New physics in IceCube with Double Bang signals

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Based in a work done with Pilar Coloma, Pedro A.N. Machado and Ian M. Shoemaker

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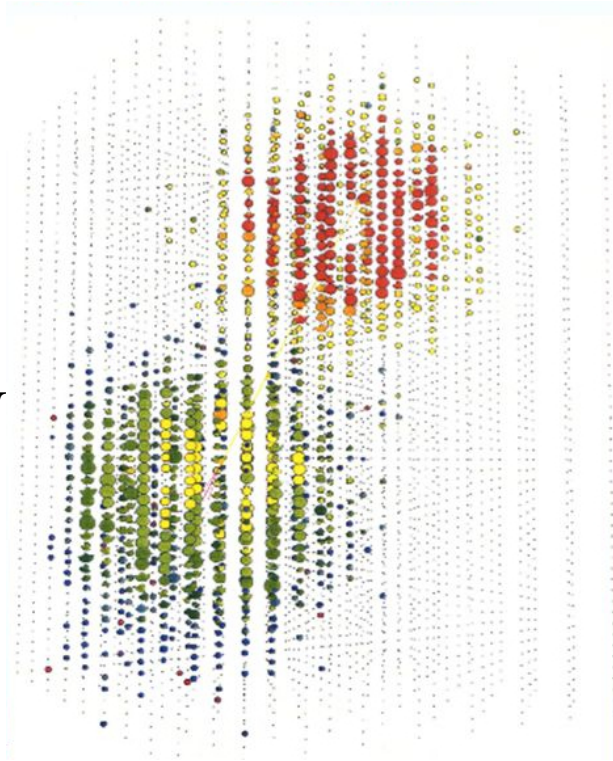
Overview

Introduction: Double Bang

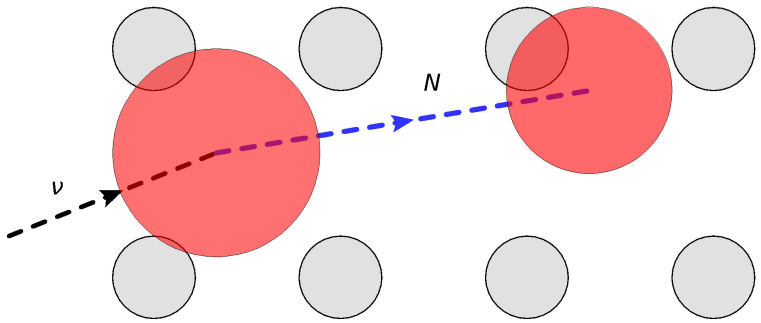
- Standard signature of ν_τ
- ν_τ CC interaction produce τ and a shower (1 shower)
- τ decay (2 shower)
  - τ emit cherenkov radiation
- For very well separates showers ($\sim$ 100m) $E_{\nu_\tau} \geq$ 2PeV
- Background negligible
- Not detected yet



Introduction: Double Bang for new physics

Double bang signals to look for new physics

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



What kind of new physics?

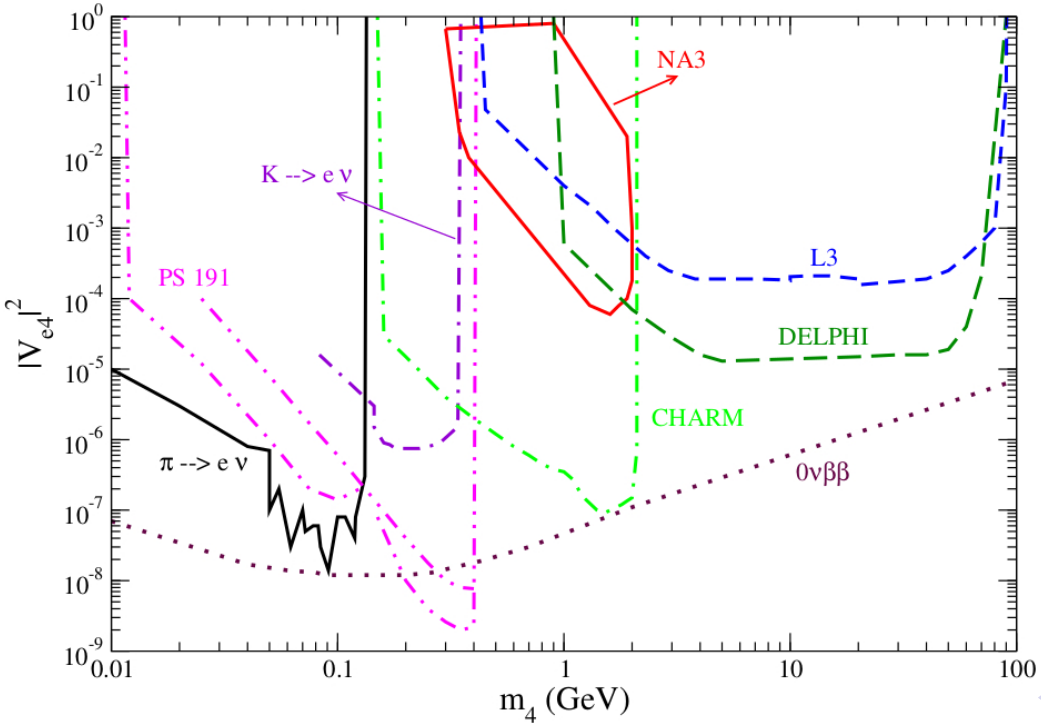
New Physics Scenario

1. BSM: Heavy sterile neutrino

Sterile posses 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



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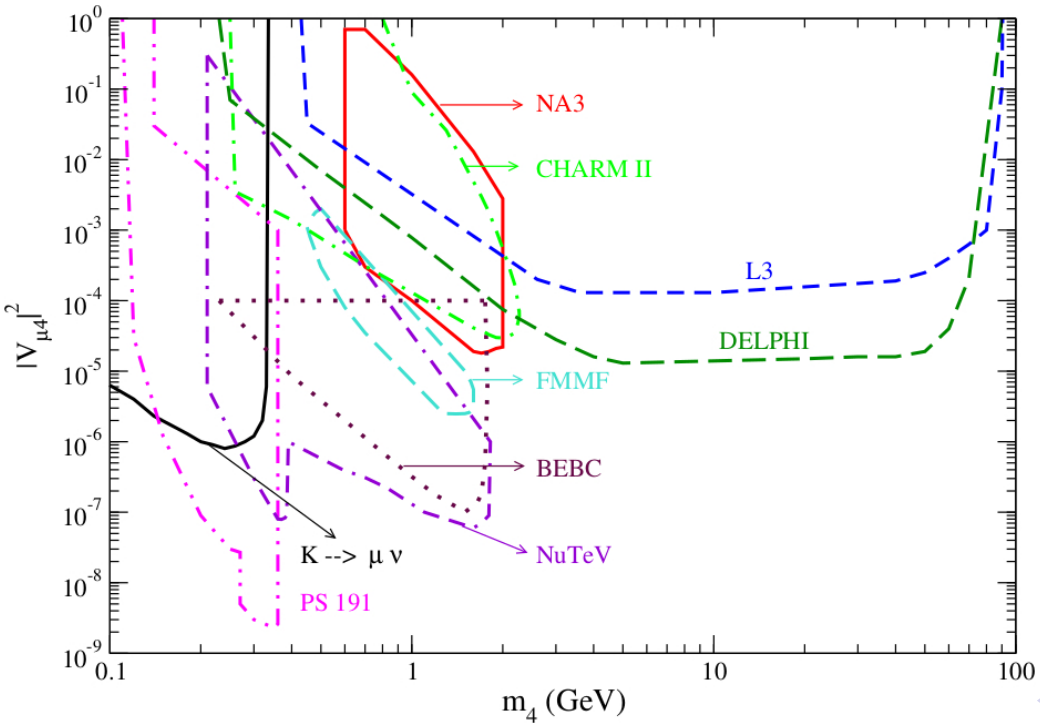


