Third Biennial Workshop on

Dark Interactions

Perspectives from Theory and Experiment

October 2 - 5, 2018

Brookhaven National Laboratory

https://www.bnl.gov/di2018/

Neutrinos and Dark Sectors

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October 4, 2018

What are “Dark Interactions”?

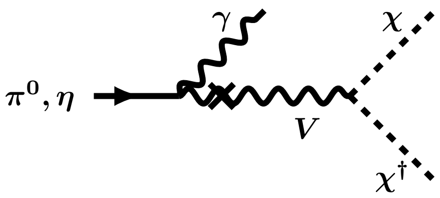
- I did a little poll yesterday among the participants. The answers were all over the places:
  - “Interactions of Dark Matter”
  - “Light mediators in the sector containing dark matter”
  - “Light mediators in hidden sectors”
  - “Particles with small masses and small cross sections. Everywhere in the universe, but hard to see and require dedicated detectors.”

What are “Dark Interactions”?

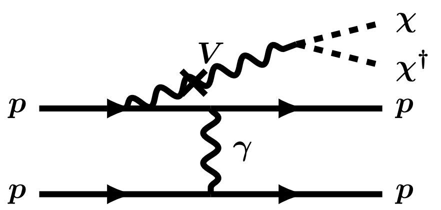
- “Particles with small masses and small cross sections. Everywhere in the universe, but hard to see and require dedicated detectors.”
  - Axions!
  - Neutrinos?..

Q1. Can neutrino experiments help us with dark interactions?

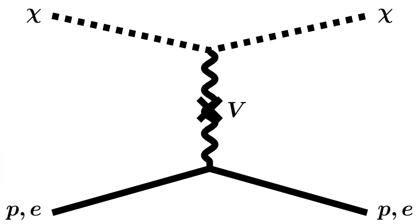
- Neutrino experiments can be used to place bounds on dark forces
    - See MiniBOONE-DM talk to follow this one!



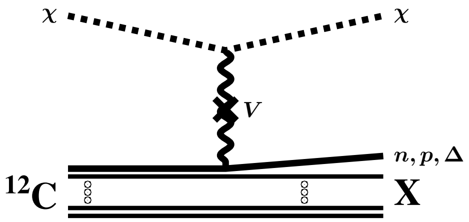
(a) Meson Decay



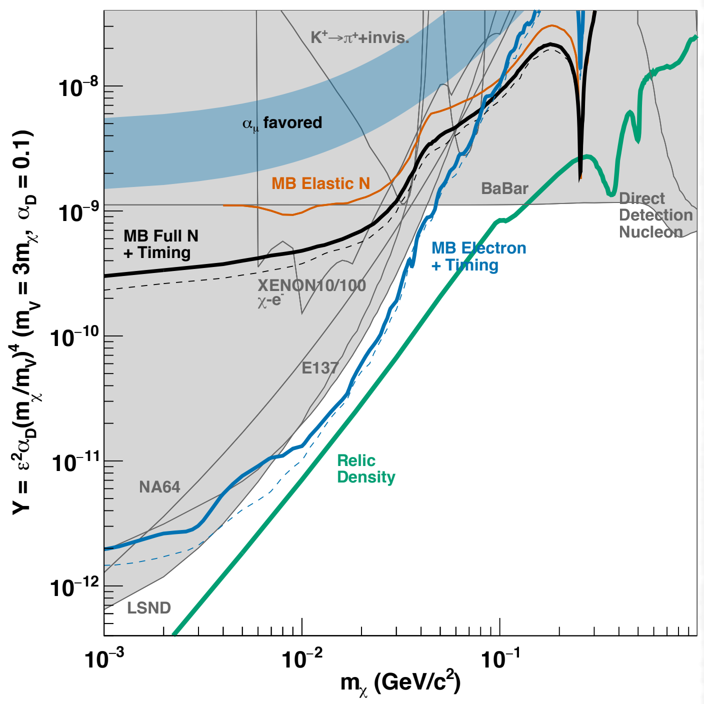
(b) Proton Bremsstrahlung + Vector-Mixing



(a) Free Protons or Electrons



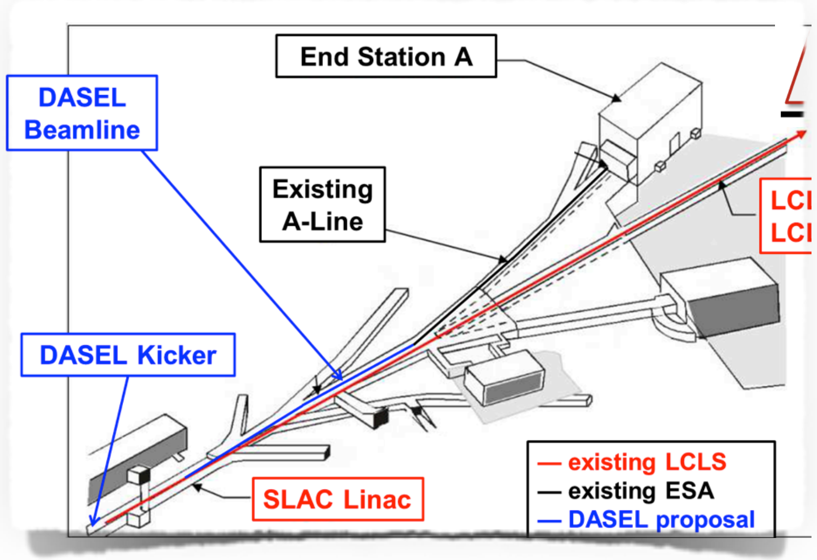
(b) Bound Nucleons

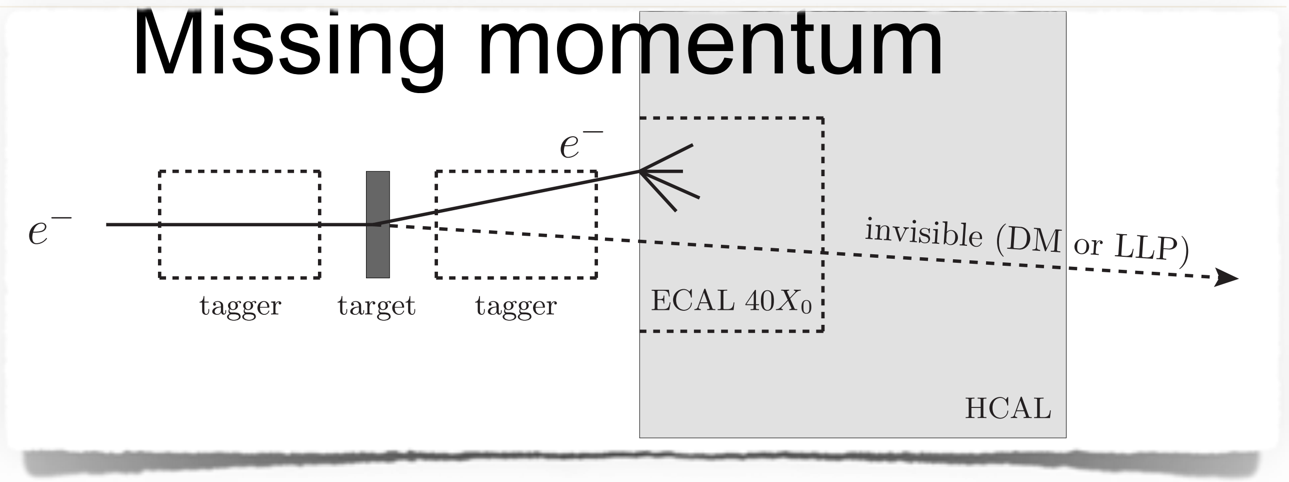


(a) vector portal ($\alpha_D = 0.1, m_V = 3m_\chi$)

Q2. Can dark interactions experiments help us with neutrinos?

- Fixed target electron scattering DM searches can be used to improve neutrino nucleus scattering physics
  - Ankowski, A.F., Schuster, Toro, under investigation



