



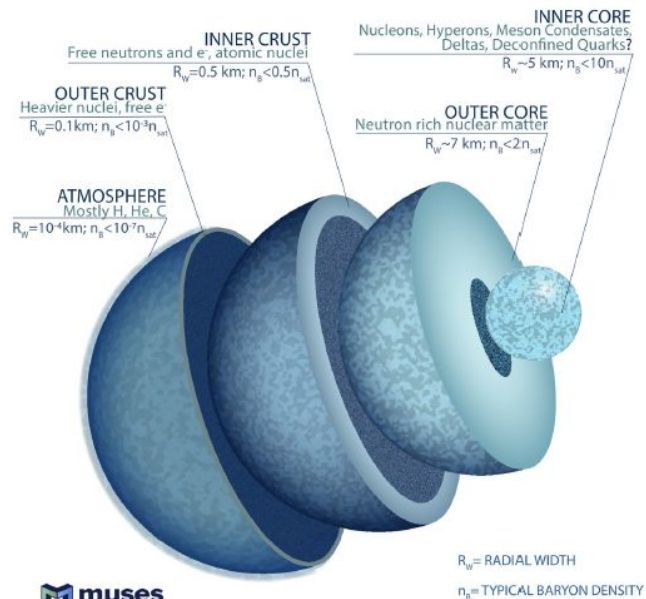
Étoiles à neutrons, supernovae et synthèse des éléments lourds

Anthea F. Fantina, Matteo Bugli, Sébastien Guillot
(GANIL, CEA-AIM, IRAP)

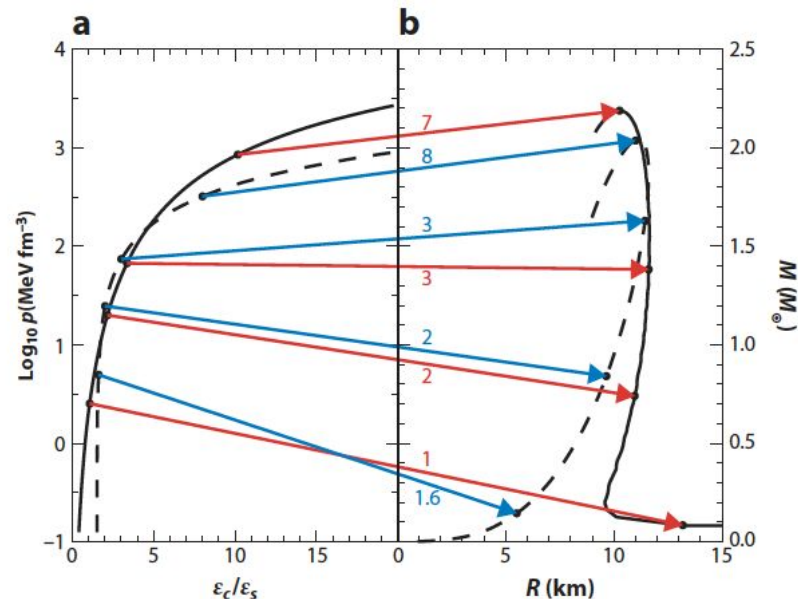
Neutron stars, full equilibrium ($T = 0$) (1)

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

- To relate astro observations and extract info on NS properties $\rightarrow$ TOV/ODE $\rightarrow$ EoS $P(n)$
 - unified, consistent (and as microscopic as possible) description of NS matter**
e.g. CompOSE database of EoSs (<https://compose.obspm.fr/>), CUTER code (Davis et al., A&A 2024; EPJA 2025)



Kumar et al., Liv. Rev. Rel. 27, 3 (2024)