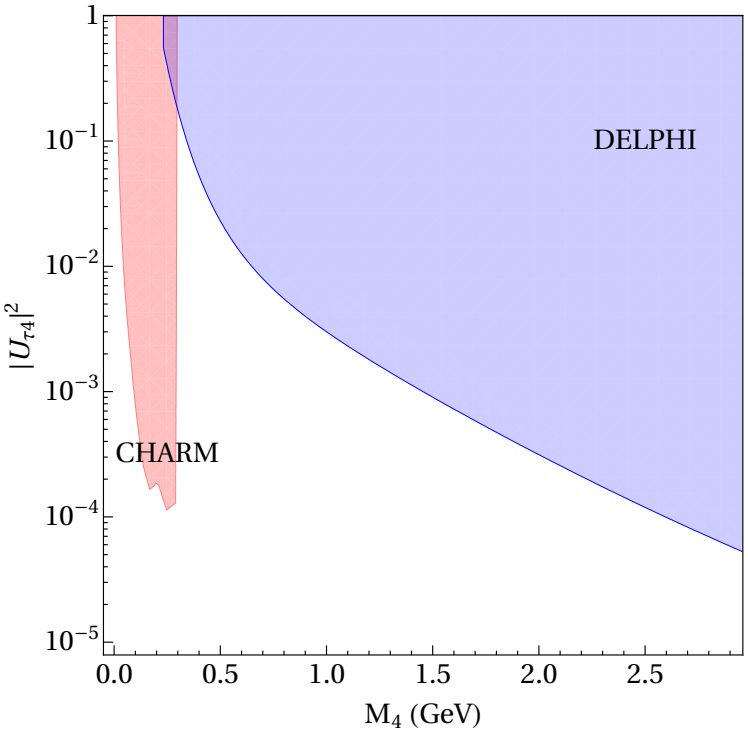
New Physics Scenario

1. Standard scenario: Heavy sterile neutrino

Sterile posses mass mixing with active neutrinos

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

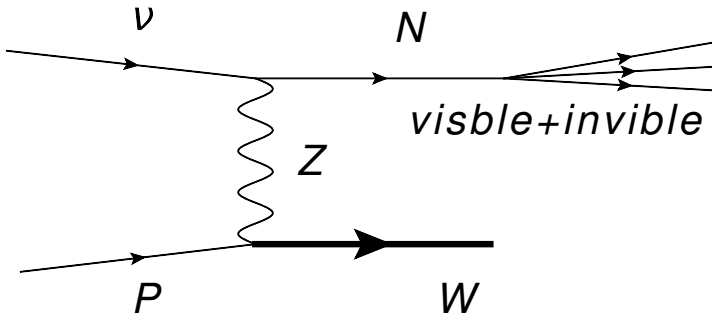
In the presence of $\nu - N - Z$ interaction: we are going to constraint $U_{\tau 4}$



Sterile neutrino via the Neutral Current

The double bang signal comes from

$$\nu_\tau + N \rightarrow N_4 + W$$
$$N_4 \rightarrow visible + invible$$

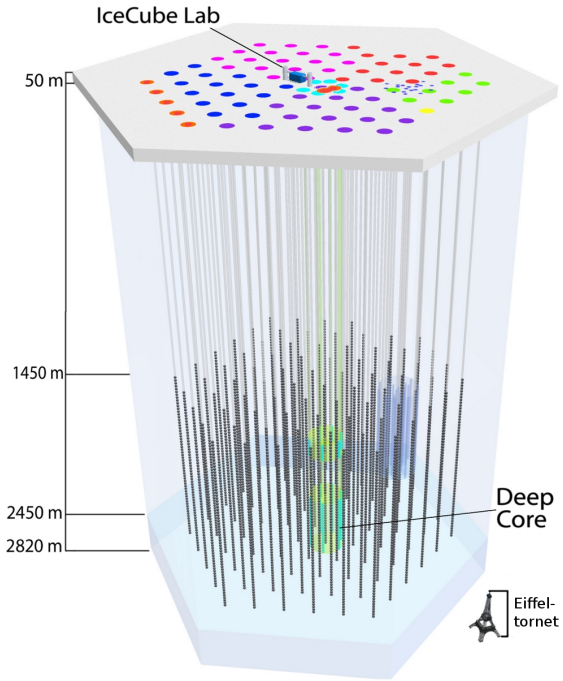


- For the decay length contribute the processes
  - $N_4 \rightarrow \nu_l P^0$ (Pseudoscalar mesons)
  - $N_4 \rightarrow \nu_l V^0$ (Neutral vector mesons)
  - $N_4 \rightarrow l^- P^+$ (Charged pseudoscalar mesons)
  - $N_4 \rightarrow l^- V^+$ (Charged vector mesons)
  - $N_4 \rightarrow \tau \nu_l l^+$ τ
  - $N_4 \rightarrow \nu_{l_1} l_2^+ l_2^-$
  - $N_4 \rightarrow \nu \nu \bar{\nu}$
- 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 $|U_{\tau 4}|^2$

IceCube detectors

- IceCube
  - Triangular grid of strings with a horizontal spacing of 125m
  - 78 vertical strings
  - 60 DOMs per string with a vertical separation of 17m

