IMPACT OF NEUTRINO FLAVOR OSCILLATIONS ON THE NEUTRINO-DRIVEN WIND NUCLEOSYNTHESIS OF AN ELECTRON-CAPTURE SUPERNOVA

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OUTLINE

- INTRODUCTION
- CORE-COLLAPSE-SUPERNOVA

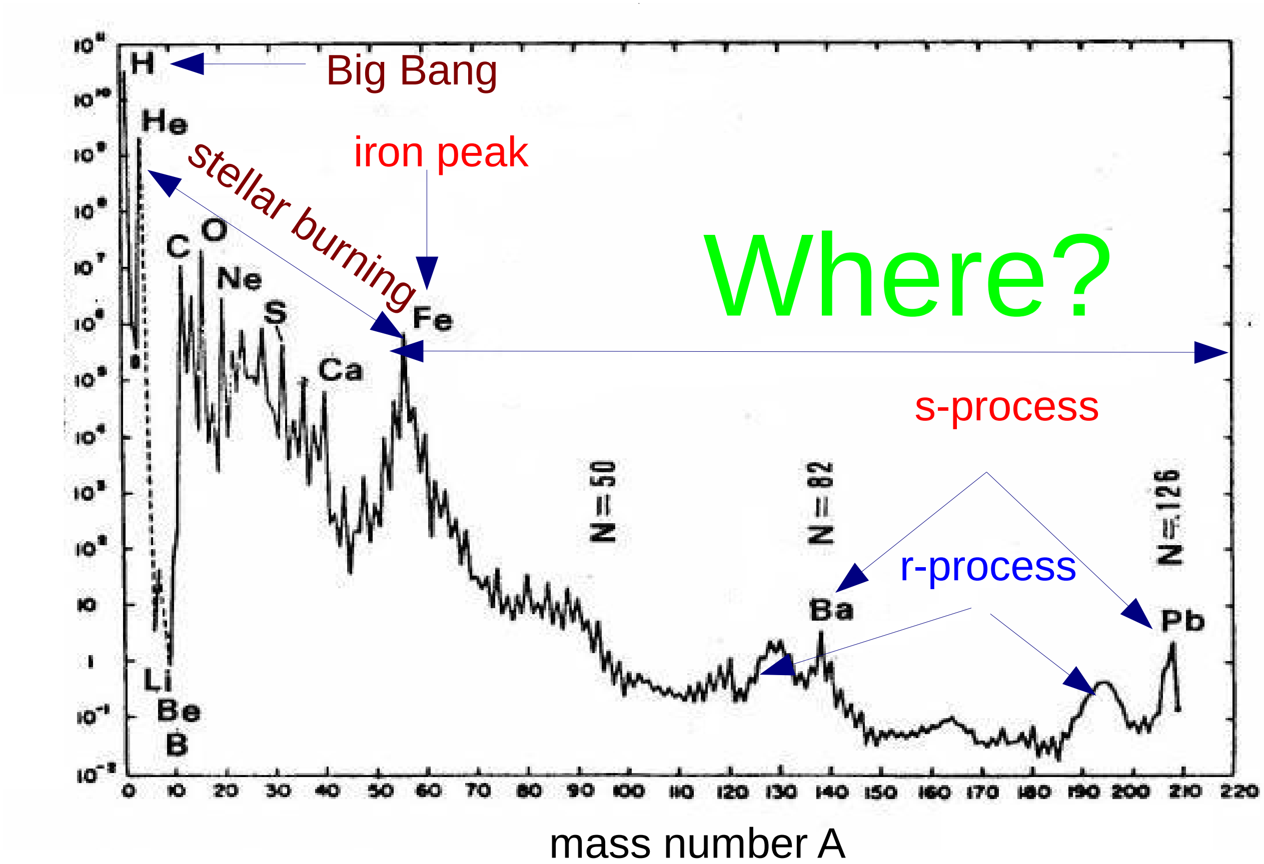
  neutrino-driven wind
- NEUTRINO OSCILLATIONS

  active-active flavor

  active-sterile flavor
- NUCLEOSYNTHESIS RESULTS
- CONCLUSIONS & PERSPECTIVES

WHERE DO THE ELEMENTS COME FROM?

Solar abundance distribution of the elements



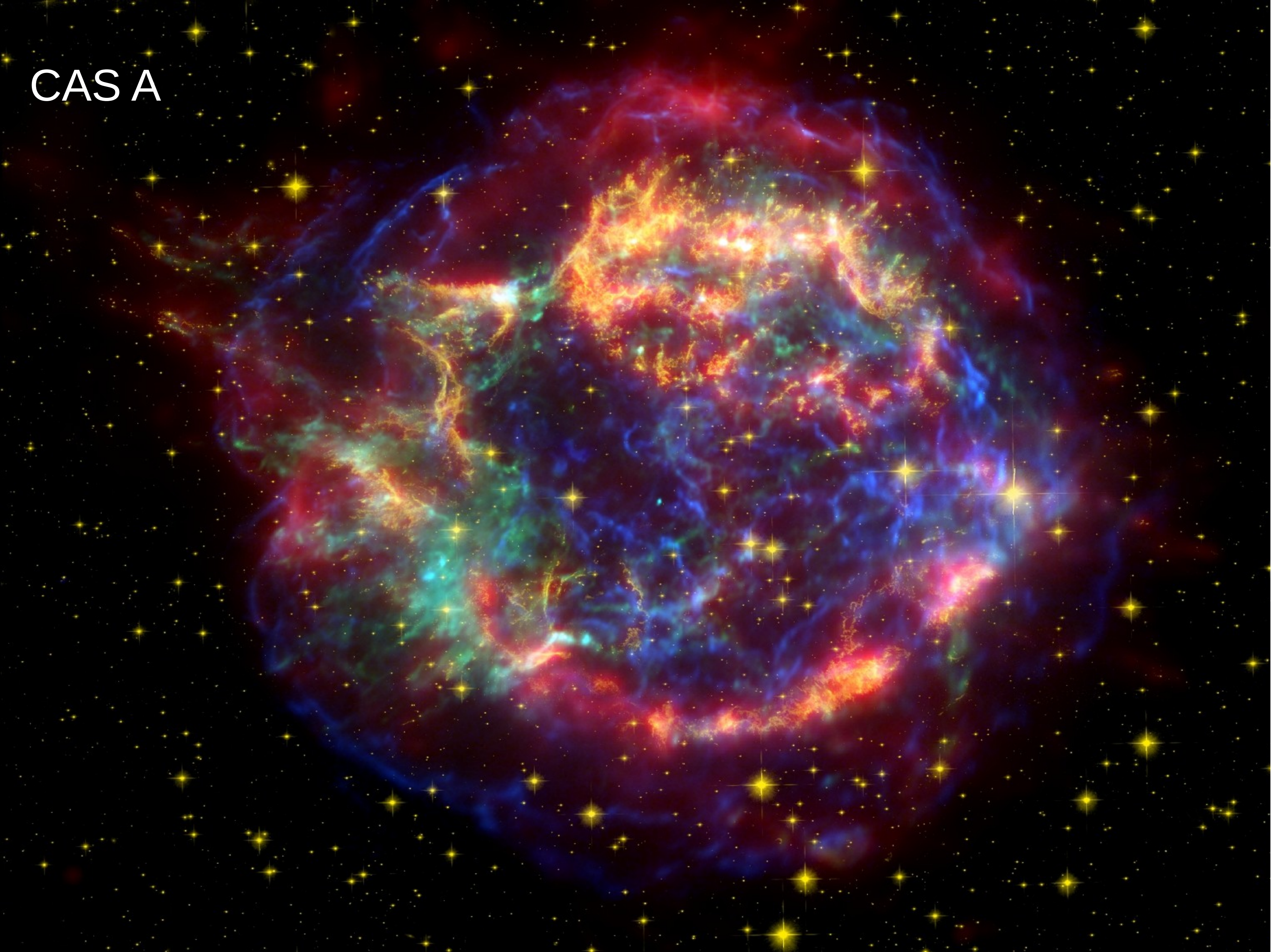
neutron capture nucleosynthesis:

s(low)-process: $N_n = 10^7 - 10^{10}\, cm^{-3} (\tau_{n-capt} \gg \tau_{\beta-decay})$

r(apid)-process: $N_n = 10^{20} - 10^{30}\, cm^{-3} (\tau_{n-capt} \ll \tau_{\beta-decay})$ →

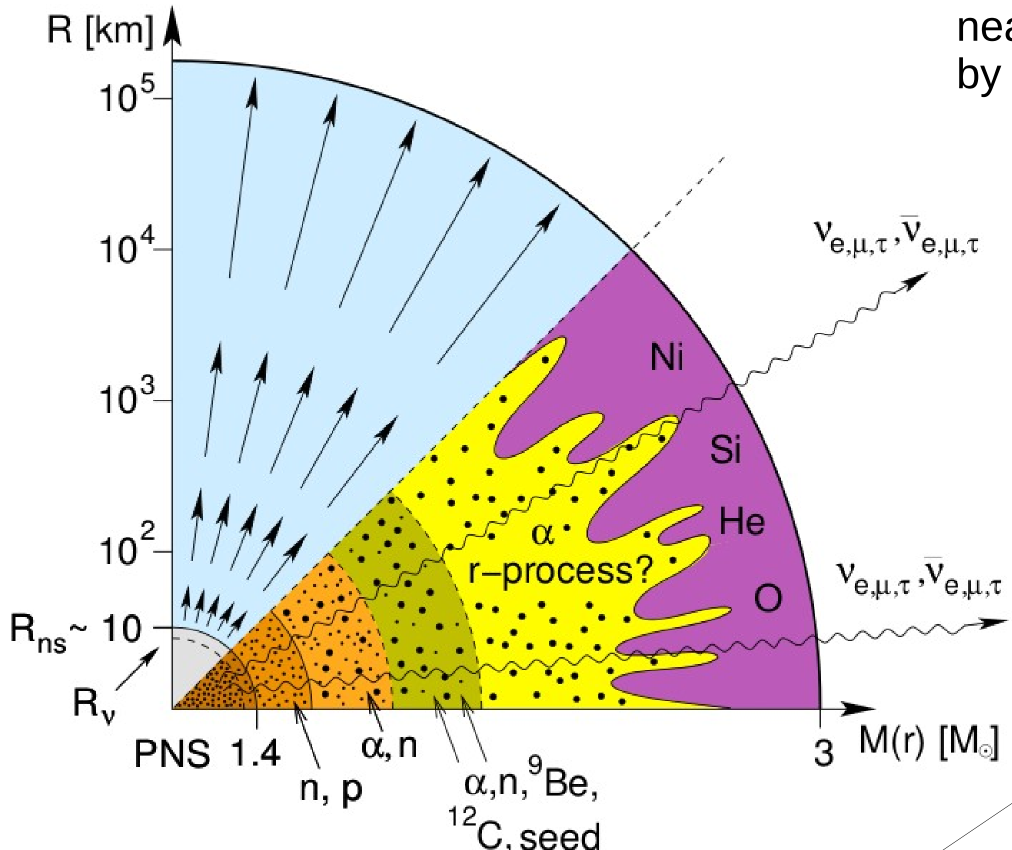
neutron density

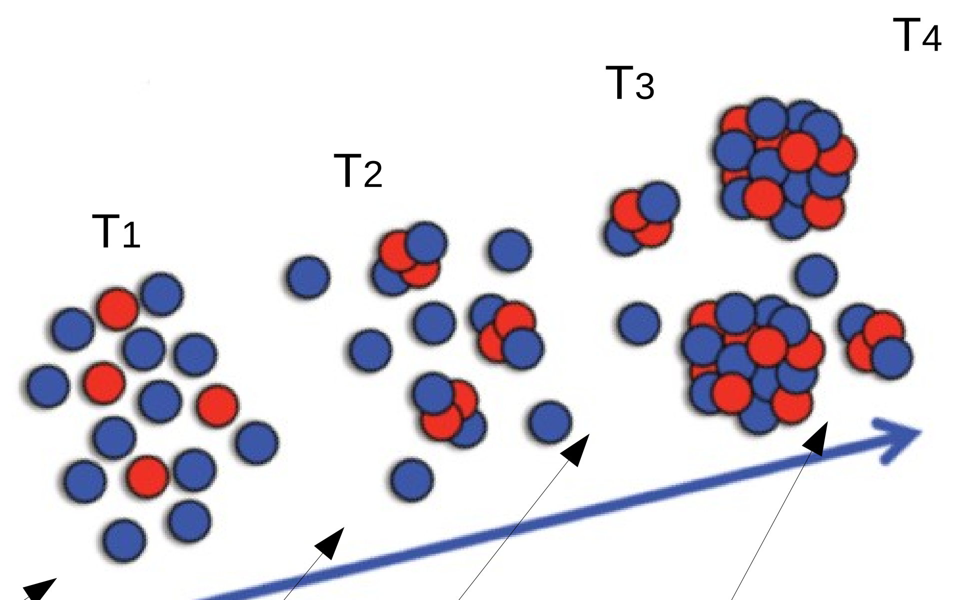
cadidate sites:
neuton stars
and
SUPERNOVAE


CAS A

SUPERNOVA NEUTRINO-DRIVEN WIND

ν-driven wind= flow of neutrons and protons from the region near to the surface of the Proto-Neutron Star (PNS) driven by the strong neutrinos and antineutrinos fluxes.





