CETUP* 2026

Spin-Flavor Precession of Solar Neutrinos

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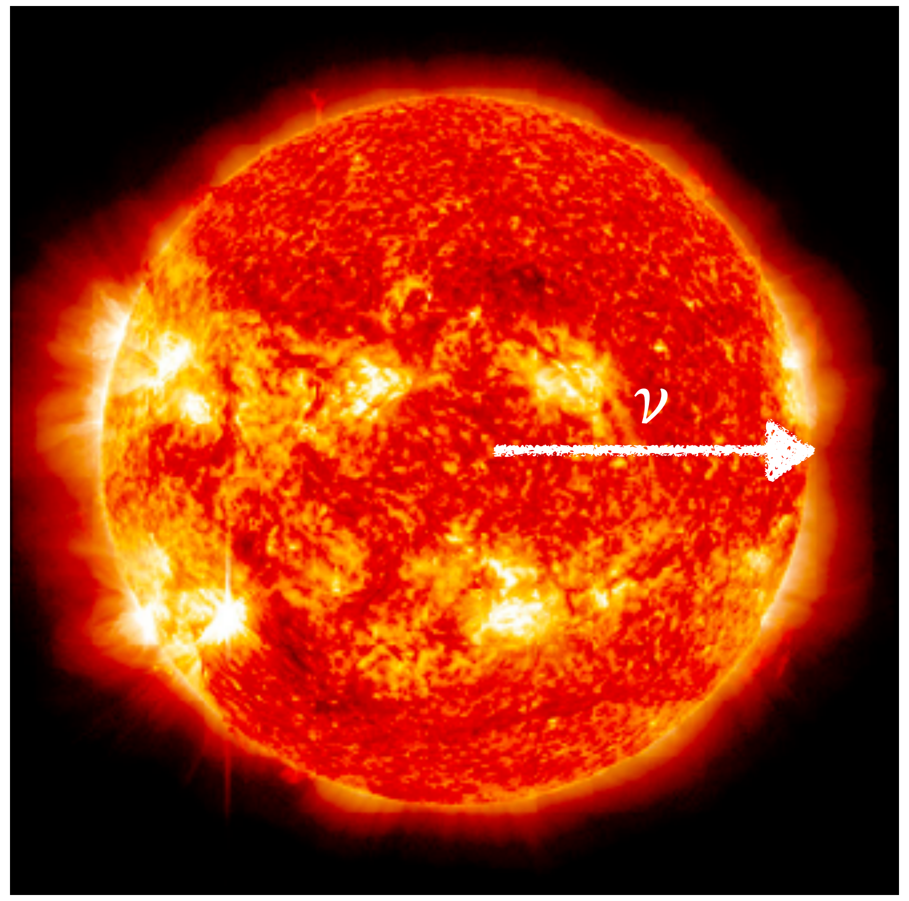
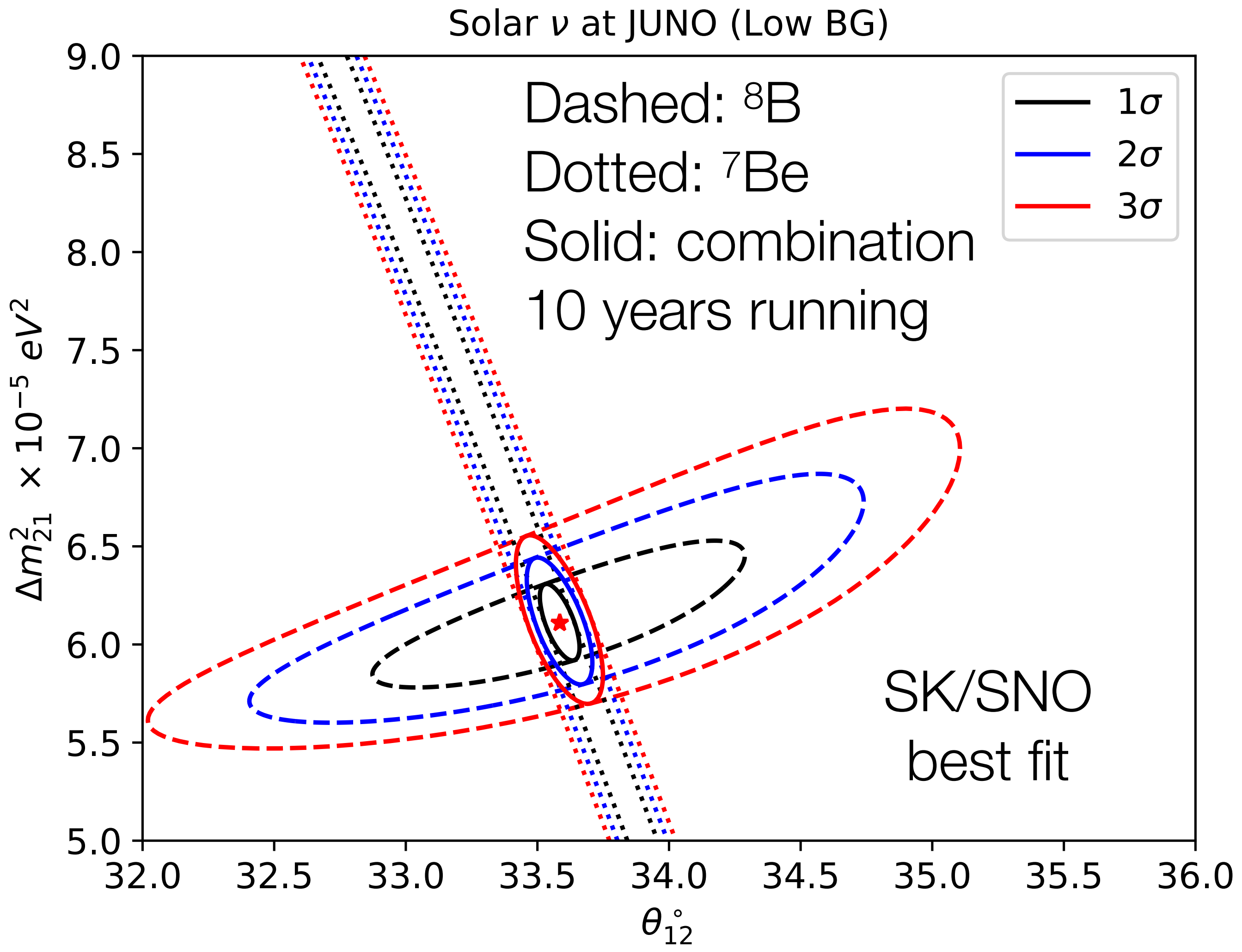
KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Work in progress with Pouya Bakhti, Sudip Jana (HCRI), Chui-Fan Kong (IBS-CTPU), Seokhoon Yun (KNU)

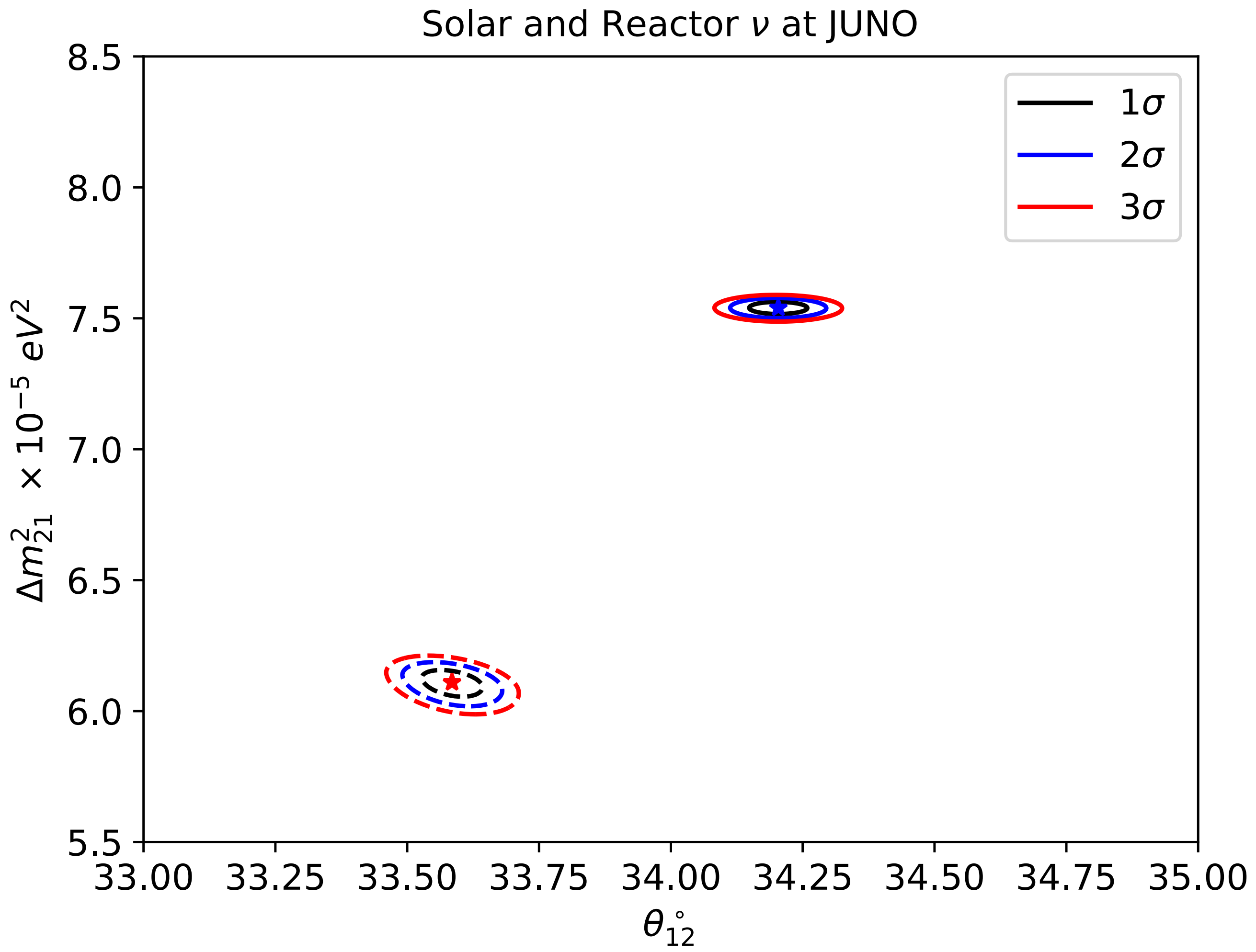
Solar Neutrino searches at Liquid Scintillator experiments

Neutrinos are produced from the Sun which is the closest star: neutrino flux is high → precise investigation possible
e.g., neutrino oscillation from the solar neutrino problem





Bakhti, Rajaee, Seo, **SS**, PRD 109, 095030 (2024)



Bakhti, Rajaee, Seo, **SS**, PRD 109, 095030 (2024)

- For example, JUNO can observe ^{8}B (5% precision after 10 years), ^{7}Be (0.15 - 1.0%), pep (3 - 17%), and possibly CNO (12-19%) after 6 years of running depending on the radiopurity level: 10^{-16} - 2×10^{-19} g/g

JUNO collaboration, JCAP 10, 022 (2023), PoS (ICRC 2025), 1041

- Combination of each measurement enables us to precisely determine the solar parameters. + reactor results

