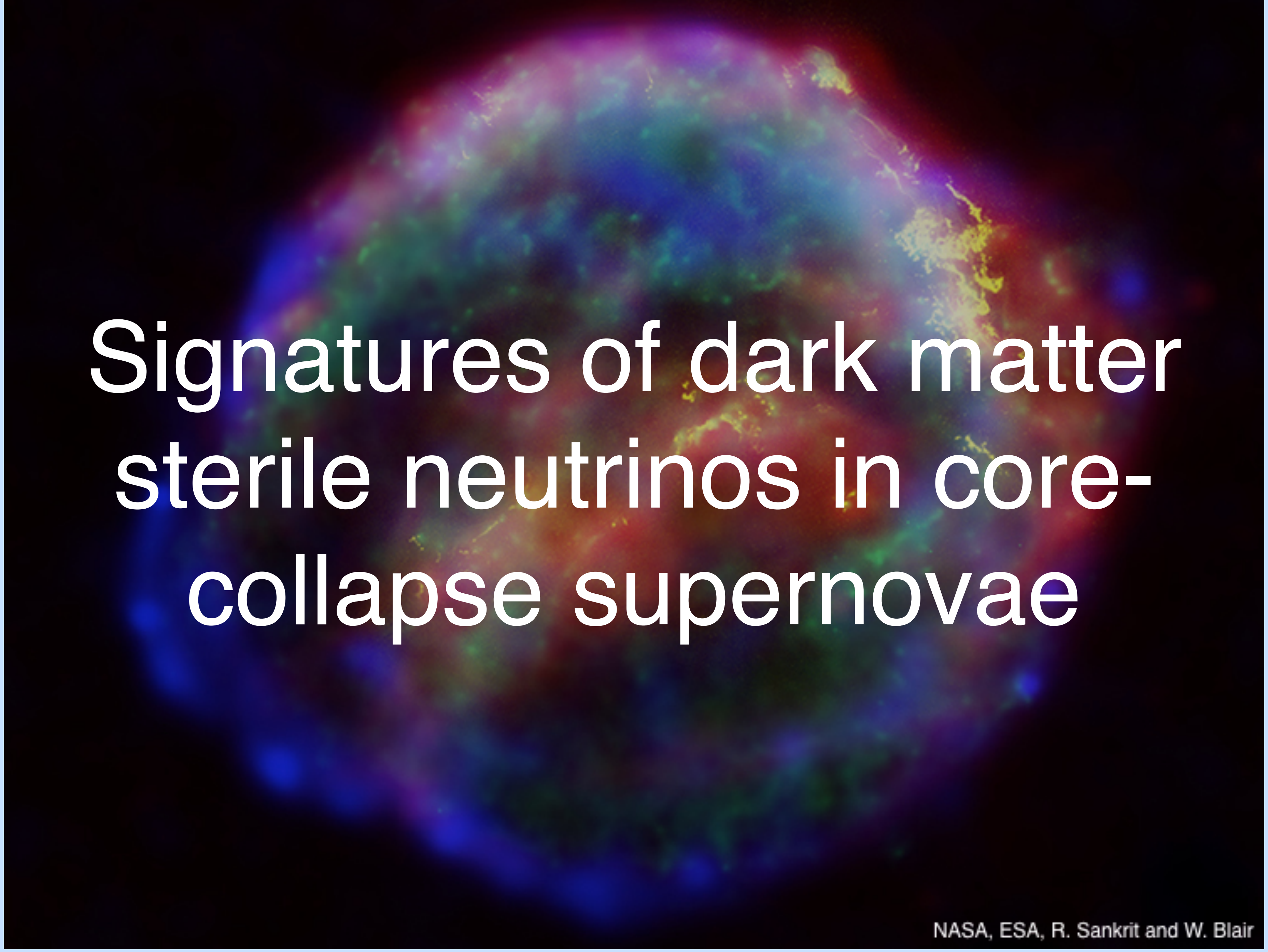
Signatures of dark matter sterile neutrinos in core-collapse supernovae

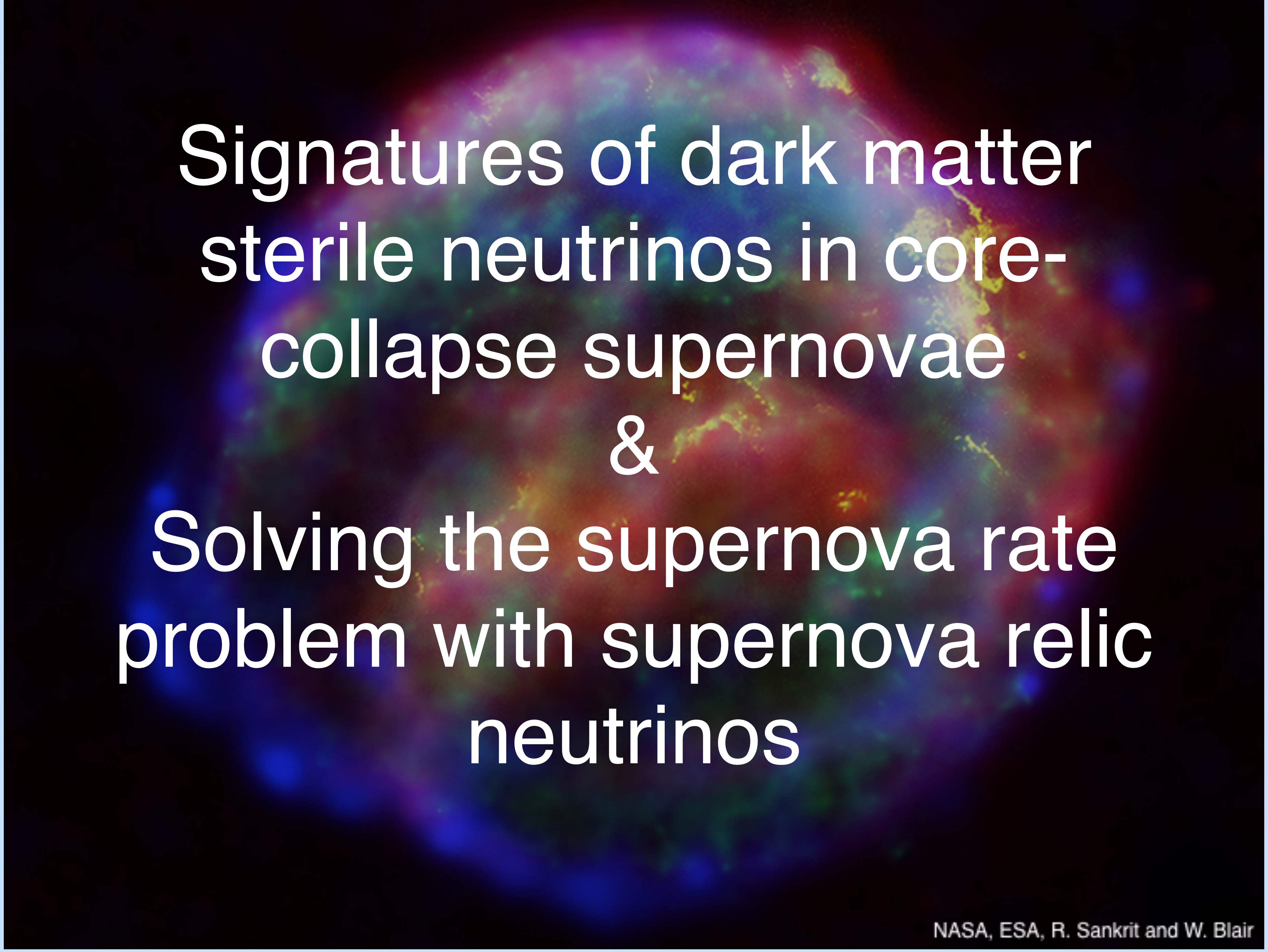


M. Warren, G. Mathews, J. Hidaka, T. Kajino, and M. Meixner

UNIVERSITY OF NOTRE DAME
College of Science

IPA 2015
May 5th, 2015

Signatures of dark matter sterile neutrinos in core-collapse supernovae & Solving the supernova rate problem with supernova relic neutrinos



