Finite temperature EoS with hyperons and Δ-isobars: $I - \lambda - \mathcal{C}$ scaling

Adriana R. Raduta
IFIN-HH, Bucharest

Collaborator: Armen Sedrakian (FIAS, Frankfurt)

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Overview

- hyperons and Δ isobars in NS's inner core
- hyperons and Δ isobars in hot stellar matter
- cold catalized matter and $(S/A = \mathrm{ct},\ Y_L = \mathrm{ct})$: chemical composition, $P(e)$ and $P(f)$
- NS properties: maximum mass, radii, moments of inertia, tidal deformability, binding energies
- scaling: $\bar{I} - \mathcal{C}$, $\tilde{I} - \mathcal{C}$, $\bar{\lambda} - \mathcal{C}$, $BE(M_B)$, $\bar{I} - \bar{\lambda}$
- conclusions

Hyperons in NS inner core

- expected to nucleate when $\mu_i \geq m^*_{Dirac,i}$
- responsible of $P(e)$ softening and $M_{\max}$ decrease
- subject to large uncertainties related to poorly known NY and YY interactions
- (most often) addressed within Relativistic Mean Field theory of baryonic matter
  - couplings of the scalar mesons σ and σ^* to Y are tuned to reproduce $U_\Lambda \approx -28$ MeV, $U_\Xi \approx -14$ MeV, $U_\Sigma \approx 30$ MeV [Gal, Hungerford, Millener, RMF (2016)], and $\Delta B_{\Lambda\Lambda} \approx 1$ MeV [Takahashi et al., PRL (2001)]
  - couplings of vector mesons ω, ρ, ϕ to Y calculated according to SU(6) or SU(3) symmetry groups
- many EoS [Weissenborn, Chatterjee & Schaffner-Bielich, PRC85 and NPA881 (2012); Miyatsu, Cheoun & Saito, Phys. Rev. C 88 (2013); Van Dalen, Colucci & Sedrakian, PLB (2014); Fortin, Avancini, Providencia & Vidana, Phys. Rev. C 95 (2017)]
  - successful in producing $2M_\odot$
  - radii and λ, linked to the nucleonic sector, low L favor small radii

Δ baryons in NS inner core

4 isobars: $\Delta^{++}(uuu)$, $\Delta^{+}(uud)$, $\Delta^{0}(udd)$, $\Delta^{-}(ddd)$,
mass=1232 MeV/c^2; lifetime= $(5.63 \pm 0.14) \times 10^{-24}$ s,
produced in heavy ion collisions, expected to be populated in NS

- relatively little studied, for unknown interactions
- experimental constraints [Kolomeitsev et al., NPA (2017)]
  - $(V_N^{(N)} - 30\ \mathrm{MeV}) \lesssim V_\Delta^{(N)} \lesssim V_N^{(N)}$ [Drago et al., PRC (2014)],
  - $x_{\sigma N} \lesssim x_{\sigma \Delta} \lesssim x_{\sigma N} + 0.2$ (electromagnetic excitations),
  - no information on $x_{\rho\Delta}$
- NS with Δs [Chen et al., PRC (2007); Drago et al., PRC (2014); Cai et al., PRC (2015); Zho et al. PRC (2016); Sahoo et al., PRC (2018); Kolomeitsev et al., NPA (2017); Li et al., PLB (2018); Ribes et al. (2019)]
  - Δs mainly impact NS radii, little (no) effect on M_{max}
  - Δs population favored by: low x_ρ, high x_σ
  - NS affected also by x_ω and m_Δ

Present work

Relativistic Mean Field Model with density dependent couplings DDME2 [Lalazissis et al., PRC (2005)]

- good description of SNM properties: $n_s = 0.1520~\mathrm{fm}^{-3}$, $E_s = -16.1$ MeV, $K_{sat} = 250.9$ MeV, $J = 32.3$ MeV, $\underline{L = 51.2~\mathrm{MeV}}$
- fair agreement with energetics of PNM, as calculated by *ab-initio* models [Gandolfi et al., PRC (2012); Hebeler et al., ApJ (2013)]
- extension to baryonic octet DDME2Y within SU(6) by [Fortin et al., PRC (2016)]; $M_{\max}^{(Y)} = 2.12 M_{\odot}$
- fixed $x_{\sigma\Delta} = 1.1$, $x_{\omega\Delta} = 1$, $x_{\rho\Delta} = 1$, DDME2YΔ
- NS properties

