Physics beyond the Standard Model in astrophysical environments

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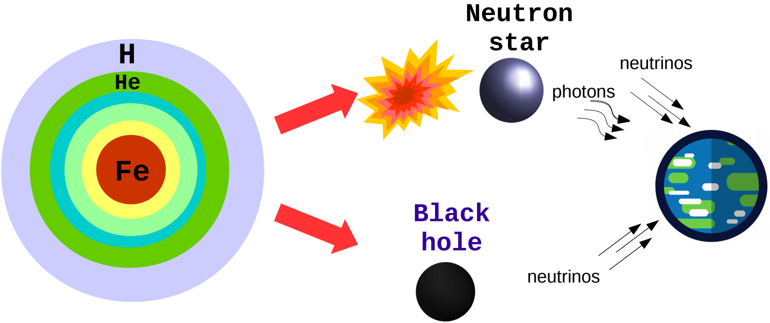
Why are neutrinos important for a core-collapse supernova?

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 (DUNE, SK, DARWIN...)

What can we learn with a variety of detectors?

- explosion mechanism
- yields of heavy elements
- compact object formation
- neutrino mixing
- non-standard physics

H. Bethe & J. Wilson (1985),
T. Fischer et al. (2011)...

S. Woosley et al. (1994),
S. Curtis et al. (2018)...

M. Warren et al. (2019),
S. Li, J. F. Beacom et al. (2020)

H. Duan et al. (2010),
I. Tamborra & S. Shalgar (2020)...

A. de Gouvêa et al. (2019),
S. Shalgar et al. (2019)...

Overview

❶ Sterile neutrinos with keV masses

❷ Non-standard mediators coupling to protons inside the Sun

❸ Astrophysical constraints on the non-standard CEνNS

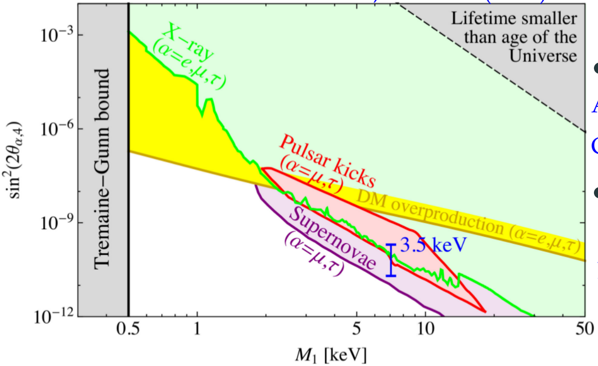
Sterile neutrinos with keV masses

Sterile neutrinos with keV masses

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

Sterile neutrino as dark matter candidate

Sterile Neutrino Dark Matter, A. Merle (2017)



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),

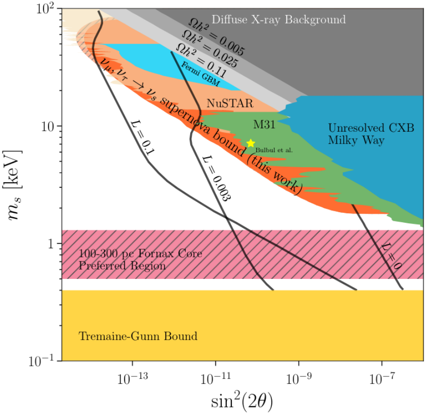
E. Bulbul et al. (2014)

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



C. A. Argüelles et al. (2016)

G. Raffelt, G. Sigl (1992),
X. Shi & G.Sigl (1994),
H. Nunokawa et al. (1997),
J. Hidaka & G. Fuller (2006),
J. Hidaka & G. Fuller (2007),
G. Raffelt & S. Zhou (2011),
M. L. Warren et al. (2014),
C. A. Argüelles et al. (2016),
A. M. Suliga et al. (2019),
V. Syvolap et al. (2019),
A. M. Suliga et al. (2020)

Sterile neutrino conversions in the stellar core — introduction

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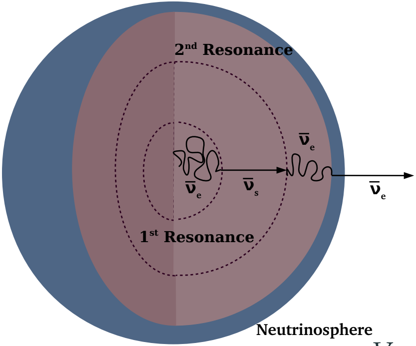


1D SN model
Garching group archive

MSW

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

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

Collisions

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

$\nu_e - \nu_s$ mixing: multiple resonances

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

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

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

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

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

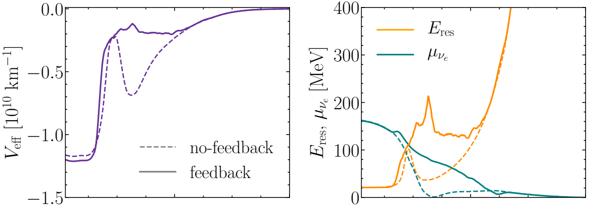
$$\Delta_{\text{res}} = \tan 2\theta \left|\frac{dV_{\text{eff}}/dr}{V_{\text{eff}}}\right|^{-1}$$

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

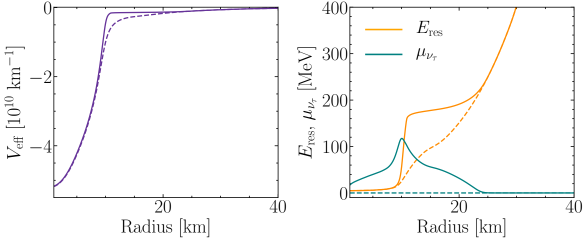
C. W. Kim et al. (1987), S. J. Parke (1987), S. P. Mikheev and A. Yu. Smirnov (2007)

Sterile neutrino conversions in the stellar core

$\nu_s - \nu_e$ mixing: multiple resonances



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



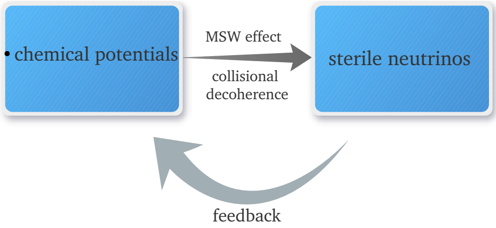
1D SN model
Garching group archive

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

- **Negative $V_{\mathrm{eff}} \rightarrow$ 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



- 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;**

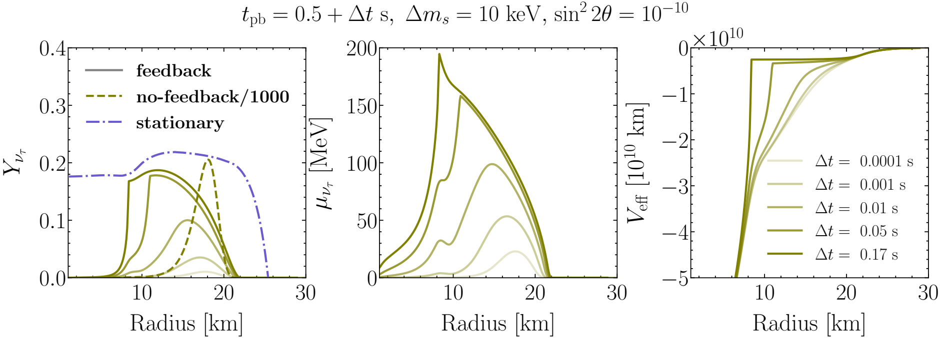
since they were **strongly coupled** to the rest of the particles in the medium,
a **new equilibrium state forms.**

