A Brief overview of SN Eos and Beyond

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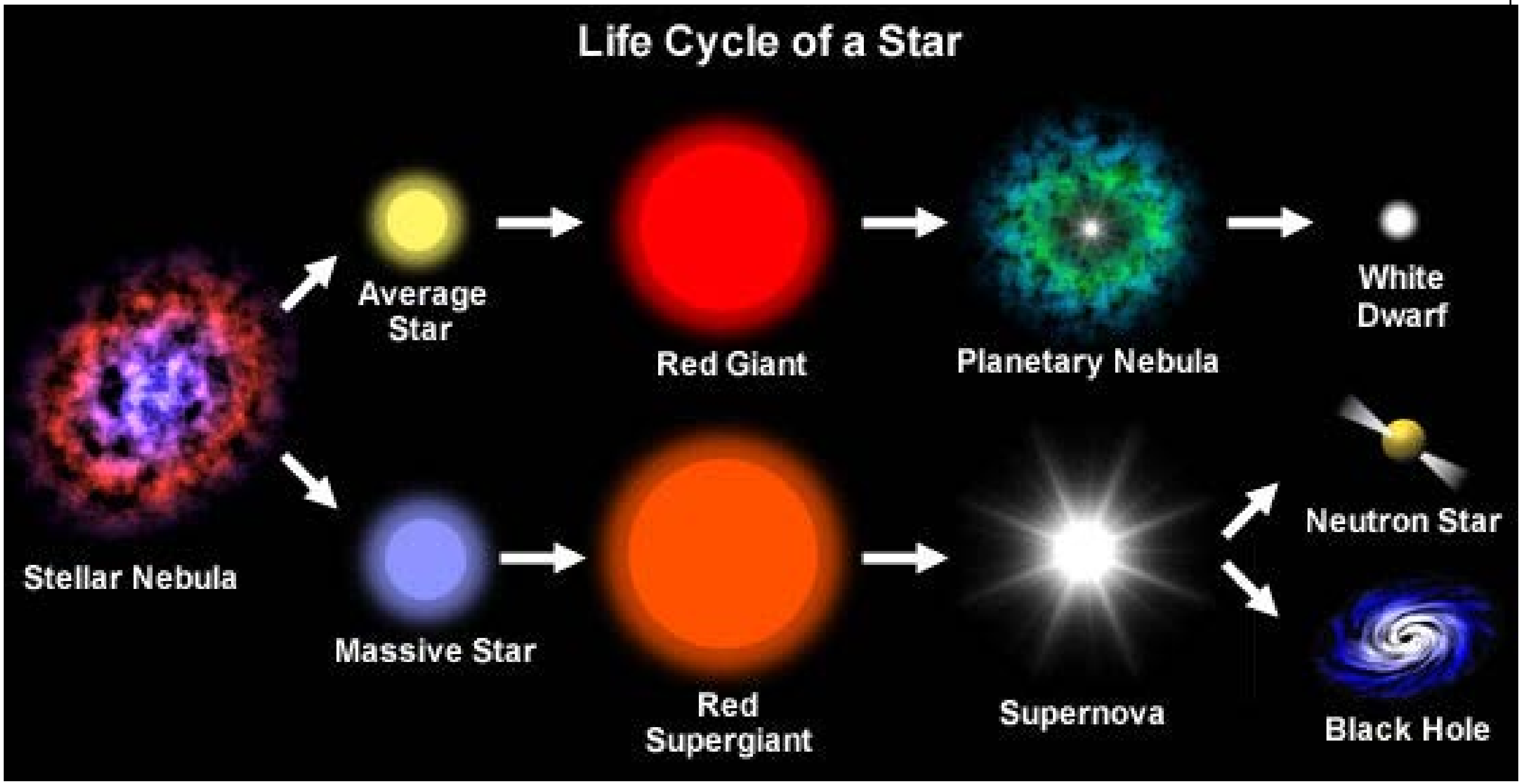
MultiDark
Multimessenger Approach for Dark Matter Detection

& Cosmic Wispers CA21106

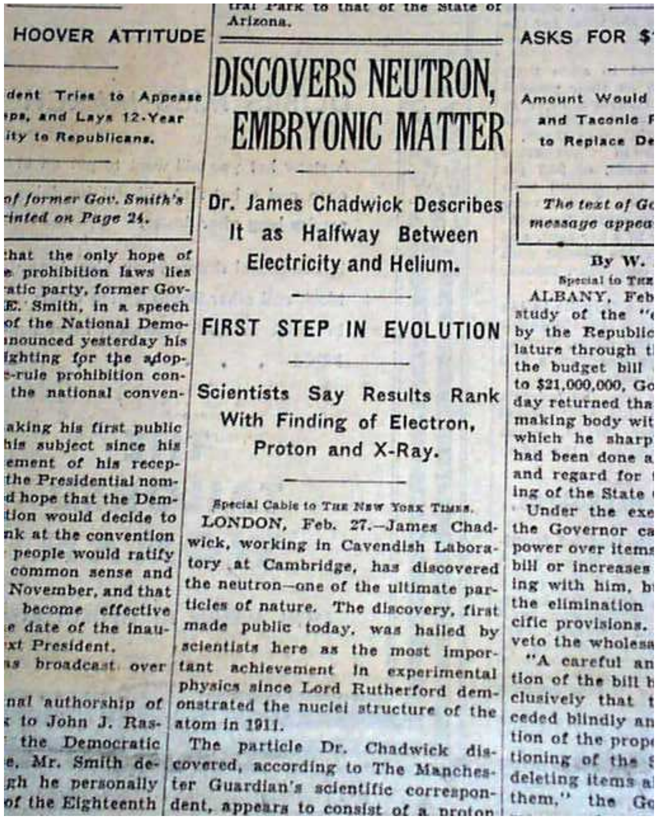
SN as an evolutionary event



Stellar progenitors with masses in the massive range beyond 8 solar masses undergo a SN explosion

Standard stellar evolution: these events give rise to a compact massive object i.e. Neutron star, Black hole and perhaps other exotic quark compact stars

SN mechanism: hadron, weak, EM and gravitational



HOOVER ATTITUDE

ASKS FOR $

DISCOVERS NEUTRON, EMBRYONIC MATTER

Dr. James Chadwick Describes It as Halfway Between Electricity and Helium.

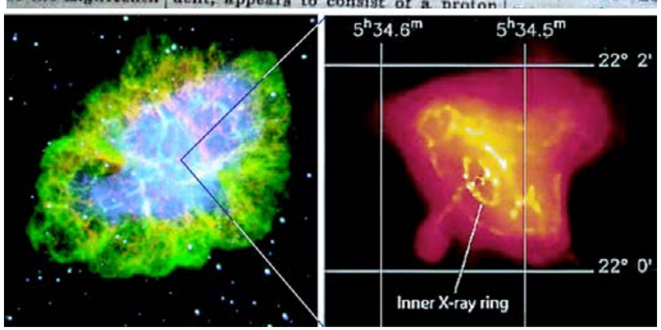
FIRST STEP IN EVOLUTION

Scientists Say Results Rank With Finding of Electron, Proton and X-Ray.

Special Cable to THE NEW YORK TIMES.

LONDON, Feb. 27.—James Chadwick, working in Cavendish Laboratory at Cambridge, has discovered the neutron—one of the ultimate particles of nature. The discovery, first made public today, was hailed by scientists here as the most important achievement in experimental physics since Lord Rutherford demonstrated the nuclei structure of the atom in 1911.

