



INSTITUTE for
NUCLEAR THEORY

The effects of sterile neutrinos on core-collapse supernovae

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**Dark Matter in Compact
Objects, Stars, and in Low
Energy Experiments**

August 18, 2022



Network for Neutrinos,
Nuclear Astrophysics,
and Symmetries

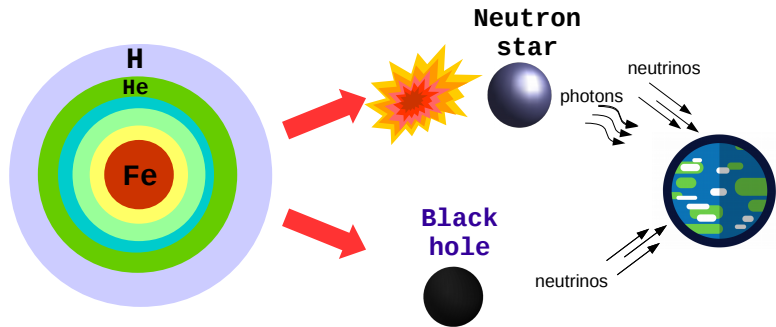
PHYSICS FRONTIER CENTER



Why are neutrinos important for a core-collapse supernova?

Neutrinos:

- $\sim 10^{58}$ of them emitted from a single core collapse
- only they (+ GW) can reveal the deep interior conditions
- only they (+ GW) are emitted from the collapse to a black hole



Why core-collapse supernovae are good physics probes?

Advantages

- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (IC, DUNE, SK, XENON & LZ...)

What can we learn with a variety of detectors?

- explosion mechanism H. Bethe & J. Wilson (1985),
T. Fischer et al. (2011)...
- nucleosynthesis S. Woosley et al. (1994),
S. Curtis et al. (2018)...
- compact object formation M. Warren et al. (2019),
S. Li, J. F. Beacom et al. (2020)...
- neutrino mixing H. Duan et al. (2010),
I. Tamborra & S. Shalgar (2020)...
- non-standard physics A. de Gouvêa et al. (2019),
S. Shalgar et al. (2019)...

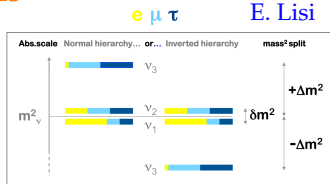
Neutrino flavor and mass states

Fermions					
Leptons	Quarks	Force carriers	Higgs boson		
	u _{up}	c _{charm}	t _{top}	γ _{photon}	H _{Higgs boson}
	d _{down}	s _{strange}	b _{bottom}	g _{gluon}	
	e _{electron}	μ _{muon}	τ _{tau}	Z _{Z boson}	
ν _e _{electron neutrino}	ν _μ _{muon neutrino}	ν _τ _{tau neutrino}	W _{W boson}		

flavor basis

mass basis

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



beam,
atmospheric

beam,
reactor

solar,
reactor

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

is ν_s (ν_4) missing?

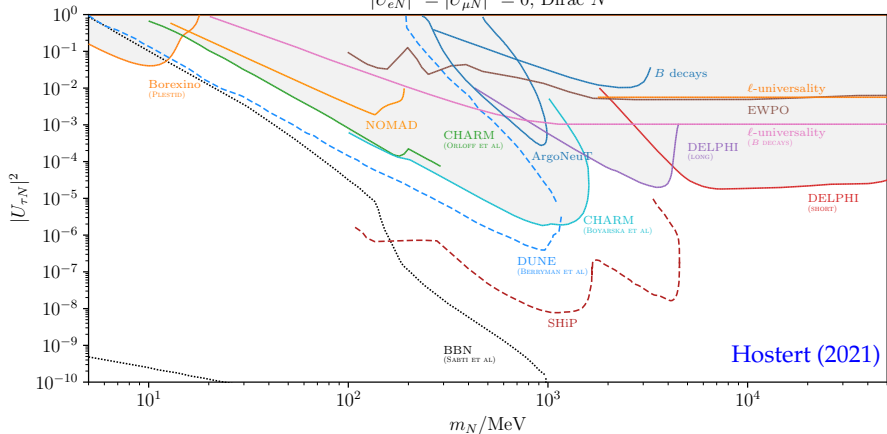
Sterile neutrinos: motivations

- **MeV-mass steriles**
 - Possible explanation of leptogenesis
 - Testable in multiple terrestrial experiments
 - **Impact on the CCSN physics**
- **keV-mass steriles**
 - Dark matter candidates
 - Testable in KATRIN/TRISTAN, HUNTER
 - **Impact on the CCSN physics**
- **eV-mass steriles**
 - Reactor and gallium anomalies
 - Miniboone, LSND, and MicroBoone anomalies
 - **Impact on the nucleosynthesis in CCSNe**

