Exotics Interpretation

Towards Theoretical Understanding of Exotic Heavy Hadrons from QCD

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research support from Department of Energy

Towards Theoretical Understanding of Exotic Heavy Hadrons from QCD

- Exotic heavy (*XYZ*) hadrons
- Lattice QCD and Effective Field Theories
- Born-Oppenheimer approach
- Summary

Exotic Heavy Hadrons

more than 2 dozen new $c\bar{c}$ and $b\bar{b}$ mesons
and several new $c\bar{c}$ baryons
discovered since 2003

- contain heavy quark and antiquark
  plus additional light constituents

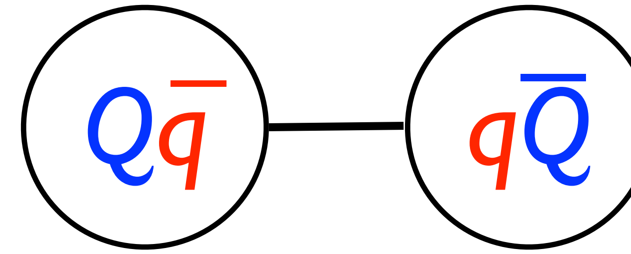
- tetraquark mesons with light quark, antiquark
  pentaquark baryons with three light quarks

- many are surprisingly narrow

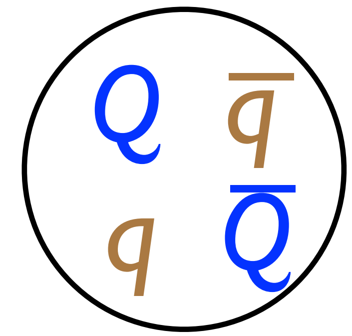
- major challenge to our understanding of QCD spectrum!

Models for XYZ Mesons

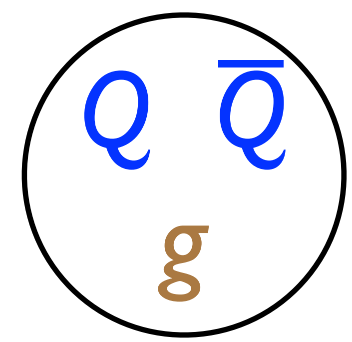
- meson molecule



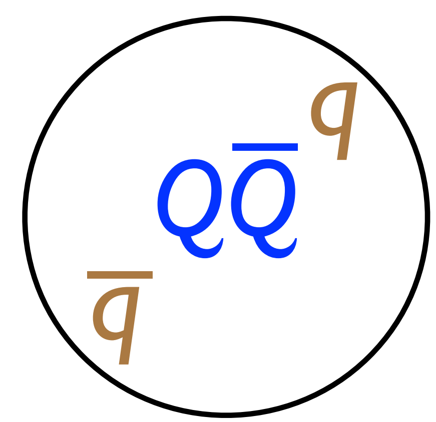
- quarkonium tetraquark



- quarkonium hybrid

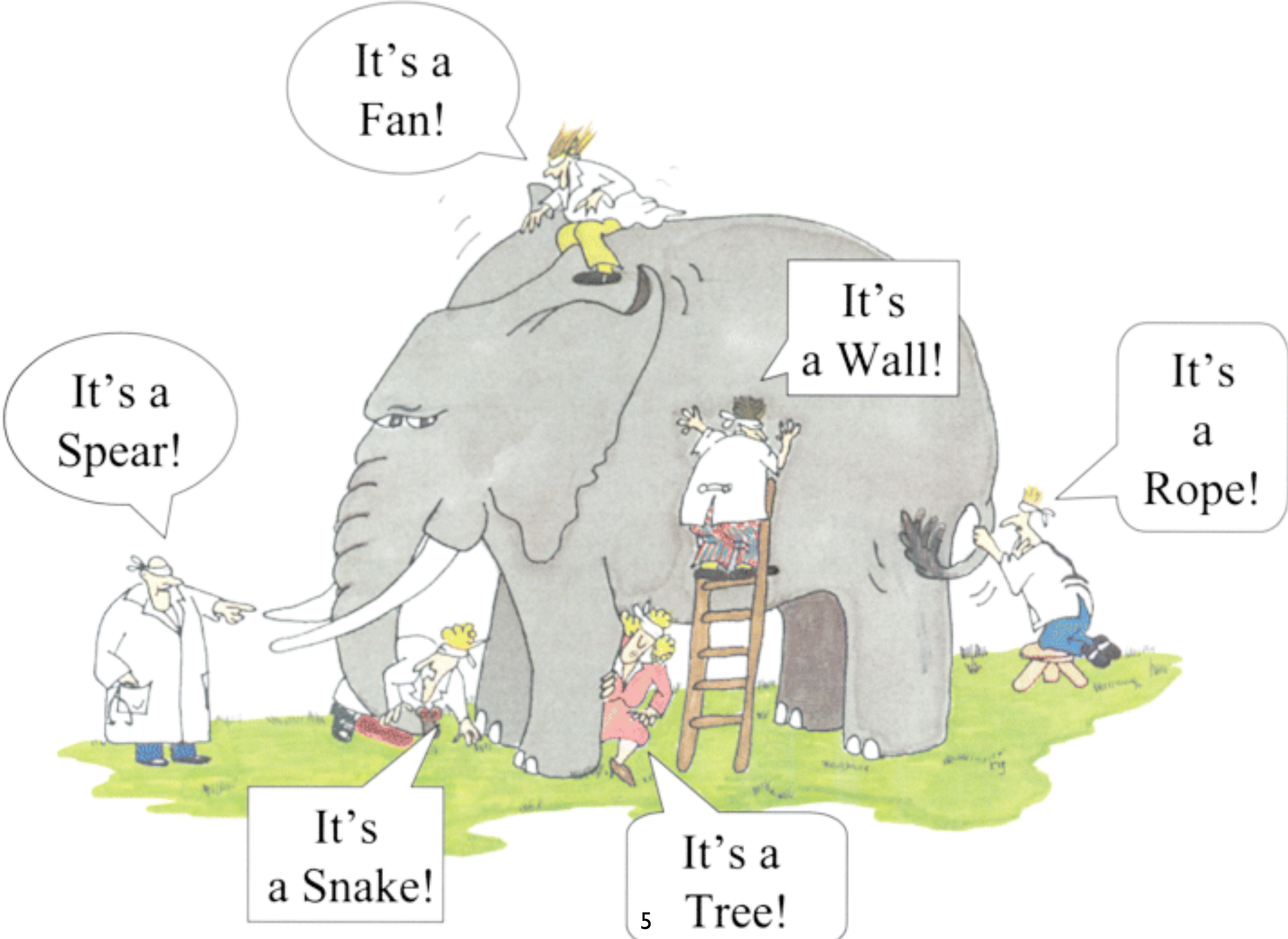


- hadro-quarkonium



- kinematic effect

Models for XYZ Mesons



Models for XYZ Hadrons

- little connection with fundamental theory QCD

  constituents: degrees of freedom from QCD

  interactions: purely phenomenological

- some success in describing individual XYZ hadrons

- no success in revealing pattern of XYZ hadrons

CHARM 2018

Novosibirsk   May 2018

Steve Olsen: "The *XYZ* mesons: what they aren't"

Compare properties for 6 *XYZ* mesons with established J^{PC}

X(3872), X(3915), Y(4220), Z_c(3900), Z_c(4020), Z(4430)

with model expectations for

molecule, tetraquark, charmonium hybrid, hadro-charmonium, kinematic effect

"No single model can satisfactorily explain all the results.
If we are ever to have a coherent comprehensive
understanding of the *XYZ* particles, a new idea is needed."

Developments since CHARM 2018

Aug 2018	BESIII	$Y(4220) \to \pi^+ D^0 D^{*-}$	1st open-charm decay of Y
Sept 2018	LHCb	$Z_c^-(4100) \to \eta_c \pi^-$	1st decay into 2 pseudoscalars
April 2019	LHCb	updated analysis of $c\bar{c}$ pentaquark decaying into $J/\psi\ p$ new narrow state $P_c(4312)$	
Dec 2019	Belle	$Y(4626) \to D_s^+ D_{s1}^-$	1st decay of Y into strange mesons
Sept 2020	LHCb	$X(2900) \to D^- K^+$	1st tetraquark with 4 flavors
Nov 2020	BESIII	$Z_c^-(3885) \to D_s^0 D^{*0}$	1st strange $c\bar{c}$ tetraquark
June 2020	LHCb	structure in J/ψ pair spectrum	1st $cc\bar{c}\bar{c}$ tetraquark ?

there is still no
"coherent comprehensive understanding of the XYZ particles"

Doubly Heavy Hadrons

heavy quarks: Q = b or c
light quarks: q = u or d or s

quarkonium: $Q\,\bar{Q}$
quarkonium hybrids: $Q\,\bar{Q}\,g$
quarkonium tetraquarks: $Q\,\bar{Q}\,q\,\bar{q}$
quarkonium pentaquarks: $Q\,\bar{Q}\,q\,q\,q$

doubly heavy baryons: $Q\,Q\,q$
doubly heavy tetraquarks: $Q\,Q\,\bar{q}\,\bar{q}$

coherent comprehensive framework ??

Approaches within QCD

fundamental fields: quarks and gluons
parameters: α_s, quark masses

- Lattice QCD
- Effective field theories (NRQCD, pNRQCD, BOEFT, ...)
- QCD Sum Rules ??

