Étoiles à neutrons, supernovae et synthèse des éléments lourds

Anthea F. Fantina & Jérôme Novak
(GANIL, Observatoire astronomique de Strasbourg)

Assemblée Générale GdR Ondes Gravitationnelles, 13-14 October 2025

Neutron stars, full equilibrium ($T = 0$)

Cold ("T=0") mature NSs, NSs in inspiral phase before merger

- To relate astro observations and extract info on NS properties → TOV/ODE → EoS ***P(ρ)***
  - **unified, consistent (and as microscopic as possible) description of NS matter**
  - **reverse engineering?** but: precision of measurements vs sensitivity?

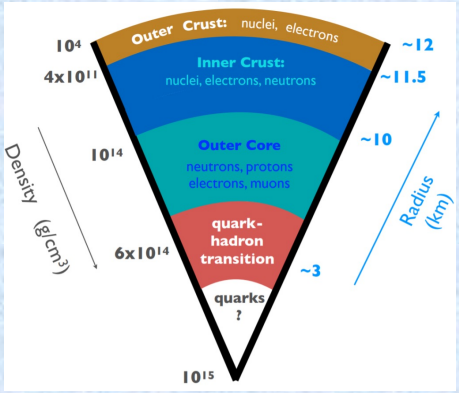
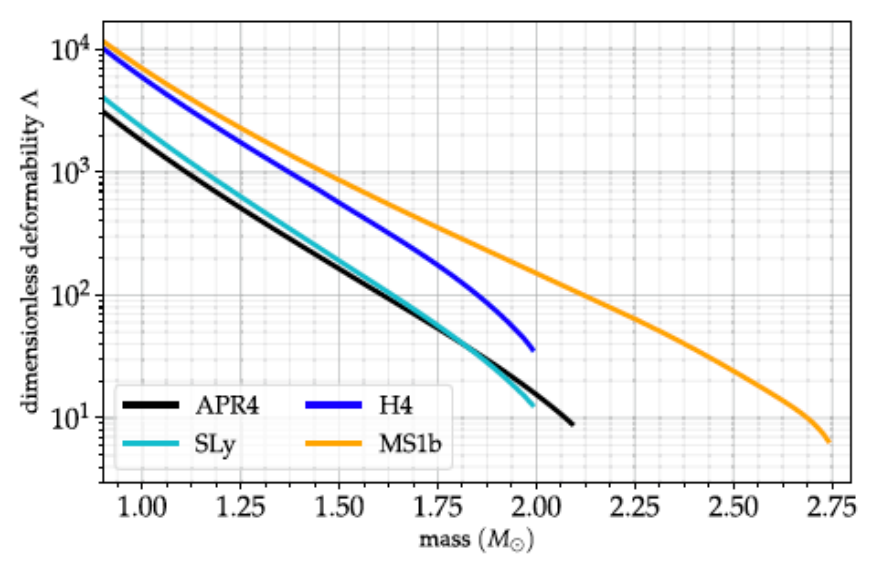
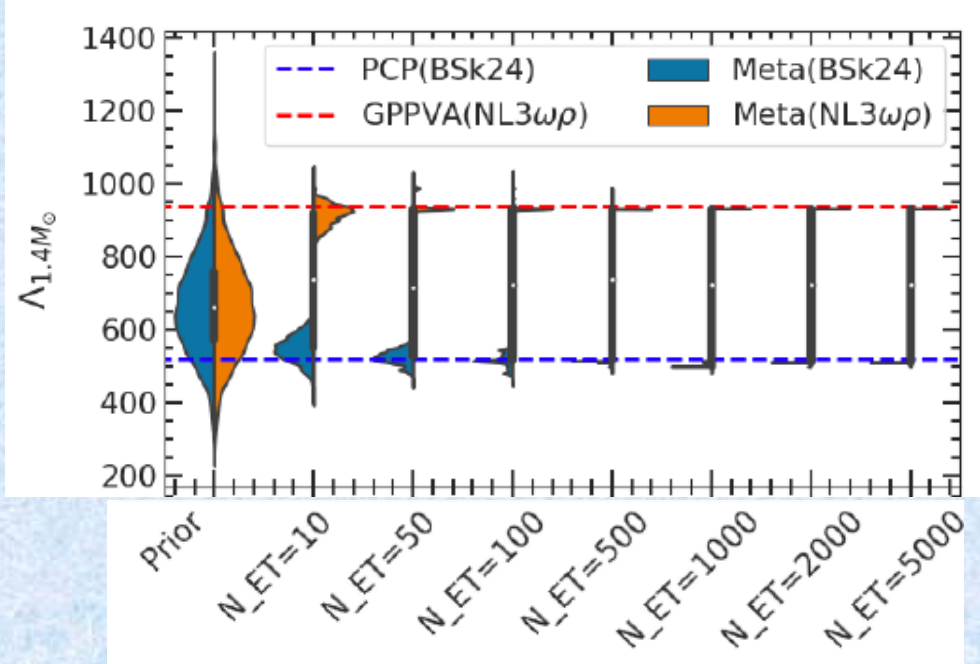


