Exotic Phases on Neutron Stars: Hyperons & d*(2380)

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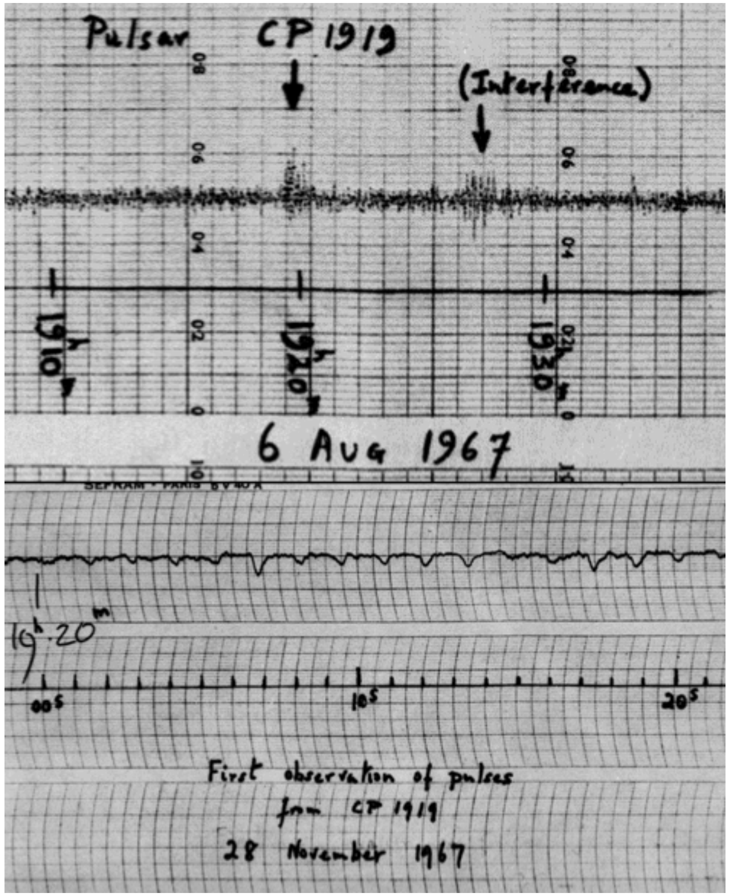
Exotic Hadron Spectroscopy 2017

December 11th-13th 2017, University of Edinburgh

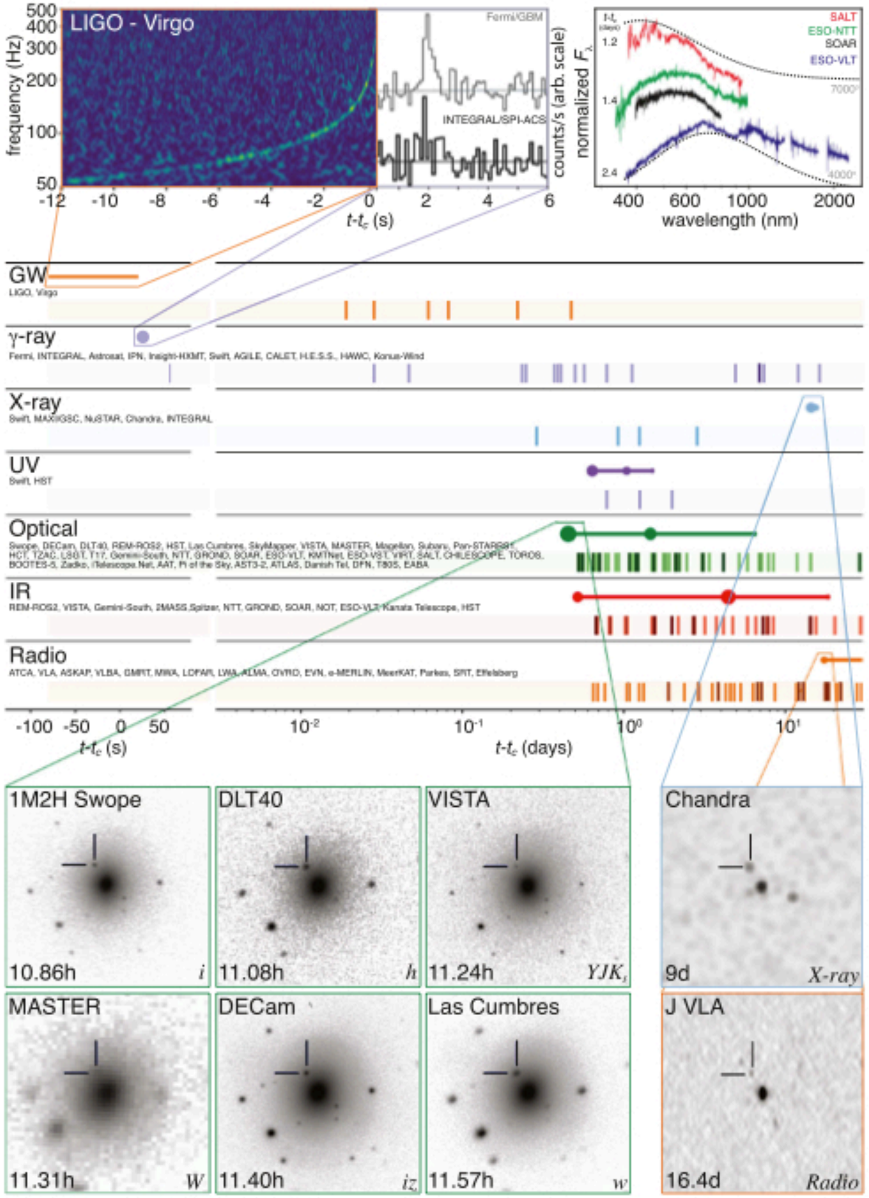
50 years of the discovery of the first radio pulsar

- radio pulsar at 81.5 MHz
- pulse period P=1.337 s



Most NS are observed as pulsars. In 1967 Jocelyn Bell & Anthony Hewish discover the first radio pulsar, soon identified as a rotating neutron star

Multi-messenger Observations of the Event GW170817



LIGO/VIRGO GW detection with associated electromagnetic events observed by over 70 observatories

- August 17th 2017 12:41:04 UTC

  GW from a BNS merger detected by Adv. LIGO & Adv. VIRGO

- + 1.7 seconds

  GRB (GRB170817A) detected by FERMI γ-ray Burst Monitor & INTEGRAL

- Next hours & days
  - New bright source of optical light (SSS17a) detected in the galaxy NGC 4993 in the Hydra constellation (+10h 52m)
  - Infrared emission observed (+11h 36m)
  - Bright ultraviolet emission detected (+15h)
  - X-ray emission detected (+9d)
  - Radio emission detected (+16d)

Recent Measurements of High NS Masses

- **PSR J164-2230** (Demorest et al. 2010)

✓ binary system (P=8.68 d)

✓ low eccentricity ($\varepsilon=1.3 \times 10^{-6}$)

✓ companion mass: $\sim 0.5 M_{\odot}$

✓ pulsar mass: $M = 1.928 \pm 0.017 M_{\odot}$

- **PSR J0348+0432** (Antoniadis et al. 2013)

✓ binary system (P=2.46 h)

