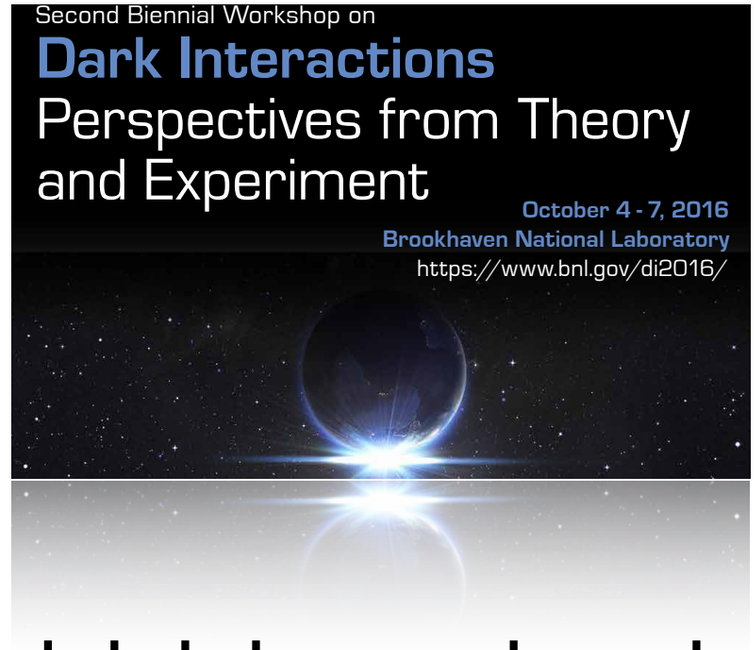


Neutrinos and hidden physics: astrophysical and cosmological constraints

Alex Friedland

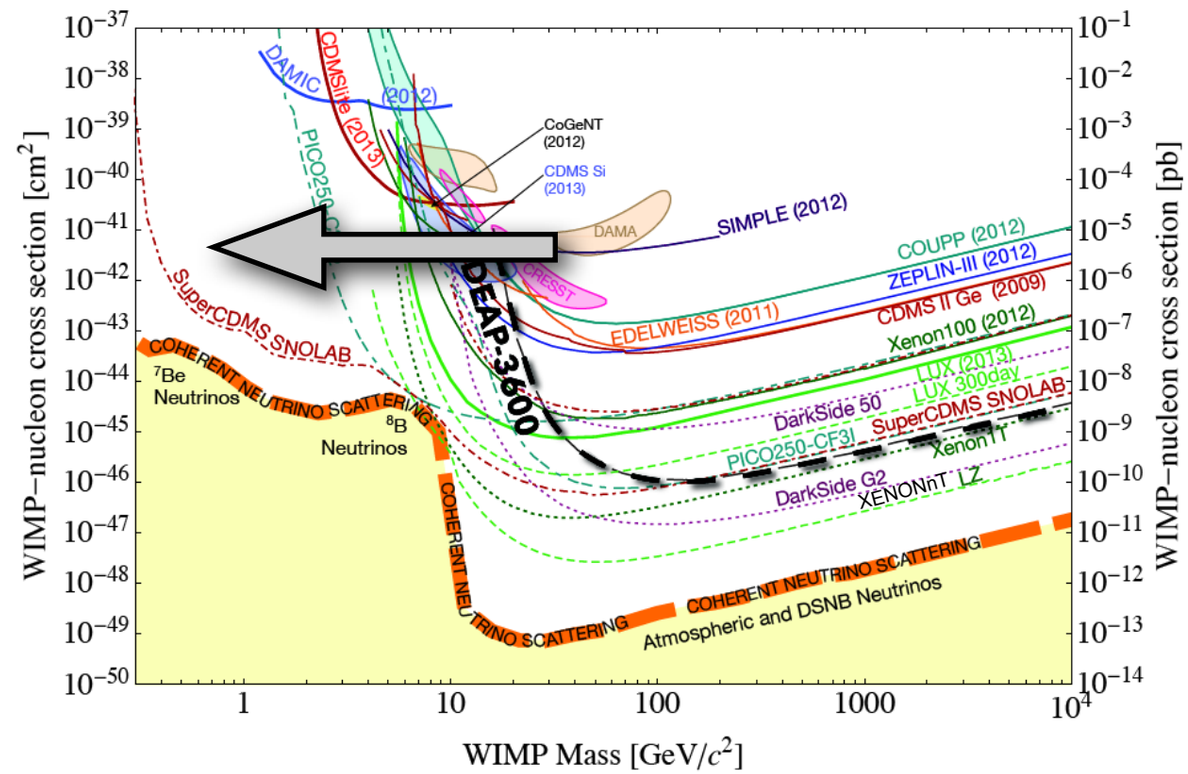
SLAC NATIONAL ACCELERATOR LABORATORY

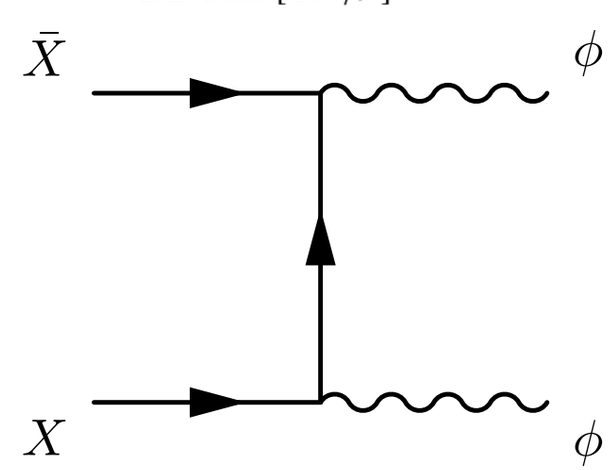
BNL

October 6, 2016

Topic of this workshop: Light secluded physics

- The concept is decades-old (think axion in 1970s, or neutrinos in 1930s!)
- A lot of recent attention motivated by models of the Dark Matter
  - PAMELA data -> Sommerfeld enhancement
  - Light DM: the annihilation cross section has to be large enough to leave sufficiently small thermal relic population, not to overclose the universe
  - Hints of small-scale structure (cusps vs cores, too-big-to-fail, etc)
- Other motivations, e.g., g-2





What scales are favored for the mediator?

- Self interactions: 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

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

  - Huge cross section! 10^2 fm^2 $\Rightarrow (10^7\ \mathrm{eV})^{-2}$
  - Not Weak Interactions
  - The mediator particle in the **<10 MeV** range could do it
  - For this physics to evade detection, it must be well secluded from the Standard Model

Search strategies

- Crucially depend on the nature of the 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 $HL\nu_R$

- Here we will instead consider the *Neutrino mixing portal*, mediated by dim 5 operator $(HL)(\eta\nu_R)/\Lambda$

Why?

- We don’t know which portal is realized, have to look everywhere
  - For example, if the hidden group is not U(1), the kinetic mixing portal is not there
  - Yet, most dark matter properties would still be addressed by the hidden interactions (relic abundance, self-interactions)
- The neutrino mixing portal is also well motivated. And there may be even some experimental hints.

Neutrino Mixing Portal: Framework

Assume the hidden sector contains a light fermion, ν_h, which couples via an A'-mediated interaction. This state mixes with the Standard Model neutrinos, ν_a. *For the sake of the argument, this could be the only link to the Hidden Sector*

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

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

- 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
- $$\mathcal{L}_{eff} \sim \frac{(LH)(\nu_D \eta)}{M}$$
- 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).

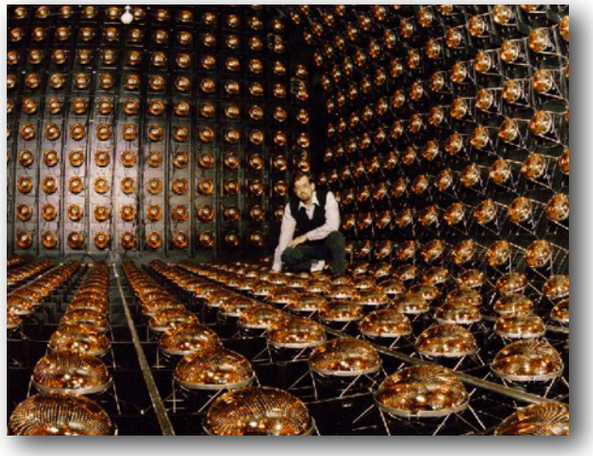
Experimental evidence? Sterile neutrinos at oscillation experiments

VOLUME 77, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1996

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

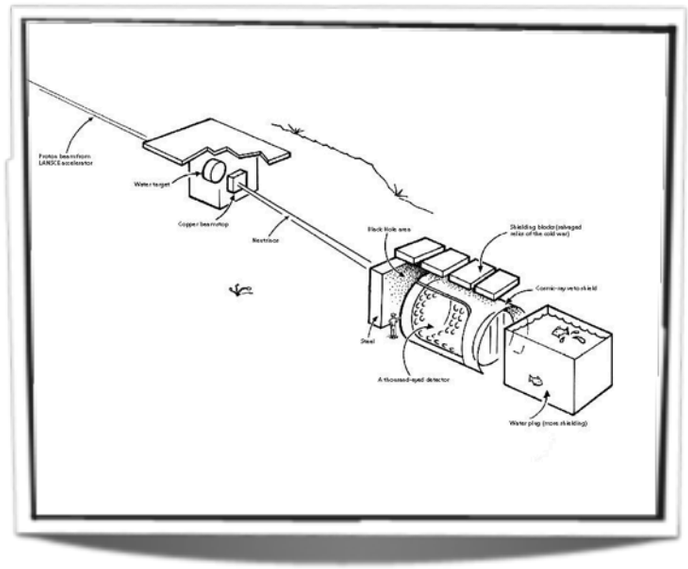
C. Athanassopoulos,[12] L.B. Auerbach,[12] R.L. Burman,[7] I. Cohen,[6] D.O. Caldwell,[3] B.D. Dieterle,[10] J.B. Donahue,[7] A.M. Eisner,[4] A. Fazely,[11] F.J. Federspiel,[7] G.T. Garvey,[7] M. Gray,[3] R.M. Gunasingha,[8] R. Imlay,[8] K. Johnston,[9] H.J. Kim,[8] W.C. Louis,[7] R. Majkic,[12] J. Margulies,[12] 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



