Earth tomography with supernova neutrinos at future neutrino detectors

based on RH, O. Mena and S. Palomares-Ruiz, arXiv:2303.09369

Rasmi Hajjar

Scuola Superiore Meridionale (SSM)
Instituto de Física Corpuscular (CSIC-UV)

rasmi.hajjar@ific.uv.es

TeVPA 2023

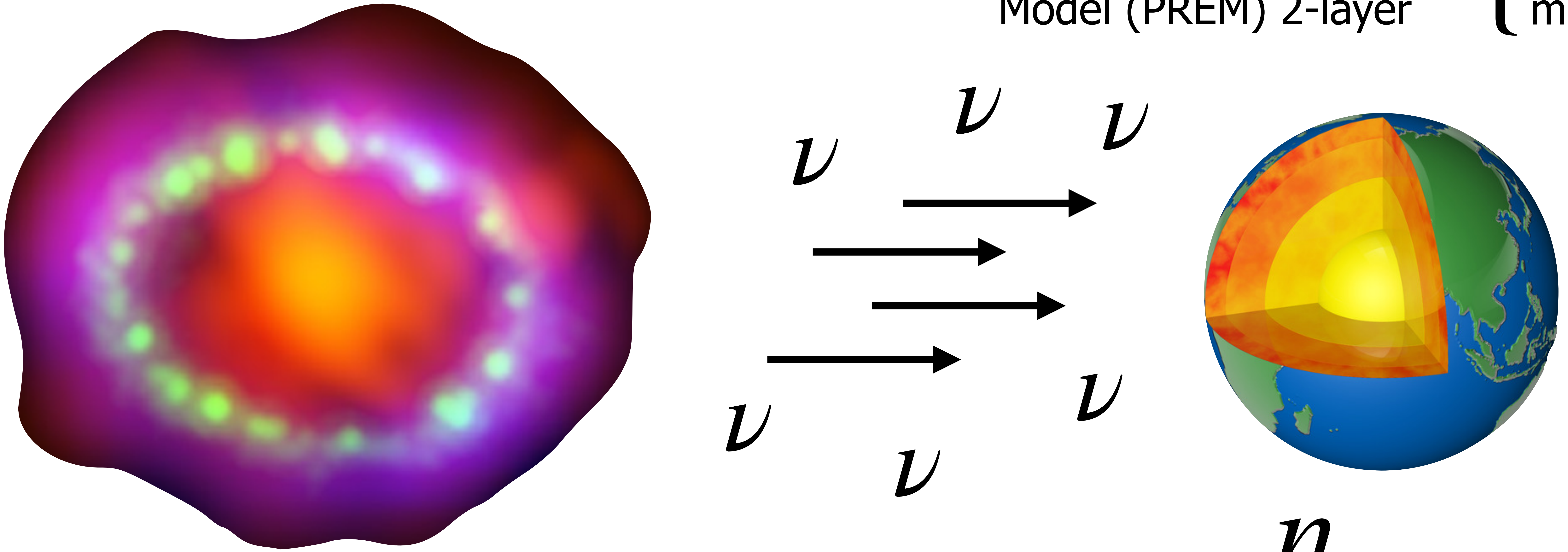
IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

SSM Scuola Superiore Meridionale

Main goal of this work

Preliminary Reference Earth Model (PREM) 2-layer { core, mantle

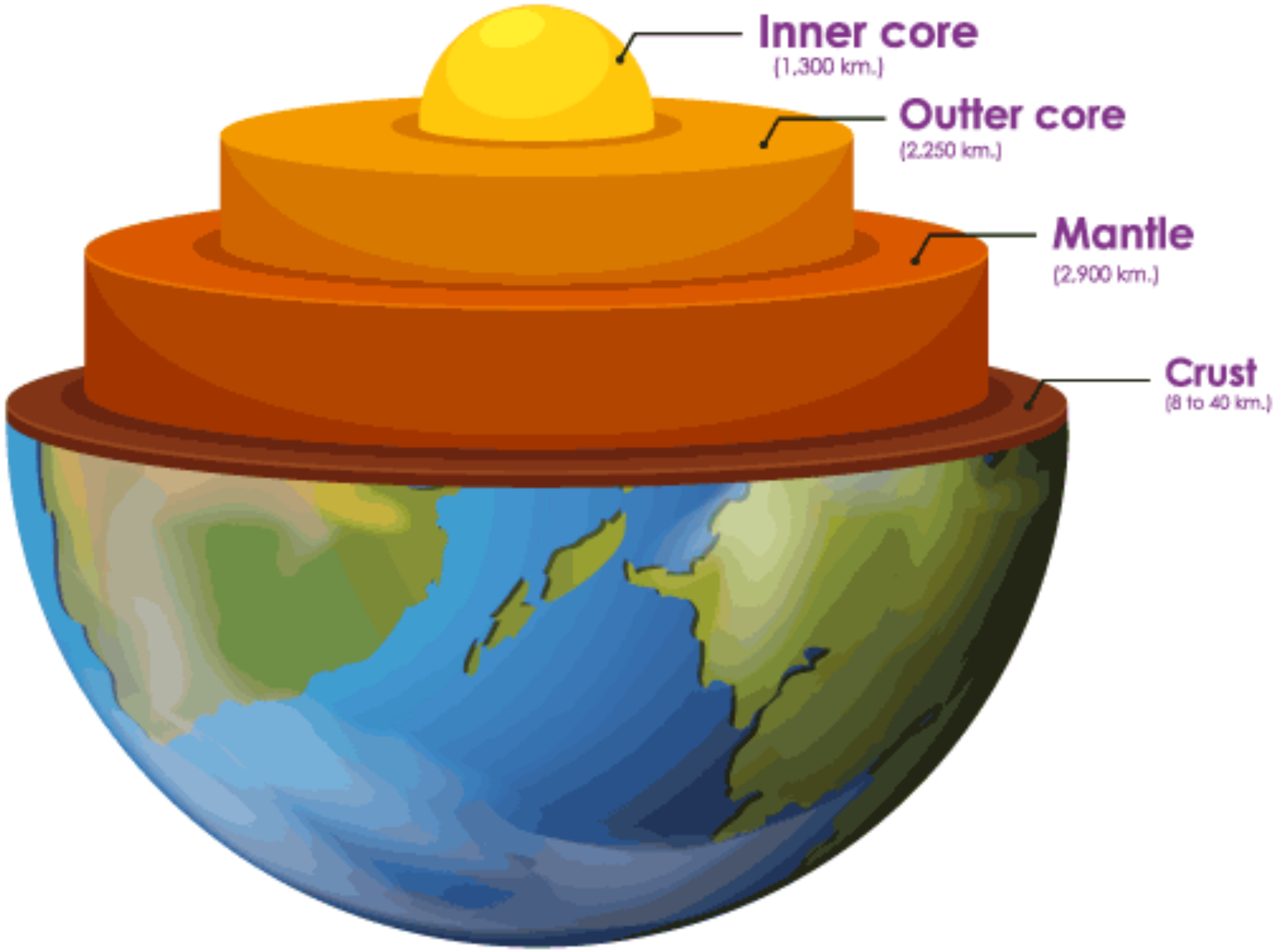


galactic SN d_{SN}~10kpc

n_{core}

Earth inner structure

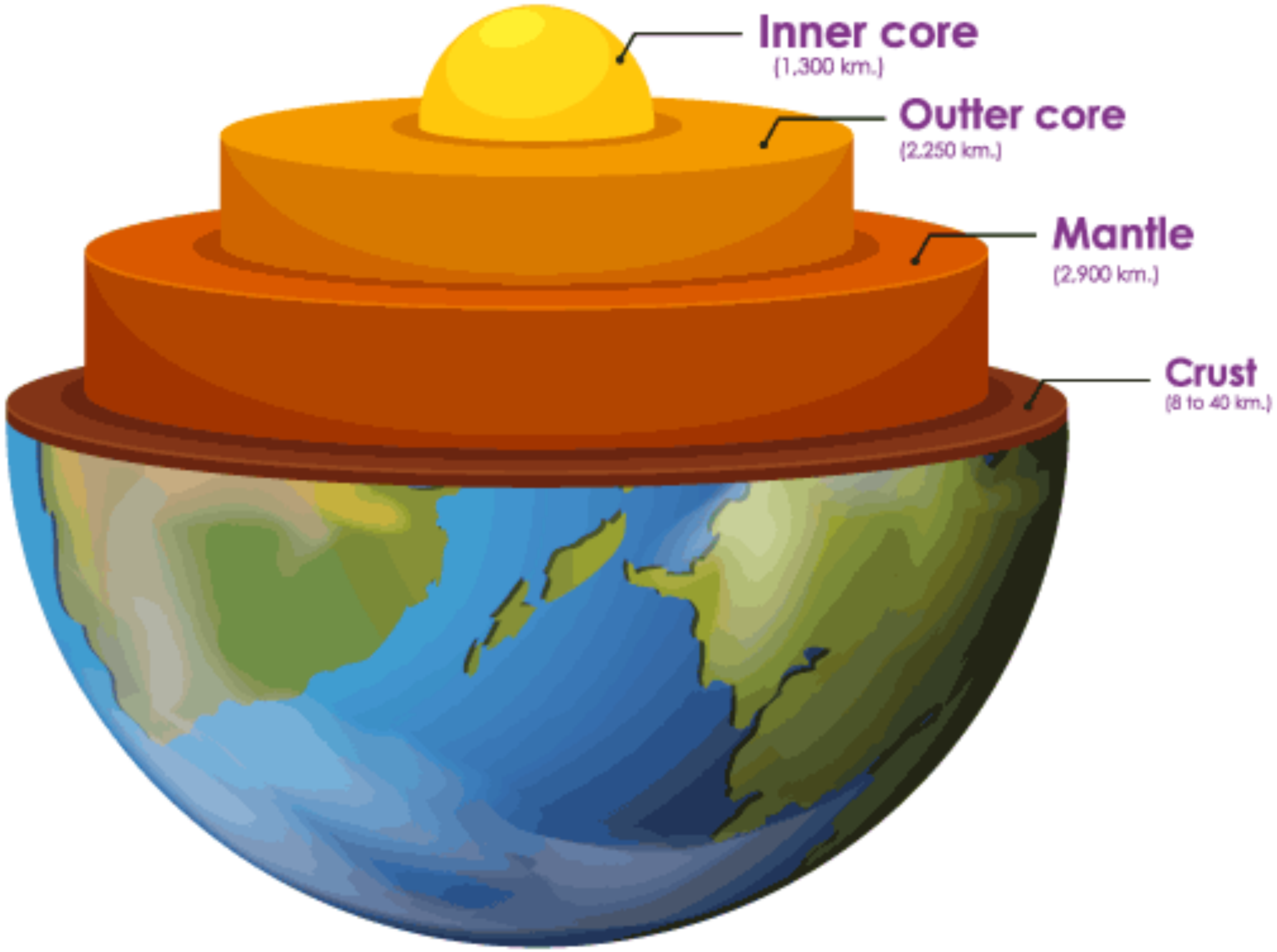
- Modern Earth model:



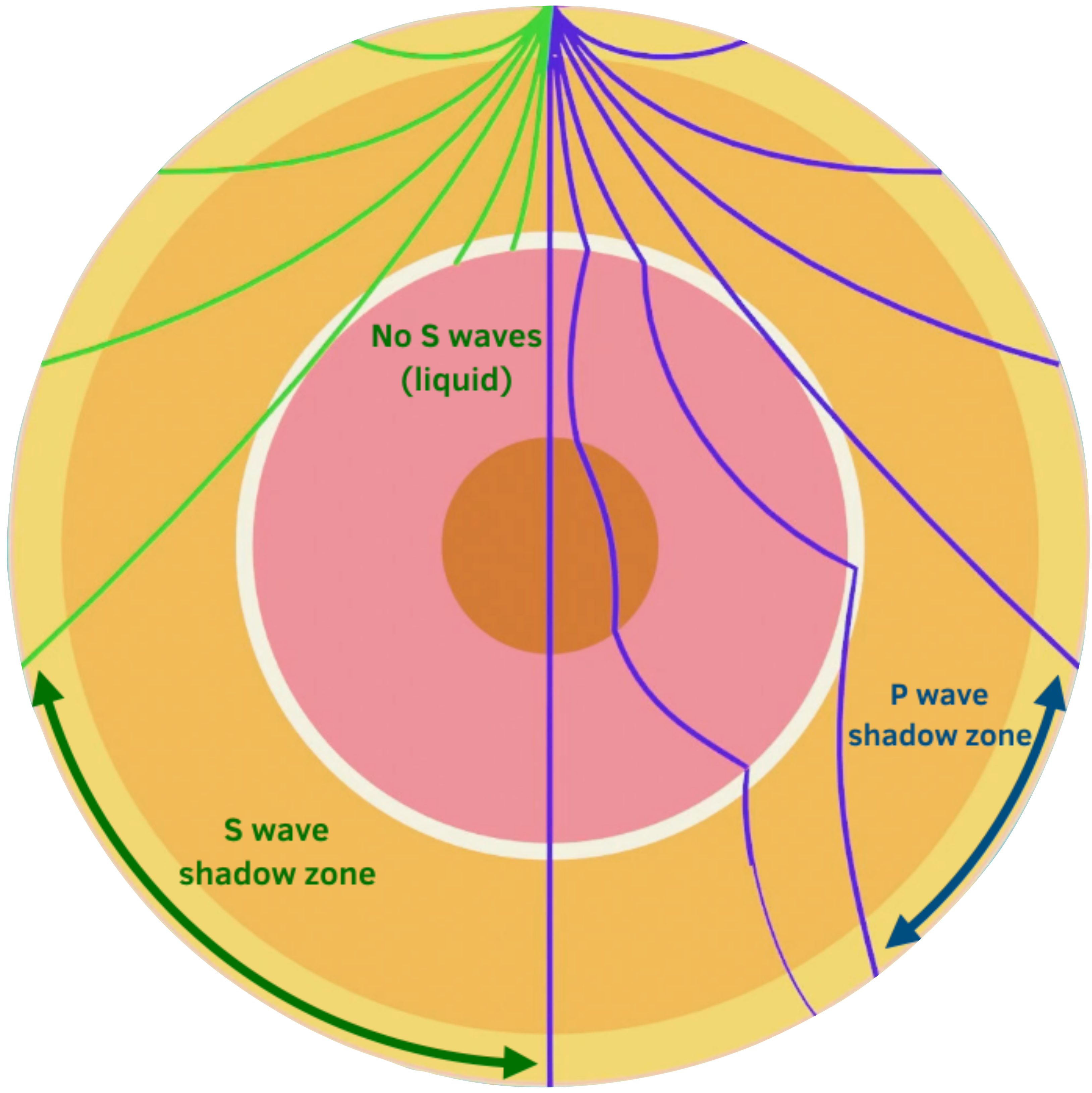
- How do we know this?