Neutrino Magnetic Dipole Moments

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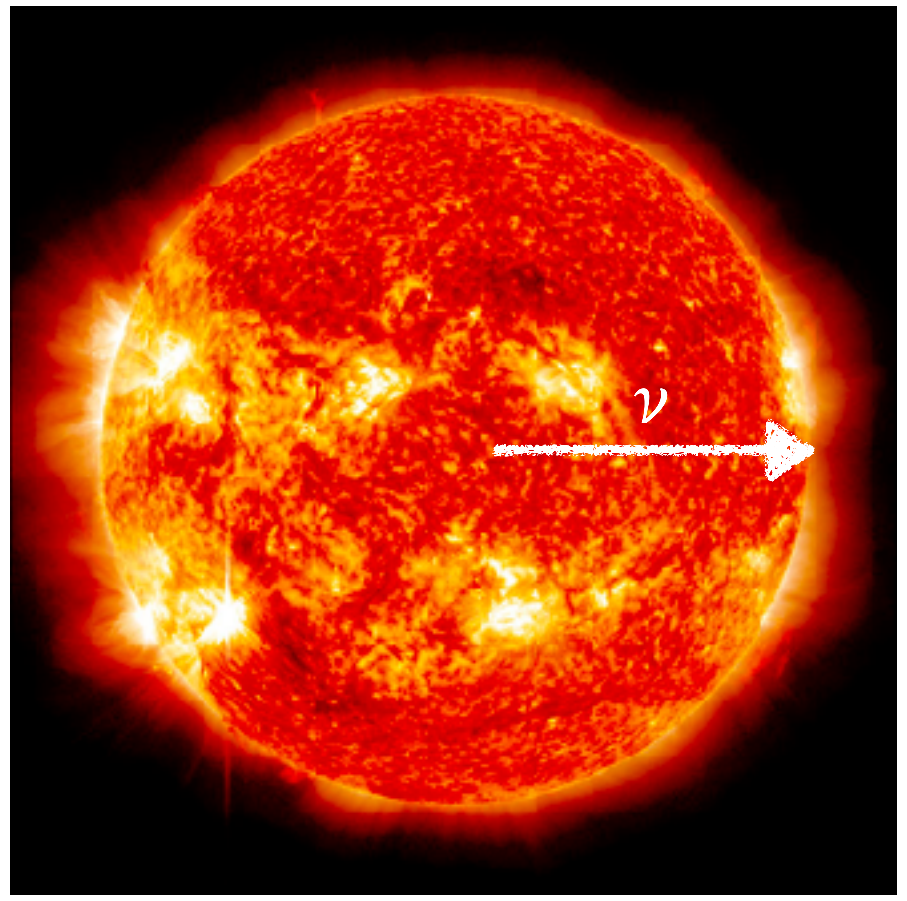
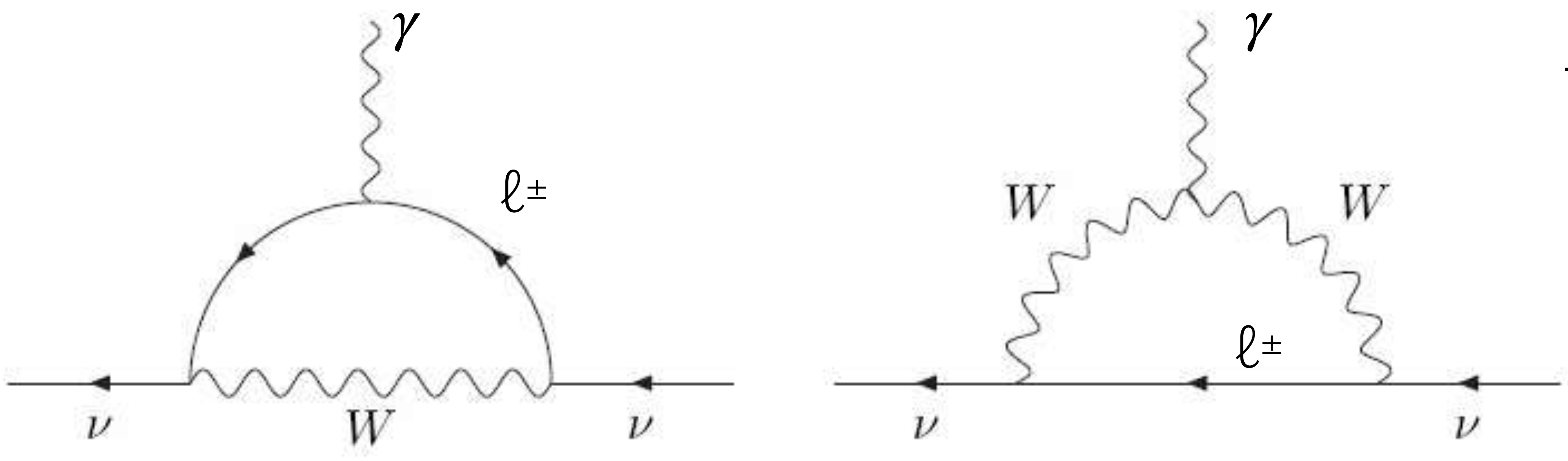




De Gouvea, Jenkins, PRD 74, 033004 (2006)

- Loop by charged particles
- Spin flip of out-going neutrino

$\sigma^{\mu\nu} F_{\mu\nu}$

- Precise investigation on the neutrino dipole moment (MDM) is also possible. *How can a neutral particle have a MDM?*

CPT invariance in QFT

μ: C-odd $\quad E = -\vec{\mu} \cdot \vec{B}$

- Effective dim. 5 operator requires the chirality flip of a neutrino

For Majorana ν, only transition moments exist!

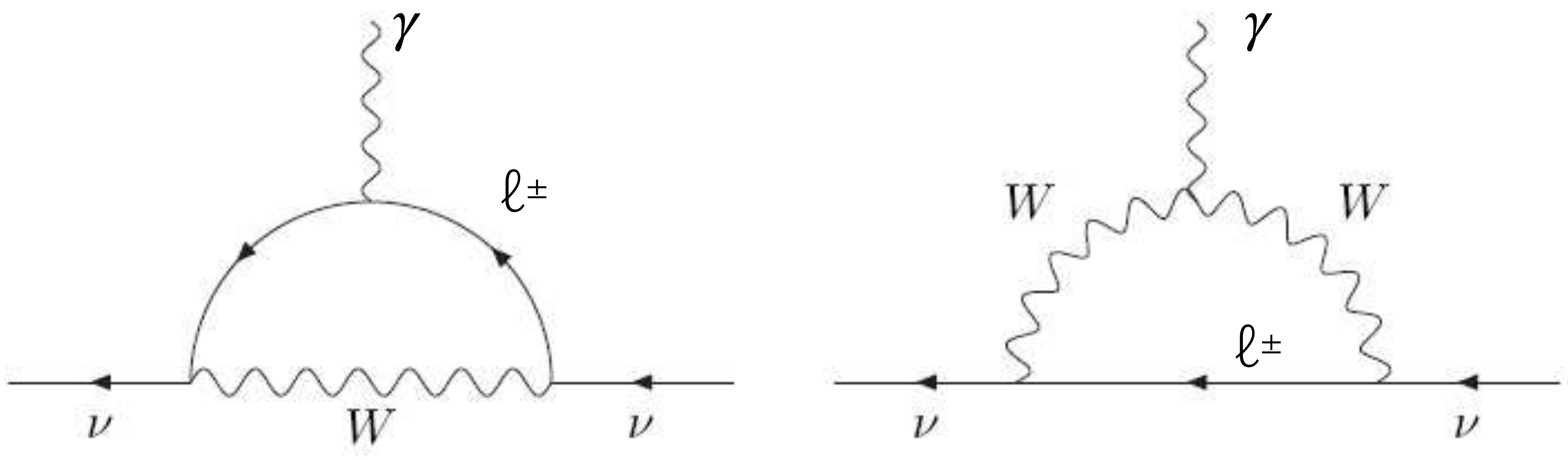
$$-\mathcal{L} \supset \frac{1}{2} \mu_\nu^{\alpha\beta} \bar{\nu}^c_{L\alpha} \sigma^{\mu\nu} \nu_{L\beta} F_{\mu\nu} + \text{h.c.}$$

$$-\mathcal{L} \supset \frac{1}{2} \mu_\nu^{\alpha\beta} \bar{\nu}_{L\alpha} \sigma^{\mu\nu} \nu_{R\beta} F_{\mu\nu} + \text{h.c.}$$

$\mu_\nu^{\alpha\beta} = -\mu_\nu^{\beta\alpha}$ ⟵ Majorana

Dirac ⟶ For Dirac ν, converted into ν_{sR}

Neutrino Magnetic Dipole Moments



De Gouvea, Jenkins, PRD 74, 033004 (2006)

- Dim. 5 effective νMDM is generically suppressed by neutrino mass due to the chirality flip of a neutrino. ($\therefore\ \mu \rightarrow \mu_{ij}$)

If only SM particles are in the loop, $$\mu_\nu \sim \frac{eG_F}{16\pi^2} m_\nu \sim 10^{-20} \mu_B \left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)$$

(simplest) Dirac

$$\mu_B = |2\mu_{e^-}| = \left|\frac{\gamma_e}{g_e}\hbar\right| = \frac{e}{2m_e}\hbar \sim 5.788 \times 10^{-5}\,\mathrm{eV/T}$$

$\mu_{\nu, a\neq b} \sim 10^{-24}\,\mu_B$ Unitarity of U_{PMNS}

Neutrino Magnetic Dipole Moments

Obs./Exp. bounds : $\mu_\nu < (10^{-11} \sim 10^{-12})\mu_B$

XENONnT: $\mu_\nu < 6.4\times10^{-12}\mu_B$

XENONnT collaboration, PRL 129, 161805 (2022)

$$\frac{d\sigma}{dE_r} \propto \frac{1}{E_r}$$

TRGB cooling: $\mu_\nu < 1.5\times10^{-12}\mu_B$

Capozzi, Raffelt, PRD 102, 083007 (2020)

cooling by $\gamma \to \nu\bar{\nu}$

GEMMA : $\mu_\nu < 2.9\times10^{-11}\mu_B$

GEMMA collaboration, Phys. Part. Nucl. Lett. 10, 139 (2013)

elastic scattering of $\bar{\nu}_e$ with e^-

$N_{\rm eff}$ for Dirac: $\mu_\nu < 2.7\times10^{-12}\mu_B$

Li, Xu, JHEP 02, 085 (2023)

very light (Dirac) 3 ν_R

Room for BSM (precise observation needed)

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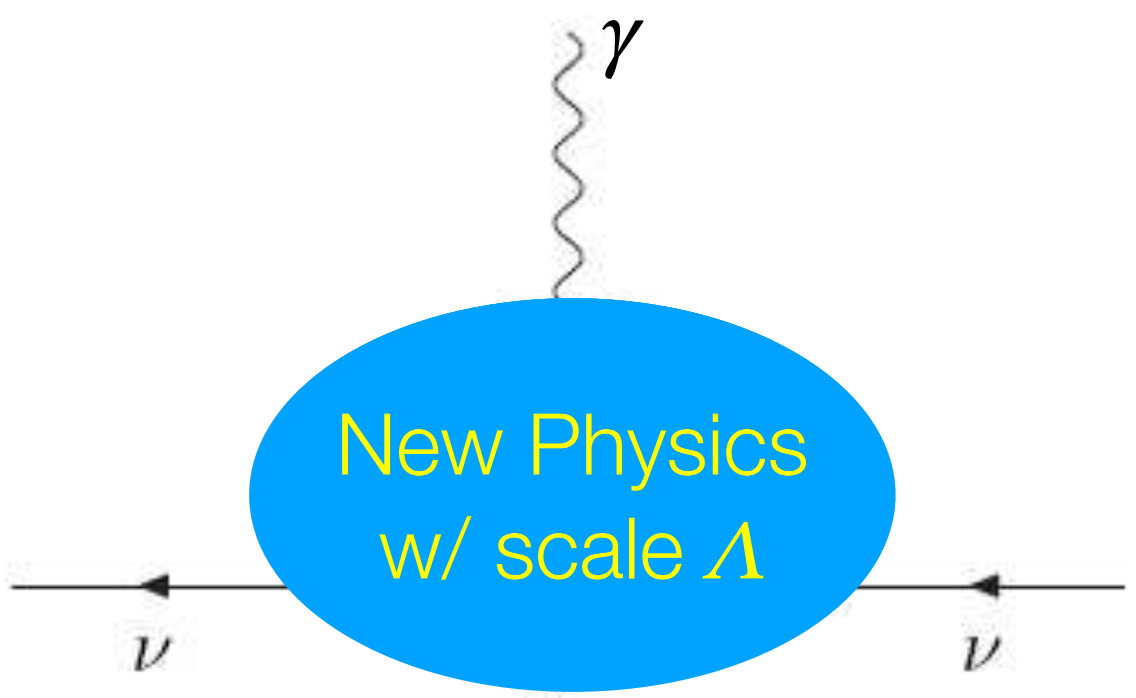
Neutrino Magnetic Dipole Moments

Diagram for μ_ν is closely related with the diagram for m_ν.



Still suppressing

$$\frac{\mu_\nu}{\mu_B} = \frac{m_e m_\nu}{\Lambda^2} \longrightarrow \mu_\nu = \frac{m_e m_\nu}{\Lambda^2}\mu_B$$

When Λ ~ TeV and m_ν ~ 0.1 eV, we still get $\mu_\nu \sim 10^{-20}\,\mu_B$

- There are two classes of new physics (NP) scenarios which can drop off m_ν and expect larger νMDM.

1. m_ν being replaced by other NP parameters, e.g., SUSY, LR symmetric models — Up to $\mu_\nu \sim 10^{-15}\,\mu_B$
2. m_ν being forbidden by (approximate) extra symmetries, e.g., global $SU(2)_H$

Voloshin symmetry (ν_L, N_R^c) loop level breaking generating m_ν — Voloshin, Sov. J. Nucl. Phys. 48, 512 (1988)

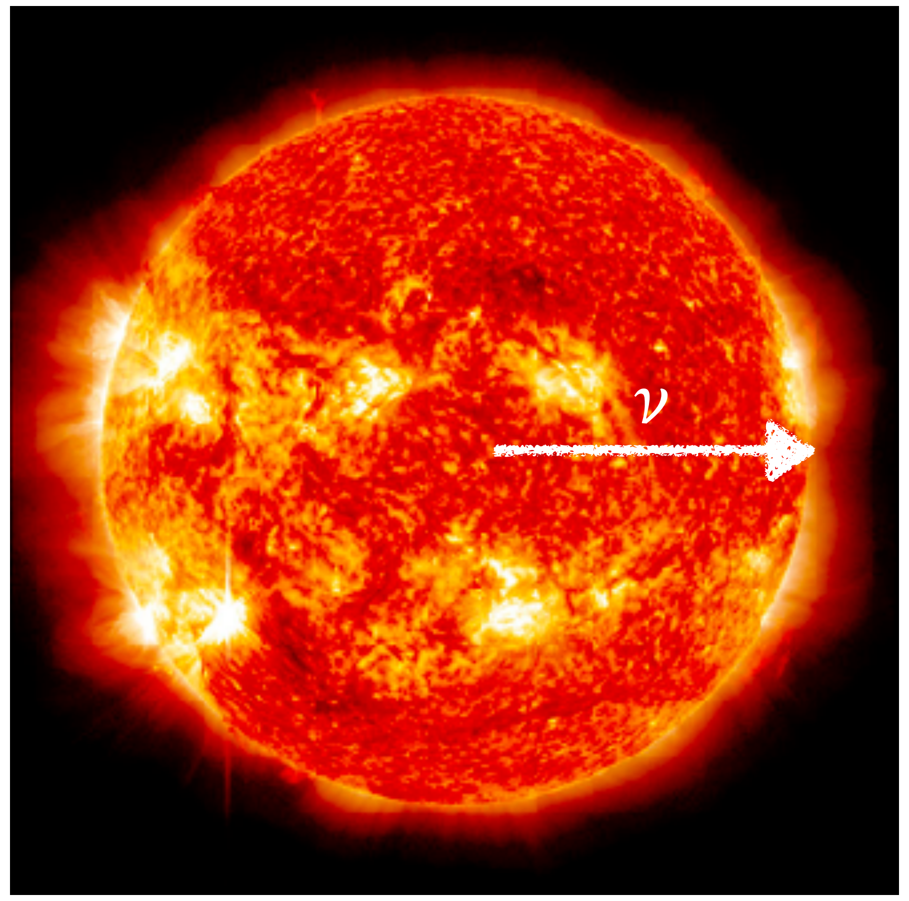
(C-conserving) Mass term is not allowed: $\bar{N}_R \nu_L + \bar{N}_R^c \nu_L^c$