Sterile neutrinos with MeV masses in CCSNe

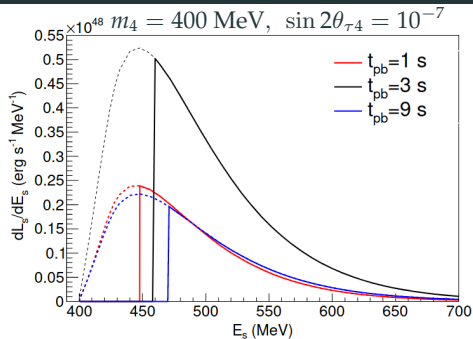
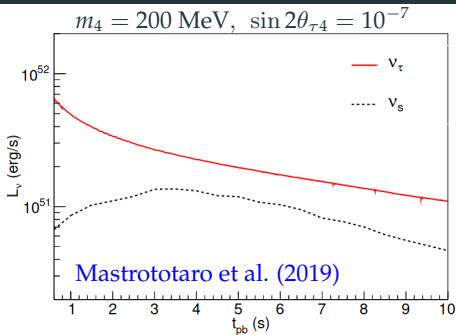
Limits: Sterile neutrinos with MeV masses

$$|U_{eN}|^2 = |U_{\mu N}|^2 = 0, \text{ Dirac } N$$



- Big Bang Nucleosynthesis
- Terrestrial experiments

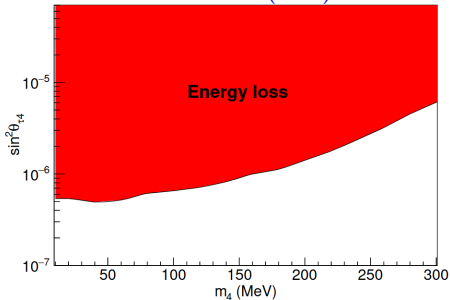
Heavy sterile neutrinos production processes in CCSN



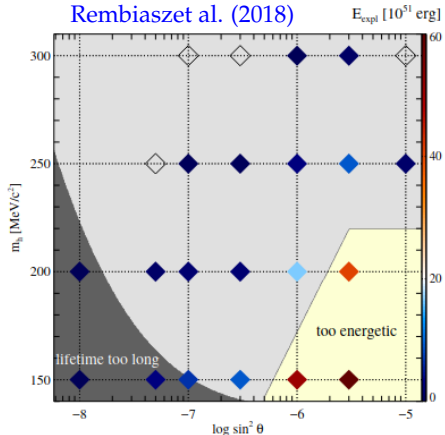
- Hot, dense, and degenerate core (e^-, p, n)
- Tau neutrinos: numerous and non-degenerate
- Production channels: $\nu_\tau + \nu_\tau \rightarrow \nu_s + \nu_\tau$

Limits on the MeV-mass sterile ν from CCSN

Mastrototaro et al. (2019)



Rembiaszet al. (2018)

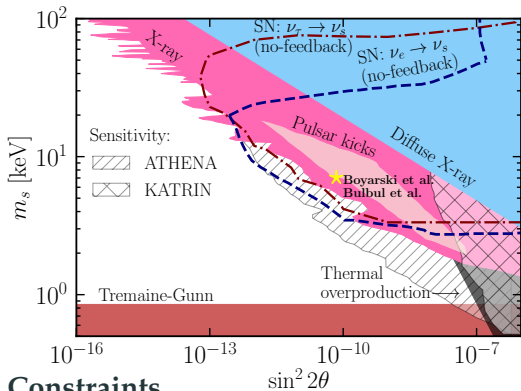


Effect of MeV ν_s on CCSN

- Cooling channel
- Heating mechanism
- Production of potentially detectable energetic neutrinos (~ 100 MeV)

