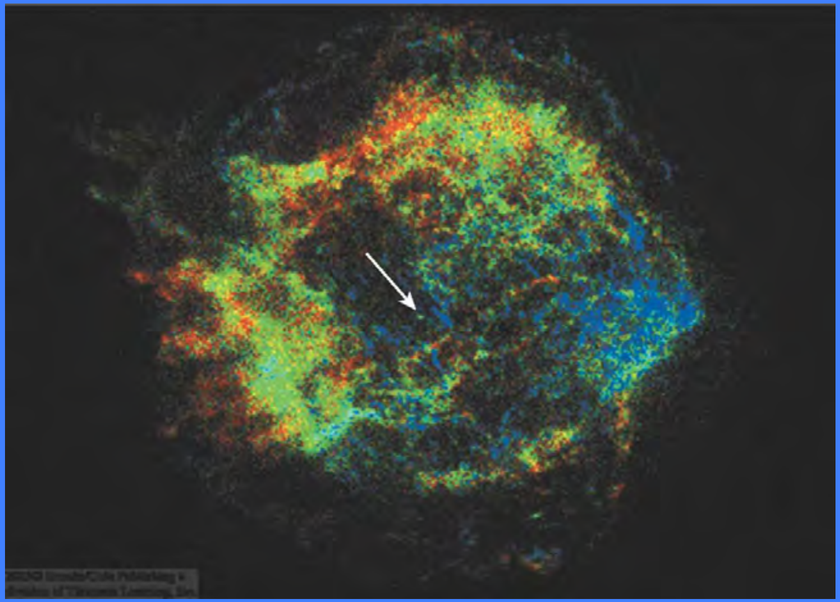
Neutrinos and Nucleosynthesis in Core Collapse Supernovae

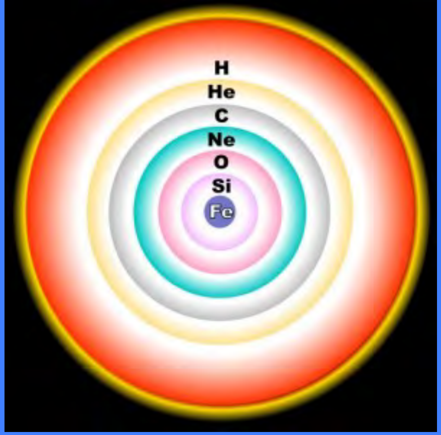
G. J. Mathews – Univ. of Notre Dame



International Symposium
on
"Physics and Astronomy of Neutron Stars and Supernovae"

National Astronomical Observatory of Japan

June 22, 2015



The Supernova Dilemma

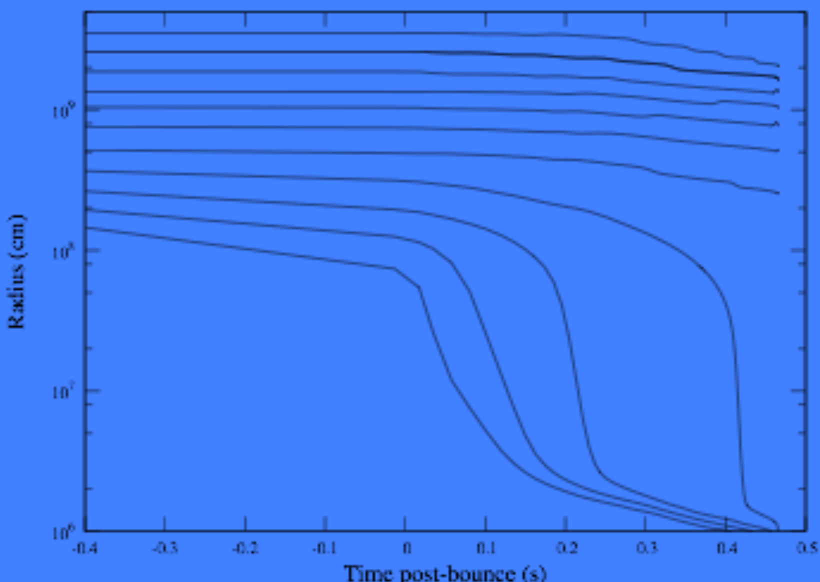
- Even after decades of numerical simulations the mechanism is not yet understood.
- E(neutron star) - E(iron core) ~ 10^{53} erg
- 10^{53} erg in neutrinos emitted over ~ 10 sec.
- Neutrino m.f.p ~ 0.2 km
- Neutrinos diffuse from the core
- How do neutrinos explode the star?

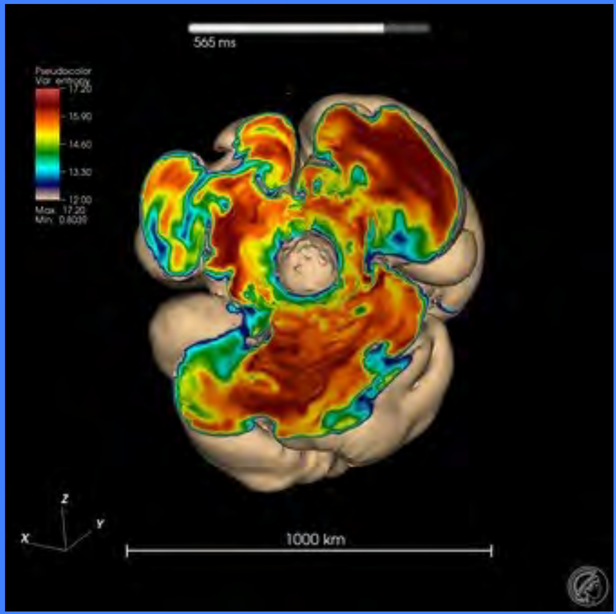
SPHERICAL GENERAL RELATIVISTIC
STELLAR CORE COLLAPSE
WITH GODUNOV TYPE METHODS

(A NEW SPHERICALLY SYMMETRIC GENERAL RELATIVISTIC HYDRODYNAMICAL CODE. J. V. Romero, J. Mª Ibañez, J. Mª Marti and J. A. Miralles. ApJ, 462,839)

Current Status

- Neutrinos alone can not induce an explosion in spherical symmetry
- Need 3D effects
  - Neutrino Heated Convection?
  - Standing Accretion Shock Instability?





http://www.rzg.mpg.de/services/visualization

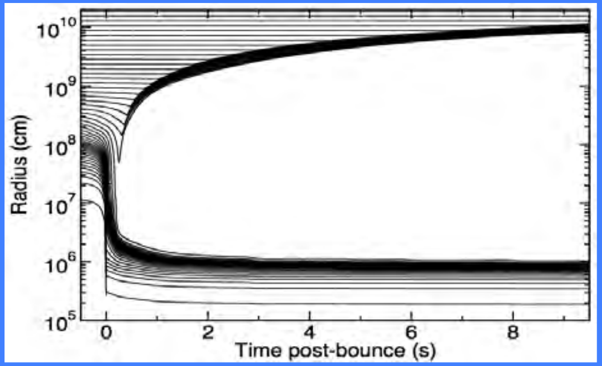
Premise of this talk

- Maybe neutrinos are telling us a message about the physics of how stars explode

- What are the messages?

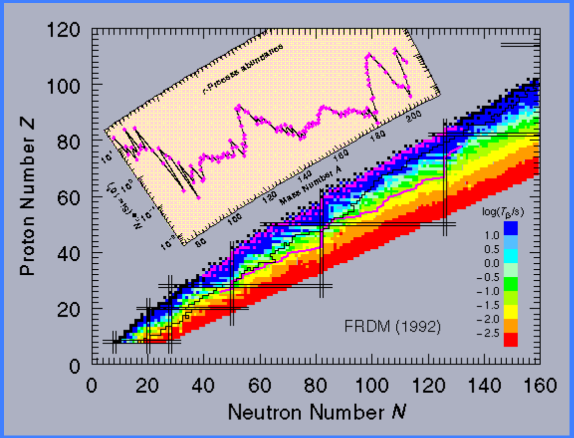
Supernova neutinos as messengers of:

1. Physics beyond the Standard Model: sterile neutrinos /dark matter?
   M. Warren, GJM et al. PRD (2014)



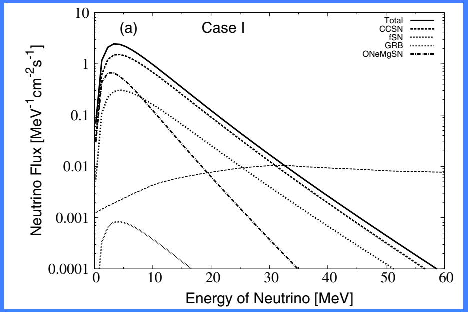
2. Nucleosynthesis of the r-process elements

S. Shibagaki et al., PRD (2014) Submitted
K. Nakamura et al .A&A (2015); IJMPE (2014)



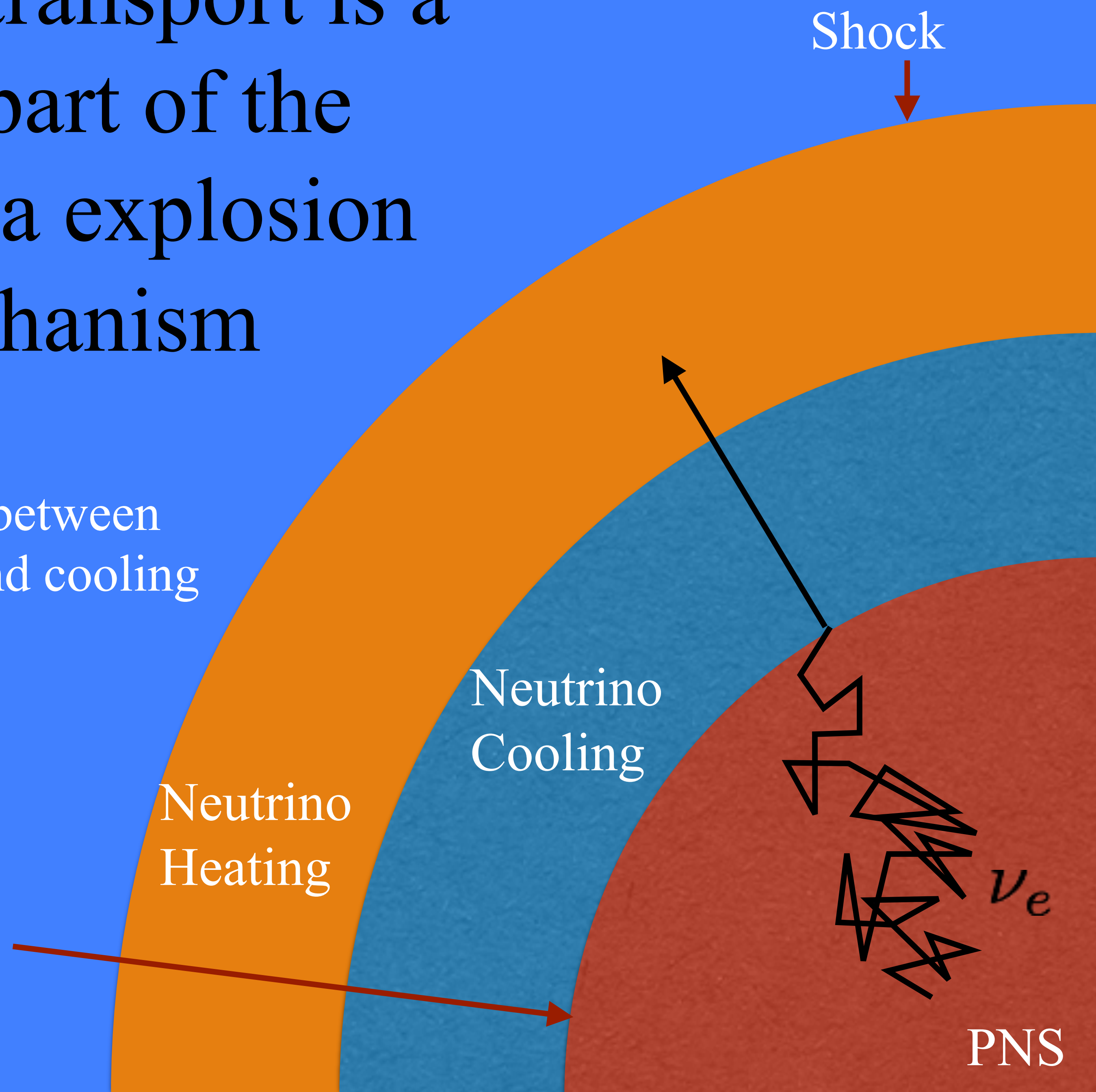
4. Relic neutino background and supernova neutrino temperatures

GJM, Warren, Hidaka,. Kajino, et al. ApJ (2014)



Neutrino transport is a crucial part of the supernova explosion mechanism

Delicate balance between neutrino heating and cooling



Neutinos affect the flow of mass-energy

$$T^{\mu\nu} = \begin{pmatrix} \frac{\rho(1+\varepsilon)}{a^2} & \frac{4\pi R^2 \rho \Phi_\nu}{a} & 0 & 0 \\ \frac{4\pi R^2 \rho \Phi_\nu}{a} & P(4\pi R^2 \rho)^2 & 0 & 0 \\ 0 & 0 & (P + W_\nu)/R^2 & 0 \\ 0 & 0 & 0 & (P + W_\nu)/R^2 \sin^2\theta \end{pmatrix}$$

$$\rho\varepsilon = \rho\varepsilon_M + E_\nu$$

$$P = P_M + P_\nu$$

$$W_\nu = \frac{(E_\nu - 3P_\nu)}{2}$$

$$E_\nu = \sum_1^6 \int F_i \, dE \, d\Omega_\nu$$

$$\Phi_\nu = \sum_1^6 \int F_i \cos(\theta) \, dE \, d\Omega_\nu$$

$$P_\nu = \sum_1^6 \int F_i \cos^2(\theta) \, dE \, d\Omega_\nu$$

Neutrinos and the flow of spacetime in core-collapse supernovae

General relativistic hydrodynamics

$$ds^2 = -a^2\left[1-\left(\frac{U}{\Gamma}\right)^2\right]dt^2 - \frac{2aU}{\Gamma^2}dR\,dt - \frac{dR^2}{\Gamma^2} + R^2(d\theta^2 + \sin^2\theta\, d\phi^2)$$

$$\Gamma = \left(1 + U^2 - \frac{2M}{R}\right)^{1/2}$$

$$T^{\mu\nu}{}_{;\,\nu} = 0$$

$$\frac{1}{a}\frac{\partial U}{\partial t} = -\frac{\Gamma}{\rho h}\left[\frac{1}{b}\frac{\partial P}{\partial m} + \frac{R^2\rho^2}{a}\frac{\partial}{\partial t}\left\{\frac{\Phi_\nu}{R^2\rho^2}\right\} - \frac{2\Gamma}{R}W_\nu\right)\right] - \frac{M}{R^2} - 4\pi RP \quad .$$

Neutrino Spectrum F_i

General Relativistic Boltzmann Equation

$$
\begin{aligned}
\frac{1}{a}\frac{\partial F_i}{\partial t} &= \frac{\mu\Gamma}{aR^2}\frac{\partial}{\partial R}(aR^2 F_i) - \Gamma\left(\frac{1}{aR} - \frac{\partial}{R}\ln a\right)\left(\frac{\partial}{\partial \mu}(F_i(1-\mu^2)\right) \\
&+ \frac{F_i}{a}\frac{\partial \ln \rho}{\partial R} + R\frac{\partial}{\partial R}\left(\frac{U}{R}\right)\left(\frac{\partial}{\partial \mu}\left[\mu(1-\mu^2)F_i\right] + \mu^2 q\frac{\partial F_i}{\partial q}\right) \\
&+ \frac{q}{a}\frac{\partial F_i}{\partial q}\frac{\partial}{\partial t}\left(\ln\frac{R}{a}\right) + \kappa_i \rho(B - F_i)\left(1 + e^{q/aT}\right)
\end{aligned}
$$

Linquist (1966)
Wilson & Mathews (2003)

$$
B \equiv g_i \left(\frac{q}{a}\right)^3 \frac{1}{e^{q/aT} + 1}
$$

Neutrino collision terms

Neutrino Interactions

$$\frac{1}{a}\frac{\partial \epsilon_M}{\partial t} = -P_M \frac{1}{a}\frac{\partial}{\partial t}\left(\frac{1}{\rho}\right) - \frac{1}{\rho}\sum_{i=1}^{6}\int \Lambda_i dE d\Omega_\nu$$

Internal Energy

$$\frac{\rho}{m_b}\frac{1}{a}\frac{\partial Y_e}{\partial t} = -\sum_i (\Lambda_i - \bar{\Lambda}_i)\frac{dq}{q} d\Omega_\nu$$

Lepton Number conservation

Charged-current Interactions:

Electron Capture

$$\nu_e + n \rightleftharpoons e^- + p \quad ,$$

$$\nu_e + A(Z,N) \rightleftharpoons e^- + A(Z+1, N-1) \quad ,$$

Electron Scattering

$$\nu_e + e^- \rightleftharpoons e^- + \nu_e \quad ,$$

$$\bar{\nu}_e + e^- \rightleftharpoons e^- + \bar{\nu}_e \quad ,$$

Annihilation

$$\nu_e + \bar{\nu}_e \rightleftharpoons e^- + e^- \quad ,$$

Neutral-current Interactions:

