Today's wrap-up: an exotic landscape of QCD

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Are there compact Multiquark states ?

- Short distance force < 0.5 fm $\Rightarrow$ quark dynamics (Oka, Yazaki)
- N- quarks in a compact configurations - quark model
  - Color-Color interaction is no important for short range N-N interaction
  - Color-spin interaction for 2 body
  - Comparison with lattice (HAL QCD) – NN interaction
  - Possible compact Flavor exotics:

Pentaquark Ps$c\bar{c}$ (uds$c\bar{c}$) $I=0,\ S=1/2$ $\Lambda + J/\psi$

$\Delta E_{CS}(m_{ud}, m_s, m_c) = -124$ MeV

Pentaquark Pcc$\bar{s}$ (udcc$\bar{s}$) $I=0,\ S=1/2$ $\Xi_{cc}^{+} + K^{+}$

$\Delta E_{CS}(m_{ud}, m_s, m_c) = -135$ MeV

Tetraquark T(ud$\bar{c}\bar{c}$) $I=0,\ S=1$ $D^0 + D^{*+}$ or $\bar{D}^0 + \bar{D}^{*-}$

$\Delta E_{CS}(m_{ud}, m_s, m_c) = -150$ MeV

Probably molecular configurations:

Tetraquark X(q$\bar{q}$c$\bar{c}$)

$\Delta E_{CS}(m_{ud}, m_s, m_c) = -40$ MeV → probably molecular type

Pentaquark Pc (uudc$\bar{c}$) (LHCb)

$\Delta E_{CS}(m_{ud}, m_s, m_c) = -34$ MeV → Can not be a compact state (Park,Park,Cho, Lee PRD95(17))

→ probably molecular type

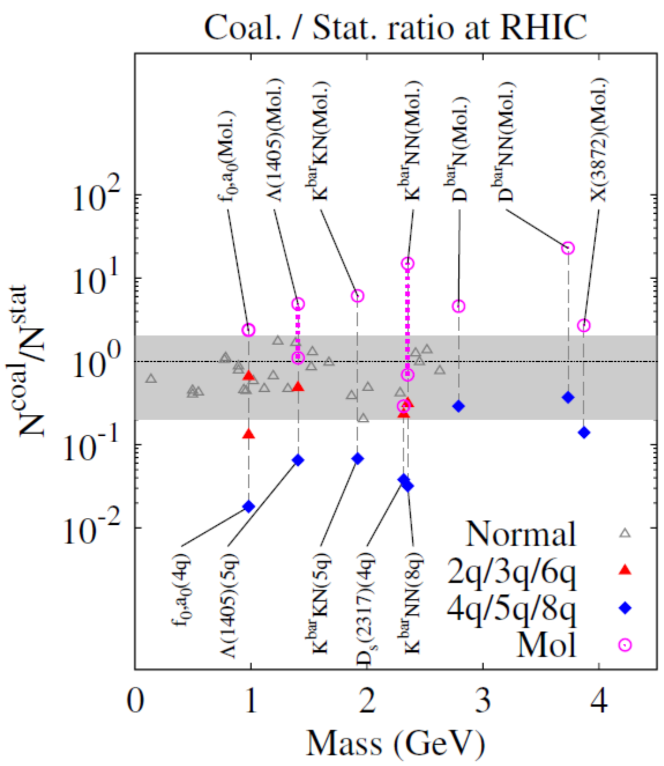
Dibaryon d*(2380) (uuuuuu) (WASA at COSY)

$\Delta E_{CS}(m_{ud}, m_s, m_c) = 0$ MeV → Can not be a compact state (Park,Park,Lee PRD92(15))

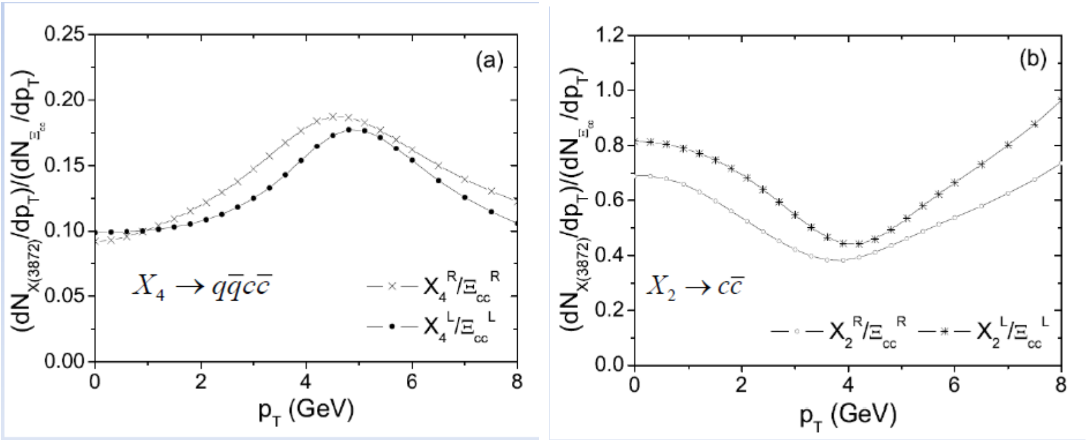
→ probably molecular type

Exotica production in HI collisions (ExHIC)

- Molecular vs Compact multi quark states production

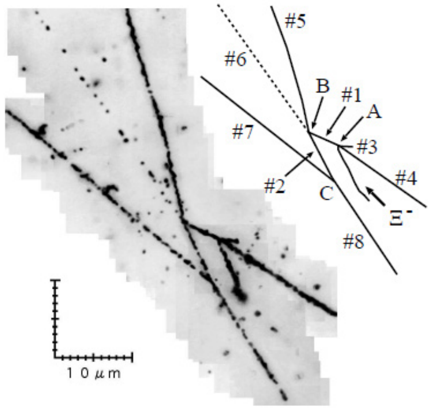


- X(3872) 2 quark vs compact 4 quark



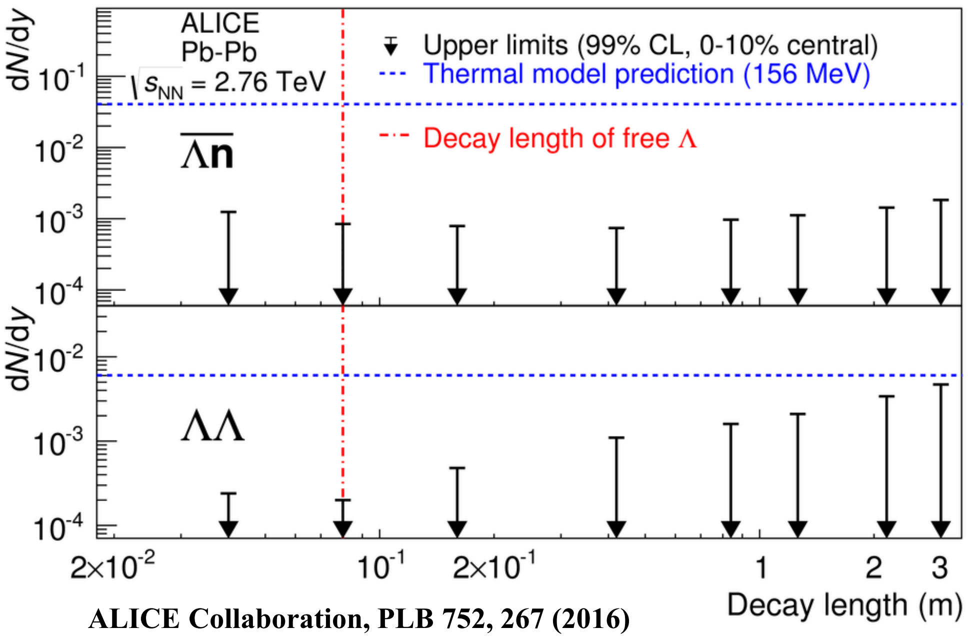
- Production yield and p_T dependence can discriminate structures !

But why no H dibaryon?



