RH is supported by the Spanish grant FPU19/03348 of Ministerio de Universidades.

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

Rasmi E. Hajjar Muñoz

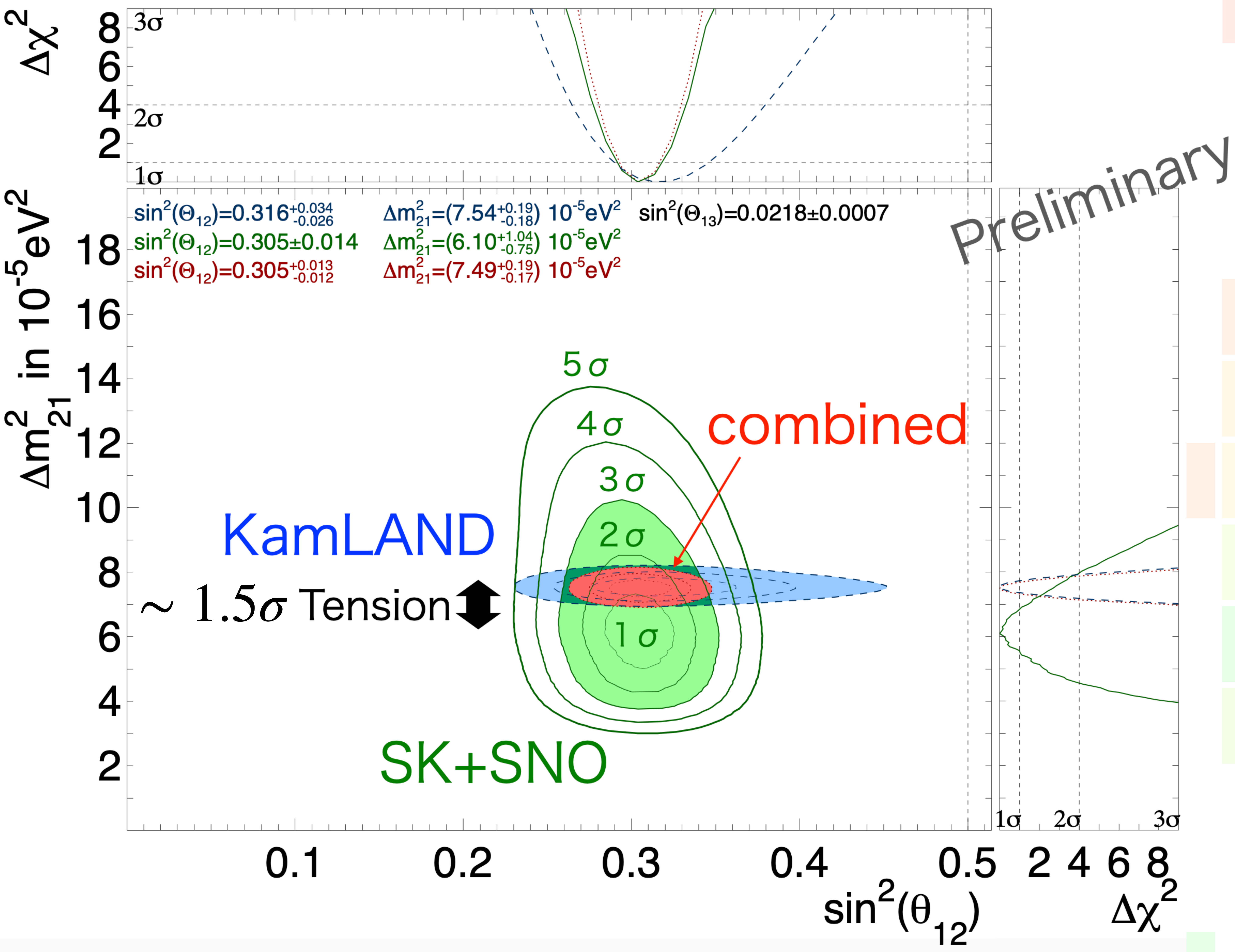
based on PLB 854 (2024) 138719 and *Phys.Rev.D* 108 (2023) 083011
with Olga Mena and Sergio Palomares-Ruiz

PLANCK2024

04/06/2024

Main goal of this work: tension?

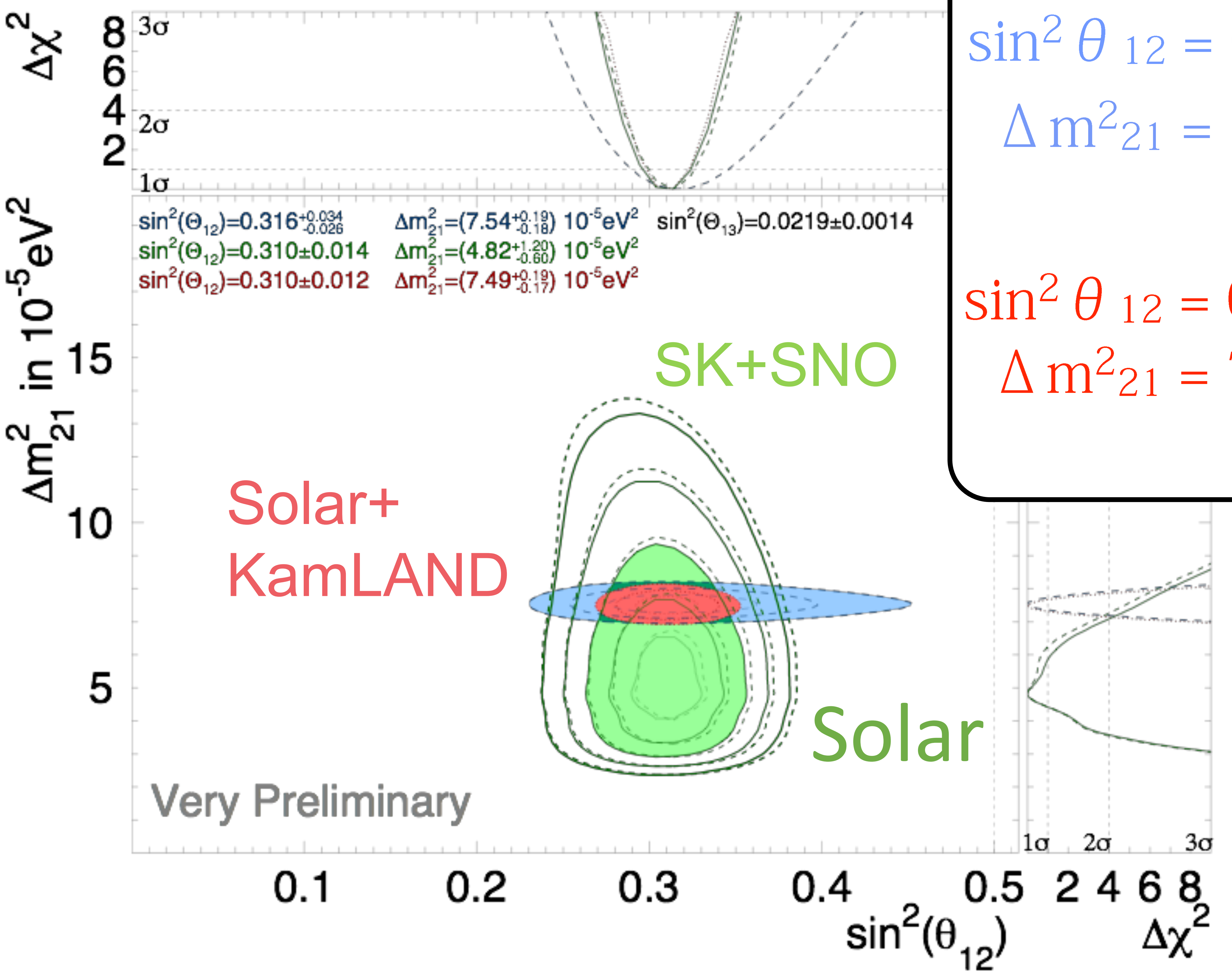
Plot extracted from Neutrino22 contribution of Yusuke Koshio, SK collaboration



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

Main goal of this work: tension!

Solar ν Angle θ12 & Ma



$\sin^2\theta_{12} = 0.310 \pm 0.014$
$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60} \times 10^{-5}\mathrm{eV}^2$

$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$

$\sin^2\theta_{12} = 0.310 \pm 0.012$
$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5}\mathrm{eV}^2$

Slide extracted from Neutrino18 contribution of Motoyasu Ikeda, SK collaboration

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- Now the tension relaxed…
- But in the past this tension was higher!
- $\sim 2.3\sigma$ tension between **KamLAND** and **SK+SNO** measurements without the last data inclusion.

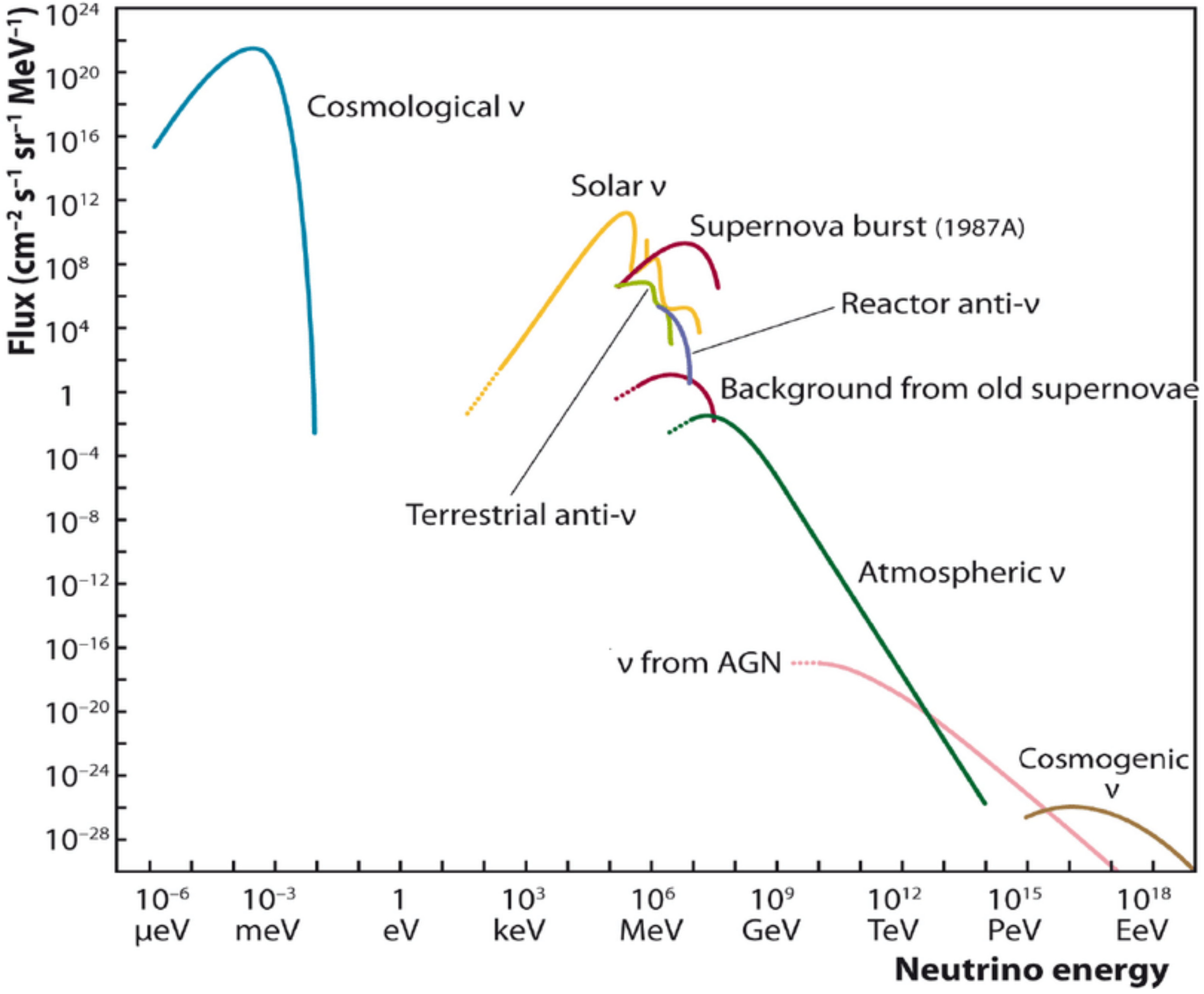
With the next galactic SN explosion we can add a measurement on this plane…

With the next galactic SN explosion we can add a measurement on this plane…

…and things could get interesting

Supernova neutrinos

U.F. Katz, Ch. Spiering, Prog.Part.Nucl.Phys. 67 (2012), 651-704



- Core-collapse SN is the violent explosion during death of massive stars.
- 99% energy of star ($\sim 10^{53}$ erg) is released in the form of neutrinos.
- Excellent source due to high flux and low background when applied temporal cut.

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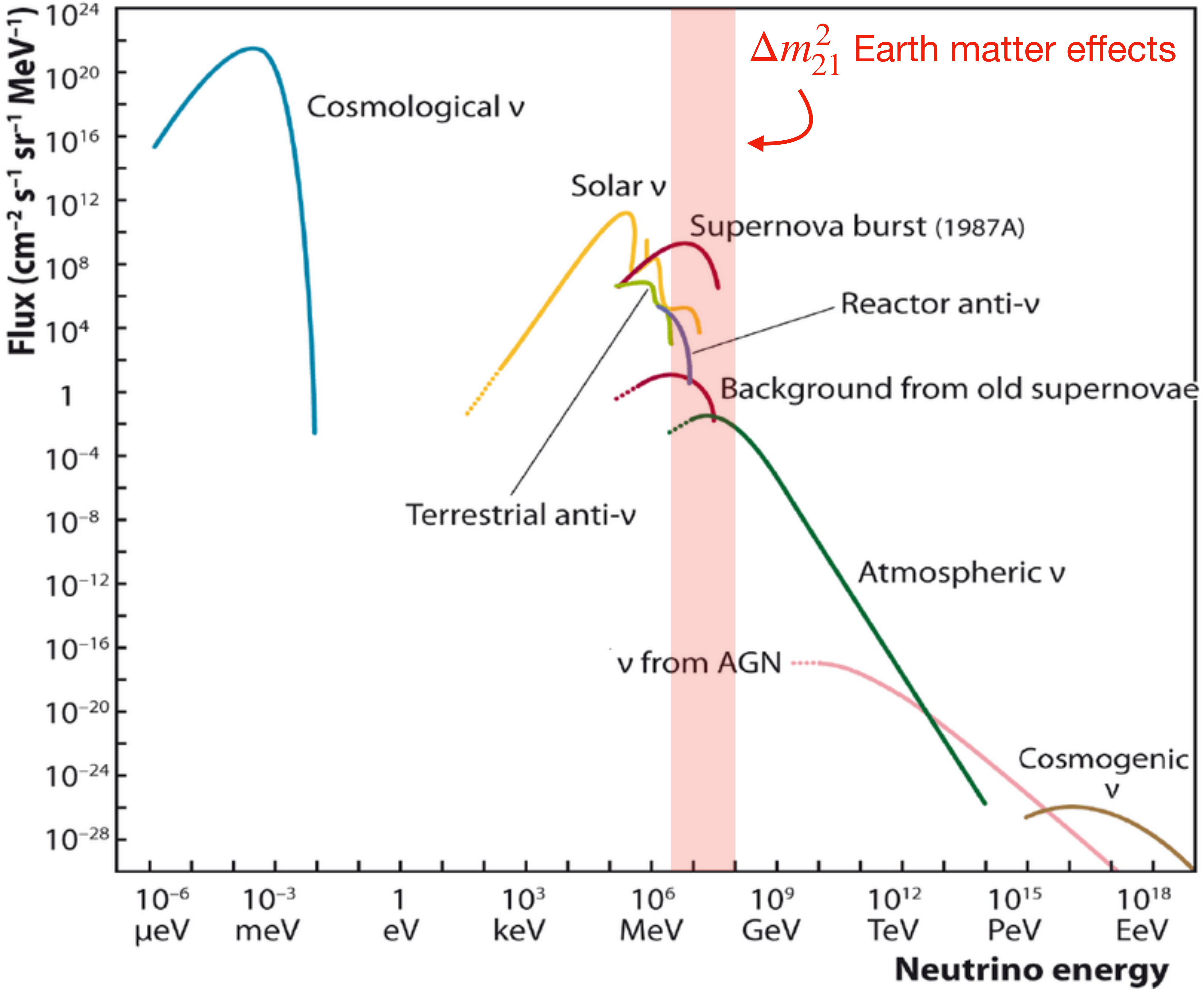

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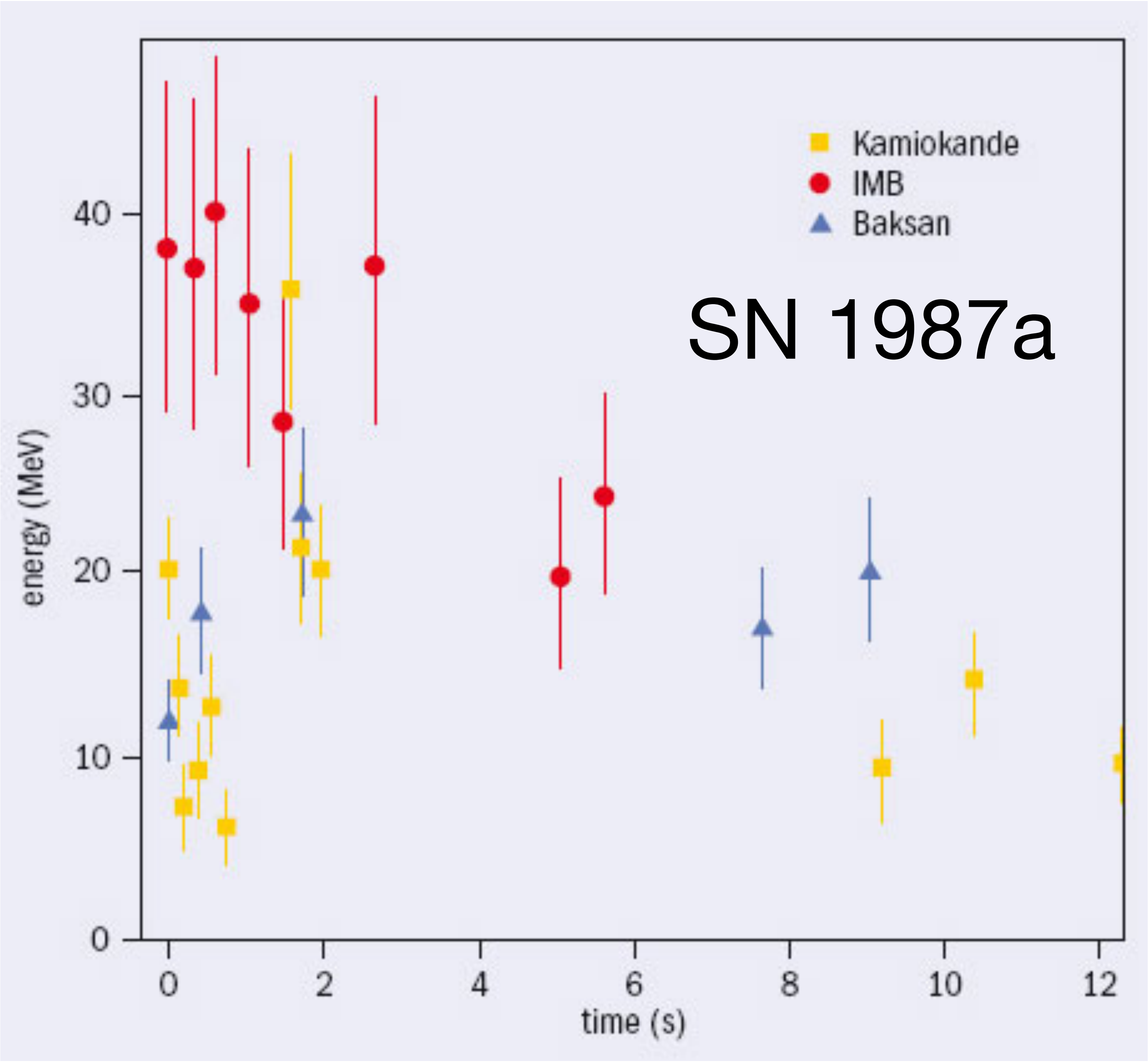
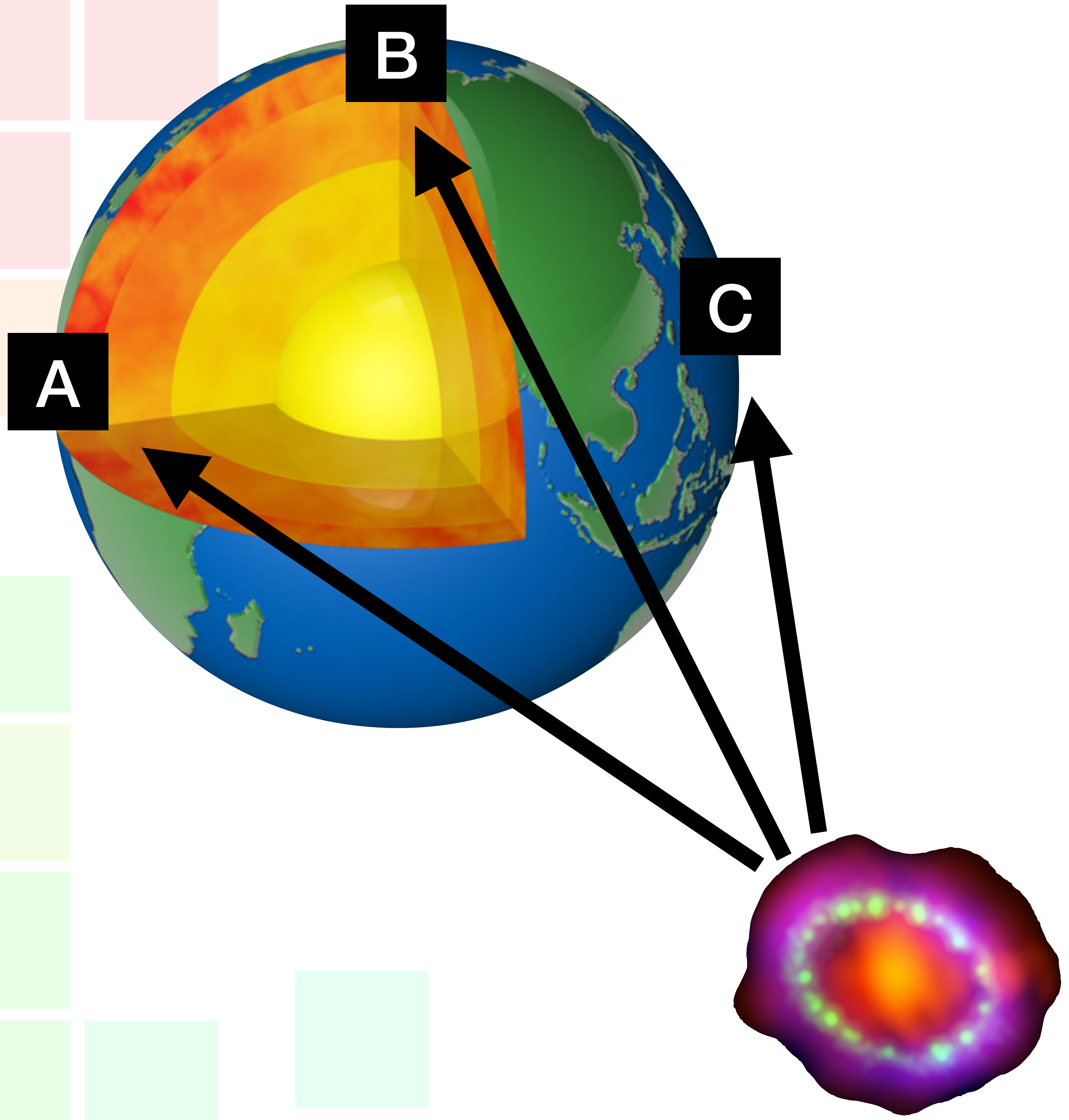
Supernova neutrinos

