Astrophysical Neutrinos

Alex Friedland

SLAC

nu@Fermilab

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Based on J. Cherry, A.F., I. Shoemaker, arXiv: 1411.1071; + to appear

JJ Cherry
LANL postdoc ->
Virginia Tech

Ian Shoemaker
LANL postdoc ->
CP3, Denmark ->
Penn State

Observed neutrinos from beyond the solar system

- Ultra-high energy (up to 2 PeV)
    - IceCube
- Neutrinos from stellar core collapse (~10^7 eV)
    - SN1987a (Kamiokande, IMB)
- Relic neutrinos (~ eV at CMB decoupling)
    - Planck + other cosmological data

Self-interacting dark matter

- To get rid of cold cores, bring them in contact with hotter components of the halo. (Spergel & Steinhardt, PRL 2000 + hundreds more)
  - DM-DM scattering. Required cross section is

$$\sigma \sim 1 \text{ cm}^2 (m_X/g) \sim 10^{-24} \text{ cm}^2 (m_X/\text{GeV})$$

  - Obtained by requiring several collisions for each DM particle in the central region ("core") over the lifetime of a galaxy
  - Huge cross section! 10^2 fm^2 $\Rightarrow (10^7$ eV$)^{-2}$. Not achievable with weak scale
  - The mediator particle(s) should be in the **<10 MeV** range

Secluded sector

- Obviously, such a light mediator must be well isolated from the Standard Model fields -> ***Secluded sector***

- Search strategies depend on the form of the “portal” between the secluded and SM sectors

  - Known portals: kinetic mixing (dark photon searches), Higgs mixing

- Another important possibility: **through neutrino mixing**

  - Suppose the secluded sector contains a light fermion, which couples to the mediator ϕ. This fermion can mix with SM neutrinos.

    - *“Neutrino Portal”*

Neutrino Portal Framework

- The dark sector has a Higgs mechanism with a field η that gives ϕ its **light** mass

$$\mathcal{L} \sim LH\nu_R + \nu_D \eta \nu_R + M\nu_R \nu_R$$

- Simple renormalizable see-saw Lagrangian. Upon integrating out the heavy right-handed ν_R , one gets a light "sterile" ν_D mixing with the usual active neutrinos in L
- $$\mathcal{L}_{eff} \sim \frac{(LH)(\nu_D \eta)}{M}$$
- cf. "Mirror world", see Berezhiani and Mohapatra, hep-ph/9505385, and others
- Also akin to "baryonic neutrino" in Pospelov, arXiv:1103.3261, only our hidden gauge group does not directly couple to the SM baryon number (which could induce large NSI)

Dark-matter interactions with neutrinos?

- Interestingly, coupling between dark matter and neutrinos may further help alleviate the small-scale structure problems
  - Boehm et al, 2001, 2002, 2004; van den Aarssen, Bringmann, and Pfrommer, 2012
  - Coupling of SM to neutrinos early would keep DM density fluctuations from collapsing, until kinetic decoupling

$$M_{halo} \sim 10^8 M_\odot \left(\frac{\mathrm{keV}}{T_{KD}} \right)^3$$

  - Again, mediator masses of <10 MeV work! (see later)

DM-DM scattering

- Different physical regimes

  - "Classical" $m_X v \gg m_\phi$

$$\sigma_T \approx \begin{cases} \frac{2\pi}{m_\phi^2} & \beta^2 \ln(1+\beta^{-2}), \beta < 1, \\ \frac{\pi}{m_\phi^2} & \left(\ln 2\beta - \ln\ln 2\beta\right)^2, \beta > 1, \end{cases}$$

where $\beta \equiv 2\alpha_X m_\phi/(m_\chi v_{\rm rel}^2)$.

  - Born regime α_X $m_X \ll m_\phi$

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

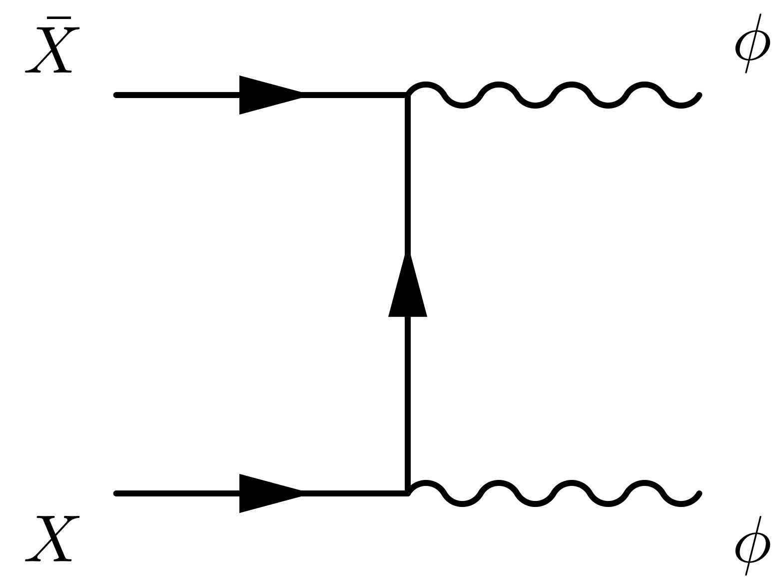
  - See Feng, Kaplinghat, Yu, PRL 2010; Tulin, Yu, Zurek, PRD 2013.

