Phase transition to hyperons in proto-neutron stars

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Peres, Oertel & Novak,
Phys. Rev. D **87**, 043006 (2013)

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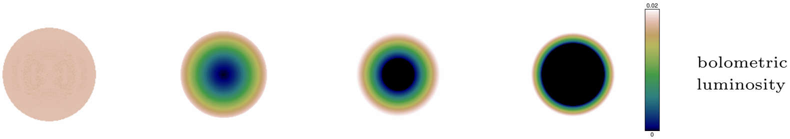
Context

How do stellar black holes form?

- Stellar-mass black holes form in the collapse of massive stars
- Beginning of collapse triggered by mass-limit of iron core
- Collapse & bounce, then collapse of the proto-neutron star triggered by accretion

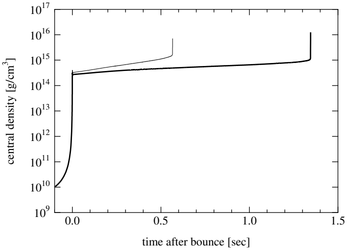
⇒very similar scenario to core-collapse supernova
⇒central engine for gamma-ray bursts (collapsar model)



Vincent *et al.* (2012)

Context

Collapse to black hole from stellar progenitor has already been studied (*e.g.* Sumiyoshi *et al.* (2007), Fischer *et al.* (2009), O'Connor & Ott (2011), Ugliano *et al.* (2012)...).



$40M_\odot$ progenitor, from Sumiyoshi *et al.* (2007)

⇒much higher densities (above nuclear saturation density) and temperatures (tens of MeV) than in supernova simulations.

Aims. . .

High density & temperature conditions $\Rightarrow$additional particles should appear (observed on Earth).

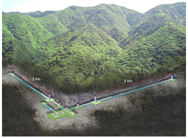
- How many “exotic” particles could appear on the way to the black hole?
- What is their influence on the collapse?
- What is their observational signature?

Reverse question:

- Can we infer nuclear matter composition from observations of black hole formation?

LIGO

Virgo



KAGRA

Physical framework

- Spherical or axial symmetry (1D/2D runs).
- Relativistic hydrodynamics, with perfect-fluid stress-energy tensor.
- General relativity in 3+1 formulation. Isotropic gauge for 1D, conformally-flat condition (CFC) in 2D.
- Apparent horizon finder (Lin & Novak 2007).
- Microphysical equation of state from Oertel *et al.* (2012).
- Deleptonization and neutrino leakage.
- Gravitational waves extracted with the modified quadrupole formula (2D).

NUMERICAL TOOLS

COCONUT code (Dimmelmeier *et al.* 2005):

- Potentially 3D code, but used only in 1D or 2D (not fully parallel, yet);
- high resolution-shock capturing schemes for the relativistic hydrodynamics (*e.g.* Font 2008)⇒conservative-form hydrodynamic equations;
- multi-domain pseudo-spectral methods for the solution of Einstein equations (*e.g.* Grandclément & Novak 2009) ⇒non-linear coupled elliptic system;
- interpolation and filtering to avoid Gibbs phenomenon.

Equation of state

Oertel *et al.* (2012), Gulminelli *et al.* (2012)

Earth-based experiments ⇒ pions and hyperons at high densities and temperatures.
Nucleonic interaction from Lattimer & Swesty (1991) ⇒ $n, p, e^-, e^+, \gamma, \alpha, A$

EoS LS220+pions

- Pions π^-, π^0, π^+
- free gas

EoS LS220+hyperons

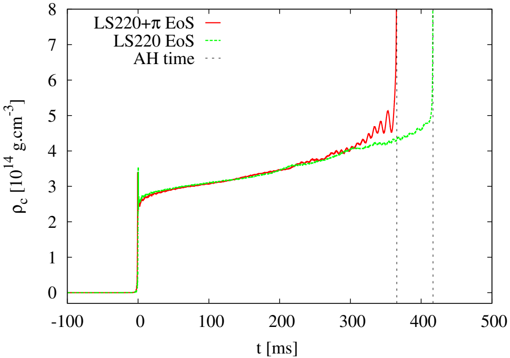
- Λ hyperons
- contains a first order phase transition to hyperonic matter