Scattering

$$\nu_e + e^- \rightleftharpoons e^- + \nu_e \quad ,$$

$$\nu_e + A(Z,N) \rightleftharpoons \nu_e + A(Z,N) \quad ,$$

$$\nu_e + p \rightleftharpoons \nu_e + p \quad ,$$

$$\nu_e + n \rightleftharpoons \nu_e + n \quad ,$$

Annihilation

$$\nu_e + \bar{\nu}_e \rightleftharpoons e^- + e^- \quad ,$$

Neutrino-nucleon scattering

$$\frac{d\sigma_0}{d\Omega} = \frac{G^2\epsilon_\nu^2}{4\pi^2}\left[c_v^2(1+\cos\theta) + c_a^2(3-\cos\theta)\right]$$

Corrections - Horowitz (2002)

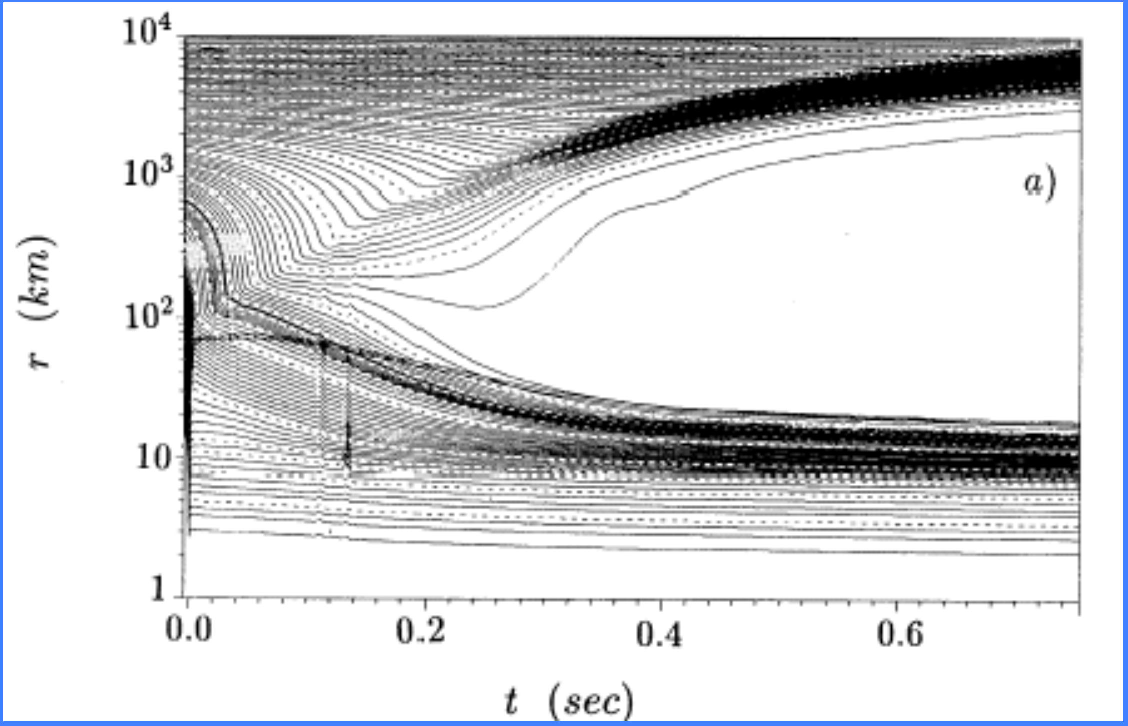
		Correction
1.		Phase space
2.		Matrix element
	a.	recoil
	b.	weak magnetism
	c.	form factors
	d.	strange quarks
3.		Pauli blocking
4.		Fermi/thermal motion of initial nucleons
5.		Coulomb interactions
6.		Mean field effects
7.		NN Correlations in RPA
8.		NN Correlations beyond RPA
9.		Meson exchange currents
10.		Other components such as hyperons
11.		Other phases such as meson condensates or quark matter
12.		Corrections from superfluid/ superconductor pairing
13.		Nonuniform matter
14.		Magnetic field effects

Is there more?

- EOS effects
- Coherent neutrino scattering?
- Neutrinos from QCD phase transition?
- Neutrino oscillations?
- Oscillations with sterile neutrinos?
- …..

EoS Canundrum in Core Collapse

- Want soft EoS in SNe => higher central core densities, neutrino fluxes, temperature
- Heavy-Ion data favor a soft EoS
- Want stiff EoS in cold NS => max mass > 2 $M_{\odot}$



Regions of the Hadronic EoS

Below Nuclear Matter density

Reaction Network

=> NSE

=> Nuclear pasta

Soft

Above Nuclear Matter density

=> pions

=> Lambdas?

=>Strange matter?

3-body repulsion

Pions Soft at high T

Transition to Quark Gluon Plasma?

⇒Coexistence

⇒QGP

⇒CSC

Soft again?

Stiff

NDL Nuclear Matter EoS

Free Energy

$$f = f_{skyrme} + f_{asym} + f_{therm}$$

Volume

$$f_{skyrme} = \frac{\hbar^2}{2m}\tau + \frac{3}{8}t_0 n + \frac{3}{8}t_{1,2}\tau n + \frac{1}{16}t_3 n^{\sigma+1}$$

Includes 2-body and 3-body terms

$K_0 = 240 \pm 10$ MeV

$n_0 = 0.16 \pm 0.01$ fm^{-3}

$$\tau = \frac{3}{5}\left(\frac{3\pi^2}{2}\right)^{2/3} n^{2/3}$$

Asymmetry

$$f_{asym} = = (1 - 2Y_p)^2 S_0(n); \quad S_0(n) \approx S_0 + \frac{L}{3}(\eta - 1) + \frac{K_{sym}}{18}(\eta - 1)^2$$

Thermal

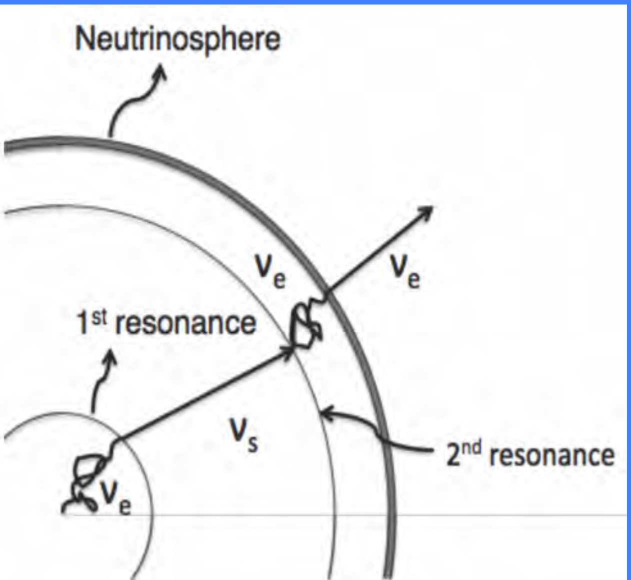
$$f_{therm} = F_{Th}(\rho, T) = \Theta(\rho, t) - \Theta(\rho, 0)$$

$$\Theta(\rho, t) = \sum_{i=N,\Delta} \int \frac{4\pi g_i dp_i p_i^2}{h^3}\left(\frac{\mu_i}{D_i} - kT \ln(D_i)\right)$$

Sterile Neutrino Dark Matter and Core Collapse Supernovae

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

PRD, 90, 103007 (2014)   arXiv:1405:6101



What are sterile neutrinos?

- Proposed fourth neutrino flavor
- Minimal extension of the Standard Model

νMSM

$$\mathcal{L} = \mathcal{L}_{SM} + i \bar{N}_I \partial_\mu \gamma^\mu N_I - \left(F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + h.c. \right)$$

Can explain active neutrino masses and mixings

$$(m_\nu)_{\alpha\beta} = - \sum_{I=1}^{\mathcal{N}} (M_D)_{\alpha I} \frac{1}{M_I} \left(M_D^T \right)_{I\beta},$$

Sterile Neutrino Dark Matter?

- Decaying dark matter candidate
- Interaction strength with normal matter

$$\theta G_F$$

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

$$\Gamma_{N_1 \rightarrow \gamma\nu} = \frac{9\alpha G_F^2}{1024\pi^4} \sin^2(2\theta_1) M_1^5 \simeq 5.5 \times 10^{-22} \theta_1^2 \left[\frac{M_1}{\mathrm{keV}}\right]^5 \mathrm{s}^{-1}$$

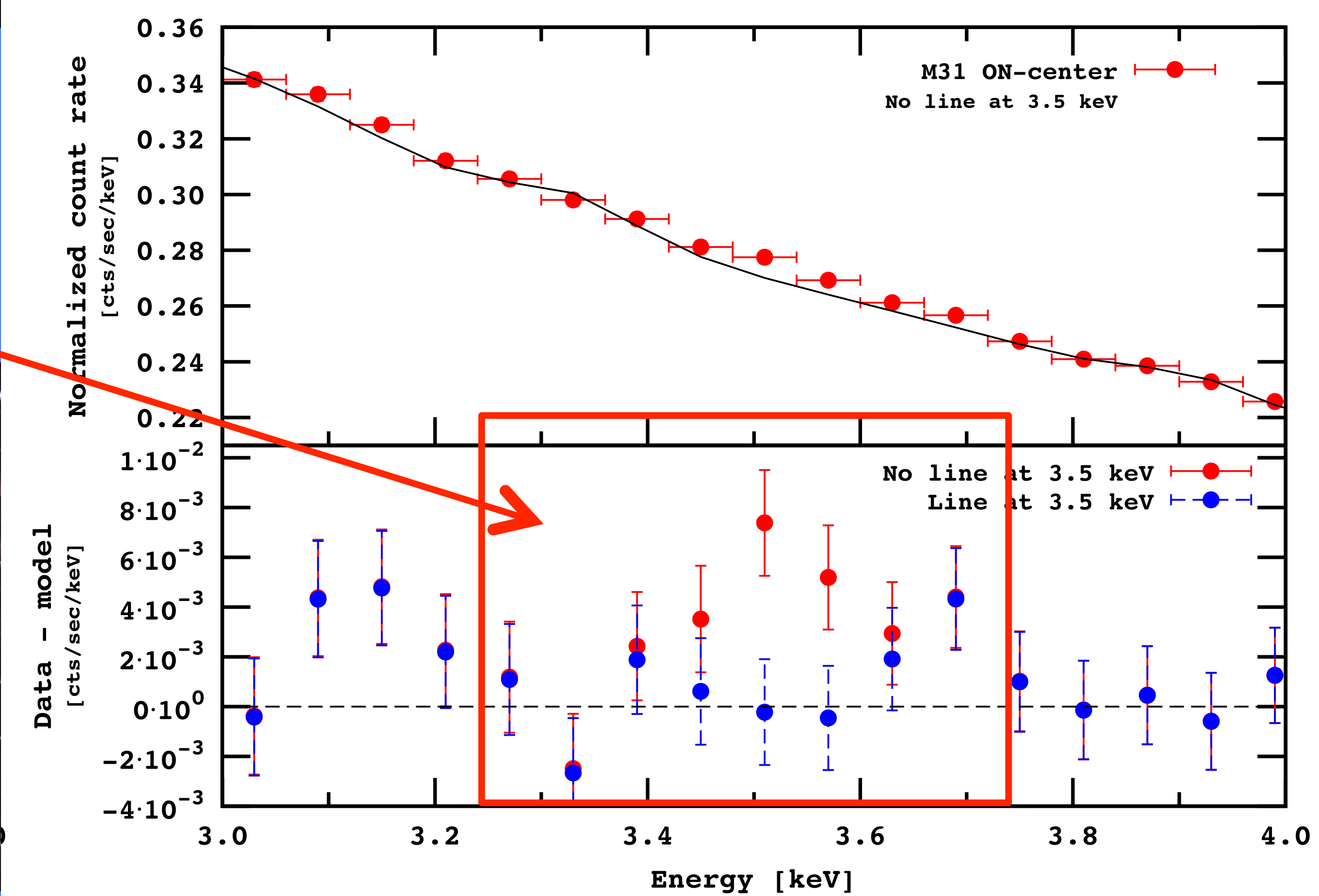
How are sterile neutrinos observable?

- Oscillations
  - Decay/Annihilation
  - Atmospheric Neutrinos
  - Anomalous LSND results?
  - <u>Affect on supernova explosion</u>

Evidence of 3.5 keV line from Andromeda and the Perseus Cluster

Boyarsky et al. (2014) arXiv:1402.4119

$$\nu_s \to \gamma + \nu_\alpha$$



Constraints on Sterile Neutrino Dark Matter

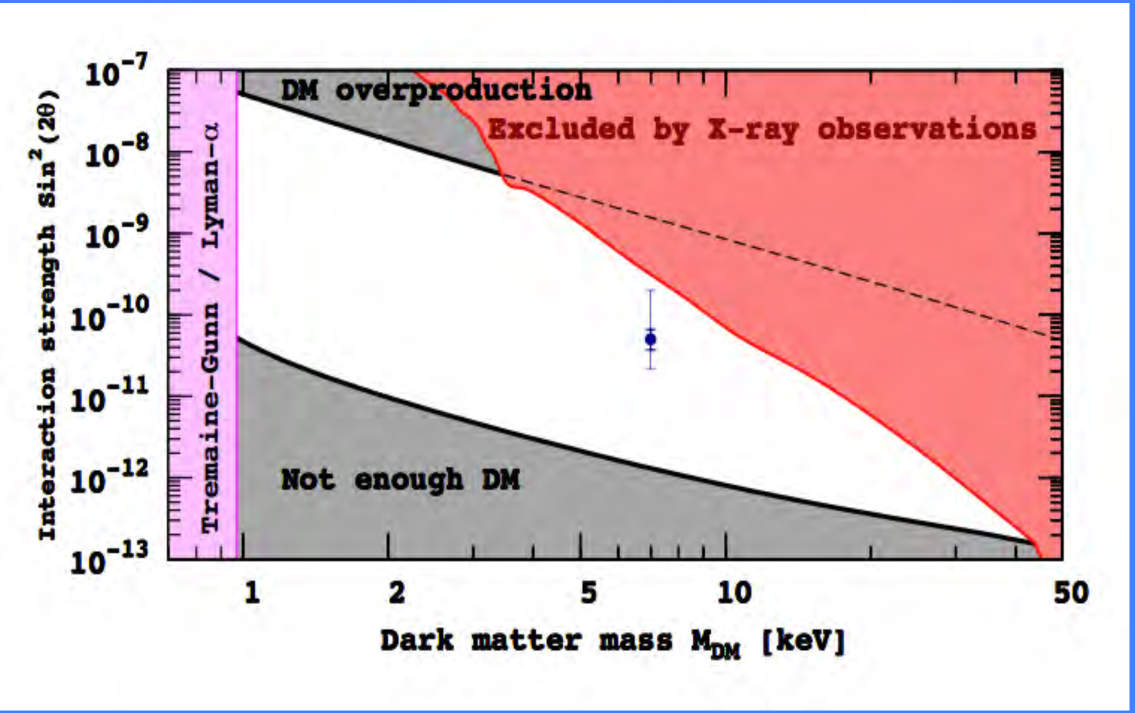
Boyarsky et al (2014)

Decaying sterile neutrinos

$$\nu_s \to \gamma + \nu_\alpha$$

Assume dark matter is 100% sterile neutrino

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



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

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

Sterile neutrinos in core-collapse supernovae

M. Warren, M. Meixner, G. Mathews
J. Hidaka, and T. Kajino
PRD, 90, 103007 (2014)   arXiv:1405:6101

Is there more?

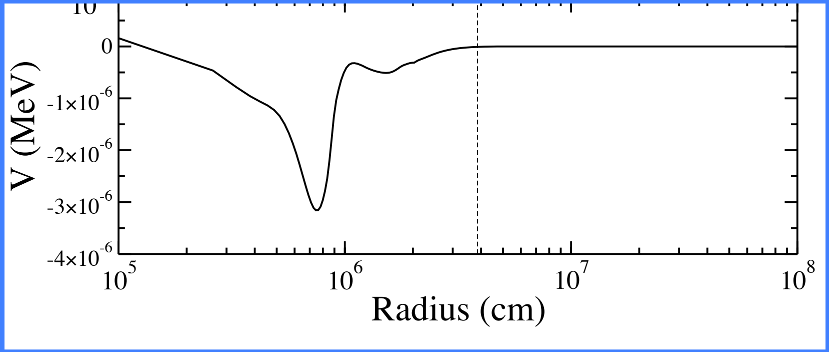
- Neutrino oscillations?
- Oscillations with sterile neutrinos?
- Coherent neutrino scattering?
- Neutrinos from QCD phase transition?
- …..
- …
- .