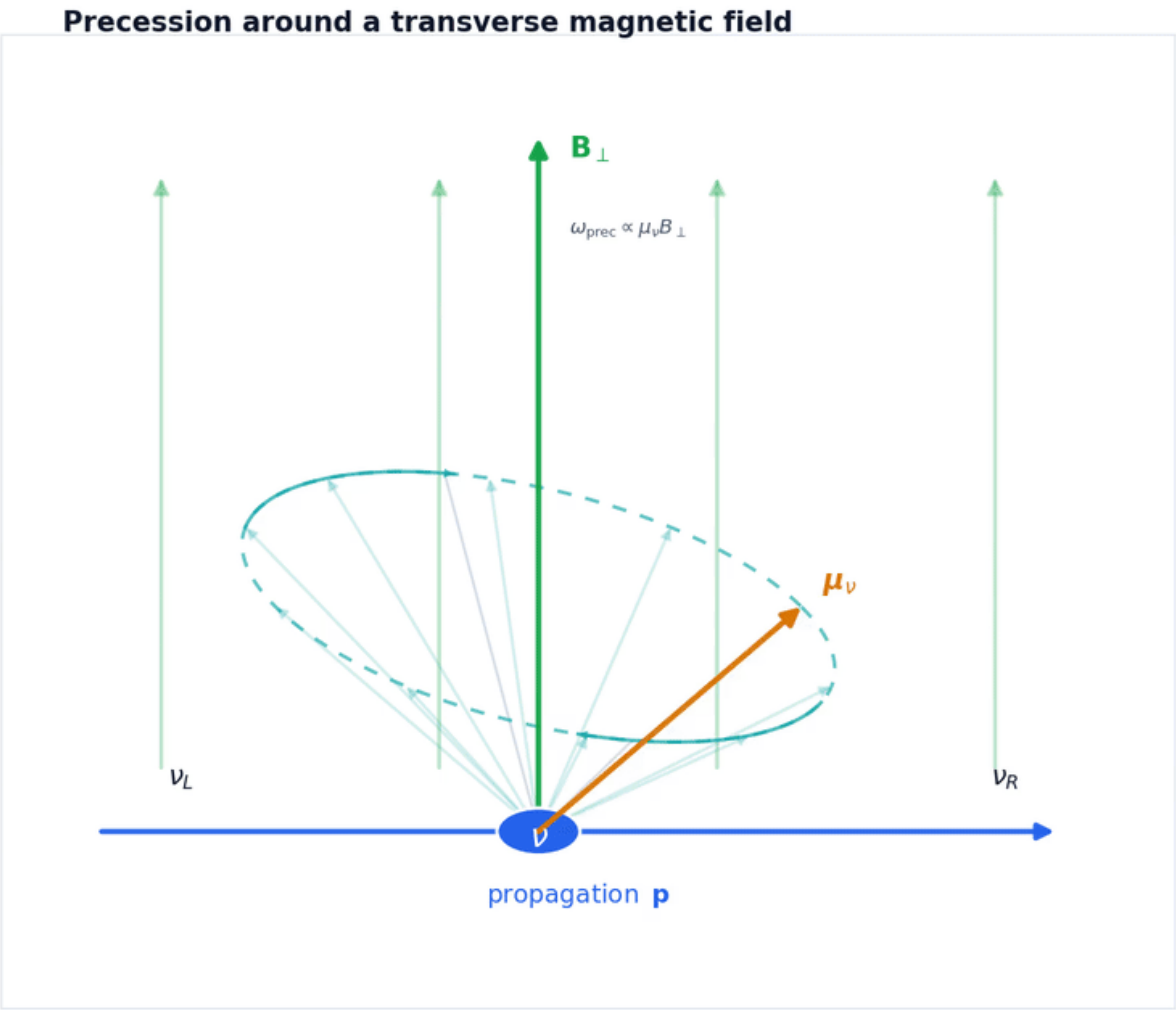
(C-violating) MDM term is allowed: $\bar{N}_R \nu_L - \bar{N}_R^c \nu_L^c$

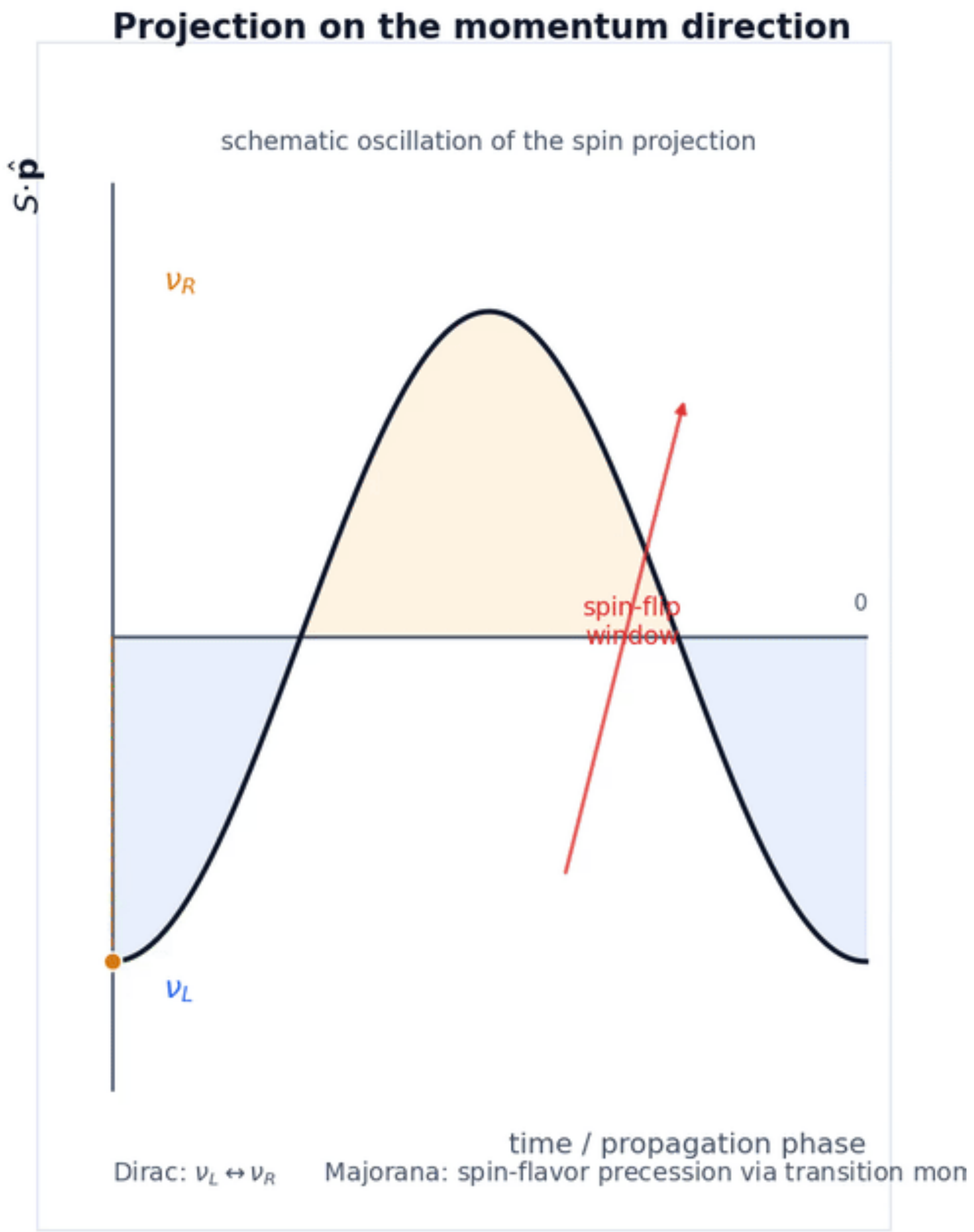
Up to $\mu_\nu \sim 10^{-10}\,\mu_B$

Spin-Flavor Precession

Solar magnetic field provides a source for the rotation of spin (c.f., Larmor precession): spin-flavor precession (SFP)







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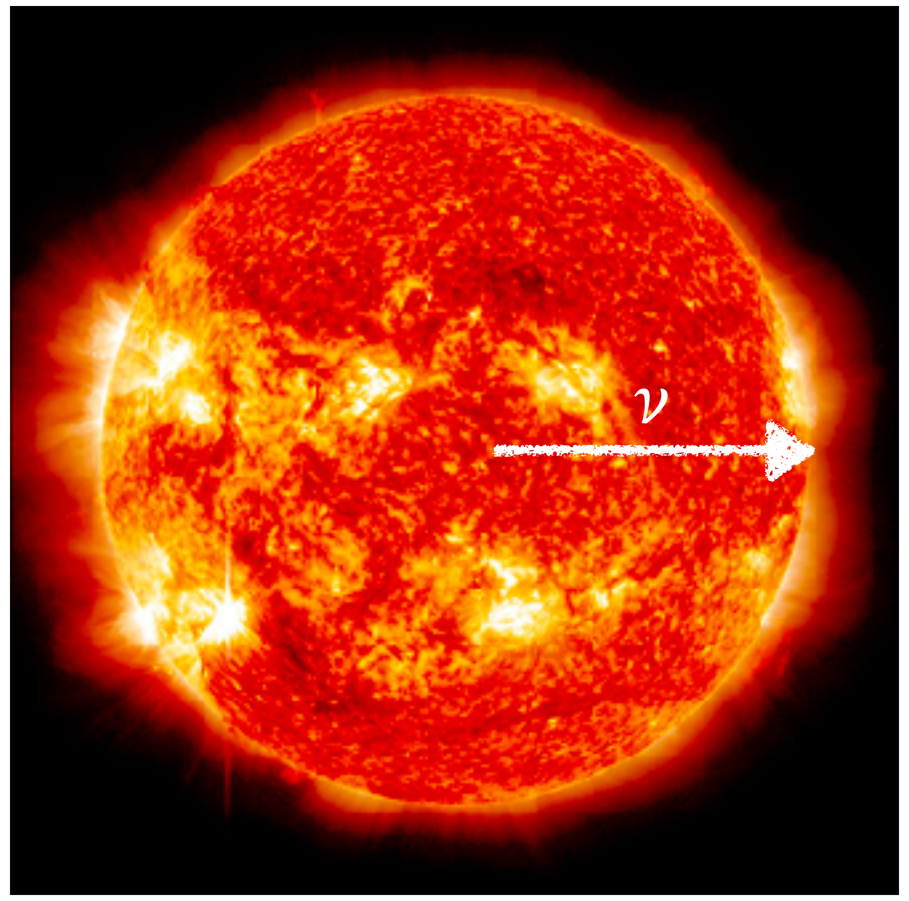

Majorana neutrino (transition into different flavor ν^c): $\nu_{eL} \xrightarrow{\text{SFP}} \bar{\nu}_{\mu R} \xrightarrow{\text{osc.}} \bar{\nu}_{eR}$

✔ Appearance of solar electron anti-neutrino via IBD

Akhmedov, PLB 255, 84 (1991)

Raghavan, Balantekin, Loreti, Bltz, Pakvasa, Pantaleone, PRD 44, 3786 (1991)

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Akhmedov, PLB 213, 64 (1988) & Sov. J. Nucl. Phys. 48, 382 (1988)

Lim, Marciano, PRD 37, 1368 (1988)

Proposed to resolve the solar ν problem

Cisneros, Astrophys. Space Sci. 10, 87 (1971)

Now, we know the LMA-MSW is the answer but RSFP can still have a subdominant effect.

