

*Exploiting a future galactic
supernova to probe neutrino
magnetic moments*

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(Unicamp)**

Talk based on [arXiv:2203.01950](https://arxiv.org/abs/2203.01950)
with Sudip Jana and Manibrata Sen

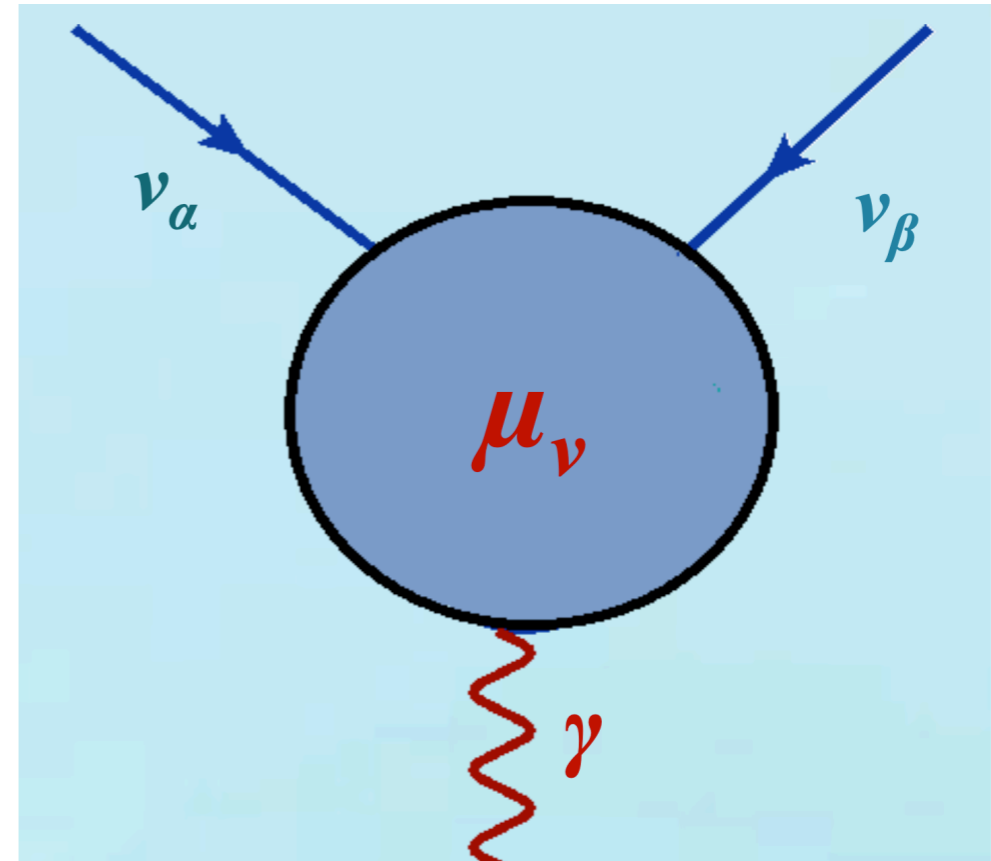


**NBIA Summer School
NBI, Copenhagen
July, 2022**



Neutrino electromagnetic properties

- Quantum loop corrections can induce EM properties of neutrinos;



SC: S. Jana

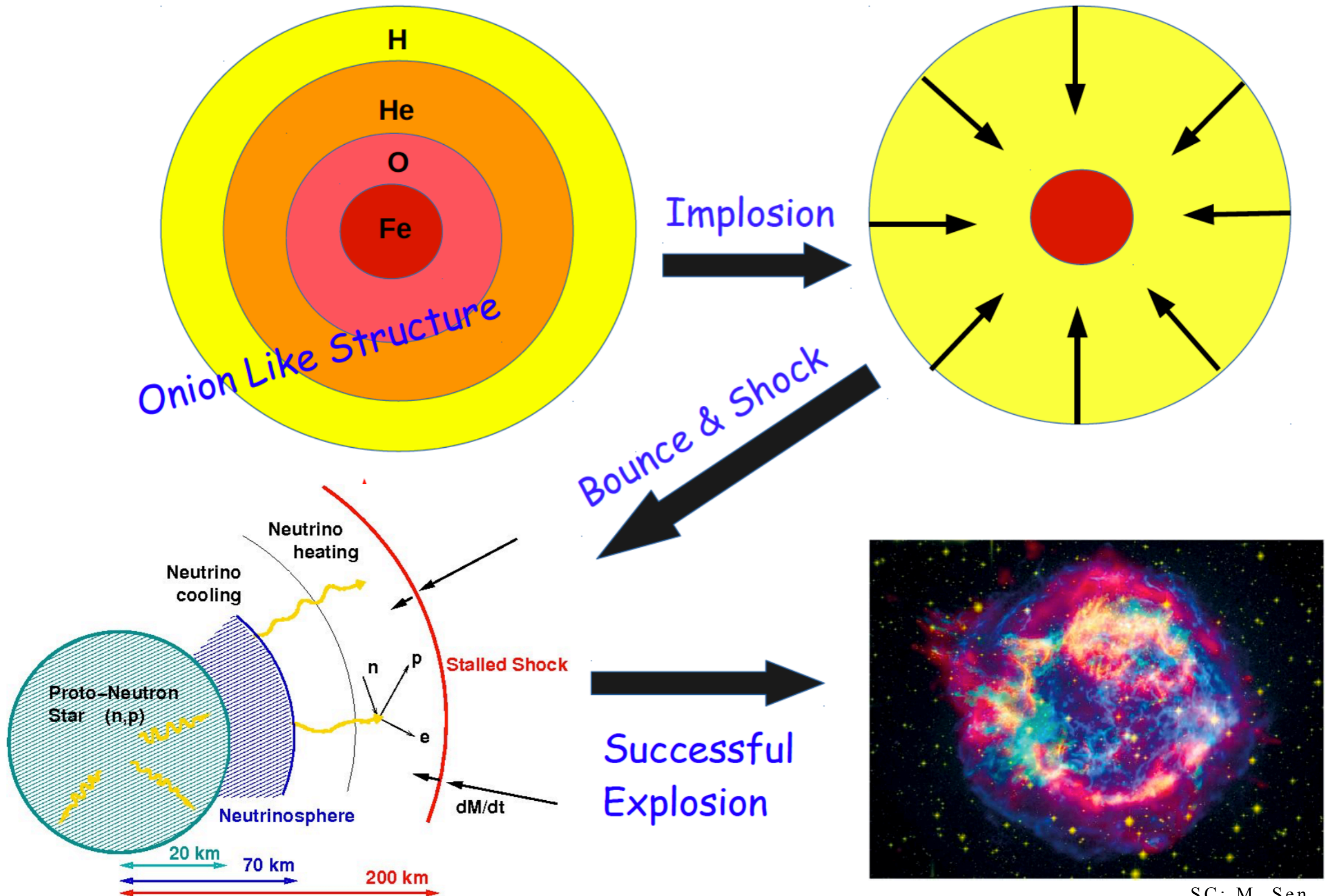
Babu, Jana, Lindner, [arXiv:2007.04291](https://arxiv.org/abs/2007.04291)

Giunti, Studenikin, [arXiv:1403.6344](https://arxiv.org/abs/1403.6344)