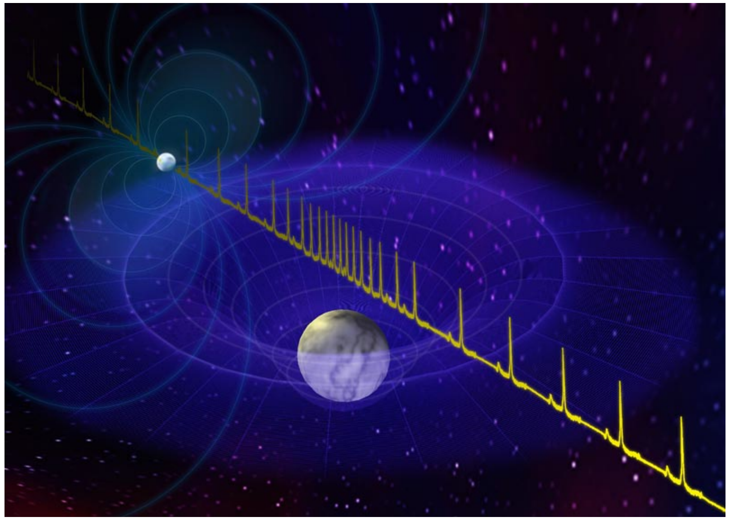
✓ very low eccentricity

✓ companion mass: $0.172 \pm 0.003 M_{\odot}$

✓ pulsar mass: $M = 2.01 \pm 0.04 M_{\odot}$

In this decade NS with $2M_{\odot}$ have been observed by measuring Post-Keplerian parameters of their orbits

- Advance of the periastron $\dot{\omega}$
- Shapiro delay (range & shape)
- Orbital decay $\dot{P}_b$
- Grav. redshift & time dilation γ

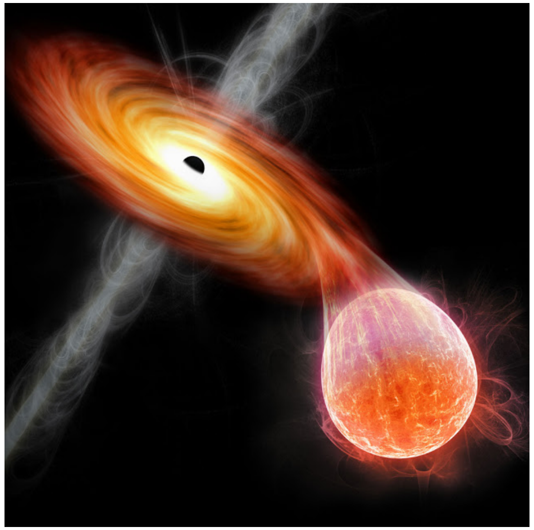


Neutron Star Radii

Radii are very difficult to measure because NS:

- ✧ are very small (~ 10 km)
- ✧ are far from us (e.g., the closest NS, RX J1856.5-3754, is at ~ 400 ly)

A possible way to measure it is to use the thermal emission of low mass X-ray binaries:

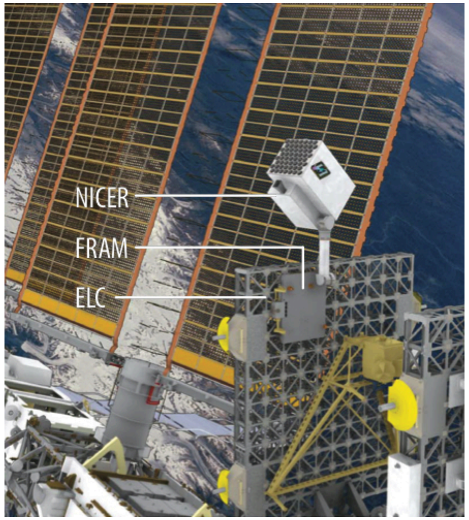


NS radius can be obtained from

- ✧ Flux measurement +Stefan-Boltzmann's law
- ✧ Temperature (Black body fit+atmosphere model)
- ✧ Distance estimation (difficult)
- ✧ Gravitational redshift z (detection of absorption lines)

$$R_\infty = \sqrt{\frac{FD^2}{\sigma_{SB} T^4}} \rightarrow R_{NS} = \frac{R_\infty}{1+z} = R_\infty \sqrt{1 - \frac{2GM}{R_{NS} c^2}}$$

NICER: Neutron Star Interior Composition Explorer



- ✧ International Space Station (ISS) payload devoted to the study of neutron stars through soft X-ray timing
- ✧ Launched aboard a SpaceX Falcon 9 rocket on June 3rd 2017

- ✧ Science objectives:
  - ➢ To resolve the nature of ultradense matter at the threshold of collapse to a black hole
  - ➢ To reveal the interior composition, dynamic processes & radiation mechanisms of neutron stars
  - ➢ To measure neutron star radii to 5% precision

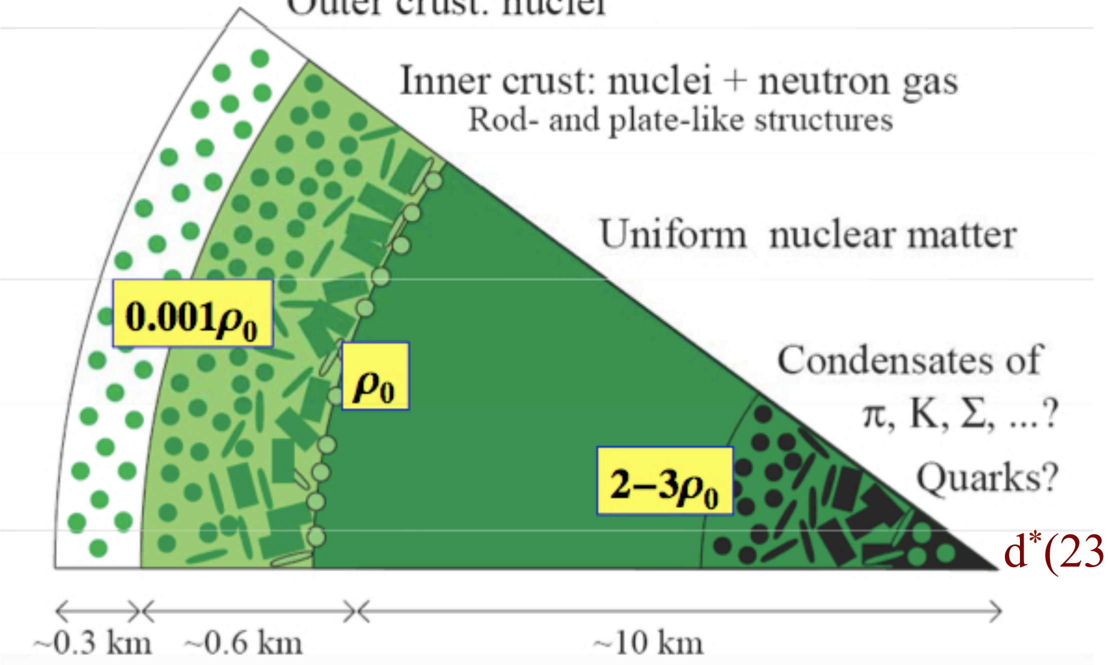
Anatomy of a Neutron Star

Equilibrium composition
determined by

- ✓ Charge neutrality

$$\sum_i q_i \rho_i = 0$$

- ✓ Equilibrium with respect to weak interacting processes



$d^*(2380)$?

