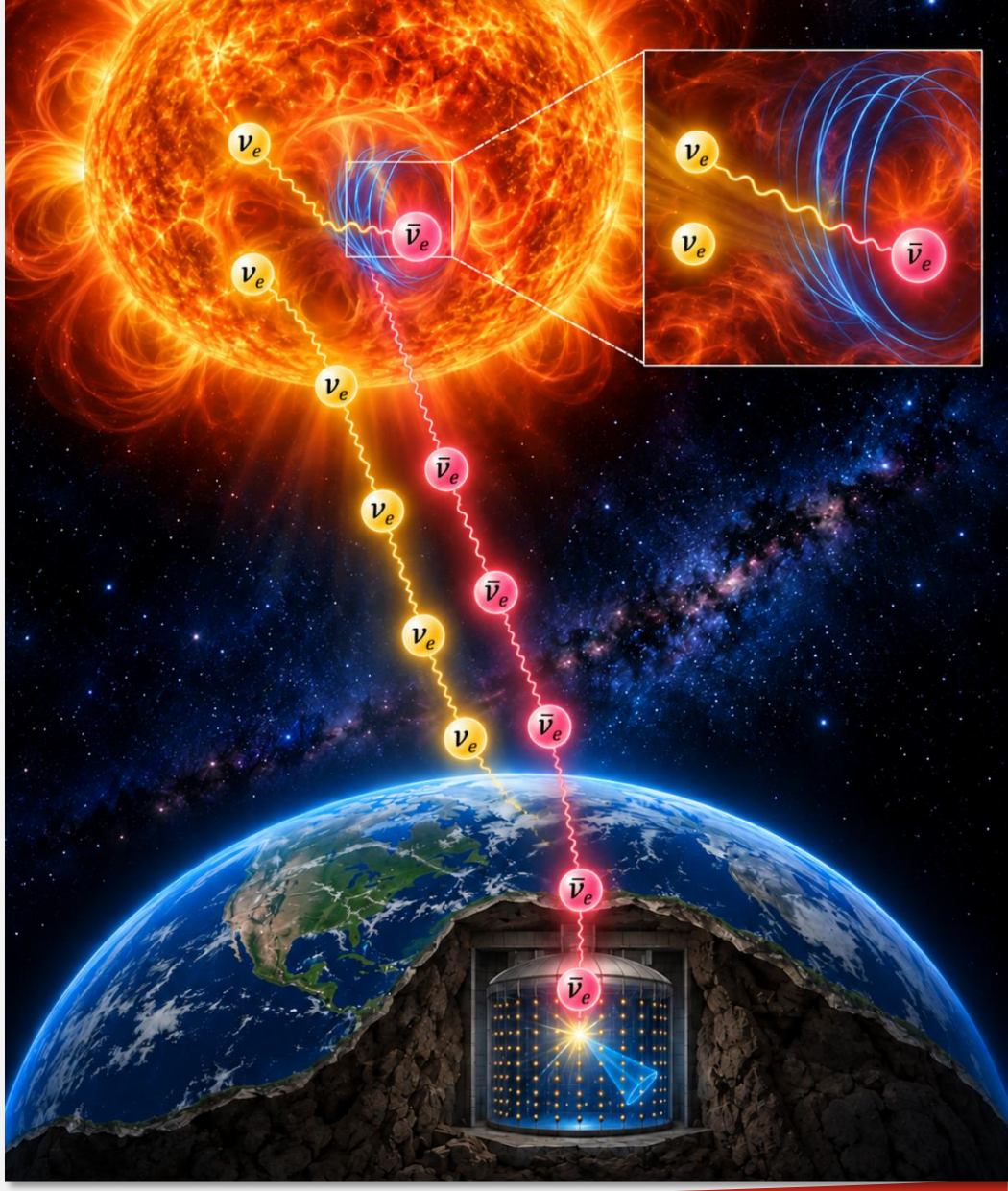
Probe of Solar Neutrino Magnetic Moments through Spin-Flavor Precession

Chui-Fan Kong
[kongcf@ibs.re.kr]
IBS-CTPU-PTC



Based on:

2609.14446 [hep-ph]

Pouya Bakhti (JBNU), Sudip Jana (HRI & HBNI), Seodong Shin (JBNU), Seokhoon Yun (KNU & IBS)

Institute for Basic Science

CPNR Workshop 2026 @ Chung-Ang University

Oct 26, 2026

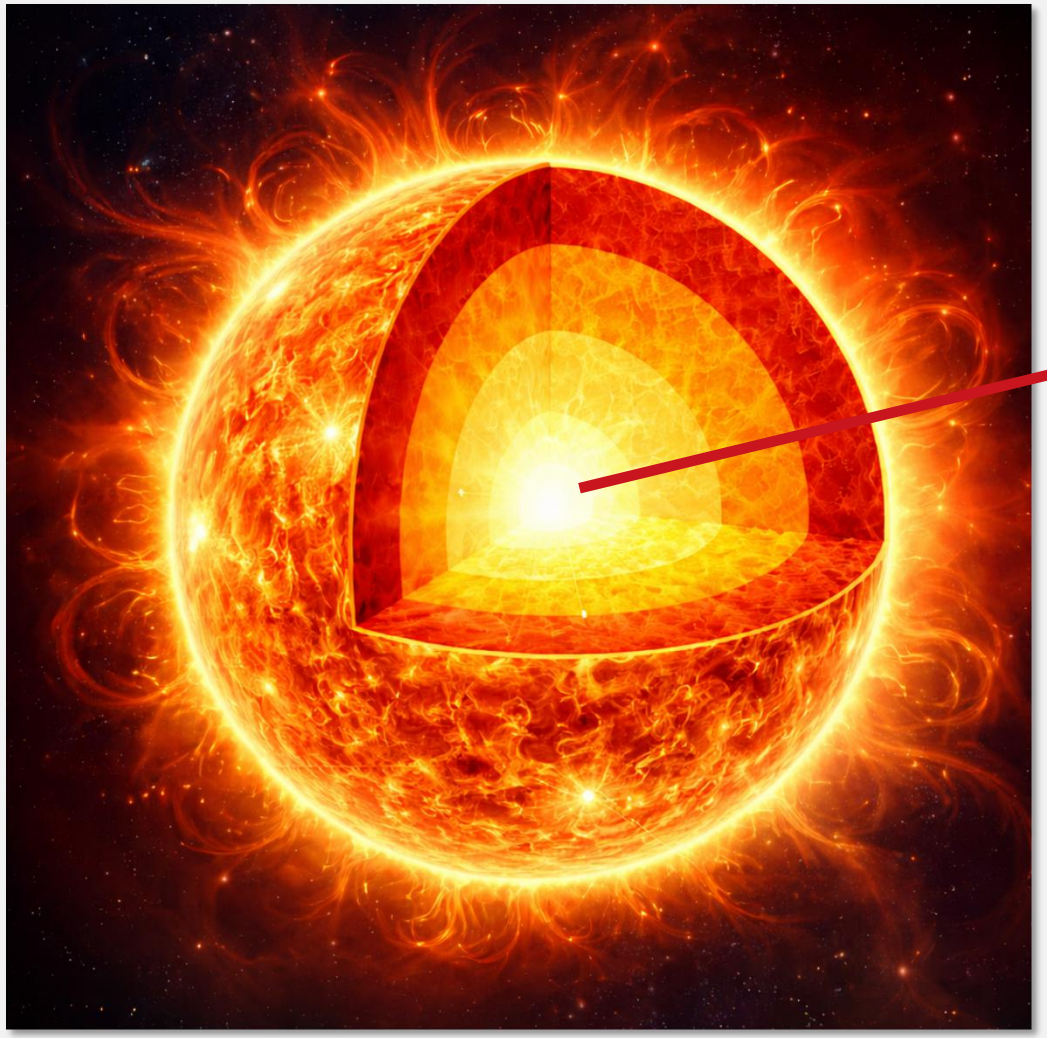
Outline

Institute for Basic Science

- A brief introduction to solar neutrinos
- Neutrino magnetic moments & spin-flavor precession
- Experimental sensitivities

How are solar neutrinos produced

Solar Environment

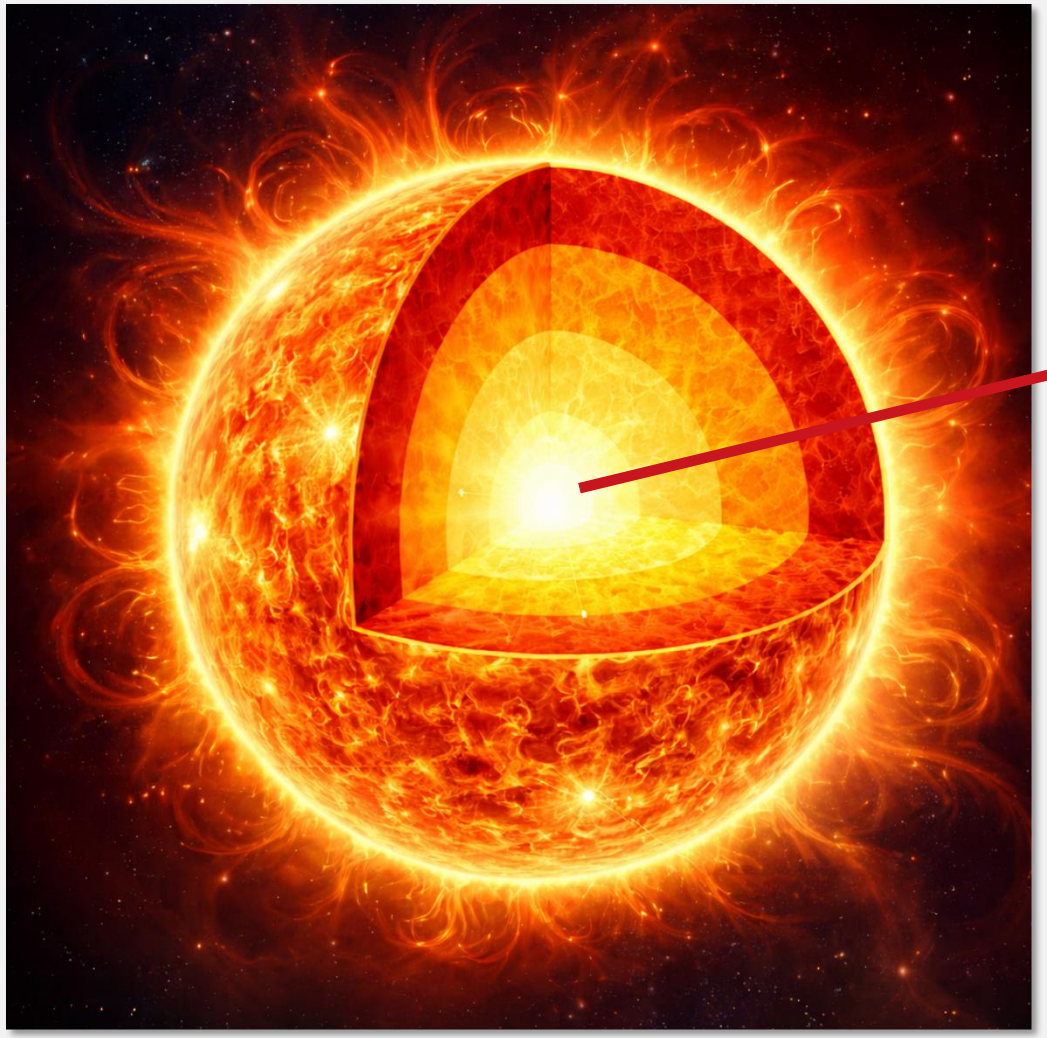


credit: alltheseworlds.US

- Hydrogen (74 %)
- Helium (24 %)
- Heavier elements (Oxygen, Carbon, Neon ..., 2%)

*Mass fraction

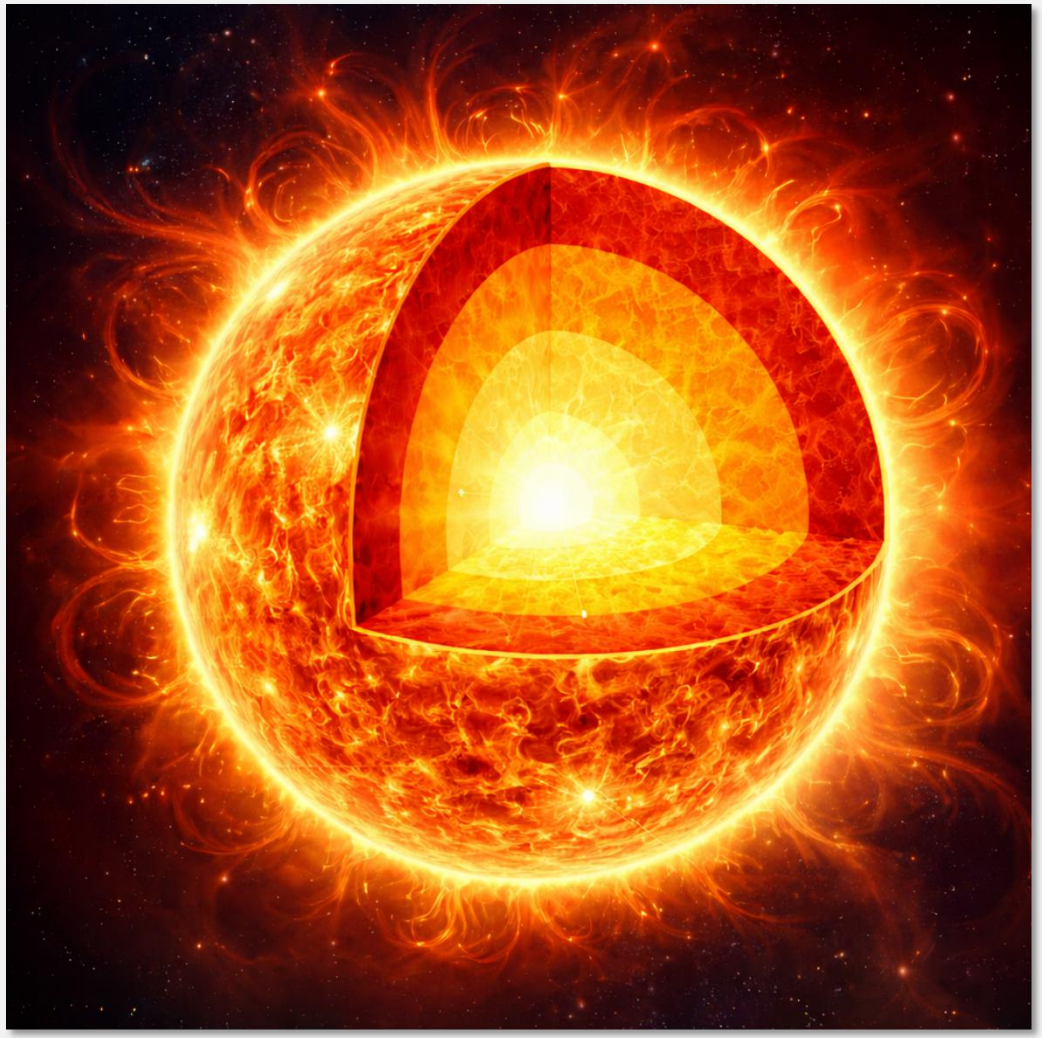
Solar Environment



credit: alltheseworlds.US

- High temperature (15 million K)
- High density (150 g/cm^3)

