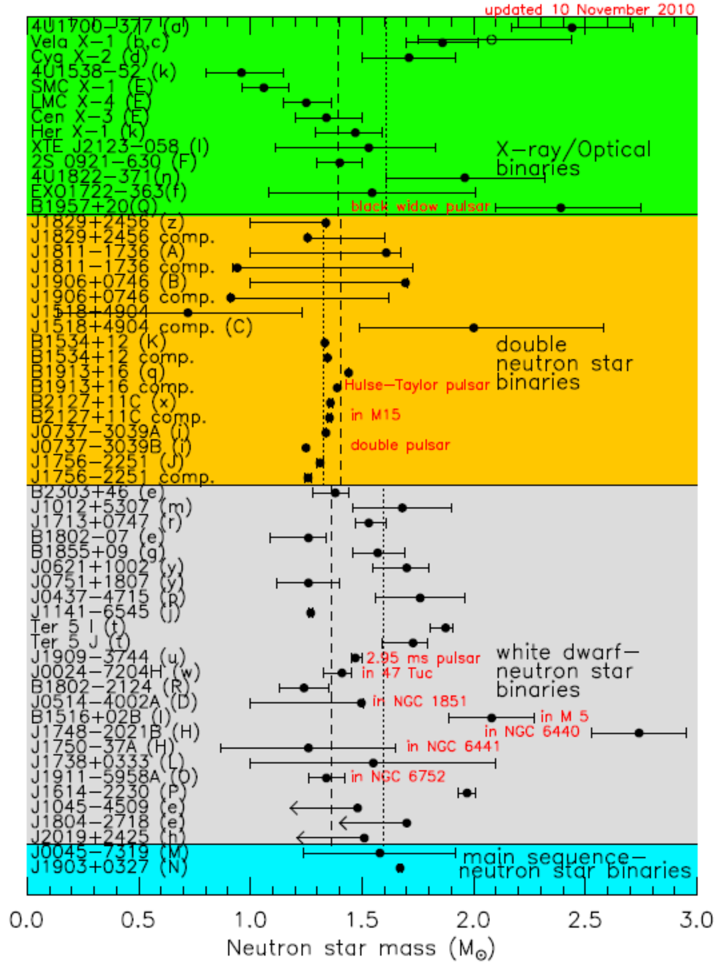
Problems and implications of the measurement of compact stars radii on the nuclear equation of state

Alessandro Drago
Ferrara

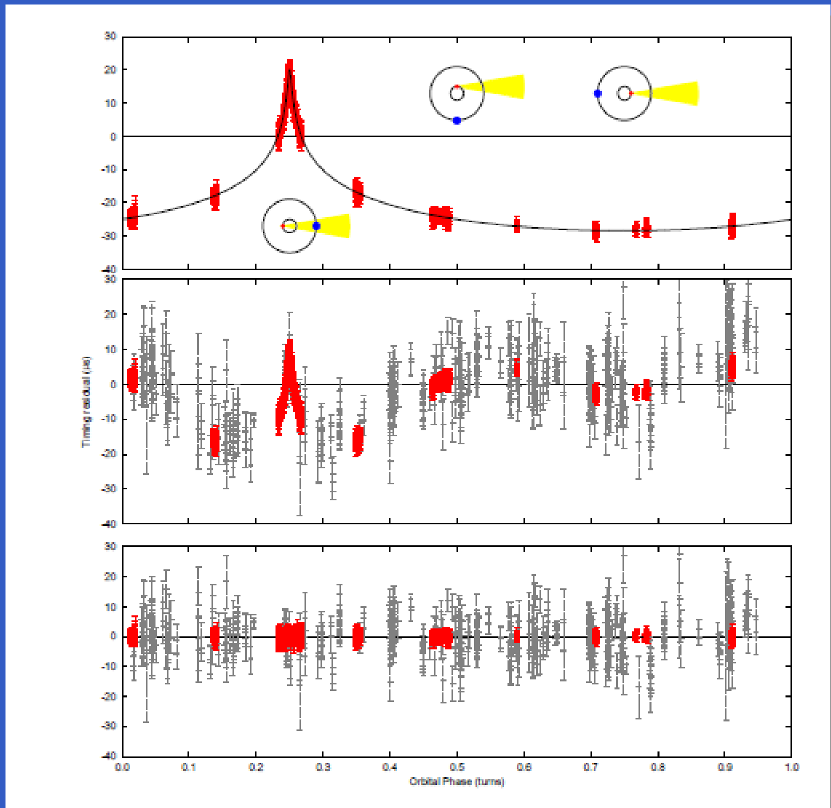
- A few crucial observational points about neutron stars
  - A 2 M_s star
  - What about radii?
  - Other observational data: fast rotation and cooling
- Hyperon production in compact stars
- Kaon condensation?
- Delta resonance production?
- Quark stars: is Witten's hypothesis still alive?
- Conclusions: which are the possibilities?

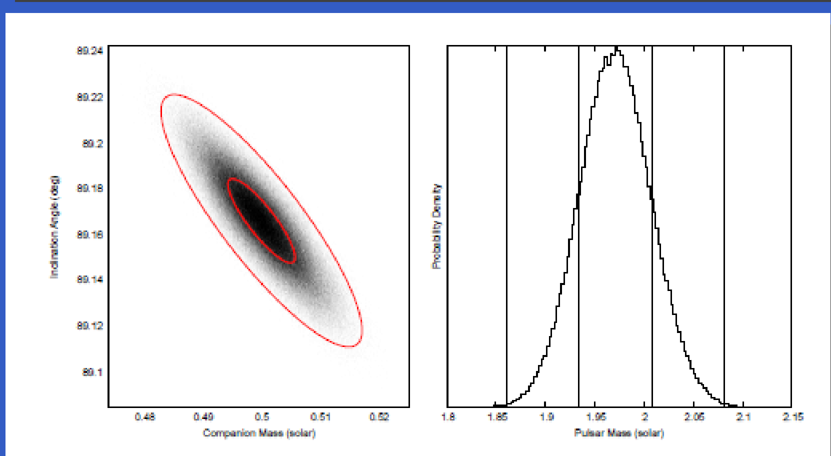
Masses of compact stars

Known masses of compact stars
Lattimer and Prakash 2010



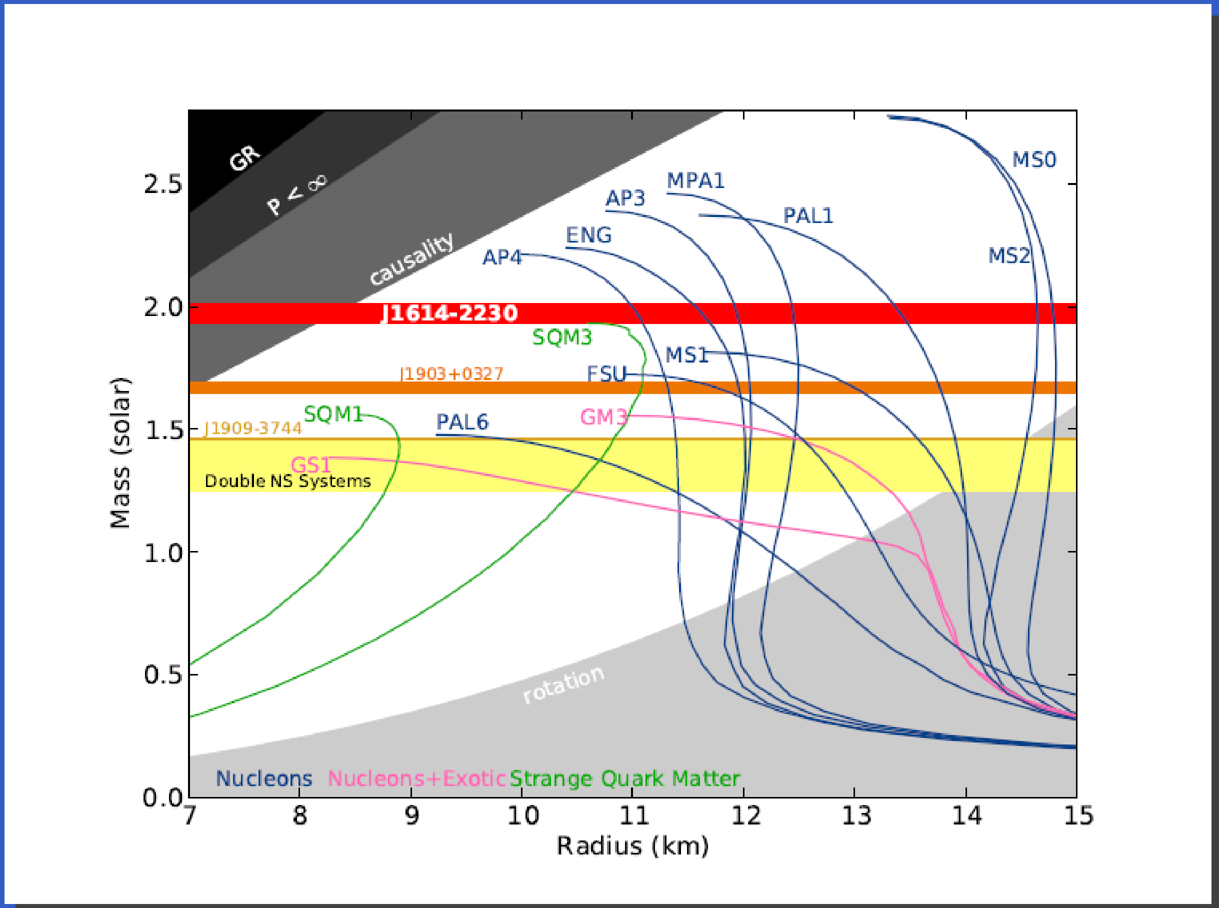
Mass measurement of pulsar PSR J1614-2230 (Demorest et al. 20





- extremely strong signal for Shapiro delay
- Shapiro delay parameters r and s alone give $M = (1.97 \pm 0.04) M_\odot$ - new record!
- by far the highest precisely measured pulsar mass!
- considerable constraints on neutron star matter properties!

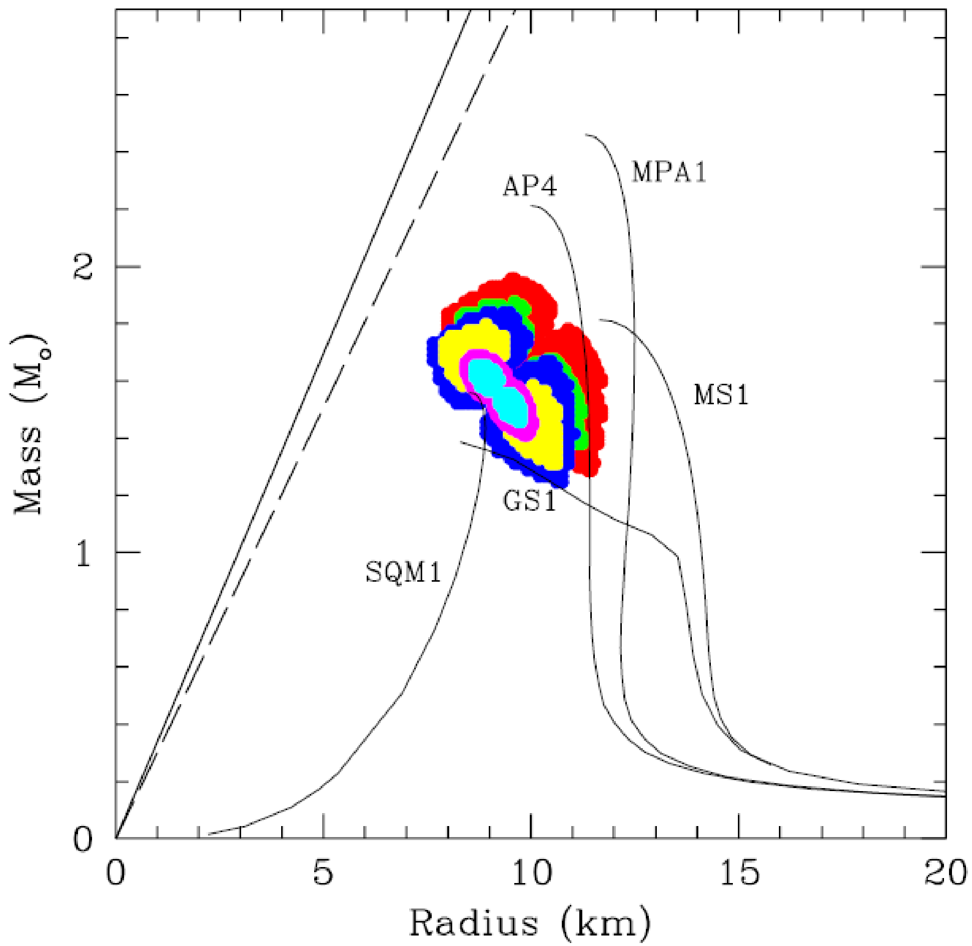
Constraints on the Mass–Radius Relation (Lattimer and Prakash 2004)



- spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4M_\odot$
- Schwarzschild limit (GR): $R > 2GM = R_s$
- causality limit for EoS: $R > 3GM$
- mass limit from PSR J1614-2230 (red band): $M = (1.97 \pm 0.04)M_\odot$

Radii of compact stars

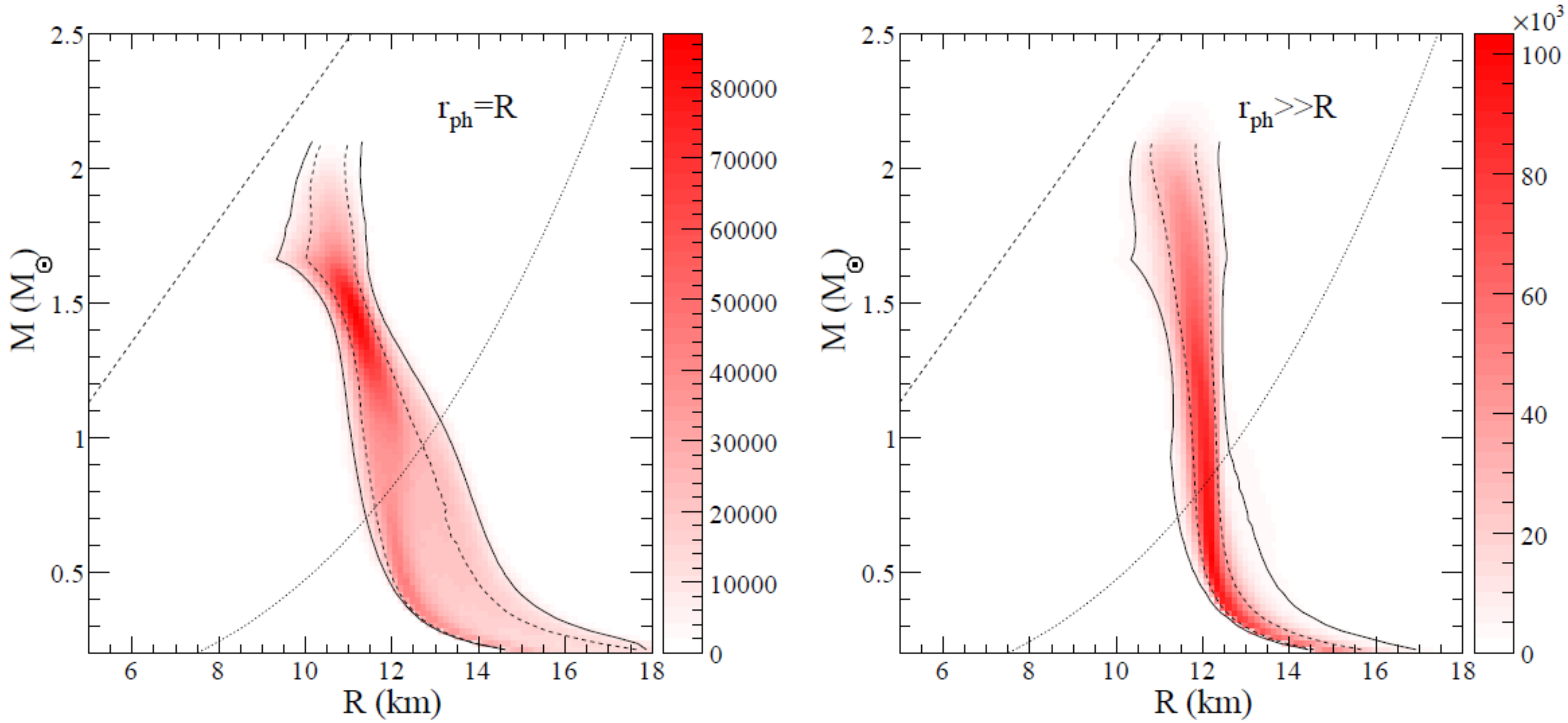
Oezel, Baym, Guever 2010
from LMXBs transient and quiescent emission



The Equation of State
from Observed Masses and Radii of Neutron Stars

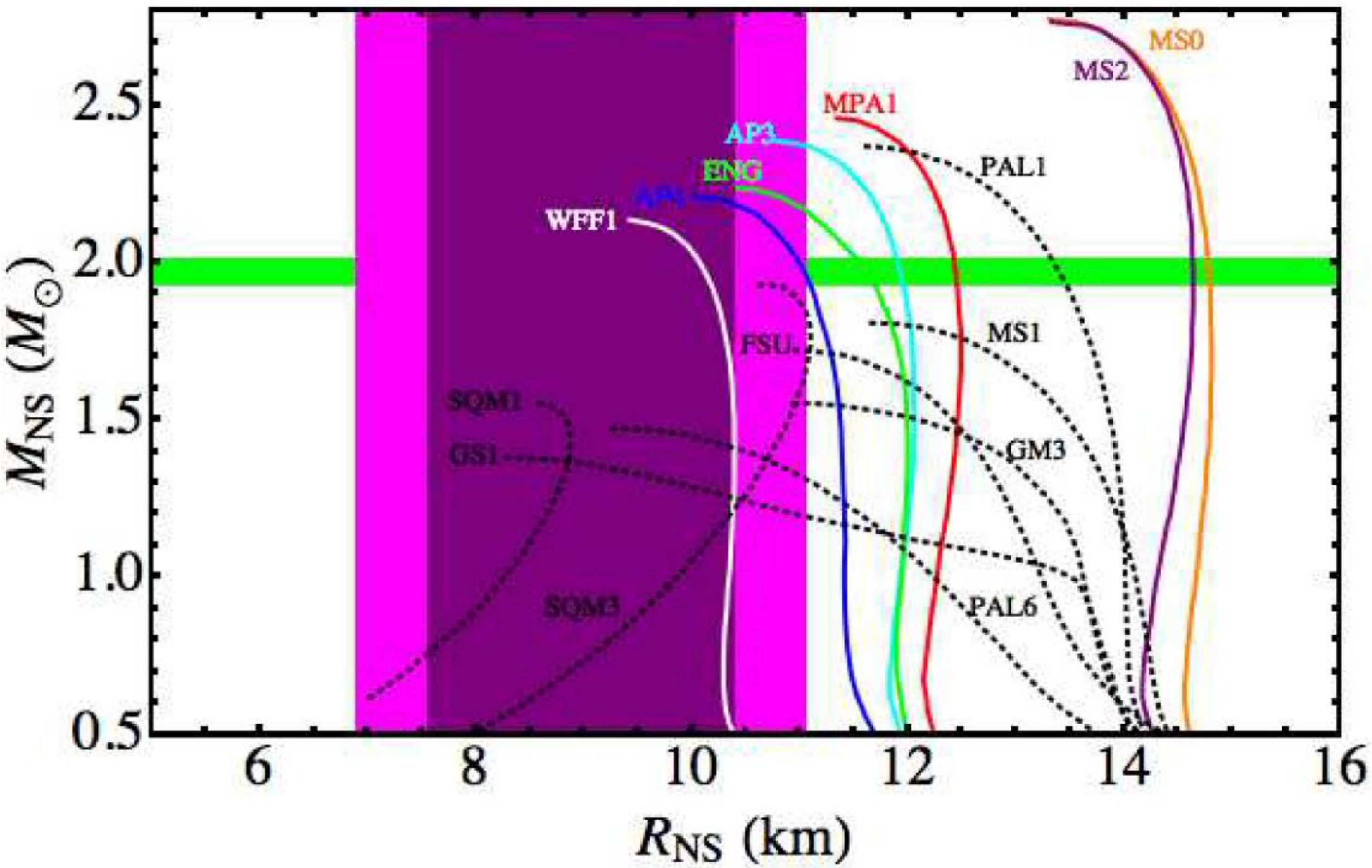
Steiner, Lattimer, Brown 2011

Bayesian analysis based on LMXBs and on x-ray bursts data

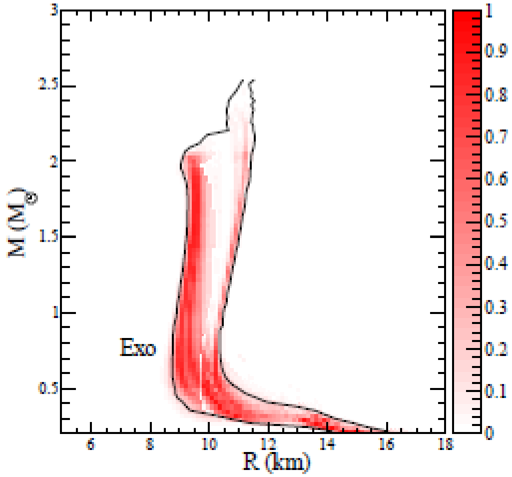


assumption that all neutron stars must lie on the same mass–radius curve

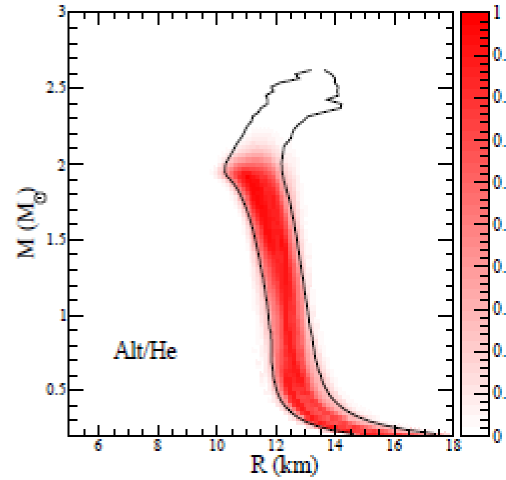
Guever et al. 2013
analysis of 5 QLMXBs

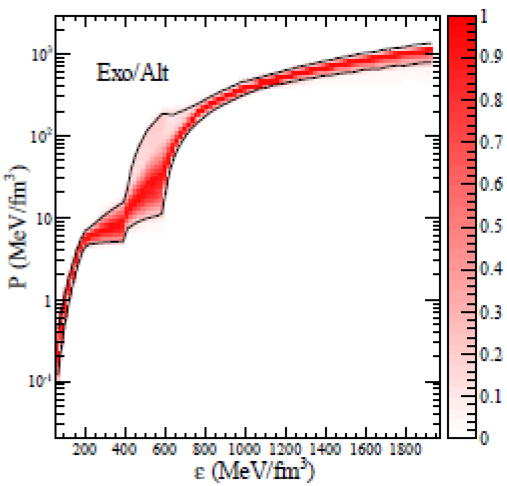


Lattimer and Steiner 2013

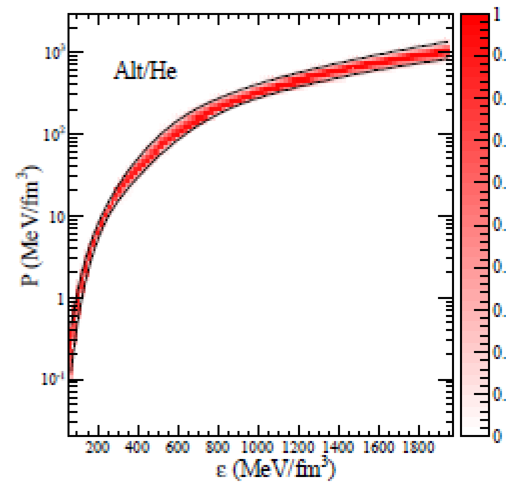


Strong dependence of the results on the composition of the atmosphere of the star, either H or He



