Physics beyond the Standard Model in astrophysical environments

Anna M. Suliga

January 27, 2021

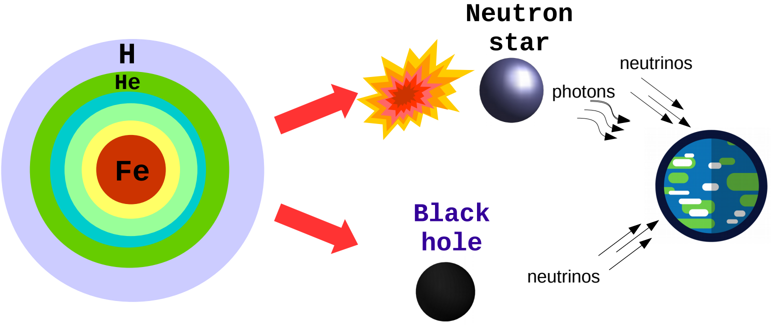
Niels Bohr Institute,
University of Copenhagen

Centre for High Energy Physics
Indian Institute of Science

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

1. Sterile neutrinos with keV masses
2. Sterile neutrino conversions in the stellar core — introduction
3. The sterile-tau neutrino mixing
4. The sterile-electron neutrino mixing
5. Conclusions: sterile neutrinos
6. Non-standard mediators coupling to protons
7. Conclusions: non-standard mediators

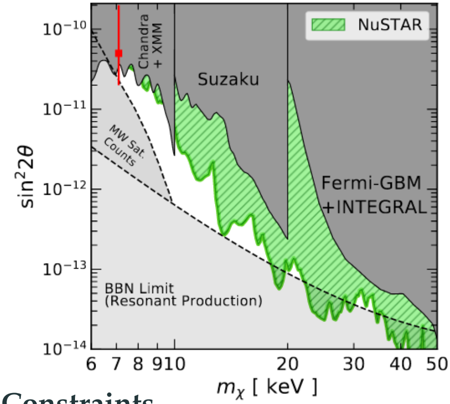
Sterile neutrinos with keV masses

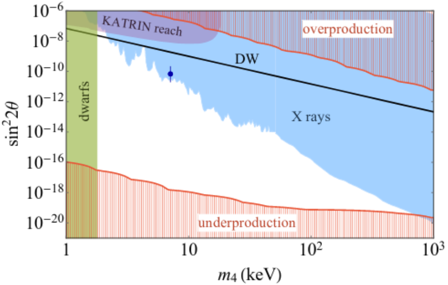
Sterile neutrinos with keV masses

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

Sterile neutrino as dark matter candidate

B. Roach, J. F. Beacom et al. (2019)





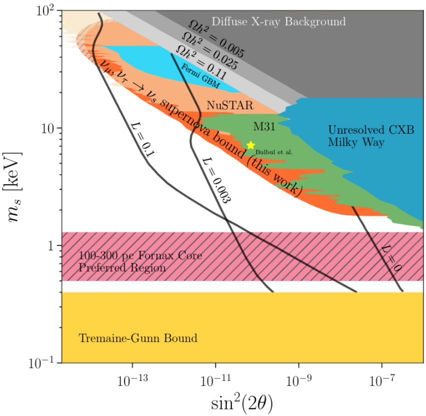
Dodelson-Widrow still viable with ν NSI
A. de Gouvêa et al. (2019)

Constraints

- DM overproduction (S. Dodelson, L. M. Widrow (1994), X. Shi, G. 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, Milky Way Satellites Counts ...

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

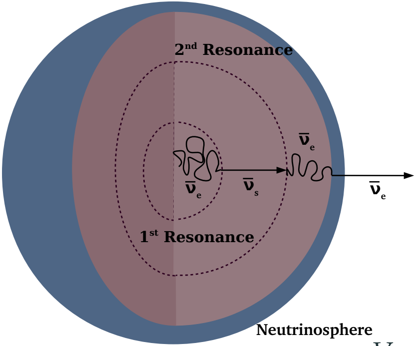


C. A. Argüelles et al. (2016)

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

Sterile neutrino conversions in the stellar core — introduction



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

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

$\nu_e - \nu_s$ mixing: multiple resonances

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

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

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

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

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

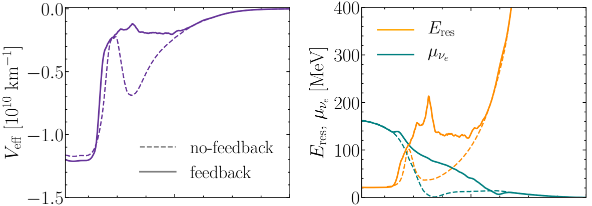
$$\Delta_{\text{res}} = \tan 2\theta \left|\frac{dV_{\text{eff}}/dr}{V_{\text{eff}}}\right|^{-1}$$