Image Credit: 3G Science White Paper



Dietrich et al., Gen. Rel. Gravit. 53, 27 (2021)



Iacovelli et al., PRD 2023 (also Mondal et al., MNRAS 2023; ET collab., arXiv:2503.12263)

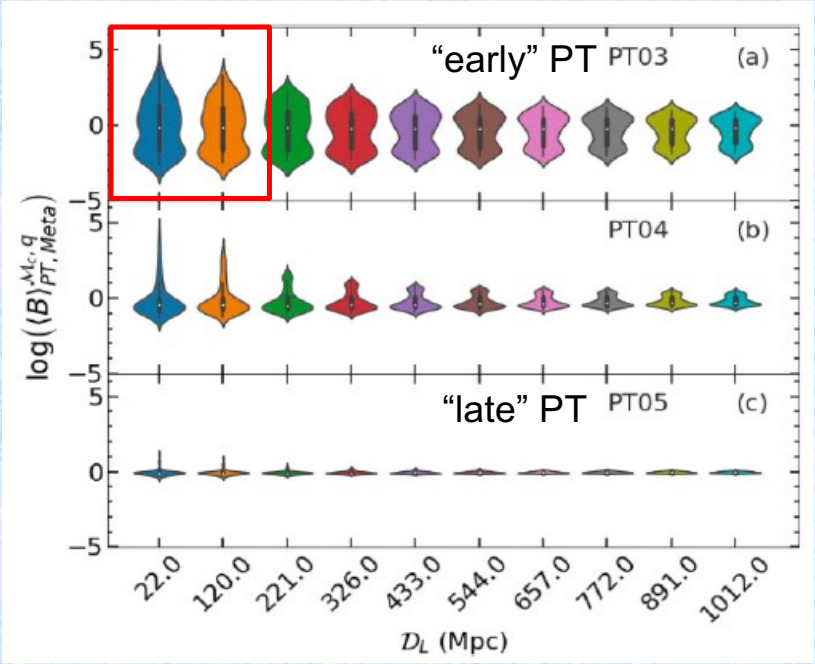
see talks by N. Chamel and G. Montefusco on microphysics, by L. Suleiman on inference

