Kaon Condensation in Neutron Stars & Related Issues

Chang-Hwan Lee

PUSAN NATIONAL UNIVERSITY

APCTP
Asia Pacific Center for Theoretical Physics
Motivations 1: why Neutron Stars?

Ultimate Testing place for physics of dense matter

- Chiral symmetry restoration
- Color superconductivity
- Color-flavor locking
- Quark-Gluon-Plasma?
- AdS/QCD?

Neutron Stars
M = 1.5 solar mass
R < 15km
A = 10^57 nucleons
composed of p, n, e, hyperons, quarks, …
Motivations 2: why Neutron Stars?

Cosmological Heavy Ion Collisions

Gravitational waves from NS-NS and NS-BH Binaries

LIGO, VIRGO, ..
Gravitation Wave from Binary Neutron Star

B1913+16
Hulse & Taylor (1975)

Effect of Gravitational Wave Radiation
1993 Nobel Prize
Hulse & Taylor

LIGO was based on the merger of DNS
NS (radio pulsar) which coalesce within Hubble time

<table>
<thead>
<tr>
<th>PSR</th>
<th>$P$ (ms)</th>
<th>$P_b$ (hr)</th>
<th>$e$</th>
<th>Total Mass $M_\odot$</th>
<th>$\tau_c$ (Myr)</th>
<th>$\tau_{GW}$ (Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0737−3039A</td>
<td>22.70</td>
<td>2.45</td>
<td>0.088</td>
<td>2.58</td>
<td>210</td>
<td>87</td>
</tr>
<tr>
<td>J0737−3039B</td>
<td>2773</td>
<td>2.45</td>
<td>0.088</td>
<td>2.58</td>
<td>50</td>
<td>87</td>
</tr>
<tr>
<td>B1534+12</td>
<td>37.90</td>
<td>10.10</td>
<td>0.274</td>
<td>2.75</td>
<td>248</td>
<td>2690</td>
</tr>
<tr>
<td>J1756−2251</td>
<td>28.46</td>
<td>7.67</td>
<td>0.181</td>
<td>2.57</td>
<td>444</td>
<td>1690</td>
</tr>
<tr>
<td>B1913+16</td>
<td>59.03</td>
<td>7.75</td>
<td>0.617</td>
<td>2.83</td>
<td>108</td>
<td>310</td>
</tr>
<tr>
<td>B2127+11C</td>
<td>30.53</td>
<td>8.04</td>
<td>0.681</td>
<td>2.71</td>
<td>969</td>
<td>220</td>
</tr>
<tr>
<td>J1141−6545†</td>
<td>393.90</td>
<td>4.74</td>
<td>0.172</td>
<td>2.30</td>
<td>1.4</td>
<td>590</td>
</tr>
</tbody>
</table>

Not important

Globular Cluster: no binary evolution

White Dwarf companion
Laser Interferometer Gravitational Wave Observatory

LIGO I: in operation (since 2004)

LIGO II: in progress (2014 ?)
Network of Interferometers

LIGO
GEO
Virgo
LCGT

LIGO Louisiana
4km

AIGO
Motivations 3: why Neutron Stars?

Origin of gamma-ray bursts (GRBs)
Gamma-ray bursts (GRBs)

Duration: milli sec - min

1970s: Vela Satellite
1990s: CGRO, Beppo-SAX
2000s: HETE-II, Swift
Triggers 105, 143, 1406, 1425, 1606, 1974, 2067, 2151, 2514, 2571, 2812, 3152

Graphs showing counts per second for each trigger.
Galactic or Extra-Galactic?

Distribution of Gamma-Ray Bursts on the Sky

Expected  Observed
2704 BATSE Gamma-Ray Bursts

Fluence, 50-300 keV (ergs cm\(^{-2}\))
- Gamma-Ray Bursts are the brightest events in the Universe.
- During their peak, they emit more energy than all the stars and galaxies in the Universe combined!
Two groups of GRBs

- **Long-duration Gamma-ray Bursts:**
  
  => HMBH Binaries

- **Short Hard Gamma-ray Bursts:**
  
  Duration time < 2 sec

  => NS-NS, NS-BH Binaries
Short-hard GRBs

No optical counterpart (?)

Origin
- Neutron star merger?
- Magnetar flare?
- Supernova?

BATSE sample

Energy fluence–averaged hardness ratio $H_{52}$

Burst duration $T_{50}$ (seconds)

Number of bursts
Signs Point to Neutron-Star Crash

Astronomers think they have witnessed their first colossal crash of two neutron stars, an event that has tantalized theorists for decades.

Shortly after midnight EDT on 9 May, a NASA satellite detected a sharp flare of energy, apparently from the fringes of a distant galaxy. The news from Swift, launched in November 2004, was quickly disseminated to ground-based astronomers, triggering hours of intense research. As Science went to press, exhausted observers verified that their early observations look a lot like a neutron-star merger. “Prudence would say that we need a strong confirmation, but we’re very excited by it,” says astronomer Joshua Bloom of the University of California, Berkeley.