Hadronic interaction different from previous studies (RMF) with additional particles (Sumiyoshi *et al.* 2009, Shen *et al.* 2011).
⇒ Compatible with $\sim 2\ M_\odot$ neutron star observations Demorest *et al.* (2010), Antoniadis *et al.* (2013).

Results

Spherical symmetry

with pions



- Maximum pion fraction $Y_{\pi^-} = 0.13$ at the onset of BH collapse
- $Y_{\pi^-} > Y_{\pi^0} > Y_{\pi^+}$ at all times

- The PNS with LS220+π EoS is slightly more compressible
- More compressible means less pressure $\rightarrow$ cannot hold as much mass as LS220 $\rightarrow$ less time post bounce accreting mass and maximum mass smaller
- PNS baryonic masses at BH collapse : $2.55\ M_\odot$ with LS220, $2.49\ M_\odot$ with LS220+π

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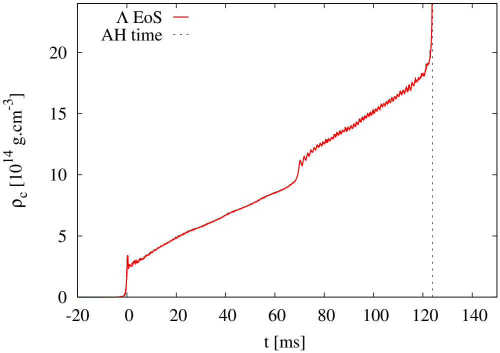
Spherical symmetry

with hyperons

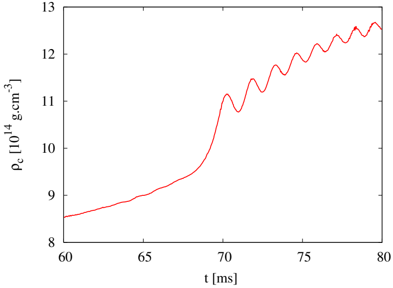


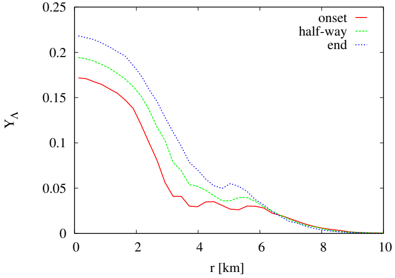
- PNS baryonic mass at BH collapse : $2.00\ M_\odot$
- Maximum of Λ hyperon fraction $Y_\Lambda = 0.41$ at the onset of BH collapse

- Presence of a phase transition to hyperonic matter (related to the high accretion rate)
- The PNS oscillates after the phase transition (PNS fundamental modes)
- Oscillations are resolved in time and stay when increasing the resolution

Phase transition

Spherical symmetry





- Phase transition only reached for progenitors with high mass accretion rate (low metallicity),
- Induces a "mini-collapse" followed by oscillations of the PNS,
- No second shock wave as in simulations with phase transition to quark matter (Sagert *et al.* 2009).