The particle Dr. Chadwick discovered, according to The Manchester Guardian's scientific correspondent, appears to consist of a proton



Crab V & X-rays (CHANDRA)

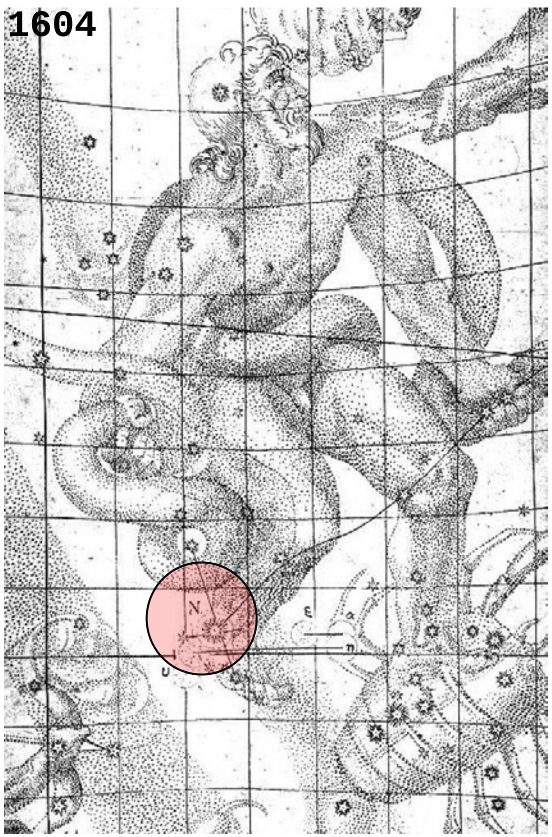
Rutherford predicted the neutron in 1920, Chadwick discovers it in 1932.

Chandrasekhar predicts the maximum WD mass supported by electrons in 1931 to be $\sim$ 1.4M Msun

Baade & Zwicky in 1934: "With all reserve we advance the view that a Supernova represents the transition of an ordinary star into a new form of star, the neutron star, which would be the end point of stellar evolution. Such a star may possess a very small radius and an extremely high density."

Since then the SN mechanism remains yet uncertain involving: weak messengers (neutrinos), EM radiation (photons) and gravitational waves(expected with generation GW detectors). Other BSM stroparticles may be around the corner (ALPs, strangelets, steriles, wimps/simps..)

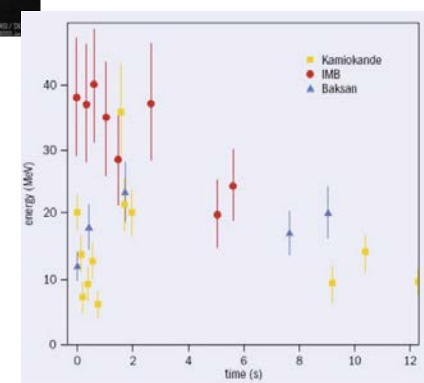
SN as transient Luminous events



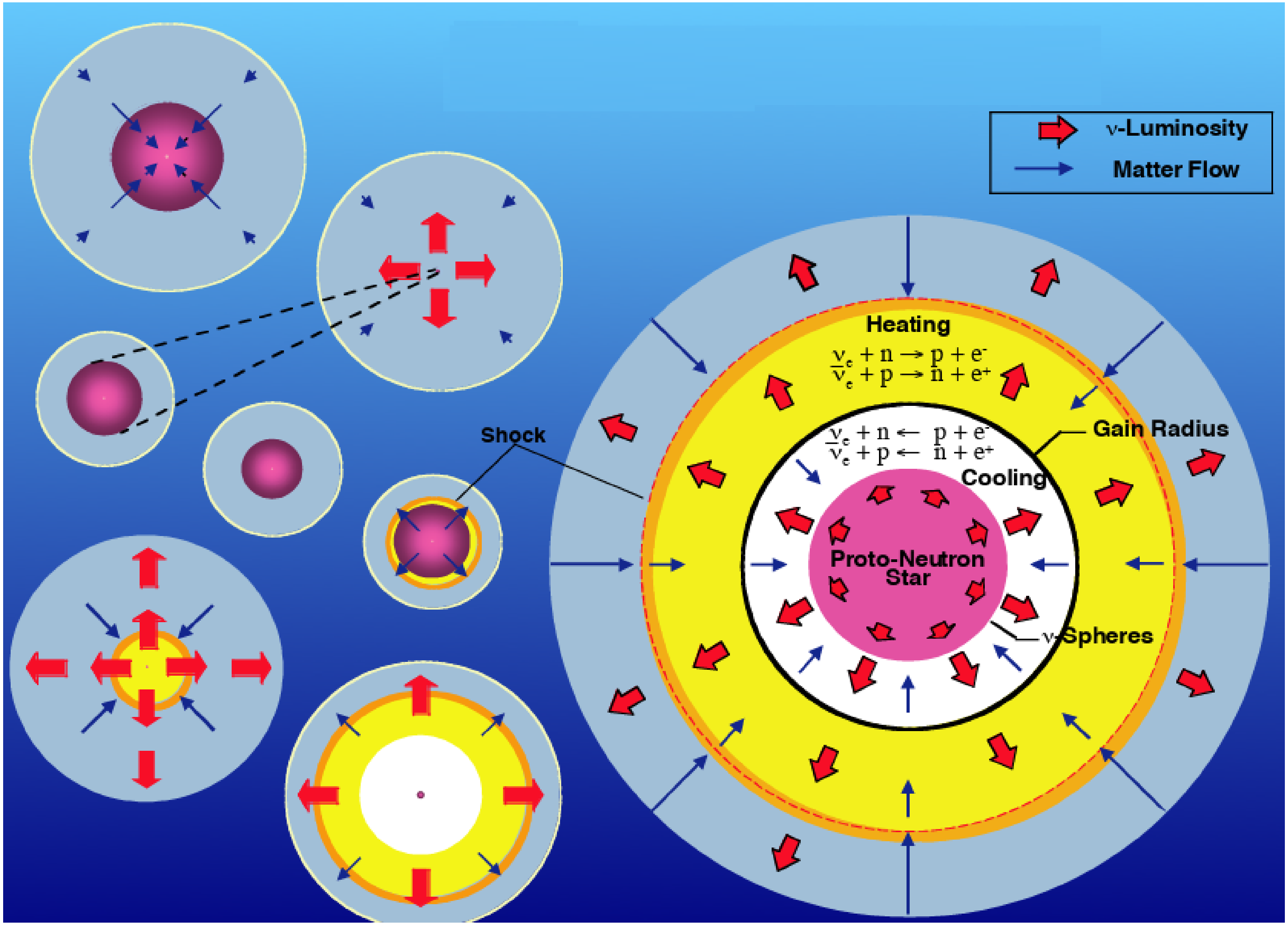
Some can be observed by naked eye for days.

Typically luminosity is 10^{10} L_sun, similar to that of Galaxy.

Nobel prizes with SN involvement: **1974 (pulsars), 2002 (neutrino astronomy), 2011 (SN ladder and cosmic expansion)**



SN standard mechanism



Type I and II SN differ in spectra and light curves,
Type I very regular.