Colliding neutron stars would help explain a puzzling variety of the titanic explosions called gamma-ray bursts (GRBs). Astronomers are
Motivations 4: Possible Connection to Heavy Ion Collisions

- NS: higher density, low $T$, long lifetime
- HIC: high density, high $T$, very short lifetime

- main difficulties for NS: cannot design experiment
  one can design detectors only,
  then, wait !!!
Summary of Motivations

- Ultimate Testing place for physics of dense matter.
- Sources for gravitational wave detector; LIGO.
  - testing place of dynamical general relativity
- Sources for gamma ray bursts
- Possible connection to Heavy Ion Collisions
Contents

- Motivations: why Neutron Stars?
- Kaon Condensation & Issues in Hadronic Physics
- Observations & Astrophysical Issues
How to treat dense matter inside NS?

- Construct Lagrangian (symmetry)
- Obtain pressure & energy density vs number density
- Solve TOV equation

Fermi Sea

# of nucleons = $O(10^{57})$
How to construct Lagrangian?

✓ All known symmetries

energy-momentum conservation, special relativity, parity, time-reversal, charge-conjugation, G-parity, …

✓ put all known (relevant) fields (particles)

proton, neutron, pion, kaon, hyperons, electron, muon, …

✓ Perturbative approach is unavoidable
Dense Matter: Conventional Approach [Serot & Walecka]

\[ \mathcal{L} = \bar{\psi}(i\gamma_\mu \partial^\mu - M)\psi \]

\[ B = \int d^3x \bar{\psi} \gamma^0 \psi = \int d^3x \, \psi^\dagger \psi \]

\[ iG^0_{\alpha\beta}(x' - x) = i \int \frac{d^4k}{(2\pi)^4} G^0_{\alpha\beta}(k) e^{-ik \cdot (x' - x)} \]

\[ G^0_{\alpha\beta}(k) = \frac{1}{2E(k)} \left\{ (\gamma_\mu K^\mu + M)_{\alpha\beta}\left[ \frac{1 - \theta(k_F - |k|)}{k_0 - E(k) + i\epsilon} + \frac{\theta(k_F - |k|)}{k_0 - E(k) - i\epsilon} \right] \right. \]

\[ \left. - (\gamma_\mu \tilde{K}^\mu + M)_{\alpha\beta}\left[ \frac{1}{k_0 + E(k) - i\epsilon} \right] \right\} \]

\[ \gamma_\mu K^\mu \equiv E(k)\gamma^0 - \gamma \cdot k \]

\[ \gamma_\mu \tilde{K}^\mu \equiv -E(k)\gamma^0 - \gamma \cdot k \]
Free propagator of baryons & antibaryons

\[ G^0_{\alpha\beta}(k) = (\not{k} + M)_{\alpha\beta}\left\{ \frac{1}{k^2 - M^2 + i\varepsilon} + \frac{i\pi}{E(k)} \delta(k_0 - E(k))\theta(k_F - |k|) \right\} \]

Effect of finite density (Pauli exclusion principle)
Scalar-Vector Theory

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Particles</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>$\psi$  Baryon</td>
<td>$p, n, \ldots$</td>
<td>$M$</td>
</tr>
<tr>
<td></td>
<td>$\phi$ Neutral scalar meson</td>
<td>$\sigma$</td>
<td>$m_\sigma$</td>
</tr>
<tr>
<td></td>
<td>$V_\mu$ Neutral vector meson</td>
<td>$\omega$</td>
<td>$m_\omega$</td>
</tr>
<tr>
<td>(b)</td>
<td>$\pi$  Charged pseudoscalar meson</td>
<td>$\pi$</td>
<td>$m_\pi$</td>
</tr>
<tr>
<td></td>
<td>$b_\mu$ Charged vector meson</td>
<td>$\varphi$</td>
<td>$m_\varphi$</td>
</tr>
</tbody>
</table>

\[
\mathcal{L}_I = \bar{\psi} \left[ \gamma_\mu (i \partial_\mu - g_\nu V_\mu) - (M - g_\phi \phi) \right] \psi + \frac{1}{2} (\partial_\mu \phi \partial^\mu \phi - m_s^2 \phi^2) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_\nu^2 V_\mu V_\nu + \delta \mathcal{L}
\]

\[
F_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu
\]
Q) How to treat quantum effects in dense matter?

✓ Mean field Approach:
Quantum effects are absorbed in the coupling constants in the effective Lagrangian

=> fixed by experiments

✓ Hartree-Fock Approach:
Explicit calculation with wave functions
summing all diagrams (with density dependent propagator)
Mean Field Approach (scalar & vector fields)

\[
\phi \rightarrow \langle \phi \rangle \equiv \phi_0 \\
V_\mu \rightarrow \langle V_\mu \rangle \equiv \delta_{\mu 0} V_0 \\
\phi_0 = \frac{g_s}{m_s^2} \langle \bar{\psi}\psi \rangle \equiv \frac{g_s}{m_s^2} \varrho_s \\
V_0 = \frac{g_v}{m_v^2} \langle \psi^\dagger \psi \rangle \equiv \frac{g_v}{m_v^2} \varrho_B
\]

\[
B \equiv \int_v d^3x \, B^0 = \int_v d^3x \, \psi^\dagger \psi
\]

\[
[i\gamma_\mu \partial^\mu - g_v \gamma^0 V_0 - (M - g_s \phi_0)]\psi = 0
\]

