NUCLEAR PHYSICS AND NEUTRON STARS OBSERVATIONS :
PROBING THE DENSE MATTER EQUATION OF STATE

Fiorella Burgio
INFN Sezione di Catania

INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

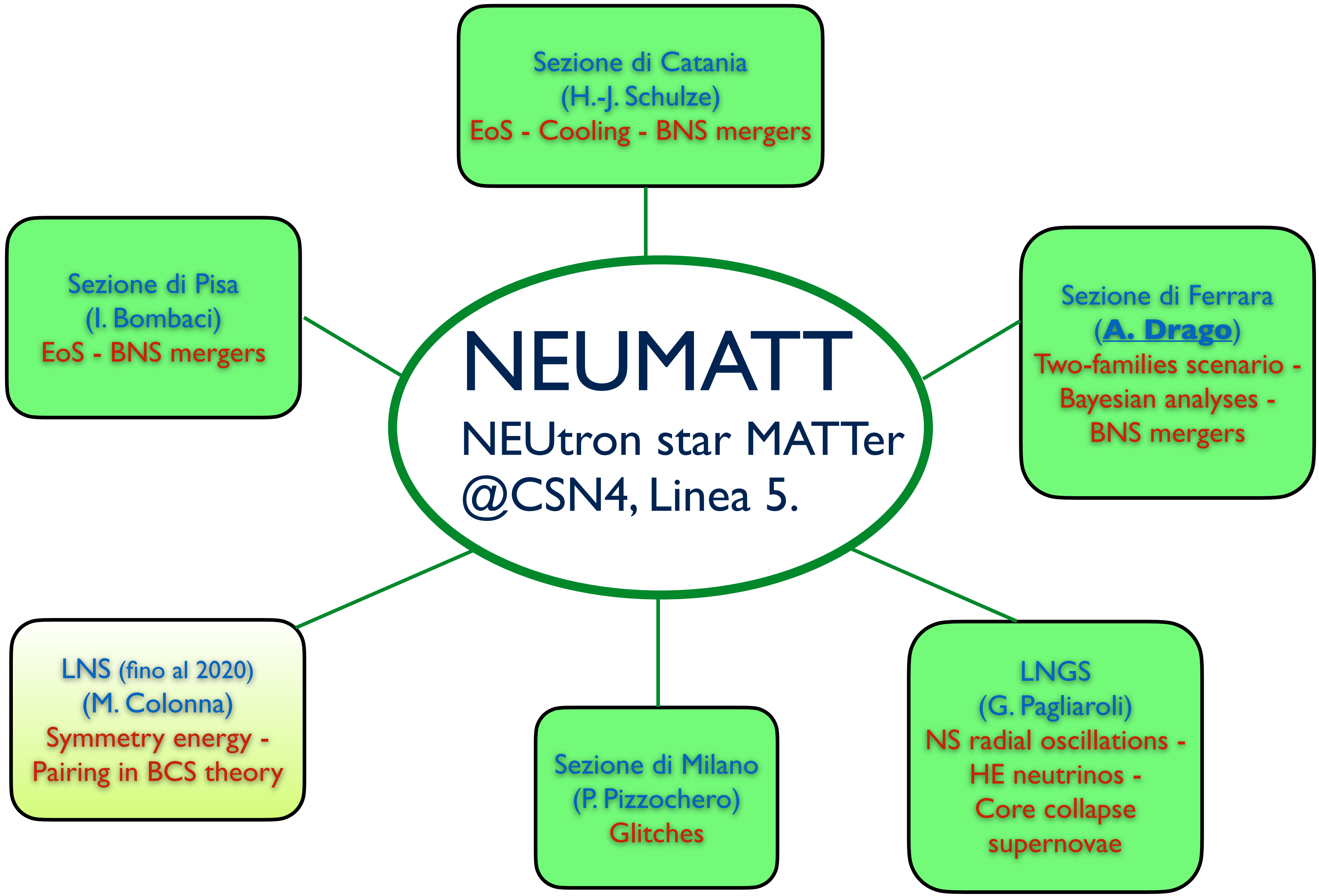
OUTLINE

Neutron stars (NS) are the densest macroscopic objects in the Universe, and represent a natural laboratory to study the fundamental properties of the matter constituents and their interaction in physical conditions not attainable in terrestrial laboratories.

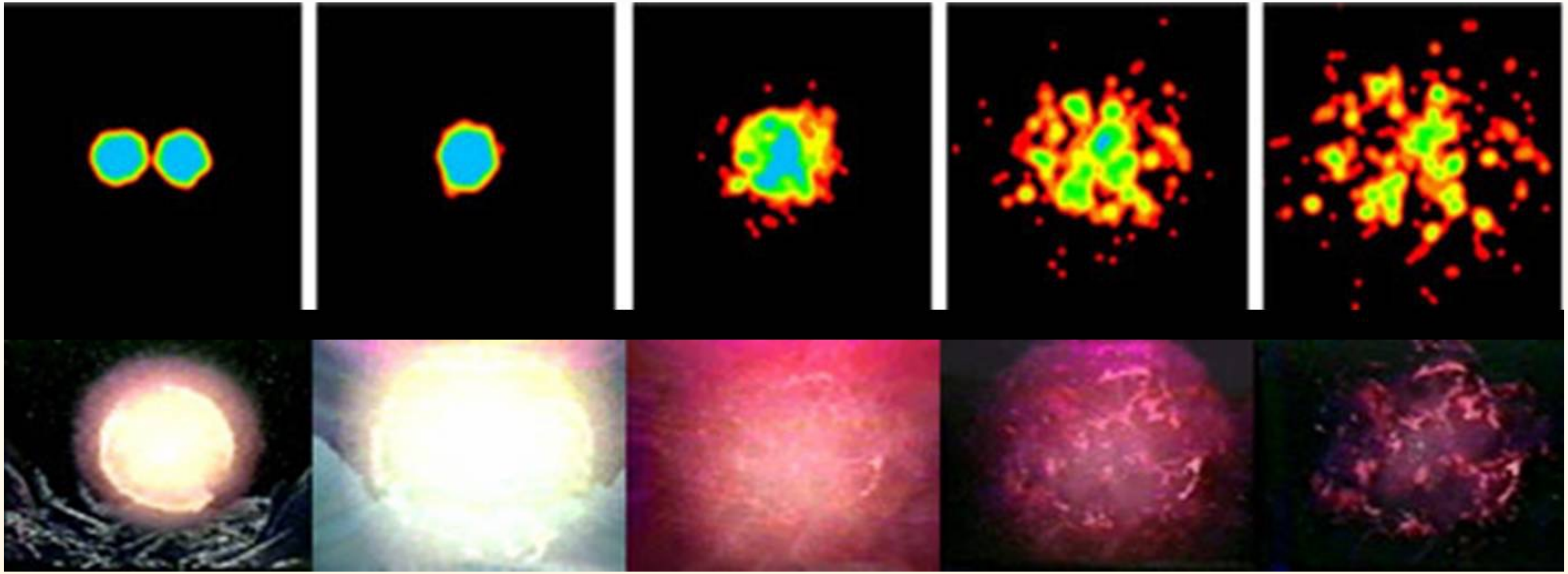
Many open issues need to be explored :

- *Equation of State : Inner structure and composition*
- *Role of theoretical many-body methods*
- *Relevance of the nucleon-nucleon interaction and three-body forces*
- *Symmetry energy*
- *Deconfinement phase transition*
- *BNS merging*
- *Cooling*
- *Pairing*
- *Glitches*
- …

Burgio, Schulze, Vidaña and Wei, Progress on Particle and Nuclear Physics **120**, 103879 (2021)
Rezzolla, Pizzochero, Jones, Rea and Vidaña, The Physics and Astrophysics of Neutron Stars, Springer (2018)


Sezione di Catania
(H.-J. Schulze)
EoS - Cooling - BNS mergers
Sezione di Pisa
(I. Bombaci)
EoS - BNS mergers
NEUMATT
NEUtron star MATTer
@CSN4, Linea 5.
Sezione di Ferrara
(A. Drago)
Two-families scenario - Bayesian analyses - BNS mergers
LNS (fino al 2020)
(M. Colonna)
Symmetry energy - Pairing in BCS theory
Sezione di Milano
(P. Pizzochero)
Glitches
LNGS
(G. Pagliaroli)
NS radial oscillations - HE neutrinos - Core collapse supernovae

Relevance of the EoS



1. Heavy ion collisions (small N/Z, high T)
2. Supernovae and Neutron Stars (high N/Z, high (small) T in SN (NS))
3. Binary NS merger and GW emission (high density, high N/Z and T)