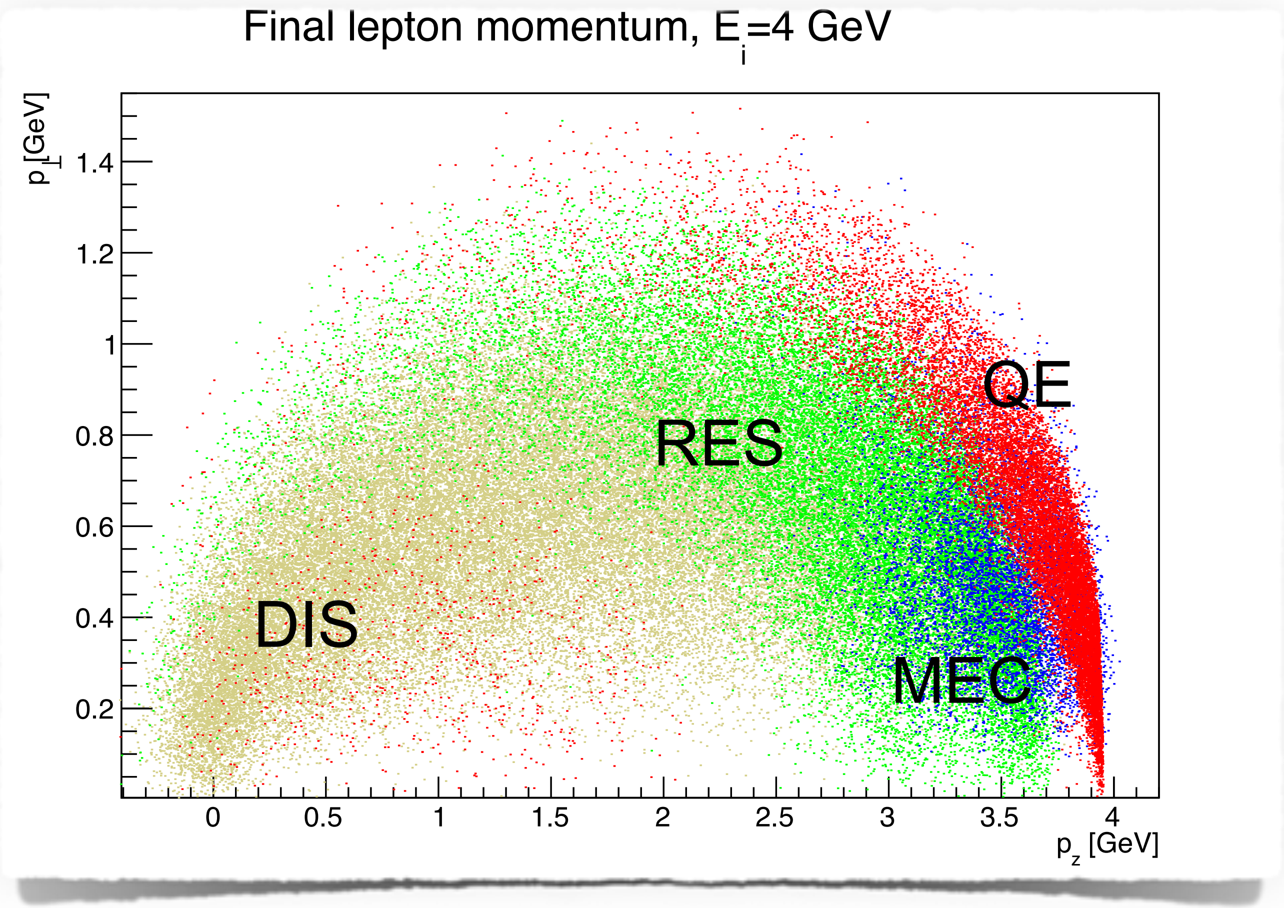

Missing momentum

Study “background”
e + N -> e + N’ + hadrons

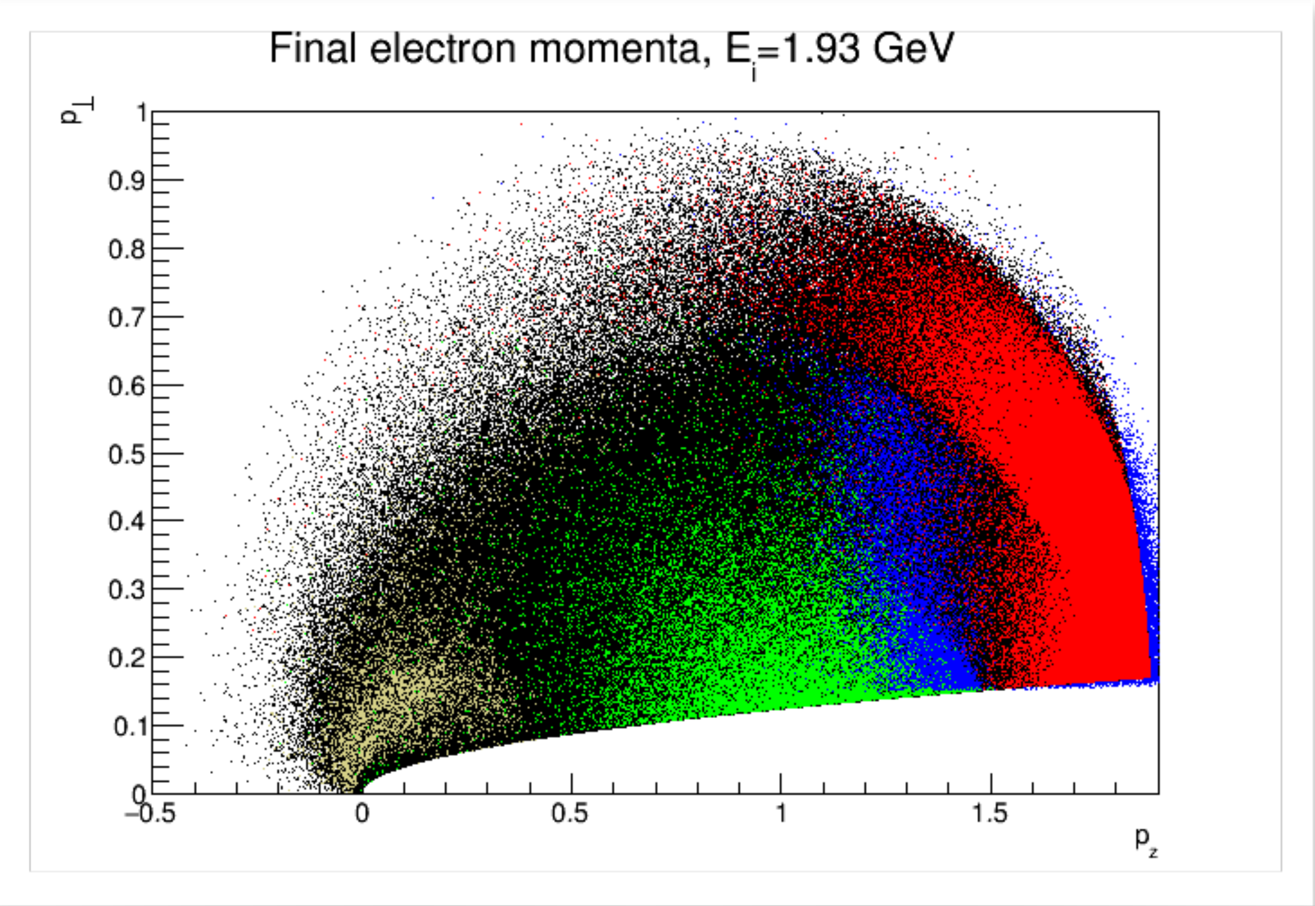
Physics of neutrino scattering

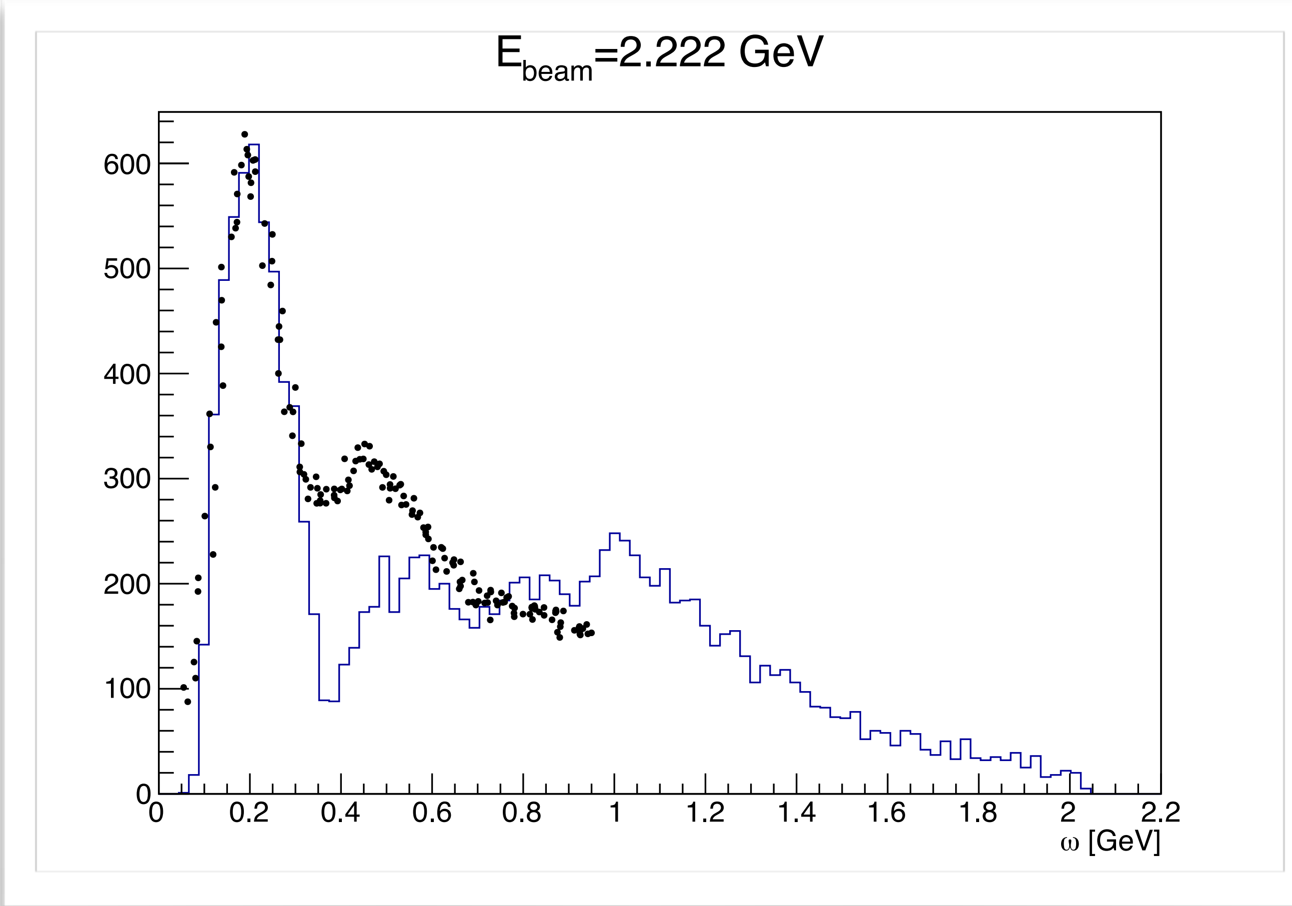
- Neutrino scattering is modeled with generator codes, e.g. GENIE

- We need to test/validate all this physics
  - how each component is constrained by the world's best data
  - how the errors in each propagate through the oscillation analysis



Electron scattering comparison





- Common physics includes
  - Initial nucleon momentum distribution (spectral function)
  - Final state interactions
  - Hadronization at several GeV, meson exchange currents, etc
- Generator predictions show considerable discrepancies with the electron scattering data collected at JLab last year
  - Ankowski, A.F., Li, in prep

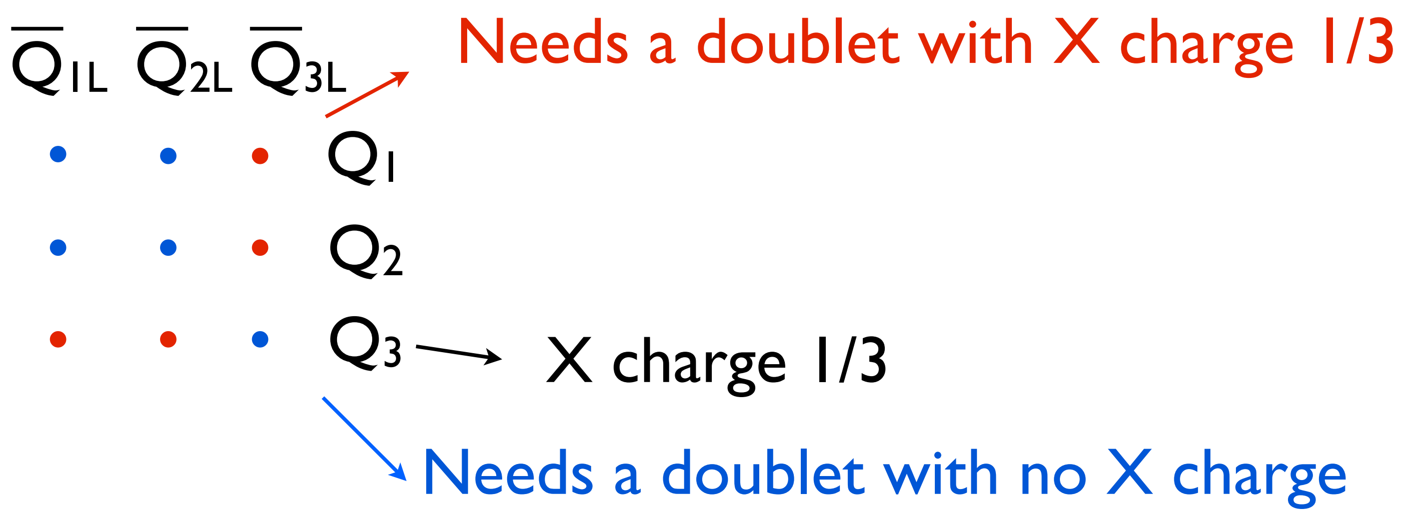
Can neutrinos themselves have “dark” interactions?