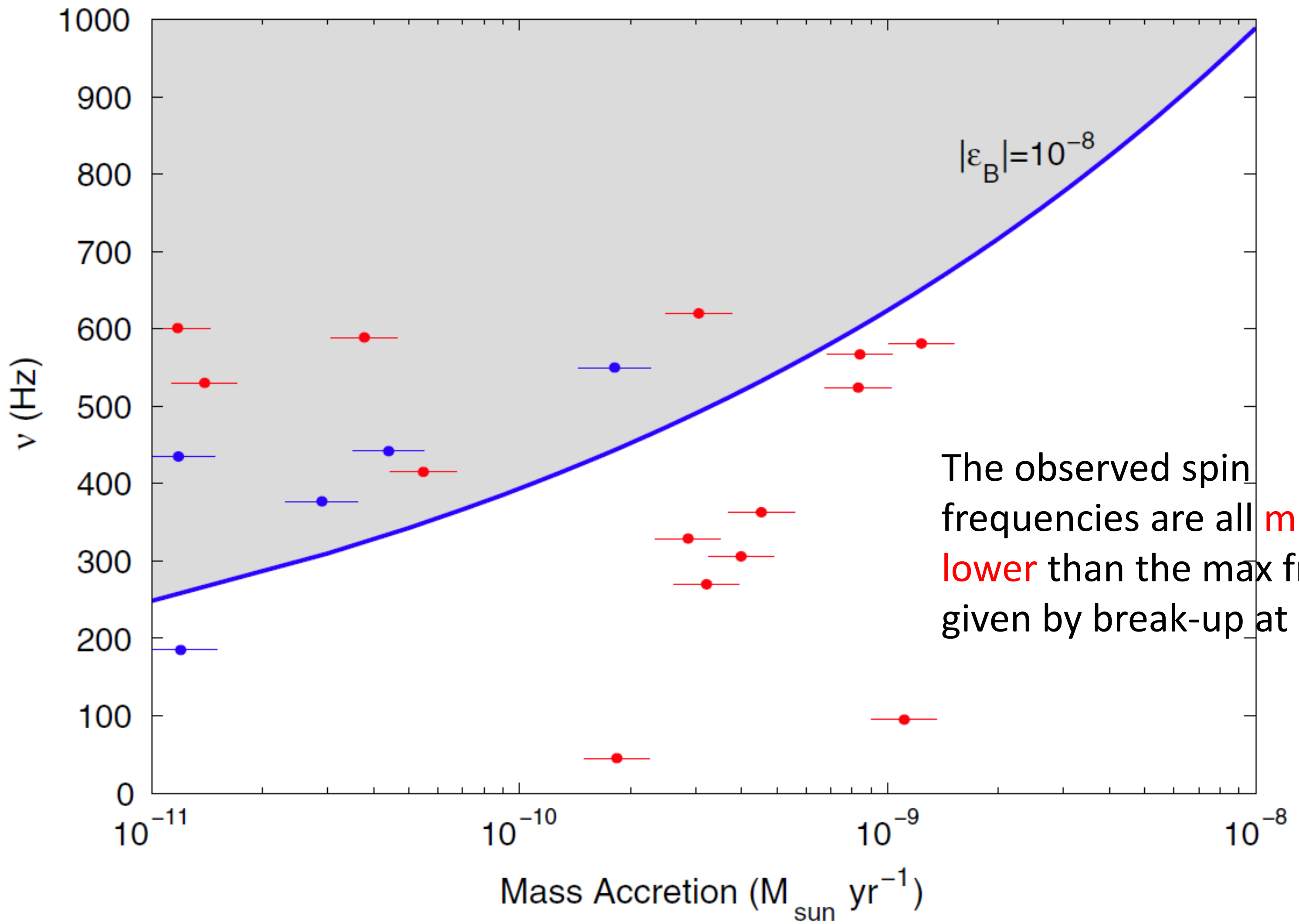


What if there are two different types of compact stars?



Other astrophysical constraints

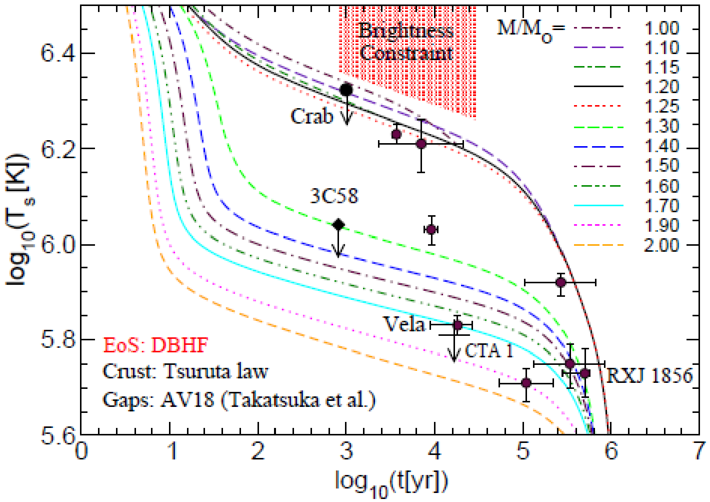
Spin frequencies of accreting compact stars

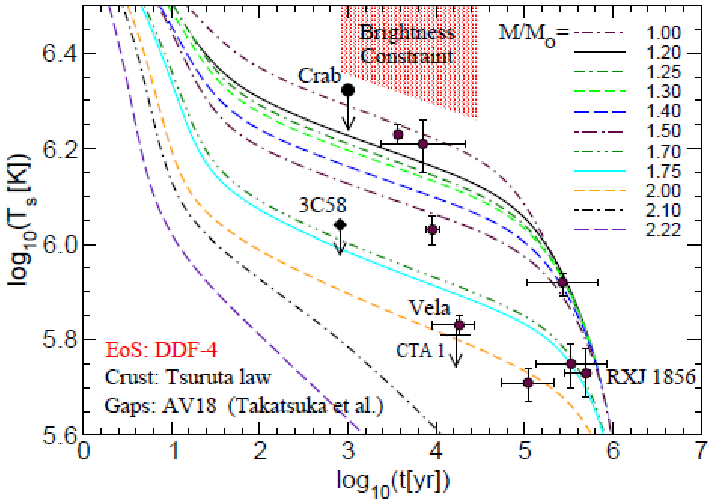


The observed spin frequencies are all much lower than the max frequency given by break-up at equator

Cooling of compact stars

Blaschke 2008



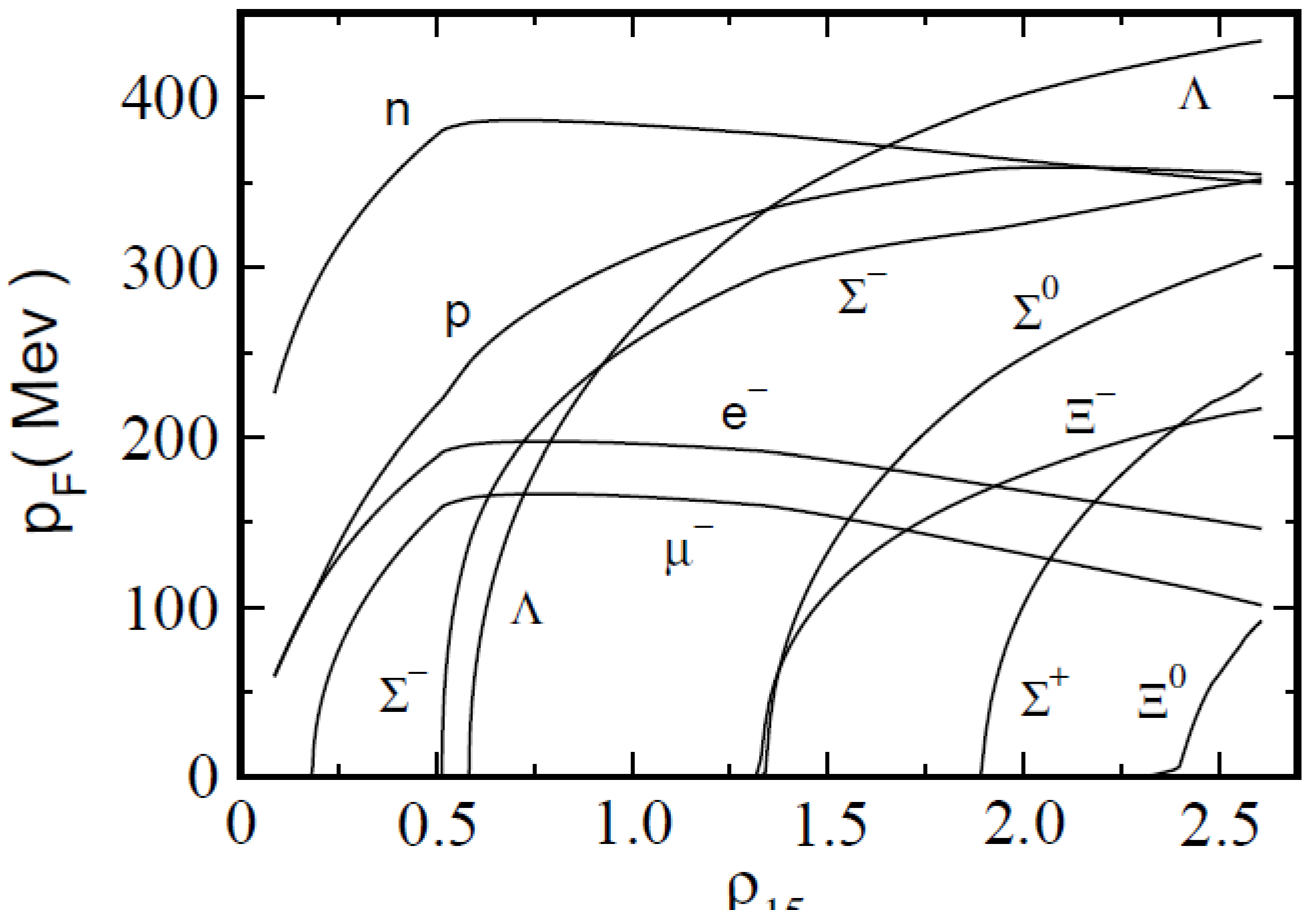


Strangeness production

- In heavy ion experiments strangeness can be produced only by strong-interaction and therefore via associated production. The typical fraction of strangeness is less than 10%
- In a compact star strangeness is mainly produced by weak interaction. Hyperons start appearing at densities above (2.5 – 3) ρ_0
- Hyperons can significantly soften the EoS: is it possible to have a