$$\begin{aligned} b_1 &\rightarrow b_2 + l + \bar{\nu}_l \\ b_2 + l &\rightarrow b_1 + \nu_l \end{aligned} \quad \longrightarrow \quad \mu_i = b_i \mu_n - q_i \left(\mu_e - \mu_{\nu_e} \right), \quad \mu_i = \frac{\partial \varepsilon}{\partial \rho_i}$$

Hyperons in Neutron Stars

Hyperons in NS considered by many authors since the pioneering work of Ambartsumyan & Saakyan (1960)

Phenomenological approaches

- Relativistic Mean Field Models: Glendenning 1985; Knorren et al. 1995; Shaffner-Bielich & Mishustin 1996, Bonano & Sedrakian 2012, …
- Non-realtivistic potential model: Balberg & Gal 1997
- Quark-meson coupling model: Pal et al. 1999, …
- Chiral Effective Lagrangians: Hanauske et al., 2000
- Density dependent hadron field models: Hofmann, Keil & Lenske 2001

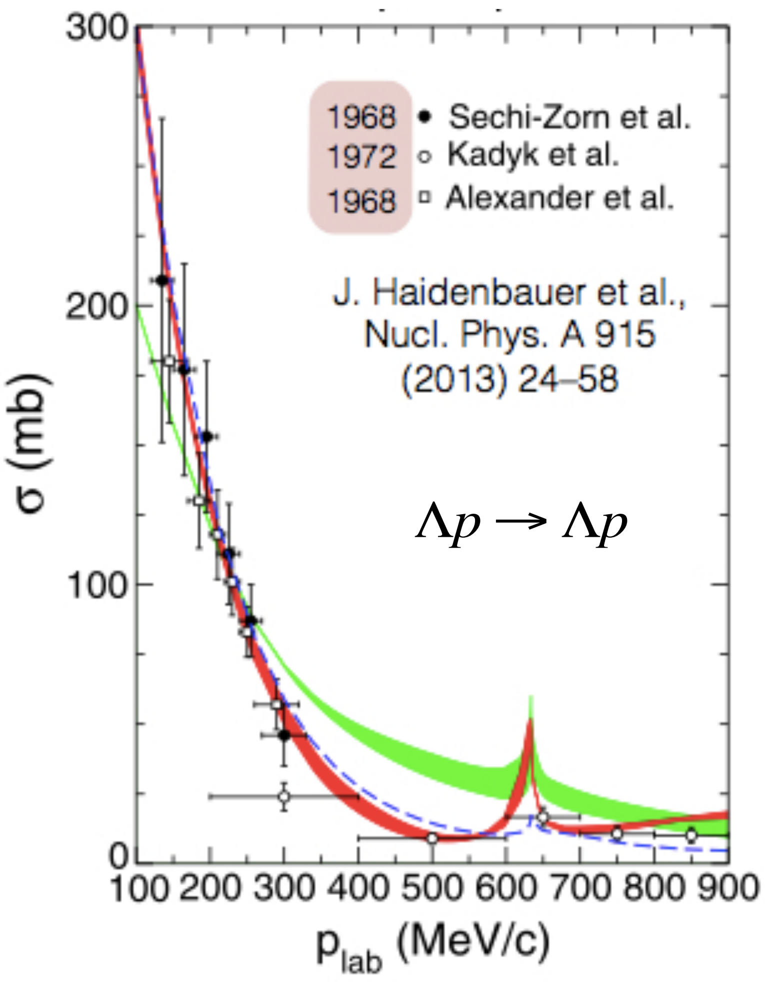
Microscopic approaches

- Brueckner-Hartree-Fock theory: Baldo et al. 2000; I. V. et al. 2000, Schulze et al. 2006, I.V. et al. 2011, Burgio et al. 2011, Schulze & Rijken 2011
- DBHF: Sammarruca (2009), Katayama & Saito (2014)
- $V_{\text{low k}}$: Djapo, Schaefer & Wambach, 2010
- Quantum Monte Carlo: Lonardoni et al., (2014)

Sorry if I missed somebody

What do we know to include hyperons in the Neutron Star matter EoS ?

Unfortunately, much less than in the pure nucleonic sector to put stringent constraints on the YN & YY interactions



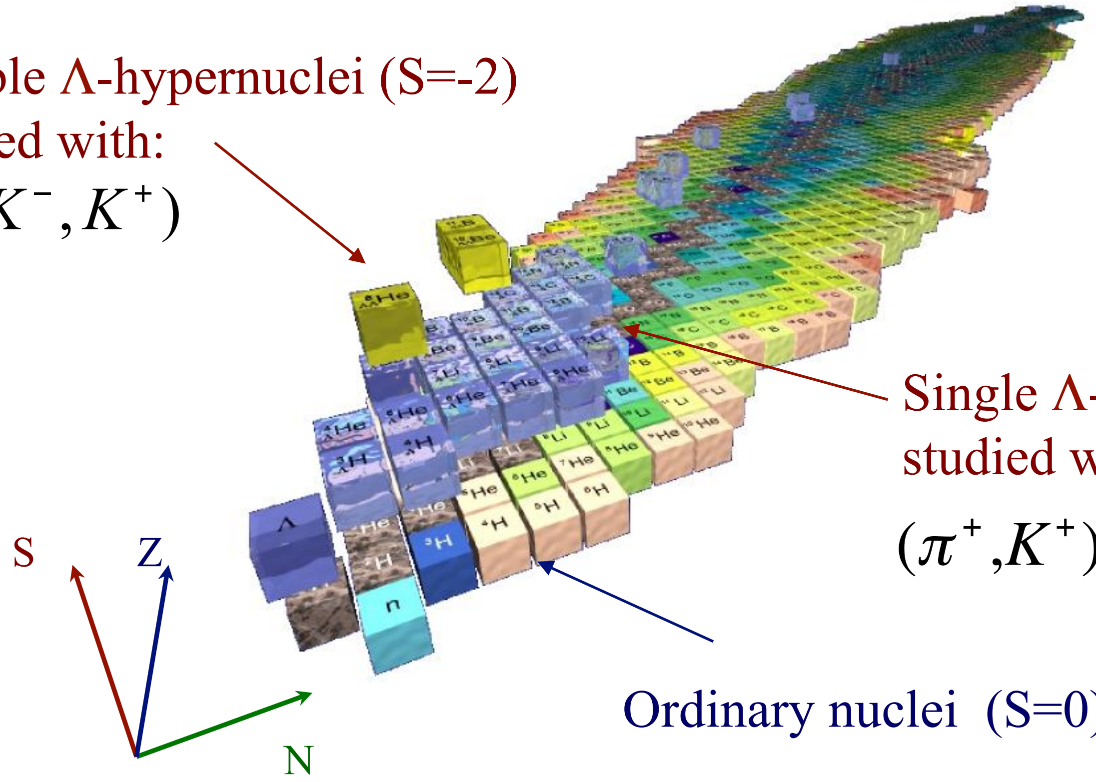
- ➢ Very few YN scattering data due to short lifetime of hyperons & low intensity beam fluxes
  - ~ 35 data points, all from the 1960s
  - 10 new data points, from KEK-PS E251 collaboration (2000)
- ➢ No YY scattering data exists

(cf. > 4000 NN data for E_{lab} < 350 MeV)

Hypernuclear Physics

Goal: Relate hypernuclear observables with the bare YN & YY interactions

- 41 single Λ-hypernuclei ⟶ ΛN attractive ($U_\Lambda(\rho_0) \sim -30$ MeV)
- 3 double-Λ hypernuclei ⟶ weak ΛΛ attraction ($\Delta B_{\Lambda\Lambda} \sim 1$MeV)
- Very few Ξ-hypernuclei ⟶ ΞN attractive ($U_\Xi(\rho_0) \sim -14$ MeV)
- Ambiguous evidence of Σ-hypernuclei ⟶ ΣN repulsive ($U_\Sigma(\rho_0) > +15$ MeV) ?



