# Exotic hadrons in s-wave chiral dynamics

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# Exotic hadrons

## Observed hadrons in experiments (PDG06) :

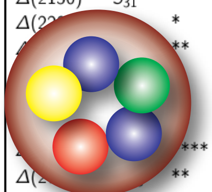
| | | |
|---|---|---|
| $p$ | $P_{11}$ | **** |
| $n$ | $P_{11}$ | **** |
| $N(1440)$ | $P_{11}$ | **** |
| $N(1520)$ | $D_{13}$ | **** |
| $N(1535)$ | $S_{11}$ | **** |
| $N(1650)$ | $S_{11}$ | **** |
| $N(1675)$ | $D_{15}$ | **** |
| $N(1680)$ | $F_{15}$ | **** |
| $N(1700)$ | $D_{13}$ | *** |
| $N(1710)$ | $P_{11}$ | *** |
| $N(1720)$ | $P_{13}$ | **** |
| $N(1900)$ | $P_{13}$ | ** |
| $N(1990)$ | $F_{17}$ | ** |
| $N(2000)$ | $F_{15}$ | ** |
| $N(2080)$ | $D_{13}$ | ** |
| $N(2090)$ | $S_{11}$ | * |
| $N(2100)$ | $P_{11}$ | * |
| $N(2190)$ | $G_{17}$ | **** |
| $N(2200)$ | $D_{15}$ | ** |
| $N(2220)$ | $H_{19}$ | **** |
| $N(2250)$ | $G_{19}$ | **** |
| $N(2600)$ | $I_{1,11}$ | *** |
| $N(2700)$ | $K_{1,13}$ | ** |

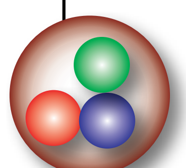
| | | |
|---|---|---|
| $\Delta(1232)$ | $P_{33}$ | **** |
| $\Delta(1600)$ | $P_{33}$ | *** |
| $\Delta(1620)$ | $S_{31}$ | **** |
| $\Delta(1700)$ | $D_{33}$ | **** |
| $\Delta(1750)$ | $P_{31}$ | * |
| $\Delta(1900)$ | $S_{31}$ | ** |
| $\Delta(1905)$ | $F_{35}$ | **** |
| $\Delta(1910)$ | $P_{31}$ | **** |
| $\Delta(1920)$ | $P_{33}$ | *** |
| $\Delta(1930)$ | $D_{35}$ | *** |
| $\Delta(1940)$ | $D_{33}$ | * |
| $\Delta(1950)$ | $F_{37}$ | **** |
| $\Delta(2000)$ | $F_{35}$ | ** |
| $\Delta(2150)$ | $S_{31}$ | * |
| $\Delta(22$[illegible] | [illegible] | * |
| [illegible] | [illegible] | ** |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | *** |
| $\Delta(2$[illegible] | [illegible] | ** |
| $\Delta(2950)$ | $K_{3,15}$ | ** |
| $\Theta(1540)^+$ | | * |

| | | |
|---|---|---|
| $\Lambda$ | $P_{01}$ | **** |
| $\Lambda(1405)$ | $S_{01}$ | **** |
| $\Lambda(1520)$ | $D_{03}$ | **** |
| $\Lambda(1600)$ | $P_{01}$ | *** |
| $\Lambda(1670)$ | $S_{01}$ | **** |
| $\Lambda(1690)$ | $D_{03}$ | **** |
| $\Lambda(1800)$ | $S_{01}$ | *** |
| $\Lambda(1810)$ | $P_{01}$ | *** |
| $\Lambda(1820)$ | $F_{05}$ | **** |
| $\Lambda(1830)$ | $D_{05}$ | **** |
| $\Lambda(1890)$ | $P_{03}$ | **** |
| $\Lambda(2000)$ | | * |
| $\Lambda(2020)$ | $F_{07}$ | * |
| $\Lambda(2100)$ | $G_{07}$ | **** |
| $\Lambda(2110)$ | $F_{05}$ | *** |
| $\Lambda(2325)$ | $D_{03}$ | * |
| $\Lambda(2350)$ | $H_{09}$ | *** |
| $\Lambda(2585)$ | | ** |

| | | |
|---|---|---|
| $\Sigma^+$ | $P_{11}$ | **** |
| $\Sigma^0$ | $P_{11}$ | **** |
| $\Sigma^-$ | $P_{11}$ | **** |
| $\Sigma(1385)$ | $P_{13}$ | **** |
| $\Sigma(1480)$ | | * |
| $\Sigma(1560)$ | | ** |
| $\Sigma(1580)$ | $D_{13}$ | * |
| $\Sigma(1620)$ | $S_{11}$ | ** |
| $\Sigma(1660)$ | $P_{11}$ | *** |
| $\Sigma(1670)$ | $D_{13}$ | **** |
| $\Sigma(1690)$ | | ** |
| $\Sigma(1750)$ | $S_{11}$ | *** |
| $\Sigma(1770)$ | $P_{11}$ | * |
| $\Sigma(1775)$ | $D_{15}$ | **** |
| $\Sigma(1840)$ | $P_{13}$ | * |
| $\Sigma(1880)$ | $P_{11}$ | ** |
| $\Sigma(1915)$ | $F_{15}$ | **** |
| $\Sigma(1940)$ | $D_{13}$ | *** |
| $\Sigma(2000)$ | $S_{11}$ | * |
| $\Sigma(2030)$ | $F_{17}$ | **** |
| $\Sigma(2070)$ | $F_{15}$ | * |
| $\Sigma(2080)$ | $P_{13}$ | ** |
| $\Sigma(2100)$ | $G_{17}$ | * |
| $\Sigma(2250)$ | | *** |
| $\Sigma(2455)$ | | ** |
| $\Sigma(2620)$ | | ** |
| $\Sigma(3000)$ | | * |
| $\Sigma(3170)$ | | * |

