# Sterile Neutrinos in Astrophysical Environments :

## Big Bang Nucleosynthesis and Supernova Neutrino process


**Speaker : Dukjae Jang (Soongsil University)**

In collaboration with

Heamin Ko (Soongsil University)

Motohiko Kusakabe (Beihang University)

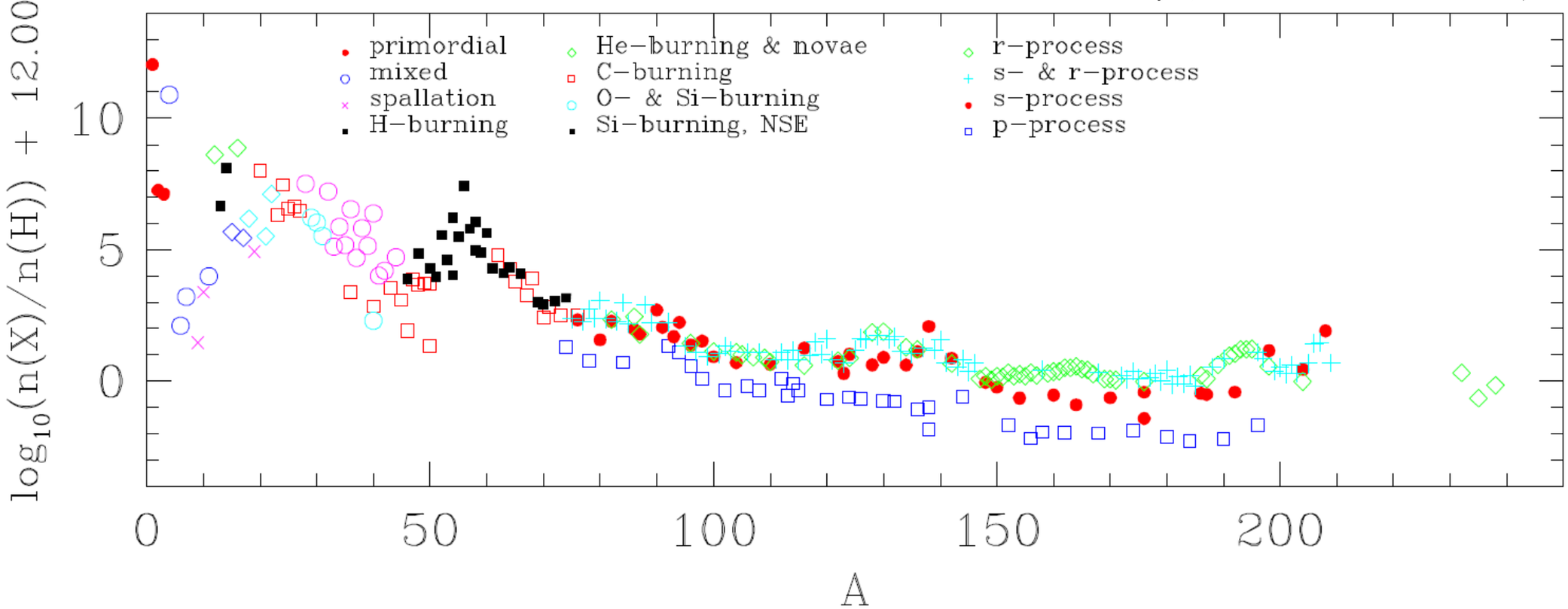
Myung-Ki Cheoun (Soongsil University)


**August 29, 2019**


**NuFACT 2019 THE 21ST INTERNATIONAL WORKSHOP ON NEUTRINOS FROM ACCELERATORS**

# Solar abundance

S. G. Ryan, Publ. Astron. Soc. Austral. **19** 238 (2002)



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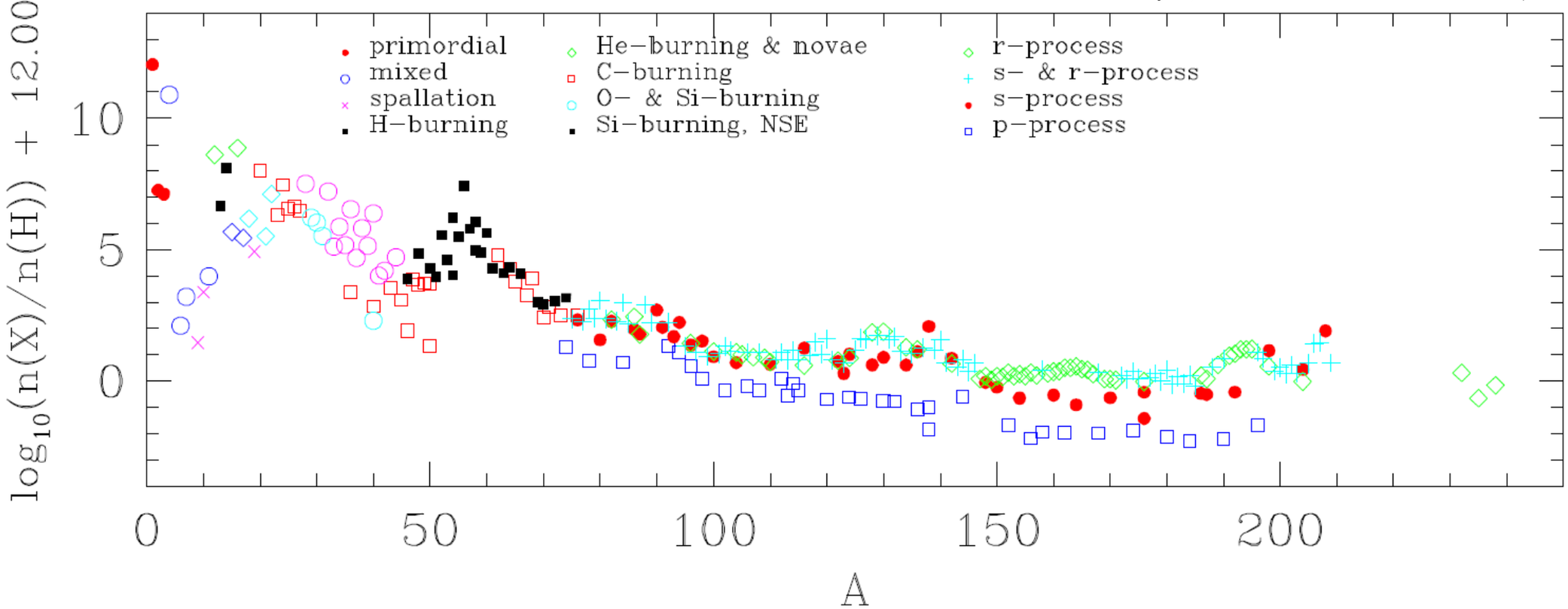


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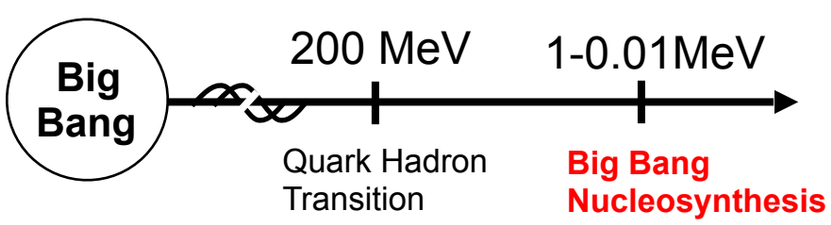


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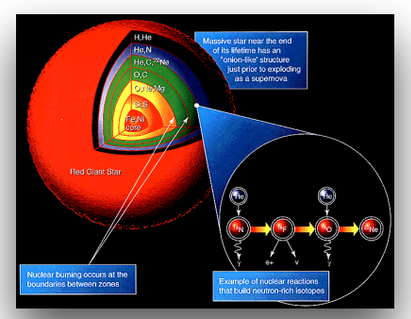
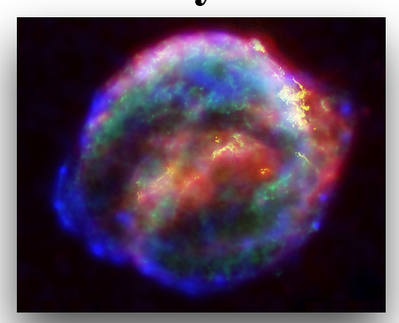


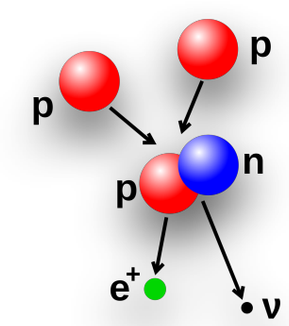
(Wikipedia)

**Supernova nucleosynthesis**



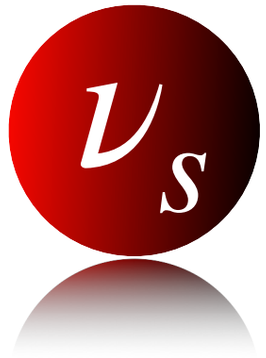
(Wikipedia)

**Cosmic ray spallation**




(Wikipedia)

# Sterile neutrinos



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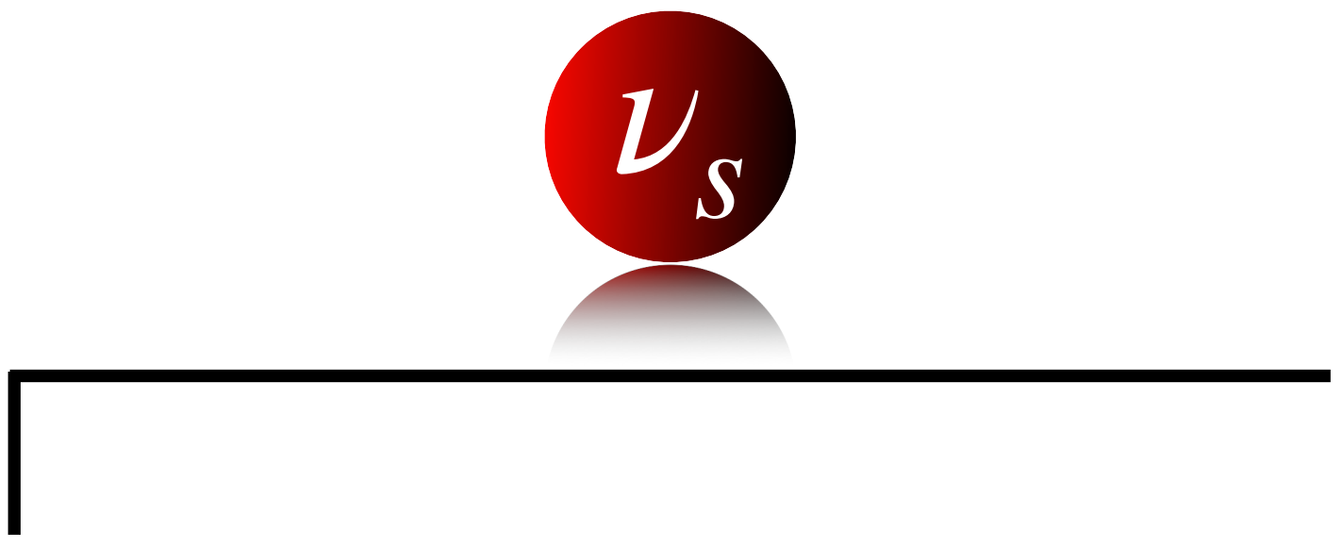


**Cosmic expansion rate**

$$H^2 \propto \rho_{\nu_s}$$

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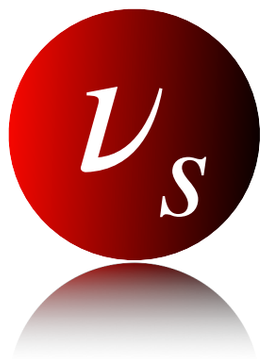


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$$\nu_s \leftrightarrow \nu_a$$

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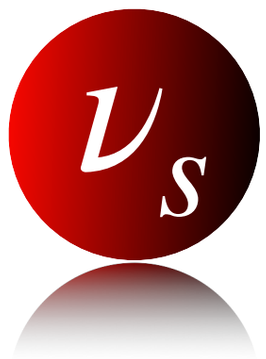


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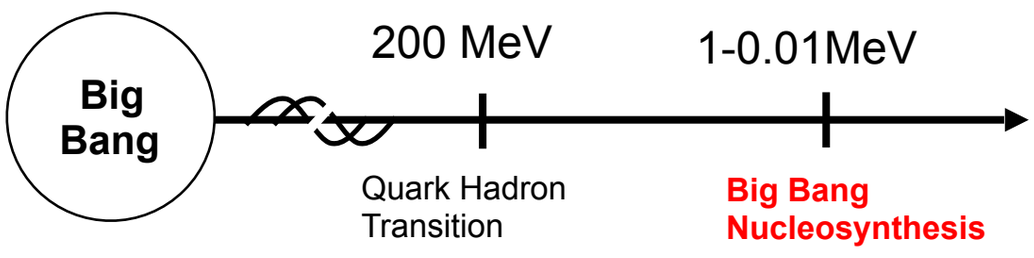

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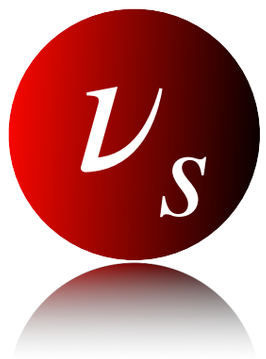


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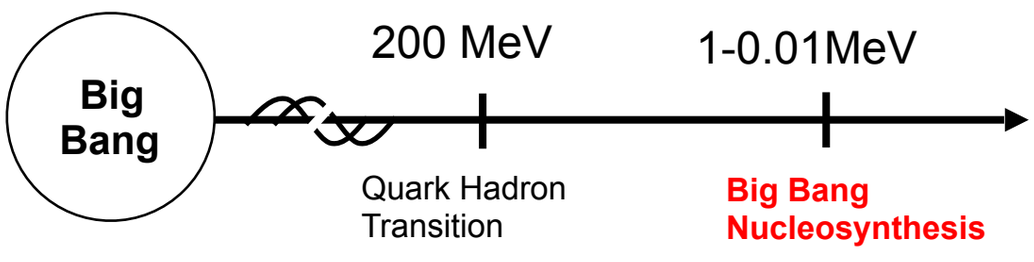


