# Light sterile neutrino and mass variables


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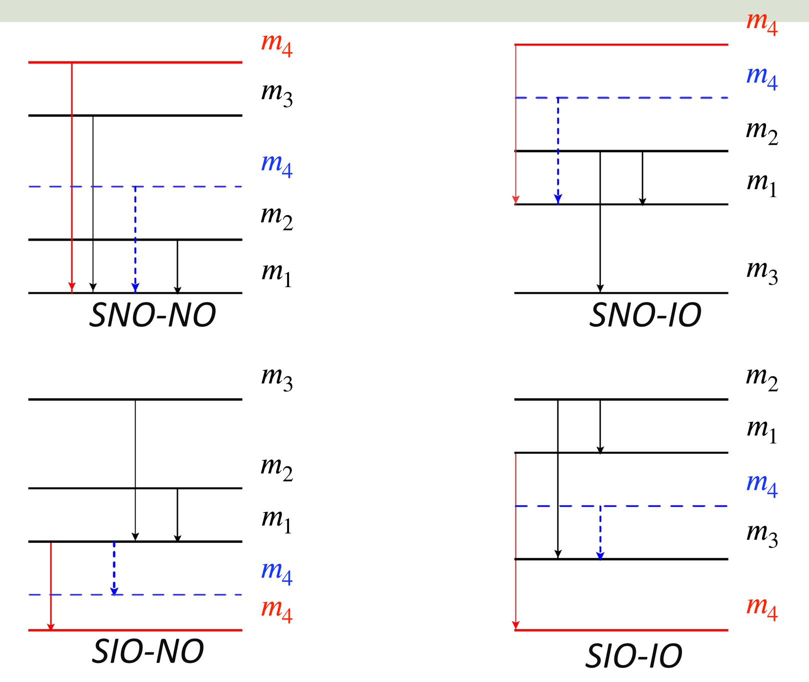
## MOTIVATION

- Excess in electron neutrino flux in the *LSND* and *MiniBooNE*, and radio chemical experiments *GALLEX*, *SAGE* and *BEST* explained with an $\sim$ eV scale sterile neutrino.
- Tension between *Tokai to Kamioka (T2K)* and *Numl off-axis Appearance (NOvA)* results can be improved by invoking one very light sterile state, $\Delta m_s^2 \sim (10^{-2} : 10^{-4})\ eV^2$
- Sterile neutrino of mass-squared difference $\sim 10^{-5}\ eV^2$ can possibly explain the non observation of upturn event in solar neutrino spectra.
- Presence of one extra sterile state imply four distinct mass spectra depending on the sign of $\Delta m_s^2$ and $\Delta m_{atm}^2$
- We study the implication of these mass spectra on the mass-related observables (i) total sum of the masses ( $\sum m_\nu$) , (ii) the kinematic mass of electron ($m_\beta$) and (iii) the effective Majorana mass ($m_{\beta\beta}$).
- Current experimental results already disfavor some scenarios and future experiments like *Project 8* and *nEXO* might be able to probe some scenarios.

## 3+1 Scenario : mass-spectra




**1.**

$$m_{lightest} = m_1 \ , \ m_2 = \sqrt{m_1^2 + \Delta m_{sol}^2}$$
$$m_3 = \sqrt{m_1^2 + \Delta m_{atm}^2} \ , \ m_4 = \sqrt{m_1^2 + \Delta m_s^2}$$

**2.**

$$m_1 = \sqrt{m_3^2 + \Delta m_{atm}^2} \ , \ m_2 = \sqrt{m_3^2 + \Delta m_{atm}^2}$$
$$m_{lightest} = m_3 \ , \ m_4 = \sqrt{m_3^2 + \Delta m_{atm}^2 + \Delta m_s^2}$$

**3.**

$$m_1 = \sqrt{m_4^2 + \Delta m_s^2} \ , \ m_2 = \sqrt{m_4^2 + \Delta m_s^2}$$
$$m_3 = \sqrt{m_1^2 + \Delta m_{atm}^2} \ , \ m_{lightest} = m_4$$

- 1. SNO-NO : $\Delta m_s^2 > 0, \ \Delta m_{atm}^2 > 0$
- 2. SNO-IO : $\Delta m_s^2 > 0, \ \Delta m_{atm}^2 < 0$
- 3. SIO-NO : $\Delta m_s^2 < 0, \ \Delta m_{atm}^2 > 0$
- 4. SIO-IO : $\Delta m_s^2 < 0, \ \Delta m_{atm}^2 < 0$

