Kavli Institute for
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The effects of sterile neutrinos on core-collapse supernovae

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**Interdisciplinary Developments
in Neutrino Physics, KITP**
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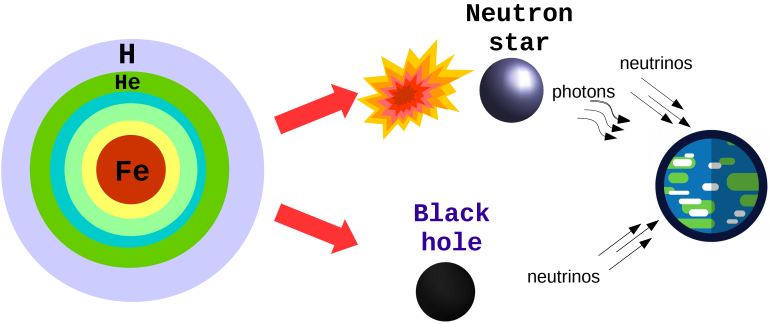
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

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



(see talk by George Fuller)

Why core-collapse supernovae are good physics probes?

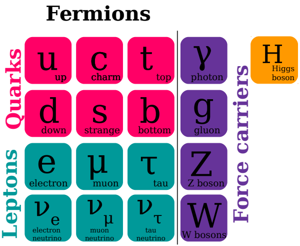
Advantages

- 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?

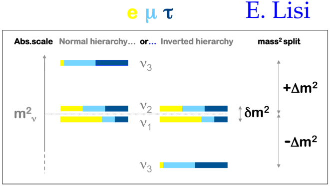
- explosion mechanism — H. Bethe & J. Wilson (1985), T. Fischer et al. (2011)...
- nucleosynthesis — S. Woosley et al. (1994), S. Curtis et al. (2018)...
- compact object formation — M. Warren et al. (2019), S. Li, J. F. Beacom et al. (2020)...
- neutrino mixing — H. Duan et al. (2010), I. Tamborra &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

Neutrino flavor and mass states



flavor basis **mass basis**

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



E. Lisi

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?

(see talks by Callum Wilkinson, Zoya Vallari, Leigh Whitehead, Michael Smy, Andre de Gouvea, Joachim Kopp, Matheus Hostert, Kaladi Babu)

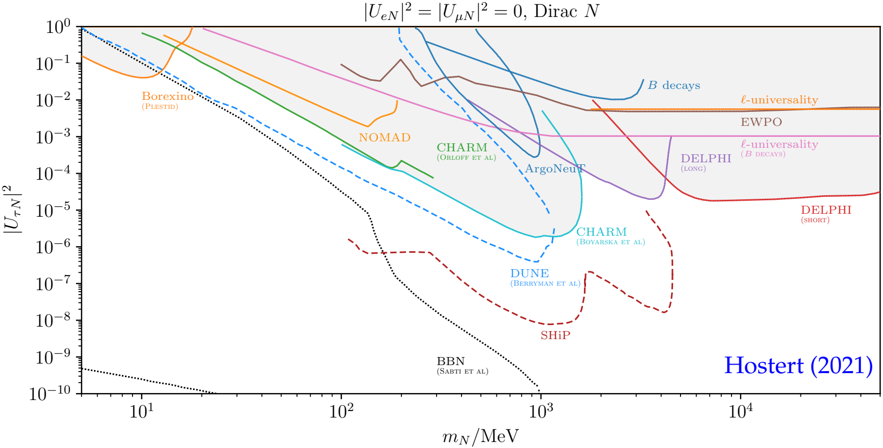
Pontecorvo (1957), Maki, Nakagawa, Sakata (1962)

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 nucleosyntesis in CCSNe

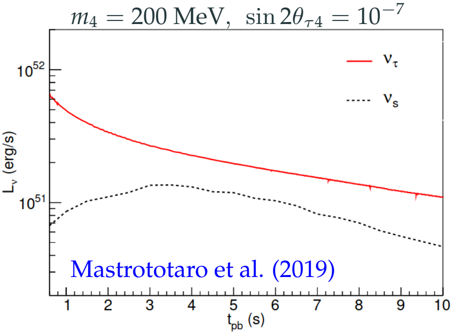
Sterile neutrinos with MeV masses in CCSNe

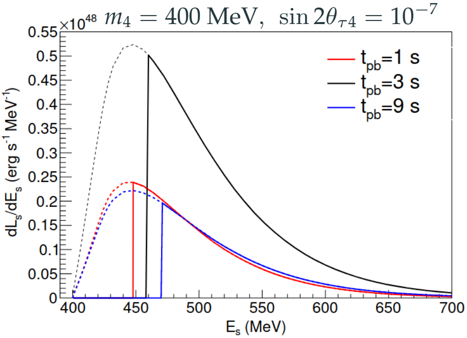
Limits: Sterile neutrinos with MeV masses



- Big Bang Nucelosyntesis (see talk by Graciela Gelmini)
- Terrestrial experiments (see talk by Matheus Hostert)