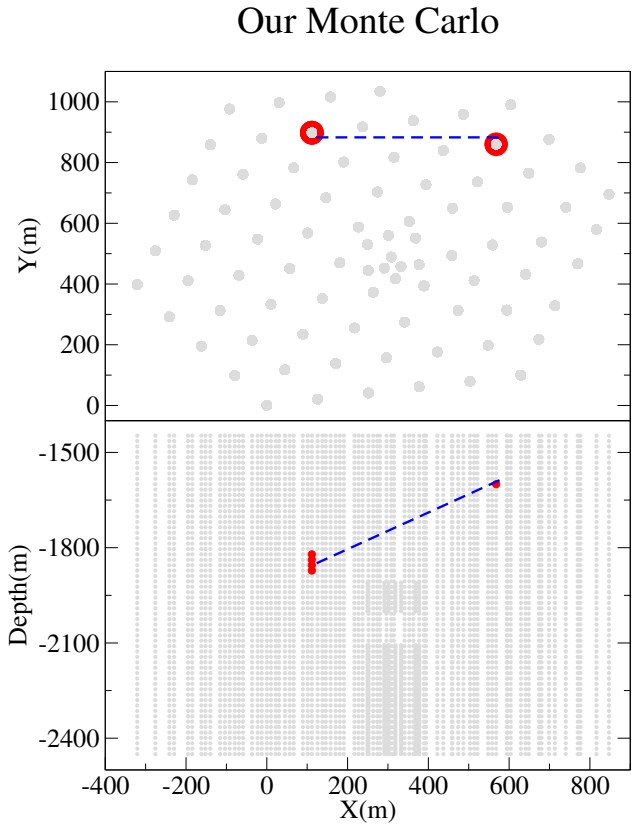
- DeepCore
  - 8 closely-spaced strings in the center of IC + 7 central IceCube strings
  - Horizontal spacing of 72m
  - 50 DOMs with vertical spacing of 7m + 10 DOMs with vertical spacing of 10m



- Event Topologies
  - Tracks
  - Showers

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



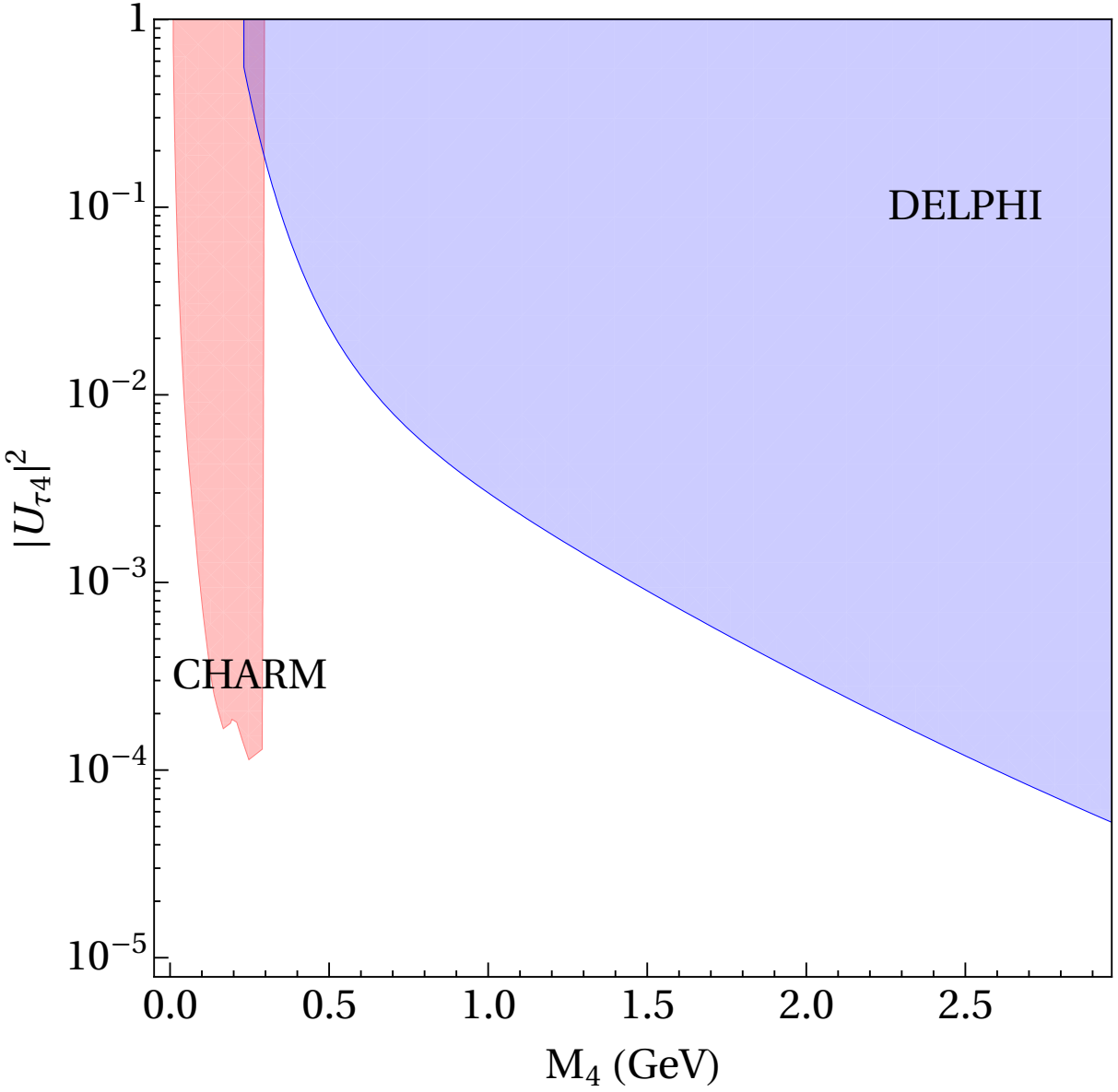
Events

The number of events in the detector is given

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

- 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 biggest contribution come 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 year.