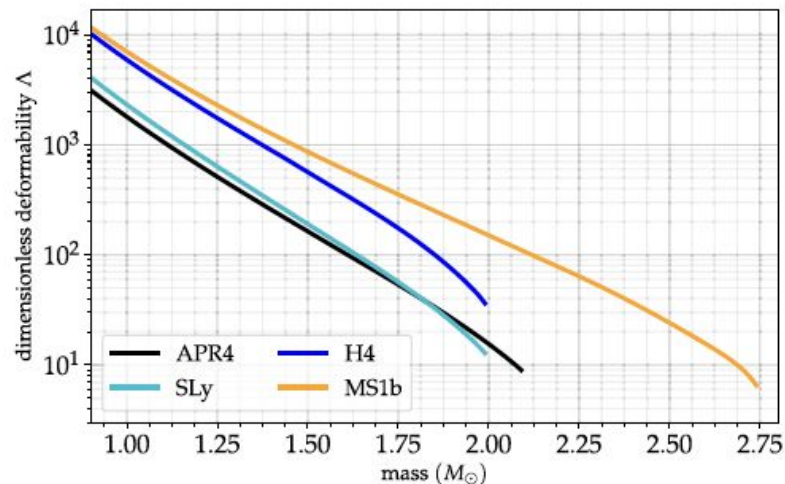
Lattimer, ARPNS 62, 485 (2012)

LPC Caen, GANIL, ObAS, IP2I Lyon, ...

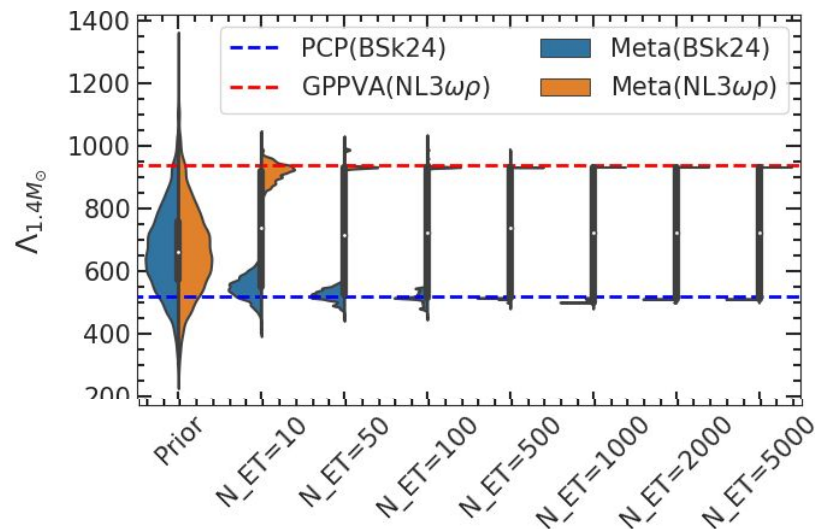
Neutron stars, full equilibrium ($T = 0$) (2)

Cold (“ $T=0$ ”) mature NSs, NSs in inspiral phase before merger

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



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

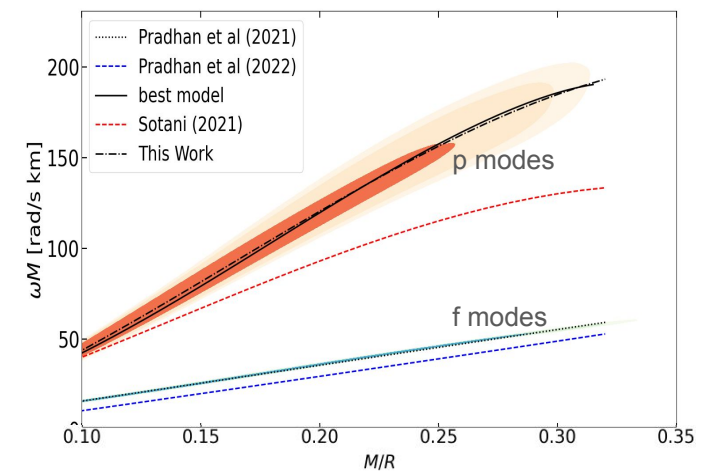


Iacovelli et al., PRD 2023 (also Abac et al., arXiv:2503.12263)

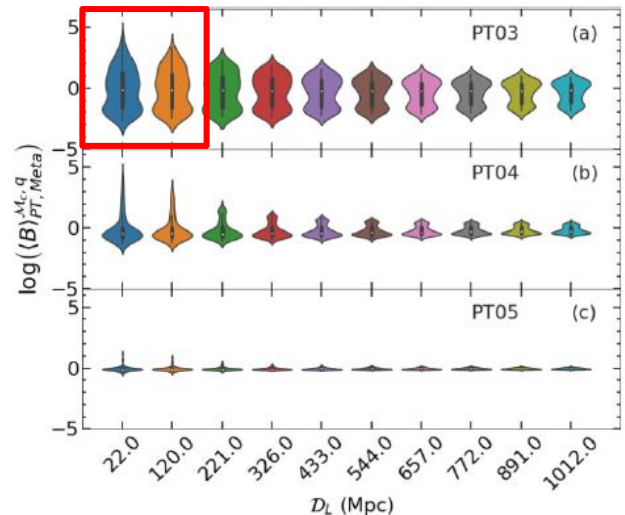
Neutron stars, full equilibrium ($T = 0$) (3)

