STRONG-NA7 Workshop & HFHF Theory Retreat 2023

Dense nuclear matter modelisations and compact star observations

Effective modelisations of QCD with quarks, nucleons and hadrons

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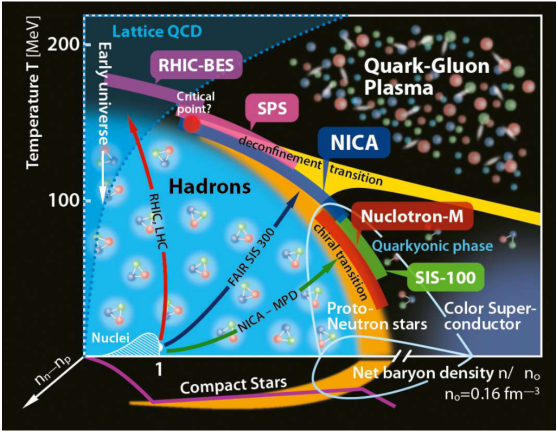
Introduction : schematic phase diagram of QCD (1)



L. Turko, CSQCD VI, `Universe 2018, 4, 52`

Known :

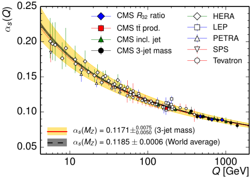
- p-QCD, LQCD, $\chi-$PT
- Earth based experiments, Compact star observations
- Etc.

Unknown :

- A general understanding of the phase structure in particular at large density/temperature (typically above the nuclear saturation density).

QCD : Quarks, gluons / confinement / chiral symmetry

$$\mathcal{L}_{QCD} = \bar{q}\,(\,i\gamma^\mu D_\mu - \hat{m}\,)\,q \;-\; \frac{1}{4}F^a_{\mu\nu}\,F^{\mu\nu}_a \;;\; D_\mu = \partial_\mu - ig\lambda^a A^a_\mu$$



Confinement :

- No asymptotic quark and gluon degrees of freedom.
- At finite temperature, invariance Z_{N_c} (center of $SU(N_c)$).

NB : Typical (nuclear) $\Lambda_{QCD} \simeq 200$ MeV $\simeq 1$ fm.

Chirality :

special relativity distinguish left (L) and right (R) fermion ; obviously boosting a massive particle changes its chirality.

QCD almost invariant (exact if $\hat{m}_{uds} = 0$; in practice, OK because small compared to Λ_{QCD}) by the $U_R(N_f = 3) \times U_L(N_f = 3)$ symmetry + spontaneous breaking + $U_A(1)$ anomaly.

Tools : effective modelisation (1)

Depending on what you want (energy, thermodynamics, type of observations, etc) :

- Choose your degrees of freedom : nucleons, hadrons, quarks (gluons)
- Choose the physics : nucleon-nucleon interactions, chiral symmetry, confinement, phase transition, etc.
- Choose a description : Lagrangian (microscopic) but also other : empirical or semi-empiral description (meta-model, quarkyonic description, etc).

$\Rightarrow$ Complementary to ab-initio description (e.g. sometimes some better understanding of a particular microscopic mechanism)
$\Rightarrow$ Flexibility (inter/extrapolation) to connect to other theory/model and experimental observations : Bayesian analysis (or other framework to constrain models).

Some modelizations of QCD (1)

1. Many approaches
   - NJL family of model : quarks + a hint of confinement
   - RMF with meson/nucleon + chiral symmetry, a hint of confinement
   - Quark/nucleon (hadron) models : Quarkyonic idea, QM model.
2. All approaches have success but of course shortcomings
   - Description of hadrons in quark models ? But if possible $\Rightarrow$ unification of quark/hadron description.
   - Nucleonic/hadronic model are more distant from QCD. $\Rightarrow$ implement QCD constraint inside the model.
   - What happens to pure hadronic models when quark degrees of freedom get excited (e.g. large densities) ? $\Rightarrow$ connect via phase transition / percolation, etc.