| | | |
|---|---|---|
| $\Xi^0$ | $P_{11}$ | **** |
| $\Xi^-$ | $P_{11}$ | **** |
| $\Xi(1530)$ | $P_{13}$ | **** |
| $\Xi(1620)$ | | * |
| $\Xi(1690)$ | | *** |
| $\Xi(1820)$ | $D_{13}$ | *** |
| $\Xi(1950)$ | | *** |
| $\Xi(2030)$ | | *** |
| $\Xi(2120)$ | | * |
| $\Xi(2250)$ | | ** |
| $\Xi(2370)$ | | ** |
| $\Xi(2500)$ | | * |
| $\Omega^-$ | | **** |
| $\Omega(2250)^-$ | | *** |
| $\Omega(2380)^-$ | | ** |
| $\Omega(2470)^-$ | | ** |
| $\Lambda_c^+$ | | **** |
| $\Lambda_c(2593)^+$ | | *** |
| $\Lambda_c(2625)^+$ | | *** |
| $\Lambda_c(2765)^+$ | | * |
| $\Lambda_c(2880)^+$ | | ** |
| $\Sigma_c(2455)$ | | **** |
| $\Sigma_c(2520)$ | | *** |
| $\Sigma_c(2800)$ | | *** |
| $\Xi_c^+$ | | *** |
| $\Xi_c^0$ | | *** |
| $\Xi_c'^+$ | | *** |
| $\Xi_c'^0$ | | *** |
| $\Xi_c(2645)$ | | *** |
| $\Xi_c(2790)$ | | *** |
| $\Xi_c(2815)$ | | *** |
| $\Omega_c^0$ | | *** |
| $\Xi_{cc}^+$ | | * |
| $\Lambda_b^0$ | | *** |