Main drawbacks

Uncertainty on fluxes



One direction per detector



Supernova neutrinos

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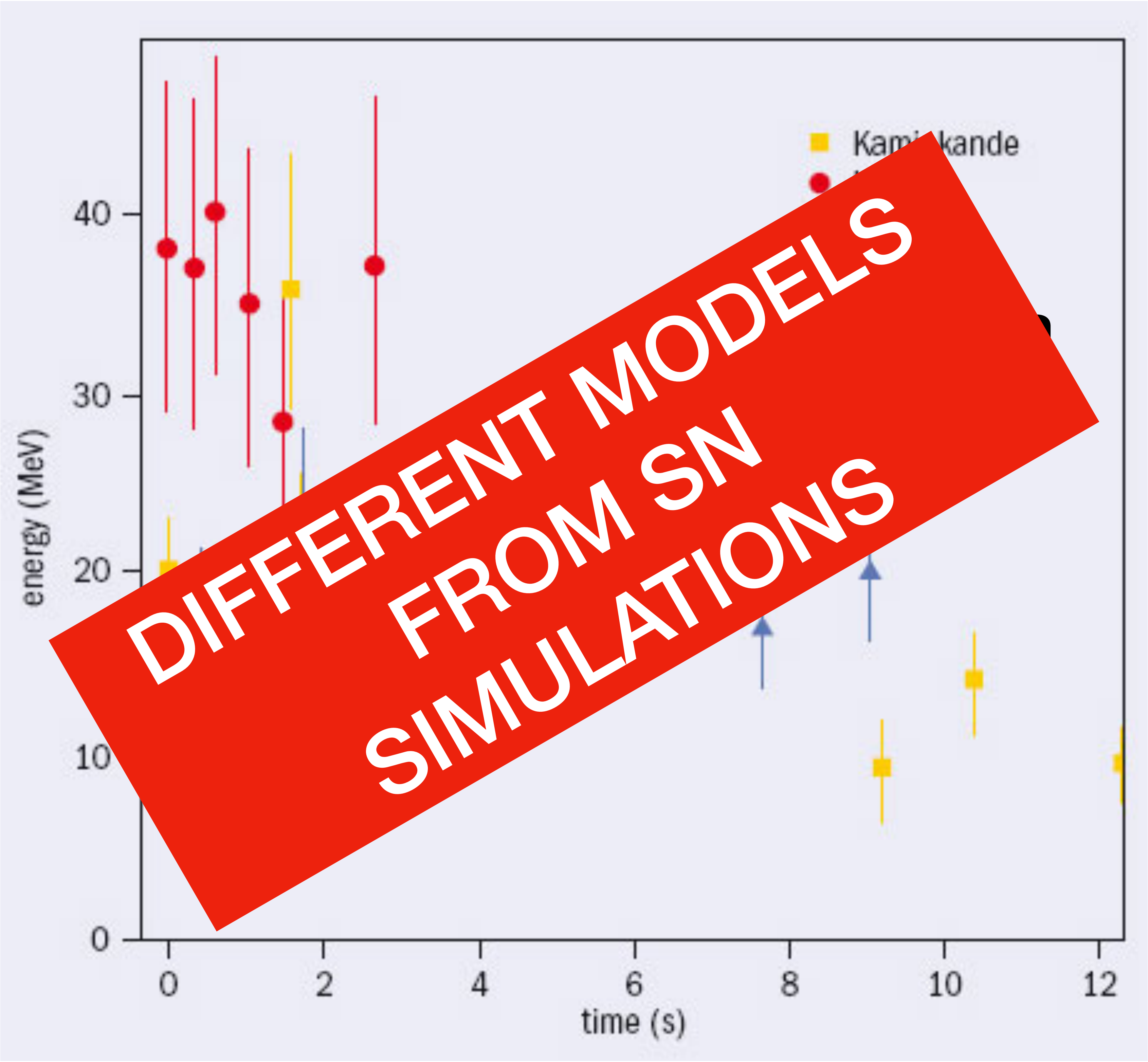

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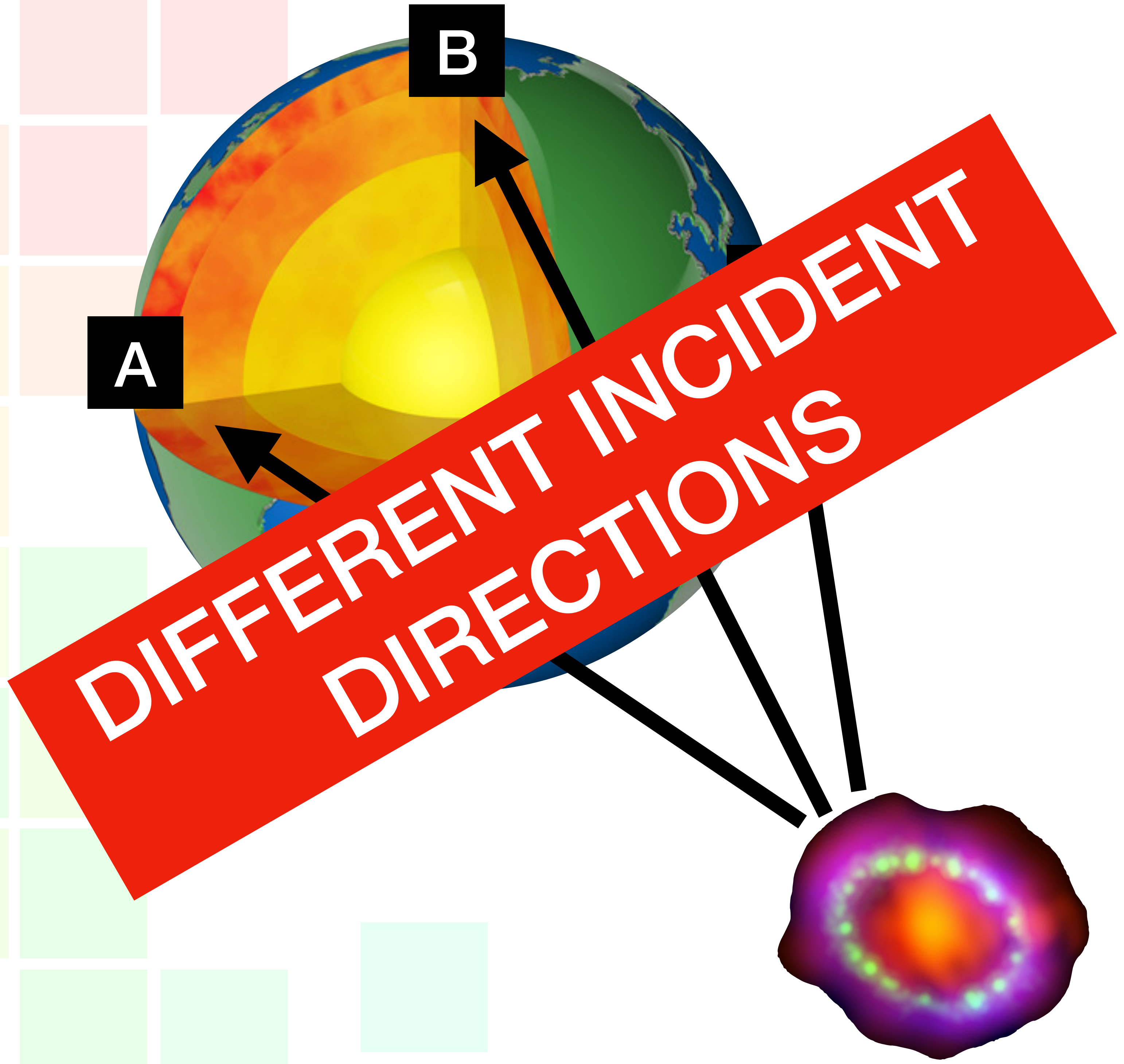
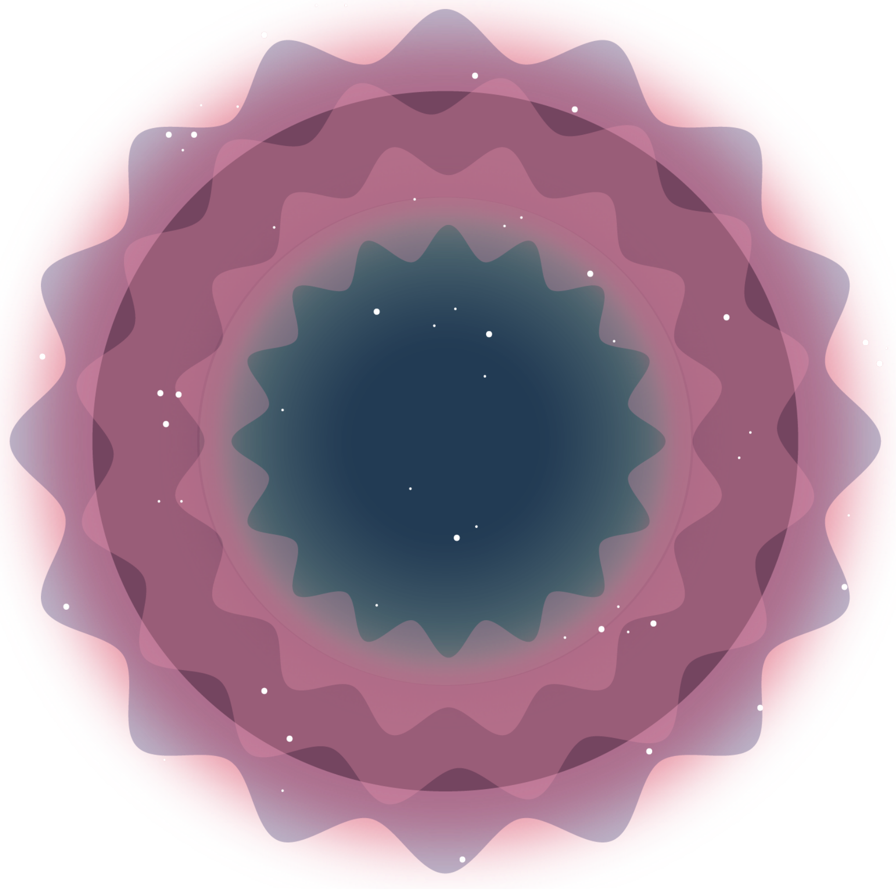
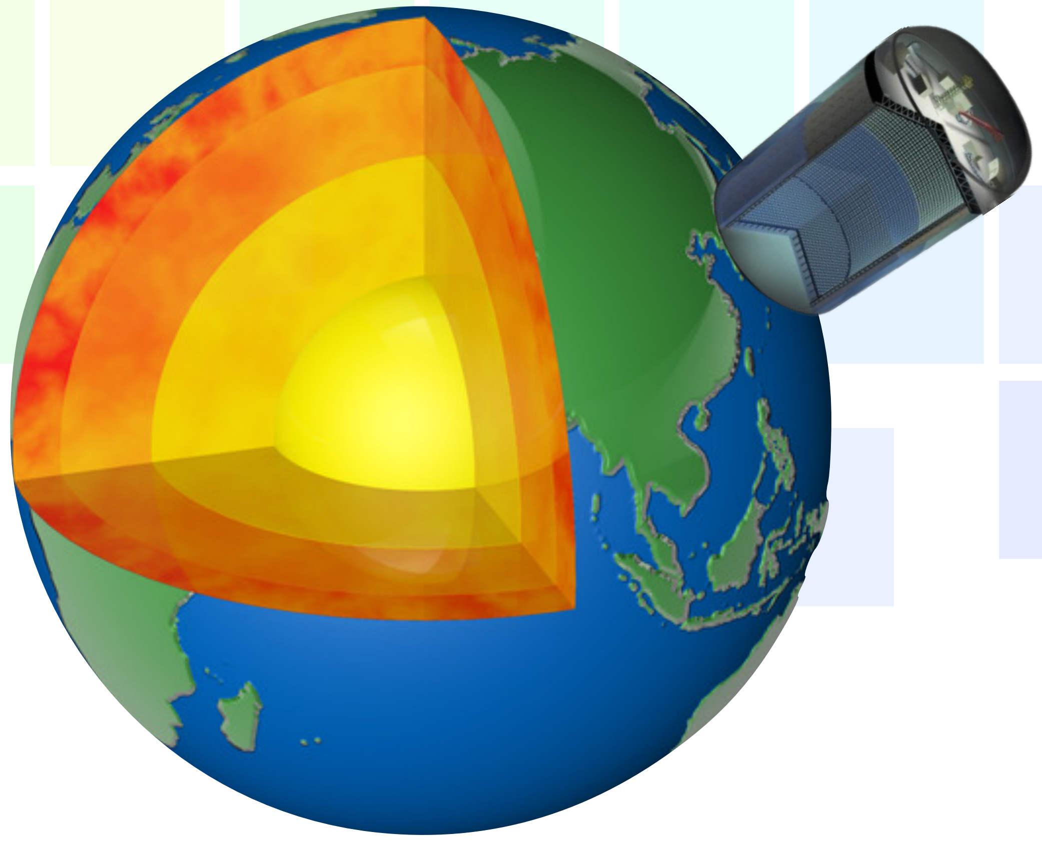


Supernova neutrino journey



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



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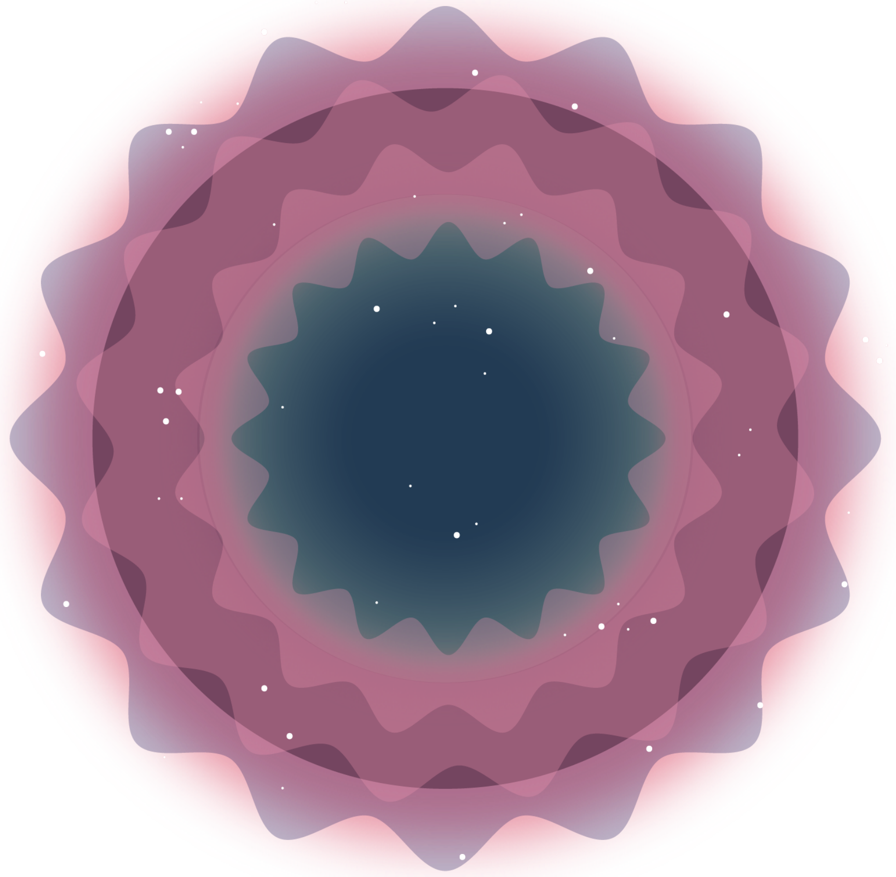
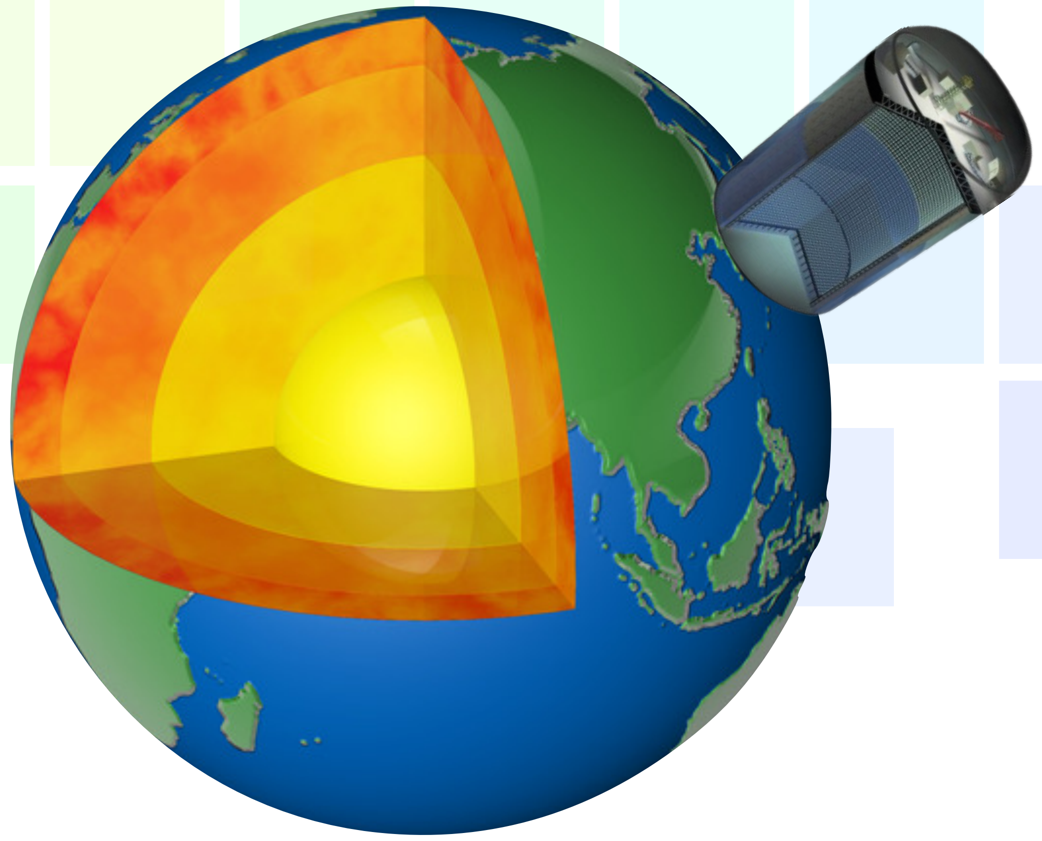


$$F^{\mathrm{D}}_{\nu_e} = p\, F^{0}_{\nu_e} + (1 - p)\ F^{0}_{\nu_x}$$



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

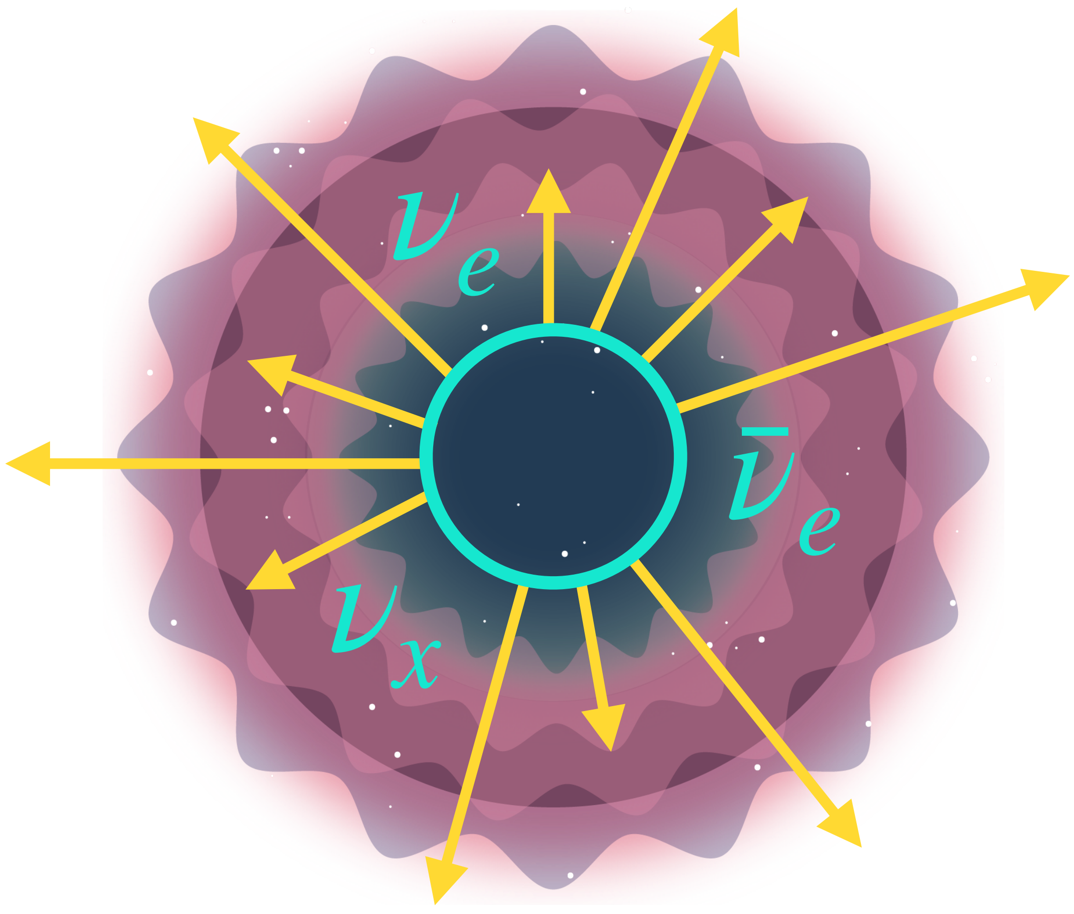
$$\mathscr{H}_{\text{flavor}} = \underbrace{\frac{1}{2E} U \mathbb{M}^2 U^{\dagger}}_{\text{Vacuum}} + \underbrace{\mathbb{V}}_{\text{Matter}}$$

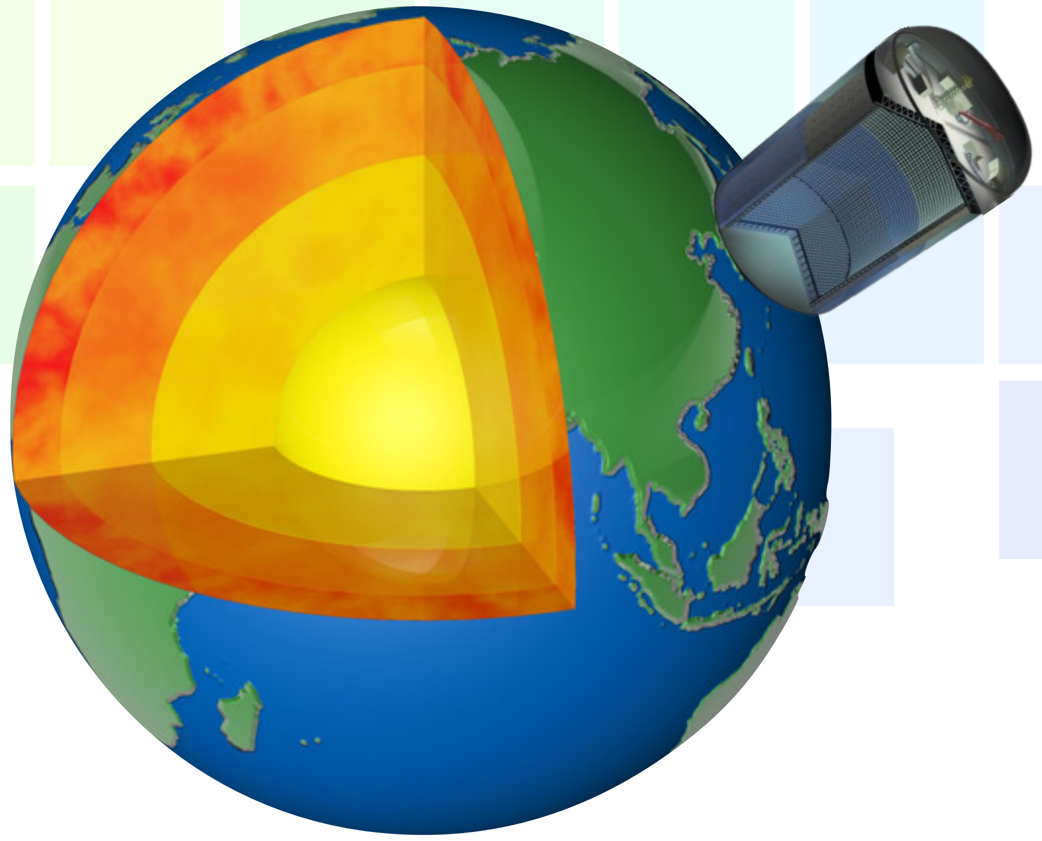
$$\mathbb{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} \qquad \mathbb{V} = \begin{pmatrix} V(n_e) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

