Hyperons: the strange ingredients of the nucler EoS

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The 4th CBM-China Workshop

April 12h-14th 2019, Yichang (China)

In this talk I will review briefly:

- Role of hyperons in neutron stars ("hyperon puzzle", cooling properties, r-mode stability, proto-neutron stars)
- YN & YY interaction models (meson exchange models, chiral EFT, $V_{low\ k}$ & lattice QCD)
- Few aspects of hypernuclei (production, spectroscopy, decay)

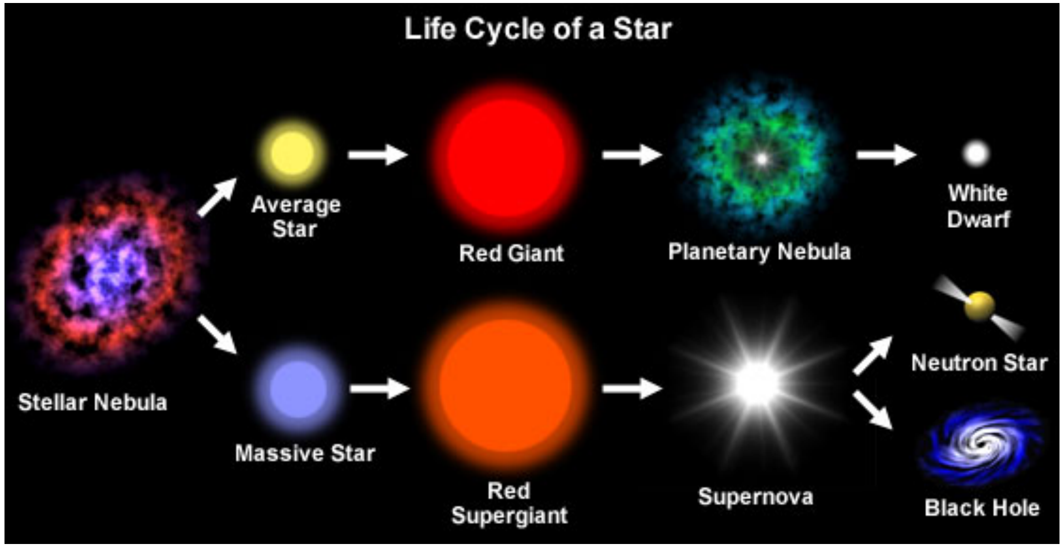
Based on: 

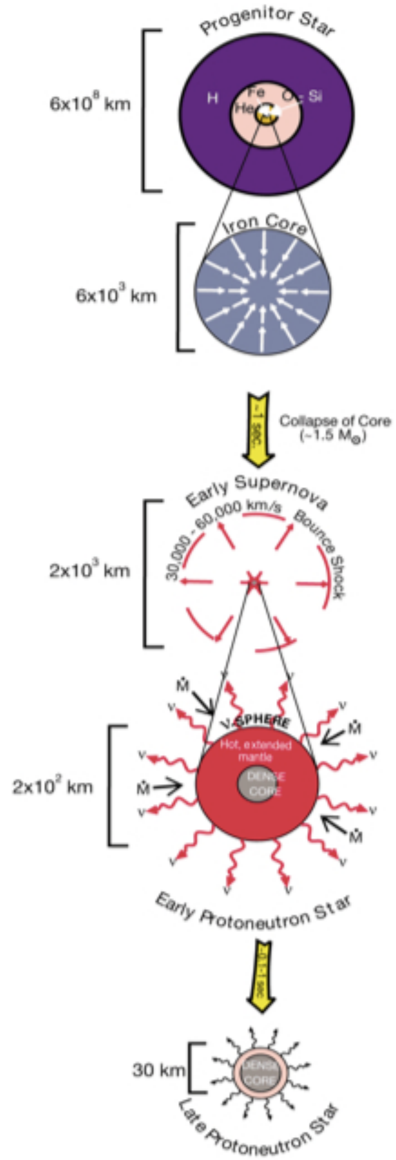
I.V. Proc. R. Soc. A 474, 0145 (2018)

I.V. Eur. Phys. J. Plus 133, 445 (2018)

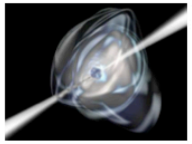
Few Generalities About Neutron Stars

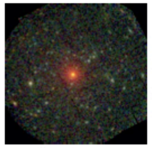
Neutron stars are a type of stellar compact remnant that can result from the gravitational collapse of a massive star ($8\ M_\odot < M < 25\ M_\odot$) during a Type II, Ib or Ic supernova event.

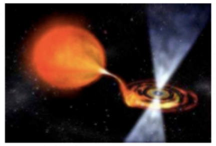




The 1001 Astrophysical Faces of Neutron Stars


Anomalous X-ray Pulsars

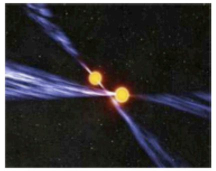

dim isolated neutron stars

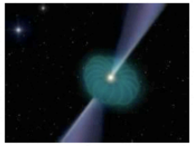

X-ray binaries

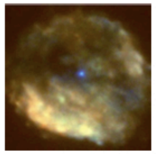

bursting pulsars

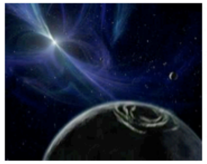

Soft Gamma Repeaters


pulsars


binary pulsars


Rotating Radio Transients


Compact Central Objects


planets around pulsar

Neutron stars can be observed as

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

✧ 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)

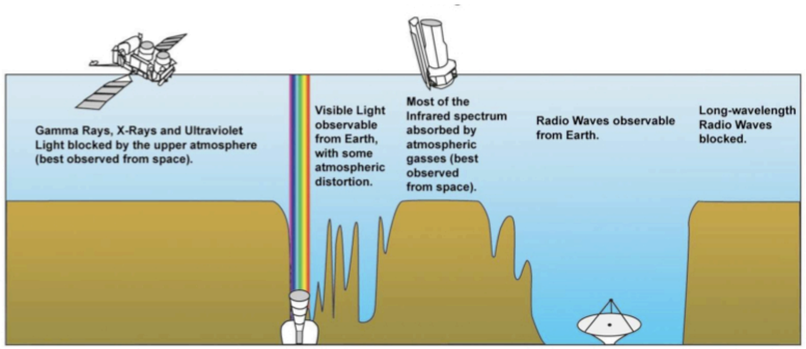
✧ Neutron stars in binary systems

- ✓ 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

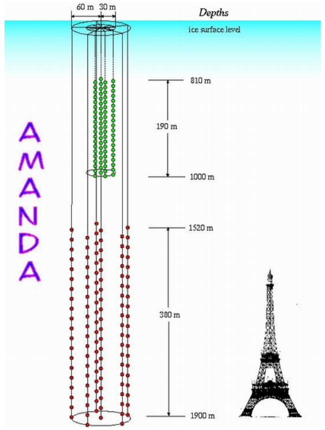
Chandra

Fermi

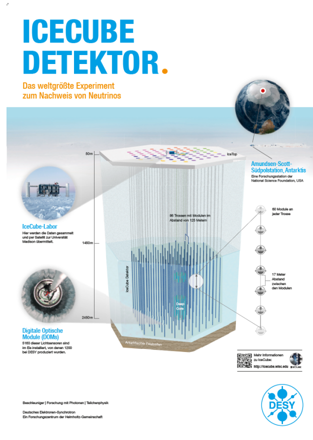
Observation of Neutron Stars: Neutrino Signals

Under-ice telescoles

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

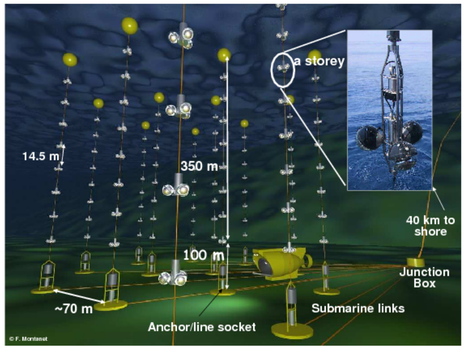


AMANDA

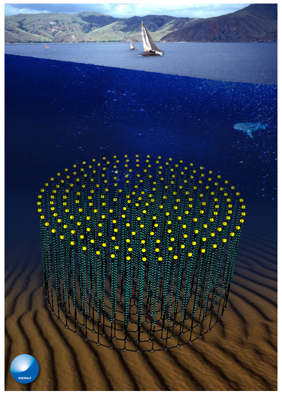


ICECUBE

Under-water telescopes

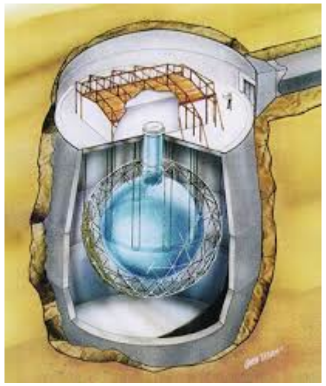


ANTARES

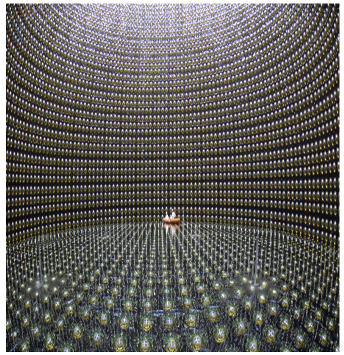


KM3NET

Under-ground telescopes



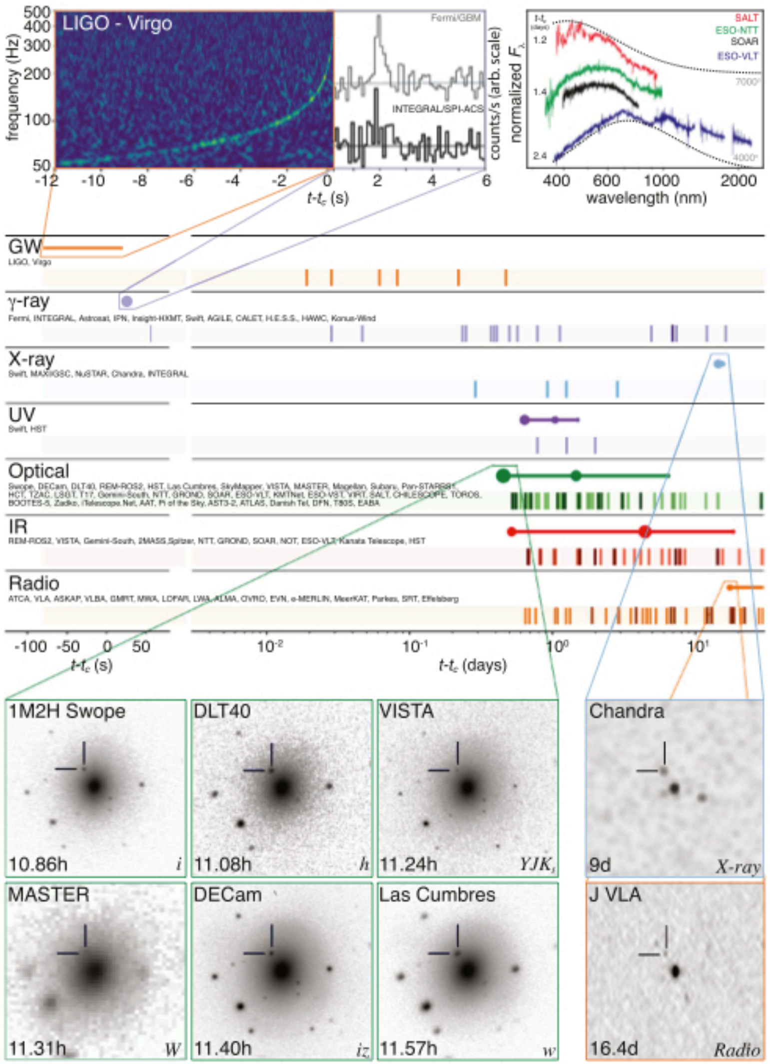
SNO



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)

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: $M = 1.928 \pm 0.017 M_\odot$

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

✓ binary system (P=2.46 h)

