Neutrino Portal Dark Matter: From Dwarf Galaxies to IceCube

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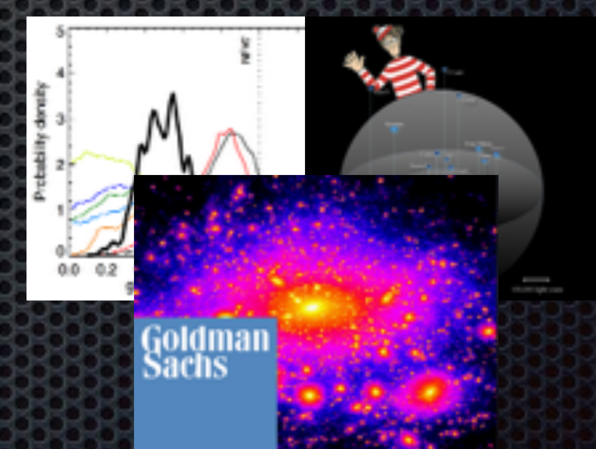
arXiv:1411.1071

IceCube Particle Astrophysics Symposium, UW Madison, May 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. Planck Collaboration, arXiv:1502.01589v2

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

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

Mixing Portal Prescription

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

Basic seesaw type operator

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

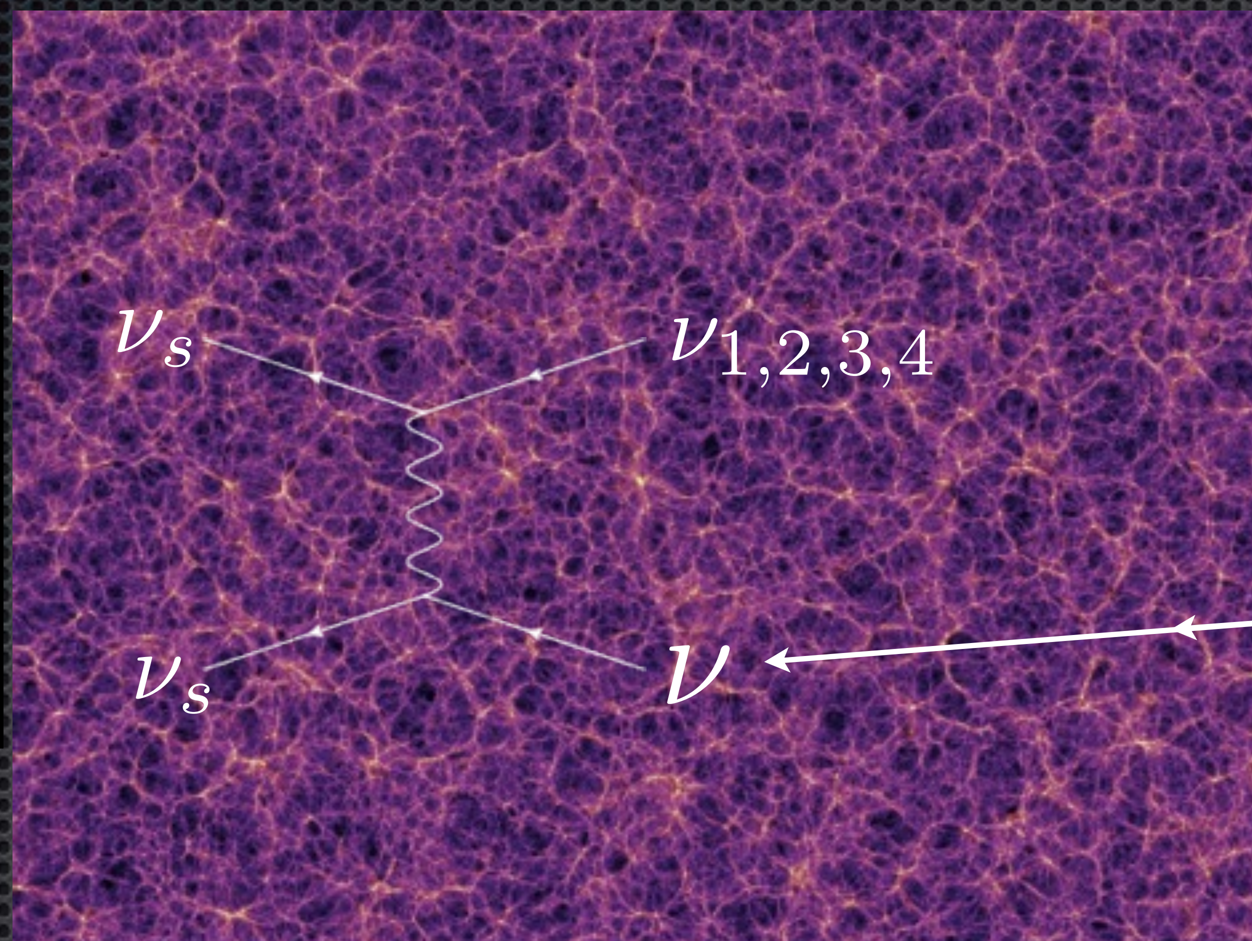
$\nu_s,\ \theta_s \qquad \langle \nu_s | \nu_{e,\mu,\tau} \rangle \equiv 0$

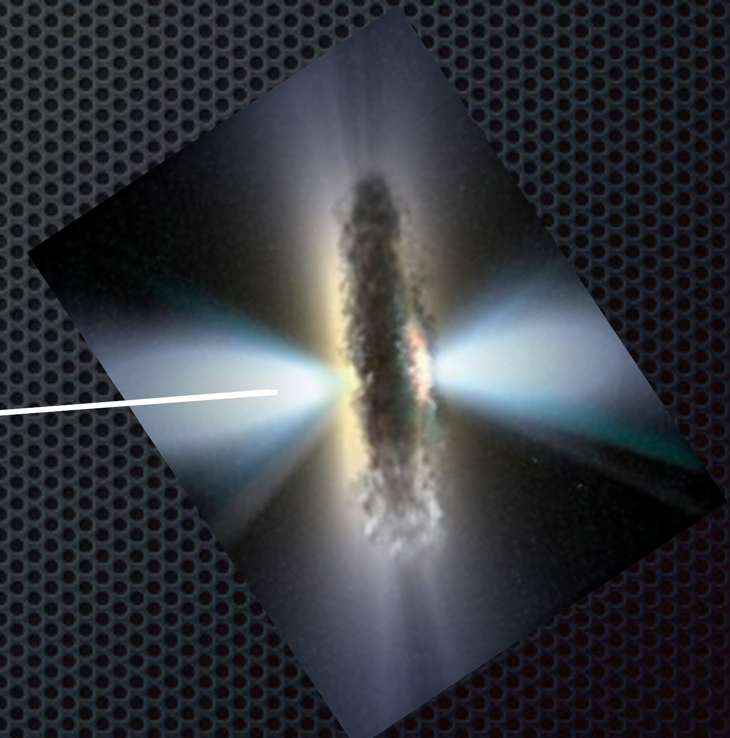
$\phi^\mu,\ m_\phi$

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

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

Scattering = Measurement

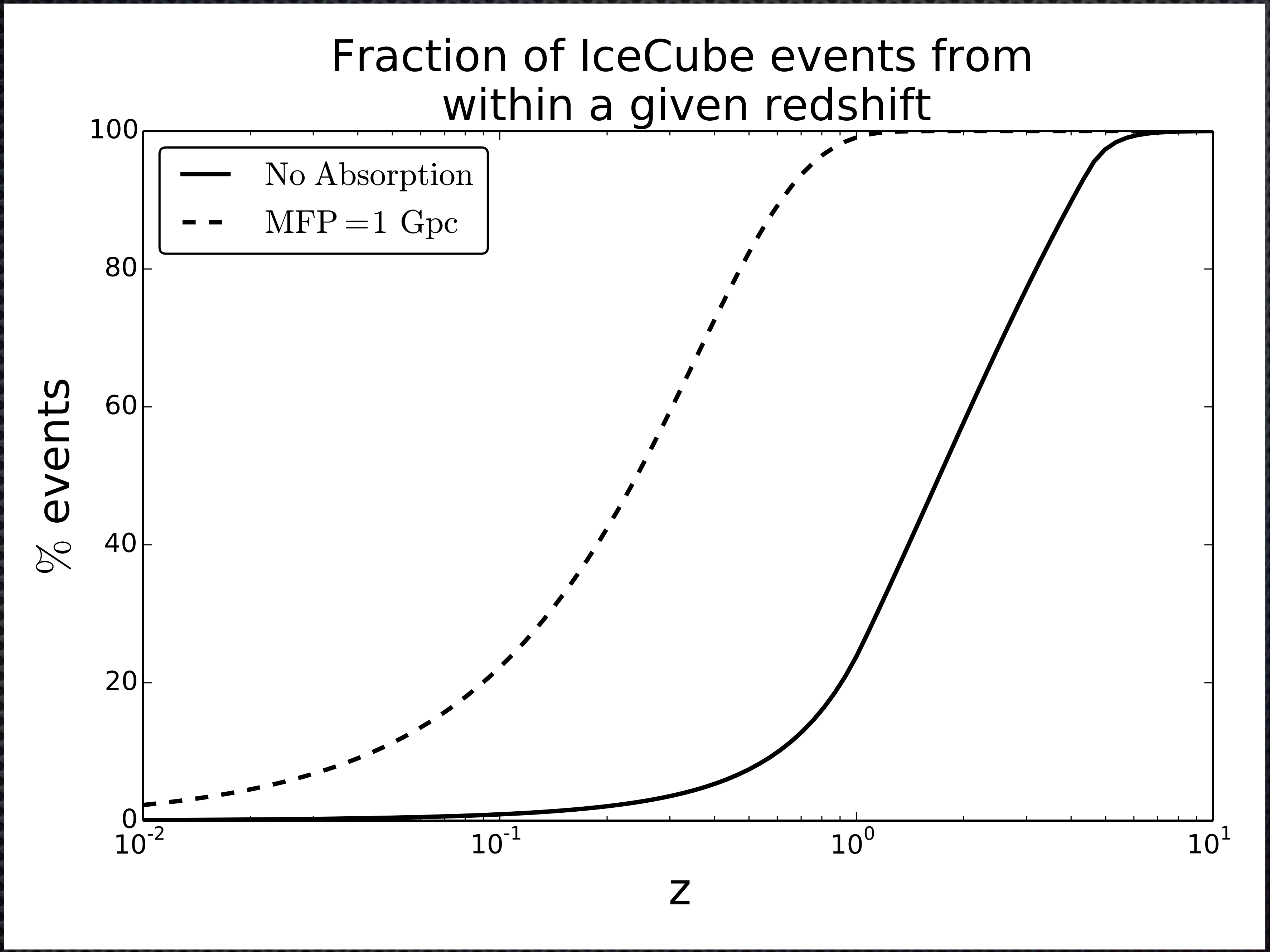




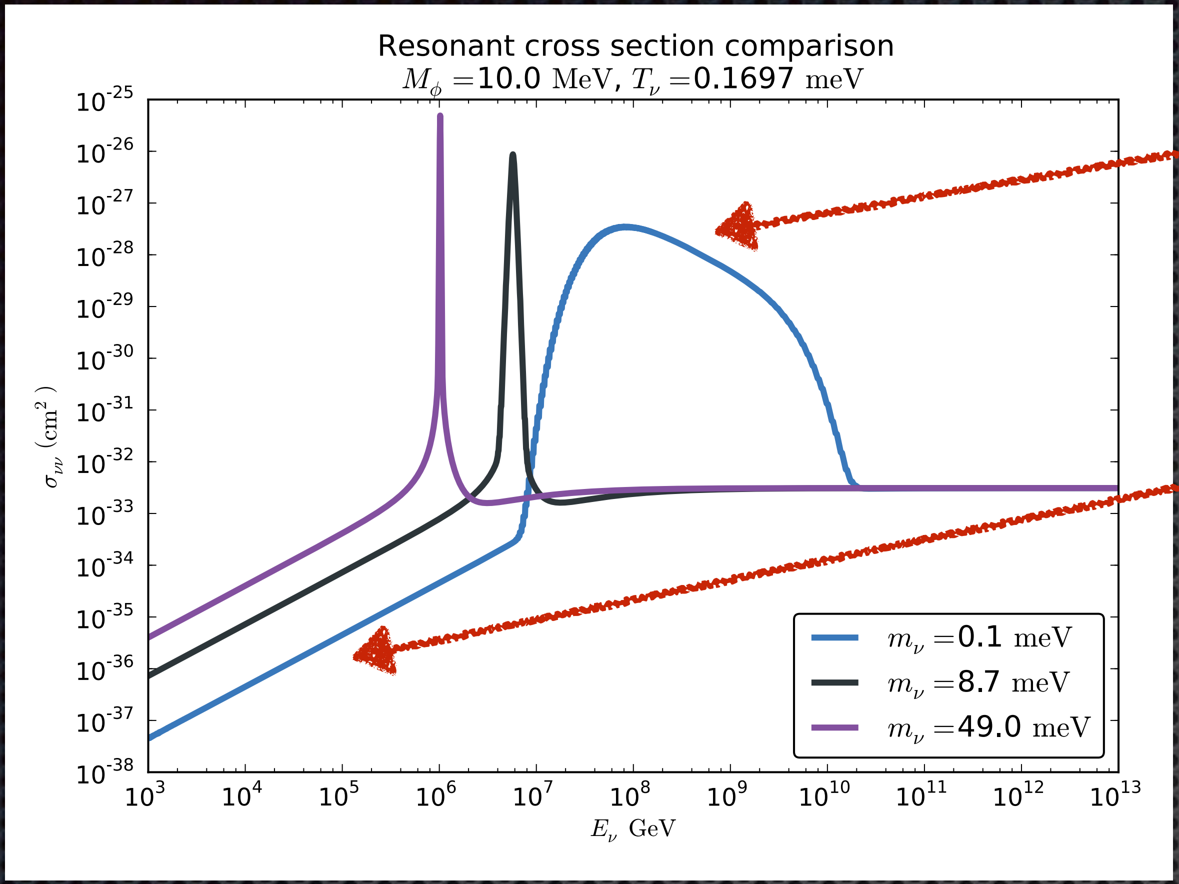
$$\langle \nu_s | \nu_{e,\,\mu,\,\tau} \rangle \equiv 0$$

