

Double-Cascade Events from New Physics in IceCube

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Based on **Double-Cascade Events from New Physics in Icecube -**
Coloma, P. et al. Phys.Rev.Lett. 119 (2017) no.20, 201804 arXiv:1707.08573

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Motivation

- ▶ 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.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{\mathcal{L}_{d=5}}{\Lambda} + \dots$$

- ▶ For $d = 5$. Weinberg operator.
 - ▶ Type-I seesaw

Motivation

Type-I seesaw

- ▶ Introduce right-handed neutrinos
- ▶ Allow L number violation

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

- ▶ For $M_R \gg v$

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

- ▶ Neutrino masses can be smaller than fermion masses
- ▶ Heavy neutrinos can hardly be tested
- ▶ Tight bounds from charged lepton flavor violating experiments

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]
 - ▶ $m_N \sim \mathcal{O}(1 - 100)$ GeV, majorana neutrinos can generate enough matter-antimatter asymmetry of the Universe
[T. Asaka and M. Shaposhnikov, Phys. Lett. B620(2005)1726]

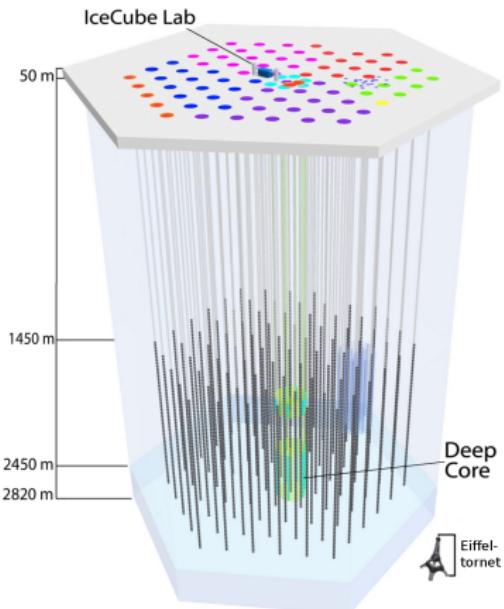
Motivation

- ▶ New Physics models with GeV right-handed neutrinos

- ▶ Double-Bang topology used to look for New Physics

- ▶ Atmospheric neutrinos are the source of the events

- ▶ The detection is studied in IceCube and DeepCore

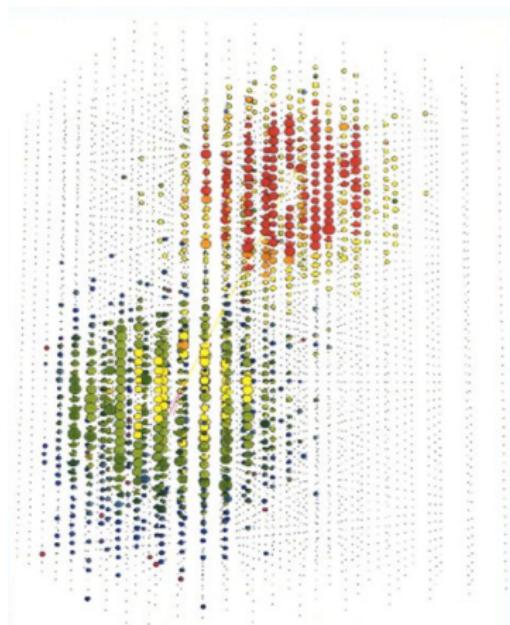


[M.G. Aartsen et al., J.Parallel Distrib.Comput. 75 (2015) 198-211]

Double bang events

(See talk by Ranjan Laha)

- ▶ Standard signature of ν_τ at very high energy
 - ▶ ν_τ CC interaction (1st shower)
 - ▶ τ decay (2st shower)
- ▶ For very well-separated showers ($\sim 100\text{m}$) $E_{\nu_\tau} \geq 2\text{PeV}$
- ▶ Background negligible
- ▶ Not detected yet

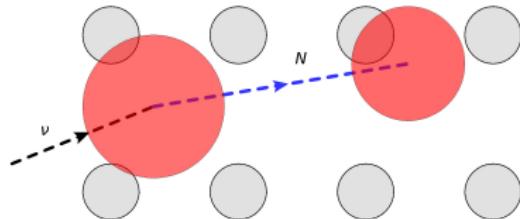


[D.Williams, The 12th international Workshop on Tau Lepton Physics]

Double Bang topology to look for New physics

Double bang signals mediated by right-handed neutrinos

- ▶ 1st shower ν interaction
- ▶ 2nd shower N decay
- ▶ No cherenkov radiation in between



