Exotic Hidden-Heavy Hadrons

and Where to Find Them

DOE
High Energy Physics

Eric Braaten
Ohio State University

EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

Exotic Hidden-Heavy Hadrons and Where to Find Them

Physics Letters B 863,139386 (2025) [arXiv:2409.00802]

with Roberto Bruschini

pioneer of the diabatic Born-Oppenheimer approximation for QCD

Hidden-Heavy Pentaquarks and Where to Find Them

with Fareed Alasiri and Roberto Bruschini (in preparation)

Hidden-heavy hadrons

Constituents include heavy quark Q and heavy antiquark $\overline{Q}$

$\Longrightarrow$ heavy flavor is <u>hidden</u>

Ordinary hidden-heavy hadrons: Quarkonium ($Q\overline{Q}$)

charmonium ($c\bar{c}$)

bottomonium ($b\bar{b}$)

<u>Exotic</u> hidden-heavy hadrons: Hybrid Mesons: $Q\overline{Q}g$?

Tetraquark Mesons: $Q\overline{Q}q\bar{q}$?

Pentaquark Baryons: $Q\overline{Q}qqq$?

Exotic Hidden-Heavy Hadrons

$X_c = \chi_{c1}(3872)$ Belle collaboration 2003

hidden-charm tetraquark meson ($c\bar{c}q\bar{q}$)

$Z_b^+ = T_{b\bar{b}1}(10610)^+, Z_b^{+'} = T_{b\bar{b}1}(10650)^+$

Belle collaboration 2011

hidden-bottom tetraquark mesons ($b\bar{b}u\bar{d}$)

$P_{c\bar{c}}(4450)^+$ LHC collaboration 2015

hidden-charm pentaquark baryon ($c\bar{c}uud$)

counting as of June 2023 Lebed

44? $c\bar{c}$ tetraquark mesons

5 $b\bar{b}$ tetraquark mesons

5 $c\bar{c}$ pentaquark baryons

Exotic Hidden-Heavy Hadrons

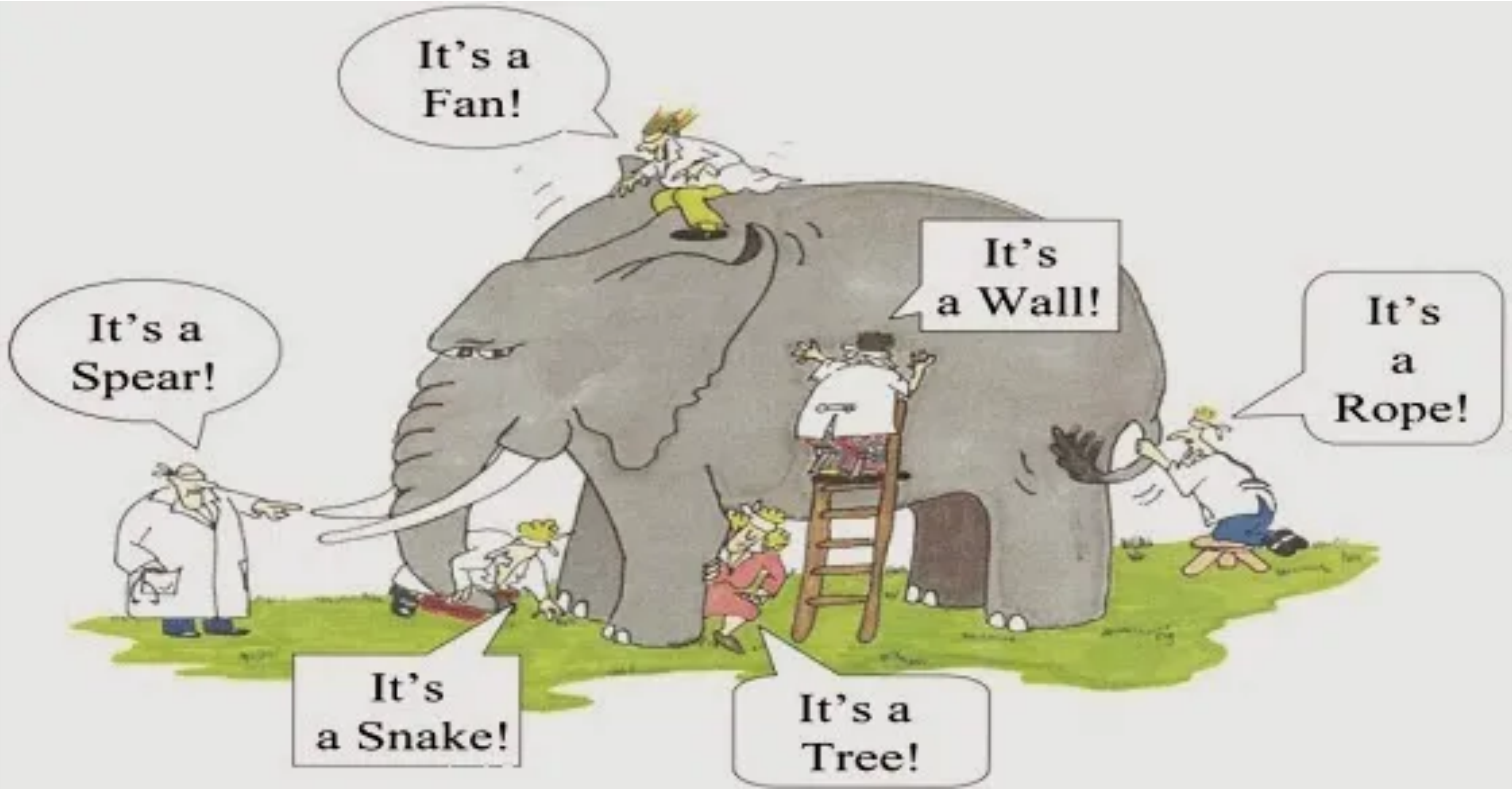
Constituent models can postdict most observed states
no compelling pattern
tenuous connections to fundamental theory QCD

Molecular models: constituents are two color-singlet heavy hadrons
natural explanation for why many Exotic Hidden-Heavy Hadrons
have masses near thresholds for pairs of heavy hadrons

Colored-constituent models:
Quark models: additional constituents are light quarks, light antiquarks
Diquark models: additional constituents include diquarks
explosion in number of predicted but unobserved states

Exotic Hidden-Heavy Hadrons

Most constituent models of Exotic Hidden-Heavy Hadrons
describe some true aspects,
but they don't come close to capturing their essence.



Exotic Hidden-Heavy Hadrons

Challenge: understand Exotic Hidden-Heavy Hadrons based on QCD

Unsolved problem for over 20 years!

Born-Oppenheimer Approximation for QCD

framework firmly based on fundamental theory

exploits heavy-quark mass $m_Q \gg$ energy scales of light quarks, gluons

Qualitative predictions: Born-Oppenheimer symmetries
heavy-quark spin symmetries

Quantitative predictions: solutions to coupled-channel Schrödinger equation

Born-Oppenheimer approximation for QCD

Juge, Kuti & Morningstar 1999

Hidden-Heavy Hadron includes heavy quark and antiquark
plus light quarks, antiquarks, and gluons

Step 1

use Lattice QCD to calculate Born-Oppenheimer potentials:
discrete energy levels of QCD with static ***3*** and ***3**** color sources
separated by variable distance *r*

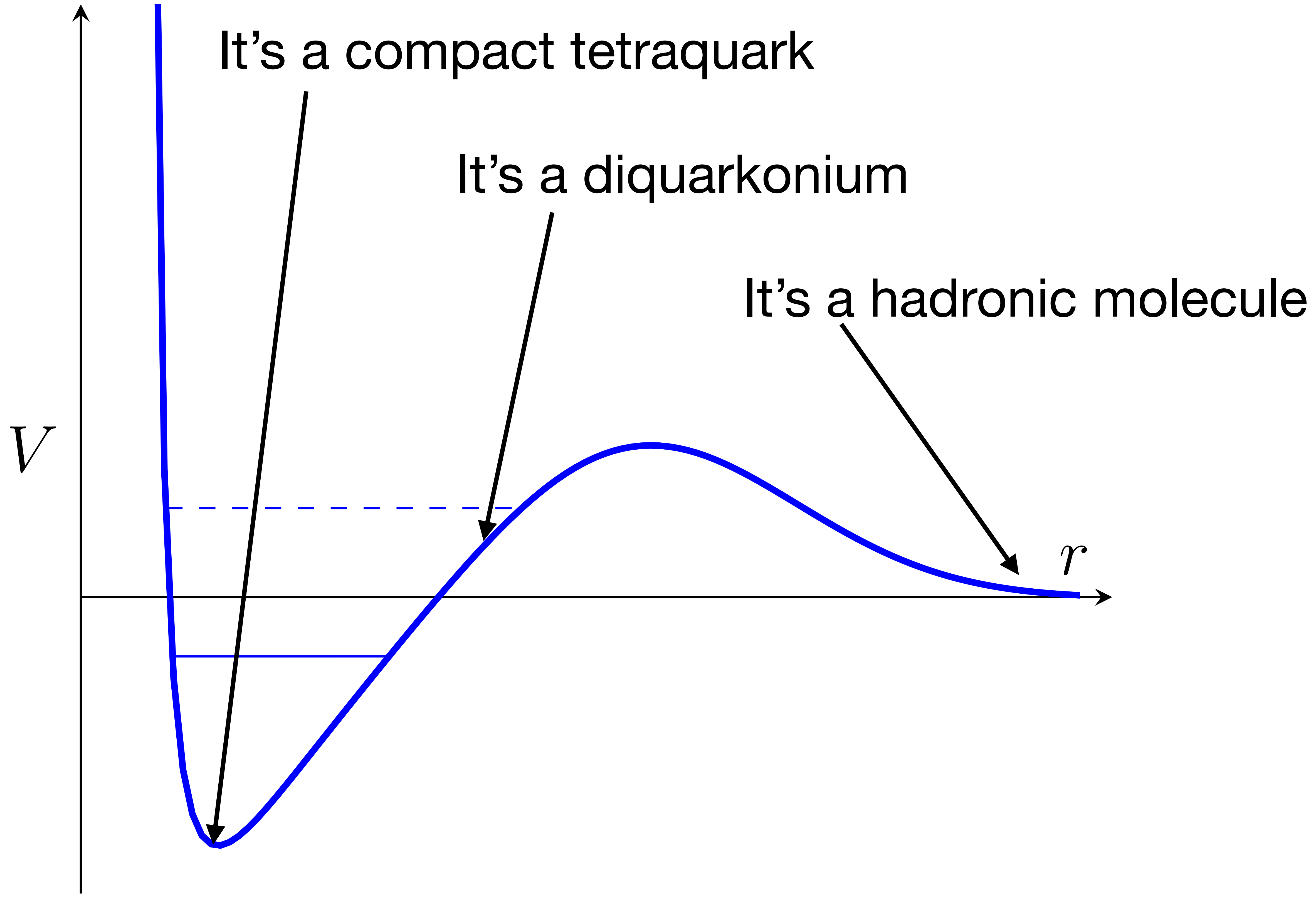
Step 2

solve Schrödinger equation for heavy quark and antiquark
in Born-Oppenheimer potentials