Heavy sterile neutrinos production processes in CCSN



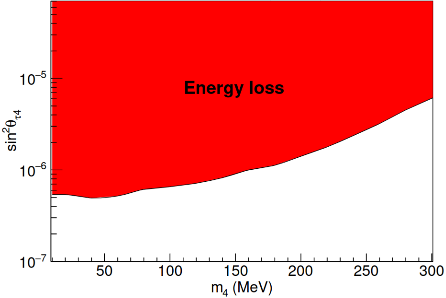


- Hot, dense, and degenerate core (e^-, p, n)
- Tau neutrinos: numerous and non-degenerate
- Production channels: $\nu_\tau + \nu_\tau \to \nu_s + \nu_\tau$

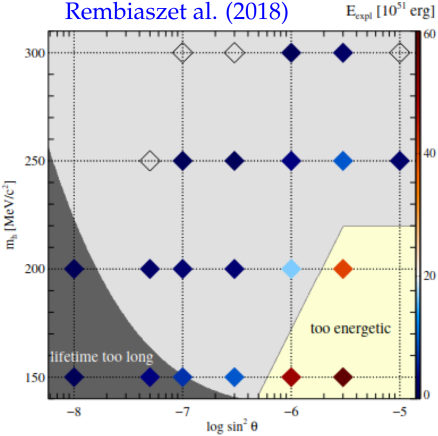
Fuller et al. (2008), Albertus et al. (2015), Rembiaszet al. (2018), Mastrototaro et al. (2019)

Limits on the MeV-mass sterile ν from CCSN

Mastrototaro et al. (2019)



Rembiaszet al. (2018)

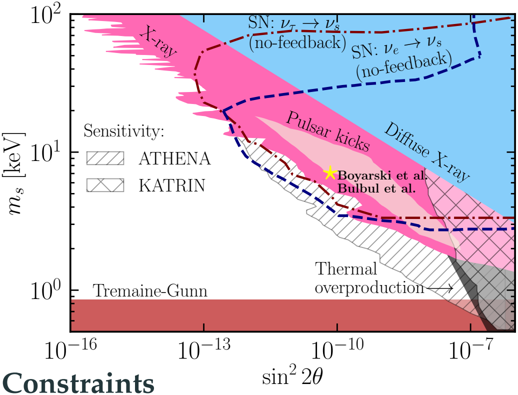


Effect of MeV ν_s on CCSN

- Cooling channel
- Heating mechanism
- Production of potentially detectable energetic neutrinos ($\sim$ 100 MeV)

Sterile neutrinos with keV masses in CCSNe

Sterile neutrino as dark matter candidate



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)

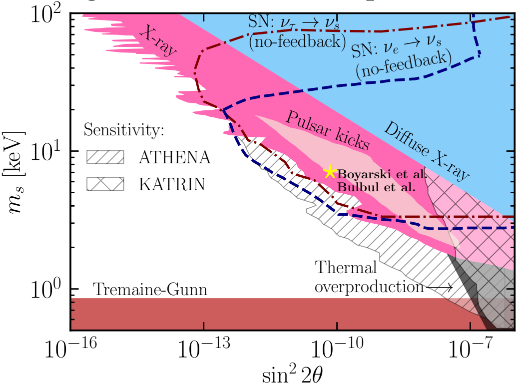
(see talks by Kevork Abazajian and Graciela Gelmini)

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))

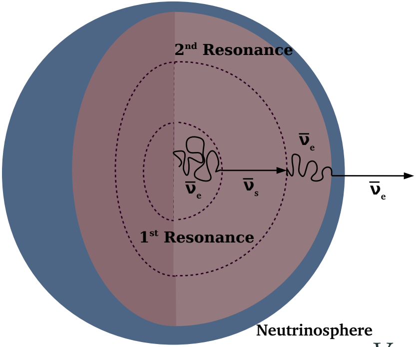
The role of sterile neutrinos in supernovae; previous studies

- 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

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

MSW

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

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

Collisions

$$\Gamma_{\nu_s} = \frac{1}{4} \sin^2 2\widetilde{\theta}\, \Gamma_{\nu_{\rm active}}$$

$\nu_e - \nu_s$ mixing: multiple resonances

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

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

Sterile neutrino conversions in the stellar core

Collisional production

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

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

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

C. W. Kim et al. (1987), S. J. Parke (1987), S. P. Mikheev and A. Yu. Smirnov (2007)

Sterile neutrino conversions in the stellar core

Collisional production

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

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

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

MSW production

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

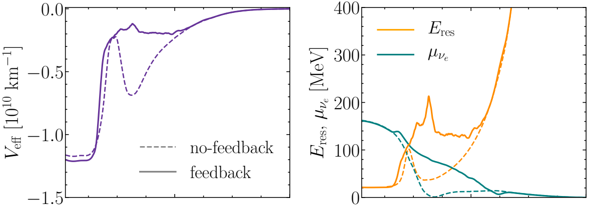
$$\Delta_{\text{res}} = \tan 2\theta\left|\frac{dV_{\text{eff}}/dr}{V_{\text{eff}}}\right|^{-1}$$