Neutrino role in the SN mechanism

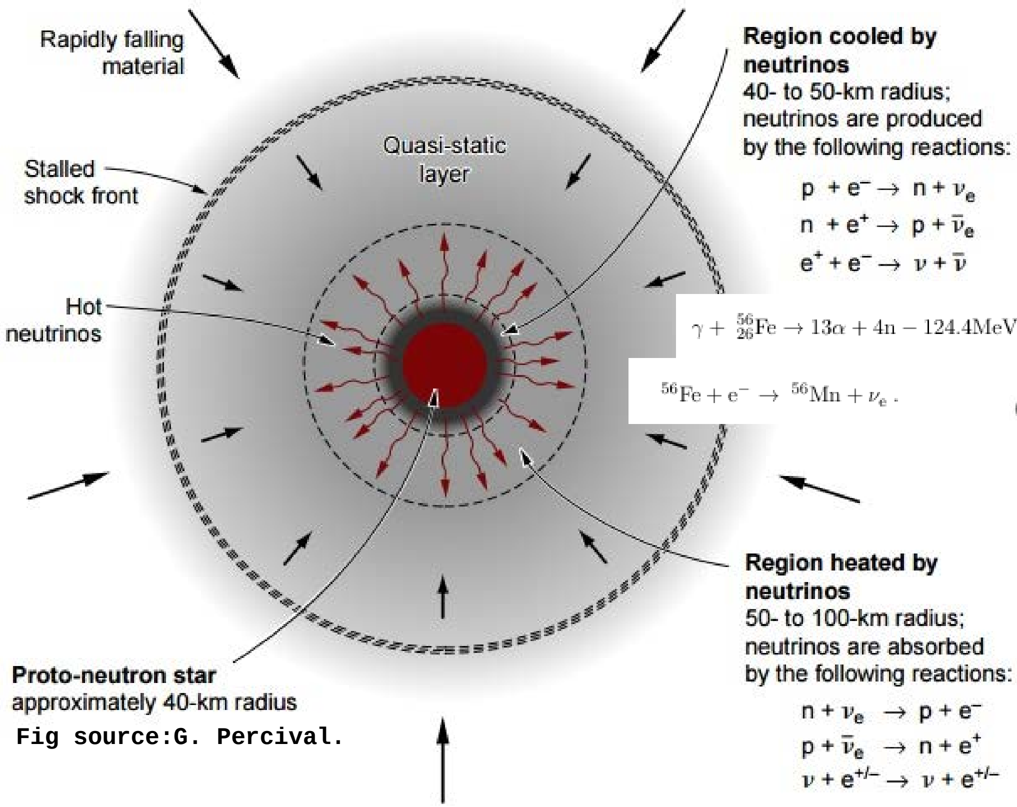


Fig source:G. Percival.

$$\gamma + {}^{56}_{26}\mathrm{Fe} \to 13\alpha + 4\mathrm{n} - 124.4\mathrm{MeV}\ .$$

$$^{56}\mathrm{Fe} + e^- \to\ ^{56}\mathrm{Mn} + \nu_e\ .$$

The **delayed-SN mechanism** is sensitive to a delicate competition of neutrino cooling between the neutrino sphere and the so-called ‘gain radius’

$$Q_\nu^- \approx 145 \left(\frac{k_B T}{2\,\mathrm{MeV}}\right)^6 \quad \left[\frac{\mathrm{MeV}}{\mathrm{s}\cdot N}\right]$$

and neutrino heating

$$Q_\nu^+ \approx 110 \cdot \left(\frac{L_{\nu_e,52}\langle\epsilon^2_{\nu_e,15}\rangle}{r_7^2\ \langle\mu\rangle_{\nu_e}} Y_n + \frac{L_{\bar{\nu}_e,52}\langle\epsilon^2_{\bar{\nu}_e,15}\rangle}{r_7^2\ \langle\mu\rangle_{\bar{\nu}_e}} Y_p \right) \quad \left[\frac{\mathrm{MeV}}{\mathrm{s}\cdot N}\right]$$

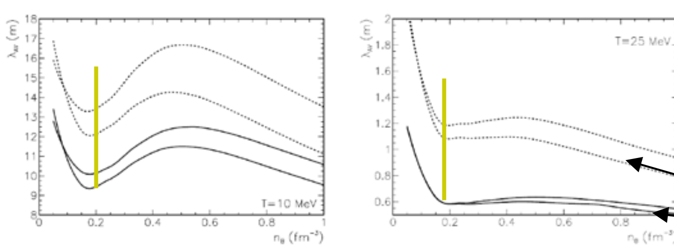
between the gain radius and the shock.

Absorption, emission, scattering, bremsstrahlung are the main processes driving the neutrino transport.

Only in case additional instabilities appear computatinal simulations find successful explosions

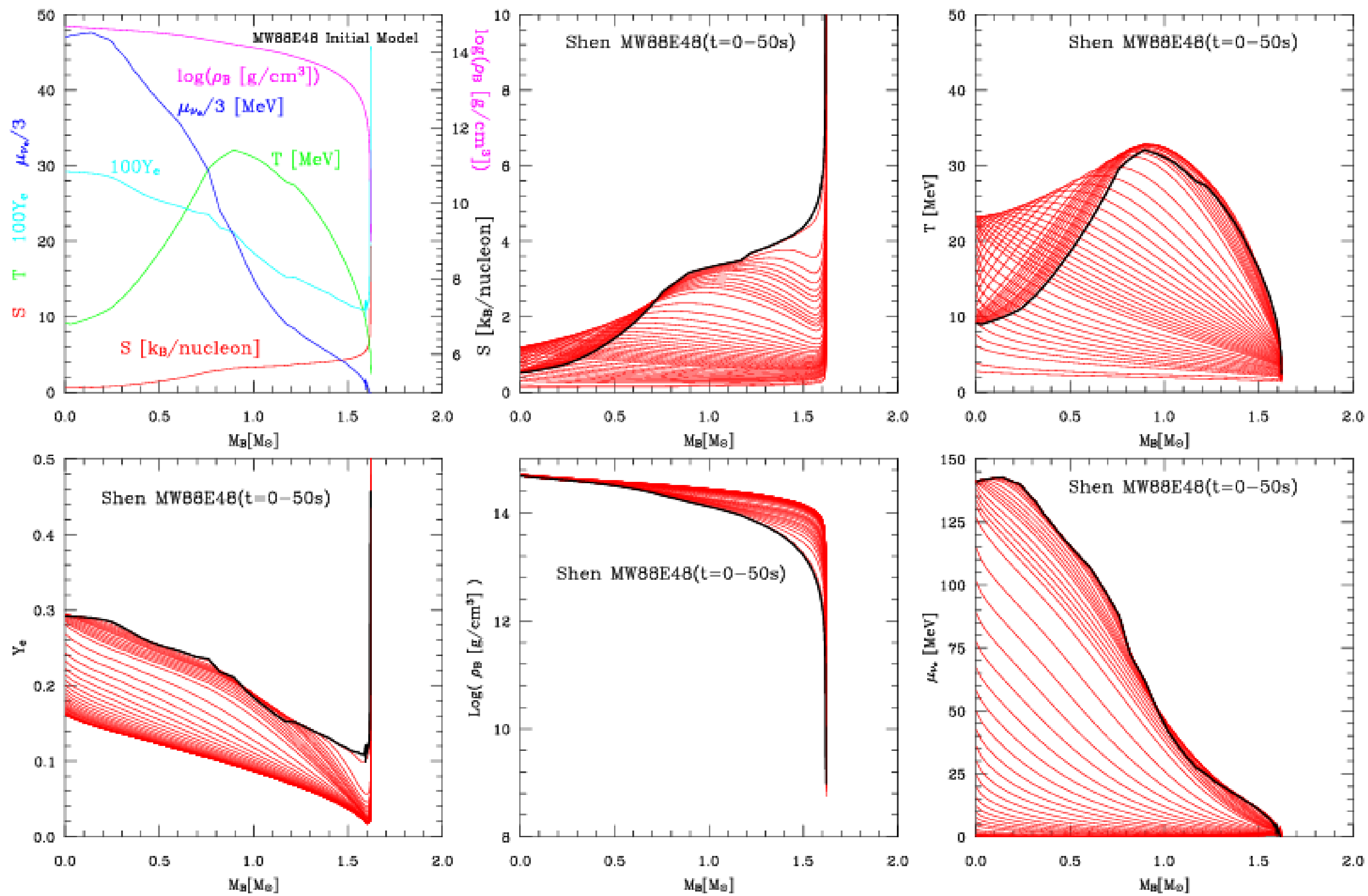
$$(Z,A) \to (Z+1,A) + e^- + \bar{\nu}_e$$

$$(Z,A) + e^- \to (Z-1,A) + \nu_e .$$



antinux_x
nu_x (PRC’03 Horowitz& PG

Computational Simulations



Suzuki, PTEP 2024

Fig. 4. Time evolution of the inner profiles of a proto-neutron star (model MW88E48). The upper left panel shows the initial profiles of density ρ_B, temperature T, electron fraction Y_e, entropy S, and neutrino chemical potential μ_{ν_e} defined as $\mu_p + \mu_e - \mu_n$. The other five panels show snapshots up to 50 s. The black lines depict the initial profiles.

Composition SN-stage

Late stages of evolution: Nuclear Statistical Equilibrium (NSE) i.e. independent of the rates for reactions mediated by the electromagnetic and strong interaction.

