Exploiting a future galactic supernova to probe neutrino magnetic moments

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Talk based on arXiv:2203.01950 with Sudip Jana and Manibrata Sen

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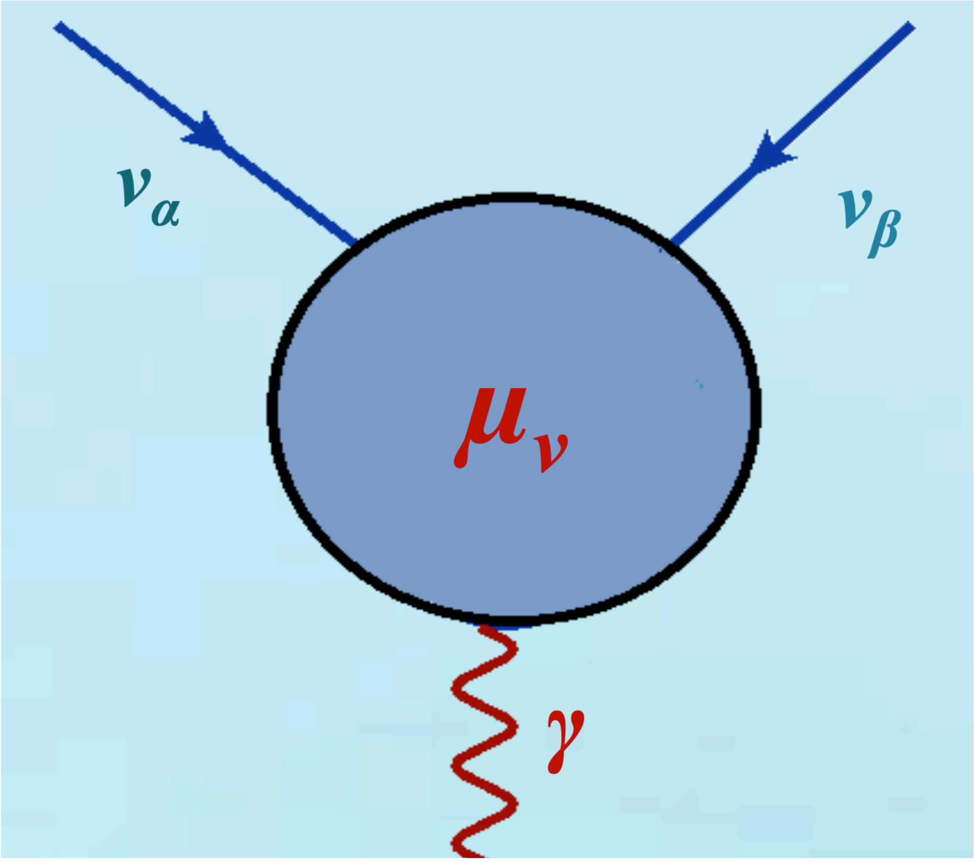
Neutrino electromagnetic properties

- In the standard model (SM) neutrinos do not have direct coupling to photons;

- Quantum loop corrections can induce EM properties of neutrinos;

- Study of neutrino EM interactions may shed light on the underlying theory.



SC: S. Jana

Babu, Jana, Lindner, arXiv:2007.04291
Giunti, Studenikin, arXiv:1403.6344
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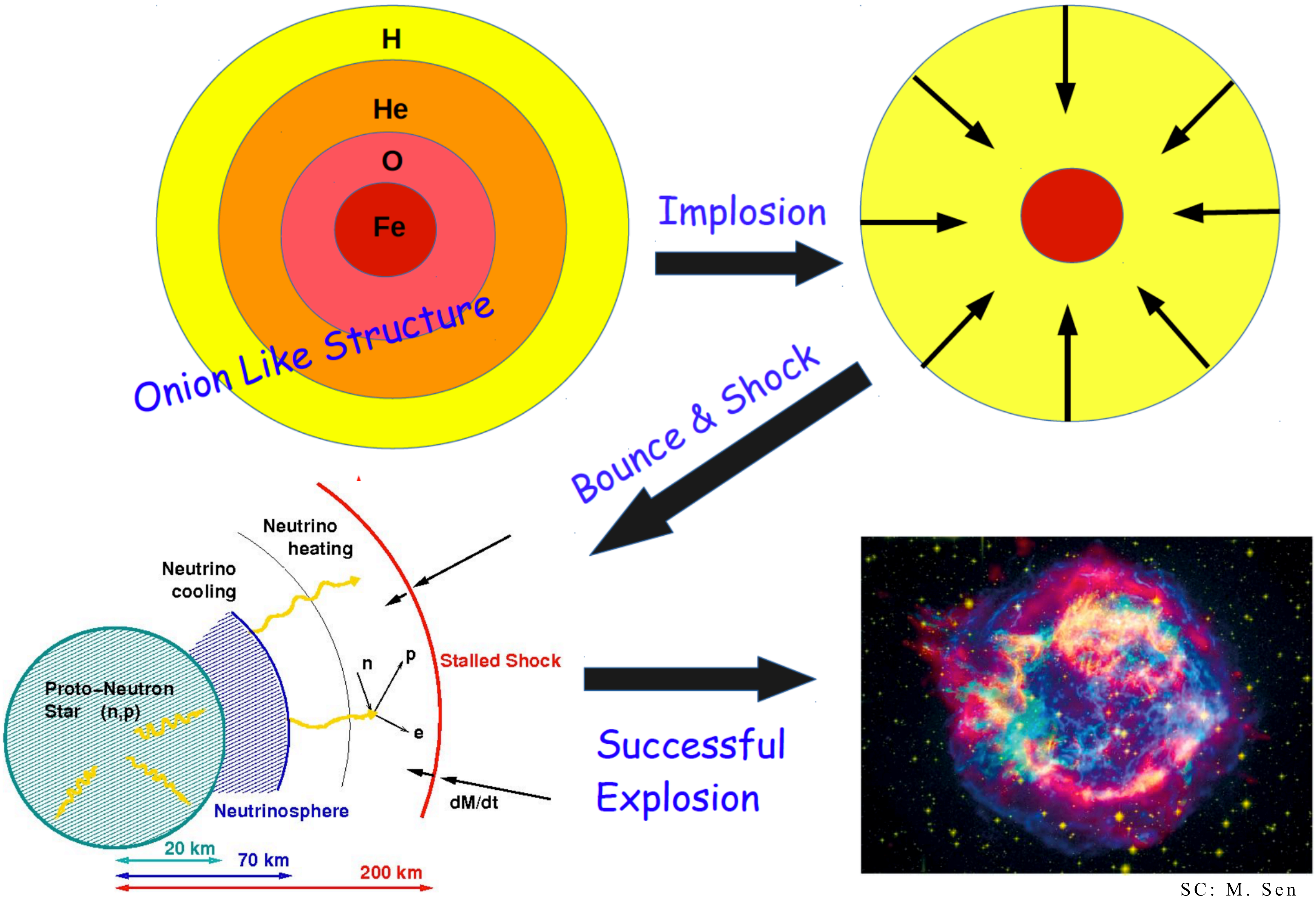
Core-collapse Supernova