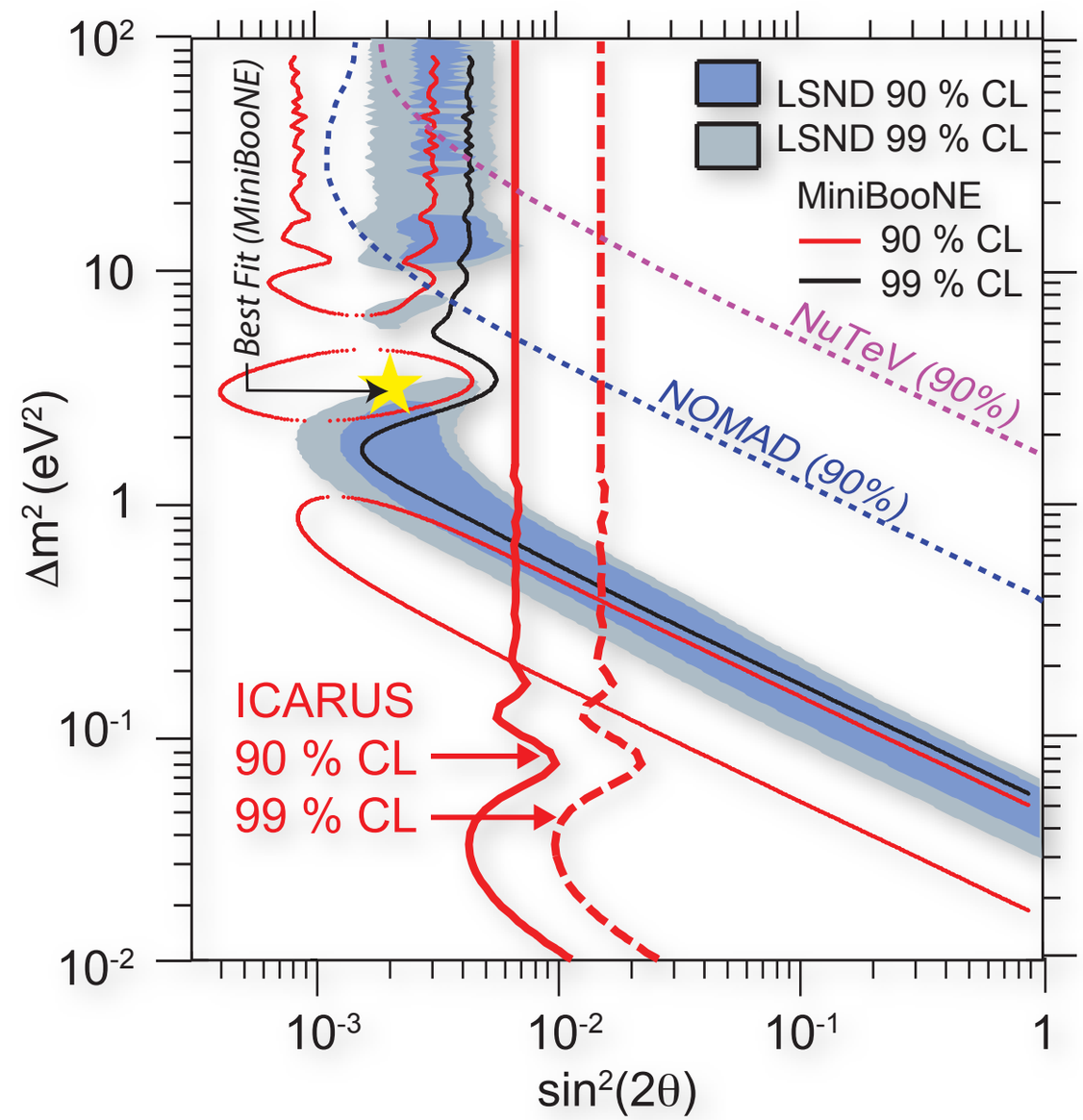
(Received 9 May 1996)

A search for $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations has been conducted at the Los Alamos Meson Physics Facility by using $\overline{\nu}_\mu$ from μ^+ decay at rest. The $\overline{\nu}_e$ are detected via the reaction $\overline{\nu}_e\, p \to e^+\, n$, correlated with a γ from $np \to d\gamma$ (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 the e^+ events between 20 and 60 MeV yields a total excess of $51.0^{+20.2}_{-19.5} \pm 8.0$ events. If attributed to $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.31 \pm 0.12 \pm 0.05)\%$.



Short-baseline oscillations?

- Hints for $\Delta m^2 \sim 1\text{-}3\ eV^2$
  - Accumulated by a number of experiments: LSND, MiniBOONE, reactor data
  - While a number of other oscillation searches have obtained valuable constraints (ICARUS, IceCube, etc), no conclusive resolution after two decades
  - See Andre's talk



ICARUS, 1307.4699

20 years in neutrino physics

- It is pretty outrageous that the issue remains open after 20 years

- 20 years is an eternity of neutrino physics

PDG 1996

http://pdg.lbl.gov/1996/www_2ltab.ps

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

No direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained. Sample limits are:

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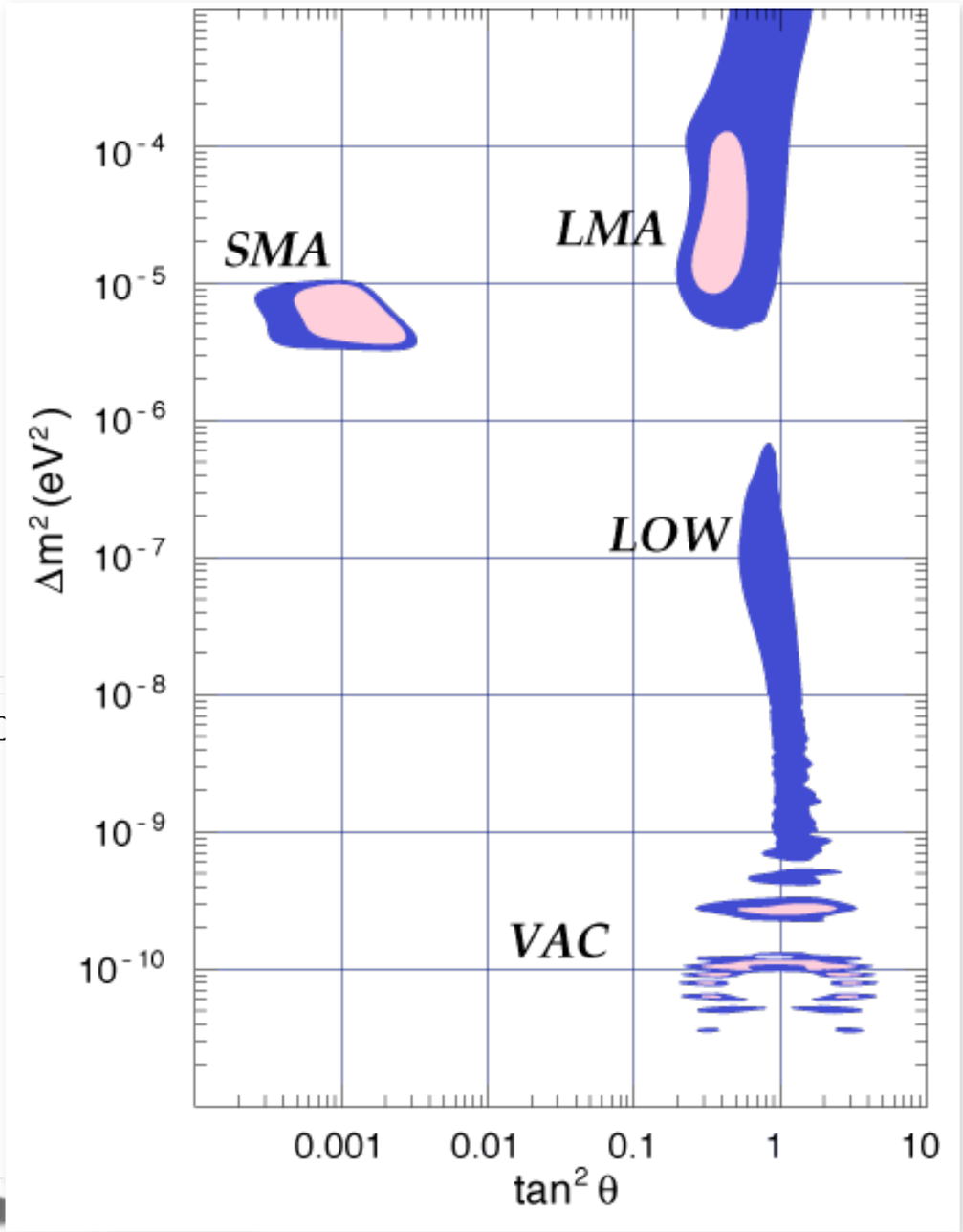