$T_1 > 10$ GK
free neutrons and protons

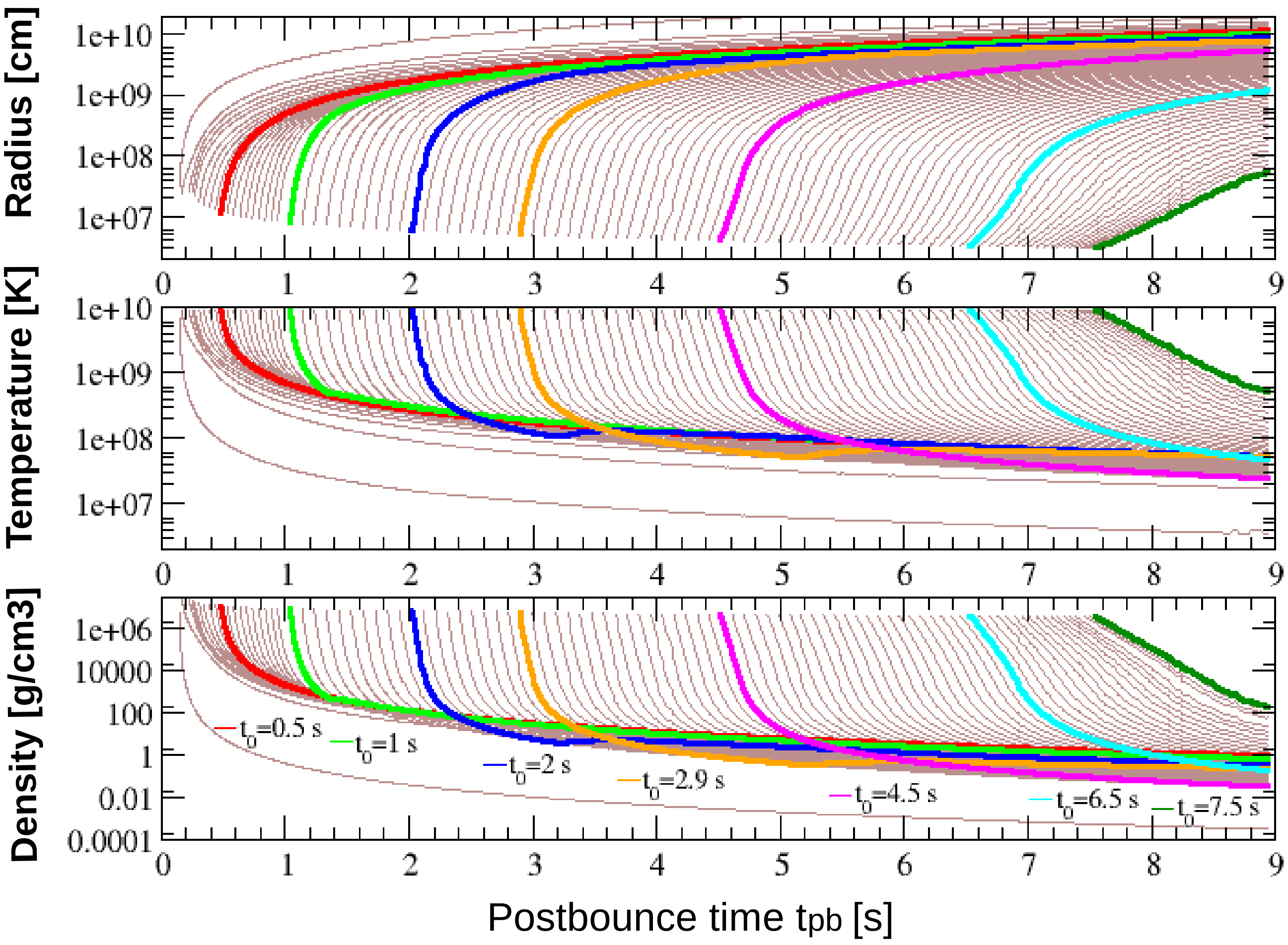
$6 \leqslant T_2 \leqslant 10$ GK
alpha particles formation

$T_3 \leqslant 5-6$ GK
ααn
ααα
reactions

$T_4 < 2$ GK
r-process
(n-rich matter)
νp-process
(p-rich matter)

INPUT NEUTRINO-DRIVEN WIND MASS-SHELL TRAJECTORIES

mass-shells



self-consistent hydrodynamical simulations:

- $M_{\star} = 8.8\, M_{sun}$
- ``O-Ne-Mg core''
- electron-capture supernova
- spherical symmetry (1D)
- full neutrino transport
- long-term simulations (until t_{pb}~10 s)

(Hüdepohl et al. 2010, Phys. Rev. Lett., 104, 25)

for our study, we choose 7 ``representative'' trajectories at postbounce times: 0.5 s, 1 s, 2 s, 2.9 s, 4.5 s, 6.5 s, and 7.5 s.

NEUTRINO DRIVEN-WIND ELECTRON FRACTION Y_e

→ Y_e determined by the following reactions:

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

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

capture rate →

$$\lambda_\nu = \frac{L_\nu}{4\pi r^2 \langle E_\nu \rangle} \langle \sigma(E_\nu) \rangle$$

luminosity

mean capture cross-section

distance from the center of PNS

mean energy

Including weak magnetism and recoil corrections:

$$\langle \sigma_{\nu_e} \rangle = k \langle E_{\nu_e} \rangle \varepsilon_{\nu_e} \left[1 + 2\frac{\Delta}{\varepsilon_{\nu_e}} + a_{\nu_e} \left(\frac{\Delta}{\varepsilon_{\nu_e}} \right)^2 \right] W_{\nu_e}$$

$$\langle \sigma_{\bar{\nu}_e} \rangle = k \langle E_{\bar{\nu}_e} \rangle \varepsilon_{\bar{\nu}_e} \left[1 - 2\frac{\Delta}{\varepsilon_{\bar{\nu}_e}} + a_{\bar{\nu}_e} \left(\frac{\Delta}{\varepsilon_{\bar{\nu}_e}} \right)^2 \right] W_{\bar{\nu}_e}$$

k: $9.3 \cdot 10^{-44}$ cm²/MeV²

Δ: 1. 293 MeV

NEUTRINO DRIVEN-WIND ELECTRON FRACTION Y_e

→ Y_e determined by the following reactions:

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

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

↓

neutrino flavor oscillations convert neutrinos into different flavors

↓

the number flux of $\nu_e, \bar{\nu}_e$ $\frac{L_\nu}{\langle E_\nu \rangle}$ could change

↓

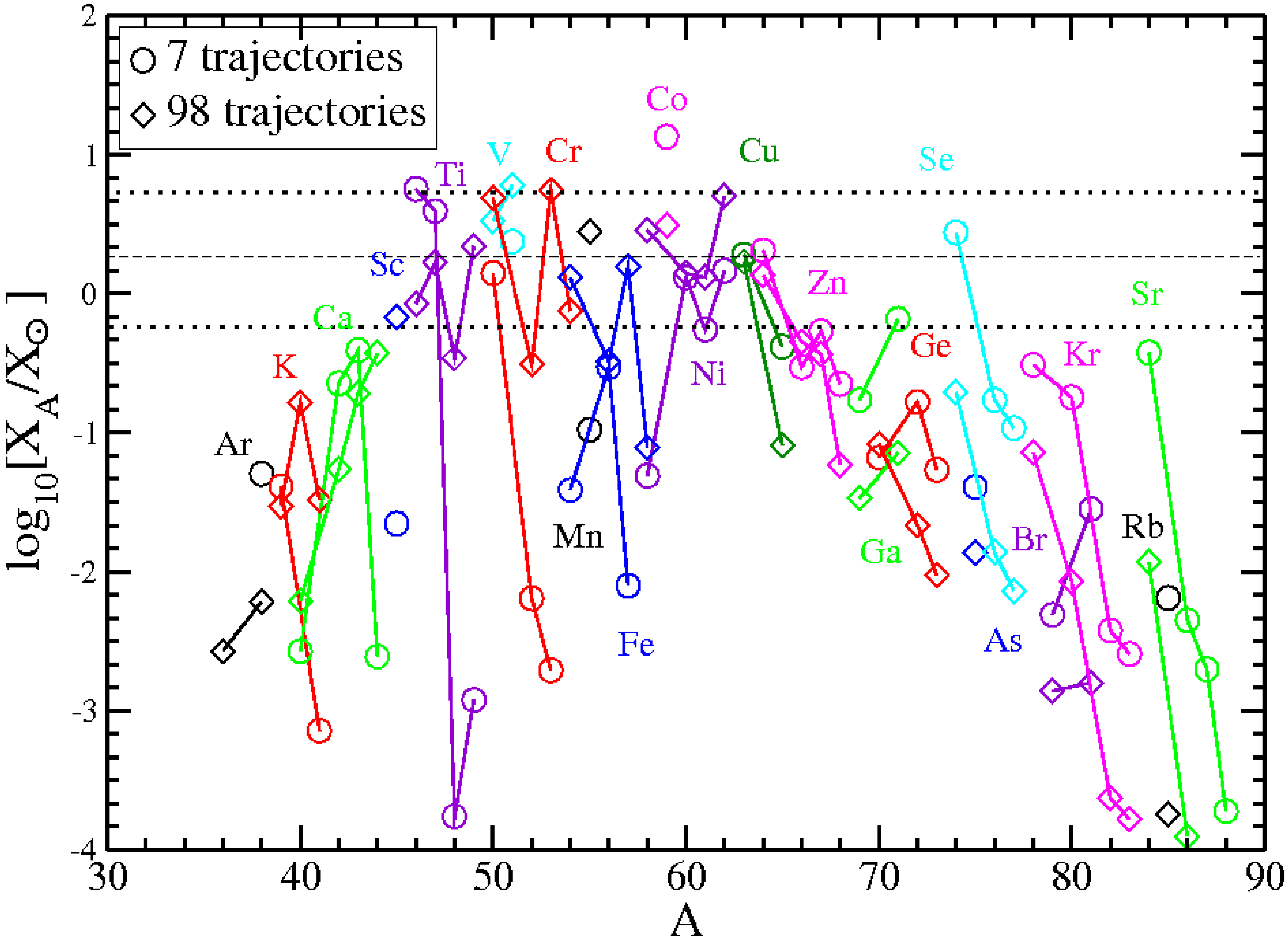
Y_e could change

$Y_e > 0.5$ proton-rich matter (νp-process)

$Y_e < 0.5$ neutron-rich matter (r-process)

NUCLEOSYNTHESIS WITHOUT NEUTRINO OSCILLATIONS

Abundance distribution of the elements
integrated from 0.5 to 7.5 s
relative to the corresponding solar values



$M_{wind} = 1.1 \cdot 10^{-2} M_{sun}$

$Y_e > 0.5$ proton-rich matter

The production factors $\log_{10}(X_{iso}/X_{sun})$ are very low compared to the 2D effects at $t_{pb} < 0.5$ s (Wanajo et al. 2011)

Without neutrino oscillations, nucleosynthesis results in 1D are not very interesting...

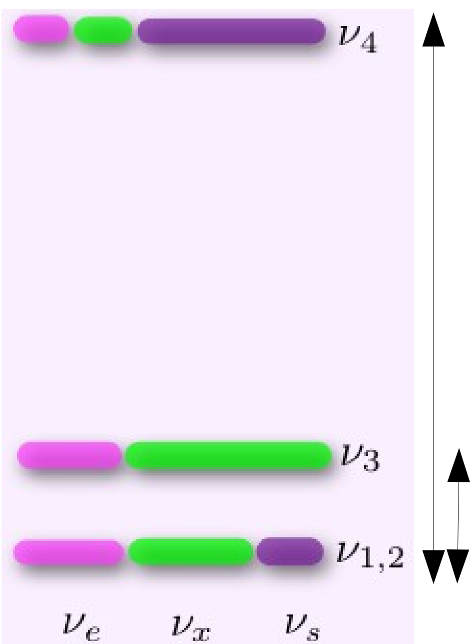
INPUT NEUTRINO MIXING PARAMETERS

Neutrino oscillations in the neutrino-driven wind due to:

1) neutrino interaction with matter → Mikheyev-Smirnov-Wolfenstein (MSW)

2) neutrino-neutrino interaction → Collective conversions

mixing parameters (from observational data):



mass difference

$$\Delta_{ste} m^2 = 2.35\, eV^2 ,$$

$$\sin^2(2\theta_{14}) = 10^{-1}$$

mixing angle

$$\Delta_{atm} m^2 = -2.35 \cdot 10^{-3} eV^2 ,$$

$$\sin^2(\theta_{13}) = 2 \cdot 10^{-2}$$

We consider two cases for neutrino oscillations:

ACTIVE-ACTIVE
(2 active flavors ν_e and ν_x)

$$\nu_e \leftrightarrow \nu_x , \quad x = \mu , \tau$$

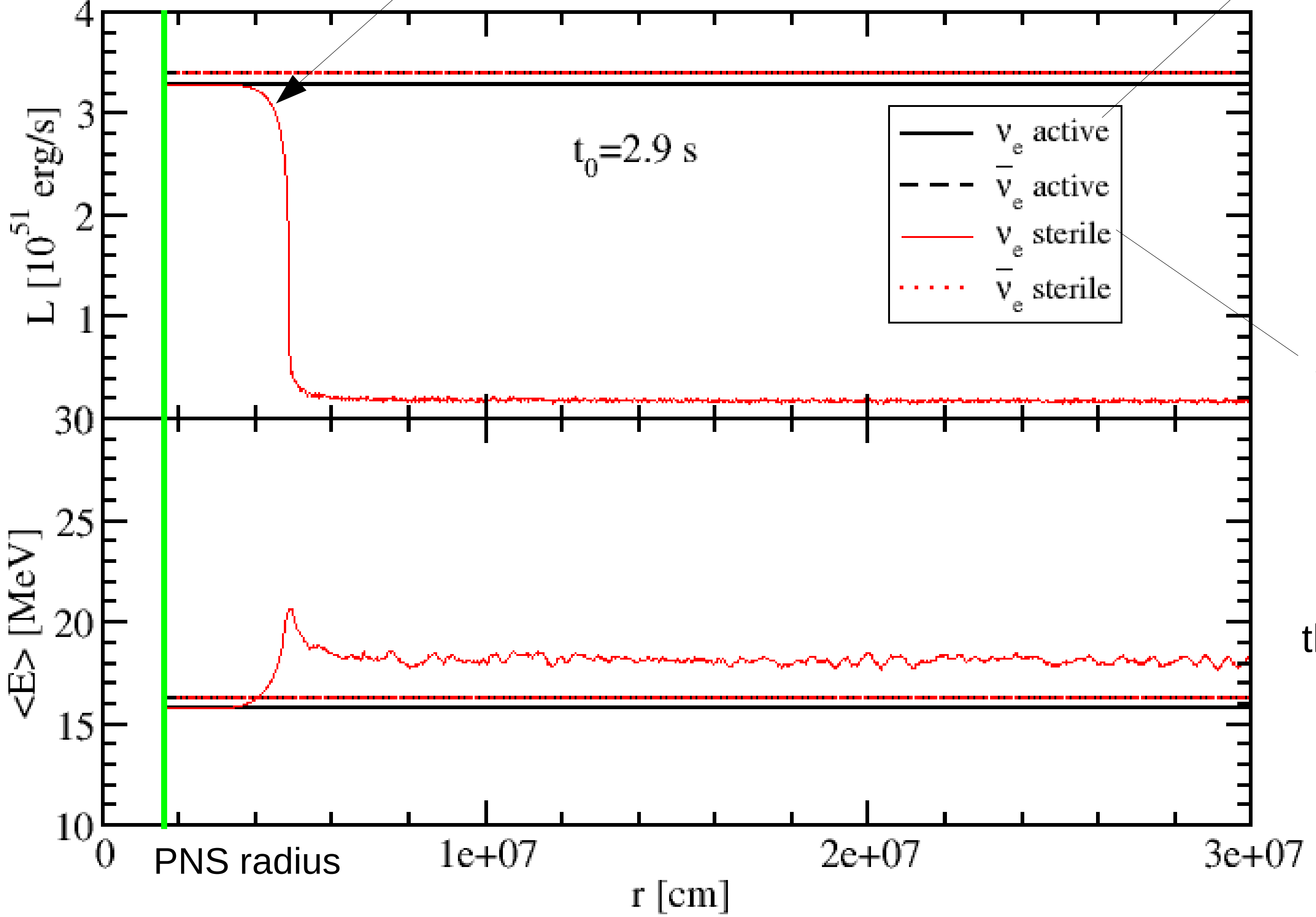
ACTIVE-STERILE
(2 active + 1 sterile flavors, ν_s)

$$\nu_e \leftrightarrow \nu_s$$

(Tamborra et al. 2012, JCAP 01, 013)

NEUTRINO OSCILLATIONS AT INTERMEDIATE POSTBOUNCE TIME (2.9 s)

MSW resonance



ACTIVE-ACTIVE conversions

$$\nu_e \leftrightarrow \nu_x$$

no impact on $N_\nu = \frac{L_\nu}{\langle E_\nu \rangle}$,

no impact on Ye!

