Abstract

Neutrino physics is a broad and diverse field, both experimentally and theoretically. As the standard oscillation picture begins to settle we are moving into an era where precise tests of the neutrino picture can be made. In this talk I will discuss the present and future status of many theoretical probes and a broad range of experiments spanning twenty orders of magnitude in neutrino energy. In particular, I will highlight the strongly interconnected nature of new physics studies in the neutrino sector.

New Physics Probes in Future Neutrino Experiments

Peter B. Denton

Brookhaven Colloquium

October 29, 2019

BROOKHAVEN NATIONAL LABORATORY

Brookhaven NDI Neutrino Discovery Initiative

White Paper on New Opportunities at the Next-Generation Neutrino Experiments (Part 1: BSM Neutrino Physics and Dark Matter)

C.A. Argüelles, A.J. Aurisano, B. Batell, J. Berger, M. Bishai, T. Boschi, N. Byrnes, A. Chatterjee, A. Chodos, T. Coan, Y. Cui, A. de Gouvêa, P.B. Denton, A. De Roeck, W. Flanagan, R.P. Gandrajula, A. Hatzikoutelis, M. Hostert, B. Jones, B.J. Kayser, K.J. Kelly, D. Kim, J. Kopp, A. Kubik, K. Lang, I. Lepetic, P. Machado, C.A Moura, F. Olness, J.C. Park, S. Pascoli, S. Prakash, L. Rogers, I. Safa, A. Schneider, K. Scholberg, S. Shin, I.M. Shoemaker, G. Sinev, B. Smithers, A. Sousa, Y. Sui, V. Takhistov, J. Thomas, J. Todd, Y.-D. Tsai, Y.-T. Tsai, D. Vanegas Forero, J. Yu, C. Zhang

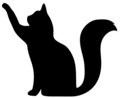
(Submitted on 18 Jul 2019 (v1), last revised 18 Oct 2019 (this version, v3))

With the advent of a new generation of neutrino experiments which leverage high-intensity neutrino beams for precision measurements, it is timely to explore physics topics beyond the standard neutrino-related physics. Given that the realm of beyond the standard model (BSM) physics has been mostly sought at high-energy regimes at colliders, such as the LHC at CERN, the exploration of BSM physics in neutrino experiments will enable complementary measurements at the energy regimes that balance that of the LHC. This is in concert with new ideas for high-intensity beams for fixed target and beam-dump experiments world-wide, e.g., those at CERN. The combination of the high intensity proton beam facilities and massive detectors for precision neutrino oscillation parameter measurements and for CP violation phase measurements will help make BSM physics reachable even in low energy regimes in accelerator based experiments. Large mass detectors with highly precise tracking and energy measurements, excellent timing resolution, and low energy thresholds will enable searches for BSM phenomena from cosmogenic origin, as well. Therefore, it is conceivable that BSM topics in the next generation neutrino experiments could be the dominant physics topics in the foreseeable future, as the precision of the neutrino oscillation parameter and CPV measurements continues to improve. In this spirit, this white paper provides a review of the current landscape of BSM theory in neutrino experiments in two selected areas of the BSM topics - dark matter and neutrino related BSM - and summarizes the current results from existing neutrino experiments to set benchmarks for both theory and experiment. This paper then provides a review of upcoming neutrino experiments throughout the next 10 - 15 year time scale and their capabilities to set the foundation for potential reach in BSM physics in the two aforementioned themes.

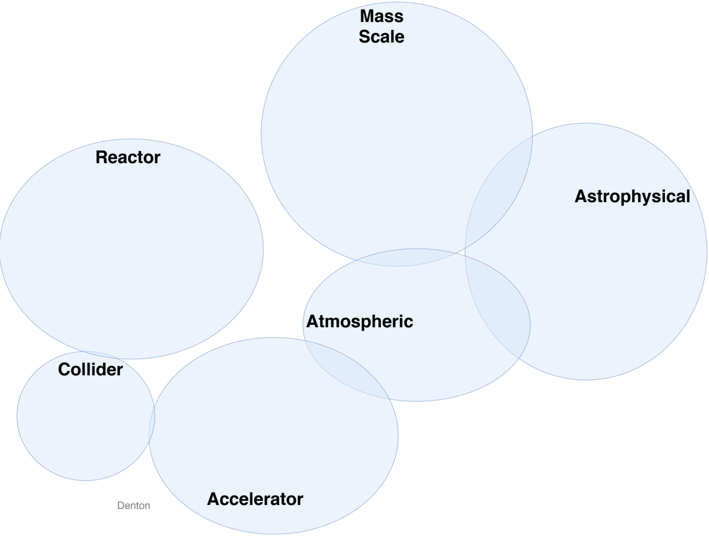
1907.08311

Why Neutrinos Are Awesome

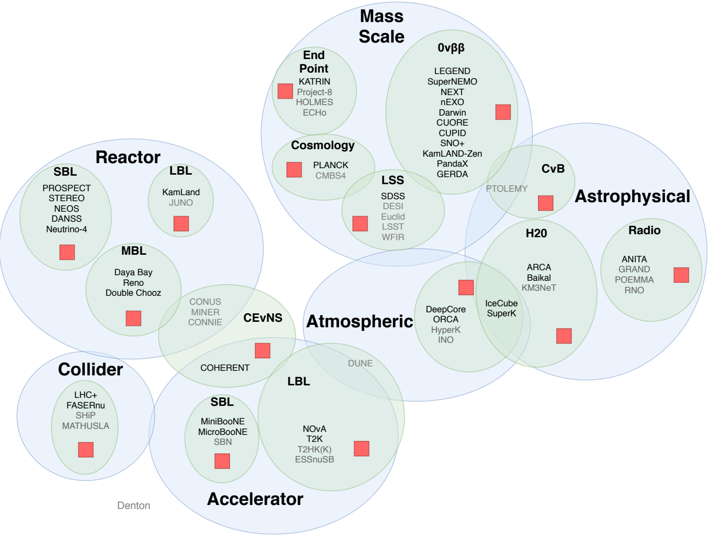
1. 7+ new parameters
   - Oscillations → 6
   - Mass scale → 1+
2. Mass generation mechanism
3. Nature of neutrinos
4. Poorly measured ⇒ great place to look for new physics
5. Resolve anomalies
6. Role of neutrinos in the early universe
7. Extreme particle physics production
8. High degree of interconnectivity



