Soft nuclear equation-of-state from heavy-ion data and implications for compact stars

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DENSE MATTER IN HEAVY-ION COLLISIONS

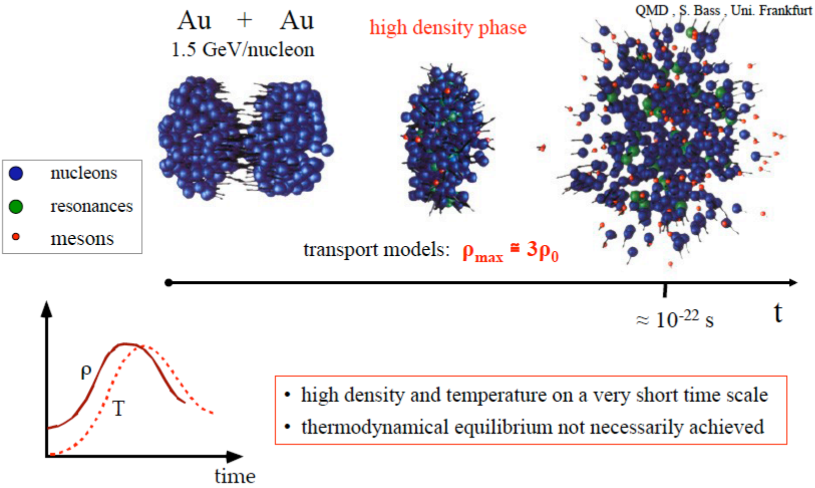


Figure: Chr. Sturm, EMMI Workshop on Dense Baronic Matter in the Cosmos and the Laboratory, Tuebingen, Germany, October 11-12, 2012

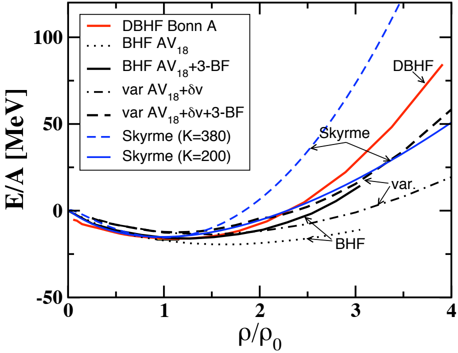


Figure: Fuchs & Wolter, EPJ 30 (2006)

- Nucleon potential serves as input in transport calculations
- Skyrme-type potential: $U(n_b) = \alpha \left(\frac{n_b}{n_0}\right) + \beta \left(\frac{n_b}{n_0}\right)^\sigma$
  $\alpha,\ \beta,\ \sigma$ are fitted to nuclear saturation density n_0, binding energy of isospin symmetric nuclear matter E/A, and compressibility K_0

INPUT INTO TRANSPORT MODELS: THE NUCLEON POTENTIAL

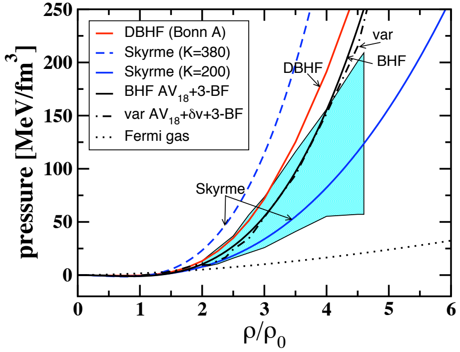


Figure: Fuchs & Wolter, EPJ 30 (2006)

From $U(n_b)$ to the bulk nuclear matter equation of state:

$$\frac{E}{A}(n_b, T=0) = m_N + E_{kin} + \frac{1}{n_b}\int U(n)dn \longrightarrow p(n_b, T, Y_i) = n_b^2 \frac{\partial}{\partial n_b}\frac{E}{A}(n_b, T, Y_i)$$