\[
M^* = M - g_s \phi_0
\]
\[ \mathcal{S}_{\text{MFT}} = \bar{\psi} [i\gamma_\mu \partial^\mu - g_v \gamma^0 V_0 - (M - g_s \phi_0)] \psi \\
- \frac{1}{2} m_s^2 \phi_0^2 + \frac{1}{2} m_v^2 V_0^2 \]

\[ \rho_B = \frac{\gamma}{(2\pi)^3} \int_0^{k_F} d^3k = \frac{\gamma}{6\pi^2} k_F^3 \]

\[ \mathcal{G} = \frac{g_v^2}{2m_v^2} \rho_B^2 + \frac{m_s^2}{2g_s^2} (M - M^*)^2 + \frac{\gamma}{(2\pi)^3} \int_0^{k_F} d^3k \frac{k^2}{(k^2 + M^*^2)^{1/2}} \]

\[ p = \frac{g_v^2}{2m_v^2} \rho_B^2 - \frac{m_s^2}{2g_s^2} (M - M^*)^2 + \frac{1}{3} \frac{\gamma}{(2\pi)^3} \int_0^{k_F} d^3k \frac{k^2}{(k^2 + M^*^2)^{1/2}} \]

\[ M^* = M - \frac{g_s^2}{m_s^2} \frac{\gamma}{(2\pi)^3} \int_0^{k_F} d^3k \frac{M^*}{(k^2 + M^*^2)^{1/2}} \]

\[ E_{F^*} = (k_F^2 + M^*^2)^{1/2} \]

\[ M^* = M - \frac{g_s^2}{m_s^2} \frac{\gamma M^*}{4\pi^2} \left[ k_F E_{F^*} - M^*^2 \ln \left( \frac{k_F + E_{F^*}}{M^*} \right) \right] \]
Constraints

\[ \left( \frac{E - BM}{B} \right)_0 = -15.75 \text{ MeV} \]

\[ k_F^0 = 1.42 \text{ fm}^{-1} \]

\[ C_s^2 \equiv g_s^2(M^2/m_s^2) = 267.1 \]

\[ C_v^2 \equiv g_v^2(M^2/m_v^2) = 195.9 \]
Nucleon Effective Mass

![Graph showing Nucleon Effective Mass vs k_F (fm⁻¹)](image)

- **Mean-Field Theory Effective Mass**
- **Neutron Matter**
- **Nuclear Matter**

- $k_F = 1.42$ fm⁻¹

**Axes:**
- $M^*/M$ on the y-axis
- $k_F$ (fm⁻¹) on the x-axis
- $g_s \phi_o$ (MeV) on the right y-axis
There are many more realistic models for dense nucleonic matter

✓ Two-body potential (fitted to NN scattering)
✓ Three-body term (suggested by theory, fitted by few body-nuclei & nuclear matter saturation property)

But, those terms are uncertain at high density. Especially symmetry energy is very uncertain
Symmetry Energy

EOS of asymmetric nuclear matter

\[ E(\rho, \delta) \approx E(\rho, \delta = 0) + E_{\text{sym}}(\rho) \delta^2, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \]

Symmetry energy

\[ E_{\text{sym}}(\rho) = E_{\text{sym}}(\rho_0) + \frac{L}{3} \left( \frac{\rho - \rho_0}{\rho_0} \right) + \frac{K_{\text{sym}}}{18} \left( \frac{\rho - \rho_0}{\rho_0} \right)^2 \]

Symmetry energy coefficient

\[ E_{\text{sym}}(\rho_0) \approx 30 \text{ MeV} \]

Slope

\[ L = 3\rho_0 \left. \frac{\partial E_{\text{sym}}(\rho)}{\partial \rho} \right|_{\rho=\rho_0} \quad \text{theoretical values} -50 \text{ to} 200 \text{ MeV} \]

Curvature

\[ K_{\text{sym}} = 9\rho_0^2 \left. \frac{\partial^2 E_{\text{sym}}(\rho)}{\partial \rho^2} \right|_{\rho=\rho_0} \quad \text{theoretical values} -700 \text{ to} 466 \text{ MeV} \]

Nuclear matter Incompressibility

\[ K(\delta) = K_0 + K_{\text{asy}} \delta^2, \quad K_{\text{asy}} = K_{\text{sym}} - 6L \]

Empirically,

\[ K_0 \sim 230 \pm 10 \text{ MeV}, \quad K_{\text{asy}} \sim -500 \pm 50 \text{ MeV}, \quad L \sim 88 \pm 25 \text{ MeV} \]

\[ E_{\text{sym}}(\rho) \sim 32 \left( \frac{\rho}{\rho_0} \right)^\gamma \text{ with } 0.7 < \gamma < 1.1 \text{ for } \rho \leq 1.2\rho_0 \]

Symmetry energy at high densities is practically undetermined!
Symmetry energy from phenomenological models

Skyrme-Hartree-Fock with 21 parameter sets

23 RMF models
Symmetry energy from Bruckner Hartree-Fock Approach

Z.H. Li et al., PRC74, 047304 (2006)
Kaon condensation in dense matter
A few remarks

✓ There are many equation of states (EoS) for NS
✓ In this talk, kaon condensation will be introduced as an example of “soft EoS”
✓ Astrophysical approaches in NS masses in this lecture are rather independent of the details of EoS as long as they are “soft”
Why strange quarks in neutron stars?