Relic DM abundance

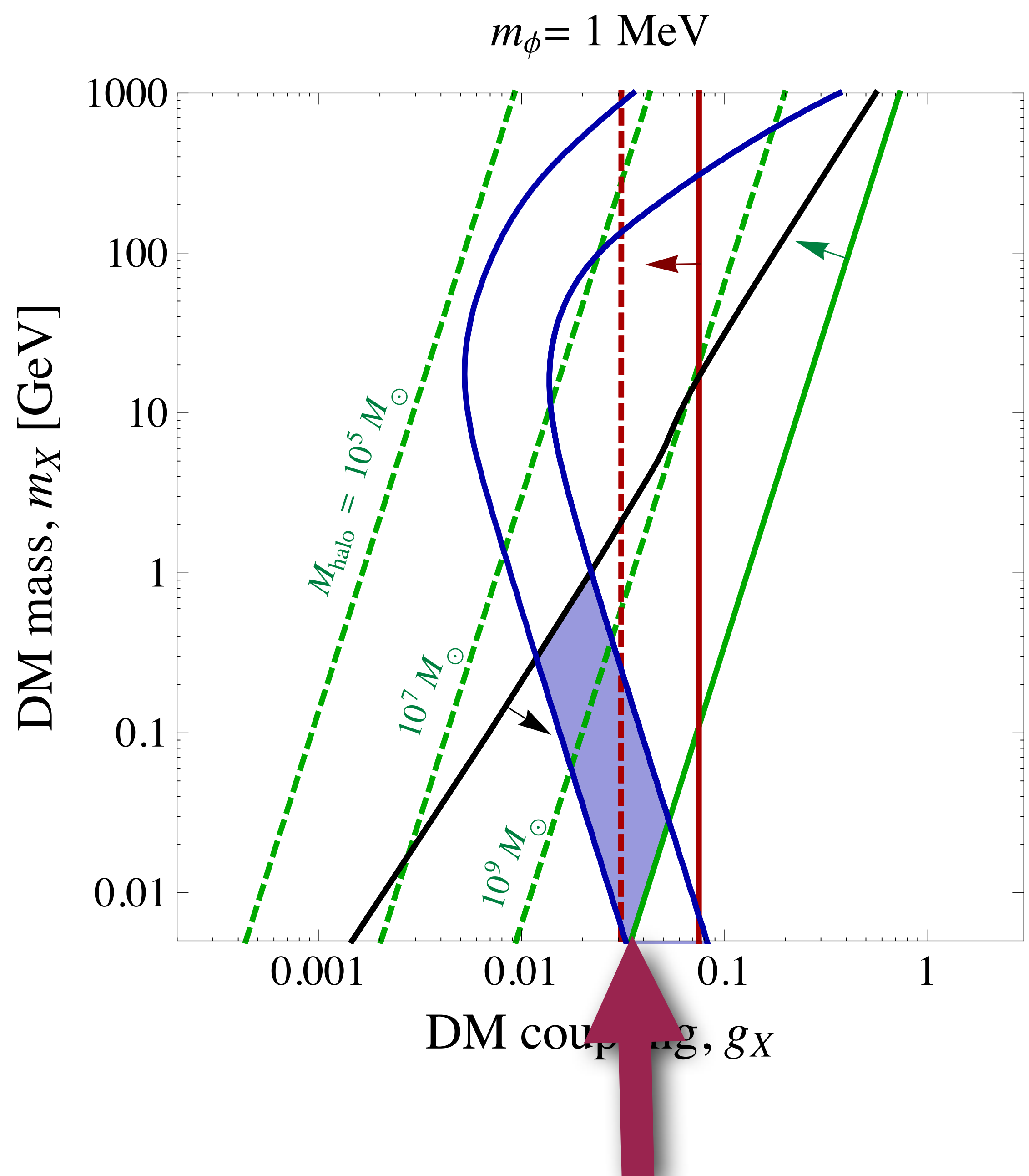
- We don't want DM to overclose the universe -> the annihilation cross section has to be large enough

- The excludes small couplings

- Larger couplings are allowed if DM is asymmetric



Results: self-interactions + kinetic decoupling + relic DM abundance



Cherry, Friedland, Shoemaker, arXiv:1411.1071

Testing neutrino-neutrino interactions?

- We have discussed DM-DM and DM-neutrino interactions.
- How about neutrino-neutrino interactions?
- This may be the hardest interaction among the SM particles to constrain!
- A classic problem!
  - Bounds of the order of 10^3-10^5 G_F have been quoted
  - For 10 MeV mediator, this is a nontrivial restriction!

Volume 32B, number 2 PHYSICS LETTERS 8 June 1970

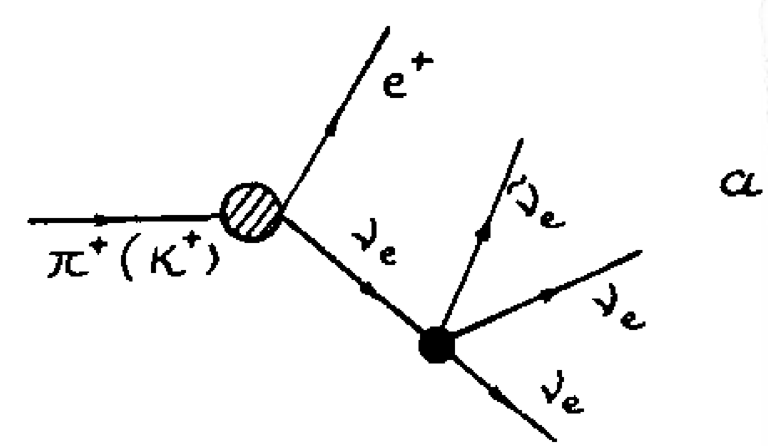
ON THE ν - ν INTERACTION

D. Yu. BARDIN, S. M. BILENKY, B. PONTECORVO
Joint Institute for Nuclear Research, Dubna, USSR

Received 28 April 1970

A new hypothetical interaction between neutrinos is considered. It is shown that even relatively strong $\nu_e - \nu_e$, $\nu_\mu - \nu_\mu$ and $\nu_e - \nu_\mu$ interactions are not in contradiction with existing data and upper limits for the corresponding interaction constant are obtained. New experiments are suggested which might give information on $\nu - \nu$ interactions.

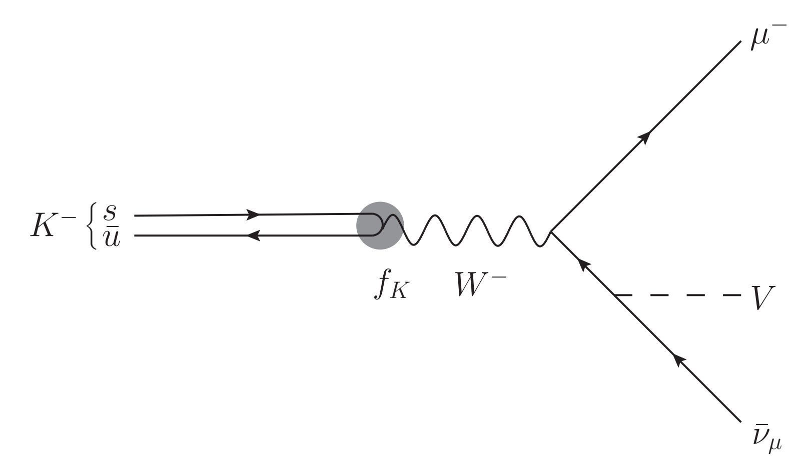
- Bardin, Bilenky, Pontecorvo (1970)
- Barger, Keung, Pakvasa (1982)
- Bilenky, Bilenky, Santamaria (1993)
- ...



Anomalous meson decay spectra

Most of these constraints are complete avoided

- The neutrino portal framework is distinct from hard 4-fermi interactions:
  - Neutrinos in laboratory are produced as flavor states, don't have the ν_S component until they oscillate.
  - Spectra measured in the laboratory detector are from 2-body final states



Astrophysical bounds

- Manohar (1987)
- Kolb & Turner (1987)
- Fuller, Mayle, Wilson (1988)

- These are more tricky!
- In dense environments such as supernova, large matter potential reduces the admixture of the “sterile” state --> Manohar (1987) does not apply.
    - Detailed analysis warranted!