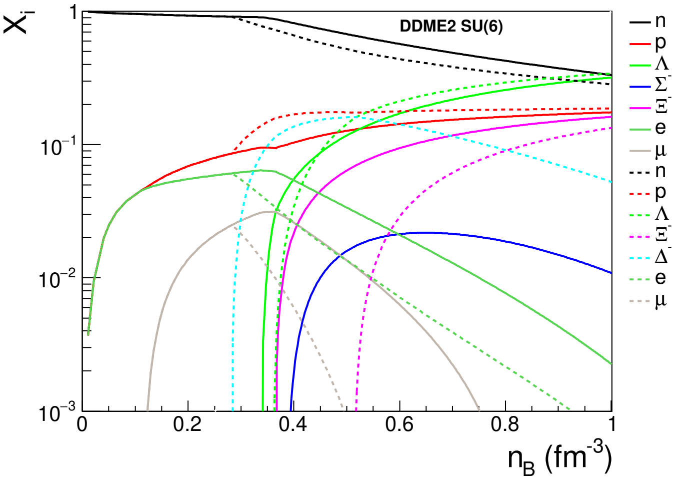
mesons	flavor	$M_{\max}$ ($M_{\odot}$)	$n_{c,\max}$ (fm^{-3})	n_{DU} (fm^{-3})	n_{Δ^-} (fm^{-3})	M_{Δ^-} ($M_{\odot}$)	n_{Λ} (fm^{-3})	M_{Λ} ($M_{\odot}$)	n_{Ξ^-} (fm^{-3})	M_{Ξ^-} ($M_{\odot}$)	$R_{1.4M_{\odot}}$ (km)
σ, ω, ρ, ϕ	SU(6)	2.11	0.9636	-	0.284	0.96	0.362	1.33	0.516	1.82	13.1

Finite-T EoS

relatively few EoS, as $\approx 10^6$ $(n_B,\ Y_Q,\ T)$ points are needed to explore $10^{-12} \leq n_B < 1.5\ \mathrm{fm}^{-3},\ 0 \leq Y_Q \leq 0.6,\ 0 \leq T \leq 80\ \mathrm{MeV}$

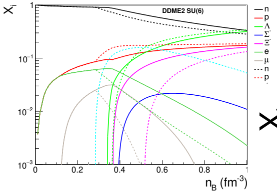
- employed for PNS structure [Prakash et al., Phys.Rep. (1997); Sumiyoshi et al., AASS (1999)], and evolution [Pons et al., ApJ (1999)]
- more recently [Oertel et al., PRC (2012); EPJA (2016); Colucci & Sedrakian, PRC (2013); Marques et al., PRC (2017); Martinon et al., PRD (2014)], including fast rotation; [Malfatti et al., PRC (2019)] with Δs
- $I - \mathrm{Love} - Q$ scaling
- structure of PNS, by accounting for
  - $n_B(r),\ Y_Q(r),\ T(r)$ from simulations
  - $(S/A,\ Y_{L,e})$; $0 \leq S/A \leq 9$; $0 \leq Y_{L,e} \leq 0.4$
- trapped ν_e impact chemical composition [Pons et al., ApJ (1999)]

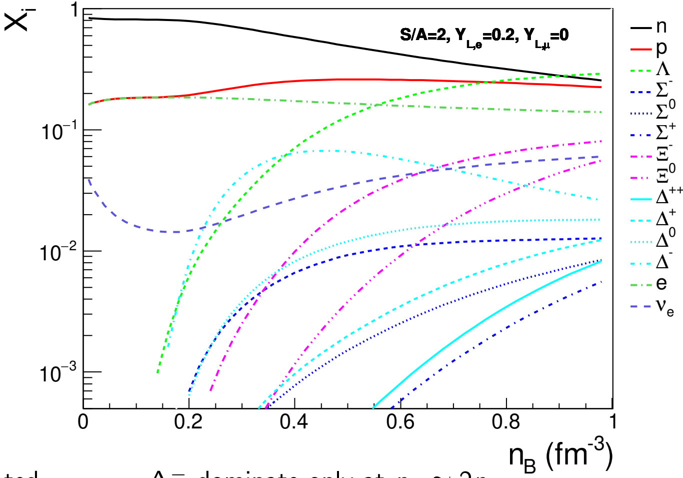
NS composition: NY vs. NYΔ at T=0



- $n_{\Delta^-} < n_\Lambda$
- Δ^- leads to suppression of Σ^-

PNS composition: (T=0, $Y_{L,e}$=0) vs. (finite T, finite $Y_{L,e}$)