Solar Environment



credit: alltheseworlds.US

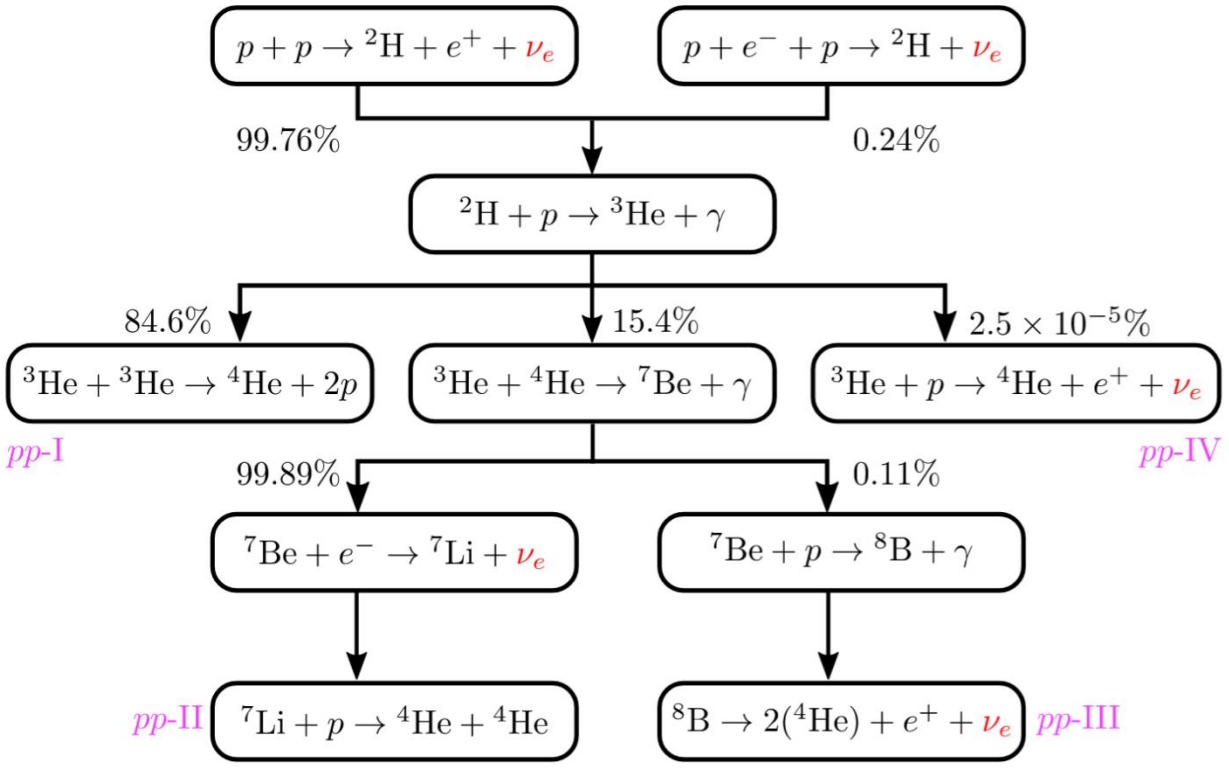
Quantum tunneling enables thermonuclear reactions:

proton-proton fusion chain (pp chain)

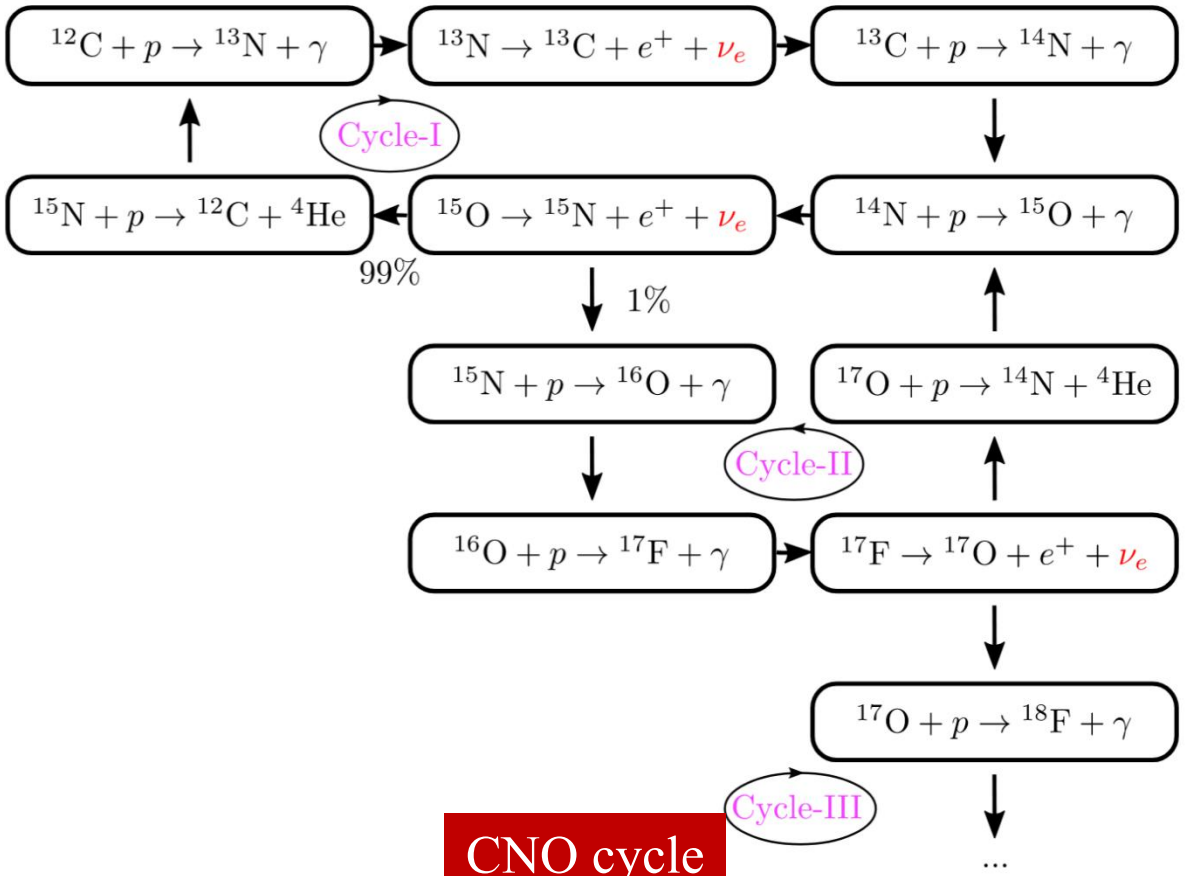
+

carbon-nitrogen-oxygen cycle (CNO cycle)

Solar Neutrino Production



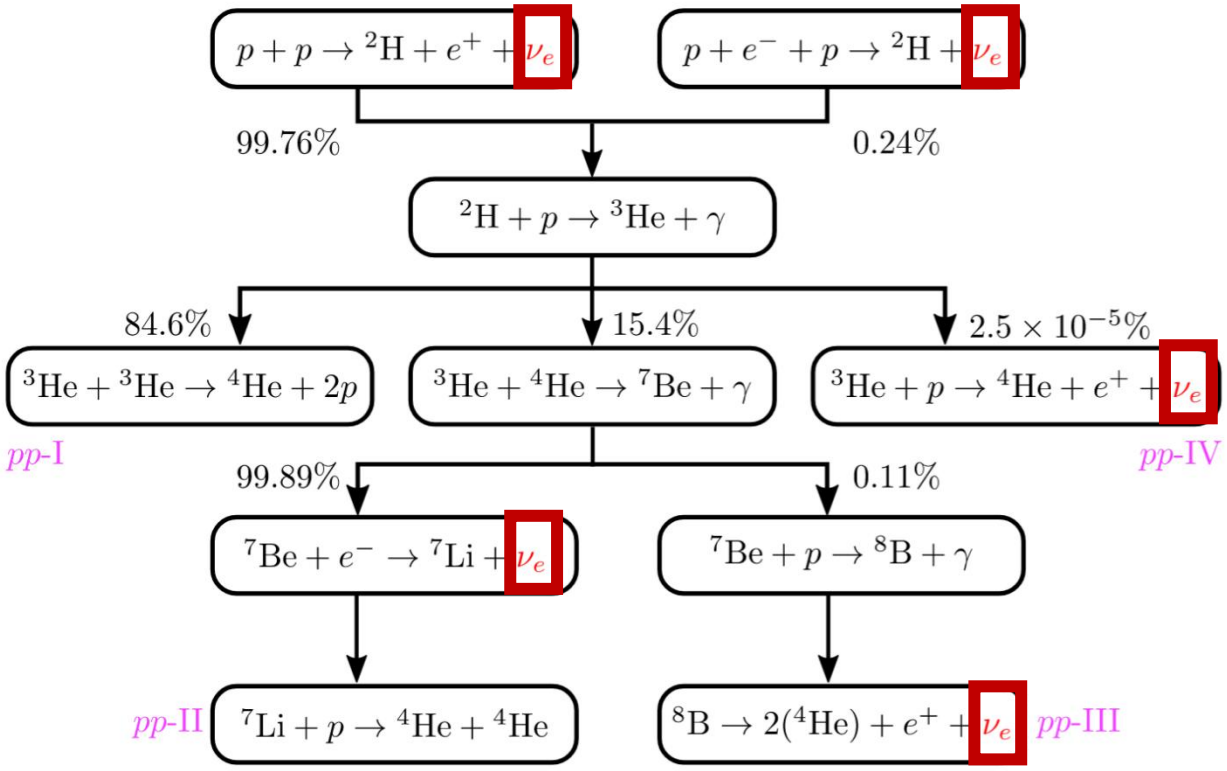
pp chain (99% solar energy)



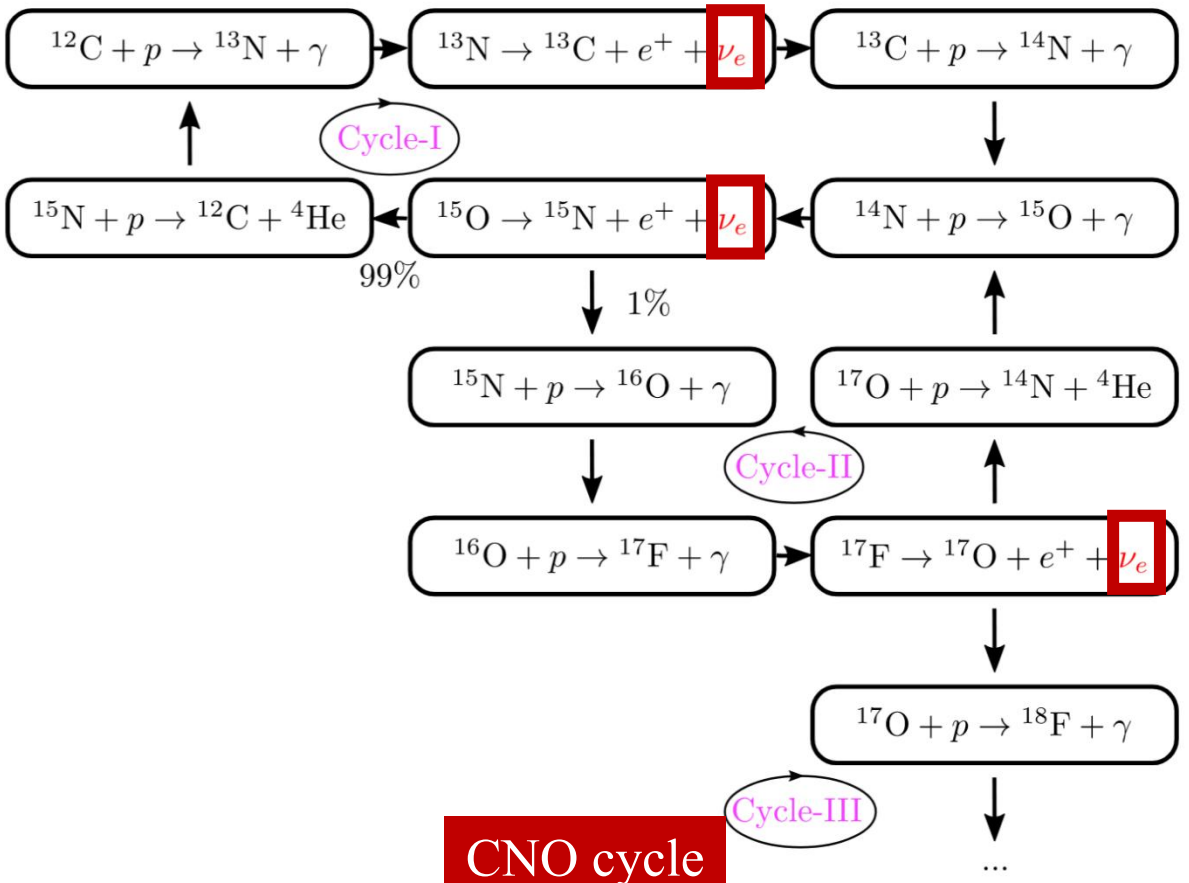
CNO cycle

S. Chen, X.-J. Xu, arXiv:2501.09971

Solar Neutrino Production



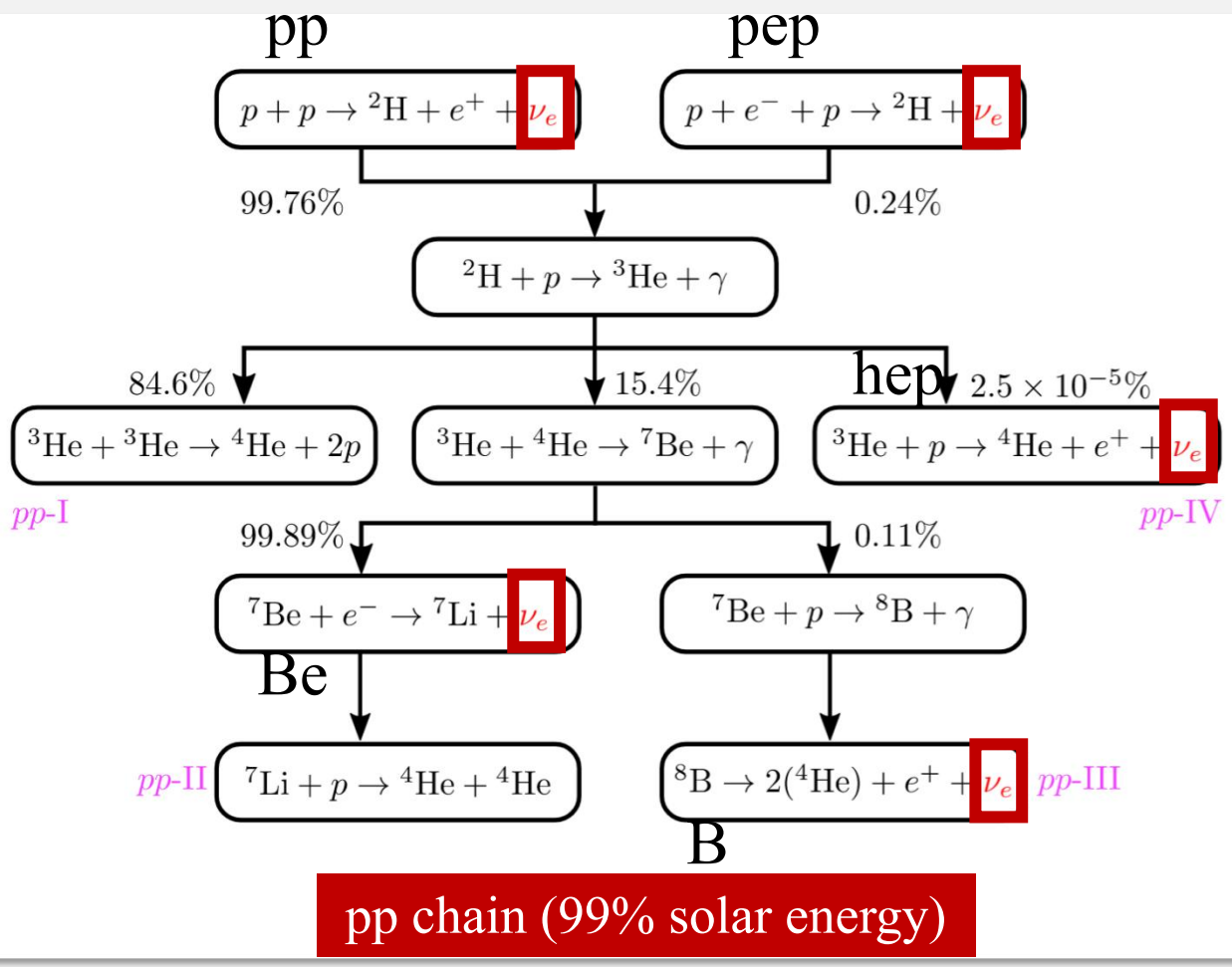
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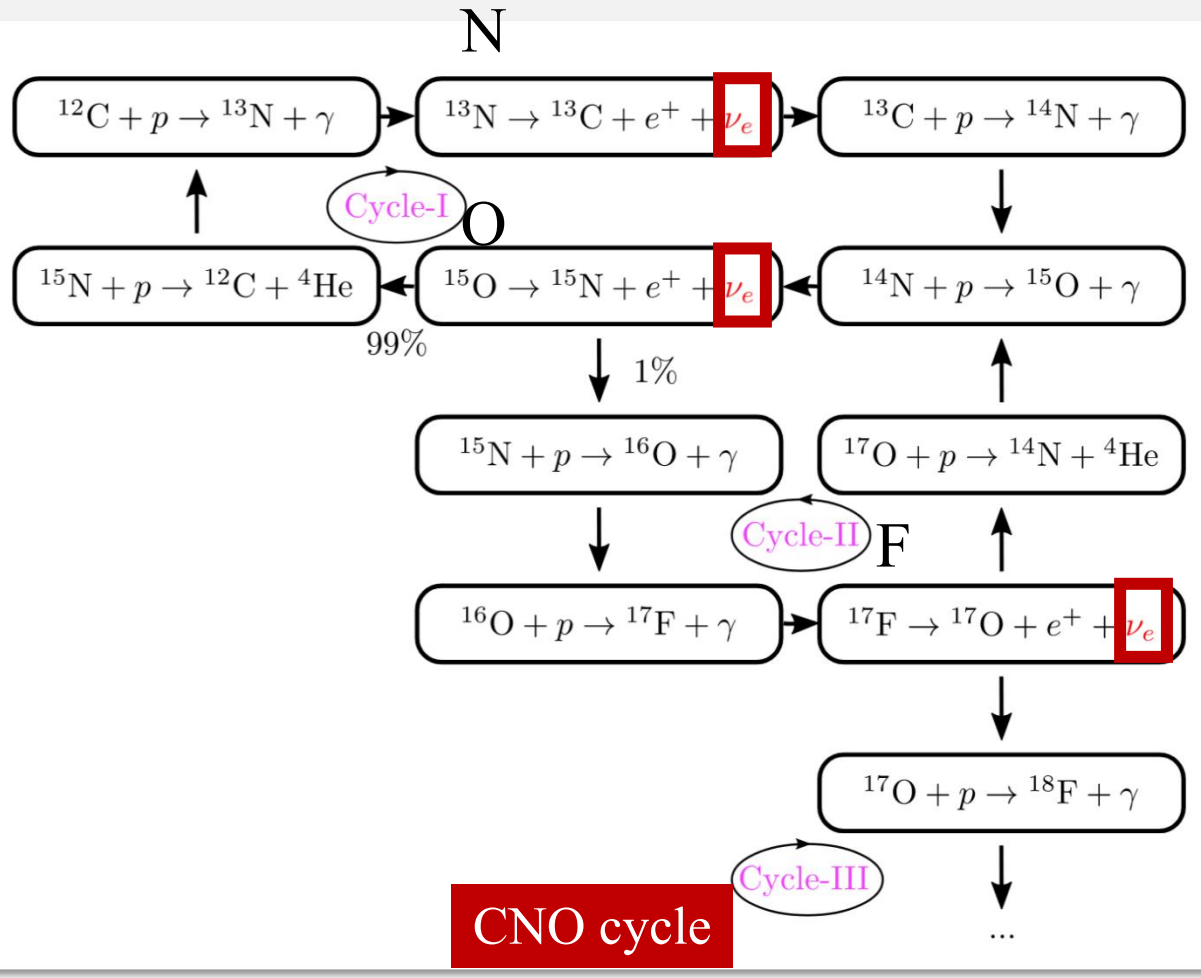


