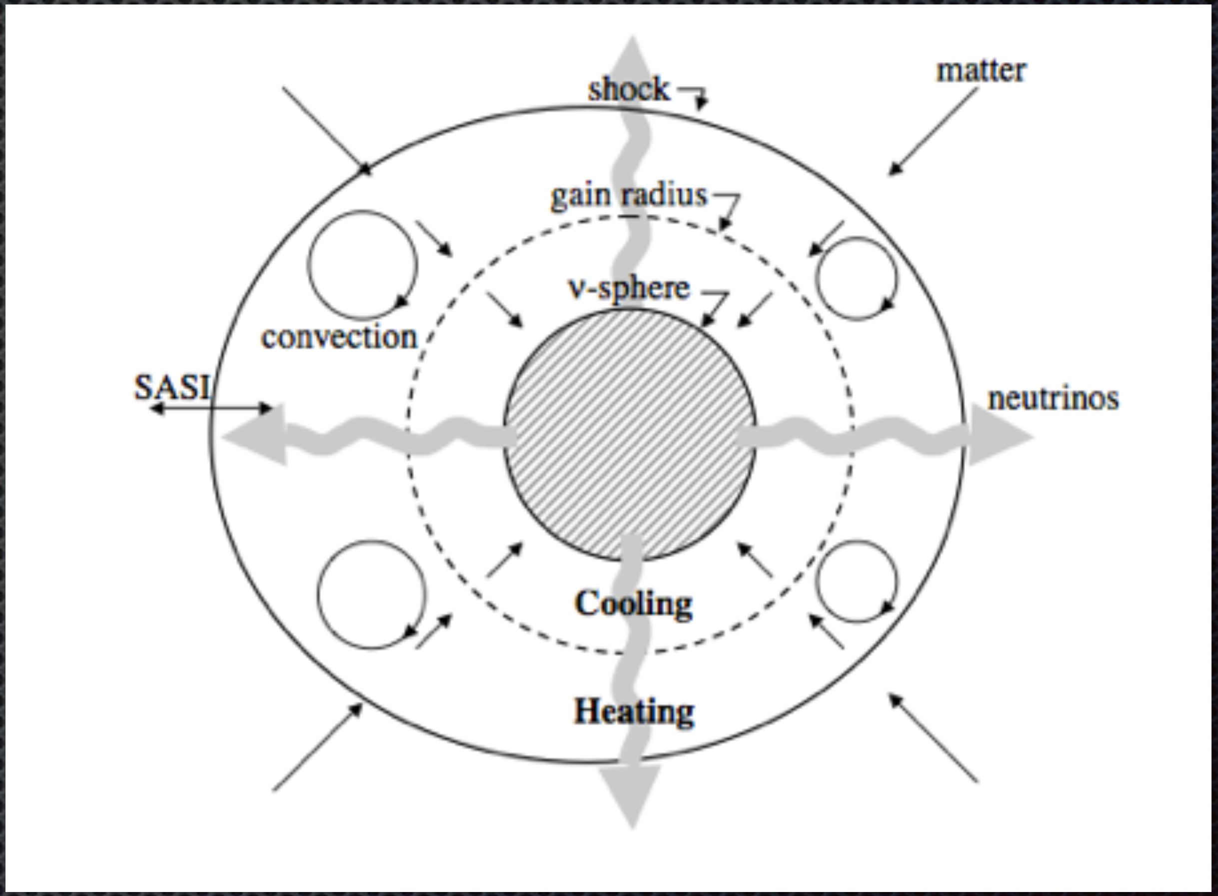
How do we test the $\nu - \nu$ portion of this idea?

- Historically venerated test of $\nu - \nu$ interactions. (Bardin, Bilenky, Pontecorvo (1970); Barger, Keung, Pakvasa (1982))
- The mixing portal will not produce 4-fermion decays inside detectors.



Core Collapse SNe?

- Hidden neutrino interactions may play havoc in the PNS core of a supernova. (Manojar (1987); Kolb, Turner (1987); Fuller, Mayle, Wilson (1988))
- Matter effects for SM neutrinos suppress the mixing angle, preventing



$$\delta m^2_{eff} \sim \mathcal{O}(\mathrm{keV}^2)$$

$\nu - \nu$ Collider?

- We could test for secluded interactions if we could collide neutrino mass Eigen states.
- Nature has furnished a better alternative.
- Icecube can be thought of as the detector element of an astrophysical $\nu - \nu$ collider, where the $\mathrm{C}\nu\mathrm{B}$ is the beam target.

Same basic idea as the Z-burst

- T. Weiler, PRL (1982): A very high energy neutrino might meet a $\mathrm{C}\nu\mathrm{B}$ neutrino and produce a Z boson on resonance.
- Simply requires the Cosmogenic neutrino to have an energy of $\sim 10^{23}\,\mathrm{eV}$.

$$E_{CM} \sim \sqrt{(100\,\mathrm{meV})(10^{23}\,\mathrm{eV})} \sim 100\,\mathrm{GeV} \sim m_Z$$

Rather than a burst, IceCube misses neutrinos

- The same basic physics as the Z-burst, but the end state “burst” is predominantly invisible secluded sector particles.
- IceCube has observed neutrinos in TeV-PeV range, which naturally makes its observations sensitive to particle resonances in the mass range:

$$\sqrt{m_\nu \times 100\,\mathrm{TeV}} \sim E_{CM} \sim \mathcal{O}(\mathrm{MeV})$$

There is a suspicious energy scale in the DM structure problems

- SIDM cross sections on small scales favor $\frac{\sigma_{XX}}{m_X} \sim 100\,\mathrm{fm}^2\,\mathrm{GeV}^{-1}$

$$100\,\mathrm{fm}^2 \sim g^4/m_\phi^2\,,\ \text{with}\ g \sim \mathcal{O}(1) \implies m_\phi \sim \mathcal{O}(\mathrm{MeV})$$

- Velocity dependent DM-DM cross sections favor

$$m_\phi \lesssim p_{\mathrm{transfer}} \implies m_\phi \lesssim \mathcal{O}(10\mathrm{MeV})$$

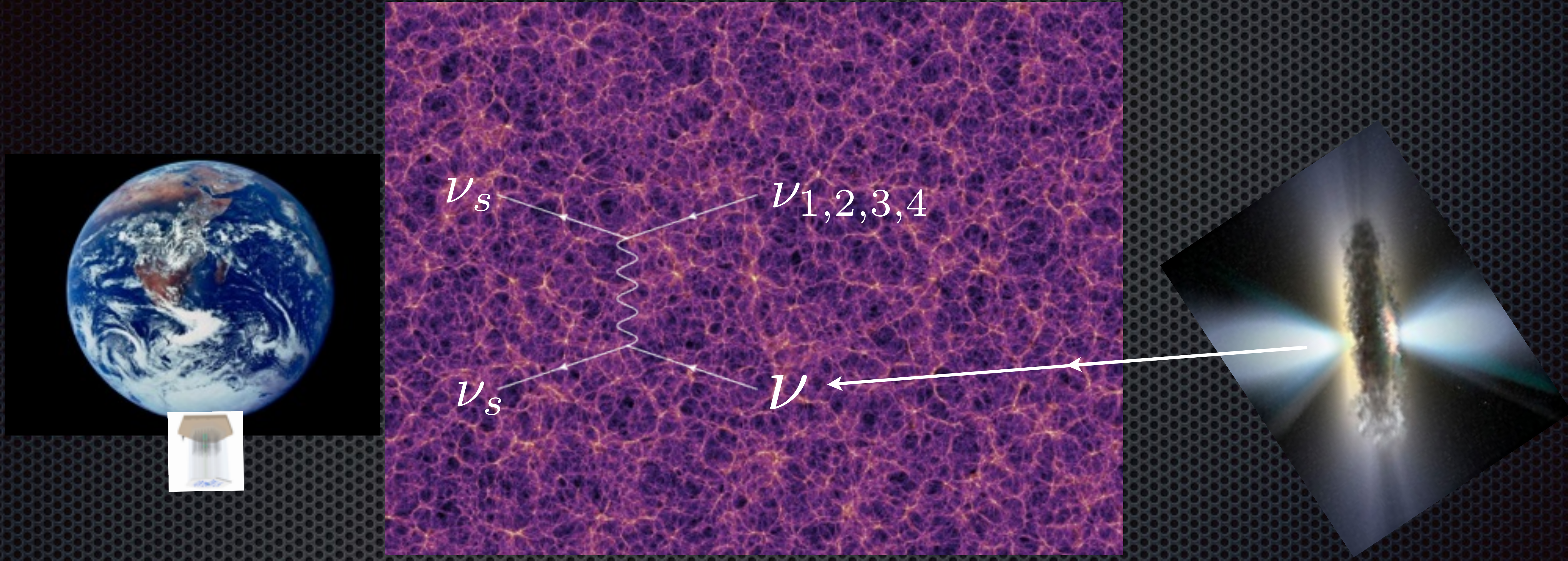
- Kinetic decoupling with a ν-like species also favors

$$\sigma_{X\nu} \sim 100\,\mathrm{fm}^2$$

- IceCube can be thought of as a $\nu - \nu$ collider with

$$\sqrt{m_\nu \times 100\,\mathrm{TeV}} \sim E_{CM} \sim \mathcal{O}(\mathrm{MeV})$$

Scattering = Measurement



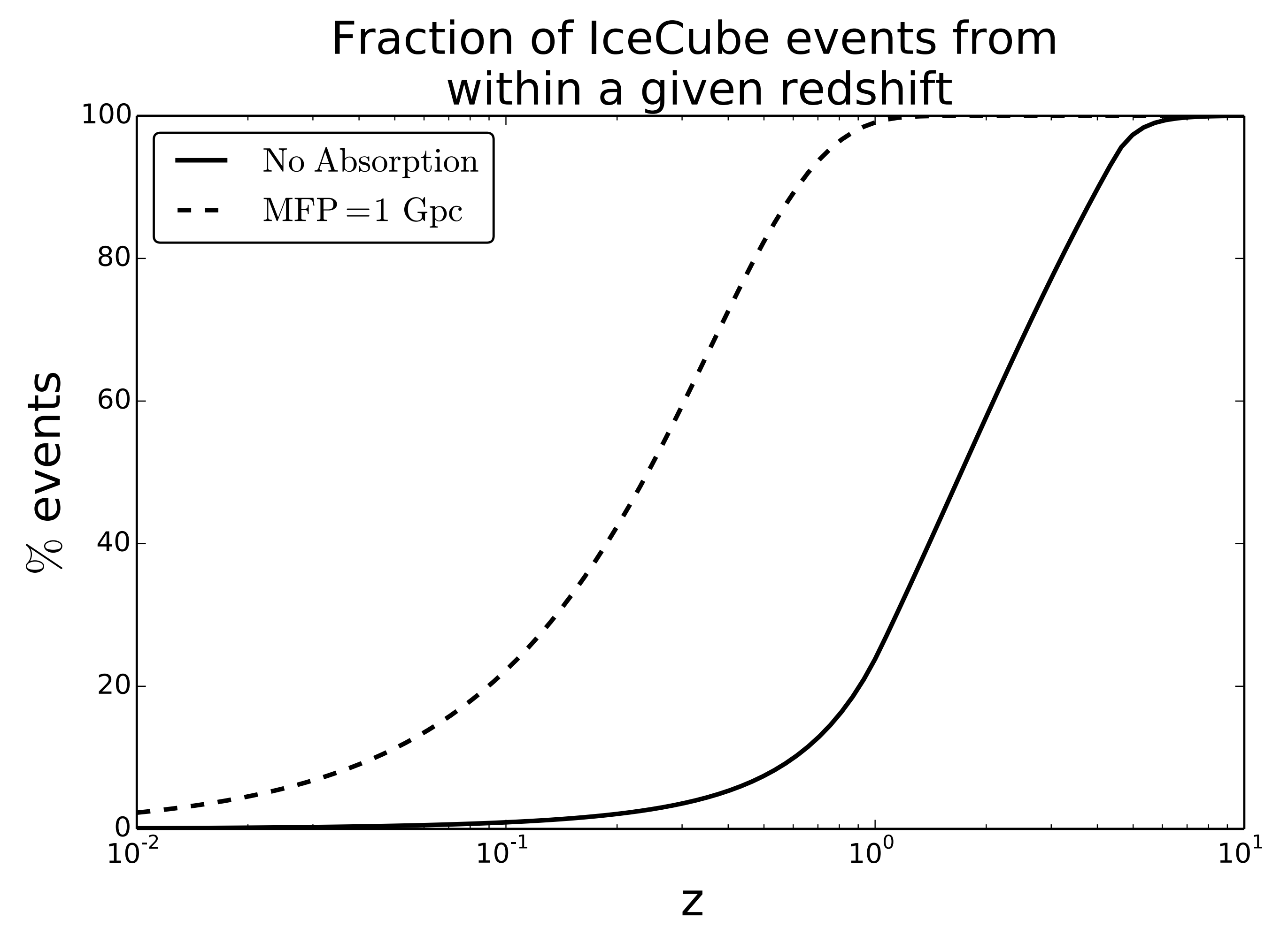
$$\sigma_{\phi\ resonance} \sim m_\phi^{-2} \sim 10^{-24}\,\mathrm{cm}^2$$

$$\sigma_{min} \sim \lambda_{mfp} \times n_{C\nu B} \sim (1\,\mathrm{Gpc}) \times (10^3\,\mathrm{cm}^{-3}) \sim 10^{-31}\,\mathrm{cm}^2$$