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

Active + sterile neutrinos

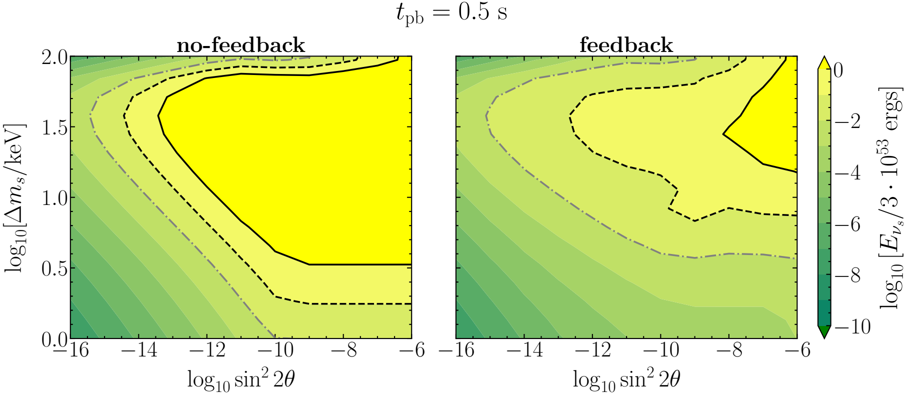
$$Y_{\nu_\tau}(r,t) = \frac{1}{n_b(r)} \int_0^t dt' \, \frac{d\left(P_{\nu_\tau \to \nu_s} n_{\nu_\tau}(r,t') - P_{\bar{\nu}_\tau \to \bar{\nu}_s} n_{\bar{\nu}_\tau}(r,t')\right)}{dt'}$$

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.

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

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

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

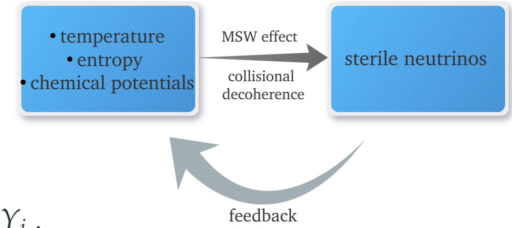
$$Y_p(r,t)+Y_n(r,t)=1\ ,$$

Charge conservation

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

Entropy change

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



- temperature
- entropy
- chemical potentials

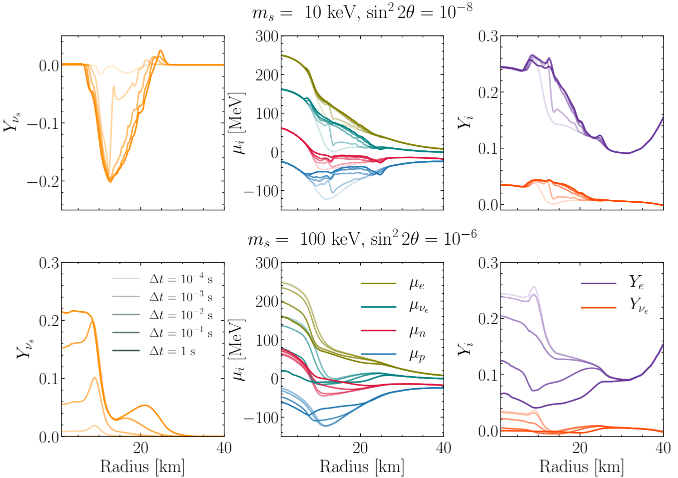
MSW effect

collisional decoherence

sterile neutrinos

feedback

Radial evolution of the asymmetry

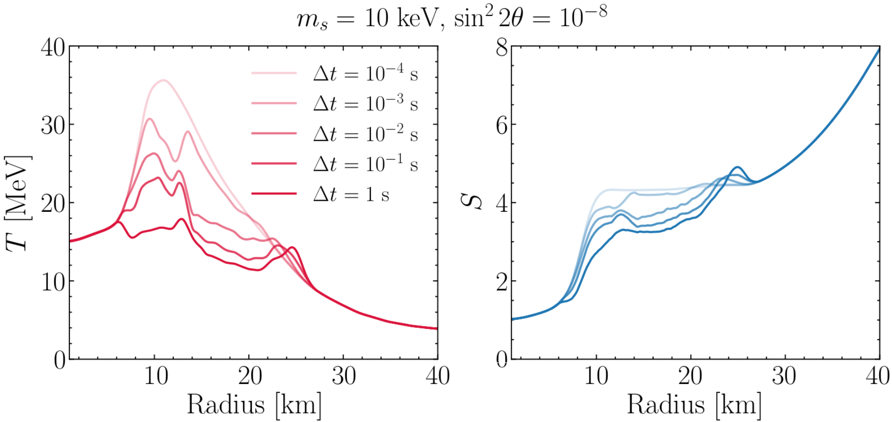


$m_s = 10$ keV, $\sin^2 2\theta = 10^{-8}$

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

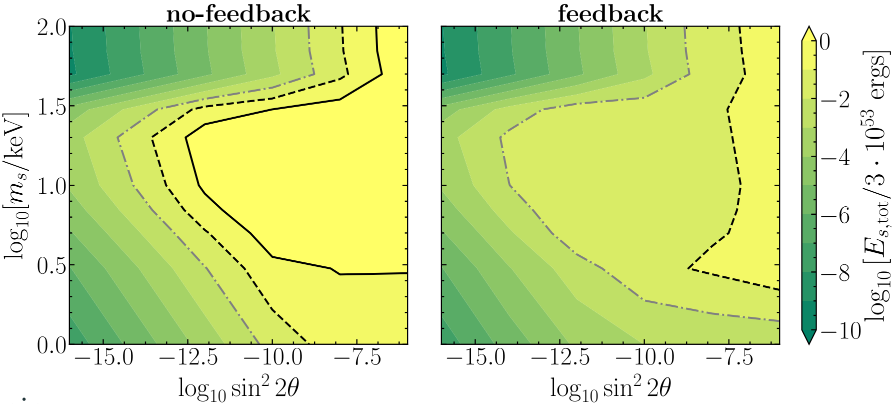
- Sterile particles modify the $Y_e,\ Y_{\nu_e},\ Y_p$ and Y_n.
- The sign of the generated change depends greatly on the m_s.

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.

