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# Probing extreme matter physics with gravitational waves

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# GW: new messengers from violent collisions in the Universe

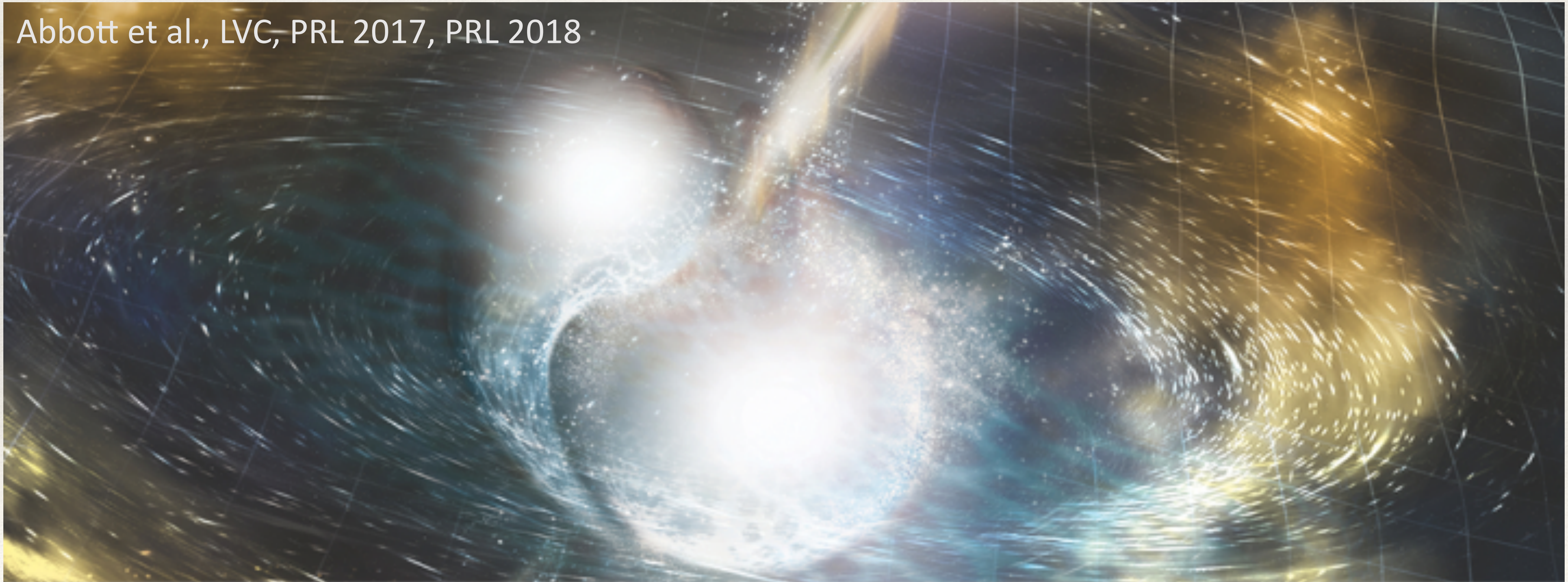
2015: first detection of GW from BBH (O1).

2017: first detection of GW from BNS (O2).

2019: first detection of GW from BHNS (O3).

→

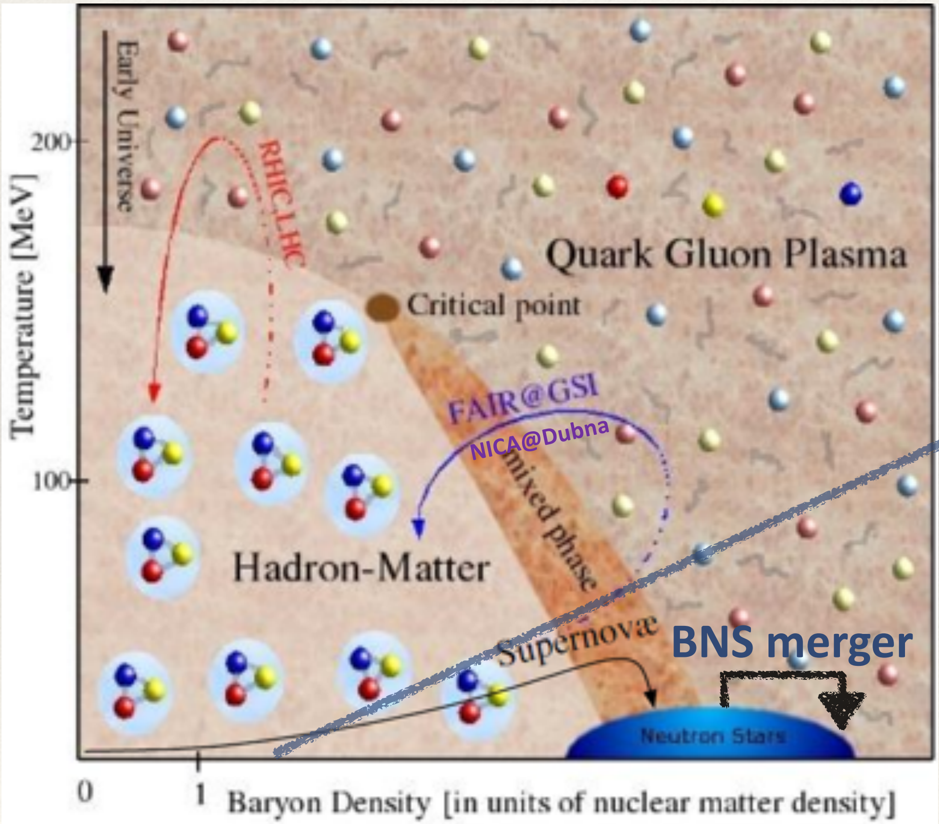
gravity and cosmology,
dark matter and dark energy,
dense matter.




*Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet*

# Probing extreme matter physics with GW

**Main questions:** How changes the **nuclear interaction** with density, isospin asymmetry, temperature?
Which **new particles** appear at supra-saturation densities (phase transition)?
Links between **deconfinement** and **chiral symmetry** restoration?

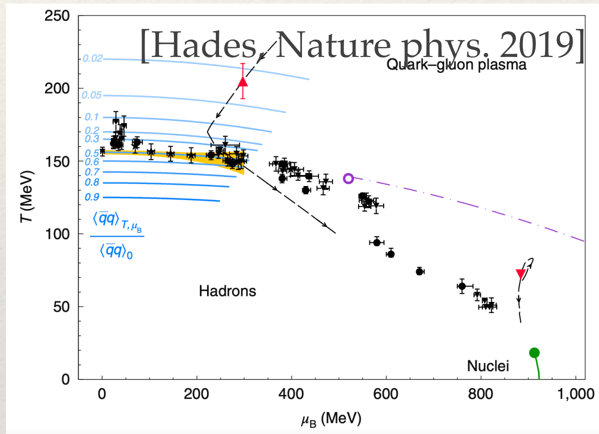



Particle and nuclear accelerators

Astrophysical observations

*Neutron stars, supernovae, kilonovae…*

**Heavy Ion collision**




Cf hadron session:
Talks by Marlene Nahrgang, Julien Serreau, …

**Probe limits of extreme matter**

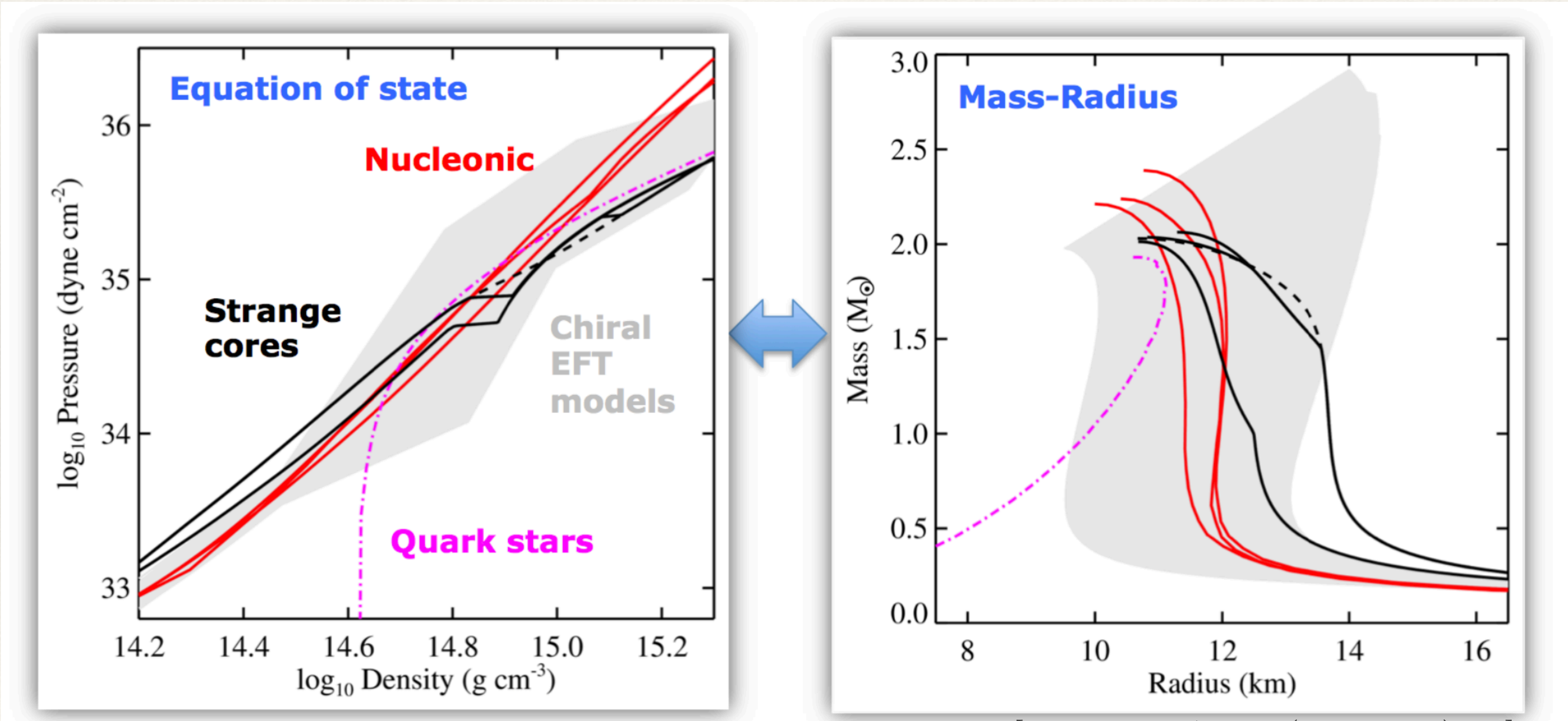
**Directly related questions:** How **neutrinos** propagate? What are the **transport properties** of extreme matter?
Are BNS the main astrophysical site for the **r-process**?