Sterile neutrinos with keV masses in CCSNe

Sterile neutrino as dark matter candidate



Constraints

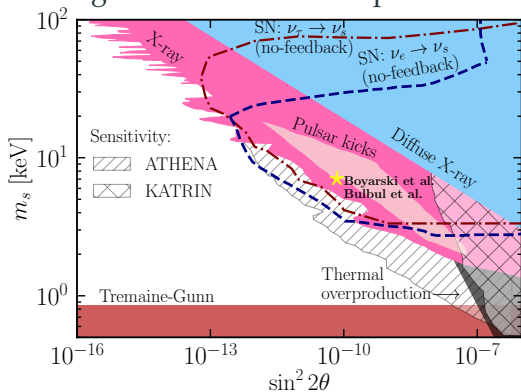
- Supernovae energy bounds (X. Shi & G. Sigl (1994)), ...
- DM overproduction (S. Dodelson, L. M. Widrow (1994), X. Shi, G. M. Fuller (1999))
- Radiative decay (NuSTAR, XMM, Chandra), K. C. Y. Ng et al. (2019), K. C. Y. Ng et al. (2015), S. Horiuchi et al. (2013)...
- Tremaine-Gunn bound (S. Tremaine, J.E. Gunn (1979))

Favorable regions

- Pulsar kicks
A. Kusenko, G. Segrè (1998),
G. Fuller, A. Kusenko, et al. (2003)
- 3.5 keV line
A. Boyarsky et al. (2014),
E. Bulbul et al. (2014)

The role of sterile neutrinos in supernovae; previous studies

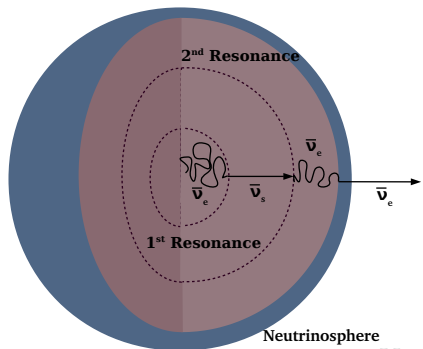
- Change of the electron or neutrino (ν_e, ν_μ, ν_τ) fractions
- Suppression/enhancement of the SN explosion
- Exclusion of a large fraction of the DM parameter space



Raffelt & Sigl (1992), Shi & Sigl (1994), Nunokawa et al. (1997), Hidaka & Fuller (2006), Hidaka & Fuller (2007), Raffelt & Zhou (2011), Warren et al. (2014), Argüelles et al. (2016), Suliga, Tamborra, Wu (2019, 2020), Syvolap et al. (2019)

Sterile neutrino conversions in the stellar core

1D SN model
Garching group
archive



MSW

$$Y_i = \frac{n_i - n_{\bar{i}}}{n_B}$$

$\nu_\tau - \nu_s$ mixing: only 1 resonance

$$V_{\text{eff}} = \sqrt{2}G_F n_B \left[\frac{1}{2}Y_e + Y_{\nu_e} + Y_{\nu_\mu} + 2Y_{\nu_\tau} - \frac{1}{2} \right]$$

Collisions

$$\Gamma_{\nu_s} = \frac{1}{4} \sin^2 2\tilde{\theta} \Gamma_{\nu_{\text{active}}}$$

$\nu_e - \nu_s$ mixing: multiple resonances

$$V_{\text{eff}} = \sqrt{2}G_F n_B \left[\frac{3}{2}Y_e + 2Y_{\nu_e} + Y_{\nu_\mu} + Y_{\nu_\tau} - \frac{1}{2} \right]$$

L. Stodolsky (1987), H. Nunokawa et al. (1997), K. Abazajian et al. (2001)...

Collisional production

$$\langle P_{\nu_{\text{active}} \rightarrow \nu_s}(E) \rangle \approx \frac{1}{2} \frac{\sin^2 2\theta}{(\cos 2\theta - 2V_{\text{eff}}E/m_s^2)^2 + \sin^2 2\theta + D^2}$$

$$\Gamma_{\nu_{\text{active}}}(E) \simeq n(r)\sigma(E, r)$$

$$D = \frac{E\Gamma_{\nu_{\text{active}}}(E)}{m_s^2}$$

Sterile neutrino conversions in the stellar core

Collisional production

$$\langle P_{\nu_{\text{active}} \rightarrow \nu_s}(E) \rangle \approx \frac{1}{2} \frac{\sin^2 2\theta}{(\cos 2\theta - 2V_{\text{eff}}E/m_s^2)^2 + \sin 2\theta^2 + D^2}$$