Results: Neutral Currents



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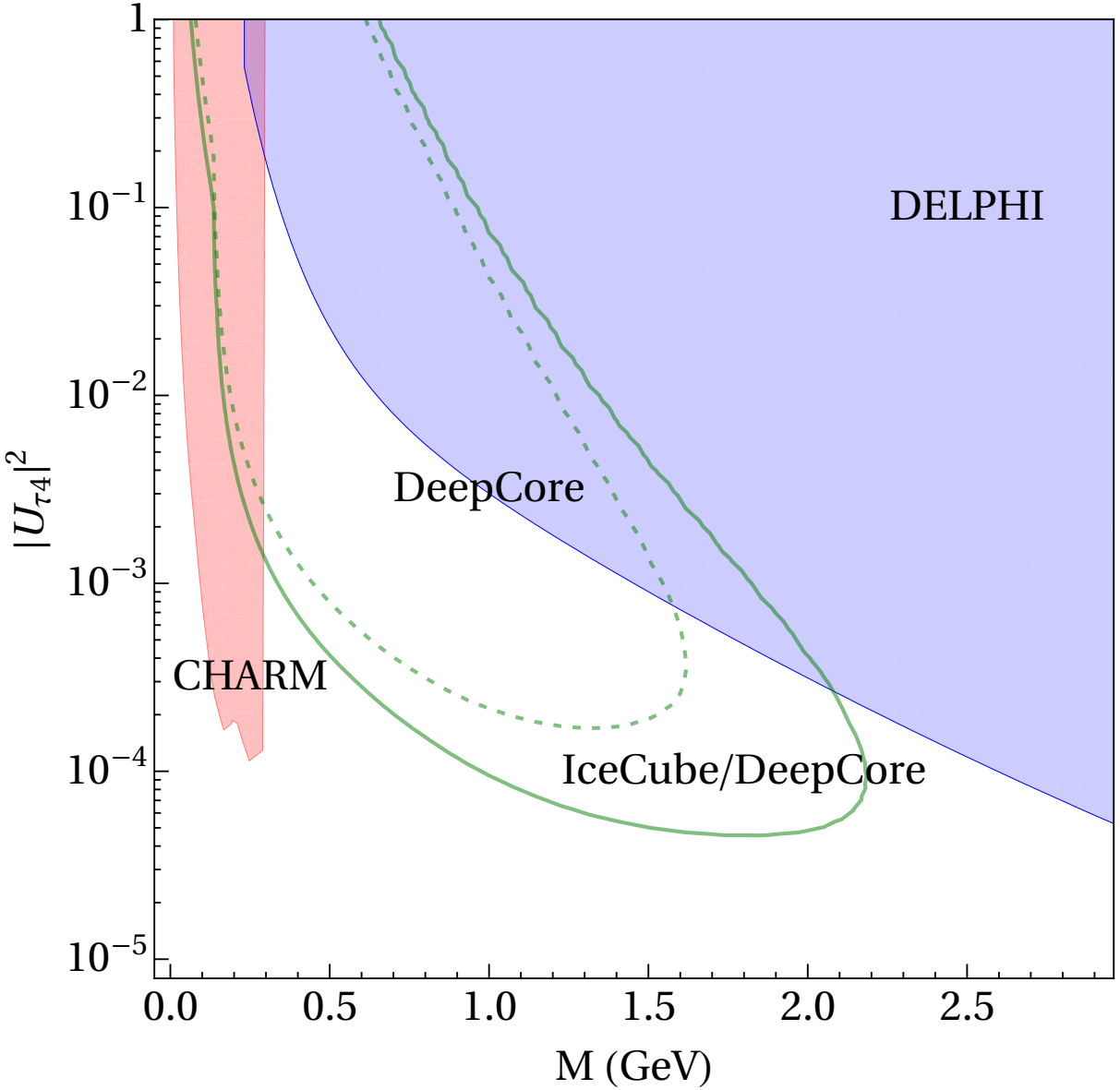

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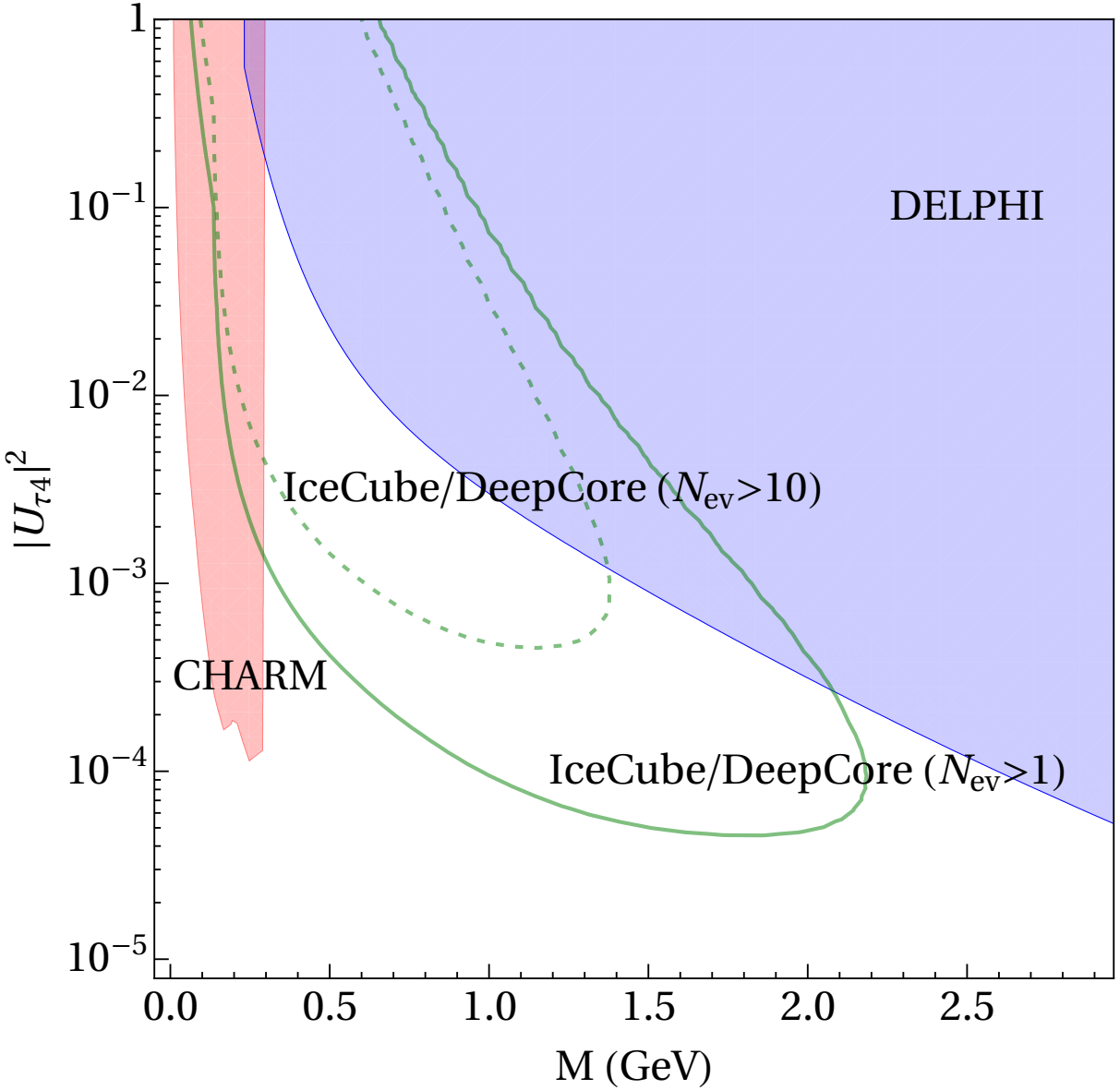
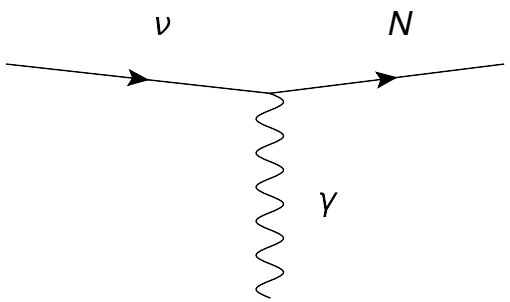