$$\sim \frac{1}{300}\,!$$

**~130 baryons**

| LIGHT UNFLAVORED ($S = C = B = 0$) | $I^G(J^{PC})$ | | $I^G(J^{PC})$ |
|---|---|---|---|
| • $\pi^\pm$ | $1^-(0^-)$ | • $\pi_2(1670)$ | $1^-(2^{-+})$ |
| • $\pi^0$ | $1^-(0^{-+})$ | • $\phi(1680)$ | $0^-(1^{--})$ |
| • $\eta$ | $0^+(0^{-+})$ | • $\rho_3(1690)$ | $1^+(3^{--})$ |
| • $f_0(600)$ | $0^+(0^{++})$ | • $\rho(1700)$ | $1^+(1^{--})$ |
| • $\rho(770)$ | $1^+(1^{--})$ | $a_2(1700)$ | $1^-(2^{++})$ |
| • $\omega(782)$ | $0^-(1^{--})$ | • $f_0(1710)$ | $0^+(0^{++})$ |
| • $\eta'(958)$ | $0^+(0^{-+})$ | $\eta(1760)$ | $0^+(0^{-+})$ |
| • $f_0(980)$ | $0^+(0^{++})$ | • $\pi(1800)$ | $1^-(0^{-+})$ |
| • $a_0(980)$ | $1^-(0^{++})$ | $f_2(1810)$ | $0^+(2^{++})$ |
| • $\phi(1020)$ | $0^-(1^{--})$ | $X(1835)$ | $?^?(?^{-+})$ |
| • $h_1(1170)$ | $0^-(1^{+-})$ | • $\phi_3(1850)$ | $0^-(3^{--})$ |
| • $b_1(1235)$ | $1^+(1^{+-})$ | $\eta_2(1870)$ | $0^+(2^{-+})$ |
| • $a_1(1260)$ | $1^-(1^{++})$ | $\rho(1900)$ | $1^+(1^{--})$ |
| • $f_2(1270)$ | $0^+(2^{++})$ | $f_2(1910)$ | $0^+(2^{++})$ |
| • $f_1(1285)$ | $0^+(1^{++})$ | • $f_2(1950)$ | $0^+(2^{++})$ |
| • $\eta(1295)$ | $0^+(0^{-+})$ | $\rho_3(1990)$ | $1^+(3^{--})$ |
| • $\pi(1300)$ | $1^-(0^{-+})$ | • $f_2(2010)$ | $0^+(2^{++})$ |
| • $a_2(1320)$ | $1^-(2^{++})$ | $f_0(2020)$ | $0^+(0^{++})$ |
| • $f_0(1370)$ | $0^+(0^{++})$ | • $a_4(2040)$ | $1^-(4^{++})$ |
| $h_1(1380)$ | $?^-(1^{+-})$ | • $f_4(2050)$ | $0^+(4^{++})$ |
| • $\pi_1(1400)$ | $1^-(1^{-+})$ | $\pi_2(2100)$ | $1^-(2^{-+})$ |
| • $\eta(1405)$ | $0^+(0^{-+})$ | $f_0(2100)$ | $0^+(0^{++})$ |
| • $f_1(1420)$ | $0^+(1^{++})$ | $f_2(2150)$ | $0^+(2^{++})$ |
| • $\omega(1420)$ | $0^-(1^{--})$ | $\rho(2150)$ | $1^+(1^{--})$ |
| $f_2(1430)$ | $0^+(2^{++})$ | $f_0(2200)$ | $0^+(0^{++})$ |
| • $a_0(1450)$ | $1^-(0^{++})$ | $f_J(2220)$ | $0^+(2\text{ or }4^{++})$ |
| • $\rho(1450)$ | $1^+(1^{--})$ | $\eta(2225)$ | $0^+(0^{-+})$ |
| • $\eta(1475)$ | $0^+(0^{-+})$ | $\rho_3(2250)$ | $1^+(3^{--})$ |
| • $f_0(1500)$ | $0^+(0^{++})$ | • $f_2(2300)$ | $0^+(2^{++})$ |
| $f_1(1510)$ | $0^+(1^{++})$ | $f_4(2300)$ | $0^+(4^{++})$ |
| • $f_2'(1525)$ | $0^+(2^{++})$ | • $f_2(2340)$ | $0^+(2^{++})$ |
| $f_2(1565)$ | $0^+(2^{++})$ | $\rho_5(2350)$ | $1^+(5^{--})$ |
| $h_1(1595)$ | $0^-(1^{+-})$ | $a_6(2450)$ | $1^-(6^{++})$ |
| • $\pi_1(1600)$ | $1^-(1^{-+})$ | $f_6(2510)$ | $0^+(6^{++})$ |
| $a_1(1640)$ | $1^-(1^{++})$ | OT[illegible] | |
| $f_2(1640)$ | $0^+(2^{++})$ | Further [illegible] | |
| • $\eta_2(1645)$ | $0^+(2^{-+})$ | | |
| • $\omega(1650)$ | $0^-(1^{--})$ | | |
| • $\omega_3(1670)$ | $0^-(3^{--})$ | | |

| STRANGE ($S = \pm1$, $C = B = 0$) | $I(J^P)$ |
|---|---|
| • $K^\pm$ | $1/2(0^-)$ |
| • $K^0$ | $1/2(0^-)$ |
| • $K_S^0$ | $1/2(0^-)$ |
| • $K_L^0$ | $1/2(0^-)$ |
| $K_0^*(800)$ | $1/2(0^+)$ |
| • $K^*(892)$ | $1/2(1^-)$ |
| • $K_1(1270)$ | $1/2(1^+)$ |
| • $K_1(1400)$ | $1/2(1^+)$ |
| • $K^*(1410)$ | $1/2(1^-)$ |
| • $K_0^*(1430)$ | $1/2(0^+)$ |
| • $K_2^*(1430)$ | $1/2(2^+)$ |
| $K(1460)$ | $1/2(0^-)$ |
| $K_2(1580)$ | $1/2(2^-)$ |
| $K(1630)$ | $1/2(?^?)$ |
| $K_1(1650)$ | $1/2(1^+)$ |
| • $K^*(1680)$ | $1/2(1^-)$ |
| • $K_2(1770)$ | $1/2(2^-)$ |
| • $K_3^*(1780)$ | $1/2(3^-)$ |
| • $K_2(1820)$ | $1/2(2^-)$ |
| $K(1830)$ | $1/2(0^-)$ |
| $K_0^*(1950)$ | $1/2(0^+)$ |
| $K_2^*(1980)$ | $1/2(2^+)$ |
| • $K_4^*(2045)$ | $1/2(4^+)$ |
| $K_2(2250)$ | $1/2(2^-)$ |
| $K_3(2320)$ | $1/2(3^+)$ |
| $K_5^*(2380)$ | $1/2(5^-)$ |
| $K_4(2500)$ | $1/2(4^-)$ |
| $K(3100)$ | $?^?(?^{??})$ |

| CHARMED ($C = \pm1$) | |
|---|---|
| • $D^\pm$ | $1/2(0^-)$ |
| • $D^0$ | $1/2(0^-)$ |
| • $D^*(2007)^0$ | $1/2(1^-)$ |
| • $D^*(2010)^\pm$ | $1/2(1^-)$ |
| $D_0^*(2400)^0$ | $1/2(0^+)$ |
| $D_0^*(2400)^\pm$ | $1/2(0^+)$ |
| • $D_1(2420)^0$ | $1/2(1^+)$ |
| $D_1(2420)^\pm$ | $1/2(?^?)$ |
| $D_1(2430)^0$ | $1/2(1^+)$ |
| • $D_2^*(2460)^0$ | $1/2(2^+)$ |
| • $D_2^*(2460)^\pm$ | $1/2(2^+)$ |
| $D^*(2640)^\pm$ | $1/2(?^?)$ |