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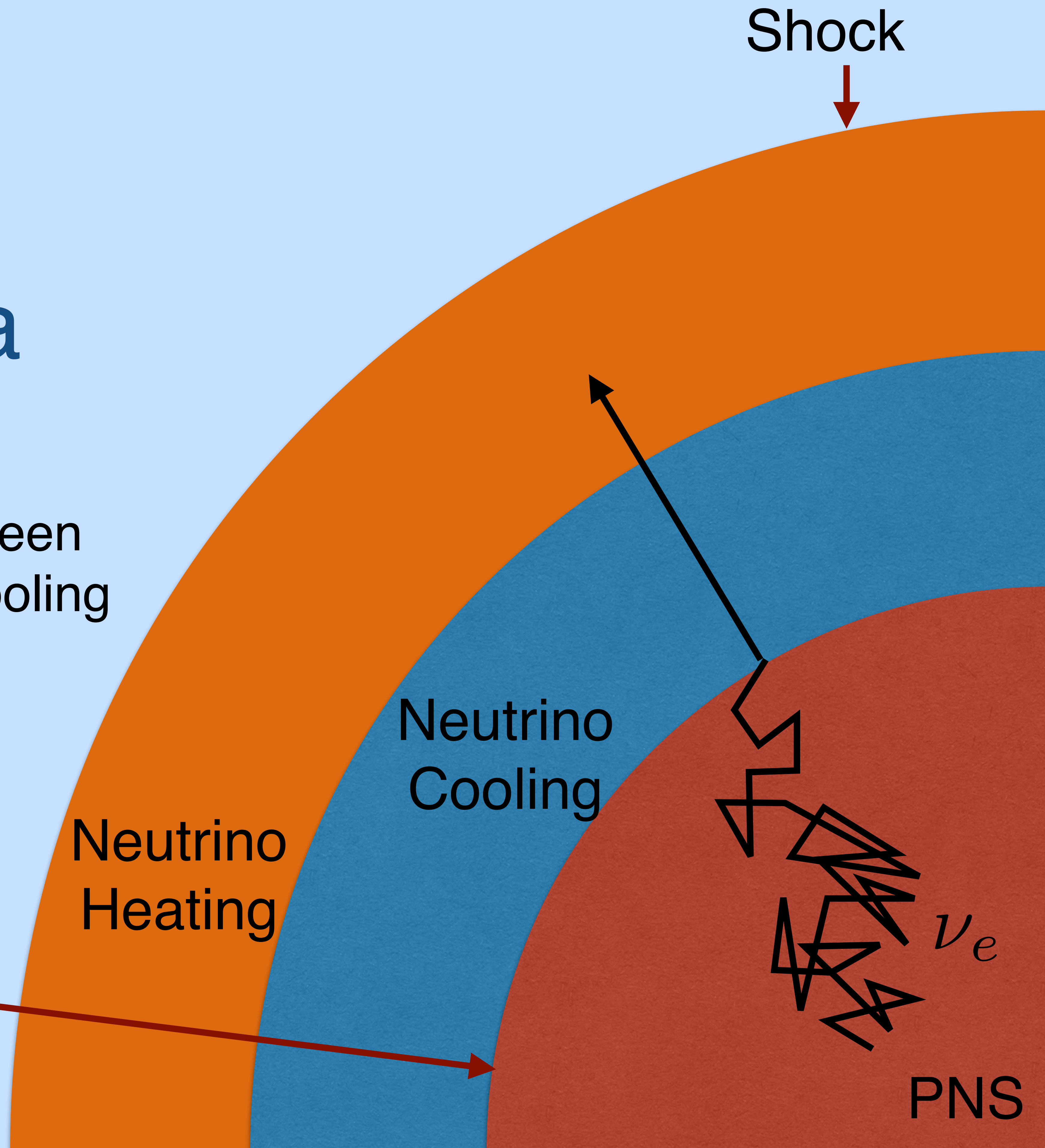
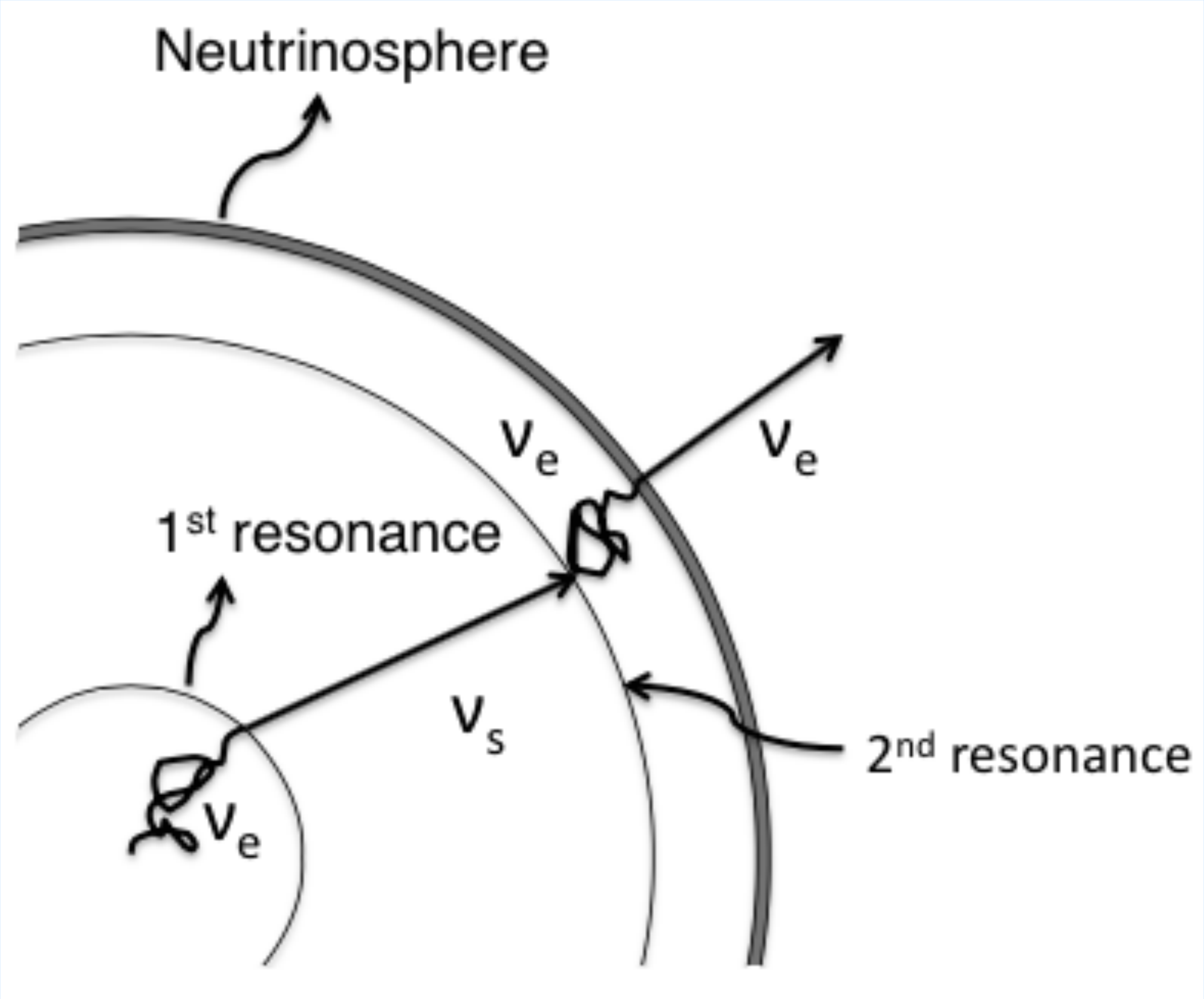
Supernova neutrinos

Delicate balance between neutrino heating and cooling



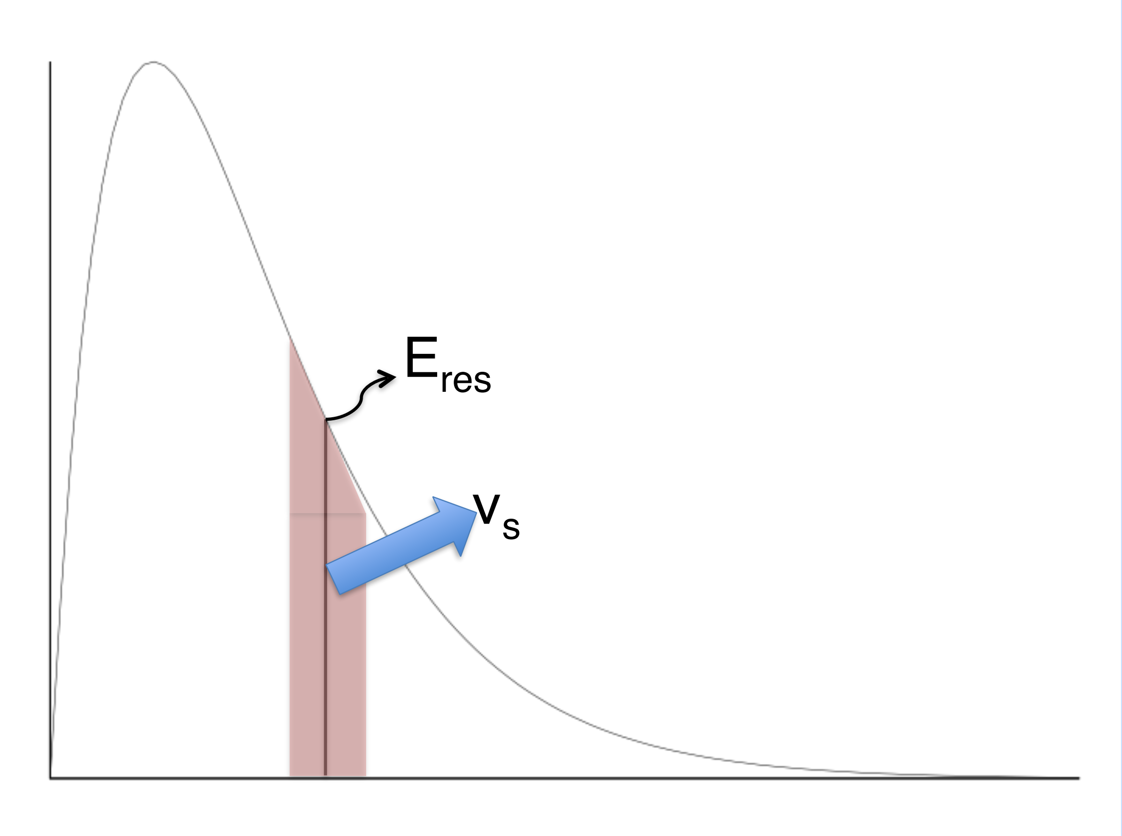
Sterile neutrinos in CCSNe



Matter-enhanced neutrino oscillations

- Neutrinos experience potential when moving through matter
    - Interactions with electrons, nucleons, other neutrinos…

$$V_e(r) = \frac{3\sqrt{2}}{2} G_F n_B \left(Y_e + \frac{4}{3} Y_{\nu_e} - \frac{1}{3} \right)$$



- Potential *difference* enhances oscillations
    - Resonance: *Maximal* mixing (even for small vacuum mixing)

$$\sin^2 2\theta_M = \frac{\left(\Delta m_s^2/2E_\nu\right)^2 \sin^2 2\theta}{\left((\Delta m_s^2/2E_\nu)\cos 2\theta - V\right)^2 + \left(\Delta m_s^2/2E_\nu\right)^2 \sin^2 2\theta}$$

$$\Rightarrow \quad E_{res} = \frac{\Delta m_s^2}{2V_e} \cos 2\theta_s$$

PHYSICAL REVIEW D **74**, 125015 (2006)

Dark matter sterile neutrinos in stellar collapse: Alteration of energy/lepton number transport, and a mechanism for supernova explosion enhancement

Jun Hidaka* and George M. Fuller†

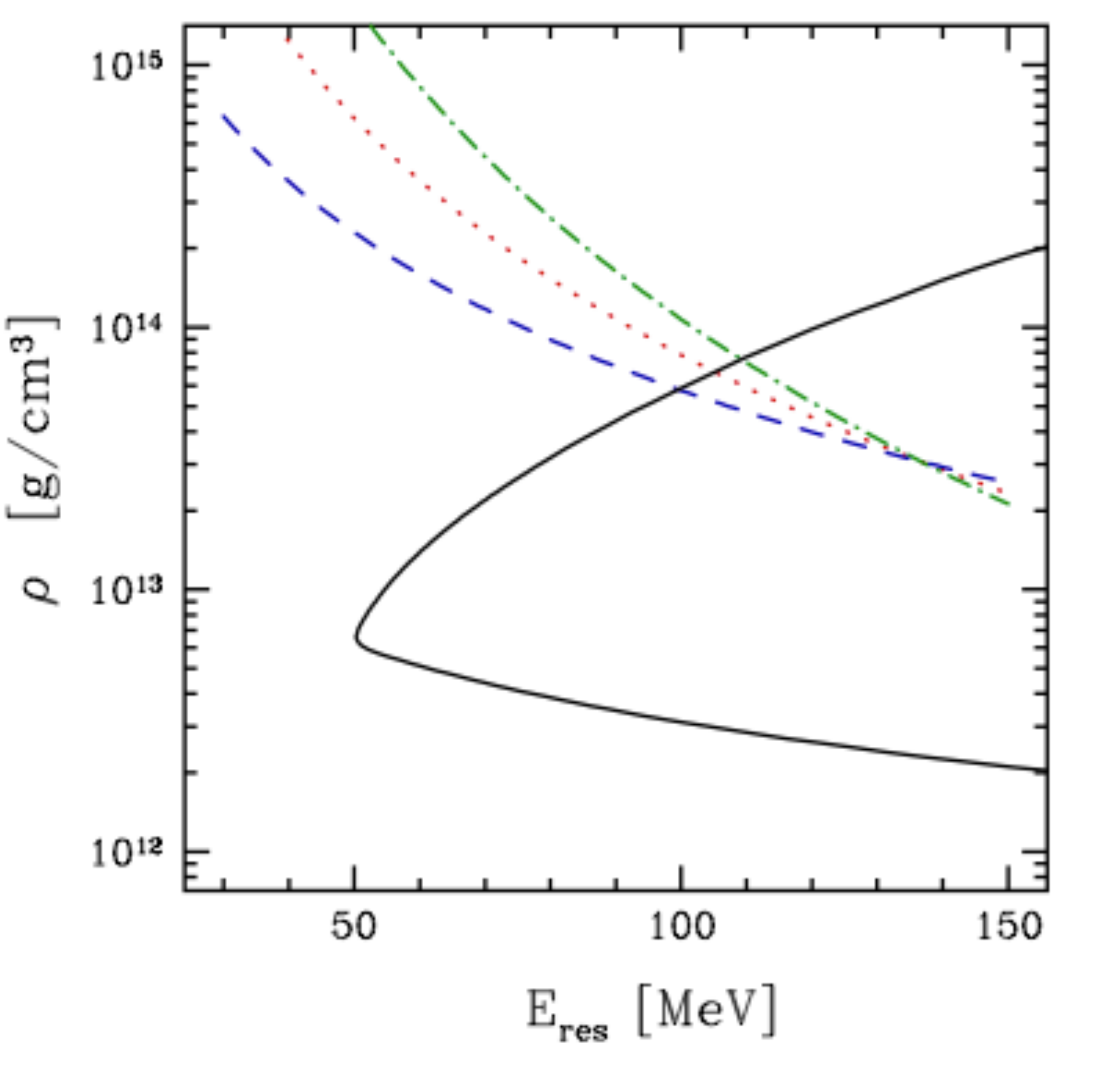
PHYSICAL REVIEW D **76**, 083516 (2007)