- Two broad classes of ideas
  - A new gauge group that couples to some subset of SM fields, including neutrinos
  - Dark force that couples only to neutrinos
    - Neutrino portal

Example: gauging the third generation

- Motivation: the 3rd generation quarks don’t like to mix with the first two
- What if they carry an additional gauge interaction? $(B-L)_3$ is anomaly-free
    - Then you can’t couple them to the first two generations using the usual SM Higgs, $Q_{1,2}H_{SM}d_3 \to Q_{1,2}H_3d_3$

We need an additional doublet to generate CKM mixing



$$\begin{array}{cccl} \overline{Q}_{1L} & \overline{Q}_{2L} & \overline{Q}_{3L} & \\ \bullet & \bullet & \bullet & Q_1 \\ \bullet & \bullet & \bullet & Q_2 \\ \bullet & \bullet & \bullet & Q_3 \end{array}$$

Needs a doublet with X charge 1/3

X charge 1/3

Needs a doublet with no X charge

For other reasons we will need a SM singlet with X charge 1/3

The new light mediator will mix with the Z

U(1)$_{B\text{-}L}^{(3)}$

$$M^2_{\mathrm{gauge}} = \frac{1}{4}\begin{pmatrix} \overset{M_Z^2}{\boxed{(g^2+g'^2)v^2}} & \overset{\text{Mixing between X and Z}}{\boxed{-2\sqrt{g^2+g'^2}\,g_X v_1^2/3}} \\ -2\sqrt{g^2+g'^2}\,g_X v_1^2/3 & \underset{M_X^2}{\boxed{4g_X^2(v_1^2+v_s^2)/9}} \end{pmatrix}$$

$$Z_\mu \simeq -s_w B_\mu + c_w W^3_\mu - s_X X^0_\mu,$$
$$X_\mu \simeq s_X(-s_w B_\mu + c_w W^3_\mu) + X^0_\mu,$$

$$s_X \equiv \frac{2}{3}\frac{g_X}{\sqrt{g^2+g'^2}}\frac{v_1^2}{v^2}$$

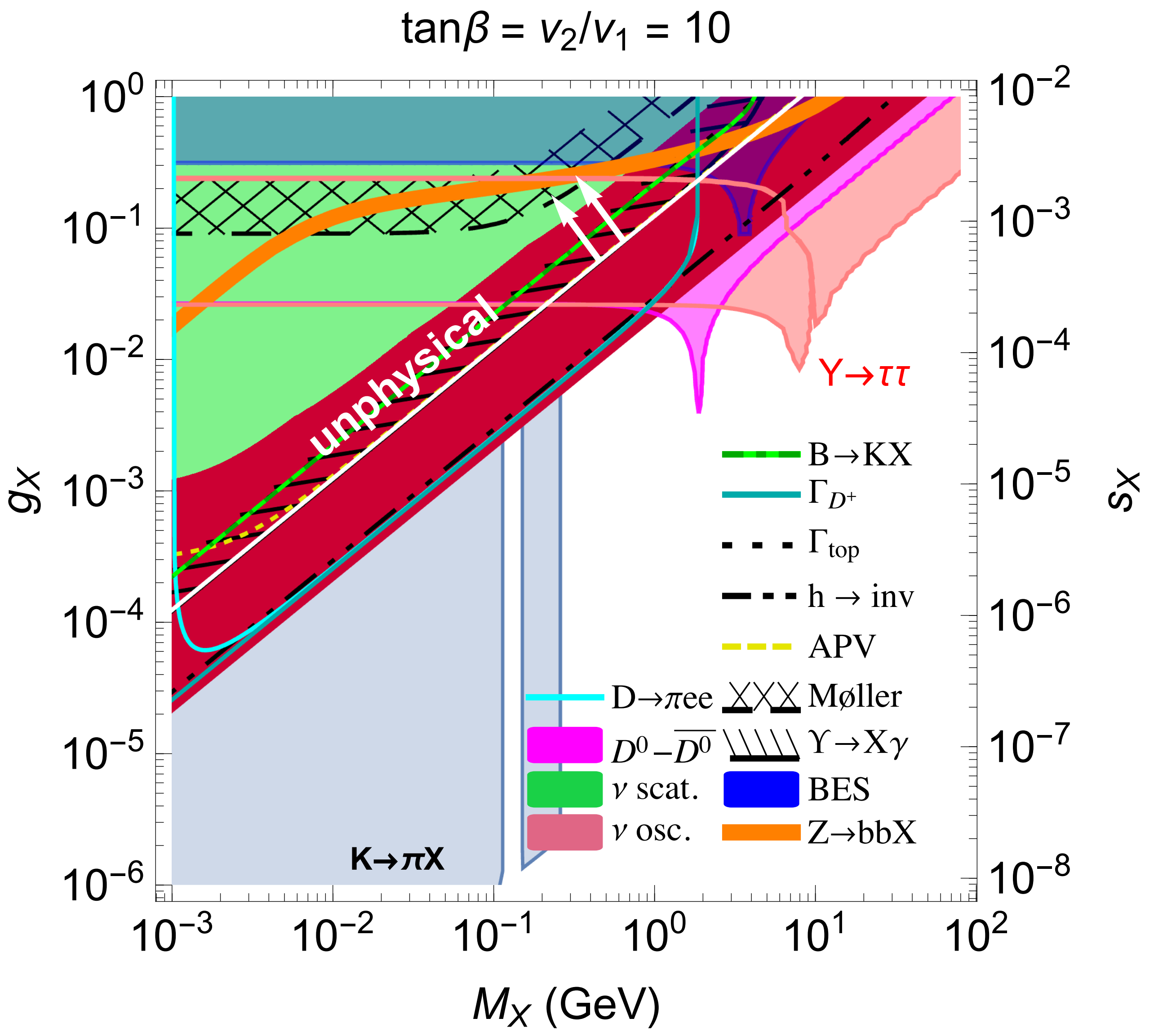
$$M_X^2 = \frac{1}{9} g_X^2 \left(\frac{v_1^2 v_2^2}{v^2} + v_s^2\right)$$

Small X-Z mixing (EW precision data) suggests small g_X
as well as M_X below the weak scale

For instance, $g_X = 10^{-3} \sim 10^{-2}$ could correspond to M_X = 100 MeV ~ 1 GeV

This will generate nonstandard neutrino interactions …

- … as well as Dozens of other constraints!
  - From rare meson decays to atomic parity violations, to nonstandard oscillation effects
- Neutrino physics intertwined with the rest of the field



See K.Babu, A. F., P. Machado, I. Mocioiu, JHEP 1712 (2017) 096 for details

Neutrino portal

- Finally, let us consider a scenario when neutrino provide the only link between the secluded sector and the Standard Model

- Standard argument: consider dim 4 operators

  - Kinetic mixing portal: $F F'$

  - Higgs portal $|H|^2|\eta|^2$

  - Neutrino portal $HL\nu_R$

This is not a portal! Only half a portal

- The neutrino portal we will consider is mediated by dim 5 operator $$\frac{(HL)(\eta\nu_h)}{\Lambda}$$

Neutrino Portal

- A light fermion in the "dark sector". The dark sector contains a broken gauge group (call the mediator ϕ).

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

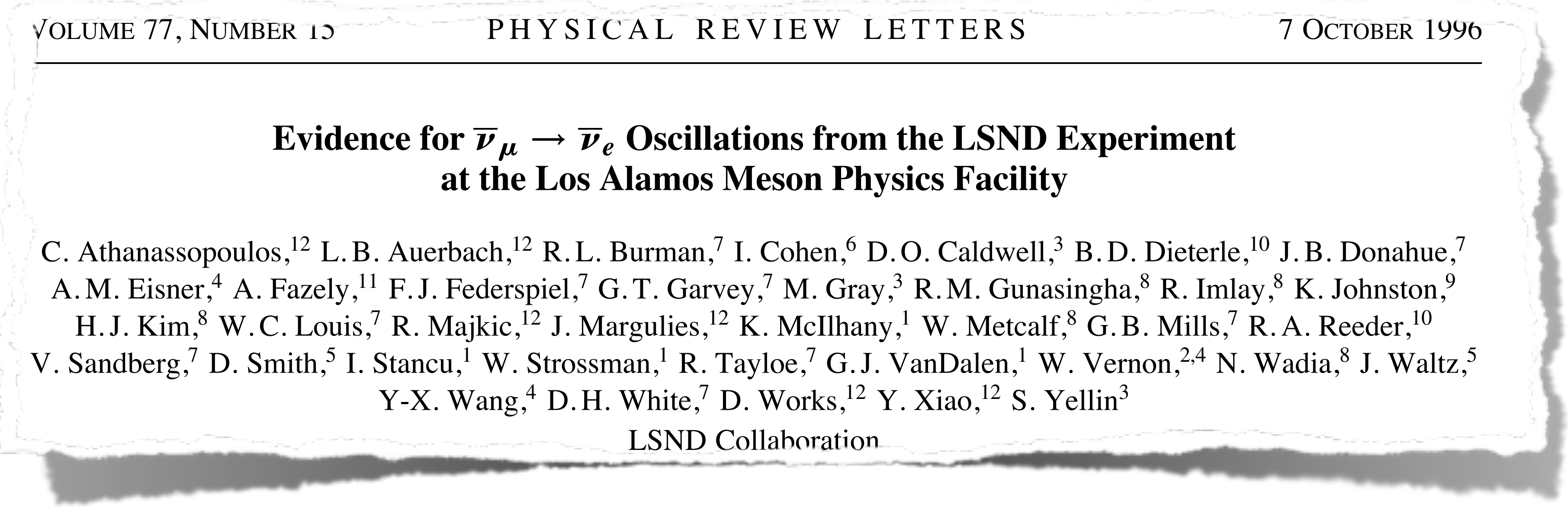
$$\mathcal{L} \sim L H \nu_R + \nu_D \eta \nu_R + M \nu_R \nu_R$$

- Simple renormalizable see-saw Lagrangian. Upon integrating out the heavy right-handed ν_R, one gets a light "sterile" ν_h mixing with the usual active neutrinos in L

- $$\frac{(HL)(\eta\nu_h)}{\Lambda}$$

- Akin to "mirror worlds" (Foot, Volkas, Mohapatra ... 1990s). See also the "baryonic neutrino" in Pospelov, arXiv:1103.3261, only we don't want the hidden gauge group to directly couple to the SM baryon number (which could induce large NSI).

