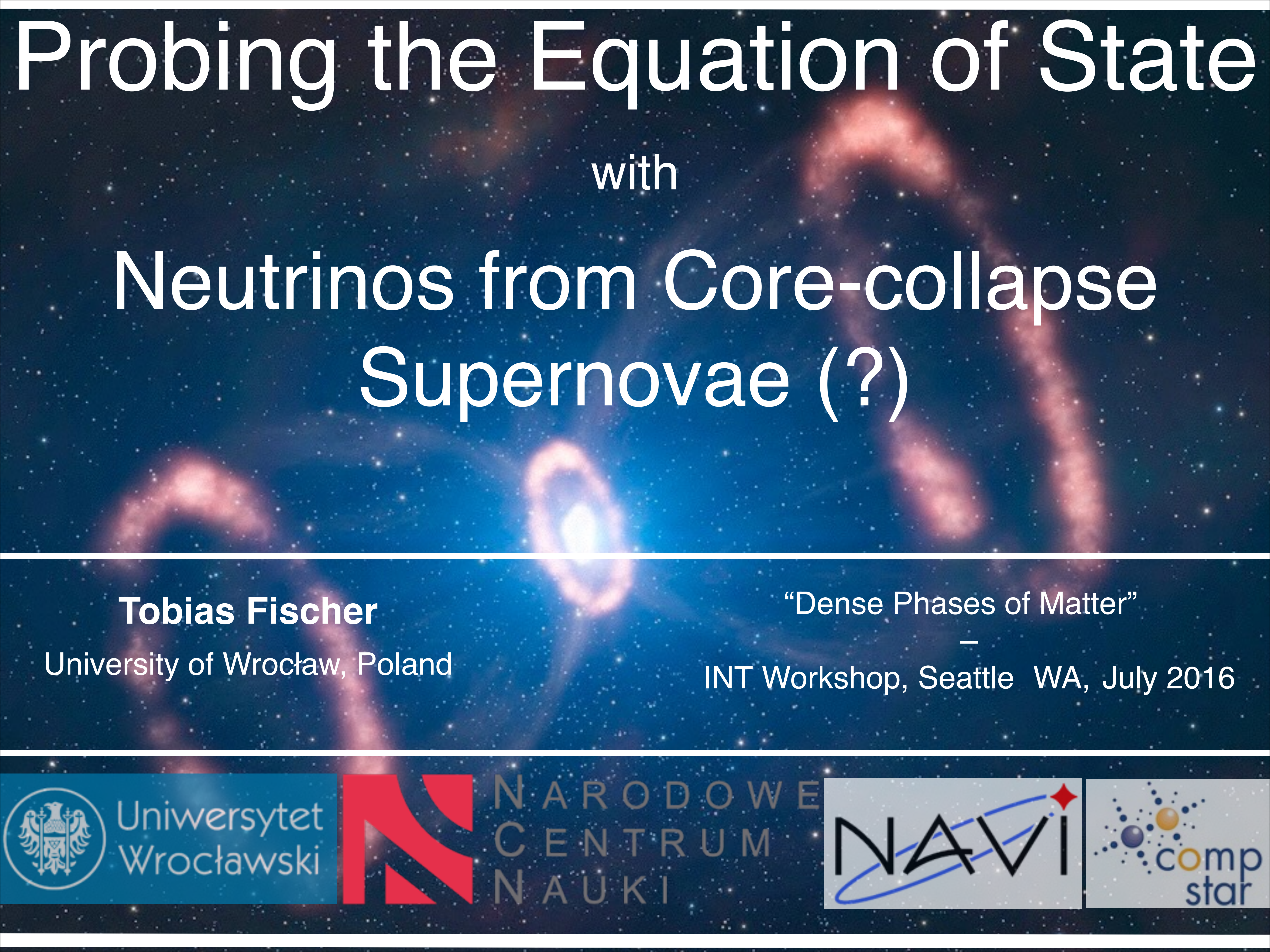


Probing the Equation of State

with

Neutrinos from Core-collapse Supernovae (?)

Tobias Fischer

University of Wrocław, Poland

“Dense Phases of Matter”

–

INT Workshop, Seattle WA, July 2016

Uniwersytet Wrocławski

Narodowe Centrum Nauki

NAVI

compstar

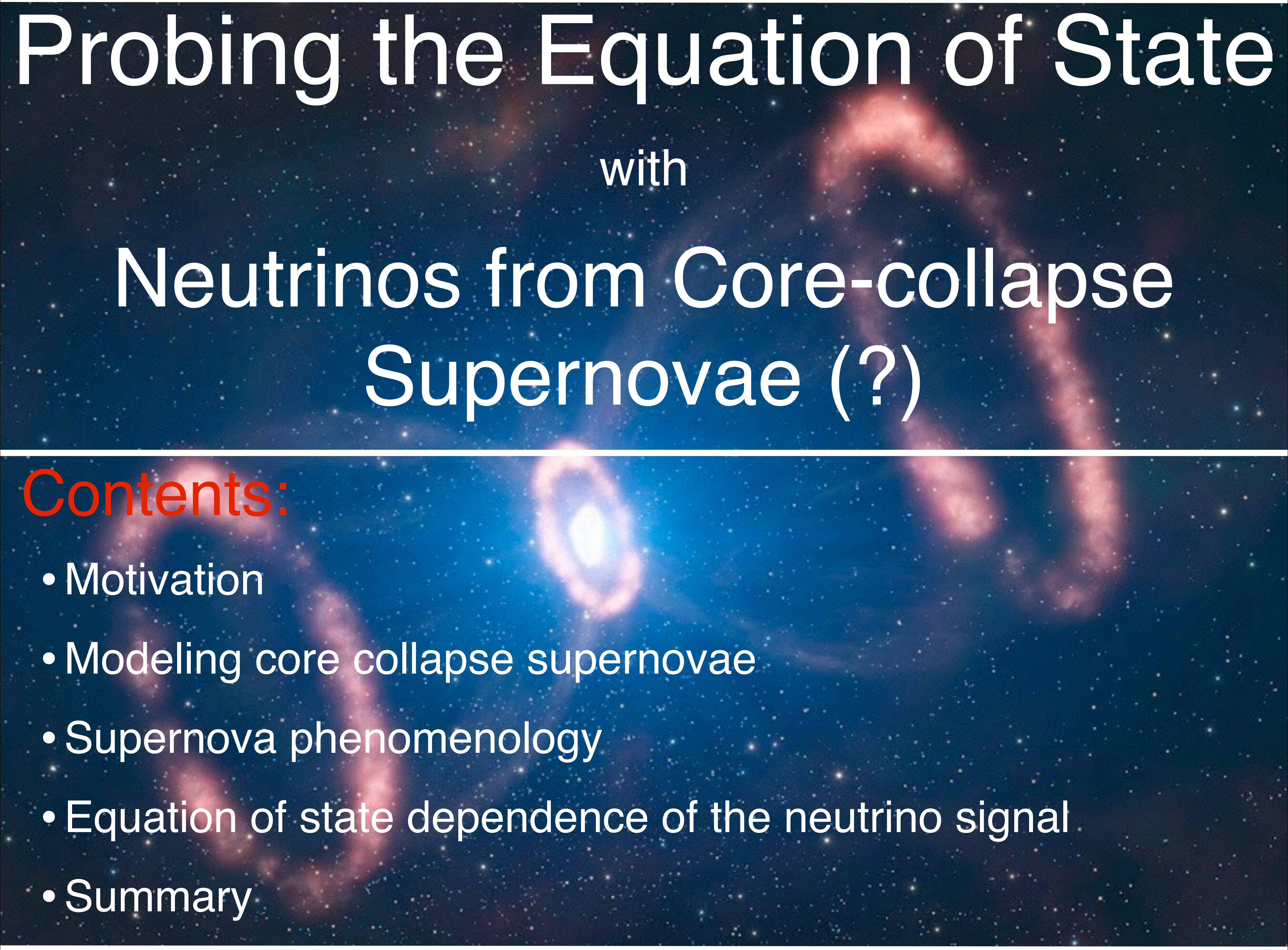
Wrocław: 3rd largest city in Poland, located in the heart of Europe

. . . at the south-west
end of Poland

~600 000 people living here.


7 Nobel Prize winners:

1. Theodor Mommsen (1817-1903)
   1902 (literature)
2. Phillip Lénàrd (1862-1947)
   1905 (physics)
3. Eduard Buchner (1860-1917)
   1907 (chemistry)
4. Paul Ehrlich (1854-1915)
   1908 (medicine)
5. Gerhart Hauptmann (1862-1946)
   1912 (literature)
6. Fritz Haber (1868-1934)
   1918 (chemistry)
7. Max Born (1882-1970)
   1954 (physics)



Probing the Equation of State

with

Neutrinos from Core-collapse Supernovae (?)

Contents:

- Motivation
- Modeling core collapse supernovae
- Supernova phenomenology
- Equation of state dependence of the neutrino signal
- Summary

Constraints (?)

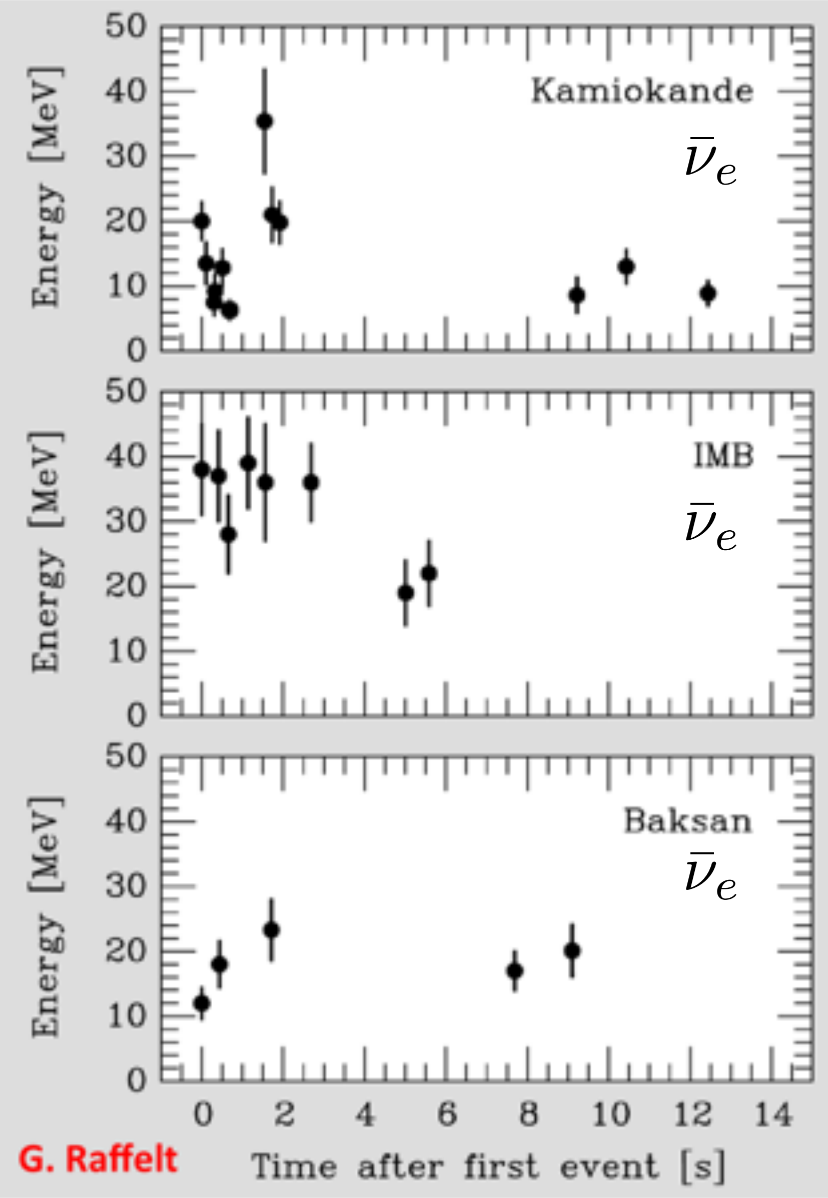
A neutron stars is born in a core-collapse supernova explosion as hot & lepton-rich protoneutron star (PNS)

PNSs develop (**deleptonize & cool**) towards neutron stars via the emission of neutrinos of all flavors for about 10–30 s

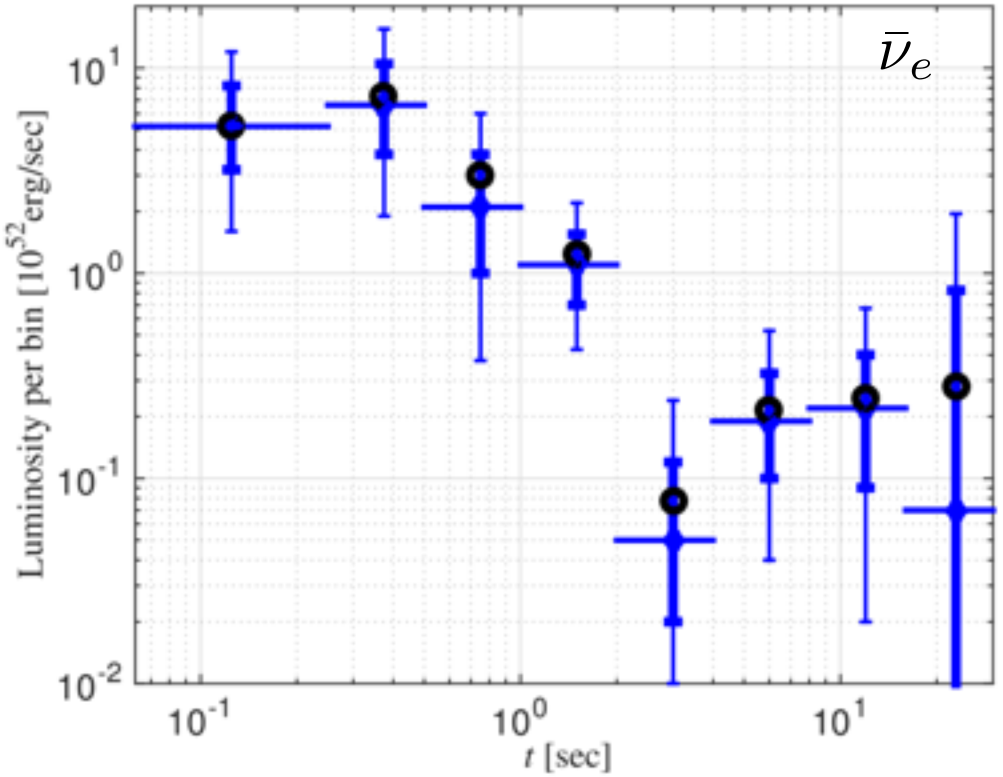
Some insights from SN1987A:

$E_{\rm expl} \sim 10^{51}$ erg , $E_\nu \sim 3 \times 10^{53}$ erg

All current supernova models (that include “accurate” **neutrino transport** !!!) are in agreement with SN1987A

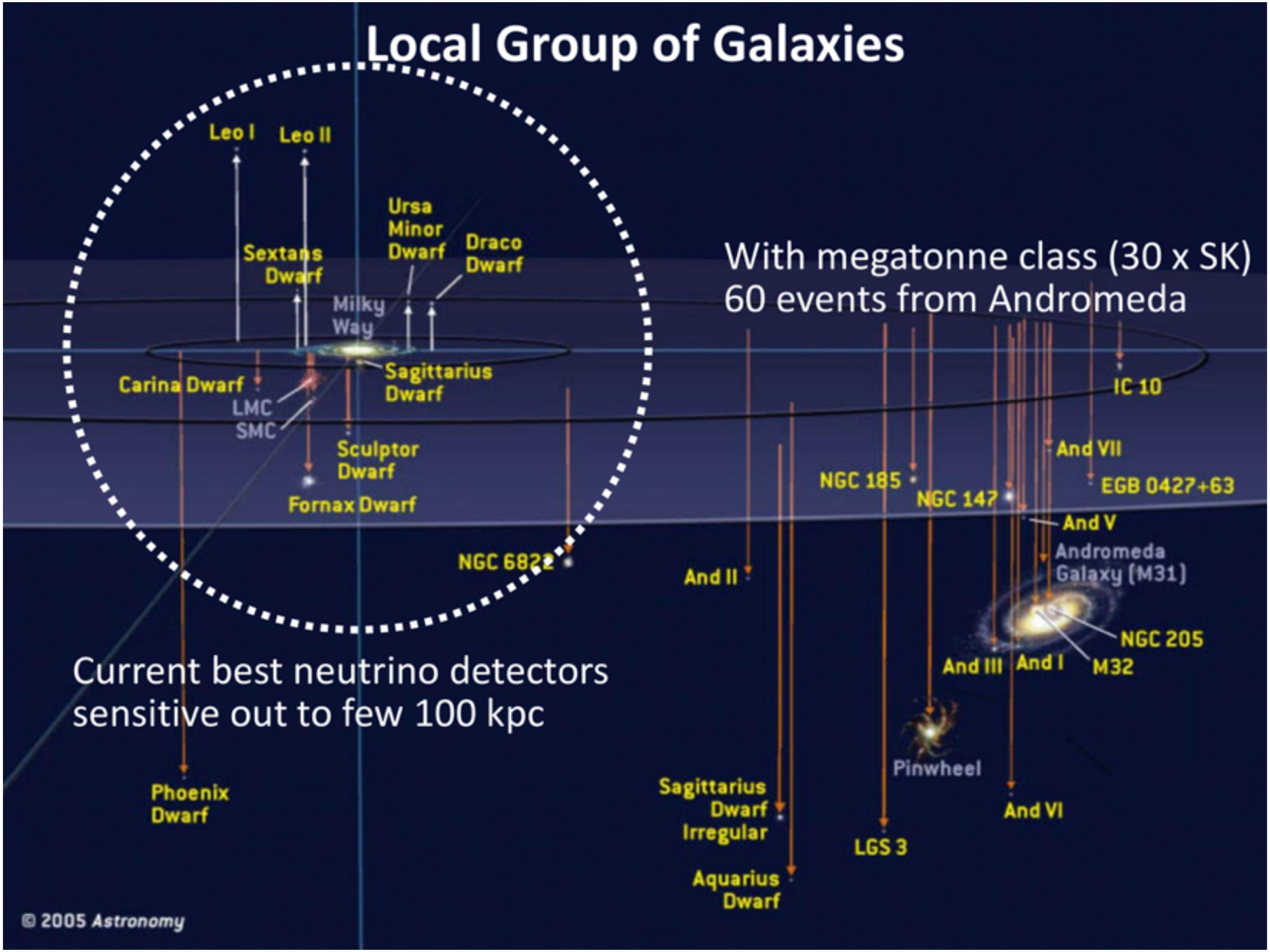


SN1987A (Feb. 23rd, 1987)



Blum & Kushnir (2016) ApJ

Neutrino detection – current and future

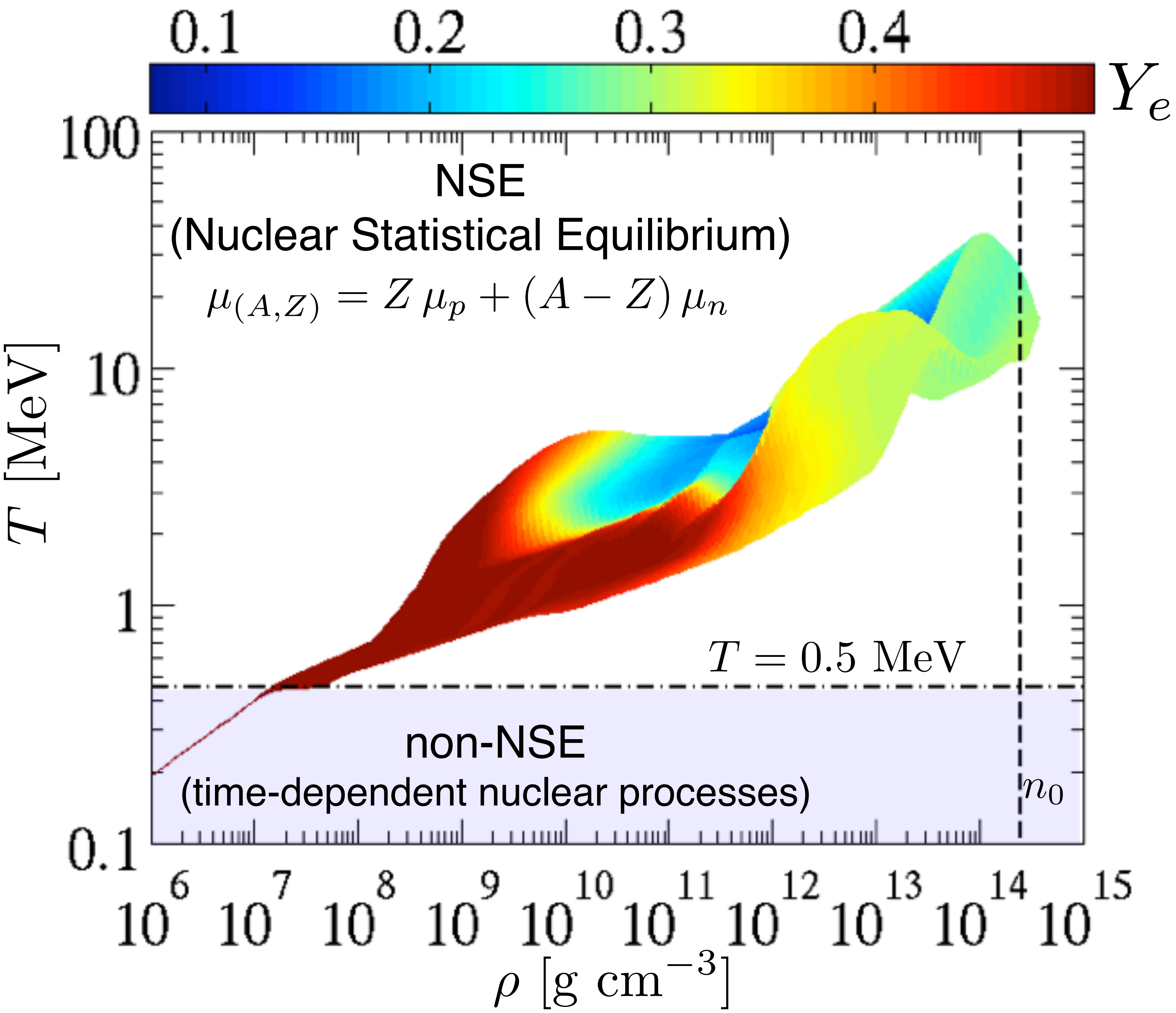


With megatonne class (30 x SK) 60 events from Andromeda

Current best neutrino detectors sensitive out to few 100 kpc

© 2005 Astronomy

Supernova equation of state



TF. et al.,(2011) ApJS 194, 39

Conditions:

$$T \simeq 10^{-2} - 50 \text{ MeV}$$
$$\rho \simeq 0 - 2 \times n_0$$
$$Y_e \simeq 0.01 - 0.6$$

(charge fraction/density)

Extends beyond a “simple” relation between pressure and energy

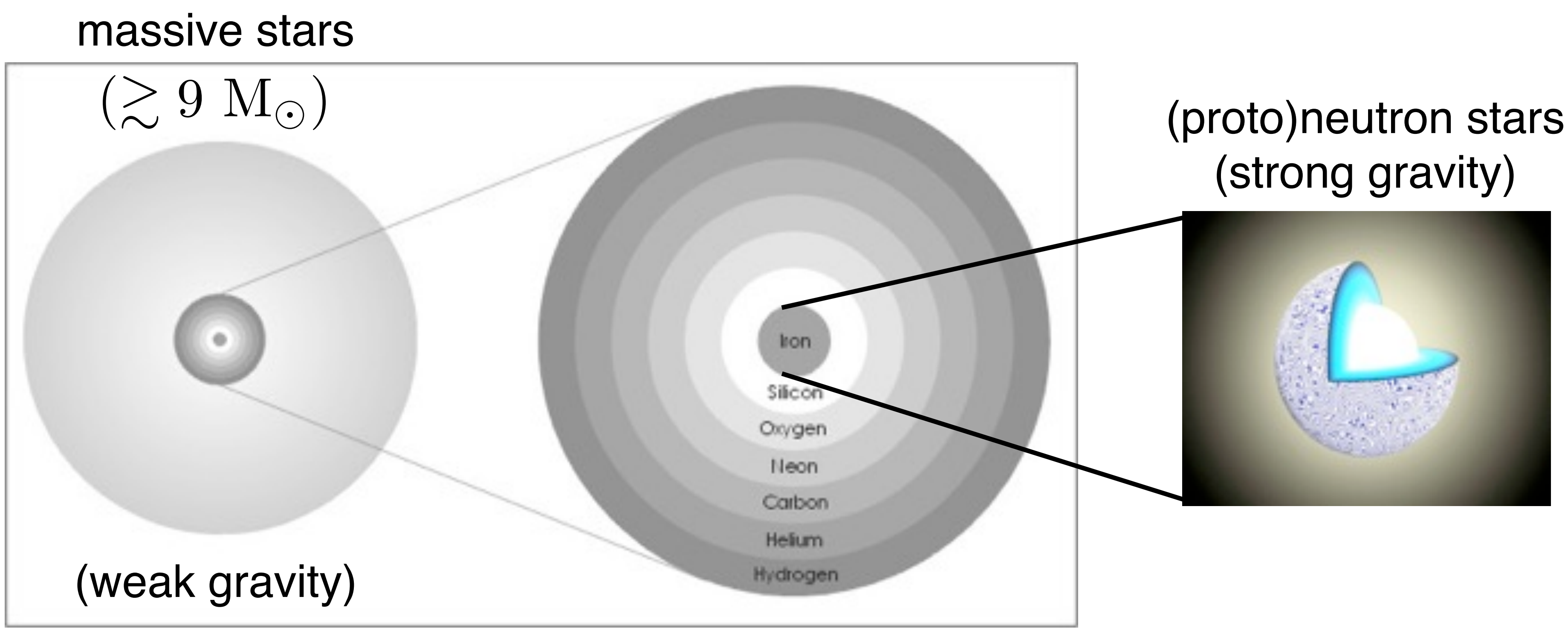
Nuclear clustering; ^{2}H, ^{3}H, ^{3}He, ^{4}He

Mott-transition to homogeneous phase

Nuclear medium modifies nucleon properties/nuclear masses (binding energy shifts)

Modeling core-collapse supernovae

General picture



$$\boxed{\triangle E_G \simeq 3-6\times 10^{53}\ \mathrm{erg} \longrightarrow (\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau})}$$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\kappa T_{\mu\nu} \qquad \text{(Einstein equation)}$$

$$ds^2 = -\alpha(t,a)^2 dt^2 + \left(\frac{r'(t,a)}{\Gamma(t,a)}\right)^2 da^2 + r(t,a)^2 d\Omega$$

$$\begin{array}{rclcc}
 & & \text{matter} & & \text{microphysics} \\
\hline
T^{tt} & = & \rho(1+e & + & J) \\
T^{ta} = T^{at} & = & & & \rho H \\
T^{aa} & = & p & + & \rho K \\
T^{\theta\theta} = T^{\phi\phi} & = & p & + & \frac{1}{2}\rho(J-K)
\end{array}$$

Core-collapse supernova converts iron-core of massive star into proto-neutron star

Binding energy gain available in form of neutrinos of all flavors

Strong gravity of PNS requires general relativity

Misner & Sharp (1964) PhyRev.136, 571
Lindquist (1966) AnnPhys.37, 487

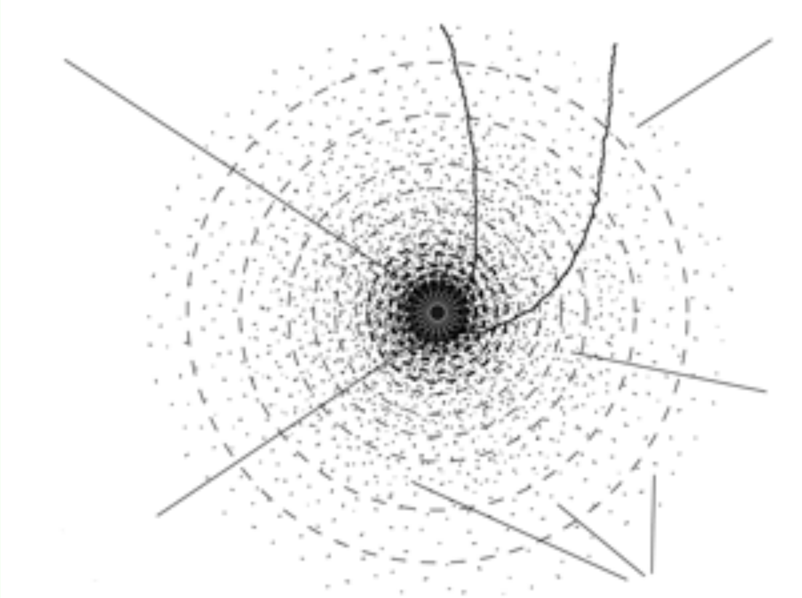
Neutrino transport . . .

