The impact of keV sterile neutrinos on core-collapse supernovae

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Overview

❶ Core-collapse supernovae

❷ Sterile neutrinos with keV masses

❸ Sterile neutrino conversions in the stellar core

❹ The sterile-tau neutrino mixing

❺ The sterile-electron neutrino mixing

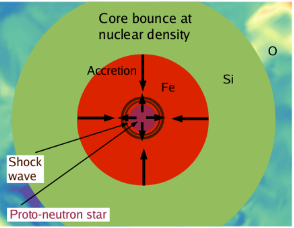
❻ Conclusions

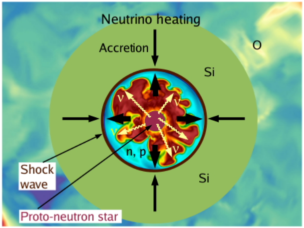
Core-collapse supernovae

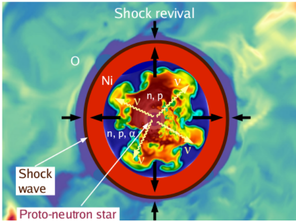
Why are neutrinos important for a core-collapse supernova?

Different phases of a core-collapse supernova explosion

- Neutronization phase, ν_e burst $\sim$ 40 ms
- Accretion phase, $\sim$ 100 ms
- Cooling phase, $\sim$ 10 s







H. T. Janka, arXiv:1702.08713

Neutrino flavors

active neutrinos

Neutrino flavors

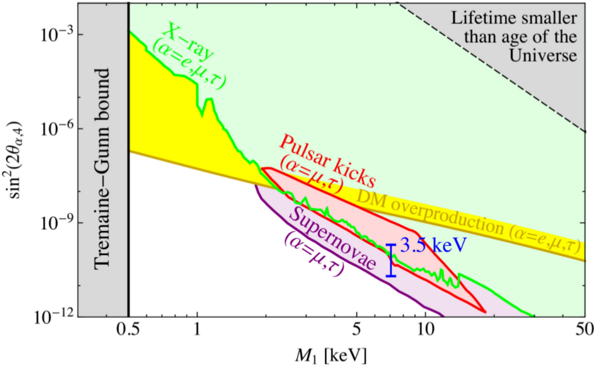
active neutrinos

+ sterile neutrino

The Particle Zoo

Sterile neutrinos with keV masses

Sterile neutrino as dark matter candidate



Favorable regions

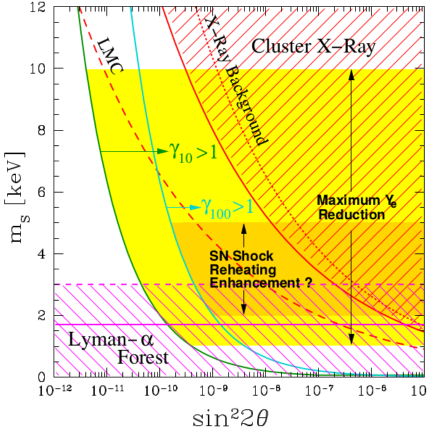
- Pulsar kicks
  (A. Kusenko (2004))
- 3.5 keV line
  (A. Boyarsky et al. (2014), E. Bulbul et al. (2014))

Constraints

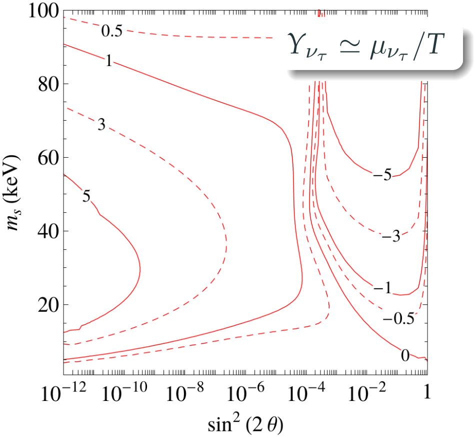
- Supernovae energy bounds (X. Shi & G.Sigl (1994))
- DM overproduction (S. Dodelson, L. M. Widrow (1994), X. Shi, G. M. Fuller (1999))
- Radiative decay (NuSTAR, XMM, Chandra)
- Tremaine-Gunn bound