The supernova bounds on the mixing parameters

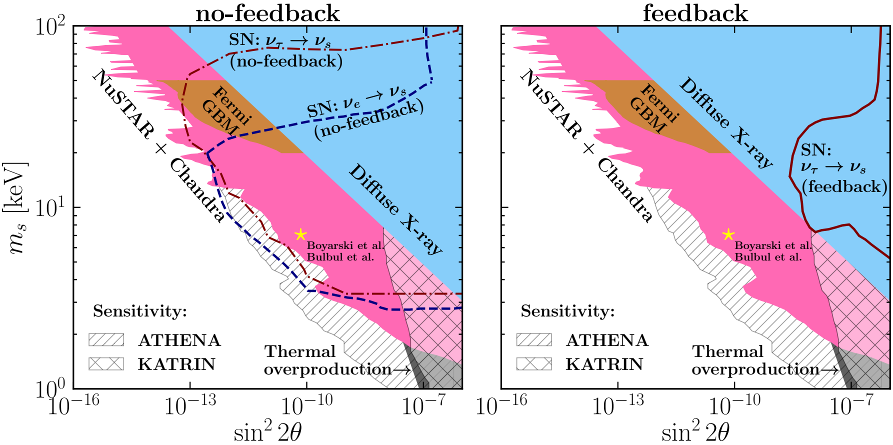


Again,

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

Conclusions: sterile neutrinos

The supernova bounds on the mixing parameters



A. M. Suliga et al. (2018), (2019)

- **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.
    - force the change of Y_e and Y_{ν_e}.
    - might aid the explosion mechanism.

- **Feedback is crucial.**

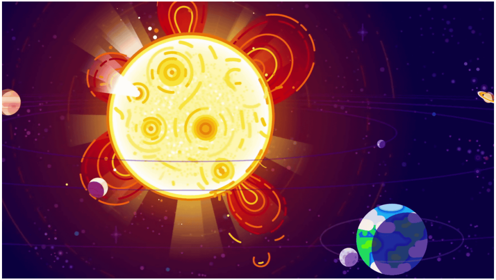
- **New treatment of active-sterile neutrino mixing in SNe challenges sterile neutrino bounds.**

Probing non-standard mediators coupling to protons inside the Sun

Probing non-standard mediators coupling to protons inside the Sun

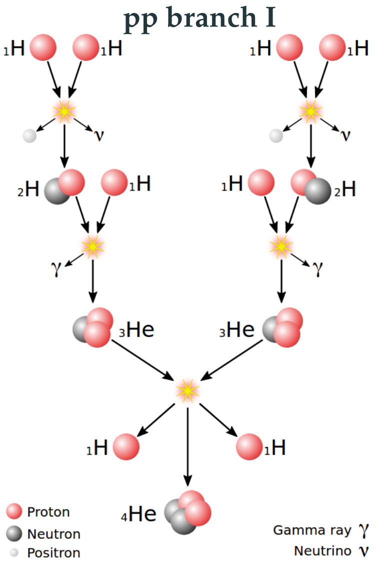
In collaboration with S. Shalgar and G. M. Fuller

Why our sun is an interesting place to look at?



The Sun

- Closest star
- Well studied and well measured
- Better measurements will come
- *pp*-chain - primary channel (99.7%)



Pictures: Kurzgesagt, Wikipedia

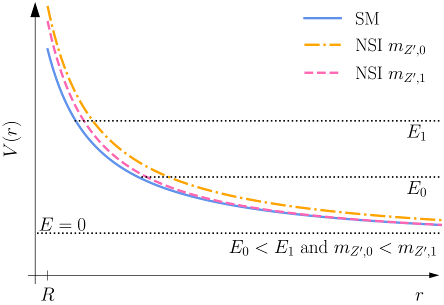
Non-standard mediators coupling to protons

vector boson (Z')

$$\mathcal{L}^{Z'} = g Z'_\mu \bar{\mathrm{p}} \gamma^\mu \mathrm{p}$$

scalar (ϕ)

$$\mathcal{L}^{\phi} = g \phi \bar{\mathrm{p}} \mathrm{p}$$



Interaction potential

$$V(r) = \frac{e^2}{r} \pm \frac{g^2}{r} \exp\left[-m_{\{Z',\phi\}} r\right]$$

Coulomb barrier penetration factor

$$P_{0,\mathrm{SM}} \approx \frac{E_c}{E} \exp\left[-\frac{2\pi e^2}{\hbar v}\right] \approx \frac{E_c}{E} \exp\left[-W_{0,\mathrm{SM}}\right]$$

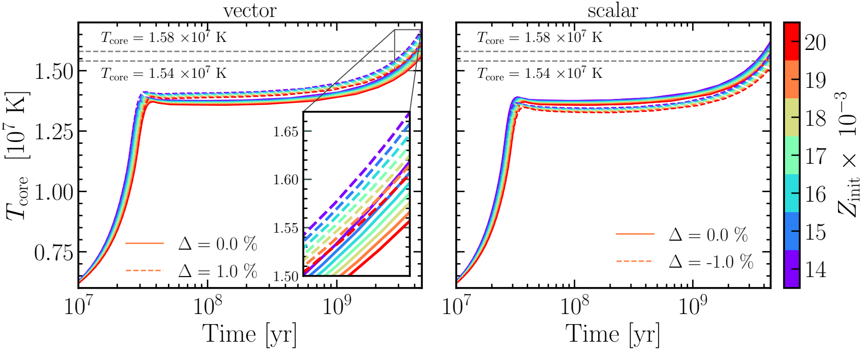
$$\Delta \approx \frac{\left| W_{0,\mathrm{NSI}}^{\frac{2}{3}} - W_{0,\mathrm{SM}}^{\frac{2}{3}} \right|}{W_{0,\mathrm{SM}}^{\frac{2}{3}}}$$

pp interaction rate

$$\Gamma_{pp} \propto \exp\left(-3.381(1 \pm \Delta) \, \left(\frac{T}{10^9\ \mathrm{K}}\right)^{\frac{1}{3}} \right)$$

D. D. Clayton, *Principles of stellar evolution and nucleosynthesis* (1968)

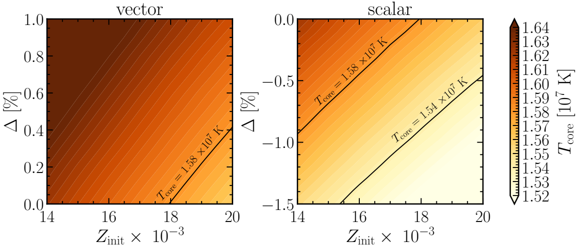
Temporal evolution of the solar core's temperature



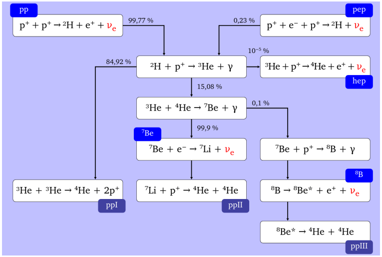
- Modules for Experiments in Stellar Astrophysics *MESA*
- Evolution until the current solar age
- Changes in the barrier and metallicity affect the outcome