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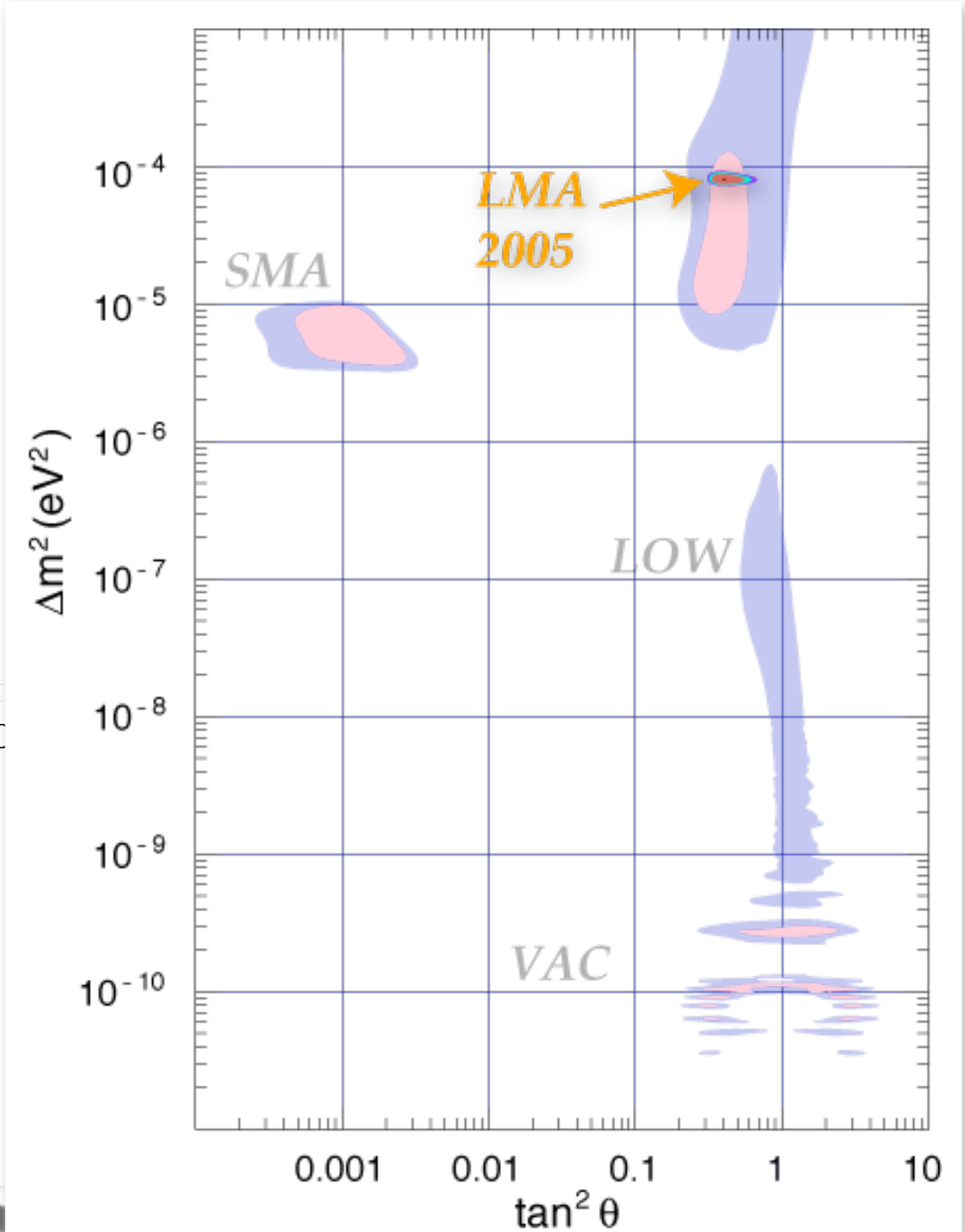
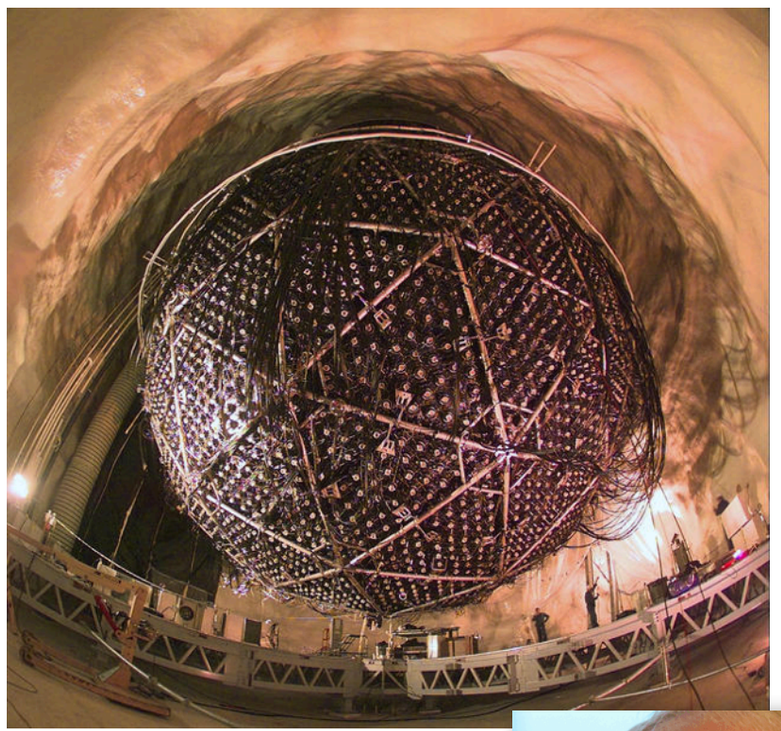
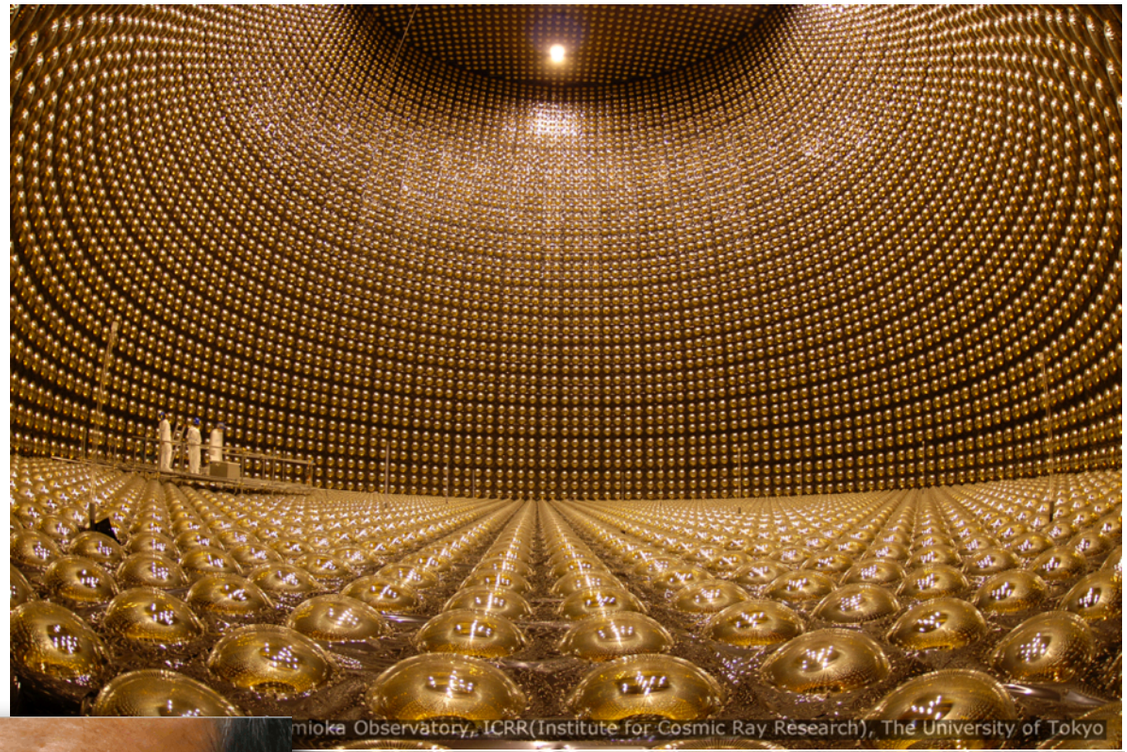


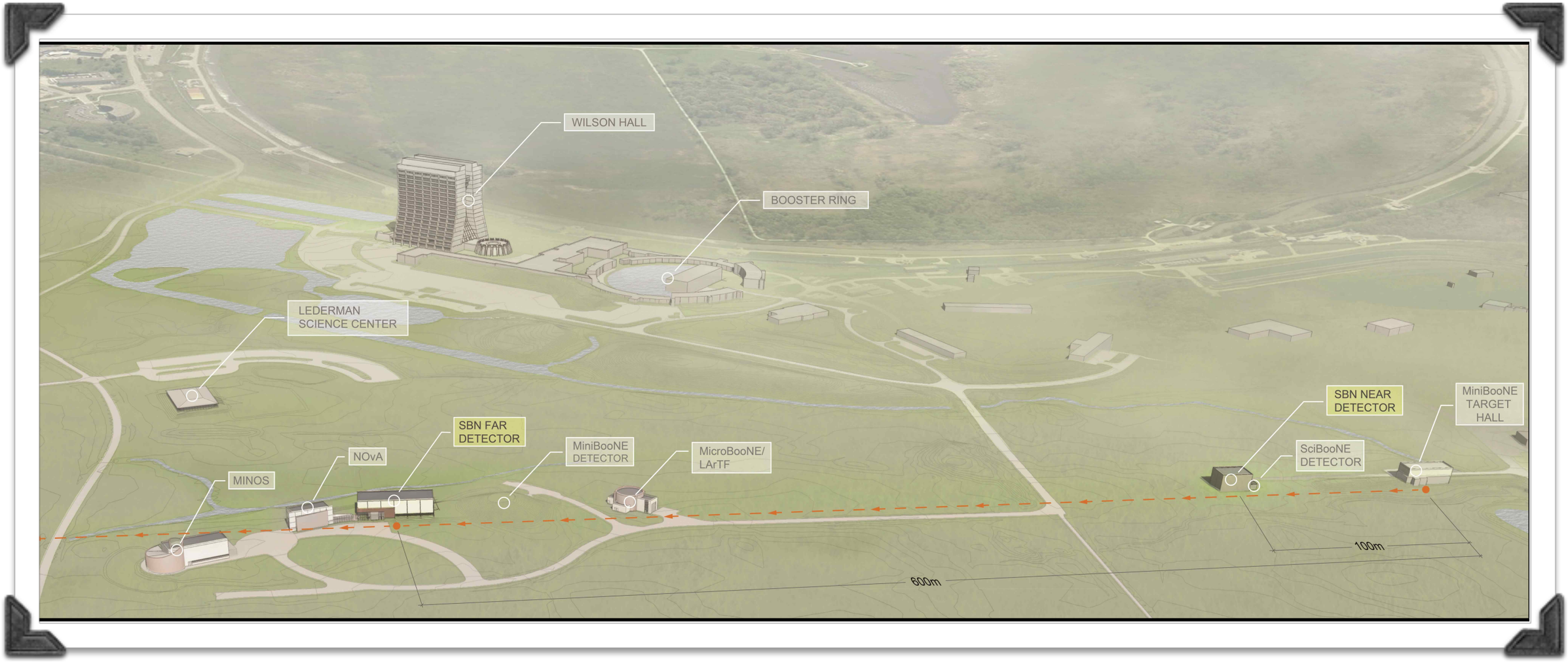
And just about a year ago





FNAL: Short-Baseline Neutrino Oscillation Program

- 3 detectors in the Booster Neutrino Beam, at different distances from the decay pipe
- Aim: to conclusively test the anomalies of LSND/MiniBooNE as oscillations

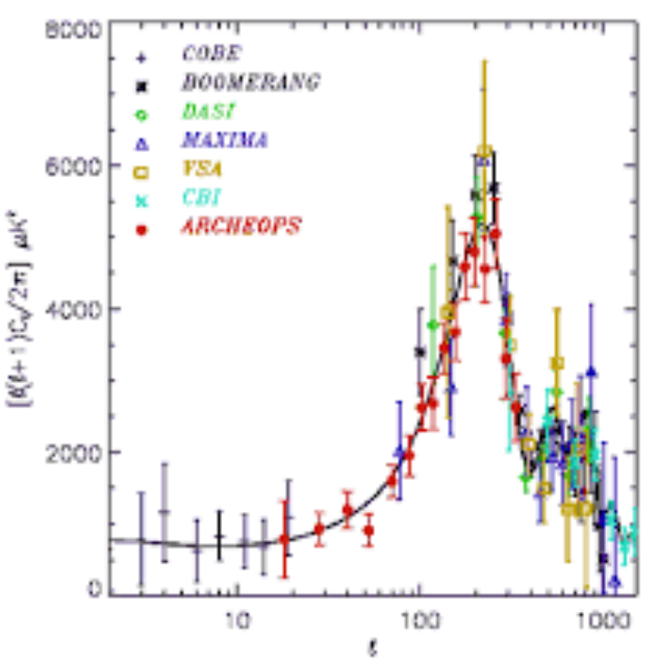


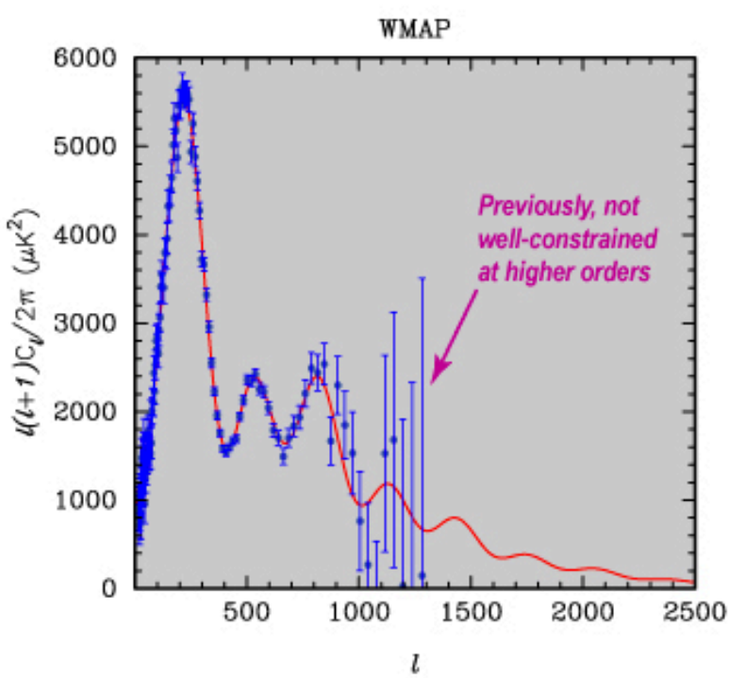
Sterile neutrinos: cosmological problems?

