HESS J1731-347 and the existence of exotic matter

Kaon condensation in neutron stars

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Pions

- Lightest mesons
- $e^- \to p^-$
- $n \geq n_0$
- Soften the EoS

Kaons

- Lightest strange mesons
- Large mass → Condensation?
- $n \geq 3n_0$
- Strong softening on the EoS

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Kaons - HESS J1731-347

Strong softening on the EoS → HESS J1731-347

$\mathrm{M} = 0.77^{+0.20}_{-0.17}\ \mathrm{M}_{\odot}$ and $R = 10.4^{+0.86}_{-0.78}$ km

Interactions

Chiral Lagrange density

$$\begin{aligned}\mathcal{L} &= \frac{1}{4}f^2\mathrm{Tr}\partial_\mu U\partial^\mu U^\dagger + c\mathrm{Tr}\left(m_q\left(U+U^\dagger-2\right)\right) + \mathrm{Tr}\bar{B}\gamma^\mu i\partial_\mu B + i\mathrm{Tr}B^\dagger[V_0,B] \\ &- D\mathrm{Tr}B^\dagger\boldsymbol{\sigma}\{A,B\} - F\mathrm{Tr}B^\dagger\boldsymbol{\sigma}[A,B] + a_1\mathrm{Tr}B^\dagger\left(\xi m_q\xi+\mathrm{h.c.}\right)B \\ &+ a_2\mathrm{Tr}B^\dagger B\left(\xi m_q\xi+\mathrm{h.c.}\right) + a_3\mathrm{Tr}B^\dagger B\mathrm{Tr}\left(m_qU+\mathrm{h.c.}\right) + \mathcal{L}_e + \mathcal{L}_\mu \end{aligned} \quad (1)$$

where the non-linear sigma field U and the ξ field are given by

$$U = \exp\sqrt{2}iM/f, \quad \xi^2 = U \quad (2)$$

and the mesonic vector and axial vector currents by

$$V_\mu = \frac{1}{2}\left(\xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger\right), \quad A_\mu = \frac{1}{2}i\left(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger\right) \quad (3)$$

Meson octet

$$M = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

Baryon octet

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0+\frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0+\frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

Quark mass

$$m_q = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

Interactions

Constants of hadronic interaction terms

$$
\begin{aligned}
m_{\Sigma} - m_N &= 2a_2 m_s, \\
m_{\Lambda} - m_N &= \frac{2}{3}\left(a_2 - 2a_1\right) m_s, \\
m_{\Xi} - m_N &= 2\left(a_2 - a_1\right) m_s
\end{aligned}
\quad \Longrightarrow \quad
\begin{cases}
a_1 m_s = -67 \text{ MeV} \\
a_2 m_s = 134 \text{ MeV}
\end{cases}
$$

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$a_3 m_s$?

↓

strangeness content of the proton + kaon-nucleon sigma term

$$a_3 m_s = [-134, -310] \text{ MeV}, \quad \Sigma^{\mathrm{KN}} = [168, 520] \text{ MeV} \tag{4}$$

Equilibrium conditions

- β-decay and inverse β-decay

$$n \to p + e^- + \bar{\nu}_e, \quad p + e^- \to n + \nu_e \tag{5}$$

- Cold matter: Neutrinos leave the system $\Rightarrow \mu_n - \mu_p = \mu_e$
- Energetically favorable for electrons to convert to muons

$$e^- \to \mu^- + \bar{\nu}_\mu + \nu_e, \quad \mu_\mu = \mu_e \tag{6}$$

- Strangeness changing processes

$$n \leftrightarrow p + K^-, \quad e^- \leftrightarrow K^- + \nu_e \tag{7}$$

- Chemical equilibrium

$$\mu_n - \mu_p = \mu, \quad \mu_e = \mu \tag{8}$$

Equilibrium conditions

Fixed baryon number state (including nuclear interactions)