✓ proton, neutron: u, d quarks

✓ By introducing strange quark
- we have one more degrees of freedom
- energy of the system can be reduced!

✓ In what form?
kaon, hyperons … …

Kaon is the lighest particle with strange quark!
✓ without electrons

Neutral kaon (d-bar, s) condensation

✓ with electrons

K⁻ (u-bar, s) condensation

quark – anti-quark attraction
Meson Exchange Model

\[ \mathcal{L}_K = \partial_\mu \overline{K} \partial_\mu K - (m_K^2 - g_{\sigma K} m_K \sigma) K \overline{K} + ig_{\omega K} \omega_0 \overline{K} \stackrel{\leftrightarrow}{\partial_\mu} K \]

Kaon is interacting with baryons through the exchange of sigma & omega mesons

\[ \omega_K = \left[ m_K^2 + k^2 - g_{\sigma K} m_K \sigma + (g_{\omega K} \omega_0)^2 \right]^{1/2} + g_{\omega K} \omega_0, \]

\[ \omega_{\overline{K}} = \left[ m_K^2 + k^2 - g_{\sigma K} m_K \sigma + (g_{\omega K} \omega_0)^2 \right]^{1/2} - g_{\omega K} \omega_0. \]

Scalar & vector : both attractive

\[ K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \quad \text{and} \quad \overline{K} = \begin{pmatrix} K^- \\ \overline{K}^0 \end{pmatrix} \]
Can we test “Dropping K- Mass” on earth?

kaon effective chemical potential
Kaon Production in Heavy Ion Collision supports Dropping $K^-$ mass!

\[ \text{Ni+Ni, } K^+ (1.0 \text{ AGeV}), K^- (1.8 \text{ AGeV}) \]

- **no kaon medium effects**
- **with kaon medium effects**

\( K^+/K^- \)

\( E_{\text{kin}} \) (GeV)

Li, Lee, Brown, PRL (1997)
Neutron Star vs Nuclear Star

Chemical Potential

$n \rightarrow p + e^-$

Neutron Star $\rightarrow$ Nuclear Star
Kaons in Nuclear Star

\[ K^- (\bar{u}s) : N (uud, udd) \]

Attraction between quark & anti-quark

\[ n, p, e \rightarrow n, p, K^- \]

Nuclear Star

Kaon Condensation in NS
Kaon Condensation in Dense Matter

\[ \rho_0 = \text{nuclear matter density} \]
Astrophysical Implications

Neutron Star

Neutrinos

High $\mu$

Kaons
Hyperons

Reduce Pressure
Soft EoS

Low $\mu$

Hard Core

Easy to make high density

Formation of low mass Black Hole
Neutron/Strange/Quark Star?
How to describe kaon condensation?

- Meson exchange model in mean field level is not sufficient
- Multiple-meson interactions has to be included
- Chiral Perturbation Approach is one of the systematic approaches with given symmetries!
SU(3) Chiral Perturbation Theory

\[ \mathcal{L} = \frac{1}{4} f^2 \text{Tr} \partial U \partial U^\dagger + \frac{1}{2} f^2 r \text{Tr} \left[ \mathcal{M}(U + U^\dagger - 2) + \text{h.c} \right]. \]

\[ U = \exp(\sqrt{2}iM/f) \]

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

\[ \mathcal{M} = \begin{pmatrix}
m_u & 0 & 0 \\
0 & m_d & 0 \\
0 & 0 & m_s
\end{pmatrix} \]
Baryon-Meson Interaction

\[ L = + \text{Tr} \, \bar{B} (i \partial - m_B) B + i \text{Tr} \, \bar{B} \gamma^\mu [V_\mu, B] \\
+ \text{DTr} \, \bar{B} \gamma^\mu \gamma_5 \{A_\mu, B\} + \text{FTr} \, \bar{B} \gamma^\mu \gamma_5 [A_\mu, B] \]

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

\[ V_\mu = \frac{1}{2} \left\{ \xi_L^\dagger \partial_\mu \xi_L + \xi_R^\dagger \partial_\mu \xi_R \right\} \]

\[ A_\mu = \frac{1}{2} i \left\{ \xi_L^\dagger \partial_\mu \xi_L - \xi_R^\dagger \partial_\mu \xi_R \right\} \]

\[ U(\phi) \equiv \xi_L(\phi) \xi_R^\dagger(\phi) \]
How to obtain EOS (equation of state) ?

- Construct Lagrangian based on symmetries
- Mean field approximation (locally uniform matter)
- momentum-eigenstates are good quantum states.
  - particles are not local
  - collective excitations (e.g. superconductivity)
- Obtain pressure/energy-density vs density: $p(r), e(r)$
- TOV equation : with given central density
Condensed Kaon Fields

\[ \langle K^- \rangle = v_K e^{-i\mu t} \quad \theta = \frac{\sqrt{2}v_K}{f} \quad x = \frac{\rho_p}{\rho} \]

\[ \varepsilon_K = -f^2 \frac{\mu^2}{2} \sin^2 \theta + 2m_K f^2 \sin^2 \frac{\theta}{2} + \mu x \rho \]
\[ -\mu (1 + x) \rho \sin^2 \frac{\theta}{2} - 2 f^2 a_K \rho \sin^2 \frac{\theta}{2}, \]

\[ n_K = -\frac{1}{V} \frac{\partial \Omega_{\text{tot}}}{\partial \mu} = f^2 (\mu \sin^2 \theta + 4b \sin^2 \frac{1}{2} \theta) \]

\[ b = \sum_B (Y_B + q_B) n_B / (4f^2) \]

