Constraining sterile neutrinos by CCSN at multiple detectors

Jian Tang (唐健)

tangjian5@mail.sysu.edu.cn

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Based on the wok in collaboration with Tse-Chun Wang, and Meng-Ru Wu

arXiv: 2005.09168, *JCAP 10 (2020) 038*

Happy new year of the ox!

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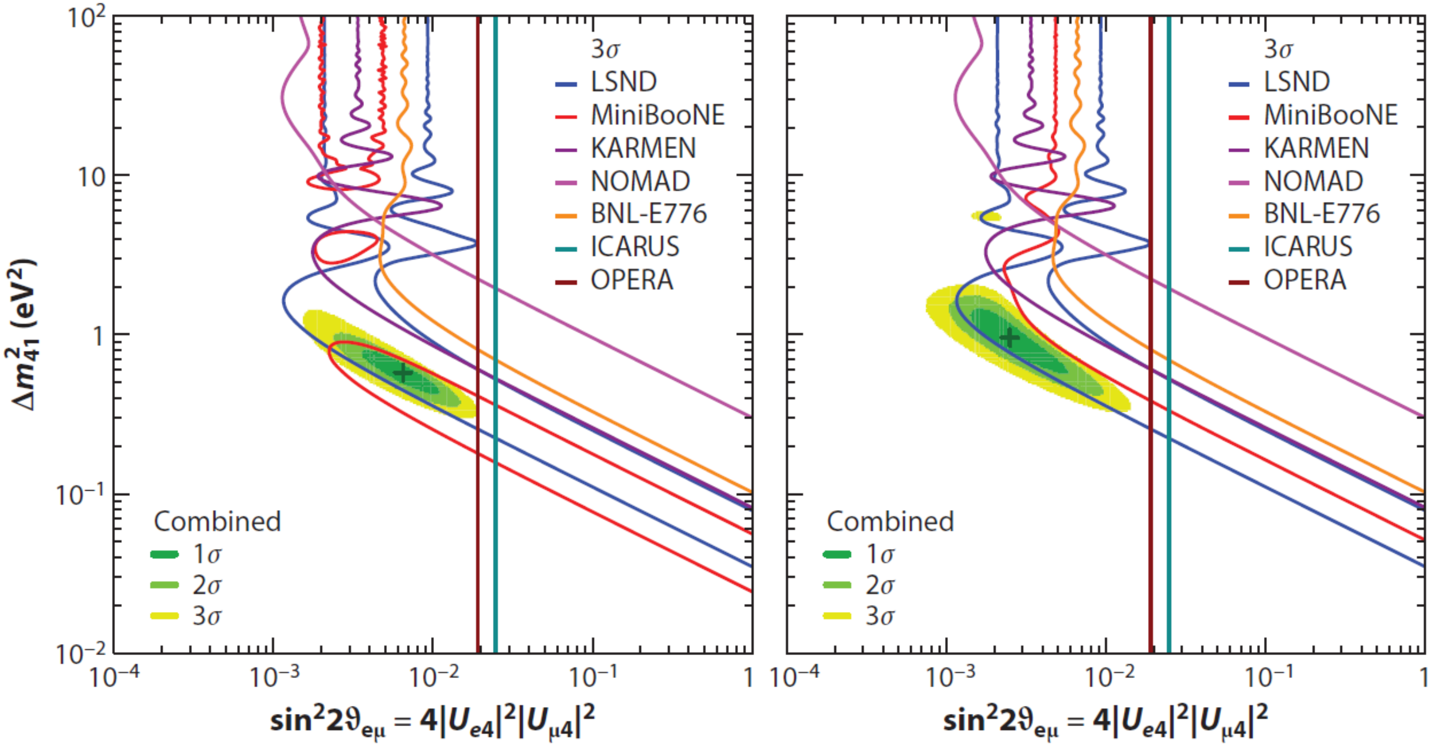
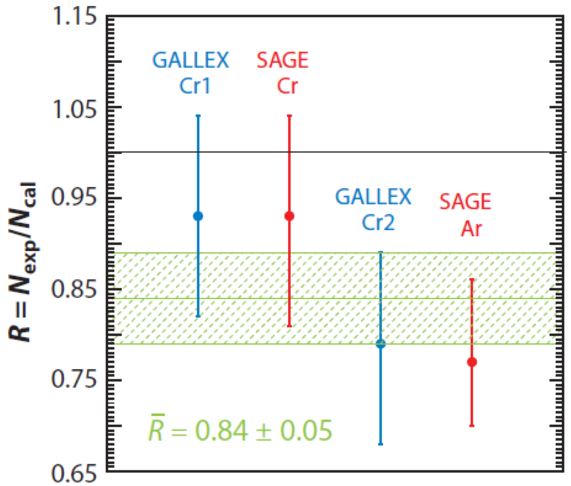
Sterile neutrinos to explain LSND anomaly

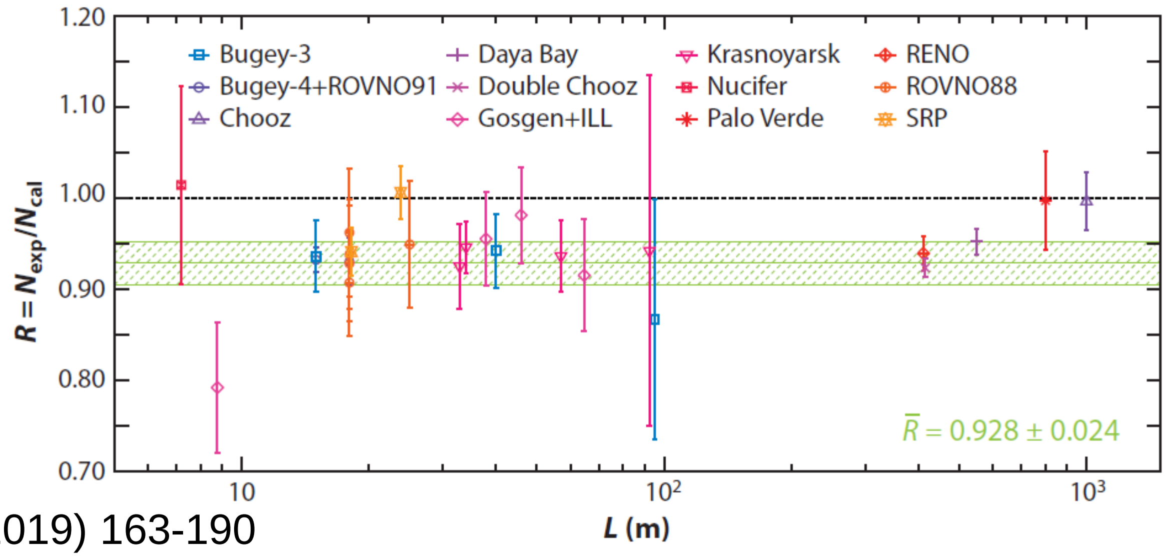


Ann.Rev.Nucl.Part.Sci. 69 (2019) 163-190

- LSND observed excess of $\bar{\nu}_\mu \to \bar{\nu}_e$
- MiniBooNE kept the anomaly unresolved but not compatible with other experiments.
- An extra sterile neutrino reconcile the tensions?