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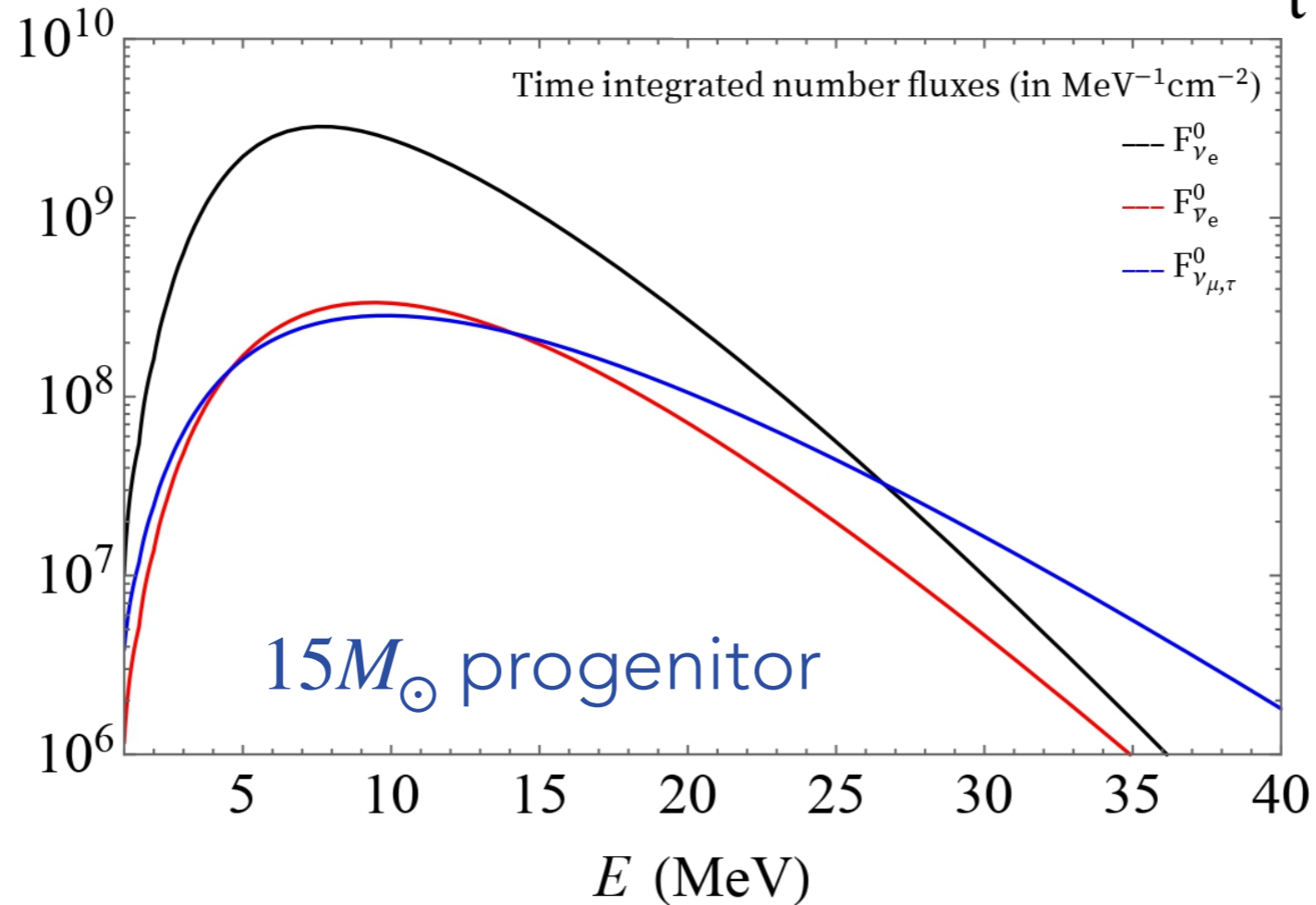
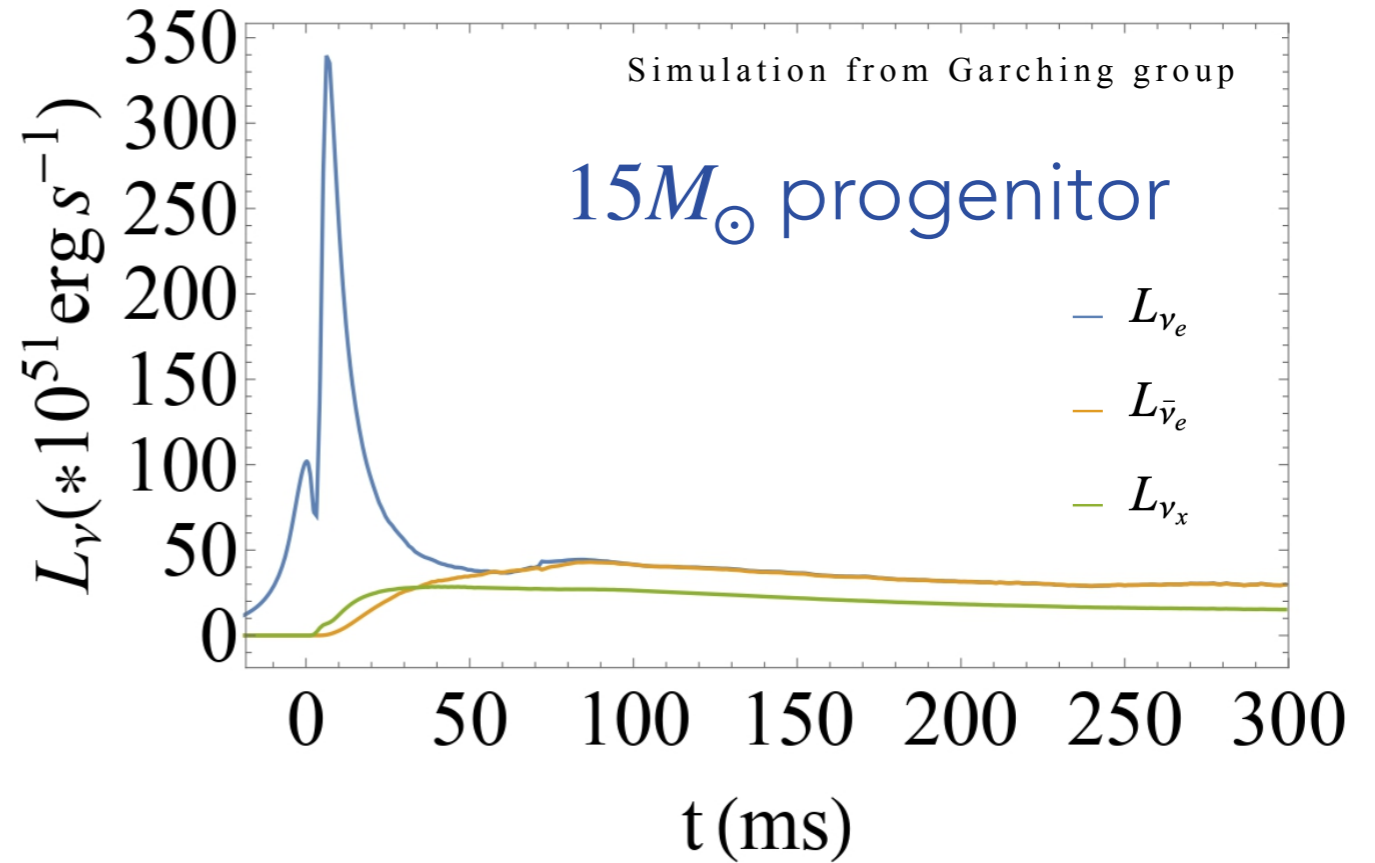
Core-collapse Supernova

(Seminar by Shashank Shalgar)



Neutronization Burst

- It lasts for 30 ms after core bounce.
- Electron capture on protons leads to large burst of ν_e .



Flavor conversion in presence of neutrino magnetic moments

- Transition magnetic moments:

$$\mathcal{L}_M \supset \mu_{\alpha\beta} \nu_{\alpha L}^T C \sigma_{\eta\delta} \nu_{\beta L} F^{\eta\delta}$$

- Neutrino evolution equation:

$$i \frac{d}{dr} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} = \begin{pmatrix} H_\nu & B_\perp M \\ -B_\perp M & H_{\bar{\nu}} \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix}$$

- Neutrino Hamiltonian in matter:

$$H_\nu = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{\nu_e} & 0 & 0 \\ 0 & V_{\nu_\mu} & 0 \\ 0 & 0 & V_{\nu_\tau} \end{pmatrix}$$

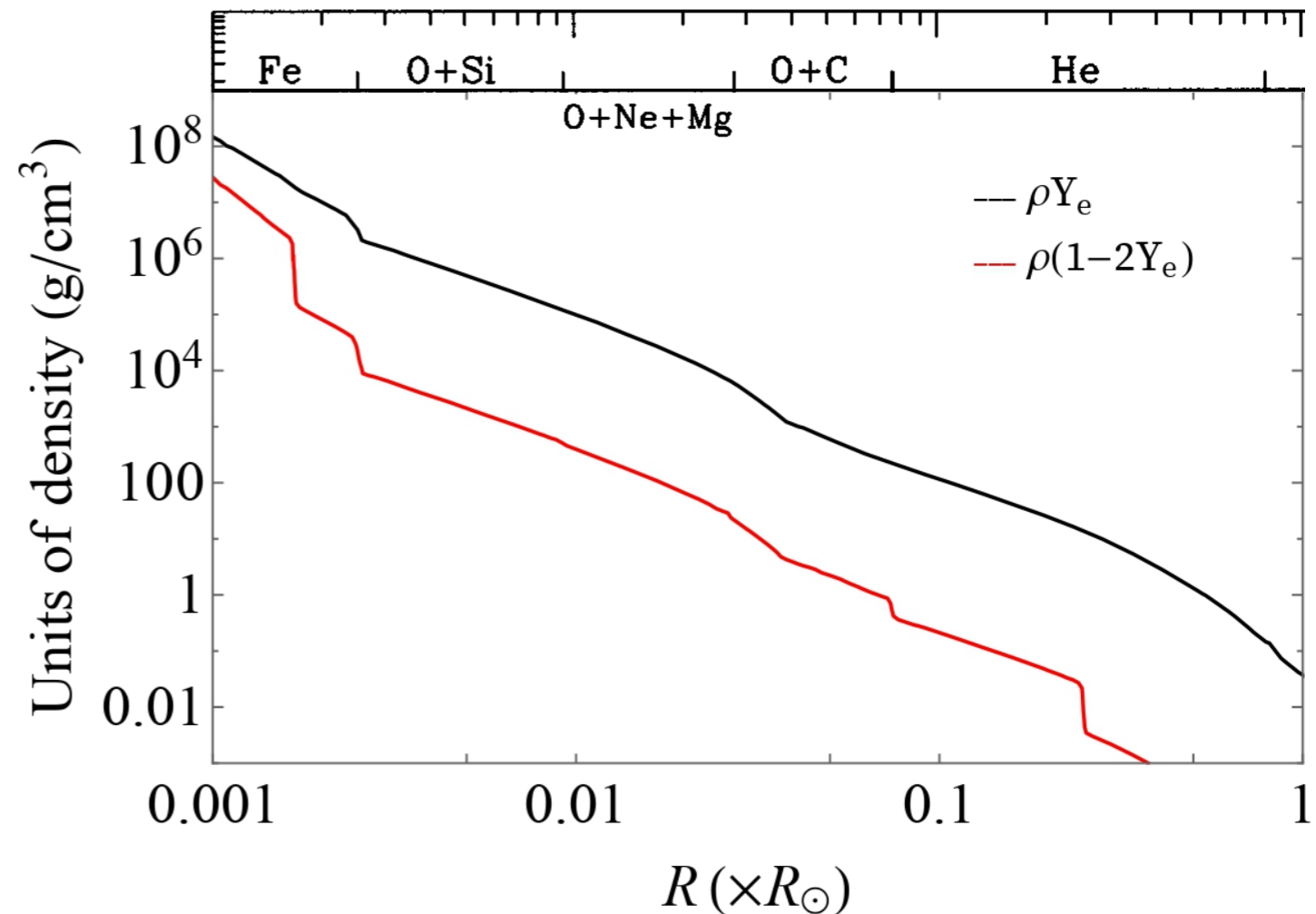
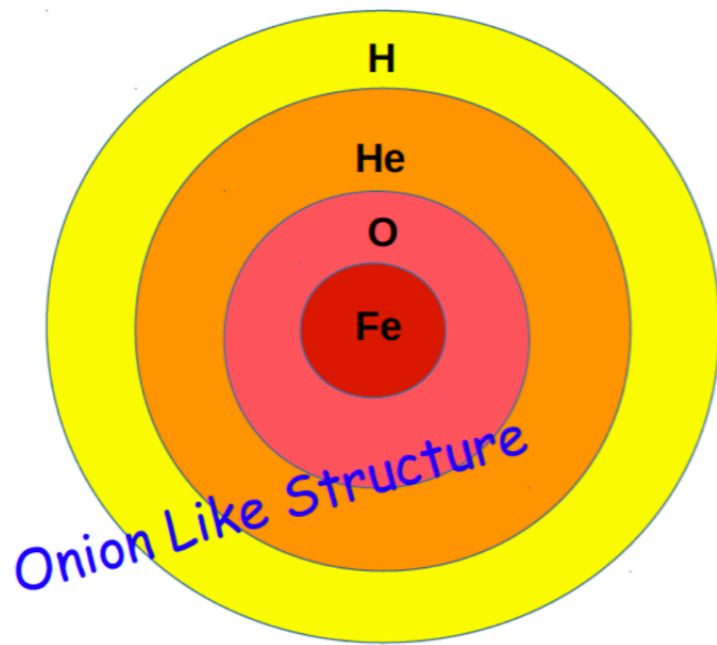
Flavor conversion in presence of neutrino magnetic moments

