Soft EoS from heavy-ion data and the implications for compact stars

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Compressibility and Mass-Radius relation of Compact stars

Punch Line: Apply a soft nuclear equation of state ($K_0 \leq 200$ MeV, deduced from heavy ion data) to study the implications on masses and radii of compact stars by calculating:

1. Maximum masses of neutron stars as a probe for nuclear matter compressibility using a phenomenological equation of state (*Prakash et al. PRL(1988)*)
2. Low mass neutron star radii as a probe for symmetry energy (*Horowitz et al.,APJ (2003), Correlation between neutron radius of ^{208}Pb and radii of low mass neutron stars*)
3. Highest possible mass of compact stars (*Rhoades and Ruffini, PRL (1974)*)

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Compressibility from Heavy Ion Data

Motivation: Compressibility of nuclear matter by KaoS Collaboration:
Direct production of K^+ by:

NN $\longrightarrow$ N Λ K^+ (E_{thr}= 1.58 GeV)
NN $\longrightarrow$ NNK^-K^+ (E_{thr}= 2.5 GeV)

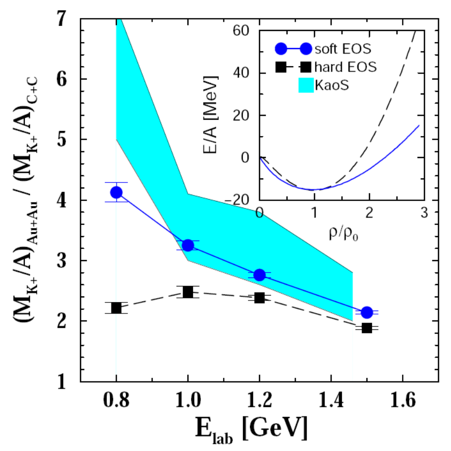
Additional multi-step processes as channels at subthreshold energies, e.g.:

NN $\longrightarrow$ N Δ

- Δ N $\longrightarrow$ N K^+ Y
- ΔN $\longrightarrow$ K^-K^+ NN
- π N $\longrightarrow$ K^+ Y

Probability increases with higher density

Trend of Kaon production up to a density of n $\sim 2.5 - 3$ n_0 is described by a soft equation of state $(K_0 \leq 200 MeV)$



Ch. Fuchs et al., PRL 86 (2001)

Phenomenological EoS

Energy per particle (*Prakash et al. 1988*):

$$E/A = m_n\left(1 - x_p\right) + m_p x_p + E_0 u^{2/3} + \frac{A}{2}u + \frac{B}{\sigma+1}u^{\sigma} + \left(1 - 2x_p\right)^2 S(u)$$

$S(u) = \left(2^{2/3} - 1\right) E_0 \left(u^{2/3} - F(u)\right) + S_0 F(u)$, $u = n_b/n_0$
$E_0 =$ average kinetic energy of symmetric matter at n_0

$Au/2 + Bu^{\sigma} / (\sigma + 1)$: describe interaction

Input Parameters:

- **Binding energy** at saturation density: - 16 MeV at $n_0 = 0.16 fm^{-3}$
- **Asymmetry energy** S_0: Energy difference between pure neutron matter and normal symmetric matter at saturation density
- **Density dependence of asymmetry energy**
  $\rightarrow$ Assume power law dependence $F(u) = u^{\alpha}$.
- **Compressibility** K_0 for symmetric nuclear matter at saturation density

In the following

Mass-radius calculations using

- Core: Phenomenological EoS:
  $E/A = m_n\left(1-x_p\right) + m_p x_p + E_0 u^{2/3} + \frac{A}{2}u + \frac{B}{\sigma+1}u^{\sigma} + \left(1-2x_p\right)^2 S(u)$
- Inner crust: Negele and Vautherin, NPA, 1973
- Outer crust: BPS, Hempel et al., Phys.Rev.C, 2006

Variation of parameters:

- $K_0 = 160$ MeV - 200 MeV *(C.Sturm et al.(2001),KaoS collaboration)*
- S_0 = 28 MeV - 32 MeV *(e.g. Steiner (2007))*
- α = 0.7 - 1.1 *(e.g. L.-W Chen et al.(2005), B.-A Li and A.W.Steiner (2006))*