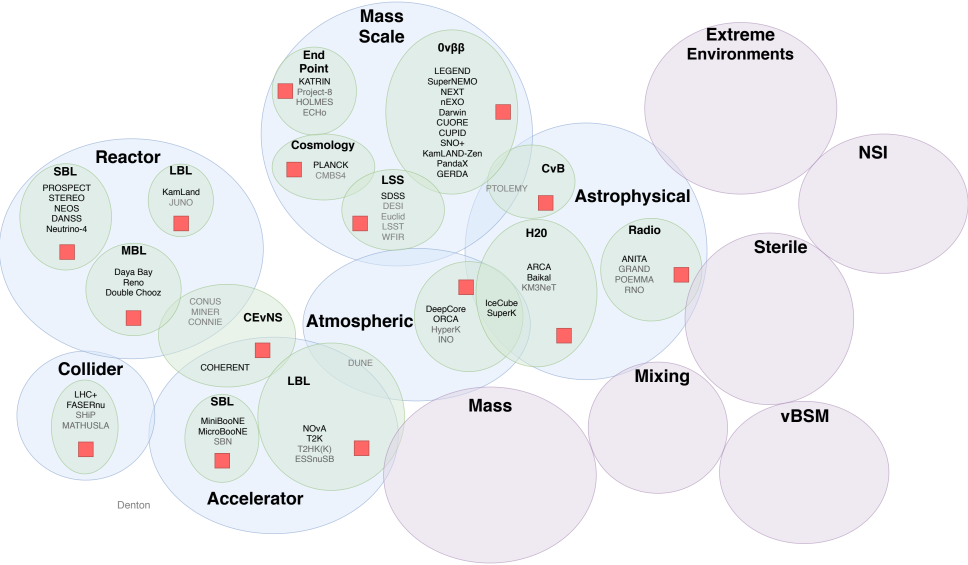
Experiments ↔ Physics



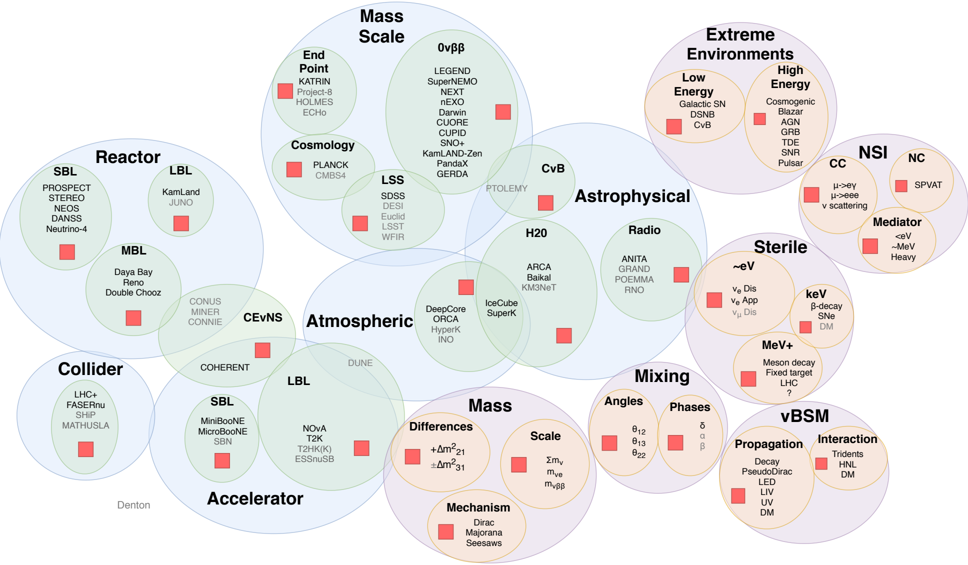
Experiments ↔ Physics



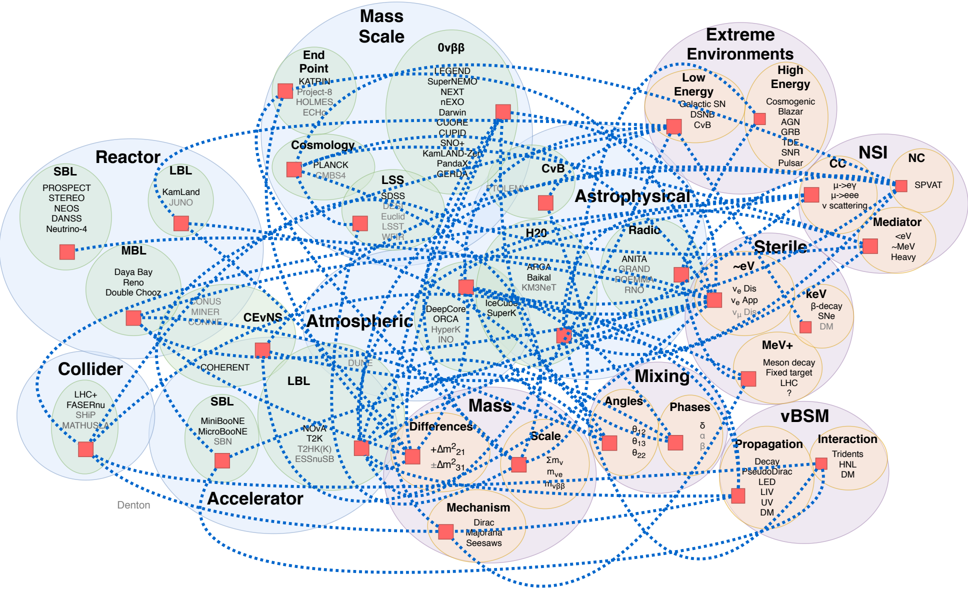
Experiments ↔ Physics



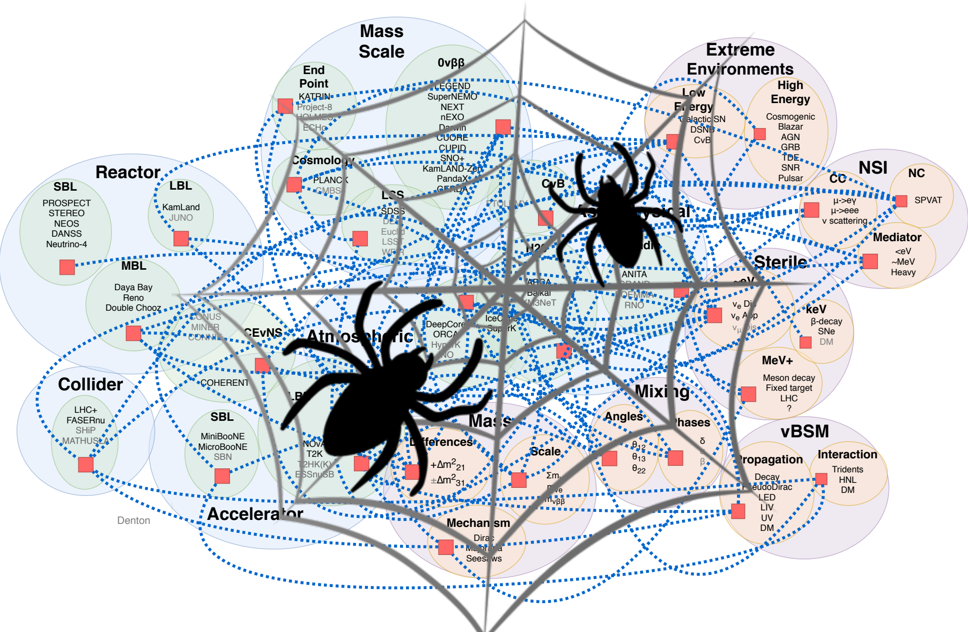
Experiments ↔ Physics



Experiments ↔ Physics



Experiments ↔ Physics



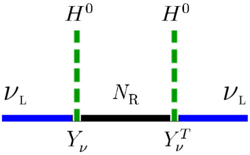
Mass Generation

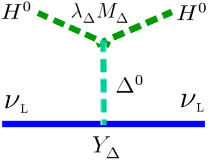
Dirac

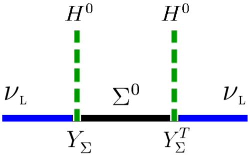
$$\mathcal{L} \supset -\bar{\ell}_L Y_\ell H E_R - \bar{\ell}_L Y_\nu \tilde{H} N_R + h.c.$$

Impose $B-L$ $\qquad$ $y_\nu / y_e \sim 10^{-6}$

Seesaw







M_ν: $\quad -\frac{1}{2} Y_\nu \frac{v^2}{M_R} Y_\nu^T \qquad \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} \qquad -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T$

H. Fritzsch, M. Gell-Mann, P. Minkowski PLB 1975

P. Minkowski PLB 1977

W. Konetschny, W. Kummer PLB 1977

D. Wyler, L. Wolfenstein NPB 1983

R. Foot, H. Lew, X. He, G. Joshi ZPC 1989

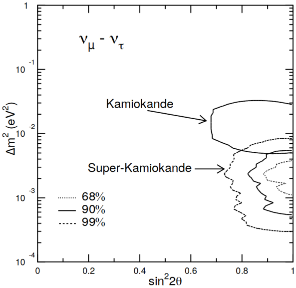
Inverse

$$M_\nu : \; M_D \frac{1}{M_S^T} \mu \frac{1}{M_S} M_D^T$$

Discovery of Oscillations

Super-KamiokaNDE

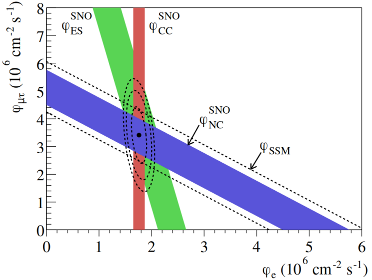
$P(\nu_\mu \to \nu_\mu) \quad \Delta m^2 \sim 10^{-3}$ eV^2



SK hep-ex/9807003

SNO

$P(\nu_e \to \nu_e) \quad \Delta m^2 \sim 10^{-5}$ eV^2



SNO nucl-ex/0204008

Oscillations $\Rightarrow v_\nu < c$

Three distinct masses

Oscillation Physics

To get oscillations, need to produce neutrinos in a different basis than how they propagate

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1}&U_{e2}&U_{e3}\\ U_{\mu1}&U_{\mu2}&U_{\mu3}\\ U_{\tau1}&U_{\tau2}&U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Lots of parameters