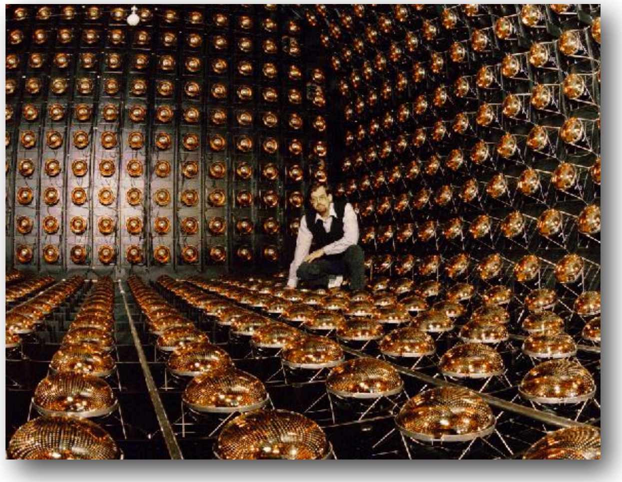
Experimental evidence? Sterile neutrinos at oscillation experiments

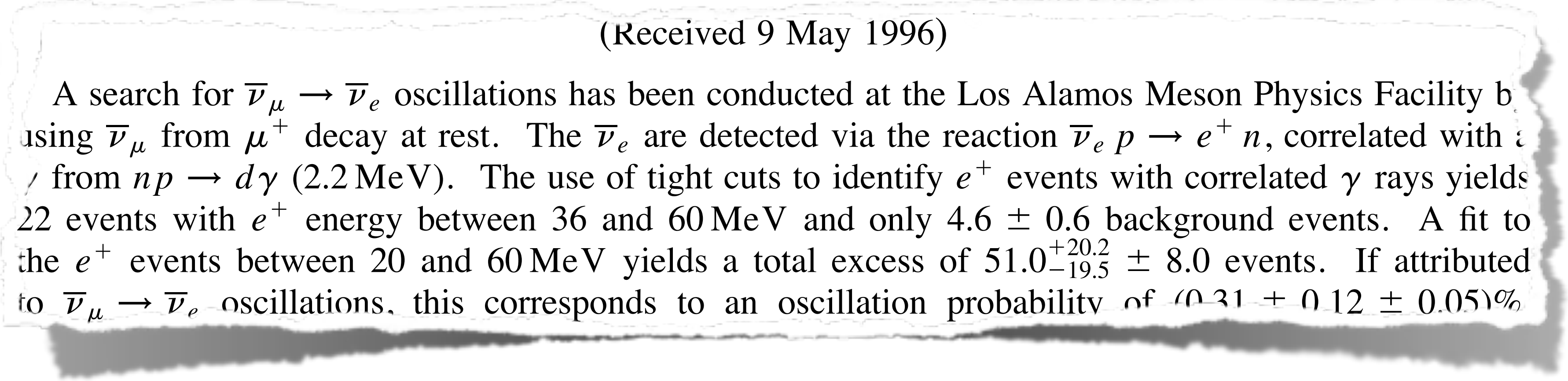


VOLUME 77, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1996

Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Oscillations from the LSND Experiment at the Los Alamos Meson Physics Facility

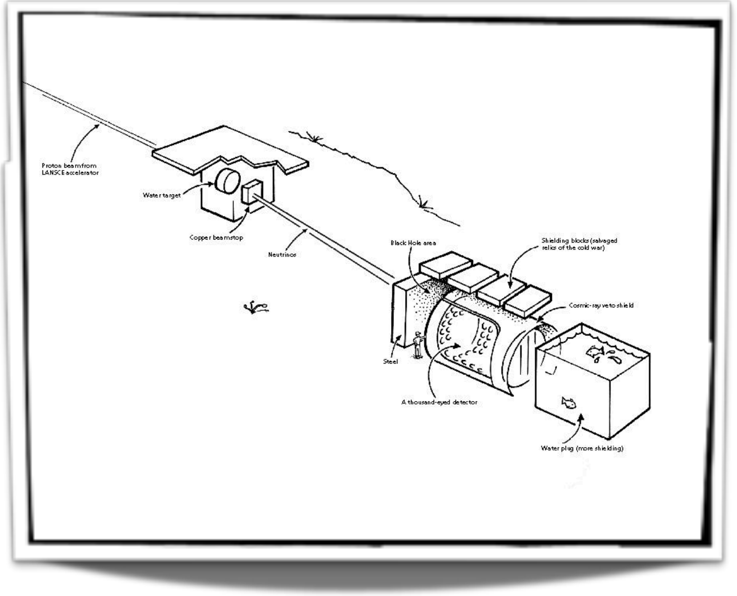
C. Athanassopoulos,[12] L.B. Auerbach,[12] R.L. Burman,[7] I. Cohen,[6] D.O. Caldwell,[3] B.D. Dieterle,[10] J.B. Donahue,[7]
A.M. Eisner,[4] A. Fazely,[11] F.J. Federspiel,[7] G.T. Garvey,[7] M. Gray,[3] R.M. Gunasingha,[8] R. Imlay,[8] K. Johnston,[9]
H.J. Kim,[8] W.C. Louis,[7] R. Majkic,[12] J. Margulies,[12] K. McIlhany,[1] W. Metcalf,[8] G.B. Mills,[7] R.A. Reeder,[10]
V. Sandberg,[7] D. Smith,[5] I. Stancu,[1] W. Strossman,[1] R. Tayloe,[7] G.J. VanDalen,[1] W. Vernon,[2,4] N. Wadia,[8] J. Waltz,[5]
Y-X. Wang,[4] D.H. White,[7] D. Works,[12] Y. Xiao,[12] S. Yellin[3]
LSND Collaboration





(Received 9 May 1996)

A search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations has been conducted at the Los Alamos Meson Physics Facility b
sing $\overline{\nu}_\mu$ from μ^+ decay at rest. The $\overline{\nu}_e$ are detected via the reaction $\overline{\nu}_e\, p \rightarrow e^+\, n$, correlated with
from $np \rightarrow d\gamma$ (2.2 MeV). The use of tight cuts to identify e^+ events with correlated γ rays yields
22 events with e^+ energy between 36 and 60 MeV and only 4.6 ± 0.6 background events. A fit to
he e^+ events between 20 and 60 MeV yields a total excess of $51.0^{+20.2}_{-19.5} \pm 8.0$ events. If attributed
o $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.31 \pm 0.12 \pm 0.05)\%$



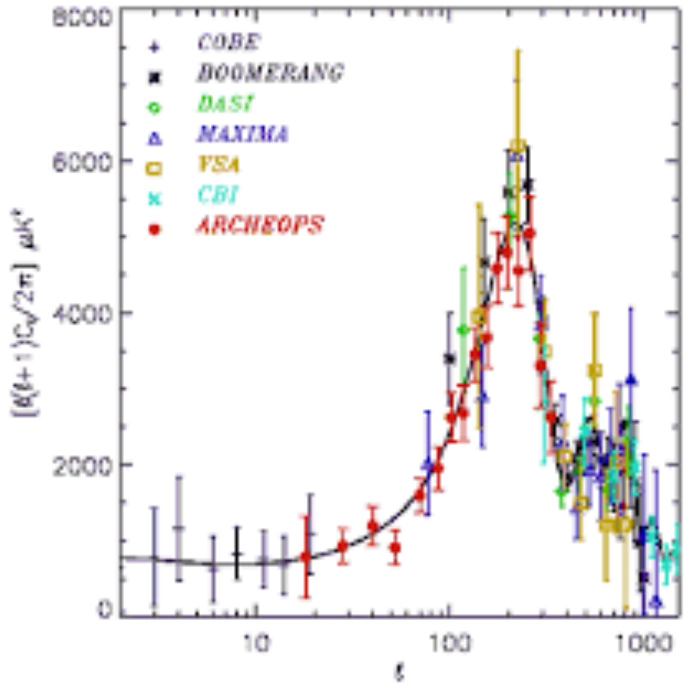
Since then, MiniBOONE, Reactor flux anomaly, gallium source anomaly. See, e.g., C. Giunti, arXiv:1609.04688 for review

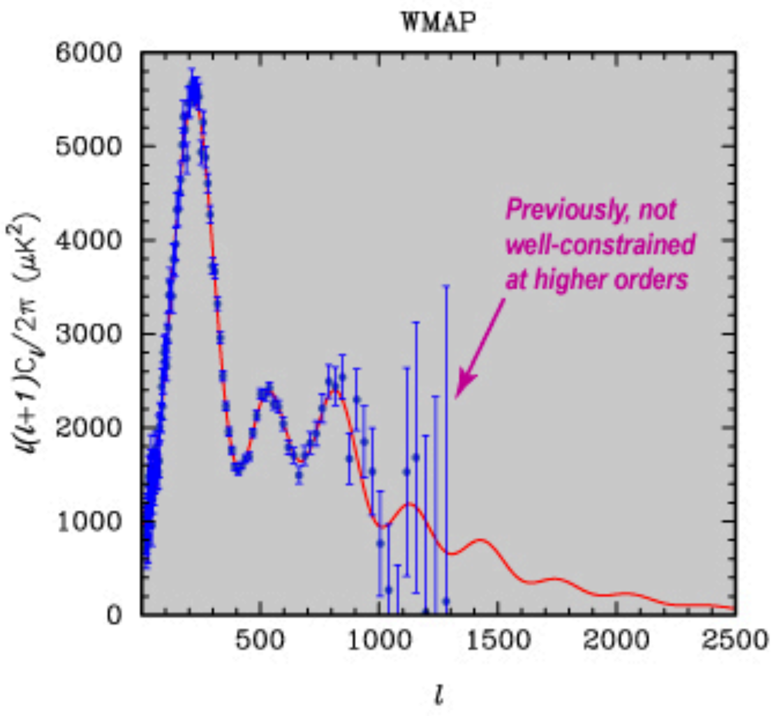
Sterile neutrinos: cosmological problems?

