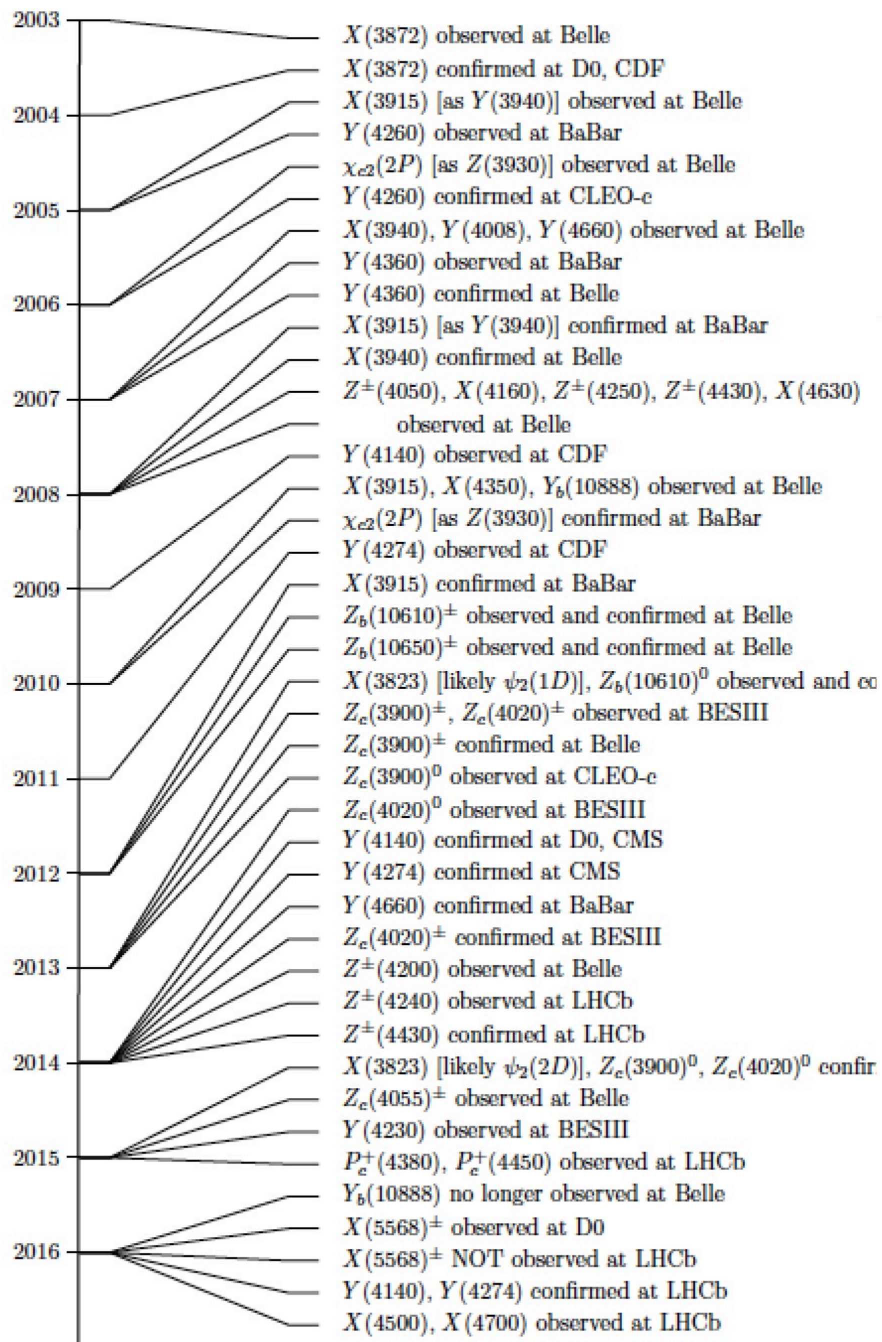
Wrap-Up
Friday session

2nd EMMI workshop:
Anti-matter, hyper-matter and exotica production at the LHC
Turin, November 6-10, 2017

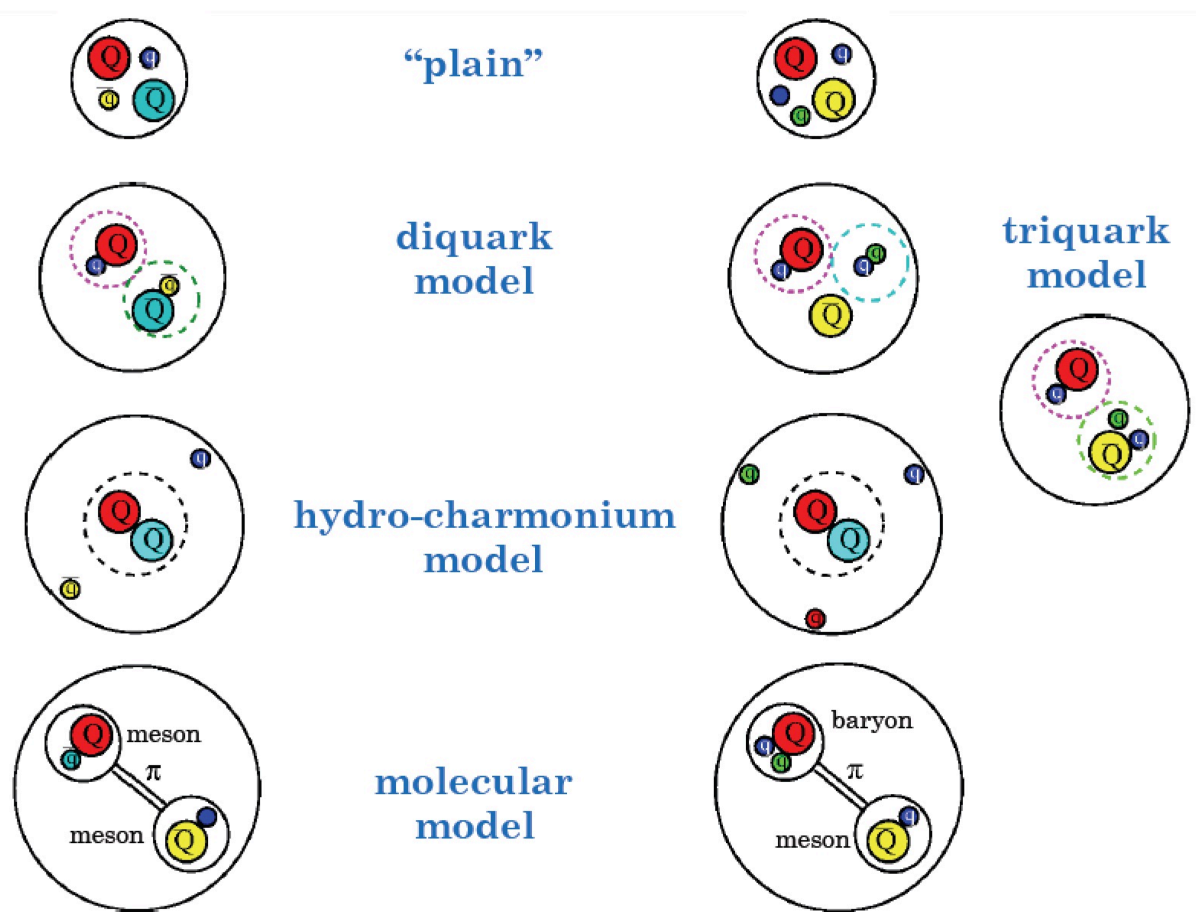
Claudia Patrignani: Exotic hadrons at LHCb

Exotic hadrons with heavy quarks



in the past decade a pletora of new states with constituent heavy $Q\bar{Q}$

which is their structure?

