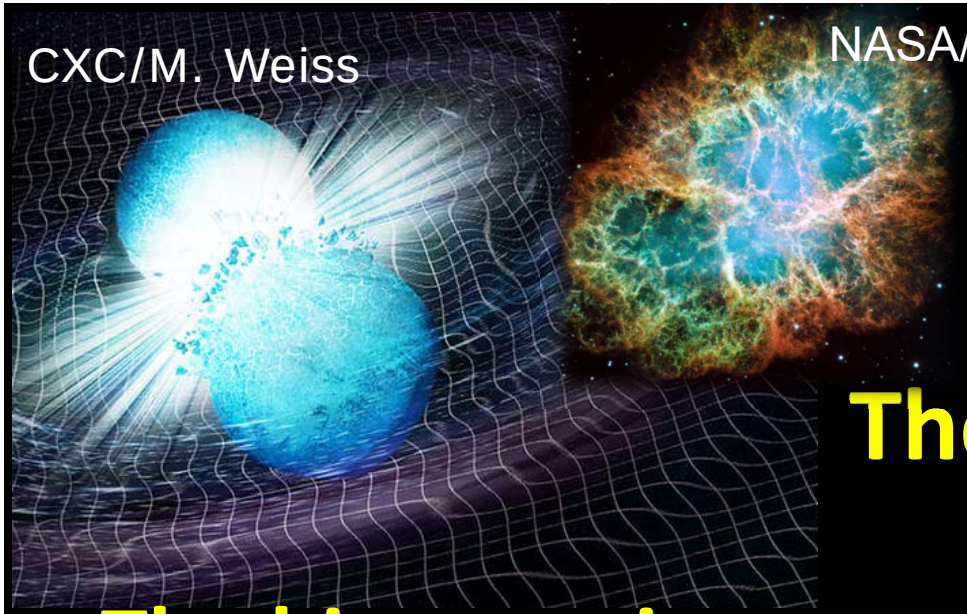
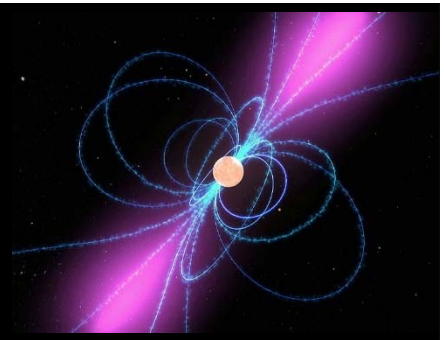
Astrophysique Nucléaire

Conseil Scientifique de l'In2p3, 29 juin 2021

F.Gulminelli, LPC Caen





The In2p3 community

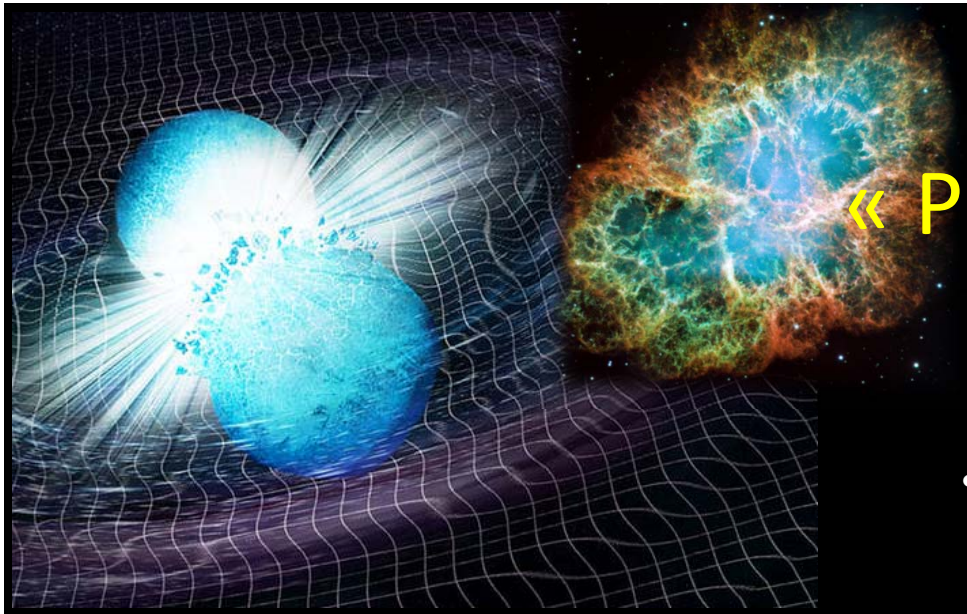
The big questions

1. **Composition of dense matter**
2. **Dynamics of compact objects**
3. **Nucleosynthesis**

In yellow, researchers with theoretical astrophysics as main research subject;
In white, researchers mainly working in other correlated subjects

- APC: F.Nitti, C.Volpe (1,2)
- CENBG: N.Smirnova (3)
- GANIL: **A.F.Fantina** (1,2)
- IP2I : D.Davesne**, J.Margueron, H.Hansen** (1,2)
- IPHC: K.Sieja (3)
- IJCLab: M.Grasso, E.Khan, **M.Urban** (1)
- LPC Caen: **F.Gulminelli** (1,2)
- LUTh : P.Grandclément, **J.Novak, M.Oertel** (1,2)
- SUBATECH: M.Nahrgang (1)