Appearance of electron anti-neutrino

$$\Phi_{\bar{\nu}_e} < 7.60 \times 10^2\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$P_{\nu_e \to \bar{\nu}_e} < 1.3 \times 10^{-4}$$

$$\mu_\nu < 6.9 \times 10^{-9} B_\perp^{-1}\,[\mathrm{kG}]\,\mu_B$$

Borexino, PLB 696, 191 (2011)

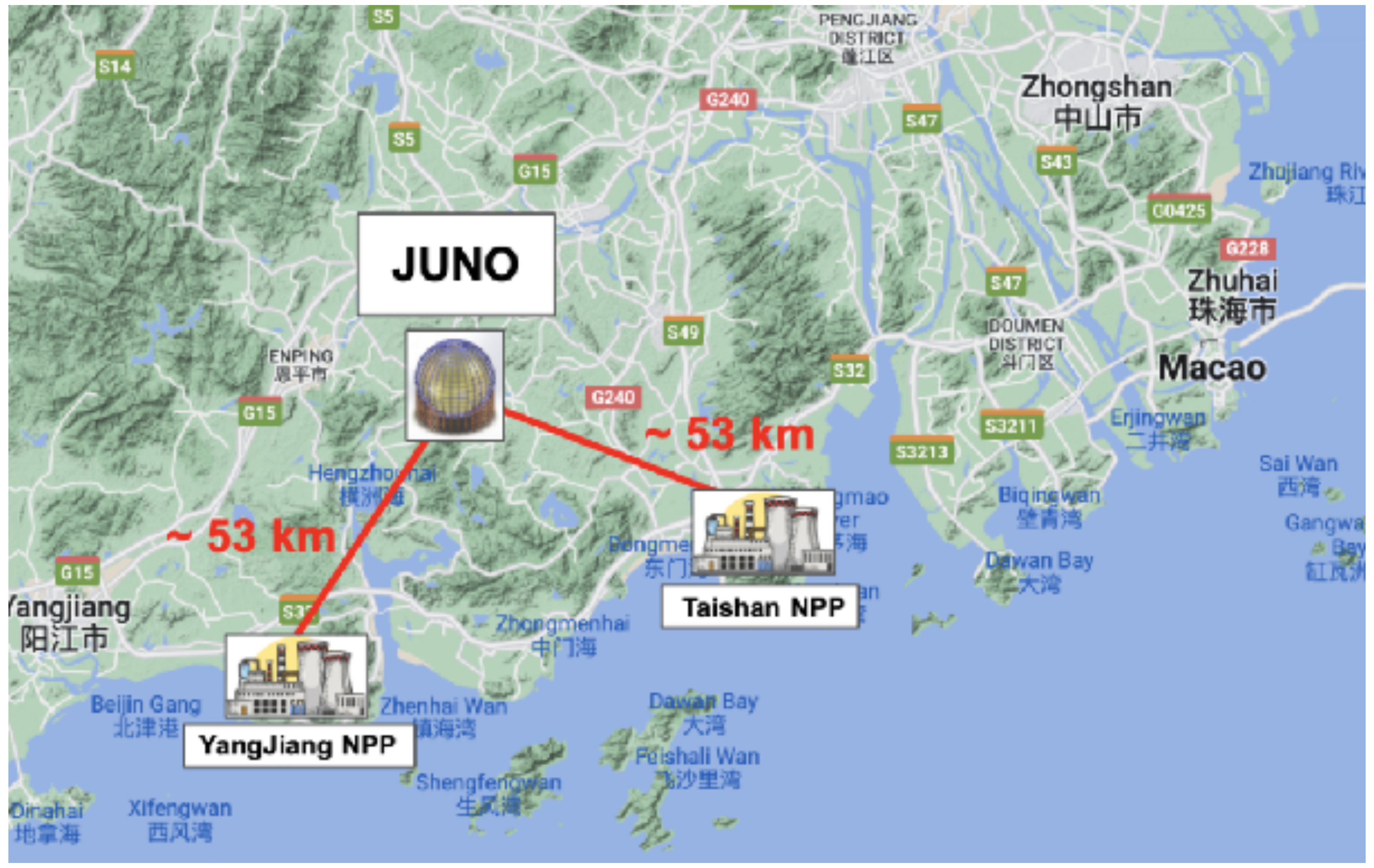
$$\Phi_{\bar{\nu}_e} < 6 \times 10^1\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$P_{\nu_e \to \bar{\nu}_e} < 3.5 \times 10^{-5}$$

$$\mu_{12} < 4.9 \times 10^{-9} B_\perp^{-1}\,[\mathrm{kG}]\mu_B$$

KamLAND, ApJ, 925, 14 (2022)

For simplicity $\mu_{23} = \mu_{13} = 0$



- Reactor neutrinos are main background: $E_{\mathrm{vis}} \in [8.0, 16.8]$ MeV preferred.

Energy (MeV)	$\Phi_{\bar{\nu}_e,\mathrm{lim}}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$P_{\nu_e \to \bar{\nu}_e}$ $[10^{-5}]$	$\mu_\nu(600\,\mathrm{G})$ $[\mu_B]$	$\mu_\nu(7\,\mathrm{MG})$ $[\mu_B]$
1.8–16.8	5.65×10^2	9.84	1.33×10^{-8}	1.13×10^{-12}
8.0–16.8	4.01×10^1	2.07	6.07×10^{-9}	5.18×10^{-13}

^{8}B ν 90% C.L., 20kt × 5 yrs

Better than the current bounds!

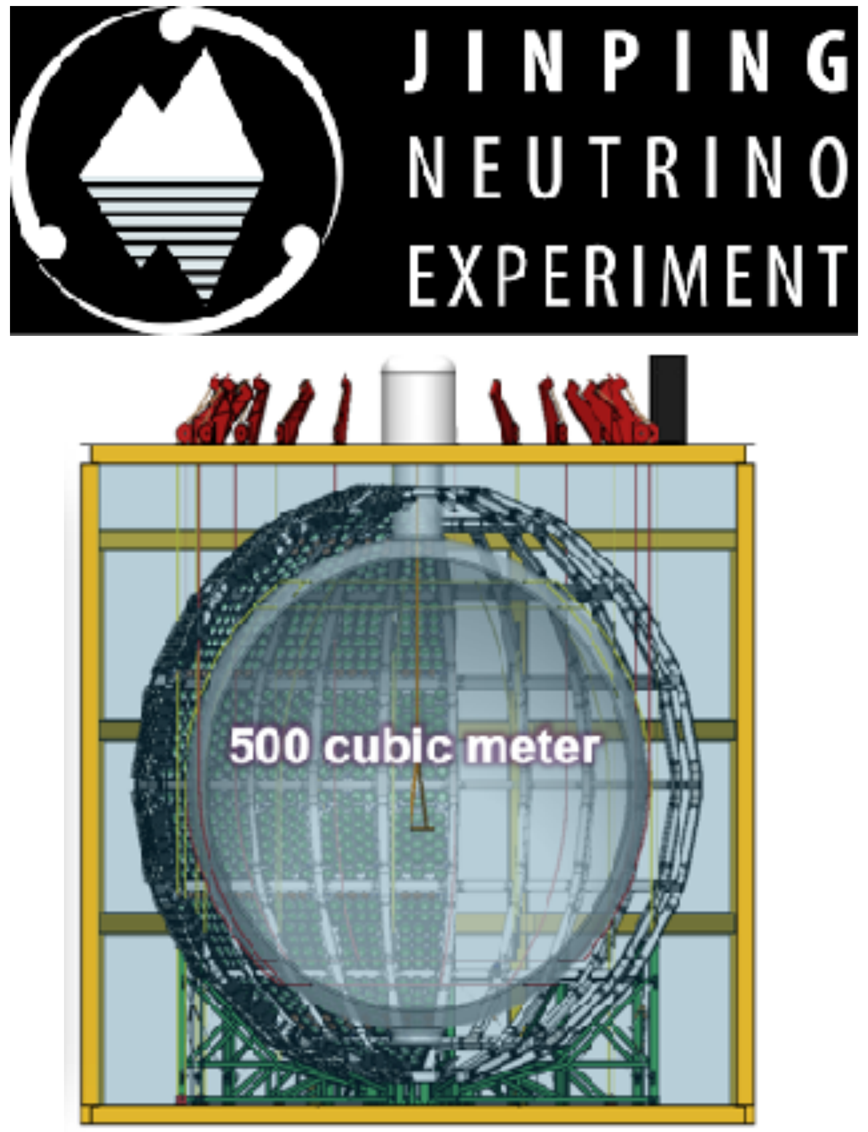
Ventura, Panibra Churata, ApJ. 996, 1 (2026)

In the solar core < 0.2 $R_\odot$, 7 MG possible from the helioseismic study.

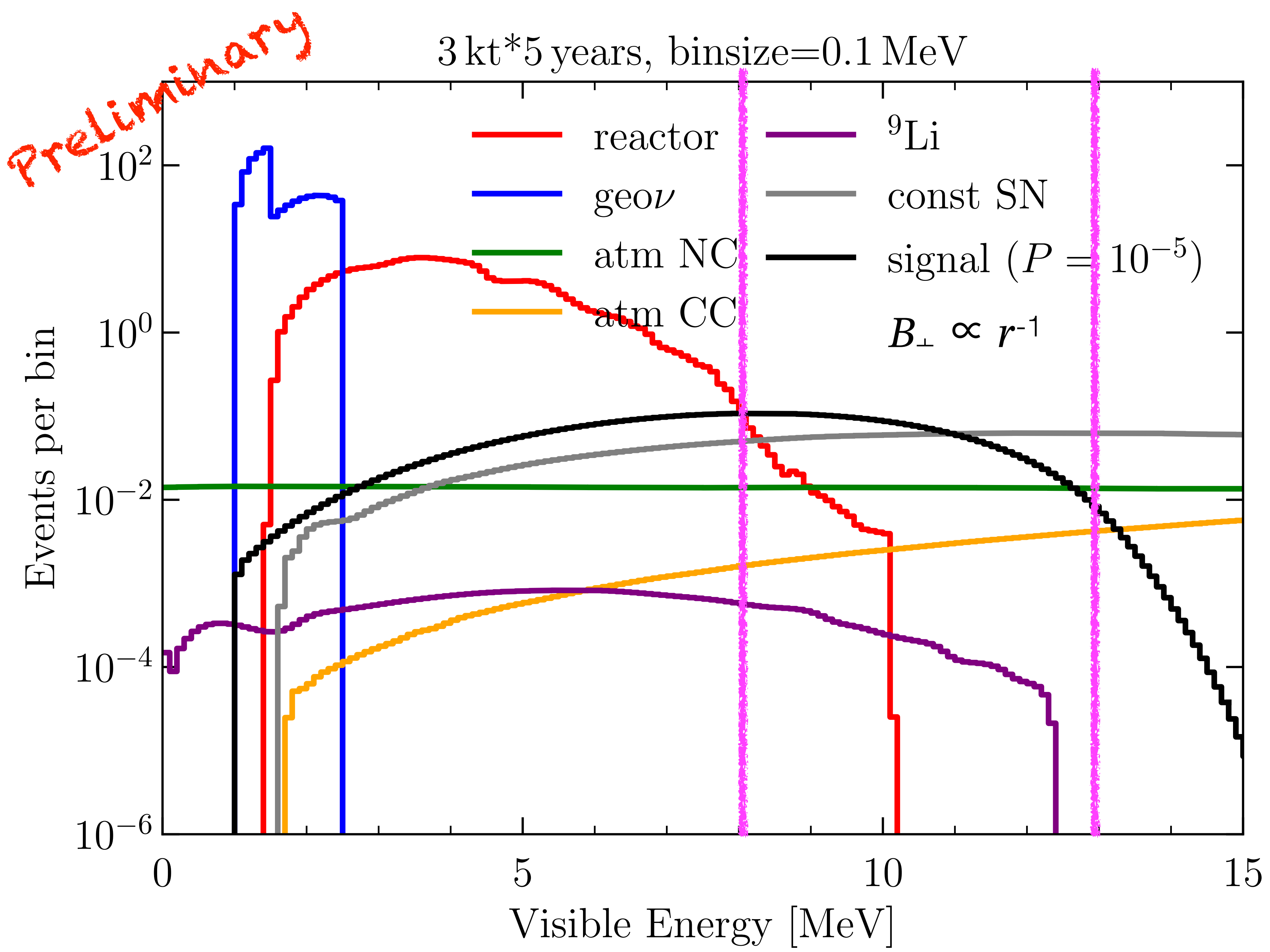
Antia, JAA 29, 85 (2008)

Appearance of electron anti-neutrino

Other experiments with less reactor neutrino contamination, e.g., Jinping, can push the sensitivity further.



LUO, ICHEP 2024



- The reactor neutrino background for $E_{\text{vis}} < 8$ MeV still dominates but the number is below % level of JUNO reactor bkg.
- For $E_{\text{vis}} > 8$ MeV DSNB is the most significant background (but still smaller than the signal for $E_{\text{vis}} \lesssim 11$ MeV).
- For $E_{\text{vis}} > 13$ MeV, the signal is suppressed even compared to the atmospheric ν background events.