- Transition magnetic moments:

$$M = \begin{pmatrix} 0 & \mu_{e\mu} & \mu_{e\tau} \\ -\mu_{e\mu} & 0 & \mu_{\mu\tau} \\ -\mu_{e\tau} & -\mu_{\mu\tau} & 0 \end{pmatrix}$$

- Magnetic field:

$$B_{\perp} = B_0 \left(\frac{r_0}{r} \right)^3$$



Woosley, Weaver, *Astrophys. J. Suppl.* 101 (1995) 181–235.

Ando, Sato, [arXiv:hep-ph/0211053](https://arxiv.org/abs/hep-ph/0211053)

Totani, Sato, [arXiv:astro-ph/9609035](https://arxiv.org/abs/astro-ph/9609035)

Conditions for MSW and RSFP resonances

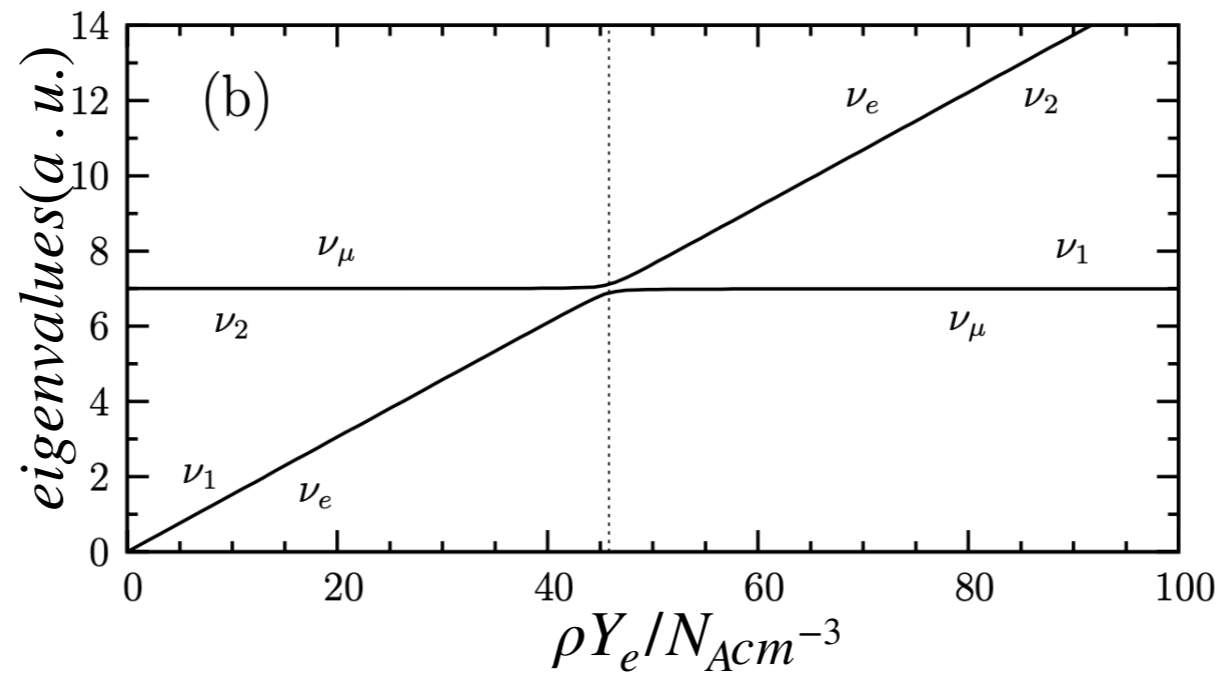
MSW (Mikheyev-Smirnov-Wolfenstein)

- MSW condition
j=2 for L and j=3 for H:

$$\sqrt{2}G_F \frac{\rho}{m_N} Y_e \approx \frac{|\Delta m_{j1}^2|}{2E} \cos 2\theta_{1j}$$

$$\nu_e \leftrightarrow \nu_\mu \quad \nu_e \leftrightarrow \nu_\tau$$

$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu \quad \bar{\nu}_e \leftrightarrow \bar{\nu}_\tau$$



(Remember the MSW matter contribution from Joachim Kopp's lecture)

Conditions for MSW and RSFP resonances

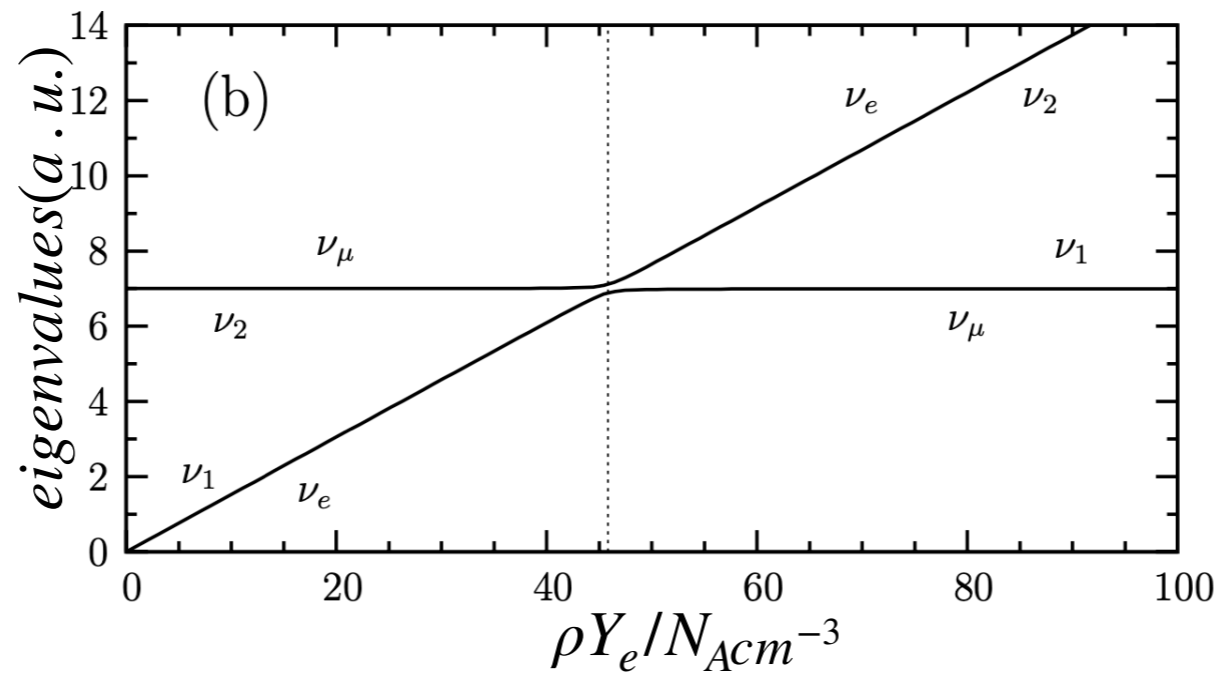
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RSFP (Resonant Spin-Flavour Precession)

- RSFP condition
j=2 for L and j=3 for H:

$$\sqrt{2}G_F \frac{\rho}{m_N} (1 - 2Y_e) \approx \frac{|\Delta m_{j1}^2|}{2E} \cos 2\theta_{1j}$$