+ 6 PhD/postdocs



Atelier « Physique Théorique des deux infinis » 7-8 juin

1. **Composition of dense matter**
2. **Dynamics of compact objects**
3. **Nucleosynthesis**

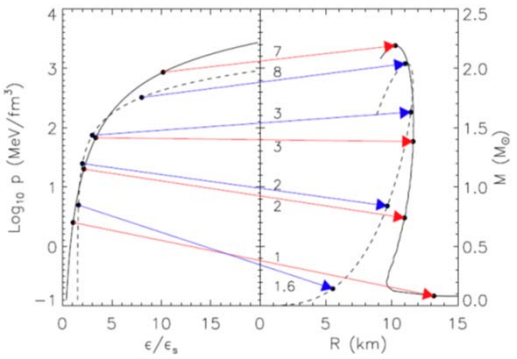
- Probing extreme matter physics with gravitational waves (J. Margueron, IP2I) **(1-2-3)**
- Supernova and compact star simulations (J. Guilet, DaP/IRFU) **(2)**
- Weak interaction rates in compact star physics (M. Oertel, LUTH) **(2-3)**
- Theoretical modeling of the neutron star crust (M. Urban, IJCLab) **(1)**
- Modelling dense matter at finite temperature in compact stars (A.F.Fantina, GANIL) **(1)**

Highlights
(2015-2020)

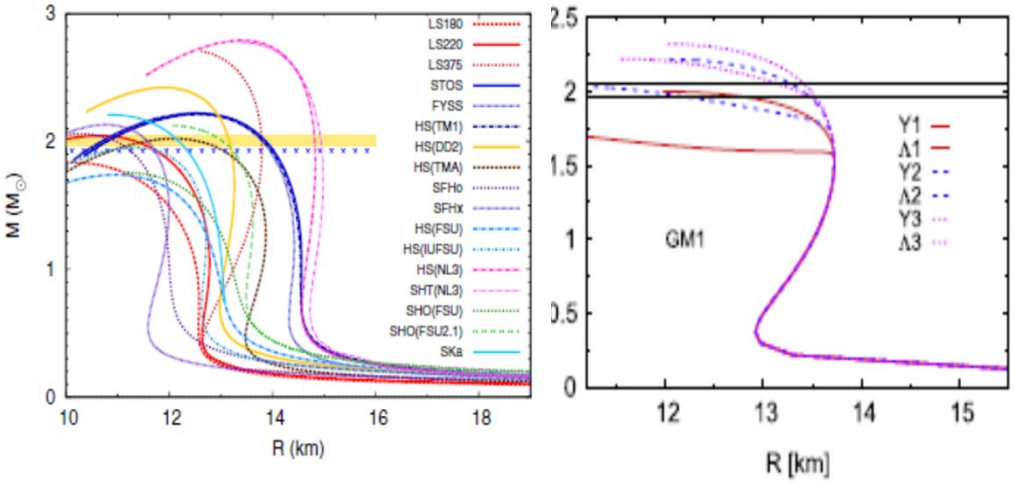
1. Static properties of neutron stars and connection to the structure of dense matter
2. Dynamics of compact stars: neutron star mergers (BNS) and core-collapse supernovae (CCSN)
3. Heavy elements nucleosynthesis: r and rp process

in parenthesis, [x] indicates the citation number on 22/6/21 (source: Google Scholar)

(1) NS(M,R,Λ) ⇔ nuclear EoS



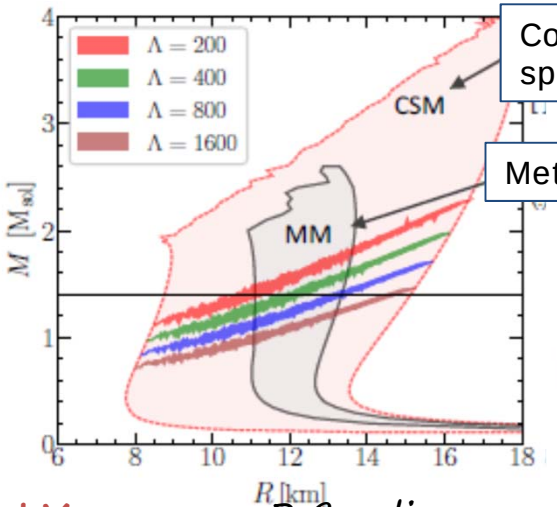
M.Oertel , M.Hempel,.. Rev.Mod.Phys.(2017) [498]



M.Oertel , C.Providencia, F.Gulminelli,.. J.Phys.G(2015) [109]

- General relativity imposes a 1-1 correspondence between the dnse matter equation of state (EoS) and the static properties of neutron stars such as
  R(M) (NICER)
  Λ(M) (VIRGO/Ligo)
  M(SKA)
- But the EoS depends on the nuclear model (couplings and composition)