| CHARMED, STRANGE ([illegible]$S = \pm1$) | |
|---|---|
| • $D_s^\pm$ | $0(0^-)$ |
| • $D_s^{*\pm}$ | $0(?^?)$ |
| • $D_{s0}^*(2317)^\pm$ | $0(0^+)$ |
| • $D_{s1}(2460)^\pm$ | $0(1^+)$ |
| • $D_{s1}(2536)^\pm$ | $0(1^+)$ |

| BOTTOM ($B = \pm1$) | $I^G(J^{PC})$ |
|---|---|
| • $B^\pm$ | $1/2(0^-)$ |
| • $B^0$ | $1/2(0^-)$ |
| • $B^\pm/B^0$ ADMIXTURE | |
| • $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE | |
| $V_{cb}$ and $V_{ub}$ CKM Matrix Elements | |
| • $B^*$ | $1/2(1^-)$ |
| $B_J^*(5732)$ | $?(?^?)$ |

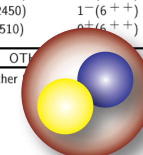
| BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$) | |
|---|---|
| • $B_s^0$ | $0(0^-)$ |
| $B_s^*$ | $0(1^-)$ |
| $B_{sJ}^*(5850)$ | $?(?^?)$ |

| BOTTOM, CHARMED ($B = C = \pm1$) | |
|---|---|
| • $B_c^\pm$ | $0(0^-)$ |

| $c\bar{c}$ | |
|---|---|
| • $\eta_c(1S)$ | $0^+(0^{-+})$ |
| • $J/\psi(1S)$ | $0^-(1^{--})$ |
| • $\chi_{c0}(1P)$ | $0^+(0^{++})$ |
| • $\chi_{c1}(1P)$ | $0^+(1^{++})$ |
| $h_c(1P)$ | $?^?(?^{??})$ |
| • $\chi_{c2}(1P)$ | $0^+(2^{++})$ |
| • $\eta_c(2S)$ | $0^+(0^{-+})$ |
| • $\psi(2S)$ | $0^-(1^{--})$ |
| • $\psi(3770)$ | $0^-(1^{--})$ |
| • $X(3872)$ | $0^?(?^{?+})$ |
| • $\chi_{c2}(2P)$ | $0^+(2^{++})$ |
| $Y(3940)$ | $?^?(?^{??})$ |
| • $\psi(4040)$ | $0^-(1^{--})$ |
| • $\psi(4160)$ | $0^-(1^{--})$ |
| $Y(4260)$ | $?^?(1^{--})$ |
| • $\psi(4415)$ | $0^-(1^{--})$ |

| $b\bar{b}$ | |
|---|---|
| $\eta_b(1S)$ | $0^+(0^{-+})$ |
| • $\Upsilon(1S)$ | $0^-(1^{--})$ |
| • $\chi_{b0}(1P)$ | $0^+(0^{++})$ |
| • $\chi_{b1}(1P)$ | $0^+(1^{++})$ |
| • $\chi_{b2}(1P)$ | $0^+(2^{++})$ |
| • $\Upsilon(2S)$ | $0^-(1^{--})$ |
| $\Upsilon(1D)$ | $0^-(2^{--})$ |
| • $\chi_{b0}(2P)$ | $0^+(0^{++})$ |
| • $\chi_{b1}(2P)$ | $0^+(1^{++})$ |
| • $\chi_{b2}(2P)$ | $0^+(2^{++})$ |
| • $\Upsilon(3S)$ | $0^-(1^{--})$ |
| • $\Upsilon(4S)$ | $0^-(1^{--})$ |
| • $\Upsilon(10860)$ | $0^-(1^{--})$ |
| • $\Upsilon(11020)$ | $0^-(1^{--})$ |

NON-$q\bar{q}$ CANDIDATES



**~160 mesons**

**Exotic hadrons are indeed exotic !!**

# Motivation 1 : Exotic hadrons

**Exotic hadrons : more than 4 valence quarks**

- non-exotic $uds, \quad u\bar{d}, \quad uds\, u\bar{u}, \quad u\bar{d}\, u\bar{u}, \ldots$
- exotic (in this talk) $uudd\bar{s}, \quad ud\bar{s}\bar{s}, \ldots$
- not considered $uuddss, \quad c\bar{c}g, \quad \bar{u}\bar{u}\bar{d}\bar{d}s, \ldots$

**Experimentally, they are exotic ~ 1/300.**

**Theoretically, are they exotic?**

--> There is no simple way to forbid exotic states in QCD, effective models, ...

--> Evidences of multiquark components in non-exotic hadrons.