Y : baryon hyper-charge
q : baryon e-charge
Charge Neutrality (Theomodynamic Potential)

\[ \Omega = \varepsilon_N + \varepsilon_{K^-} + \varepsilon_L - \mu (\rho_p - \rho_{K^-} - \rho_e - \rho_{\mu}) \]

\[ \mu = \mu_n - \mu_p = \mu_e = \mu_{\mu} = \mu_{K^-} \]

\[ \varepsilon_L = \varepsilon_e + \eta (\mu - m_{\mu}) \varepsilon_{\mu} \]

\[ \varepsilon_e = \frac{\mu^4}{4\pi^2} \quad \varepsilon_{\mu} = \frac{m_{\mu}^4}{8\pi^2} \left[ t(1 + 2t^2) \sqrt{1 + t^2} - \ln(t + \sqrt{1 + t^2}) \right] \]

\[ t = \frac{k_{F\mu}}{m_{\mu}}, \text{ and } k_{F\mu}^2 = \mu^2 - m_{\mu}^2 \]
Comparison of EOS with/without kaon
\[ \frac{dm}{dr} = 4\pi r^2 \rho, \]

\[ \frac{dP}{dr} = -\frac{\rho m}{r^2} \left(1 + \frac{P}{\rho}\right) \left(1 + \frac{4\pi P r^3}{m} \right) \left(1 - \frac{2m}{r}\right)^{-1}, \]

\[ \frac{d\Phi}{dr} = -\frac{1}{\rho} \frac{dP}{dr} \left(1 + \frac{P}{\rho}\right)^{-1}. \]

\[ P = \rho^2 \left(\frac{\partial (\varepsilon/\rho)}{\partial \rho}\right) \]

\[ \text{No Kaon} \]

\[ \text{with Kaon} \]

\[ E_{\text{bin}} (\text{MeV}) \]

\[ P (\text{MeV}/\text{fm}^3) \]

\[ u (\rho/\rho_0) \]
Cold neutron star: an example
Role of kaon condensation

![Graph showing the mass of black holes and neutron stars as a function of central density with and without kaon condensation](image)

- **Black Holes**
- **Neutron Stars**

- **No Kaon**
- **With Kaon**
Is kaon-nuclear attraction is strong enough to trigger kaon condensation?

Yamazaki et al.
Discovery of a strange tribaryon $S^0(3115)$ in $^4$He(stopped $K^-$, $p$) reaction

T. Suzuki$^a$, H. Bhang$^b$, G. Franklin$^c$, K. Gomikawa$^a$, R.S. Hayano$^a$, T. Hayashi$^{d,1}$, K. Ishikawa$^d$, S. Ishimoto$^e$, K. Itahashi$^f$, M. Iwasaki$^{f,d}$, T. Katayama$^d$, Y. Kondo$^d$, Y. Matsuda$^f$, T. Nakamura$^d$, S. Okada$^{d,2}$, H. Outa$^{e,2}$, B. Quinn$^c$, M. Sato$^d$, M. Shindo$^a$, H. So$^b$, P. Strasser$^{f,3}$, T. Sugimoto$^d$, K. Suzuki$^{a,4}$, S. Suzuki$^e$, D. Tomono$^d$, A.M. Vinodkumar$^d$, E. Widmann$^a$, T. Yamazaki$^f$, T. Yoneyama$^d$
Kaonic Nuclei - Mini Strange Star

\[ ^3\text{He} \]

\[ ^3\text{He} + K^- \]

(a) \(^3\text{He}\)

(b) \(^3\text{He}K^-\)

(c) Proton

(d) Neutron

(e) \(K^-\)

FIG. 1: Calculated density contours of \(\text{ppmK}^-\). Comparison between (a) usual \(^3\text{He}\) and (b) \(^3\text{He}K^-\) is shown in the size of 7.5 by 7.5 fm. Individual contributions of (c) proton, (d) neutron and (e) \(K^-\) are given in the size of 4.5 by 4.5 fm.
**Kaonic Nuclei - Mini Strange Star**

**Very strong $K^-$-p attraction**

- deep discrete bound states: with binding energy $\sim 100$ MeV
- Strong in-medium KN interactions.
- Precursor to kaon condensation.
What is critical density for kaon condensation?

Kaon Condensation `a la Vector Manifestation

✓ Conventional approach (bottom-up):
  - from zero density to higher density

✓ Top-down approaches:
  - from fixed point (high density) to lower density
  - possibility in AdS/CFT
Problems in bottom-up approach

✓ Problem in K⁻p Scattering amplitude:
  experiment : - 0.67 + i 0.63 fm (repulsive)
  chiral symmetry : + (attractive !)

✓ Problem of L(1405)
  pole position of L(1405)
  $\rightarrow$ only 30 MeV below KN threshold

Perturbation breaks down in bottom-up approach !
Far below $\Lambda(1405)$ pole, $\Lambda(1405)$ is irrelevant!

