Hyperons & Neutron Stars

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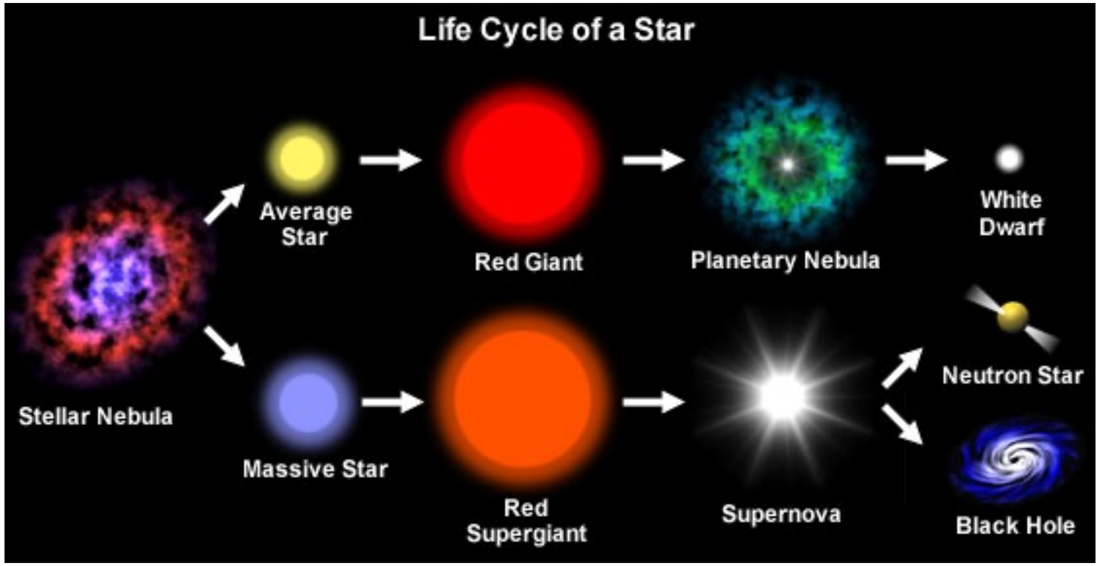
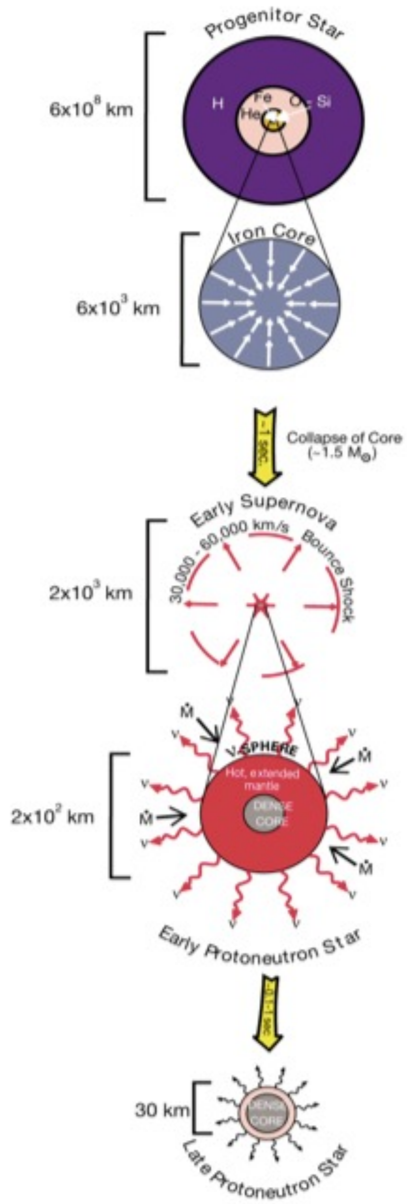
What is a Neutron Star ?

A neutron stars is a type of stellar compact remnant that can result from the gravitational collapse of a massive star ($8\ M_\odot < M < 25\ M_\odot$) during a Type II, Ib or Ic supernova event.

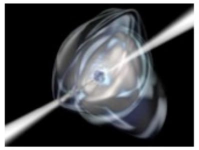


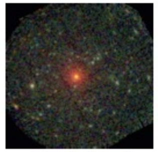


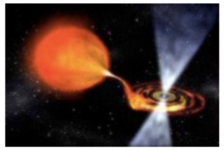
The 1001 Astrophysical Faces of Neutron Stars

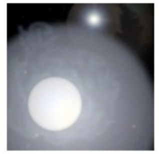
Neutron stars can be observed as

- ✧ isolated objects
- ✧ forming binary systems with other NS, ordinary stars or BH


Anomalous X-ray Pulsars

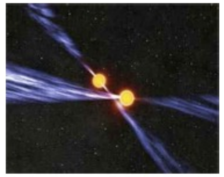

dim isolated neutron stars

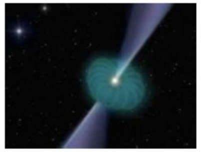

X-ray binaries

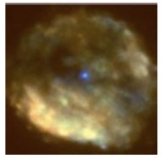

bursting pulsars


Soft Gamma Repeaters


pulsars


binary pulsars


Rotating Radio Transients


Compact Central Objects


planets around pulsar

✧ Isolated neutron stars

- ✓ Mostly detected as radio pulsars, X-ray pulsar or γ-ray pulsars
- ✓ Radio-quite isolated neutron stars: CCOs & DINS
- ✓ Soft gamma repeaters (SGRs) & Anomalous X-ray pulsars (AXPs)

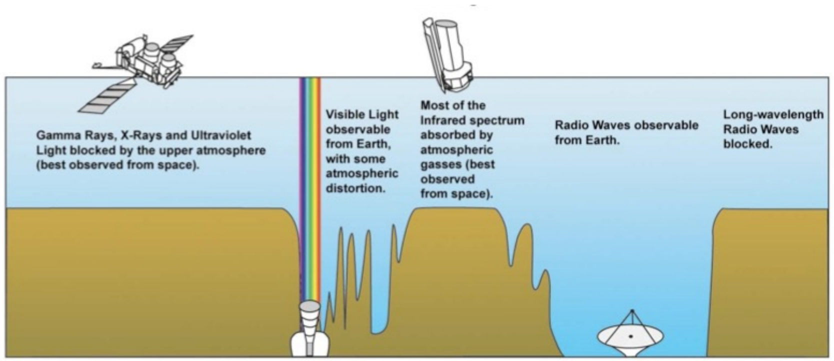
✧ Neutron stars in binary systems

- ✓ No mass exchange: NS behave as isolated objects
- ✓ Mass exchange: observed as X-ray sources: X-ray pulsars, X-ray bursters or quasiperiodic X-ray oscillations. Classified as HMXRBs or LMXRBs depending on the mass of the companion or as persistent or transient sources according to the regularity or irregularity of their activity

Observation of Neutron Stars: Electromagnetic Signals

Neutron stars are observed in all bands of the electromagnetic spectrum

Their observation requires different types of ground-based & on-board telescopes



Radio:

Arecibo: d= 305 m

Green Banks: d= 100 m

Nançay : d ~ 94 m

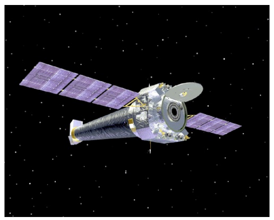
Infrared & Optical

VLT

Ultraviolet & Optical

HST (Hubble)

Extreme ultraviolet, X- & γ-ray



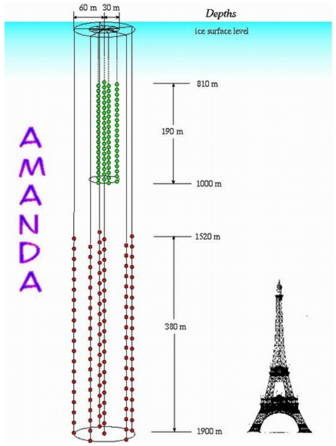
Chandra

Fermi

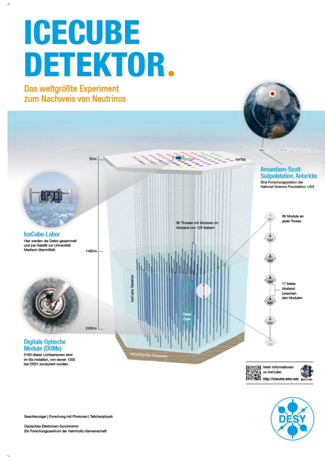
Observation of Neutron Stars: Neutrino Signals

Neutron stars are observed also through the detection of the neutrinos emitted during the supernova explosion that signals the birth of the star