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

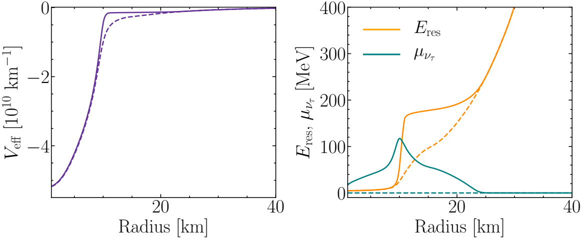
C. W. Kim et al. (1987), S. J. Parke (1987), S. P. Mikheev and A. Yu. Smirnov (2007)

Sterile neutrino conversions in the stellar core

$\nu_s - \nu_e$ mixing: multiple resonances



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



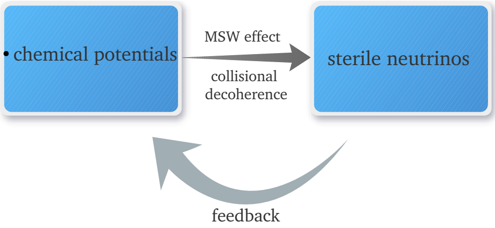
1D SN model
Garching group archive

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

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

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

The sterile-tau neutrino mixing: growth of the asymmetry



- chemical potentials

MSW effect

collisional decoherence

sterile neutrinos

feedback

Only active neutrinos

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

The active neutrinos after being **converted to sterile ones effectively disappear;**

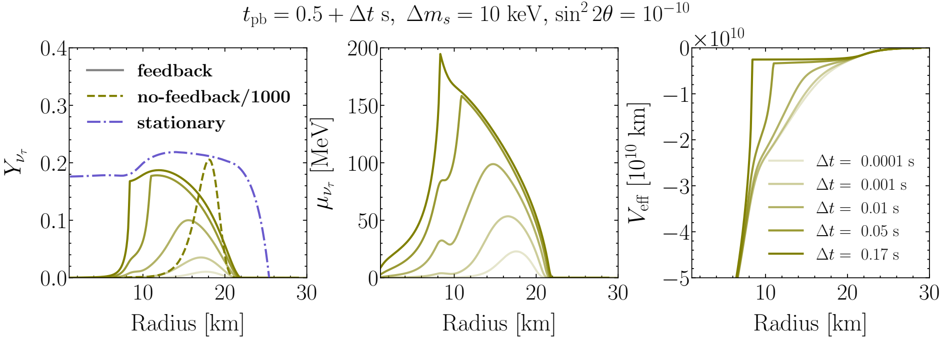
since they were **strongly coupled** to the rest of the particles in the medium,
a **new equilibrium state forms.**

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

Active + sterile neutrinos

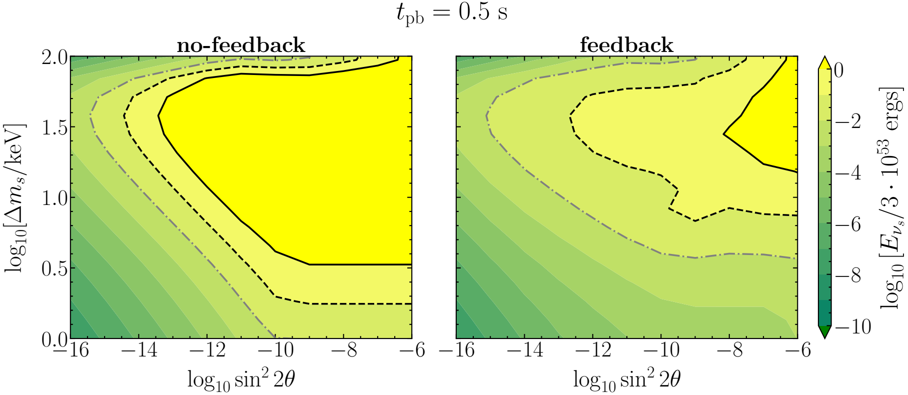
$$Y_{\nu_\tau}(r,t) = \frac{1}{n_b(r)} \int_0^t dt' \, \frac{d\left(P_{\nu_\tau \to \nu_s} n_{\nu_\tau}(r,t') - P_{\bar{\nu}_\tau \to \bar{\nu}_s} n_{\bar{\nu}_\tau}(r,t')\right)}{dt'}$$