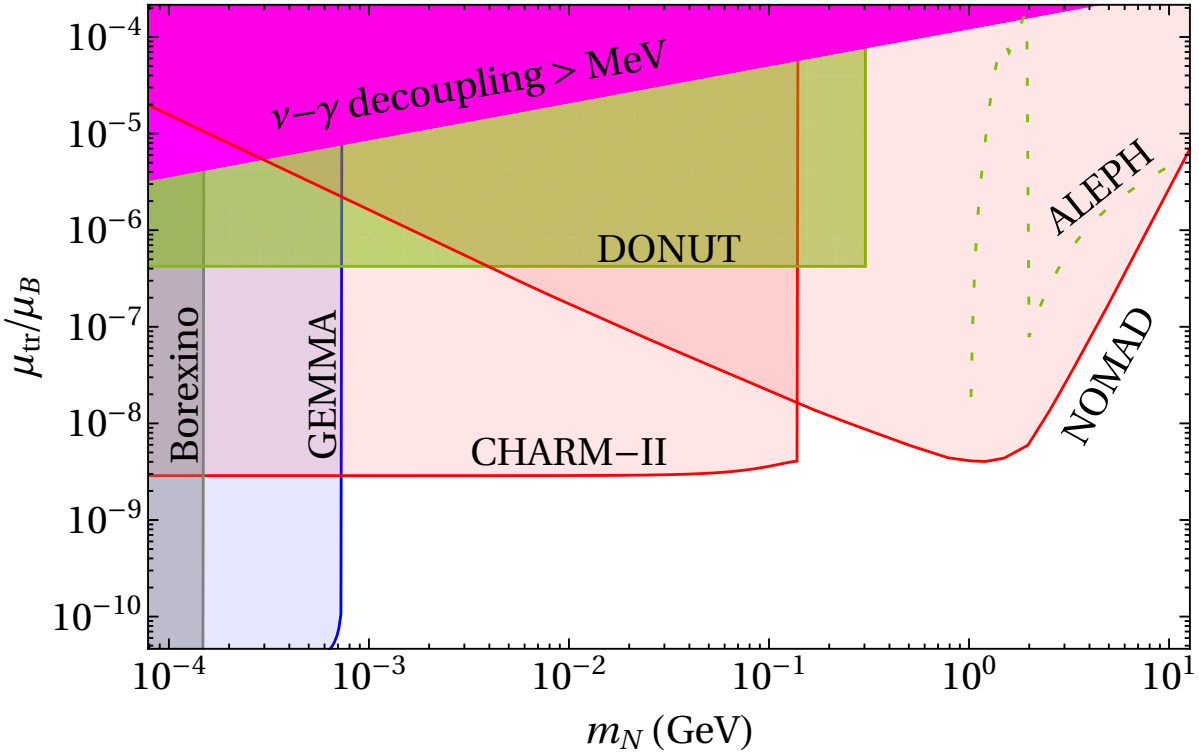
New Physics Scenario

2. Neutrino magnetic moment

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

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





Transition magnetic moment

We have included the interaction with nucleons and electrons

- For nucleons. In the DIS regime

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

- For electrons

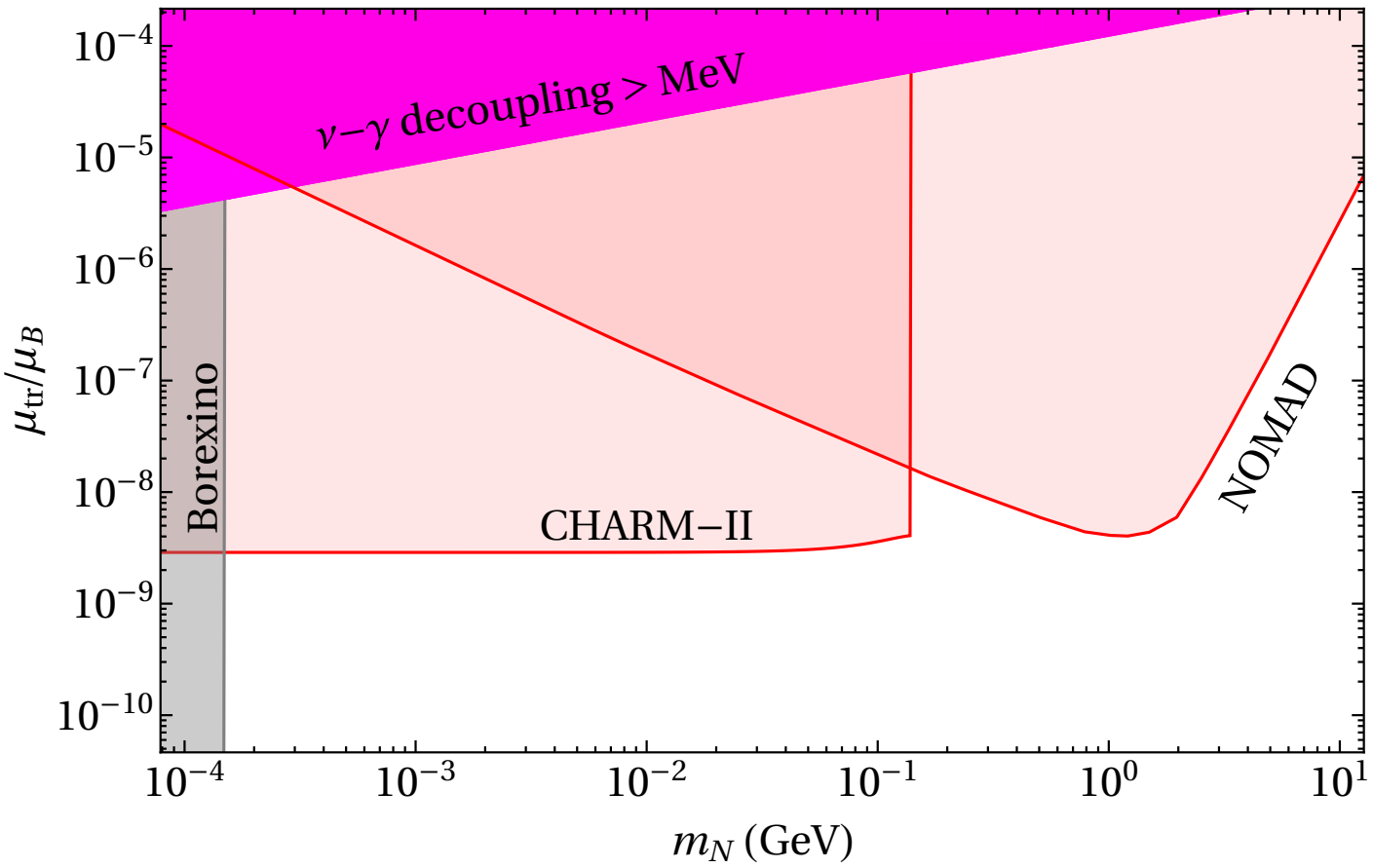
$$\frac{d\sigma_e}{d\nu} = \mu_\nu^2\alpha_{em}\left(\frac{(\nu-M_e)M_4^4}{8\nu^2E^2M_e^2} + \frac{(\nu-2E-M_e)M_4^2}{4\nu E^2M_e} + \frac{1}{\nu} - \frac{1}{E}\right)$$

