New physics in IceCube

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Based on works done with Pilar Coloma, Pedro A.N. Machado and Ian M. Shoemaker, arXiv:1707.08573
and
M. C. Gonzalez-Garcia, Michele Maltoni, Ivan Martinez-Soler and Ningqiang Song, Astropart.Phys. 84 (2016) 15-22 arXiv:1605.08055

Summer Institute for Neutrino Theory

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Overview

Motivation: ν mass

- In SM neutrinos are massless.
  - No dirac mass term for neutrinos. No right-handed neutrino.
  - From oscillation experiment ($m_\nu \neq 0$)

- SM can be considered as low energy effective model.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{\mathcal{L}_{d=5}}{\Lambda} + \frac{\mathcal{L}_{d=6}}{\Lambda^2} + \cdots$$

  - For $d = 5$. Weinberg operator.
    - ★ Type-I seesaw
  - For $d = 6$. NSI

Motivation

Type-I seesaw

- Introduce right-handed neutrinos
- Allow L number violation

$$\mathcal{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N^c_R} N_R + h.c.$$

$$m_\nu \sim \frac{Y_\nu^\dagger Y_\nu v^2}{M_R} \qquad m_N \approx M_R + \mathcal{O}\left(m_\nu\right)$$

- For $M_R \gg v$
  - Neutrino masses can be smaller than fermion masses
  - Heavy neutrinos can hardly be tested
  - Worsen hierarchy problem

Motivation

Low-scale Type-I seesaw

- Y_ν small
- They may be tested in experiments with meson decays and muon decays
- Right-handed neutrinos with very high masses can be a partial solution for other problems
    - keV neutrino can be a candidate for dark matter
      [A. Kusenko,Phys. Rept.481(2009) 128]
    - $m_N \sim \mathcal{O}\left(1-100\right)$ GeV, majorana neutrinos can generate enough matter-antimmater asymetry of the Universe
      [T. Asaka and M. Shaposhnikov,Phys. Lett.B620(2005)1726]

Motivation

NSI-NC

- Described by effective four-fermion operators

$$\mathcal{L} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fP} \left(\bar{\nu}_\alpha \gamma^\mu \nu_\beta\right) \left(\bar{f} \gamma_\mu P f\right)$$

  - Not gauge invariant
  - Charged lepton flavour violation processes impose tight constraints
    [M. B. Gavela, D. Hernandez, T. Ota and W. Winter, Phys. Rev. D79 (2009) 013007]
  - NSI are generated well below de EW scale
    [K. S. Babu, A. Friedland, P. A. N. Machado and I. Mocioiu, arXiv:1705.01822]

- Modify the forward -coherent scattering in regions with matter

- Can be constrained by measuring neutrino cross section with other fermions
  [C. Biggio, M. Blennow and E. Fernandez-Martinez, JHEP 08 (2009) 090,
  S. Davidson, C. Pena-Garay, N. Rius and A. Santamaria, JHEP 03 (2003) 011]

Motivation

Constraints to NSI-NC parameter from oscillation experiments

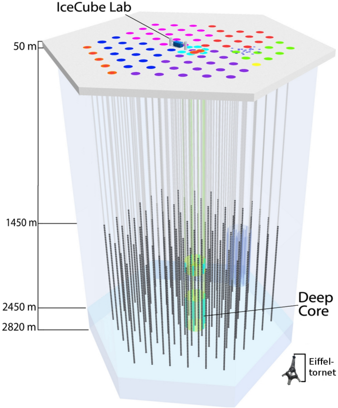
	$90\% CL$	$3\sigma CL$
$\epsilon^q_{ee} - \epsilon^q_{\mu\mu}$	$[+0.02, +0.51]$	$[-0.09, +0.71]$
$\epsilon^q_{\tau\tau} - \epsilon^q_{\mu\mu}$	$[-0.01, +0.03]$	$[-0.03, +0.19]$
$\epsilon^q_{e\mu}$	$[-0.09, +0.04]$	$[-0.16, +0.11]$
$\epsilon^q_{e\tau}$	$[-0.13, +0.14]$	$[-0.38, +0.29]$
$\epsilon^q_{\mu\tau}$	$[-0.01, +0.01]$	$[-0.03, +0.03]$

[M. C. Gonzalez-Garcia and M. Maltoni, JHEP09(2013)152]

IceCube/DeepCore

- IceCube
  - Triangular grid of strings / horizontal distance of 125m
  - 78 vertical strings
  - 60 DOMs per string / vertical distance of 17m

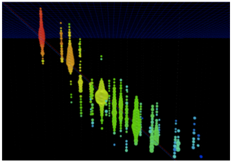
- DeepCore
  - 8 closely-spaced strings + 7 central IceCube strings
  - Horizontal distance of 72m
  - 50 DOMs (vertical distance 7m) + 10 DOMs (10m)