QCD Sum Rules

tetraquark meson *T*

4-quark interpolating operator $\mathscr{T}(x)$ with $\langle T|\mathscr{T}(x)|\varnothing\rangle \neq 0$

Operator Product Expansion: $\mathscr{T}^\dagger(x)\mathscr{T}(y) = \sum_n C_n(x\text{-}y)\ \mathscr{O}_n((x+y)/2)$

vacuum expectation value, insert complete set of states, Fourier transform

$$\sum_X \langle\emptyset|\mathcal{T}|X\rangle\langle X|\mathcal{T}^\dagger|\emptyset\rangle = \sum_n C_n\ \langle\emptyset|\mathcal{O}_n|\emptyset\rangle$$

Borel transform to suppress higher energy states

assume sum over *X* is dominated by tetraquark state *T*

Lucha, Melhikov & Sazdijan arXiv:1706.06003, 1710.08316, 1810.09986, 1901.03881

Fierz transformations ⇒ there are meson-meson states M_1M_2 with

$$\langle M_1M_2|\mathscr{T}(x)|\varnothing\rangle \neq 0$$

sum over *X* is actually dominated by meson-meson states!

<u>fatal problem</u> ??

for all previous applications of QCD sum rules to tetraquarks

Lattice QCD

discretize QCD on a Euclidean spacetime lattice

- lattice spacing in time direction: a_t
- lattice spacing in spatial directions: a_s

calculate cross-correlators of many operators

$$\langle \mathcal{O}_i(t)\mathcal{O}_j(0)\rangle \longrightarrow \sum_n \sqrt{Z_{in}}\sqrt{Z_{jn}}e^{-E_n t}$$

- determine discrete eigenenergies E_n
- overlap factors $\sqrt{Z_{in}}$ have information about structure

extrapolate to zero lattice spacing: $a_t \to 0$, $a_s \to 0$

chiral extrapolation to physical *u*,*d* quark masses:
$m_\pi = 140$ MeV

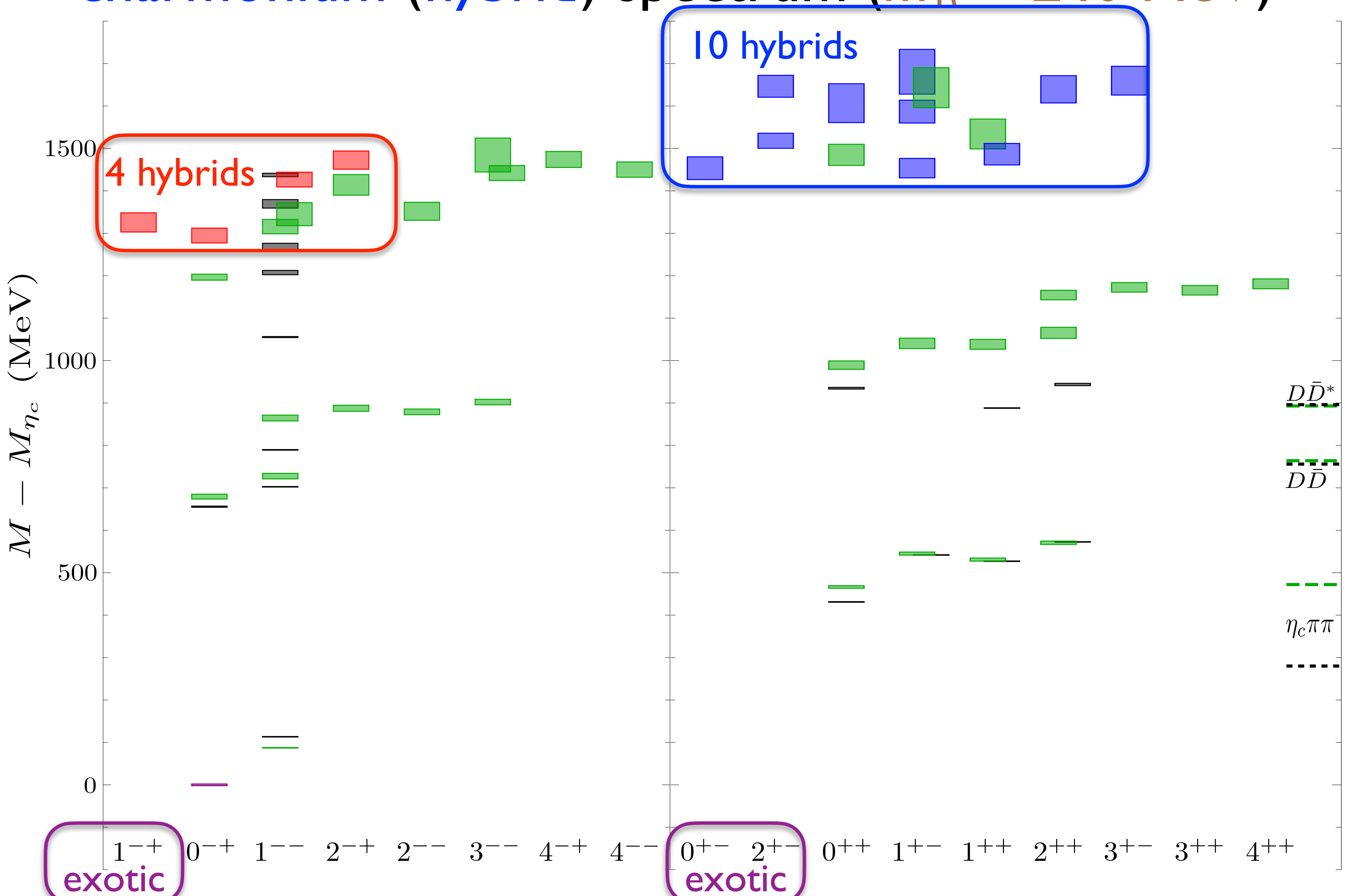
determine infinite-volume spectrum (masses, widths)
from discrete eigenenergies

Quarkonium (hybrid) Spectrum

Hadron Spectrum Collaboration

charmonium m_π = 391 MeV 2012
charmonium m_π = 240 MeV 2016
bottomonium m_π = 391 MeV 2021

charmonium (hybrid) spectrum (m_π = 240 MeV)



Doubly Heavy Tetraquarks

$QQ\bar{q}\bar{q}$ tetraquark can have mass below strong decay threshold

Manohar & Wise (1997) stable in limit $M_Q \to \infty$

$bb\bar{q}\bar{q}$ ($q = u,d$) ground state: $I=0$, $J^P=1^+$

		binding energy (MeV)
Bicudo, Scheunert & Wagner	Born-Oppenheimer	-59^{+30}_{-38}
Karliner & Rosner (2017)	quark/diquark model	−215 (±12 ?)
Eichten & Quigg (2017)	heavy quark expansion	−122
BHM (2020)*		−133 ± 25*
Leskovec et al. (2019)	lattice QCD	−128 ± 24 ±10

* arXiv:2006.08650 (with He & Mohapatra)
error bars by taking all inputs from experiment or lattice QCD
See talk by Abhishek Mohapatra Thursday at 13:00

Doubly Heavy Tetraquarks

$bb\bar{s}\bar{q}$ $(q = u,d)$: $I=½$, $J^P=1^+$ — binding energy (MeV)

Eichten & Quigg (2017)	heavy quark expansion	−49
BHM (2020)*		−48 ± 26*

$bc\bar{q}\bar{q}$ $(q = u,d)$: $I=½$, $J^P=1^+$

Karliner & Rosner (2017)	quark/diquark model	−10 (±12 ?)
Eichten & Quigg (2017)	heavy quark expansion	+ 85
BHM (2020)*		+104 ± 37*

$cc\bar{q}\bar{q}$ $(q = u,d)$: $I=½$, $J^P=1^+$

Karliner & Rosner (2017)	quark/diquark model	+ 7 (±12 ?)
Eichten & Quigg (2017)	heavy quark expansion	+93
BHM (2020)*		+62 ± 11*

* arXiv:2006.08650 (with He & Mohapatra)

Effective Field Theories for QCD

QCD: each quark flavor is Dirac spinor field: $\psi^i(x), i=1,2,3$

integrate out scale of heavy quark mass M

Nonrelativistic QCD (NRQCD)

heavy quark/antiquark is two Pauli spinor fields $\psi^i(\vec{r},t), \chi^i(\vec{r},t), i=1,2,3$

integrate out momentum scale Mv

Potential NRQCD (pNRQCD)

(for heavy-quark pair near lowest adiabatic potential)

heavy quark/antiquark pair is color-singlet field $S(\vec{R},\vec{r},t)$

color-octet field $O^a(R, r, t), i=1,2,\ldots,8$

Pineda & Soto (1997), Brambilla, Pineda, Soto & Vairo (1999), Kniehl & Penin (1999)

Born-Oppenheimer EFT (BOEFT)

(for heavy-quark pair near other Born-Oppenheimer potentials)

Berwein, Brambilla, Tarrus Castella & Vairo arXiv:1510.04299
Brambilla, Krein, Tarrus Castella & Vairo arXiv:1707.09647
Soto & Tarrus Castella (2020) arXiv:2005.00552

