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Shedding light on the Δm^2_{21} tension with supernova neutrinos

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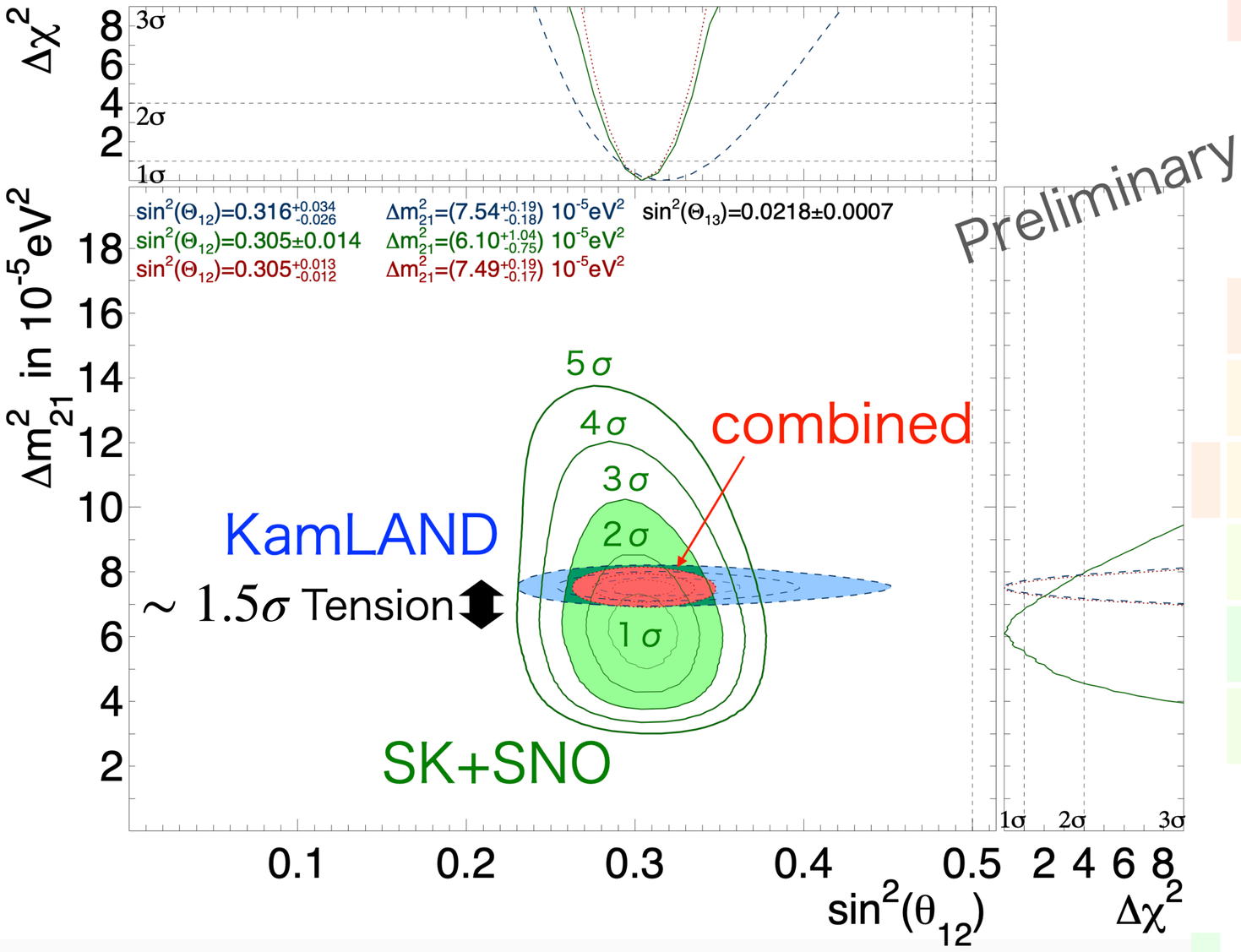
based on arXiv:2307.09509 and arXiv:2303.09369
with Olga Mena and Sergio Palomares-Ruiz

Invisibles Workshop 2023

29/08/2023

Solar parameters tension

Plot extracted from Neutrino22 contribution of Yusuke Koshio, SK collaboration



- There is a $\sim 1.5\sigma$ tension between **KamLAND** and **SK+SNO** measurements.
- **KamLAND**: reactor neutrinos.
- **SK+SNO**: solar neutrinos sensitive to Earth matter effects.
- **OUR MAIN GOAL:** solve tension using SN neutrinos sensitive to Earth matter effects.

