A Possible Scenario about Neutrino mass

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Outline

- About sterile neutrino
- Relevant neutrino future experiments
- Information on neutrino mass from each experiment
- A scenario on neutrino mass
- Conclusion

Q. Examine one or more “interesting” scenarios (i.e. non-trivial) for combining DUNE, CMB S4, KATRIN, and future neutrino-less double beta decay experiment results from the perspective of understanding (and precisely measuring) the neutrino masses.

About sterile neutrino

- Even the lowest allowed region of LSND result

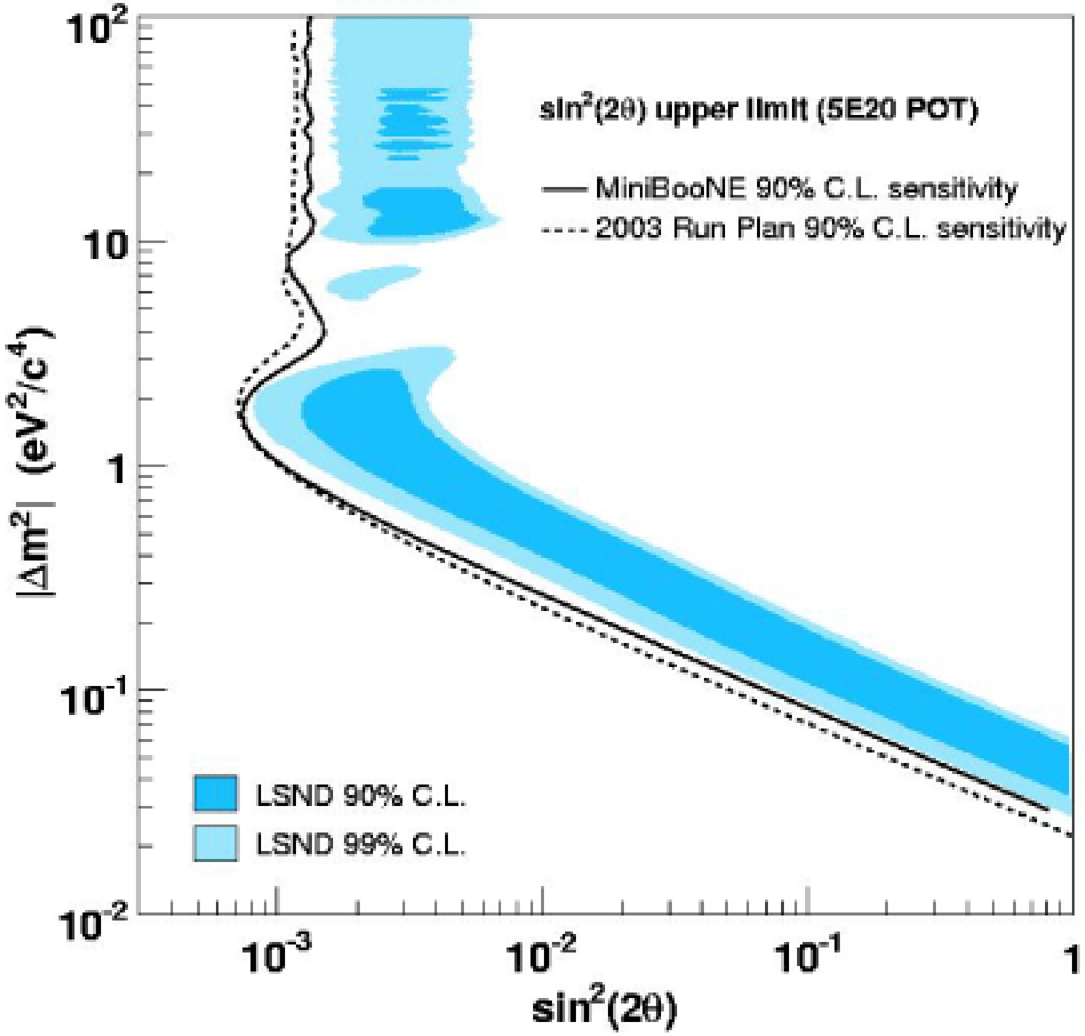
⇒ Violate the summation law

$\Delta(m_{13}^2) = \Delta(m_{12}^2) + \Delta(m_{23}^2)$

- Other reactor anti-ν anomaly

⇒ GALLEX and SAGE

- 3+1 scenario
- An additional massive ν with mass at the eV scale and ***mass of other 3 much smaller***



Some Future ν-Exp

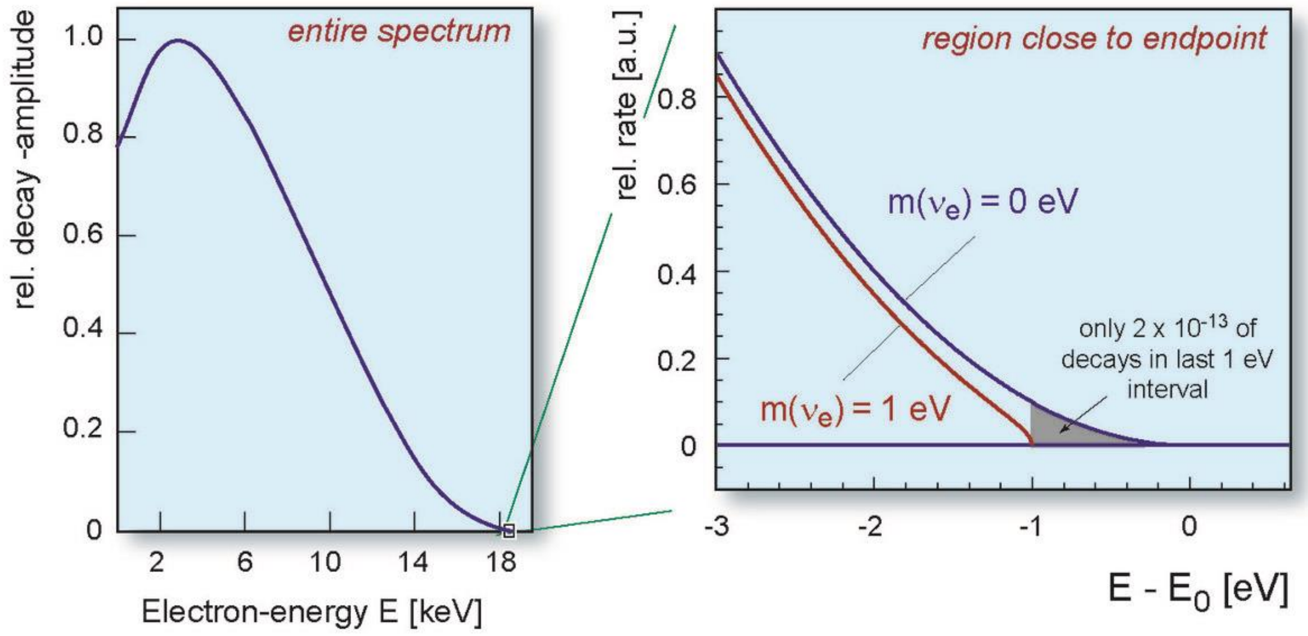
KATRIN(KArlsruhe TRItium Neutrino exp)

$$\frac{dN}{dE_e} = C_p(E + m_e)(E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m_\nu^2}\, F(E_e)\theta(E_0 - E_e - m_\nu)$$