Radial evolution of the asymmetry w and w/o feedback



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

Supernova bounds on the mixing parameters



- 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

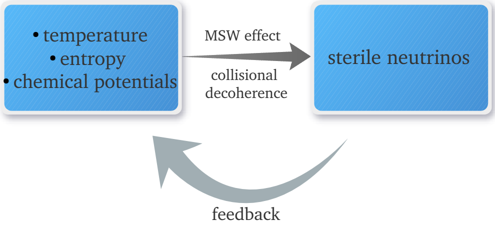
$$Y_p(r,t) + Y_n(r,t) = 1 \, ,$$

Charge conservation

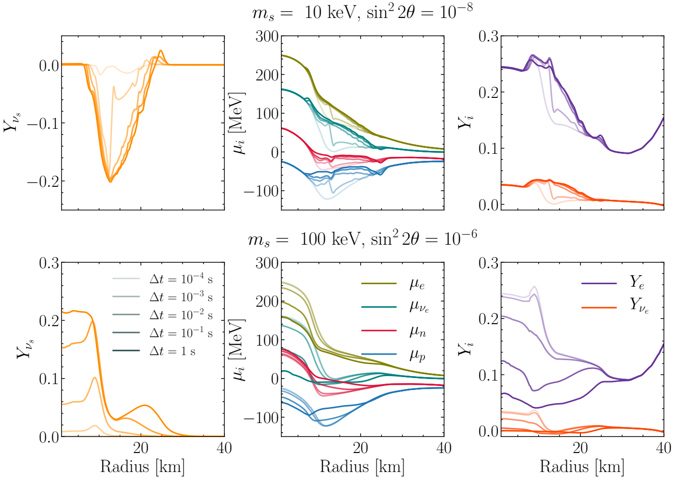
$$Y_p(r,t) = Y_e(r,t) \, ,$$

Entropy change

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

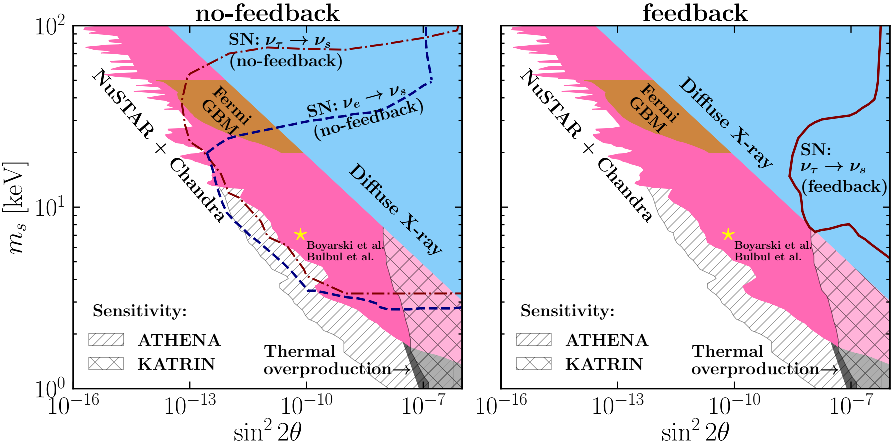


Radial evolution of the asymmetry



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

Supernova bounds on the mixing parameters

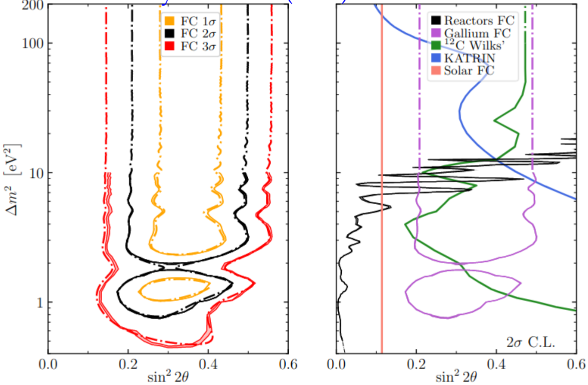


- **The inclusion of feedback greatly reduces the excluded region.**
- **CC-SNe cannot exclude any region of the DM parameter space.**

Sterile neutrinos with eV masses in CCSNe

Limits and hints: eV sterile neutrinos

Berryman et al. (2021)

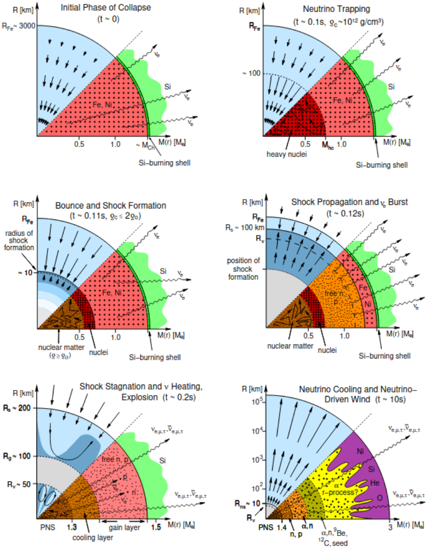


(see talks by Ornella Palamara, Karsten Heeger, Joachim Kopp)

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

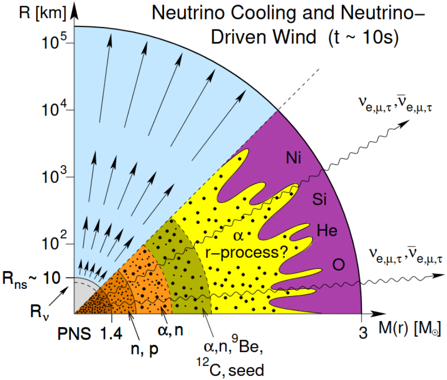
Neutrino driven wind and nucleosynthesis in CCSN

Janka et al. 2006



Neutrino driven wind and nucleosynthesis in CCSN

Janka et al. 2006



Source of the wind: neutrino heating

$$\nu_e + n \to e^- + p$$

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

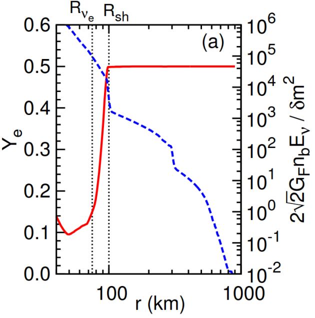
(see talks by Amol Patwardhan and Gail McLaughlin)

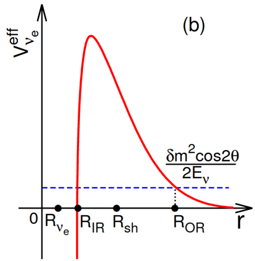
- r-process nucleosynthesis extremely sensitive to Y_e
- Y_e sensitive to the ratio of ν_e and $\bar{\nu}_e$
- The ratio of ν_e and $\bar{\nu}_e$ determined by neutrino conversions

Woosley & Baron (1992), Woosley & Hoffman (1992), Meyer et al. (1992), Woosley et al. (1994), Witti 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)...