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

A cartoon example

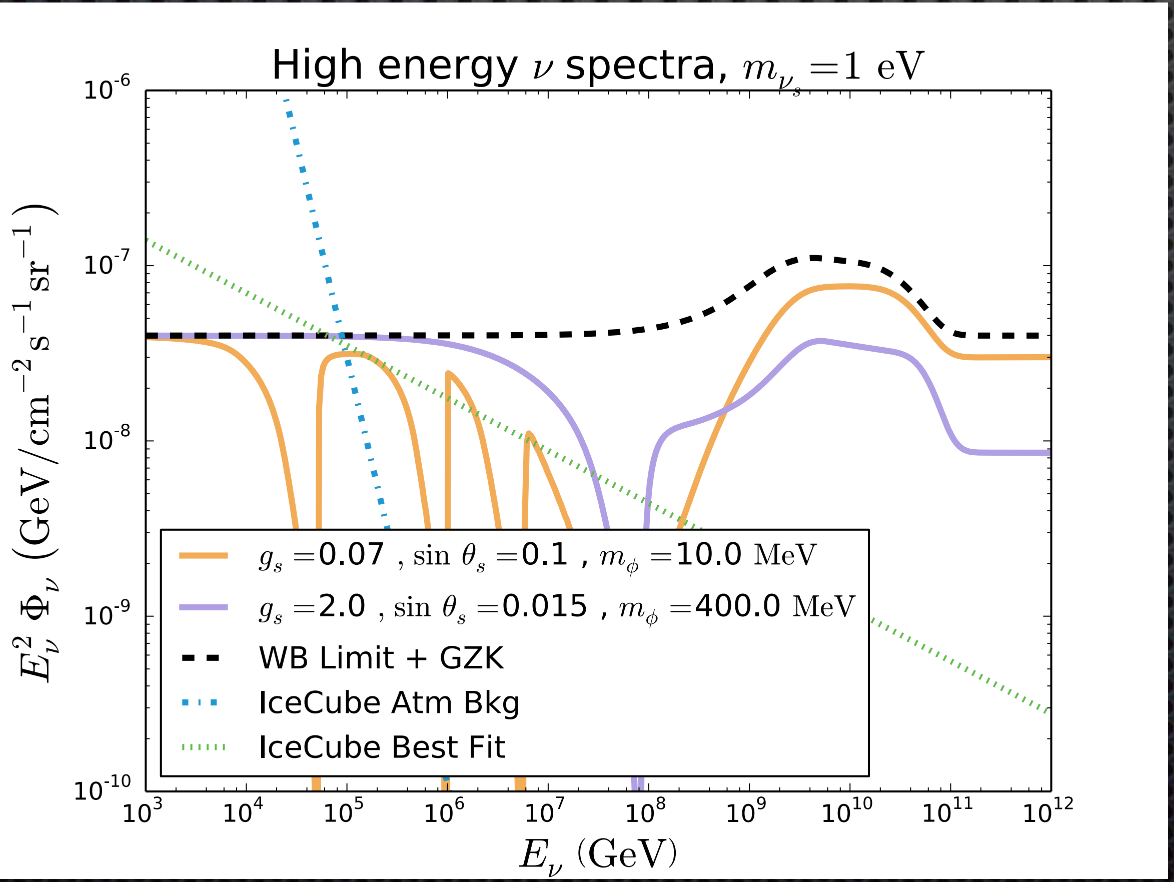


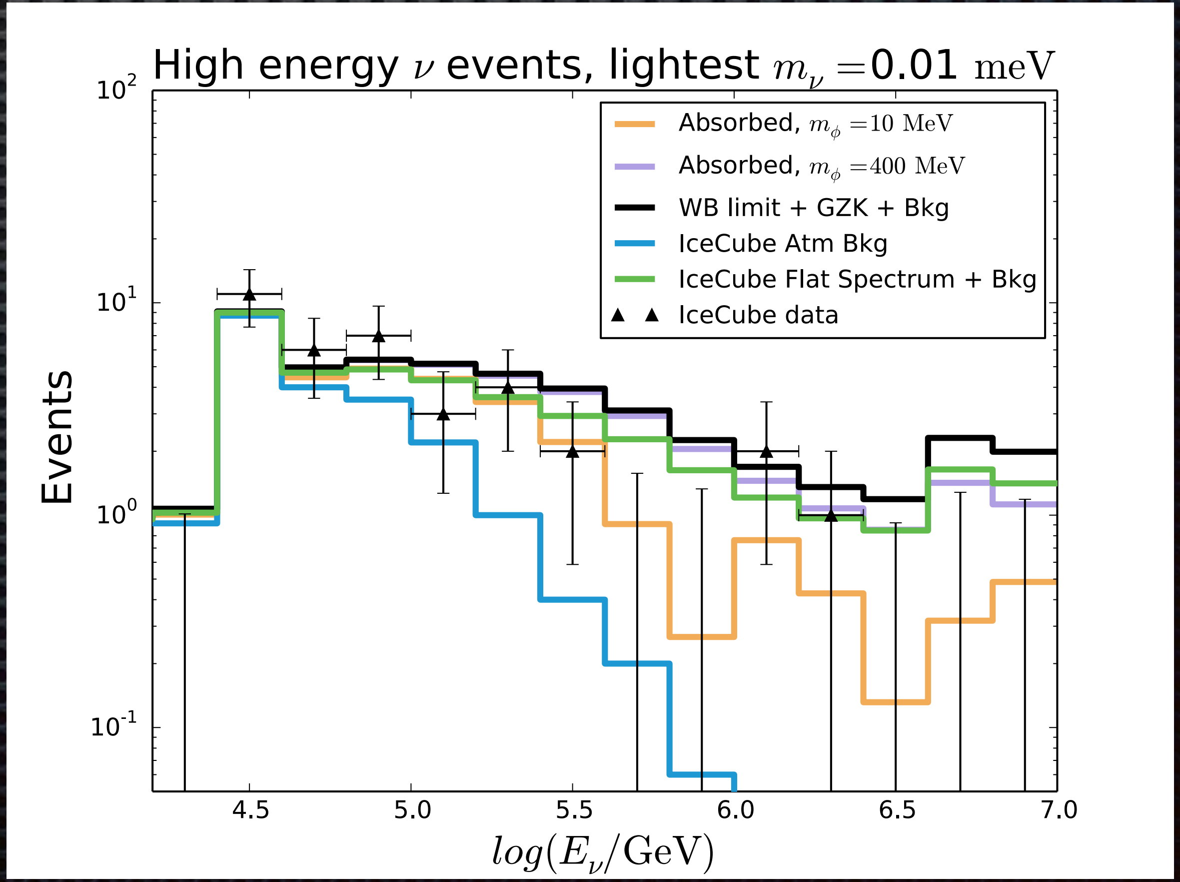
Another cartoon example



Resonant absorption creates gaps

Contact interaction limit shifts the observed spectral index by -1





Let us not be cavalier

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

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

- 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.

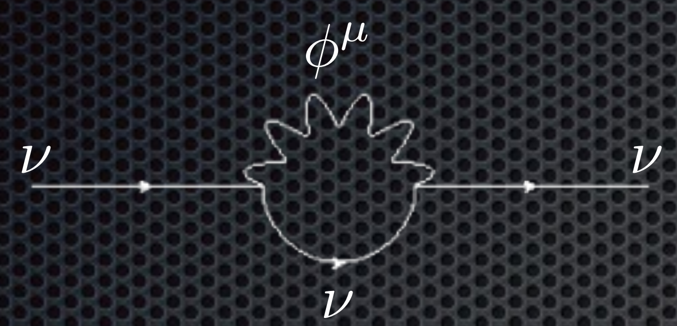
$$\Delta N_{\rm eff} = 1$$

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

Relic Sterile Abundance

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

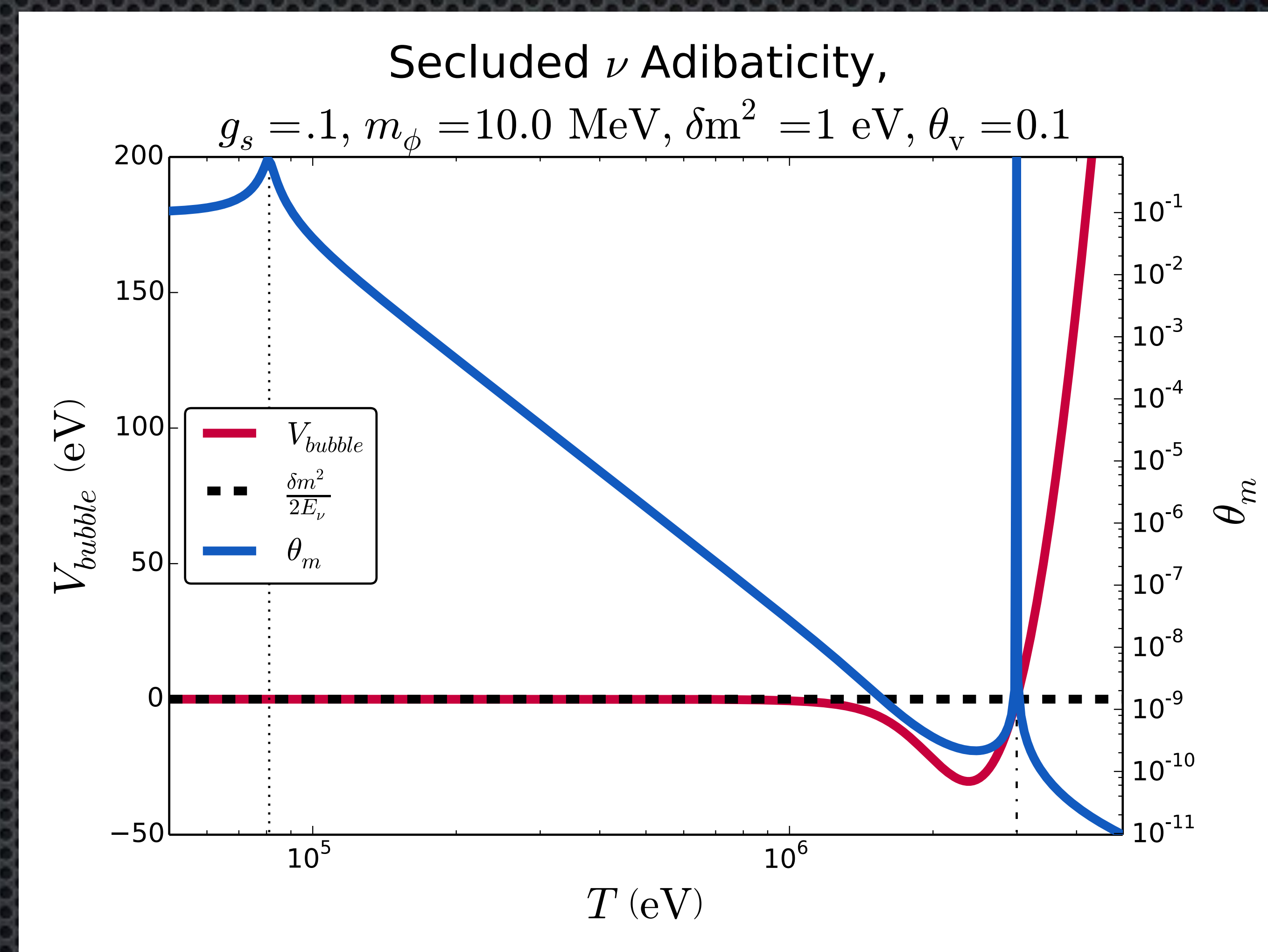
$$\Sigma_{bubble}\left(k\right) = -i\frac{g_s^2}{4\pi}\int \frac{d^4p}{\left(2\pi\right)^4}\gamma^\mu P_L iS\left(p+k\right)\gamma^\nu iD_{\mu\nu}\left(p\right)$$



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

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

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



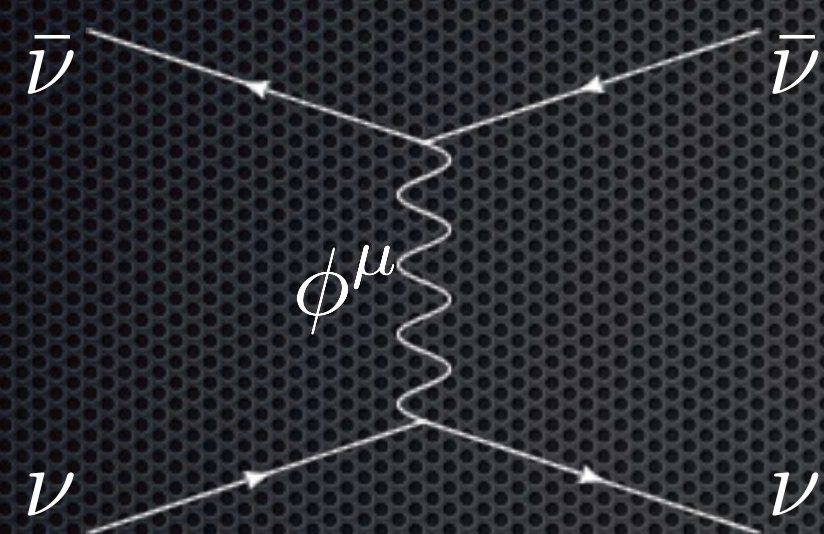
$$V^{bubble} \simeq \begin{cases} -\dfrac{7g_s^2\pi^2 E_\nu T_s^4}{45m_\phi^4} & \text{for} \quad T_s, E_s << m_\phi \\ \dfrac{g_s^2 T_s^2}{2E_\nu} & \text{for} \quad T_s, E_s >> m_\phi \end{cases}$$