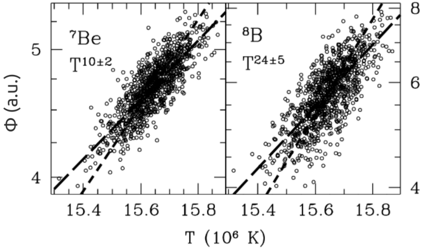
Changes in the solar parameters

Sun's core temperature



- vector boson mediator
  temperature increase
- scalar mediator
  temperature decrease



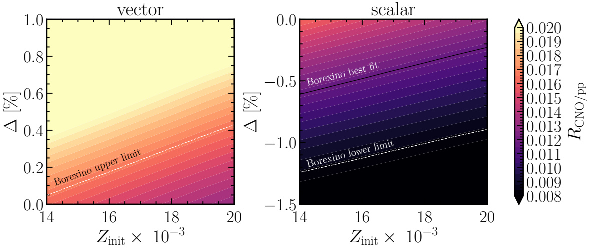


Wikipedia

J. N. Bahcall, A. Ulmer (1996)

Changes in the solar parameters

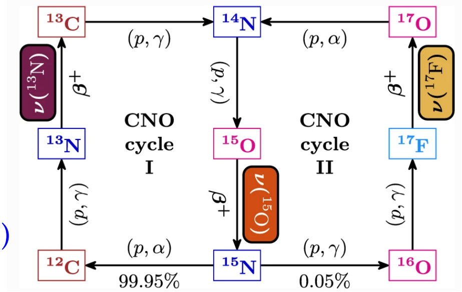
CNO to *pp* ratio, $R_{CNO/pp}$



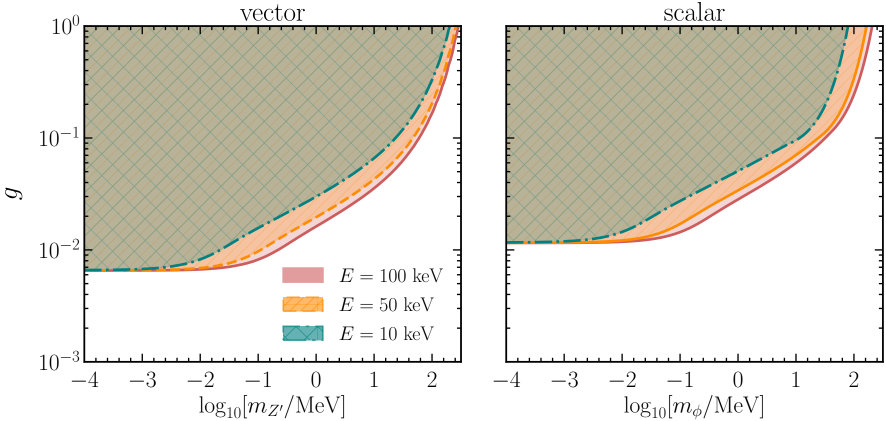
- $R_{CNO/pp}$ – the same trends
- degeneracy between initial metallicity and NSI

CNO cycle

- sub-percent contribiution to the solar energy generation
- neutrinos recently observed by the Borexino collaboration (2020)



Sensitivity bounds on the non-standard mediators



- low mediator mass → limits insensitive to the mediator mass
- higher proton energies → the excluded region grows
- conservative bounds → there is a room for an improvement

Sensitivity of the results

Bottelnecks:

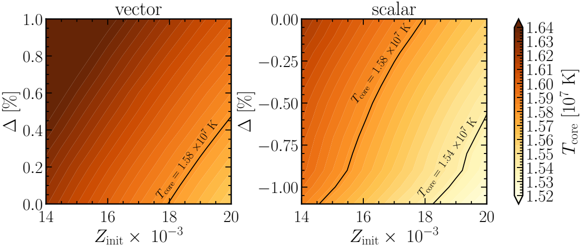
- pp-chain: $\mathrm{p} + \mathrm{p} \rightarrow \mathrm{D} + \nu_e + e^+$
  easy to calculate, not measured
- CNO cycle: $\mathrm{p} + {}^{14}\mathrm{N} \rightarrow {}^{15}\mathrm{O} + \gamma$
  not calculated exactly yet, possible to measure

Question marks in the extrapolated cross section

- measurements at higher energies than in the solar interior
- extrapolation procedures
- plagued by high uncertainty 20-25%

Changes in the solar parameters

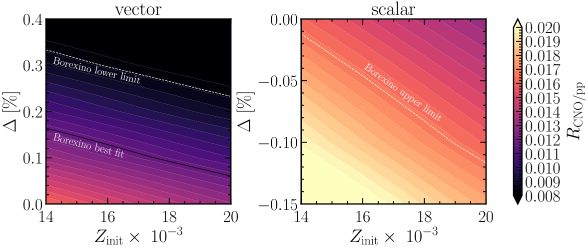
Sun's core temperature



- vector boson mediator
  temperature increase
- scalar mediator
  temperature decrease

CNO to *pp* ratio, $\mathrm{R_{CNO/pp}}$

- $\mathrm{R_{CNO/pp}}$ – flipped trends
- more roobost changes in CNO bottelneck reaction



Conclusions: non-standard mediators coupling to protons

Conclusions

Non-standard mediators

- affect the Coulomb potential felt by the charge particles
- change the temperature of the core of the Sun
- can be constrained with the solar neutrino fluxes
- can affect nuclear reactions in less/more massive objects

The perspective sensitivity bounds for protons

- most constraining for mediators with masses above 50 keV
- will improve with better measurements of the metallicity and CNO neutrinos

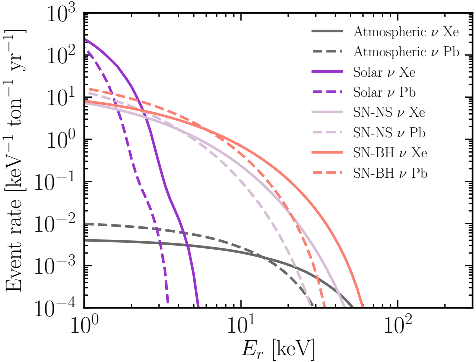
Our work calls for an improved measurements of the solar reactions involvig Coulomb barriers

Astrophysical constraints on the non-standard coherent neutrino-nucleus scattering

Astrophysical constraints on the non-standard coherent neutrino-nucleus scattering

In collaboration with I. Tamborra

Astrophysical neutrino fluxes



Supernova neutrinos

- large flux for Galactic SN
- transient event

Solar neutrinos

$^8\mathrm{B} \to {}^8\mathrm{Be}^* + e^+ + \nu_e$

$^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$

- neutrino energies up to ∼15 MeV

Atmospheric neutrinos

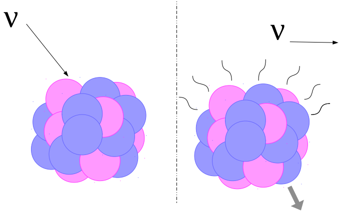
$\pi^+ \to \mu^+ + \nu_\mu$ and $\pi^- \to \mu^- + \bar{\nu}_\mu$