Under-ice telescoles

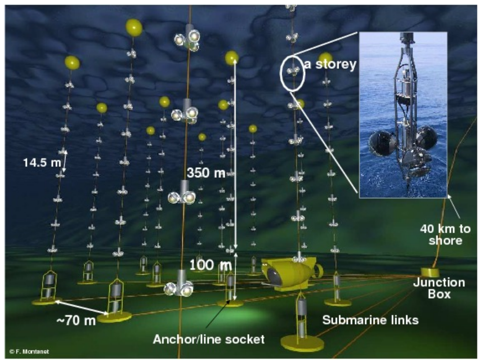


AMANDA

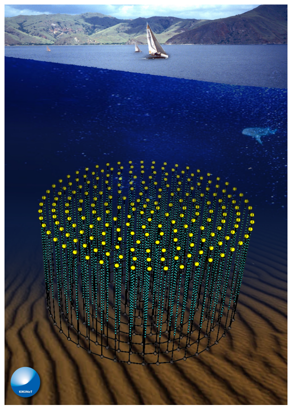


ICECUBE

Under-water telescopes

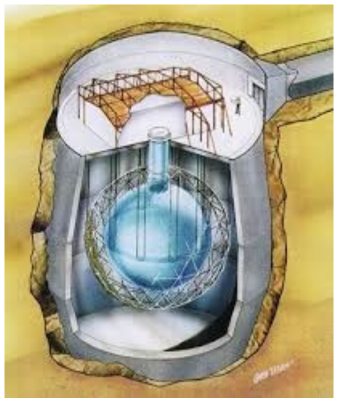


ANTARES

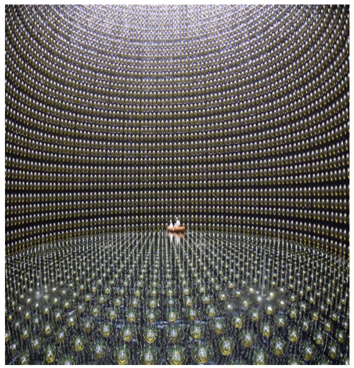


KM3NET

Under-ground telescopes



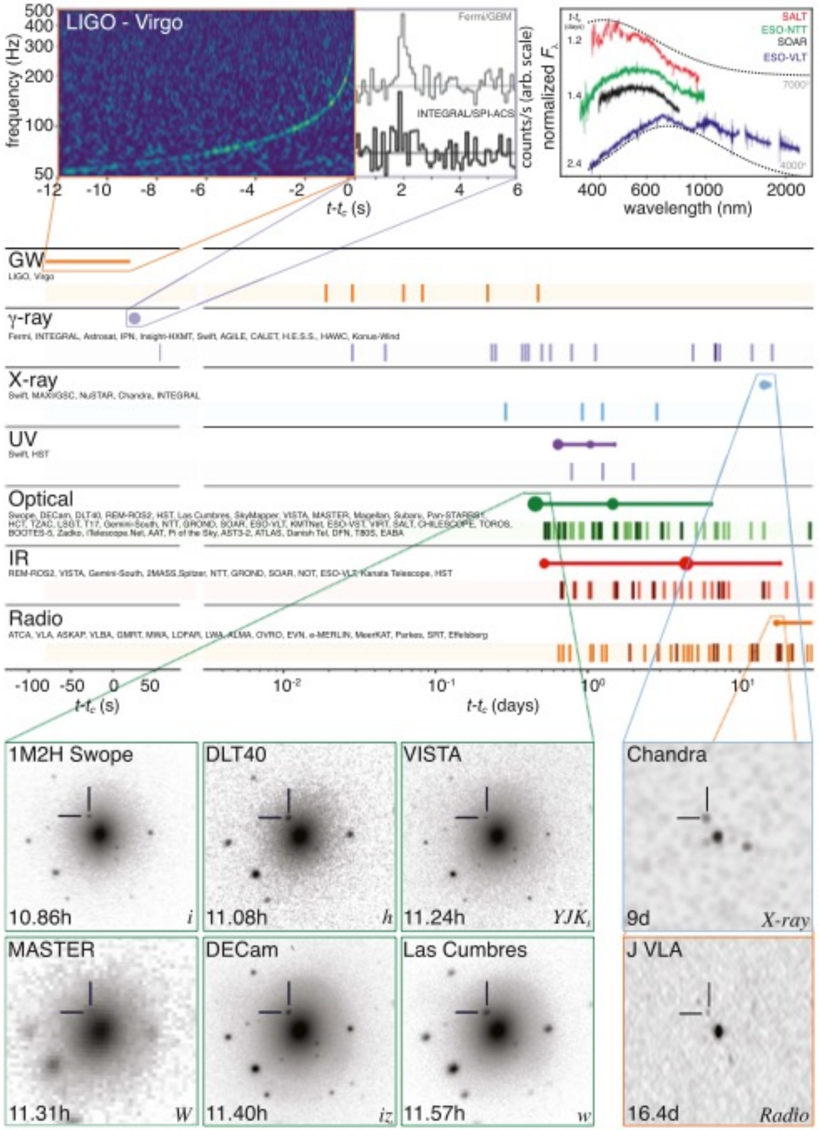
SNO



KAMIOKA

GW: A New Way of Observing Neutron Stars

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**

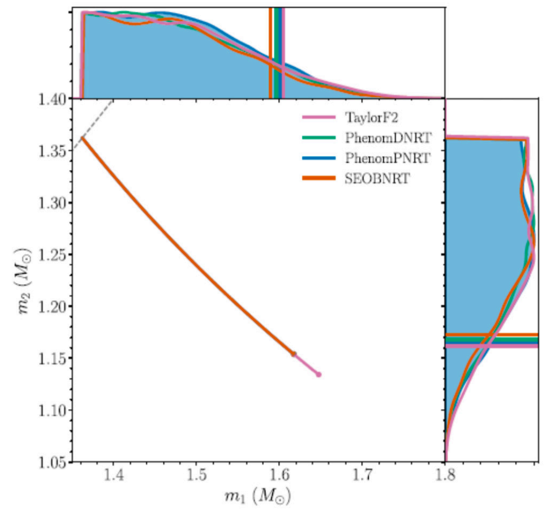
  GRB (GRB170817A) detected by FERMI γ-ray Burst Monitor & INTEGRAL

- **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)

GW170817: the first NS-NS merger

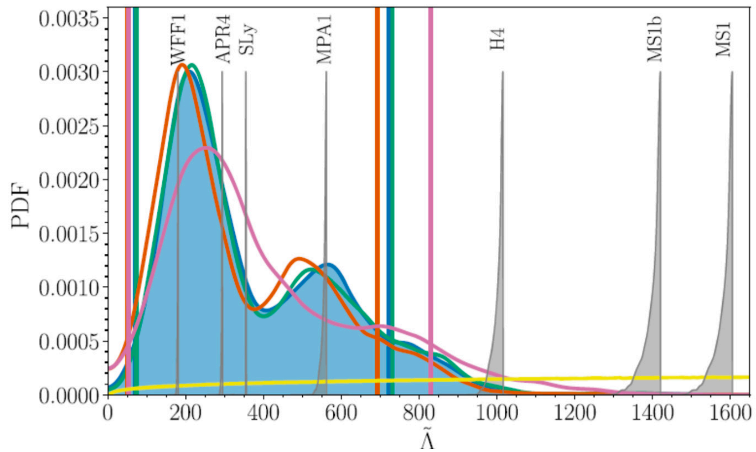
✧ Masses estimated from the chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



✧ Radius from the tidal deformability

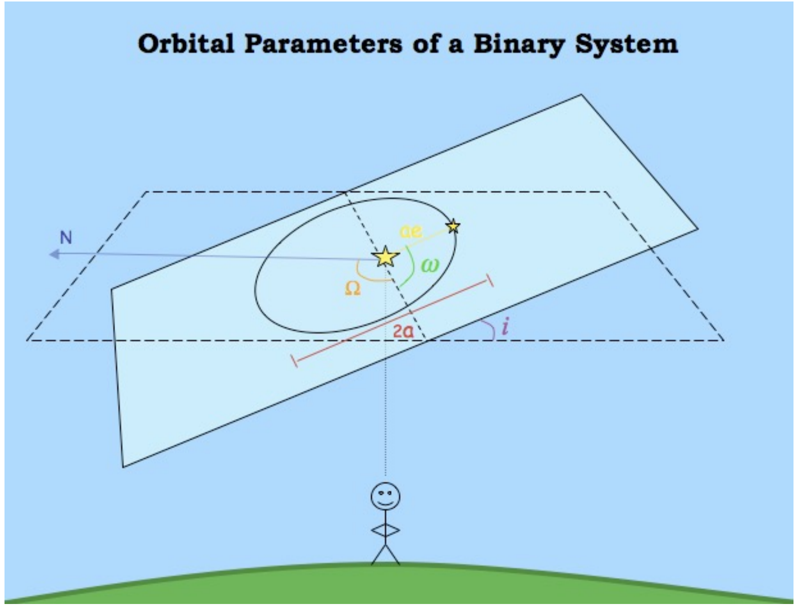
$$\tilde{\Lambda} = \frac{16}{13}\frac{(1+12q)\Lambda_1 + (q+12)\Lambda_2}{(1+q)^5}$$