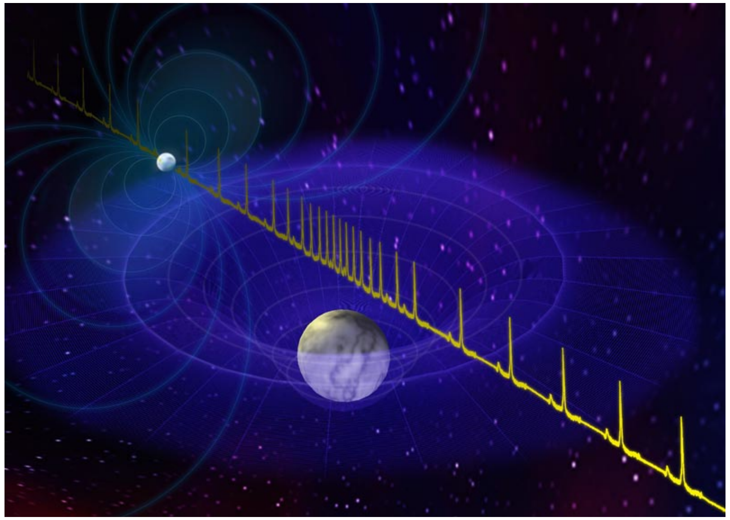
✓ very low eccentricity

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

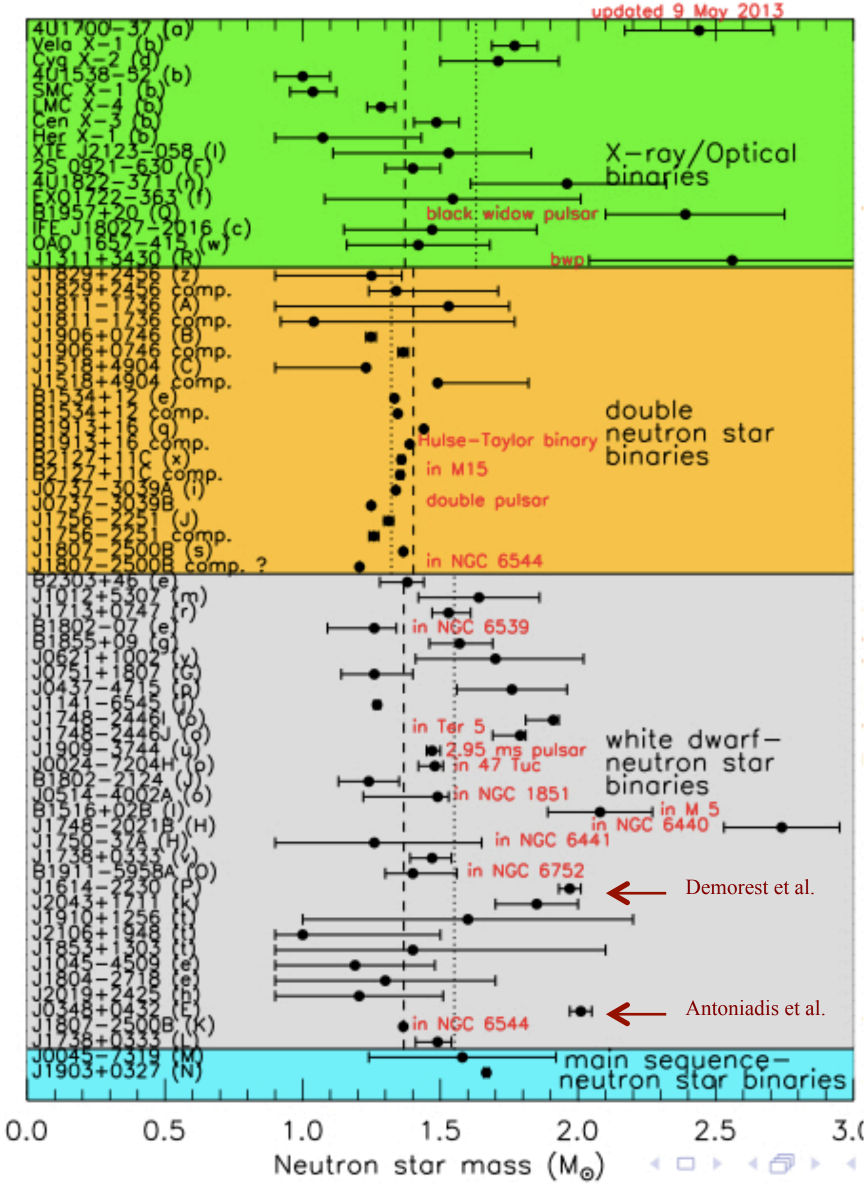
✓ pulsar mass: $M = 2.01 \pm 0.04 M_\odot$

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



Measured Neutron Star Masses (2019)



updated from Lattimer 2013

Observation of ~ 2 $M_\odot$ neutron stars imposes a very stringent constraint

Any reliable nuclear EoS should satisfy

$$M_{\max}\left[EoS\right] > 2M_\odot$$

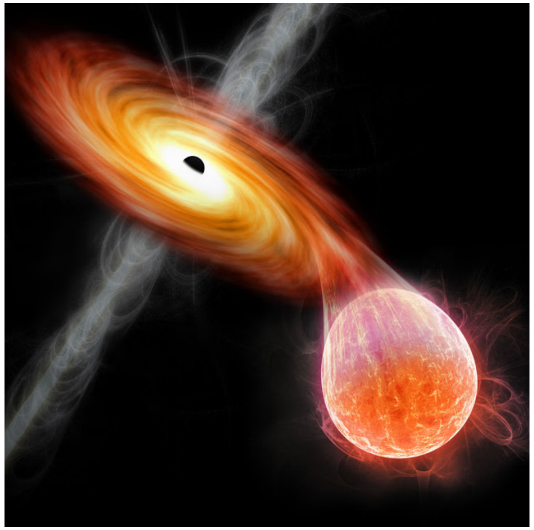
otherwise is rule out

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:

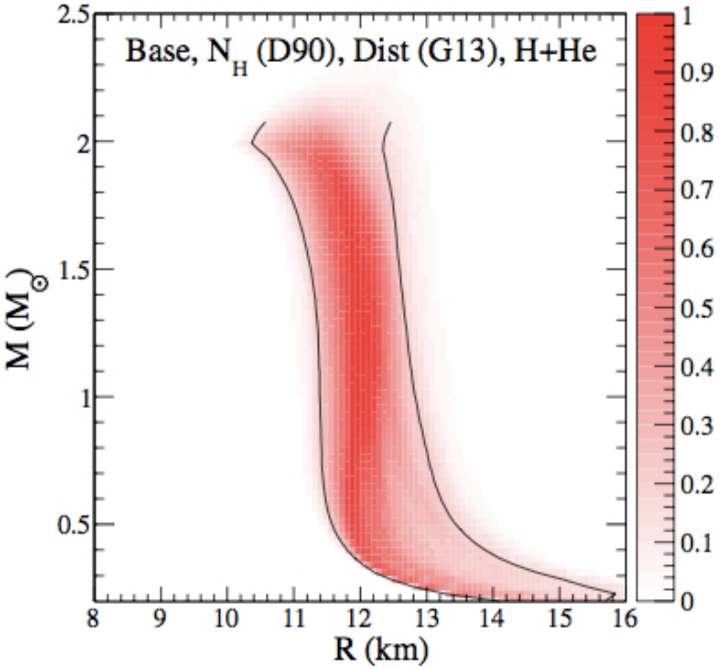
- ✧ Flux measurement +Stefan-Boltzmann's law
- ✧ Temperature (Black body fit+atmosphere model)
- ✧ Distance estimation (difficult)
- ✧ Gravitational redshift z (detection of absorption lines)

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

Recent Estimations of Neutron Star Radii

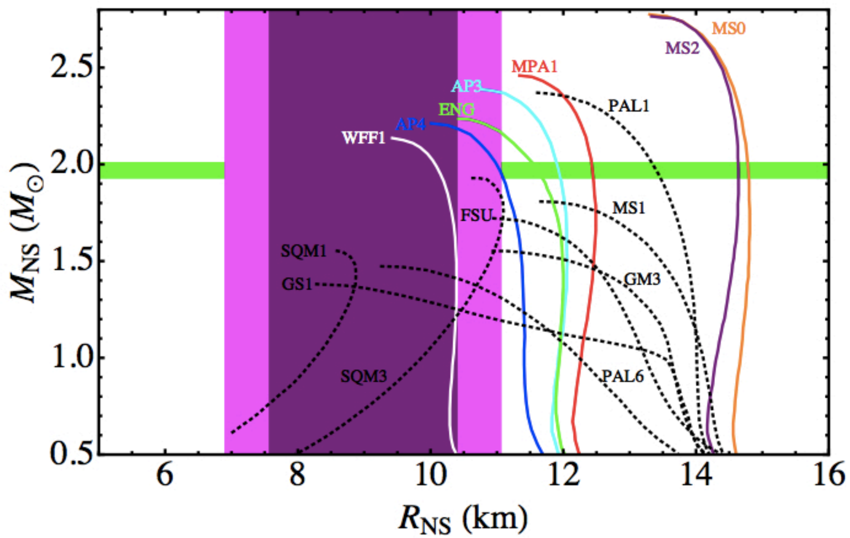
The recent analysis of the thermal spectrum from 5 quiescent LMXB in globular clusters is still controversial

Steiner et al. (2013, 2014)



$$R = 12.0 \pm 1.4 km$$

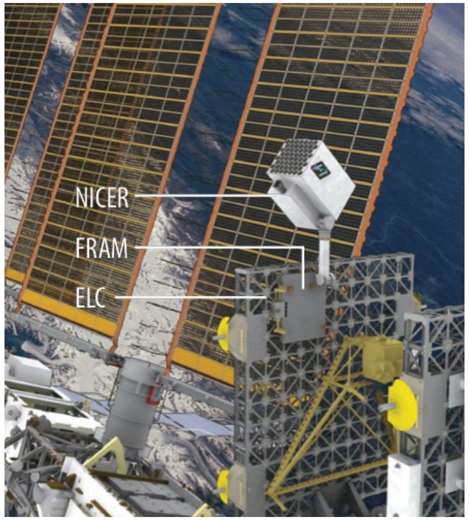
Guillot et al. (2013, 2014)



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

$$R = 9.4 \pm 1.2 km$$ 2014 analysis

NICER: Neutron Star Interior Composition Explorer



✧ 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

From observation we know …

- Mass: M ~ 1 - 2 $M_\odot$
- Radius: R ~ 10 - 12 km

Density: $\rho \sim 10^{14} - 10^{15}$ g/cm^3

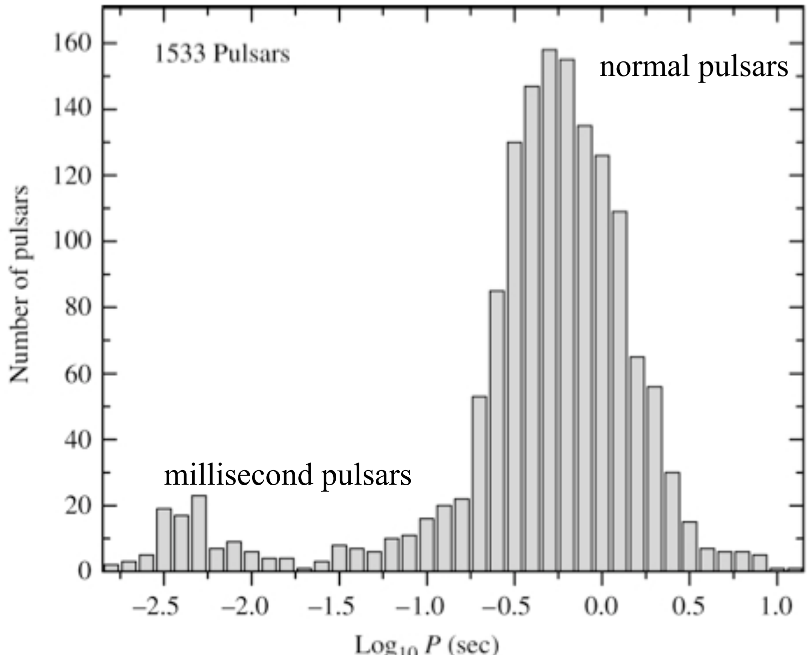
Baryonic number: $N_b \sim 10^{57}$

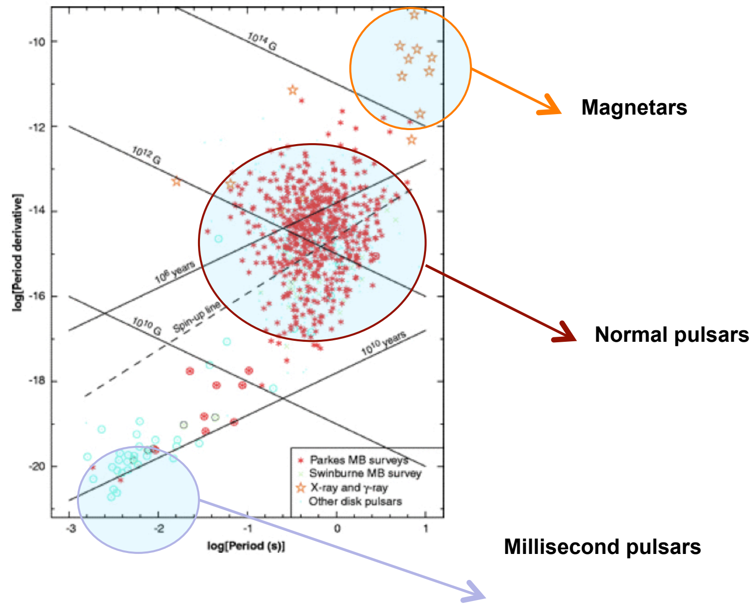
- Most NS observed as pulsars (but not all as seen before)

More than 2000 pulsars known
(~ 1900 radio, ~ 40 X-ray, ~ 60 γ-ray)

- Rotational period distribution
  ➔ two types of pulsars:

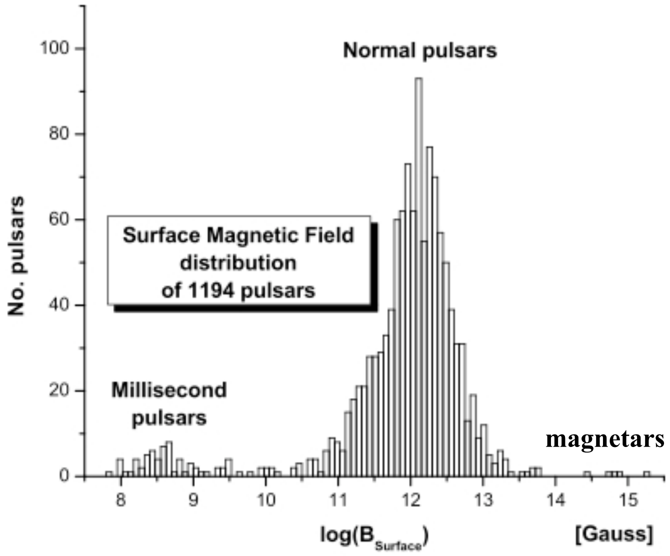
  - normal pulsars with P ~ s
  - millisecond pulsars with P ~ ms



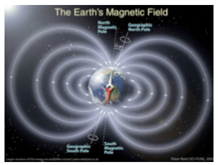
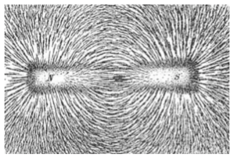
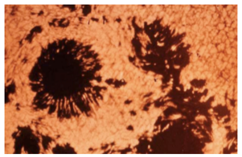
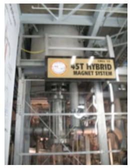


- Magnetic field

Type of Pulsar	Surface magnetic field
Millisecond	$10^8 – 10^9$ G
Normal	10^{12} G
Magnetar	$10^{14} – 10^{15}$ G



Extremely high compared to …

Earth	Magnet	Sun spots	Largest continuous field in lab. (USA)	Largest magnetic pulse in lab. (Russia)
				