$$\begin{aligned}\tilde{\varepsilon}(u,x,\mu,\theta) &= \varepsilon_{\rm MDI}(u,x) + un_0(1-2x^2)S(u) \\ &- f^2\frac{\mu^2}{2}\sin^2\theta + 2m_K^2 f^2\sin^2\frac{\theta}{2} \\ &+ \mu u n_0 x - \mu u n_0\,(1+x)\sin^2\frac{\theta}{2} \\ &+ (2a_1x + 2a_2 + 4a_3)\,m_s u n_0 \sin^2\frac{\theta}{2} \\ &+ \tilde{\varepsilon}_e + \eta(|\mu| - m_\mu)\tilde{\varepsilon}_\mu \end{aligned} \tag{9}$$

where the symmetry energy is given by

$$S(u) = \varepsilon_{\rm MDI}(u,x=0) - \varepsilon_{\rm MDI}(u,x=1/2) \tag{10}$$

Why the MDI?

- reproduces with high accuracy the properties of symmetric nuclear matter
- reproduces correctly the microscopic calculations of the Chiral model and the results of state-of-the-art calculations of Akmal et al[1]
- predicts M_{max} at least higher than the observed ones

[1] A. Akmal, V. R. Pandharipande, and D. G. Ravenhall, Phys. Rev. C **58**, 1804 (1998).

Thermodynamics of the system

Energy density of the ground state

$$\frac{\partial\tilde{\varepsilon}}{\partial x}=0, \quad \frac{\partial\tilde{\varepsilon}}{\partial \mu}=0, \quad \frac{\partial\tilde{\varepsilon}}{\partial \theta}=0 \tag{11}$$

⇓

$$\mu = 4(1-2x)S(u)\sec^2\frac{\theta}{2} - 2a_1 m_s \tan^2\frac{\theta}{2} \tag{12}$$

$$f^2\mu\sin^2\theta + un_0(1+x)\sin^2\frac{\theta}{2} - xun_0 + \frac{\mu^3}{3\pi^2} + \eta(|\mu|-m_\mu)\frac{(\mu^2-m_\mu^2)^{3/2}}{3\pi^2} = 0 \tag{13}$$

$$\theta = \cos^{-1}\left[\frac{1}{\mu^2}\left(m_K^2 - \frac{\mu}{2f^2}un_0(1+x) + \frac{un_0}{2f^2}(2a_1x+2a_2+4a_3)m_s\right)\right] \tag{14}$$

Energy density and Pressure

The energy density and pressure of the model are calculated as

$$\begin{aligned}\varepsilon(u,x,\mu,\theta) &= \varepsilon_{\rm MDI}(u,x)+un_0(1-2x^2)S(u)\\ &+ f^2\frac{\mu^2}{2}\sin^2\theta+2m_K^2f^2\sin^2\frac{\theta}{2}\\ &+ (2a_1x+2a_2+4a_3)\,m_s un_0\sin^2\frac{\theta}{2}\\ &+ \varepsilon_e+\eta(|\mu|-m_\mu)\varepsilon_\mu \end{aligned} \quad (15)$$

$$P(u,x,\mu,\theta)=P_b(u,x,\mu)+P_K(u,x,\mu,\theta)+\sum_l P_l(u,x,\mu), \quad (16)$$

where

$$P_b(u,x,\mu)=u^2\frac{\partial}{\partial u}\left(\frac{\varepsilon(u,x,\mu)}{u}\right) \quad (17)$$

Equations of state - Parameters

- **Slope parameter**
  - $L = 3n_0 \frac{dS(n)}{dn}\Big|_{n_0}$
- **Incompressibility**
  - $K = 9n_0^2 \frac{d^2\varepsilon(n,0)}{dn^2}\Big|_{n_0}$

strangeness of the proton

$$a_3 m_s = -134, -222, -310 \text{ MeV} \rightarrow \text{no strangeness}, 10\%, 20\%$$