KAON PRODUCTION IN HEAVY-ION COLLISIONS

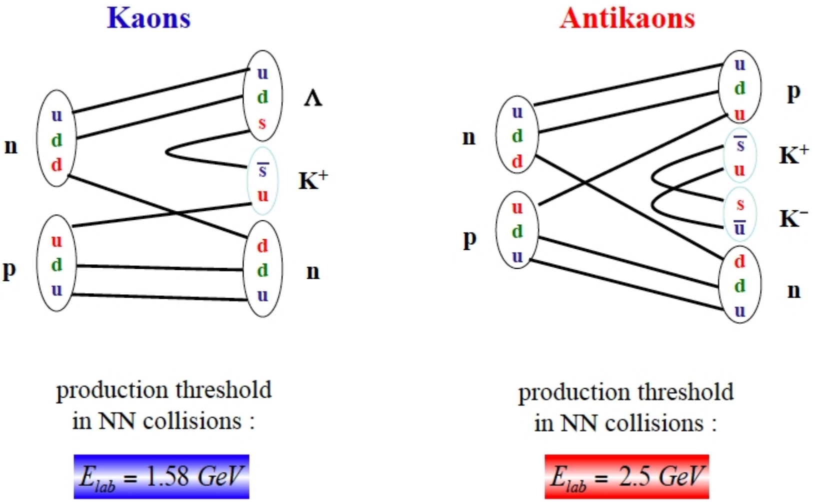


Figure: Chr. Sturm, EMMI Workshop on Dense Baronic Matter in the Cosmos and the Laboratory, Tuebingen, Germany, October 11-12, 2012

Kaon production at $E < E_{\rm thr}$ (Y = Λ, Σ):

- NN $\rightarrow$ N Δ
  - Δ N $\rightarrow$ N K^+ Y
  - Δ N $\rightarrow$ K^- K^+ NN
  - π N $\rightarrow$ K^+ Y
- Probability for multi-step processes increases with baryon density
- Kaons are produced predominantly in the high density phase at $n_b \sim (2-3)n_0$
- Due to their large mean-free-path, K^+ can leave the high density region and serve as probes

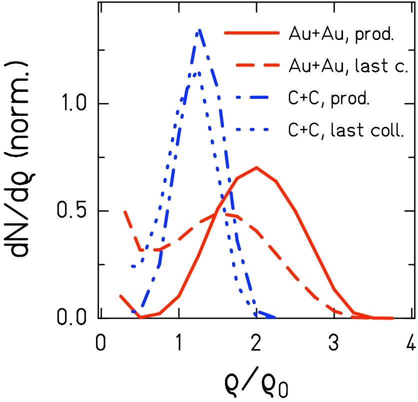


Figure: Central Au+Au and C+C collisions with IQMD at 1.5 AGeV; Hartnack, Oeschler, Leifels, Bratkovskaya, Aichelin, Phys. Rep. 510 (2012)

- Subthreshold K^+ meson production in Au+Au and C+C collisions
- Measurements were performed with the Kaon Spectrometer (KaoS) at GSI, Darmstadt
- Double ratio in K^+ multiplicities:

$$\frac{(M_{K^+}/A)_{\mathrm{Au+A}}}{(M_{K^+}/A)_{\mathrm{C+C}}} \propto \left(\frac{\rho_{\mathrm{Au}}}{\rho_{\mathrm{C}}}\right)^{\gamma}$$

- Number of multi-step processes to produce Kaons $\gamma > 1$

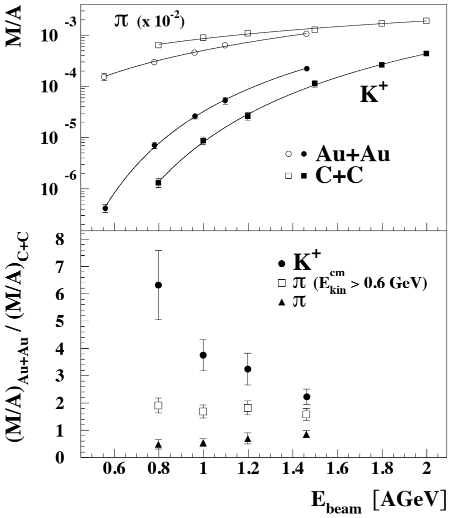


Figure: Sturm et al. (KaoS Collaboration), PRL 86 (2001)