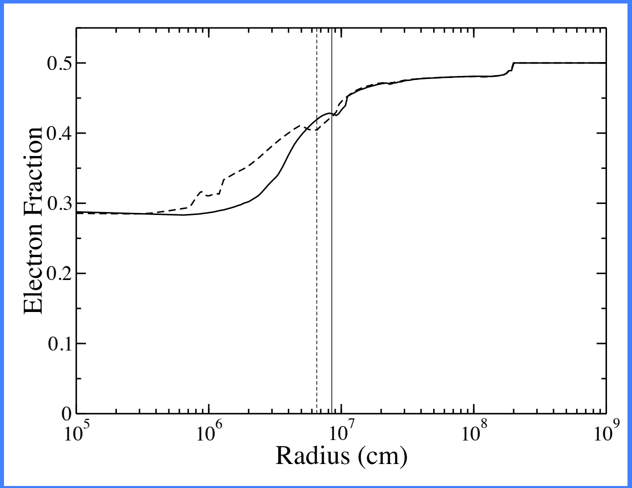
Matter-enhanced neutrino oscillations

Neutrinos experience a potential when moving through matter via interactions with electrons, nucleons, other neutrinos…

$$V(r) = \sqrt{2} G_F \left((n_{e^-} - n_{e^+}) + 2(n_{\nu_e} - n_{\bar{\nu}_e}) \right.$$
$$\left. (n_{\nu_\mu} - n_{\bar{\nu}_\mu}) + (n_{\nu_\tau} - n_{\bar{\nu}_\tau}) - n_n/2 \right)$$

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

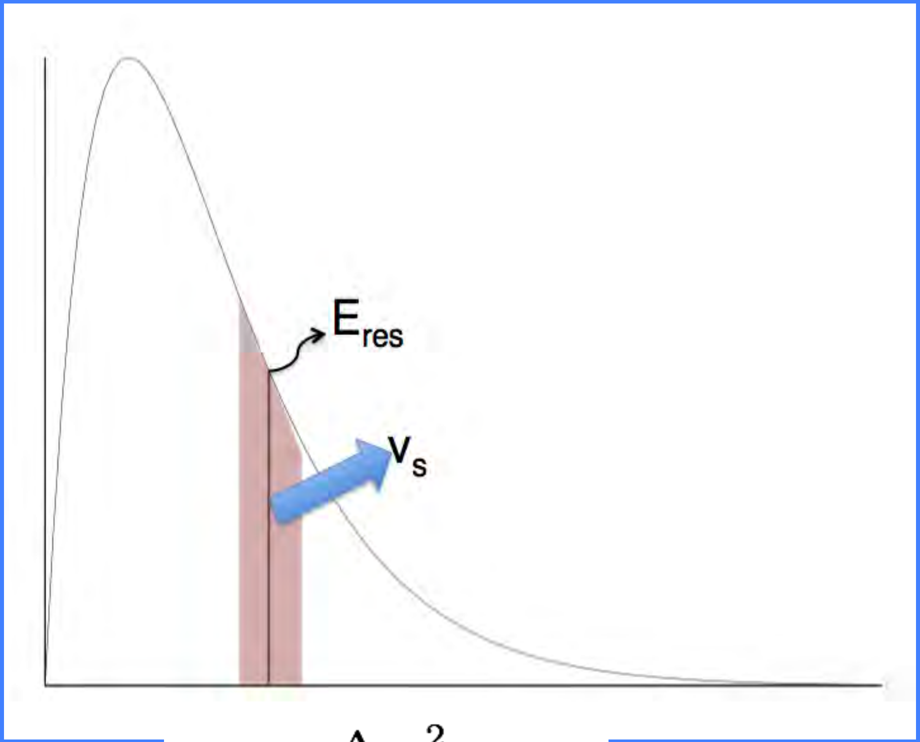




Matter-enhanced neutrino oscillations

Potential *difference* enhances oscillations

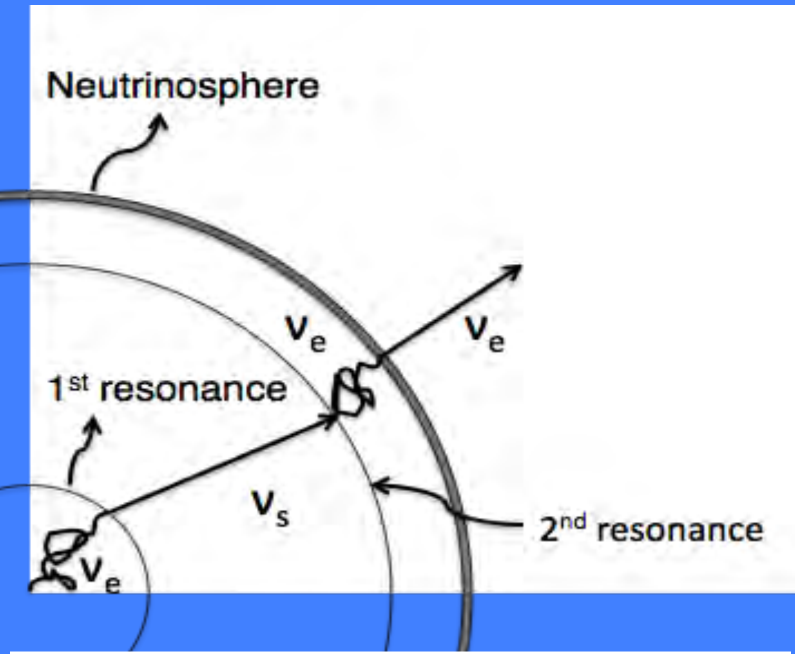
Resonance: *Maximal* mixing (even for small vacuum mixing angle)

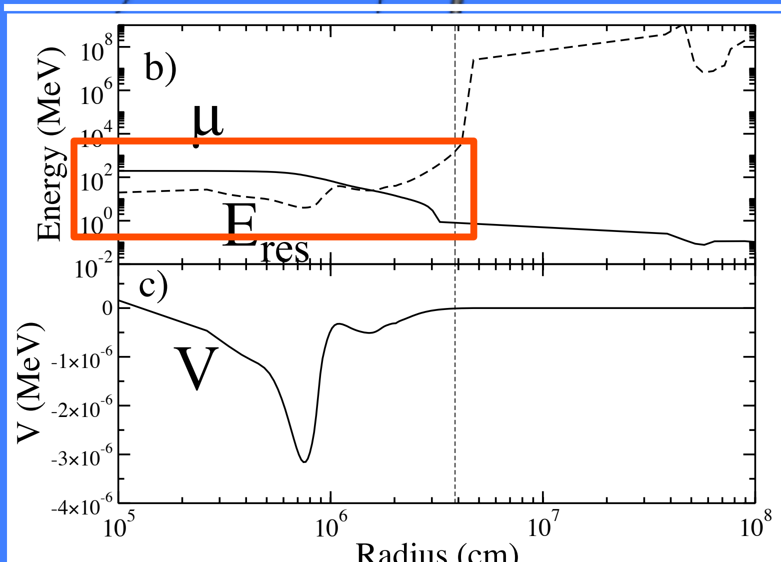


$$E_{res} = \frac{\Delta m_s^2}{2V_e}\cos 2\theta_s$$

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

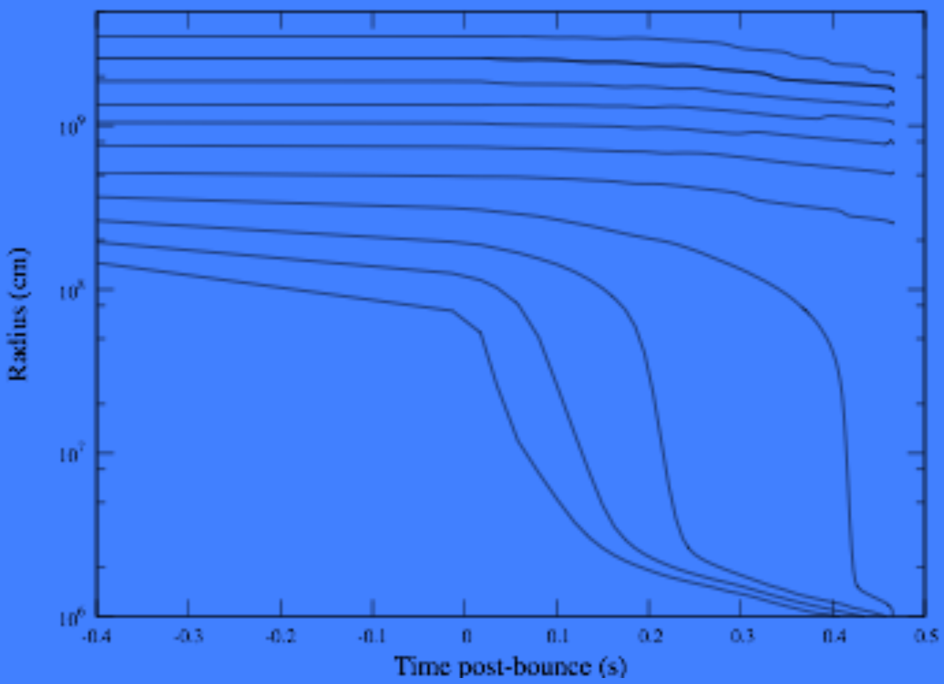
How sterile neutrinos affect the explosion



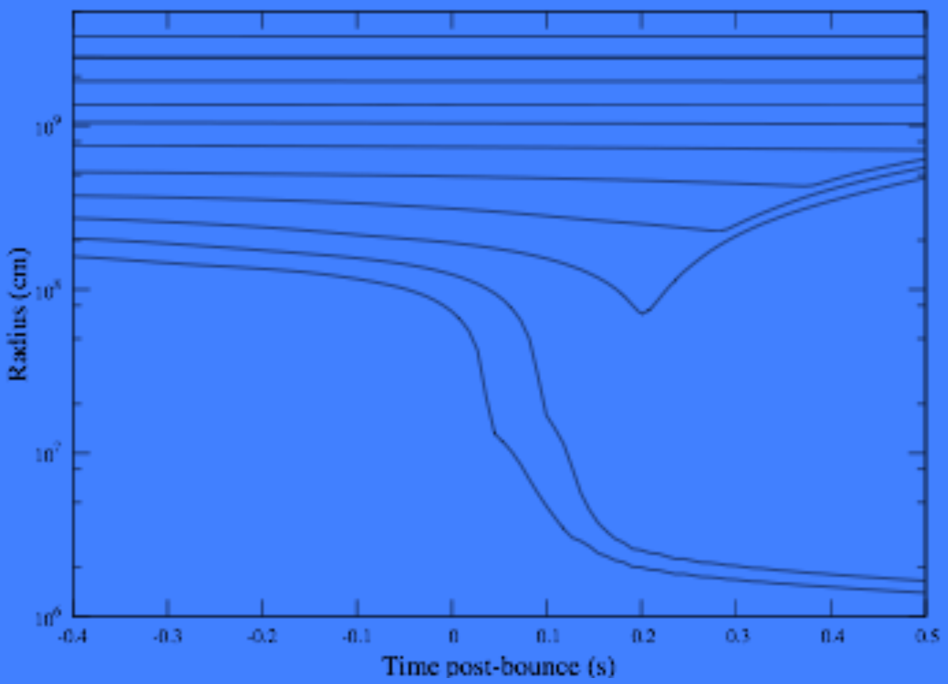


- Diffusion time greatly diminished as electron neutrinos transfrom to freely streaming sterile neutinos then back again
- Neutrino Luminosity = (Neutrino internal energy) / (Diffusion time)
- =>Enhanced Luminosity and heating near the neutrinosphere

Successful explosion in a model that would not otherwise explode



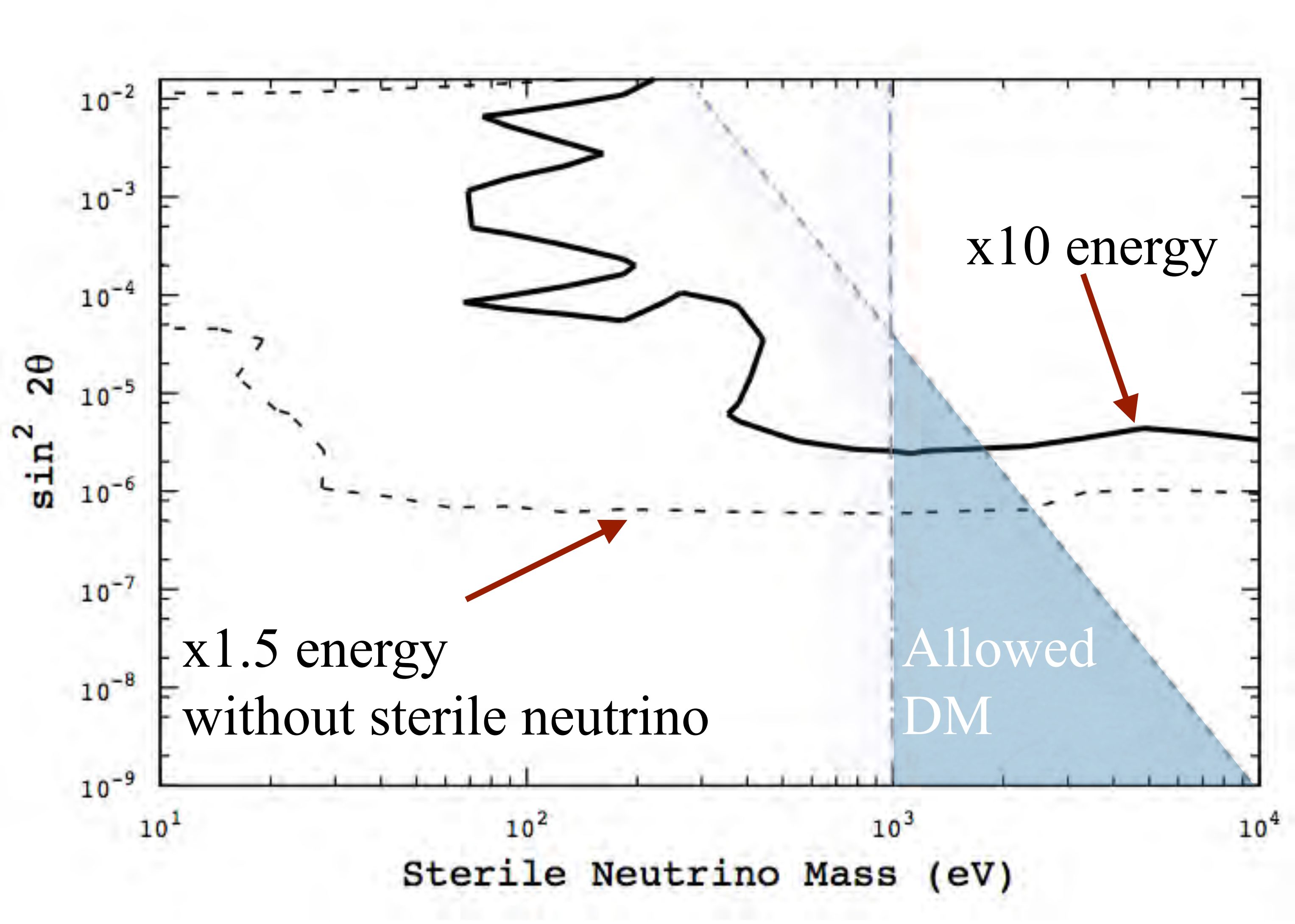
Without sterile neutrinos



With sterile neutrinos

M. Warren, Meixner, Mathews, Hidaka, and Kajino *PRD, 90, 103007 (2014)* *arXiv:1405:6101*

Enhancement of Explosion Energy



DM bounds from Boyarsky et al (2006)

Constraints on Sterile Neutrino Dark Matter

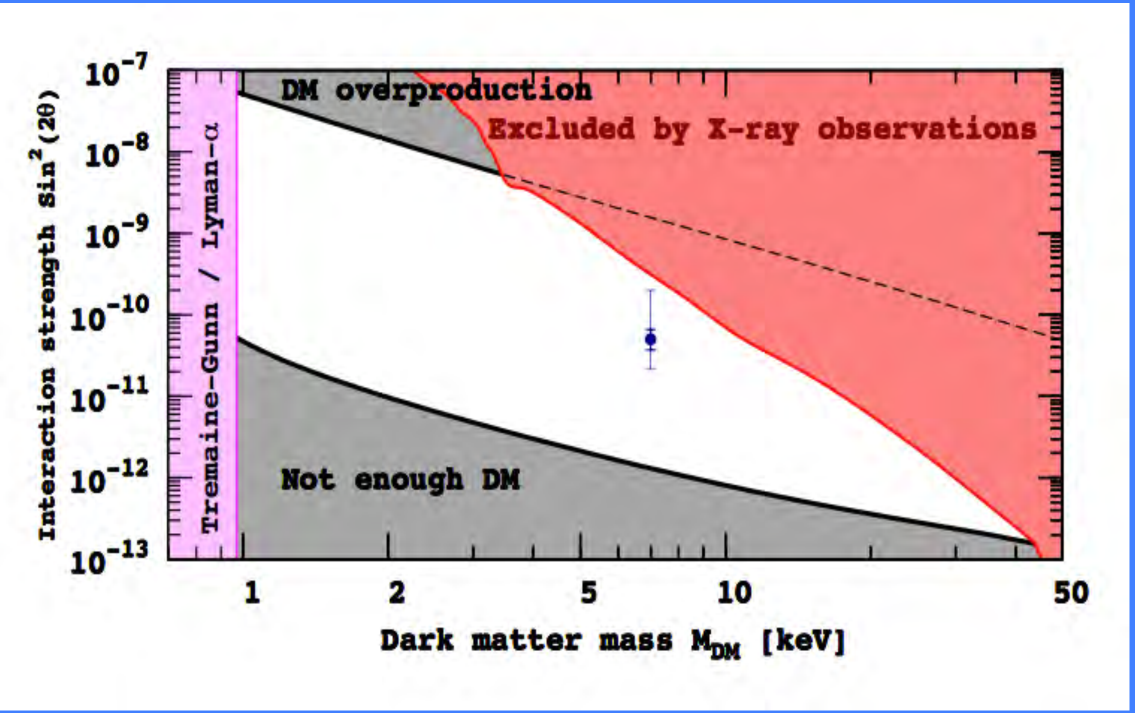
Boyarsky et al (2014)