- The decay length $\nu_4 \to \nu_i\gamma$

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

Results: Magnetic moment

$\nu_\mu - N$ transition



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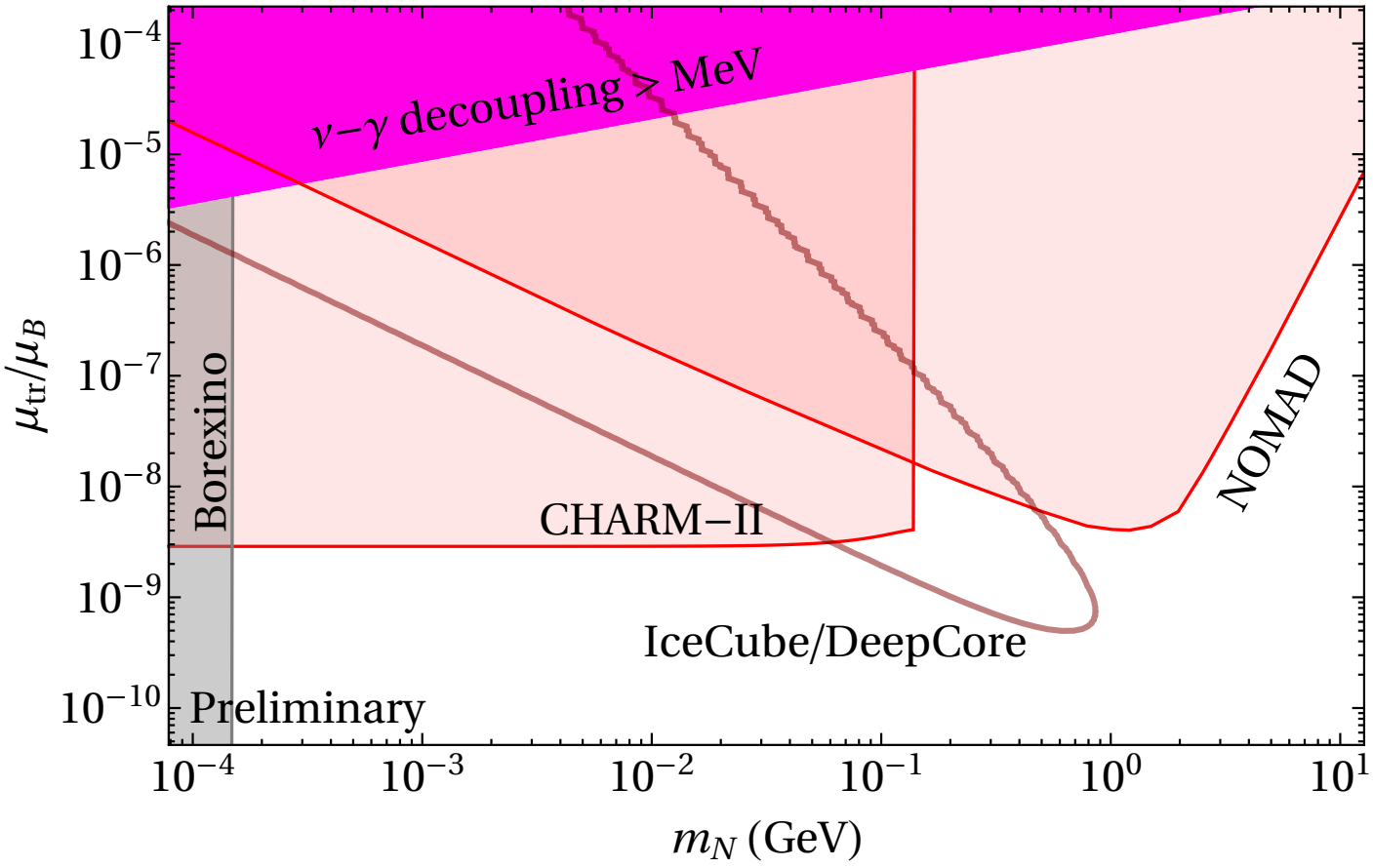

