Sterile neutrinos in stellar core-collapse

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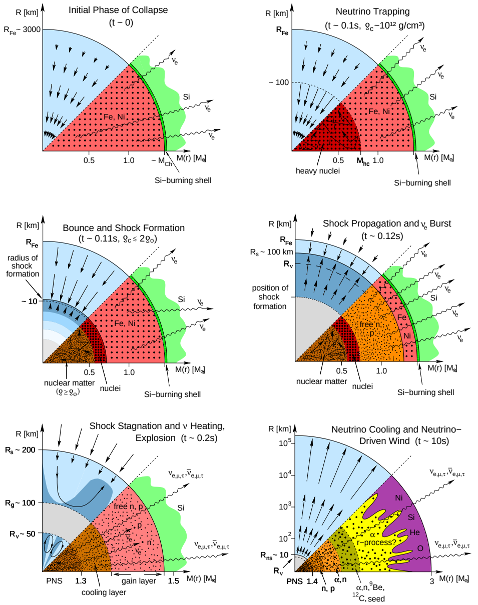
The Supernova Mechanism



The biggest roles in SN mechanisms are played by

- active neutrinos
- standing accretion shock instability (SASI)
- convection
- in some cases magnetic fields (MRI)
- sterile neutrinos??

Left panels from Janka et al. (2007)

Fuller et al. 2009 sterile neutrino model

- sterile neutrino mass: $m_h = 145\text{–}250\ \mathrm{MeV}$
- dominant production channels (via W,Z bosons) $\nu_{\tau/\mu} + \nu_{\tau/\mu} \to \nu_h + \nu_{\tau/\mu}$, etc ...

$$Q_{\mathrm{FKP}} \approx 3 \cdot 10^{34} \left(\frac{\sin^2\theta}{5\cdot 10^{-8}}\right)^2 \left(\frac{Tk_{\mathrm{B}}}{35\,\mathrm{MeV}}\right)^{7.2} \exp\left(-\frac{m_h c^2}{Tk_{\mathrm{B}}}\right) \frac{\mathrm{erg}}{\mathrm{cm^3\,s}},$$

where $\sin^2\theta = 10^{-8}\text{–}10^{-7}$

- main decay channel $\nu_h \to \nu_{\mu,\tau}\pi^0 \to \nu_{\mu,\tau}\gamma\gamma$

$$\tau_h \approx 65\ \mathrm{ms} \left(\frac{5\cdot 10^{-8}}{\sin^2\theta}\right) \left(\frac{200\left(200^2 - 135^2\right)\ \mathrm{MeV}^3}{m_h\left(m_h^2 - m_\pi^2\right)c^6}\right)$$

- no other interactions with "normal matter"

Albertus et al. 2015 sterile neutrino model

- sterile neutrino mass: $m_h = 50\text{–}80\ \mathrm{MeV}$
- dominant production channel (electromagnetic) $e^+e^- \to \bar{\nu}_h\nu_h$

$$Q_{\mathrm{AMP}} \approx 1.5{\cdot}10^{36} \left(\frac{\mu}{10^{-6}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{Tk_{\mathrm{B}}}{25\,\mathrm{MeV}}\right)^{7.4} \exp\left(-\frac{m_h c^2 + \mu_e}{3Tk_{\mathrm{B}}}\right) \frac{\mathrm{erg}}{\mathrm{cm}^3\,\mathrm{s}}$$

- main decay mode (also electromagnetic) $\nu_h \to \nu_{\mu,\tau}\gamma\,.$

$$\tau_h \approx 2.6\ \mathrm{ms}\ \left(\frac{10^{-8}\,\mathrm{GeV}^{-1}}{\mu_{\mathrm{tr}}}\right)^2 \left(\frac{50\ \mathrm{MeV}}{m_h c^2}\right)\,,$$