ACTIVE-STERILE conversions

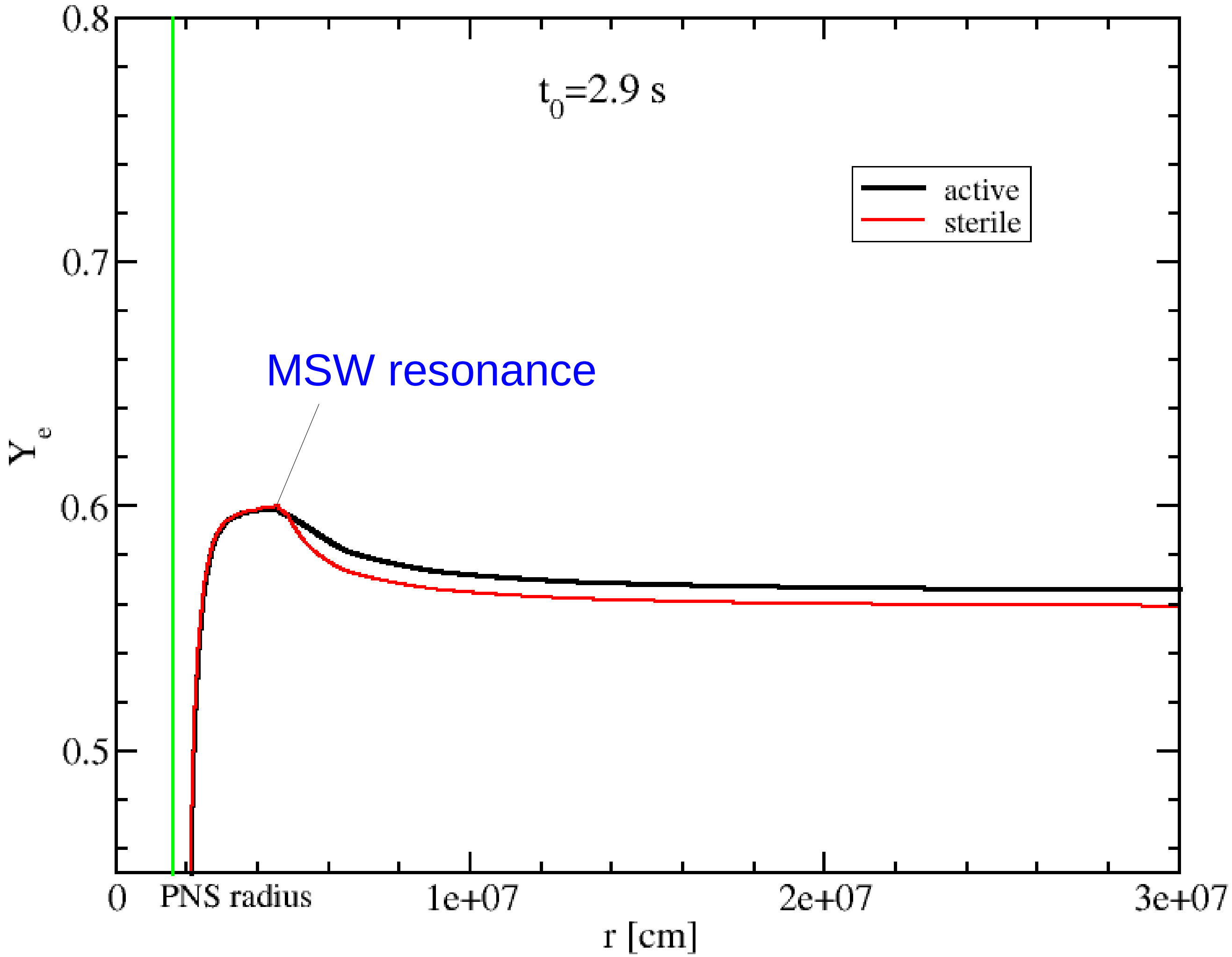
$$\nu_e \rightarrow \nu_s$$

the flux $\frac{L_{\nu_e}}{\langle E_{\nu_e} \rangle}$ decreases a lot!

Does Ye decrease a lot???

IMPACT OF NEUTRINO OSCILLATIONS ON THE ELECTRON FRACTION Ye AT INTERMEDIATE POSTBOUNCE TIMES

Network calculation results



$$Y_e = X_p + \frac{X_\alpha}{2} + \sum \frac{Z_A}{A} \cdot X_A$$

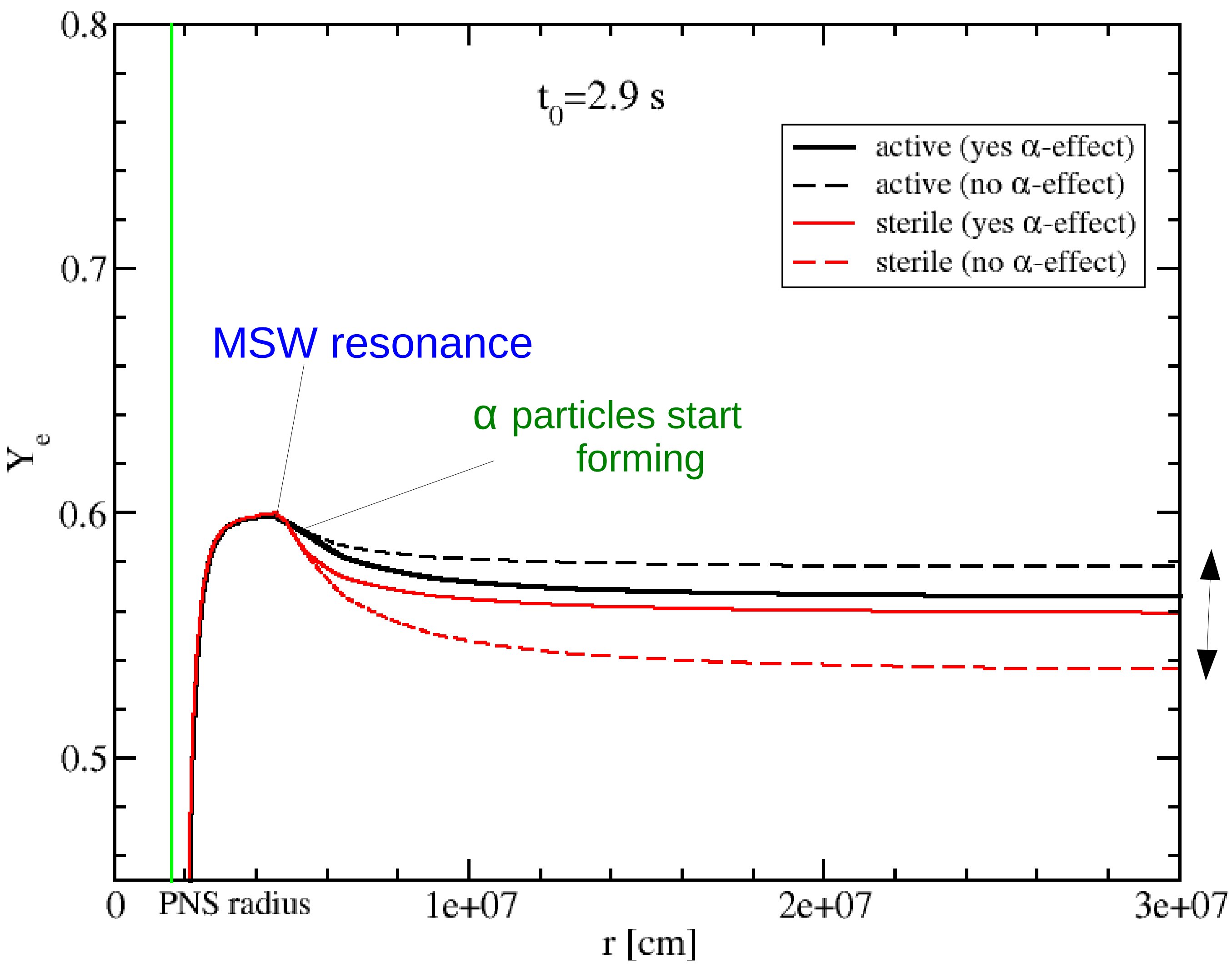
Charge neutrality

mass fraction of elements with Z>3 and mass number A

Despite the important conversions of electron neutrinos into sterile neutrinos, we see **a very small difference in Ye!!!**

WHY?? → ALPHA-EFFECT!