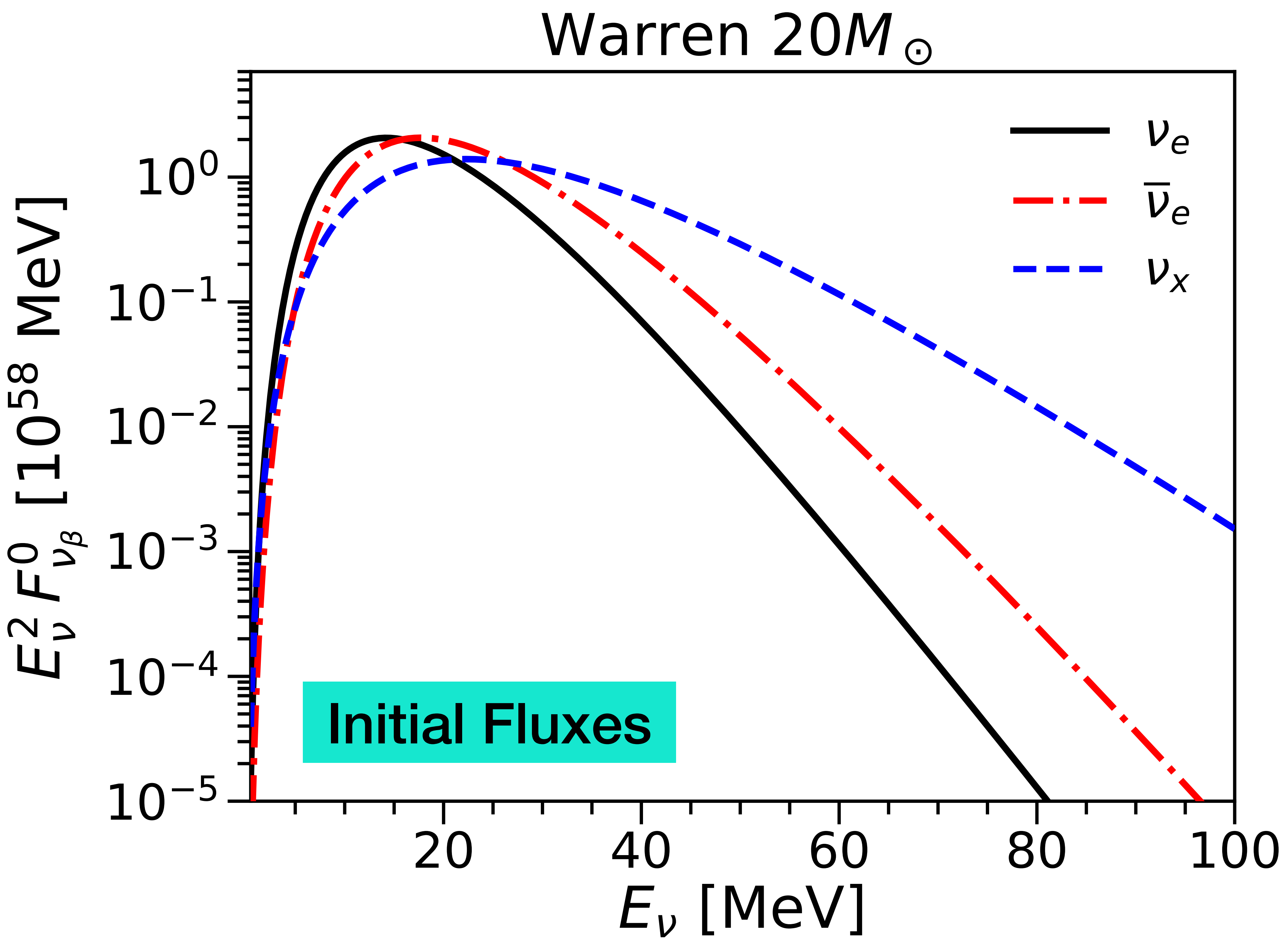
$$U = U_{23} \Gamma_{\delta} U_{13} U_{12}$$

PMNS matrix

Supernova neutrino journey







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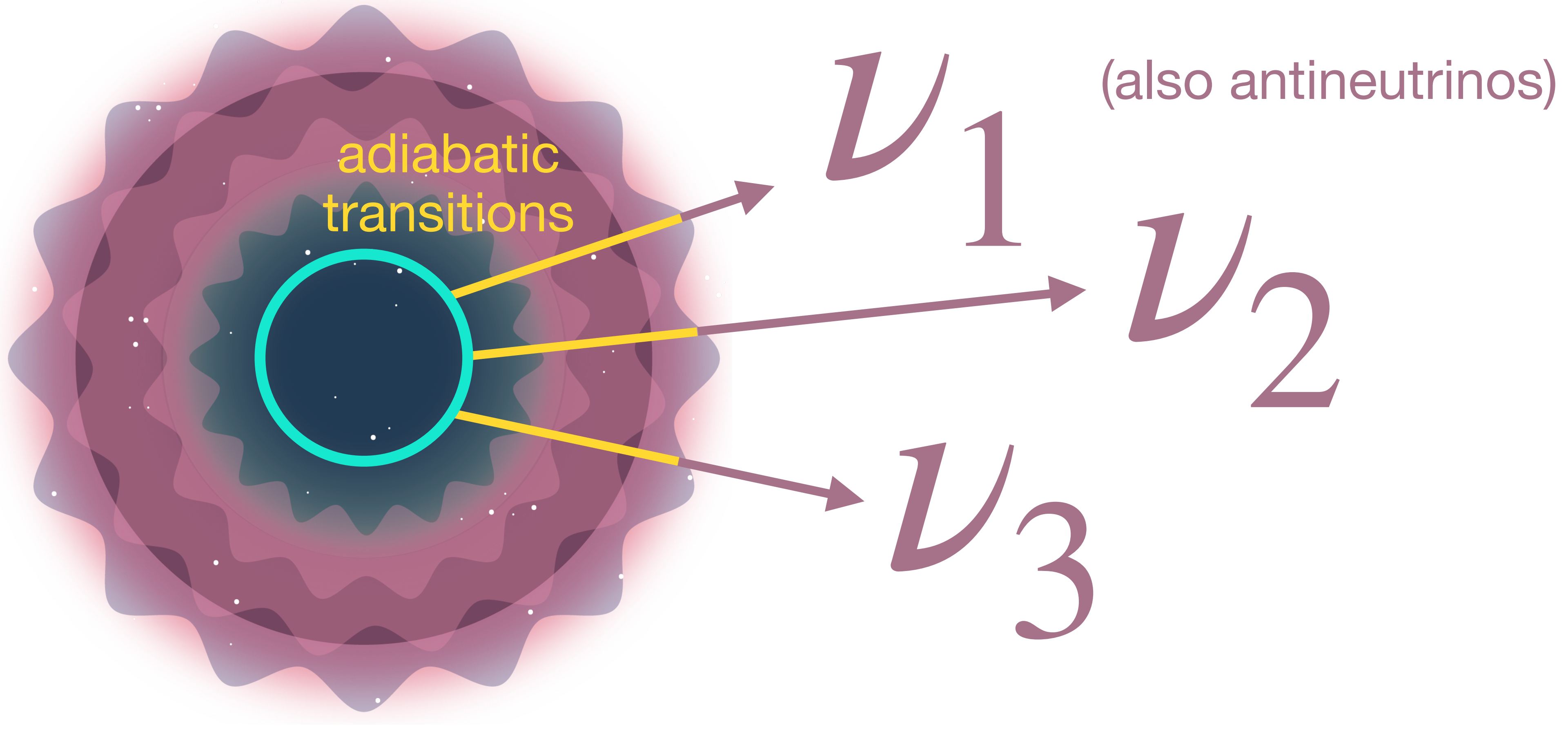
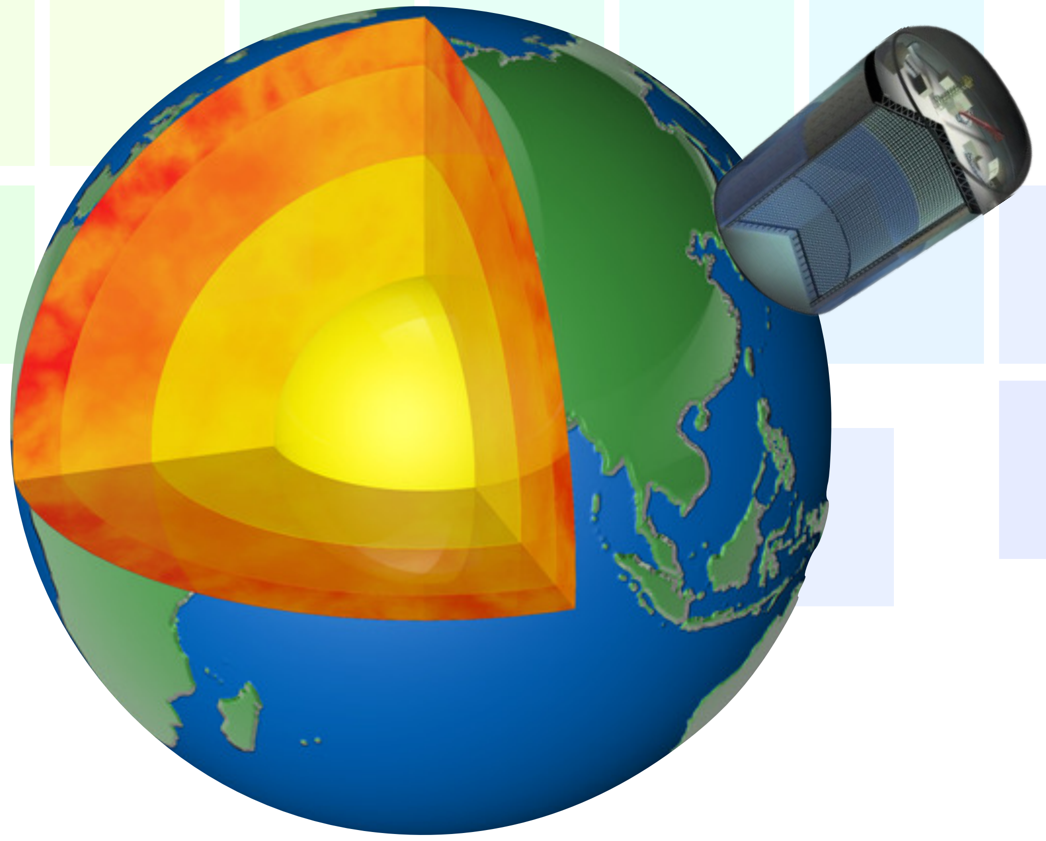
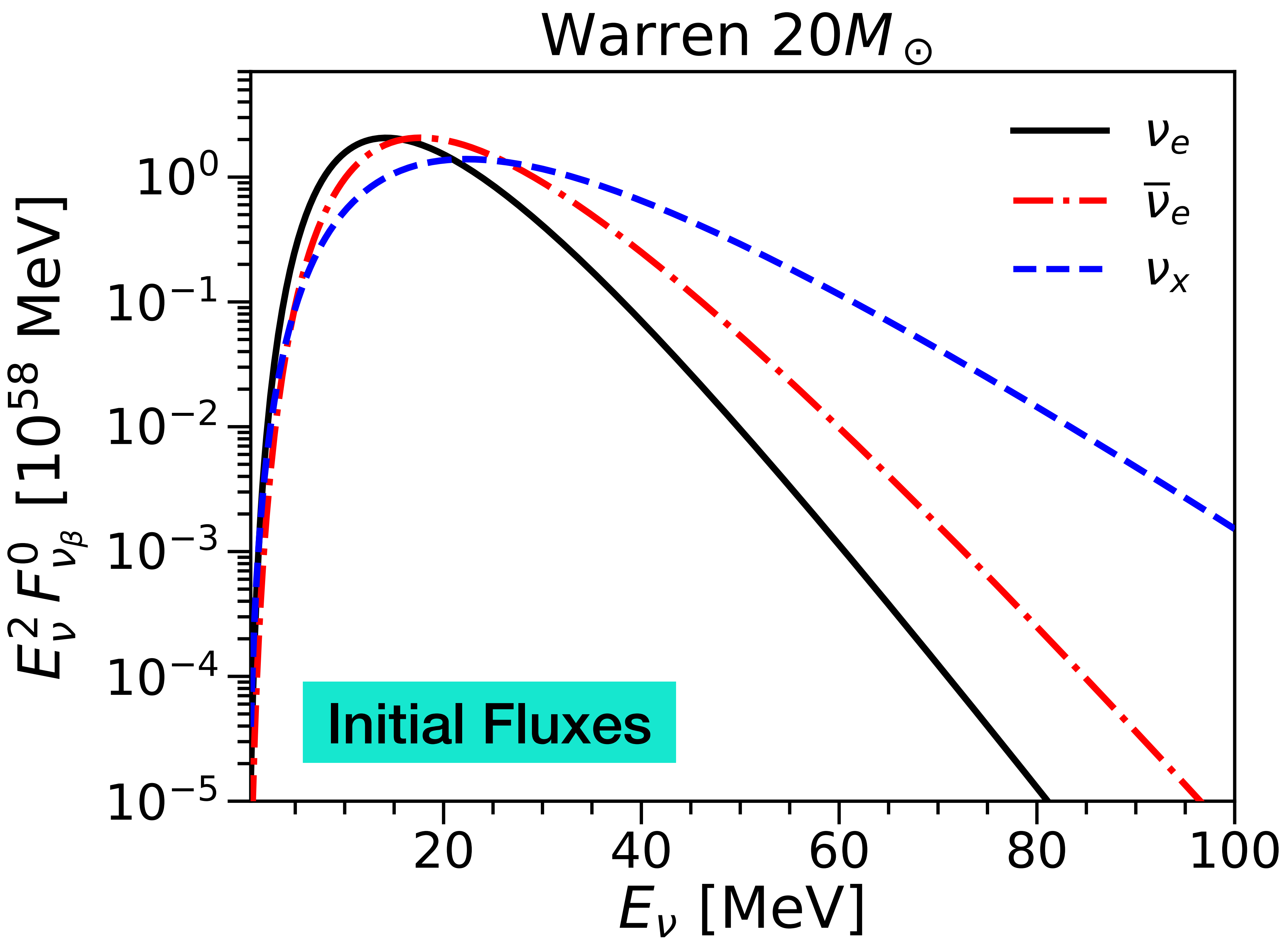