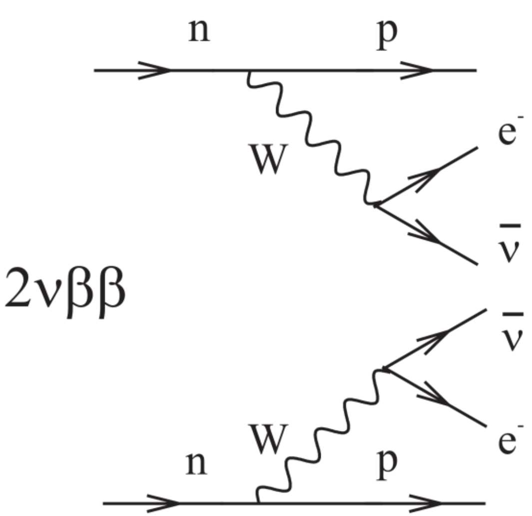
- End point of E – spectrum

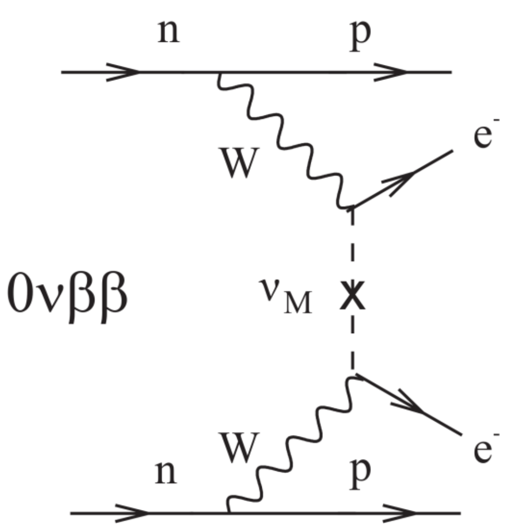
→ quantifies m_β

- $^3H \rightarrow {}^3He + e^- + \overline{\nu_e}$



ν-less $\beta\beta$ decay





$$T_{0\nu}^{-1} = G^{0\nu}|M^{0\nu}|^2|m_{\beta\beta}|^2$$

$$|m_{\beta\beta}| = |\sum_i U_{ei}^2 m_i|$$

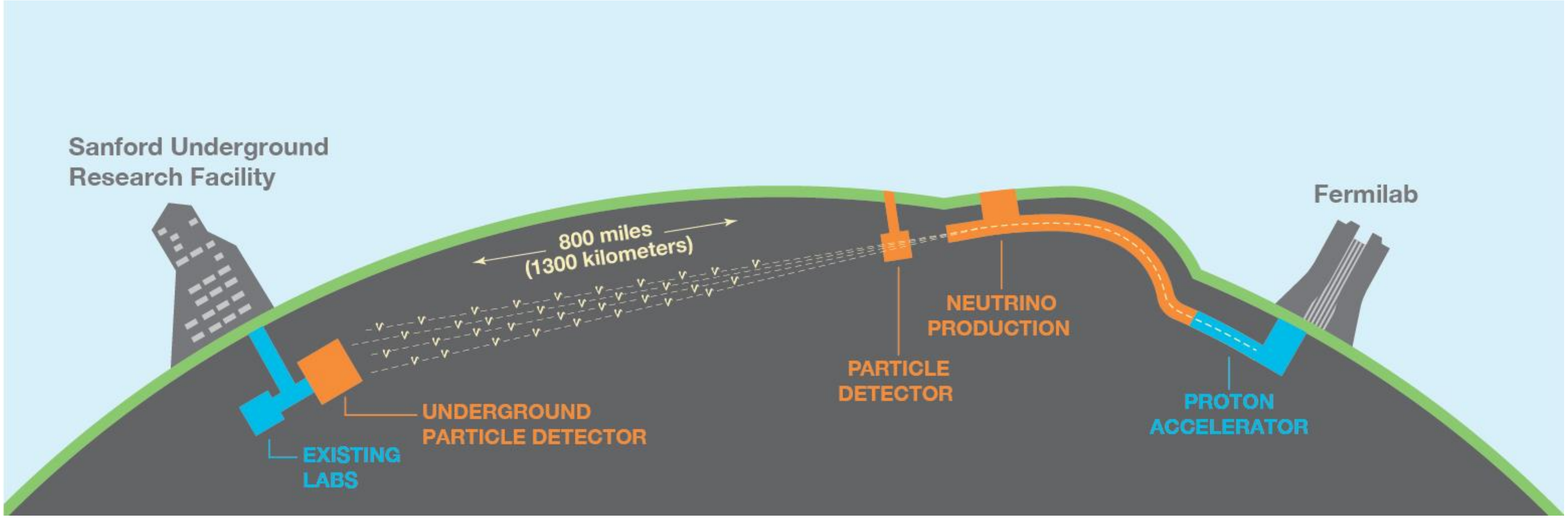
- GERDA
- SNO+
- KamLAND-ZEN
- EXO-200, nEXO