IceCube/DeepCore signals

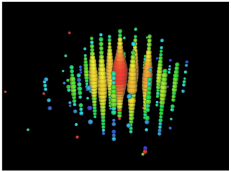
Tracks

- Through-going muons
- Direction resolution $\leq 1^o$



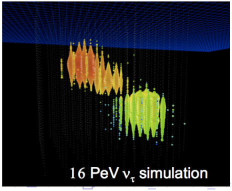
Showers

- ν_α NC + ν_e and ν_τ CC
- Energy resolution $\sim 10\%$

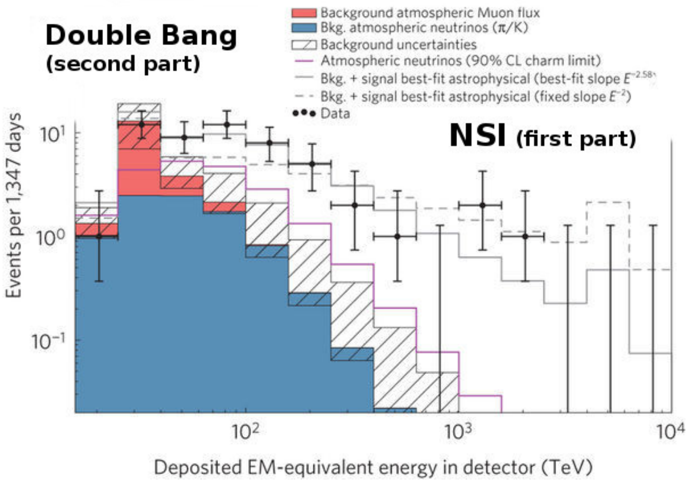


Composites

- Starting ν_μ CC and high energy ν_τ CC
- Good energy and direction resolutions



IceCube measurements



[Figure taken from: Francis Halzen, Nature Physics 13, 232238 (2017)]

New Physics at high energies in IceCube/DeepCore

New physics at high energies

Considering $d = 6$ effective field operator (NSI)

- Diferent mechanism can contribute flux of high energy neutrino.
  - Pion-muon decay chain, single μ-flux, neutron decay, decay charm mesons, ...
  - Flavor composition at the detector can allow to differenciate.
  - Standard oscillation modify the flavor content.
    - Uncertainties on oscillation parameters $(\theta_{12}, \theta_{23}, \theta_{31}, \delta_{cp})$ determines the possible flavor content.
- New Physics: non-standard interactions of the neutrinos in the Earth matter.
  - Introduce new flavor oscillation when neutrino travel through the earth.
  - We quantify the modification of the neutrino flavor composition at the detector in terms NSI parameters.

Coherent/Incoherent effects

Neutrino fluxes at the detector (at the earth surface $d \to \oplus$)

$$\phi_\beta^d(E) = \sum_\alpha \int dE' \mathcal{P}_{\alpha\beta}^{s\to d}(E,E')\,\phi_\alpha^s(E')$$

- Coherent evolution:

$$\mathcal{P}_{\alpha\beta}^{s\to d}(E,E') = \left|\sum_\gamma A_{\alpha\gamma}^{s\to\oplus} A_{\gamma\beta}^{\oplus\to d}(E)\right|^2 \delta(E-E')$$

- Incoherent evolution:
  - Considering only the dominant attenuation factors

$$\mathcal{P}_{\alpha\beta}^{s\to d}(E,E') \simeq \left|\sum_\gamma A_{\alpha\gamma}^{s\to\oplus} A_{\gamma\beta}^{\oplus\to d}(E)\right|^2 F_{att}^{\oplus\to d}\delta(E-E')$$

  - No flavor distortion

Non-standard interaction formalism

The matter part of the hamiltonian

$$H_{mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{e\mu} & \epsilon_{e\tau} \end{pmatrix} = W D_{mat} W^\dagger$$

$$\epsilon_{\alpha\beta} = \epsilon^e_{\alpha\beta} + Y_u \epsilon^u_{\alpha\beta} + Y_d \epsilon^d_{\alpha\beta} \qquad H_{vac} = U D_{vac} U^\dagger$$

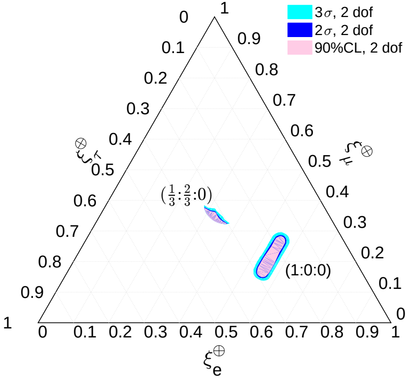
The oscillation probabilities are

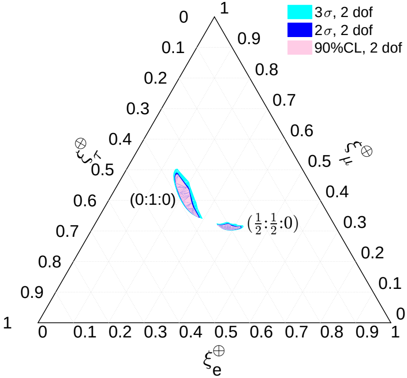
$$\left| \sum_\gamma A^{s\to\oplus}_{\alpha\gamma} A^{\oplus\to d}_{\gamma\beta}(E) \right|^2 = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 - 2 \sum_{\gamma\eta k l i} \mathcal{R}\left(W_{\beta k} W^*_{\beta l} W_{\gamma l} W^*_{\eta k} U_{\eta i} U^*_{\gamma i} |U_{\alpha i}| \right) \sin^2\left(d_e \frac{\Delta\epsilon_{kl}}{2} \right)$$
$$+ \sum_{\gamma\eta k l i} \mathcal{I}\left(W_{\beta k} W^*_{\beta l} W_{\gamma l} W^*_{\eta k} U_{\eta i} U^*_{\gamma i} |U_{\alpha i}| \right) \sin\left(d_e \Delta\epsilon_{kl} \right)$$