**Why aren't the exotics observed??**

# Motivation 2 : Chiral unitary approaches

**Hadron excited states ~ $\pi$ $T$**

- ○ **Interaction <-- chiral symmetry**
- ○ **Amplitude <-- unitarity**

R.H. Dalitz, and S.F. Tuan, Ann. Phys. (N.Y.) 10, 307 (1960)
J.H.W. Wyld, Phys. Rev. 155, 1649 (1967)

N. Kaiser, P. B. Siegel and W. Weise, Nucl. Phys. A594, 325 (1995)
E. Oset and A. Ramos, Nucl. Phys. A635, 99 (1998)
J. A. Oller and U. G. Meissner, Phys. Lett. B500, 263 (2001)
M.F.M. Lutz and E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002)

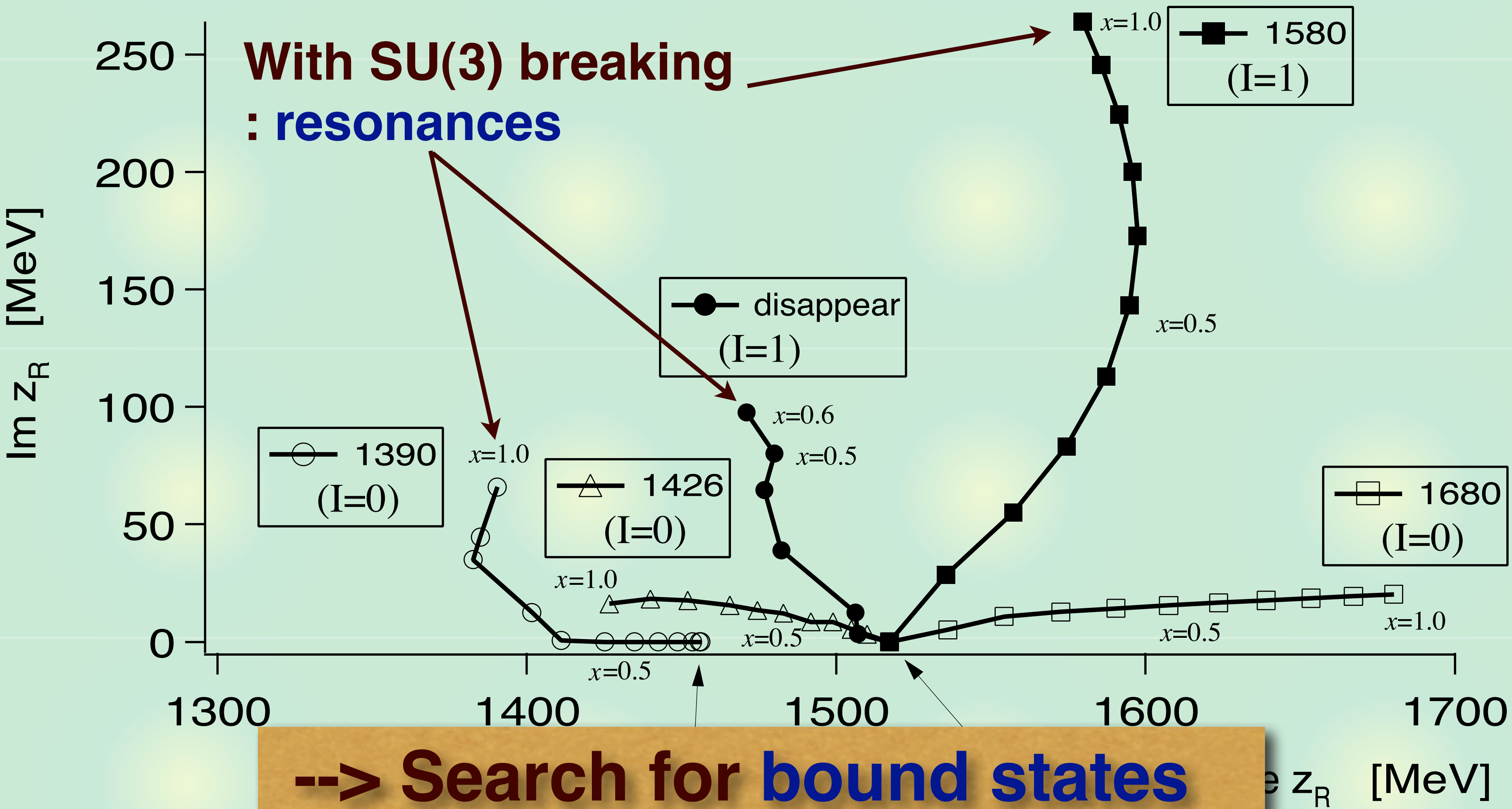
**Many hadron resonances (Λ(1405), N(1535), Λ(1520), $D_s$(2317),... ) are well described.**

**What about exotic hadrons?**

# Origin of the resonances

## Trajectory of poles

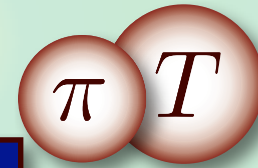
D. Jido, *et al.*, Nucl. Phys. A 723, 205 (2003)