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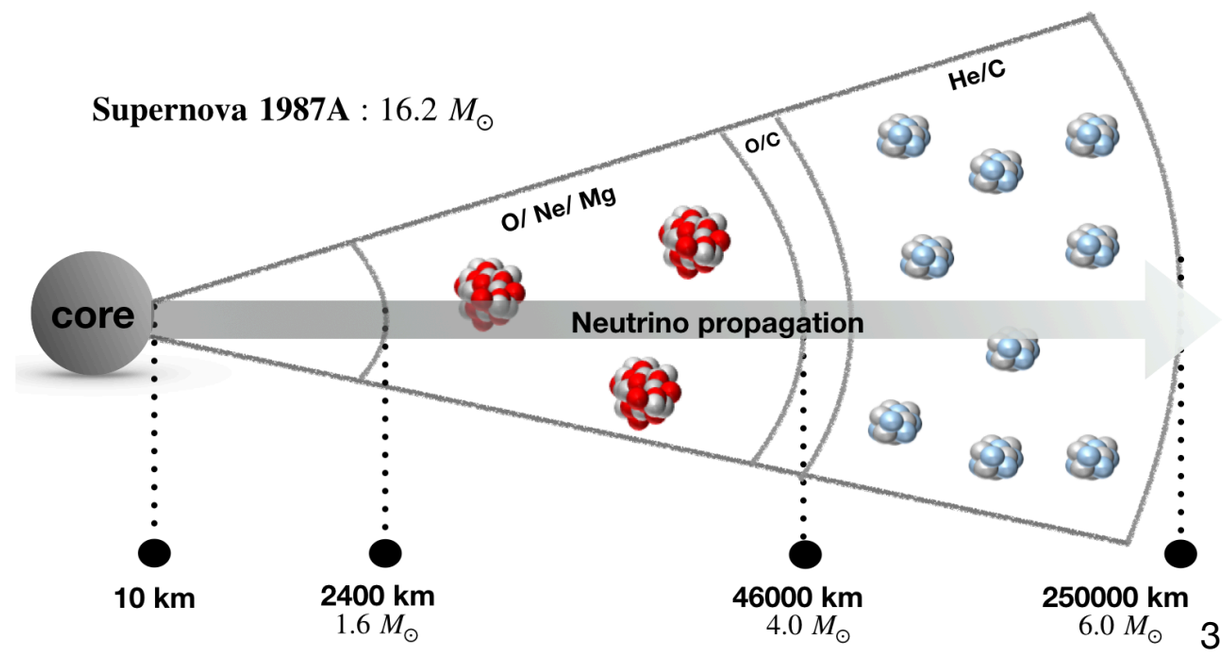

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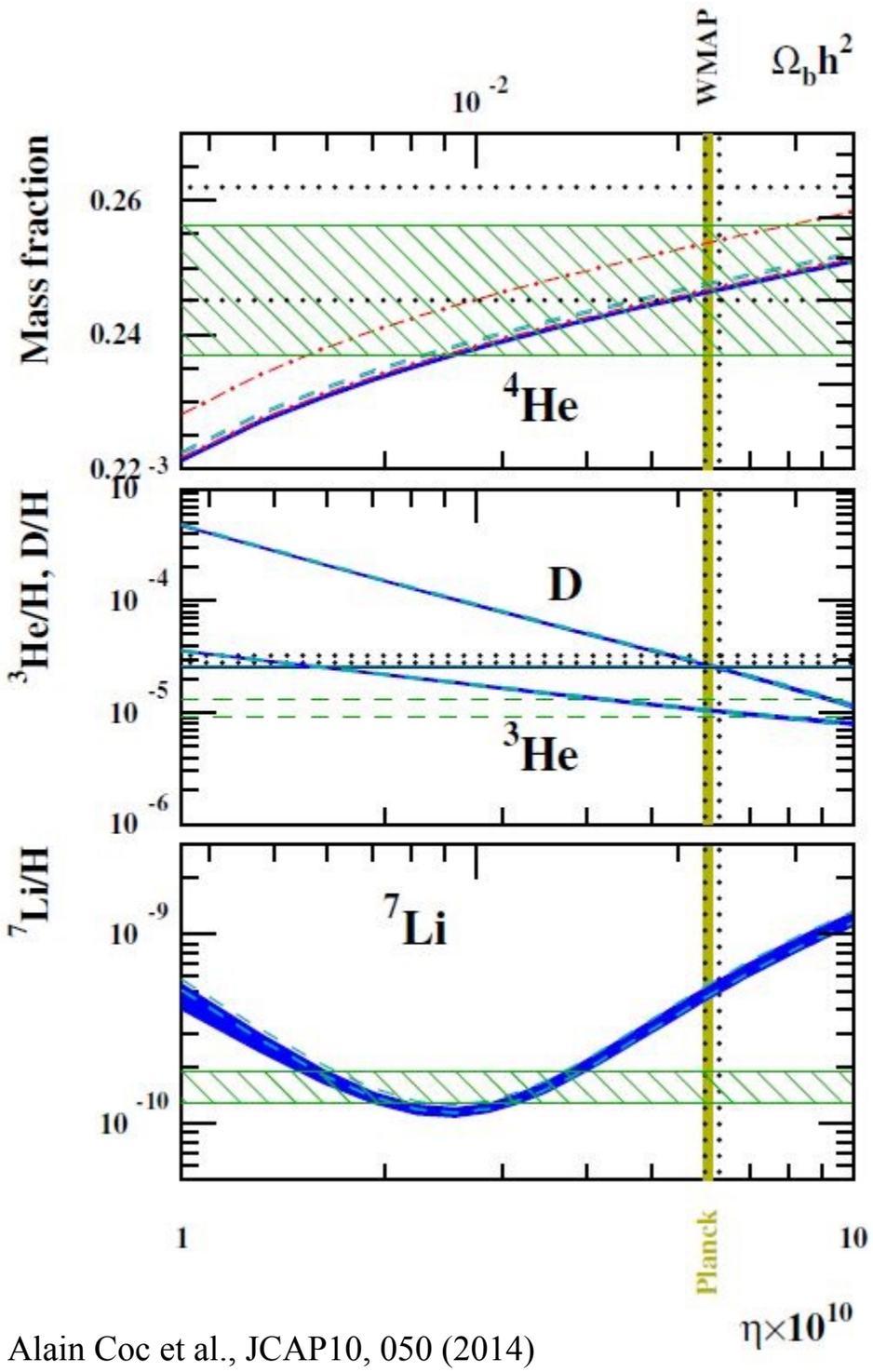


Alain Coc et al., JCAP10, 050 (2014)

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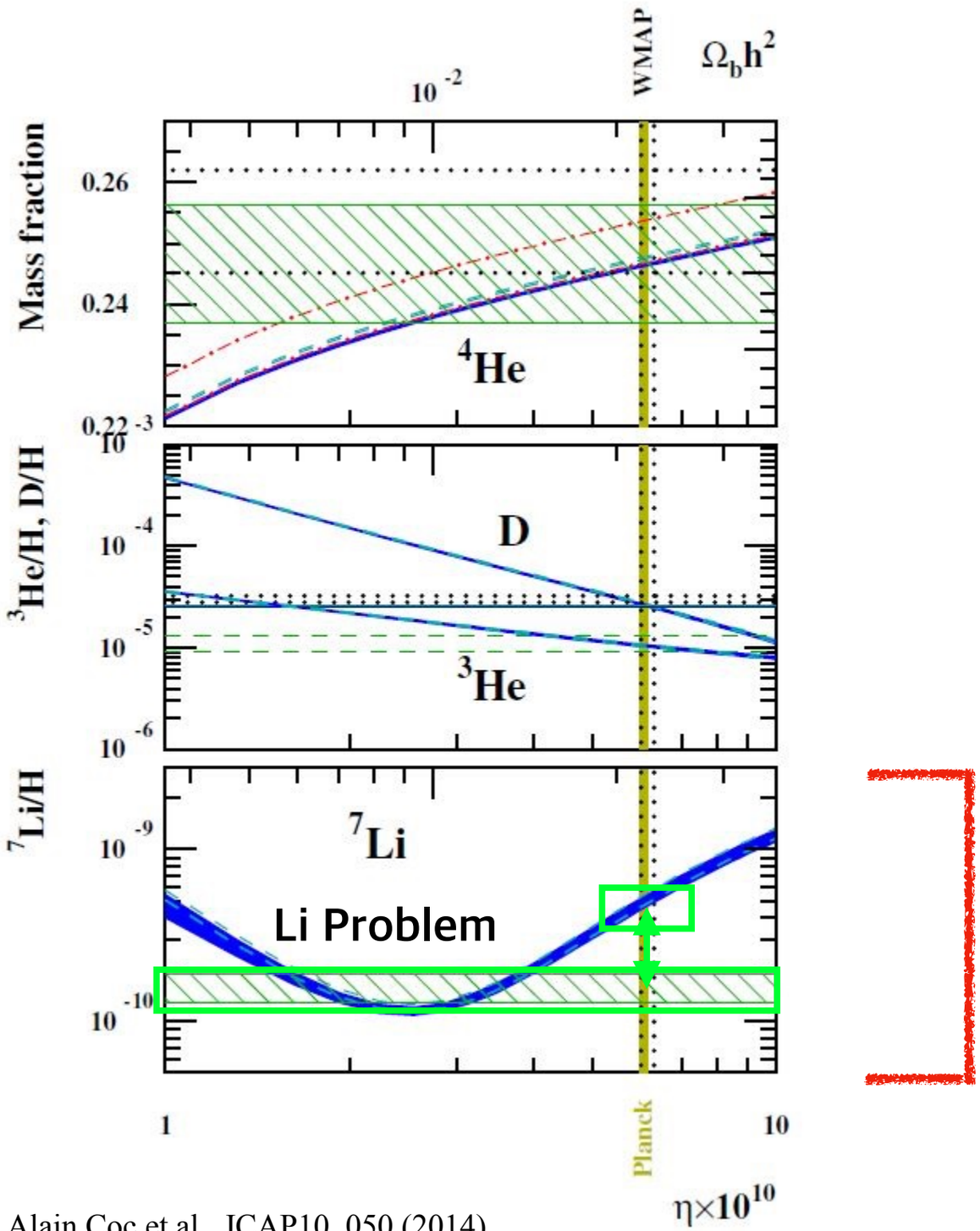


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Primordial lithium problem

: Hints for new physics

or

Corrections of SBBN

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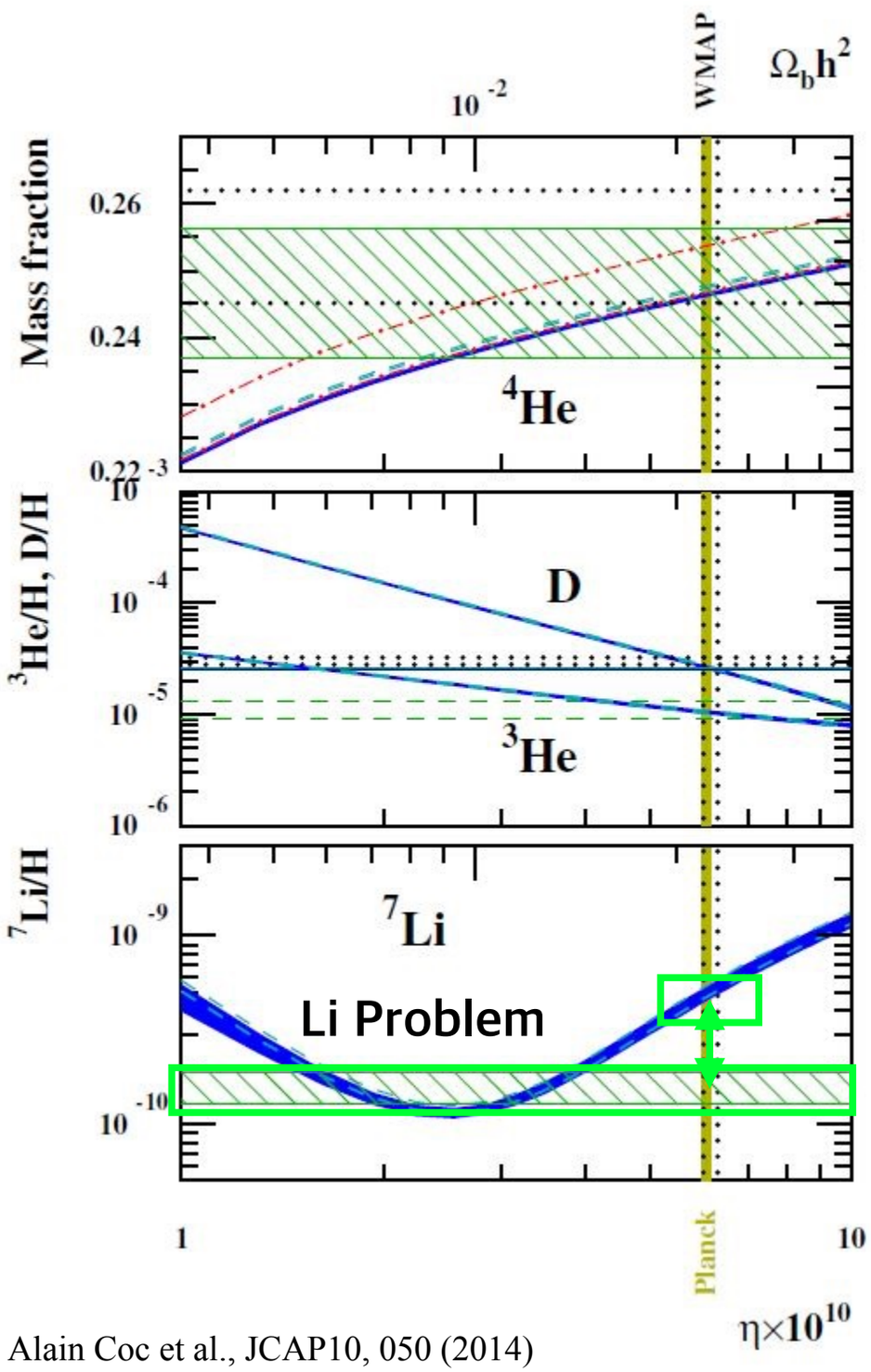


Alain Coc et al., JCAP10, 050 (2014)

**Good prediction of SBBN**

**: Cosmological constraint**

**(1) Modified gravity model**

**ex:** Modified gravity model of f(R)

Kusakabe et al., PRD **91**, 104023 (2015)

**(2) Test of dark matter model**

**ex :** Scalar field dark matter

Bohea Li et al., PRD **89**, 083536 (2014)