Sterile Neutrino Dark Matter, A. Merle (2017)

The role of sterile neutrinos in supernovae



J. Hidaka and G. M. Fuller (2006)



$Y_{\nu_\tau} \simeq \mu_{\nu_\tau}/T$

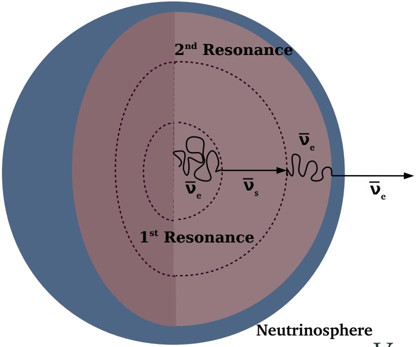
G. G. Raffelt and S. Zhou (2011)

- Suppression /enhancement of the SN explosion
- Change of the electron or neutrino (ν_e, ν_μ, ν_τ) fractions

H. Nunokawa et al. (1997), M. L. Warren et al. (2016), C. A. Argüelles et al. (2016) ...

Sterile neutrino conversions in the stellar core

Sterile neutrino conversions in the stellar core



1D SN model
Garching group archive

MSW

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

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

Collisions

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

$\nu_e - \nu_s$ mixing: multiple resonances

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

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

Sterile neutrino conversions in the stellar core

Collisional production

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

MSW production

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

$$\Gamma_\nu(E) \simeq n(r)\sigma(E, r)$$

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

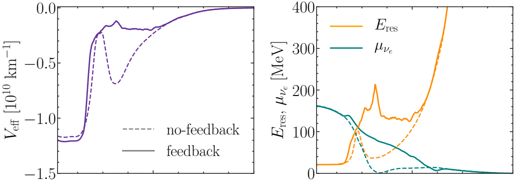
$$\Delta_{\text{res}} = \tan 2\theta \left| \frac{dV_{\text{eff}}/dr}{V_{\text{eff}}} \right|^{-1}$$

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

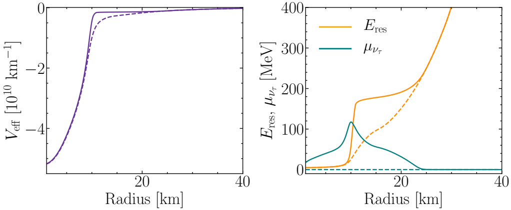
C. W. Kim et al. (1987), S. J. Parke (1987), S. P. Mikheev and A. Yu. Smirnov (2007)

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

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

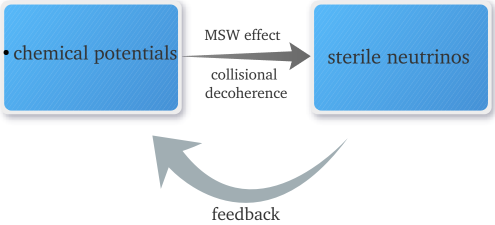
- **Negative $V_{\rm eff} \rightarrow$ MSW resonances only for antineutrinos.**
- **Growing chemical potential slows down $\bar{\nu}_s$ production.**