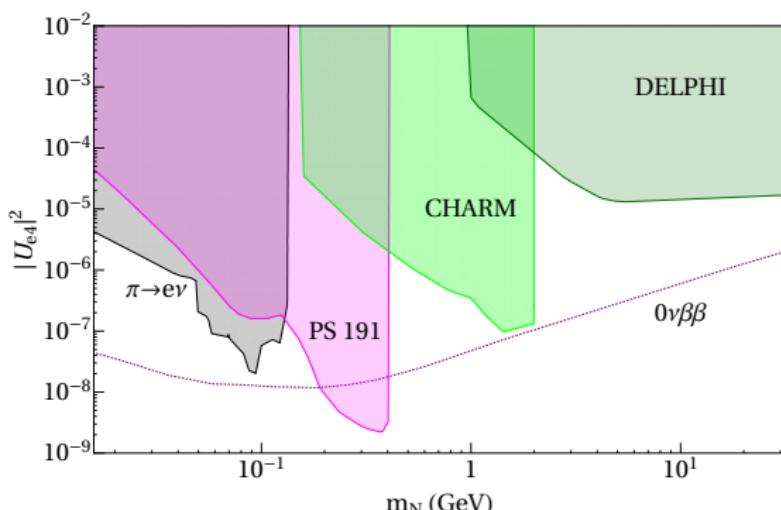
What kind of new physics?

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



Strong bounds on
 U_{e4} and $U_{\mu 4}$

[A. Atre, T. Han, S. Pascoli, and
B. Zhang, JHEP 05,030 (2009)]

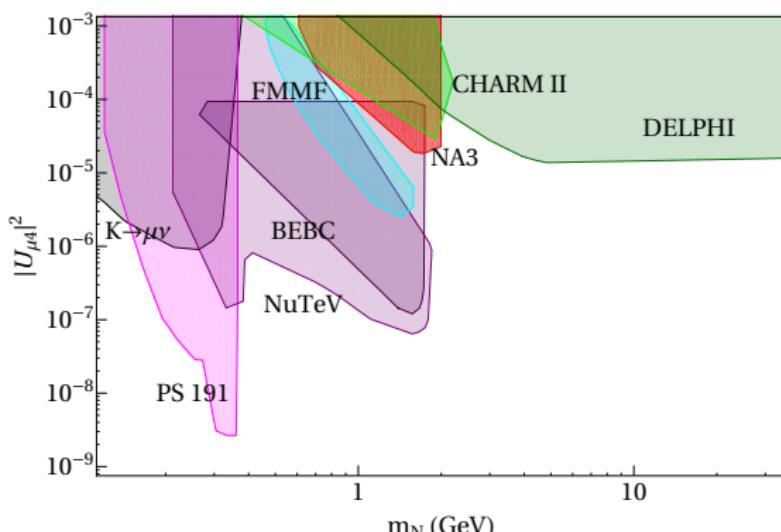
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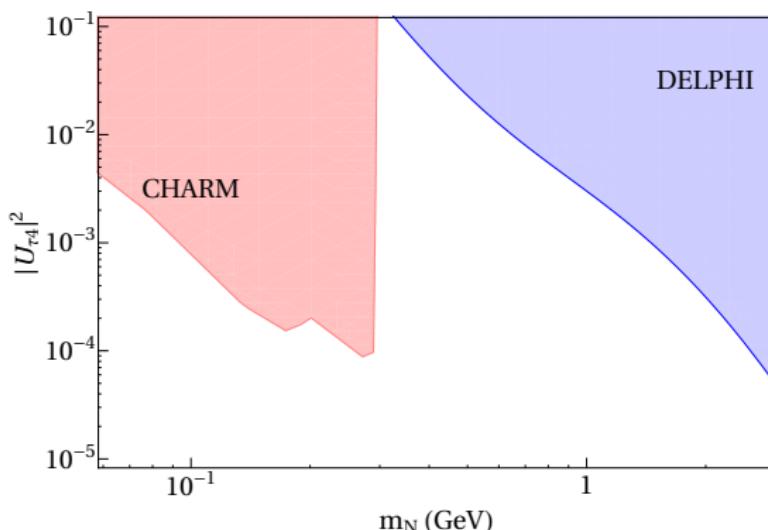
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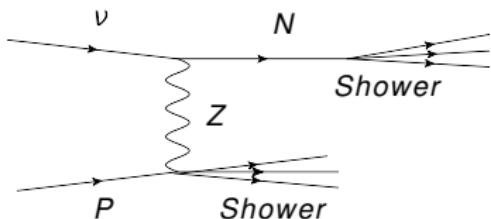
Weaker constraints
over $U_{\tau 4}$