Cold (“ $T=0$ ”) mature NSs, NSs in inspiral phase before merger

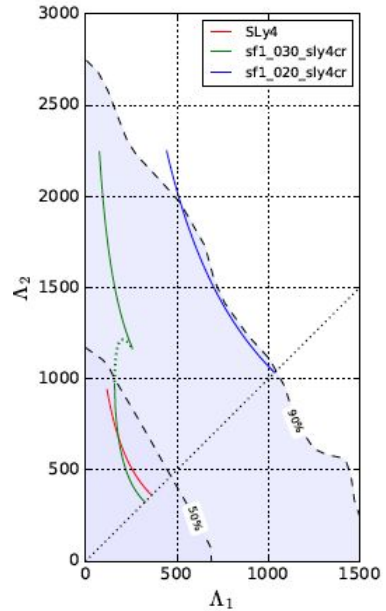
- To relate astro observations and extract info on NS properties $\rightarrow$ TOV/ODE $\rightarrow$ EoS $\mathbf{P(n)}$
 - **unified, consistent (and as microscopic as possible) description of NS matter**
 - **reverse engineering?** but: precision of measurements vs sensitivity?
 - **identification of phase transition (PT)?** but: “masquerade” effect!



Montefusco et al., A&A 694, A150 (2025)



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



Blaschke&Chamel, ASSL 457, 337 (2018)

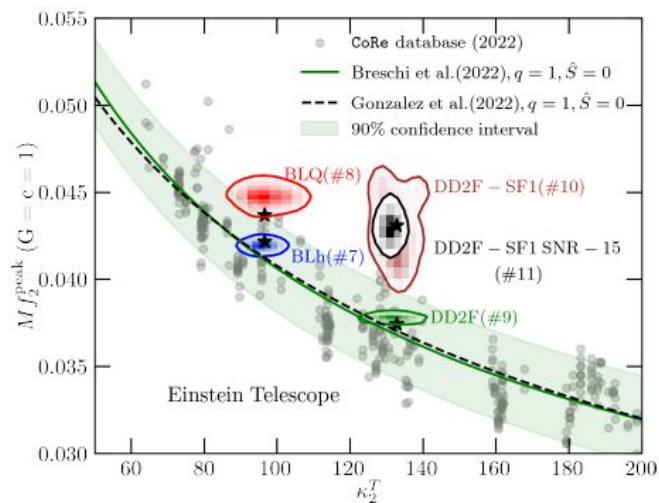
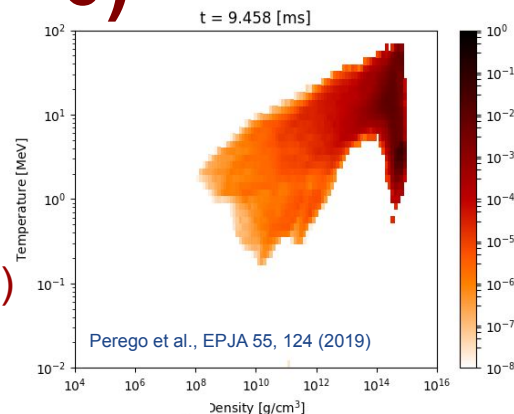
LPC Caen, GANIL, ObAS, IP2I Lyon, ...

see talk by L. Suleiman

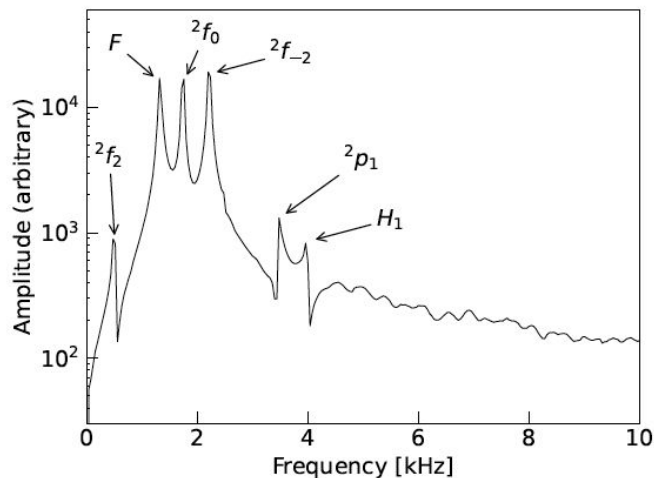
Neutron stars, out-of-equilibrium ($T > 0$)