**--> Search for bound states in SU(3) symmetric limit.**

# Outline

## Hadron-NG boson bound state




### Chiral Symmetry

**s-wave low energy interaction**

$$V_\alpha = -\frac{\omega}{2f^2} C_{\alpha,T} \qquad C_{\text{exotic}} = 1$$

### Scattering theory

**Critical strength for a bound state**

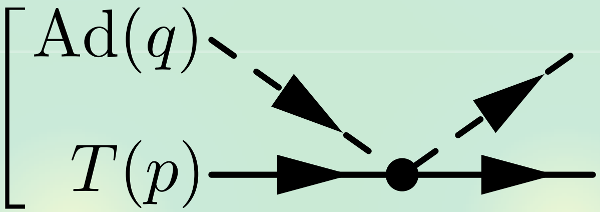
$$C_{\text{crit}} = \frac{2f^2}{m[-G(M_T + m)]}$$

**physical values :** $C_{\text{exotic}} < C_{\text{crit}}$

→ **No exotic state exists.**

# Low energy s-wave interaction

## Scattering of a target (T) with the pion (Ad)

$\alpha$ 


$$= \frac{1}{f^2}\frac{p\cdot q}{2M_T}\langle \boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle_\alpha + \mathcal{O}\left((m/M_T)^2\right)$$

## s-wave : Weinberg-Tomozawa term

$$V_\alpha = -\frac{\omega}{2f^2}C_{\alpha,T}$$

$$C_{\alpha,T} \equiv -\langle 2\boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle_\alpha = C_2(T) - C_2(\alpha) + 3 \quad (\text{for } N_f = 3)$$

## Coupling : pion decay constant

## model-independent interaction at low energy

Y. Tomozawa, Nuovo Cim. 46A, 707 (1966)

S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

# Coupling strengths : Examples

## Coupling strengths : (positive is attractive)

$$C_{\alpha,T} = C_2(T) - C_2(\alpha) + 3$$

| $\alpha$ | $\mathbf{1}$ | $\mathbf{8}$ | $\mathbf{10}$ | $\overline{\mathbf{10}}$ | $\mathbf{27}$ | $\mathbf{35}$ |
|---|---|---|---|---|---|---|
| $T = \mathbf{8}(N, \Lambda, \Sigma, \Xi)$ | 6 | 3 | 0 | 0 | $-2$ | |
| $T = \mathbf{10}(\Delta, \Sigma^*, \Xi^*, \Omega)$ | | 6 | 3 | | 1 | $-3$ |

| $\alpha$ | $\overline{\mathbf{3}}$ | $\mathbf{6}$ | $\overline{\mathbf{15}}$ | $\mathbf{24}$ |
|---|---|---|---|---|
| $T = \overline{\mathbf{3}}(\Lambda_c, \Xi_c)$ | 3 | 1 | $-1$ | |
| $T = \mathbf{6}(\Sigma_c, \Xi_c^*, \Omega_c)$ | 5 | 3 | 1 | $-2$ |

- ○ **Exotic channels : mostly repulsive**
- ○ **Attractive interaction : C = 1**

# Coupling strengths : General expression

## For a general target $T = [p, q]$

| $\alpha \in [p,q] \otimes [1,1]$ | $C_{\alpha,T}$ | sign |
|---|---|---|
| $[p+1, q+1]$ | $-p-q$ | repulsive |
| $[p+2, q-1]$ | $1-p$ | |
| $[p-1, q+2]$ | $1-q$ | |
| $[p, q]$ | $3$ | attractive |
| $[p, q]$ | $3$ | attractive |
| $[p+1, q-2]$ | $3+q$ | attractive |
| $[p-2, q+1]$ | $3+p$ | attractive |
| $[p-1, q-1]$ | $4+p+q$ | attractive |

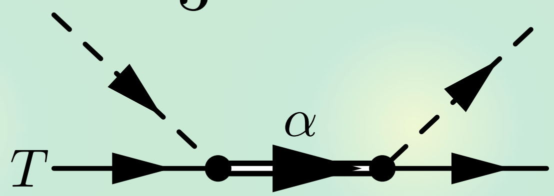
- Strength should be integer.
- Sign is determined for most cases.

# Exotic channels

## Exoticness : minimal number of extra $\bar{q}q$.

$$E = \epsilon\theta(\epsilon) + \nu\theta(\nu) \qquad \epsilon \equiv \frac{p+2q}{3} - B, \quad \nu \equiv \frac{p-q}{3} - B$$

$\Delta E = E_\alpha - E_T = +1$ is realized when




- $\alpha = [p+1, q+1] : C_{\alpha,T} = -p-q$

  **repulsive**

- $\alpha = [p+2, q-1] : C_{\alpha,T} = 1-p$

  attraction : $p = 0$ then $\nu_T \geq 0 \rightarrow B \geq -q/3$

  **not considered here**

- $\alpha = [p-1, q+2] : C_{\alpha,T} = 1-q$

  attraction : $q = 0$ then $\nu_T \leq 0 \rightarrow B \geq p/3$ **OK!**

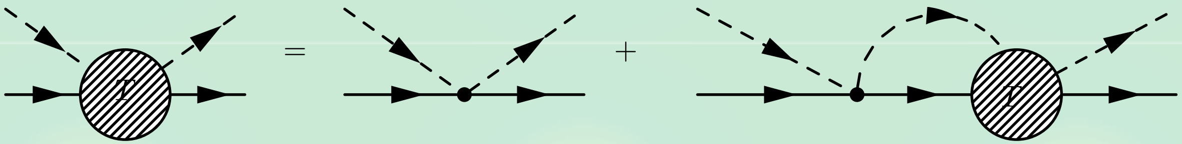
## Universal attraction for more “exotic” channel

$$C_{\text{exotic}} = 1 \quad \text{for} \quad T = [p, 0], \quad \alpha = [p-1, 2]$$