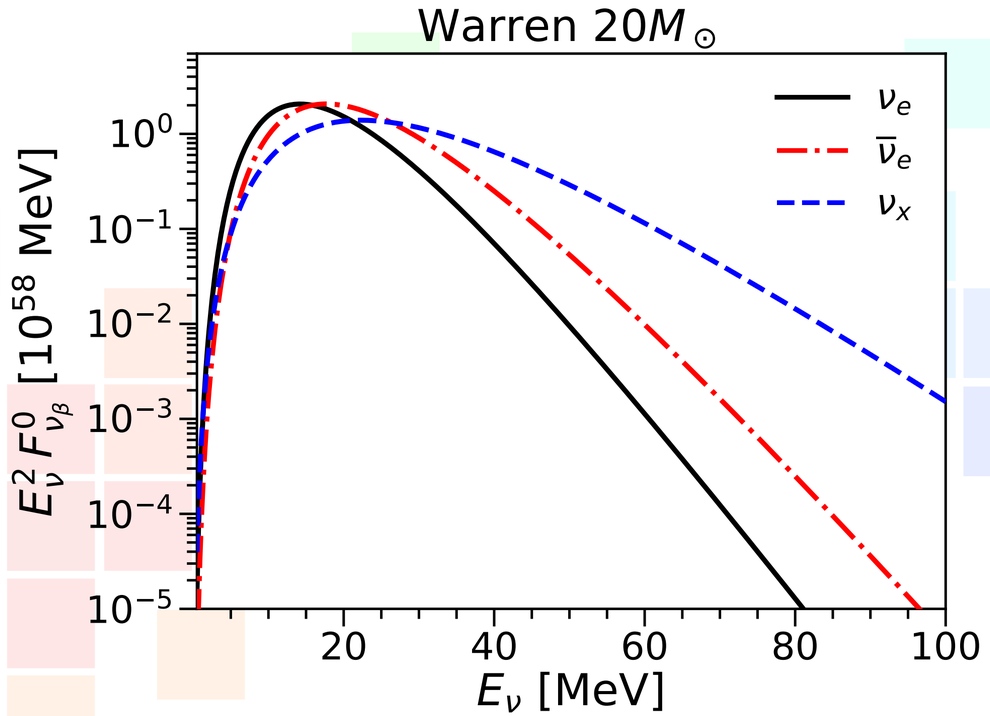
Supernova neutrinos

- Fluxes at the detector:

$$F^{\mathrm{D}}_{\nu_e} = p(\epsilon)\, F^{0}_{\nu_e} + \left(1 - p(\epsilon)\right)\, F^{0}_{\nu_x}$$

$$\epsilon \equiv \frac{2\, E_\nu\, V}{\Delta m^2_{21}} \simeq 0.12 \left(\frac{E_\nu}{20\ \mathrm{MeV}}\right) \left(\frac{Y_e\, \rho}{3\ \mathrm{g/cm^3}}\right) \left(\frac{7.5 \times 10^{-5}\ \mathrm{eV}^2}{\Delta m^2_{21}}\right)$$

- Earth matter effects contain information on the solar mixing parameters: Δm^2_{21} and θ_{12}.



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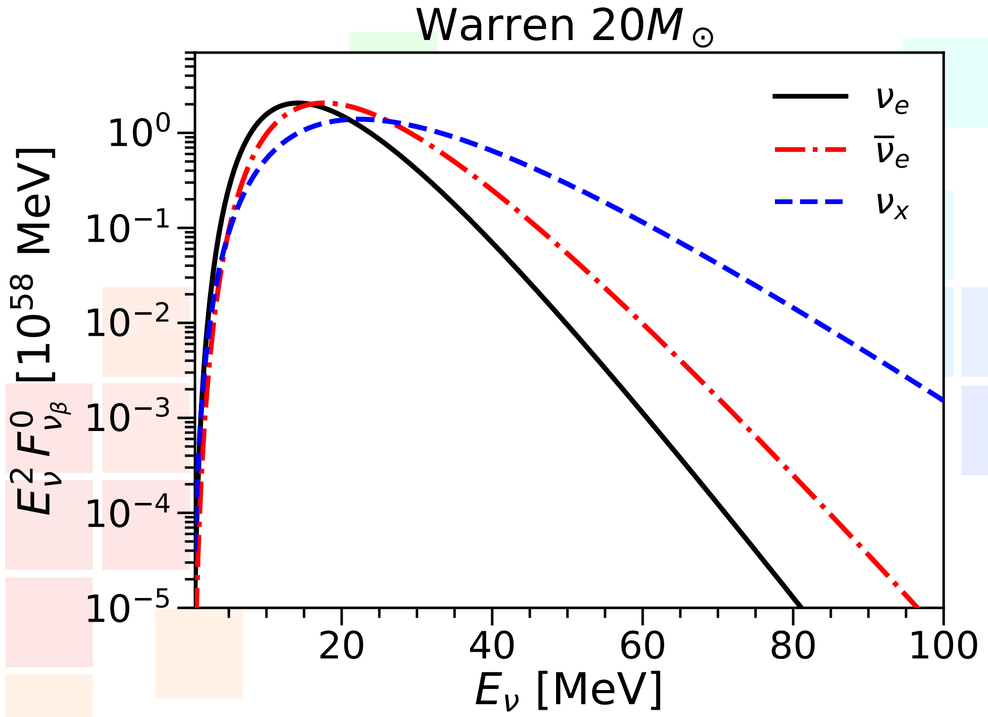