There is a first presupernova stage taken as initial spherical configuration

Later on SM conservation laws hold: weak decay, charge neutrality and conservation of (B,l) number must be imposed: e,mu,p,n,nu along with nuclei(Z,A)

conditions	In-medium equilibrium
weak decay $n \to p + e + \bar{\nu}_e$	$\mu_n = \mu_p + \mu_e$
elec.charge neutrality $n_p = n_e + n_\mu$	$\mu_p = \mu_e + \mu_\mu$
conservation baryon number	$\rho_B = \rho_n + \rho_p$

Reaction	Equation
Electron emission	${}^A_Z X \to {}^A_{Z+1} X + e^- + \bar{\nu}_e$
Positron emission	${}^A_Z X \to {}^A_{Z-1} X + e^+ + \nu_e$
Electron capture	${}^A_Z X + e^- \to {}^A_{Z-1} X + \nu_e$
Positron capture	${}^A_Z X + e^+ \to {}^A_{Z+1} X + \bar{\nu}_e$
Electron annihilation	$e^- + e^+ \to \nu_e + \bar{\nu}_e$
Electron annihilation	$e^- + e^+ \to \nu + \bar{\nu}$
Neutrino capture	${}^A_Z X + \overset{(-)}{\nu}_e \to {}^A_{Z\mp1} X + e^\pm$
$e^-\nu$ scattering	$e^- + \overset{(-)}{\nu}_e \to e^- + \overset{(-)}{\nu}_e$
$e^-\nu$ scattering	$e^\pm + \overset{(-)}{\nu}_e \to e^\pm + \overset{(-)}{\nu}_e$
Neutrino scattering	${}^A_Z X + \overset{(-)}{\nu} \to {}^A_Z X + \overset{(-)}{\nu}$

$$\nu_\mu + n \leftrightarrows p + \mu^-$$
$$\bar{\nu}_\mu + p \leftrightarrows n + \mu^+$$

$$\nu_\mu + \mu^\pm \leftrightarrows \mu'^\pm + \nu'_\mu$$
$$\bar{\nu}_\mu + \mu^\pm \leftrightarrows \mu'^\pm + \bar{\nu}'_\mu$$

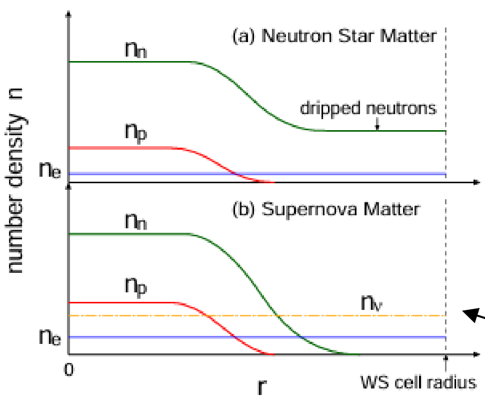
$$\nu_\mu + e^- \leftrightarrows \mu^- + \nu_e$$
$$\bar{\nu}_\mu + e^+ \leftrightarrows \mu^+ + \bar{\nu}_e$$
$$\nu_\mu + \mu^+ \leftrightarrows e^+ + \nu_e$$
$$\bar{\nu}_\mu + \mu^- \leftrightarrows e^- + \bar{\nu}_e$$

Chemical potentials include protons, neutrons, electrons and muons along with neutrinos and their antiparticles if early trapped. Finite T $Y_e = n_e^- - n_e^+$ **also muons play a role.**

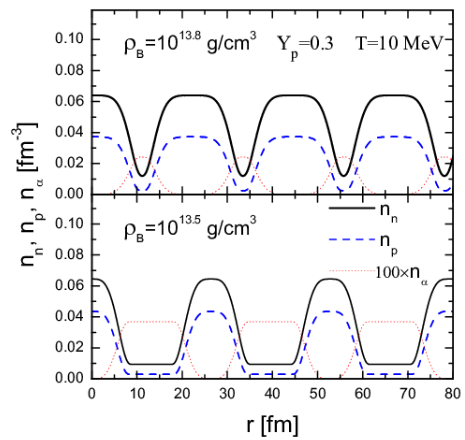
NSE used for around 1000 nuclear species and the relativistic (or not) mean field models for the unbound nucleons.

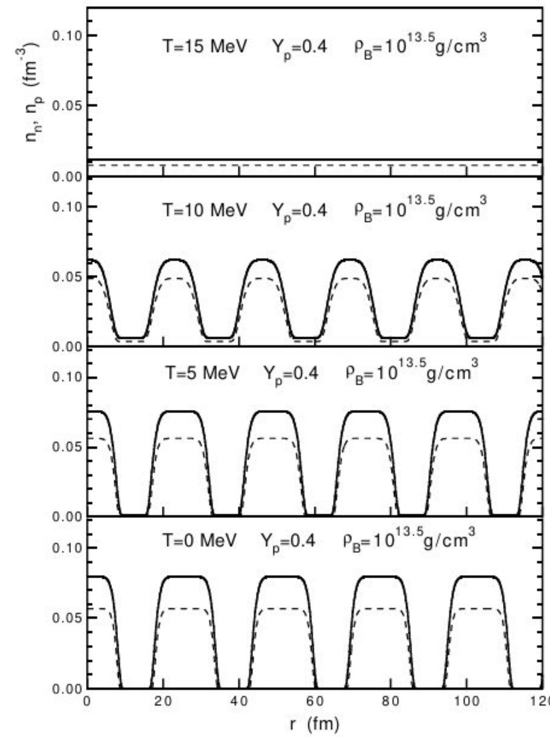
Lattimer-Swesty EoS

Considers p, n, alpha nuclei and a single heavy nucleus obtained by minimization of Free energy in Wigner-Seitz cell.



trapped nus





$$F_i - \mu_n N_i - \mu_p Z_i = F_i^{(e)} - \mu_i^{(e)} + V_i \left(f_{HM} - \mu_n n_{gn} - \mu_p n_{gp} + f_e - \mu_e n_e\right.$$

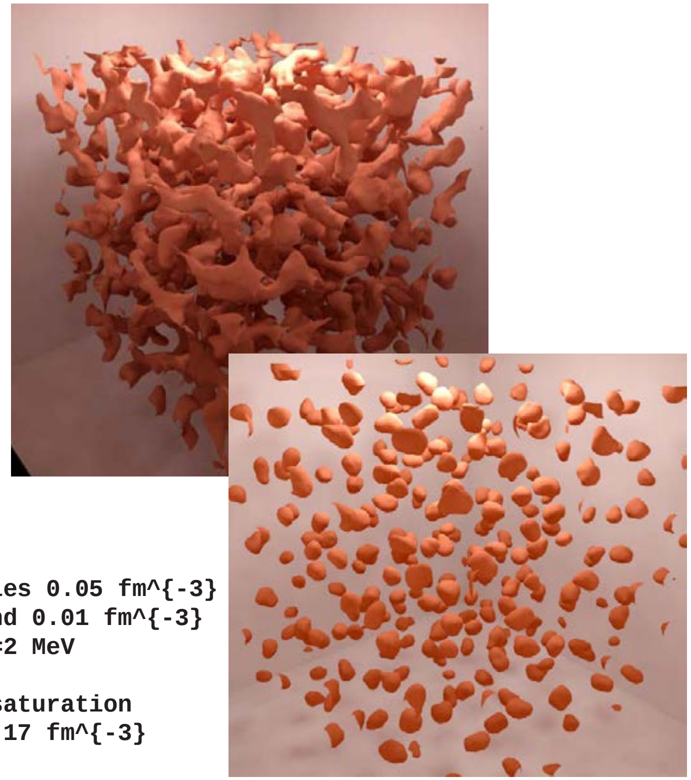
For each Wigner-Seitz cell min F

contains a single cluster with baryon number Ai and atomic number Zi.

Densities of free electrons (ne) and unbound protons (ngp) neutrons (ngn) in the different cells are the same.

