Dense Matter in Gravity-Assisted Colliders

Sourendu Gupta
TIFR

Meeting on the Physics of ALICE, CBM, STAR
VECC Kolkata (Jan 30, 2024)

Heavy-ion Collisions: Jan-e and Subhasis

Jan-e Alam

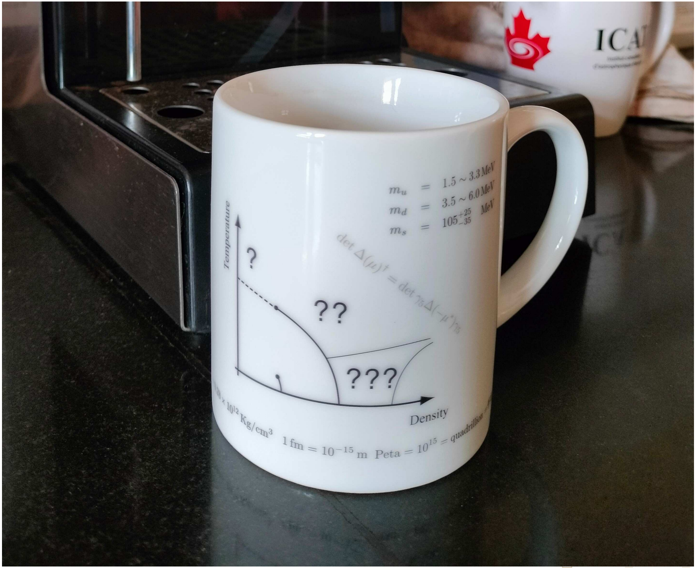
Wide-ranging and prolific phenomenologist.

- Heavy quark: drag and diffusion constants in QGP (2010)
- Photons: using photons for thermometry of QGP (2000)
- Jets: stopping of partons in the QGP using LO QCD (2005)

In one year 24 preprints!

Subhasis Chattopadhyay

Current conjectures about QCD phase diagram



Gravity assisted colliders

Simple design: place two nuclei of mass number A at distance r_0 apart and let them accelerate towards each other under gravity: $\sqrt{S} \approx 2GA^2 m_p^2 / r_0$.

Since $G = 6.7 \times 10^{-39}/\text{GeV}^2$, we find

$$\sqrt{S} = 1.3 \times 10^{-39} \frac{A^2}{r_0} \text{ GeV}$$

Looks too small to be useful.

Gravity assisted colliders

Simple design: place two nuclei of mass number A at distance r_0 apart and let them accelerate towards each other under gravity: $\sqrt{S} \approx 2GA^2 m_p^2/r_0$.

Since $G = 6.7 \times 10^{-39}/\text{GeV}^2$, we find

$$\sqrt{S} = 1.3 \times 10^{-39} \frac{A^2}{r_0} \text{ GeV}$$

Looks too small to be useful.

But take $A = 2M_\odot/m_p \approx 2.3 \times 10^{57}$ and $r_0 = 100$ Km$= 10^{20}$ fm. Then $\sqrt{S} \approx 3 \times 10^{55}$ GeV.

Gravity assisted colliders

Simple design: place two nuclei of mass number A at distance r_0 apart and let them accelerate towards each other under gravity: $\sqrt{S} \approx 2GA^2 m_p^2/r_0$.

Since $G = 6.7 \times 10^{-39}/\mathrm{GeV}^2$, we find

$$\sqrt{S} = 1.3 \times 10^{-39} \frac{A^2}{r_0} \ \mathrm{GeV}$$

Looks too small to be useful.

But take $A = 2M_\odot/m_p \approx 2.3 \times 10^{57}$ and $r_0 = 100$ Km$= 10^{20}$ fm. Then $\sqrt{S} \approx 3 \times 10^{55}$ GeV.

Also $\sqrt{S}/A \simeq 0.03$ GeV. This could explore the end point of the first order line, or more of the phase diagram at higher density.

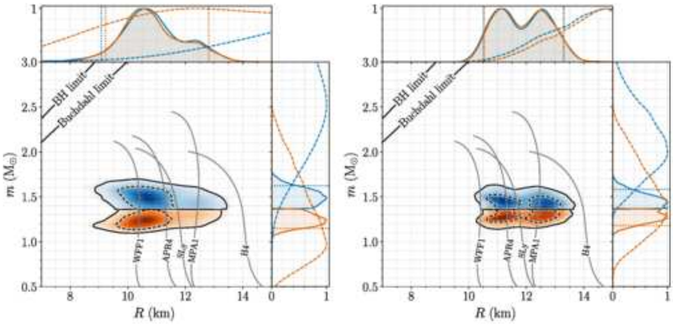
August revolution

Observations

- **Gravity wave**: LIGO/Virgo saw a clear merger of two neutron stars about 40 Mpc away (GW-170817).
- **Gamma rays**: 1.7 seconds later the Fermi telescope observed a short GRB (GRB-170817A).
- **Optical**: 11 hours later the Swope Supernova Survey saw the event in optical wavelengths (SSS17A).
- **UV to IR**: This was followed by multiple observations from UV to near-IR over weeks.