Double Λ-hypernuclei (S=-2)
studied with:

$$(K^-,K^+)$$

Single Λ-hypernuclei (S=-1)
studied with:

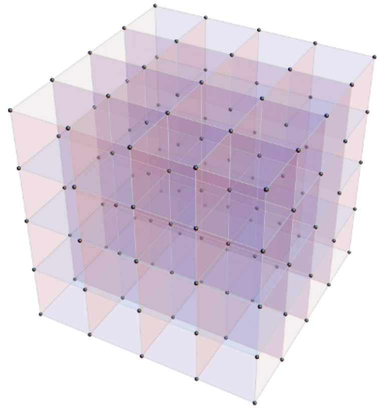
$$(\pi^+,K^+),(K^-,\pi^-),(e,e'K^+)$$

Ordinary nuclei (S=0)

Unfortunately, there are always problems …

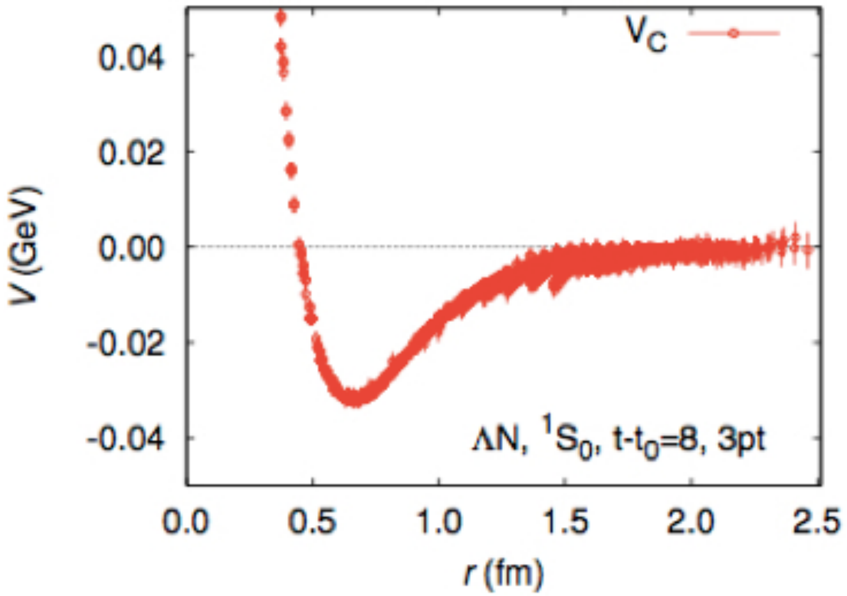
- ✧ Limited amount of scattering data not enough to fully constrain the bare YN & YY interactions ⟶ Strategy: start from a NN model & impose $SU(3)_f$ constraints to build YN & YY (e.g., Juelich & Nijmegen models)
- ✧ Bare YN & YY is not easy to derive from hypernuclei. Hyperons in nuclei are not free but in-medium. Hypernuclei provide effective hyperon-nucleus interactions
- ✧ Amount of experimental data on hypernuclei is not enough to constrain the uncertainties of phenomenological models. Parameters are most of the times arbitrarily chosen
- ✧ Ab-initio hypernuclear structure calculations with bare YN & YY interactions exists but are less accurate than phenomenological ones due to the difficulties to solve the very complicated nuclear many-body problem

Lattice QCD

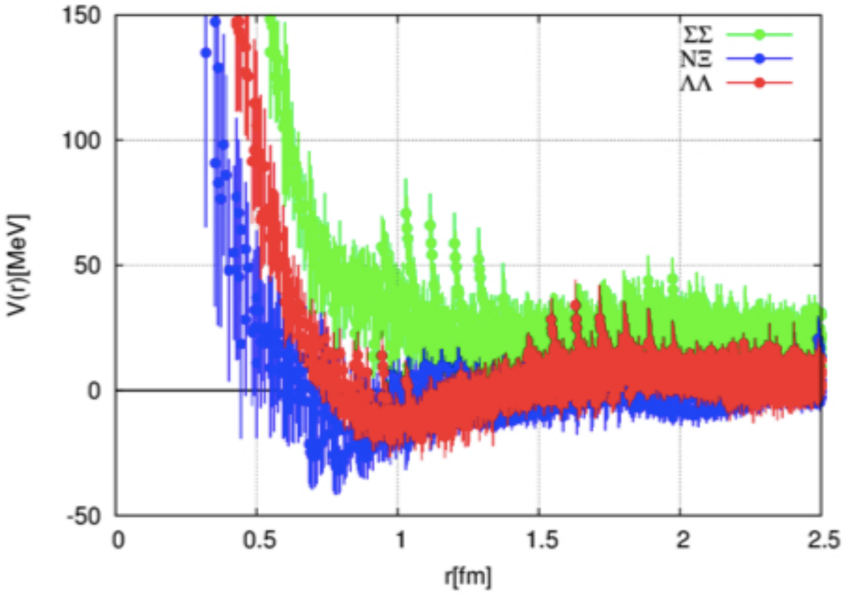


Lattice QCD calculations can provide the much required YN, YY & hyperonic TBFs.

ΛN (I=0) $^1S_0$ (m_π=570 MeV)



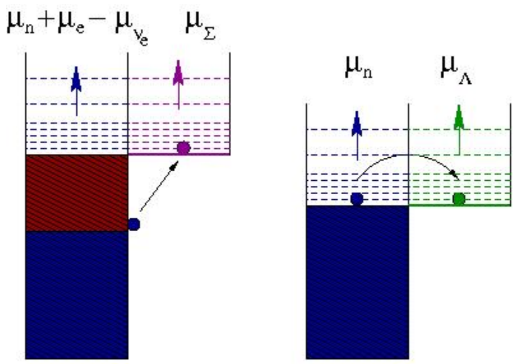
$\Lambda\Lambda$, $N\Xi$ & $\Sigma\Sigma$ (I=0) $^1S_0$ (m_π=145 MeV)



Hal QCD collaboration, HYP2015

Effect of Hyperons on the EoS and M_{max} of Neutron Stars: The Hyperon Puzzle

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$ when μ_N is large enough to make the conversion of N into Y energetically favorable.