IceCube neutrinos as probes of new physics

Neutrino-neutrino collider?

- We need to collide neutrino mass eigenstates, which have admixture of the "sterile" component that endows them with new interactions

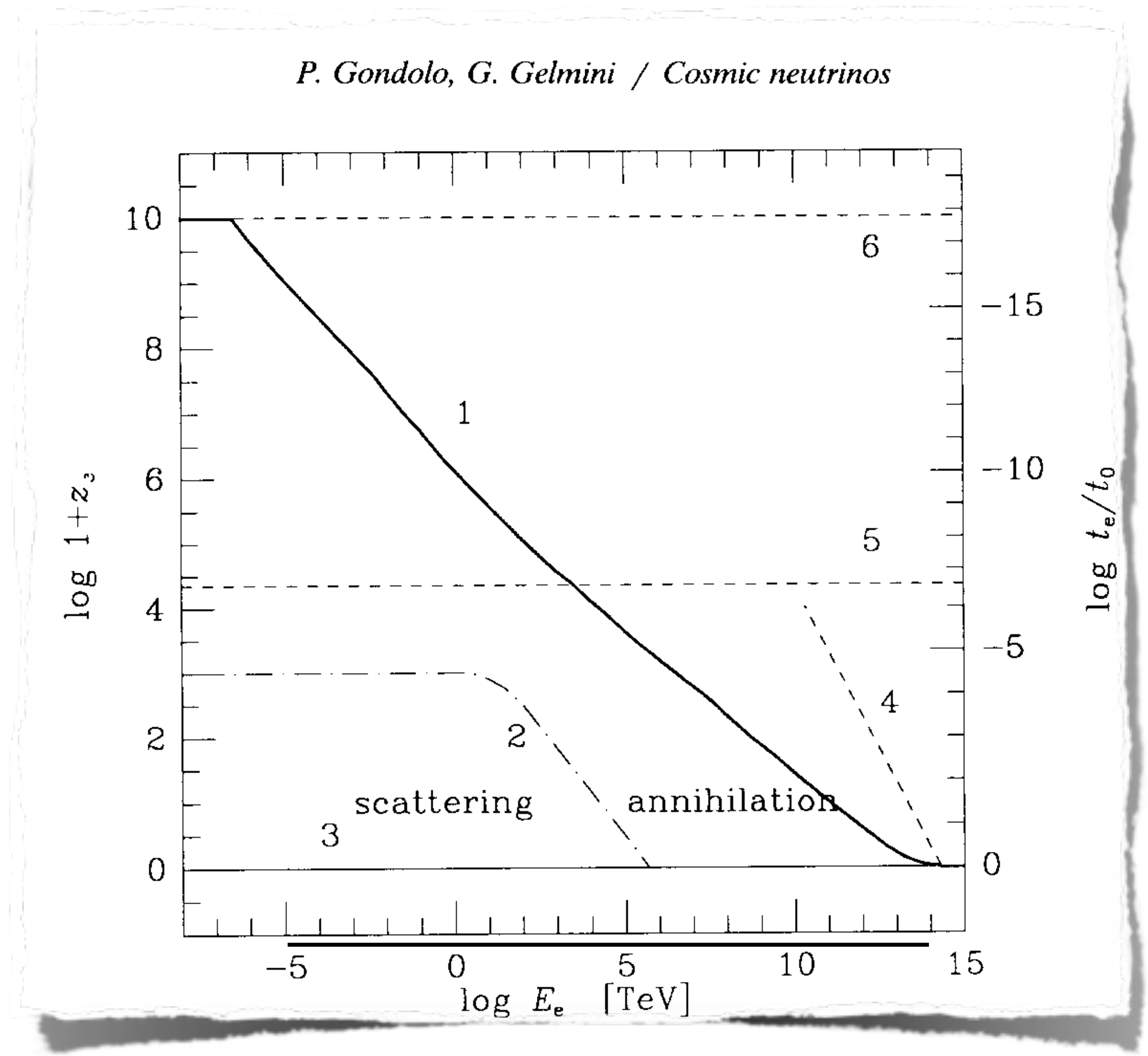
- Not feasible in a terrestrial lab, but we can use the universe as the lab

- **Icecube** has observed neutrinos in the PeV energy range, that likely originate from cosmological distances

- These neutrinos on their way to us travel through the relic neutrino background. Both the beam and the background had enough time to oscillate and separate into mass eigenstates.

Standard model: Z-bursts

- It is well known that in the SM the universe is transparent to neutrinos with energies below ~10^{22} eV
- At those ~10^{22} eV, the neutrinos finally get scattered/absorbed because of the s-channel Z-boson resonance
  - T. Weiler, PRL 1982



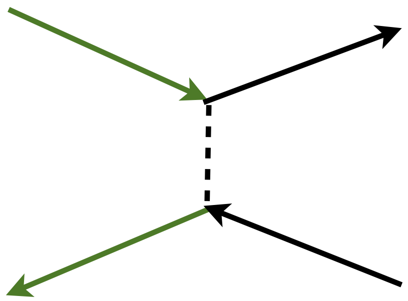
Gondolo, Gelmini, 1993

$$E_{c.m.} \sim \sqrt{(10^{-1}\ \text{eV})(10^{23}\ \text{eV})} \sim 10^2\ \text{GeV} \sim m_Z$$

Light mediator

- The standard transparency conclusion is based on standard physics only

- We now have a light mediator particle



  - resonant condition
    $$m_\phi^2 = s \approx 2m_\nu E_\nu$$
    $$\Longrightarrow m_\phi \sim \sqrt{(10^{-1}\ \mathrm{eV})(10^{15}\ \mathrm{eV})} \sim 10^7\ \mathrm{eV}$$

  - ***<u>The same mass scale as for the dark matter self-interactions!</u>***

  - After scattering, neutrinos are mostly converted into the “sterile” state, disappear from the observed flux