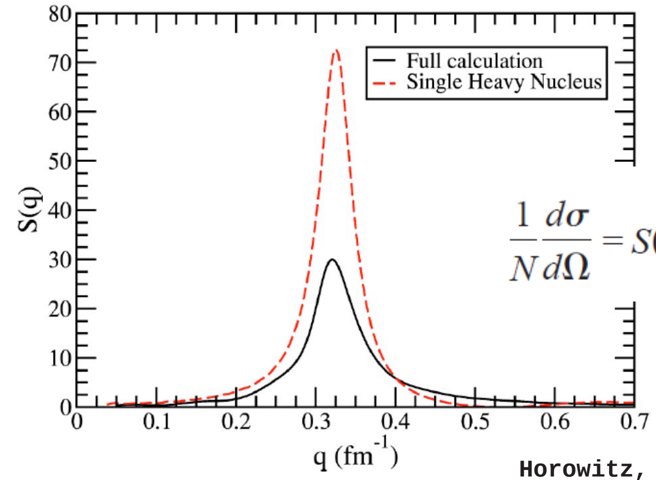
The cell volume is given by the neutrality condition, Vi = Zi/ne.
NSE used for around 1000 nuclear species and the relativistic (or not) mean field models for the unbound nucleons.

Non-homogenous matter EoS: pasta



At densities 0.05 fm^{-3} (above) and 0.01 fm^{-3} (right) T=2 MeV

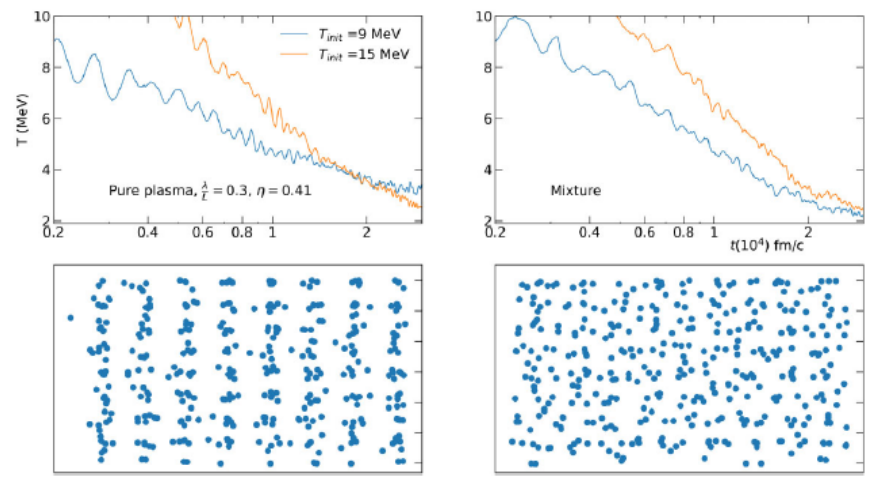
(typical saturation density 0.17 fm^{-3})



$$\frac{1}{N}\frac{d\sigma}{d\Omega} = S(\mathbf{q})\frac{G_F^2 E_\nu^2}{4\pi^2}\frac{1}{4}(1+\cos\,\theta).$$

Horowitz, PG et al PRC'04

FIG. 23. (Color online) Neutron static structure factor $S(q)$ as a function of the momentum transfer q at a density of ρ $=0.025$ fm^{-3} (black solid line). Also shown (red dashed line) is the prediction from the ion static structure factor in Fig. 21 including the square of the cluster form factor, as explained in the text.



Effects of warm ion mixtures is key to understand effects of cooling.

Anomalous thermal relaxation of plasmas arise so that form factor decrease as ordered configuration dissolve.

Barba, PG et al MNRAS '25

Figure 4. Top panel: Temperature $T(t)$ for a pure sample with $(Z, A) = (38, 128)$ (left) versus a mixture in which 40 per cent of the original ions have been

Nuclear input & fermion+meson fields: Shen EoS

In the dense stellar core after the SN explosion high T of dozens of MeV drive system to a mixture of nucleons, leptons. Relativistic field theories are well-suited to describe this system with EM fields

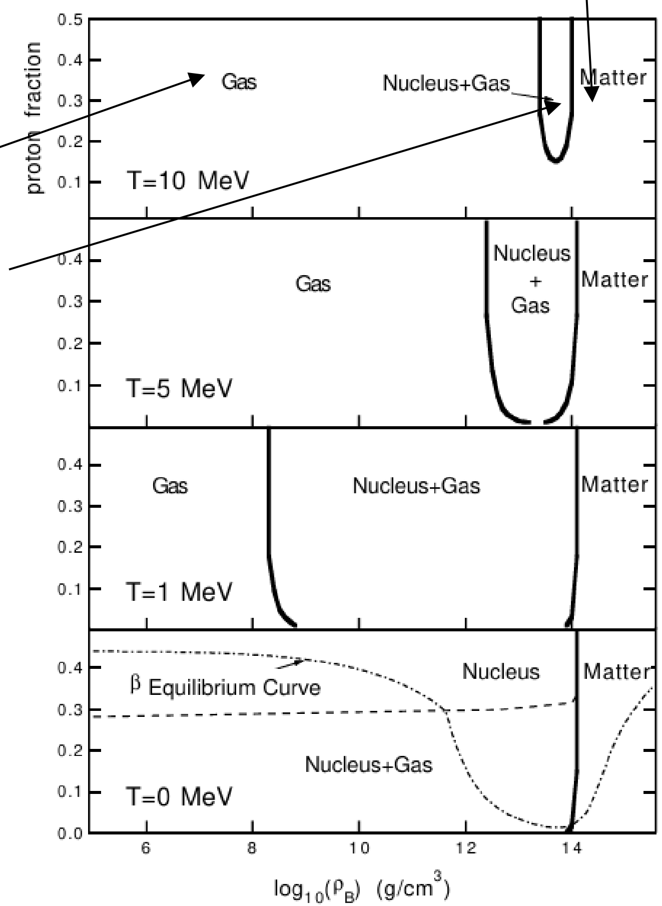
$$\mathcal{L}_{RMF} = \bar{\psi}\left[i\gamma_\mu\partial^\mu - M - g_\sigma\sigma - g_\omega\gamma_\mu\omega^\mu - g_\rho\gamma_\mu\tau_a\rho^{a\mu} - e\gamma_\mu\frac{1-\tau_3}{2}A^\mu\right]\psi$$
$$+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4$$
$$-\frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}c_3\left(\omega_\mu\omega^\mu\right)^2$$
$$-\frac{1}{4}R^a_{\mu\nu}R^{a\mu\nu} + \frac{1}{2}m_\rho^2\rho^a_\mu\rho^{a\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu},$$

Shen et al NPA’98, Shen et al ApJ TM1’11

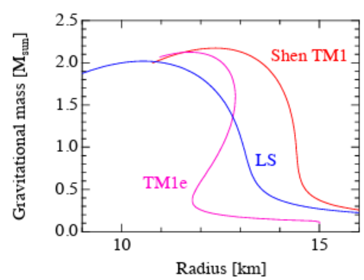
RMF nucleon+ lepton gas

ideal

Nucleon gas+ ion mixture



$$\varepsilon = \sum_{i=p,n}\frac{1}{\pi^2}\int_0^\infty dk\,k^2\sqrt{k^2+M^{*2}}\left(f^k_{i+}+f^k_{i-} \quad +\frac{1}{2}m_\omega^2\omega^2+\frac{3}{4}c_3\omega^4+\frac{1}{2}m_\rho^2\rho^2\right.$$
$$+\frac{1}{2}m_\sigma^2\sigma^2+\frac{1}{3}g_2\sigma^3+\frac{1}{4}g_3\sigma \quad +3\Lambda_v\left(g_\omega^2\omega^2\right)\left(g_\rho^2\rho^2\right),$$