Earth inner structure

- Modern Earth model:



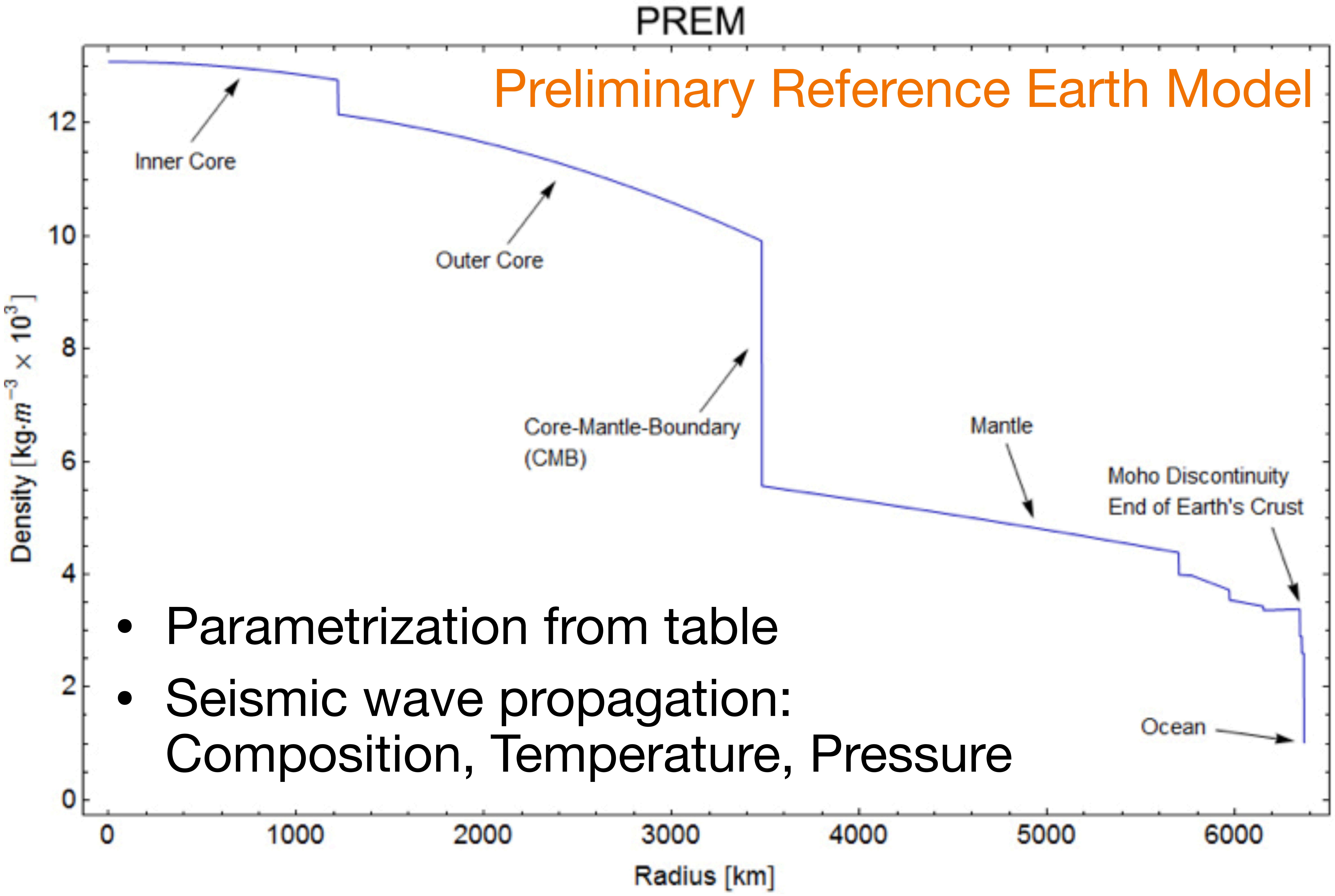
- How do we know this? Seismic waves!



Earth inner structure

A.M. Dziewonski, D.L. Anderson,
Phys.Earth Planet.Interiors 25 (1981), 297-356

LEVEL	RADIUS KM	DEPTH KM	DENSITY G/CCM
1	0.	6371.0	13.08848
2	100.0	6271.0	13.08630
3	200.0	6171.0	13.07977
4	300.0	6071.0	13.06888
5	400.0	5971.0	13.05364
6	500.0	5871.0	13.03404
7	600.0	5771.0	13.01009
8	700.0	5671.0	12.98178
9	800.0	5571.0	12.94912
10	900.0	5471.0	12.91211
11	1000.0	5371.0	12.87073
12	1100.0	5271.0	12.82501
13	1200.0	5171.0	12.77493
14	1221.5	5149.5	12.76360
15	1221.5	5149.5	12.16634
16	1300.0	5071.0	12.12500
17	1400.0	4971.0	12.06924
18	1500.0	4871.0	12.00989
19	1600.0	4771.0	11.94682
20	1700.0	4671.0	11.87990

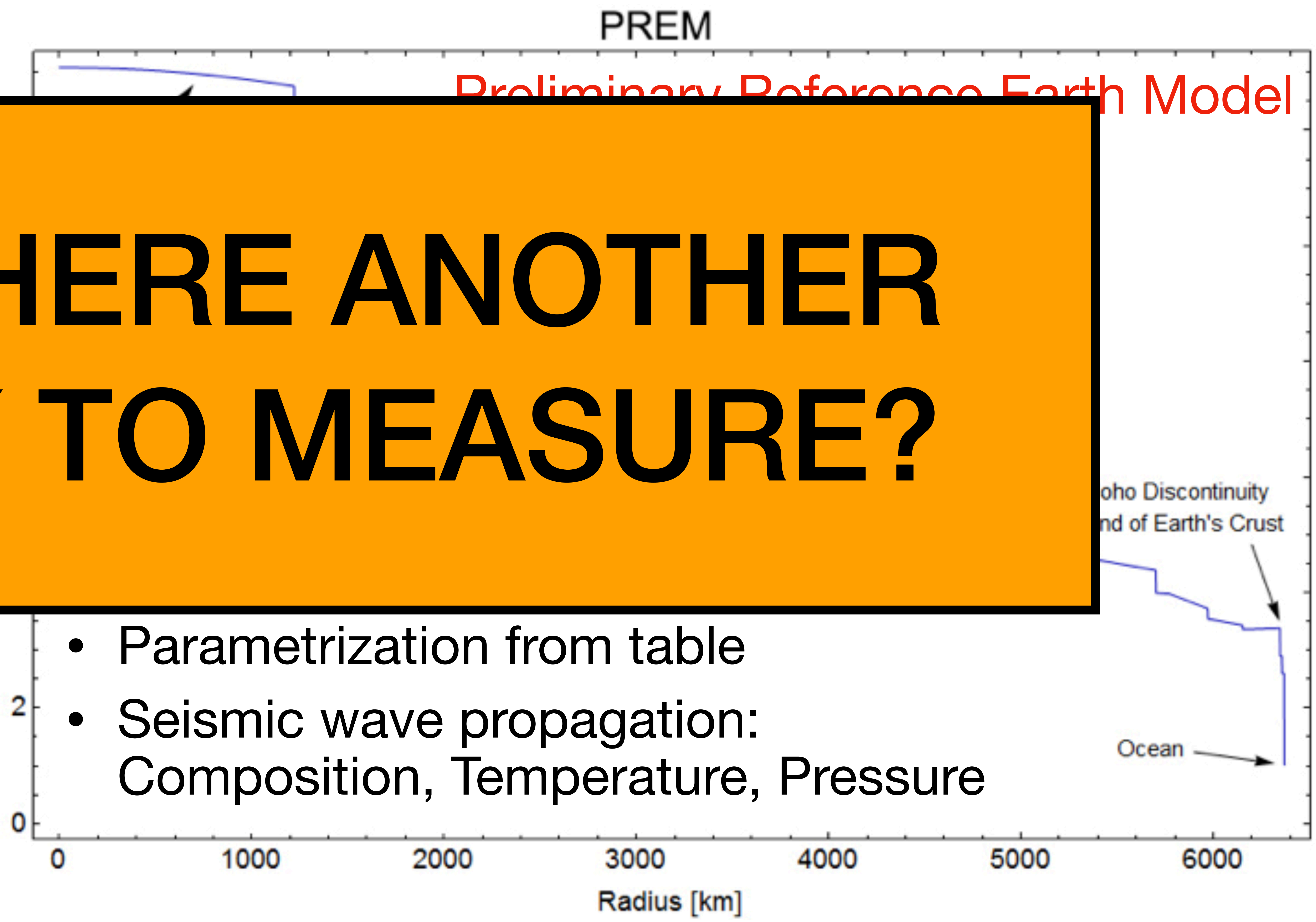


- Parametrization from table
- Seismic wave propagation:
  Composition, Temperature, Pressure

Earth inner structure

A.M. Dziewonski, D.L. Anderson,
Phys.Earth Planet.Interiors 25 (1981), 297-356

LEVEL	RACIUS KM		
1	0.		
2	100.0		
3	200.0		
4	300.0		
5	400.0		
6	500.0		
7	600.0		
8	700.0		
9	800.0		
10	900.0		
11	1000.0		
12	1100.0		
13	1200.0		
14	1221.5	5149.5	12.76360
15	1221.5	5149.5	12.16634
16	1300.0	5071.0	12.12500
17	1400.0	4971.0	12.06924
18	1500.0	4871.0	12.00989
19	1600.0	4771.0	11.94682
20	1700.0	4671.0	11.87990



- Parametrization from table
- Seismic wave propagation:
  Composition, Temperature, Pressure

IS THERE ANOTHER WAY TO MEASURE?

Earth inner structure

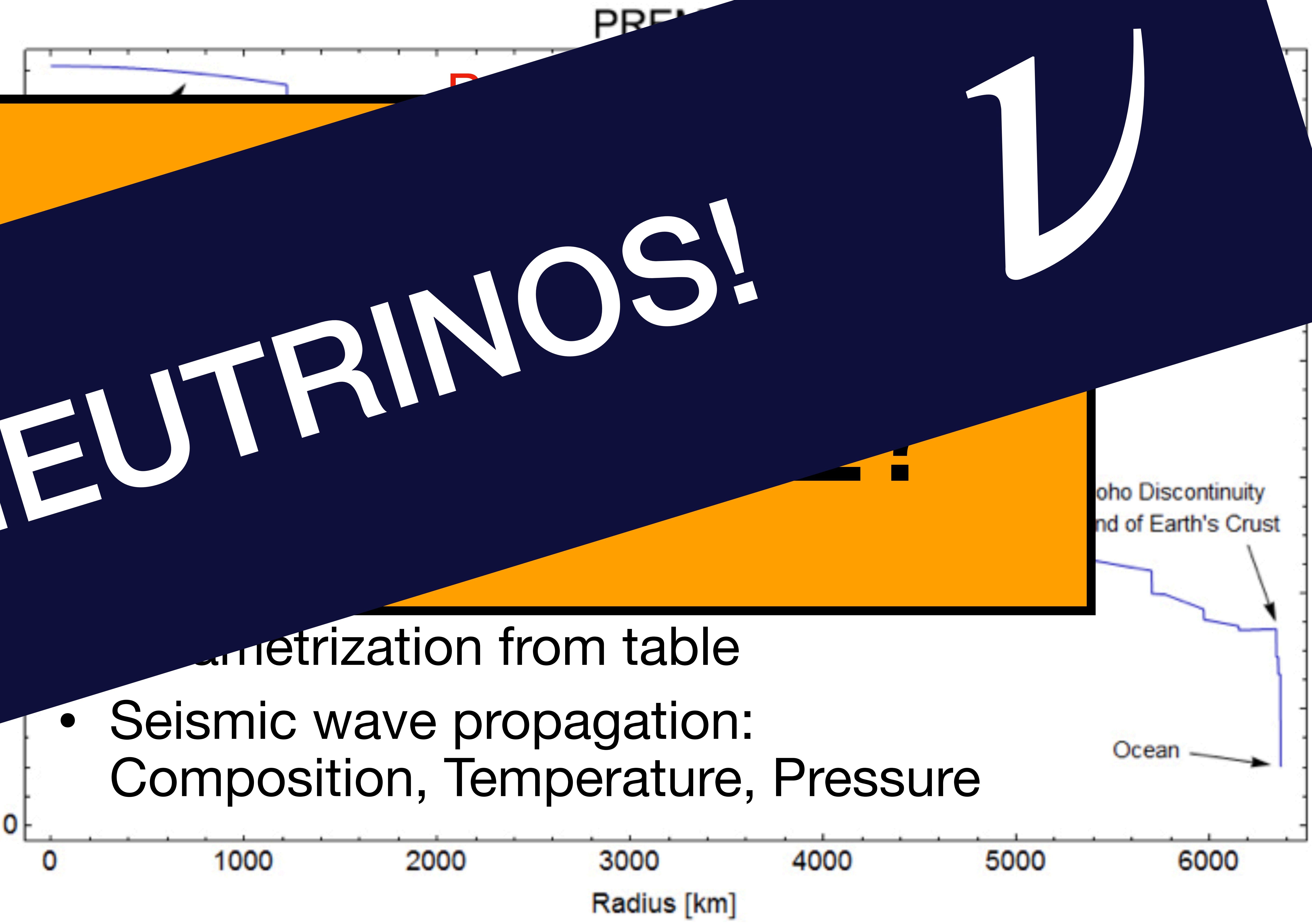
A.M. Dziewonski, D.L. Anderson,
Phys.Earth Planet.Interiors 25 (1981), 297-356

LEVEL	RACIUS KM		
1	0.		
2	100.0		
3	200.0		
4	300.0		
5	400.0		
6	500.0		
7			
19			11.94682
20	.0		11.87990

IS T

NEUTRINOS!