NSs after merger

- Simulation of post-merger $\rightarrow$ hydro + micro
 - **EoS $P(n, T, Y_q)$ out-of-equilibrium (+ rates)**
 $\rightarrow$ **identification of PT?** but: **strong PT!**
 - **hydrodynamic modelling (including rotation, oscillation, ...)**
but: **computation time vs systematics?**



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



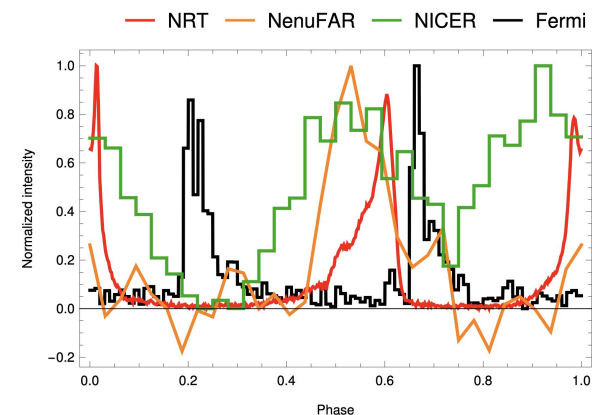
Jaraba et al., A&A 708, A133 (2026)

LPC Caen, GANIL, ObAS, IP2I Lyon, ...

Neutron stars, modelling and observations

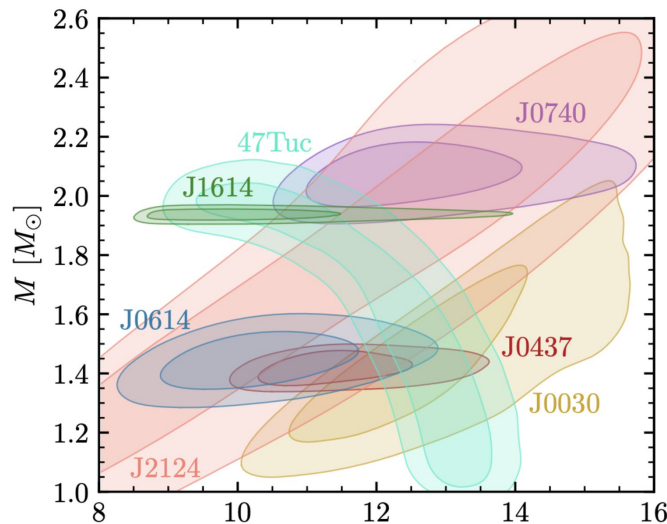
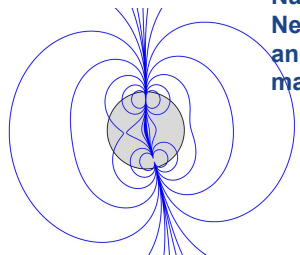
Magnetosphere, emission mechanisms, and macroscopic properties

- Link the astrophysical observations to the magnetosphere and to the interior properties
 - **Pulsars emitting in the radio, X-rays and gamma-rays**
 - **Measurements of NS M and R with NICER, other telescopes, and in the future**



Combining observations from Nançay Radio Telescope, NenuFAR (at Nançay), NICER and Fermi, to understand the magnetosphere of pulsars.