Results: Standard oscillation

- Flavor ratio $\xi_\beta^\oplus = \phi_\beta^\oplus / \sum_\gamma \phi_\gamma^\oplus = \sum_\alpha \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 \xi_\alpha^s$

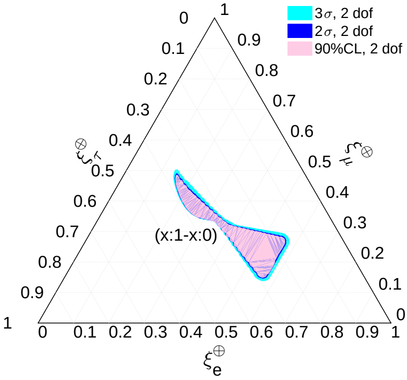
- Projection of six oscillation parameters χ^2 of the global NuFIT analysis.
  [M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, JHEP11(2014)052]

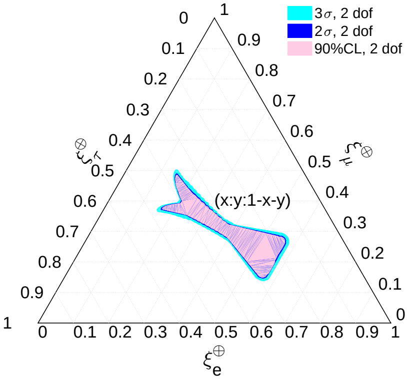




Results: Standard oscillation

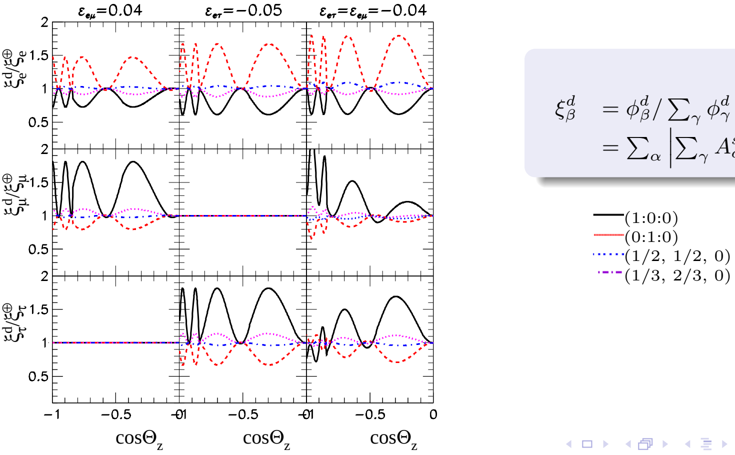
Several production processes in the source





NSI in the earth

New oscillations induced by $\epsilon_{\alpha\neq\beta} \neq 0$.

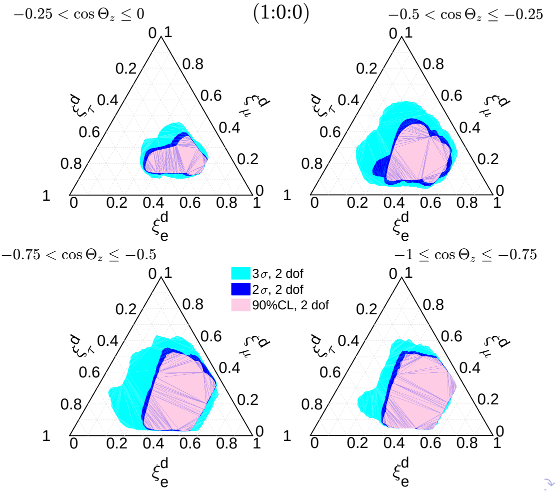


$$
\begin{aligned}
\xi^d_\beta &= \phi^d_\beta / \sum_\gamma \phi^d_\gamma \\
&= \sum_\alpha \left| \sum_\gamma A^{s\to\oplus}_{\alpha\gamma} A^{\oplus\to d}_{\gamma\beta}(E) \right|^2
\end{aligned}
$$

Flavor ratios in presence of NSI

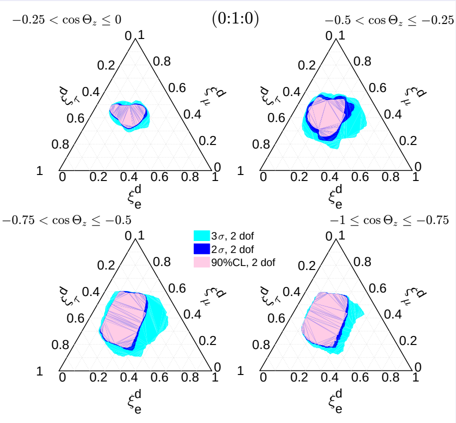
Neutron decay

- The range of flavor ratios increase.
- Included $(1/3, 1/3, 1/3)$.
- The largest values of $\epsilon_{\alpha\beta}$ averaged out.
- The largest effect for "less equal" ratios at the earth surface.