A 1.36$M_\odot$ has a radius of 10.4 km (WFF1), 11.3 km (APR4), 11.7 km (Sly), 12.4 km (MPA1), 14.0 (H4), 14.5 (MS1b) and 14.9 km (MS1)

Neutron Star Masses

NS masses can be inferred directly from observations of binary systems



- 5 orbital (Keplerian) parameters can be precisely measured:
  - ✓ Orbital period (P)
  - ✓ Projection of semimajor axis on line of sight (a sin i)
  - ✓ Orbit eccentricity (ε)
  - ✓ Time of periastron (T_0)
  - ✓ Longitude of periastron (ω_0)
- 3 unknowns: M_1, M_2, i

Kepler's 3rd law

$$\frac{G(M_1+M_2)}{a^3} = \left(\frac{2\pi}{P}\right)^2 \rightarrow$$

$$f(M_1,M_2,i) \equiv \frac{(M_2 \sin i)^3}{(M_1+M_2)^2} = \frac{P v^3}{2\pi G}$$

mass function

In few cases small deviations from Keplerian orbit due to GR effects can be detected

Measure of at least 2 post-Keplerian parameters → High precision NS mass determination

$$\dot{\omega} = 3T_{\otimes}^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-\varepsilon}\left(M_p + M_c\right)^{2/3}$$ → Advance of the periastron

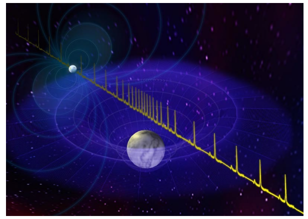
$$\gamma = T_{\otimes}^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3}\varepsilon\frac{M_c\left(M_p + 2M_c\right)}{\left(M_p + M_c\right)^{4/3}}$$ → Time dilation & grav. redshift

$$r = T_{\otimes}M_c$$ → Shapiro delay "range"

$$s = \sin i = T_{\otimes}^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3}x\frac{\left(M_p + M_c\right)^{2/3}}{M_c}$$ → Shapiro delay "shape"

$$\dot{P}_b = -\frac{192\pi}{5}T_{\otimes}^{5/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}f(\varepsilon)\frac{M_p M_c}{\left(M_p + M_c\right)^{1/3}}$$ → Orbit decay due to GW emission

Recent Measurements of High NS Masses



- <u>PSR J164-2230</u> (Demorest et al. 2010)

  ✓ binary system (P=8.68 d)

  ✓ low eccentricity (ε=1.3 x 10^{-6})

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

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

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

- <u>PSR J0348+0432</u> (Antoniadis et al. 2013)

  ✓ binary system (P=2.46 h)

  ✓ very low eccentricity

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

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

- <u>MSP J0740+6620</u> (Cromartie et al. 2020)

  ✓ binary system (P=4.76 d)

  ✓ low eccentricity (ε=5.10(3) x 10^{-6})

  ✓ companion mass: $0.258(8) M_{\odot}$

  ✓ pulsar mass: $M = 2.14^{+0.10}_{-0.0.9} M_{\odot}$ (68.3% c.i.)

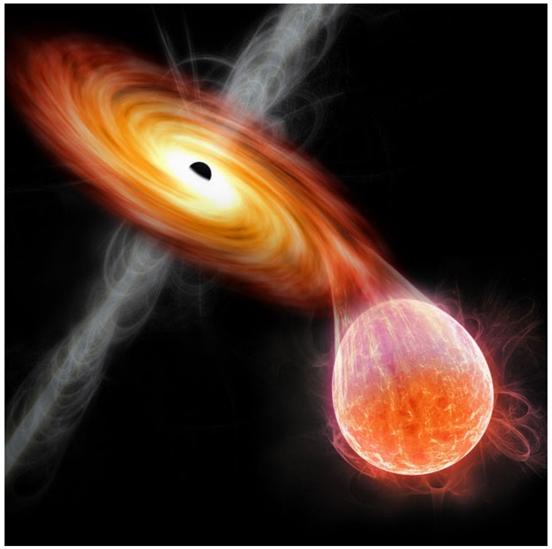
  $M = 2.14^{+0.20}_{-0.018} M_{\odot}$ (95.4% c.i.)

The desired measurement of 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:

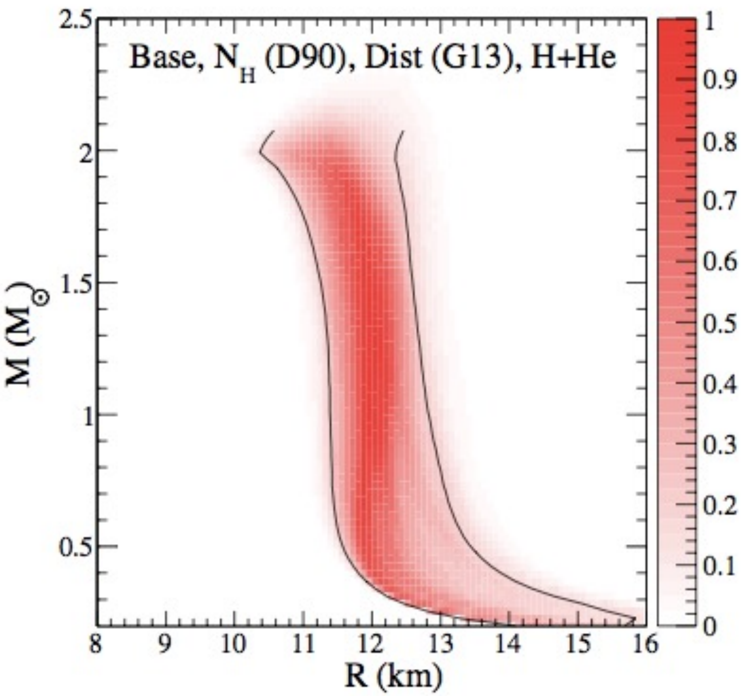
- ✧Flux measurement +Stefan-Boltzmann’s law
- ✧Temperature (Black body fit+atmosphere model)
- ✧Distance estimation (difficult)
- ✧Gravitational redshift z (detection of absorption lines)

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

Estimations of Neutron Star Radii

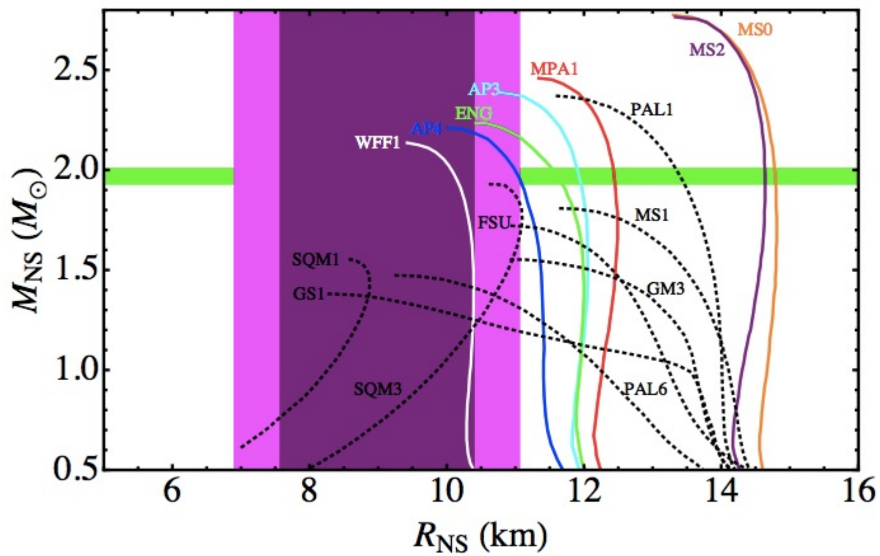
The conclusion from past analysis of the thermal spectrum from 5 quiescent LMXB in globular clusters was controversial

Steiner et al. (2013, 2014)



$$R = 12.0 \pm 1.4 km$$

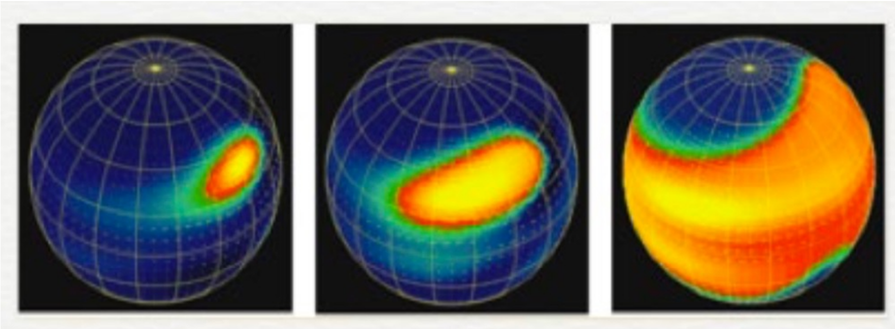
Guillot et al. (2013, 2014)