Pétri et al. 2025

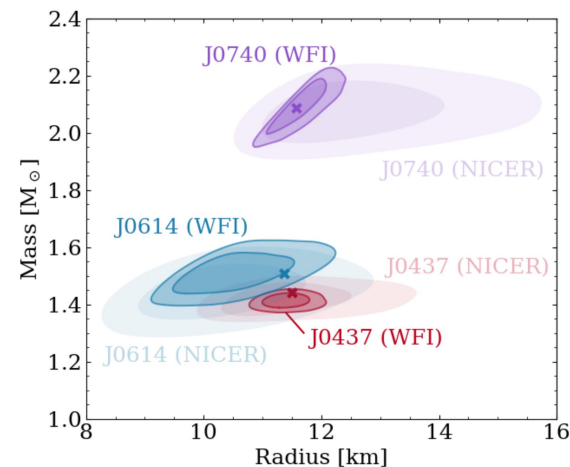


Latest M-R results R [km]

J1614: Mauviard et al. 2026,

47Tuc: Kazantsev et al. 2025,

J2124: Gonzalez-Caniulef et al. 2026



Comparing NICER and NewAthena-WFI

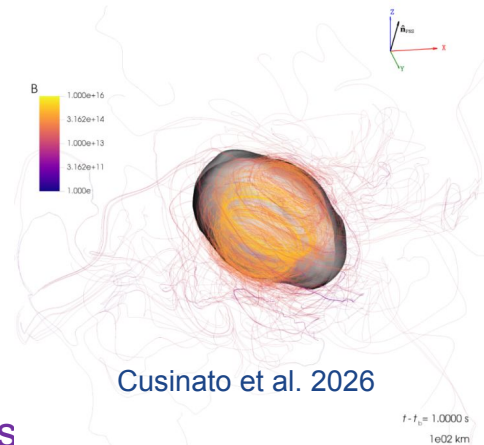
Guillot et al., in prep. (preliminary)

ObAS, IRAP, LPC2E, APC, LAB, ...

Supernovae, out-of-equilibrium ($T > 0$) (1)

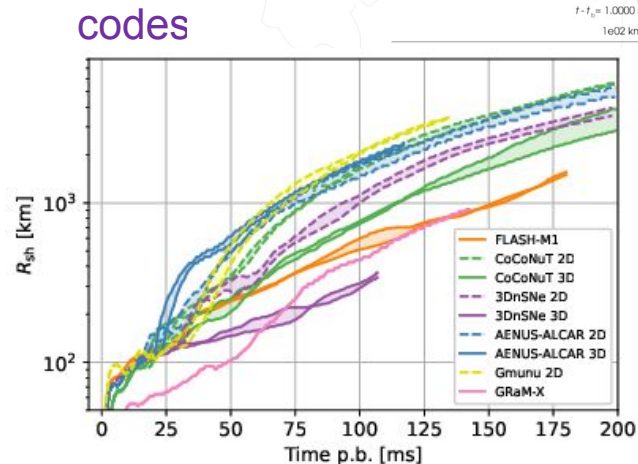
Core-collapse + explosion mechanism

- (G)R + (magneto)hydro + micro $\rightarrow$ EoS $P(n, T, Y_q)$ + neutrinos
 - (magneto)hydrodynamic modelling (progenitor, rotation, B)
 - Neutrino transport + neutrino rates (+ oscillations?)
 - High-density EoS $\rightarrow$ quantitative impact on dynamics
- but: high computation time (3D) + large parameter space



- Tensions between different hydrodynamic codes (e.g. explodability, final energies, remnant properties...)

- Code Comparison on Extreme CCSN (e.g. long GRB)
 - Same initial conditions, different codes/numerics
 - Qualitative agreement between all major groups
- but: significant deviations + numerical systematics



Bugli et al., in prep.

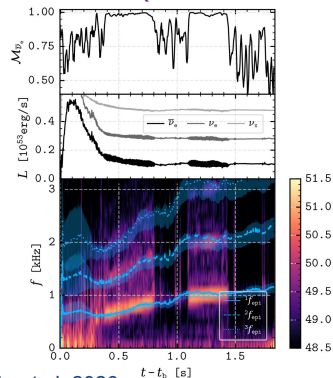
Supernovae, out-of-equilibrium ($T > 0$) (2)

Multi-messenger signals

- GW emission

- Direct probe for explosion mechanism, instabilities, and EoS (e.g. SASI, low $T/|W|$, resonances)
- Polarization analysis (detection, rotation, asymmetries...)
- GW from neutrinos (anisotropic emission) → (0.1-10) Hz → LISA/DECIGO frequencies

but: large parameter space + incomplete parameter estimations (use of LLMs?)



Cusinato et al. 2026

- Neutrino light-curves and spectra

- Correlated signals + complementary LoS
- Role of fast flavor oscillations?