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

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

Size of the mixing angle is critical

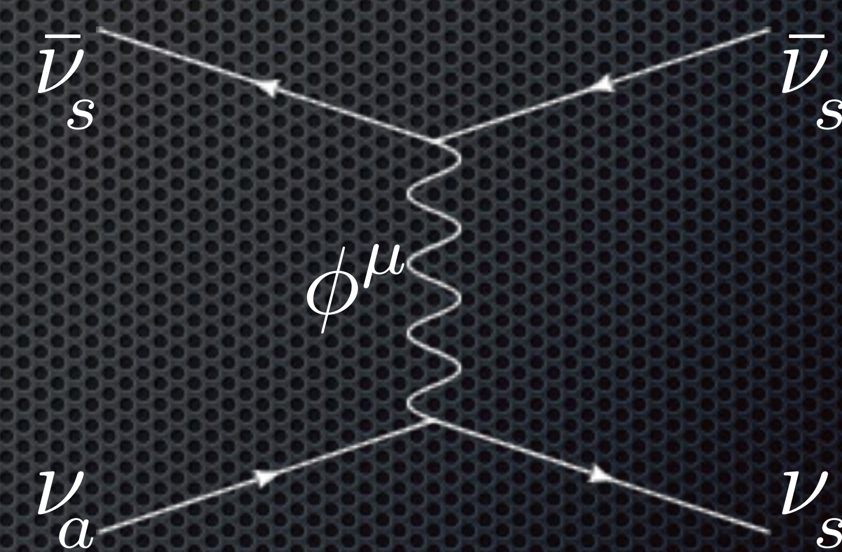
$$\nu_a \leftrightarrow \nu_s$$

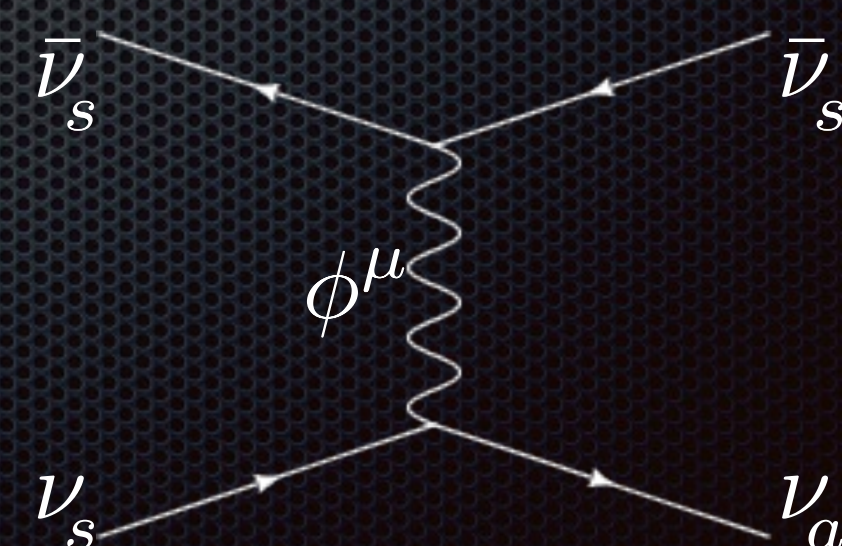


$$\sigma_{\nu\nu} \propto \theta^2_{\rm eff}, \theta^4_{\rm eff}, \theta^6_{\rm eff}$$

In the Early Universe $\Longrightarrow$

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





The N effective limit

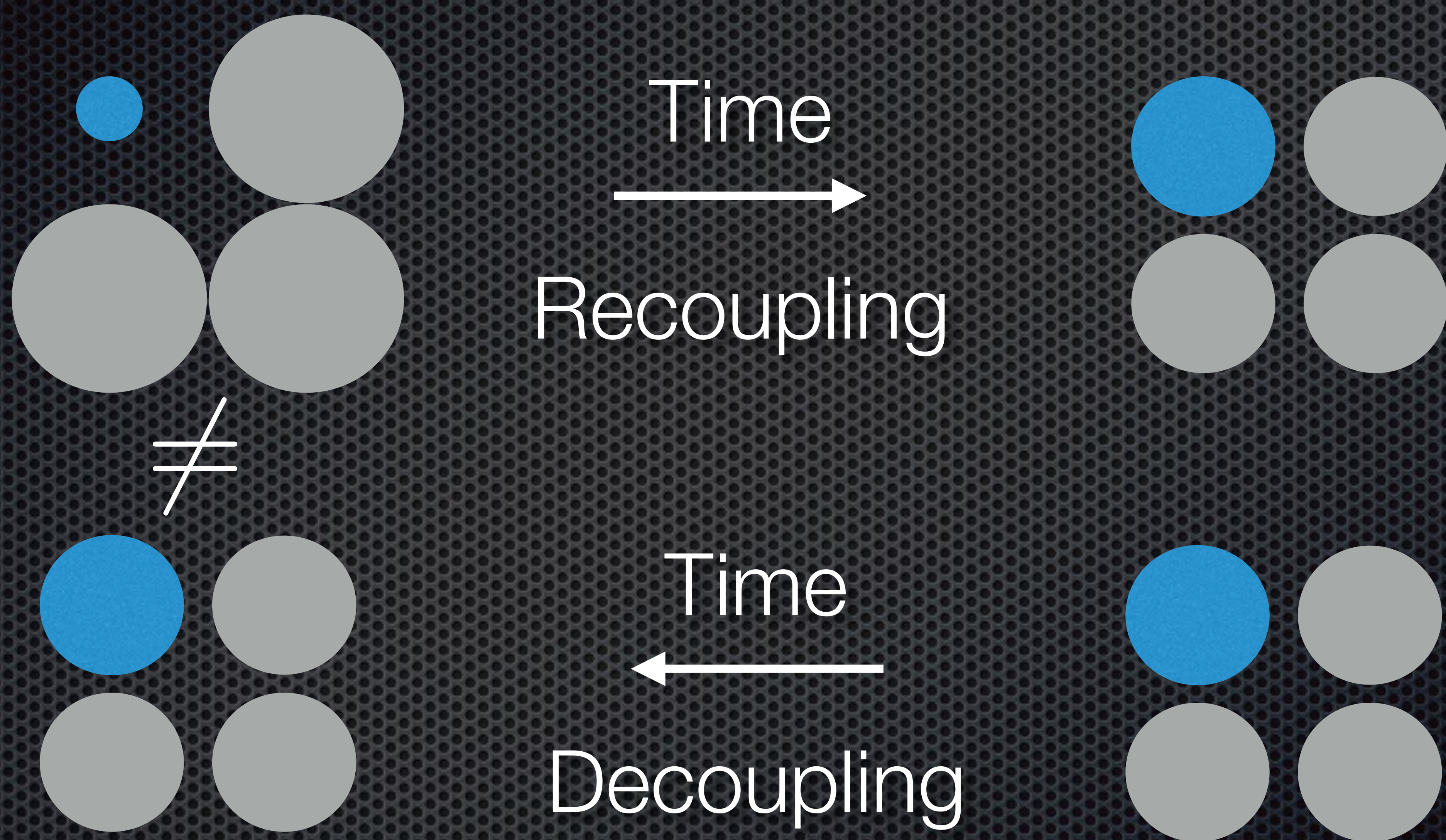
- The dark sector decouples at some high temperature scale and dilution from freeze out of SM degrees of freedom reduces the dark sector temperature:

$$T_{\rm dark} = \left(\frac{g_{*,\rm pre-BBN}}{g_{*,\rm dark\, freezout}} \right)^{1/3} T_\gamma$$

- At sufficiently low temperature, the mixing angle suppression will cease and the dark sector $\nu' s$ will recouple to the SM $\nu' s$.
- This must happen **after** $e^+ + e^- \leftrightarrow \nu + \bar{\nu}$ goes out of equilibrium to avoid re-population of the ν_s radiation.

Mixing Portal Recoupling

Co-moving Entropy is not conserved!



This process is irreversible, therefore only Co-moving energy density is conserved.

Mixing Portal Recoupling

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

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

- There are three distinct recoupling regimes.
- The Weldon regime: $T_\nu \gg m_\phi$
- The Notzold-Raffelt regime: $T_\nu \ll m_\phi$

$\Big\}$ Asymptotically small mixing

- The Resonant regime: $T_\nu \sim m_\phi$

Asymptotic Recoupling

$$\sin\theta_m = \frac{\delta m^2 \sin 2\theta_V}{4E_\nu V^{bubble}}$$

Recoupling Temperature scale: $T_0 = \left[\left(\delta m^2 \sin 2\theta_V\right)^2 m_{pl}\right]^{1/5}$

$$\langle\sigma v\rangle \approx \frac{g_s^4}{m_\phi^4} s \ \text{Notzold} - \text{Raffelt} \implies T_{rec} \equiv T_0^{5/9} m_\phi^{4/9}$$

$$\langle\sigma v\rangle \approx \frac{g_s^4}{m_\phi^2} \ \text{Weldon} \implies T_{rec} \equiv T_0^{5/3} m_\phi^{-2/3}$$

Resonant Recoupling

- Also MSW resonance $\Longrightarrow$ SM neutrinos acquire some extra probability to be in the secluded state via level crossing.

$$\gamma = 1 - P_{\mathrm{cross}} \approx 2\pi \frac{\left(\sin 2\theta_V \delta m^2/4E_\nu\right)^2}{|V'|}$$

- $|V'|$ can be be estimated parametrically

$$|V'| \approx \frac{dV}{dT}\frac{dT}{dt} \approx \left(\alpha_s m_\phi\right)\left(m_\phi^2/m_{pl}\right)$$

- This gives the additional secluded state probability as:

$$\gamma \sim \frac{T_0^5}{g_s^2 m_\phi^5}$$

Resonant Recoupling cont'

- After the SM neutrinos acquire some additional probability to occupy secluded interaction states, their cross section are quite large:

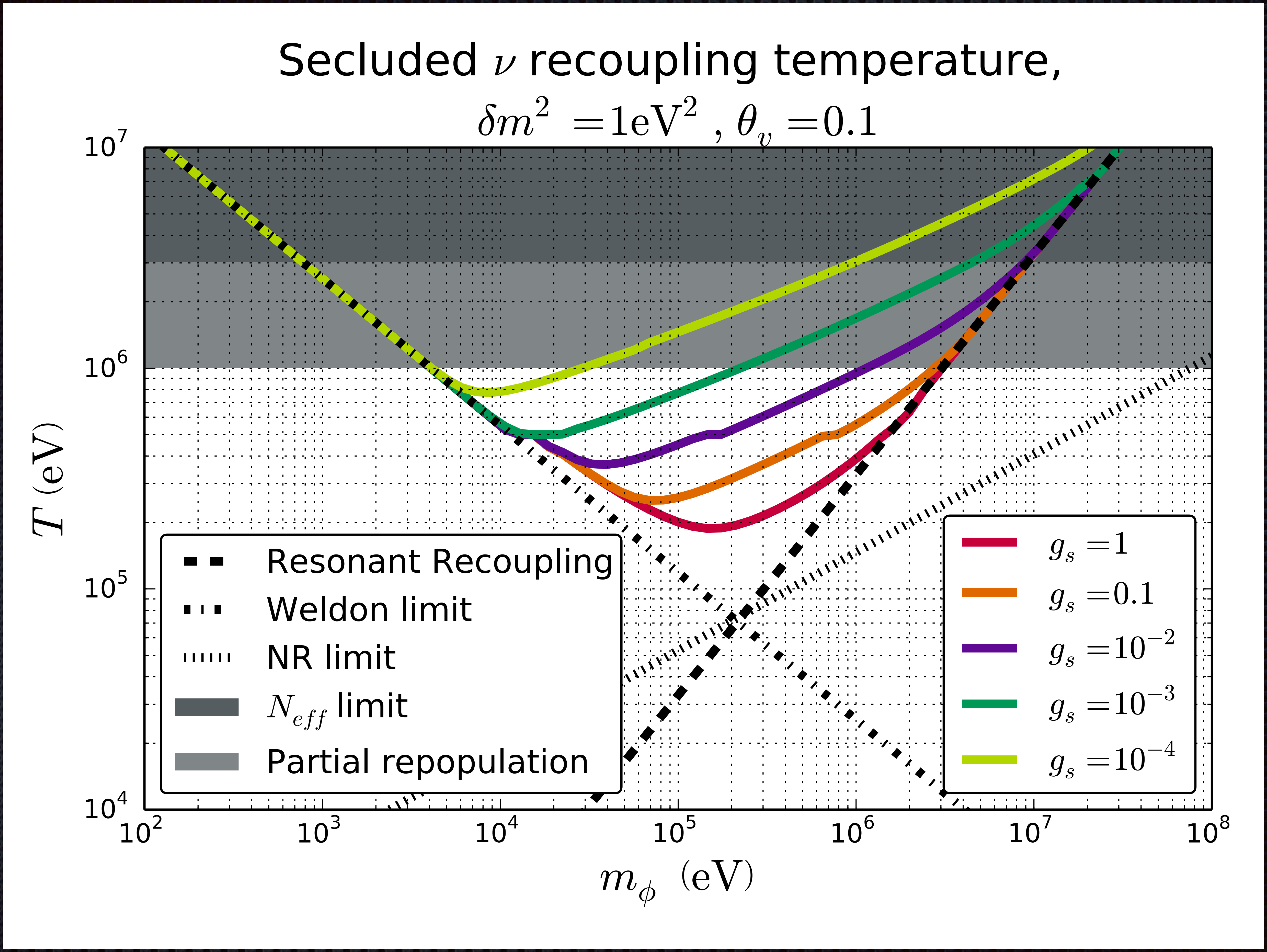
$$\langle \sigma v \rangle \approx \frac{g_s^2}{m_\phi^2}$$

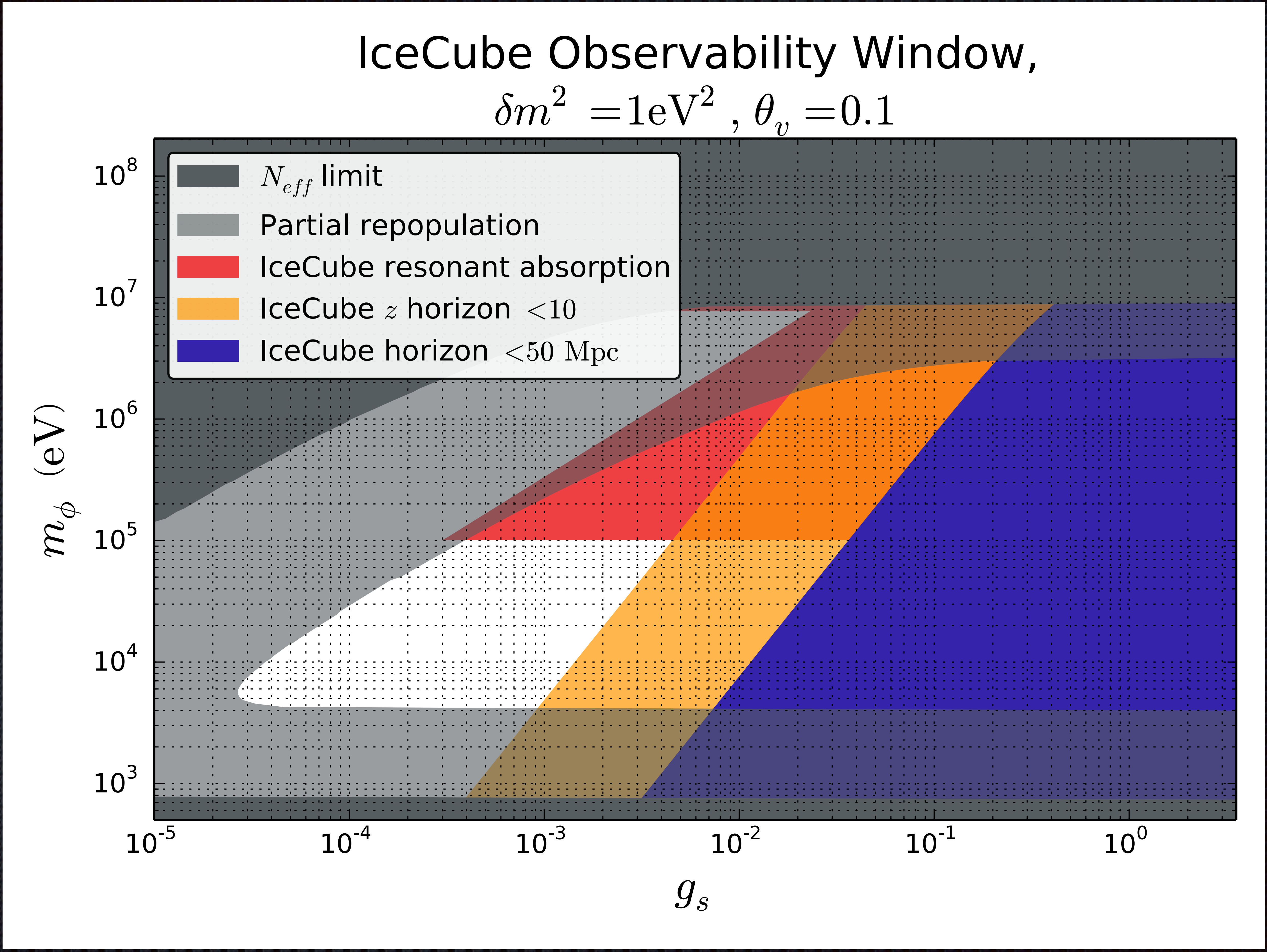
- Again we compare:

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

- Which gives a upper bound:

$$m_\phi \lesssim \left(m_{pl} T_0^5\right)^{1/6} = 1\,\mathrm{GeV}\left(\frac{\delta m^2}{1\,\mathrm{eV}^2}\right)^{1/3}\left(\frac{\sin 2\theta_V}{0.1}\right)^{1/3}$$


Secluded ν recoupling temperature,
$\delta m^2 = 1\mathrm{eV}^2$, $\theta_v = 0.1$
T (eV)
m_ϕ (eV)
10^7
10^6
10^5
10^4
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Resonant Recoupling
Weldon limit
NR limit
N_{eff} limit
Partial repopulation
$g_s = 1$
$g_s = 0.1$
$g_s = 10^{-2}$
$g_s = 10^{-3}$
$g_s = 10^{-4}$

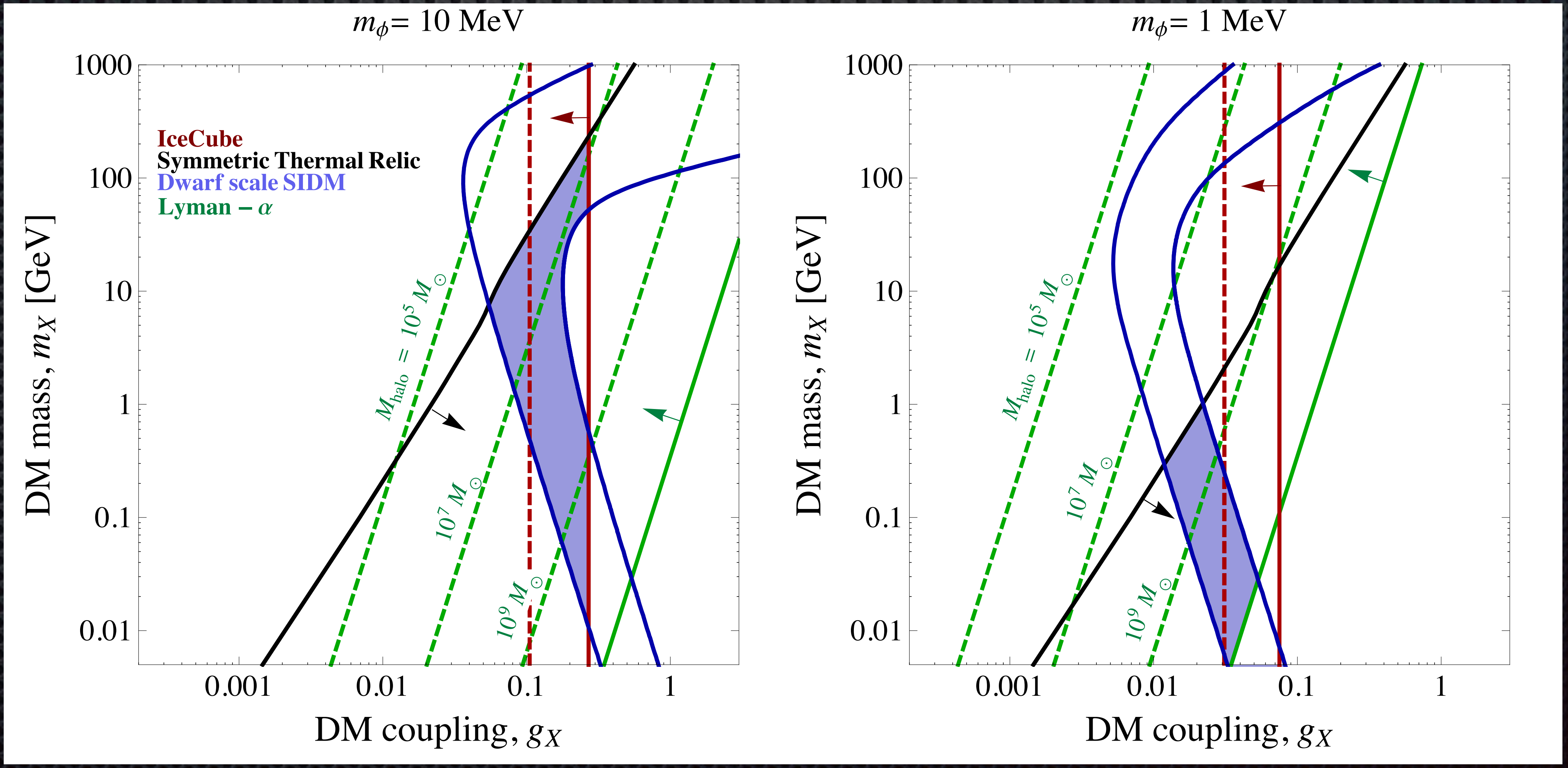


IceCube Observability Window,
$\delta m^2 = 1\mathrm{eV}^2$, $\theta_v = 0.1$
N_{eff} limit
Partial repopulation
IceCube resonant absorption
IceCube z horizon <10
IceCube horizon <50 Mpc
10^8
10^7
10^6
10^5
10^4
10^3
m_ϕ (eV)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
g_s

How does all of this fit with SIDM?

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

$$g_X = g_s$$



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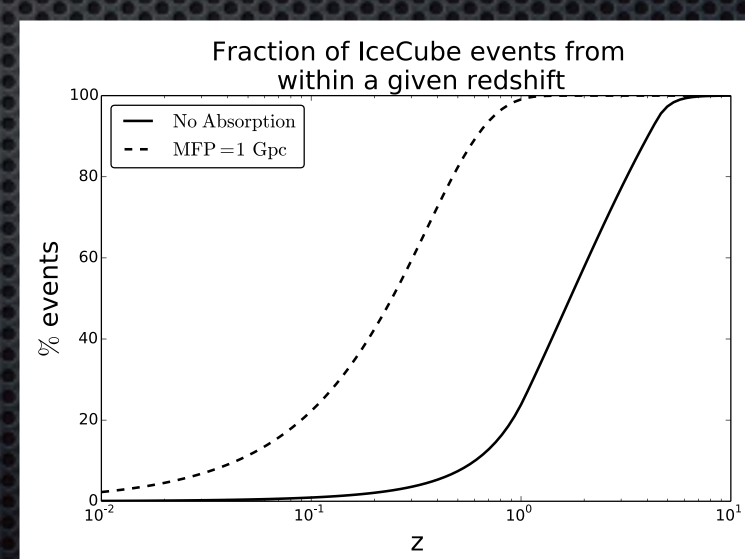
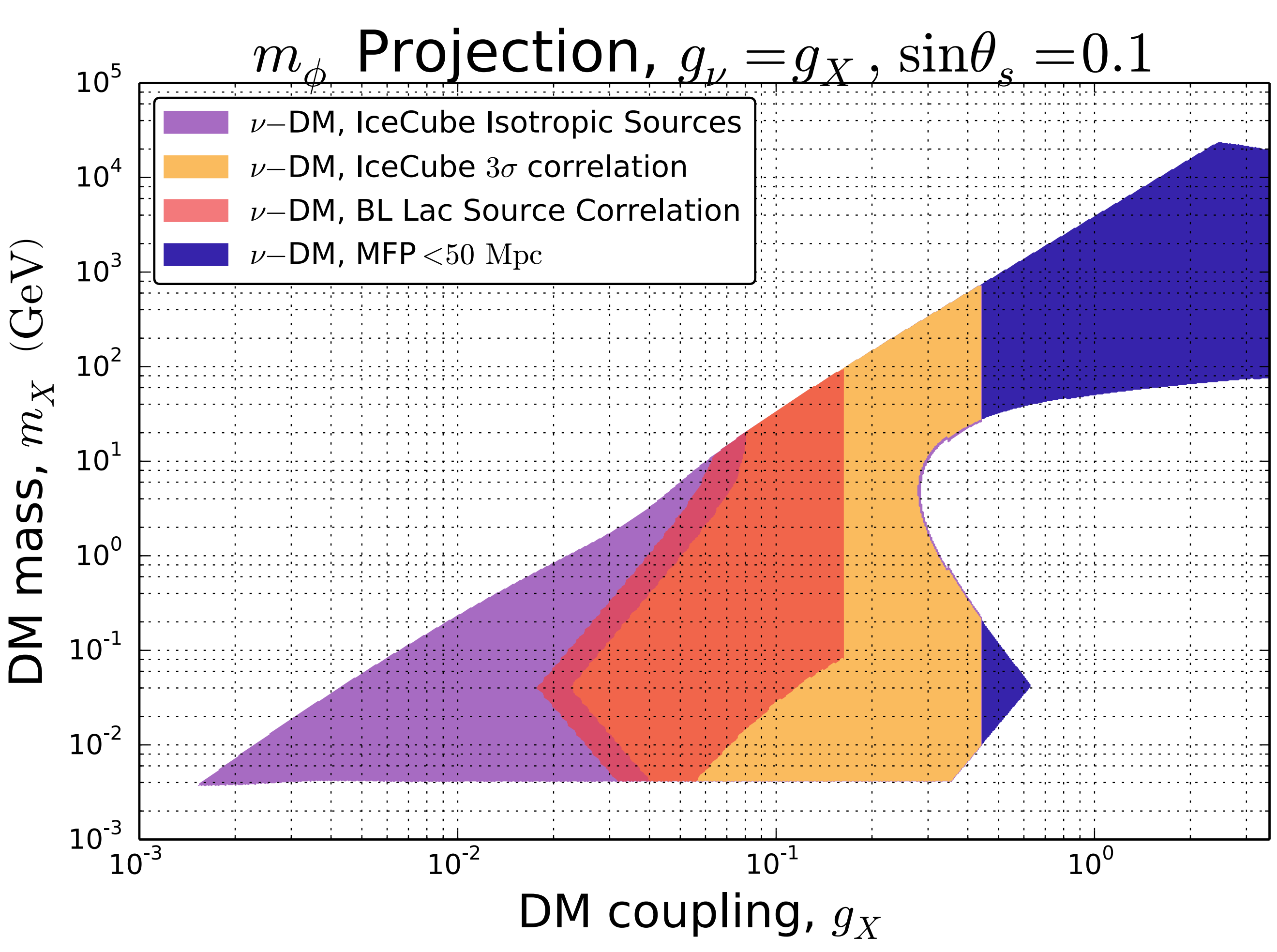
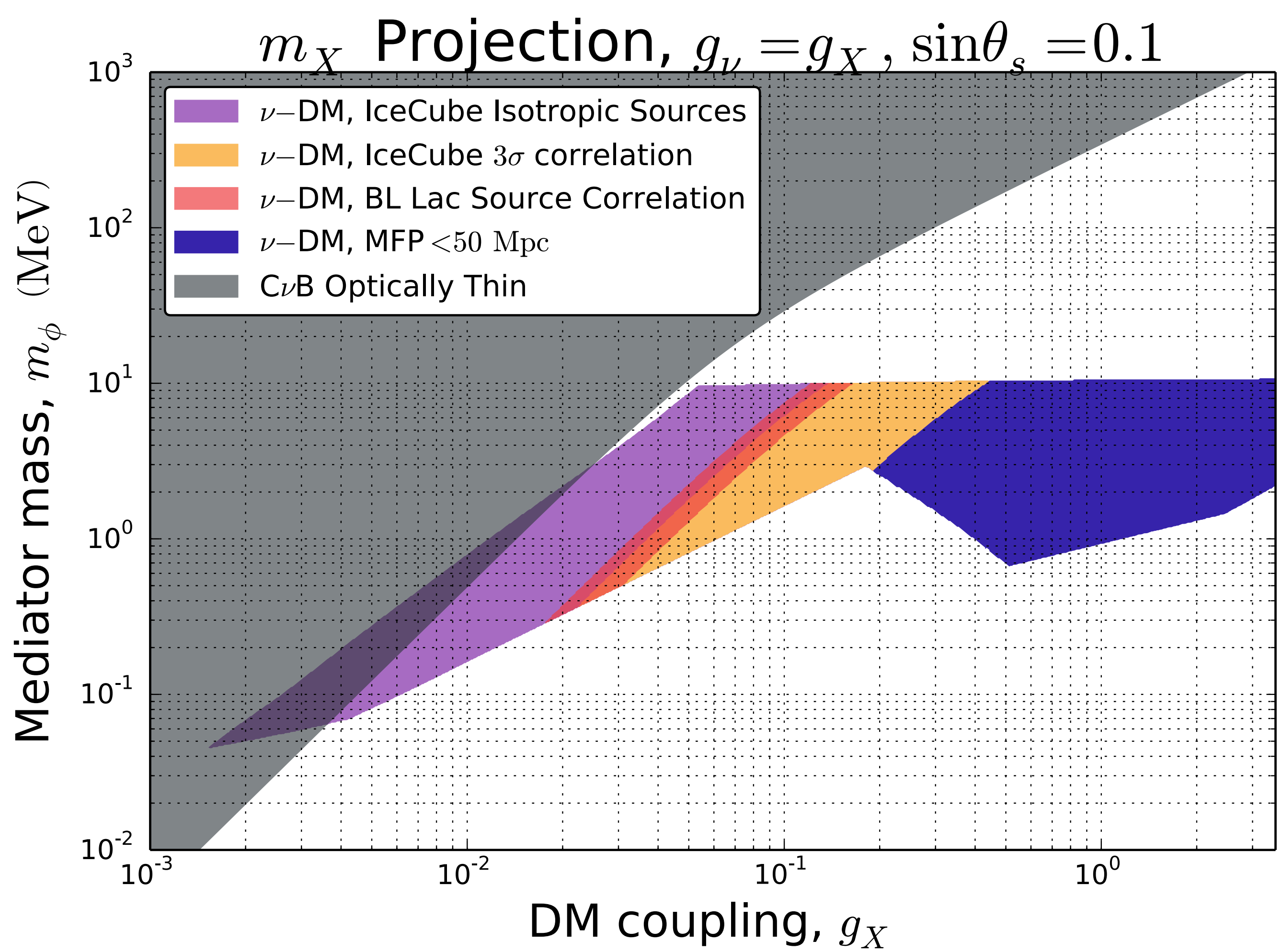
9 IceCube events found correlated with gamma ray point sources:
2 from galactic pulsar wind nebulae
7 from BL Lacs (AGN), 3 from sources less than z < 0.212



expect only 0.3 events!