  2 M_s compact star with hyperons? Yes, but…

Hyperons in β-stable matter



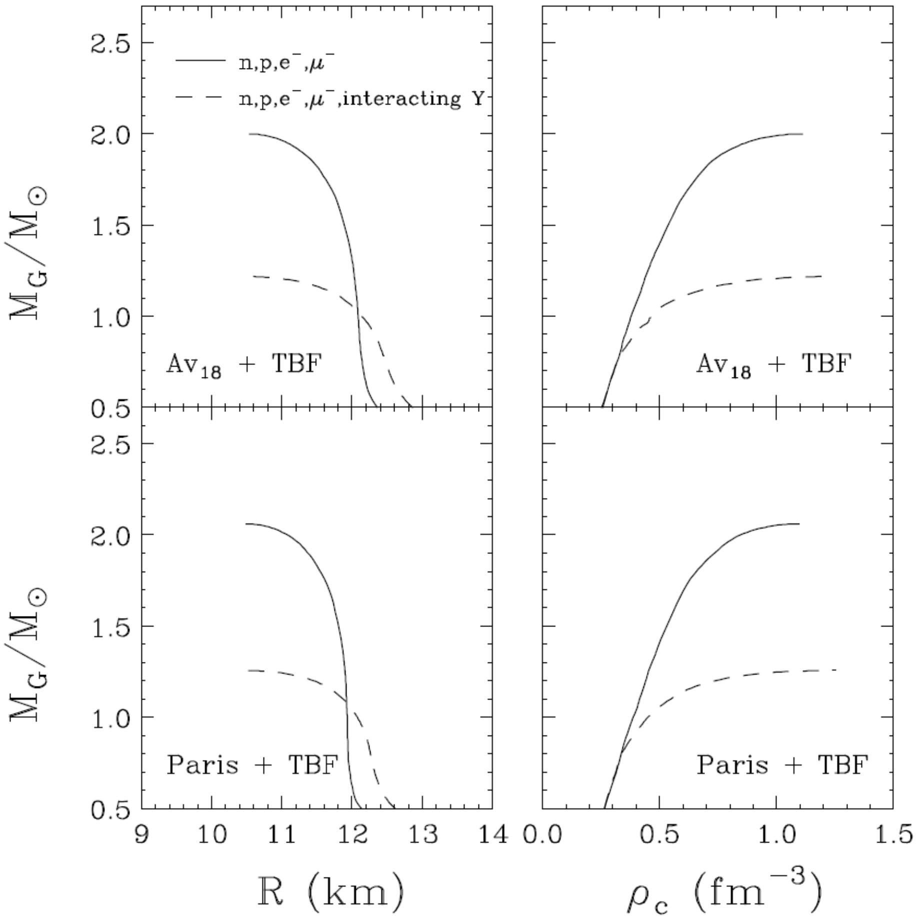
Stone, Guichon and Thomas 1012.2919, in connection with the discovery by Demorest at al. of the 2 Ms star:

"…Rather than being a surprise to find hyperons it would stretch our understanding of fundamental strong and weak interaction processes to breaking point if they were not to appear. It is certainly inconceivable that a nucleon-only EoS could be realistic at such large densities."

The problem of the maximum mass

Hyperonic stars in a non-relativistic BHF

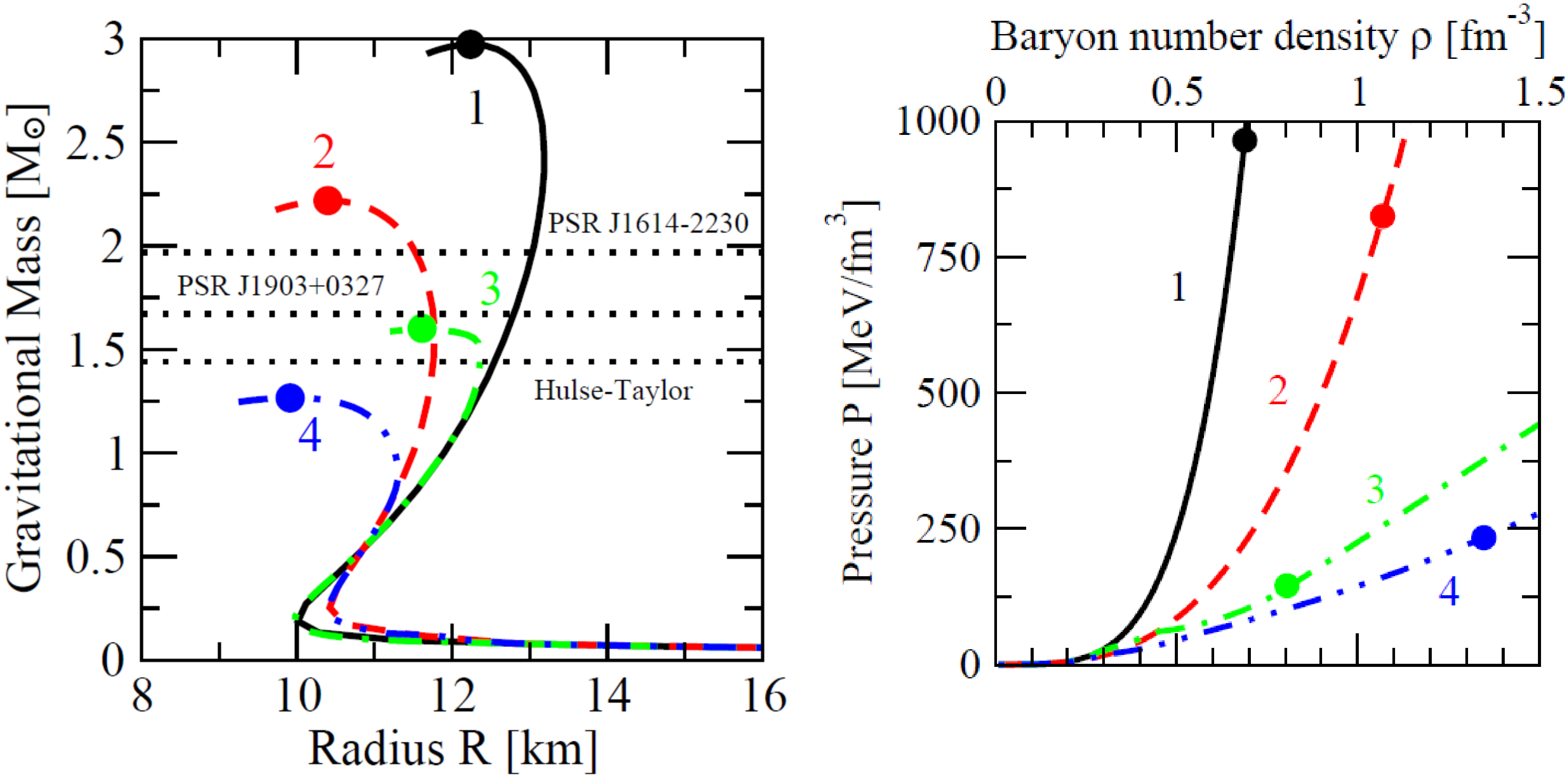
Baldo,Burgio, Schulze Phys.Rev. C61 (2000) 055801



The maximum mass of a hyperonic star in BHF is smaller than 1.4 Ms !

Hyperonic stars in a non-relativistic BHF with parametrised 3-body forces between hyperons

Vidana et al. Europhys.Lett. 94 (2011) 11002



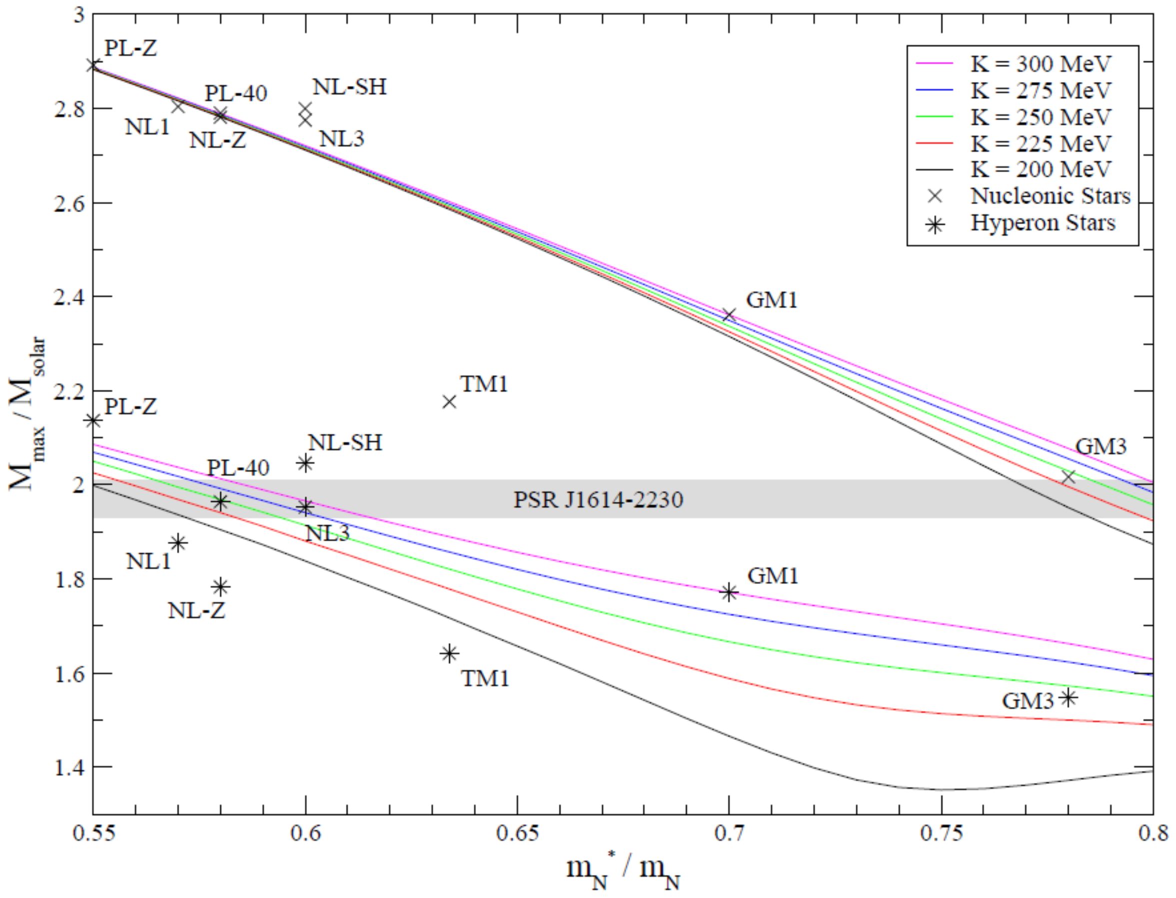
3-body forces are not sufficent to reach two solar masses

Note that the central density is very large, 5 – 9 ρ_0

A relativistic approach could be needed

Hyperonic stars in a relativistic mean-field with a repulsive vector ϕ-meson interaction

Weissenborn, Chatterjee, Schaffner-Bielich Nucl.Phys. A881 (2012) 62



SU(6) symmetry imposed

Large maximum masses can be obtained but only if the effective mass of the nucleon is strongly reduced

Hyperonic stars in a relativistic mean-field with a repulsive vector ϕ-meson interaction