$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ and $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

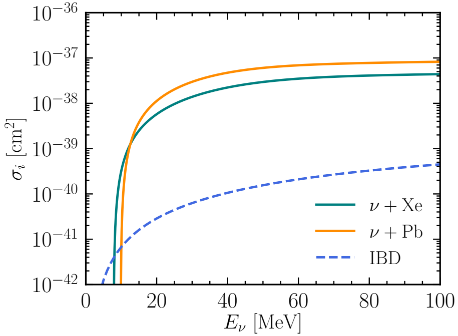
- the highest neutrino energies among the considered sources
- high uncertainty $\sim 20\%$

E. Vitagliano et al. (2019), M. Honda et al. (2011), J. L. Newstead et al. (2020)

Coherent elastic neutrino-nucleus scatterings (CEνNS)



$$\nu + T(A,Z) \rightarrow \nu + T(A,Z)$$



Cross section

$$\frac{d\sigma_{\mathrm{SM}}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q),\ \ Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

- coherently enhanced by the square of the neutron number
- flavor insensitive
- coherent up to ~ 50 MeV

D. Z. Freedman

Non-standard coherent neutrino-nucleus scatterings

$g = \sqrt{|g_{q,i}g_{\nu,i}|},\ g_{q,i}g_{\nu,i} > 0$

new vector mediator

Z'

new scalar mediator

ϕ

Lagrangian terms

$$\mathcal{L}^{Z'} = g_{\nu,Z'} Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{q} \gamma^\mu g_{q,Z'} q$$

$$\mathcal{L}^{\phi}_{\text{LNC}} = g_{\nu,\phi} \phi \bar{\nu}_R \nu_L + \phi \bar{q} g_{q,\phi} q$$

$$\mathcal{L}^{\phi}_{\text{LNV}} = g_{\nu,\phi} \phi \nu^c_L \nu_L + \phi \bar{q} g_{q,\phi} q$$

Cross sections

$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{G_F^2 m_T}{\pi} |\xi|^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q)$$

$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{d\sigma_{\text{SM}}}{dE_r} + \frac{d\sigma_\phi}{dE_r}$$

$$\xi = -\frac{Q_w}{2} + \frac{g_{\nu,Z'} Q'_w}{\sqrt{2} G_F (2m_T E_r + m_{Z'}^2)}$$

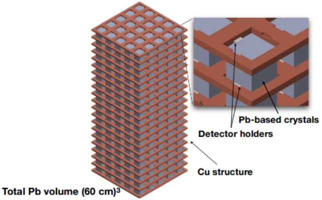
$$\frac{d\sigma_\phi}{dE_r} = \frac{(g_{\nu,\phi} g_{q,\phi} Q_s)^2}{2\pi(2E_r m_T + m_\phi^2)^2} \frac{m_T^2 E_r}{2E_\nu^2} F^2(Q)$$

D. G. Cerdeno et al. (2016), Y. Farzan et al.(2018), D. Aristizabal Sierra et al. (2019)

Event rates at future generation detectors

Future generation CEνNS detectors

RES-NOVA (L. Pattavina et al. (2020))

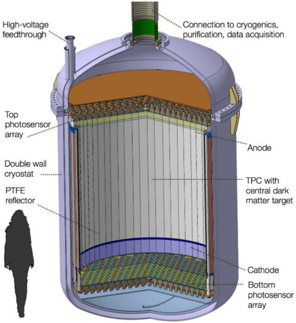


fiducial volume: 2.4 - 456 ton

target material: Pb

threshold: 1 keV

DARWIN (J. Aalbers et al. (2016))



fiducial volume: 40 ton

target material: Xe

threshold: 1 keV

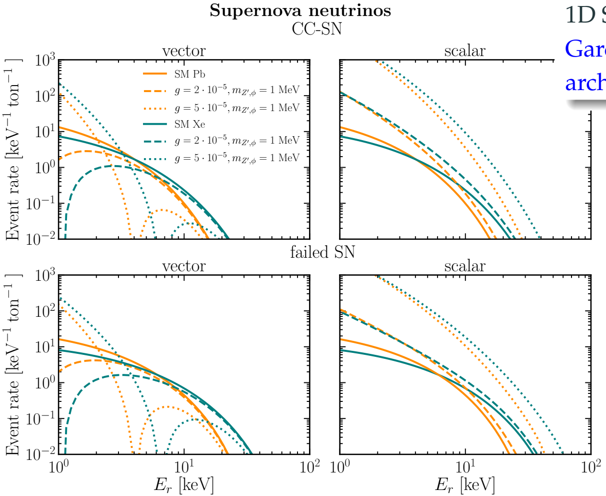
efficiency: XENON1T - 100%

Scattering rate

$$\frac{dR_{\nu N}}{dE_r dt} = N_T \, \epsilon(E_r) \int dE_\nu \, \frac{d\sigma_{\nu N}}{dE_r} \, \psi(E_\nu, t) \, \Theta(E_r^{\max} - E_r)$$

$$E_r^{\max} = \frac{2E_\nu^2}{m_T + 2E_\nu}$$

Event rates for supernova neutrinos

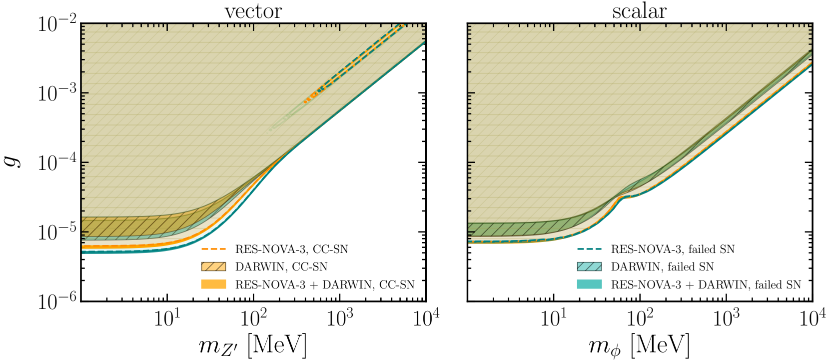


1D SN models
Garching group archive

- Failed SN: hotter neutrino spectrum → longer recoil spectrum
- Heavier target: higher number of events but shorter recoil spectrum

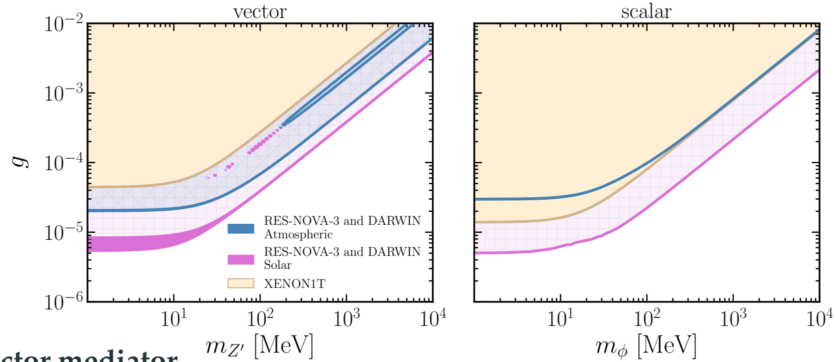
Sensitivity bounds on the mass and coupling of the new mediators