CNO cycle

S. Chen, X.-J. Xu, arXiv:2501.09971

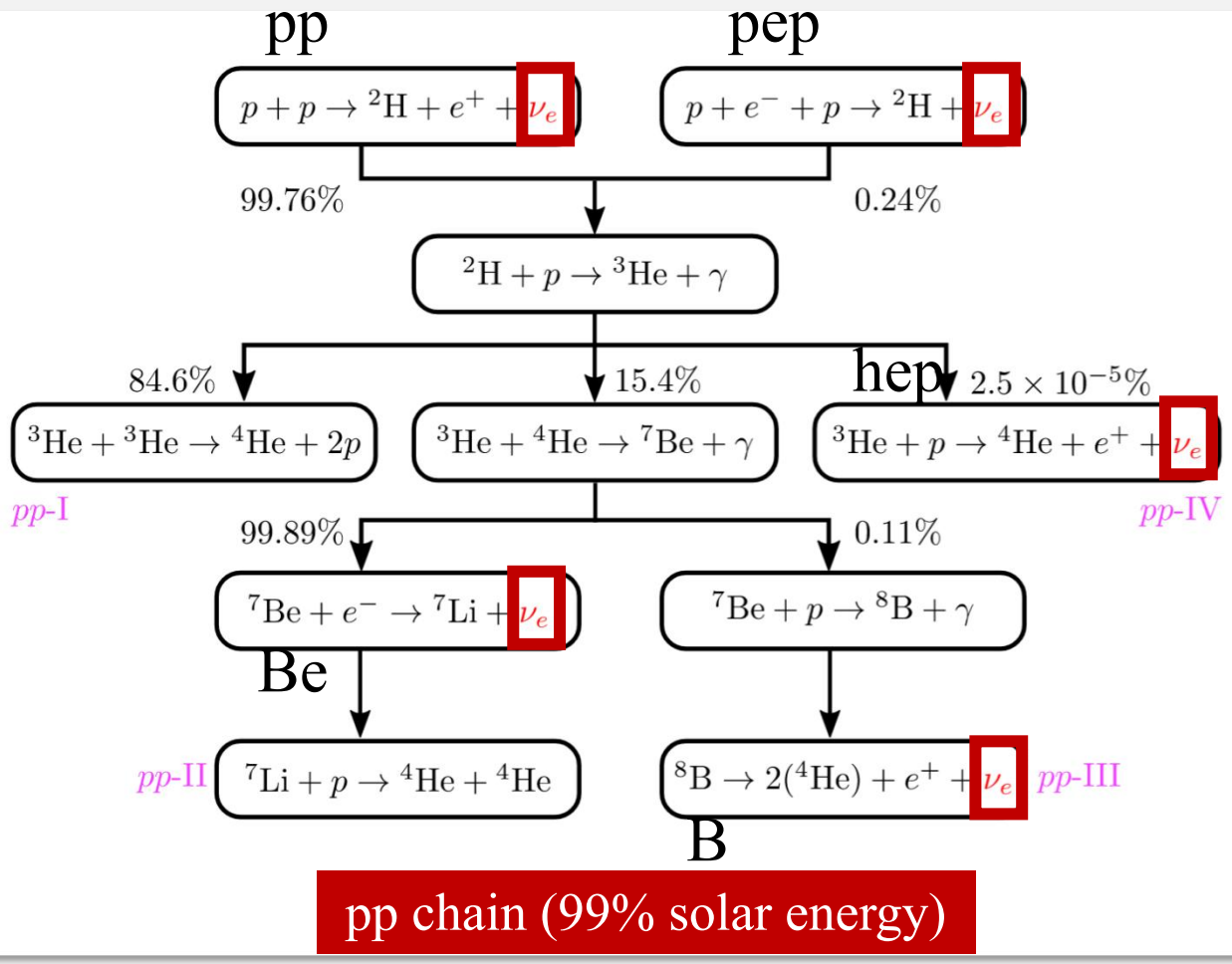
Solar Neutrino Production



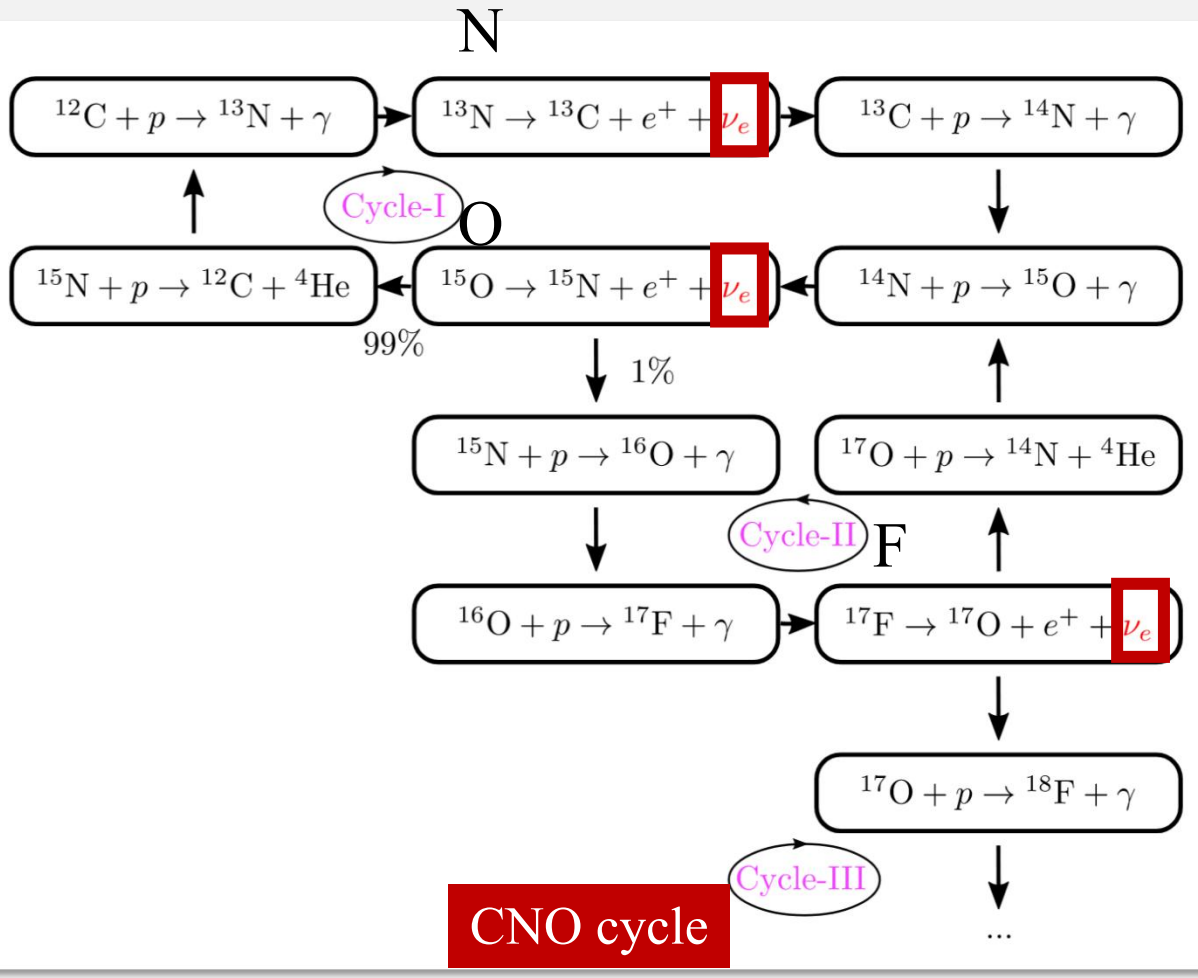


S. Chen, X.-J. Xu, arXiv:2501.09971

Solar Neutrino Production



pp chain (99% solar energy)

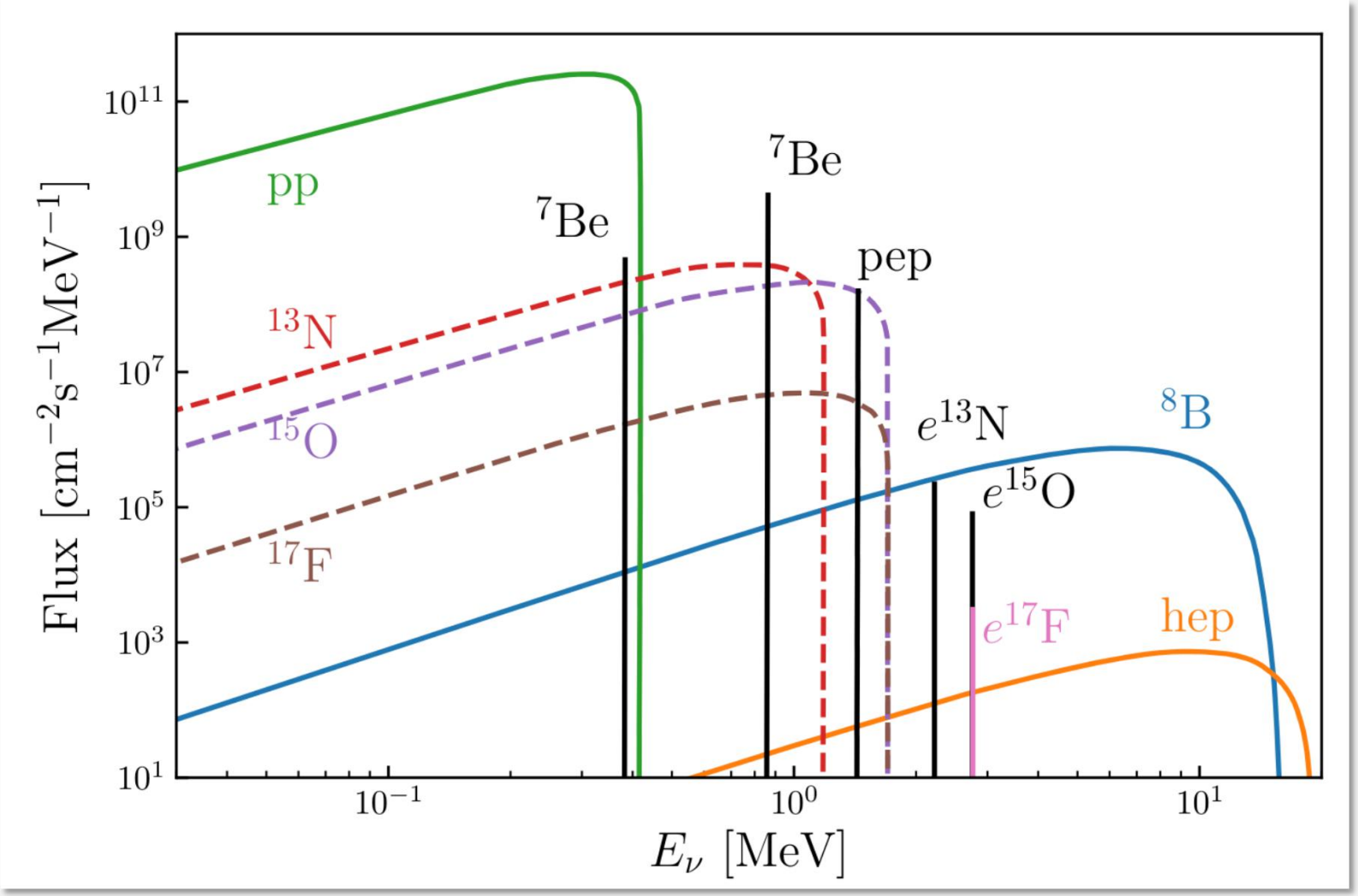


CNO cycle

S. Chen, X.-J. Xu, arXiv:2501.09971

ν_e only!