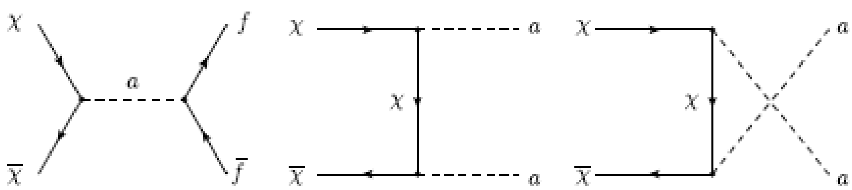
Sumiyoshi’21

$$P = \sum_{i=p,n}\frac{1}{3\pi^2}\int_0^\infty dk\,k^2\frac{k^2}{\sqrt{k^2+M^{*2}}}\left(f^k_{i+}+f^k_{i-}\right)$$
$$-\frac{1}{2}m_\sigma^2\sigma^2-\frac{1}{3}g_2\sigma^3-\frac{1}{4}g_3\sigma^4$$
$$+\frac{1}{2}m_\omega^2\omega^2+\frac{1}{4}c_3\omega^4+\frac{1}{2}m_\rho^2\rho^2$$
$$+\Lambda_v\left(g_\omega^2\omega^2\right)\left(g_\rho^2\rho^2\right).$$

But is this all? Perhaps not. .
BSM dark matter and SN EoS: some examples

$$\mathcal{L}_{\mathcal{I}} = -i\frac{g_\chi}{\sqrt{2}} a\bar{\chi}\gamma_5\chi - i g_0 \frac{g_f}{\sqrt{2}} a\bar{f}\gamma_5 f \,;$$

Coy DM from C. Boehm et al '14



Cermeño, Perez-Garcia, Lineros, ApJ '18

$$m_\chi < m_{Higgs}; m_a < m_\chi$$

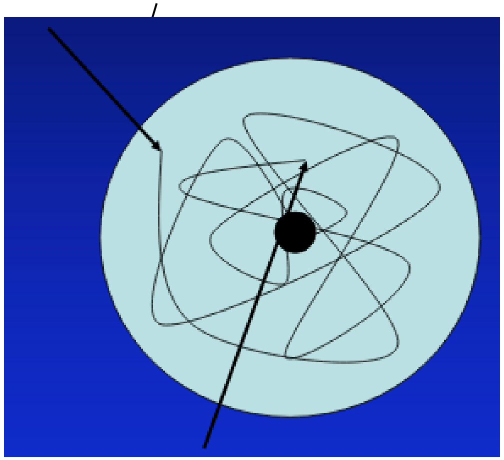
Model	m_χ [GeV]	m_a [GeV]	g_χ	g_0
A	0.1	0.05	7.5×10^{-3}	7.5×10^{-3}
B	1	0.05	1.2×10^{-1}	2×10^{-3}
C	30	1	6×10^{-1}	5×10^{-5}

Table 1: Parameters used Coy DM. Flavour-universal $g_f = 1$.

Massive progenitors accumulate thermalized DM, most likely from scattering SI or SD interactions or direct production

Hybrid stars with dark content are indeed possible if CS is above critical threshold

$$r_{th}(t) = \left(\frac{3k_B T_c(t)}{2\pi G \rho_c(t) m_\chi}\right)^{1/2},$$



$$XX \to \nu\overline{\nu}$$

$$XX \to aa, a \to \nu\overline{\nu}$$

Neutrino emissivity from DM

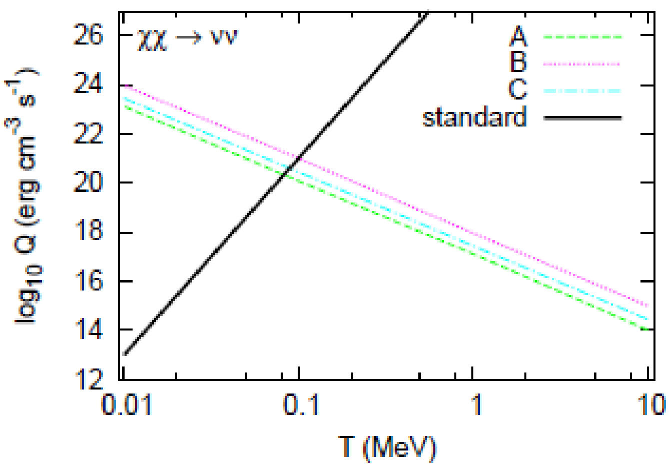
Early cooling by neutrinos may be influence by annihilation processes under the emissivity (energy per unit volume unit time) $12 \to 34$

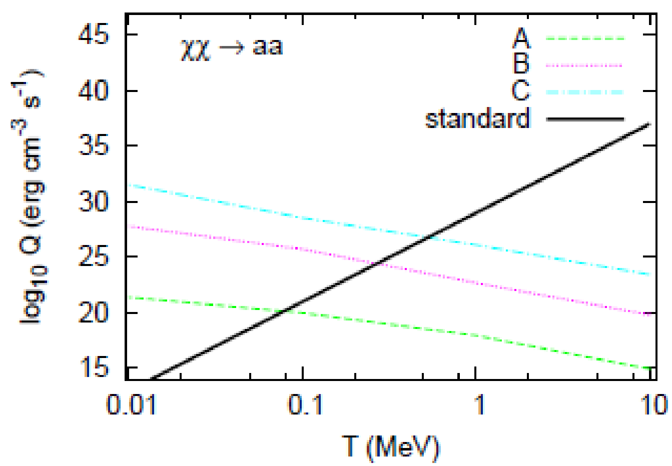
$$Q_E = 4 \int d\Phi(E_1 + E_2)\, |\overline{\mathcal{M}}|^2\, f(f_1, f_2, f_3, f_4)$$

with $$d\Phi = \frac{d^3p_1}{2(2\pi)^3 E_1}\frac{d^3p_2}{2(2\pi)^3 E_2}\frac{d^3p_3}{2(2\pi)^3 E_3}\frac{d^3p_4}{2(2\pi)^3 E_4}(2\pi)^4\delta^4(p_1 + p_2 - p_3 - p_4)$$

and matrix element $XX \to \nu\overline{\nu}$ $\qquad XX \to aa$

Neutrino emissivities from Coy DM have genuinely different T behavior than Modified URCA+ SM processes





reaction $\chi\chi \to aa$ could provide emissivities $Q_E^{aa} \sim 4 \times 10^{22}\ \mathrm{erg\,cm^{-3}\,s^{-1}}$ Higher than for the $Q_{MX1659-29} \sim 1.7 \times 10^{21}$ $\mathrm{erg\,cm^{-3}\,s^{-1}}$ for $T \sim 10^8$ K.

Channel	Model	$\log_{10} Q_0$	$N_{0,\chi}$
$\chi\chi \to \nu\nu$	A	17.3	4.1×10^{44}
$\chi\chi \to \nu\nu$	B	18	2.4×10^{44}
$\chi\chi \to \nu\nu$	C	17.6	5×10^{38}
$\chi\chi \to aa$	A	18	4.1×10^{44}
$\chi\chi \to aa$	B	22.5	2.4×10^{44}
$\chi\chi \to aa$	C	27	5×10^{38}

$$Q_E(T, N_\chi) = Q_0 \left(\frac{N_\chi}{N_{0,\chi}}\right)^2 \left(\frac{T}{1\,\mathrm{MeV}}\right)^{-3}$$

Cermeño,Perez-Garcia,Lineros ApJ '18

Neutrino emissivity: example from coy DM

Early cooling by neutrinos may be influence by annihilation processes under the emissivity (energy per unit volume unit time) $12 \to 34$

with

$$d\Phi = \frac{d^3p_1}{2(2\pi)^3E_1}\frac{d^3p_2}{2(2\pi)^3E_2}\frac{d^3p_3}{2(2\pi)^3E_3}\frac{d^3p_4}{2(2\pi)^3E_4}(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)$$