LPC Caen, GANIL, Obs. astronomique Strasbourg, IP2I Lyon, …

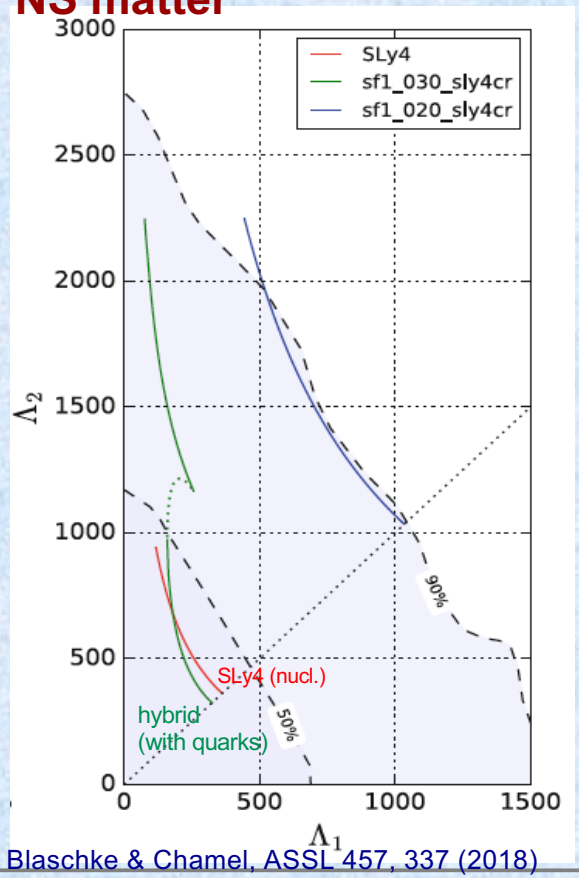
Neutron stars, full equilibrium ($T = 0$)

Cold ("T=0") mature NSs, NSs in inspiral phase before merger

- To relate astro observations and extract info on NS properties → TOV/ODE → EoS ***P(ρ)***
  - **unified, consistent (and as microscopic as possible) description of NS matter**
  - **reverse engineering?** but: precision of measurements vs sensitivity?
  - **identification of phase transition (PT)?** but: "masquerade effect"!



Mondal et al., MNRAS 524, 3464 (2023)



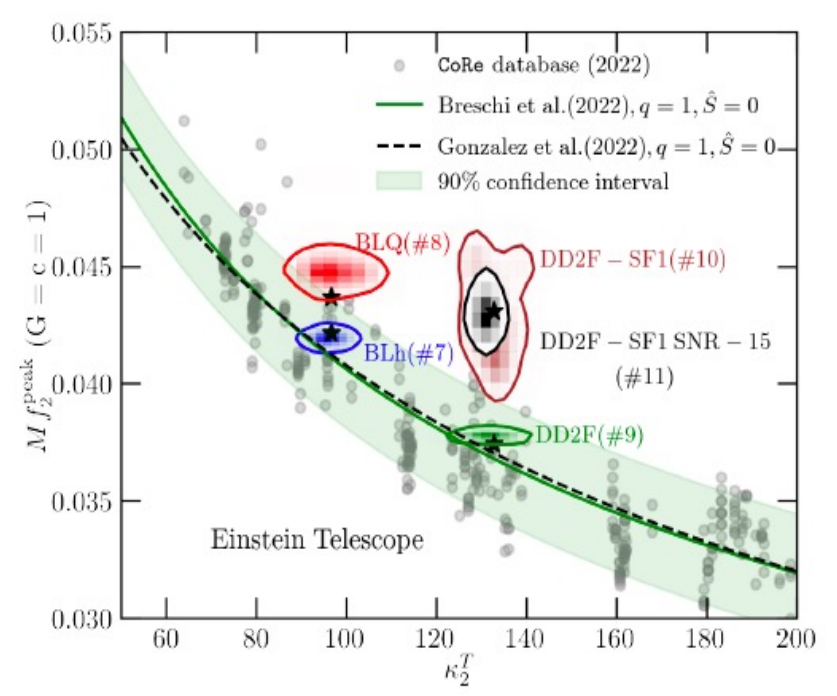
Blaschke & Chamel, ASSL 457, 337 (2018)

see talks by N. Chamel and G. Montefusco on microphysics, by L. Suleiman on inference