ν ν



- ...metrization from table
- Seismic wave propagation:
  Composition, Temperature, Pressure

Neutrino tomography types

OSCILLATION TOMOGRAPHY

$$\frac{d\phi(E,x)}{dx} = -i\,\mathcal{H}_{\text{flavor}}\,\phi(E,x)$$

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

Vacuum — Matter

$$P_{2\nu}(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_m \, \sin^2\left(\frac{\Delta_m L}{4E}\right)$$

$$\Delta_m = \sqrt{(\Delta m^2 \sin 2\theta \mp 2E\,\mathbf{V})^2 + (\Delta m^2 \cos 2\theta)^2}$$

$$\sin^2 2\theta_m = \sin^2 2\theta \left(\frac{\Delta m^2}{\Delta_m}\right)^2$$

- Man-made beams
- Solar neutrinos
- Supernova neutrinos
- Atmospheric Neutrinos

Neutrino tomography types

OSCILLATION TOMOGRAPHY

$$\frac{d\phi(E,x)}{dx} = -i\,\mathscr{H}_{\text{flavor}}\,\phi(E,x)$$

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

$$P_{2\nu}(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_m \, \sin^2\left(\frac{\Delta_m L}{4E}\right)$$

$$\Delta_m = \sqrt{(\Delta m^2 \sin 2\theta \mp 2E\,\mathbb{V})^2 + (\Delta m^2 \cos 2\theta)^2}$$

$$\sin^2 2\theta_m = \sin^2 2\theta \left(\frac{\Delta m^2}{\Delta_m}\right)^2$$

MeV

- Man-made beams
- Solar neutrinos
- Supernova neutrinos
- Atmospheric Neutrinos

ABSORPTION TOMOGRAPHY

$$\frac{d\phi(E,x)}{dx} = -n(x)\,\sigma\,\phi(E,x)$$

GeV

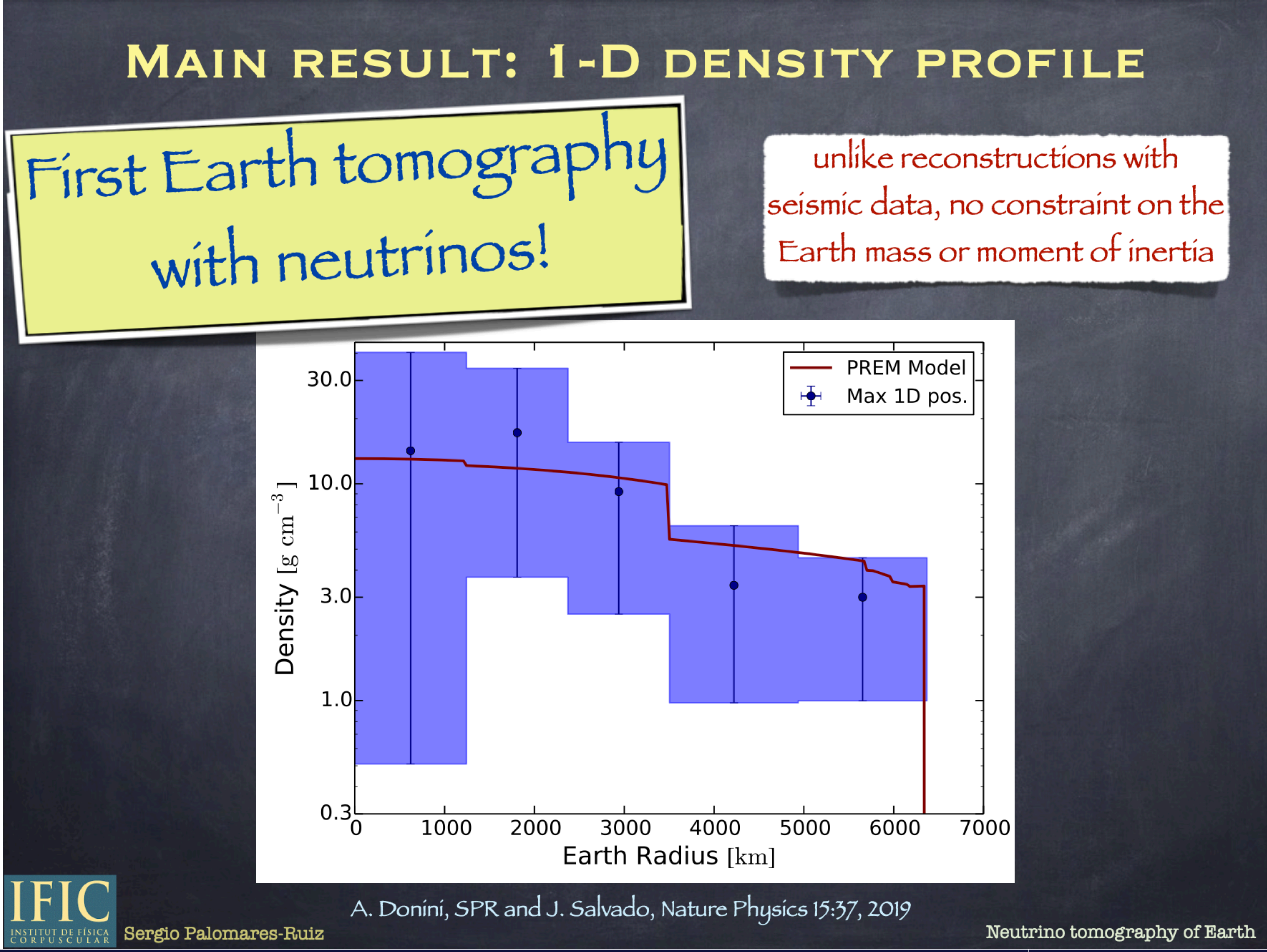
- Man-made beams
- Cosmic neutrinos
- Atmospheric neutrinos

Neutrino tomography results!

Slide taken from S. Palomares-Ruiz talk

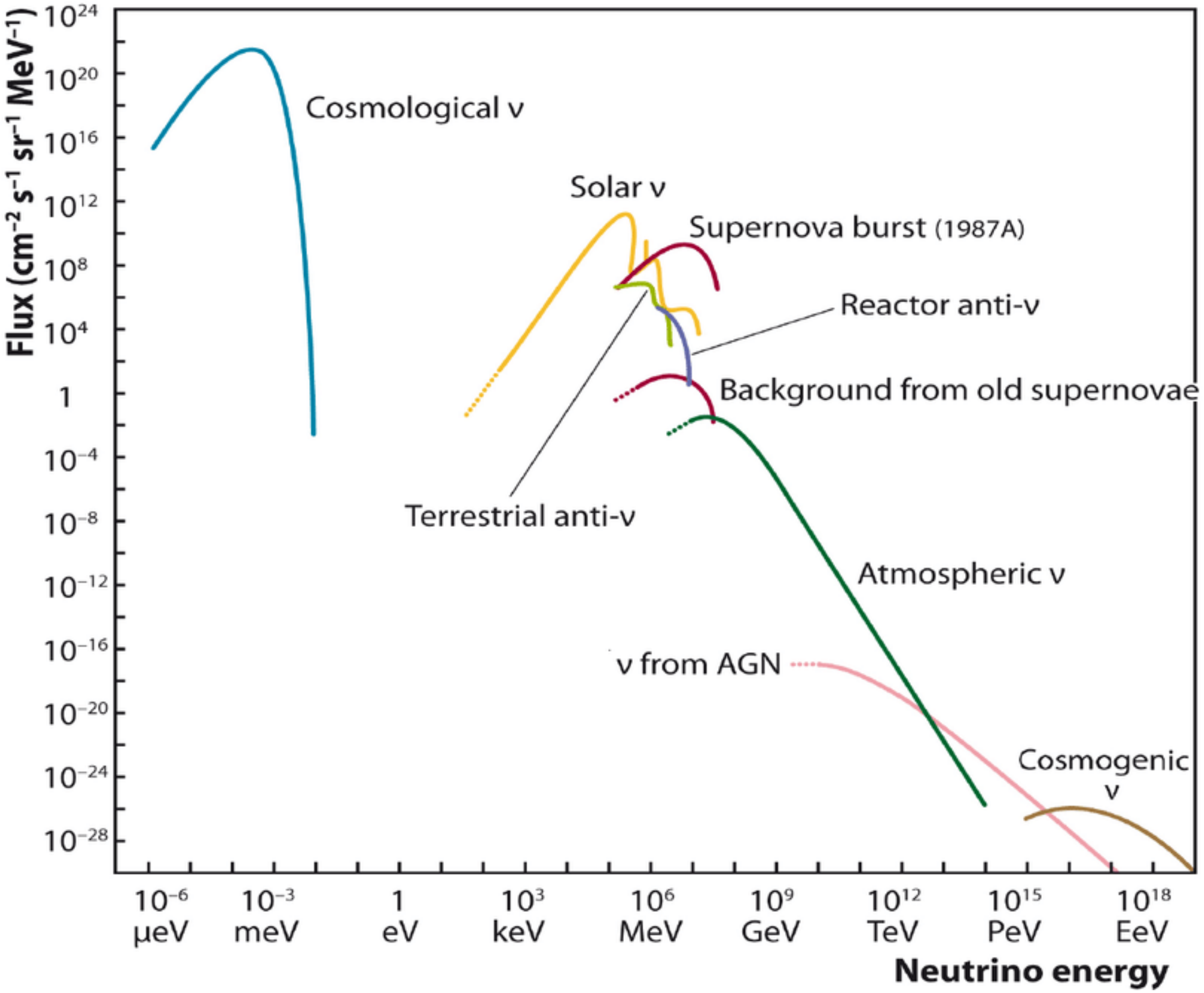
https://drive.google.com/file/d/1yaF_Wo9SiDd92Ub34jiOOs5Yylpc9JHU/view

- 1 year data of atmospheric neutrinos at Ice-Cube neutrino detector



Supernova neutrinos

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



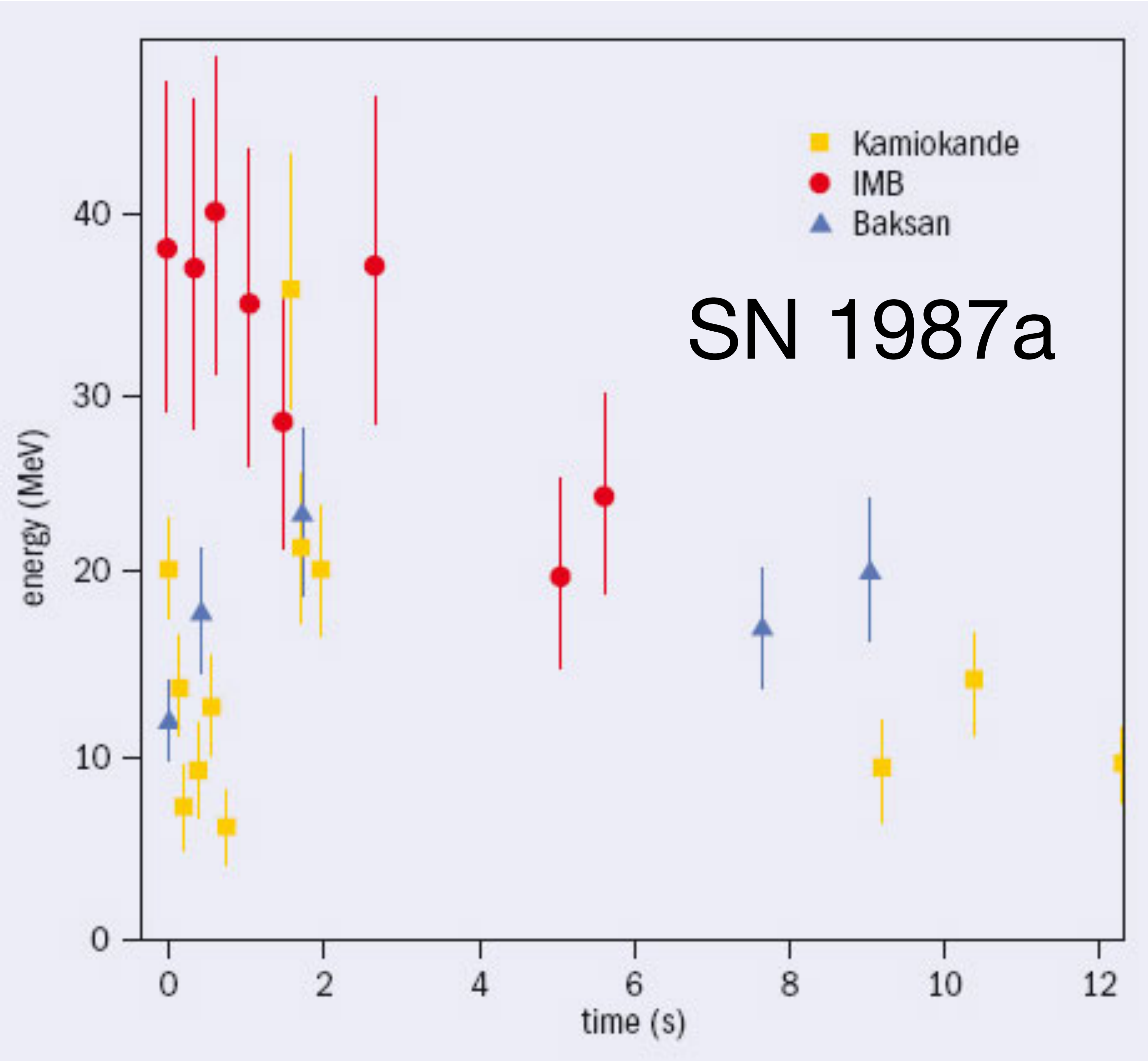
- Core-collapse SN is the violent explosion during death of massive stars.
- 99% energy of star ($\sim 10^{53}$ erg) is released in the form of neutrinos.