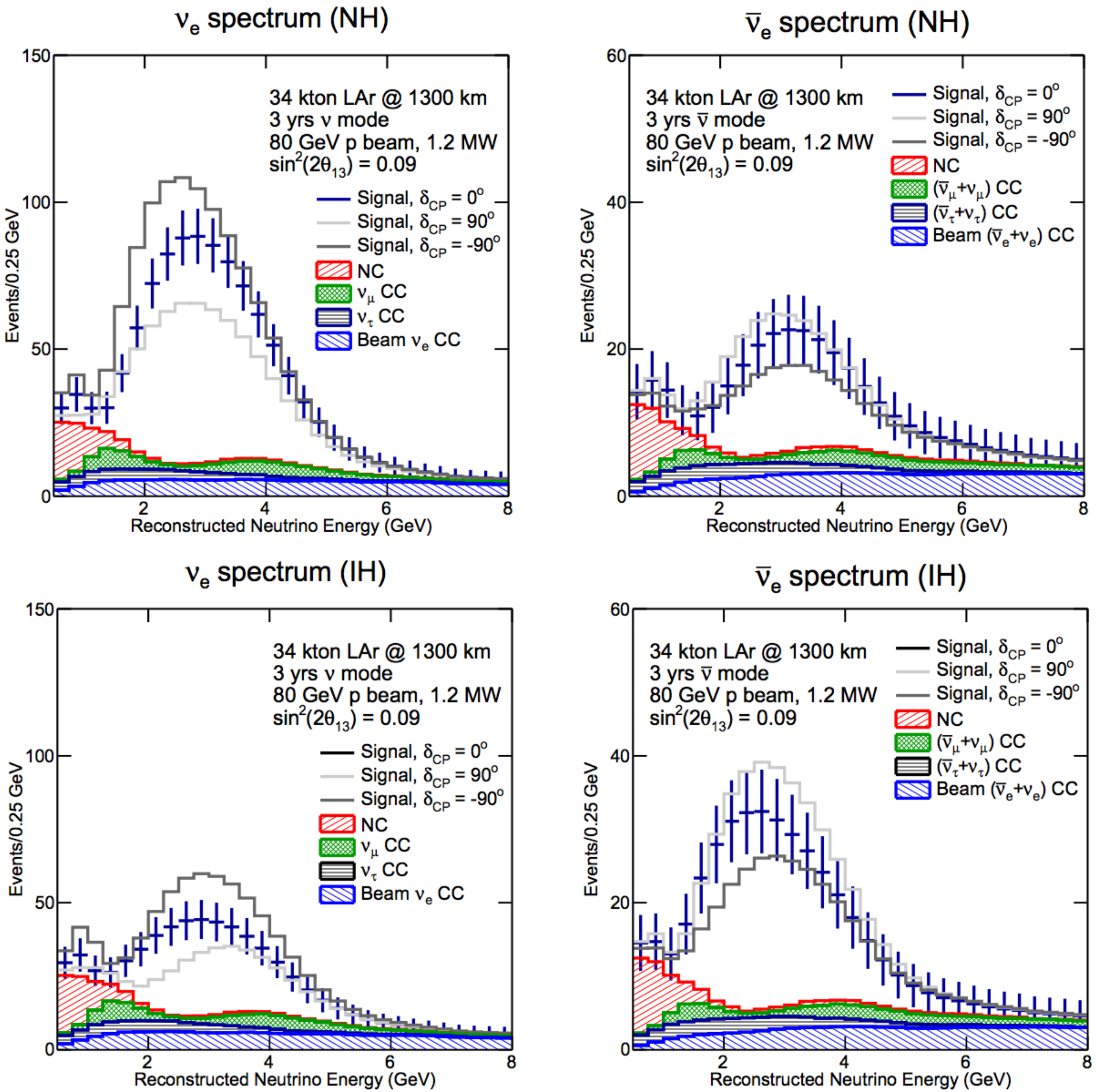
Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \to ^{48}Ti$	4.271	0.187
$^{76}Ge \to ^{76}Se$	2.040	7.8
$^{82}Se \to ^{82}Kr$	2.995	9.2
$^{96}Zr \to ^{96}Mo$	3.350	2.8
$^{100}Mo \to ^{100}Ru$	3.034	9.6
$^{110}Pd \to ^{110}Cd$	2.013	11.8
$^{116}Cd \to ^{116}Sn$	2.802	7.5
$^{124}Sn \to ^{124}Te$	2.228	5.64
$^{130}Te \to ^{130}Xe$	2.533	34.5
$^{136}Xe \to ^{136}Ba$	2.458	8.9
$^{150}Nd \to ^{150}Sm$	3.367	5.6

DUNE

- **Deep Underground Neutrino Experiment**
- Long base line neutrino experiment (prototype)
- 40 kt *Liquid Argon (Ar)* detector at Sanford research facility
- Neutrino Oscillation Experiment ($\nu_\mu \rightarrow \nu_e, \overline{\nu_\mu} \rightarrow \overline{\nu_e}$)





ν_e spectrum (NH)
34 kton LAr @ 1300 km
3 yrs ν mode
80 GeV p beam, 1.2 MW
$\sin^2(2\theta_{13}) = 0.09$
Signal, $\delta_{CP} = 0^o$
Signal, $\delta_{CP} = 90^o$
Signal, $\delta_{CP} = -90^o$
NC
ν_μ CC
ν_τ CC
Beam ν_e CC
Events/0.25 GeV
Reconstructed Neutrino Energy (GeV)
$\bar{\nu}_e$ spectrum (NH)
34 kton LAr @ 1300 km
3 yrs $\bar{\nu}$ mode
80 GeV p beam, 1.2 MW
$\sin^2(2\theta_{13}) = 0.09$
Signal, $\delta_{CP} = 0^o$
Signal, $\delta_{CP} = 90^o$
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NC
$(\bar{\nu}_\mu+\nu_\mu)$ CC
$(\bar{\nu}_\tau+\nu_\tau)$ CC
Beam $(\bar{\nu}_e+\nu_e)$ CC
Events/0.25 GeV
Reconstructed Neutrino Energy (GeV)
ν_e spectrum (IH)
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3 yrs ν mode
80 GeV p beam, 1.2 MW
$\sin^2(2\theta_{13}) = 0.09$
Signal, $\delta_{CP} = 0^o$
Signal, $\delta_{CP} = 90^o$
Signal, $\delta_{CP} = -90^o$
NC
ν_μ CC
ν_τ CC
Beam ν_e CC
Events/0.25 GeV
Reconstructed Neutrino Energy (GeV)
$\bar{\nu}_e$ spectrum (IH)
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$(\bar{\nu}_\mu+\nu_\mu)$ CC
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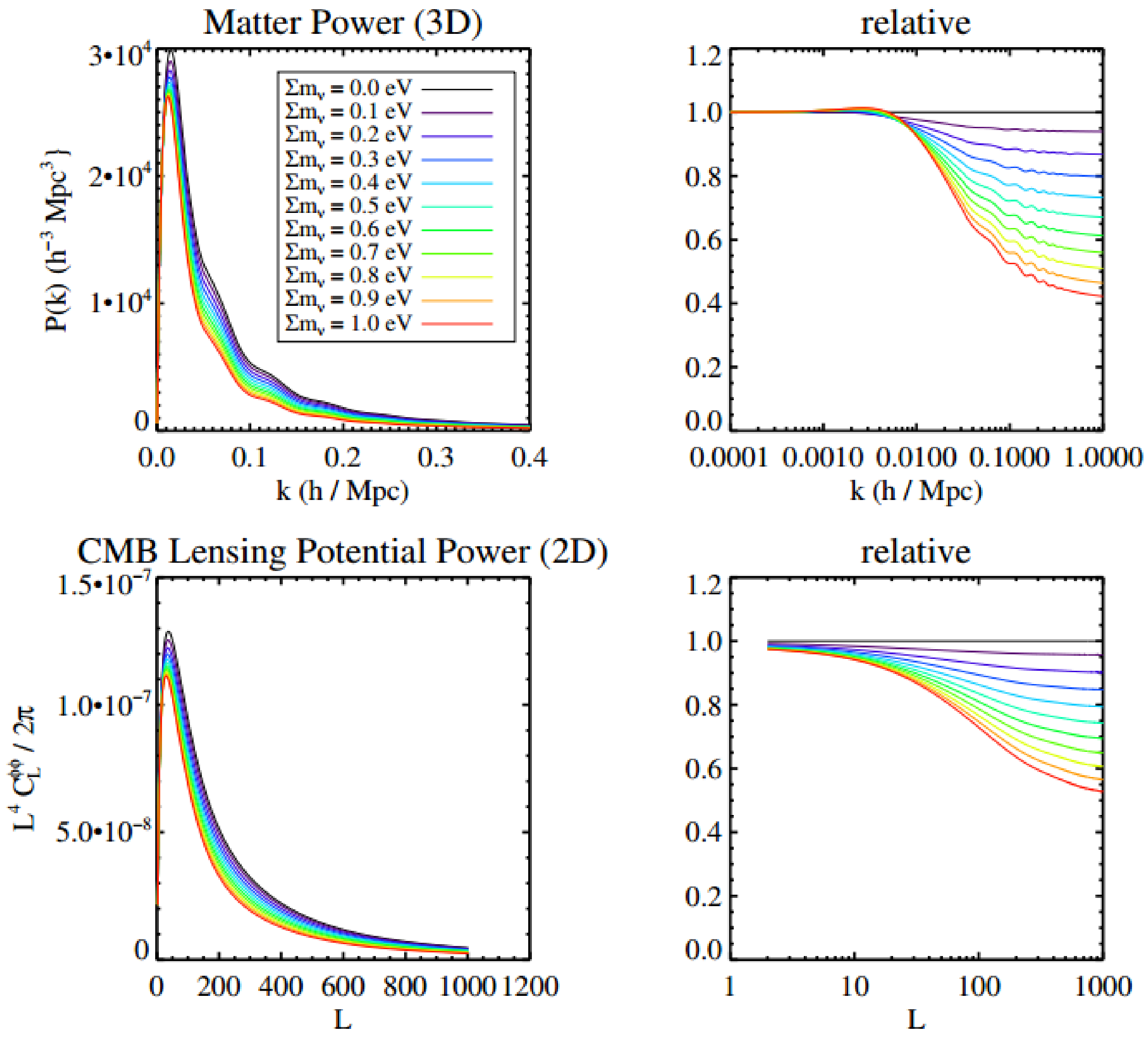
Beam $(\bar{\nu}_e+\nu_e)$ CC
Events/0.25 GeV
Reconstructed Neutrino Energy (GeV)