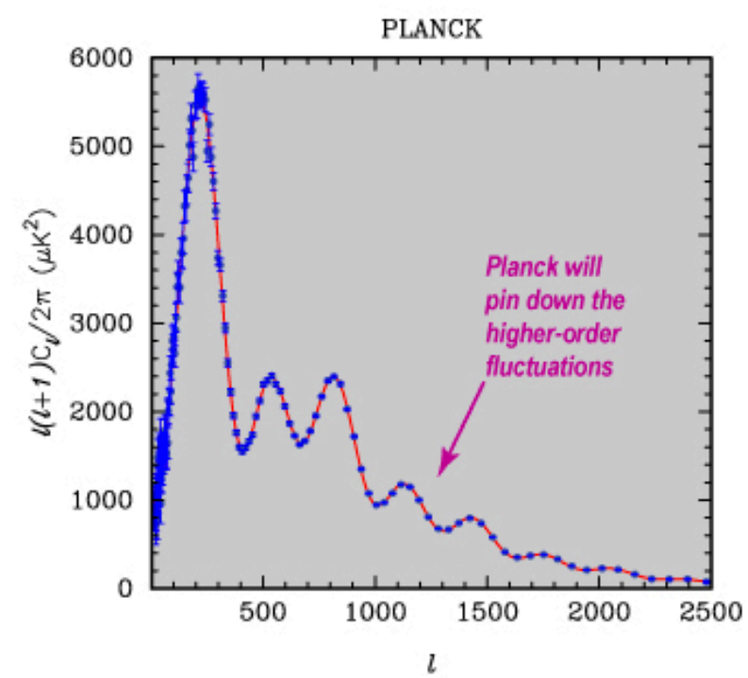
- Recent results from Planck measure relativistic energy density in the universe at matter/rad equality -> CMB decoupling

- 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?*







Sterile neutrinos in cosmology: basics

Radiation in the early universe: ν's and γ's

- By the CMB epoch (T ~ 1/4 eV), the standard model neutrinos are decoupled from the plasma. Sterile even more so.

- The effect of these neutrinos on CMB is imprinted by gravity only

- The abundance of neutrinos relative to photons is set earlier. When?

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

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

- If sterile neutrinos are brought into equilibrium with active by this epoch, dangerous!

Sterile neutrino production in the early universe

- Oscillations + collisions!

- 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:

$$G_F^2 T^2 T^3 (1/2)\sin^2 2\theta_{as}$$

- Sterile neutrino **decoupling**: Dolgov & Barbieri (1990) + hundreds more since

$$G_F^2 T^2 T^3 \sin^2 2\theta_{as} \sim T^2/M_{pl}$$
$$\to T_{dec}^{sterile} \sim (G_F^2 M_{pl} \sin^2 2\theta_{as})^{-1/3} \sim T_{dec}^{SM} (\sin^2 2\theta_{as})^{-1/3} \sim 4 \text{ MeV}$$

Active-sterile conversion: earlier times

- We saw that active-sterile conversion decouples shortly before active neutrinos decouple from photons through weak freeze-out

- The interesting thing is that these conversions are also frozen at early times

- Two reasons: I. When collisions are more frequent than the oscillation length, the oscillations are rest too soon (the Quantum Zero effect)

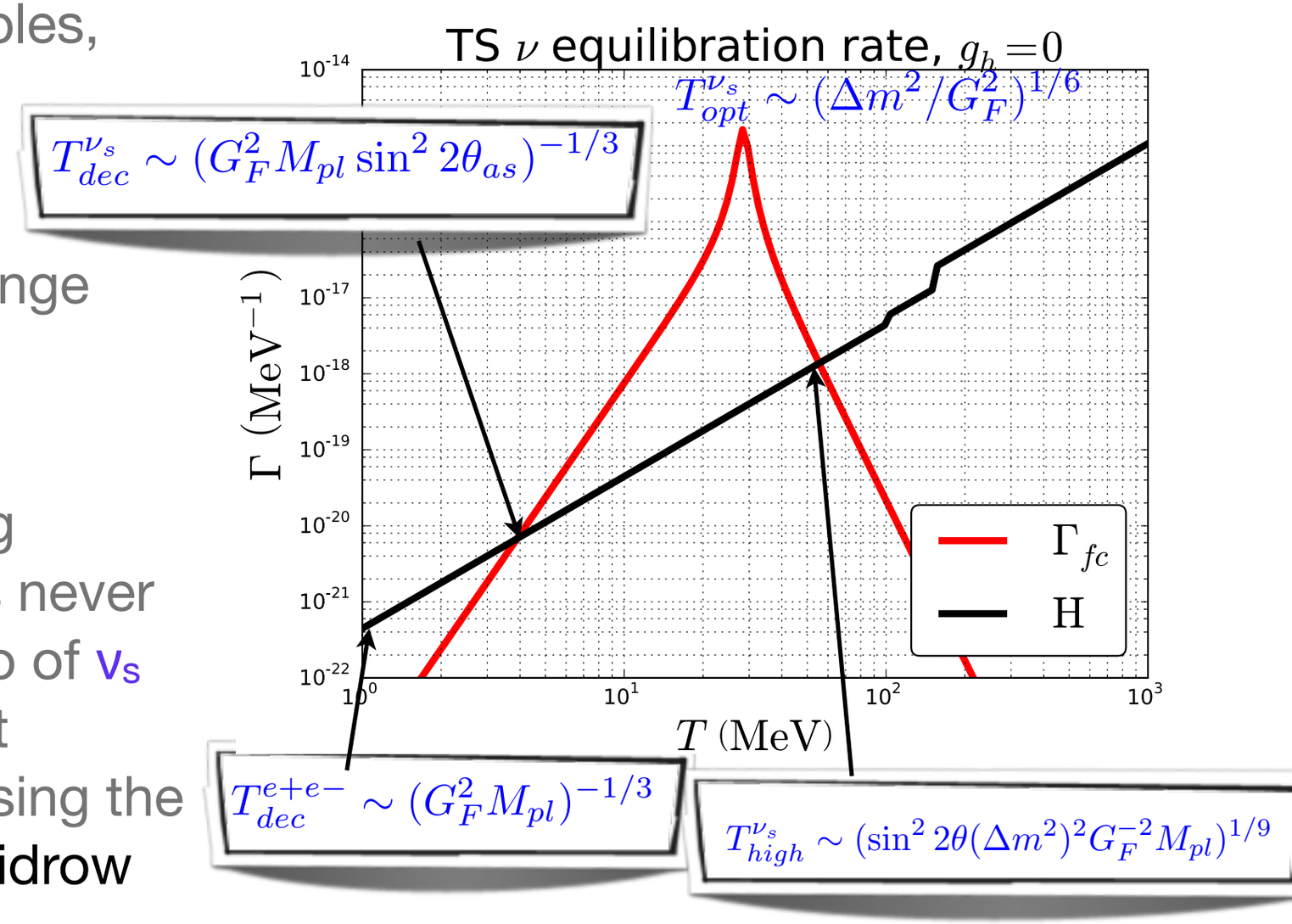
$$G_F^2 T^2 T^3 \gtrsim \Delta m^2/T \rightarrow T \gtrsim (\Delta m^2/G_F^2)^{1/6} \sim 50 \text{ MeV}$$

- II. The (CP-symmetric) medium creates an MSW potential for neutrinos, ~ $G_F^2\, T^5$, that suppresses oscillations [Notzold and Raffelt (1988)]. Same order effect as collisions.

  - Weak Interactions are not strong enough to qualitatively change the evolution (prevent thermalization)

Sterile neutrino coupling window

- The active-sterile system couples, then decouples!
- Several ways around this: change mixing, splitting, or G_F
  - 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)]



Hidden interactions to the rescue?

- What if sterile neutrinos were actually not sterile, but interacting through their own force?

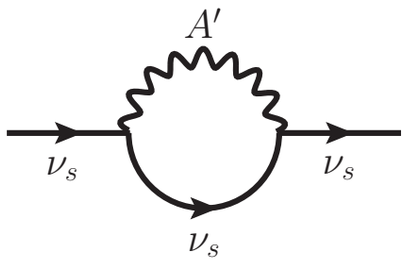
- Once there is some population of hidden neutrinos, this would induce an MSW potential that would suppress mixing between ν_a and ν_h . Would that shut off $\nu_a \rightarrow \nu_h$ thermalization?