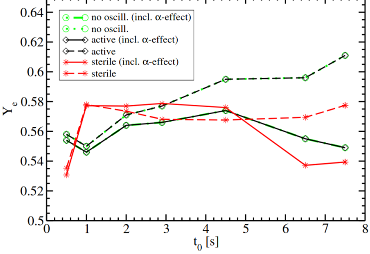
Sterile neutrino conversions outside of the core

Wu et al. (2013)





Pllumbi, Tamborra et al. (2014)



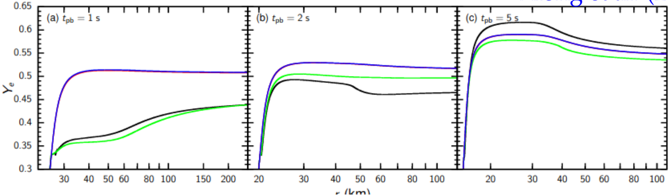
Effects of eV ν_s on CCSN

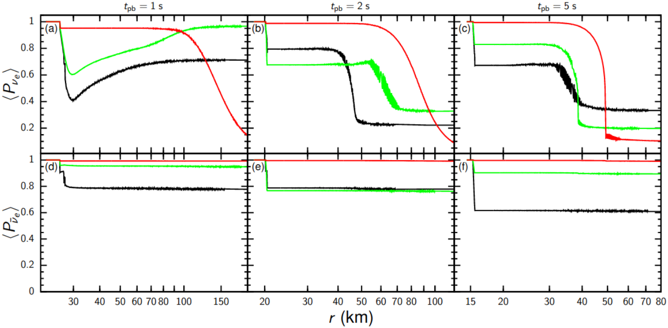
- 1st resonance less adiabatic
- depletion of ν_e leads to lowering of Y_e

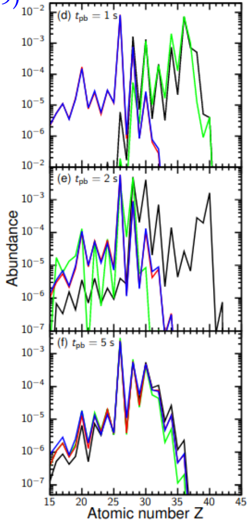
Qian et al. (1993), Nunokawa et al. (1997), McLaughlin et al. (1999), Fetter et al. (2002), Tamborra et al. (2011), Wu et al. (2013), Pllumbi et al. (2014), Xiong et al. (2019)

Effects of eV-sterile neutrinos on nucleosyntesis

Xiong et al. (2019)







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

Summary and Conclusions

Summary and Conclusions

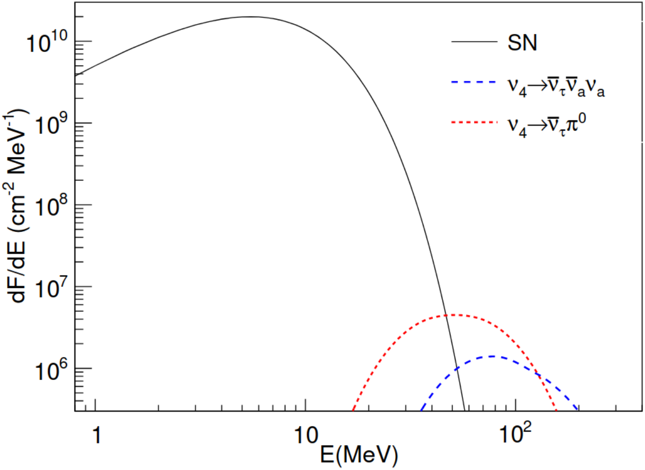
- **Sterile neutrinos with eV-MeV masses**
  - have a major impact on the SN physics.
  - lead to the growth of neutrino asymmetries.
  - are responsible for the change of Y_e and Y_{ν_e}.
  - might affect the explosion mechanism.
  - might affect the nucleosyntesis.
  - might lead to detectable features.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

Exciting times ahead: more work needs to be done.

Thank you for the attention!