NEUTRINO OSCILLATIONS AT INTERMEDIATE POSTBOUNCE TIMES AND THE ALPHA-EFFECT ON Ye



Ye determined by:

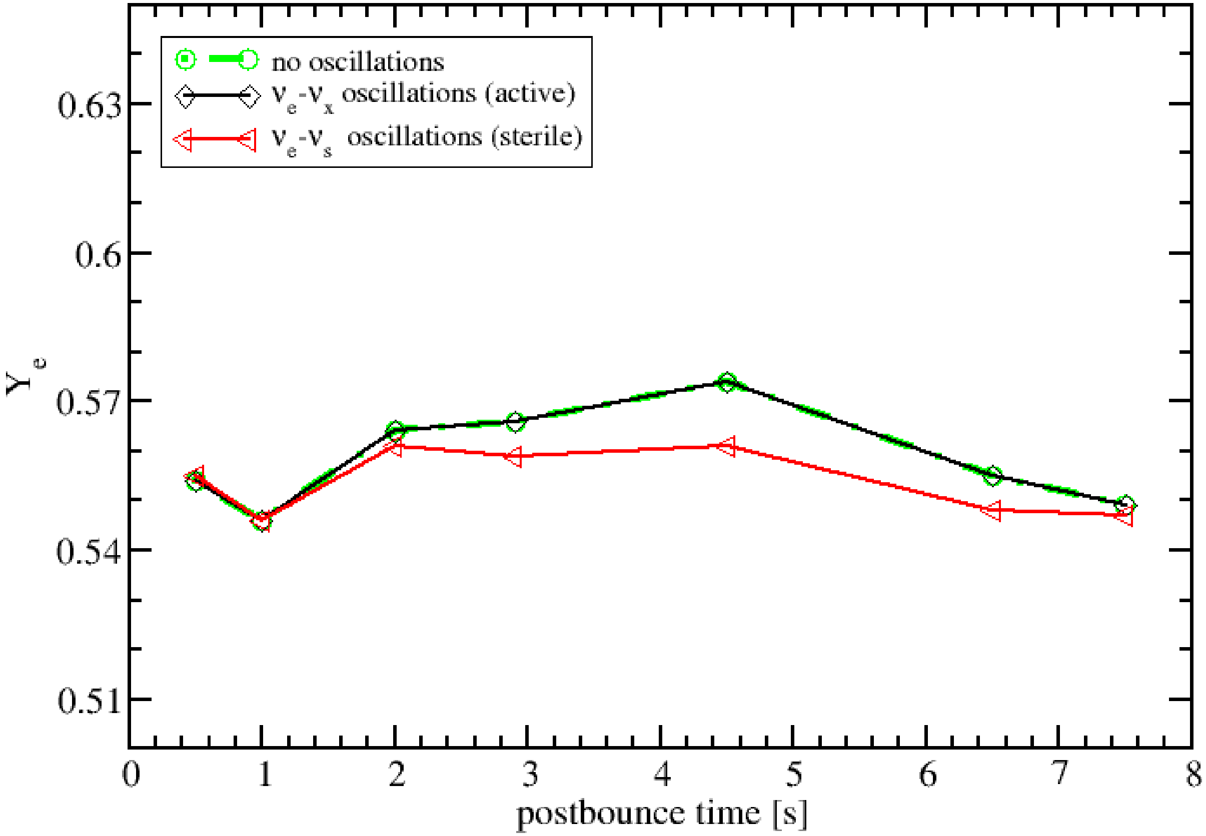
$$\nu_e + n \rightarrow p + e^-$$

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

difference due just to neutrino oscillations

``Alpha-effect'': the formation of each α particle takes two free neutrons and protons, damping the efficiency of neutrino oscillations, and it pushes $Y_e \rightarrow 0.5$.

ELECTRON FRACTION AS FUNCTION OF POSTBOUNCE TIME



Because of the alpha-effect, we do not see any important impact of neutrino oscillations on Ye, which is > 0.5

↓

no significant impact on the nucleosynthesis yields

CAVEAT: in our hydro simulations we do not include mean-field nucleon potential corrections for charged-current neutrino opacities, which can make Y_e<0.5!

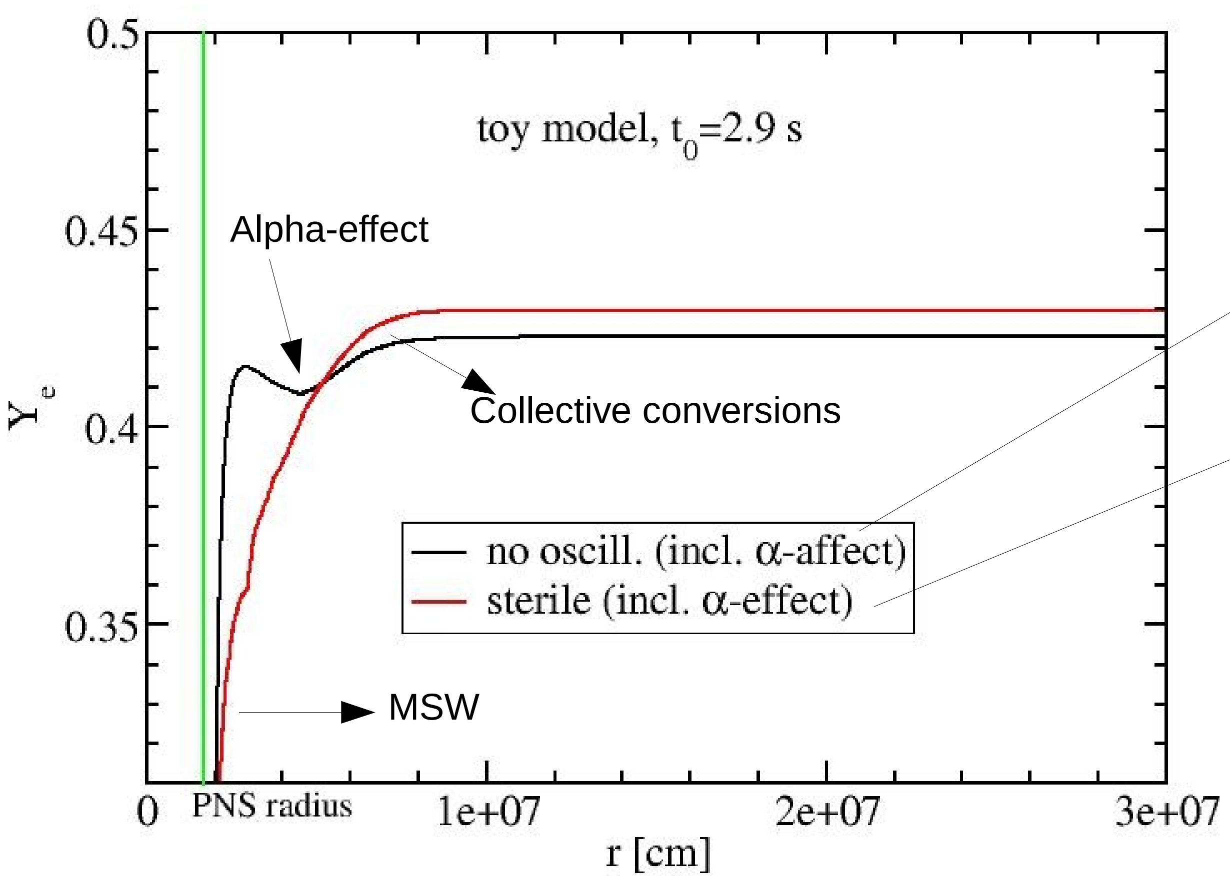
What would happen if we did?