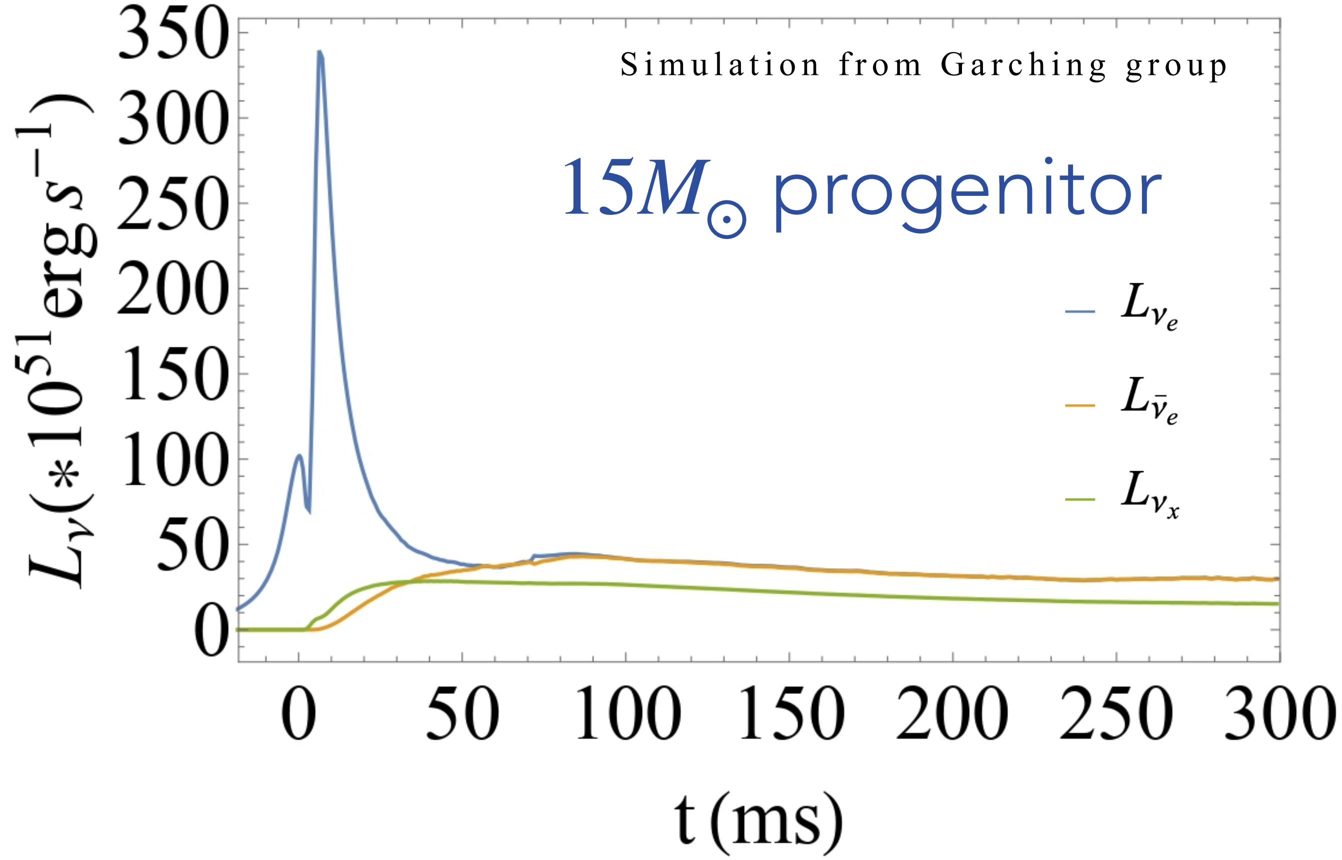


SC: M. Sen

Neutronization Burst

- It lasts for 30 ms after core bounce.

- Electron capture on protons leads to large burst of ν_e.