Sterile neutrino-enhanced supernova explosions

Jun Hidaka* and George M. Fuller†

Allow for $\nu_e \leftrightarrow \nu_s$ oscillations:

$m_s = 3\,\mathrm{keV} \;\; \sin^2 2\theta_s = 10^{-9}$



Sterile Neutrino Dark Matter

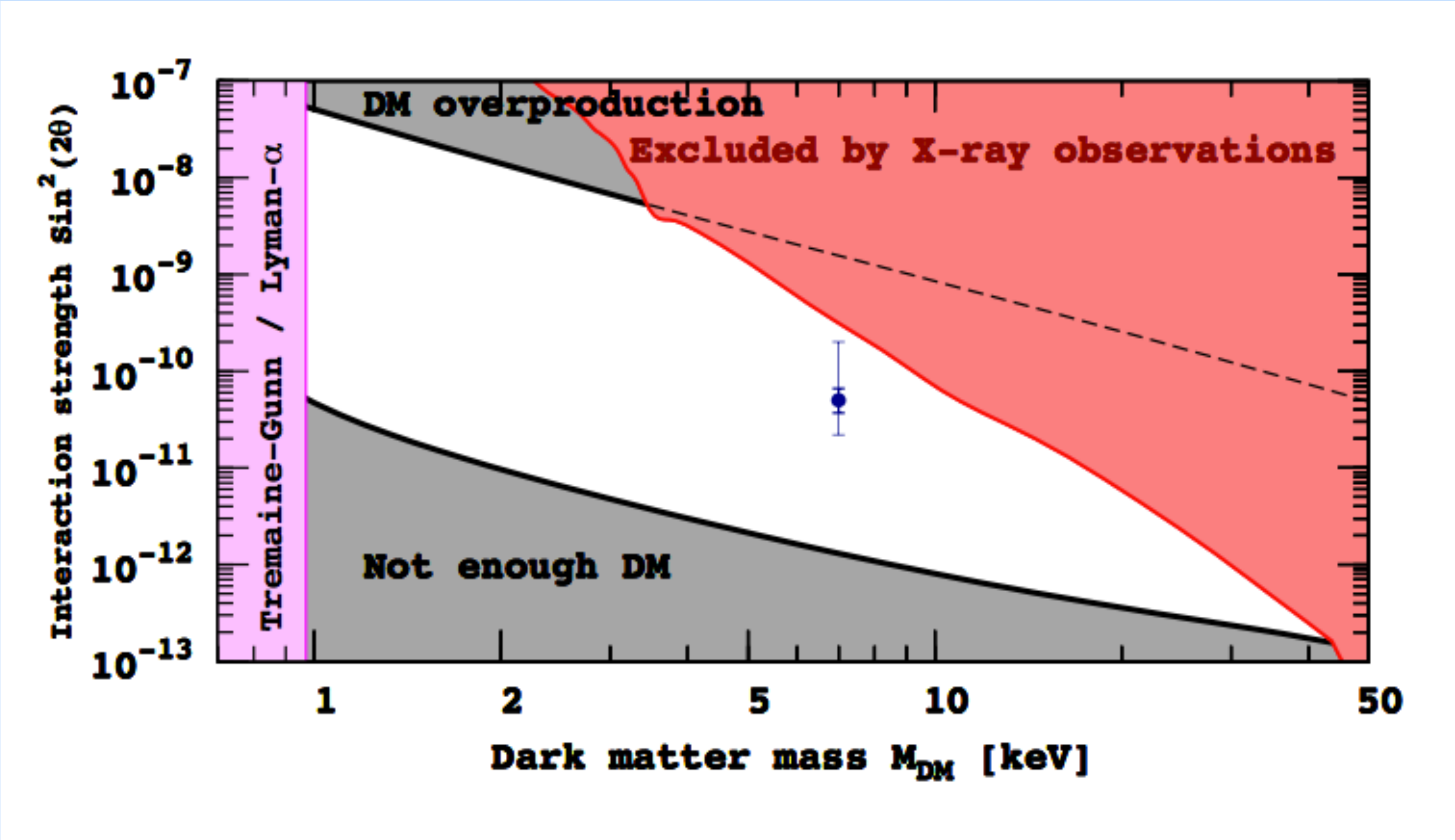
- Decaying sterile neutrinos

$$\nu_s \rightarrow \gamma + \nu_\alpha$$

- Decay width in νMSM

$$\Gamma_{\nu_s \rightarrow \gamma \nu_\alpha} \sim \sin^2 2\theta_s m_s^5$$

- Compare x-ray background with flux from galaxy or cluster
- Measured in Andromeda galaxy and Perseus cluster (Boyarsky et al (2014))
- Assume dark matter is 100% sterile neutrino



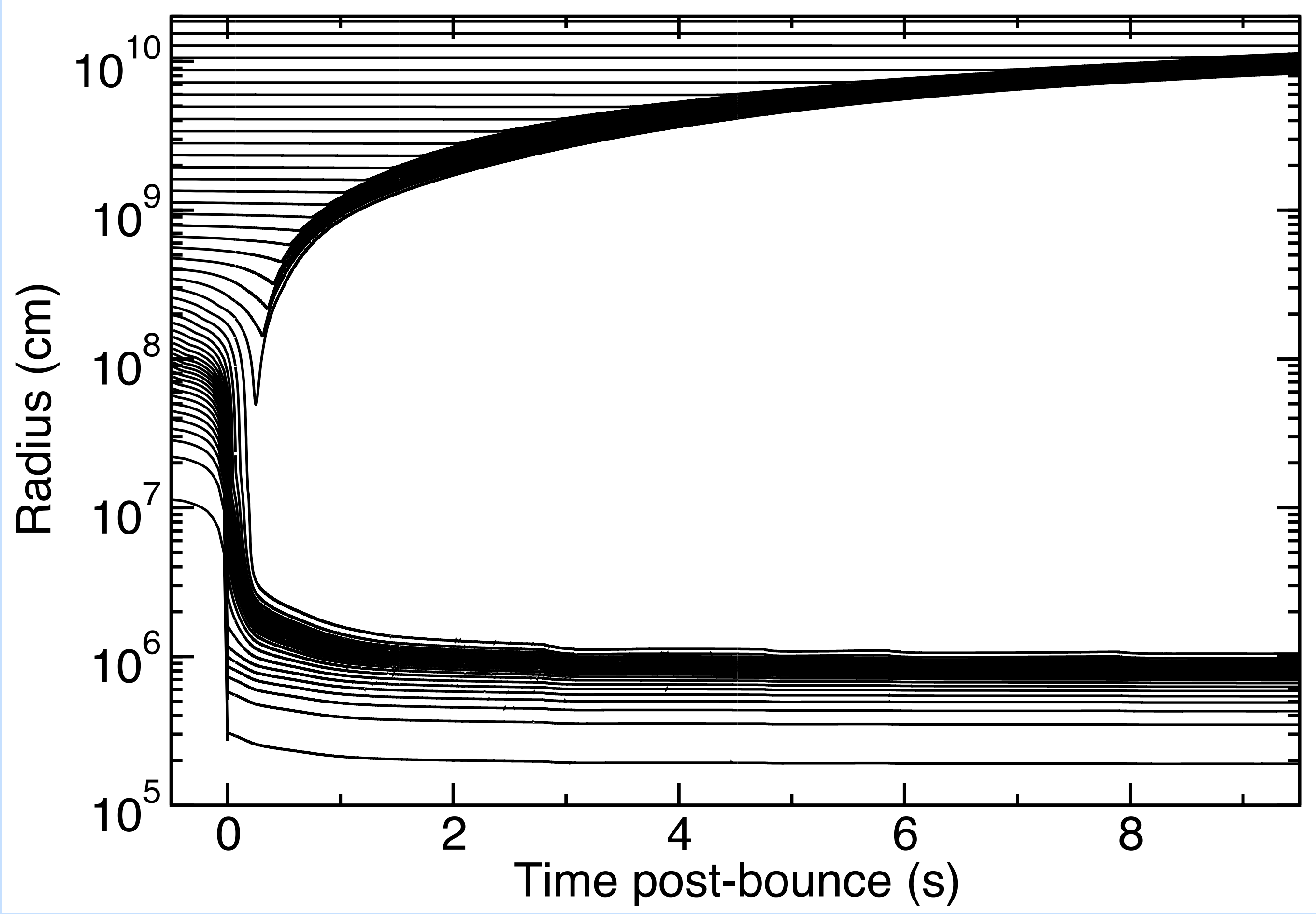
Boyarsky et al (2014)