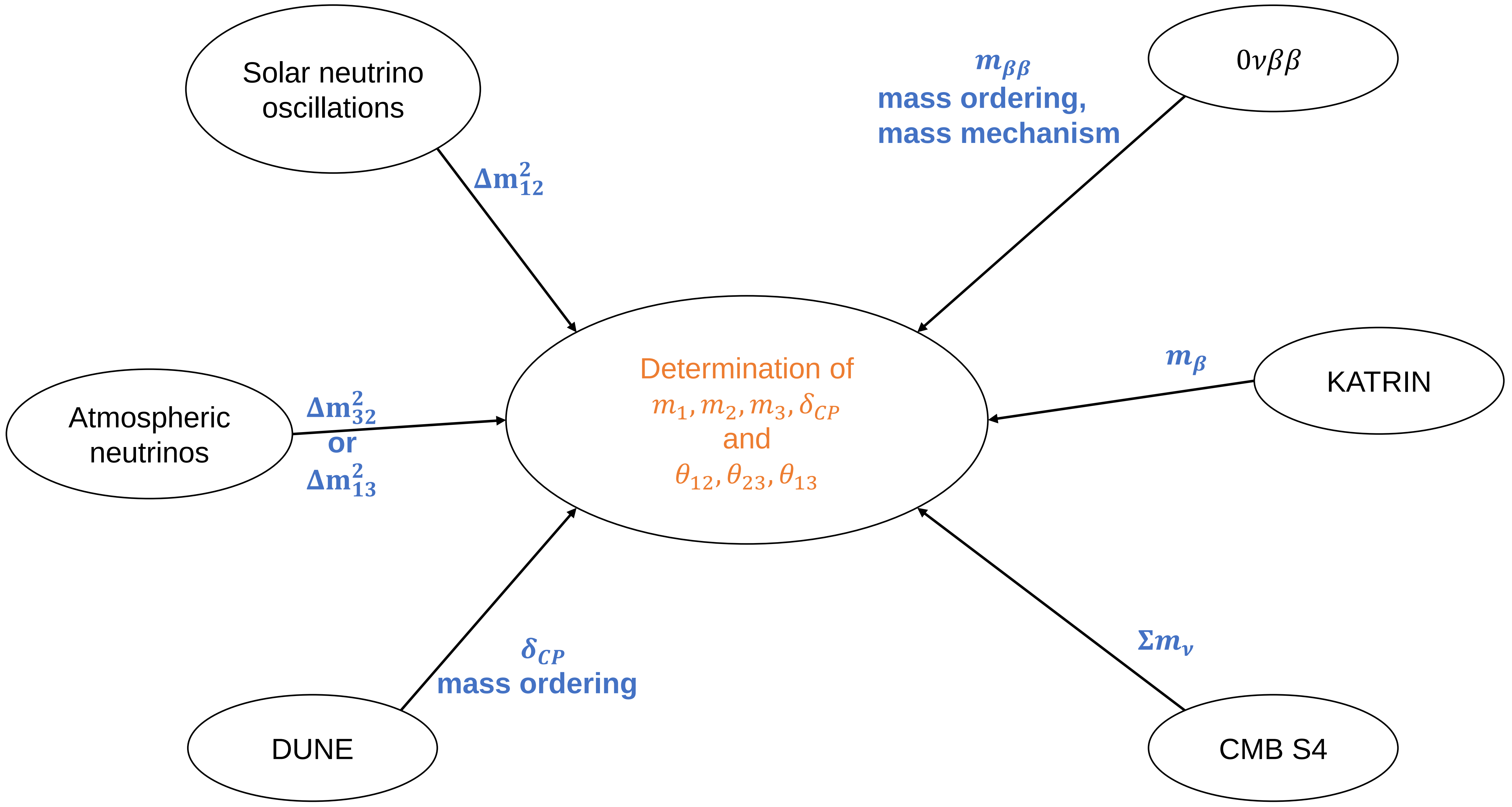
CMB-Stage 4

- The greater neutrino mass

→ the small scale of matter power spectrum ↓

→ the small scale of CMB lensing potential power spectrum ↓





Solar neutrino oscillations
Δm^2_{12}
$0\nu\beta\beta$
$m_{\beta\beta}$
mass ordering,
mass mechanism
Atmospheric neutrinos
Δm^2_{32}
or
Δm^2_{13}
Determination of
$m_1, m_2, m_3, \delta_{CP}$
and
$\theta_{12}, \theta_{23}, \theta_{13}$
KATRIN
m_β
DUNE
δ_{CP}
mass ordering
CMB S4
Σm_ν

In 3+1 scenario..with sterile ν

- Effective ν_e mass(absolute scale of ν mass)
- Mass sum $\Sigma = m_1 + m_2 + m_3$ $m_\beta = \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}$

→ Sterile ν is already non-relativistic after mat-rad equality (T=0.75eV)

- If ν is ***Majorana***, then Effective Majorana ν mass

→ $$|m_{\beta\beta}| = \left|\mu_1 + \mu_2 e^{i\alpha_2} + \mu_3 e^{i\alpha_3} + \mu_4 e^{i\alpha_4}\right|$$