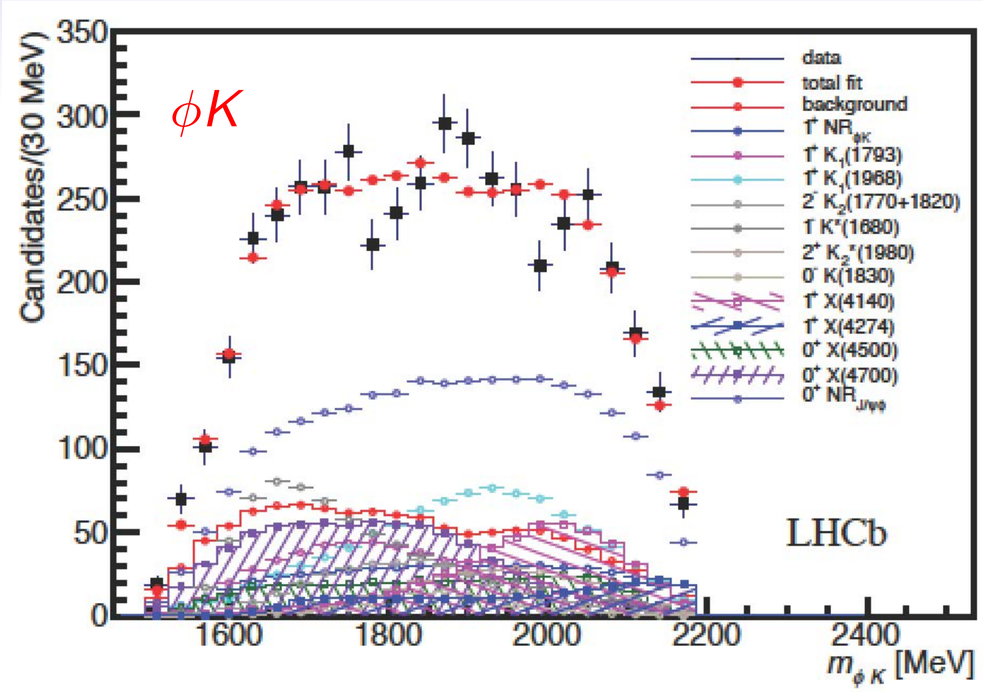


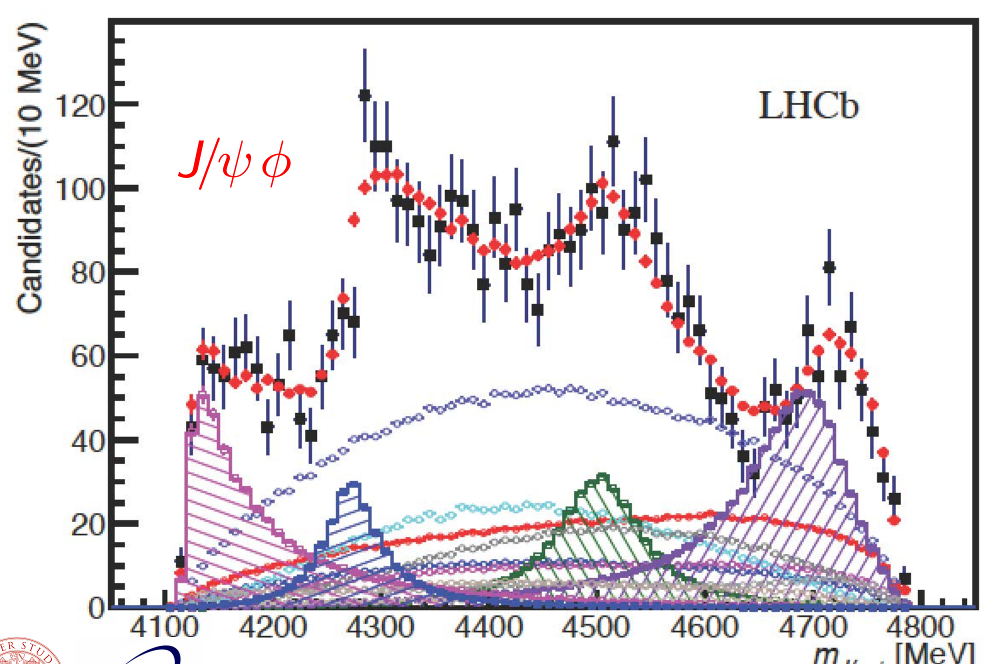
B mesons – and their decay products – copiously produced at hadron machines

Claudia Patrignani: Exotic hadrons at LHCb

Fits allowing exotic components

PRL 118 (2017) 022003
PRD 95 (2017) 012002





Add X and Z^+ components with various quantum numbers

Tetraquark states !

Z^+ components improve fit marginally

Two 1^{++} and two 0^{++} states with large significance

Contribution	Sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13.0\pm3.2\ ^{+4.7}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-\ 3.6}$	$56\pm11\ ^{+\ 8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF	[26]	$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS	[23]	$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$NR_{J/\psi\,\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

Significance of $J^{PC} = 1^{++}$ incl. syst.:
$X(4140)$: 5.7σ $X(4274)$: 5.8σ

Significance of $J^{PC} = 0^{++}$ incl. syst. :
$X(4500)$: 4.0σ $X(4700)$: 4.5σ

Claudia Patrignani: Exotic hadrons at LHCb

$\Lambda_b^0 \to J/\psi p K^-$

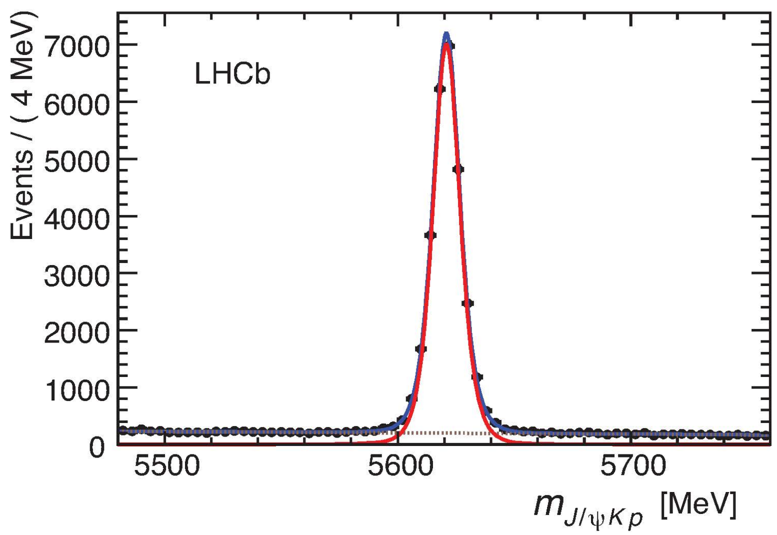
PRL 115 (2015) 072001

This decay mode, not observed before, found to have large rates and low background

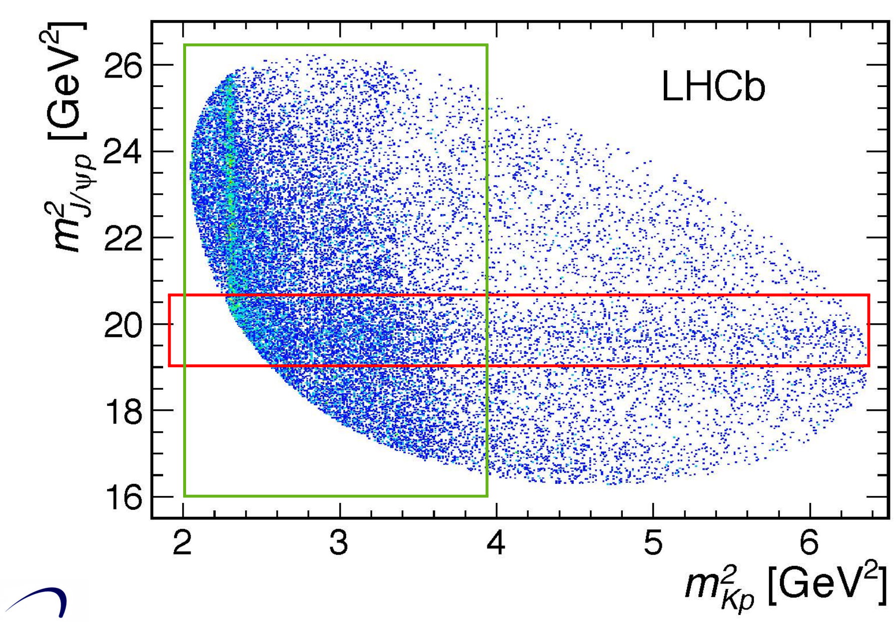
Pentaquark state !

Used to measure the Λ_b^0 lifetime with 1 fb^{-1} collected in 2011

PRL 111 (2013) 102003



Clean signal of 26,000 candidates with 5.4% background within $\pm 2\sigma$ in the whole Run 1 data sample (3 fb^{-1})



... but the Dalitz plot has unusual features:

vertical bands for Λ^*'s

Horizontal band???