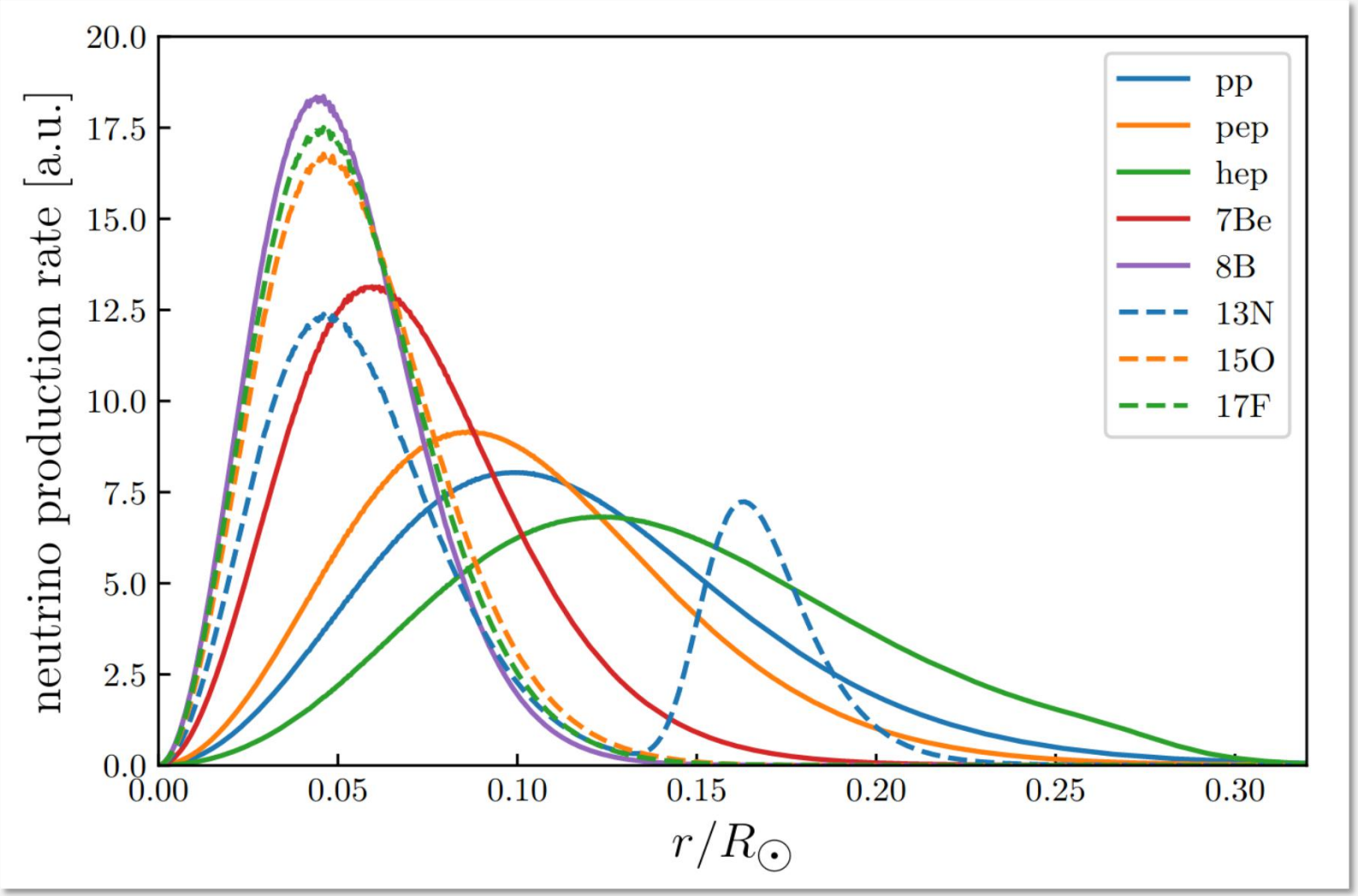
Solar Neutrino Energy Spetrum



$$\mathcal{O}(0.1) \sim \mathcal{O}(1)\,\mathrm{MeV}$$

S. Chen, X.-J. Xu, arXiv:2501.09971

Solar Neutrino Spatial Distribution



Around the core

S. Chen, X.-J. Xu, arXiv:2501.09971

What is neutrino magnetic moment

Neutrino Electromagnetic Interactions

Institute for Basic Science

In the Standard Model, neutrinos are neutral particles.

Do they have electromagnetic interactions?

Neutrino Electromagnetic Interactions

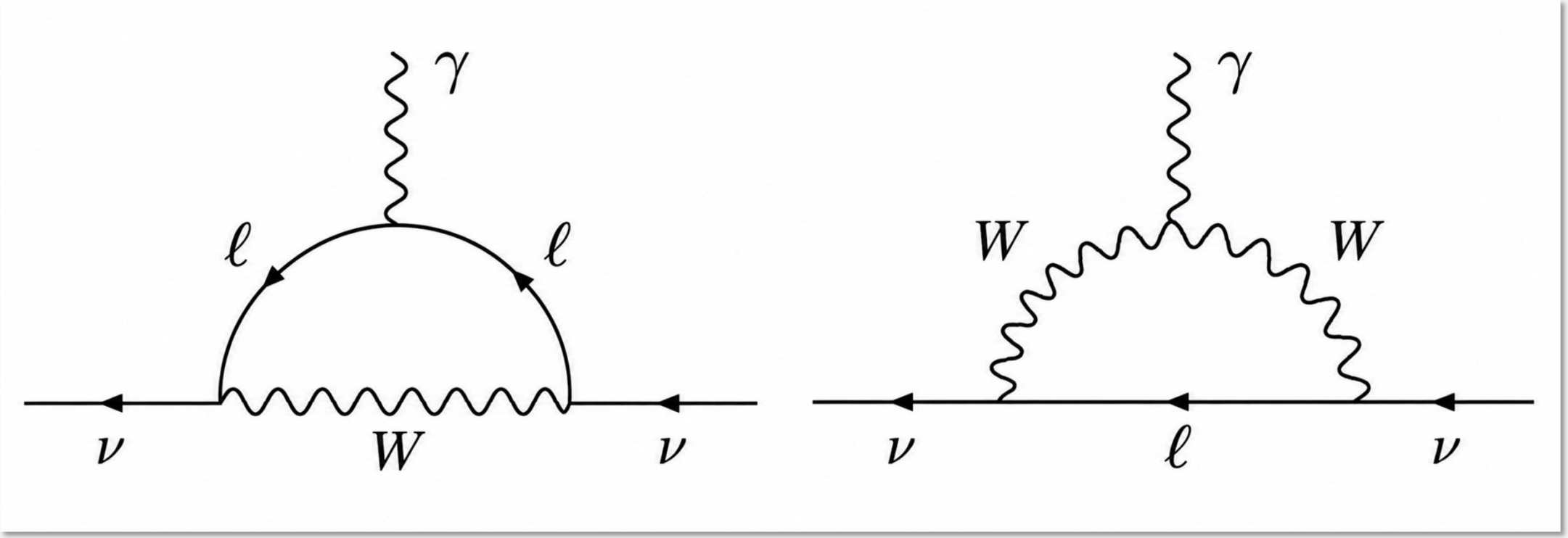
Institute for Basic Science

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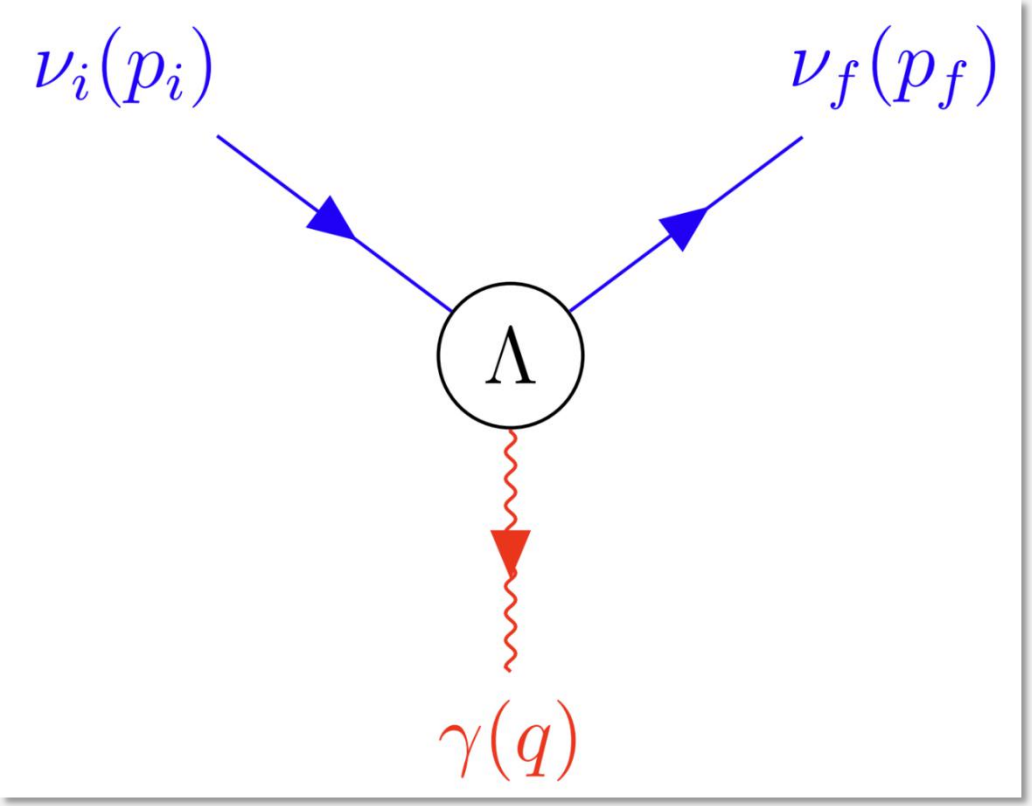
At tree level, no.
At loop level, yes!

Neutrino Electromagnetic Interactions



A. De Gouvea, J. Jenkins, arXiv:hep-ph/0603036

Neutrino Electromagnetic Interactions



C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
arXiv:2411.03122

A general description:

Effective interaction Hamiltonian

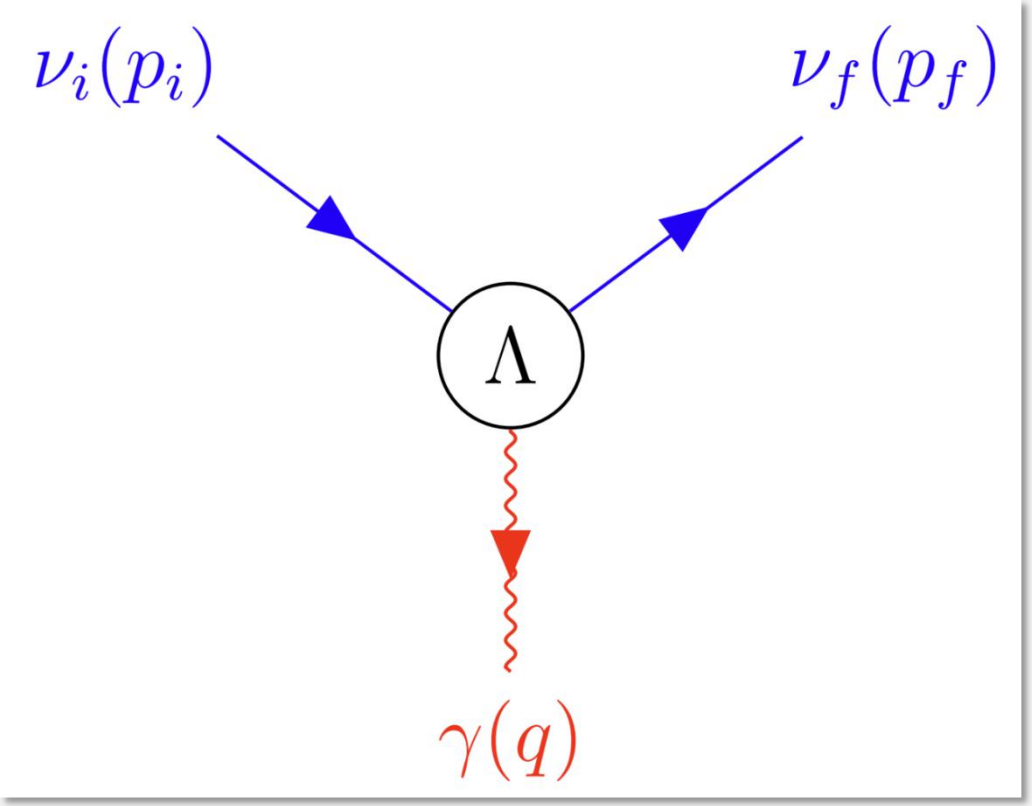
$$\mathcal{H}^{(\nu)}_{\rm em}(x) = j^{\mu}_{(\nu)}(x) A_{\mu}(x)$$

with effective EM current

$$j^{\mu}_{(\nu)}(x) = \sum_{k,j} \overline{\nu_k}(x) \hat{\Lambda}^{\mu}_{kj} \nu_j(x)$$

$\hat{\Lambda}^{\mu}_{kj}$: effective EM operator

Neutrino Electromagnetic Interactions



C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
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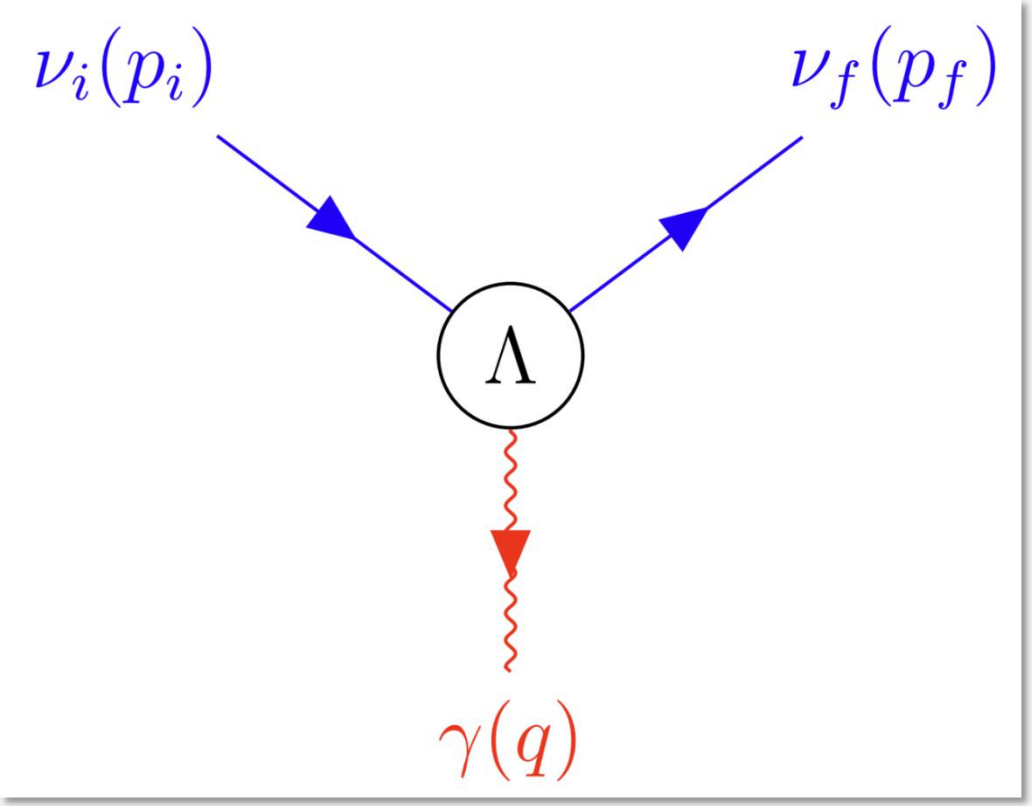
Effective EM current acts between two neutrino massive states:

$$\langle \nu_f(p_f)|j^{\mu}_{(\nu)}(x)|\nu_i(p_i)\rangle = e^{i(p_f-p_i)x}\overline{u_f}(p_f)\Lambda^{\mu}_{fi}(q)u_i(p_i)$$

The requirement of hermiticity of Hamiltonian and gauge invariance gives

$$\Lambda^{\mu}_{fi}(q) = \left(\gamma^{\mu} - \frac{q^{\mu}\not{q}}{q^2}\right)\left[F^{Q}_{fi}(q^2) + F^{A}_{fi}(q^2)q^2\gamma_5\right] - i\sigma^{\mu\nu}q_{\nu}\left[F^{M}_{fi}(q^2) + iF^{E}_{fi}(q^2)\gamma_5\right]$$

Neutrino Electromagnetic Interactions



C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
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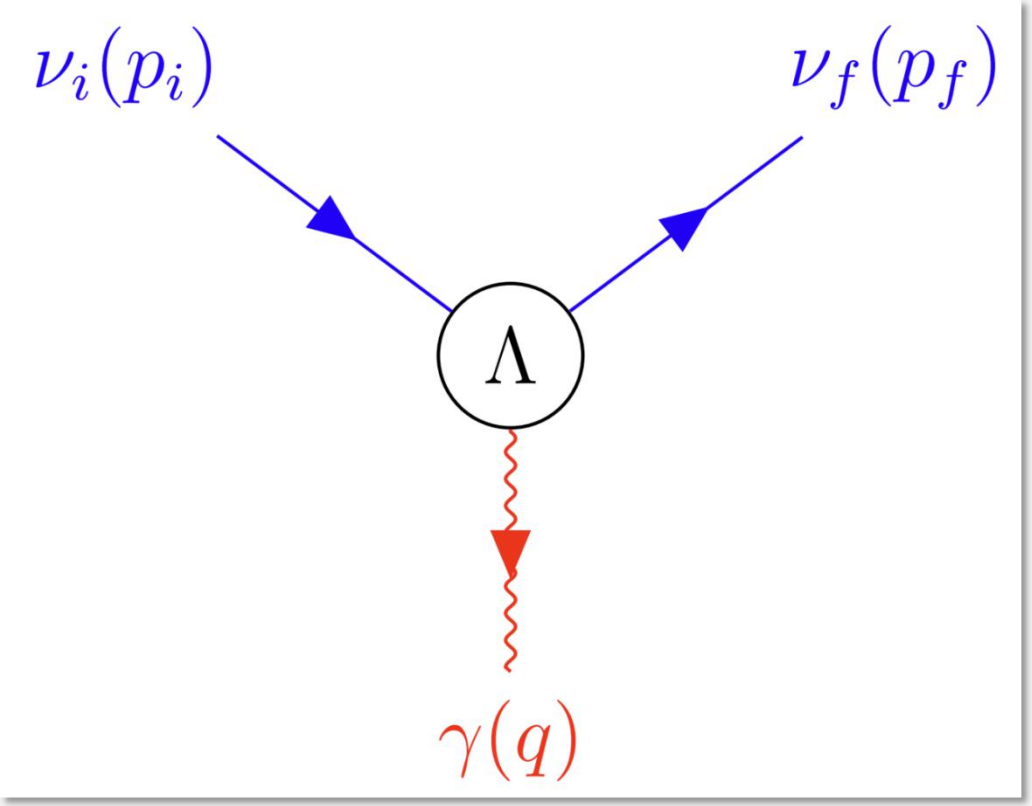
$$\langle \nu_f(p_f)|j^{\mu}_{(\nu)}(x)|\nu_i(p_i)\rangle = e^{i(p_f-p_i)x}\overline{u_f}(p_f)\Lambda^{\mu}_{fi}(q)u_i(p_i)$$

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Form factors for charge, anapole, magnetic, electric

Neutrino Magnetic Moment



C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
arXiv:2411.03122

For the coupling with a real photon ($q^2=0$),

$$F_{fi}^{M}(q^2) \xrightarrow{q^2=0} \boxed{\mu_{fi}}$$

neutirno magnetic moment (NMM)

Neutrino Magnetic Moment (NMM)

Institute for Basic Science

What is neutrino spin-flavor precession

Neutrino Magnetic Moment (NMM)

Why people are interested in NMM?