Sterile neutrinos to explain reactor anomalies





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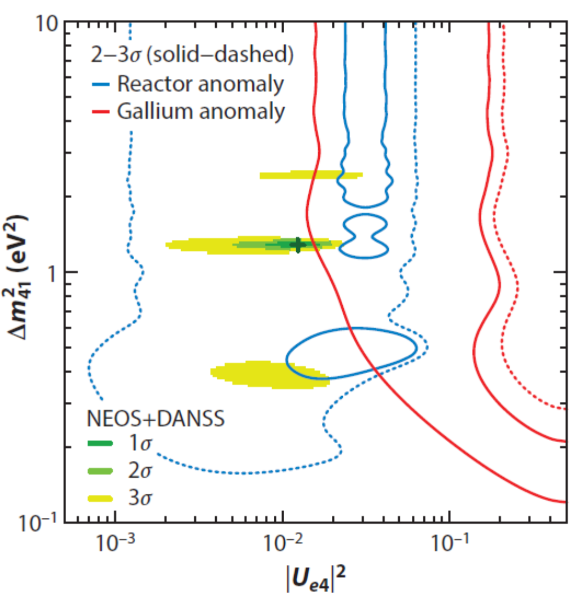
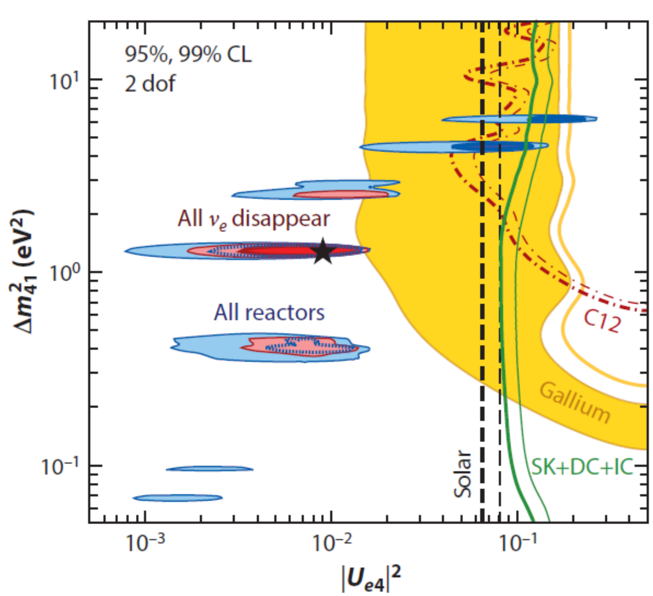
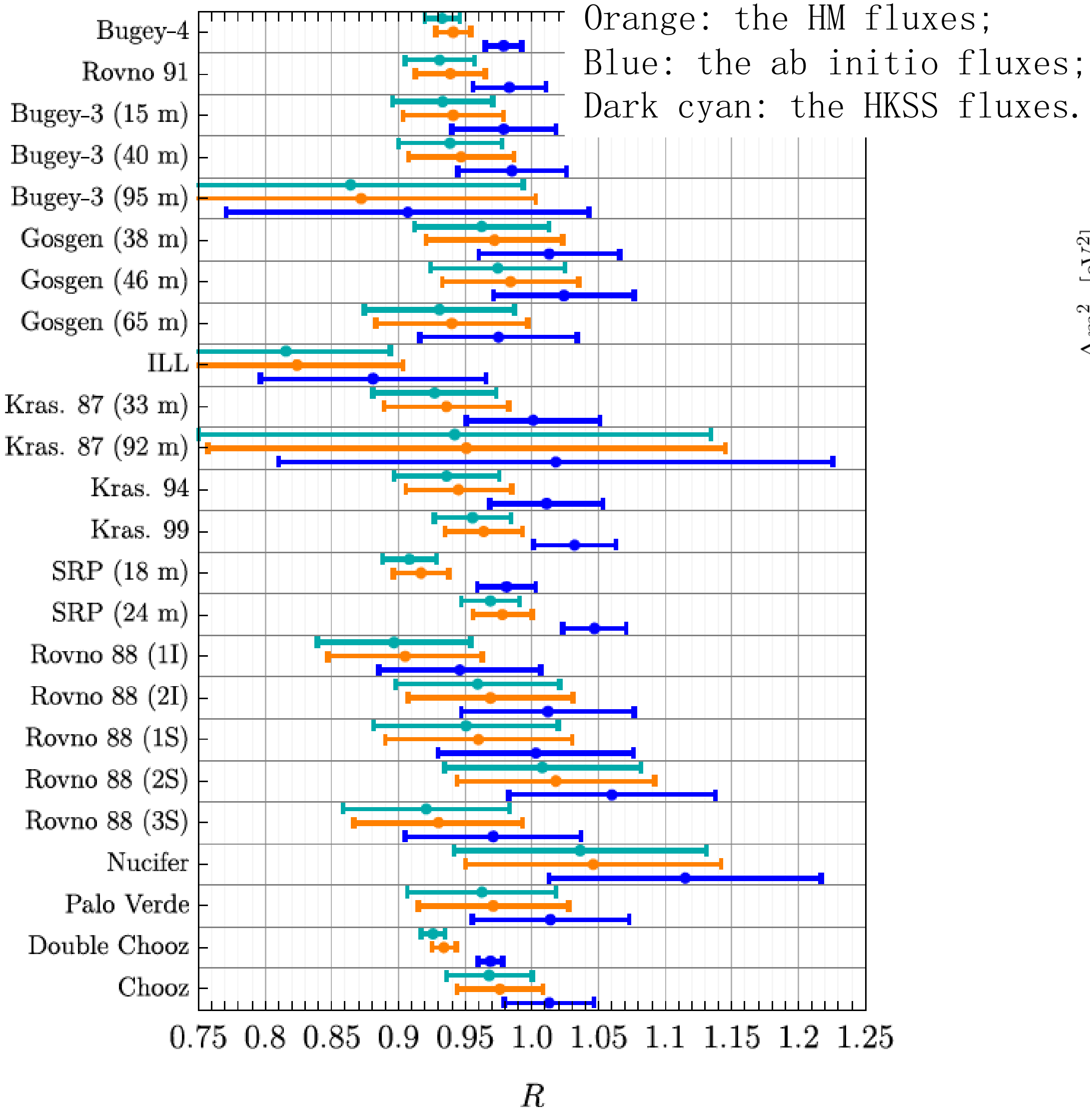
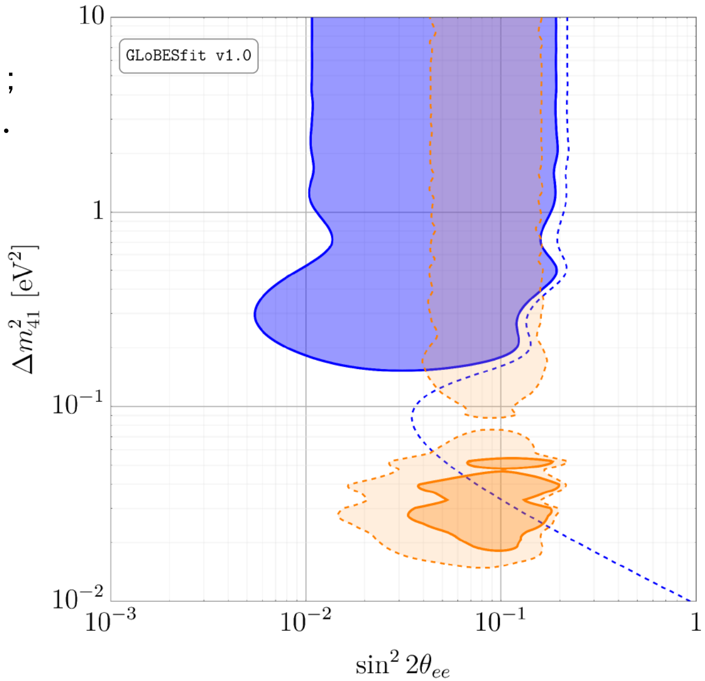




- Rate excess of ~6% in model compared to previous short-baseline measurements.
- Discrepancy confirmed by Double Chooz, Daya Bay and RENO near detectors.
- An extra sterile neutrino reconcile the tensions?

Sterile neutrinos to explain reactor anomalies





GLoBESfit, arXiv: 2005.01756 P. Huber and Jeffrey Berryman

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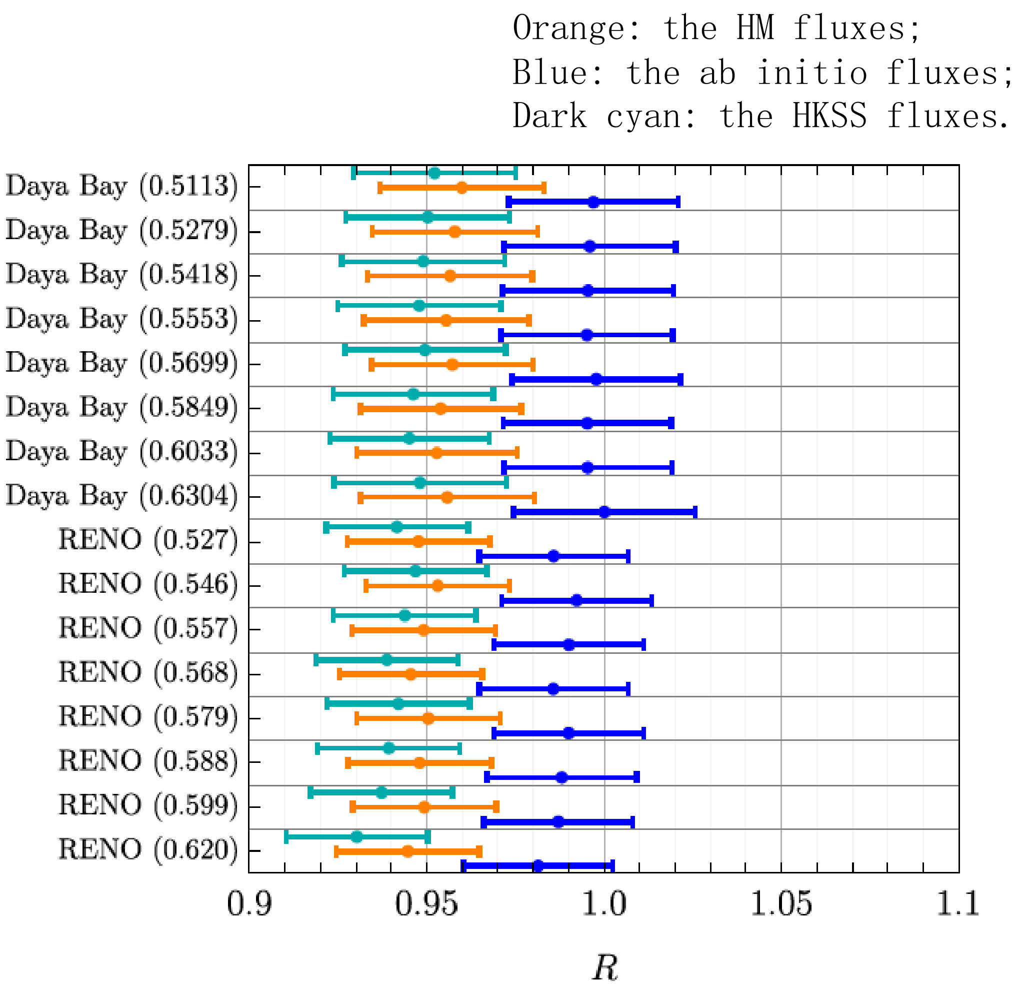
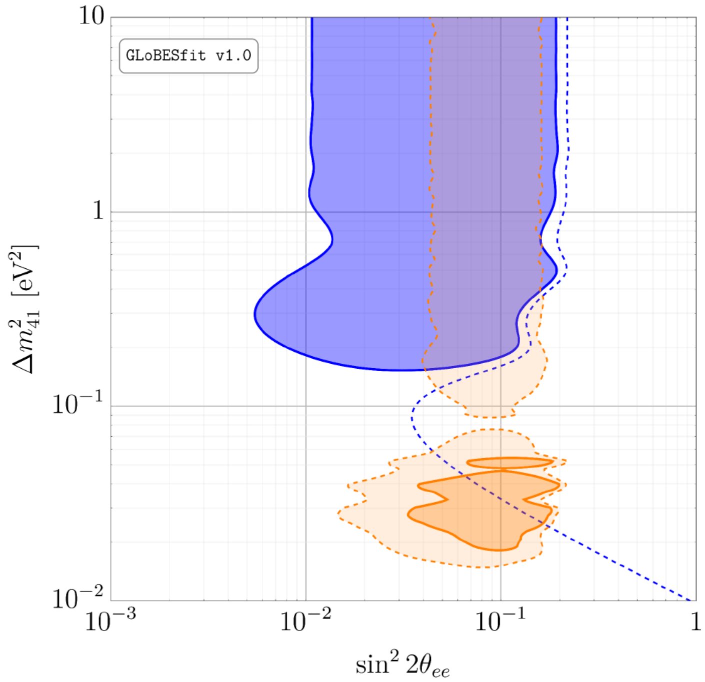
Sterile neutrinos to explain reactor anomalies



Different U-235 fission fractions in nuclear fuel.