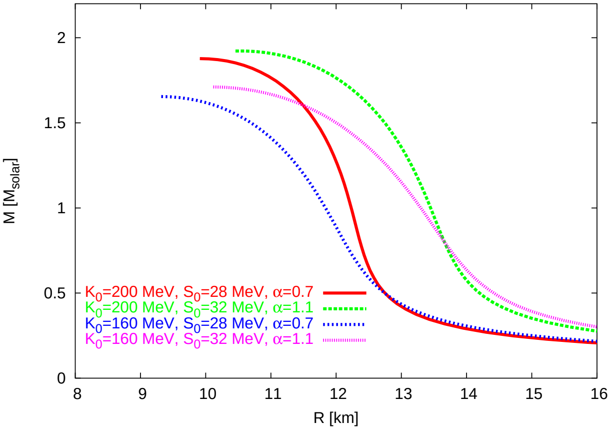
In addition:Compare to frequently used EoS

	BE [MeV]	ρ_0 [fm^{-3}]	S_0 [MeV]	K_0 [MeV]
Bsk8 (Goriely et al., NPA 750 (2005))	-15.824	0.1589	28.0	230.2
Sly4 (Chabanat et al., NPA 635 (1998))	-15.969	0.160	32.0	229.9
TM1 (Y.Sugahara and H.Toki, NPA 579 (1994))	-16.3	0.145	36.9	281

Maximum Mass - Motivation

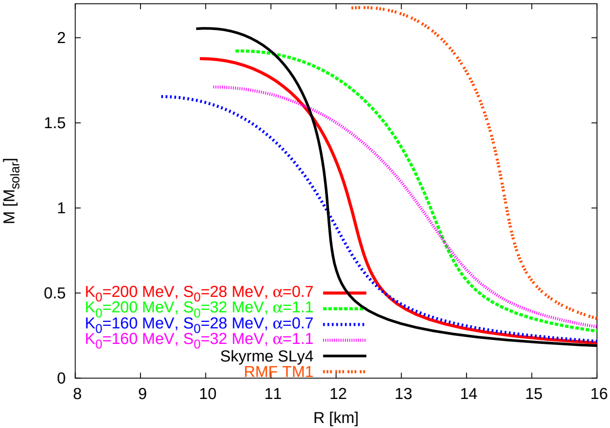
- KaoS Experiment: $K_0 \leq$ 200 MeV up to 2.5 - 3 n_0
- Compressiblility of nuclear matter controls the maximum mass of neutron stars and its central density
- $\rightarrow$ What are the consequences of a soft EoS for the maximum mass configuration?

Maximum Mass - Phenomenological EoS



- Maximum masses $K_0 = 200$ MeV (soft EoS, compatible with KaoS) ~ 1.9 M$_\odot$, central densities of maximum mass configuration $\sim 8n_0$
- Maximum masses for $K_0 = 160$ MeV $\rightarrow \sim 1.65$ M$_\odot$, central density $\sim 9n_0$
- Note: Radii of low mass neutron stars are sensitive to symmetry energy

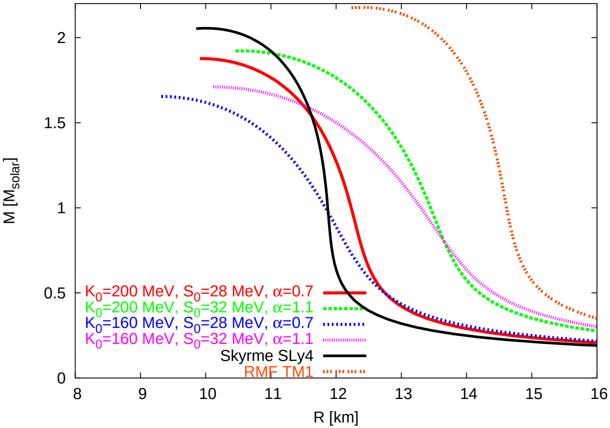
Maximum Mass - Skyrme and RMF EoS



Maximum masses for SLy4 Skyrme EoS: ~2.05 $M_\odot$ (central density: $\sim 8n_0$)

Maximum masses for TM1 RMF EoS: $\sim$ 2.17 $M_\odot$ (central density: $\sim 6.4n_0$)

Maximum Mass - Summary

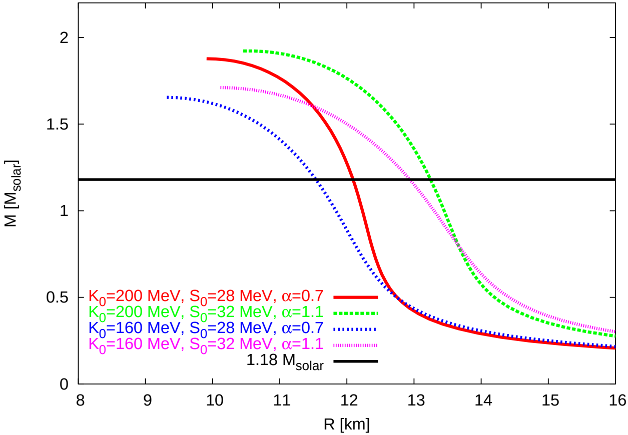


- Maximum masses for a soft skyrme type EoS (compatible with KaoS) up to ~ 2 $M_\odot$
- **But**: Central densities in maximum mass configurations are between 8 - 9 n_0
- Requirement for stiffening of EoS for higher densities or onset of exotic physics
- Relativistic mean field EoS: TM1 $\longrightarrow$ central densities at maximum mass $\sim 6.4 n_0$