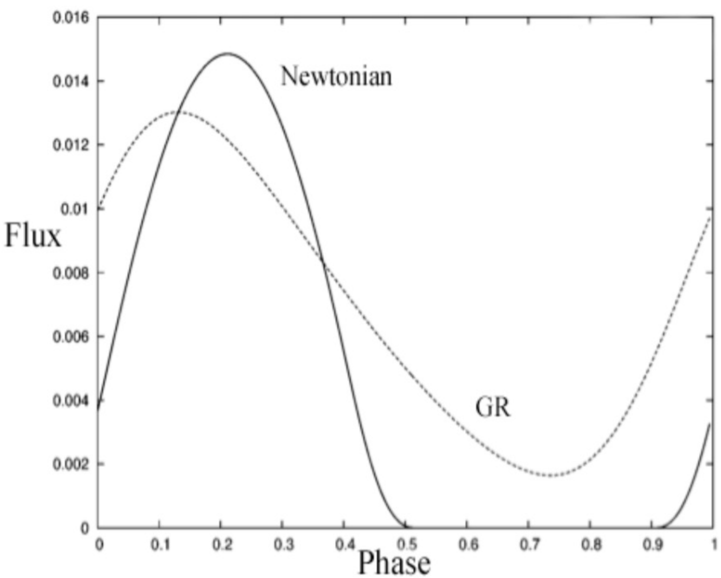
$R = 9.1^{+1.3}_{-1.5} km$ 2013 analysis

$R = 9.4 \pm 1.2 km$ 2014 analysis

NICER: Neutron Star Interior Composition Explorer



A new way of measuring M & R from rapidly spinning compact stars with a hot spot, based on GR corrections of the signal (M/R) and on Doppler effect (R)



✧ PSR J0740+6620

$$M = 2.072^{+0.067}_{-0.066} M_\odot$$

$$R = 13.7^{+2.6}_{-1.5} \; km$$ Miller et al., arXiv:2105.06979

$$R = 12.39^{+1.30}_{-0.98} \; km$$ Riley et al., arXiv:2105.06980

✧ PSR J0030+0451

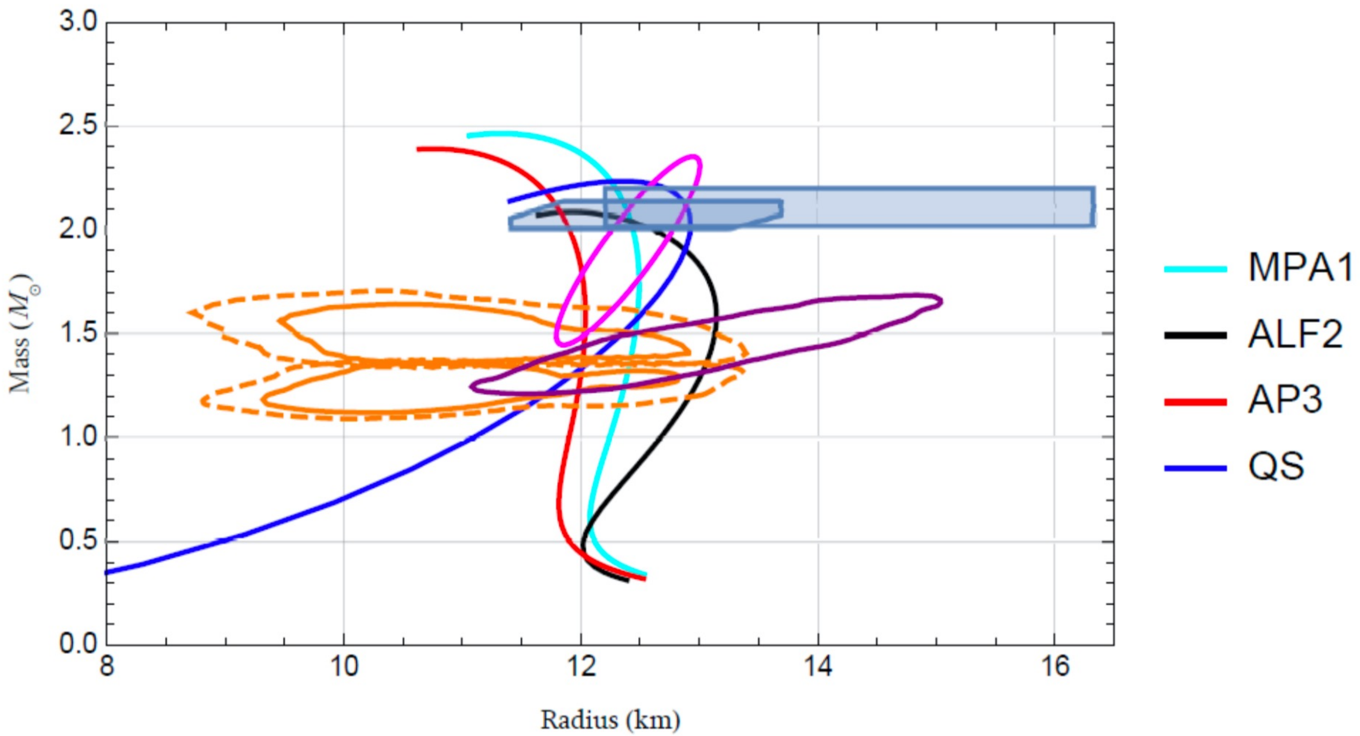
$$M/R = 0.156^{+0.008}_{-0.010}$$

$$R = 13.02^{+1.24}_{-1.06} \; km$$ Miller et al., ApJ 887 L24 (2019)

$$R = 12.71^{+1.14}_{-1.19} \; km$$ Riley et al., APJ 887 L21 (2019)

Combined analysis of a few astrophysical data

- ✧ NICER PSR J0740+6620 & PSR J0030+0451 (bands)
- ✧ GW170817 (from tidal deformability, orange solid/dashed lines)
- ✧ RXTE results for the cooling tail spectra of 4U1702-429 (violet line)



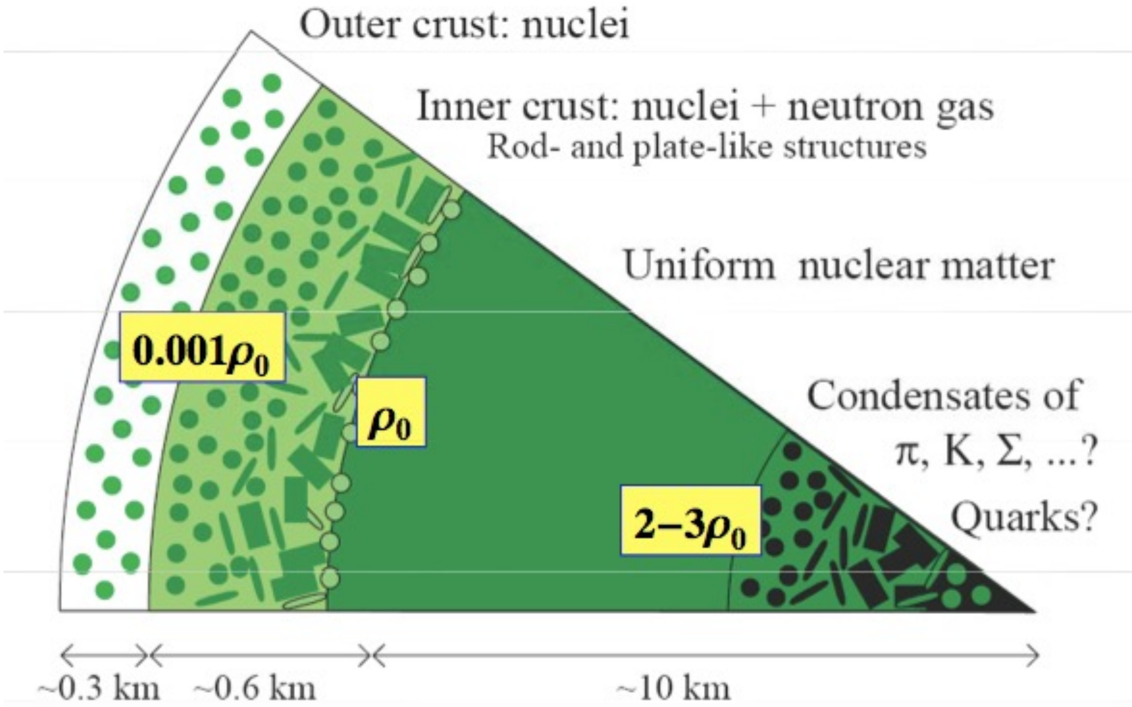
Anatomy of a Neutron Star

Equilibrium composition determined by

✓ Charge neutrality

$$\sum_i q_i \rho_i = 0$$

✓ Equilibrium with respect to weak interacting processes



$$b_1 \rightarrow b_2 + l + \bar{\nu}_l$$
$$b_2 + l \rightarrow b_1 + \nu_l$$

$$\longrightarrow \quad \mu_i = b_i \mu_n - q_i \left(\mu_e - \mu_{\nu_e} \right), \quad \mu_i = \frac{\partial \varepsilon}{\partial \rho_i}$$

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-relativistic 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

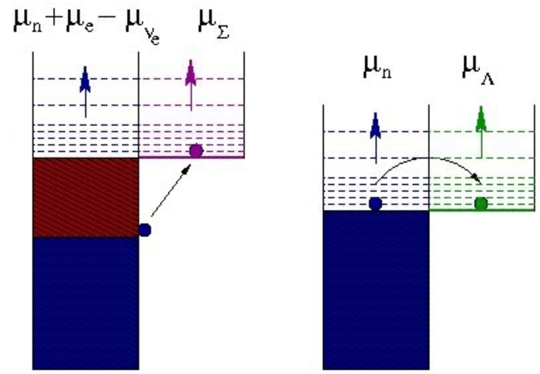
Microscopic approaches

- 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)
- $V_{low\ k}$: Djapo, Schaefer & Wambach, 2010
- Quantum Monte Carlo: Lonardoni et al., (2014)

Sorry if I missed somebody

The Hyperon Puzzle: An Open Problem

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.