Many negative searches

- H dibaryon channel: Flavor breaking effect weakens attraction

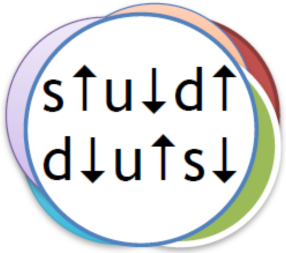


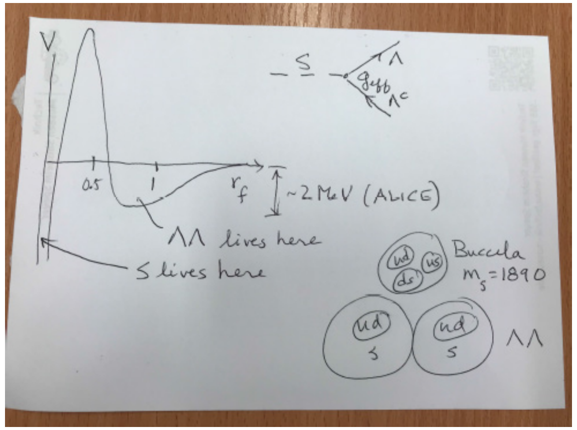
ALICE Collaboration, PLB 752, 267 (2016)

Nagara event: $_{\Lambda\Lambda}{}^{6}$He

- $B_{\Lambda\Lambda}(_{\Lambda\Lambda}{}^{6}\mathrm{He})$ = 6.91±0.16 MeV
- A: Ξ^- capture $\Xi^- + {}^{12}\mathrm{C} \to {}_{\Lambda\Lambda}^{\;6}\mathrm{He} + t + \alpha$
- B: weak decay ${}_{\Lambda\Lambda}^{\;6}\mathrm{He} \to {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$ (no ${}_{\Lambda\Lambda}^{\;6}\mathrm{He} \to {}^{4}\mathrm{He} + H$)
- To forbid ${}_{\Lambda\Lambda}^{\;6}\mathrm{He} \to \mathrm{H} + {}^{4}\mathrm{He}$, impose $B(\mathrm{H}) \leq 7$ MeV. A bound H most likely overbinds ${}_{\Lambda\Lambda}^{\;6}\mathrm{He}$ [Gal, PRL 110 (2013) 179201].
- LQCD: a weakly bound H becomes unbound. $SU(3)_f$ breaking pushes it to $\approx N\Xi$ threshold, $\approx$26 MeV in $\Lambda\Lambda$ continuum [HALQCD, NPA 881 (2012) 28; Haidenbauer & Meißner, ibid. 44].
- Search for $m(\mathrm{H}) \leq 2.05$ GeV by BaBar in $\Upsilon(2S,3S) \to \mathrm{H}\bar{\Lambda}\bar{\Lambda}$ is negative [PRL 122 (2019) 072002].

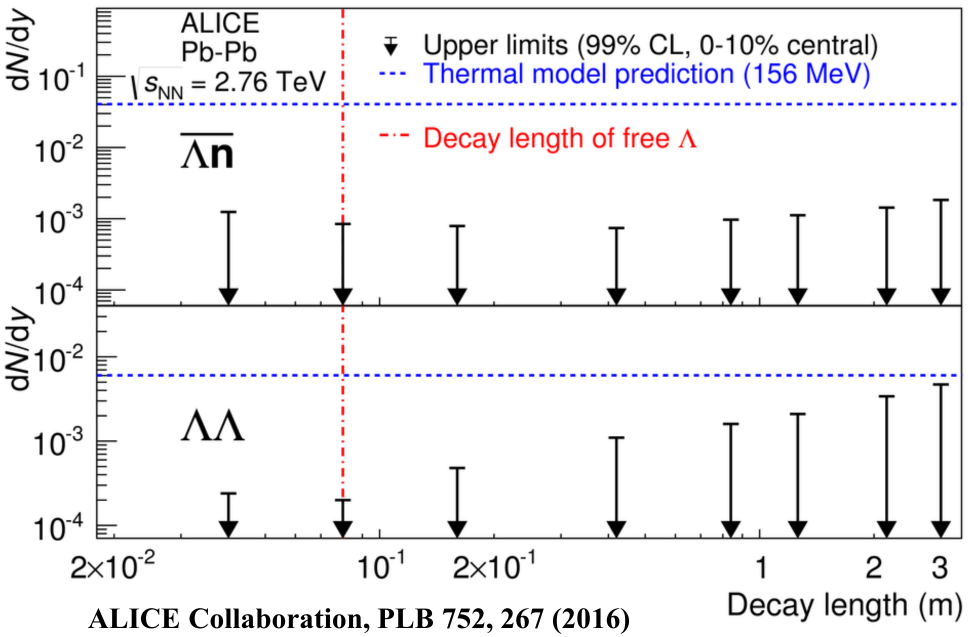
But why no H dibaryon?





Many negative searches

- H dibaryon channel: Flavor Breaking effect weakens attraction in Flavor 1

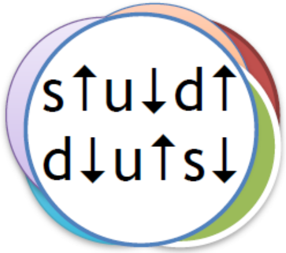


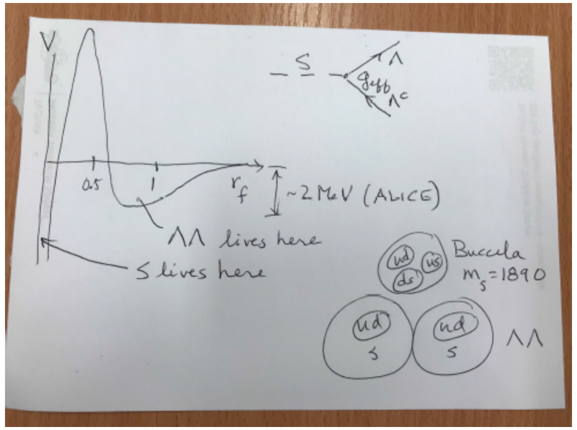
ALICE Collaboration, PLB 752, 267 (2016)

Sexaquark

- How could we have missed a stable particle made of quarks?
- S Same quark content as H-dibaryon, but different physics: not a loosely bound di-Λ
- looked for H-dibaryon through decays (but S is stable)
- mainly restricted to mass > 2 GeV (but m_S < 2 GeV)
- Wave function overlap with baryons is very small

But why no H dibaryon?





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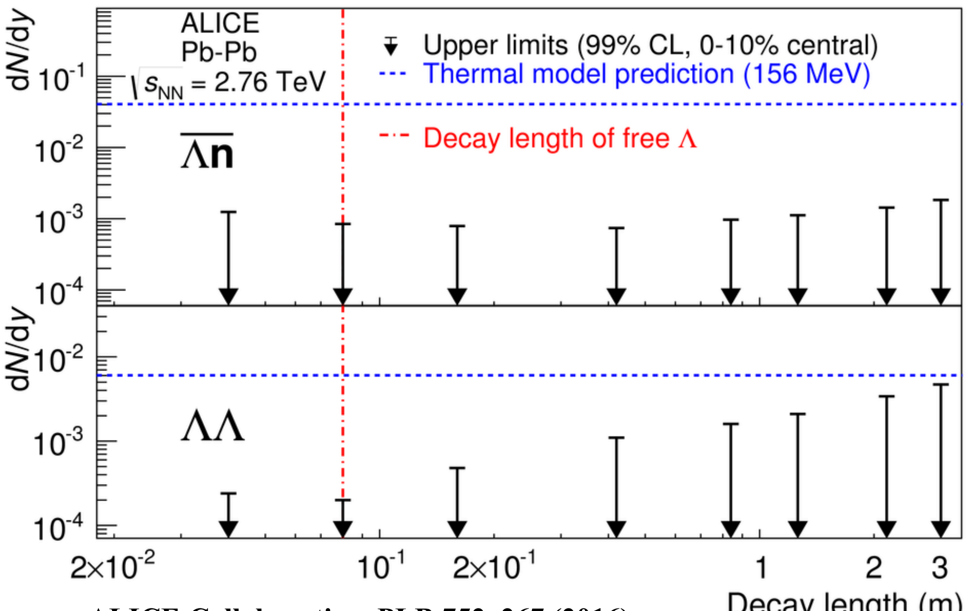

