Core-collapse supernovae as probes of new neutrino physics

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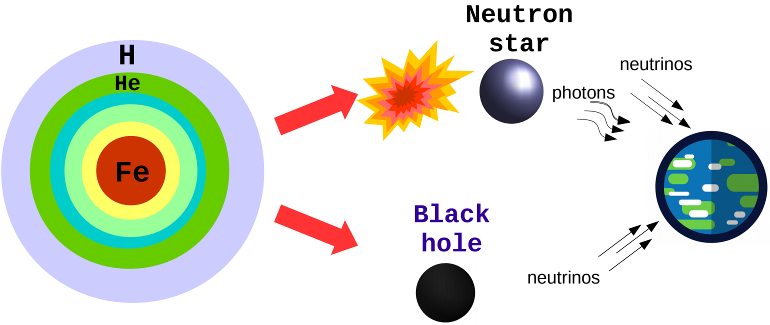
Why are neutrinos important for a core-collapse supernova?

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?

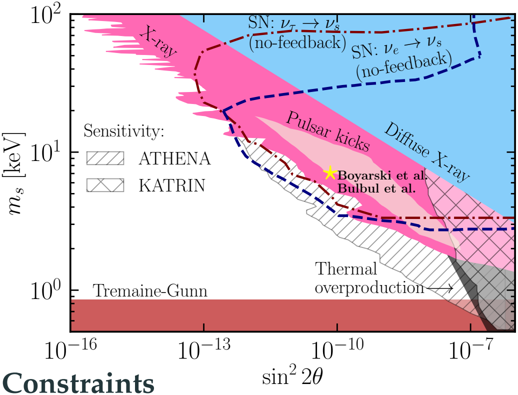
- explosion mechanism — H. Bethe & J. Wilson (1985), T. Fischer et al. (2011)...
- yields of heavy elements — S. Woosley et al. (1994), S. Curtis et al. (2018)...
- compact object formation — M. Warren et al. (2019), S. Li, J. F. Beacom et al. (2020)...
- neutrino mixing — H. Duan et al. (2010), I. Tamborra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

Sterile neutrinos with keV masses in supernovae

In collaboration with I. Tamborra and M-R. Wu

JCAP 12 (2019) 019 and JCAP 08 (2020) 018

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),

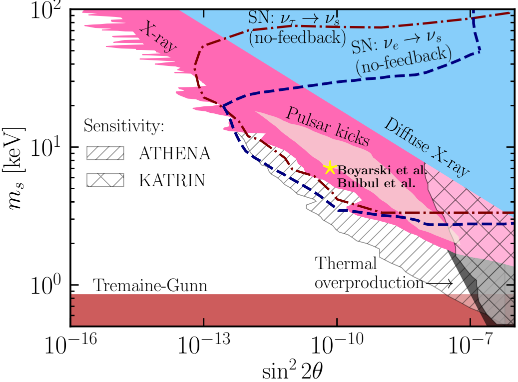
E. Bulbul et al. (2014)

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))

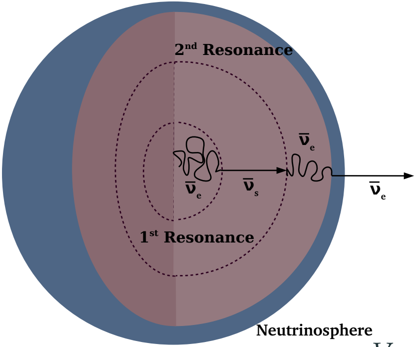
The role of sterile neutrinos in supernovae; previous studies

- 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 et al. (2019)**, Syvolap et al. (2019), **Suliga et al. (2020)**

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

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

Collisions

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

$\nu_e - \nu_s$ 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)...

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

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MSW production

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

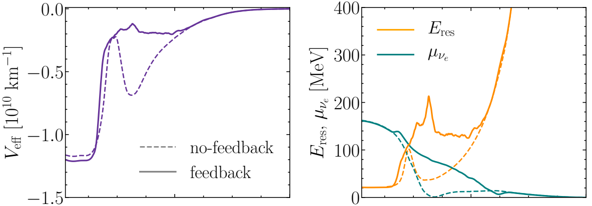
$$\Delta_{\rm res} = \tan 2\theta \left|\frac{dV_{\rm eff}/dr}{V_{\rm eff}}\right|^{-1}$$