- Recent results from Planck measure relativistic energy density in the universe at matter/rad equality -> CMB decoupling

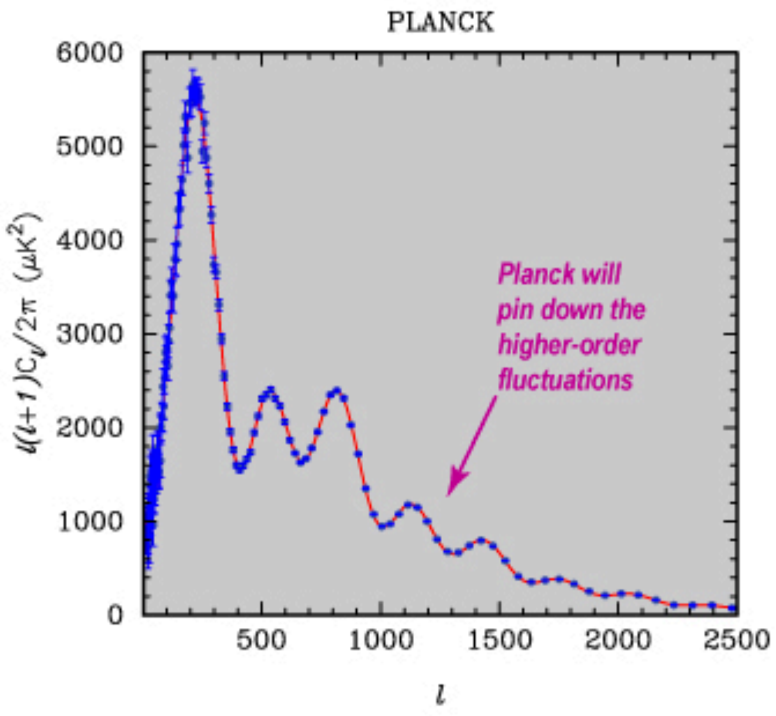
- Planck 2015 [arXiv:1502.01589] reports $N_{eff}=3.15\pm0.23$ and for the mass $m_\nu < 0.23$ eV

- *Are sterile neutrinos that the SBN program plans to search for already ruled out by cosmology?*





Previously, not well-constrained at higher orders



Planck will pin down the higher-order fluctuations

Hidden interactions to the rescue?

- What if sterile neutrinos were actually not sterile, but interacting through their own force?
- Once there is some population of hidden neutrinos, this would induce an MSW potential that would suppress mixing between ν_a and ν_h. Would that shut off $\nu_a \rightarrow \nu_h$ thermalization?
- This is the Babu-Rothstein framework
  - Babu & Rothstein, Phys.Lett. B275 (1992) 112-118

Why is suppression of mixing not enough?

- New interactions, while solving one problem, introduce another
- While they suppress collisions due to Weak Interactions, they themselves mediate collisions
- Can flavor recoupling due to the new force can be delayed until T ~ 1 MeV?
- Quantitative question: compare rates
- Flavor conversion rate: $\Gamma_{fl} = P(\nu_a \to \nu_h)\Gamma_{coll}$
  - In the regime when collisions are less frequent then oscillations, this gives

$$\Gamma_{fl} = \frac{\sin^2 2\theta}{2}\sigma n$$

Careful analysis required, many effects

- Heavy mediator, Light mediator, Resonant, Oscillation dominated, Collision dominated, Non-freestreaming at CMB epoch ...

- We find that for the oscillation parameters suggested by the oscillation "anomalies" the thermalization temperature has a fundamental lower limit

$$T_0 \sim (\sin^2 2\theta (\Delta m^2)^2 M_{pl})^{1/5} \sim 200 \text{ keV}$$

- This is close to 1 MeV of weak decoupling. The BR mechanism is thus only marginally successful.

Cherry, A. F., Shoemaker, arXiv:1605.06506

Let’s do an example calculation

- Light mediator, recoupling at temperatures above the mediator mass

$$\sin 2\theta_m \simeq \frac{\Delta m^2 \sin 2\theta_v}{E|V_m|}.$$

$$\sin^2 2\theta_m \sigma(T) T^3 \sim \frac{T^2}{M_{pl}}$$

$$V_m \sim +\frac{g^2 T^2}{E}, \ T, E \gg M$$

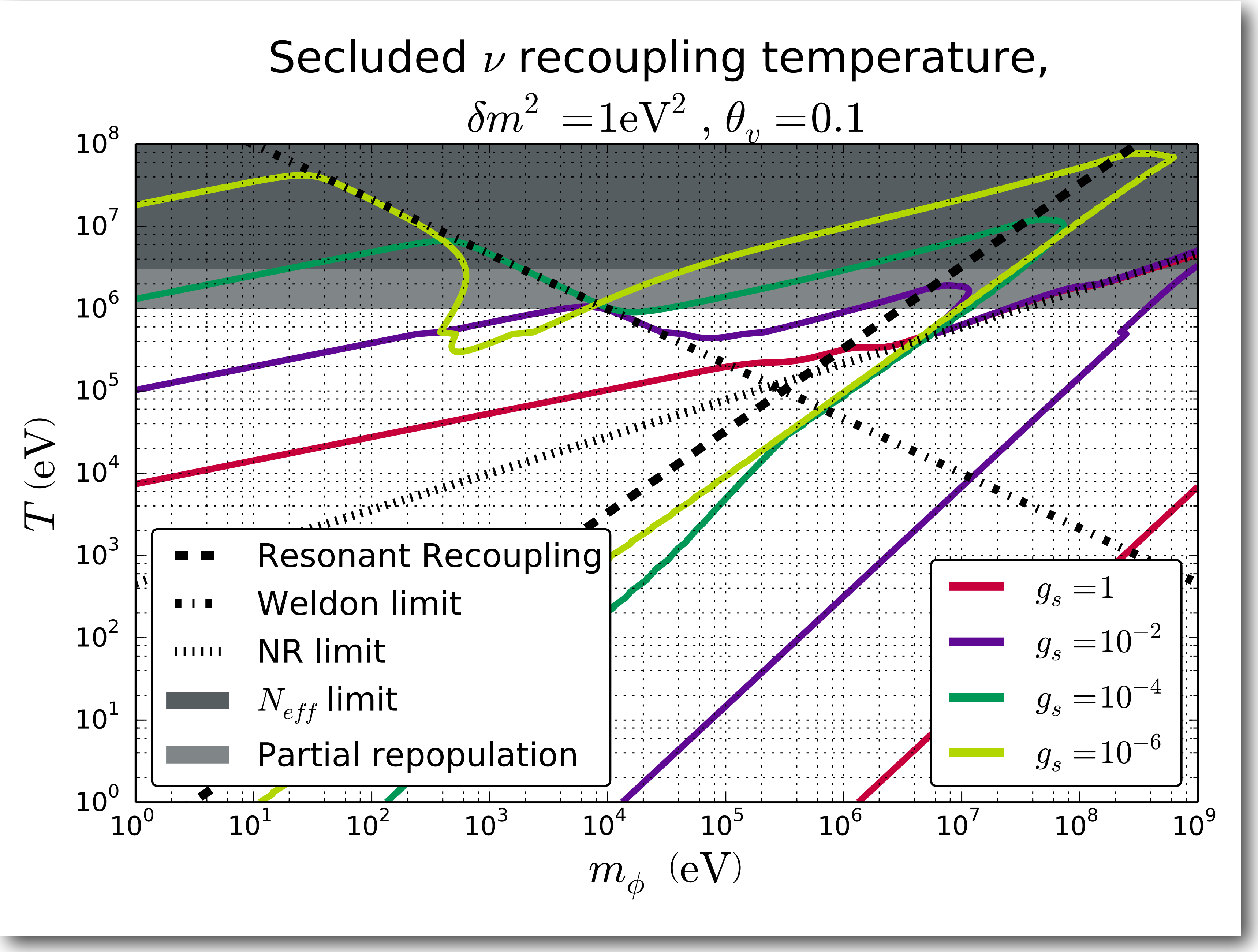
$$\left(\frac{\Delta m^2 \sin 2\theta_v}{E g^2 T^2 / E}\right)^2 \frac{g^4}{M^2} T^3 \sim \frac{T^2}{M_{pl}}$$

$$\boxed{T_{recoupling} \sim T_0^{5/3} M^{-2/3}}$$

$$T_0 = [(\Delta m^2 \sin 2\theta_v)^2 M_{pl}]^{1/5} \sim 10^5 \text{ eV} \left(\frac{\Delta m^2}{1 \text{ eV}^2}\right)^{2/5} \left(\frac{\sin 2\theta_v}{0.1}\right)^{2/5}.$$