Born-Oppenheimer approximation for QCD

Born-Oppenheimer wave function

can incorporate aspects of various constituent models
in different spacial regions
and through different components of wave function



Effective Field Theories

EFT's for Heavy Quarkonium

Integrate out scale m_Q $\Longrightarrow$ NonRelativistic QCD (NRQCD)

Lepage & 199x

Integrate out scale $m_Q v$ $\Longrightarrow$ potential NRQCD (pNRQCD)

Brambilla, Pineda, Soto & Vairo 2000

EFT's for Hidden-Heavy and Double-Heavy Hadrons

extension of pNRQCD:

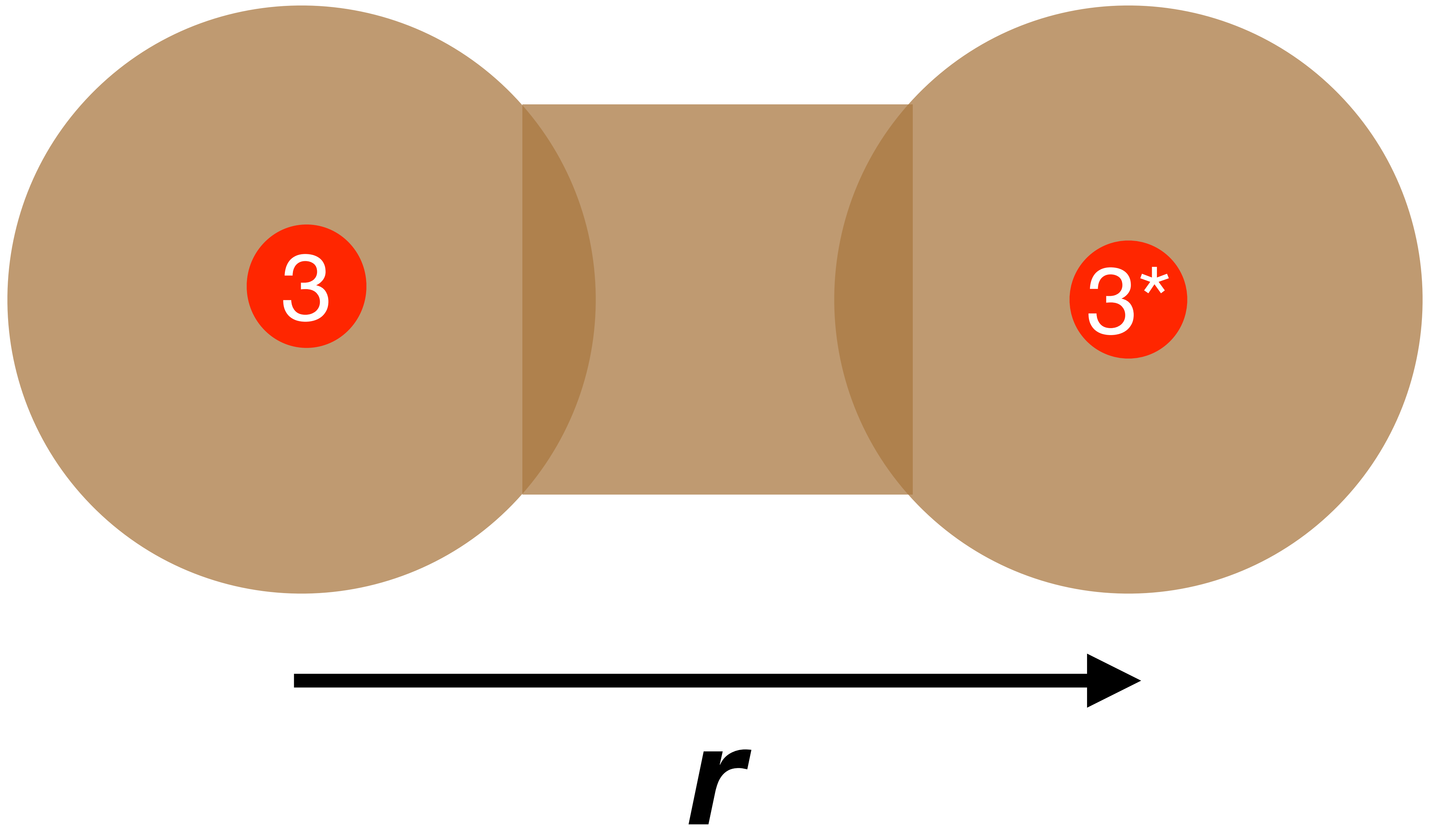
Born-Oppenheimer Effective Field Theory (BOEFT)

Berwein, Brambilla, Tarrus Castella & Vairo 2015
Oncala & Soto 2017
Brambilla, Krein, Tarrus Castella & Vairo 2017
Soto & Tarrus Castella 2020
Berwein, Brambilla, Mohapatra & Vairo 2024

Born-Oppenheimer Potentials for QCD

Born-Oppenheimer potentials:

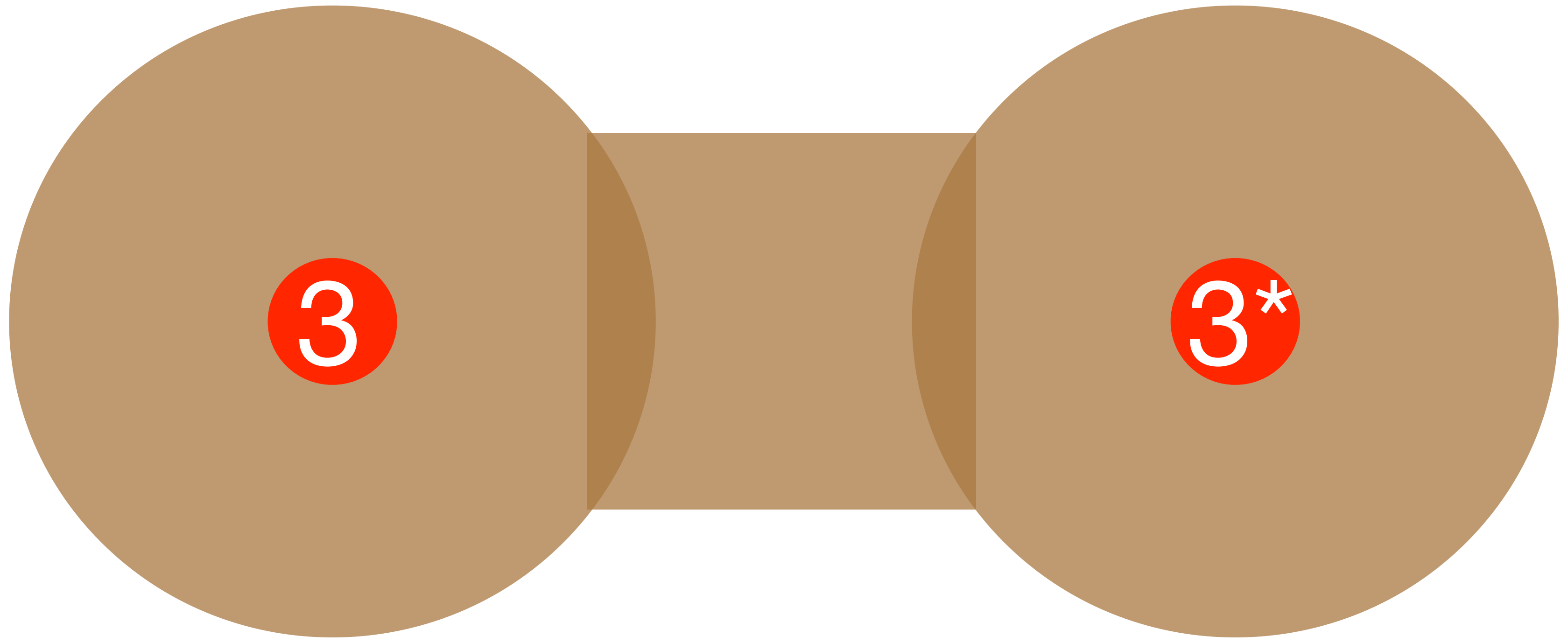
discrete energy levels of QCD with static ***3*** and ***3**** color sources
separated by variable distance *r*



Born-Oppenheimer Potentials for QCD

Born-Oppenheimer symmetries

<u>symmetries</u>	<u>quantum numbers</u>
cylindrical	$\lambda = 0, \pm 1, \pm 2, \ldots$
$P \times C$	$CP = +1, -1$
reflection R	$R = +1, -1$



traditional Born-Oppenheimer quantum numbers from atomic physics: Λ_η^ϵ

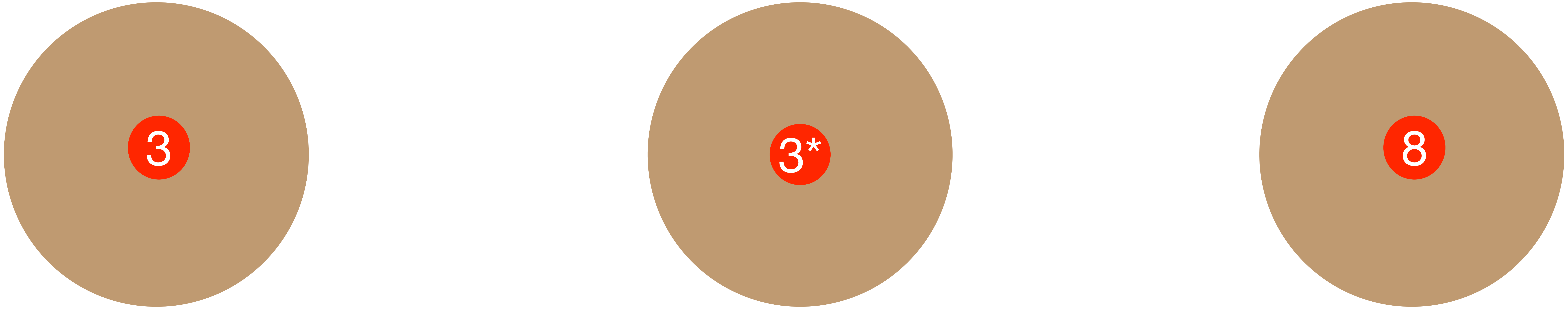
- $\Lambda = \Sigma, \Pi, \Delta, \ldots$ for $|\lambda| = 0,1,2,\ldots$
- $\eta = g, u$ for $CP = +1, -1$
- $\epsilon = +, -$ for $R = +1, -1$