KamLAND

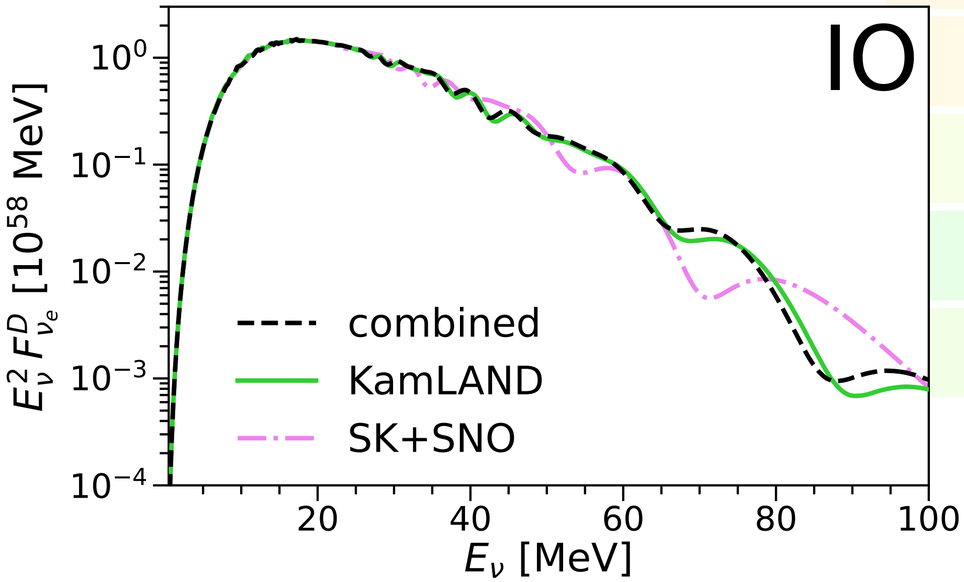
$\sin^2\theta_{12} = 0.316 \pm 0.007$

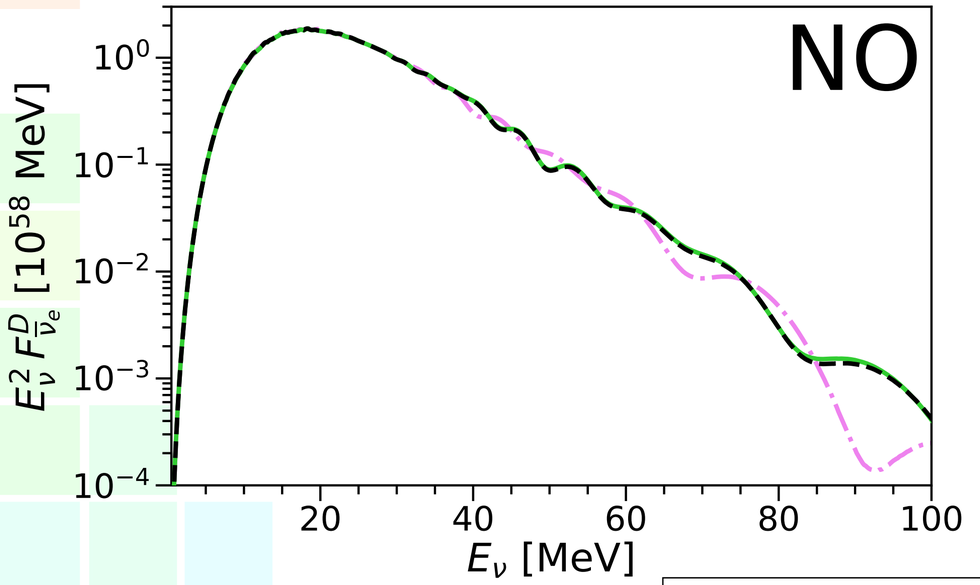
$\Delta m^2_{21} = \left(7.54\,^{+0.26}_{-0.24}\right) \times 10^{-5}\ \mathrm{eV}^2$

