Probing Non-Standard Neutrino Interactions with Supernova Simulations

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Main Reference: XH & S. Zha & L.W. Chen, arXiv:2110.07249

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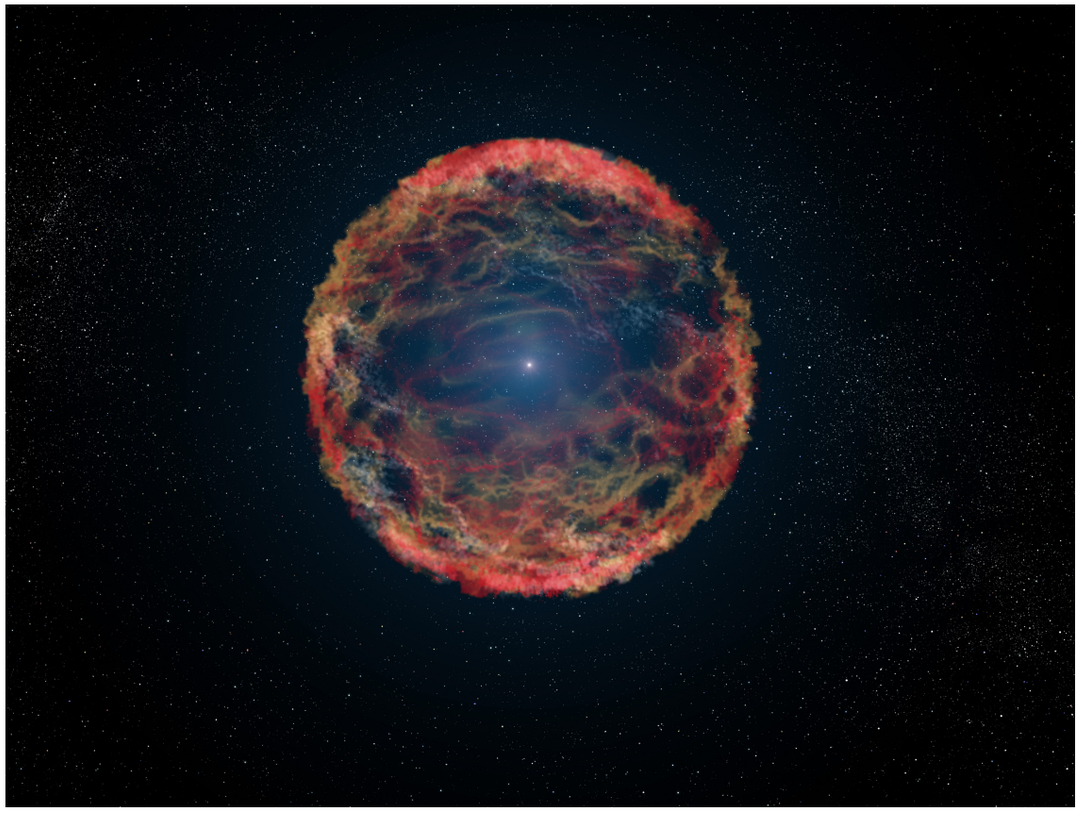
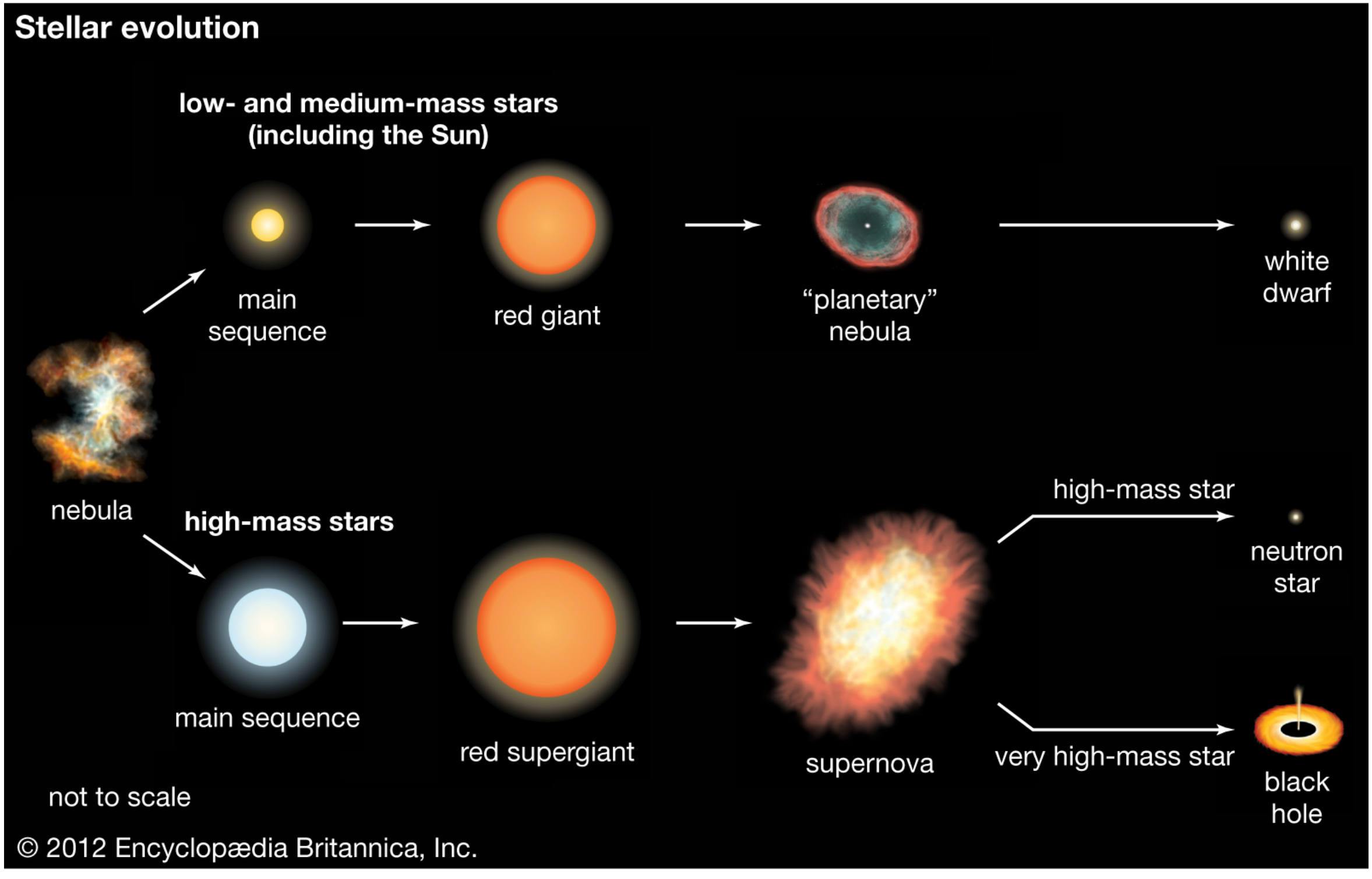