Neutrino Magnetic Moment (NMM)

Why people are interested in NMM?

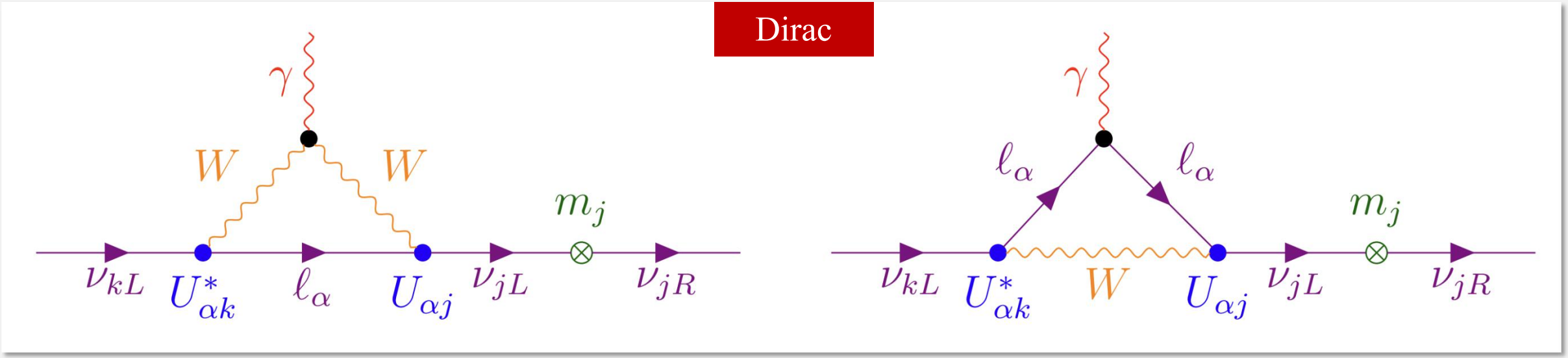
For BSM studies, NMM can be generated in many models with massive neutrinos.

Neutrino Magnetic Moment (NMM)

Why people are interested in NMM?

For BSM studies, NMM can be generated in many models with massive neutrinos.

Dirac



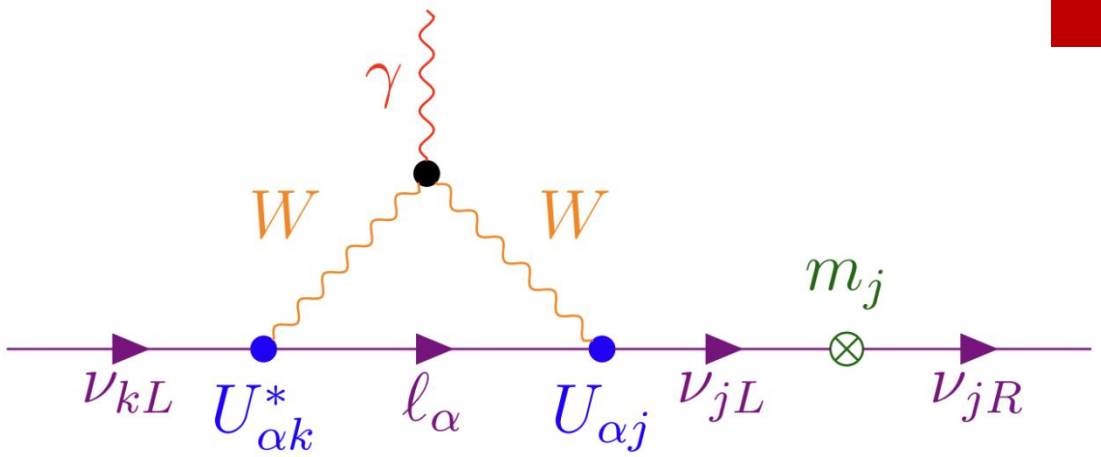
C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
arXiv:2411.03122

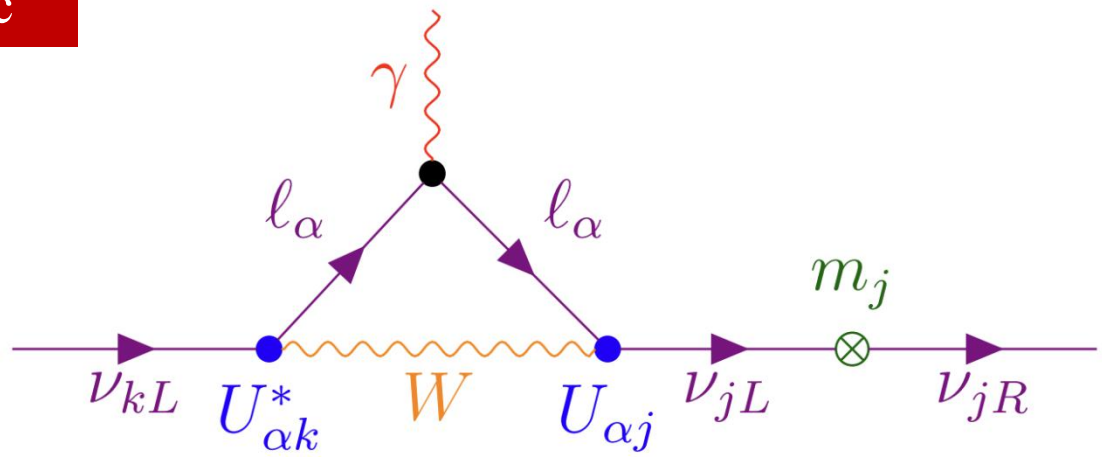
Effective dimension-five interaction Lagrangian:

$$\mathcal{L}^{\text{Dirac}}_{\text{mag}} = -\frac{1}{2}\sum_{k,j}\overline{\nu_{kL}}\sigma^{\mu\nu}\mu^{\text{D}}_{kj}\nu_{jR}F_{\mu\nu} + \text{h.c.},$$

Neutrino Magnetic Moment (NMM)

Dirac



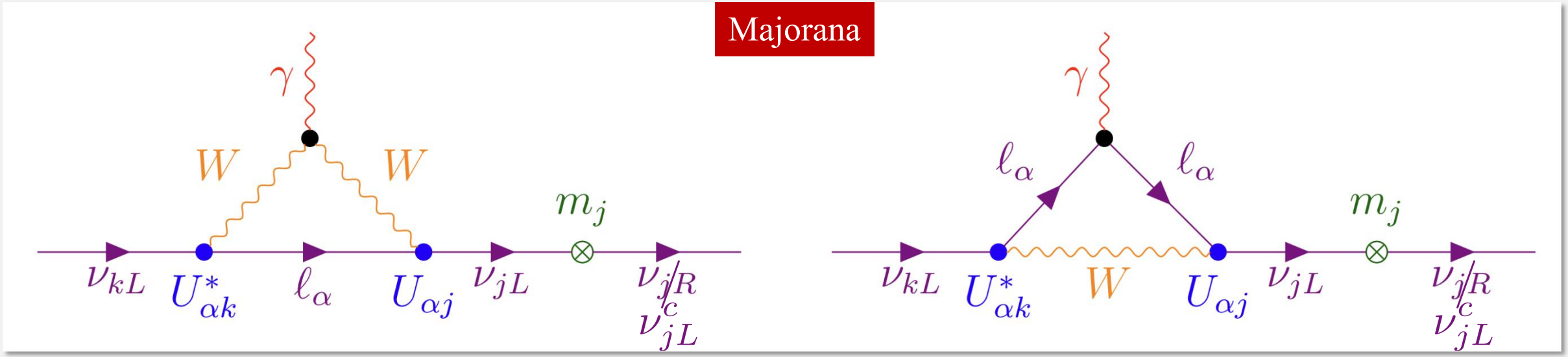


C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
arXiv:2411.03122

$$\nu_{kL} \xrightarrow[\text{flavor change}]{\text{spin flip}} \boxed{\nu_{jR}\,(\text{sterile})}$$

undetectable

Neutrino Magnetic Moment (NMM)

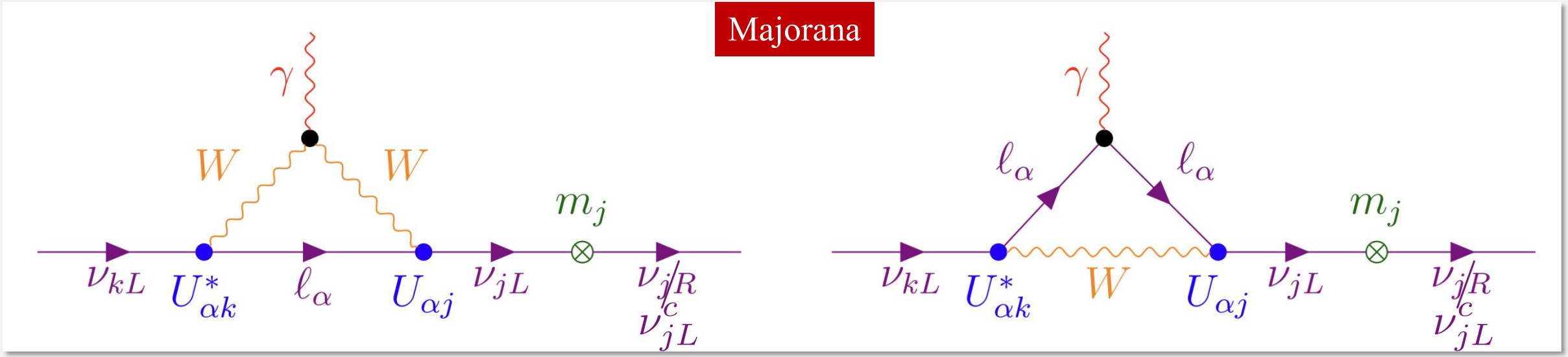


C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
arXiv:2411.03122

Effective dimension-five interaction Lagrangian:

$$\mathcal{L}^{\text{Majorana}}_{\text{mag}} = -\frac{1}{4}\sum_{k,j} \overline{\nu_{kL}}\sigma^{\mu\nu}\mu^{\text{M}}_{kj}\nu^c_{jL}F_{\mu\nu} + \text{h.c.}$$

Neutrino Magnetic Moment (NMM)



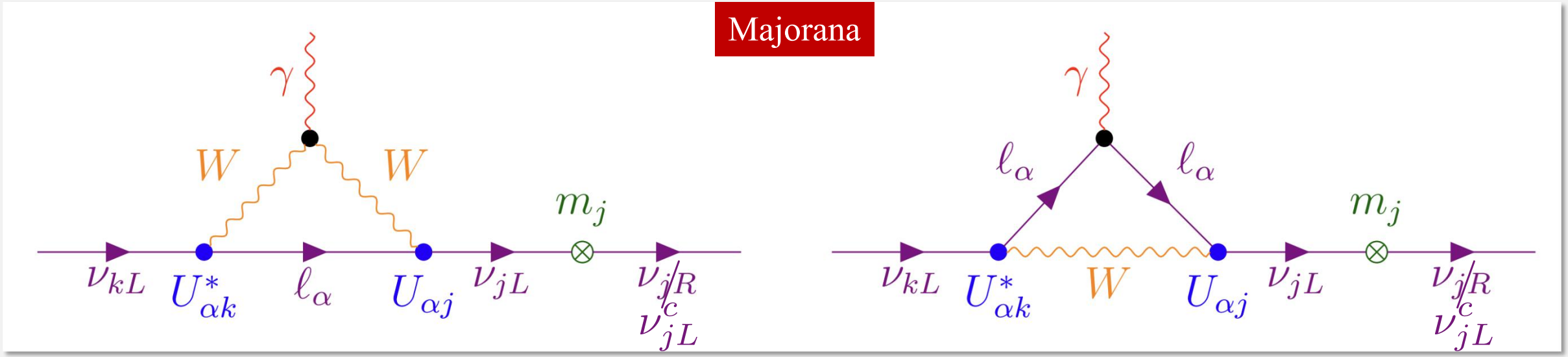
C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
arXiv:2411.03122

$$\nu_{kL} \xrightarrow[\text{flavor change}]{\text{spin flip}} \boxed{\nu^c_{jL}}$$

detectable!

Neutrino Magnetic Moment (NMM)

Institute for Basic Science



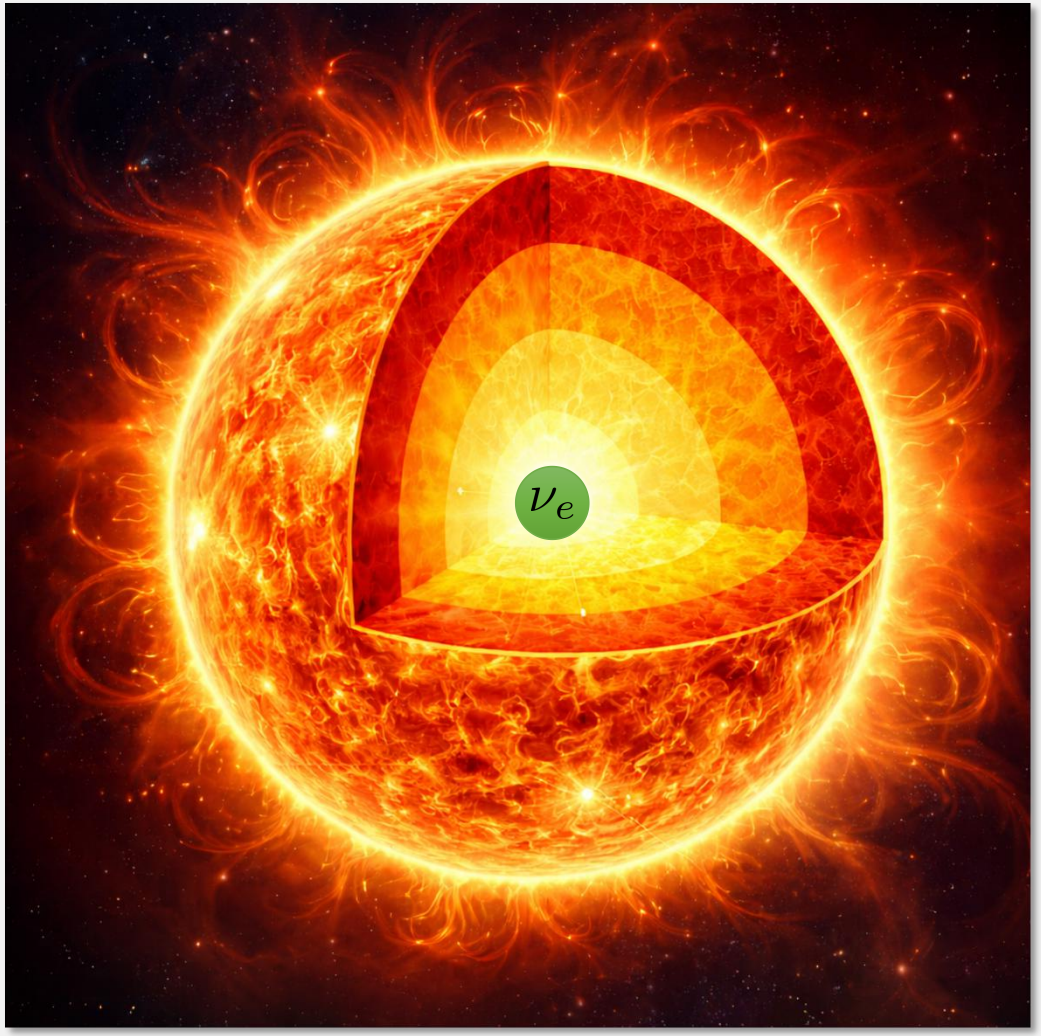
C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin
arXiv:2411.03122

$$\nu_{kL} \xrightarrow[\text{flavor change}]{\text{spin flip}} \nu^c_{jL}$$

Spin-flavor precession (SFP)