SK+SNO

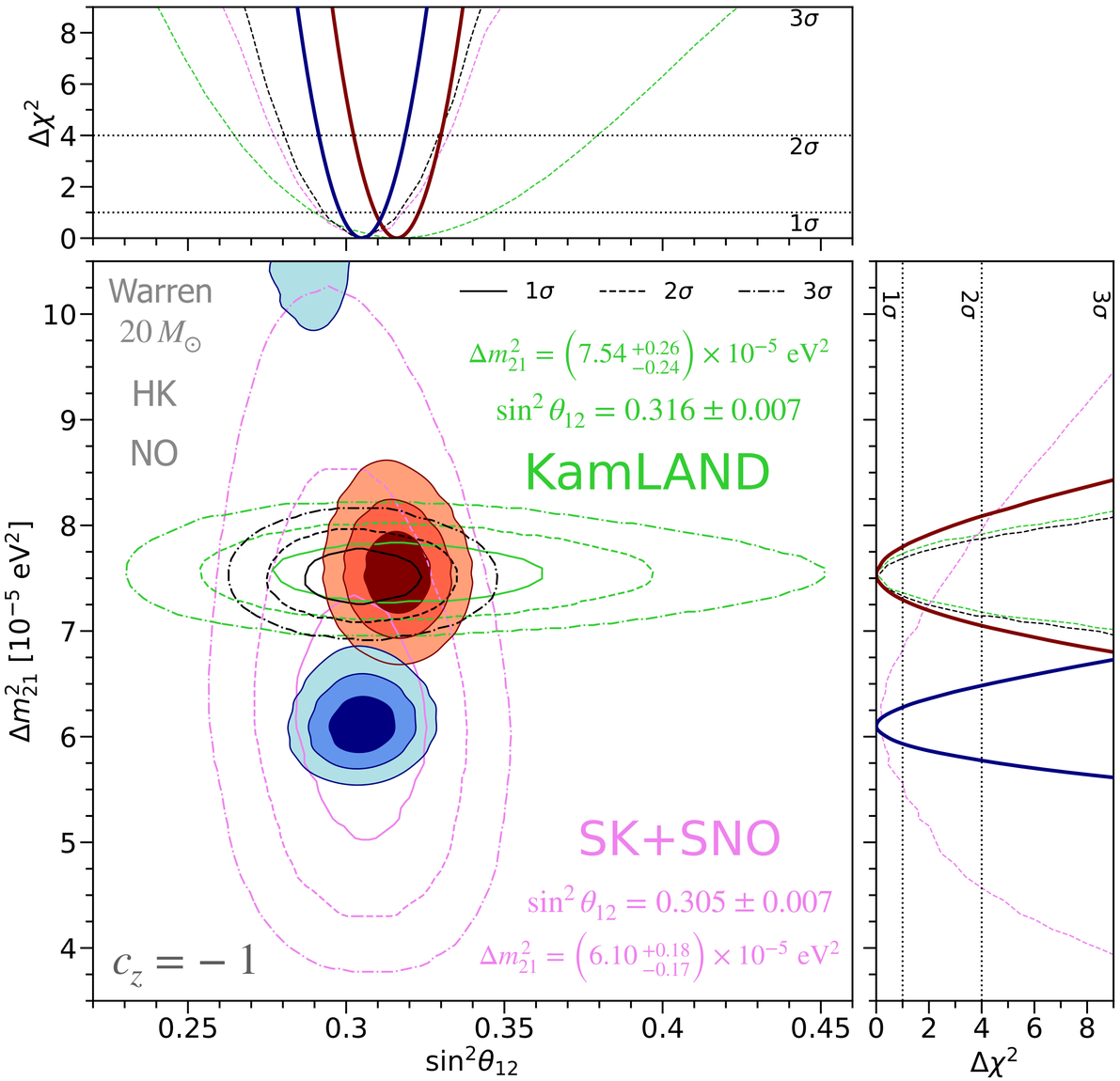
$\sin^2\theta_{12} = 0.305 \pm 0.007$

$\Delta m^2_{21} = \left(6.10\,^{+0.18}_{-0.17}\right) \times 10^{-5}\ \mathrm{eV}^2$