(1) NS(M,R,Λ) ⇔ nuclear EoS

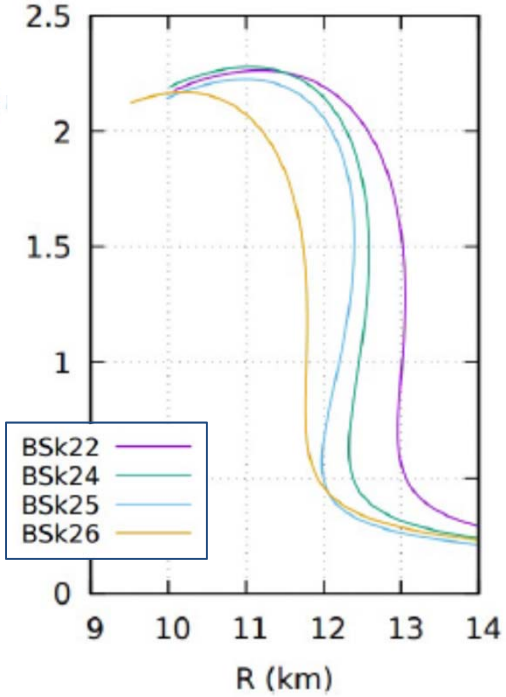


Constant sound speed model

Meta-model

J.Margueron, R.Casali, F.Gulminelli PRC(2018) [105]

I.Tews, J.Margueron, S.Reddy PRC(2018) [183] EPJA(2019) [59]



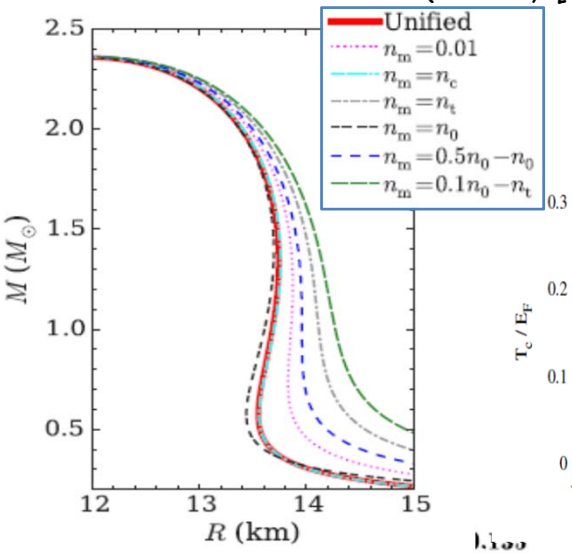
A.Potekhin, A.Fantina,... A&A (2013) [173] ; MNRAS(2018)2994 [74]

Two complementary strategies:

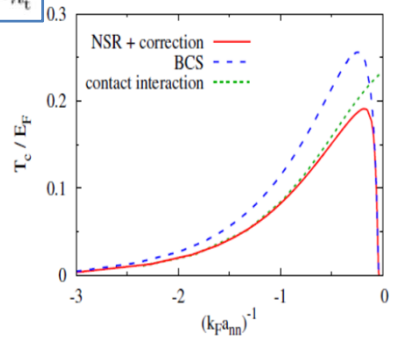
- Microscopic (HFB) functionals optimized on nuclear theory and data + analytical representations
  => predictions
- Agnostic approach (meta-model) exploring all possible forms + Bayesian inference
  => hypotheses testing , extraction of constraints

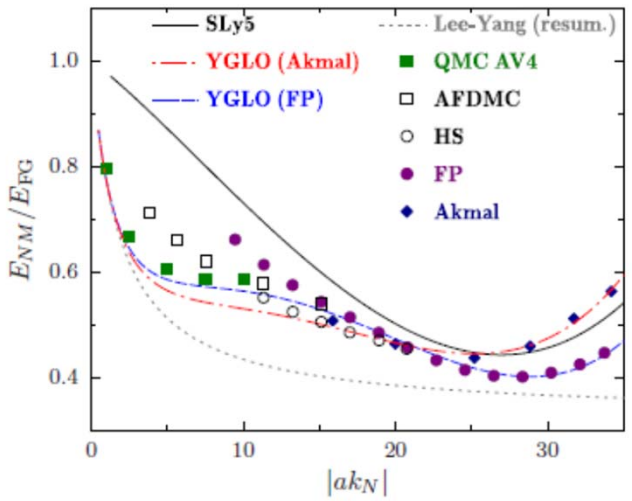
(1) NS(M,R,Λ) ⇔ nuclear EoS

.M.Fortin,... F.Gulminelli,.. PRC(2016) [177]



G.Strinati, ..., M.Urban
Phys.Rep.(2018) [136]

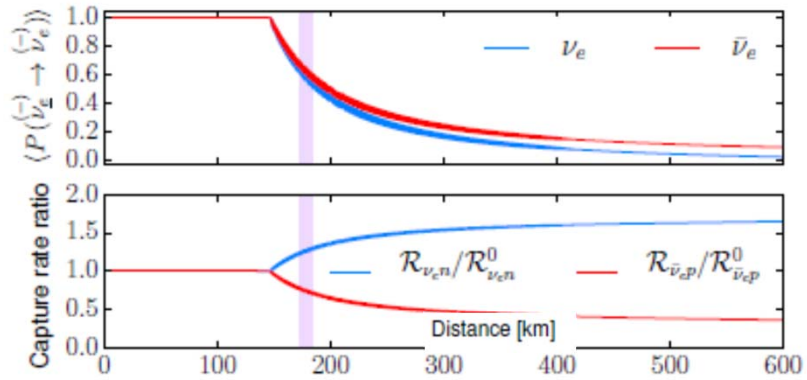




C.Yang, M.Grasso, D.Lacroix
PRC(2016) [21]