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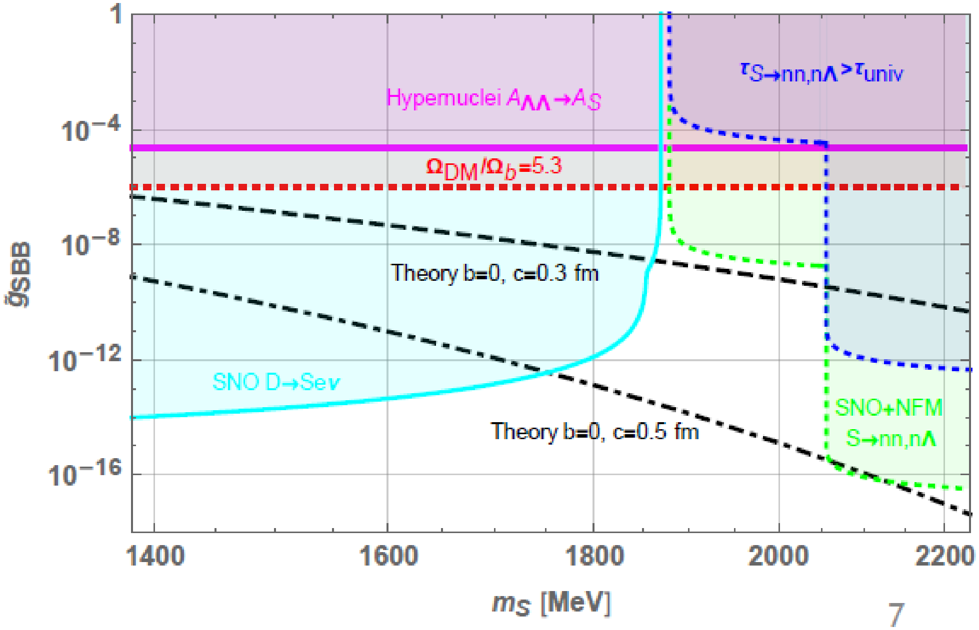
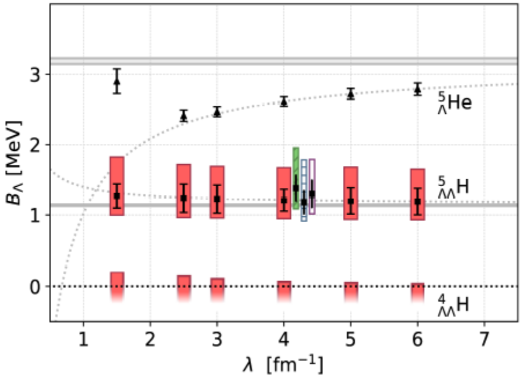


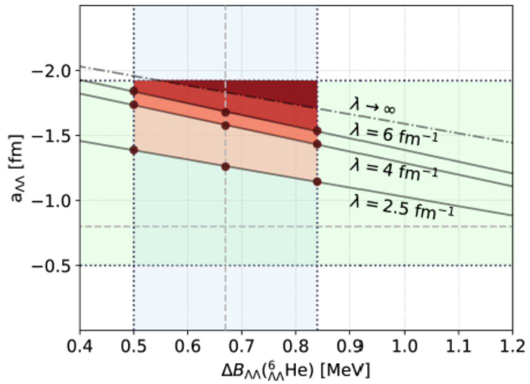
Light ΛΛ hypernuclei predictions

Recent $\not\pi$EFT ΛΛ calculations



B_Λ vs. $\not\pi$EFT cutoff λ

$_{\Lambda\Lambda}^{5}$H bound, $_{\Lambda\Lambda}^{4}$H unlikely

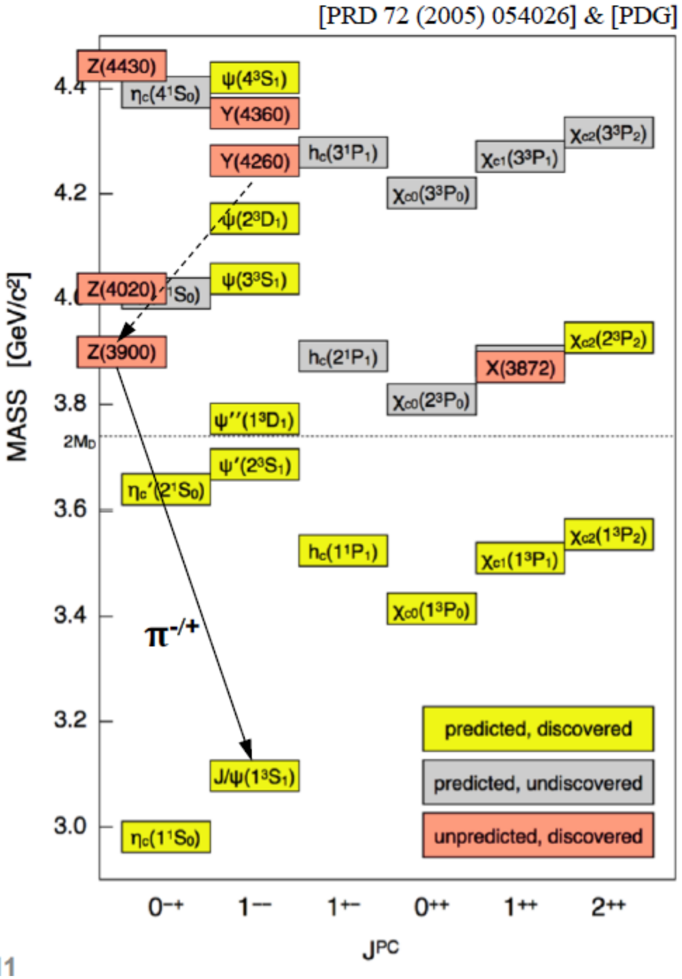


minimum $|a_{\Lambda\Lambda}|$ to bind $_{\Lambda\Lambda}^{4}$H is over 1.5 fm, too large!

- Contessi-Schafer-Barnea-Gal-Mareš, PLB 797 (2019) 134893.
- Neutral systems ΛΛn & ΛΛnn safely unbound.
- Argue that ΛΛ–ΞN coupling effect is minor.

- $^5_\Lambda$He overbinding problem resolved.
- Role of ΛNN forces in $^A_\Lambda Z$ & neutron stars?
- $^3_\Lambda$n (Λnn) is unbound.
- Onset of ΛΛ binding: $_{\Lambda\Lambda}^{4}$H or $_{\Lambda\Lambda}^{5}$Z? (E07, P75).
- $_{\Lambda\Lambda}^{3}$n (ΛΛn) and $_{\Lambda\Lambda}^{4}$n (ΛΛnn) are unbound.
- Shell model works well for g.s. beyond $_{\Lambda\Lambda}^{6}$He.
- Study excited states by slowing down Ξ^- from $\bar{p}p \to \Xi^-\bar{\Xi}^+$ in FAIR (PANDA).

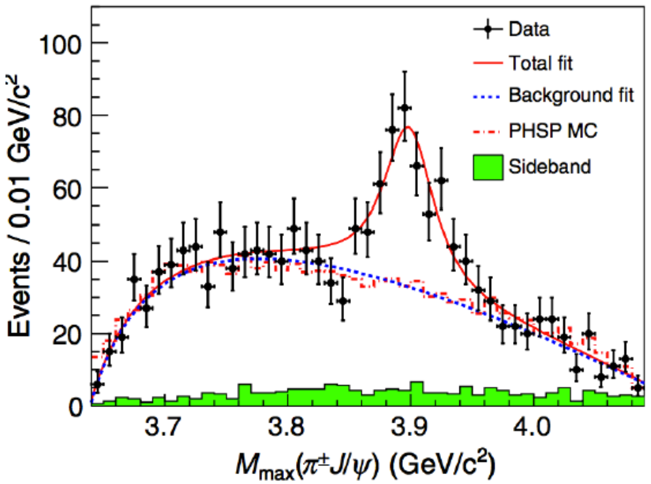
The puzzle of XYZ states



- Below open charm threshold:
  - Good agreement theory vs. experiment
- Above open charm threshold:
  - Many predicted states not discovered
  - Many unexpected states observed

BESIII: Study conventional as well as charmonium-like (exotic) XYZ states

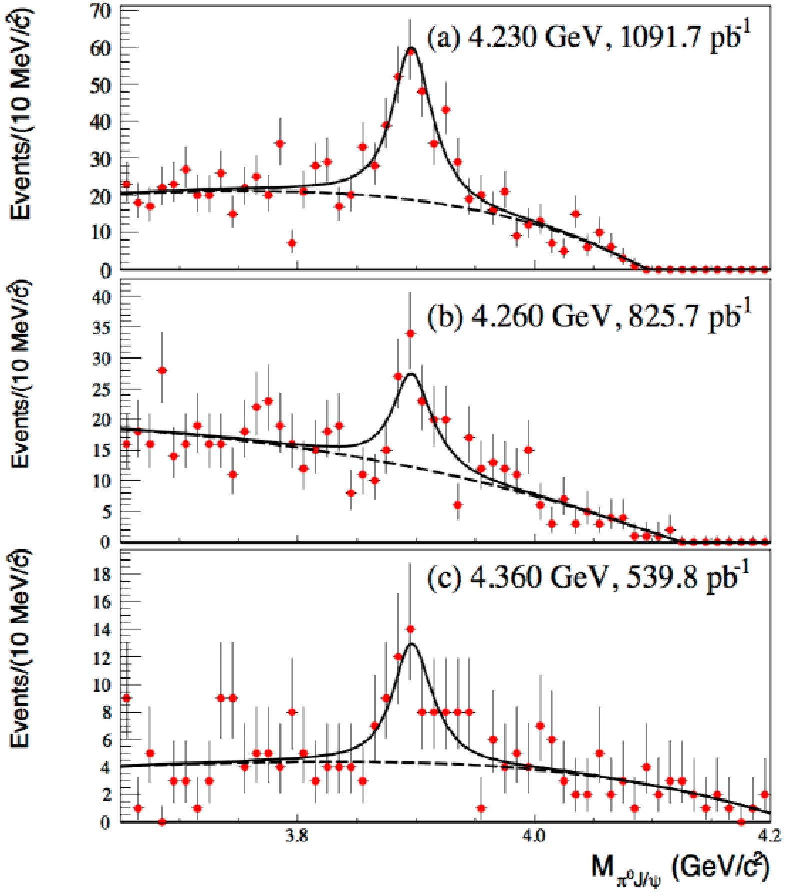
- Direct access to Y states (1^{--}) in direct formation (e^+e^- annihilation)
- Study (charged & neutral) Z states
- Study X states in radiative decays