$$\Gamma_{\nu_{\text{active}}}(E) \simeq n(r)\sigma(E, r)$$

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MSW production

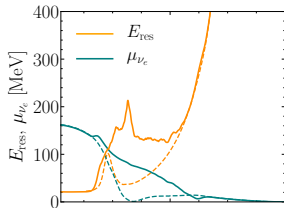
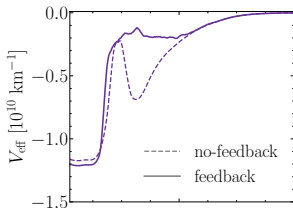
$$P_{\nu_{\text{active}} \rightarrow \nu_s}(E_{\text{res}}) = 1 - \exp\left(-\frac{\pi^2}{2}\gamma\right), \quad \gamma = \Delta_{\text{res}}/l_{\text{osc}}$$

$$\Delta_{\text{res}} = \tan 2\theta \left| \frac{dV_{\text{eff}}/dr}{V_{\text{eff}}} \right|^{-1}$$

$$l_{\text{osc}}(E_{\text{res}}) = (2\pi E_{\text{res}})/(m_s^2 \sin 2\theta)$$

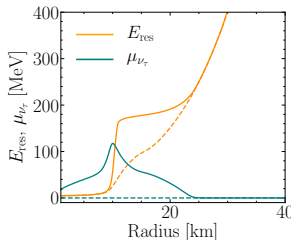
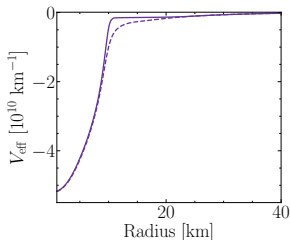
Sterile neutrino conversions in the stellar core

$\nu_s - \nu_e$ mixing: multiple resonances



1D SN model
Garching group
archive

$\nu_s - \nu_\tau$ mixing: only 1 resonance



$$E_{\text{res}} = \frac{\cos 2\theta \Delta m_s^2}{2V_{\text{eff}}}$$

$$m_s = 10 \text{ keV},$$

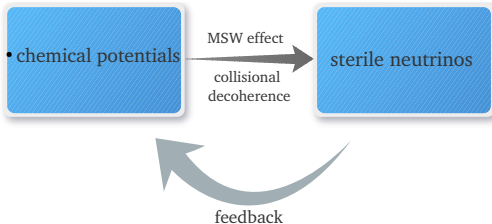
$$\sin^2 2\theta = 10^{-8}$$

- Negative $V_{\text{eff}} \rightarrow$ MSW resonances only for antineutrinos.
- Growing chemical potential slows down $\bar{\nu}_s$ production.

The sterile-tau neutrino mixing: growth of the asymmetry

Only active neutrinos

$$Y_{\nu_\tau}(r, t) \equiv 0$$



Active + sterile neutrinos

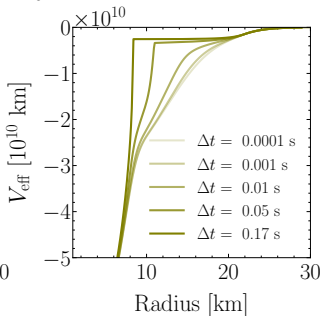
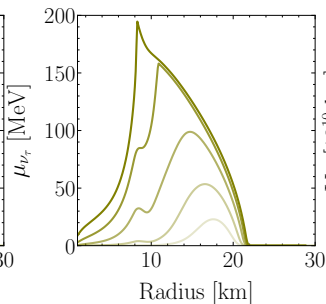
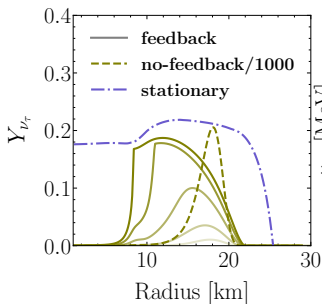
The active neutrinos after being **converted to sterile ones** effectively disappear; since they were **strongly coupled** to the rest of the particles in the medium, a **new equilibrium state** forms.