Born-Oppenheimer Potentials for QCD

Born-Oppenheimer potentials:

limiting behaviors at large r and at small r are determined by discrete energy levels of QCD with single static color source

color-triplet (***3***) source | color-antitriplet (***3****) source | color-octet (***8***) source



triplet hadron | antitriplet hadron | adjoint hadron

Symmetries: rotations, parity, charge conjugation

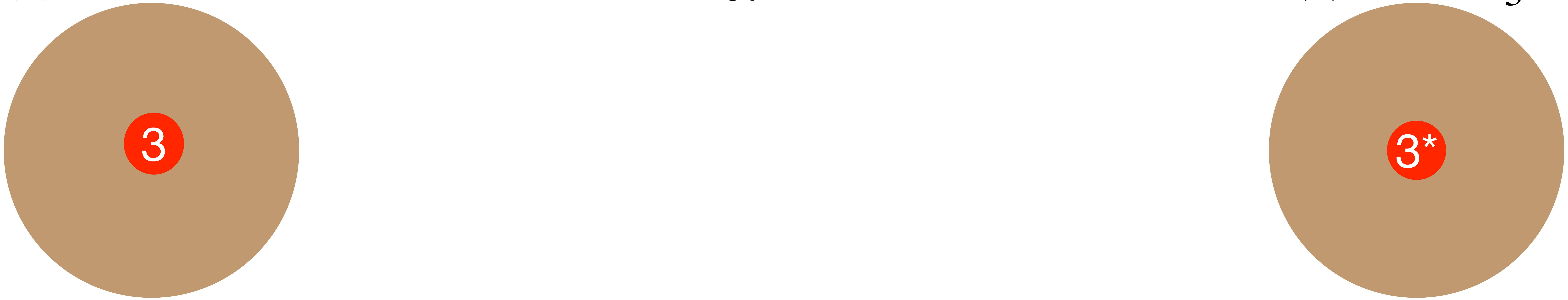
$\Longrightarrow$ discrete energy levels labeled by J^{PC}

Born-Oppenheimer Potentials for QCD

Born-Oppenheimer potential at large *r*

EITHER increases linearly in *r* (from energy of gluon flux tube): $V(r) \longrightarrow \sigma r$

OR approaches constant equal to energy of two static hadrons: $V(r) \longrightarrow E_3 + E_{3*}$



triplet hadron

antitriplet hadron

Born-Oppenheimer Potentials for QCD

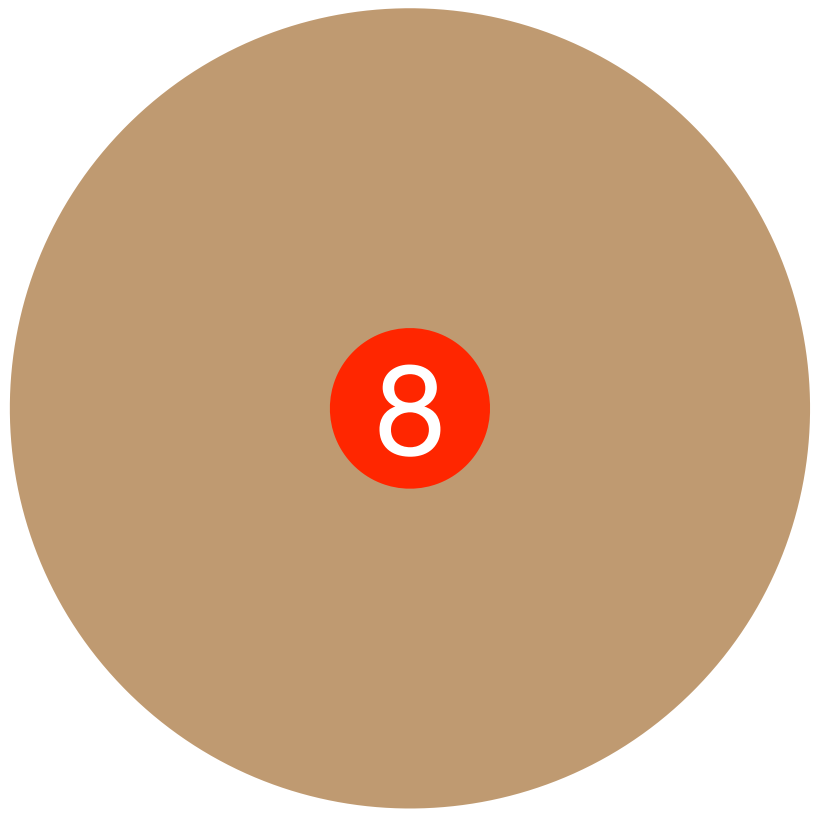
Born-Oppenheimer potential at small *r*

3 and ***3**** color sources with small *r* reduce to
linear combination of color-singlet (***1***) and color-octet (***8***) sources: $3 \otimes 3^* = 1 \oplus 8$

QCD vacuum

attractive color-Coulomb potential:

$$V(r) \longrightarrow -\frac{4}{3}\alpha_s / r$$



adjoint hadron

repulsive color-Coulomb potential:

$$V(r) \longrightarrow +\frac{1}{6}\alpha_s / r$$

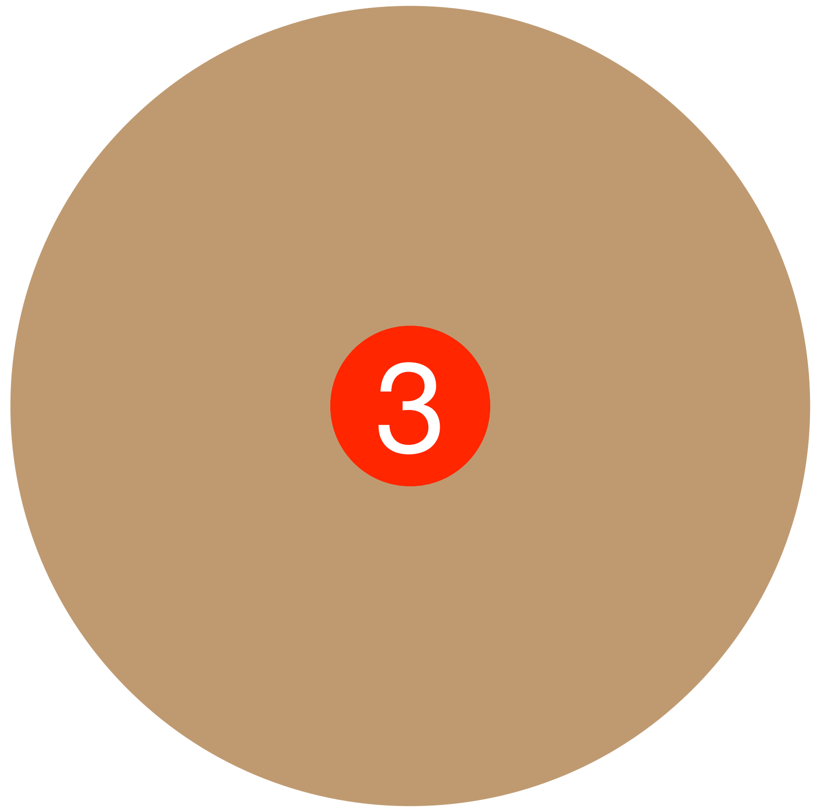
offset by adjoint-hadron energy

QCD with color-triplet source

3 color source:

discrete energy levels: “triplet hadrons”

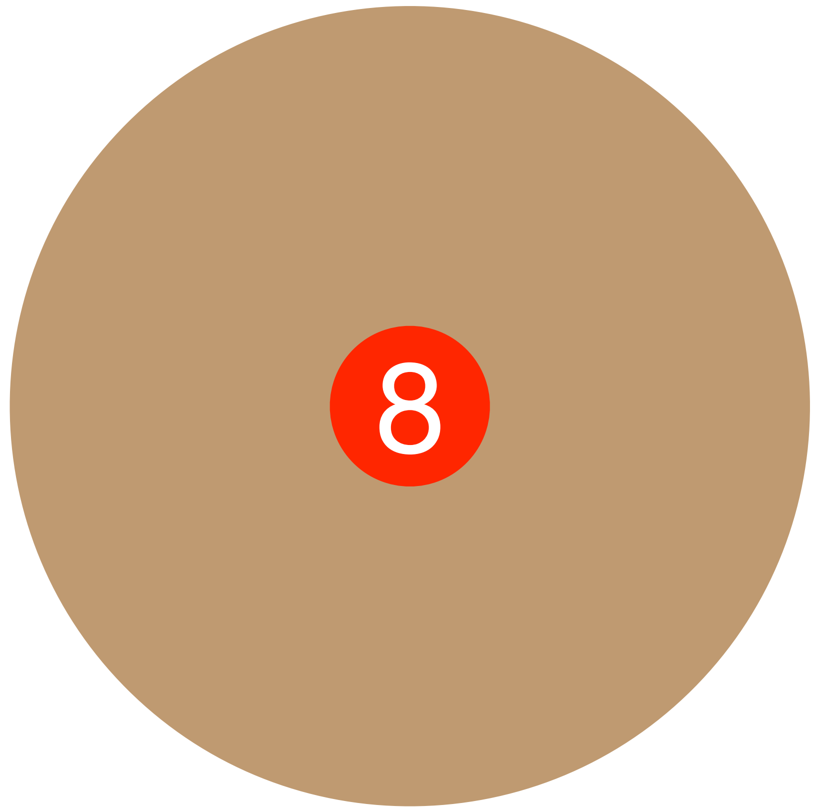
- spectrum: calculate using Lattice QCD
- spectrum: extrapolate charm hadrons and bottom hadrons to infinite quark mass



Ground state triplet meson $(3\bar{q})$: $J^P = \frac{1}{2}^-$

Lowest energy triplet baryon $(3qq)$: $J^P = 0^+$, higher energy by 500 MeV

QCD with color-octet source



8 color source:

discrete energy levels: "adjoint hadrons"