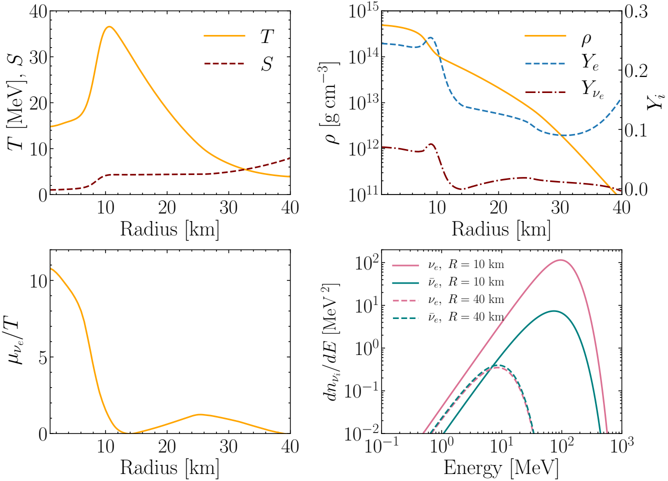
Backup slides

Events from sterile neutrino decay

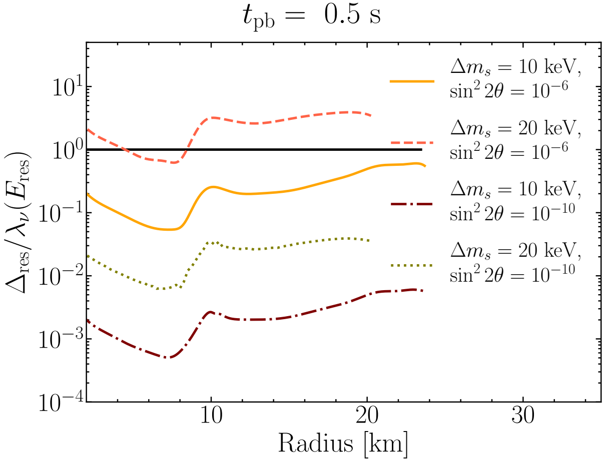


Channel	Number of events	
	NH	IH
SN $\bar{\nu}_e$	5280	5640
$\nu_4 \rightarrow \pi^0 \bar{\nu}_\tau$	141	470
$\nu_4 \rightarrow \nu_\tau \nu_a \bar{\nu}_a$	115	182

Initial conditions



Will they collide or undergo MSW resonance?

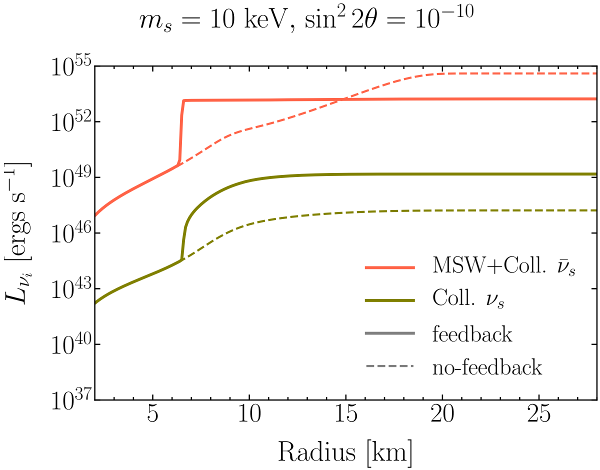


$$\Delta_{\rm res} = \tan 2\theta \left| \frac{dV/dr}{V} \right|^{-1}$$

$$\Delta_{\rm res} < \lambda_\nu(E_{\rm res})\ ?$$

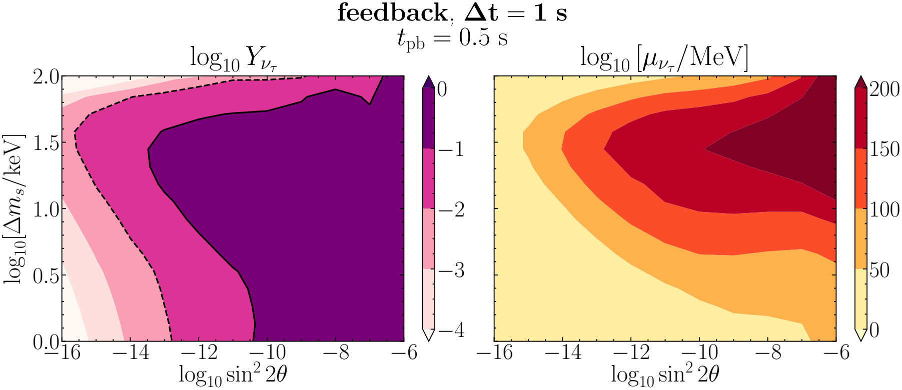
$$\lambda_\nu(E_{\rm res}) \simeq \frac{1}{n(r)\sigma(E,r)}$$

Tau-sterile mixing: sterile neutrino luminosity



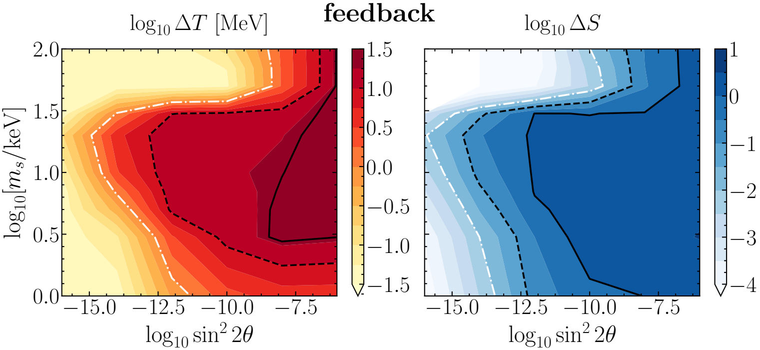
- The total luminosity $(\nu_s + \bar{\nu}_s)$ decreases with time.