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

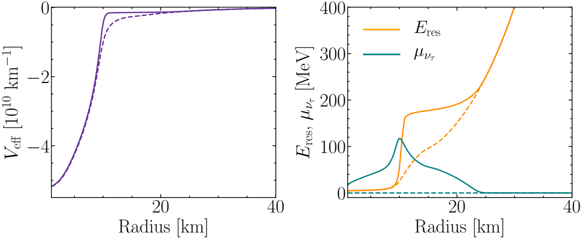
C. W. Kim et al. (1987), S. J. Parke (1987), S. P. Mikheev and A. Yu. Smirnov (2007)

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

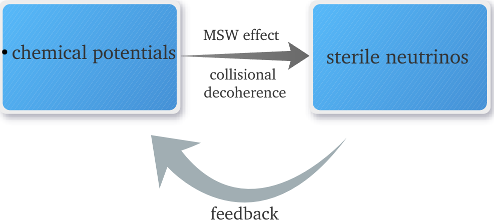
$$E_{\rm res} = \frac{\cos 2\theta \Delta m_s^2}{2V_{\rm eff}}$$

- **Negative $V_{\rm eff}$ → 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



- 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.**

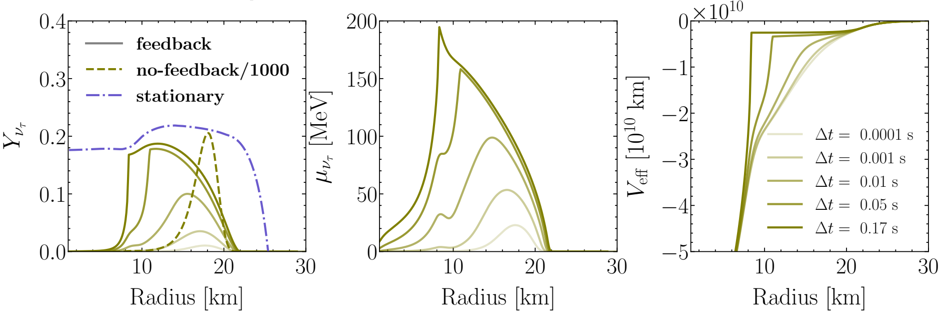
The change imposed on the SN medium is referred to as the **dynamical feedback.**

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

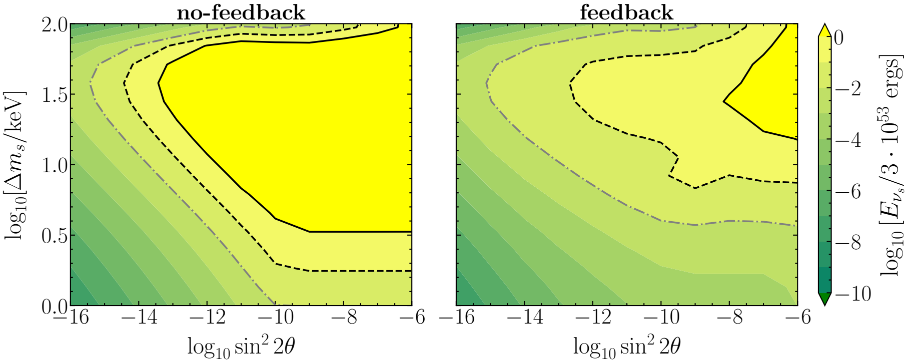
$t_{\rm pb} = 0.5 + \Delta t$ s, $\Delta m_s = 10$ keV, $\sin^2 2\theta = 10^{-10}$