$$E_\gamma = 3.518^{+0.019}_{-0.022} \text{ keV}$$

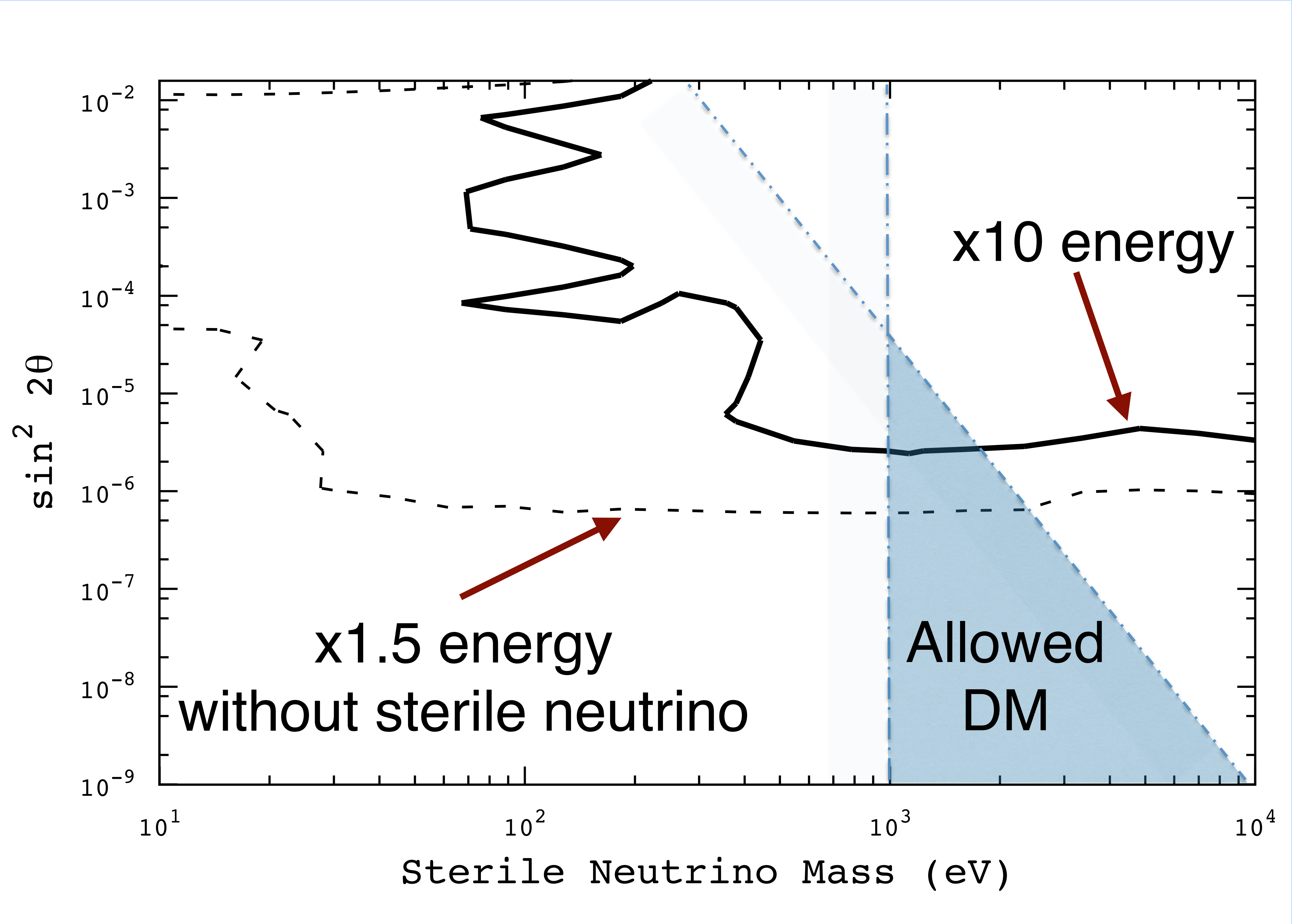
$$m_s = 7.06 \pm 0.05 \text{ keV}$$

University of Notre Dame/Lawrence Livermore National Laboratory Model

- Spherically symmetric model
  - General relativistic hydrodynamics
  - Neutrino transport and interactions
  - Nuclear burning
  - Equation of state

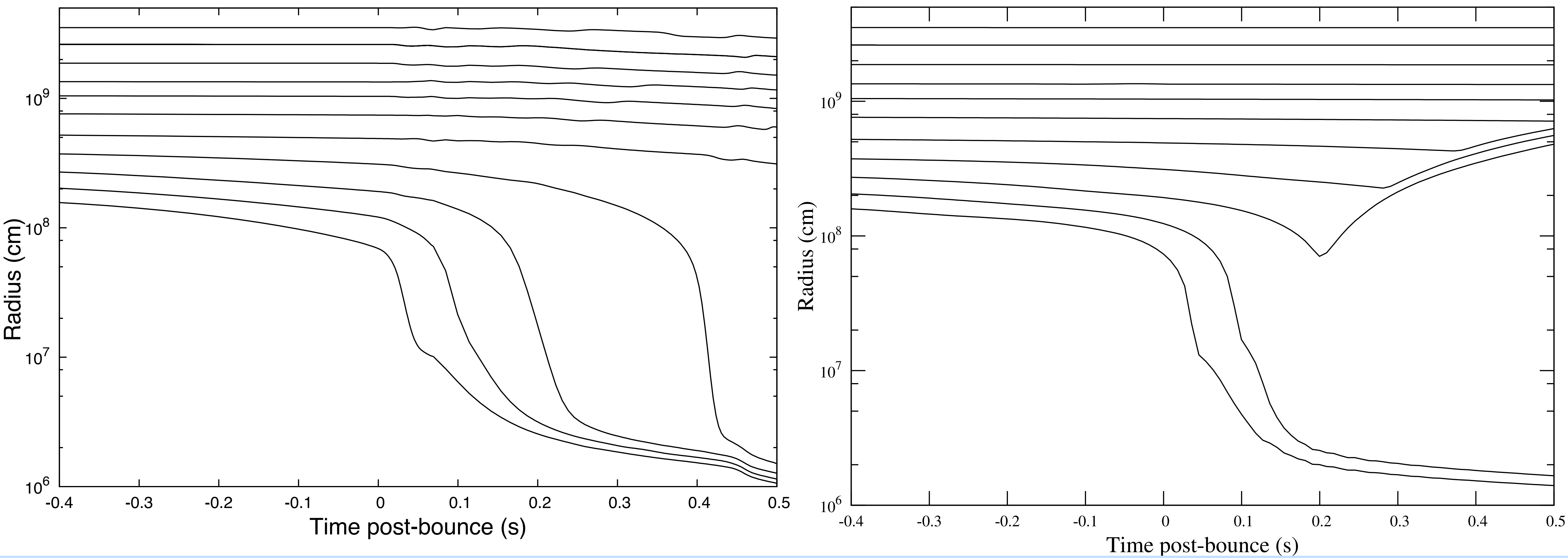


Enhanced Explosion Energy



Warren et al (2014) DM bounds from Boyarsky et al (2006)

Successful explosion in a model that would not otherwise explode

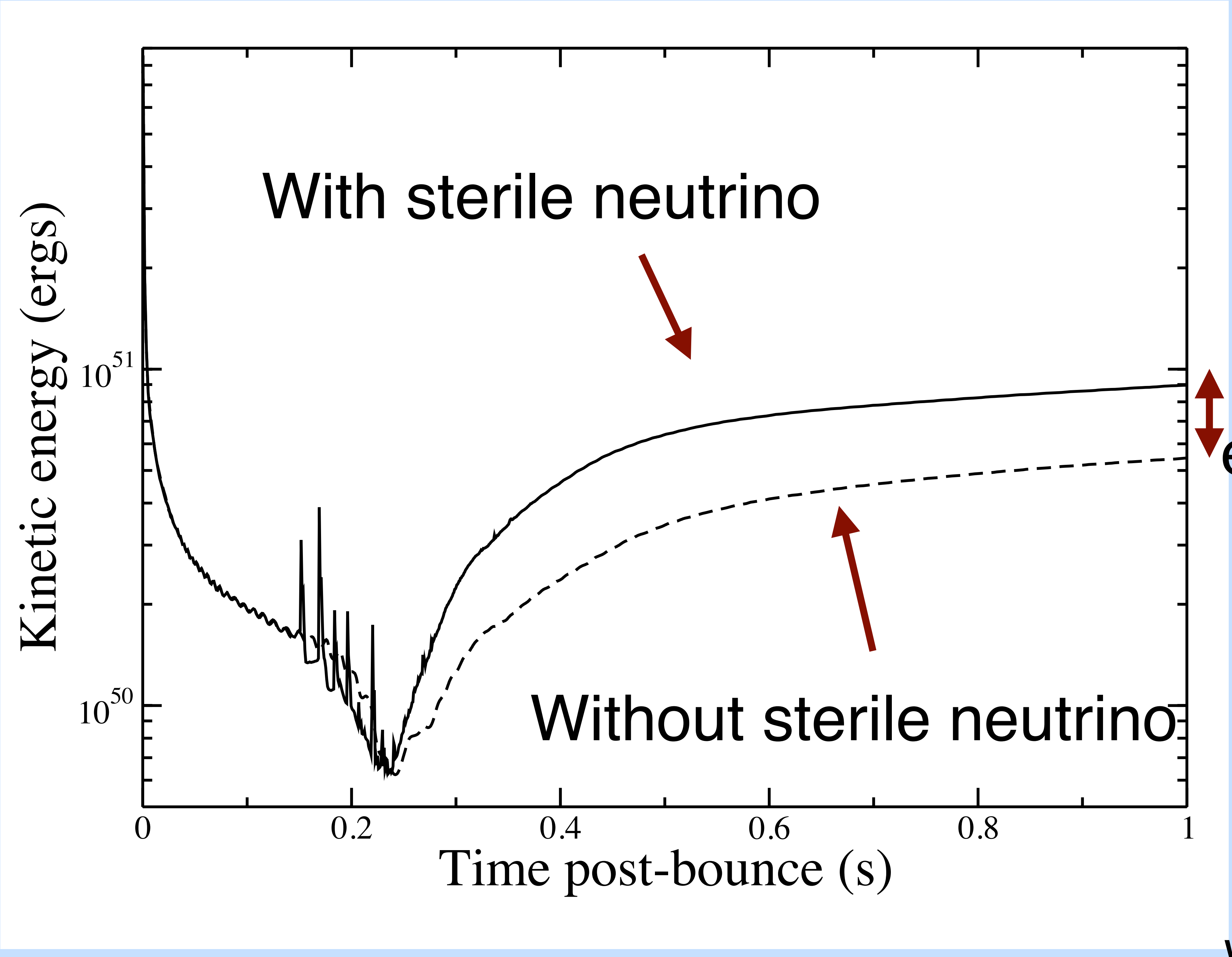


Without sterile neutrino

With sterile neutrino

Warren et al (2014)