[A. Atre, T. Han, S. Pascoli, and
B. Zhang, JHEP 05,030 (2009)]

Sterile neutrino via the Neutral Current

- ▶ Heavy neutrinos can travel long distance with low initial energies.
- ▶ ν_τ arrive at IceCube by the flavor oscillation of atmospheric neutrinos
- ▶ The double bang signal comes from:

$$\begin{aligned}\nu_\tau + N &\rightarrow N_4 + \text{shower} \\ N_4 &\rightarrow \text{shower}\end{aligned}$$



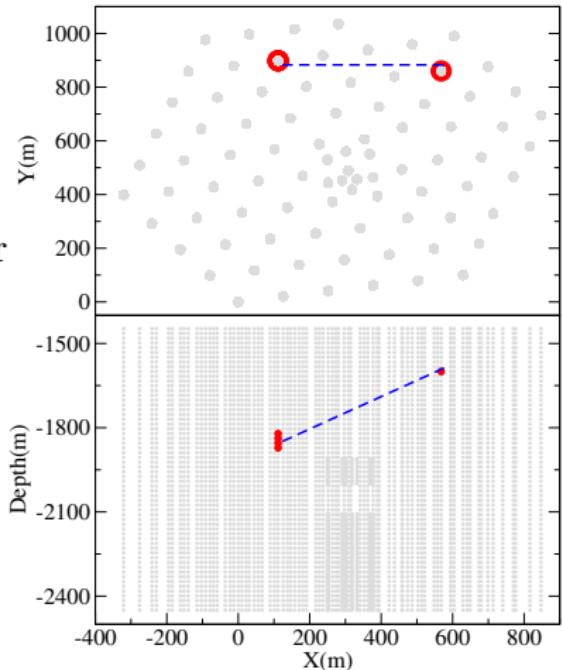
- ▶ The decay length depends on M_4 and on $|U_{\tau 4}|^2$
- ▶ Cross section proportional to mixing parameter $|U_{\tau 4}|^2$

Effective Volume

Monte Carlo integration

- ▶ Simulation of 2 showers in the full detector
- ▶ Minimum distance between both showers of 20m
- ▶ Energy threshold of 5GeV/shower
- ▶ Maximum distance covered by light of 36m
- ▶ Simulation include DOMs position and triggers
- ▶ Background
 - ▶ Coincident atmospheric cascades
 - ▶ $N_{\text{bkg}} < 10^{-11} \text{yr}^{-1}$