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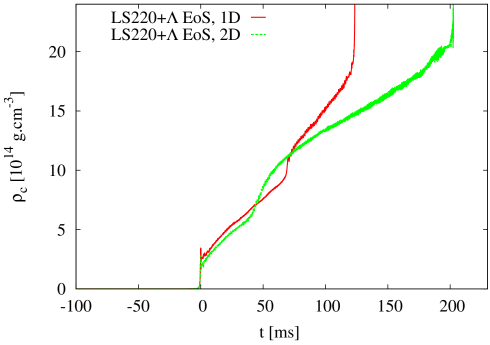
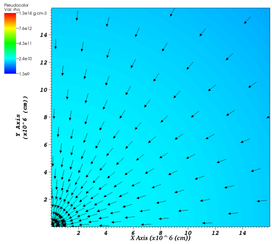
Phase transition

Rotational symmetry

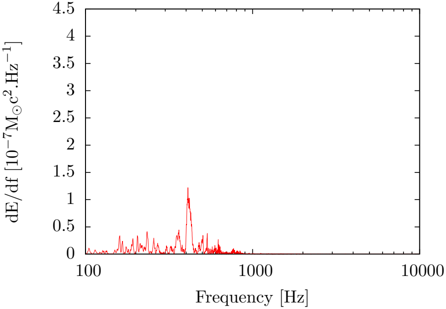
- 2D in axisymmetry
- Progenitor rotation profile : slow and differential
- All other settings similar to 1D settings

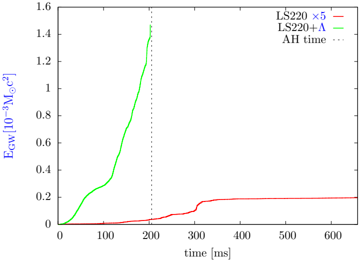


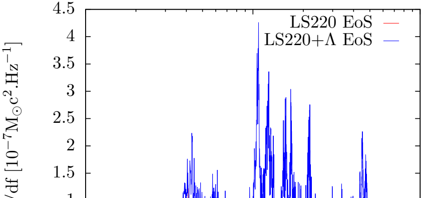


Gravitational waves

With the modified quadrupole formula







Summary / Outlook

- EoS for core-collapse based on Lattimer & Swesty (1991), with additional particles (π, Λ), compatible with recent observations of $2M_\odot$ neutron stars.
- Softens the PNS, which collapses more rapidly and eventually undergoes a phase transition to hyperonic matter.
- Phase transition "softened" in 2D simulations $\Rightarrow$implications for QGP phase transition?
- Possibly observable with gravitational waves.

- Improvement of resolution in 2D
- Better (full?) neutrino transport (Peres *et al.* 2014)

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Neutrino leakage

- Only one opaque (⇒fluid) zone and one transparent (⇒free-streaming) zone (*e.g.* van Riper *et al.* 1981)
- No transport, cheap in CPU time, but number of approximations and drawbacks
- No semi-transparent regime, no self-consistent heating ⇒not good to revive the shock.

⇒computation of "optical" depth for three species of neutrinos: $\nu_e, \bar{\nu}_e, \nu_x$. Loss of energy & momentum taken into account.

Creation processes

- $p + e^- \to \nu_e + n$
- $(A, Z) + e^- \to (A, Z-1) + \nu_e$
- $e^- + e^+ \to \nu_i + \bar{\nu}_i$
- $\tilde{\gamma} \to \nu_i + \bar{\nu}_i$

Opacity processes

- $\nu_i + N \to \nu_i + N$
- $\nu_i + (A, Z) \to \nu_i + (A, Z)$
- $\nu_e + n \to p + e^-$
- $\bar{\nu}_e + p \to n + e^+$

Parameters & Initial models

PROGENITOR

- From Woosley *et al.* (2002), $40M_\odot$ ZAMS and $10^{-4}\times$ solar metallicity

LEAKAGE

- β-equilibrium density 1.2×10^{12} g.cm^{-2}
- ν escape time $t_{esc} = 3(R_{\nu-\text{sphere}} - r)\tau$
- power lost by the fluid in the trapped regime $Q_E = -1.1 \langle \epsilon_\nu \rangle \dfrac{Y_\nu}{t_{esc}}$

EOS

- Values of the parameters for $Y-N$ and $Y-Y$ interactions compatible with hyperonic data and PSR J 1614-2230 (marginally).