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

The supernova bounds on the mixing parameters

$t_{\mathrm{pb}} = 0.5$ 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

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

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

Baryon number conservation

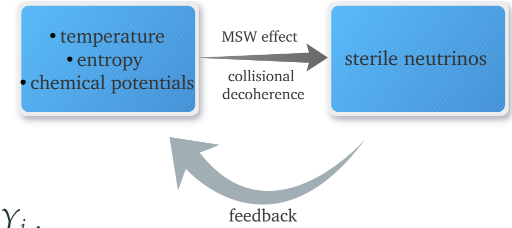
$$Y_\mathrm{p}(r,t) + Y_\mathrm{n}(r,t) = 1\ ,$$

Charge 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

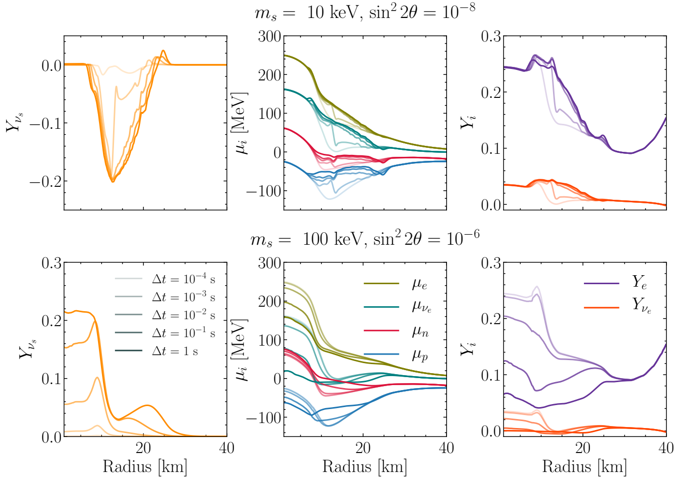
MSW effect

collisional decoherence

sterile neutrinos

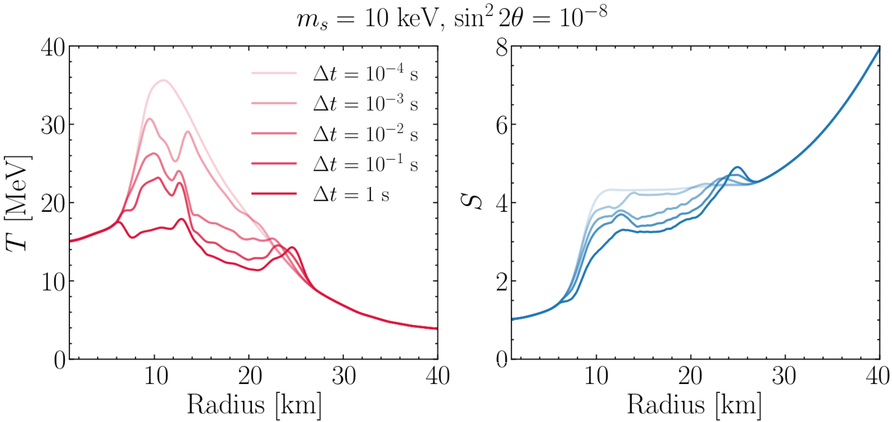
feedback

Radial evolution of the asymmetry



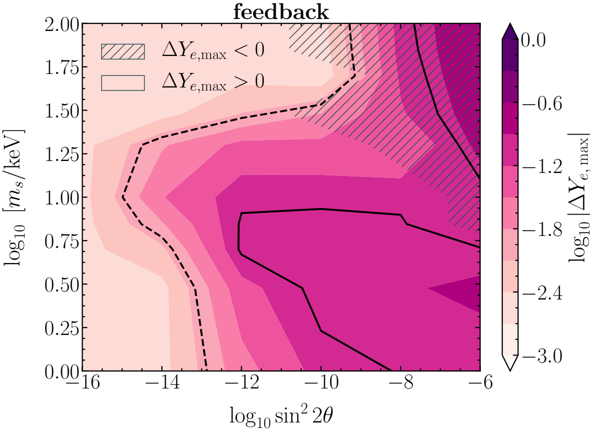
- Sterile particles modify the $Y_e,\ Y_{\nu_e},\ Y_p$ and Y_n.
- The sign of the generated change depends greatly on the m_s.