Our Monte Carlo



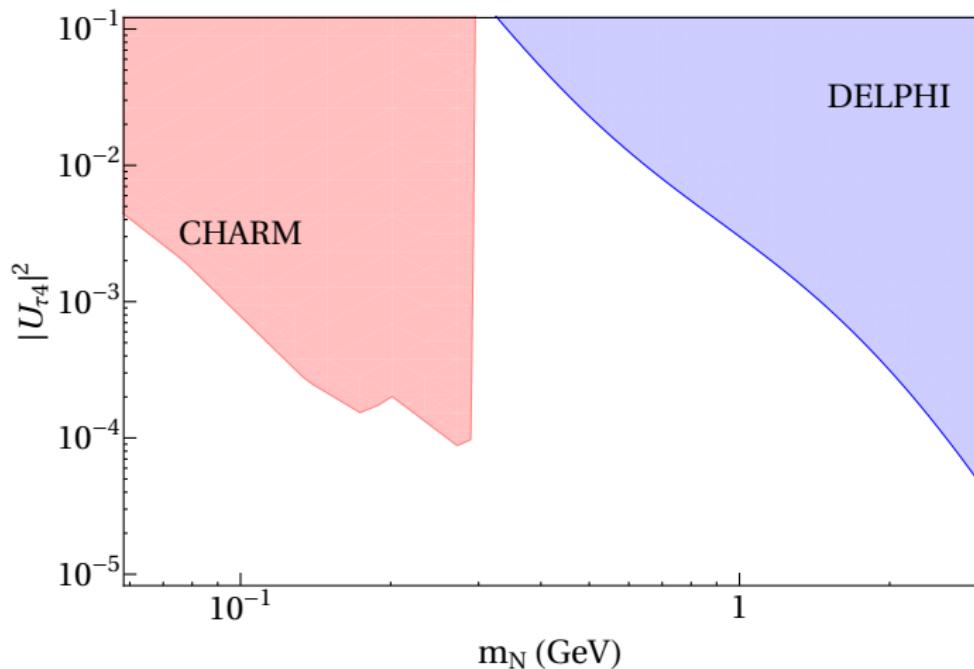
Events

The number of events in the detector is given by

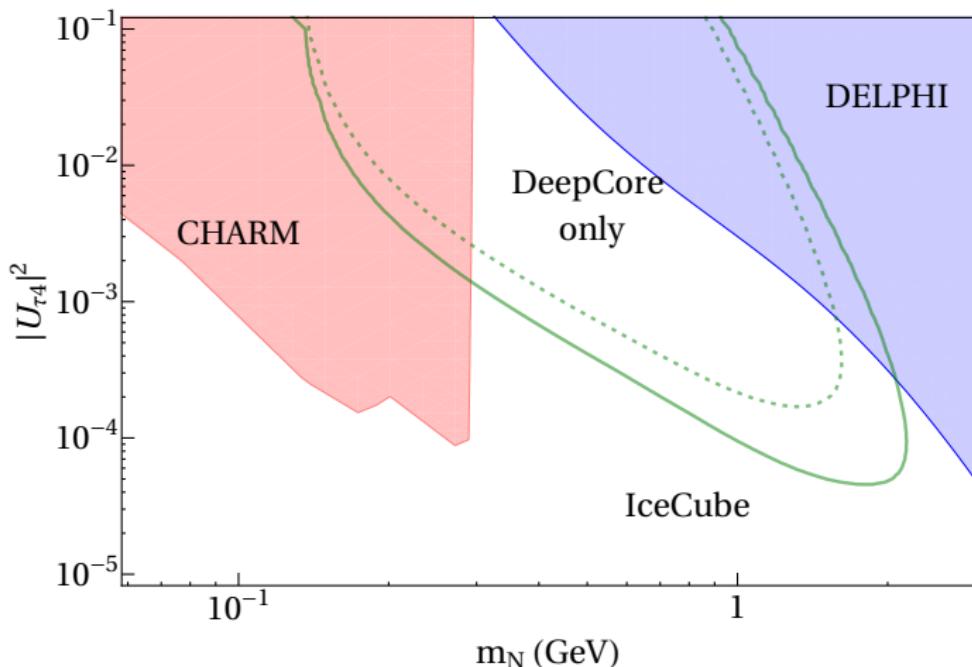
$$N(L) \propto T \int dE d\cos\theta dE' \mathcal{B} \frac{d\phi_{\nu_\mu}}{dEd\cos\theta} P_{\mu \rightarrow \tau}(E, \cos\theta) \frac{d\sigma_{\nu_\tau \nu_4}}{dEdE'} P_d(L) V_{eff}(L, \cos\theta)$$

- ▶ ϕ_{ν_μ} atmospheric flux [M. Honda, M.S. Athar, T. Kajita, K. Kasahara, S. Midorikawa Phys.Rev. D92 (2015) no.2, 023004]
 - ▶ The largest contribution comes from low energy neutrinos ($\phi \sim E^{-2.7}$)
- ▶ $P_{\mu \rightarrow \tau}$
- ▶ The differential cross section $d\sigma_{\nu_\tau \nu_4}/dEdE'$
- ▶ Decay probability $P_d(L) = e^{-L/\Gamma}/\Gamma$
- ▶ The results correspond with $T = 6$ years.