- NS crust is a laboratory for many-body theory (clustering, superfluidity, ab-initio)
- A coherent treatment between crust and core is essential for a correct evaluation of the observables (M(R) but also glitches, cooling, oscillations..)
- New functionals with low density behavior controlled by the Yang-Lee expansion + ChPT

(2) BNS, CCSN ⇔ multi-scale dynamics



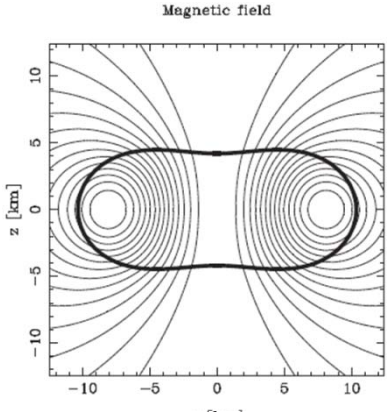
M.Frensel, M.Wu, C.Volpe,.. PRD(2017) [41]

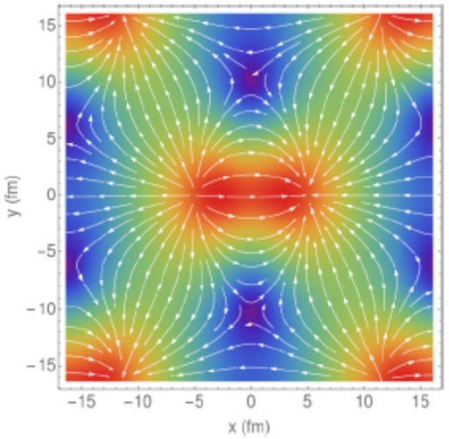
T.Foglizzo, .., J.Novak, M.Oertel, J.Margueron,.. PASA(2015) [127]

- ν dynamics: transport (complex multi-group schemes), different interactions with hadrons and leptons, flavour conversion (MSW, collective modes,..)
- Hydro-dynamics 3D => instabilities, turbulence…
- Magnetic fields
- New degrees of freedom at high temperature (Y, N^*,q,…)
- « general purpose » EoS: (n,T,y_e) **https://compose.obspm.fr/**

(2) BNS, CCSN ⇔ multi-scale dynamics

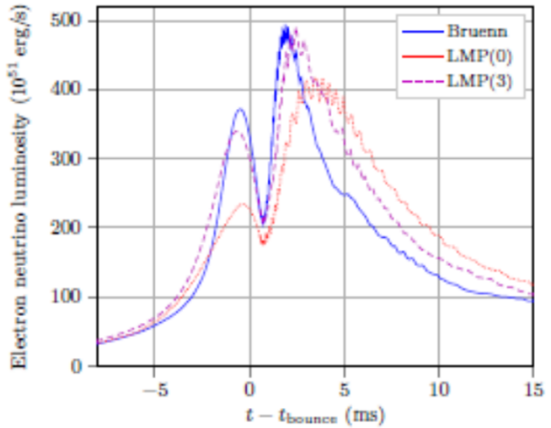
D.Chatterjee, T.Elghozi, J.Novak, M.Oertel MNRAS(2015) [101]





(c) Velocity field ($z = L/4$)

N.Martin, M.Urban PRC(2016) [36]



A.Pascal, S.Giraud, A.Fantina, F.Gulminelli, J.Novak,M.Oertel, .. PRC(2020) [11]

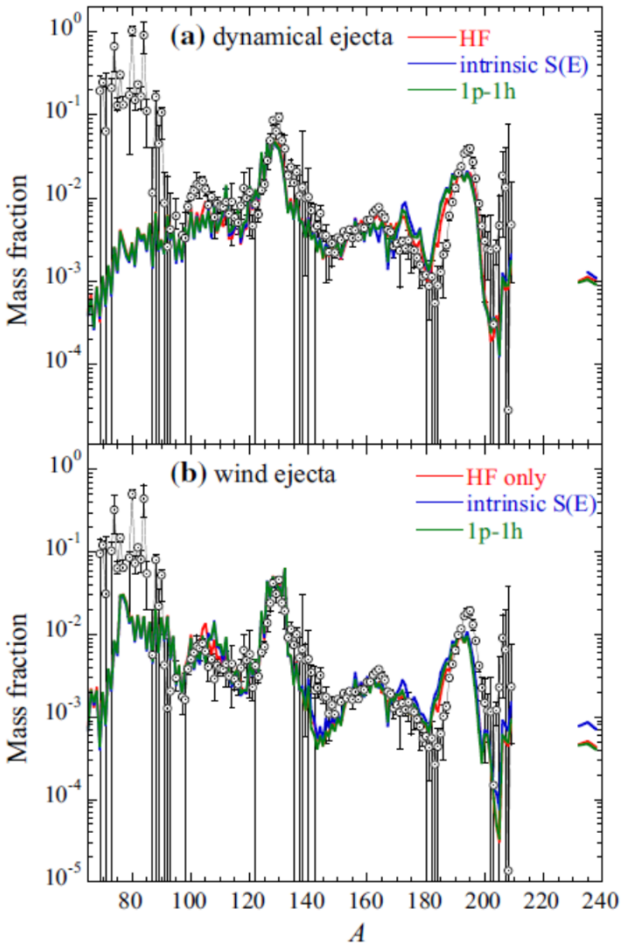
- Insufficient expertise/means for realistic simulations in 3D => international collaborations
- Numerical librairies: spectral methods in general relativity with B>0 and detailed microphysics

https://lorene.obspm.fr
https://kadath.obspm.fr
E.Gourgoulhon, P.Grandclément, J.Novak 2016 -> auj.