- elastic scattering with protons $\sigma_s \approx 7.5 \cdot 10^{-42}\,\mathrm{cm}^2\ \left(\frac{\mu_{\mathrm{h}}}{10^{-8}\,\mathrm{GeV}^{-1}}\right)^2\,.$
- capture through inelastic collisions with charged particles: $\nu_h X \to \nu_{\mu,\tau} X$,
  $\sigma_a^X = a_X\,10^{-45}\,\mathrm{cm}^2\ \left(\frac{\mu_{\mathrm{tr}}}{10^{-8}\,\mathrm{GeV}^{-1}}\right)^2\,,$
  with $a_p = 0.9$ and $a_e = 2.1$ for proton and electron, respectively.

Sterine neutrino models

Fuller et al. 2009 (FKP09)

- mass: $m_h = 145\text{–}250\ \mathrm{MeV}$
- production rate (cooling)

  $Q_{\mathrm{FKP}} \approx 3 \cdot 10^{34} \left(\frac{\sin^2\theta}{5{\cdot}10^{-8}}\right)^2 \times \left(\frac{Tk_{\mathrm{B}}}{35\,\mathrm{MeV}}\right)^{7.2} \exp\left(-\frac{m_h c^2}{Tk_{\mathrm{B}}}\right) \frac{\mathrm{erg}}{\mathrm{cm^3\,s}}$
- lifetime $\tau_h \approx$

$65\ \mathrm{ms} \left(\frac{5{\cdot}10^{-8}}{\sin^2\theta}\right) \left(\frac{200\left(200^2-135^2\right)\,\mathrm{MeV}^3}{m_h\left(m_h^2-m_\pi^2\right)c^6}\right)$

Albertus et al. 2015 (AMP15)

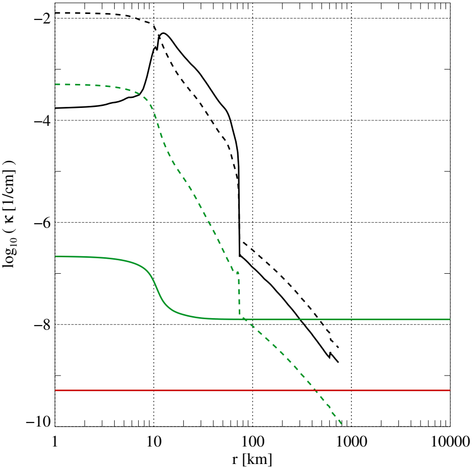
- mass: $m_h = 50\text{–}80\ \mathrm{MeV}$
- production rate (cooling)

  $Q_{\mathrm{AMP}} \approx 1.5 \cdot 10^{36} \left(\frac{\mu}{10^{-6}\,\mathrm{GeV}^{-1}}\right)^2 \times \left(\frac{Tk_{\mathrm{B}}}{25\,\mathrm{MeV}}\right)^{7.4} \exp\left(-\frac{m_h c^2+\mu_e}{3Tk_{\mathrm{B}}}\right) \frac{\mathrm{erg}}{\mathrm{cm^3\,s}}$
- lifetime $\tau_h \approx$

  $2.6\ \mathrm{ms} \left(\frac{10^{-8}\,\mathrm{GeV}^{-1}}{\mu_{\mathrm{tr}}}\right)^2 \left(\frac{50\,\mathrm{MeV}}{m_h c^2}\right)$,

Neutrino opacities

$$\kappa = \kappa_a + \kappa_s \ [\text{cm}^{-1}]$$



We approximate $v_h \approx c$ and $\gamma\beta = 1$.

$$\kappa_a = 1/(\tau_h v_h) + n\sigma_a$$

$$\kappa_s = n\sigma_s$$

FKP

$$\kappa_a = 9.4 \cdot 10^{-10} \left[\left(\frac{m_h c^2}{200 \ \mathrm{MeV}} \right)^3 - 0.46 \left(\frac{m_h c^2}{200 \ \mathrm{MeV}} \right) \right]$$