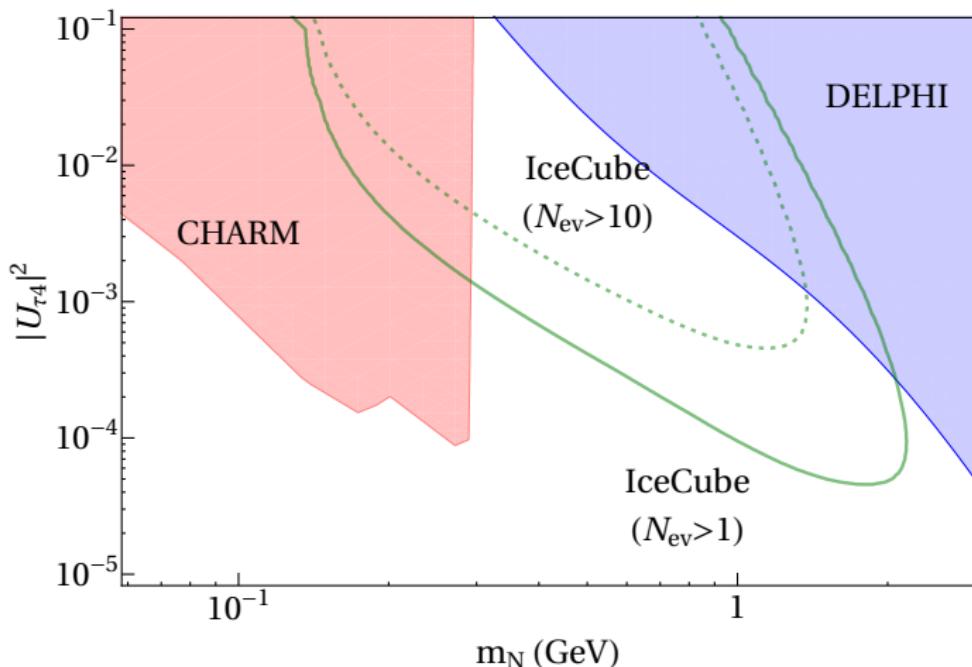
Results: Neutral Currents



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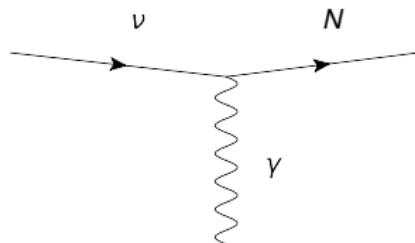


New Physics Scenario

2. Neutrino magnetic moment

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

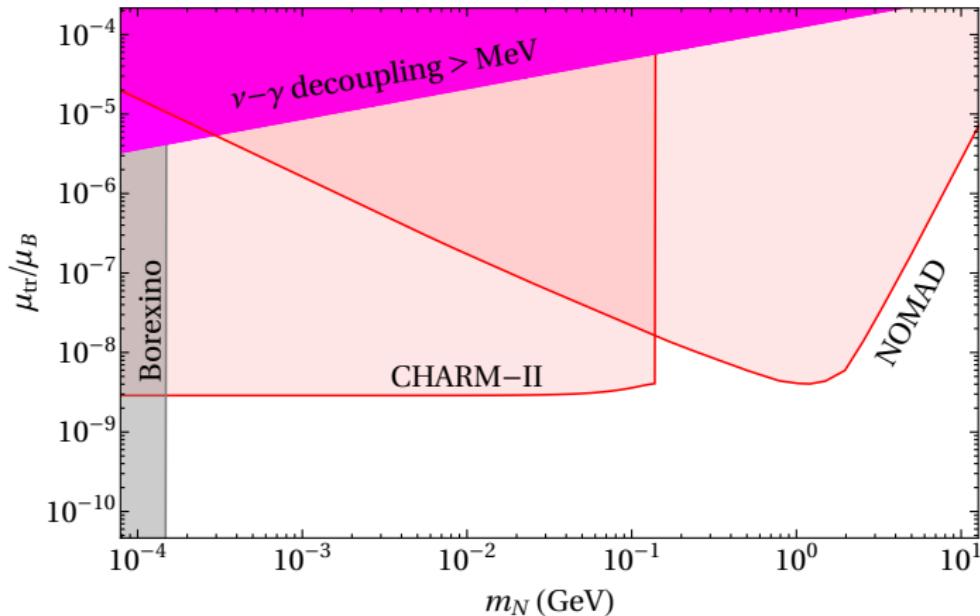
$$\mathcal{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$



- ▶ The main contribution to our signal events comes from DIS on nucleons
- ▶ The decay length $N \rightarrow \nu_i \gamma$