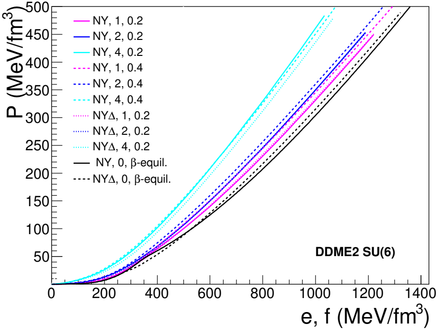


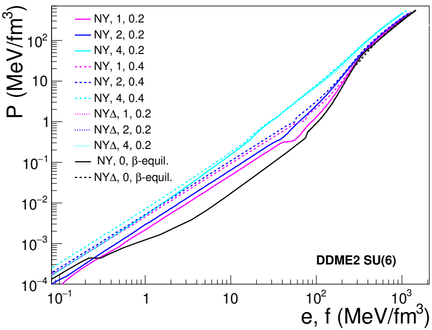


- all species are populated

Δ^- dominate only at $n_B \approx 2n_0$

Equation of State: zoom on high/low densities





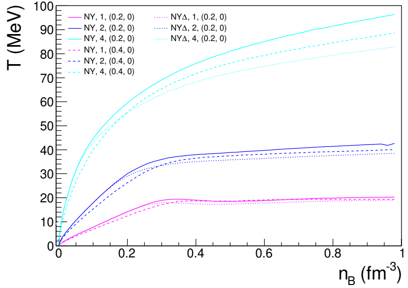
High densities:

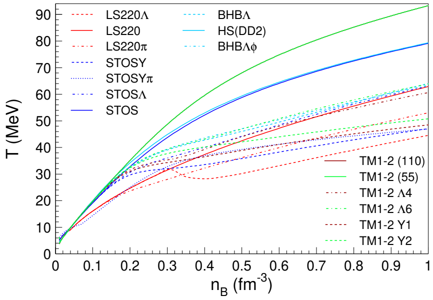
- T=0: Δ softens/stiffs the EoS at low/high n_B
- EoS stiffness increases with S/A

Low densities:

- at $n \lesssim n_0$ matter gets clusterized; HS (DD2) EoS by Hempel, NPA (2010)
- large/low Y_L lead to soft/stiff $P(f)$

T vs. n_B for S/A=const.



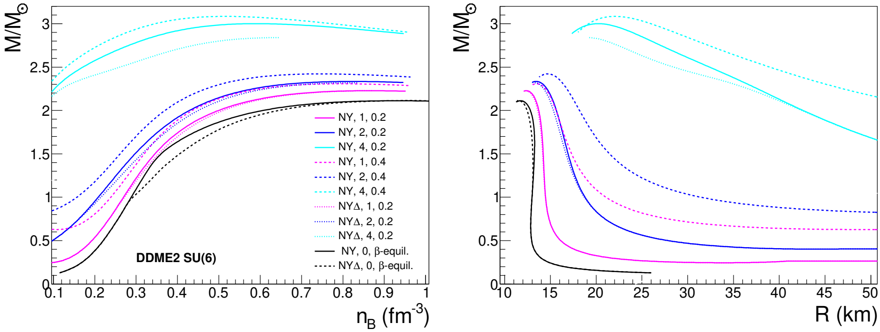


$S/A = 2,\ Y_L = 0.1$
[Oertel et al., EPJA (2016)]

- more bound matter has lower T
- for S/A=const., large dispersion of T due to nucleonic EoS, particle degrees of freedom, Y_L