The change imposed on the SN medium is referred to as the **dynamical feedback**.

$$Y_{\nu_\tau}(r, t) = \frac{1}{n_b(r)} \int_0^t dt' \frac{d(P_{\nu_\tau \rightarrow \nu_s} n_{\nu_\tau}(r, t') - P_{\bar{\nu}_\tau \rightarrow \bar{\nu}_s} n_{\bar{\nu}_\tau}(r, t'))}{dt'}$$

Radial evolution of the asymmetry w and w/o feedback

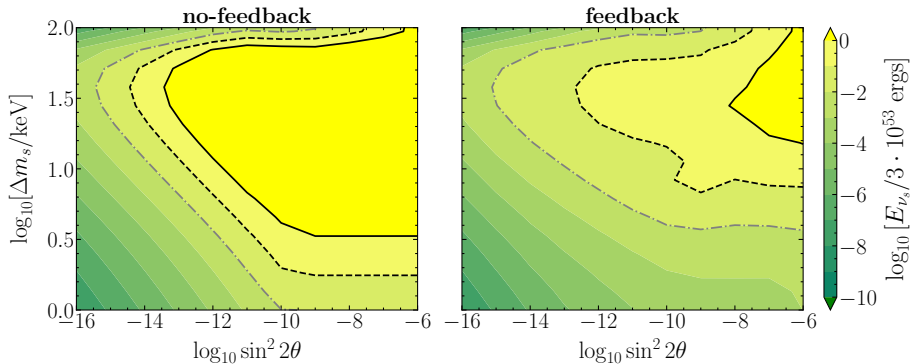
$$t_{\text{pb}} = 0.5 + \Delta t \text{ s}, \quad \Delta m_s = 10 \text{ keV}, \quad \sin^2 2\theta = 10^{-10}$$



- Feedback inhibits Y_{ν_τ} from unphysical growth.
- The ν_τ chemical potential grows significantly.

Supernova bounds on the mixing parameters

$$t_{\text{pb}} = 0.5 \text{ s}$$



- The inclusion of feedback greatly reduces the excluded region.
- Large region of the parameter space still compatible with SNe

The sterile-electron neutrino mixing: dynamical feedback

$$e^+ + p \leftrightarrow \nu_e + n \quad \text{and} \quad e^- + n \leftrightarrow \bar{\nu}_e + p .$$