Stellar Evolution



Supernova

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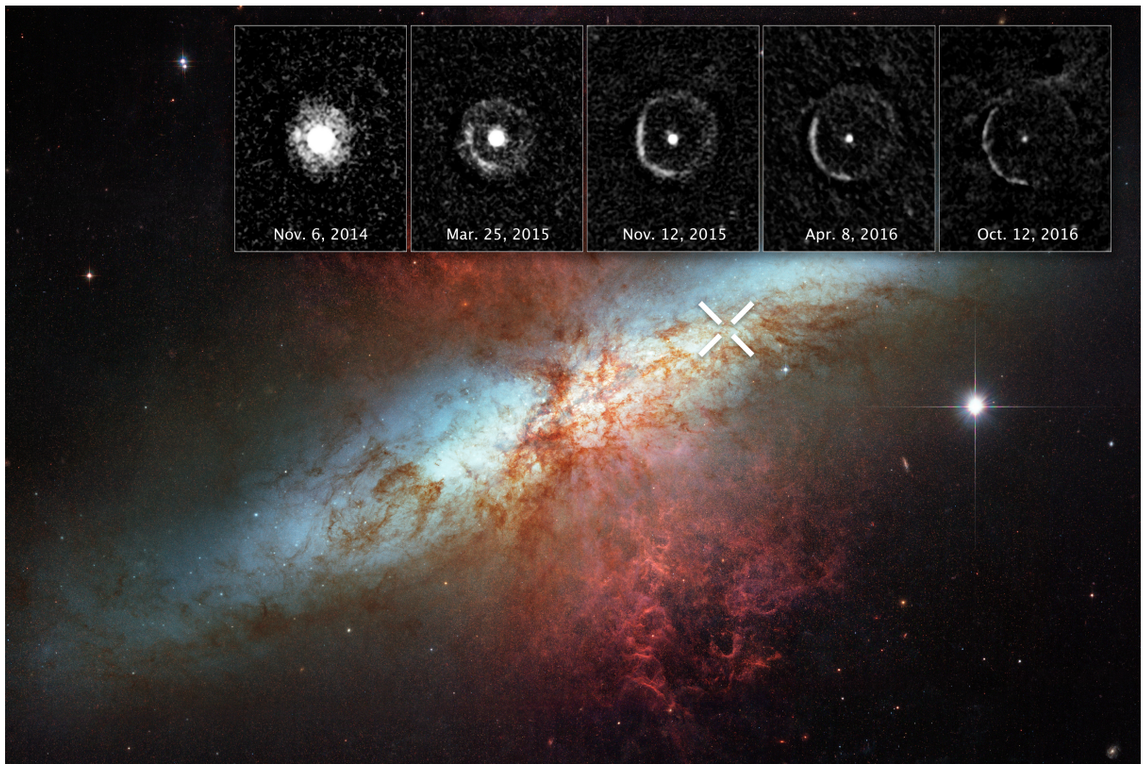
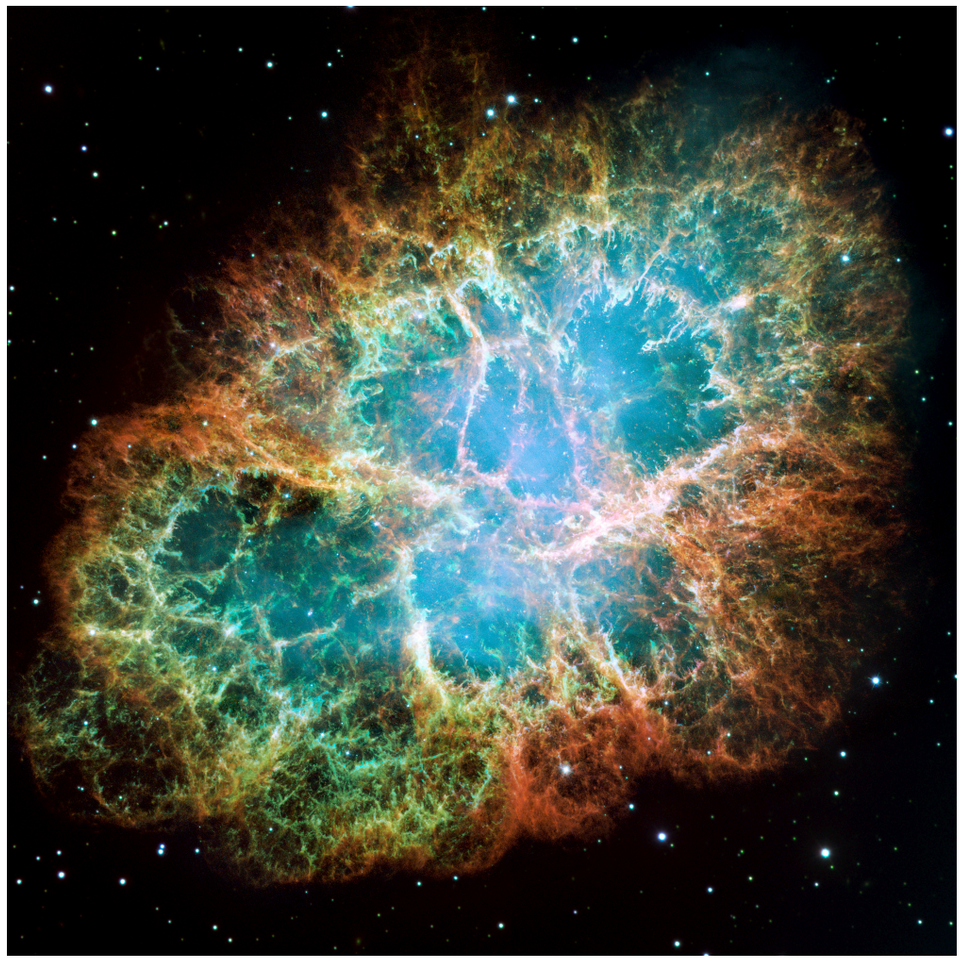


- Messengers: photons, neutrinos and gravitational waves
- Classification: type I (no H), type II (H)