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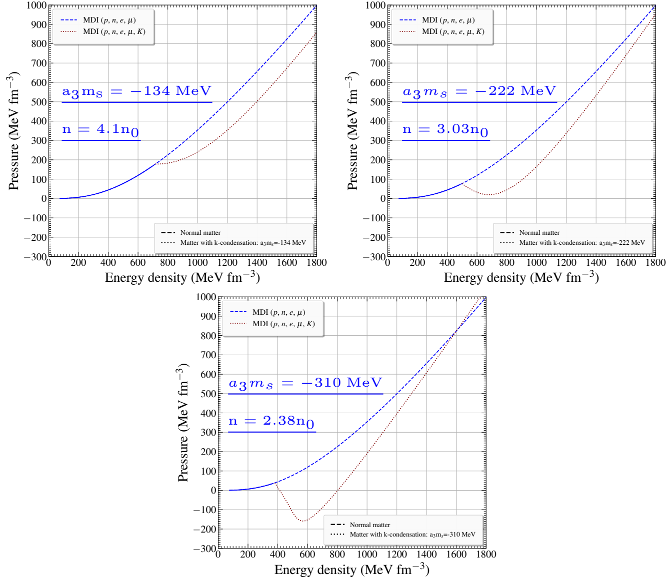
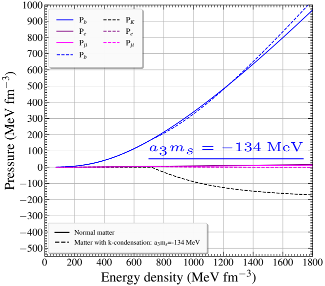
- EoSs based on various slope parameters, incompressibilities and symmetry energies in the ranges $[70, 90]$ MeV, $[200, 260]$ MeV, and $[30 - 34]$ MeV, respectively.

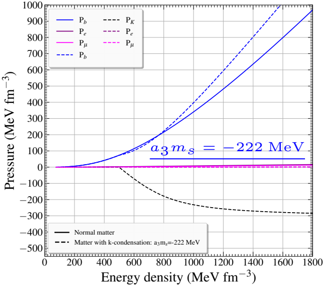
- Presented case: $L = 80$ MeV, $K_0 = 240$ MeV, and $S_0 = 32$ MeV.

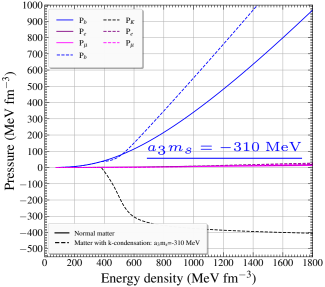
Pressure - Energy relation



Pressure contribution

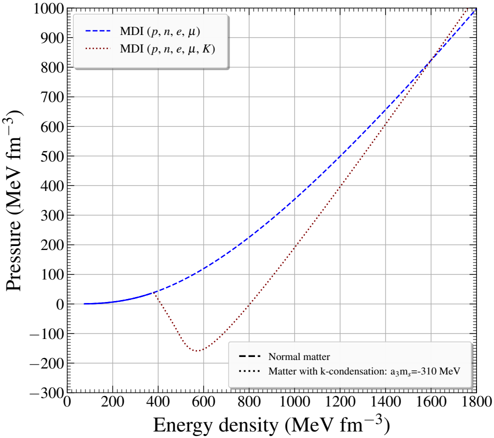






Second → First order phase transition

▶ $a_3 m_s = -310$ MeV, $n = 2.38 n_0$



- Second order phase transition
- Compressibility at threshold is negative
- Maxwell construction → positive compressibility

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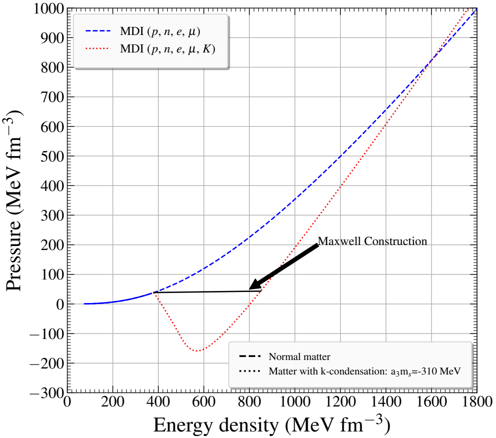