- This is the Babu-Rothstein framework

  - Babu & Rothstein, Phys.Lett. B275 (1992) 112-118

Recent resurgence of interest

- Persistent short-baseline anomalies on the one hand and Planck's constraints on Neff on the other brought about renaissance of the BR idea



B. Dasgupta, J. Kopp, PRL (2014);
S. Hannestad, R. S. Hansen, and T. Tram, PRL (2014);
plus a number of others (see later)

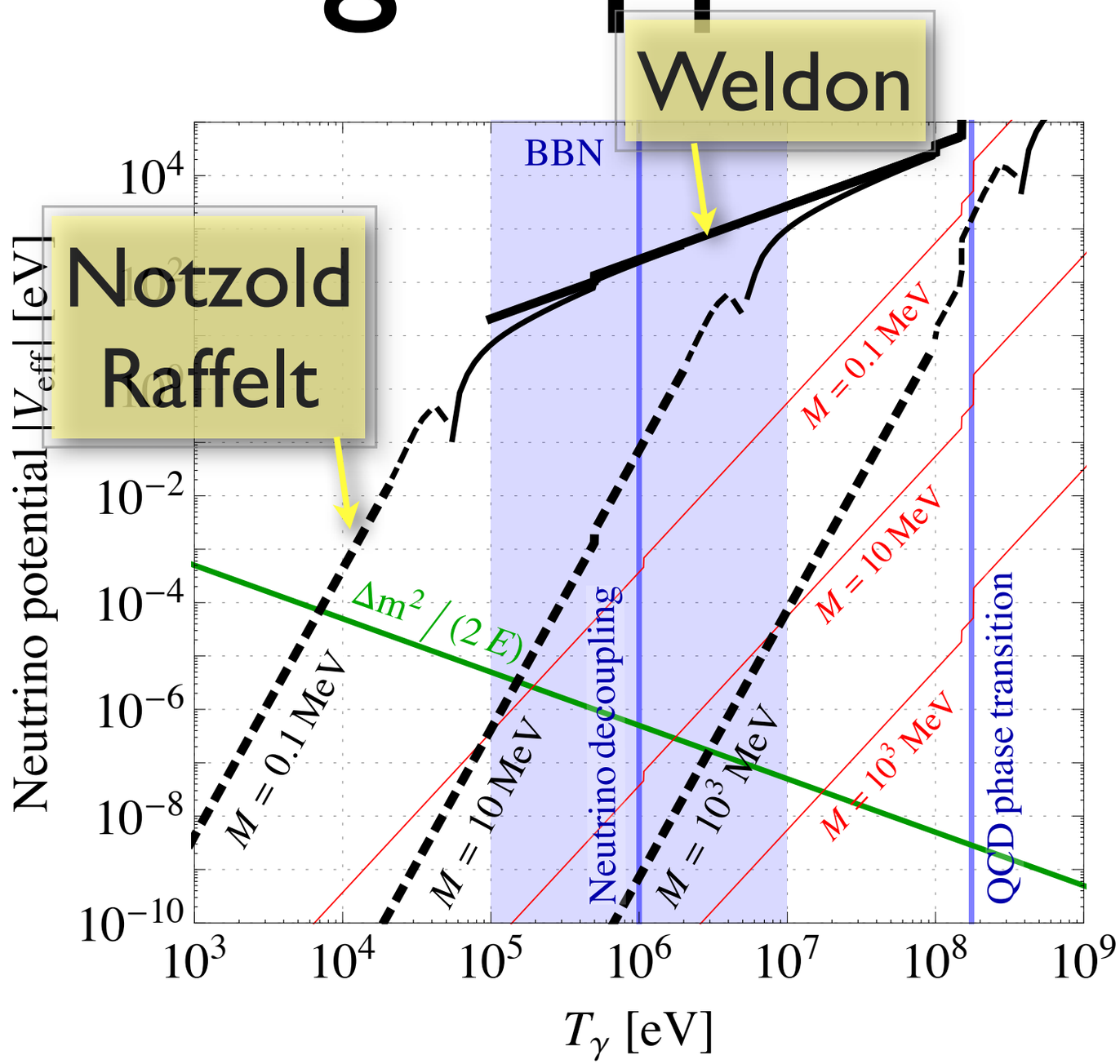
- The contribution to the MSW potential is found by analogy with Weak Interactions, massless QED.

- $$V \sim -\frac{g^4 E T^4}{M^4}, \; T, E \ll M$$ 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]

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

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.
- BOTTOM LINE: The accepted paradigm is that the BR mechanism is efficient: hidden interactions can delay recoupling indefinitely.

We do not agree!

- We carefully analyzed the numerous physical regimes of the problem:
  - 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

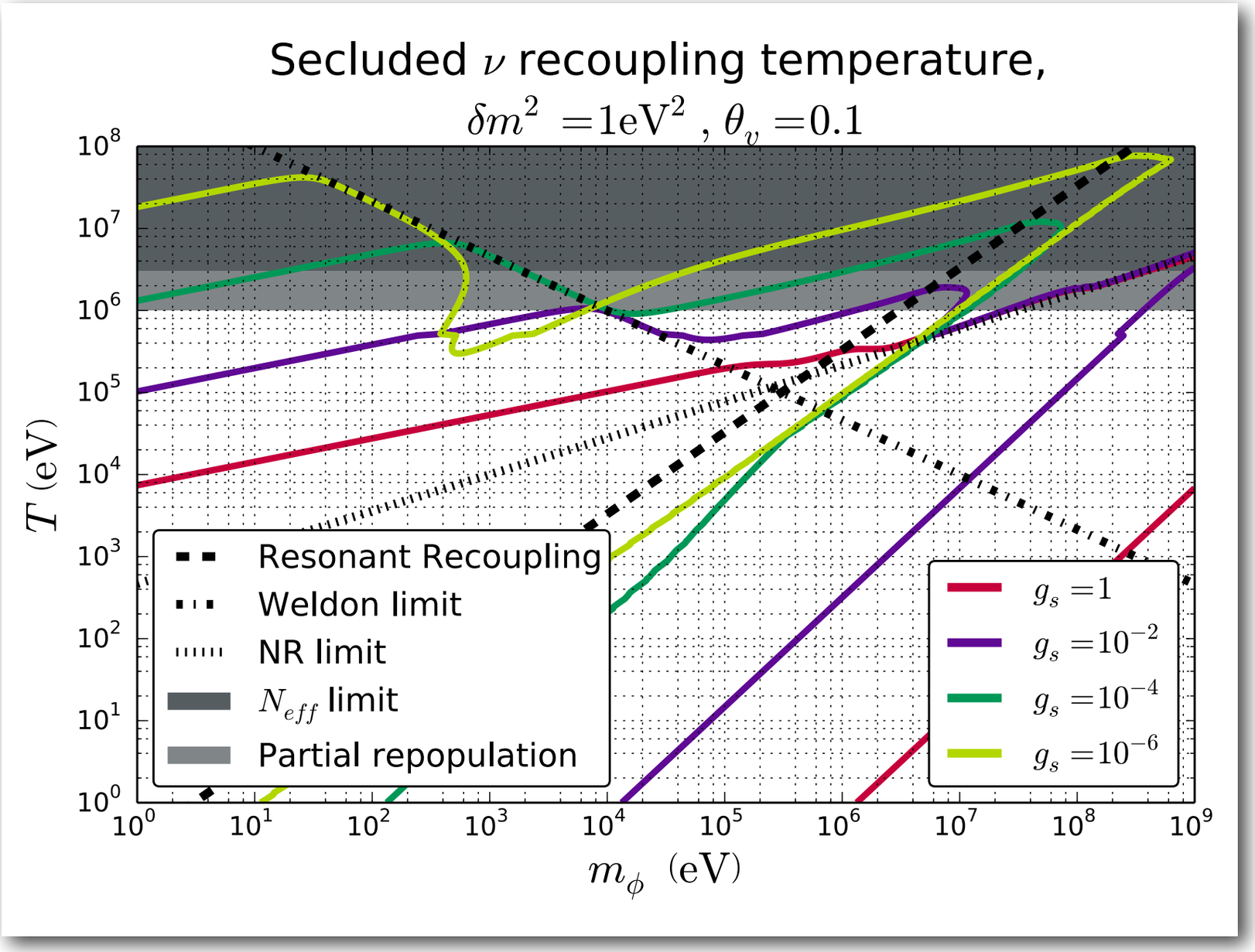
$$T_0 \sim (\sin^2 2\theta (\Delta m^2)^2 M_{pl})^{1/5} \sim 200 \text{ keV}$$

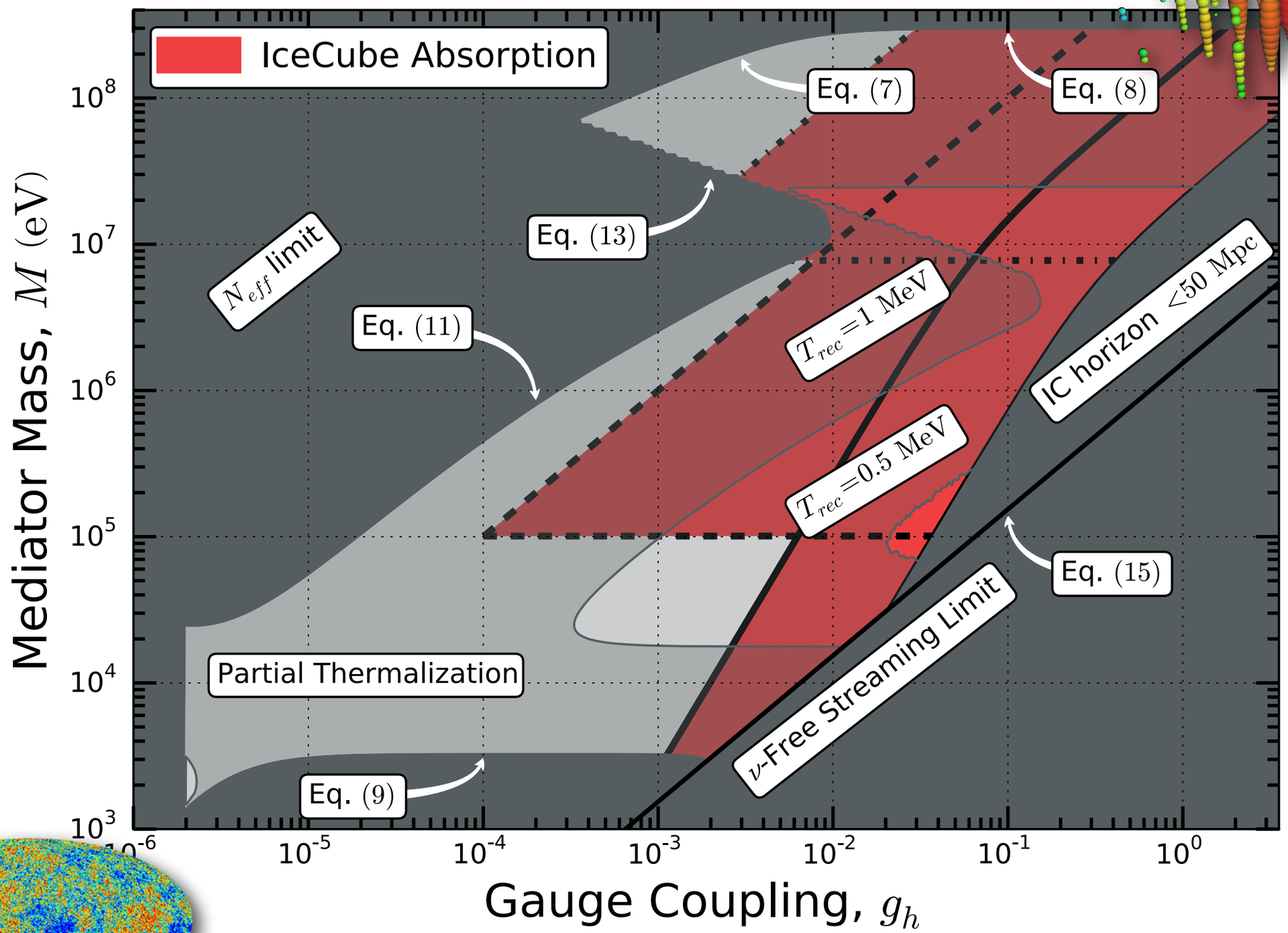
- This is close to 1 MeV of weak decoupling. The BR mechanism is thus only marginally successful.
- We derive the region of parameters where it is viable. The mediator masses are in the range ~ 10^{-3}-10^{2} MeV.
- We then show that this enter range will be probed in the near future.