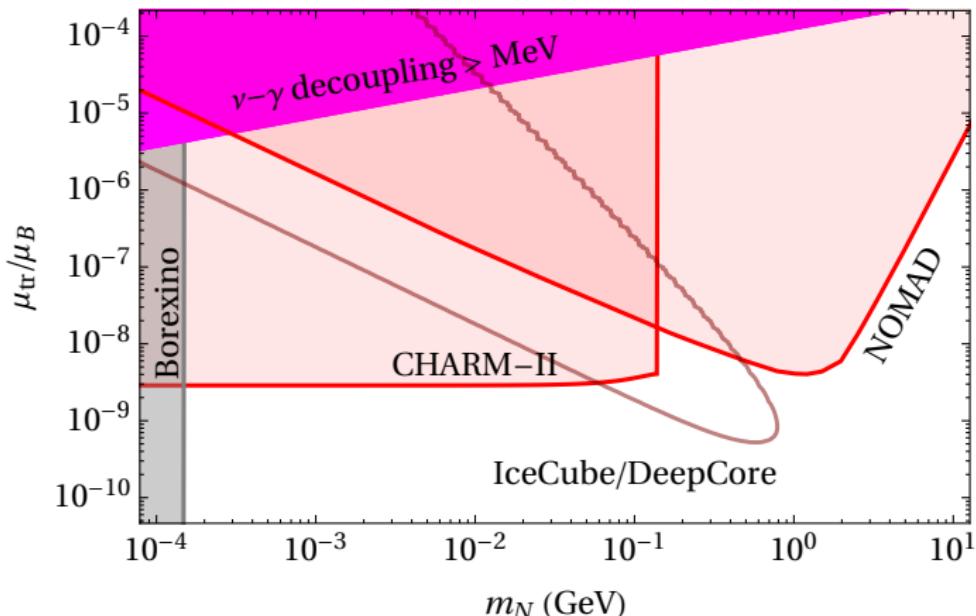
Results: Magnetic moment

$\nu_\mu - N$ transition



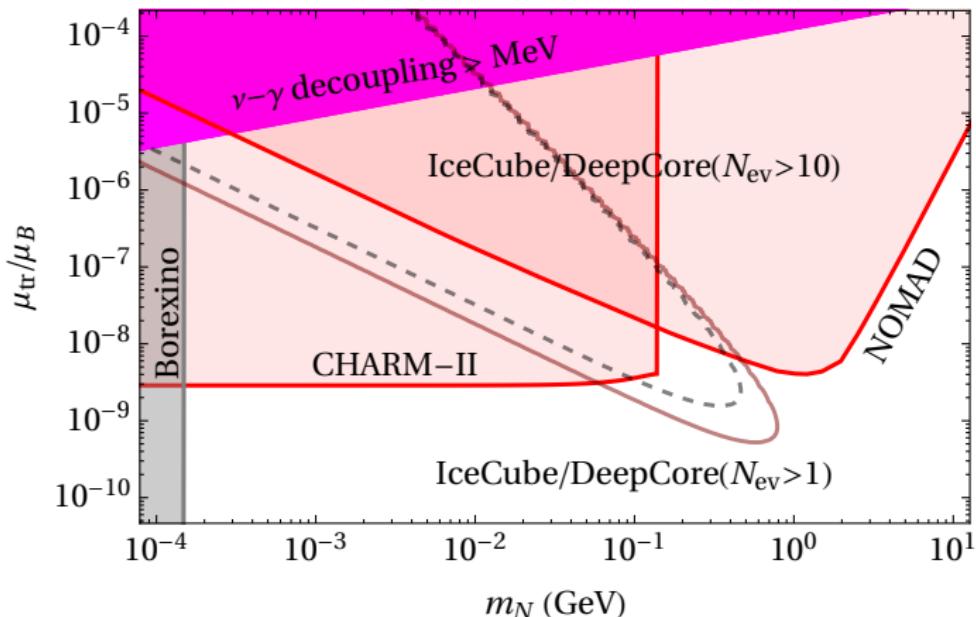
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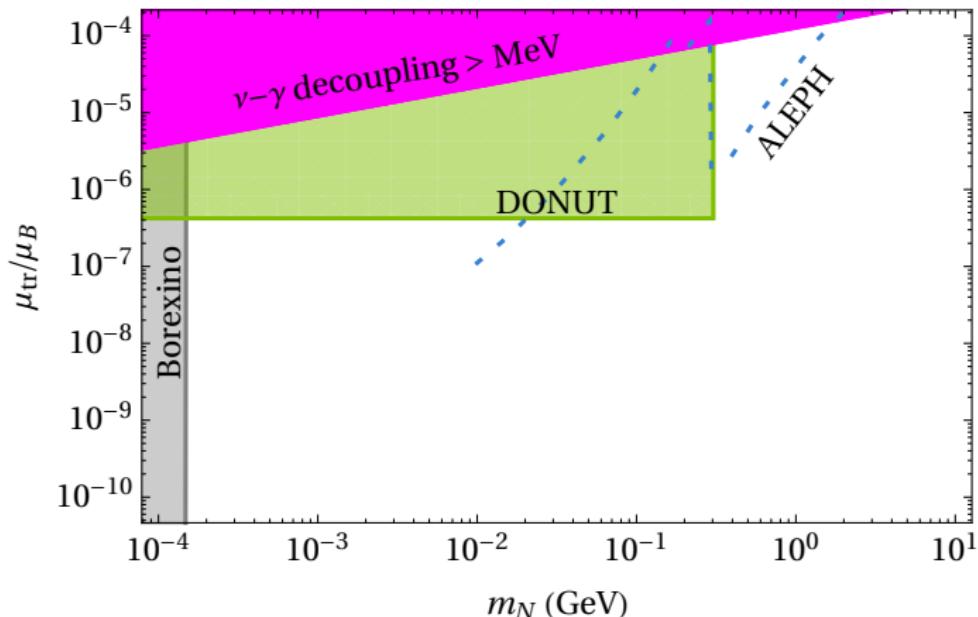
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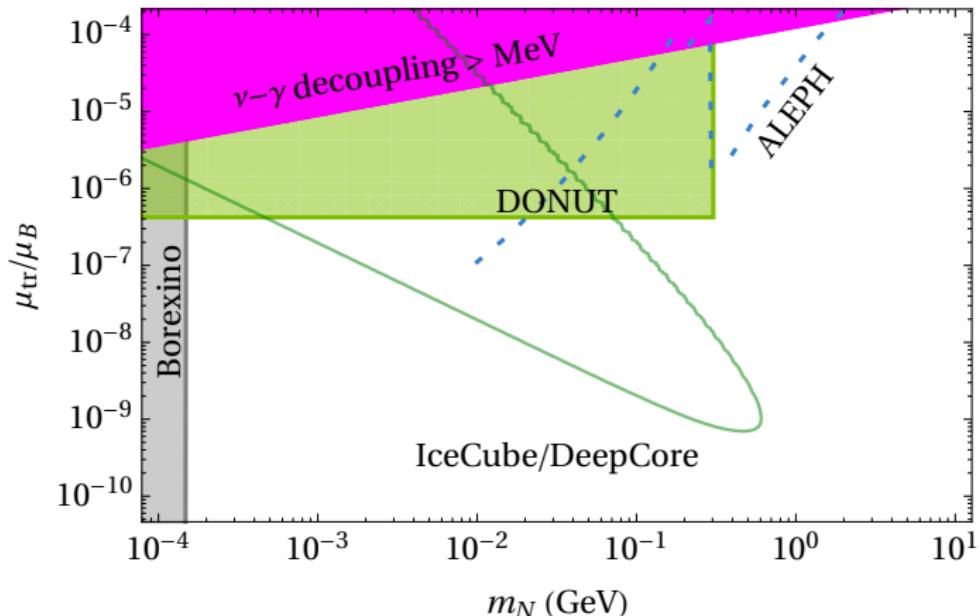
Results: Magnetic moment