**4.**

$|\Delta m_s^2| > |\Delta m_{atm}^2|$

$$m_1 = \sqrt{m_1^2 + \Delta m_s^2}\ , \ m_2 = \sqrt{m_1^2 + \Delta m_s^2}$$
$$m_3 = \sqrt{m_1^2 + \Delta m_s^2 - \Delta m_{atm}^2} \ , \ m_{lightest} = m_4$$

$|\Delta m_s^2| < |\Delta m_{atm}^2|$

$$m_1 = \sqrt{m_3^2 + \Delta m_{atm}^2}\ , \ m_2 = \sqrt{m_3^2 + \Delta m_{atm}^2}$$
$$m_{lightest} = m_3 \ , \ m_4 = \sqrt{m_3^2 + \Delta m_{atm}^2 - \Delta m_s^2}$$

## RESULTS AND DISCUSSION

### Cosmology

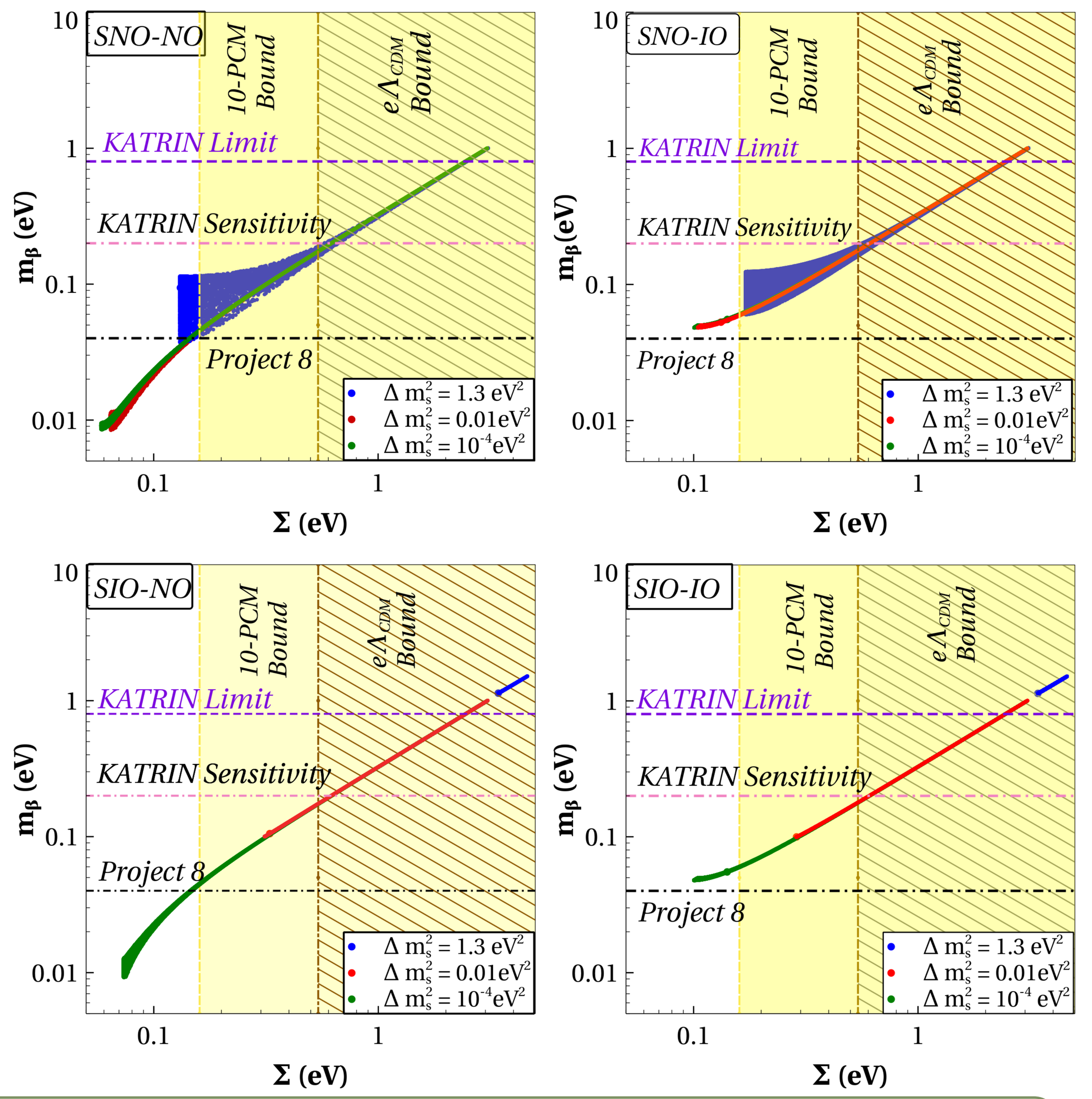
- Light sterile neutrino scenarios gets stronger constraint from Cosmological parameters namely $N_{\rm eff}$ and $\sum m_\nu$
$$\sum m_\nu = m_1 + m_2 + m_3 + m_s^{\rm eff}$$
- $m_s^{eff}$ and physical mass can be related as
  - $m_s^{\rm eff} = \Delta N_{\rm eff}^{3/4}\ m_4$ if the neutrino produced thermally
  - $m_s^{\rm eff} = \Delta N_{\rm eff}\ m_4$, for non thermal productions
- Cosmological parameters depend on cosmological datasets and different cosmological model.