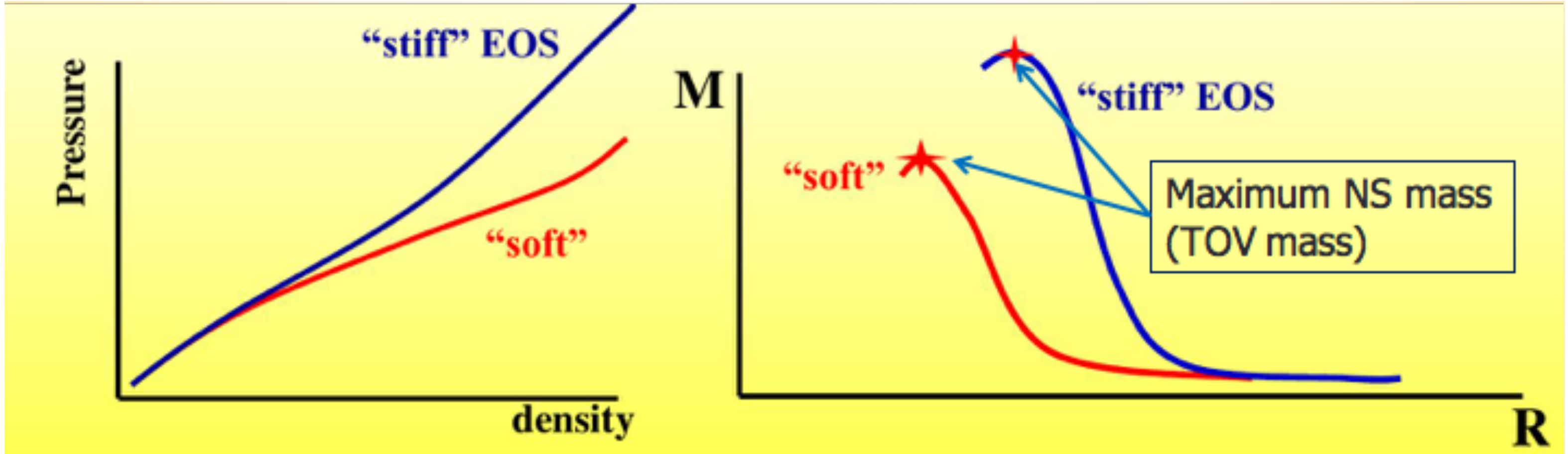
Quite different physical conditions in each case !

A nuclear matter theory must be able to treat all these physical situations.

Need an Equation of State $P = P(\varrho, x_i, T)$

Soft or Stiff ?

Given an EoS, compute the sequence of equilibrium models :
The Mass-Radius relation

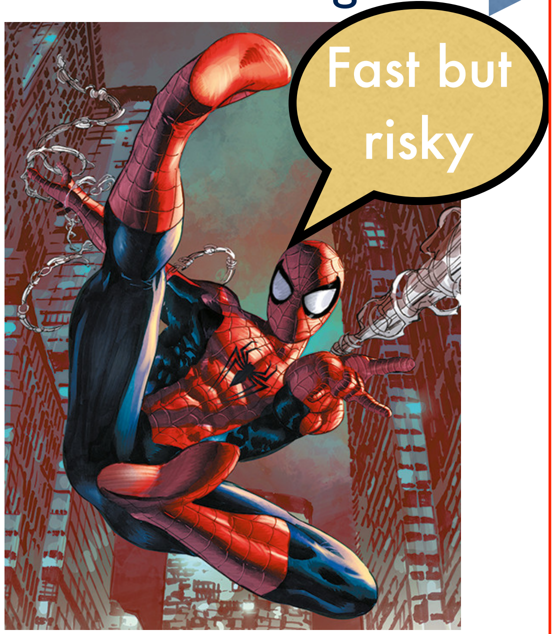


Two Different Philosophies To Solve the Nuclear Many-Body Problem

Starting point : the two- and three-body realistic nuclear interactions.

- Perturbative : *BBG, SCGF, DBHF, chiral-EFT.*
- Variational : *APR, FHNC, CBF.*
- Monte Carlo : *VMC, GFMC, AFDMC.*

Ab-initio vs. Phenomenological



Starting point : Effective density-dependent nuclear interaction with parameters fitted on g.s. nuclei properties.

- Liquid Drop Models
- Relativistic Mean Field Models
- Hartree-Fock models
- Statistical models

CAVEAT ! Nuclear interaction unknown at large density —-> extrapolation !

CHECK *WRT* NUCLEAR PHYSICS CONSTRAINTS

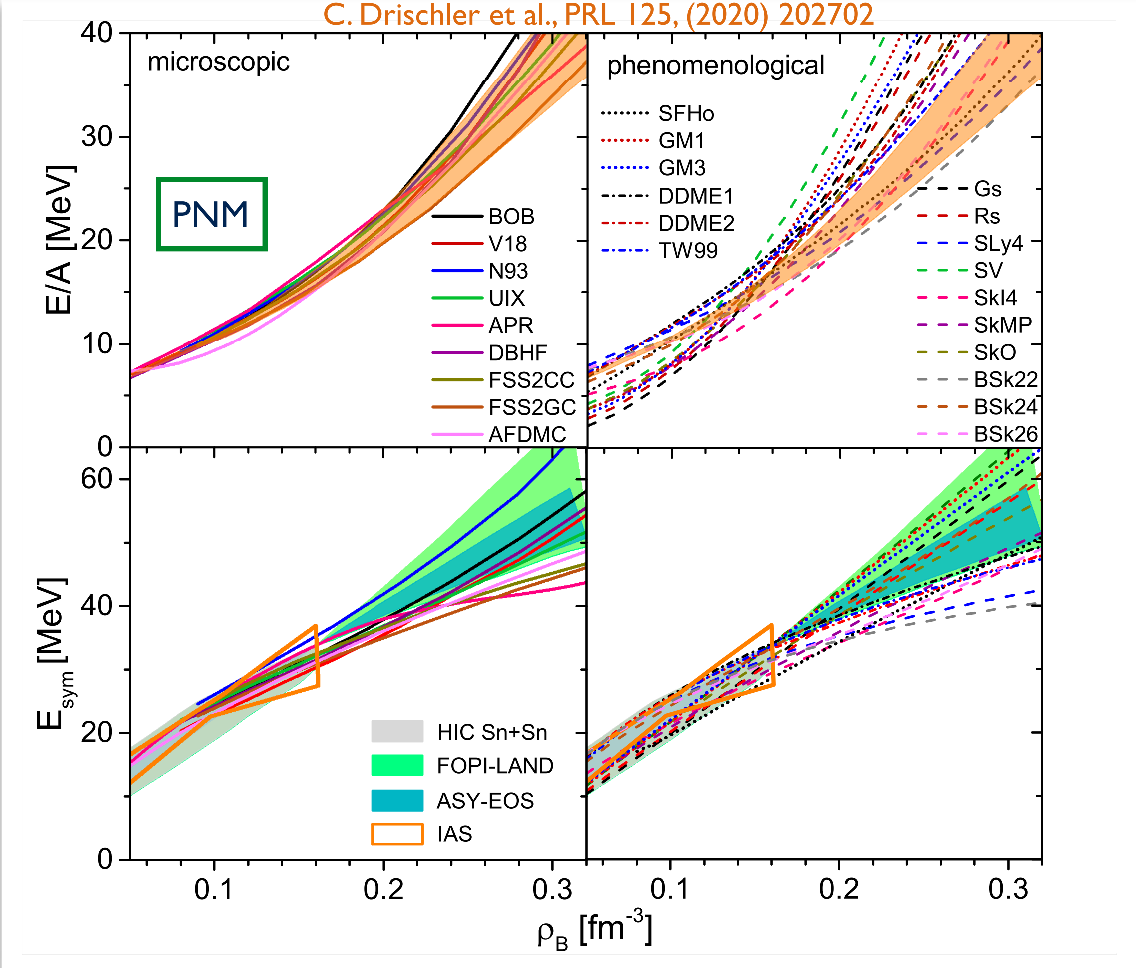
Microscopic EoS

- BHF with Argonne V18 or Nijmegen 93 2NF and microscopic 3NF (BOB,V18, N93,UIX)
- BHF with FSS2 NN interaction (quark d.o.f. explicitly taken into account)
- Variational APR with Argonne V18 and 3NF of Urbana UIX type
- Relativistic DBHF (Bonn A)
- AFDMC with modified V18

Phenomenological EoS

- Skyrme forces (Gs,Rs,SLy4,SV etc…)
- Brussels-Montreal group BSk22,24,26
- NLWM (SFHo, GM1,3), RMF models with different parameterizations.
- DDM, RMF model with density dependent coupling constants.

Orange : predictions from the χEFT up to N3LO order
C. Drischler et al., PRL 125, (2020) 202702



PNM and Symmetry energy behave well for the microscopic approaches.