- Discovery of $Z_c(3900)^{\pm} \rightarrow J/\psi\pi^{\pm}$
  - $e^+e^- \rightarrow J/\psi\pi^+\pi^-$
  - at $\sqrt{s}$ = 4.26 GeV (525 pb^{-1}, >8σ)
- Mass close to $D\bar{D}^*$ threshold
- $m = (3899.0 \pm 3.6 \pm 4.9)\,\mathrm{MeV}/c^2$
  $\Gamma = (46 \pm 10 \pm 20)\,\mathrm{MeV}$
- Manifestly exotic:
  - decays to J/ψ => contains $c\bar{c}$
  - electrical charged => contains $u\bar{d}$

  => First 4-quark state observation (?!)
- Confirmed by Belle and CLEO-c

BESIII: two Z_c triplets established

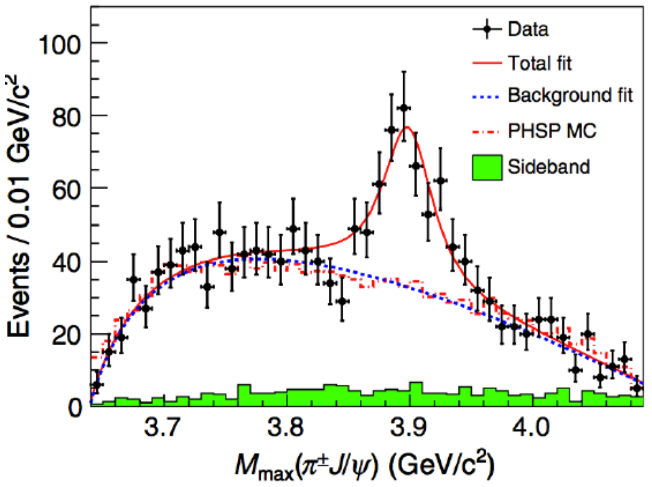


[PRL 115 (2015) 112003]

- Observation of $Z_c(3900)^0 \to J/\psi\pi^0$
  - in $e^+e^- \to J/\psi\pi^0\pi^0$ GeV (2.8 fb^{-1}, 10.4σ)
  - confirms earlier evidence in CLEO-c data
- Parameters consistent with those of $Z_c(3900)^\pm$
- $m = 3894.8 \pm 2.3 \pm 2.7\,\mathrm{MeV}/c^2$
  $\Gamma = 29.6 \pm 8.2 \pm 8.2\,\mathrm{MeV}$

=> Establishes an isospin triplet $Z_c(3900)$

- Confirmed by Belle and consistent with CLEO-c data



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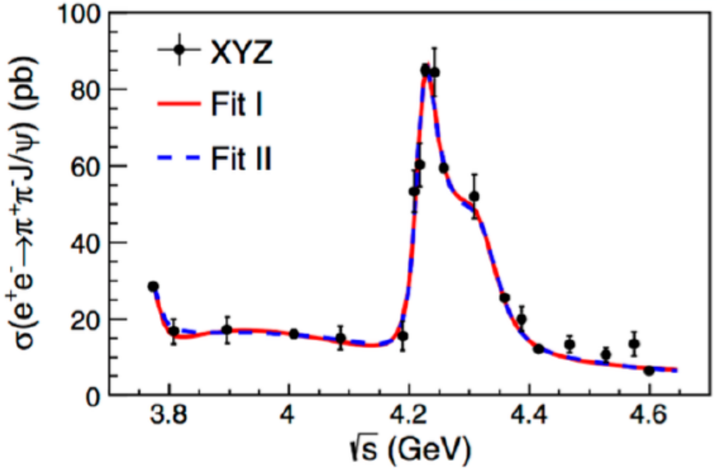
BESIII: direct access to Y states

BESIII result, published

$e^+e^- \to J/\psi\ \pi^+\pi^-$ at BESIII (direct)

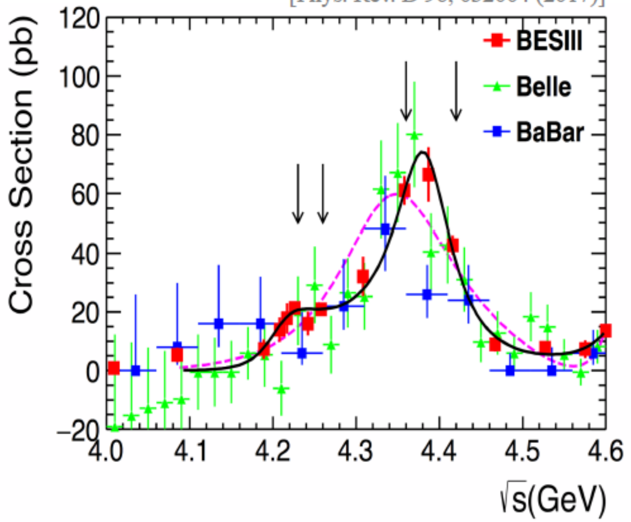
[PRL 118, 092001 (2017)]



- Cross-section in-consistent with a single peak for the Y(4260) !
  - two peaks favoured over one by >7σ

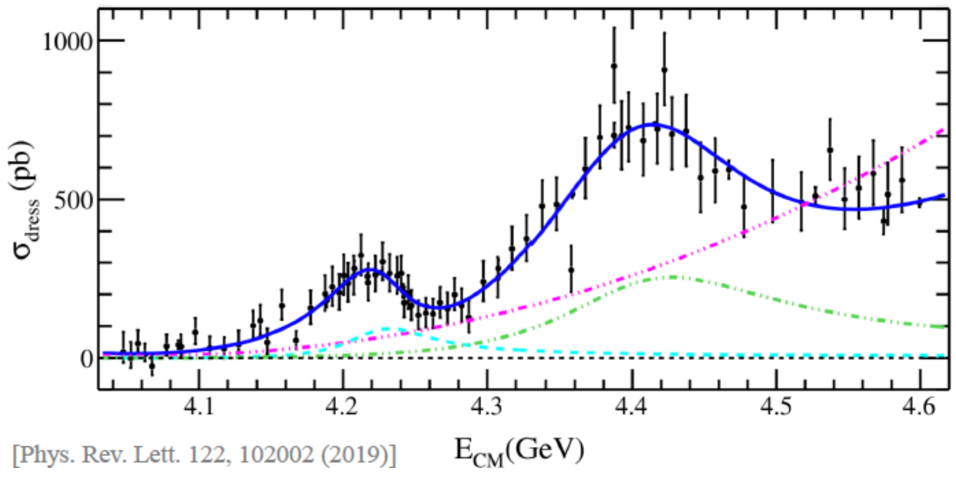
$e^+e^- \to \psi(2S)\ \pi^+\pi^-$ at BESIII (direct)

[Phys. Rev. D 96, 032004 (2017)]



- BESIII much higher precision (5.8σ)
- 3 coherent BW fit: Y(4220) and Y(4390)

$e^+e^- \to D^0D^{*-}\pi^+$



[Phys. Rev. Lett. 122, 102002 (2019)]

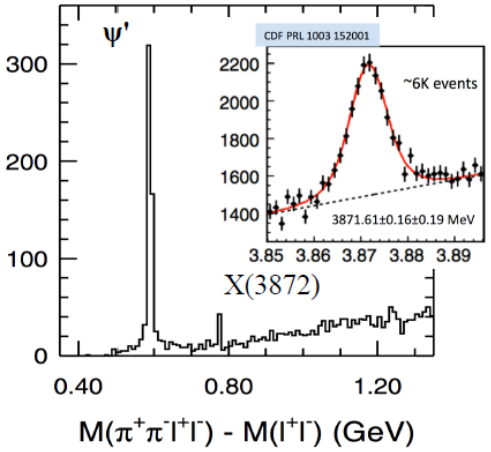
Two structures consistently observed: Y(4220) & Y(4390)

=> Y(4260) → Y(4220) ?