Results supernova neutrinos



- failed SN: higher number of events → better constraints
- RES-NOVA-3 drives the limits due to to higher volume
- vector mediator small unconstrained region due to the interference term
- limits on the vector mediator better for low mediator masses

Results solar and atmospheric neutrinos



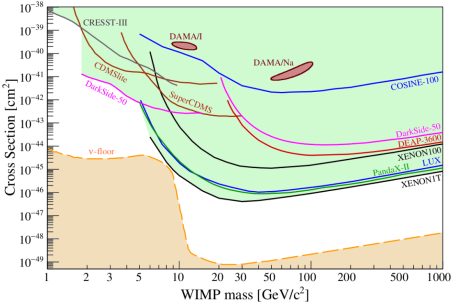
Vector mediator

- Solar neutrinos: bounds driven by Xe based detector
- Atmospheric neutrinos: bounds driven by Pb detector

Scalar mediator

- Bounds driven by Pb detector

XENON1T results

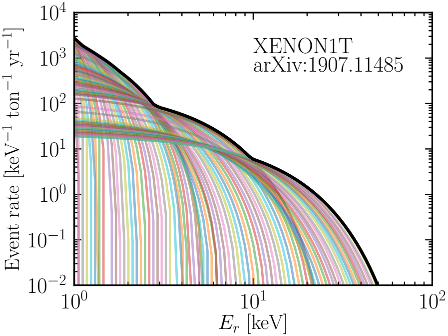


M. Schumann (2019)

neutrino floor

unavoidable background

in the future dark matter detectors



WIMP's limits

on the mass and cross section

↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓

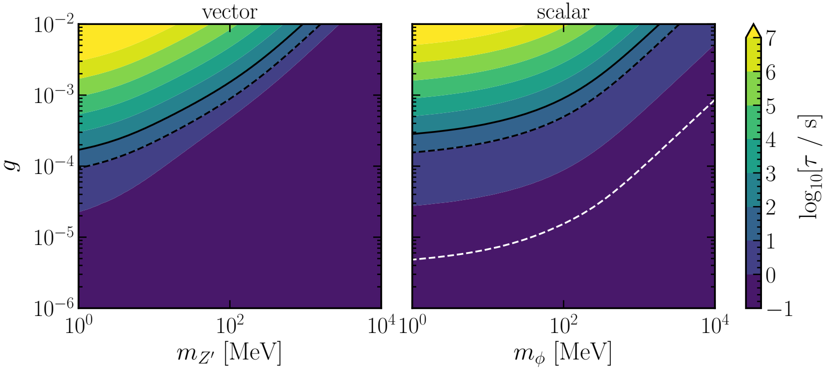
limits on the mass and coupling

of the non-standard mediators

J. Aalbers et al. wimprates, E. Aprile et al. (2019)

Non-standard coherent scattering in the supernova core

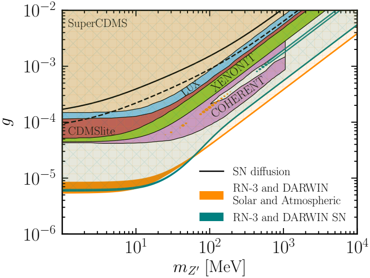
Non-standard coherent scattering in the supernova core



- prolonged diffusion time → possible change in the star's fate
- prolonged diffusion time → changed duration of the neutrino signal
- LNC scalar mediator → new cooling channel due to ν_R

Conclusions

Conclusions



Future dark matter (CEνNS) detectors

- sensitive to astrophysical neutrinos
- flavor insensitive neutrino channel
- high cross section & low thresholds
- open an extra window to probe New Physics
- promise to place most competitive bounds on new mediators

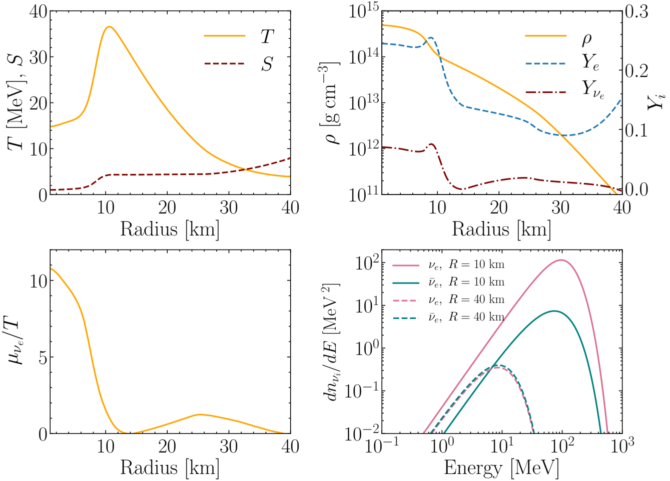
Core-collapse supernovae

- non-standard mediators affect the diffusion time of neutrinos
- scalar LNC mediator → new cooling channel

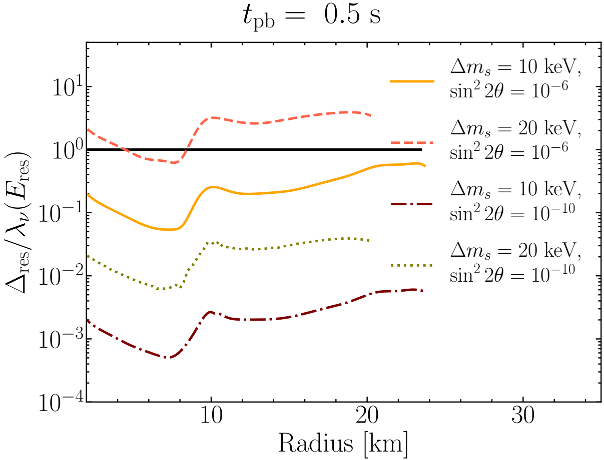
Thank you!

Backup slides

Initial conditions



Will they collide or undergo MSW resonance?