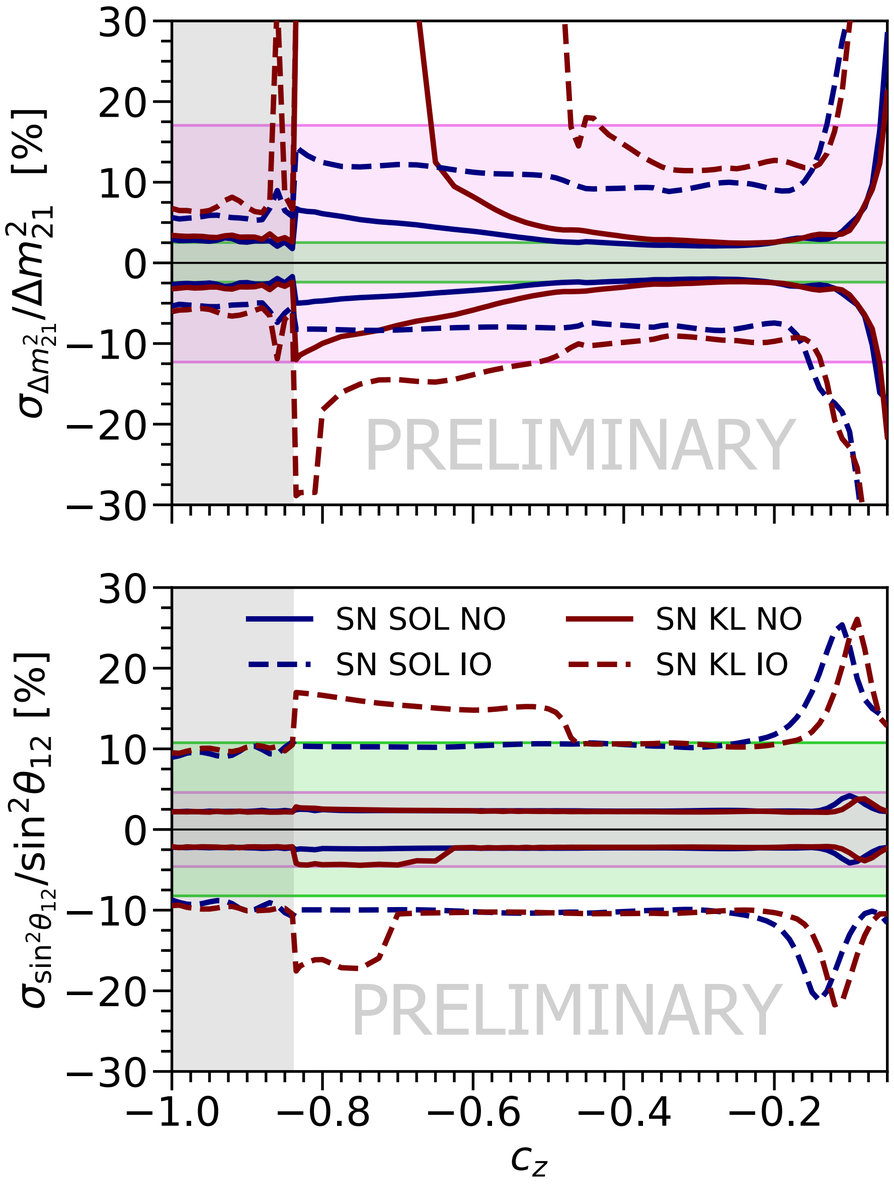


Results

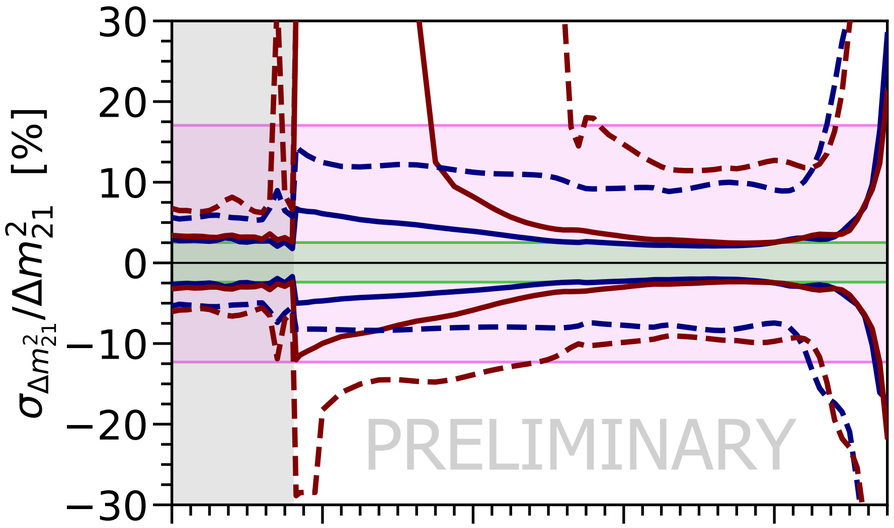


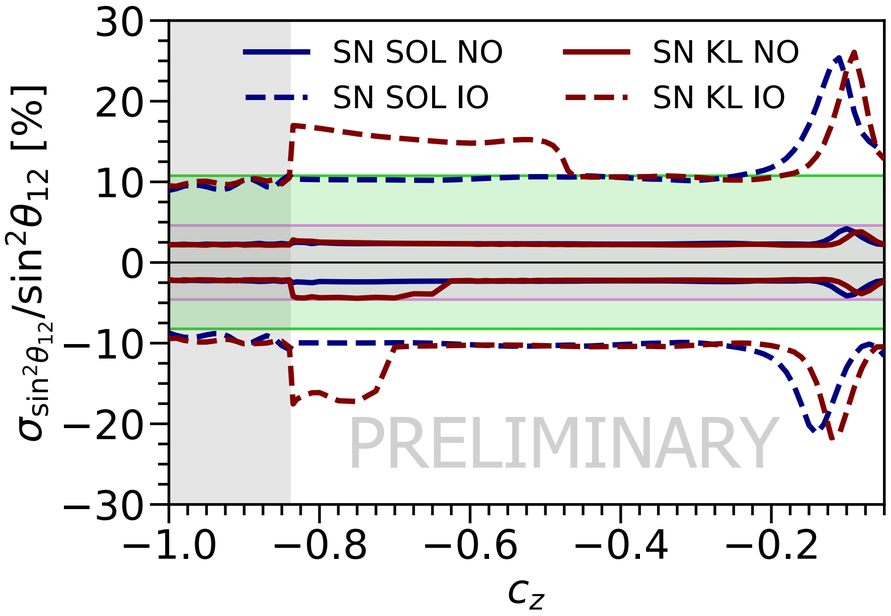
- Forecasts for a SN burst at 10 kpc.
- Current KamLAND allowed regions
- Current SK+ SNO allowed regions
- Forecast assuming as “true=nature” value KamLAND best fit
  - Alleviate tension between reactor and Earth matter effects.
- Forecast assuming as “true” value SK+SNO best fit
  - Increase tension between reactor and Earth matter effects.

Results: Projected uncertainties



Results: Projected uncertainties and tension





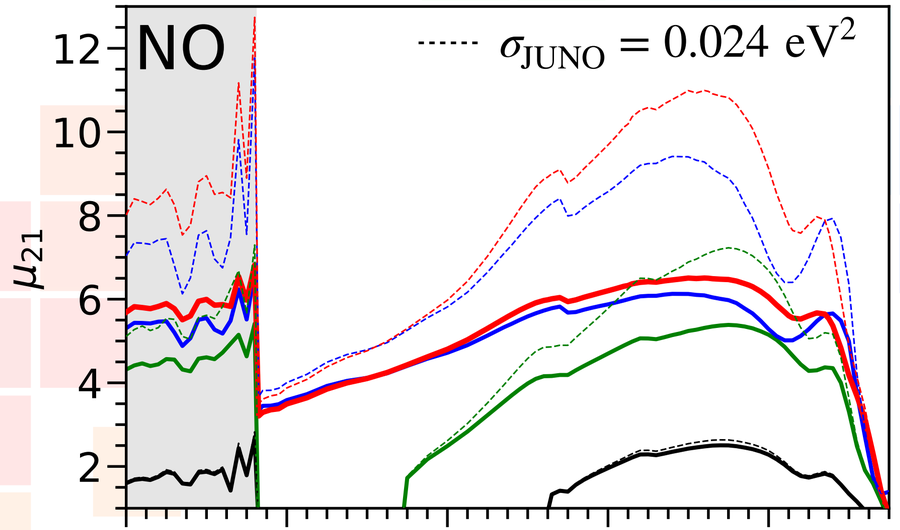
$$\mu_{21} = \frac{\Delta m^2_{21}|_{\mathrm{KL}} - \Delta m^2_{21}|_{\mathrm{solar}}}{\sqrt{\sigma^2_{\mathrm{KL}} + \sigma^2_{\mathrm{SN}}(c_z)}}$$