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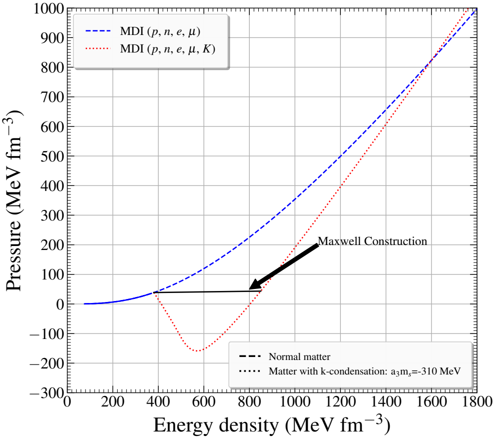
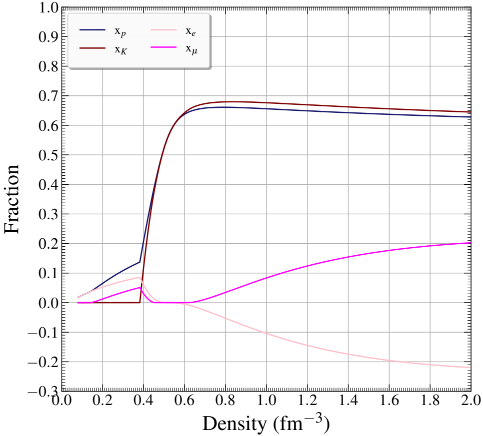


- Second order phase transition
- Compressibility at threshold is negative
- Maxwell construction $\rightarrow$ positive compressibility
- $\Delta\mathcal{E} \simeq 400$ MeV fm^{-3} $\rightarrow$ Twin stars

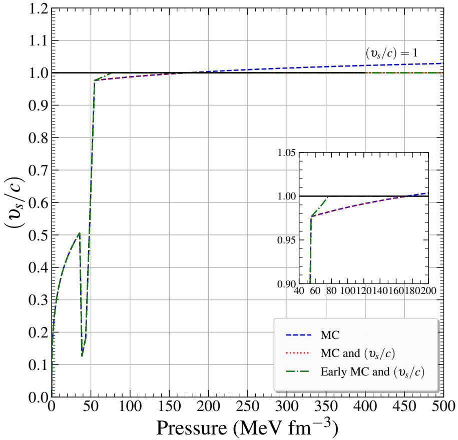
Particle Fractions



- Large x_p is required in presence of a x_k
- Net negative charge in kaon fields causes the lepton concentrations to decrease
- Existence of a density where leptons start producing $\rightarrow$ production of positrons

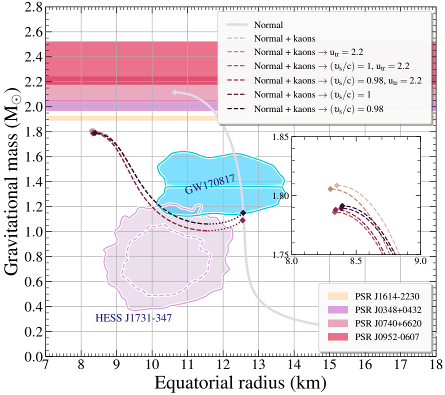
Speed of sound

- Speed of sound must be causal up to densities that correspond to $\mathrm{M}_{\mathrm{max}}$



- ✓ MC to fix the gap
- ✓ MC to fix the gap and the speed of sound
- ✓ Early MC to fix the gap and the speed of sound

Mass-radius diagram and the HESS J1731-134



- ✓ Strong softening on the EoS → $M_{max} = 2.1\ M_\odot$ to $M_{max} = 1.8\ M_\odot$
- ✓ The 2 approximations have insignificant effect on the M_{max}
- ✓ Transition density is related to the boundaries of the HESS J1731-347
- ✓ M_{max} constraints are not fulfilled

Concluding remarks - Pending work

- The strangeness of the proton plays critical role in the location of the transition density
- Transition density is directly related to the region of HESS J1731-347
- kaon condensation can be an explanation of the HESS J1731-347
- Constraints for the $\mathrm{M}_{\mathrm{max}}$ are not fulfilled

Future work

- Gibbs construction
- Hadronic EoS with $\mathrm{M}_{\mathrm{max}} \sim 2.4\ \mathrm{M}_{\odot}$
- Relativistic Mean Field model

Thank you for your attention!

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