Excellent source due to high flux and low background (applying temporal cut ~ 10 s).

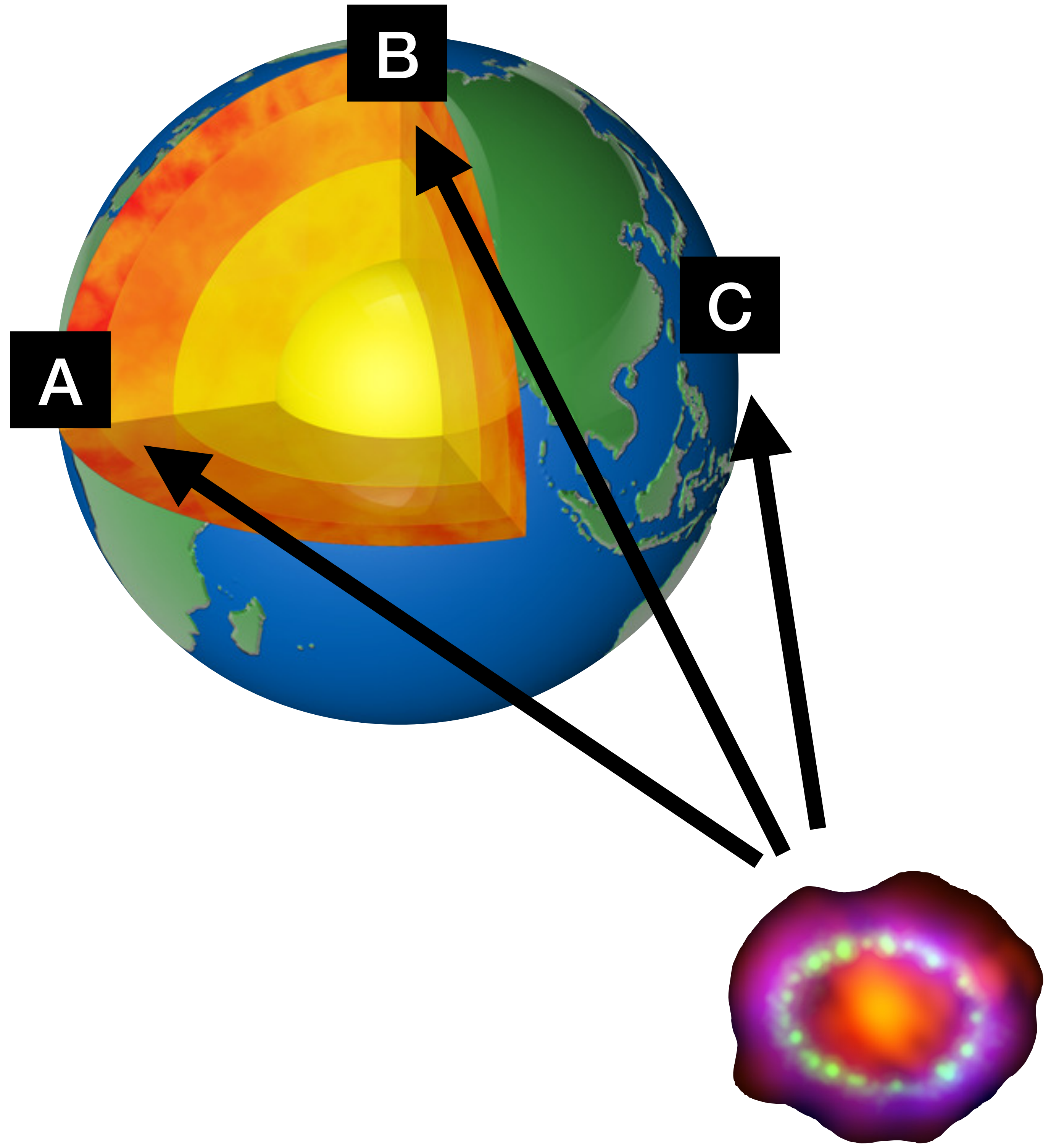
Supernova neutrinos

Main drawbacks

Uncertainty on fluxes



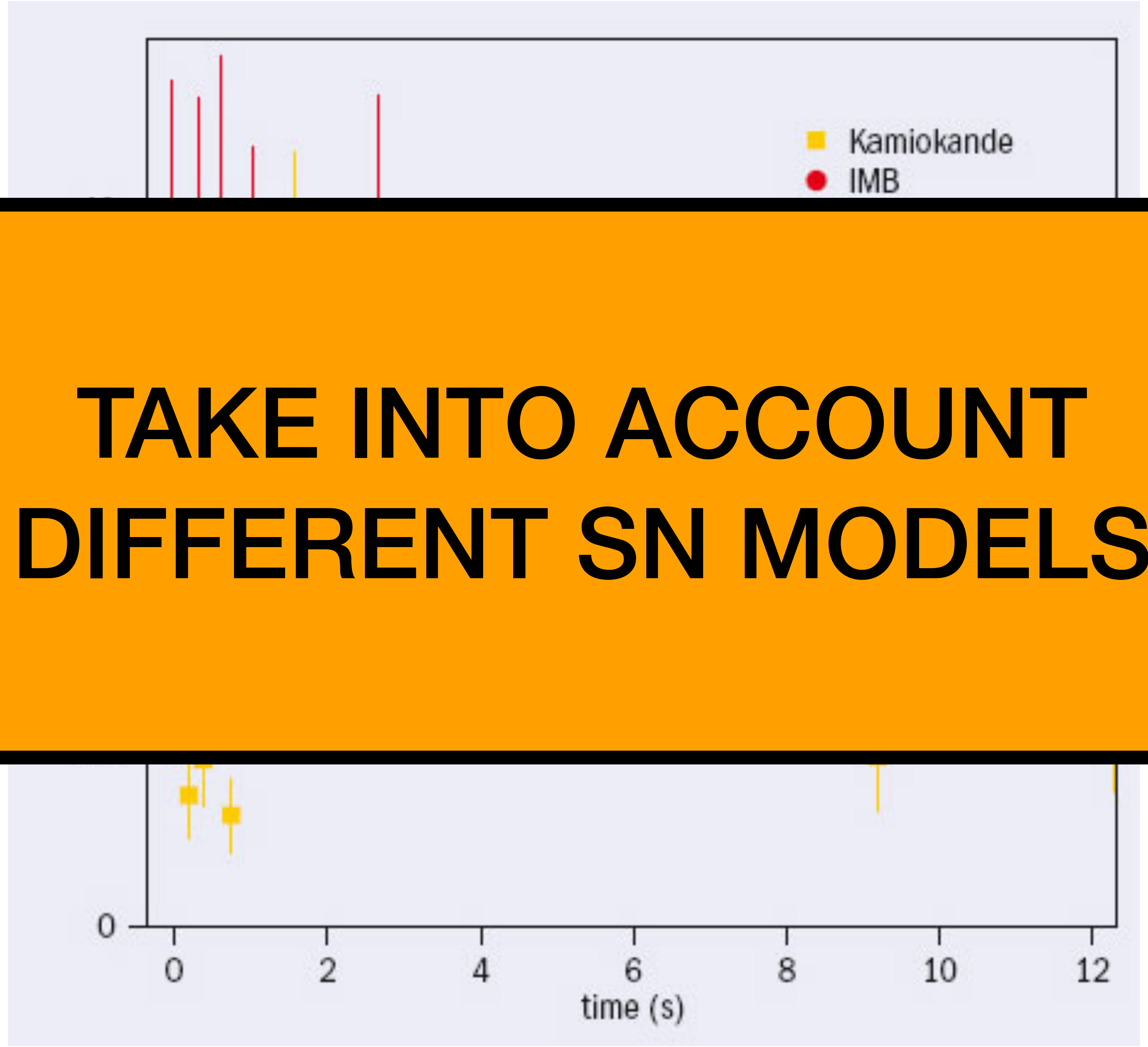
One direction per detector



Supernova neutrinos

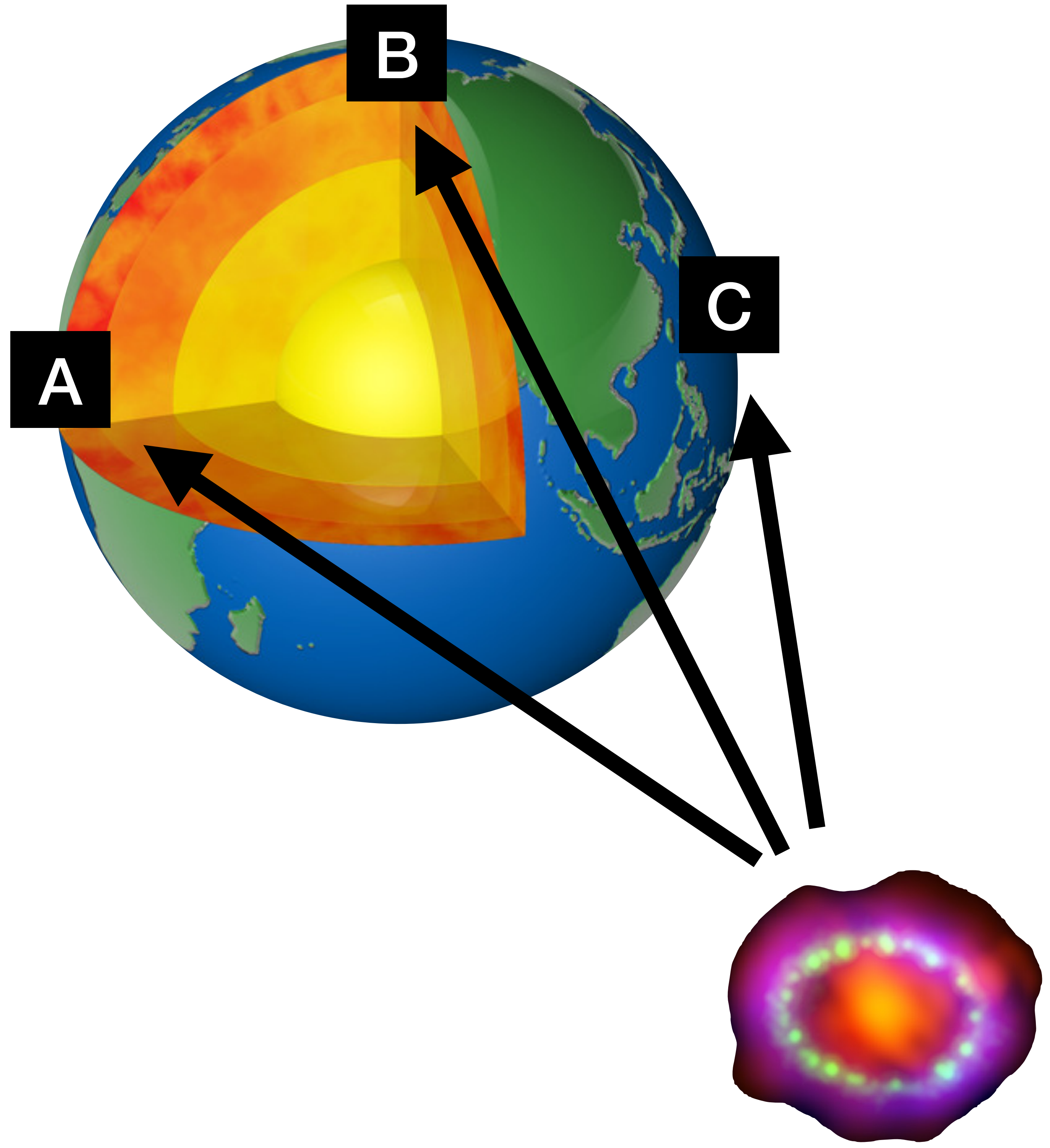
Main drawbacks

Uncertainty on fluxes



TAKE INTO ACCOUNT
DIFFERENT SN MODELS

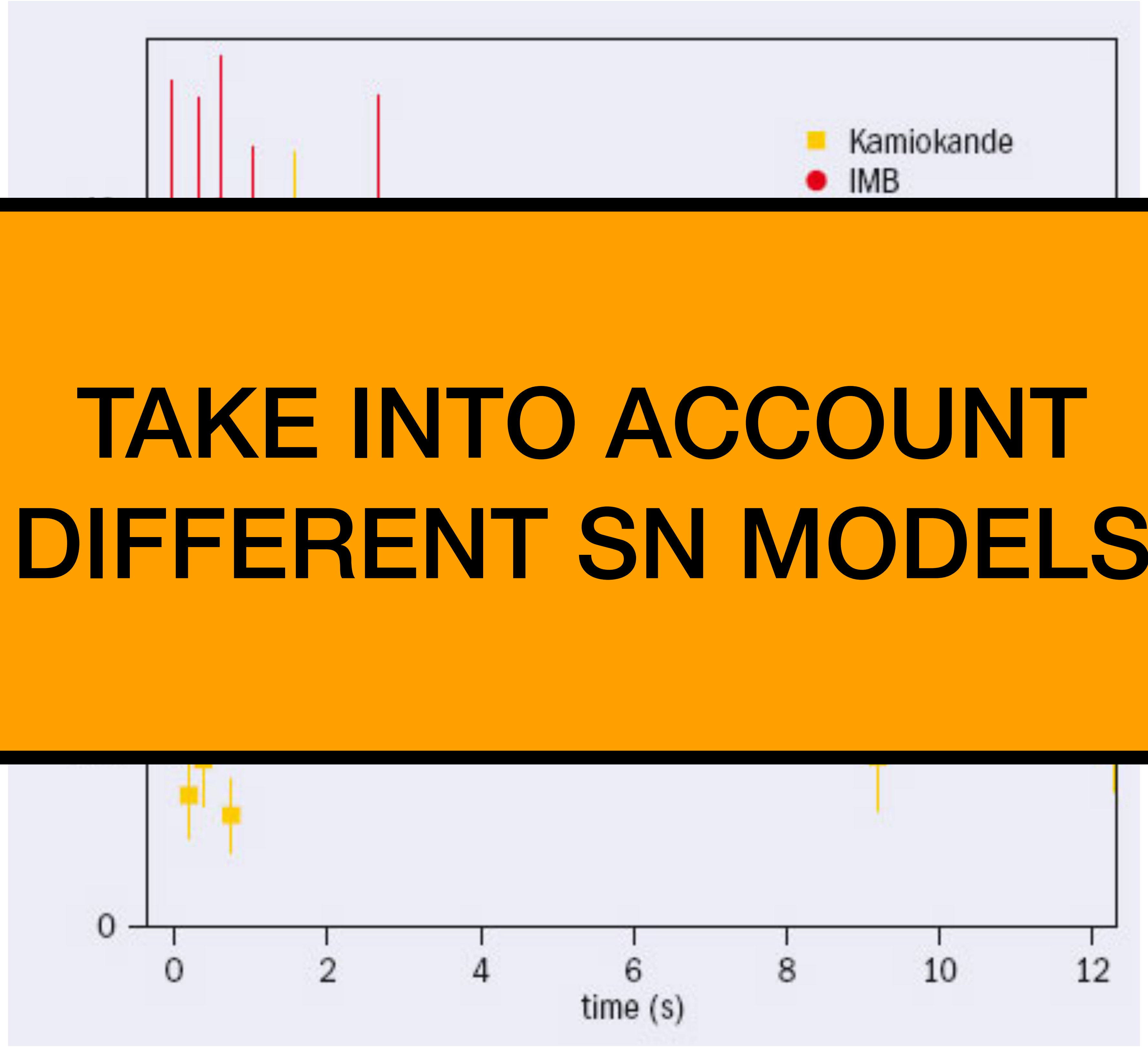
One direction per detector



Supernova neutrinos

Main drawbacks

Uncertainty on fluxes



TAKE INTO ACCOUNT DIFFERENT SN MODELS