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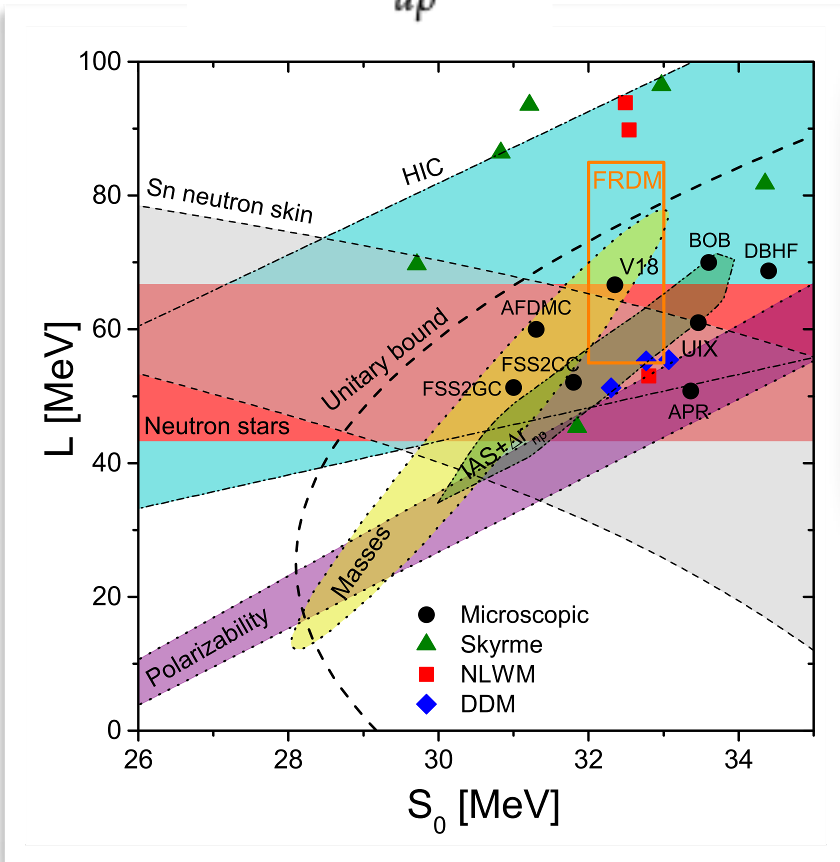
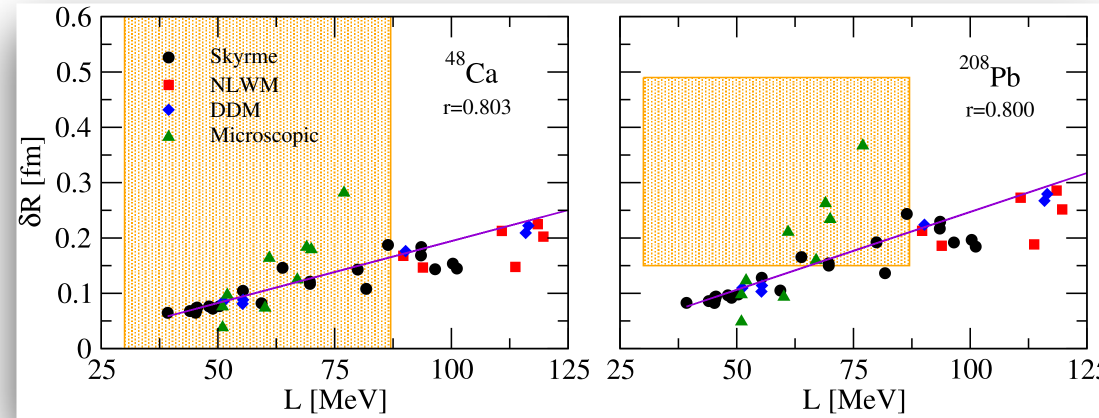
$$L \equiv 3\rho_0 \frac{dE_{\mathrm{sym}}}{d\rho}(\rho_0)$$



L parameter does not exclude any of the microscopic EoS, but several phenomenological models predict too large values.

The neutron skin thickness



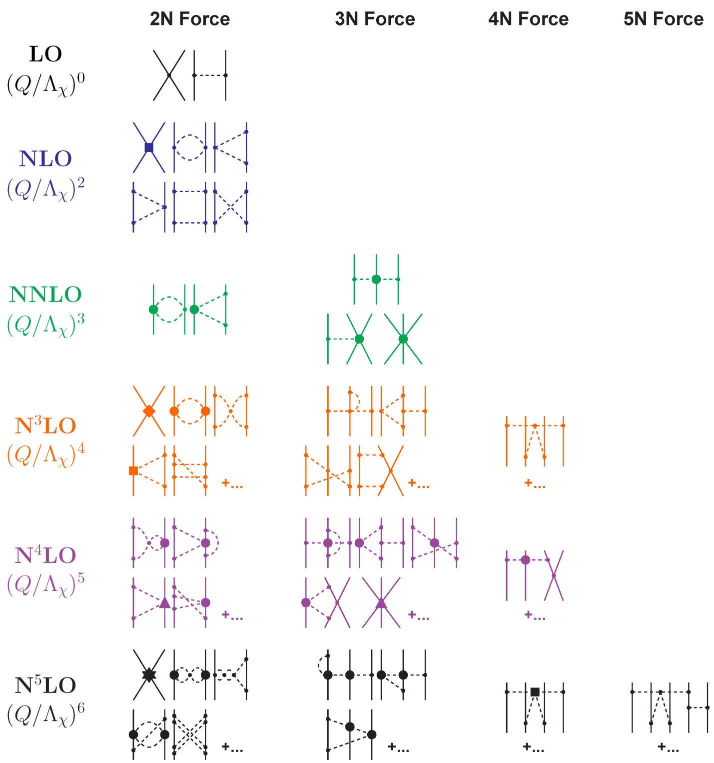
- The orange bands : predicted data for ^{48}Ca and experimental data (PREX) for ^{208}Pb.
- Linear increase of δR with L —-> the thickness is determined by pressure difference between neutrons and protons, which is proportional to the parameter L.
- Some correlation between the neutron skin thickness and L exists.
- Almost all the microscopic EoS turn out to be compatible with the PREX experimental data, whereas some phenomenological models give predictions out of the experimental range.

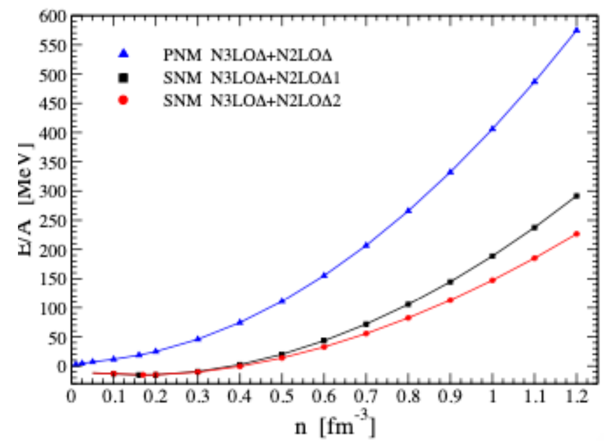
Pisa

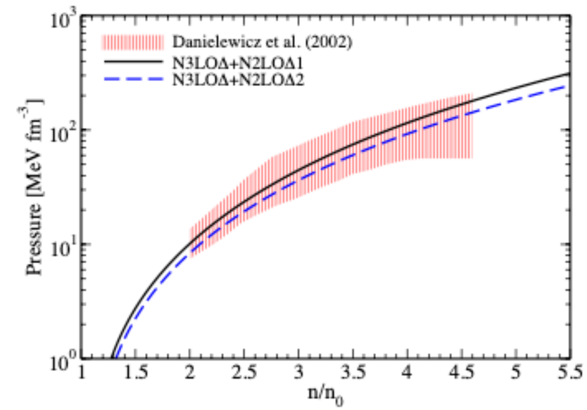
2NF+3NF INTERACTIONS DERIVED IN CHIRAL PERTURBATION THEORY

I. Bombaci & D. Logoteta, A&A 609, A128 (2018)

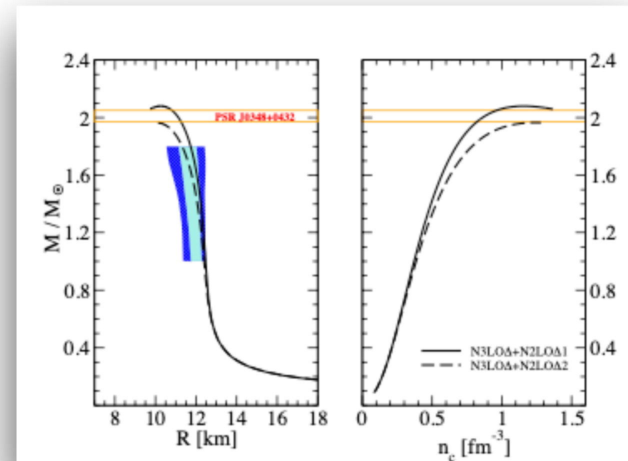
ChPT provides the most general scheme accommodating all possible interactions among nucleons, Δ isobars, and pions compatible with the relevant symmetries of low-energy QCD.



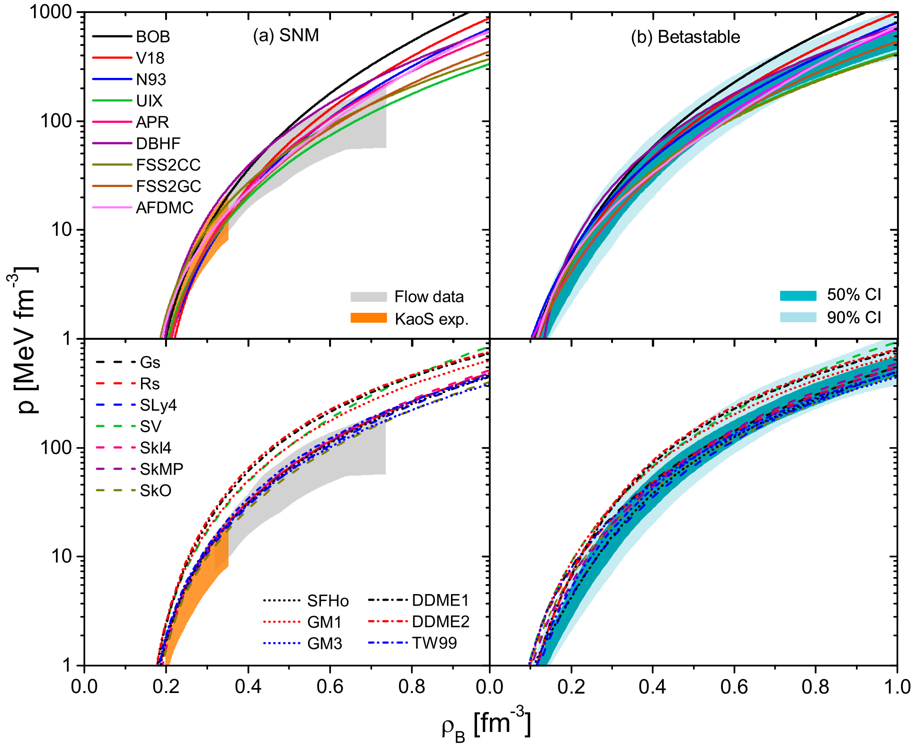




Realistic 2NF+3NF including the Δ(1232) isobar intermediate state.