Appearance of electron anti-neutrino

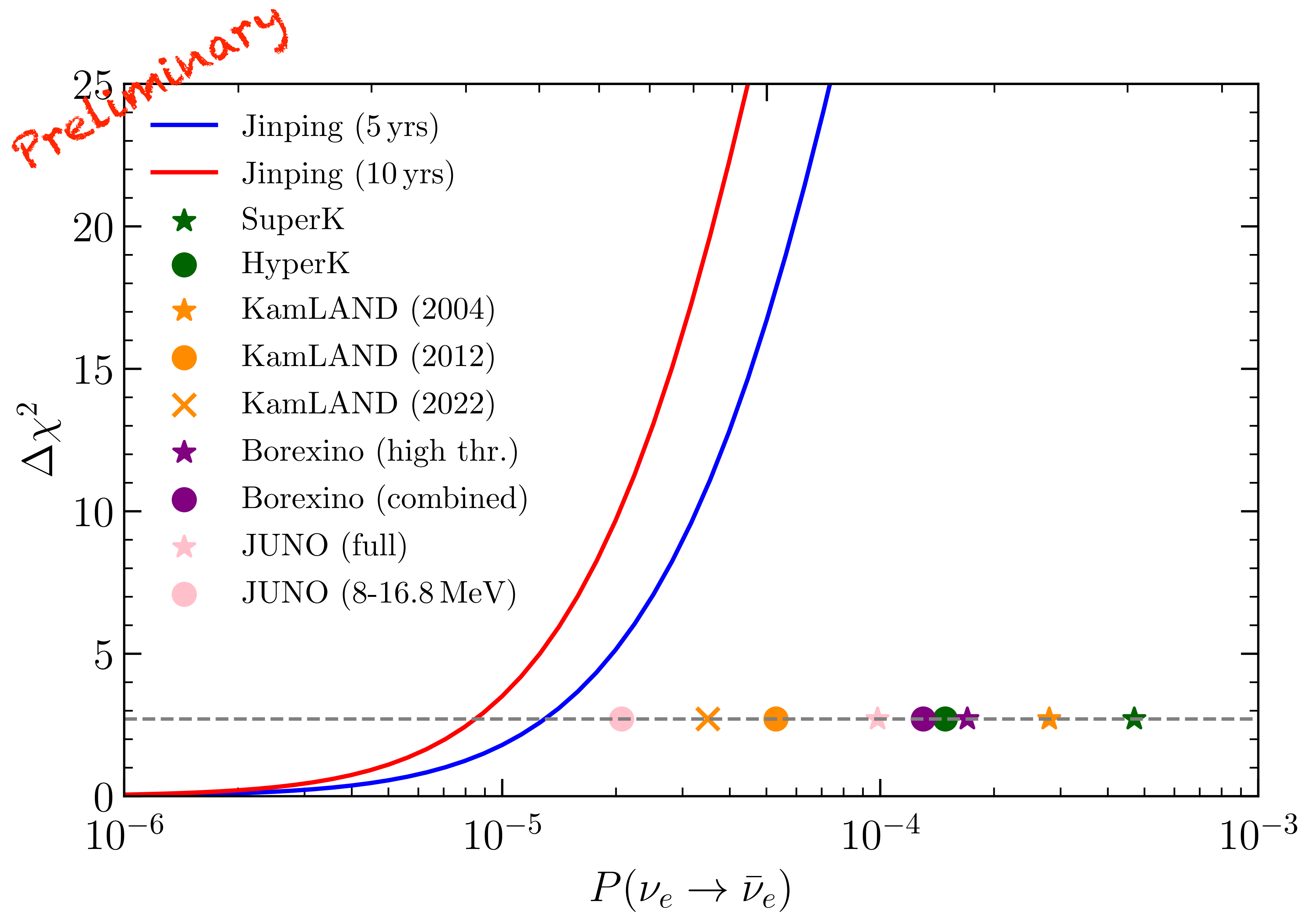
- For the LS detectors, $\Sigma\,(T_e + E_{\gamma \mathrm{ann.}}) = E_{\mathrm{vis}} = E_\nu$ - 0.78 MeV.

- Two signal regions: i) Low-background SR $E_\nu \in$ [8.78, 13.78] MeV
  ii) Full SR of IBD $E_\nu \in$ [1.8, 16.8] MeV (16.8 MeV is for comparison with JUNO result)

		Low-background SR	Full SR
		$E_{\mathrm{vis}} \in [8, 13]$ MeV	$E_{\mathrm{vis}} \in [1.02, 16.02]$ MeV
		$E_\nu \in [8.78, 13.78]$ MeV	$E_\nu \in [1.8, 16.8]$ MeV
Background	Reactor $\bar{\nu}_e$	0.49	230.77
	Geo-$\bar{\nu}_e$	0.00	286.53
	Atmospheric CC	0.13	0.39
	Atmospheric NC	0.68	2.08
	^{9}Li	0.01	0.05
	DSNB (const-SN model)	2.91	6.75
	Total background	4.22	526.57
Signal	$\nu_e \to \bar{\nu}_e$	35.35	60.37

15 kt·yr at Jinping experiment for $B_\perp = 10^7$ G and $\mu_{12} = 10^{-12}\mu_B$

Appearance of electron anti-neutrino



Jinping better than JUNO (7 times larger)

c.f., solar neutrino measurement expectations & constraints

JUNO 100 kt·yr (8 - 16.8 MeV): $\mu_{12} \lesssim 5.18 \times 10^{-13}\, \mu_B$

KamLAND (2022): $\mu_{12} \lesssim 6.74 \times 10^{-12}\, \mu_B$

$$B_\perp = 7\,\mathrm{MG}$$

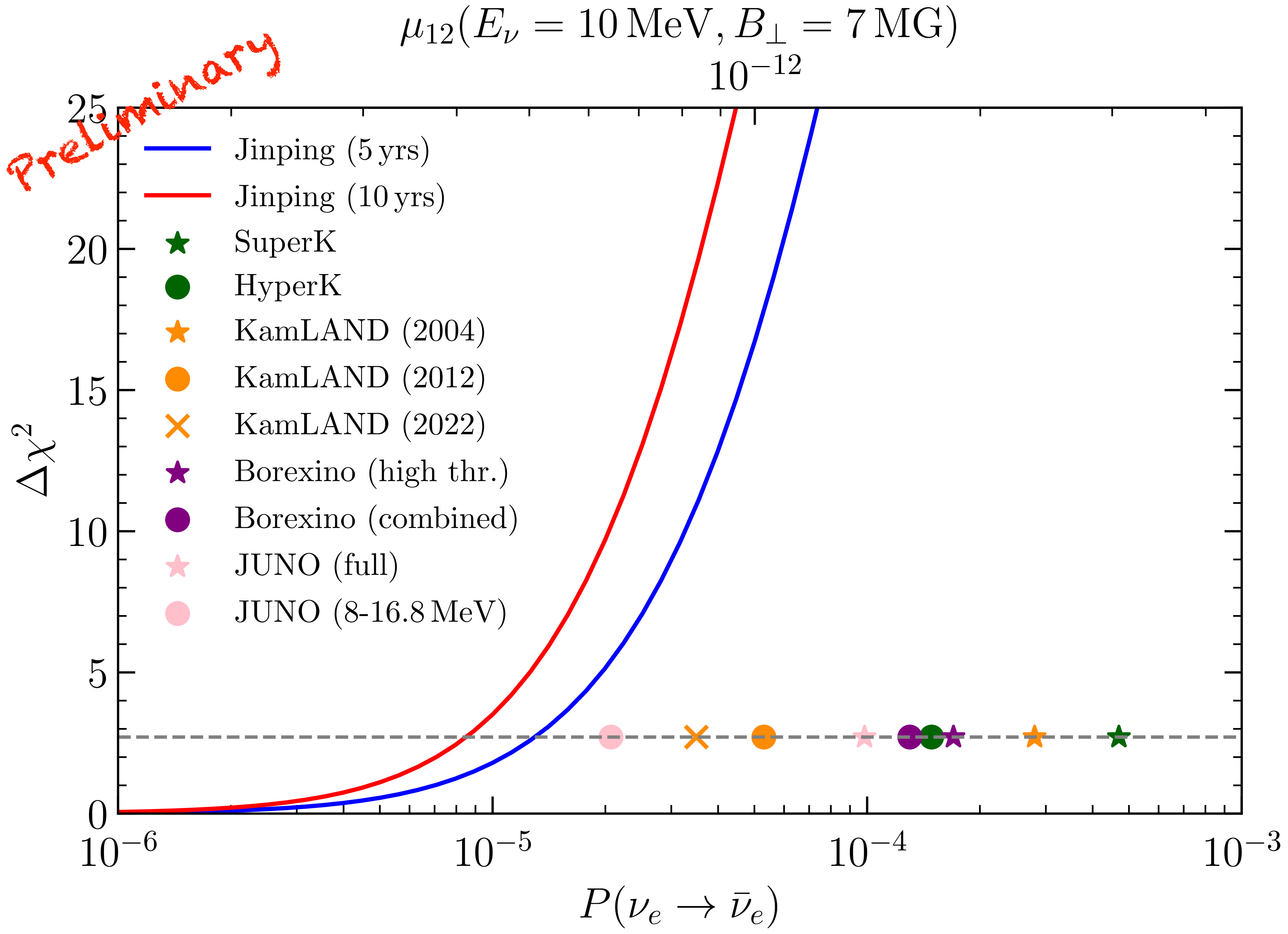
- Jinping 15 kt·yr (30 kt·yr) data can provide a better sensitivity: $P(\nu_e \to \bar{\nu}_e) \lesssim 1.2 \times 10^{-5}$ $\quad \mu_{12} \lesssim 4.10 \times 10^{-13}\, \mu_B$

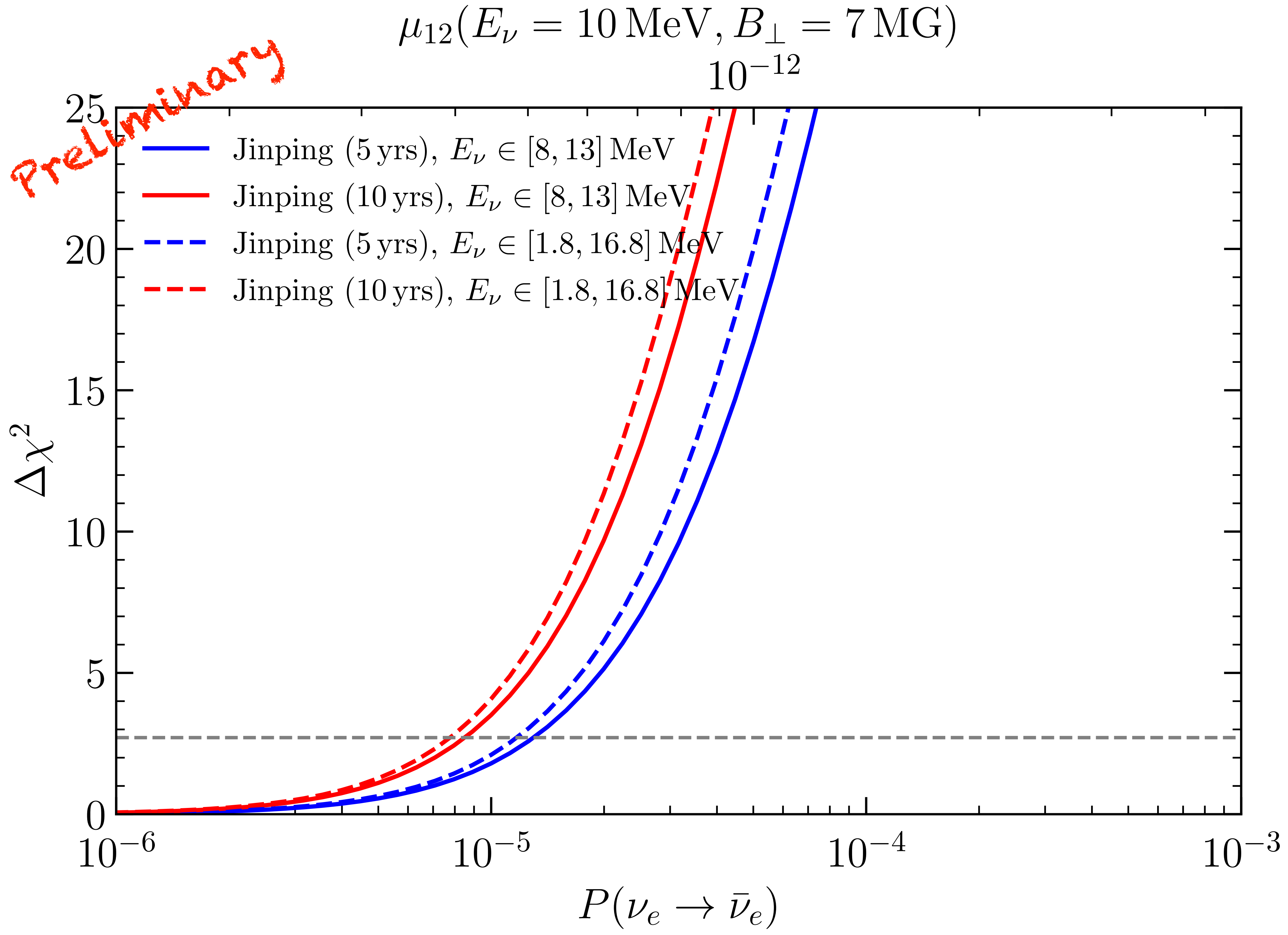
  $P(\nu_e \to \bar{\nu}_e) \lesssim 8 \times 10^{-6}$ $\quad \mu_{12} \lesssim 3.33 \times 10^{-13}\, \mu_B$

- The sensitivities are translated into μ_{12} (for a maximally possible $B_\perp$) using the 3-flavor neutrino framework.