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

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

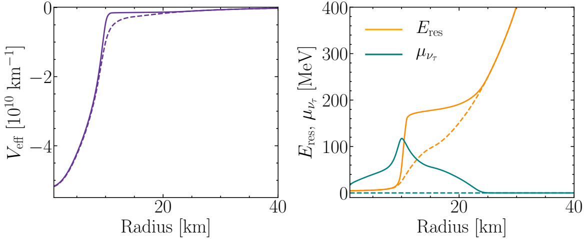
Sterile neutrino conversions in the stellar core

$\nu_s - \nu_e$ **mixing: multiple resonances**



1D SN model
Garching group archive

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



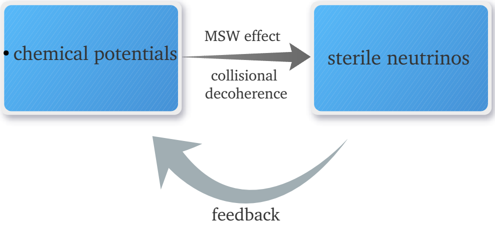
$$E_{\rm res} = \frac{\cos 2\theta \Delta m_s^2}{2V_{\rm eff}}$$

$m_s = 10$ 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

Only active neutrinos



- chemical potentials

MSW effect

collisional decoherence

sterile neutrinos

feedback

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

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

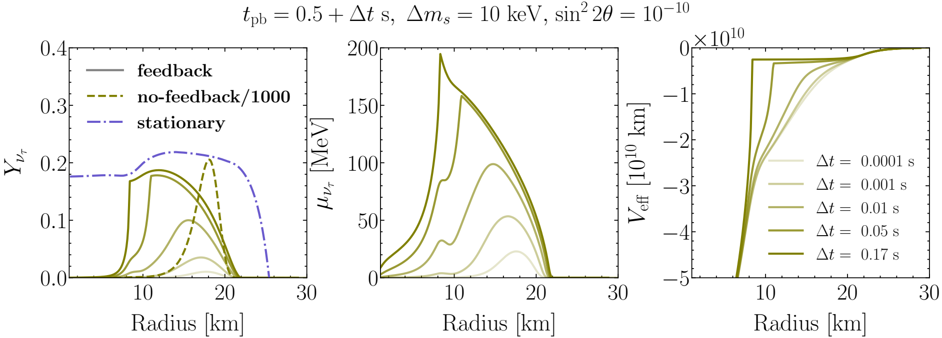
since they were **strongly coupled** to the rest of the particles in the medium,
a **new equilibrium state forms.**

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

Active + sterile neutrinos

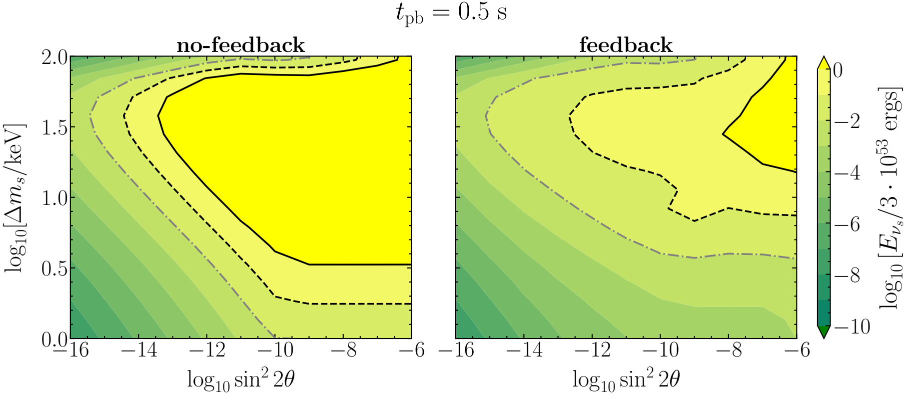
$$Y_{\nu_\tau}(r,t) = \frac{1}{n_b(r)} \int_0^t dt' \, \frac{d\left(P_{\nu_\tau \to \nu_s} n_{\nu_\tau}(r,t') - P_{\bar{\nu}_\tau \to \bar{\nu}_s} n_{\bar{\nu}_\tau}(r,t')\right)}{dt'}$$