	18
Unitarity	9
Charged lepton rephasing	6
Neutral lepton rephasing	4

$$\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta$$

Oscillations Pedagogy

Standard parameterization of lepton mixing matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Many other unitary matrices, all valid

H. Fritzsch, Z-z. Xing hep-ph/0103242

CP violation governed by the Jarlskog

$$J = s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23}\sin\delta$$

Neutrino Masses → Oscillations

1. Neutrinos propagate in mass eigenstates
2. Each mass state accumulates a phase

$$\phi_i = \frac{m_i^2}{2E} x$$

3. Interference cares about phase differences, sensitive to $m_i^2 - m_j^2 \equiv \Delta m_{ij}^2$
4. Oscillations insensitive to <u>absolute</u> mass scale

Experiment to Oscillation Parameters

Six oscillation parameters: θ_{12}, θ_{13}, θ_{23}, δ, Δm^2_{21}, Δm^2_{31}

- Atmospheric ν_μ disappearance $\to \sin 2\theta_{23}$, $|\Delta m^2_{31}|$

  SuperK, IMB, IceCube
- Solar ν_e disappearance $\to \pm\cos 2\theta_{12}$, $\pm\Delta m^2_{21}$

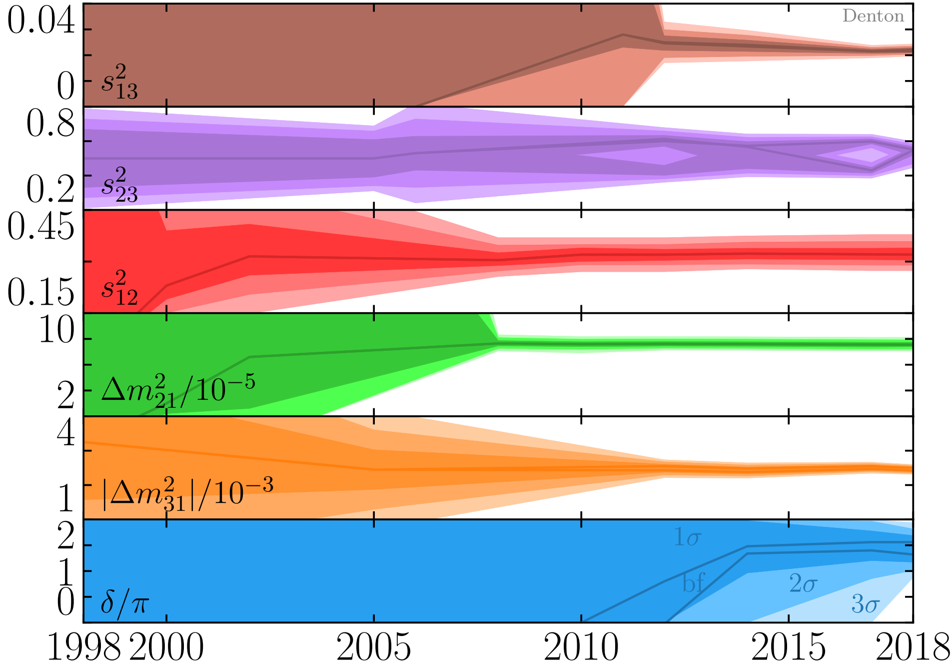
  SNO, Borexino, SuperK
- Reactor ν_e disappearance:
  - LBL $\to \sin 2\theta_{12}$ and $|\Delta m^2_{21}|$

    KamLand
  - Future LBL $\to \pm\Delta m^2_{31}$

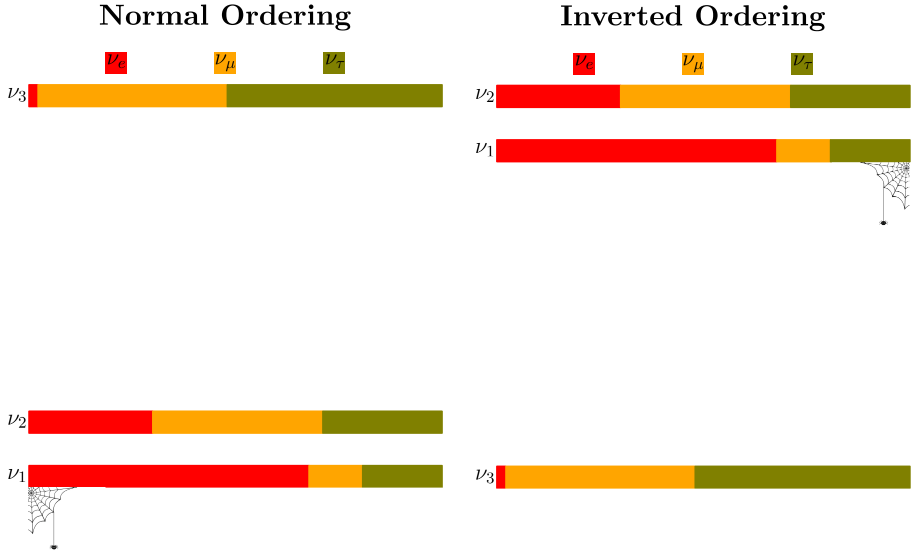
    JUNO
  - MBL $\to \theta_{13}$, $|\Delta m^2_{31}|$

    Daya Bay, RENO, Double Chooz
- Accelerator LBL ν_e appearance: $\pm\Delta m^2_{31}$, $\pm\cos 2\theta_{23}$, θ_{13}, δ

  T2K, NOvA, T2HK, DUNE

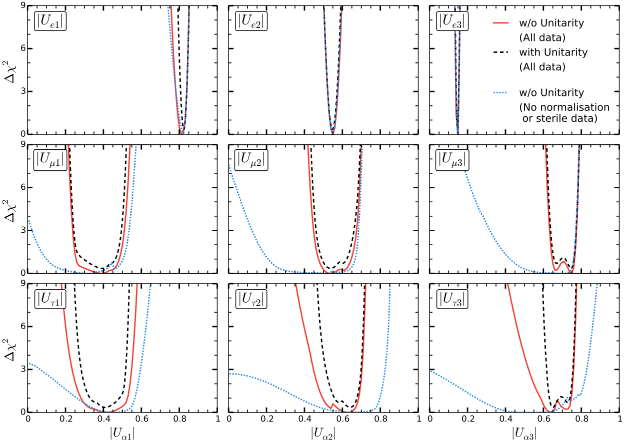

Denton
0.04
0
s_{13}^2
0.8
0.2
s_{23}^2
0.45
0.15
s_{12}^2
10
2
$\Delta m_{21}^2/10^{-5}$
4
1
$|\Delta m_{31}^2|/10^{-3}$
2
1
0
δ/π
1σ
bf
2σ
3σ
1998
2000
2005
2010
2015
2018

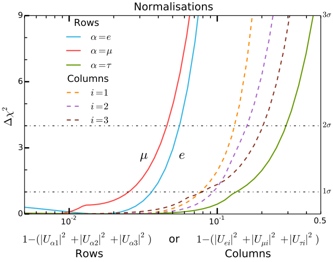
Are Neutrinos Normal or Not?

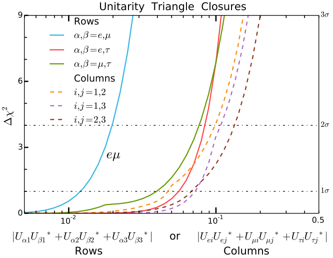


m_3? $\sin^2\theta_{23}$?