- Rate excess of ~6% in model compared to previous short-baseline measurements.
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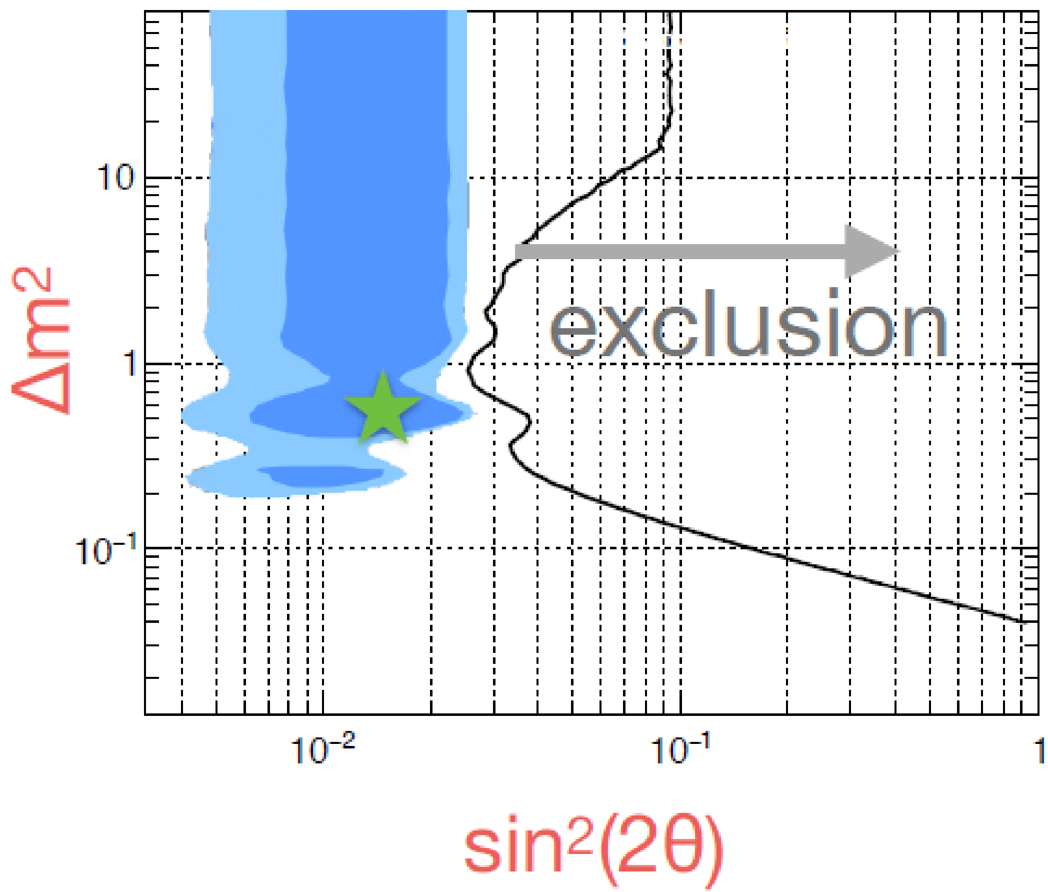
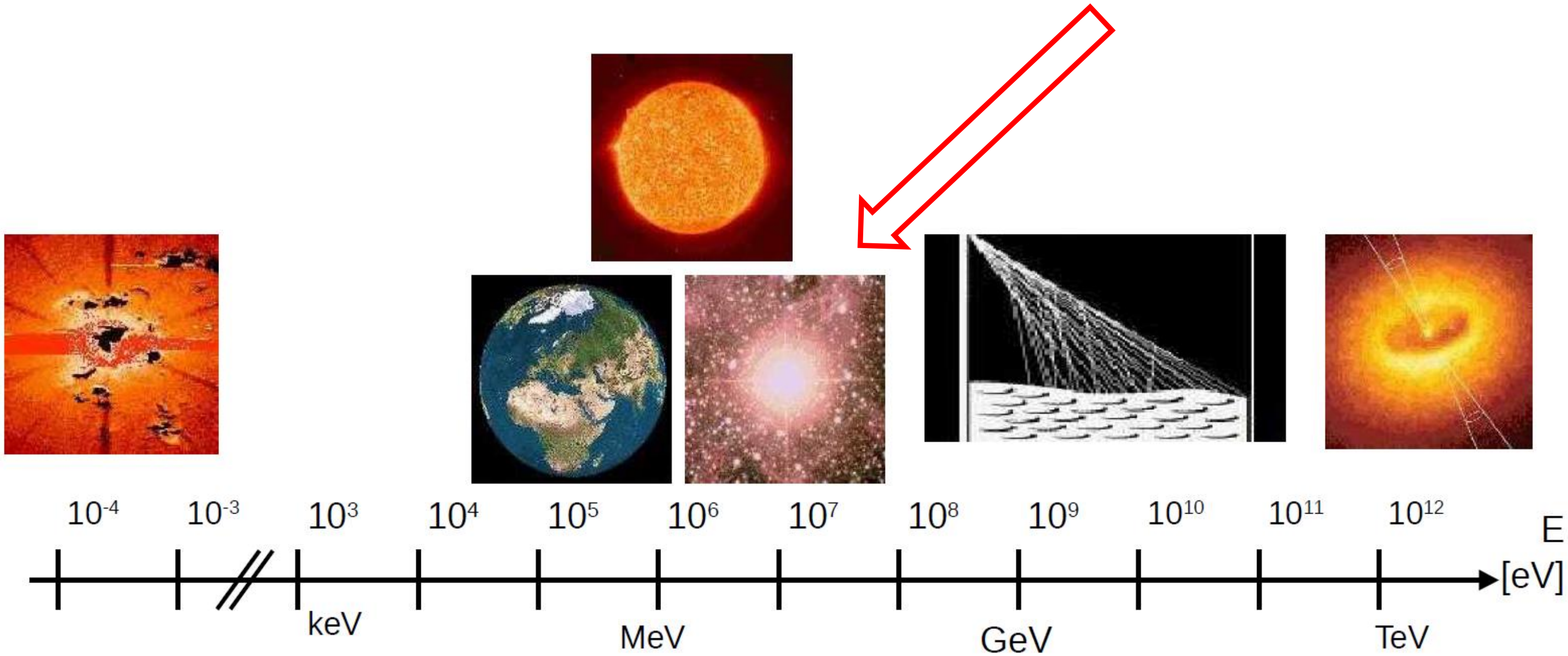
Working principle to search for sterile neutrinos

- Oscillation parameters ($\sin^2 2\theta$, Δm^2) are tested against data
  - Sterile neutrino oscillation hypothesis ⇒ **contour plot + best fit**
  - Null hypothesis ⇒ **exclusion plot**

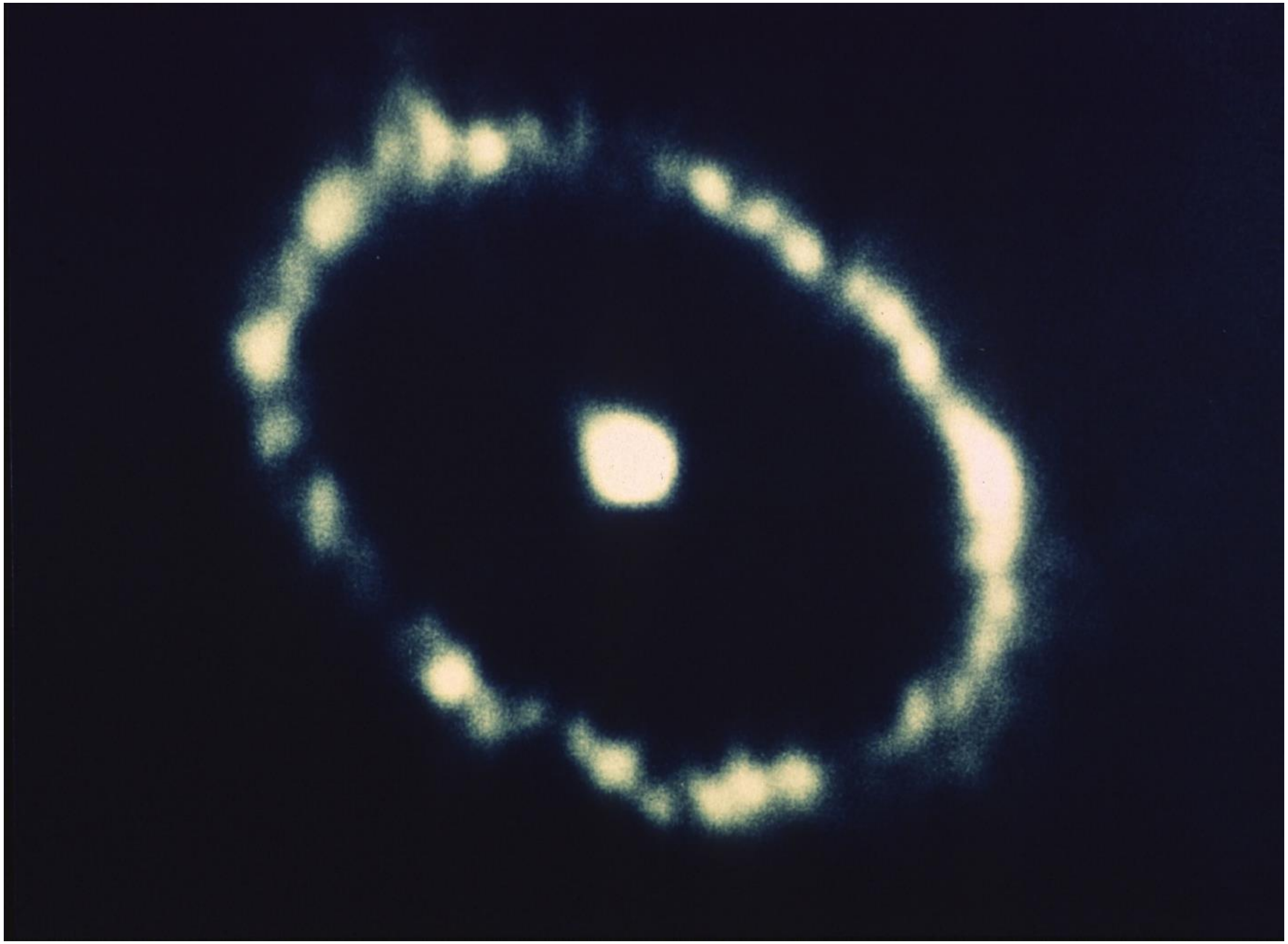


Independent of reactor/accelerator neutrinos

- In history, neutrinos from SN 1987A were detected within a few seconds by the groups Kamiokande-II, Baksan and Irvine-Michigan-Brookhaven to provide the first glimpse of core collapse supernova.
- It is promising that we can observe core-collapse supernova neutrinos next decades. New physics beyond standard neutrino mixings deserves further study. What if there is a light sterile neutrino in core-collapse supernova explosion?
- Complementary to the search of sterile neutrinos in accelerator/reactor experiments, CCSN will have independent perspectives on this topic.