$0.3-0.5G$	10^3-10^4G	10^5G	$4.5x10^5G$	$2.8x10^7G$

- Electric field: E ~ 10^{18} V/cm
- Temperature: T ~ $10^{6…11}$ K

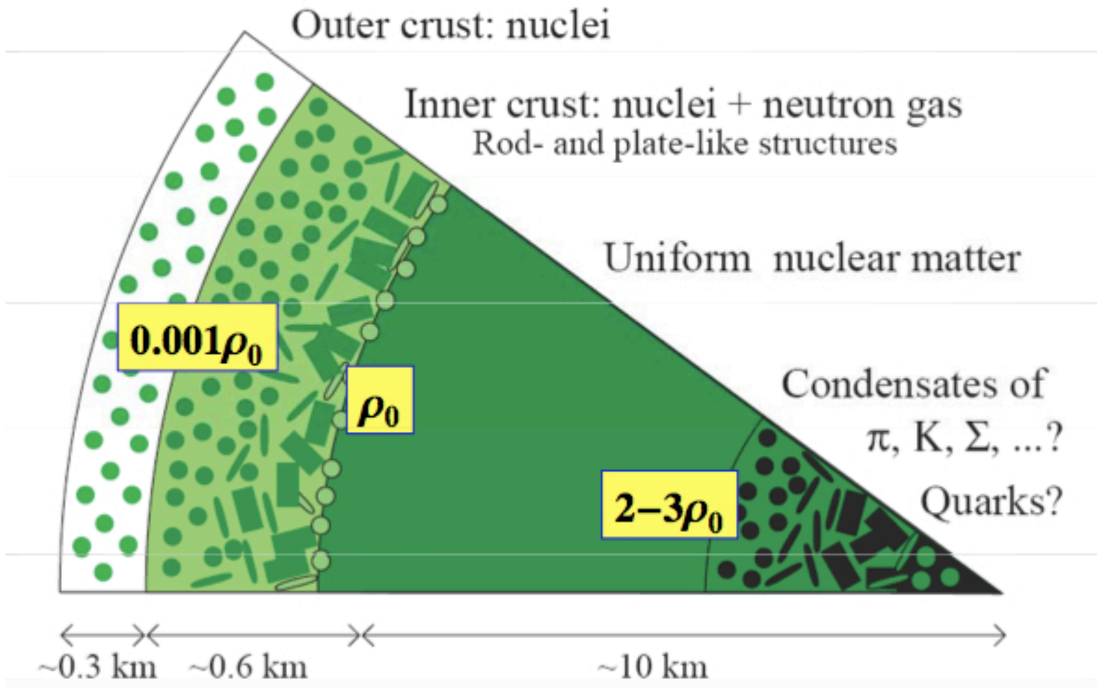
Anatomy of a Neutron Star

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

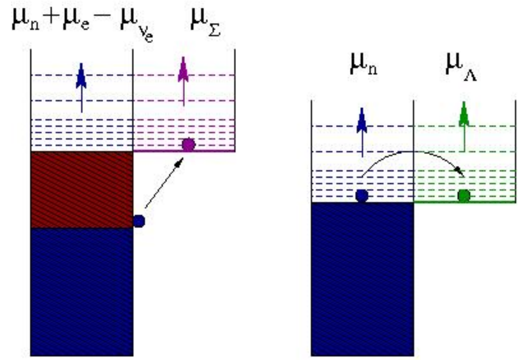
Microscopic approaches

- 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

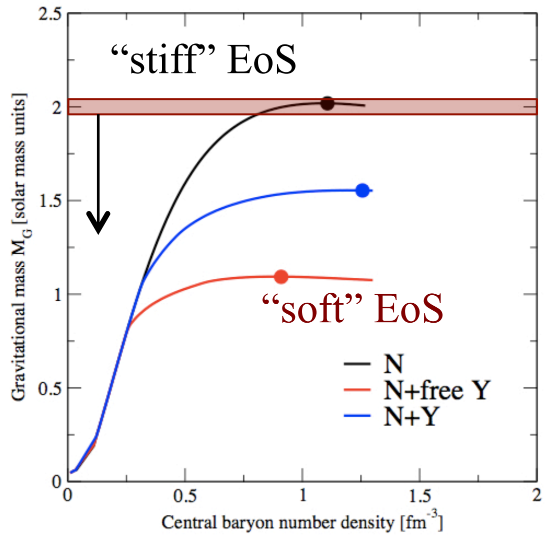
The Hyperon Puzzle: An Open Problem

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 → 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

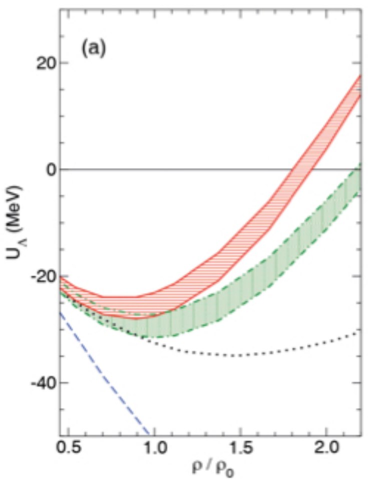
YN & YY

- YY vector meson repulsion

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

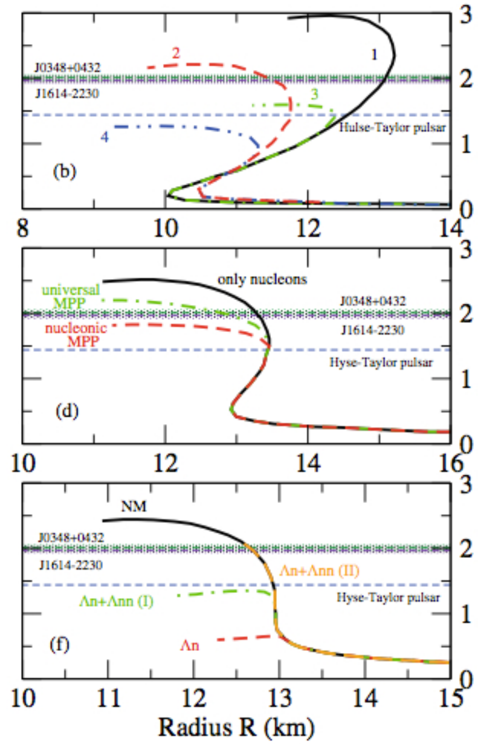
- Chiral forces

  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. **Results still not conclusive**



Quark Matter

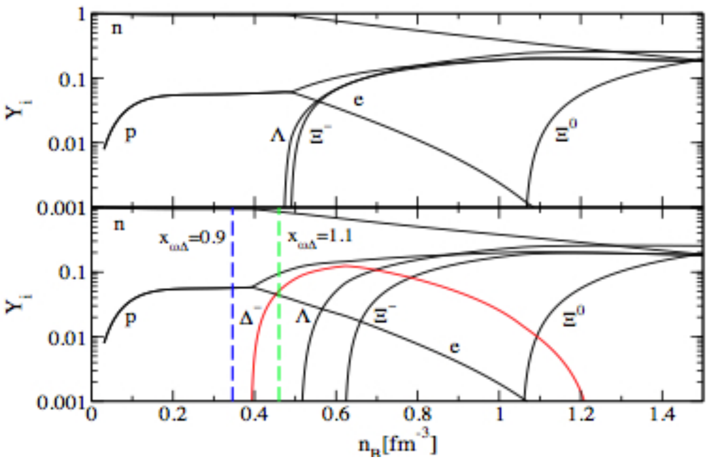
Phase transition to deconfined QM at densities lower that hyperon threshold

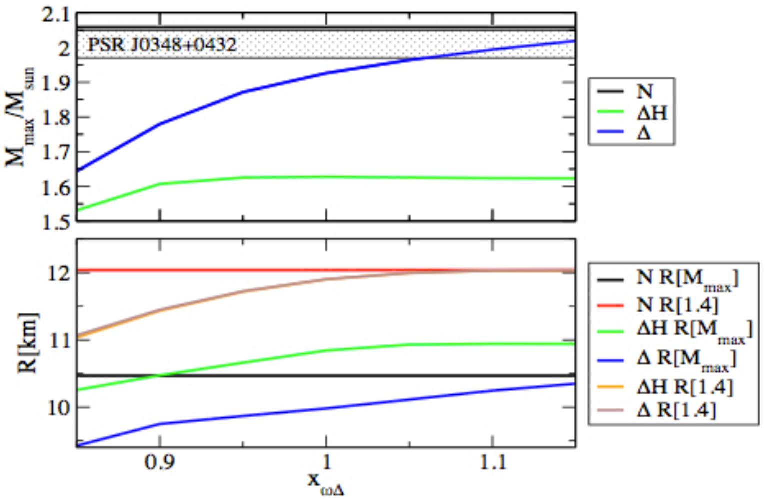
To yield $M_{max} > 2M_\odot$ QM should be

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

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

Take as a grain of salt, but the problem can be much more difficult to solve if this is confirmed …

THE ASTROPHYSICAL JOURNAL, IN PRESS.
Preprint typeset using LaTeX style emulateapj v. 12/16/11

PEERING INTO THE DARK SIDE: MAGNESIUM LINES ESTABLISH A MASSIVE NEUTRON STAR IN PSR J2215+5135

M. LINARES[1,2], T. SHAHBAZ[2,3], J. CASARES[2,3]

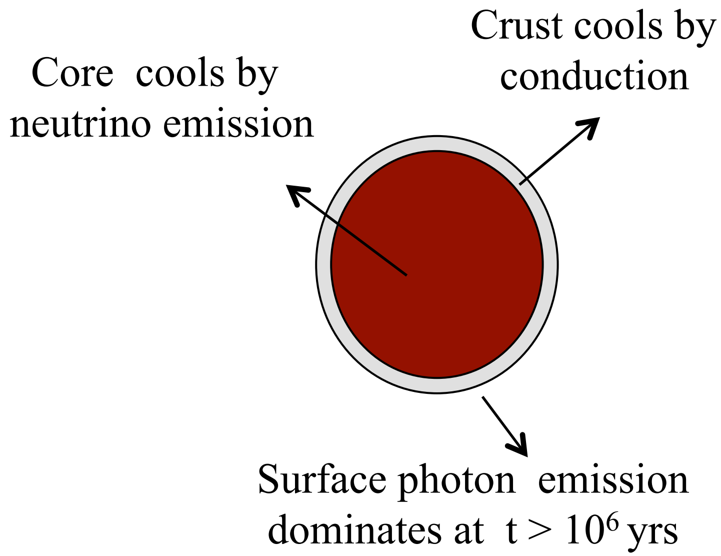
The Astrophysical Journal, in press.

ABSTRACT

New millisecond pulsars (MSPs) in compact binaries provide a good opportunity to search for the most massive neutron stars. Their main-sequence companion stars are often strongly irradiated by the pulsar, displacing the effective center of light from their barycenter and making mass measurements uncertain. We present a series of optical spectroscopic and photometric observations of PSR J2215+5135, a "redback" binary MSP in a 4.14 hr orbit, and measure a drastic temperature contrast between the dark/cold ($T_N=5660^{+260}_{-380}$ K) and bright/hot ($T_D=8080^{+470}_{-280}$ K) sides of the companion star. We find that the radial velocities depend systematically on the atmospheric absorption lines used to measure them. Namely, the semi-amplitude of the radial velocity curve of J2215 measured with magnesium triplet lines is systematically higher than that measured with hydrogen Balmer lines, by 10%. We interpret this as a consequence of strong irradiation, whereby metallic lines dominate the dark side of the companion (which moves faster) and Balmer lines trace its bright (slower) side. Further, using a physical model of an irradiated star to fit simultaneously the two-species radial velocity curves and the three-band light curves, we find a center-of-mass velocity of $K_2=412.3\pm5.0$ km s^{-1} and an orbital inclination $i=63.9^{\circ}{}^{+2.4}_{-2.7}$. Our model is able to reproduce the observed fluxes and velocities without invoking irradiation by an extended source. We measure masses of $M_1=2.27^{+0.17}_{-0.15}$ $M_\odot$ and $M_2=0.33^{+0.03}_{-0.02}$ $M_\odot$ for the neutron star and the companion star, respectively. If confirmed, such a massive pulsar would rule out some of the proposed equations of state for the neutron star interior.

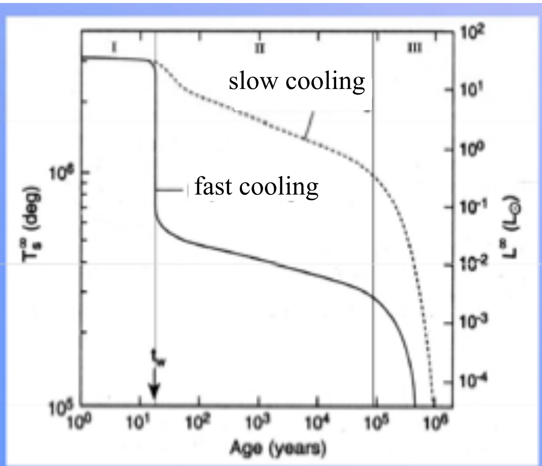
M. Linares et al., ApJ 859, 54 (2018)

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”

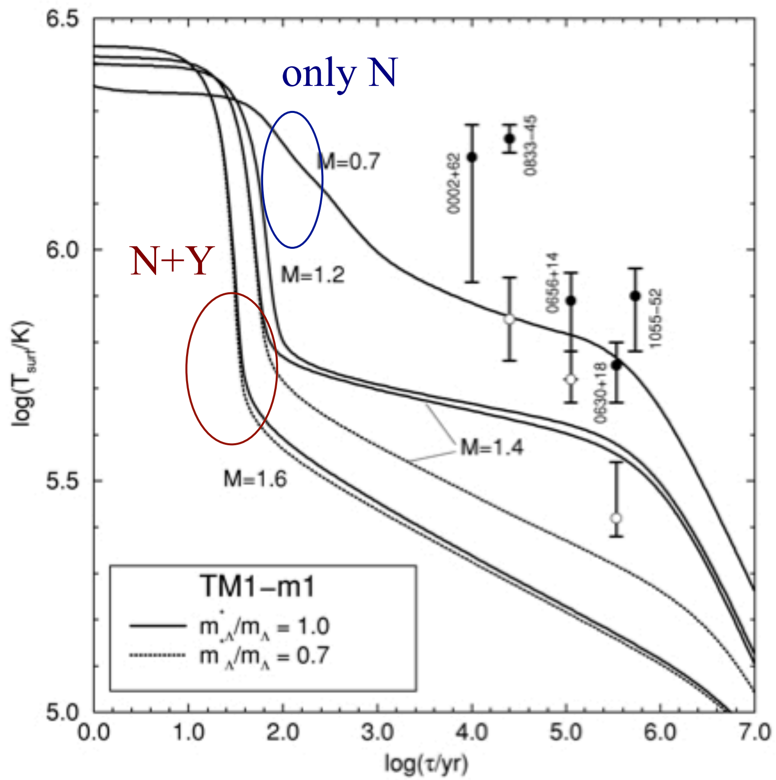
Hyperonic DURCA processes possible as soon as hyperons appear (nucleonic DURCA requires $x_p > 11\text{-}15\ \%$)