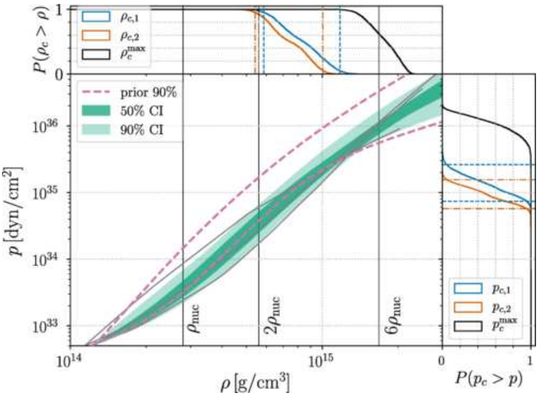
This was the beginning of multimessenger astrophysics. In future possible observations also in ν. Long event duration gives possibility of very detailed observation. Event rate estimate is 1.5/yr within 100 Mpc^3.

"Day 1 Physics" (1)



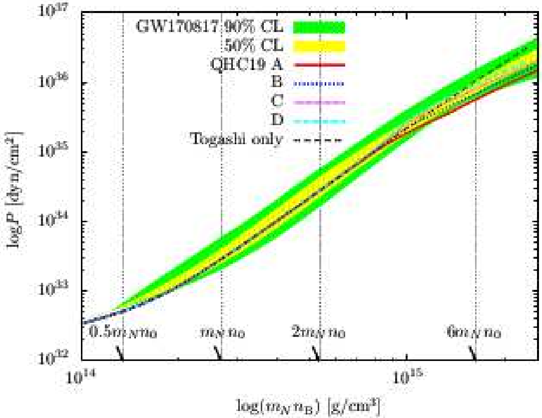
Pre-merger waveform yielded measurements of neutron star sizes, masses, spin, pressure at supernuclear densities, tidal deformability of the NS.
(LIGO-Virgo, doi:10.1103/PhysRevLett.121.161101)

"Day 1 Physics" (2)



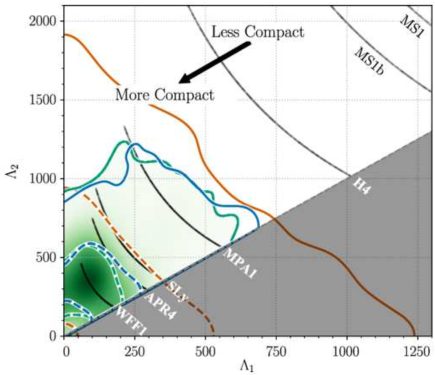
EoS for ideal gas: $p = c_s^2 \rho$. First look at the speed of sound yields a mystery: $c_s^2 > 1/3$.
(LIGO-Virgo, doi:10.1103/PhysRevLett.121.161101)

Possible explanation for $c_s^2 > 1/3$



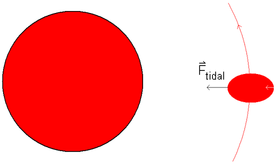
Quark-hadron crossover: peak in c_s at crossover, because of non-uniformity in the relation between p and ρ.
(Baym et al, doi:10.1088/1361-6633/aaae14)

"Day 1 Physics" (3)



$\Lambda = (2/3)k_2/C^5$ and k_2 is a Love number, $C = m/r$. **Love numbers** are related to compressibility of matter: a new observable for theories of dense matter.
(LIGO-Virgo, doi:10.1103/PhysRevLett.121.161101)

Love numbers



Dimensionless constants relating tidal deformation and external gravitational potential. In weak-field Newtonian gravity limit written as

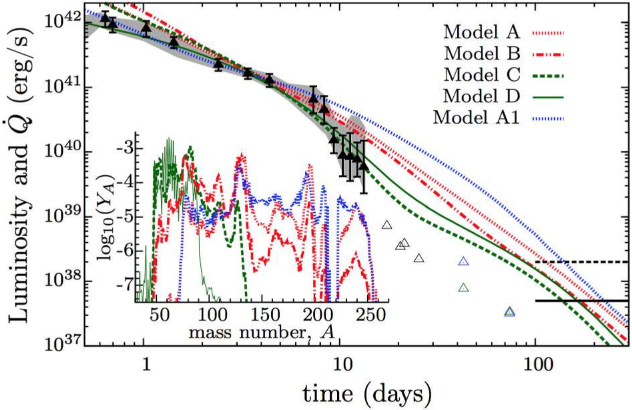
$$Q_{ij} = k_2 R^5 \nabla_i \nabla_j U, \quad \text{where} \quad U = \frac{M}{R}, \quad Q_{ij} = \int d^3x \rho x_i x_j.$$

Gravitational natural units: $G = c = 1$, gives $[M] = [E] = [L]$, so k_2 is dimensionless. **Quantum natural units**: $\hbar = c = 1$, gives $[M] = [E] = 1/[L]$, so k_2 has dimension $1/M^2$.