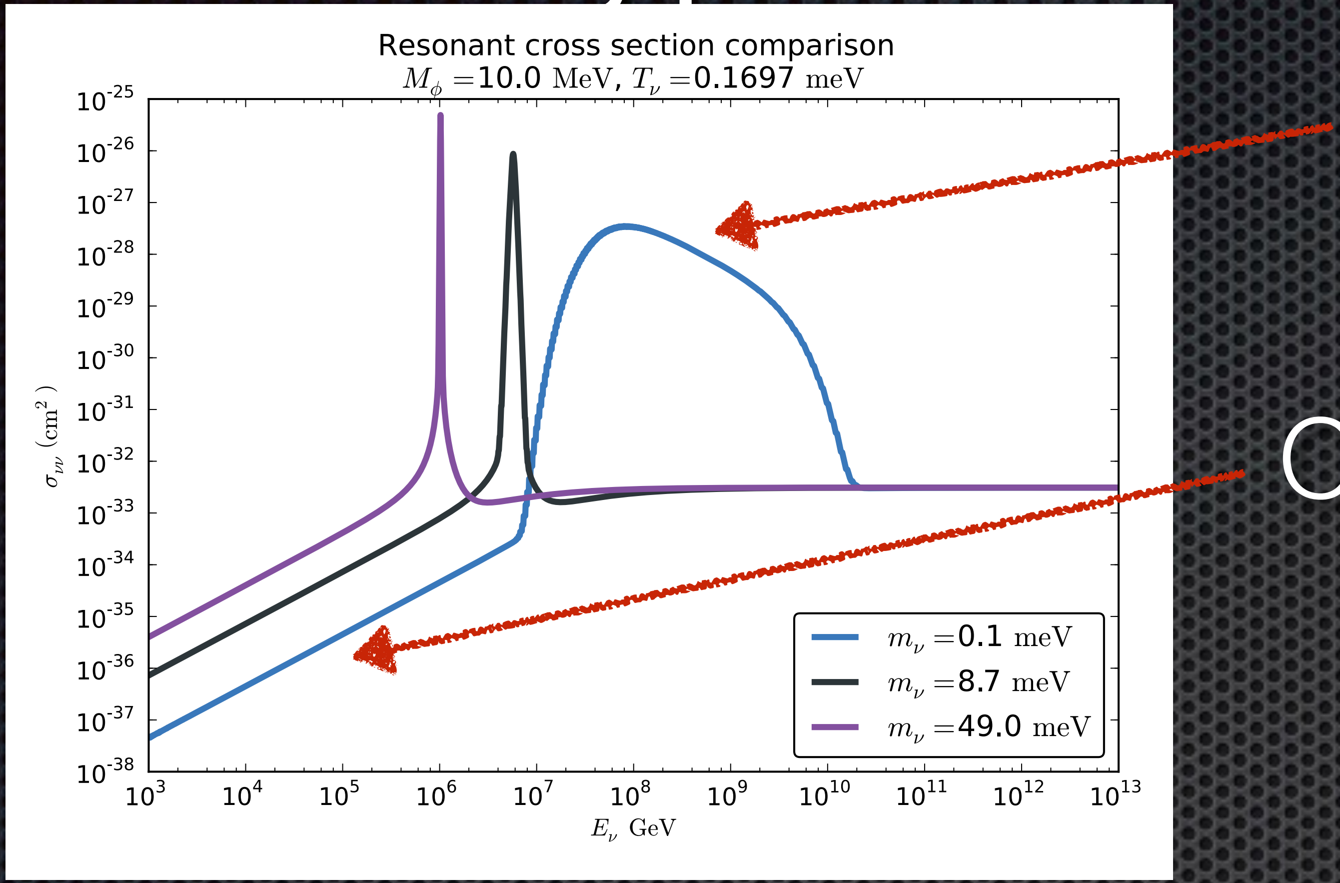
We can put our differences behind us. For Science.
You monster.

GZK-like horizon

- Continuum limit scattering will also produce apparent absorption of SM neutrinos.
- This could be detected through correlation of low redshift sources with IC events.

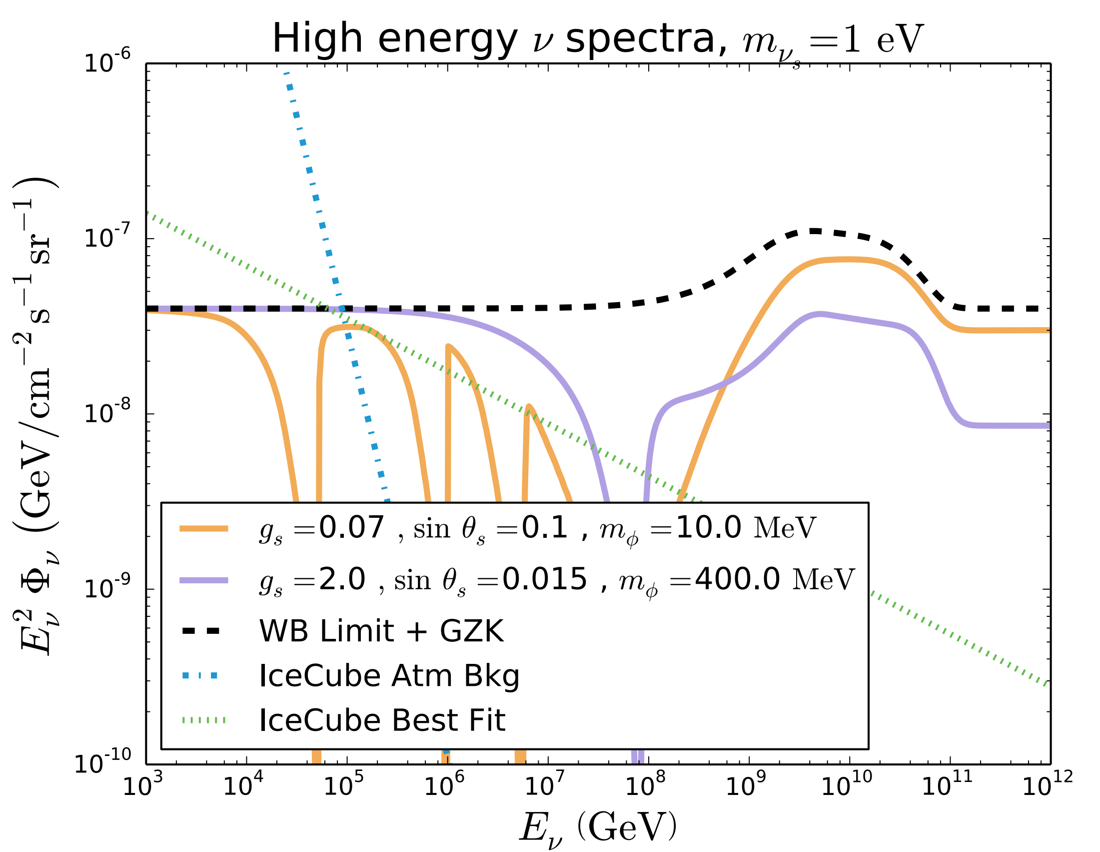


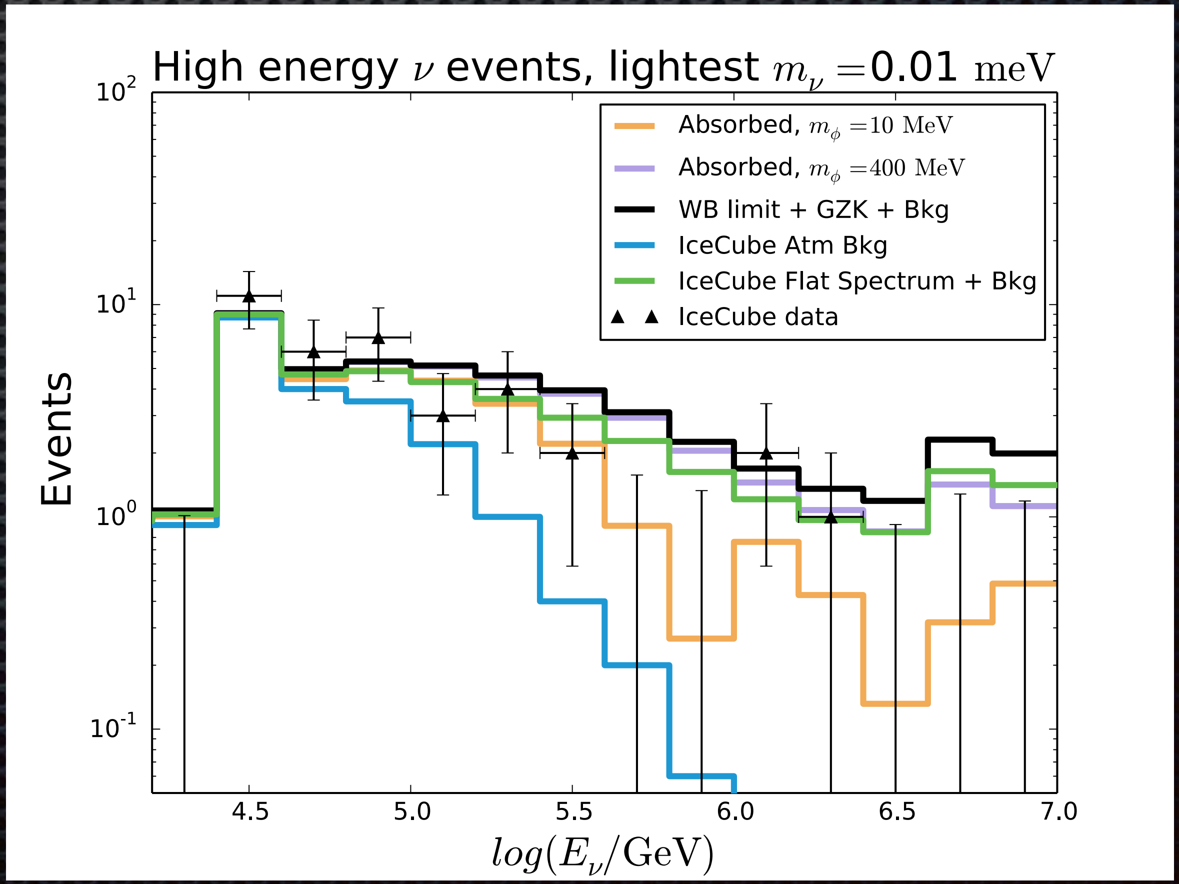
More types of absorption



Resonant absorption creates gaps

Contact interaction limit shifts the observed spectral index by -1





LSND/MiniBooNE sterile ν

- The Planck 2015 data places strong constraints the relic abundance of new neutrinos.

$$\left.\begin{array}{r} N_{\text{eff}} < 3.7 \\ m_{\nu,\text{sterile}}^{eff} < 0.52eV \end{array}\right\} \quad 95\% \, CI$$

- Hamann, J. and Hasenkamp, J. , JCAP **10**, 044 (2013) : These limits rule out plain vanilla sterile neutrino models which have large mixing angles and ~eV masses.