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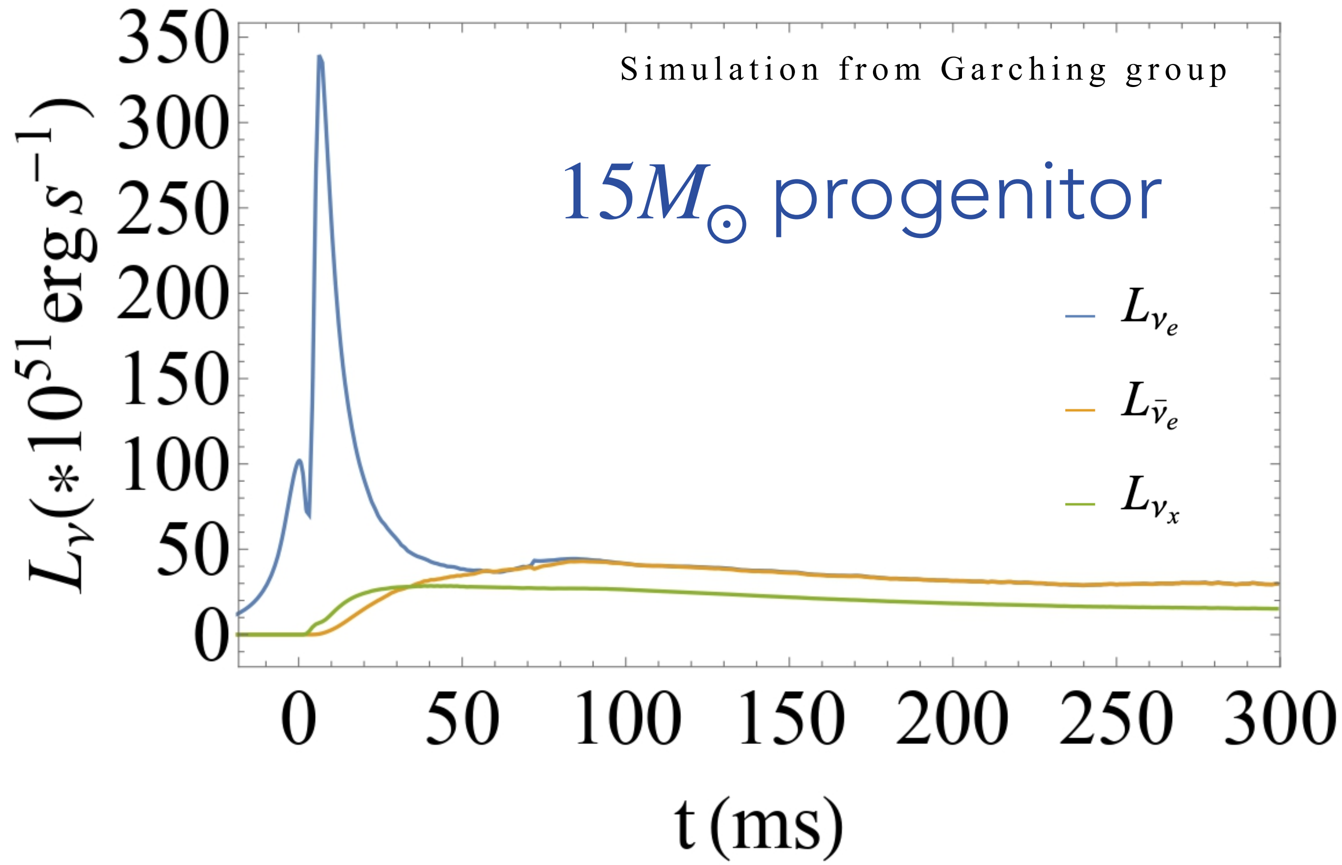
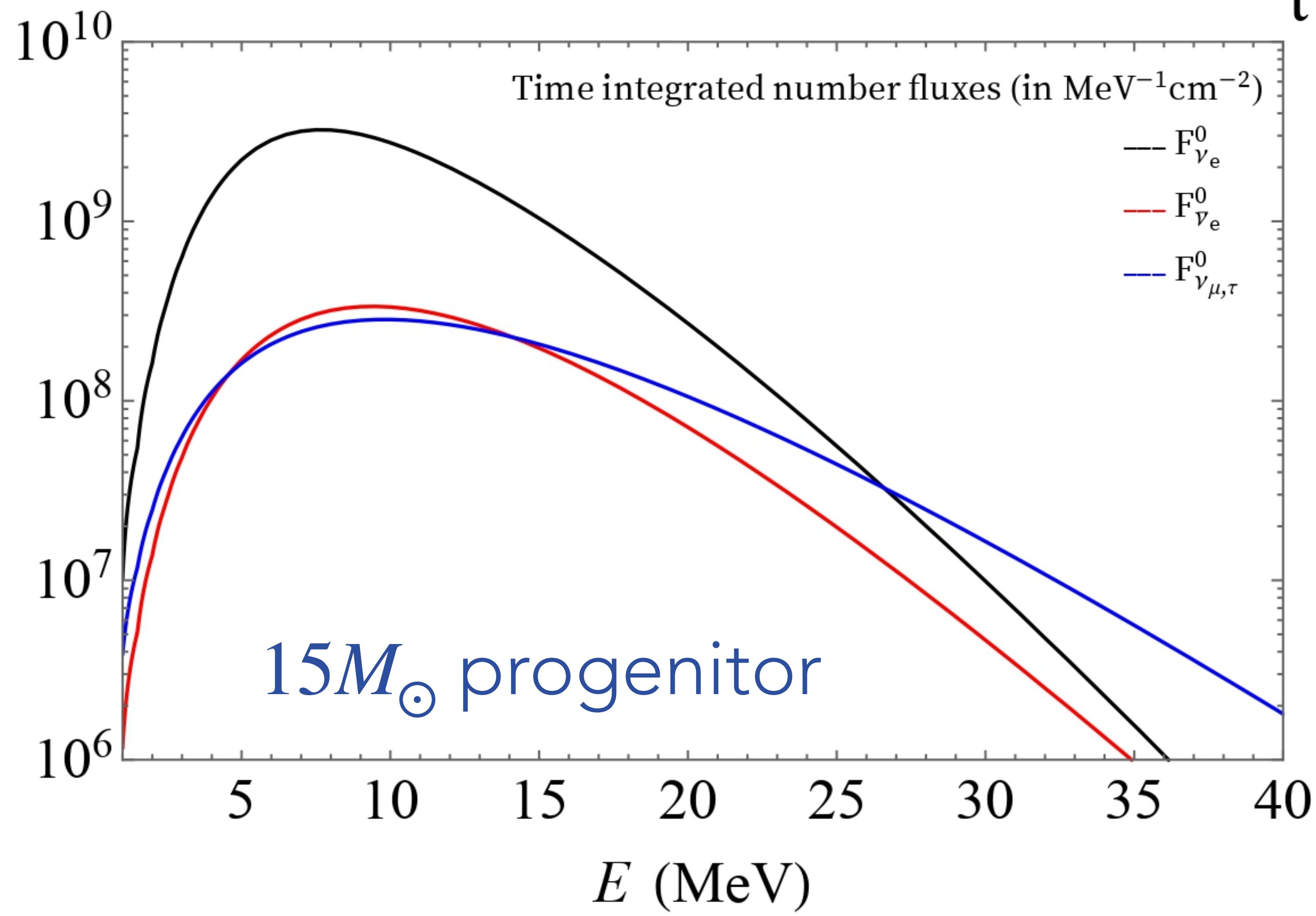




Flavor conversion in presence of neutrino magnetic moments

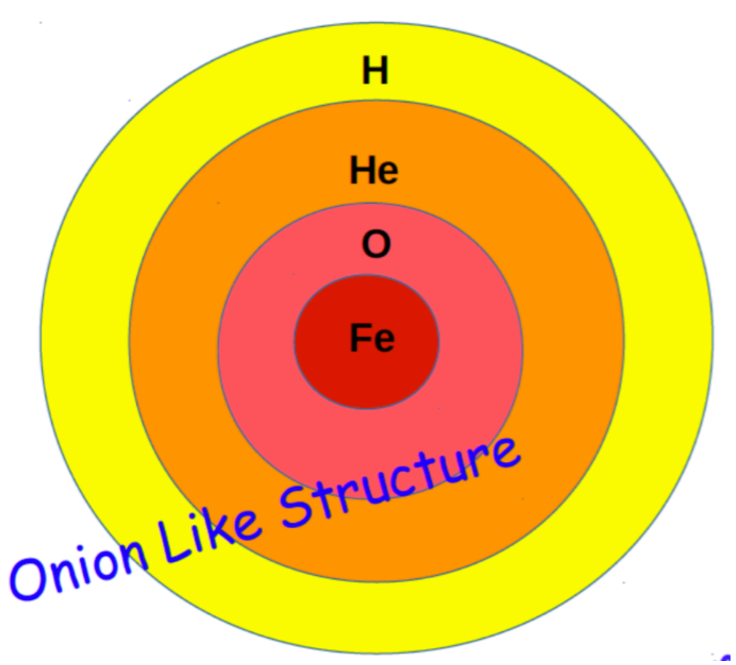
- Transition magnetic moments: $$\mathscr{L}_M \supset \mu_{\alpha\beta}\nu^T_{\alpha L} C \sigma_{\eta\delta} \nu_{\beta L} F^{\eta\delta}$$