Some rough estimates

- Resonant cross section is bigger than SM on the Z pole, since ϕ is lighter

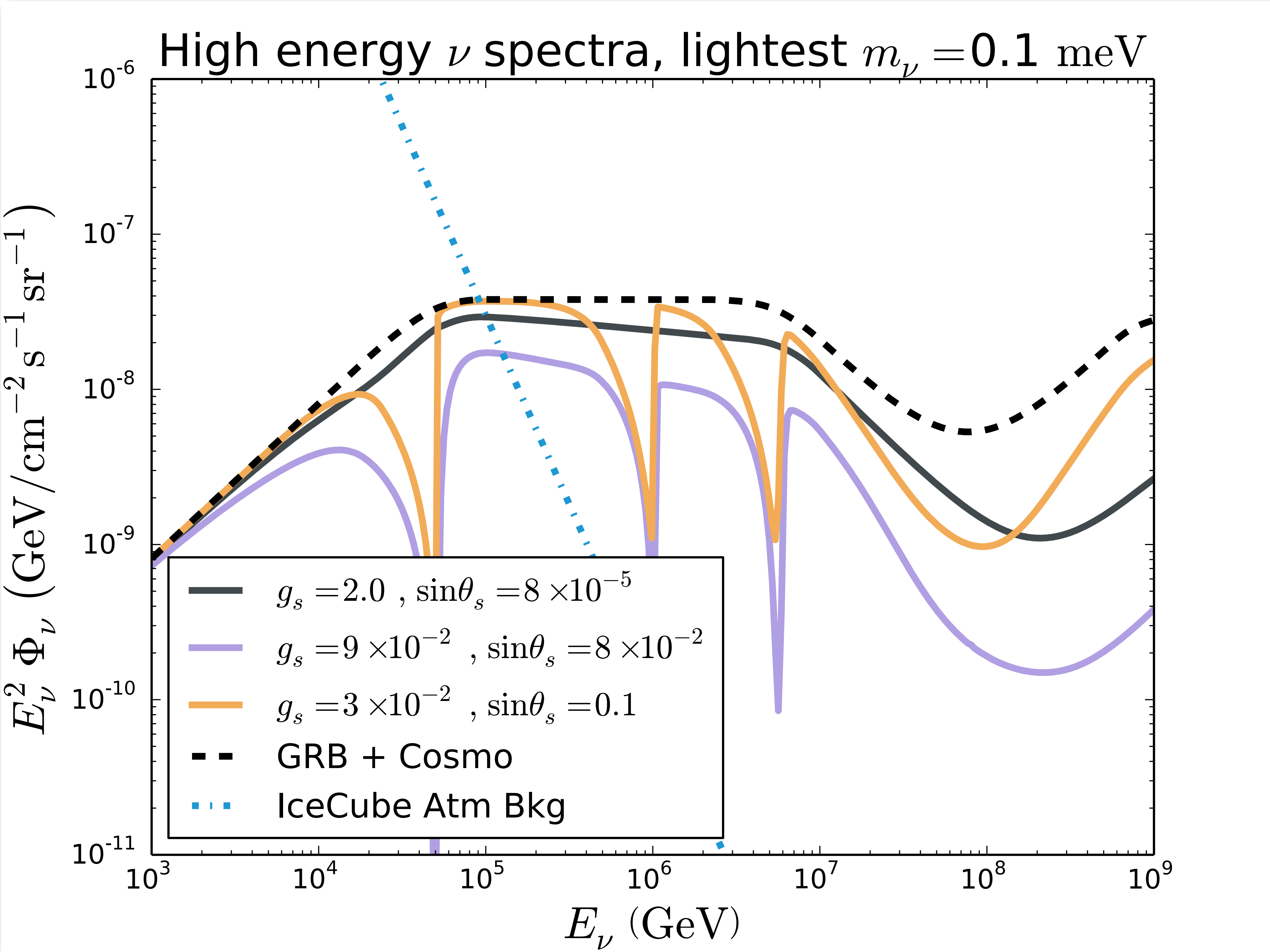
$$\sigma_{res} \sim (\#) m_\phi^{-2} \sim (\#) 10^{-24}\ \mathrm{cm}^2$$

- Given relic neutrino number density ~ 10^3 (we assume astrophysical sources at z of several), we can (first very roughly) estimate that

$$\sigma_{intersting} \sim (l \times n)^{-1} \sim (\mathrm{Gpc} \times 10^3\ \mathrm{cm}^{-3})^{-1} \sim 10^{-31} cm^2$$

- Therefore, there is plenty of room for the numerical coefficient in the cross section formula to be small (due to small coupling and/or small mixing)

- Also, there is room for the redshift effects to work (see later)



Example calculation

Sources are GBRs (Waxman-Bahcall) + AGNs at high E

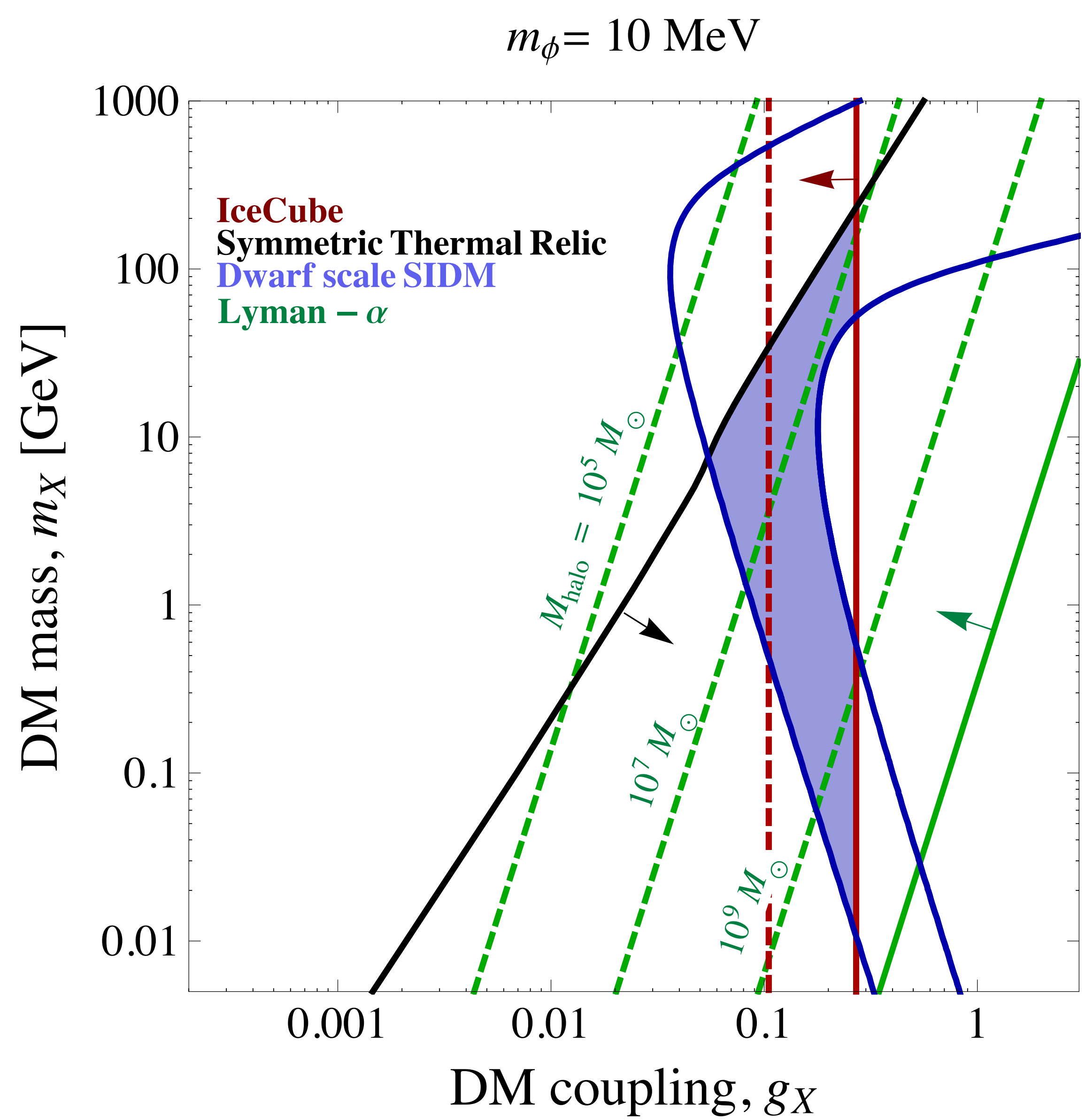
More interesting implications: source correlations