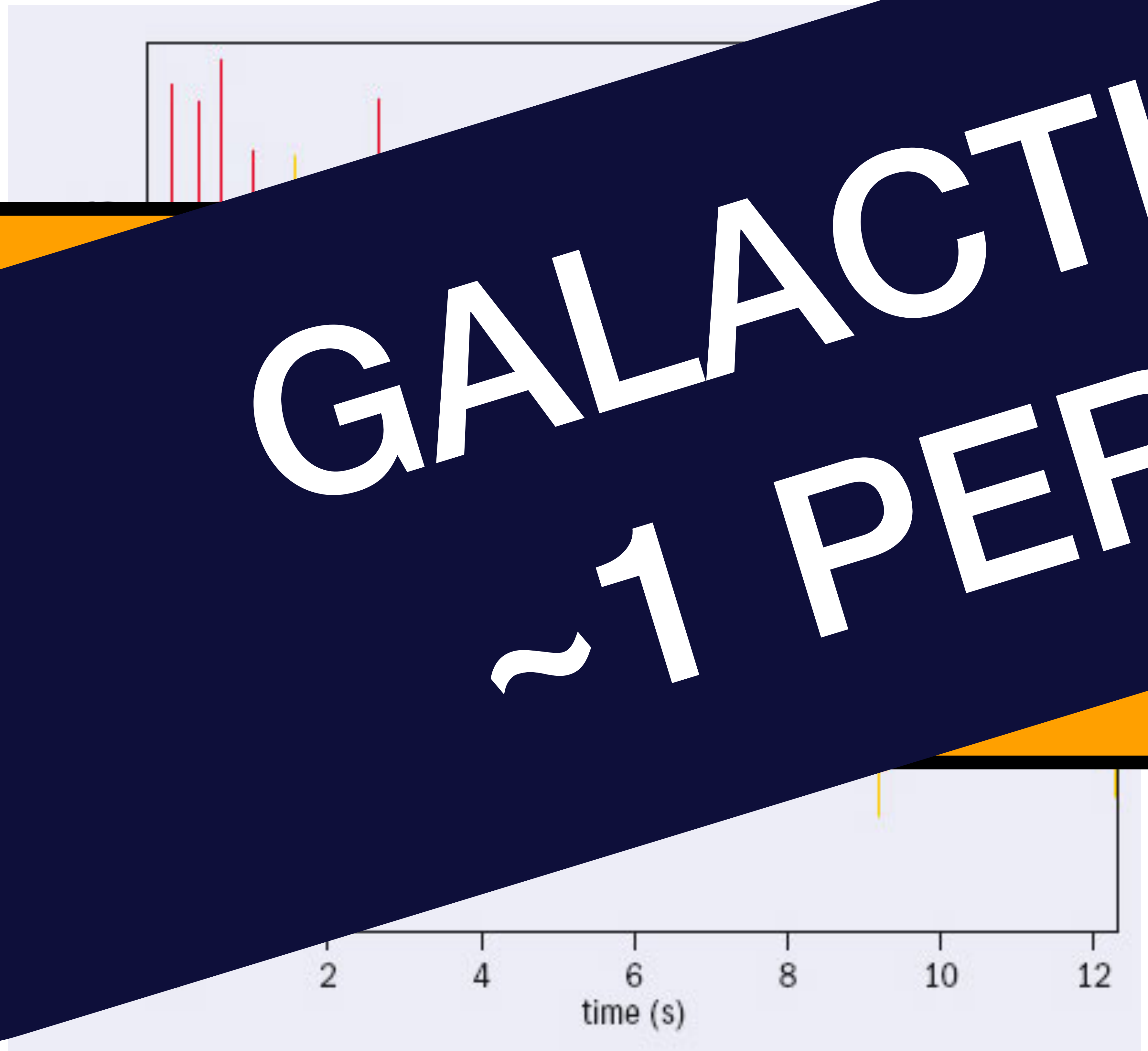
One direction per detector

TAKE INTO ACCOUNT DIFFERENT INCIDENT DIRECTIONS

Supernova neutrinos

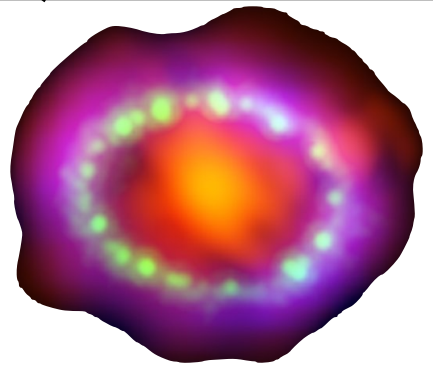
Main drawbacks

Uncertainty on fluxes



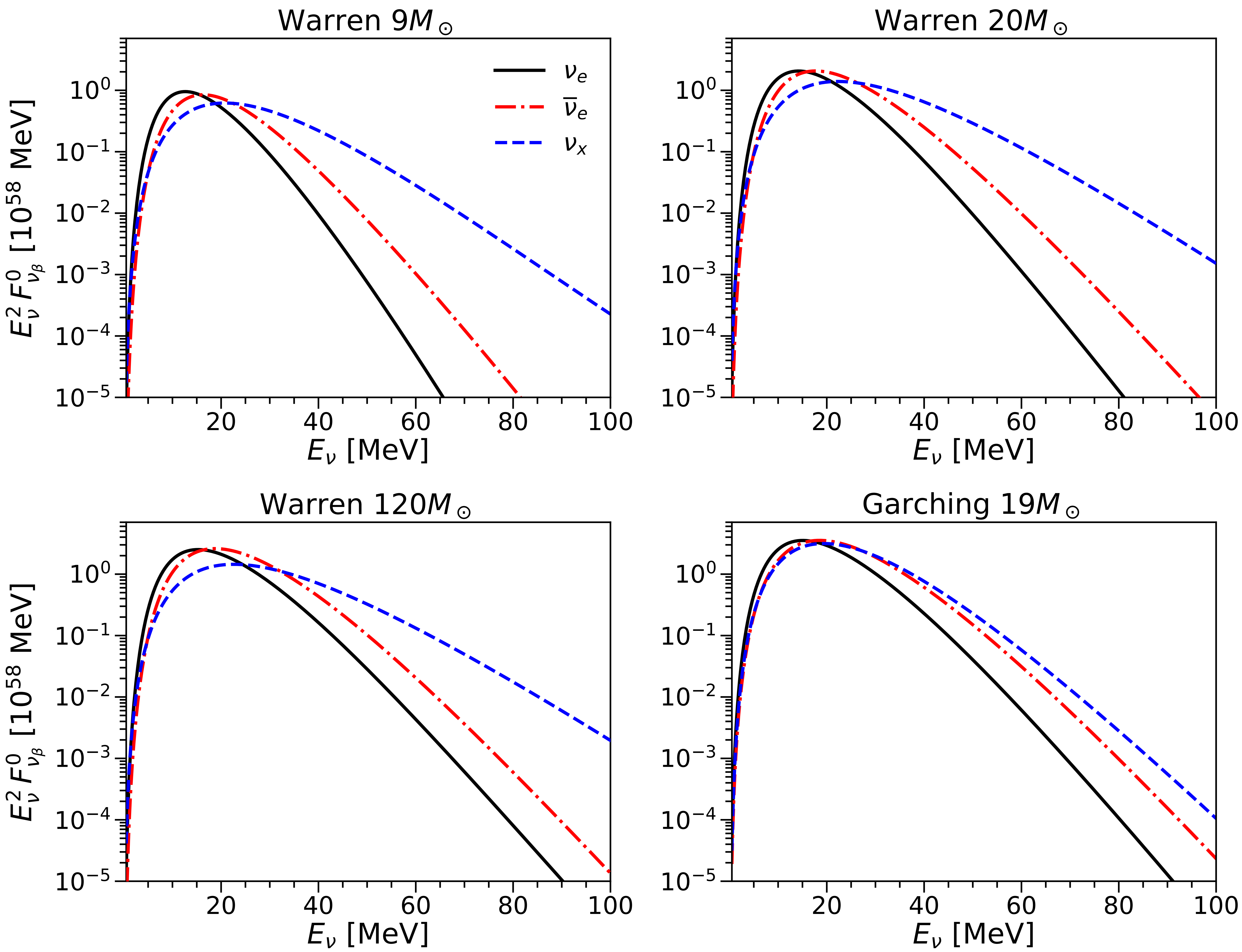
GALACTIC SN RATE:
~1 PER CENTURY

CCOUNT
ERENT INCIDENT
DIRECTIONS



Supernova neutrinos

- Initial fluxes from different simulations and masses:
  - **Garching**: R.Bollig et. al. Astrophys.J. 915 (2021) 1, 28
  - **Warren**: M.L. Warren et. al. Astrophys.J. 898 (2020) 2, 139