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

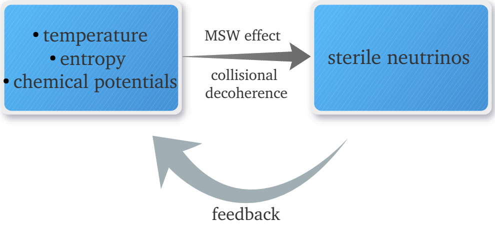
$$Y_p(r,t) + Y_n(r,t) = 1\ ,$$

Charge conservation

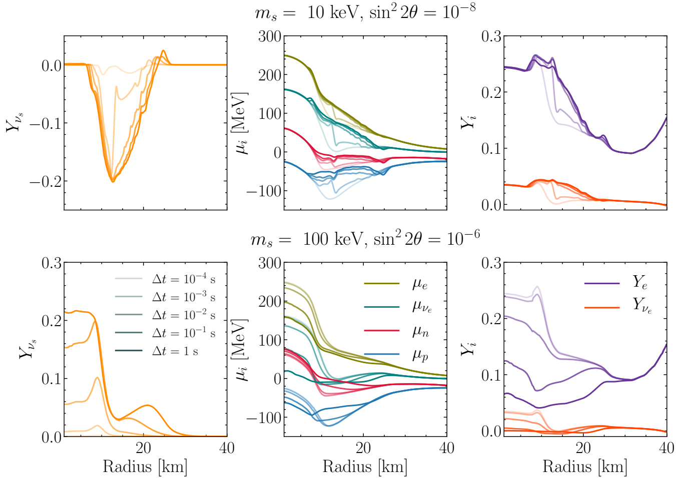
$$Y_p(r,t) = Y_e(r,t)\ ,$$

Entropy change

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

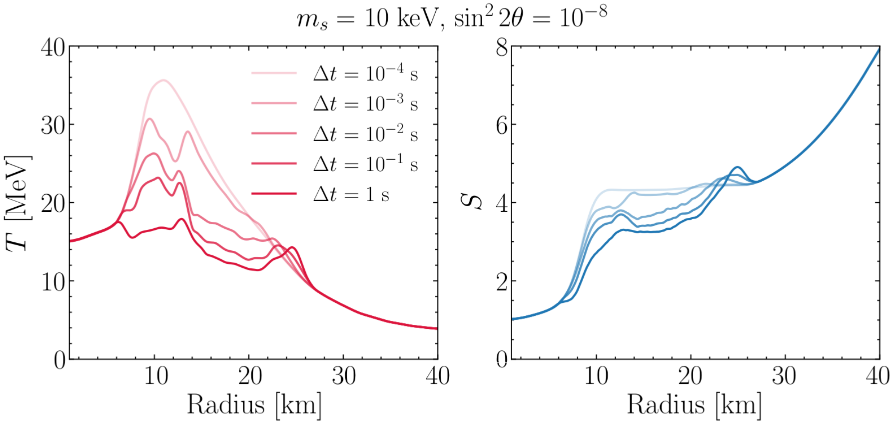


Radial evolution of the asymmetry



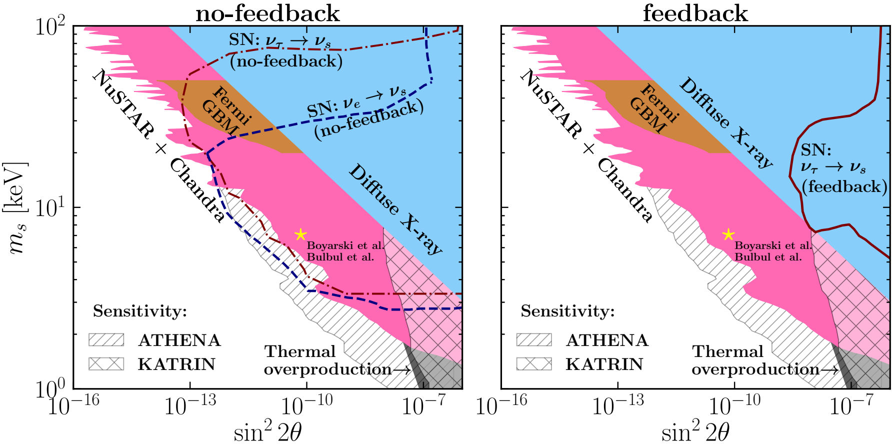
- Sterile neutrinos modify $Y_e,\ Y_{\nu_e},\ Y_p$ and Y_n.
- Feedback on the physical quantities depends greatly on the m_s.

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.

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.**

Conclusions: sterile neutrinos

- **Sterile neutrinos with keV mass**
  - have a major impact on the SN physics.
  - lead to the growth of Y_{ν_τ} asymmetry.
  - are responsible for the change of Y_e and Y_{ν_e}.
  - might affect the explosion mechanism.