- RSFP-E

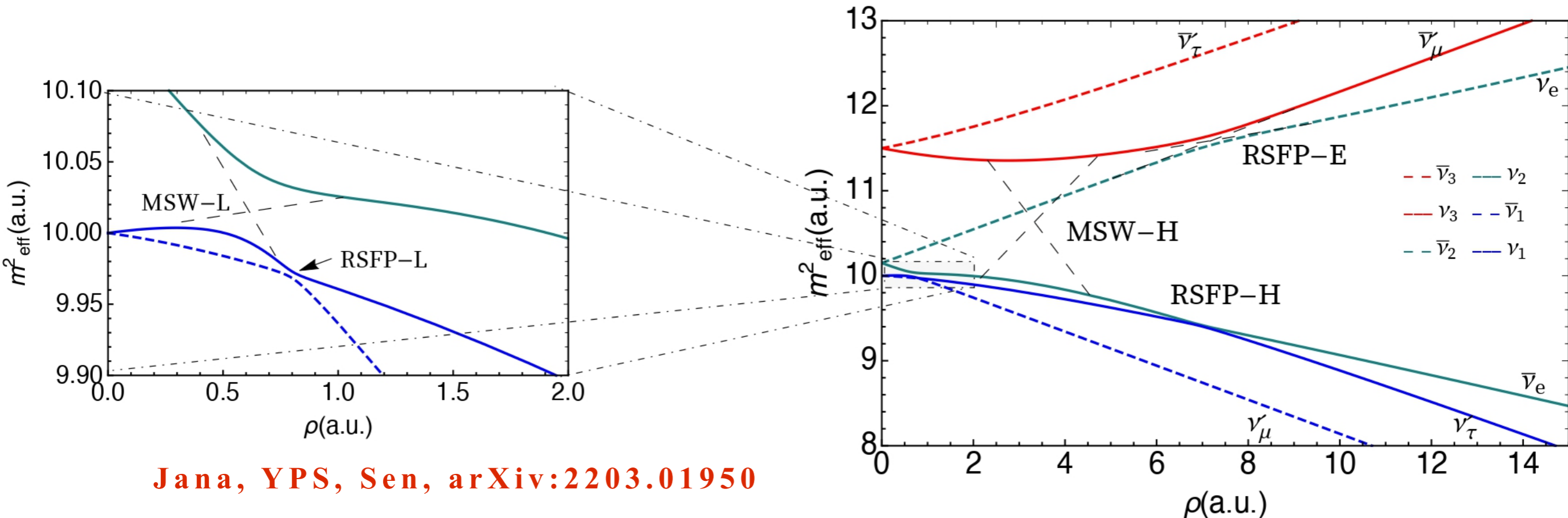
$$\nu_e \leftrightarrow \bar{\nu}_\tau \quad \nu_e \leftrightarrow \bar{\nu}_\mu$$

$$\bar{\nu}_e \leftrightarrow \nu_\mu \quad \bar{\nu}_e \leftrightarrow \nu_\tau$$

Level crossing diagram (normal ordering)

- Five resonances: RSFP-H, RSFP-L (non-ad), RSFP-E (non-ad), MSW-H (ad) and MSW-L (ad).
- RSFP-H is partially adiabatic: $0.5 \times 10^{-3} \mu_B G \lesssim \mu_\nu B_0 \lesssim 10^{-2} \mu_B G$
- Results depend on the hopping probability at RSFP-H: $p_H = e^{-\frac{\pi}{2} \gamma_{RSFP-H}}$

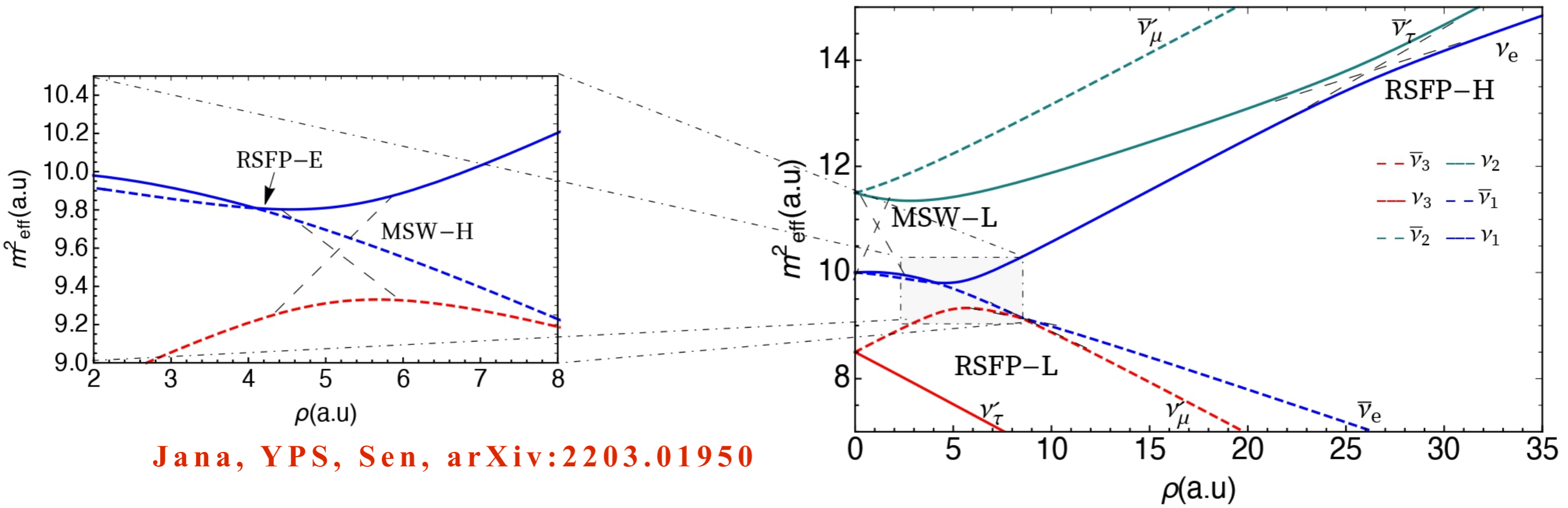
$$\begin{aligned}
 F_{\nu_e} &= F_{\nu_e}^{MSW} - |U_{e2}|^2 (1 - p_H) (F_{\nu_x}^0 - F_{\bar{\nu}_e}^0) \\
 F_{\bar{\nu}_e} &= F_{\bar{\nu}_e}^{MSW} + |U_{e1}|^2 (1 - p_H) (F_{\nu_x}^0 - F_{\bar{\nu}_e}^0)
 \end{aligned}$$



Level crossing diagram (inverted ordering)

- Five resonances: RSFP-H, RSFP-L (non-ad), RSFP-E (non-ad), MSW-H (ad) and MSW-L (ad).
- RSFP-H is partially adiabatic: $0.5 \times 10^{-3} \mu_B G \lesssim \mu_\nu B_0 \lesssim 10^{-2} \mu_B G$
- Results depend on the hopping probability at RSFP-H: $p_H = e^{-\frac{\pi}{2} \gamma_{RSFP-H}}$

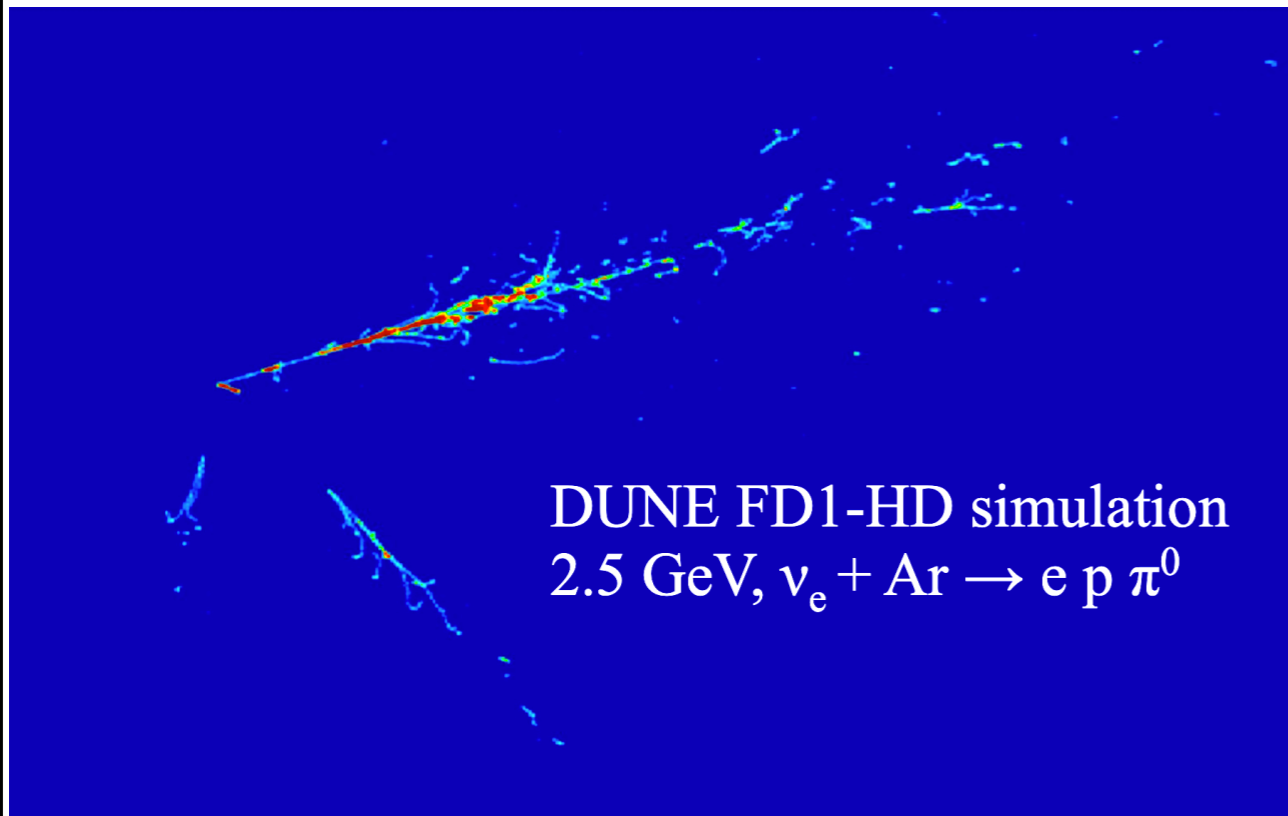
$$\begin{aligned}
 F_{\nu_e} &= F_{\nu_e}^{MSW} - |U_{e2}|^2 (1 - p_H) (F_{\nu_e}^0 - F_{\nu_x}^0) \\
 F_{\bar{\nu}_e} &= F_{\bar{\nu}_e}^{MSW} + |U_{e1}|^2 (1 - p_H) (F_{\nu_e}^0 - F_{\nu_x}^0)
 \end{aligned}$$