A chiral confining RMF model (1)

1. Model of Chanfray, Ericson et al.

$$\mathcal{L} = \psi i\gamma^\mu \partial_\mu \psi + \mathcal{L}_s + \mathcal{L}_{meson}$$

$$\mathcal{L}_s = -M_N^*(s)\overline{\psi}\psi - V(s) + \frac{1}{2}\partial^\mu s \partial_\mu s$$

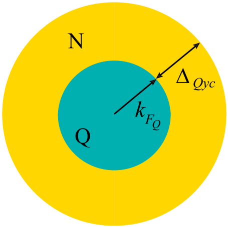
$$M_N^*(s) = M_N + g_S s + \frac{1}{2}\kappa_{NS} s^2 + O(s^3)$$

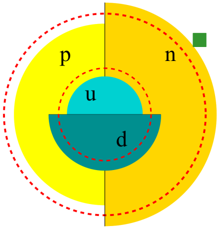
- Nucleons (ψ) + mesons as interactions
- A scalar field s (radial fluctuation of the chiral condensate) $\Leftrightarrow$ σ meson of usual relativistic theory
- Chiral properties via a scalar chiral potential $V(s)$
- Polarizabilty of the nucleon in the presence of the nuclear scalar field (effect of the quark substructure – Guichon) $\Rightarrow$ Related to confinement.
- Associated parameters :
  - g_S the nucleon scalar coupling constant
  - κ_{NS} the scalar susceptibility.

A chiral confining RMF model (2)

2. Success
   - The polarizabilty term generates a repulsive 3-body force providing a saturation mechanism.
   - Parameters can be related to two chiral properties of the nucleon given by LQCD ⇒ constraints on the model ($M_N(m_\pi^2)$)
3. Recent results
   (G. Chanfray, M. Chamseddine, HH, J. Margueron, R. Somasundaram, Eur.Phys.J.A 59 (2023) 8, 177 ; 2304.01036)
   - Anchored in QCD via parameters computed on lattice ; parametrized with Bayesian analysis.
   - Scalar chiral potential as the NJL potential (bring the needed repulsion)
   - Anchored in QCD via the field correlator method ⇒ justification of the NJL potential for the chiral part + confining potential to fix the polarizabilty.

The quarkyonic model (1)

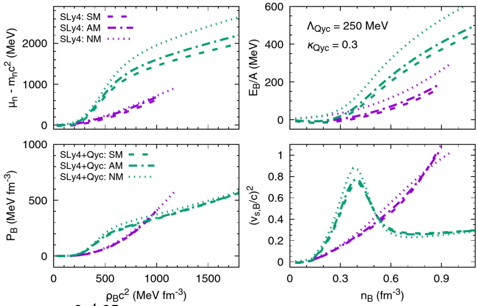




- Symmetric matter + large N_c properties : Mc Lerran, Pisarski

$$E_N(k_{f,N} - \Delta_{qyc}) = N_c E_Q(k_{f,Q})$$

$$\Delta_{qyc} = \frac{\Lambda_{qyc}^3}{k_{f,N}} + \kappa_{qyc} \frac{\Lambda_{qyc}}{N_c^2}$$



- Extension for any isospin-flavor asymmetry (J. Margueron, HH, P. Proust, G. Chanfray, Phys. Rev. C 104, 055803 (2021))

$$k_{f,Q} = \frac{k_{f,N} - \Delta_{qyc}}{N_c} \Theta(k_{f,N} - \Delta_{qyc})$$

$\Rightarrow$ One result for today : smooth phase transition to quark matter (see v_s^2).

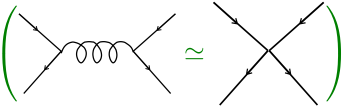
NJL model family (1)

1. Chiral symmetry and « confinement » implemented at quark level

PNJL chiral model ($q = (q_u, q_d, q_s)$ the light quark fields) :

$$\mathcal{L}_{PNJL} = \overline{q}(i\gamma_\mu D^\mu - \hat{m})q$$

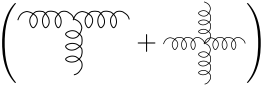
$$+ \frac{1}{2} g_S \sum_{a=0}^{8} \left[(\overline{q}\,\lambda^a\,q)^2 + (\overline{q}\,i\,\gamma_5\,\lambda^a\,q)^2 \right]$$



$$+ g_D \{\det[\overline{q}(1+\gamma_5)q] + \det[\overline{q}(1-\gamma_5)q]\}$$

$$+ \textit{Scalar and Axial diquark couplings}$$

$$- \mathcal{U}\left(\Phi[A], \overline{\Phi}[A]; T\right)$$



In principle « easy » (...) to compute in the whole phase diagram.