- **Feedback is crucial.**

- **New treatment of active-sterile neutrino mixing in SNe challenges sterile neutrino bounds.**

Conclusions: sterile neutrinos

- **Sterile neutrinos with keV mass**
  - have a major impact on the SN physics.
  - lead to the growth of Y_{ν_τ} asymmetry.
  - are responsible for the change of Y_e and Y_{ν_e}.
  - might affect the explosion mechanism.

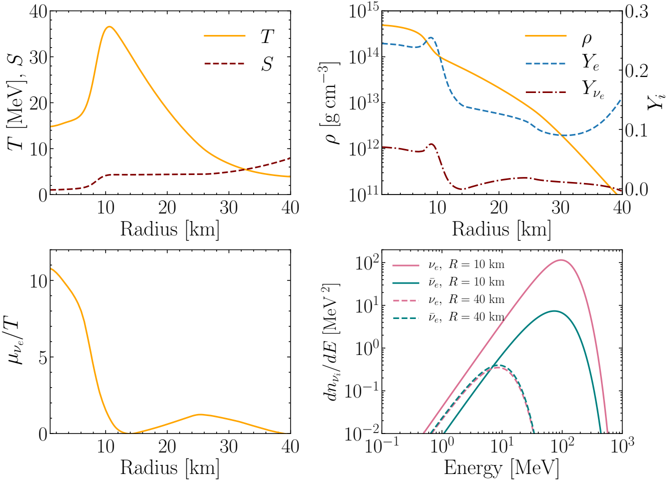
- **Feedback is crucial.**

Thank you for the attention!

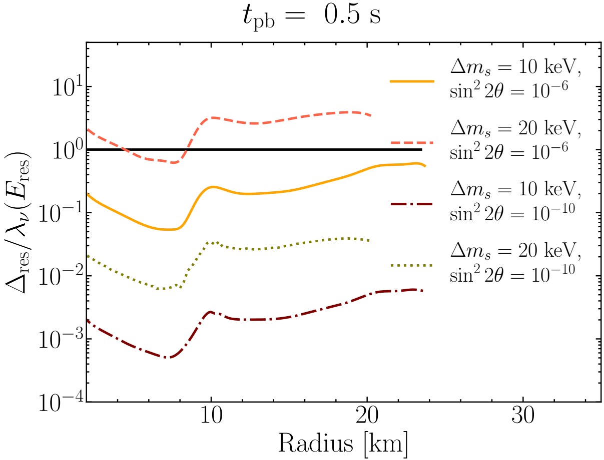
- **New treatment of active-sterile neutrino mixing in SNe challenges sterile neutrino bounds.**

Backup slides

Initial conditions



Will they collide or undergo MSW resonance?

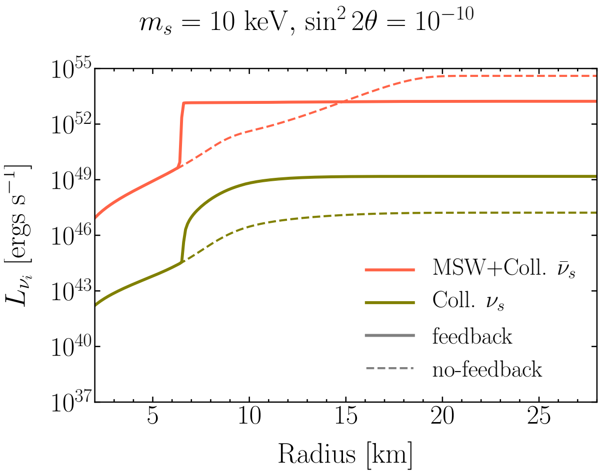


$$\Delta_{\rm res} = \tan 2\theta \left| \frac{dV/dr}{V} \right|^{-1}$$

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

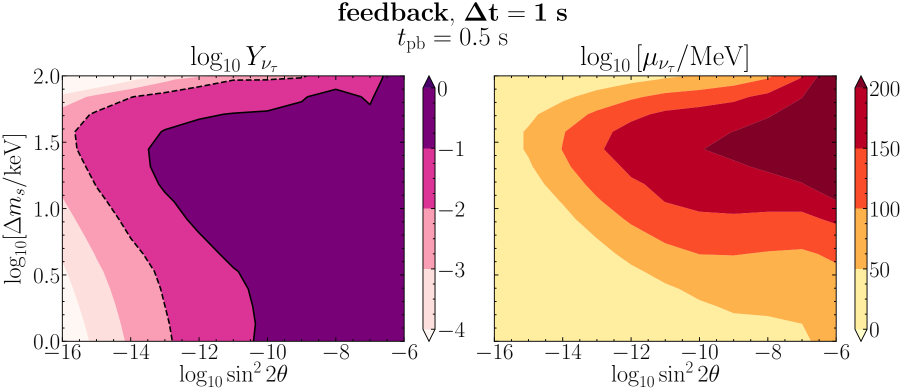
$\Delta_{\rm res} < \lambda_\nu(E_{\rm res})$?