Cf talks by J. Guillet, M. Oertel, M. Urban, A. Fantina

# EoS [nuclear] <=> NS (M,R) [astro]

**Tolmann-Oppenheimer-Volkov (TOV) GR equations**

P(n) (M,R)($n_c$)

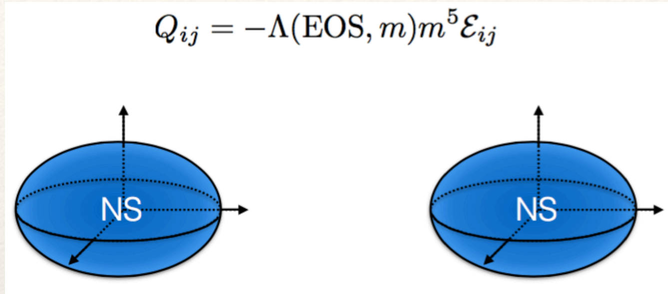



[A. Watts et al., PoD (AASKA 14) 043]

Reverse engineering,
Bayesian statistics

# EoS [nuclear] <=> BNS GW [astro]

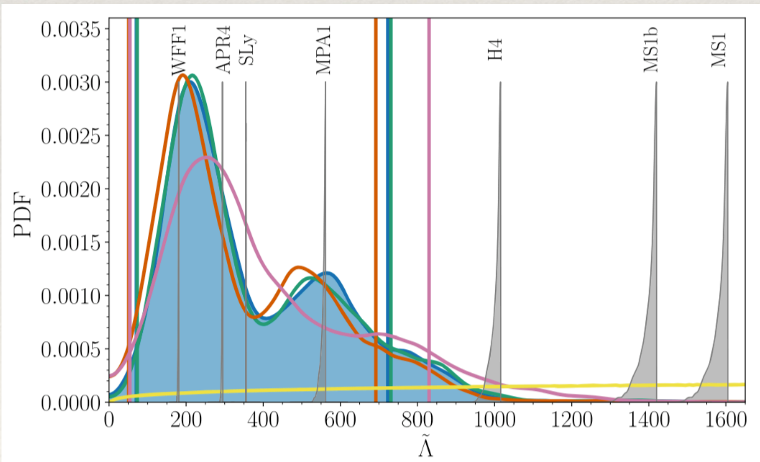
- Tidal field $E_{ij}$ from companion star induces a quadrupole moment $Q_{ij}$ in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability $\Lambda$.



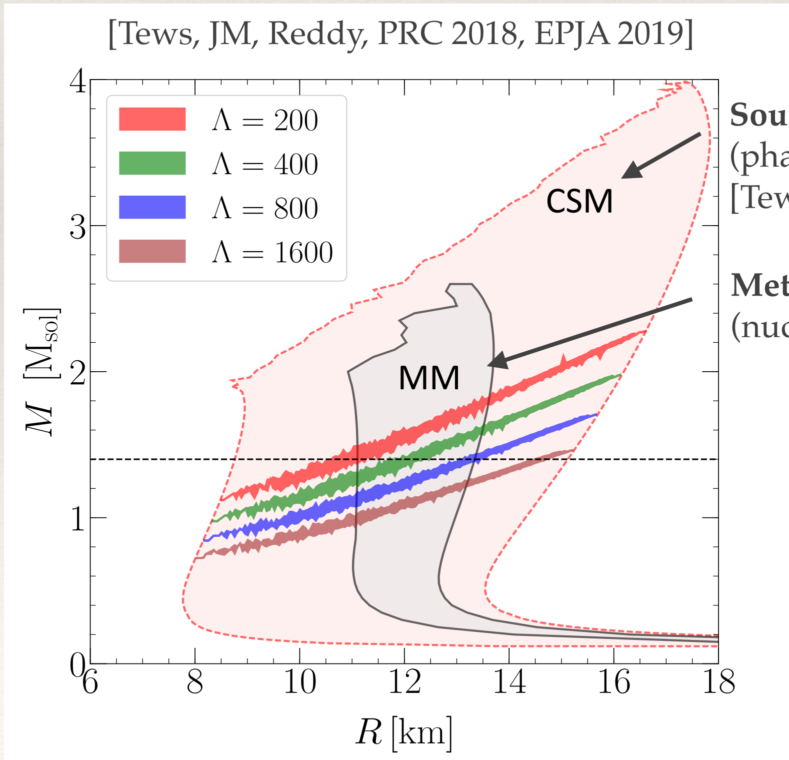

Post-Newtonian expansion of the waveform: Tidal effect enters at 5th order.

Hinderer+ 2008, Blanchet, Damour

LVC, Phys. Rev. X 9, 011001 (2019)