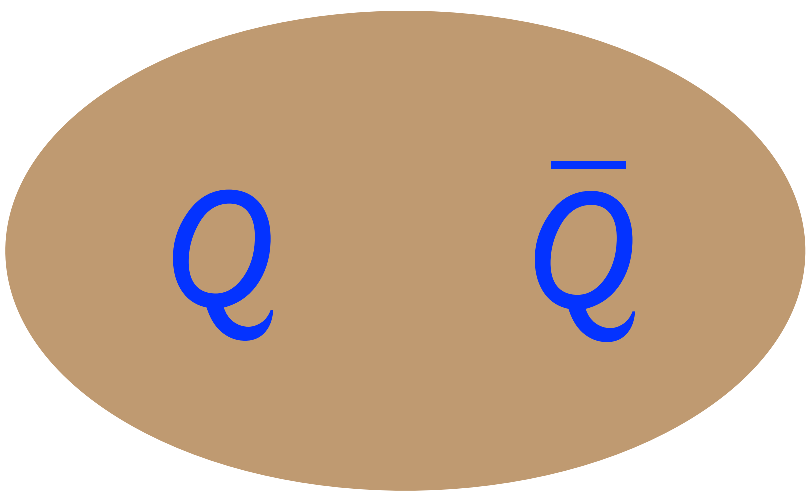
Born-Oppenheimer Approximation for Quarkonium Hybrids

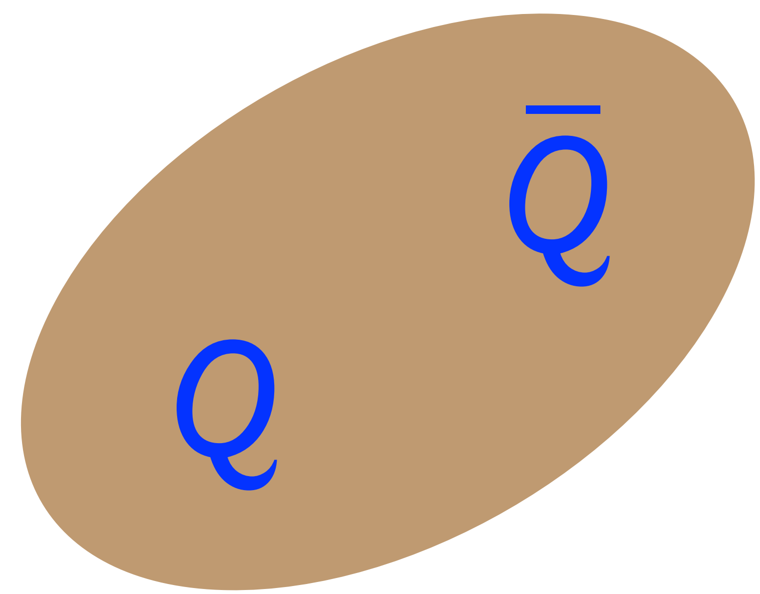
pioneered by Juge, Kuti, Morningstar 1999

- heavy quark mass $\gg \Lambda_{QCD}$
- Q and $\bar{Q}$ move nonrelativisticly
- gluons respond almost instantaneously to the motion of the Q and $\bar{Q}$

B-O approximation: hybrids

- given the positions of the Q and $\bar{Q}$,
  the gluon fields are in a stationary state
  in the presence of static Q and $\bar{Q}$ sources

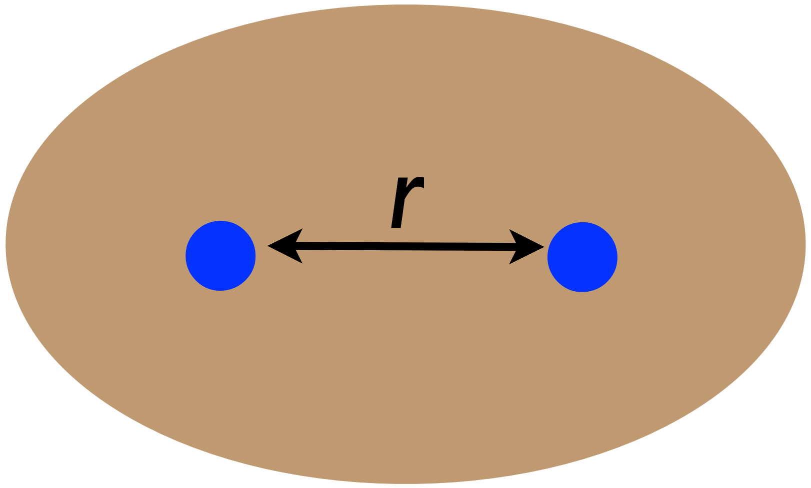




- as the positions of the Q and $\bar{Q}$ change,
  the gluon fields remain adiabatically
  in that stationary state

B-O approximation: hybrids

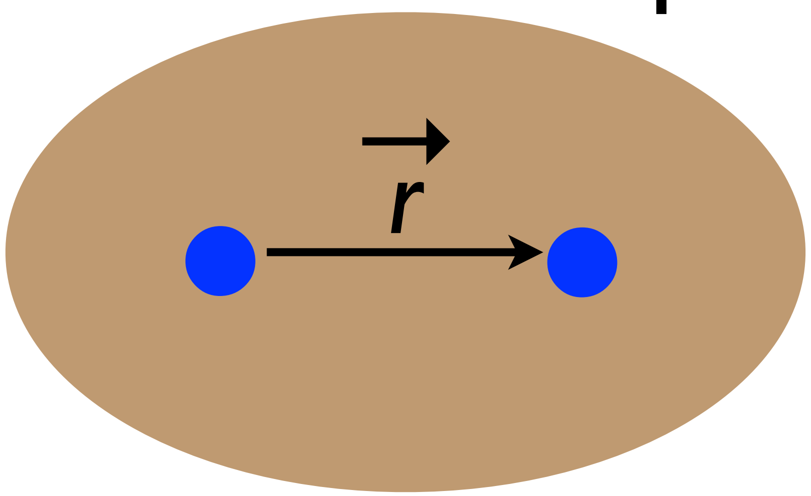
- energy of stationary state of gluon fields in presence of static Q and $\bar{Q}$ sources separated by distance r defines Born-Oppenheimer potential $V(r)$



- Born-Oppenheimer approximation: motion of Q and $\bar{Q}$ is described by Schroedinger equation in potential $V(r)$

B-O approximation: hybrids

stationary states for gluon fields
in presence of static Q and $\bar{Q}$ sources
separated by vector $\vec{r}$



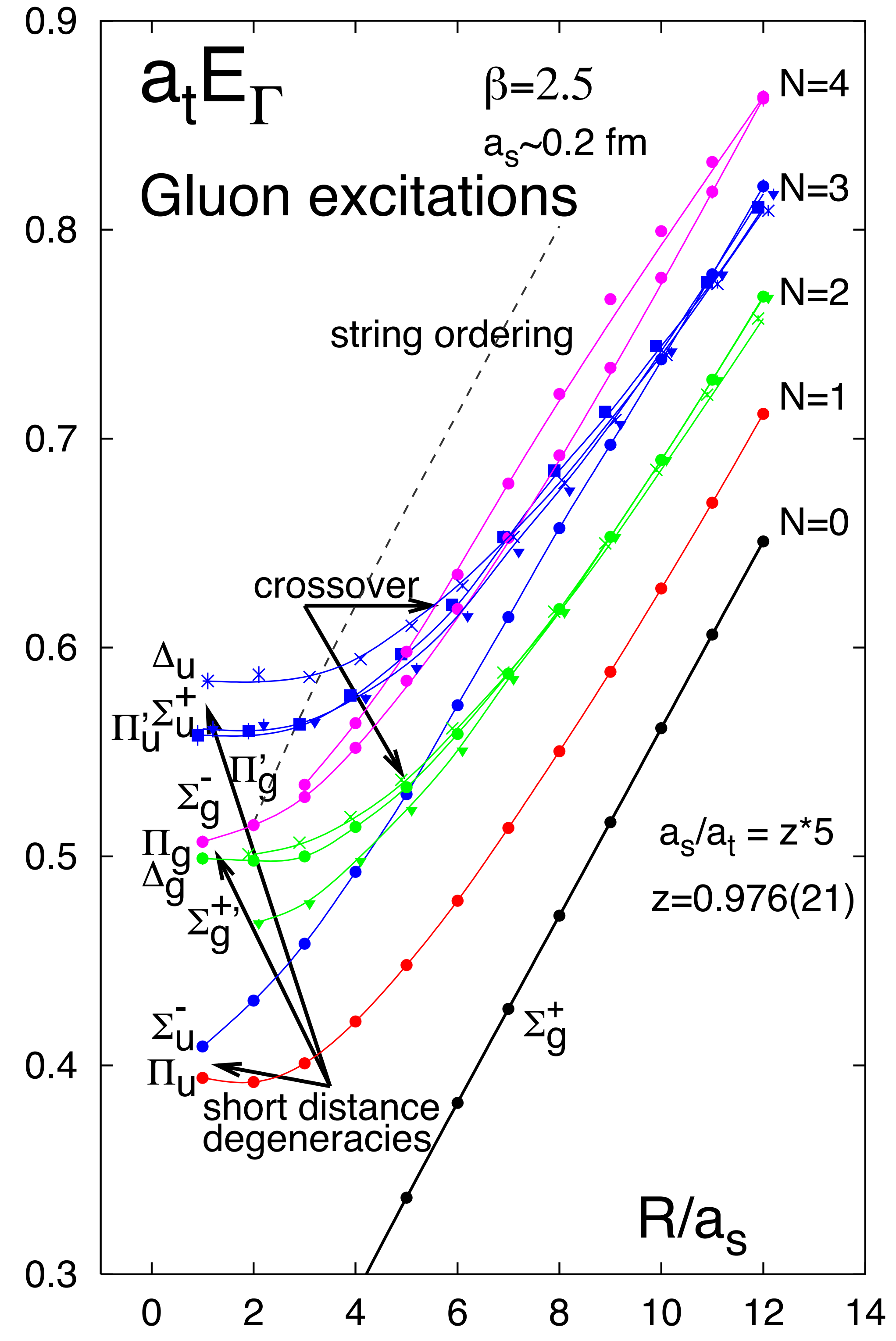
conserved quantum numbers: Λ_η^ϵ

- absolute value of component of angular momentum
  $|\hat{r}\cdot\vec{J}_{light}| \equiv \Lambda = 0, 1, 2, \ldots$ (or $\Sigma, \Pi, \Delta, \ldots$)
- product of charge conjugation and parity
  $(CP)_{light} \equiv \eta = +1, -1$ (or g, u)
- reflection through plane containing sources
  $R_{light} \equiv \epsilon = +1, -1$ (or $+, -$)