One has to start below $\Lambda(1405)$ pole!

$$D^{-1}(\omega) = \omega^2 - M_K^2 - \Pi(\omega)$$
Essense of KN scattering & kaon condensation puzzle

\[
\Pi(\omega) \simeq -\rho_p \mathcal{T}^{K^-p} - \rho_n \mathcal{T}^{K^-n}
\]

\[
\mathcal{T}^{K^-p} = \frac{1}{f^2} \left\{ \omega + \Sigma_{KN} \left( 1 - 0.37 \frac{\omega^2}{M_K^2} \right) - g^2_{\Lambda(1405)} \left( \frac{\omega^2}{\omega + m_B - m_{\Lambda(1405)}} \right) \right\}
\]

\[
\mathcal{T}^{K^-n} = \frac{1}{f^2} \left\{ \frac{\omega}{2} + \Sigma_{KN} \left( 1 - 0.37 \frac{\omega^2}{M_K^2} \right) \right\}
\]

Near \( \omega = M_K/2 \), \( \Lambda(1405) \) is irrelevant!

\[
\Pi_{K^-}(\omega) \approx -\rho_p \mathcal{T}^{K^-p} - \rho_n \mathcal{T}^{K^-n} \approx -\frac{3}{2f^2} \rho \Sigma_{KN}.
\]

\[
\Delta U_{K^-} \approx \frac{1}{2} \frac{\Pi_{K^-}}{M_K(1 + M_K/m_p)} \approx -135 \text{MeV} \frac{\rho}{\rho_0}
\]
An example of Top-down approaches

Q) Is there a proper way to treat kaon condensation which doesn’t have problems with the irrelevant terms, e.g., \( \Lambda(1405) \), etc, from the beginning?

Kaon Condensation `a la HY Vector Manifestation

→ All irrelevant terms are out in the analysis from the beginning!
Kaon condensation from fixed point

Lots of problems due to irrelevant terms

Vector Manifestation

chiral symmetry restoration

\( \mu_K \)

\( \mu_e \)

\( n_c \)
A Hybrid-Approach: Weinberg-Tomozawa term

✓ most relevant from the point of view of RGE `a la VM
✓ $\omega, \rho$ exchange between kaon & nucleon

\[ V_N(\omega) = -3 V_{K^-}(\omega). \]

\[ V_{K^-}(\omega) = -\frac{3}{8F^2}\frac{n}{n_0} \simeq -57 \text{ MeV} \frac{n}{n_0} \]

|\(V_N(\omega)\)| = 171 MeV at \(n_0\) is well below experimental 270 MeV

BR scaling is needed!
\[ F_\pi \to f_\pi^* \approx 0.8 F_\pi \]

Deeply bound pionic atoms [Suzuki et al.]

\[
\frac{g^*}{m_{\rho}^*} = \frac{1}{a^* F_\pi^*} \approx \frac{1}{a^* \left( \frac{1}{0.8 F_\pi} \right)^2}
\]

\[ \alpha \equiv \left( \frac{F_\sigma}{F_\pi} \right)^2 \]

\[ m_{\rho}^2 = 2 F_\pi^2 g^2 \]

fixed point of VM \[\Rightarrow\] \[a^* = 1\] (Harada et al.)

\[
\frac{[g^*/m_{\rho}^*]_{\text{fixed point}}}{[g^2/m_{\rho}^2]_{\text{zero density}}} = \frac{[a F_\pi^2]_{\text{zero density}}}{[a^* F_\pi^*]^2}_{\text{fixed point}} \approx \frac{2}{0.8^2} \approx 3.1.
\]

Enhancement at fixed point due to BR & VM
Fixed point of chiral symmetry restoration

\[ N_{\text{ChiralSR}} = 4 \, n_0 \]

\( \rho \)-mass drops to zero around \( 4 \, n_0 \)

Kaon potential at critical density without BR & VM

\[ V_{K^-} = -\frac{1}{aF^2\pi} \left( \frac{x_n}{2} + x_p \right) n_c = -129 \text{ MeV} \]

10% p, \( n_c = 3.1 n_0 \)

Kaon potential at fixed point (4\( n_0 \)) with BR + VM

\[ V_{K^-} \approx -\frac{4}{3.1} \times 3.1 \times 129 \text{ MeV} = -516 \text{ MeV} \lesssim -m_{K^-} \]

BR scaling & HM-VM

Enough attraction to bring kaon effective mass to zero at VM fixed point!

At fixed point, kaon effective mass goes to zero!
Simple extrapolation from fixed point (maybe too simple)

\[ a^* (4n_0) = 1 \quad \quad a^* (3n_0) = \frac{4}{3} \]

Value at the matching scale
\[ \Lambda_M = 1.1 \text{ GeV} \]

\[ m_K^*(3n_0) = a^* \frac{m_K}{4} = 165 \text{ MeV} \]

Essence of kaon condensation

Fixed-point approach gives
the essential part of kaon condensation
Kaon condensation from fixed point approach

Only EOS which gives $\rho_C < \rho_{\chi_{SB}}$ is acceptable!
All the arguments against kaon condensation (which is based on bottom-up approach) is irrelevant at densities near VM fixed point!