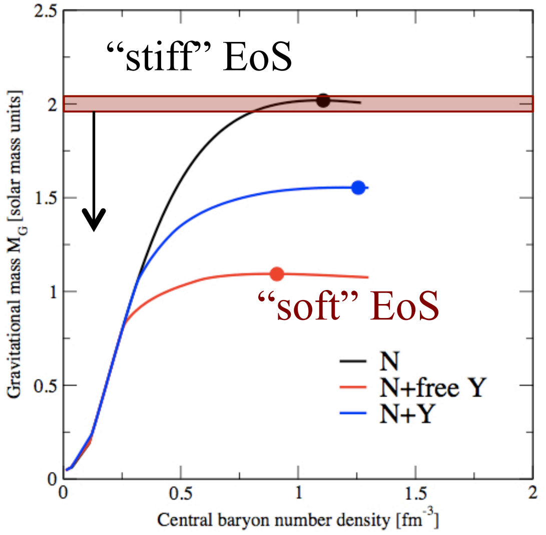


But

The relieve of Fermi pressure due to its appearance → EoS softer → reduction of the mass to values incompatible with observation

Observation of $\sim 2\,M_\odot$ NS → Any reliable EoS of dense matter should predict $M_{max}[EoS] > 2M_\odot$

Can hyperons be present in the interior of neutron stars in view of this new constraint ?



Possible Solutions to the Hyperon Puzzle

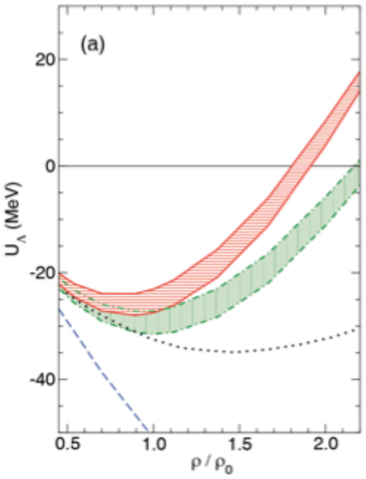
YN & YY

- YY vector meson repulsion

ϕ meson coupled only to hyperons yielding strong repulsion at high ρ

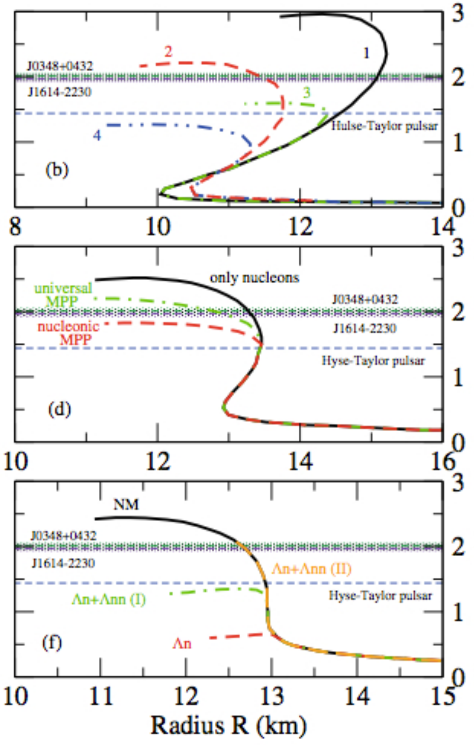
- Chiral forces

YN from χEFT predicts Λ s.p. potential more repulsive than those from meson exchange



Hyperonic TBF

Natural solution based on the known importance of 3N forces in nuclear physics



Quark Matter

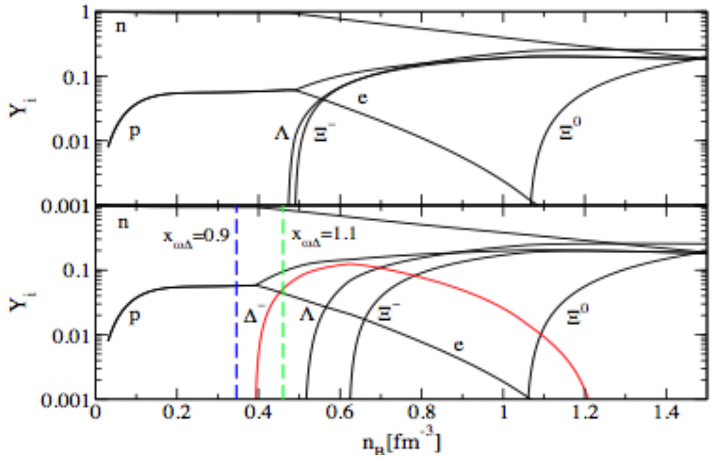
Phase transition to deconfined QM at densities lower that hyperon threshold

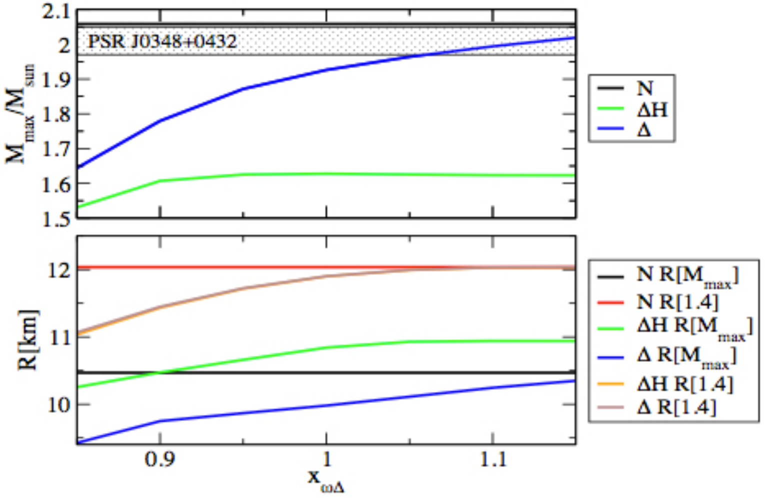
To yield $M_{\max} > 2M_\odot$ QM should be

- significantly repulsive to guarantee a stiff EoS
- attractive enough to avoid reconfinement

Is there also a Δ isobar puzzle ?

The recent work by Drago et al. (2014) calculation have studied the role of the Δ isobar in neutron star matter





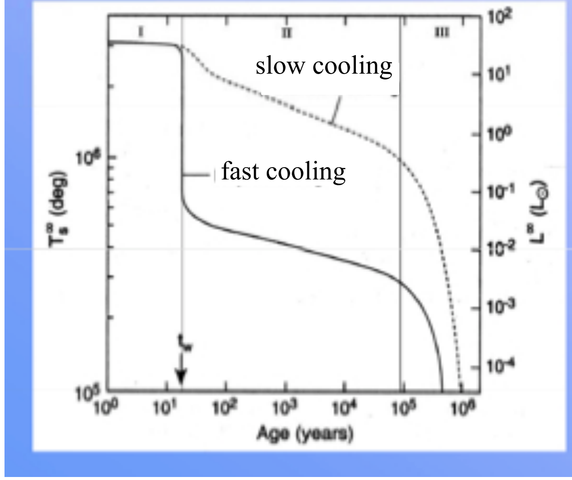
- Constraints from L indicate an early appearance of Δ isobars in neutron stars matter at ~ 2-3 ρ_0 (same range as hyperons)
- Appearance of Δ isobars modify the composition & structure of hadronic stars
- M_{max} is dramatically afected by the presence of Δ isobars

If Δ potential is close to that indicated by π−, e-nucleus or photoabsortion nuclear reactions then EoS is too soft ⟶ Δ puzzle similar to the hyperon one