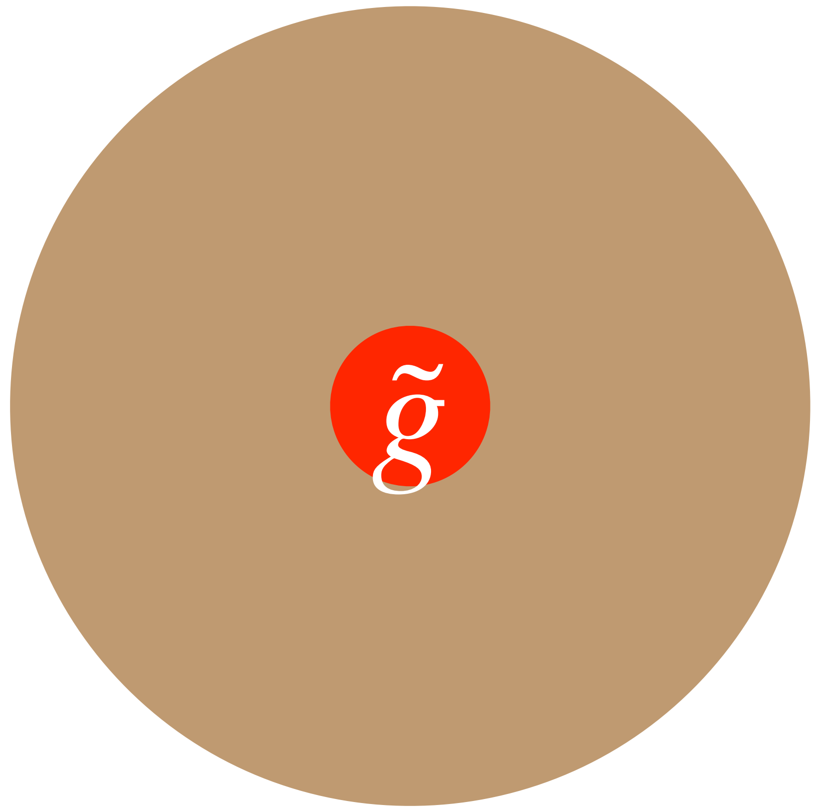
SU(3)-flavor singlets are "gluelumps"

- spectrum: calculate using Lattice QCD

  gluelumps: Foster & Michael (1999), Marsh & Lewis (2014), Herr, Schlosser & Wagner (2023)
  adjoint mesons ?
  adjoint baryons ?

Ground state is not known! gluelump (8g) with $J^{PC} = 1^{+-}$?
adjoint meson ($8q\bar{q}$) ?
adjoint baryon ($8qqq$) ?

- spectrum of adjoint hadrons is same as for gluino hadrons
  (QCD fields bound to a heavy gluino)
  up to additive constant associated with the gluino mass

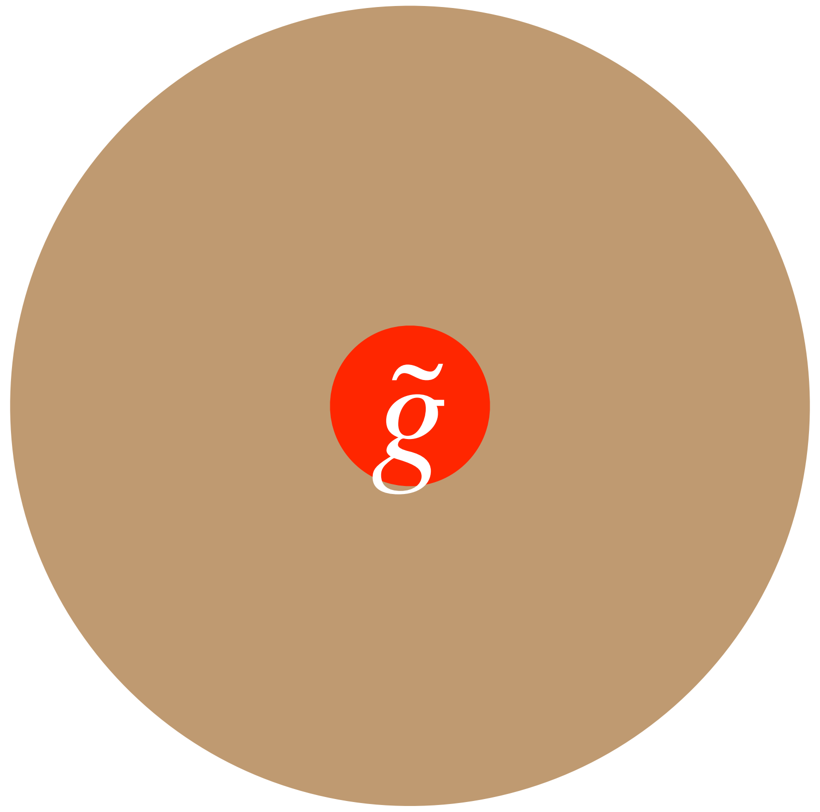


Gluino Hadrons

gluino ($\tilde{g}$): spin 1/2, octet (8) color charge

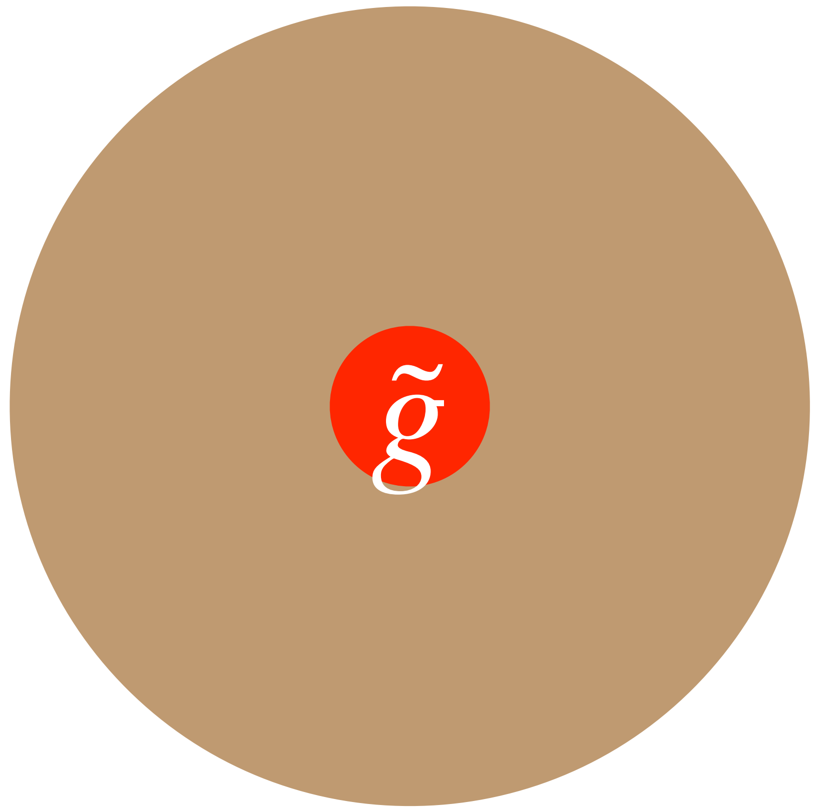
SUSY models for BSM predict heavy gluino
Heavy gluino could be produced at Large Hadron Collider
Long-lived gluino would hadronize into gluino hadrons inside LHC detectors
Signature for gluino depends on spectrum of gluino hadrons

Spectrum of gluino hadrons has been predicted by models
Ground state depends on the model: gluelump ($\tilde{g}g$) ?
adjoint meson ($\tilde{g}q\bar{q}$)?
adjoint baryon ($\tilde{g}qqq$) ?



Exotic Hidden-Heavy Hadrons

spectrum of adjoint hadrons = spectrum of gluino hadrons
spectrum can be calculated using Lattice QCD



Hindsight:

if spectrum of gluino hadrons
had been calculated using Lattice QCD,
existence of Exotic Hidden-Heavy Hadrons
could have been predicted decades ago!