→ Additional Fast Cooling Processes

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

+ partner reactions generating neutrinos, Hyperonic MURCA, …

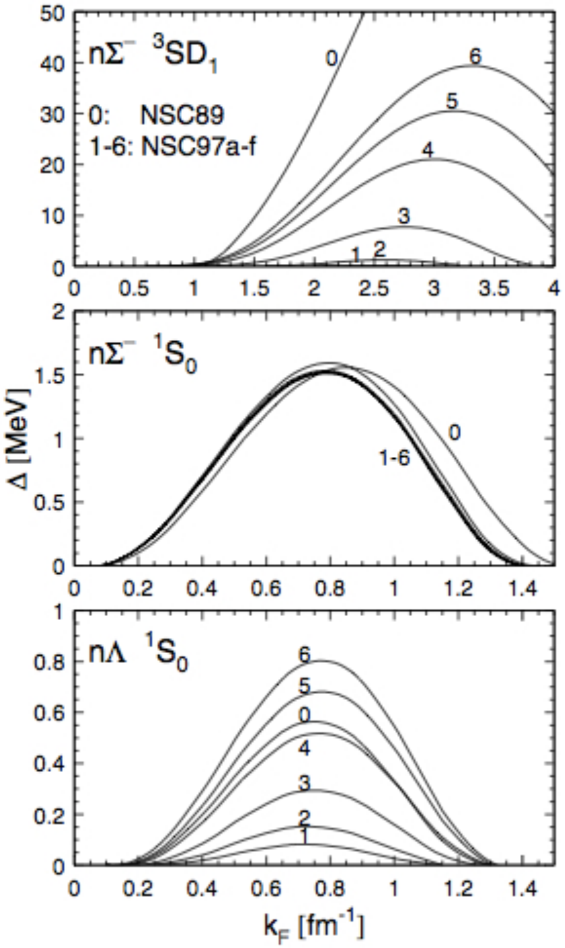
(Schaab, Shaffner-Bielich & Balberg 1998)



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

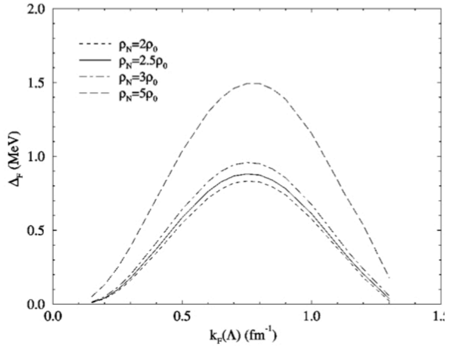
Pairing Gap ⟶ suppression of C_v & ε by $\sim e^{(-\Delta/k_B T)}$

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

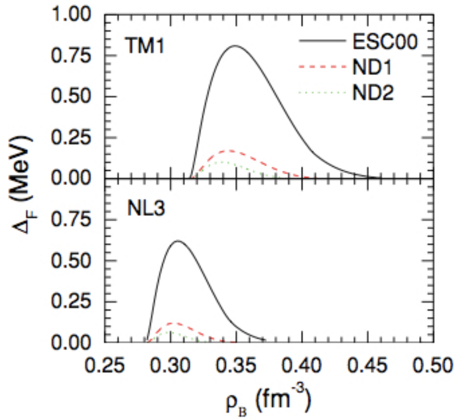


(Zhou, Schulze, Pan & Draayer 2005)

- $^1S_0$ $\Lambda\Lambda$ gap

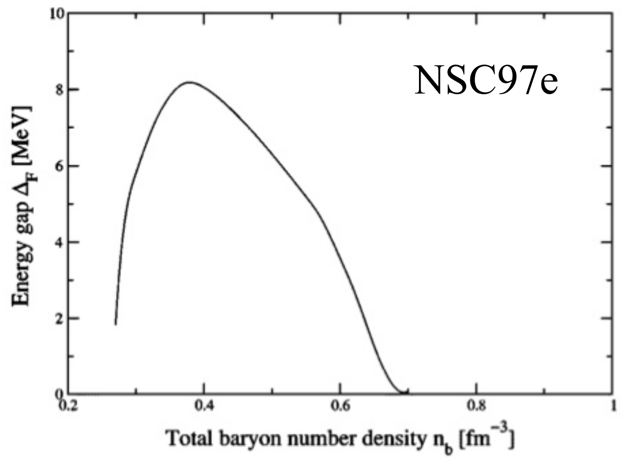


(Balberg & Barnea 1998)



(Wang & Shen 2010)

- $^1S_0$ $\Sigma\Sigma$ gap

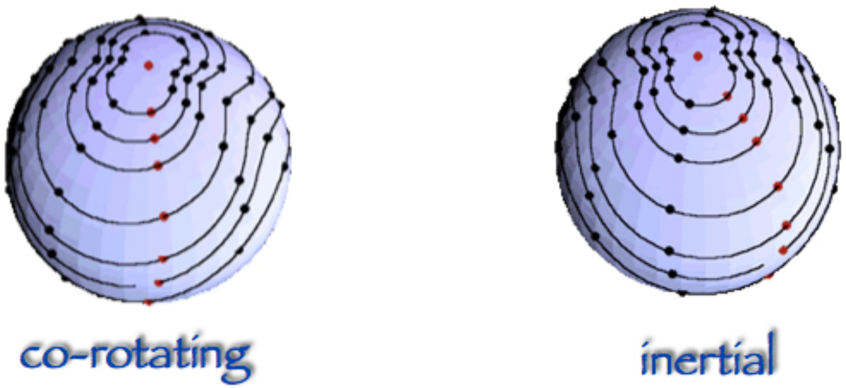


(IV & Tolós 2004)

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

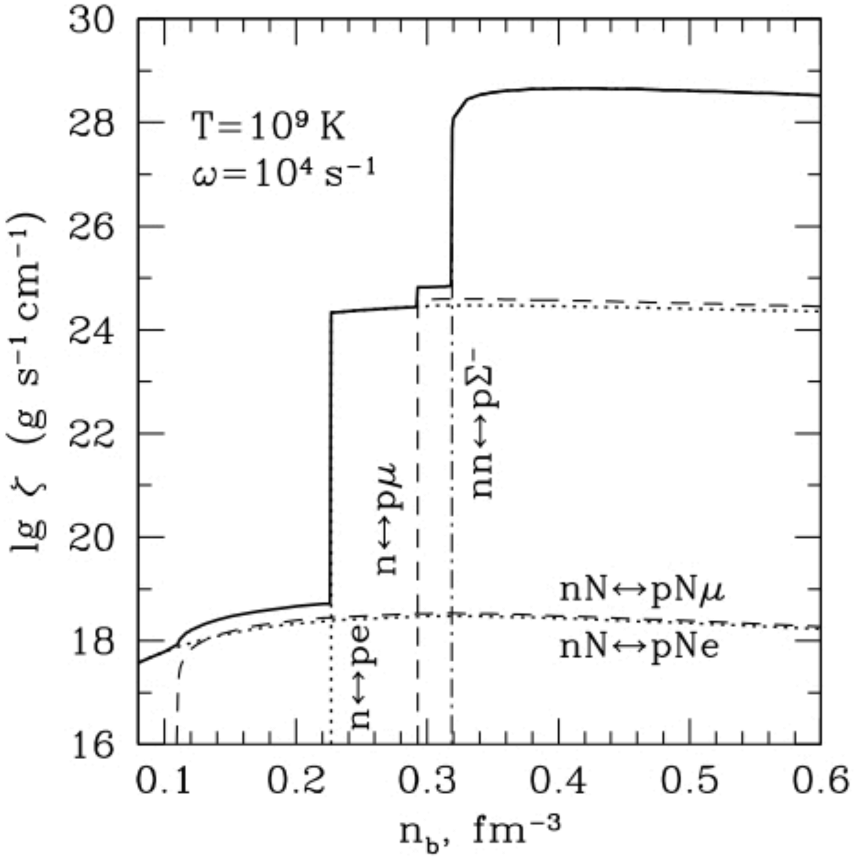
Hyperon Bulk Viscosity ξ_Y

(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	$Y \to B+l+\bar{\nu}_l$ $B'+Y \to B'+B+l+\bar{\nu}_l$
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: $A \propto A_o e^{-i\omega(\Omega)t - t/\tau(\Omega)}$

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

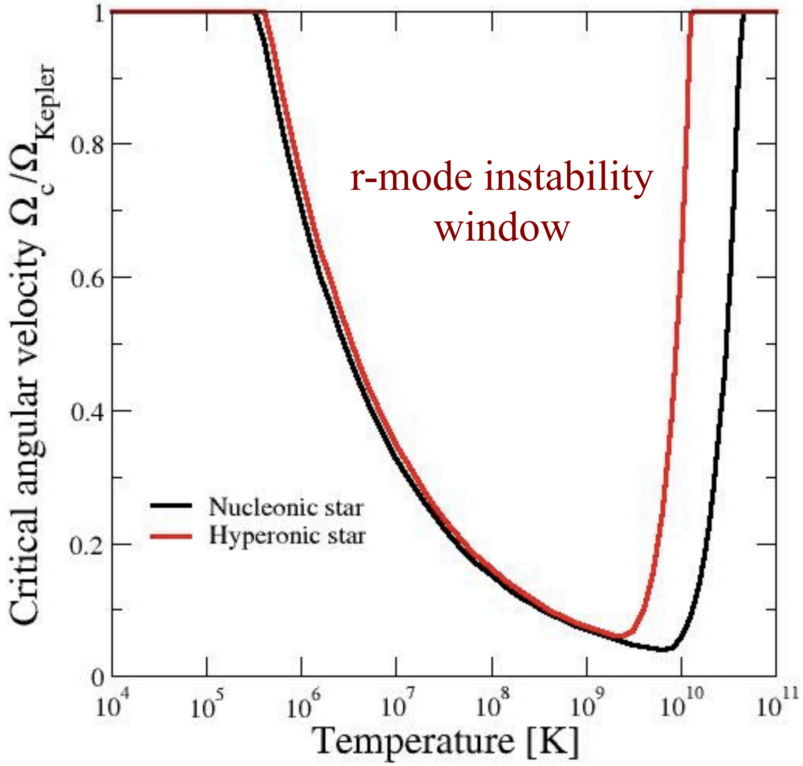
➔ $\frac{1}{\tau(\Omega_c,T)} = 0$ r-mode instability region

$\Omega < \Omega_c$ stable

$\Omega > \Omega_c$ unstable

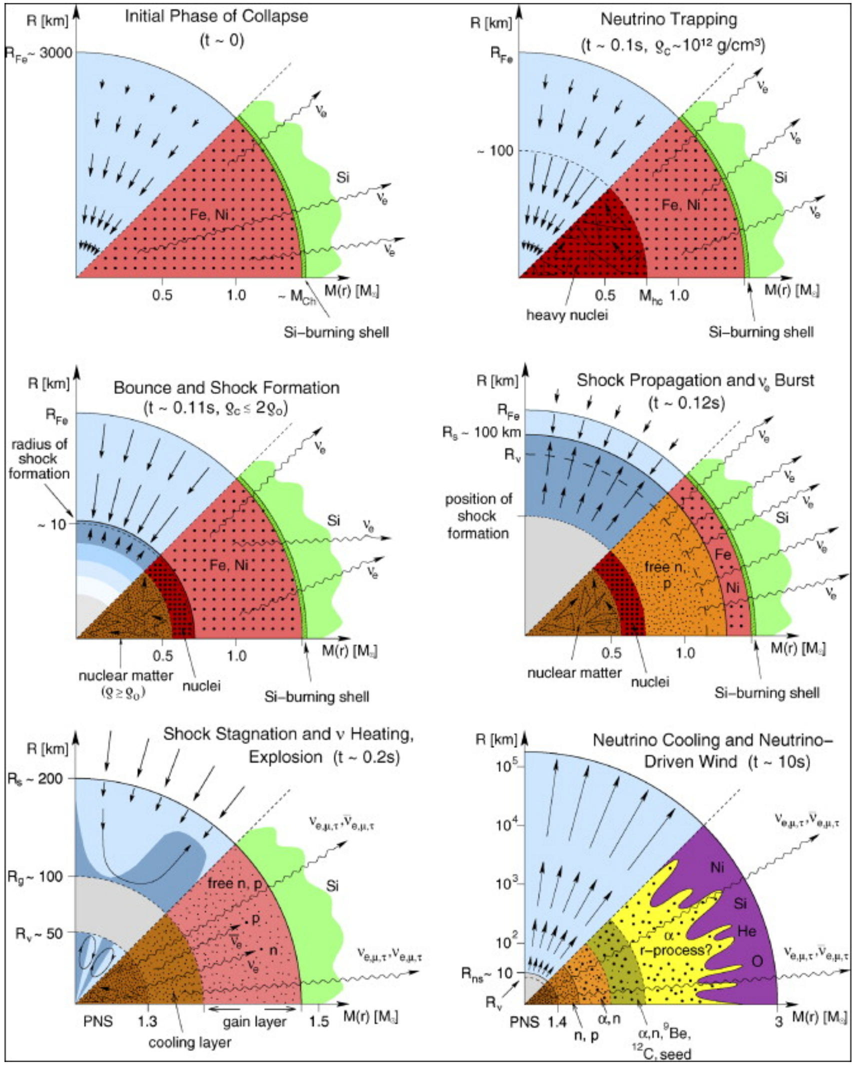
As expected:
smaller r-mode instability region
due to hyperons