BESIII: radiative transitions to X states

Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]

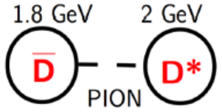


- The first unexpected states
  - and the most intriguing one
- First observed by Belle in 2003
  - $X(3872) \to J/\psi\ \pi\pi$
  - very narrow state with $J^{PC} = 1^{++}$
- Both, Belle & BaBar report signal in
  - $X(3872) \to D^0\bar{D}^{*0}$ ($D^0D^0\pi^0$ and $D^0D^0\gamma$)

- Mass: $m(X) - m(\bar{D}^{*0}) - m(D^0) =$
  $= -0.12 \pm 0.19\ \mathrm{MeV}/c^2$
- Width: Upper limit by Belle
  - $\Gamma_{X(3872)} < 1.2$ MeV (90% c.l., 2011)

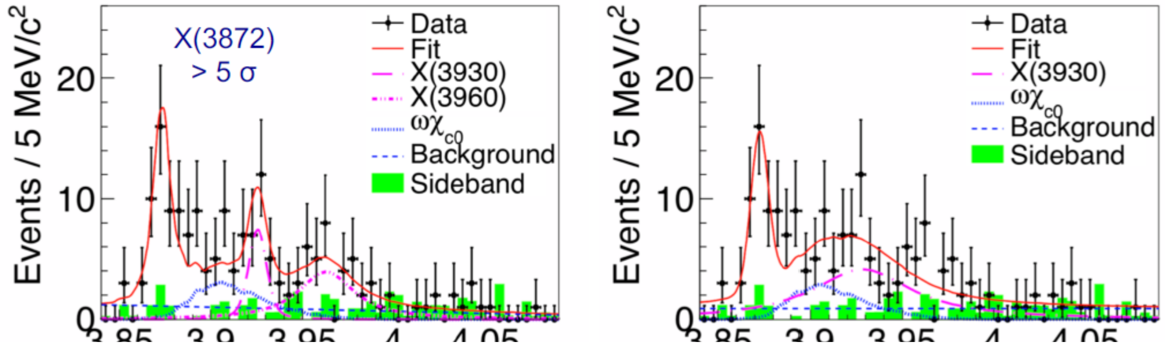
"binding energy" of -0.12+-0.19 MeV ?

Intriguing Analogon

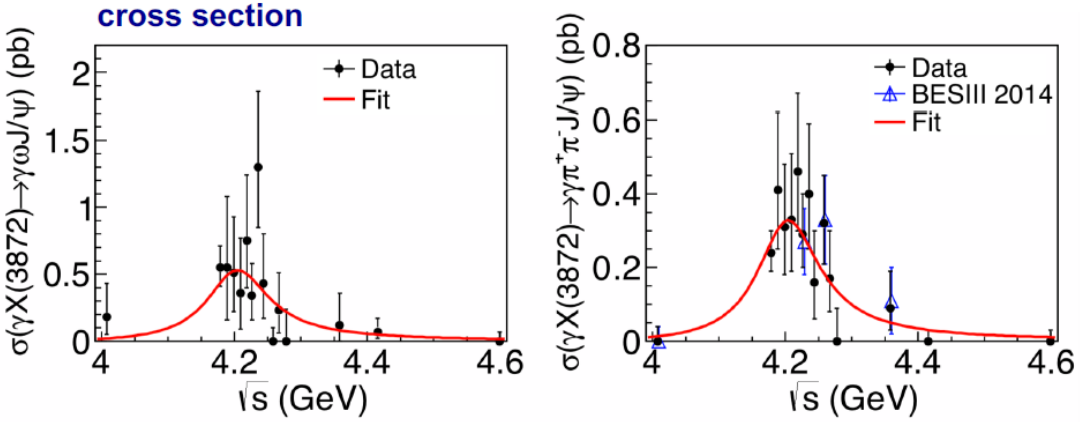


Molecule ?
$(q\bar{q})_1(q\bar{q})_1$

For clarification: Precision measurement of $\Gamma_{X(3872)}$ in the sub-MeV range needed!



cross section



- $m = (4200.6^{+7.9}_{-13.3} \pm 3.0\ \mathrm{MeV}/c^2$
- $\Gamma = (115^{+38}_{-26} \pm 12\ \mathrm{MeV}/c^2$

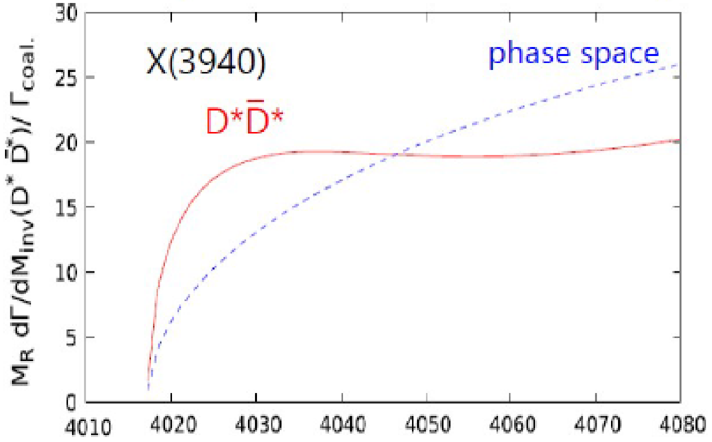
- Cross-section shape consistent with production via a Y state

[Phys. Rev. Lett., 122, 232002 (2019)]

Coupled Channel Description of Charmed Exotica

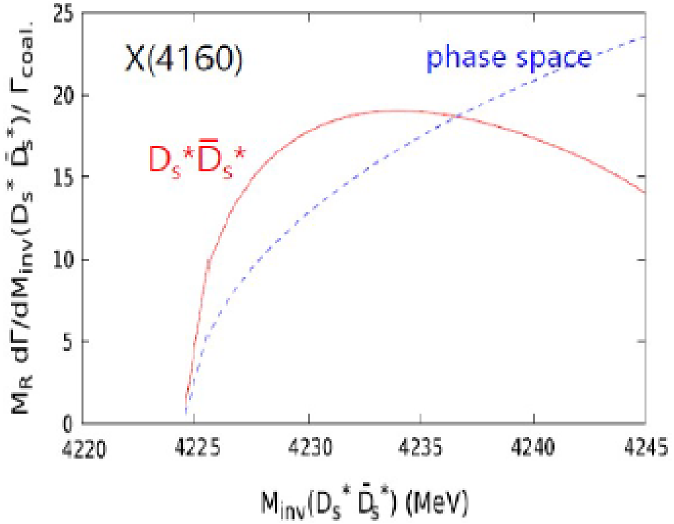
- The chiral unitary approach with coupled channels provides a simple and natural explanation of charmed exotica
- $X(3872) \Rightarrow D\bar{D}^*$;   PDG: $X(3872) \Rightarrow \chi_{c1}(3872)$!!!
- $X(3940) \Rightarrow D^*\bar{D}^*$
- $X(4160) \Rightarrow D_s^*\bar{D}_s^*$
- $Y(4260) \Rightarrow \bar{D}(\rho D)_{D_1(2420)}$ PDG: $Y(4260) \Rightarrow \psi(4260)$!!!

  The FCA to the Faddeev equations is an effective tool to deal with multi-hadron interaction
- $Z_c(3940) \Rightarrow \bar{D}D^*$ $(I = 1)$



Shape of D*D̄* invariant mass distribution is different from the phase space.

<= due to the presence of a resonance below threshold that couples strongly



Constraints on Neutron Stars EOS

Neutron star mass measurements with binary radio pulsars

MSP with period P=3.15 ms

Pb = 8.68 d, e=0.00000130(4)

Inclination angle = 89.17(2) degrees !