Akhmedov, Martinez-Mirave, JHEP 10, 144 (2022)

Appearance of electron anti-neutrino





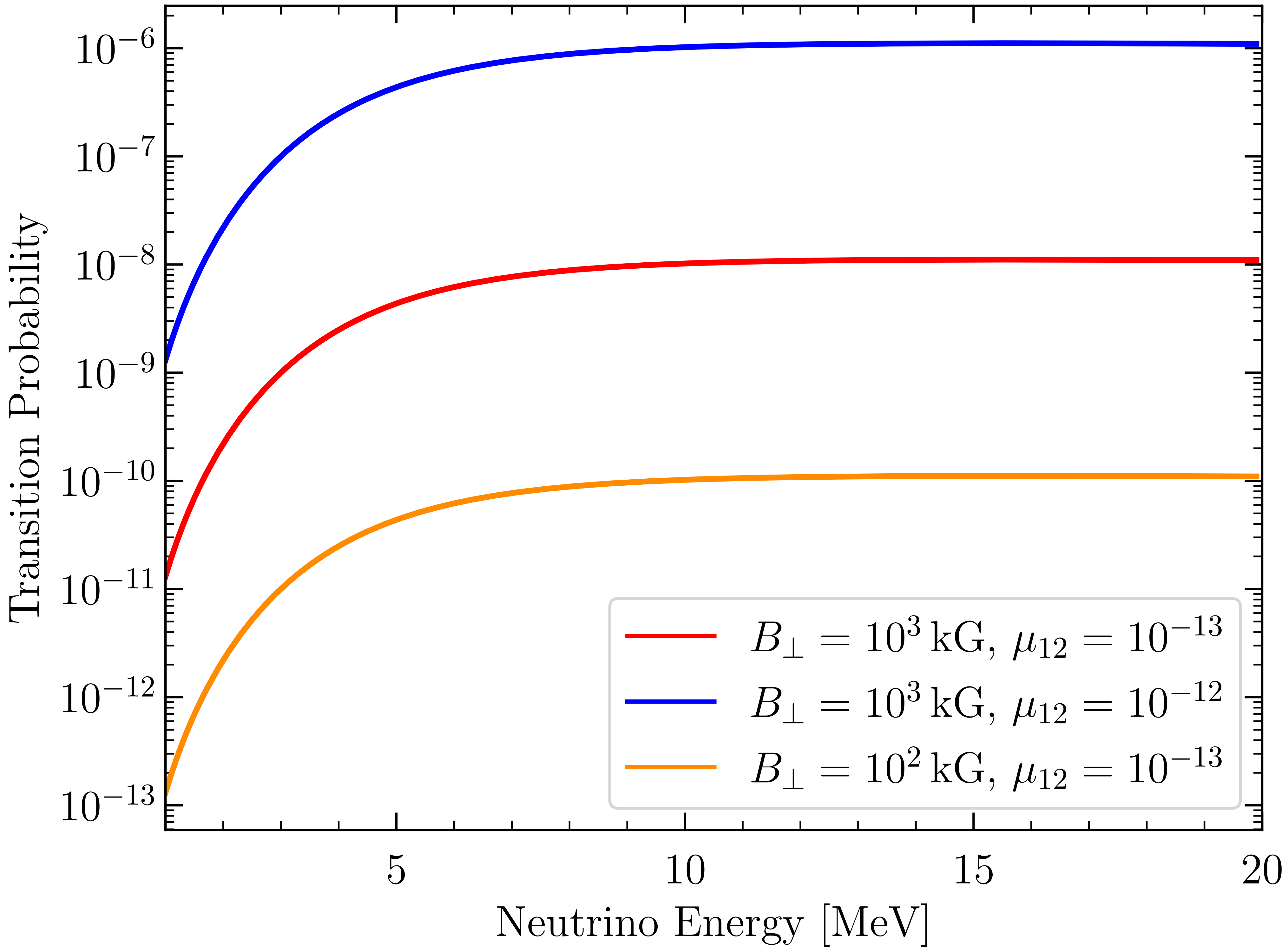
- Inclusion of the Full SR $E_\nu \in [1.8, 16.8]$ MeV provides slightly better sensitivities albeit with more background contamination.

Appearance of electron anti-neutrino

$$P(\nu_{eL} \to \bar{\nu}_{eR}) = \frac{1}{2} c_{13}^2 \sin^2 2\theta_{12} B_\perp^2(r_0) \left[c_{13}^2 |\mu_{e'\mu'}|^2 \left(\frac{\cos^2\tilde{\theta}(r_0)}{g_1'(r_0)} + \frac{\sin^2\tilde{\theta}(r_0)}{g_2'(r_0)} \right)^2 + \left(\frac{s_{13}|\mu_{\mu'\tau'}|}{2\Delta} \right)^2 - 2\mathrm{Re}\{\mu^*_{e'\mu'}\mu_{\mu'\tau'}\} \left(\frac{\cos^2\tilde{\theta}(r_0)}{g_1'(r_0)} + \frac{\sin^2\tilde{\theta}(r_0)}{g_2'(r_0)} \right) \frac{s_{13}c_{13}}{2\Delta} \right] + s_{13}^2 B_\perp^2(r_0) \left(\frac{c_{13}|\mu_{e'\tau'}|}{2\Delta} \right)^2$$

Approximated analytic formula in the 3-flavor framework

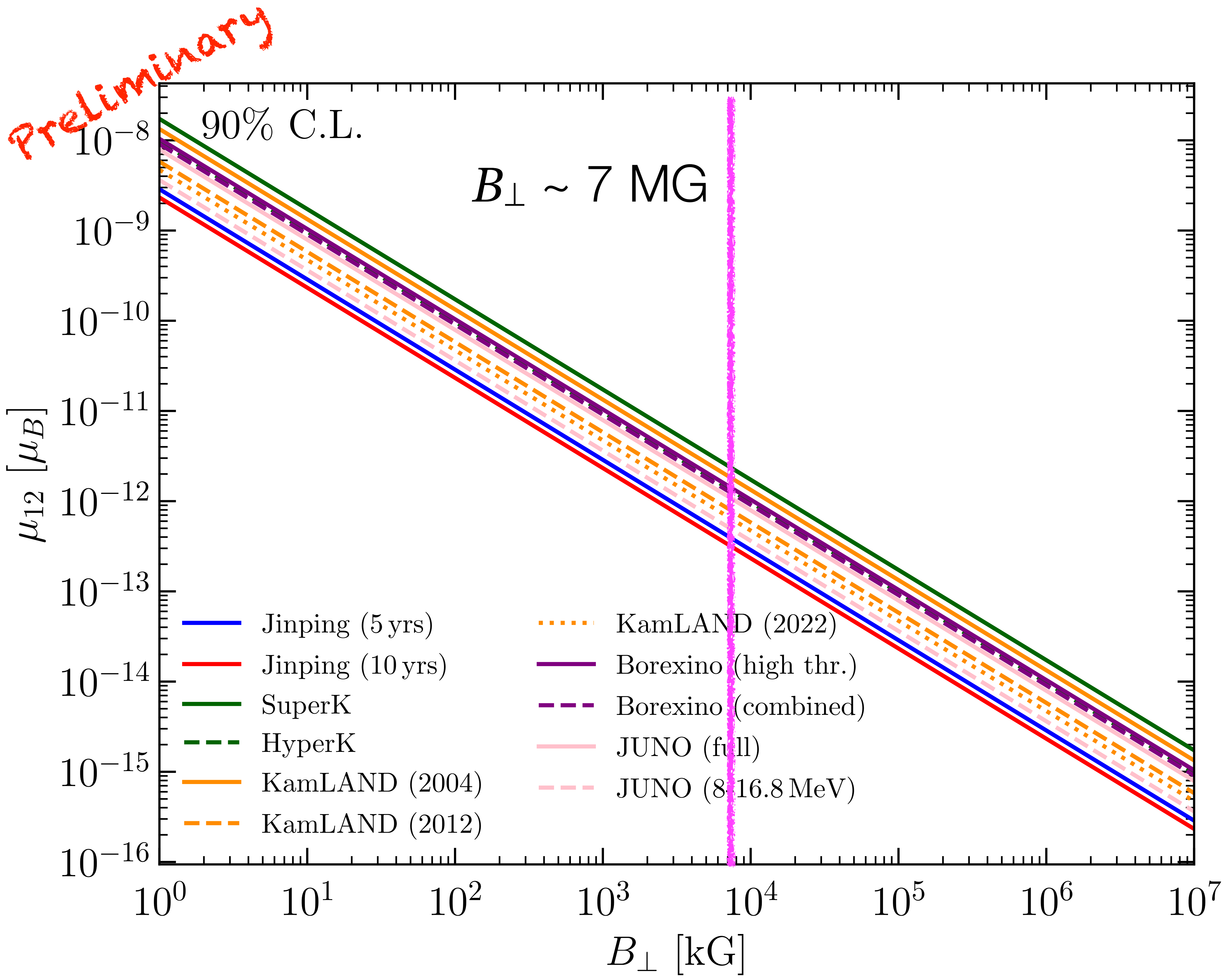
Akhmedov, Martinez-Mirave, JHEP 10, 144 (2022)

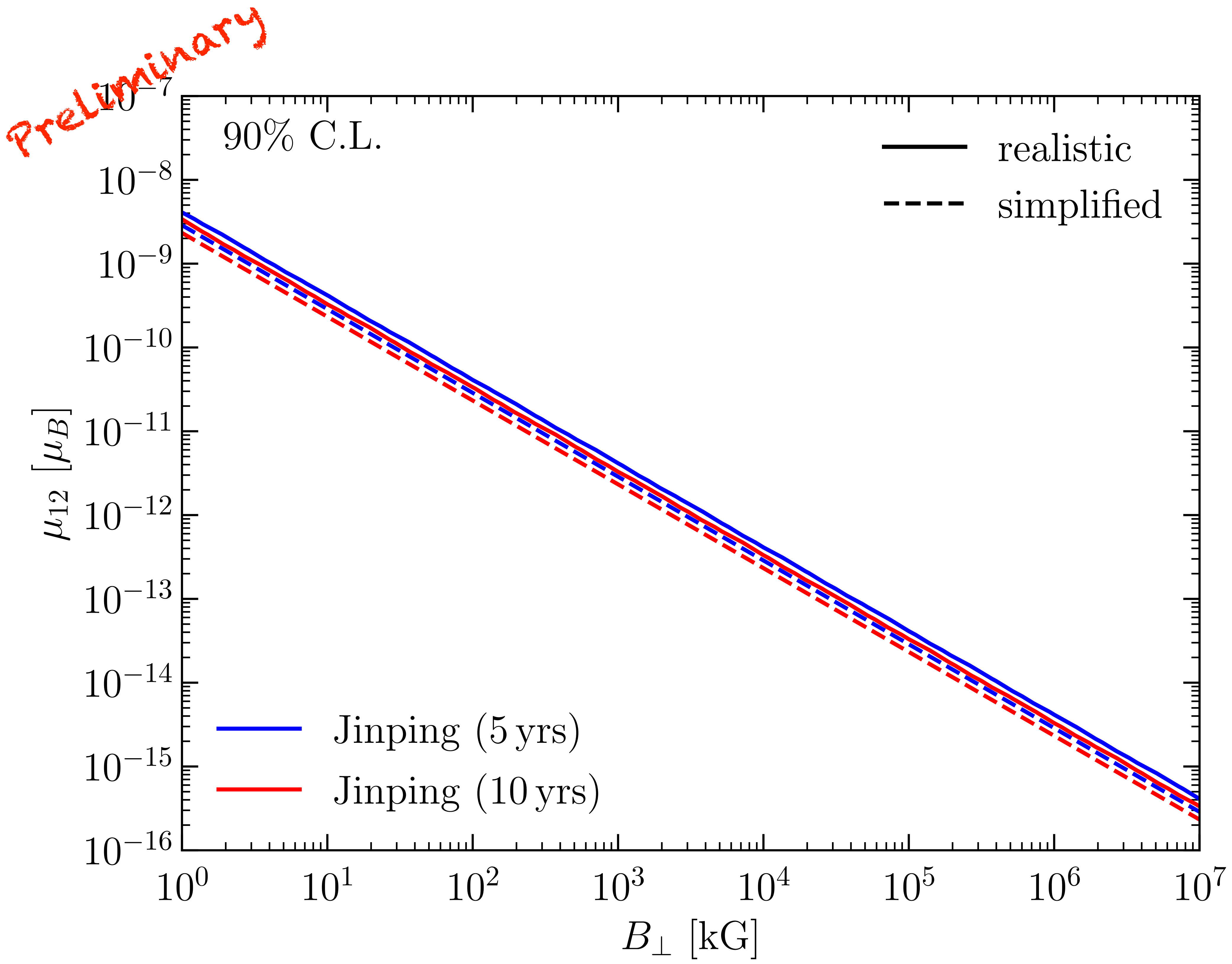


- The transition probability $P(\nu_e \to \bar{\nu}_e)$ is a function of E_ν, μ_{12}, and $B_\perp$ at the location of production.