Kilonova

Kilonova and multimessenger astrophysics

NS mergers lead to a **kilonova**: a short-lived bright object in optical and near-IR.



(Smartt et al, doi:10.1038/nature24303)

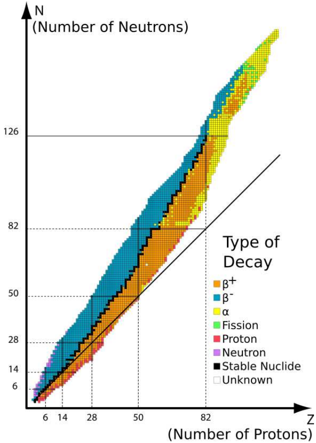
Heavy element nucleosynthesis

About 0.03–0.05 solar mass of material was ejected from the merger event. It expanded to 50 AU in 1.5 days, implying a speed of expansion of about 0.2c.

Initially optically thick material developed Lanthanide absorption lines, with [La] peaking after 2.5 days.
(Pian et al, doi:10.1038/nature24298)

Classic theory: Lanthanides are synthesized in the neutron-rich debris of kilonovae by rapid neutron capture (r-process). The competition of capture and subsequent beta-decays are strongly influenced by neutron drip-line physics.
(doi:10.1016/j.physrep.2007.06.002)

Stable nuclei



The drip line is defined as a barely bound nucleus: adding another nucleon makes it unbound. Study of the drip-lines part of India's Mega-Science Vision.

Drip line physics

Since the binding energy scales are much less than m_π, this is low energy nuclear physics. Apart from older numerical model computations, there is scope for new Effective Field Theory methods.

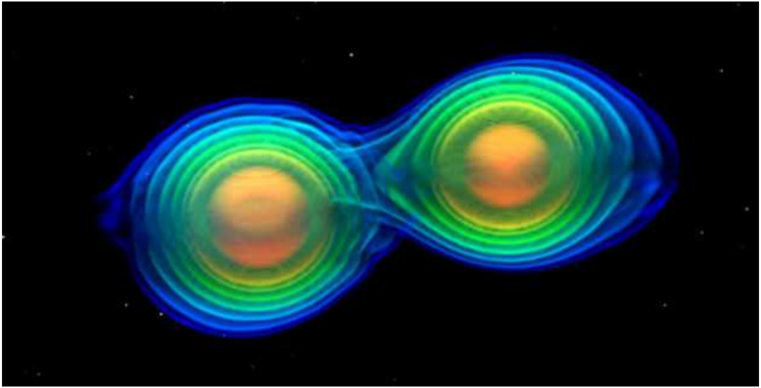
Related physics of halo nuclei: nuclear size much larger than $r_0\sqrt[3]{A}$, *i.e.*, last nucleons have a relatively low separation energy. The small parameter for the expansion is $\mathrm{BE(halo)/BE(core)}$. (Bertulani et al, doi:10.1016/S0375-9474(02)01270-8; Bedaque et al, doi:10.1016/j.physletb.2003.07.049)

Another interesting observation due to Son and collaborators: unnuclear physics. Large scattering lengths imply near conformal physics of multi-neutron states and large anomalous dimensions. (Hammer and Son, doi:10.1073/pnas.2108716118)

Related phenomena under investigation at ANURI

Monsters

Binary mergers of neutron stars



Matter falls through the L_1 Lagrange point (Roche lobe) in streams. Streams with large angular momentum miss the second NS. NS crust is 33% of the total volume, but very low density, so 10^{-4} of the mass. Ejecta contains more than crust.

Long-lived monsters

Does the kilonova ejecta contain monster nuclei? As in a NS, local charge neutrality requires $n_e = n_p$, so one has $\mu = E_e^F / E_p^F = m_p / m_e \approx 2000$. Also $n_n \approx \mu^{3/2} n_e = \mu^{3/2} n_p$ for β-stability. Baryon density of $1/\mathrm{fm}^3$ gives $E_e^F \approx 300$ MeV.

- Spontaneous fission requires deformation of the nucleus into two lobes and separation by Coulomb repulsion of the lobes: prevented by local charge neutrality.
- α decay prevented since the decay $\mathrm{monster} \to \mathrm{monster}' + \alpha$ requires $\mathrm{monster}'$ to be negatively charged. Then the α is bound into a Bohr radius smaller than the size of the monster.
- QED vacuum breakdown averted since the highest filled e-orbital is within the monster. Possible when $A > (a_0/r_0)\mu$ with Bohr parameter $a_0 \approx 500$fm and $r_0 \simeq 1$ fm.

But no gravity, so neutrons can evaporate from surface. Slow if $T \simeq 1$ eV (near IR)

Outlook

Outlook

- Very clear overlap of interests between nuclear physics and astrophysics + gravity wave physics.
- NP Mega-Science Vision program is closely aligned with the astrophysics of the near future.