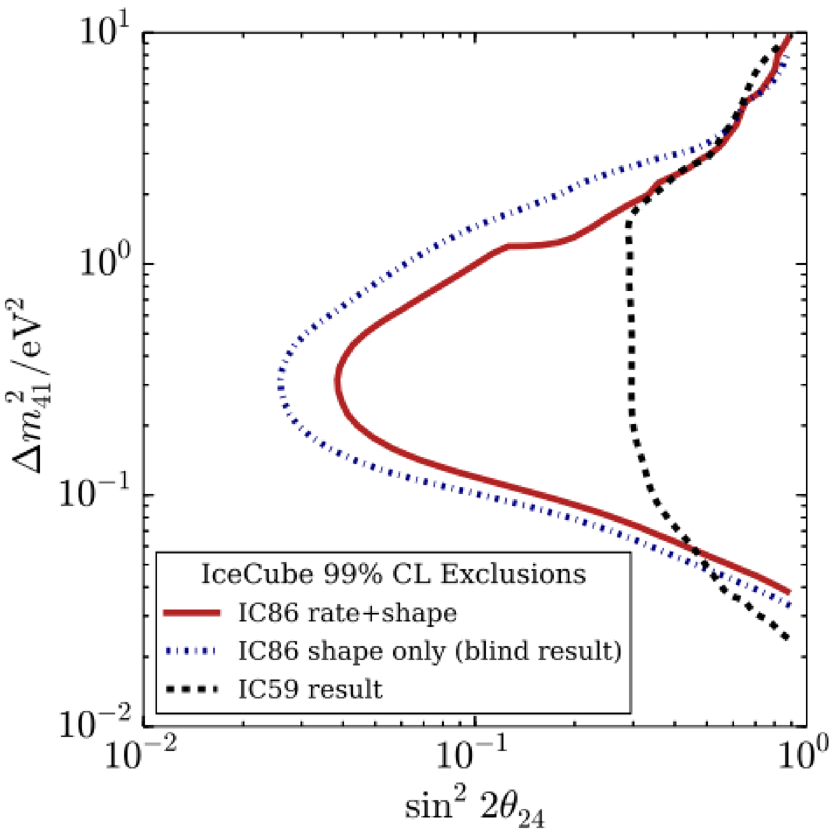
with $\mu_k = |U_{ek}|^2 m_k$ and

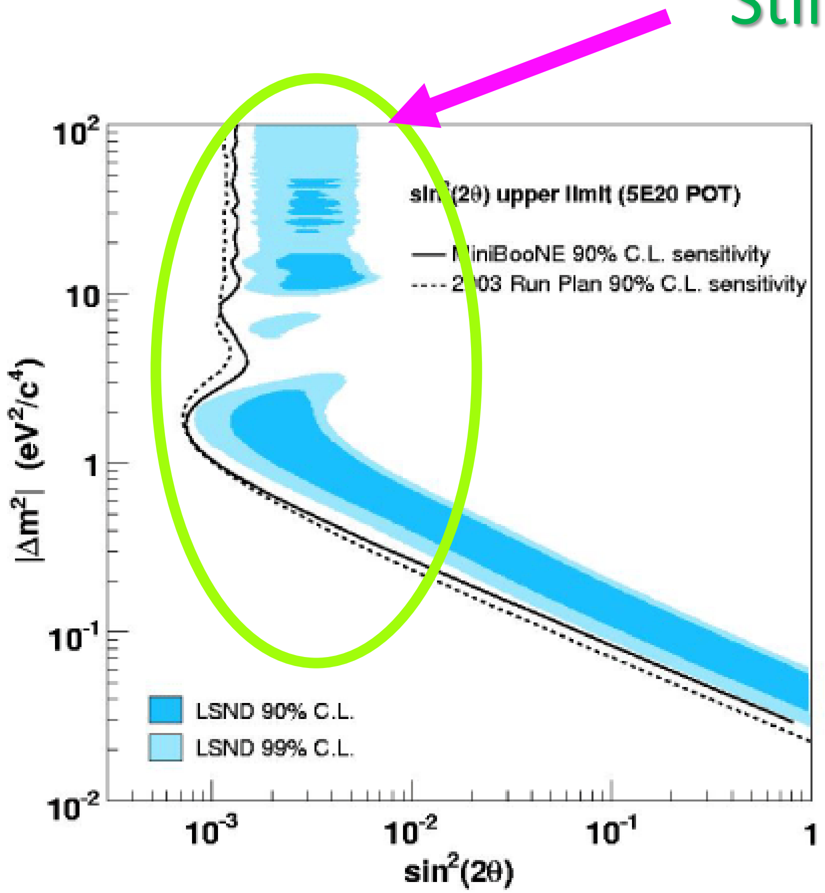
$$\begin{aligned}
|U_{e1}| &= \cos\vartheta_{14}\cos\vartheta_{13}\cos\vartheta_{12},\\
|U_{e2}| &= \cos\vartheta_{14}\cos\vartheta_{13}\sin\vartheta_{12},\\
|U_{e3}| &= \cos\vartheta_{14}\sin\vartheta_{13},\\
|U_{e4}| &= \sin\vartheta_{14}.
\end{aligned}$$

Appealing mass scenario

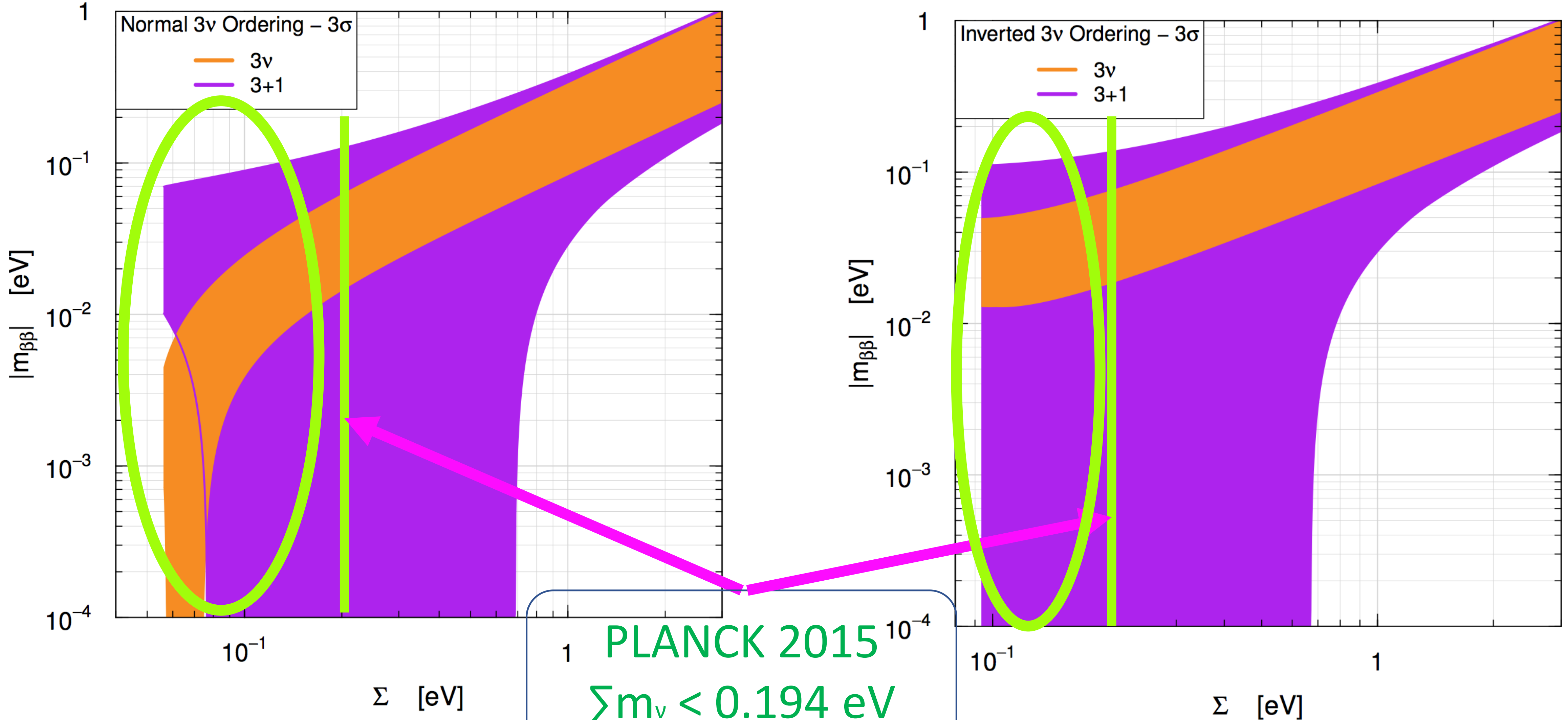
- Q. Mass Parameter Space for consistency of all mentioned exp?
- Ice Cube excluded only part of LSND anomaly