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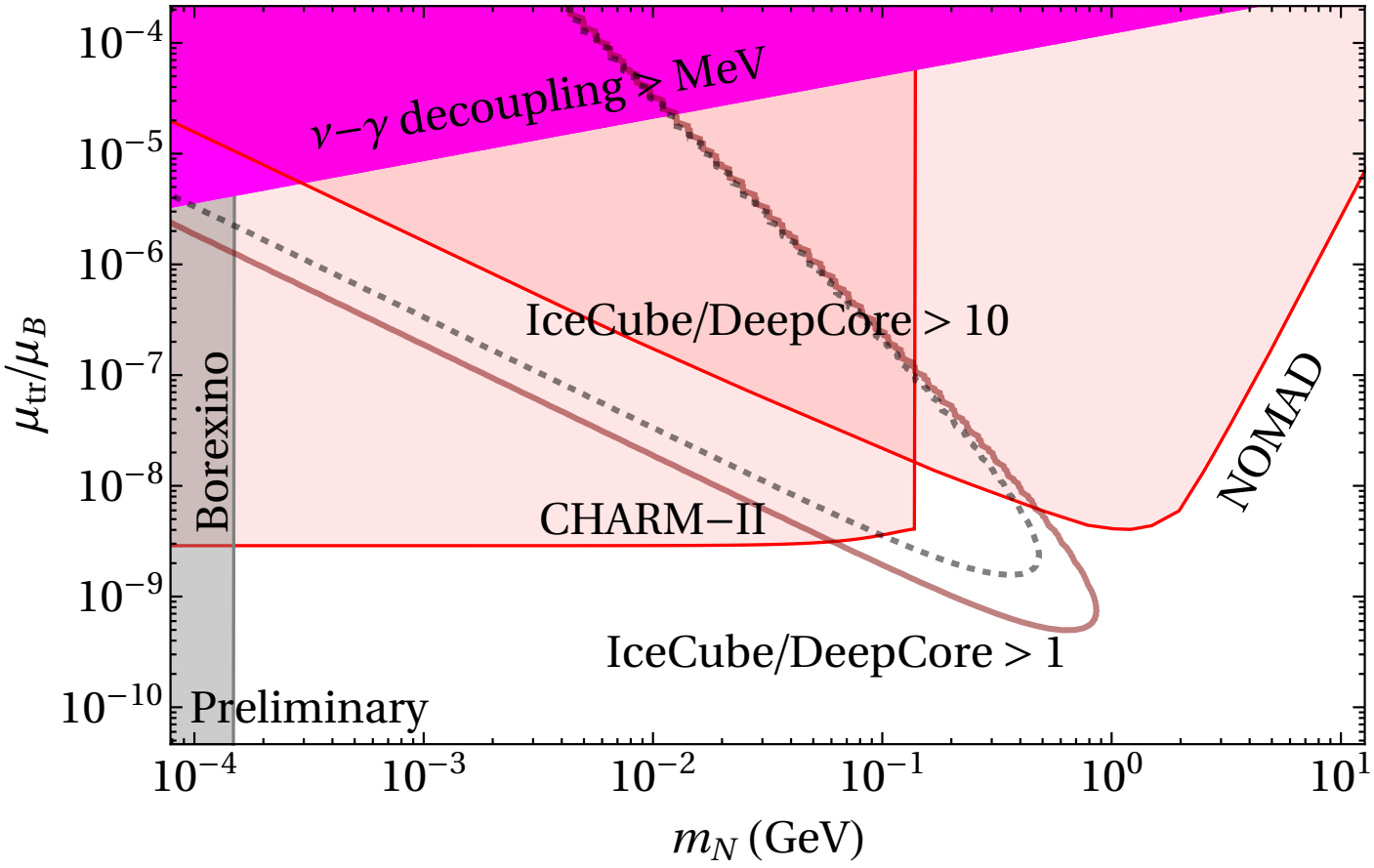
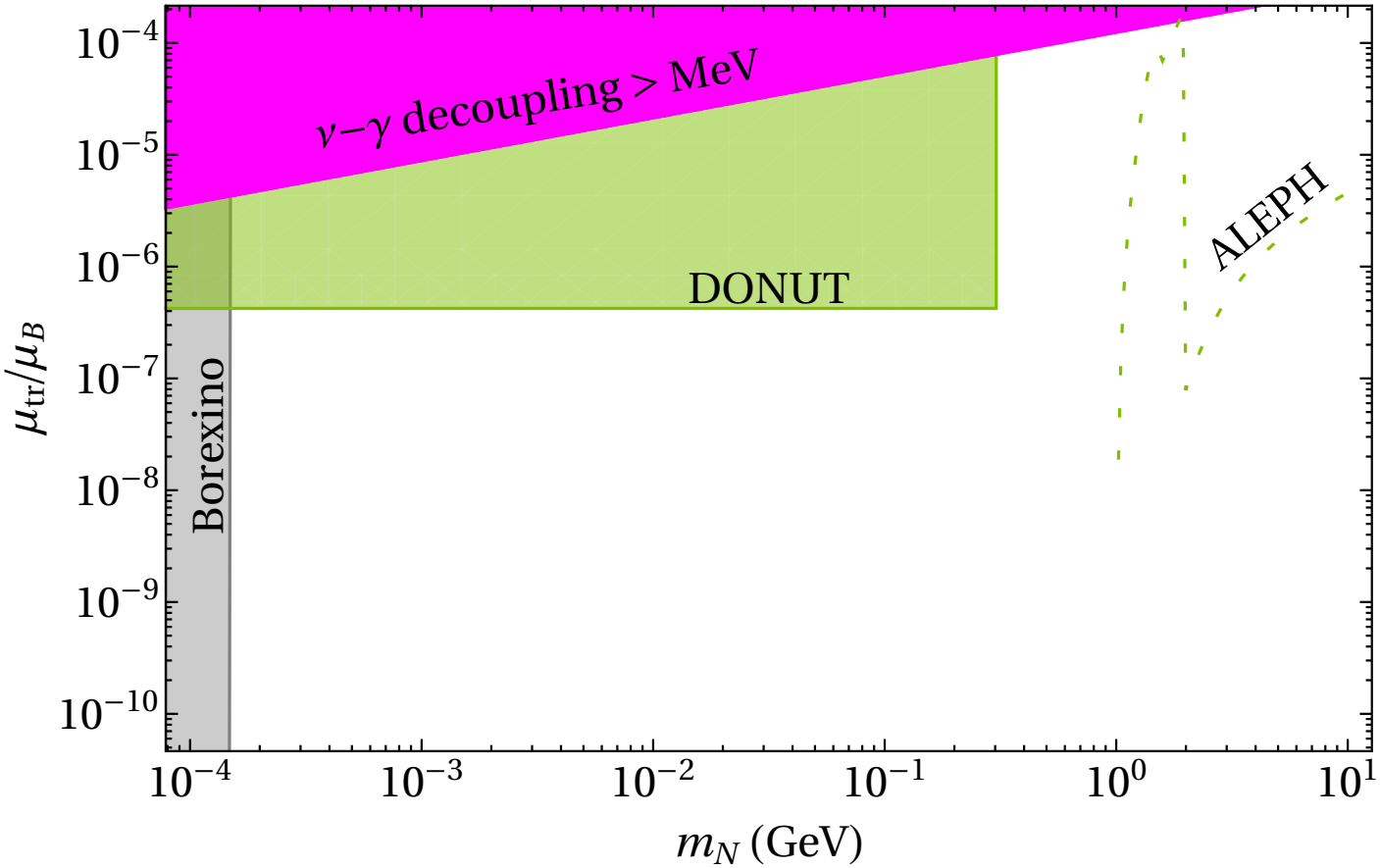