Decaying sterile neutrinos

$$\nu_s \to \gamma + \nu_\alpha$$

Assume dark matter is 100% sterile neutrino

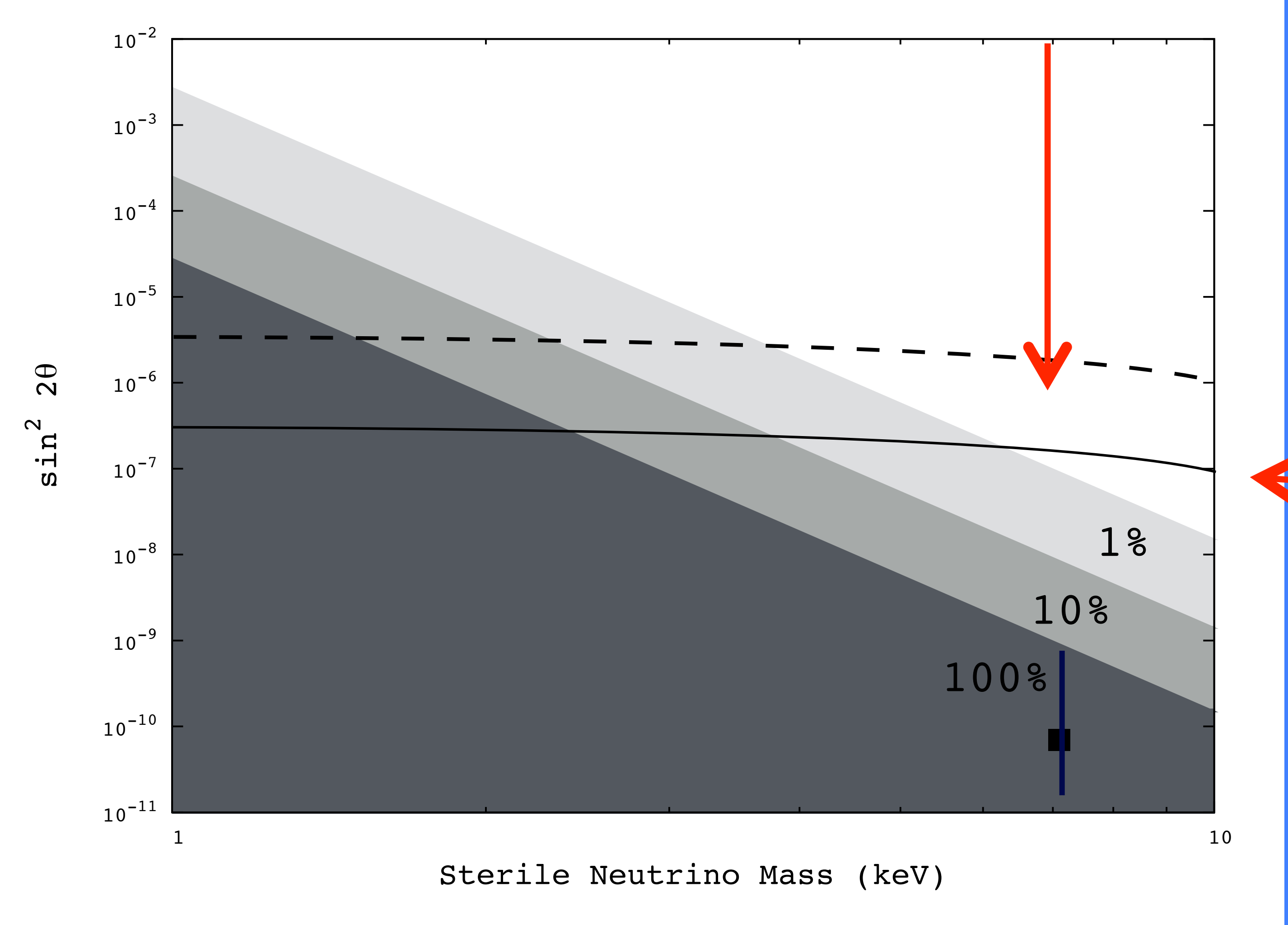
$$\Gamma_{\nu_s \to \gamma \nu_\alpha} \sim \sin^2 2\theta_s m_s^5$$



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

$m_s = 7.06 \pm 0.05$ keV

Dark Matter fraction in sterile neutrinos



Mixing needed to affect explosion

Fraction of DM

Analysis of Explosion Dynamics

Kinetic Energy

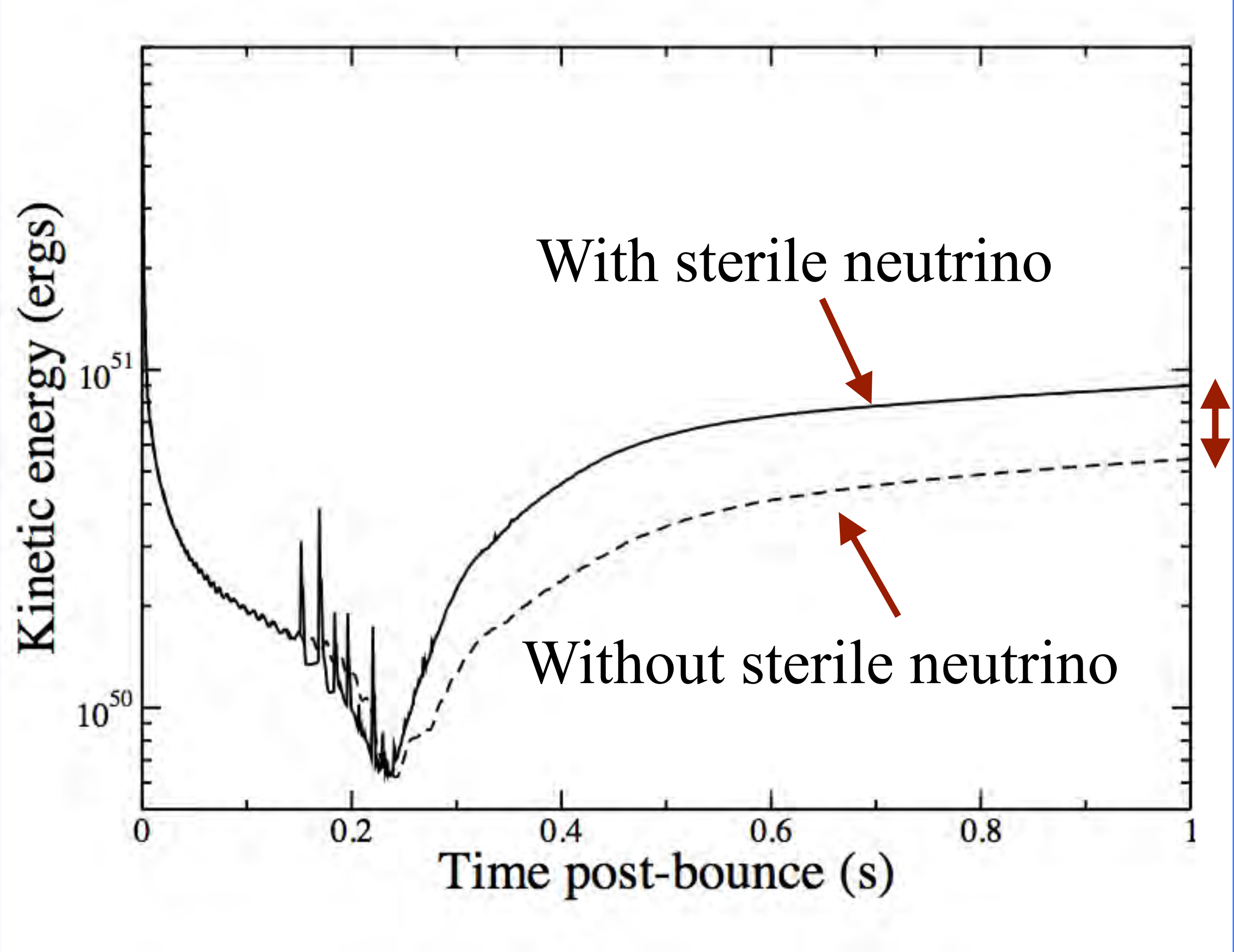
Neutrino light curve

Location of Neutrinosphere

Example:

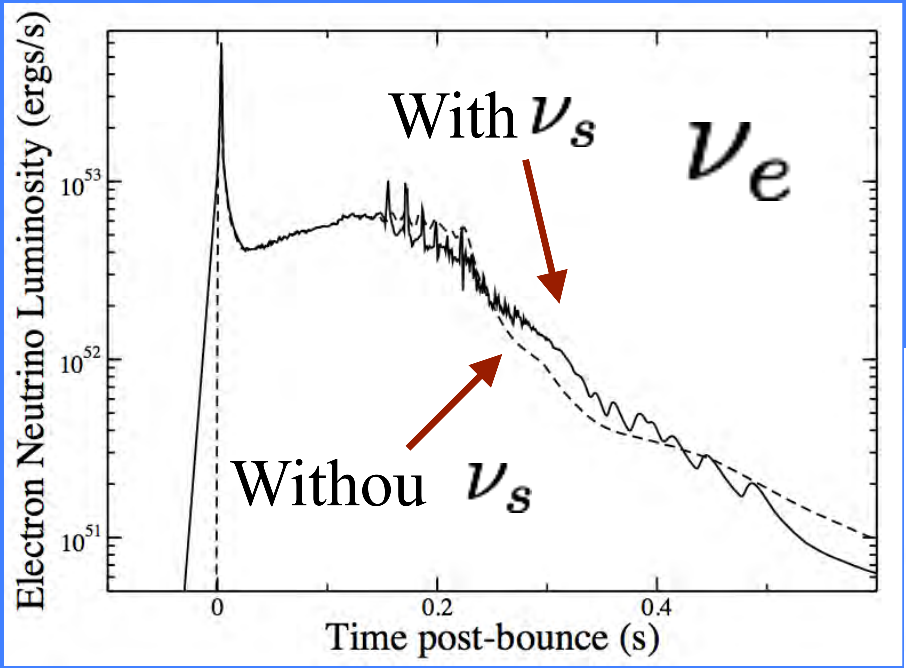
$$m_s = 5.0 \quad \text{keV}$$

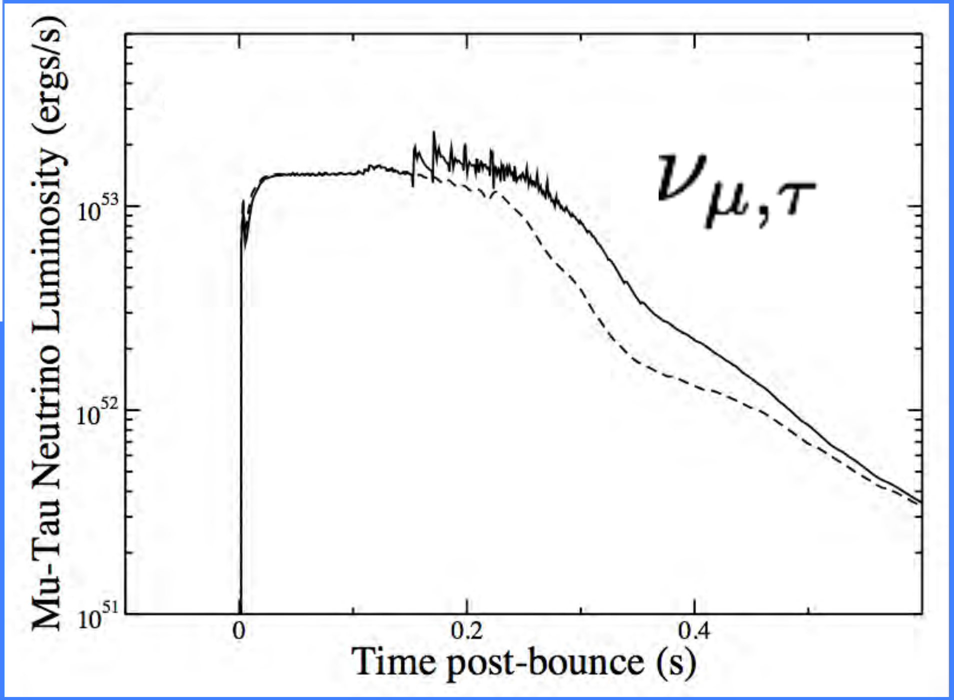
$$\sin^2 2\theta_s = 1.12 \times 10^{-5}$$

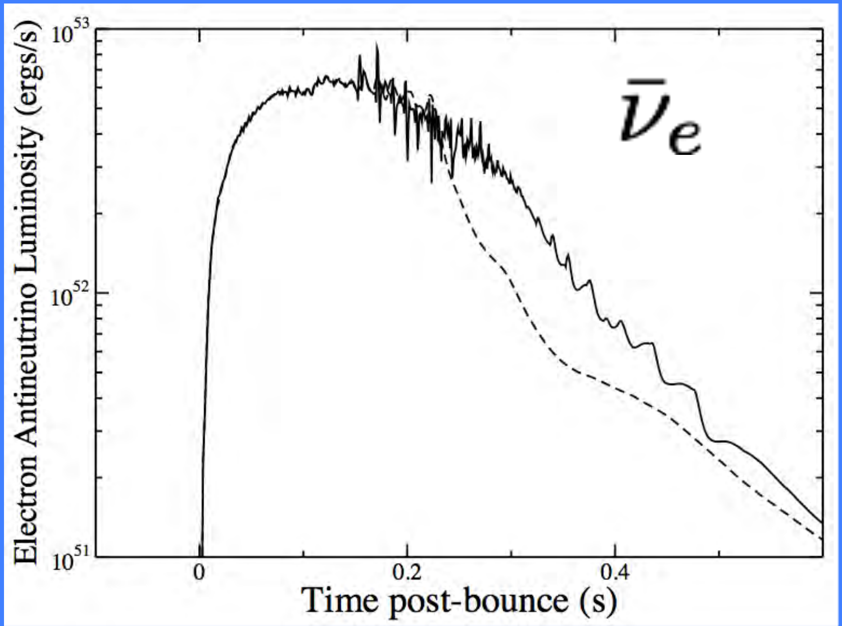


~1.3x enhancement

Observable Luminosities

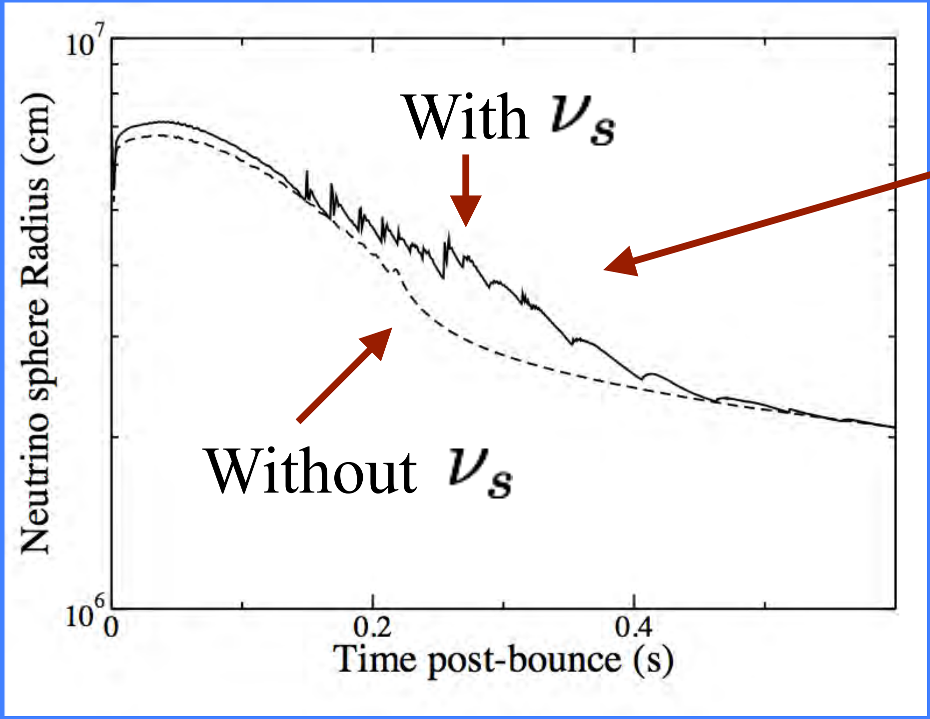




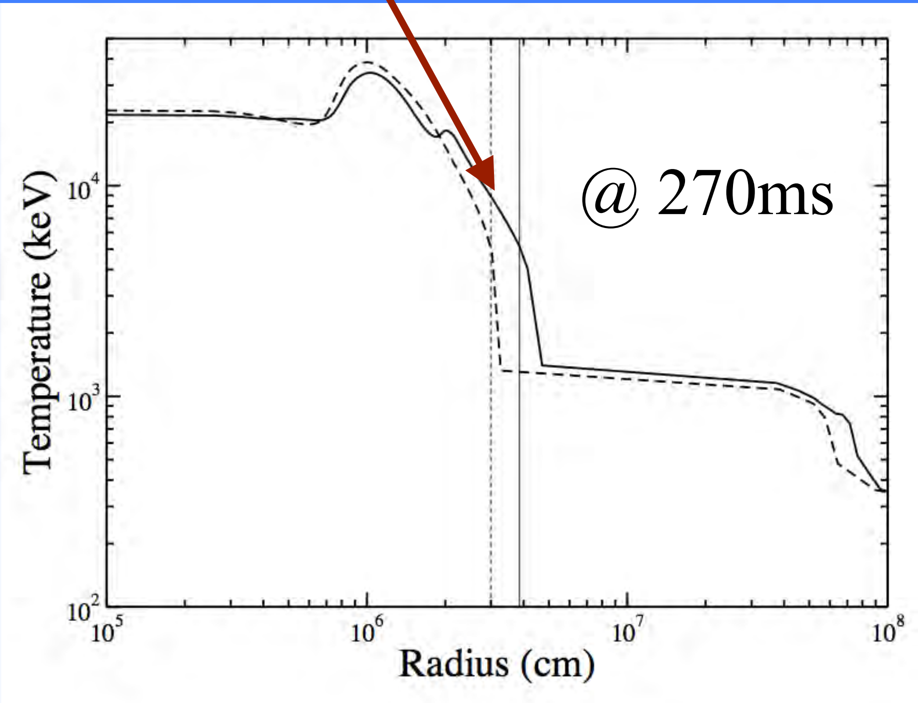


Episodic variation due to sudden decrease in diffusion time followed by depletion of spectrum