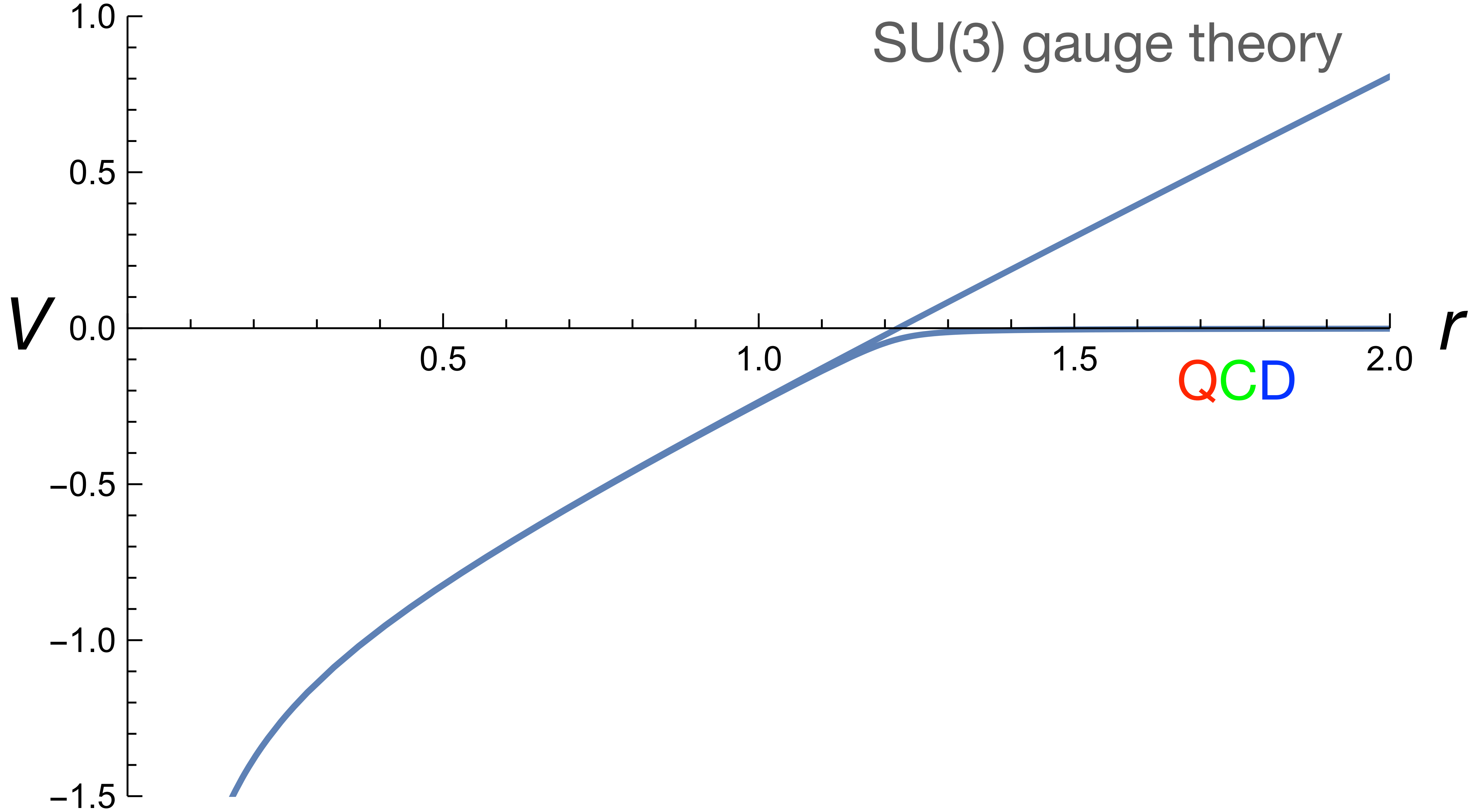
History of Born-Oppenheimer potentials

~ 1985: first calculations of quarkonium Σ_g^+ potential

using pure *SU(3)* Lattice gauge theory

consistent with attractive color-Coulomb potential at small *r*

increases linearly at large *r*

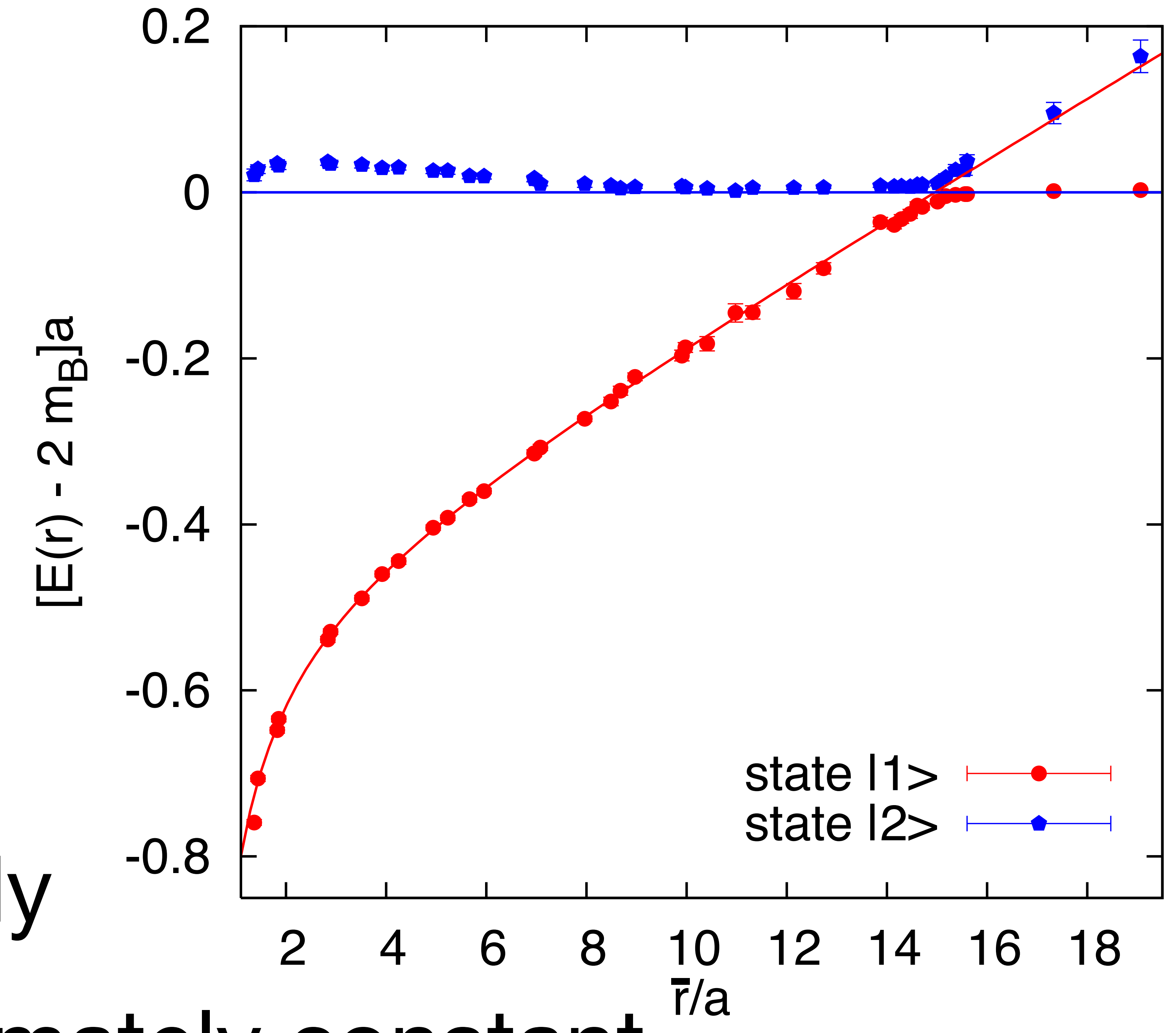


~ 1995: first calculations of quarkonium Σ_g^+ potential

using Lattice QCD with dynamical light quarks

approaches a constant at large *r* ?

History of Born-Oppenheimer potentials



Bali et al. 1995

calculated first two Σ_g^+ potentials

using Lattice QCD with 2 flavors of light quarks

narrow avoided crossing near 1.2 fm between

quarkonium Σ_g^+ potential that increases linearly

static-meson-pair Σ_g^+ potential that is approximately constant

(and equal to twice ground-state energy of static meson)

Hindsight:

for every pair of static hadrons, there must be potentials approaching static-hadron-pair threshold at large r

what happens to them at smaller r ?

History of Born-Oppenheimer potentials

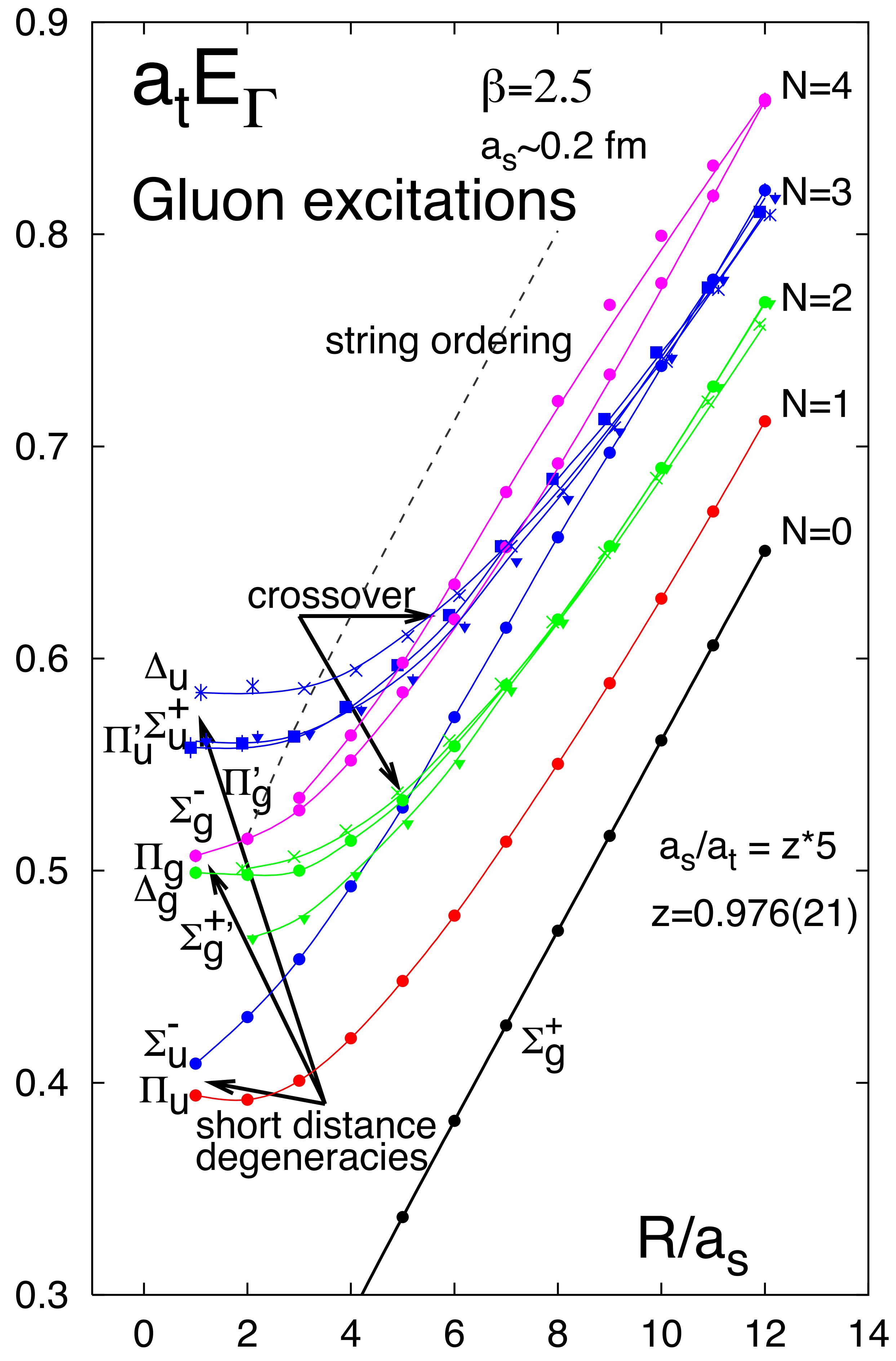
Juge, Kuti, and Morningstar 1999, 2002

calculated excited B-O potentials: $\Pi_u, \Sigma_u^-, \Sigma_g^{+\prime}, \ldots$

using pure *SU(3)* Lattice gauge theory

potentials increase linearly at large *r*

how do they behave at small *r* ?



pNRQCD: Brambilla, Pineda, Soto & Vairo 1999

excited B-O potentials at small *r* :

repulsive color-Coulomb potentials offset by gluelump energy

Hindsight:

for every adjoint hadron, there must be

repulsive color-Coulomb potentials offset by adjoint-hadron energy at small *r*

what happens to them at larger *r* ?