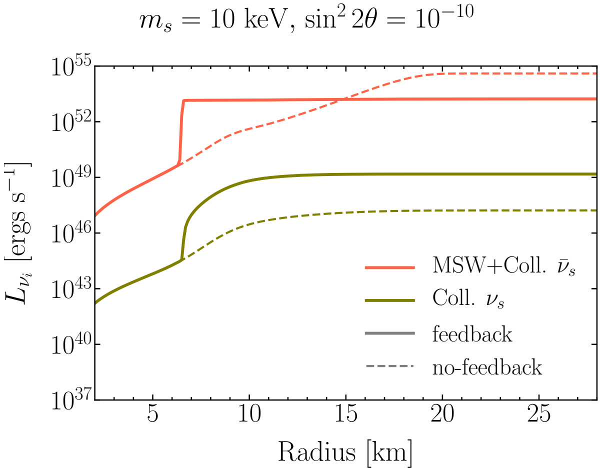


$$\Delta_{\rm res} = \tan 2\theta \left|\frac{dV/dr}{V}\right|^{-1}$$

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

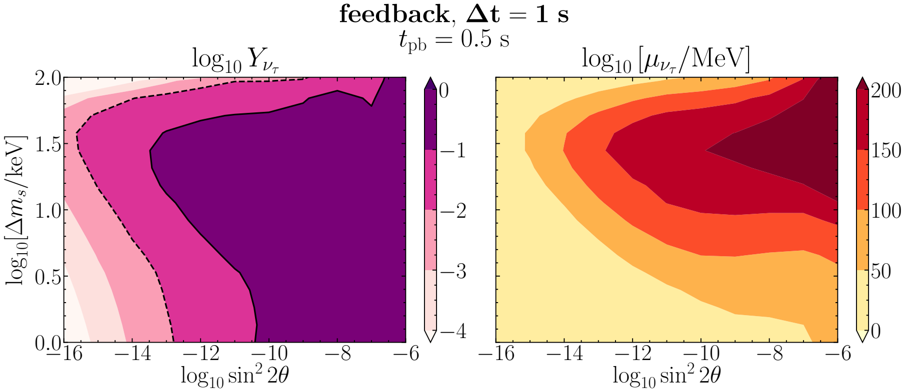
$\Delta_{\rm res} < \lambda_\nu(E_{\rm res})$?

Tau-sterile mixing: sterile neutrino luminosity



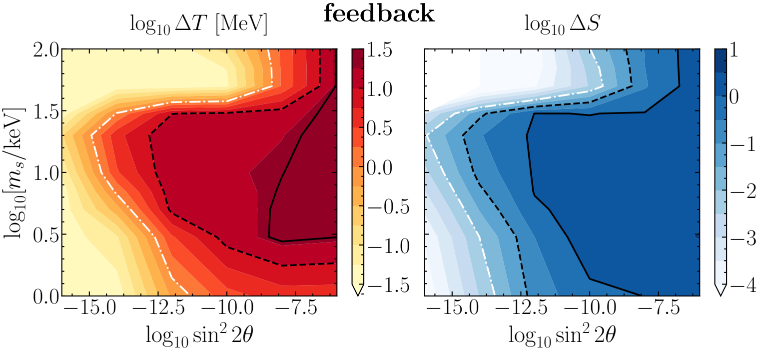
- The total luminosity ($\nu_s + \bar{\nu}_s$) decreases with time.

Contour plot of tau fraction



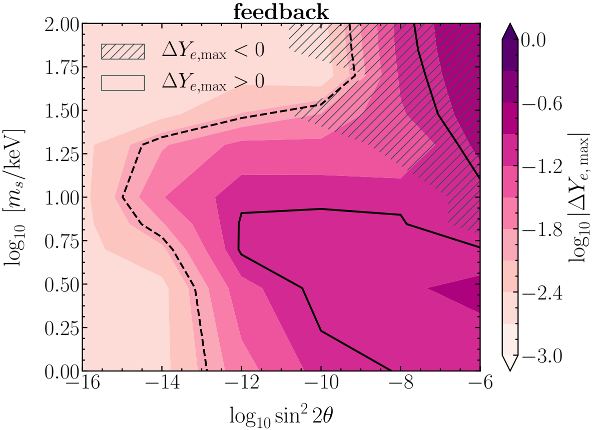
- Higher mixing angles reach the saturation value faster.
- More massive sterile neutrinos reach smaller saturation values, fewer energy modes have enhanced conversion probability.

Contour plot: temperature and entropy



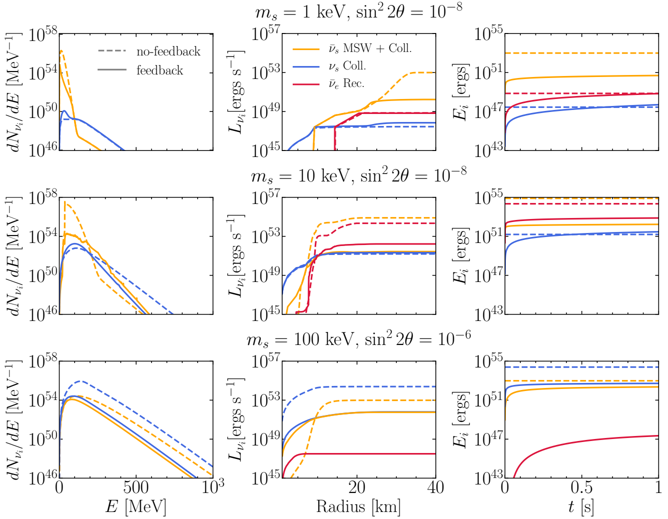
- Large variations for high mixing angles due to
  - adiabatic conversions,
  - high number of sterile neutrinos produced by collisions.

Contour plot: electron fraction



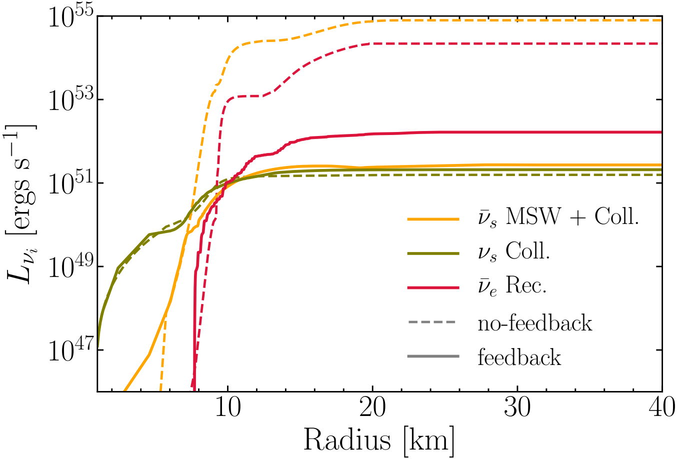
- The change in Y_e can be negative or positive.
- Might considerably affect the evolution of the proto-neutron star.