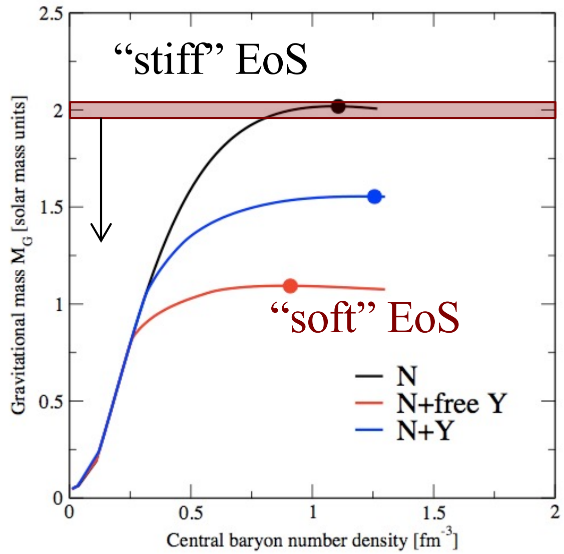


But

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

Observation of $\sim 2\,M_\odot$ NS $\longrightarrow$ 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

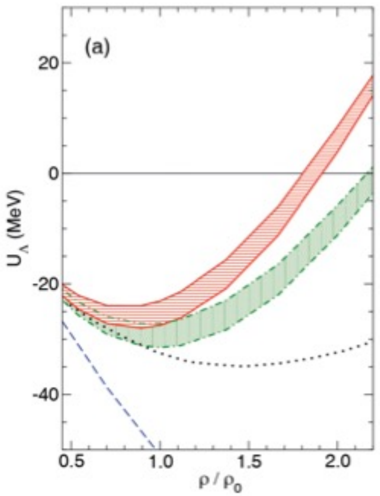
YN & YY

- YY vector meson repulsion

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

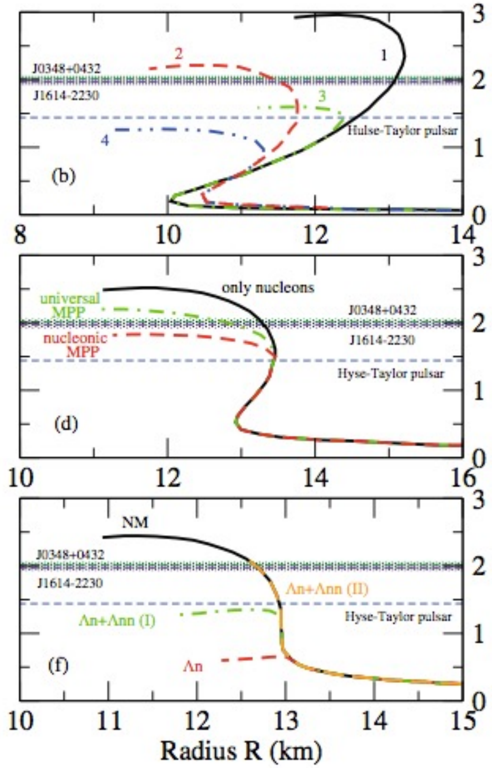
- Chiral forces

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. **Results still not conclusive**



Quark Matter

Phase transition to deconfined QM at densities lower that hyperon threshold

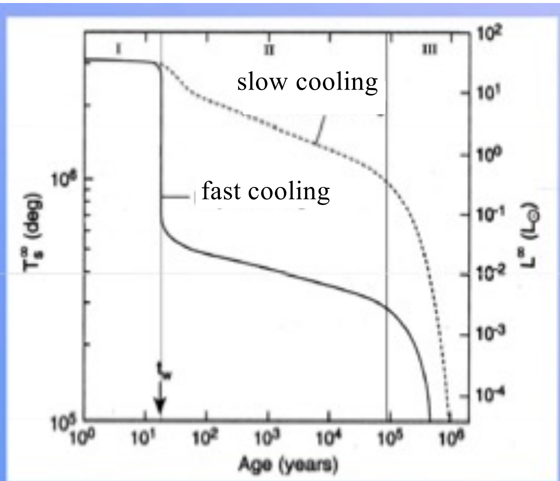
To yield $M_{max} > 2M_{\odot}$ QM should be

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

Hyperons & Neutron Star Cooling

Two cooling regimes

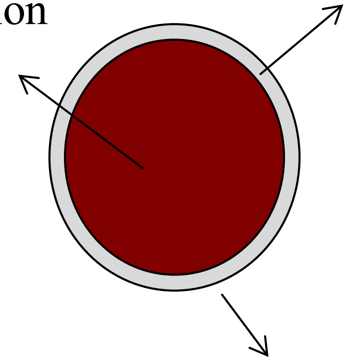
Slow	Fast
Low NS mass	High NS mass



I. Core relaxation epoch

II. Neutrino cooling epoch

III. Photon cooling epoch



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

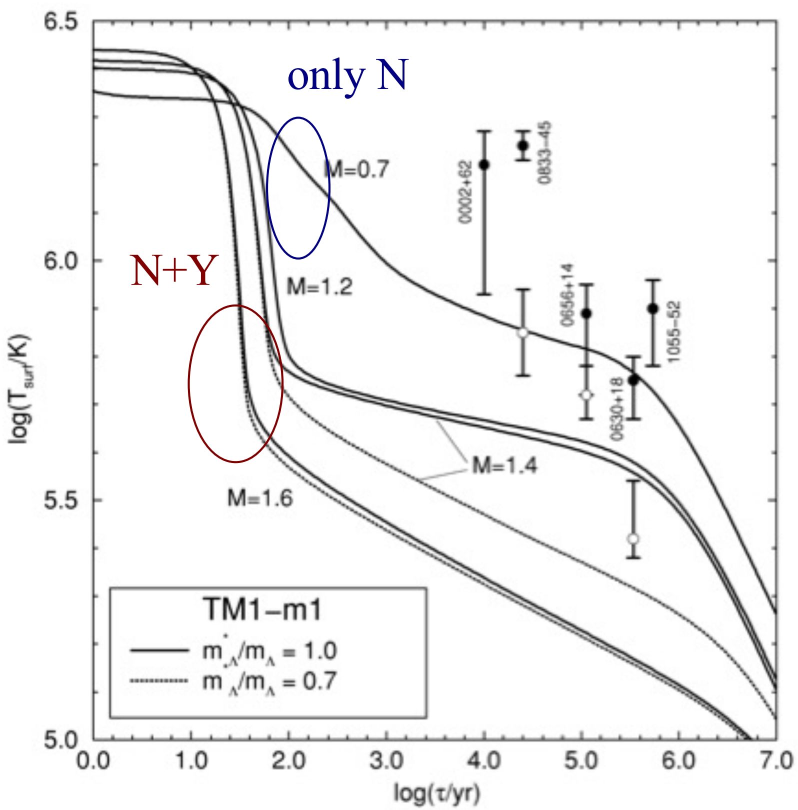
- ✓C_v: specific heat
- ✓L_γ: photon luminosity
- ✓L_ν: neutrino luminosity
- ✓H: “heating”

Hyperonic DURCA processes possible as soon as hyperons appear (nucleonic DURCA requires x_p > 11-15 %) ➔ 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, …