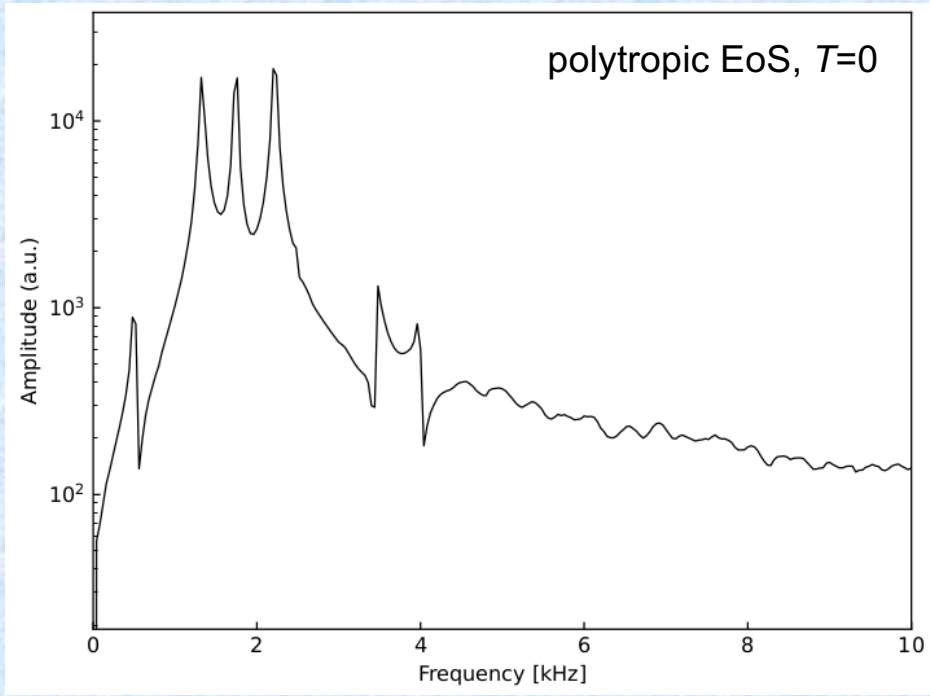
Neutron stars, out-of-equilibrium $T > 0$

NSs after merger

- Simulations of post-merger → hydro + micro → EoS $P(\rho, T, Y_e)$
  - **EoS $P(\rho, T, Y_e)$ out-of-equilibrium (+ rates) → identification of phase transition?** but: strong PT!
  - **hydrodynamic modelling (including rotation, oscillation, etc.)**, but: computation time vs systematics?



Prakash et al., PRD 109, 103008 (2024)



courtesy of S. Jaraba & J. Novak

see talk by S. Jaraba

Supernovae, out-of-equilibrium $T > 0$

Core-collapse + explosion mechanism

- Core-collapse → hydro + micro → EoS ***P(ρ,T,Y$_e$)*** + electron capture (EC) + neutrinos
  - **consistent EoS + EC rates**
  - **hydrodynamic modelling (including rotation, etc.) + ν transport (+ ν oscillations?)**

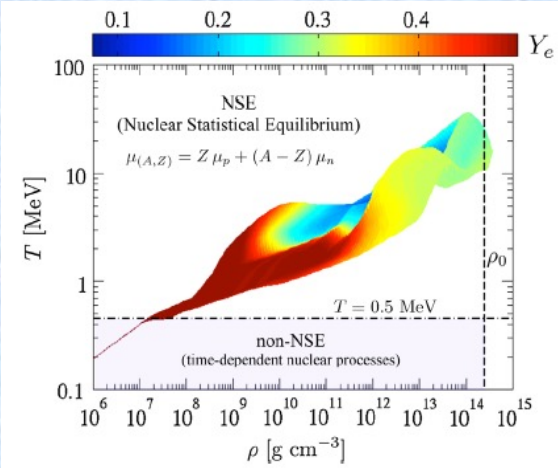
    but: computation time vs accuracy vs systematics?