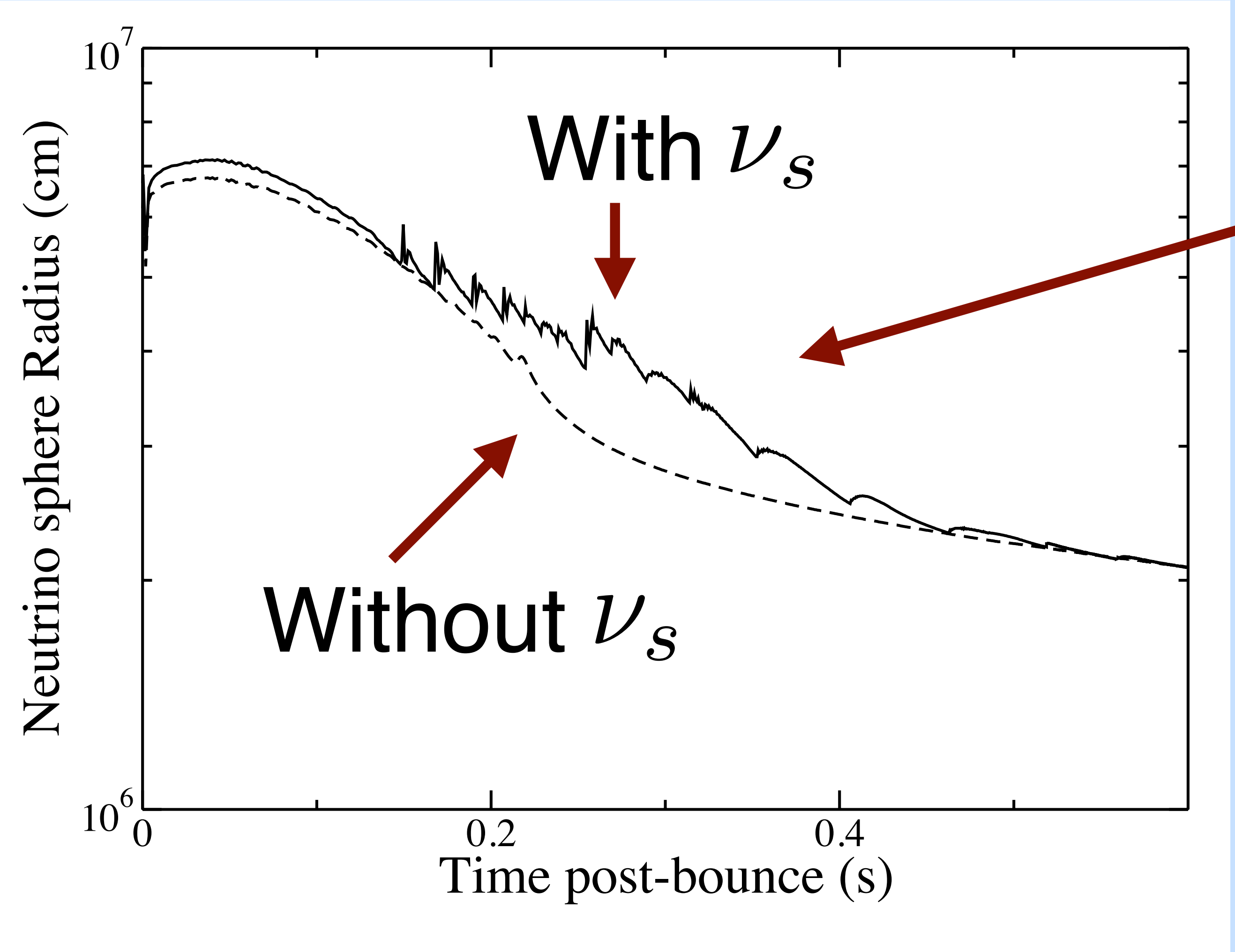
Example: $m_s = 5.012\,\text{keV}$ and $\sin^2 2\theta_s = 1.12 \times 10^{-5}$



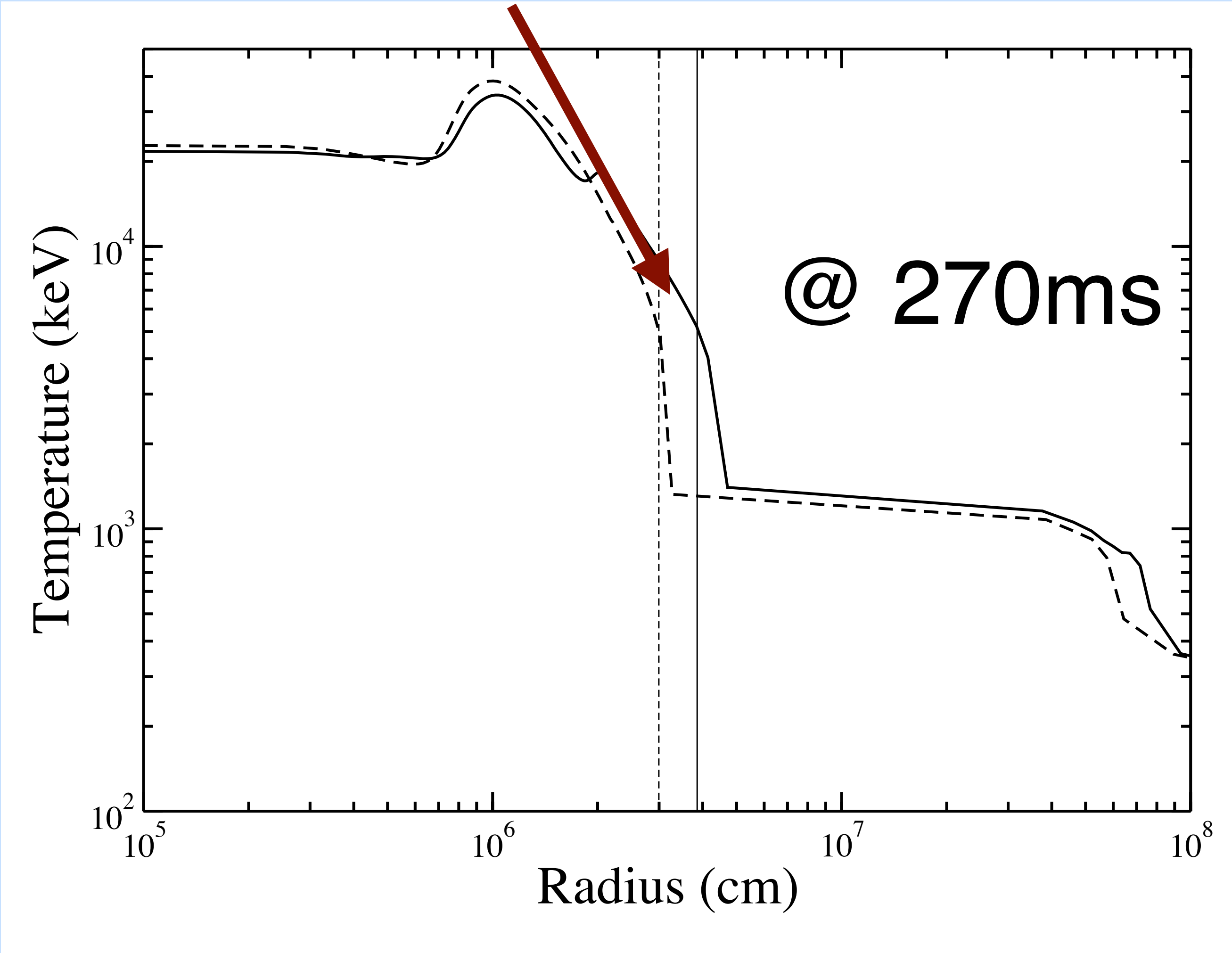
~1.3x enhancement

Warren et al (2014)