Claudia Patrignani: Exotic hadrons at LHCb

Conclusions: pentaquarks

- Observation of $P_c(4450)^{\pm}$ and $P_c(4380)^{\pm} \to J/\psi\, p$ in $\Lambda_b^0 \to J/\psi\, pK^-$ from both amplitude analysis and model independent approach
  - $c\bar{c}uud \Longrightarrow$ pentaquark!
  - resonant behaviour of $P_c(4450)^{\pm}$ amplitude
  - resonant behaviour inconclusive for $P_c(4380)^{\pm}$
- Evidence for exotic hadrons in $\Lambda_b^0 \to J/\psi\, p\pi^-$
  - compatible with P_c states in different decay mode
  - amplitude analysis limited by sample size
- $\Lambda_b^0 \to \chi_c pK^-$ and $\Xi_b^- \to J/\psi\, \Lambda K^-$
  - investigate new $P_c(4450)$ decay modes and search for further pentaquarks

    new decay modes observed
  - might have sufficient statistics for amplitude analysis by the end of upcoming data taking

Still a lot to understand – and a lot of data at LHC!

already on disk and more in the near future

Laura Tolos:
Heavy Flavour in Nuclear Collisions

Spectroscopy of excited charmed baryons

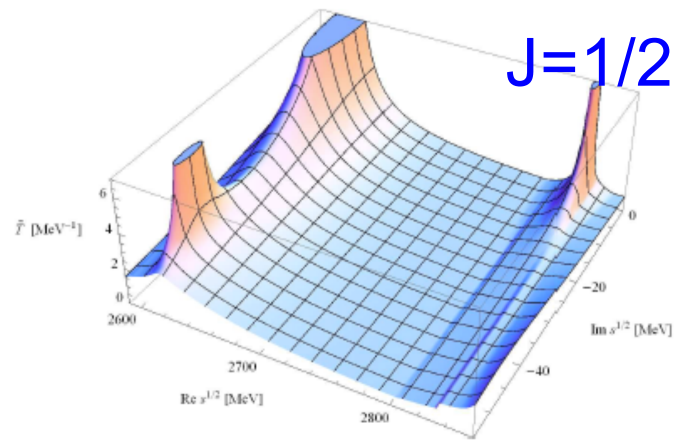
Λ_c : C=1,S=0,I=0

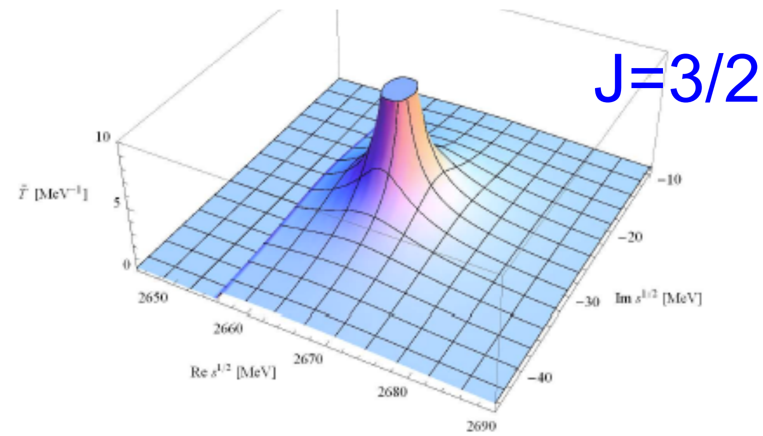
Garcia-Recio et al.'09;
Romanets et al. '12

$$T_{ij}(s) \approx \frac{g_i g_j}{\sqrt{s} - \sqrt{s_R}}$$

coupling constant

mass and width





SU(8) irrep	SU(6) irrep	SU(3) irrep	M_R	Γ_R	Couplings to main channels	Status PDG	J
168	$15_{2,1}$	3^*_2	2617.3	89.8	$g_{\Sigma_c\pi} = \mathbf{2.3}$, $g_{ND} = 1.6$, $g_{ND^*} = 1.4$, $g_{\Sigma_c\rho} = 1.3$		1/2
168	$15_{2,1}$	3^*_4	2666.6	53.7	$g_{\Sigma_c^*\pi} = \mathbf{2.2}$, $g_{ND^*} = 2.0$, $g_{\Sigma_c\rho} = 0.8$, $g_{\Sigma_c^*\rho} = 1.3$	$\Lambda_c(2625)$ ***	3/2
168	$21_{2,1}$	3^*_2	2618.8	1.2	$g_{\Sigma_c\pi} = 0.$[illegible], $g_{ND} = 3.5$, $g_{ND^*} = 5.6$, $g_{\Lambda D_s} = 1.4$, $g_{\Lambda D_s^*}$ = [illegible], g[illegible] $= 0.9$	$\Lambda_c(2595)$ ***	1/2
120	$21_{2,1}$	3^*_2	2828.4	0.8	$g_{ND} = \mathbf{0.3}$, $g_{\Lambda_c\eta} = 1.1$, $g_{\Xi_c K} = 1.6$, $g_{\Lambda D_s^*} = 1.1$, $g_{\Sigma_c\rho} = 1.1$, $g_{\Sigma_c^*\rho} = 1.0$, $g_{\Xi_c^* K^*} = 0.8$		1/2

- $\Lambda_c(2595)$ has large DN and D*N components
- Double-pole pattern for $\Lambda_c(2595)$, like for $\Lambda(1405)$
- Identification of $\Lambda_c(2625)$

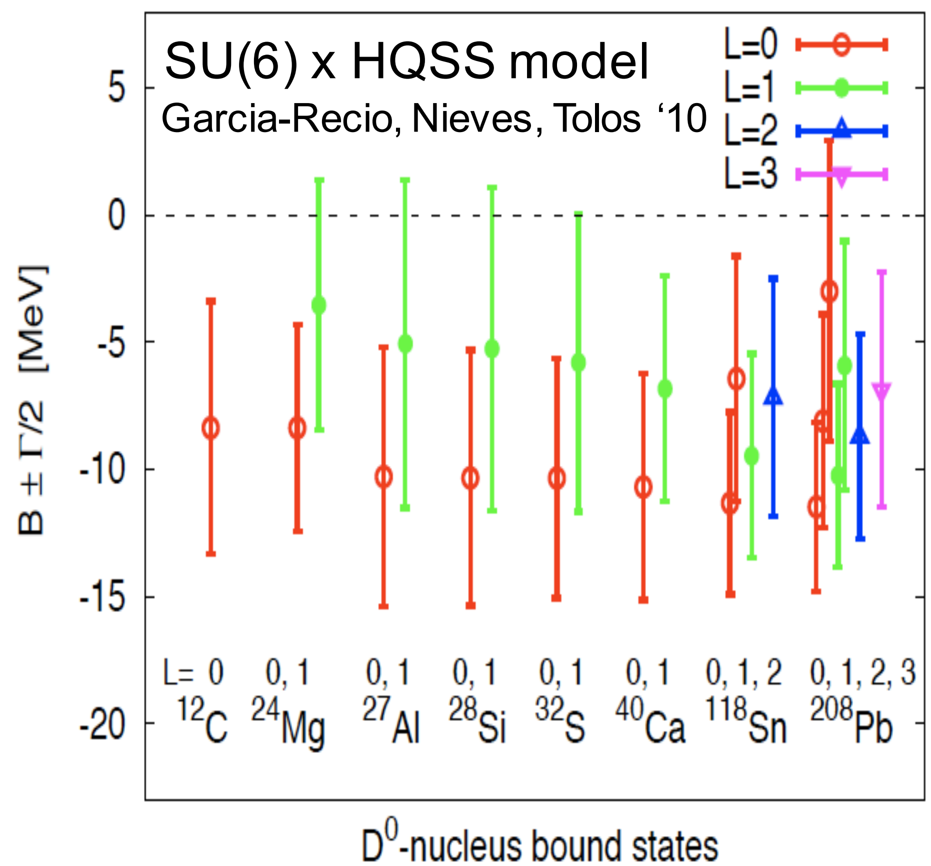
Laura Tolos:
Heavy Flavour in Nuclear Collisions

D-mesic nuclei

Solving Schroedinger or Klein-Gordon equation with
- potential from QMC model
- potential from SU(6) x HQSS model
- potential from π exchange model with HQS

Detection at PANDA, JPARC?