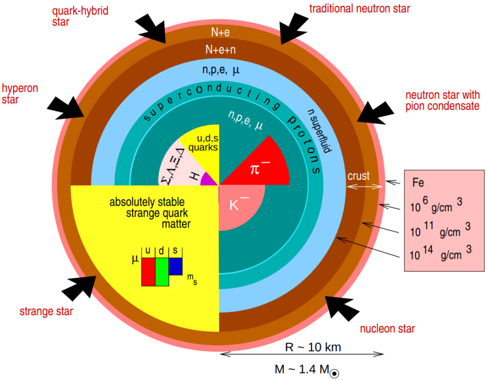
NJL model family (2)

2. Unified description of quark/meson/baryon
   - Mean Field capture quark properties as the chiral symmetry breaking in vacuum.
   - Ring (RPA) approximation incorporate mesonic fluctuations
   - Faddeev allow to build baryons (but also Nambu–Gorkov for diquarks, static approximation)
3. Parametrization in the vacuum
   (A. Pfaff, HH, J. Aichelin, J. Torres-Rincon, Phys. Rev. C 107, 045204 (2023))
   - To have as best a description of the phenomenology in the vacuum as possible before extrapolation in medium.
   - Incorporate baryon mass spectrum in a bayesian calculation

   Scalar diquarks need to be strongly bound.
   Confirm the need of a large quark mass.

« Neutron » star (NS) observations (1)

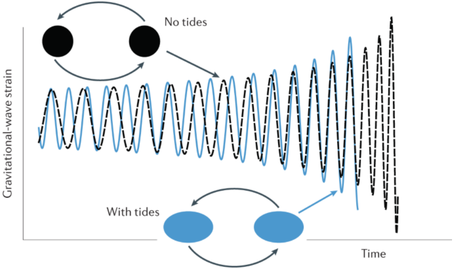
Weber J.Phys.G27 :465-474,2001



- Multi-messenger observation : X (Nicer), Gravitational Wave (GW) as seen by LIGO–VIRGO–Kagra collaboration.
- Dense matter « laboratory »
- $\simeq 8n_{sat}$
- Quarks ? Other dofs ?
- In the future (Einstein Telescope, Cosmic Explorer), dense AND hot matter laboratory (post-merger observations)

« Neutron » star (NS) observations (2)

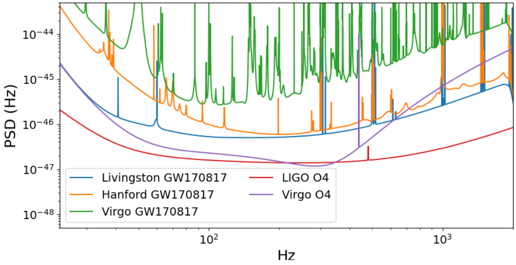
1. Potential to constraining models : the LVK O4 (current) run
   (J.F. Coupechoux, R. Chierici, HH, J. Margueron, R. Somasundaram, V. Sordini, Phys. Rev. D 107, 124006 (2023))
   An illustration of the constraining potential of the observations of GW during neutron stars mergers.
2. The tidal deformability Λ



- Mergers of NS probe the matter (EoS) at large density (and temperature post-merger) via deformability
- Expected good discriminative power if well measured $\Rightarrow$ precisely what we will study here.

« Neutron » star (NS) observations (3)

3. PSD



Exploiting the planned improvement of noise PSD for O4 run (spring 2023)

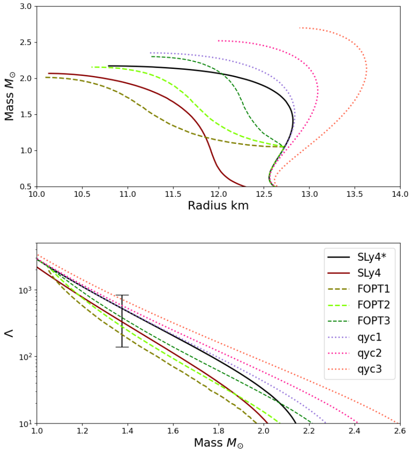
« Neutron » star (NS) observations (4)

4. GW170817
   $D = 40$ Mpc, $M_{chirp} \simeq 1.188 M_{sol}$, asymmetry $q \simeq 0.9$
5. Method
   - Pick up your favorite EoS
   - Inject the expected waveform from a merger with given characteristics (e.g. GW170817) into the LVC analysis pipeline with the expected noise PSD of the (current) O4 run.
     NB : probability to observe an event such as GW170817 with O4 :

$$R^{-1} = \left(\tau_{BNS} \frac{4\pi}{3} D^3 \right) = 12^{+36}_{-7} \text{ yr.}$$

     at nominal noise PSD.