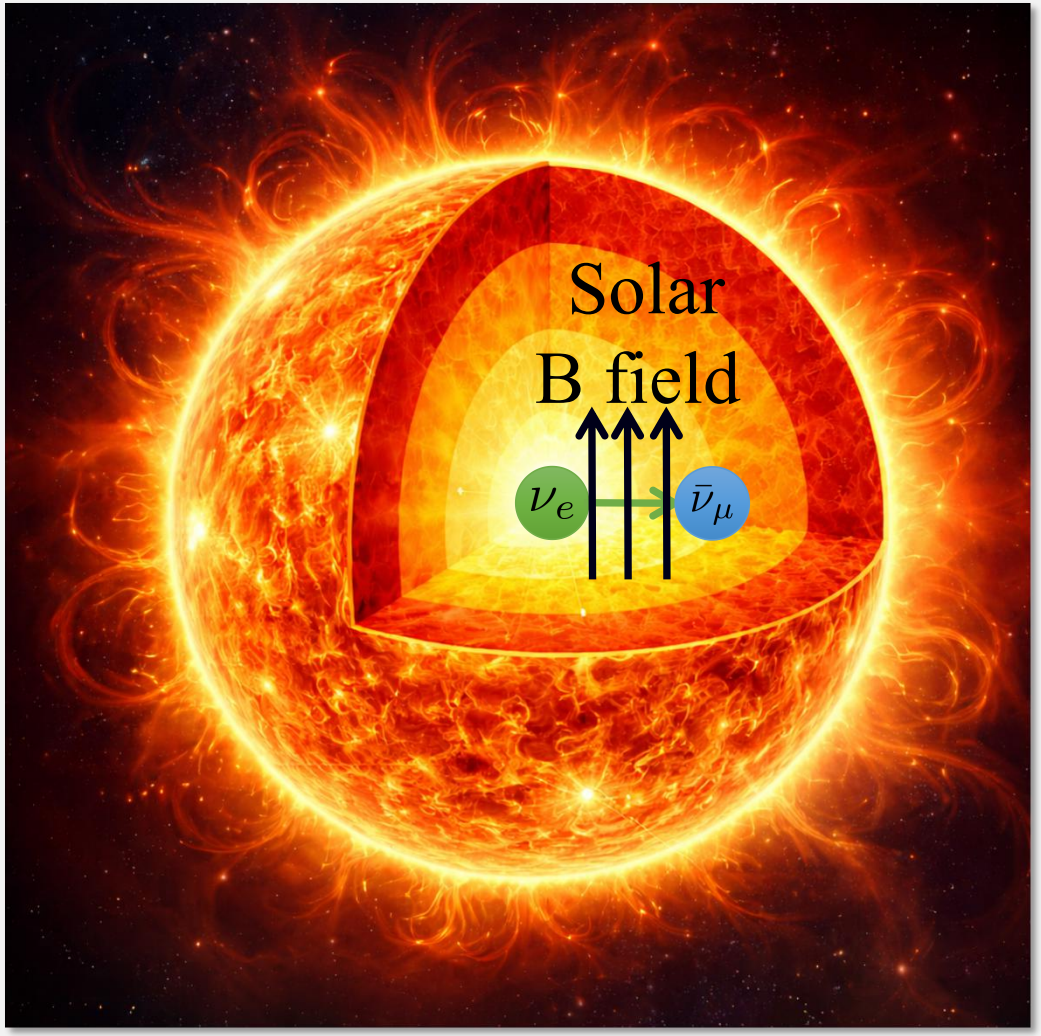
How to costrain on NMM experimentally

Physical Picture



electron neutrinos are produced near the core

Physical Picture

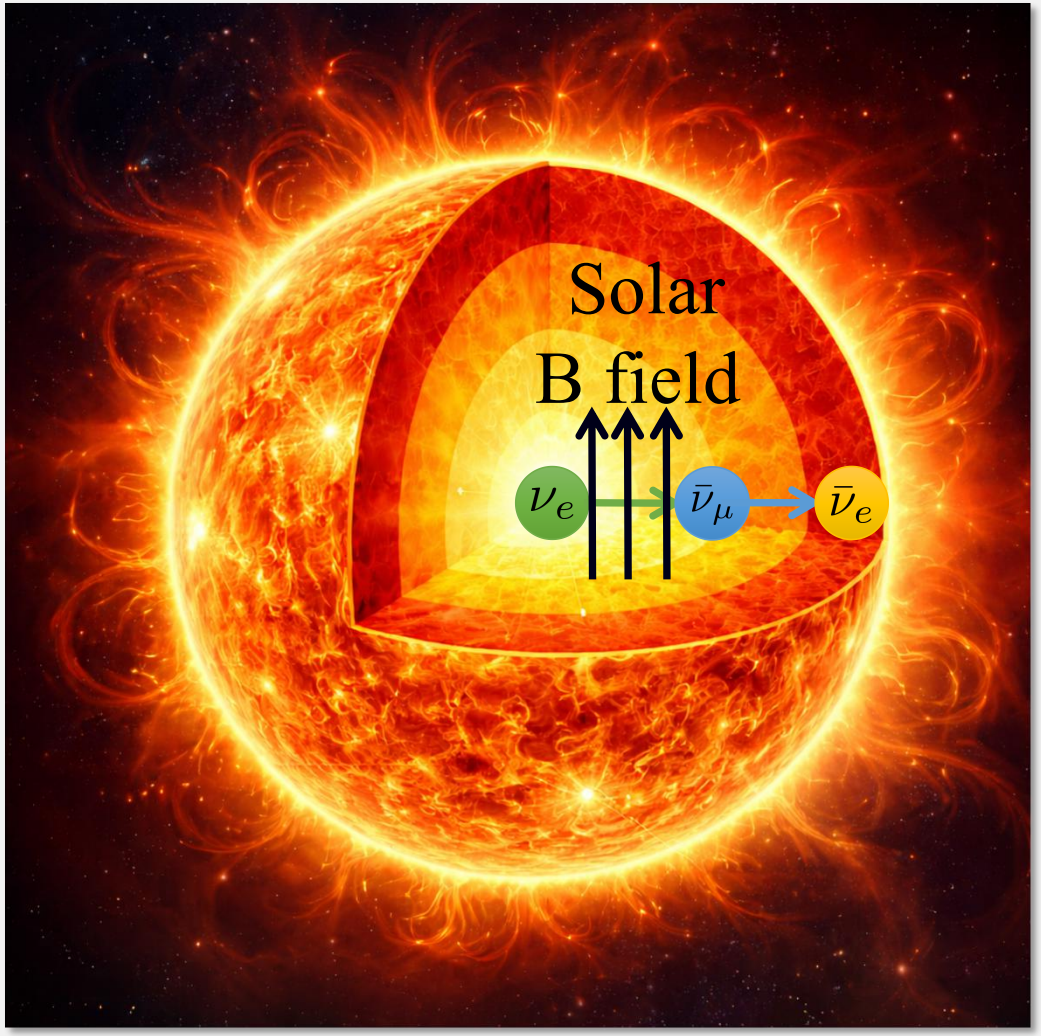


electron neutrinos are produced near the core

↓

SFP due to the magnectic field inside

Physical Picture



electron neutrinos are produced near the core

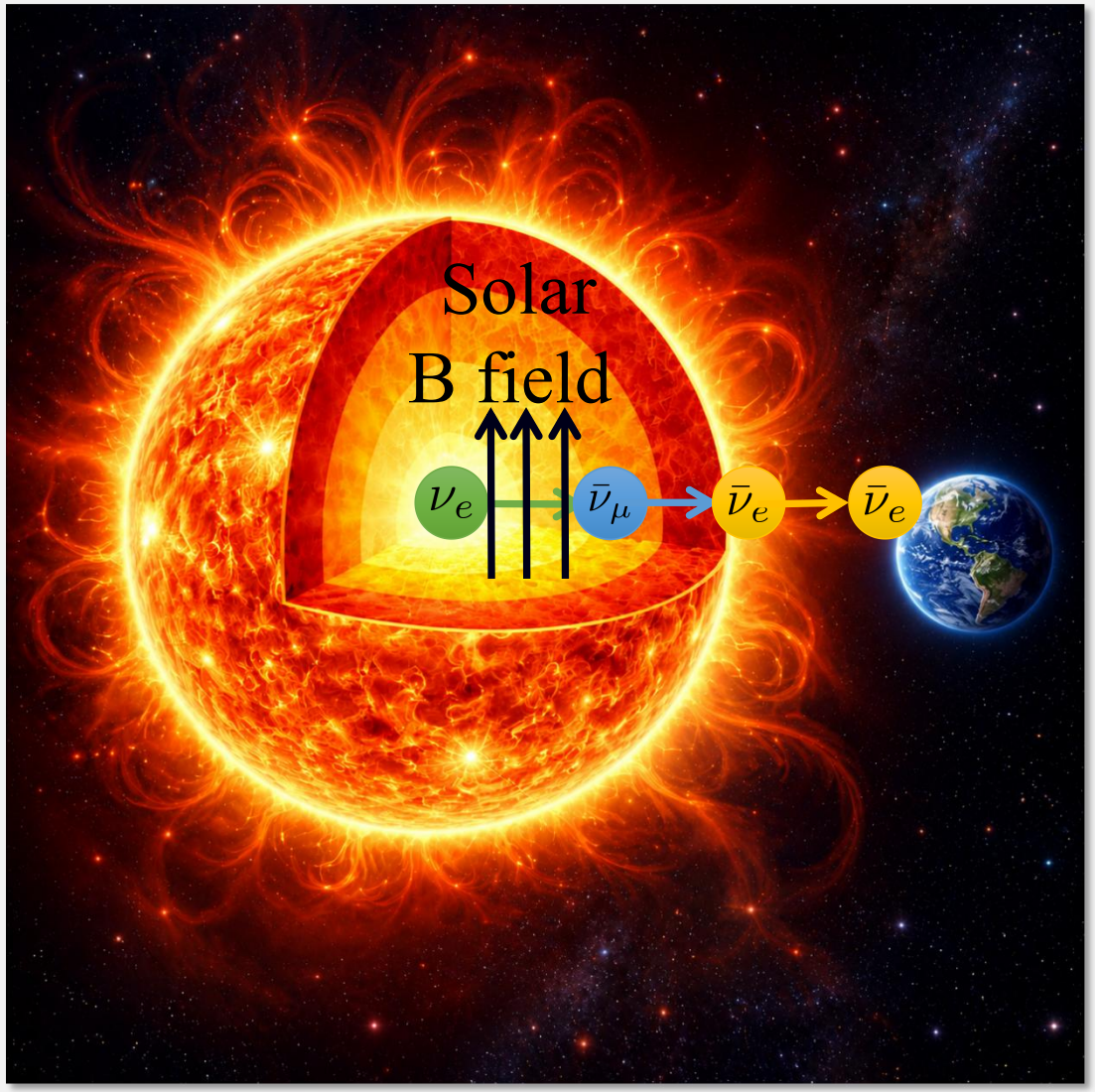
↓

SFP due to the magnectic field inside

↓

oscillated into electron antineutrino

Physical Picture



electron neutrinos are produced near the core

↓

SFP due to the magnectic field inside

↓

oscillated into electron antineutrino

↓

constrained by experiments

Experimental sensitivities

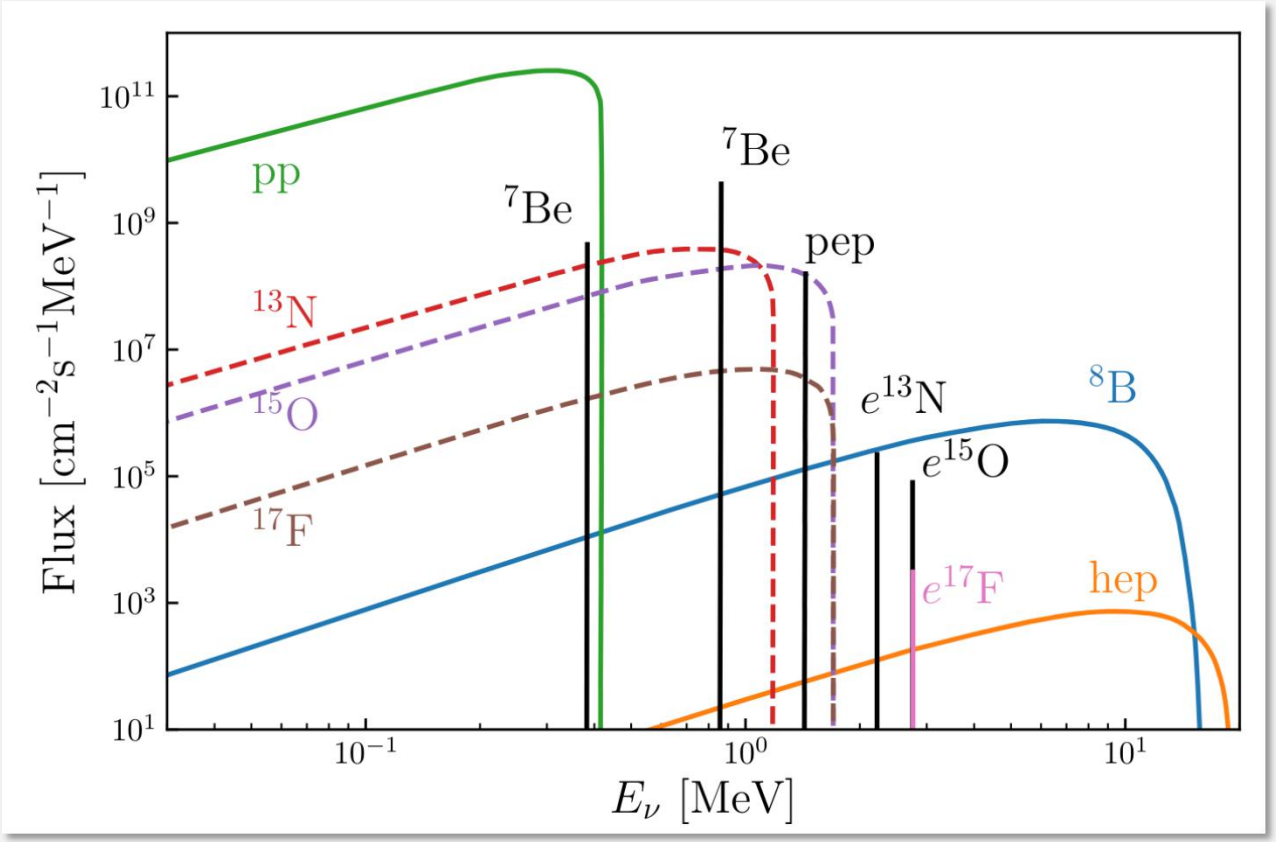
Physical Process

Source → Propagation → Detection

Neutrino Source

Source → Propagation → Detection

ν_e



S. Chen, X.-J. Xu, arXiv:2501.09971

Neutrino Propagation

Source → Propagation → Detection

$$\nu_e \qquad \nu_e \xrightarrow[\text{flavor change}]{\text{spin flip}} \bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e$$