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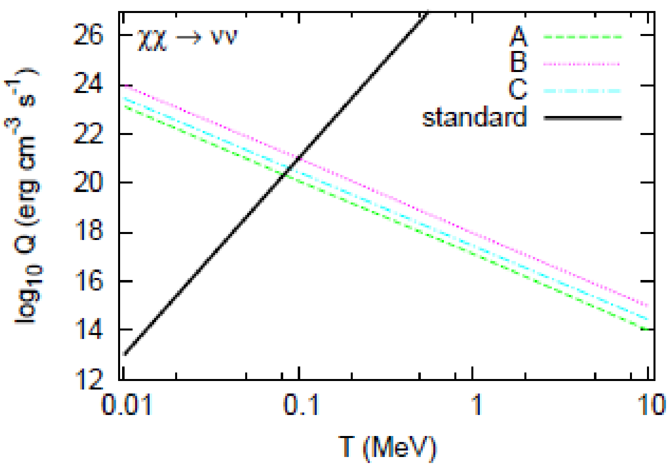

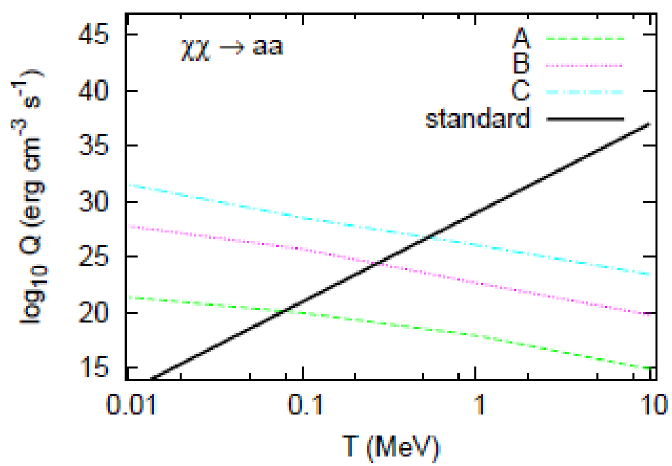

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Cermeño,Perez-Garcia, Lineros ApJ '18

SN EoS and sterile neutrinos

Yet another possibility BSM shows how sensitive SN EoS is

$$\mathcal{L}_{\rm eff} = \mu\,\bar{\nu}_h \sigma_{\mu\nu} \nu_h\, \partial^\mu A^\nu\,, \qquad \mu \approx e\,\frac{g_R^2}{16\pi^2}\,\frac{m_E}{M_R^2} \approx 10^{-6}\,{\rm GeV}^{-1}\,.$$

$$\mathcal{L}_{\rm eff} = \frac{1}{2}\,\mu_{\rm tr}\,\overline{\nu}_h\,\sigma_{\mu\nu}\,(1-\gamma_5)\,\nu\,\partial^\mu A^\nu + {\rm h.c.}\,, \qquad \mu_{\rm tr} \approx \sin\theta\,\mu \qquad \nu_h \to \nu\,\gamma$$

- **Active and sterile mixing** $N' = \cos\theta\, N + \sin\theta\, \nu \nu' = -\sin\theta\, N + \cos\theta\, \nu.$
- **We will assume the mixing is** $\sin^2\theta < 10^{-3}$ **in order not to conflict with cosmological bounds**
- **The dominant production channel will be electromagnetic** $e^+e^- \to \bar{\nu}_h \nu_h$

$$\frac{{\rm d}\sigma}{{\rm d}t} = \frac{\alpha\mu^2}{s^2 - 4sm_e^2}\left(-t + 2m_h^2 + m_e^2 - \frac{t^2 - 2(m_h^2 + m_e^2)t + (m_h^2 - m_e^2)^2}{s}\right)$$

- **Also active-sterile mixing** $\nu X \to \nu_h X$ **scattering** $\nu_h\, X \to \nu_h\, X$ **absorption**

Emissivity in the medium

Energy emissivity

$$Q_E(e^+e^- \to \bar{\nu}_h \nu_h) = \frac{dE}{dtdV}$$

$$Q_E = \frac{4}{(2\pi)^8} \int \frac{d^3p_1}{2E_1} \frac{d^3p_2}{2E_2} \frac{d^3p_3}{2E_3} \frac{d^3p_4}{2E_4} \, \delta^4(p_1+p_2-p_3-p_4) \, (E_1+E_2) \, |\bar{\mathcal{M}}|^2 \, f(f_1, f_2, f_3, f_4)$$

$$|\bar{\mathcal{M}}(e^+e^- \to \bar{\nu}_h \nu_h)|^2 = 4e^2 \mu_h^2 \left(-t + 2m_h^2 + m_e^2 - \frac{t^2 - 2(m_h^2 + m_e^2)t + (m_h^2 - m_e^2)^2}{s} \right)$$

The dense and hot medium

Albertus, Masip, PG, PLB'15

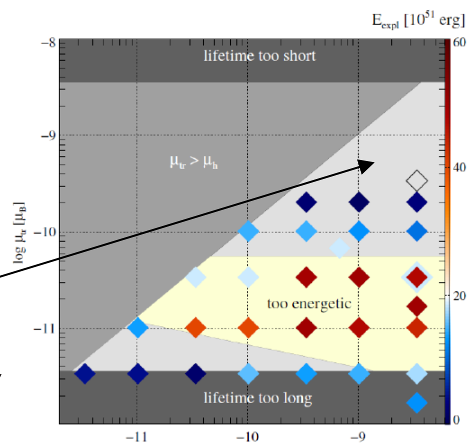
$$f_i(E) = \frac{1}{e^{(E-\mu_i)/T} + 1}$$

$$\mu_{e-} = -\mu_{e+} 100\,\mathrm{MeV}$$

$$T = 25\,\mathrm{MeV}$$

Fit Energy emissivity

$$Q_E \approx 1.5 \times 10^{36} \left(\frac{\mu}{10^{-6}\,\mathrm{GeV}^{-1}} \right)^2 \left(\frac{T}{25\,\mathrm{MeV}} \right)^{7.4} e^{-\frac{m_h + \mu_e}{3T}} \, \frac{\mathrm{erg}}{\mathrm{s\ cm}^3} \, .$$



Light gray regions
not excluded

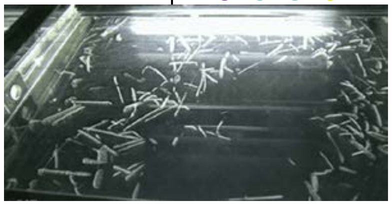
Rembiasz, Obergaulinger, PG et al PRD'18

$$m_h = 50 - 80\ \mathrm{MeV}/c^2$$

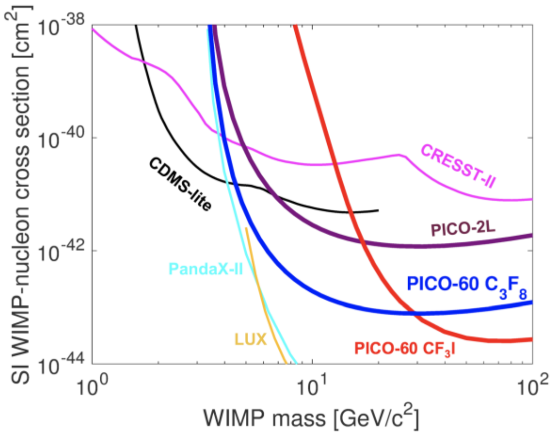
T	μ_e	Q_{50}	Q_{80}
5	20	$1.53656 \cdot 10^{26}$	$5.66121 \cdot 10^{21}$
5	40	$1.36192 \cdot 10^{26}$	$5.65149 \cdot 10^{21}$
5	60	$6.62017 \cdot 10^{25}$	$5.38001 \cdot 10^{21}$
5	80	$1.40457 \cdot 10^{25}$	$3.70775 \cdot 10^{21}$
5	100	$1.57973 \cdot 10^{24}$	$1.36088 \cdot 10^{21}$
5	120	$1.14701 \cdot 10^{23}$	$2.67659 \cdot 10^{20}$
5	140	$5.92976 \cdot 10^{21}$	$3.23395 \cdot 10^{19}$