Most Generic Three Flavor Consistency Check



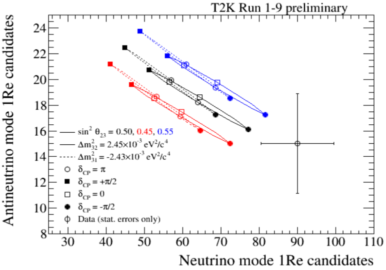




S. Parke, M. Ross-Lonergan 1508.05095

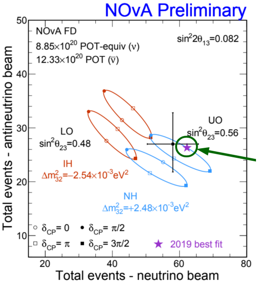
Long Baseline Oscillations: Present

295 km



G. Feldman 1901.09431

810 km



NOvA FNAL Users Meeting '19

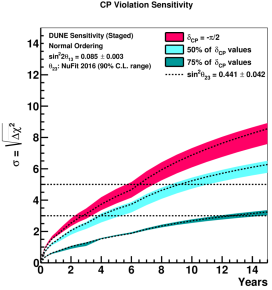
Mass ordering separation $\propto N_e L s_{23}^2$

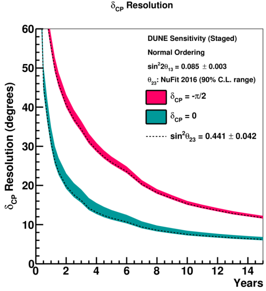
Matter effect $\Rightarrow$ mass ordering

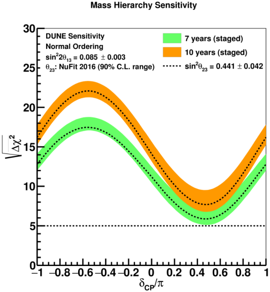
L. Wolfenstein PRD 1978

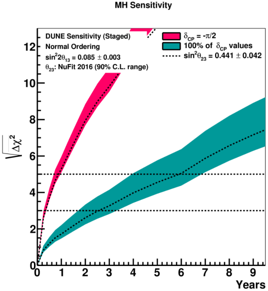
Long Baseline Oscillations: Future

DUNE





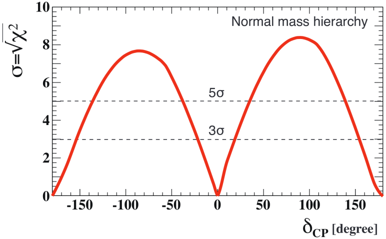




$\Delta\theta_{23} \sim 1^\circ$

DUNE 1807.10334

T2HK



MO $\sim 3\ \sigma$

$\Delta\theta_{23} \sim 1^\circ$

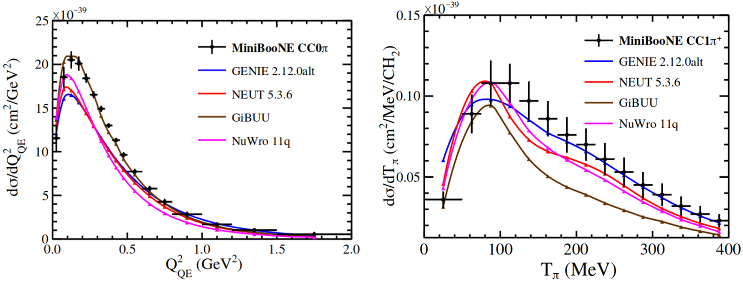
T2HK 1412.4673

Second maximum

ESSnuSB 1611.06118

T2HKK 1309.7022

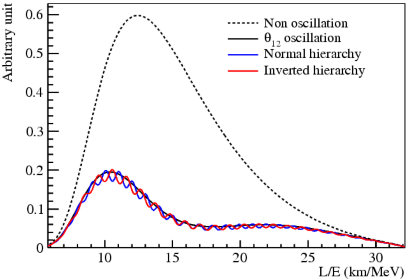
Long Baseline Oscillations: Cross Sections



M. Betancourt, et al. 1805.07378

JUNO: Mass Ordering

1. 53 km baseline
2. Targeting $3\%/\sqrt{E/\text{MeV}}$ resolution
3. Expected to open in 2021



JUNO 1507.05613

ND is necessary

F. Capozzi, E. Lisi, A. Marrone 1508.01392

H. Wang, et al. 1602.04442

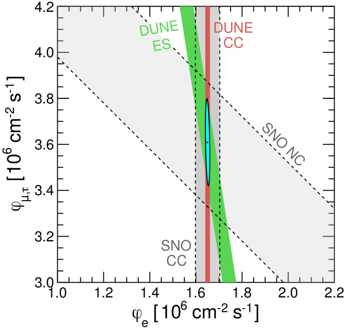
D. Forero, R. Hawkins, P. Huber 1710.07378

ND isn't necessary

D. Danielson, A. Hayes, G. Garvey 1808.03276

DUNE: Beyond LBL Oscillations

Solar



F. Capozzi, et al. 1808.08232

May be possible to measure:

$$\pm\Delta m^2_{31},\ \theta_{23},\ \delta,\ \theta_{13},\ \Delta m^2_{21},\ \text{and}\ \theta_{12}!$$

Atmospheric

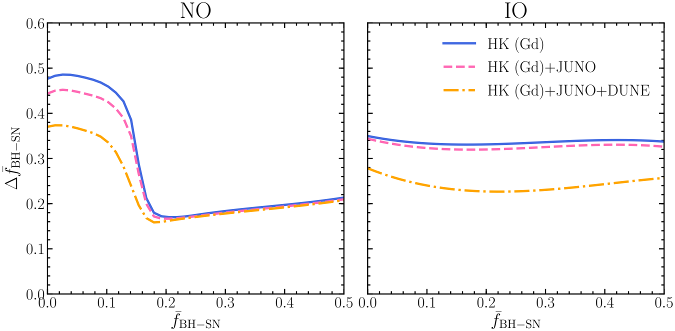
K. Kelly, et al. 1904.02751

Supernova Neutrinos

Galactic SN → Mass Ordering

K. Scholberg 1707.06384

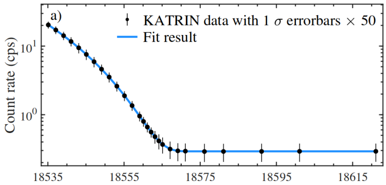
Diffuse Supernova Neutrino Background can constraint $R_{\rm SN}$ and $f_{\rm BH}$



K. Møller, A. Suliga, I. Tamborra, PBD 1804.03157

Neutrino Mass Scale

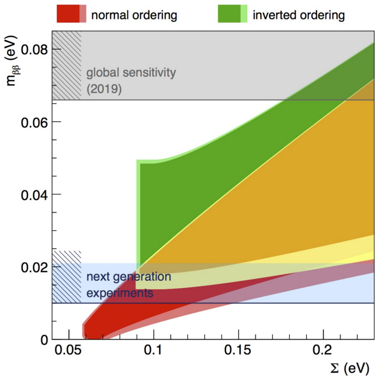
Endpoint: $\sqrt{m_e^2} < 1.1$ eV



KATRIN 1909.06048

$m_e^2 = \sum |U_{ei}|^2 m_i^2$

$0\nu\beta\beta$: $m_{\beta\beta} \lesssim 0.65$ eV



APPEC 1910.04688

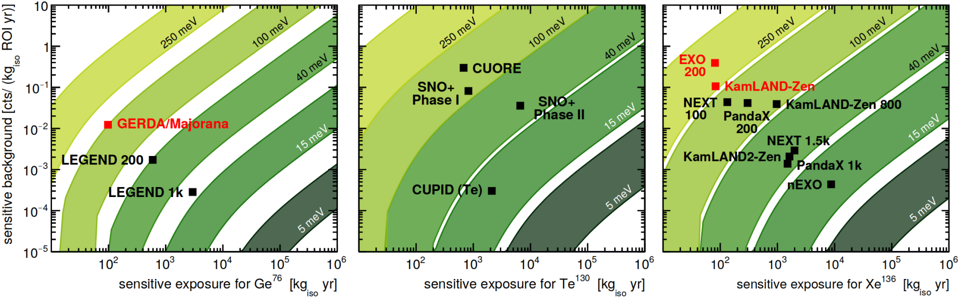
$m_{\beta\beta} = |\sum U_{ei}^2 m_i|$

Considerable nuclear uncertainties

Cosmology: $\sum m_i < 0.12$ eV

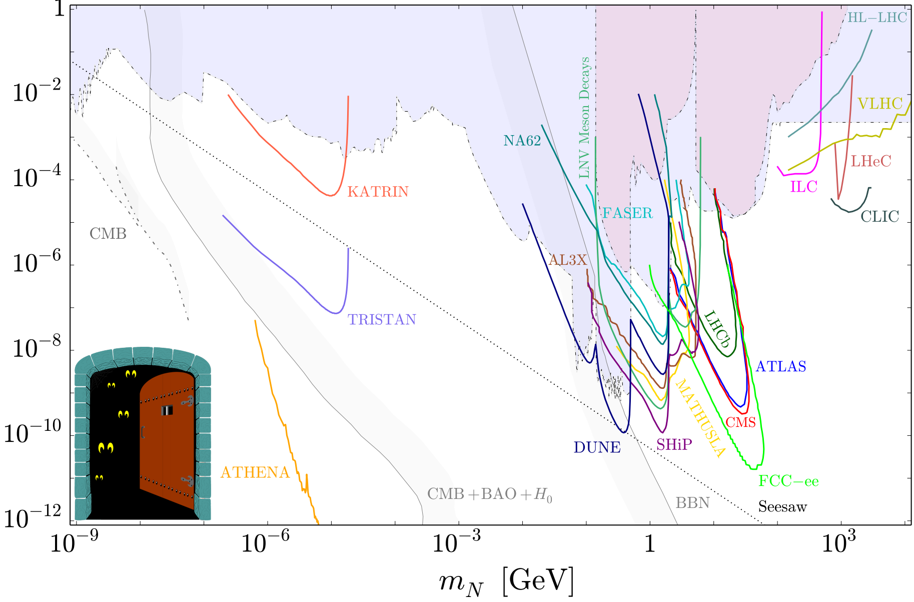
Planck 1807.06209

Neutrinoless Double Beta Decay: Prospects



M. Agostini, G. Benato, J. Detwiler 1705.02996

Sterile Neutrinos: Where are they Hiding?