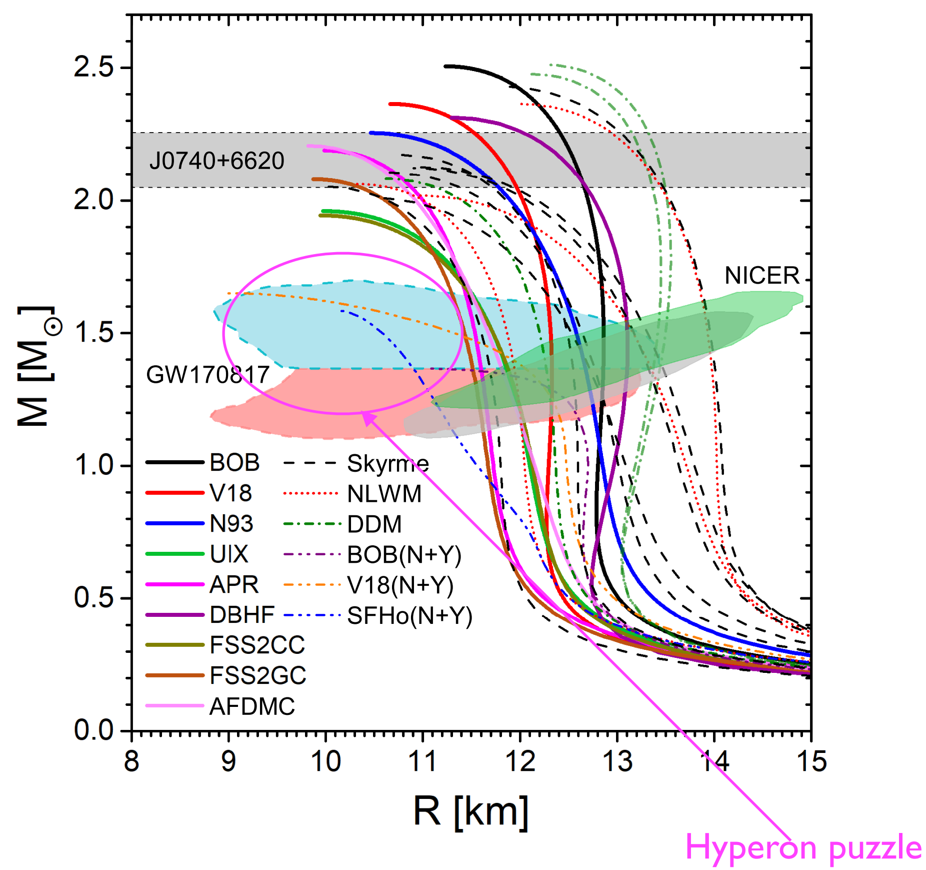


COMPARISON WITH OBSERVATIONS



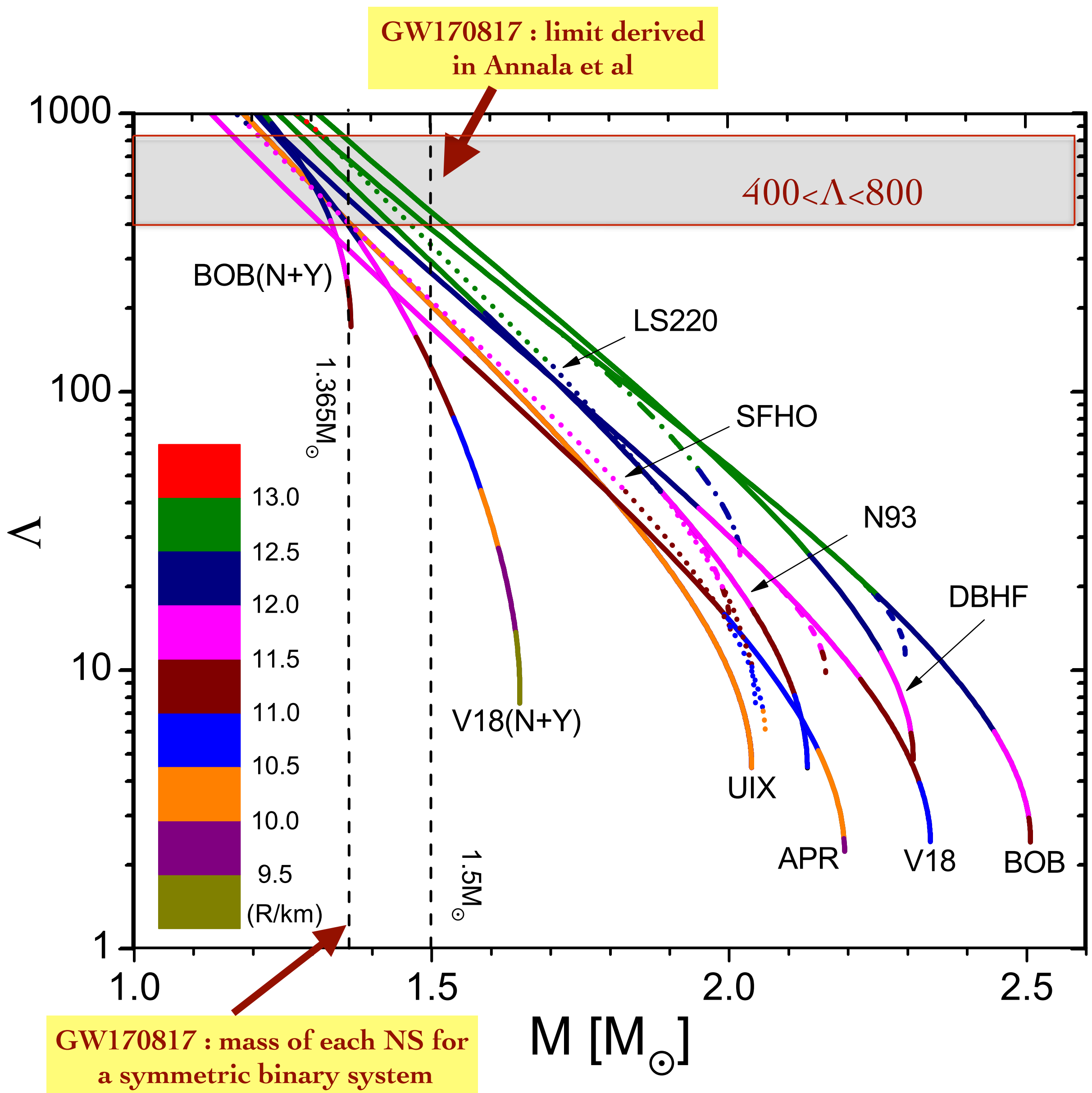
Pressure vs. baryon density for the symmetric case (left), and the beta-stable case (right).
Limits deduced by the GW170817 event are labelled by blue bands in the right panels.

Mass-Radius relations



Constraining the EoS from GW170817 and the kilonova signal AT2017gfo

Correlations between M, R and Λ



- Fixed chirp mass

$$\mathcal{M}_c = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}} = 1.188\, M_\odot$$

$$q = \frac{M_2}{M_1} = 0.7 - 1$$

- The conditions $M_1=M_2=1.365$ M_0 and 400<Λ<800 imply **12<R<13 km**
- Compatible EoS : V18(N+Y), UIX, V18, N93, BOB(N), DBHF, LS220, DS1, DS2.
- Not compatible : APR, BOB(N+Y), and SFHO (marginally).