SN1987A



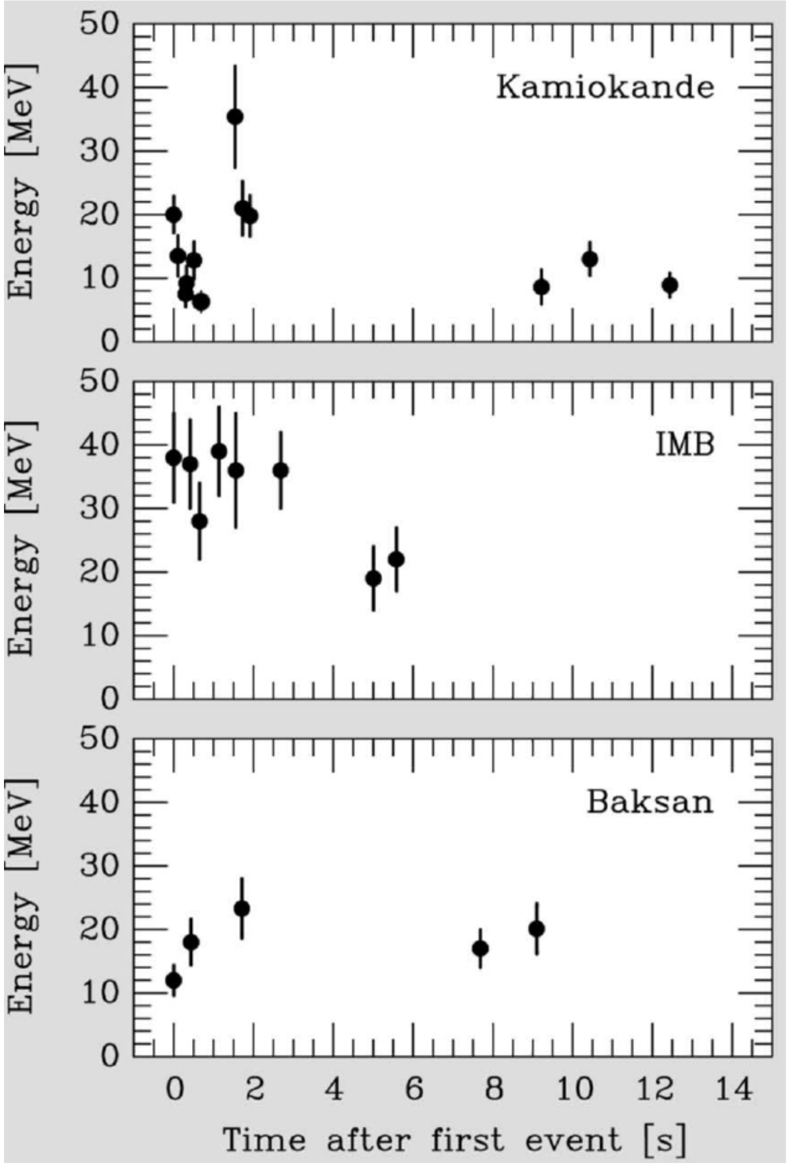
A NASA Hubble Space Telescope image of a gaseous ring surrounding SN1987A

https://hubblesite.org/contents/media/images/1991/03/34-Image.html

Neutrinos from SN-1987A detected in history

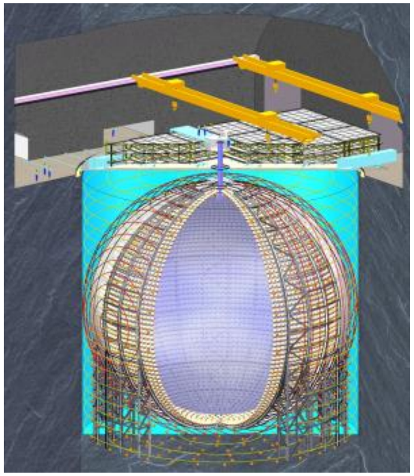
- In the Large Magellanic Cloud, 50 kpc away, 18 solar mass.
- Kamiokande-II: WC detector
- IMB: WC detector
- Baksan: LSc detector
- Complementary to the optical observations (SN ν earlier)
- Confirm our basic understanding of the mechanism behind CCSN explosion

Phys.Rev. D76 (2007) 083007

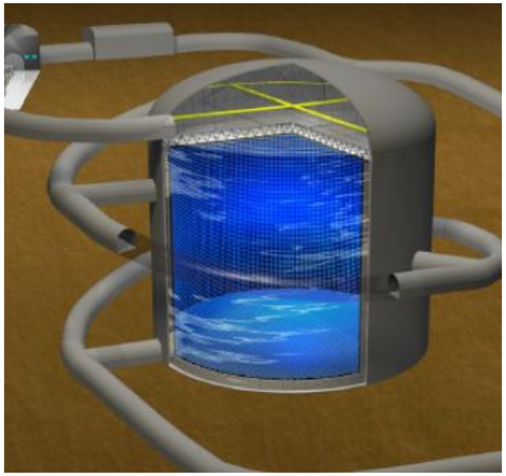


Capture SN neutrinos by future detectors

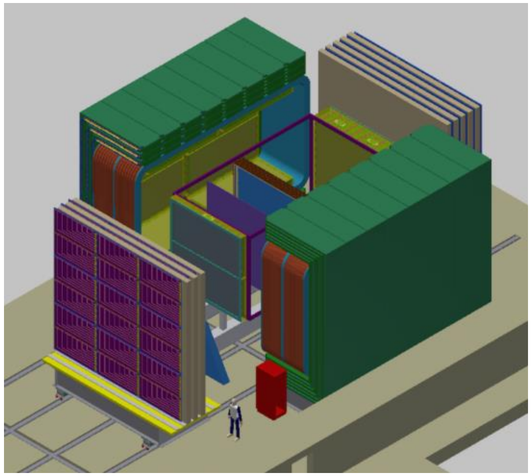
- In history, neutrinos from SN 1987A were detected within a few seconds by the groups Kamiokande-II, Baksan and Irvine-Michigan-Brookhaven to provide the first glimpse of core collapse supernova.
- Neutrino telescopes like JUNO, HyperK and DUNE are on the way.
- It is promising that we can observe core-collapse supernova neutrinos next decades. New physics beyond standard neutrino mixings deserves further study. What if there is a light sterile neutrino in core-collapse supernova explosion?
- Complementary to the search of sterile neutrinos in accelerator/reactor experiments, CCSN will have independent perspectives on this topic.



JUNO



HyperK



DUNE

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A comparison of different detector techniques

- JUNO: LSc, double colorimeters
- DUNE: LAr TPC
- HyperK: WC

Ref: Phys. Rev. D **66**, (2002) 033001

Experiment	Channels	Detector	Sensitive neutrino flavors
DUNE	ArCC	40-kton Liquid Argon	ν_e
Hyper-K	eES	370-kton Water	$\nu_e,\ \nu_x,\ \bar{\nu}_e,\ \bar{\nu}_x$
JUNO	eES and pES	20-kton Liquid Scintillator	$\nu_e,\ \nu_x,\ \bar{\nu}_e,\ \bar{\nu}_x$

$$\frac{\sigma_{tot}(\nu_\mu + e^-)}{\sigma_{tot}(\nu_\mu + p)} \sim \frac{G_F^2 E_\nu m_e}{G_F^2 E_\nu^2} \sim \frac{m_e}{E_\nu}$$

$$\frac{d\sigma_{\nu e}(E_\nu)}{dT_e} = \frac{2m_e G_F^2}{\pi}\left[\epsilon_-^2 + \epsilon_+^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - \epsilon_-\epsilon_+\frac{m_e T_e}{E_\nu^2}\right]$$

	ϵ_-	ϵ_+
ν_e	$-1/2 - \sin^2\theta_W$	$-\sin^2\theta_W$
ν_x	$1/2 - \sin^2\theta_W$	$-\sin^2\theta_W$

$$\frac{d\sigma_{\nu p}(E_\nu)}{dT_p} \approx 4.83 \times 10^{-42}\mathrm{cm}^2\mathrm{MeV}^{-1} \times \left[1 + 466\left(\frac{T_p}{\mathrm{MeV}}\right) \times \left(\frac{MeV}{E}\right)^2\right]$$

$$T_p'(T_p) \approx \int_0^{T_p} \frac{dE}{1 + k_{\mathrm{B}}\langle dE/dx\rangle}$$

- Electron-ν_e elastic scattering is more promising while $\bar{\nu}_e - e^-$ is helicity suppressed.
- Muon- and tau-flavour (anti)neutrino signals from SNe can only be extracted on the statistical basis after we subtract the electron (anti)neutrino contributions from the measured NC interactions.
- Neutrino-proton elastic scattering, low-energy protons lose energy quickly by ionization. A 10 MeV proton will be brought to rest in less than about 0.1 cm.