Recoupling isocontours

arXiv:1605.06506 for details

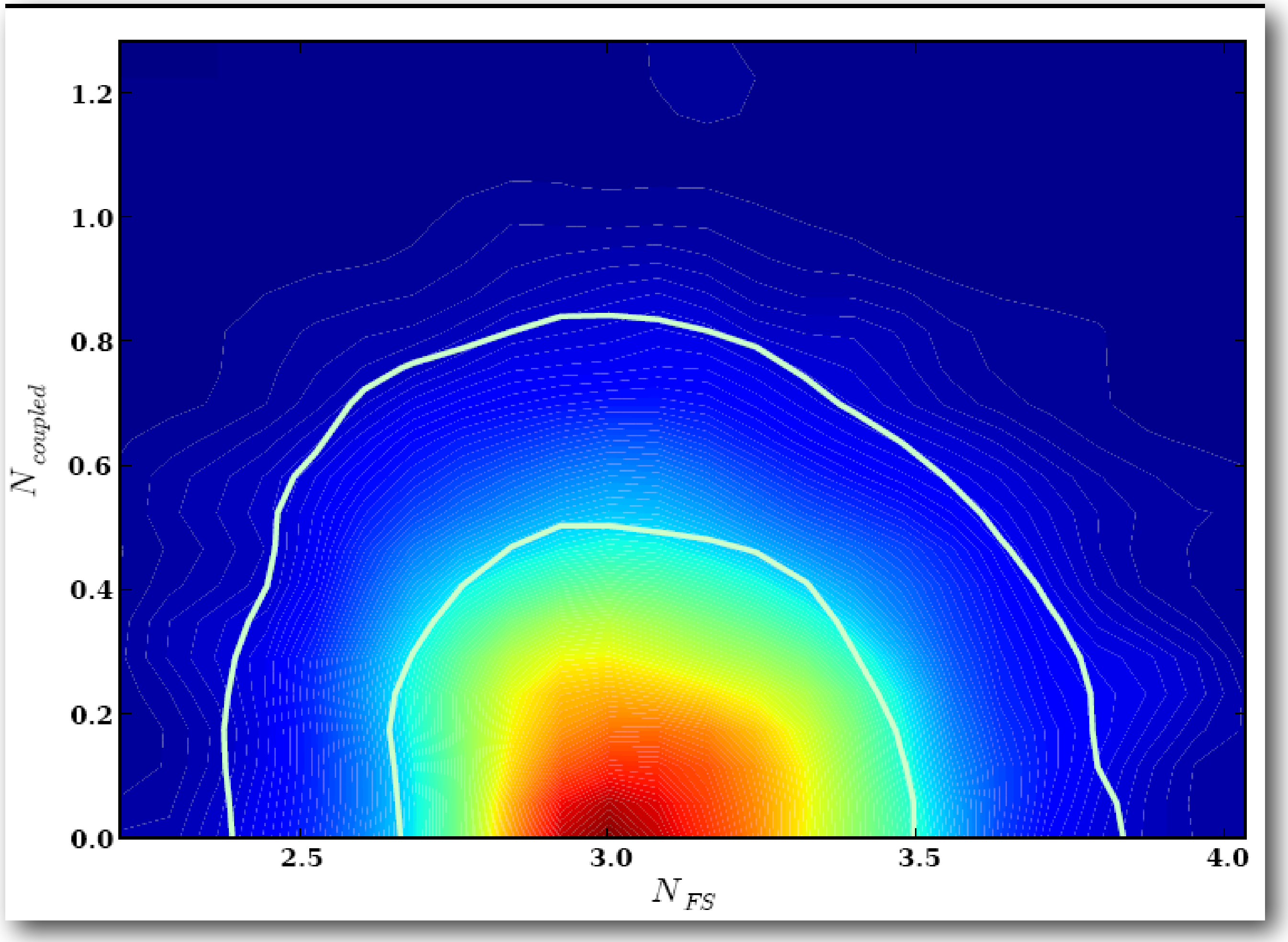


Light mediators: excluded by free-streaming

- For sufficiently large coupling, neutrinos, even the ones predominantly active, scatter even at the CMB epoch

- In conflict with PLANCK

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



Friedland, Zurek, Bashinsky, 0704.3271

$$g_{eff} < 10^{-7}(m_\phi/1\text{ eV})$$

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

What is the physics of Planck’s sensitivity?

- Comparing the same populations of free-streaming and coupled neutrinos, the “background” effects on the expansion rate is the same

- The difference is in the evolution of perturbations: the scalar mediated interactions could turn neutrinos into a fluid

- Fluid density perturbations evolve differently from free-streaming neutrinos

- Gravity of neutrino perturbations during radiation domination affects the evolution of the perturbations in photon-baryon plasma

- The effect is not large, at ~20% level for density fluctuations

    - P. J. E. Peebles, Astrophys. J. 180, 1 (1973)

Free-streaming neutrinos and CMB

- Suppress the power of CMB fluctuations

$$\delta C_l / C_l \sim -0.5 \rho_{FS} / \rho_{rad}$$

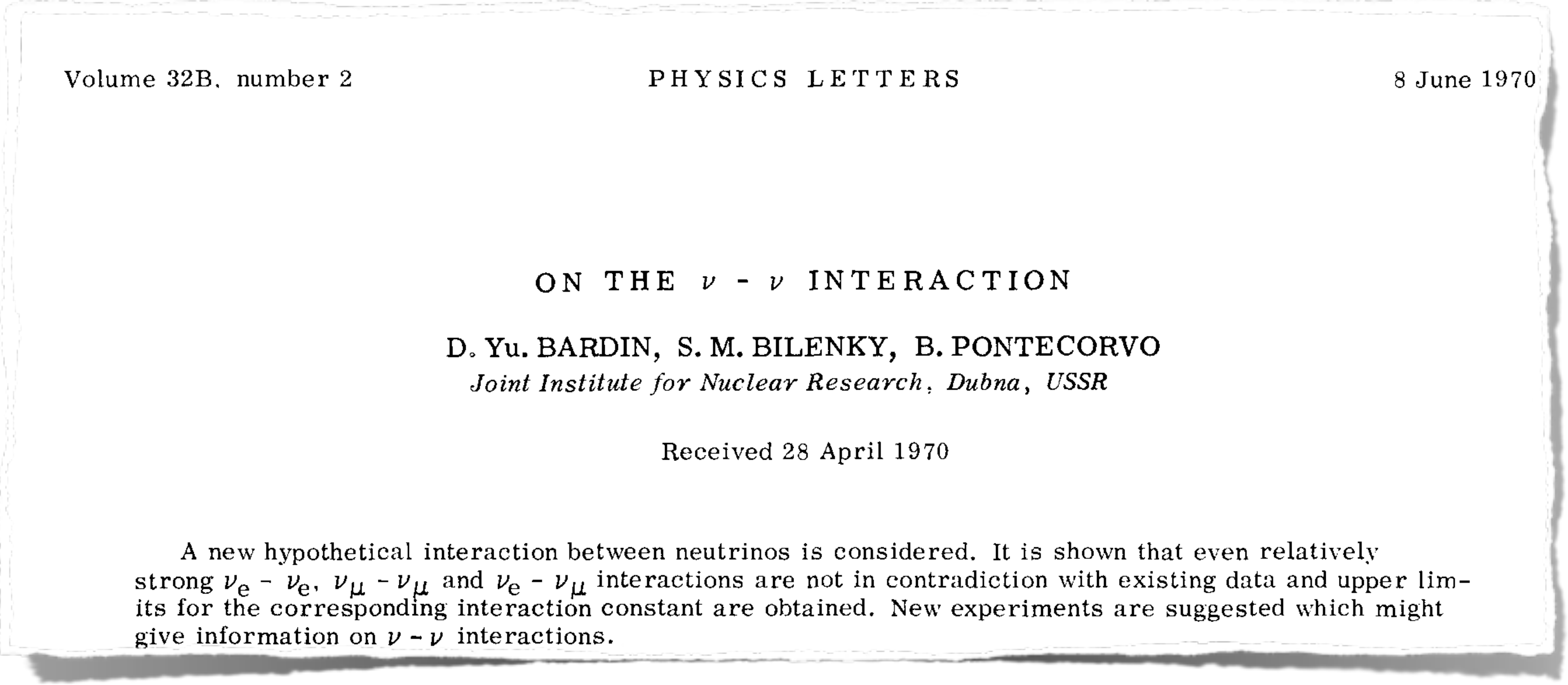
Hu & Sugiyama, Astrophys. J. 1996

- Shift the peaks by

$$\delta l \sim -57 \rho_{FS} / \rho_{rad}$$

Bashinsky & Seljak, Phys. Rev. D 2004

- Effect only present for multipoles that enter horizon before matter-radiation equality, z_{eq}.



Volume 32B, number 2 PHYSICS LETTERS 8 June 1970

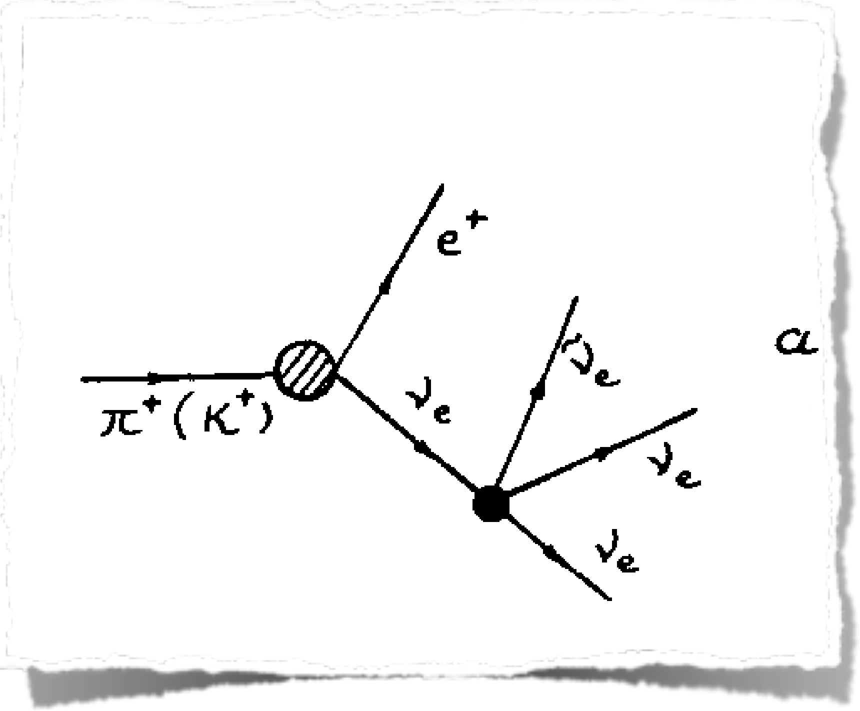
ON THE ν - ν INTERACTION

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)
- Manohar (1987)
- Kolb & Turner (1987)
- Fuller, Mayle, Wilson (1988)
- Bilenky, Bilenky, Santamaria (1993)
- None of these bounds apply! New interactions only appear after neutrinos oscillate



Neutrino-neutrino collider?

- We need to collide neutrino mass eigenstates, which have admixture of the “sterile” component that gives them new interactions