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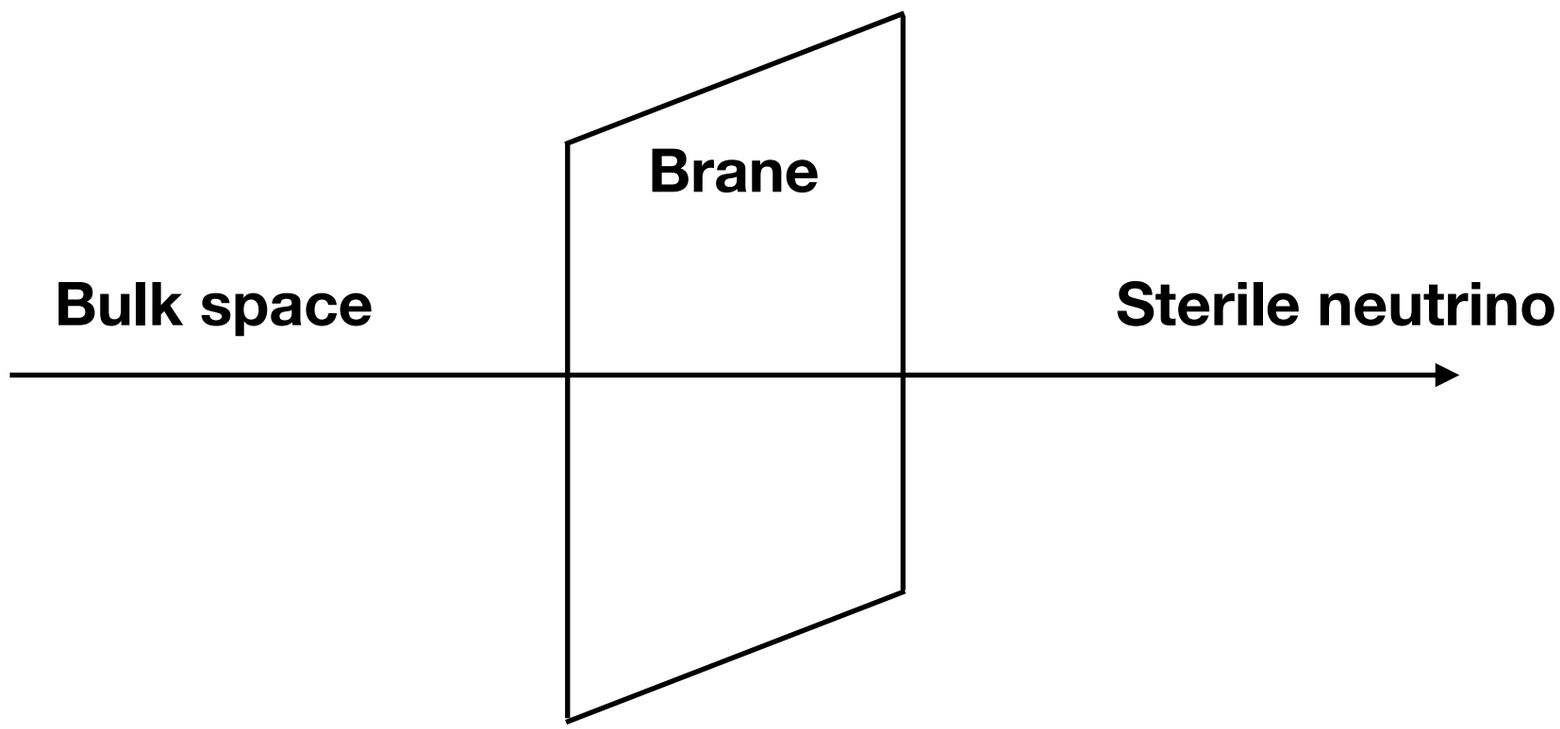
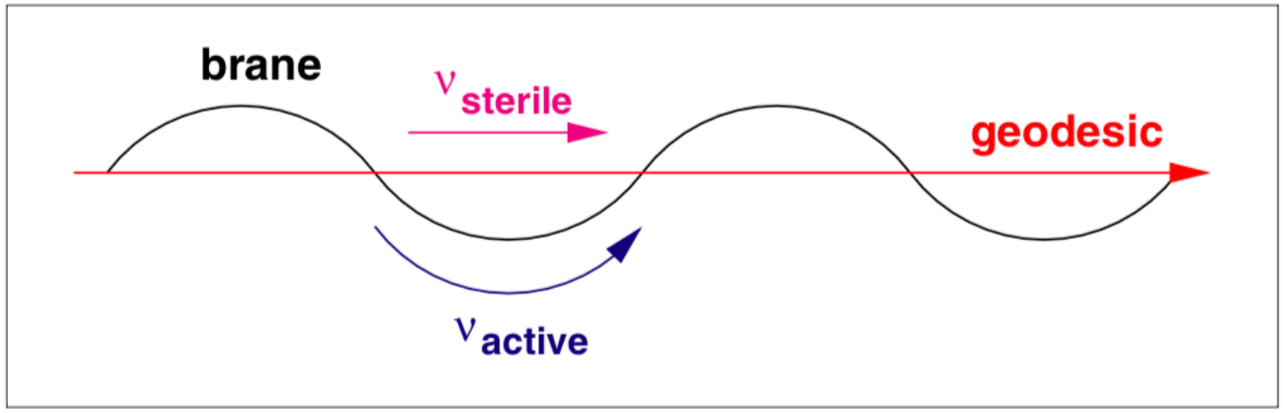
PHYSICAL REVIEW D **72,** 095017 (2005)

# Sterile-active neutrino oscillations and shortcuts in the extra dimension

Heinrich Päs,[1] Sandip Pakvasa,[1] and Thomas J. Weiler[2]



Pas et al., PRD 72 095017




**Different trajectory (proper time) between bulk and brane**

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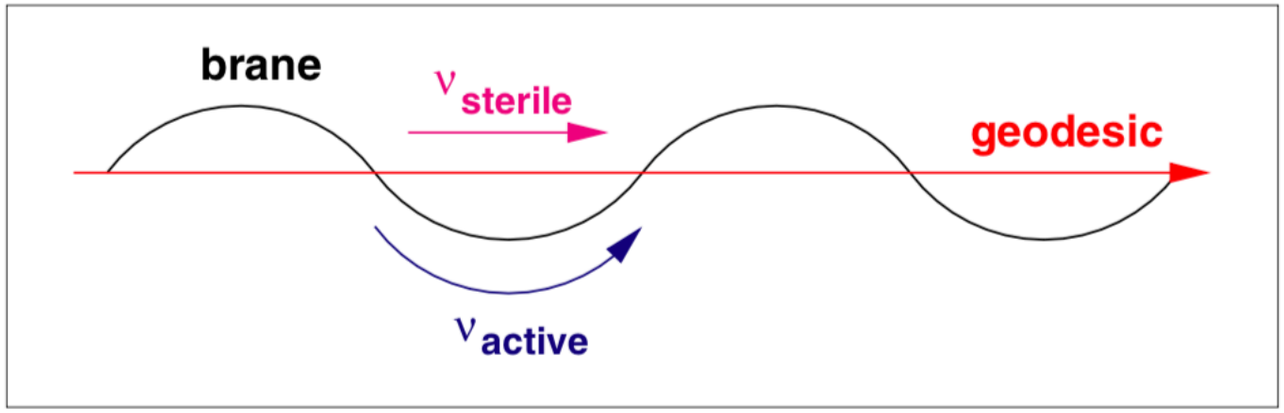


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**Time evolution of sterile-active neutrino**

$$i\frac{d}{dt}\begin{pmatrix}\nu_a(t)\\ \nu_s(t)\end{pmatrix} = H_F\begin{pmatrix}\nu_a(t)\\ \nu_s(t)\end{pmatrix}$$

$$H_F = \frac{\delta m^2}{4E}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix} + E\frac{\epsilon}{2}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

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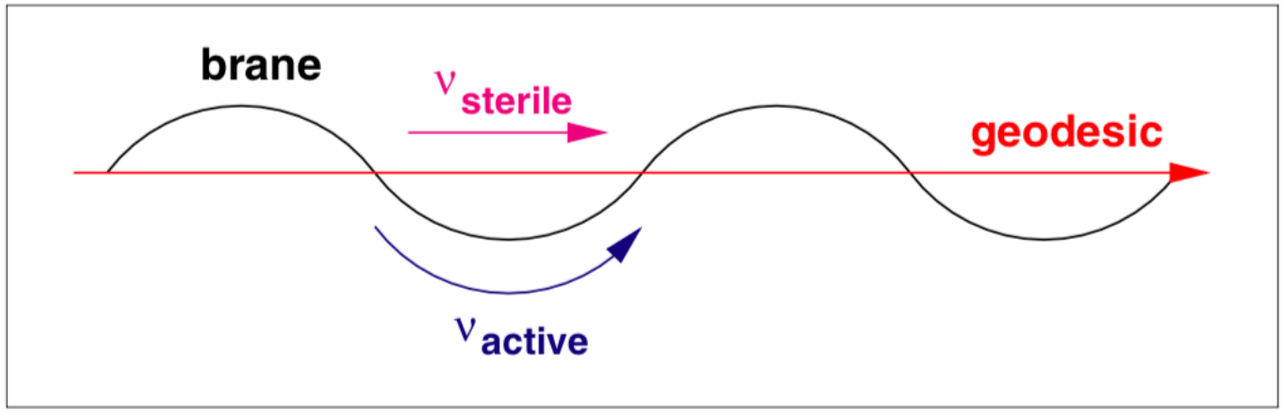


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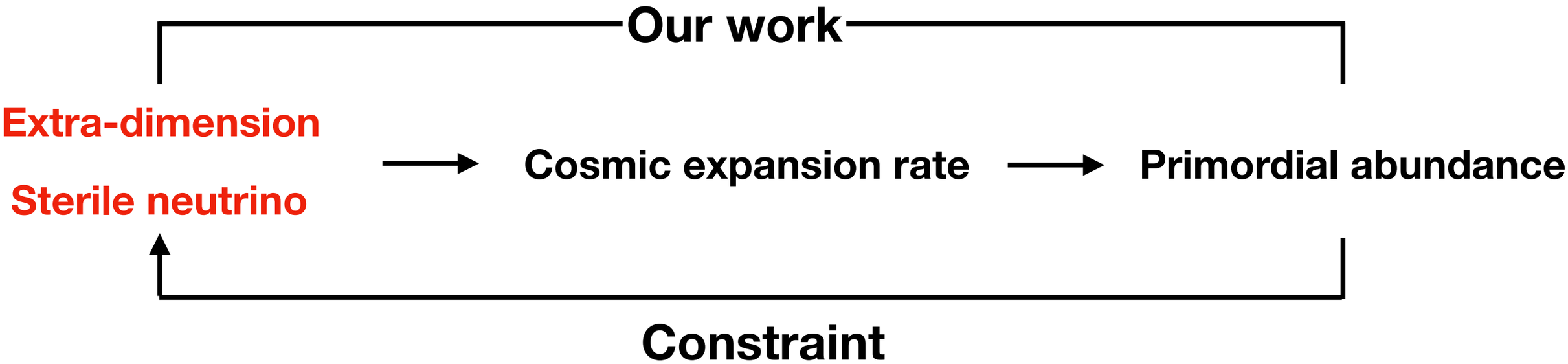
**Effective mixing angle**

$$\sin^2 2\tilde{\theta} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \cos^2 2\theta\left[1-\left(\frac{E}{E_{res}}\right)^2\right]^2}$$

**Resonance energy**

$$E_{res} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\epsilon}}$$


Our work
Extra-dimension
Sterile neutrino
Cosmic expansion rate
Primordial abundance
Constraint

# BBN calculation

## 1. Extra dimension effect

**Five dimensional FRW Metric** $\longrightarrow$ $$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\mathscr{E}}{a^4}$$

Binetruy et al. Phys. Lett. B **477**, 285 (2000)

$H$ : cosmic expansion rate $a$ : scale factor Dark radiation term

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- **Rate equation**

$$\frac{x}{Y_{EQ}}\frac{dY_{\nu_s}}{dx} = -\frac{\Gamma_{\nu_s}}{H}\left[\left(\frac{Y_{\nu_s}}{Y_{EQ}}\right)^2 - 1\right]$$

where $x = m_{\nu_s}/T,\ \ Y_{EQ} = n_{EQ}/s,\ Y_{\nu_s} = n_{\nu_s}/s$

Production rate of $\nu_s$ : $\Gamma_{\nu_s} = P_{as}\left\langle \Gamma_{weak} \right\rangle$

- **Effective mixing angle**

$$\sin^2 2\tilde{\theta} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \cos^2 2\theta\left[1 + \frac{C_\alpha G_F^2 T^4 E^2}{\cos 2\theta \alpha \delta m^2} - \left(\frac{E}{E_{res}}\right)^2\right]^2}$$

**Matter potential**

- **Rate equation**

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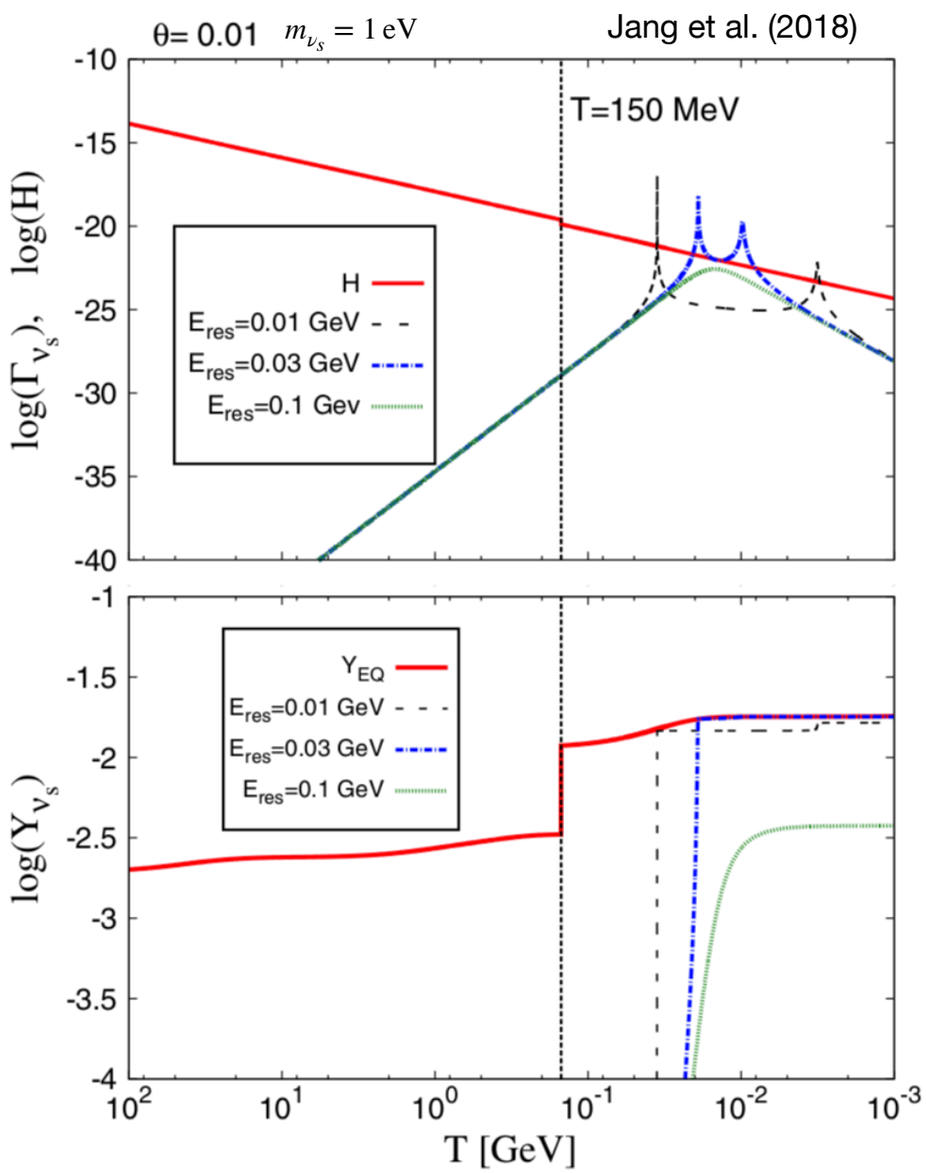