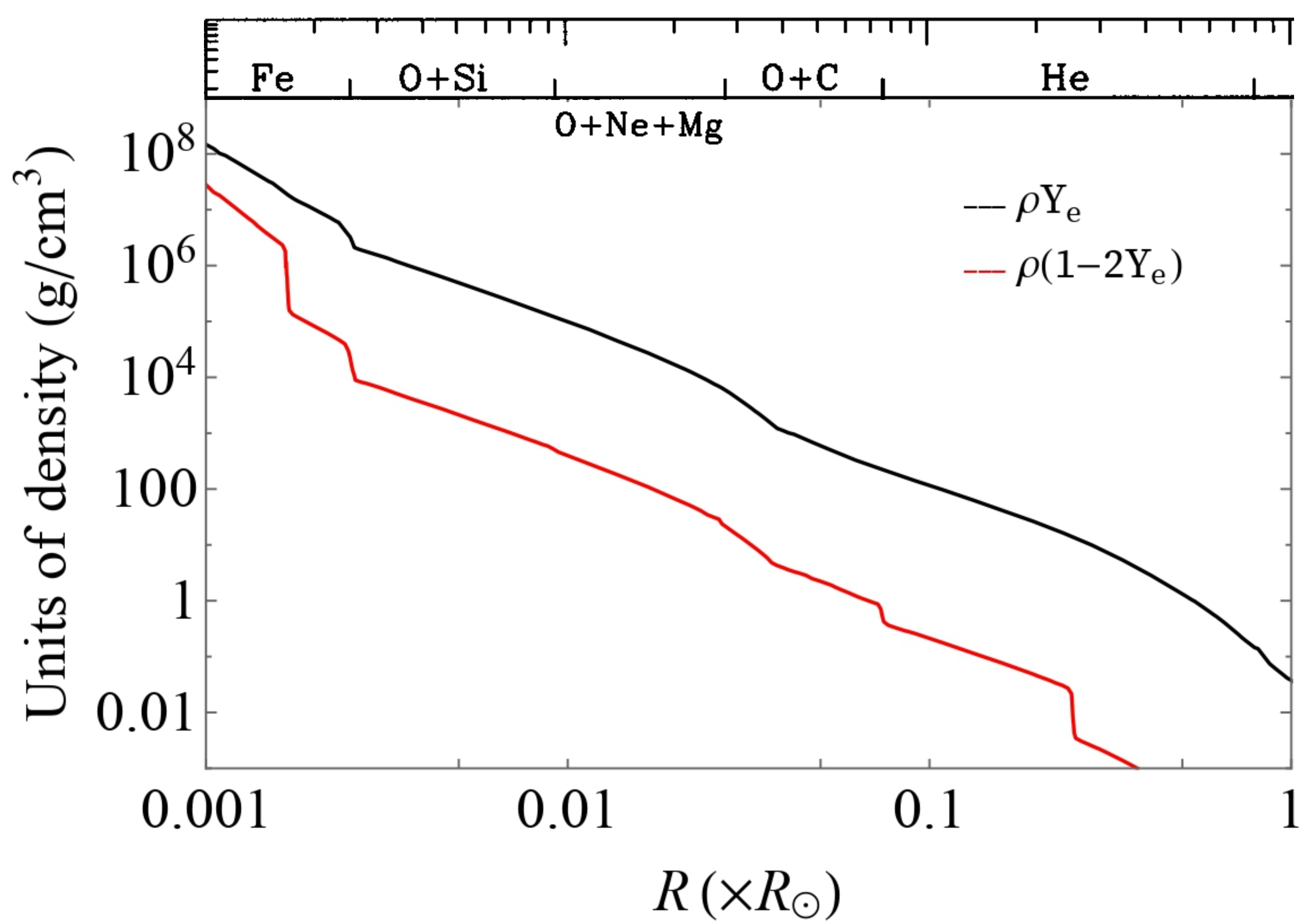
- Neutrino evolution equation: $$i\frac{d}{dr}\begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} = \begin{pmatrix} H_\nu & B_\perp M \\ -B_\perp M & H_{\bar{\nu}} \end{pmatrix}\begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix}$$

- Neutrino Hamiltonian in matter: $$H_\nu = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} V_{\nu_e} & 0 & 0 \\ 0 & V_{\nu_\mu} & 0 \\ 0 & 0 & V_{\nu_\tau} \end{pmatrix}$$

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
Totani, Sato, arXiv:astro-ph/9609035

Conditions for MSW and RSFP resonances

MSW (Mikheyev-Smirnov-Wolfenstein)

Mikheyev, Smirnov (1986)

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

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

- MSW-L/H adiabaticity parameter:

$$\gamma_{\text{MSW-H(L)}} = \frac{\sin^2 2\theta_{1j}}{\cos 2\theta_{1j}} \frac{\Delta m^2_{j1}}{2E} \left| \frac{1}{\rho Y_e} \frac{d(\rho Y_e)}{dr} \right|^{-1}$$

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

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RSFP (Resonant Spin-Flavour Precession)

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

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

- RSFP-L/H adiabaticity parameter:

$$\gamma_{\text{RSFP-H(L)}} \simeq \frac{8E}{\Delta m^2_{j1}}(\mu_{e\beta'}B_\perp)^2\left|\frac{1}{\rho(1-2Y_e)}\frac{d(\rho(1-2Y_e))}{dr}\right|^{-1}$$

- And we still have the RSFP-E (see Akhmedov & Fukuyama arXiv:hep-ph/0310119)

$\nu_e \leftrightarrow \bar{\nu}_\tau$ $\nu_e \leftrightarrow \bar{\nu}_\mu$ $\bar{\nu}_e \leftrightarrow \nu_\mu$ $\bar{\nu}_e \leftrightarrow \nu_\tau$