Expanded Neutrinosphere



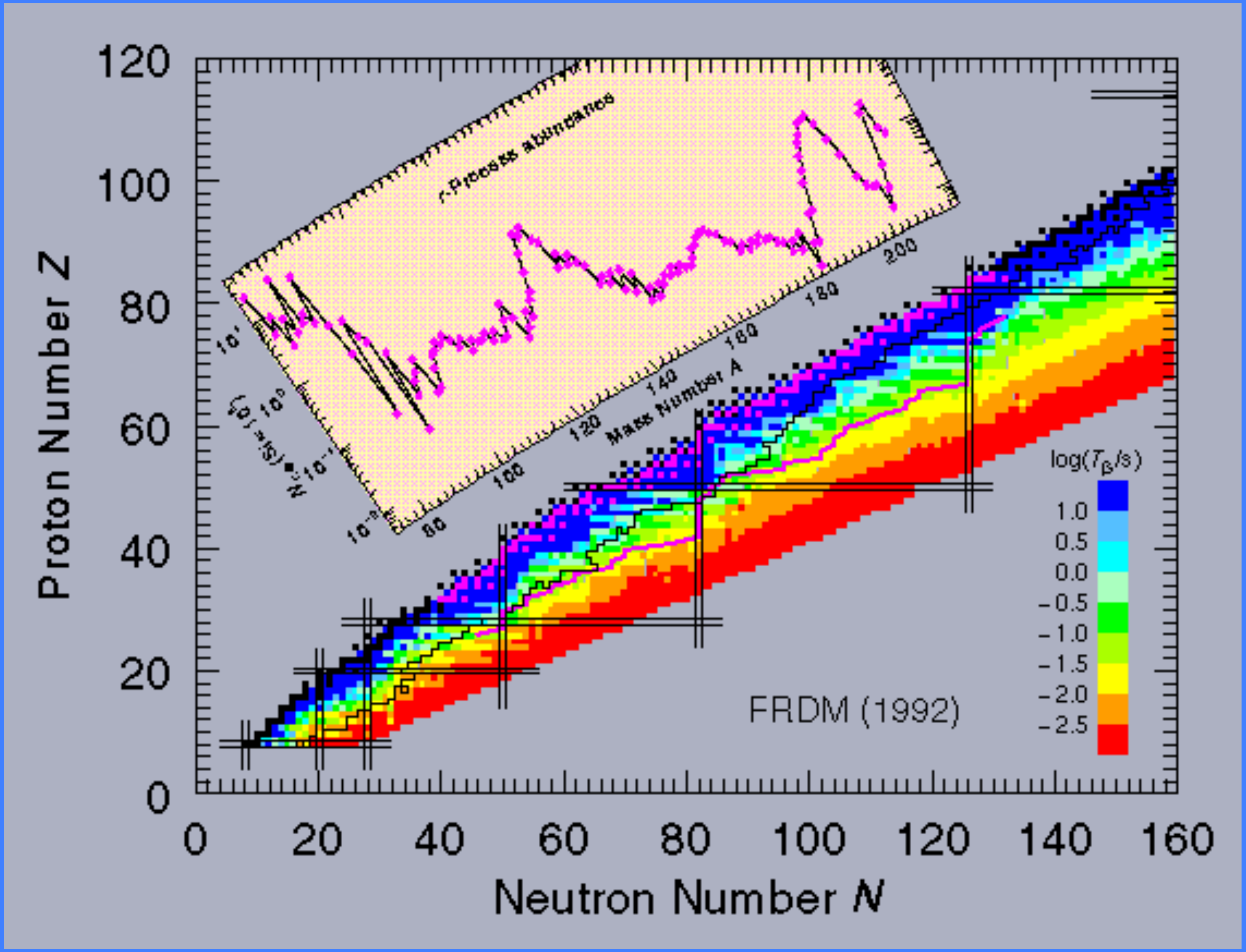
Neutrinosphere radius increased,
temperature unchanged



Summary

1. Sterile Neutrinos are a natural DM candidate
2. Supernova models don't explode
   (Or explode with too little energy…)
3. Sterile neutrinos can enhance explosion energies and lead to an explosion in models that would otherwise not explode
4. Effects on SN neutrino emission might be detectable

Supernova neutrinos and r-process nucleosynthesis

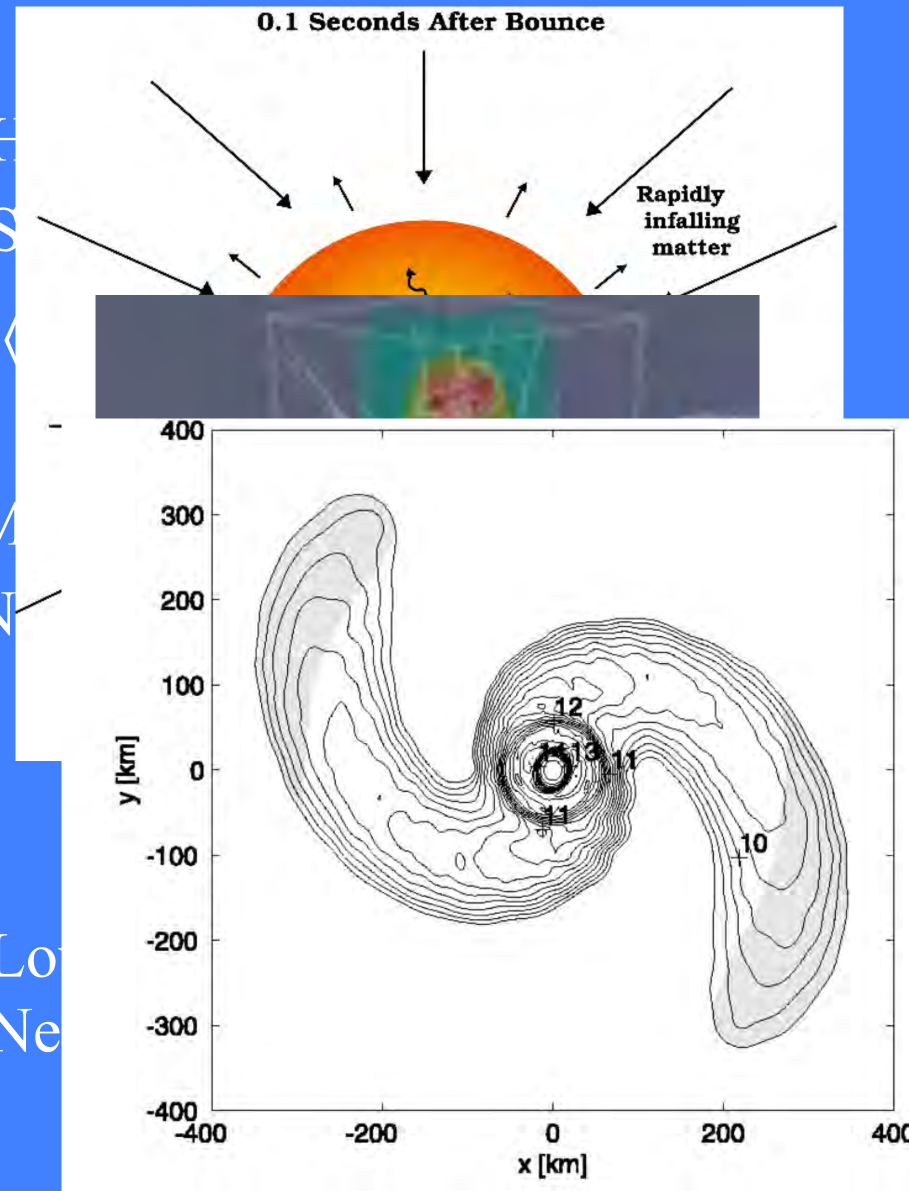


Models for the *r*-Process

Neutrino Driven Winds in the High Entropy Supernova Bubble

Ejection of neutronized core material in a low-mass supernovae or MHD jets

Neutron star mergers



There are large differences in the emitted neutrino energies and spectra depending upon how one solves for the neutrino transport

Fischer et al, PRD (2012)
Roberts, Reddy & Shen (2012)

This dramatically affects the nucleosynthesis of heavy elements in the r-process

Nakamura, Sato, Harikae, Kajino, Mathews, IJMPE, 22, 1330022 (2013)
Shibagaki, Kajino, Chiba, Mathews, Nishimura, Lurosso, PRD, (2014) Submitted

Best recent models have $Y_e \sim 0.5$ in the neutrino wind driven r-rrocess

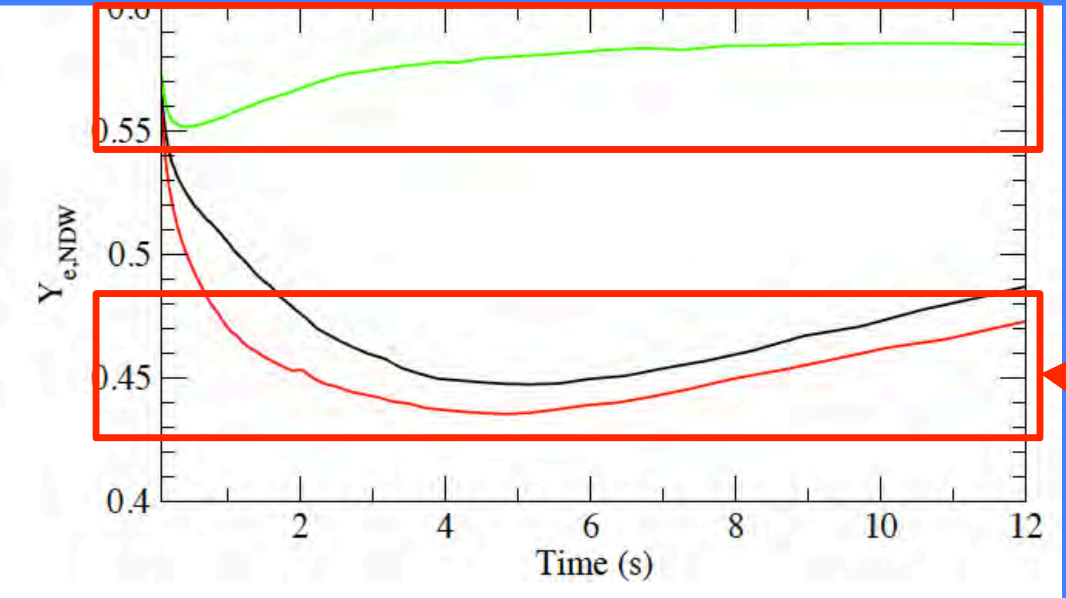
$$p + \bar{\nu}_e \rightarrow n + e^+$$

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

$$\Delta = m_n - m_p = 1.2935 \text{ MeV}$$

$$Y_{e,\mathrm{NDW}} \approx \left[1 + \frac{\dot{N}_{\bar{\nu}_e} \langle \sigma(\epsilon)_{p,\bar{\nu}_e} \rangle}{\dot{N}_{\nu_e} \langle \sigma(\epsilon)_{n,\nu_e} \rangle} \right]^{-1}$$

- $Y_e = p/(n + p) \sim 0.5$
- Few excess neutrons
- => no r-process

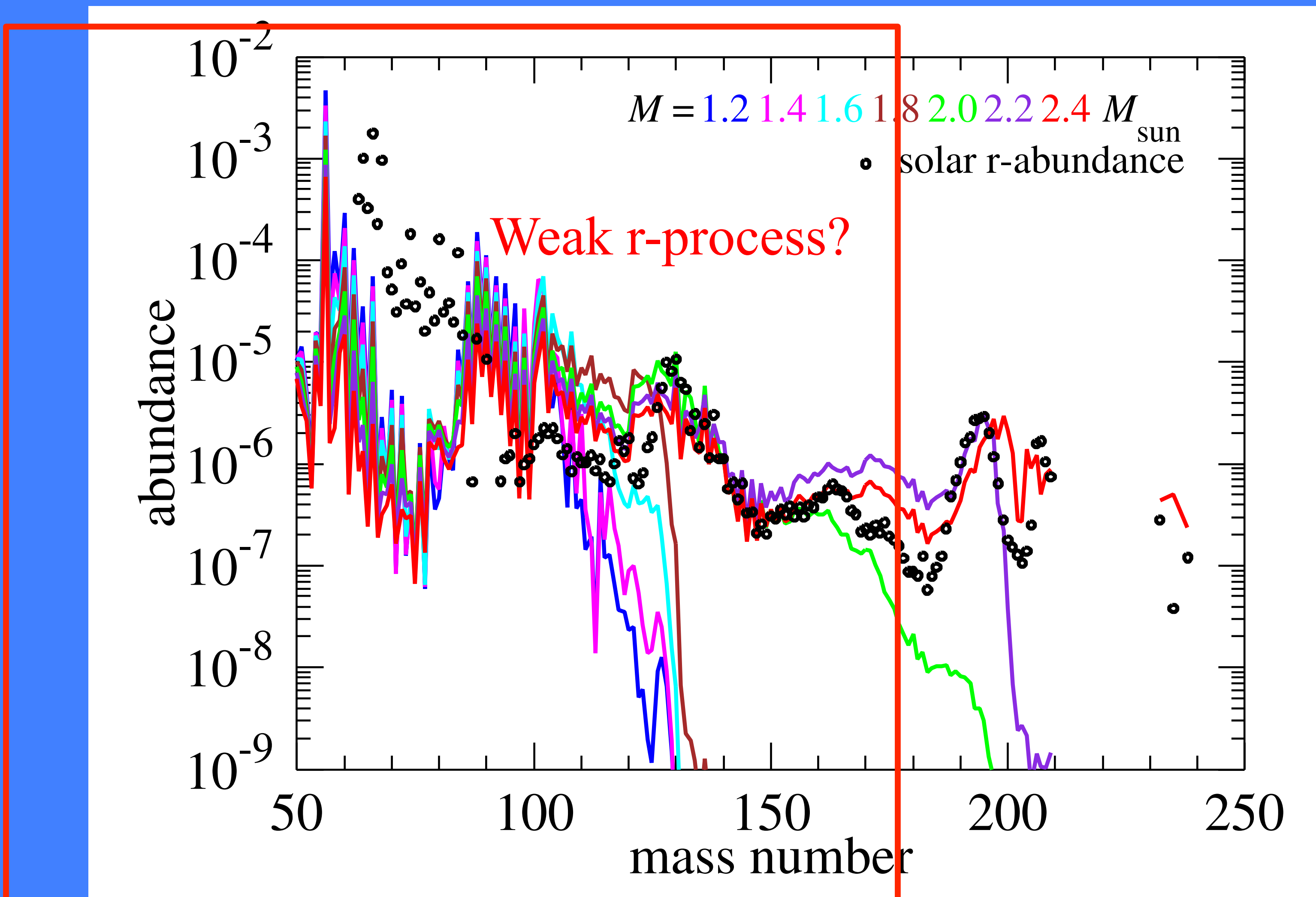


Fischer et al.(2012)

Roberts & Reddy(2012)