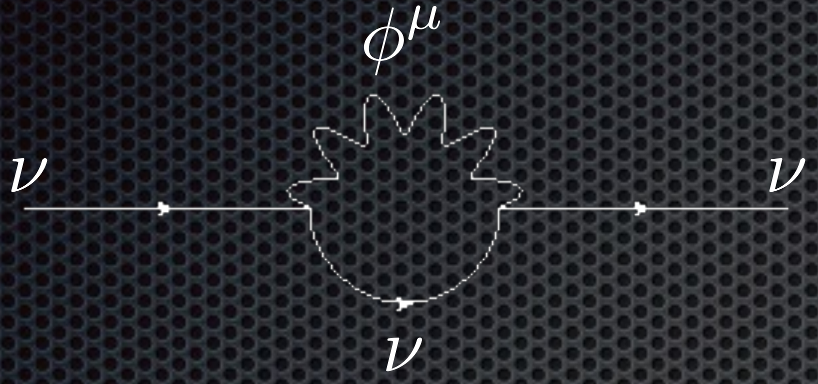
$$\Delta N_{\text{eff}} = 1$$

$$m_{\nu,\text{sterile}}^{eff} = \Delta N_{\text{eff}} \times m_{\nu,\text{sterile}} \sim 1\,\text{eV}$$

Sterile Interactions Suppress Mixing

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

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

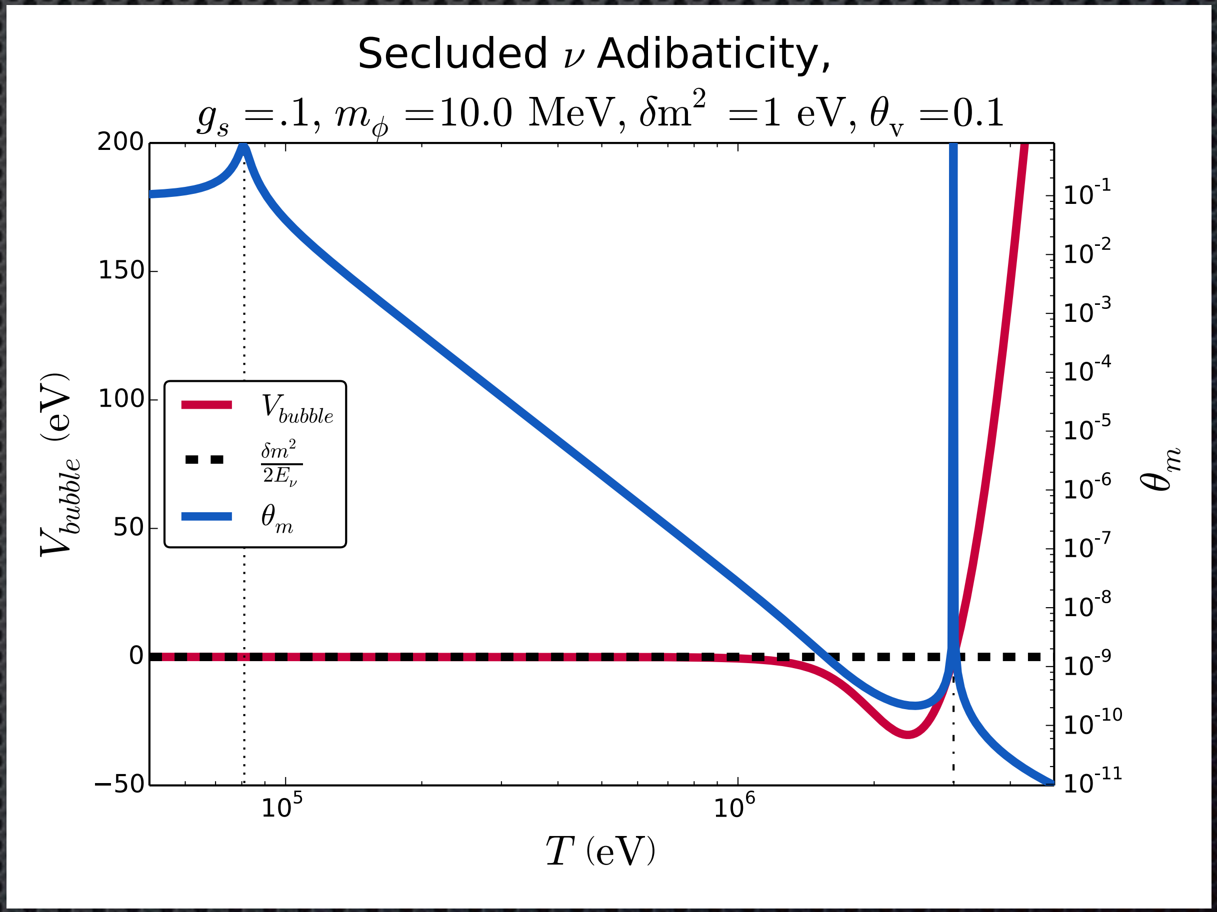


Full numerical treament:
C. Quimbay and S. Vargas-Castrillon, Nucl.Phys. B451, 265 (1995)

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

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

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



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

D. Notzold, G. Raffelt, Nucl. Phys. **B307**, 924 (1988);

H. A. Weldon, Phys. Rev. **D26**, 2789 (1982)

Neutrino Mixing

Effective mass term

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

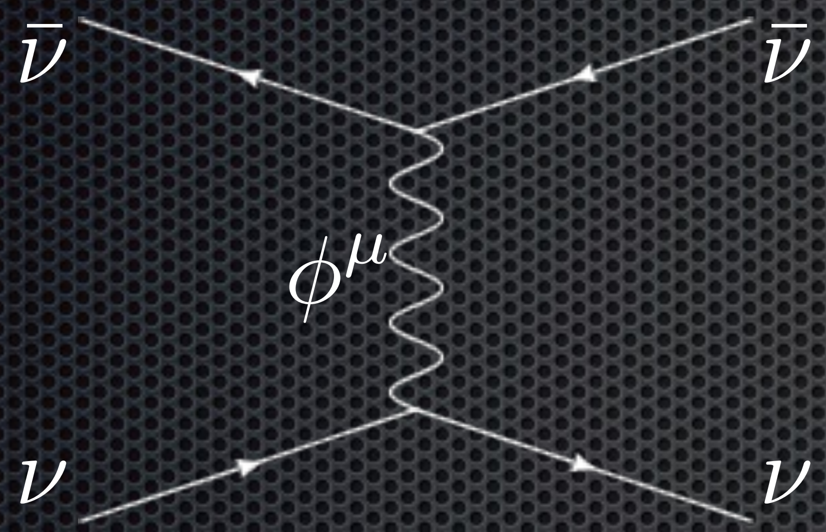
$$\sin 2\theta_{\rm eff} = \frac{\frac{\delta m^2_V}{2E_\nu}\sin 2\theta_V}{\sqrt{\left(\frac{\delta m^2_V}{2E_\nu}\cos 2\theta_V + A\right)^2 + \left(\frac{\delta m^2_V}{2E_\nu}\sin 2\theta_V\right)^2}}$$

Asymptotic
approximation

$$\sin\theta_{\rm eff} \approx \frac{\delta m^2}{4E_\nu|A|}\sin 2\theta_V$$

Size of the mixing angle is critical

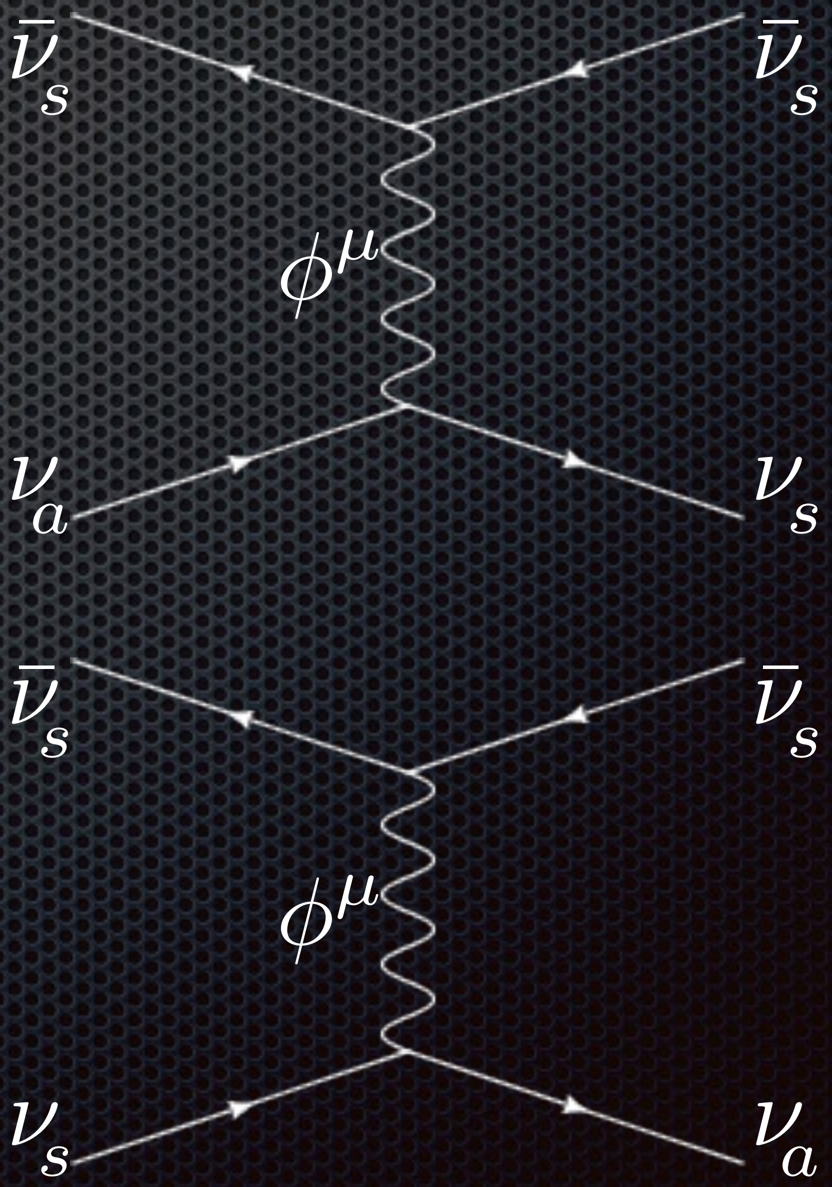
$\nu_a \leftrightarrow \nu_s$



$\sigma_{\nu\nu} \propto \theta^2_{\text{eff}}, \theta^4_{\text{eff}}, \theta^6_{\text{eff}}$

In the Early Universe $\Longrightarrow$

$\sigma_{\nu\nu} \propto \theta^2_{eff}$



Controversy!

- Dasgupta and Kopp, PRL **112**, 031803 (2014) -> Secret interactions suppress the active-sterile mixing angle in the early Universe
- Hannestad, Hansen, and Tram, PRL **112**, 031802 (2014) -> Mixing + collisions don’t violate N_eff bounds for heavy mediators.
- Mirizzi, Mangano, Pianti, and Saviano, Phys. Rev. D **91**, Jan. 2015 -> These models agree with Planck, but only marginally.
- Archidiacono, Hannestad, Hansen, and Tram, Phys. Rev. D **91**, March 2015 -> Everything works great for VERY low mass mediators.
- Chu, Dasgupta, Kopp, arXiv:1505.02795 -> There is more allowable parameter space than Mirizzi et al. found.

Even More Controversial

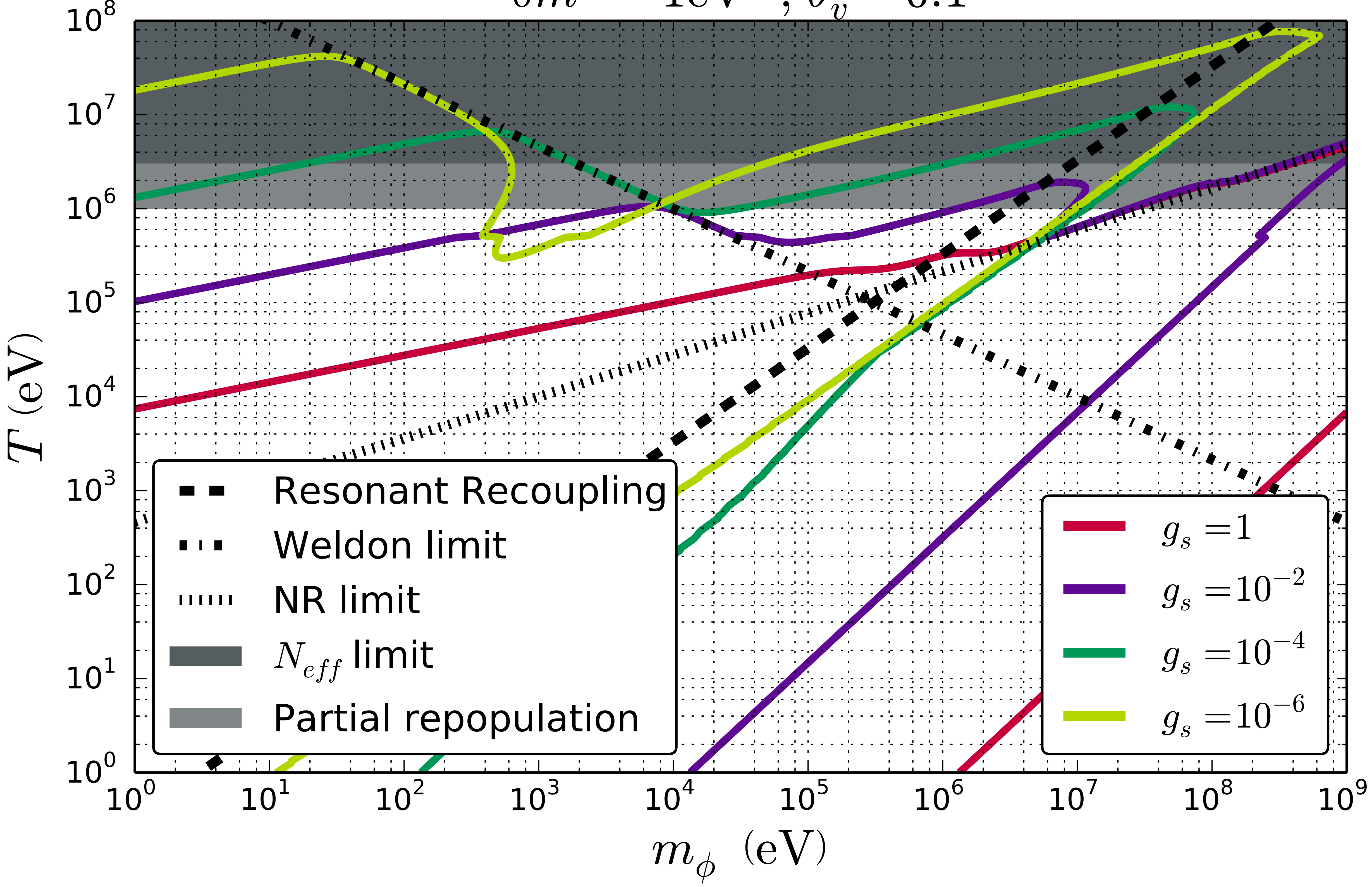
- We think they’ve all made some important physics errors.