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: $0.5 \times 10^{-3}\mu_B\mathrm{G} \lesssim \mu_\nu B_0 \lesssim 10^{-2}\mu_B\mathrm{G}$
- 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}
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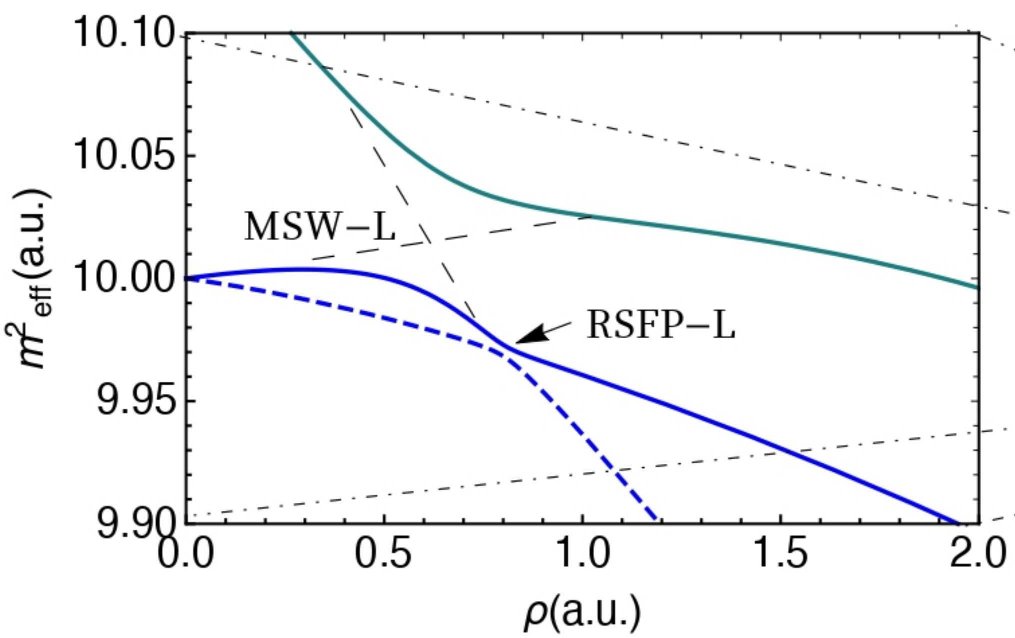
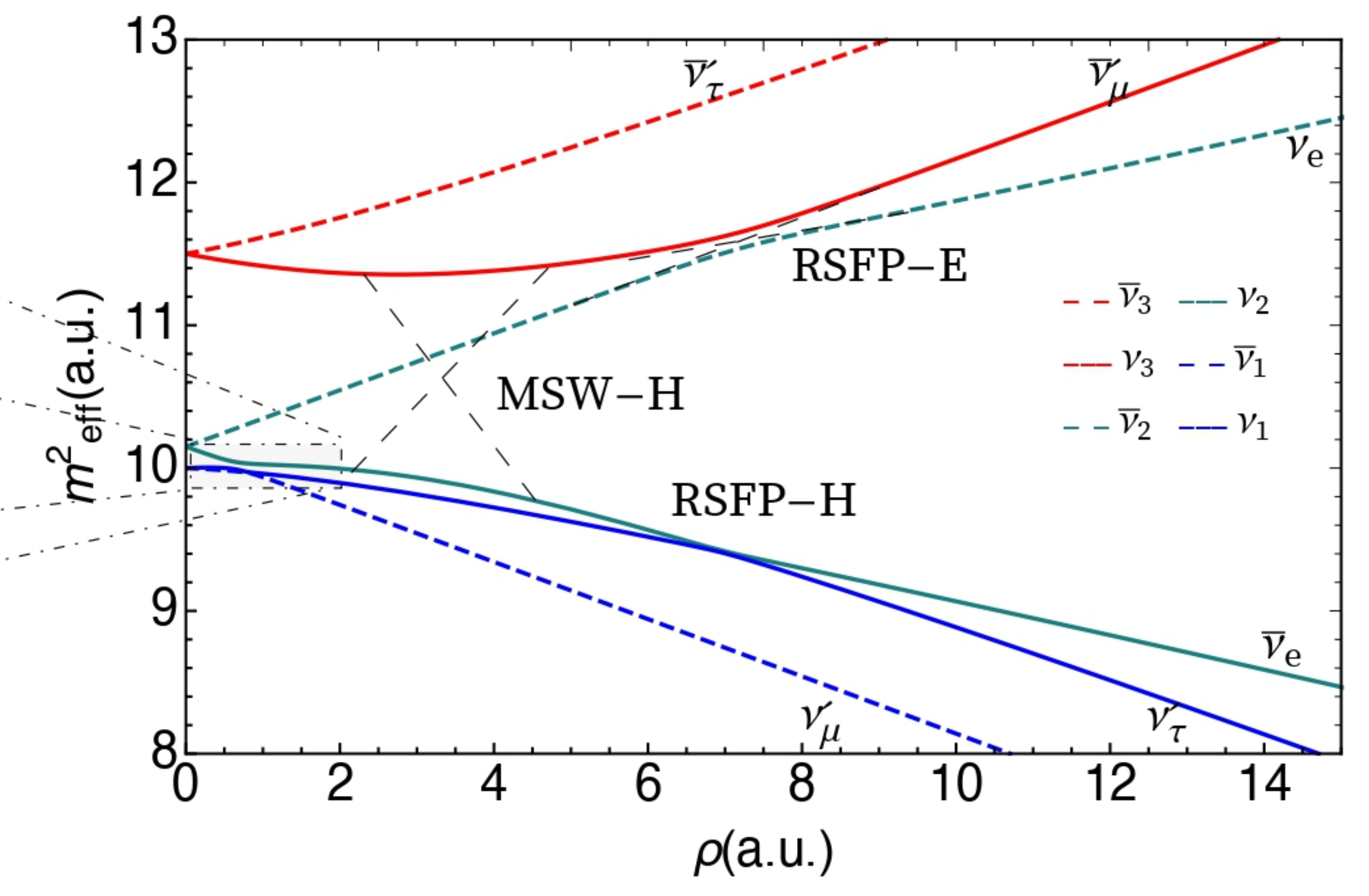


Jana, YPS, Sen, arXiv:2203.01950



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: $0.5 \times 10^{-3} \mu_B \mathrm{G} \lesssim \mu_\nu B_0 \lesssim 10^{-2} \mu_B \mathrm{G}$
- Results depend on the hopping probability at RSFP-H: $p_H = e^{-\frac{\pi}{2}\gamma_{RSFP-H}}$

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F_{\nu_e} &= F_{\nu_e}^{MSW} - |U_{e2}|^2 (1 - p_H)(F_{\nu_e}^0 - F_{\nu_x}^0) \\
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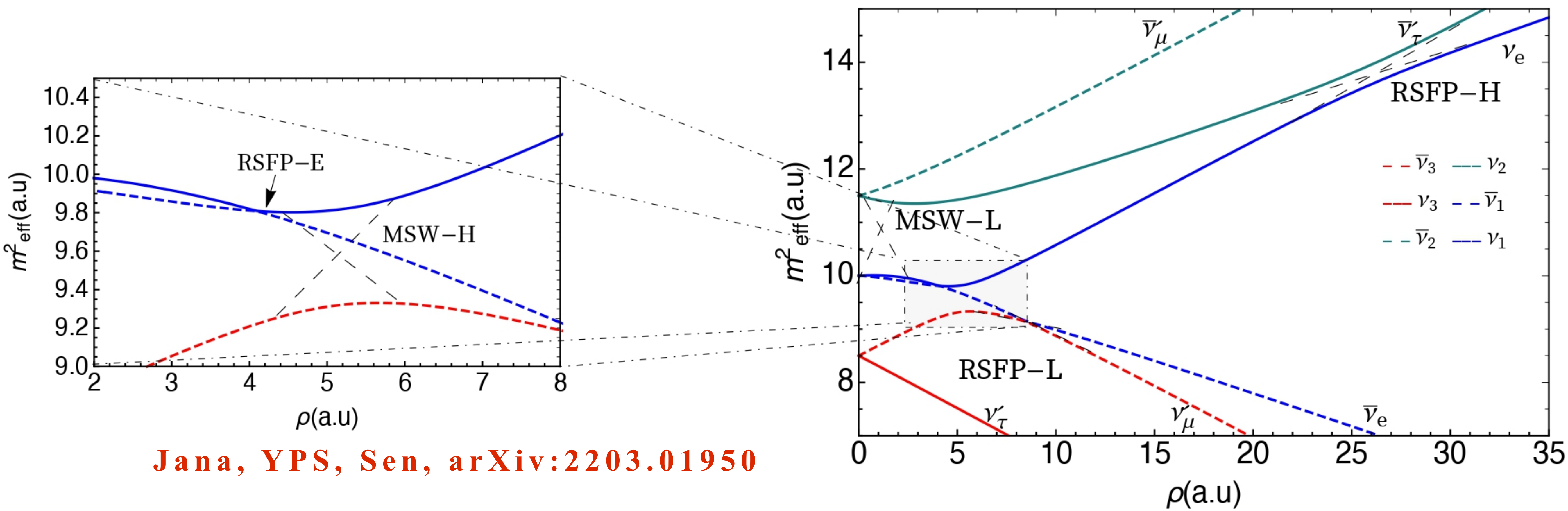