B-O approximation: hybrids

Born-Oppenheimer potentials

labelled by $\Lambda_\eta^\varepsilon = \Sigma_g^+, \Pi_u^\pm, \Sigma_u^-, \ldots$



calculate using lattice QCD

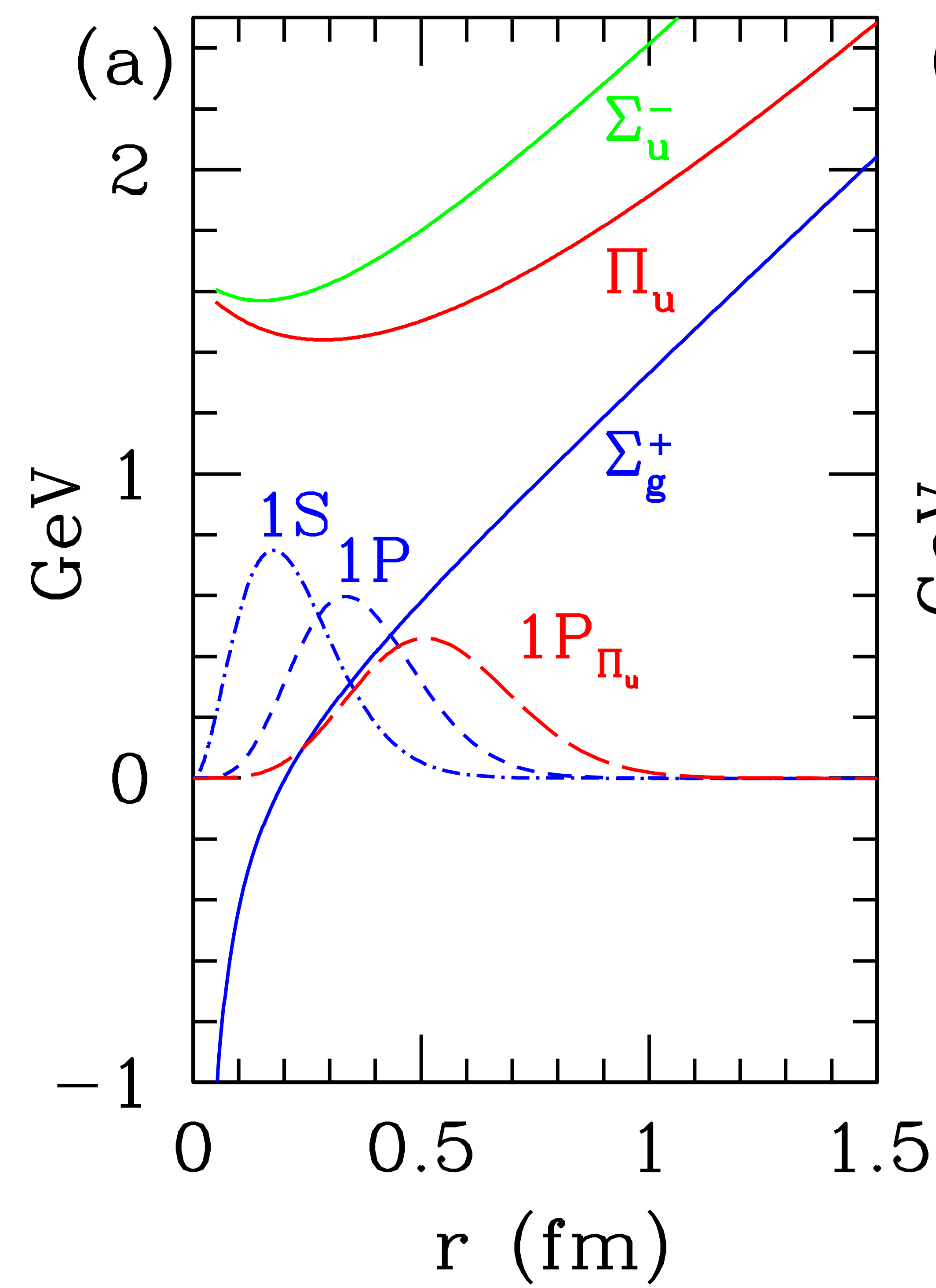
Juge, Kuti, Morningstar 1999

- anisotropic lattice: $10^3 \times 30$
- lattice spacing: a = 0.2 fm
- quenched: no virtual quark-antiquark pairs!

B-O approximation: hybrids

solve Schroedinger equation in Born-Oppenheimer potentials
Juge, Kuti, Morningstar 1999

energy levels labelled by nL
radial quantum number: $n = 1,2,3,...$
orbital angular momentum: $L \geq \Lambda$
$L = 0, 1, 2, ...$ or $S, P, D, ...$