Comparison for different mixing parameters



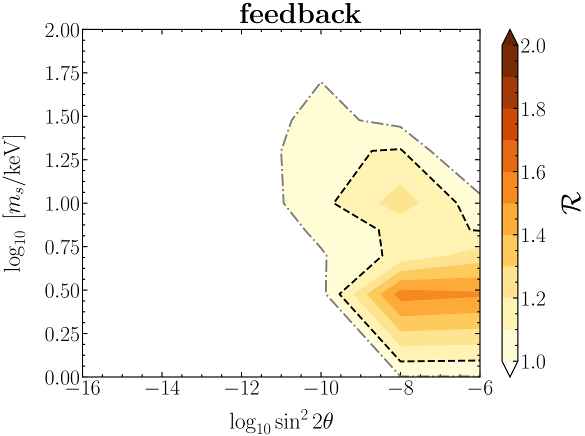
Electron-sterile mixing: sterile neutrino luminosity

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



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

The region of a possible supernova explosion enhancement

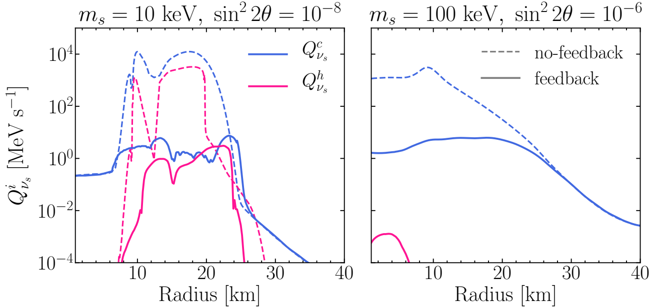


$$\mathcal{R} = \frac{E_{G,\mathrm{out}} + E_{\nu_s\to\nu_i} - E_{\nu_s}}{E_{G,\mathrm{out}}}$$

- 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

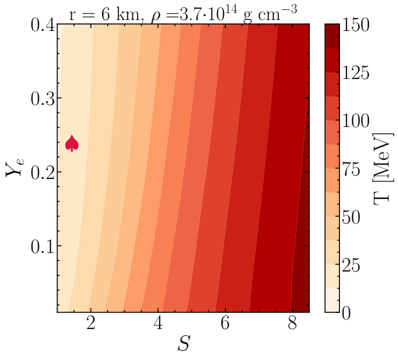


$$\dot{E}^c_\nu(r,t) \sim V(r)\Delta r^{-1} \sum_{k=1}^{L} P_{\mathrm{es}}(E_k,r,t)\,\frac{dn_\nu}{dE_k}(r,t)\,dE_k E_k$$

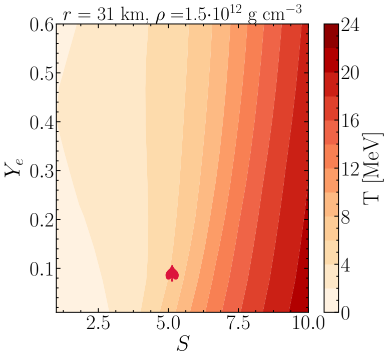
$$\dot{E}^h_\nu(r,t) \sim$$

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

Temperature interpolation

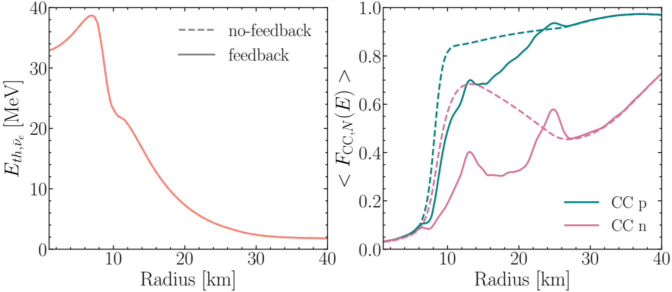


r = 6 km, $\rho = 3.7 \cdot 10^{14}$ g cm^{-3}



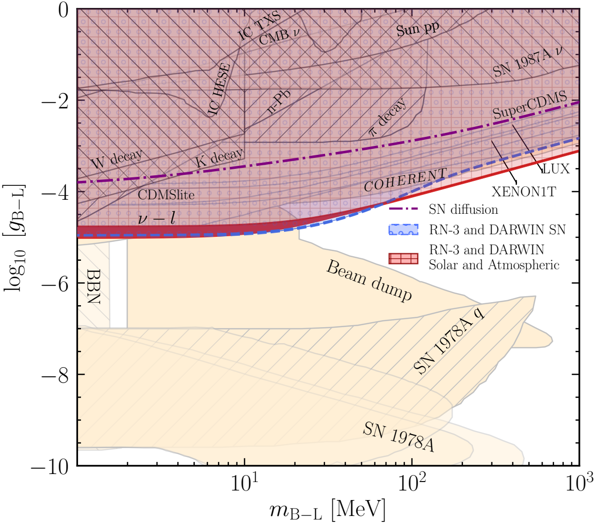
r = 31 km, $\rho = 1.5 \cdot 10^{12}$ g cm^{-3}

Pauli blocking

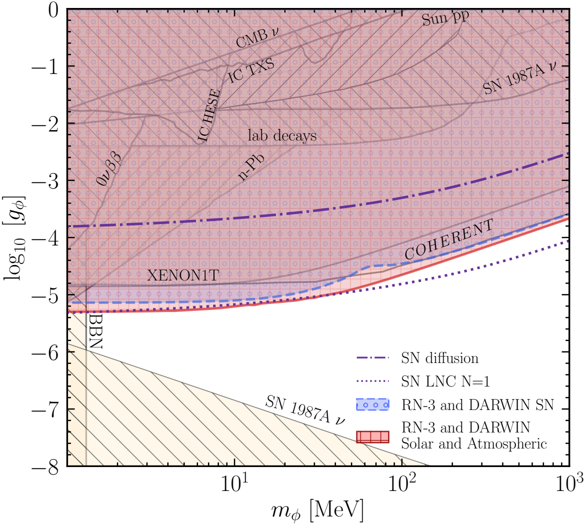


- In the region affected by the sterile neutrino production $\langle FCC, p(n)(E)_N \rangle$ decreases (increases) following the Ye increase (decrease).

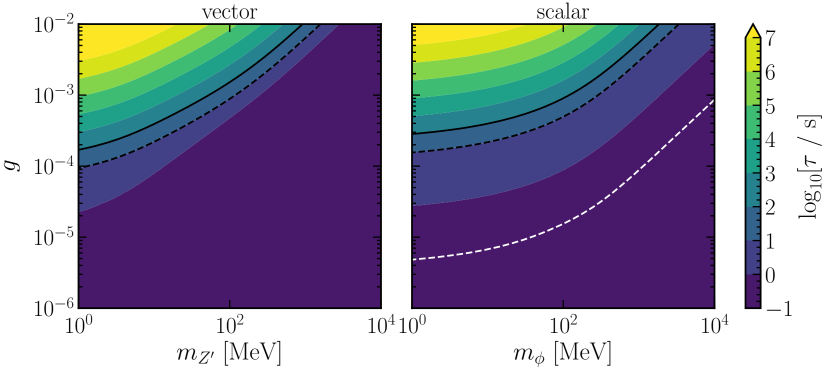
Comparision of limits from specific new physics models



Comparision of limits from specific new physics models



Non-standard coherent scattering in the supernova core



- mean-free path

$$\lambda_{\nu_\beta} = \sum_{\mathrm{CC,NC}} \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta}) E_{\nu_\beta}^2}{n_t \int dE_{\nu_\beta} f(E_{\nu_\beta}) E_{\nu_\beta}^2 \sigma_i(E_{\nu_\beta})}$$

- diffusion time

$$\tau_{\nu_\beta} = \int_{R_1}^{R_2} dr \frac{r}{\lambda_{\nu_\beta}(r)}$$

- number of scatters

$$N = \int_0^{R_2} \frac{2r}{\lambda(r)^2}\, dr$$

$R_1 = 10$ km
$R_2 = 40$ km