- Not feasible in the lab, but we can use the universe as the experimental setup

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

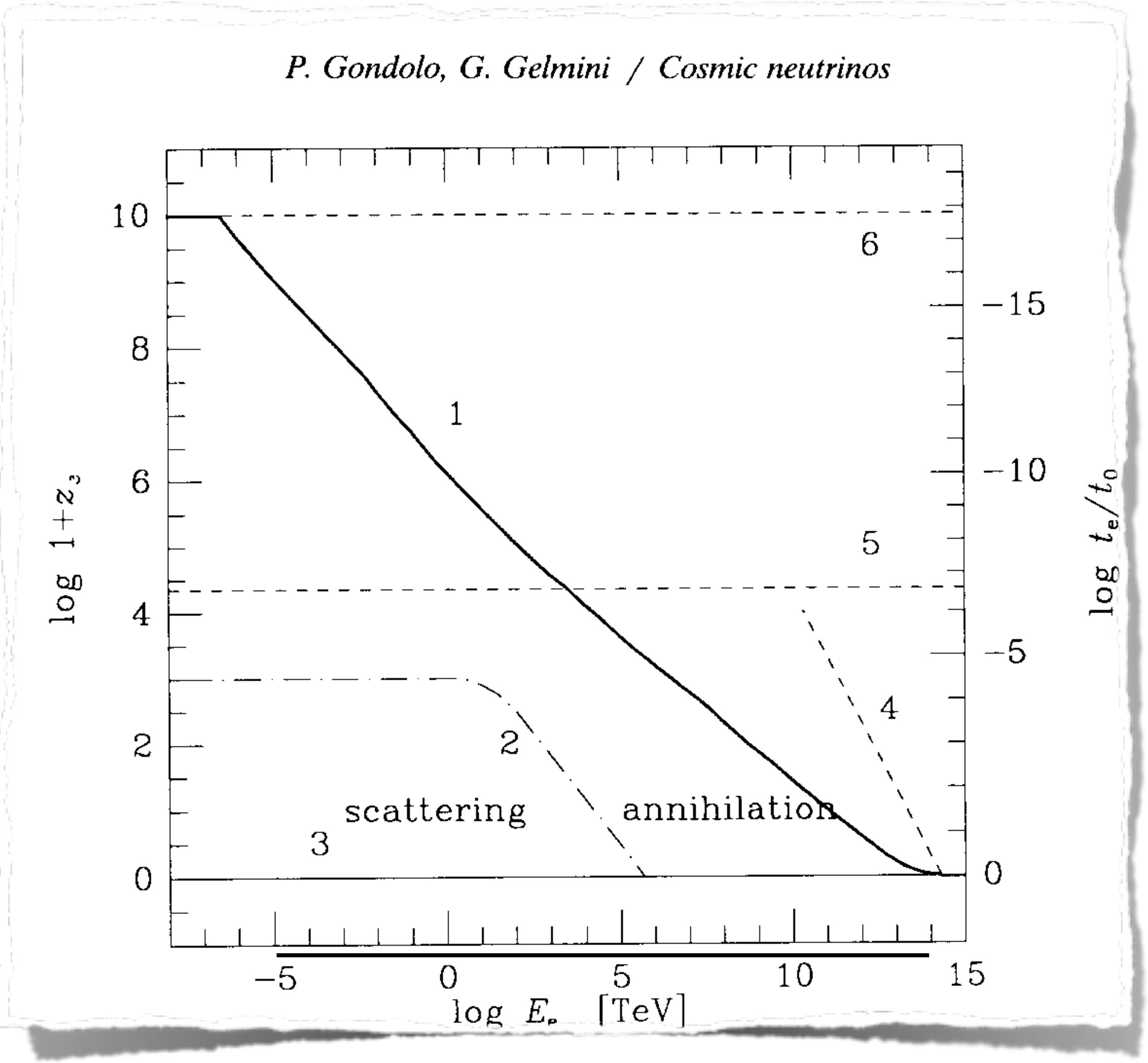
- These neutrinos on their way to us travel through the relic neutrino background. Both the beam and the background had enough time to oscillate and separate into mass eigenstates.

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



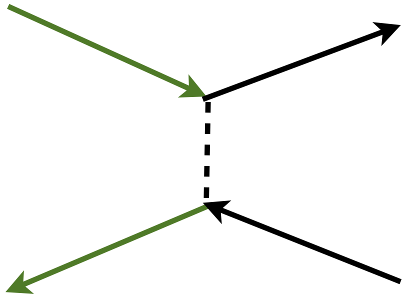
Gondolo, Gelmini, 1993

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

Light mediator

- The standard transparency conclusion is based on standard physics only

- We now have a light mediator particle?



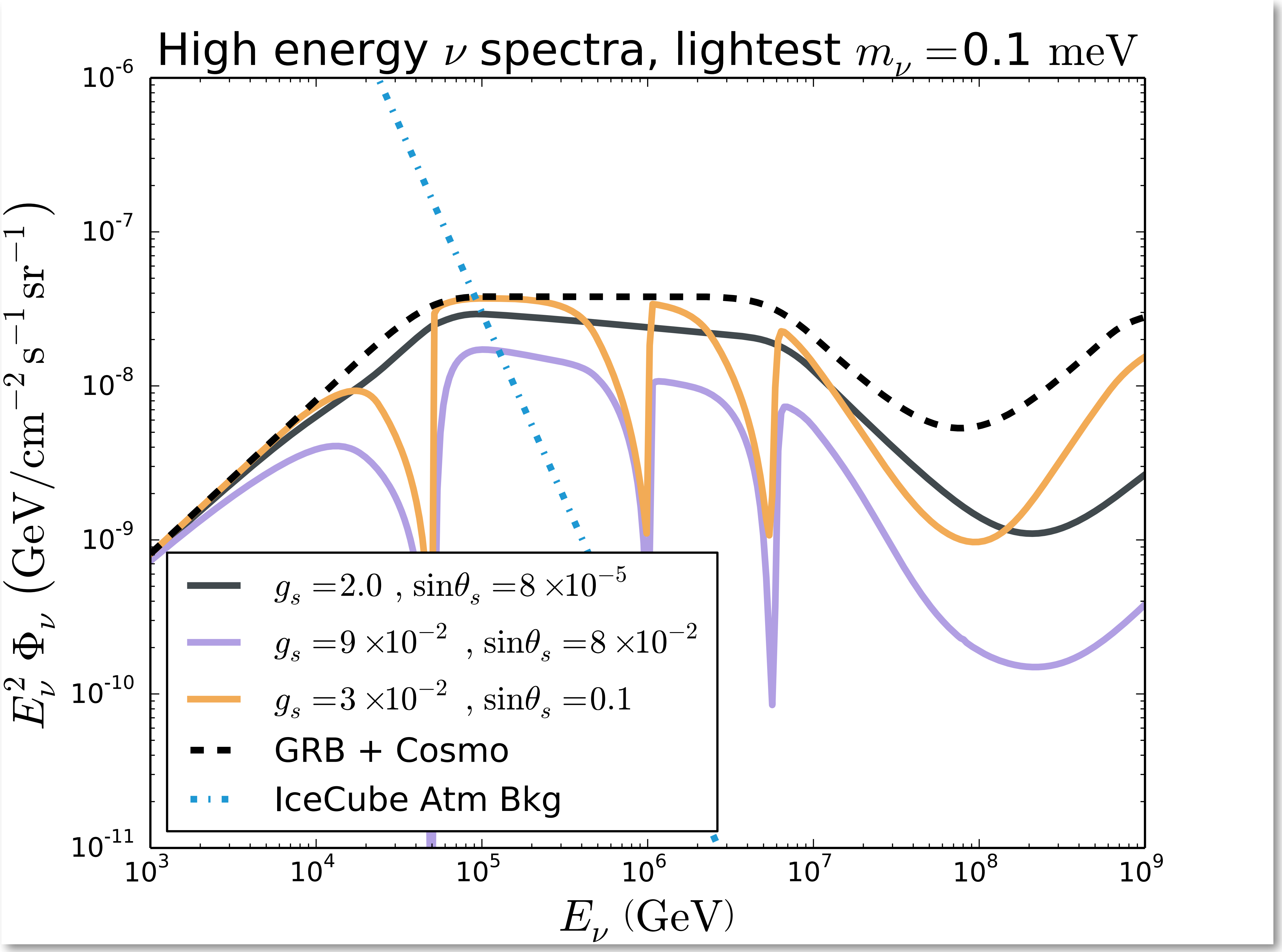
  - resonant condition

$$m_\phi^2 = s \approx 2m_\nu E_\nu$$

$$\implies m_\phi \sim \sqrt{(10^{-1}\ \mathrm{eV})(10^{15}\ \mathrm{eV})} \sim 10^7\ \mathrm{eV}$$

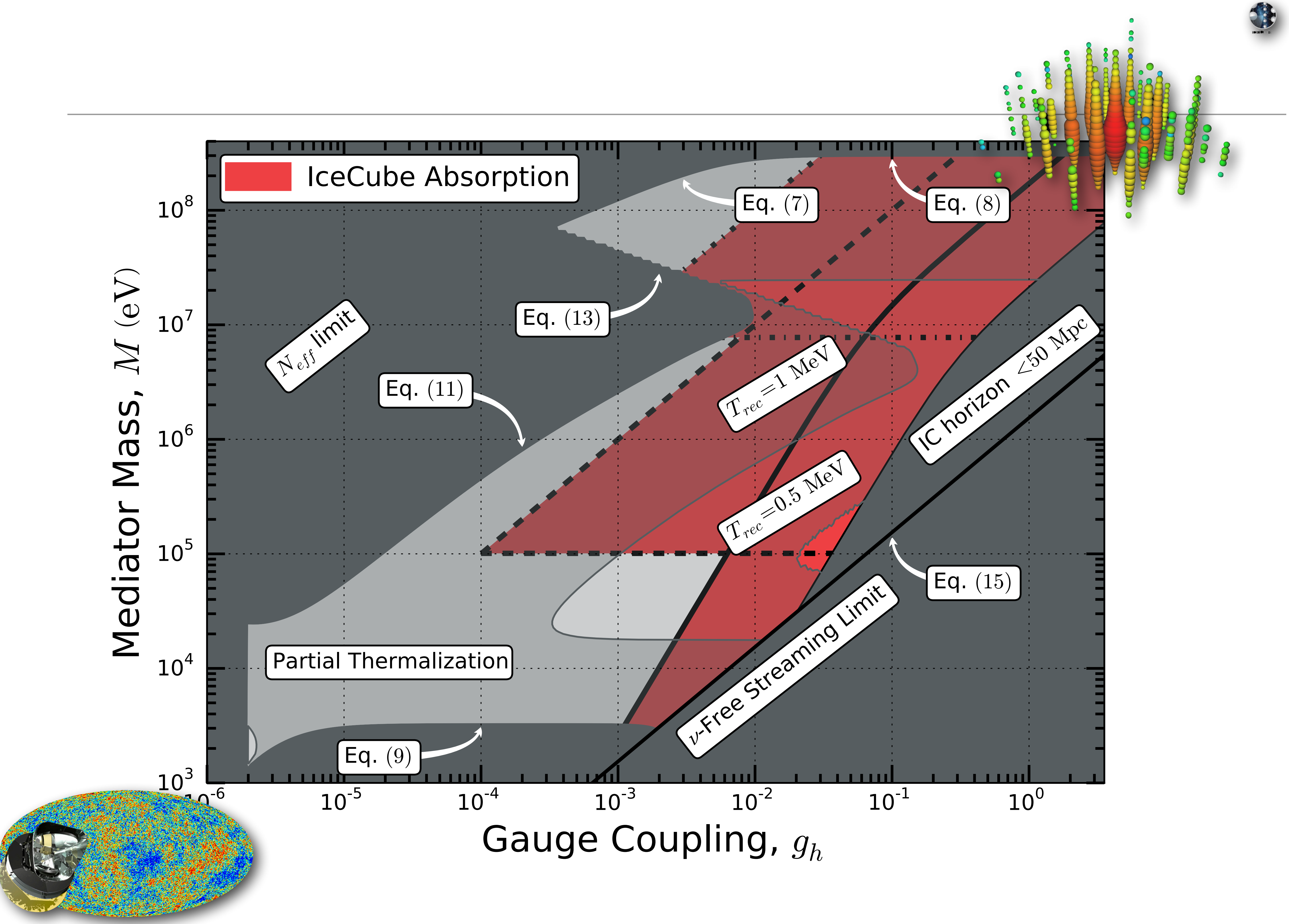
  - ***The same mass scale as needed by Short-Baseline + PLANCK!***