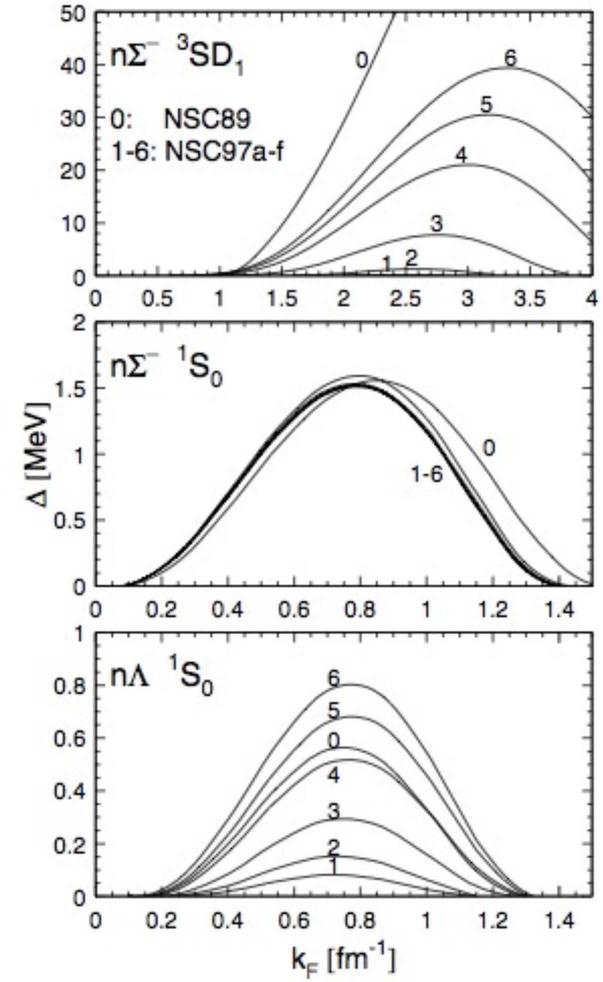
(Schaab, Shaffner-Bielich & Balberg 1998)



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

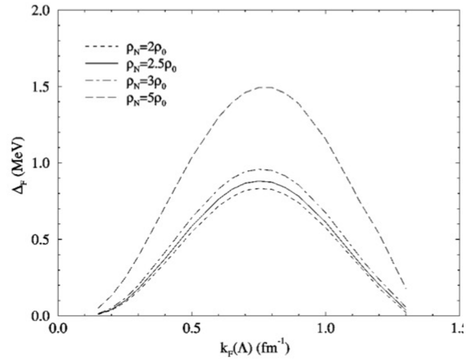
Pairing Gap ⟶ suppression of C_v & ε by $\sim e^{(-\Delta/k_B T)}$

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

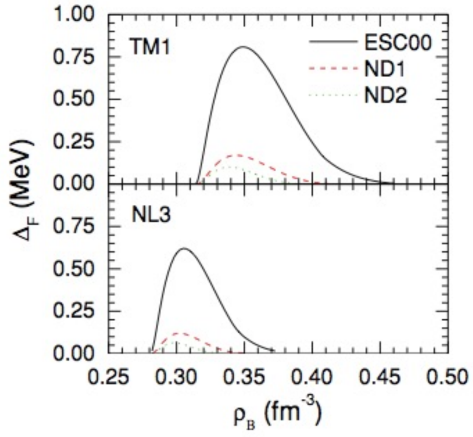


(Zhou, Schulze, Pan & Draayer 2005)

- $^1S_0$ ΛΛ gap

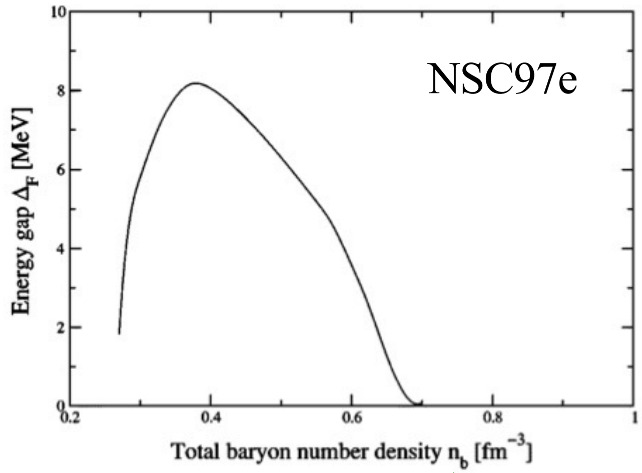


(Balberg & Barnea 1998)



(Wang & Shen 2010)

- $^1S_0$ ΣΣ gap

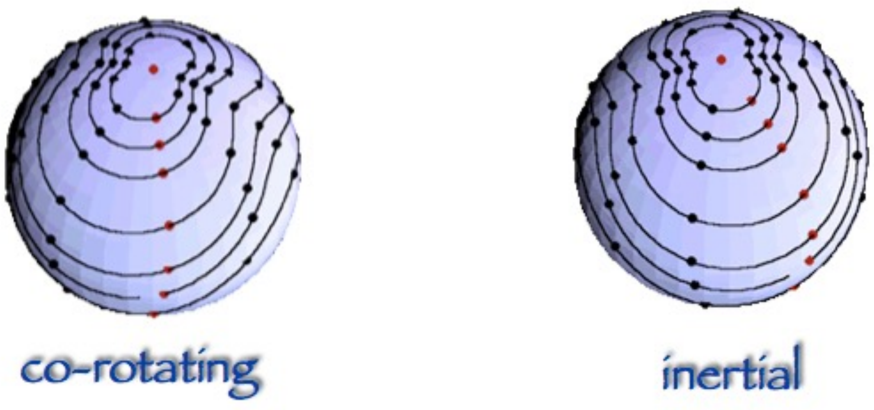


(IV & Tolós 2004)

Hyperons & the r-mode instability of NS

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

Instabilities prevent NS to reach Ω_{Kepler}



✓ 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

- $\tau_{\xi\eta} >> \tau_{GW}$: r-mode unstable, star spins down
- $T_{\xi\eta} << \tau_{GW}$: r-mode damped, star can spin rapidly