| $\Lambda_{CDM}$ *Model* (6 parameters) | 10 Parameter *Model* (10 PCM) | $e\Lambda_{CDM}$) *Model* (12 parameters) |
|---|---|---|
| $N_{eff} = 2.96^{+0.34}_{-0.33}$, $\sum m_\nu < 0.12$ | $N_{eff} = 3.11^{+0.37}_{-0.36}$, $\sum m_\nu < 0.16$ | $N_{eff} = 3.11^{+0.52}_{-0.48}$, $\sum m_\nu < 0.52$ |

### Tritium Beta Decay

- In 3+1 scenario,
$$m_\beta^2 = c_{12}^2 c_{13}^2 c_{14}^2\ m_1^2 + s_{12}^2 c_{13}^2 c_{14}^2\ m_2^2 + s_{13}^2 c_{14}^2\ m_3^2 + s_{14}^2\ m_4^2$$
- Mixing angles taken from the allowed regions of *MINOS* , *MINOS*$^+$, *Daya-Bay* and *Bugey* data
- SIO-NO and SIO-IO ruled out from *KATRIN's* current limit for $\Delta m_s^2 = 1.3\ eV^2$
- *Project 8* (sensitivity $m_\beta < 0.04\ eV$) able to probe SNO-IO and SIO-IO for all $\Delta m_s^2$ and almost SNO-NO for $\Delta m_s^2 = 1.3\ eV^2$

| Parameters | CASE I | CASE II | CASE III |
|---|---|---|---|
| $\Delta m_s^2$ | $10^{-4} eV^2$ | $10^{-2} eV^2$ | $1.3 eV^2$ |
| $\sin^2\theta_{14}$ | (0.1:0.2) | (0.5:5) | (0.1:1) |




### Neutrinoless Double Beta Decay

- If neutrinos are majorana, then neutrinoless double beta decay process can happen through neutrino mass insertion
- *KamLAND-Zen* limit on $T_{\frac{1}{2}} > 1.07 \times 10^{26}\ Yr$
- In future *nEXO* will reach a half life sensitivity of $T_{\frac{1}{2}} > 1.35\ \times 10^{28}\ Yr$
- Lower limits on the half lives translated to upper limit of effective Majorana mass ($m_{\beta\beta}$) ,

$$T_{\frac{1}{2}}^{-1} = \mathscr{G}_{0\nu} \left|\mathscr{M}_{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$\mathscr{G}_{0\nu} =$ Phase Space Factor = $\sim 10^{-15}\ Yr^{-1}$