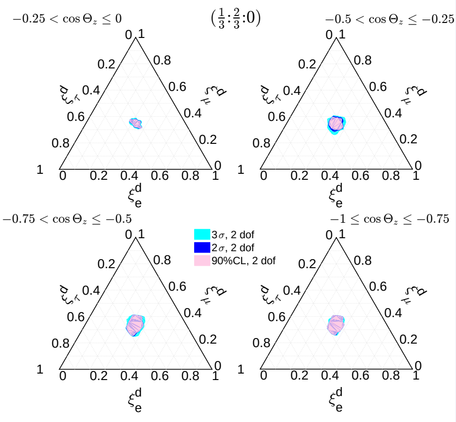


Flavor ratios in presence of NSI

Single μ-flavor flux.



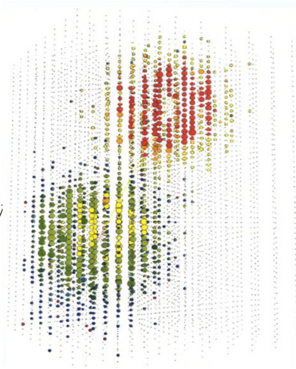
No large deviation from $(1/3, 1/3, 1/3)$ for fluxes produced by $\pi - \mu$ decay chain.



New Physics at low energies in IceCube/DeepCore

Double bang events

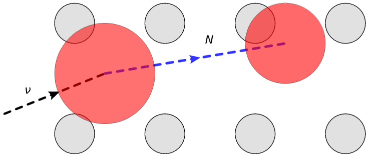
- Standard signature of ν_τ at very high energy
- ν_τ CC interaction produce a τ and a shower (1 shower)
- τ decay (2 shower)
  - τ emits cherenkov radiation
- For very well-separated showers (~ 100m) $E_{\nu_\tau} \geq 2$PeV
- Background negligible
- Not detected yet



New physics at low energies

Double bang signals to look for new physics at low energy

- Two bangs inside the detector
  - 1st shower ν interaction
  - 2nd shower N decay
  - No cherenkov radiation in between



What kind of new physics?

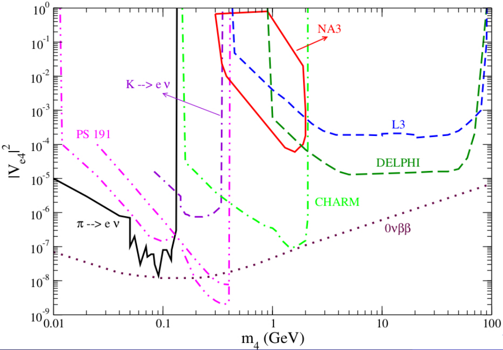
New Physics Scenario

1. BSM: Heavy sterile neutrino

Sterile mass mixing with active neutrinos

$$\nu_{\alpha L} = \sum U_{\alpha m} \nu_{mL} + U_{\alpha 4} N_{4L}$$

In the presence of $\nu - N - Z$ interaction: strongs bounds on the mixing between N and ν_e, ν_μ
[A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP 05,030 (2009)]



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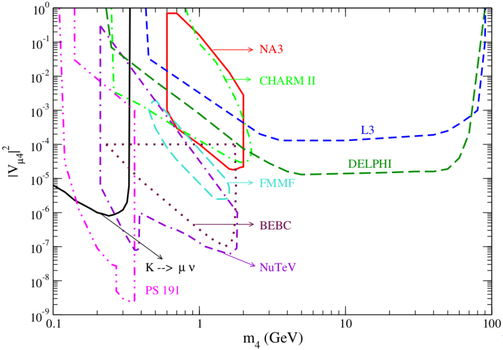


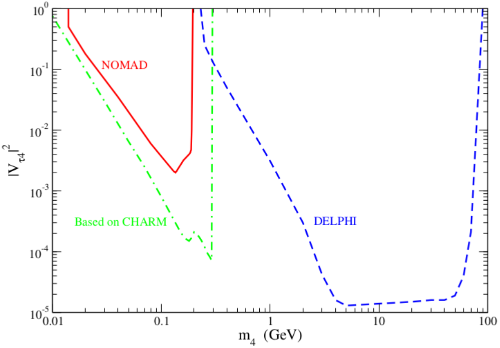
New Physics Scenario

1. Standard scenario: Heavy sterile neutrino

Sterile mass mixing with active neutrinos

$$\nu_{\alpha L} = \sum U_{\alpha m} \nu_{mL} + U_{\alpha 4} N_{4L}$$

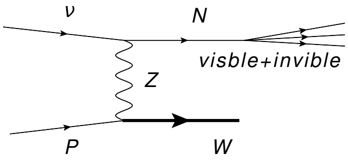
In the presence of $\nu - N - Z$ interaction: we are going to constrain $U_{\tau 4}$
[A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP 05,030 (2009)]