Comments on backgrounds

- General backgrounds for SNe neutrino signals:
  - ❑ reactor, solar and atmospheric neutrinos, expect high-rate SNe neutrinos
  - ❑ cosmic muon-induced backgrounds, overburden for underground labs
  - ❑ background events from radioactive isotopes, radiopurity control of detector components
  - ❑ …
- For neutrino-proton elastic scatterings for muon/tau (anti)neutrinos, electron (anti)neutrino channel can be statistically subtracted by means of neutrino-electron elastic scatterings.
  - ❑ IBD contributions subtracted by tight coincident conditions.
  - ❑ NC excitation of the 15.11 MeV state in ^{12}C identified by narrow spectrum
  - ❑…

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- Motivations
- Detection processes at different detectors
- Core-Collapse Supernova neutrinos with 3+1 mixings
- Constraints on $\sin^2 2\theta_{14}$ and Δm^2_{41}
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Core-Collapse Supernova neutrinos with 3+1 mixings

- Pre-supernova phase during which neutrinos are emitted via various weak processes before the core bounces.
- Neutronization burst at the millisecond level after the core-bounce as shown below: ν_e dominated processes, robust feature of all simulations.
- Mass accretion onto the freshly-formed Proto-Neutron Star (PNS) at O(100) ms as the SN shock stalls: all flavors
- Focus on the neutronization burst phase in this study.

Neutrino fluence: the modified Fermi-Dirac distribution

$$\Phi(E_\nu) = \frac{1}{4\pi D^2}\frac{\epsilon_\nu}{\langle E_\nu\rangle}\frac{dN_\nu}{dE_\nu}(E_\nu)$$

- total neutrino energy ϵ
- the mean energy <E>
- the shape-related index γ
- D: the distance between SNe and the detector

$$\frac{dF_\nu^m}{dE_\nu}(E_\nu) = A\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\gamma_\nu}\exp\left[-(\gamma_\nu+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

$$A = \frac{(\gamma_\nu+1)^{\gamma_\nu+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}$$

$$\gamma_\nu = \frac{2\langle E_\nu\rangle^2 - \langle E_\nu^2\rangle}{\langle E_\nu^2\rangle - \langle E_\nu\rangle^2}$$

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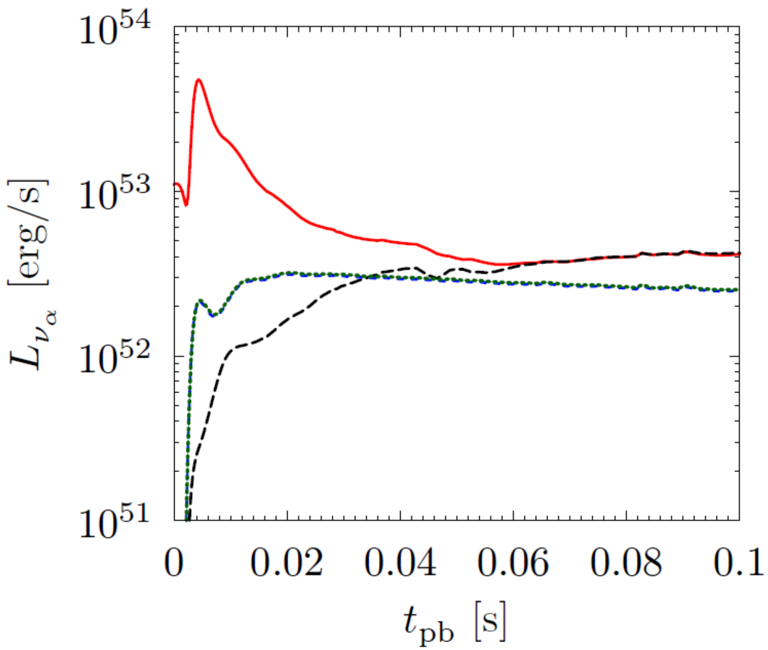
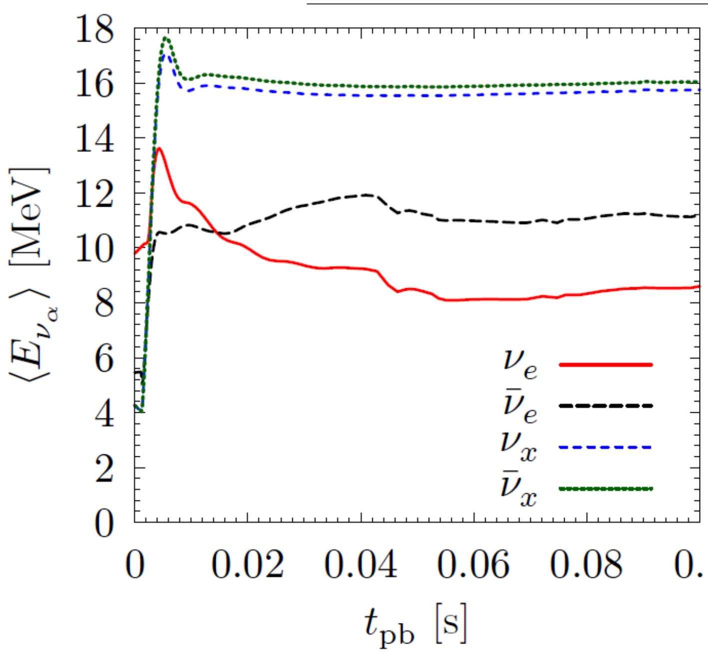
	ϵ_{ν_α} [10^{50} erg]	$\widehat{\langle E_{\nu_\alpha} \rangle}$ [MeV]	$\hat{\gamma}_{\nu_\alpha}$
ν_e	24.8	12.3	3
$\bar{\nu}_e$	0.396	10.6	3
ν_x	1.36	15.7	3
$\bar{\nu}_x$	1.39	16.1	3





Neutrino flavor conversions with MSW effects

$$H = \frac{UM^2U^\dagger}{2E_\nu} + V$$

$$V_{\rm CC} \equiv \sqrt{2}G_{\rm F}N_e$$
$$V_{\rm NC} \equiv \sqrt{2}G_{\rm F}N_n$$

$$\frac{UM^2U^\dagger}{2E_\nu} = \frac{1}{2E_\nu}\begin{pmatrix} m^2_{ee} & m^2_{e\mu} & m^2_{e\tau} & m^2_{es} \\ m^2_{\mu e} & m^2_{\mu\mu} & m^2_{\mu\tau} & m^2_{\mu s} \\ m^2_{\tau e} & m^2_{\tau\mu} & m^2_{\tau\tau} & m^2_{\tau s} \\ m^2_{se} & m^2_{s\mu} & m^2_{s\tau} & m^2_{ss} \end{pmatrix} \qquad V = \begin{pmatrix} V_{\rm CC} - V_{\rm NC} & 0 & 0 & 0 \\ 0 & -V_{\rm NC} & 0 & 0 \\ 0 & 0 & -V_{\rm NC} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- Under the two-neutrino mixing assumption, the resonance condition is:

$$\cos 2\theta_{14} = \frac{2V_{ee}E_\nu}{\Delta m^2_{41}} = \frac{2\sqrt{2}E_\nu G_{\rm F}N_e(3Y_e-1)}{2Y_e\Delta m^2_{41}}$$

$$V_{ee} = V_{\rm CC}(3Y_e-1)/(2Y_e)$$
$$Y_e \equiv N_e/N_b$$

Slow-changing density $\Rightarrow$ Adiabatic case

Transition probability between mass eigenstates 1&4:

$$\gamma_{14} \equiv \frac{(\Delta m^2_{41})^2\sin^2 2\theta_{14}}{4E^2_\nu}\left|\frac{dV_{ee}}{dr}\right|^{-1}_{\rm res} \gg 1$$

$$p_{14} \simeq \exp(-\pi\gamma_{14}/2)$$

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- Pre-supernova phase during which neutrinos are emitted via various weak processes before the core bounces.
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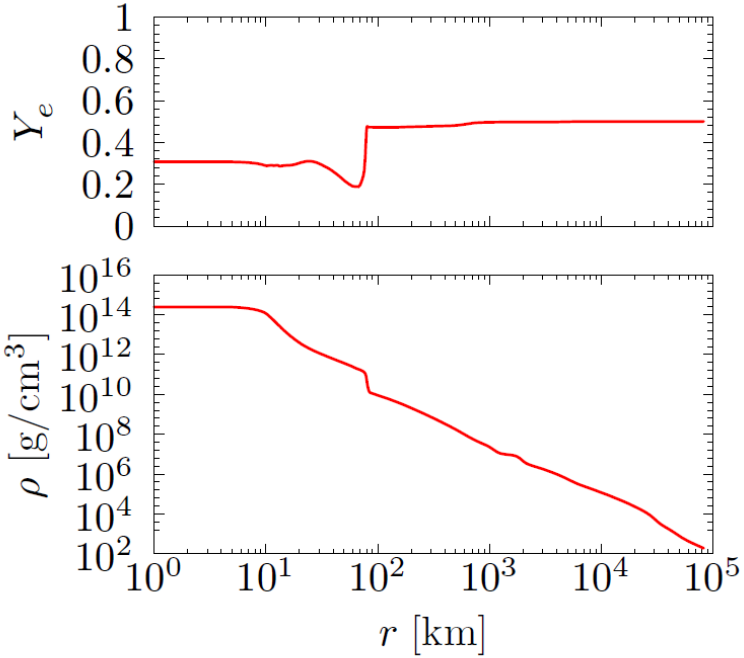