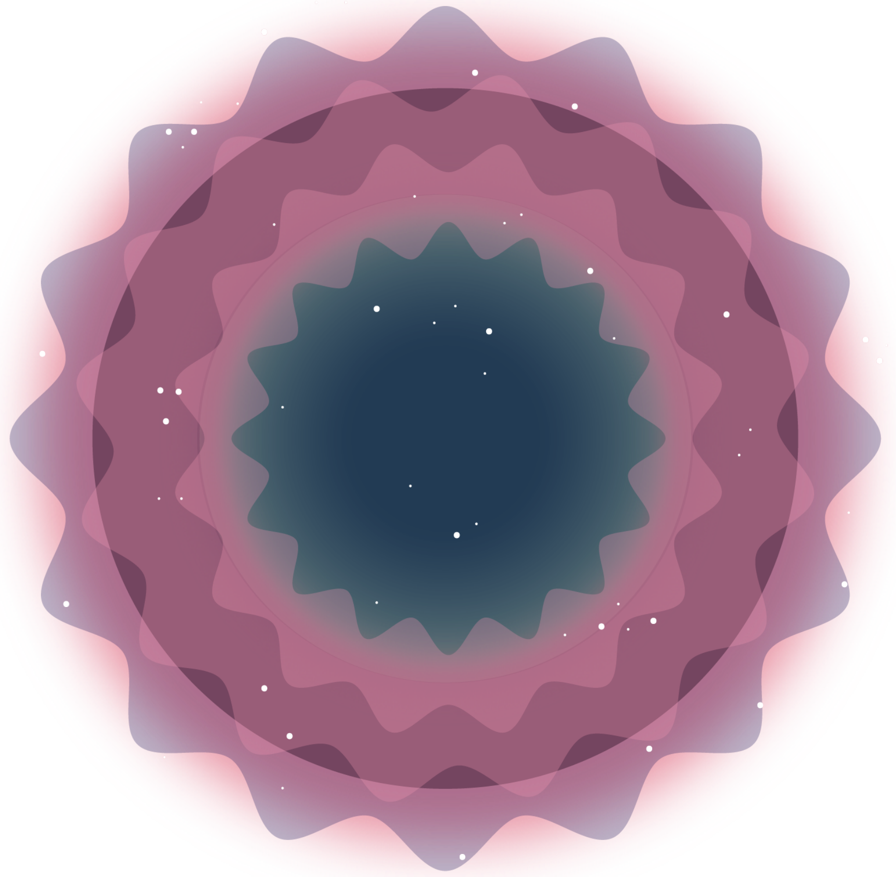
SN adiabatic transitions in NO

$$\nu_e \rightarrow \nu_3$$
$$\bar{\nu}_e \rightarrow \bar{\nu}_1$$

SN adiabatic transitions in IO

$$\nu_e \rightarrow \nu_2$$
$$\bar{\nu}_e \rightarrow \bar{\nu}_3$$

Supernova neutrino journey

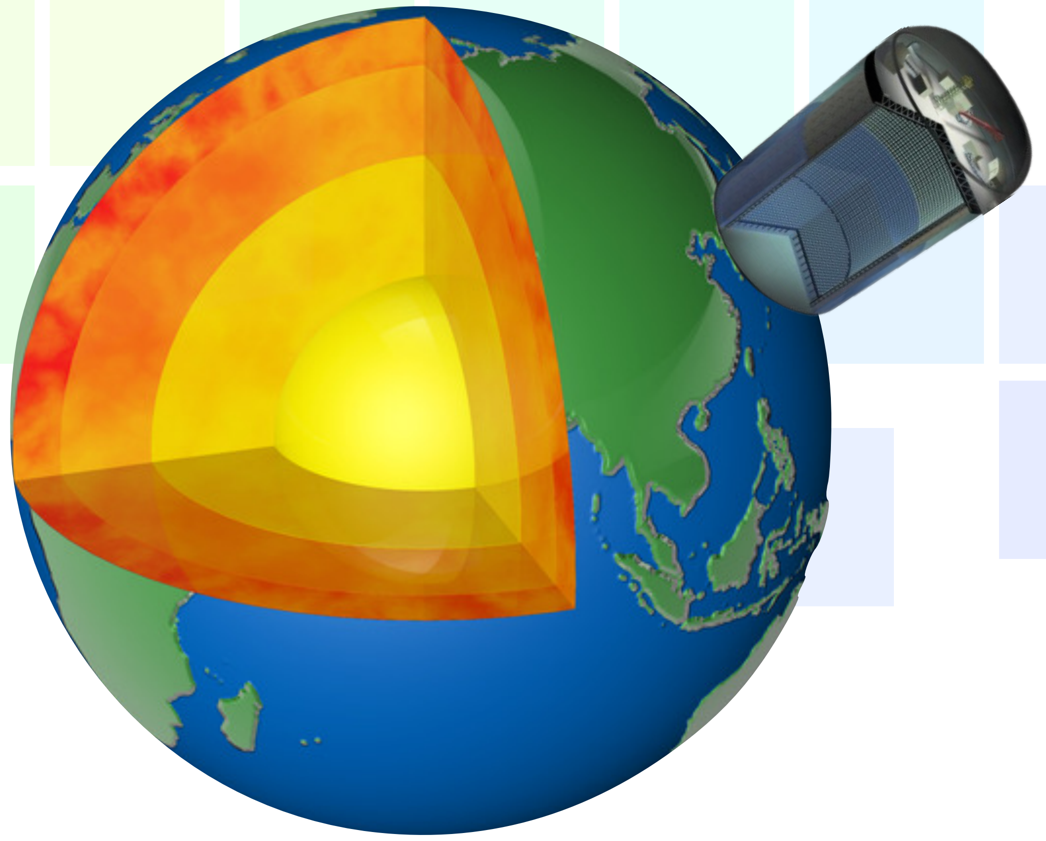


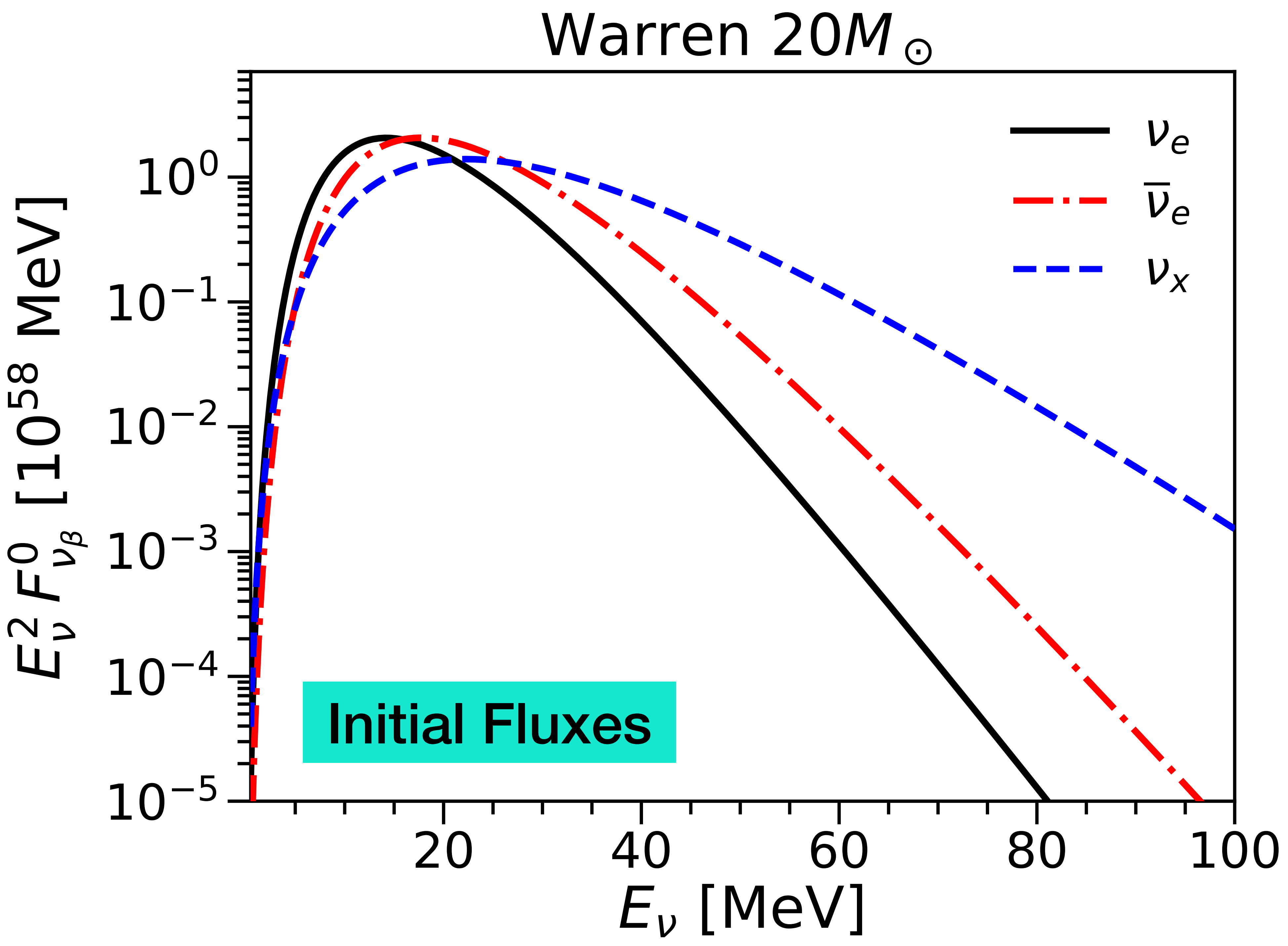
vacuum

$\nu_1 \dashrightarrow \nu_1$

$\nu_2 \dashrightarrow \nu_2$

$\nu_3 \dashrightarrow \nu_3$





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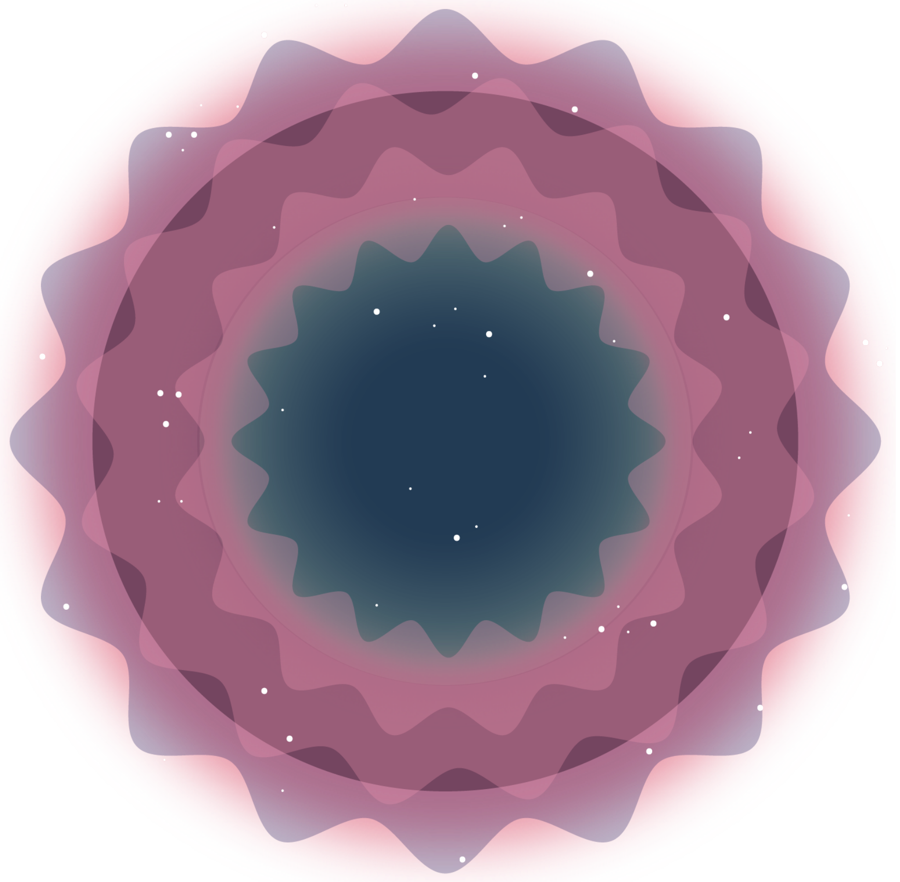
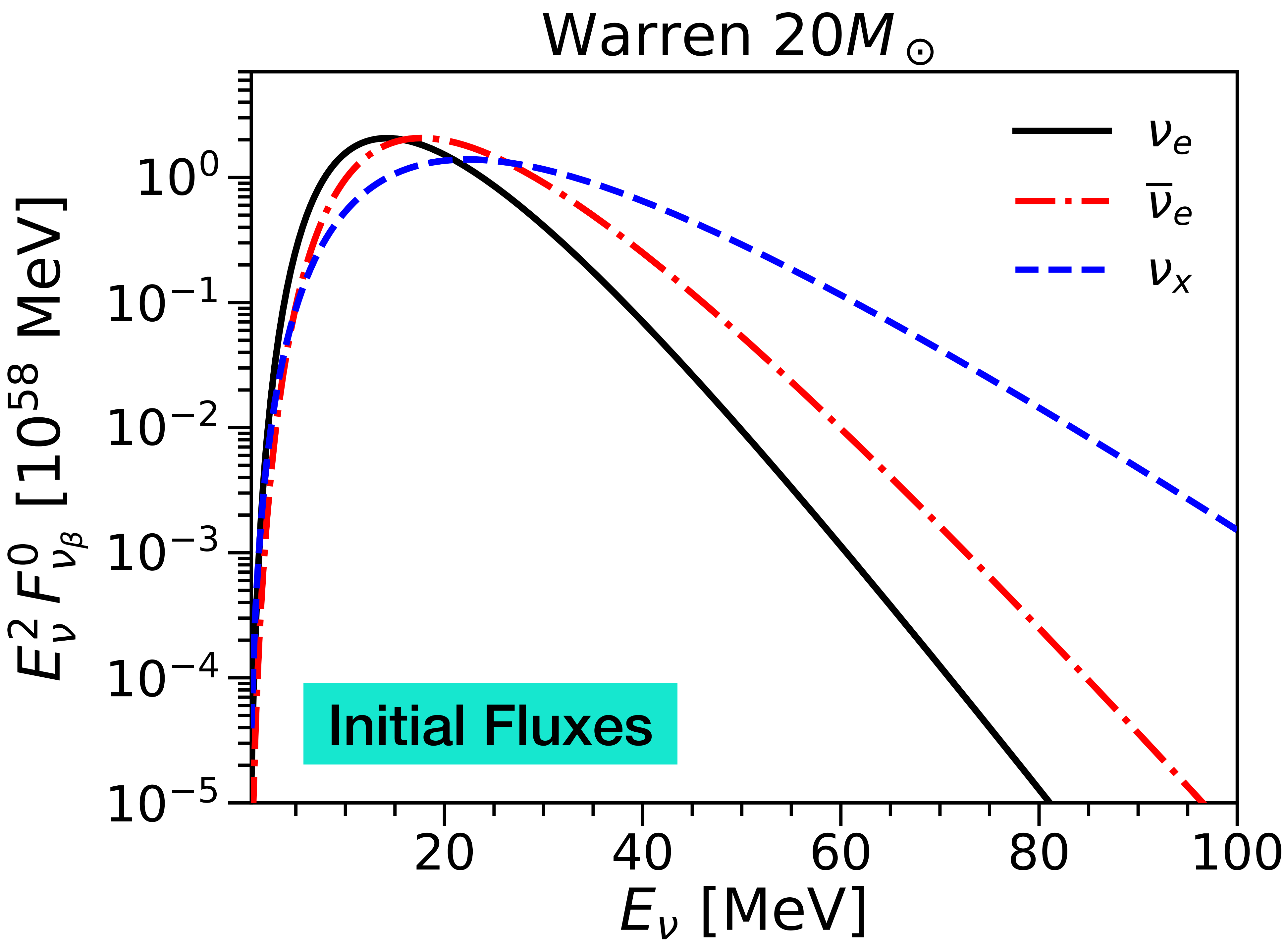
Vacuum transport

$$\mathscr{H}_{\text{mass}} = \frac{1}{2E}\mathbb{M}^2$$

$$\mathbb{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}$$

Supernova neutrino journey





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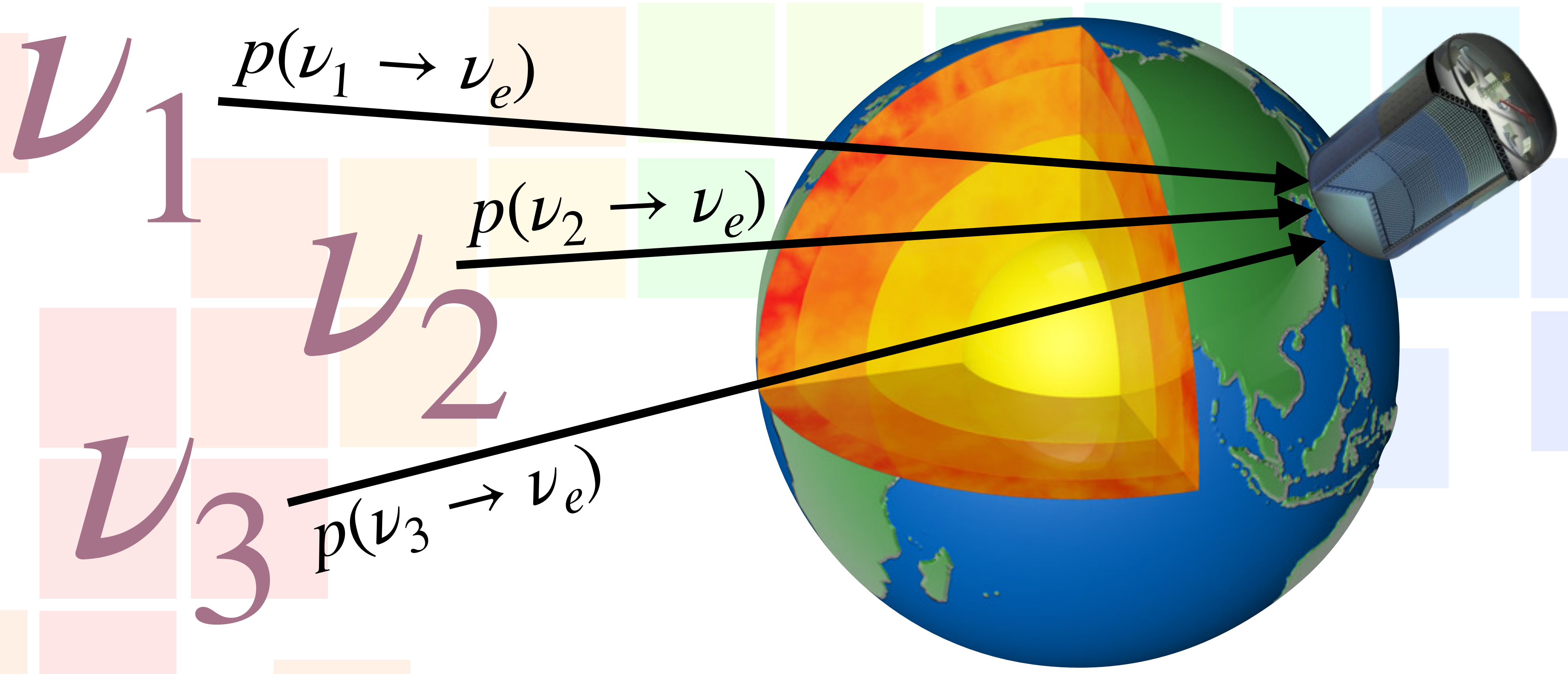

Earth matter effects

(constant ρ)

$$p_\oplus^{\rm NO} \equiv P_\oplus(\nu_3 \to \nu_e) \simeq \sin^2\theta_{13}$$

$$\bar{p}_\oplus^{\rm NO} \equiv P_\oplus(\bar{\nu}_1 \to \bar{\nu}_e) \simeq \cos^2\theta_{13}\,\left(1 - \bar{P}_\oplus^{2\nu}\right)$$

$$p_\oplus^{\rm IO} \equiv P_\oplus(\nu_2 \to \nu_e) \simeq \cos^2\theta_{13}\,P_\oplus^{2\nu}$$

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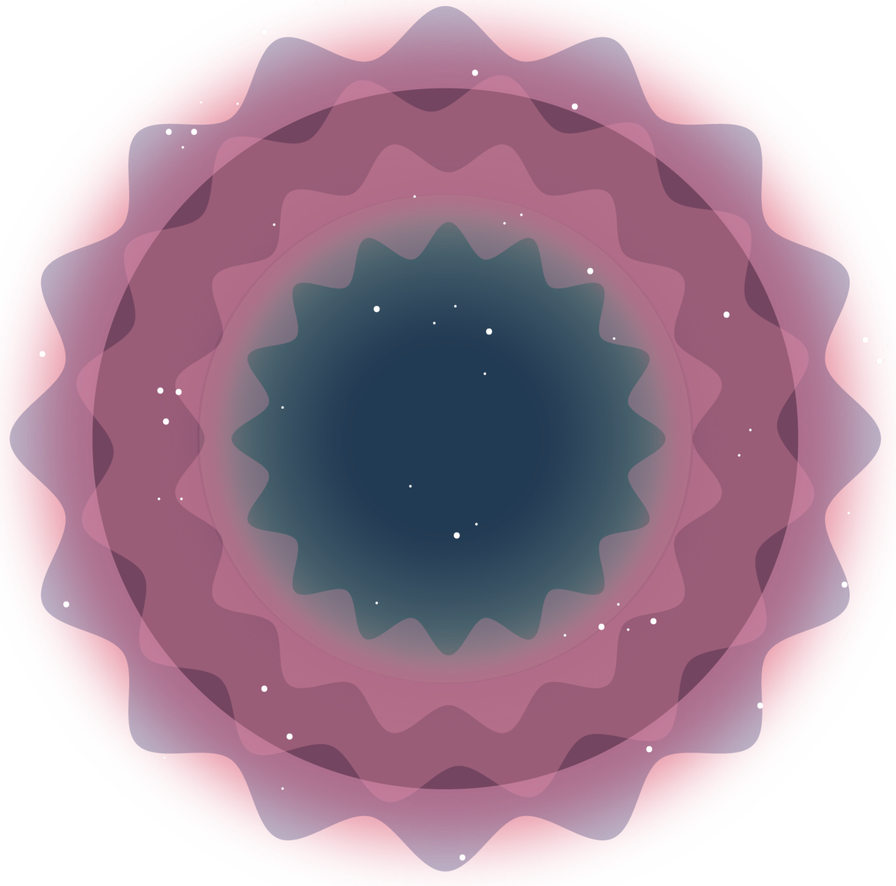
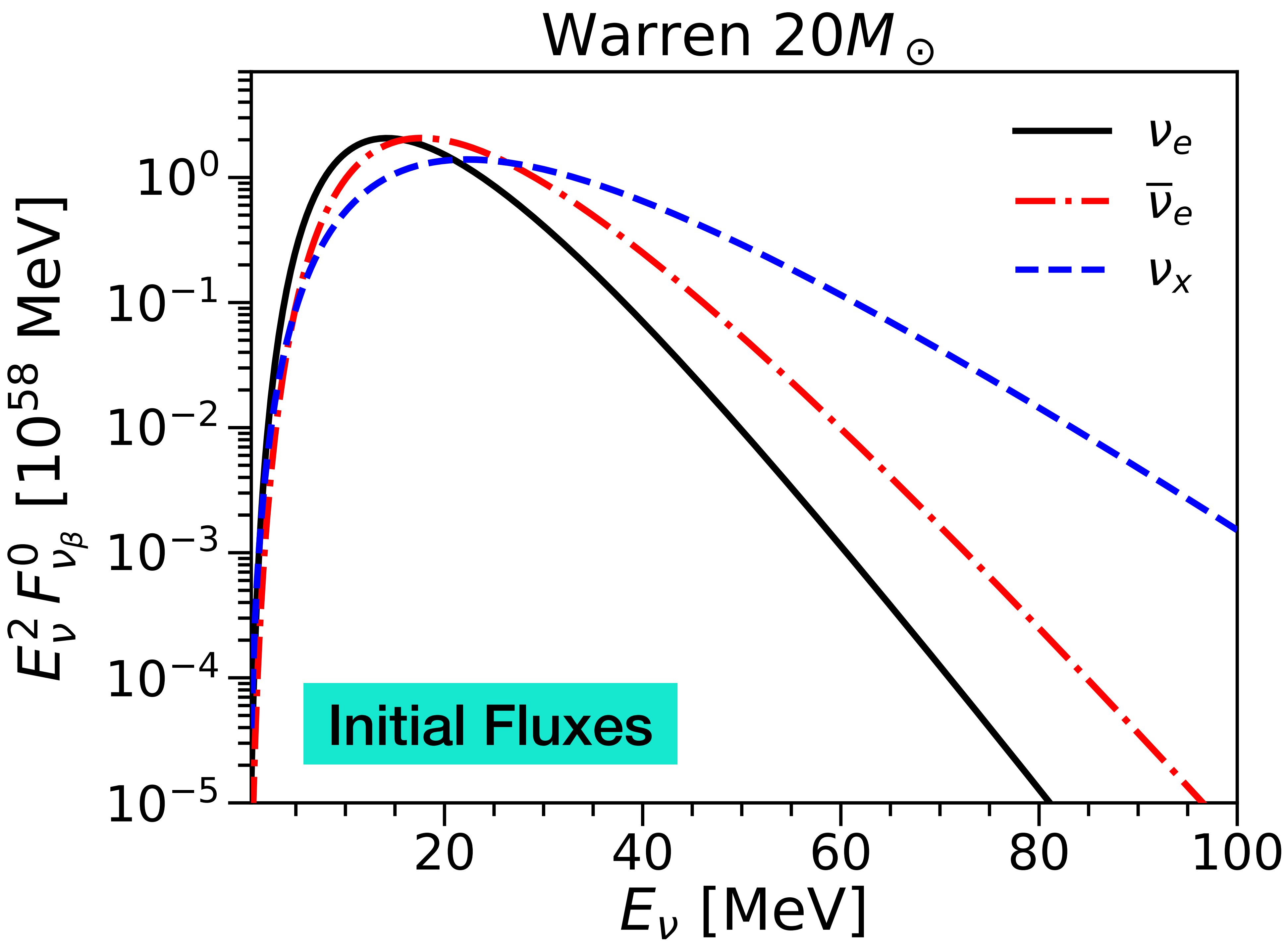
Supernova neutrino journey





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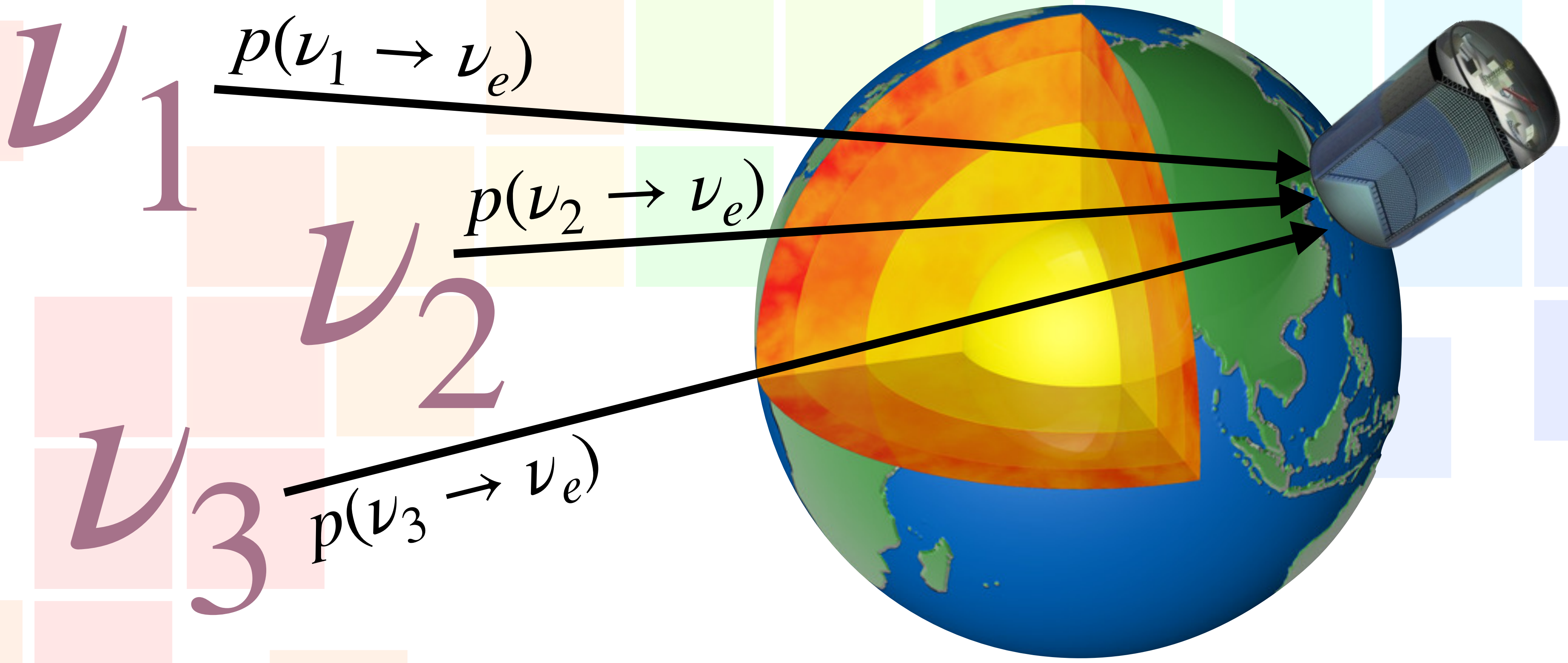