Sterile neutrino via the Neutral Current

The double bang signal comes from

$$\nu_\tau + N \to N_4 + W$$
$$N_4 \to visible + invisible$$

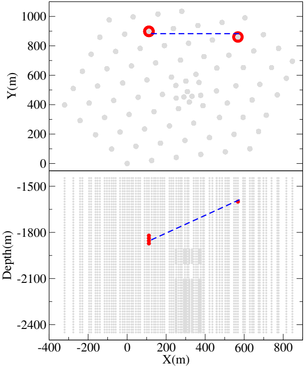


- The decay length depens on M_4 and on $|U_{\tau 4}|^2$
- Cross section calculated with GENIE (Coherence + Resonance + DIS)
  - Proportional to mixing parameter $|U_{\tau 4}|^2$

Effective Volume

- Double Pulse (2 separate showers in the full detector)
  - Minimum distance betweeen showers defined by DOMs resolution wave form
  - $\geq$ 20m between showers
- Energy threshold of 5GeV per shower
  - Minimum energy detected by DeepCore
- Maximum distance covered by light of 36m
- Simulation include DOMs position and triggers
  - SMT3 for DeepCore
  - SMT4 for IceCube
- Background
  - Coincident atmospheric cascades
  - 0.05/year

Our Monte Carlo



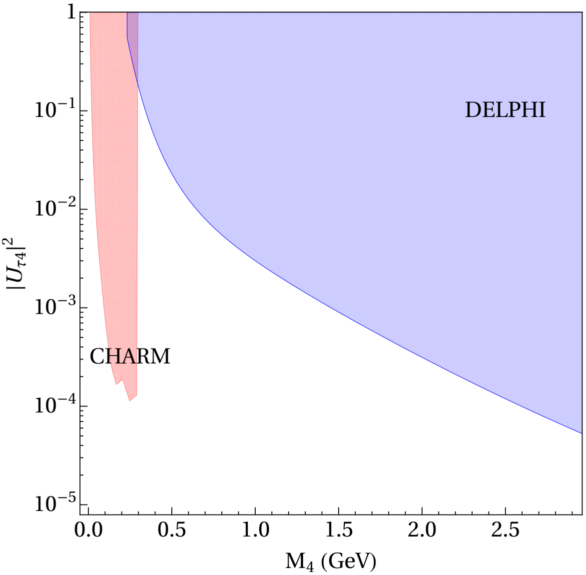
Events

The number of events in the detector is given by

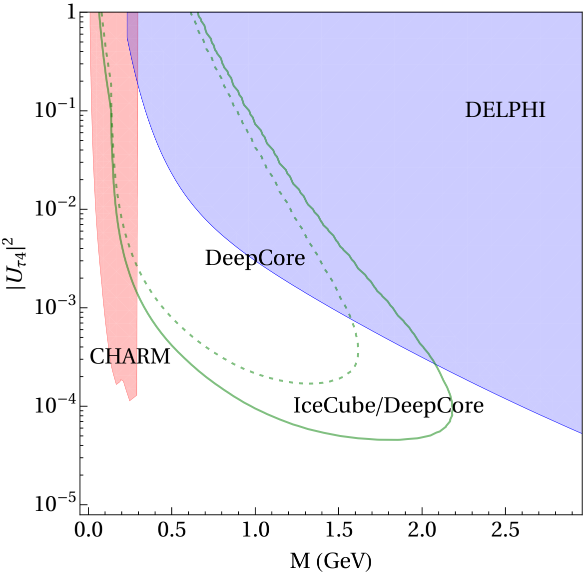
$$N(L) \propto T \int dE d\cos\theta dE' \frac{d\phi_{\nu_\mu}}{dE d\cos\theta} P_{\mu\to\tau}(E, \cos\theta) \frac{d\sigma_{\nu_\tau \nu_4}}{dE dE'} P_d(L) V_{eff}(L, \cos\theta)$$

- We consider $E \in [10, 100]$ GeV
  - The energy of the heavy neutrino $5GeV \leq E' \leq E - 5GeV$
  - The showers $\geq 5GeV$
- ϕ_{ν_μ} atmospheric flux
  - $\phi \sim E^{-2.7}$ The largest contribution comes from low energy neutrinos
- $P_{\mu\to\tau}$ 3 neutrino oscillation
- Decay probability $P_d(L) = e^{-L/\Gamma}/\Gamma$
- The results correspond with 6 years.