Upcoming neutrino detectors

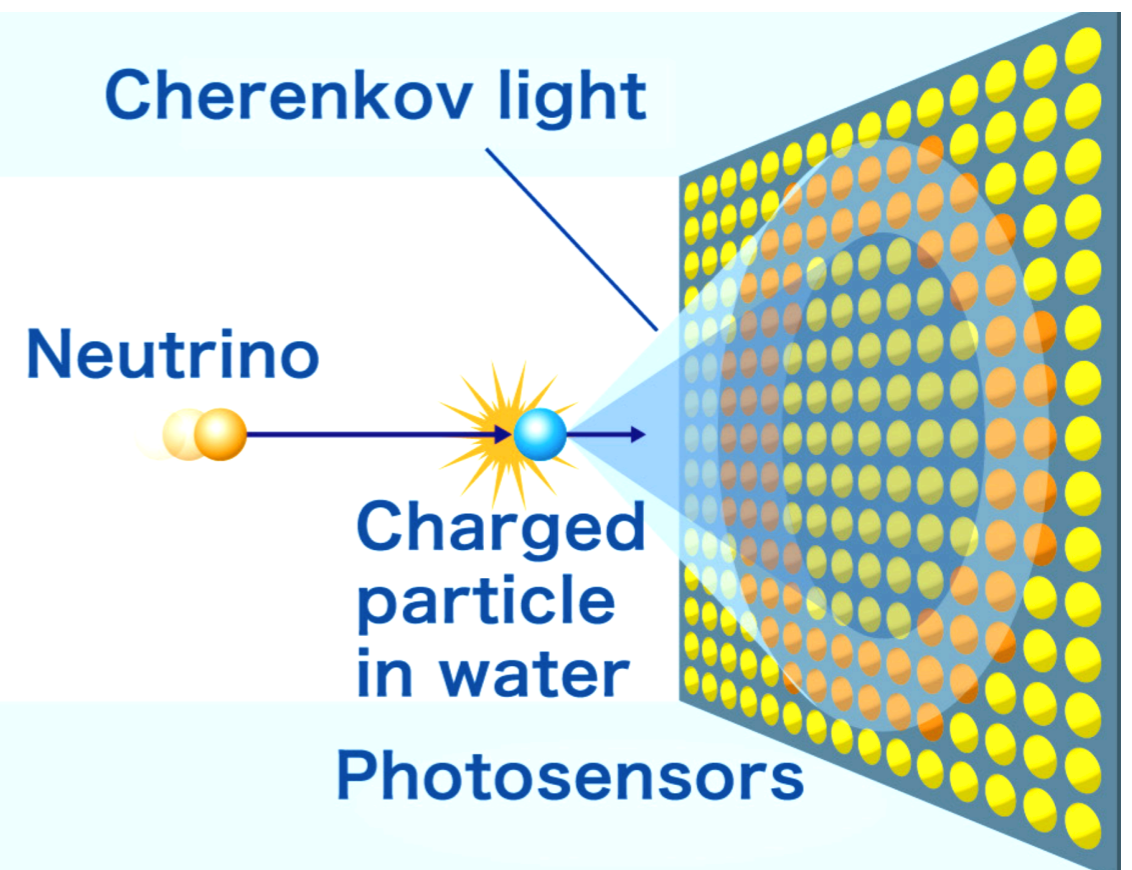
DUNE

- 40-kton of liquid argon time projection chamber;
- $\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$;
- $\sigma_E/E_r \sim 5\%$ at 10 MeV.