Precise masses derived from Shapiro delay only:

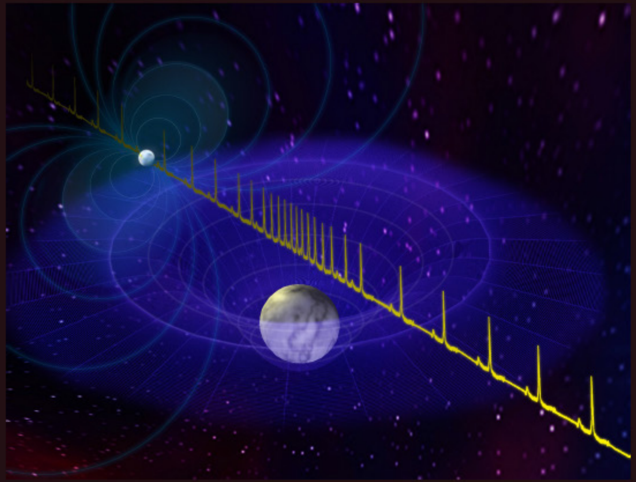
$M_P = 1.97(4)\ M_\odot$
$M_C = 0.500(6)\ M_\odot$

Update [Fonseca et al. (2016)]

$M_P = 1.928(17)\ M_\odot$

Update [Arzoumanian et al. (2018)]
Mp = 1.908(16) Mo

PSR J1614-2230
Demorest et al., Nature (2010)

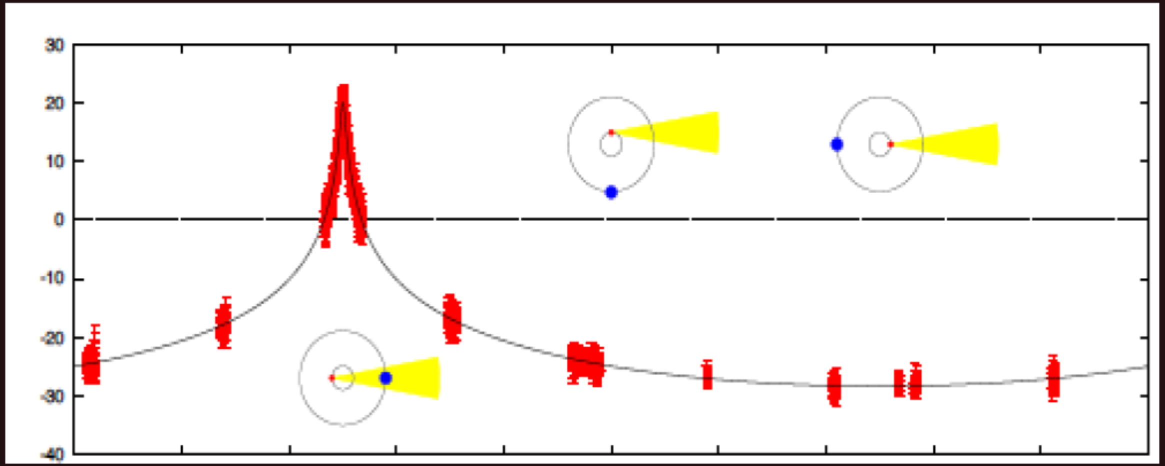


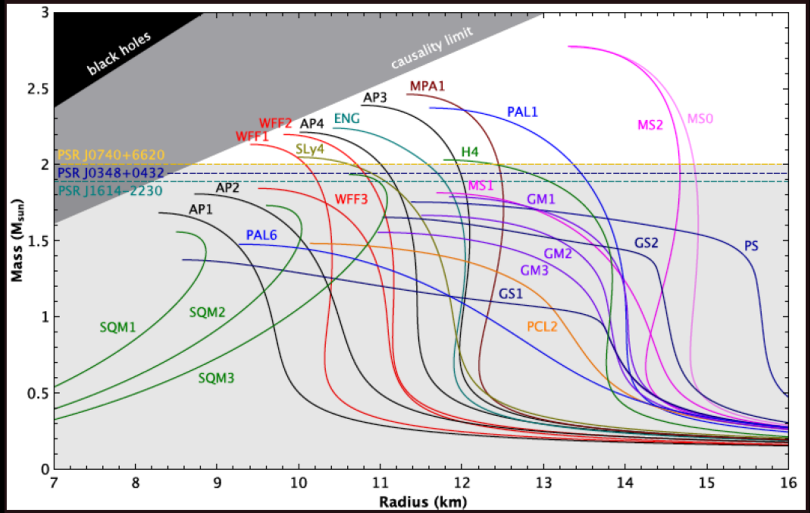
PSR J0740+6620
Cromartie et al., arXiv:1904.06759 (2019)

Precise mass derived from Shapiro delay only:

$2.17^{+0.11}_{-0.10}\ M_\odot$

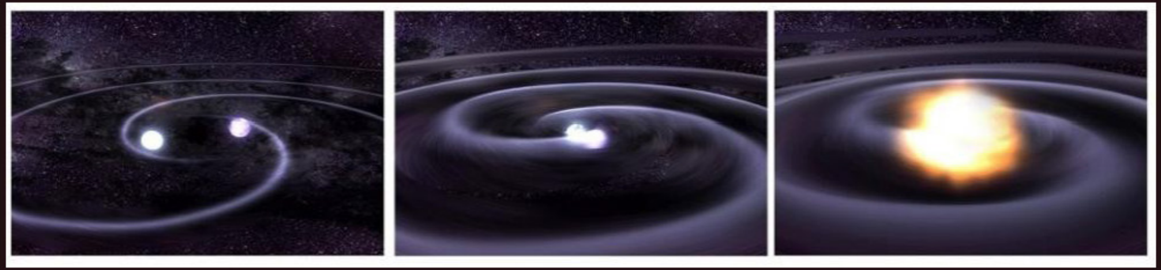
Shapiro delay:

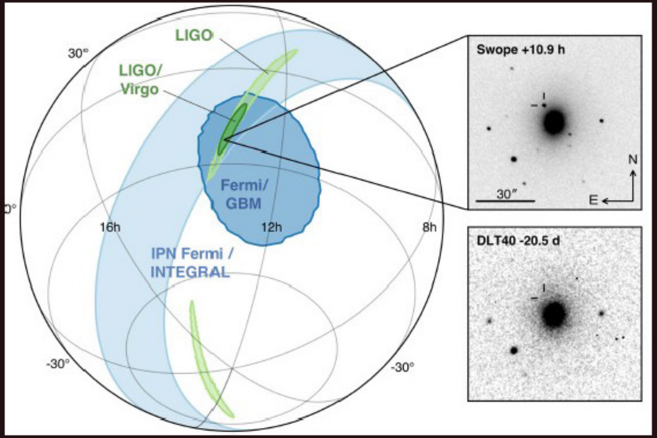


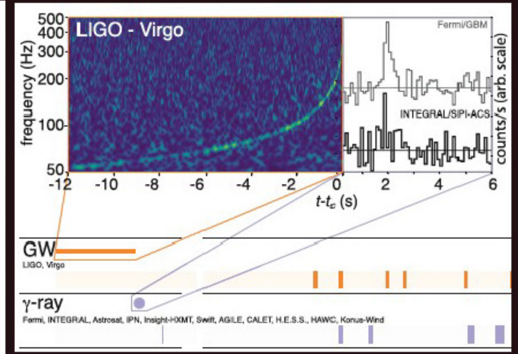


Constraints on Neutron Stars EOS

Discovery: neutron star merger !







GW170817A , announced 16.10.2017 *)

*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

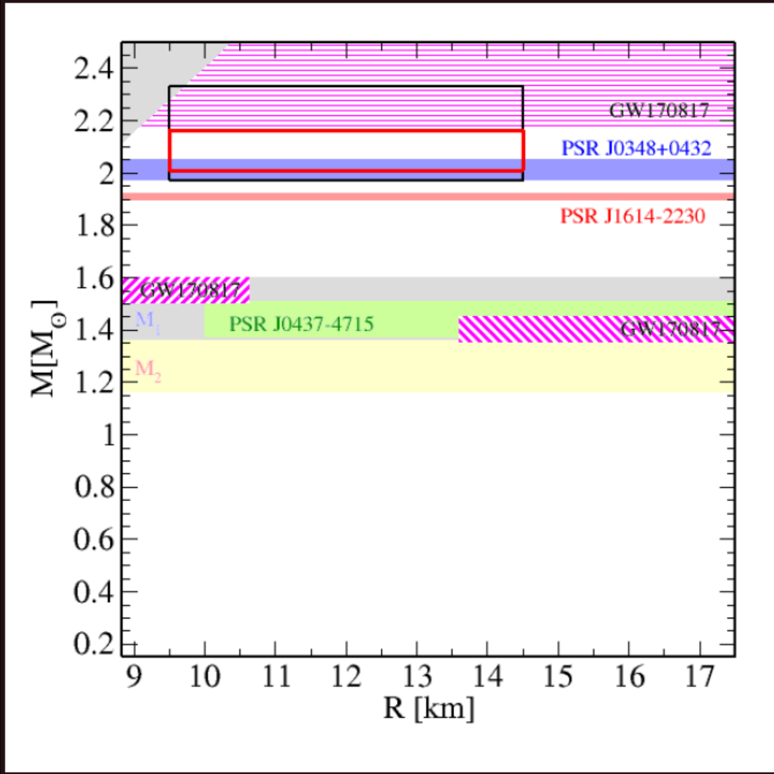
	Low-spin priors ($\|\chi\| \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

Dimensionless tidal deformability

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

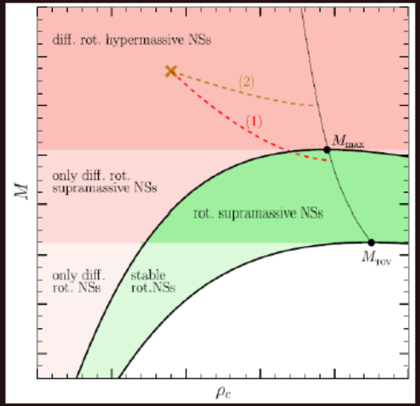
Constraints on NS mass and radii !