Weissenborn, Chatterjee, Schaffner-Bielich Phys.Rev. C85 (2012) 065802

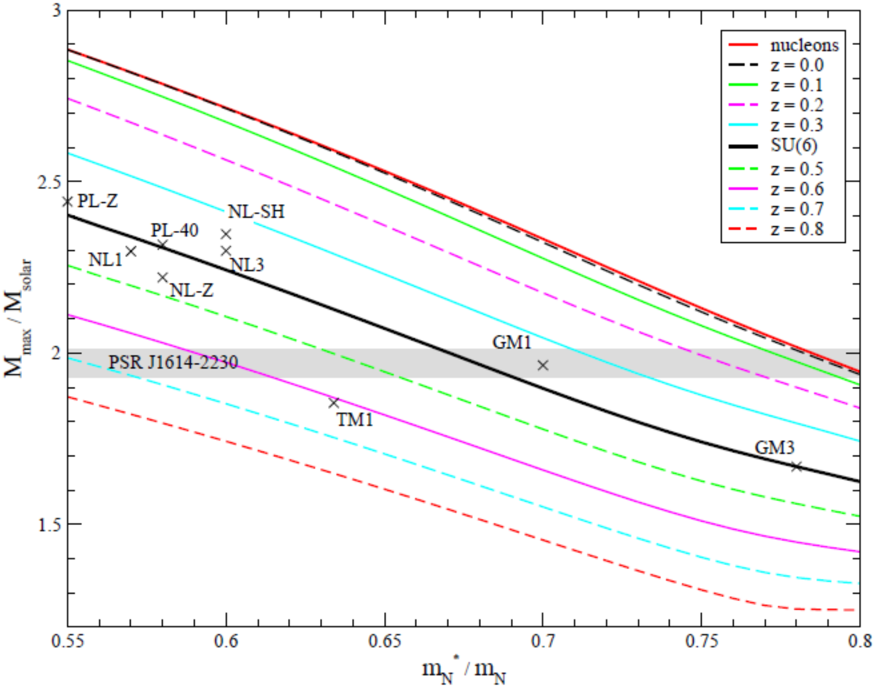


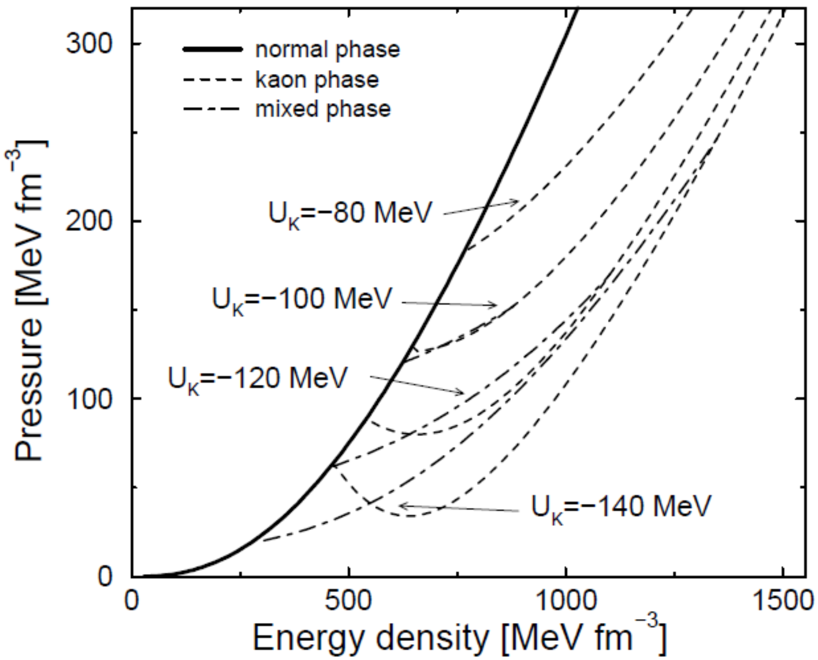
Figure 6: Maximum masses of hyperonic neutron stars as functions of effective nucleon mass m_N^* for different values of the g_8/g_1 ratio z. For comparison, a line for nucleonic stars and points to mark RMF sets e.g. TM1, NL3 corresponding to the SU(6) case are also given.

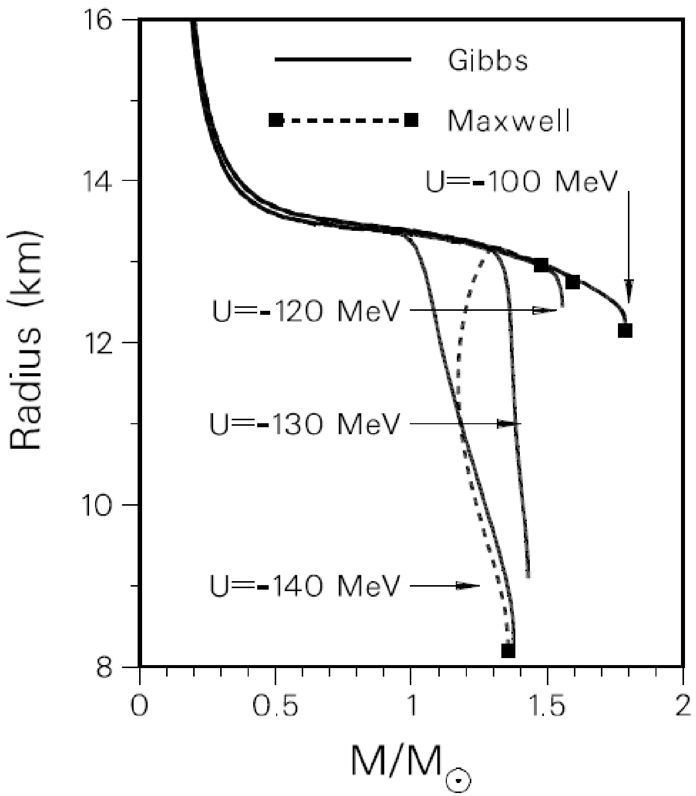
Beyond SU(6)
Ideal mixing
for vector
mesons, but
g_8/g_1 = z free

$$\mathcal{L}_{int} = -g_8\sqrt{2}\left[\alpha Tr\left([\overline{B}, M_8]B\right) + (1-\alpha)Tr\left(\{\overline{B}, M_8\}B\right)\right] - g_1\sqrt{\frac{1}{3}}Tr(\overline{B}B)Tr(M_1)$$

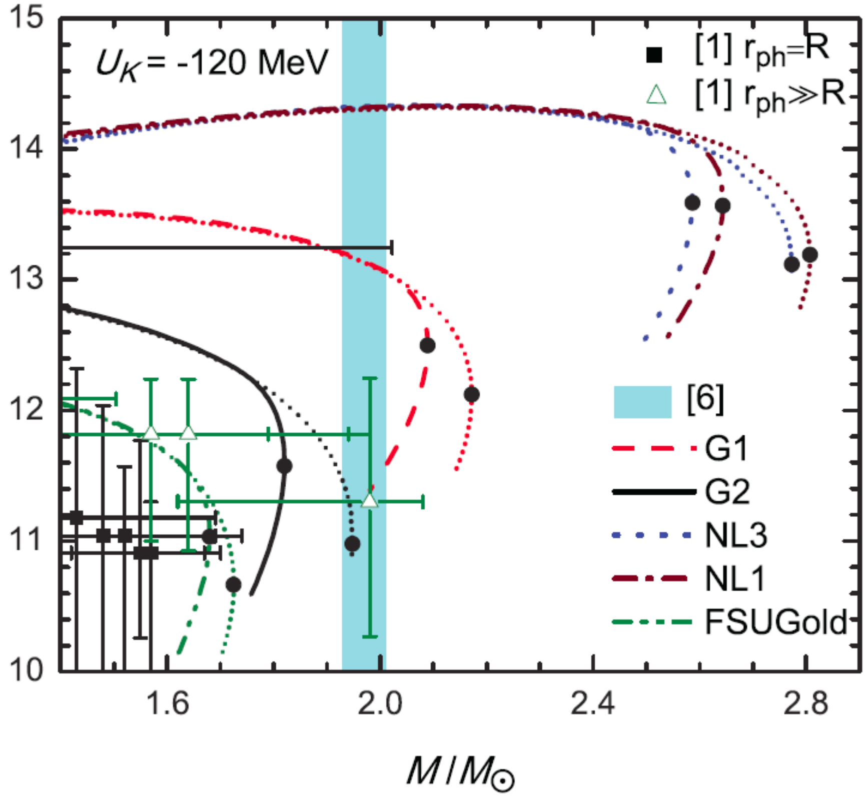
Kaon condensation?