The sterile-tau neutrino mixing

Development of the neutrino lepton asymmetry

Only active neutrinos

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



- chemical potentials

MSW effect

collisional decoherence

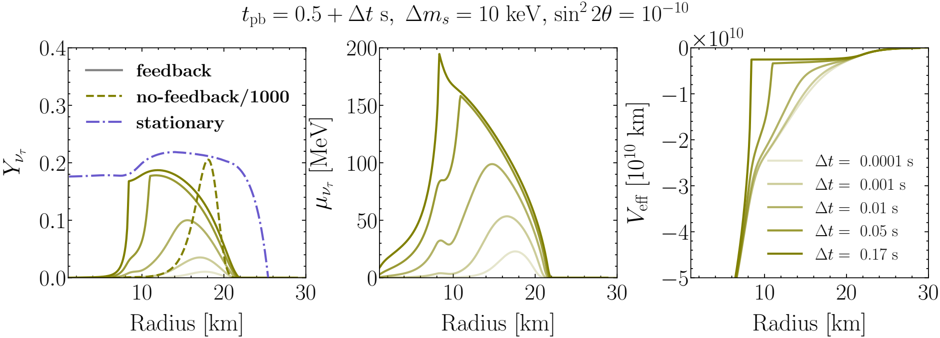
sterile neutrinos

feedback

Active + sterile neutrinos

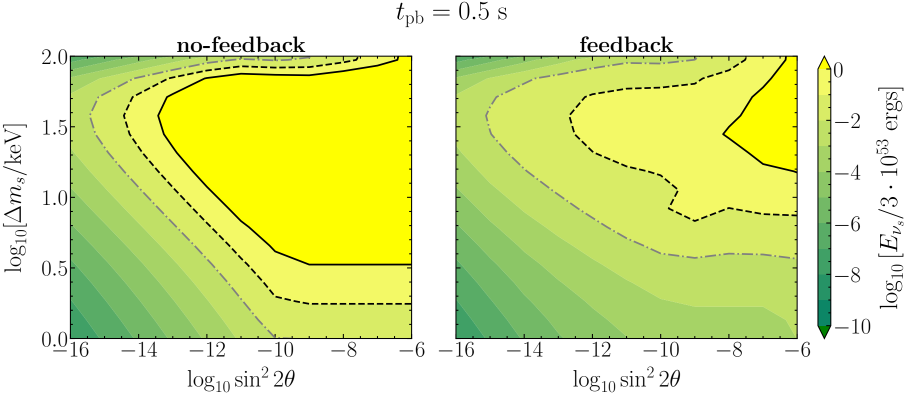
$$Y_{\nu_\tau}(r,t) = \frac{1}{n_b(r)} \int_0^t dt' \, \frac{d\left(P_{\nu_\tau \to \nu_s} n_{\nu_\tau}(r,t') - P_{\bar{\nu}_\tau \to \bar{\nu}_s} n_{\bar{\nu}_\tau}(r,t')\right)}{dt'}$$

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.

The 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

Equations describing the dynamical feedback

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

β equilibrium

$$\mu_e(r,t)+\mu_\mathrm{p}(r,t)+m_\mathrm{p}=\mu_{\nu_e}(r,t)+\mu_\mathrm{n}(r,t)+m_\mathrm{n}\ ,$$

Lepton number conservation

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

Charge conservation

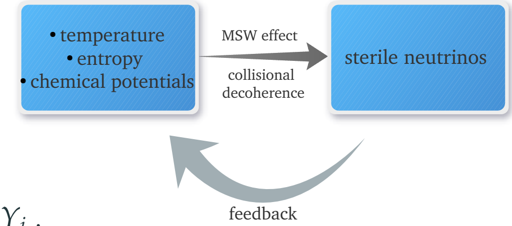
$$Y_\mathrm{p}(r,t)+Y_\mathrm{n}(r,t)=1\ ,$$