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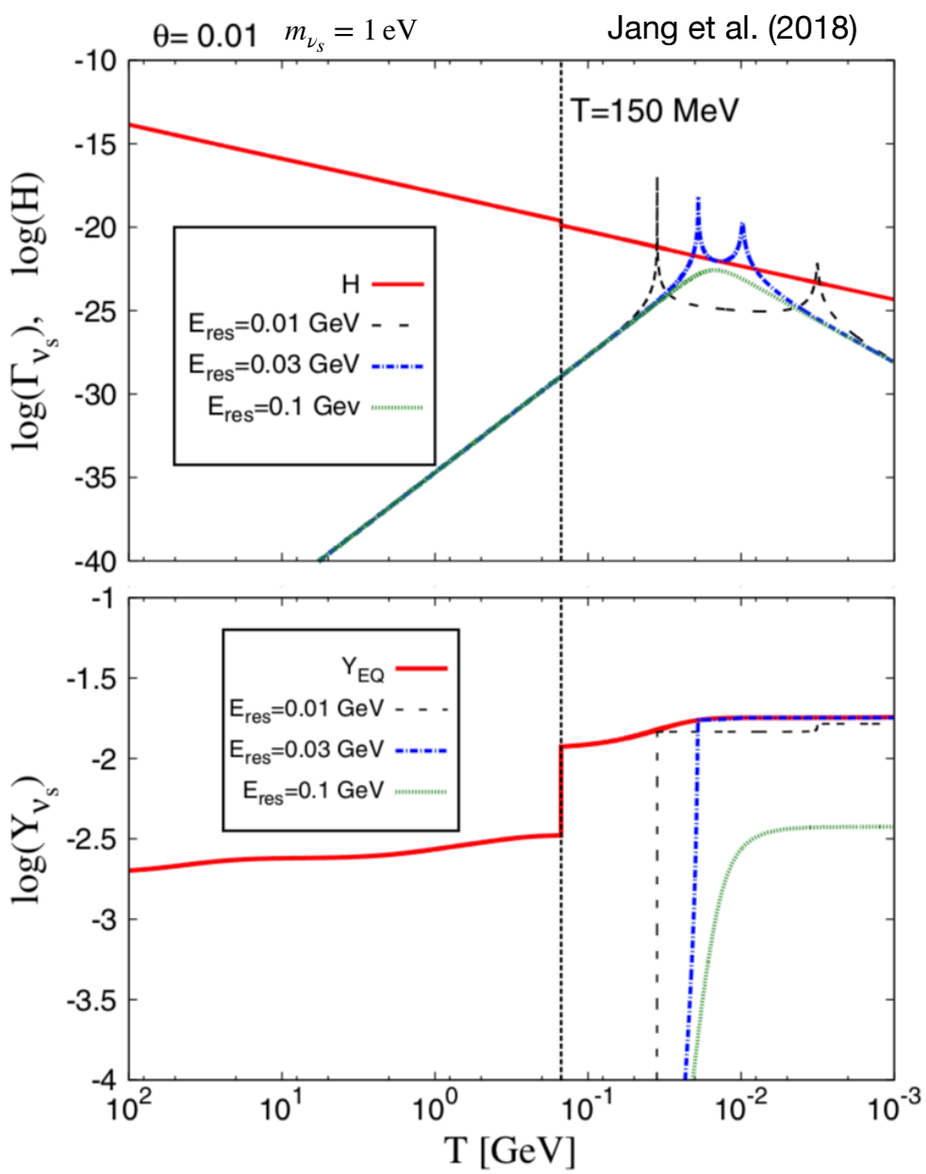
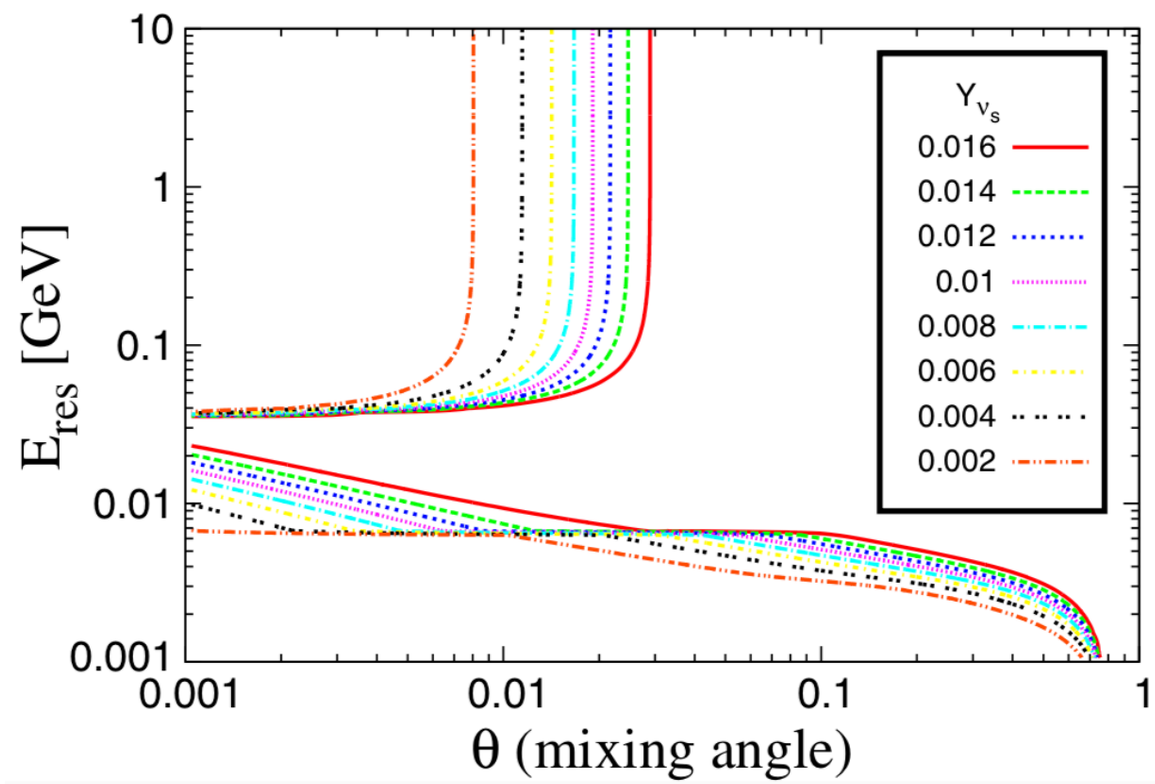



**Yields of sterile neutrino** $(m_{\nu_s} = 1\,\mathrm{eV})$




Jang et al. (2018)

## BBN constraint $(m_{\nu_s} = 1\,\mathrm{eV})$

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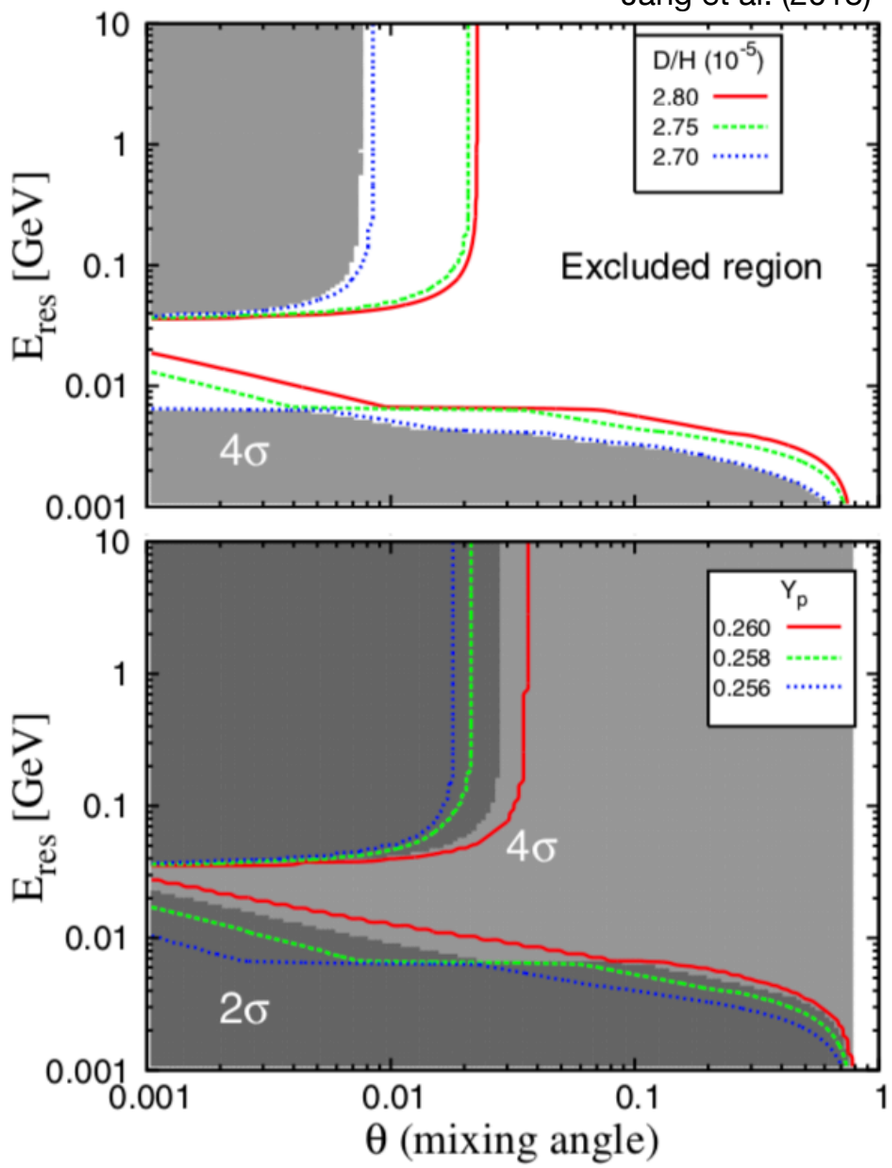

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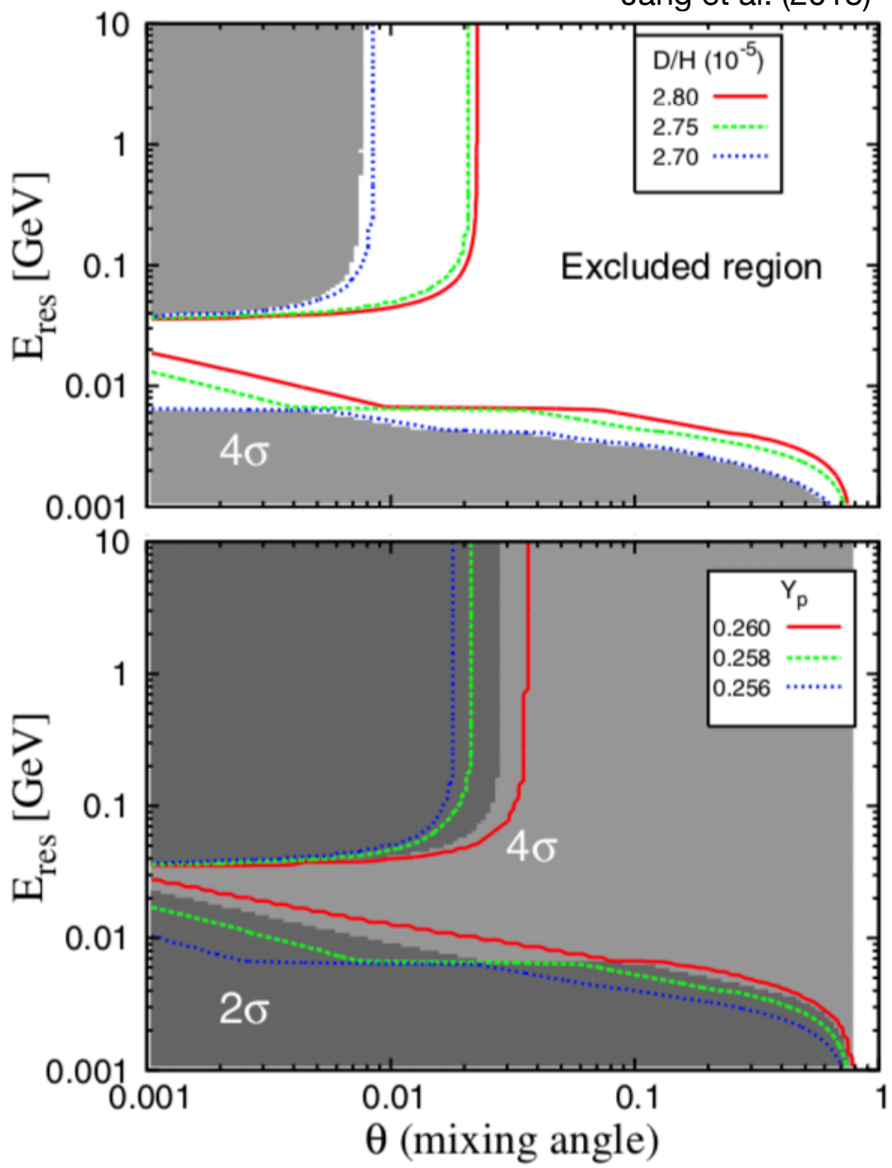


## Cold Dark Matter Constraint

The energy density of the cold dark matter

$$\rho_c = (0.1261 \pm 0.0033) \times 10^{-5}\,\mathrm{GeV cm^{-3}}$$

P. A. R. Ade et al. (*Planck* Collaboration), Astron. Astrophys. **571**, A16 (2014).

**For the relic sterile neutrinos,** $\rho_{\nu_s} \leq \rho_c$

**Case :** $m_{\nu_s} = 1\,\mathrm{eV}$

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**All parameter space is allowed by CMB.**

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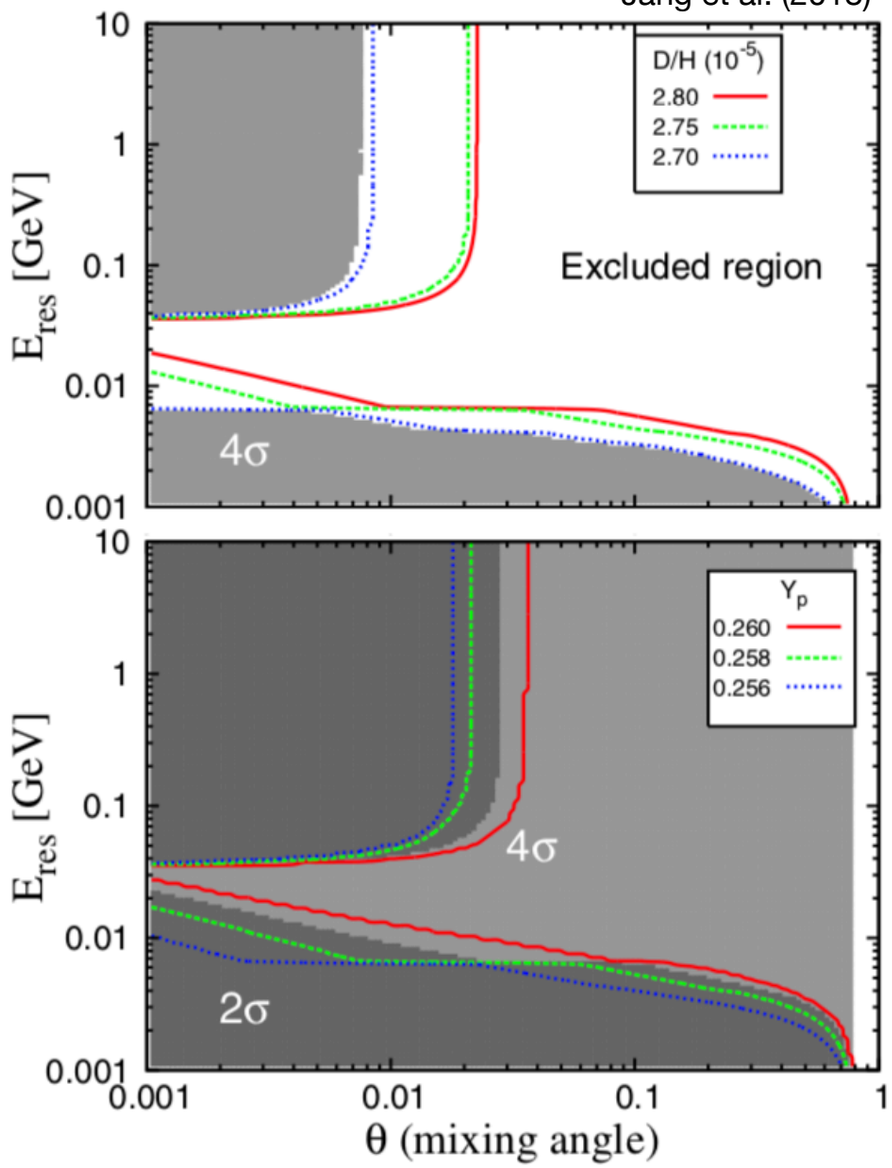