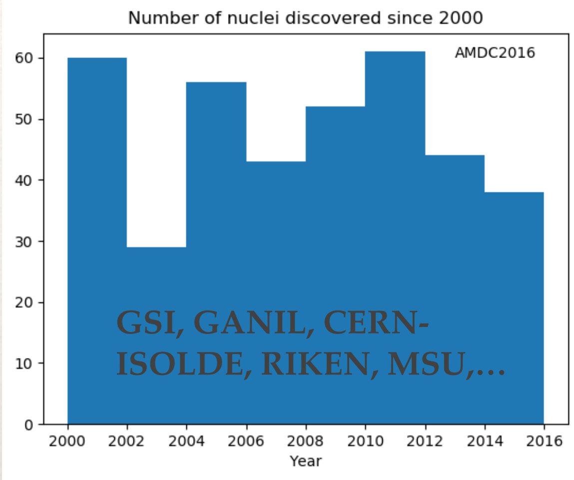

**GW170817**
**→ 70 ≤ Λ ≤ 720 (90% CL)**
**→ +E-M 300 ≤ Λ ≤ 800**

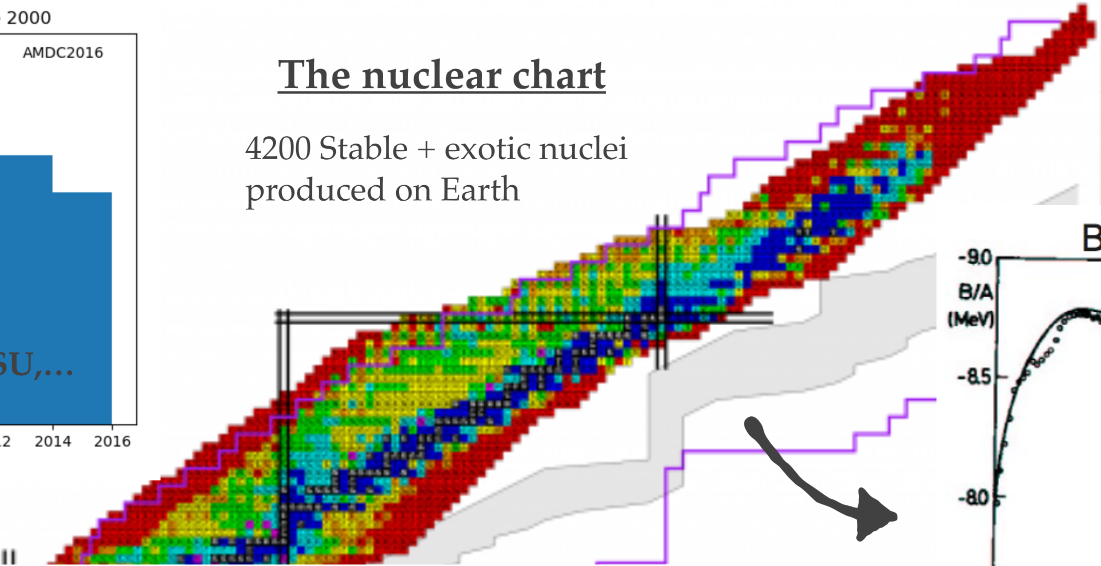


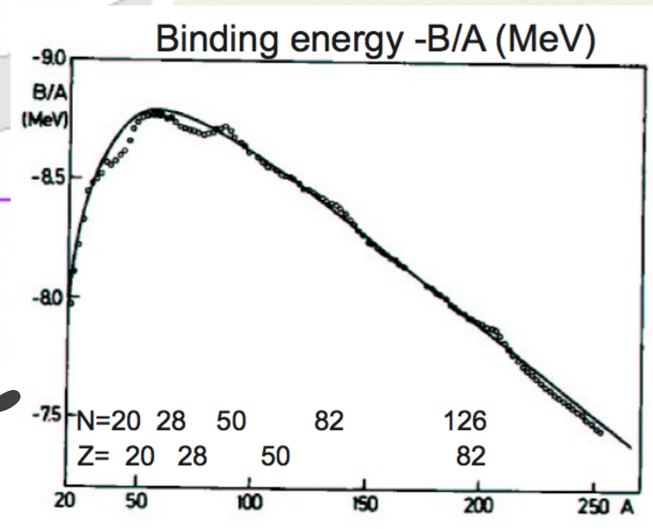

**Sound-speed Model** (phases transitions) [Tews+ 2018]

**Meta-Model** (nucleonic)

# Predictions governed by nuclear physics knowledge



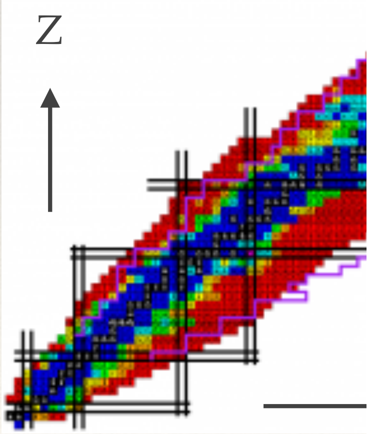



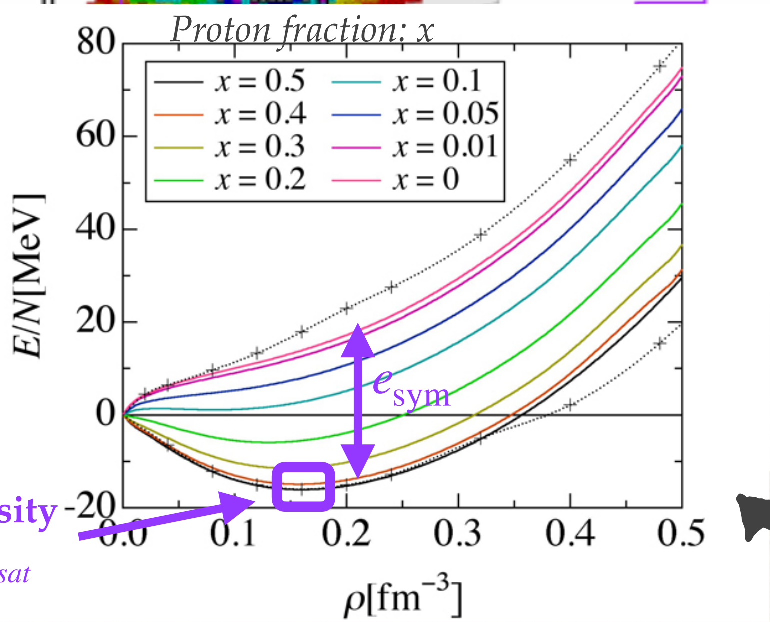




Empirical Bethe-Weizsäcker mass formula

$$E_{tot} = E_{bulk} + E_{sym} I^2 + E_{surf} + E_{Coul.} Z^2$$

Equation of state of uniform matter



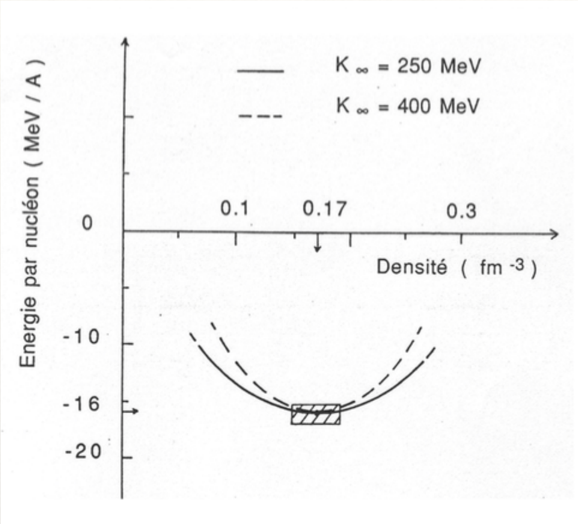




**Saturation density** $n_{sat}$ **& energy** $E_{sat}$

**Complemented by EDF, chiral EFT, etc…**

# Nuclear physics: contraints from the collective breathing mode

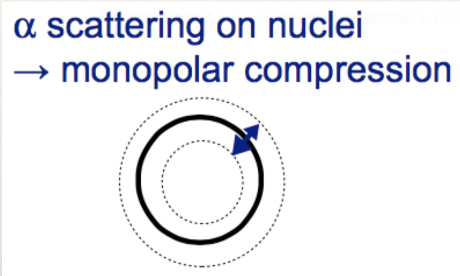