(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

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

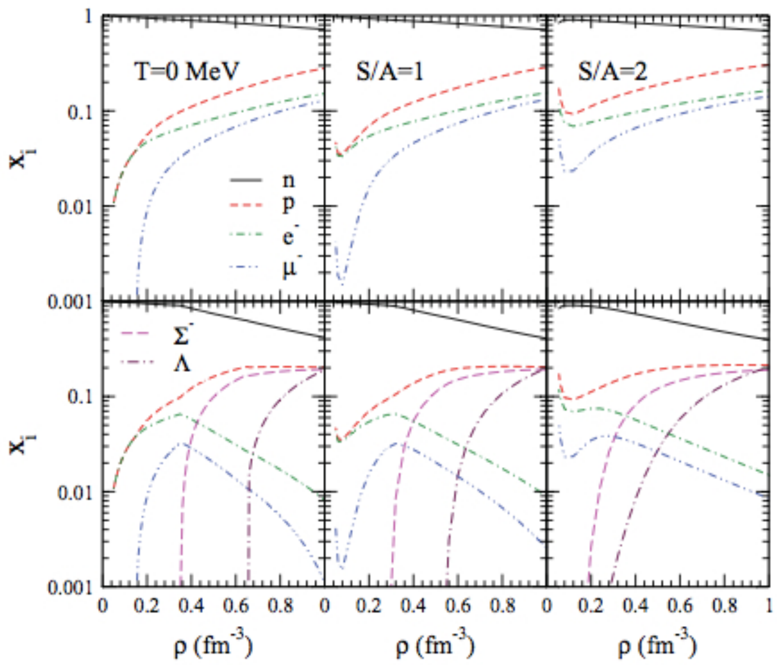
- Neutrino trapping

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

Hyperons & Proto-Neutron Stars: Composition

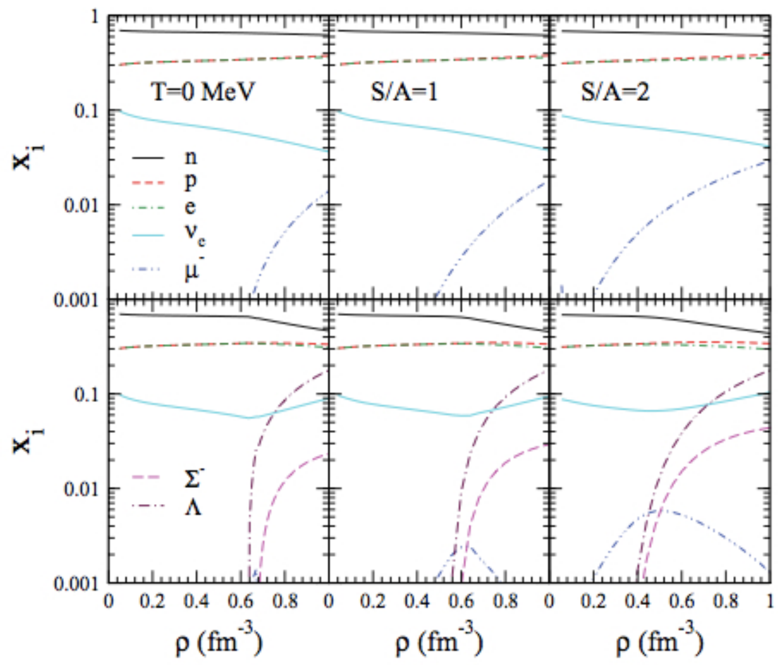
- Neutrino free $\mu_\nu = 0$

(Burgio & Schulze 2011)



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

(Burgio & Schulze 2011)

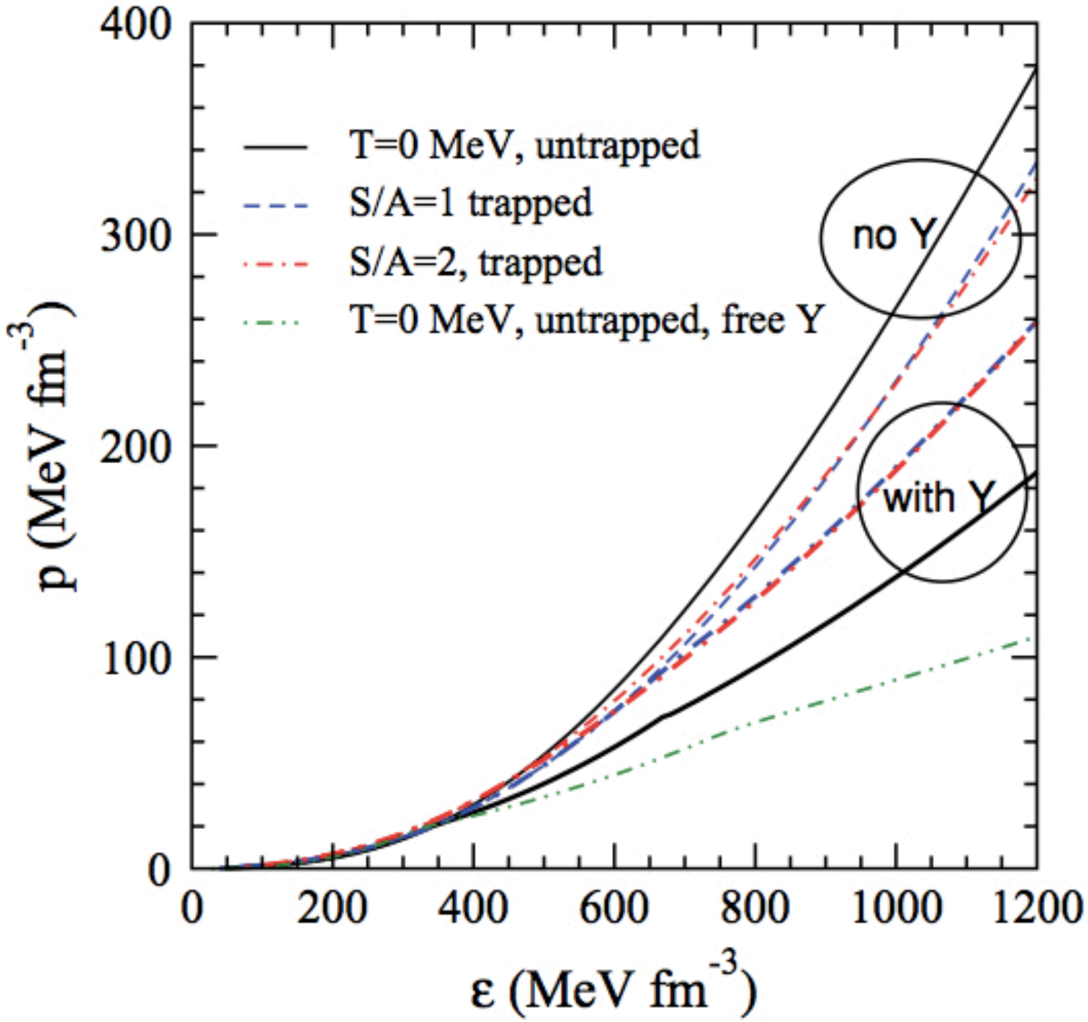


<u>Neutrino trapped</u> ➔

- ✓ Large proton fraction
- ✓ Small number of muons
- ✓ Onset of Σ^-(Λ) 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

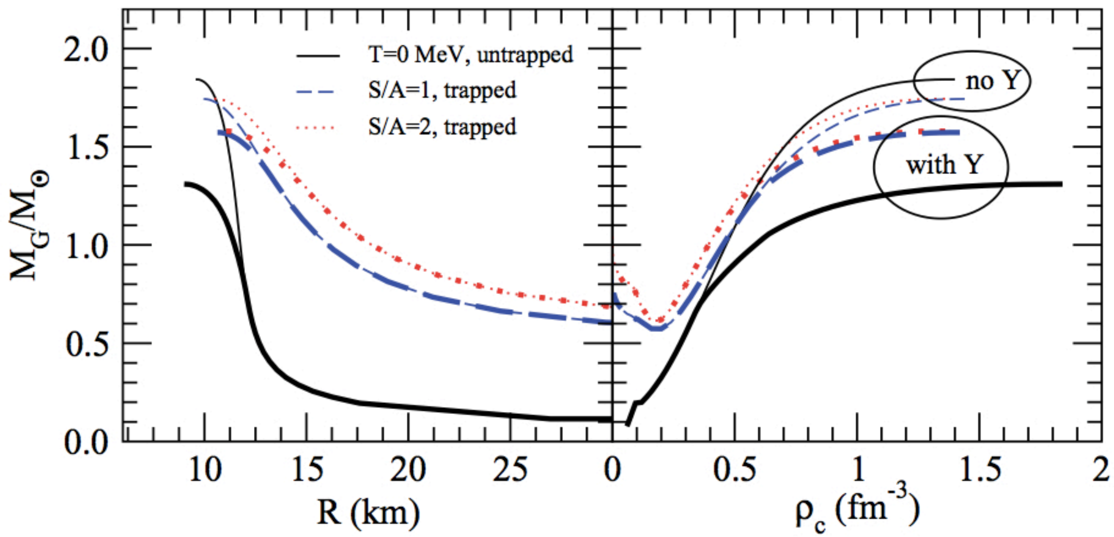
- Hyperonic matter

✧ ν-trapping + temperature → stiffer EoS

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

Hyperons & Proto-Neutron Stars: Structure

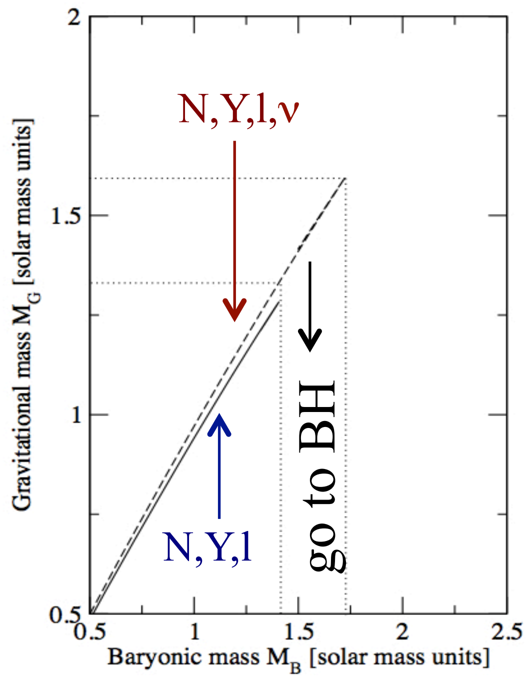
(Burgio & Schulze 2011)



- Nucleonic matter

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

(I.V. et al. 2003)



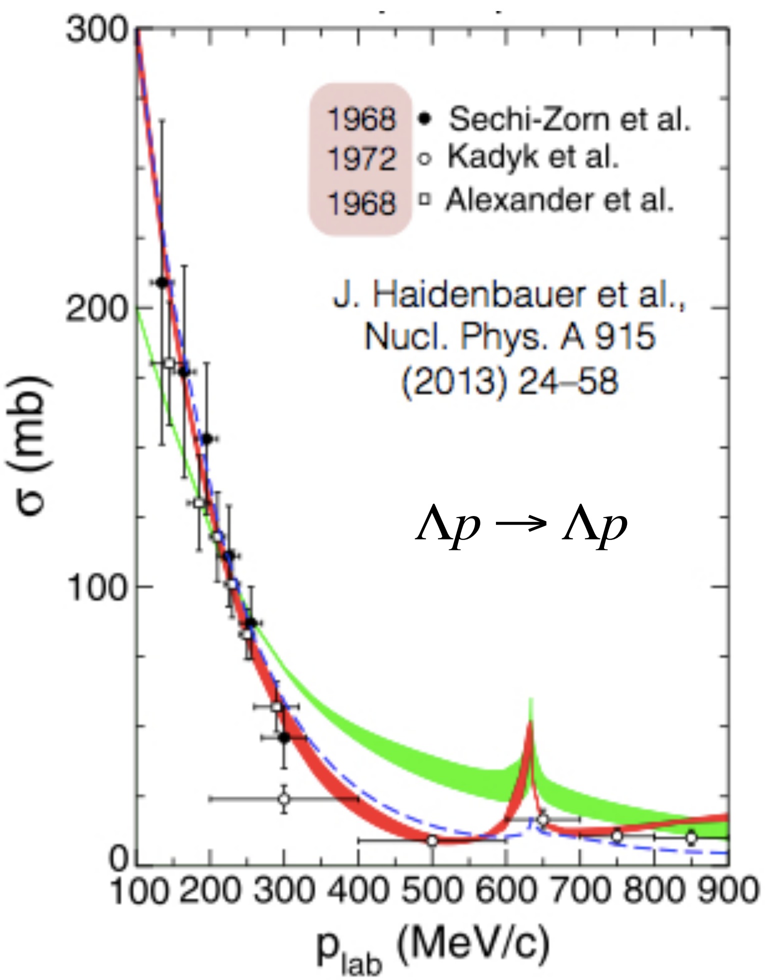
- Hyperonic matter

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

→ delayed formation of a low mass BH

How much do we know to include hyperons in the nuclear 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)

Building YN & YY Interactions

YN meson-exchange models

Strategy: start from a NN model & impose $SU(3)_{flavor}$ constraints

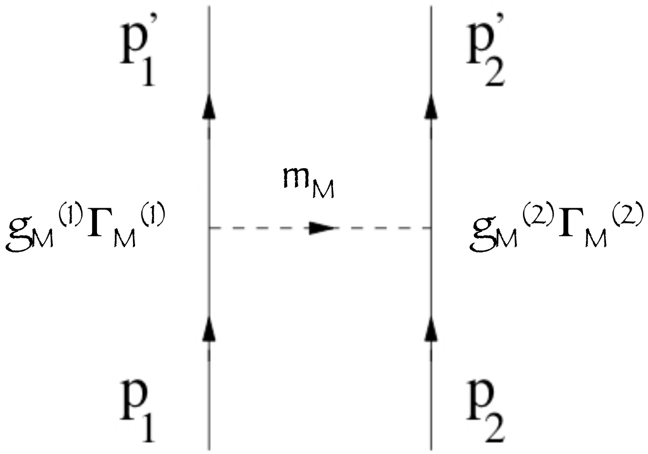
$$L = g_M \Gamma_M \left(\overline{\Psi}_B \Psi_B\right)\phi_M$$

- scalar: σ,δ $\qquad \Gamma_s = 1$
- pseudocalar: π,K,η $\qquad \Gamma_{ps} = i\gamma^5$
- vector: ρ,K,ω, ϕ $\qquad \Gamma_v = \gamma^\mu\,, \quad \Gamma_T = \sigma^{\mu\nu}$

$$\langle p_1' p_2' | V_M | p_1 p_2 \rangle = \bar{u}(p_1') g_M^{(1)} \Gamma_M^{(1)} u(p_1) \frac{P_M}{(p_1 - p_1')^2 - m_M^2} \bar{u}(p_2') g_M^{(2)} \Gamma_M^{(2)} u(p_2)$$

⬇

$$V(r) = V_0(r) + V_S(r)(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + V_T(r) S_{12} + V_{ls}(r)(\vec{L} \times \vec{S}^+) + V_{als}(r)(\vec{L} \times \vec{S}^-)$$