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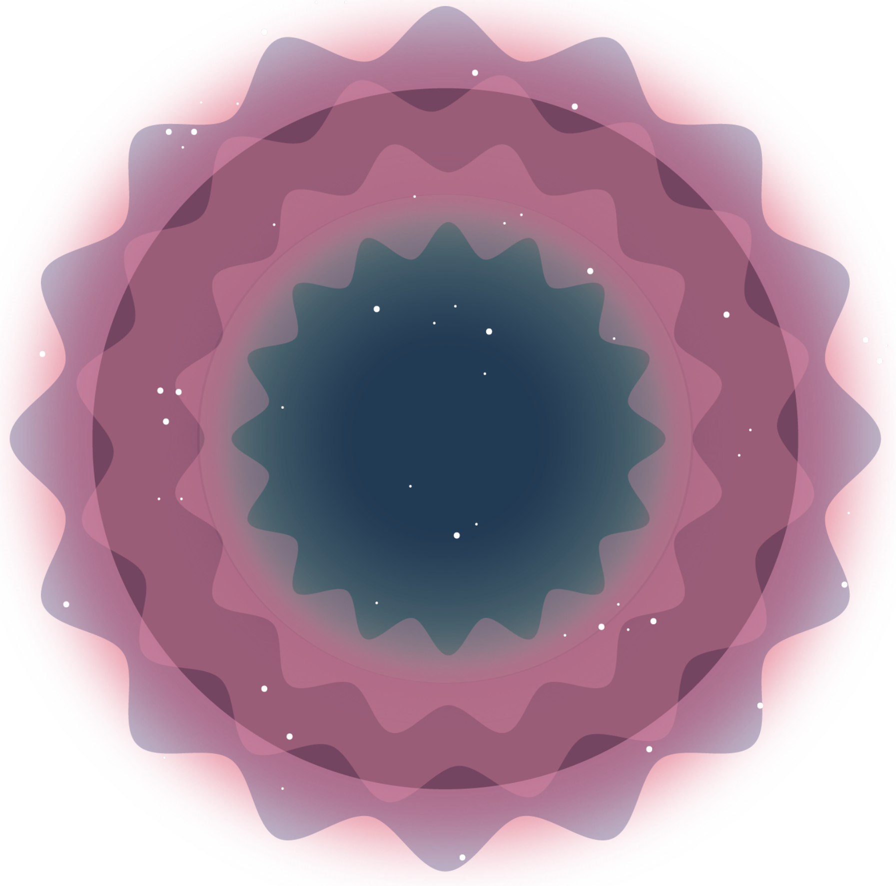
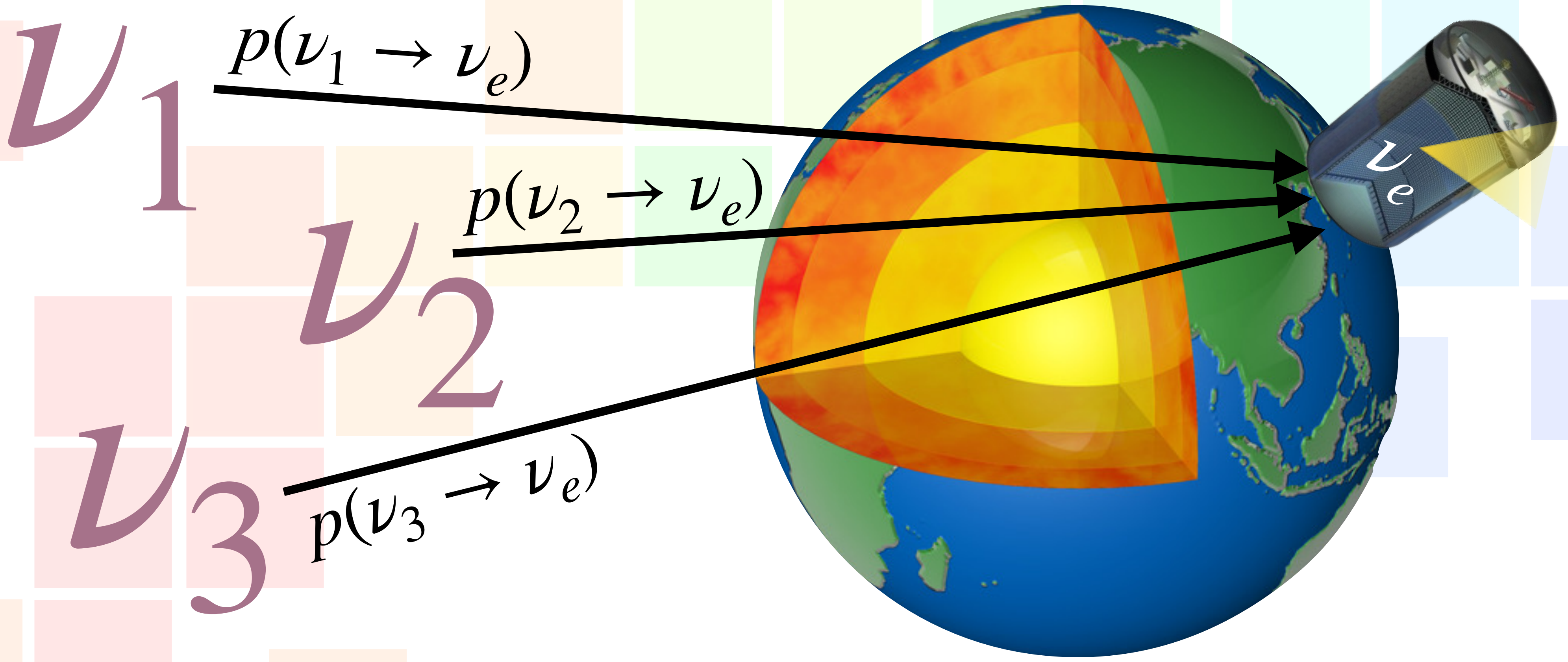
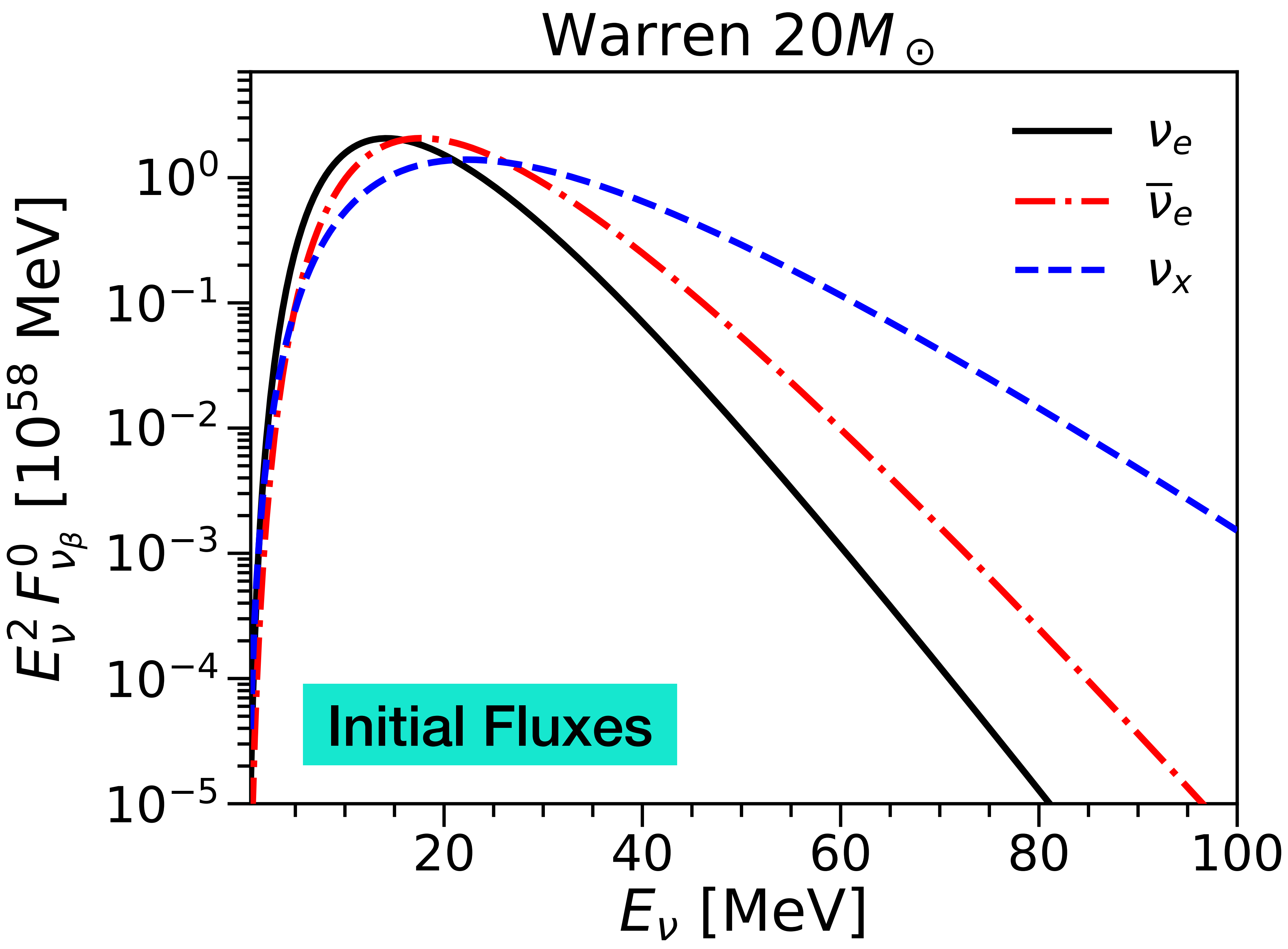
Sensitive to solar mixing parameters!

Supernova neutrino journey







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HK detection

$\bar{\nu}_e + p \to e^+ + n$

$\nu_e + {}^{16}\mathrm{O} \to e^- + \mathrm{X}$

$\bar{\nu}_e + {}^{16}\mathrm{O} \to e^+ + \mathrm{X}$

$N_t^p = 2.94 \cdot 10^{34}$

0.9 IBD

0.1 IBD + $\nu_e\mathrm{O} - \mathrm{CC}$ + $\bar{\nu}_e\mathrm{O} - \mathrm{CC}$

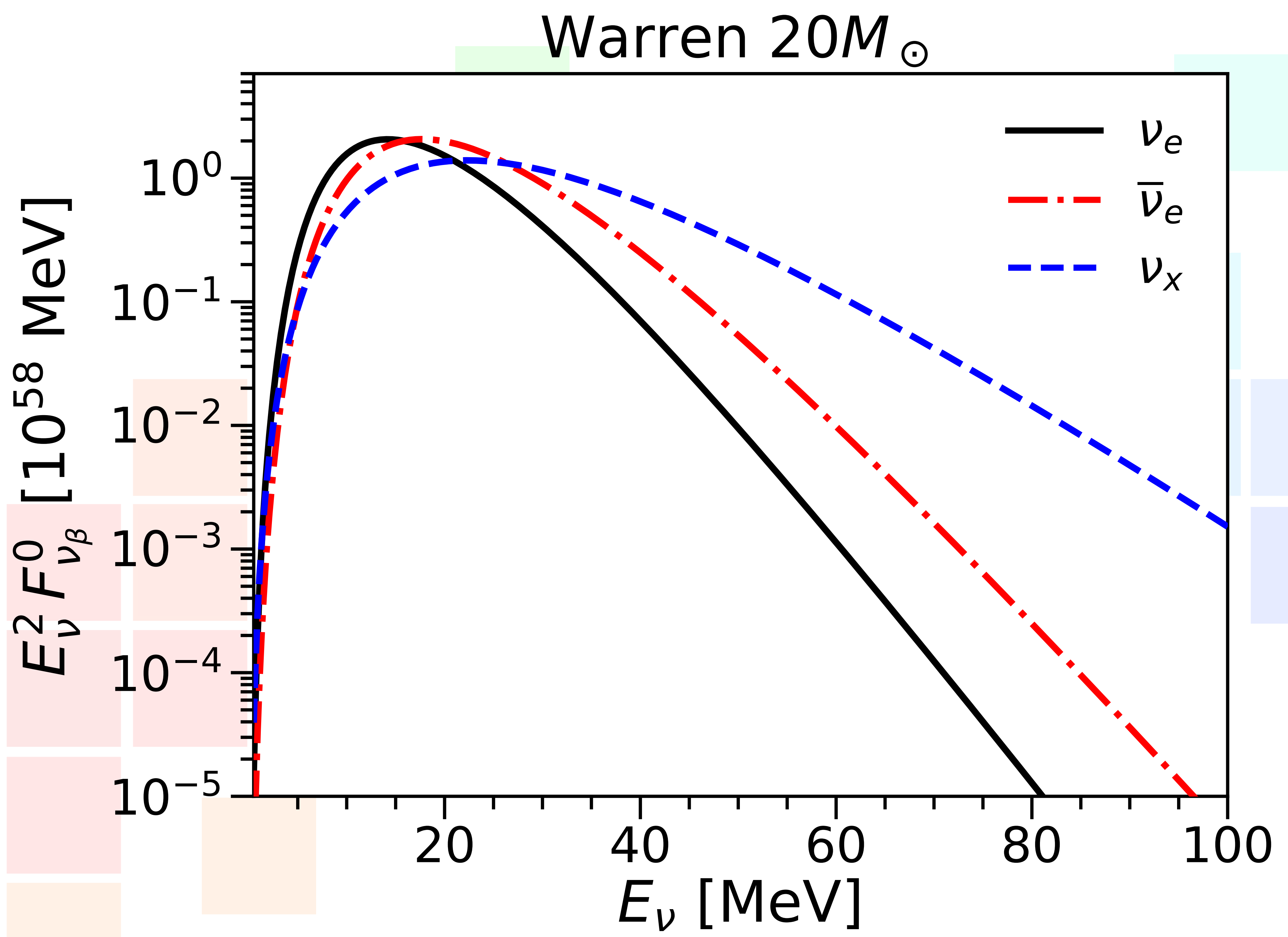
Solar mixing parameters

- Fluxes at the detector:

$$F^{\rm D}_{\nu_e} = p(\epsilon)\, F^0_{\nu_e} + \big(1 - p(\epsilon)\big)\; F^0_{\nu_x}$$

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

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



Solar mixing parameters

- Fluxes at the detector:

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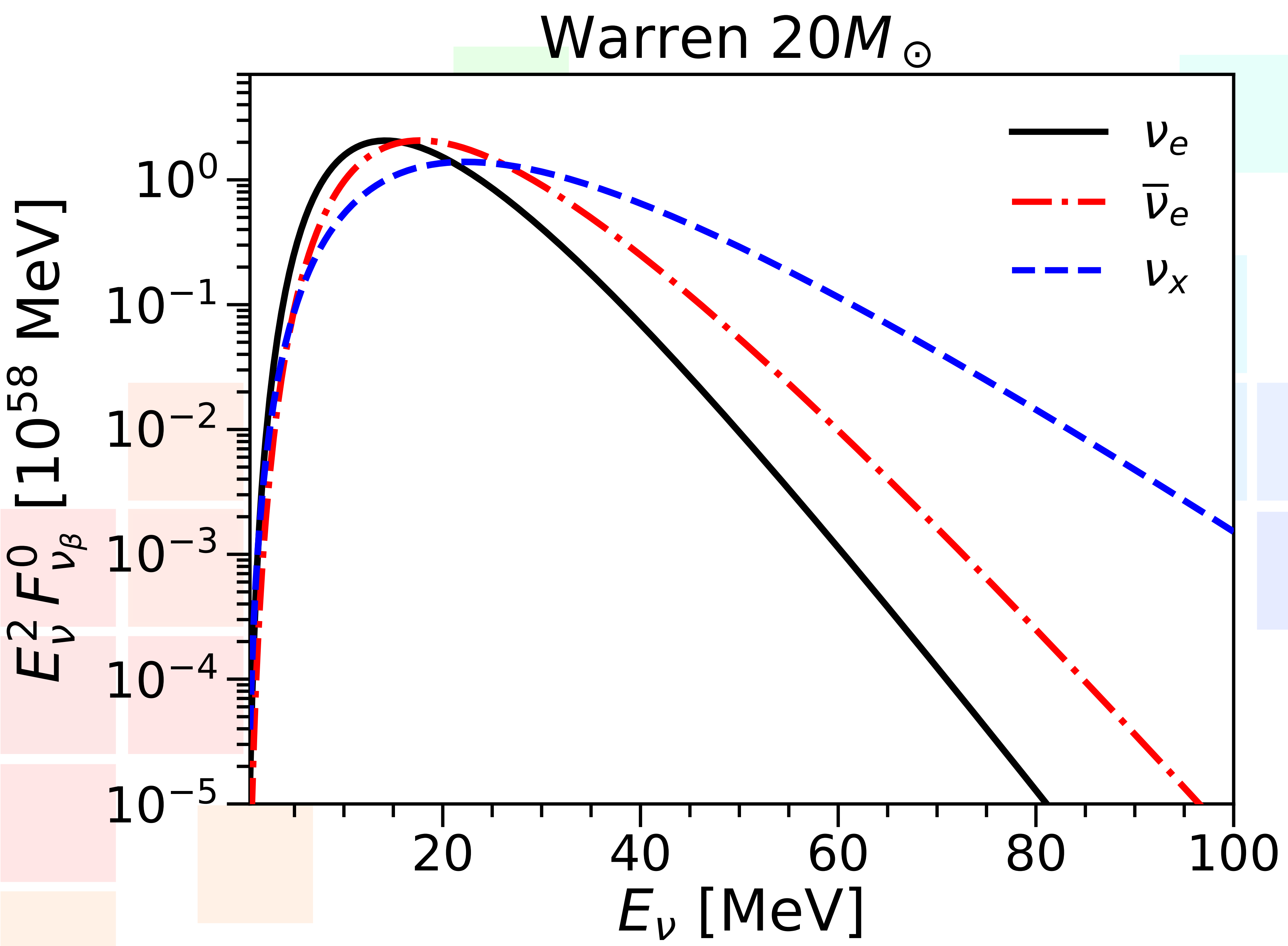


KamLAND

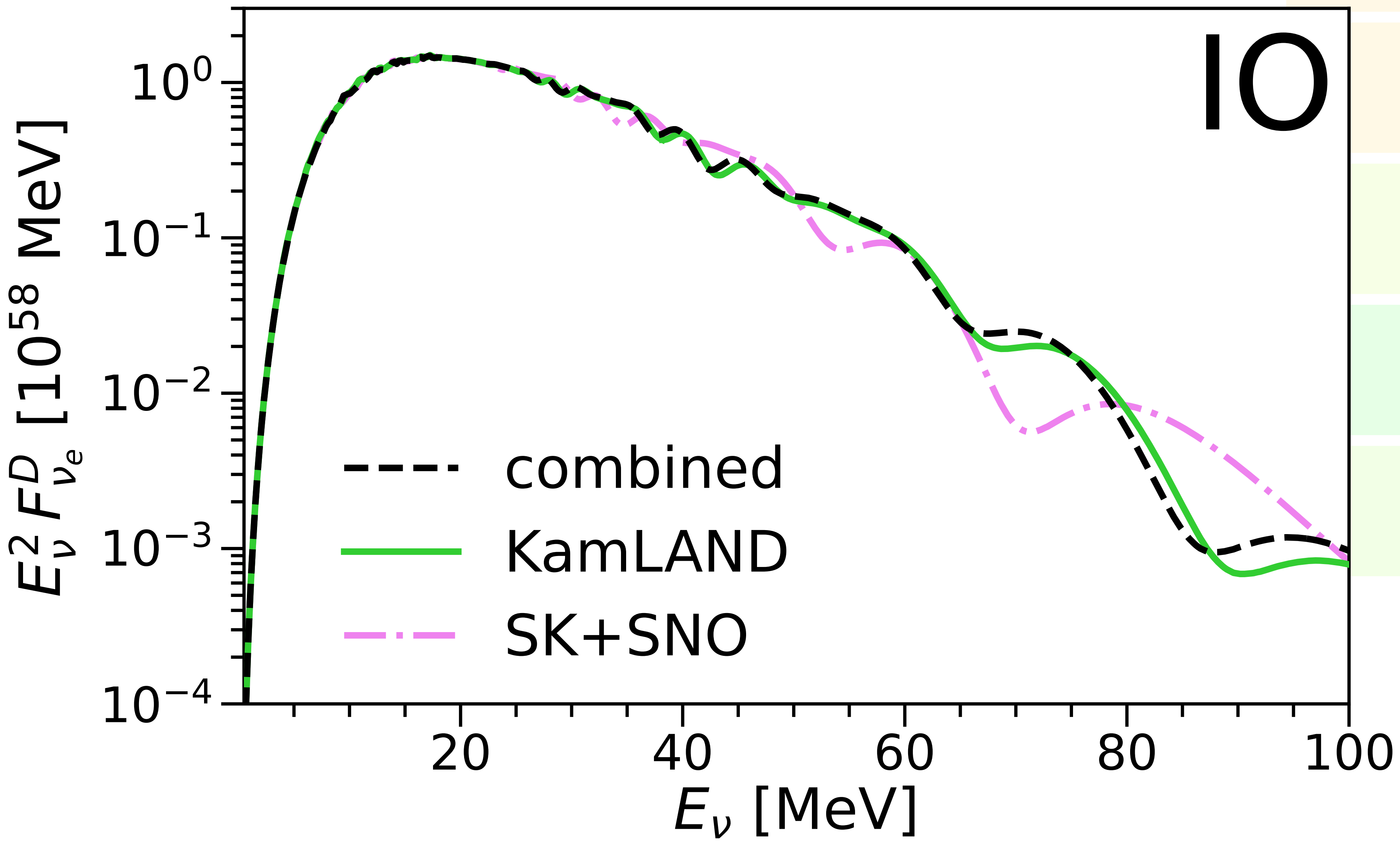
$\sin^2\theta_{12} = 0.316 \pm 0.007$

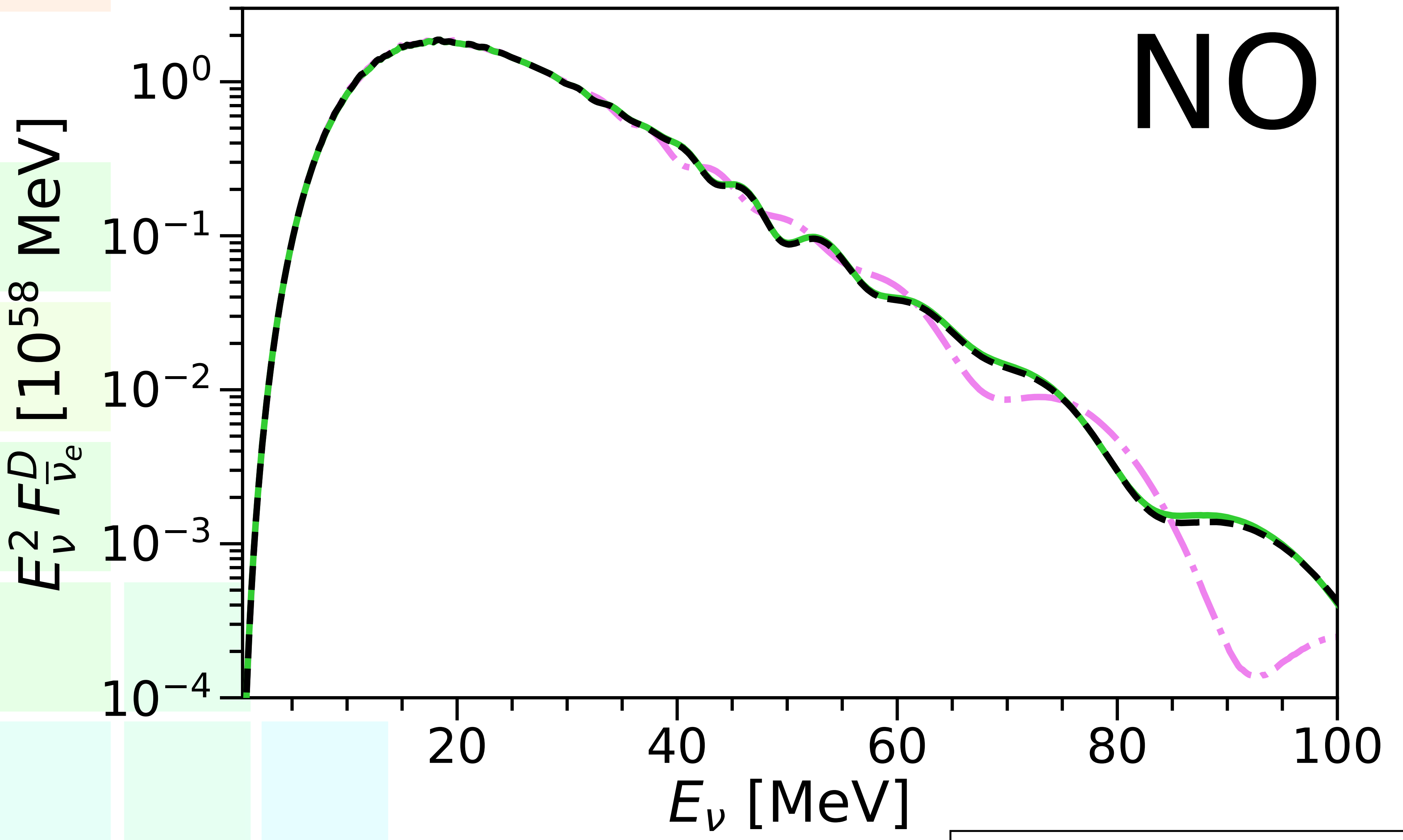
$\Delta m^2_{21} = \left(7.54^{+0.26}_{-0.24}\right)\times10^{-5}\text{ eV}^2$