$\nu_\tau - N$ transition



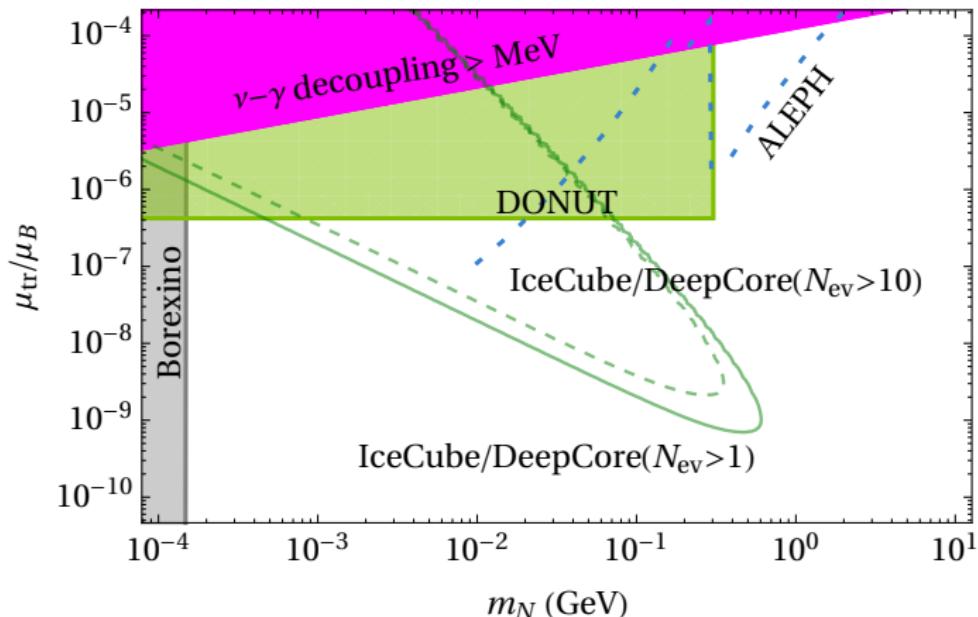
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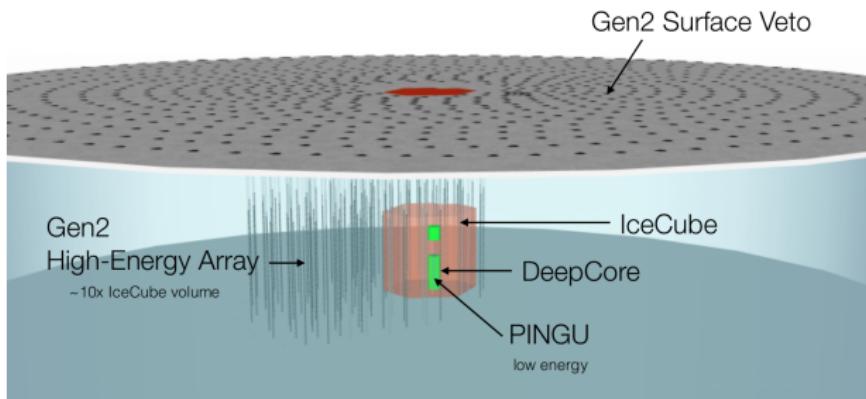
Conclusion