Lindquist (1966) AnnPhys.37, 487

Neutrinos are light-like geodesics in curved spacetime; massless ultra-relativistic particles.

$$F_\nu\left(t,\vec{x},\vec{v}\right) \longrightarrow F_\nu(t,a,\mu=\cos\theta,E) = \frac{f_\nu(t,a,\mu,E)}{\rho}$$

$$dN_\nu = F_\nu(t,a,\mu,E)\,E^2\,dE\,d\mu\,da$$



$$\begin{aligned}
\frac{\partial F}{\alpha\partial t}(\mu,E) &= -\frac{\mu}{\alpha}\frac{\partial}{\partial a}\left(4\pi r^2\alpha\rho F\right)\\
&- \Gamma\left(\frac{1}{r}-\frac{1}{\alpha}\frac{\partial\alpha}{\partial r}\right)\frac{\partial}{\partial\mu}\left[\left(1-\mu^2\right)F\right]\\
&- \left(\frac{\partial\ln\rho}{\alpha\partial t}+\frac{3u}{r}\right)\frac{\partial}{\partial\mu}\left[\mu\left(1-\mu^2\right)F\right]\\
&+ \mu\Gamma\frac{1}{\alpha}\frac{\partial\alpha}{\partial r}\frac{1}{E^2}\frac{\partial}{\partial E}\left(E^3F\right)\\
&- \left[\mu^2\left(\frac{\partial\ln\rho}{\alpha\partial t}+\frac{3u}{r}\right)-\frac{u}{r}\right]\frac{1}{E^2}\frac{\partial}{\partial E}\left(E^3F\right)\\
&+ \left.\frac{\partial F}{\alpha\partial t}\right|_{\mathrm{coll}}(\mu,E)
\end{aligned}$$

propagation of the neutrinos along geodesics with changing local angle μ

Doppler shift and the angular aberration between adjacent comoving observers for $\mu\neq 0$

red/blueshift spectra

Liebendörfer et al.,(2004) ApJS 150, 263

Mezzacappa & Bruenn (1993) ApJ 405, 669
Mezzacappa & Bruenn (1993) ApJ 410, 740

Collision integral

$$\left.\frac{\partial F}{\alpha \partial t}(\mu, E)\right|_{\text{collision}} = j(E)\left(\frac{1}{\rho} - F(\mu, E)\right) - \frac{1}{\lambda(E)} F(\mu, E)$$

emissivity

opacity/absorptivity

Charged current

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

$$e^- + \langle A, Z\rangle \leftrightarrows \langle A, Z-1\rangle + \nu_e$$

Juodagalvis et al. (2010), NPA 848, 454

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

Collision integral

Mezzacappa & Bruenn (1993) ApJ 405, 669
Mezzacappa & Bruenn (1993) ApJ 410, 740

$$
\begin{aligned}
\left.\frac{\partial F}{\alpha \partial t}(\mu, E)\right|_{\text{collision}} &= j(E)\left(\frac{1}{\rho} - F(\mu, E)\right) - \frac{1}{\lambda(E)} F(\mu, E) \\
&+ \frac{1}{c}\frac{E^2}{(h\,c)^3}\int d\mu'\, R_{\nu N}(\mu', \mu, E)\, F(\mu', E) - \frac{1}{c}\frac{E^2 F(\mu, E)}{(h\,c)^3}\int d\mu'\, R_{\nu N}(\mu', \mu, E) \\
&+ \frac{1}{c}\frac{E^2}{(h\,c)^3}\left(\frac{1}{\rho} - F(\mu, E)\right)\int d\mu'\, dE'\, E'^2\, R^{\text{IN}}_{\nu e^\pm}(\mu, \mu', E, E')\, F(\mu', E') \\
&- \frac{1}{c}\frac{E^2}{(h\,c)^3} F(\mu, E)\int d\mu'\, dE'\, E'^2\, R^{\text{OUT}}_{\nu e^\pm}(\mu, \mu', E, E')\left(\frac{1}{\rho} - F(\mu', E')\right)
\end{aligned}
$$

Charged current

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

$$e^- + \langle A, Z\rangle \leftrightarrows \langle A, Z-1\rangle + \nu_e$$

Juodagalvis et al. (2010), NPA 848, 454

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

scattering

$$\nu + N \rightleftharpoons \nu + N \qquad (N = n, p)$$

$$\nu + \langle A, Z\rangle \rightleftharpoons \nu + \langle A, Z\rangle$$

$$\nu + e^\pm \rightleftharpoons \nu + e^\pm$$

pair reactions

$$e^- + e^+ \rightleftharpoons \nu + \bar{\nu}$$

$$N + N \rightleftharpoons N + N + \nu + \bar{\nu} \quad (N = n, p,)$$

Hannestadt & Raffelt, (1998), ApJ 507, 339

$$\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$

$$\langle A, Z\rangle^* \rightleftarrows \langle A, Z\rangle + \nu + \bar{\nu}$$

Fuller & Meyer (1991) ApJ 376, 701
TF. et al. (2013), PRC 88, 065804

Neutrino opacity and EoS

Reddy et al.,(1998) PRD 58, 013009

$$\boxed{\nu_e + n \longrightarrow e^- + p}$$

Here: $S_V = S_A \equiv S(q_0, q)$
(density and spin response functions)

Charged-current absorption; nucleons are not free gas

$$1/\lambda(E_{\nu_e}) = \frac{G_F^2 V_{ud}^2}{\pi \hbar c}(g_V^2 + 3g_A^2) \int \frac{d^3p_e}{(2\pi\hbar c)^3}(1 - F_e(E_e))\, S(q_0, q)$$

$$q_0 = E_\nu - E_e \ , \qquad q = \mathbf{p}_\nu - \mathbf{p}_e$$

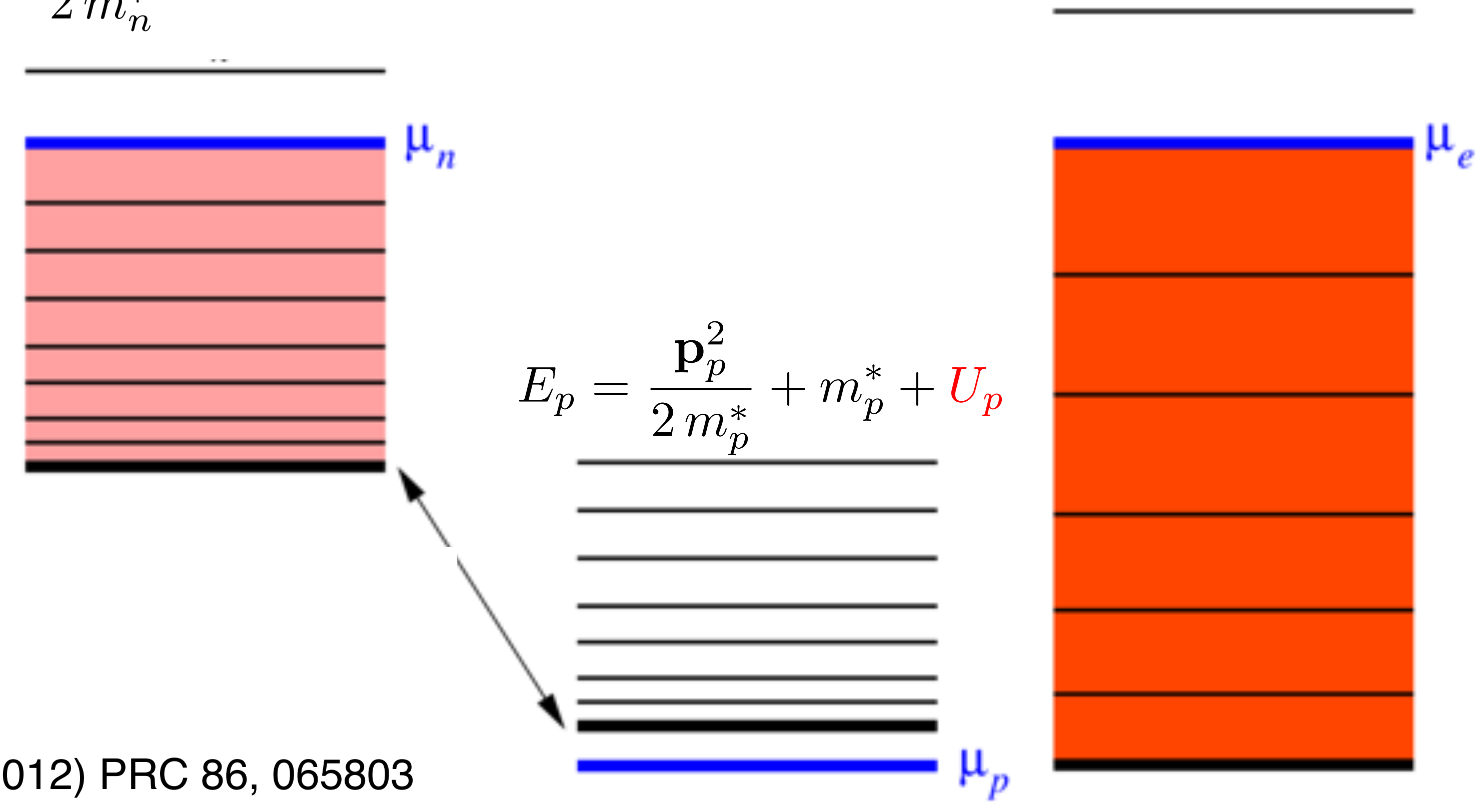
$$S(q_0, q) = 4\pi \int \frac{d^3p_n}{(2\pi\hbar c)^3}\delta(q_0 + E_n - E_p) f_n(E_n)(1 - f_p(E_p))$$

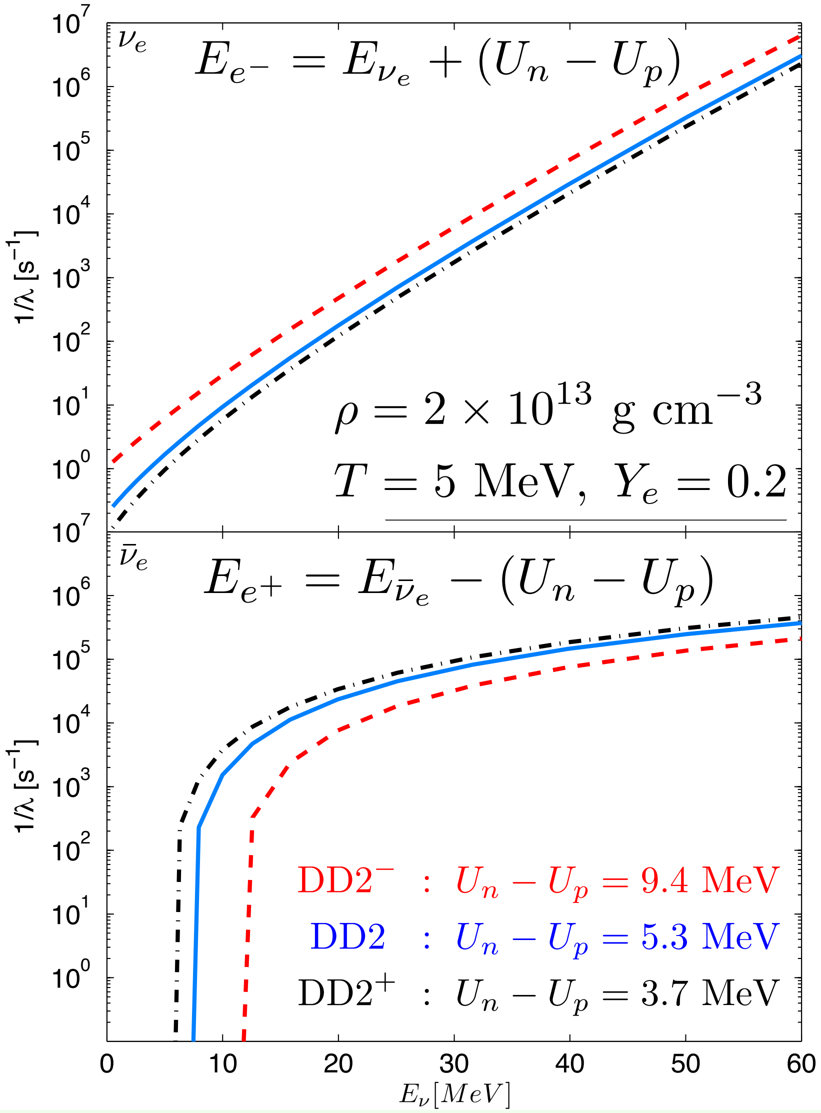
Lowest order medium modification of the weak rate; depends on the EoS (symmetry energy):

$$E_n = \frac{\mathbf{p}_n^2}{2\, m_n^*} + m_n^* + U_n$$

$$\boxed{U_n - U_p \propto S^F(T, \rho)}$$

$$E_p = \frac{\mathbf{p}_p^2}{2\, m_p^*} + m_p^* + U_p$$





Roberts et al., (2012) PRC 86, 065803
Horowitz et al., (2012) PRC 86, 065806
Martinez-Pinedo & TF et al., (2012) PRL109, 251104

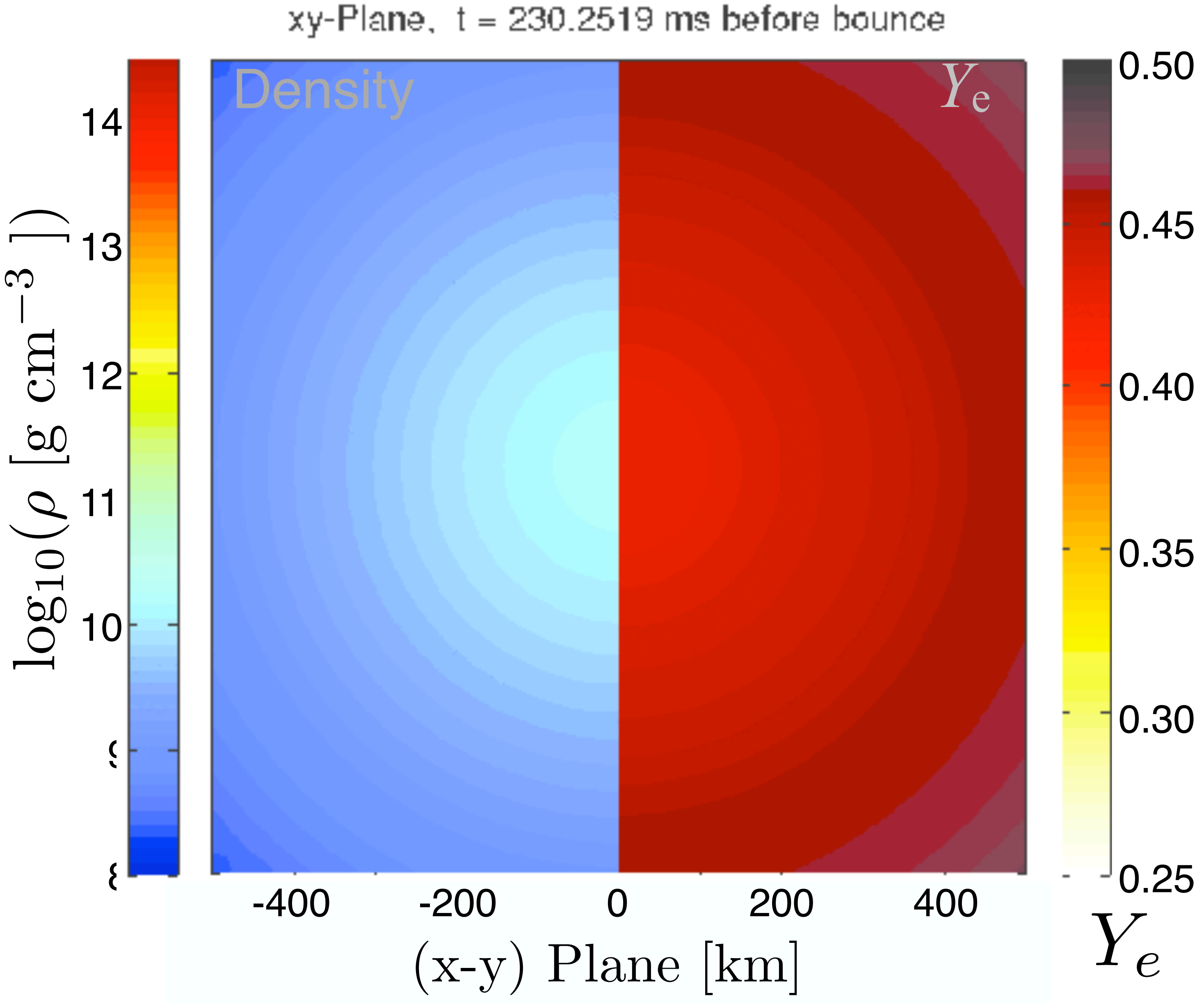
Core-collapse supernova phenomenology

Stellar core collapse

$(Y_e = n_p/n_\mathrm{B})$

$(Y_e < 0.5 : \text{ neutron excess }) \longrightarrow M_\mathrm{core} > M_\mathrm{Ch} \simeq 1.44 \left(\frac{Y_e}{0.5}\right)^2 \mathrm{M}_\odot$

$(Y_e > 0.5 : \text{ neutron defficient })$

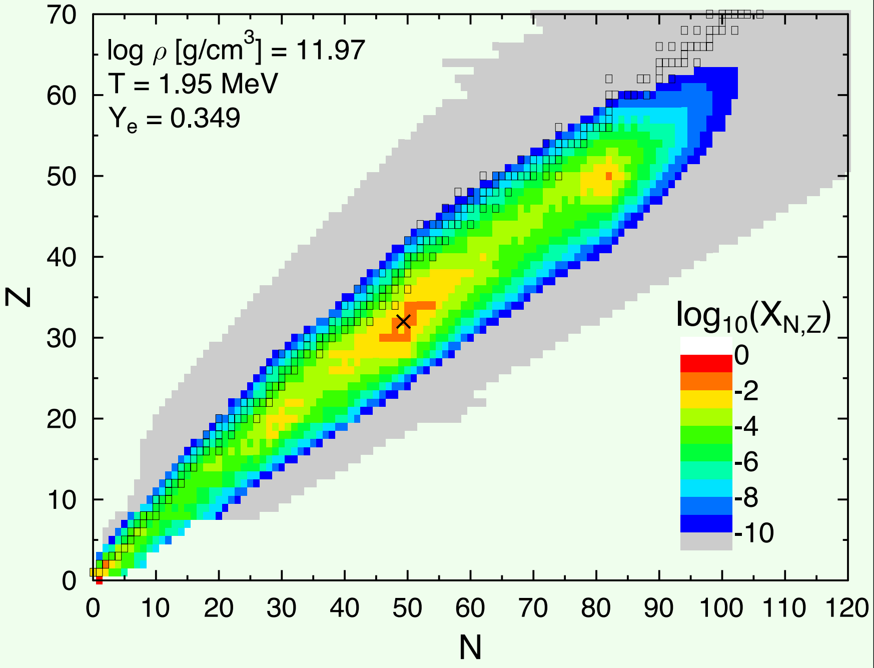


Implosion of the stellar core due to pressure loss; triggered from e⁻ captures on protons bound in nuclei

$$\left.\begin{aligned} e^- + {}^{56}\mathrm{Mn} &\longrightarrow {}^{56}\mathrm{Fe} + \nu_\mathrm{e} \\ e^- + {}^{56}\mathrm{Fe} &\longrightarrow {}^{56}\mathrm{Co} + \nu_\mathrm{e} \\ e^- + {}^{56}\mathrm{Co} &\longrightarrow {}^{56}\mathrm{Ni} + \nu_\mathrm{e} \end{aligned}\right\} \text{Neutrino losses}$$

$\ldots\ldots$

$$e^- + \langle A, Z\rangle \longrightarrow \langle A, Z-1\rangle + \nu_e$$



(Hempel & TF et al.,(2012) ApJ 748, 27)

Collapsing stellar core neutronizes; electron fraction drops; collapse proceeds adiabatically/ super-sonically

Stellar core collapse

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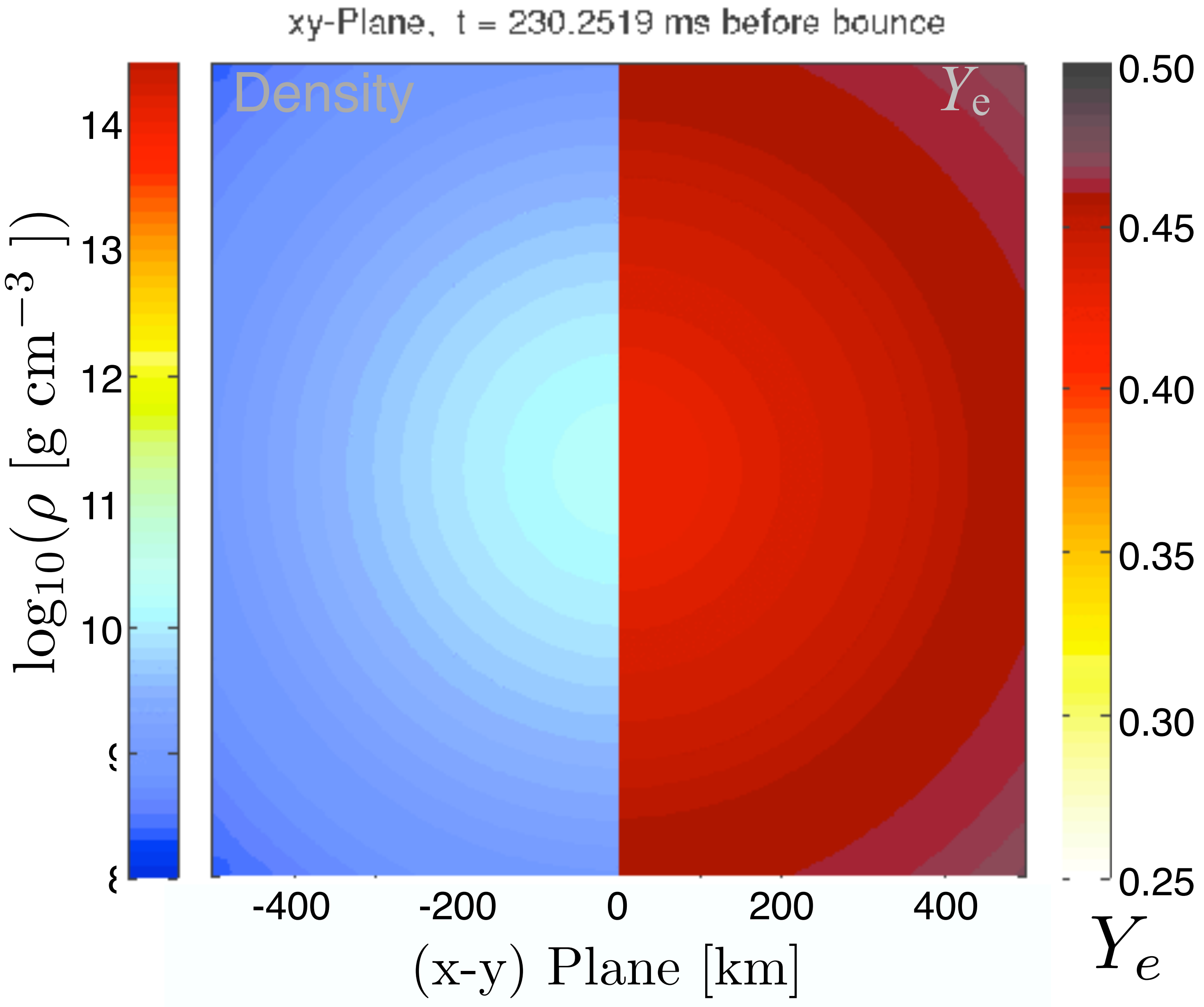

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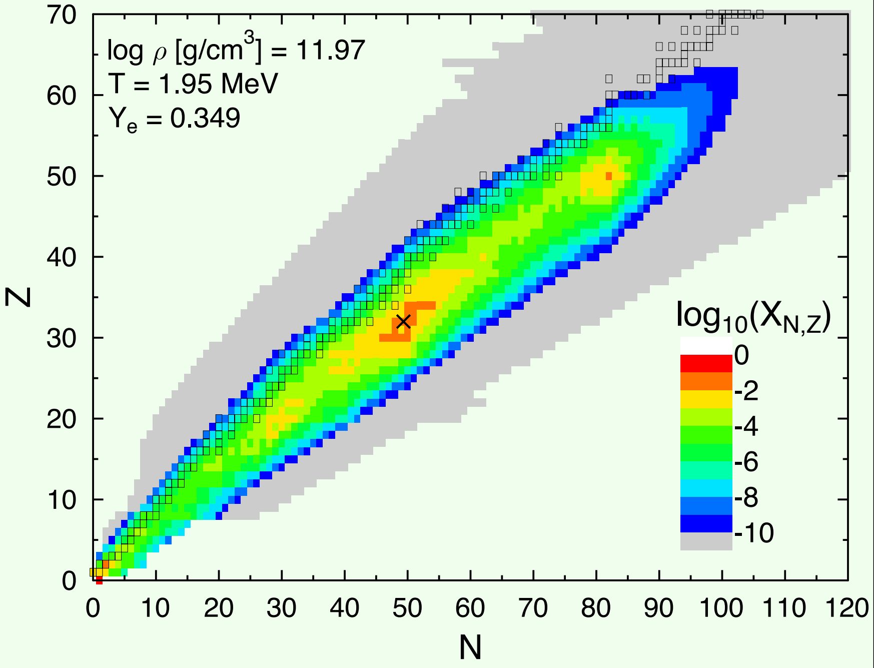
$$\ldots\ldots$$

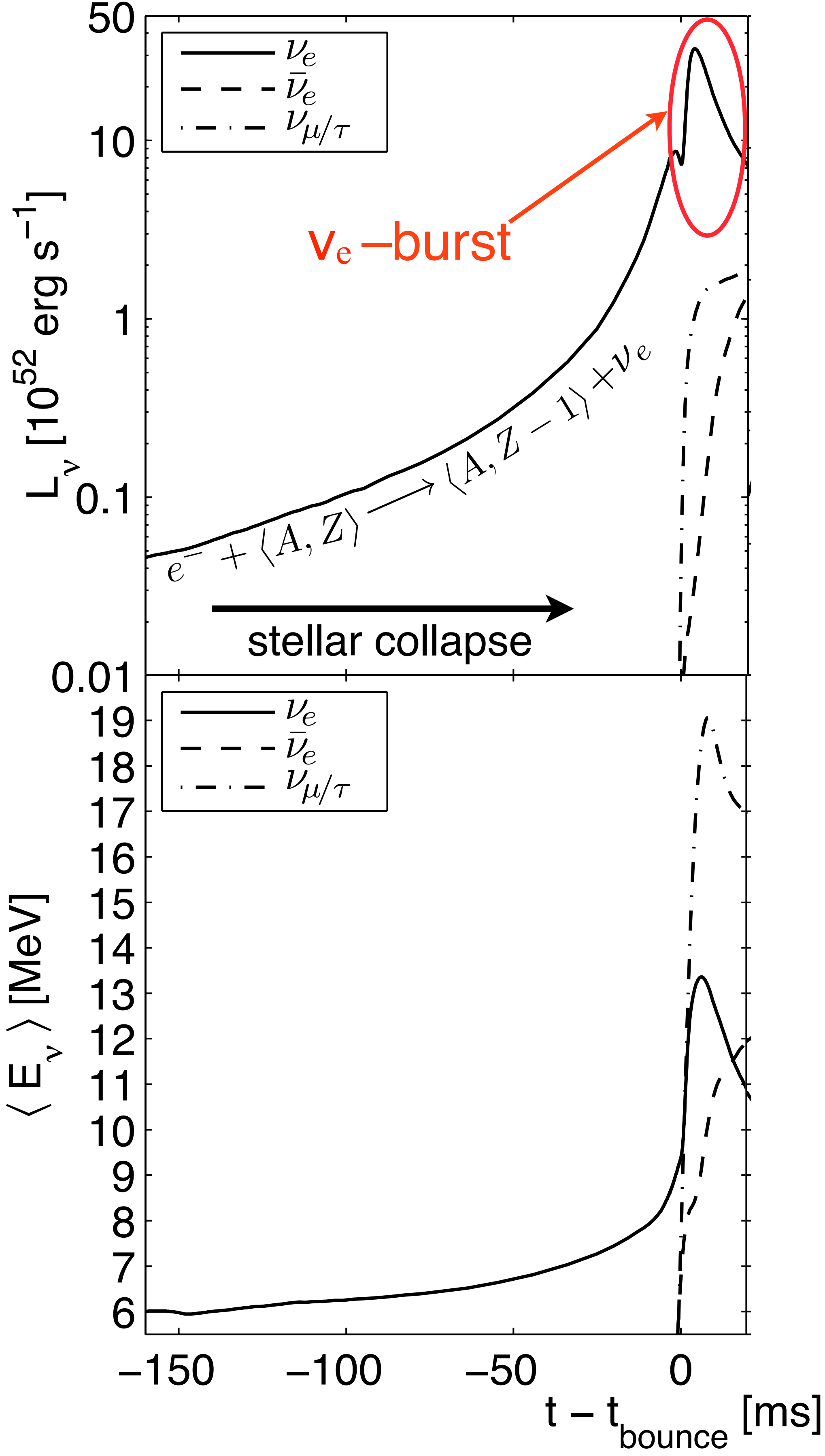
$$e^- + \langle A, Z\rangle \longrightarrow \langle A, Z-1\rangle + \nu_e$$