F. Deppisch CERN Neutrino Platform '19

Sterile Neutrinos: the eV puzzle

Experimental evidence for $m_4 \sim 1$ eV:

- LSND + MiniBooNE: 3.8 σ + 4.7 σ

LSND hep-ex/0104049

MiniBooNE 1805.12028

- Reactor Antineutrino Anomaly: 3 σ

G. Mention, et al. 1101.2755

Daya Bay 1704.01082

A. Hayes, E. McCutchan, A. Sonzogni, et al. 1707.07728

- Gallium anomaly: 3 σ

C. Giunti, M. Laveder 1006.3244

2.3 σ: J. Kostensalo, J. Suhonen, C. Giunti, P. Srivastava 1906.10980

- NEOS, DANSS, Neutrino-4: ~ 3 σ, 2.8 σ, 2.8 σ

NEOS Neutrino, '18

DANSS Neutrino, '18

Neutrino-4 1809.10561

Sterile Neutrinos: eV Constraints

Experimental constraints from:

- IceCube 1605.01990
- MINOS/MINOS+ 1710.06488
- Super-K 1410.2008
- KARMEN hep-ex/0203021
- CDHS PLB 134, 281 (1984)
- Daya Bay, MINOS, Bugey-3 1607.01177
- OPERA 1303.3953
- ICARUS 1209.0122
- NOvA 1706.04592
- PROSPECT 1806.02784

⋮

$3 + N$ doesn't help

J. Kopp, et al. 1303.3011

Cosmology needs to be accommodated

LSND, MiniBooNE Alternatives

CPT violation

H. Murayama, T. Yanagida hep-ph/0010178

G. Barenboim, L. Borissov, J. Lykken hep-ph/0212116

Dark Energy

D. Kaplan, A. Nelson, N. Weiner hep-ph/0401099

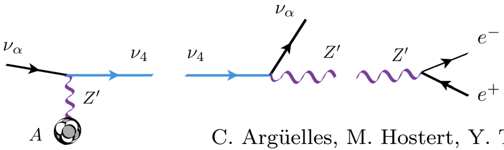
Extra dimensions

H. Pas, S. Pakvasa, T. Weiler hep-ph/0504096

Many non-sterile BSM explanations ruled out

J. Jordan, et al. 1810.07185

Upscatter to unstable ν_s which promptly decays



C. Argüelles, M. Hostert, Y. Tsai 1812.08768

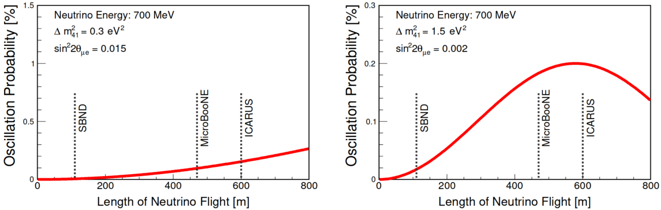
E. Bertuzzo, et al. 1807.09877

Short Baseline Neutrino Program

1. Leverage LAr to discriminate photons from electrons

μB 1910.02166

2. L is easier to measure than E



P. Machado, O. Palamara, D. Schmitz 1903.04608

3. Test bed for LAr technology

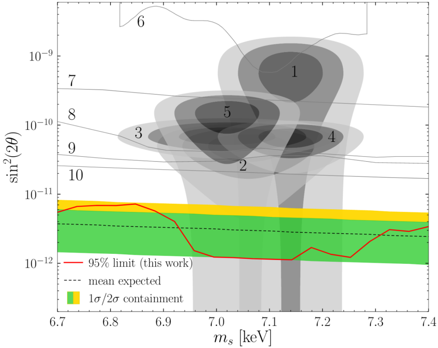
Sterile Neutrinos: keV range

- $m_4 \gtrsim 1$ keV $\Rightarrow$ DM

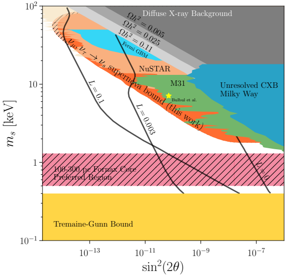
S. Dodelson, L. Widrow, hep-ph/9303287

- 7 keV sterile from X-ray line

E. Bulbul, et al. 1402.2301



C. Dessert, N. Rodd, B. Safdi 1812.06976

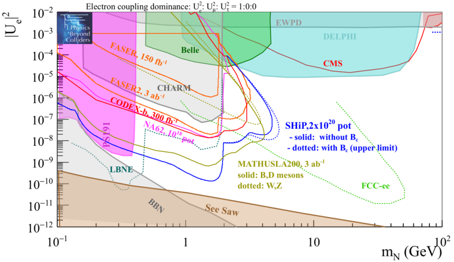


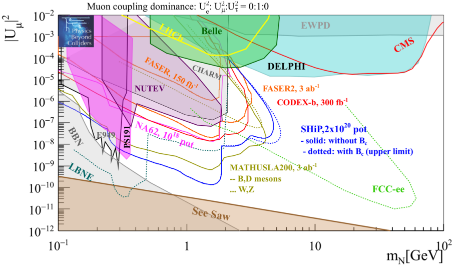
C. Argüelles, V. Brdar, J. Kopp 1605.00654

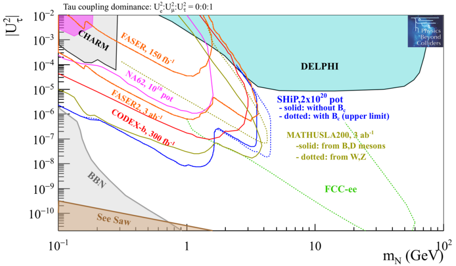
A. Suliga, I. Tamborra, M. Wu 1908.11382

Heavy Neutral Lepton Searches

Above m_Z, new neutrino states could be ν_R or ν_L $\Rightarrow$ HNL not "sterile"

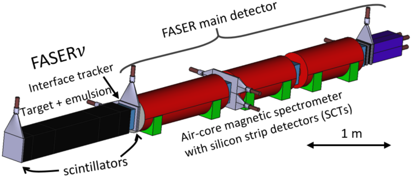


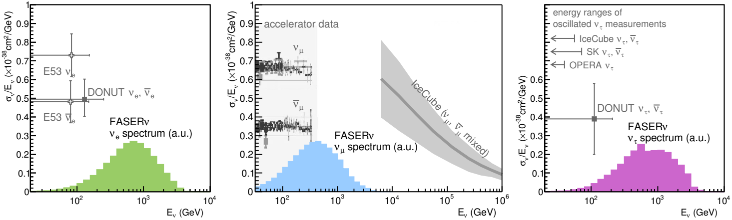




Physics Beyond Colliders group 1901.09966

Neutrinos at the LHC with FASER





FASER, PBD 1908.02310

- Cross sections $E_\nu \sim 1$ TeV
- ν_τ measurements
- Sterile $\Delta m^2 \sim 10^3$ eV^2
- Prompt neutrino production
- CC NSI
- $\sin^2\theta_W$

Neutrino Non-Standard Interactions

Generalized framework
connects oscillations to scattering

$$\mathcal{L}_{\rm NC,NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar\nu_\alpha \gamma^\mu P_L \nu_\beta)(\bar f \gamma_\mu P f)$$

$P \in \{P_L, P_R\}$, $f \in \{e, u, d\}$, NC & CC, SPVAT

L. Wolfenstein PRD 1978

M. Lindner, W. Rodejohann, X-J. Xu 1612.04150

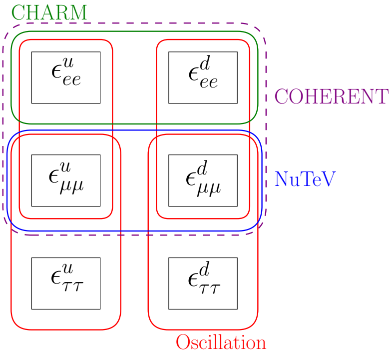
135 parameters!