D^0 and D^+



- SU(6) x HQSS model: weakly bound D^0-nucleus states with important widths in contrast to previous QMC model

^{208}Pb

State	$D^0(V^q_\omega)$
1s	−96.2
1p	−93.0
2s	−88.5

Tsushima et al. '99
Krein et al '17 (review)

- SU(6) x HQSS model:
D^+ does not bind

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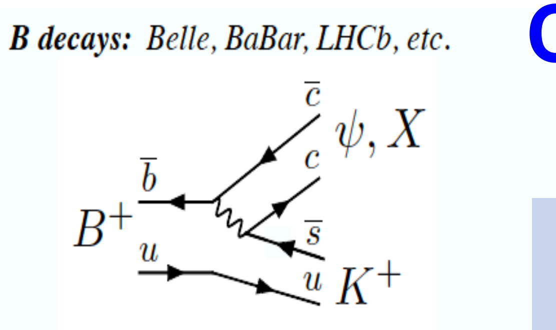
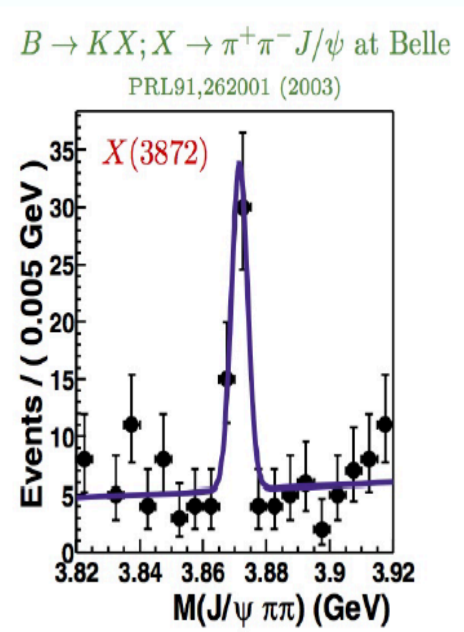
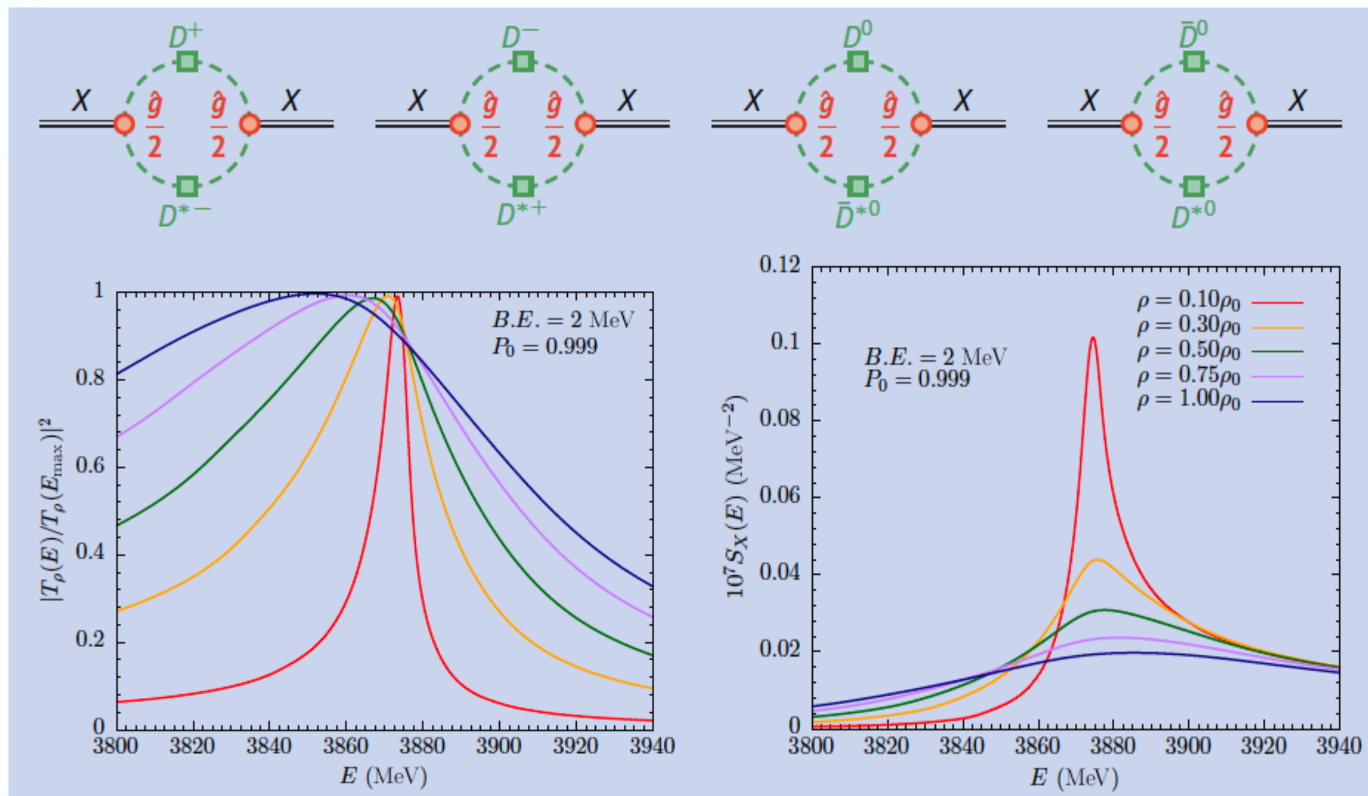




Charm resonances in matter: X(3872)

as D $\bar{\text{D}}$* molecule



	$P_0 = 0.999$	
ρ/ρ_0	E_{max} (MeV)	E_{qp} (MeV)
0.10	3873.3	3878.0
0.30	3870.8	—
0.50	3866.9	—
0.75	3860.3	—
1.00	3851.9	—

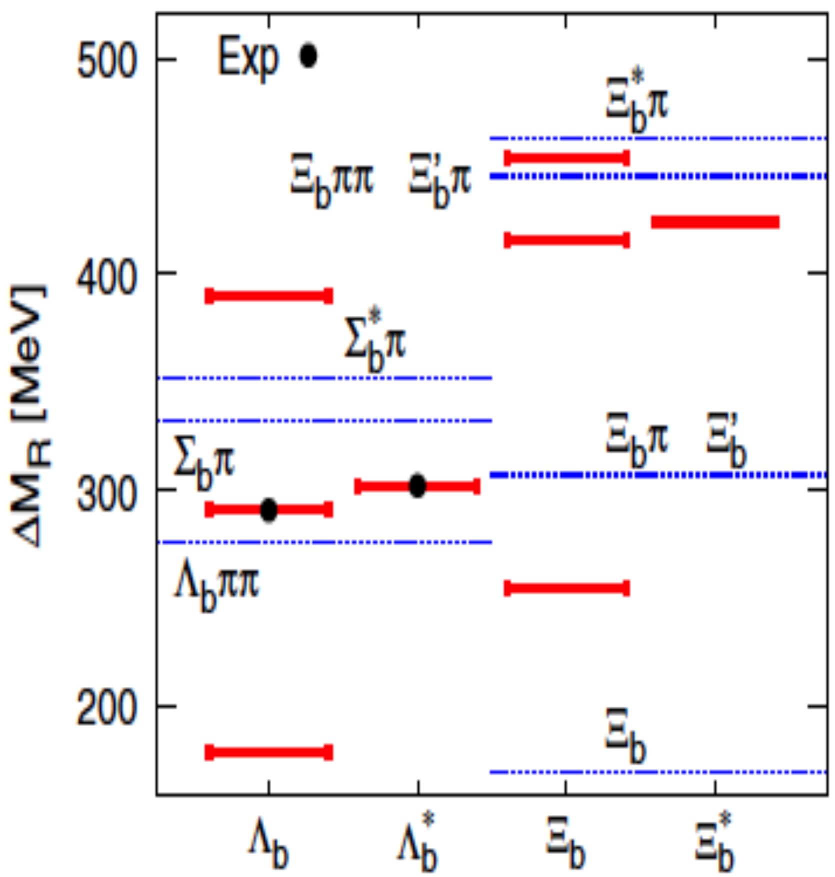
- Spectral function:
$$S_X^{(\rho)}(E) = -\frac{1}{\pi}\mathrm{Im}\Delta_\rho(E) = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi_\rho(E)}{(E^2 - m_0^2 - \mathrm{Re}\Pi_\rho(E))^2 + (\mathrm{Im}\Pi_\rho(E))^2}$$
- Quasi-particle peak:
$$E_{qp}^2 - m_0^2 - \mathrm{Re}\Pi(E_{qp}) = 0.$$