Baryon number conservation

$$Y_\mathrm{p}(r,t)=Y_e(r,t)\ ,$$

Entropy change

$$dS=Q/T+P/TdV-\sum_i \mu_i/TdY_i\ .$$



- temperature
- entropy
- chemical potentials

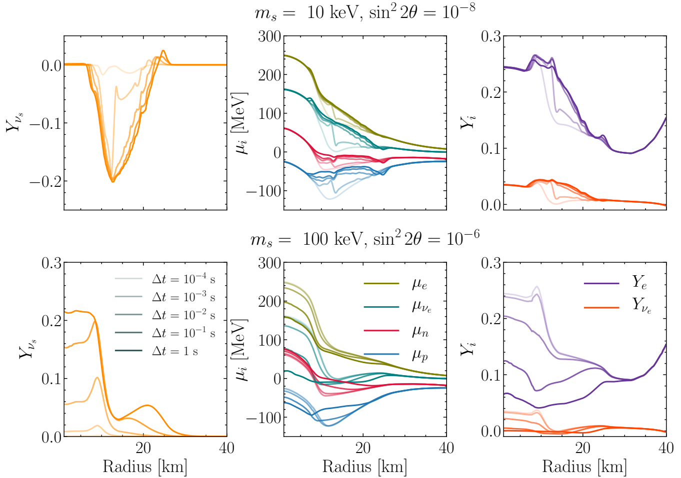
MSW effect

collisional decoherence

sterile neutrinos

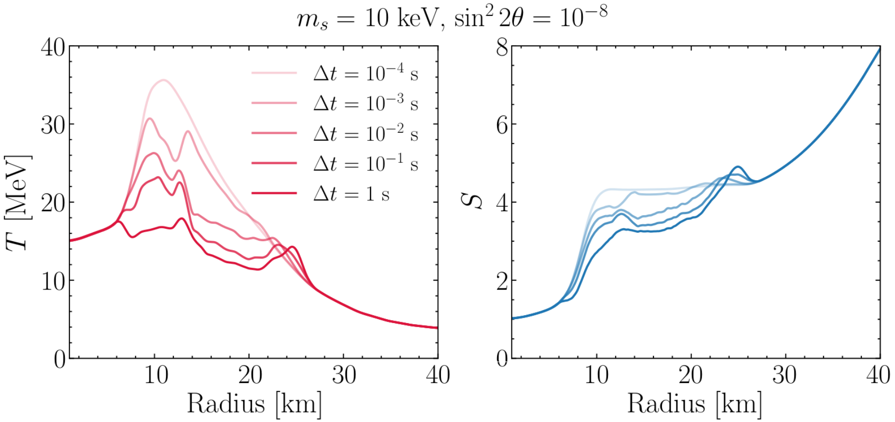
feedback

Radial evolution of the asymmetry



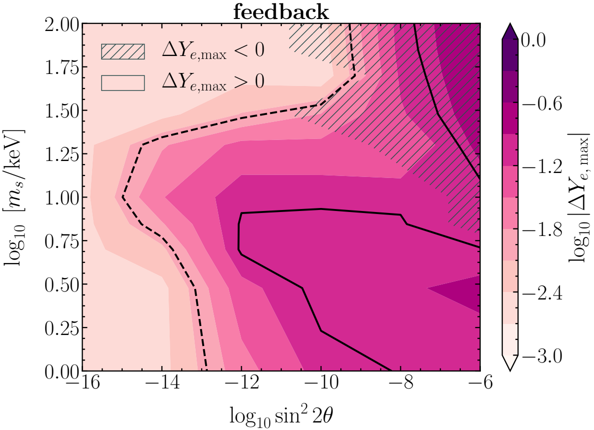
- Sterile particles modify the $Y_e,\ Y_{\nu_e},\ Y_p$ and Y_n.
- The sign of the generated change depends greatly on the m_s.

Radial evolution of the temperature and entropy per baryon



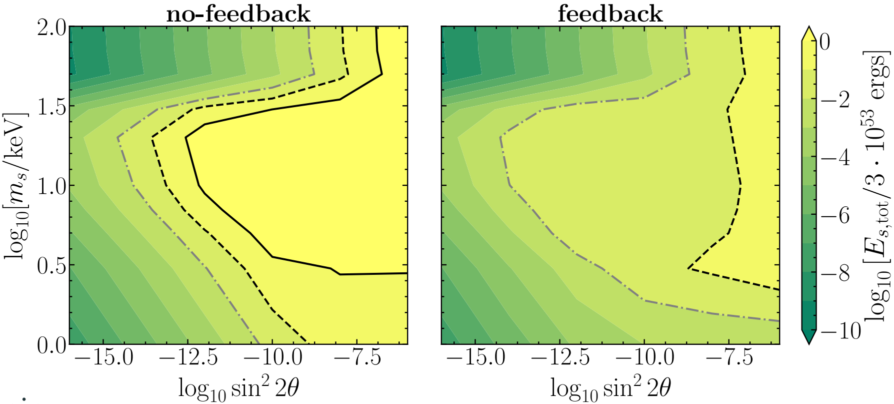
- The $\nu_s - \nu_e$ mixing induces large variations on
    - the entropy per baryon,
    - the supernova medium temperature.