- For $E_\nu \gtrsim 8$ MeV, the transition probability asymptotically energy independent. $P(\nu_e \to \bar{\nu}_e) \simeq 1.1 \times 10^{-10} \left(\frac{\mu_{12} B_\perp}{10^{-12}\,\mu_B \cdot 10\,\mathrm{kG}} \right)^2$

Appearance of electron anti-neutrino





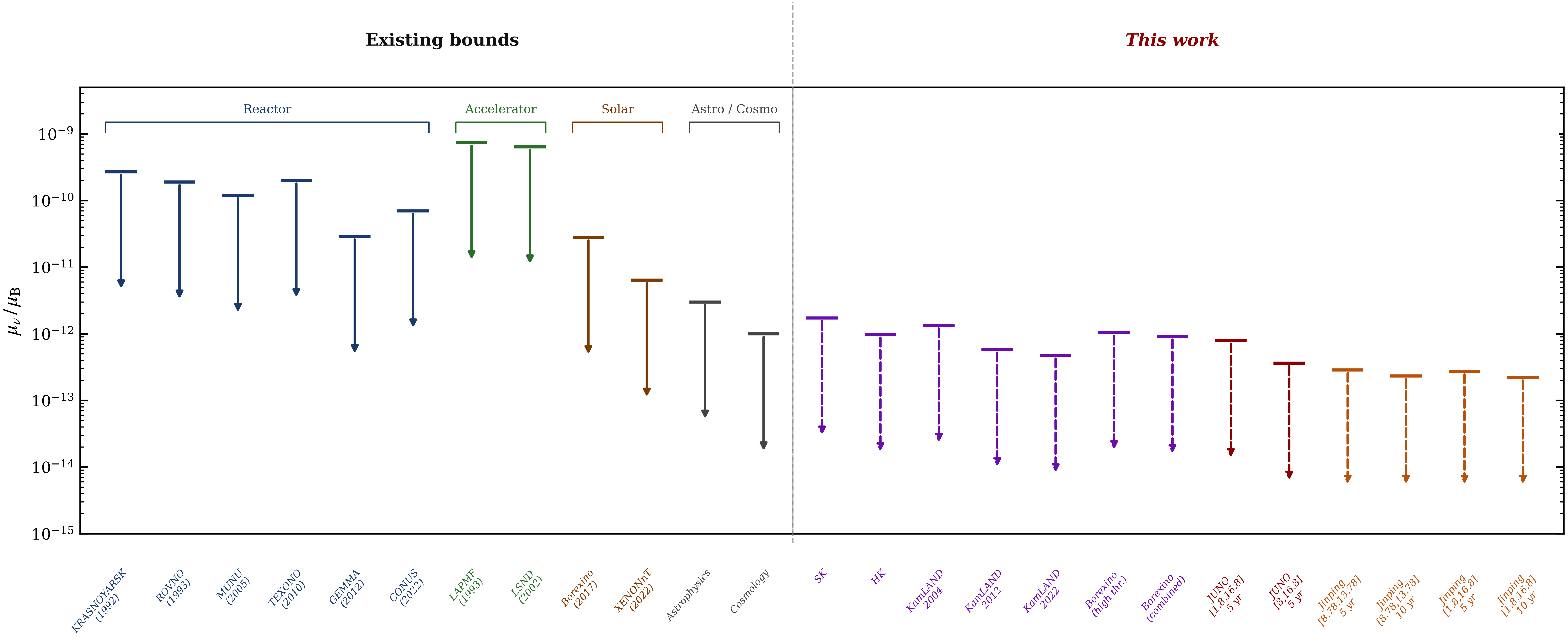
- For a wide range of 1kG < $B_\perp$ < 10 BG, the expected sensitivities on μ_{12} range from $10^{-9}\mu_B$ to $10^{-16}\mu_B$.

- The conversion of the sensitivities into MDM rely on the calculation methods. Our realistic results expect about 1.4 weaker values than the widely used simplified results.

$$P(\nu \to \bar{\nu}) \approx 1.8\times10^{-10} \sin^2 2\theta \left(\frac{\mu_\nu}{10^{-12}\mu_B} \frac{B_\perp(0.05R_\odot)}{10\text{kG}} \right)^2$$

Akhmedov, Pulio, PLB 553, 7 (2003)

Appearance of electron anti-neutrino



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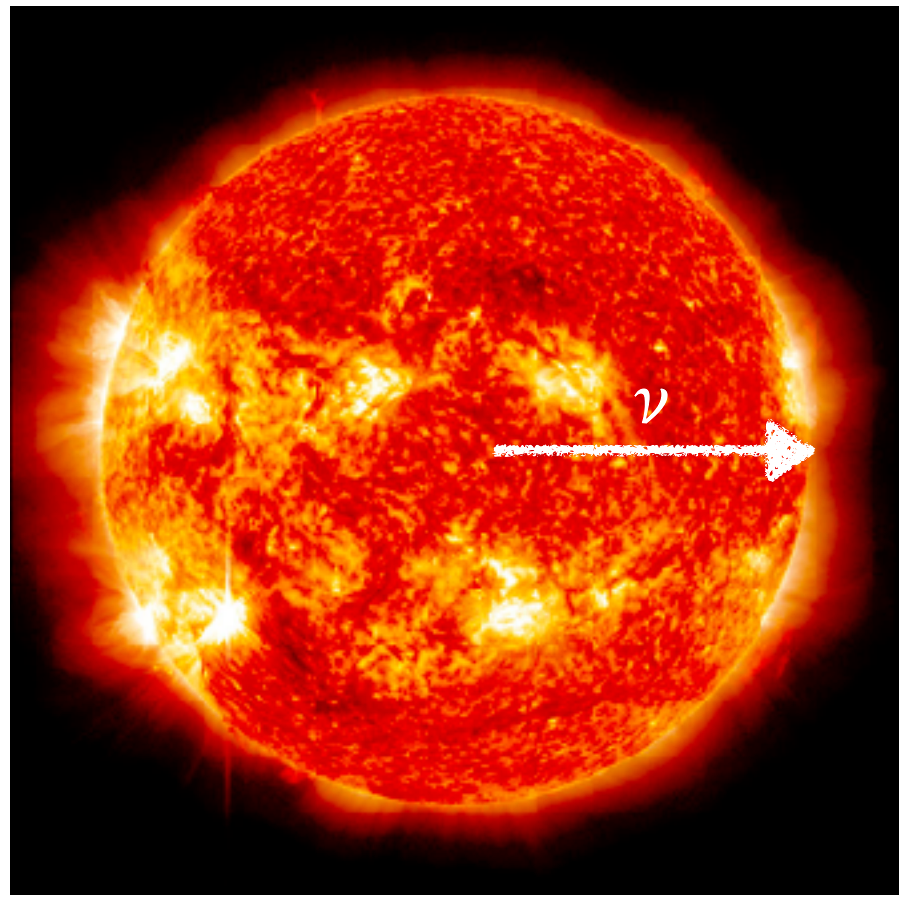

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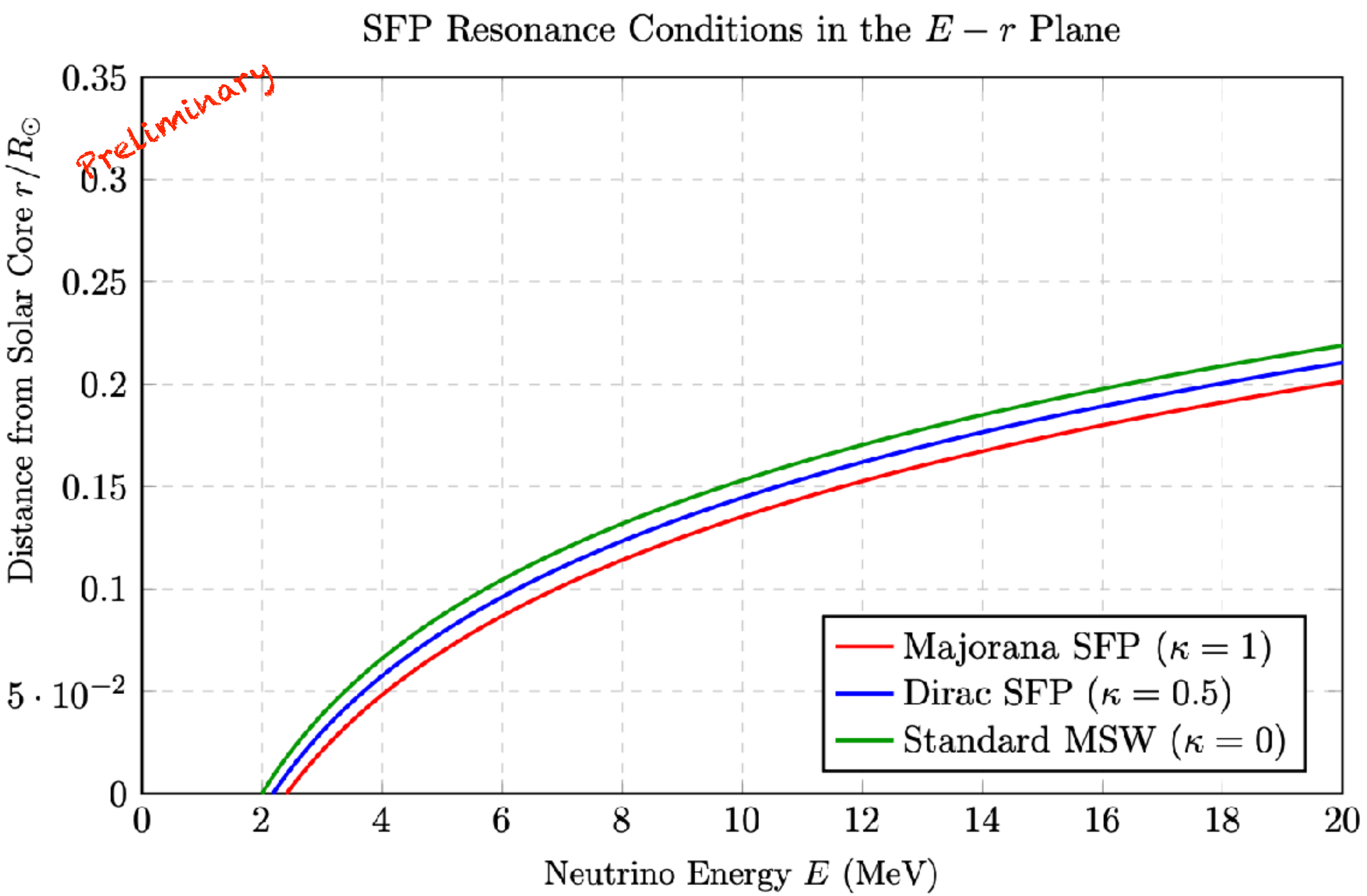
- 3 flavor: Majorana (strongly constrained by the appearance), Dirac scenarios

depends on the solar magnetic field profile (unknown)

Disappearance of solar neutrino



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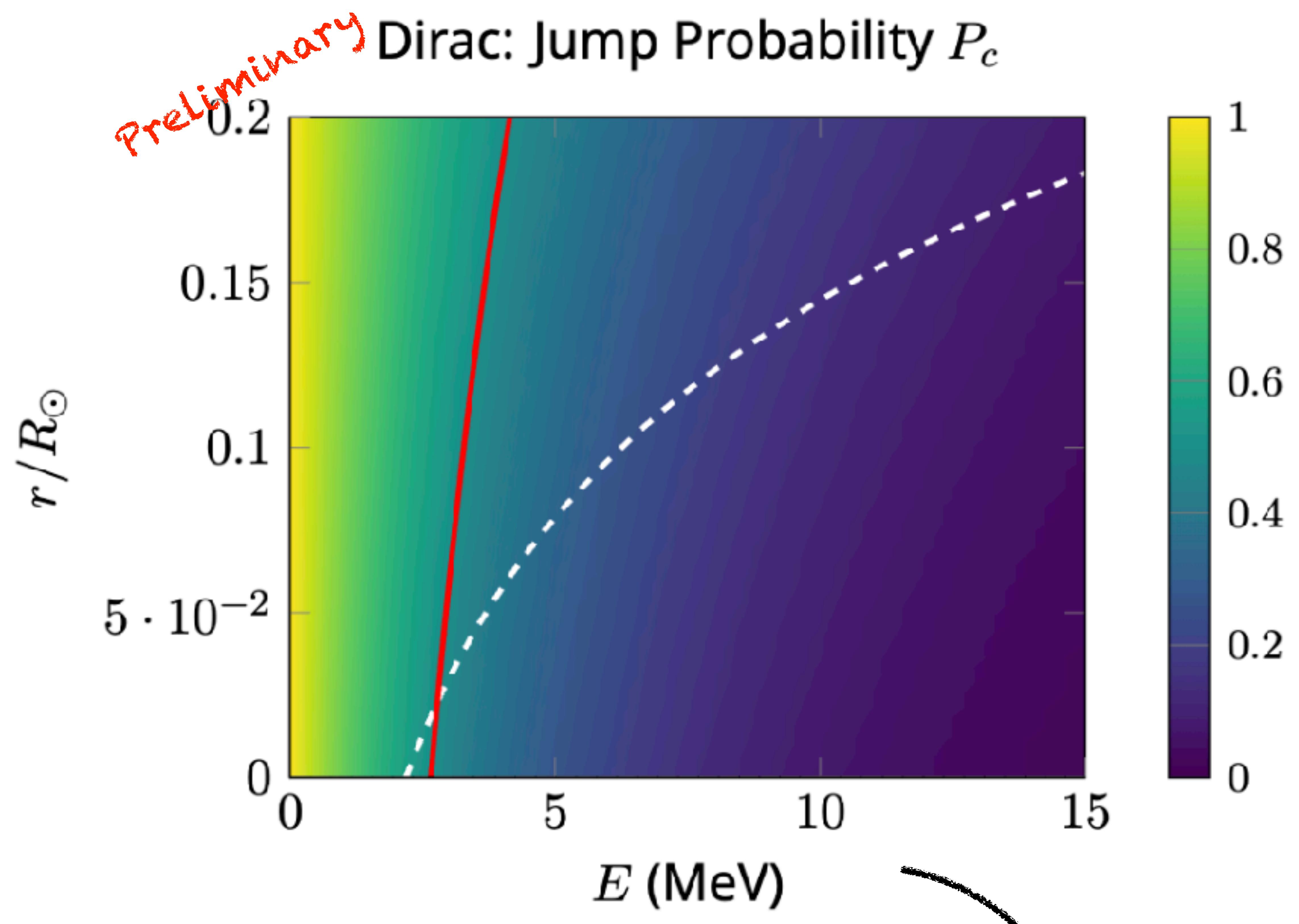