Hyperons & Neutron Star Cooling

Two cooling regimes

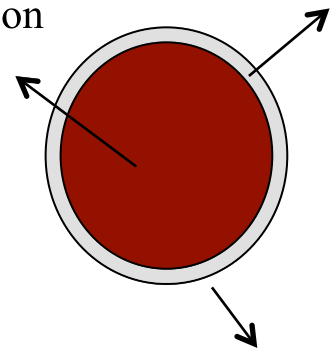
Slow	Fast
Low NS mass	High NS mass



I. Core relaxation epoch

II. Neutrino cooling epoch

III. Photon cooling epoch



Core cools by neutrino emission

Crust cools by conduction

Surface photon emission dominates at t > 10^6 yrs

$$\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\gamma - L_\nu + H$$

- ✓ C_v: specific heat
- ✓ L_γ: photon luminosity
- ✓ L_ν: neutrino luminosity
- ✓ H: “heating”

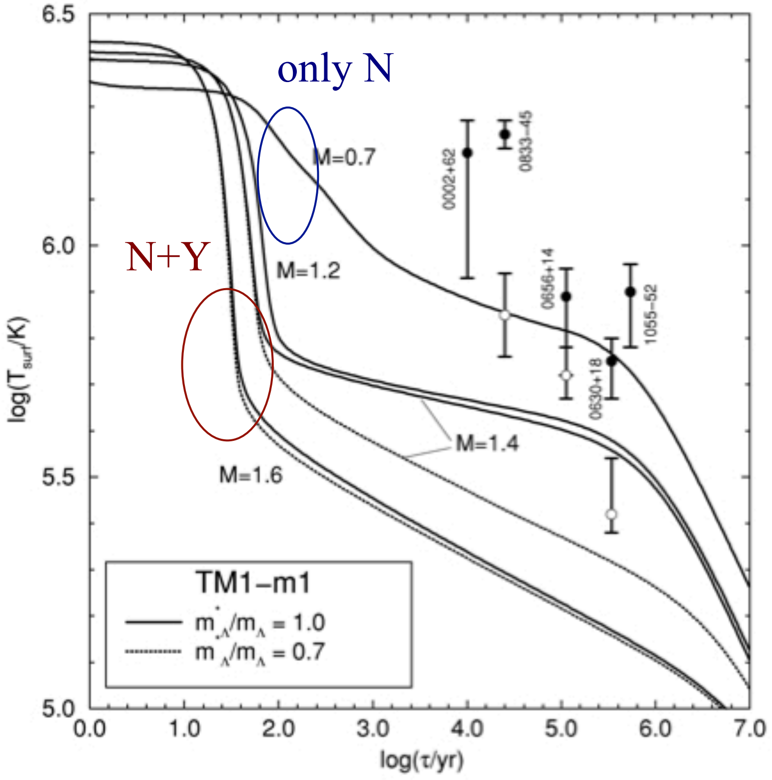
Hyperonic DURCA processes possible
as soon as hyperons appear
(nucleonic DURCA requires $x_p > 11\text{-}15\ \%$)

→ Additional Fast Cooling Processes

Process	R
$\Lambda \rightarrow p + l + \bar{\nu}_l$	0.0394
$\Sigma^- \rightarrow n + l + \bar{\nu}_l$	0.0125
$\Sigma^- \rightarrow \Lambda + l + \bar{\nu}_l$	0.2055
$\Sigma^- \rightarrow \Sigma^0 + l + \bar{\nu}_l$	0.6052
$\Xi^- \rightarrow \Lambda + l + \bar{\nu}_l$	0.0175
$\Xi^- \rightarrow \Sigma^0 + l + \bar{\nu}_l$	0.0282
$\Xi^0 \rightarrow \Sigma^+ + l + \bar{\nu}_l$	0.0564
$\Xi^- \rightarrow \Xi^0 + l + \bar{\nu}_l$	0.2218

+ partner reactions generating neutrinos,
Hyperonic MURCA, …

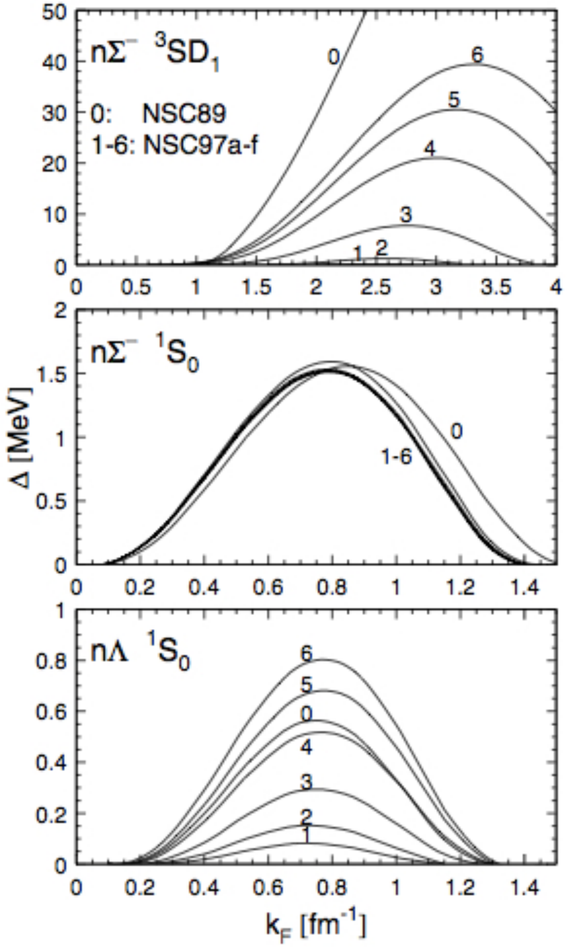
(Schaab, Shaffner-Bielich & Balberg 1998)



R: relative emissitivy w.r.t. nucleonic DURCA

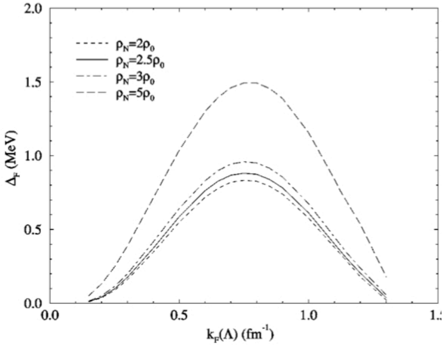
Pairing Gap → suppression of C_v & ε by $\sim e^{(-\Delta/k_BT)}$

- $^1S_0$, $^3SD_1$ ΣN & $^1S_0$ ΛN gap

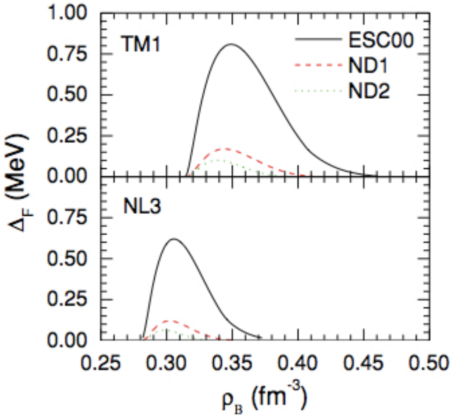


(Zhou, Schulze, Pan & Draayer 2005)