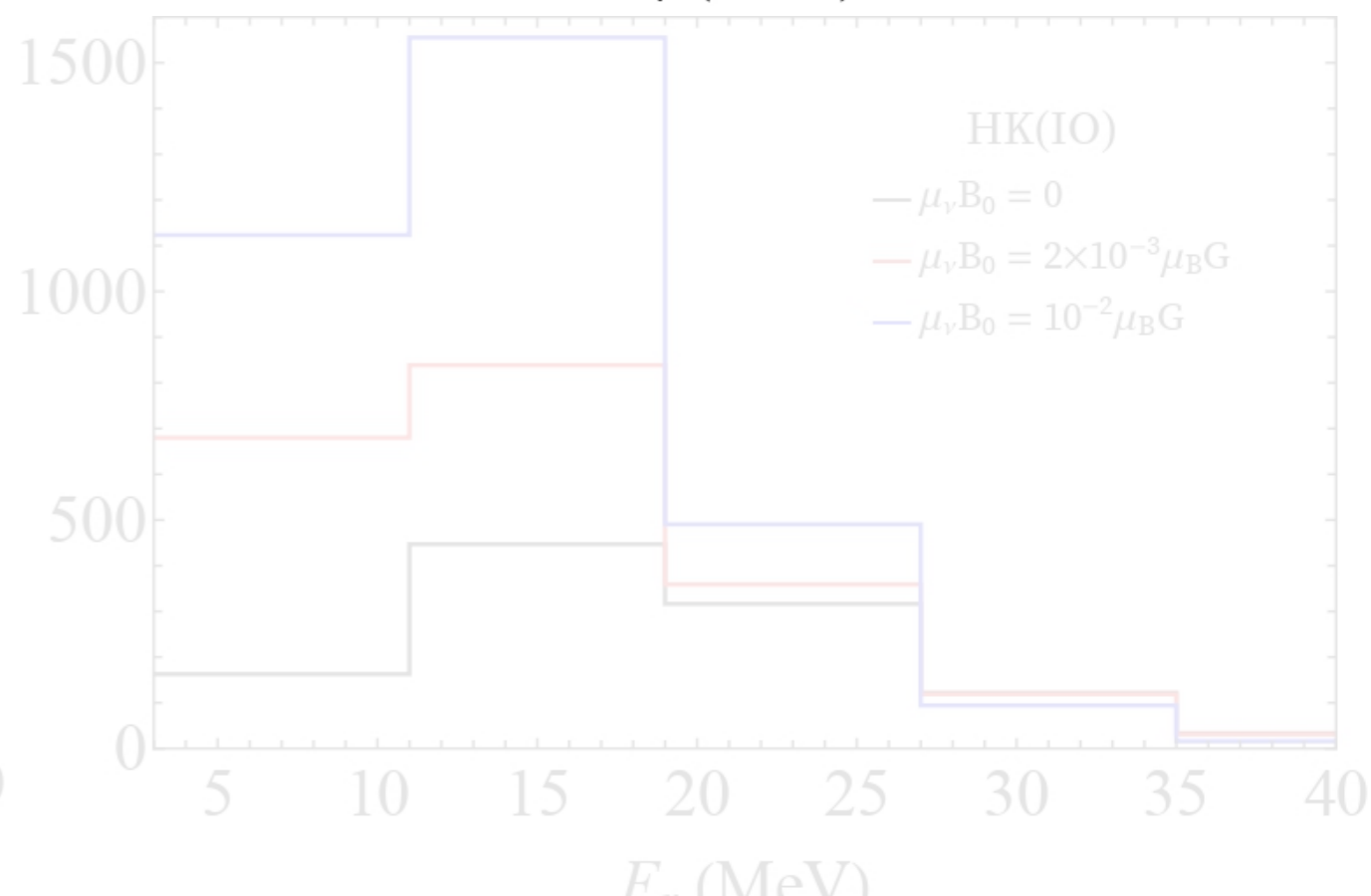
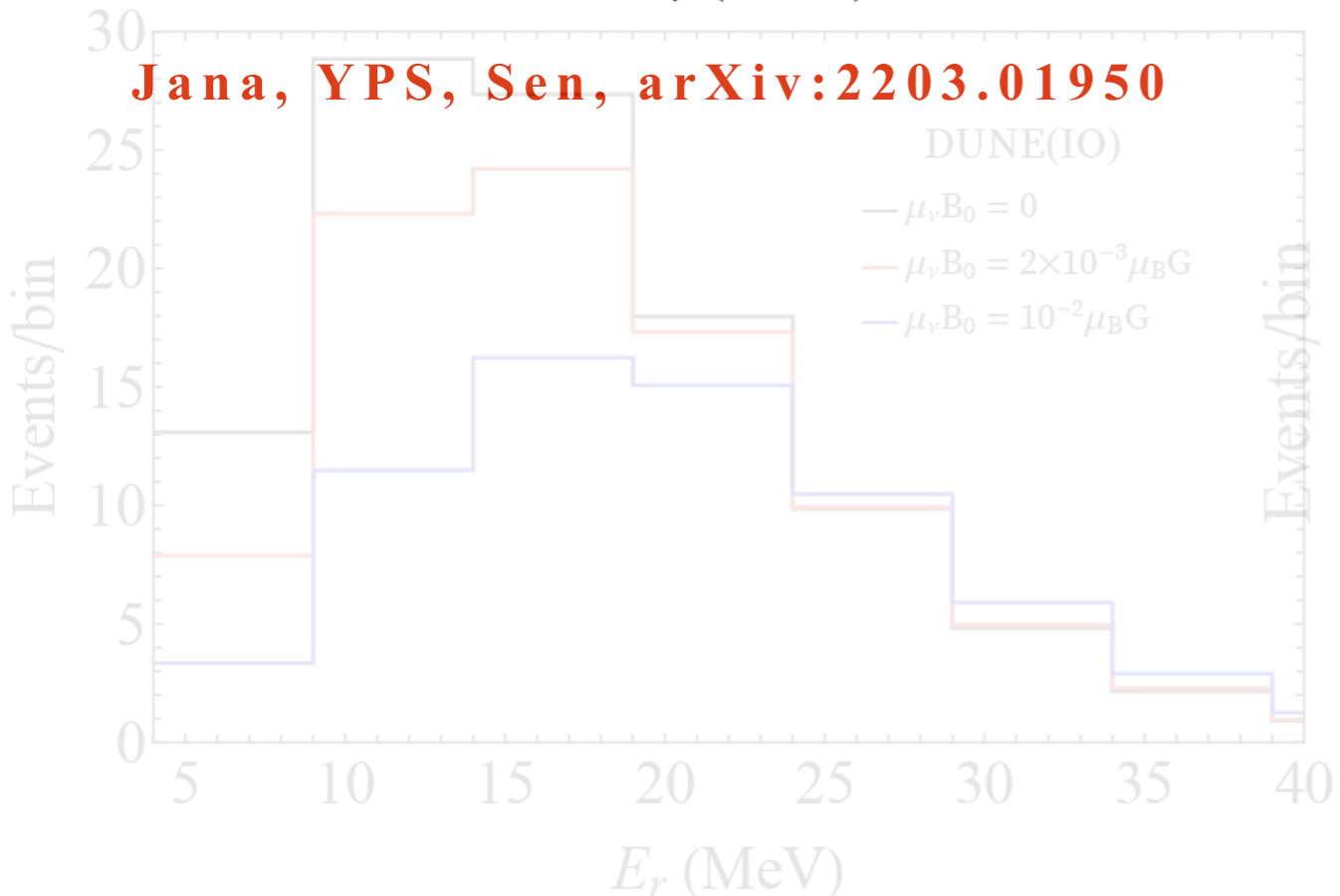
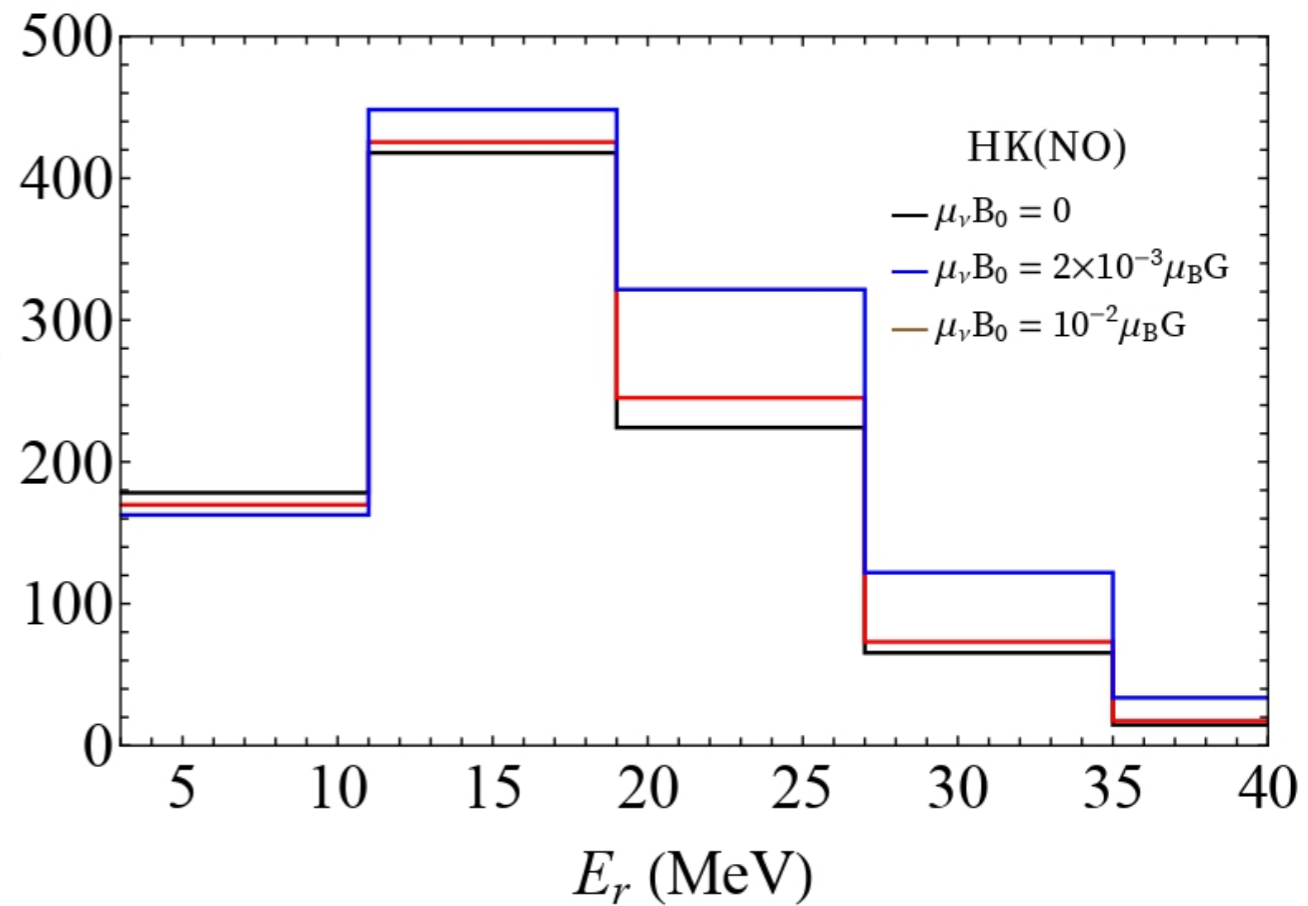
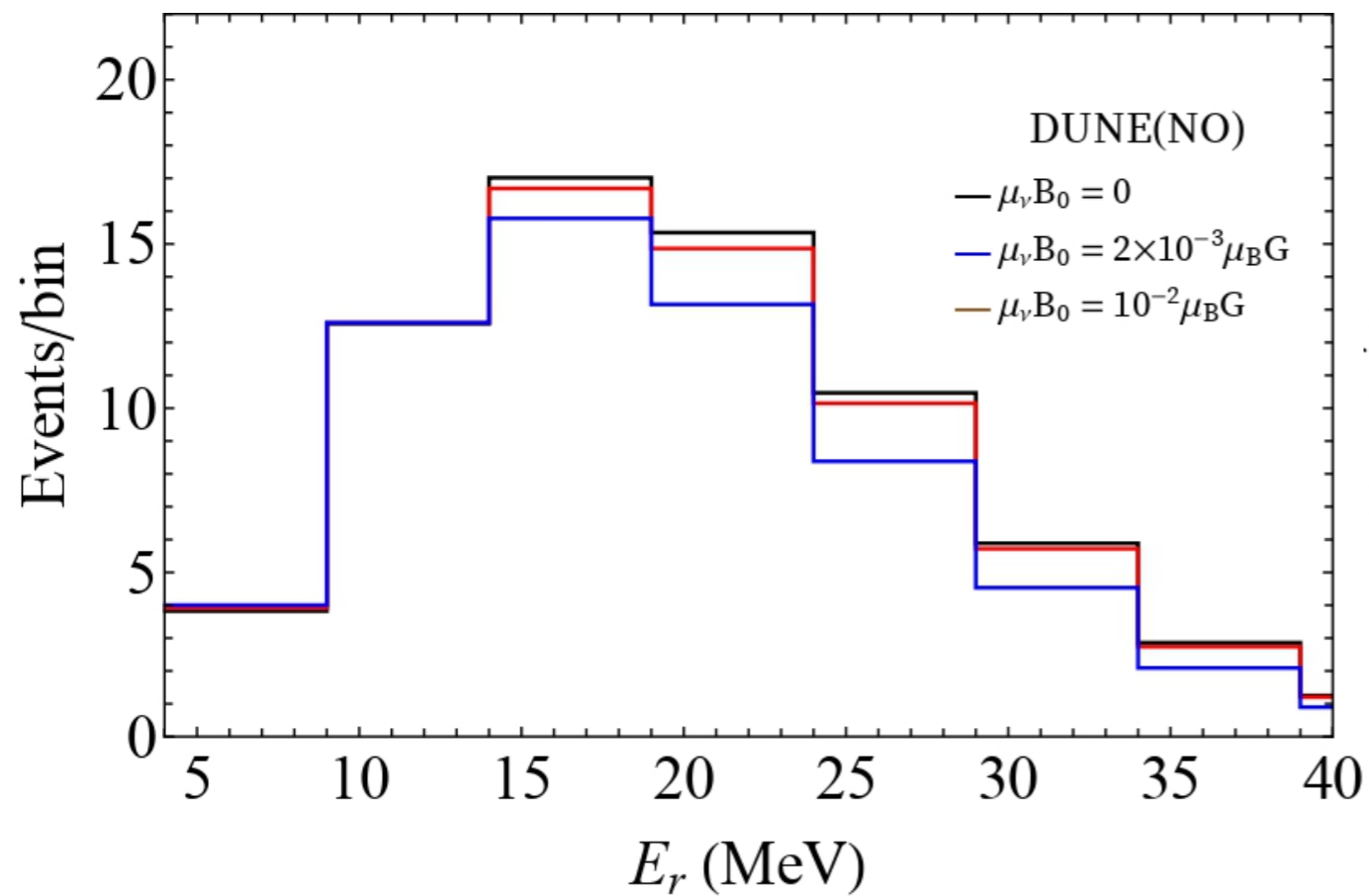