AMP

$$\kappa_a = \left[(0.9 n_p + 2.1 n_e) 10^{-45} + 1.2 \cdot 10^{-11} \left(\frac{m_h c^2}{50 \, \mathrm{MeV}} \right)^3 \right] \left(\frac{\mu_{\mathrm{tr}} (\hbar c)^{-3/2}}{10^{-8} \ \mathrm{GeV}^{-1}} \right)^2$$

$$\kappa_s = 7.5 \cdot 10^{-42} n_p \left(\frac{\mu (\hbar c)^{-3/2}}{10^{-6} \mathrm{GeV}^{-1}} \right)^2$$

Numerical code

- finite-volume Eulerian relativistic (M)HD code AENUS (Obergaulinger 2008)
- TOV gravity
- M1 transport for active neutrinos
- M1 transport for sterile neutrinos (grey approximation)
- HLL Riemann solvers
- MP5 reconstruction (Suresh & Huynh 1997)
- RK3 time integration

Two-moment neutrino transport

- 0^{th} moment: conservation law for neutrino energy:

$$\partial_t E + \nabla_j (F^j + v^j E) + \mathcal{V}_0 + \mathcal{G}_0 = \mathcal{C}^0.$$

- 1^{st} moment: and for neutrino momentum

$$\partial_t F^i + c^2 \nabla_j (P^{ij} + v^j F^i) + \mathcal{V}_1^i + \mathcal{G}_1^i = \mathcal{C}^{1,i}.$$

- P, the neutrino pressure tensor, is a local function of E and $\vec{F}$, which interpolates between the limits of diffusion, $P = 1/3E\,\mathrm{diag}(1,1,1)$, and free streaming, $P^{ij} = E\,F^i F^j / F^2$.
- $\mathcal{V}$, $\mathcal{G}$ are the velocity and gravity terms coupling neutrino energy bins
- $\mathcal{C}$ are the neutrino-matter interaction terms: emission, absorption, scattering (potentially quite stiff).

Simulation setup

- 15 $M_\odot$ progenitor with solar metalicity of Woosley, Heger & Weaver (2002)
- LS220 EOS
- spherical symmetry (1D)
- box length of 10^6 km resolved with 608 zones
- 16 energy bins for active neutrinos
- simulations run for 1 s post-bounce (if possible)

List of models

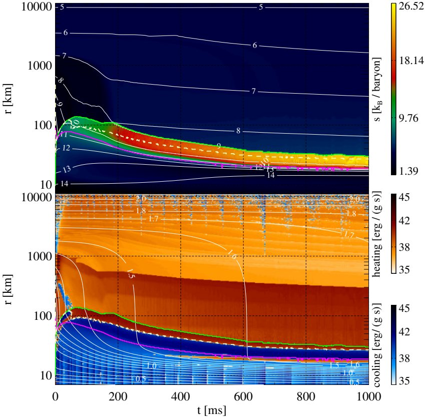
#	$m_h c^2$ [MeV]	q	$\mu_{\rm tr}(\hbar c)^{-3/2}$ $[10^{-8}{\rm GeV}^{-1}]$	$\tau_h c$ [km]	$t_{\rm expl}$ [ms]	$r_{\rm expl}$ [km]	$M_{\rm c}$ $[M_\odot]$	$E_{\rm expl}$ [erg]	$t_{\rm end}$ [ms]
R	–	–	–	–	–	–	–	–	1000
A1	50	1	10	7.9	–	–	–	–	1000
A2	50	1	5	32	193	25	1.36	$4.4 \cdot 10^{51}$	405
A3	50	1	1	790	36	40	1.26	$4.2 \cdot 10^{52}$	168
A4	50	1	0.5	3200	38	50	1.30	$4.4 \cdot 10^{52}$	132
A5	50	1	0.1	$7.9 \cdot 10^{4}$	65	1700	1.49	$1.8 \cdot 10^{52}$	288
A6	50	1	0.05	$3.2 \cdot 10^{5}$	90	3600	1.63	$9.9 \cdot 10^{51}$	499
A7	50	0.1	1	790	68	43	1.32	$4.5 \cdot 10^{52}$	229
A8	50	10^{-2}	1	790	132	57	1.40	$1.3 \cdot 10^{52}$	246
A9	50	10^{-3}	1	790	230	62	1.47	$2.7 \cdot 10^{51}$	323
A10	50	10^{-4}	1	790	–	–	–	–	657+
A11	50	0.2	2	200	67	34	1.27	$1.9 \cdot 10^{52}$	284
A12	80	1	1	190	73	41	1.26	$1.9 \cdot 10^{52}$	227
F1	150	0.2	–	$6.6 \cdot 10^{5}$	870	$2.6 \cdot 10^{4}$	2.55	$6.6 \cdot 10^{49}$	1000
F2	150	1	–	$1.3 \cdot 10^{5}$	464	6300	1.85	$3.0 \cdot 10^{51}$	1000
F3	200	1	–	$2.0 \cdot 10^{4}$	582	4600	1.75	$1.3 \cdot 10^{51}$	1000
F4	250	1	–	7700	–	–	–	–	1000
F5	250	2	–	3800	761	860	1.62	$2.6 \cdot 10^{50}$	820