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger + \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

B. Dev, PBD, et al. 1907.00991

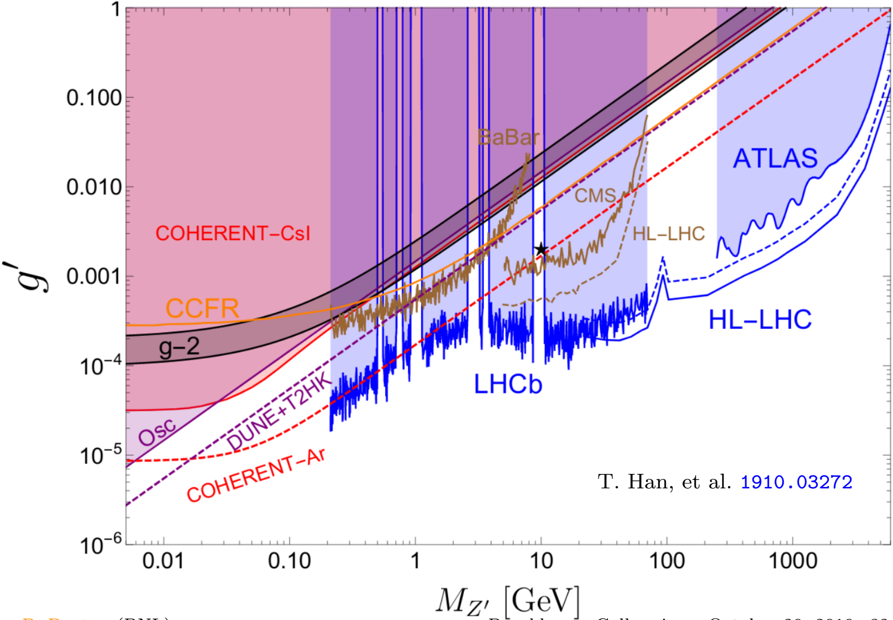
NSIs: Oscillation - Scattering Synergy

	Oscillations	**Scattering**
Mediator mass	Nearly any	$M_{Z'} \gtrsim \sqrt{Q^2}$
Degeneracies	LMA-Dark Diagonal	Direct probe
ν_τ sector	Can probe	Need ν_τ's

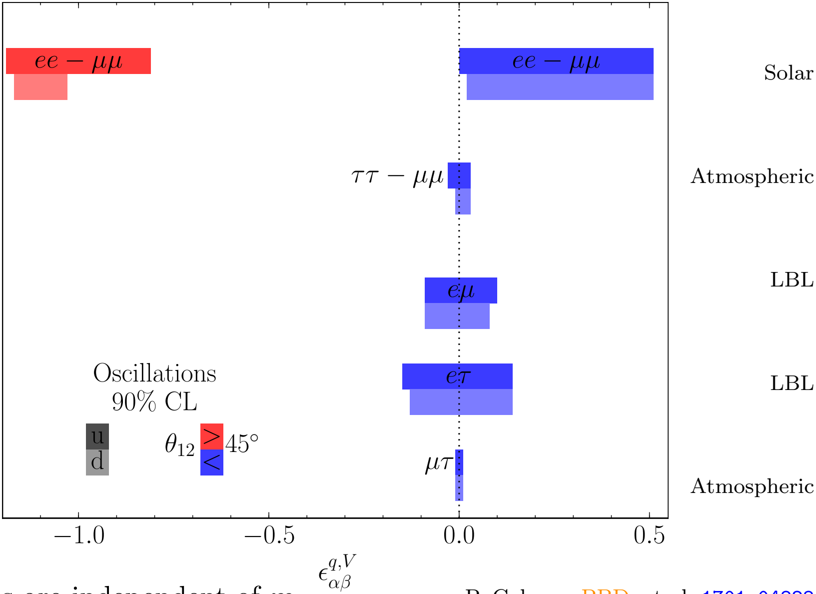


LMA-Dark: P. Coloma, T. Schwetz 1604.05772

Neutrino Non-Standard Interactions: Scattering



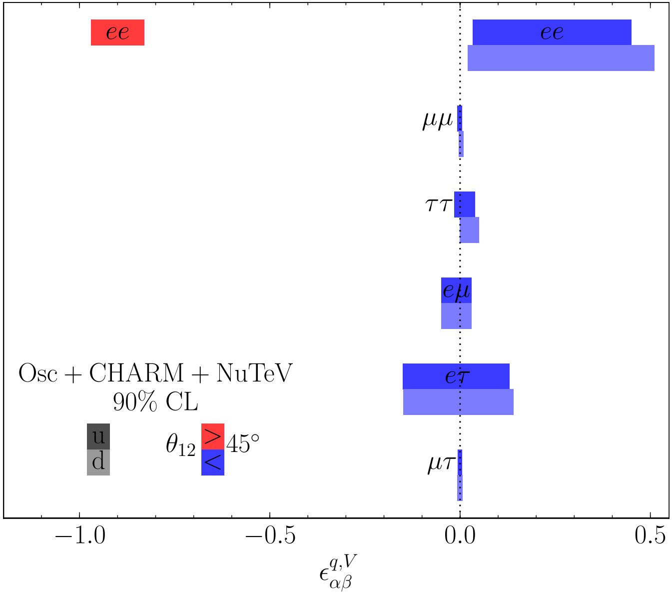
NSI Global Fit: Oscillations



Oscillations are independent of $m_{Z'}$.

P. Coloma, PBD, et al. 1701.04828

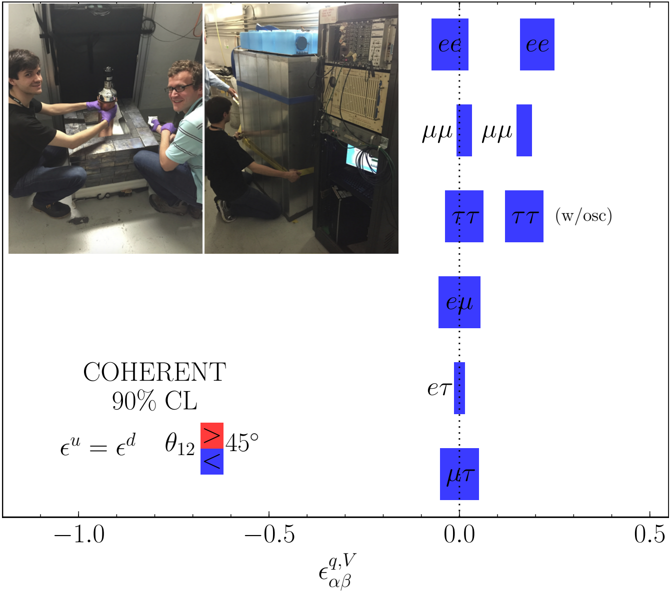
Heavy NSI Global Fit: CHARM & NuTeV



Heavy $\Rightarrow m_{Z'} \gtrsim 1$ GeV.