The Nijmegen & Jülich models

Nijmegen

(Nagels, Rijken, de Swart, Maessen)

- ✧ Based on Nijmegen NN potential.
- ✧ Momemtum & Configuration Space.
- ✧ Exchange of nonets of pseudo-scalar, vector and scalar.
- ✧ Strange vertices related by SU(3) symmetry with NN vertices.
- ✧ Gaussian Form Factors:

$$F_M(k^2) = e^{-\frac{k^2}{2\Lambda_M^2}}$$

Jülich

(Holzenkamp, Reube, Holinde, Speth, Haidenbauer, Meissner, Melnitchouck)

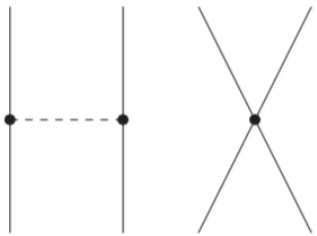
- ✧ Based on Bonn NN potential.
- ✧ Momemtum Space & Full energy-dependence & non-locality structure.
- ✧ higher-order processes involving π- and ρ-exchange (correlated 2π-exchange) besides single meson exchange.
- ✧ Strange vertices related by SU(6) $=SU(3)_{flavor}xSU(2)_{spin}$ symmetry with NN vertices.
- ✧ Dipolar Form Factors:

$$F_M(k^2) = \left(\frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - k^2}\right)^2$$

Chiral Effective Field Theory for YN

Strategy: start from a chiral effective lagrangian in a way similar to the NN case. Recently developed by the Juelich-Bonn-Munich group

- Leading Order (LO)



✧ One-pseudoscalar meson exchange

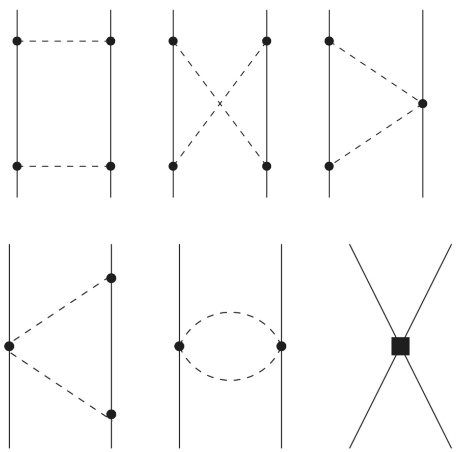
$$V^{BB}_{OBE} = -f_{B_1B_2P}f_{B_2B_4P}\frac{(\boldsymbol{\sigma}_1\cdot\boldsymbol{q})(\boldsymbol{\sigma}_2\cdot\boldsymbol{q})}{\boldsymbol{q}^2+m^2_{ps}}\mathcal{I}_{B_1B_2\to B_3B_4}$$

✧ Contact terms

$$\mathcal{L}^1 = C^1_i\langle\bar{B}_a\bar{B}_b(\Gamma_iB)_b(\Gamma_iB)_a\rangle,$$
$$\mathcal{L}^2 = C^2_i\langle\bar{B}_a(\Gamma_iB)_a\bar{B}_b(\Gamma_iB)_b\rangle$$
$$\mathcal{L}^3 = C^3_i\langle\bar{B}_a(\Gamma_iB)_a\rangle\langle\bar{B}_b(\Gamma_iB)_b\rangle.$$

$$\longrightarrow \quad V^{BB}_{LO} = C^{BB}_S + C^{BB}_T\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2.$$

- Next to Leading Order (NLO)



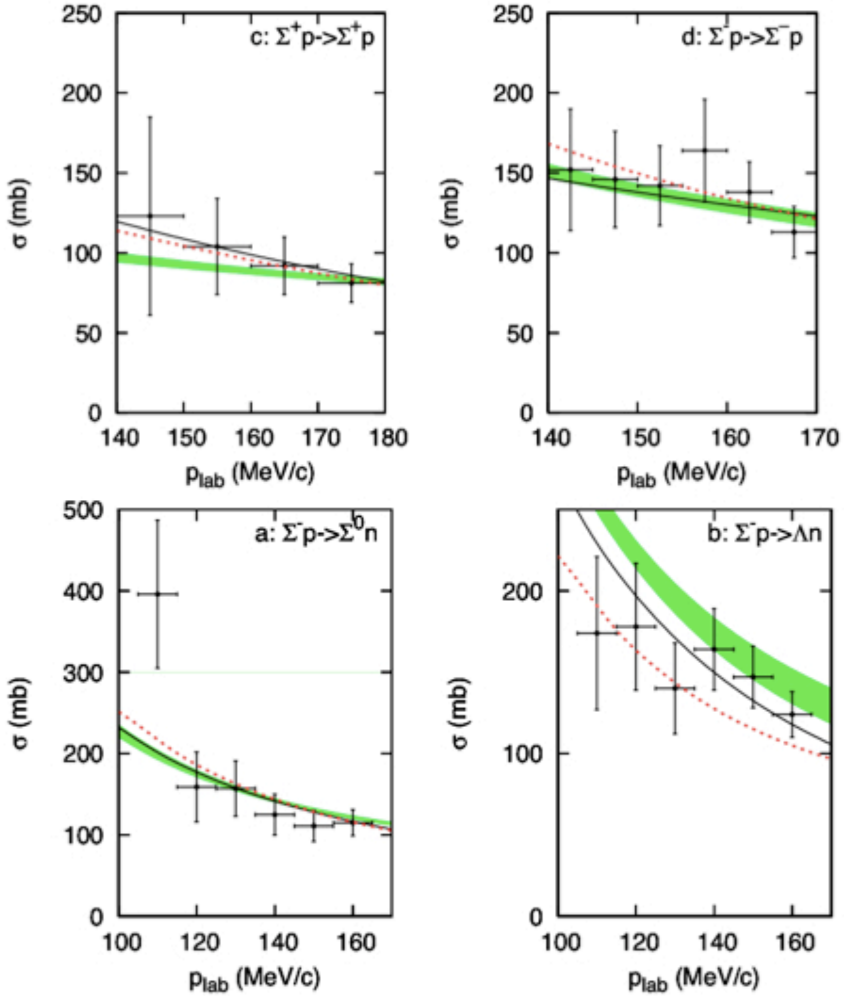
✧ Contact terms

$$V^{BB}_{NLO} = C_1\boldsymbol{q}^2 + C_2\boldsymbol{k}^2 + (C_3\boldsymbol{q}^2 + C_4\boldsymbol{k}^2)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + \frac{i}{2}C_5(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot(\boldsymbol{q}\times\boldsymbol{k})$$
$$+ C_6(\boldsymbol{q}\cdot\boldsymbol{\sigma}_1)(\boldsymbol{q}\cdot\boldsymbol{\sigma}_2) + C_7(\boldsymbol{k}\cdot\boldsymbol{\sigma}_1)(\boldsymbol{k}\cdot\boldsymbol{\sigma}_2) + C_8(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot(\boldsymbol{q}\times\boldsymbol{k})$$

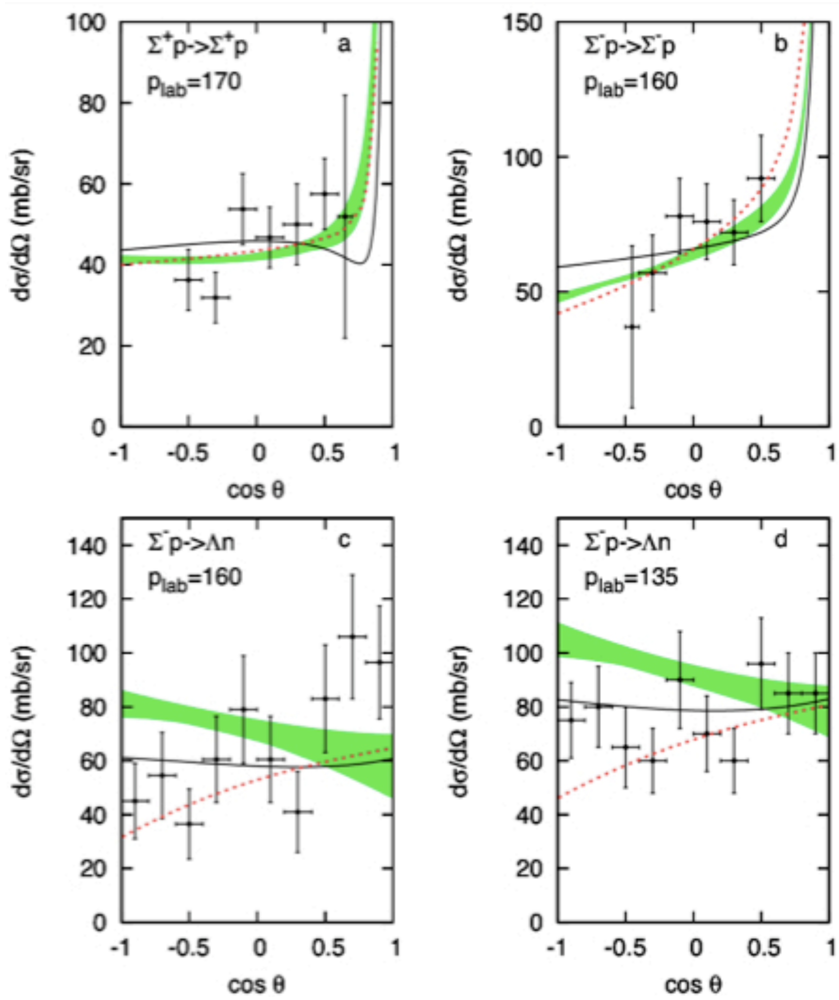
✧ Two-pseudoscalar meson exchange (rather cumbersome)

NPA 779, 244 (2006); NPA 915, 24 (2013)

Total cross YN sections



Differential YN cross sections



Solid: NSC97f

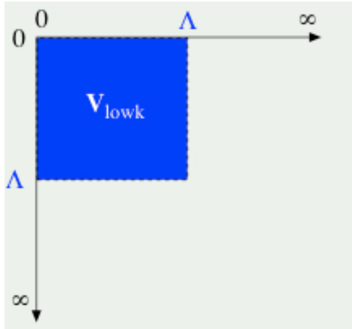
NPA 779, 224 (2006)

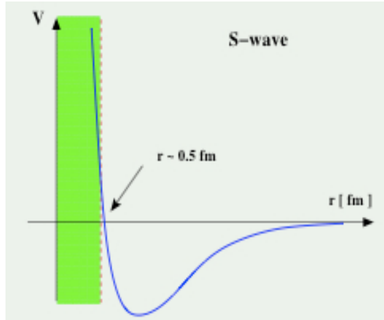
Green band: EFT

Dashed: Jülich04

Low-momentum YN interaction

Idea: start from a realistic YN interaction & integrate out the high-momentum components in the same way as as been done for NN.





↓

$V_{\text{low k}}$

- ✓ phase shift equivalent
- ✓ energy independent
- ✓ softer (no hard core)
- ✓ hermitian

B. -J. Schaefer et al., Phys. Rev. C 73, 011001 (2006)

Lippmann-Schwinger Equation

$$T(k',k;E_k) = V_{low\,k}(k',k) + \frac{2}{\pi} P \int_0^{\Lambda} dq q^2 V_{low\,k}(k',q) \frac{1}{E_k - H_0(q)} T(q,k;E_k)$$

Conditions

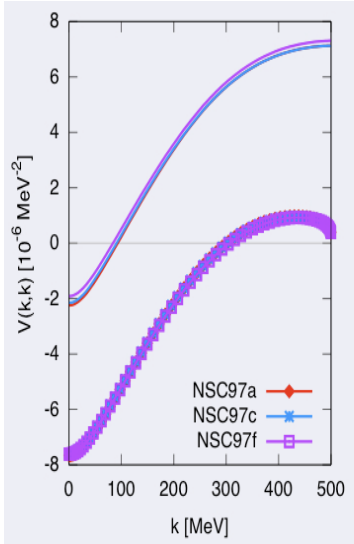
$$\frac{dT_\Lambda}{d\Lambda} = 0; \quad V_{low\,k} = \Lambda \qquad \Lambda \to \infty : V_{low\,k} = V_{bare}$$

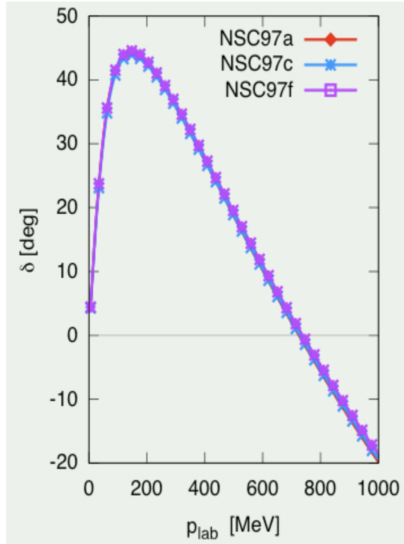
Renormalization Group Flow Equation

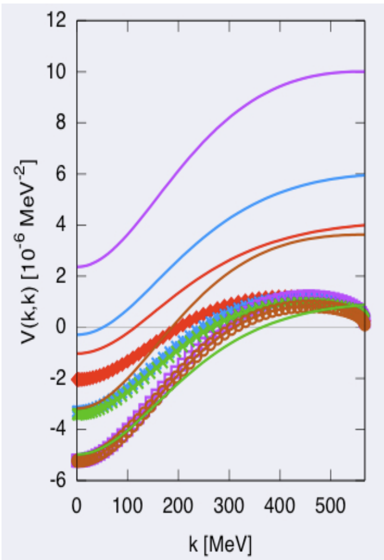
$$\frac{d}{d\Lambda} V_{low\,k}(k',k) = -\frac{2}{\pi} \frac{V_{low\,k}(k',\Lambda) T(\Lambda,k;\Lambda^2)}{E_k - H_0(\Lambda)}$$

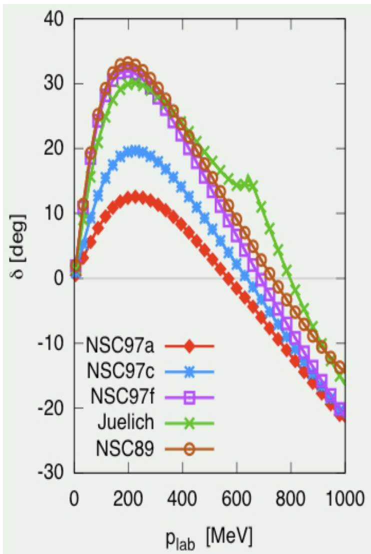
$^{1}S_{0}$ (I=3/2)matrix elements and phase-shift for ΣN➔ΣN