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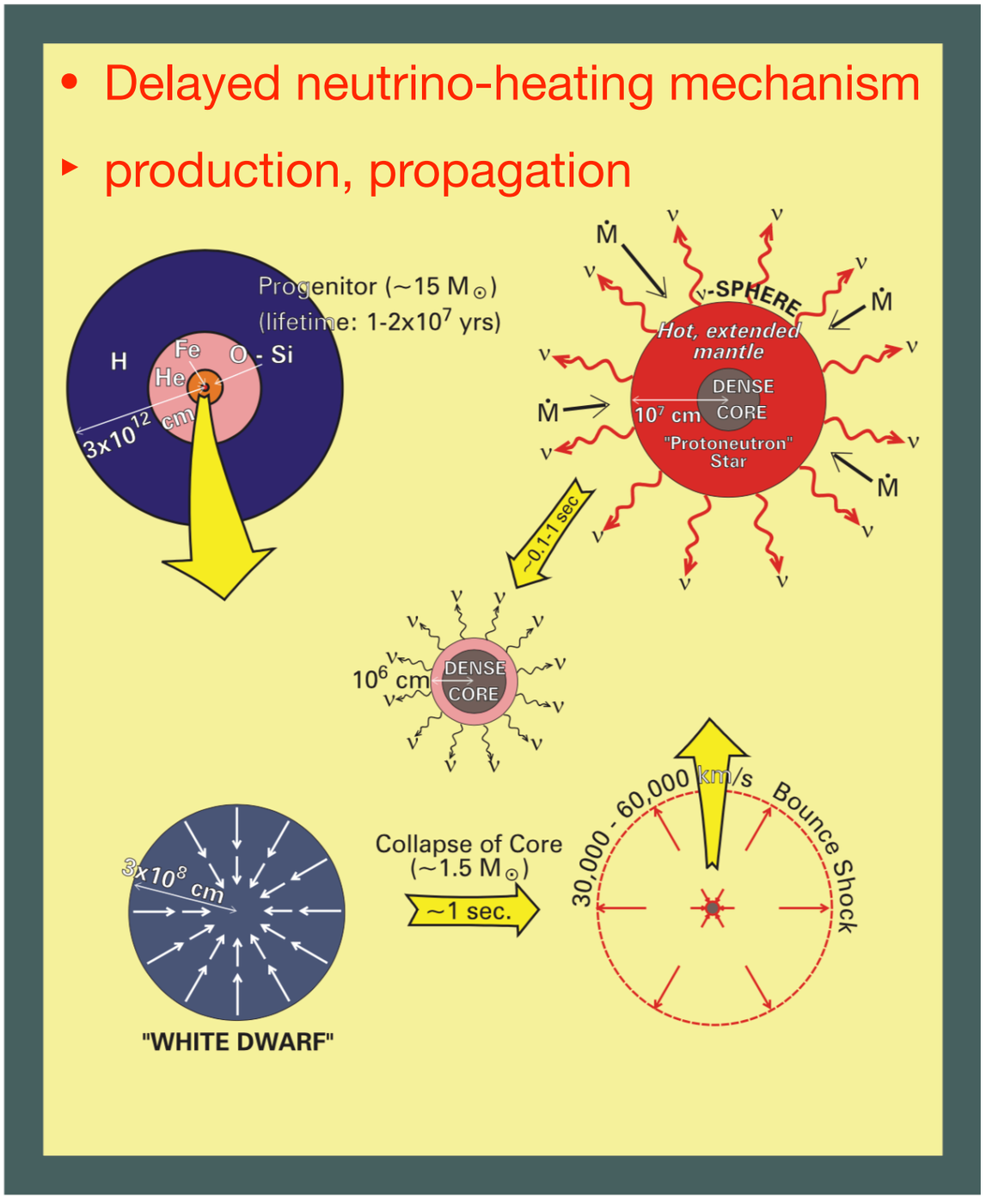
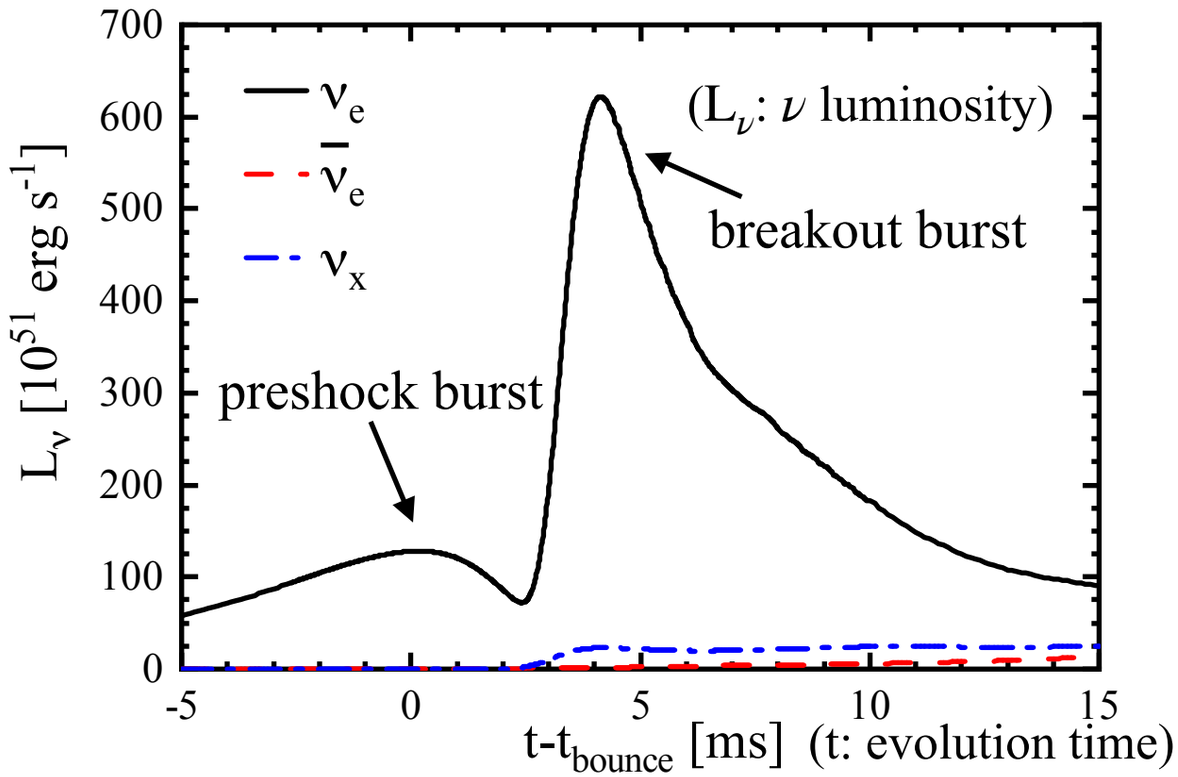
- Explosion mechanism:
  - thermal runaway: type Ia
  - core collapse: type II, type Ib, type Ic, etc.