Tau-sterile mixing: sterile neutrino luminosity



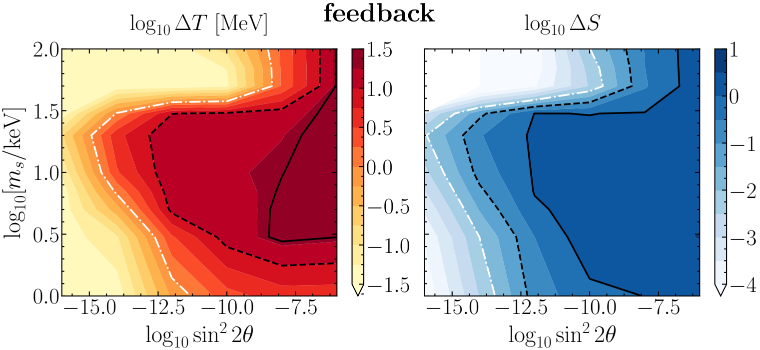
- The total luminosity ($\nu_s + \bar{\nu}_s$) decreases with time.

Contour plot of tau fraction



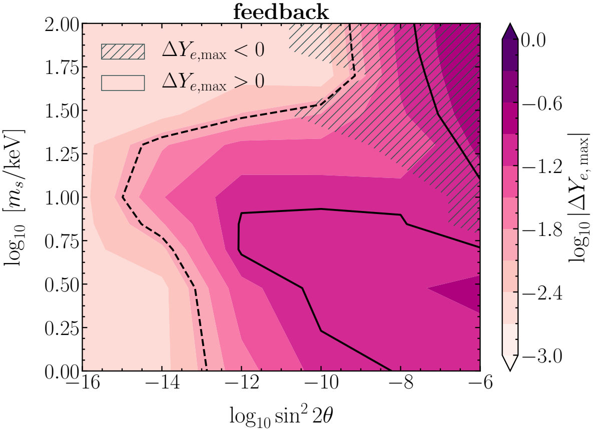
- Higher mixing angles reach the saturation value faster.
- More massive sterile neutrinos reach smaller saturation values, fewer energy modes have enhanced conversion probability.

Contour plot: temperature and entropy



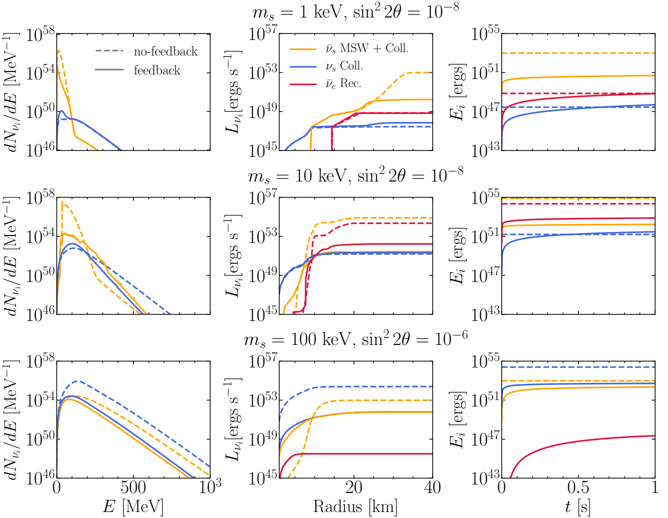
- Large variations for high mixing angles due to
  - adiabatic conversions,
  - high number of sterile neutrinos produced by collisions.