(P)NS properties: gravitational mass vs. n_B and radius

non-rotating NS in spherical symmetry

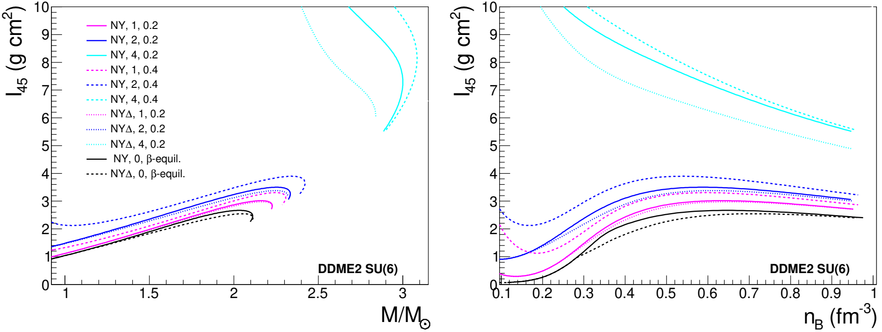


- $M_{\max}$ monotonically increase with S/A
- $n_{B,\max}$ decreases with S/A
- nucleation of Δs diminishes $M_{\max}$; the effect augments with S/A
- high Y_L lead to to high $M_{\max}$ and large radii; radii increase is due to the softening of EoS at low n_B

(P)NS properties: moment of inertia

I are calc. in spherical sym., ass. rigid and slow rotation [Hartle, ApJ (1967)].

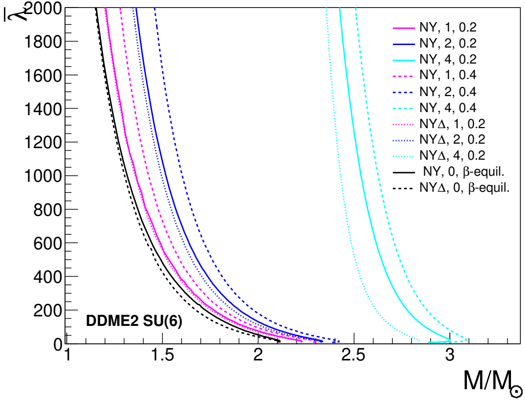
$$I = \frac{8\pi}{3\Omega}\int_0^R drr^4 \frac{e(r)+p(r)}{\sqrt{1-2M(r)/r}}\left[\Omega-\omega(r)\right]\exp\left(-\nu(r)\right), \quad \frac{d\nu}{dr} = -\frac{dp}{dr}\frac{1}{(p(r)+e(r))}$$



- by increasing R, thermal effects increase I

(P)NS properties: tidal deformability

lin. perturb. in the leading order onto spherical sym. [Hinderer, ApJ (2008)]

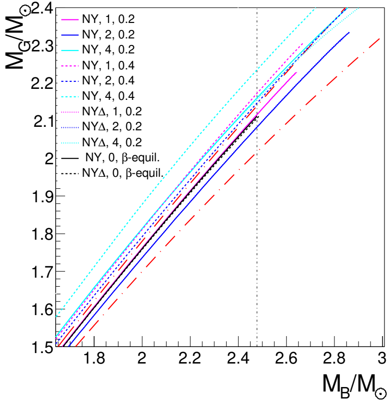


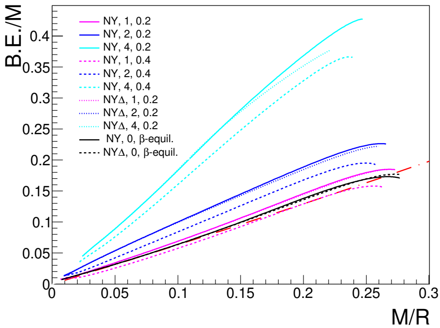
$\bar{\lambda} = \lambda / M^5$

- thermal effects render the matter more deformable

(P)NS properties: binding energy

$B.E. = M_B - M_G$
$B.E./M_G = c_1\mathcal{C}/(1 - c_2\mathcal{C})$ [Lattimer & Prakash (2001)]