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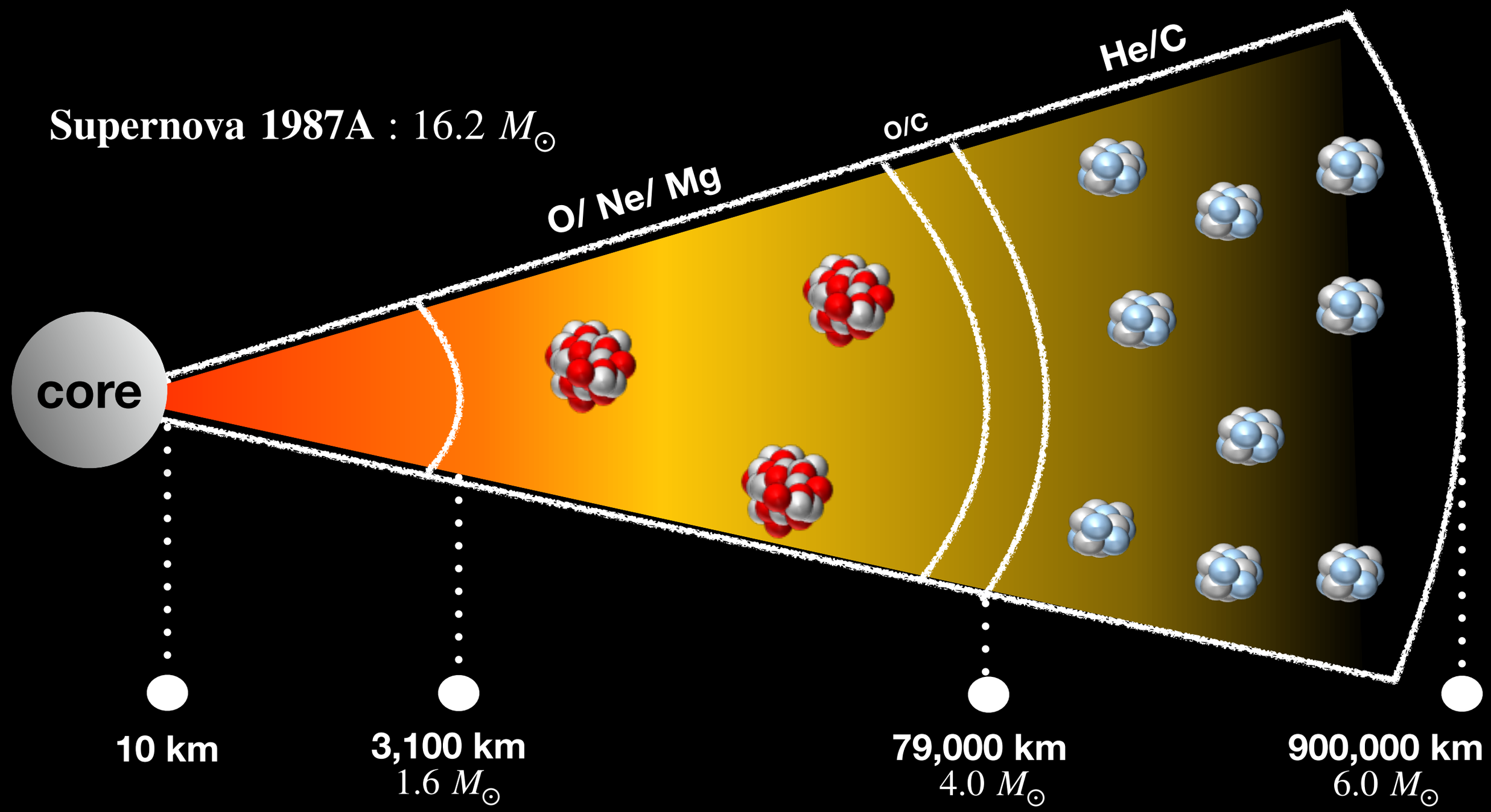
D. Jang et al., Phys. Rev. D **97** 043005

# Part II

The viability of 3+1 neutrino model on the supernova neutrino process

- **Supernova neutrino process**



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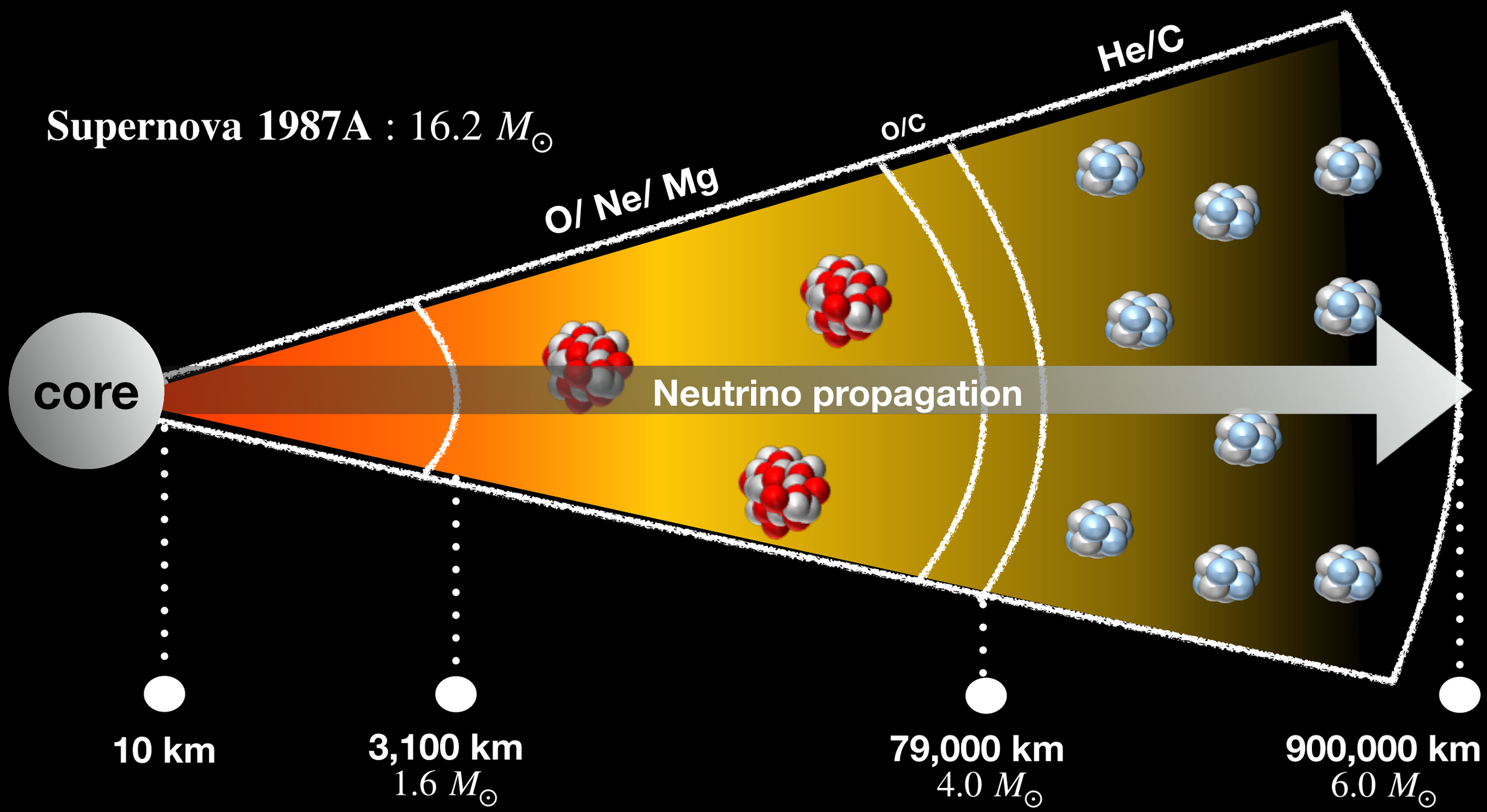

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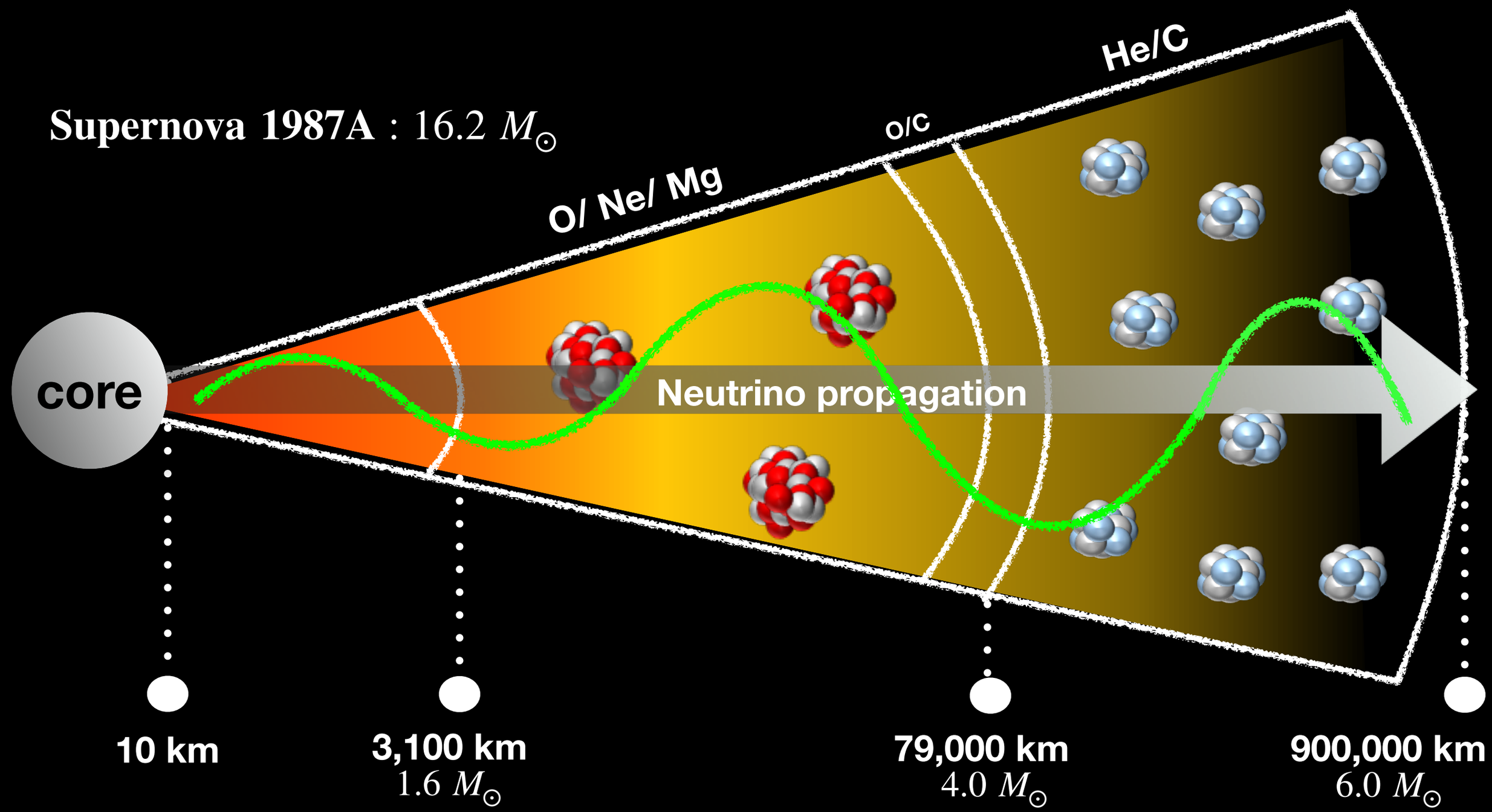

## $^{7}$Li, $^{11}$B, $^{19}$F, $^{138}$La, $^{180}$Ta

S.E. Woosley et al., APJ 356 : 272-301 (1990), A. Heger et al., PLB 606 258 (2005)

## Neutrino process


$^{98}$Tc

T. Hayakawa, Heamin Ko, MK Cheoun et al., PRL 121, 102701 (2018)

**3 active neutrinos**


**Sterile neutrinos**

## 3+1 Neutrino oscillation in Supernova Explosion

$$i\frac{d}{dt}\psi_{\nu_\alpha} = H_{tot}\,\psi_{\nu_\alpha} \qquad H_{tot} = H_{vacuum} + V_{matter}$$

**+**

**Supernova 1987A model**
**Hydrodynamical model in Kusakabe et al.**

APJ **872**, 2, 164 (2019)

$$H_{vacuum} = U diag(0, \frac{\Delta m_{21}^2}{2E_\nu}, \frac{\Delta m_{31}^2}{2E_\nu}, \frac{\Delta m_{41}^2}{2E_\nu}) U^\dagger$$

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**- Neutrino mixing parameters**

$\theta_{13} = 33.8^\circ, \theta_{23} = 45^\circ$ and $\theta_{13} = 9.3^\circ$

$\Delta m_{21}^2 = 7.54 \times 10^{-5}$ [eV$^2$], $|\Delta m_{31}^2| = 2.4 \times 10^{-3}$ [eV$^2$]

[PDG], Chin.Phys. C **38,** 090001 (2014)

$\theta_{14} = 9.44^\circ, \theta_{24} = 6.93^\circ$ and $\theta_{34} = 0^\circ$

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G.H. Collin et al., PRL **117,** 221801 (2016)