- 1-D models (CoCoNuT, ACCEPT) => collapse, or mesoscopic approaches with superfluidity => glitches

(3) Nucleosynthesis ⇔ reaction rates

K.Sieja, S.Goriely, EPJA(2021)



- rp process (X bursts, novae): p capture on N~Z nuclei
- r process (BNS): n capture on N>>Z nuclei
- Large scale shell model calculations of different nuclear structure ingredients: spectroscopic factors, energy spectra, gamma decay widths => references for alternative more systematic approches (RPA)
- Explicit evaluation of the rates with detailed inputs of nuclear structure

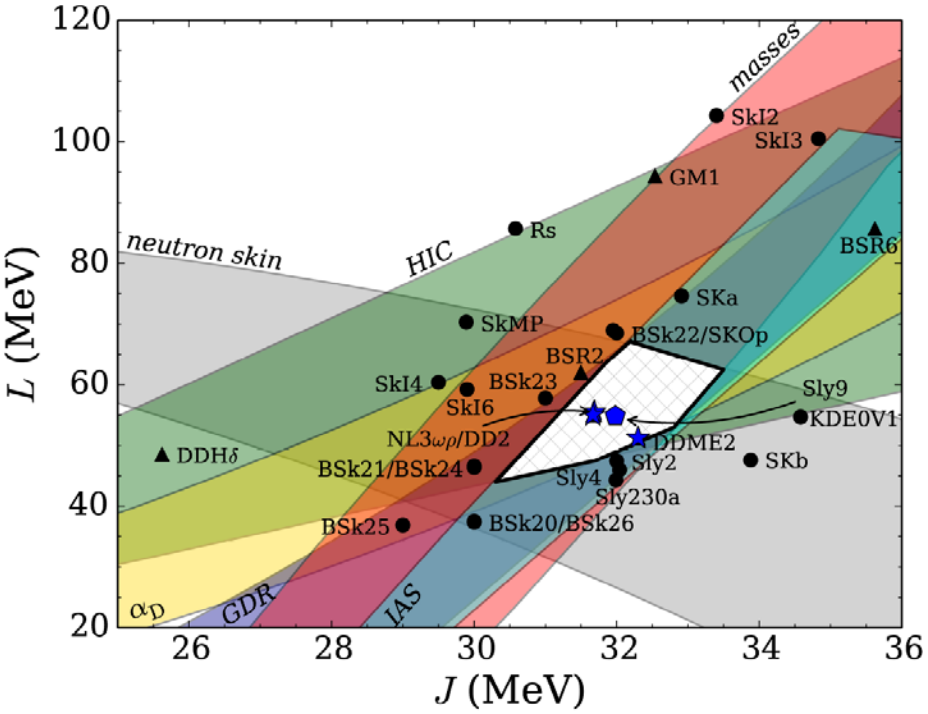
Relations with experiment

(2015-2020)

1. The contribution of nuclear physics experiments *(structure/reactions)*
2. The connection with observations
   (OG/X/radio/ν eg.SNEWS)

…. and also strong connections with theoreticians in nuclear structure (**=> *talk D.Lacroix***), hadronic physics (**=> *talk I.Schienbein***), astroparticles (**=> *talk J.Lavalle***), as well as with non-In2p3 astrophysicists (Dap/IRFU,IAP,IRAP)

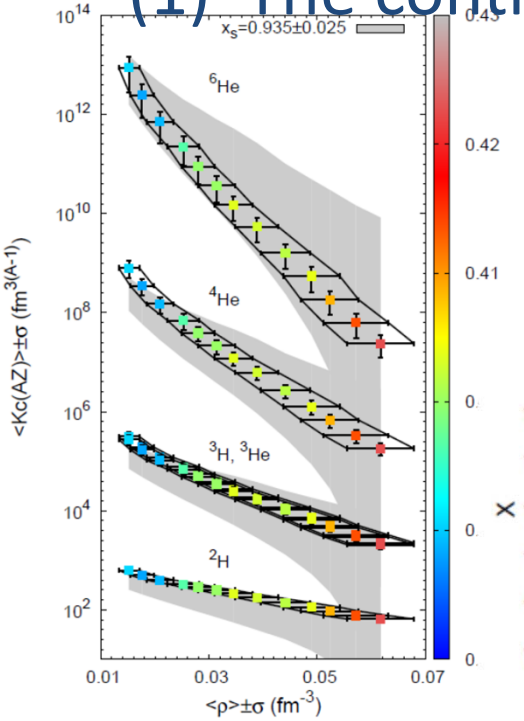
(1) The contribution of nuclear physics experiments



.M.Fortin,... F.Gulminelli,.. PRC(2016) [177]

- The EoS density dependence is parametrized by a set of coefficients that can be constrained by comparing the predictions of the different functionals to nuclear data
- Observables: GR, HIC, masses, IAS, neutron skin….
- The confidence intervals are used to calibrate the EoS meta-model
- Strong synergy with experiment also on model optimization for the calculation of the reaction rates **=> *talk D.Lacroix***