- Too much absorption would be mean no isotropy of sources

- Intermediate range could mean absorption from far sources

  - GZK-type horizon for neutrinos

  - Look for source correlations!

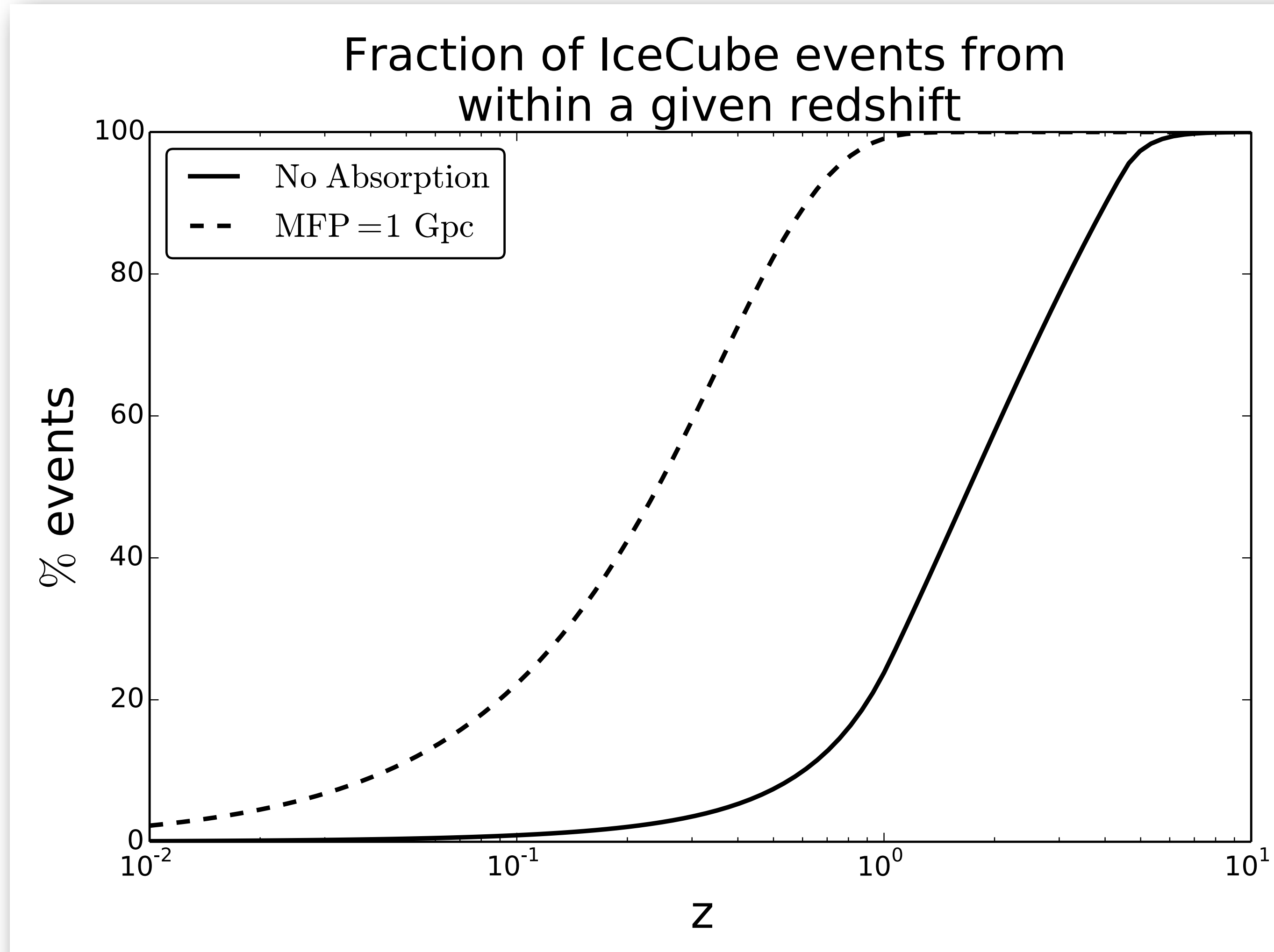


GZK-type horizon for neutrinos

- With putative absorption, UHE neutrinos are detected only from close sources, which could potentially be correlated with known objects

- In future high-statistics data, look for anisotropies, especially correlated with the local structure

- Absence of 10^{18} GeV neutrinos from AGNs, GZK neutrinos?