(Hempel & TF et al.,(2012) ApJ 748, 27)

Collapsing stellar core neutronizes; electron fraction drops; collapse proceeds adiabatically/ supersonically

Neutrino signal – infall phase



nuclear de-excitations

$$\langle A,Z\rangle^* \longrightarrow \langle A,Z\rangle + \nu + \bar{\nu}$$

Fuller & Meyer (1991), ApJ 376, 701
TF et al.,(2013) PRC 88, 065804

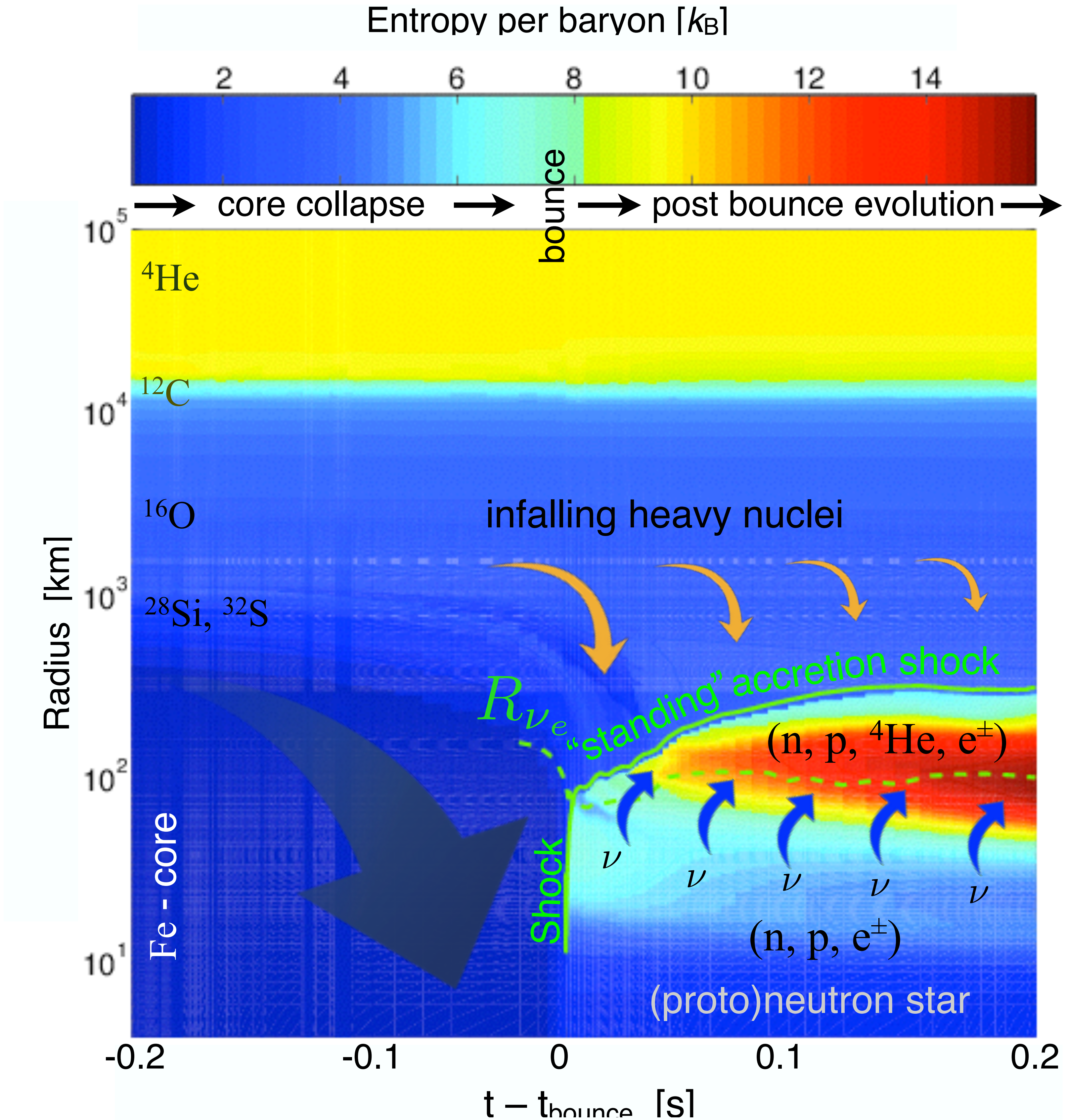
Supernova shock propagation across the sphere of last inelastic scattering (ν-sphere)

ν_e–deleptonization burst is generic feature

charged current reactions

$$e^- + p \leftrightarrows n + \nu_e$$
$$e^+ + n \leftrightarrows p + \bar{\nu}_e$$

Supernova evolution in a nutshell



Collapse halts at saturation density where the core bounces back with the **formation of shock wave**

Rapid shock acceleration to radii of about 100–200 km

Still gravitationally unstable outer layers of the stellar core; stellar collapse continues

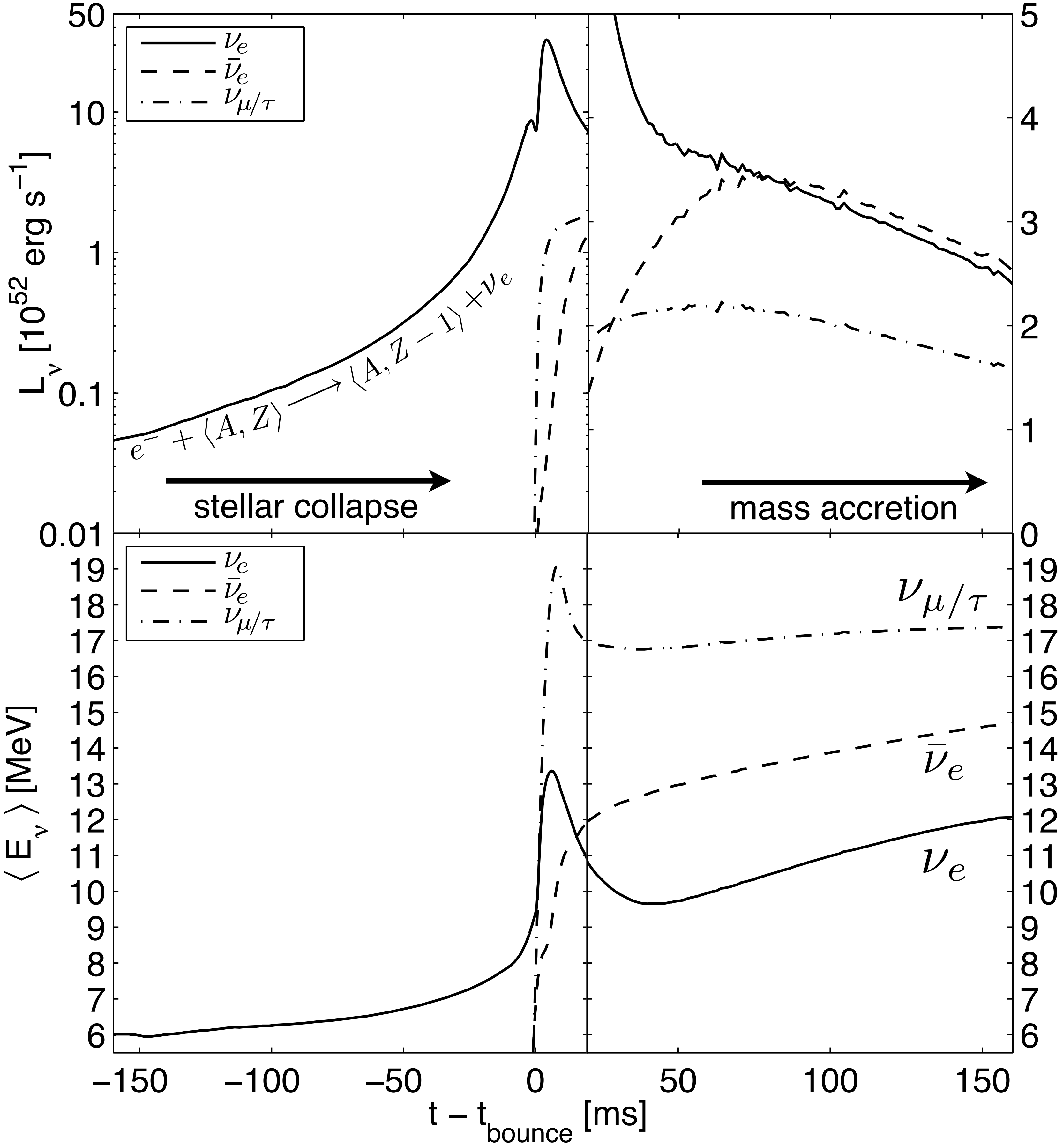
Shock stalling due to energy losses – **no prompt explosions**

Later evolution determined from energy-balance due to:

(a) ram pressure from mass accretion; infalling material ahead of shock

(b) energy liberation (transport) deposition behind accretion shock

Neutrino signal – post-bounce



charged current reactions

$$e^- + p \leftrightarrows n + \nu_e$$
$$e^+ + n \leftrightarrows p + \bar{\nu}_e$$

pair processes

$$e^- + e^+ \leftrightarrows \nu + \bar{\nu}$$
$$N + N \leftrightarrows N + N + \nu + \bar{\nu}$$
$$\nu_e + \bar{\nu}_e \leftrightarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$

elastic scattering

$$\nu + N \leftrightarrows \nu' + N$$

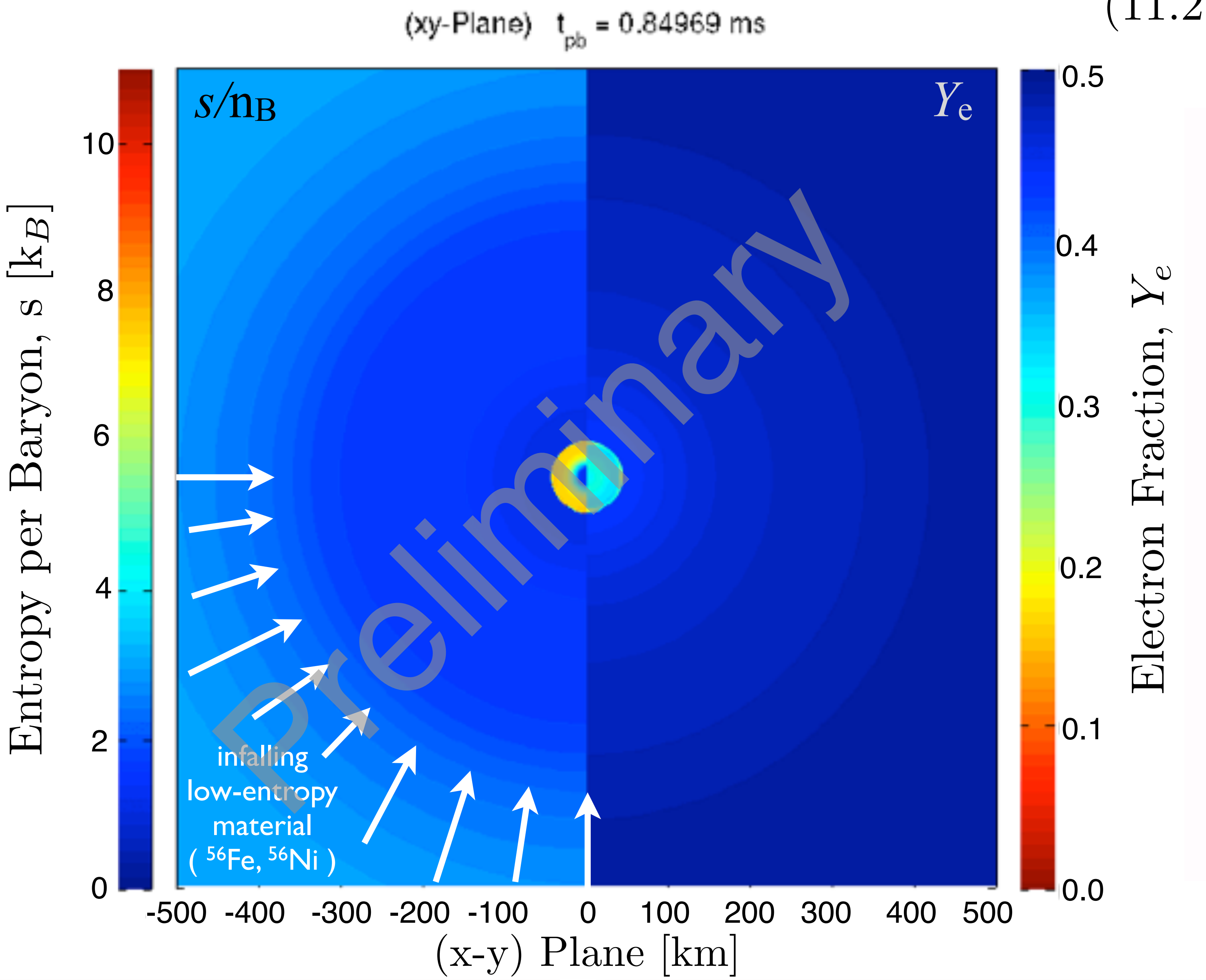
inelastic scattering

$$\nu + e^\pm \leftrightarrows \nu' + e^\pm$$

Neutrino-energy hierarchy reflects strength of coupling to matter

Triggering the explosion onset

(11.2 $M_\odot$)



<u>Neutrino heating (& cooling):</u>

E_ν = 3 – 6 x 10^{53} erg (available)

E_{expl} ~ 10^{50} – 10^{51} erg
(kinetic energy of ejecta)

(Bethe & Wilson (1985) ApJ 295, 14)

<u>Alternative scenarios:</u>

Magnetic fields
(Le Banc & Wilson (1970) ApJ 161, 542)

Sound waves
(Burrows et al.,(2006) ApJ 640, 878)

High-density phase transition
(Sagert & TF et al.,(2009) PRL 102, 081101)

General concept: Energy liberation from central protoneutron star (PNS) to standing shock

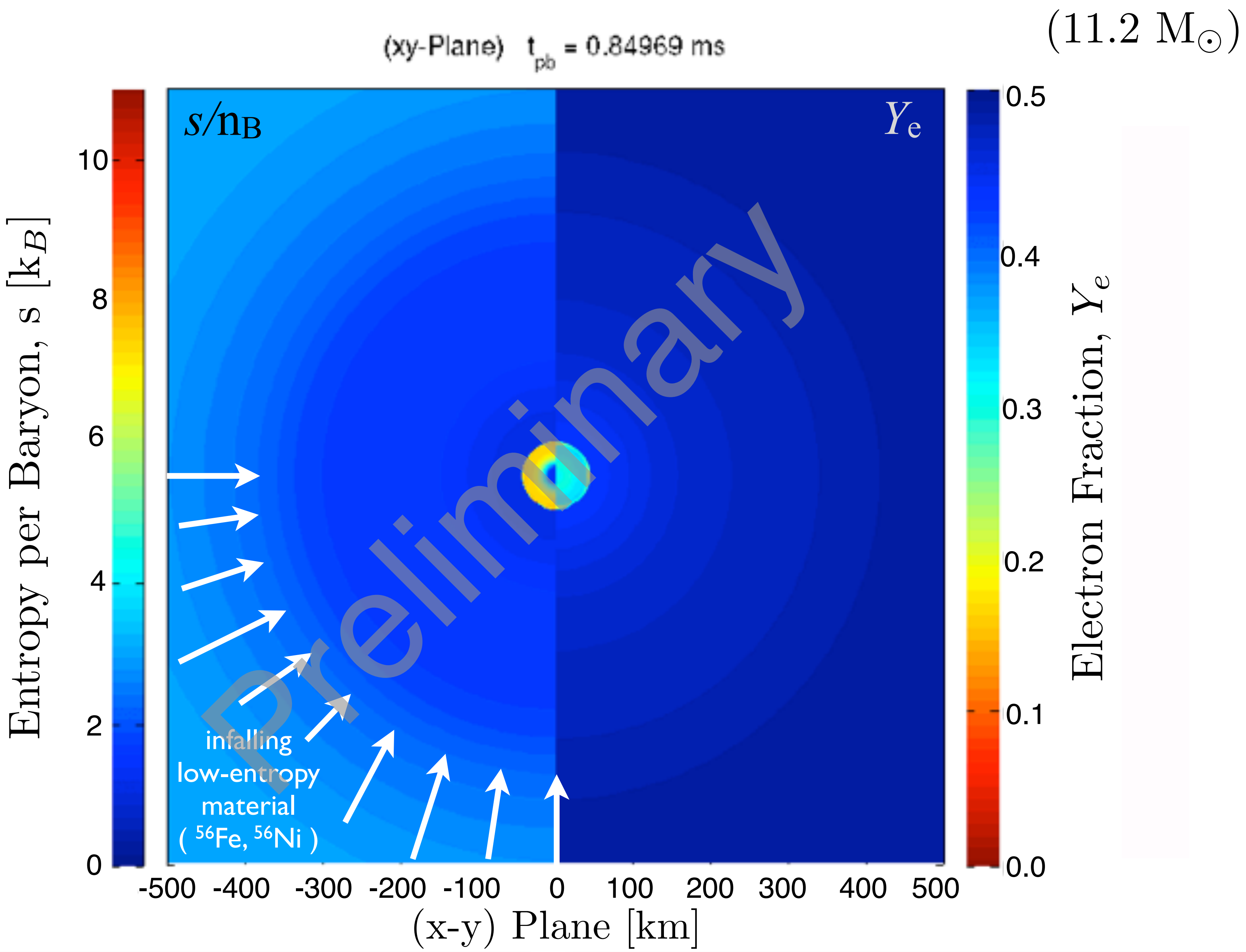
Continuous energy deposition that drives shock to increasingly larger radii
(timescale: ~100 milliseconds)

Ejection of the stellar mantle; leaves *bare* PNS behind

Yam & Leonard (2009) Nature 458
A massive hypergiant star as the progenitor of the supernova SN 2005gl

“. . . was a single star and that it indeed vanished following the explosion of SN 2005gl . . . On the basis of its luminosity, such a star is likely to be an extreme member of the group of luminous blue variable stars (LBVs), which are thought to be very massive (>50 M_{solar}) short-lived stars.”

Triggering the explosion onset



Neutrino heating (& cooling):

$E_\nu = 3 - 6\ x\ 10^{53}$ erg (available)

$E_{expl} \sim 10^{50} - 10^{51}$ erg
(kinetic energy of ejecta)

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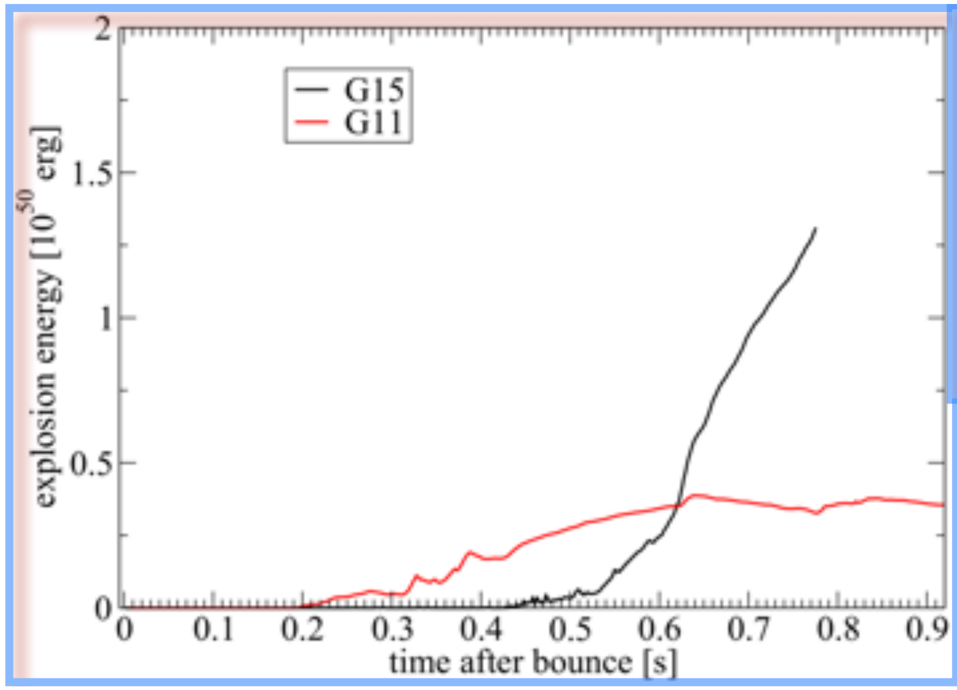
Neutrino-driven supernova success stories



- Müller et al.,(2012) ApJ 756, 22 (2D, energy- and angle-dependent neutrino transport; ray-by-ray approximation) $(9.6,\ 11.2,\ 15,\ 27\ \mathrm{M}_\odot)$

- Sumiyoshi et al.,(2014) ApJS 216, 37 (static field, angle- and energy-dependent Boltzmann-like transport; comparison with ray-by-ray approximation)

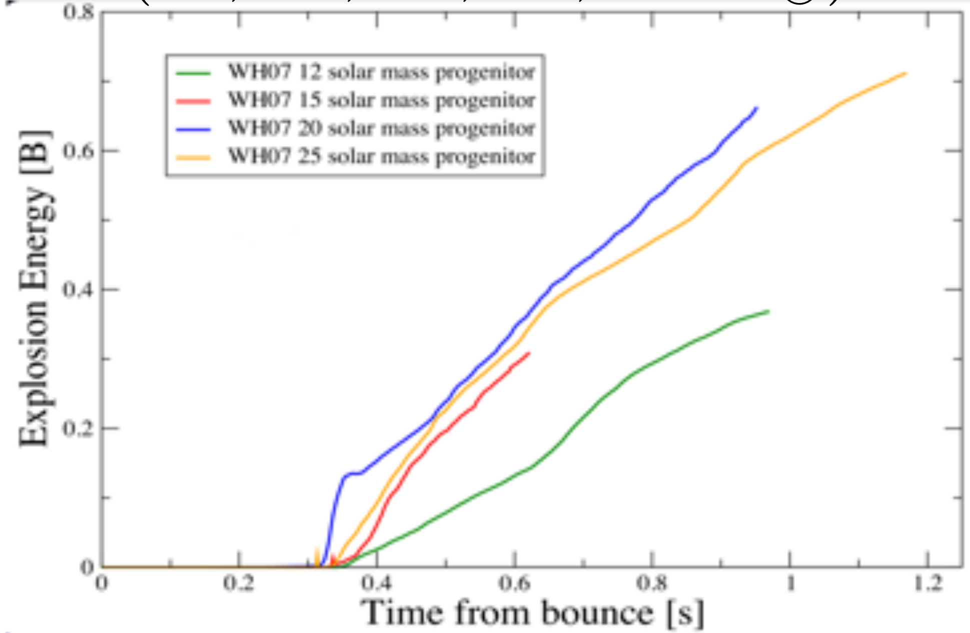
- Roberts et al.,(2016) astro-ph/arXiv 1604.07848 $(27\ \mathrm{M}_\odot)$ (full 3D, energy-dependent transport @ 3D Cartesian grid)

- Pan et al.,(2016) ApJ 817, 33

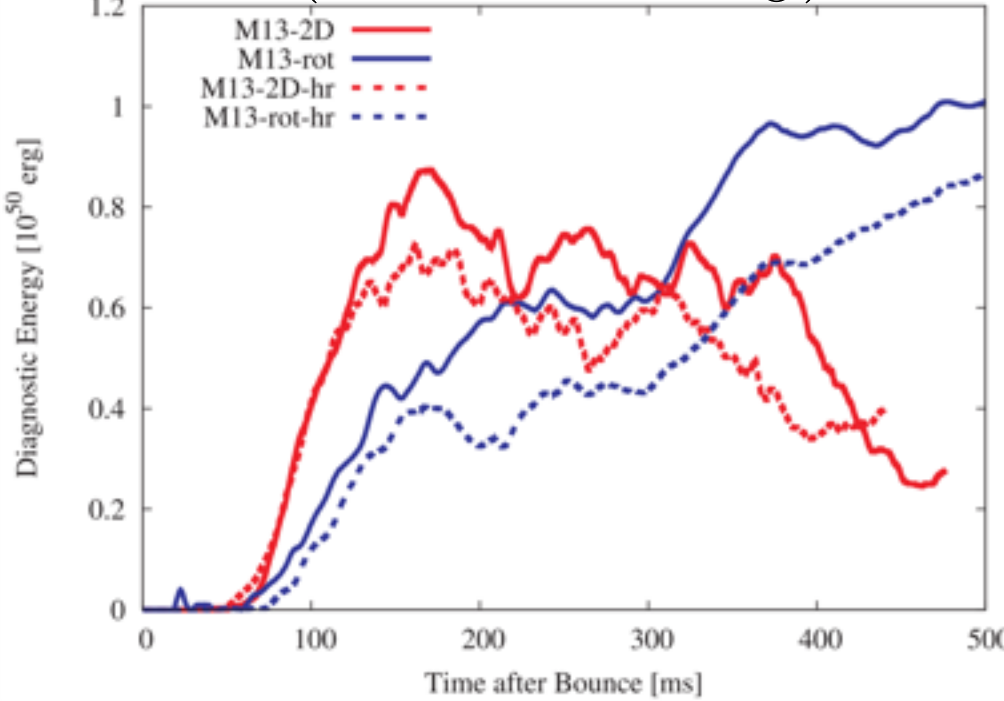
  (2D, energy-dependent isotropic diffusion source approximation)

  $(15,\ 20\ \mathrm{M}_\odot)$

- Bruenn et al.,(2013) ApJ 767, L6 (2D, energy-dependent multi-group flux-limited diffusion approximation) $(12,\ 13,\ 15,\ 20,\ 25\ \mathrm{M}_\odot)$



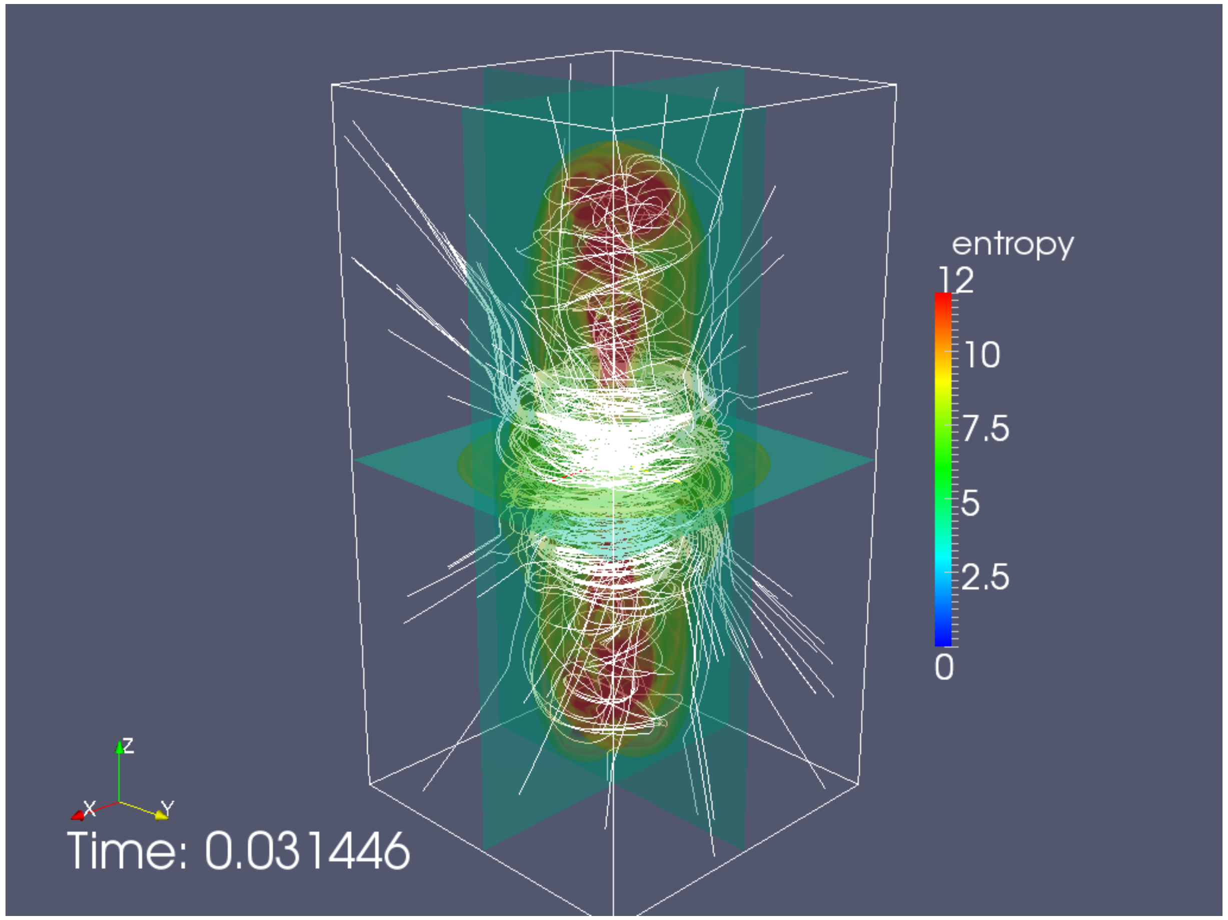
- Suwa et al.,(2013) ApJ 764, L6 (2D, energy-dependent isotropic diffusion source approximation) $(11.2,\ 13,\ 15\ \mathrm{M}_\odot)$



Not "complete" story yet - supernova problem not fully solved !