Radial evolution of the temperature and entropy per baryon



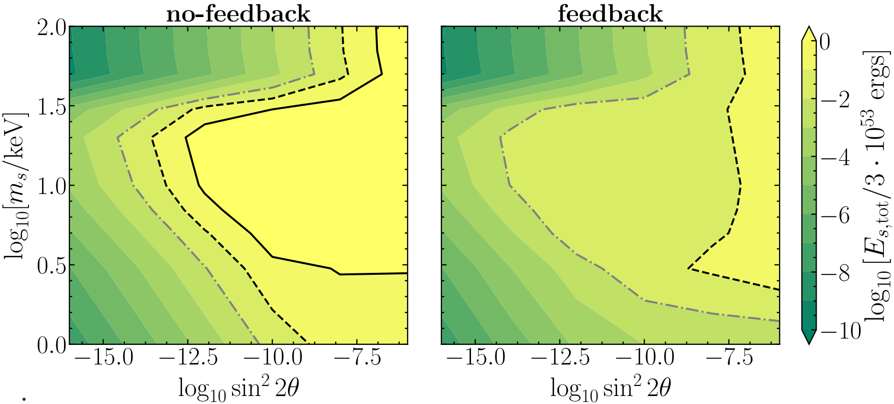
- The $\nu_s - \nu_e$ mixing induces large variations on
  - the entropy per baryon,
  - the supernova medium temperature.

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

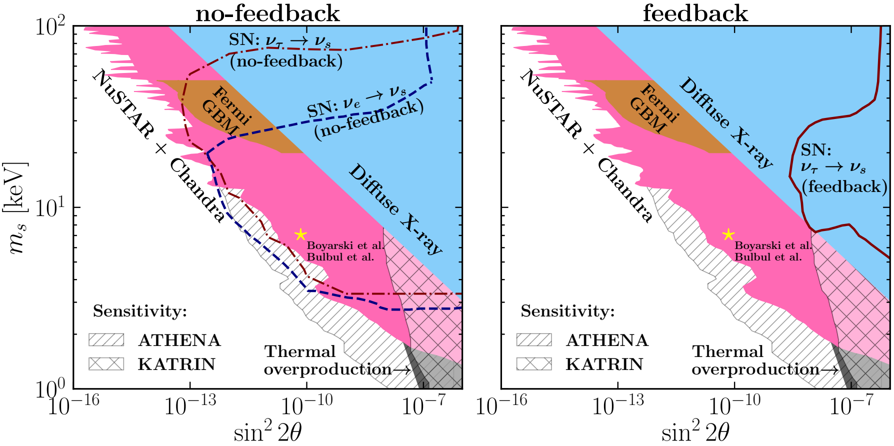


Again,

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

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.**

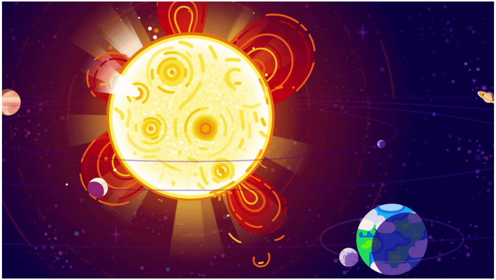
- **New treatment of active-sterile neutrino mixing in SNe challenges sterile neutrino bounds.**

Non-standard mediators coupling to protons

Non-standard mediators coupling to protons

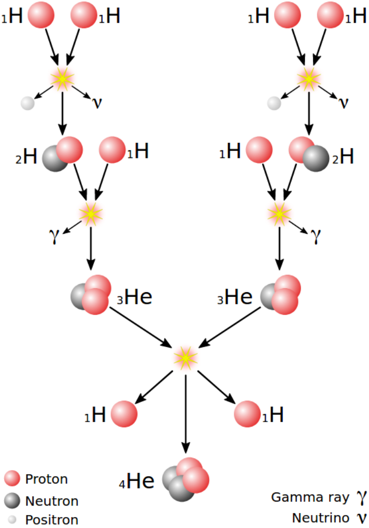
In collaboration with S. Shalgar and G. M. Fuller

Why our sun is an interesting place to look at?