Numerous physical scenarios

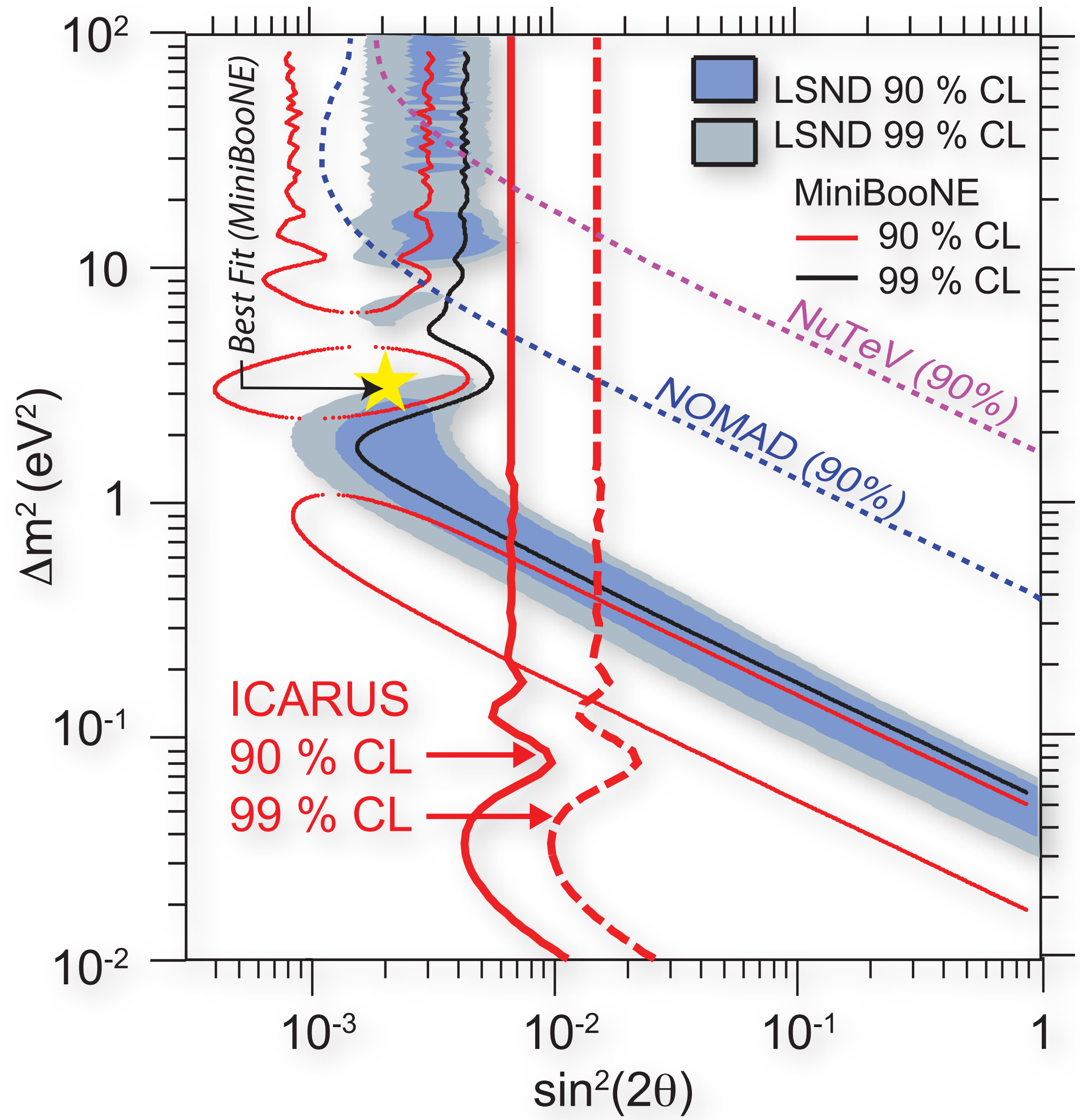
- In general, one can vary:
  - Mixing angles and couplings
  - Overall mass scale of light neutrinos
  - Mass hierarchy
  - Cosmological abundance of “sterile” neutrinos (model-dependent)
- It could be a theorist’s dream
  - ...and an experimentalist’s nightmare!

Secluded neutrinos and cosmological data

Is MiniBooNE ruled out by Planck?

Sterile neutrinos: Short-baseline oscillations vs cosmological data

- Aim: to conclusively test the anomalies of LSND/MiniBooNE as oscillations
- Hints for $\Delta m^2 \sim 1\ \mathrm{eV}^2$
  - Not one of the standard splittings between the known flavors
  - Additional neutrino states required
- Two-step conversion: $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$



ICARUS, 1307.4699

Sterile neutrino production in the early universe

- Oscillations + collisions!

- SM neutrino decoupling from electron-positron plasma: σ n ~ expansion rate

$$G_F^2 T^2 T^3 \sim T^2/M_{pl} \to T_{dec}^{SM} \sim (G_F^2 M_{pl})^{-1/3} \sim 2 \text{ MeV}$$

- If sterile neutrinos are brought into equilibrium with active earlier, dangerous!

- Oscillations alone:

$$P(\nu_a \to \nu_s) = \sin^2 2\theta_{as} \sin^2(\Delta m^2/4Et) \to (1/2) \sin^2 2\theta_{as}$$ for t> 4E/Δm^2

- Collisions are flavor-sensitive; project the state on the |e>, |s> flavor basis state, allows oscillations to restart. Rate of flavor change: $G_F^2 T^2 T^3 (1/2) \sin^2 2\theta_{as}$

Dolgov & Barbieri (1990) + hundreds more since

- Equilibration: $G_F^2 T^2 T^3 \sin^2 2\theta_{as} \sim T^2/M_{pl} \to T_{eq}^{SM} \sim (G_F^2 M_{pl} \sin^2 2\theta_{as})^{-1/3} \sim 10 \text{ MeV}$

Active-sterile conversion: earlier times

- We saw that

$$T_{eq}^{SM} \sim (G_F^2 M_{pl} \sin^2 2\theta_{as})^{-1/3} \sim 10 \text{ MeV}$$

- The situation changes when

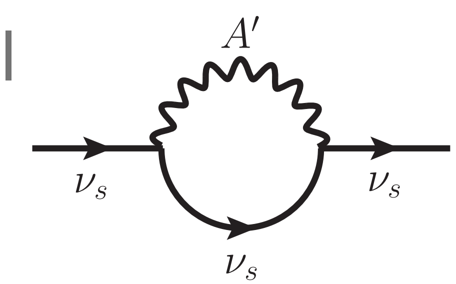
$$G_F^2 T^2 T^3 \gtrsim \Delta m^2/T \rightarrow T \gtrsim (\Delta m^2/G_F^2)^{1/6} \sim 50 \text{ MeV}$$

- The active-sterile system was again not in equilibrium earlier!
  - When collisions are more frequent than the oscillation length, the oscillations are reset too soon (the Quantum Zero effect)
  - The (CP-symmetric) medium creates an MSW potential, ~ $G_F^2 T^5$, that suppresses oscillations [Notzold and Raffelt (1988)]
- For sufficiently small mixing angles, the ν_s production is never equilibrated; in the scenario of ν_s DM, this allows making just enough ν_s, without overclosing the universe [Dodelson and Widrow (1994)]

New interactions in the hidden sector

- Can sterile neutrinos with the mixing angle required by the short-baseline anomaly be reconciled with cosmology?