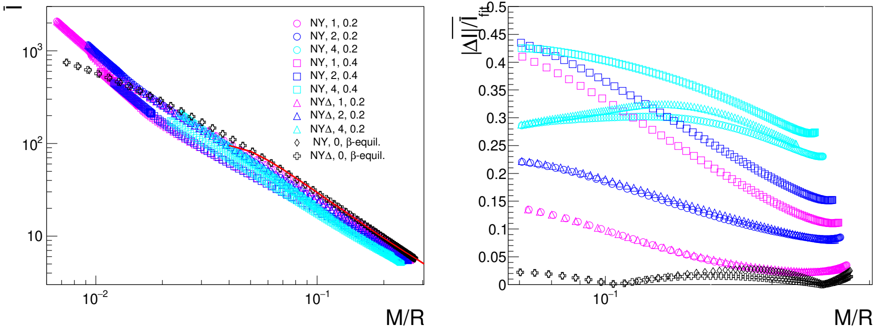




left: fit from [Prakash et al., Phys. Rep. (1997)]
right: fit from [Lattimer & Prakash (2001)]
with $c_1 = 0.6213$, $c_2 = 0.1941$ [Breu & Rezzolla, MNRAS (2016)]

Scaling: I vs. $\mathcal{C}$

$$\bar{I} = I/M_G^3$$
$$\bar{I} = \bar{a}_1\mathcal{C}^{-1} + \bar{a}_2\mathcal{C}^{-2} + \bar{a}_3\mathcal{C}^{-3} + \bar{a}_4\mathcal{C}^{-4}$$



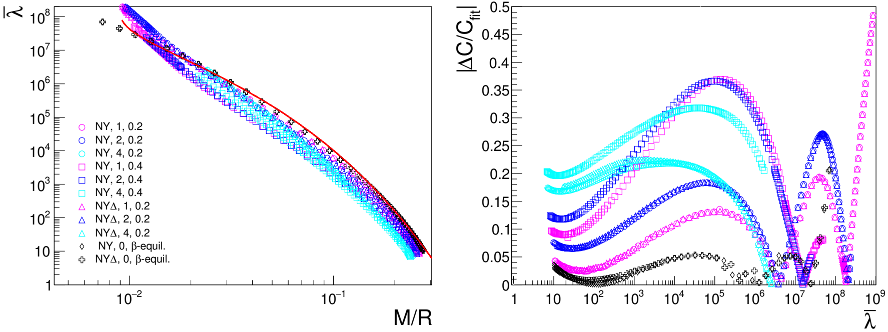
fit param. from [Breu & Rezzolla, MNRAS (2016)]

- deviations increase with thermal effects

Scaling: λ vs. $\mathcal{C}$

$\bar{\lambda} = \lambda / M_G^5$

$\mathcal{C} = a_0 + a_1 \ln \bar{\lambda} + a_2 \left(\ln \bar{\lambda}\right)^2$ [Maselli et al., PRD (2013)]



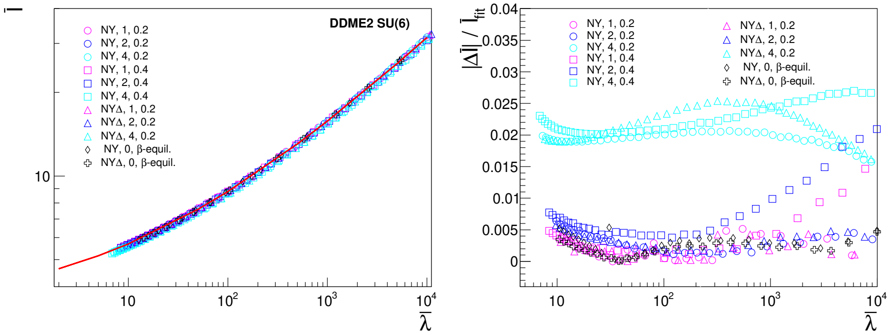
fit param. from [Maselli et al., PRD (2013)]

- deviations increase with thermal effects

Scaling: I vs. λ

$\bar{\lambda} = \lambda / M_G^5$; $\bar{I} = I / M_G^3$

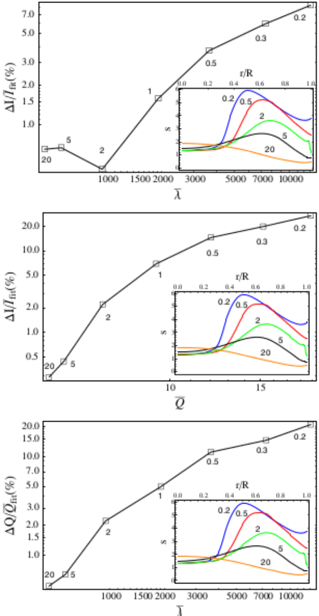
$\bar{I} = a + b \ln \bar{\lambda} + c \left(\ln \bar{\lambda} \right)^2 + d \left(\ln \bar{\lambda} \right)^3 + e \left(\ln \bar{\lambda} \right)^4$ [Yagi & Yunes, PRD (2013)]



fit param. from [Yagi & Yunes, PRD (2013)]