Core-Collapse SN & ν Emission

- Delayed neutrino-heating mechanism
- production, propagation





- Progenitor stars: $\gtrsim 8\ M_\odot$
- Stellar collapse & bounce shock
- Neutrino heating & shock revival
- Neutrino emission: $\sim 10^{53}$ erg, ~ 10 MeV
- Compact remnant: neutron star or black hole

Burrows, Rev. Mod. Phys. 85, 245 (2013)

Physics bSM in Neutrino Sector

Physics beyond the standard model (SM):

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{\mathscr{L}_{d=5}}{\Lambda} + \frac{\mathscr{L}_{d=6}}{\Lambda^2} + \dots$$

- for d = 5, Weinberg operator
- for d = 6, non-standard interactions

$$\mathscr{L}_{\text{CC-NSI}} = -2\sqrt{2}G_F\epsilon^{ff'X}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L l_\beta)(\bar{f}'\gamma_\mu P_X f)$$

$$\mathscr{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\epsilon^{fX}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

Non-standard neutrino properties:

- non-standard neutrino interactions (NSI)
- non-standard neutrino self-interactions
- neutrino electromagnetic properties
- …

For updated constraints, see: Eseban et al., JHEP 08,180 (2018); Coloma et al., JHEP 02,023 (2020)

Farzan & Tortola, FP. 6, 10 (2018)

	90% C.L. range	Origin
NSI WITH QUARKS		
ϵ^{dL}_{ee}	[−0.3, 0.3]	CHARM
ϵ^{dR}_{ee}	[−0.6, 0.5]	CHARM
ϵ^{dV}_{ee}	[0.030, 0.55]	Oscillation data + COHERENT
ϵ^{uV}_{ee}	[0.028, 0.60]	Oscillation data + COHERENT
$\epsilon^{dV}_{\mu\mu}$	[−0.042, 0.042]	Atmospheric + accelerator
$\epsilon^{uV}_{\mu\mu}$	[−0.044, 0.044]	Atmospheric + accelerator
$\epsilon^{dA}_{\mu\mu}$	[−0.072, 0.057]	Atmospheric + accelerator
$\epsilon^{uA}_{\mu\mu}$	[−0.094, 0.14]	Atmospheric + accelerator
$\epsilon^{dV}_{\tau\tau}$	[−0.075, 0.33]	Oscillation data + COHERENT
$\epsilon^{uV}_{\tau\tau}$	[−0.09, 0.38]	Oscillation data + COHERENT
$\epsilon^{qV}_{\tau\tau}$	[−0.037, 0.037]	Atmospheric
NSI WITH ELECTRONS		
ϵ^{eL}_{ee}	[−0.021, 0.052]	Solar + KamLAND
ϵ^{eR}_{ee}	[−0.07, 0.08]	TEXONO
$\epsilon^{eL}_{\mu\mu}, \epsilon^{eR}_{\mu\mu}$	[−0.03, 0.03]	Reactor + accelerator
$\epsilon^{eL}_{\tau\tau}$	[−0.12, 0.06]	Solar + KamLAND
$\epsilon^{eR}_{\tau\tau}$	[−0.98, 0.23]	Solar + KamLAND and Borexino
	[−0.25, 0.43]	Reactor + accelerator
$\epsilon^{eV}_{\tau\tau}$	[−0.11, 0.11]	Atmospheric

Non-Standard Neutrino Interactions

- Low-energy effective NC neutrino interaction in the SM:

$$\mathscr{L}_{\rm SM} = -2\sqrt{2}G_F g_X^f(\bar{\nu}\gamma^\mu P_L\nu)(\bar{f}\gamma_\mu P_X f)$$

- Non-standard NC neutrino interactions:

$$\mathscr{L}_{\rm NSI} = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{fX}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

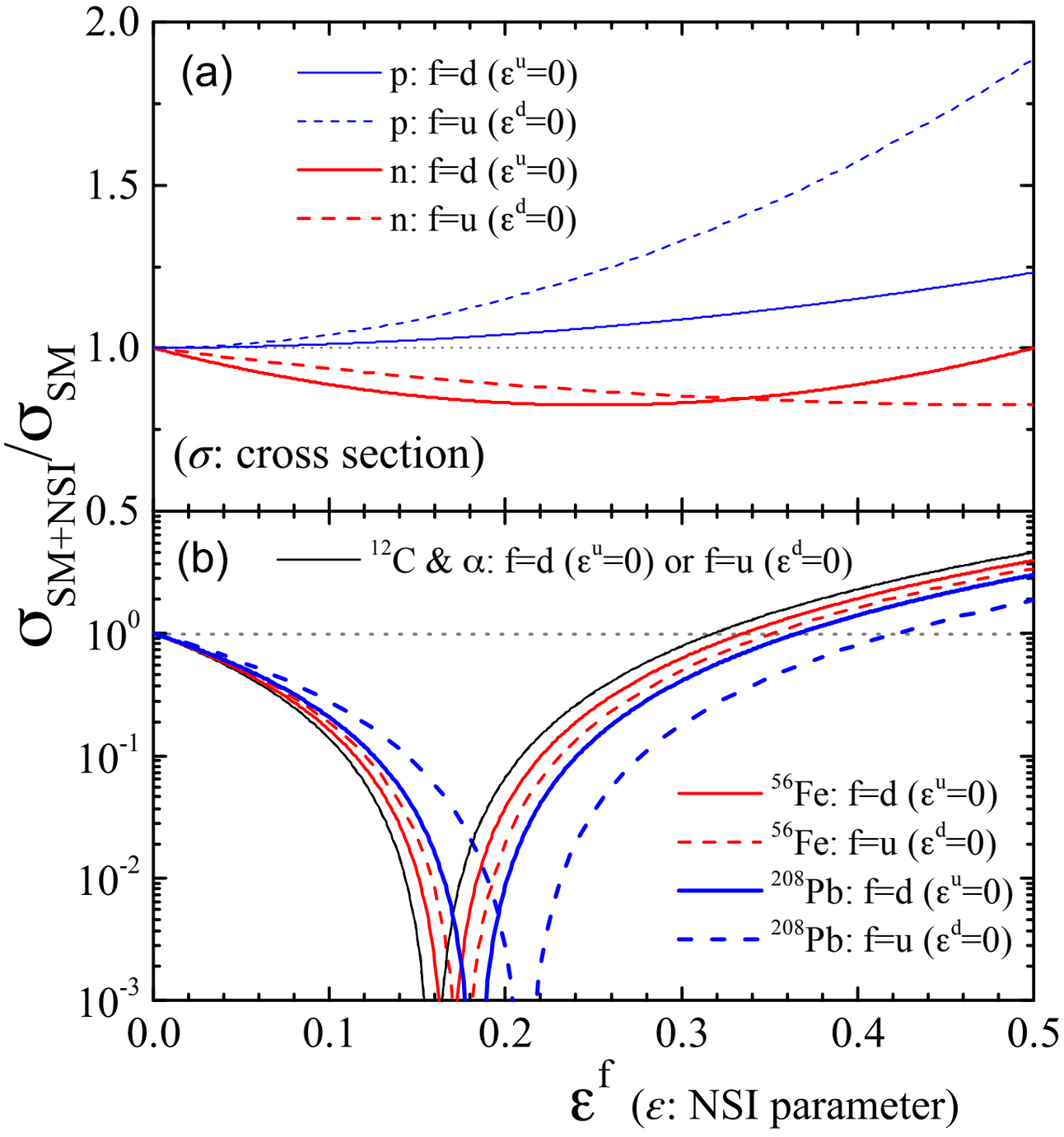
Fermion	g_V^f	g_A^f
e,μ,τ	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}$
u,c,t	$+\frac{1}{2}-\frac{4}{3}\sin^2\theta_W$	$+\frac{1}{2}$
d,s,b	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2}$