After kaon condensation, the system will follow the line guided by fixed-point analysis.
**Open Question:**

Given the theoretical uncertainties, which one is the right one?
Contents

- Motivations: why Neutron Stars?
- Kaon Condensation & Issues in Hadronic Physics
- Observations & Astrophysical Issues
A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest¹, T. Pennucci², S. M. Ransom¹, M. S. E. Roberts³ & J. W. T. Hessels⁴,⁵

Nature 467, 1081 (Oct. 28, 2010)

PSR J1614-2230

(Millisecond Pulsars & White Dwarf Binary)

1.97 ± 0.04 Msun

(measurement based on Shapiro delay)
Astronomers Discover Most Massive Neutron Star Yet Known

Why do they claim that this is the most massive NS yet known?
- What happened to other NS's whose masses were estimated to be bigger than 2 solar mass?
- What's wrong with them?

Lattimer & Prakash (2007)
What's wrong with these observations?
Q) Higher (than 1.5 Msun) neutron star masses?

1. X-ray Binaries
2. Millisecond Pulsar J1903+0327
3. Radio pulsars with white dwarf companion
   \textit{Nature 467, 1081 (2010)}: J1614-2230 (1.97 Msun)
1. X-ray Pulsars

- Mass measurements are highly uncertain
- Many recent efforts to improve the estimates

Lattimer & Prakash (2007)
Q) X-ray Binary [Vela X-1] > 2 Msun?

“The best estimate of the mass of Vela X-1 is 1.86 $M_{\text{sun}}$. Unfortunately, no firm constraints on the equation of state are possible since systematic deviations in the radial-velocity curve do not allow us to exclude a mass around 1.4 $M_{\text{sun}}$ as found for other neutron stars.” [Barziv et al. 2001]
<table>
<thead>
<tr>
<th>Object</th>
<th>( M (M_\odot) )</th>
<th>( R ) (km)</th>
<th>( M (M_\odot) )</th>
<th>( R ) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( r_{ph} = R )</td>
<td></td>
<td>( r_{ph} \gg R )</td>
<td></td>
</tr>
<tr>
<td>4U 1608–522</td>
<td>1.52(^{+0.39}_{-0.18} )</td>
<td>11.04(^{+0.57}_{-0.95} )</td>
<td>1.64(^{+0.35}_{-0.40} )</td>
<td>11.70(^{+0.51}_{-0.72} )</td>
</tr>
<tr>
<td>EXO 1745–248</td>
<td>1.45(^{+0.21}_{-0.27} )</td>
<td>11.30(^{+0.49}_{-1.11} )</td>
<td>1.34(^{+0.50}_{-0.27} )</td>
<td>11.82(^{+0.46}_{-0.66} )</td>
</tr>
<tr>
<td>4U 1820–30</td>
<td>1.57(^{+0.15}_{-0.17} )</td>
<td>10.91(^{+0.45}_{-0.87} )</td>
<td>1.59(^{+0.34}_{-0.33} )</td>
<td>11.82(^{+0.40}_{-0.79} )</td>
</tr>
<tr>
<td>M13</td>
<td>1.43(^{+0.21}_{-0.63} )</td>
<td>11.18(^{+1.01}_{-1.22} )</td>
<td>0.901(^{+0.27}_{-0.12} )</td>
<td>12.21(^{+0.17}_{-0.59} )</td>
</tr>
<tr>
<td>( \omega ) Cen</td>
<td>1.38(^{+0.29}_{-0.59} )</td>
<td>11.30(^{+0.98}_{-1.01} )</td>
<td>0.925(^{+0.59}_{-0.14} )</td>
<td>12.09(^{+0.27}_{-0.64} )</td>
</tr>
<tr>
<td>X7</td>
<td>0.81(^{+1.23}_{-0.02} )</td>
<td>13.25(^{+0.48}_{-3.40} )</td>
<td>1.94(^{+0.14}_{-0.29} )</td>
<td>11.43(^{+0.77}_{-1.13} )</td>
</tr>
<tr>
<td>RX J1856–3754</td>
<td>1.48(^{+0.35}_{-0.30} )</td>
<td>11.18(^{+0.73}_{-0.98} )</td>
<td>1.55(^{+0.42}_{-0.35} )</td>
<td>11.82(^{+0.40}_{-0.86} )</td>
</tr>
</tbody>
</table>

\( r_{ph} \) = radius of photosphere
The Mass and Radius of the Neutron Star in EXO 1745–248

Feryal Özel¹, Tolga Güver and Dimitrios Psaltis¹

arXiv:1810.1521

tightly constrained pairs of values

\[ M = 1.7 \, M_\odot \text{ and } R = 9 \, \text{km}. \]
\[ M = 1.4 \, M_\odot \text{ and } R = 11 \, \text{km}. \]

2 sigma error
2. Millisecond Pulsar J1903+0327


- Orbital period: $P = 95.1741$ days
- Spin period: $P = 2.14991$ ms (recycled pulsar)
- Highly eccentricity: $e = 0.43668$
- Mass estimate = 1.74(4) $M_{\odot}$
- Observations of NS-MS (main sequence) binary requires different evolution process
Note that *OBSERVERS* considered PSR J1903+0327 as the most massive NS observed until 2009.
Lattimer & Prakash (2007)