Magnetically-driven supernova explosions

Burrows et al.,(2007) ApJ 669, 585



Winteler et al.,(2013) ApJ 750, L22

Rapid rotation and amplification of magnetic field
(Le Banc & Wilson (1970) ApJ 161, 542)

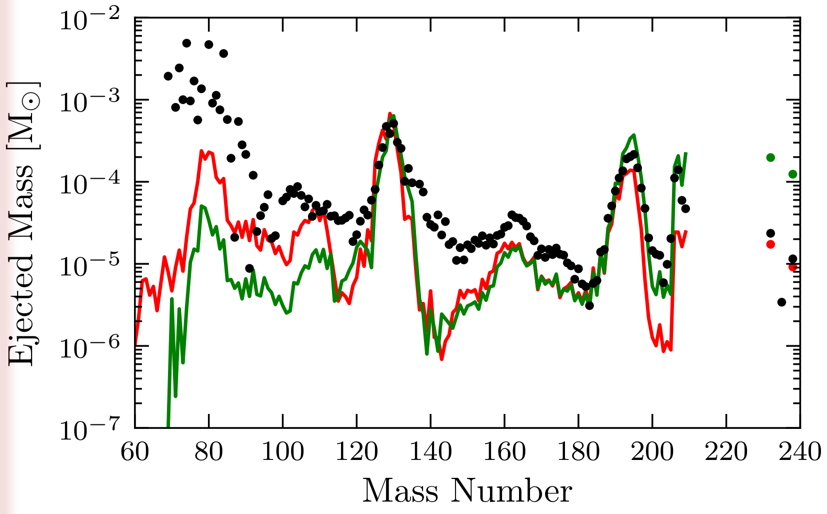
Energetic bi-polar explosions

May explain existence of magnetars

Caveat: requires very high core spin and/or initial magnetic field of stellar core

Perhaps few rare events

Associated with production of *r*-process elements:



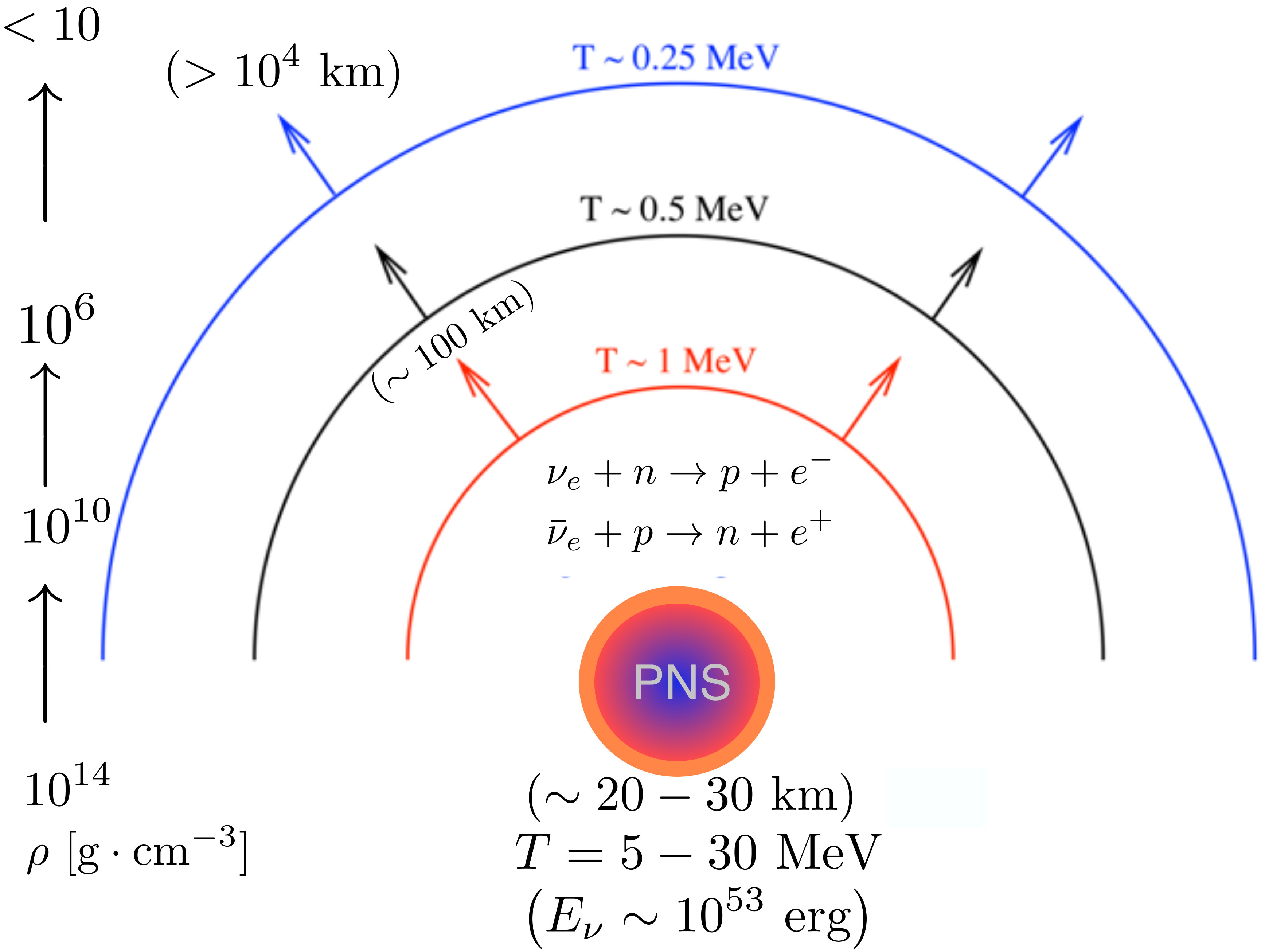
PNS deleptonization

Beyond supernova explosion onset – once the stellar mantle is ejected . . .

The supernova story continues for more than 10 seconds!

Mildly independent from details of the supernova explosion mechanism

Can be modeled in spherical symmetry



low-mass outflow:
“ν-driven wind”
(mass ejection from
PNS surface)

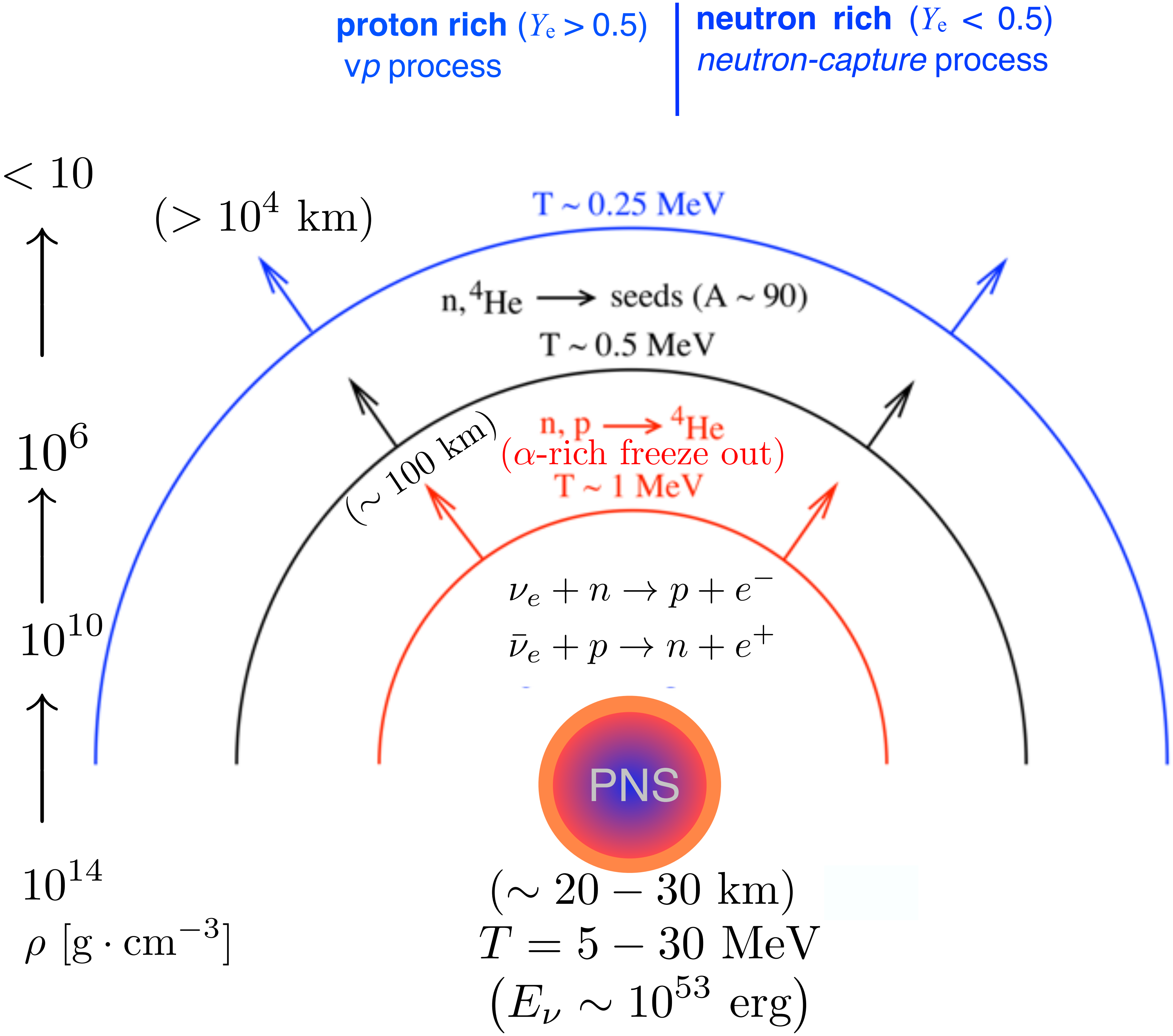
↑

neutrino heating at PNS surface

PNS deleptonization
(neutrino diffusion)

Pons et al., (1999) ApJ 513, 780

PNS deleptonization



formation of heavy nuclei ?

↑

formation of seed nuclei

↑

low-mass outflow:
“ν-driven wind”
(mass ejection from
PNS surface)

↑

**neutrino
heating at
PNS surface**

**PNS
deleptonization**
(neutrino diffusion)

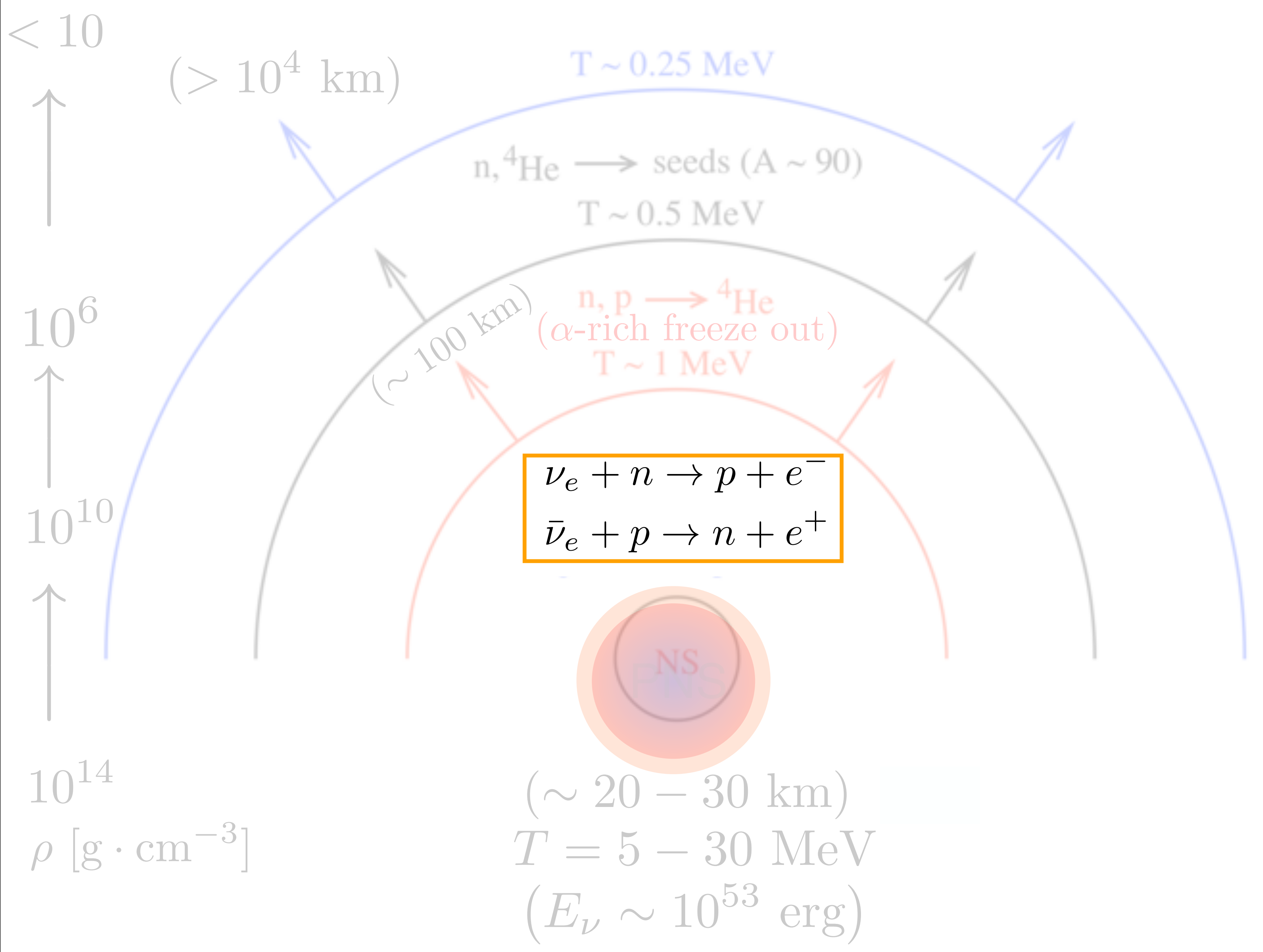
PNS deleptonization

Nucleosynthesis is determined at ν–decoupling

Deleptonization timescale:
$t = 10 - 30 \text{ s}$

proton rich ($Y_e > 0.5$)
νp process

neutron rich ($Y_e < 0.5$)
neutron-capture process



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

formation of heavy nuclei ?

formation of seed nuclei

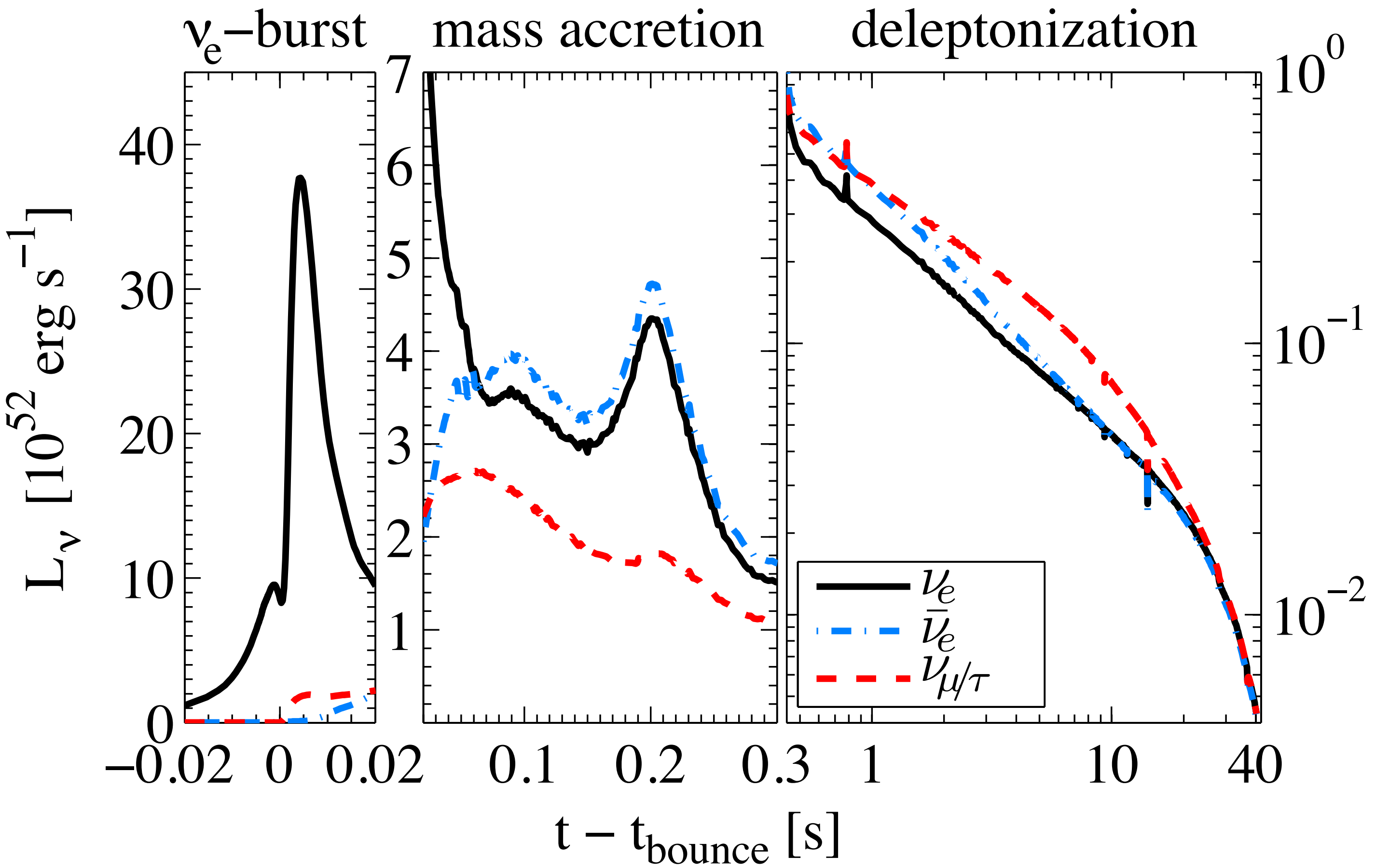
low-mass outflow:
“ν-driven wind”
(mass ejection from PNS surface)

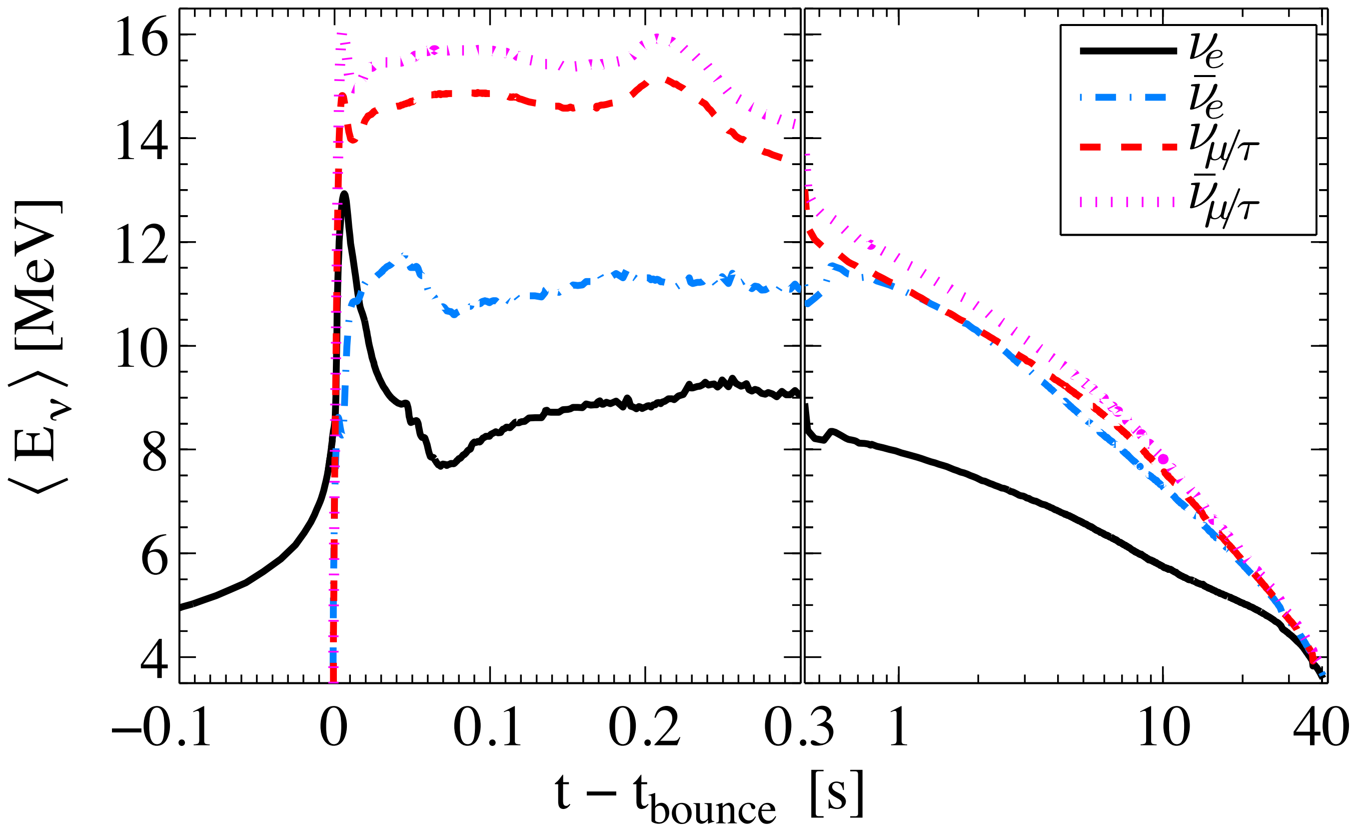
neutrino heating at PNS surface

PNS deleptonization
(neutrino diffusion)

Neutrino signal

TF et al.,(2016) PRD (submitted)





Roberts et al., (2012) PRC 86, 065803 Hüdepohl et al.,(2010) PRL 104, 251101

Qian et al., (1996) ApJ 471, 331

Current models predict small spectral difference;

$$Y_e \simeq \left(1 + \frac{\varepsilon_{\bar{\nu}_e} - 2Q + 1.2Q^2/\varepsilon_{\bar{\nu}_e}}{\varepsilon_{\nu_e} - 2Q + 1.2Q^2/\varepsilon_{\nu_e}}\right)^{-1}$$

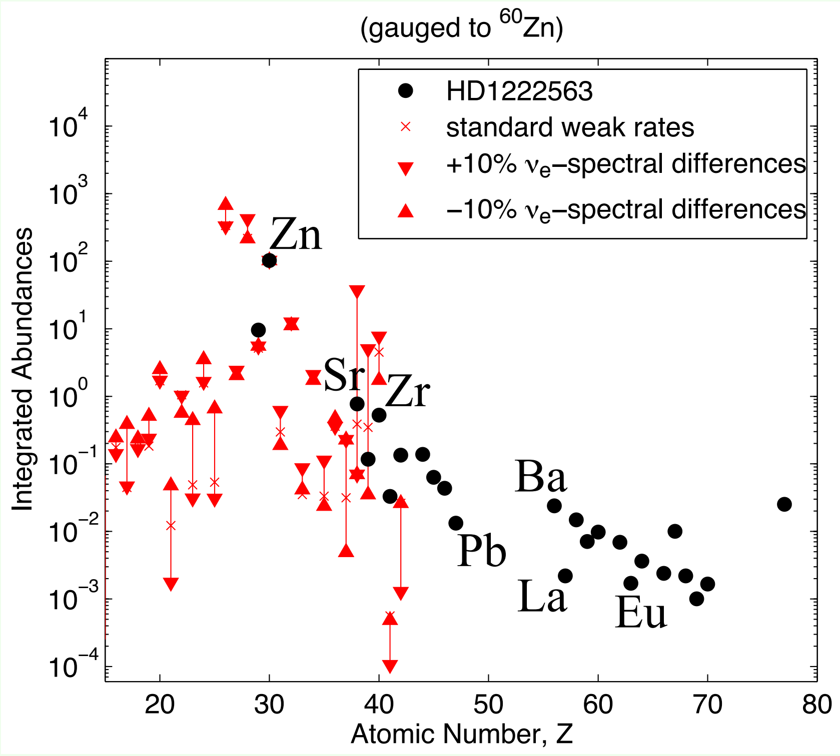
(similar neutrino luminosities)

$$\langle\varepsilon_{\bar{\nu}_e}\rangle - \langle\varepsilon_{\nu_e}\rangle \begin{cases} \gtrsim 5\ \text{MeV} & (Y_e < 0.5) \\ & \text{neutron rich} \\ < 5\ \text{MeV} & (Y_e > 0.5) \\ & \text{proton rich} \end{cases}$$

$$(\ \langle\varepsilon_\nu\rangle = \langle E_\nu^2\rangle / \langle E_\nu\rangle\ )$$

Light neutron-capture elements 38<Z<45:

Martinez-Pinedo & TF et al., (2014) JPG 41, 044008

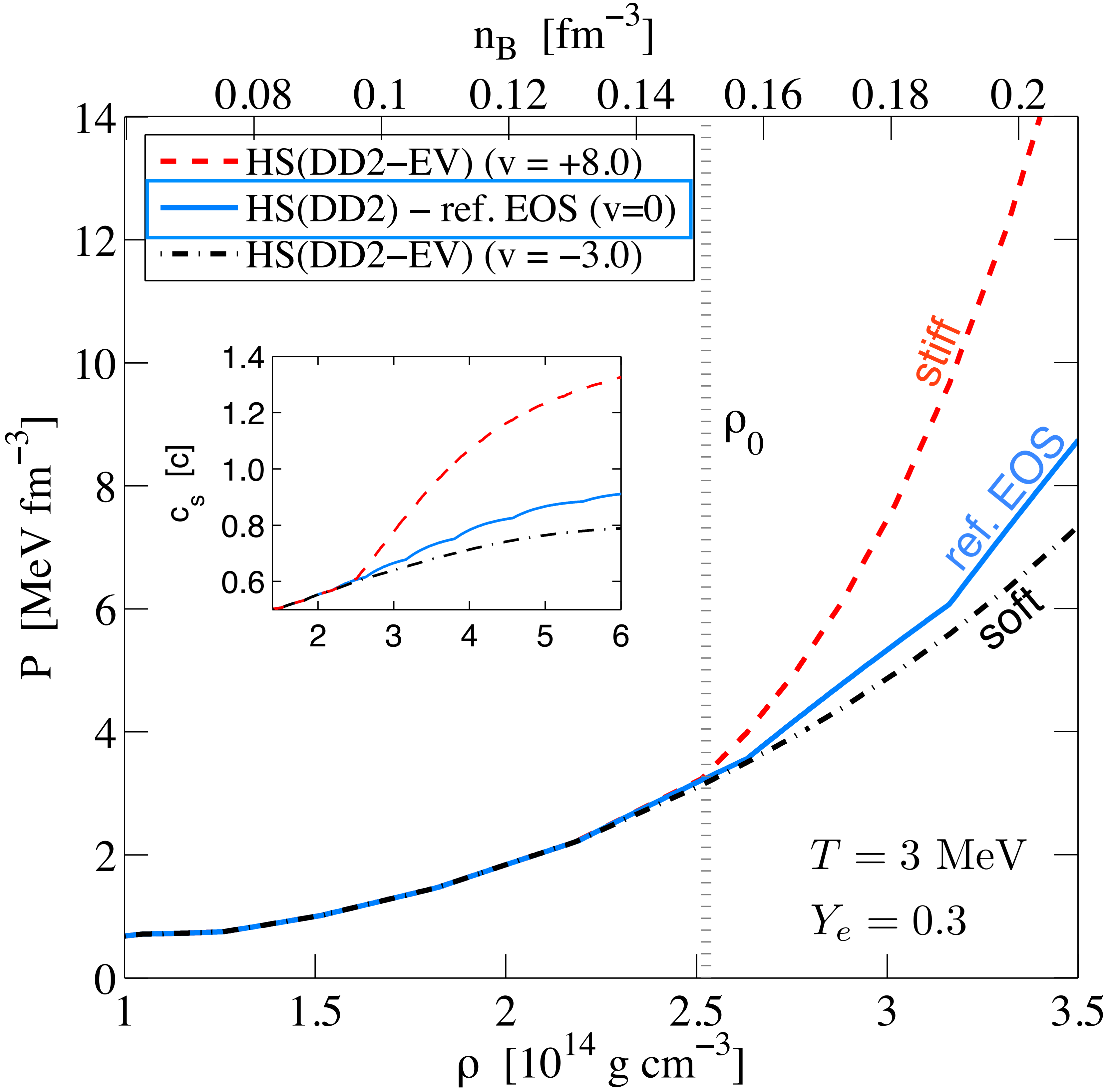


(integrated nucleosynthesis)

Equation of state dependence of the neutrino signal

Excluded volume approach

S.Typel (2016) EPJA 52,16



Geometric approach; modifying the available volume:

$$V_i = V\,\phi_i$$

$$\phi_i = 1 - \sum_j \mathrm{v}_j n_j$$

Excluded volume parameter:

$$\mathrm{v} \equiv \mathrm{v}_n = \mathrm{v}_p$$

$$\phi(\rho;\mathrm{v}) = \exp\left\{-\frac{\mathrm{v}|\mathrm{v}|}{2}(\rho-\rho_0)^2\right\}$$

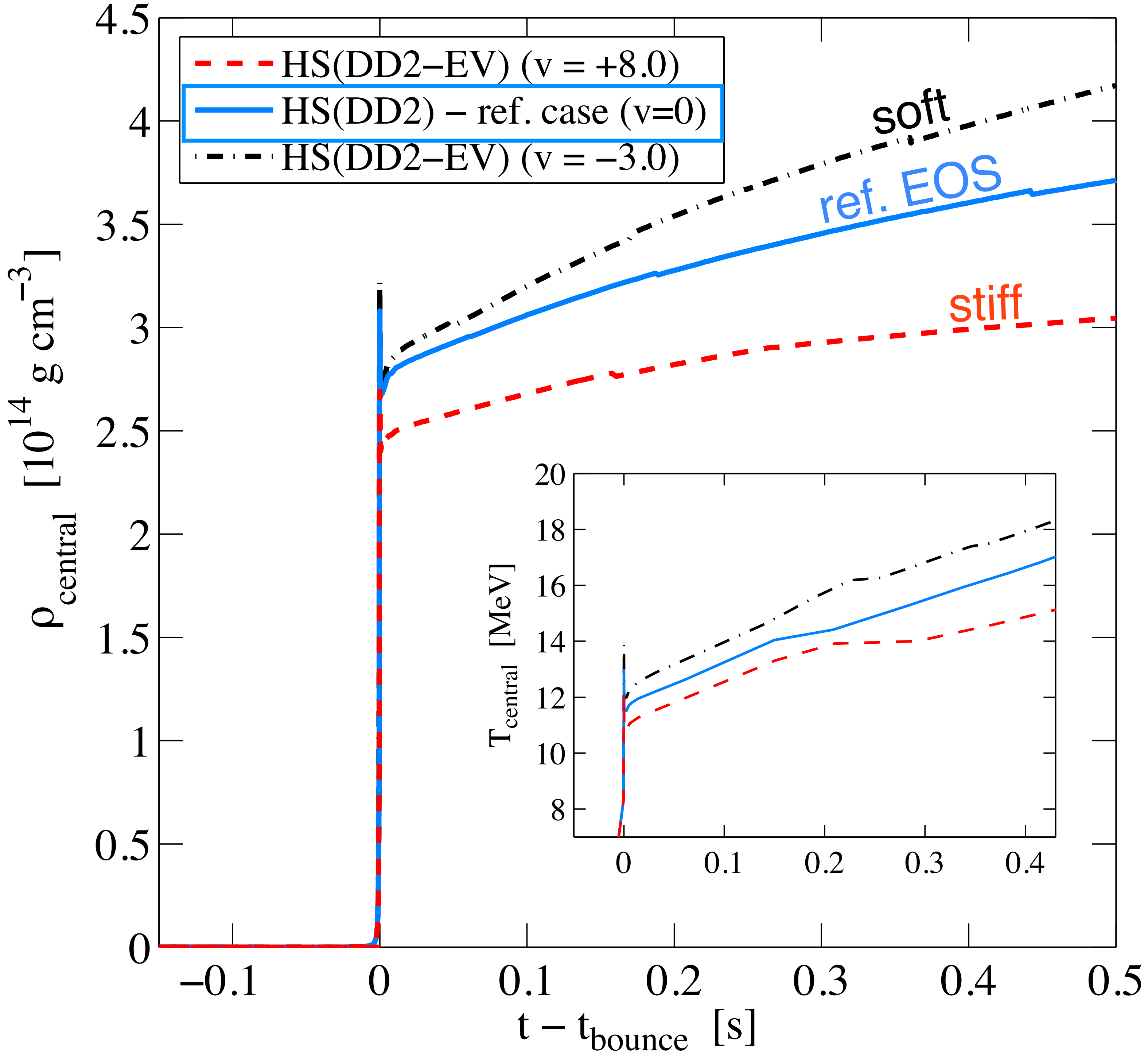
(Gauss-functional)

DD2 – RMF parameters:
$K = 243$ MeV
$S = 31.67$ MeV
$L = 55.04$ MeV

Excluded volume approach

TF (2016) EPJA 52, 54

(Evolution of central density and temperature)



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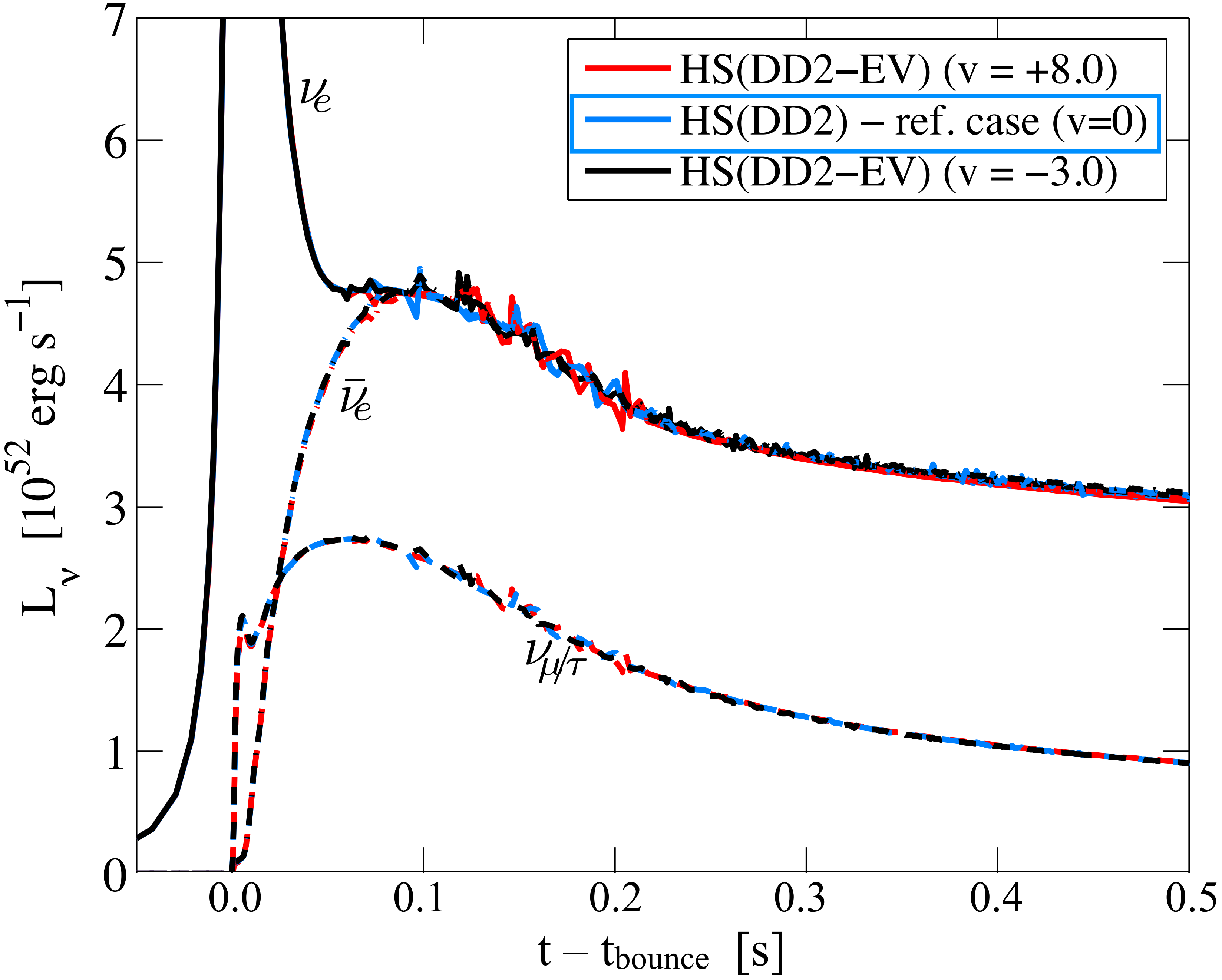
TF (2016) EPJA 52, 54



Supernova neutrino signal is insensitive to supra-saturation density EOS

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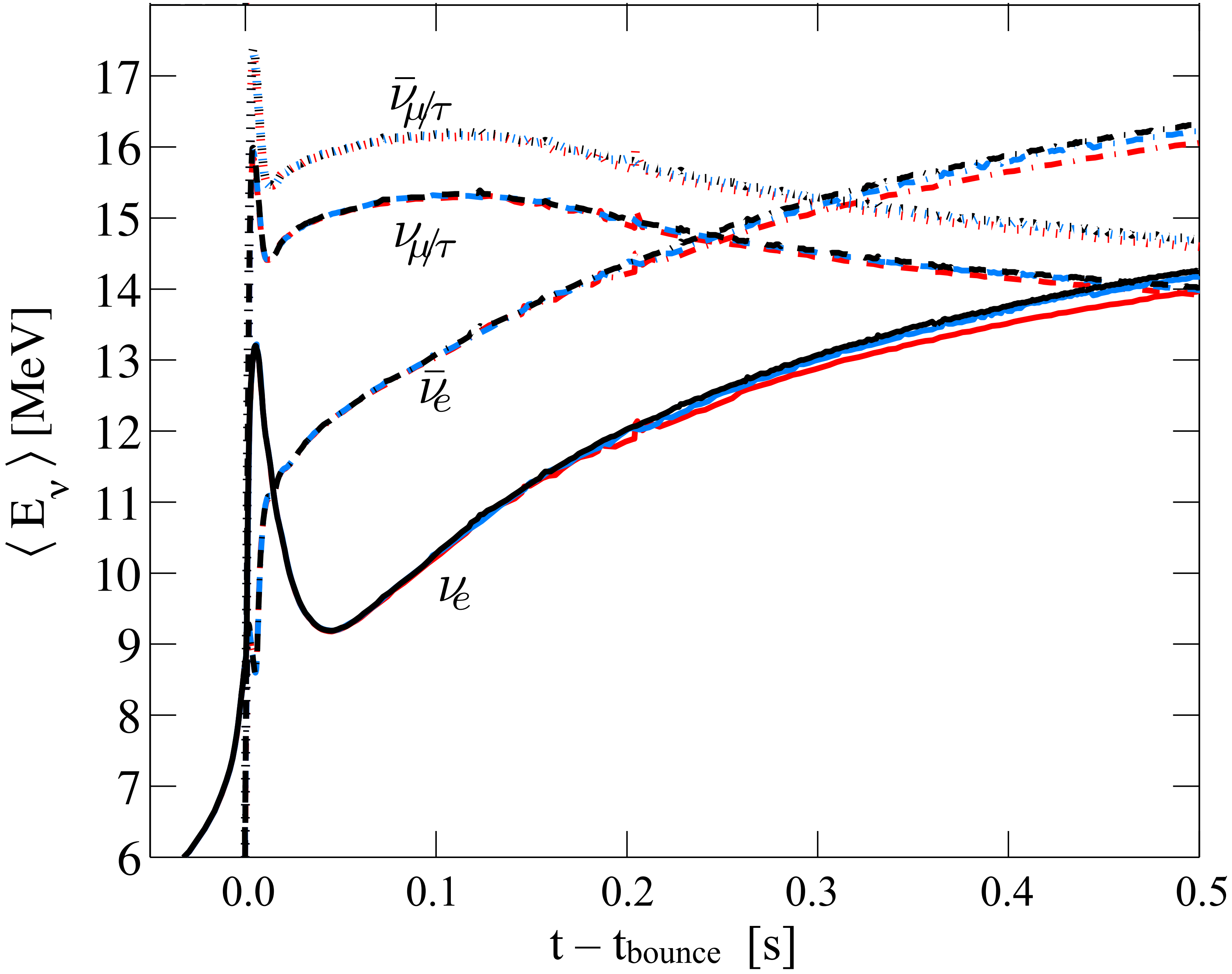
(Gauss-functional)

Affects only super-saturation density EoS; all other nuclear matter properties remain unchanged

Excluded volume approach

TF (2016) EPJA 52, 54



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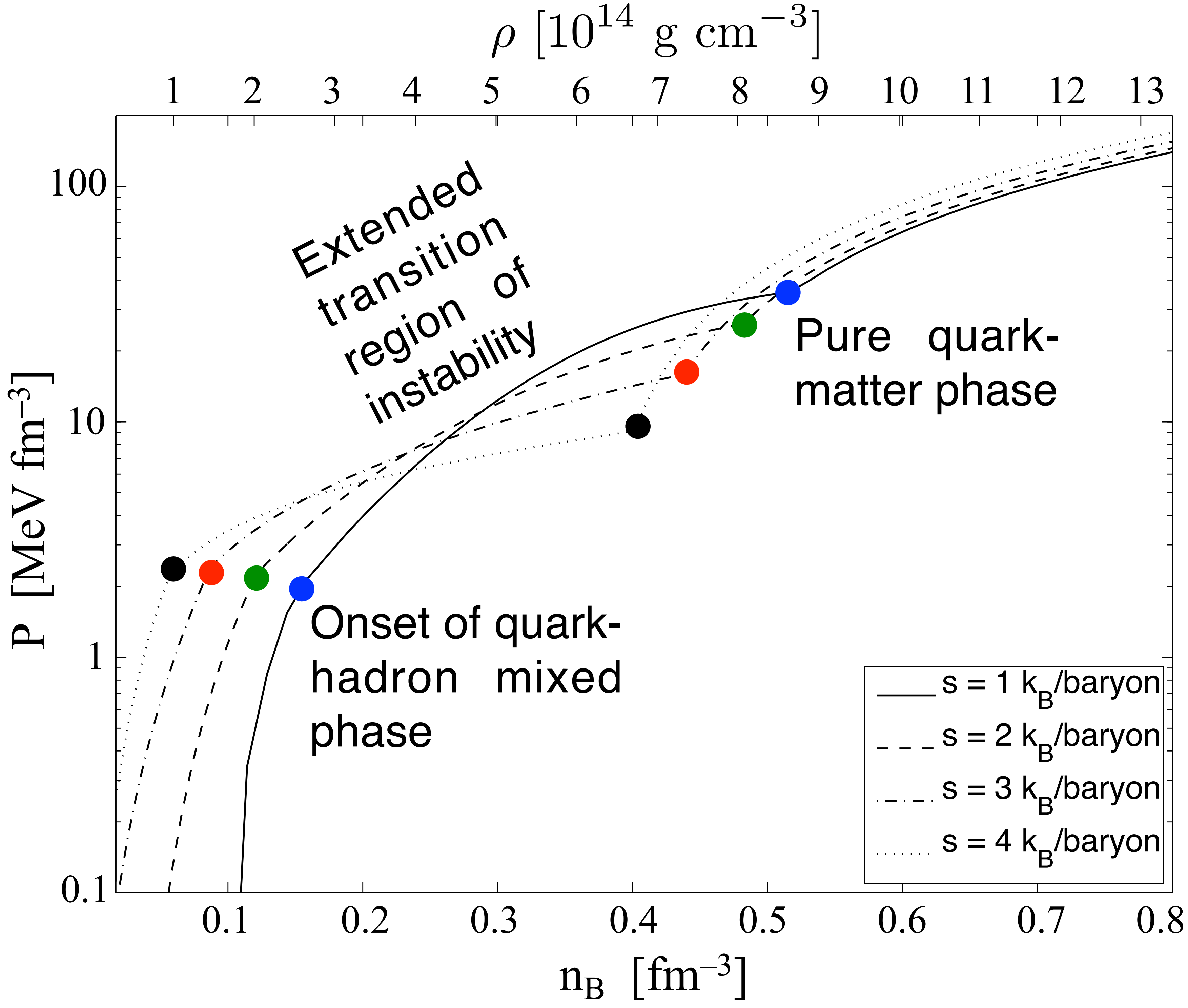
Quark-hadron phase transition



Sagert & TF et al.,(2009) PRL 102, 081101

TF et al., (2011) ApJS 194, 28

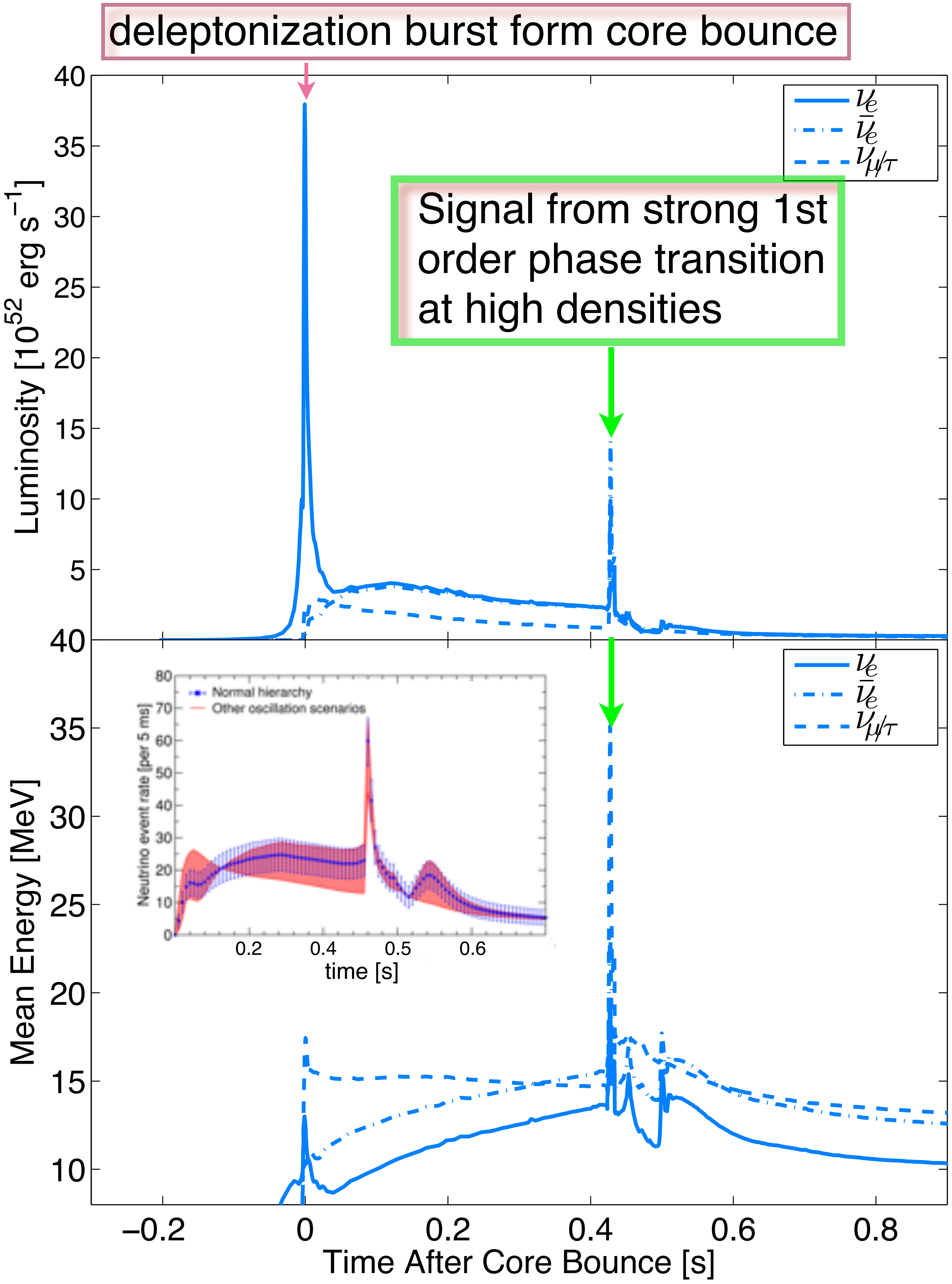
Quark matter EoS: bag model with fixed bag pressure

Transition from some nuclear model (TM1)

Hadron-quark transition region: extended phase of instability; large latent heat

Quark-hadron phase transition

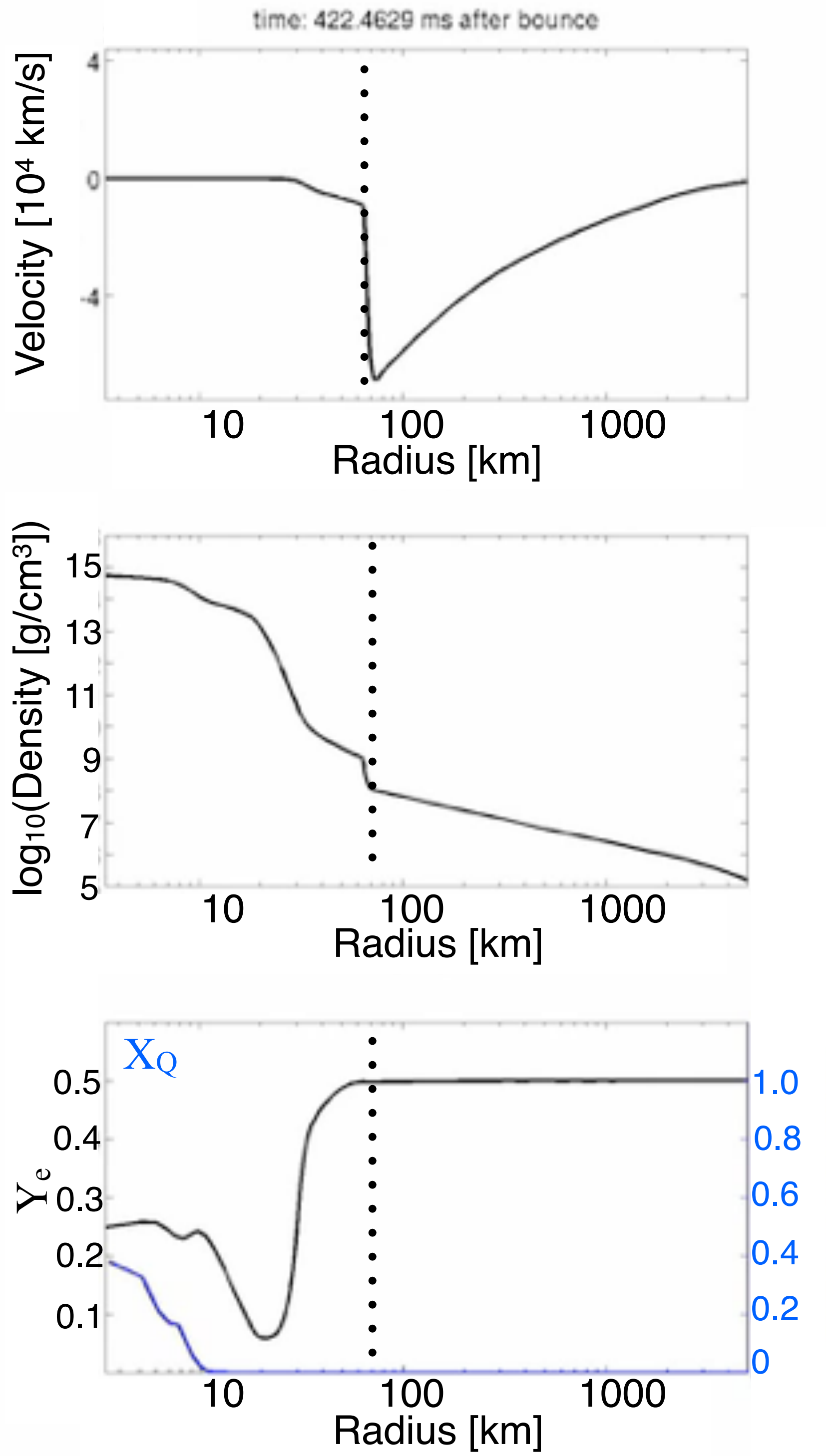
Sagert & TF et al. (2009), PRL 102, 081101



deleptonization burst form core bounce

Signal from strong 1st order phase transition at high densities

Dasgupta & TF et al. (2010), PRC 81



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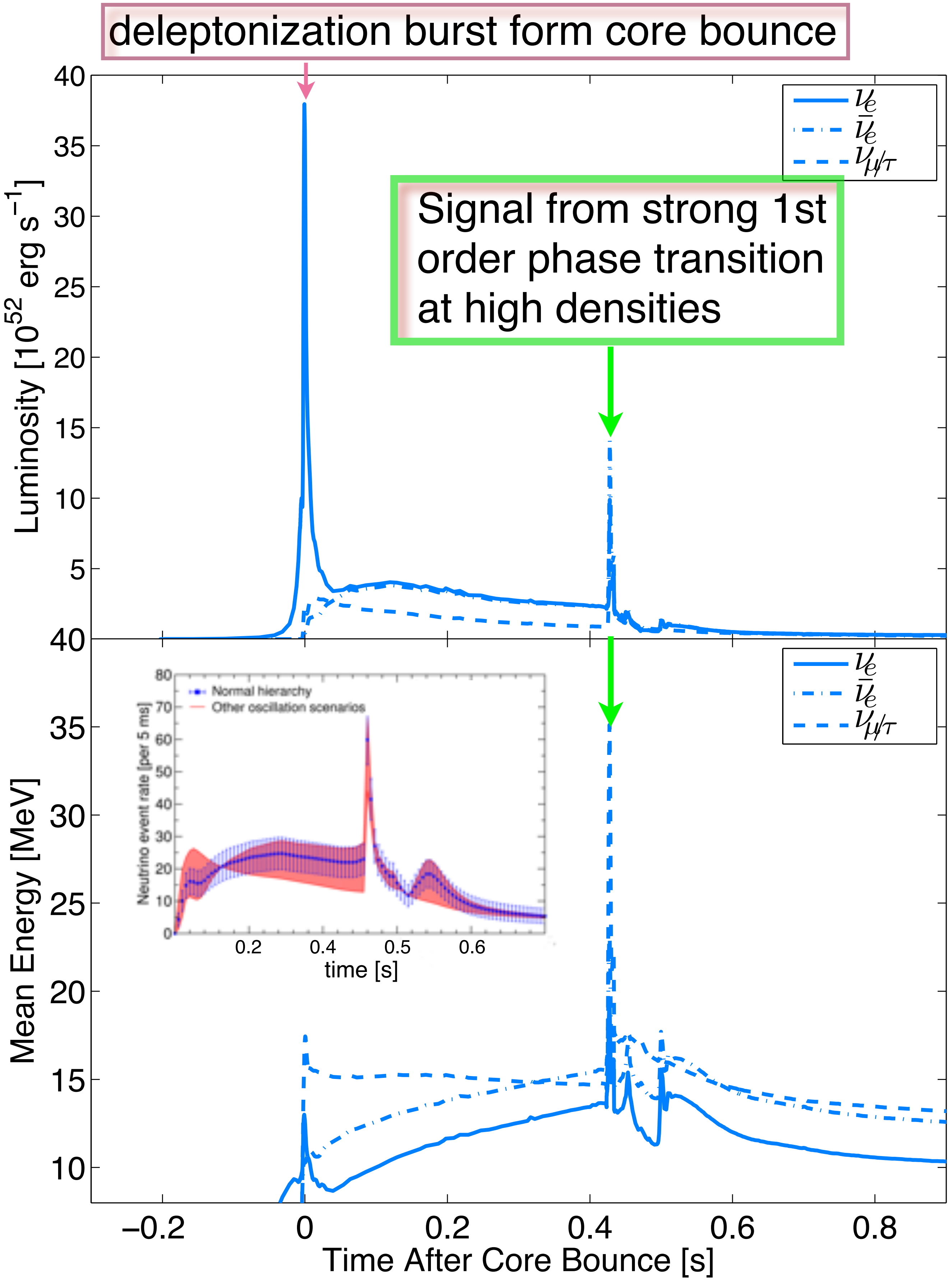
Sagert & TF et al. (2009), PRL 102, 081101