- P_X $(X = L, R)$: chirality projection operators
- vector(axial) coupling constants:

$$g_V^f = g_L^f + g_R^f \ , \ g_A^f = g_L^f - g_R^f$$

- Flavor-diagonal NC vectorial NSI couplings: $\varepsilon^f = \varepsilon_{ee}^{fL} + \varepsilon_{ee}^{fR}$, $f \in \{u, d\}$
- relatively larger parameter space: $\varepsilon^f \in [0.0,0.5]$
- other parameters: $\lesssim 0.1$
- SNO experiments ➡ small NSI axial interactions, $\varepsilon_{ee}^{fL} \approx \varepsilon_{ee}^{fR}$

NSI Effects in ν-Matter Interactions



- Reactions to be modified (ν_e & $\bar{\nu}_e$):

$$\nu_e + p \longleftrightarrow \nu_e + p\ ,\ \nu_e + n \longleftrightarrow \nu_e + n$$

$$\nu_e + \alpha \longleftrightarrow \nu_e + \alpha\ ,\ \nu_e + X \longleftrightarrow \nu_e + X$$

- Effective NSI couplings to nucleons:

$$\varepsilon^p = 2\varepsilon^u + \varepsilon^d, \quad \varepsilon^n = \varepsilon^u + 2\varepsilon^d$$

- NSI modifications to cross sections:
  - nucleon: $g_V^{p(n)\prime} = g_V^{p(n)} + \varepsilon^{p(n)}$
  - nucleus: $Q_W' = Q_W + Q_W^{NSI}$

$$Q_W^{NSI} = -2(Z\varepsilon^p + N\varepsilon^n)$$

- For nucleus: $\sigma_{SM+NSI}/\sigma_{SM} \approx Q_W'^2/Q_W^2$

Cross Sections in the SM

- $\nu_e + p/n \longleftrightarrow \nu_e + p/n$:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{G_F^2 E_\nu^2}{4\pi^2}\left[g_V^2(1+\cos\theta) + g_A^2 f_A^2(0)(3-\cos\theta)\right]$$

Nucleon	g_V	g_A
p	$\frac{1}{2} - 2\sin^2\theta_W$	$\frac{1}{2}$
n	$-\frac{1}{2}$	$-\frac{1}{2}$

- $\nu_e + X \longleftrightarrow \nu_e + X$:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2} A^2 \left[\mathscr{W}\mathscr{C}_{FF} + \mathscr{C}_{LOS}\right]^2 \left\langle \mathcal{S}_{ion} \right\rangle (1+\cos\theta)$$

- $\mathscr{W} = Q_W/A$, $Q_W = -2(Zg_V^p + Ng_V^n)$
- Corrections (little effect on SN): Burrows et al. NPA777(2006)

✓ $\left\langle \mathcal{S}_{ion} \right\rangle$: ion-ion correlation function, mostly by Coulomb interaction

✓ $\mathscr{C}_{FF}$: form factor, nuclear structure, strong interaction

✓ $\mathscr{C}_{LOS}$: electron polarization correction, electron

Simulation Setup

- Simulation code: GR1D & NuLib

✓ 1-D, general-relativistic hydrodynamics

✓ M1 neutrino transport scheme

O'Connor & Ott, CQG. 27 114103 (2010)
O'Connor, ApJS. 219, 24 (2015)

- Ingredients:

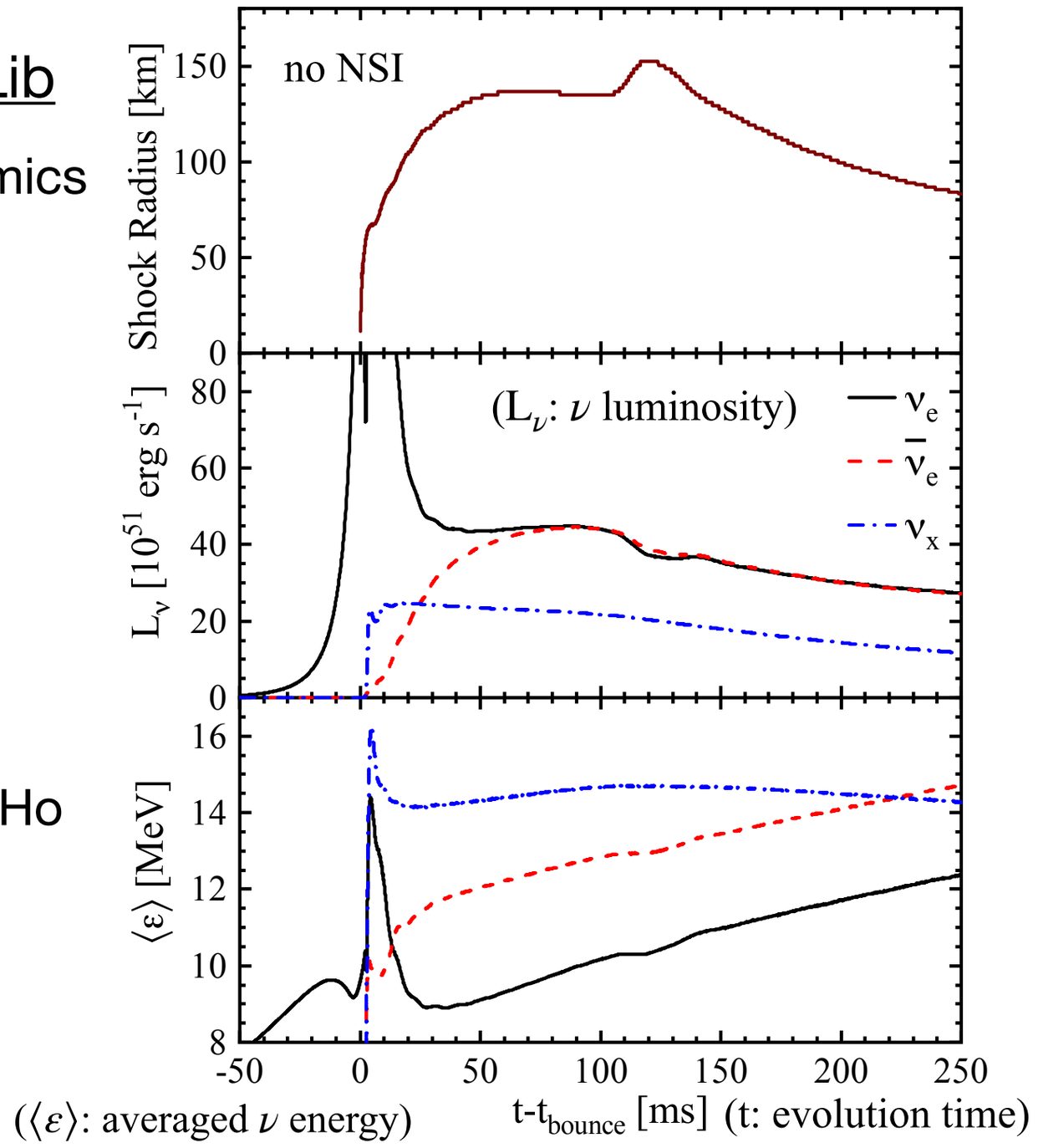
- progenitor star: s15s7b2

Woosley & Weaver, ApJS. 101,181 (1995)