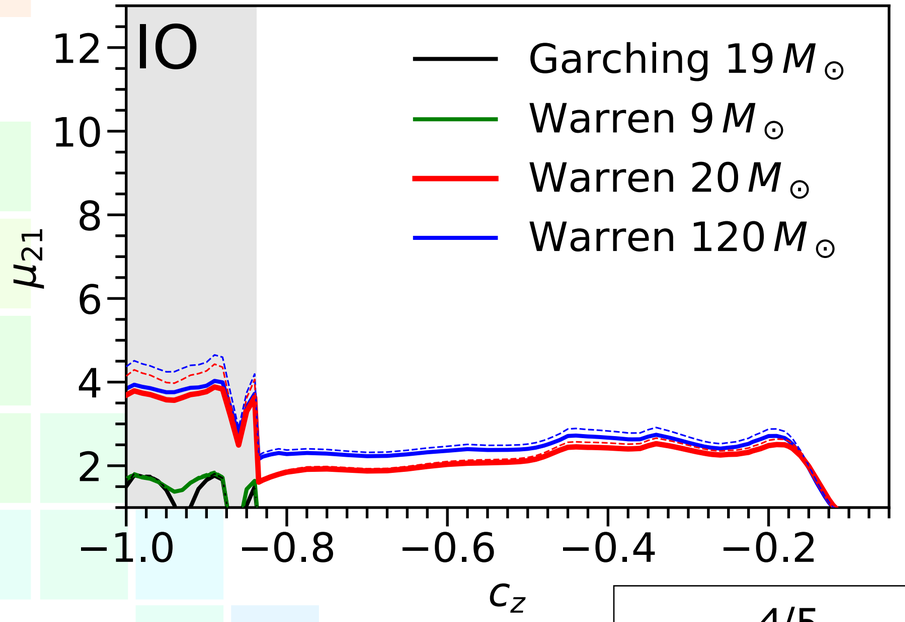
Tension exacerbates for NO.

Tension much larger for Warren high progenitor star mass models.

Tension increases with matter effects.

Tension could be $> 10\sigma$ in future detectors





Take home message

A future galactic SN explosion could provide:

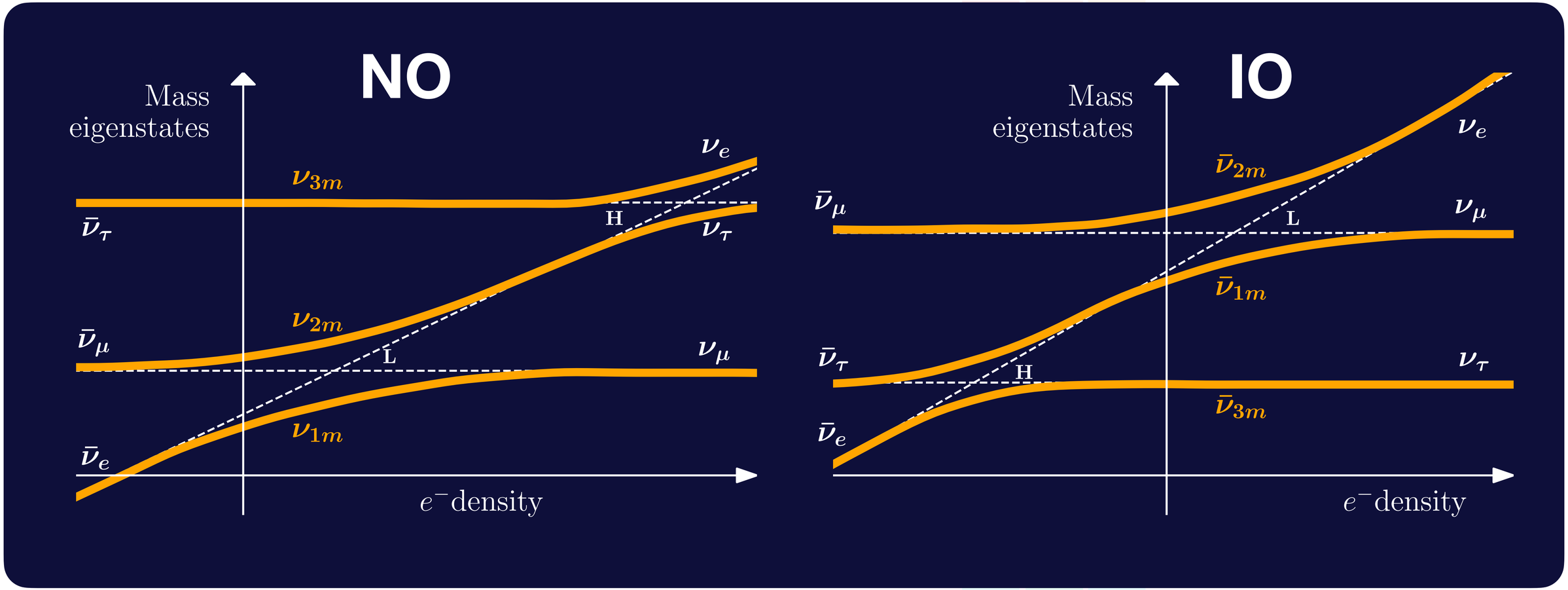
- A competitive measurement of Δm^2_{21}
- A reduction of the uncertainty on $\sin^2\theta_{12}$.
- A solution to the longstanding tension between solar neutrino and reactor antineutrino data.