Mixing Portal Recoupling

- We should compute the rate for scattering with the secluded interaction and compare it to the Hubble rate.

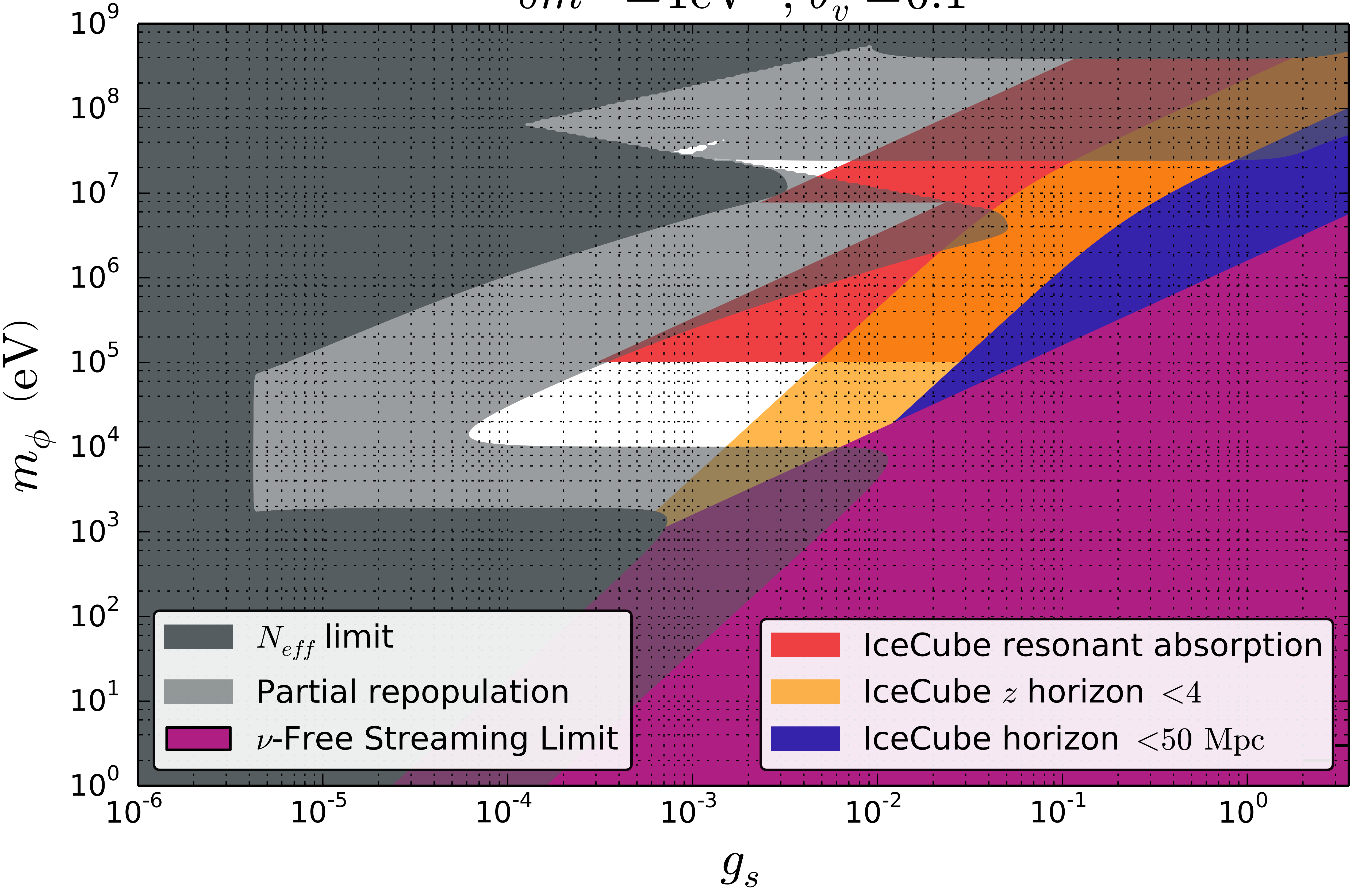
$$\Gamma_s = P_{as}\langle \sigma v \rangle n_s \qquad \Gamma_H = \frac{1.66\sqrt{g_*}T_\gamma^2}{m_{pl}}$$

Secluded ν recoupling temperature, $\delta m^2 = 1\mathrm{eV}^2$, $\theta_v = 0.1$



IceCube Observability Window,

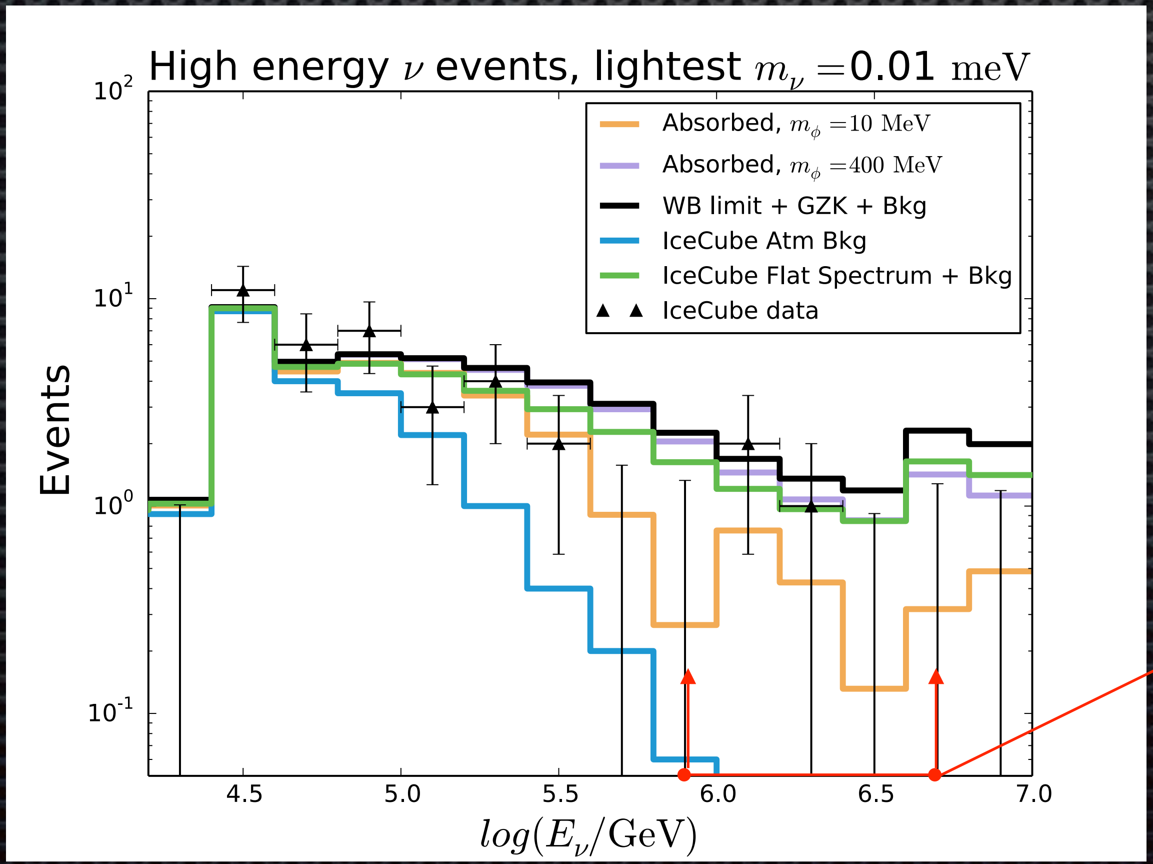
$\delta m^2 = 1\mathrm{eV}^2$, $\theta_v = 0.1$



Mass squared splitting

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

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



Δm_{atm}^2

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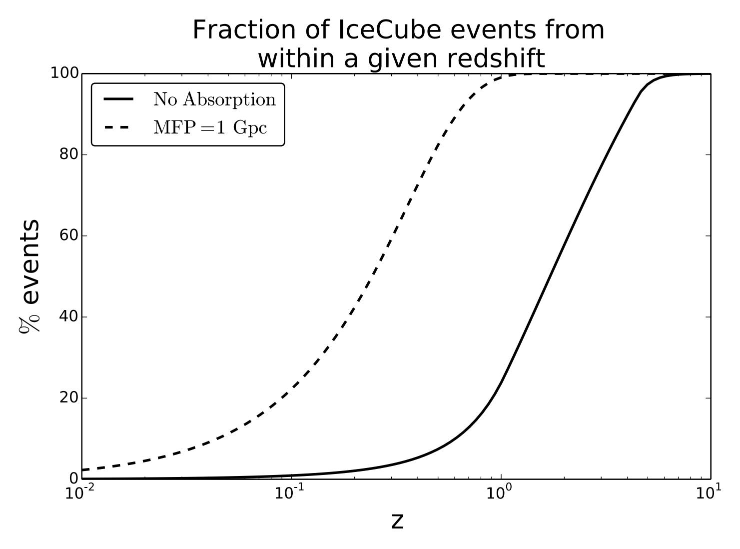
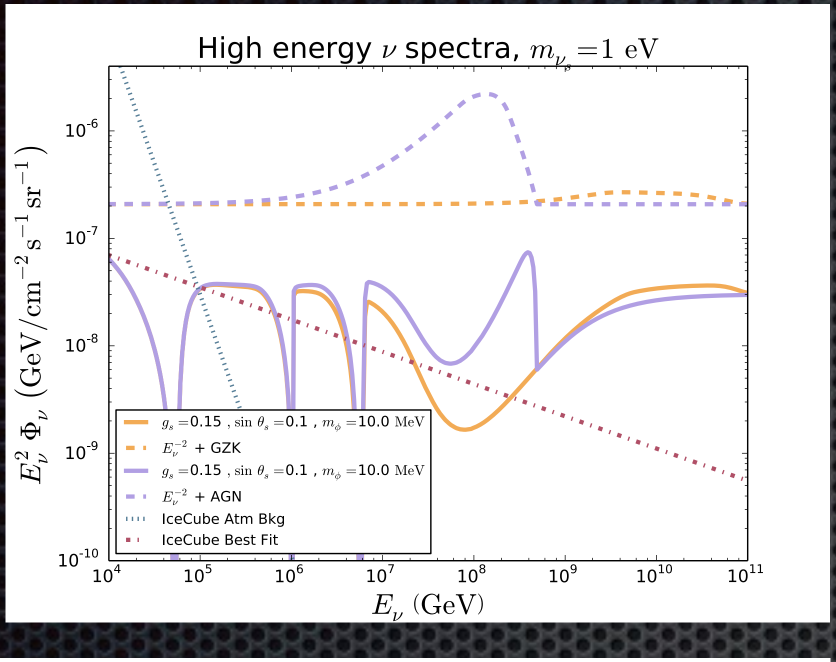
[1] http://icecube.wisc.edu
[2] In this paper neutrino means both neutrino and antineutrino.