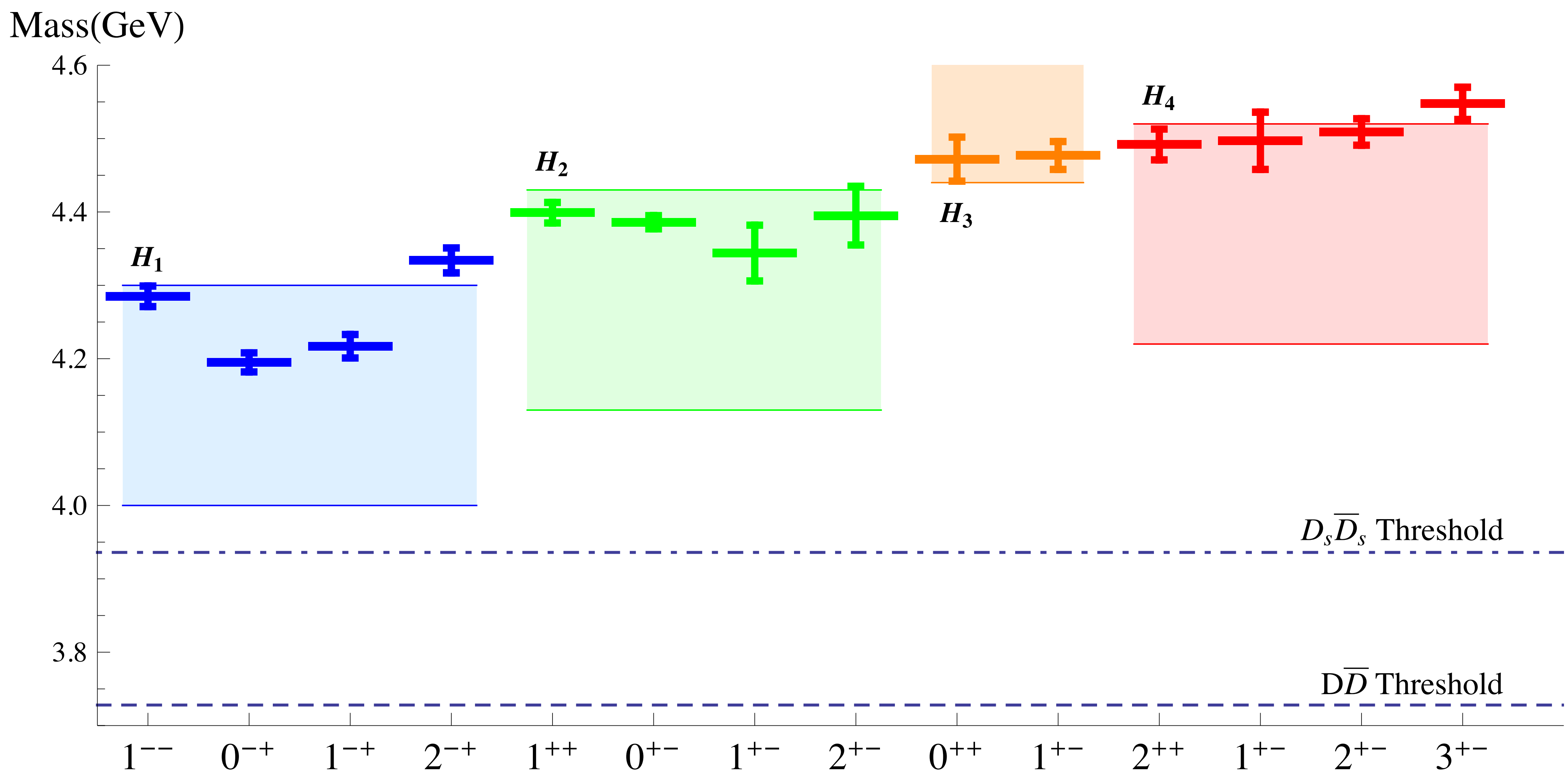


energy levels in Σ_g^+ potential:
quarkonium

energy levels in $\Pi_u^\pm$, Σ_u^-, ... potentials:
quarkonium hybrids

energy splittings: semiquantitative agreement with lattice NRQCD

Charmonium Hybrids



BOEFT

error bands from lattice QCD calculation of gluelump mass

Berwein, Brambilla, Tarrus Castella & Vairo arXiv:1510.04299

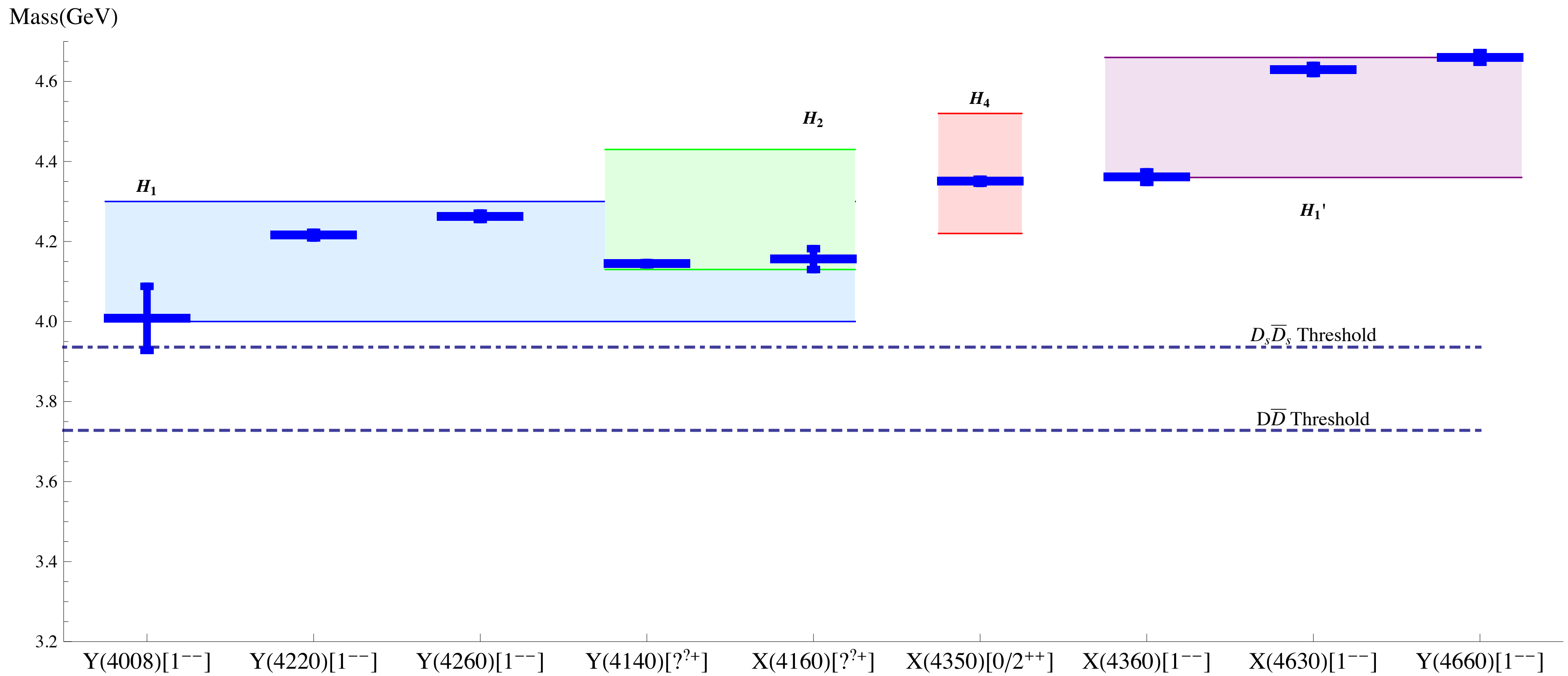
Lattice QCD

points with error bars for m_π = 400 MeV

Hadron Spectrum collaboration arXiv:1204.5425

Charmonium Hybrids

possible identifications with X and Y mesons



BOEFT error bands

Berwein, Brambilla, Tarrus Castella & Vairo arXiv:1510.04299

Lattice QCD data points

Hadron Spectrum collaboration arXiv:1204.5425

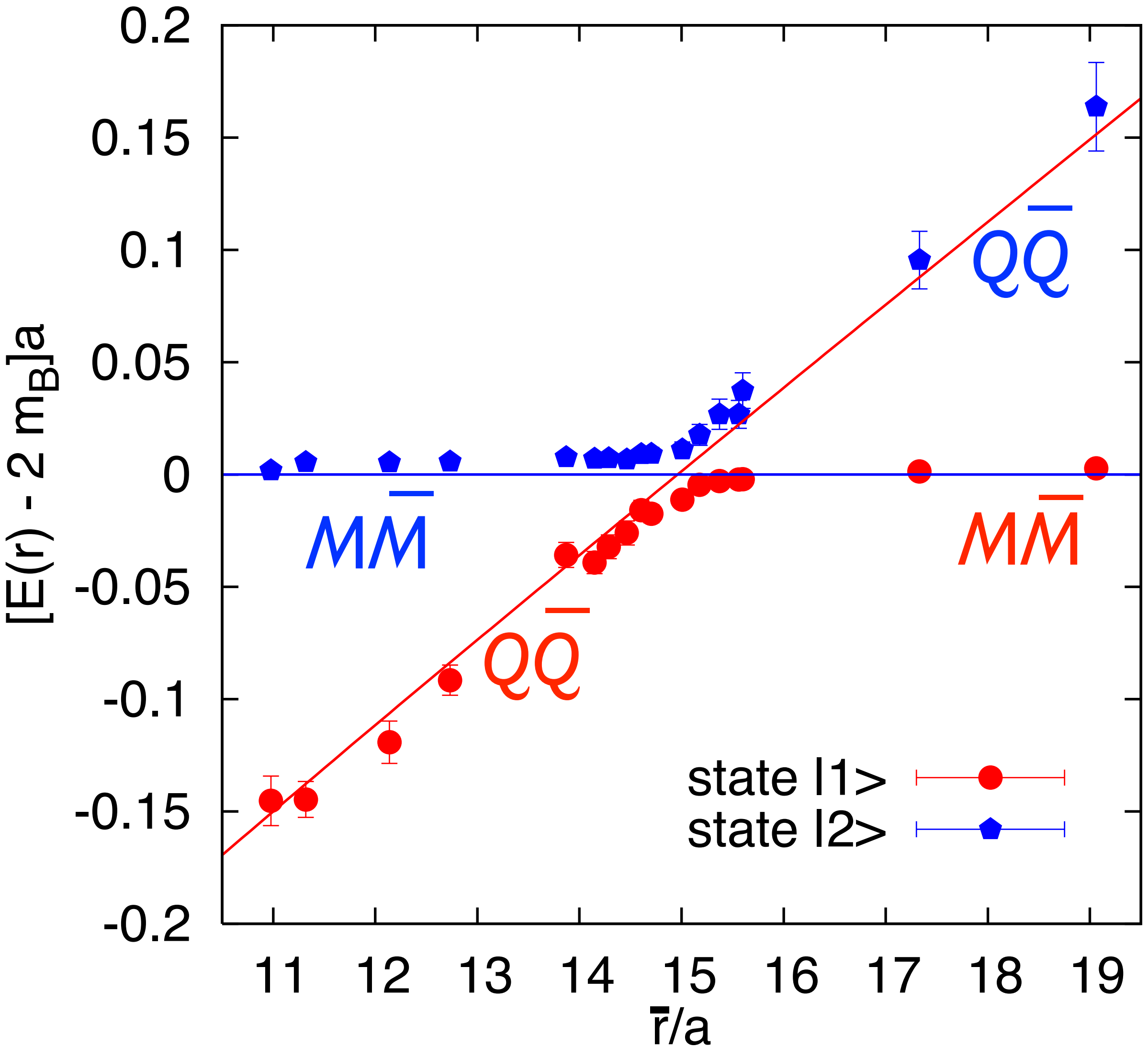
Born-Oppenheimer potentials

B-O potentials

- include potentials that approach meson-pair thresholds at large *r*
- have avoided crossings
- both can be calculated using lattice QCD

$Q\bar{Q}$ (Σ_g^+) and $M\bar{M}$ potentials

SESAM hep-lat/0505012



Quarkonium Tetraquarks

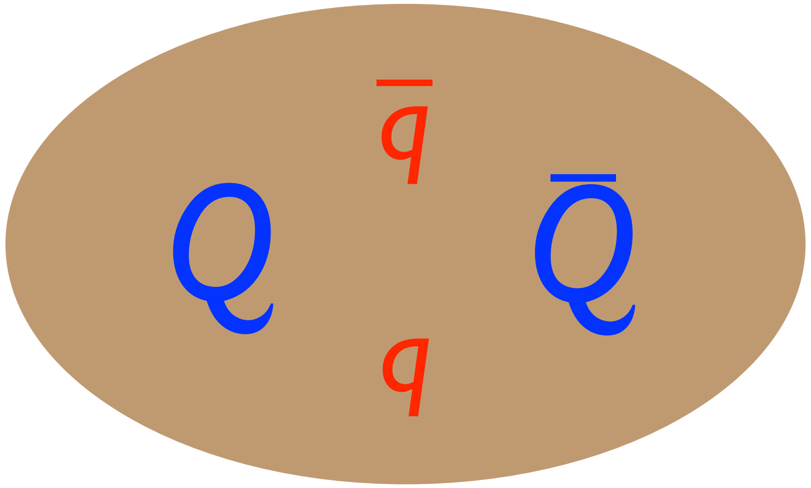
XYZ mesons with positive electric charge have constituents $Q\bar{Q}u\bar{d}$

first discoveries

$c\bar{c}$ tetraquarks: $Z^+(4430)$ — *Belle (2007)*
$b\bar{b}$ tetraquarks: $Z_b^+(10610)$, $Z_b^+(10650)$ — *Belle (2011)*
$c\bar{c}$ tetraquarks: $Z_c^+(3900)$, … — *BESIII (2013)*