- Suppress mixing angle with a new term in the MSW potential



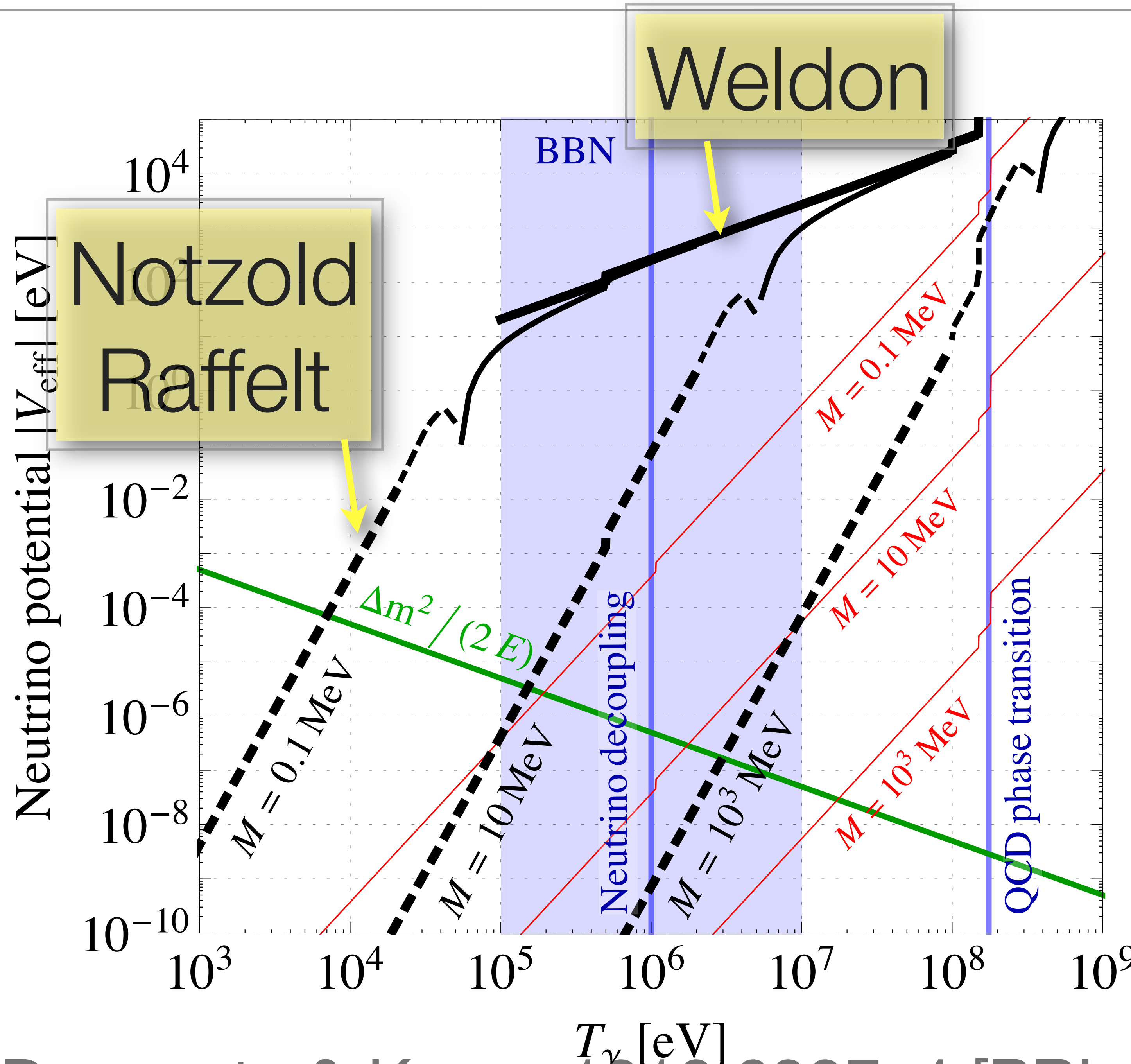
B. Dasgupta, J. Kopp, PRL (2014);
S. Hannestad, R. S. Hansen, and T. Tram, PRL (2014);
originally Babu & Rothstein, Phys.Lett. B275 (1992) 112-118

- Imagine that the sterile neutrinos are not sterile, they carry a hidden gauge quantum number. That would generate a new potential.

  - Repeating the standard arguments, one finds two regimes for the potential
  - $$V \sim -\frac{g^4 E T^4}{M^4}, \ T, E \ll M$$ Notzold & Raffelt (1988)
    $$V \sim +\frac{g^2 T^2}{E}, \ T, E \gg M$$ Weldon (1982)

K. Enqvist, K. Kainulainen, and J. Maalampi, Nucl.Phys. B349, 754 (1991).
C. Quimbay and S. Vargas-Castrillon, Nucl.Phys. B451, 265 (1995), hep-ph/9504410.

Mixing suppression



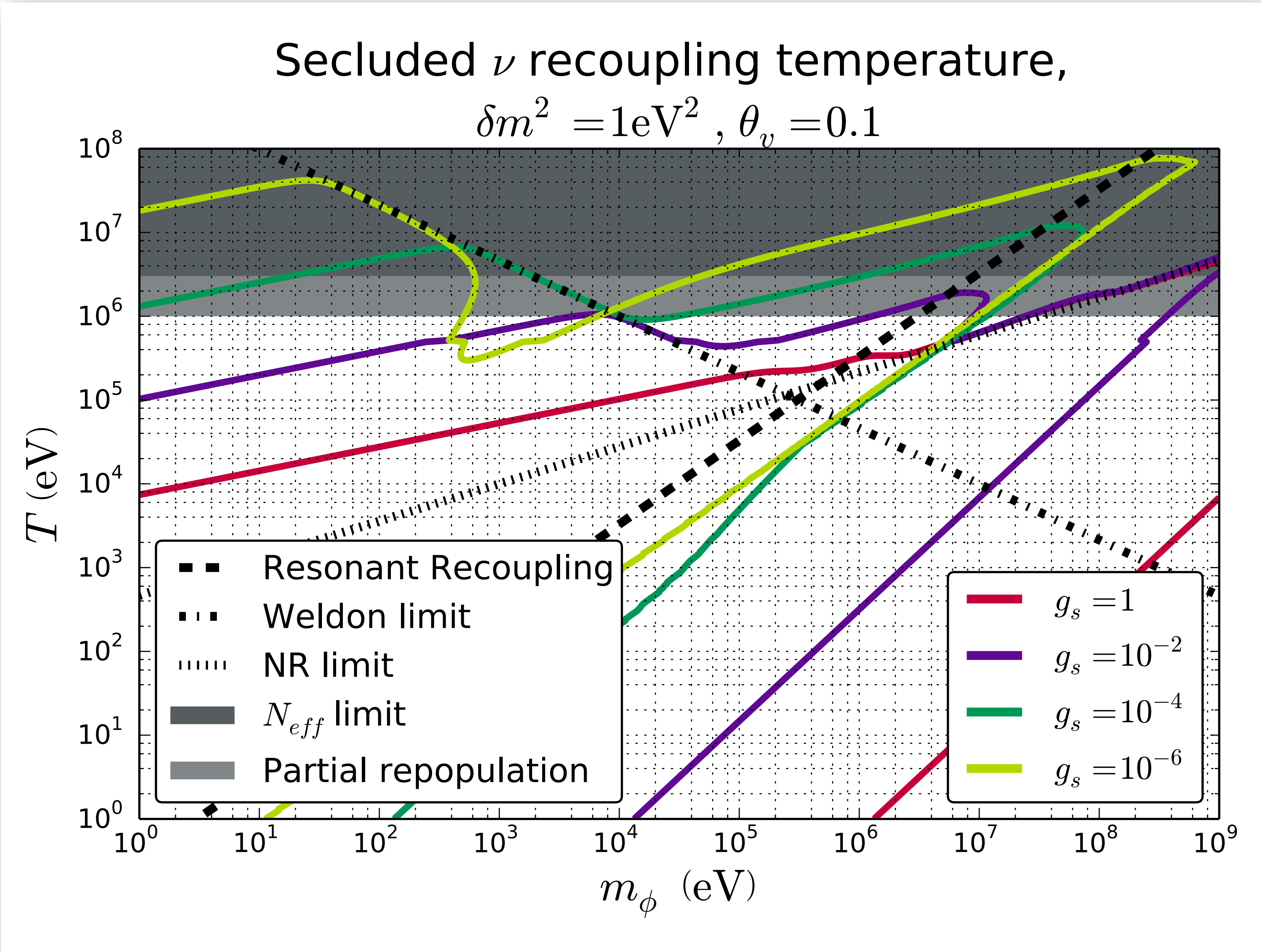
- From Dasgupta & Kopp, 1310.6337v4 [PRL 2014]