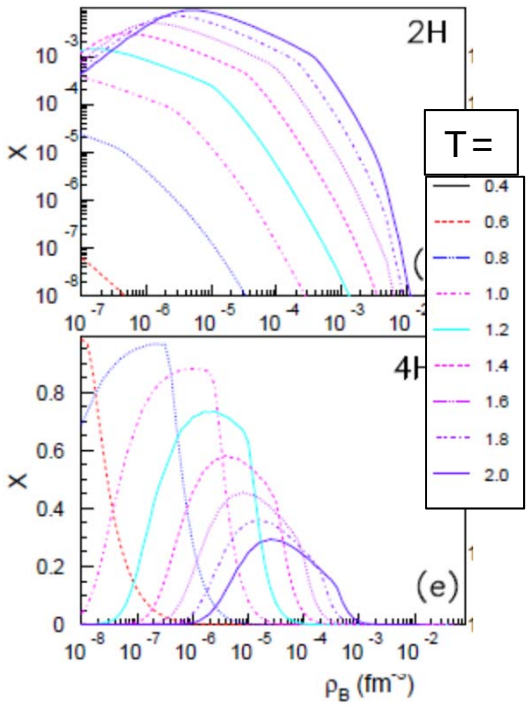
(1) The contribution of nuclear physics experiments



H.Pais,.R.Bougault, F.Gulminelli,.. PRL(2020) [18]

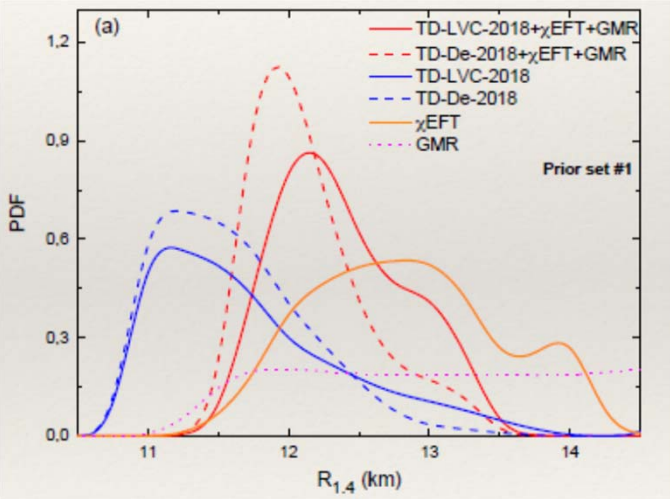
Data: INDRA/FAZIA

F.Gulminelli, A.Raduta.. PRC(2016) [80]



- Nuclear binding energies are modified in the stellar medium
- The modification of the couplings can be calibrated on chemical constants measured in heavy ion collisions
- Light nuclei abundances to be tabulated inside « general purpose » EoS https://compose.obspm.fr/

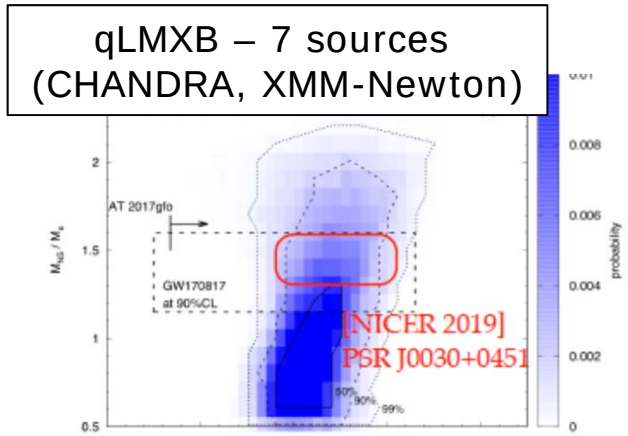
(2) The connection with observation



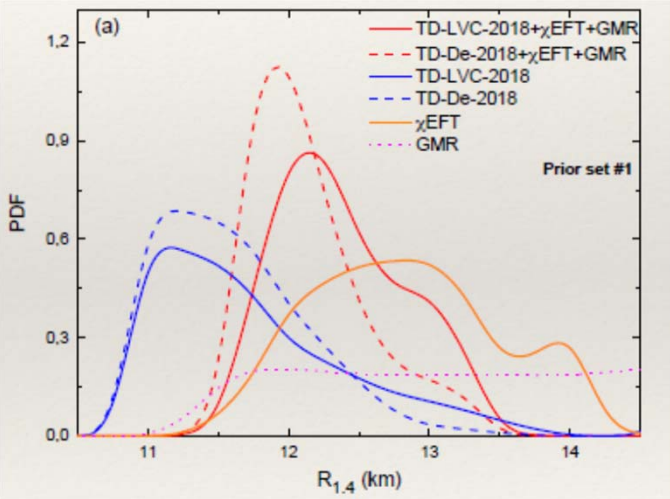
- Data prediction and interpretation
  - Different hypotheses on the core composition can be compared to measured pdf (here: Ligo/VIRGO)

H.Guven, K.Bozkurt, E.Khan, J.Margueron
PRC(2020) [12]