History of Born-Oppenheimer potentials

Discovery of hidden-heavy tetraquark mesons with electric charge

$Z_b^+ = T_{b\bar{b}1}(10610)^+, Z_b^{+'} = T_{b\bar{b}1}(10650)^+$ Belle collaboration 2011

$Z_c^+ = T_{c\bar{c}1}(3900)^+$ BESIII, Belle collaborations 2013

hidden-heavy tetraquark mesons with electric charge
are bound states in isospin-1 B-O potentials !

Braaten, Langmack & Smith 2014

Assumptions

isospin-1 B-O potentials have same qualitative behavior
as excited B-O potentials for pure *SU(3)* gauge theory

- repulsive color-Coulomb potentials
  offset by isospin-1 adjoint-meson energy at small *r*
- increasing linearly at large *r*

Hindsight:

isospin-1 B-O potentials could approach static-meson-pair threshold at large *r*

Born-Oppenheimer Potentials for QCD

Born-Oppenheimer potentials

- repulsive color-Coulomb potential offset by adjoint-hadron energy at small r,
  but what happens at larger r ?
- potential approaching static-hadron-pair threshold at large r,
  but what happens at smaller r ?

Spectrum of QCD in the presence of color sources is smooth function of r !

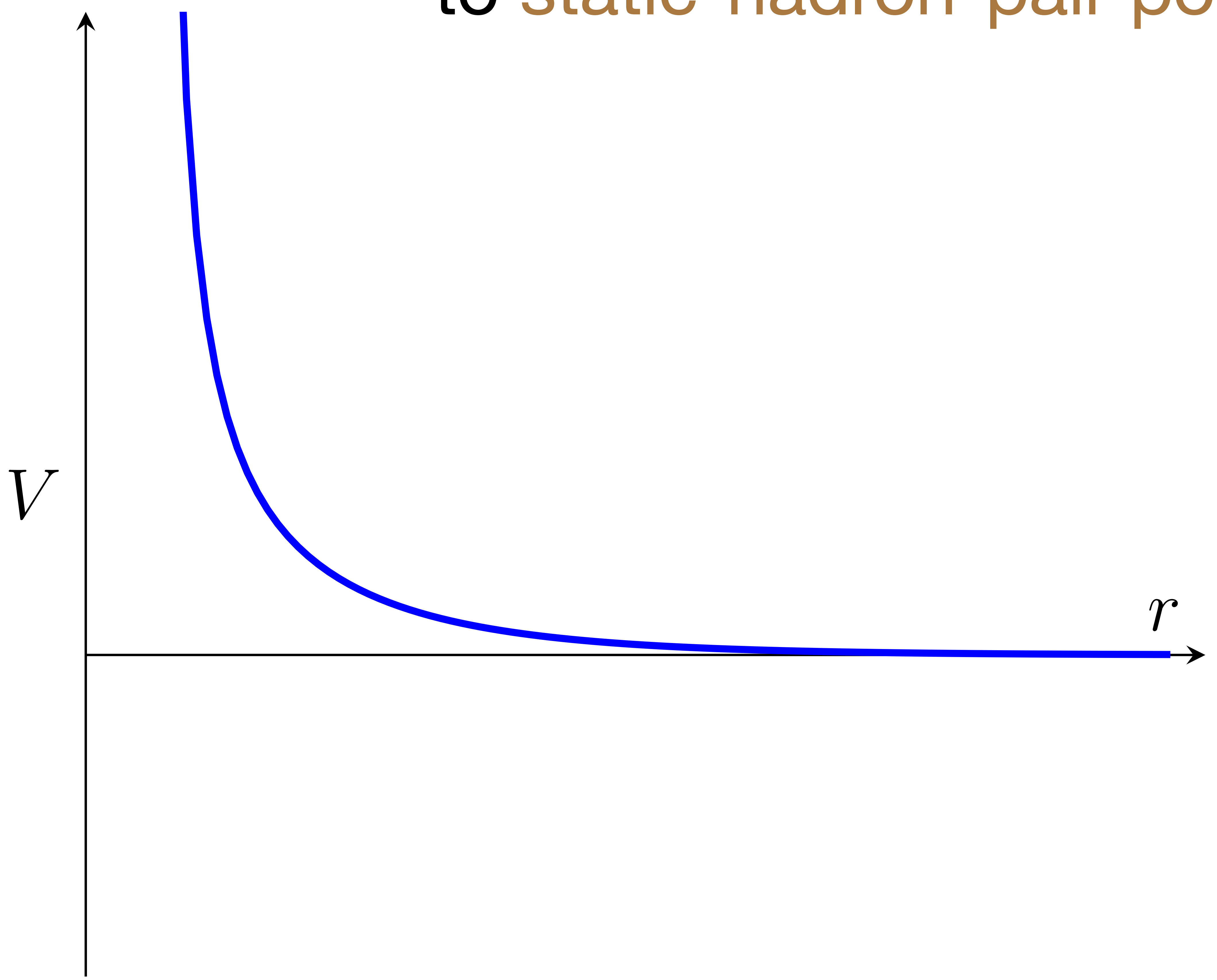
$\Longrightarrow$ adiabatic adjoint-hadron potentials at small r
must connect smoothly to adiabatic static-hadron-pair potentials at large r

Braaten & Bruschini 2024
Berwein, Brambilla, Mohapatra & Vairo 2024

Repulsive color-Coulomb potentials at small r
connect smoothly to constant static-meson-pair thresholds at large r !

Born-Oppenheimer Potentials for Hidden-heavy Hadrons

Adjoint-hadron potential at small *r* connects smoothly
to static-hadron-pair potential at large *r*



Simplest possibility

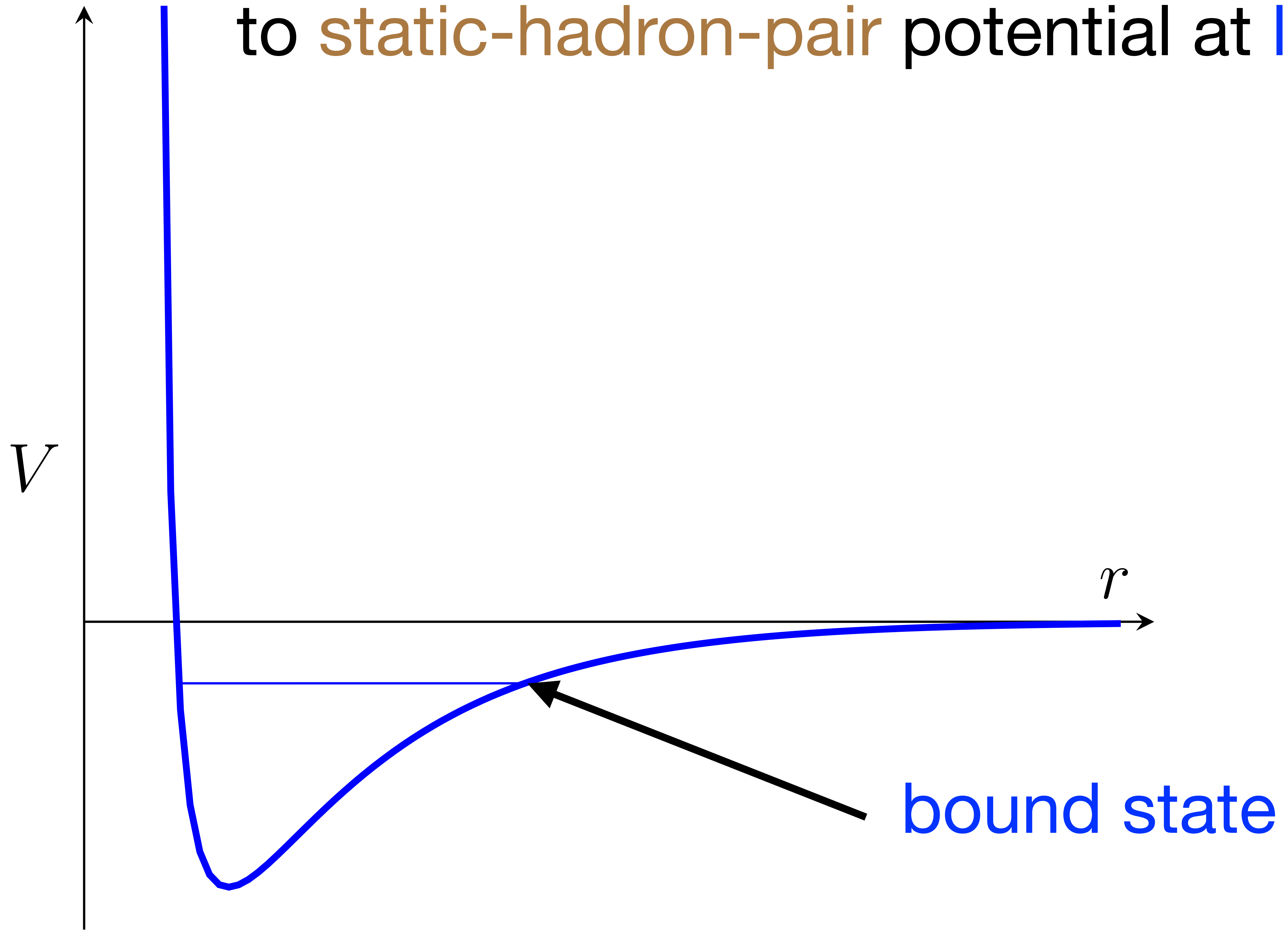
It approaches static-hadron-pair threshold from above