# Renormalization and bound states

## Solve the scattering problem with $V_\alpha = -\frac{\omega}{2f^2} C_{\alpha,T}$

$$T = \frac{1}{1 - VG} V$$




## Unitarity : OK

## Renormalization parameter : condition

$$G(\mu) = 0, \quad \Leftrightarrow \quad T(\mu) = V(\mu) \quad \text{at} \quad \mu = M_T$$

**K. Igi, and K. Hikasa, Phys. Rev. D59, 034005 (1999)**

**M.F.M. Lutz, and E. Kolomeitsev, Nucl. Phys. A700, 193-308 (2002)**

## Scale at which ChPT works.

## Matching with the u-channel amplitude : OK

## Bound state:

$$1 - V(M_b)G(M_b) = 0 \qquad M_T < M_b < M_T + m$$

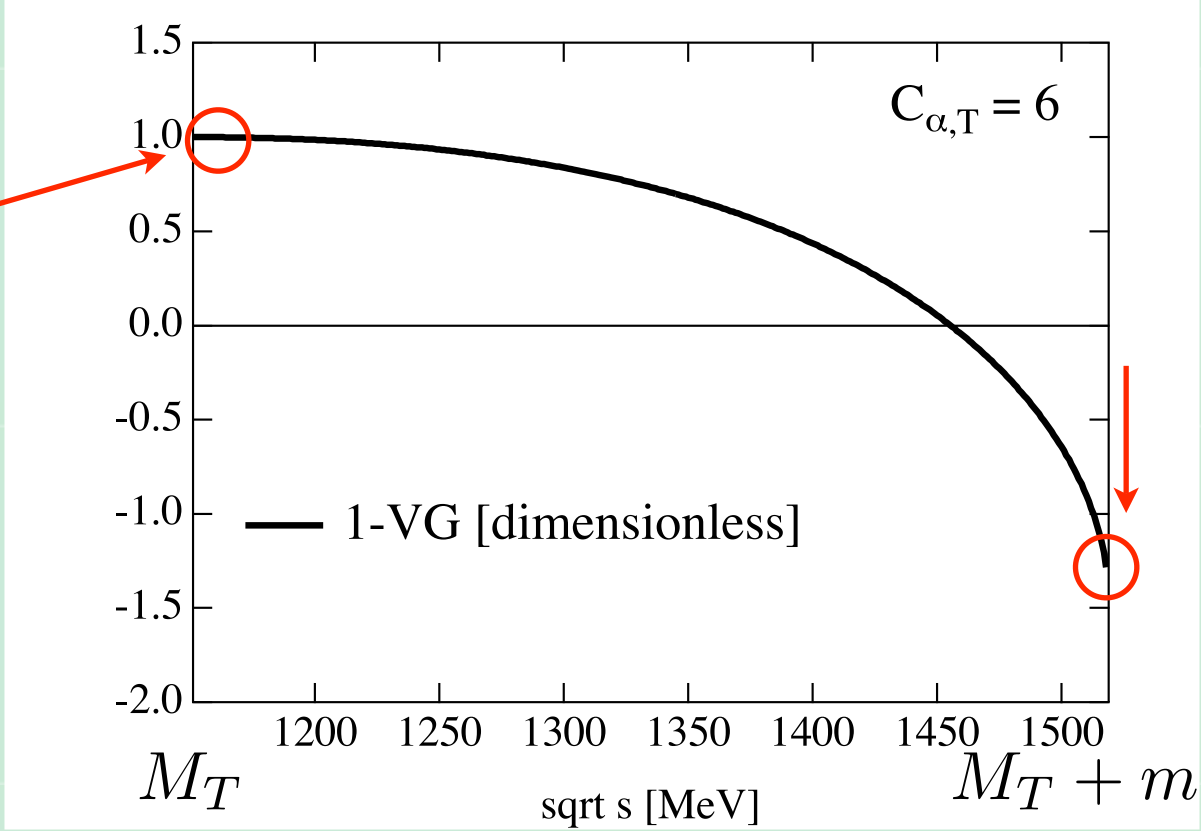
# Critical attraction

$1 - V(\sqrt{s})G(\sqrt{s})$ **: monotonically decreasing.**

**Fixed**

$G(M_T) = 0$

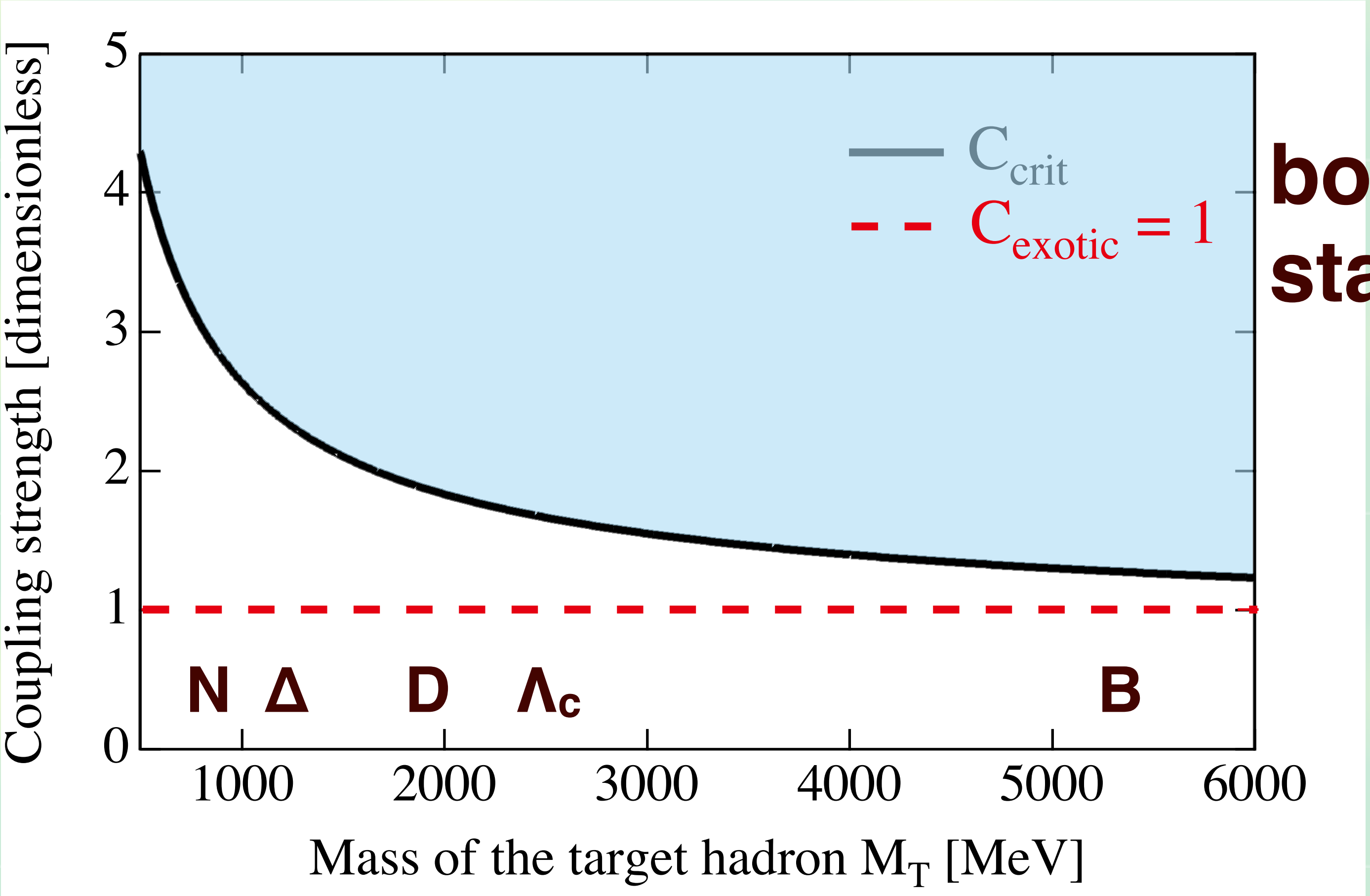
$1 - VG = 1$




**Critical attraction :** $1 - VG = 0$ at $\sqrt{s} = M_T + m$

$$\Rightarrow \quad C_{\rm crit} = \frac{2f^2}{m[-G(M_T + m)]}$$

# Critical attraction and exotic channel




**bound state**

$$m = 368 \text{ MeV and } f = 93 \text{ MeV}$$

➡ **Strength is not enough.**

# Summary 1 : SU(3) limit

We study the exotic bound states in s-wave chiral dynamics in flavor SU(3) limit.

- The interaction in exotic channels is in most cases repulsive.
- There are attractive interactions in exotic channels, with universal and the smallest strength : $C_{\text{exotic}} = 1$
- The strength is not enough to generate a bound state : $C_{\text{exotic}} < C_{\text{crit}}$

The result is model independent as far as we respect chiral symmetry.

# Summary 2 : Physical world

## Caution!

- The exotic hadrons here are the s-wave meson-hadron molecule states ($1/2^-$ for $\Theta^+$).
- We do not exclude the exotics which have other origins (genuine quark state, soliton rotation,...).
- In practice, SU(3) breaking effect, higher order terms,...

**In Nature, it is difficult to generate exotic hadrons as in the same way with Λ(1405), Λ(1520),... based on chiral interaction.**

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. Lett. 97, 192002 (2006)
T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. D 75, 034002 (2007)