KAOS EXPERIMENT

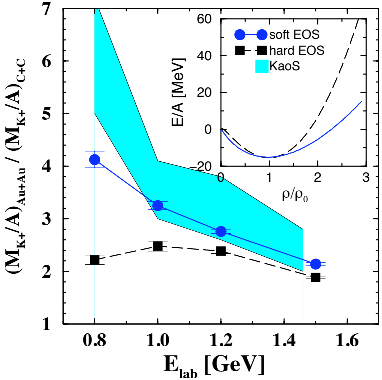
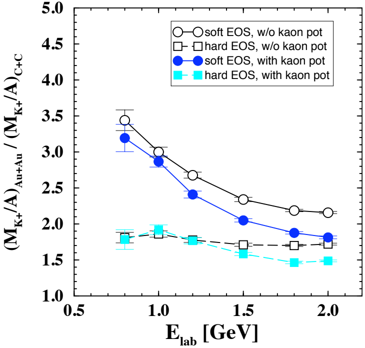


Figure: Fuchs, Faessler, Zabrodin, Zheng, PRL 86 (2001)

- Transport calculation with Skyrme-type $U(n_b)$ resulting in $K_0 = 200$ MeV (soft EoS) and $K_0 = 380$ MeV (stiff EoS)
- Multiplicity trend indicates high compression
- Soft equation of state at $(2-3)n_0$ compatible with $U(n_b)$ corresponding to $K_0 = 200$ MeV

STABILITY OF EQUATION OF STATE DEPENDENCE



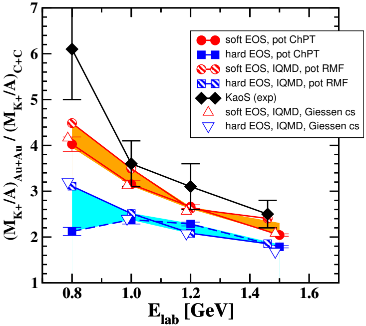


Figure: Fuchs, Faessler, Zabrodin, Zheng PRL 86 (2001); Fuchs & Wolter EPJ 30 (2006)

- Variation of transport models, cross-sections, KN potentials (Fuchs et al., PRL 86 (2001), Hartnack, Oeschler, Aichelin, PRL 96 (2006))
- Tested with Skyrme EoS Skp, Sly6, Ska, SIII (Zhao-Qing Feng, PRC 83 (2011))

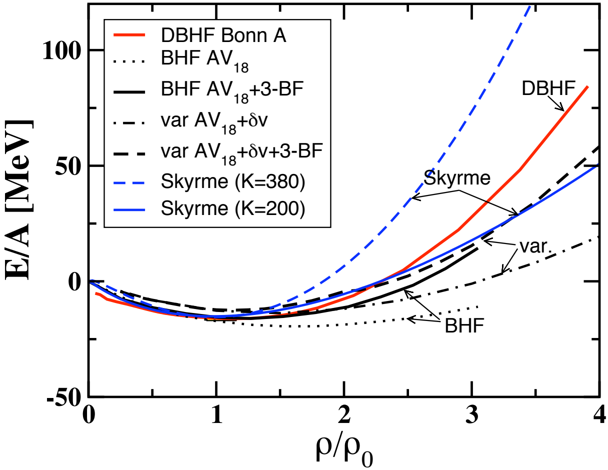


Figure: Fuchs & Wolter, EPJ 30 (2006)