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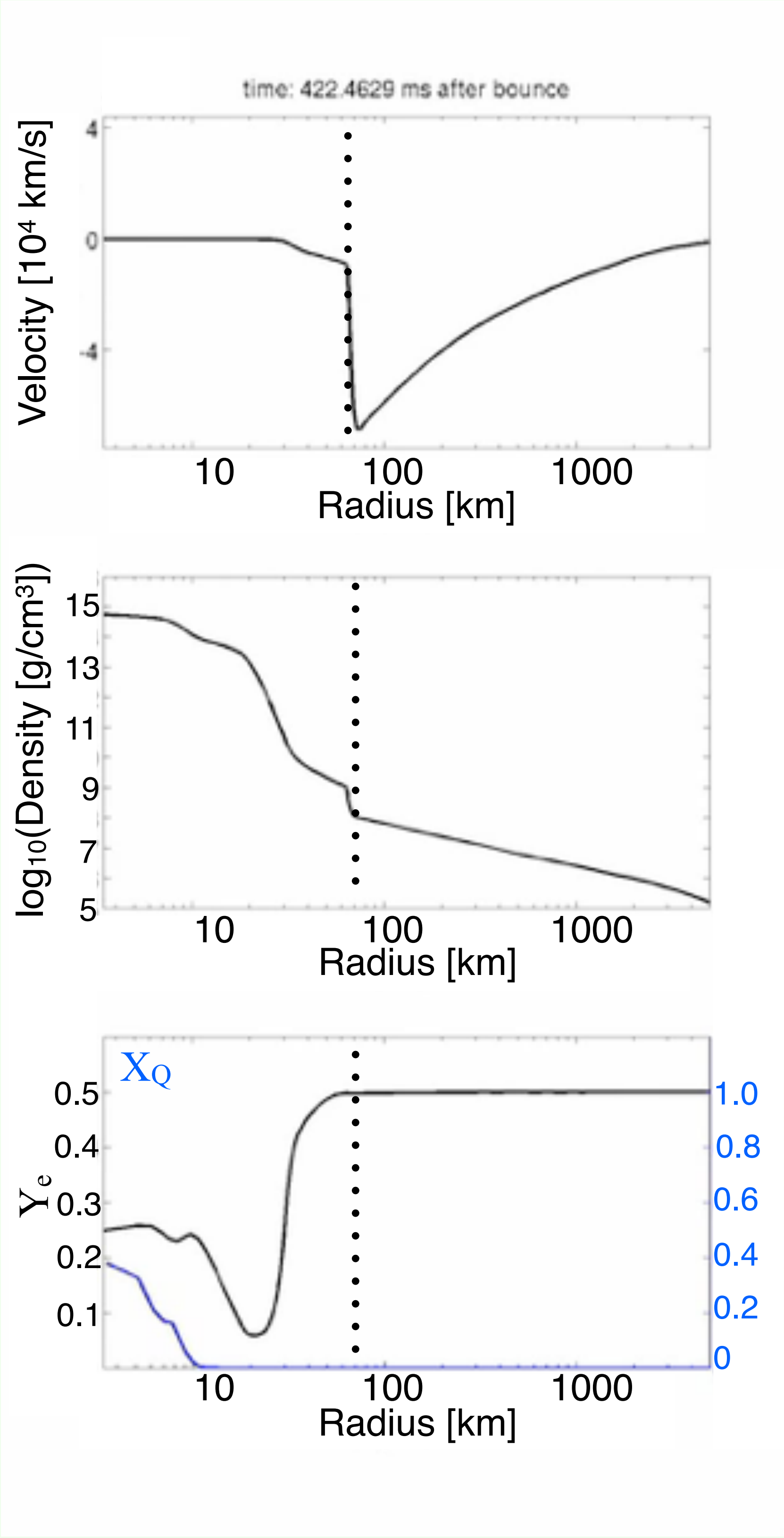

Summary

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Neutrino signal from core-collapse supernovae mildly insensitive to supra-saturation density EoS

Great progress in modeling, in particular in view of multi-dimensional nature

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Neutrino signal from core-collapse supernovae mildly insensitive to supra-saturation density EoS

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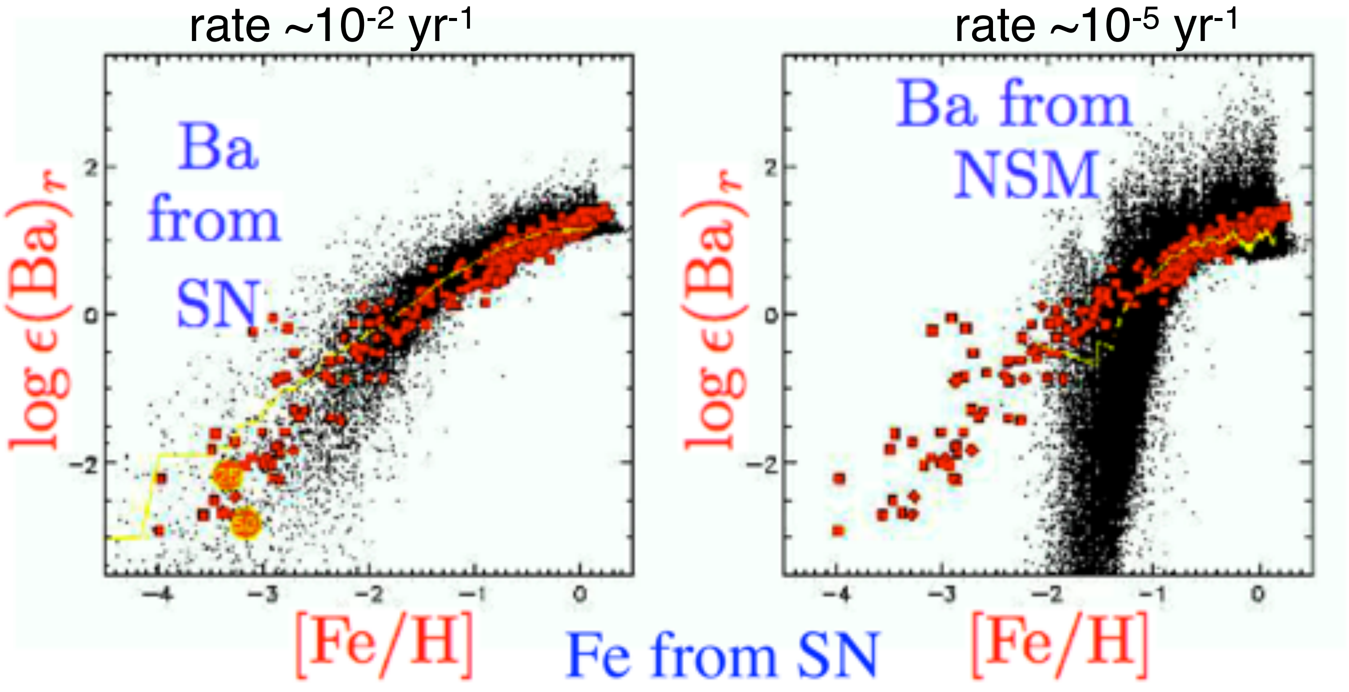
Massive star explosions (canonical) cannot explain galactic enrichment of **heavy** neutron-capture elements; $38<Z<45$

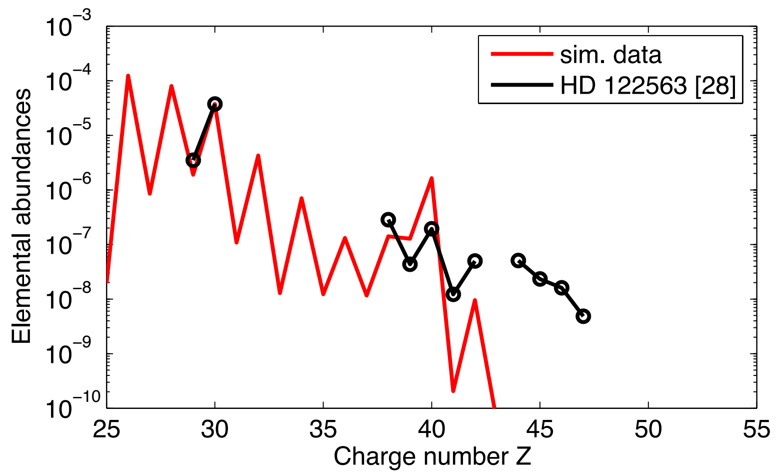
Puzzle at low metallicity (?) – chemical evolution models:

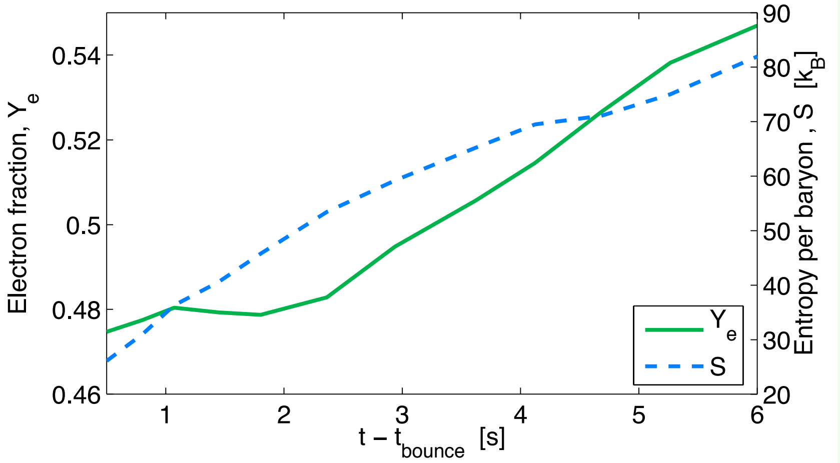
(a) Core-collapse supernovae (SNe) (b) Neutron star merger (NSM)



Argast et al., (2004) A&A 416, 997

Yuan et al.,(2016) MNRAS 456, 3253





Consistent with metal-poor star observations (HD 122563)

Summary

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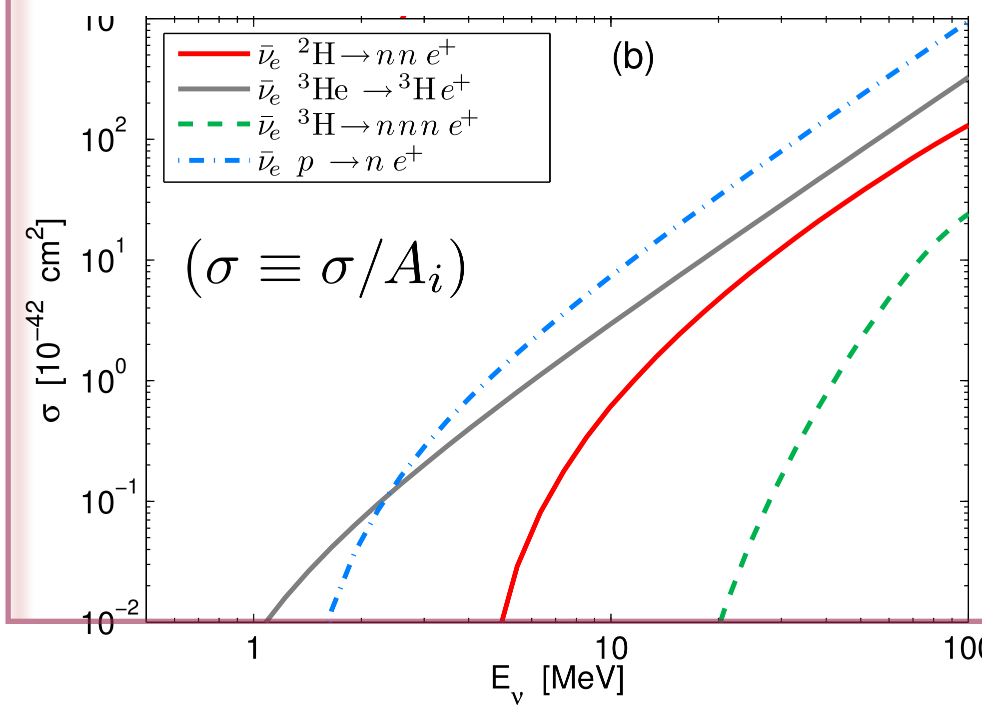
Puzzle at low metallicity (?) – chemical evolution models:

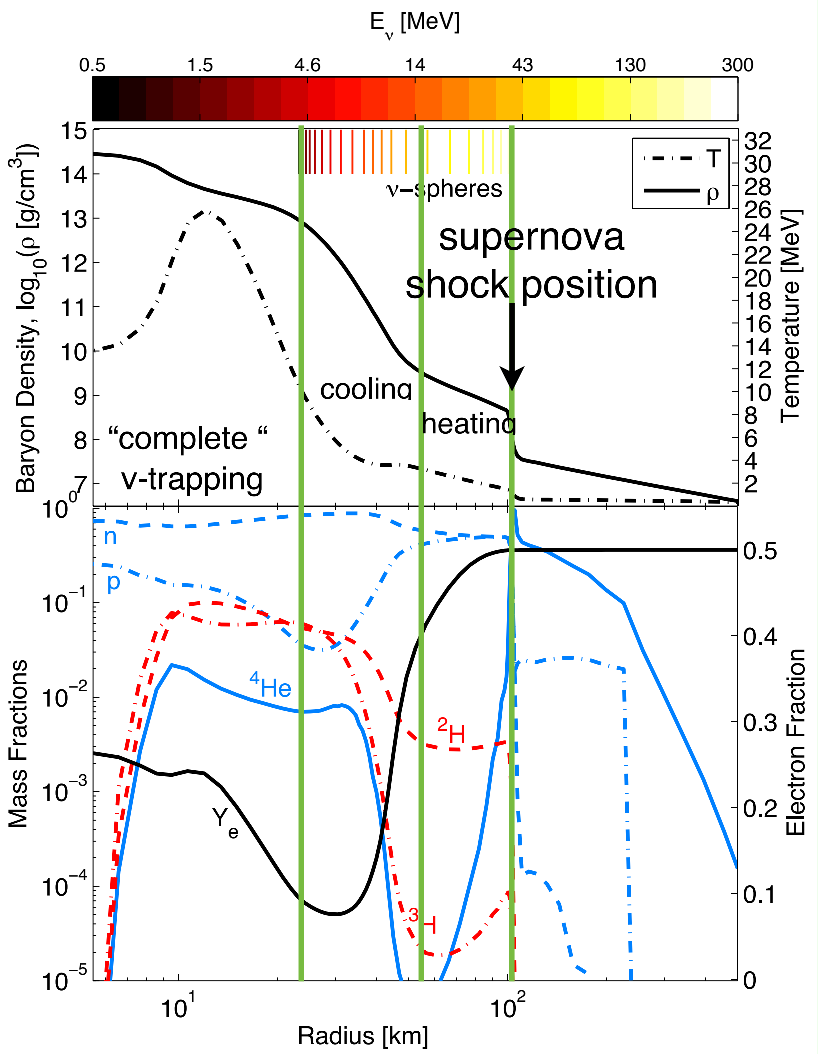
Role of light nuclear clusters (?) Requires consideration of associated weak processes consistent with EoS

TF. et al.,(2016) EPJWC.10906002F



Nakamura et al.,(2001) PRC63, 034617
Furusawa et al.,(2013) ApJ 774, 13
Nasu et al.,(2015) ApJ 801, 12

$$
\begin{array}{c}
\hline\hline
\nu_e\, {}^2\mathrm{H} \rightleftarrows p\,p\,e^- \\
\bar{\nu}_e\, {}^2\mathrm{H} \rightleftarrows n\,n\,e^+ \\
\nu_e\, n\,n \rightleftarrows {}^2\mathrm{H}\,e^- \\
\bar{\nu}_e\, p\,p \rightleftarrows {}^2\mathrm{H}\,e^+ \\
\nu_e\, {}^3\mathrm{H} \rightleftarrows n\,p\,p\,e^- \\
\bar{\nu}_e\, {}^3\mathrm{H} \rightleftarrows n\,n\,n\,e^+ \\
\nu_e\, {}^3\mathrm{H} \rightleftarrows {}^3\mathrm{He}\,e^- \\
\bar{\nu}_e\, {}^3\mathrm{He} \rightleftarrows {}^3\mathrm{H}\,e^+ \\
\hline
\nu\, {}^2\mathrm{H} \rightleftarrows p\,n\,\nu \\
\nu\, {}^2\mathrm{H} \rightleftarrows {}^2\mathrm{H}\,\nu \\
\nu\, {}^3\mathrm{H} \rightleftarrows {}^3\mathrm{H}\,\nu \\
\nu\, {}^3\mathrm{He} \rightleftarrows {}^3\mathrm{He}\,\nu \\
\hline
\end{array}
$$



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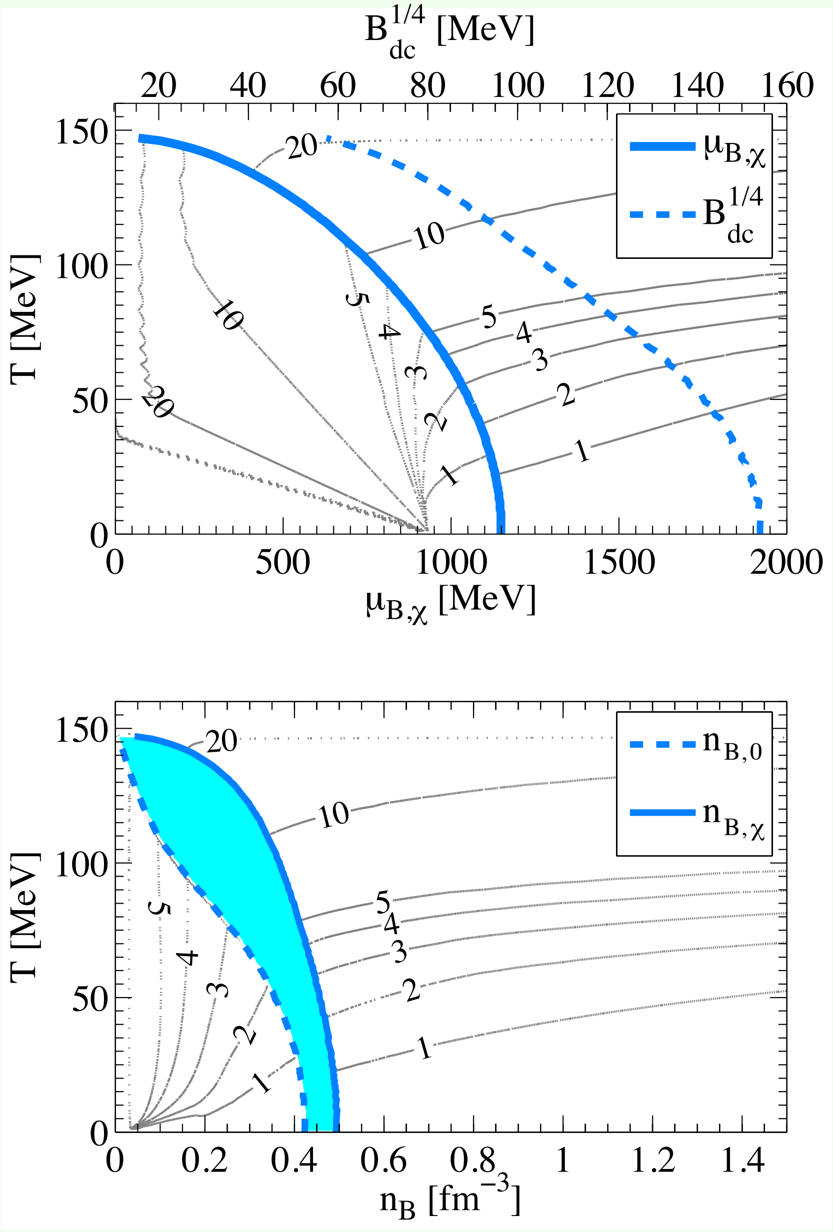
Role of light nuclear clusters (?) Requires consideration of associated weak processes consistent with EoS

Any chance for quark matter (???) Develop more sophisticated (microscopic) quark matter EoS; chiral physics, finite temperatures and isospin asymmetry

$$M_{\max} \simeq 2\ \mathrm{M}_\odot$$



Klähn & TF (2015) ApJ 810, 8

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Thanks for your attention

In collaboration with:

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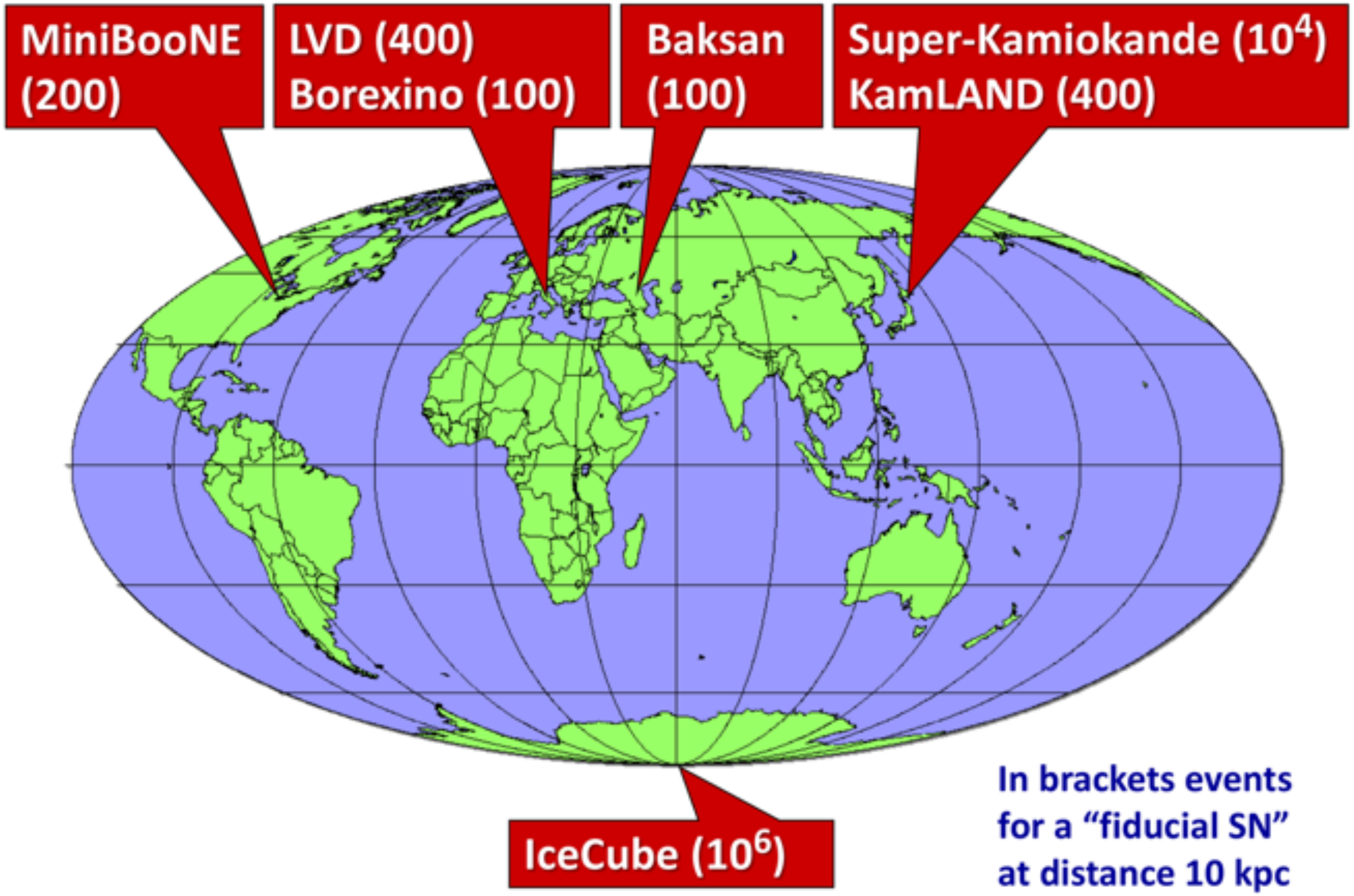
K. Langanke
A. Lohs
G. Martínez-Pinedo
G. Röpke
F.-K. Thielemann
Y. Suwa
S. Typel
M. R. Wu

Neutrino detection



MiniBooNE (200)

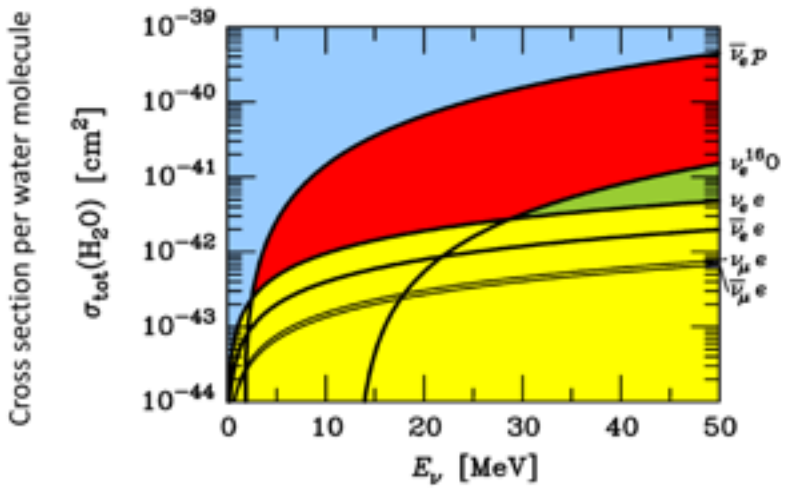
LVD (400)
Borexino (100)