Supernova neutrinos

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

NO

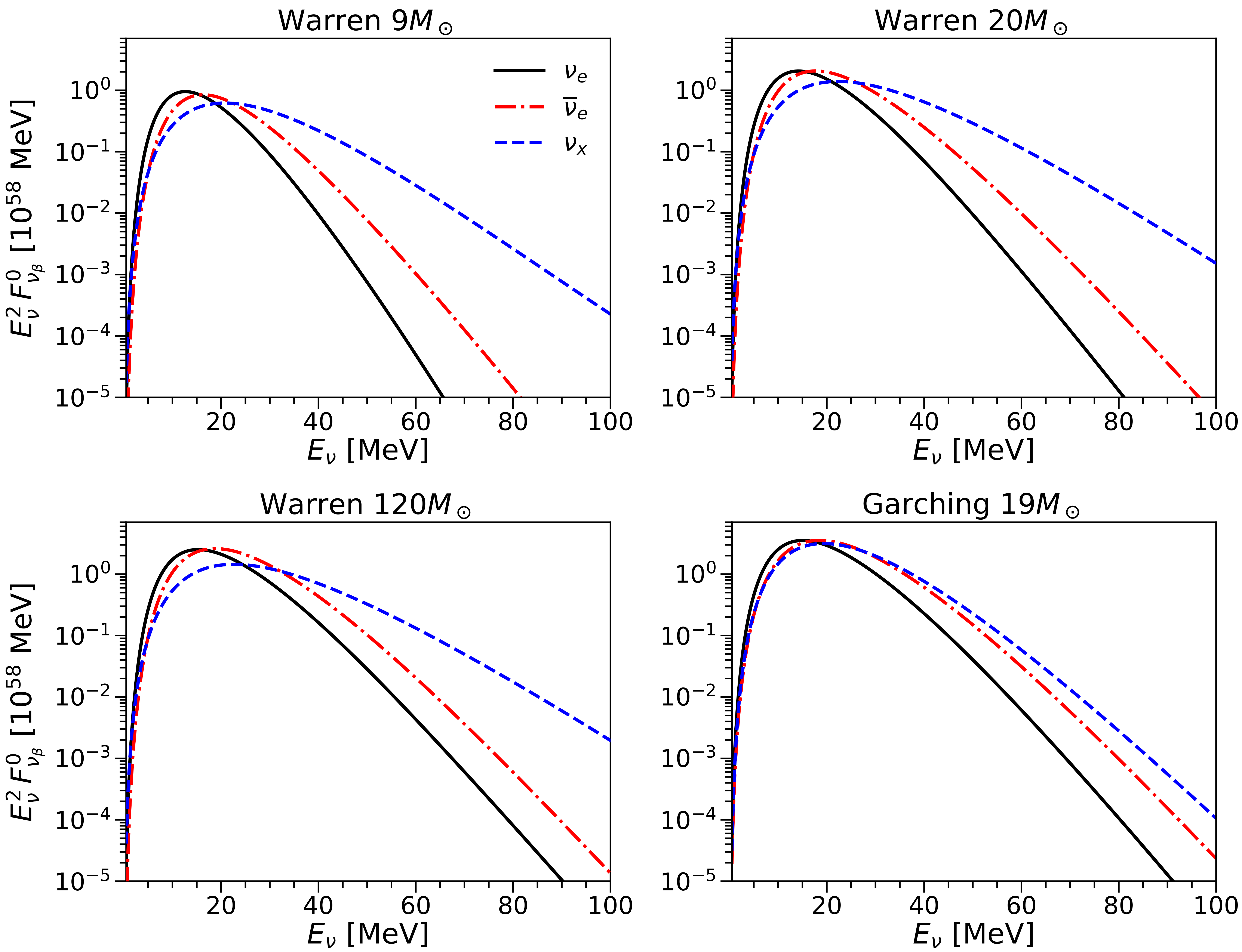
$$F^0_{\nu_3} = F^0_{\nu_e}$$

$$F^0_{\bar{\nu}_1} = F^0_{\bar{\nu}_e}$$

IO

$$F^0_{\nu_2} = F^0_{\nu_e}$$

$$F^0_{\bar{\nu}_3} = F^0_{\bar{\nu}_e}$$

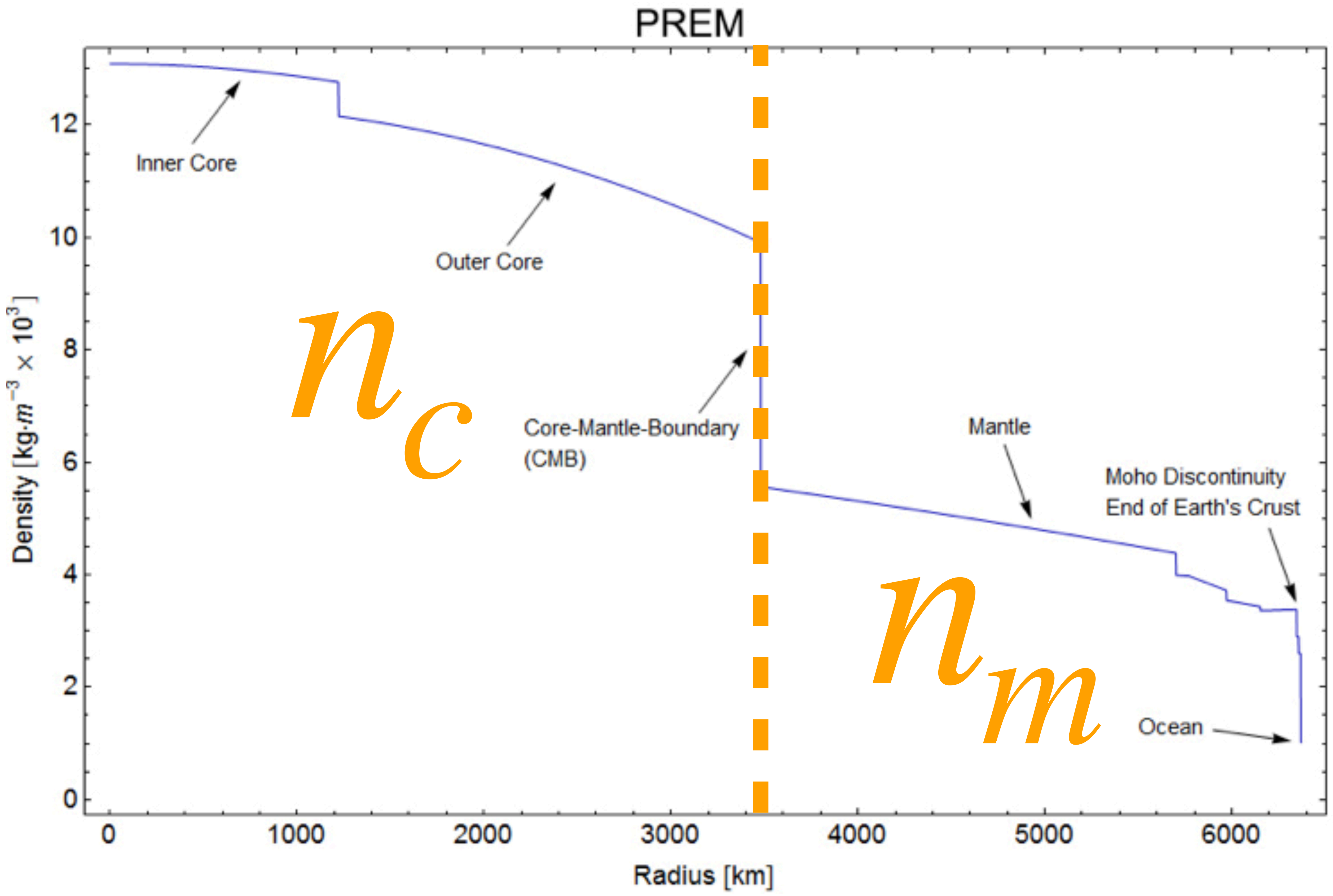


Earth matter effects

$$\rho_{\oplus}(n_c) = \begin{cases} n_c\, \rho^{\mathrm{PREM}}(r) \ , & 0 \le r \le R_c \ , \\ n_m\, \rho^{\mathrm{PREM}}(r) \ , & R_c < r \le R_{\oplus} \ , \end{cases}$$

2-layer profile:
PREM normalized

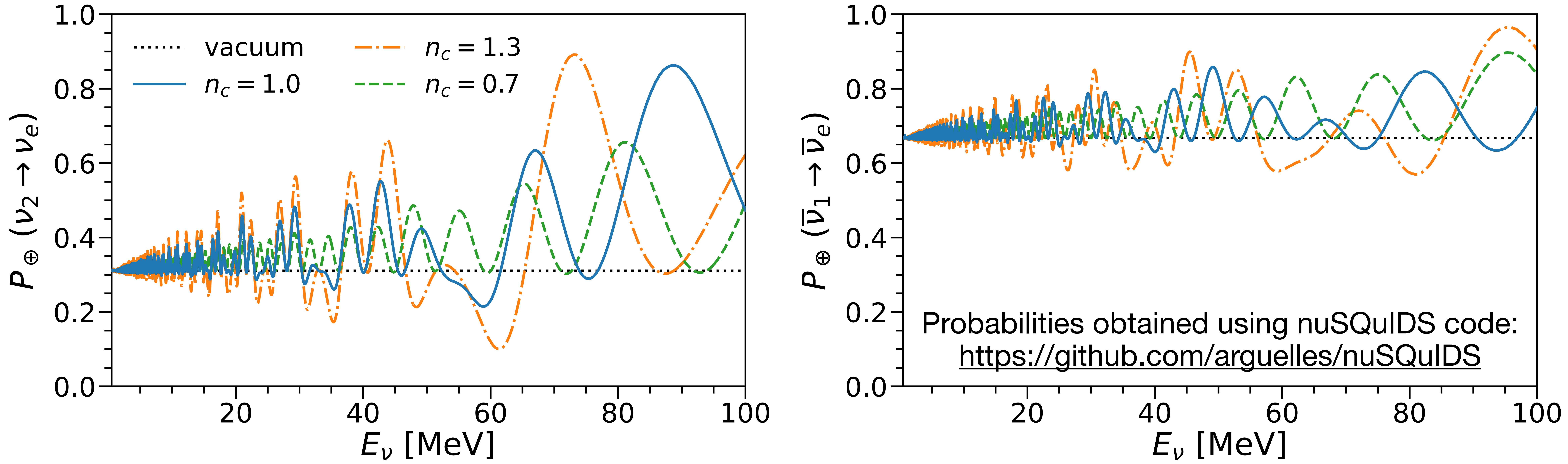
- PREM model with only one free parameter: core norm (n_c)
- We fix mantle norm (n_m) imposing we know the mass of the Earth
- Density also depends on the incident direction ($\cos\theta_z \equiv c_z$)



Earth matter effects

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

- We aim to be sensitive to these changes on the probabilities.
- Neutrinos have maximal matter effects at E ~ (40-100) MeV driven by the solar mass squared difference: $\Delta m^2_{21} = 7.5 \cdot 10^{-5}\ \mathrm{eV}^2$ (direction dependent).