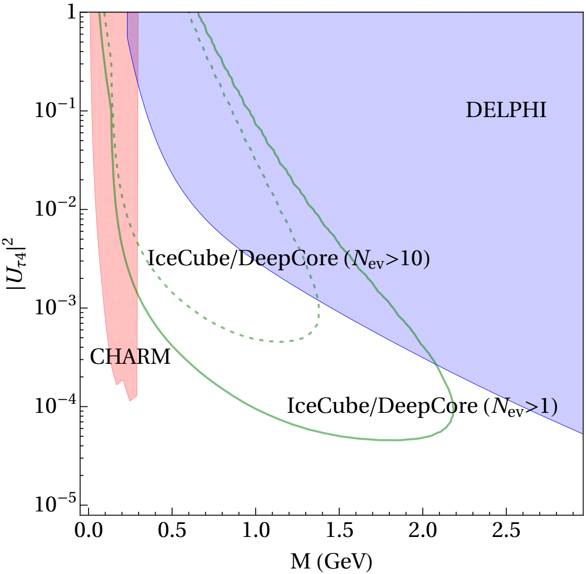
Results: Neutral Currents



Results: Neutral Currents



Results: Neutral Currents

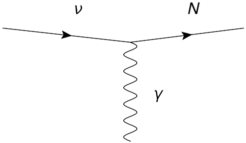


New Physics Scenario

2. Neutrino magnetic moment

- We are interested in a transition magnetic moment
- Weak constraints

$$\mathcal{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$



The main contribution to our signal events comes from DIS on nucleons

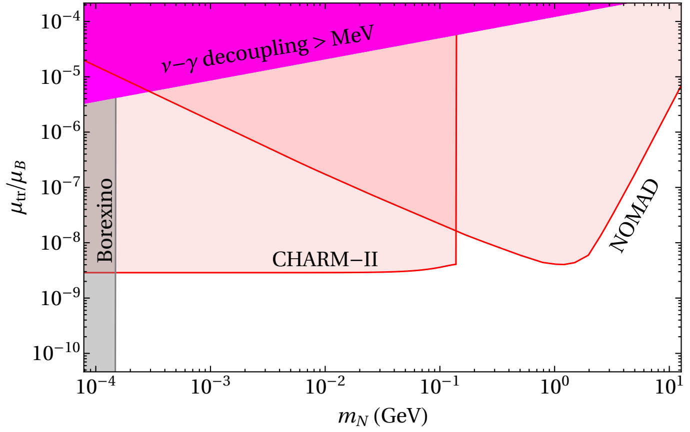
$$\frac{d^2\sigma_N}{dx\,dy} = g_e^2 \mu_\nu^2 \left(\sum_q e_q^2 f_q(x)\right)\left(\frac{(2-y)^2}{y} - y\right)$$

The decay length $N \to \nu_i \gamma$

$$\Gamma = \frac{\mu_\nu^2 M_4^3}{16}$$

Results: Magnetic moment

$\nu_\mu - N$ transition



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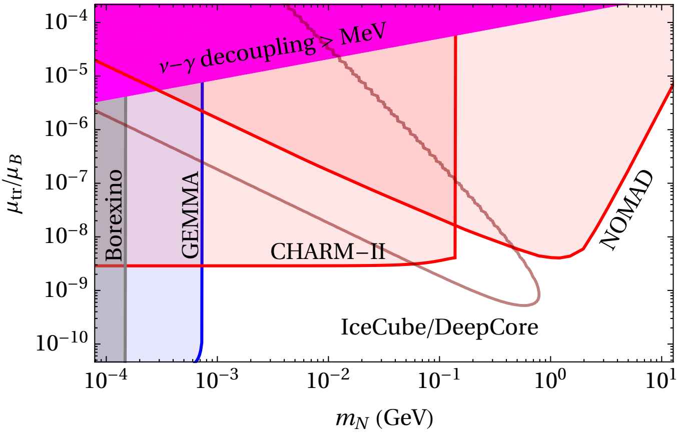

Results: Magnetic moment

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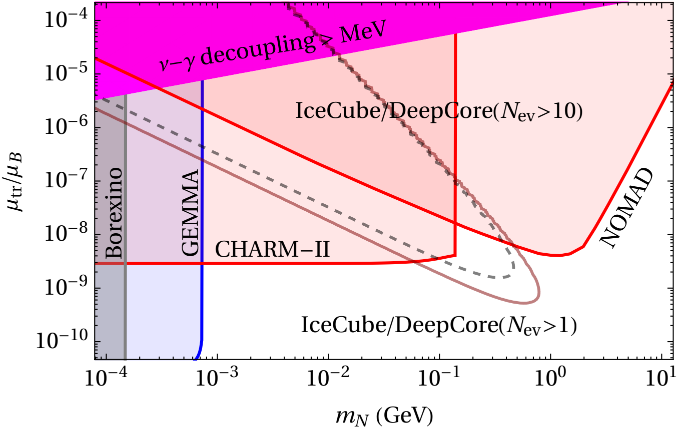
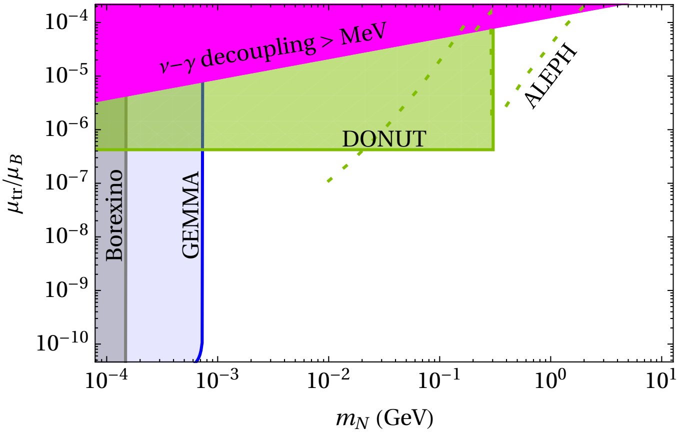