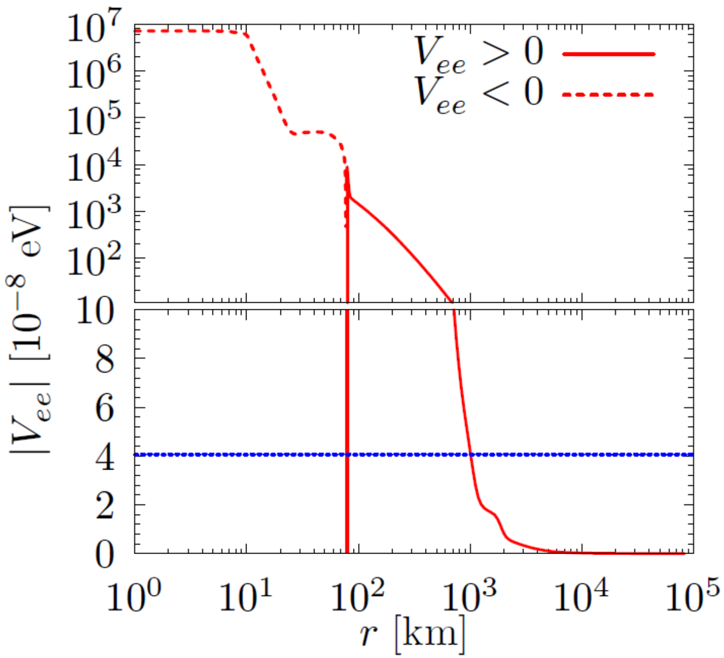

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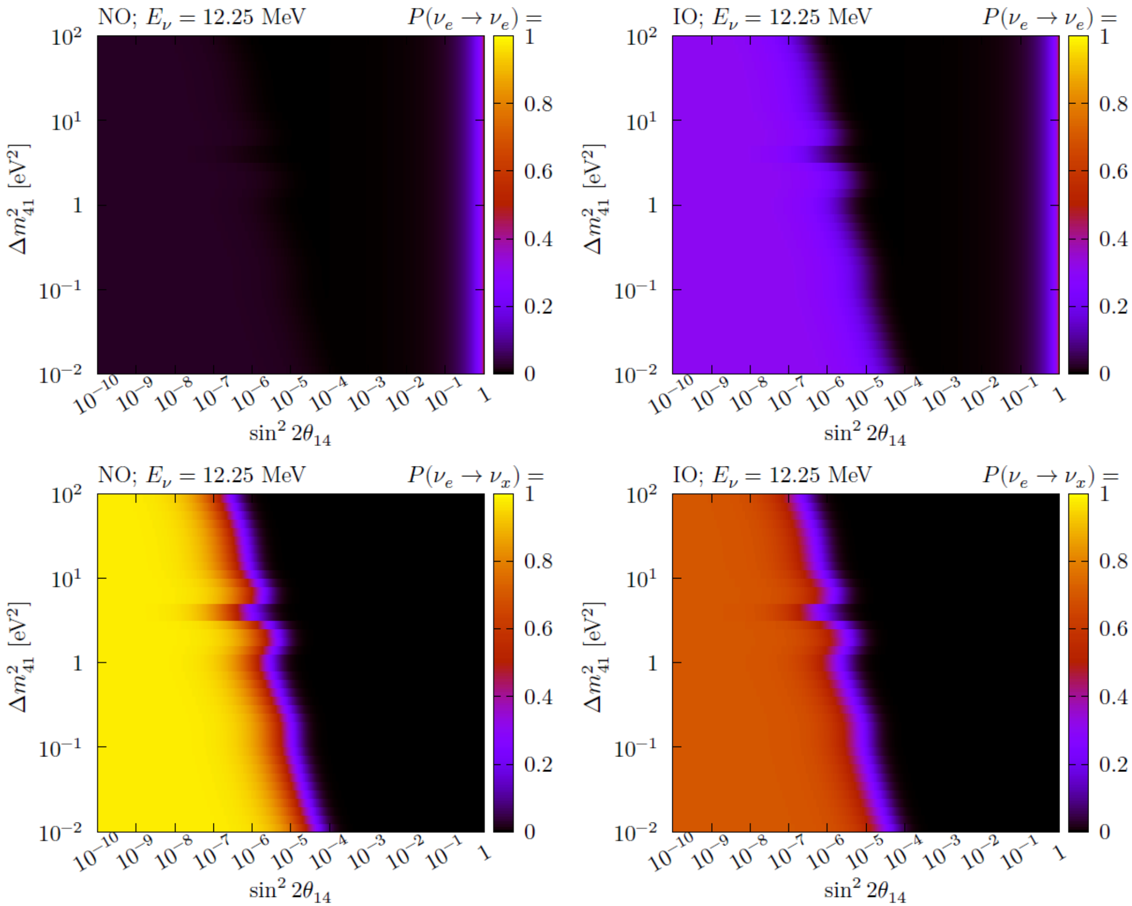

$10^{-7} < \sin^2 2\theta_{14} < 10^{-4}$
Transition takes place.

IO is more promising than NO.

$$F_{\nu_e} = \left\{|U_{e3}|^2 p_{14} + |U_{e4}|^2(1-p_{14})\right\} F^0_{\nu_e} + \left(|U_{e1}|^2 + |U_{e2}|^2\right) F^0_{\nu_x},$$
$$F_{\nu_x} = (|U_{\mu 3}|^2 + |U_{\tau 3}|^2) p_{14} F^0_{\nu_e} + \left(|U_{\mu 1}|^2 + |U_{\tau 1}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2\right) F^0_{\nu_x},$$
$$F_{\bar\nu_e} = |U_{e1}|^2 F^0_{\bar\nu_e} + \left(|U_{e2}|^2 + |U_{e3}|^2\right) F^0_{\bar\nu_x},$$
$$F_{\bar\nu_x} = (|U_{\mu 1}|^2 + |U_{\tau 1}|^2) F^0_{\bar\nu_e} + \left(|U_{\mu 2}|^2 + |U_{\tau 2}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2\right) F^0_{\bar\nu_x},$$

$$P(\nu_e \to \nu_e) = |U_{e3}|^2 p_{14} + |U_{e4}|^2(1-p_{14})$$
$$P(\nu_e \to \nu_x) = (|U_{\mu 3}|^2 + |U_{\tau 3}|^2) p_{14}$$

Predicted SNe event rates within the 3+1 framework

ν_e; @10 kpc (NO)	DUNE ArCC	Hyper K eES	JUNO eES	JUNO pES
3-ν mixing	12.8	36.5	2.2	9.1
$\sin^2 2\theta_{14} = 10^{-9}$, $\Delta m^2_{41} = 10^2$ eV^2	12.8	36.2	2.2	9
$\sin^2 2\theta_{14} = 10^{-7}$, $\Delta m^2_{41} = 10^2$ eV^2	12.1	27.2	1.7	7.7
$\sin^2 2\theta_{14} = 10^{-5}$, $\Delta m^2_{41} = 10^2$ eV^2	10.2	11.3	0.7	3.3
$\sin^2 2\theta_{14} = 10^{-3}$, $\Delta m^2_{41} = 10^2$ eV^2	10.3	11.3	0.7	3.3
$\sin^2 2\theta_{14} = 10^{-9}$, $\Delta m^2_{41} = 1$ eV^2	12.8	36.3	2.2	9
$\sin^2 2\theta_{14} = 10^{-7}$, $\Delta m^2_{41} = 1$ eV^2	12.7	35.4	2.1	8.9
$\sin^2 2\theta_{14} = 10^{-5}$, $\Delta m^2_{41} = 1$ eV^2	10.4	12.2	0.7	3.9
$\sin^2 2\theta_{14} = 10^{-3}$, $\Delta m^2_{41} = 1$ eV^2	10.3	11.3	0.7	3.3
$\sin^2 2\theta_{14} = 10^{-9}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	12.8	36.3	2.2	9
$\sin^2 2\theta_{14} = 10^{-7}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	12.8	36.2	2.2	9
$\sin^2 2\theta_{14} = 10^{-5}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	12.4	31.3	1.9	8.4
$\sin^2 2\theta_{14} = 10^{-3}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	10.3	11.3	0.7	3.3

ν_e; @10 kpc (IO)	DUNE ArCC	Hyper K eES	JUNO eES	JUNO pES
3-ν mixing	41.9	65.3	3.9	9.1
$\sin^2 2\theta_{14} = 10^{-9}$, $\Delta m^2_{41} = 10^3$ eV^2	41.8	64.8	3.9	8.9
$\sin^2 2\theta_{14} = 10^{-7}$, $\Delta m^2_{41} = 10^3$ eV^2	32.1	45.2	2.7	7.6
$\sin^2 2\theta_{14} = 10^{-5}$, $\Delta m^2_{41} = 10^3$ eV^2	7.3	10.5	0.6	3.3
$\sin^2 2\theta_{14} = 10^{-3}$, $\Delta m^2_{41} = 10^3$ eV^2	7.3	10.6	0.6	3.3
$\sin^2 2\theta_{14} = 10^{-9}$, $\Delta m^2_{41} = 1$ eV^2	41.9	65	3.9	8.9
$\sin^2 2\theta_{14} = 10^{-7}$, $\Delta m^2_{41} = 1$ eV^2	40.8	63	3.8	8.8
$\sin^2 2\theta_{14} = 10^{-5}$, $\Delta m^2_{41} = 1$ eV^2	9.2	12.4	3.8	3.8
$\sin^2 2\theta_{14} = 10^{-3}$, $\Delta m^2_{41} = 1$ eV^2	7.3	10.6	0.6	3.3
$\sin^2 2\theta_{14} = 10^{-9}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	41.9	65	3.9	8.9
$\sin^2 2\theta_{14} = 10^{-7}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	41.9	56	3.9	9
$\sin^2 2\theta_{14} = 10^{-5}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	37	54.2	3.2	8.3
$\sin^2 2\theta_{14} = 10^{-3}$, $\Delta m^2_{41} = 10^{-2}$ eV^2	7.3	10.6	0.6	3.3