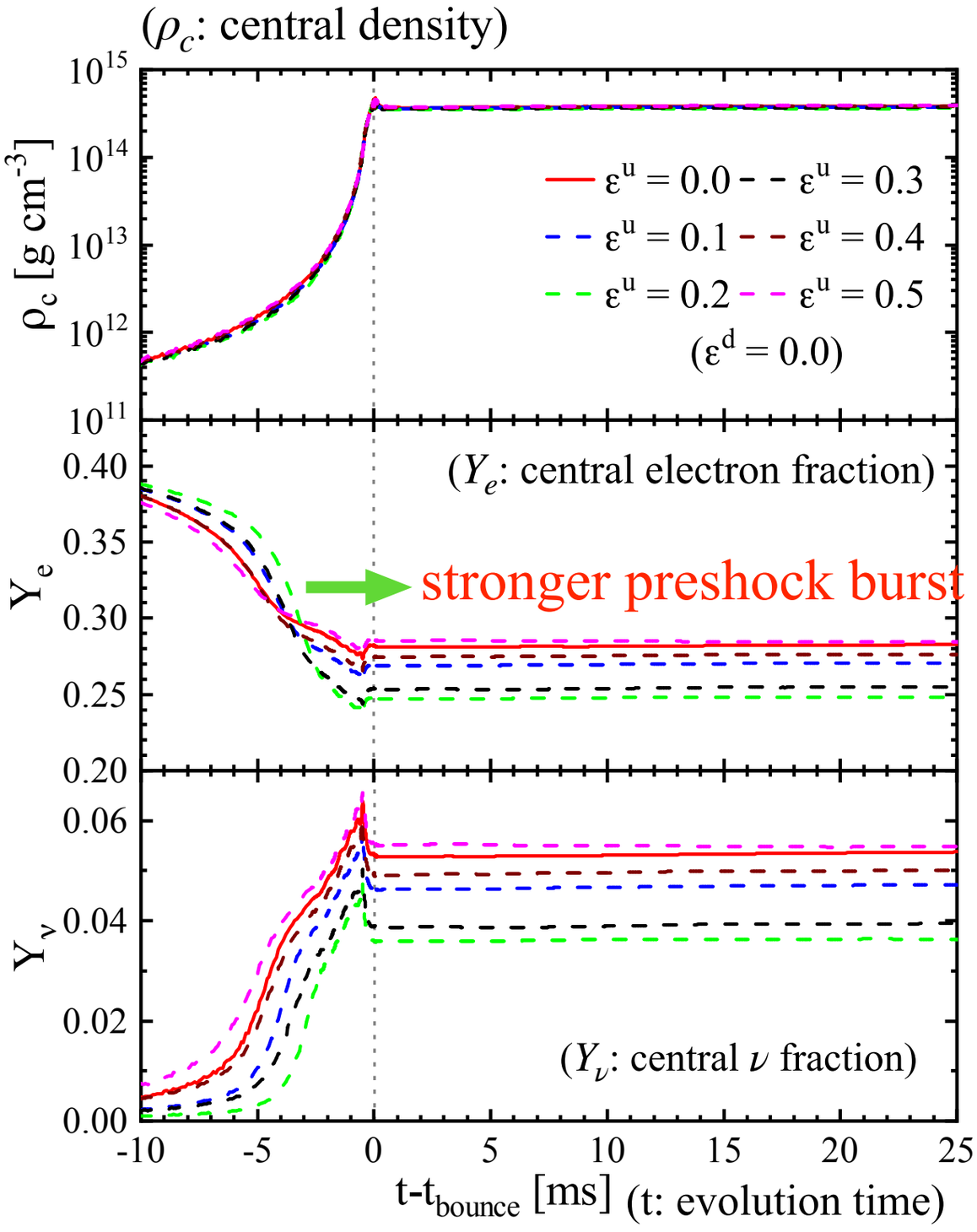
- nuclear equation of state (EOS): SFHo

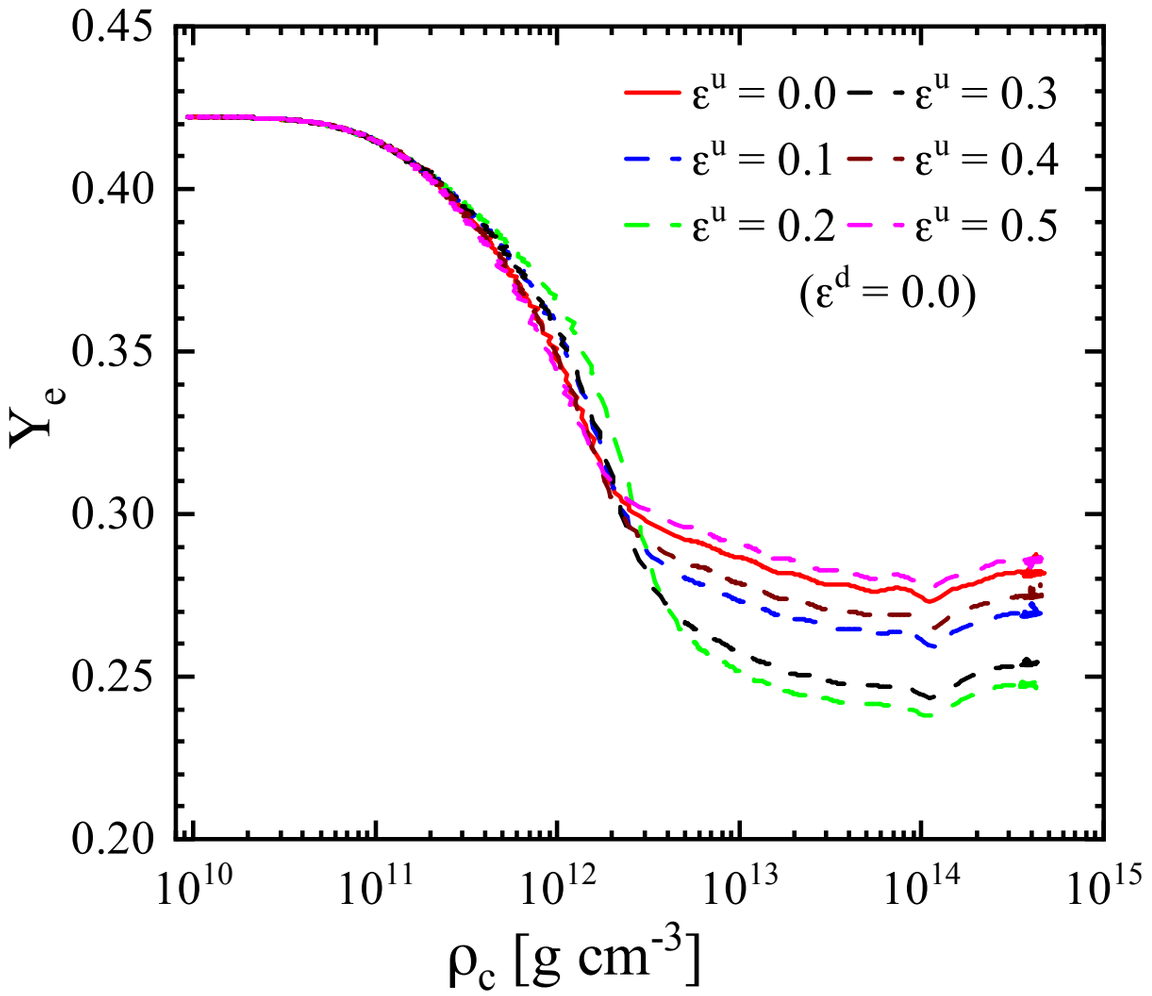
Steiner, Hempel & Fisher, ApJ. 774,17 (2013)