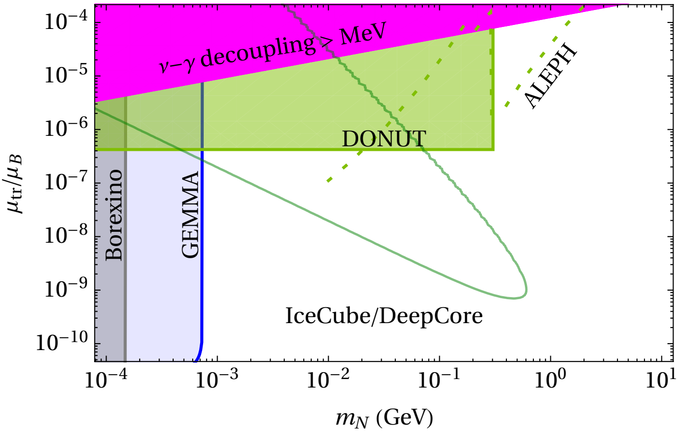
Results: Magnetic moment

$\nu_\tau - N$ transition



Results: Magnetic moment

$\nu_\tau - N$ transition



Results: Magnetic moment

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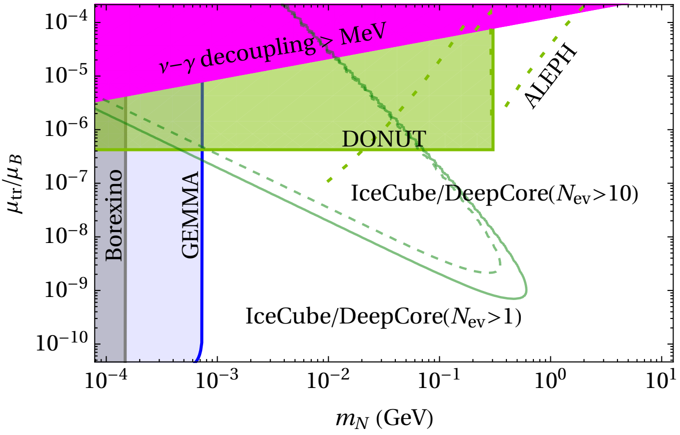
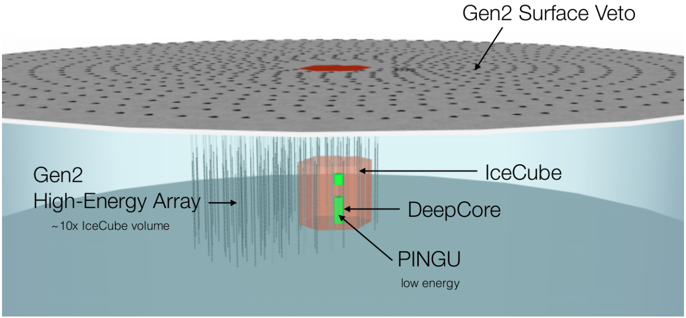


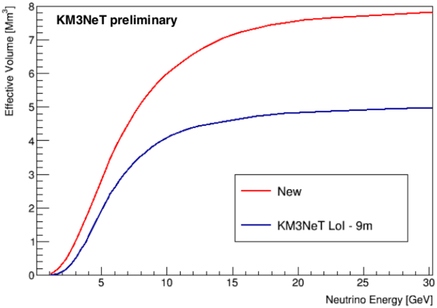
Future Projects: IceCube-Gen2

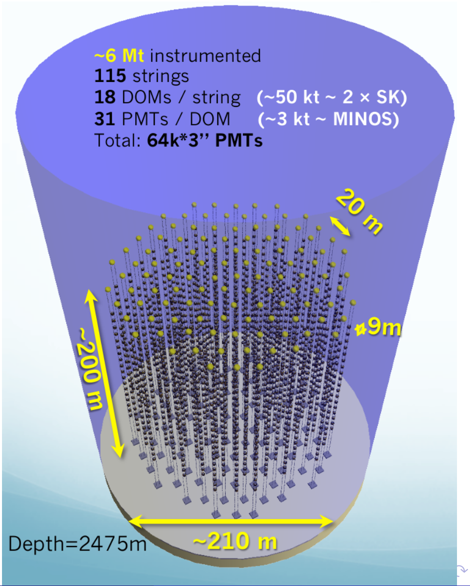
- PINGU
  - Effective mass of 6 Mton
  - Energy threshold 1 GeV
  - Increase the number of events by a factor 1.6
- High energy array
  - Fiducial volume 10 km^3 (120 additional strings)
    - ★ Reduce the lower limit of m_N by a factor 1.4
  - Increase in the effective volume ~ 2.7
- Total increase of the number of events by a factor 3.3



Future Projects: KM3NeT

- Proposed experiment in Mediterranean sea.
- Energy threshold of 3 GeV.
- Effective mass of 3.5 Mton for neutrinos with 10 GeV
- The number of events expected is a factor 0.3 smaller.