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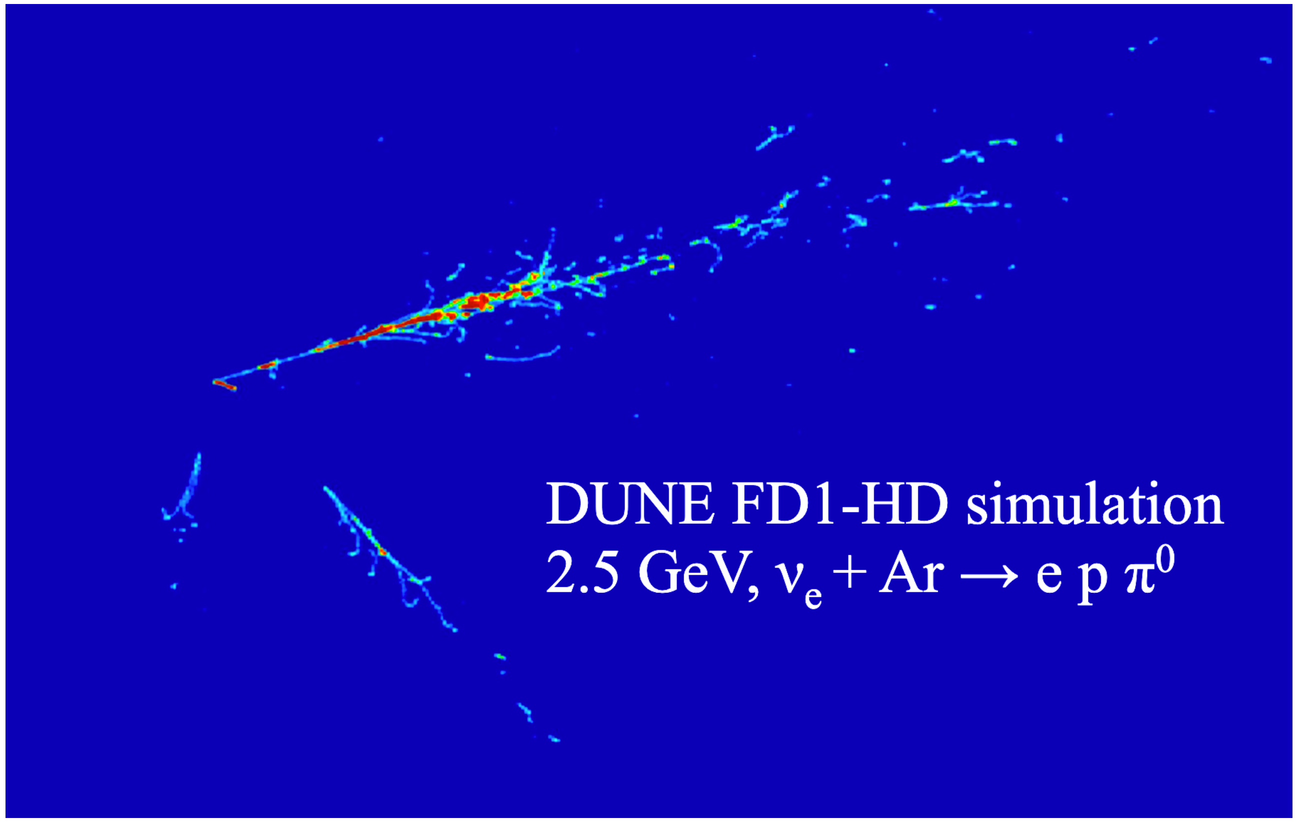
Upcoming neutrino detectors