**Density dependence of the energy around $n_{sat}$**




Compressible liquid-drop: $B(\rho) \approx B(\rho_0) + \frac{1}{2} K_\infty \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2$

**Incompressibility**

**How is incompressibility measured?**




**Measured in different nuclei**

Extracted

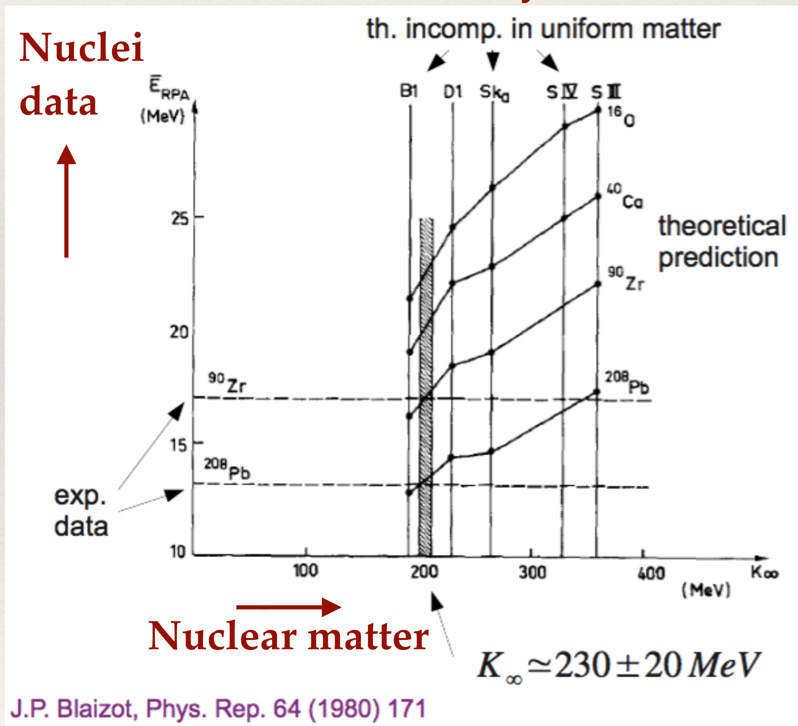
vibration frequency: $\hbar\omega = \hbar \sqrt{\frac{K_A}{m r_0^2}} A^{-1/3}$

$$K_A = K_\infty + K_s A^{-1/3} + K_{sym} \left( \frac{N-Z}{N+Z} \right)^2 + K_{coul} \frac{Z^2}{A^{4/3}}$$

Uniform matter

Finite size effects

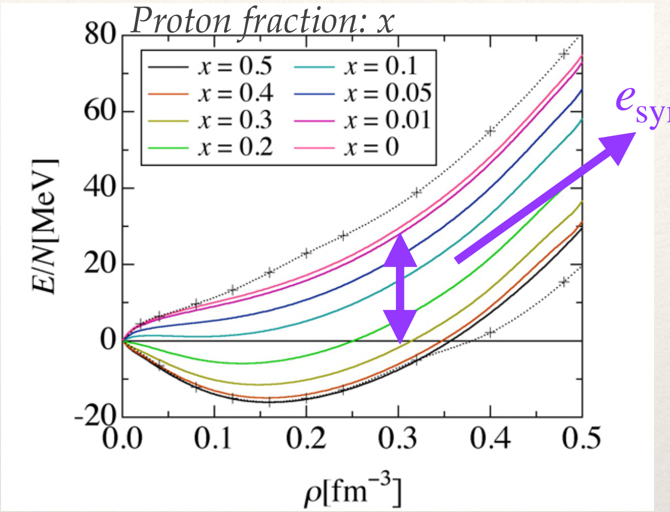
**Correlation analysis**




**Model dependence?**

[Khan, JM, Vidaña PRL 2012]

# Nuclear physics: isovector channel (towards neutron stars)




**Symmetry energy**

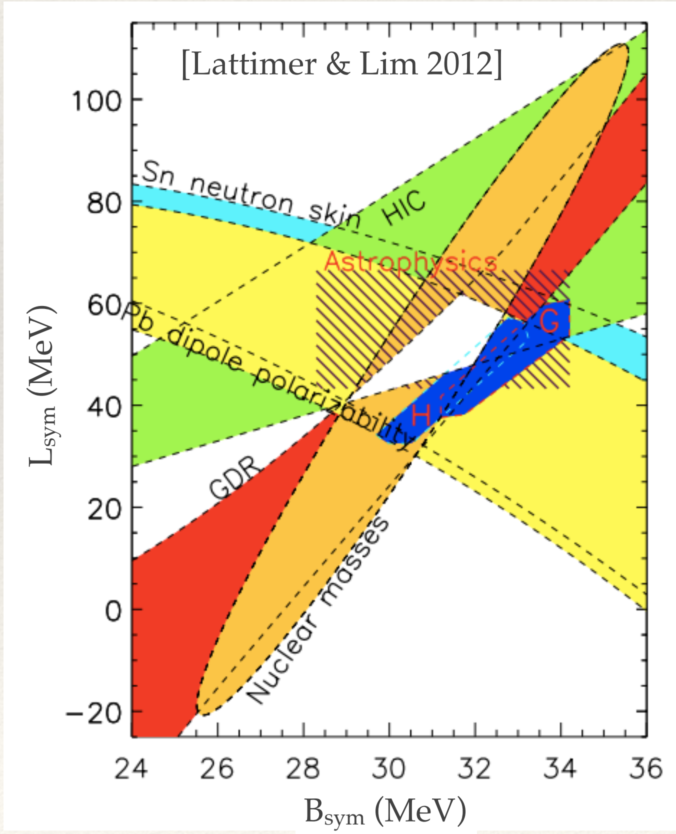
$$E_{sym} = \frac{\partial^2 E/A}{\partial I^2} \approx \frac{E}{A}(I=1) - \frac{E}{A}(I=0)$$