Conclusion

- IceCube can probe BSM at different scales of energy

High energy (PeV)

- NSI in the earth can modify the neutrino flavor at the detector.
- The ranges for all neutrino flavor fractions at the detector increase in presence of NSI.
  - The effect dominates for fluxes with one flavor at source.

Low Energy (GeV)

- Double Bang signals can probe new physics
- Sterile neutrino via neutral current
- Neutrino transition magnetic moment
  - IceCube can put a competitive bound on μ_ν for ν_τ and ν_μ

Thank you very much!

Backup

Constraints to NSI parameter from oscillation experiments + scattering

[P. Coloma, P. B. Denton, M. C. Gonzalez-Garcia, M. Maltoni, and T. Schwetz, JHEP 04 (2017) 116]

Light			
PRESENT (OSC)		+COHERENT(SM)	
$\epsilon_{ee}^{u,V} - \epsilon_{\mu\mu}^{u,V}$	$[-1.19, -0.81] \oplus [0.00, 0.51]$	$\epsilon_{ee}^{u,V}$	$[0.002, 0.049] \oplus [0.28, 0.42]$
$\epsilon_{\tau\tau}^{u,V} - \epsilon_{\mu\mu}^{u,V}$	$[-0.03, 0.03]$	$\epsilon_{\mu\mu}^{u,V}$	$[-0.026, 0.033] \oplus [0.36, 0.38]$
		$\epsilon_{\tau\tau}^{u,V}$	$[-0.025, 0.047] \oplus [0.36, 0.39]$
$\epsilon_{e\mu}^{u,V}$	$[-0.09, 0.10]$		$[-0.08, 0.04]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.14]$		$[-0.17, 0.14]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.01, 0.01]$		$[-0.01, 0.01]$
$\epsilon_{ee}^{d,V} - \epsilon_{\mu\mu}^{d,V}$	$[-1.17, -1.03] \oplus [0.02, 0.51]$	$\epsilon_{ee}^{d,V}$	$[0.022, 0.023] \oplus [0.25, 0.38]$
$\epsilon_{\tau\tau}^{d,V} - \epsilon_{\mu\mu}^{d,V}$	$[-0.01, 0.03]$	$\epsilon_{\mu\mu}^{d,V}$	$[-0.024, 0.029]$
		$\epsilon_{\tau\tau}^{d,V}$	$[-0.023, 0.039]$
$\epsilon_{e\mu}^{d,V}$	$[-0.09, 0.08]$		$[-0.07, 0.04]$
$\epsilon_{e\tau}^{d,V}$	$[-0.13, 0.14]$		$[-0.14, 0.12]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.01, 0.01]$		$[-0.009, 0.007]$

Heavy		
	PRESENT (OSC+CHARM+NuTeV)	+COHERENT(SM)
$\epsilon_{ee}^{u,V}$	$[-0.97, -0.83] \oplus [0.033, 0.450]$	$[0.014, 0.032] \oplus [0.24, 0.41]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.008, 0.005]$	$[-0.007, 0.005]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.015, 0.04]$	$[-0.006, 0.04]$
$\epsilon_{e\mu}^{u,V}$	$[-0.05, 0.03]$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$	$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.006, 0.005]$	$[-0.006, 0.004]$
$\epsilon_{ee}^{d,V}$	$[0.02, 0.51]$	$[0.26, 0.38]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.003, 0.009]$	$[-0.003, 0.009]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.001, 0.05]$	$[-0.001, 0.05]$
$\epsilon_{e\mu}^{d,V}$	$[-0.05, 0.03]$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{d,V}$	$[-0.15, 0.14]$	$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.007, 0.007]$	$[-0.007, 0.007]$

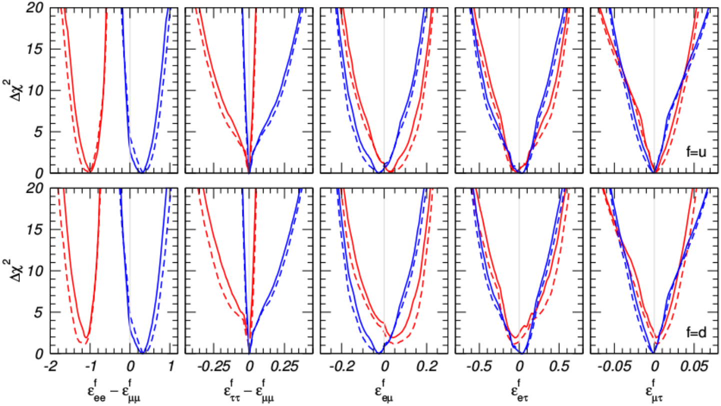
Backup

Transition magnetic moment. Electron cross section.

$$\frac{d\sigma_e}{d\nu} = \mu_\nu^2 \alpha_{em} \left(\frac{(\nu - M_e) M_4^4}{8\nu^2 E^2 M_e^2} + \frac{(\nu - 2E - M_e) M_4^2}{4\nu E^2 M_e} + \frac{1}{\nu} - \frac{1}{E} \right)$$

Backup

Constraints to NSI parameter from oscillation experiments



[M. C. Gonzalez-Garcia and M. Maltoni, JHEP09(2013)152]