Still possible !



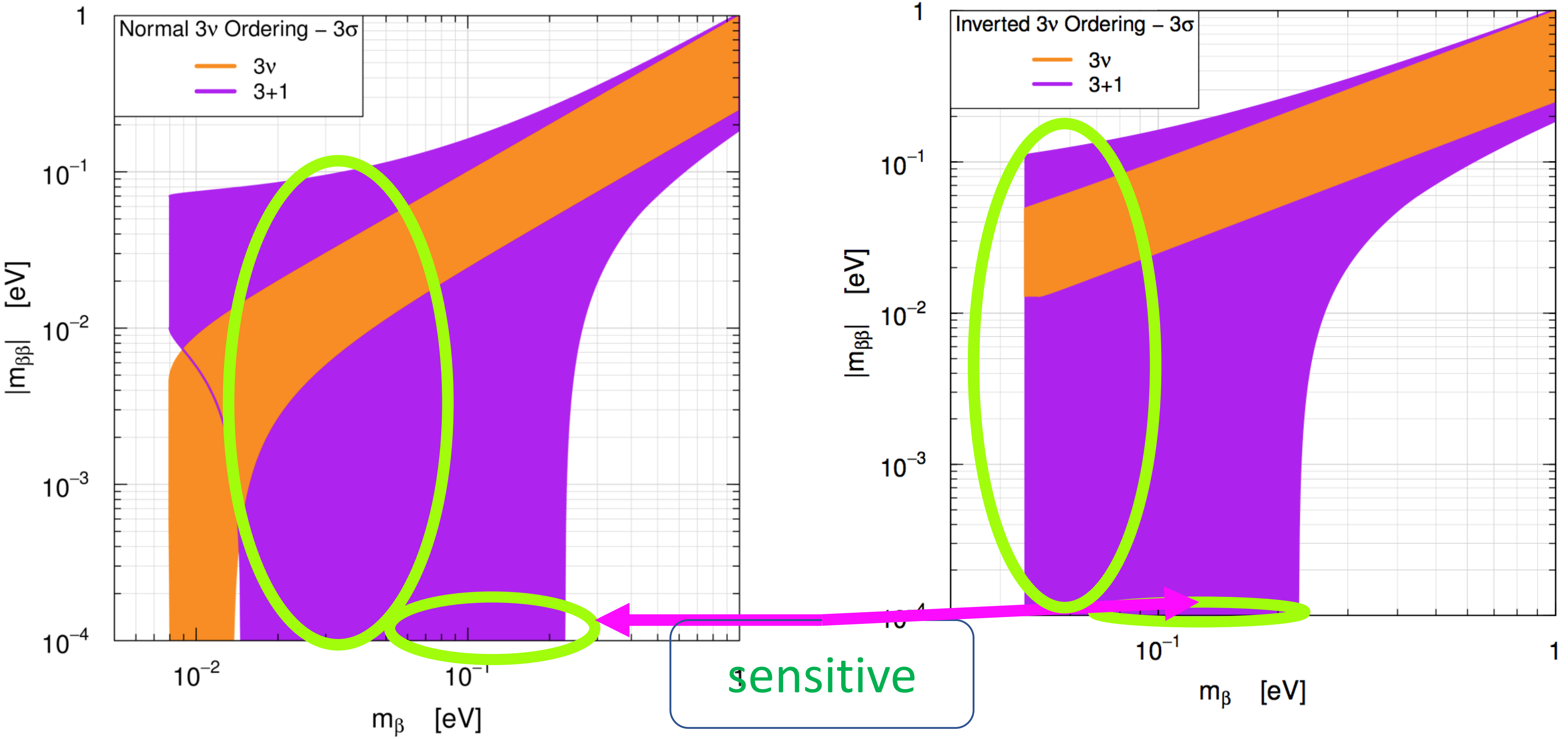


CMB S4 and $0\nu\beta\beta$

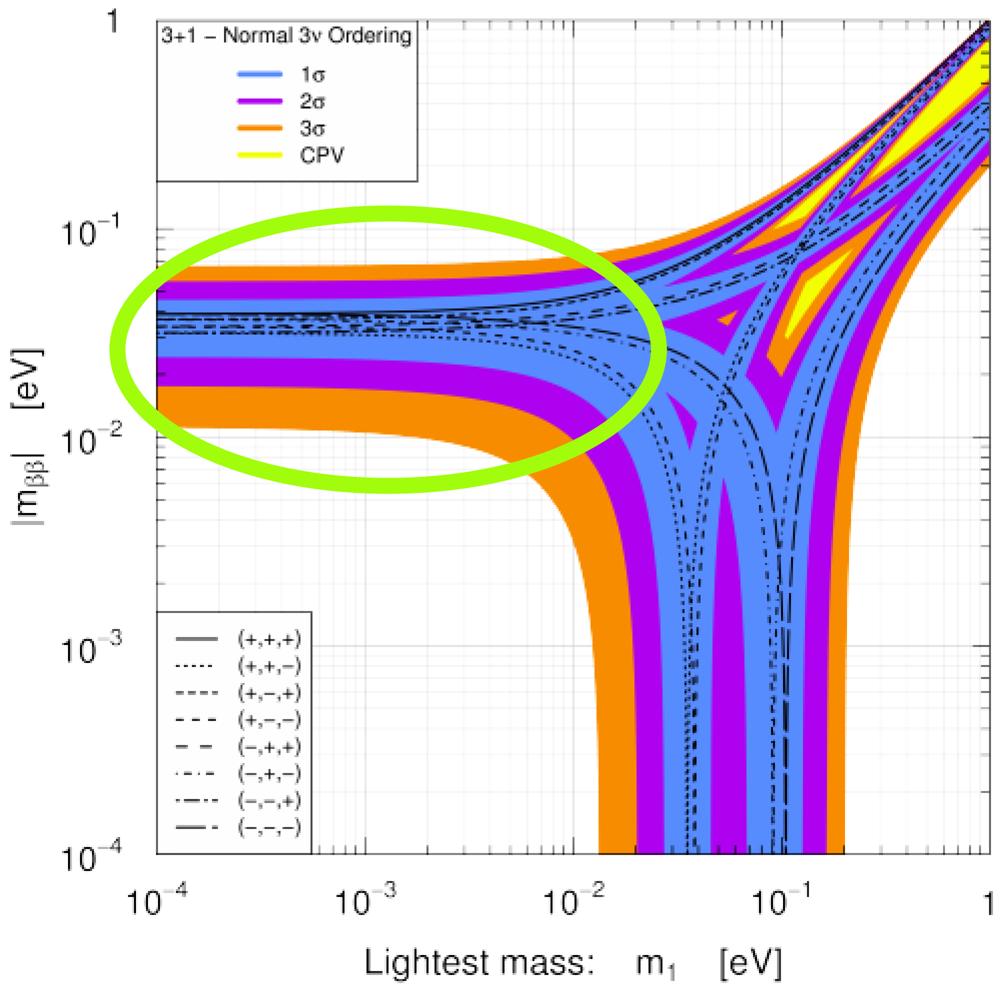


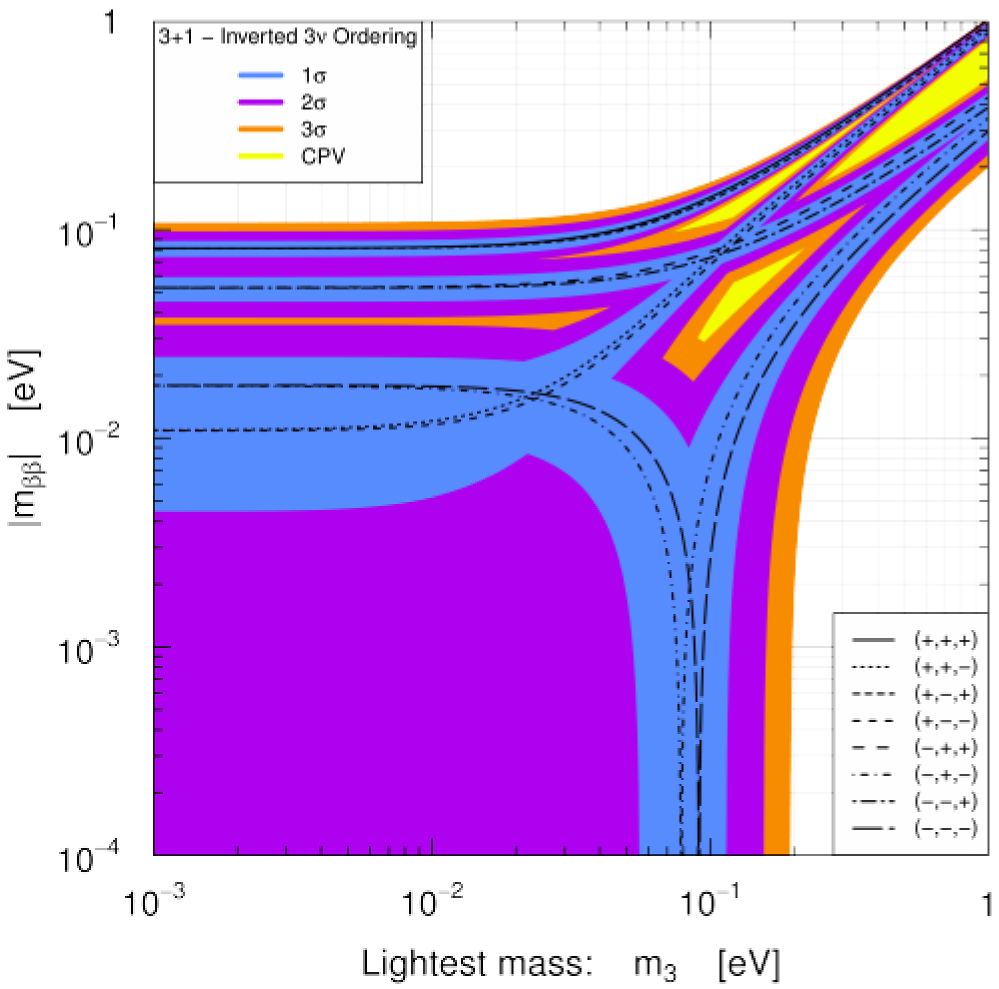
PLANCK 2015
$\sum m_\nu < 0.194$ eV

KATRIN and $0\nu\beta\beta$

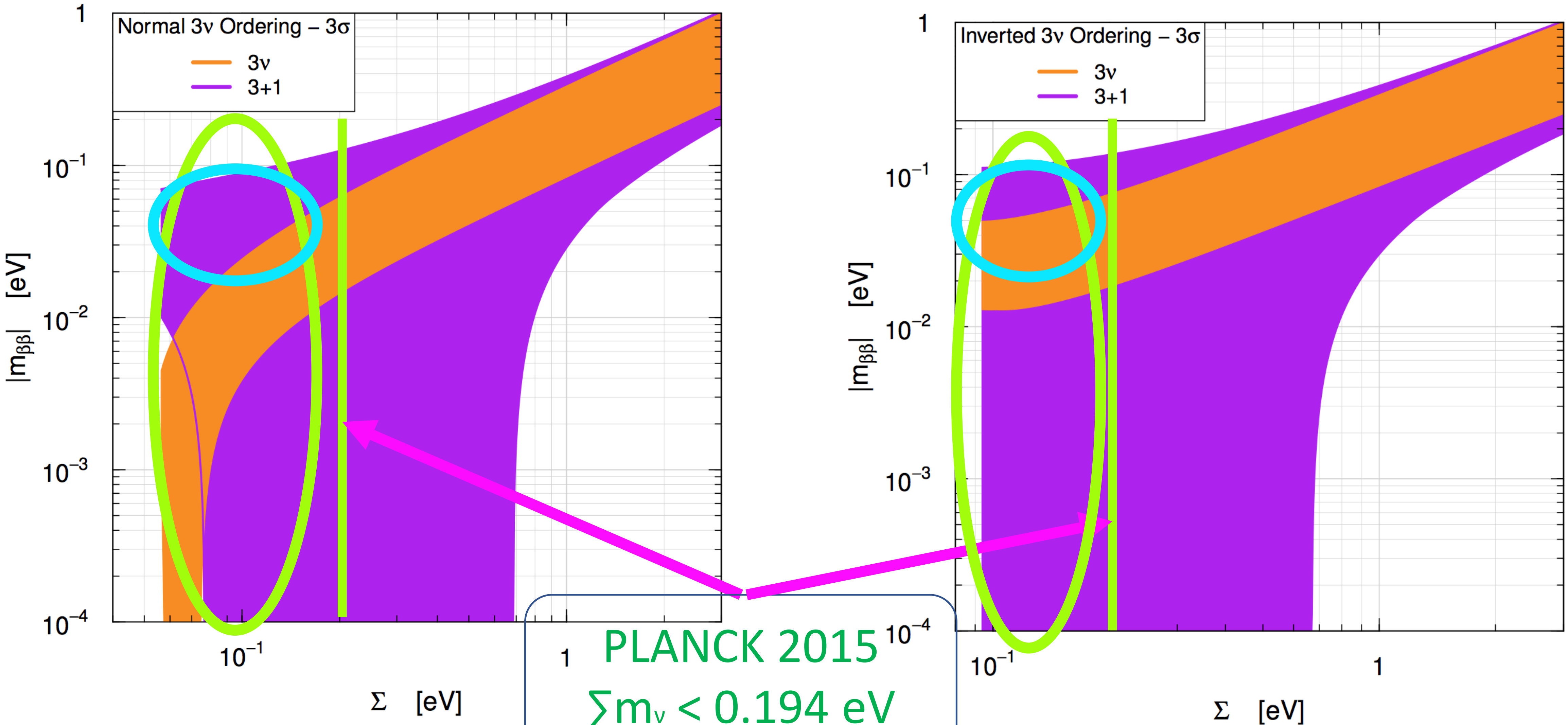


The lightest ν mass ?





CMB S4 and $0\nu\beta\beta$



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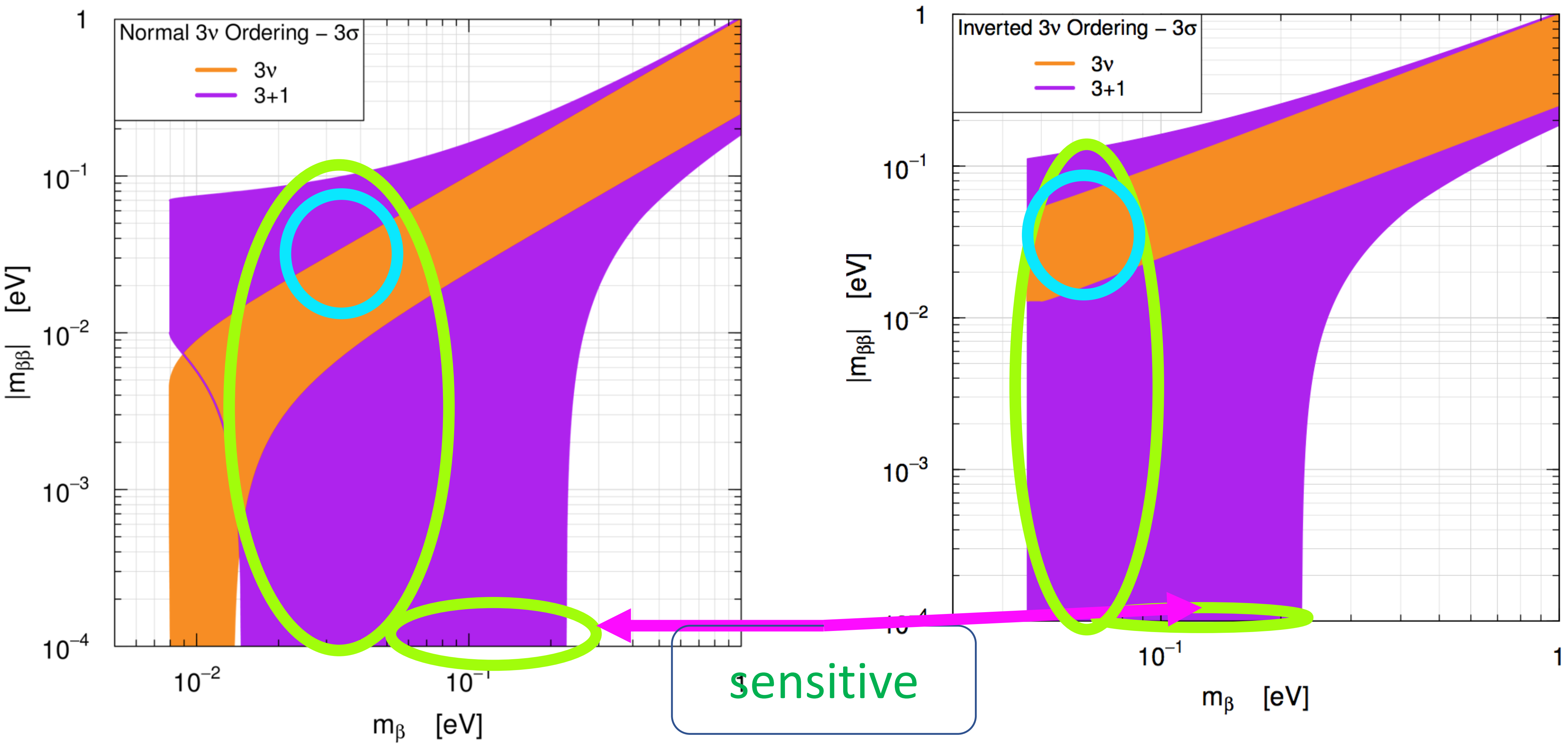
$\sum m_\nu < 0.194$ eV

KATRIN and $0\nu\beta\beta$



The lightest neutrino mass in tension with Ω_m

- If 3+1 scenario holds and ν is Majorana,
- In NO, for $m_{\beta\beta} \approx 2X10^{(-2)}$ eV ~ $6X10^{(-2)}$ eV,
- $m_1 \sim 0.001$ eV ⇒ $m_2 \sim 0.0087$ eV and $m_3 \sim 0.0497$eV