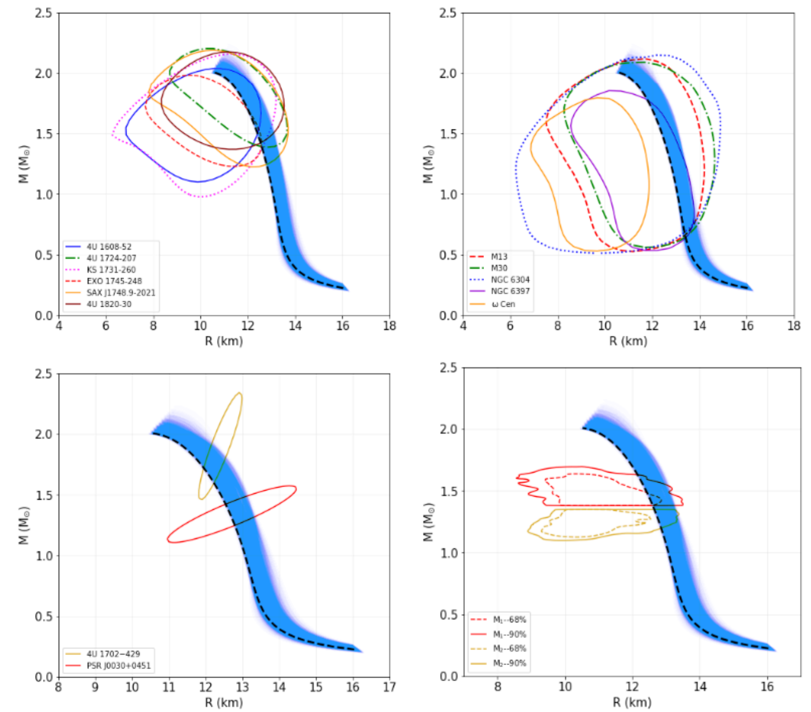
Selection of the EoS !

BAYESIAN ANALYSIS APPROACH : A DIFFERENT POINT OF VIEW

Steiner, 2010

The Bayesian method allows to include the a priori knowledge on the low density and symmetric EOS and to explore, in a controlled way, the wide space of parameters which determine the neutron star EOS.

- Bayesian analysis in order to constrain the EoS of dense matter by exploiting the available data from symmetric nuclear matter at saturation and from observations of compact X-ray sources and from the gravitational wave event GW170817.
- Analysis performed with RMF models, which allow to consistently construct an equation of state in a wide range of densities, isospin asymmetries and temperatures.
- By exploring different types of priors, one finds the most likely equations of state (in RMF, those featuring a strong reduction of the effective mass of the nucleons in dense matter.)



S. Traversi, P. Char and G. Pagliara, ApJ 897, 165 (2020)

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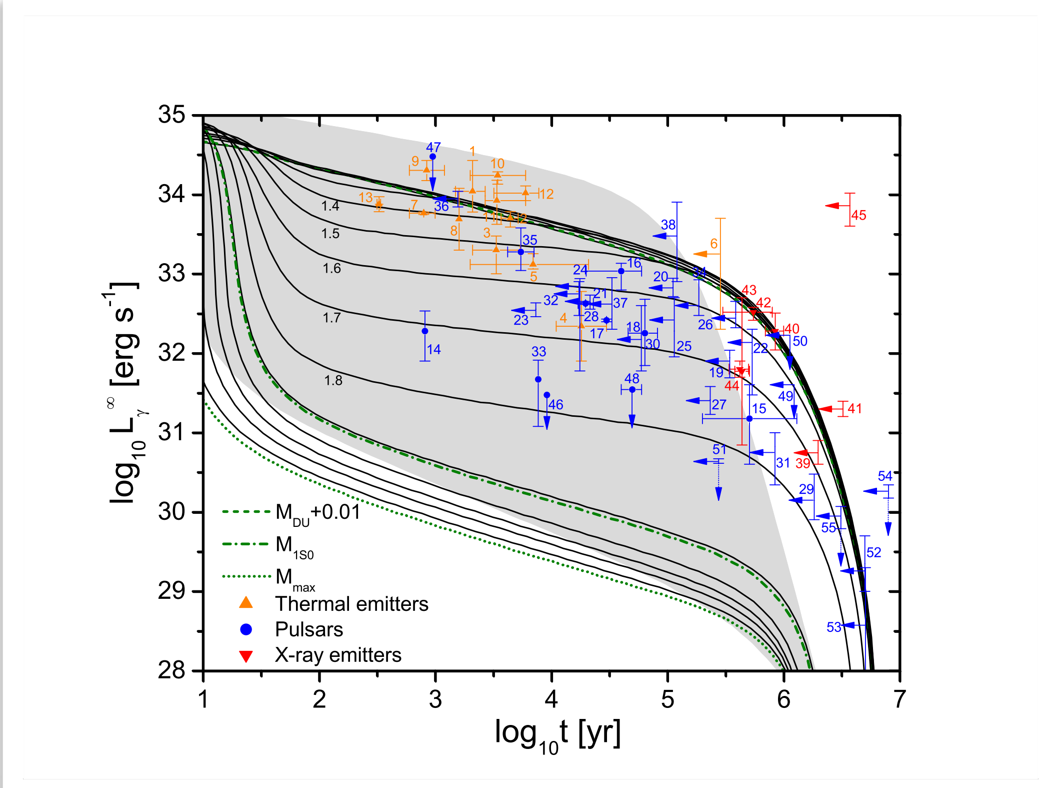
NS COOLING

- **Nuclear forces determine via the EoS not only the NS structure, but also the composition of NS cores and superfluid gaps of baryons, which are crucial for the computation of neutrino emission rates in NS cores.**
- **These quantities govern the cooling of middle-aged isolated NSs, which can be confronted with astrophysical data on luminosity for NSs of known or estimated age.**
- **No selection of the EoS ! NS masses are unknown.**

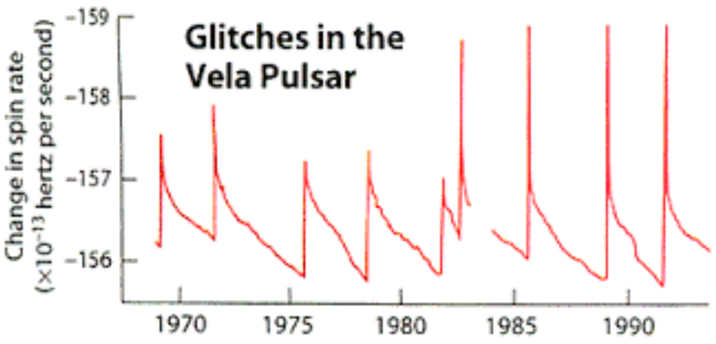


- Cooling diagram for the BHF V18 EoS with p1S0 BCS gap and no n3P2 pairing, for different NS masses M/M⊙ = 1.0,1.1,...,2.3 (decreasing black curves).
- The dashed green curve marks the NS mass MDU + 0.01 M⊙ = 1.02 M⊙ at which the DURCA process has just set in, and the dotted green curve corresponds to M_{max} = 2.34M⊙.
- The black curves obtained with a Fe atmosphere (shaded areas obtained with a light-elements atmosphere).

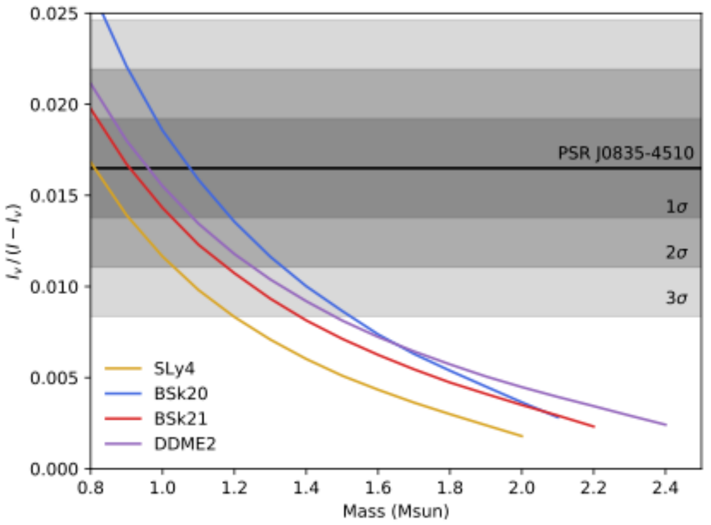
Jin-Biao Wei, PhD thesis, XXXV ciclo, Università di Catania

HELPFUL HINTS FROM GLITCHES

Goal : *Find a realistic and physically meaningful scenario to explain these sudden spin-ups in rotational frequency, which are observed in many pulsars and which may be direct evidence for the presence of nucleon superfluidity in their interior.*



- Study of the activity parameter $\mathscr{G}$, an observational quantity measured for any frequently glitching pulsar. This parameter can set constraints on the superfluid component moment of inertia $\frac{I_\nu}{I - I_\nu} > \mathscr{G}$ and the Vela mass can be estimated.



- Study of the glitches amplitude : superfluidity is important for explaining activity and the large glitch observed in Vela (2016). It is not large enough to put constraints in the superfluidity gaps, just in its extension over a large region of the outer core.
- EoS is important for constructing the density profiles and composition.