- $^1S_0$ ΛΛ gap

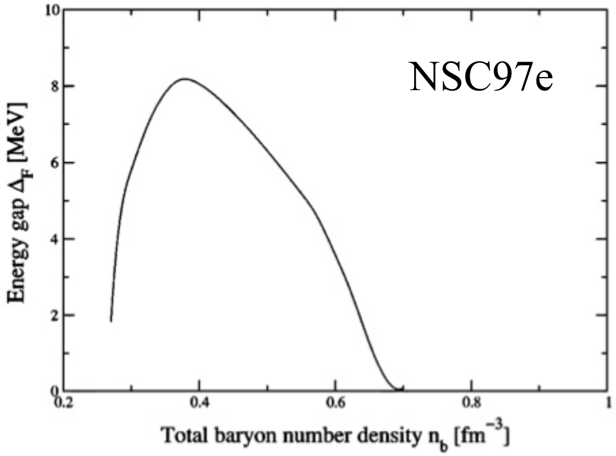


(Balberg & Barnea 1998)



(Wang & Shen 2010)

- $^1S_0$ ΣΣ gap

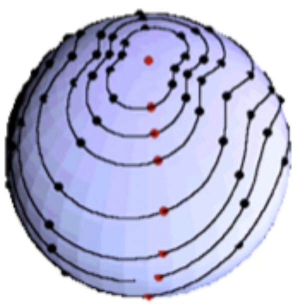


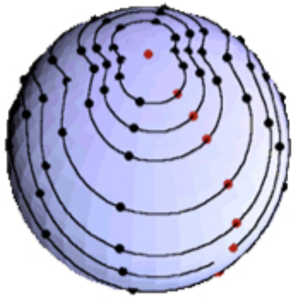
(IV & Tolós 2004)

Hyperons & the r-mode instability of NS

Ω_{Kepler} : Absolute Upper Limit of Rot. Freq.

Instabilities prevent NS to reach Ω_{Kepler}


co-rotating


inertial

- ✓ r-mode instability: toroidal model of oscillation generic to all rotating NS
- ✓ restoring force: Coriolis
- ✓ emission of GW in hot & rapidly rotating NS: (CFS mechanism)

- ✓ Damped by (shear, bulk) viscosity: depends on the composition of the NS interior
  - Shear viscosity: from momentum transfer due to particle scattering
  - Bulk viscosity: from variation in pressure & density when the system is driven away from chemical equilibrium
- ✓ Timescale associated with growth/dissipation
  - $\tau_{\xi\eta} \gg \tau_{GW}$: r-mode unstable, star spins down
  - $T_{\xi\eta} \ll \tau_{GW}$: r-mode damped, star can spin rapidly

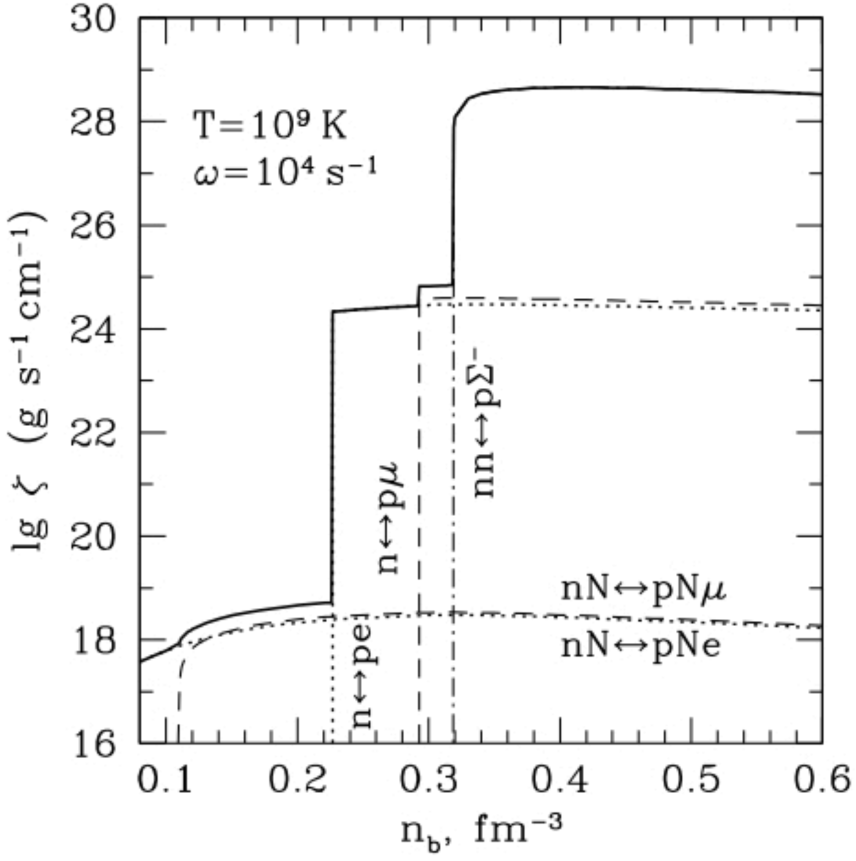
Hyperon Bulk Viscosity ξ_Y

(Lindblom et al. 2002, Haensel et al 2002, van Dalen et al. 2002, Chatterjee et al. 2008, Gusakov et al. 2008, Shina et al. 2009, Jha et al. 2010,…)

Sources of ξ_Y:

non-leptonic weak reactions	$N+N \leftrightarrow N+Y$ $N+Y \leftrightarrow Y+Y$
Direct & Modified URCA	$Y \rightarrow B+l+\bar{\nu}_l$ $B'+Y \rightarrow B'+B+l+\bar{\nu}_l$
strong reactions	$N+Y \leftrightarrow N+Y$ $N+\Xi \leftrightarrow Y+Y$ $Y+Y \leftrightarrow Y+Y$

(Haensel, Levenfish & Yakovlev 2002)



Reaction Rates & ξ_Y reduced by hyperon superfluidity but (again) hyperon pairing gaps are poorly known

Critical Angular Velocity of Neutron Stars

- r-mode amplitude: $A \propto A_o e^{-i\omega(\Omega)t - t/\tau(\Omega)}$

$$\frac{1}{\tau(\Omega,T)} = -\frac{1}{\tau_{GW}(\Omega)} + \frac{1}{\tau_\xi(\Omega,T)} + \frac{1}{\tau_\eta(T)}$$

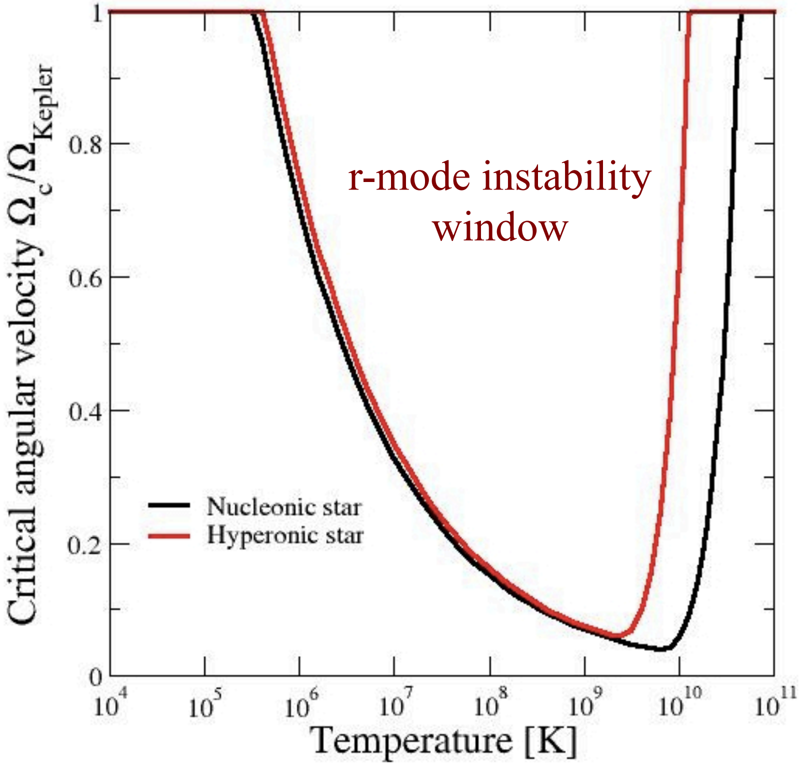
➔ $\frac{1}{\tau(\Omega_c,T)} = 0$ r-mode instability region

$\Omega < \Omega_c$ stable

$\Omega > \Omega_c$ unstable

As expected:
smaller r-mode instability region
due to hyperons

(I.V. & C. Albertus in preparation)



BHF: NN (Av18)+NY (NSC89)
(M=1.27$M_\odot$)

The d*(2380) in NS: a new degree of freedom ?