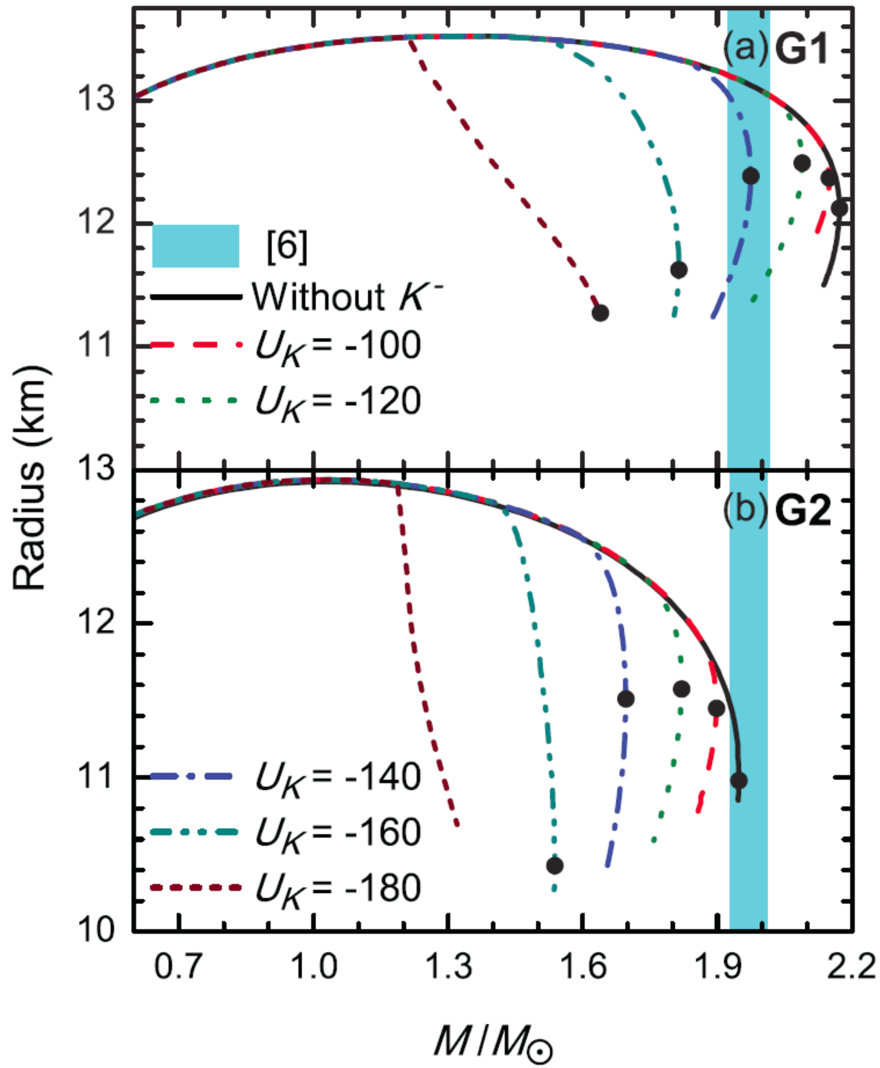
Glendenning & Schaffner-Bielich 1998





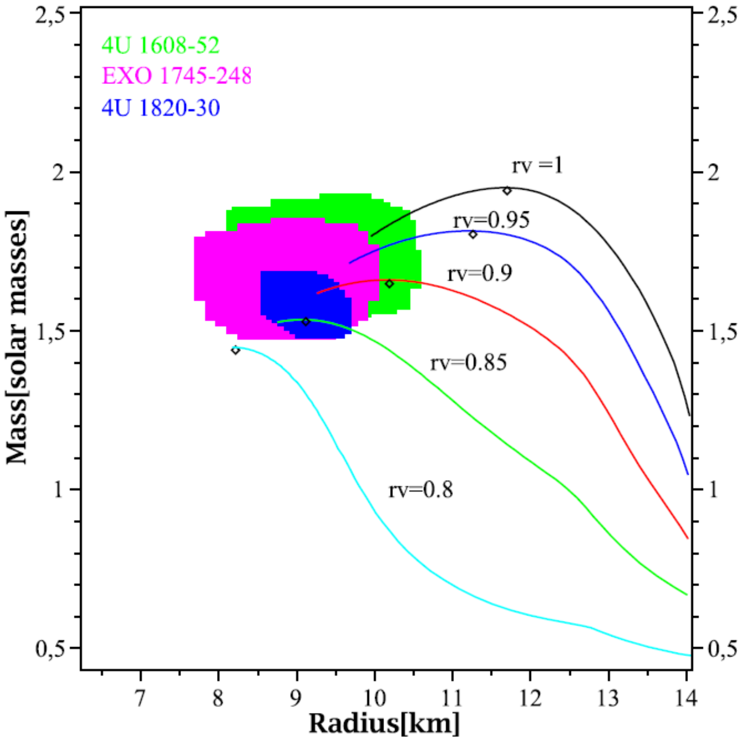
Gupta & Arumugam 2012



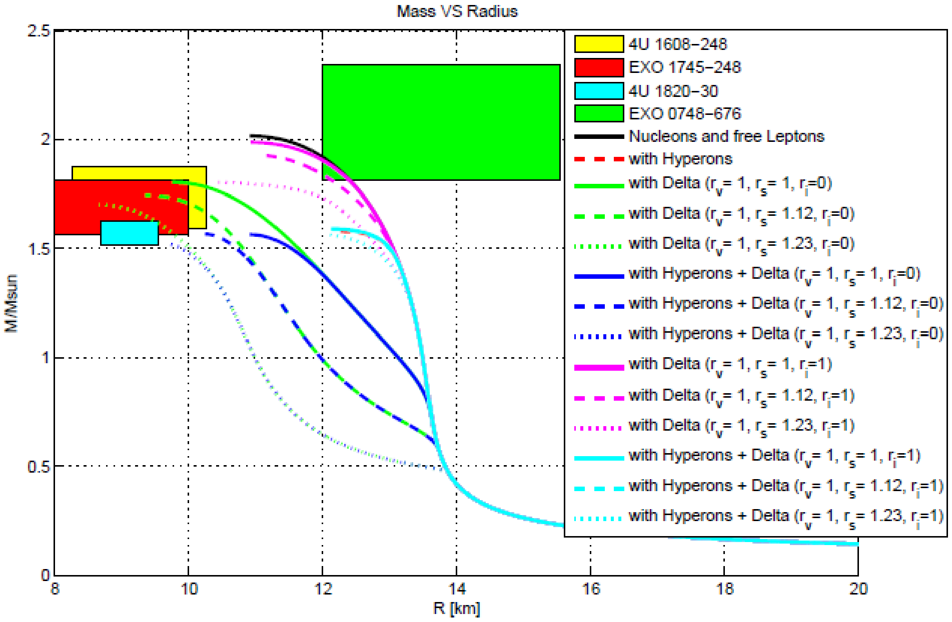


Taking into account also Delta resonances

Schurhoff, Schramm, Dexheimer 2010



Lavagno et al, in preparation



Implications and speculations

- Hyperons, kaons and Delta resonances can appear more or less in the same density range, about 2-3 ρ_0
- Their effect is to soften the EOS, making it difficult to obtain a 2 M_s star
- Somehow similar to heavy ion situation where the hadron resonance gas seems too soft to explain the data
- Transition to a new and stiffer phase of matter?

What about quarks?

Hyperons and quarks in β-stable matter

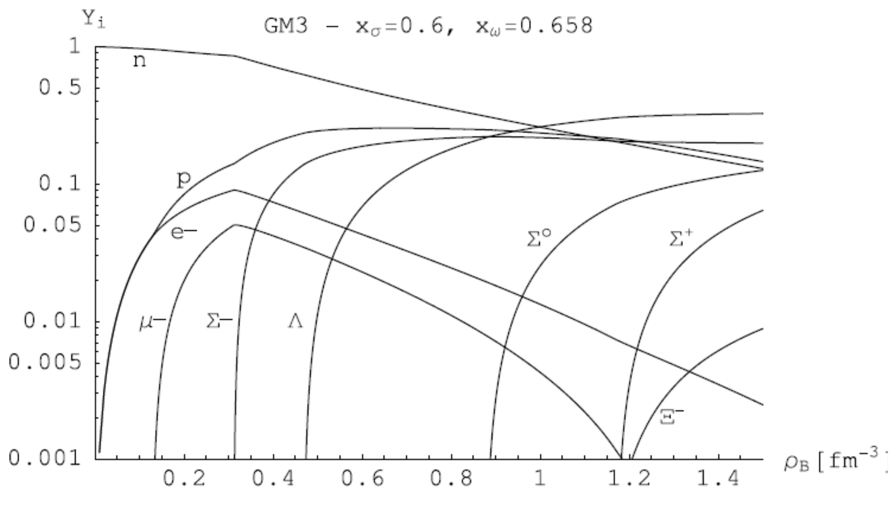


FIG. 1.—Particle fractions Y_i of neutral and β-stable hadronic matter as func tions of baryonic density ρ_B for the GM3 hadronic equation of state of Glendennin & Moszkowski (1991).

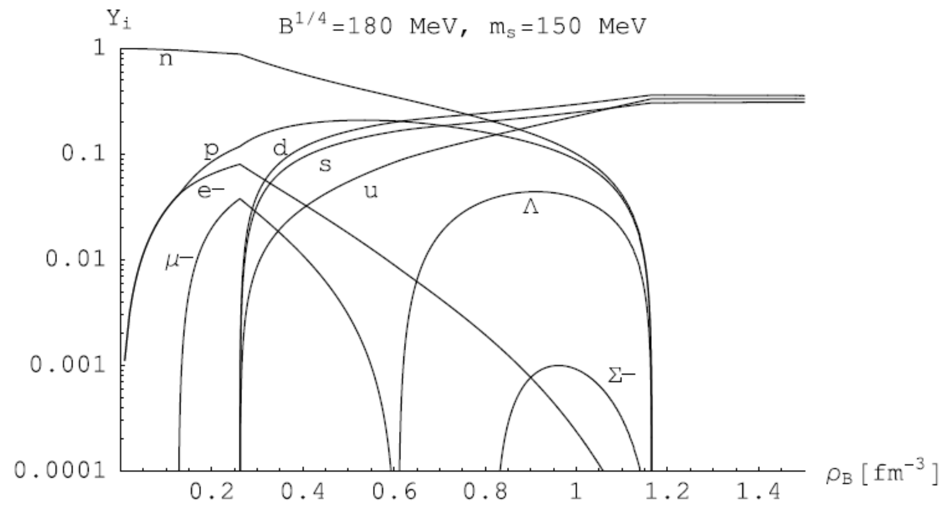
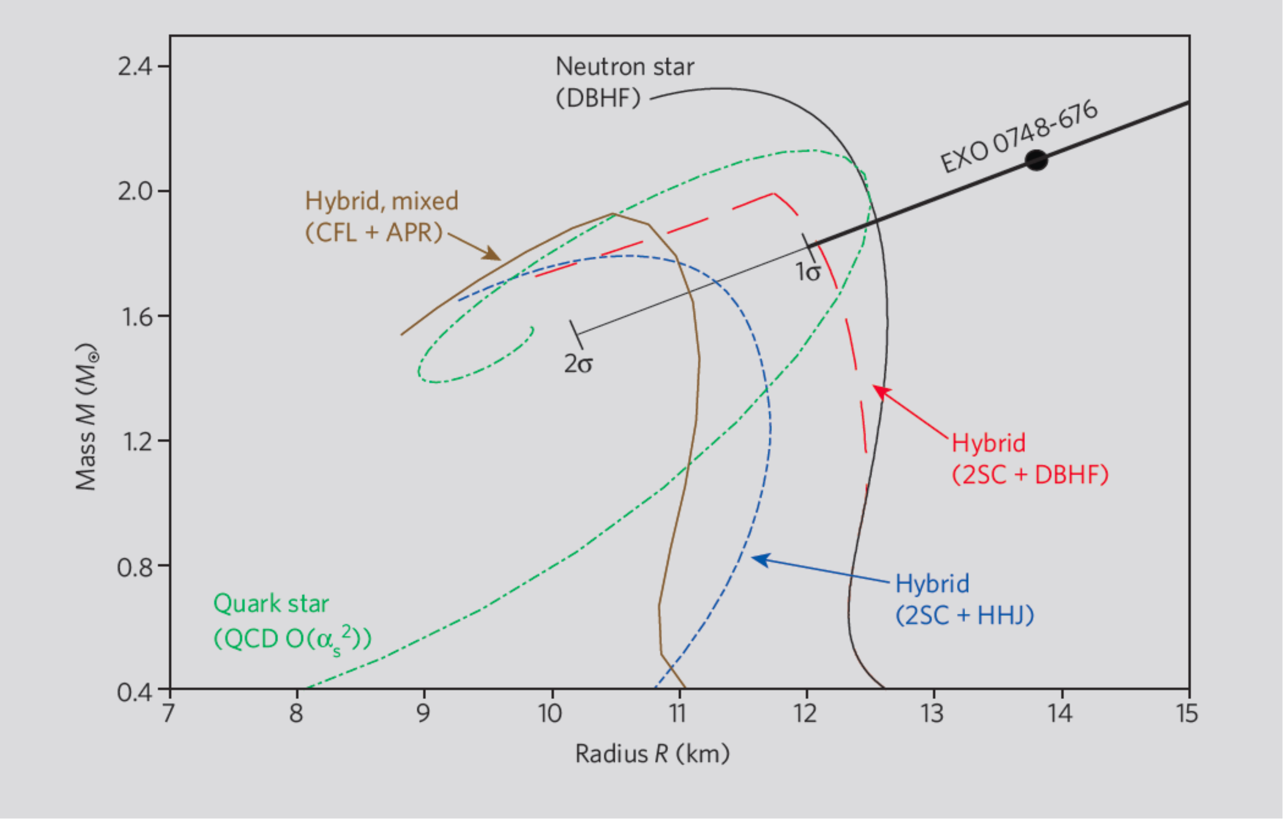


FIG. 3.—Particle fractions Y_i of neutral and β-stable hadronic and quark matter as functions of baryonic density ρ_B for the same GM3 hadronic equation of state used in Fig. 1 and using the MIT bag model with $B^{1/4} = 180$ MeV to describe the quark phase.

Hybrid and quark stars can be massive

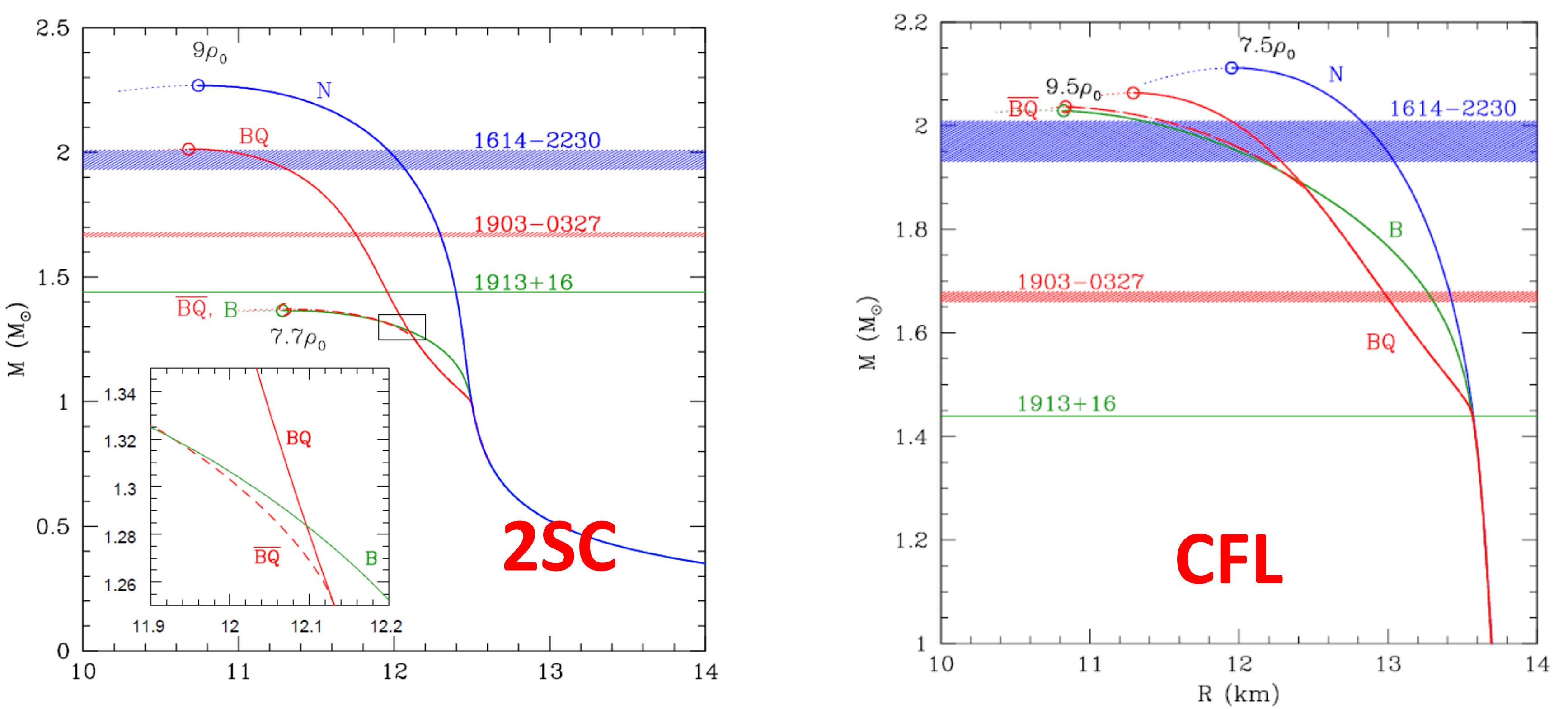
Alford, Blaschke, Drago, Klaehn, Pagliara, Schaffner-Bielich   Nature 445, E7 (2007)