- neutrino-matter interactions



Simulation Results: Dynamics





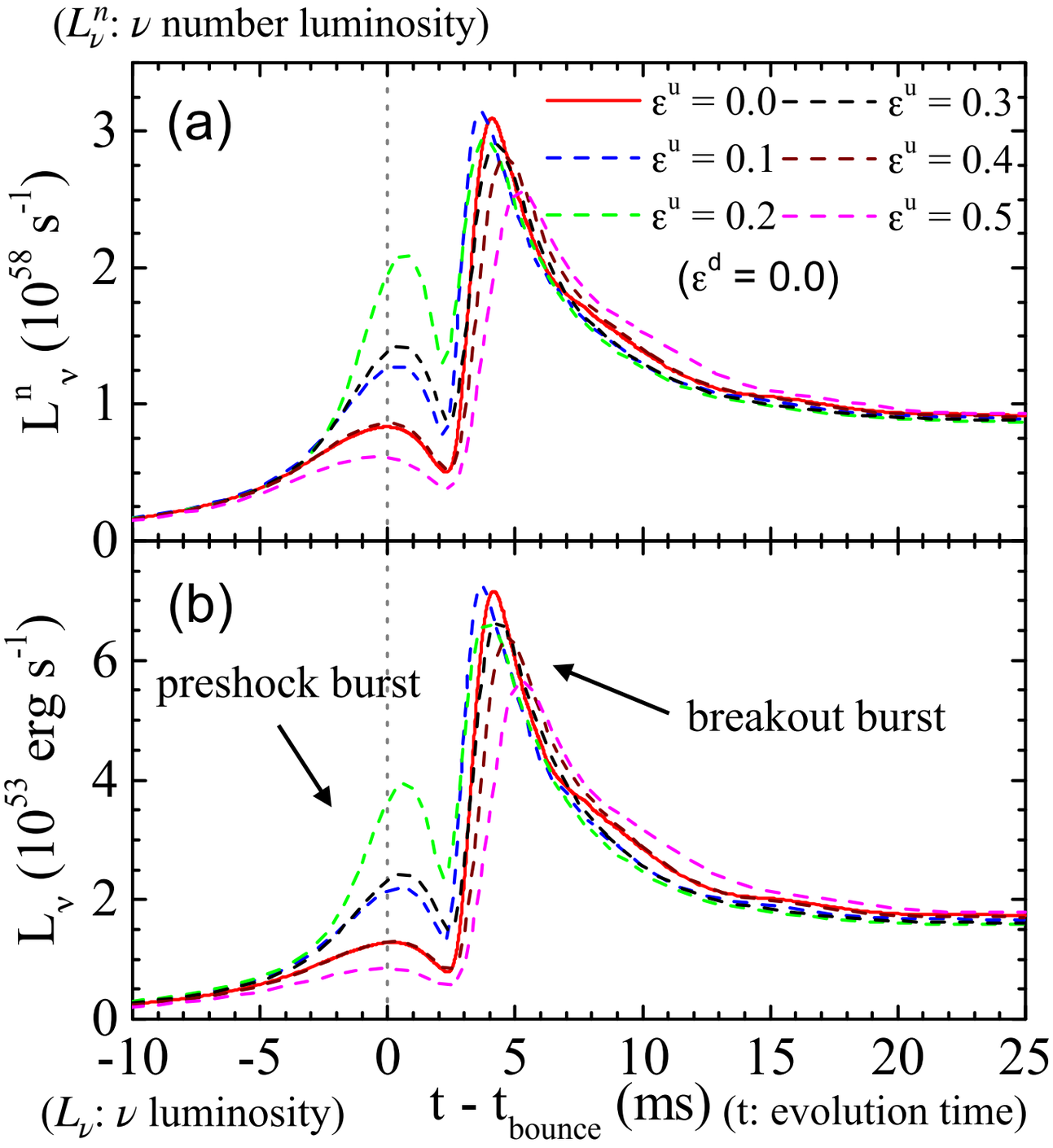
- collapse *vs* electron capture (EC)