β equilibrium

$$\mu_e(r, t) + \mu_p(r, t) + m_p = \mu_{\nu_e}(r, t) + \mu_n(r, t) + m_n ,$$

Lepton number conservation

$$Y_e(r, t) + Y_{\nu_e}(r, t) + Y_{\nu_s}(r, t) = \text{const.} ,$$

Baryon number conservation

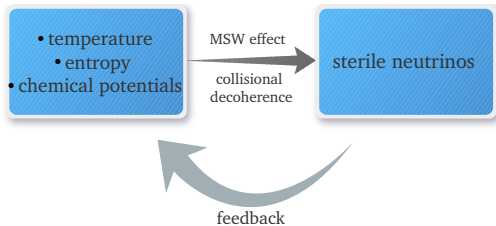
$$Y_p(r, t) + Y_n(r, t) = 1 ,$$

Charge conservation

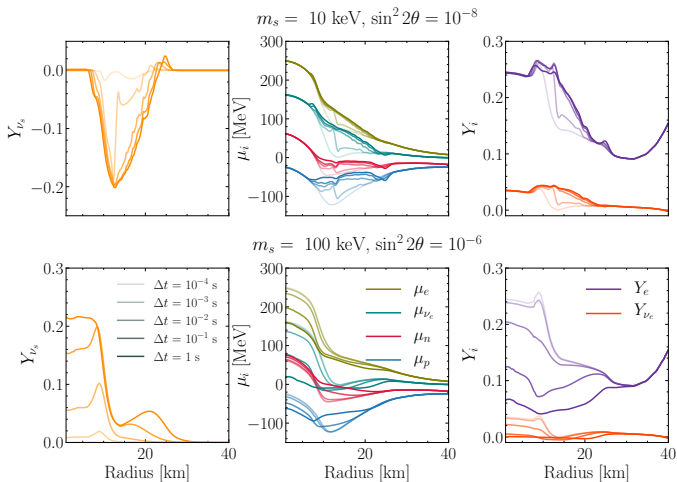
$$Y_p(r, t) = Y_e(r, t) ,$$

Entropy change

$$dS = \frac{dQ}{T} + \frac{P}{T}dV - \sum_i \frac{\mu_i}{T}dY_i .$$

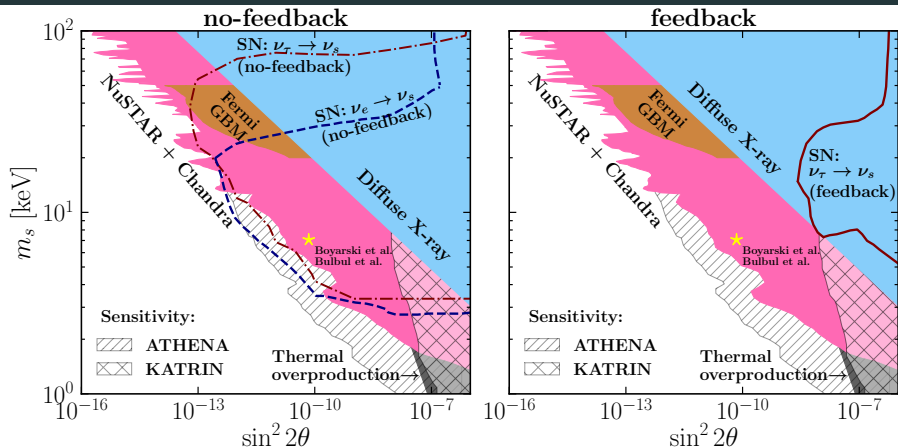


Radial evolution of the asymmetry



- Sterile neutrinos modify Y_e , $Y_{\nu e}$, Y_p and Y_n .
- Feedback on the physical quantities depends greatly on the m_s .

Supernova bounds on the mixing parameters

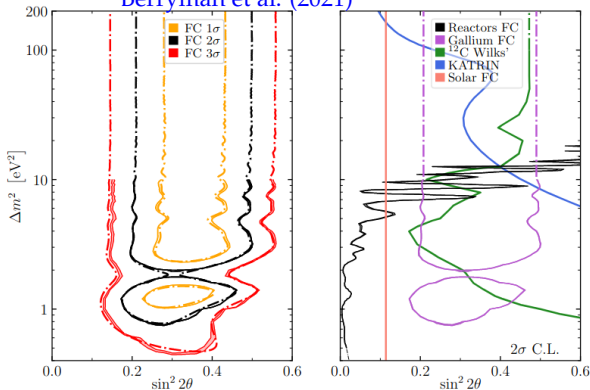


- The inclusion of feedback greatly reduces the excluded region.
- CC-SNe cannot exclude any region of the DM parameter space.

Sterile neutrinos with eV masses in CCSNe

Limits and hints: eV sterile neutrinos

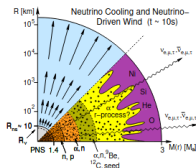
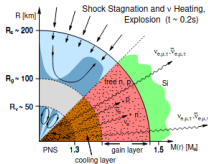
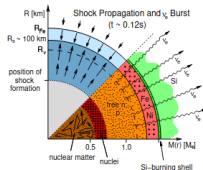
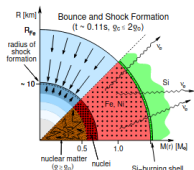
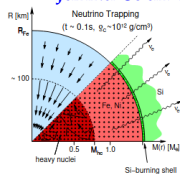
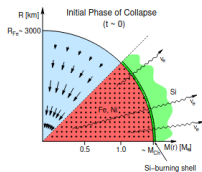
Berryman et al. (2021)



- **hints for eV steriles:**
from reactor experiments, gallium anomaly, MicroBooNE
- **limits for eV steriles:**
solar neutrinos, reactor experiments, KATRIN, PROSPECT,

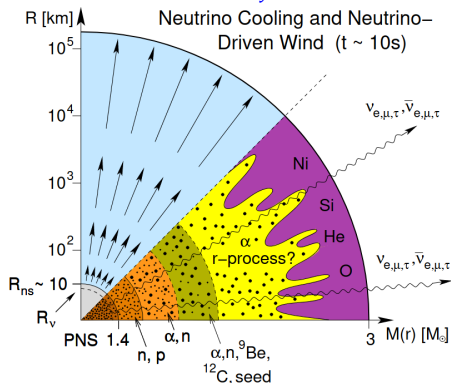
Neutrino driven wind and nucleosynthesis in CCSN