SK+SNO

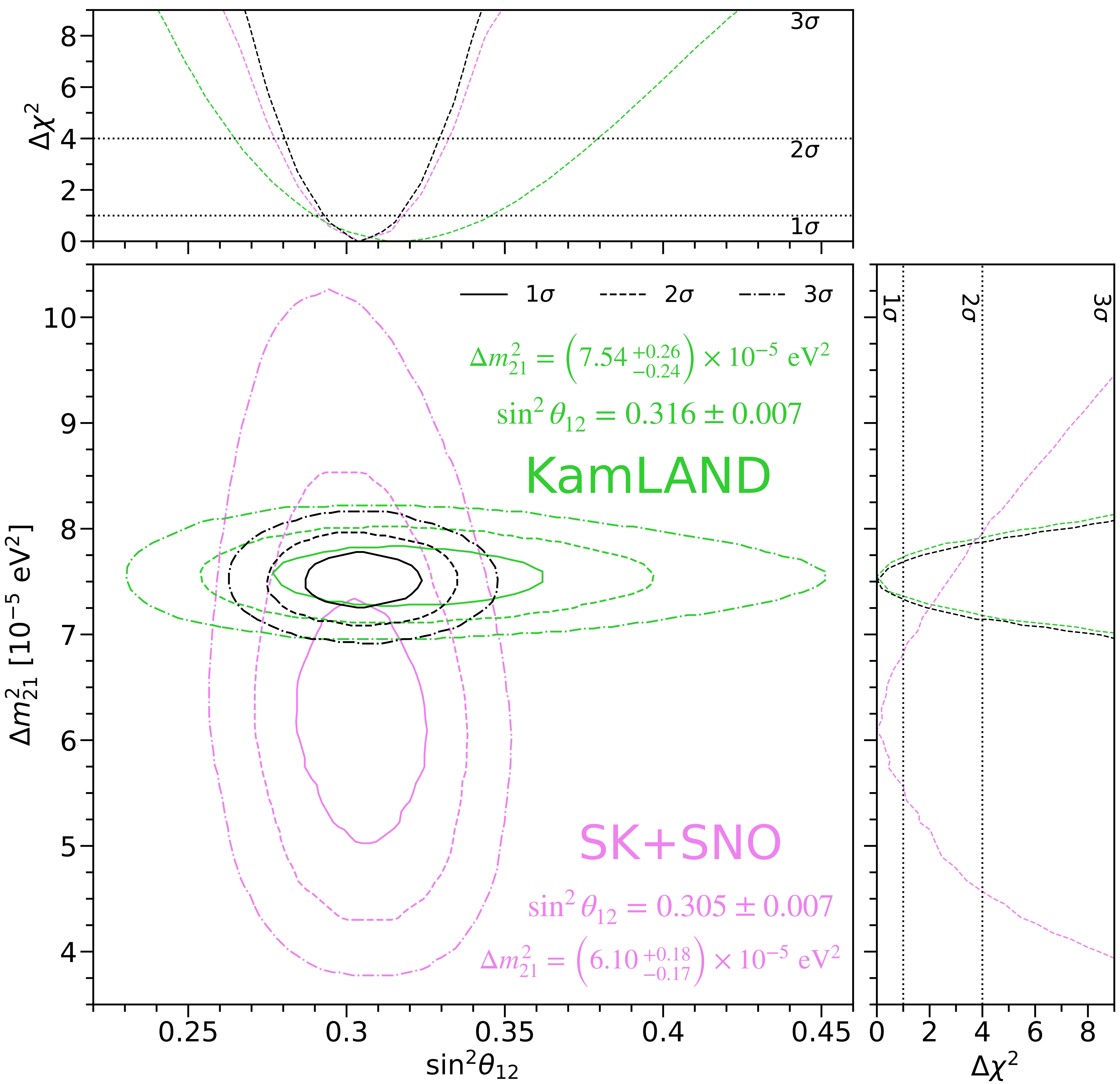
$\sin^2\theta_{12} = 0.305 \pm 0.007$

$\Delta m^2_{21} = \left(6.10^{+0.18}_{-0.17}\right)\times10^{-5}\text{ eV}^2$



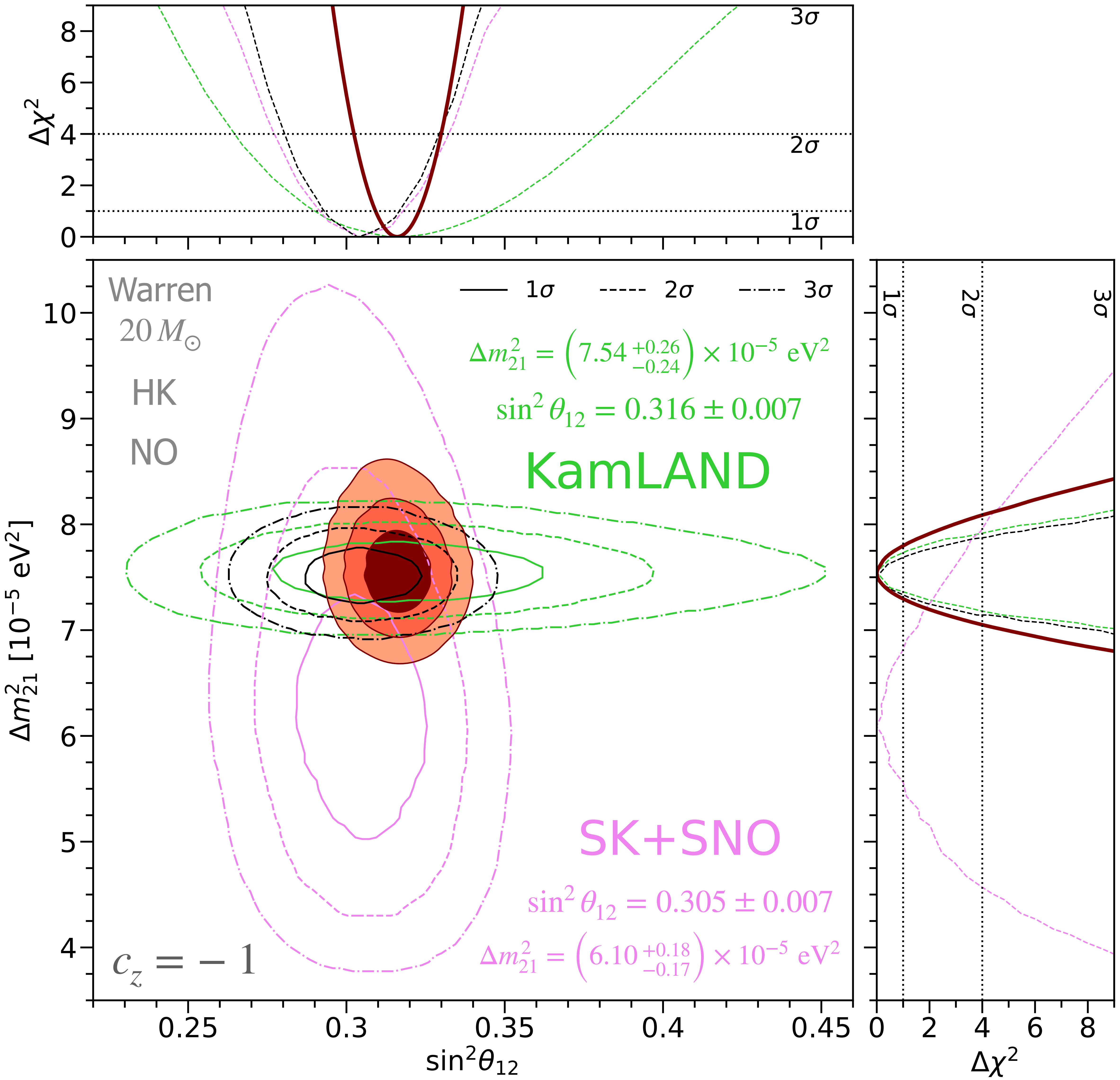


Results



- Forecasts for a SN burst at 10 kpc.
- Current KamLAND allowed regions
- Current SK+ SNO allowed regions

Results



- Forecasts for a SN burst at 10 kpc.
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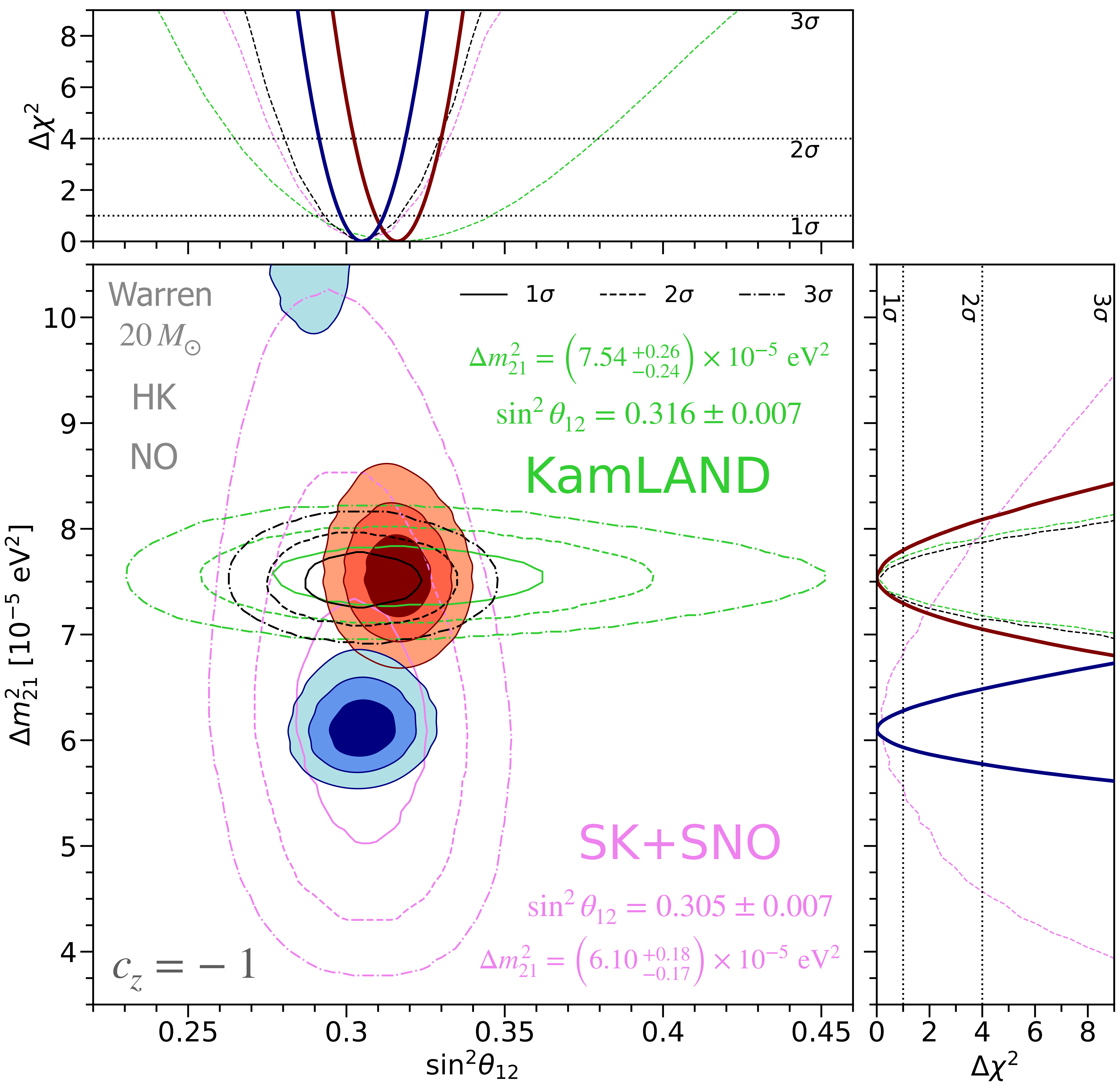
- Forecast assuming as “true=nature” value KamLAND best fit
  - Alleviate tension between reactor and matter effects.

Results



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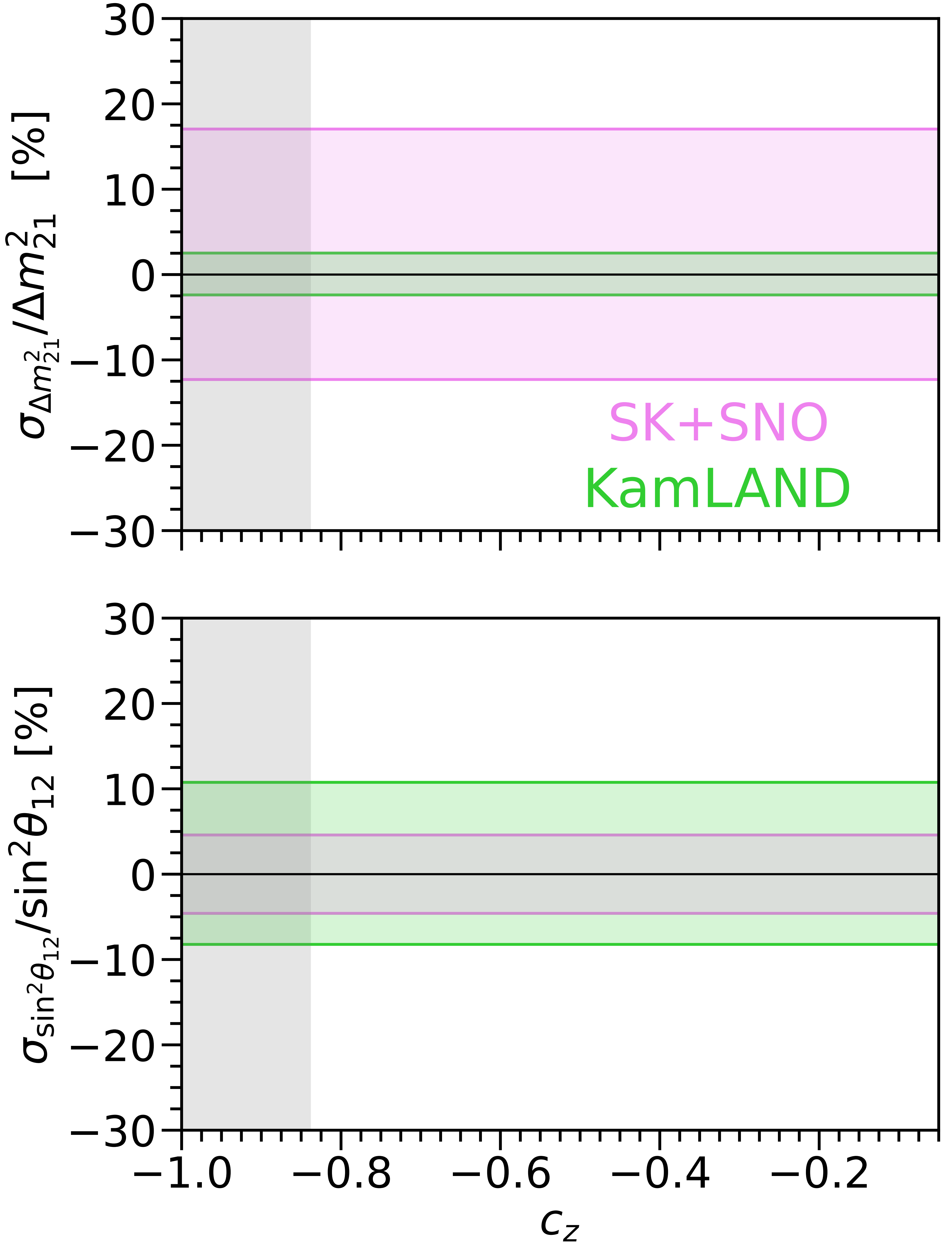
- Forecast assuming as “true=nature” value KamLAND best fit
  - Alleviate tension between reactor and matter effects.
- Forecast assuming as “true=nature” value SK+SNO best fit
  - Increase tension between reactor and matter effects.

Results: Projected 1σ errors



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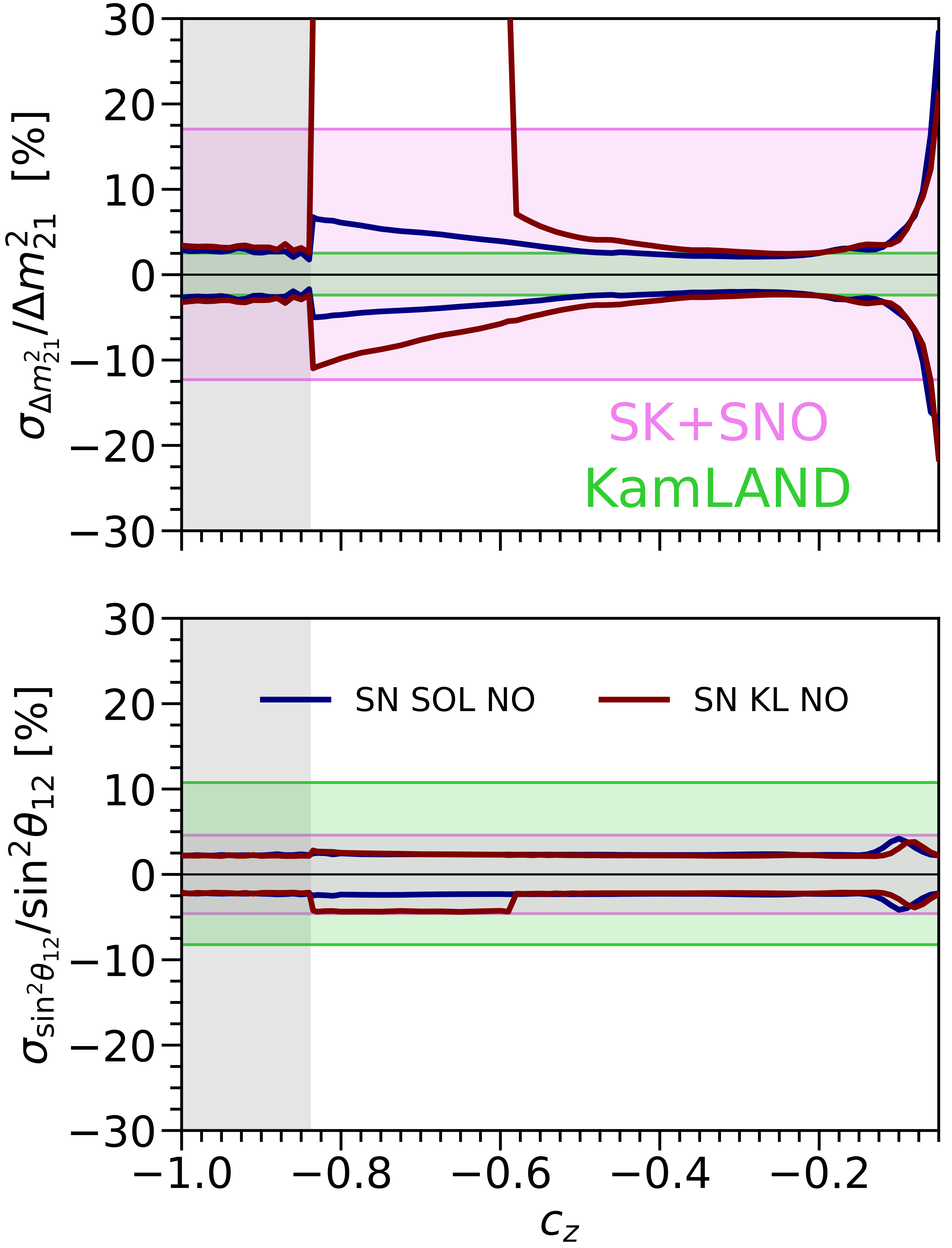

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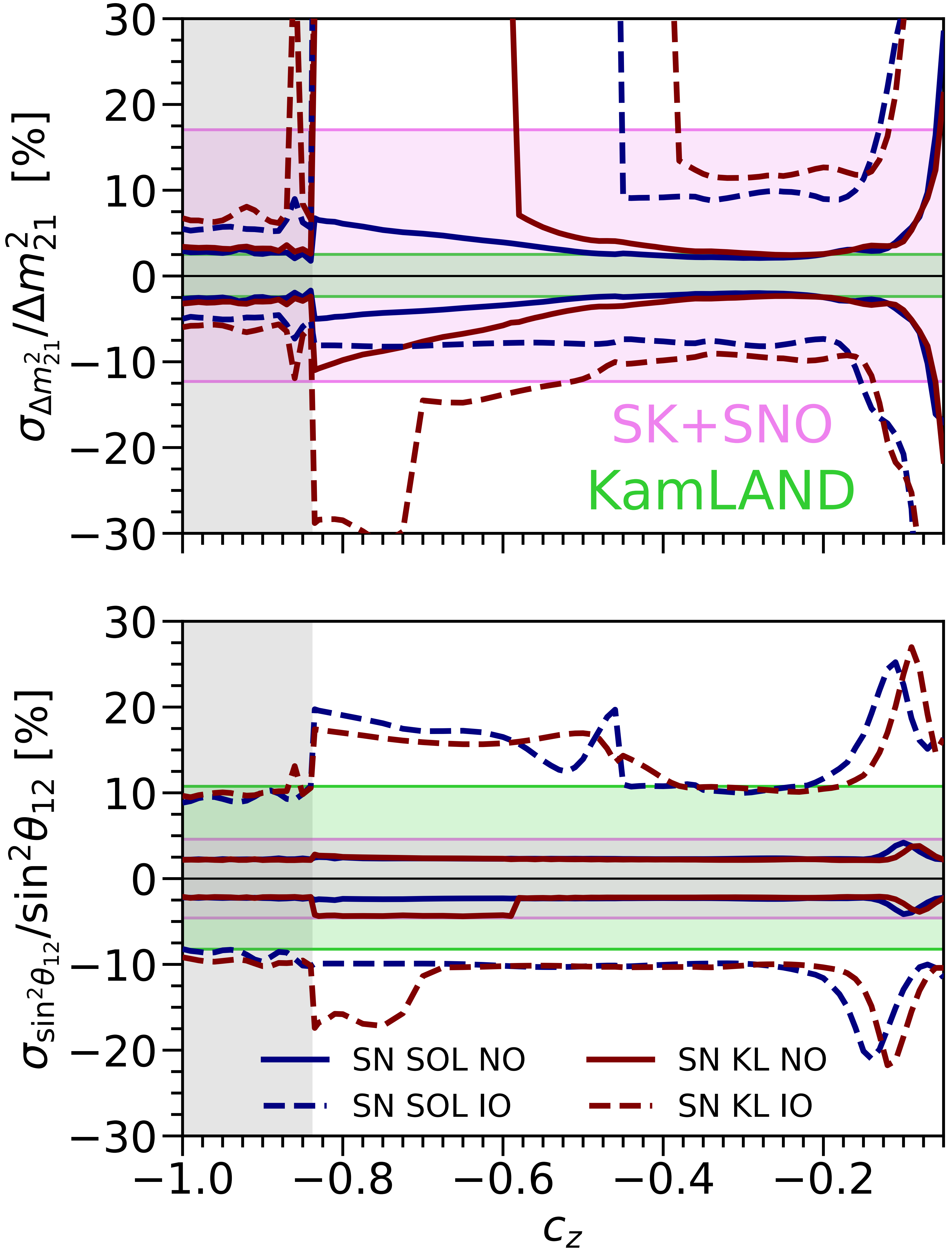
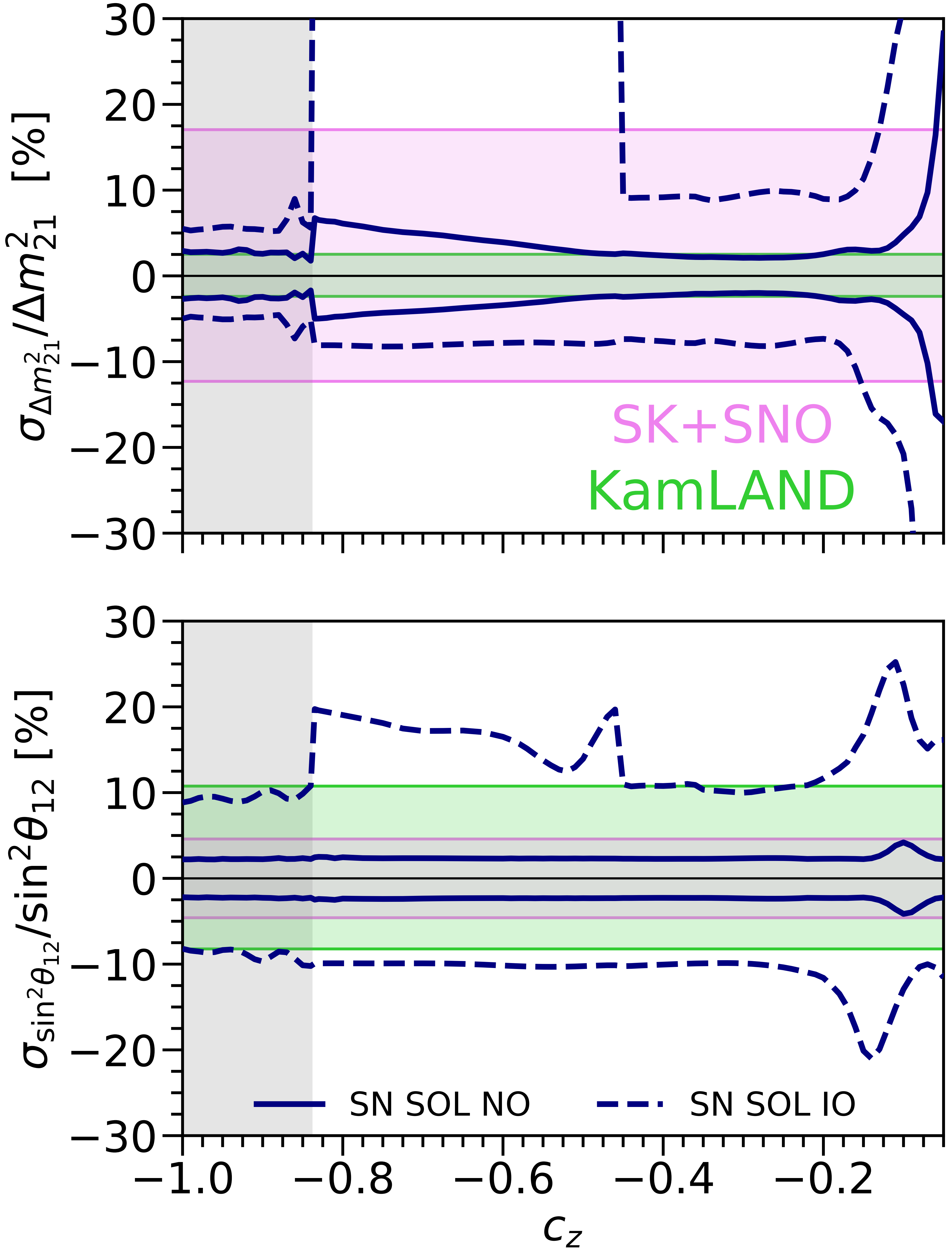