Difference between PNM and SNM

[Ex: Somasundaram+ PRC 2021]

Major impact on the **beta equilibrium** in neutron stars

$$\mu_e = \mu_n - \mu_p = 4(1-2x)e_{sym}(n)$$




**Empirical Bethe-Weizsäcker mass formula:**

$$B(N,Z) = B_v A - B_s A^{2/3} - \frac{1}{2} B_{sym} \left(\frac{N-Z}{N+Z}\right)^2 - \frac{3}{5} B_{Coul} \frac{e^2}{r_0} \frac{Z}{A^{1/3}} + 12\,\delta(A,Z) A^{-1/3}$$

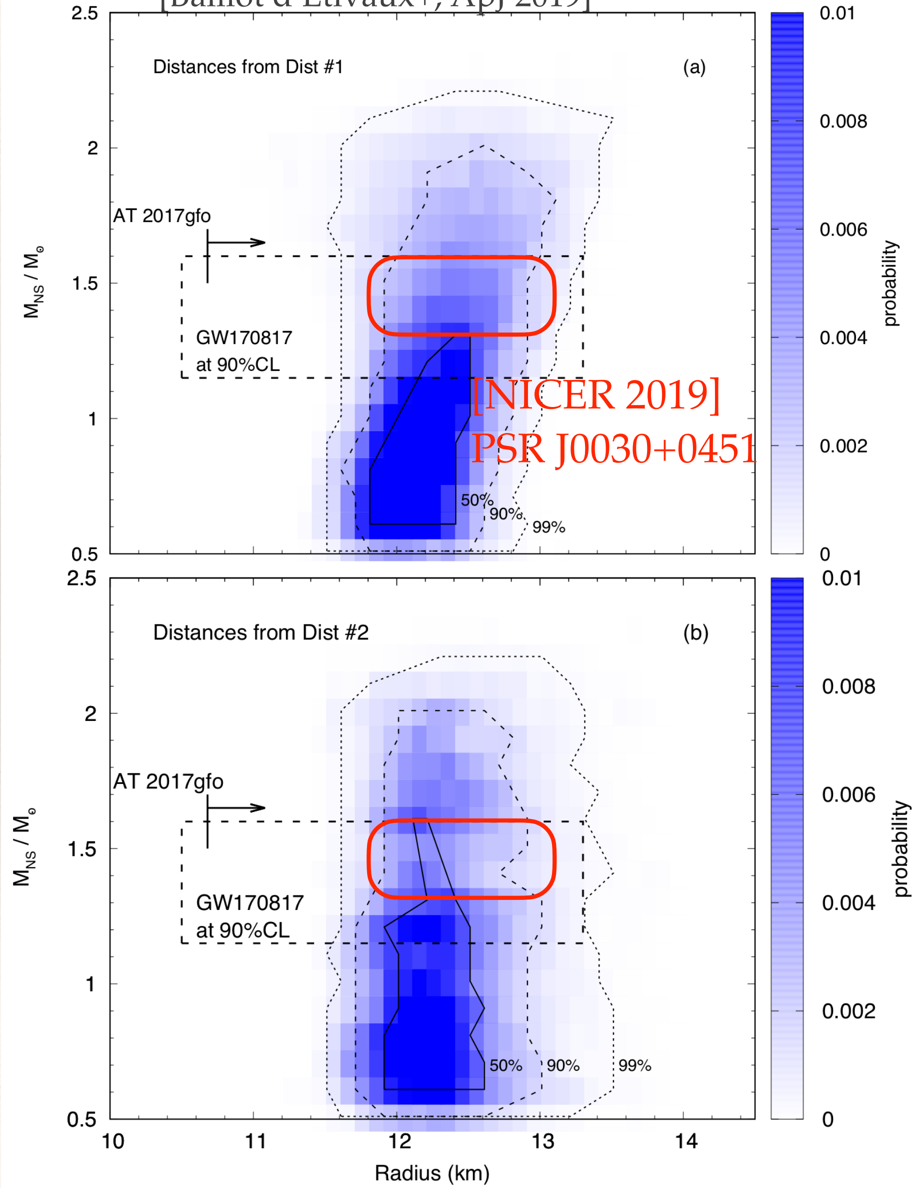
**Slope of the symmetry energy (density dependence):**

$$L_{sym} = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}$$

# Astrophysical observations: qLMXB thermal emission

**quiescent Low Mass X-ray binaries**

[Baillot d'Étivaux+, ApJ 2019]







Black body like emission: F # $T^4(R_{inf}/D)^2$

—> Bayesian analysis considering 7 sources in globular clusters, where the EoS is directly injected into the data analysis (first time).
**Average radii** (12-13km) preferred.

—> The comparison with other approaches (GW170817, AT2017gfo) provides a consistent understanding of the data.