Constraint on maximum mass

$2.01 < M_{TOV}/M_o < 2.16$

(Rezzolla et al., arxiv:1710.05938)



Constraint on minimal radius

$R_{1.6} > 10.68$ km

(Bauswein et al., arxiv:1710.06843)

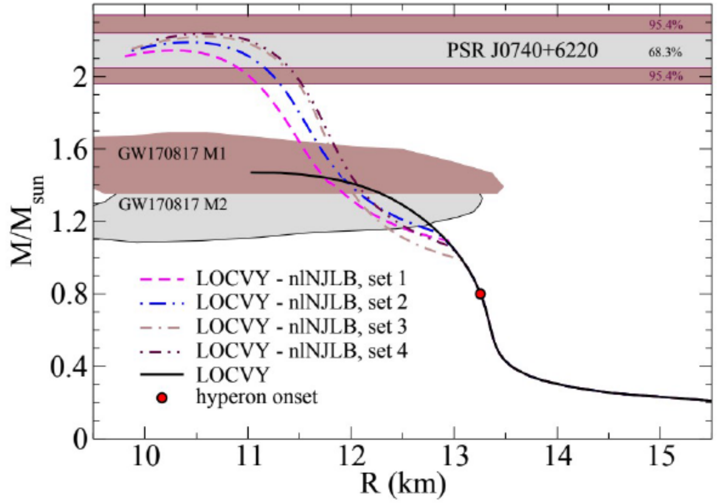
Constraint on maximal radius

$R_{1.4} < 13.6$ km

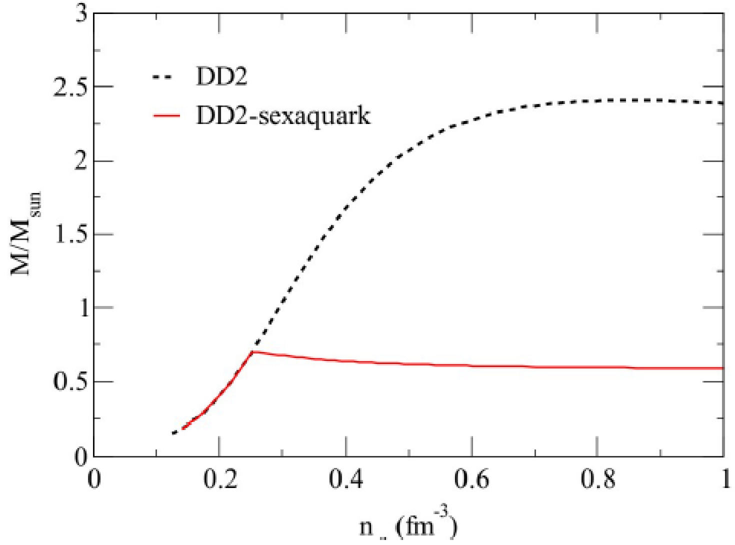
(Annala et al., arxiv:1711.02644)

Strange matter and exotica in NS

- Hyperon puzzle: an update due to 2 M_sun constraint
- Hyperon puzzle: deconfinement solution



- Sexaquarks in CS matter?
  - This induces a gravitational collapse !
    For hadronic EoS at M ~ 0.7 M_sun
  - Sexaquark dissociation



Formation and evaporation of strangelets during the merger of two compact stars

Why quark matter?

Merger of compact objects August 2017 → Limit on $\tilde{\Lambda}$ from the inspiral phase

$2 < M_{max} < 2.2 M_{\odot}$, $R_{1.5} < 13.5\ km$ ← Limit on ejecta from the Kilonova signal

What are we left with?

- $11.5 < R_{1.5} < 13\ km$: hyperons and delta from $1.5 M_{\odot}$, hybrid stars

Radii measurements from x-ray binaries ≈ 11 km

- $R_{1.5} < 11.5\ km$: only disconnected solutions of the TOV → Two different configurations

1. **Hadronic Matter**
2. **Partially or totally deconfined quark matter**

Kilonova?

❖ the radii of the two compact objects are both rather small, the system is asymmetric and the threshold mass is large

❖ Issue: fate of quark matter
Strangelets evaporation?

Production of strangelets at a critical temperature of ≈ 100 MeV

Lumps of strange matter with baryon number A:

- 3A quarks in quark-matter phase
- radius ≈ $A^{1/3}$
- mass = eA where e ≈ 860 – 880 MeV → **ionization energy ≈ 50 – 70 MeV**

Conclusions

- ❖ Most of the strangelets ejected during the merger evaporate
- ❖ non-evaporating strangelets are massive $A \sim 10^{30}$ and their number is small and so they are very unlikely to be detected in experiments
- ❖ evaporation is dominated by neutrons and therefore the initial electron fraction of the material is really low: same KN as NS-NS

Beyond Exotica: from a first order transition in QCD with up, down and strange quarks to a dark QCD matter scenario

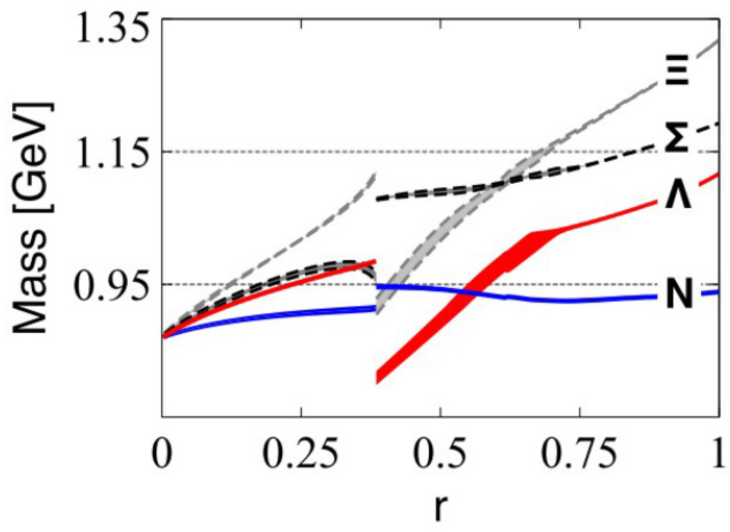
✔ **Chiral extrapolation of baryon octet and decuplet masses**

- resummed χPT : use on-shell masses in the loops
  - solve system of coupled and non-linear equations
  - chiral expansion with up, down and strange quarks is well convergent
  - reproduce the QCD Lattice data set at $m_{\pi,K} < 600$ MeV
  - predict a large number of low-energy constants for the chiral Lagrangian of QCD
- predict first order transition for the baryon masses
  - the nature of the baryonic ground state in QCD depends on the quark masses
  - the nature of the baryonic ground state depends on the choice of Higgs field

✔ **A dark matter scenario with Λ baryons in a Higgs bubble**

- Generalize the Higgs potential to support two degenerate minima
  - large fraction of (dark) baryonic matter in Higgs bubbles (here $M_\Lambda < M_N$)
  - derive a maximum radius of such bubbles (< 800 km)
- future request: derive equation of state of Λ baryons in the Higgs bubble ...
- possibility of strange dark matter objects with masses larger than neutron stars