Results: Projected 1σ errors and tension

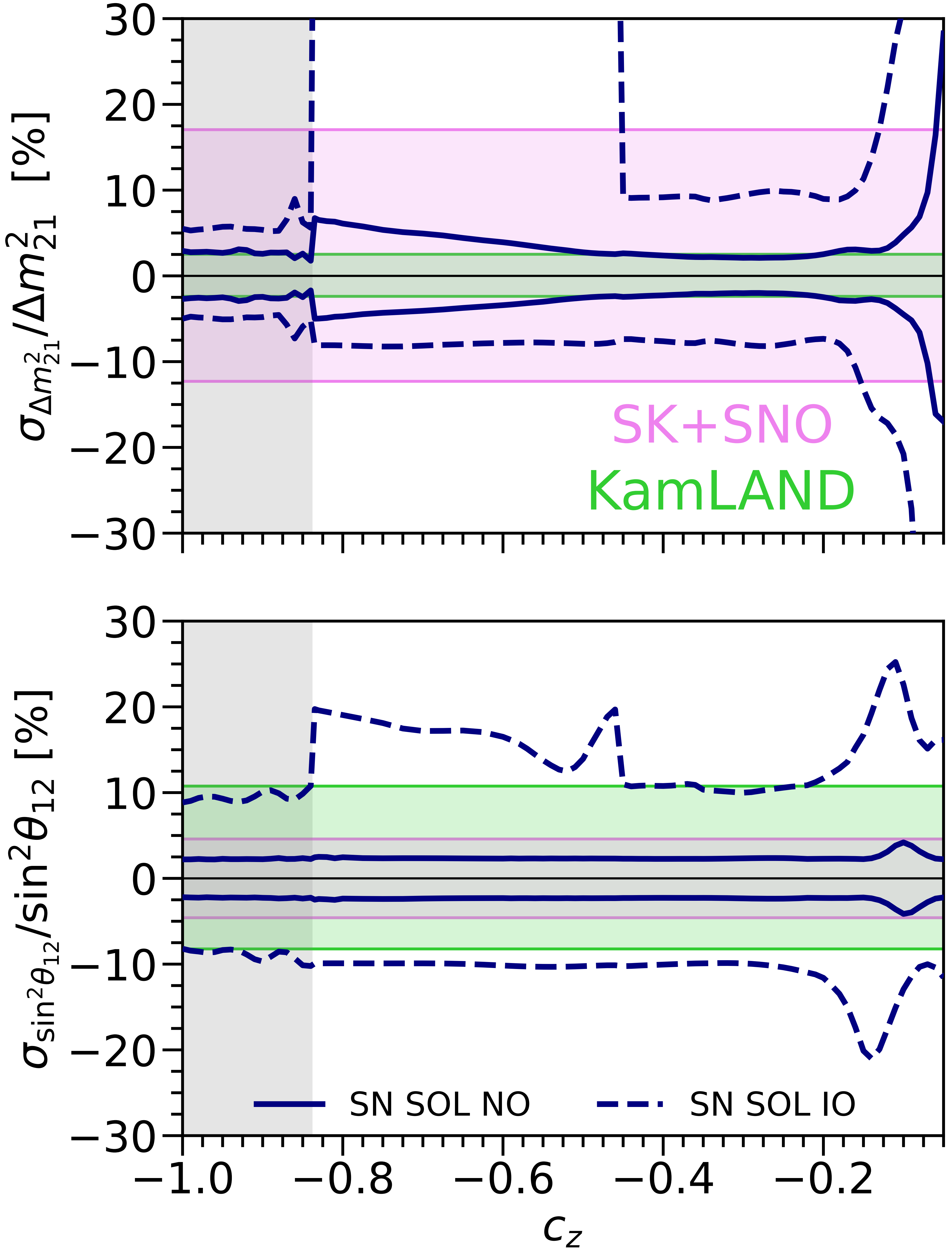


$$\mu_{21} = \frac{\Delta m^2_{21}|_{\rm KL} - \Delta m^2_{21}|_{\rm solar}}{\sqrt{\sigma^2_{\rm KL} + \sigma^2_{\rm SN}(c_z)}}$$

With SN SOL we can define tension with reactor measurement

Matter vs Vacuum oscillations measurements

Results: Projected 1σ errors and tension



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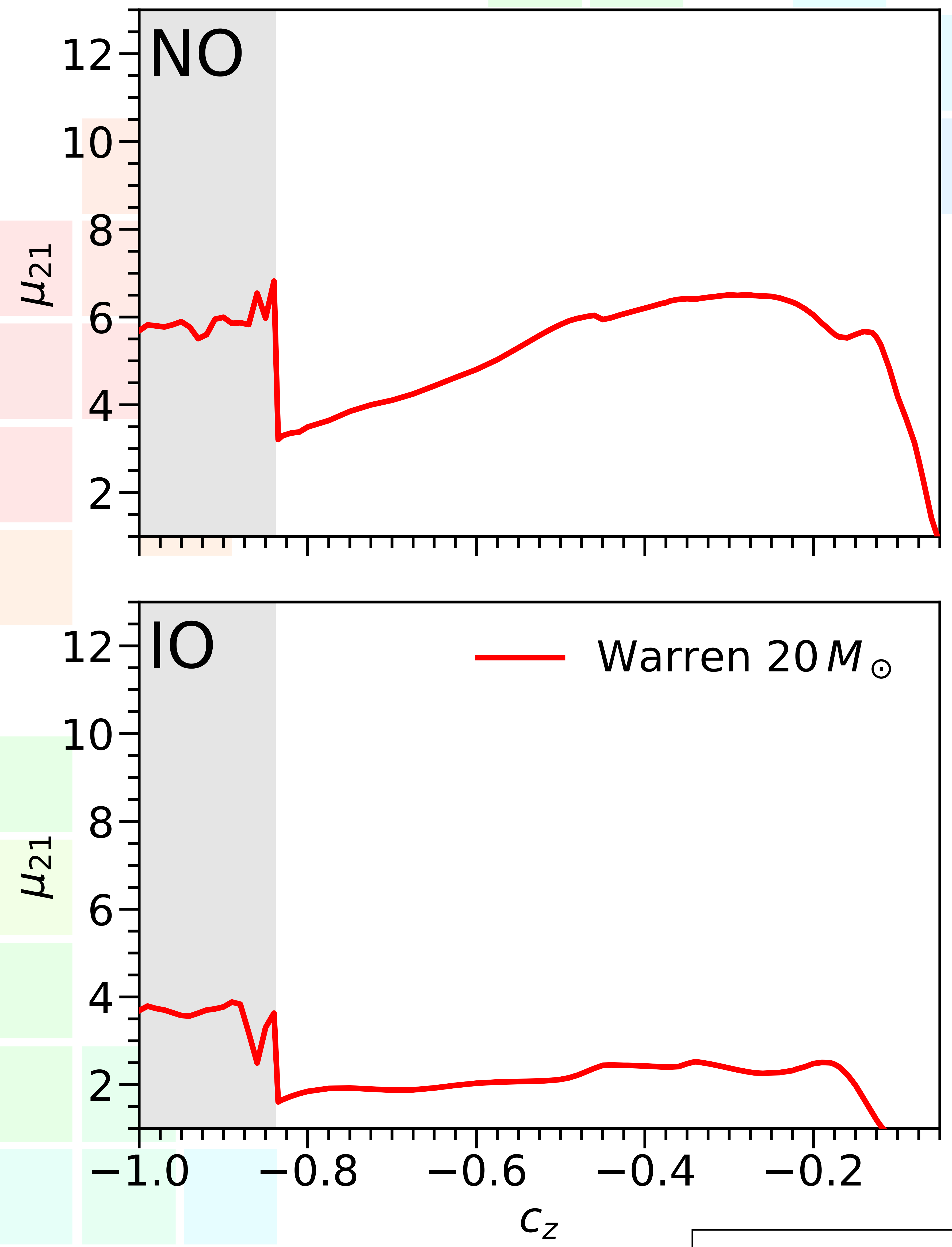
Tension exacerbates for NO.

Tension increases with matter effects.



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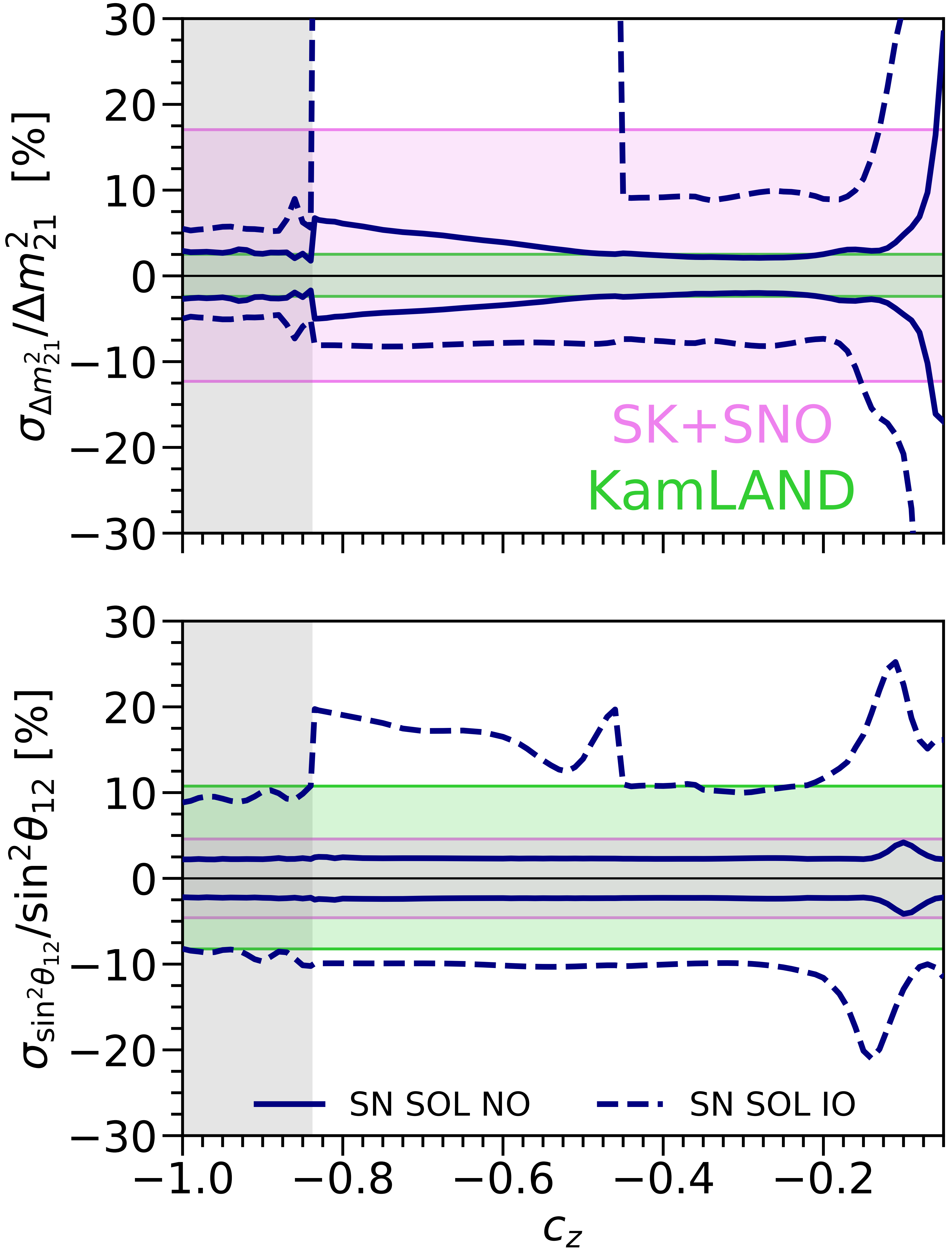

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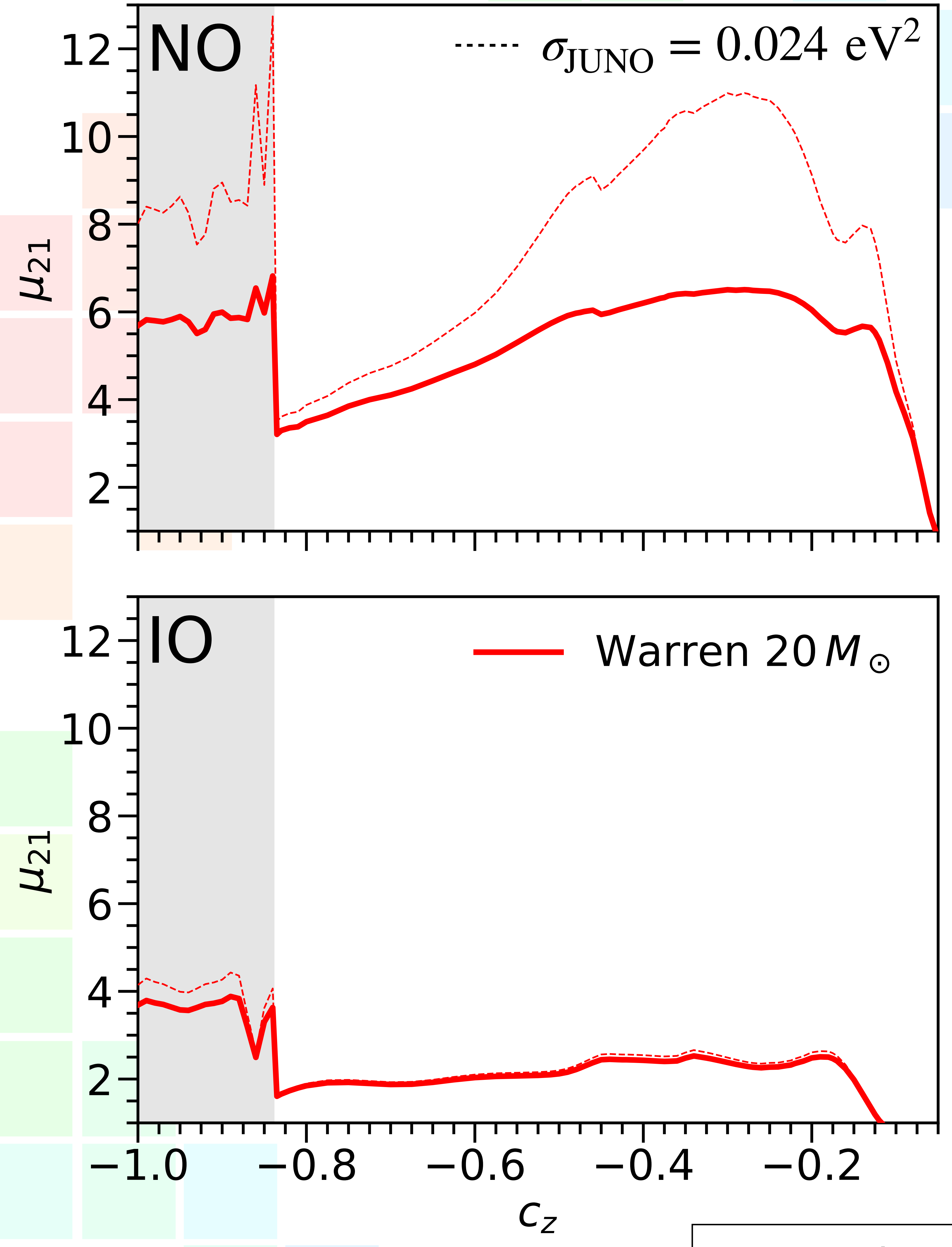
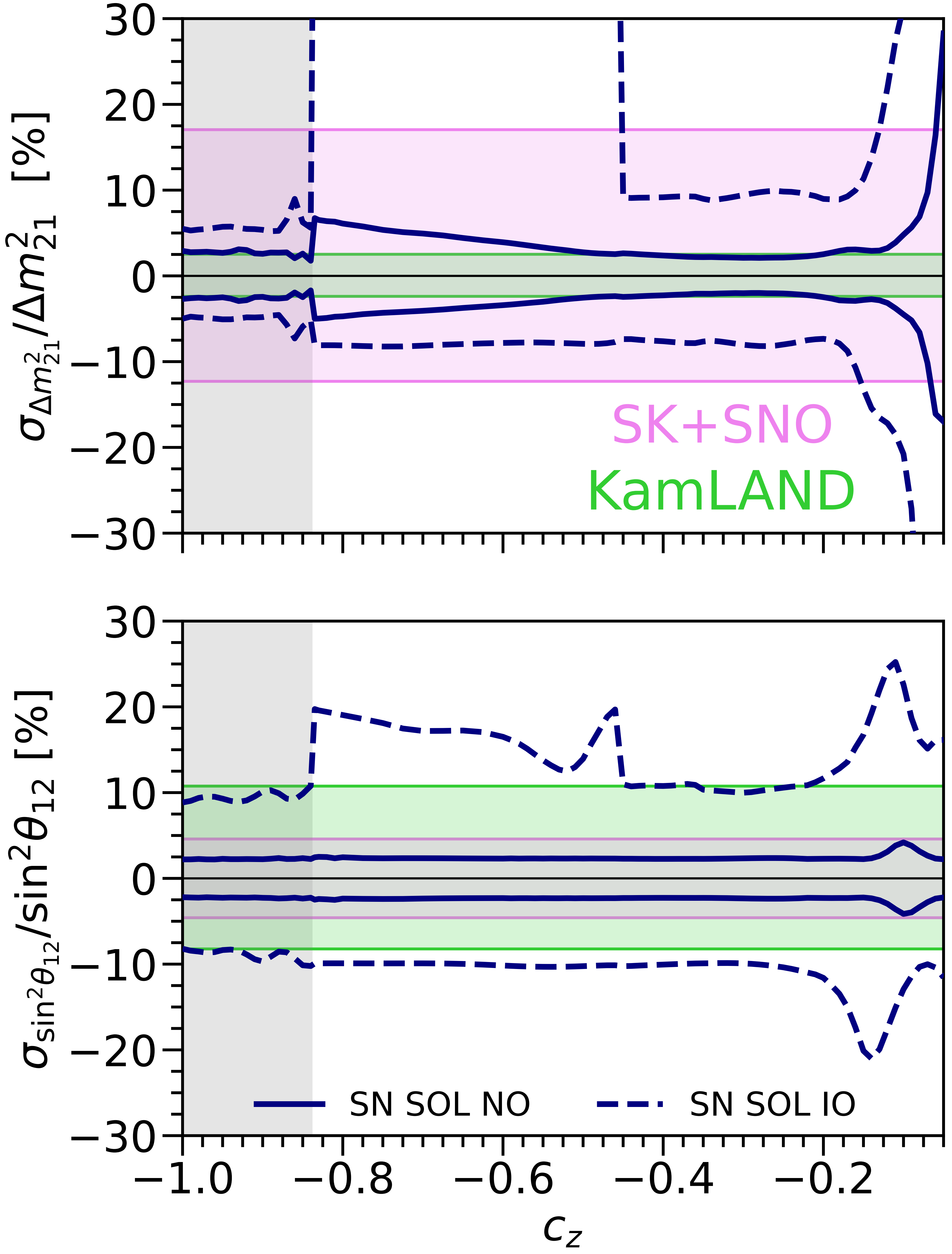
Tension increases with matter effects.

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



Results: Tension for different models



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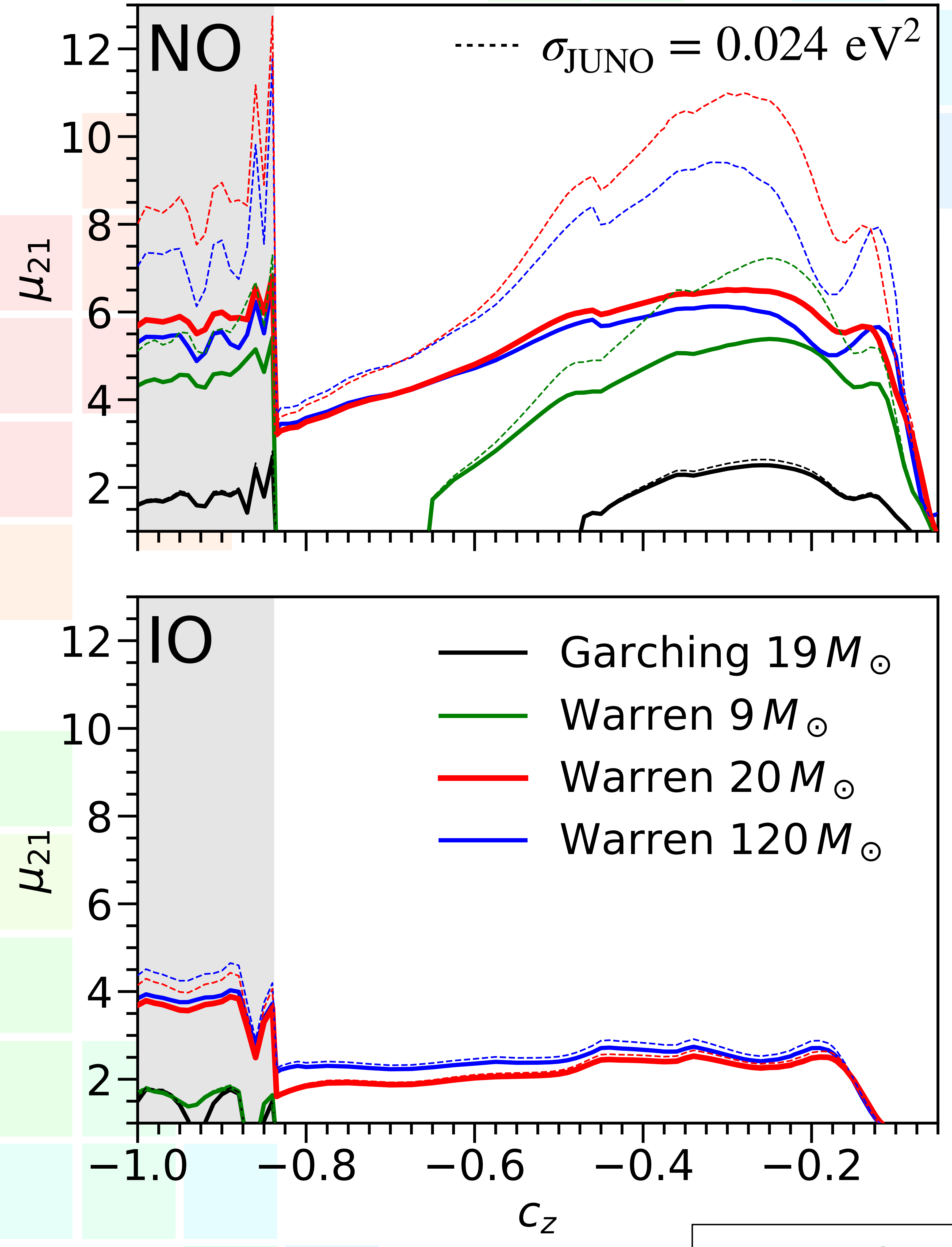
Tension exacerbates for NO.