✓ suppression on ν-nucleus scattering

✓ more ν transparent & weaken ν pressure

✓ faster collapse ➡ less sufficient EC

Simulation Results: Observables



- Preshock burst as a probe of the NSI

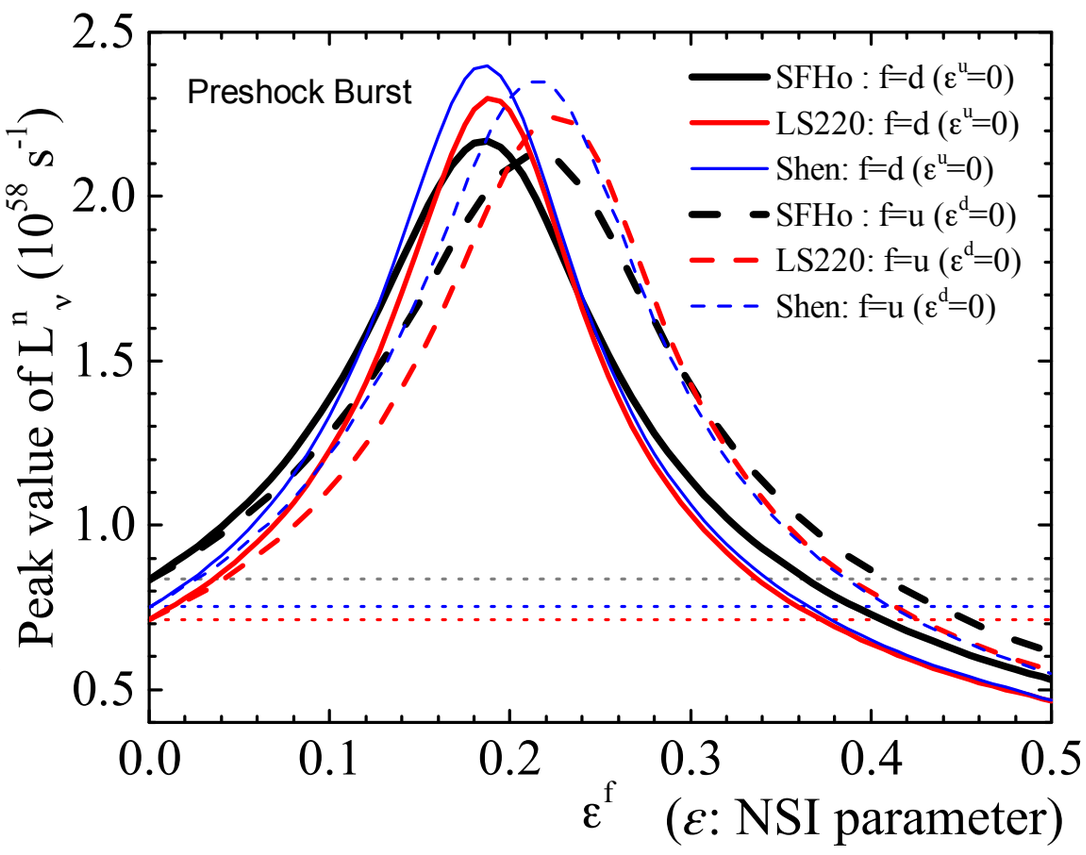
✓ great sensitivity to the NSI

✓ relatively simpler dynamics

✓ weak model dependence on EOS

✓ slightly depend on the progenitor

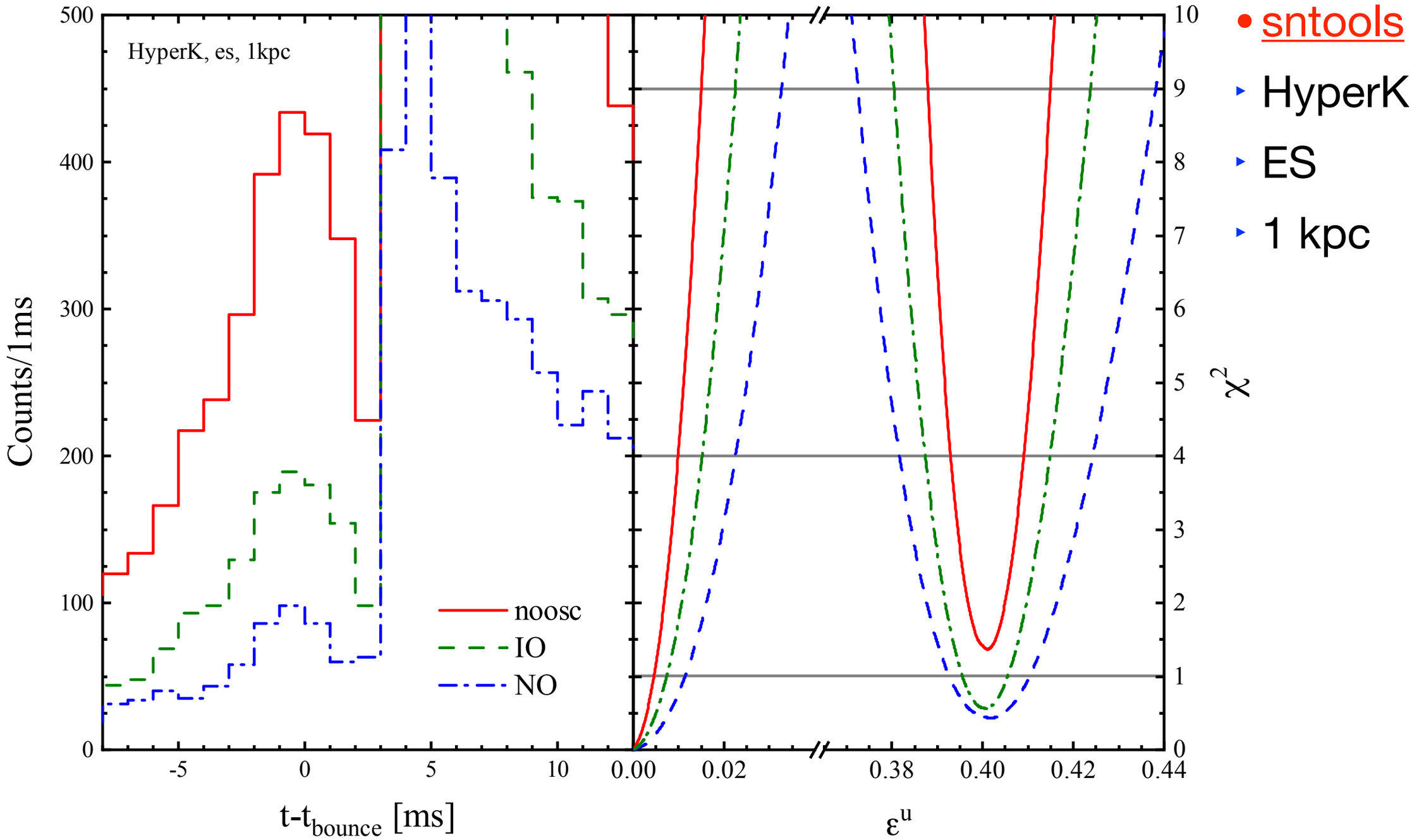
✓ similar predictions in 1-D and 3-D



Thank you!

Q & A

Terrestrial Detection



Neutrino Interactions in `NuLib`

Production	
Charged-current Interactions	Thermal Processes
$\nu_e + n \rightarrow p + e^-$	$e^- + e^+ \rightarrow \nu_x + \bar{\nu}_x$
$\bar{\nu}_e + p \rightarrow n + e^+$	$N + N \rightarrow N + N + \nu_x + \bar{\nu}_x$
$\nu_e + (A, Z) \rightarrow (A, Z+1) + e^-$	
Scattering	
Isoenergetic Scattering	Inelastic Scattering
$\nu + \alpha \rightarrow \nu + \alpha$	$\nu_i + e^- \rightarrow \nu_i' + e^{-\prime}$
$\nu_i + p \rightarrow \nu_i + p$	
$\nu_i + n \rightarrow \nu_i + n$	
$\nu + (A, Z) \rightarrow \nu + (A, Z)$	O'Connor, ApJS. 219, 24 (2015)