Janka et al. 2006



Neutrino driven wind and nucleosynthesis in CCSN

Janka et al. 2006



Source of the wind:
neutrino heating

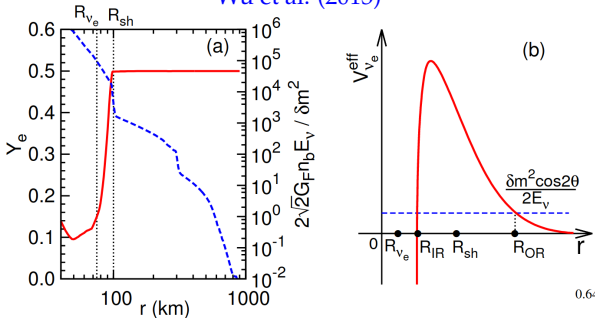


- r -process nucleosynthesis extremely sensitive to Y_e
- Y_e sensitive to the ratio of ν_e and $\bar{\nu}_e$
- The ratio of ν_e and $\bar{\nu}_e$ determined by neutrino conversions

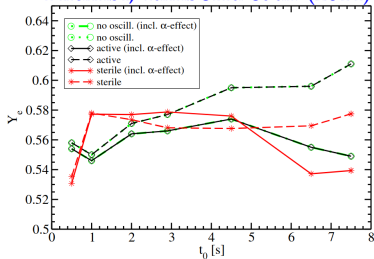
Woosley & Baron (1992), Woosley & Hoffman (1992), Meyer et al. (1992), Woosley et al. (1994), Witt et al. (1994), Takahashi et al. (1994), Qian & Woosley (1996), Hoffman et al. (1997), Wanajo et al. (2001), Thompson et al. (2001), Roberts et al. (2010), Wanajo (2013)...

Sterile neutrino conversions outside of the core

Wu et al. (2013)



Pllumbi, Tamborra et al. (2014)

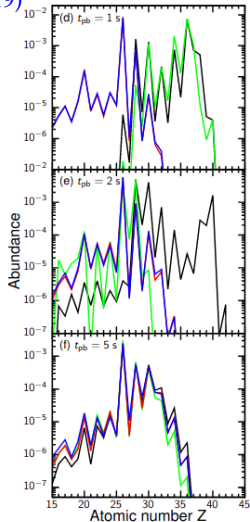
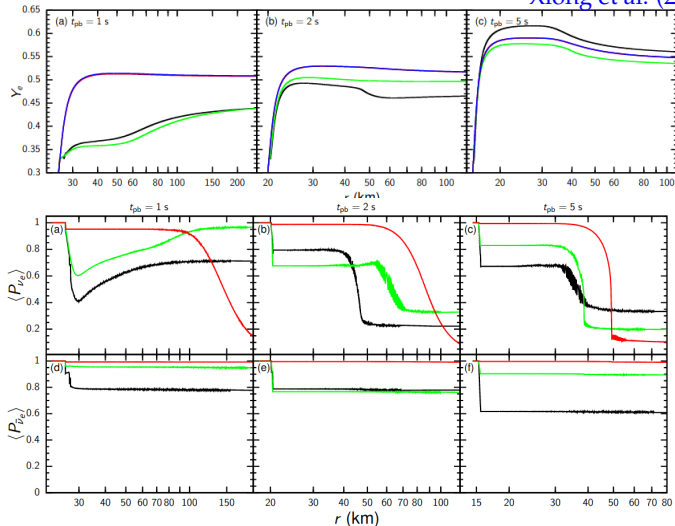


Effects of eV ν_s on CCSN

- 1st resonance less adiabatic
- depletion of ν_e leads to lowering of Y_e

Effects of eV-sterile neutrinos on nucleosynthesis

Xiong et al. (2019)



- $\nu_e - \nu_s$ conversions affect nucleosynthesis in the early cooling phase

Summary and Conclusions

Summary and Conclusions

- **Sterile neutrinos with eV-MeV masses**
 - have a major impact on the SN physics.
 - lead to the growth of neutrino asymmetries.
 - are responsible for the change of Y_e and Y_{ν_e} .
 - might affect the explosion mechanism.
 - might affect the nucleosynthesis.
 - might lead to detectable features.
 - **Full picture only when the sources are accurately modeled.**
- Exciting times ahead: more work needs to be done.**

Thank you for the attention!