Transitions from a purely hadronic configuration to a configuration containing at least in part deconfined quark matter are possible. Energies of the order of a few 10^{53} erg are liberated in the transition

Hybrid stars are possible

Zdunik and Haensel 2012



Density jumps at the phase transitions have to be small and sound speeds in quark matter large

Are quark stars ruled out?

Phys.Rev.Lett. 103 (2009) 011101

Mass ejection by strange star mergers and observational implications

A. Bauswein,[1] H.-T. Janka,[1] R. Oechslin,[1] G. Pagliara,[2] I. Sagert,[3] J. Schaffner-Bielich,[2] M. M. Hohle,[4,5] and R. Neuhäuser[4]

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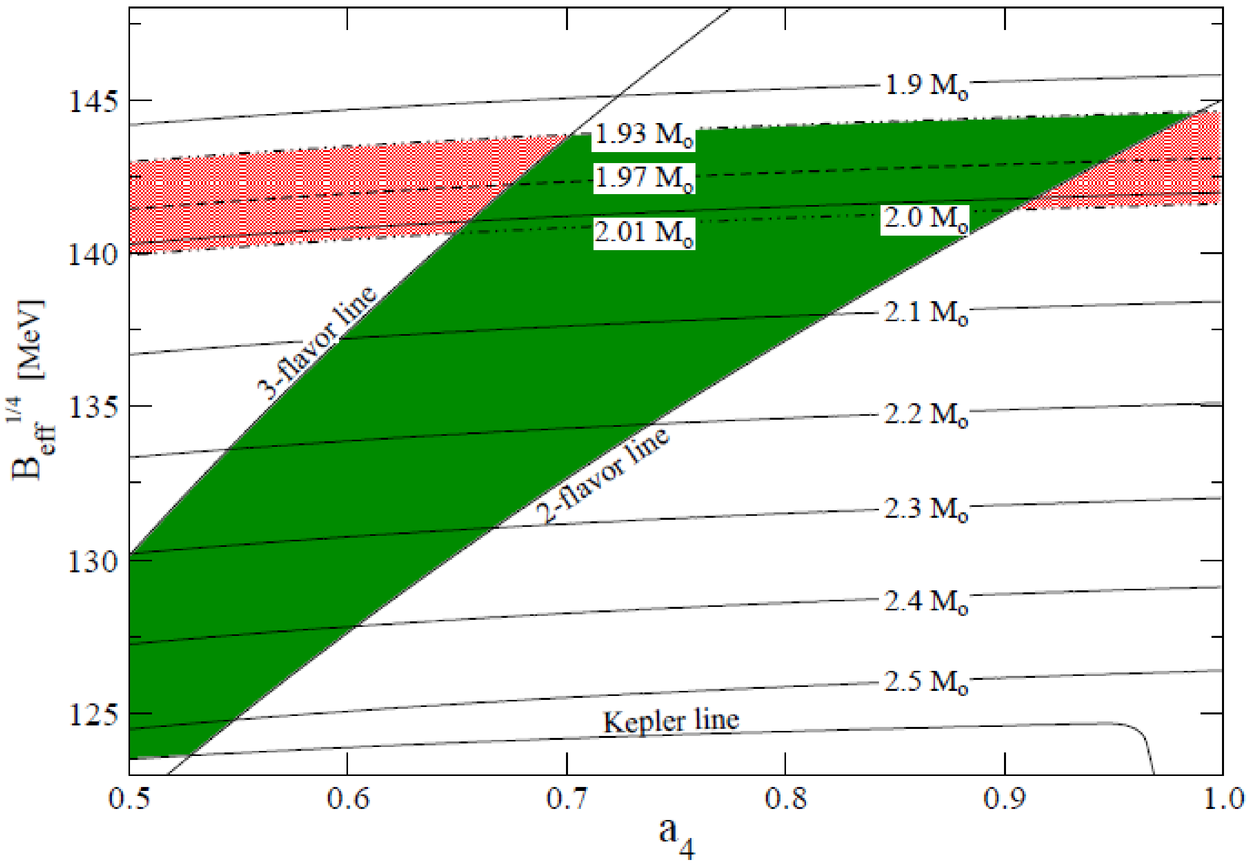
[5] *Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany*

(Dated: June 30, 2009)

We determine the Galactic production rate of strangelets as a canonical input to calculations of the measurable cosmic ray flux of strangelets by performing simulations of strange star mergers and combining the results with recent estimates of stellar binary populations. We find that the flux depends sensitively on the bag constant of the MIT bag model of QCD and disappears for high values of the bag constant and thus more compact strange stars. In the latter case strange stars could coexist with ordinary neutron stars as they are not converted by the capture of cosmic ray strangelets. An unambiguous detection of an ordinary neutron star would then *not* rule out the strange matter hypothesis.

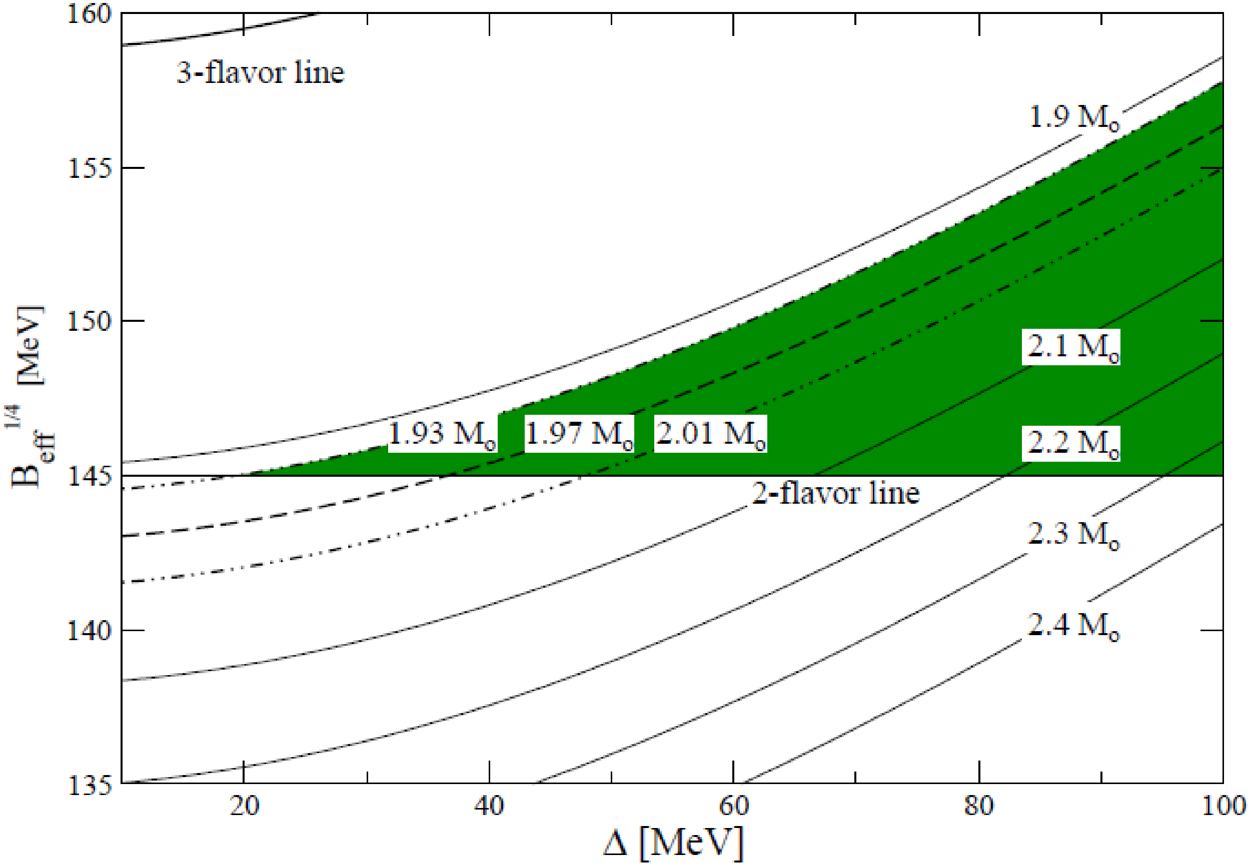
Maximum masses for quark stars
MIT-bag model with gluonic interaction

Weissenborn et al. Astrophys.J. 740 (2011) L14



Maximum masses for quark stars
MIT-bag model with CFL condensate

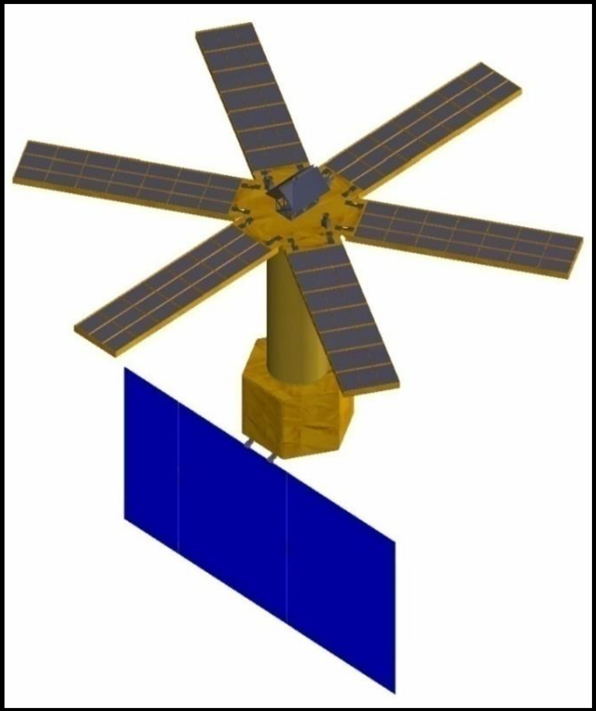
Weissenborn et al. Astrophys.J. 740 (2011) L14

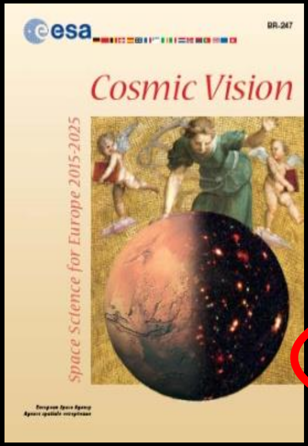


Maximum masses up to 2.2 Ms can be obtained

The role of LOFT

LOFT: the Large Observatory For x-ray Timing





3. What are the fundamental physical laws of the Universe?

3.1 Explore the limits of contemporary physics

Use stable and weightless environment of space to search for tiny deviations from the standard model of fundamental interactions