Expanded Neutrinosphere

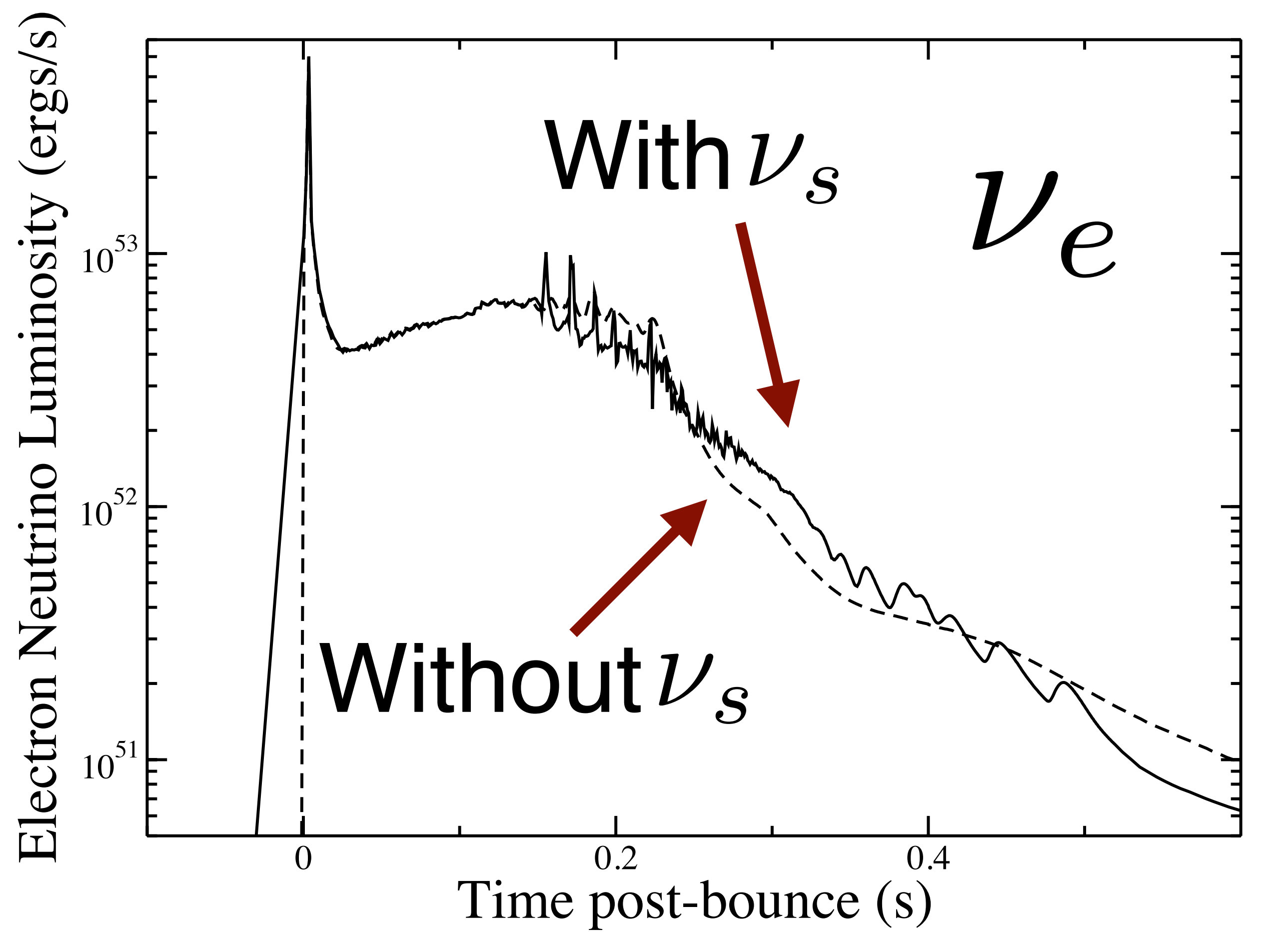


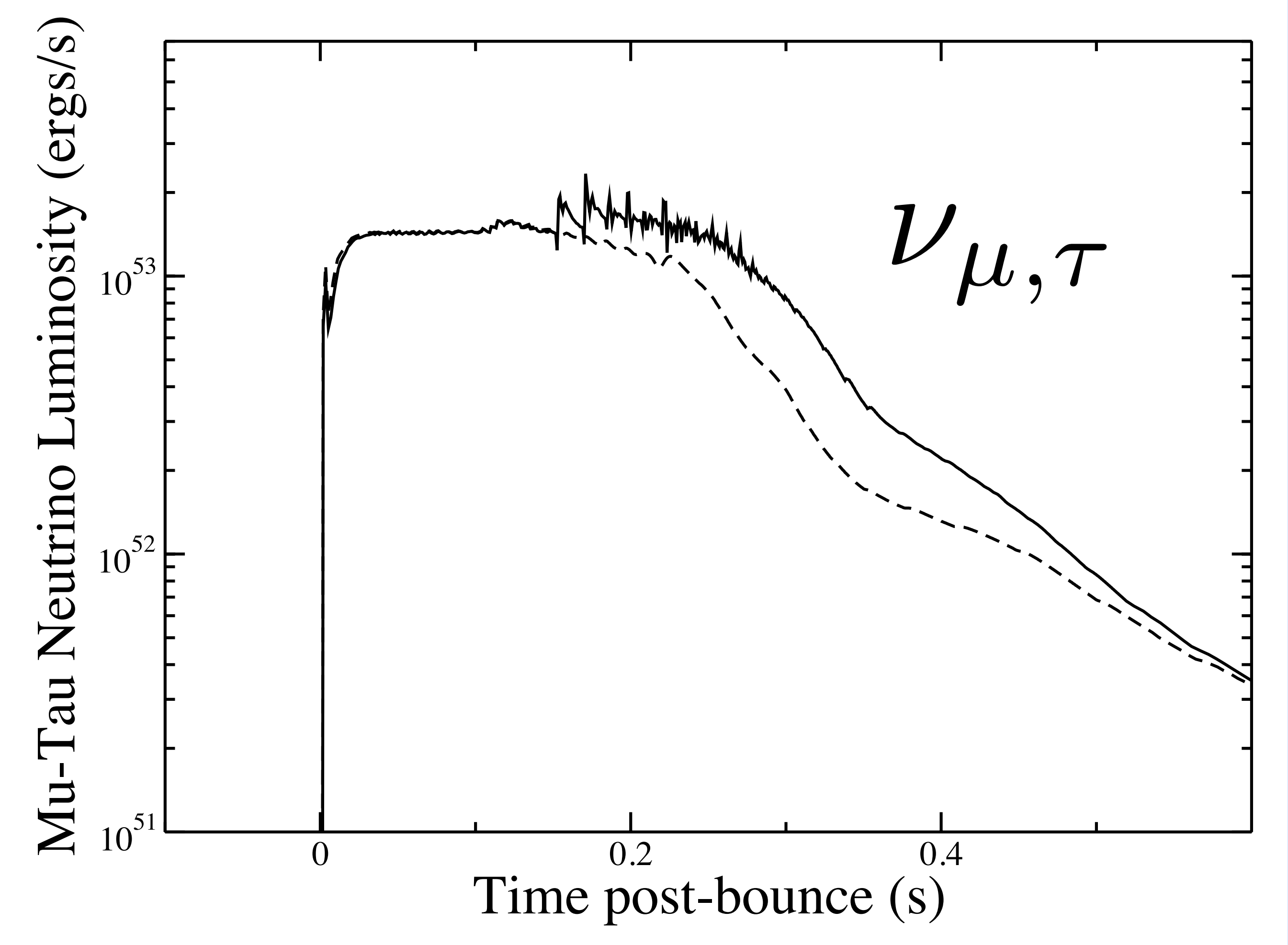
Protoneutron star radius increased, temperature unchanged

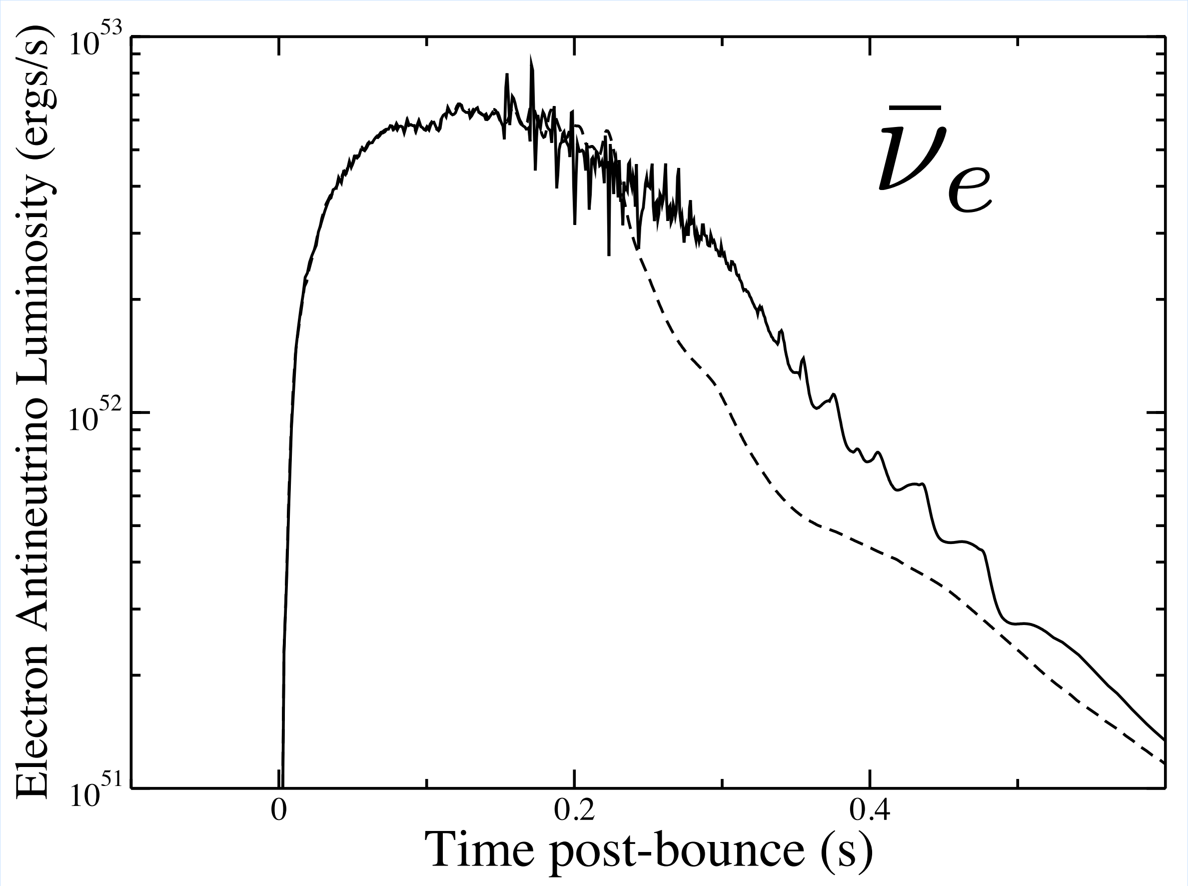


Warren et al (2014)

Observable Luminosities



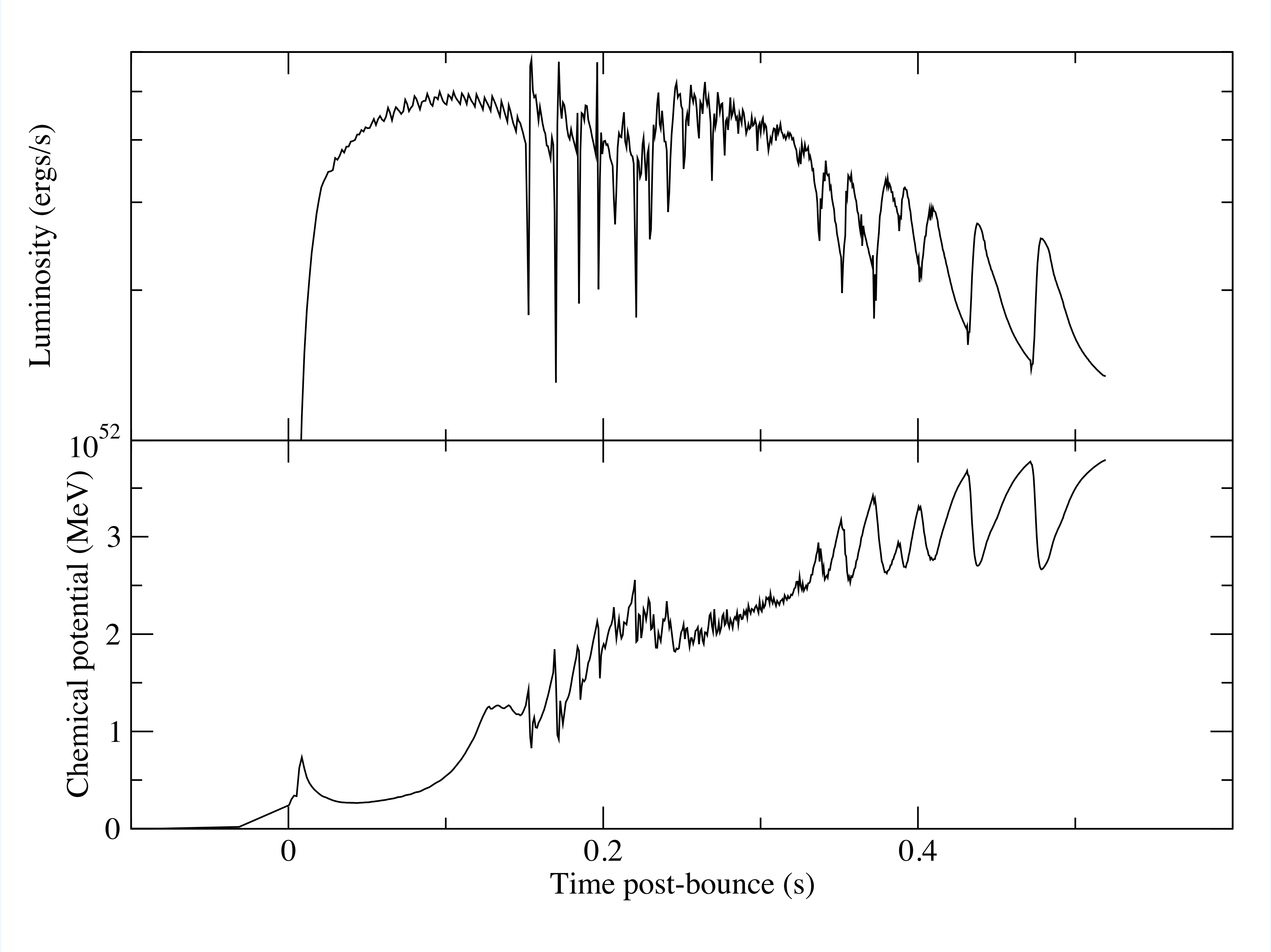




$$L = \sigma T^4 4\pi R^2$$

Warren et al (2014)

Luminosity Fluctuations



Warren et al (2014)

In conclusion (part I)