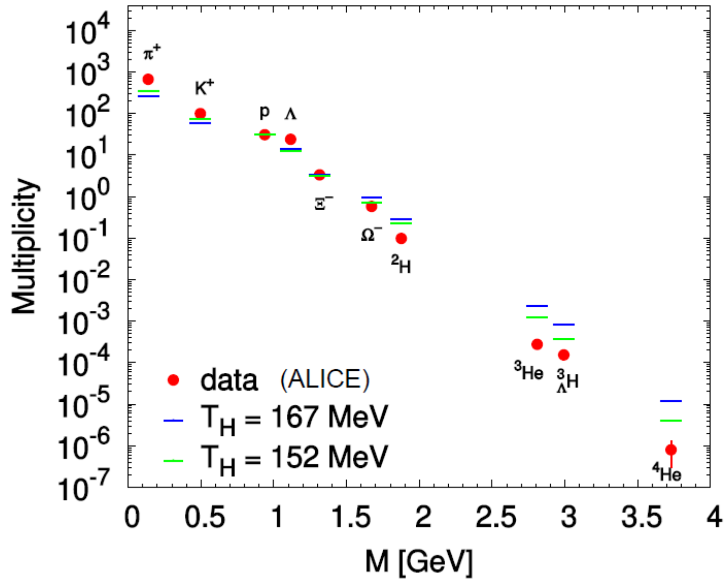
Baryon masses depend on the Higgs field



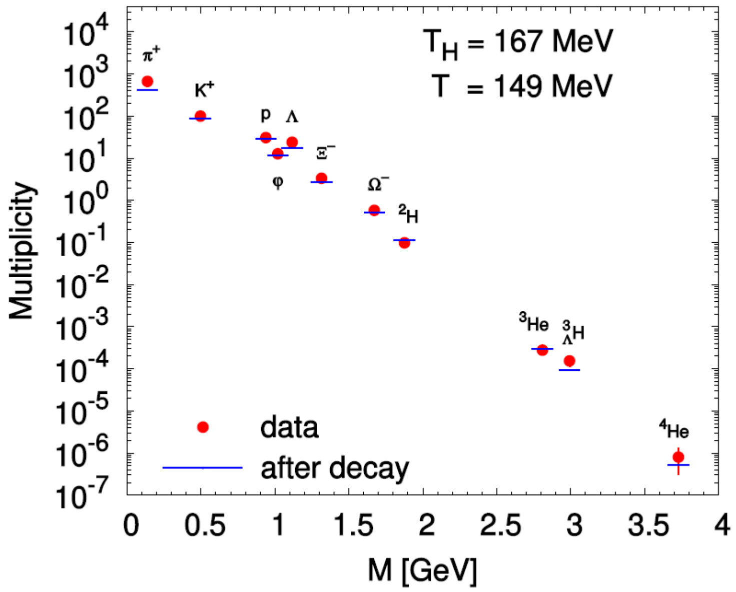
ıark masses in QCD are proportional to $v \sim r$

Hagedorn States and (anti-)(hyper-)nuclei production in HIC

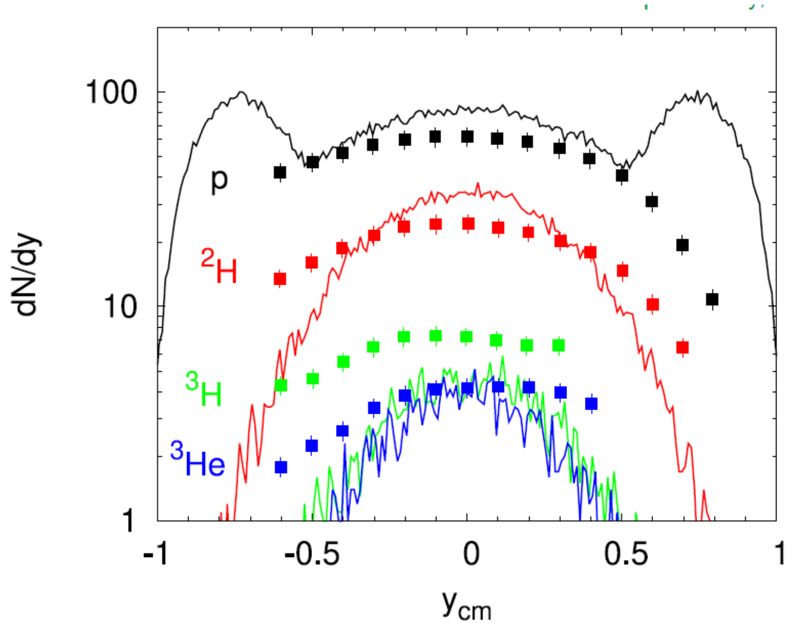
- Lattice QCD doesn't support point-like Hagedorn states. The situation can be different if eigenvolumes are considered.
- Work in progress…



Single Hagedorn decay chain

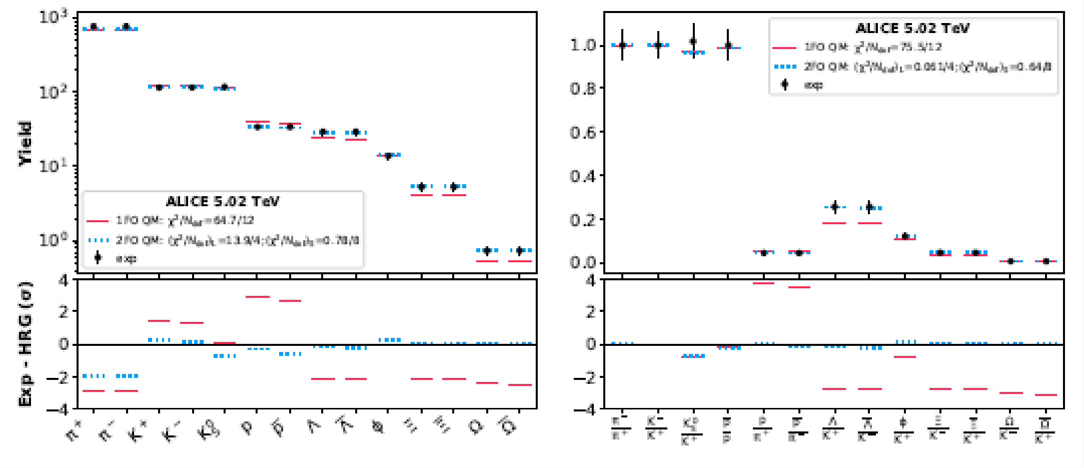


Thermal Hagedorn gas

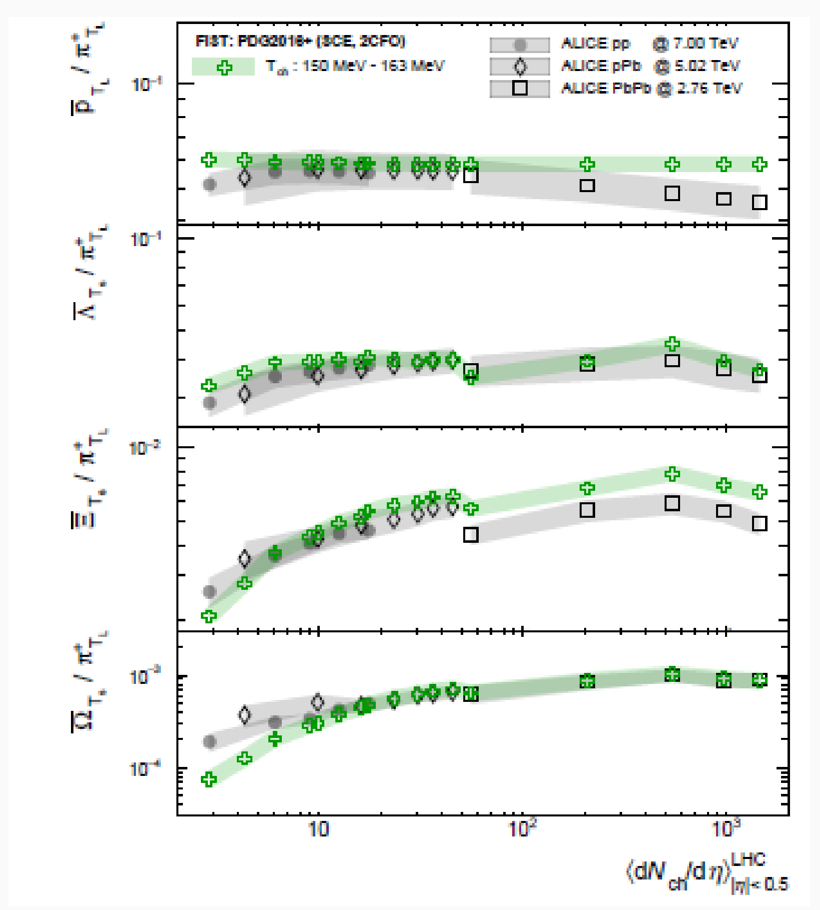


HADES rapidity spectra

Multi-freeze-out scenario



$$\text{1FO: } T_{\rm FO} = 147.9 \pm 1.3\,\text{MeV}$$
$$\text{2 FO: } T_{\rm FO}^{\rm light} = 140.9 \pm 1.6\,\text{MeV},\ T_{\rm FO}^{\rm strange} = 158.2 \pm 1.9\,\text{MeV}$$



- A multi-freeze-out scenario could improve the quality of the fit
- A multi-freeze-out scenario could provide a simple explanation of strangeness enhancement
- Also in small systems, 2FO scenario improves on 1FO
- Exotica preliminary predictions: yields of strange penta-quarks would go up

Upcoming PANDA exp at FAIR

- Complementary production mechanisms and measurements needed
- Precise knowledge of decay width and line shape essential
- Complete the exotic multiplets
- Advantages of Anti-Protons
  - Access to all fermion-antifermion quantum numbers *(not in e+e-)*
  - Access to states of high spin J
- *High statistics*
- *Precision resonance scans*