- ▶ Double Bang signals can probe new physics
- ▶ Sterile neutrino via neutral current
 - ▶ IceCube could increase the current bound by 1 or 2 orders of magnitude and probe small mixing as $|U_{\tau 4}|^2 \sim 5 \cdot 10^{-5}$
- ▶ Neutrino transition magnetic moment
 - ▶ IceCube can put a competitive bound on μ_ν for ν_τ and ν_μ for $M_4 \in [10^{-3}, 1] \text{GeV}$ by several orders of magnitude.

Thank you very much!

Backup: IceCube-Gen2

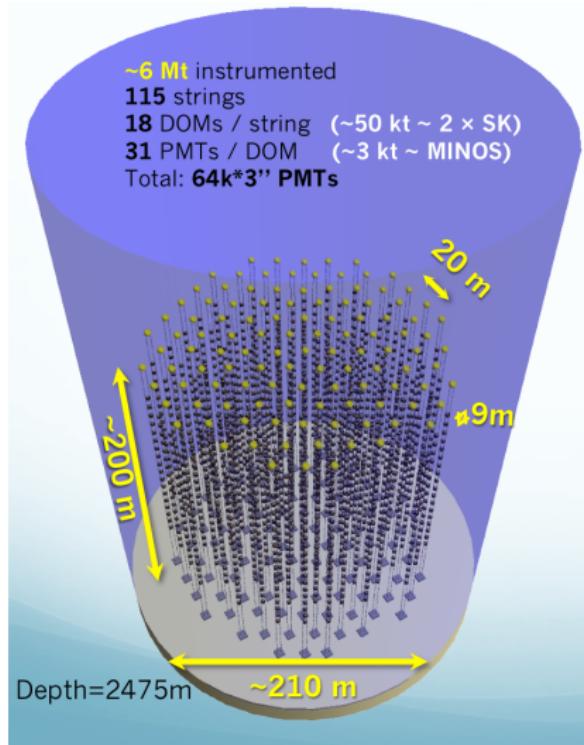
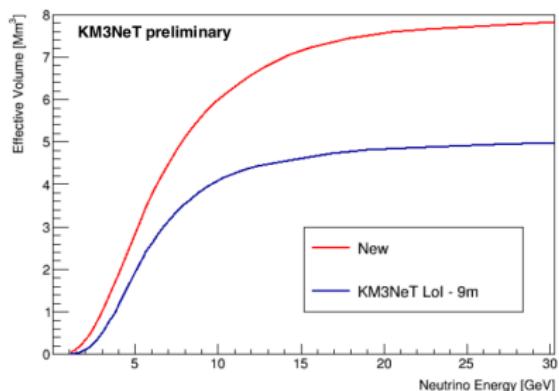
- ▶ Low energy array
 - ▶ Effective mass of 6 Mton
 - ▶ Energy threshold 1 GeV
 - ▶ Increase the number of events by a factor 1.6
- ▶ High energy array
 - ▶ Fiducial volume 10 km^3 (120 additional strings)
 - ▶ Reduce the lower limit of m_N by a factor 1.4
 - ▶ Increase in the effective volume ~ 2.7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



[A. Spiering,
arXiv:1711.08266]

Backup: 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.



Backup: Transition magnetic moment

Nucleon cross section

$$\frac{d^2\sigma_N}{dxdy} = 16\pi\alpha_{em}\mu_{tr}^2 \left(\sum_q e_q^2 f_q(x) \right) \left(\frac{(2-y)^2}{y} - y \right)$$

Electron cross section

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