Albaladejo, Nieves and LT, in preparation

Laura Tolos:
Heavy Flavour in Nuclear Collisions

Beauty under Extreme Conditions

Spectroscopy of excited beauty baryons



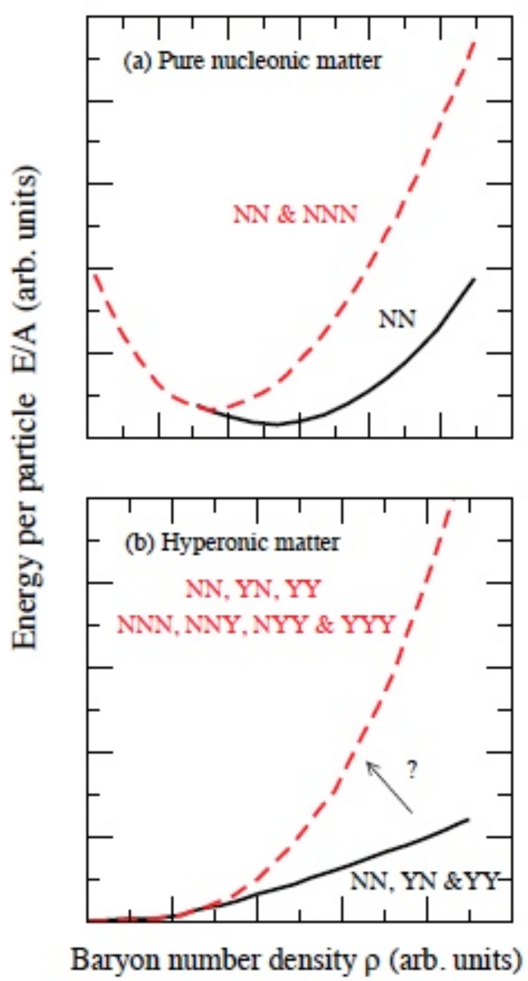
Garcia-Recio, Nieves, Romanets, Salcedo and LT '13

Λ_b(5912) and Λ^*_b(5920) found by LHCb* collaboration are described as meson-baryon molecular states belonging to a HQSS doublet. New HQSS partners are predicted: Ξ_b(6035) and Ξ_b(6043)

* Aaij et al (LHCb) '12

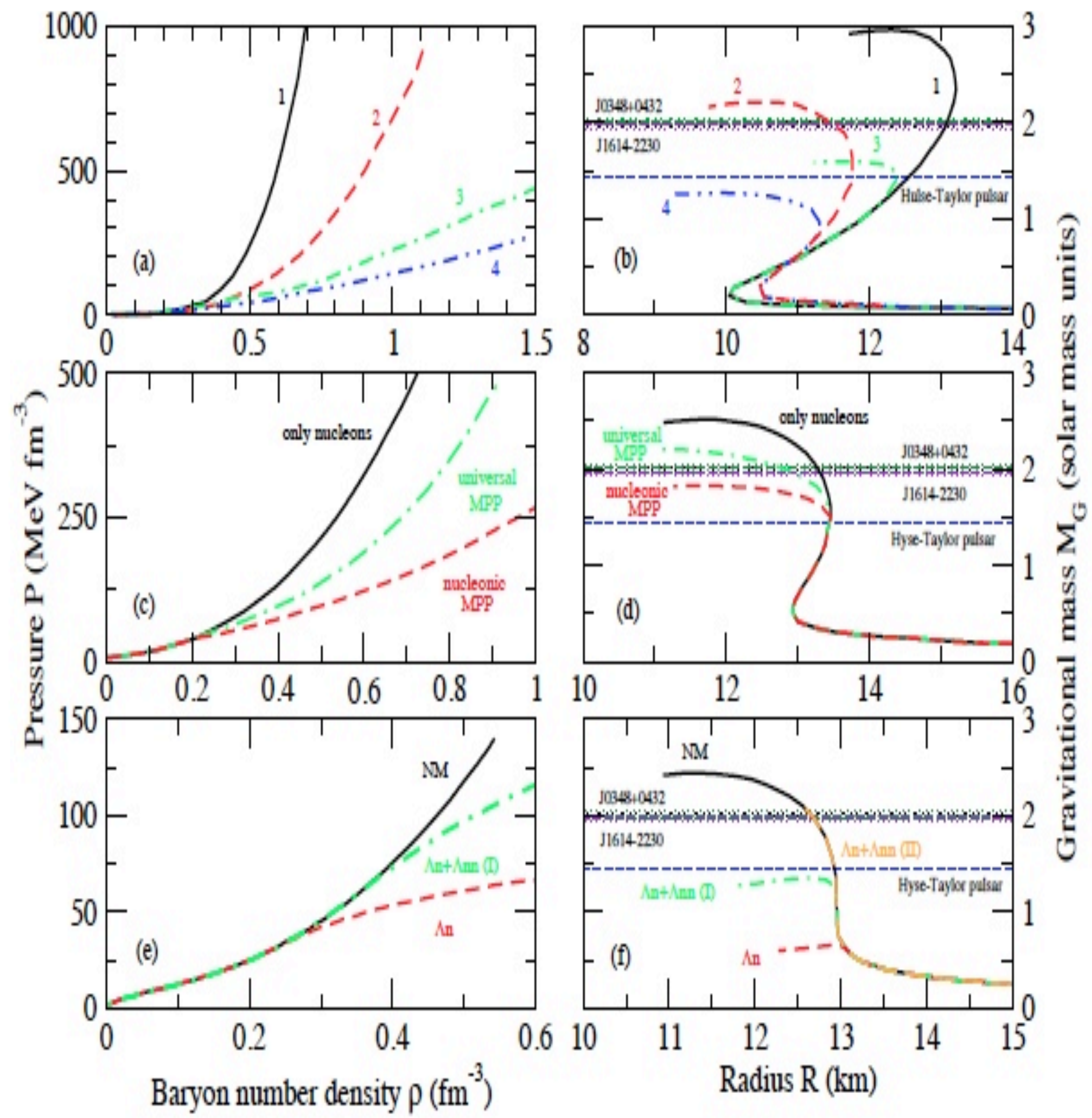
Debarati Chatterjee: Hyperonic Equation of State and Astrophysical Applications

SOLVING THE HYPERON PUZZLE: HYPERONIC 3-BODY FORCES



Effect of 3N and hyperonic 3BF on energy/particle of NM and HM

D.C. and I. Vidaña, EPJA 52 (2016) 29



EoS and M-R relations using

(a)-(b) BHF,

(c)-(d) MPP,

(e)-(f) Quantum MC

Vidaña+, EPL 94 (2011)

Yamamoto+, PRC 88 (2013)

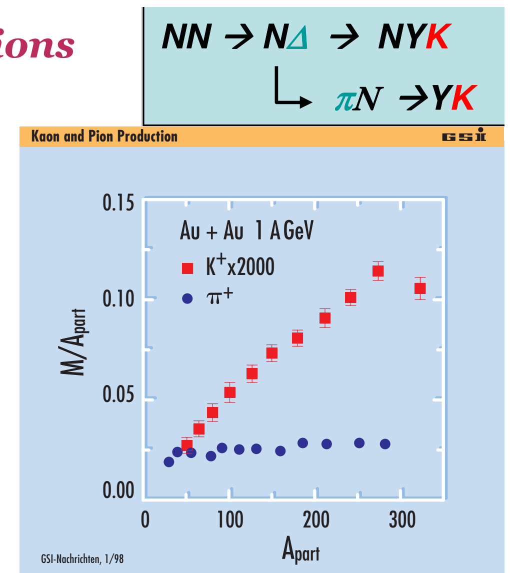
Lonardoni+, PRL 114 (2015)

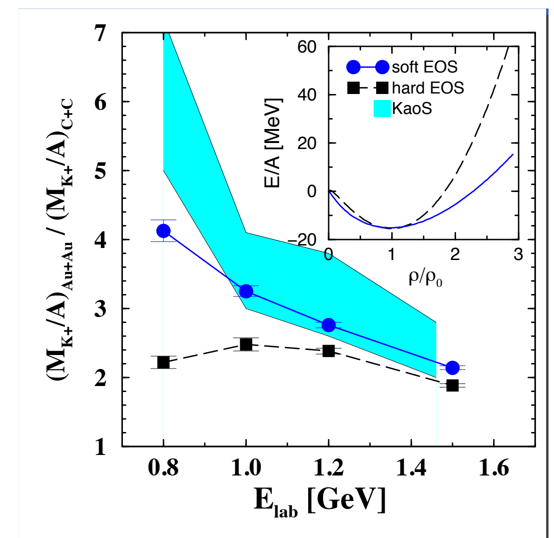
Debarati Chatterjee: Hyperonic Equation of State and Astrophysical Applications