3.2 The gravitational wave Universe

Make a key step toward detecting the gravitational radiation background generated at the Big Bang

3.3 Matter under extreme conditions

Probe gravity theory in the very strong field environment of black holes and other compact objects, and the state of matter at supra-nuclear energies in neutron stars

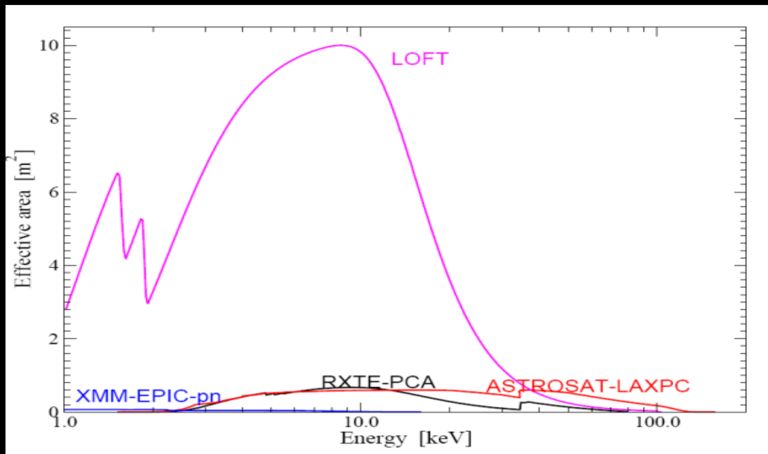
LOFT Consortium: national representatives:

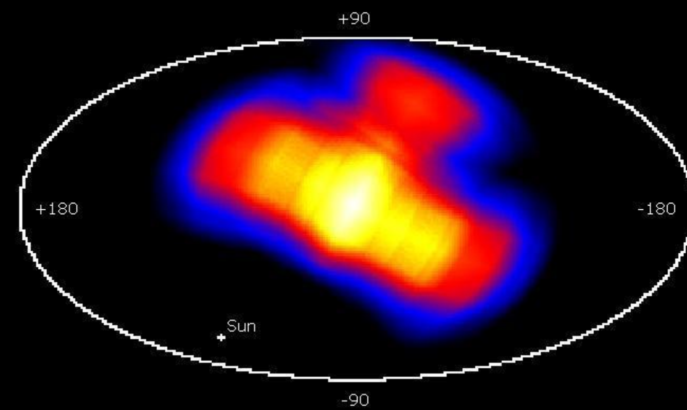
Jan-Willem den Herder SRON, the Netherlands
Marco Feroci INAF/IAPS-Rome, Italy
Luigi Stella INAF/OAR-Rome, Italy
Michiel van der Klis Univ. Amsterdam, the Netherlands
Thierry Courvousier ISDC, Switzerland
Silvia Zane MSSL, United Kingdom
Margarita Hernanz IEEC-CSIC, Spain
Søren Brandt DTU, Copenhagen, Denmark
Andrea Santangelo Univ. Tuebingen, Germany
Didier Barret IRAP, Toulouse, France
Renè Hudec CTU, Czech

LOFT Science Team composed of scientists from:

Australia, Brazil, Canada, CzechRepublic, Denmark, Finland, France, Germany, Greece, Ireland, Israel, Italy, Japan, theNetherlands, Poland, Spain, Sweden, Switzerland, Turkey, United Kingdom, USA

LOFT Instruments





LAD - Large Area Detector	
Effective Area	4 m² @ 2 keV 8 m² @ 5 keV 10 m² @ 8 keV 1 m² @ 30 keV
Energy range	2-30 keV primary 30-80 keV extended
Energy resolution FWHM	260 eV @ 6 keV 200 eV @ 6 keV (45% of area)
Collimated FoV	1 degree FWHM
Time Resolution	10 µs
Absolute time accuracy	1 µs
Dead Time	<1% at 1 Crab
Background	<10 mCrab (<1% syst)
Max Flux	500 mCrab full event info 15 Crab binned mode

WFM– Wide Field Monitor	
Energy range	2–50 keV primary 50–80 keV extended
Active Detector Area	1820 cm²
Energy resolution	300 eV FWHM @ 6 keV
FOV (Zero Response)	180°x90° + 90°x90°
Angular Resolution	5↗ x 5↗
Point Source Location Accuracy (10–σ)	1↗ x 1↗
Sensitivity (5–σ, on-axis) Galactic Center, 3 s Galactic Center, 1 day	270 mCrab 2.1 mCrab
Standard Mode	5–min, energy resolved images
Trigger Mode	Event–by–Event (10µs res) Realtime downlink of

LOFT and ESA's Cosmic Vision program

3.3 Matter under extreme conditions

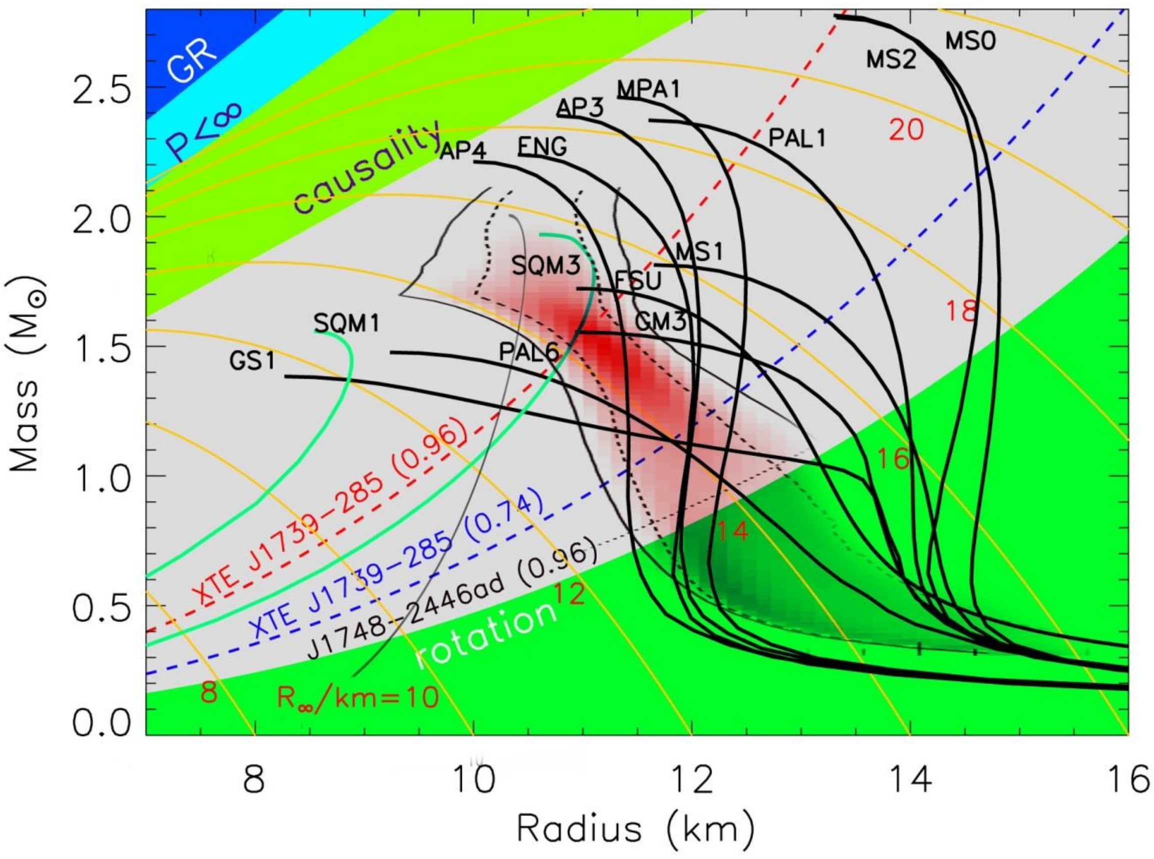
Probe gravity theory in the very strong field environment of black holes and other compact objects, and the state of matter at supra-nuclear energies in neutron stars

- Does matter orbiting close to a Black Hole event horizon follow the predictions of General Relativity?
- What is the Equation of State of matter in Neutron Stars?

→ Strong Gravity

→ Dense Matter

LOFT: measuring masses and radii with (5-10)% precision



Conclusions

- Astrophysical possibilities:
  - If radii of all stars are larger than about 11-12 Km just one type of compact stars probably exists, not yet clear if it is made of nucleons, of hyperons or if it is a hybrid star
  - If stars with radii smaller than about 10 Km exist than it is possible that there are two types of compact stars, one made of soft matter and one made of stiffer matter. Possible transition from one type to the other?
- Hadronic physics implications:
  - Strangeness plays a crucial role in the composition and the evolution of compact stars
  - Measuring the potentials of Λ and Σ in nuclear matter would allow to fix the critical densities of production of hyperonic matter
  - Measuring the potential of the $\Lambda\Lambda$ in nuclear matter would allow to put constraints on the hyperon-hyperon interaction and therefore on the high density behaviour
  - A large value of an attractive kaon potential in nuclear matter would likely indicate a dramatic instability of matter at high densities

The Galileo Galilei Institute for Theoretical Physics
Arcetri, Florence

The Structure and Signals of Neutron Stars, from Birth to Death

March 10, 2014 - April 17, 2014

The main topics of the workshop include:

- Equation of state of dense matter, including hyperon, kaon and quark degrees of freedom
- Neutrino emission and cooling of compact stars
- **Superconductivity**-superfluidity
- Constraints from EM observations; transients
- Gravitational wave emission
- Models for Supernovae and for Gamma Ray Bursts
- Magnetars

Neutron stars (NSs) represent an active area of research, from their birth following the collapse of massive stars in supernova explosions; to their lives as hot thermal sources, radio pulsars and/or magnetars; to their catastrophic demise (when they reside in compact binaries) following gravitational wave-driven coalescence. Progress in understanding the structure and signals of neutron stars demands expertise across a wide range of disciplines, from theoretical and observational astrophysics; to nuclear and particle physics; to computational relativity and gravitational wave (GW) physics. Several recent developments suggest that time is ripe for a workshop which **focuses** on all facets of NS science. These include the recent discovery of a 2 solar mass neutron star; evidence for cooling of the NS in Cas A, suggesting a possible transition to neutron superfluidity; `advanced' generation GW detectors LIGO and Virgo coming online in 2015; new observations challenging traditional models for gamma-ray bursts; new lab experiments which aim to probe the conditions of matter at ultrahigh densities and temperatures (e.g. NICA - Dubna coming online in 2015); and new or planned electromagnetic observatories at radio (LOFAR/ ASKAP/ MeerKAT/ SKA), optical (e.g. LSST), X-ray (NICER/ LOFT/ AXTAR/ Athena+), and gamma-ray (e.g. CTA) wavelengths.
This workshop will bring together theoretical and observational astrophysicists from across the electromagnetic and GW spectrum, as well as nuclear physicists interested in the behavior of matter under extreme conditions. The goal is to explore what has been learned from current observations; review what is expected from new facilities; and assess what exploratory work is required to lay the groundwork for these new capabilities. Throughout the workshop, senior researchers will deliver pedagogical lectures to PhD students, young postdoctoral researchers, and to other senior researchers wishing to expand their own knowledge. Lectures will **cover** topics in computational relativistic astrophysics, gamma-ray bursts, r-process nucleosynthesis, nucleonic and hadronic EoSs, constraints from EM observations, and GW physics. A general conference will also be organized during the workshop.

Local organizer: Daniele Dominici

Organizing Committee:
Fiorella Burgio (INFN Catania) - Alessandro Drago (University of Ferrara)
Ian Jones (Southampton University) - Brian Metzger (Columbia University)
Pierre Pizzochero (University of Milano) - Anna Watts (API Amsterdam)

GGI: http://www.ggi.fi.infn.it/

Deadline for the applications - 30 September 2013