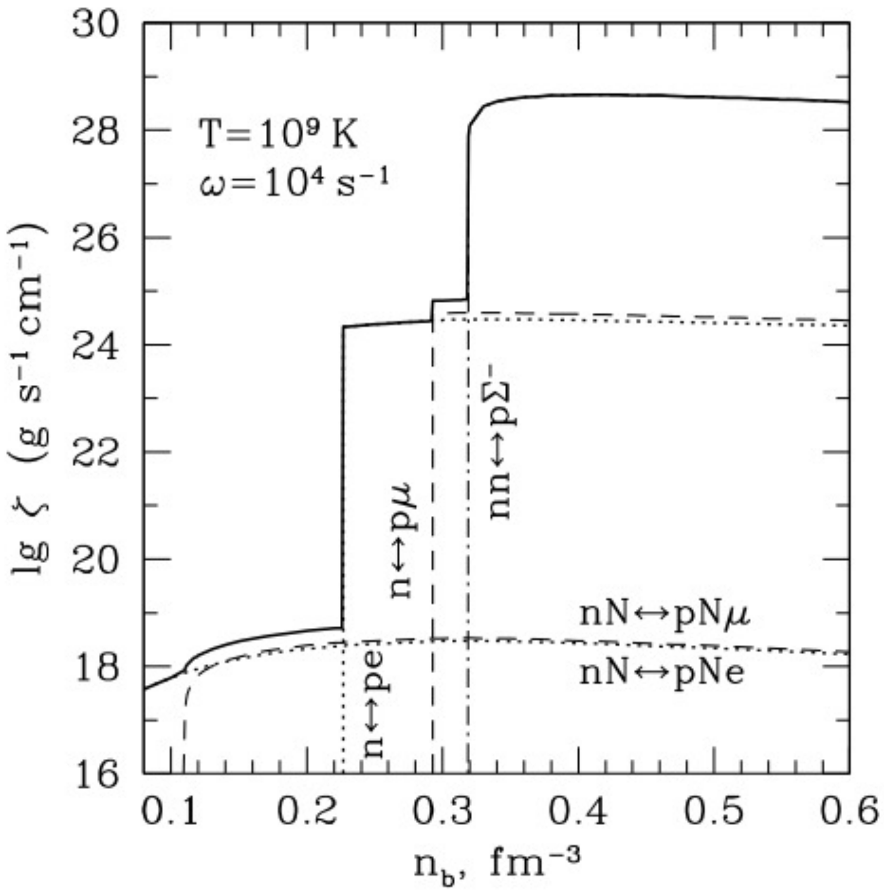
Hyperon Bulk Viscosity ξ_Y

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

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

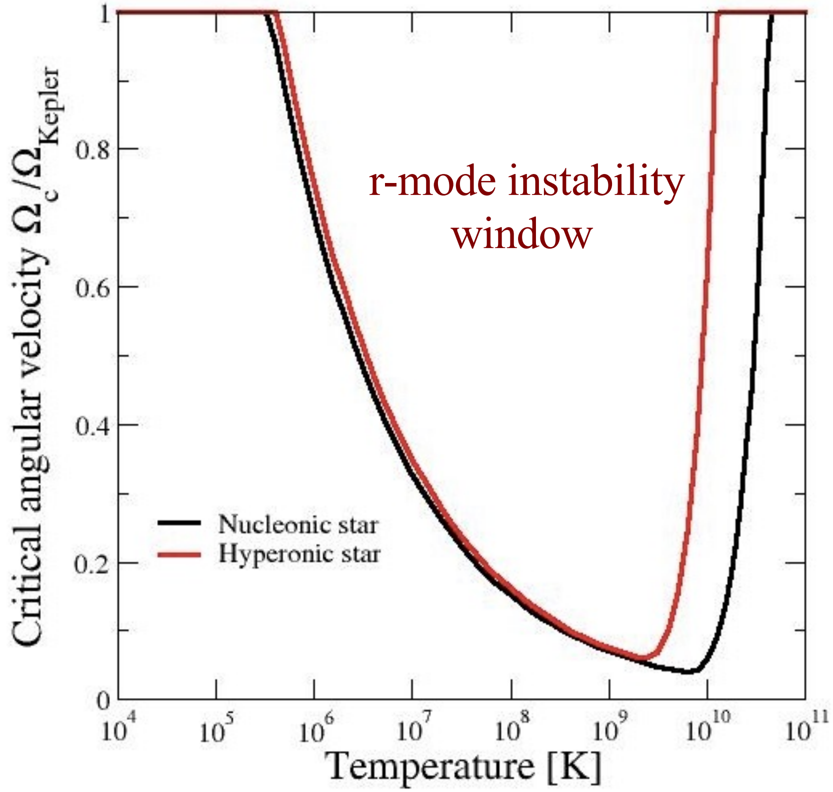
➔ $\frac{1}{\tau(\Omega_c,T)} = 0$ r-mode instability region

$\Omega < \Omega_c$ stable

$\Omega > \Omega_c$ unstable

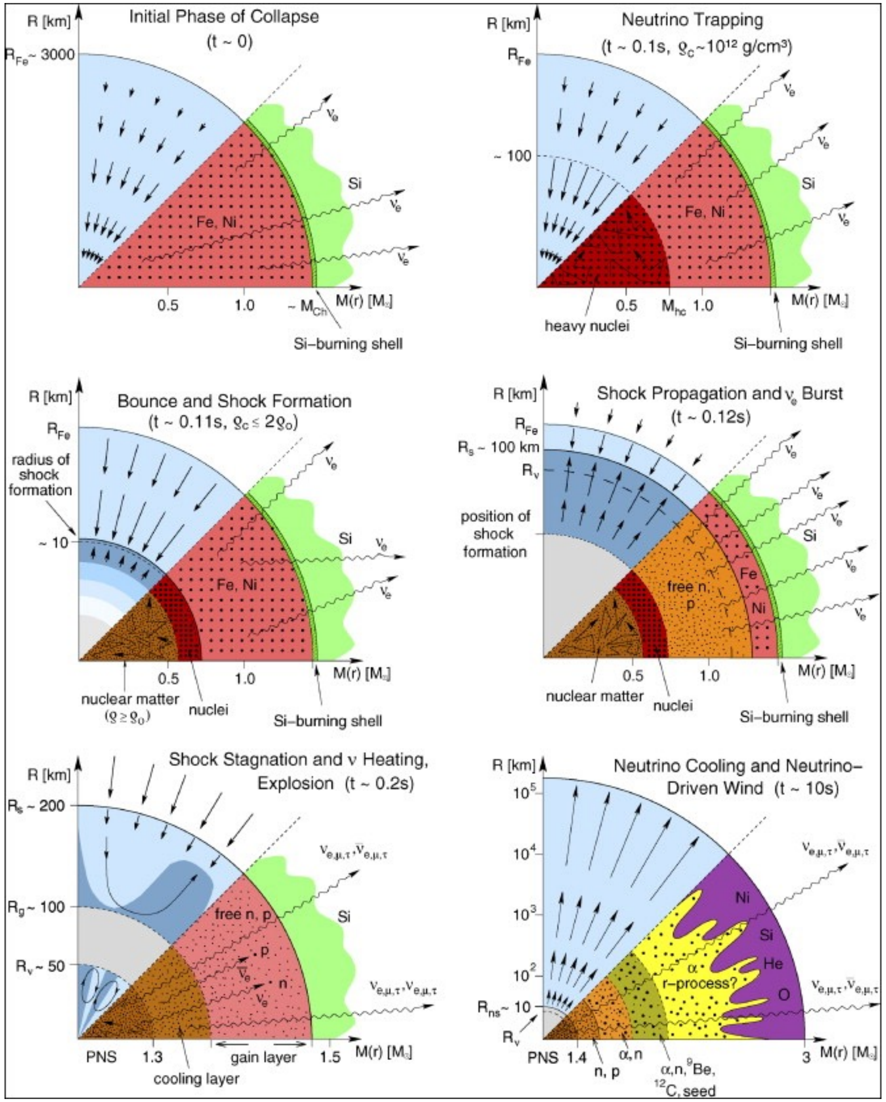
As expected:
smaller r-mode instability region
due to hyperons

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



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

Hyperons & Proto-Neutron Stars



(Janka, Langanke, Marek, Martinez-Pinedo & Muller 2006)

New effects on PNS matter:

- Thermal effects

$$T \cong 30-40 \quad MeV$$
$$S/A \cong 1-2$$

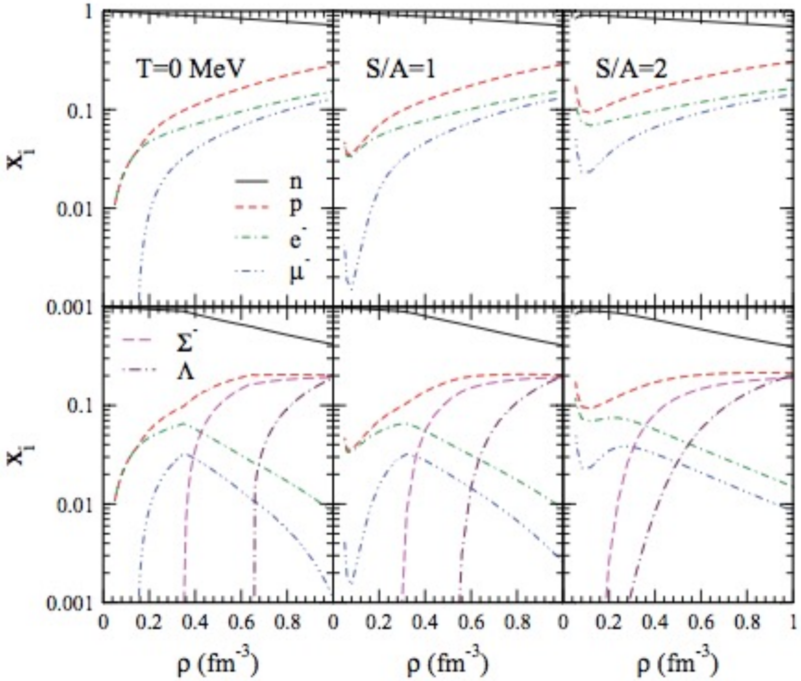
- Neutrino trapping

$$\mu_\nu \neq 0$$
$$Y_e = \frac{\rho_e + \rho_{\nu_e}}{\rho_B} \approx 0.4$$
$$Y_\mu = \frac{\rho_\mu + \rho_{\nu_\mu}}{\rho_B} \approx 0$$

Hyperons & Proto-Neutron Stars: Composition

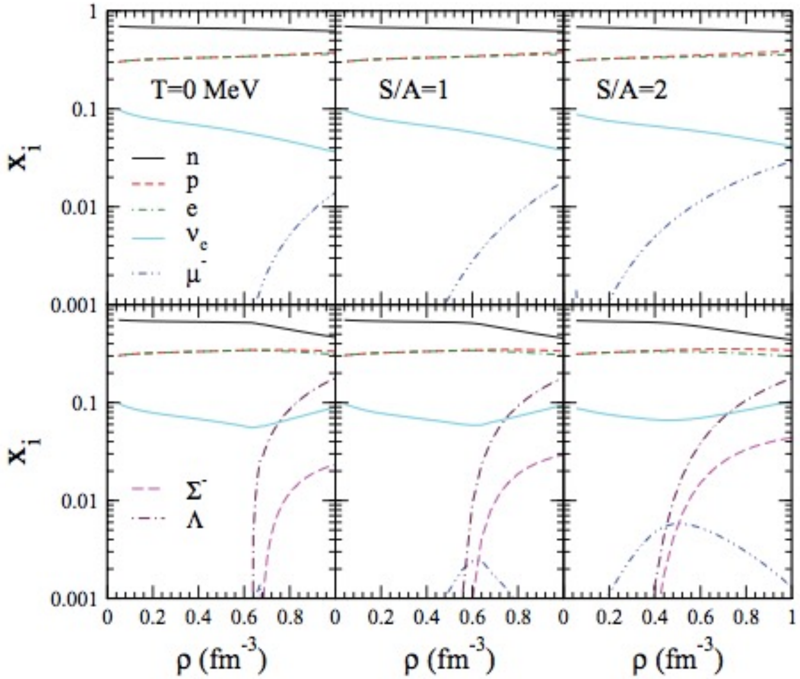
- Neutrino free $\mu_\nu = 0$

(Burgio & Schulze 2011)