- excellent scaling for all NS compactnesses

Scaling at finite-T: I – Love – Q

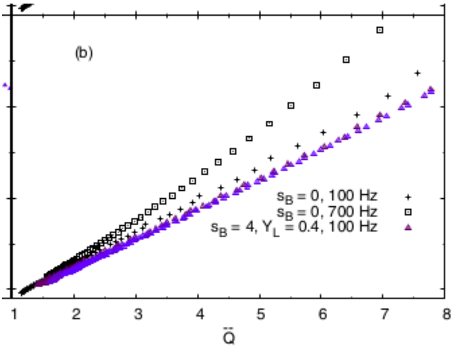


[Martinon et al., PRC (2014)]

- deviations from the fit $\propto$ non-uniformity of the radial entropy profile: large/small at early/late moments from the birth of PNS
- affect the three laws by Yagi & Yunes (2013)
- our results on $I - \lambda$ agree with these ones

Scaling at finite-T: $I - Q$

$\bar{I}$



[Marques et al., PRC (2017)]

- $s_B = 0$ vs. $(s_B = 4, Y_L = 0.4)$: the scaling is broken

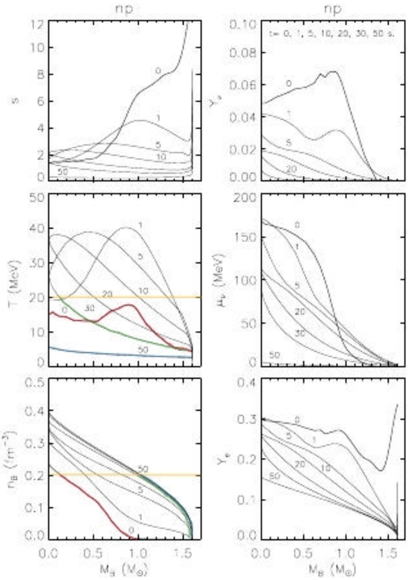
- scaling violations is attributed to thermal effects

- our results are not incompatible with these as temperature/entropy gradient effects might manifest themselves differently at higher orders in spin

Conclusions

- finite-T EoS with hyperons and Δs based on the nucleonic DDME2 parametrization
- NS properties (mass, binding energy, radius, mom. of inertia, tidal deformability) are calculated assuming $S/A = \mathrm{ct}$ and $Y_L = \mathrm{ct}$
- $\bar{I} - \mathcal{C}$ and $\bar{\lambda} - \mathcal{C}$ scaling relations are violated by thermal effects
- $\bar{I} - \bar{\lambda}$ scaling holds

Radial profiles of thermodyn. observables

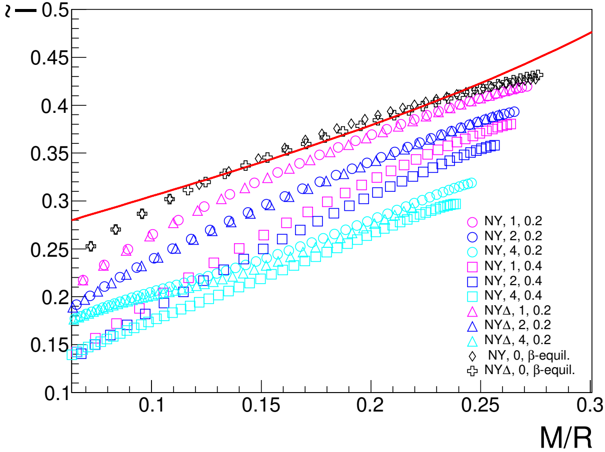


by Pons et al., ApJ 513, 780 (1999)

Scaling: $\tilde{I}$ vs. $\mathcal{C}$

$\tilde{I} = I/MR^2$

$\tilde{I} = \tilde{a}_0 + \tilde{a}_1\mathcal{C} + \tilde{a}_2\mathcal{C}^2$ [Lattimer & Schutz, ApJ (2005)]



fit param. from [Breu & Rezzolla, MNRAS (2016)]

- deviations increase with thermal effects