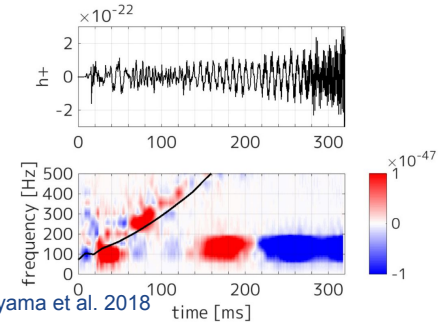
but: post-processing vs. subgrid models

$$T_{\text{SASI}} = 19\text{ms} \left(\frac{r_{\text{sh}}}{100\text{km}} \right)^{\frac{3}{2}} \log \left(\frac{r_{\text{sh}}}{r_{\text{ns}}} \right)$$

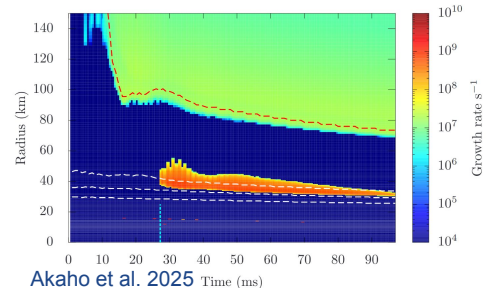
Müller & Janka+14

$$\frac{T_{\text{SASI}}^0}{10.42\text{ms}} \equiv \frac{\left(\frac{r_{\text{sh}}}{100\text{km}} \right)^{\frac{3}{2}} \left(\frac{1.7M_{\odot}}{M_{\text{ns}}} \right)^{\frac{1}{2}} \log \left(\frac{r_{\text{sh}}}{r_{\text{v}}} \right)}{0.56773 + 0.28628R_1 - 0.031763R_1^2}$$

Foglizzo 2024



Hayama et al. 2018

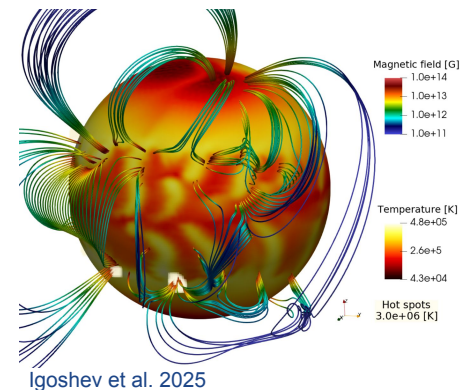
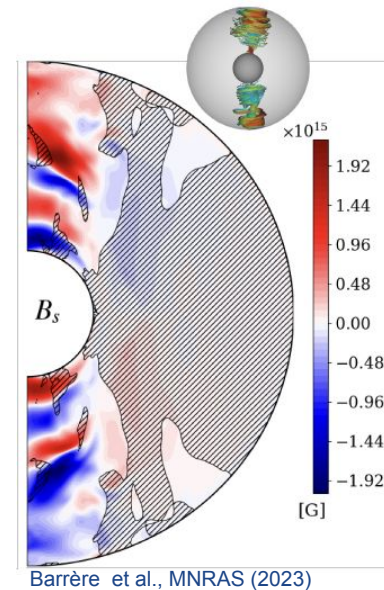