SOFT EOS FROM HEAVY-ION DATA

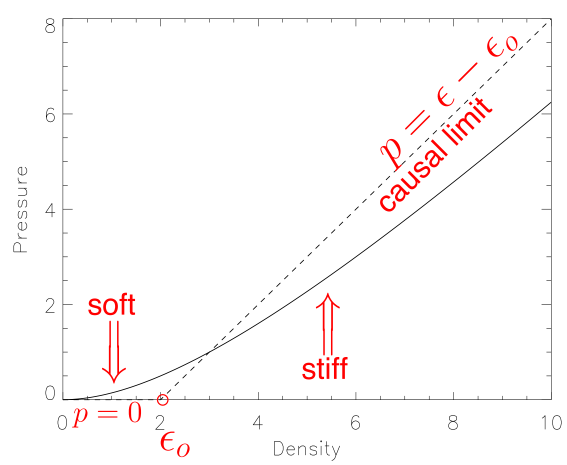
K^+ meson production in heavy-ion collisions

KaoS experiment, GSI Darmstadt

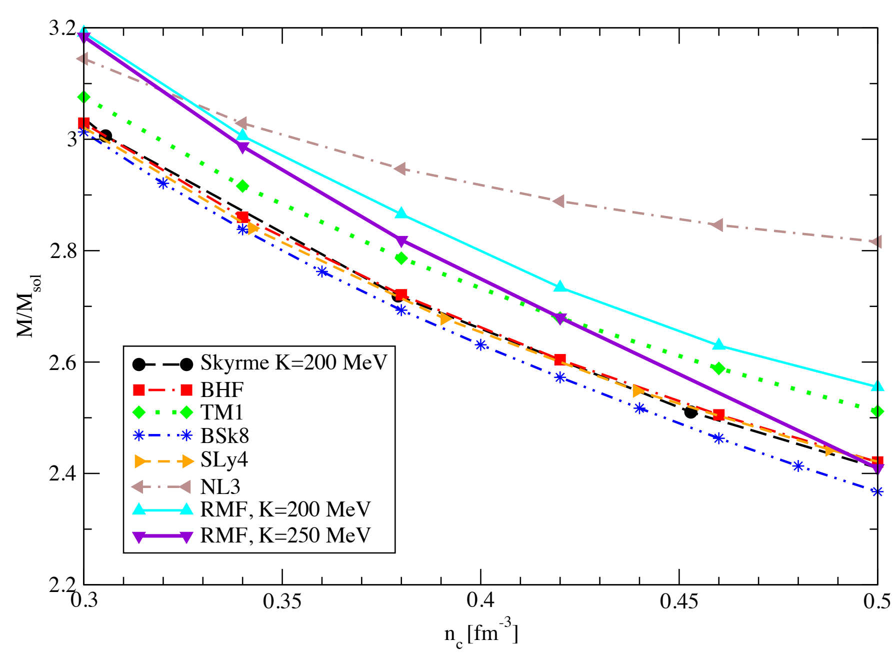




Sturm et al. (KaoS collaboration), PRL 2001



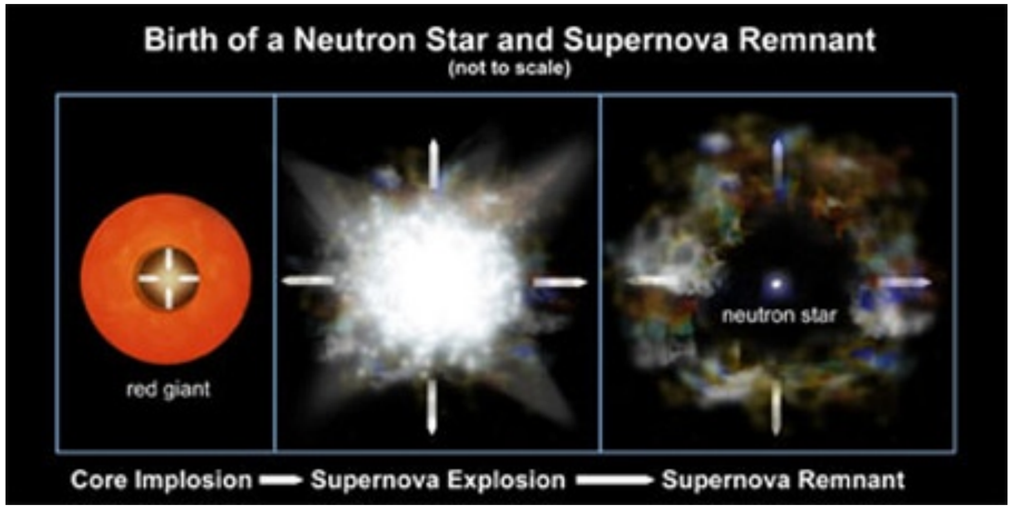
Lattimer, GSI, 2010

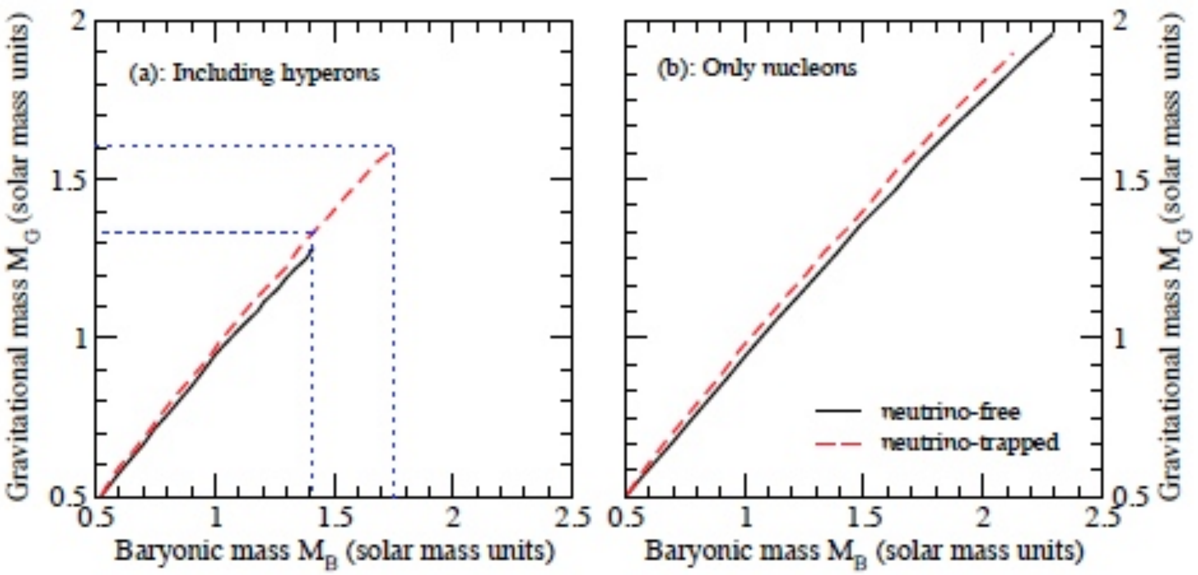


I. Sagert, C. Sturm, D. C., L.Tolos and J. Schaffner-Bielich, PRC 85 (2012)

Debarati Chatterjee: Hyperonic Equation of State and Astrophysical Applications

IMPLICATIONS ON ASTROPHYSICS: BH FORMATION





M_G vs M_B for neutrino-free and neutrino-trapped matter

D.C. and I. Vidaña, EPJA 52 (2016) 29

Debarati Chatterjee: Hyperonic Equation of State and Astrophysical Applications

IMPLICATIONS ON ASTROPHYSICS: R-MODES

Possible sources of bulk viscosity

- *Leptonic weak processes*

  direct Urca process:

$$n \to p + e^- + \bar{\nu}_e$$
$$p + e^- \to n + \nu_e$$

  modified Urca process:

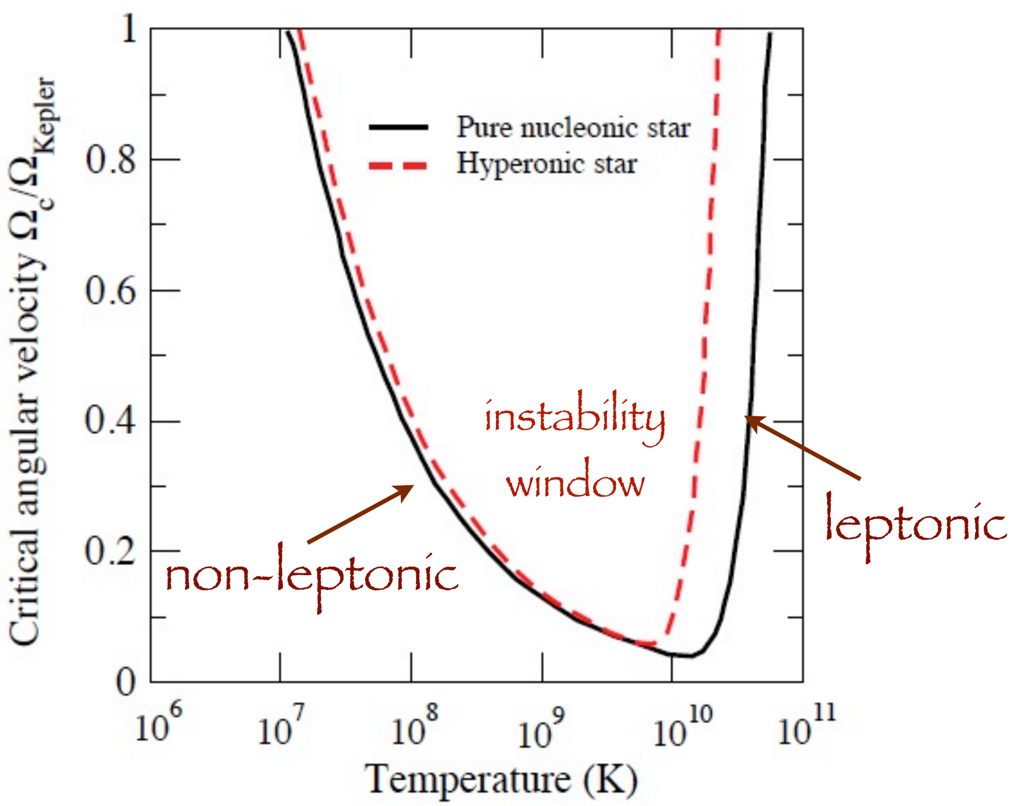
$$n + N \to p + e^- + \bar{\nu}_e + N$$
$$p + e^- + N \to n + \nu_e + N$$

  hyperon Urca process :

$$Y \to B + l + \bar{\nu}_l$$

- *Non-leptonic processes involving hyperons*

$$n + p \leftrightarrow p + \Lambda$$
$$n + n \leftrightarrow n + \Lambda$$



- *r-mode instability damped by leptonic bulk viscosity at high T and non-leptonic bulk viscosity at low T*

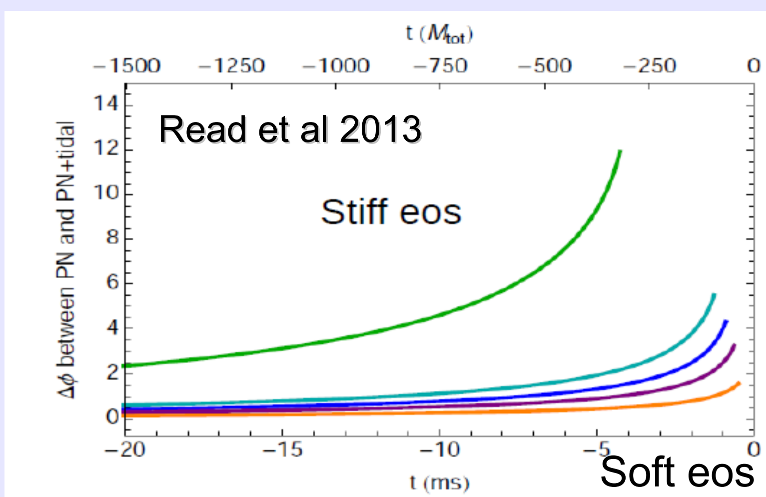
- *In the intermediate T regime, there exists an Instability window*

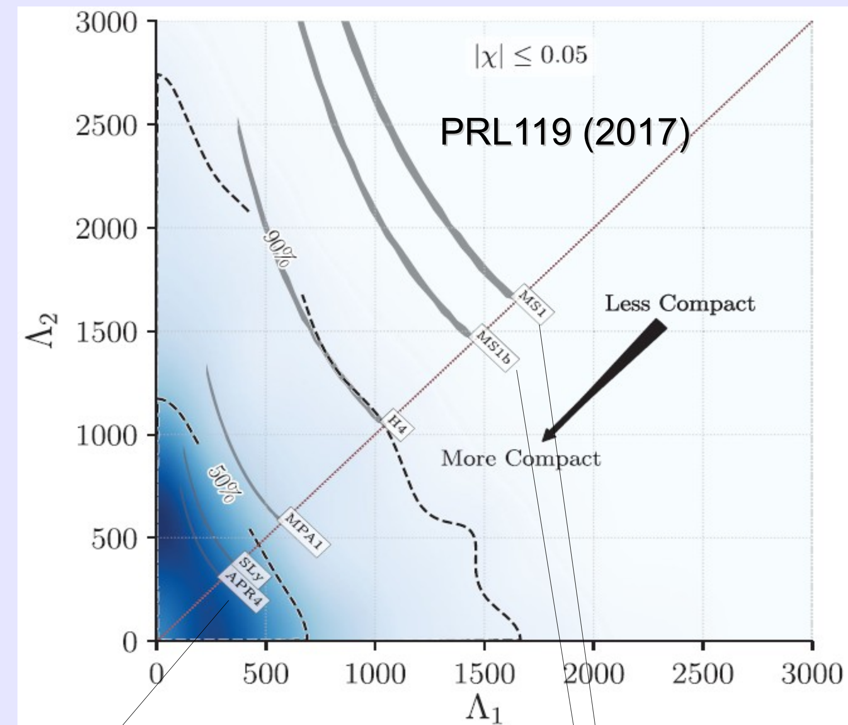
D.C. and D. Bandyopadhyay, PRD 74 (2006)

Giuseppe Pagliara: Strangeness Production within the GW170817 event?

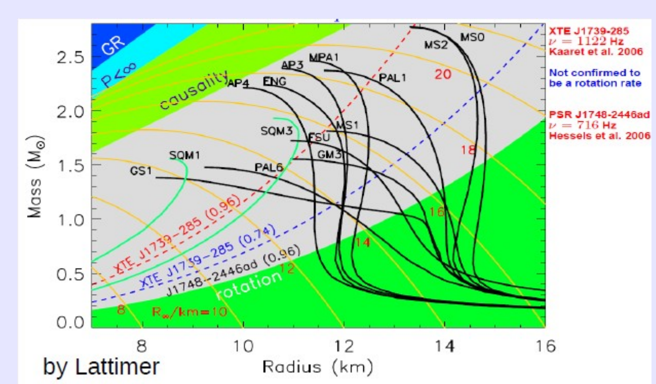
Compactness constraints

The deviations from point-like GW sources depend on the tidal deformability Λ: the phase departure depend on the compactness of the stars and thus on the equation of state. The stiffer the EoS the larger the radius, the larger the deviation.





Ruled out, ingredients: just nucleons, no strangeness. Large radii.



Sly and APR4: again just nucleons, but consistent with the astro-data. Are they consistent with (hyper)nuclear physics ??

Giuseppe Pagliara: Strangeness Production within the GW170817 event?