HK

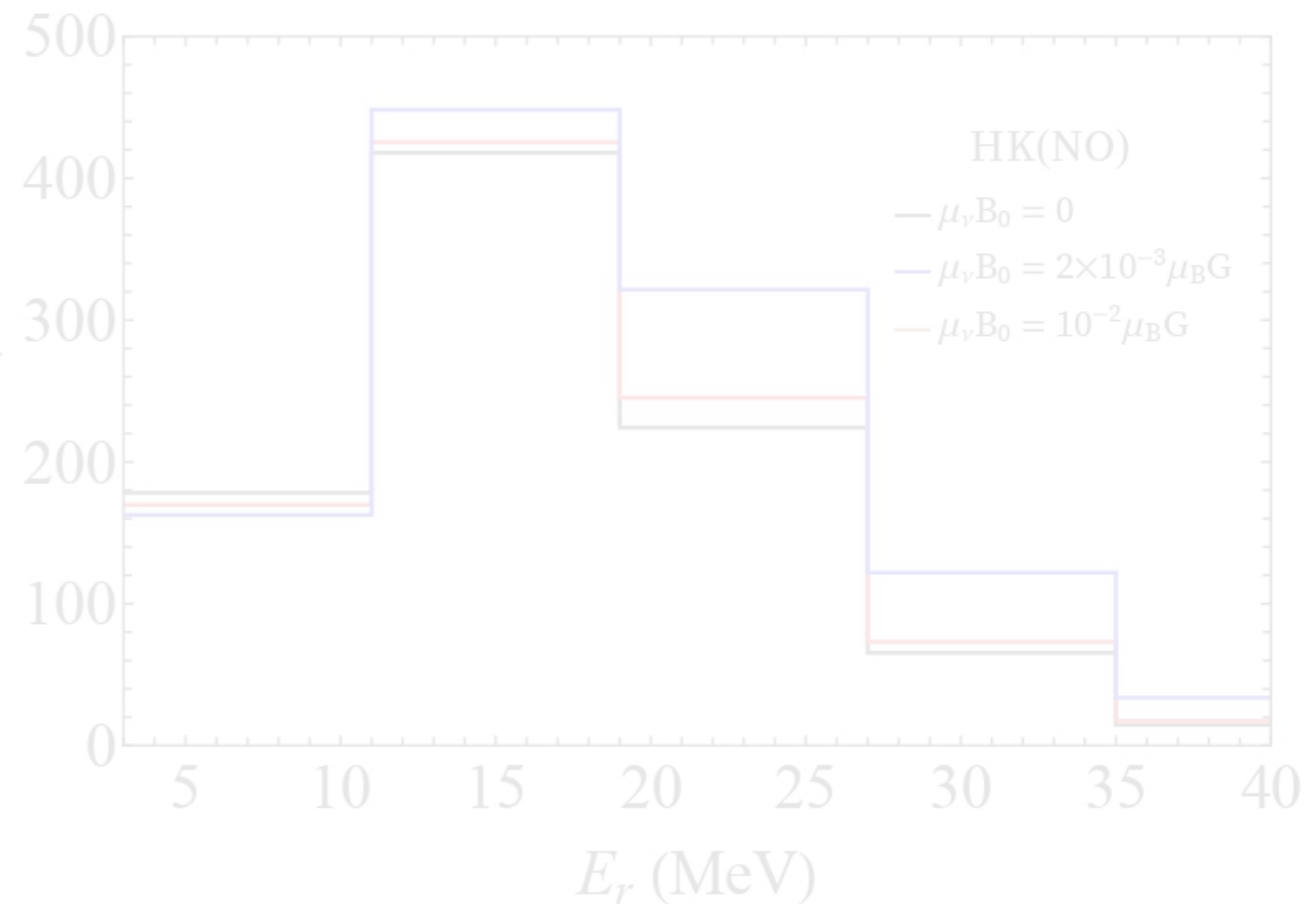
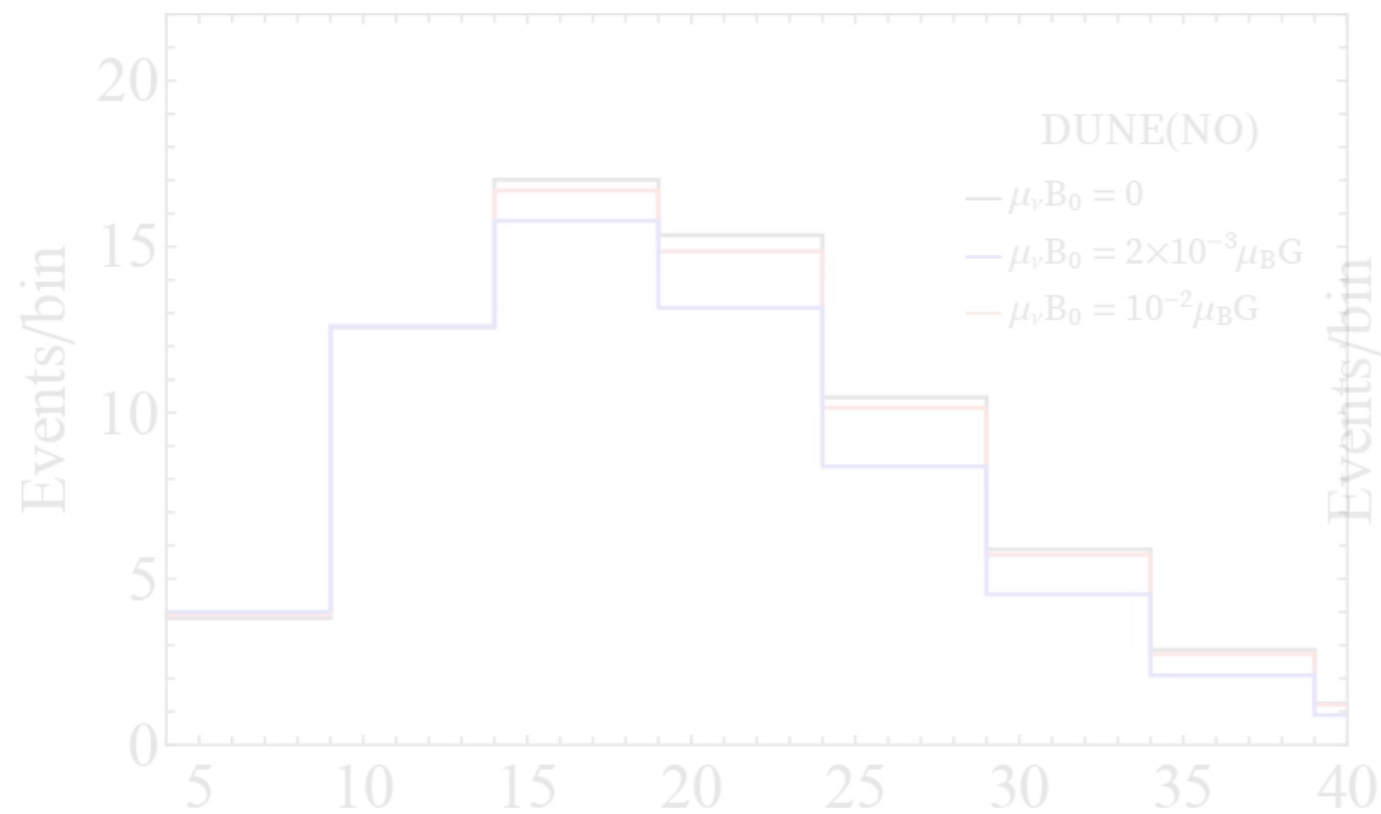
- Water Cherenkov detector, fiducial volume 187 kt in each of two tanks;
- $\bar{\nu}_e + p \rightarrow e^+ + n$;
- $\sigma_E/E_r \sim 20\%$ at 10 MeV.