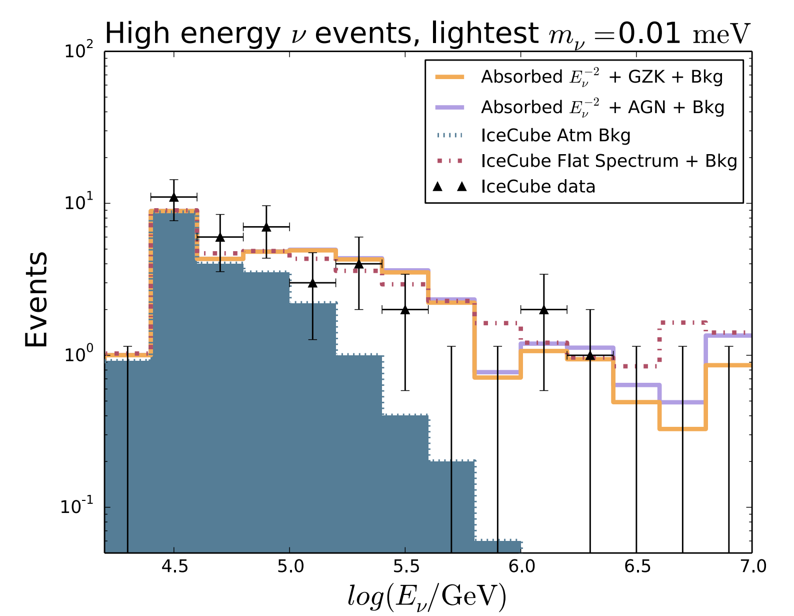
9 IceCube events found correlated with gamma ray point sources:
2 from galactic pulsar wind nebulae
7 from BL Lacs (AGN), 3 from sources less than z < 0.212



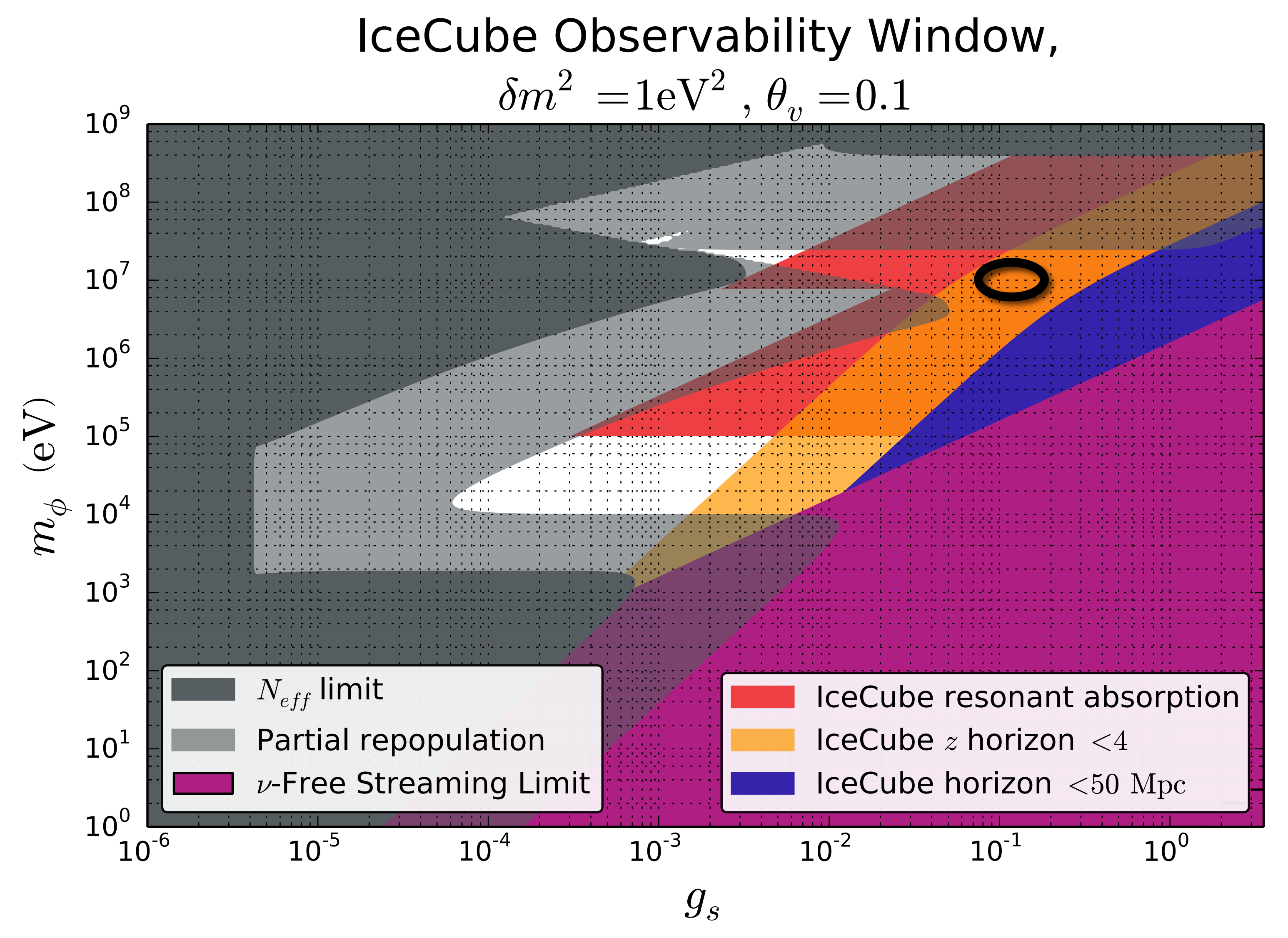
expect only 0.3 events!