Constraining the equation of state: maximum mass

By using the hyp. that the remnant is not a supramassive star, three different papers lead to a maximum mass for cold and non-rotating star $M_{max} \leq 2.2\ M_{sun}$ (see also Margalit et al 2017)

Ruiz et al 2017:

$$M_{\rm NSNS} \approx 2.74 \lesssim M_{\rm thresh} \approx \alpha M^{\rm sph}_{\rm max}.$$

$$M_{\rm NSNS} \approx 2.74 \gtrsim M^{\rm sup}_{\rm max} \approx \beta M^{\rm sph}_{\rm max}$$

$$M^{\rm sph}_{\rm max} = 4.8 \left(\frac{2\times10^{14}\ {\rm gr/cm^3}}{\rho_m/c^2}\right)^{1/2} M_\odot$$

$$M^{\rm sup}_{\rm max} = 6.1 \left(\frac{2\times10^{14}\ {\rm gr/cm^3}}{\rho_m/c^2}\right)^{1/2} M_\odot$$

$$\beta \approx 1.27.$$

$$2.74/\alpha \lesssim M^{\rm sph}_{\rm max} \lesssim 2.74/\beta$$

(simple argument based on causality)

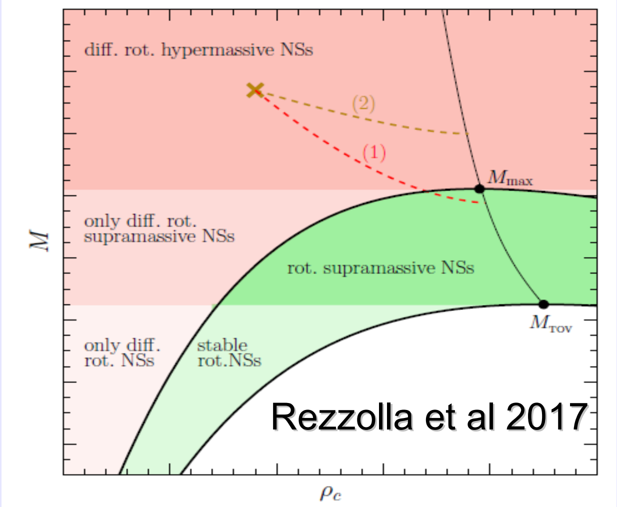
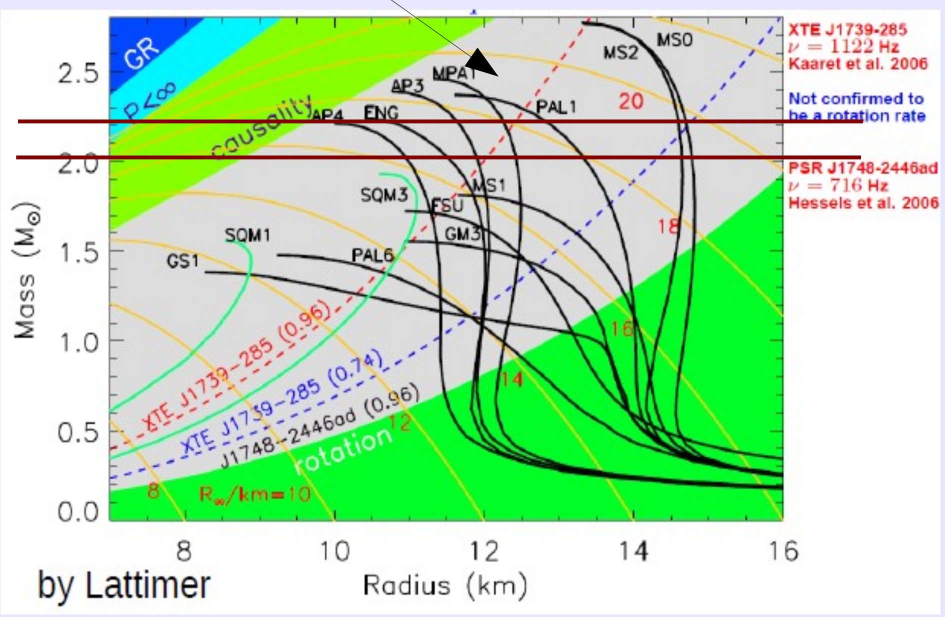


FIG. 1.— Schematic diagram of the different types of equilibrium models for neutron stars. The golden cross marks the initial position of the merger product and the dashed lines its possible trajectories in the (M, ρ_c) plane before it collapses to a black hole.

Ruling out very stiff equations of state!!



Giuseppe Pagliara: Strangeness Production within the GW170817 event?

Two families of compact stars?

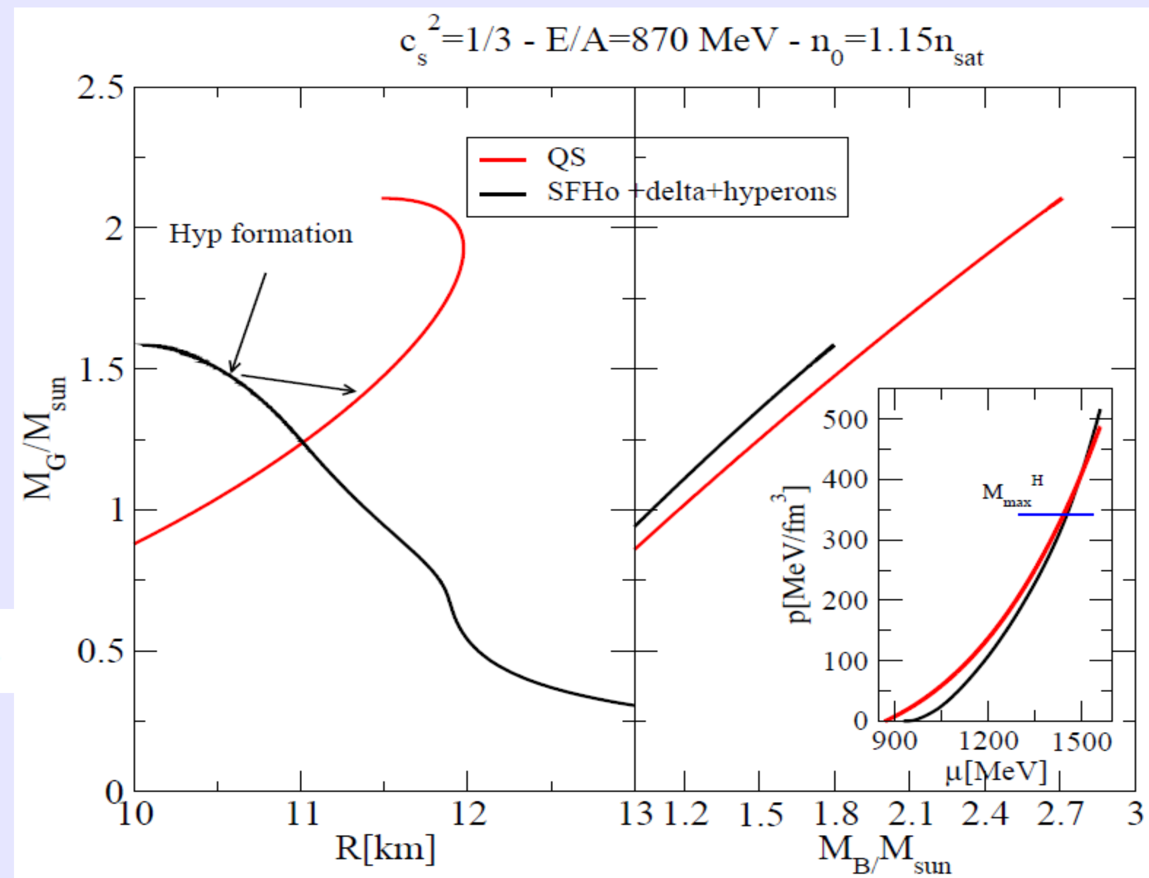
(exercise with constant speed of sound quark EoS, Dondi et al 2016)

Three parameters:
Speed of sound, energy density and baryon density at pressure=0

$$p = c_s^2(e - e_0)$$

$$k = \frac{e_0 c_s^2}{1+c_s^2}$$

$$p = k((n/n_0)^{1+c_s^2} - 1)$$



Hadronic stars would fulfill the small radii limits while strange stars would fulfill the large masses limits. Note: at fixed baryon mass, strange stars could be energetically convenient even if the radius is larger than the corresponding hadronic star configuration.

Giuseppe Pagliara: Strangeness Production within the GW170817 event?

Summary:

a) Maximum mass smaller than about $2.2M_{sun}$
b) Radius of the canonical $1.4M_{sun}$ smaller than about 13km (from deformability and from the mass ejected).

↓

Strangeness must appear in compact stars in some form: hyperons, quark matter (hybrid or quark stars)
GW170817 produced strange matter (which is then "eaten up" by the BH)!!

One possible solution of the hyperons puzzle: strong Λ-Λ repulsion → late appearance of hyperons.
Stiff nucleonic equation of state → small central densities.
The $2M_{sun}$ stars have central densities below the threshold.
This solution is disfavored because produces large radii for a wide range of masses.

Lonardoni, PRL 2015