Projecting over all m_ϕ





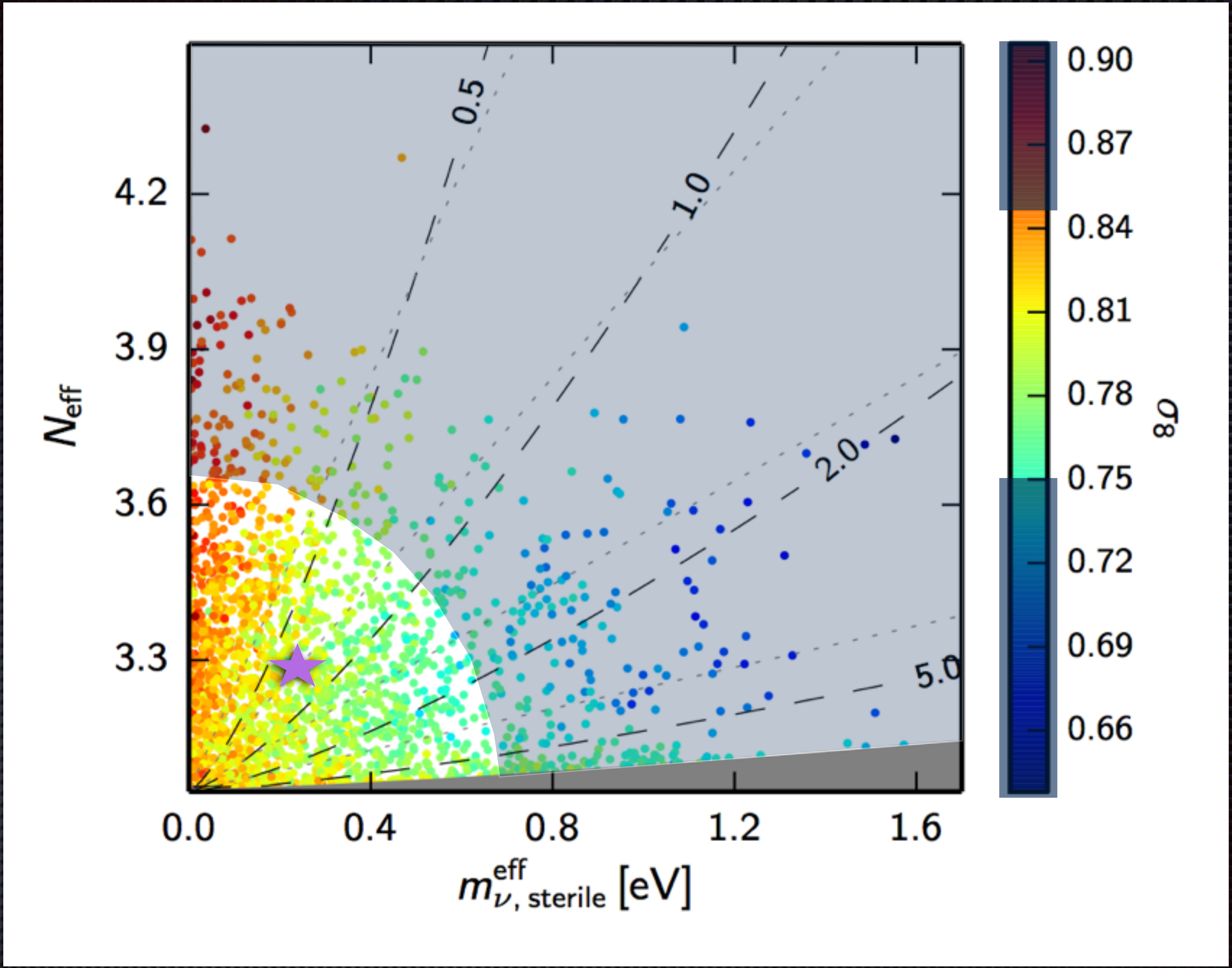
Nearby source correlation is significant at the 3σ level

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

Conclusions:

- IceCube is the perfect experiment to probe neutrino portals to the dark sector!
- 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/ Miniboone or reactor sterile neutrino anomalies with Precision Cosmology data.

Thank you very much!



Planck Collaboration, arXiv:1502.01589v2

Neutrino Mixing

Effective mass term

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

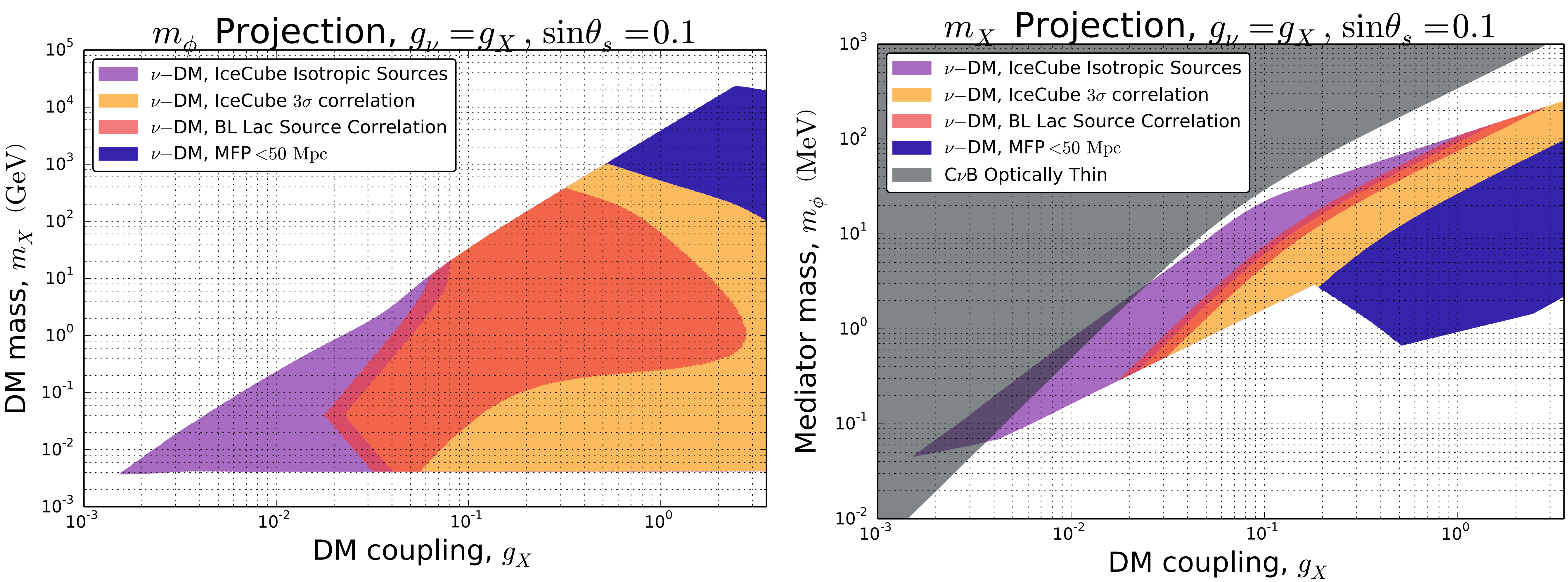
$$\sin 2\theta_{\text{eff}} = \frac{\frac{\delta m^2_V}{2E_\nu}\sin 2\theta_V}{\sqrt{\left(\frac{\delta m^2_V}{2E_\nu}\cos 2\theta_V + A\right)^2 + \left(\frac{\delta m^2_V}{2E_\nu}\sin 2\theta_V\right)^2}}$$

Asymptotic approximation

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

More Evidence!

Projecting over all m_ϕ



Nearby source correlation is significant at the 3σ level

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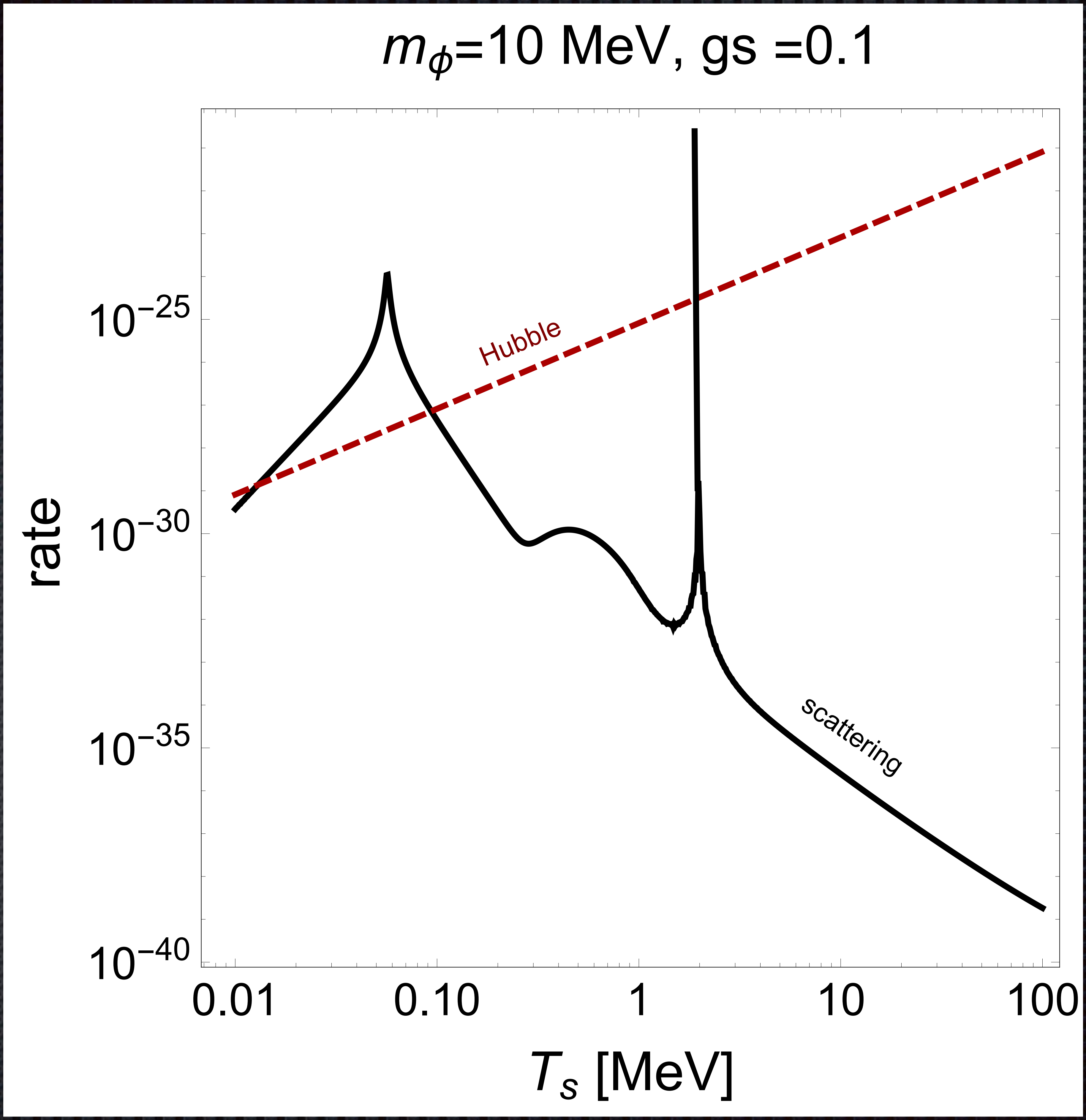


m_ϕ=10 MeV, gs =0.1
rate
T_s [MeV]
Hubble
scattering
10^{-25}
10^{-30}
10^{-35}
10^{-40}
0.01
0.10
1
10
100

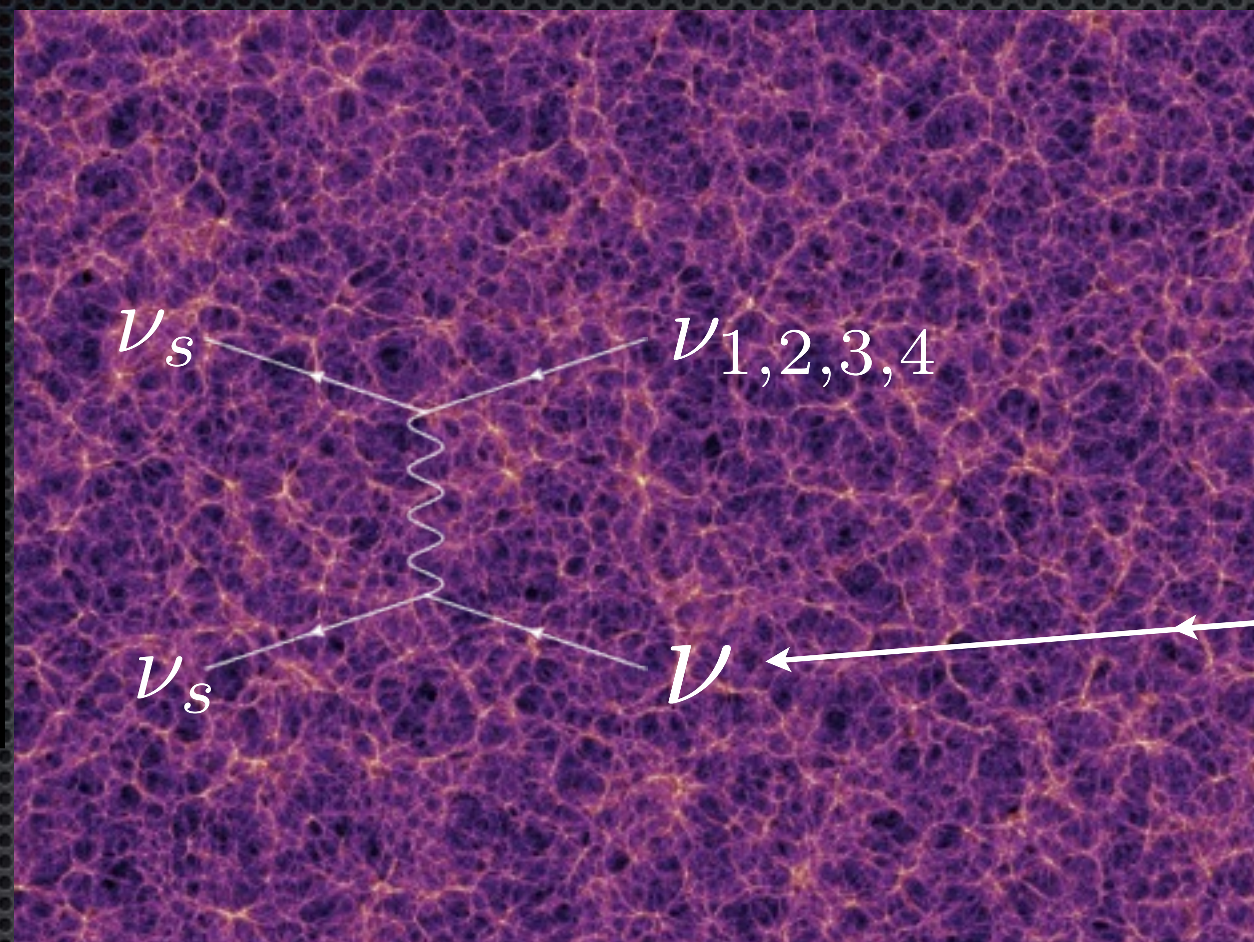
More ordinary decoupling scenario: $T_d = 1\,\mathrm{TeV}$