A TOY MODEL TO ACCOUNT FOR NUCLEON POTENTIAL EFFECTS ON Ye:
NEUTRINO OSCILLATIONS IN NEUTRON-RICH NEUTRINO-DRIVEN WIND

Toy model neutrino parameters:

1) we keep the same luminosities as from hydro simulations

2) we artificially lower $\langle E_{\nu_e} \rangle$ and increase $\langle E_{\bar{\nu}_e} \rangle$ ⟷ Ye is artificially set to ~0.42 taking into account the alpha-effect and without neutrino oscillations



NO OSCILLATIONS (or ACTIVE-ACTIVE conversions)

ACTIVE-STERILE conversions

↓

Ye increases, and doesn't decrease as we would expect!

↓ Why???

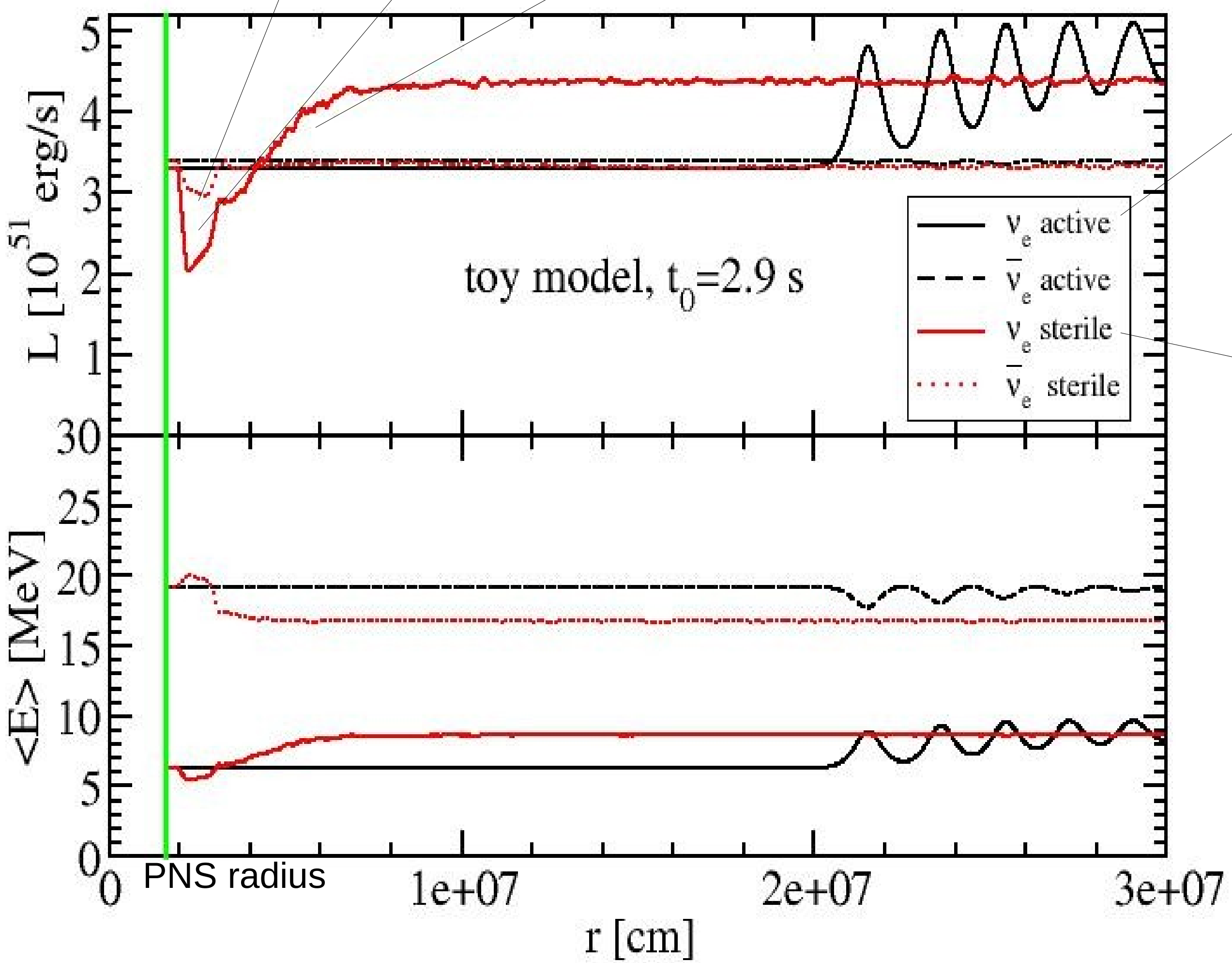
Let's have a look at the neutrino luminosities and mean energies!

A TOY MODEL TO ACCOUNT FOR NUCLEON POTENTIAL EFFECTS on Ye: NEUTRINO OSCILLATIONS IN NEUTRON-RICH NEUTRINO-DRIVEN WIND

Alpha-effect

MSW

Collective conversions



ACTIVE-ACTIVE conversions

↓

take place to far away to have any significant impact on Ye

ACTIVE-STERILE conversions

↓

impact on both ν_e and $\bar{\nu}_e$ fluxes

$$\frac{L_{\nu_e}}{\langle E_{\nu_e} \rangle} > \frac{L_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e} \rangle}$$

↓

Ye INCREASES!!!

CONCLUSIONS & PERSPECTIVES

- We study an $8.8 M_{sun}$ self-consistent 1D neutrino-driven wind nucleosynthesis (with and without neutrino oscillations).

- We see a very strong competition between the ``alpha-effect'' and the oscillation of neutrinos on the electron fraction.

- Independently from the neutrino oscillations, the neutrino-driven wind matter is proton-rich, confirming the 1D long-term simulation hydrodynamic results

↓

neutrino oscillations are not enough to enable the r-process.

- The study of other stars is needed in order to better understand the nucleosynthesis in the neutrino-driven winds.


Thank you very much for your attention!