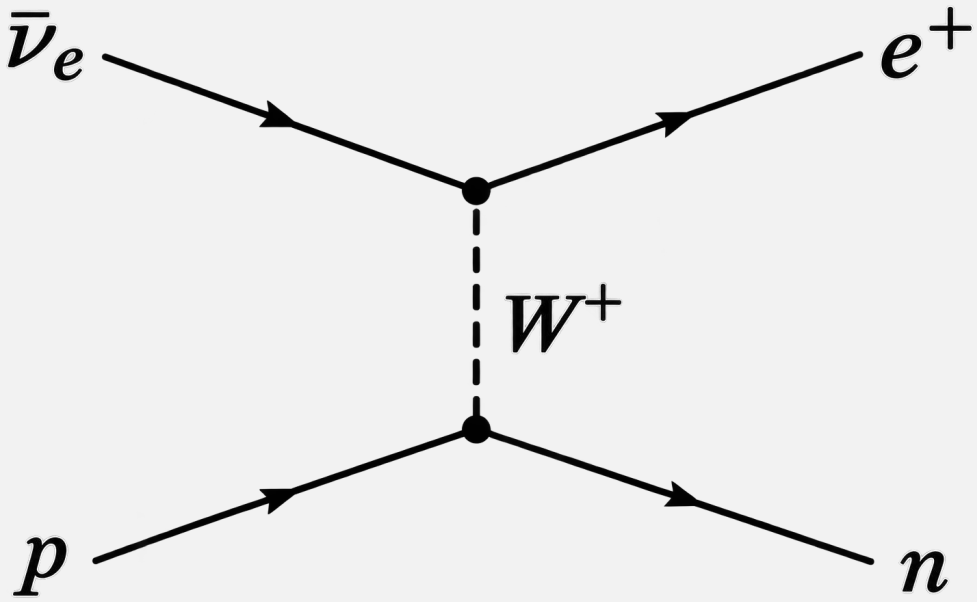
$$P(\nu_{eL} \to \bar{\nu}_{eR}) = \frac{1}{2} c_{13}^2 \sin^2 2\theta_{12} B_\perp^2(r_0) \left[c_{13}^2 |\mu_{e'\mu'}|^2 \left(\frac{\cos^2\tilde{\theta}(r_0)}{g_1'(r_0)} + \frac{\sin^2\tilde{\theta}(r_0)}{g_2'(r_0)} \right)^2 \right.$$
$$\left. + \left(\frac{s_{13}|\mu_{\mu'\tau'}|}{2\Delta} \right)^2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

E. Akhmedov, P. Martínez-Miravé
arXiv:2207.04516

Neutrino Detection

Source → Propagation → Detection

ν_e $\quad$ $\nu_e \xrightarrow[\text{flavor change}]{\text{spin flip}} \bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e$ $\quad$ $\bar{\nu}_e$



Inverse Beta Decay (IBD)

Constraints on NMM

Institute for Basic Science

There is no antineutrino in the standard solar neutrino



A non-detection of antineutrino can constrain on NMM

Constraints on NMM



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

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

$$\mu_{12} < 6.9 \times 10^{-9} B_{\perp}^{-1}[\mathrm{kG}]\, \mu_B$$



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

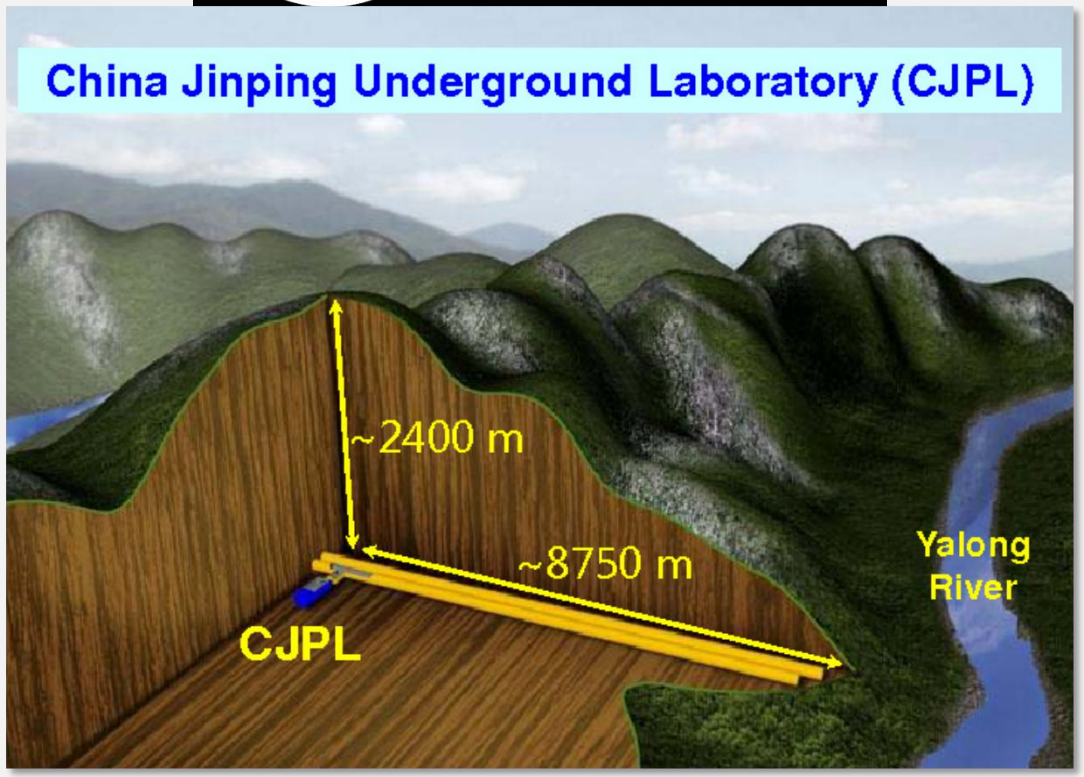
$$P_{\nu_e \to \bar{\nu}_e} < 3.5 \times 10^{-5}$$