$\Longrightarrow$ It cannot support bound states

Born-Oppenheimer Potentials for Hidden-heavy Hadrons

Adjoint-hadron potential at small *r* connects smoothly

to static-hadron-pair potential at large *r*



<u>Next-simplest possibility</u>

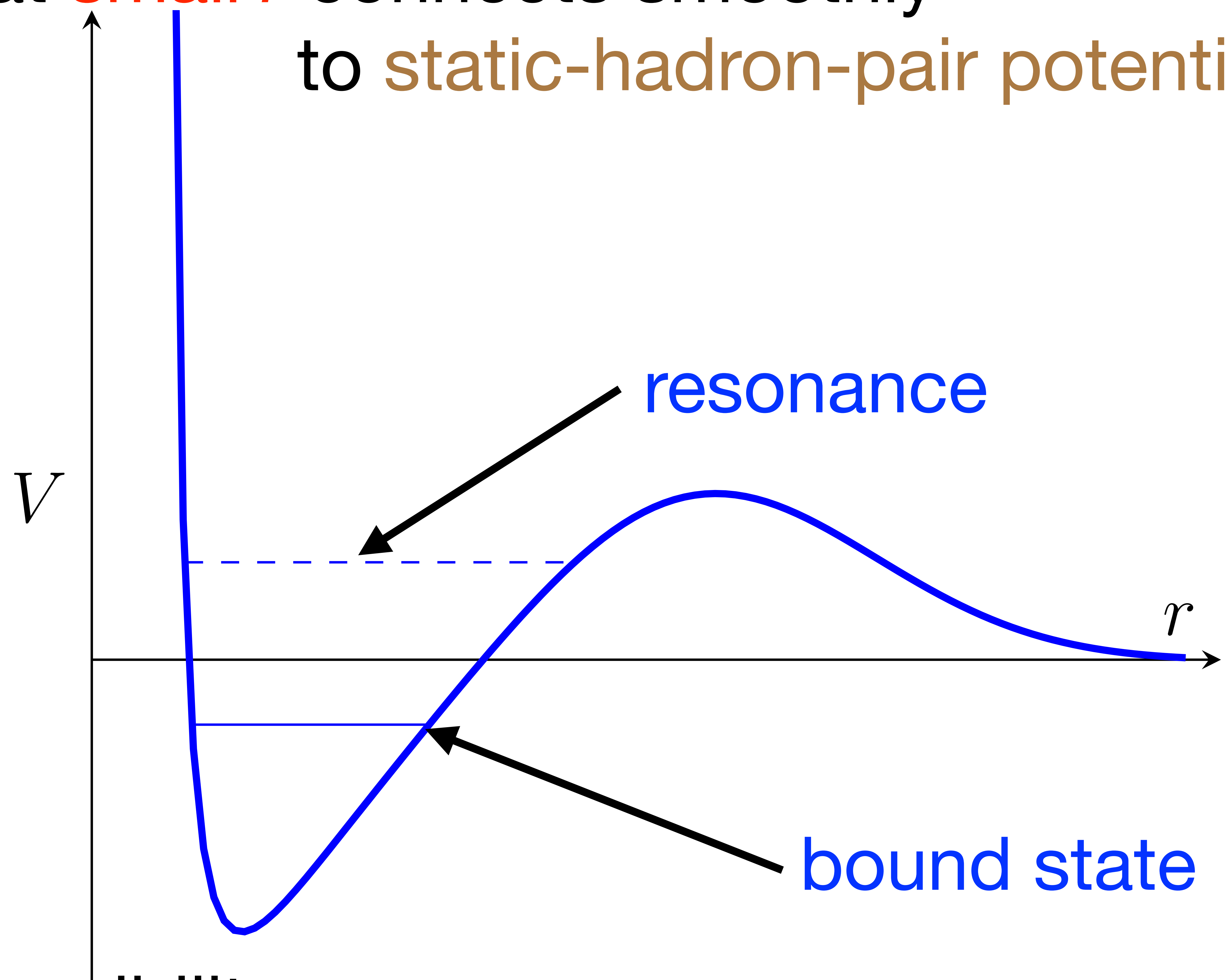
It crosses static-hadron-pair threshold and then approaches it <u>from below</u>

$\Longrightarrow$ It can support bound states if potential is deep enough

Depth of potential determined by adjoint-hadron energy

Born-Oppenheimer Potentials for Hidden-heavy Hadrons

Adjoint-hadron potential at small *r* connects smoothly
to static-hadron-pair potential at large *r*



<u>Next-to-next-simplest possibility</u>

It crosses static-hadron-pair threshold twice and then approaches it <u>from above</u>

$\Longrightarrow$ It may support bound states and/or resonances

Depth of potential determined by adjoint-hadron energy

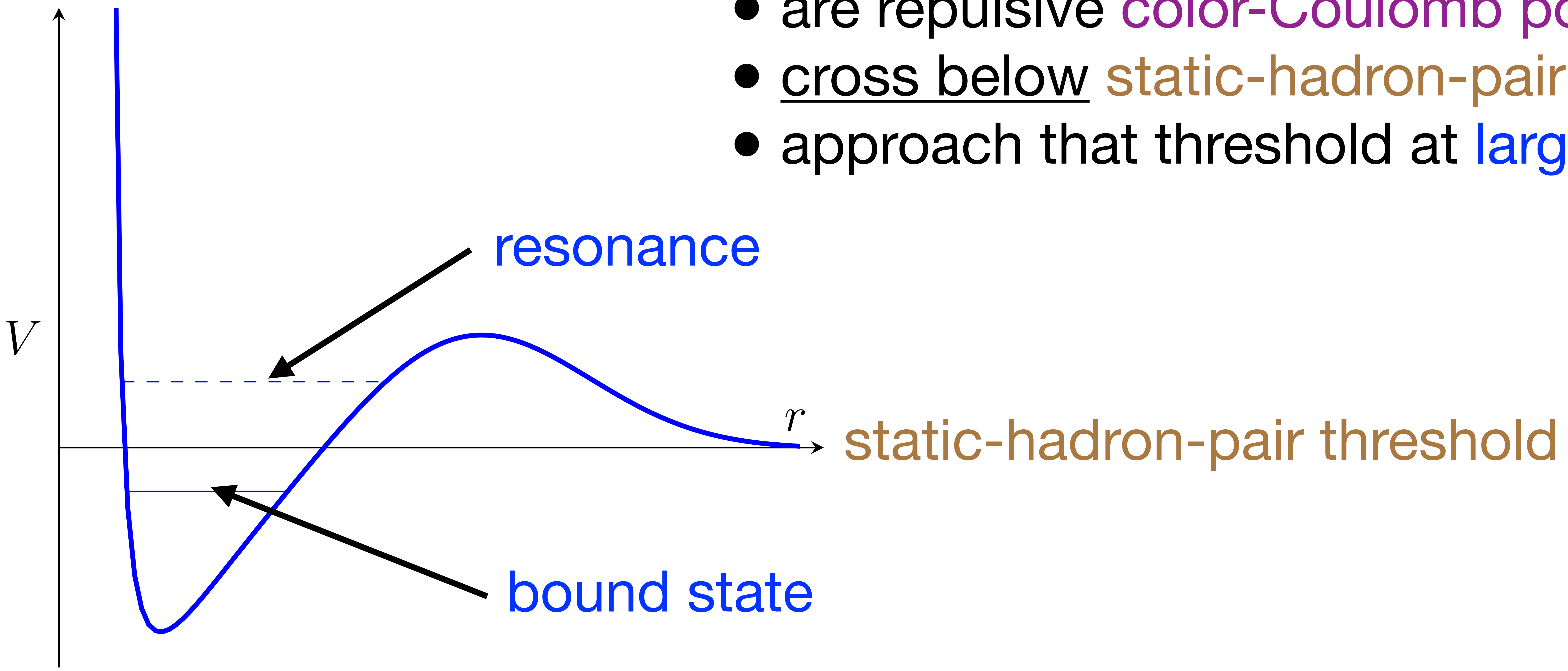
Solution to Exotic Hidden-Heavy Hadron Problem

Braaten & Bruschini 2024

Exotic Hidden-Heavy Hadrons:

bound states (or resonances) in Born-Oppenheimer potentials that

- are repulsive color-Coulomb potentials at small *r*
- <u>cross below</u> static-hadron-pair threshold
- approach that threshold at large *r*



- explains why most Exotic Hidden-Heavy Hadrons have mass near a heavy-hadron-pair threshold

Solution to Exotic Hidden-Heavy Hadron Problem

$Z_b = T_{b\bar{b}1}(10610)$ has mass above $B^*\bar{B}$ threshold by 3 MeV

$\Longrightarrow$ almost bound hidden-bottom tetraquark

$Z_c = T_{c\bar{c}1}(3900)$ has mass above $D^*\bar{D}$ threshold by 130 MeV

$\Longrightarrow$ hidden-charm tetraquark resonance

that can decay into $D^*\bar{D}$

Z_b and Z_c are energy levels of $b\bar{b}$ and $c\bar{c}$

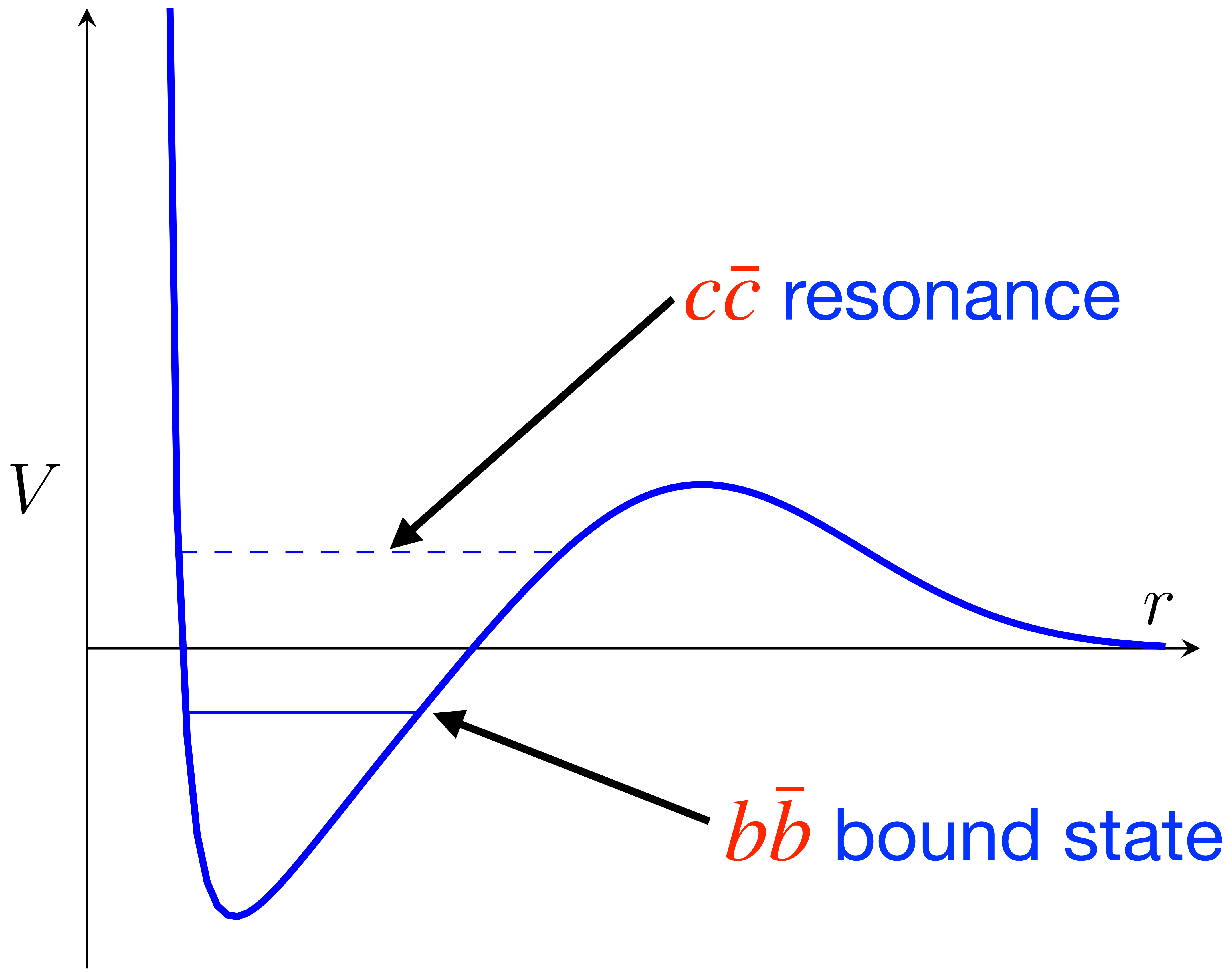
in same isospin-1 Π_g, $\Sigma_g^{+\prime}$