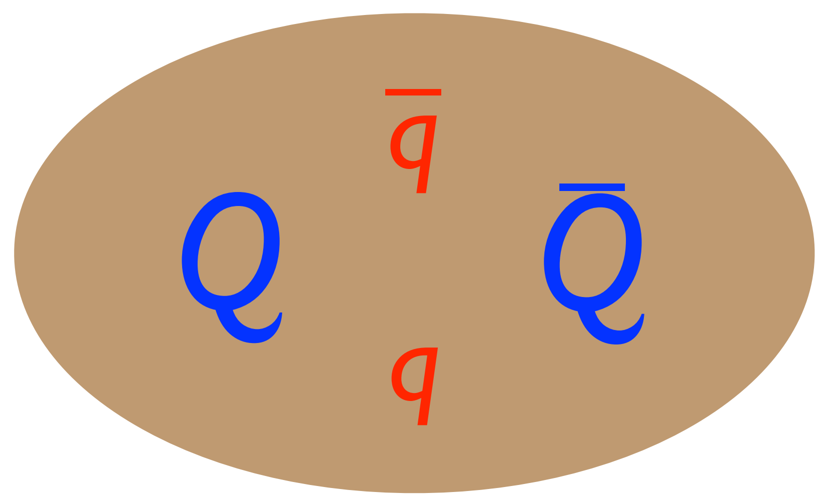
Q. How can charged quarkonium tetraquarks be reconciled with Born-Oppenheimer approximation for QCD?

A. Light QCD fields in the presence of static $Q\ \bar{Q}$ sources can have light-quark flavors $q\ \bar{q}$! — Braaten arXiv:1305.6905



B-O approximation: tetraquarks

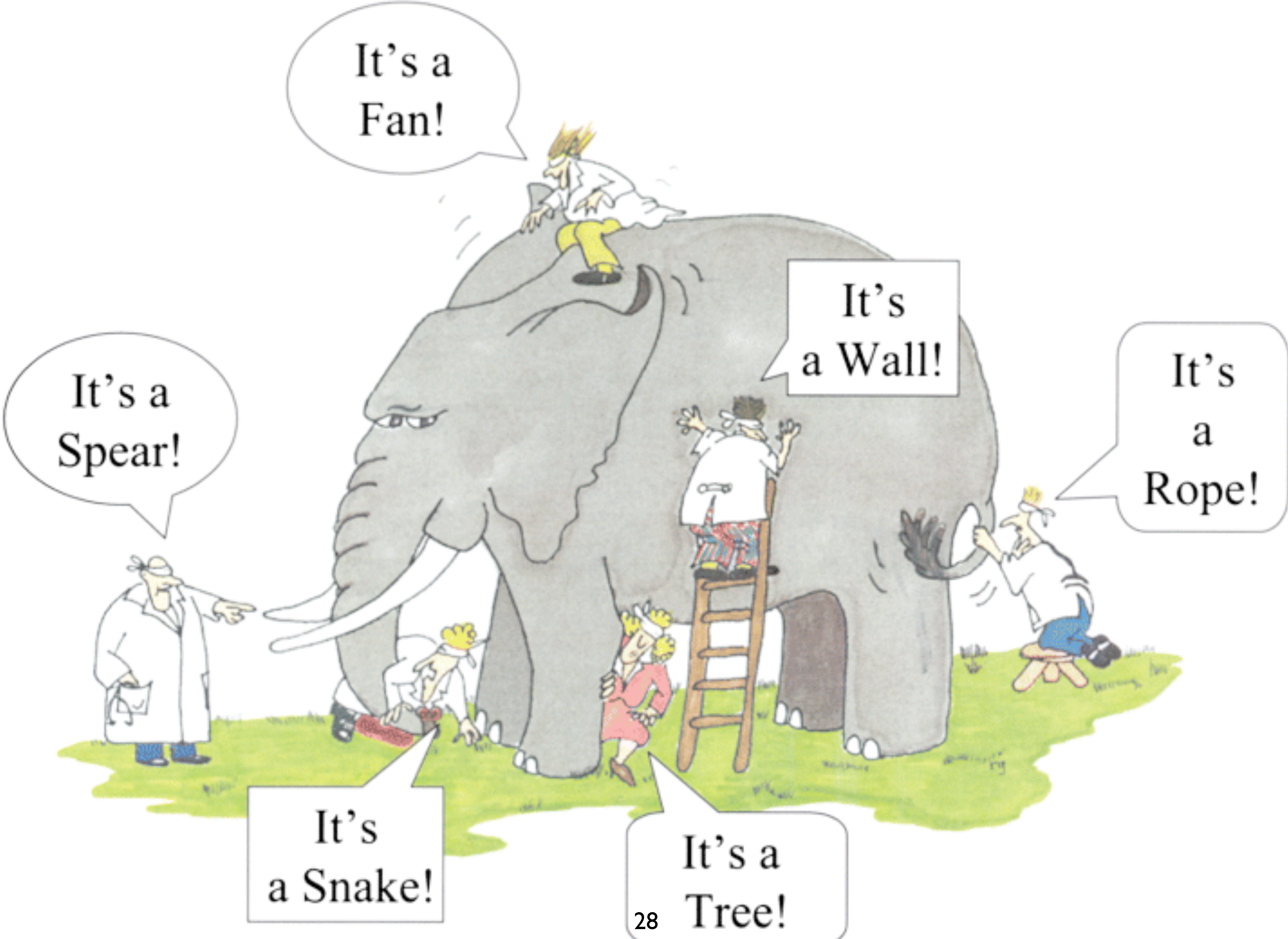
Light quarks can respond almost instantaneously
to the motion of the heavy quarks,
just like gluon fields



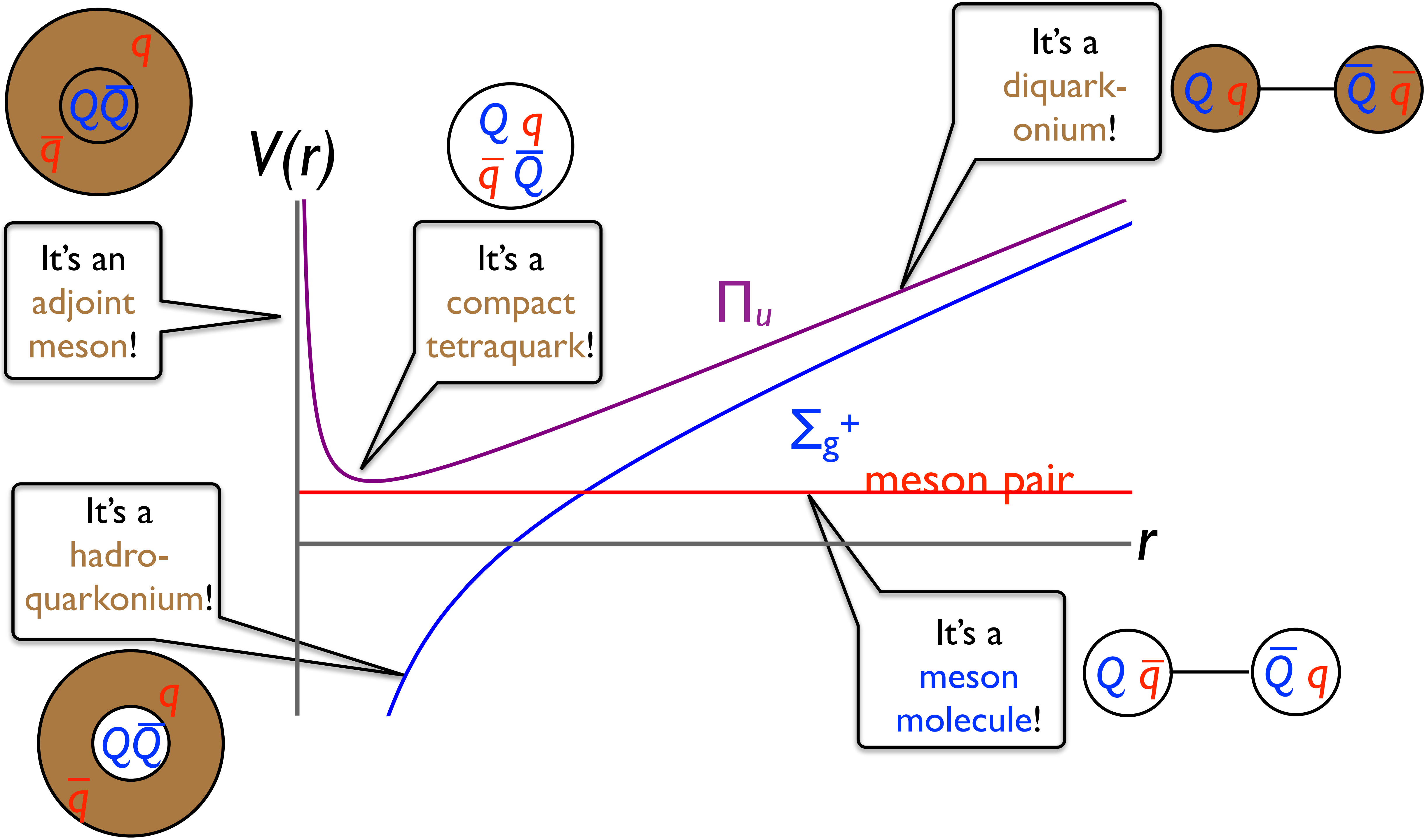
Quarkonium Tetraquarks
can be treated using the Born-Oppenheimer approximation
just like Quarkonium Hybrids
except that the stationary state of gluons and light quarks
has B-O quantum numbers Λ_η^ϵ
and also light-quark flavors

Braaten arXiv:1305.6905

What is an XYZ Meson?