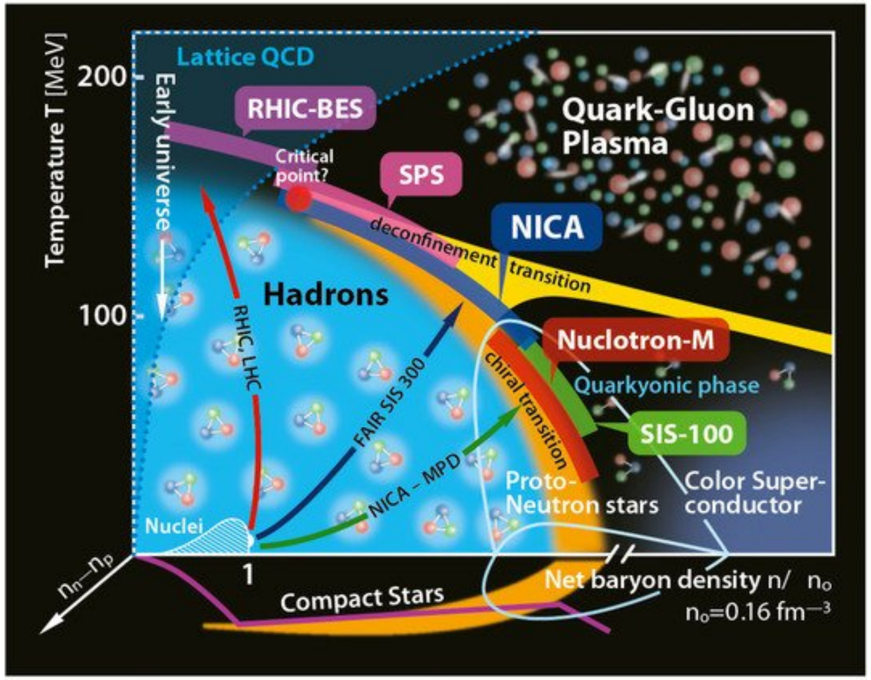
M. Antonelli, A. Montoli, B. Haskell, F. Magistrelli, P. Pizzochero, arXiv:2012.01539, MNRAS **475** (2018), 5403; A&A **642**, A223 (2020).

NEUTRON STARS IN THE QCD PHASE DIAGRAM

Hadron gas :
- ✓ Moderate temperatures and densities
- ✓ Quarks and gluons are confined
- ✓ Chiral symmetry is spontaneously broken

Quark-gluon plasma :
- ✓ Very high temperatures and densities
- ✓ Deconfined quarks and gluons
- ✓ Chiral symmetry restored

Color superconductor :
- ✓ T < 100 MeV and very high densities
- ✓ Quarks form boson pairs in analogy with BCS theory



Full QCD is solved from first principles on a discrete Euclidean space-time grid

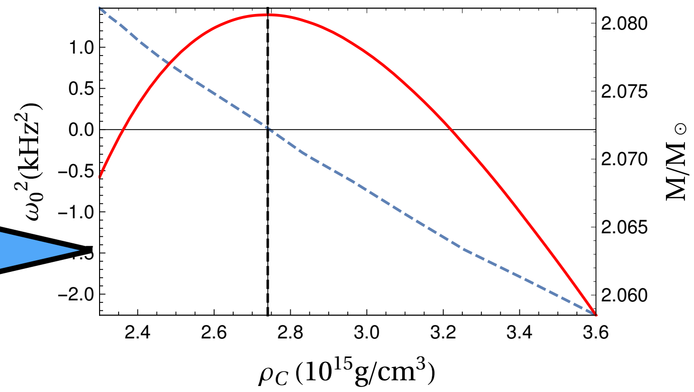
✓ Predicts a cross-over from hadronic matter to QGP for μ=0 at $T_c \approx 170$ MeV

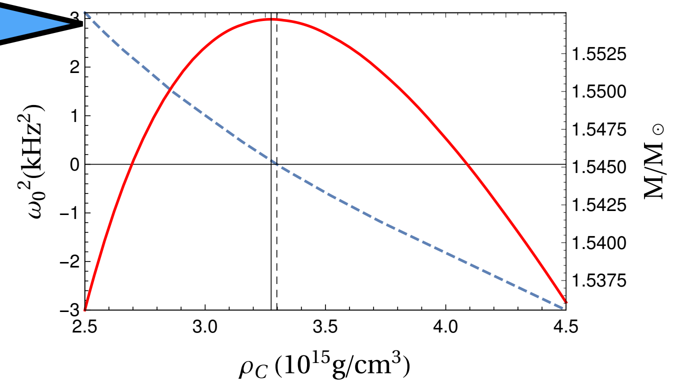
👉 **Lattice QCD calculations are presently not feasible at T=0 and large μ_b !**

RADIAL OSCILLATIONS OF COMPACT STARS

Di Clemente, Mannarelli, Tonelli, PRD **101**, 103003 (2020)

- A new strategy to correctly deal with the star boundaries and the interfaces between layers.
- Solution of the Sturm-Liouville eqs.
- Without interface discontinuity, the fundamental radial eigenmode becomes unstable exactly at the critical central energy density corresponding to the largest gravitational mass.
- With interface discontinuity, there exist stable configurations with a central density exceeding the critical one and with a smaller gravitational mass.





Twin compact stars, i.e. stars with the same mass but different radii, BUT the radius difference is just of few hundred meters → they can be hardly discriminated by observation

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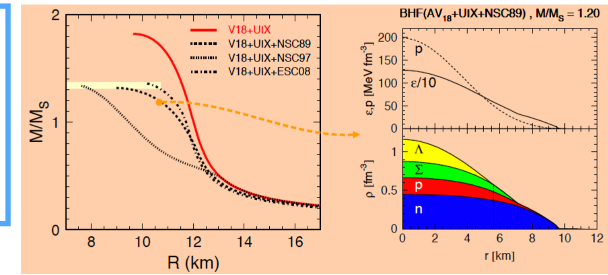
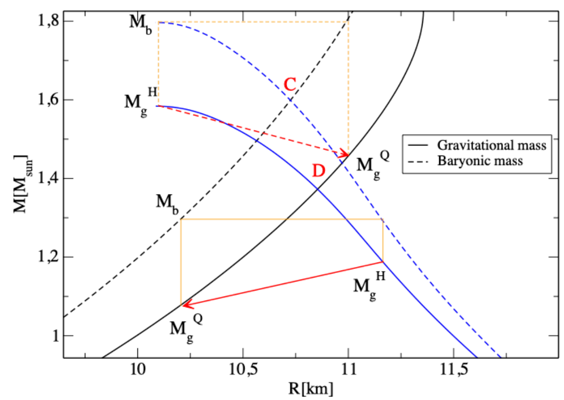
THE TWO-FAMILIES SCENARIO

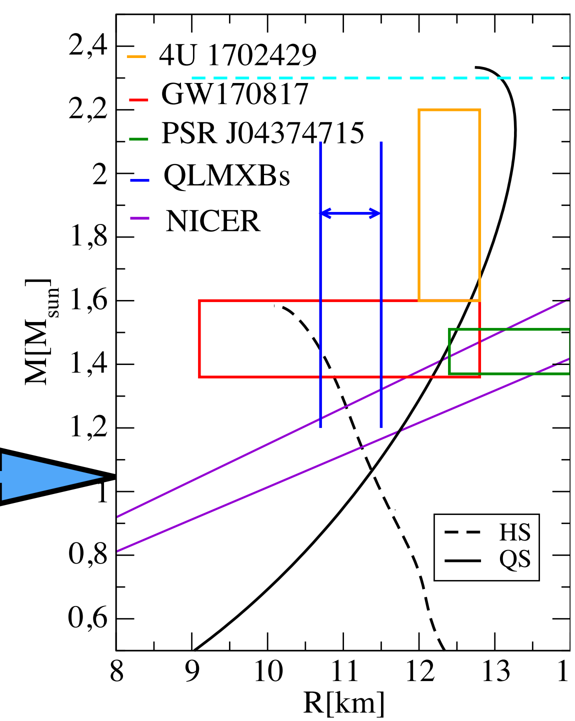
A. Drago and G. Pagliara, PRD **102,** 063003 (2020); ApJ **852**, L32(2018);EPJ A**52,** (2016) 41; ApJ **846**, (2017) 163

Coexistence of two families of stars: hadronic stars composed of nucleons, hyperons/delta with mass < 1.6M₀, and strange quark stars with larger mass and radii. EoS stiff enough to support 2M₀ stars, with the possible indication of small radii for some objects.



Conversion process of a hadronic star into a strange quark star with a larger radius increases the total binding energy, therefore it is energetically convenient at a fixed baryon mass.





Model vs. Observations The data from NICER could correspond either to a HS with a mass of about 1.2M$_\odot$ and a radius of about 11km or to a QS with a mass of about 1.4M$_\odot$ and a radius of about 12.5 km.

Testing the two-families scenario in BNS merger events !

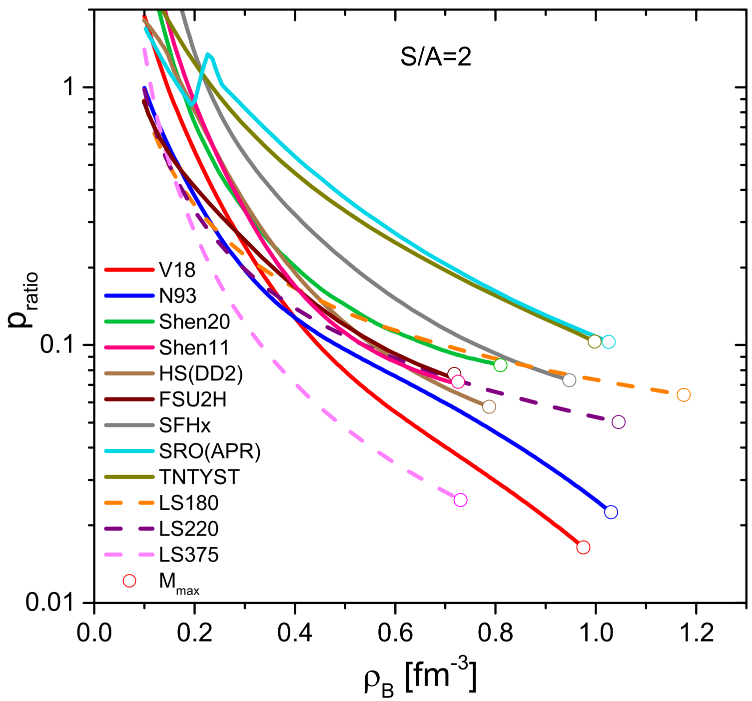
WAS GW190814 A BLACK HOLE - STRANGE QUARK SYSTEM ?