- Neutrino trapped $\mu_\nu \neq 0$

(Burgio & Schulze 2011)

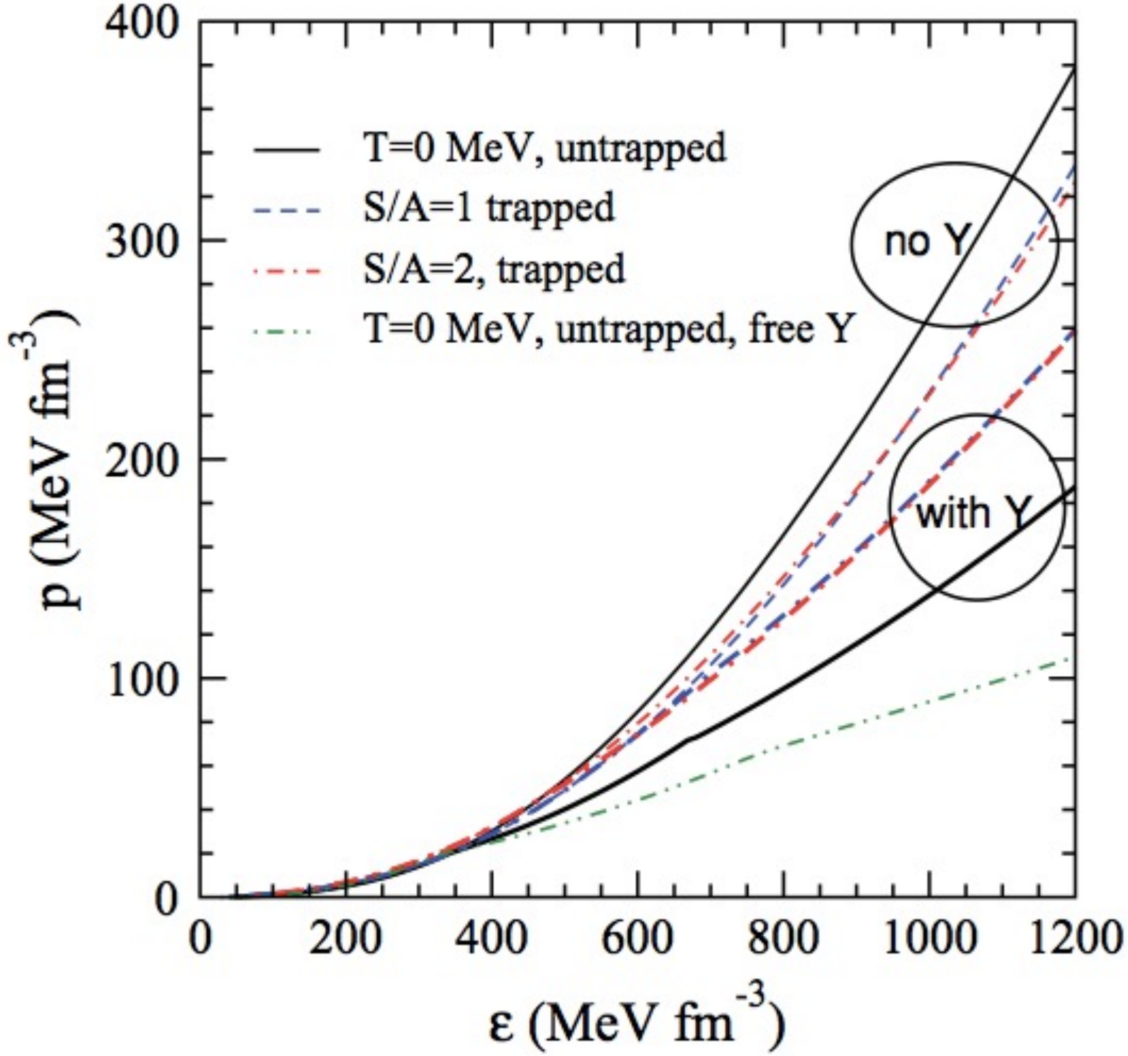


Neutrino trapped ➔

- ✓ Large proton fraction
- ✓ Small number of muons
- ✓ Onset of $\Sigma^-(\Lambda)$ shifted to higher (lower) density
- ✓ Hyperon fraction lower in ν-trapped matter

Hyperons & Proto-Neutron Stars: EoS

(Burgio & Schulze 2011)



- Nucleonic matter

✧ ν-trapping + temperature

⟶ softer EoS

- Hyperonic matter

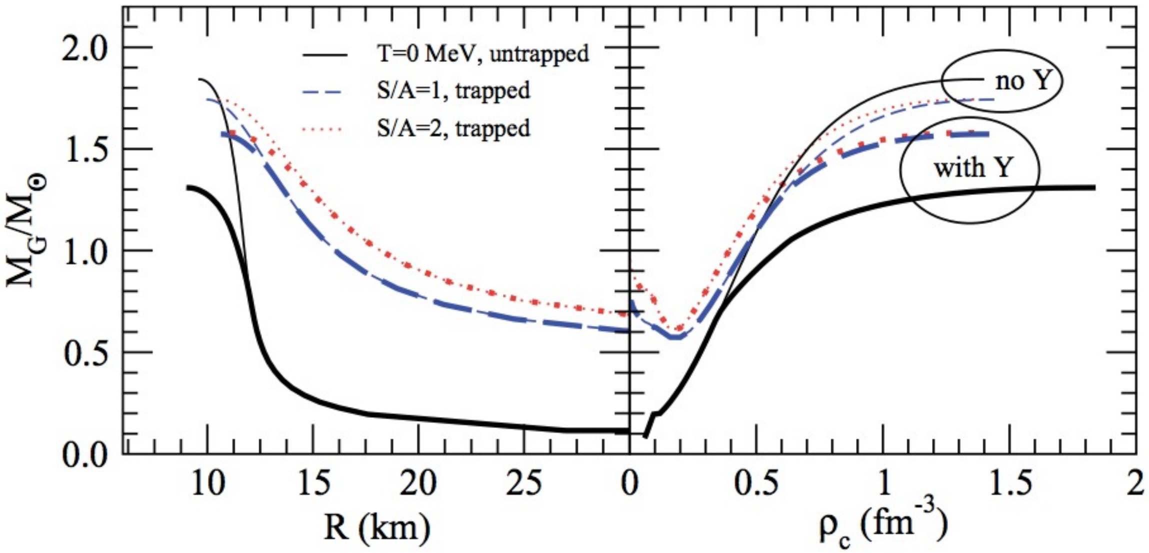
✧ ν-trapping + temperature

⟶ stiffer EoS

✧ More hyperon softening in ν-untrapped matter (larger hyperon fraction)

Hyperons & Proto-Neutron Stars: Structure

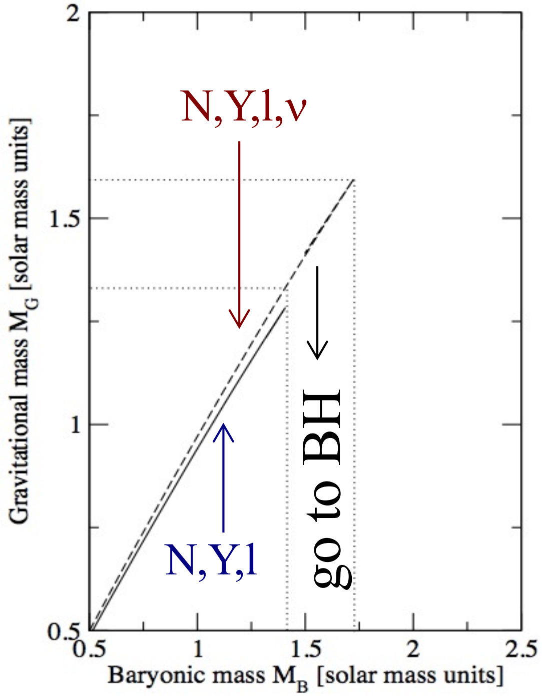
(Burgio & Schulze 2011)



- Nucleonic matter

  ν-trapping + T:
  reduction of M_{max}

(I.V. et al. 2003)



- Hyperonic matter

  ν-trapping + T:
  increase of M_{max} → delayed formation of a low mass BH

The final message of this talk

Hyperons in Neutron Stars

✓Strong softening of EoS & reduction of NS Mass

➔ Hyperons & Massive NS still an open question

✓Additional Fast Cooling Processes

✓Reduction of r-mode instability region

} But hyperon pairing gaps are poorly known !!

✓Modification of PNS properties (composition, EoS, Mass, …)

For details see e.g:

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

✧ You for your time & attention

✧ The organizers for their kind invitation