Baksan (100)

Super-Kamiokande (10^4)
KamLAND (400)

IceCube (10^6)

In brackets events for a “fiducial SN” at distance 10 kpc

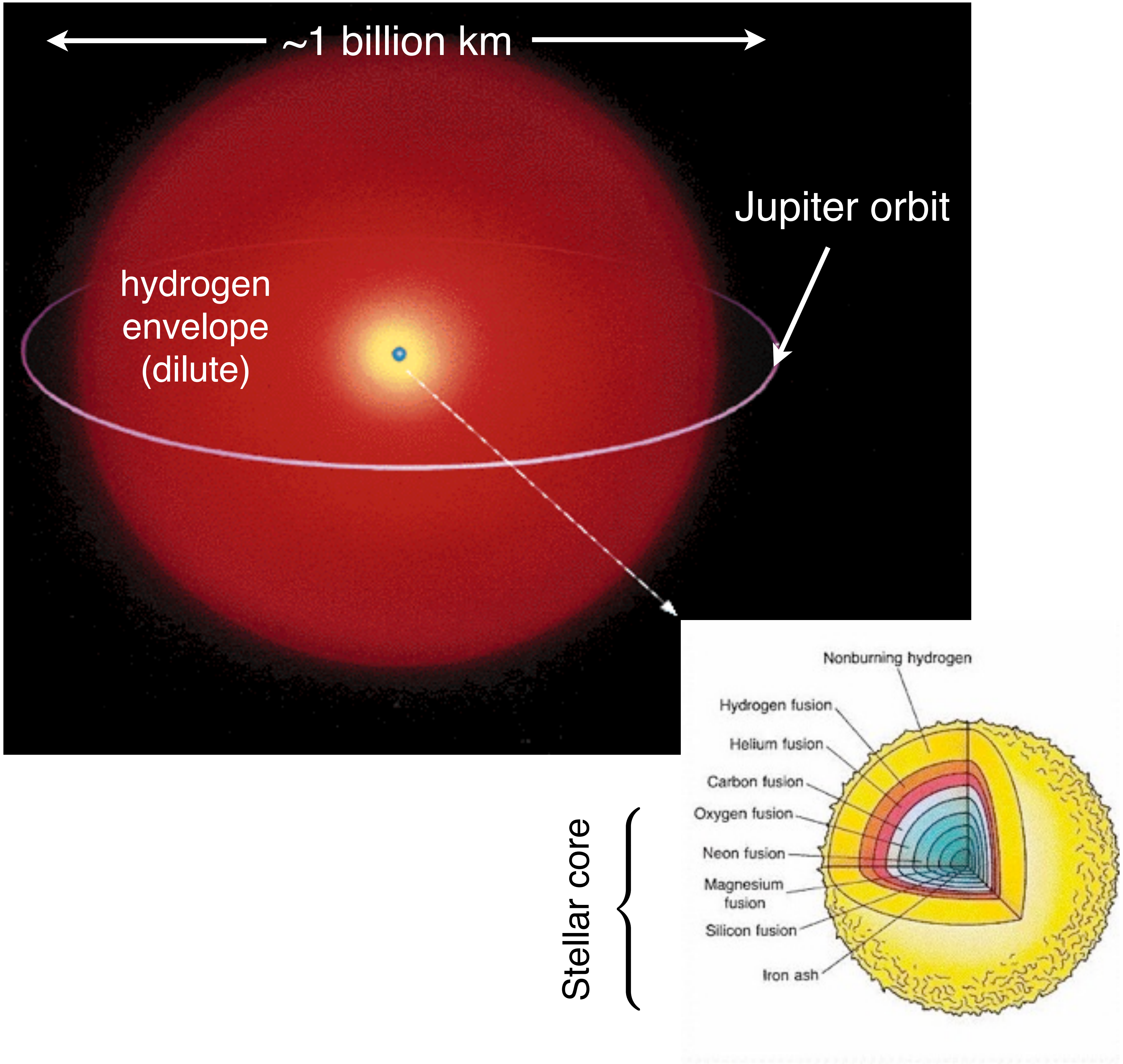


$\bar{\nu}_e + p \rightarrow n + e^+$ dominates for SN neutrinos
$\nu_e + e \rightarrow e + \nu_e$ dominates for solar neutrinos

Neutrino cross section in a water target detector

(G.G.Raffelt)

The end of a massive star ($\gtrsim 9\ \mathrm{M}_\odot$)



Implosion of the stellar core due to pressure loss; triggered from e⁻ captures on protons bound in nuclei

$$
\begin{aligned}
e^- + {}^{56}\mathrm{Mn} &\longrightarrow {}^{56}\mathrm{Fe} + \nu_\mathrm{e} \\
e^- + {}^{56}\mathrm{Fe} &\longrightarrow {}^{56}\mathrm{Co} + \nu_\mathrm{e} \\
e^- + {}^{56}\mathrm{Co} &\longrightarrow {}^{56}\mathrm{Ni} + \nu_\mathrm{e} \\
&\cdots\cdots
\end{aligned}
$$

$$e^- + \langle A, Z\rangle \longrightarrow \langle A, Z-1\rangle + \nu_e$$

Collapsing stellar core neutronizes; electron fraction drops

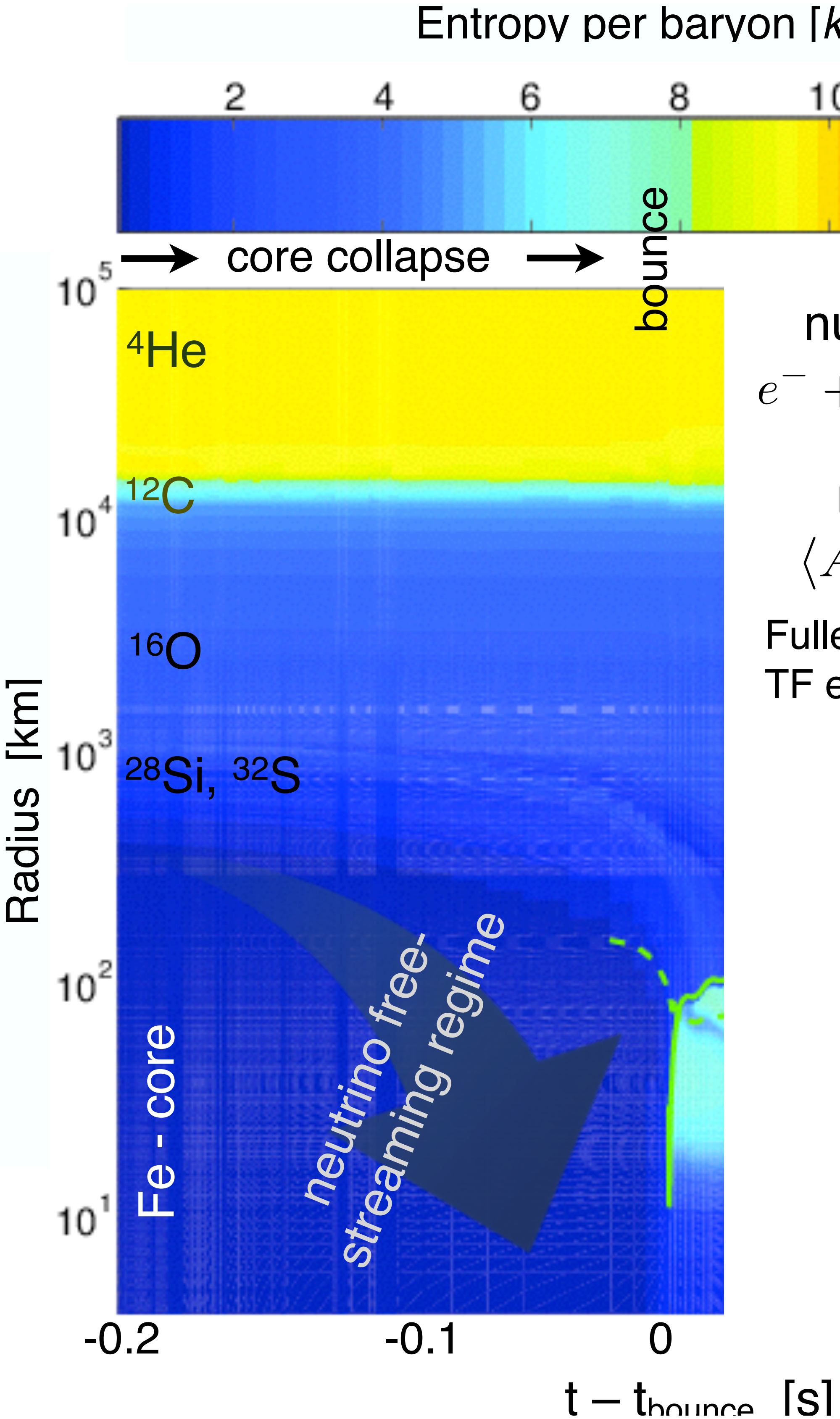
$(Y_e = n_p/n_\mathrm{B})$

$Y_e > 0.5$: neutron rich

$Y_e > 0.5$: proton rich

$\mathrm{M}_{\mathrm{Core}} > \mathrm{M}_{\mathrm{CH}}$

Stellar core collapse



nuclear electron captures

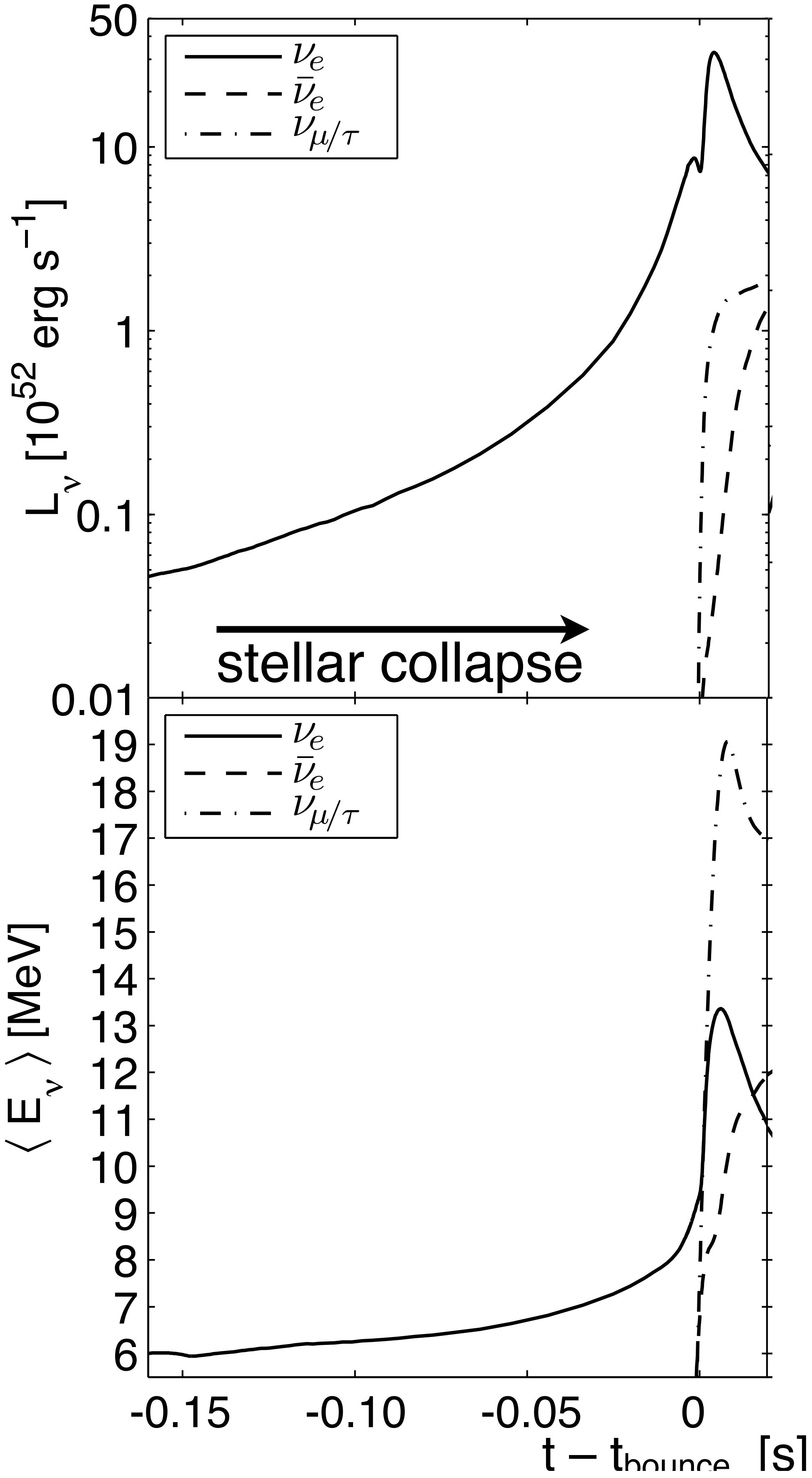
$$e^- + \langle A, Z\rangle \longrightarrow \langle A, Z-1\rangle + \nu_e$$

nuclear de-excitations

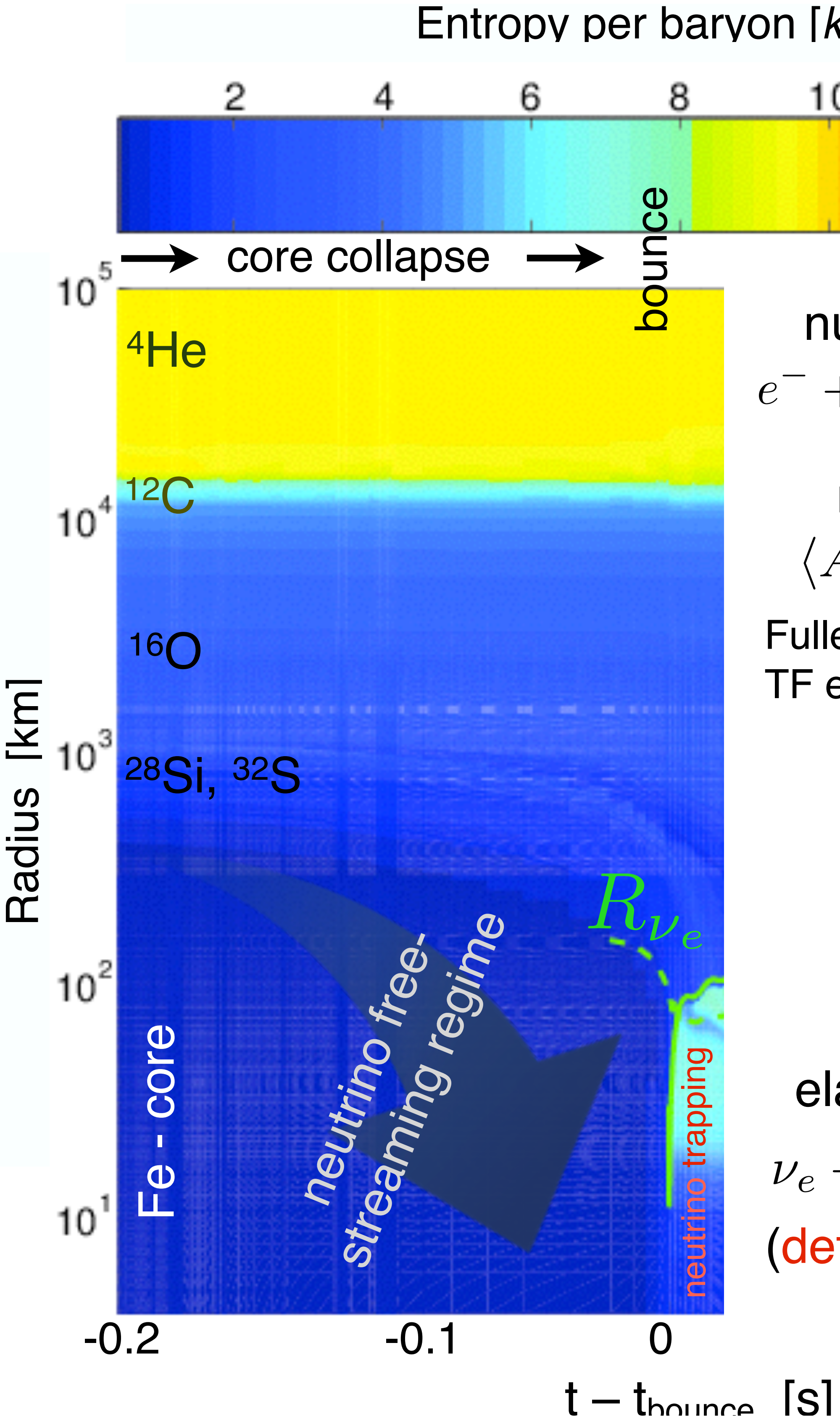
$$\langle A, Z\rangle^* \longrightarrow \langle A, Z\rangle + \nu + \bar{\nu}$$

Fuller & Meyer (1991), ApJ 376, 701
TF et al.,(2013) PRC 88, 065804

(suppressed)



Stellar core collapse



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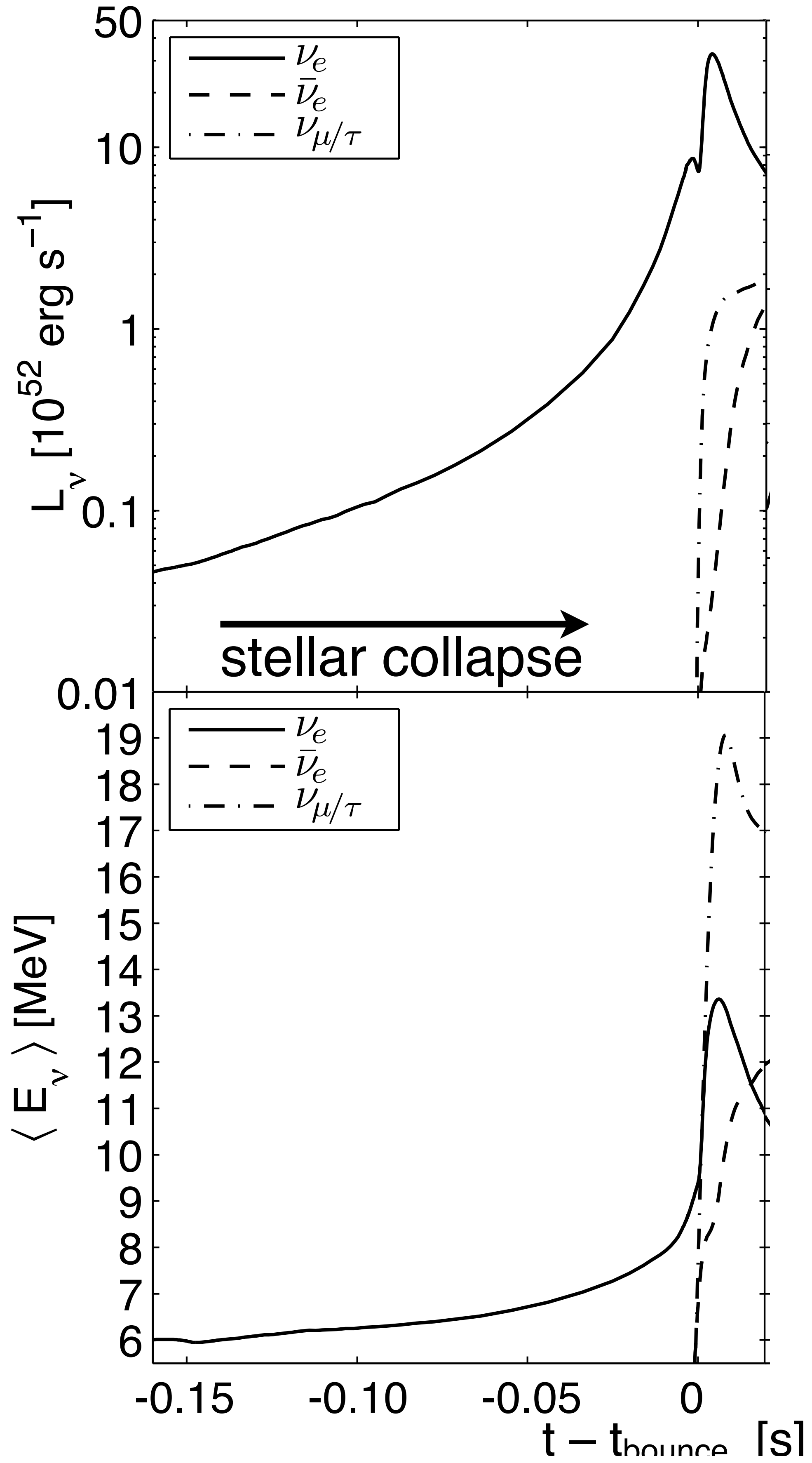
Fuller & Meyer (1991), ApJ 376, 701
TF et al.,(2013) PRC 88, 065804

(suppressed)

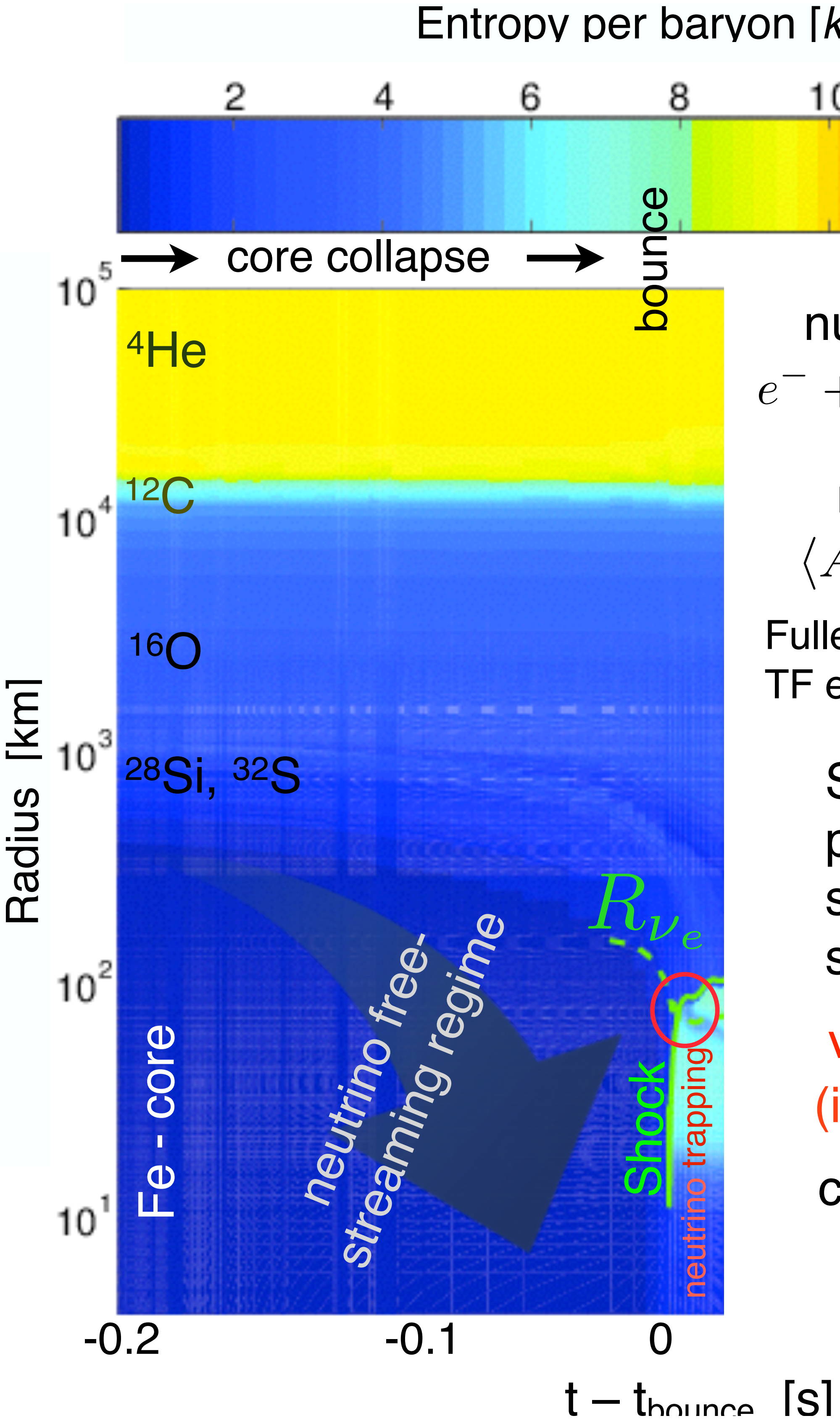
elastic scattering on nuclei

$$\nu_e + \langle A,Z\rangle \longrightarrow \langle A,Z\rangle + \nu_e$$

(determines neutrino trapping)



Core bounce and shock formation



nuclear electron captures

$$e^- + \langle A,Z\rangle \longrightarrow \langle A,Z-1\rangle + \nu_e$$

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$$\langle A,Z\rangle^* \longrightarrow \langle A,Z\rangle + \nu + \bar{\nu}$$

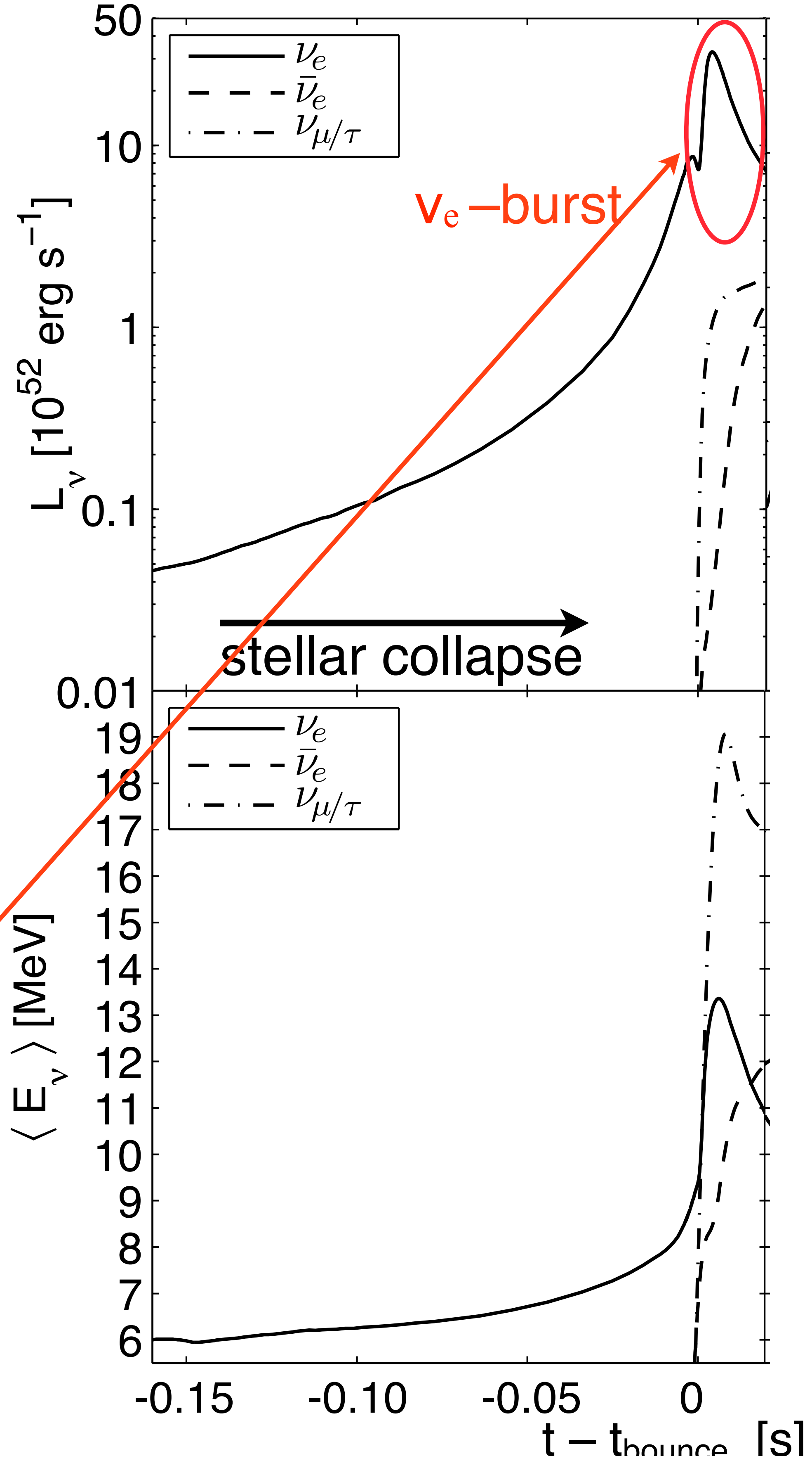
Fuller & Meyer (1991), ApJ 376, 701
TF et al.,(2013) PRC 88, 065804