1. Supernova models don't explode

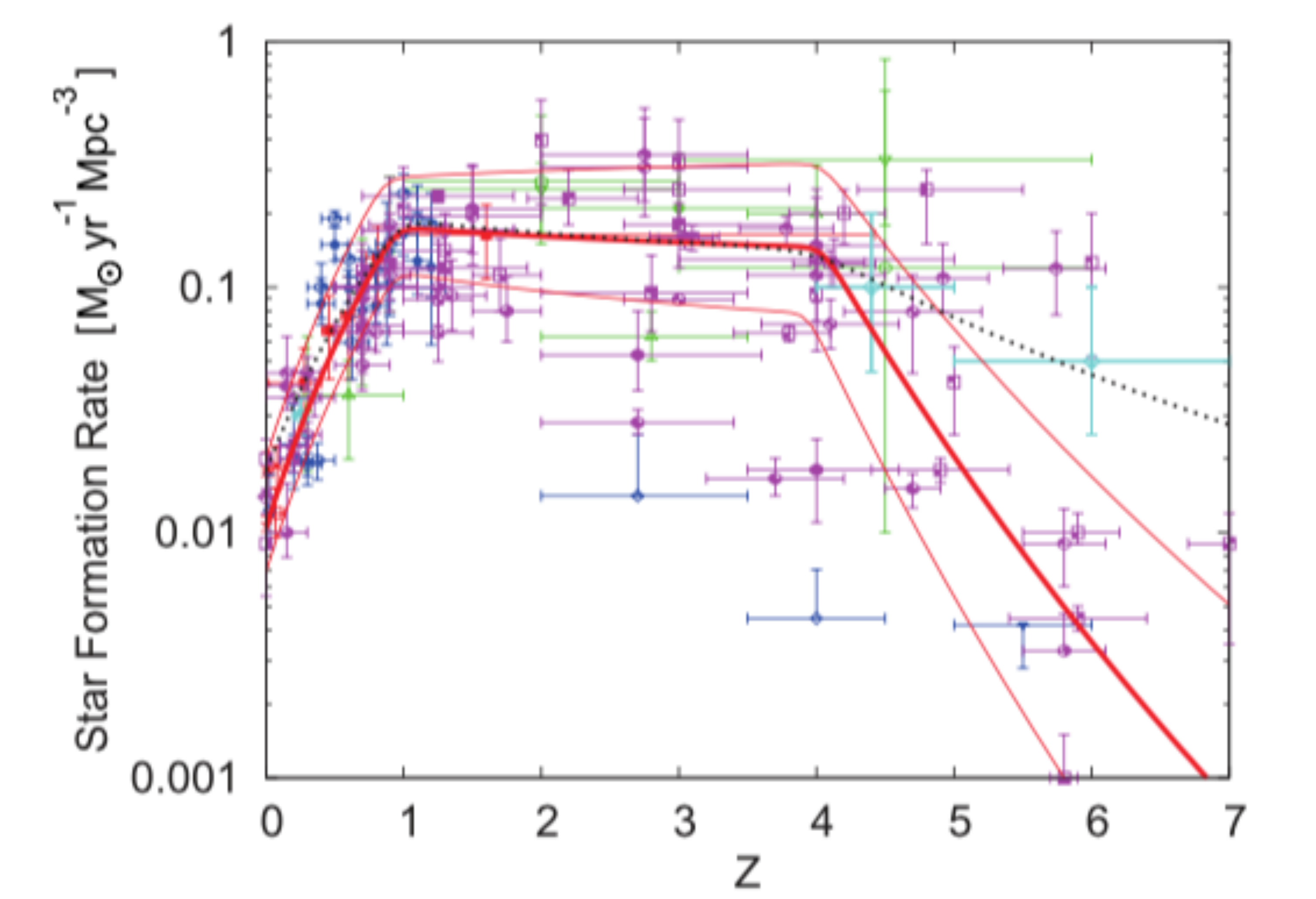
   (Or explode with too little energy…)

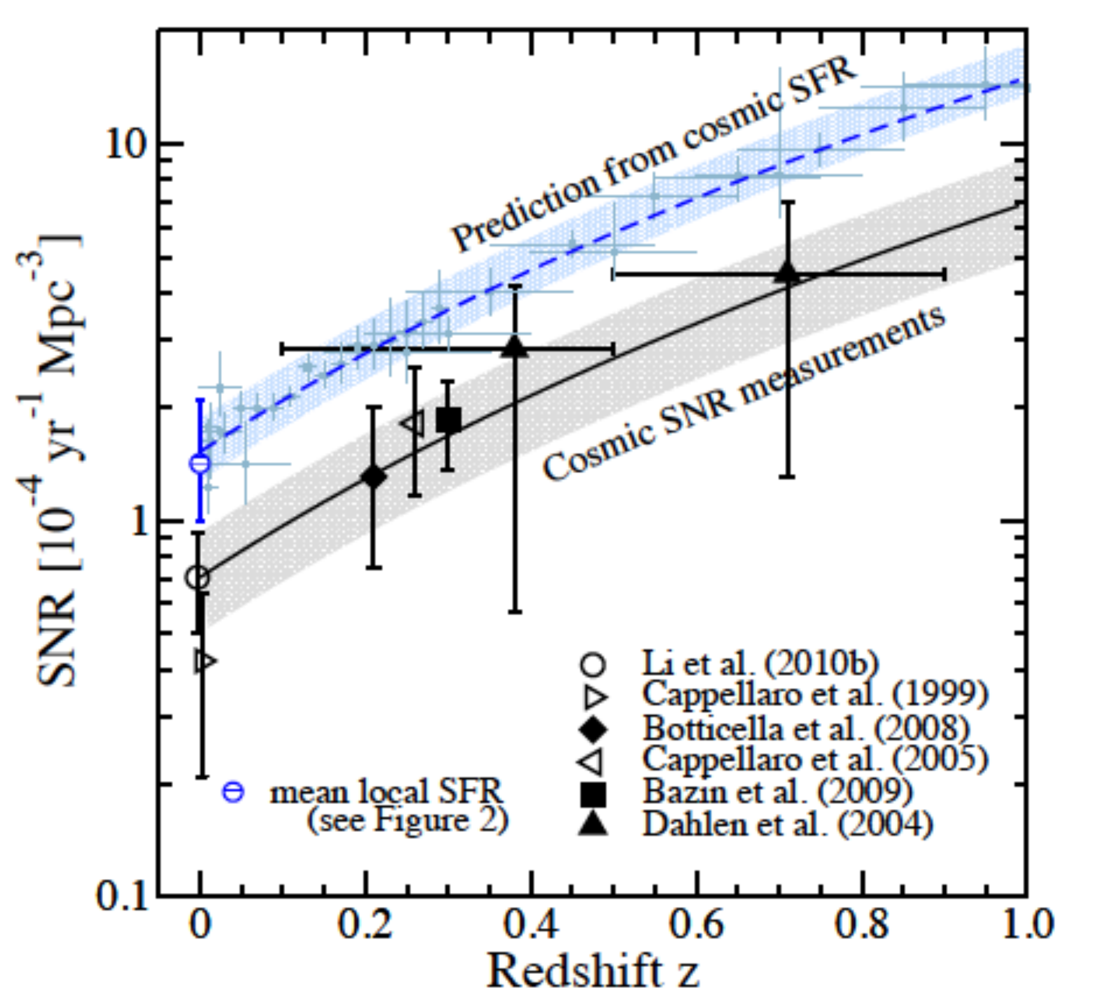
2. Sterile neutrinos can enhance explosion energies

3. Parameter space overlaps with sterile neutrino dark matter candidates

   Happy coincidence or …?

Supernova Rate Problem





Mathews et al (2014)

Multiple wavelength observations of massive star formation regions

Horiuchi et al (2011)