What is an XYZ Meson?



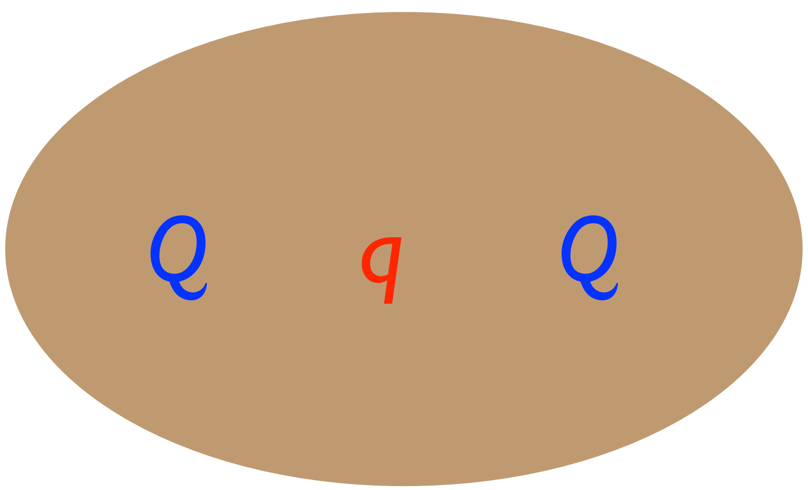
Each model describes some region of the Born-Oppenheimer wavefunction

Doubly Heavy Hadrons

Born-Oppenheimer approximation

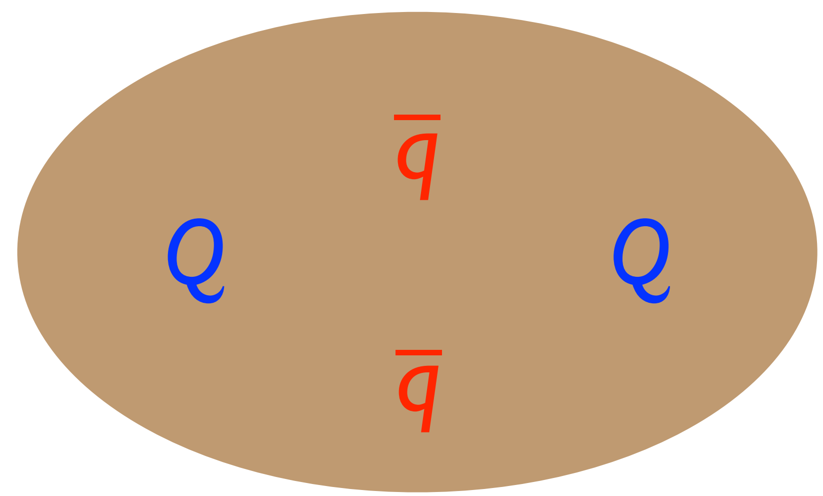
Light QCD fields in the presence of static Q Q sources
can have light-quark flavor q or $\bar{q}$ $\bar{q}$!

doubly heavy baryon



Maiani, Polosa & Riquer
arXiv:1903.10253
Soto & Tarrus Castella
arXiv:2005.00551

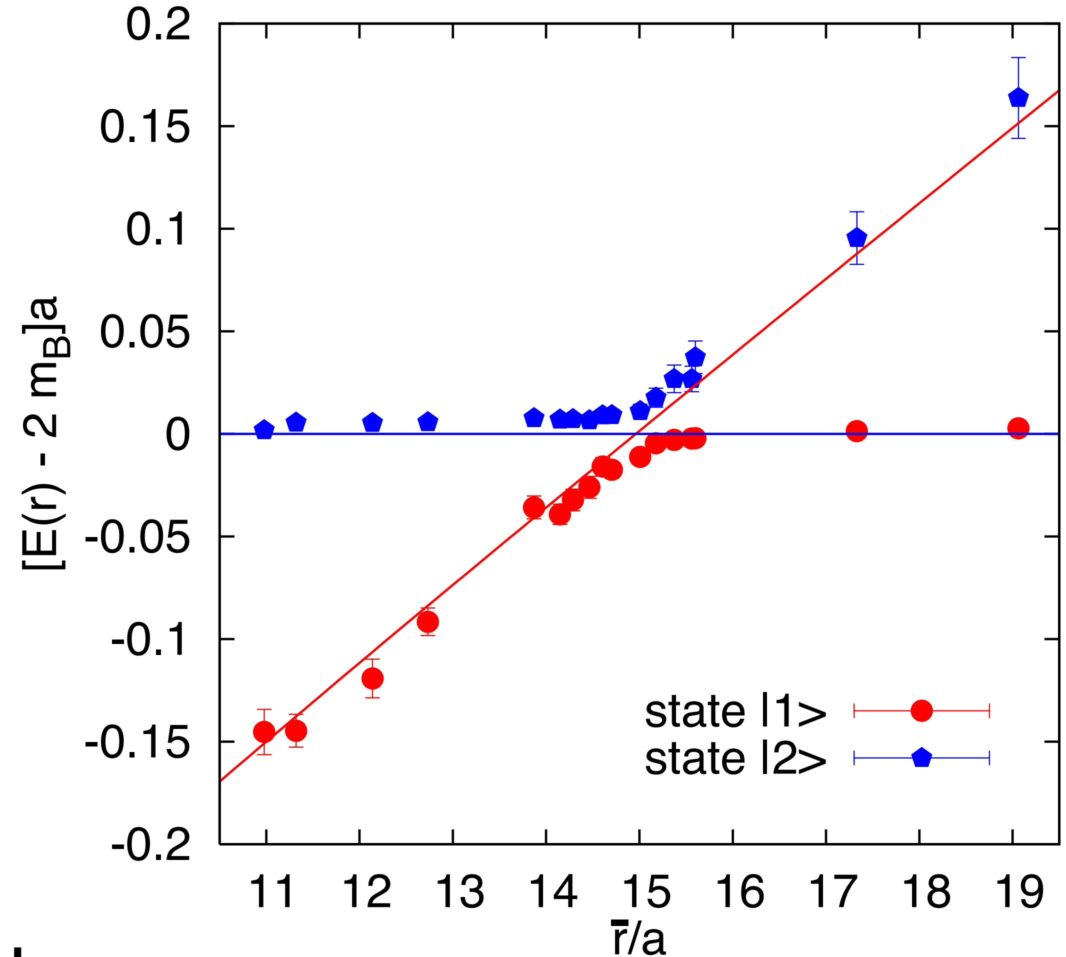
doubly heavy tetraquark



Bicudo & Wagner
arXiv:1209.6724
Maiani, Polosa & Riquer
arXiv:1903.10253

Diabatic Representation

Bruschini & Gonzales arXiv:2007.07693, 2101.04636, 2105.04401



Adiabatic representation

- heavy particles interact through
  Born-Oppenheimer potentials
  with avoided crossings

Diabatic representation

- heavy particles interact through
  Born-Oppenheimer potentials that cross
- can be obtained by a unitary transformation
- allows more accurate treatment of scattering states

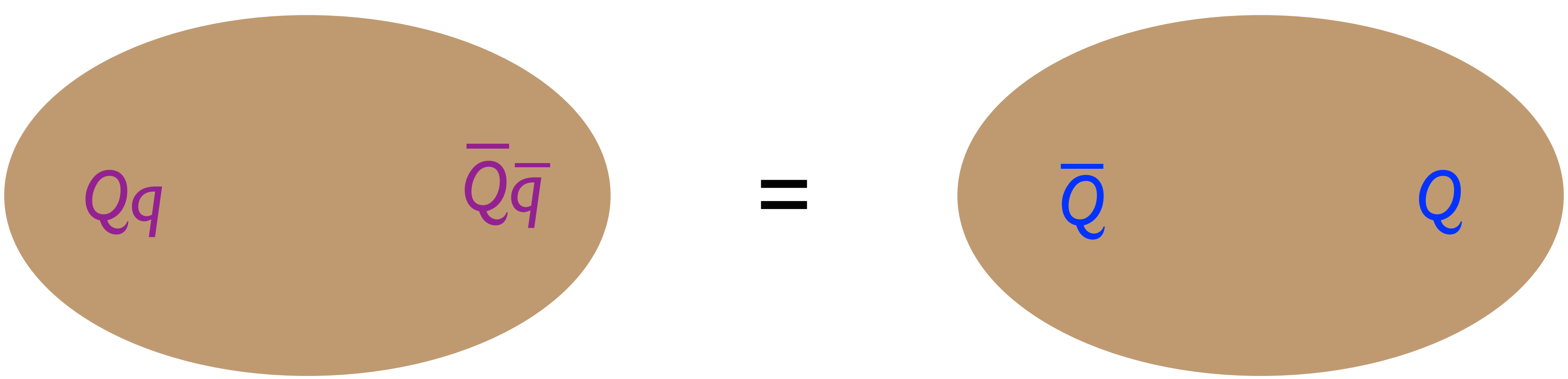
may be essential for XYZ hadrons near hadron-pair thresholds

Dynamical Diquark Model

Lebed	arXiv:1709.06097
Giron et al.	arXiv:1903.04551, 1907.08546
Giron & Lebed	arXiv:2005.07100
Gens et al.	arXiv:2102.1259