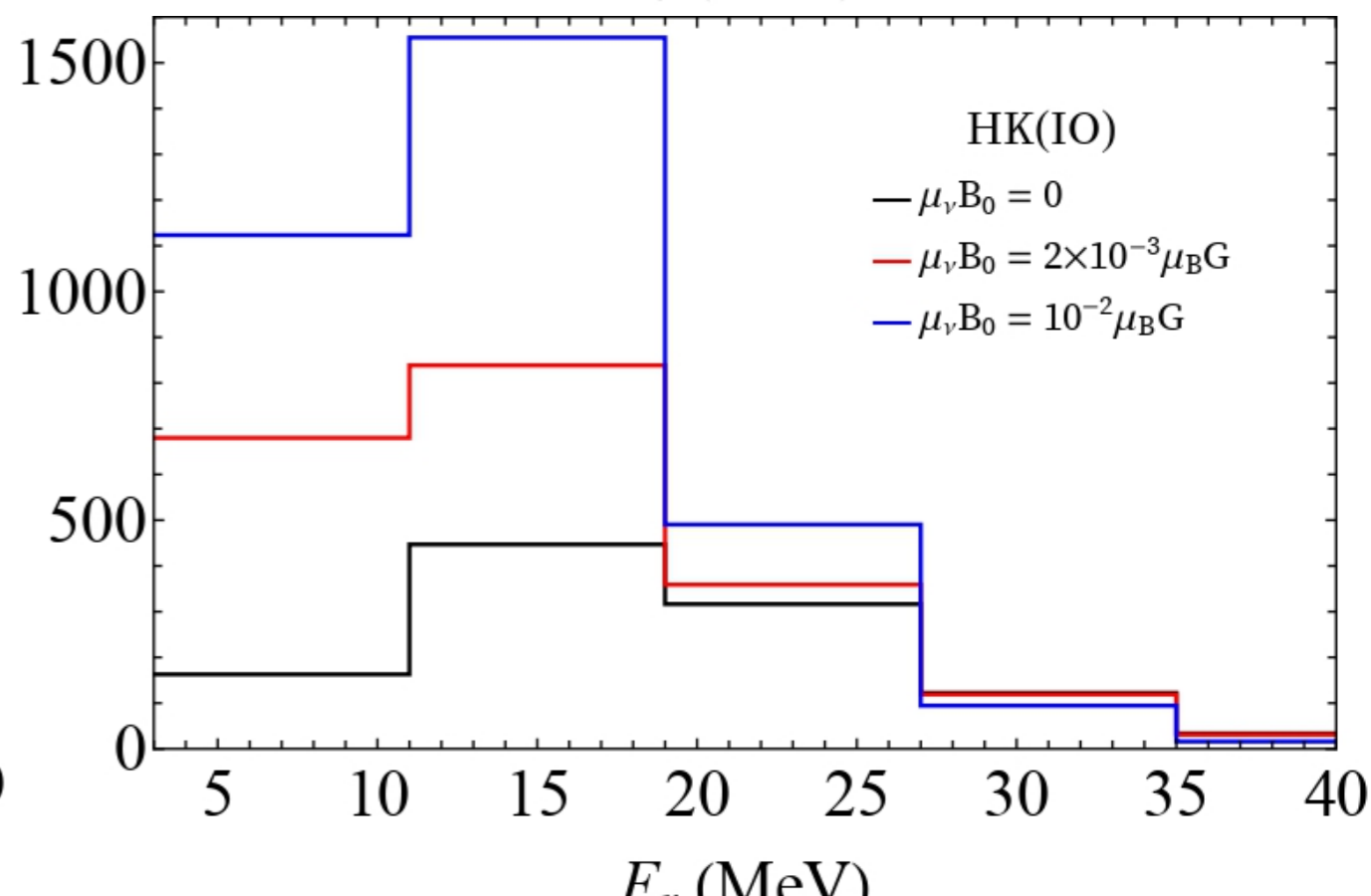
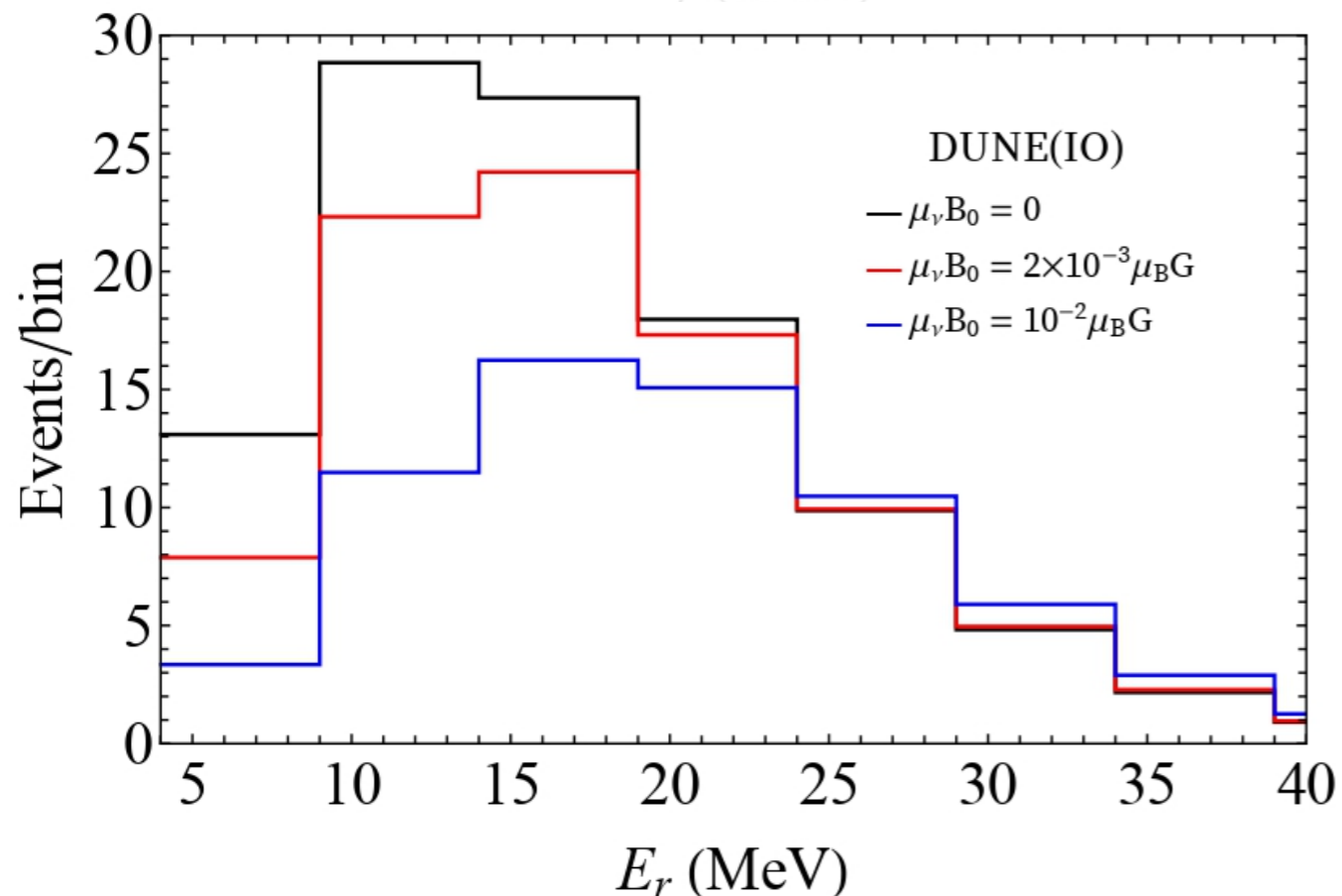
Event spectra (normal ordering)



Event spectra (inverted ordering)



Jana, YPS, Sen, [arXiv:2203.01950](https://arxiv.org/abs/2203.01950)



Neutrino magnetic moments sensitivities

- For illustration: we set both $\mu_{e\mu}$ and $\mu_{e\tau}$ are equal, set to μ_ν (free parameter) for one benchmark point.
- We perform a χ^2 analysis assuming $\mu_\nu = 0$ as the true hypothesis to find the sensitivities below (assuming $B_0 = 10^{10}$ G and $d = 10$ kpc):

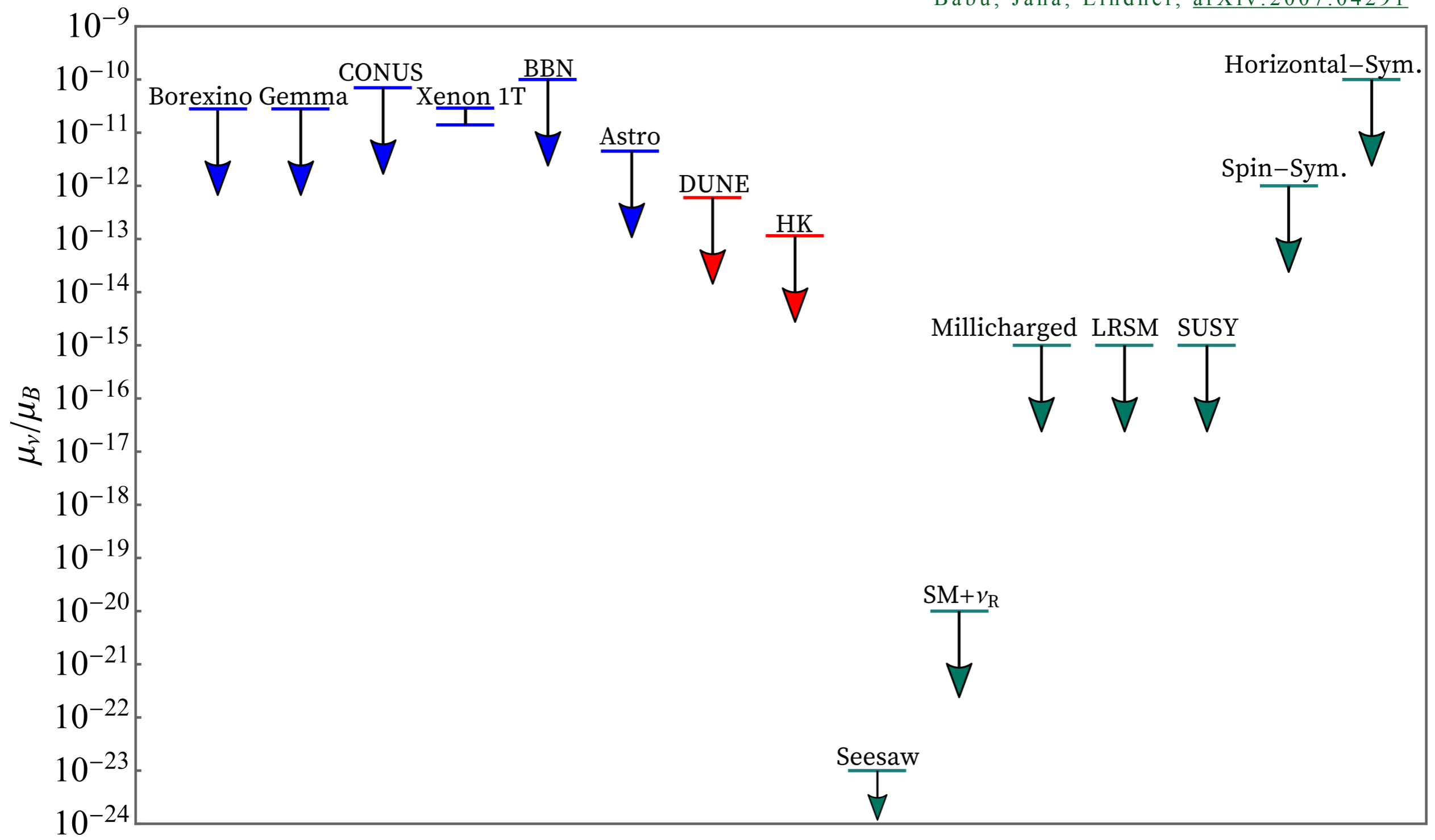
Sensitivities (in μ_B)

Experiments	NO	IO
HK	4.5×10^{-13}	6×10^{-14}
DUNE	—	3×10^{-13}

Jana, YPS, Sen, arXiv:2203.01950

Summary of sensitivities

Babu, Jana, Lindner, [arXiv:2007.04291](https://arxiv.org/abs/2007.04291)



Jana, YPS, Sen, [arXiv:2203.01950](https://arxiv.org/abs/2203.01950)

Implication for neutrino properties

- Dirac μ_ν over $10^{-14}\mu_B$ would generate unacceptably large neutrino masses. Therefore, for the values of μ_ν considered here, more likely for neutrinos to be Majorana.
- Removing the photon line from the diagram that generates μ_ν a neutrino mass term is generated.

Take away message

- Spin-flavor + MSW conversion leads to a suppression of ν_e while enhancing $\bar{\nu}_e$ spectra during neutronization burst phase.
- For a galactic SN, DUNE and HK can probe μ_ν from $O[10^{-11}]\mu_B$ up to $O[10^{-14}]\mu_B$.
- The detection of these values of μ_ν can shed light on the neutrino nature and its mass mechanism.

Thank you