The d*(2380) is an interesting new candidate for an exotic d.o.f. in the interior of neutron stars

- Being the quantum mechanical environment of NS very different from that of atomic nuclei, once formed the dominant decay channels of the d*(2380)

$$d^*(2380) \rightarrow \Delta\Delta \rightarrow NN\pi\pi, \qquad d^*(2380) \rightarrow NN$$

would be Pauli blocked and, therefore, once created the d*(2380) can be considered as an effectively stable particle in neutron stars

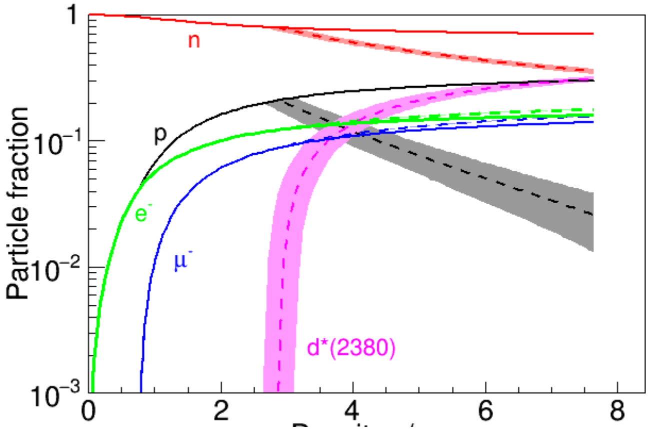
- The bosonic nature of the d*(2380) allows the possible formation of a Bose-Einstein condensate of d*(2380) in neutron stars

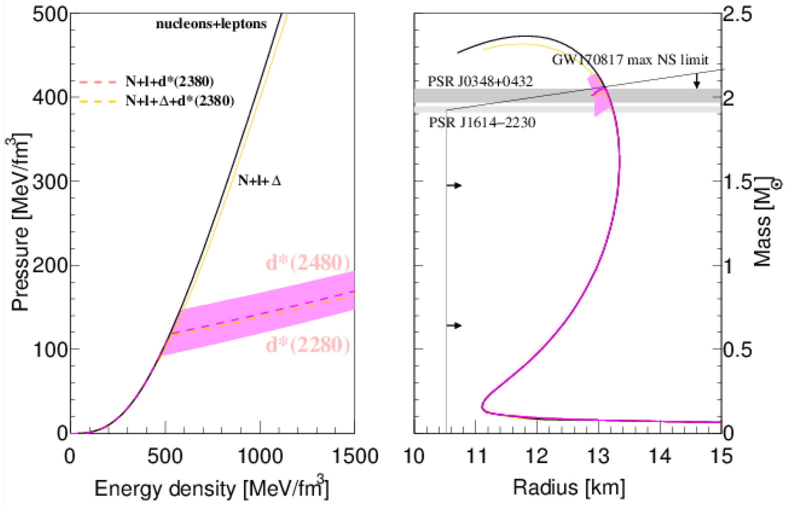
I.V., M. Bashkanov, D. Watts & A. Pastore, arXiv:1706.09701

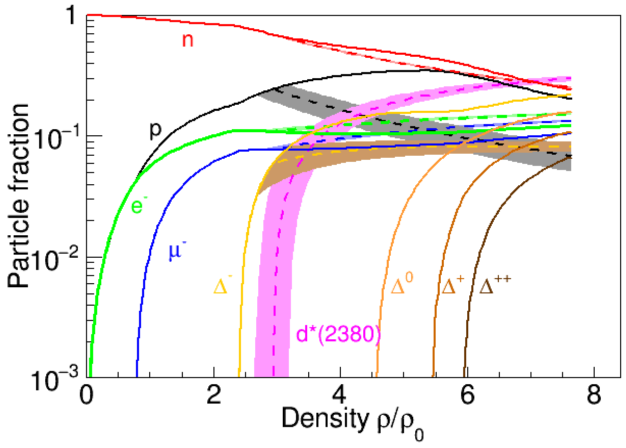
The $d^*(2380)$ in NS: composition, EoS & Mass

First calculation of the role of $d^*(2380)$ in NS based on a RMF description of nucleonic + Δ degrees of freedom supplemented by a free gas of point-like bosons for $d^*(2380)$

- d^* (2380) appears between 2.7-3.2ρ_0. Induces a significant reduction of neutrons & protons. Shift the onset of Δ^0, Δ^+ & Δ^{++} to very large densities. Increase of lepton fraction
- EoS soften & M_{max} reduced to 1.9-2.1 $M_\odot$







I.V., M. Bashkanov, D. Watts & A. Pastore, arXiv:1706.09701

Consequences of d*(2380) in Neutron Stars

✧ Cooling

The presence of the d*(2380) in the interior of neutron stars can lead to new mechanism fot the cooling of these objects such as the dibaryon-URCA

$$d^*(2380) \rightarrow nne^+\nu_e, \qquad d^*(2380) \rightarrow nn\mu^+\nu_\mu$$

or the weak processes

$$nn \rightarrow d^*(2380)e^-\bar{\nu}_e, \qquad nn \rightarrow d^*(2380)\mu^-\bar{\nu}_\mu$$

✧ Rotation dynamics & Neutron Stars Magnetic Fields

The formation of the d*(2380 takes two units of angular momentum ⟶ consequences in the rotational dynamics & the magnetic fields

✧ Neutron Stars Mergers

Influence on the ejecta. Further studies to assess the possibility of detecting astronomical signatures of d*(2380) during mergers are needed. Detection of monoenergetic γ from $d^*(2380) \rightarrow d\gamma$ would be a signal

I.V., M. Bashkanov, D. Watts & A. Pastore, arXiv:1706.09701

The final message of this talk

✧ I have reviewed the role of hyperons on Neutron Stars

- ✓ EoS & M_{max} of NS (hyperon puzzle & possible solutions)
- ✓ Neutron Star Cooling
- ✓ R-mode instability of Neutron Stars

✧ I have presented the first calculation of the effect of the $d^*(2380)$ in the interior of Neutron Stars & briefly analyzed its consequences

For details see:

D.Chatterjee & I. V. EPJA 52, 29 (2016)

I.V., M. Bashkanov, D. Watts & A. Pastore,
arXiv:1706.09701

- ✧ You for your time & attention
- ✧ The organizers for their invitation
- ✧ My collaborators: Mikhail Bashkanov, Daniel Watts & Alessandro Pastore