Models (1)



3 families covering different cases in the model space :

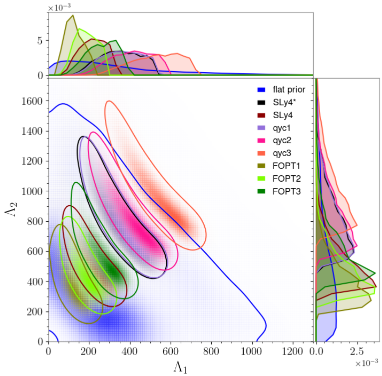
- Nucleonic (Sly4) : smooth (no transition)
- First order phase transition (FOPT) : SLy4 connected to fixed speed of sound
- Quarkyonic (qyc) : smooth transition

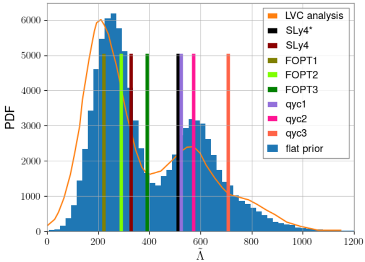
GW170817 analysis (1)

Bayesian analysis of the genuine signal with flat prior or knowledge of the EoS :

1. Flat prior
   19 parameters : distance, spin, etc., chirp mass $\mathcal{M}$, asymmetry q and tidal deformabilties $\Lambda_{1,2}$
   Bayesian analysis to find the parameters $\Rightarrow$ heavily rely on (simplified) mergers simulation : 1 analysis $\Leftrightarrow$ 1 day on 160 CPU.
   For all this work : $\simeq$ 4 million CPU hours at Jean Zay computer, IDRIS (GENCI) – France $\Rightarrow$ this work is also a benchmark for faster method
   NB : And it is NOT full hydro simulation but Post-Newtonian (PN at 5th order for Λ to appear) + Pheno (based on full simulation) wave form.
2. With knowledge
   19 - 2 parameters, $\Lambda_{1,2}$ for the two star is fixed from the EoS.

GW170817 analysis (2)





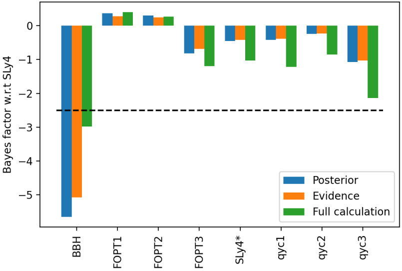
$\tilde{\Lambda}$: effective tidal deformability (function of $\Lambda_{1,2}$).

$\Rightarrow$ As already known : limited discriminative potential for this quite « loud » event.

GW170817 analysis (3)

3. Bayes factor

   Quantitative factor to assess which model is favored (2.5 : moderate evidence ; 5 : strong evidence) :
   With SLy4 as reference (origin) :



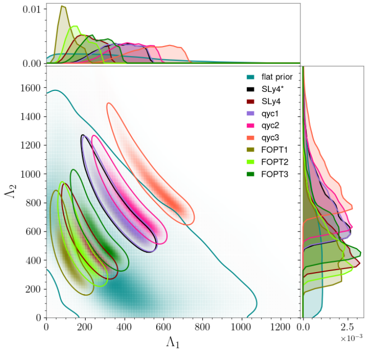
⇒ no model really favored ; black hole (BH) excluded

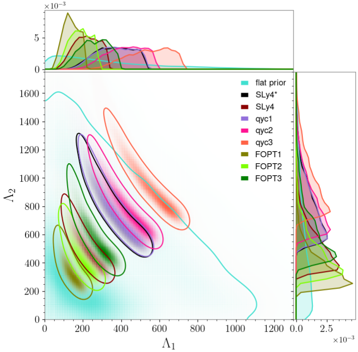
Injection of a signal (1)

Same analysis as before but with a simulated signal with a given EoS and with O2 PSD, at 40 Mpc.