(2) The connection with observation



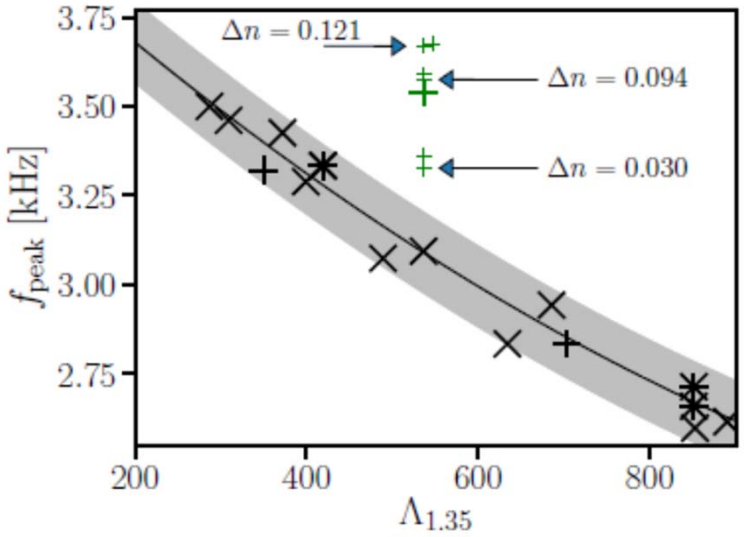
N.Baillot d'Etivaux, S.Guillot, J.Margueron,..
ApJ(2019) [20]



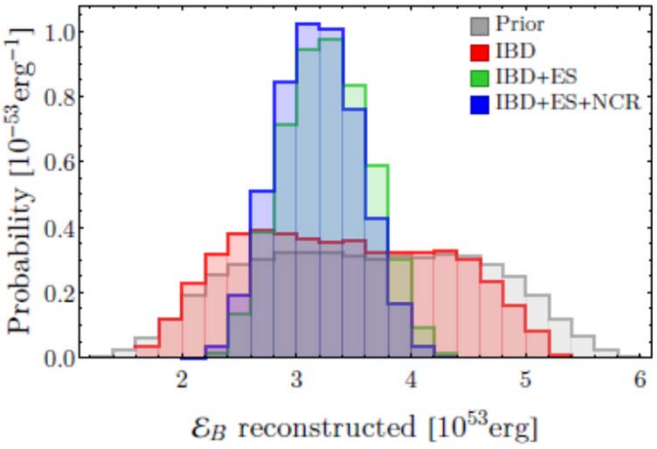
H.Guven, K.Bozkurt, E.Khan, J.Margueron
PRC(2020) [12]

- Data analysis:
  - Nuclear models and the associated constraints can (must) be directly included in the analysis (here: CHANDRA, XMM-Newton)
- Data prediction and interpretation
  - Different hypotheses on the core composition can be compared to measured pdf (here: Ligo/VIRGO)

(2) The connection with observation



A.Bauswein, …, M.Oertel PRL(2019) [110]



A.Rosso, …, C.Volpe JCAP(2017) [12]

- Data analysis:
  - Nuclear models and the associated constraints can (must) be directly included in the analysis (here: CHANDRA, XMM-Newton)
- Data prediction and interpretation
  - Different hypotheses on the core composition can be compared to measured pdf (here: Ligo/VIRGO)
- Preparation of new physics cases
  - post-merger oscillations and ET
  - EoS NS and SKA
  - PNS properties and DUNE/HK

F. Acero *et al*, "*French SKA White Book* " – Sect. 2.6.3 "Neutron star equation of state" (2018), . (*J.Novak, M.Oertel, A.F.Fantina, J.Margueron, F.Gulminelli*) : ***hal-01686223***

structure of the community

(2016-2021)

- **Master Projet** modelisation des astres compacts (MAC) (9 participants, 4 labos, *responsable: F.Gulminelli*) (2016-2019)
- **Master Projet** New-MAC (22 participants, 5 labos, *responsable: F.Gulminelli*) (2019-2022) http://mac.in2p3.fr/
- **GDR** Réactions, Structure et Astrophysique Nucléaire : Expériences et Théories (RESANET) (*responsable: J.Margueron, CS: F.Gulminelli, E.Khan, WG4: M.Oertel*) (2018-2023)
- **GDR** Ondes Gravitationnelles (OG) (*CS: J.Novak, WG* NS, SN et synthèse des éléments lourds: *A.F.Fantina, J.Novak*) (2018-2023)
- **Groupe théorie Caen-Meudon@VIRGO** (8 participants, *coordinateur: J.Novak* (MoA 23/12/2020)
- **Action COST** NewCOMPSTAR (*SA nuclear physics: M.Oertel*) (2014-2017)
- **Action COST** PHAROS (2017-2021)
- **PICS** France-Belgique "Core-collapse Supernovae" *(coordinator: A.F.Fantina)* (2018-2020)
- **IRP** France-Belgique « Origine des éléments lourds dans l'Univers : astres compacts et nucléosynthèse » (ACNu) *(coordinator: A.F.Fantina*) (2021-2026)

…. And numerous international collaborations and bilateral agreements

Bilateral agreements

- **IEA France-Belgique** "Radiative n-capture: models and applications") (*coordinator K.Sieja*) (2021-2022)
- **IEA France-Italie** "Impact des champs magnétiques et de l'équation d'état sur les observations multi-messagers des coalescences d'étoiles à neutrons » (*coordinator J.Margueron*) (2021-2022)
- **CEFIPRA France-Inde** no.5804-F « Phase transitions in sub-saturation nuclear matter and applications to core collapse supernova and nuclear experiments » *(coordinator F.Gulminelli)* (2017-2021)
- **CEFIPRA (France-India)** no.6304-4 "Pairing in neutron-star matter with renormalization-group based low-momentum interactions", *(coordinator: M.Urban)* (2020-2023)
- **CAPES/COFECUB France-Brasil** Ph-315 « Hadron and nuclear physics : models and applications » *(coordinator F.Gulminelli)* (2015-2018)
- **PICS France-USA** "nuclear physics inputs for violent phenomena in the universe" (*coordinator: J.Margueron*) (2019-2021)