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

Recoupling isocontours

arXiv:1605.06506 for details




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

Light mediators: excluded by free-streaming

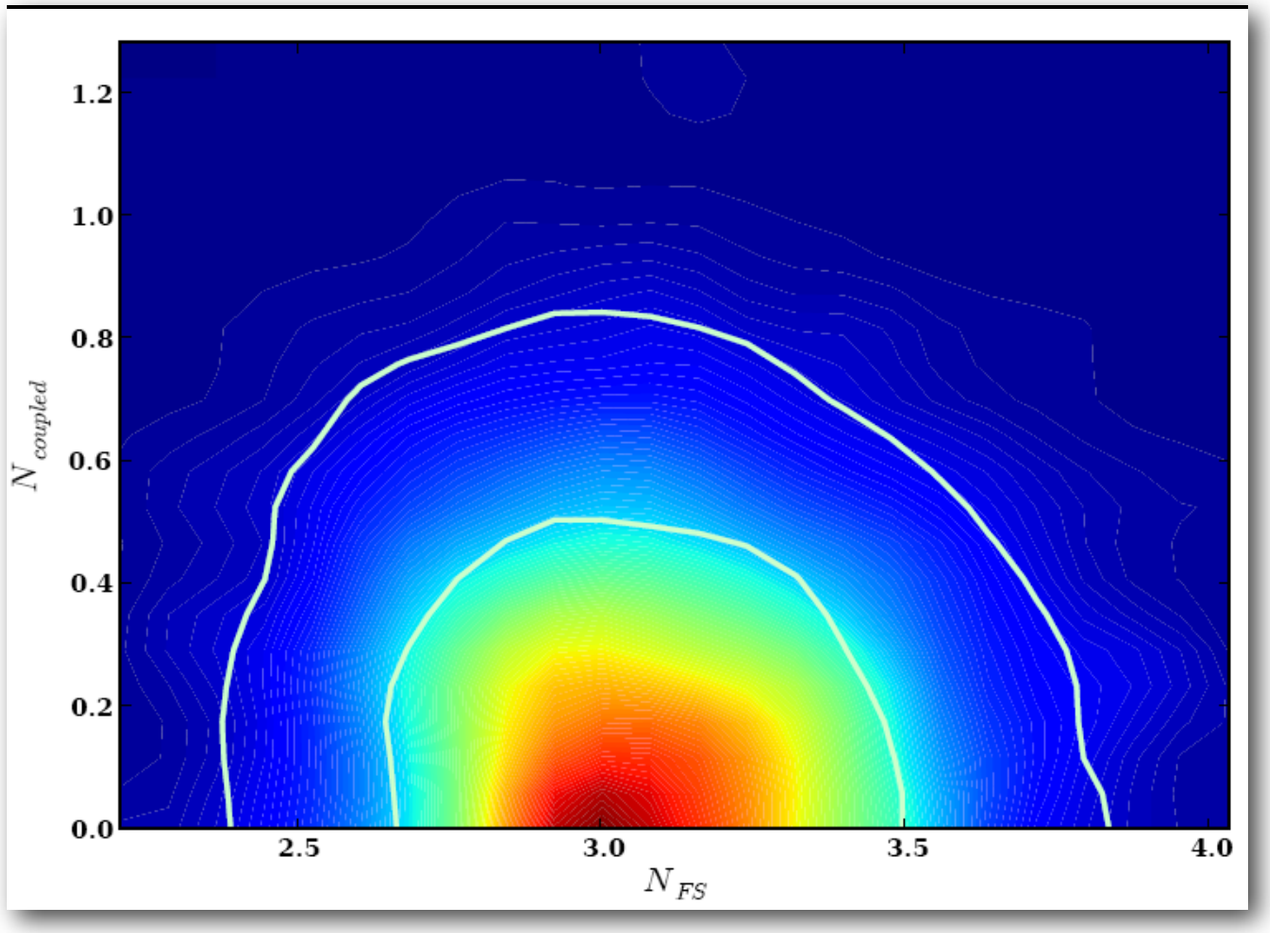
- For sufficiently large coupling, neutrinos, even the ones predominantly active, scatter even at the CMB epoch

- In conflict with PLANCK

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

Friedland, Zurek, Bashinsky, 0704.3271

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



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

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}.

Cosmological degeneracies

- The real challenge is to establish the size of the residual differences of the CMB predictions in the two scenarios, in comparison to the experimental resolution, after the ``nuisance'' parameters are appropriately adjusted.

- These residual differences turn out to be much smaller than the starting differences

- Difficult to write down a simple estimate for the predicted sensitivity of the experiments

- Detailed numerical scans of the multidimensional parameter space

  - (N_{FS}, $N_{coupled}$, $\Omega_b h^2$, $\Omega_c h^2$, θ, τ, Y, n_s, n_{run}, $\log[10^{10} A_s]$)

How can we probe this physics?

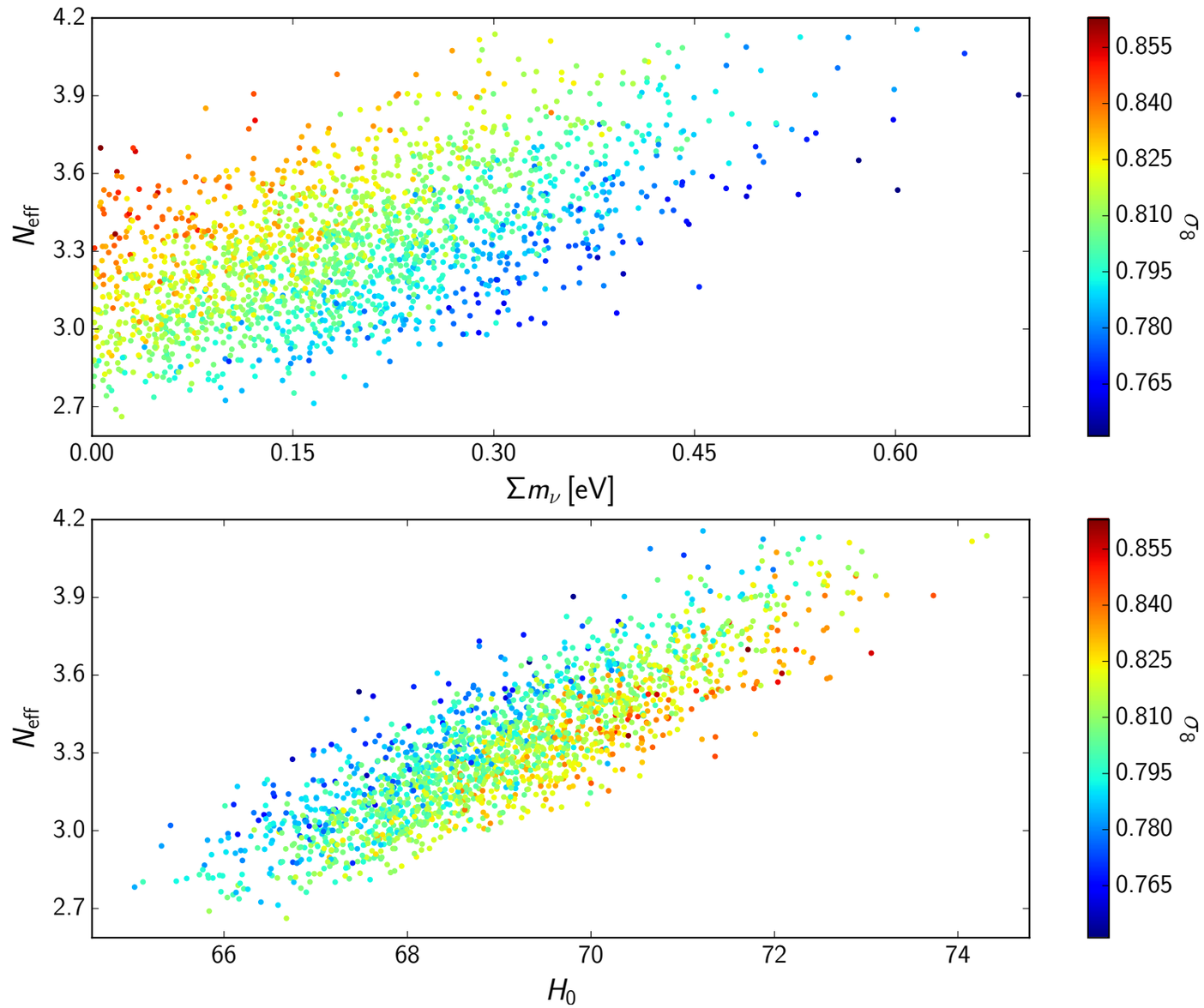
I. Cosmology

- 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!

From Co, A.F., Horowitz, Zurek, in progress

- Task for CMB-S4!



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?

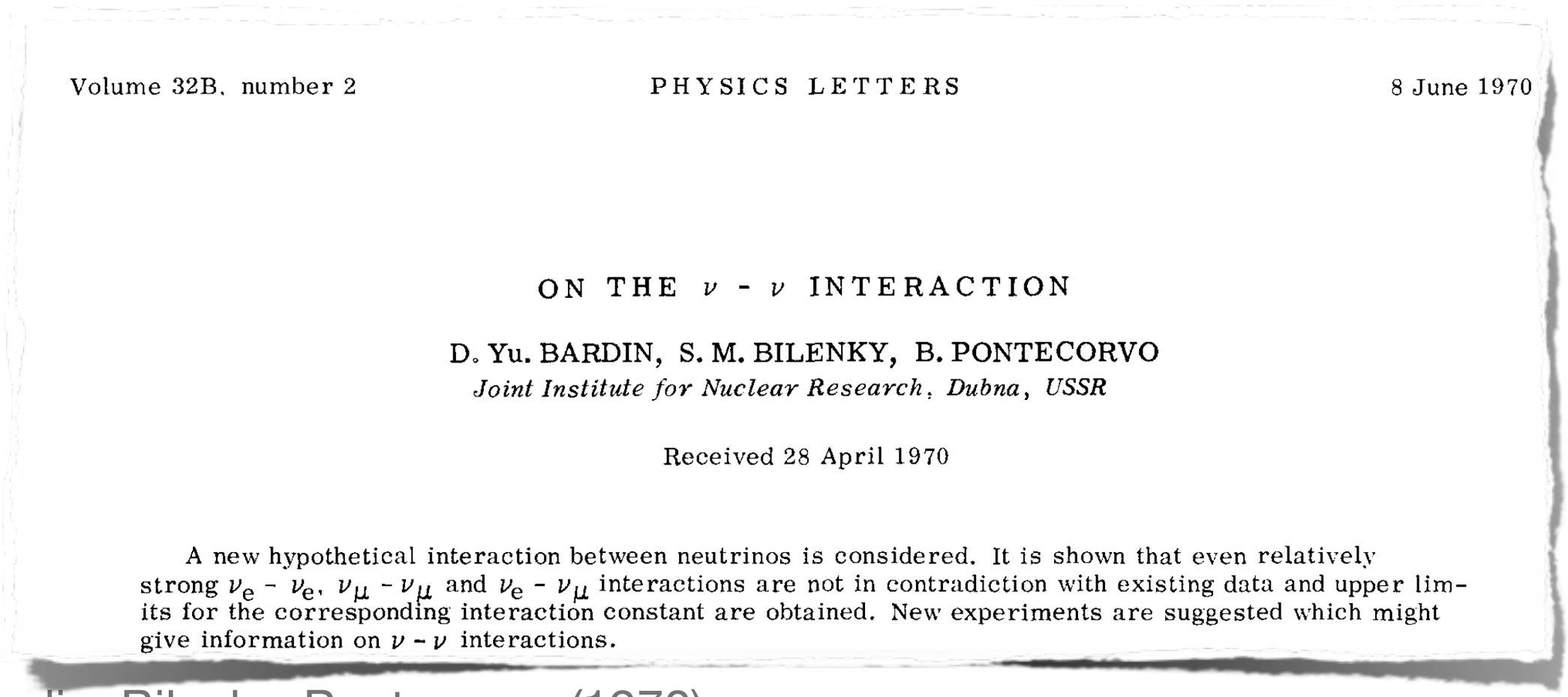
- Interestingly, coupling between dark matter and neutrinos may further help alleviate the structure problems
  - Boehm et al, 2001, 2002, 2004; van den Aarssen, Bringmann, and Pfrommer, 2012
  - Coupling of SM to neutrinos early would keep DM density fluctuations from collapsing, until kinetic decoupling