3. Neutron Stars with White Dwarf companions

WD-NS Binary

X-ray pulsar

NS-NS

Neutron star mass ($M_\odot$)
Proven uncertainties in high-mass NS in NS-WD

Pulsar J0751+1807

2.1 $\pm$ 0.2 solar mass

Nice, talk@40 Years of Pulsar, McGill,
Aug 12-17, 2007

1.26 $^{+0.14}_{-0.12}$ solar mass
difficulties in Bayesian analysis for WD mass
et al. 2006). The result of $1.5\,M_\odot$ brings us into conflict with the recent measurement by Nice et al. (2005) of $2.1 \pm 0.2 \,M_\odot$ for PSR J0751+1807. The lower limit for this NS at 95% confidence is $1.6\,M_\odot$. We evolve in our model of hypercritical accretion the masses of pulsars and companions in NS-NS binaries, the result of which is that the pulsars would have substantially greater masses than their companions if a $2.1\,M_\odot$ neutron star were to be stable. We find that our calculated distribution could be made consistent with current observations, the most important of which require the pulsar mass to be no greater than $1.8\,M_\odot$. Thus, we may have to raise our calculated upper limit by $0.2\,M_\odot$, but we believe that the lower end of the mass measurement for J0751+1807 is favored.
A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest\textsuperscript{1}, T. Pennucci\textsuperscript{2}, S. M. Ransom\textsuperscript{1}, M. S. E. Roberts\textsuperscript{3} & J. W. T. Hessels\textsuperscript{4,5}

Nature 467, 1081 (Oct. 28, 2010)

PSR J1614-2230

(Millisecond Pulsars & White Dwarf Binary)

1.97 ± 0.04 Msun

(measurement based on Shapiro delay)
Shapiro delay

Additional red shift due to the gravity of companion star
If this limit is firm, maximum neutron star mass should be at least 1.97 Msun
Q) IF maximum NS mass is confirmed to be 1.97 Msun

- Why all well-measured NS masses in NS-NS binaries are < 1.5 Msun?
- Maybe, new-born NS mass is constrained by the stellar evolution, independently of maximum mass of NSs.

Lattimer & Prakash (2007)
Double NS binaries

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1518+49</td>
<td>1.56^{+0.13}_{-0.44}</td>
<td>1.05^{+0.45}_{-0.11}</td>
<td>1.3332^{+0.0010}_{-0.0010}</td>
<td>1.3452^{+0.00010}_{-0.0010}</td>
<td>1.4408^{+0.0003}_{-0.0003}</td>
<td>1.3873^{+0.003}_{-0.0003}</td>
<td>1.363^{+0.040}_{-0.040}</td>
<td>1.250^{+0.005}_{-0.005}</td>
<td>1.337^{+0.005}_{-0.005}</td>
<td>1.250^{+0.005}_{-0.005}</td>
<td>1.40^{+0.02}_{-0.03}</td>
<td></td>
</tr>
</tbody>
</table>

• All masses are < 1.5 M☉
Astrophysical Issues

Formation & Evolution of NS Binaries
Accretion process is essential in understanding NS binaries.
One has to understand formation of black hole/neutron star
Fe core mass

Neutron Star

In close Binaries
Fresh NS mass from Fe core collapse

Both in single & close binaries

Fe core mass \(\xrightarrow{\text{\red arrow}}\) NS mass = 1.3 - 1.5 M\(\text{sun}\)

This value is independent of NS equation of state.

Q) What is the fate of primary (first-born) NS in binaries?

Note: Accurate mass estimates of NS come from binaries.
Question) Final fate of first-born NS?

Evolution of Companion

Accretion

1st-born NS

Fe

He

NS + accretion

2nd NS/WD

Graph showing stages of evolution with labeled stages: H core burning, H shell burning, He core burning.
Supercritical Accretion onto first-born NS

- Eddington Accretion Rate: photon pressure balances the gravitation attraction
- If this limit holds, neutron star cannot be formed from the beginning (e.g. SN1987A; $10^8$ Eddington Limit).
- Neutrinos can take the pressure out of the system allowing the supercritical accretion when accretion rate is bigger than $10^4$ Eddington limit!
  ($T > 1$ MeV: Thermal neutrinos dominates!)

Q) What is the implications of supercritical accretion?
Case 1: $\Delta T < 1\%$

Formation of NS-NS Binary

No accretion: nearly equal mass NS-NS binary!
Case 2: $\Delta T > 10\%$

Formation of NS-WD Binary

Supercritical Accretion:
First born NS should accrete $0.9 \, M_\odot$!
Consequences of Supercritical Accretion

- **NS-NS Binary**
  - nearly equal mass progenitors
  - no time for the accretion after NS formation
  - NS masses in NS-NS binaries are all below 1.5 msun

- **High-mass NS-WD Binary**
  - mass difference of progenitors are large
  - some time for the supercritical accretion after NS birth
  - formation of higher-mass NS

- Many other possibilities depending on the initial conditions of binaries
Open Question?

Are these different approaches consistent with each other?

- Neutron Star Equation of States: Both in bottom-up & top-down approaches
- Neutron Star Observations (Radio, X-ray, Optical, …)
- Formation & Evolution Neutron Star Binaries
- Gravitational Waves from Colliding Neutron Stars
- Soft-Hard Gamma-ray Bursts from Colliding Neutron Stars
- Properties of Dense Matter from Heavy Ion Collisions
- … …
Many Thanks