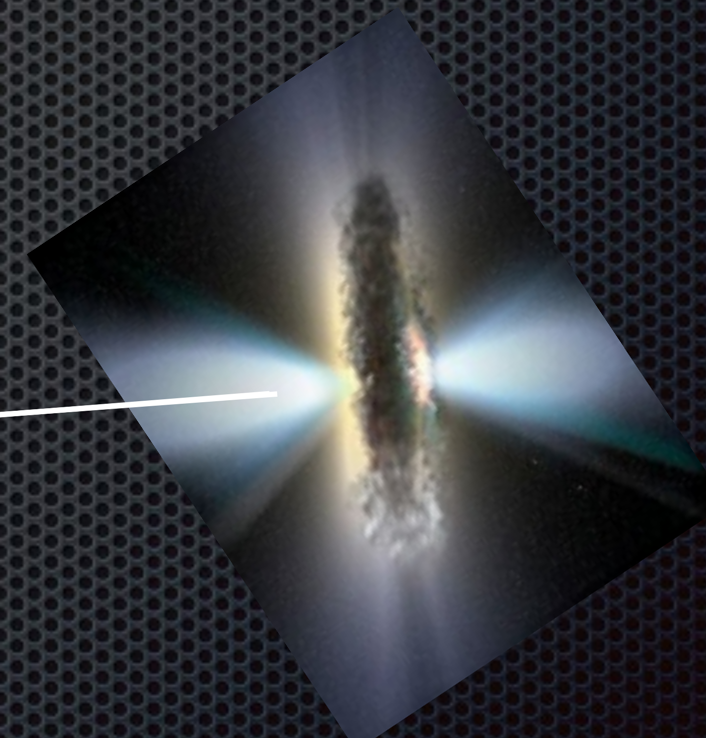
$$\left.\frac{T_s}{T_\gamma}\right|_{T_{KD}} = \left[\frac{g_{*,s}(T_d) \quad g_{*,SM}(T_{KD})}{g_{*,SM}(T_d) \quad g_{*,s}(T_{KD})}\right]^{1/3}$$

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

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

Testing the presence of ν_s





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

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

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:

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

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

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

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 $\mathrm{z_i} = 10$

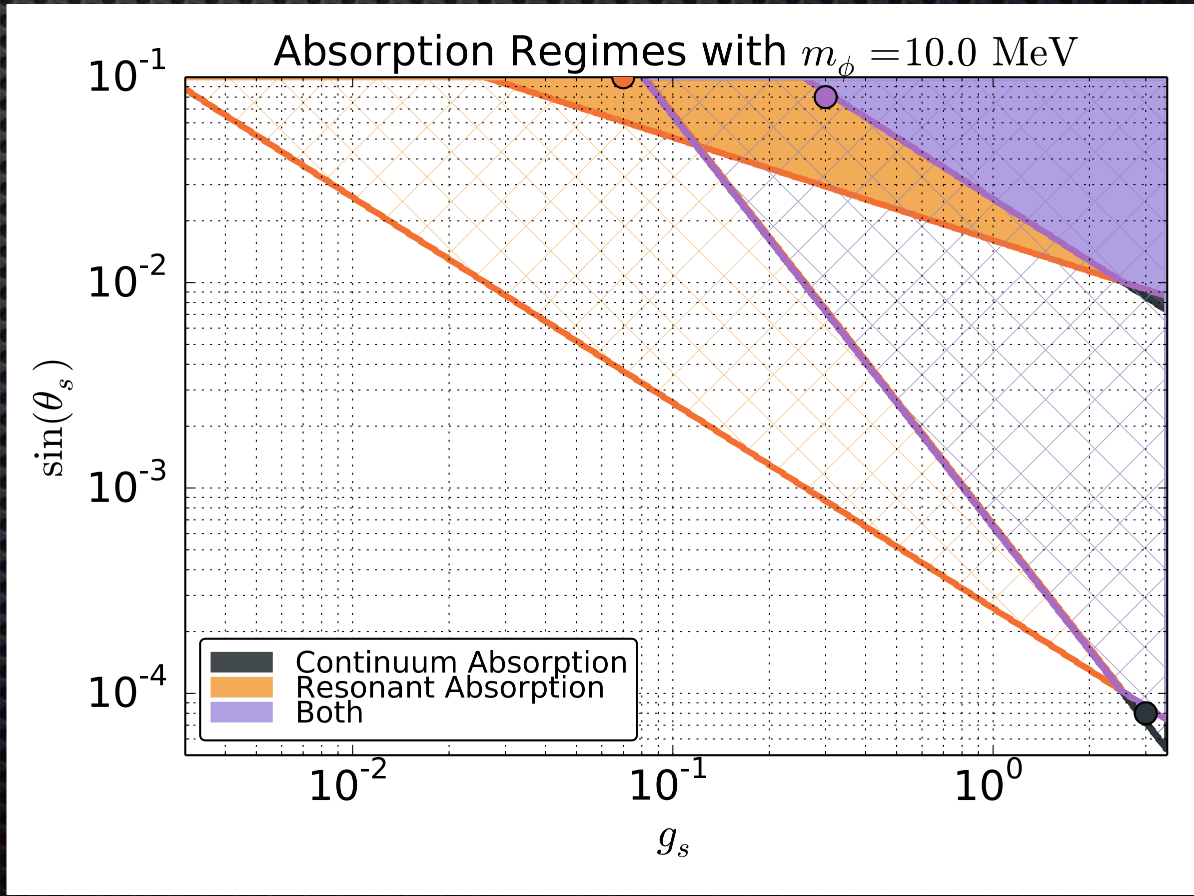
Optical Depth

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

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

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

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:

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

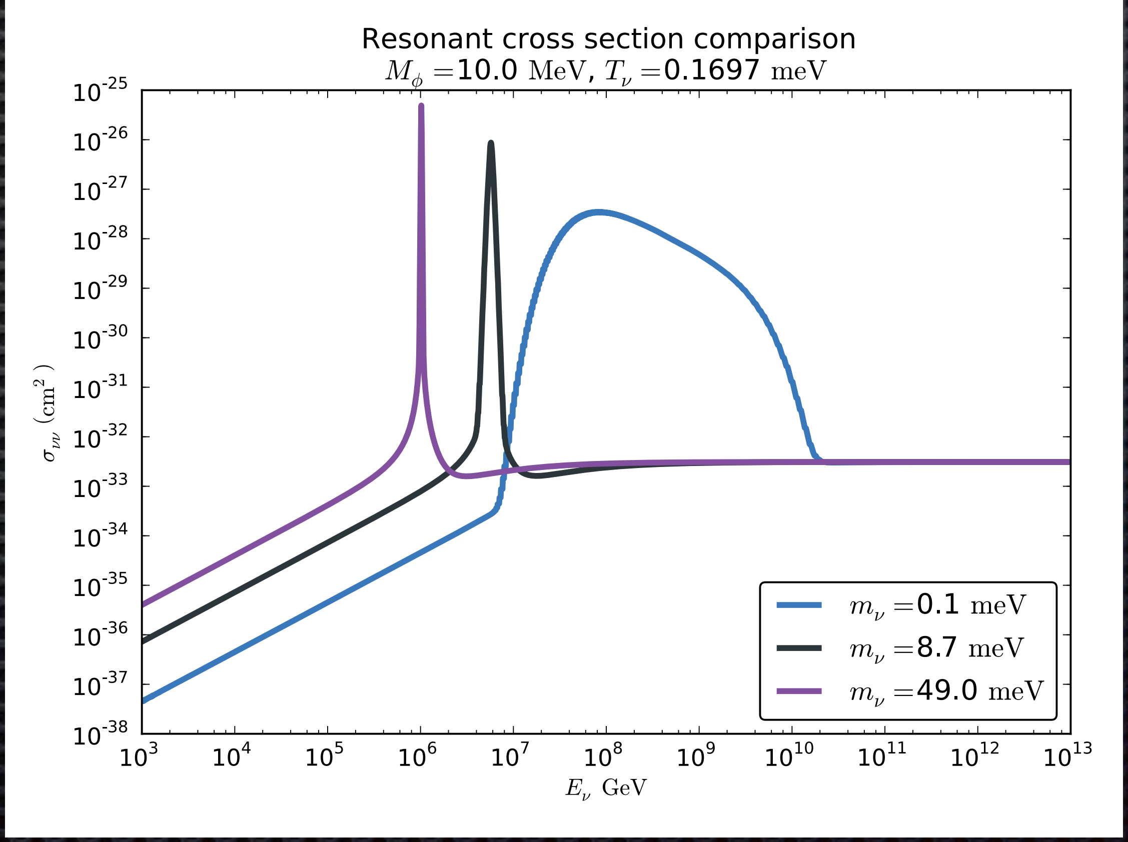
- So our cross sections must be convolved with the thermal motion of the $C\nu B$:

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

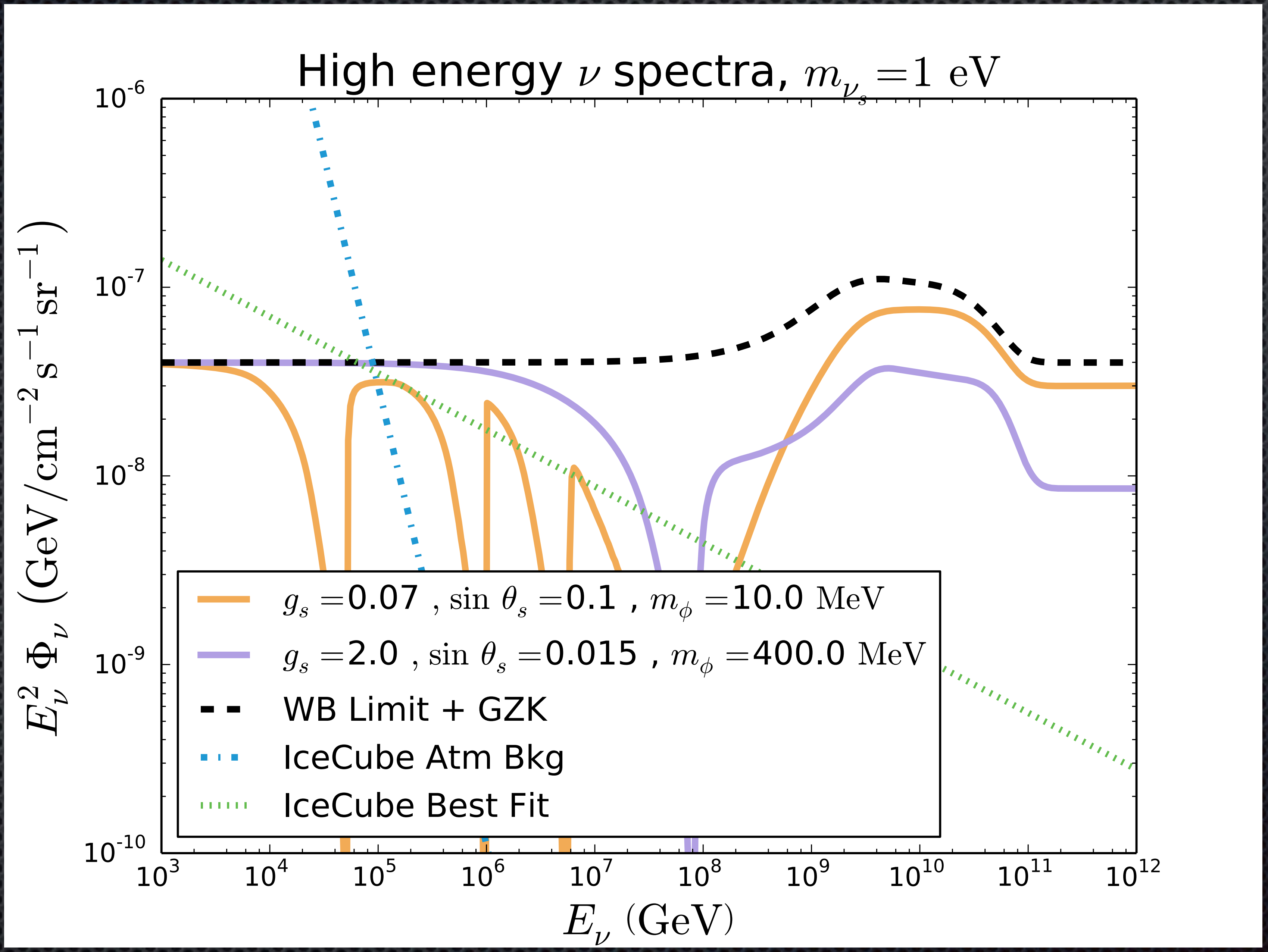
Thermal Broadening

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

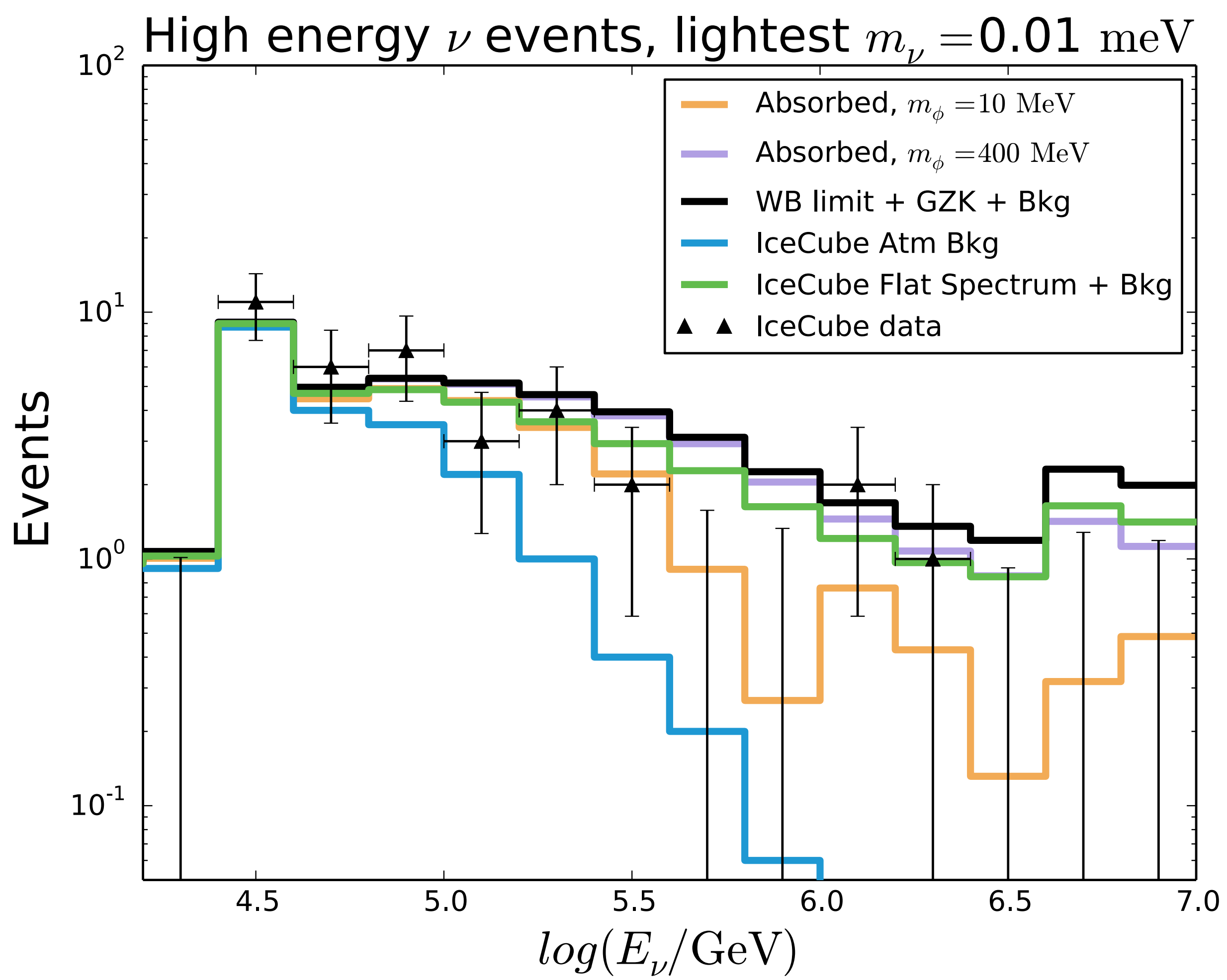
$$\sigma\left(\bar{\nu}\nu \to \bar{\nu}\nu\right) \propto \int_{-1}^{1} \frac{g_\nu^4}{16\pi s} \left[\frac{t^2 + u^2}{\left(s - m_\phi^2\right)^2 + \left(m_\phi \Gamma_\phi\right)^2} \right] d\cos\theta + \ldots$$

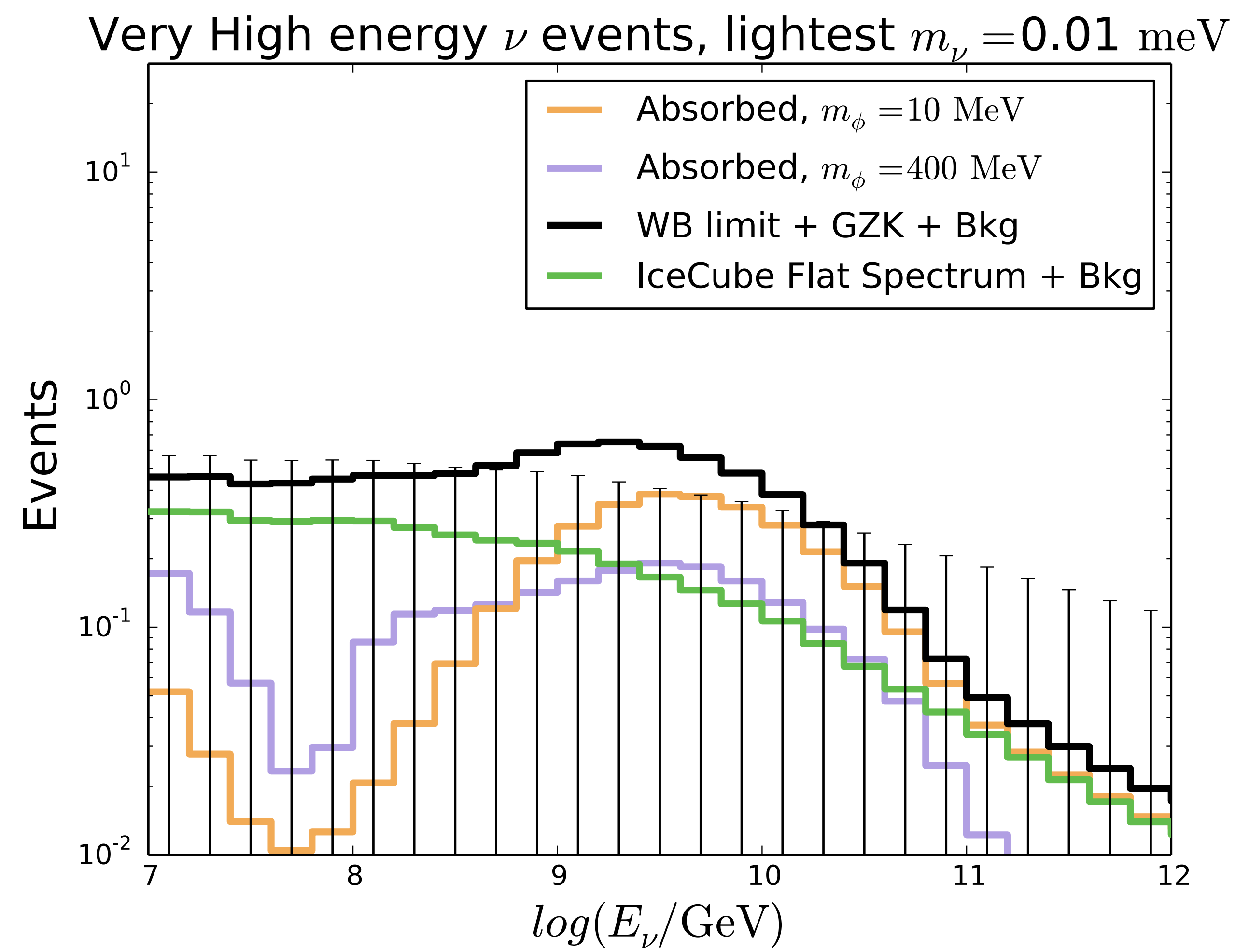


Some results, fitting the gaps in the IceCube data:

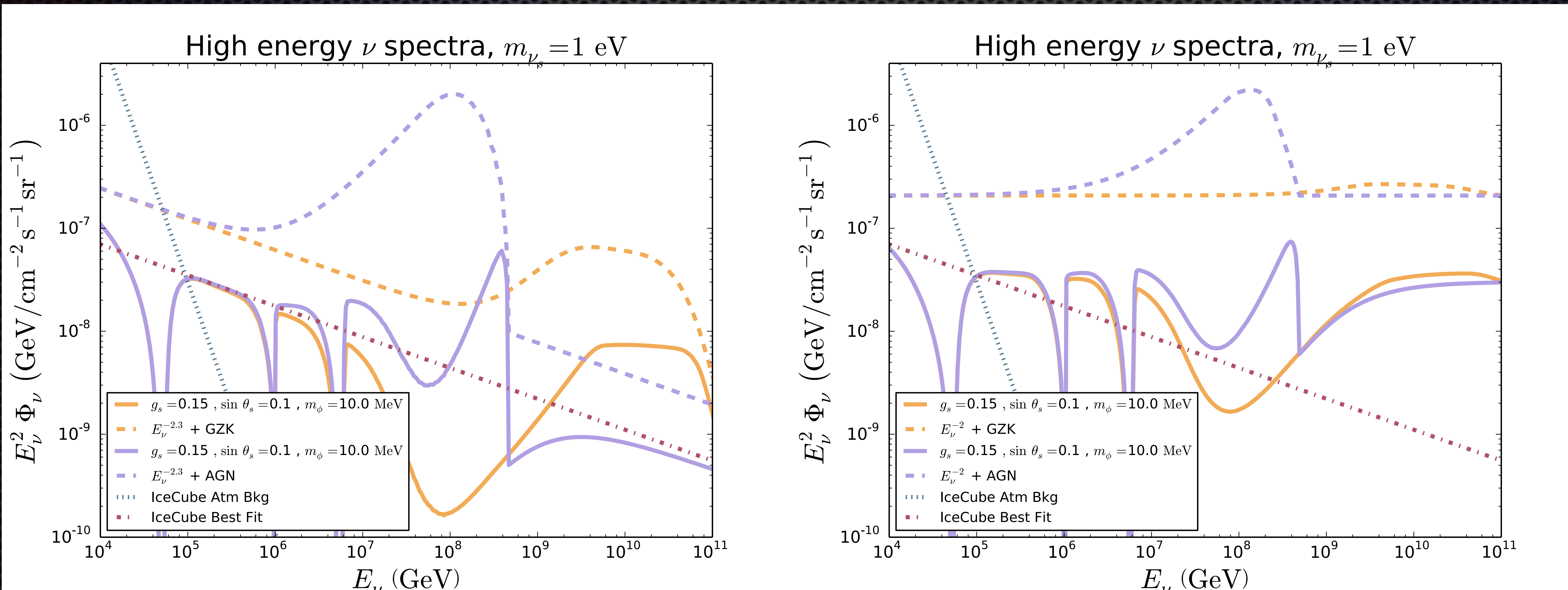


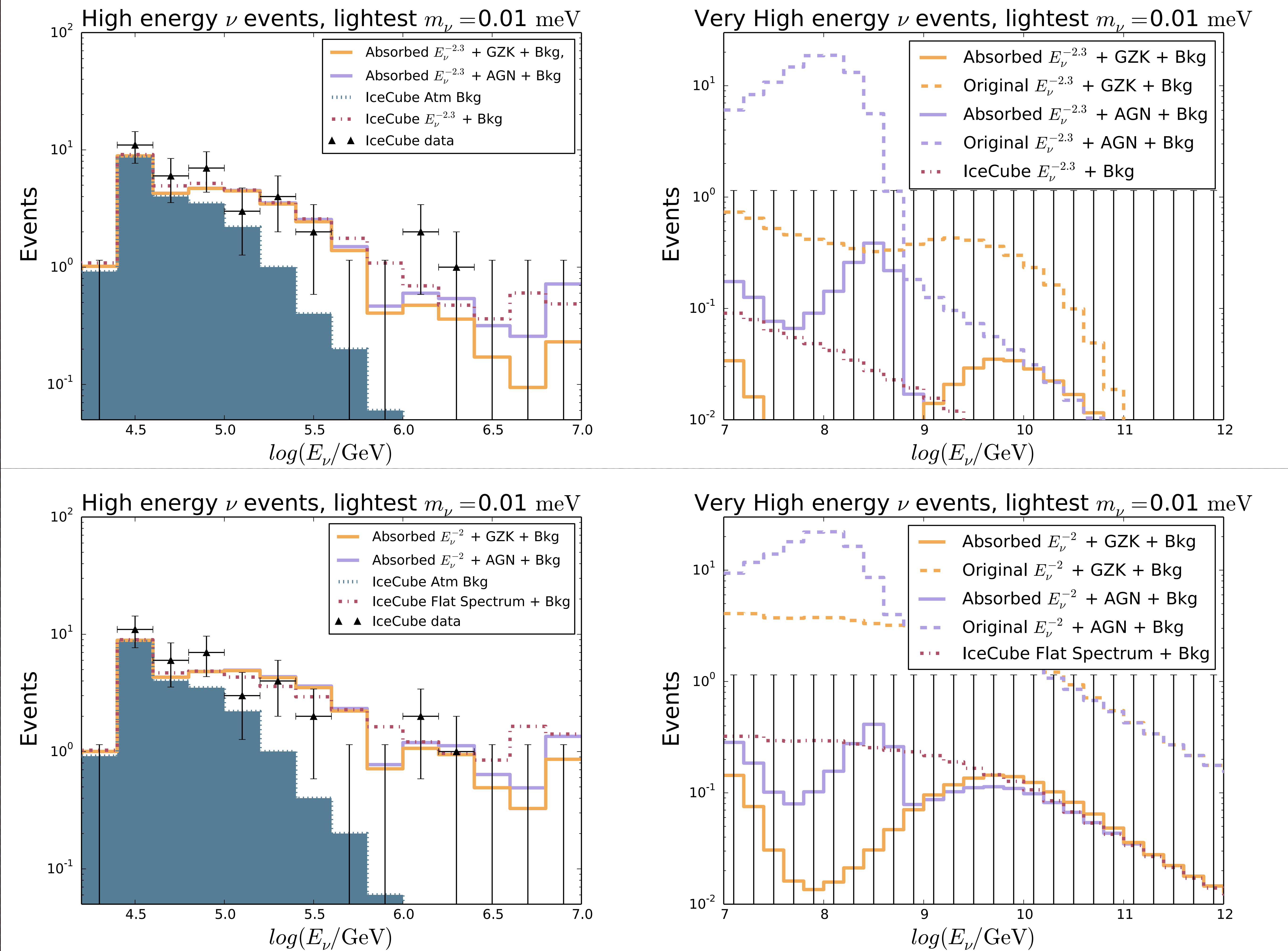
How does this fit with the observed IceCube data?