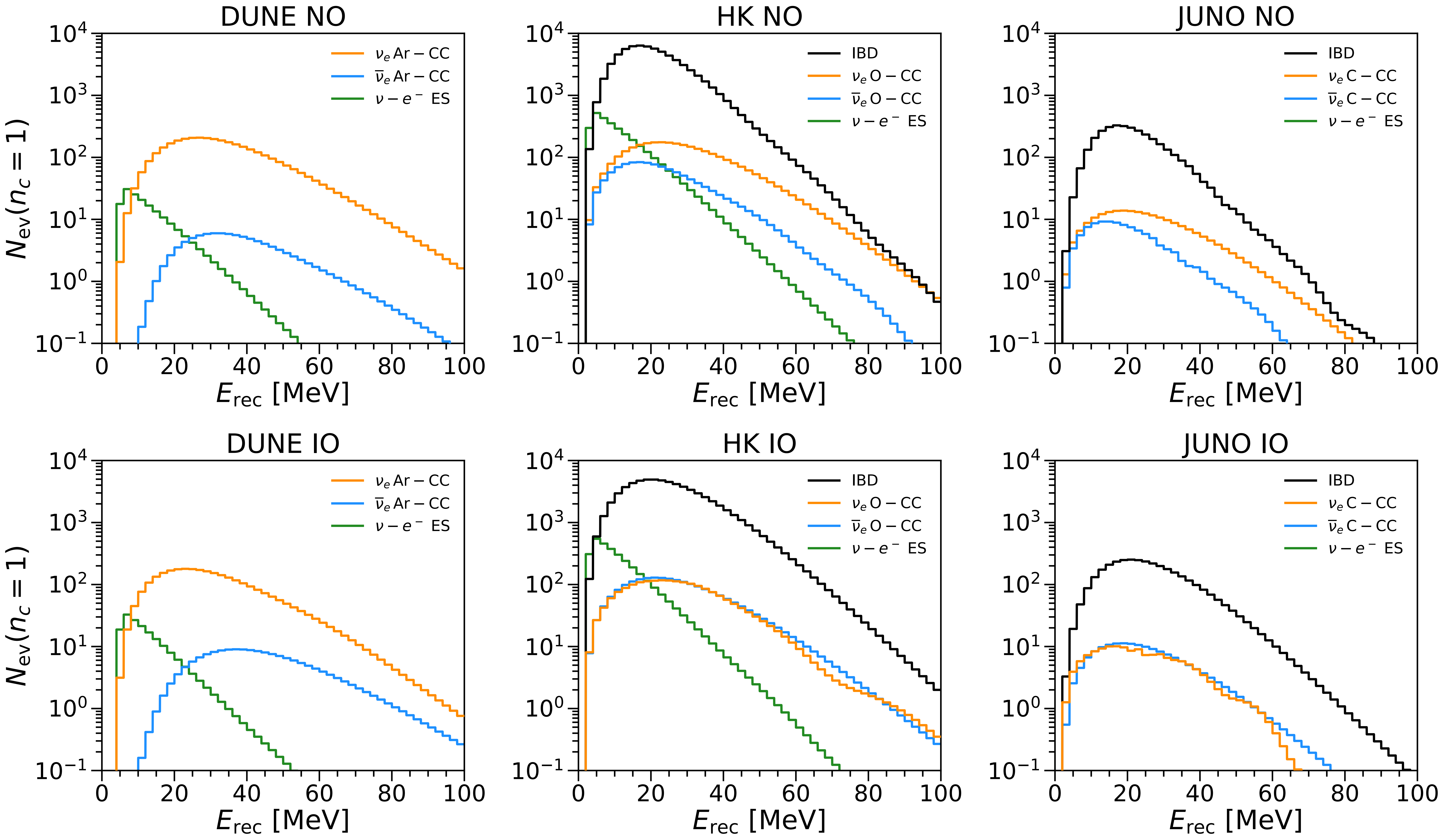


Future detection of Supernova neutrinos

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

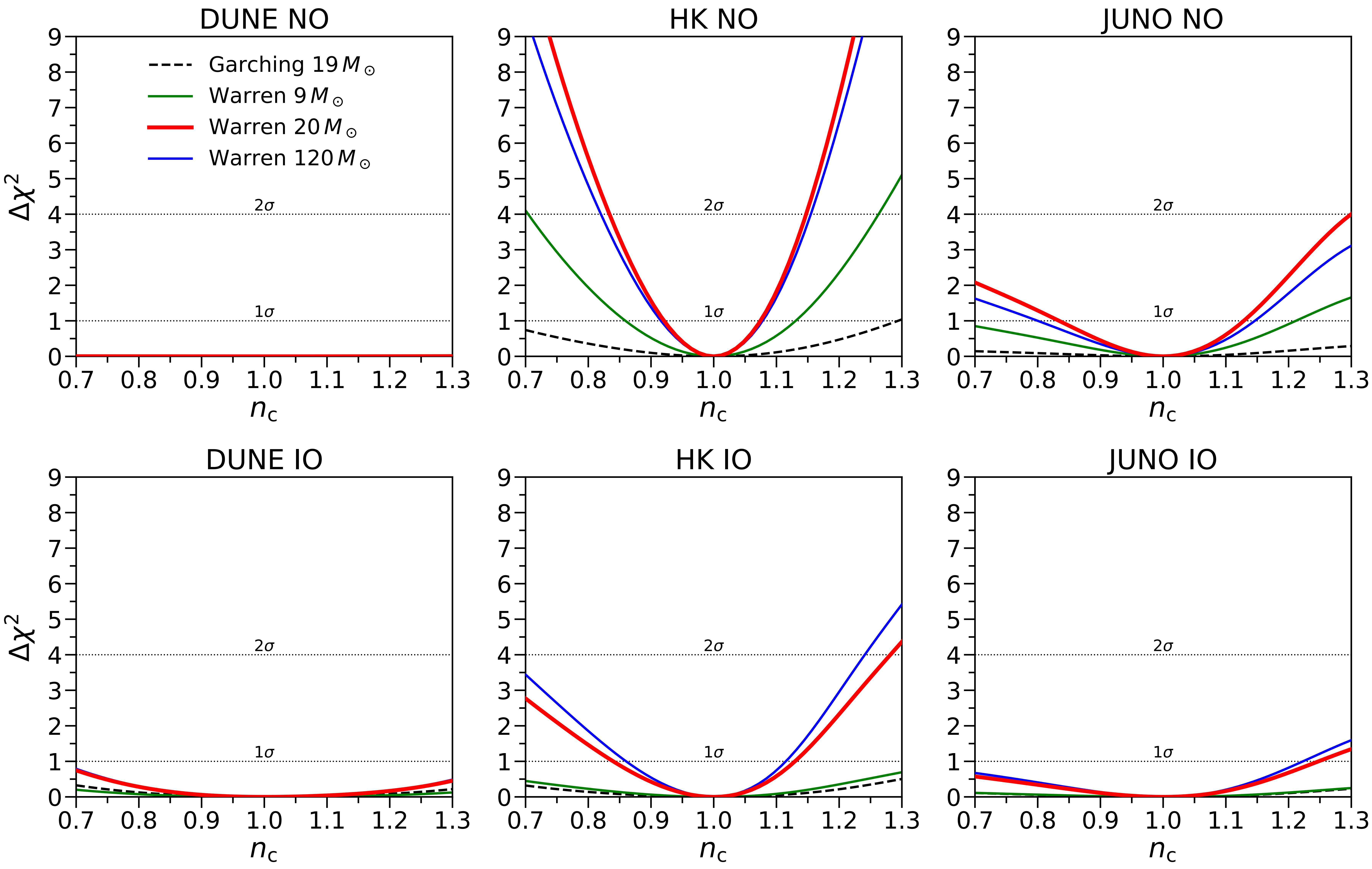
NO: effect in antineutrinos

IO: effect in neutrinos



Sensitivity to Earth density profile

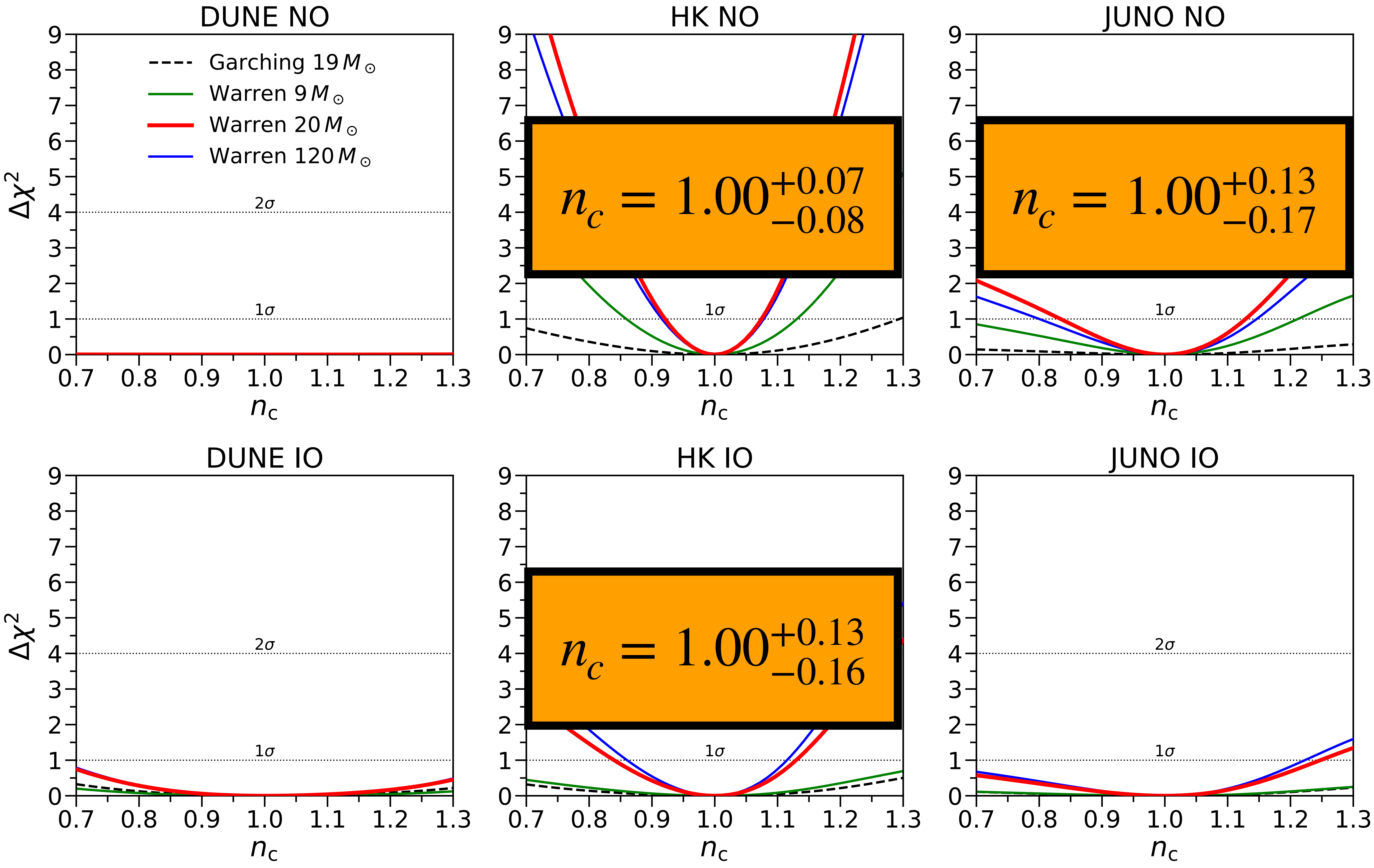
- Sensitivity for different models of SN neutrino burst.
- $c_z = -1$, $d_{SN} = 10$ kpc
- Very model dependent!
- HK will be the detector providing the best results.



Sensitivity to Earth density profile

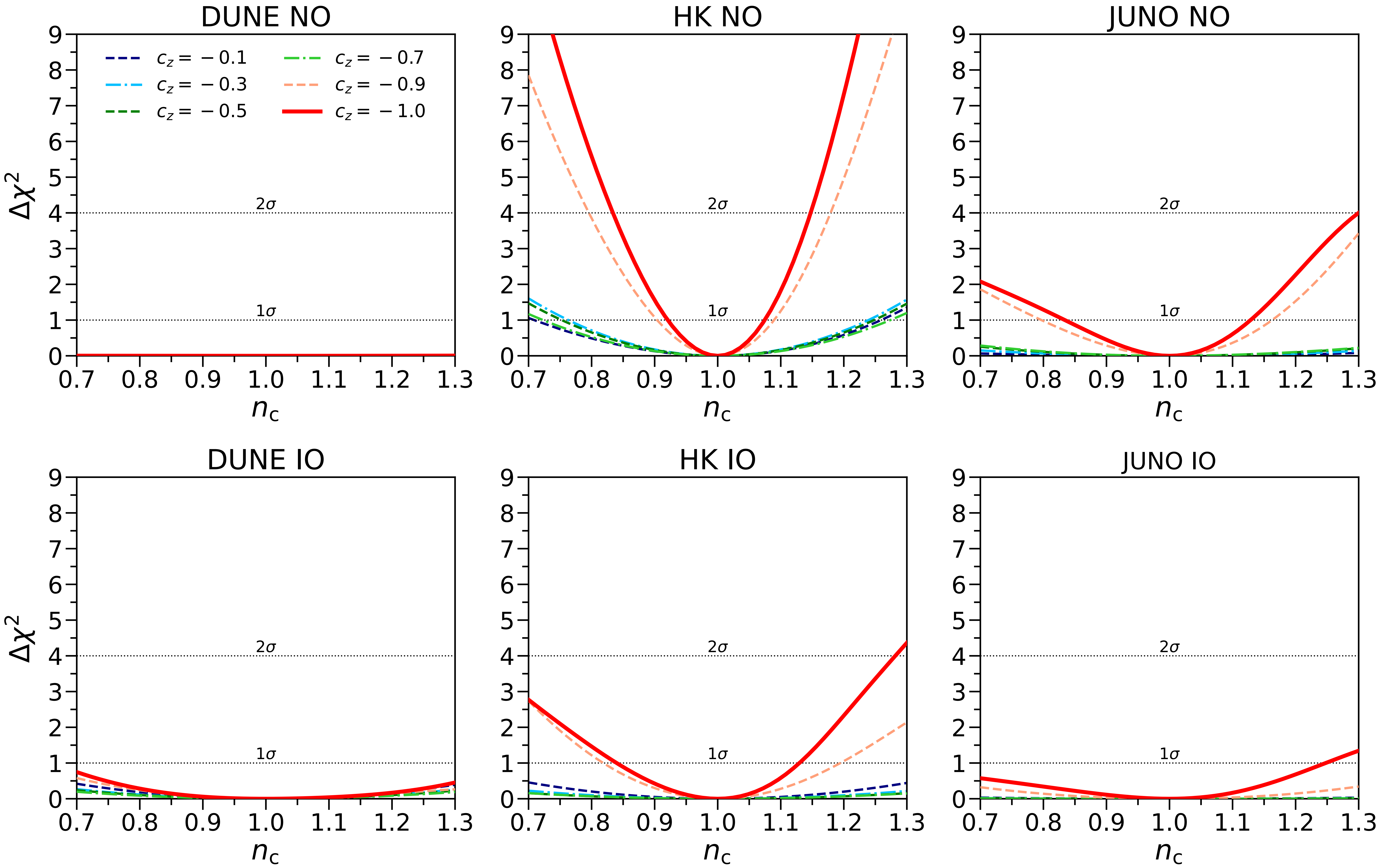
Warren $20M_\odot$

- Sensitivity for different models of SN neutrino burst.
- $c_z = -1$, $d_{SN} = 10$ kpc
- Very model dependent!
- HK will be the detector providing the best results.



Sensitivity to Earth density profile

- Effect of incident direction of the SN neutrinos
- Warren20, $d_{\mathrm{SN}} = 10$ kpc
- HK and JUNO NO: core trajectories.
- We need luck: SN neutrinos through core!



Conclusions

- We forecast an oscillation tomography of the Earth with SN neutrinos at future neutrino detectors DUNE, HK and JUNO.
- Assuming adiabatic transitions in the SN, Earth matter effects happen mainly in antineutrinos for NO and neutrinos in IO.
- We studied a different set of initial fluxes and incident directions.
- Most optimistic case: HK and JUNO could determine the average Earth's core density within $\lesssim 10\,\%$ at 1σ CL with galactic SN neutrinos (at 10 kpc).

A future SN burst could aid in future neutrino Earth tomography studies, and be competitive with, and complementary to other analyses.

Conclusions

- We forecast an oscillation tomography of the Earth with SN neutrinos at future neutrino detectors DUNE, HK and JUNO.
- Assuming adiabatic transitions in the SN, Earth matter effects happen mainly in antineutrinos for NO and neutrinos in IO.
- We studied a different set of initial fluxes and incident directions.
- Most optimistic case: HK and JUNO could determine the average Earth's core density within $\lesssim 10\,\%$ at 1σ CL with galactic SN neutrinos (at 10 kpc).

A future SN burst could aid in future neutrino Earth tomography studies, and be competitive with, and complementary to other analyses.

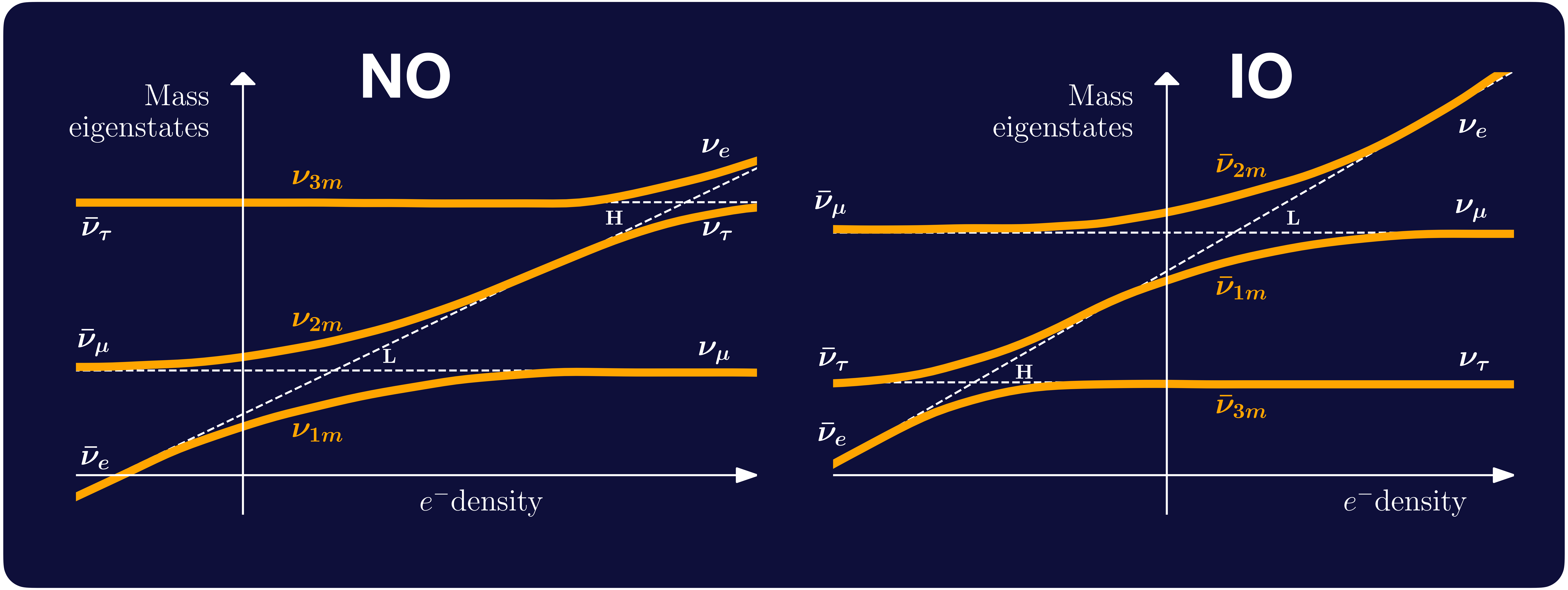
But we need luck!