Not enough neutrons for the heaviest *r*-process nuclides

S. Wanajo, ApJL, L22 (2013)

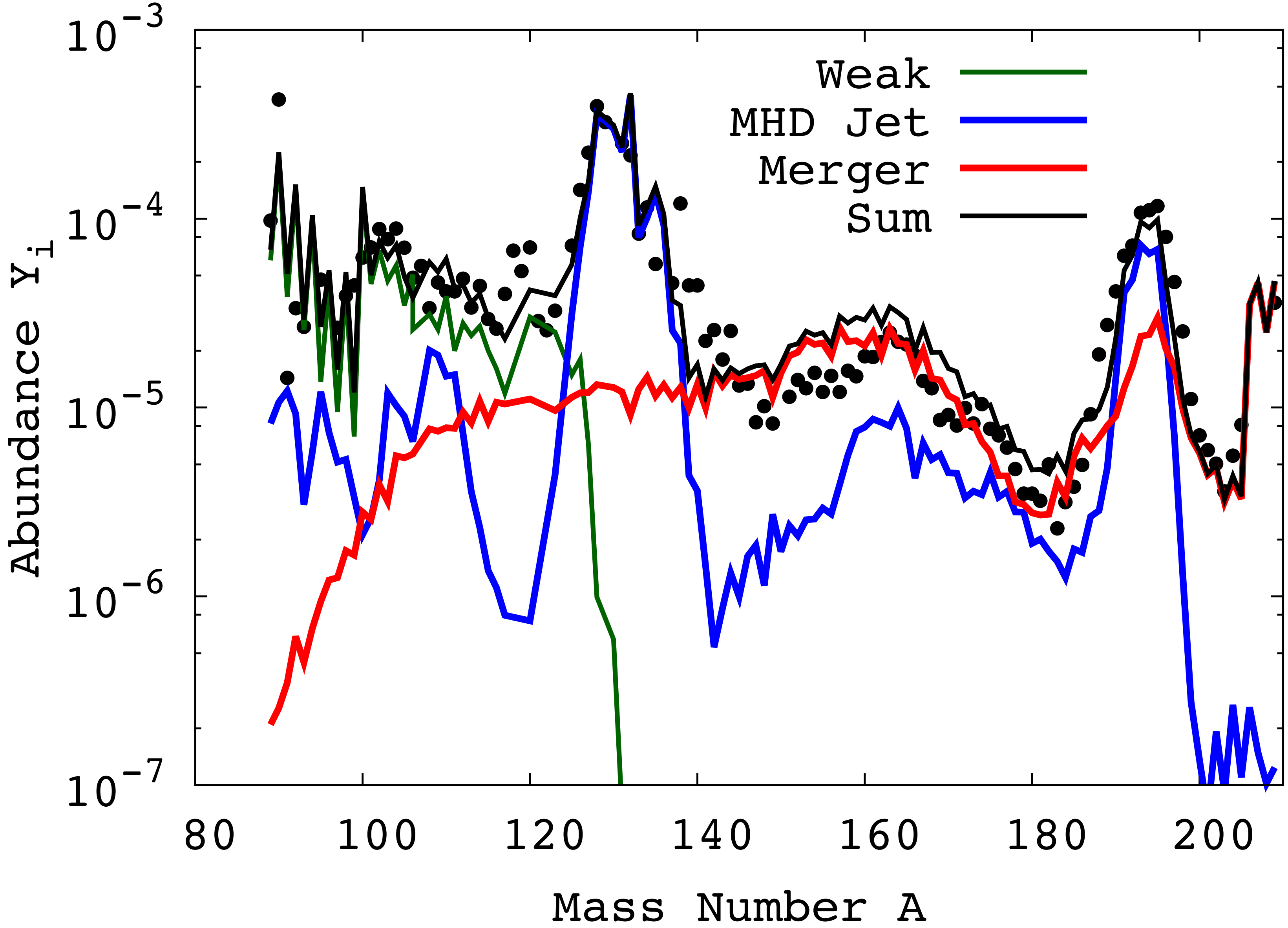


Most likely the NDW only produces the light r-process elements

What can make heavier r-process elements?

MHD jets?

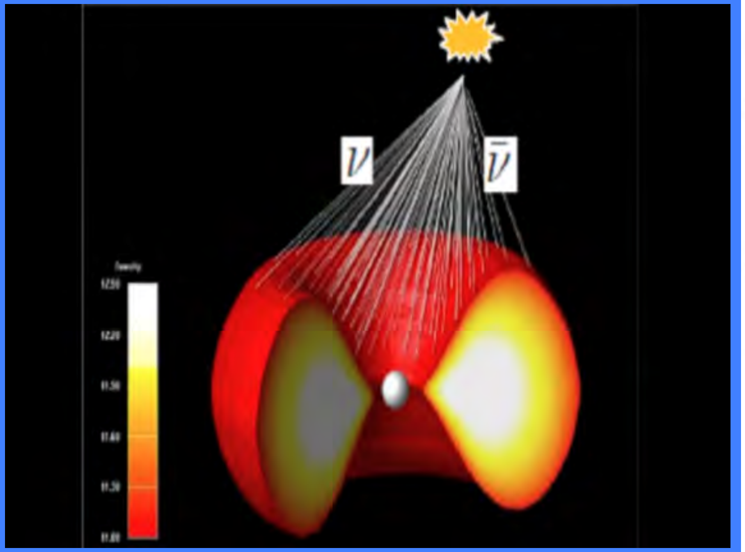
Neutron star mergers?

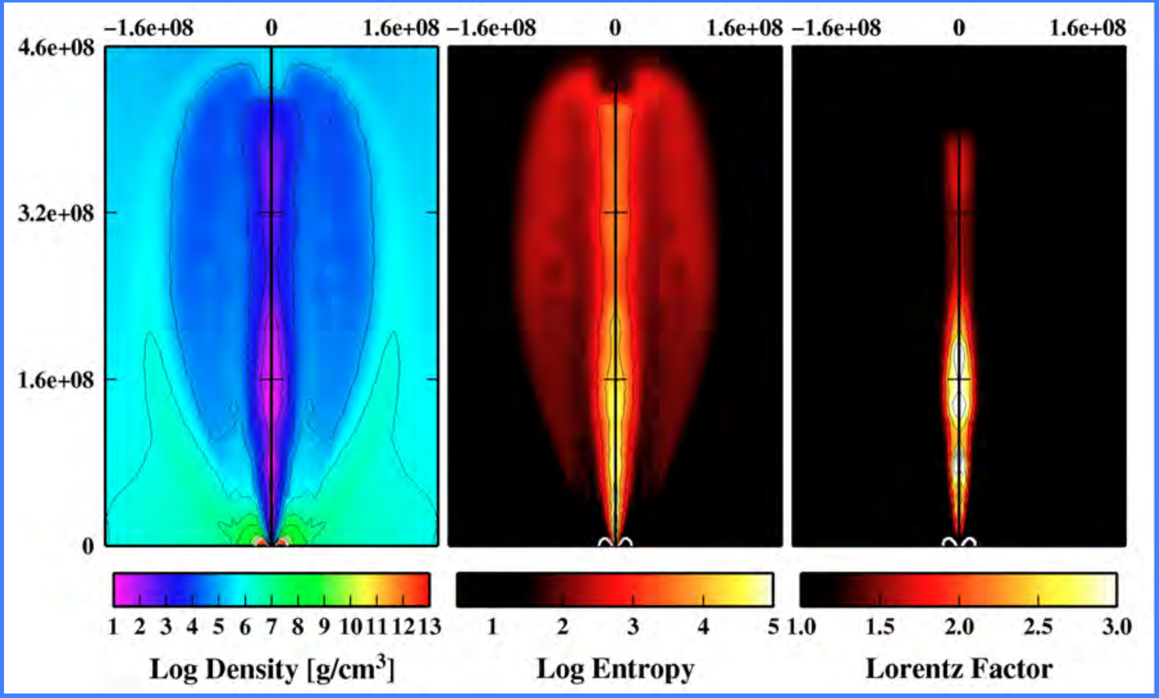


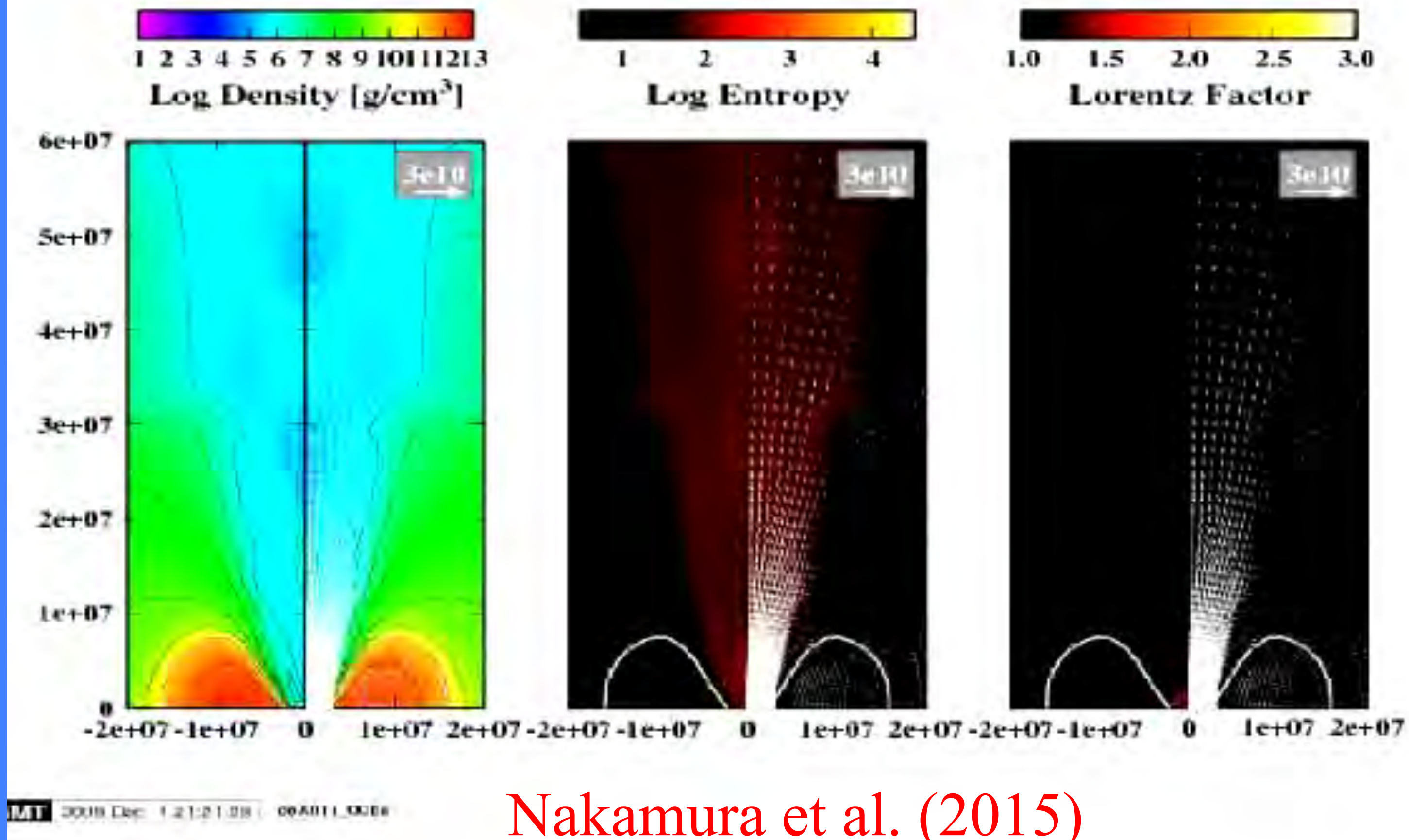
Shibagaki , Kajino, Chiba, Mathews, Nishimura, Lorusso., PRC (2014) Submitted

NEUTRINO-PAIR HEATING and R-PROCESS NUCLEOSYNTHESIS COLLAPSAR JETs

K. Nakamura, S. Sato, S Harikae, T. Kajino, and GJM,
IJMPE, 22, 1330022 (2013); A&A (2015) in press







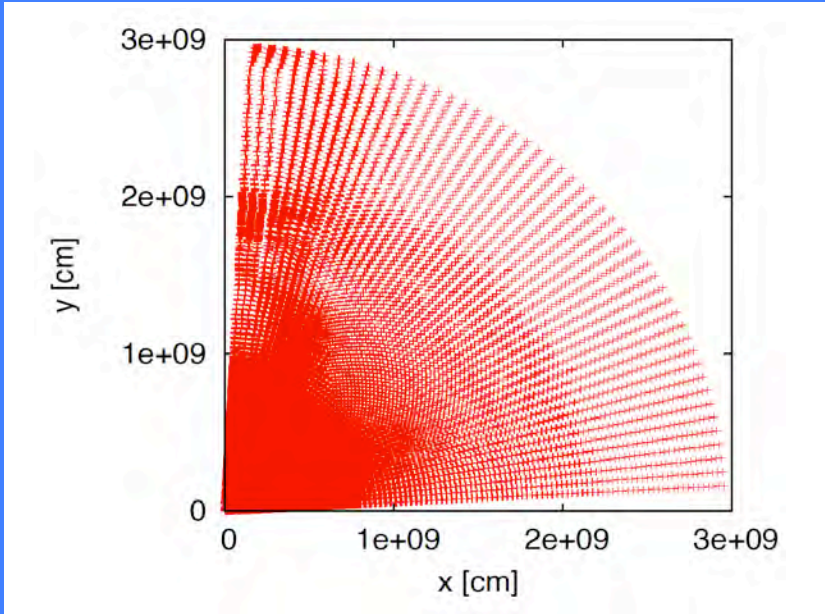
Nakamura et al. (2015)

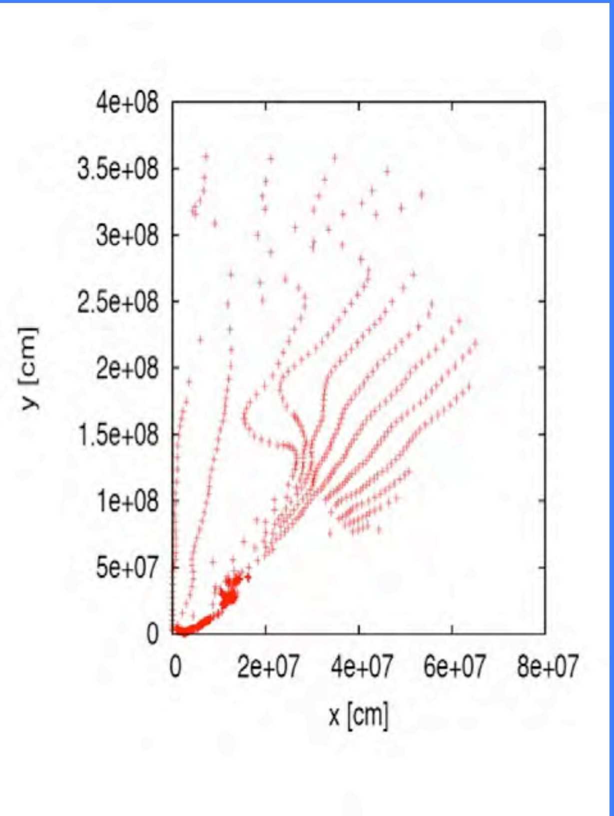
Modeling the r-process

K. Nakamura, et al A&A (2015) in press

- Extend the jet beyond the MHD+neutrino pair heating using 2D hydo
- Attach tracer particles to evolve the flow of material into the accretion disk and out into the jet