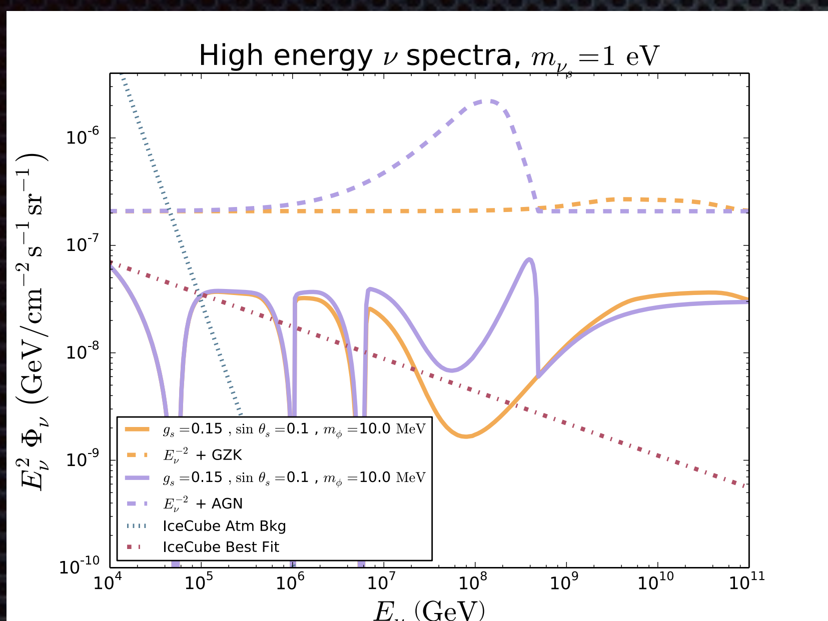
Some results, fitting the overabundance of low z sources:

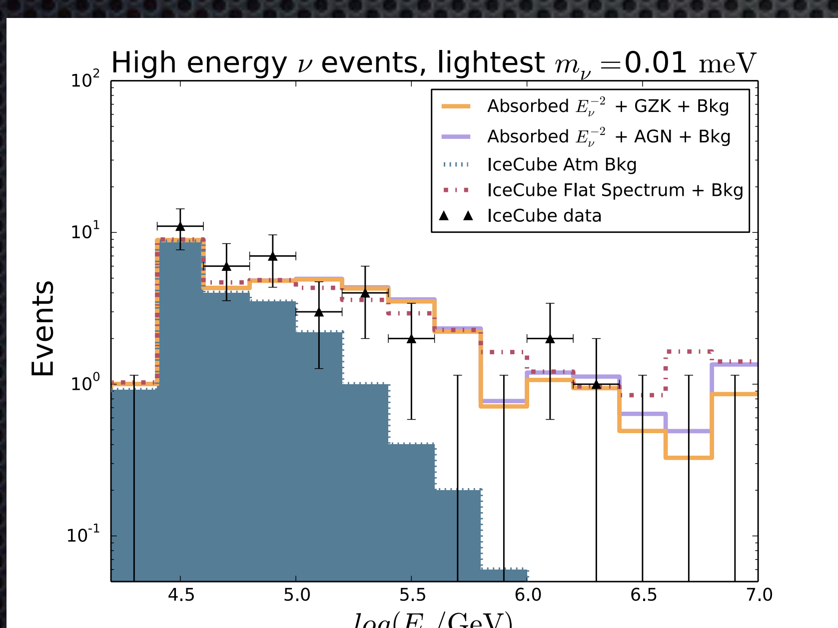


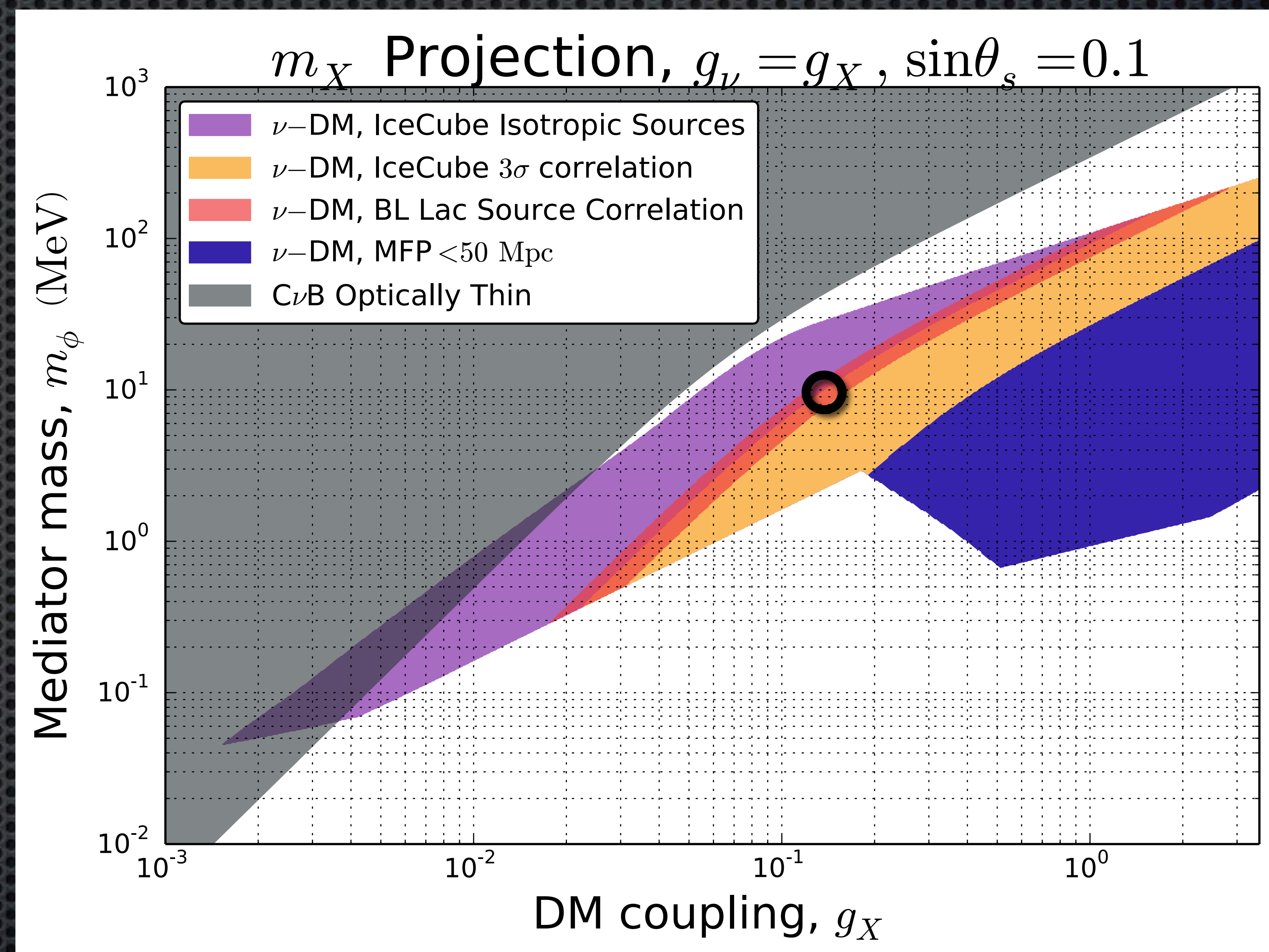


High energy ν events, lightest m_ν =0.01 meV
Absorbed $E_\nu^{-2.3}$ + GZK + Bkg,
Absorbed $E_\nu^{-2.3}$ + AGN + Bkg
IceCube Atm Bkg
IceCube $E_\nu^{-2.3}$ + Bkg
IceCube data
Events
$log(E_\nu/\mathrm{GeV})$
Very High energy ν events, lightest m_ν =0.01 meV
Absorbed $E_\nu^{-2.3}$ + GZK + Bkg
Original $E_\nu^{-2.3}$ + GZK + Bkg
Absorbed $E_\nu^{-2.3}$ + AGN + Bkg
Original $E_\nu^{-2.3}$ + AGN + Bkg
IceCube $E_\nu^{-2.3}$ + Bkg
Events
$log(E_\nu/\mathrm{GeV})$
High energy ν events, lightest m_ν =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
$log(E_\nu/\mathrm{GeV})$
Very High energy ν events, lightest m_ν =0.01 meV
Absorbed E_ν^{-2} + GZK + Bkg
Original E_ν^{-2} + GZK + Bkg
Absorbed E_ν^{-2} + AGN + Bkg
Original E_ν^{-2} + AGN + Bkg
IceCube Flat Spectrum + Bkg
Events
$log(E_\nu/\mathrm{GeV})$

The IceCube best fit combined with correlation data



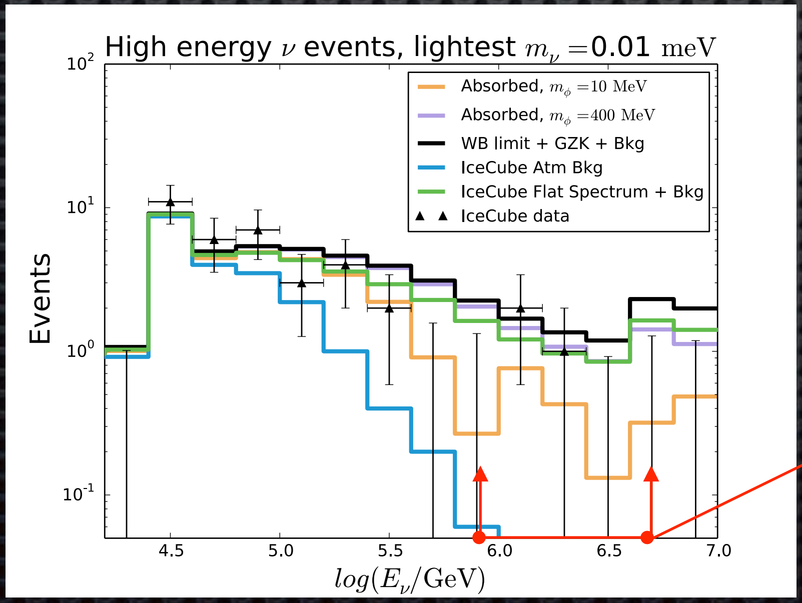




Side bonus: We might be able to measure the ν mass scale!

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

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



Δm^2_{atm}

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. For TeV decoupling, $.12 \leq \Delta N_{eff} \leq .3$
- Late time re-coupling creates a good deal of neutrino rest mass. Does this violate the bounds on the sum of light neutrino masses? (Hint: probably not)
- Neutrino self interactions with MeV scale mediators *will* do something in core collapse supernovae.

The canonical AGN neutrino flux prediction from 1997 - 2009:

THE ASTROPHYSICAL JOURNAL, 488:669–674, 1997 October 20

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

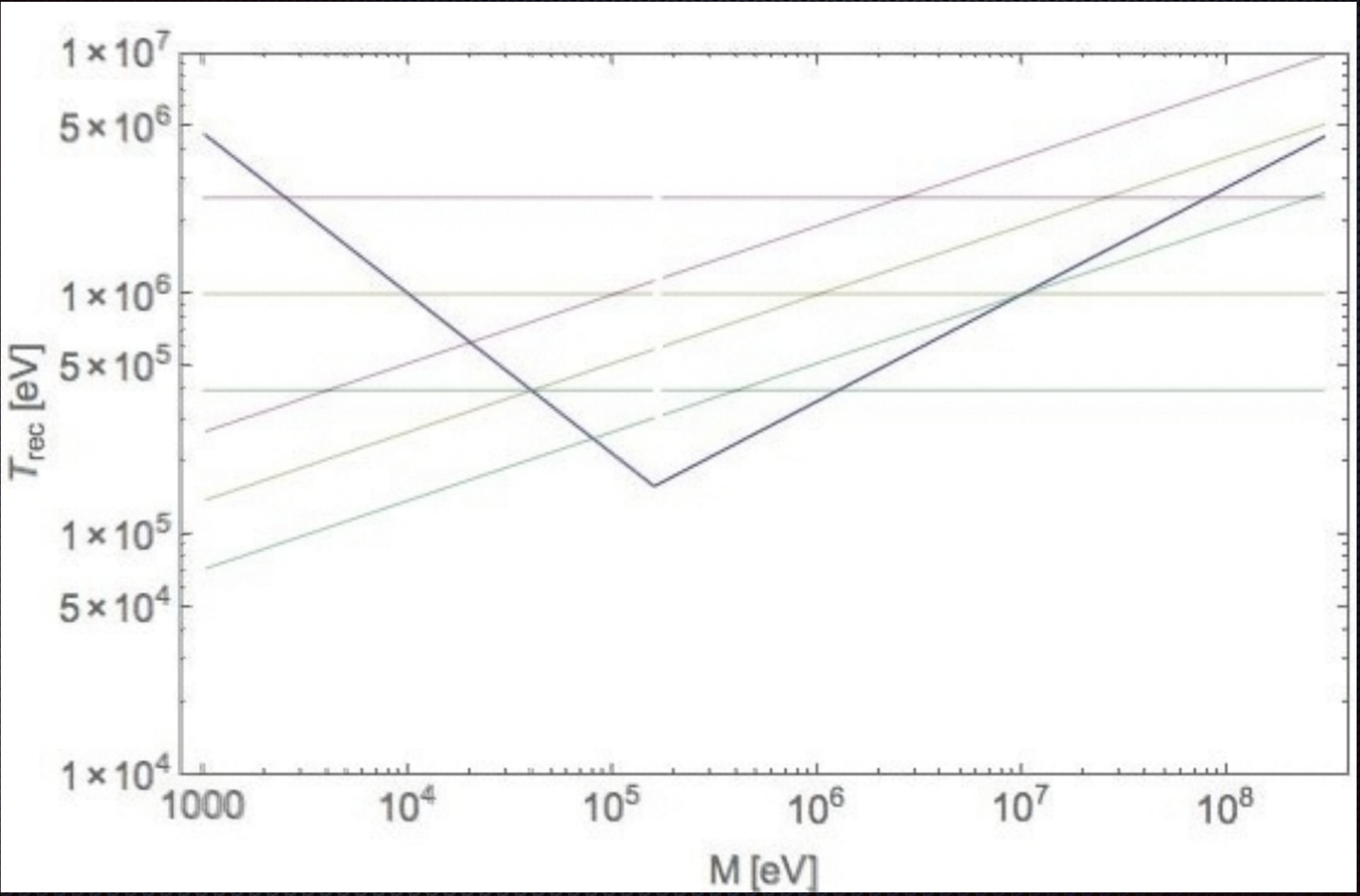
1. INTRODUCTION

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]