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

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

III. Testing for 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



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ON THE ν - ν INTERACTION

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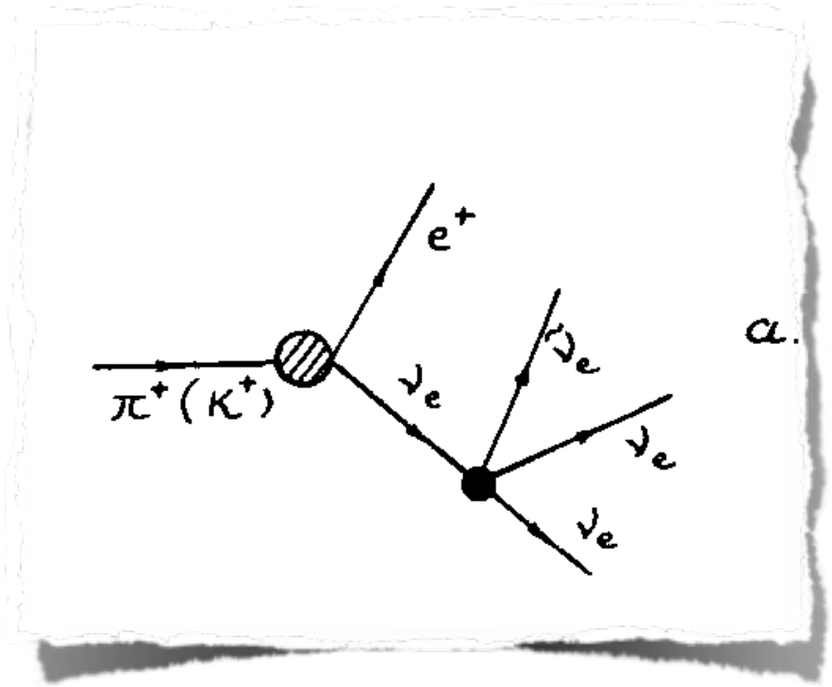
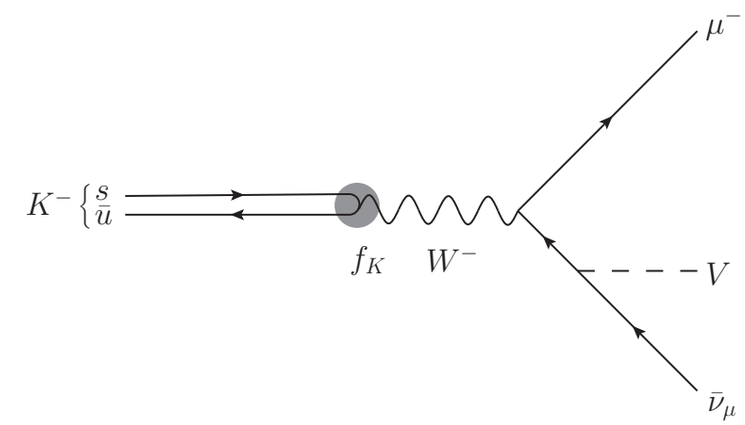
A new hypothetical interaction between neutrinos is considered. It is shown that even relatively strong ν_e - ν_e, ν_μ - ν_μ and ν_e - ν_μ interactions are not in contradiction with existing data and upper limits for the corresponding interaction constant are obtained. New experiments are suggested which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

- Bardin, Bilenky, Pontecorvo (1970)
- Barger, Keung, Pakvasa (1982)
- Manohar (1987)
- Kolb & Turner (1987)
- Fuller, Mayle, Wilson (1988)
- Bilenky, Bilenky, Santamaria (1993)
- ...



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_D component until they oscillate. For example, processes of the type considered by Laha, Dasgupta & Beacom, arXiv:1304.3460 (a la Barger et al 1982) don't occur in the detector



- In dense environments such as supernova, large matter potential reduces the admixture of the "sterile" state --> Manohar 1987 does not apply

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

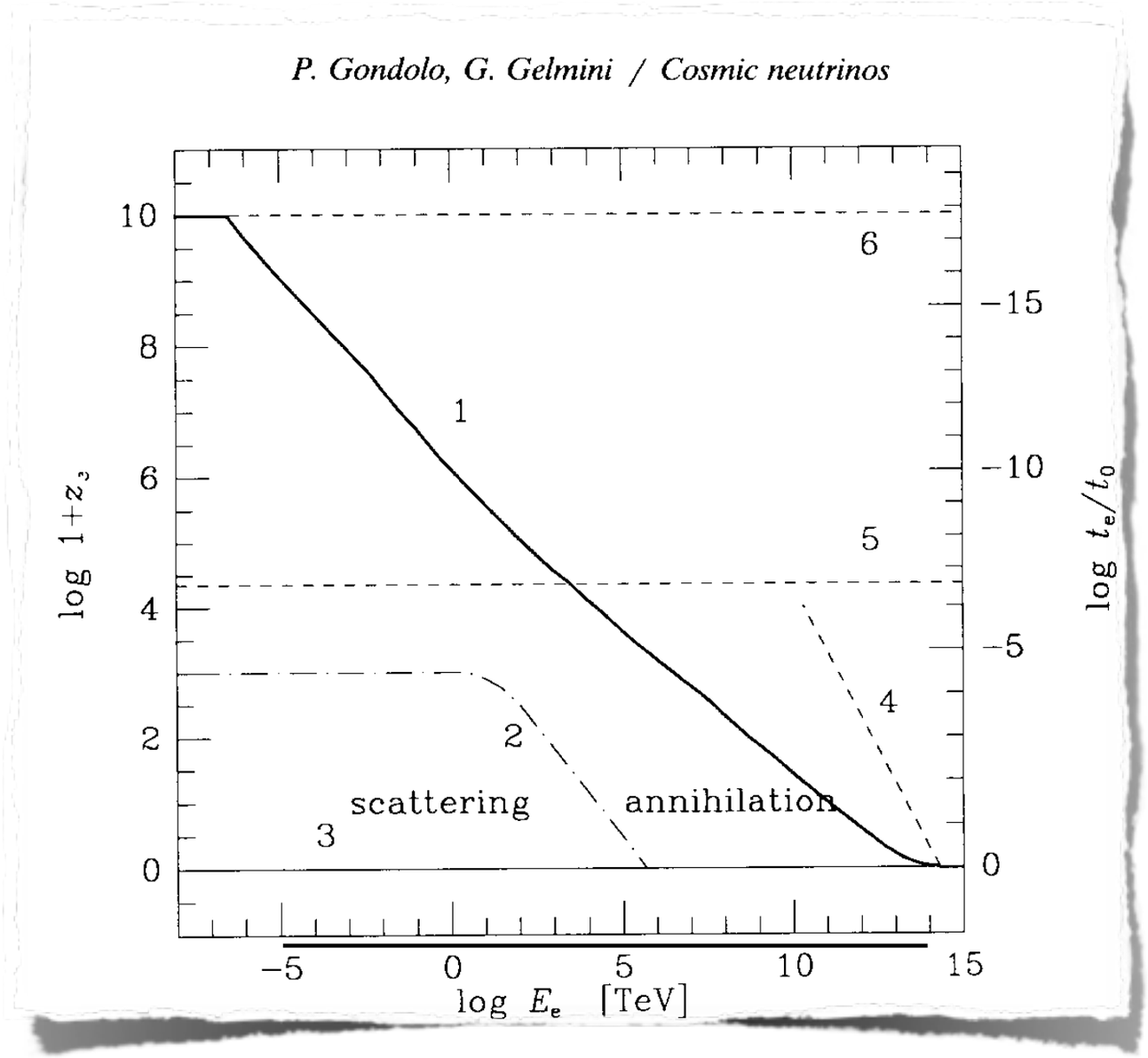
- These neutrinos on their way to us travel through the relic neutrino background. Both the beam and the background had enough time to oscillate and separate into mass eigenstates.