The IceCube best fit combined with correlation data

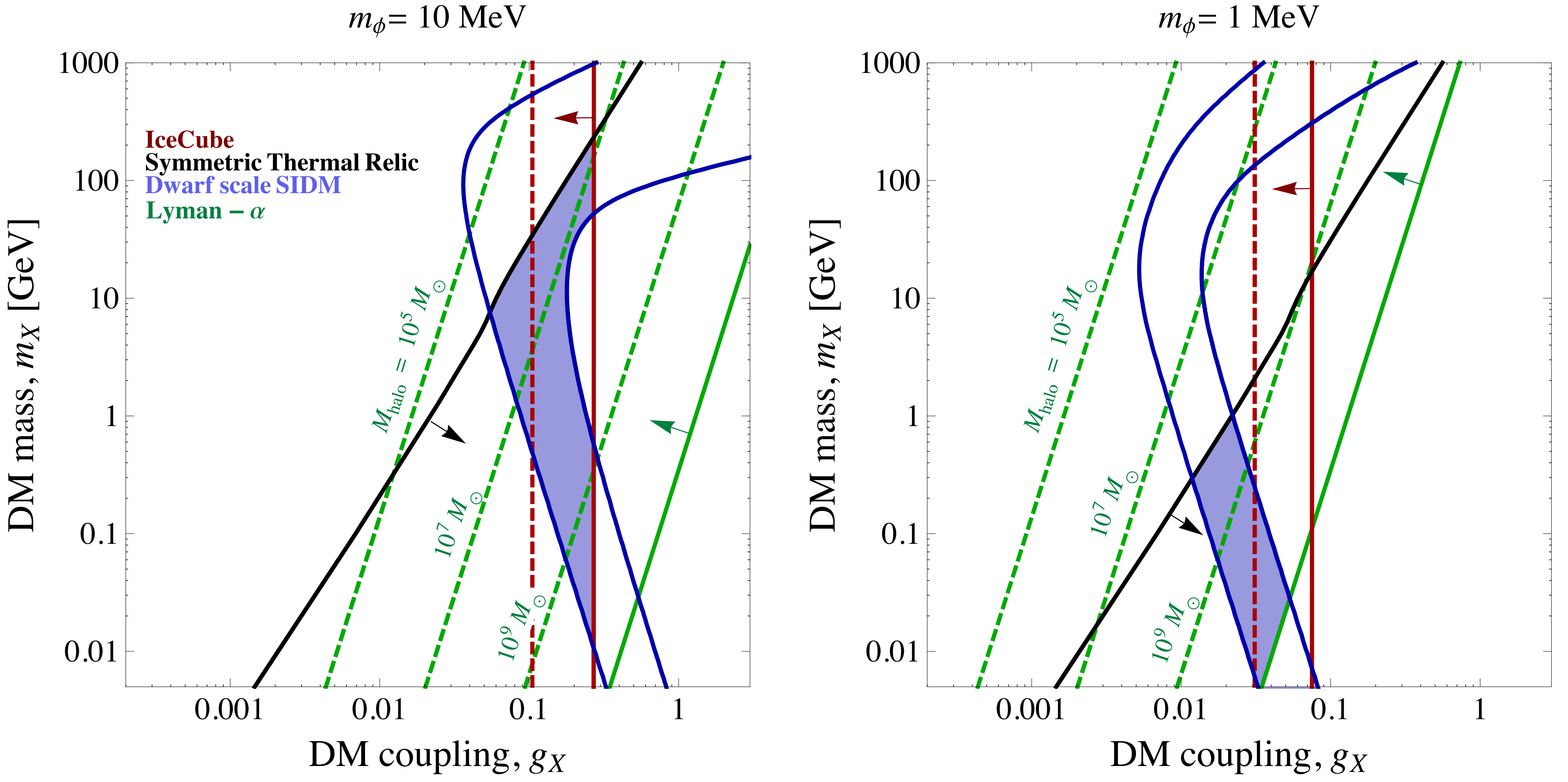




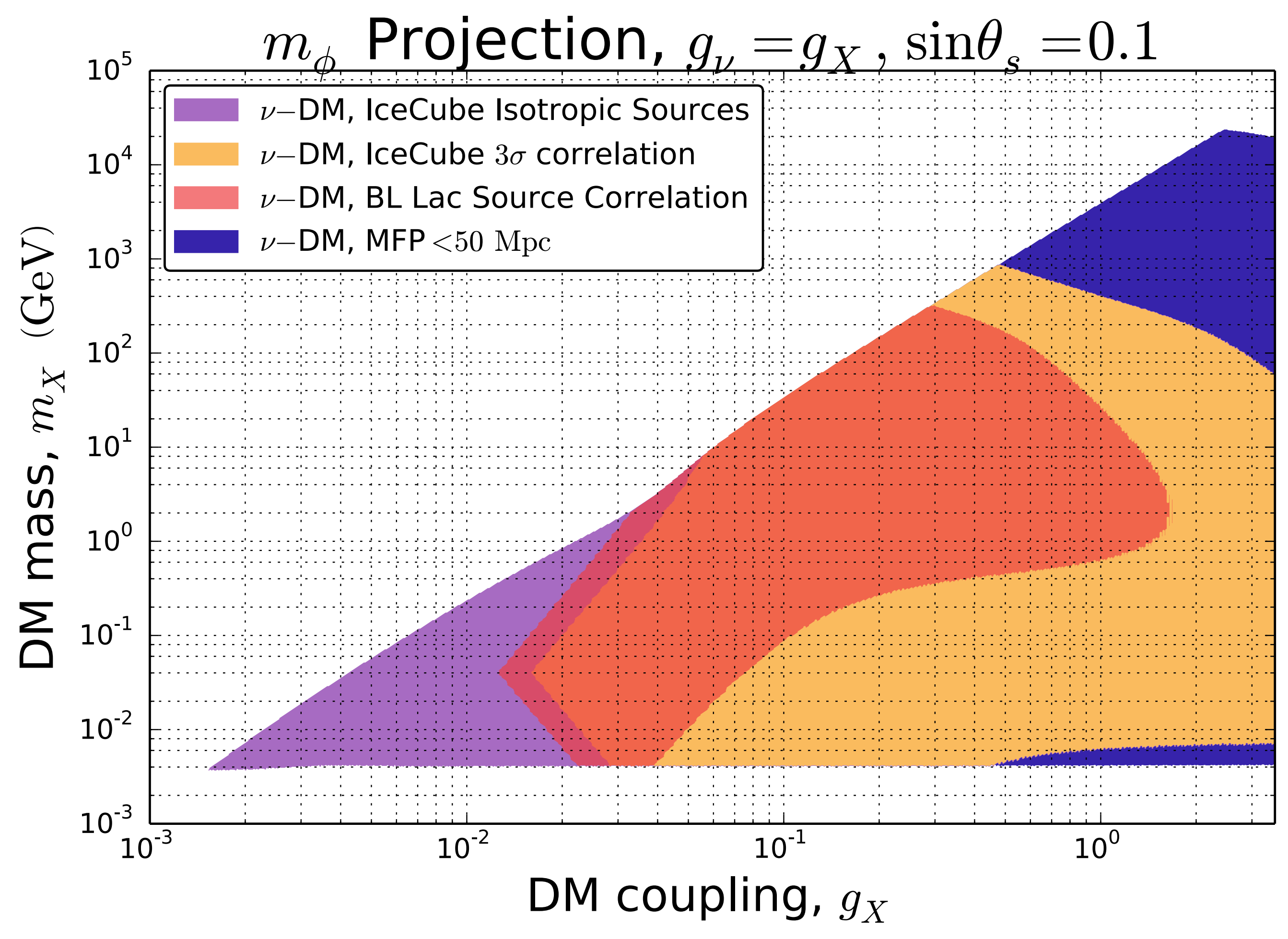
$\Longrightarrow$

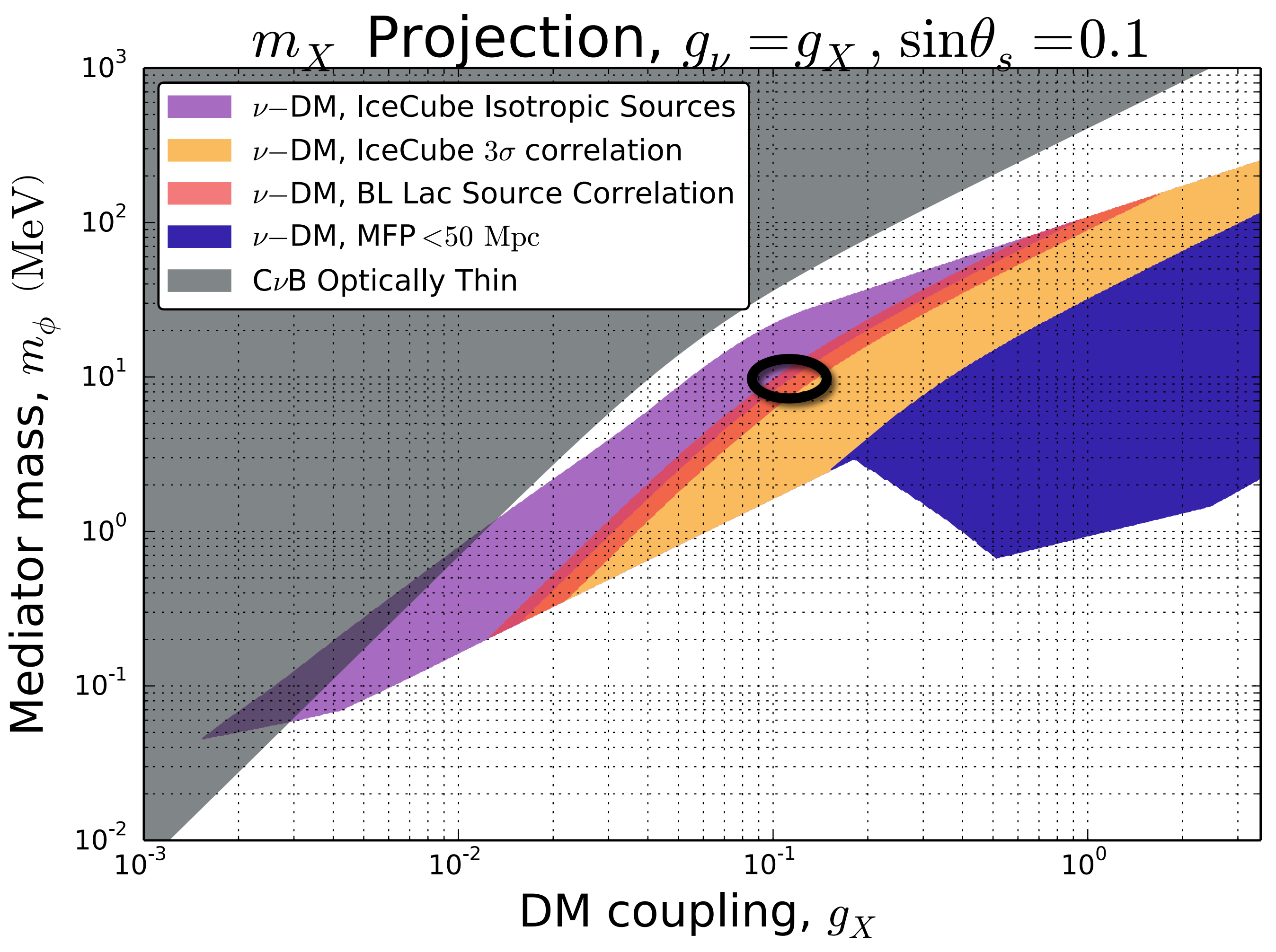


Now we can see how IceCube constraints and observations fit with SIDM



Projecting over all m_ϕ





Nearby source correlation is significant at the 3σ level

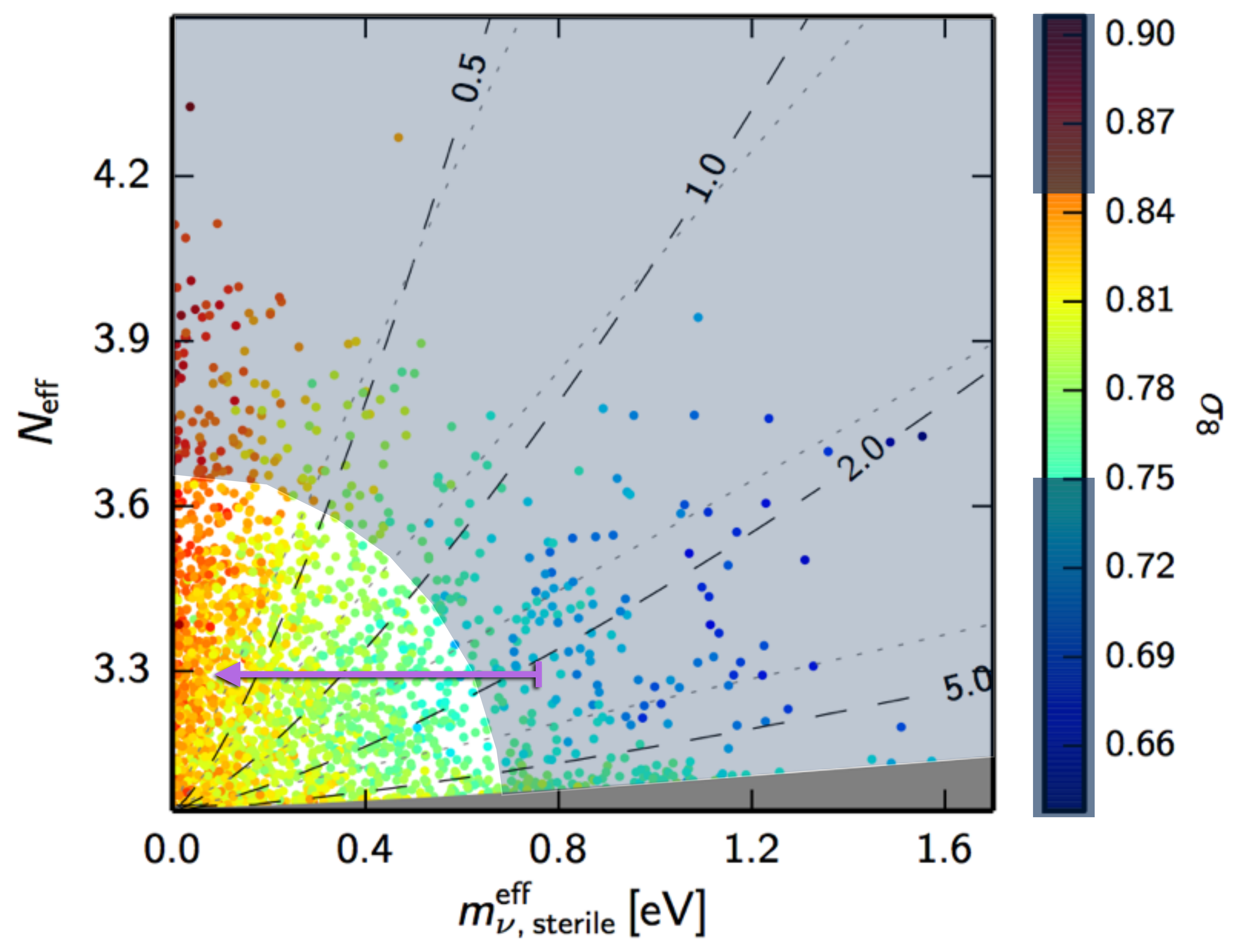
Nearby (z<.212) event correlation is consistent with the original predictions for AGN!

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

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

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

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



Planck Collaboration, arXiv:1502.01589v2

Conclusions:

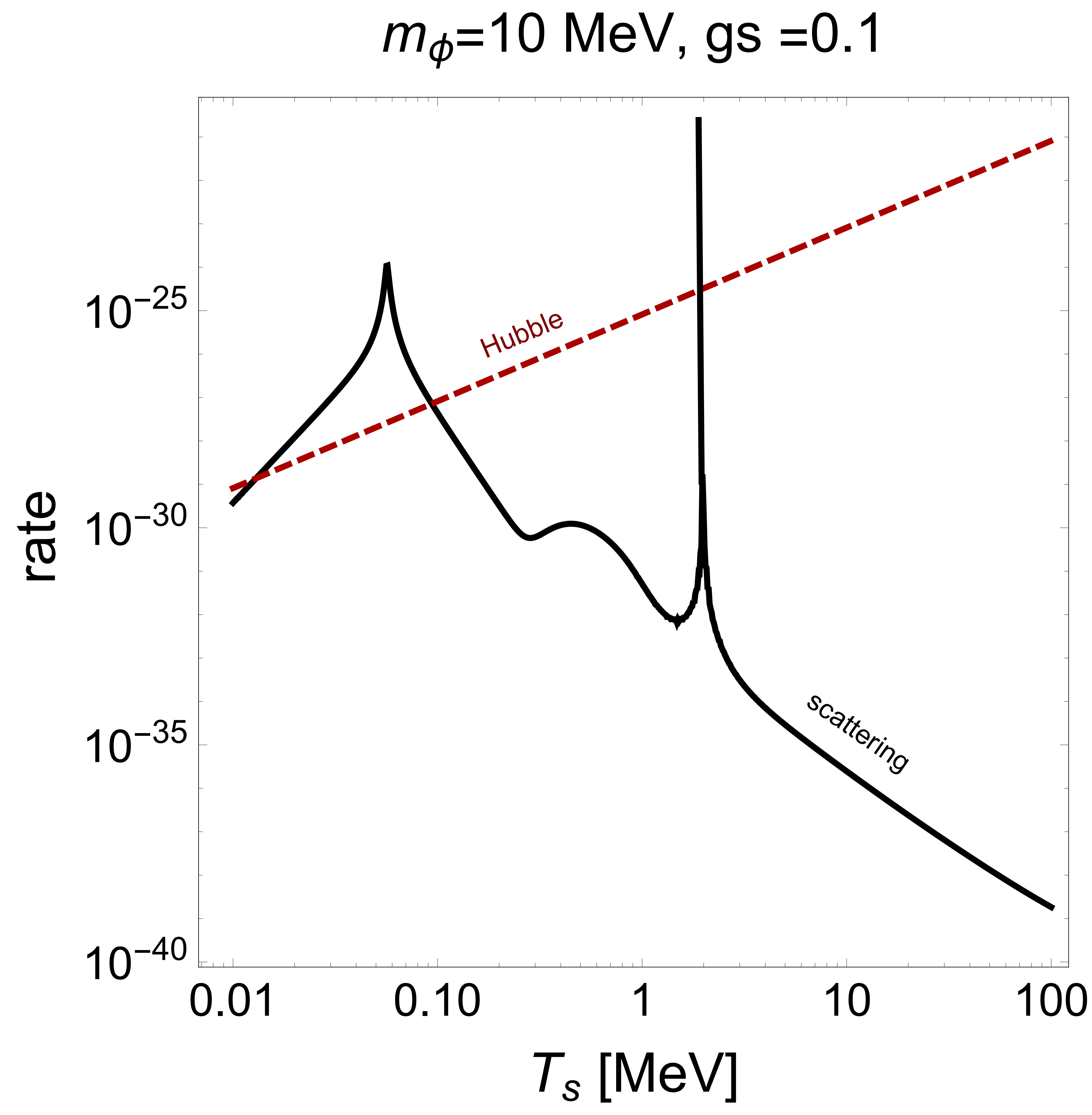
- Hidden neutrino interactions provide a novel model of the high energy neutrino signal in IceCube.
- If these hidden interactions are a byproduct of a neutrino portal to the dark sector, an astonishing chain of coincidental solutions to dark matter structure problems issue forth.
- The secluded interaction also reconciles LSND or reactor sterile neutrino anomalies with Precision Cosmology data.
- IceCube is taking data right now, and will eventually make a definitive statement on this model!

Thank you very much!

More Evidence!

Right Handed Helicity Fracture!

Sterile Neutrino: CONFIRMED


m_ϕ=10 MeV, gs =0.1
rate
10^{-25}
10^{-30}
10^{-35}
10^{-40}
0.01
0.10
1
10
100
T_s [MeV]
Hubble
scattering

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: $H\left(z\right)^2 = H_0^2\left[\Omega_\Lambda + \Omega_m\left(1+z\right)^3 + \Omega_{rad}\left(1+z\right)^4\right]$
- Use FRW scaling of relevant quantities:

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

$$T_\nu\left(z\right) = T_{\nu,0}\left(1+z\right) \qquad dr_p\left(z\right) = \frac{c\,dz}{\left(1+z\right)H\left(z\right)}$$

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

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:

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

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

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

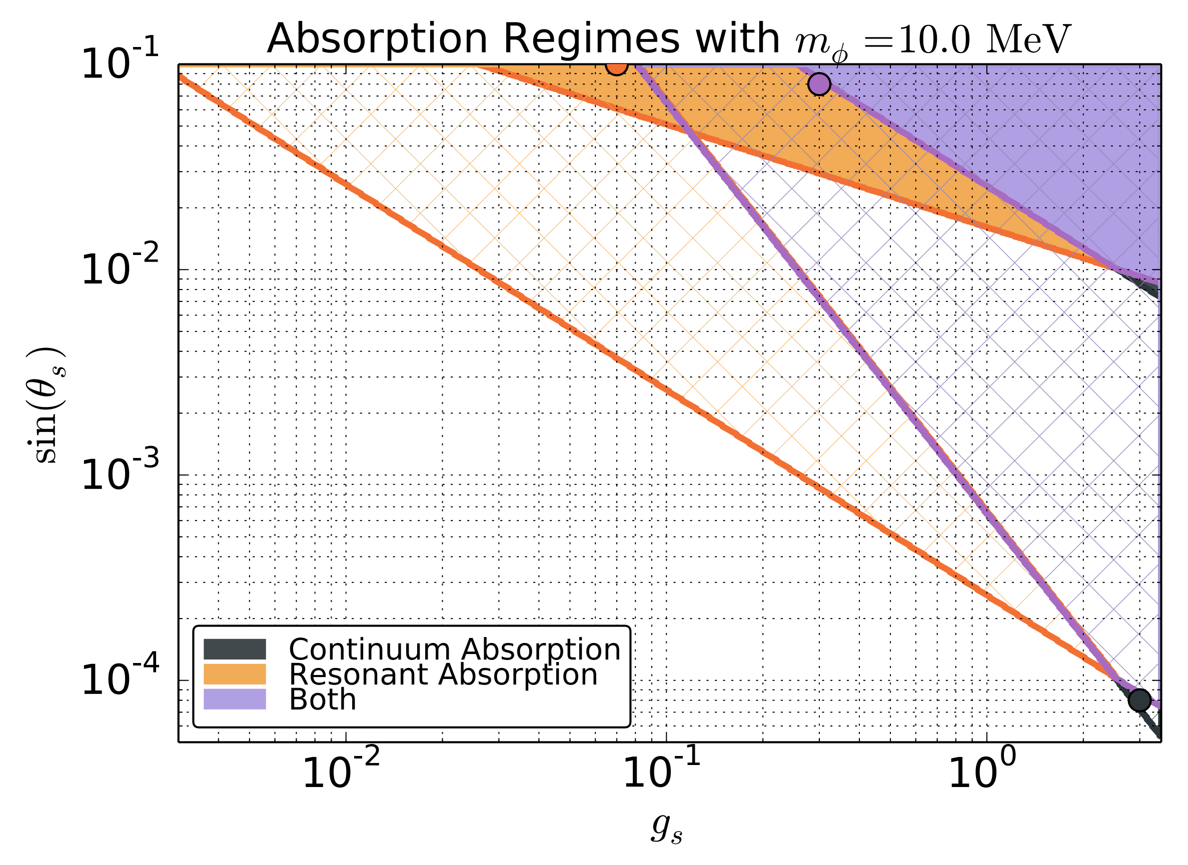
Optical Depth

$$\tau\left(z\right) = \left\langle \sigma_{\nu\nu} \right\rangle \left(z\right) n_\nu^{\mathrm{eff}}\left(z\right) dr_p\left(z\right)$$

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

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

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



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:

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

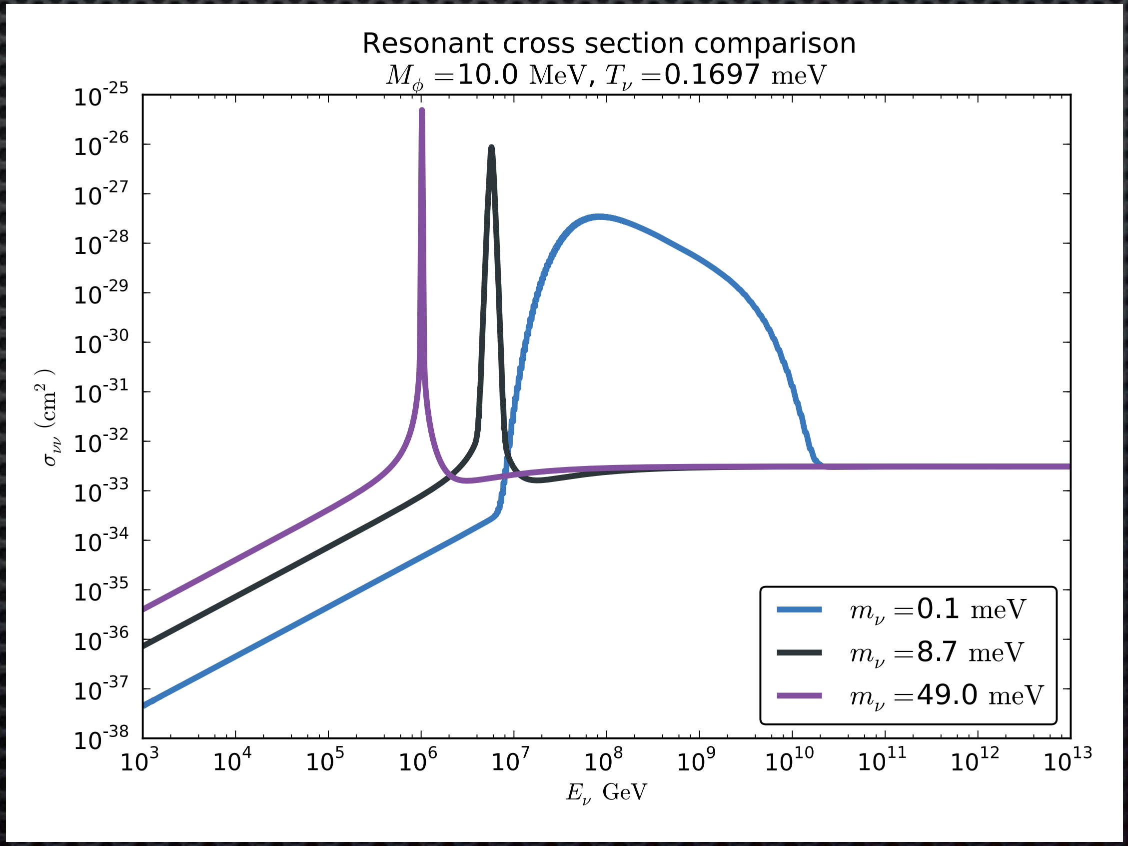
- So our cross sections must be convolved with the thermal motion of the $C\nu B$:

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

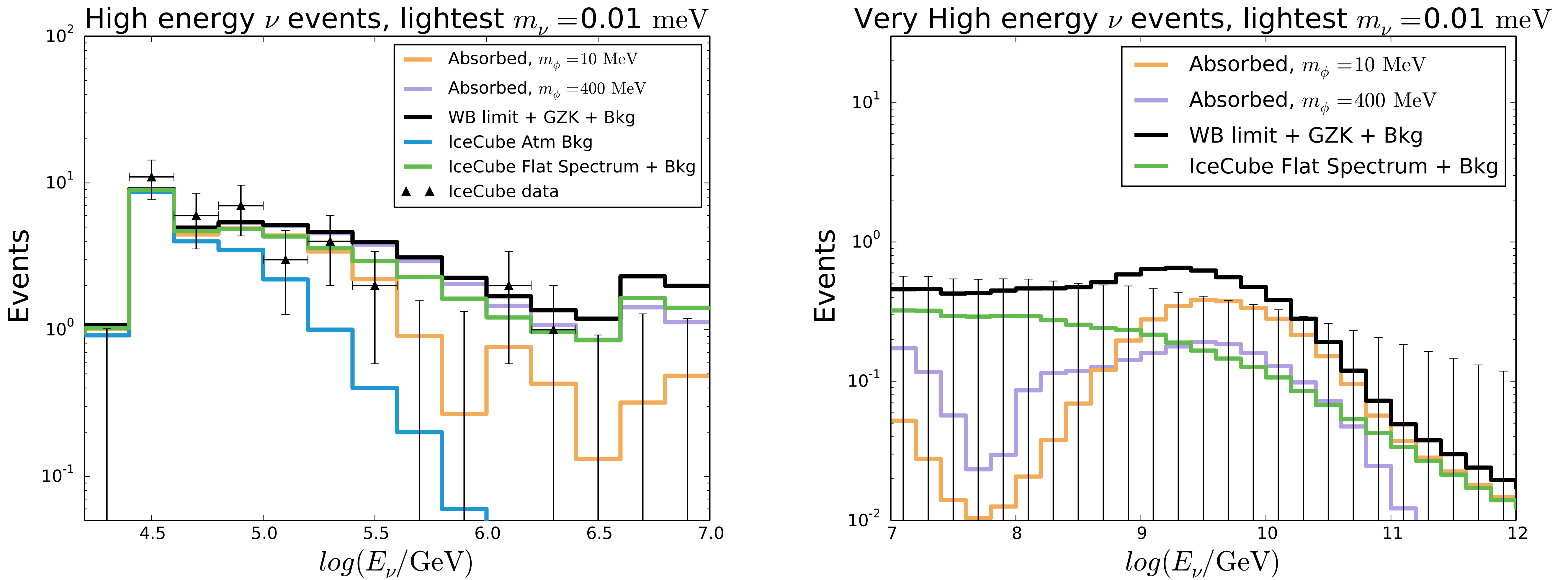
Thermal Broadening

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

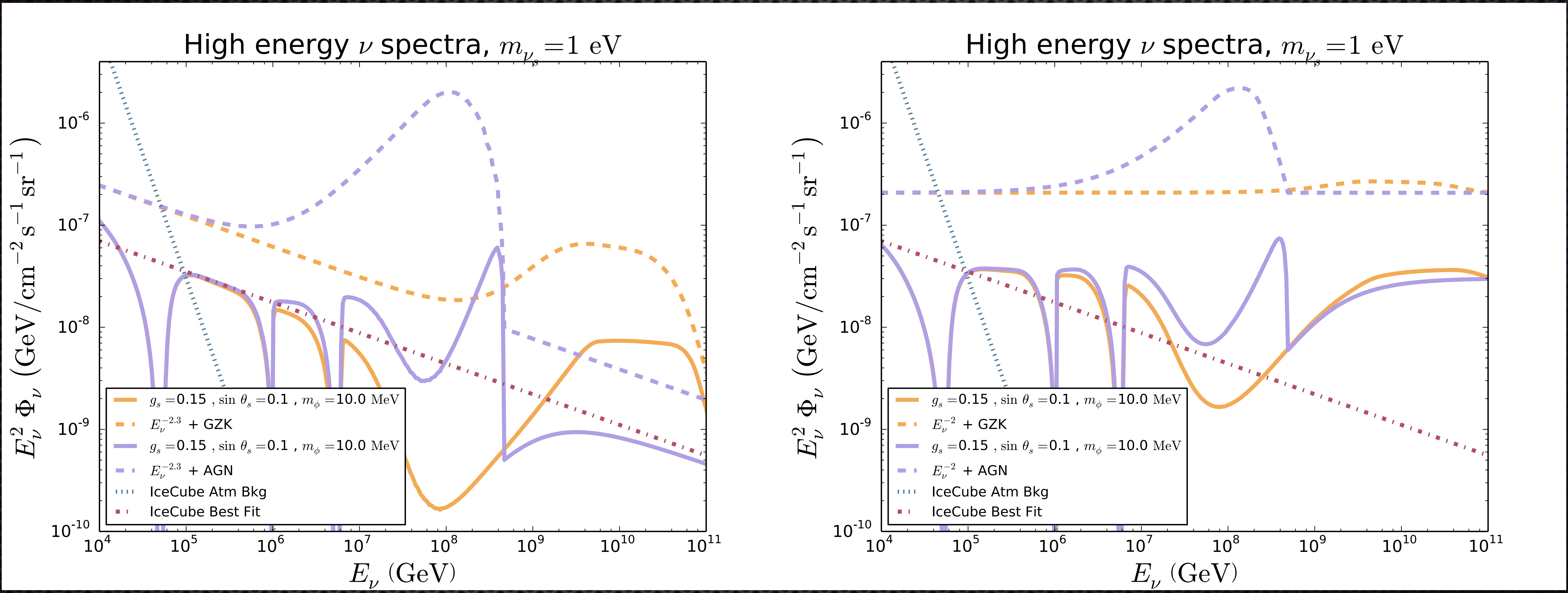
$$\sigma\left(\bar{\nu}\nu \to \bar{\nu}\nu\right) \propto \int_{-1}^{1} \frac{g_\nu^4}{16\pi s} \left[\frac{t^2 + u^2}{\left(s - m_\phi^2\right)^2 + \left(m_\phi \Gamma_\phi\right)^2}\right] d\cos\theta + \ldots$$