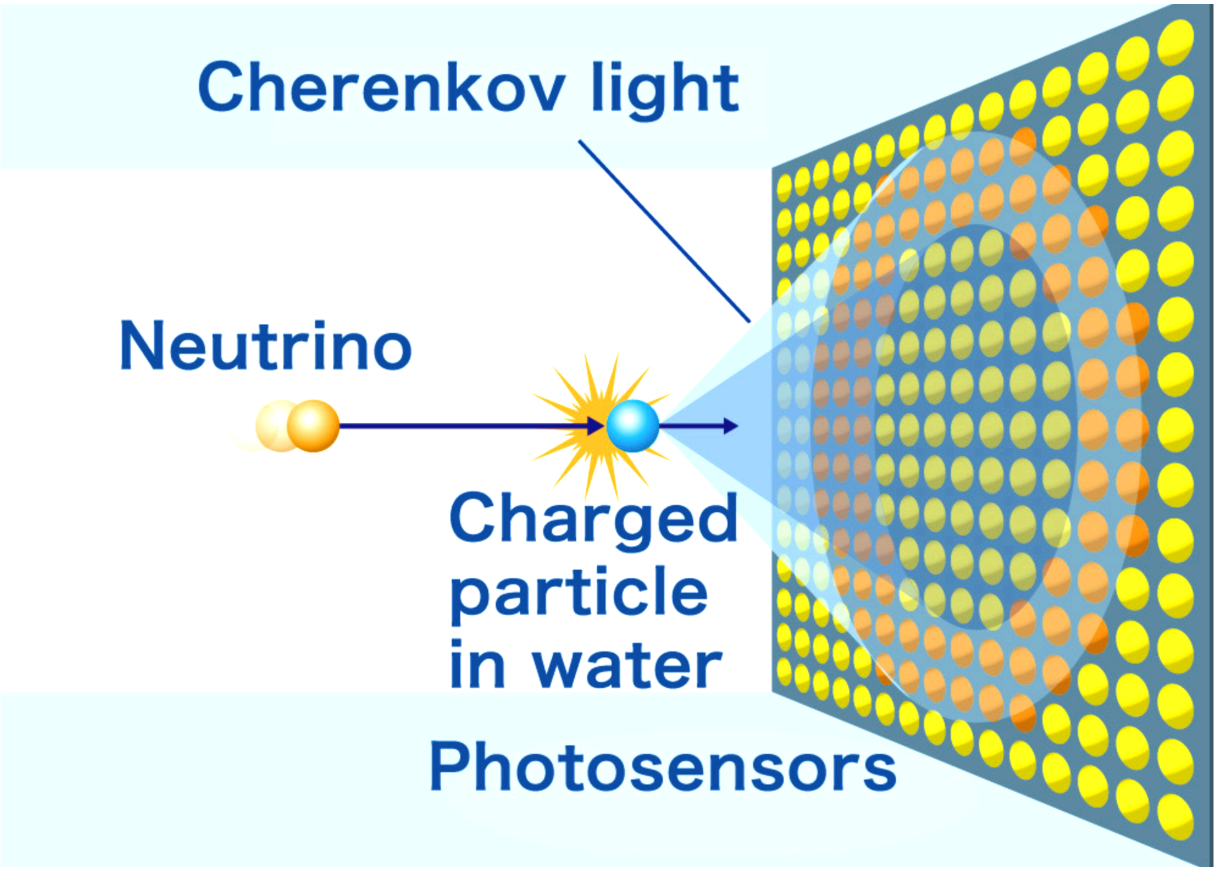
DUNE

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

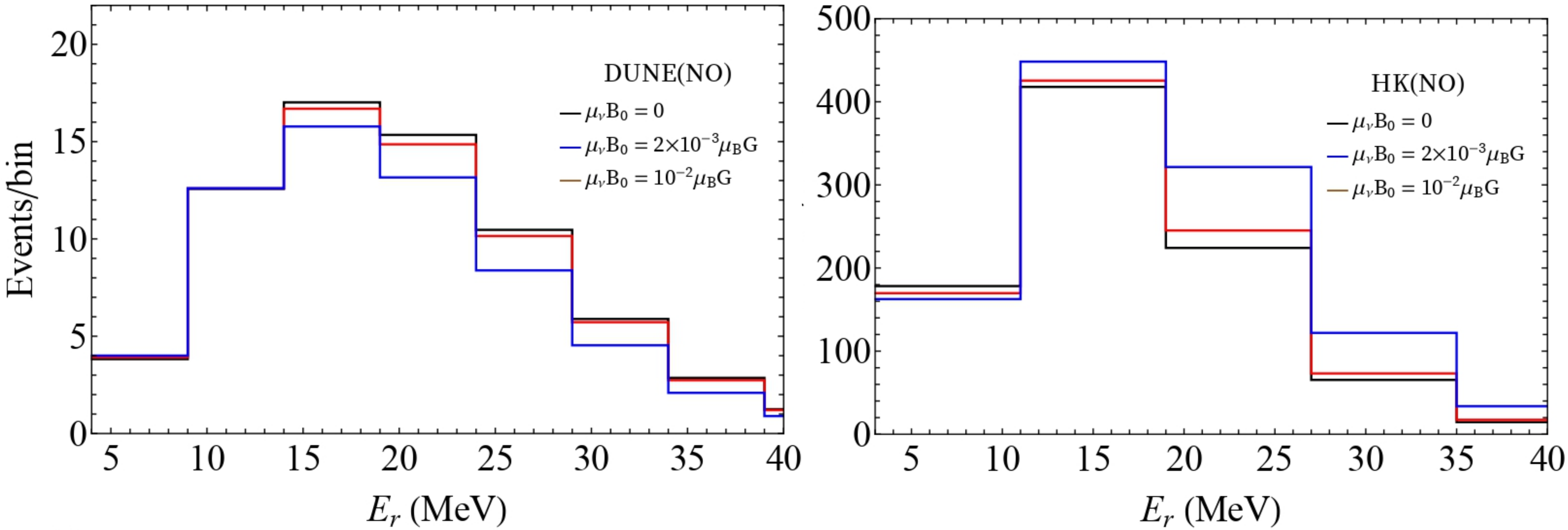


HK

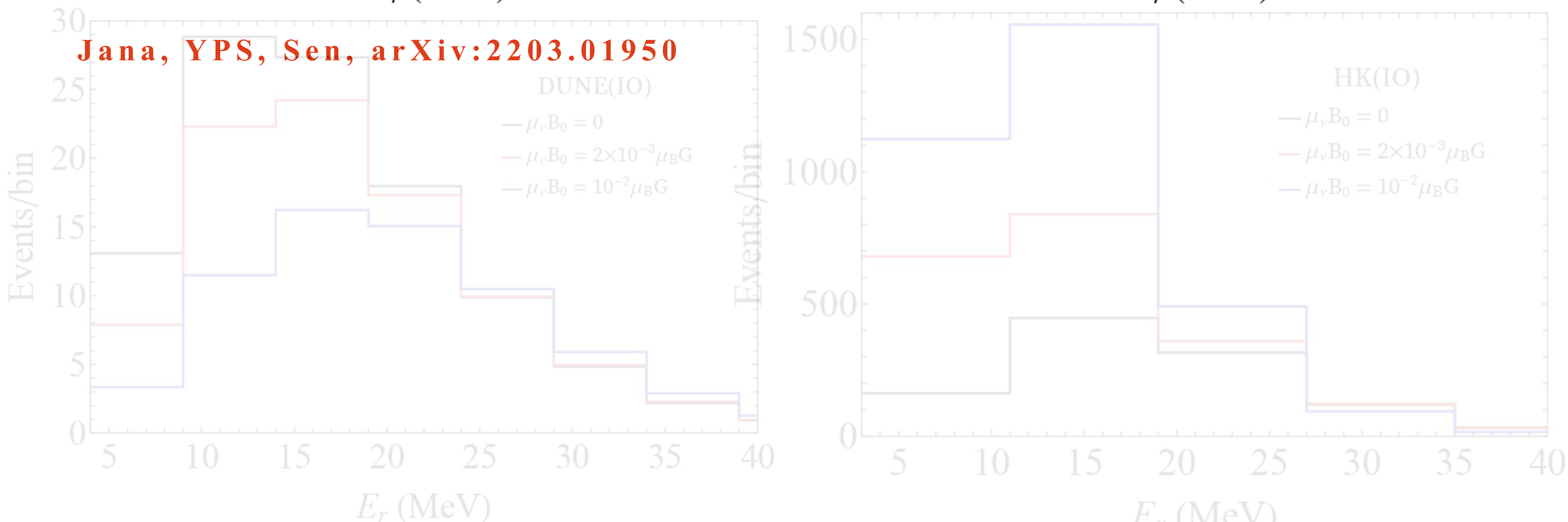
- Water cherenkov detector, fiducial volume 187 kt in each of two tanks;
- $\bar{\nu}_e + p \to e^+ + n$;
- $\sigma_E/E_r \sim 20\,\%$ at 10 MeV.