Contour plot of tau fraction



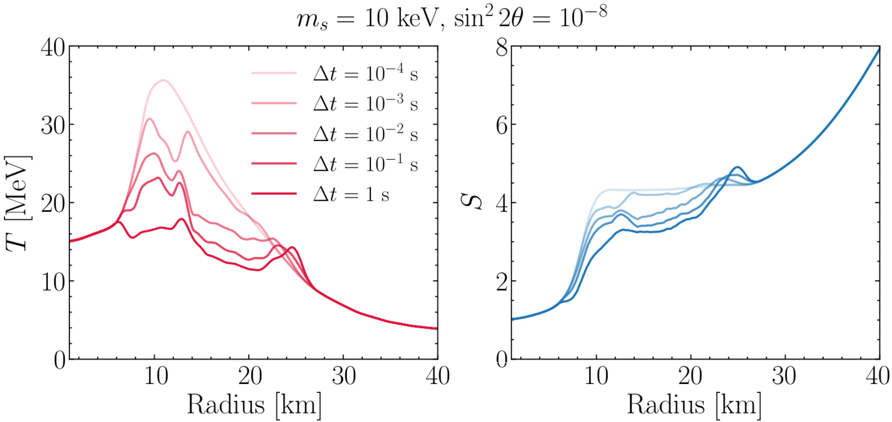
- Higher mixing angles reach the saturation value faster.
- More massive sterile neutrinos reach smaller saturation values, fewer energy modes have enhanced conversion probability.

Contour plot: temperature and entropy



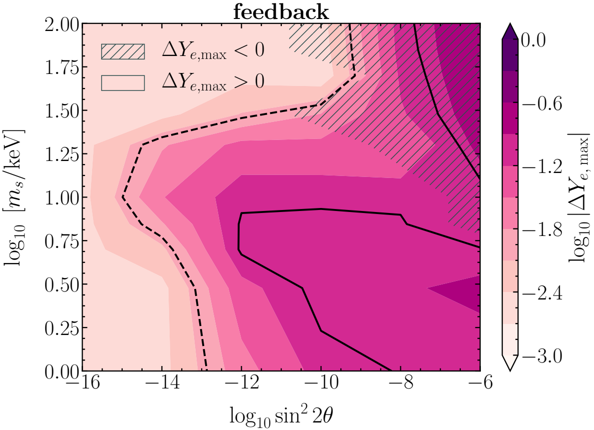
- Large variations for high mixing angles due to
  - adiabatic conversions,
  - high number of sterile neutrinos produced by collisions.

Radial evolution of temperature and entropy per baryon



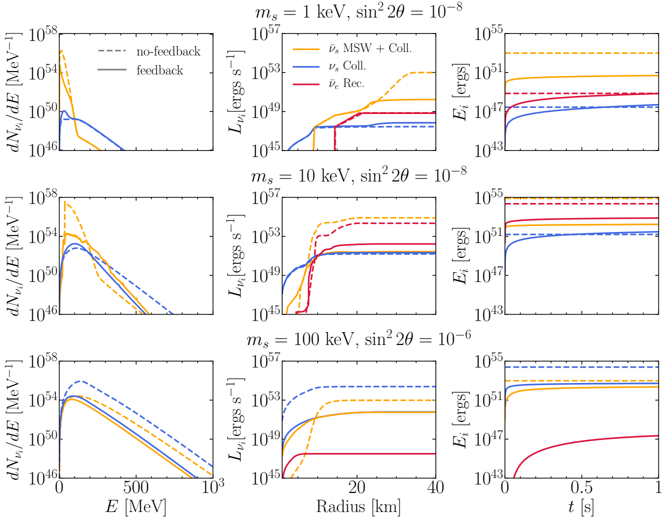
- The $\nu_s - \nu_e$ mixing induces large variations on
  - the entropy per baryon,
  - the supernova medium temperature.

Contour plot: electron fraction

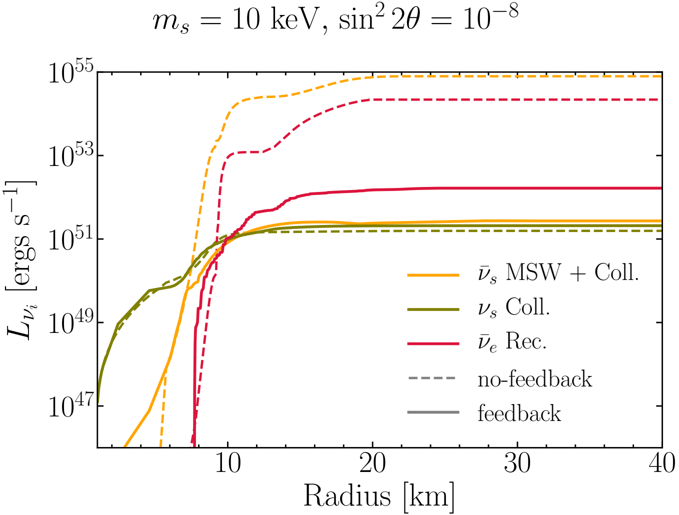


- The change in Y_e can be negative or positive.
- Might considerably affect the evolution of the proto-neutron star.