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** (2015) These models agree with Planck, but only marginally.
- Archidiacono, Hannestad, Hansen, and Tram, Phys. Rev. D **91 (**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.

We do not agree with any of them!

Cherry, Friedland, Shoemaker, to appear



Large coupling: excluded by free-streaming

- Notice that for for large coupling, neutrinos, even the ones predominantly active, become non-free-streaming at the CMB epoch

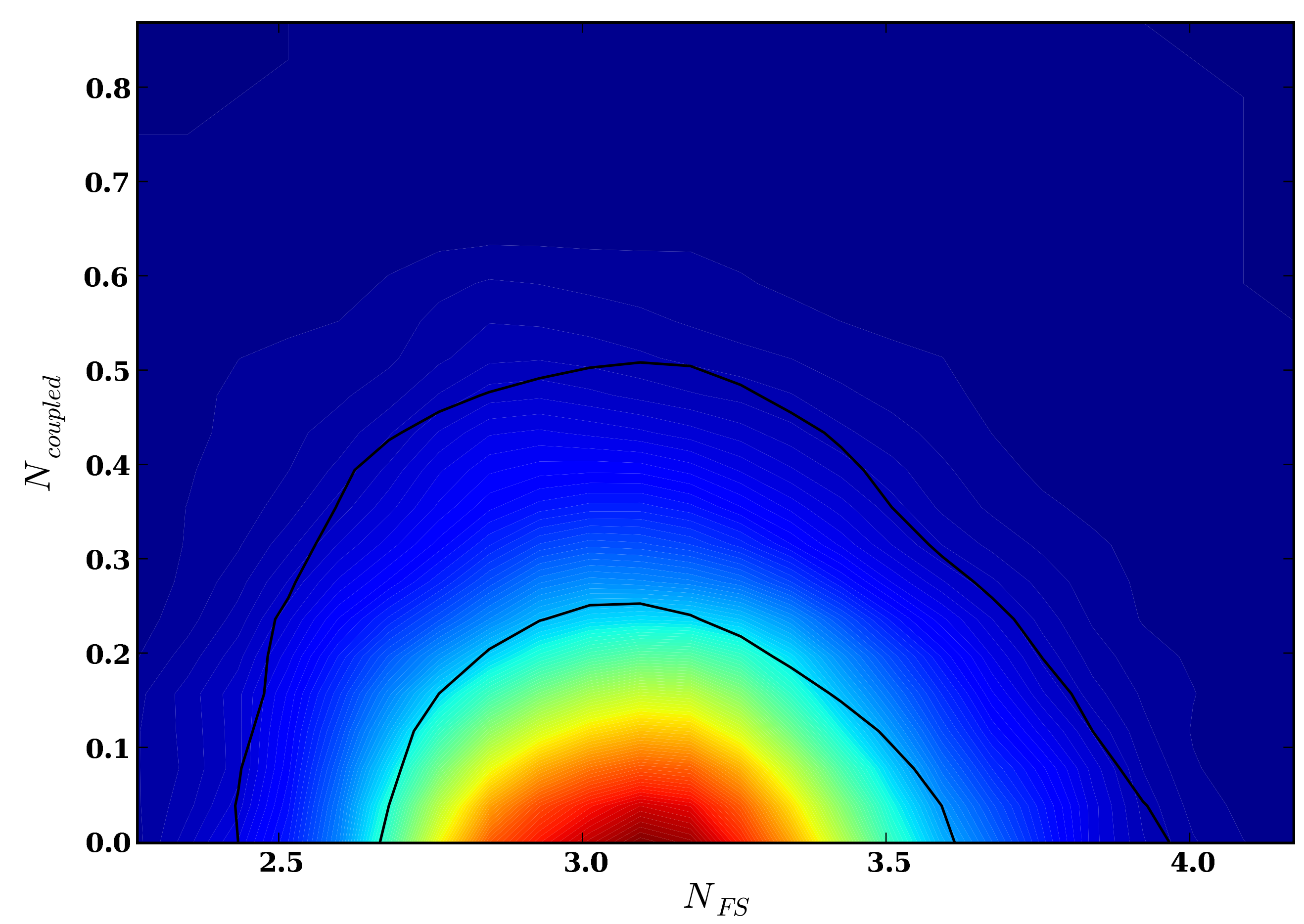
- This would be in conflict with PLANCK

$$g_{eff} < (T_{rec}/M_{pl})^{1/4}(M/T_{rec})$$

Friedland, Zurek, Bashinsky, 0704.3271

$$g_{eff} < 10^{-7}(M/1\ \mathrm{eV})$$

Here, g_{eff} is effective coupling, g sin$\boldsymbol{\theta}$□ □



- Planck 2015 [arXiv: 1502.01589] reports N_{eff}=3.15±0.23 and for the mass m_ν < 0.23 eV

Summary

- Several astrophysical hints may be pointing to the existence of a light, well-secluded sector
- An independent set of hints is furnished by the short-baseline anomalies
- UHE neutrinos detected by Icecube may be direct probes of this type of new physics
    - Valid whether of not the small-scale structure deficit stands the test of time
- A number of smoking-gun signatures, including absorption troughs and source correlations, due to the existence of the GZK-type horizon for neutrinos
- The cosmological part of the story is fascinating! (Whether SBN anomalies can survive PLANCK et al)