Interdisciplinary connections

- **GDR** Neutrinos (*convener WG3 "Neutrinos de l'Univers": C.Volpe 2005-2017*)

Conclusions

- ***Summary:*** A well organized and interconnected community with internationally recognized contributions in the physics of compact stars
- ***Evolution:*** Two new In2p3 permanent positions in 2021/2022 (1CR@LPC: Marco Antonelli, 1IR@LPC) + one PR@IP2I (?) => teams strenghtening, particularly the interface between microphysics and macrophysics
- ***Perspectives:*** to reach a strong impact in the novel multi-messanger astrophysics, we should develop in a coordinate way :
  - *EoS & reaction rates at T>0, B>0,*
  - *Large scale simulations in numerical relativity,*
  - *modeling the conversion of r process into light.*

From the observational point of view, the post-merger study requires an increased sensitivity in the kHz domain => Einstein Telescope

backup

Modélisation des Astres Compacts (NewMAC) : structure internationale

List of collaborations which lead to common publications in peer-reviewed journals
In the period august 2016 - october 2020

Allemagne

- *Frankfurt Institute for Advanced Studies (FIAS):* A.Sedrakian
- *Helmholtzzentrum für Schwerionenforschung (GSI), Darmstadt:* A.Bauswein, S.Blacker
- *Institut für Theoretische Physik, Justus-Liebig-Universität, Gießen:* K.Otto, B.J.Schaefer
- *Institut für Physik, Universität Rostock* : G.Roepke
- *Technische Universität Darmstadt: Darmstadt (Allemagne):* S.Typel

Belgique

- *Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles*: N. Chamel, S. Goriely

Brésil

- *Universidad de Florianopolis:* D.Menezes, C.Barros Junior, M.Benghi Pinto,U.Furtado

Canada

- *Université de Montréal* : J.M.Pearson

Etats Unis

Los Alamos National Lab, New Mexico: I.Tews
Lawrence Berkeley National Laboratory (LBNL), Berkeley : C.Drischler
Department of Physics, University of Washington, Seattle: S.Reddy
Florida State University, Florida: J.Piekarewicz
California State University, Long Beach (USA) : T.Klahn

India

Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune: D.Chatterje
Variable Energy Cyclotron Center (VECC), Kolkata : G.Chaudhuri, S.Mallik

Pologne

Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Varsovie : P. Haensel, J.L. Zdunik M.Fortin

Portugal

Universidad de Coimbra : C.Providencia, H.Pais

Roumanie

Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucarest: Ad.R.Raduta

Russie

Ioffe Physical-Technical Institute, St.Petersburg : A.Y. Potekhin

Suisse

Université de Basel: M.Hempel

Turquie

Yildiz Technical University, Istanbul: K.Bozkurt

Vietnam

Institute for Nuclear Science & Technology, Hanoi: D.T.Khoa

Modélisation des Astres Compacts (NewMAC) : résultats

DEPUIS 5 ANS (aout 2016-aout 2020)

70 Publications
60 Communications/seminaires
40 Conférences invitées
12 Présentations ou posters des PhD
22 Conférences grand publique
3 Chapitres de livres
6 thèses soutenues

N.Baillot d'Etivaux, Lyon
H.Guven, Orsay
S.Giraud, Caen
T.Carreau, Caen
M.Marques, LUTH
A.Sourie, LUTH

ANNÉE 2016 (aout-décembre)

10 publications
4 communications

ANNÉE 2017

12 publications
19 communications

ANNÉE 2018

14 publications
21 communications

ANNÉE 2019

11 publications
8 communications

ANNÉE 2020

23 publications
8 communications

Contributions to VIRGO

(MoA 23/12/2020)

New expertise in nuclear physics to the LIGO-Virgo-Kagra community / insertion in the CBC group, particularly for “Studies of extreme matter" working group.

Science project :

- provide an (as) complete (as possible) database of nuclear matter EoS (parametrized models / microscopic calculations) => O4
- develop flexible and fast code for oscillating (HM/P)NS => relating oscillation/ GW spectra to the properties of fundamental physics => end of O4.
- Integrate these equation of state models into parameter estimation codes (LALinference & Bilby) => O5 ?

Strategy, collaboration & operations :

- Possible service works : review of results and paper writing within area of expertise, publication review on various topics, outreach.
- Interpretation of results about EoS models, NS physics, . . .
- Contribution to the science case for Virgo post-O5, also in relation with further optimization of the detector

Numerical ressources

- **GANIL, LPC, IPHC,CENBG**: local clusters => enough
- **IJCLAB**: local clusters + CC In2p3 => enough
- **LUTH**: local cluster, MesoPSL, GENCI => enough
- **APC:** CC In2p3 => insufficient time limit
- **I2PI**: local clusters (CC In2p3 not ideal for parallel computing) => not enough for MHD in 3D (1000 to 2000 CPU, >10 Mh) => application to GENCI, Exascale?