- M and R are governed by general relativity and the nuclear EoS $p = f(\epsilon)$
- Lightest star
  PSR J1756-2251:
  $M = 1.258^{+0.018}_{-0.017}\ M_\odot$
  (Ferdman (2008))
- Most massive stars
  PSR J1614-2230:
  $M = 1.97 \pm 0.04\ M_\odot$
  (Demorest et al., Nature 467 (2010))
  PSR J0348+0432:
  $M = 2.01 \pm 0.04\ M_\odot$
  (Antoniadis et al., Science 26 (2013))

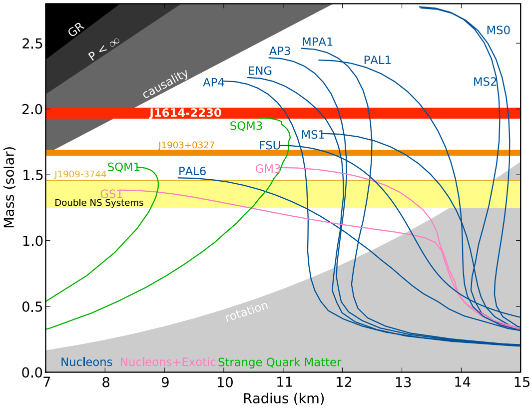


Figure: Demorest et al., Nature 467 (2010)

- Neutron star radii and moments of inertia:
  Steiner, Lattimer, Brown, ApJL 765 (2013); Suleimanov, Poutanen, Revnivtsev, Werner, ApJ 742 (2011); Guillot, Servillat, Webb, Rutledge, ApJ 772 (2013); Guillemot et al. MNRAS 422 (2012), ...

Light neutron stars have low central densities

- Radii and moments of inertia are most sensitive to symmetry energy (Lattimer & Prakash, ApJ 550 (2001); Carriere, Horowitz, Piekarewicz ApJ 593 (2003), Li & Steiner, PLB 642 (2006) ...)
- Large Observatory For X-ray Timing (LOFT) resolve neutron star radii with a 10% accuracy (Mignani et al., Proc. Intl. Astron. Union 372 (2011))
- Presence of quarks or hyperons unlikely
- Use information from KaoS data on isospin symmetric nuclear matter and explore the influence of the symmetry energy

LOW-MASS NEUTRON STARS

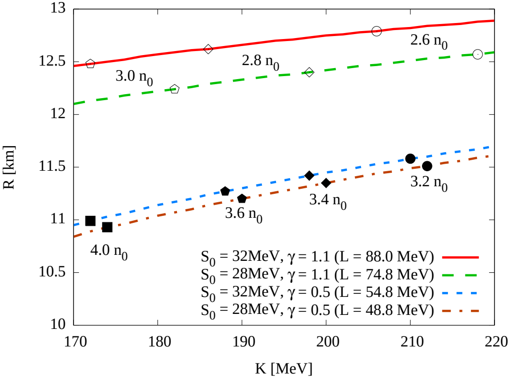


Figure: IS, Tolos, Chatterjee, Schaffner-Bielich, Sturm PRC (2012)

Phenomenological EoS ($u = n_b/n_0$) (Prakash, Lattimer, Ainsworth PRL 61 (1988)):

$$E/A = m_N + E_{kin} + \frac{\alpha}{2}u + \frac{\beta}{\sigma+1}u^\sigma + S_0 u^\gamma \left(1 - 2Y_p\right)^2$$

Parameters fitted to $n_0 = 0.17$ fm^{-3}, $E/A = -16$ MeV, $K_0 = (160 - 240)$ MeV, $S_0 = 28$ MeV and 32 MeV, $\gamma = 0.5$ and 1.1 ($L = (48.8 - 88)$ MeV)