$\mathscr{M}_{0\nu} =$ Nuclear Matrix Element

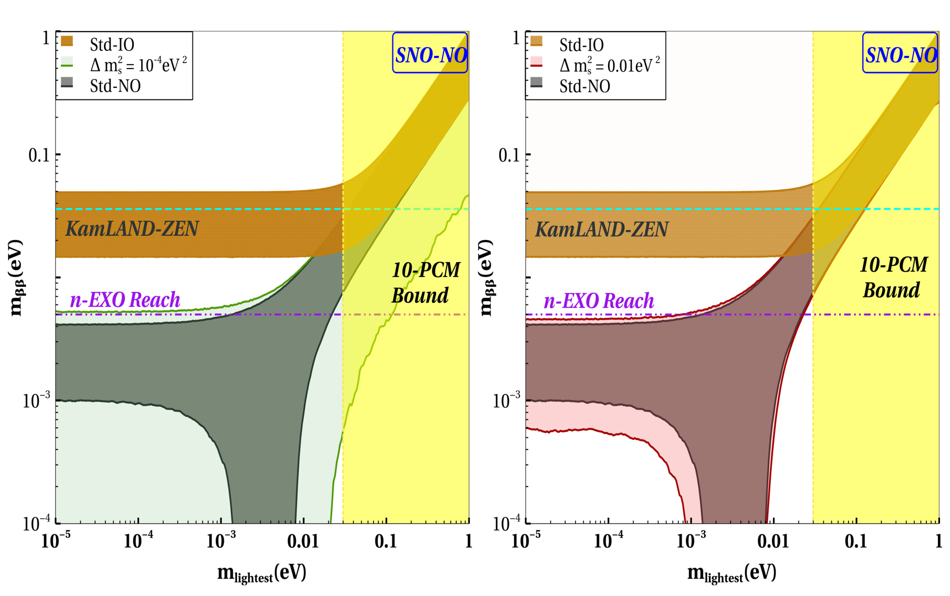
$m_e =$ Mass of electron

$$m_{\beta\beta} = \sum U_{ei}^2\ m_i = c_{12}^2 c_{13}^2 c_{14}^2\ m_1 + s_{12}^2 c_{13}^2 c_{14}^2\ m_2\ e^{i\alpha} + s_{13}^2 c_{14}^2\ m_3 e^{i\beta} + s_{14}^2\ m_4 e^{i\gamma}$$

**SNO-NO**

$$m_{\beta\beta}^{SNO-NO} = m_{\beta\beta}^{std-NO} + s_{14}^2 m_4 e^{i\gamma}$$

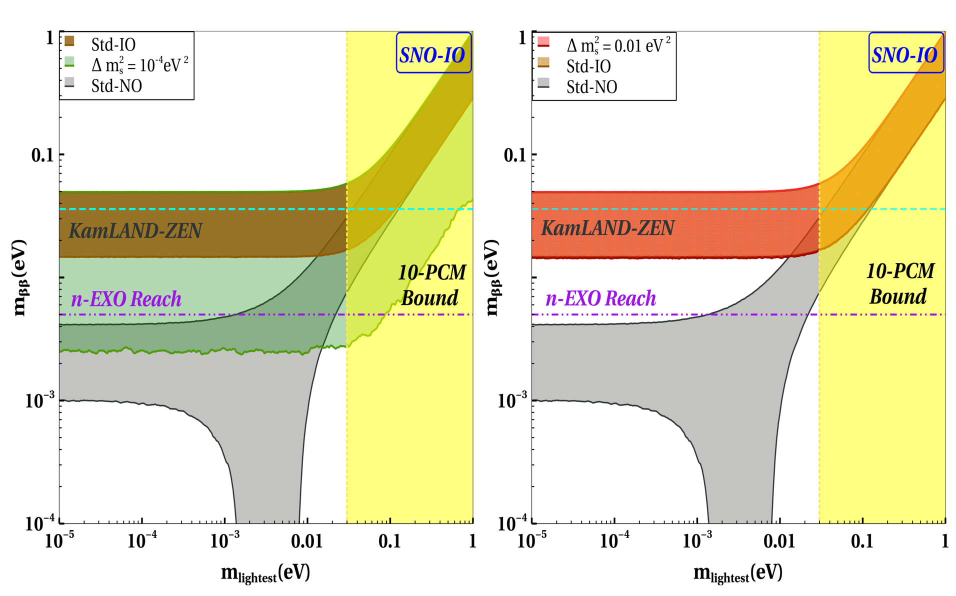
- $\Delta m_s^2 = 10^{-4}$: Cancellation region occurs at $m_{lightest} \approx 0$
- 0.01 $eV^2$: sterile neutrino contribution to $m_{\beta\beta}$ is small.
- Can not be probed in future experiments




**SNO-IO**

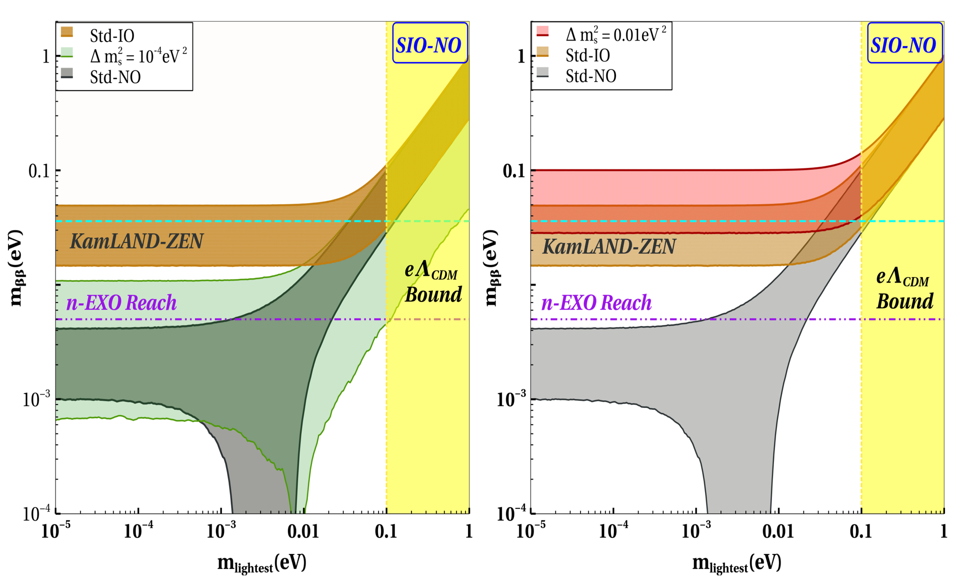
$$m_{\beta\beta}^{SNO-IO} = m_{\beta\beta}^{std-IO} + s_{14}^2 m_4 e^{i\gamma}$$