Event spectra (normal ordering)

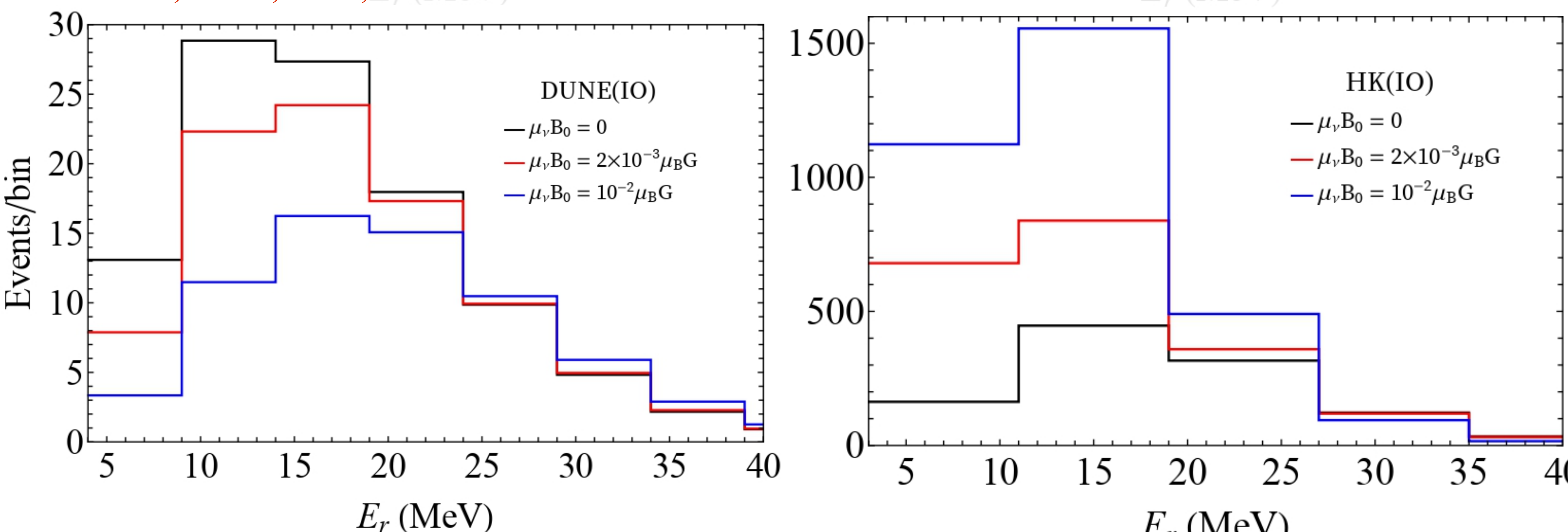


Jana, YPS, Sen, arXiv:2203.01950



Event spectra (inverted ordering)

Jana, YPS, Sen, arXiv: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):

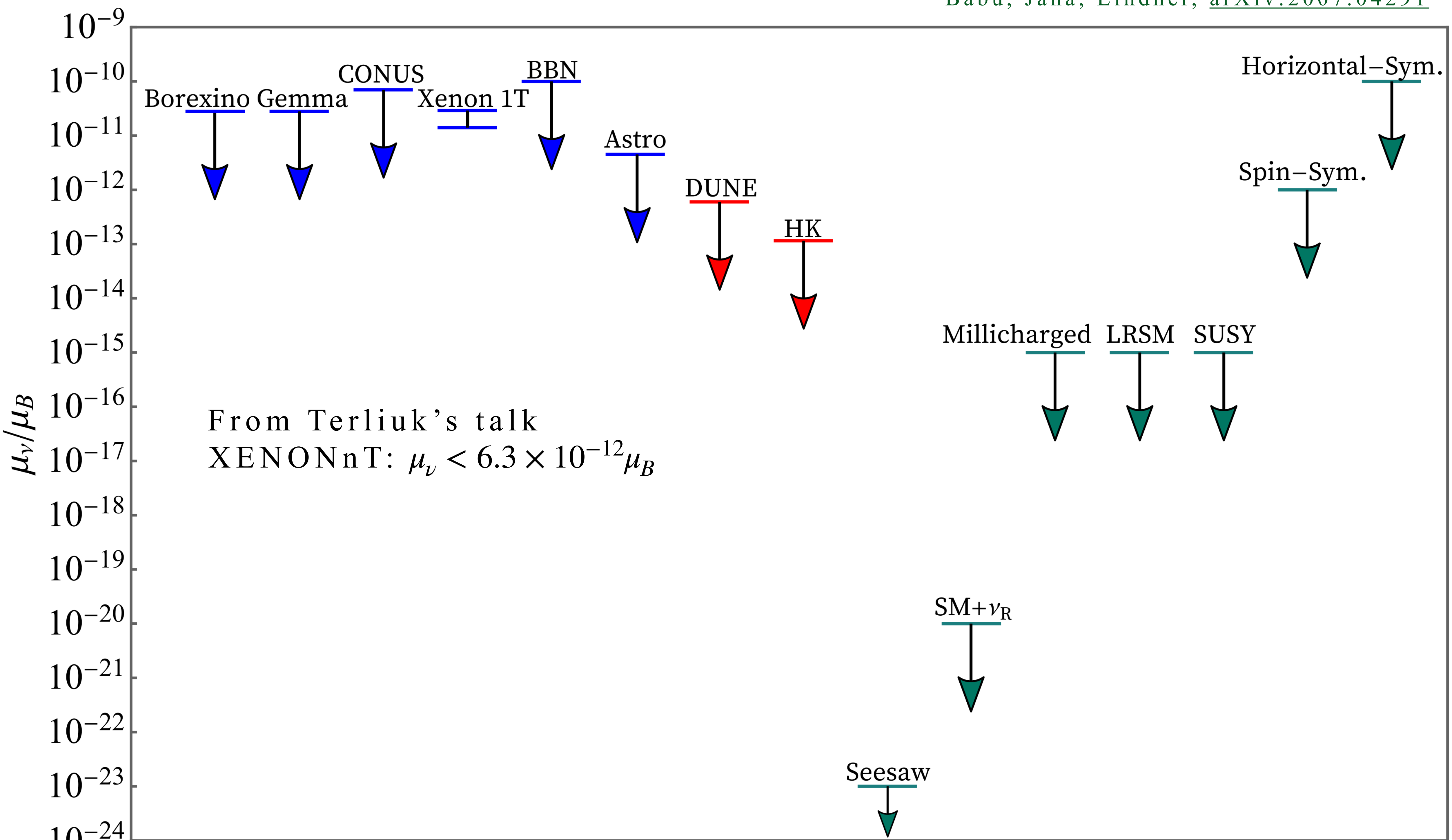
Sensitivities (in μ_B)

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



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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!