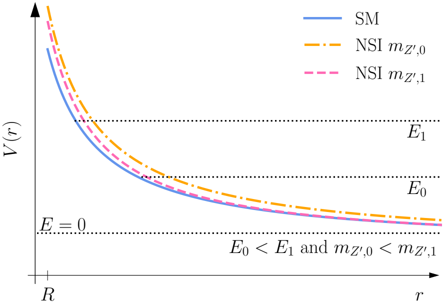
The Sun

- 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

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

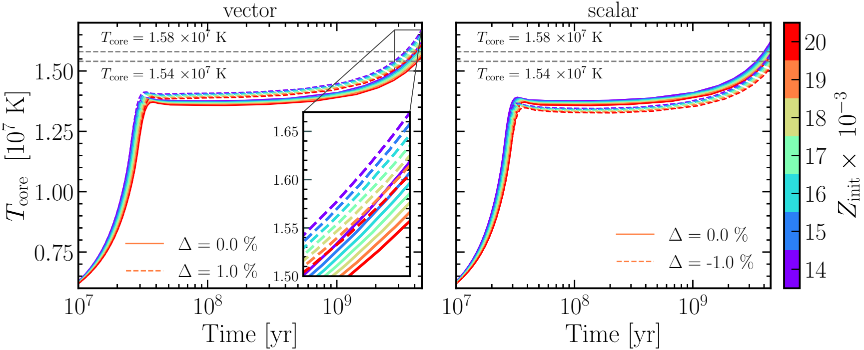
$$\Delta \approx \frac{\left| W_{0,\mathrm{NSI}}^{\frac{2}{3}} - W_{0,\mathrm{SM}}^{\frac{2}{3}} \right|}{W_{0,\mathrm{SM}}^{\frac{2}{3}}}$$

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)

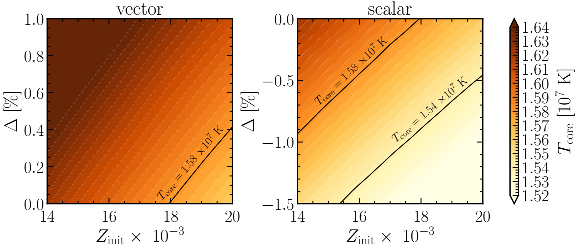
Temporal evolution of the solar core's temperature



- 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

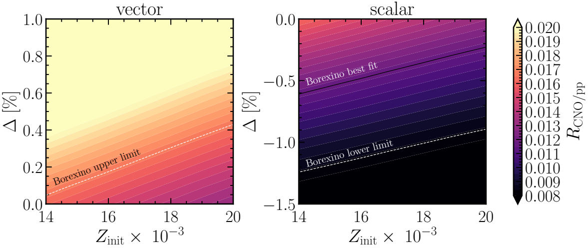
Sun's core temperature



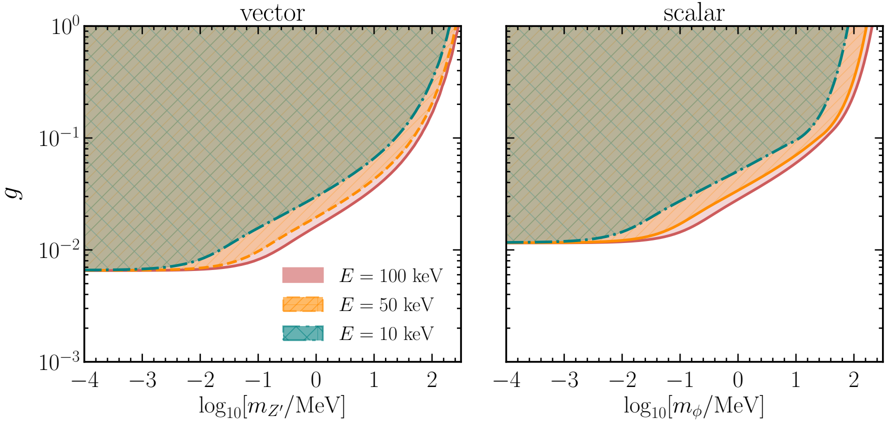
- vector boson mediator temperature increase
- scalar mediator temperature decrease

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

- $\mathrm{R}_{\mathrm{CNO/pp}}$ – the same trends
- degeneracy between initial metallicity and NSI



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

Conclusions: non-standard mediators

Conclusions: non-standard mediators coupling to protons

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 more massive stars

The calculated sensitivity bounds

- most constraining for mediators with masses above 50 keV
- will improve with better determination of the metallicity

Thank you!