Earth tomography with supernova neutrinos at future neutrino detectors

BACKUP SLIDES

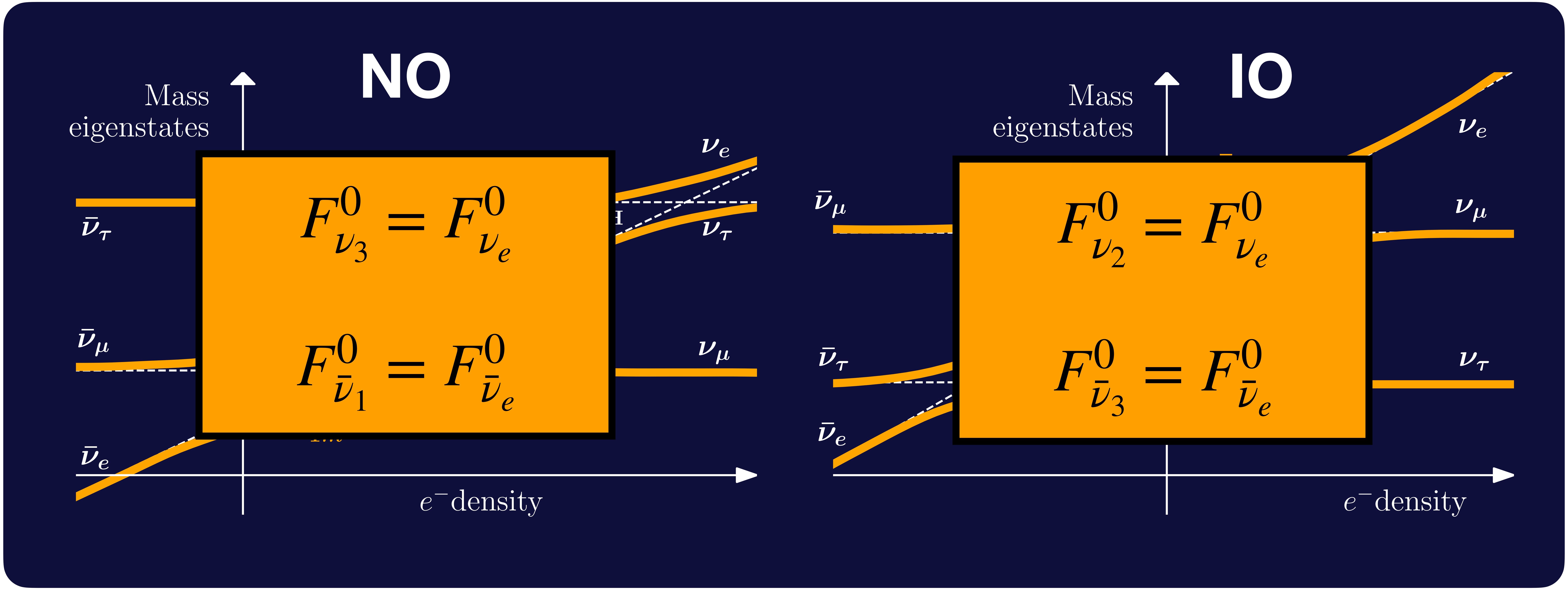
Supernova neutrinos

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



Supernova neutrinos

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



$$F^0_{\nu_3} = F^0_{\nu_e}$$

$$F^0_{\bar{\nu}_1} = F^0_{\bar{\nu}_e}$$

$$F^0_{\nu_2} = F^0_{\nu_e}$$

$$F^0_{\bar{\nu}_3} = F^0_{\bar{\nu}_e}$$

Earth matter effects

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

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

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

If $F^0_{\nu_e} = F^0_{\nu_x}$ we are not sensitive to the matter effects!

p and $\overline{p}$ are the probability of transition from an initial mass state that depends on the neutrino mass ordering (SN emission) to a final flavor state that depends on the detection channel

Earth matter effects

- 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:

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

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

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

PMNS matrix

Earth matter effects

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

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

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

Vacuum probabilities

$$p^{\mathrm{NO}}_{\mathrm{vac}} \equiv P_{\mathrm{vac}}(\nu_3 \to \nu_e) = |U_{e3}|^2 = \sin^2\theta_{13}$$
$$\bar p^{\mathrm{NO}}_{\mathrm{vac}} \equiv P_{\mathrm{vac}}(\bar\nu_1 \to \bar\nu_e) = |U_{e1}|^2 = \cos^2\theta_{12}\, \cos^2\theta_{13}$$
$$p^{\mathrm{IO}}_{\mathrm{vac}} \equiv P_{\mathrm{vac}}(\nu_2 \to \nu_e) = |U_{e2}|^2 = \sin^2\theta_{12} \cos^2\theta_{13}$$
$$\bar p^{\mathrm{IO}}_{\mathrm{vac}} \equiv P_{\mathrm{vac}}(\bar\nu_3 \to \bar\nu_e) = |U_{e3}|^2 = \sin^2\theta_{13} \quad .$$

$V \neq 0$ →

Constant density probabilities

$$p^{\mathrm{NO}}_{\oplus} \equiv P_{\oplus}(\nu_3 \to \nu_e) \simeq \sin^2\theta_{13}$$ ✗
$$\bar p^{\mathrm{NO}}_{\oplus} \equiv P_{\oplus}(\bar\nu_1 \to \bar\nu_e) \simeq \cos^2\theta_{13}\, (1 - \bar P^{2\nu}_{\oplus})$$
$$p^{\mathrm{IO}}_{\oplus} \equiv P_{\oplus}(\nu_2 \to \nu_e) \simeq \cos^2\theta_{13}\, P^{2\nu}_{\oplus}$$
$$\bar p^{\mathrm{IO}}_{\oplus} \equiv P_{\oplus}(\bar\nu_3 \to \bar\nu_e) \simeq \sin^2\theta_{13}$$ ✗

Future detection of Supernova neutrinos

$$\frac{dR\left(E_{\rm rec}\right)}{dE_{\rm rec}} = N_t \int dE_{\rm true}\, dE_\nu\, \varepsilon(E_{\rm true})\, \underline{\mathscr{R}\left(E_{\rm true}, E_{\rm rec}\right)}\, \frac{d\Phi_\nu^{\rm D}(E_\nu)}{dE_\nu}\, \frac{d\sigma(E_\nu, E_e)}{dE_e}$$

$$\mathscr{R}\left(E_{\rm true}, E_{\rm rec}\right) = \frac{1}{\sqrt{2\pi}\,\sigma_{\rm det}} \exp\left(-\frac{\left(E_{\rm true} - E_{\rm rec}\right)^2}{2\,\sigma_{\rm det}^2}\right)$$

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

Sensitivity to Earth density profile

- Binned poissonian χ^2 distribution with 1 degree of freedom (n_c):

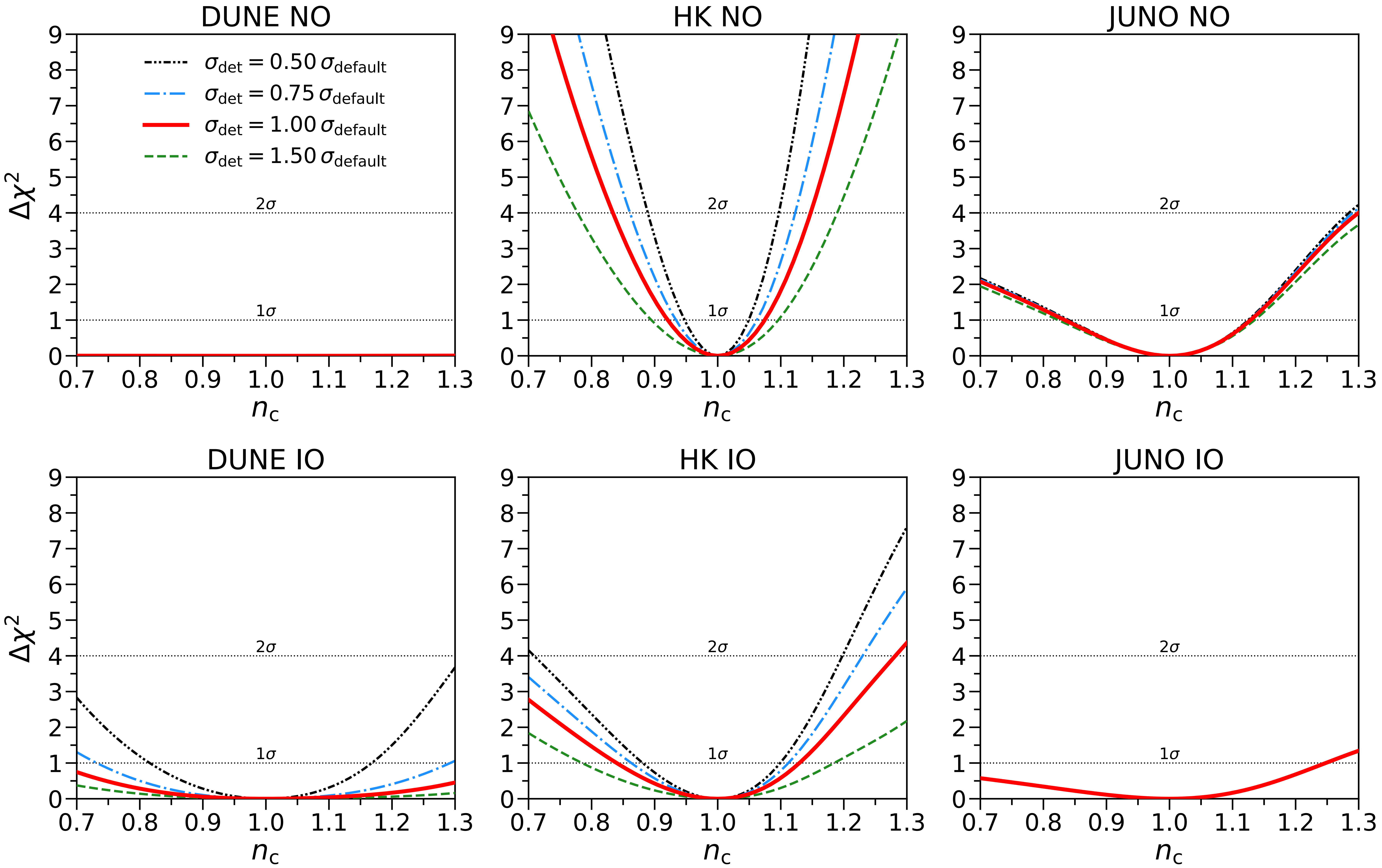
$$\Delta\chi^2(n_c\,;c_z) = 2\sum_{i,s}\left[N_{i,s}(n_c\,;c_z) - N_{i,s}(n_c=1\,;c_z) + N_{i,s}(n_c=1\,;c_z)\,\ln\left(\frac{N_{i,s}(n_c=1\,;c_z)}{N_{i,s}(n_c\,;c_z)}\right)\right]$$

- Detection channels of each detector (different topologies):

DUNE (LIQUID ARGON)	**HK** (WATER CHERENKOV)	**JUNO** (LIQUID SCINTILLATOR)
$\nu_e\mathrm{Ar}-\mathrm{CC}+\bar{\nu}_e\mathrm{Ar}-\mathrm{CC}$ $\nu-e^-\mathrm{ES}$	$0.9\,\mathrm{IBD}$ $0.1\,\mathrm{IBD}+\nu_e\mathrm{O}-\mathrm{CC}+$ $+\bar{\nu}_e\mathrm{O}-\mathrm{CC}+\nu-e^-\mathrm{ES}$	$0.95\,\mathrm{IBD}$ $0.05\,\mathrm{IBD}+\nu_e\mathrm{O}-\mathrm{CC}+$ $+\bar{\nu}_e\mathrm{O}-\mathrm{CC}+\nu-e^-\mathrm{ES}$

Sensitivity to Earth density profile

- Effect of energy resolution of detectors
- Warren20, $c_z = -1$, $d_{SN} = 10$ kpc
- JUNO has a superb resolution.
- DUNE and HK have huge improvements.



Sensitivity to Earth density profile

- Effect of solar mass splitting
- Warren20, $d_{SN} = 10$ kpc
- Optimistic result in Lindner et. al. Astropart. Phys. 19, 755 (2003) with

$$\Delta m_{21}^2 = 5 \cdot 10^{-5} \, eV^2$$