Model for Quarkonium Tetraquarks:

diquark Qq and anti-diquark $\bar{Q}\bar{q}$ are assumed to interact through same B-O potentials Σ_g^+, $\Pi_u^\pm$, Σ_u^-, ... as $\bar{Q}$ and Q in quarkonium and quarkonium hybrid

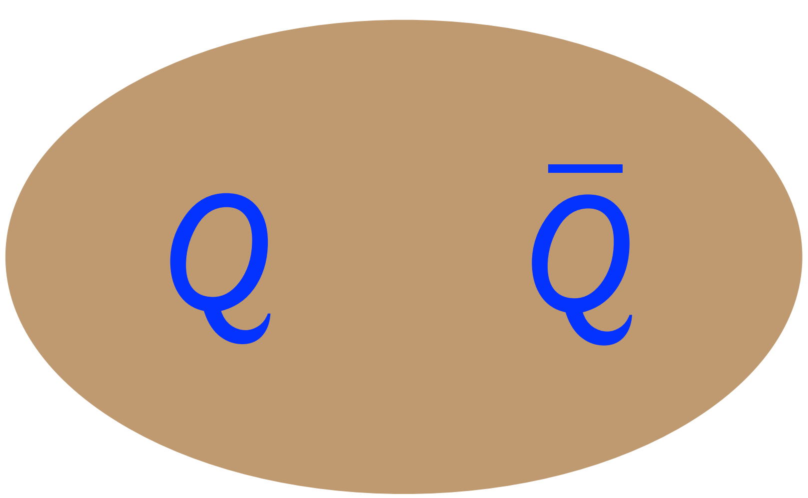


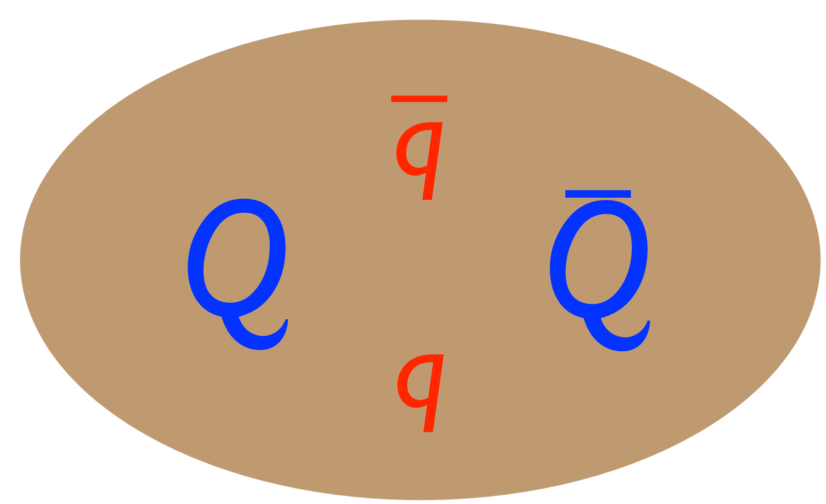
Conclusions

The discoveries of Exotic Heavy (XYZ) Hadrons
have revealed a serious gap in our understanding
of the QCD spectrum

Constituent models for the *XYZ* mesons
have not provided a compelling pattern
and make little contact with QCD

Born-Oppenheimer Effective Field Theory
has not yet provided a compelling pattern for the *XYZ* hadrons
but it is based firmly on QCD

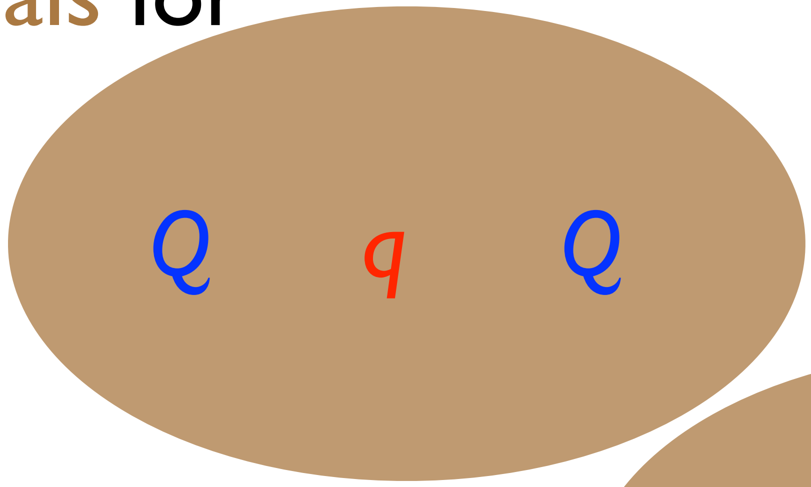




What is needed from Lattice QCD

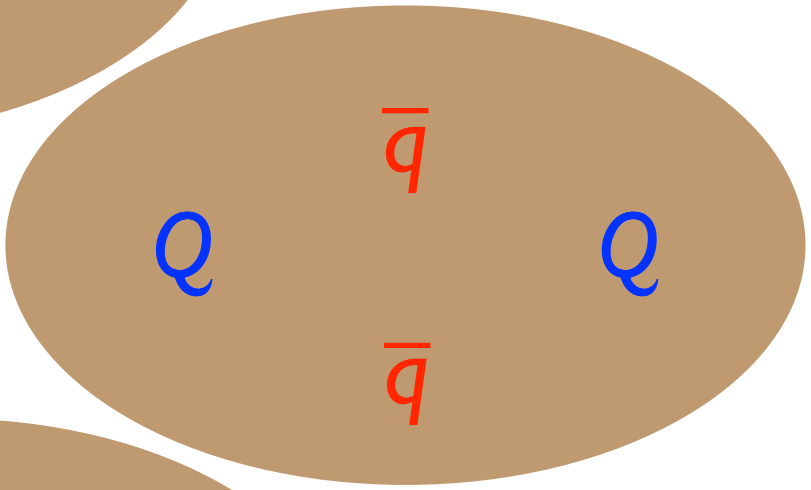
- Born-Oppenheimer potentials for

doubly heavy baryons



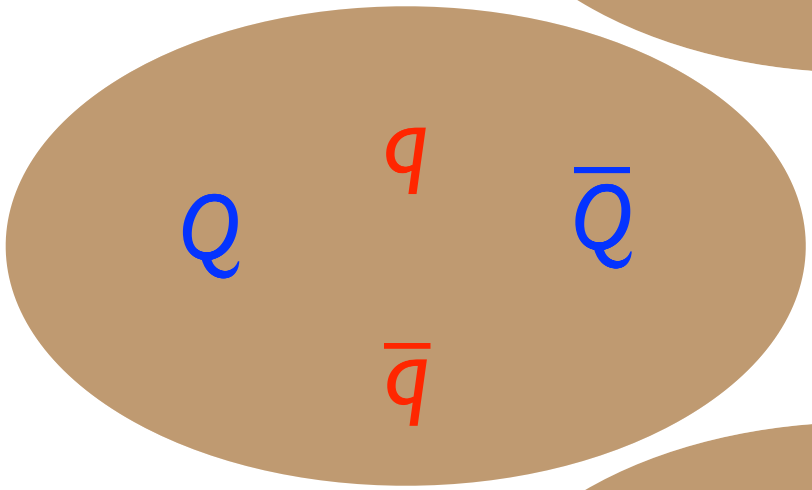
doubly heavy tetraquarks

Bicudo, Wagner et al.

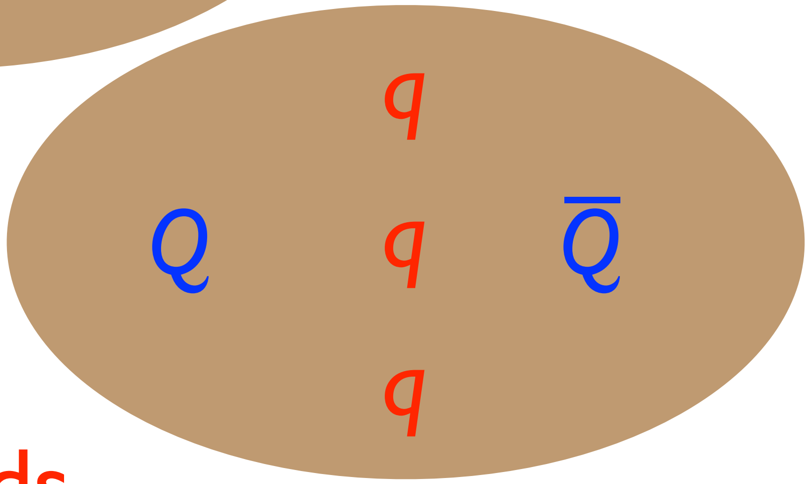


quarkonium tetraquarks

Prelovsek, Bahtiyar & Petkovic



quarkonium pentaquarks



- avoided crossings with meson-pair thresholds

Future experiments on the *XYZ* hadrons

- e^+e^- experiments
  BESIII
  Belle II

- LHC experiments
  ATLAS and CMS
  LHCb

- PANDA: $p\bar{p}$ annihilation at resonance
  into charmonium (and hybrids and tetraquarks)

What is needed from experiment

- more J^{PC}'s
- more transitions (hadronic and radiative)
- more *XYZ* hadrons

Conclusions

What is needed from non-lattice theory

use Born-Oppenheimer EFT to calculate

- spectrum of doubly heavy baryons
  doubly heavy tetraquarks
  quarkonium hybrids
  quarkonium tetraquarks
  quarkonium pentaquarks
- radiative and hadronic transitions to quarkonium

there is hope for a
"coherent comprehensive understanding of the *XYZ* particles"
that is based firmly on QCD