Λ≈500 MeV







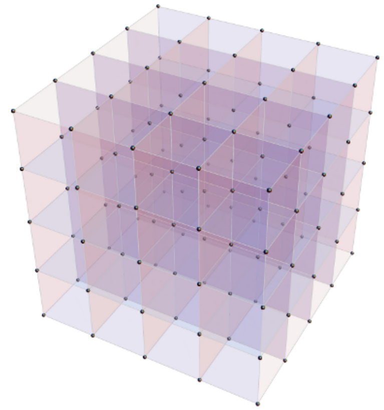


$^{1}S_{0}$ (I=1/2)matrix elements and phase-shift for ΛN➔ΛN

Λ≈500 MeV

B. -J. Schaefer et al., Phys. Rev. C 73, 011001 (2006)

Lattice QCD



Great progress to derive baryon-baryon interactions form HALQCD & NPLQCD collaborations

- HALQCD

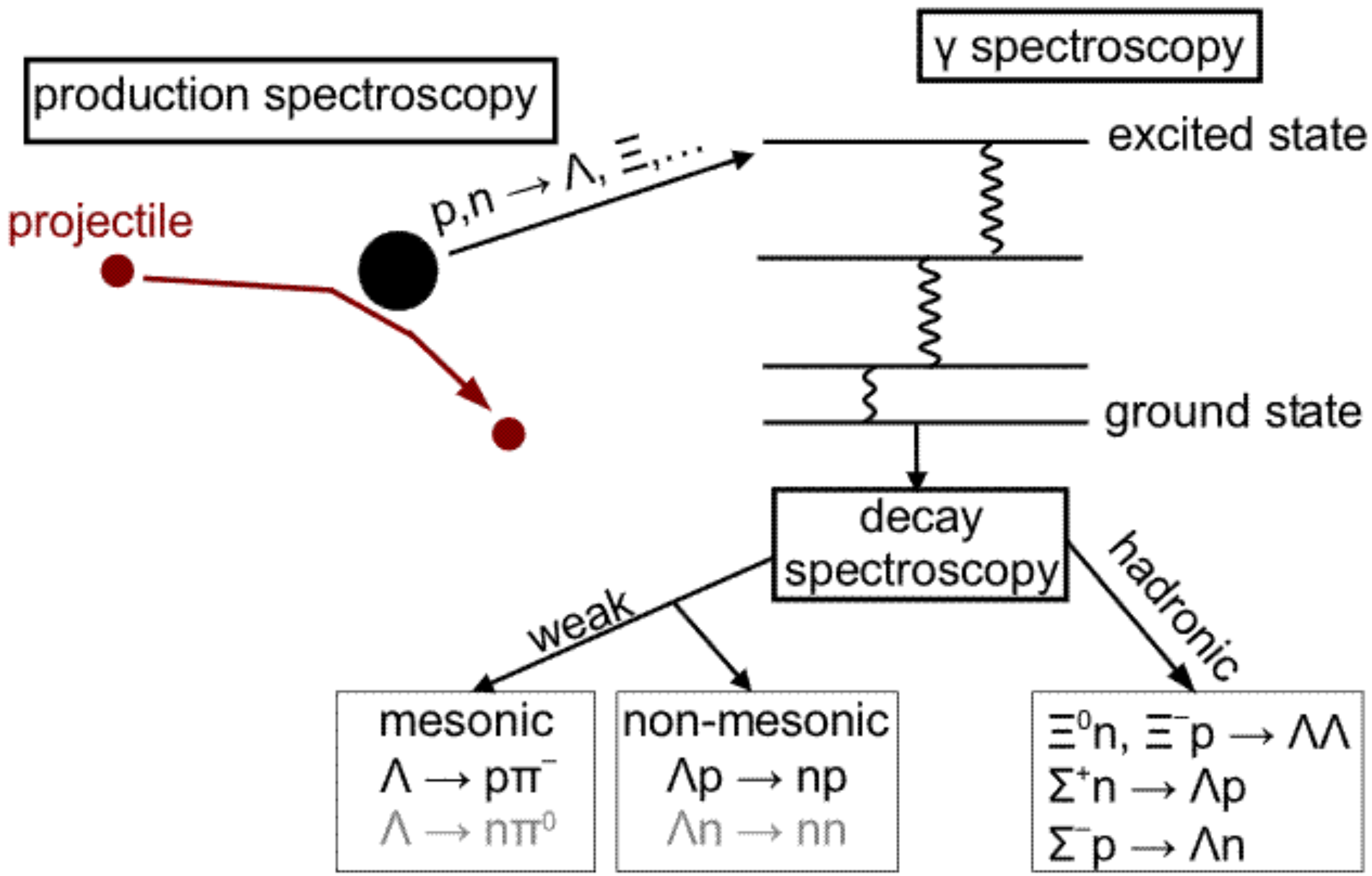
BB potentials extracted from Nambu-Bethe-Salpeter wave function measured on the lattice. Recent results for NN, YN and YY obtained close to the physical mass at single value of lattice volume & spacing

- NPLQCD

Combines calculations of correlation functions at several light quark masses with low-energy effective field theory. Determination of the binding energies of ${}^{3}_{\Lambda}He$, ${}^{4}_{\Lambda}He$ and ${}^{4}_{\Lambda\Lambda}He$

Hypernuclear Physics

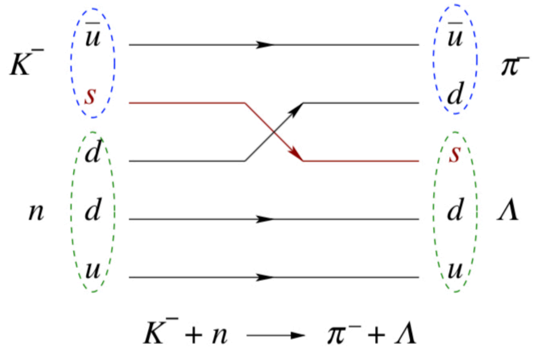
Goal: Relate hypernuclear observables with the bare YN & YY interactions



Production of single-Λ hypernuclei

✧ **Strangeness exchange (BNL, KEK, JPARC)**

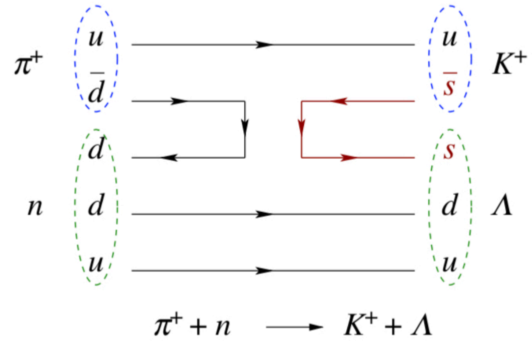
$$K^- + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$



(replace an u or d quark by an s one)

✧ **Associate production (BNL, KEK, GSI)**

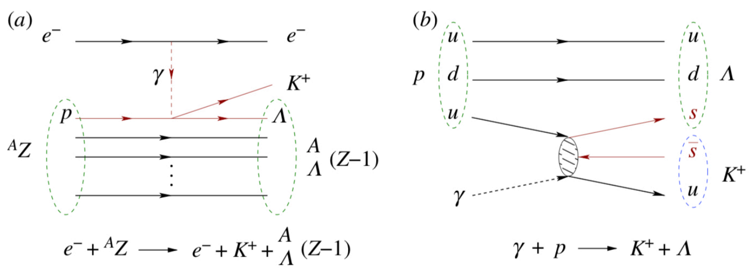
$$\pi^+ + {}^AZ \rightarrow {}^A_\Lambda Z + K^+$$



(produce an $s\bar{s}$ pair)

✧ **Electroproduction (JLAB, MAMI-C)**

$$e^- + {}^AZ \rightarrow e^{-\prime} + K^+ + {}^A_\Lambda(Z-1)$$



✧ **Hypernuclei production in relativistic heavy ion collisions (HypHII collaboration FAIR/ GSI)** (see Take's talk)

First experiment with ^{6}Li beam on ^{12}C target at 2GeV. Λ, $^{3}_{\Lambda}$H & $^{4}_{\Lambda}$H observed.

Production of Σ hypernuclei

Production mechanisms similar to the ones considered for Λ hypernuclei like, e.g., strangeness exchange $(K^-,\pi^\pm)$

However, the existence of Σ hypernuclei has not been experimentally confirmed yet without ambiguity, suggesting that the Σ nucleon interaction is most probably repulsive.

The production of double Λ hypernuclei

A two step reaction is required:

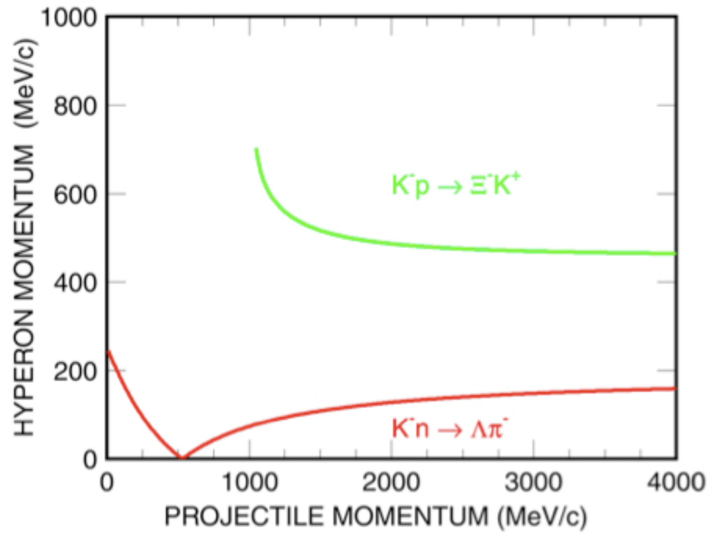
✧ Ξ^- production:

✓ (K^-,K^+) reaction (BNL, KEK)

$$K^- + p \rightarrow \Xi^- + K^+$$

✓ Antiproton production (PANDA@FAIR)

$$p + \overline{p} \rightarrow \Xi^- + \overline{\Xi}^+$$



✧ Ξ^- conversion in two Λ's:

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5\,MeV$$

What do we know about double Λ hypernuclei ?

Much less than about single Λ hypernuclei

Revised 0.67 +/-0.17 MeV

	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)		
${}^{6}_{\Lambda\Lambda}He$	10.9 ± 0.5	4.7 ± 0.6	Prowse	(1966)
${}^{6}_{\Lambda\Lambda}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$	KEK-E373	(2001)
${}^{10}_{\Lambda\Lambda}Be$	17.7 ± 0.4	4.3 ± 0.4	Danysz	(1963)
${}^{10}_{\Lambda\Lambda}Be$	8.5 ± 0.7	-4.9 ± 0.7	KEK-E176	(1991)
${}^{13}_{\Lambda\Lambda}B$	27.6 ± 0.7	4.8 ± 0.7	KEK-E176	(1991)
${}^{10}_{\Lambda\Lambda}Be$	$12.33^{+0.35}_{-0.21}$		KEK-E373	(2001, unpublished)

Nagara event

same event

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

Production of Ξ hypernuclei

Can be produced through the reactions

$$K^- + p \rightarrow \Xi^- + K^+$$ and $$p + \bar{p} \rightarrow \Xi^- + \bar{\Xi}^+$$

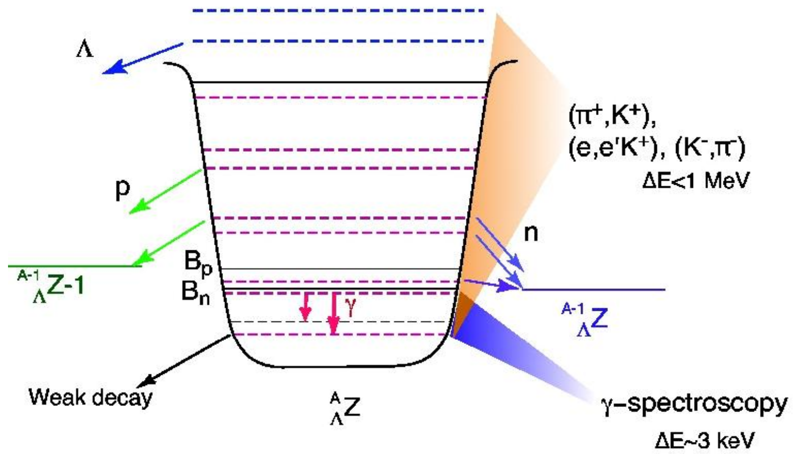
- Analysis of $^{12}C(K^-,K^+)^{12}_{\Xi^-}Be$ [1] → attractive Ξ-nucleus interaction of ~ 14 MeV. But other analysis [2] indicates that a zero potential is preferred

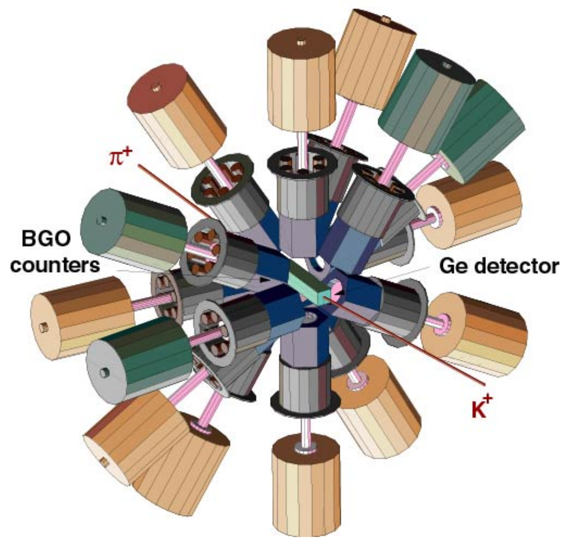
- Recent observation [3] of a deeply bound state of a Ξ^--^{14}Ni system with a binding energy of 4.38 +/- 0.25 MeV

[1] Khaustov et al PRC 61, 054603 (2000)
[2] M. Khono et al, PTP 123, 157 (2010); NPA 835, 358 (2010)
[3] Nakazawa et al., PTEP, 033D02 (2015)

Hypernuclear γ-ray spectroscopy

- Produced hypernuclei can be in an excited state.
- Energy released by emission of neutrons or protons or γ-ray when hyperon moves to lower states.