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



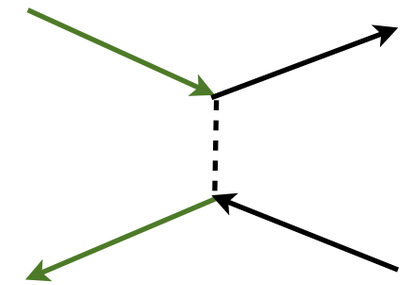
Gondolo, Gelmini, 1993

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

Light mediator

- The standard transparency conclusion is based on standard physics only

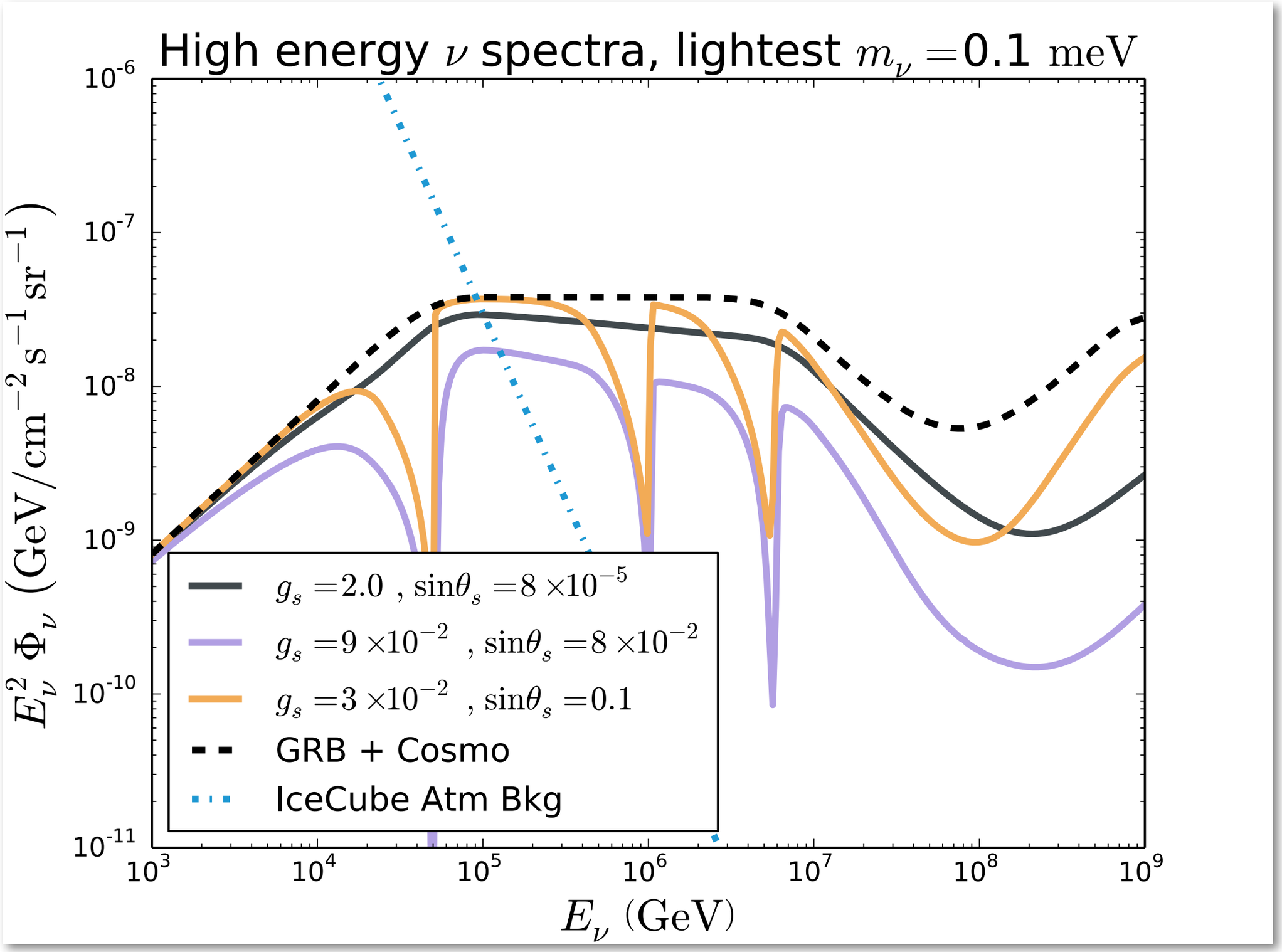
- We now have a light mediator particle?



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

  - ***<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

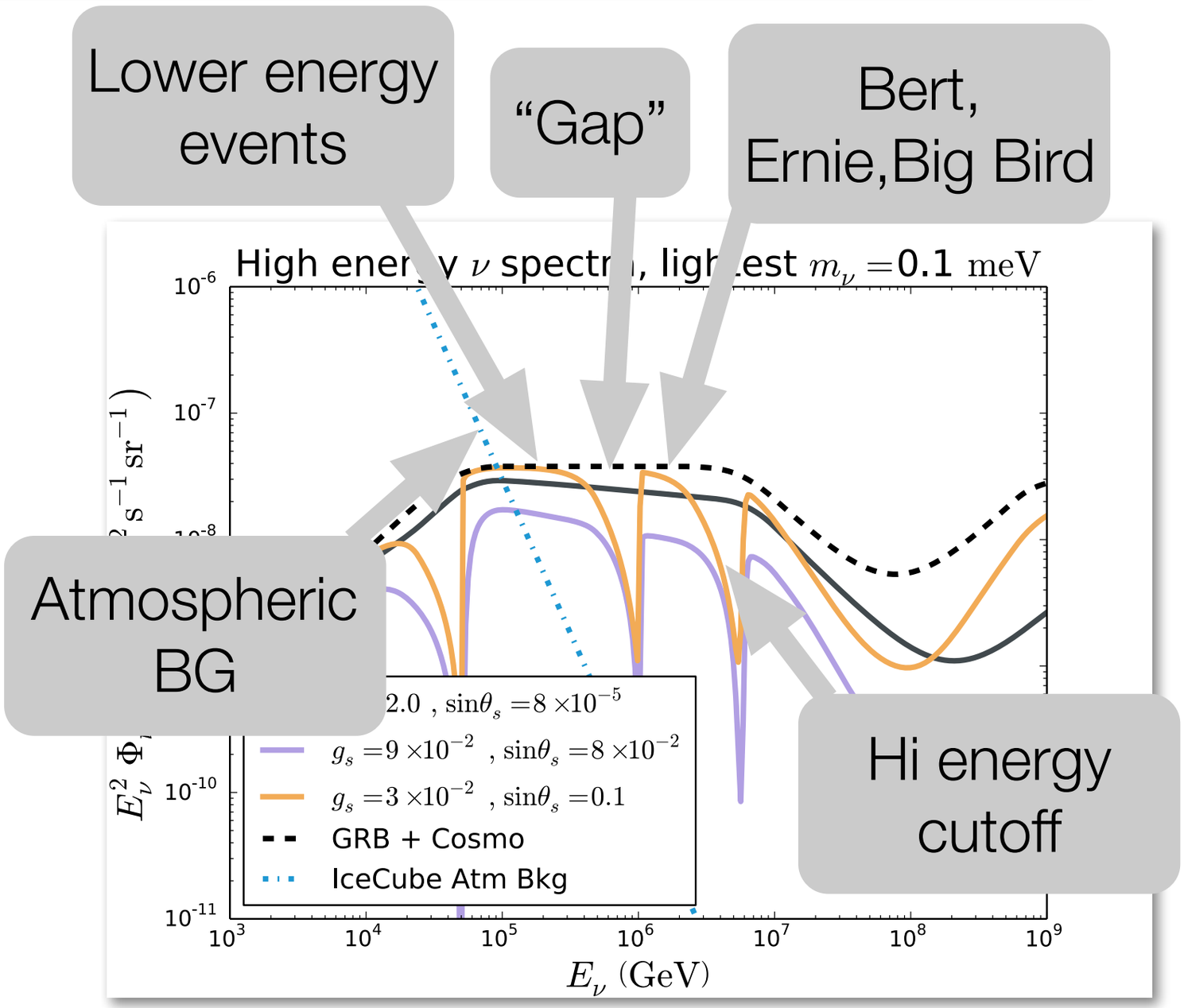


Example calculation

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

Discussion of the results

- Notice the width of the absorption band between 0.3 and 1 PeV. This is where IceCube sees no events
  - This width is obtained automatically, as a consequence of the distribution of GRBs with redshift
  - The absorption line sweeps through that part of the spectrum as the universe expands

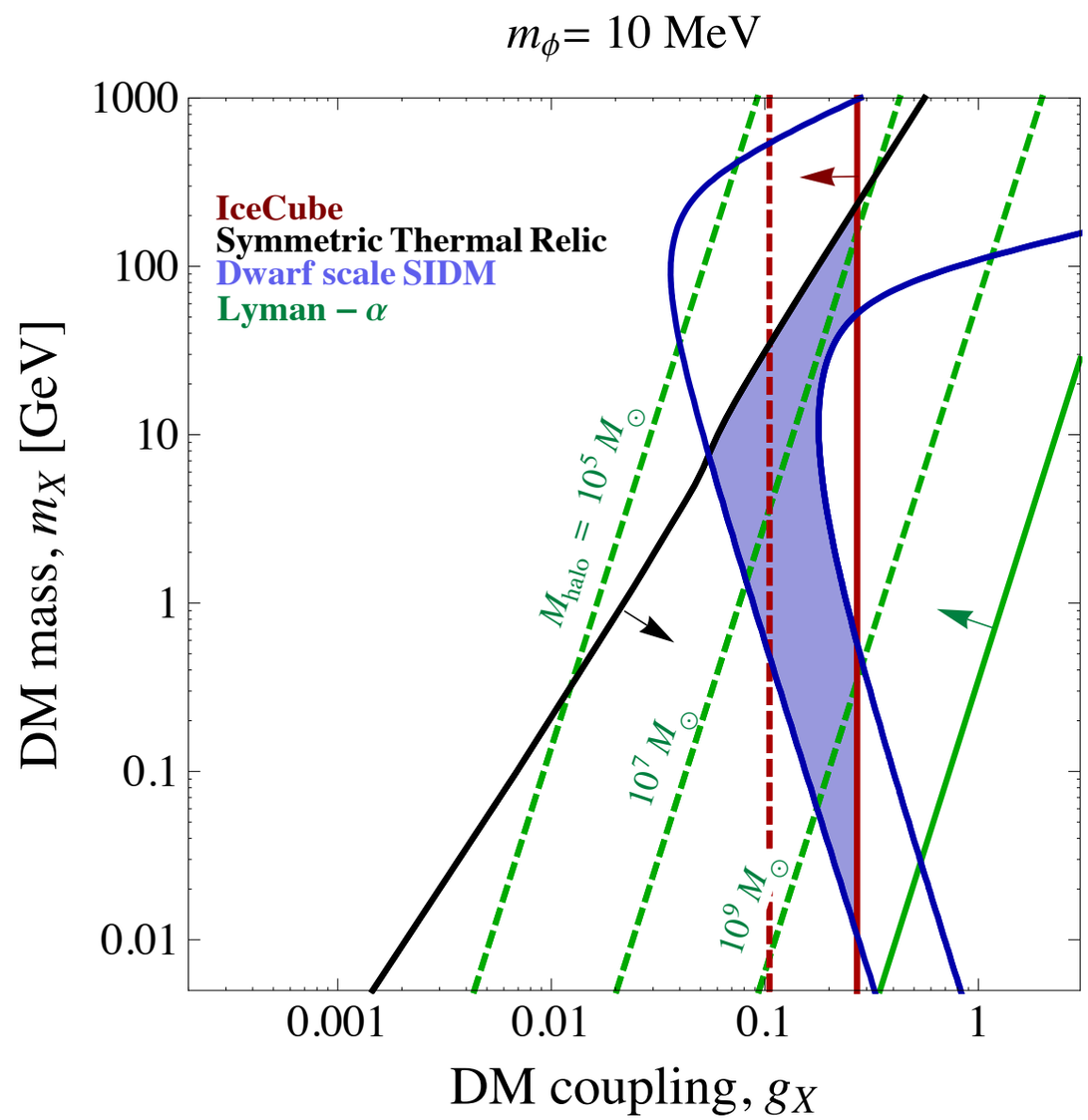


Some interesting implications: source correlations

- Too much absorption would be mean no isotropy of sources
- Intermediate range could mean absorption from far sources
  - -> Source correlations!
-

Concordance

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



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

In summary

- Short-baseline oscillations could be reconciled with cosmology with additional physics in the hidden sector, but the mechanism is only marginally successful

- 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***

- May resolve tensions between CMB data of Planck and local H0, sigma8

  - A variety of signatures in IceCube, spectral features as well as source correlations

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