Born-Oppenheimer potentials

$\Longrightarrow$ next-to-next-simplest possibility:

potentials have (almost) bound state for $b\bar{b}$

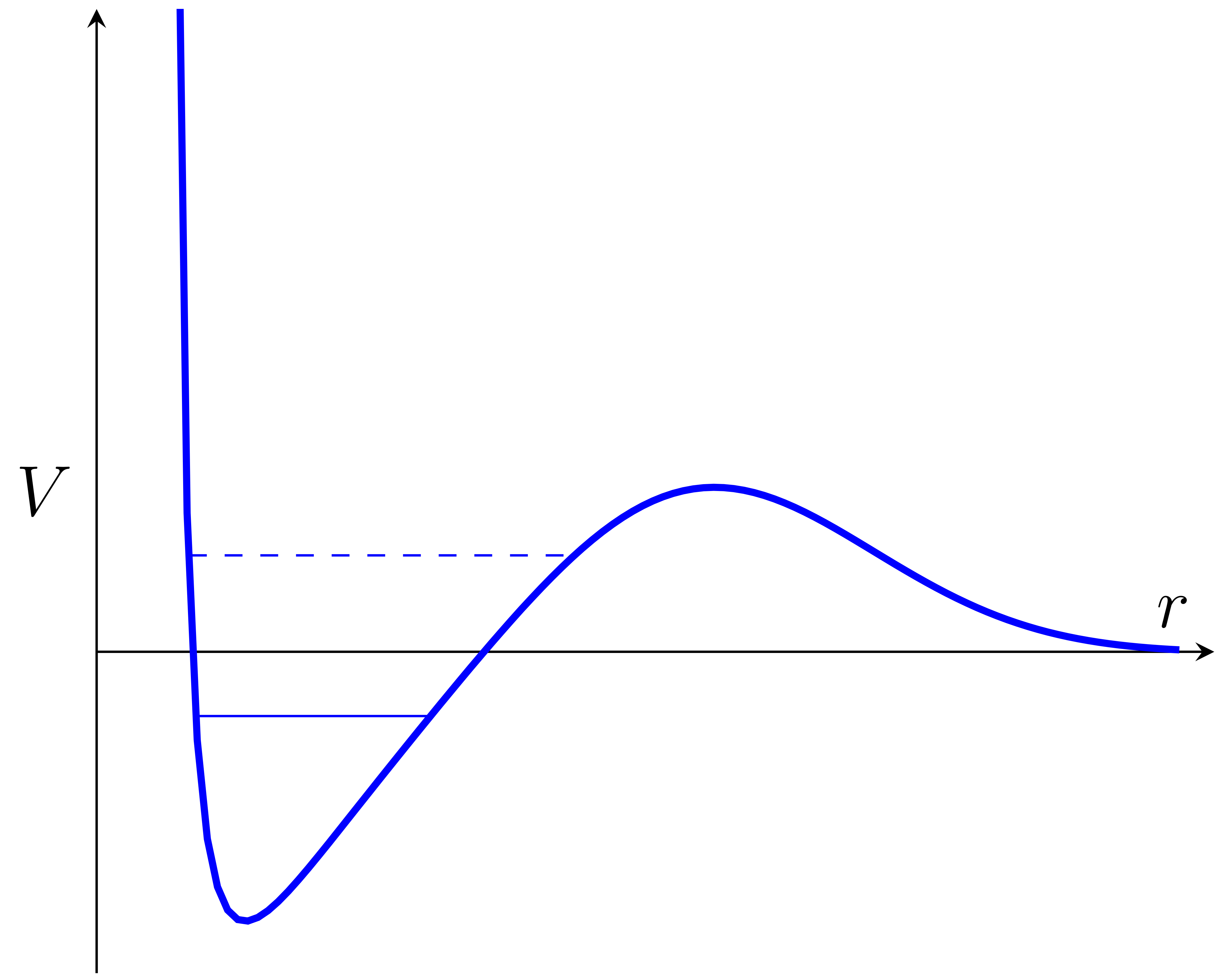
resonance for $c\bar{c}$



Solution to Exotic Hidden-Heavy Hadron Problem

solution avoids explosion in number of predicted Exotic Hidden-Heavy Hadrons

only those adjoint-hadron potentials
associated with the lowest-energy adjoint hadrons
cross below the static-hadron-pair threshold
before approaching it



Exotic Hidden-Heavy Hadrons
are associated only with the lowest-energy adjoint hadrons !

Qualitative Aspects of Hidden-Heavy Tetraquarks

$Z_b = T_{b\bar{b}1}(10610)$ has mass above $B^*\bar{B}$ threshold by 3 MeV
$Z'_b = T_{b\bar{b}1}(10650)$ has mass above $B^*\bar{B}^*$ threshold by 3 MeV
$\Longrightarrow$ fine tunings of energies of isospin-1 adjoint meson with $J^P = 1^-$
and isospin-1 adjoint meson with $J^P = 0^-$
to near critical energies for $b\bar{b}$ ground state at threshold

estimate of energy difference between isospin-1 adjoint mesons with $J^P = 1^-,\ 0^-$
can be compared with lattice QCD !

Most remarkable aspect of Z_b, Z'_b system:
Z'_b does not decay into $B^*\bar{B}$ or $B\bar{B}^*$ despite being 48 MeV higher in energy
quantum interference effect explained by Born-Oppenheimer symmetries !

Qualitative Aspects of Hidden-Heavy Tetraquarks

$X_c = \chi_{c1}(3872)$ has mass within 100 keV of $D^{*0}\bar{D}^0$ threshold

$\Longrightarrow$ fine tuning of energy of isospin-0 adjoint meson with $J^{PC} = 1^{--}$

to near <u>critical energy</u> for $c\bar{c}$ ground state at threshold

energy relative to isospin-1 adjoint mesons can be compared to lattice QCD !

see also Brambilla, Mohapatra, Scarpa & Vairo [arxXiv:241114306]

$Z_b = T_{b\bar{b}1}(10610)$ has mass above $B^*\bar{B}$ threshold by 3 MeV

$Z_c = T_{c\bar{c}1}(3900)$ has mass above $D^*\bar{D}^*$ threshold by 130 MeV

$\Longrightarrow$ $b\bar{b}$ ground state is near <u>critical energy</u> for bound state at threshold

$\Longrightarrow$ lowest energy $c\bar{c}$ state is resonance above threshold

ground-state adjoint hadron is likely to be isospin-0 adjoint meson with $J^{PC} = 1^{--}$
can be verified by lattice QCD !

Qualitative Aspects of Hidden-Heavy Pentaquarks

Nonstrange Hidden-charm Pentaquarks

$P_{c\bar{c}}(4310)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$

$\Longrightarrow$ fine tuning of energy of isospin-$\frac{1}{2}$ adjoint baryon

to near critical energy for $c\bar{c}$ ground state at threshold

Strange Hidden-charm Pentaquarks

$P_{c\bar{c}s}(4338)^0$, $P_{c\bar{c}s}(4459)^0$

$\Longrightarrow$ fine tuning of energy of isospin-0 adjoint baryon

to near critical energy for $c\bar{c}$ ground state at threshold

See *Hidden-Heavy Pentaquarks* and Where to Find Them
Alasiri, Braaten & Bruschini (in preparation)

Quantitative Born-Oppenheimer Predictions

Develop models for Born-Oppenheimer potentials that interpolate between

repulsive color-Coulomb potential offset by adjoint hadron energy at small r

and constant static-hadron-pair threshold at large r

Solve coupled-channel Schroedinger equations for $c\bar{c}$ and $b\bar{b}$

in model Born-Oppenheimer potentials

to determine energies of bound states and resonances

Tune parameters of potentials to reproduce energies

of observed Exotic Heavy-hidden Hadrons

Predict energies of heavy-quark-spin-symmetry partners

Quantitative Born-Oppenheimer Predictions

Short-term goals

$X_c = \chi_{c1}(3872)$: $J^{PC} = 1^{++}$

heavy-quark spin-symmetry partners have $J^{PC} = 1^{+-}, 0^{++}, 2^{++}$

Use diabatic Born-Oppenheimer approximation
including charm-meson mass splittings
to predict their masses to within a few MeV

Predict masses of X_b and its heavy-quark spin-symmetry partners

$Z_b = T_{b\bar{b}1}(10610), Z'_b = T_{b\bar{b}1}(10650)$: $J^P = 1^+$

heavy-quark spin-symmetry partners have $J^P = 0^+, 0^+, 1^+, 2^+$

Use diabatic Born-Oppenheimer approximation
including bottom-meson mass splittings
to predict their masses to within a few MeV

Predict masses of Z_c, Z'_c and their heavy-quark spin-symmetry partners

Exotic Hidden-Heavy Hadrons:

bound states or resonances in Born-Oppenheimer potentials

- repulsive color-Coulomb potentials at small *r*
- cross below static-meson-pair threshold
- approach that threshold at large *r*

Where to Find Them:

near those heavy-hadron-pair thresholds
whose static-hadron-pair potential
connects to adjoint-hadron potential
for the <u>lowest-energy</u> adjoint hadrons

Braaten & Bruschini, Physics Letters B 863,139386 (2025) [arXiv:2409.00802]