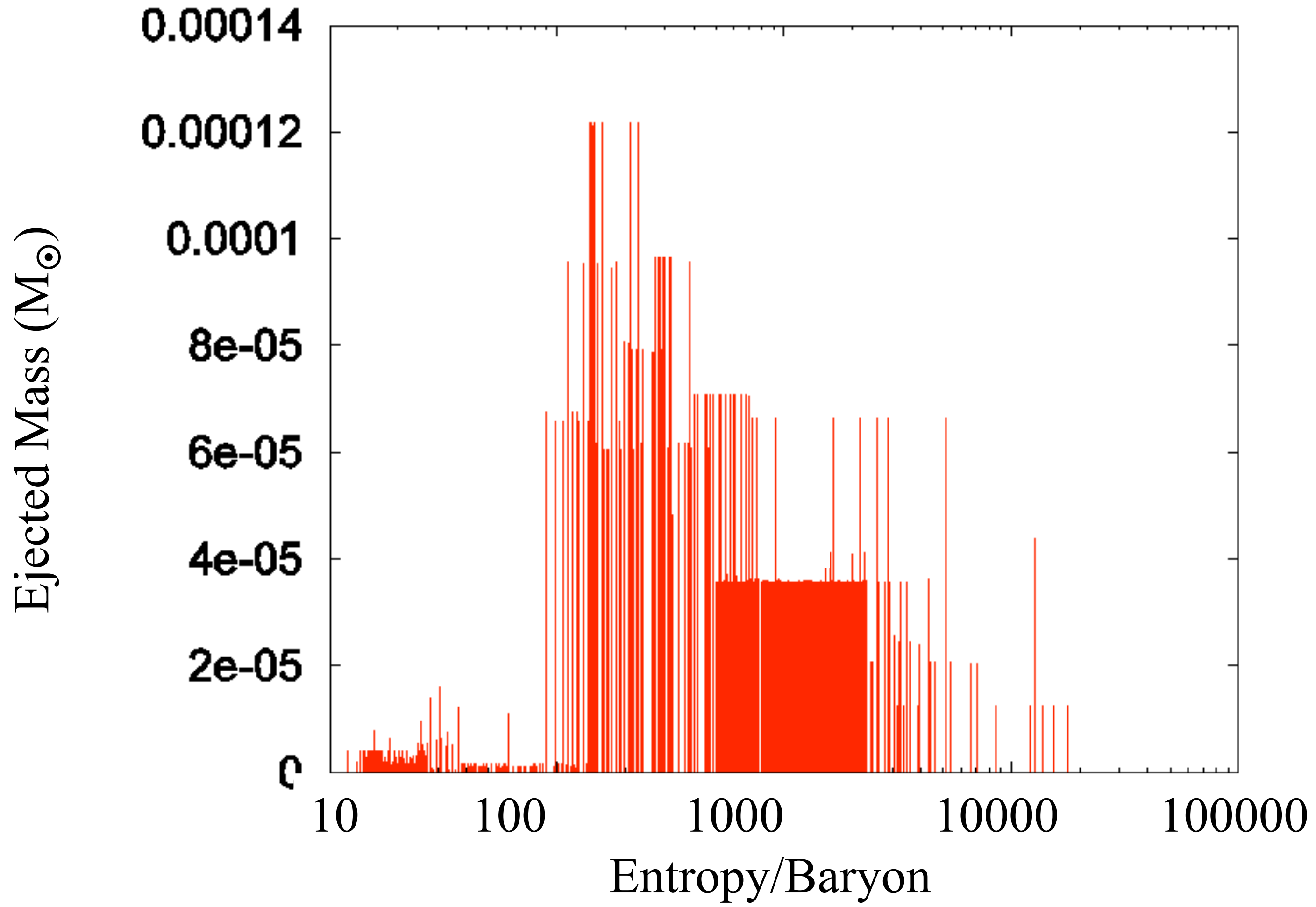
20,000 tracer particles

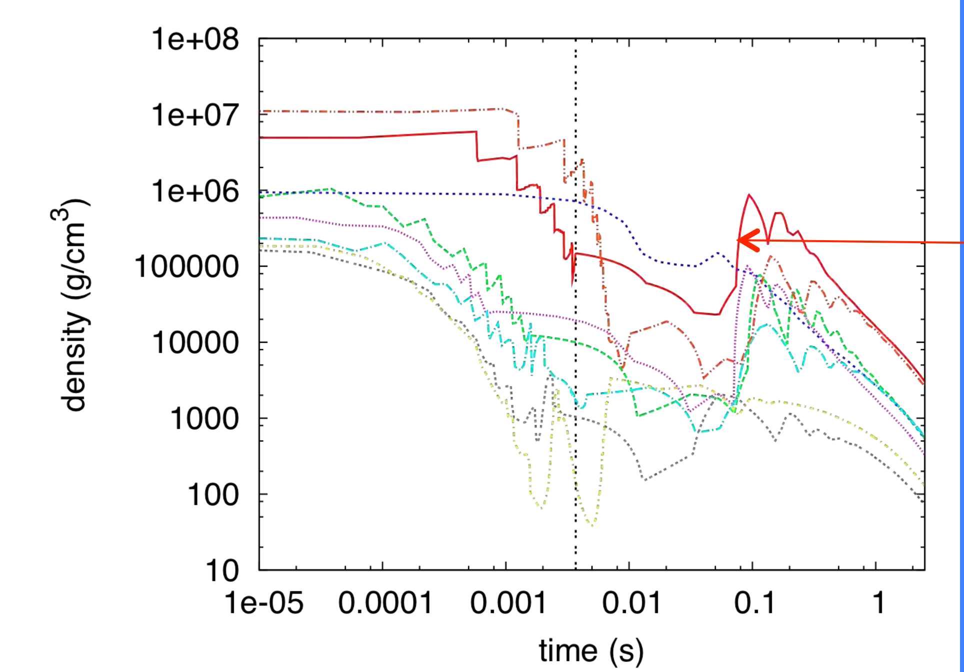




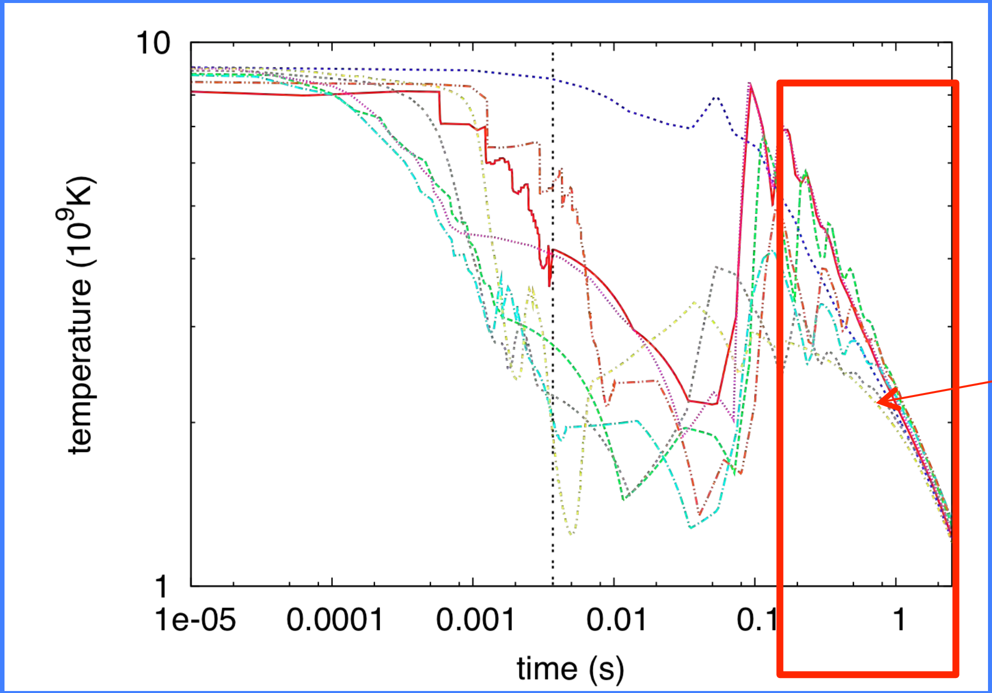
1208 trajectories with positive energy

Entropy in the jet



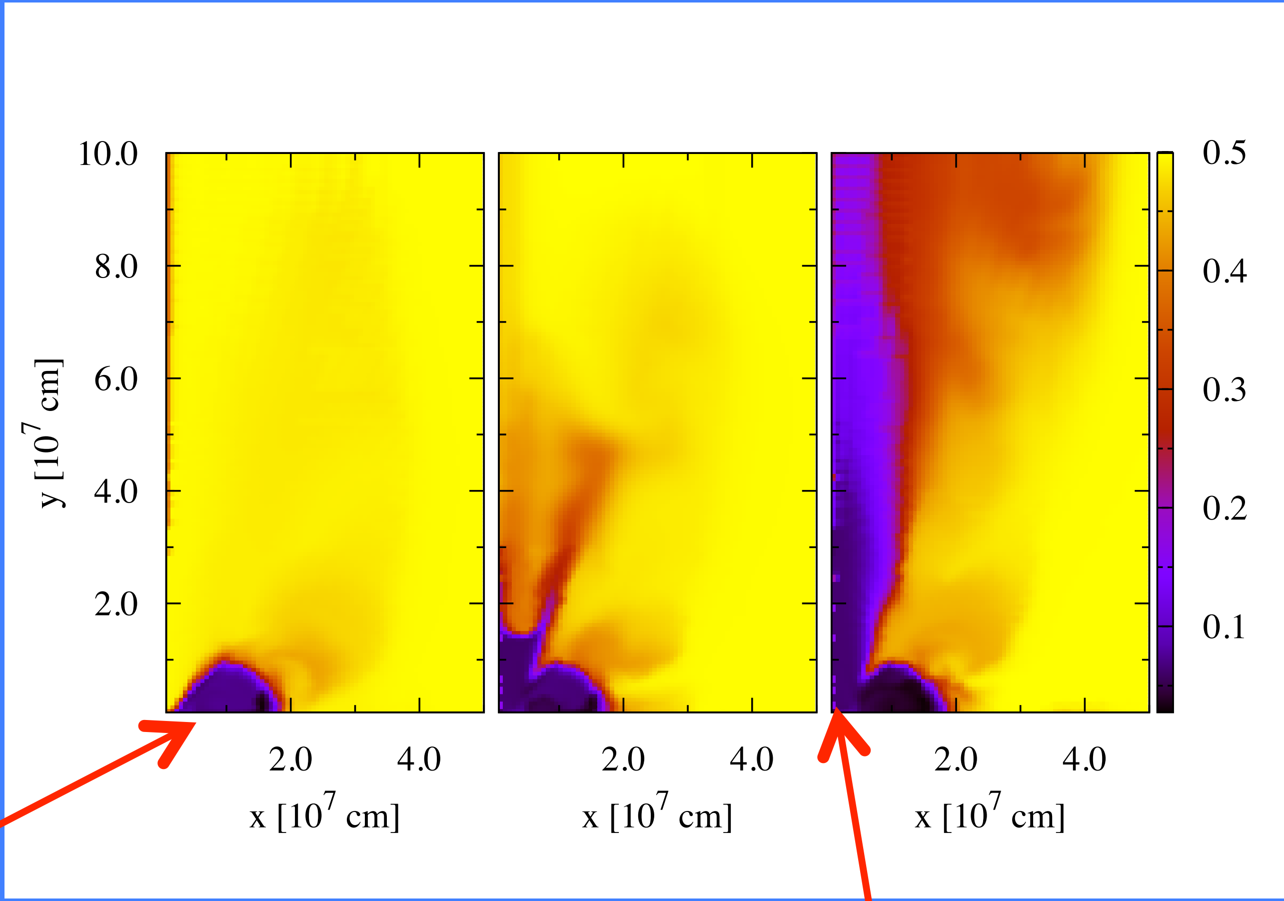


Rayleigh-Taylor overturn



r-process conditions

Evolution of low-Ye neutron-rich material

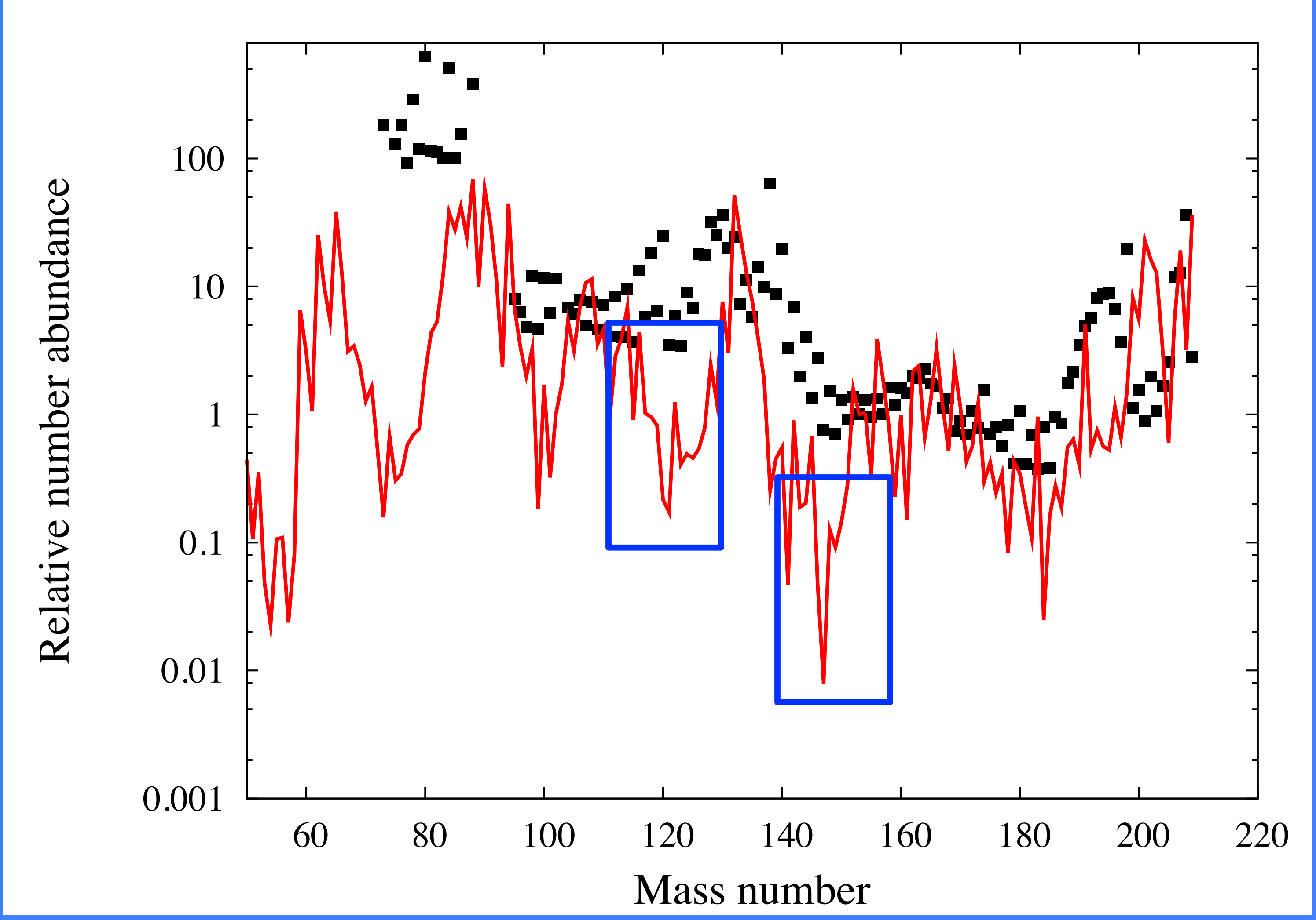


Neutronized accretion-disk material

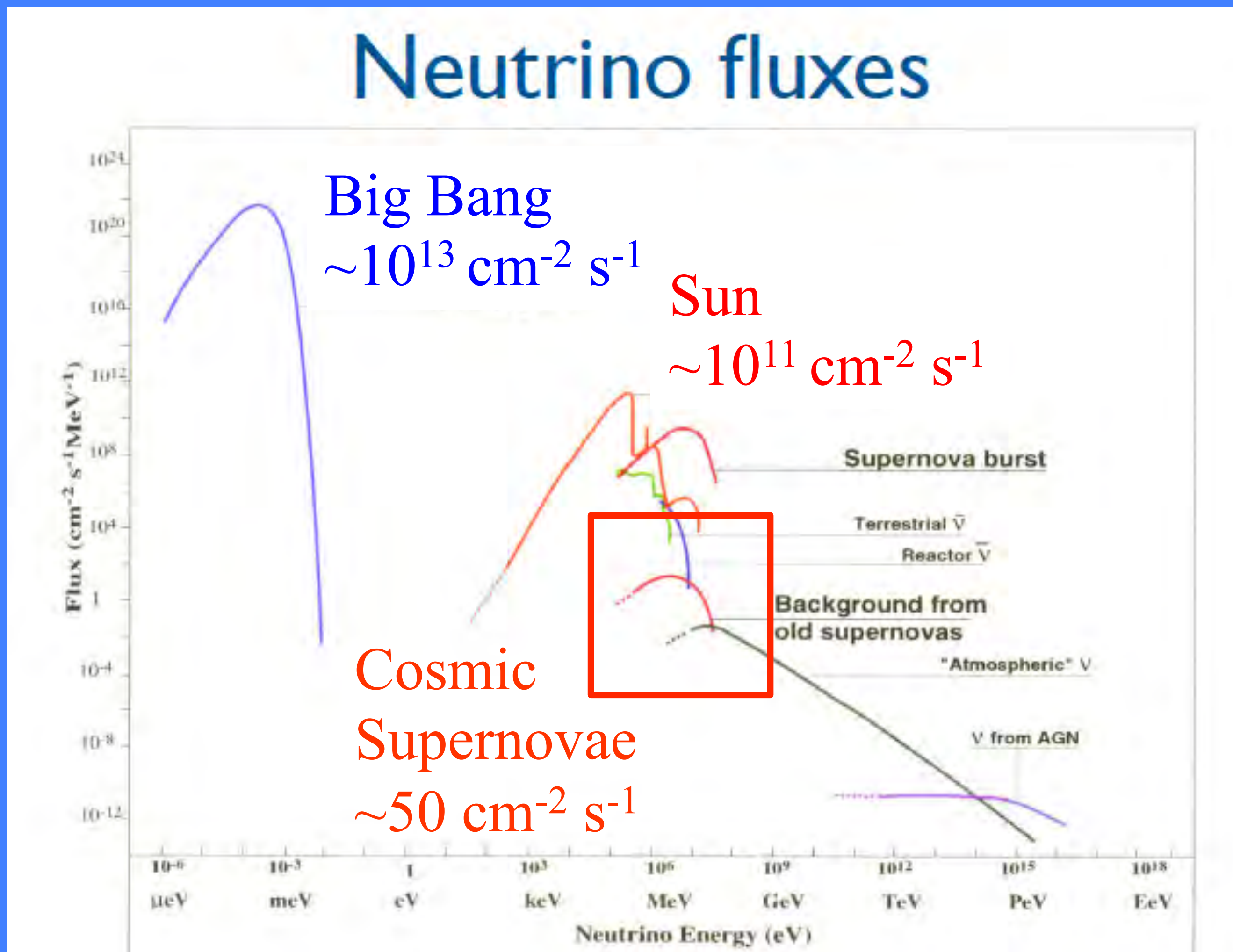
Flows into the jet

R-Process in the collapsar jet?