Results: Magnetic moment

$\nu_\tau - N$ transition



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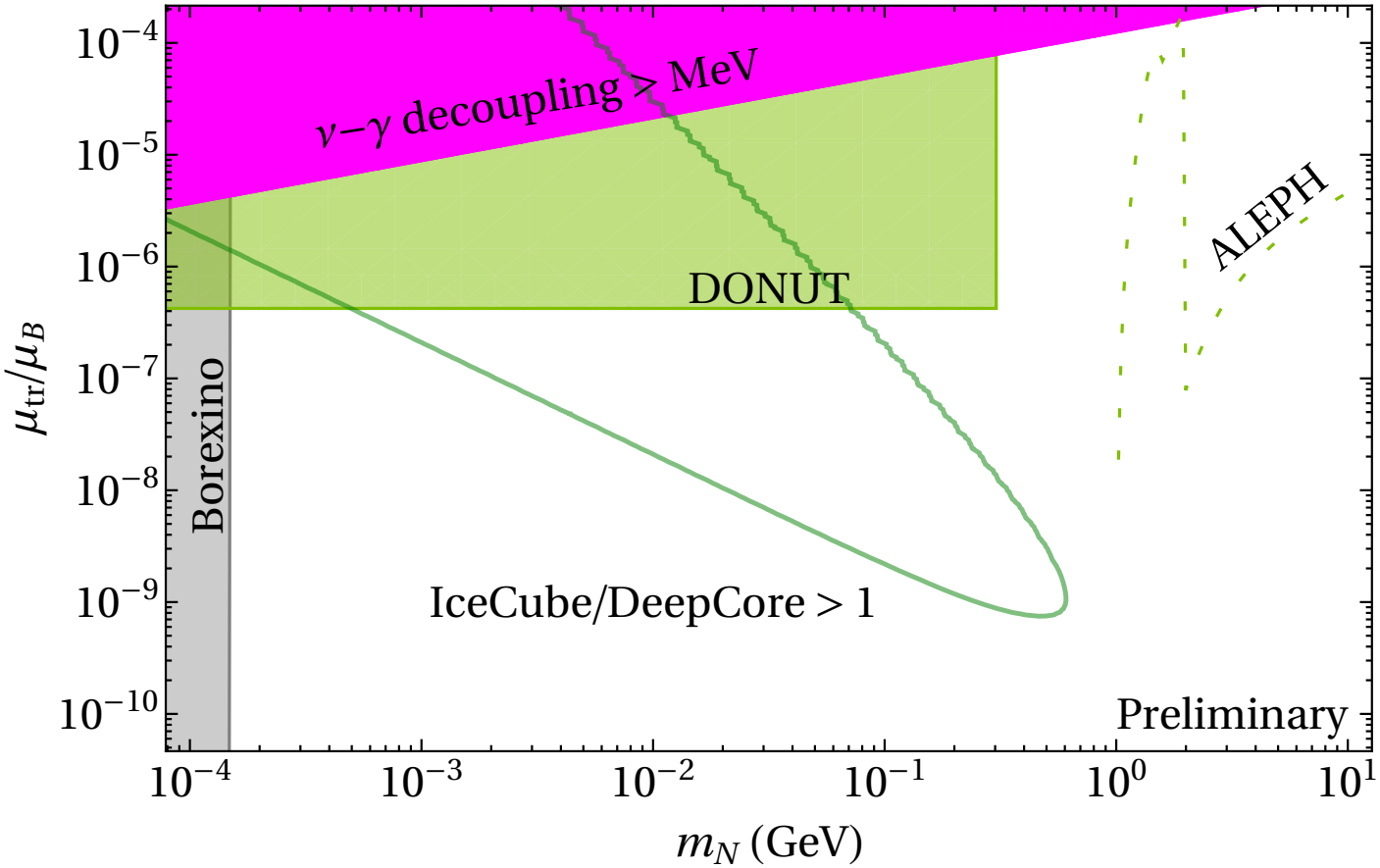

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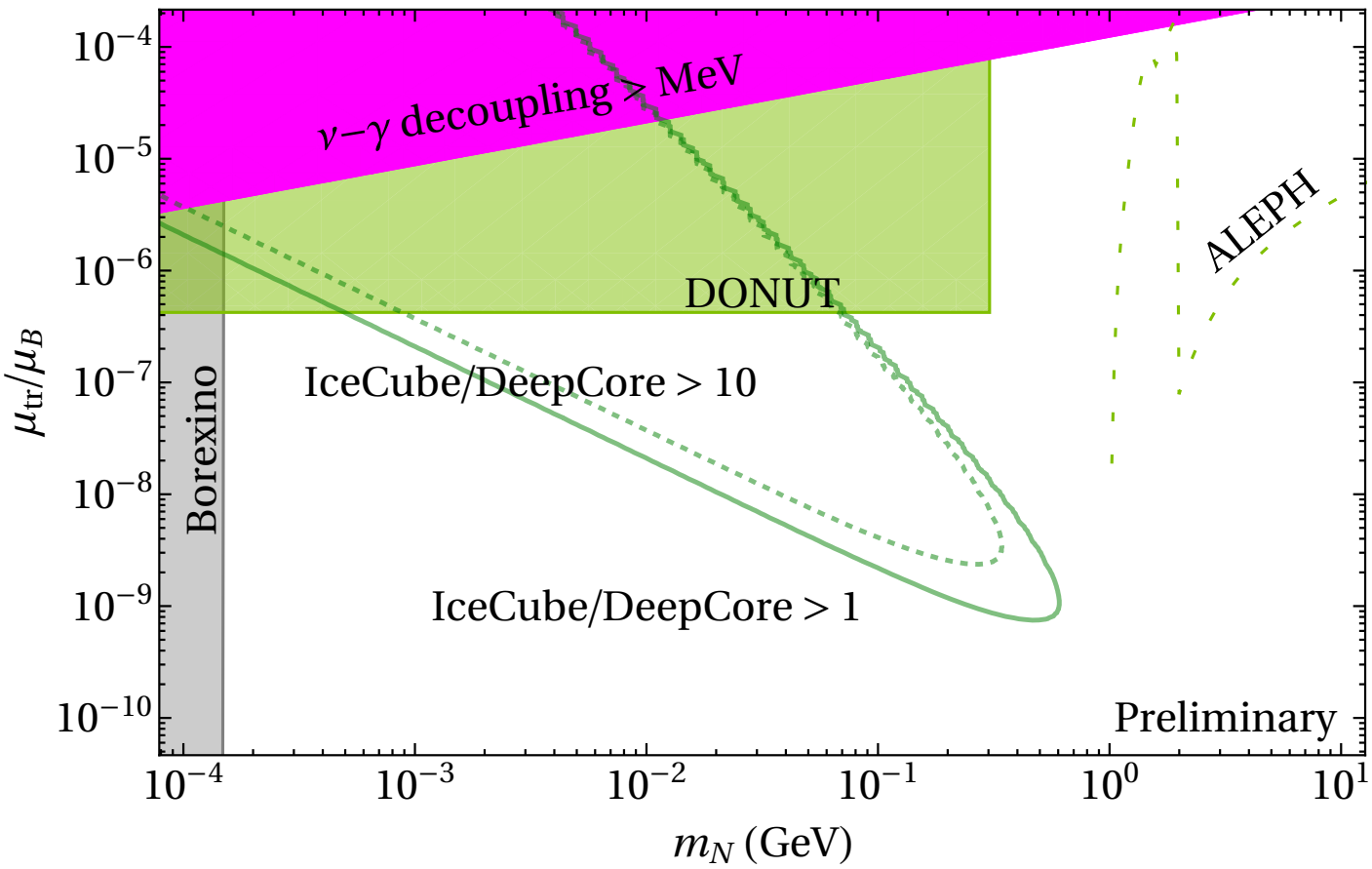

Conclusion

- Double Bang signals can probe new physics
- Sterile neutrino via neutral current
  - IceCube can put a competitive bound on $M_4 \in [0.1, \sim 2.5] GeV$ and $|V_{\tau 4}|^2 \in [10^{-5}, 1]$
- Neutrino transition magnetic moment
  - IceCube can put a competitive bound on μ_ν for ν_τ and ν_μ for $M_4 \in [10^{-3}, 1] GeV$ and $\mu_\nu \sim 10^{-9}$