Current global fit results at NuFit4.1 are taken here

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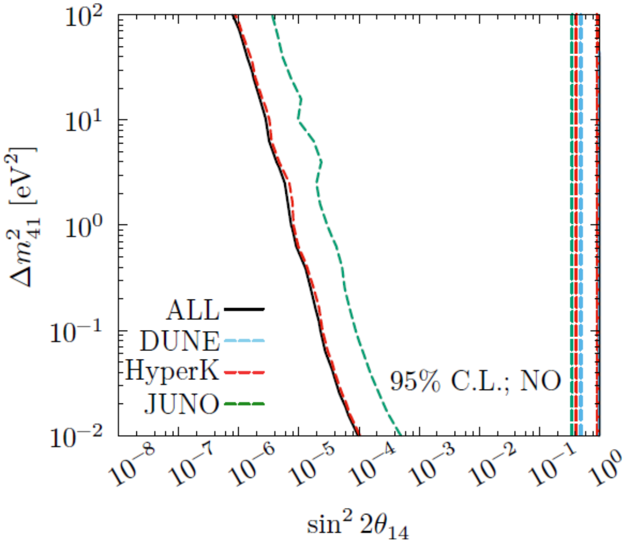
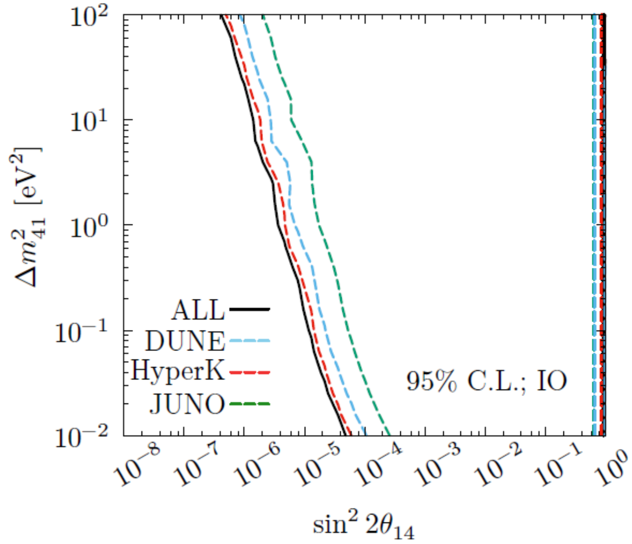
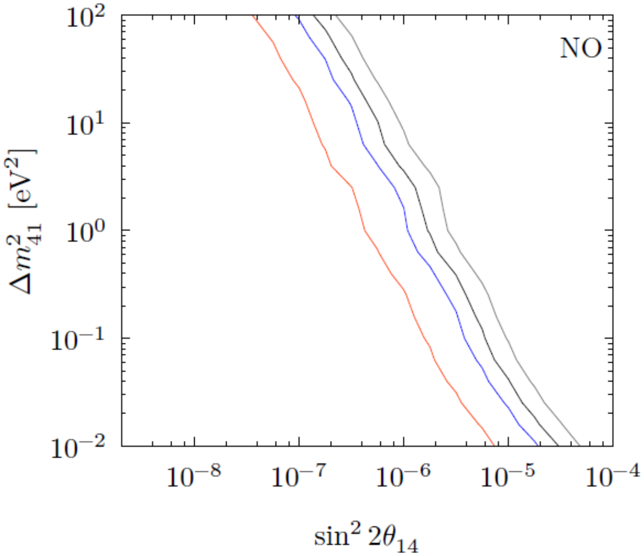
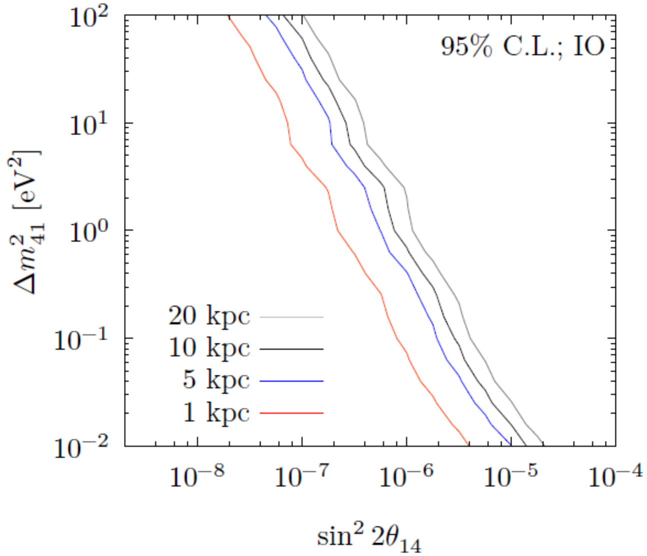
Constraints on sterile neutrino mixings by CCSN events





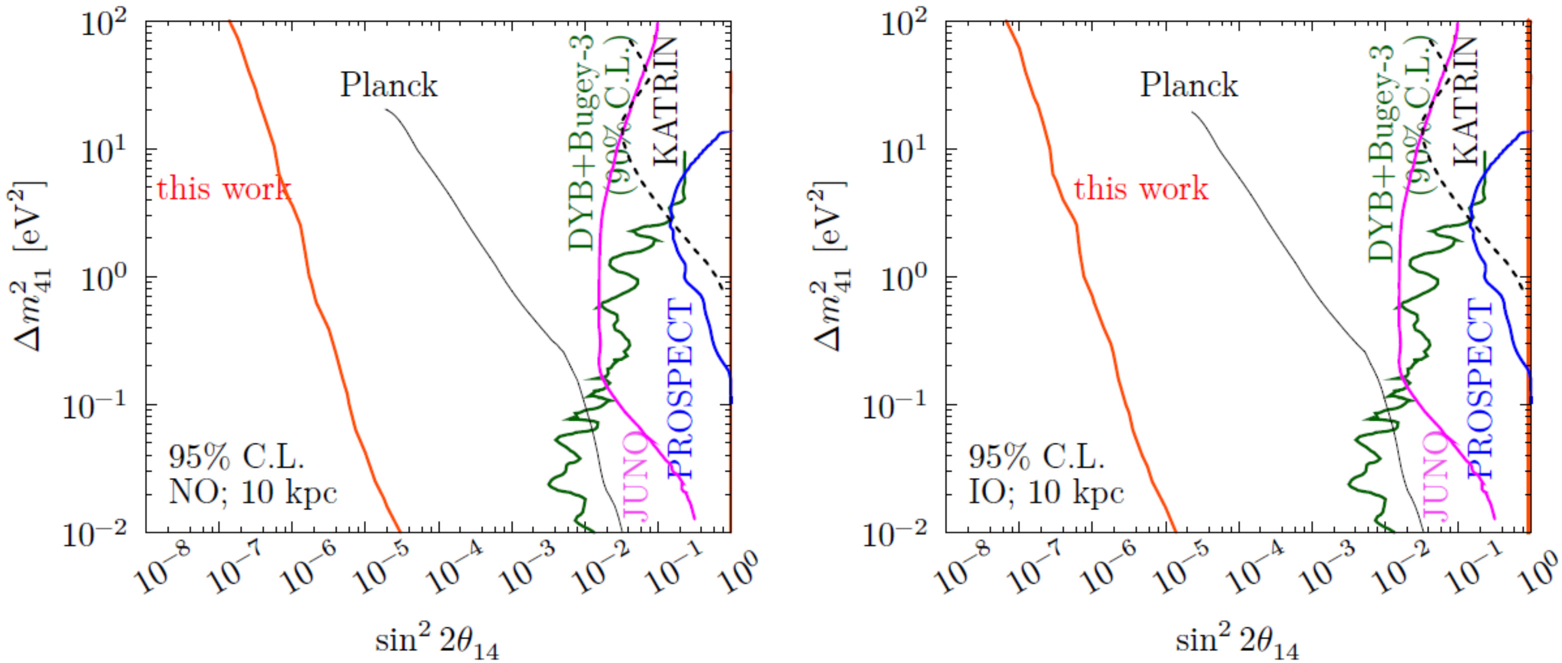
Fix the distance at 10 kpc





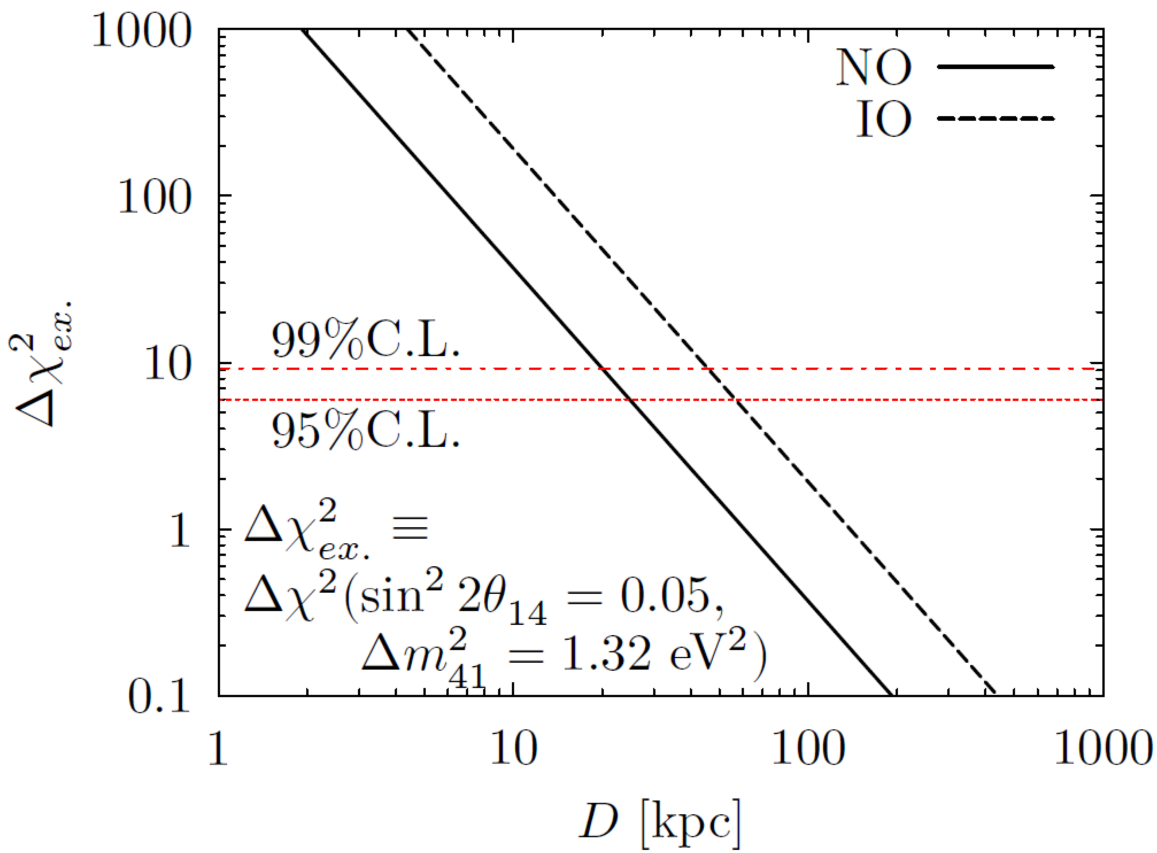
Fix at 95% CL

CCSN sensitivity compared with other measurements



- We make a comparison among expected sensitivities in JUNO-reactor neutrino oscillations, current bounds from reactor experiments like DYB+Bugey-3, PROSPECT, and cosmological observation PLANCK.
- Complementary to each other.
- CCSN can have a much better probe in the small mixing angle region for the 3+1 model.