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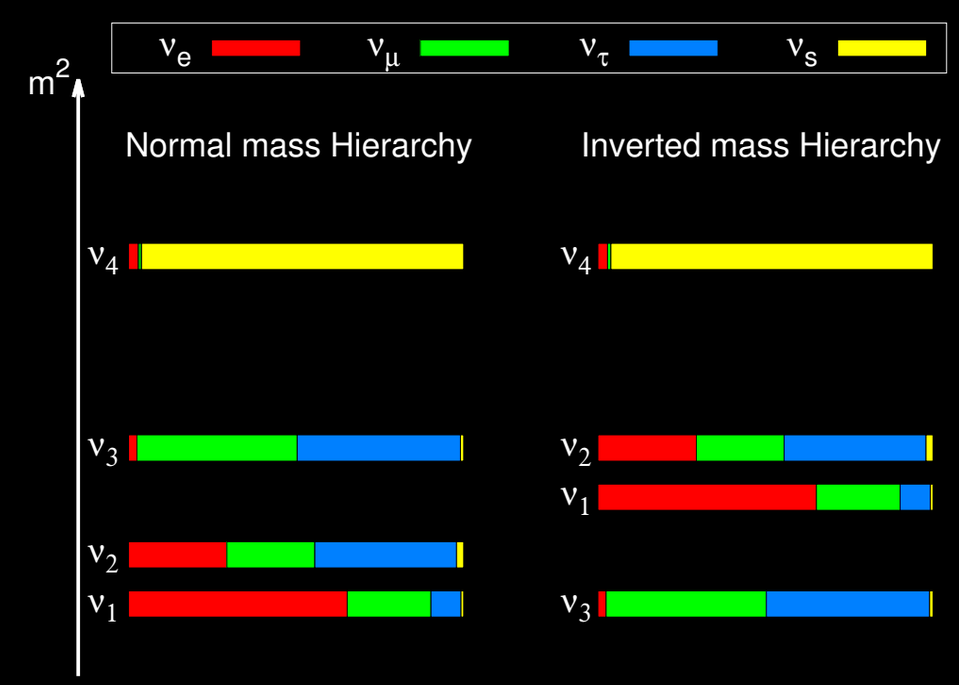
**Mass hierarchy in 3+1 model**



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**Sterile neutrino luminosity**

$$L_{\nu_s} \ll L_{\nu_a} \Rightarrow L_{\nu_s} = 0$$

**( ∵ High density of Core)**

**- Neutrino mixing parameters**

$\theta_{13} = 33.8^\circ, \theta_{23} = 45^\circ$ and $\theta_{13} = 9.3^\circ$

$\Delta m_{21}^2 = 7.54 \times 10^{-5}$ [eV$^2$], $|\Delta m_{31}^2| = 2.4 \times 10^{-3}$ [eV$^2$]

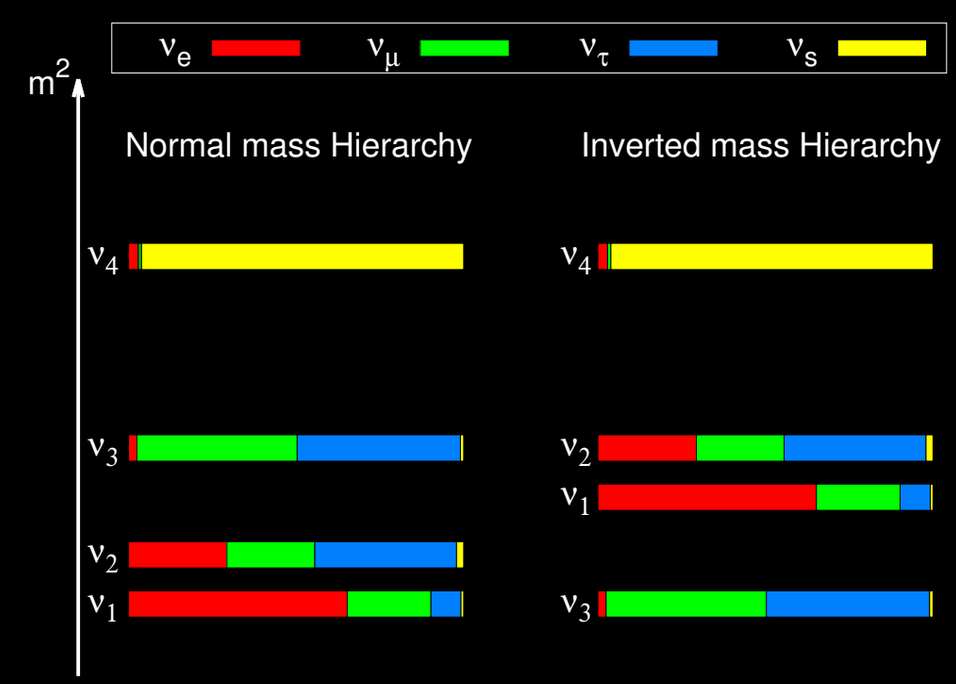
[PDG], Chin.Phys. C **38,** 090001 (2014)

$\theta_{14} = 9.44^\circ, \theta_{24} = 6.93^\circ$ and $\theta_{34} = 0^\circ$

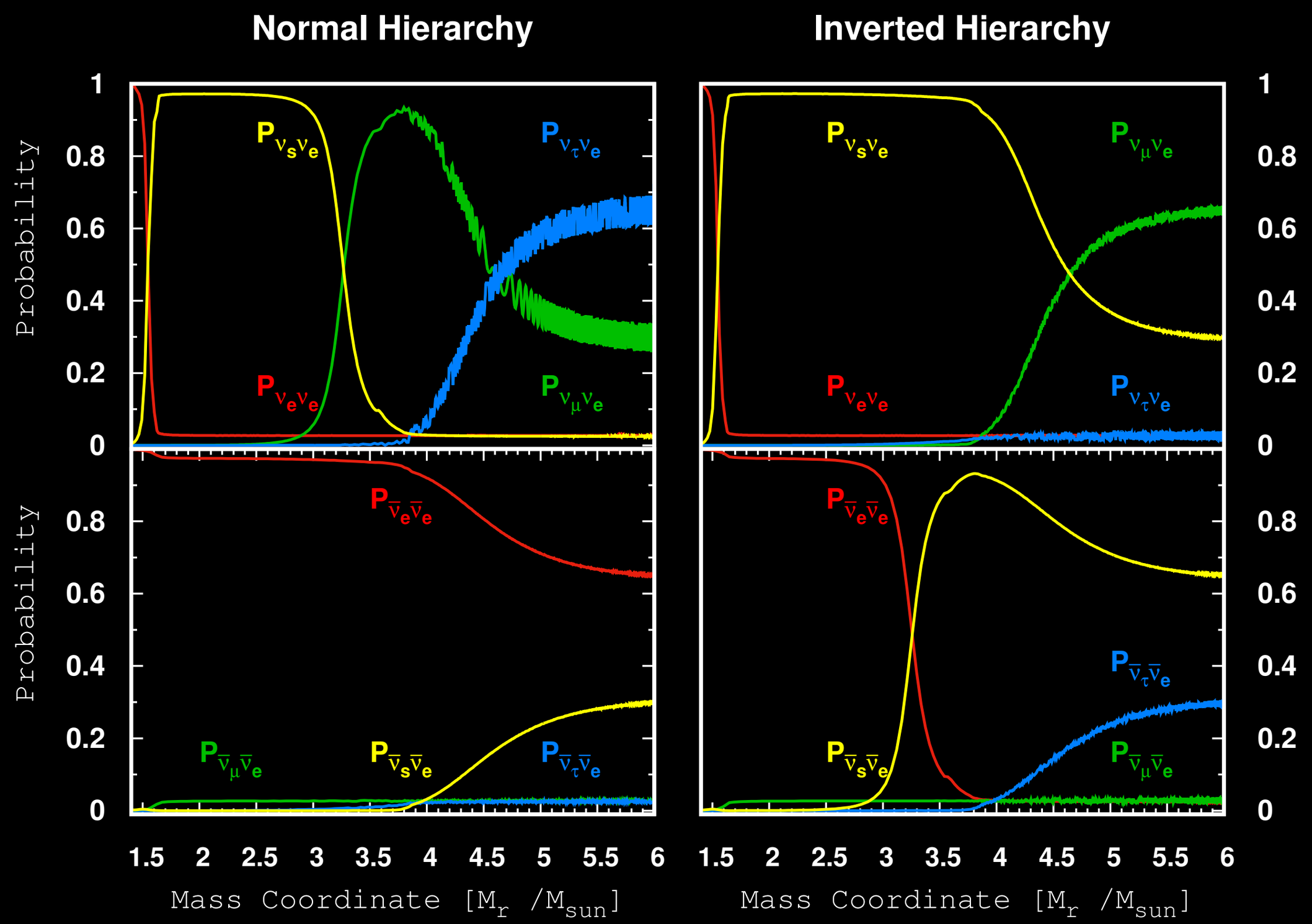
$\Delta m_{41}^2 = 1.75$ [eV$^2$]

G.H. Collin et al., PRL **117,** 221801 (2016)

**Mass hierarchy in 3+1 model**



# Survival probability of electron neutrinos



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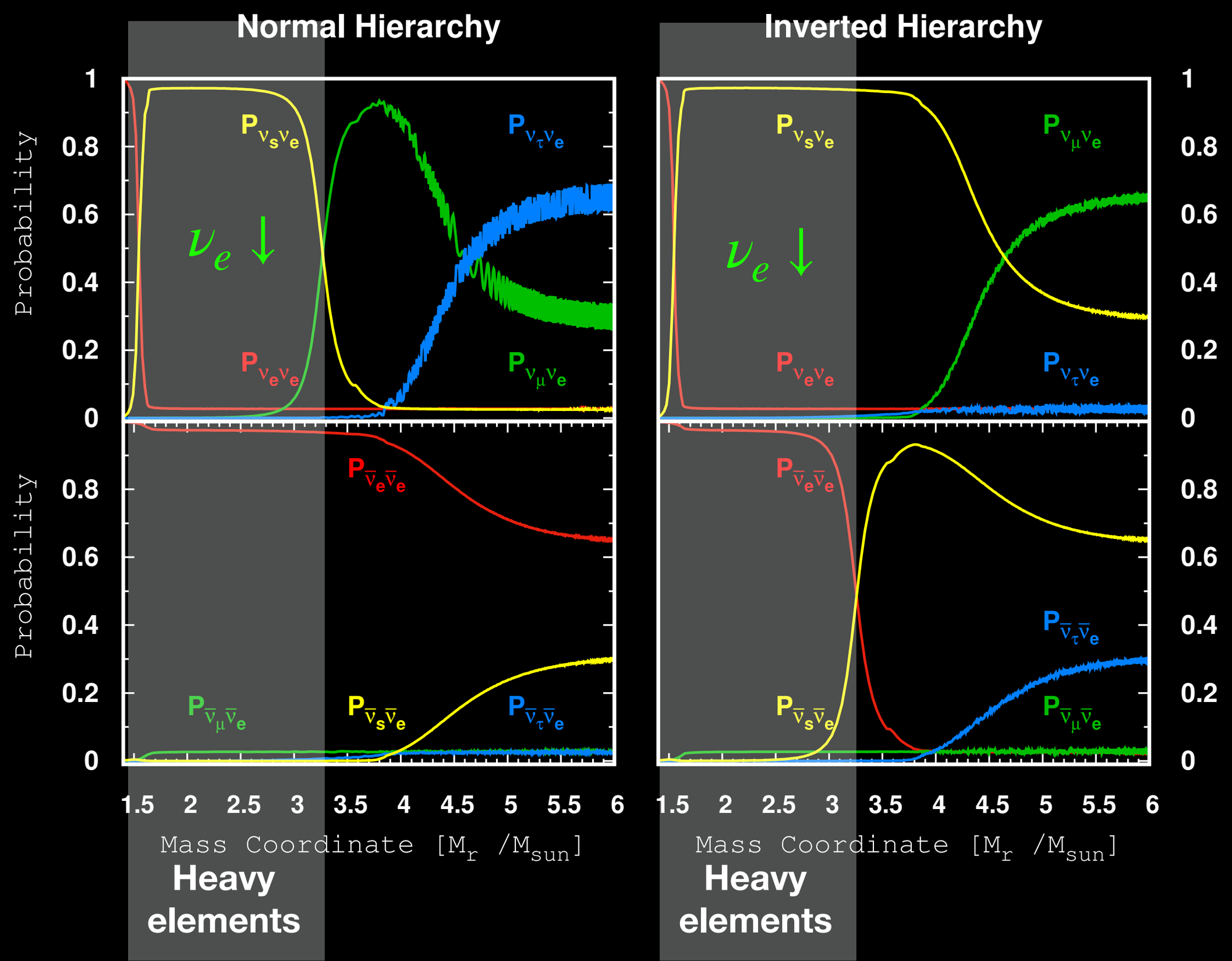
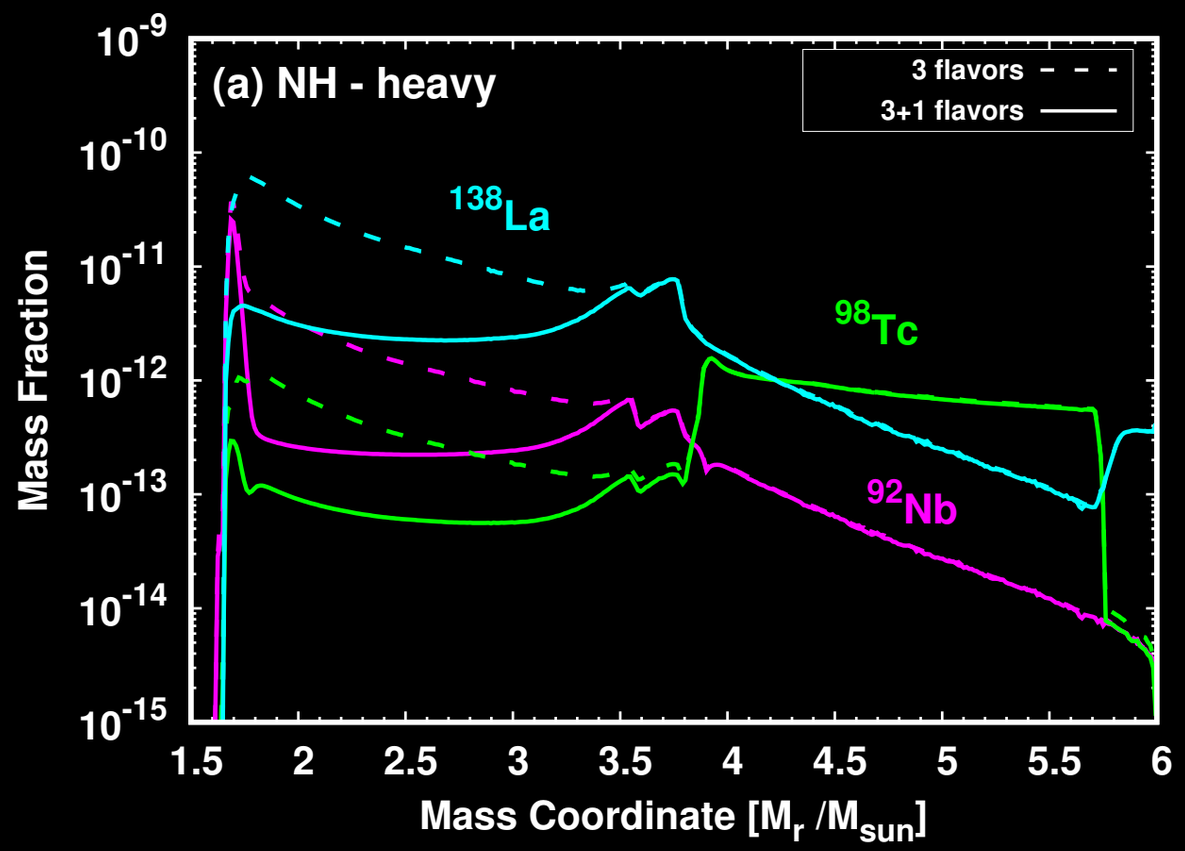
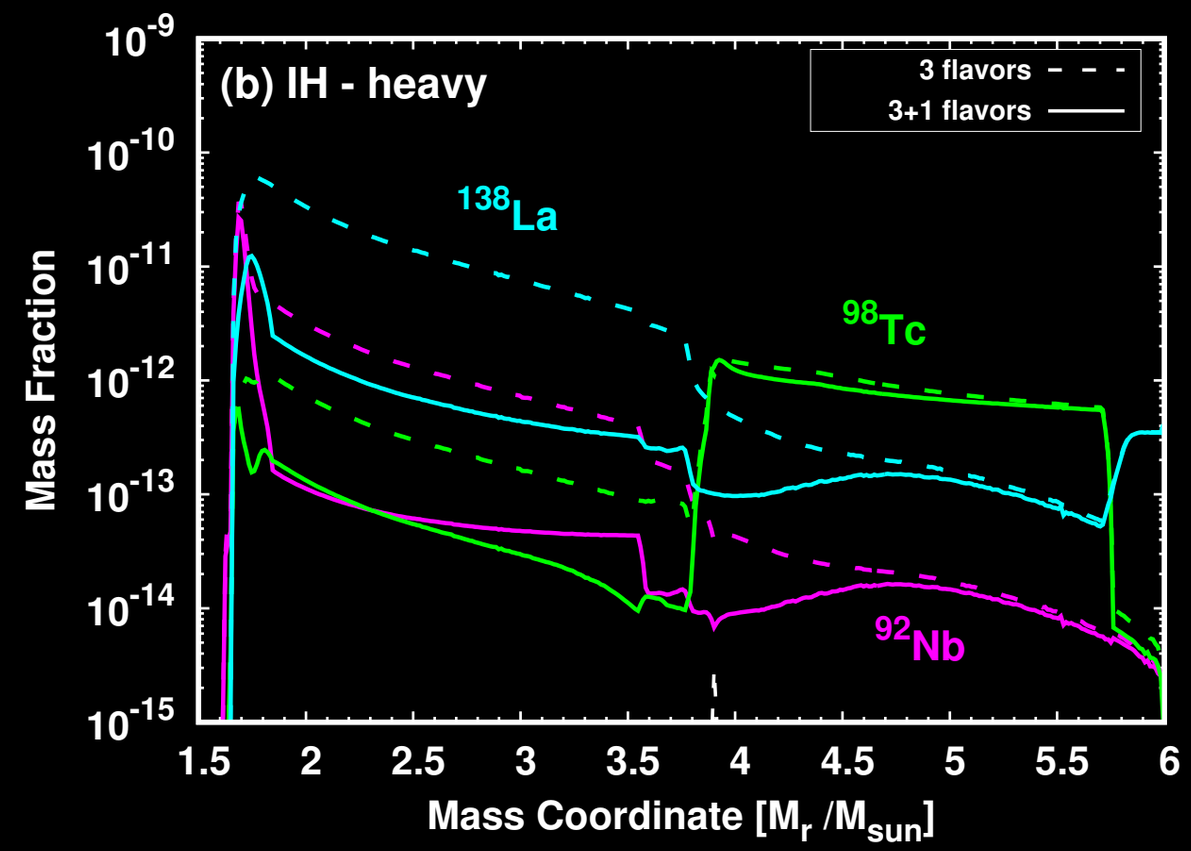