Shedding light on the Δm^2_{21} tension with supernova neutrinos

BACKUP SLIDES

Supernova neutrinos

- Adiabatic transitions make neutrinos go out from the SN as mass eigenstates.



Supernova neutrinos

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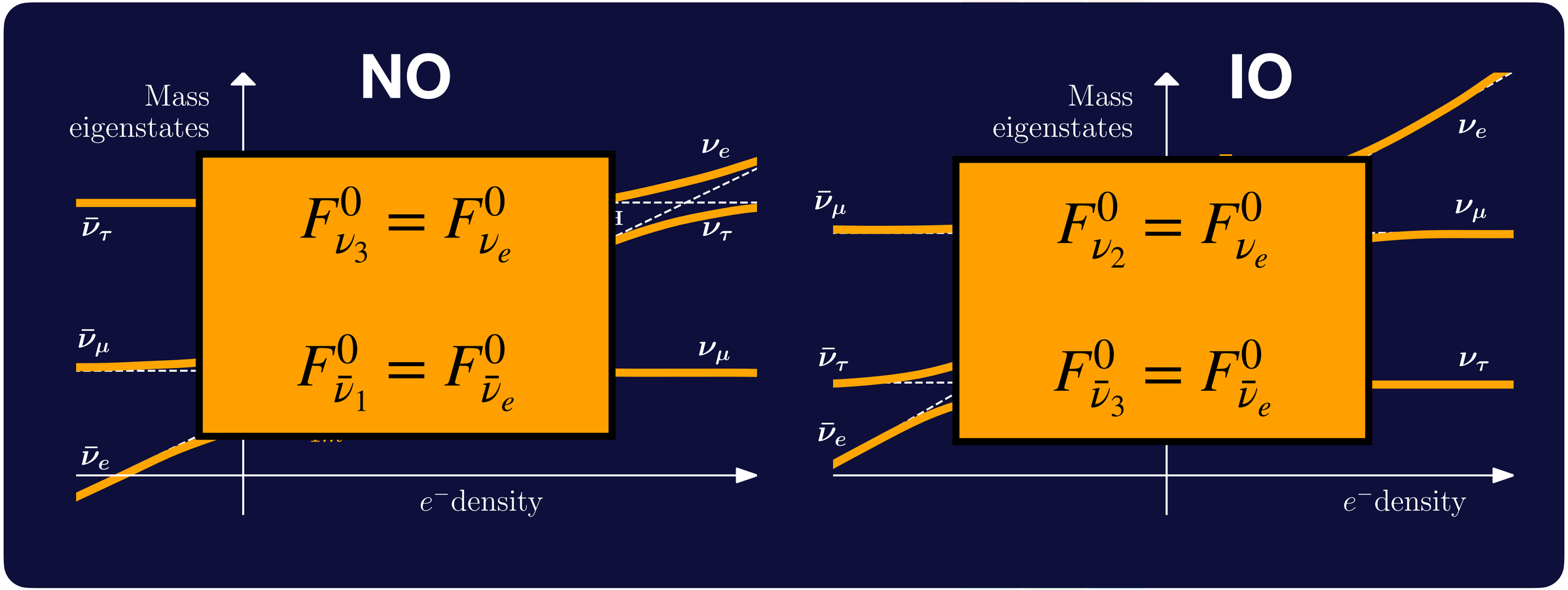

Supernova neutrinos

- Fluxes at detectors are a combination of fluxes at production:

$$F^{\mathrm{D}}_{\nu_e} = p\,F^{0}_{\nu_e} + (1-p)\,F^{0}_{\nu_x} \qquad F^{\mathrm{D}}_{\nu_x} = \frac{1-p}{2}\,F^{0}_{\nu_e} + \frac{1+p}{2}\,F^{0}_{\nu_x}$$

$$F^{\mathrm{D}}_{\bar{\nu}_e} = \bar{p}\,F^{0}_{\bar{\nu}_e} + (1-\bar{p})\,F^{0}_{\nu_x} \qquad F^{\mathrm{D}}_{\bar{\nu}_x} = \frac{1-\bar{p}}{2}\,F^{0}_{\bar{\nu}_e} + \frac{1+\bar{p}}{2}\,F^{0}_{\nu_x}$$