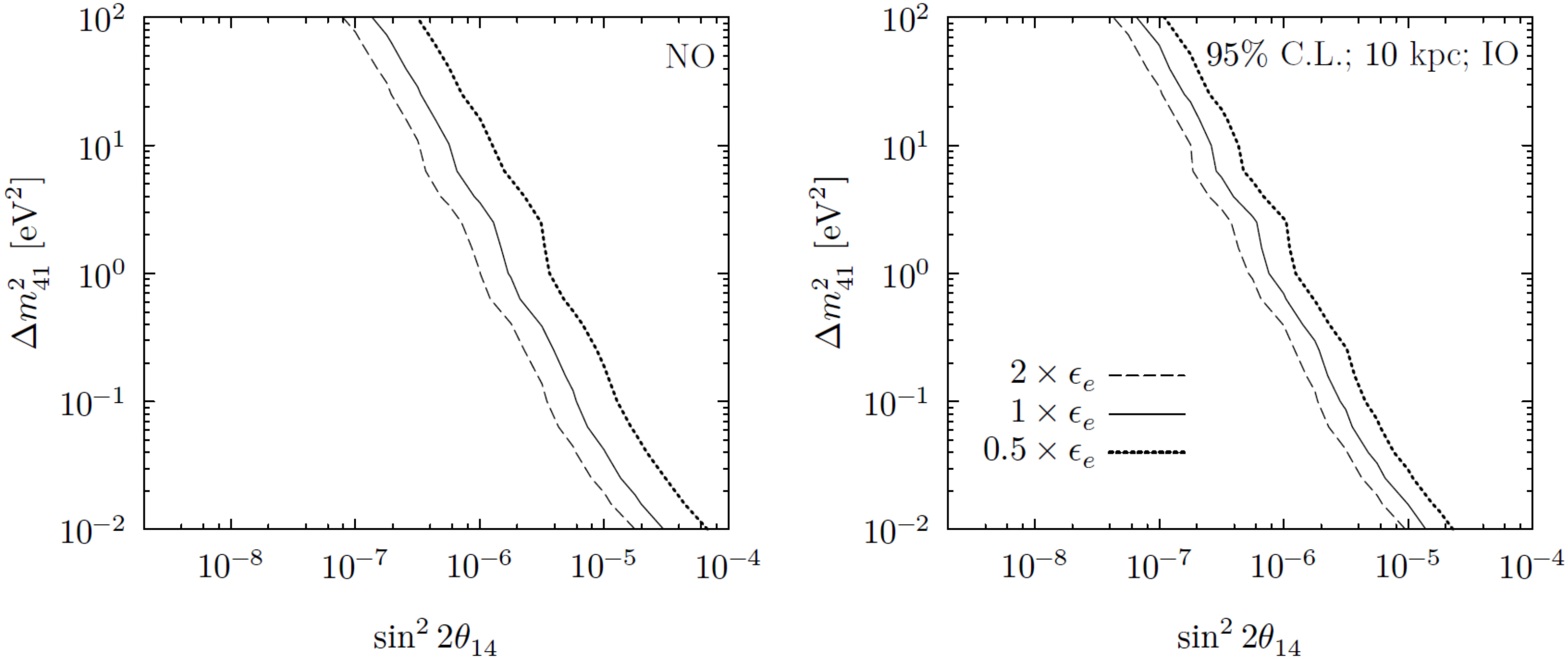
Constraints on sterile neutrino mixings by CCSN events



- The exclusion capability can be greater than 99% C.L. for even D<=30 kpc for IO. Within the Milky way, we can put strong constraints on sterile neutrinos by counting registered SNe events in all detectors given the inverted mass ordering.
- Poor result for NO: only be sensitive by CCSN within 12 kpc at 99% CL.

Constraints on sterile neutrino mixings by CCSN events

Impacts from fluence parameters



- Fluence parameters highly depend on SNe modelings.
- We hardly know the probability distribution function for each fluence parameter.
- Varying the total energy release by ν_e due to its dominant role in the neutronization burst stage is a good starting point.
- More observations of CCSN like SN1987A will reflect the truth.

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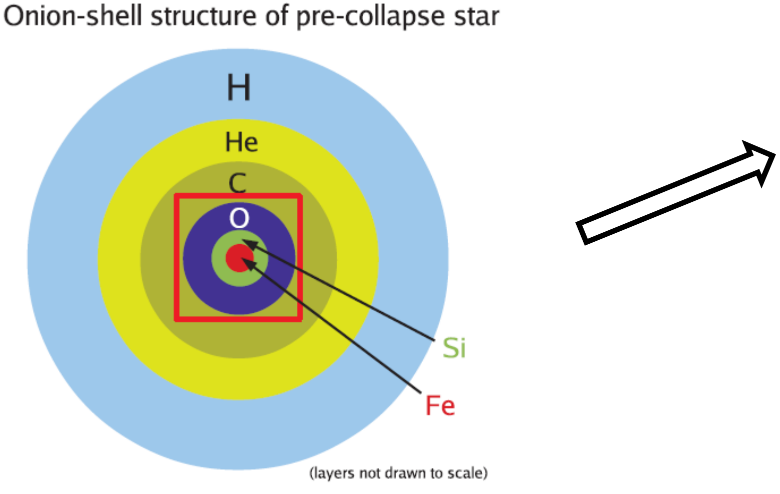
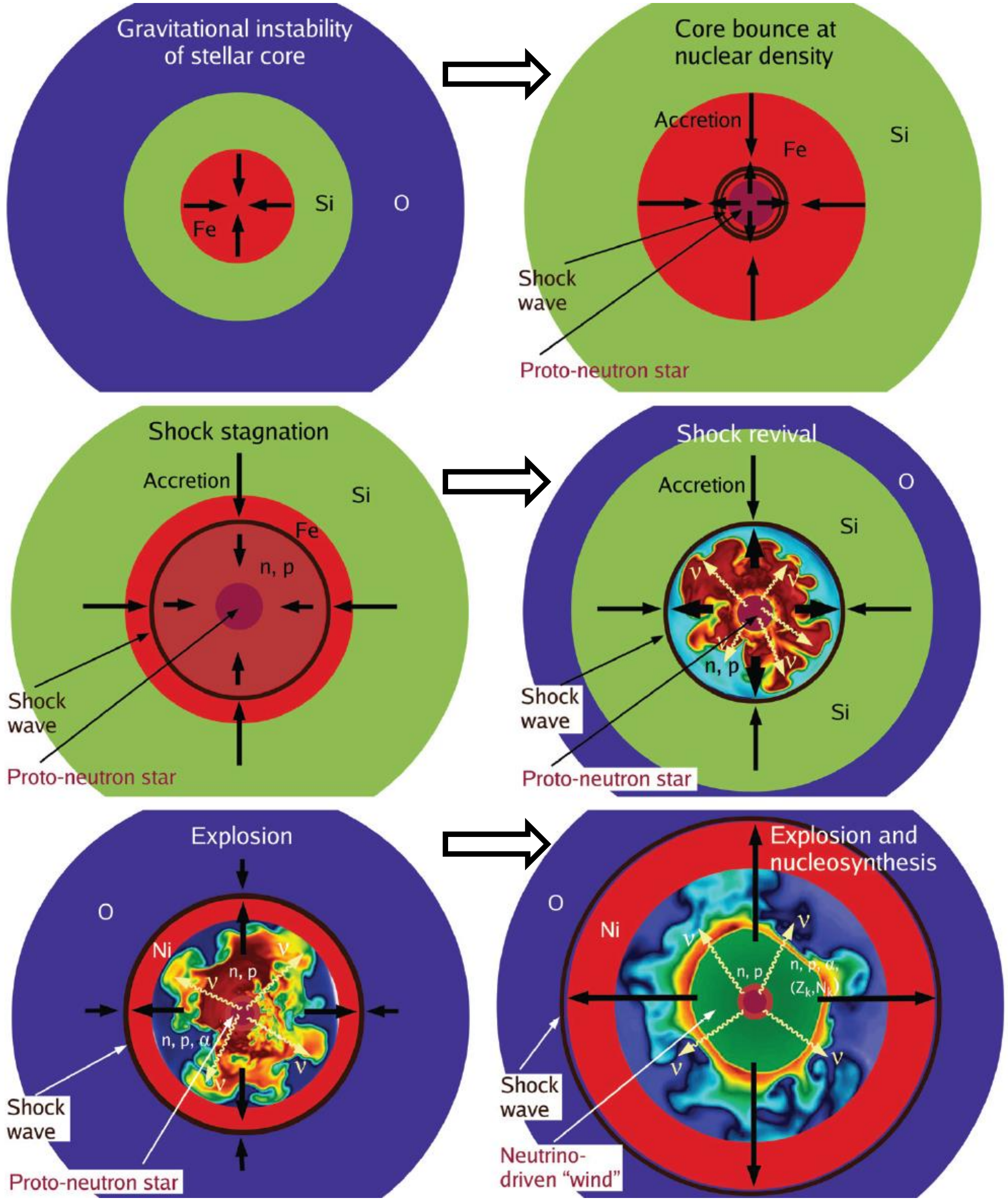
Summary

- Neutrino physics is part of CCSN modeling while more detected events from SNe will reveal the better picture and feed on the understanding of neutrino properties.
- If there exist sterile neutrinos, they should enter in the CCSN and leave imprints in an observation of SNe neutrino signals. The lucky story in 1987 was the nail but could not tell the full story yet. More signals are to be seen by future neutrino telescopes.
- Electron neutrinos from CCSN are the most important flavor to search for new physics.
- For a supernova occurring within 10 kpc, the difference in the event numbers with and without sterile neutrinos allows to exclude the sterile neutrino hypothesis at more than 99% C.L. robustly. Better than results from cosmology and on-going or proposed reactor experiments.
- Distance between CCSN and the detector can easily eliminate the sensitivity on sterile neutrinos in the current study. We still need a piece of luck or look forward to new technologies towards DSNB detections.
- Global efforts like SNEWS are pushing forward the promising area. Multiple sites with different detection technologies can compensate with each other and might confirm the surprising new physics ahead of the current knowledge.
- More study on different CCSN model predictions with/without new physics beyond three neutrino mixings should be further developed.

THANK YOU

Basic understanding of CCSN after SN1987A





- Review by Hans-Thomas Janka in arXiv: 1211.1378.
- More than 99% of energy is carried away by neutrinos.
- CCSN is a good probe of internal dynamics and neutrino physics.