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



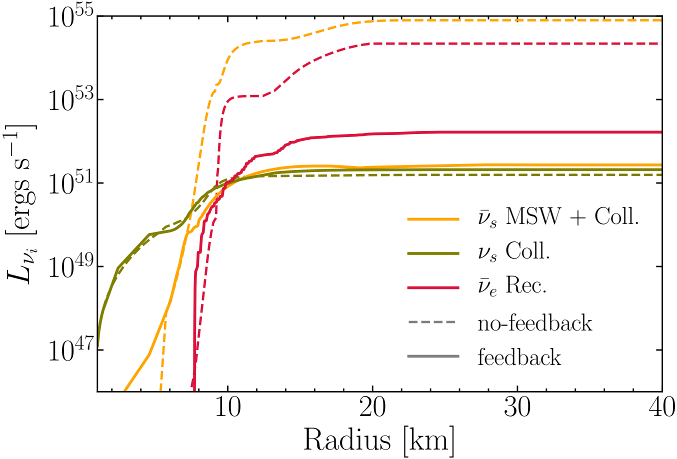
$m_s = 1$ keV, $\sin^2 2\theta = 10^{-8}$

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

$m_s = 100$ keV, $\sin^2 2\theta = 10^{-6}$

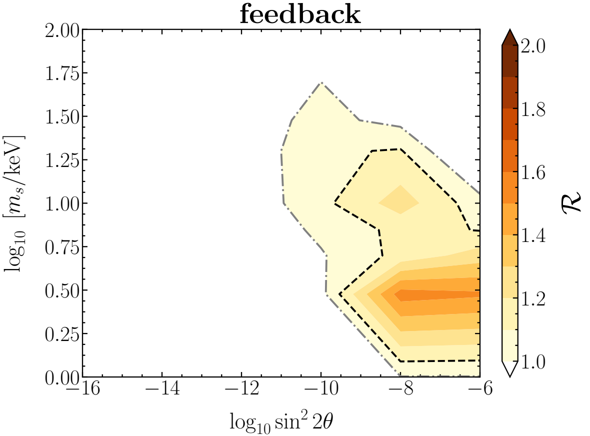
Electron-sterile mixing: sterile neutrino luminosity

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



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

The region of a possible supernova explosion enhancement

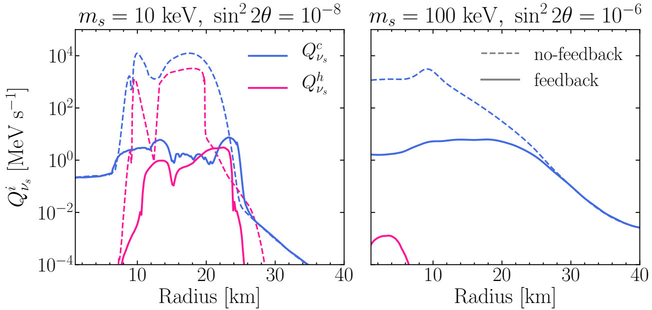


$$\mathcal{R} = \frac{E_{G,\mathrm{out}} + E_{\nu_s \to \nu_i} - E_{\nu_s}}{E_{G,\mathrm{out}}}$$

- 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)

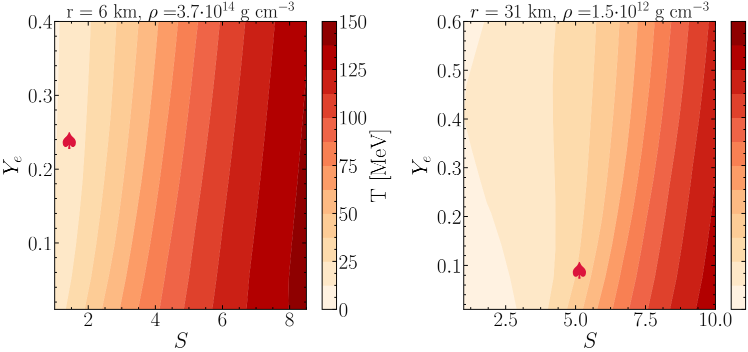
Sterile neutrino heating and cooling



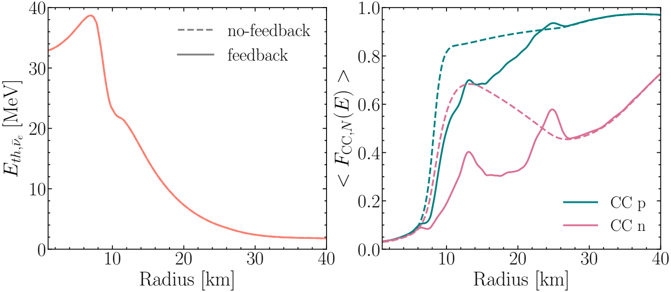
$$\dot{E}^c_\nu(r,t) \sim V(r)\Delta r^{-1} \sum_{k=1}^{L} P_{\rm es}(E_k,r,t)\, \frac{dn_\nu}{dE_k}(r,t)\, dE_k E_k$$

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

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).