- Post-bounce + explosion → hydro + micro
  - **EoS P(ρ,*T*,*Y*$_e$) + phase transitions?**
  - **multi-D hydro (including rotation, instability, B, etc.)**,

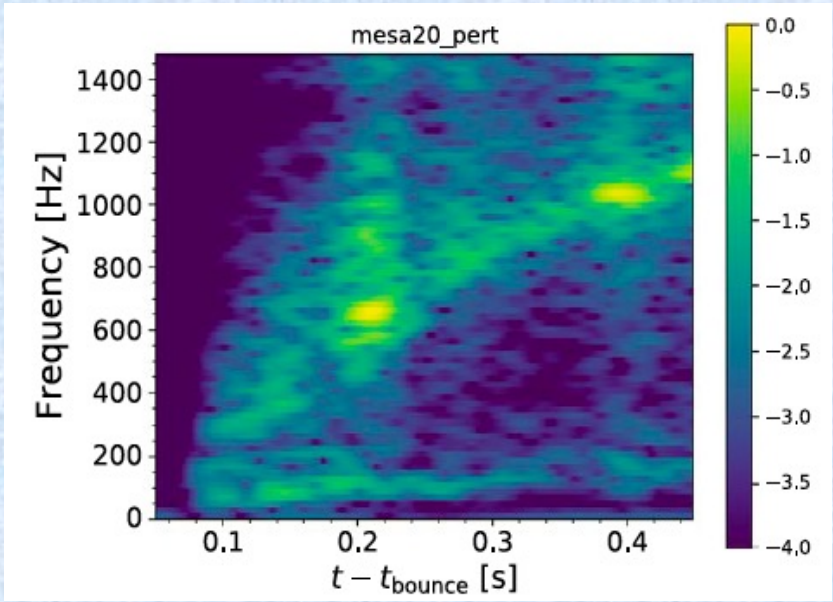
    but: computation time vs systematics? disentangle effects?

- GW emission
  - **explosion mechanism, role of instabilities?**

    but: computation time vs systematics? Use of ML?



Oertel et al., Rev. Mod. Phys. 89, 015007 (2017)



O'Connor & Couch, ApJ 865, 81 (2018)