Contour plot: electron fraction



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

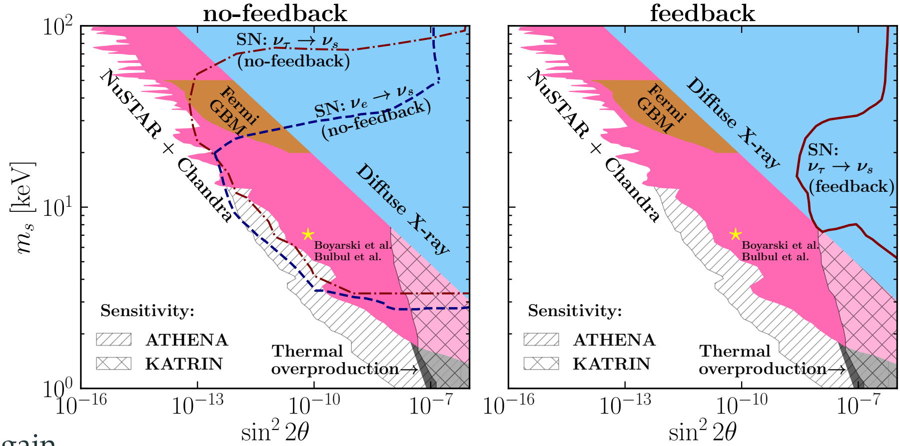
The supernova bounds on the mixing parameters



Again,

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

The supernova bounds on the mixing parameters

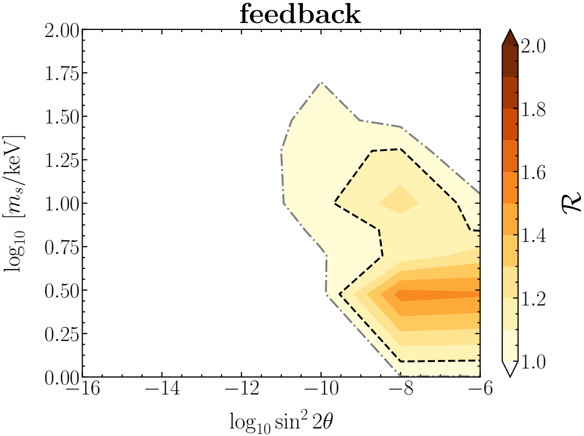


Again,

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

K. C. Y. Ng et al. (2019), K. C. Y. Ng et al. (2015), S. Horiuchi et al. (2013), K. N. Abazajian et al. (2006), A. Boyarsky et al. (2005), ...

The region of a possible supernova explosion enhancement



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

Conclusions

Conclusions

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

- **Feedback is crucial.**

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

Conclusions

- **Sterile neutrinos with keV mass**
  - have a major impact on the SN physics.
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  - force the change of Y_e and Y_{ν_e}.
  - might aid the explosion mechanism.

- **Feedback is crucial.**

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

Thank you!

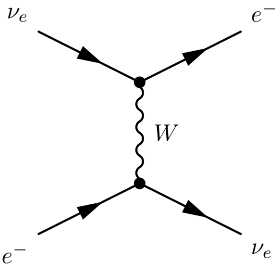
Backup slides

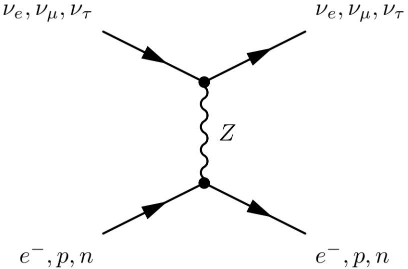
Neutrino oscillations in matter

$$P(\nu_e \to \nu_\mu) = \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$$

$V_{CC} \propto N_e$

- $V_{CC} \to 0$, vacuum oscillations
- $V_{CC} \to \infty$, suppression of oscillations
- $V_{CC} = \frac{\Delta m^2}{2E} \cos 2\theta$, resonance enhancement of oscillations