—> But more recent GW170817 analyses prefer **lower radii**:

- $R_{1.4} = 11^{+0.9}_{-0.6}$ km [Capano, Tews+ nature 2020]
- $R_{1.4} \approx 11$ km [Güven+ PRC 2020]

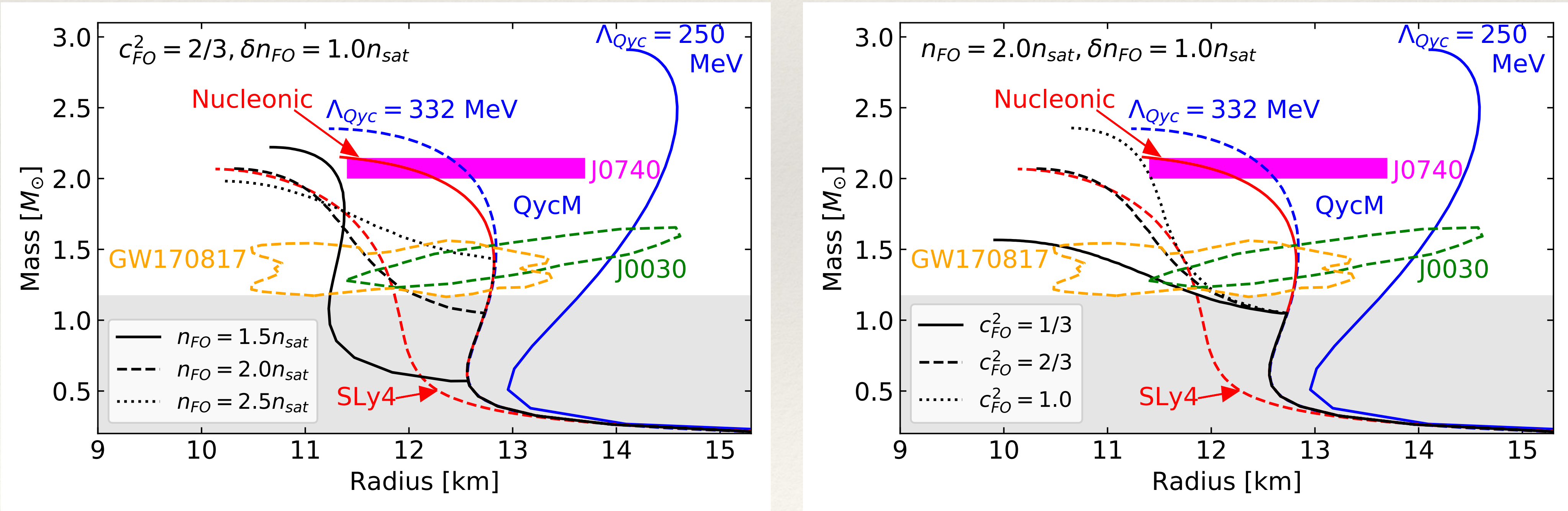
# Astrophysical observations: NICER X-ray observations of J0030 (2019) and J0740 (2021)


Confront different EoS modelings:

- SLy4 (often used in GW papers).
- First order phase transition to exotic matter.
- Quarkyonic matter (cross-over transition to quark matter).

Against data:
GW170817 and NICER (J0030 + J0740).

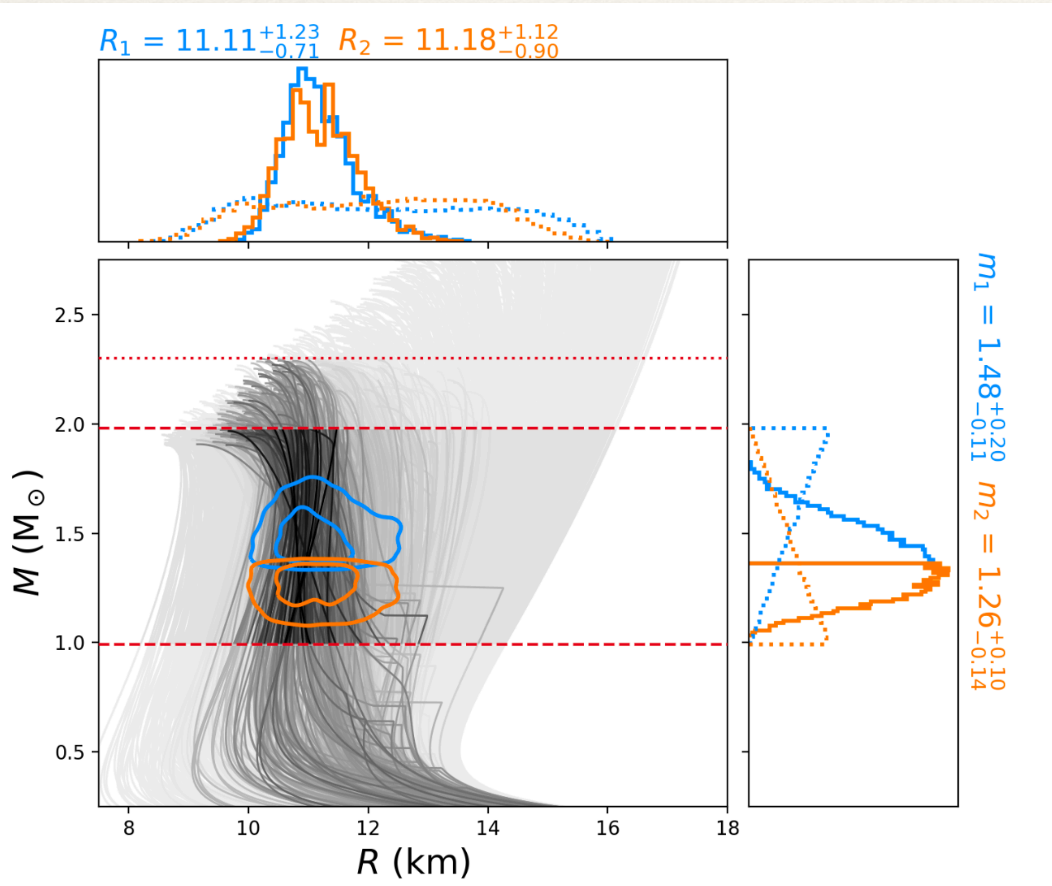
[Somasundaram+, arXiv 2021]