AMP: $q \equiv (\mu(\hbar c)^{-3/2}/(10^{-6}\mathrm{GeV}^{-1}))^2$

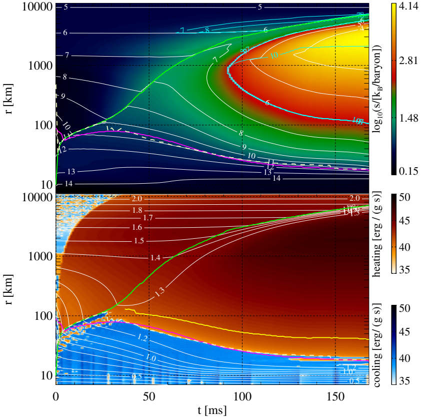
FKP $q \equiv (\sin^2\theta/(5\cdot 10^{-8})^2$

Simulation results

Reference model (R)



AMP with default pars (A3)



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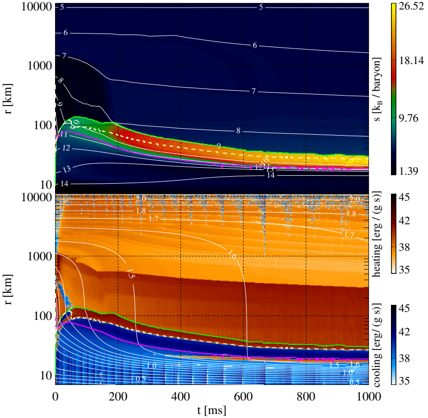
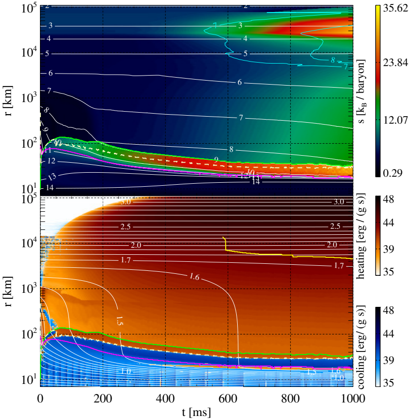


FKP with default pars (F3)