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



Example calculation

See talk at Miami 2014:
https://cgc.physics.miami.edu/Miami2014/Friedland2014.pdf


IceCube Absorption
🟥
Eq. (7)
Eq. (8)
Eq. (13)
N_{eff} limit
Eq. (11)
T_{rec}=1 MeV
T_{rec}=0.5 MeV
IC horizon <50 Mpc
Eq. (15)
ν-Free Streaming Limit
Partial Thermalization
Eq. (9)
Mediator Mass, M (eV)
10^3
10^4
10^5
10^6
10^7
10^8
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
Gauge Coupling, g_h

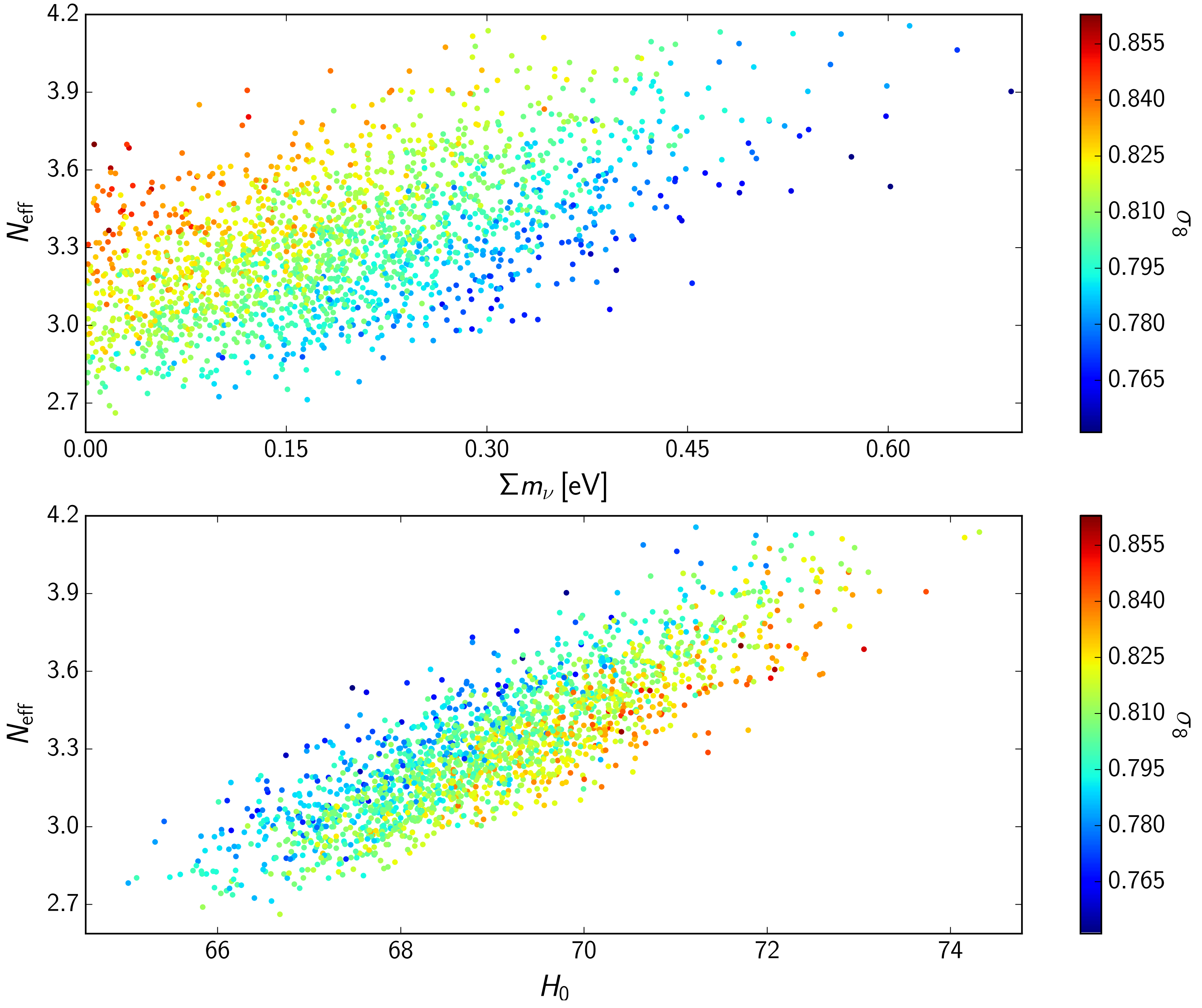
How can we probe this physics?

I. Cosmology

- As we saw, Planck already provides valuable constraints
- Thanks to late recoupling, we can have a fractional N_{eff}
- 1 eV sterile neutrino with a fractional population could help alleviate some issues between the Planck measured sigma8 and the Hubble constant and the local measurements
    - See Planck papers, arXiv:1303.5076v3 and 1502.01589
    - Well explained in Wyman, Rudd, Vanderveld and W. Hu, arXiv:1307.7715.
    - Does not work with standard sterile neutrinos a la MiniBOONE!

Adding a bit of hidden neutrino helps!

Task for CMB-S4



II. Dark matter

- Long-standing debate about whether collisionless cold dark matter predicts too much structure on small scales
  - **Cusp-vs-core:** numerical simulations predict higher DM concentrations in the central regions of galaxies than observed
  - **Missing satellites**: the number of small satellite galaxies is less than observed
  - “**Too-big-to-fail**”: the most massive subhaloes in CDM simulations are too massive to host the satellites of the Milky Way, yet should be luminous given the observed dwarfs

II. Self-interacting dark matter?

- As already mentioned, DM self-interactions could help with small-scale structure
  - DM-DM scattering. Required cross section is

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

  - The mediator particle in the **<10 MeV** range could do it
  - Just what we have in our secluded window

Dark-matter interactions with neutrinos?

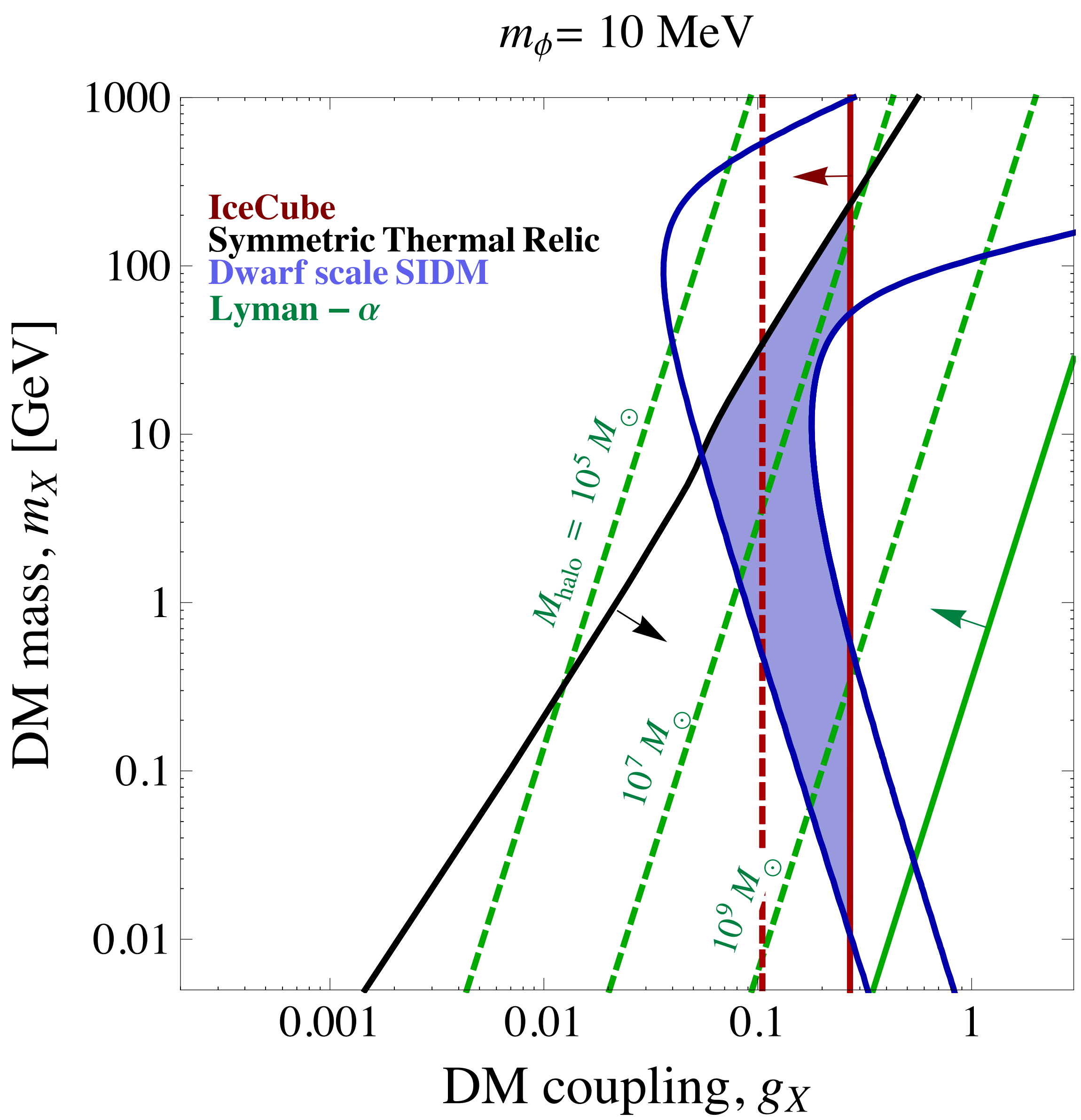
- Interestingly, coupling between dark matter and neutrinos may further help alleviate the structure problems
  - Boehm et al, 2001, 2002, 2004; van den Aarssen, Bringmann, and Pfrommer, 2012
  - Coupling of SM to neutrinos early would keep DM density fluctuations from collapsing, until kinetic decoupling

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

  - Mediator masses of <10 MeV work! (see later)

Concordance

- Relic abundance (black)
- DM self-interactions (purple)
- DM-neutrino interactions (green)
- IceCube (red)



Cherry, A.F., Shoemaker,
arXiv:1411.1071

In summary

- There are a number of experimental synergies between neutrino physics and dark sector searches

- Neutrinos can themselves couple to dark forces. Signatures depend on the mechanism

- Short-baseline oscillations could be reconciled with cosmology with “nu” dark force

- A very specific window of mediator parameters allowed, will be completely covered in the near future (CMB-S4, IceCube-Gen2).

    - CMB and UHE neutrinos sensitivities are ***complementary***

- This window happens to have the right properties for self-interacting and neutrino-coupled dark matter