- $10^{-4}\ eV^2$ : $m_{\beta\beta}$ get contribution in the deserted region
- $10^{-2}\ eV^2$ : no change from standard IO
- *nEXO* can probe $10^{-2}\ eV^2$ completely and $10^{-4}\ eV^2$ partially



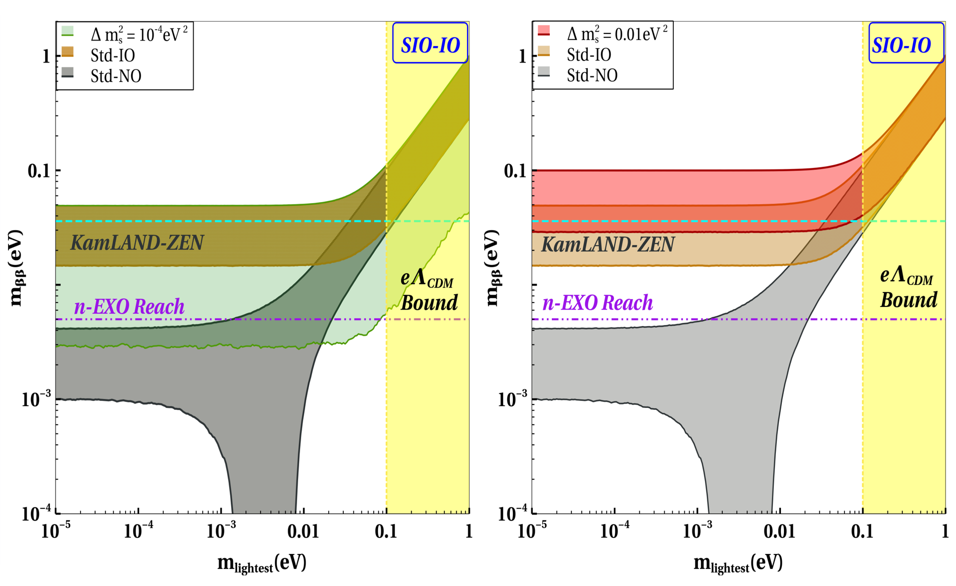

**SIO-NO**

- $10^{-4}\ eV^2$: no cancellation for low $m_{lightest}$ , but around $m_{lightest} \approx 0.01$, cancellation occurs $\alpha = \beta = \gamma = \pi$.
- $\Delta m_s^2 = 0.01\ eV^2$: Most parameter space is ruled out from *KamLAND-Zen* whereas *nEXO* will probe the rest




**SIO-IO**

- $10^{-4}\ eV^2$: mass spectra of SIO-IO is similar to SNO-IO, so, the behaviour of $m_{\beta\beta}$ is also similar.
- $10^{-2}\ eV^2$ : SIO-IO is similar to SIO-NO
- *nEXO* can probe $10^{-2}\ eV^2$ completely and *KamLAND-Zen* can probe partially.




## CONCLUSIONS

- For $\Delta m_s^2 = 1.3\ eV^2$ , SIO scenarios disfavoured by current limit of *KATRIN* and *KamLAND-Zen* experiment and SNO-IO can be probed in *Project 8* experiment
- For $\Delta m_s^2 = 0.01\ eV^2$ , *KATRIN's* projected limit probe $m_{lightest} > 0.2\ eV$ but *Project 8* might be useful in probing SNO-IO, SIO-NO and SIO-IO scenarios completely.
- The scenarios with $\Delta m_s^2\ (\le 10^{-4}\ eV^2)$ is compatible with the cosmological limits and direct mass measurement experiment limits but proposed *Project 8* will be crucial to probe these either completely and partially.
- In neutrinoless double beta process, the signature of different mass spectra is different and future generation experiment like *nEXO* might be able to probe some parts of the parameter space of these scenarios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