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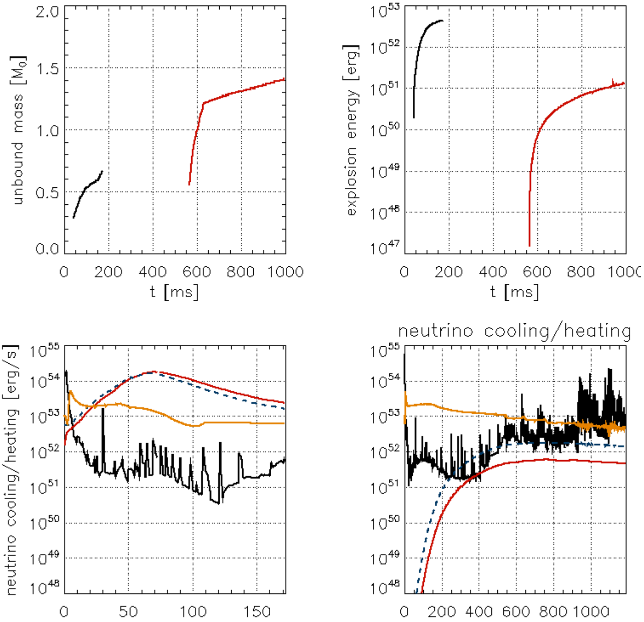

List of models

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Simulation results

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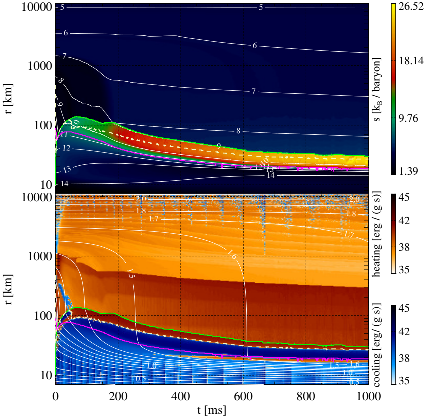
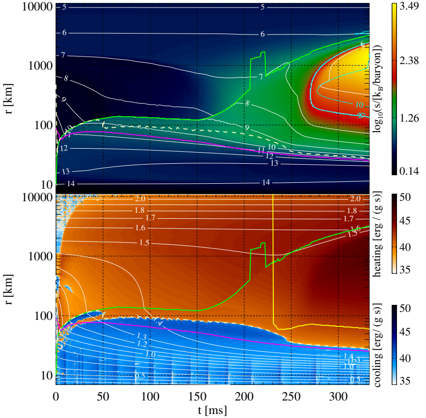
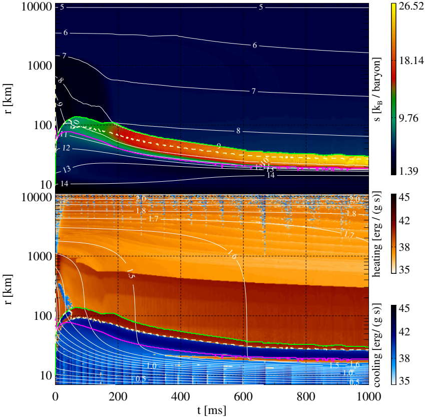


AMP $q = 1e-3$ (A9)

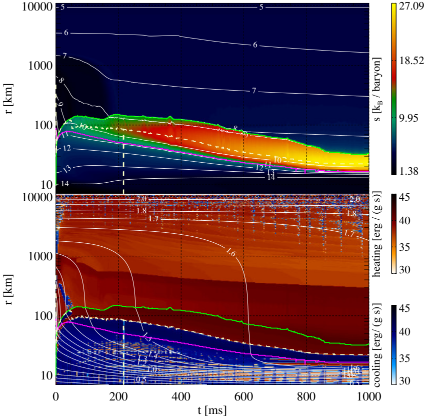


Simulation results

Reference model (R)



AMP $\mu_{\rm tr} = 10$ (A1)



Summary & outlook

- succesful explosions in 1D (good news! we don't need multi-D simulations anymore) for both sterile neutrino models
- different explosion mechanisms
- some explosions too energetic! (constraints on sterile neutrino models)
- influence on convection t.b.d.
- nucleosynthesis imprint t.b.d.

Thank you for your attention!