I. Bombaci, A. Drago, D. Logoteta, G. Pagliara and I. Vidaña, PRL 126, 162702 (2021)

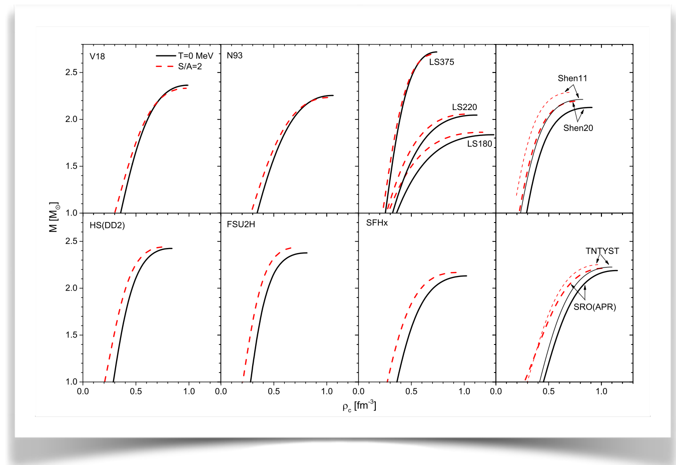
Models Extension at finite Temperature

J.B. Wei, F.B., A. Raduta and H.-J. Schulze, PRC 104, 065806 (2021)

$$p_{ratio} = \frac{p_{th}}{p_0}(\rho, T) = \frac{p(\rho, x_T, T) - p(\rho, x_0, 0)}{p(\rho, x_0, 0)}$$

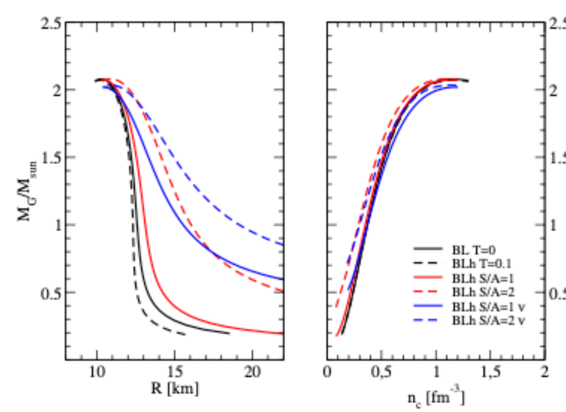


Thermal effects on the pressure are below 3% for the microscopic models, and can reach 10% for the phenomenological ones.



Change of the maximum mass is very small, just a few percent !

ChPT approach



D. Logoteta, A. Perego, and I. Bombaci, A&A 646, A55 (2021)

Dynamical simulations of a spherically symmetric CCSN.

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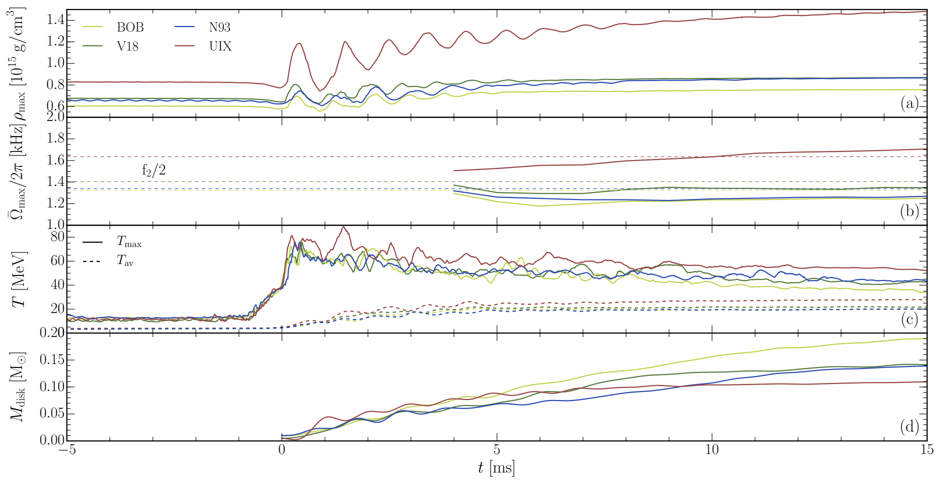
Simulation of equal-mass binaries with M_G=1.35 $M_\odot$,
and initial separation 45 km.



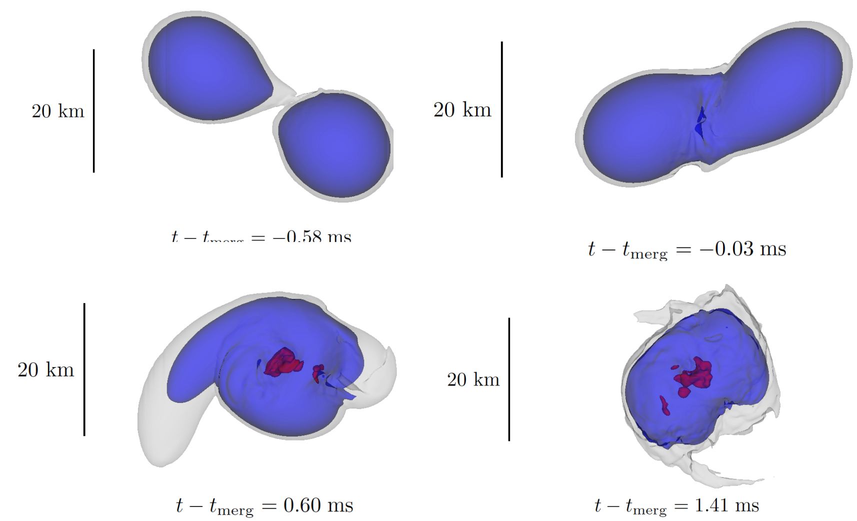
(a) Evolution of the maximum rest-mass density ρ_{max}
(b) Max differential rotation frequency Ω_{max}
(c) Maximum and density-weighted aver. temperature, T_{max} and <T>
(d) Mass of the disk

Features strongly related to the EoS stiffness.
BOB (the stiffest EOS) reaches the smallest maximum density and temperature, whereas the (too) soft UIX case exhibits increasing central density, i.e. possible collapse after the merger. Stable profiles for BOB,V18 and N93.
Temperatures lower than 70 MeV.
Disk mass. The disk masses are increasing, but tend to become stable, between 0.1 and 0.2 $M_\odot$,

Figura et al., PRD **103**, 083012 (2021)

Pisa

BL EoS + MIT bag model at finite T.
Signatures of HQ phase transition in BNS mergers.
Prakash, Radice et al., PRD **104**, 083029 (2021)



The softening of the EOS due to the phase transition causes the merger remnants to be more compact and to collapse to a black hole (BH) at earlier times. The phase transition is imprinted on the postmerger gravitational wave (GW) signal duration, amplitude, and peak frequency, and also on dynamical ejecta, and remnant disk masses.