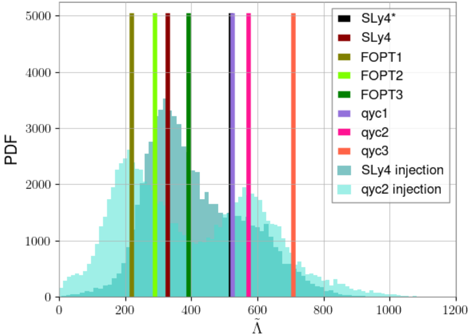
1. At 40 Mpc
   SLy4 injection

   Qyc injection





Injection of a signal (2)



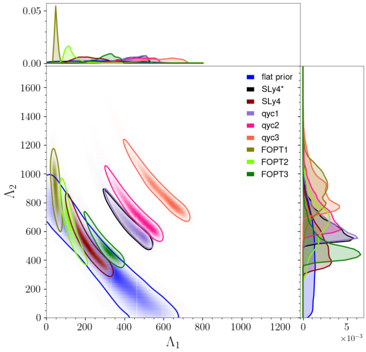
⇒ Even if EoS known, cannot discriminate.
⇒ Still double peak.

Injection of a signal (1)

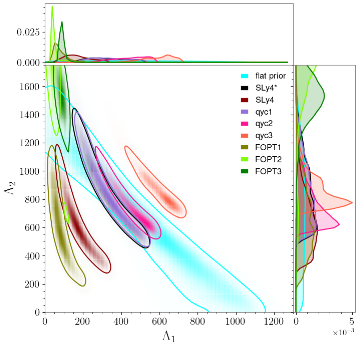
Same analysis as before but with a simulated signal with a given EoS and with O4 PSD, at 40 Mpc.

1. At 40 Mpc

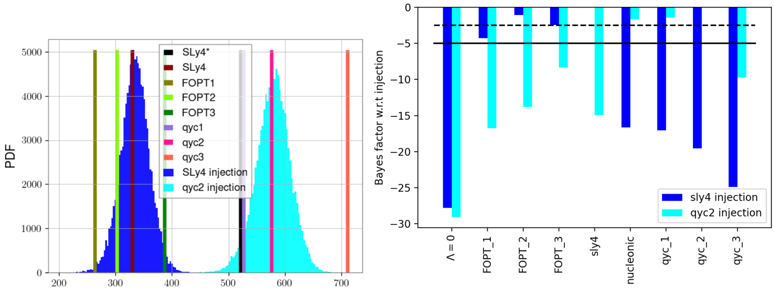
   SLy4 injection



Qyc injection



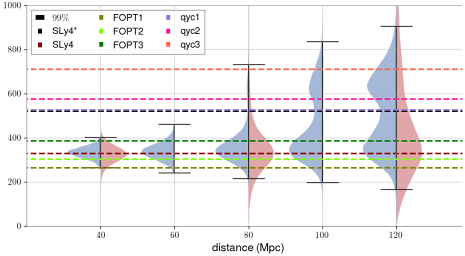
Injection of a signal (2)



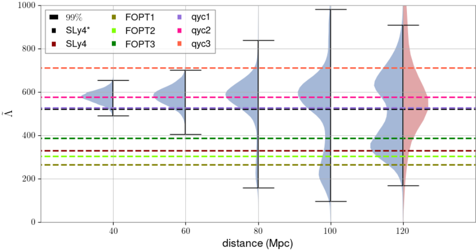
⇒ Strongly favors one family, very good discrimination

Injection of a signal (3)

2. As a function of the distance



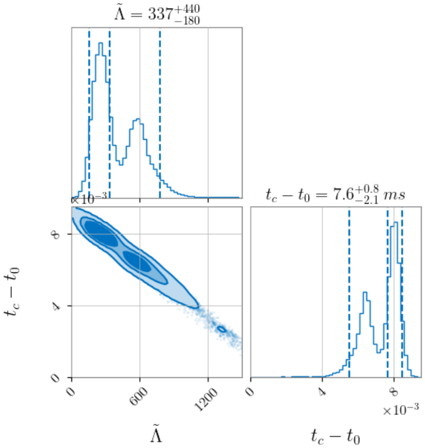
SLy4 injection



Qyc injection

Till 100 Mpc (rate 9^{+27}_{-25} months) : reasonable discrimination between families of EoS

Double peak in Λ (1)



The double peak structure seen in Λ ?
May be related to the geocentric time (duration of the event is dependant of the EoS).
Disappear with better SNR.

Correlation with the geocentric time of the event

Conclusion (1)

- Effective modelisations are complementary to ab-initio theoretical calculations, in particular to interpolate between theory and experiment in the whole phase diagram.
- They can allow to understand the effect of a given microscopic mechanism e.g. chiral restoration.
- They can also cover more easily a large portion of the phase diagram.
- They allow to do « experiments » e.g. to discuss the constraining power of one particular observable on a given sector of the theory.
- For what concern compact star observations, LVC O4, O5 but also in the future ET/CE (post-mergers !) are awaited with great anticipation.