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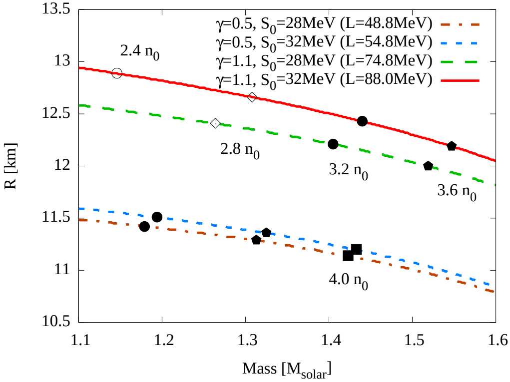

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ABSOLUTE LIMIT ON NEUTRON STAR MAXIMUM MASSES

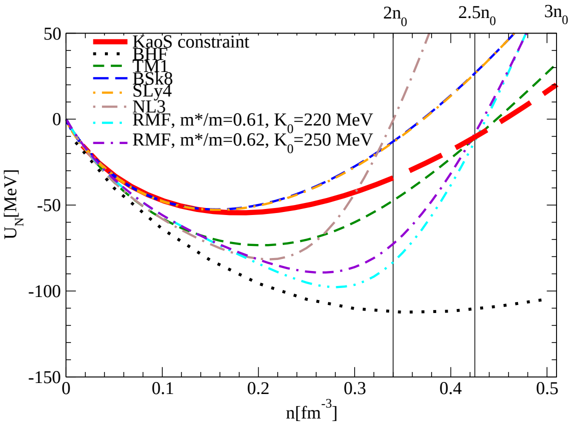

Figure: IS, Tolos, Chatterjee, Schaffner-Bielich, Sturm PRC (2012)

- Highest possible compact star mass
- For $n_b \leq n_{\text{crit}}$: Known nuclear equation of state (from KaoS)
- For $n_b > n_{\text{crit}}$: Stiffest causal equation of state $p(\epsilon) = p_{crit} + \epsilon - \epsilon_{crit}$
- Rhoades & Ruffini (1974); Hartle Phys. Rep. 46 (1987); Kalogera & Baym, ApJL 470 (1996); Akmal, Pandharipande, Ravenhall PRC 56 (1998); Lattimer & Prakash (2011)

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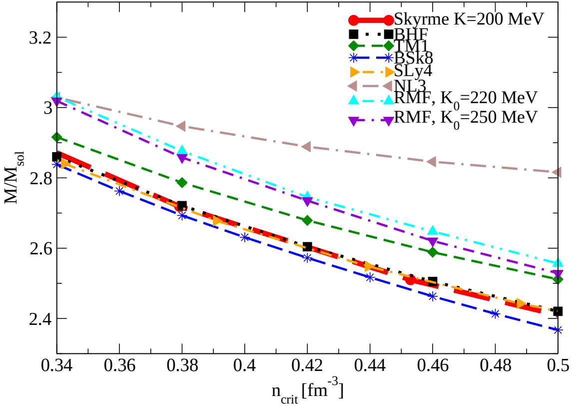

Figure: IS, Tolos, Chatterjee, Schaffner-Bielich, Sturm PRC (2012)

- Highest possible mass: $M_{\rm high} = 4.1\ {\rm M}_\odot(\epsilon_{crit}/\epsilon_0)^{-1/2}$ (Kalogera & Baym (1996))
- Depending on the critical/validity density if the KaoS data, we can restrict the highest possible neutron star mass from $M_{\rm hight} < 3\ {\rm M}_\odot$ to $M_{\rm hight} < 2.6\ {\rm M}_\odot$

SUMMARY

- K^+ measurements from Au+Au and C+C collisions suggest that the nuclear equation of state is soft at $(2-3)\rho_0$
- Knowing the properties of isospin symmetric nuclear matter from KaoS up to $3\rho_0$ could allow a direct study of the nuclear symmetry energy via radius/moment of inertia measurements of light neutron stars ($M \lesssim 1.3\,M_\odot$) without considering a large impact of hyperons or quarks
- Soft nuclear equations of state fulfilling the KaoS constraints confirm an upper mass limit for compact stars of $M_{\rm high} < 3\,M_\odot$