Tension increases with matter effects.

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

Results very model dependent!



Take home message

A future galactic SN explosion could provide:

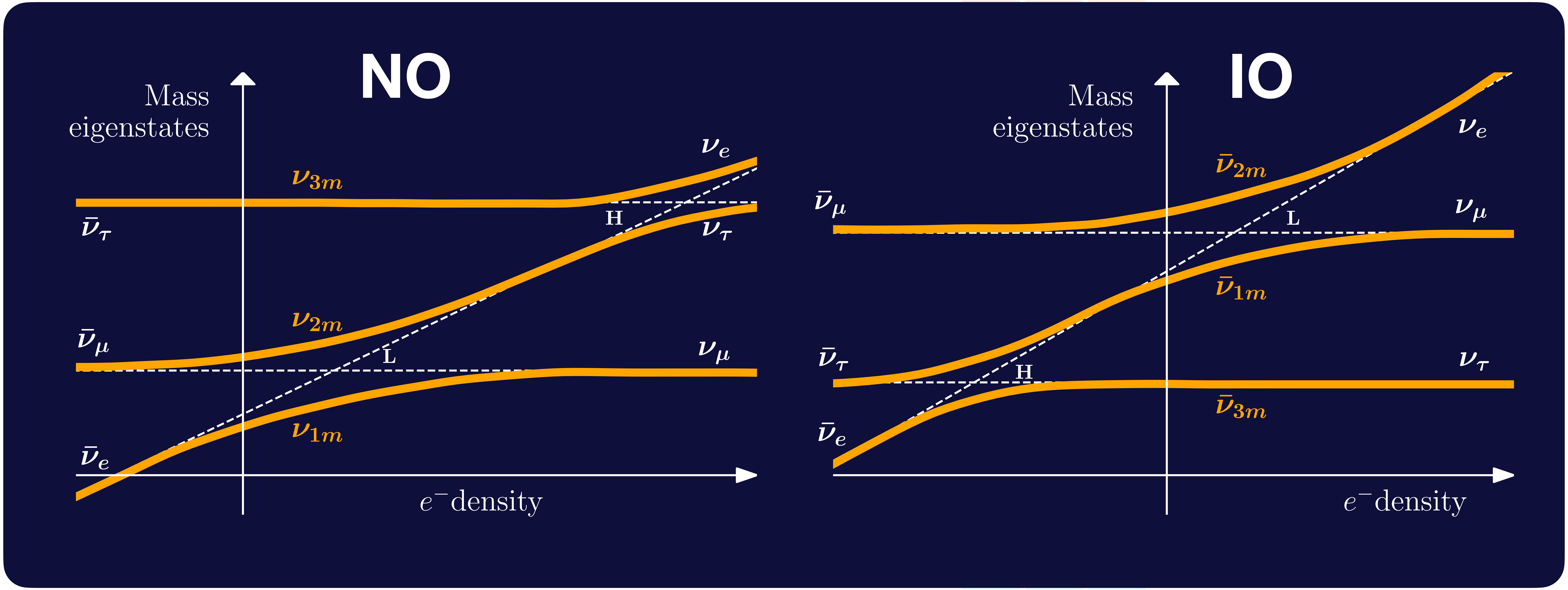
- A competitive measurement of Δm^2_{21}.
- A reduction of the uncertainty on $\sin^2\theta_{12}$.
- A solution to the longstanding tension between solar neutrino and reactor antineutrino data.

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

BACKUP SLIDES

Supernova neutrinos: adiabatic transitions

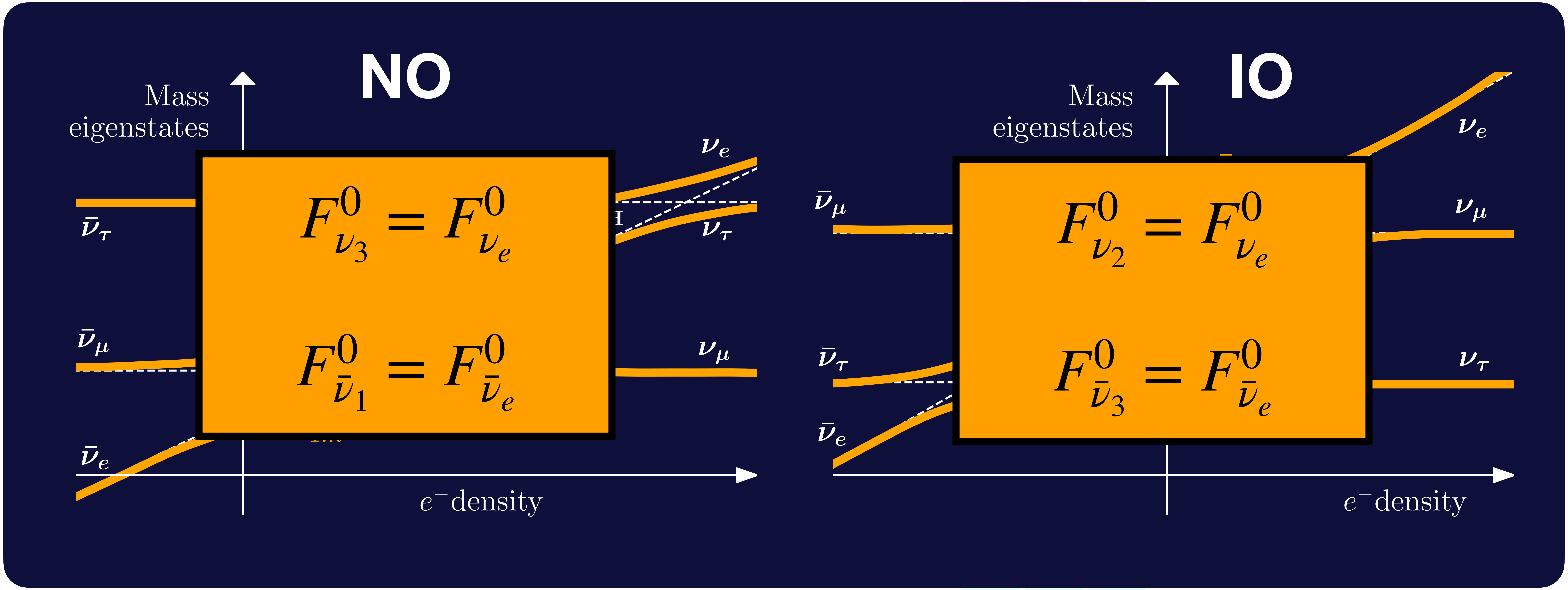
- Adiabatic transitions make neutrinos go out from the SN as mass eigenstates.



BCK1

Supernova neutrinos: adiabatic transitions

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



BCK1

Neutrino oscillations in matter

- Coherent effect in neutrino propagation

$$\frac{\mathrm{d}\phi_\nu(E_\nu, x)}{\mathrm{d}x} = -i\left(\underbrace{\frac{1}{2E}U\mathbb{M}^2U^\dagger}_{\text{Vacuum}} + \underbrace{\mathbb{V}}_{\text{Matter}}\right)\phi_\nu(E_\nu, x)$$

- For 2 families and constant density

$$P_{2\nu}(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta^m)\ \sin^2\left(\frac{\Delta^m L}{4E}\right)$$

Effect of mixing parameters

$$\Delta^m = \sqrt{(\Delta m^2 \cos 2\theta \mp 2EV)^2 + (\Delta m^2 \sin 2\theta)^2}\ , \quad \sin^2 2\theta^m = \sin^2 2\theta \left(\frac{\Delta m^2}{\Delta^m}\right)^2$$

Supernova neutrino fluxes

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

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

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

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

$$p^{\rm NO}_{\oplus} \equiv P_{\oplus}(\nu_3 \to \nu_e) \simeq \sin^2\theta_{13}$$ ✗

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

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

$$\bar p^{\rm IO}_{\oplus} \equiv P_{\oplus}(\bar\nu_3 \to \bar\nu_e) \simeq \sin^2\theta_{13}$$ ✗

Detector configurations

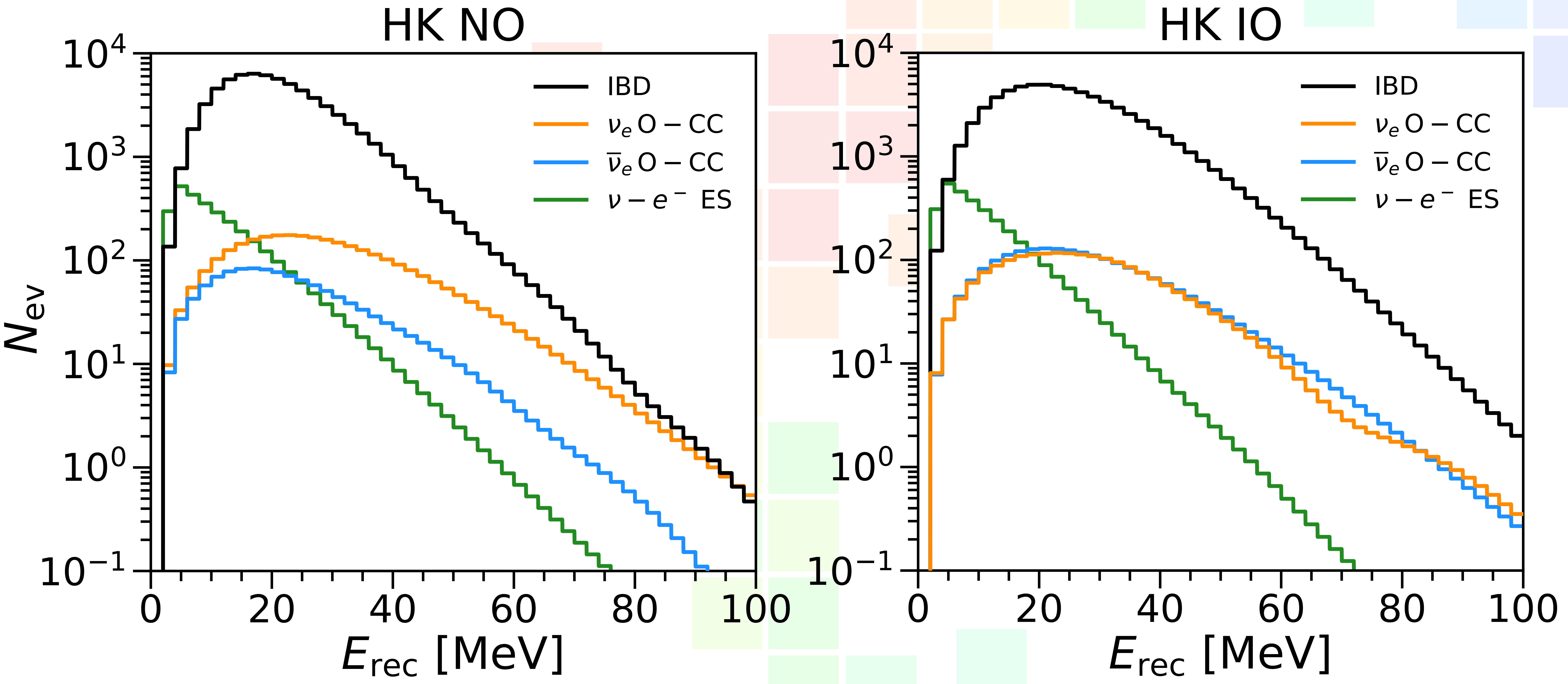
DUNE (LIQUID ARGON)	HK (WATER CHERENKOV)	JUNO (LIQUID SCINTILLATOR)
$\nu_e\mathrm{Ar-CC}: \quad \nu_e + ^{40}\mathrm{Ar} \to e^- + \mathrm{X}$, $\bar{\nu}_e\mathrm{Ar-CC}: \quad \bar{\nu}_e + ^{40}\mathrm{Ar} \to e^+ + \mathrm{X}$, $\nu - e^-\ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$.	$\mathrm{IBD}: \quad \bar{\nu}_e + p \to e^+ + n$, $\nu_e\mathrm{O-CC}: \quad \nu_e + ^{16}\mathrm{O} \to e^- + \mathrm{X}$, $\bar{\nu}_e\mathrm{O-CC}: \quad \bar{\nu}_e + ^{16}\mathrm{O} \to e^+ + \mathrm{X}$, $\nu - e^-\ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$.	$\mathrm{IBD}: \quad \bar{\nu}_e + p \to e^+ + n$, $\nu_e\mathrm{C-CC}: \quad \nu_e + ^{12}\mathrm{C} \to e^- + \mathrm{X}$, $\bar{\nu}_e\mathrm{C-CC}: \quad \bar{\nu}_e + ^{12}\mathrm{C} \to e^+ + \mathrm{X}$, $\nu - e^-\ \mathrm{ES}: \quad \nu + e^- \to \nu + e^-$.
$N_t^{Ar} = 6.03 \cdot 10^{32}$ 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 neutrino event rates at HK

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

NO effect in antineutrinos

IO effect in neutrinos

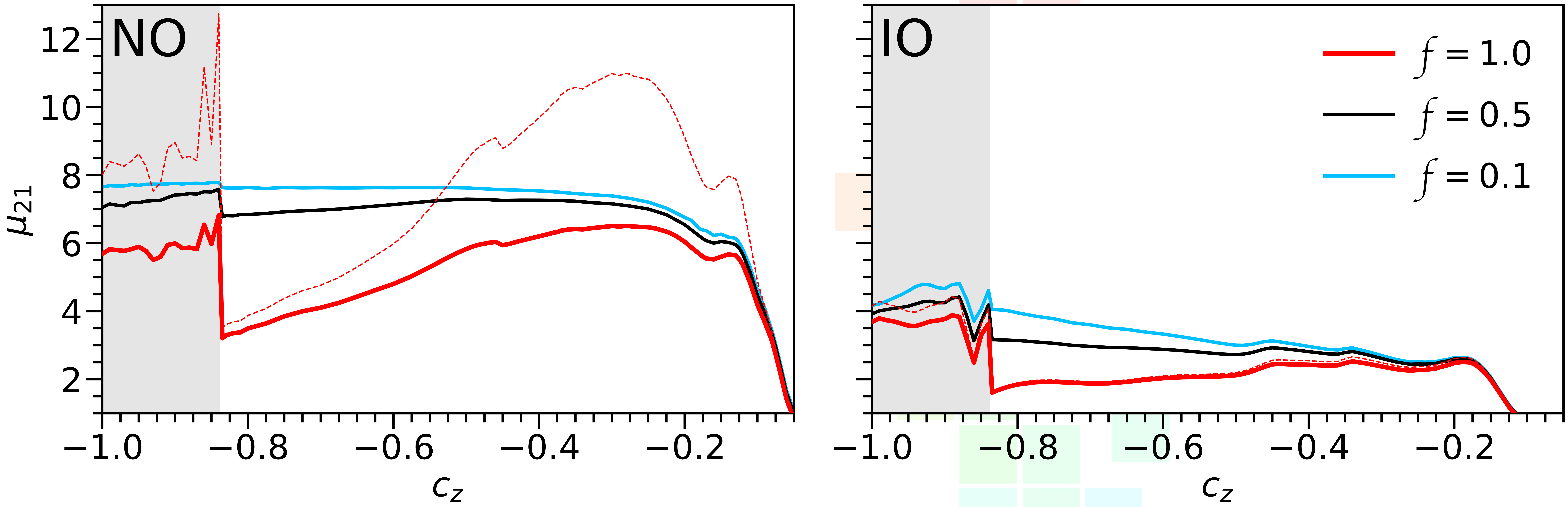


BCK5

Results: effect of detector resolution

Effect of resolution of the detector in the final result:

$$\sigma_{\text{detector}} = f\,\sigma_{\text{HK}}$$



BCK6

Reactor neutrinos

KamLAND measured neutrinos from reactors: $\langle E_{\bar{\nu}_e}^{\text{reactor}} \rangle \sim 1\,\text{MeV}$

Oscillation probability:

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4\,E}\right) = \sin^2(2\theta)\ \sin^2\left(1.27\,\frac{\Delta m^2[\text{eV}^2]\,L[\text{m}]}{E[\text{MeV}]}\right)$$

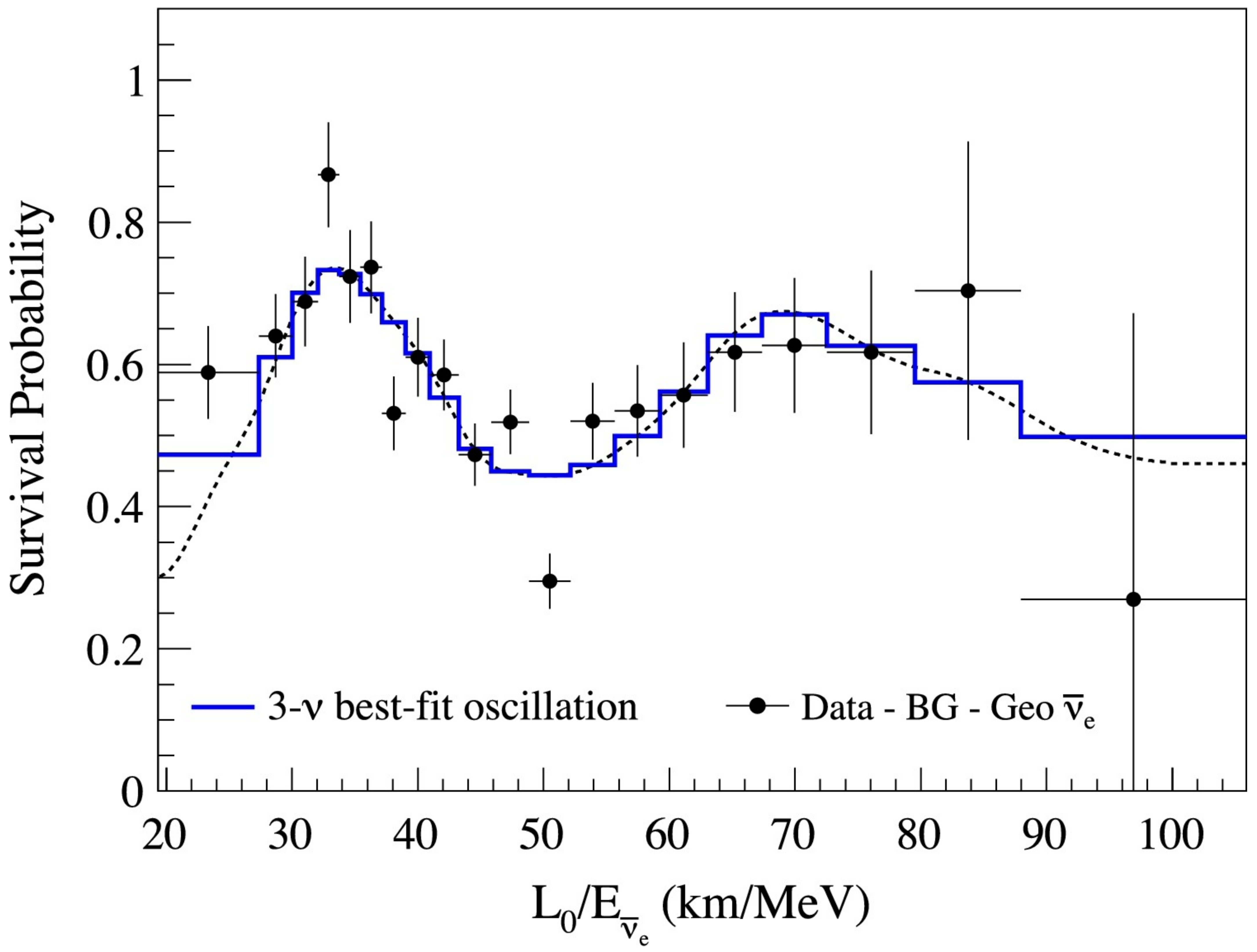
Once we had hints from solar measurements of $\Delta m_{21}^2 \sim 10^{-5}\,\text{eV}^2$

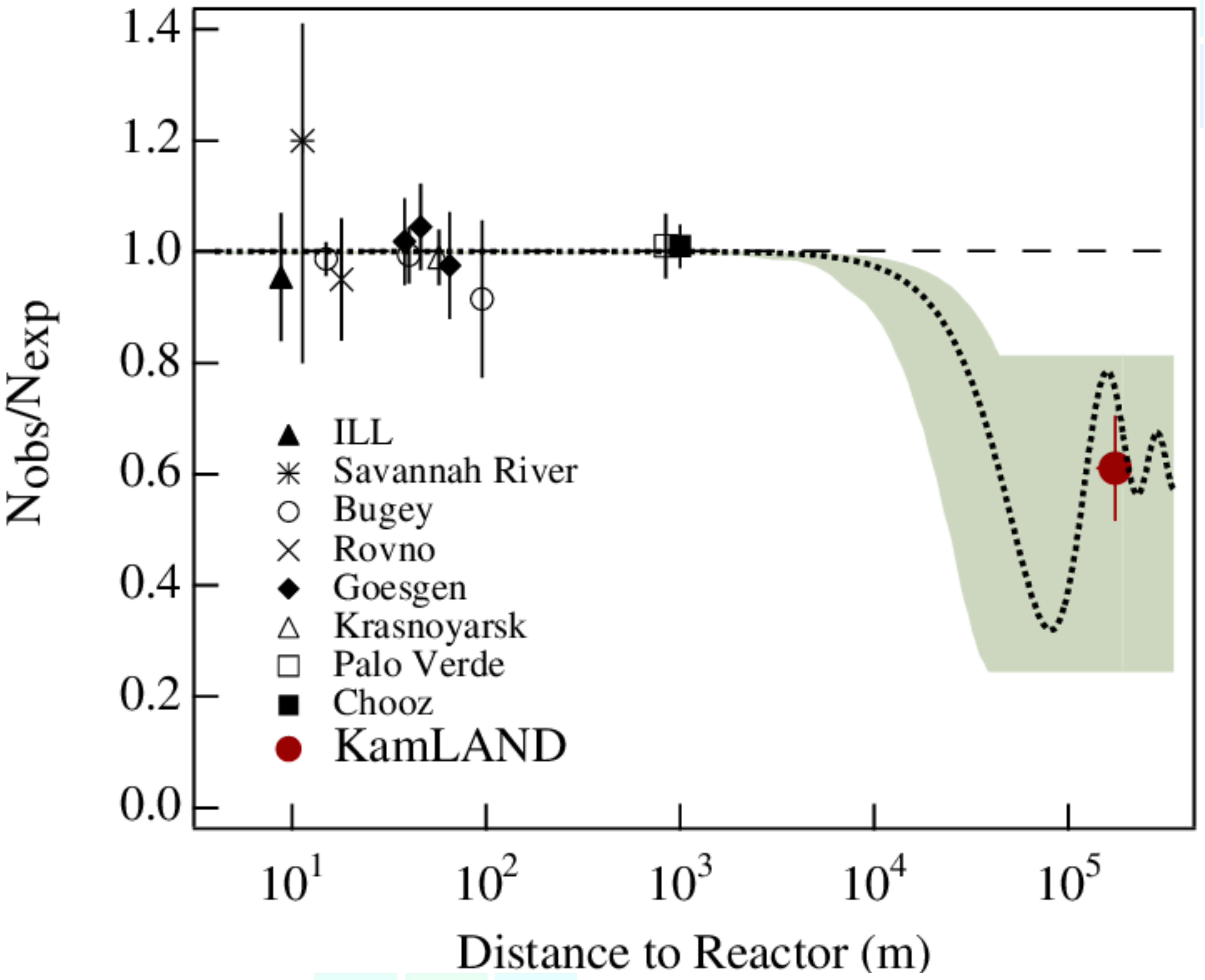
So to test that mass splitting they just needed to place a detector at a distance of

$$L[\text{m}] \sim \frac{E[\text{MeV}]}{\Delta m^2[\text{eV}^2]} \sim \frac{1\,\text{MeV}}{10^{-5}\,\text{eV}^2} \sim 10^5$$

Reactor neutrinos

$$L[\text{m}] \sim \frac{E[\text{MeV}]}{\Delta m^2[\text{eV}^2]} \sim \frac{1\ \text{MeV}}{10^{-5}\ \text{eV}^2} \sim 10^5$$





BCK8