P. Coloma, PBD, et al. 1701.04828

NSI Constraints: COHERENT

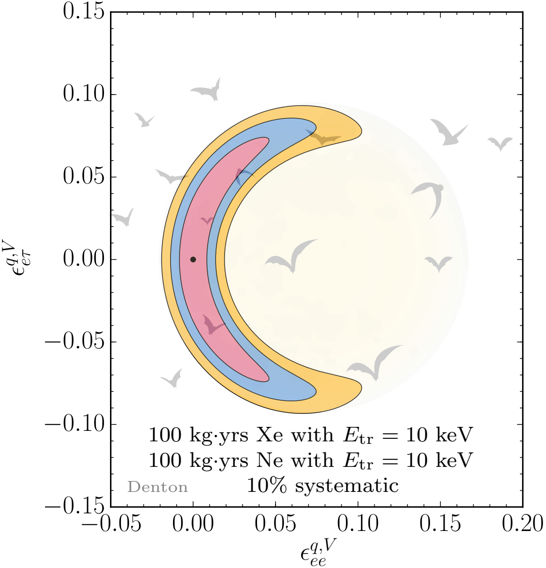


Valid down to $m_{Z'} \gtrsim 10$ MeV

PBD, Y. Farzan, I. Shoemaker, 1804.03660

Looking to the COHERENT Future

Interference of different materials is powerful



$$\epsilon_{ee,\rm deg}^{q,V} = \frac{1}{3}\frac{Y_n - (1-4\sin^2\theta_W)}{Y_n+1}$$

$$Y_n \in [1, 1.43]$$

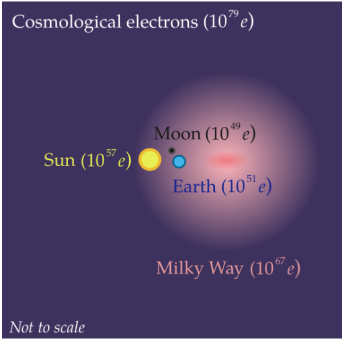
$$\epsilon_{ee,\rm deg}^{q,V} \in [0.15, 0.18]$$

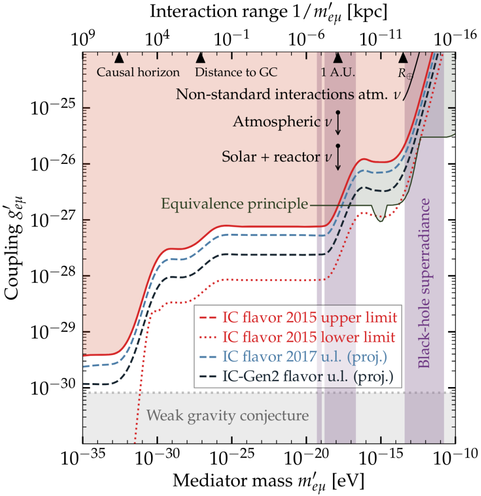
$Y_n = N_n/N_p$

Solar upturn?

Ultra-light Neutrino Non-Standard Interactions

E.g. $L_e - L_\mu$ or $L_e - L_\tau$ symmetries

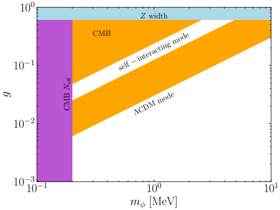


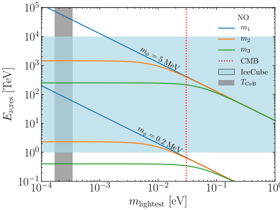


M. Bustamante, S. Agarwalla 1808.02042

Neutrino Non-Standard Self Interactions

NSI → NSSI → CMB → Inflation → H_0 → IceCube → ν_4 → K-decay



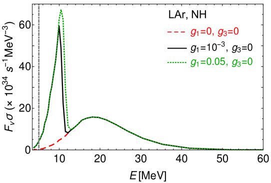


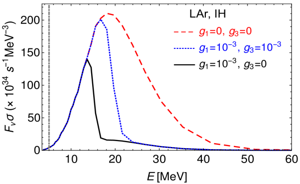
G. Barenboim, PBD, I. Oldengott 1903.02036

C. Kreisch, F-Y. Cyr-Racine, O. Doré 1902.00534

N. Blinov, et al. 1905.02727

Supernova:

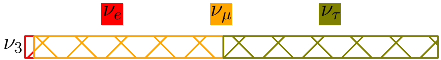




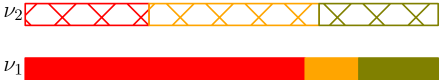
A. Das, A. Dighe, M. Sen 1705.00468

A Neutrino Decay Example

We want to explain IceCube anomaly in flavor and energy



Mr. Stark,
I don't feel so good...



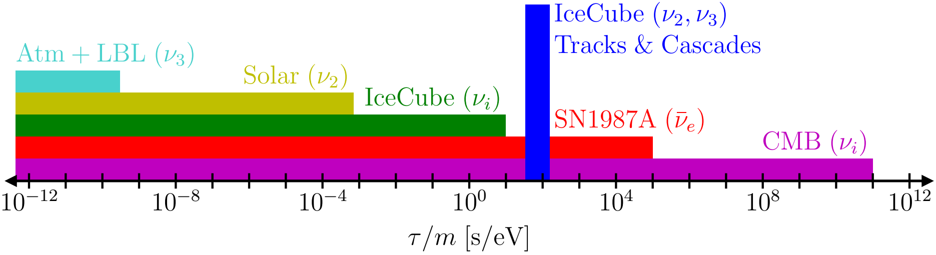
Model recipe:

1. ν-decay depletes ν's at low energy
2. Want fewer ν_μ at low energy
3. Let ν_2 and ν_3 decay
4. Keep ν_1 stable

Preferred over SM $> 3\ \sigma$

PBD, I. Tamborra 1805.05950

Invisible ν Decay Constraints and Evidence



The ν_μ spectrum is different than the ν_e, ν_τ at IceCube

IC 1607.08006

IC PoS ICRC2015 (2016) 1109

ν_2, ν_3-decay explains this, $> 3\ \sigma$

PBD, I. Tamborra, 1805.05950

S. Hannestad, G. Raffelt, hep-ph/0509278

Kamiokande-II, PRL 58 1490 (1987)

G. Pagliaroli, et al., 1506.02624

J. Berryman, A. de Gouvea, D. Hernandez, 1411.0308

M. Gonzalez-Garcia and M. Maltoni, 0802.3699

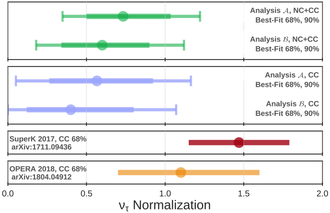
The Tau Neutrino: Status

The tau neutrino is the poorest measured particle

Lepton universality?

$(g-2)_\mu \quad , \qquad \frac{\Gamma(B\to D^{(*)}\tau\bar\nu)}{\Gamma(B\to D^{(*)}\ell\bar\nu)}$

Some indirect detections:



$\sim$16 direct detections

DONuT 0711.0728

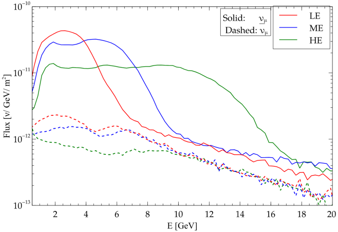
OPERA 1804.04912

IC 1901.05366

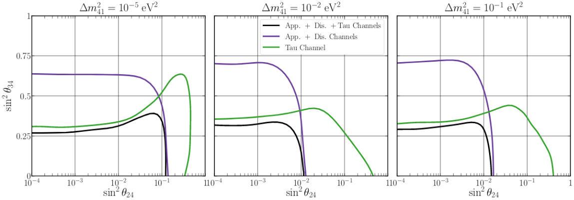
SK 1711.09436

The Tau Neutrino: Terrestrial Prospects

DUNE

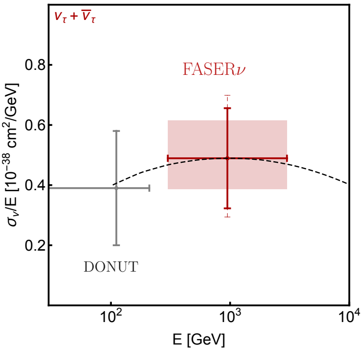


M. Masud, M. Bishai, P. Mehta 1704.08650



A. de Gouvêa, et al. 1904.07265

FASERν

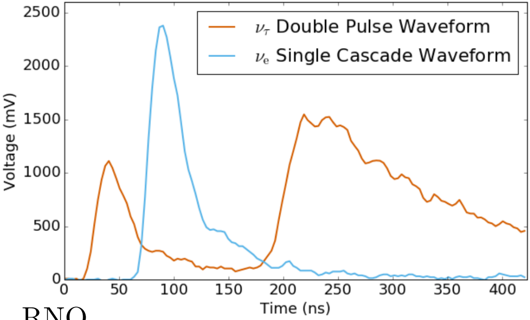


FASER, PBD, et al. 1908.02310

The Tau Neutrino: Astrophysical Prospects

IceCube double bang/pulse signature: Two candidates

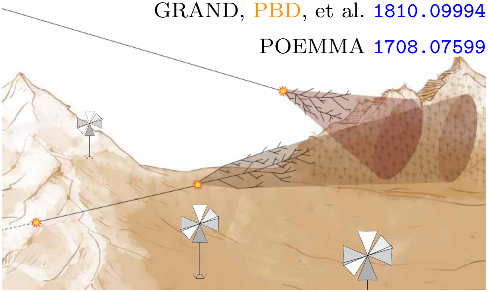
IC 1909.05162

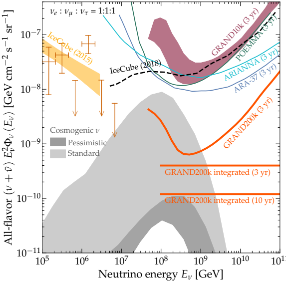


ANITA, GRAND, POEMMA, RNO,

GRAND, PBD, et al. 1810.09994

POEMMA 1708.07599





The ANITA Anomaly

Two upcoming showers $E_{\rm sh} \sim 1$ EeV, $\theta \sim 30^\circ$

ANITA 1603.05218

ANITA 1803.05088

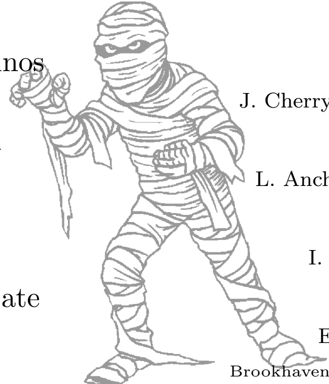
Problems:

1. Absorption $\Rightarrow > 10^6$ more Earth-skimming events
2. IceCube and Auger have comparable $\to$ larger sensitivity

A. Romero-Wolf, et al. 1811.07261

BSM solutions:

- Sterile neutrinos — J. Cherry, I. Shoemaker 1802.01611
- DM in Earth — L. Anchordoqui, et al. 1803.11554
- Axions — I. Esteban, et al. 1905.10372
- Long-lived state — E. Dudas, et al. 1805.07342

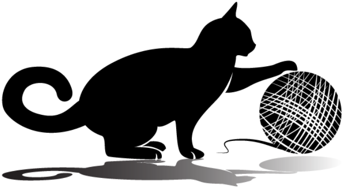


Didn't Discuss

CνB
Radioactive sources
Unitarity violation
LIV, CPT violation
Large extra dimensions
ν - DM connections
DM searches at neutrino experiments
Neutrino searches at DM experiments

Key Points

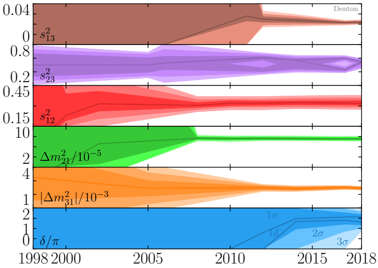
- Oscillation parameters becoming measured
- Strong BSM constraints will follow
- Mass scale probable
- Experiments in dark hallways
- Investigate experimental/theoretical combinations



Thanks and happy **Halloween**!

Backups

References



SK hep-ex/9807003

M. Gonzalez-Garcia, et al. hep-ph/0009350

M. Maltoni, et al. hep-ph/0207227

SK hep-ex/0501064

SK hep-ex/0604011

T. Schwetz, M. Tortola, J. Valle 0808.2016

M. Gonzalez-Garcia, M. Maltoni, J. Salvado 1001.4524

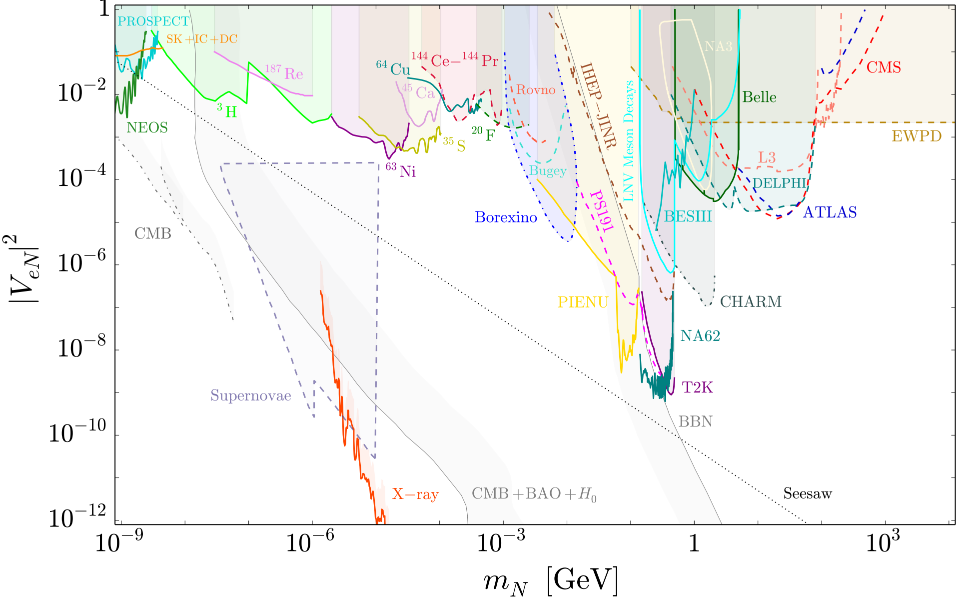
T2K 1106.2822

D. Forero, M. Tortola, J. Valle 1205.4018

D. Forero, M. Tortola, J. Valle 1405.7540

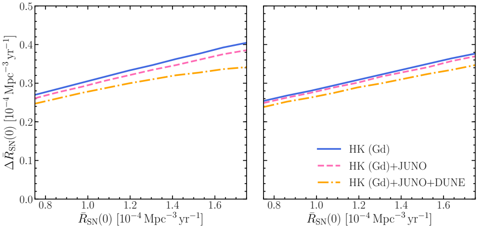
P. de Salas, et al. 1708.01186

Sterile Neutrinos: Where are they Hiding?



F. Deppisch CERN Neutrino Platform '19

Supernova Neutrinos



K. Møller, A. Suliga, I. Tamborra, PBD 1804.03157

NSI Global Fit

Solar
Chlorine, Gallex/GNO, SAGE, Super-K, Borexino, and SNO.

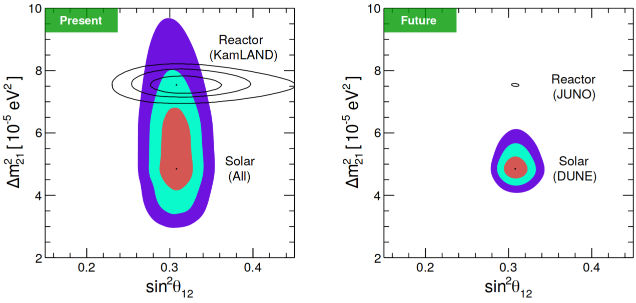
Atmospheric
Super-K, MINOS, and T2K.

Reactor
CHOOZ, Palo Verde, Double CHOOZ, Daya Bay, and RENO.

Short baseline
Bugey, ROVNO, Krasnoyarsk, ILL, Gösgen, and SRP.

Global fit to oscillation data
P. Coloma, PBD, et al. 1701.04828

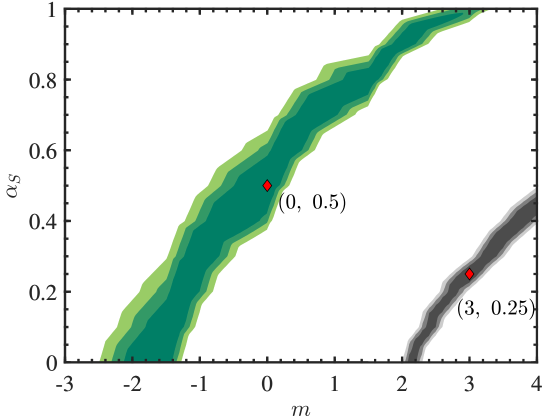
Solar Parameters with DUNE and JUNO



F. Capozzi, et al. 1808.08232

GRAND Cosmic Ray Parameter Estimation

GRAND can constrain the redshift evolution of the UHECR sources m, and the the nuclear composition of the UHECRs α_S



K. Møller, PBD, I. Tamborra 1809.04866