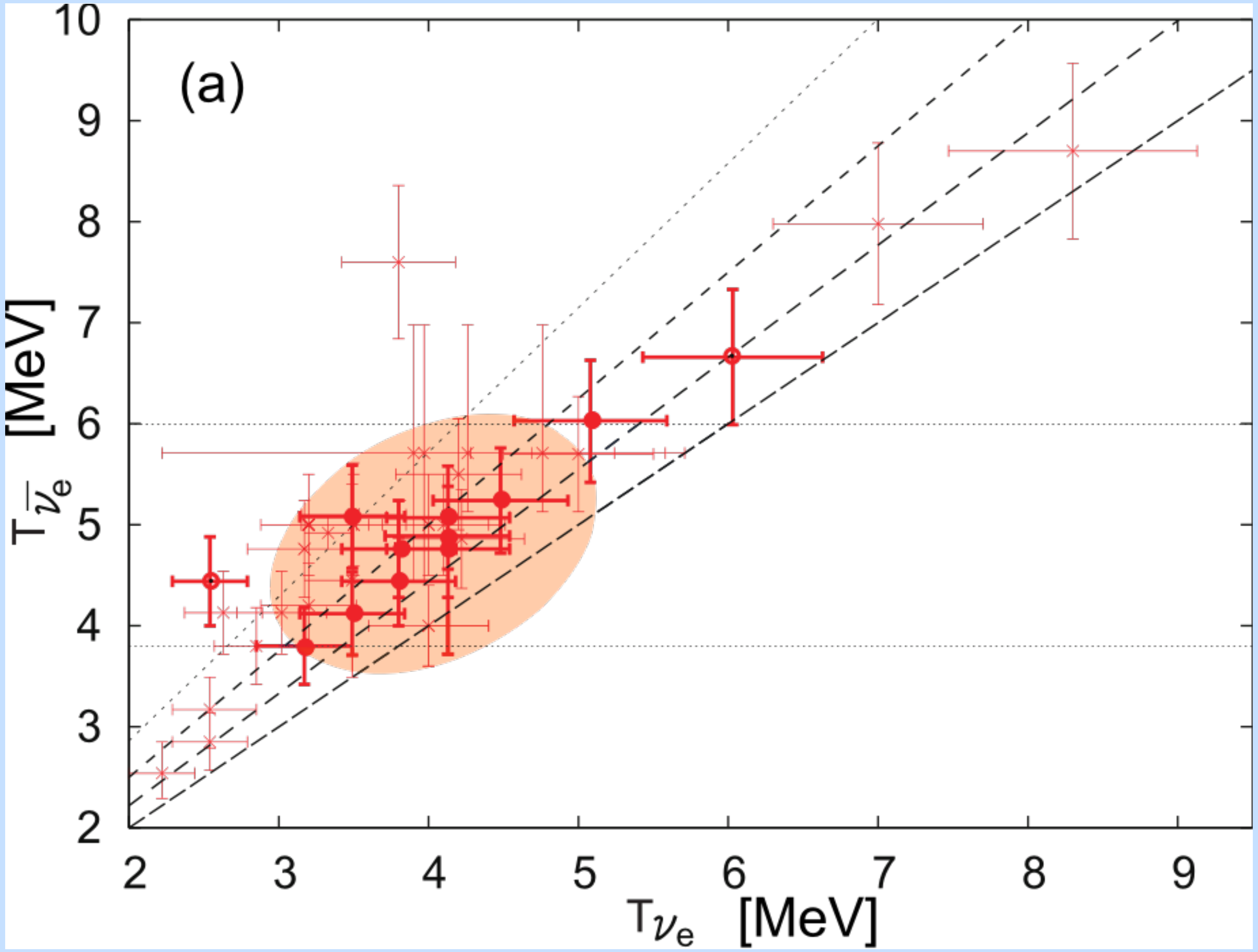
Possible Solutions

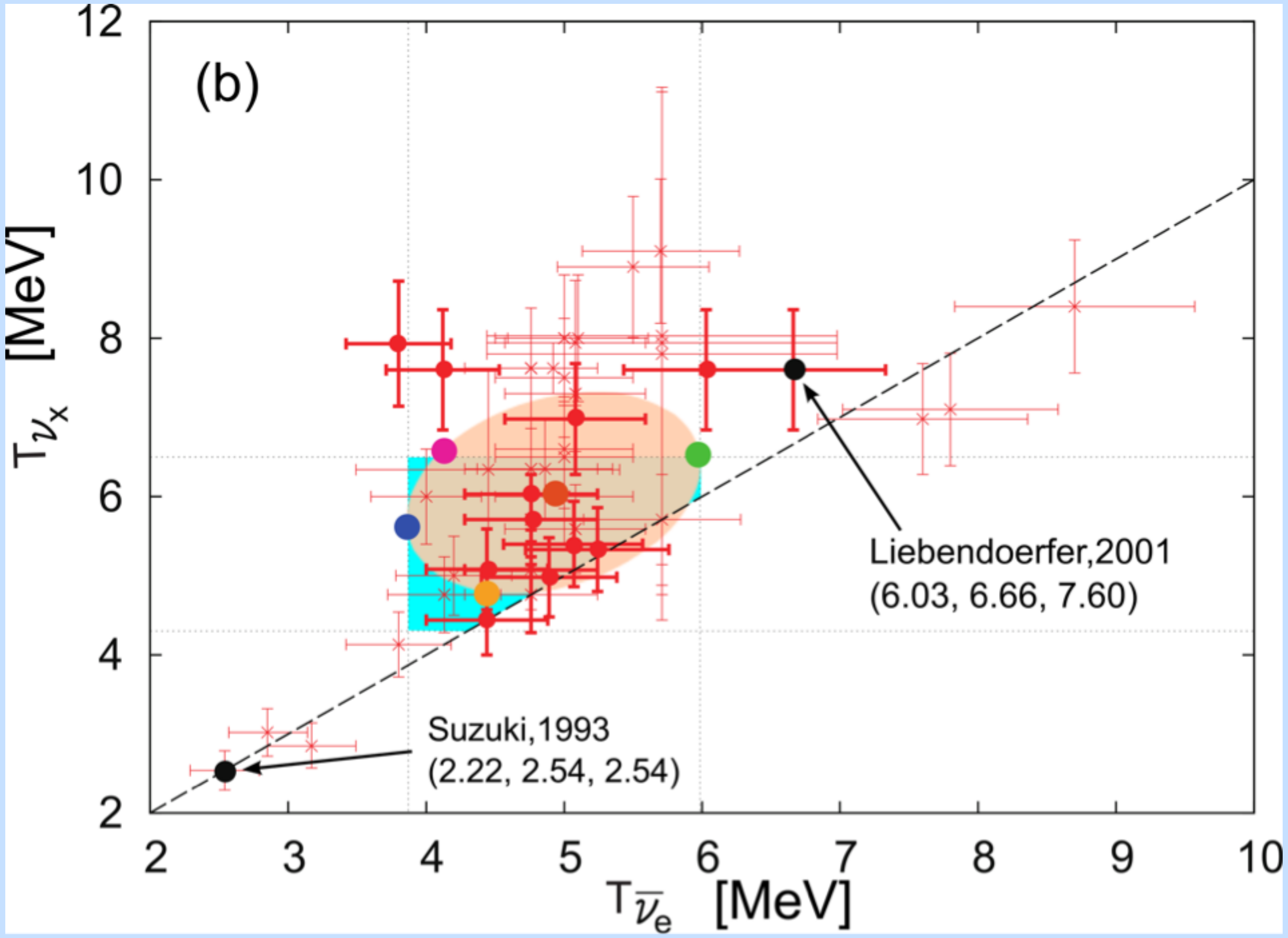
1. O-Ne-Mg SNe : M ~ 10-12 $M_\odot$
   - Optically dim, but large neutrino flux
2. Failed SNe : M > 25 $M_\odot$ black hole formation
   - Optically dim, but large short-duration neutrino flux

Question: Can one distinguish these possibilities by detecting supernova relic neutrinos?

$$\frac{dN_\nu}{dE_\nu} = \frac{c}{H_0} \int_0^{z_{max}} R_{SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

Model Uncertainties





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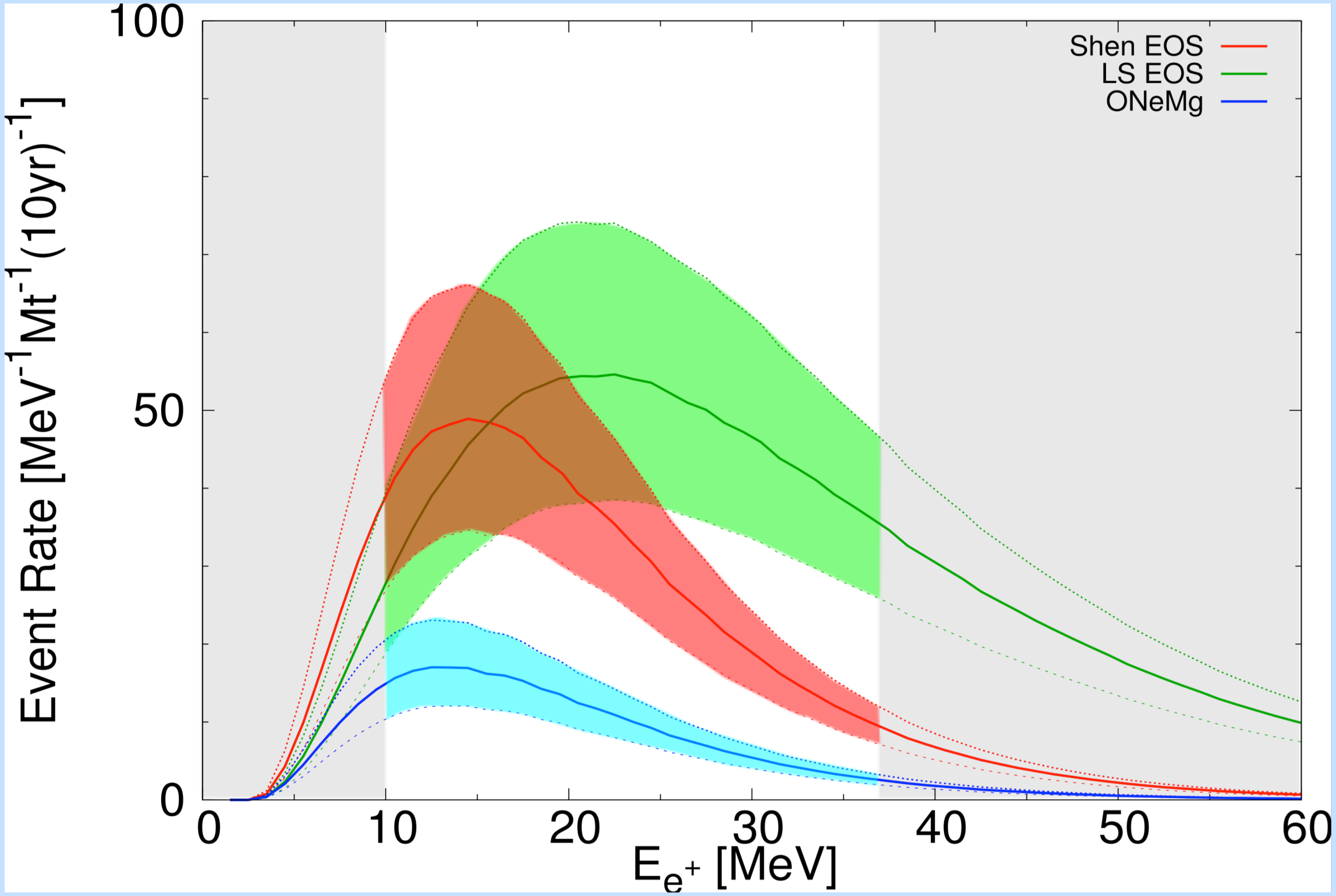
Mathews et al (2014)

Distinguishing Features



- Hyper-Kamiokande
- Assumes all of missing SNe are fSNe or ONeMg

Peak and spectrum shifts for:

- Equation of state
- Mass hierarchy
- Neutrino oscillations

Kajino et al (2014)

In conclusion (part 2)

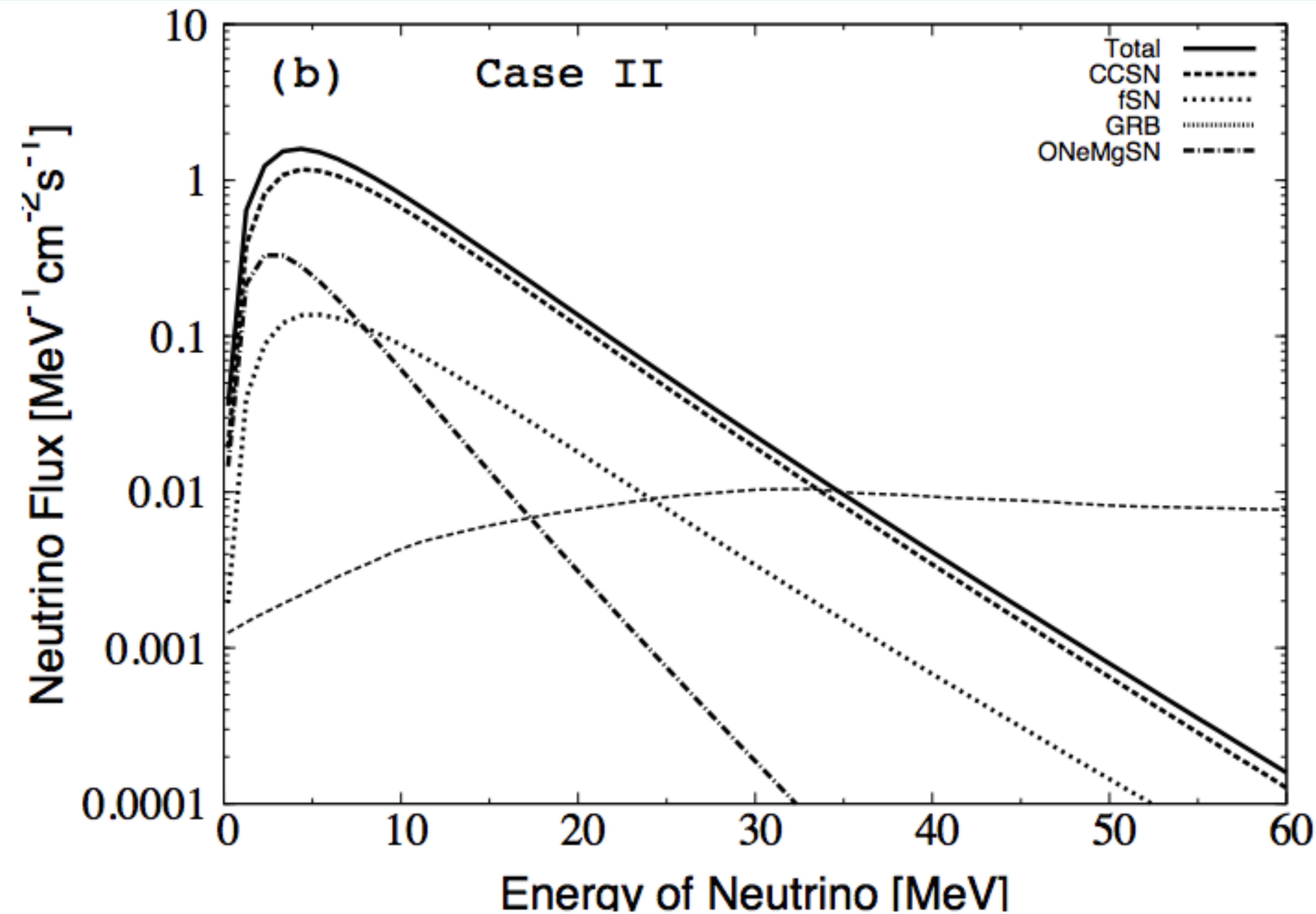
- Many uncertainties
  - Primarily from SN models

- Detecting the relic neutrino background may provide insight into:
  - Supernova rate problem
  - Nature of neutrinos
  - Supernova environment

Thank you!

Sterile Neutrinos:
arXiv:1405.6101
PhysRevD **90**, 103007 (2014)
In prep (2015)

Relic Neutrino Background:
arXiv:1405.0458
ApJ **790**, 115 (2014)
In prep (2015)



Mathews et al (2014)