Low mass neutron stars - Motivation

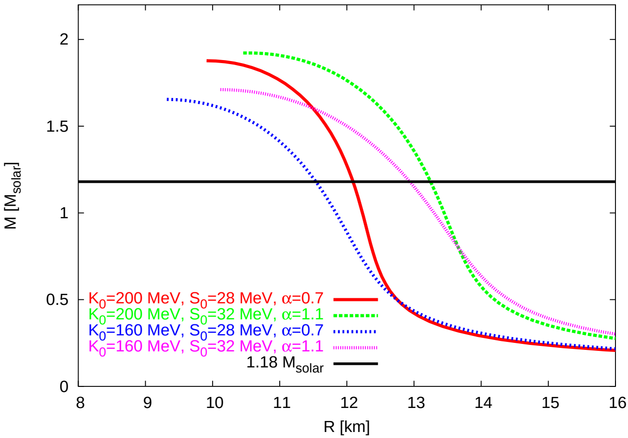
- Smallest pulsar mass know so far from observation: 1.18 ± 0.02 $M_\odot$ (J1756-2251)
- Central densities in low-mass neutron stars might be ≤ 3 n_0 $\rightarrow$ within the density region explored by KaoS
- As seen: Radius of low mass neutron stars sensitive to the asymmetry term

Low mass neutron stars - $M_{psr} = 1.18 \pm 0.02\ M_\odot$



K_0 [MeV]	S_0 [MeV]	α	n [n_0]	R [km]
200	32	1.1	2.4	$\sim$ 13.2
200	28	0.7	2.9	$\sim$ 12.1
160	32	1.1	2.8	$\sim$ 12.9
160	28	0.7	3.7	$\sim$ 11.5

Low mass neutron stars - $M_{psr} = 1.18 \pm 0.02\ M_\odot$



- For K_0=200 MeV $\rightarrow$ densities are in the upper range of the probed densities by KaoS.
- Radius variation due to symmetry energy term: $\sim$ 1 km

Highest possible mass - Motivation

Motivation:(*Rhoades and Ruffini, RRL (1974)*)

- For densities below a critical value use known equation of state: Harrison - Wheeler EoS
- For higher densities: stiffest possible (i.e. causal) equation of state with

$$p(\epsilon) = \epsilon - \epsilon_0$$

  ϵ_0: parameter to fit stiffest EoS on soft EoS
- Result: Largest possible masses for neutron stars
- $\rightarrow$ for $\rho_{crit} = 4.6 \cdot 10^{14}$ g/cm^3 highest possible mass of 3.2 M$_\odot$

Update:(*Kalogera and Baym, ApJ 470 (1996)*)

- For densities below critical value: EoS by Wiringa et al. (Phys.Rev.C, 38, 1988), for $\rho < 2.5 \cdot 10^{14}$ g/cm^3 equation of state of Baym, Pethick and Sutherland (1971)
- Result:

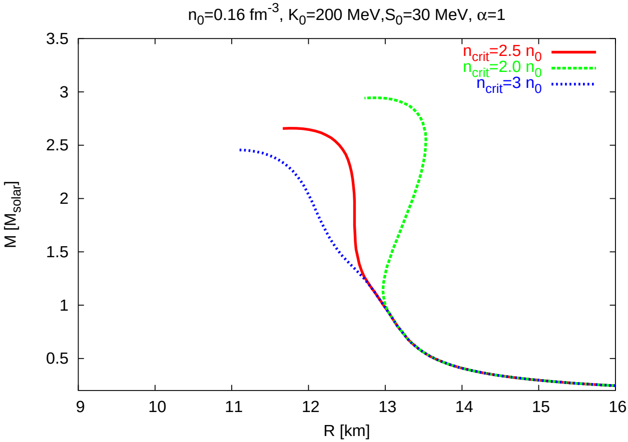
$$M_{max} = 6.7 M_\odot \left(\frac{\rho_c}{10^{14} g/cm^3} \right)^{-1/2}$$

  for critical density of 2 $\rho_0 \rightarrow$ M$_{max} = 2.9$ M$_\odot$

Here:

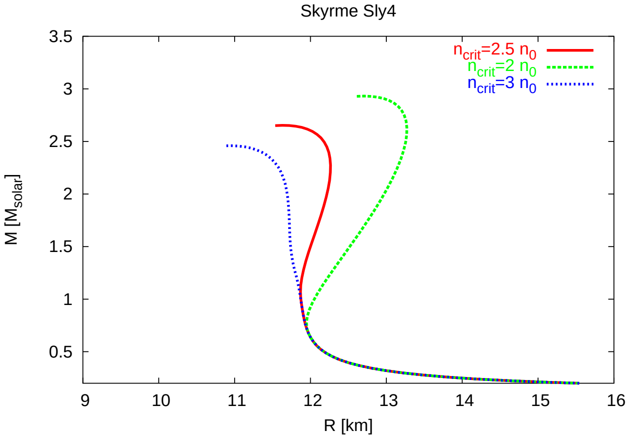
- Here: For low densities ($n \leq 3 n_0$): EoS should fullfil results from KaoS

Highest possible mass - Phenomenological EoS



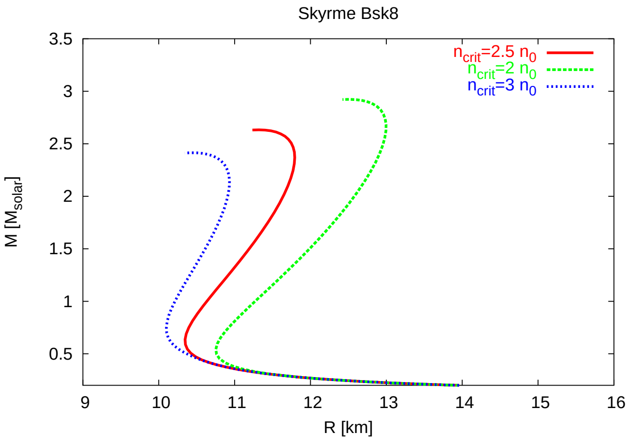
For $n_0 = 0.16$ fm^{-3} and assuming that the “phase transition” takes place for $n > 2.5n_0$
$\rightarrow$ M$_{limit}$ $\lesssim$ 2.7 M$_\odot$

Highest possible mass - Skyrme SLy4



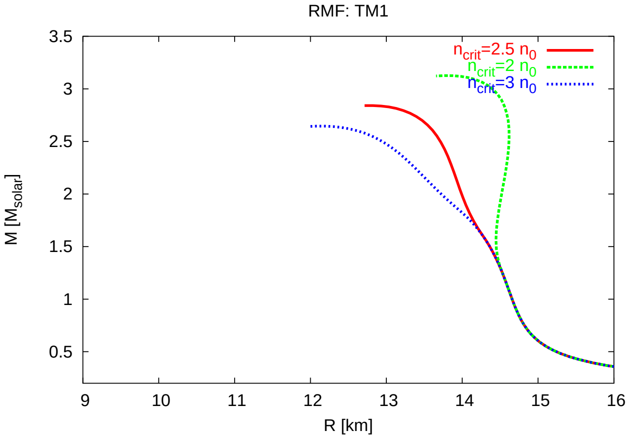
Similar result for SLy4 Skyrme equation of state with $K_0 = 230$ MeV, $S_0 = 32$ MeV

Highest possible mass - Skyrme Bsk8



Similar result for Bsk8 Skyrme equation of state with $K_0 = 230$ MeV, $S_0 = 28$ MeV

Highest possible mass - RMF TM1



Slightly higher masses for TM1

Summary

- Heavy Ion Data (KaoS Collaboration) $\longrightarrow$ soft nuclear equation of state with $K_0 \leq 200$ MeV up to $n \sim 3\ n_0$
- Applying soft equation of state gives maximal masses $M \lesssim 2\ M_\odot$ with large central densities $\longrightarrow$ onset of exotic matter ?
- For low mass neutron stars: central densities are in the range of 2.5 - 3 n_0 (within the density range probed by KaoS), Neutron star radii show strong dependence on symmetry energy term
- Applying the stiffest equation of state in combination with the KaoS data can restricts the highest possible pulsar mass
  ($M \lesssim 2.7$ for $n_{crit} \geq 2.5\ n_0$;
  for TM1 (relativistic mean field EoS): $M \lesssim 2.84$ for $n_{crit} \geq 2.5\ n_0$)

Thank You for your Attention