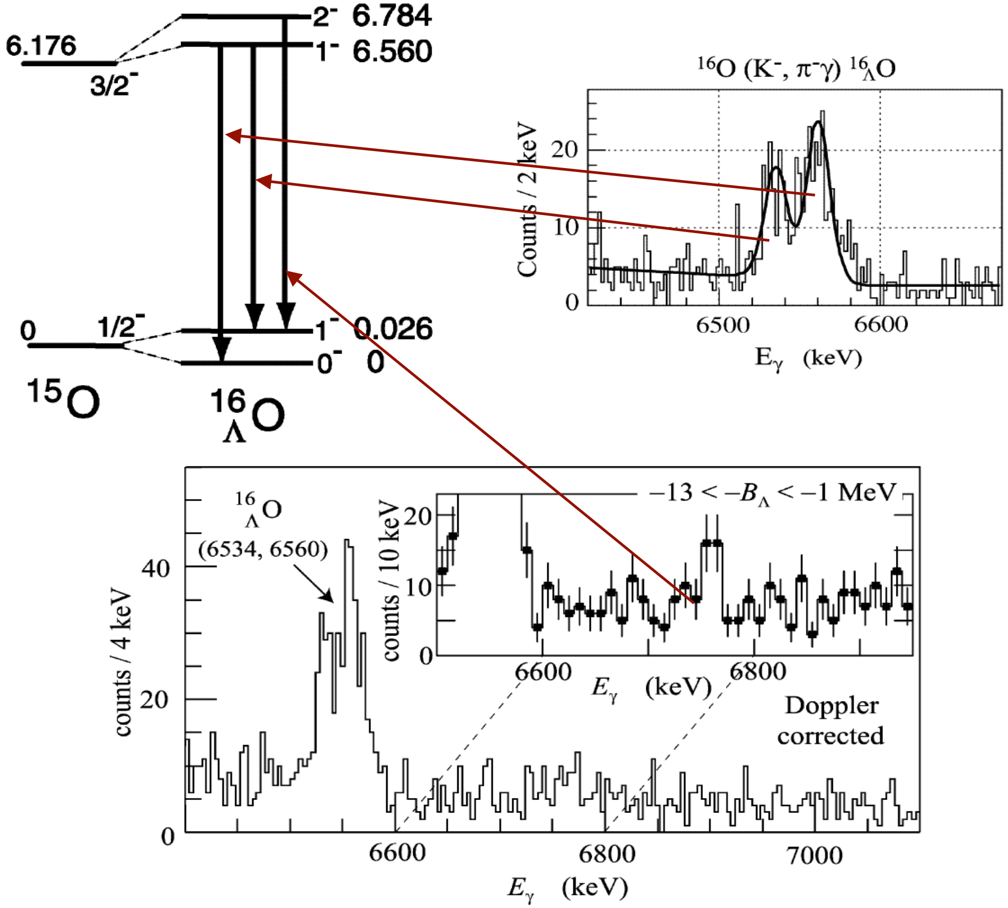


Hyperball

- Excellent resolution with Ge (NaI) detectors.
- Λ depth potential in nucleus ~ 30 MeV ➔ observation of γ-rays limited to low excitation region.
- γ-ray transition measures only energy difference between two states. Measurement of two γ rays in coincidence might help to resolve it

γ-ray spectrum of $^{16}{}_{\Lambda}O$

- ✧ Observed twin peaks demonstrate hypernuclear fine structure for $^{16}{}_{\Lambda}O$ ($1^- \rightarrow 1^-, 0^-$) transitions.
- ✧ Small spacing in twin peaks caused by spin-dependent ΛN interaction.
- ✧ Recent analysis revealed another transition at 6758 keV corresponding to $^{16}{}_{\Lambda}O$ ($2^- \rightarrow 0^-$).



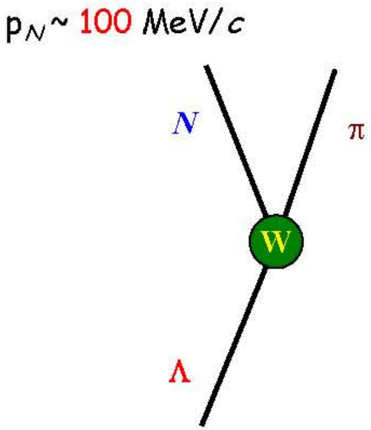
M. Ukai et al., Phys. Rev. C 77, 05315 (2008)

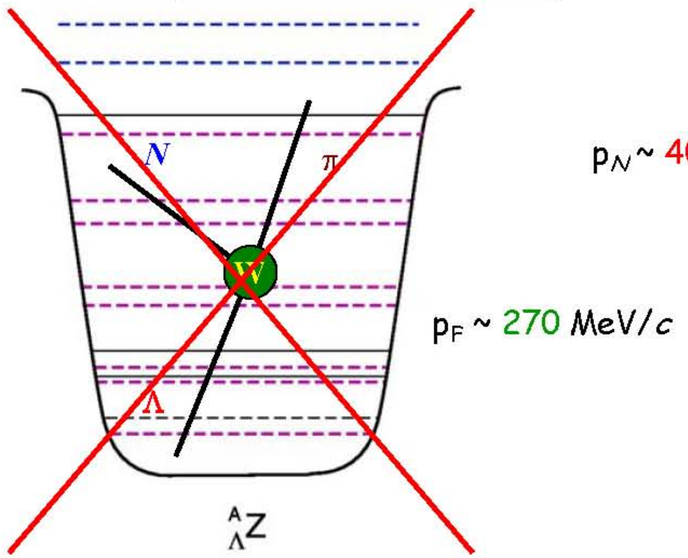
The Weak Decay of Λ hypernuclei

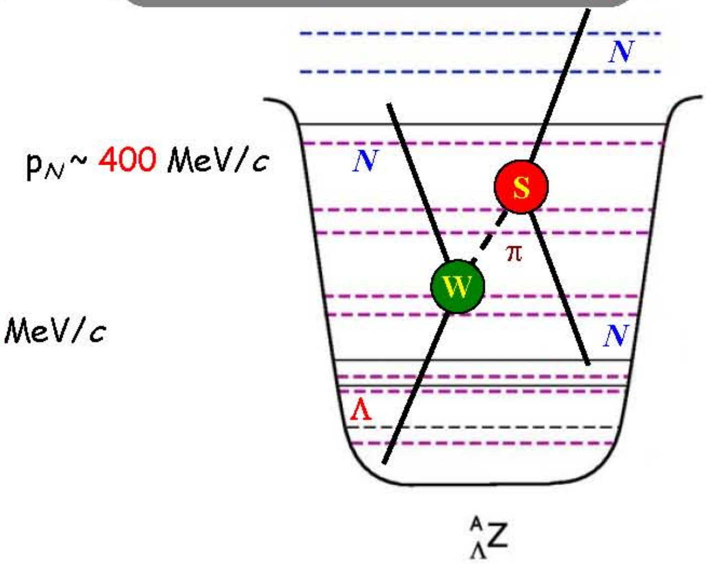
free Λ decay

hypernucleus mesonic decay

hypernucleus non-mesonic decay







$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)

$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)

$\tau_\Lambda = 263$ ps

suppressed by Pauli blocking

$\Lambda + n \rightarrow n + n + 176$ MeV

$\Lambda + p \rightarrow n + p + 176$ MeV

Decay observables

$$\Gamma \sim \Gamma_\Lambda^{free} = 3.8 \times 10^9\ s^{-1}$$

Hypernuclear lifetimes-Decay Rates

$$\Gamma = \Gamma_M + \Gamma_{NM} + \Gamma_{2N}$$

$$= \Gamma_{\pi^0} + \Gamma_{\pi^-} + \Gamma_n + \Gamma_p + \Gamma_{np}$$

$\Lambda \to N\pi$

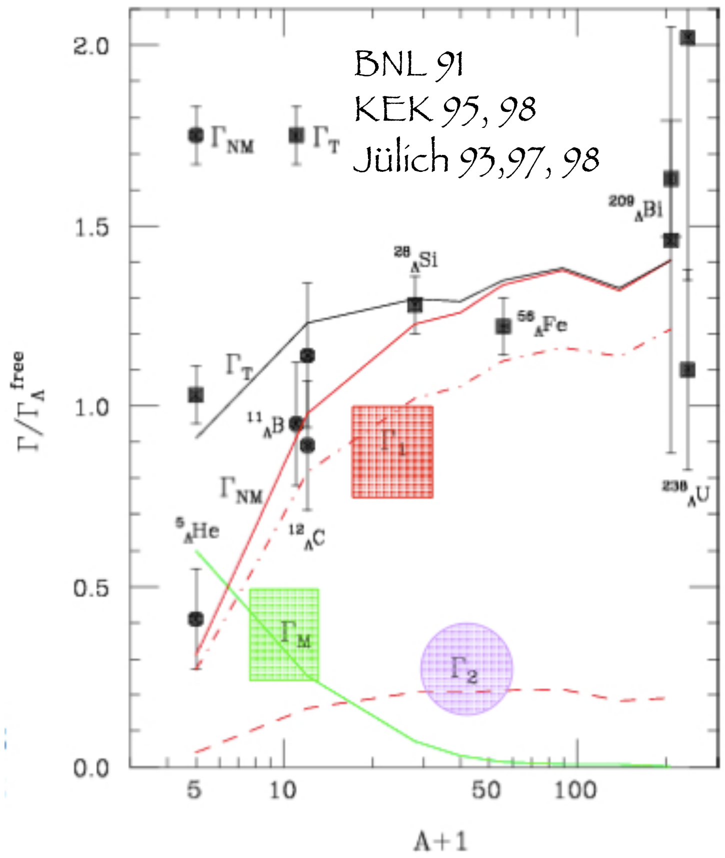
$p_N \sim 100\ MeV$

$\Lambda N \to NN$

$p_N \sim 420\ MeV$

$\Lambda NN \to NNN$

$p_N \sim 340\ MeV$

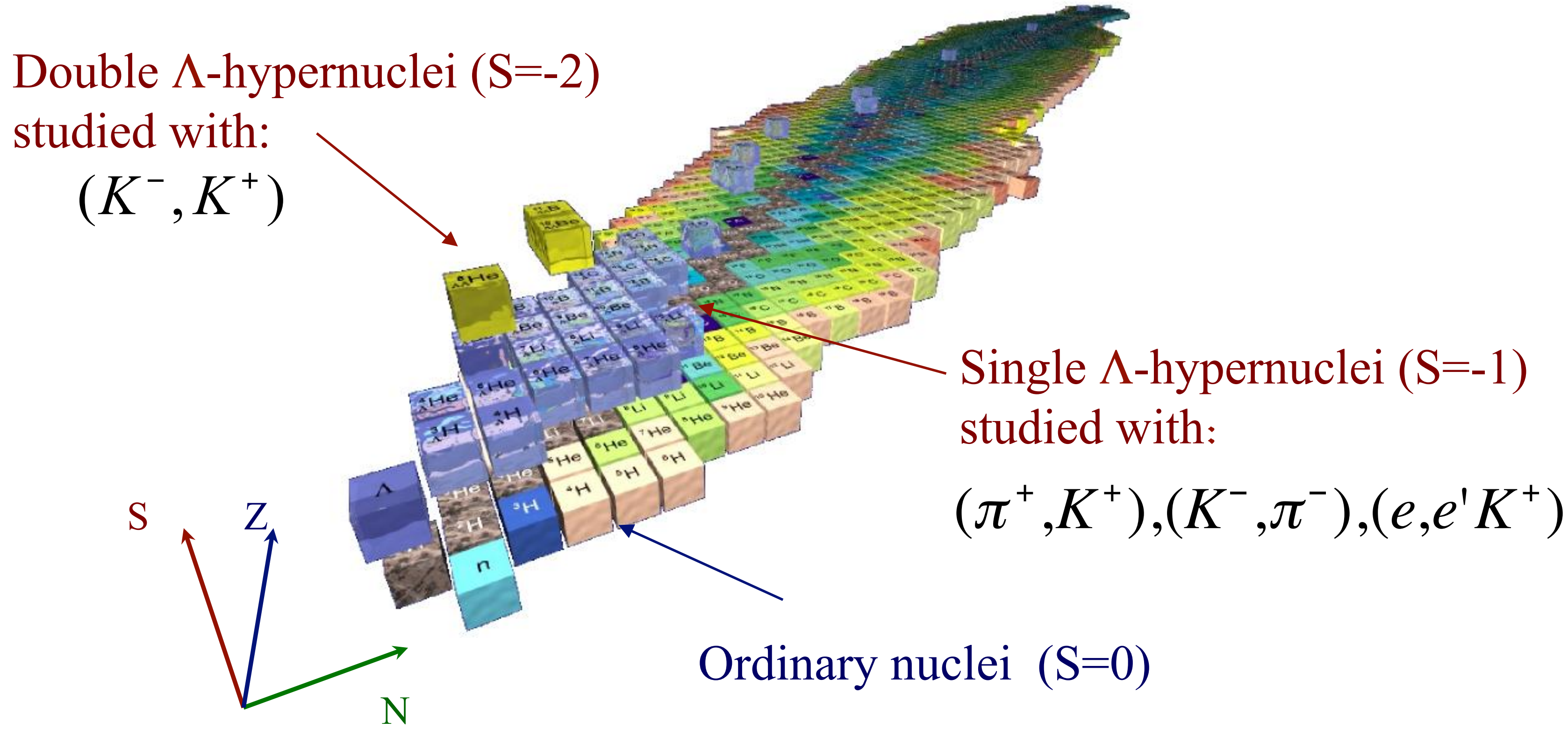


W. M. Alberico et al., Phys. Rev. C 61, 044314 (2000)

(well reproduced by theoretical models)

Summary of our present knowledge & ignorance

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



Unfortunately, there are always problems …

- 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.

- 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

Shopping List

We need:

- ✧ More & updated hypernuclear data (FAIR, JLAB, J-PARC)
- ✧ Measurements of multi-strange hypernuclei (FAIR)
- ✧ Study of light hypernuclei (role of hyperonic TBFs)
- ✧ More YN and (hopefuly) YY scattering data
- ✧ Lattice QCD calculations
- ✧ Analysis of YN & YY correlations in HIC
- ✧ Astronomical data sensitive to the strangeness content of NS

- ✧ You for your time & attention
- ✧ The organizers for their kind invitation