# Heavy elements : $^{138}$La, $^{98}$Tc, $^{92}$Nb



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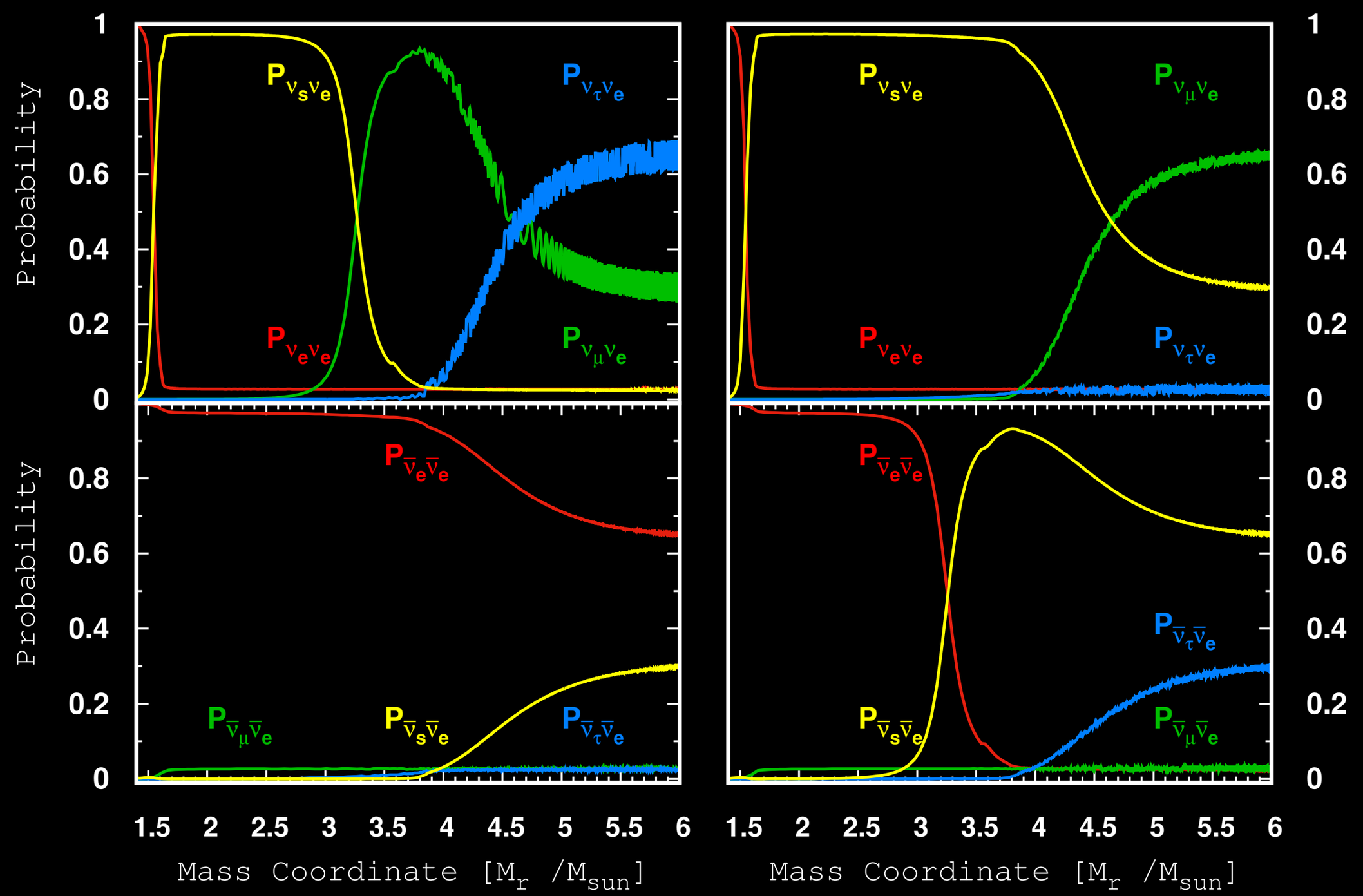

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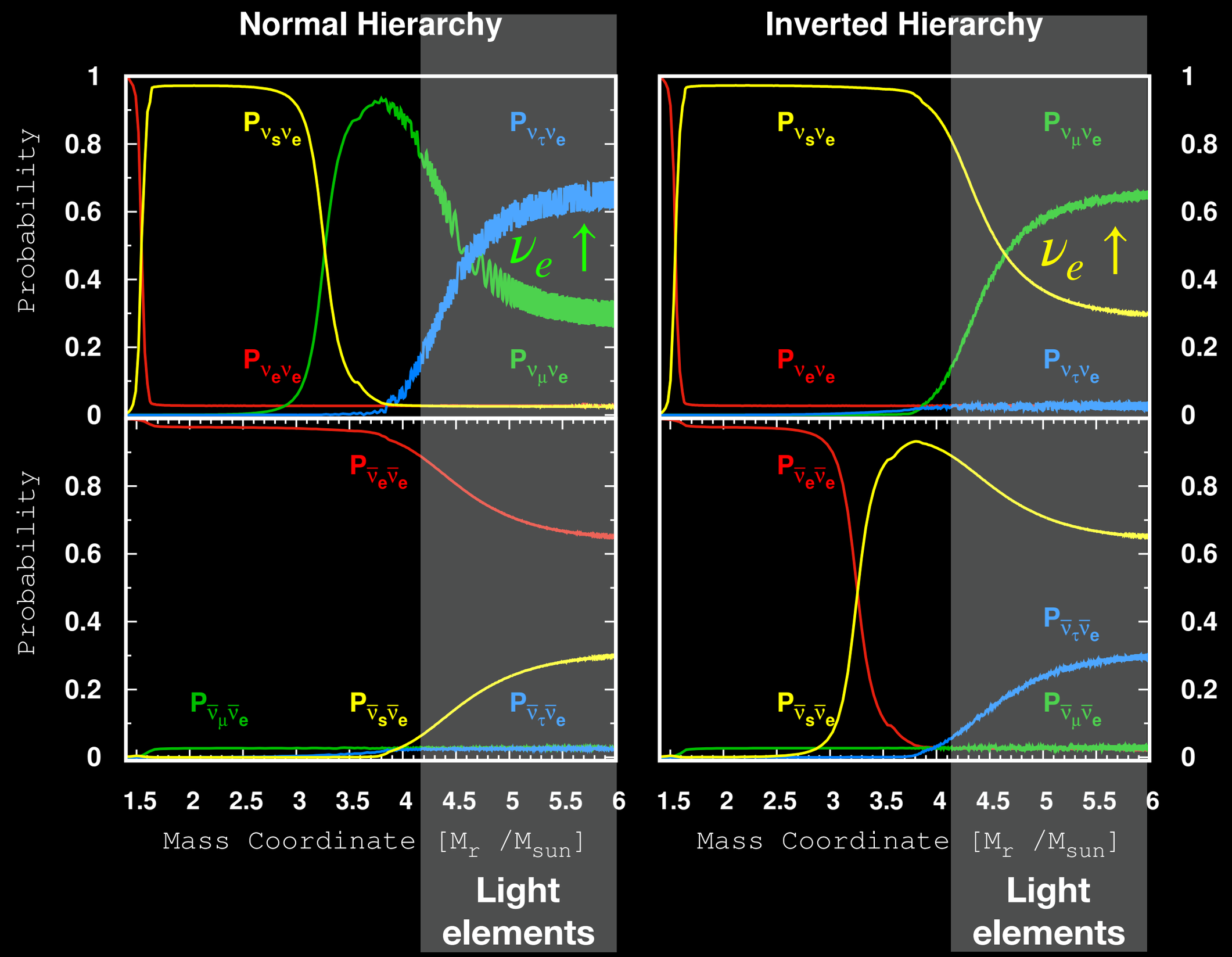
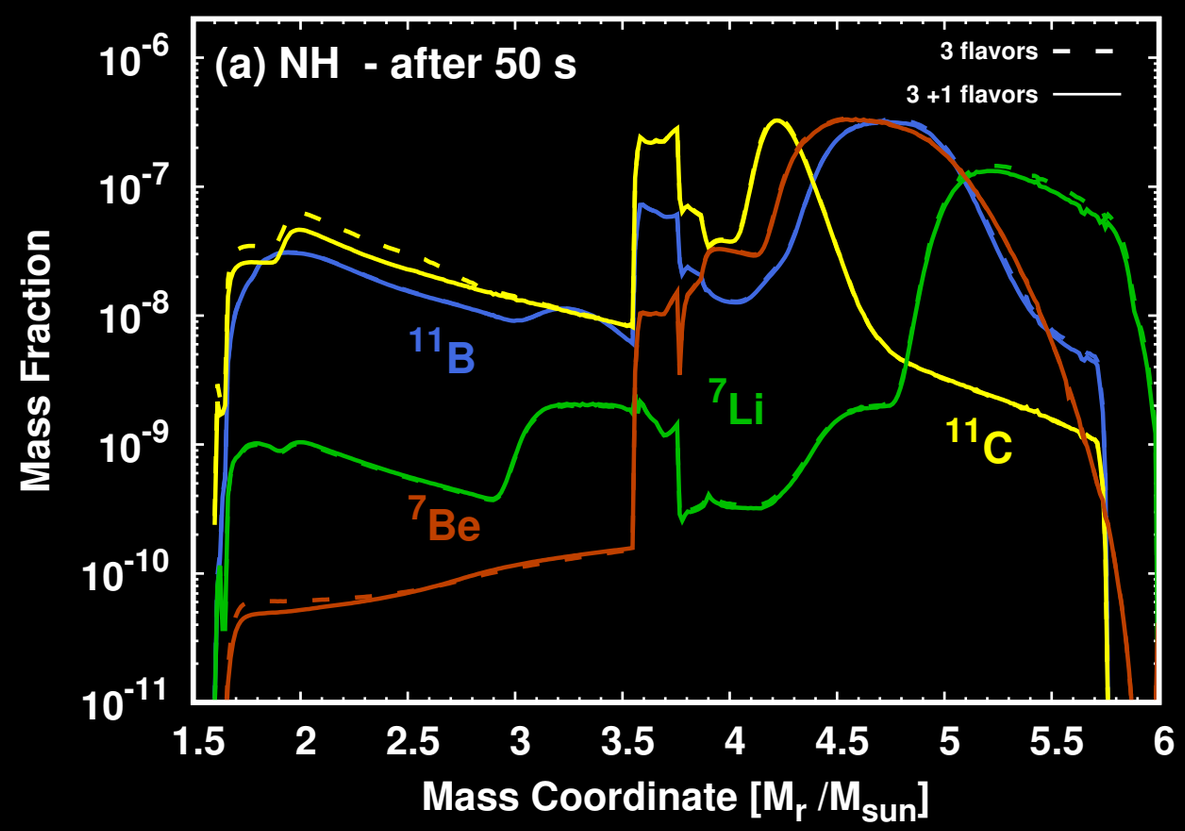
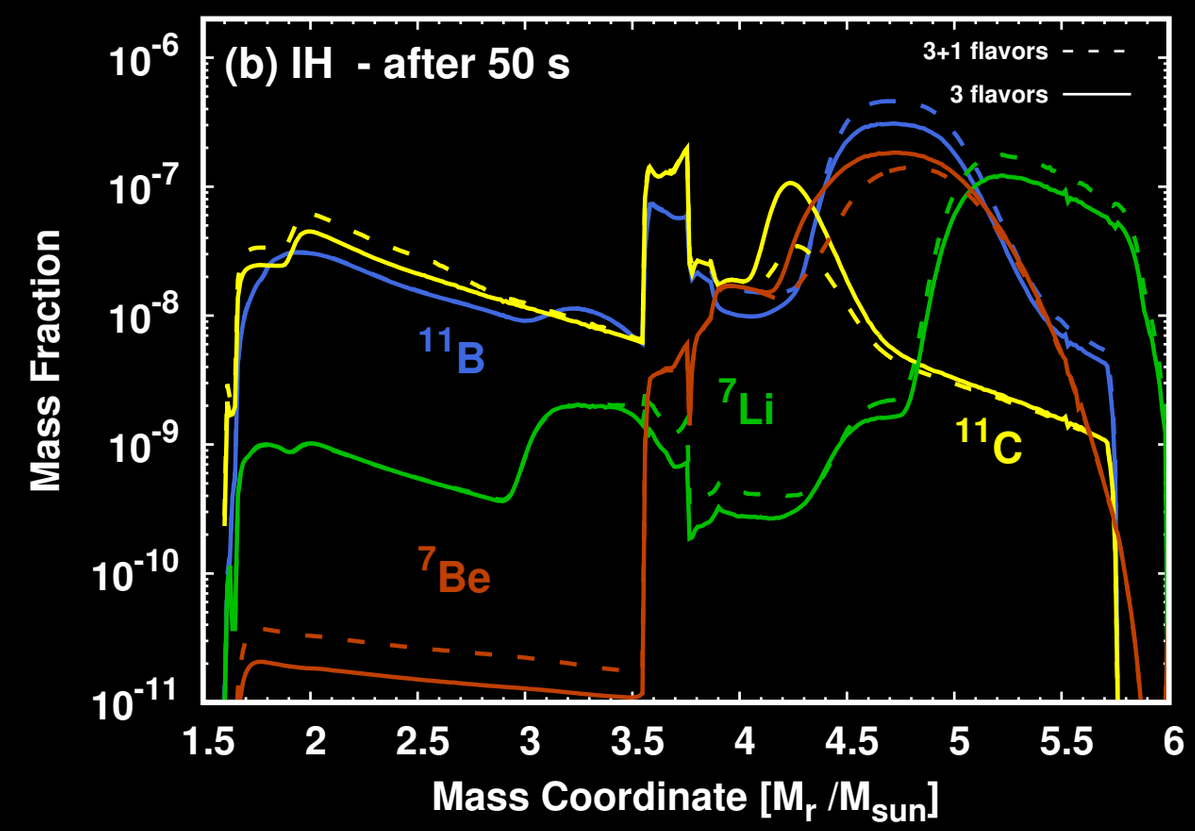