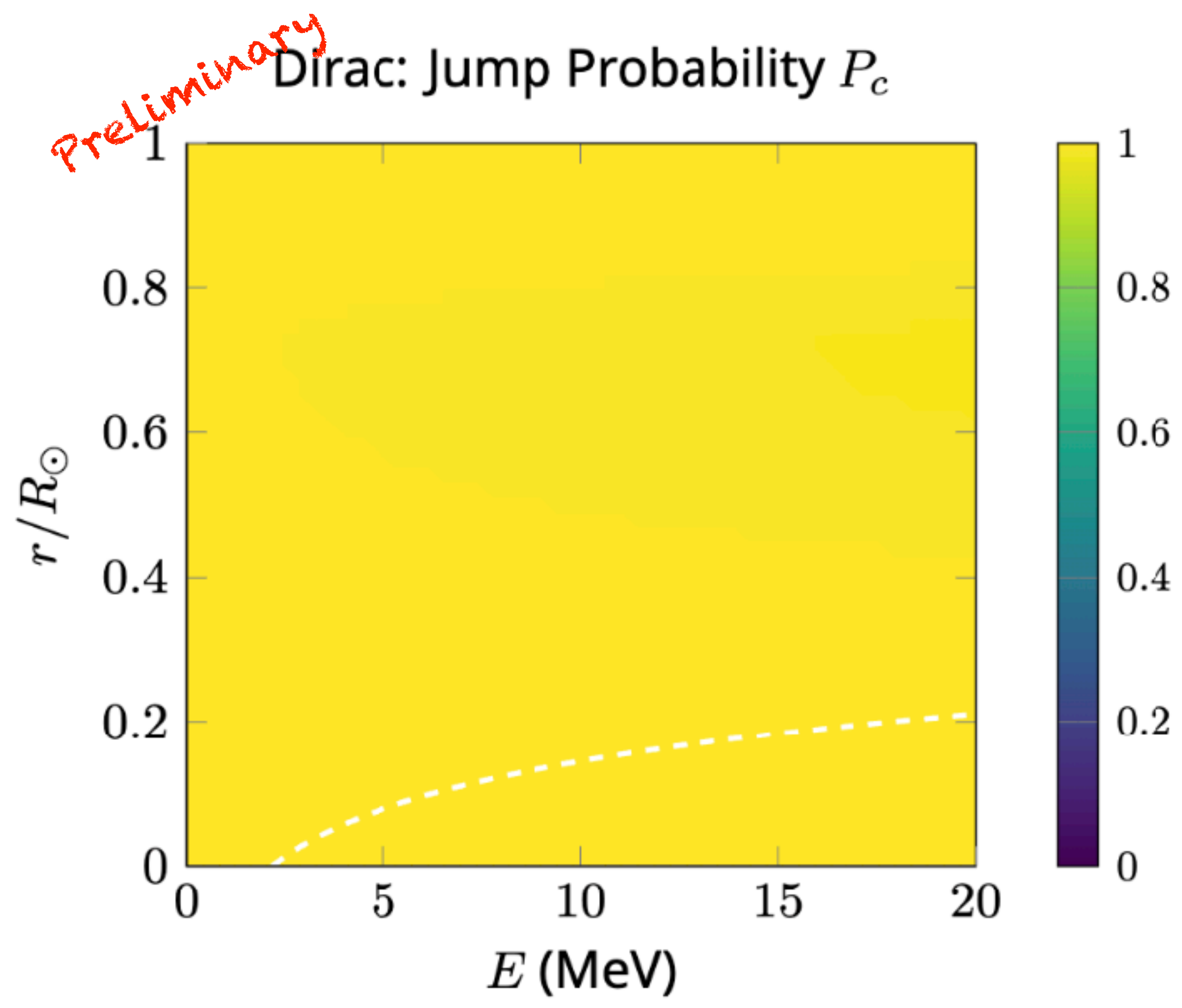

$$B_\perp(r) = 7368421 \times \left(1 - \frac{r}{R_\odot}\right)$$

$$B_\perp(r) = \begin{cases} \frac{B_0}{\cosh[6(r/R_\odot - 0.71)]} & r/R_\odot \leq 0.71 \\ \frac{B_0}{\cosh[15(r/R_\odot - 0.71)]} & r/R_\odot > 0.71 \end{cases}$$

Constrained by the solar neutrino measurements: subdominant effect

Disappearance of solar neutrino

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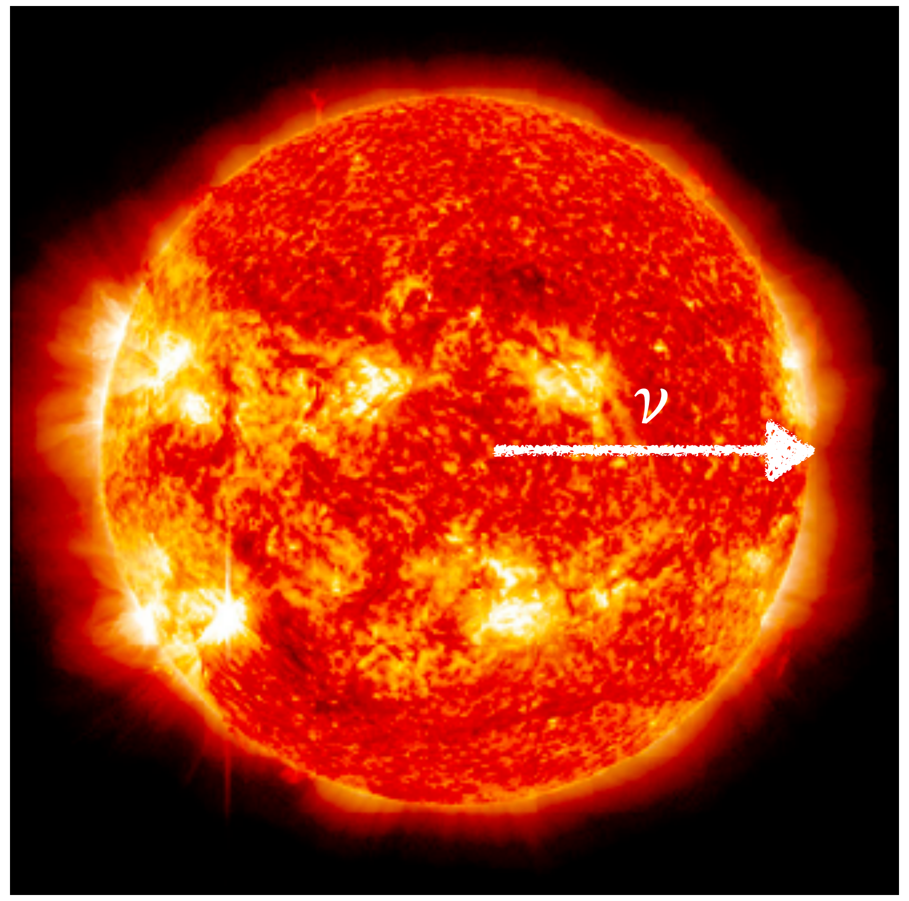

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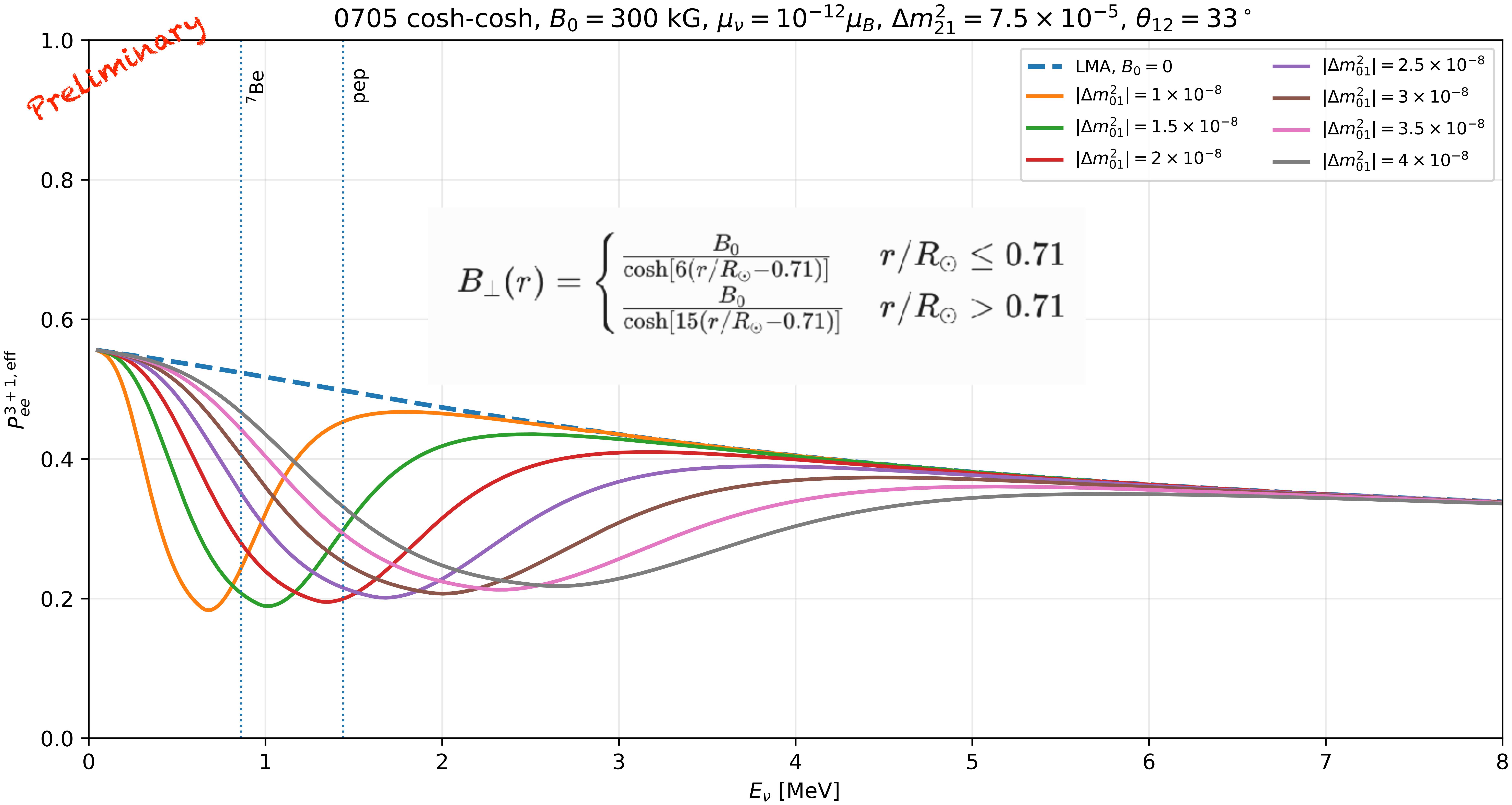
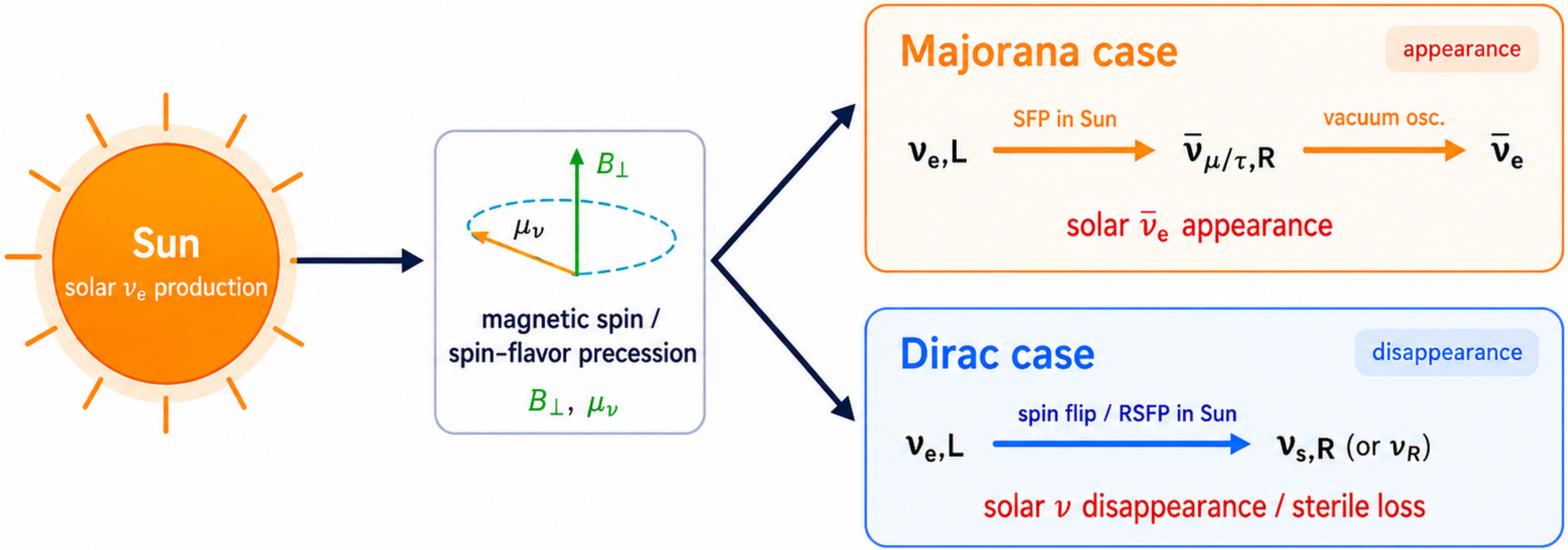
- 3 flavor: Majorana (strongly constrained by the appearance), Dirac scenarios
- 3 + 1 flavor: Majorana, Dirac scenarios w/ conversion into the SM singlet Δm^2_{01} Solar magnetic field profile

Disappearance of solar neutrino



Conclusions

Solar spin-flavor precession: Majorana appearance vs Dirac disappearance



- Hints for BSM expecting νMDM $\lesssim \mathcal{O}(10^{-13}\,\mu_B)$
- Identify the EM properties of ν and the nature of ν mass