# Multi-messenger/physics constraints on NS radii

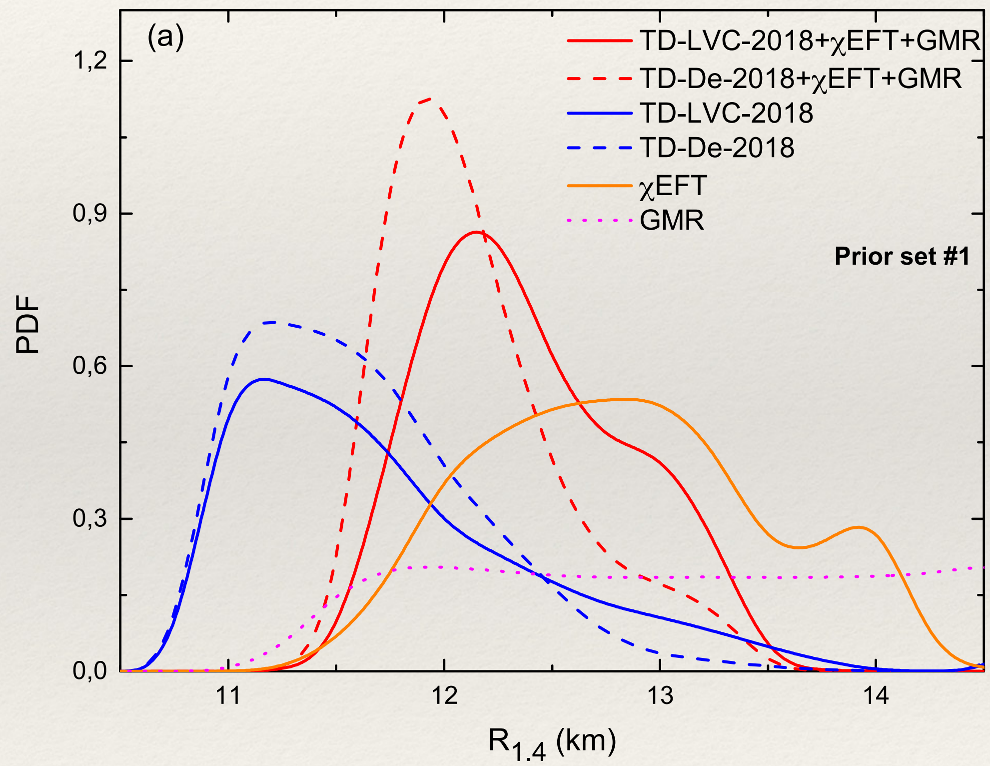
Direct comparison of the GW waveforms to the raw data, with EoS modeling + $M_{total} \leq M_{thresh}(\approx 2.3 M\odot)$.

[Capano, Tews + Nature 2020]




Bayesian analysis of $\Lambda$−pdf confronted to nuclear physics knowledge (xEFT, GMR).

[Güven+ PRC 2020]




—> **Low NS radii** also seems to be preferred by GW + multi messenger analyses.

# Global strategy: multi-messenger and multi-physics

**Nuclear experiments** ↔ **Theory for dense matter** ↔ **Global astrophysical modeling** ↔ **Observational facilities**

**Nuclear experiments**

**CERN** (*LHC, NA60, …*) **GANIL**, **GSI** (*FAIR*), **DUBNA** (*NICA*), etc…

**Theory for dense matter**

**Equation of state** (*ComPOSE*), **Neutrino diffusion**, **Transport coefficients**.

**Global astrophysical modeling**

**Neutron stars** (*Lorene library, meta-model*), **BH & NS mergers** (*Einstein toolkit, Whisky-THC, Spritz, …*), **Kilonova**, **Supernova** (*COCONUT*), **Galactic chemical evolution.**

**Observational facilities**

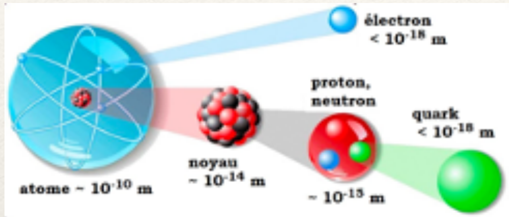
**GW** (*LIGO-Virgo*), **GRB** (*FERMI-LAT, XMM Newton*), **E-M** (*GRANDMA, ZTF, …*).

**Improved understanding of extreme matter physics** ↔ **Cross-fertilisation** ↔ **Improved understanding of astrophysical objects**

**Strongly interdisciplinary research:**
IN2P3: #nuclear, #hadron, # particle, #astro-particle
+ INP + INSU + CEA.

Simulation is the key to confront dense matter physics with observations.
See talk by J. Guilet.

# Probing extreme matter physics with GW




+ multi-messenger

Nuclear matter

Quark matter

→ Compact stars → Mergers GW

↓

Cosmic chemical evolution

**This is truly the physics of two infinities**

**Multi-messenger observation**: BNS GW + kilonovae EM signal + GRB (+ neutrinos?).
**Variety of GW sources:** BNS, BH-NS, CCSN, continuous emission, etc…
**(Futur) post-merger GW signal:** investigation of phase transitions.

**Blooming future: upgrades and new telescopes (lots of new data):**
GW interferometers: upgrades of LIGO-Virgo (KAGRA, LIGO India).
E-M follow-up: GRANDMA, ZTF → (future) LSST.
3rd generation (~2030-2040): Cosmic Explorer, Einstein Telescope.
Space interferometer (LISA ~2035): low frequencies (trigger future mergers).