- In order to obtain p we need to know neutrino evolution:

$$\mathscr{H}_{\text{flavor}} = \underbrace{\frac{1}{2E}U\mathbb{M}^2U^{\dagger}}_{\text{Vacuum}} + \underbrace{\mathbb{V}}_{\text{Matter}}$$

$$\mathbb{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} \qquad \mathbb{V} = \begin{pmatrix} V(n_e) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$U = U_{23}\Gamma_{\delta}U_{13}U_{12}$$

PMNS matrix

Supernova neutrinos

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Vacuum probabilities

$$p^{\rm NO}_{\rm vac} \equiv P_{\rm vac}(\nu_3 \to \nu_e) = |U_{e3}|^2 = \sin^2\theta_{13}$$
$$\bar p^{\rm NO}_{\rm vac} \equiv P_{\rm vac}(\bar\nu_1 \to \bar\nu_e) = |U_{e1}|^2 = \cos^2\theta_{12}\,\cos^2\theta_{13}$$

$$p^{\rm IO}_{\rm vac} \equiv P_{\rm vac}(\nu_2 \to \nu_e) = |U_{e2}|^2 = \sin^2\theta_{12}\cos^2\theta_{13}$$
$$\bar p^{\rm IO}_{\rm vac} \equiv P_{\rm vac}(\bar\nu_3 \to \bar\nu_e) = |U_{e3}|^2 = \sin^2\theta_{13} \quad .$$

$V \neq 0$

Constant density probabilities

$$p^{\rm NO}_{\oplus} \equiv P_{\oplus}(\nu_3 \to \nu_e) \simeq \sin^2\theta_{13}$$
$$\bar p^{\rm NO}_{\oplus} \equiv P_{\oplus}(\bar\nu_1 \to \bar\nu_e) \simeq \cos^2\theta_{13}\,\left(1 - \bar P^{2\nu}_{\oplus}\right)$$

$$p^{\rm IO}_{\oplus} \equiv P_{\oplus}(\nu_2 \to \nu_e) \simeq \cos^2\theta_{13}\,P^{2\nu}_{\oplus}$$
$$\bar p^{\rm IO}_{\oplus} \equiv P_{\oplus}(\bar\nu_3 \to \bar\nu_e) \simeq \sin^2\theta_{13}$$

Supernova neutrinos

DUNE (LIQUID ARGON)	HK (WATER CHERENKOV)	JUNO (LIQUID SCINTILLATOR)
$\nu_e\mathrm{Ar}-\mathrm{CC}: \quad \nu_e + {}^{40}\mathrm{Ar} \to e^- + \mathrm{X}\ ,$ $\bar{\nu}_e\mathrm{Ar}-\mathrm{CC}: \quad \bar{\nu}_e + {}^{40}\mathrm{Ar} \to e^+ + \mathrm{X}\ ,$ $\nu - e^-\,\mathrm{ES}: \quad \nu + e^- \to \nu + e^-\ .$	$\mathrm{IBD}: \quad \bar{\nu}_e + p \to e^+ + n\ ,$ $\nu_e\mathrm{O}-\mathrm{CC}: \quad \nu_e + {}^{16}\mathrm{O} \to e^- + \mathrm{X}\ ,$ $\bar{\nu}_e\mathrm{O}-\mathrm{CC}: \quad \bar{\nu}_e + {}^{16}\mathrm{O} \to e^+ + \mathrm{X}\ ,$ $\nu - e^-\,\mathrm{ES}: \quad \nu + e^- \to \nu + e^-\ .$	$\mathrm{IBD}: \quad \bar{\nu}_e + p \to e^+ + n\ ,$ $\nu_e\mathrm{C}-\mathrm{CC}: \quad \nu_e + {}^{12}\mathrm{C} \to e^- + \mathrm{X}\ ,$ $\bar{\nu}_e\mathrm{C}-\mathrm{CC}: \quad \bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + \mathrm{X}\ ,$ $\nu - e^-\,\mathrm{ES}: \quad \nu + e^- \to \nu + e^-\ .$
$N_t^{Ar} = 6.03 \cdot 10^{32}$ 20% ENERGY RESOLUTION	$N_t^{p} = 2.94 \cdot 10^{34}$ MEDIUM ENERGY RESOLUTION	$N_t^{p} = 1.47 \cdot 10^{33}$ GOOD ENERGY RESOLUTION
$\nu_e\mathrm{Ar}-\mathrm{CC}+\bar{\nu}_e\mathrm{Ar}-\mathrm{CC}$ $\nu - e^-\mathrm{ES}$	$0.9\,\mathrm{IBD}$ $0.1\,\mathrm{IBD}+\nu_e\mathrm{O}-\mathrm{CC}+$ $+\bar{\nu}_e\mathrm{O}-\mathrm{CC}+\nu-e^-\mathrm{ES}$	$0.95\,\mathrm{IBD}$ $0.05\,\mathrm{IBD}+\nu_e\mathrm{O}-\mathrm{CC}+$ $+\bar{\nu}_e\mathrm{O}-\mathrm{CC}+\nu-e^-\mathrm{ES}$

Supernova neutrinos

- Warren20,
  $c_z = -1,$
  $d_{\mathrm{SN}} = 10\ \mathrm{kpc}$

NO effect in antineutrinos

IO effect in neutrinos