Comparison for different mixing parameters

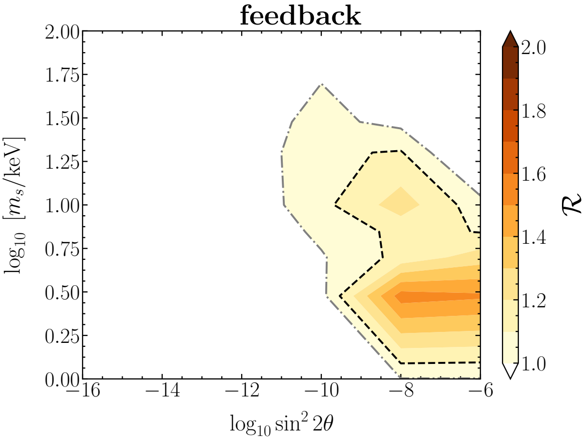


Electron-sterile mixing: sterile neutrino luminosity



- The total luminosity ($\nu_s + \bar{\nu}_s$) decreases with time.

The region of a possible supernova explosion enhancement

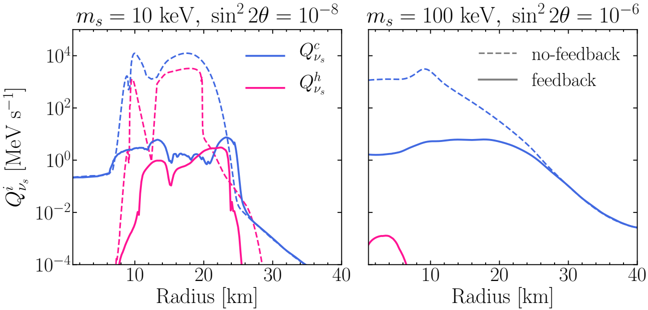


$$\mathcal{R} = \frac{E_{G,\mathrm{out}} + E_{\nu_s \to \nu_i} - E_{\nu_s}}{E_{G,\mathrm{out}}}$$

- Heating of the outer layers → emission of high energy $\nu_e, \bar{\nu}_e$
- Increased energy deposition in the stalled shock → easier explosion

M. L. Warren et al. (2014)

Sterile neutrino heating and cooling

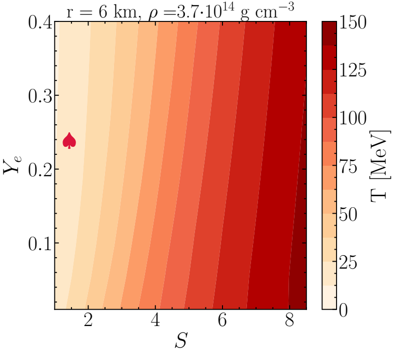


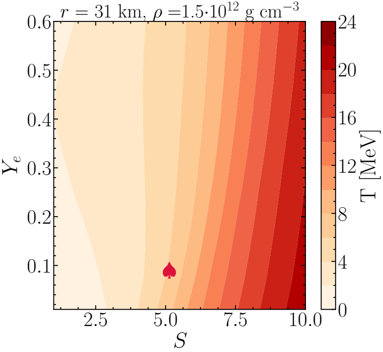
$$\dot{E}^c_\nu(r,t) \sim V(r)\Delta r^{-1} \sum_{k=1}^{L} P_{\rm es}(E_k,r,t)\, \frac{dn_\nu}{dE_k}(r,t)\, dE_k E_k$$

$$\dot{E}^h_\nu(r,t) \sim$$

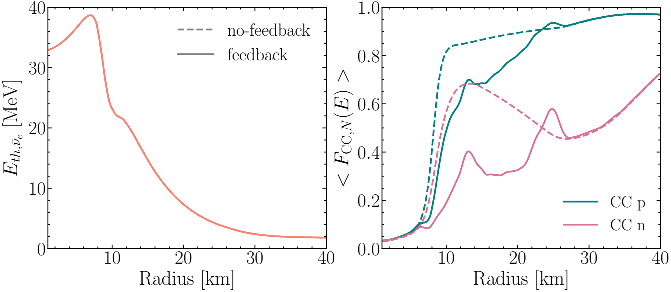
$$\sum_{k=1}^{L} \left[P_{\rm se}(E_k,r,t)\Theta\left(\frac{\Delta r}{\lambda_\nu(E_k,r)}\right) \sum_{j=1}^{i-1} P_{\rm es}(E_k,r_j,t)\, \frac{dn_\nu}{dE}(r_j,t)\, \frac{r_j^2}{r_i^2}\, dE_k E_k \right] \times V(r)\Delta r^{-1}$$

Temperature interpolation





Pauli blocking



- In the region affected by the sterile neutrino production $\langle FCC, p(n)(E)_N \rangle$ decreases (increases) following the *Ye* increase (decrease).