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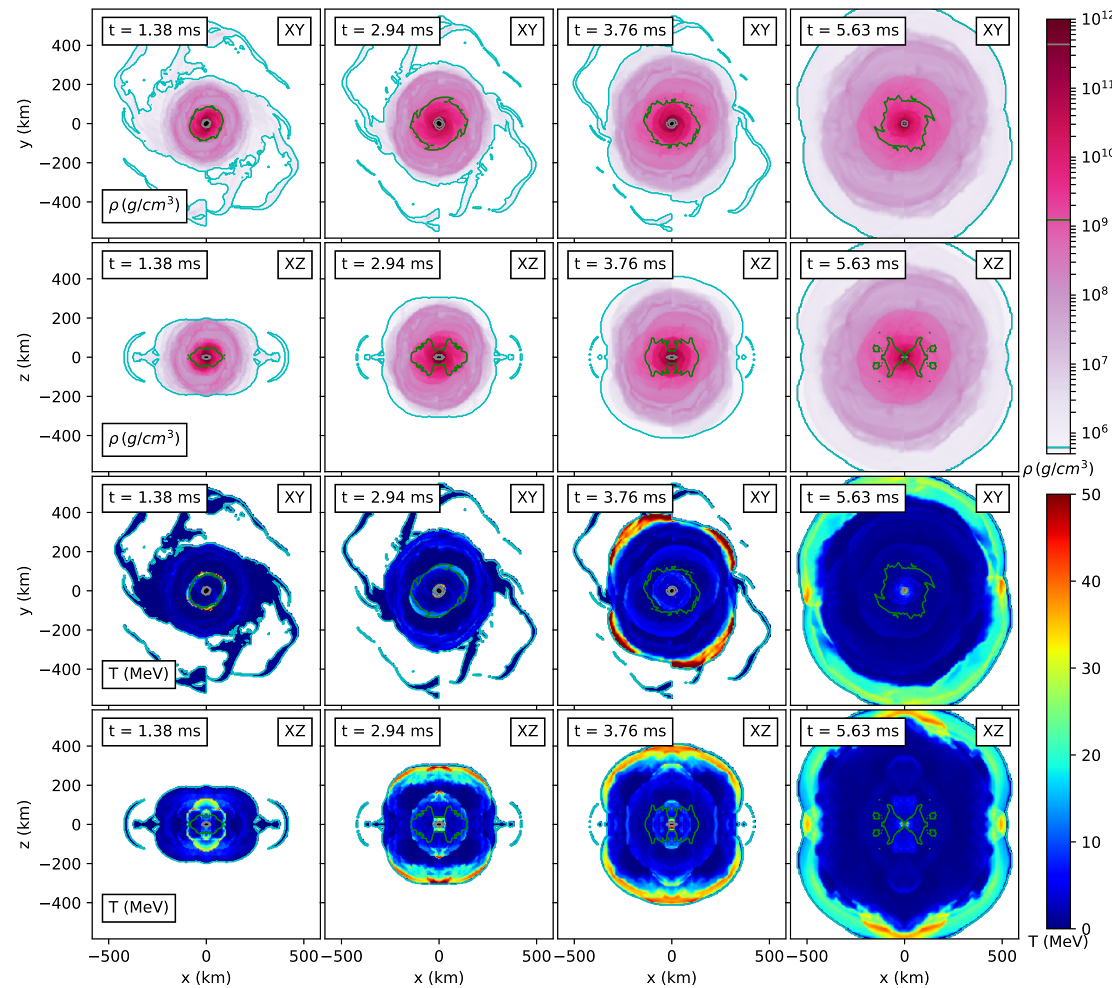
MERGER OF COMPACT STARS IN THE TWO-FAMILIES SCENARIO

De Pietri et al., ApJ 881, 122 (2019)



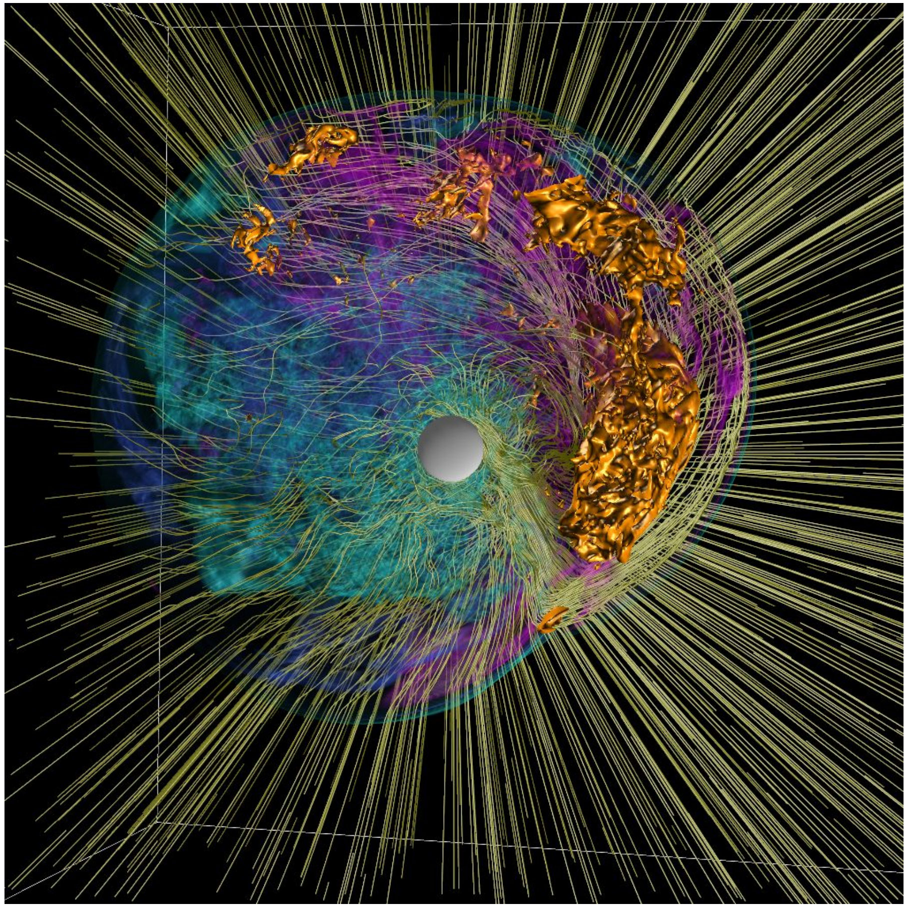
Relevant signatures of the two-families scenario are proposed.

- rapid collapse to a black hole for masses even smaller than the ones associated to GW170817;
- oscillations of the postmerger remnant at frequencies higher than the ones obtained in the one-family scenario;
- a large value of the mass dynamically ejected and a small mass of the disk, for binaries of low total mass.

GW EMISSION FROM CORE-COLLAPSE SUPERNOVAE

- Ernazar Abdikamalov, Giulia Pagliaroli, David Radice, arXiv:2010.04356

- Odysse Halim, Claudio Casentini, Marco Drago, Viviana Fafone, Kate Scholberg, Carlo Francesco Vigorito, Giulia Pagliaroli, JCAP 11 (2021) 021



Gravitational waves (GWs) from core-collapse supernovae are expected to play a role in the supernova explosion mechanism, but their modelling is challenging due to the stochastic nature of the dynamics and the vast possible progenitors. Low-energy neutrinos will be emitted enormously during the core-collapse explosion and can help for the gravitational wave counterpart search.

The LNGS group keeps on investigating how to improve the detection efficiency of gravitational waves bursts that are expected from core-collapse supernovae along with neutrino detection.

“EXOTIC" NS

Hyperons in Neutron and Proto-neutron stars with a special emphasis on the well-known "hyperon puzzle".

A possible solution proposed in [***Logoteta, et al., Eur. Phys. J. A (2019) 55:207***] by the Pisa-Catania Units; Inclusion of the nucleon-nucleon-lambda (NNΛ) three-body force on neutron star structure. This leads to an equation of state stiff enough such that the resulting neutron star maximum mass is compatible with the largest currently measured neutron star masses with M ~2 $M_{\odot}$. Extension of this approach in order to include the Σ hyperons (Σ^-, Σ^0, Σ^+) in neutron star matter.

Dark Matter in NS

Study of the oscillation of neutron into mirror neutron, its mass degenerate partner from dark mirror sector, that can gradually transform the neutron stars into the mixed stars consisting in part of mirror dark matter.

Study of the structure of mixed stars, derivation of the mass-radius scaling relations between the configurations of purely neutron star and maximally mixed star containing equal amounts of ordinary and mirror components. Possible implications for the gravitational waves from the neutron star mergers and associated electromagnetic signals.

Zurab Berezhiani, Riccardo Biondi, Massimo Mannarelli, and Francesco Tonelli, Eur.Phys.J.C 81 (2021) 11, 1036

COSA RISERVA IL FUTURO ?

eXTP:
M-R with a precision less than 5%

La missione eXTP (enhanced X-ray Timing and Polarimetry) costerà circa 450 milioni Euro, lancio previsto nel 2025. Partnership Europa-Cina.

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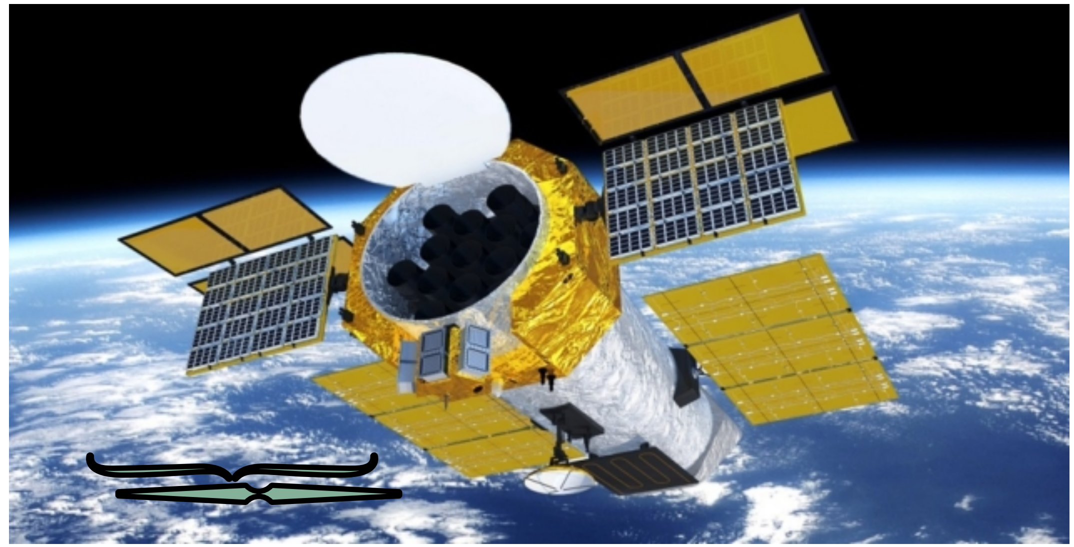

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Grazie per la Vostra attenzione