Akaho et al. 2025

Proto-neutron stars

PNS cooling + NS/magnetar formation

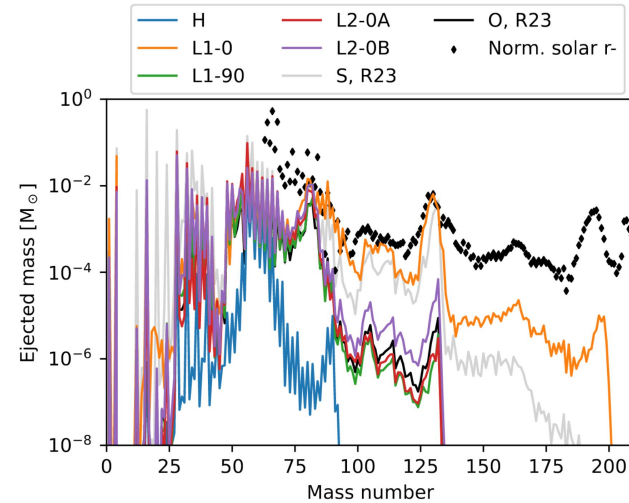
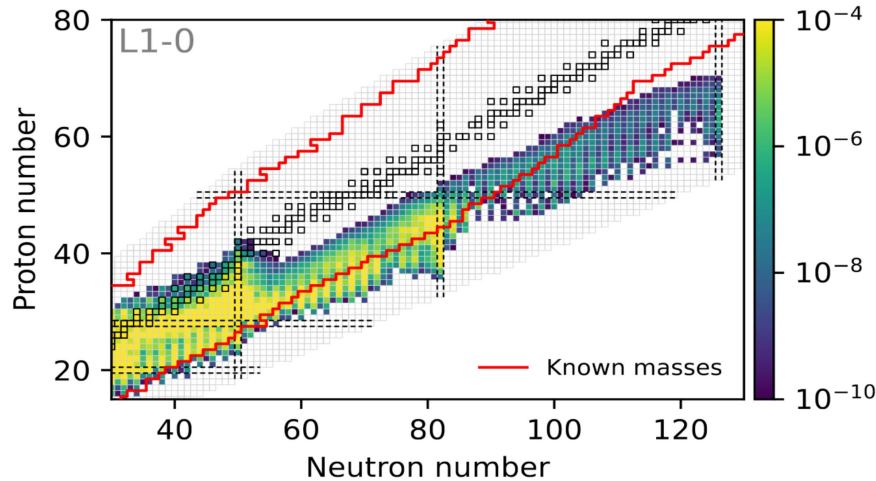
- PNS modelling: formation and cooling
 - **consistent EoS $P(r, T, Y_e)$ (out-of-equilibrium)**
 - **different timescales + multi-D hydro modelling + ν treatment**
 - **magnetar formation (role of B, rotation, dynamo)**
but: complex global modeling (dynamo+collapse)
- GW emission (convection)
 - **Signatures of dynamo action and inertial modes**
 - **Scaling relations with PNS rotation rate**
but: complex global modeling
- Late-time evolution ($\sim s \rightarrow \sim \text{Myrs}$)
 - **Long-term field relaxation $\rightarrow$ NS/Magnetar observations**
 - **Crucial step: from dynamo fields to crust formation ($\sim \text{min}$)**
but: large scale separation + large parameter space



Nucleosynthesis

SN (+ NS mergers)

- Reaction network calculations
 - multiple nuclear physics inputs (nuclear masses, fission, EC/beta decay, etc.)
 - Based on particle trajectories from dynamic simulations → nucleosynthetic yields



Reichert et al. 2024

- Nucleosynth. calcul.: collaboration with European partners (Uni. Valencia, INAF Abruzzo, ULB Belgium...) in France: nucl.-phys. exper. → reactions/cross sections ([GANIL](#), [LP2I Bordeaux](#), [IJCLab](#), [SUBATECH](#), ...) + theory → nuclear structure, fission, n-capture rates ([CEA-DAM](#), [IPHC Strasbourg](#), ...) [AIM-CEA/IRFU/DAP](#) + [IAP](#) + collaborators

Next events of our WG

❖ If you are interested, please register to our WG at:
<https://gdr gw.in2p3.fr/>

❖ **WG meeting on 17 - 18 November 2026 in Paris, please register:**
<https://indico.in2p3.fr/event/40670/>

GdR Ondes gravitationnelles: meeting of the working group "Neutron stars, supernovae and nucleosynthesis of heavy elements"

📅 17 Nov 2026, 14:00 → 18 Nov 2026, 13:00 Europe/Paris

📍 Salle du Conseil, IAP

👤 Anthea FANTINA (GANIL (CNRS\UPR3266)) , Matteo Bugli (Institut d'astrophysique de Paris - CNRS) , Sebastien Guillot (IRAP)

Description The working group "Neutron stars, supernovae and nucleosynthesis of heavy elements" (« Étoiles à neutrons, supernovas et synthèse des éléments lourds ») of the Groupement de Recherche (GdR) *Ondes Gravitationnelles* organises a meeting on the 17 (afternoon) and 18 (morning) November 2026 at Salle du Conseil of IAP (Paris). The aim is to involve a large proportion of the "astrophysics and nuclear physics" community with an interest in the detection of gravitational waves.

Contact ✉ matteo.bugli@cea.fr

Registration 🗳 Participants

📝 Register