# Light elements : $^{7}$Li, $^{7}$Be, $^{11}$B, $^{11}$C



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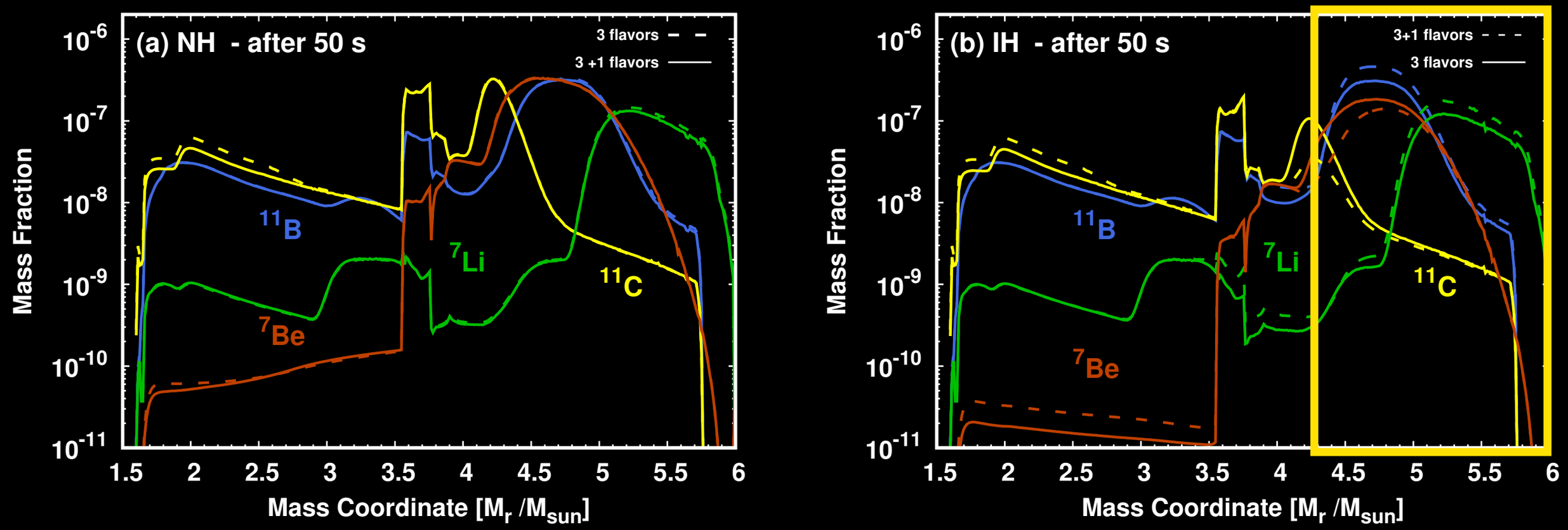

# $^{7}\mathrm{Li}_{\nu}/^{11}\mathrm{B}_{\nu}$ Ratio

**with null luminosity model**

| | Normal Hierarchy | Inverted Hierarchy | Observation of SiC-X grains |
|---|---|---|---|
| **3 flavors** | 1.22 | 0.80 | $\leq 0.95$ $(3\sigma,\ 99.7\,\%\,\mathrm{C.L.})$ |
| **3+1 flavors** | 1.27 | 1.04 | $\leq 1.37$ $(4\sigma,\ 99.9\,\%\,\mathrm{C.L.})$ |

G. J. Mathews et al., PRD 85, 105023 (2012)

# Sterile neutrinos

$\nu_S$

**I. Big Bang Nucleosynthesis**
**: sterile neutrino in extra dimension**

**II. Supernova Neutrino process**
**: 3+1 neutrino model in SN nu-process**

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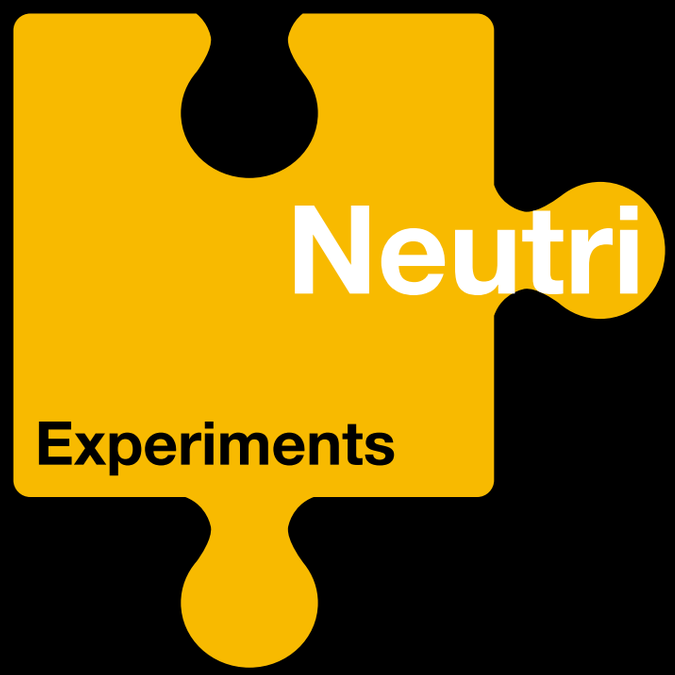

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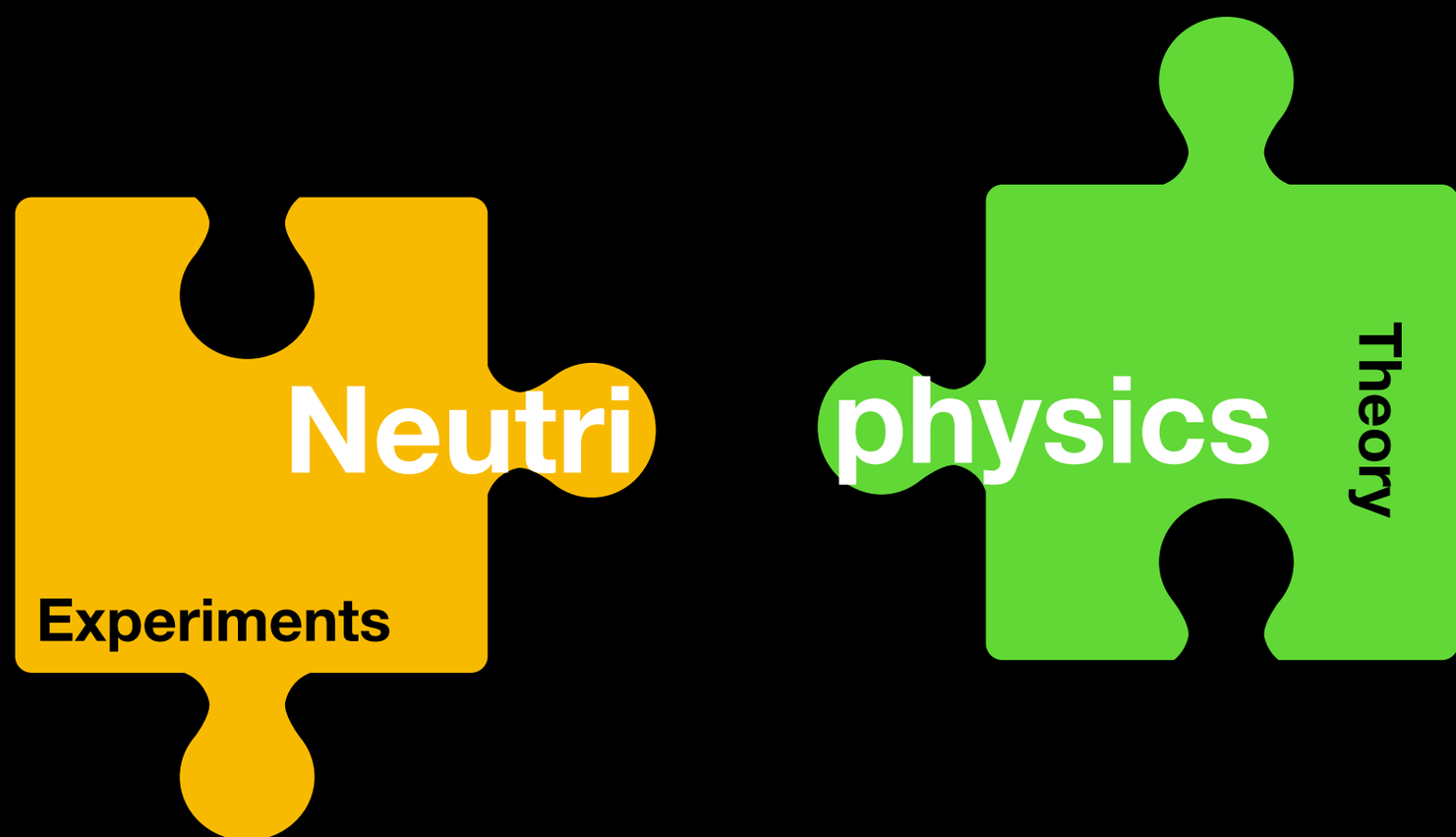

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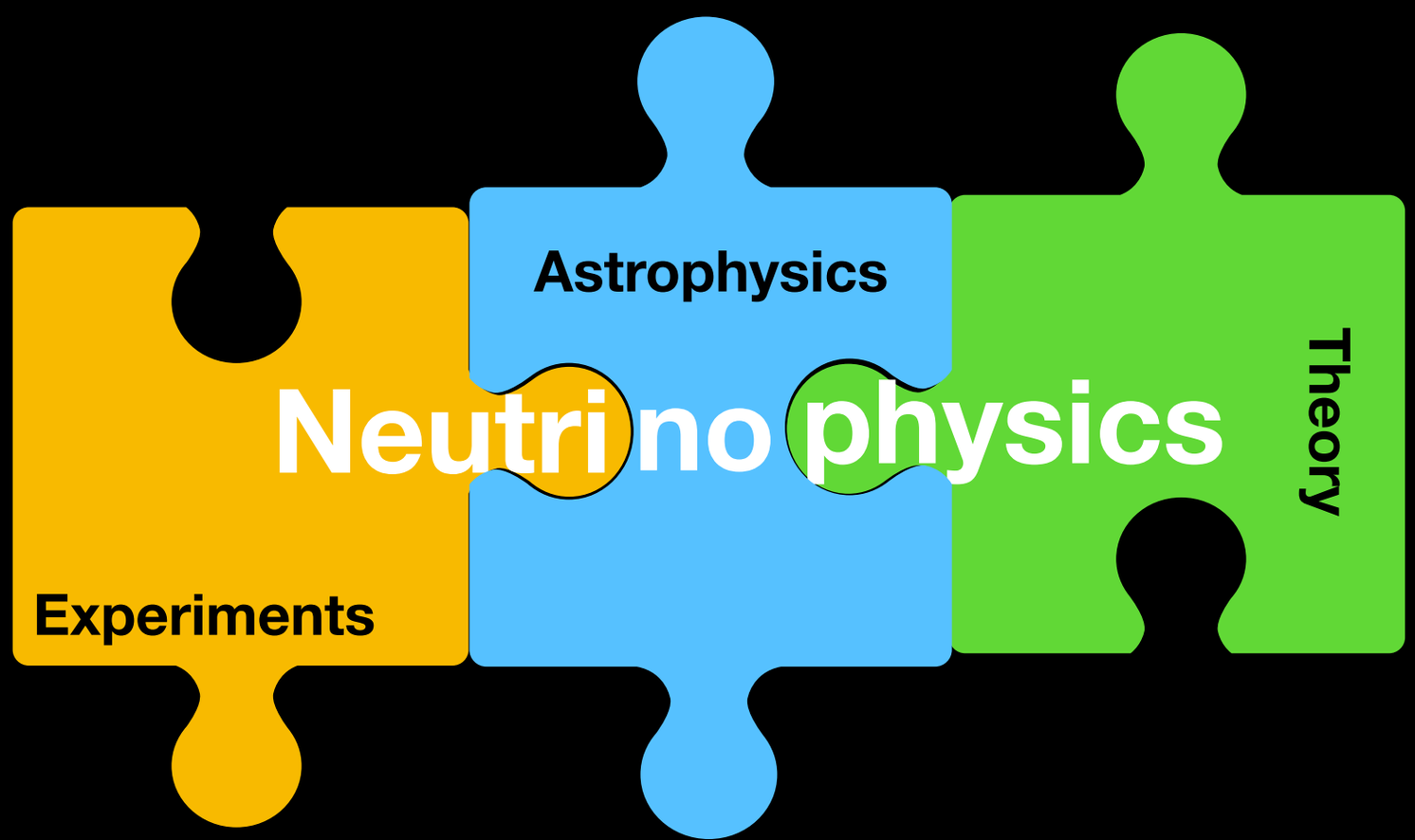

**Thank you for your attention !**

**감사합니다.**

# $^{7}\mathrm{Li}_{\nu}/^{11}\mathrm{B}_{\nu}$ Ratio

**with equivalent luminosity model**

| MH \ $T_{\nu_s}$ | 7 MeV | 8 MeV | 9 MeV | 10 MeV | **Observation of SiC-X grains** |
|---|---|---|---|---|---|
| **NH** | 0.88 | 0.82 | 0.78 | 0.78 | $\leq 0.95$ ($3\sigma$, 99.7 % C.L.)<br>$\leq 1.37$ ($4\sigma$, 99.9 % C.L.)<br>**G. J. Mathews et al., PRD 85, 105023 (2012)** |
| **IH** | 0.91 | 1.02 | 1.15 | 1.15 | |

$$L_{\nu_s} \simeq n_e n_{\nu_e} A \sigma_{ee} V \langle E \rangle$$

E. W. Kolb et al., phys. Rev. Lett 77 3066 (1996).