⇒ $\sum m_\nu \approx 0.059$eV (in tension with the lower bound from Ω_m=0.058eV)

- In IO, for for $m_{\beta\beta} \approx 2X10^{(-2)}$ eV ~ $6X10^{(-2)}$ eV,
- $m_3 \sim 0.001$eV

⇒ $m_1 \sim 0.049$eV, $m_2 \sim 0.0497$eV

⇒ $\sum m_\nu \approx 0.0997$eV (exceed the lower bound from Ω_m)

We can set the upper bound on the $m_{lightest} < O(10^{(-3)})$

Conclusion

- Still need to consider 3+1 scenario
- Within 3+1, there is a scenario of ν masses satisfying
- (1) oscillation exp result (DUNE)   (2) lower bound of $\sum m_\nu$ from Ω_m
- (3) upper bound of $\sum m_\nu$ from CMB-S4
- (4) sensitive to next generation of KATRIN
- (5) ν is Majorana (success of 0 νββ)
- $m_{lightest}$ ~ or < O(10^(-4))

References

- C. Giunti and E. Zavanin, arXiv:1505.00978
- CMB S4 science book, arXiv:1610.02743
- Long Baseline Neutrino Experiment , arXiv:1307.7335
- Neutrinoless double beta decay review , arXiv:1601.07512
- Searches for Sterile Neutrinos with the IceCube Detector, arXiv:1605.01990
- https://www.katrin.kit.edu/
- http://www.dunescience.org/
- Talks by L Kaufman, H Tanaka, A Friedland

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$m_\beta = \left[\sum\nolimits_i |U_{ei}|^2 m_i^2\right]^{\frac{1}{2}} = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}},$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i2\phi_2} + s_{13}^2 m_3 e^{i2\phi_3}\right|,$$