T	μ_e	Q_{50}	Q_{80}
20	20	$5.91745 \cdot 10^{34}$	$1.46498 \cdot 10^{34}$
20	40	$5.40009 \cdot 10^{34}$	$1.40987 \cdot 10^{34}$
20	60	$4.55643 \cdot 10^{34}$	$1.29812 \cdot 10^{34}$
20	80	$3.52661 \cdot 10^{34}$	$1.12208 \cdot 10^{34}$
20	100	$2.51089 \cdot 10^{34}$	$8.99522 \cdot 10^{33}$
20	120	$1.65963 \cdot 10^{34}$	$6.67171 \cdot 10^{33}$
20	140	$1.02932 \cdot 10^{34}$	$4.59968 \cdot 10^{33}$

SN collapse and trigger QCD EoS



SN core collapse involves high T and large densities in the inner core. There is a long-sought possibility of producing bubble nucleation
Self-annihilating DM act as a Trojan Horse mechanism and final state photon injection $XX \to q\bar{q} \to N\gamma$



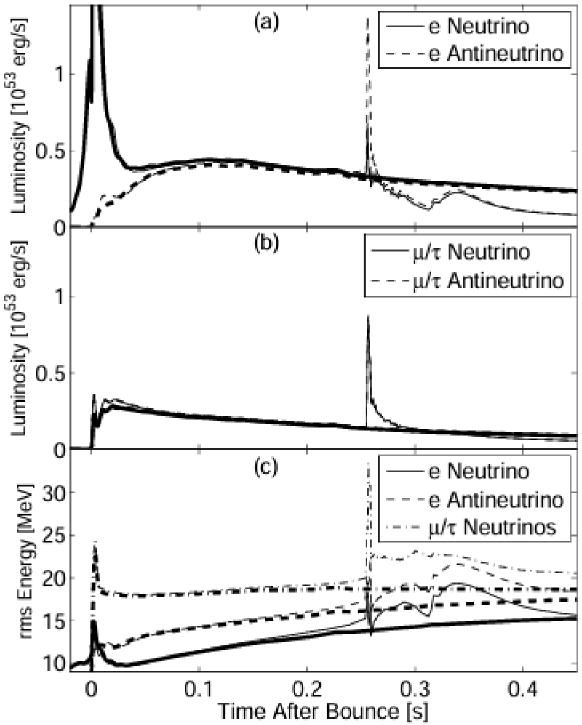
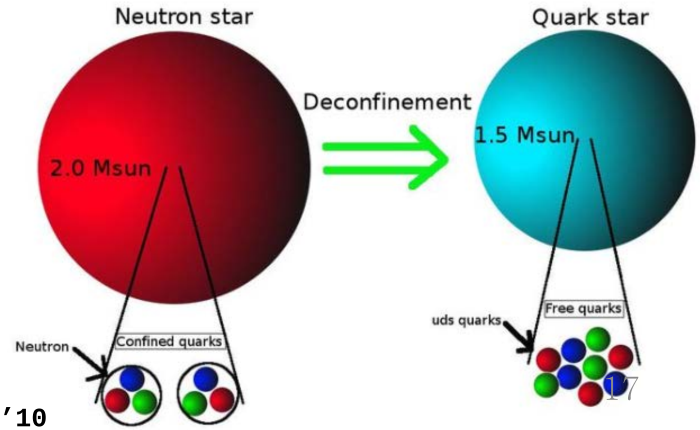


FIG. 2: Neutrino luminosities (a) and (b) and rms-energies (c) measured at 500 km distance for a 10 $M_\odot$ progenitor model. The results of the quark EoS *eos1* (thin lines) are compared to the results of the pure hadronic EoS [18] (thick lines). A second neutrino burst is clearly visible at ~ 260 ms after bounce.

hadronic system could suffer a phase transition from a metastable phase (Hadron) to a more stable one (Quark-gluon) if right thermodynamical conditions

MIT Bag model required to be on the B=160 MeV^{-1}

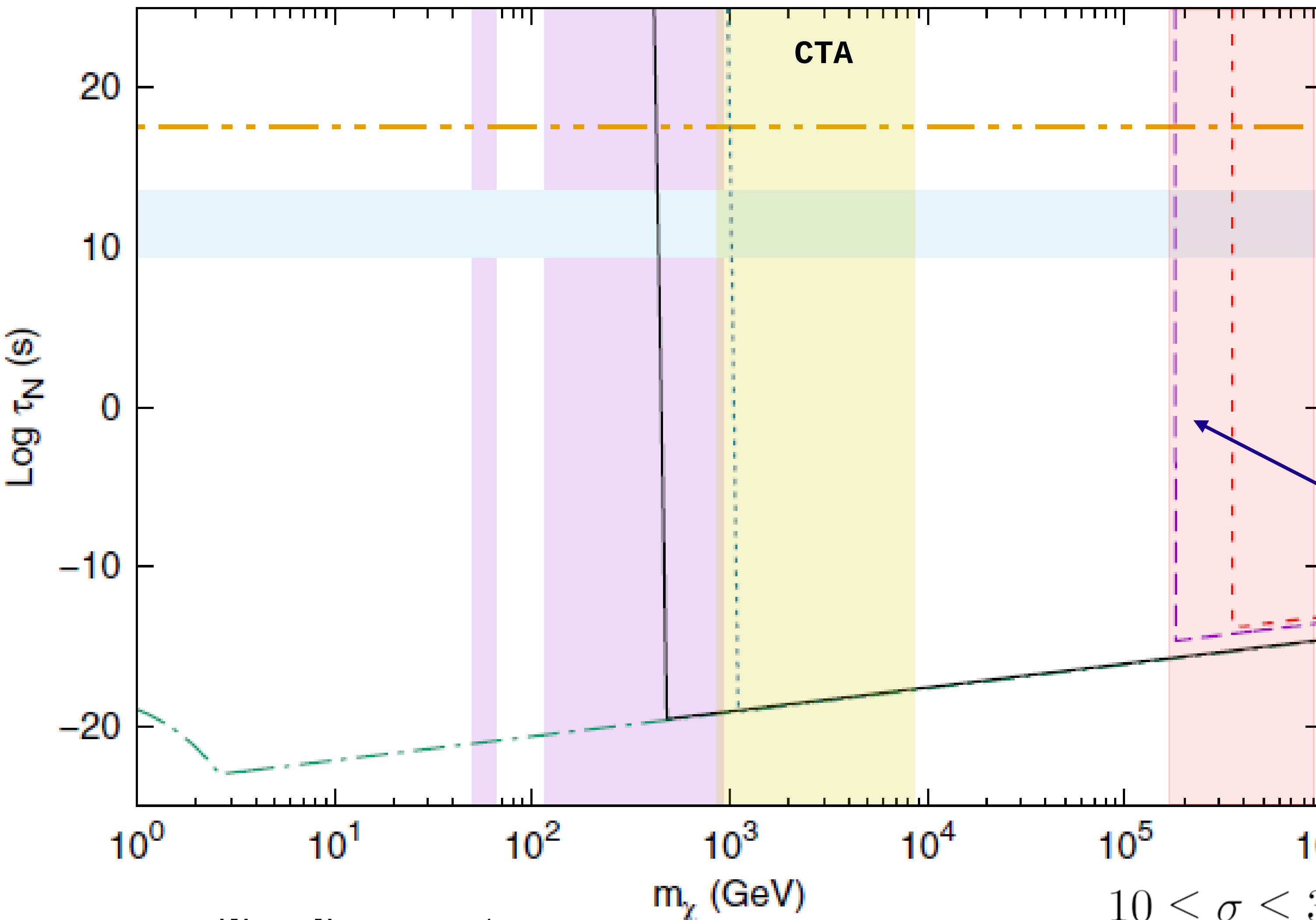
Distinctive double neutrino burst.



Sagert et al PRL'08

PG, Silk & Stone PRL'10

SUSY preferred



τ_U

$\tau_{\rm NS}$ *ages*

Values preferred from chiral models, QCD and NS masses

$$10 \leq \sigma \leq 30\,\mathrm{MeV\,fm}^{-2}$$
$$70 \leq B \leq 150\,\mathrm{MeV\,fm}^{-3}$$

Herrero, PG, Silk & Albertus PRD '19

Yet many things to understand. Thank you.