K. Nakamura, S. Sato, S Harikae, T. Kajino, and GJM,
IJMPE, 22, 1330022 (2013); A&A (2015) in press



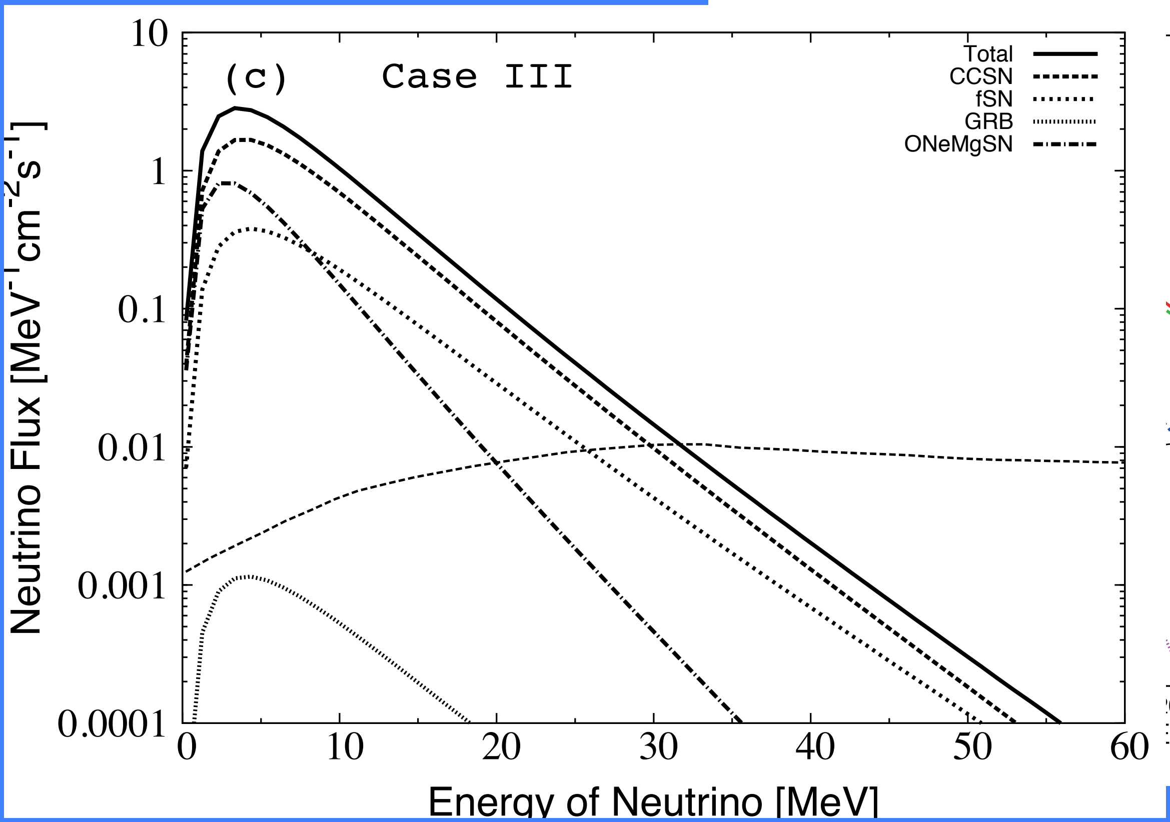
Supernova relic neutrino background as a messenger of supernova physics

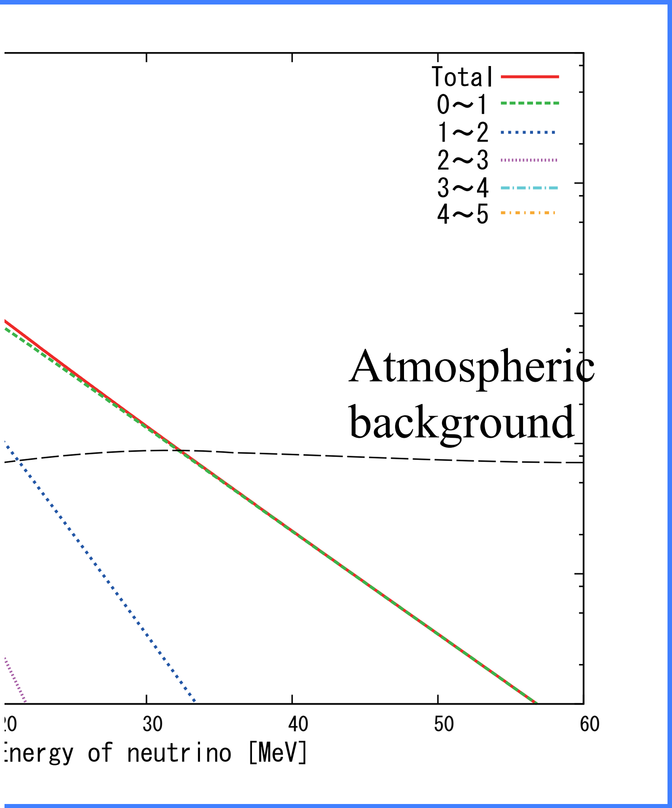


Calculated Relic Neutrino Spectrum

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

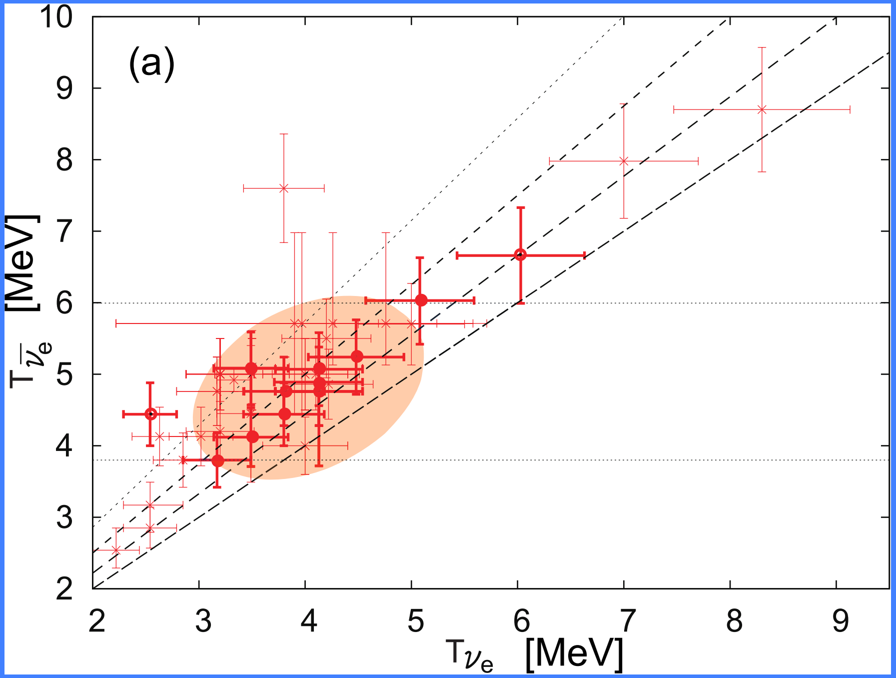
GJM, Hidaka, Kajino, Suzuki ApJ (2014)

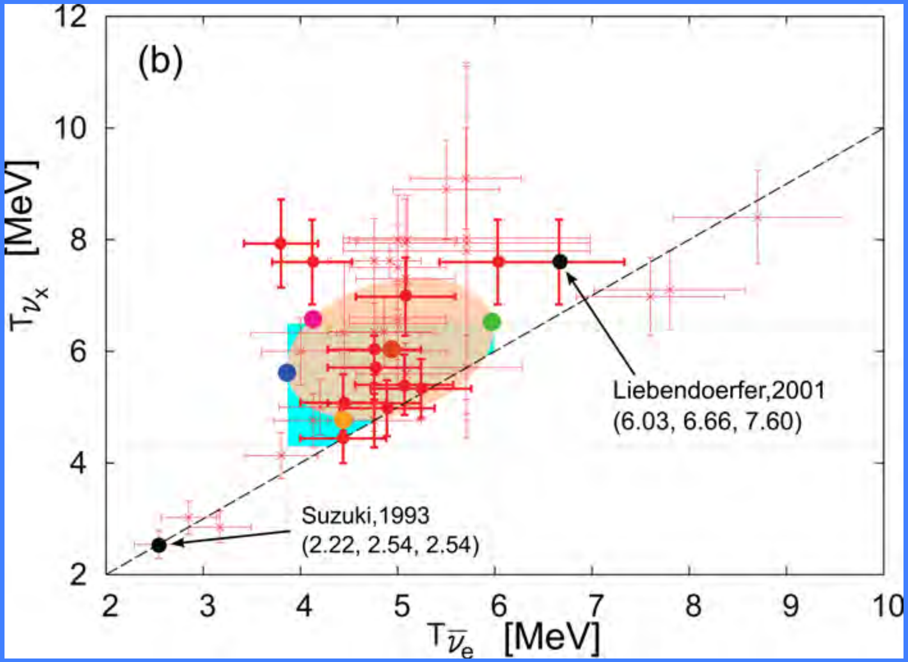




Supernova model neutrino temperatures contribute the largest error in predicted detection rate

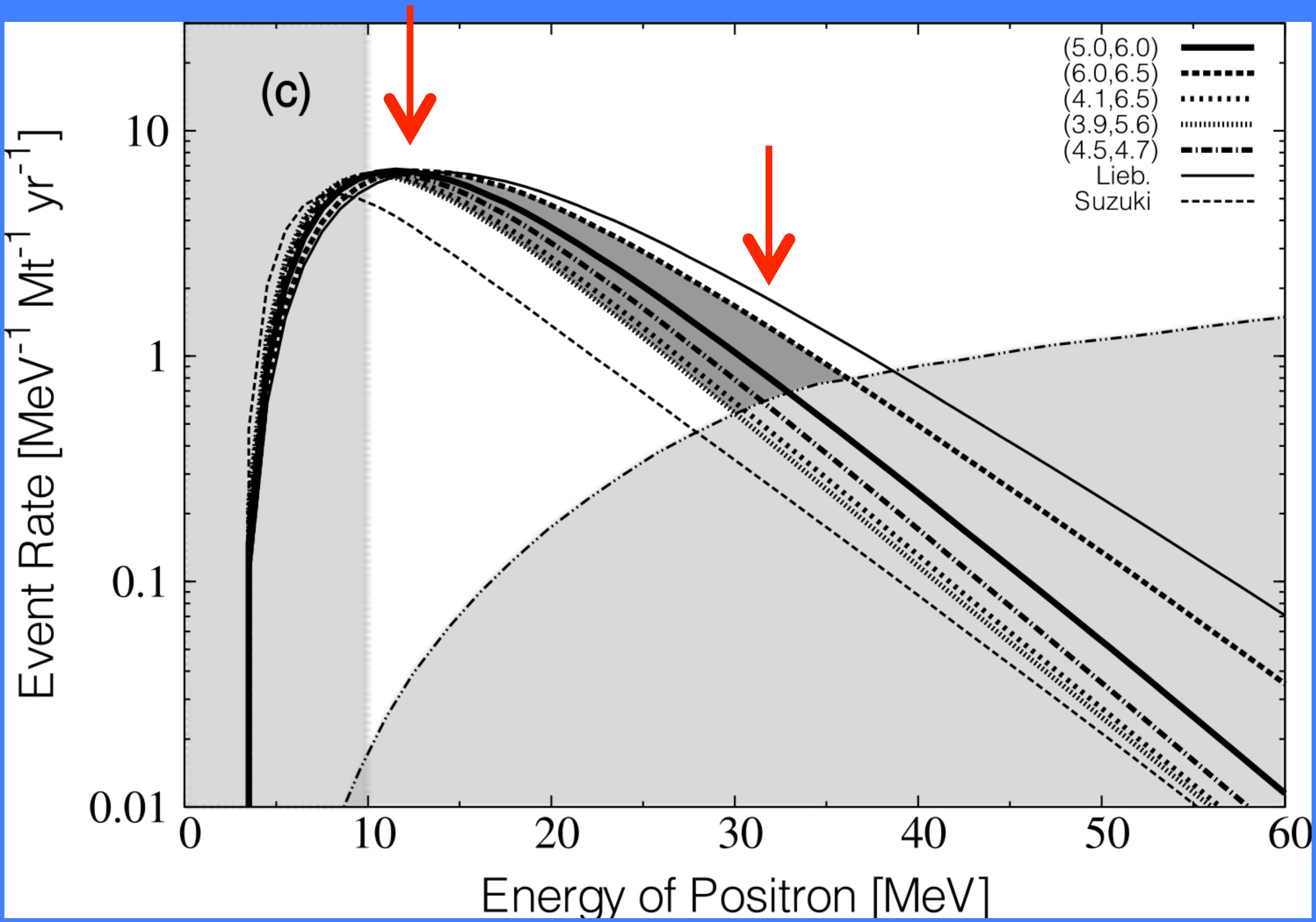
GJM, Hidaka, Suzuki, Kajino ApJ, 790, 115 (2014)



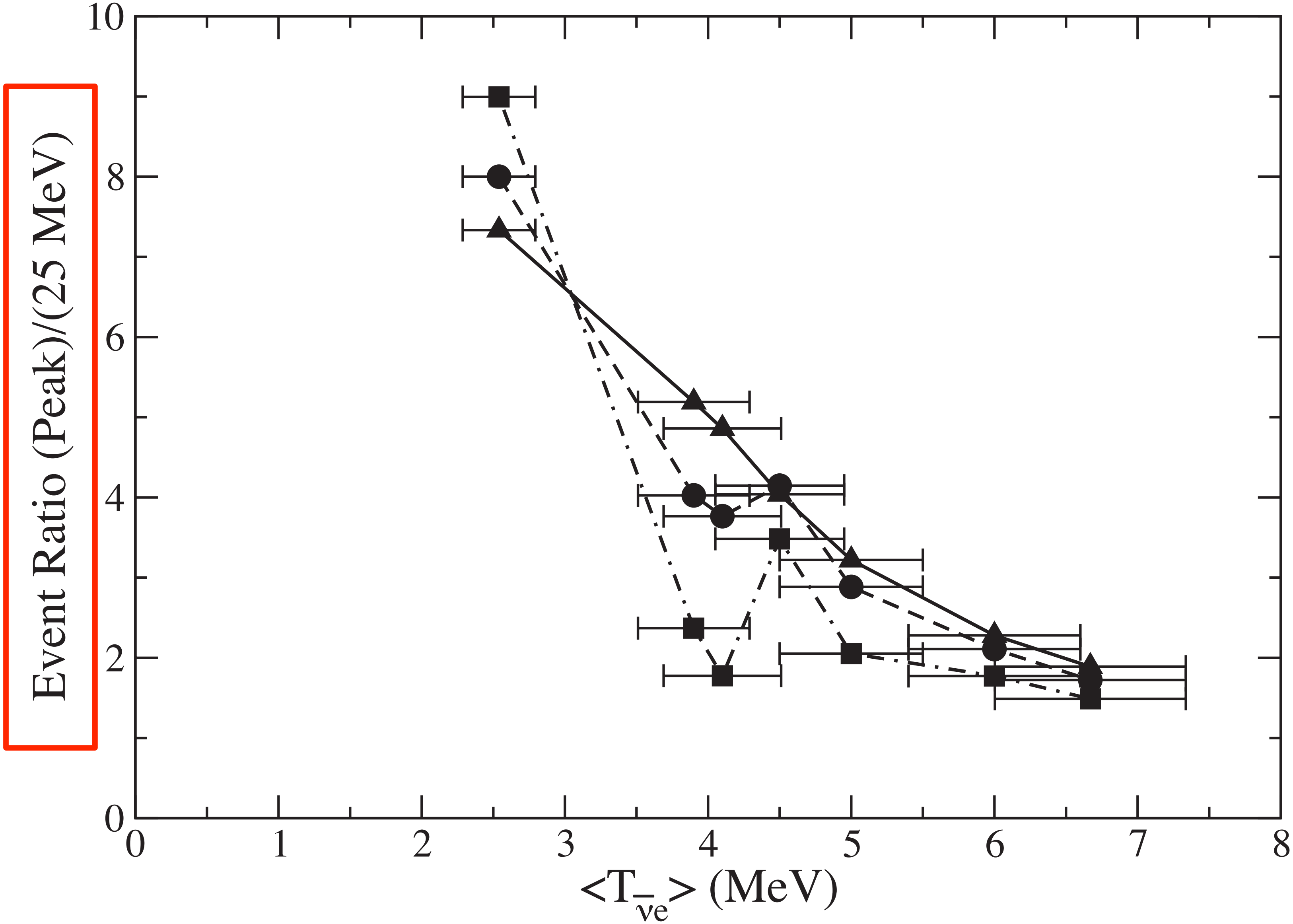


Detection Rate is Sensetive to neutrino temperature

$$\frac{dN_{event}}{dE_{e^+}} = N_{target} \cdot \varepsilon(E_\nu) \cdot \frac{1}{c} \cdot \frac{dF_\nu}{dE_\nu} \cdot \sigma(E_\nu) \cdot \frac{dE_\nu}{dE_{e^+}}$$



GJM, Hidaka, Suzuki, Kajino ApJ, 790, 115 (2014)



Conclusions

- Supernova neutrinos and nucleosynthesis provide insight into:
  - Beyond standard model physics
  - Site for r-process nucleosynthesis
  - Relic neutrino spectrum and the temperature at the neutrinosphere