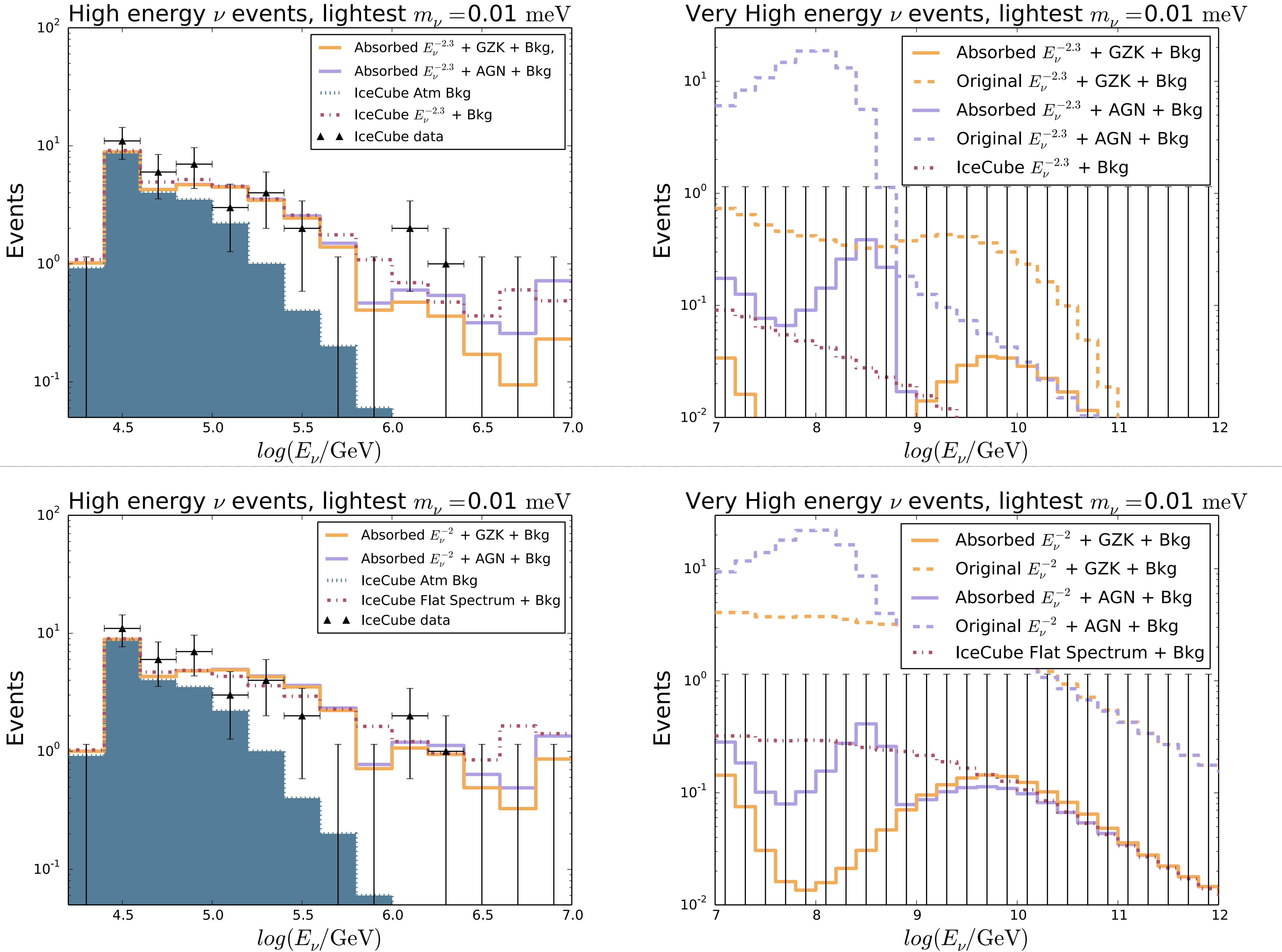


How does this fit with the observed IceCube data?



Some results, fitting the overabundance of low z sources:




High energy ν events, lightest $m_\nu = 0.01$ meV
Absorbed $E_\nu^{-2.3}$ + GZK + Bkg,
Absorbed $E_\nu^{-2.3}$ + AGN + Bkg
IceCube Atm Bkg
IceCube $E_\nu^{-2.3}$ + Bkg
IceCube data
Events
10^{2}
10^{1}
10^{0}
10^{-1}
4.5
5.0
5.5
6.0
6.5
7.0
$log(E_\nu/\mathrm{GeV})$
Very High energy ν events, lightest $m_\nu = 0.01$ meV
Absorbed $E_\nu^{-2.3}$ + GZK + Bkg
Original $E_\nu^{-2.3}$ + GZK + Bkg
Absorbed $E_\nu^{-2.3}$ + AGN + Bkg
Original $E_\nu^{-2.3}$ + AGN + Bkg
IceCube $E_\nu^{-2.3}$ + Bkg
Events
10^{1}
10^{0}
10^{-1}
10^{-2}
7
8
9
10
11
12
$log(E_\nu/\mathrm{GeV})$
High energy ν events, lightest $m_\nu = 0.01$ meV
Absorbed E_ν^{-2} + GZK + Bkg
Absorbed E_ν^{-2} + AGN + Bkg
IceCube Atm Bkg
IceCube Flat Spectrum + Bkg
IceCube data
Events
10^{2}
10^{1}
10^{0}
10^{-1}
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Original E_ν^{-2} + GZK + Bkg
Absorbed E_ν^{-2} + AGN + Bkg
Original E_ν^{-2} + AGN + Bkg
IceCube Flat Spectrum + Bkg
Events
10^{1}
10^{0}
10^{-1}
10^{-2}
7
8
9
10
11
12
$log(E_\nu/\mathrm{GeV})$

The canonical AGN neutrino flux prediction from 1997 - 2009:

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NEUTRINO FLUXES FROM ACTIVE GALAXIES: A MODEL-INDEPENDENT ESTIMATE

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ABSTRACT

There are tantalizing hints that jets, powered by supermassive black holes at the center of active galaxies, are true cosmic proton accelerators. They produce photons of TeV energy, possibly higher, and may be the enigmatic source of the highest energy cosmic rays. Photoproduction of neutral pions by accelerated protons on UV light may be the source of the highest energy photons in which most of the bolometric luminosity of some galaxies is emitted. The case that proton beams power active galaxies is, however, far from conclusive. Neutrinos from the decay of charged pions represent an incontrovertible signature for the proton-induced cascades. We show that their flux can be estimated by model-independent methods, based on dimensional analysis and textbook particle physics. Our calculations also demonstrate why different models for the proton blazar yield very similar results for the neutrino flux that are consistent with the ones obtained here. As regards astrophysics, they illustrate that proton beams are required to generate TeV photons without fine-tuning.

Subject headings: acceleration of particles — galaxies: active — galaxies: jets — radiation mechanisms: thermal

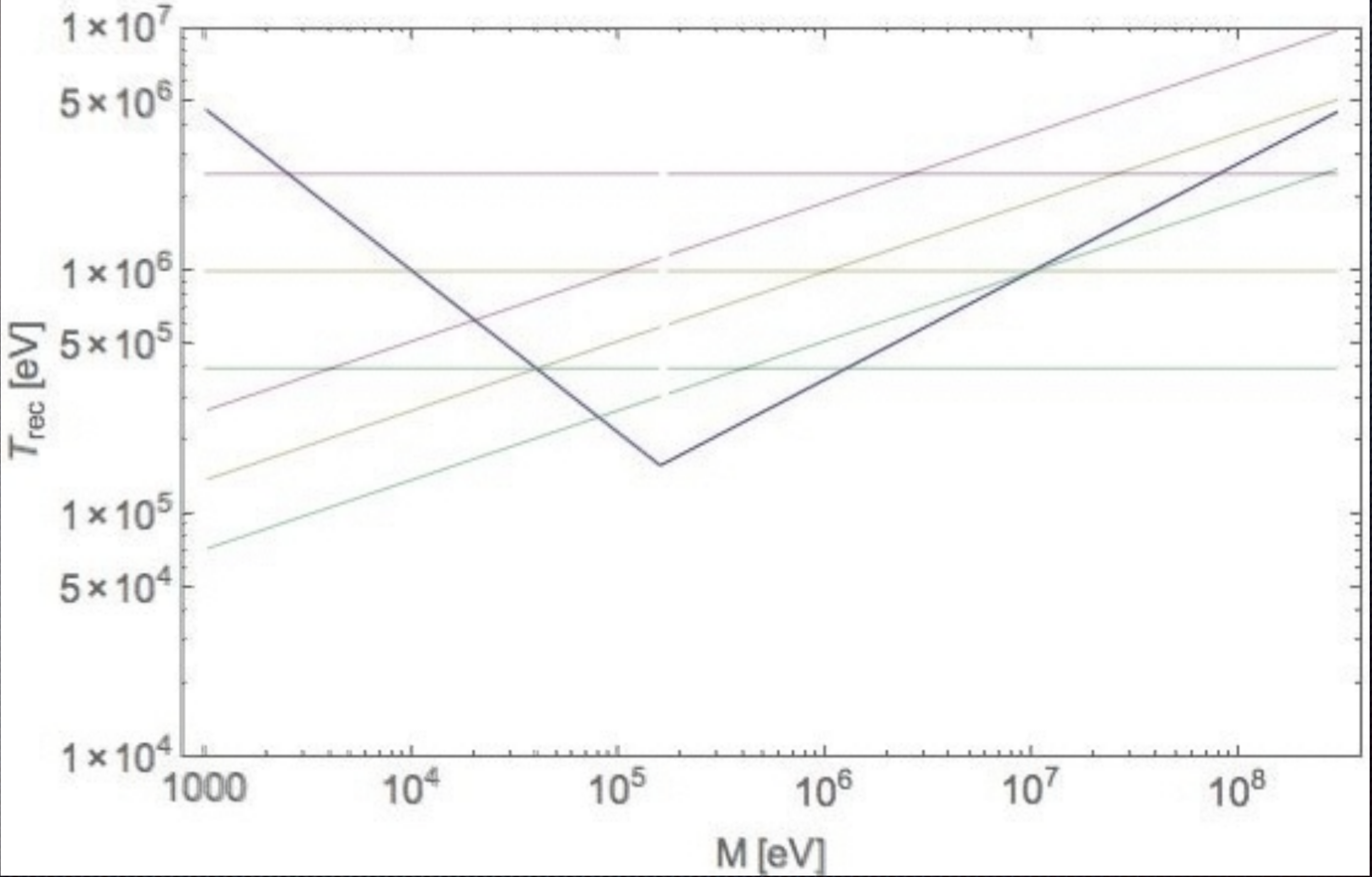
1. INTRODUCTION

In recent years, cosmic-ray experiments have revealed the existence of cosmic particles with energies in excess of 10^{20} eV. Incredibly, we have no clue as to where they come from and how they have been accelerated to this energy (Auger 1997). The highest energy cosmic rays are almost certainly of extragalactic origin. Searching the sky beyond our Galaxy, the nuclei of active galaxies (AGNs) stand out as the most likely sites of magnetic fields that are sufficiently strong and expansive for the acceleration of particles to joules of energy. The idea is rather compelling, because AGNs are also the source of the highest energy photons, detected with air Cerenkov telescopes (Punch et al. 1992; Quinn et al. 1995; Schubnell et al. 1997).

AGNs are the brightest sources in the universe. Their engines must be not only powerful but also extremely compact, because their high-energy luminosities are observed to flare by over an order of magnitude over time periods as short as 1 day (Jang & Miller 1995). Only sites in the vicinity of black holes, a billion times more massive than our Sun, can possibly satisfy the constraints of the problem. Highly relativistic and confined jets of particles are a common feature of these objects. It is anticipated that beams, accelerated near a black hole, are dumped on the radiation in the galaxy, which consists mostly of thermal photons with densities of order 10^{14} cm^{-3}. The multiwavelength spectrum from radio waves to TeV γ-rays is produced in the interactions of the accelerated particles with the magnetic fields and the ambient light in the galaxy. In the more conventional electron models, the highest energy photons are produced by Compton scattering of accelerated electrons on thermal UV photons, which are scattered from 10 eV up to TeV energy (Sikora, Begelman, & Rees 1994 and references therein). The energetic γ-rays will subsequently lose energy by electron pair production in photon-photon interactions with the radiation field of the jet or the galactic disk. An electromagnetic cascade is thus initiated, which, via pair production on the magnetic field and photon-photon interactions, determines the emerging γ-ray spectrum at lower energies. The lower energy photons, observed by conventional astronomical techniques, are, as a result of the cascade process, several generations removed from the primary high-energy beams.

The EGRET instrument on the *Compton Gamma Ray Observatory* has detected high-energy γ-ray emission in the range 20 MeV–30 GeV from over 100 sources (Thompson et al. 1995a, 1995b). Of these sources, 16 have been tentatively and 42 solidly identified with radio counterparts. All belong to the "blazar" subclass, mostly being flat spectrum radio quasars, while the rest are BL Lacertae objects (Mattox et al. 1997). In a unified scheme of AGNs, they correspond to radio-loud AGNs, viewed from a position illuminated by the cone of a relativistic jet (Padovani & Urry 1995). Moreover, of the five TeV γ-ray emitters identified by the air Cerenkov technique, three are extragalactic and are also nearby BL Lacertae objects (Punch et al. 1992; Quinn et al. 1995; Schubnell et al. 1997). The data therefore strongly suggest that the highest energy photons originate in jets that are beamed to the observer. Several of the sources observed by EGRET have shown strong variability, a factor of ~2 over a timescale of several days (Jang & Miller 1995). Time variability is more spectacular at higher energies. On 1996 May 7, the Whipple telescope observed an increase of the TeV emission from the blazar Markarian 421 by a factor 2 in 1 hr, which reached, eventually, a value 50 times larger than the steady flux. At this point, the telescope registered 6 times more photons from the Markarian blazar, which is more distant by a factor of 10^5, than from the Crab supernova remnant (Macomb et al. 1995).

Does pion photoproduction by accelerated protons play a central role in blazar jets? This question has been extensively debated in recent years (Stecker & Salamon 1996). If



1×10^7
5×10^6
1×10^6
5×10^5
1×10^5
5×10^4
1×10^4
T_rec [eV]
1000
10^4
10^5
10^6
10^7
10^8
M [eV]