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

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

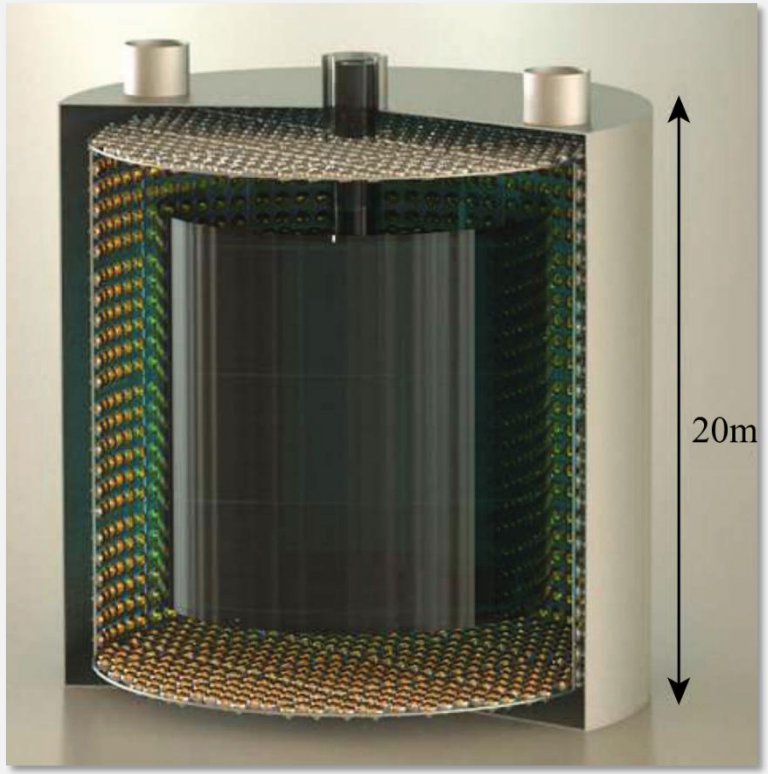
Jinping Experiment

JINPING NEUTRINO EXPERIMENT



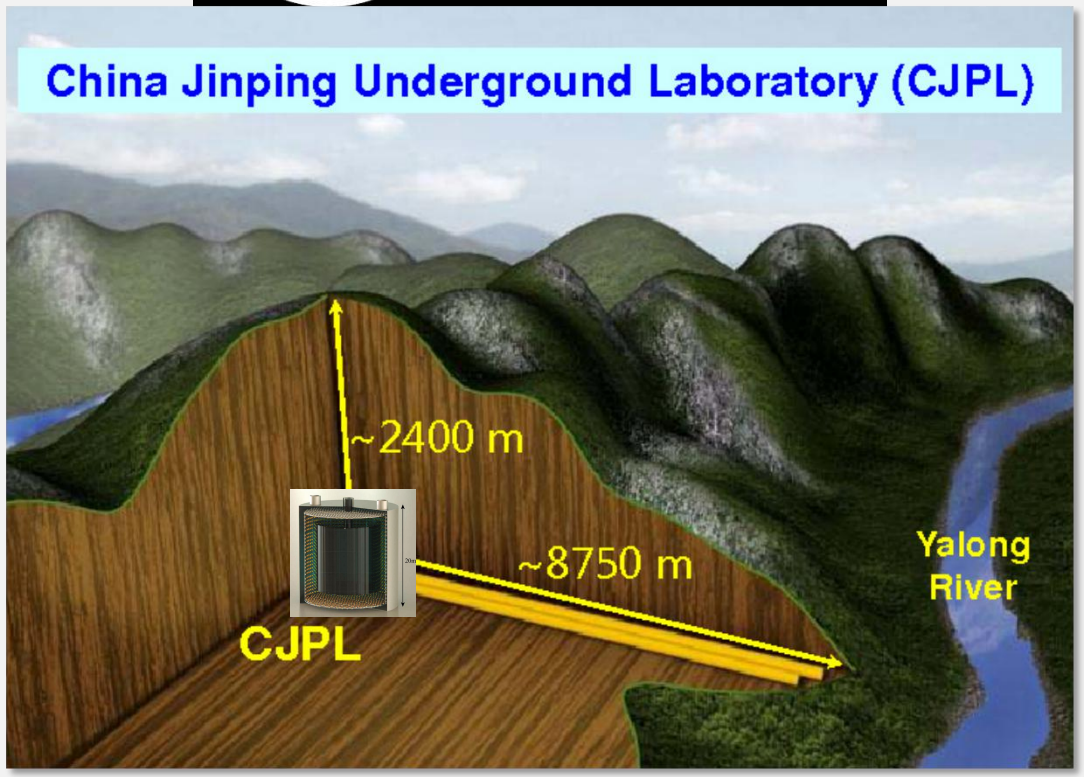
credit: CJPL

A proposed liquid scintillator detector w/ 3 kt fiducial mass

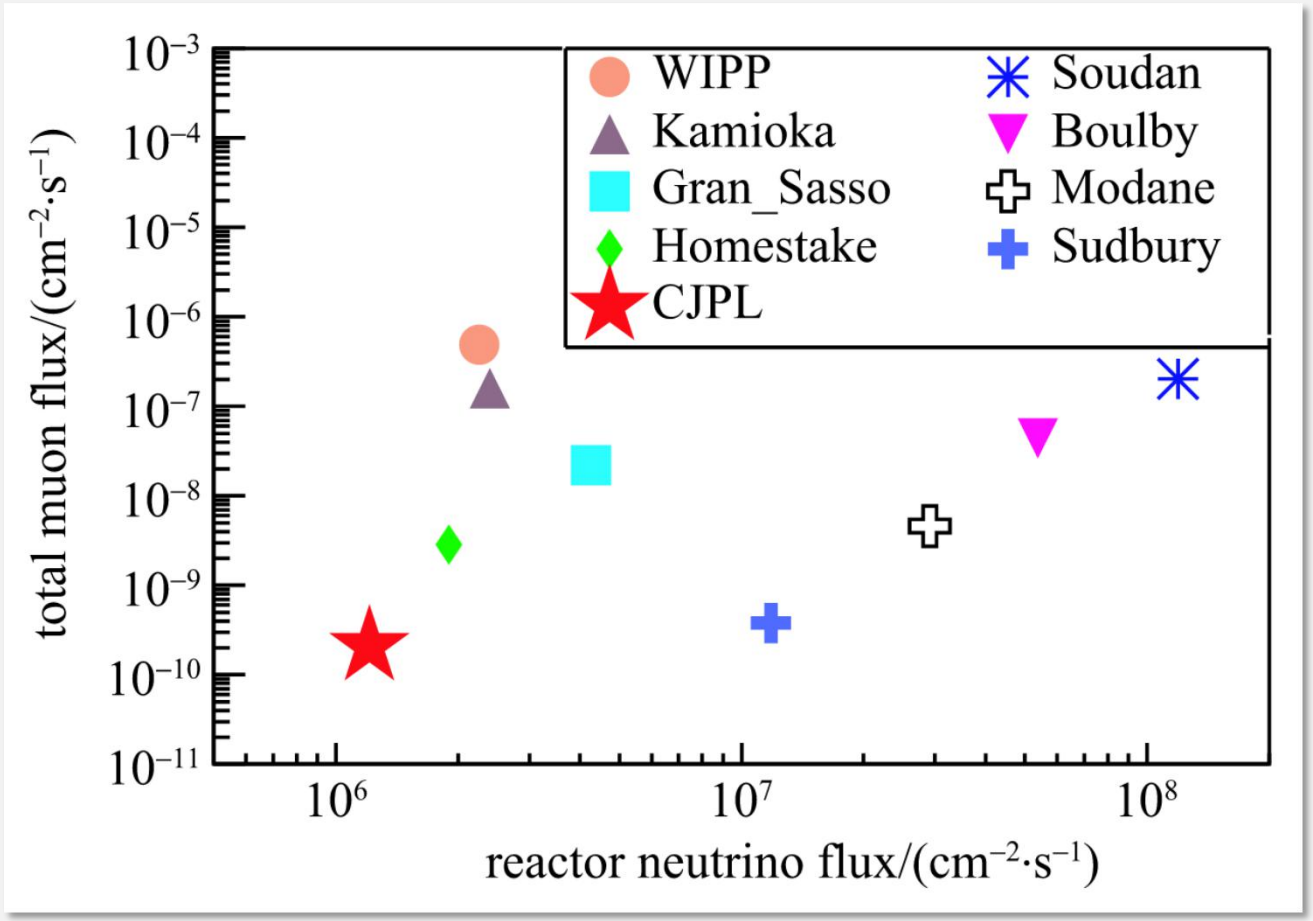


Jinping Experiment

JINPING NEUTRINO EXPERIMENT

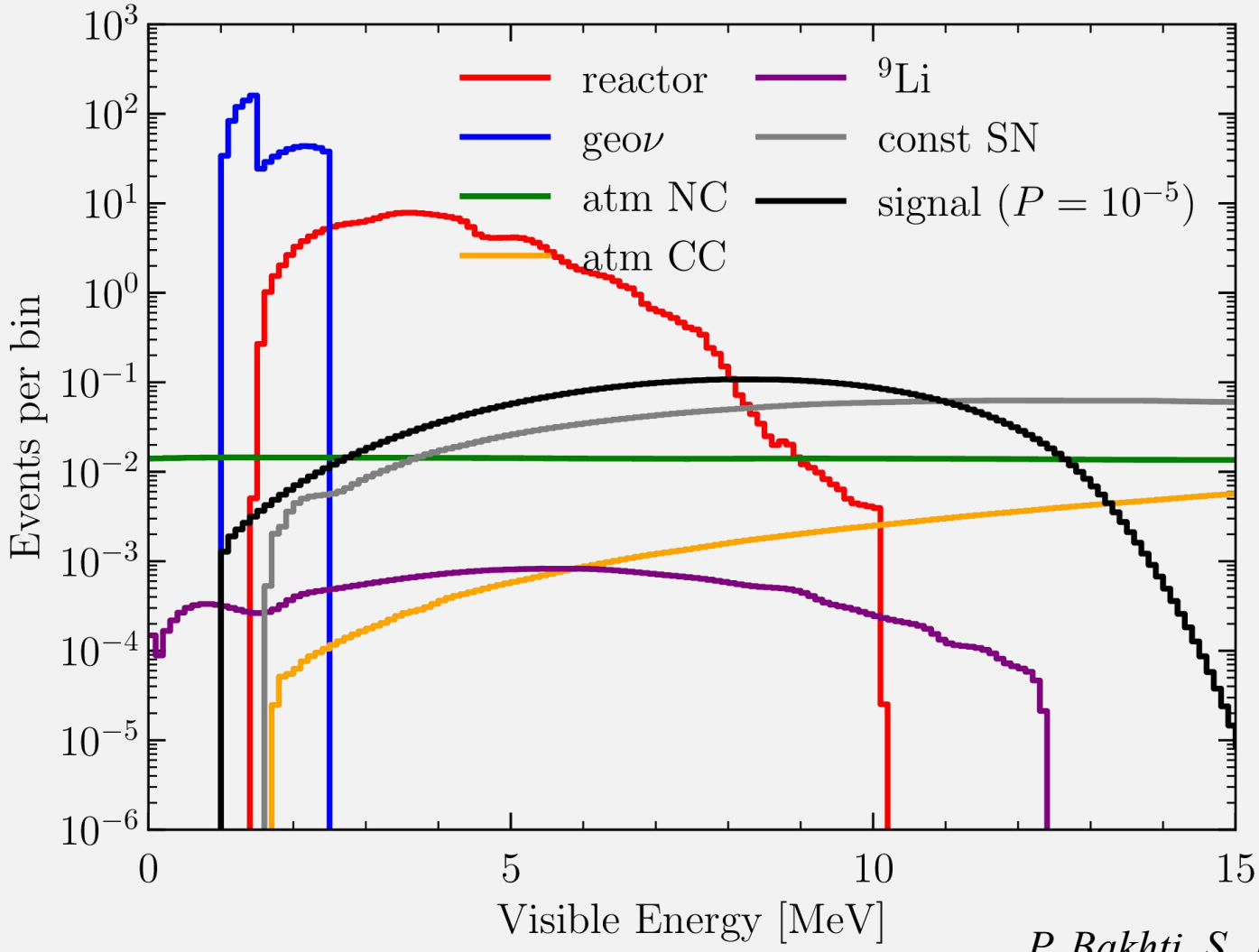


credit: CJPL



J. F. Beacom et al, arXiv: 1602.01733

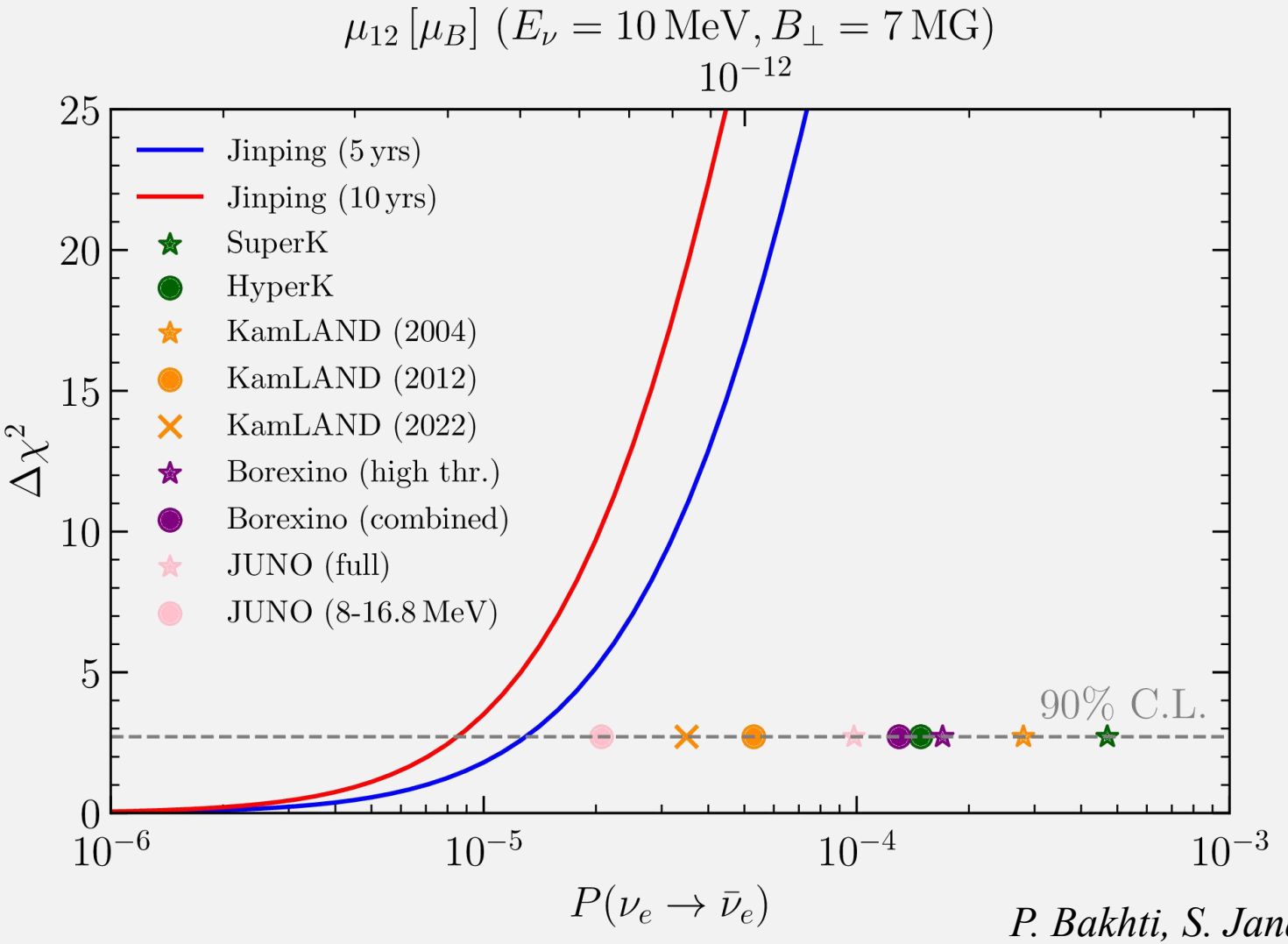
Jinping Experimental Sensitivities



$E_{\rm vis} \approx E_\nu - 0.78\,{\rm MeV}$

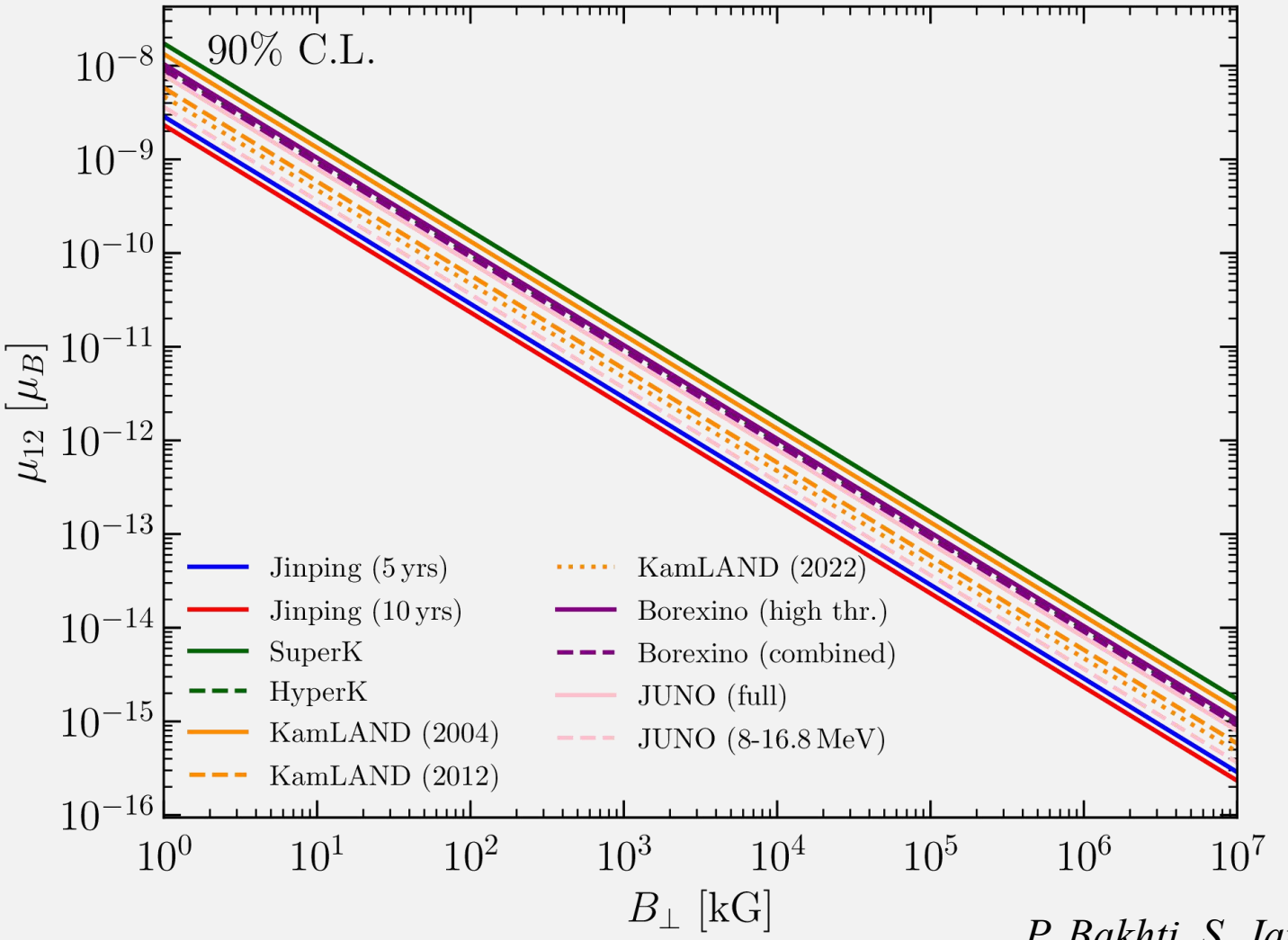
P. Bakhti, S. Jana, ***CFK****, S. Shin, S. Yun*
arXiv:2609.14446

Jinping Experimental Sensitivities



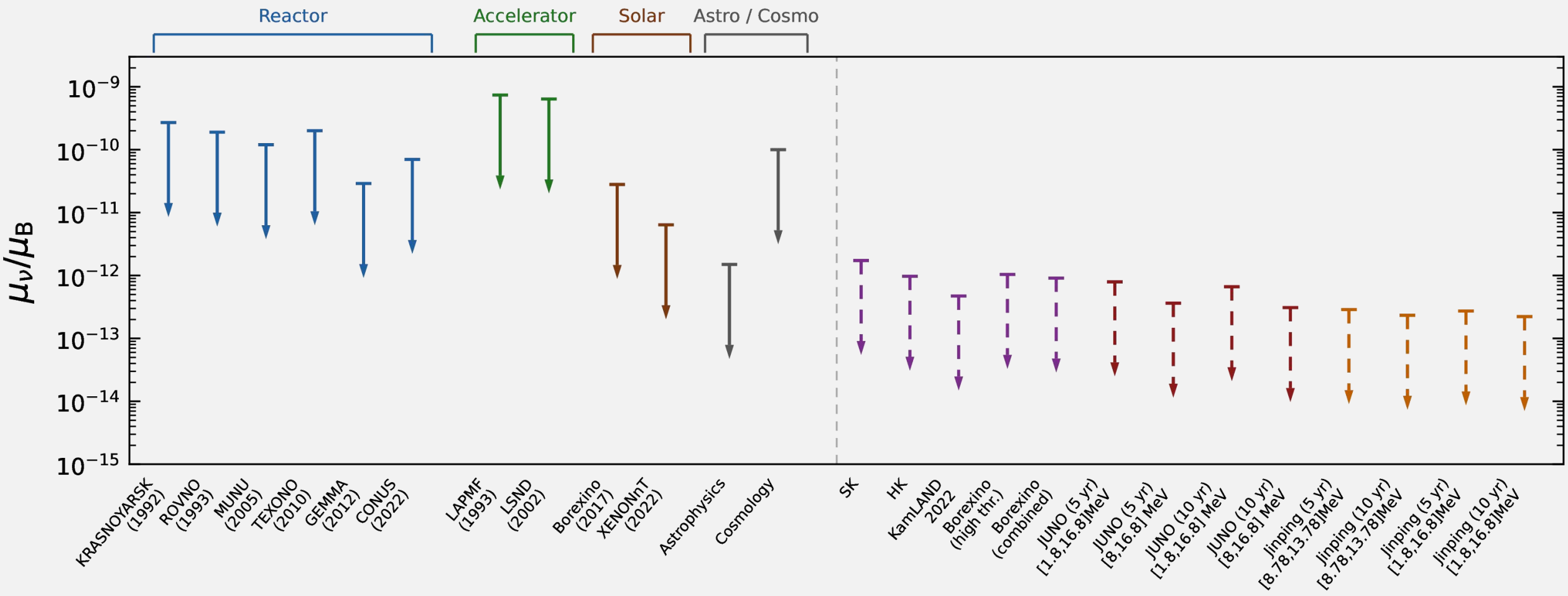
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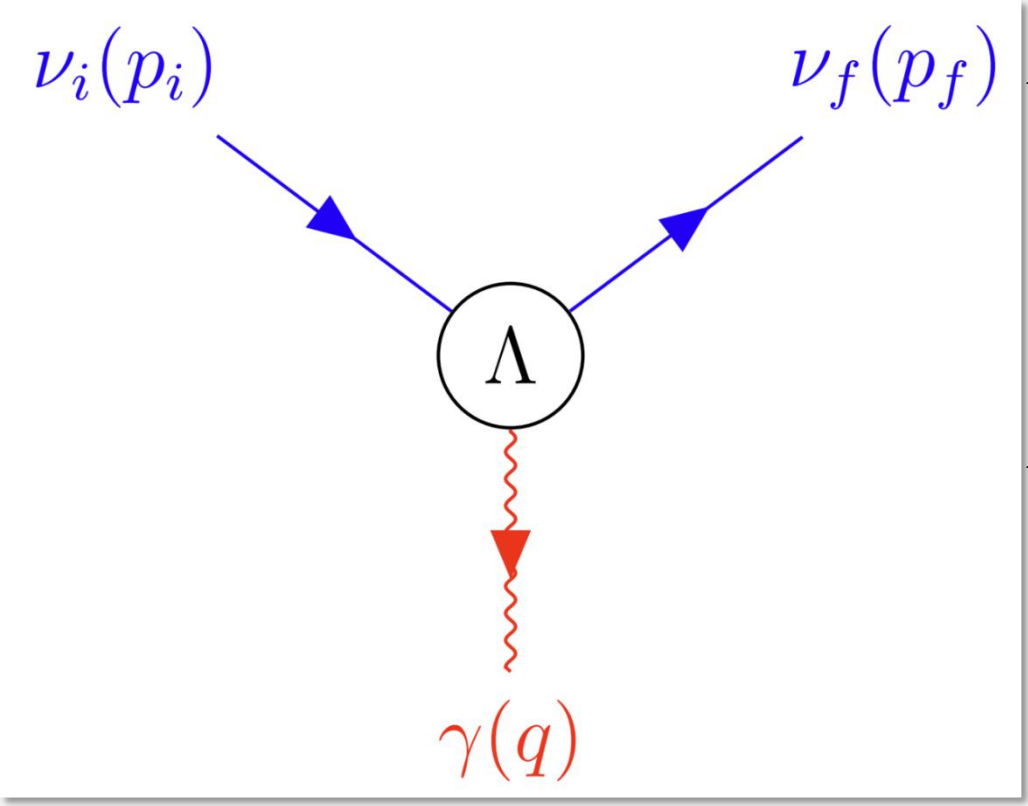
Summary

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- Neutrino magnetic moment is well motivated in BSM
- Due to the pure neutrino flavor and strong magnetic field, the sun provides an ideal source
- Searching for electron antineutrino transited from electron neutrino at Jinping can set strong constraint on NMM

Back up

Neutrino EM Form Factors



C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin arXiv:2411.03122

- The matrix of F^M is Hermitian:

$$F^M = F^{M\dagger} \leftrightarrow F^M_{fi} = (F^M_{if})^*$$

the diagonal form factors F^M_{ii} are real

- For antineutrinos,

$$\overline{F}^M = -(F^M)^T = -(F^M)^*$$
$$\updownarrow$$
$$\overline{F}^M_{fi} = -F^M_{if} = -(F^M_{fi})^*$$

the diagonal form factors are real with opposite sign

- For Majorana neutrinos, neutrino-antineutrino equality

$$F^M = -(F^M)^T = -(F^M)^*$$
$$\updownarrow$$
$$F^M_{fi} = -F^M_{if} = -(F^M_{fi})^*$$

diagonal form factors are zero and only imaginary off-diagonal form factors

Dirac & Majorana Neutrinos

Institute for Basic Science

$$\mathcal{L}^D_{CC} = -\frac{g}{\sqrt{2}}\left[W^-_\mu \bar{e}\gamma^\mu P_L \nu + W^+_\mu \bar{\nu}\gamma^\mu P_L e\right]$$

$$\nu_L \sim a_- u_- + b^\dagger_+ v_+$$

$$\overline{\nu_L} \sim a^\dagger_- \bar{u}_- + b_+ \bar{\nu}_+$$

$$\nu_e + n \to e^- + p$$

$$\bar{\nu}_e + p \to e^+ + n$$

$$\mathcal{L}^M_{CC} = -\frac{g}{\sqrt{2}}\left[W^-_\mu \bar{e}\gamma^\mu P_L N + W^+_\mu \overline{e^c_L}\gamma^\mu N_R + W^+_\mu \bar{N}\gamma^\mu P_L e\right]$$

$$N_L \sim a_- u_- + a^\dagger_+ v_+$$

$$N^c_L = N_R \sim a_+ u_+ + a^\dagger_- v_-$$

$$\nu_e + n \to e^- + p$$

$$\nu^c_e + p \to e^+ + n$$

Transition Probability