"Fundamentals of Neutrino Physics and Astrophysics", C. Giunti and C. W. Kim

Sterile neutrino conversions in the stellar core

Collisional production

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

MSW production

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

$$\Gamma_\nu(E) \simeq n(r)\sigma(E, r)$$

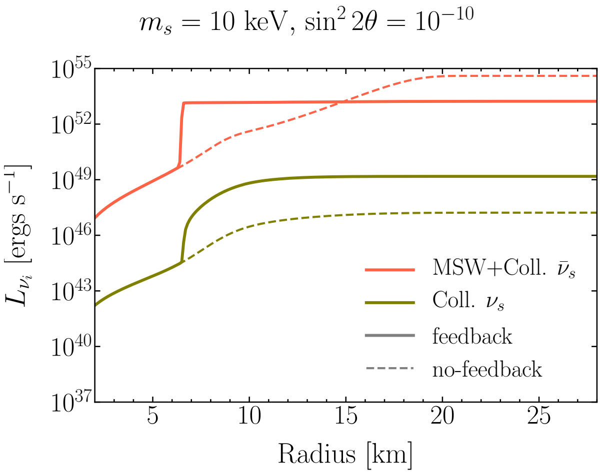
$$D = \tfrac{E\Gamma_\nu(E)}{\Delta m_s^2}$$

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

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

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

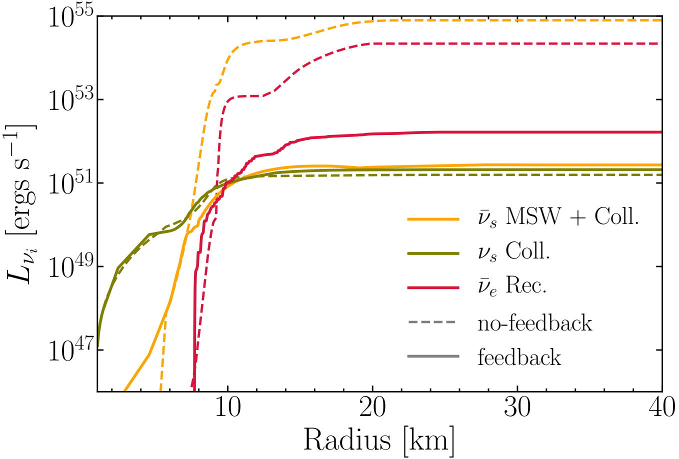
Tau-sterile mixing: Sterile neutrino luminosity



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

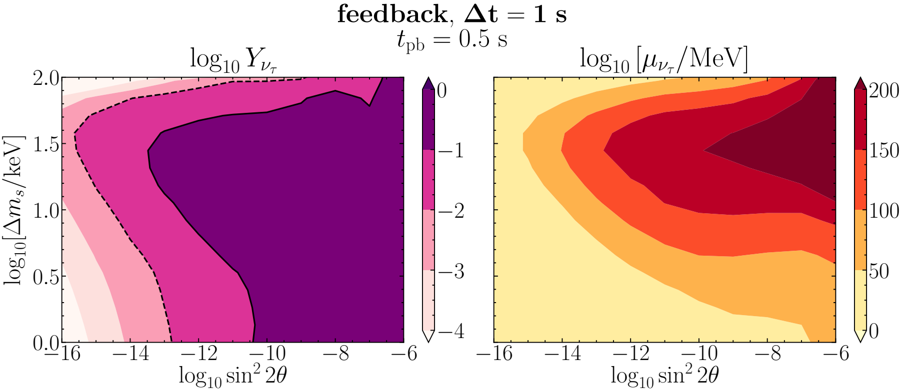
Electron-sterile mixing: Sterile neutrino luminosity

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



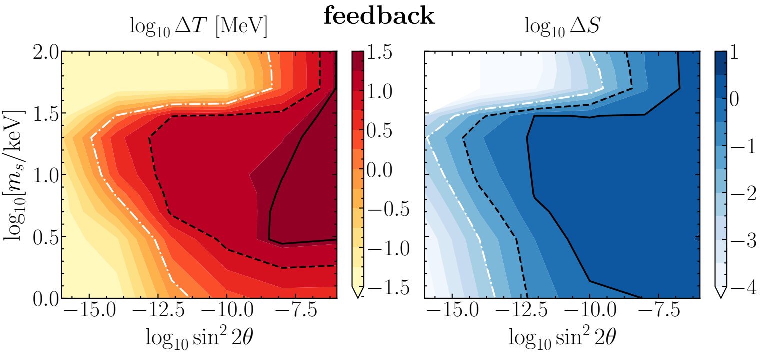
- The total luminosity ($\nu_s + \bar{\nu}_s$) decreases with time.

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.