Supernova shock propagation across the sphere of last inelastic scattering (ν-sphere)

ν_e–deleptonization burst (is generic feature)

charged current reactions

$$\begin{array}{ccc} e^- + p & \leftrightarrows & n + \nu_e \\ e^+ + n & \leftrightarrows & p + \bar{\nu}_e \end{array}$$



Post bounce mass accretion

charged current reactions

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

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

pair processes

$$e^- + e^+ \leftrightarrows \nu + \bar{\nu}$$

$$N + N \leftrightarrows N + N + \nu + \bar{\nu}$$

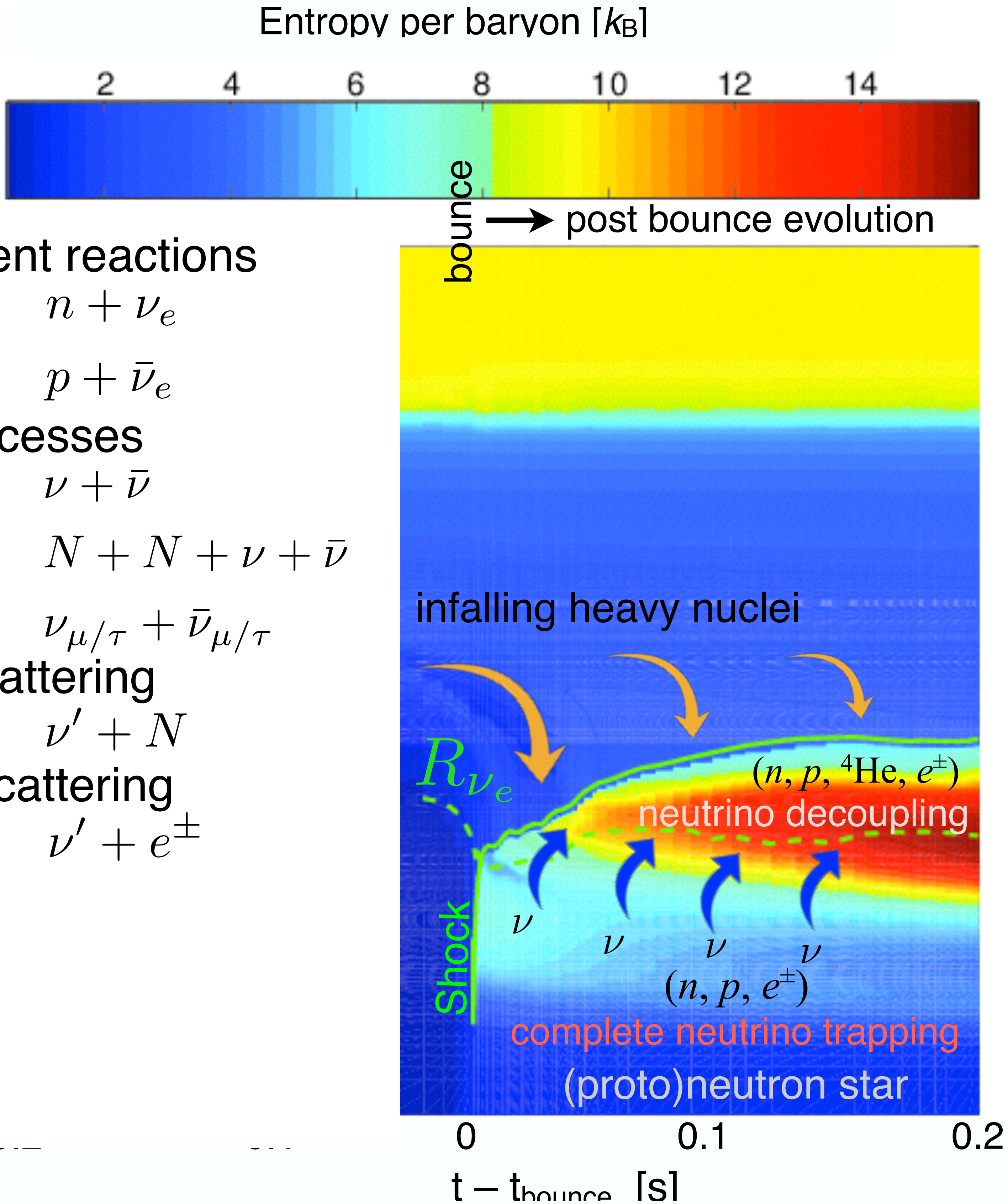
$$\nu_e + \bar{\nu}_e \leftrightarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$

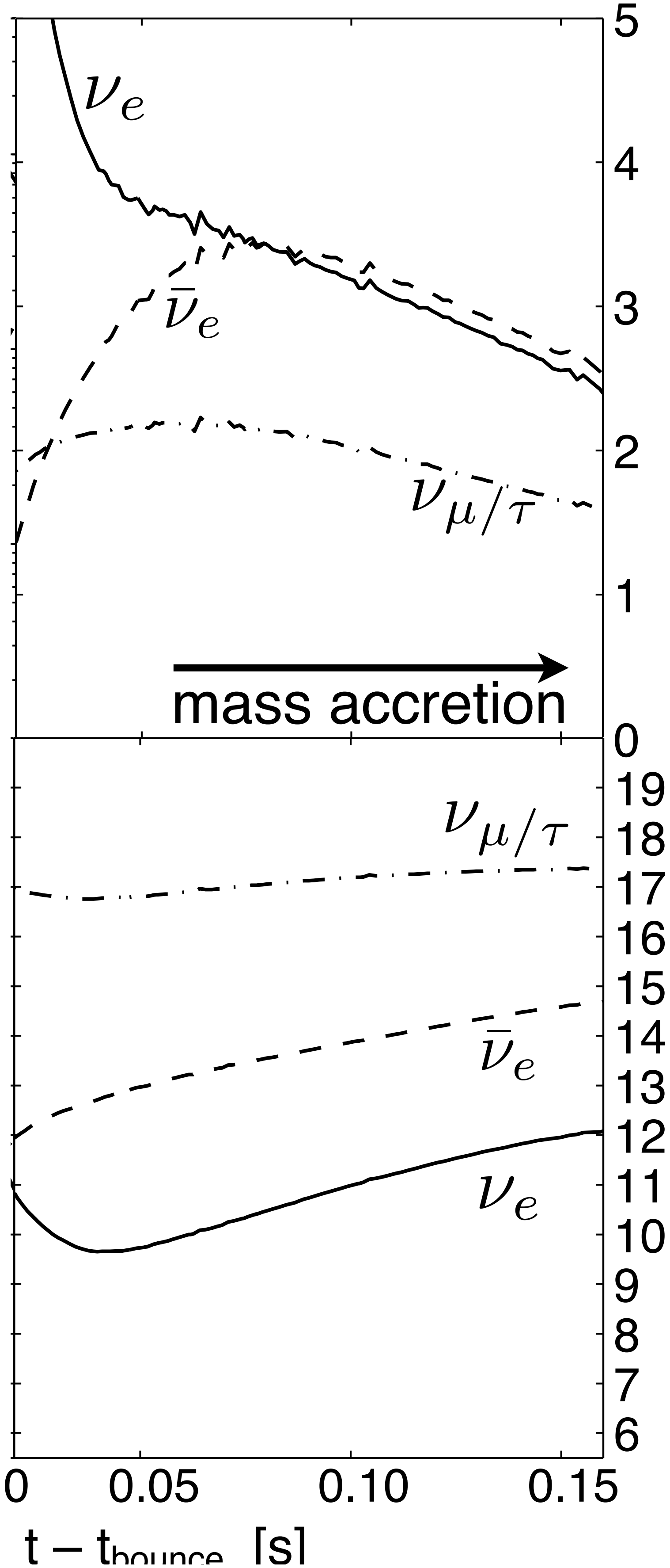
elastic scattering

$$\nu + N \leftrightarrows \nu' + N$$

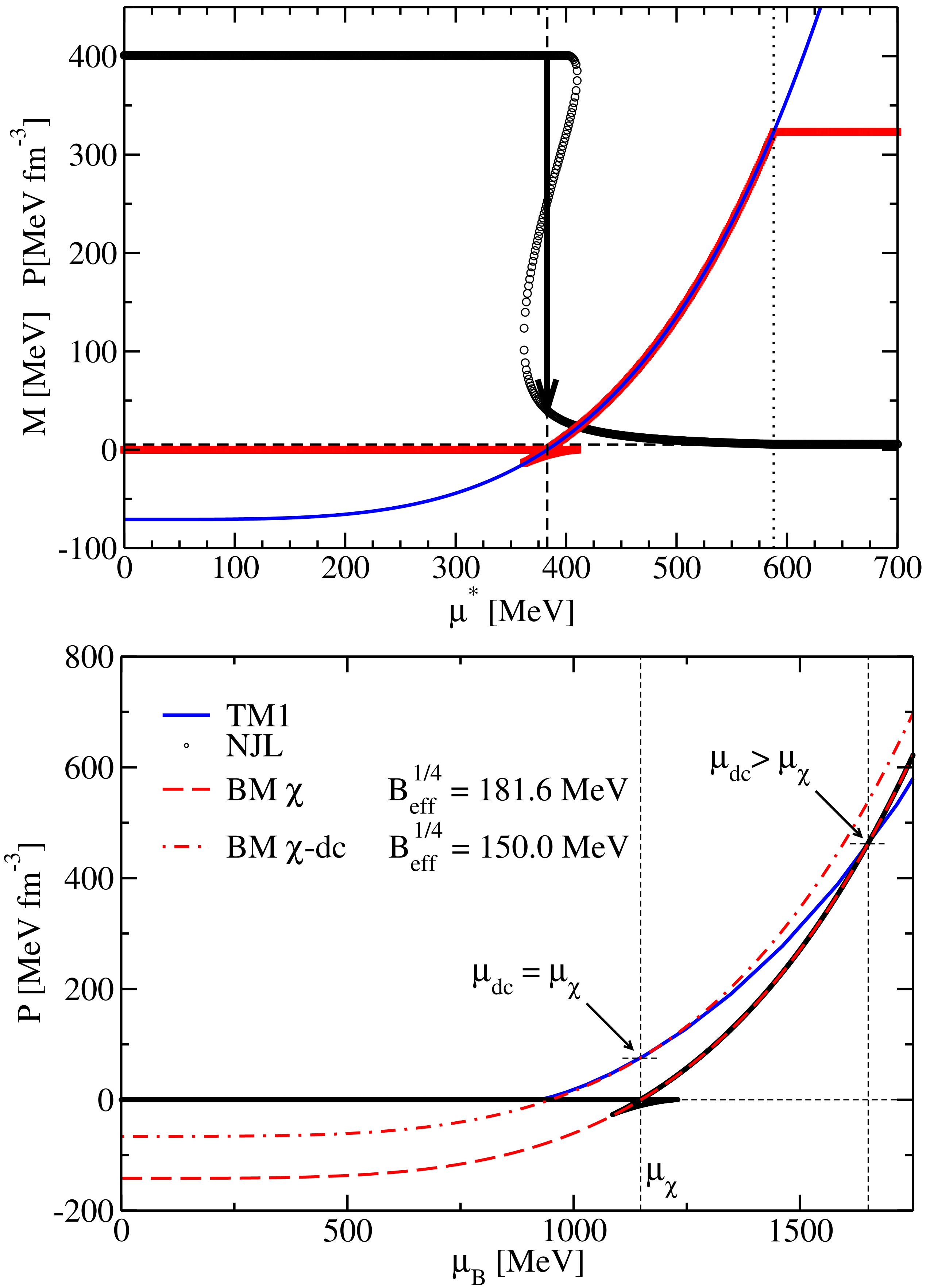
inelastic scattering

$$\nu + e^\pm \leftrightarrows \nu' + e^\pm$$

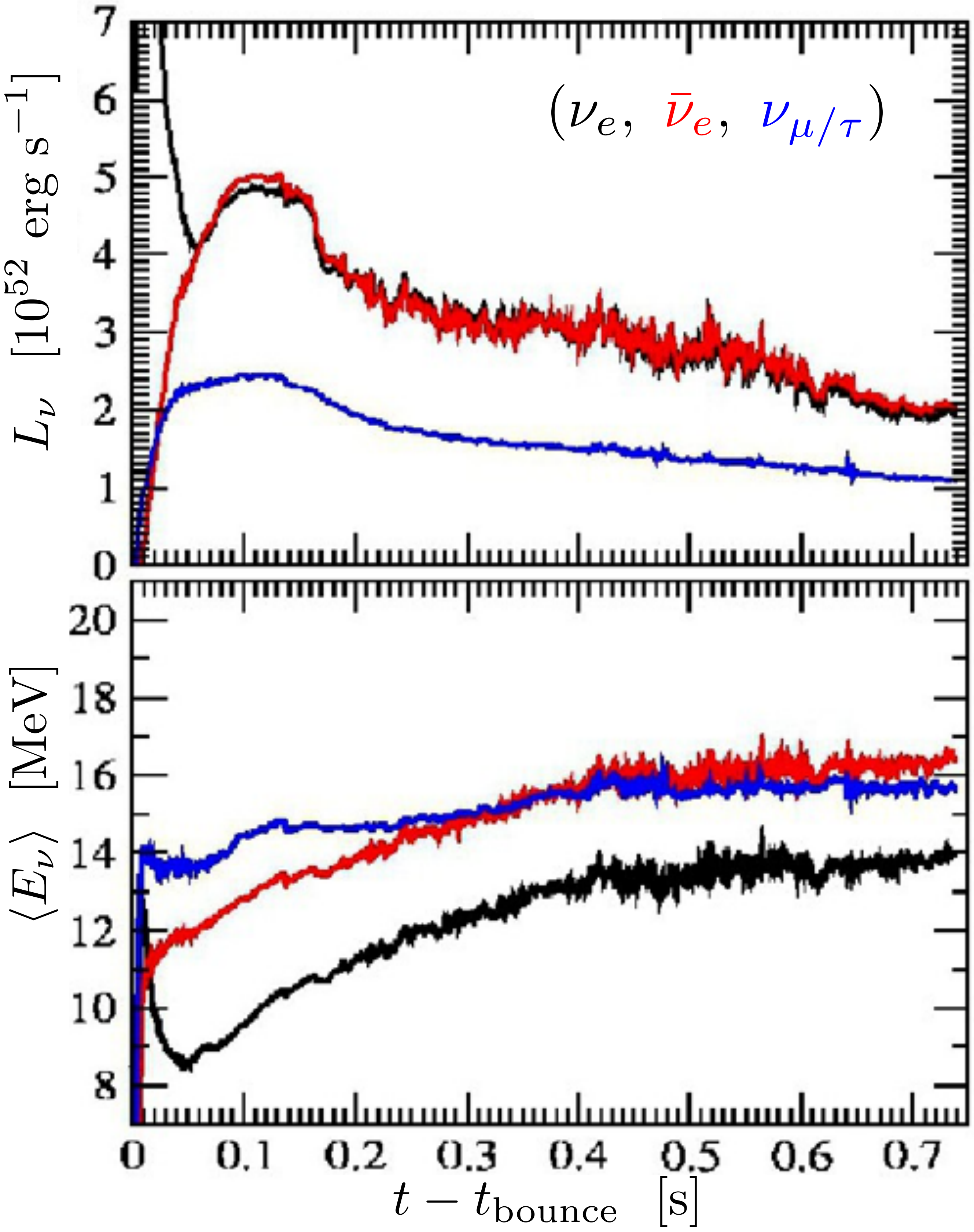




vBag approach to quark matter



Neutrino signal in multi-dim'l simulations



Müller & Janka (2014) ApJ 788, 82

Presence of millisecond variations of the neutrino signal

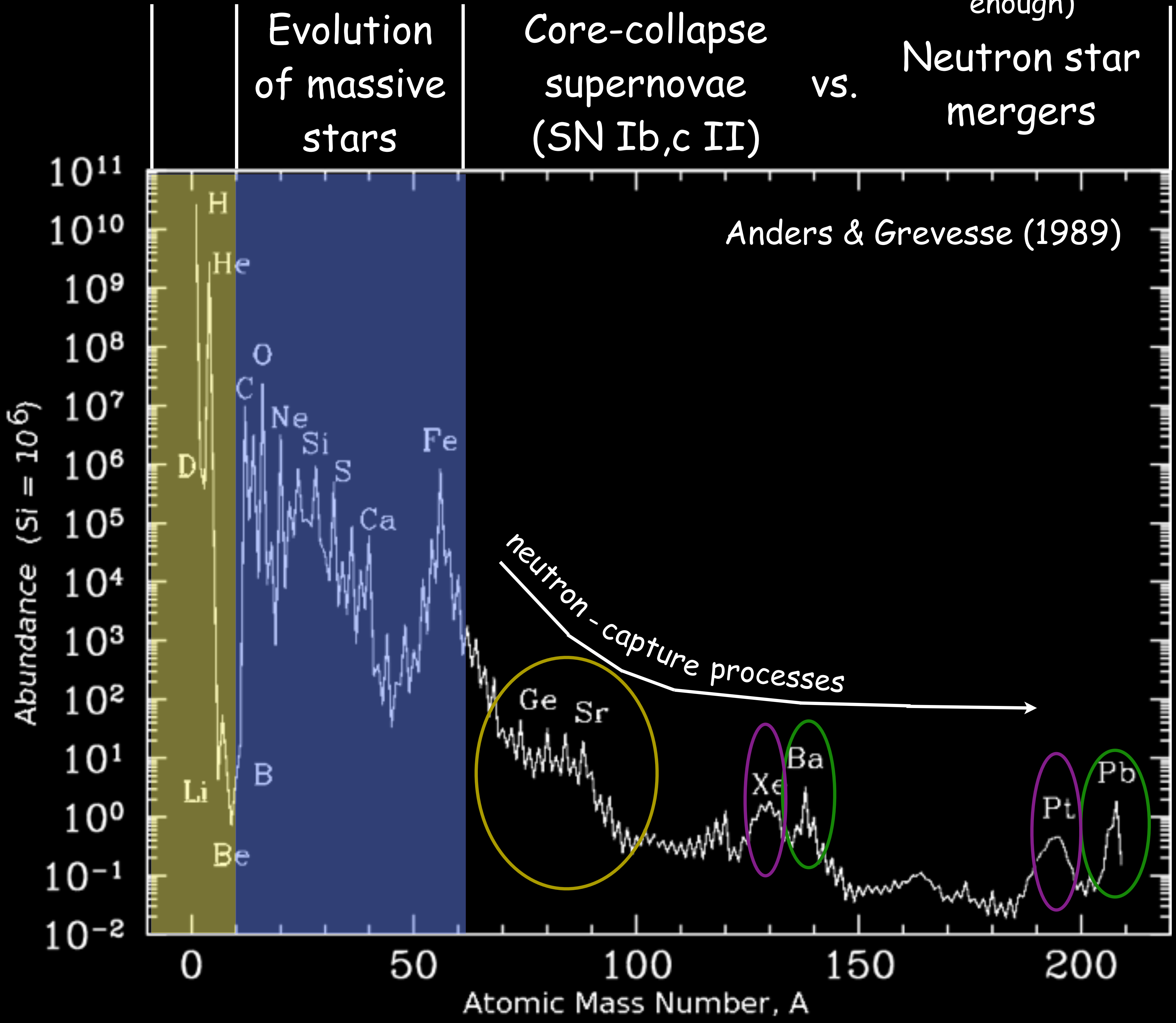
Induced from convection and associated shock oscillations

Persist even in detection on Earth

May allow distinction of strong bi-polar explosions

Production of heavy-element

Argast et al.(2004) AA416,997



Evolution of massive stars

Core-collapse supernovae (SN Ib,c II)

vs.

(too late, not frequent enough)

Neutron star mergers

Anders & Grevesse (1989)

neutron-capture processes

- slow (s) process
  (n-capture << decay)
  ➡ Stellar evolution

- rapid (r) process
  (n-capture >> decay)
  ➡ Explosive environment

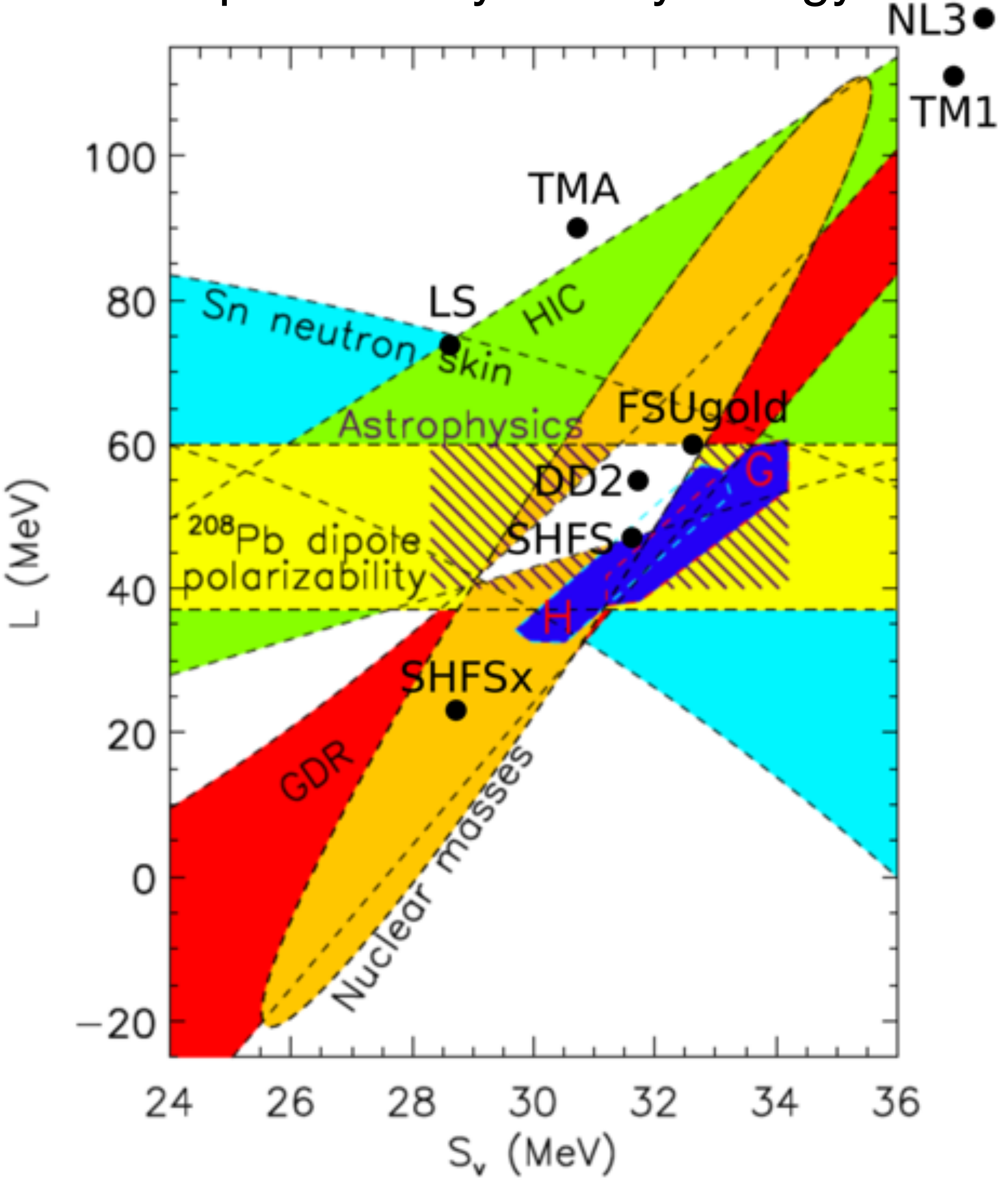
- neutrino-induced
  (intermediate mass elements?)

Some relevant current equation of state constraints

S . . . nuclear symmetry energy

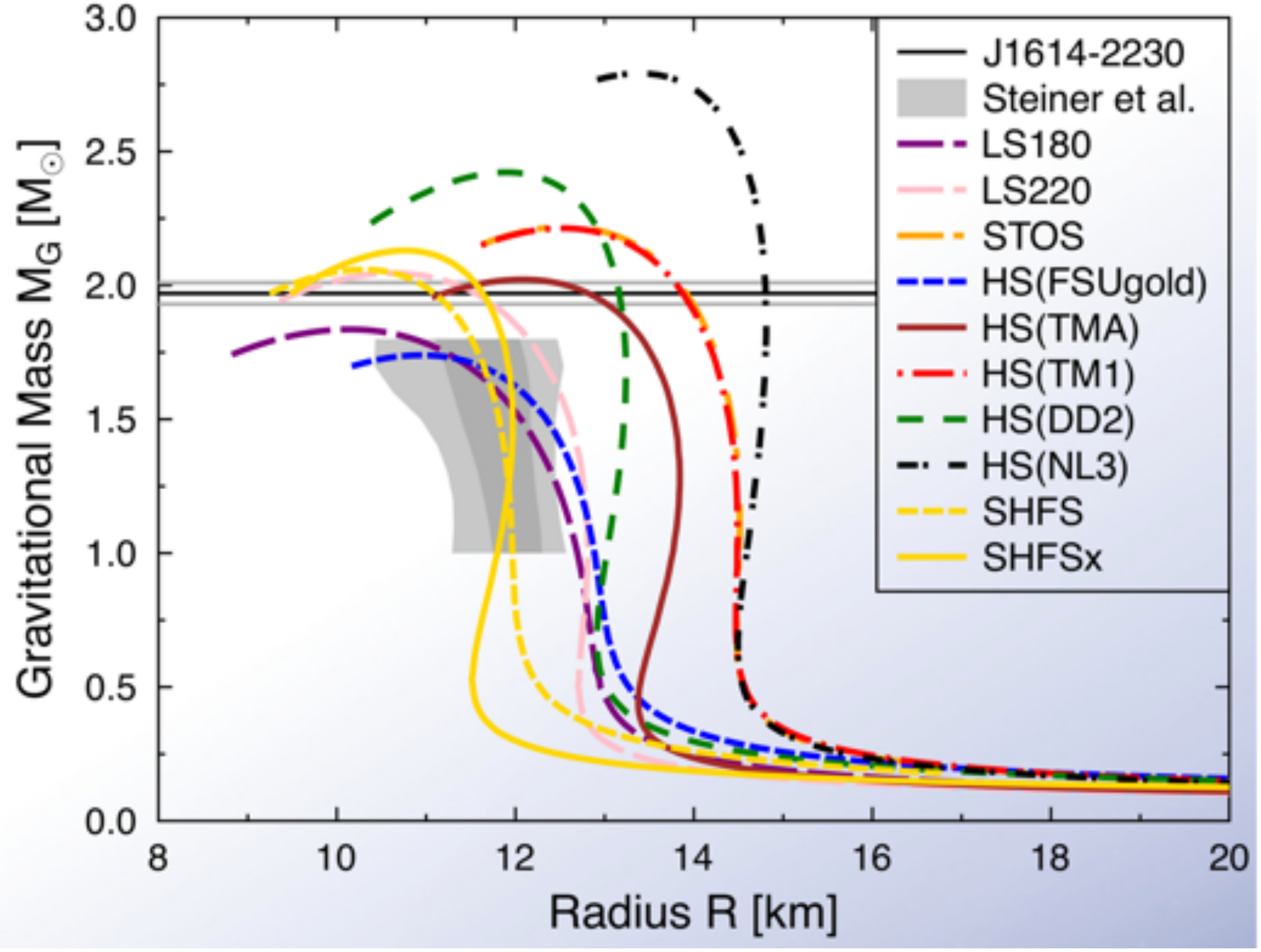
L . . . slope of the symmetry energy

(Astronomy/Astrophysics; neutron stars)



Lattimer & Lim (2013) ApJ 771, 14

Each EoS has a unique Mass-Radius relation



Steiner et al., (2010) ApJ 722
(low-mass X-ray binary source analysis)

Demorest et al.,(2010) Nature 09466
Antoniadis et al.,(2013) Science 340, 448