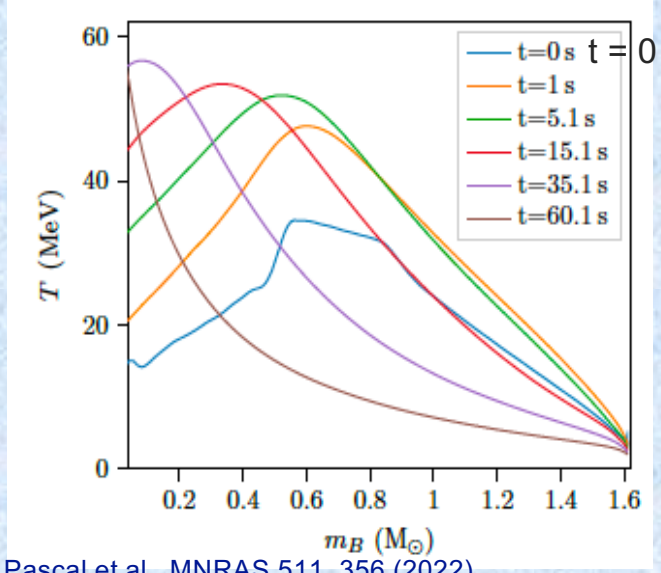
see talk by M. Bugli

Proto-neutron stars

PNS cooling + NS/magnetar formation

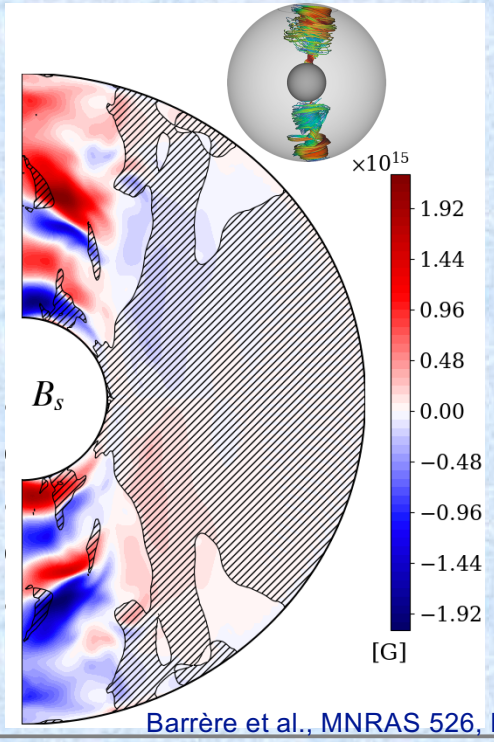
- PNS modelling: formation and cooling → EoS $P(\rho, T, Y_e)$
  - **consistent EoS $P(\rho, T, Y_e)$ (out-of-equilibrium)**
  - **different timescales (μs→ms→mins) + multi-D hydro modelling + ν treatment**
  - **magnetar formation (role of B, rotation, dynamo?)**

- GW emission
  - anisotropic mass ejection and neutrino emission → LISA frequency ?



t = 0 → 500ms after bounce

Pascal et al., MNRAS 511, 356 (2022)

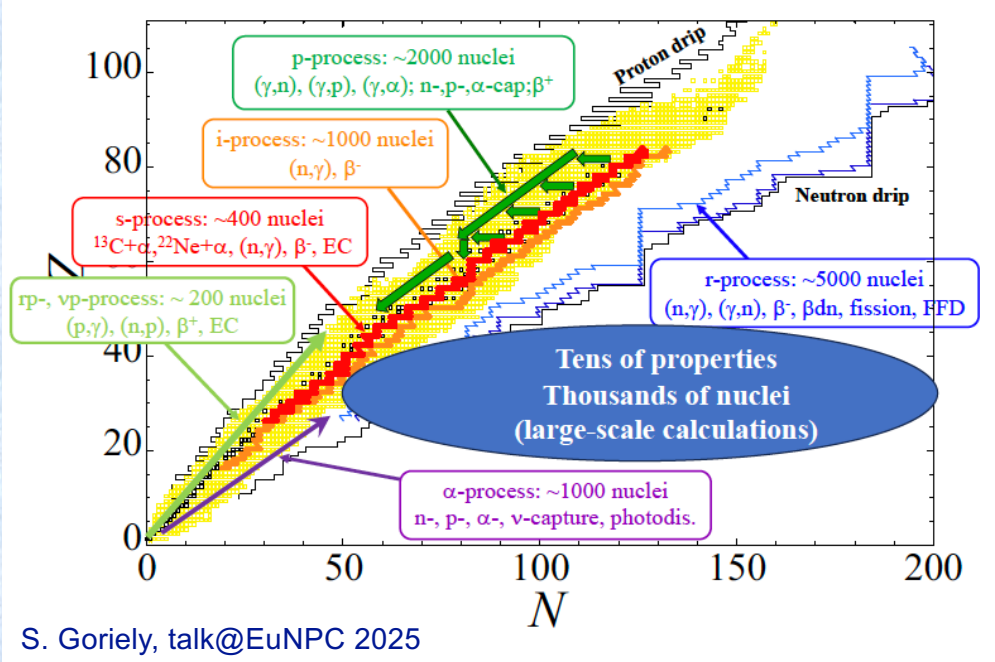


Barrère et al., MNRAS 526, L88 (2023)

Nucleosynthesis

SN + NS mergers (r process)

- No nucleosynthesis calculations in France → collaboration with Belgium (ULB) – IAP, Garching, …
- Reaction-network calculations
  - **multiple nuclear physics inputs (nuclear masses, fission, EC/β decay, etc.)**



S. Goriely, talk@EuNPC 2025

- In France: nuc.-phys. experiments → reactions / cross sections (GANIL, LP2I Bordeaux, IJCLab, SUBATECH, …)
  + theory → nuclear structure, fission, n-capture rates, … (CEA-DAM, IPHC Strasbourg, …)