Hadrons in medium

— nuclear bound heavy and light quarkonia

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HADRONIC PHYSICS
WITH LEPTON AND HADRON BEAMS
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Motivation
— heavy quarkonia in medium

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Nothing really ambitious

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We want to understand matter that
amounts to 5% of the mass of the universe

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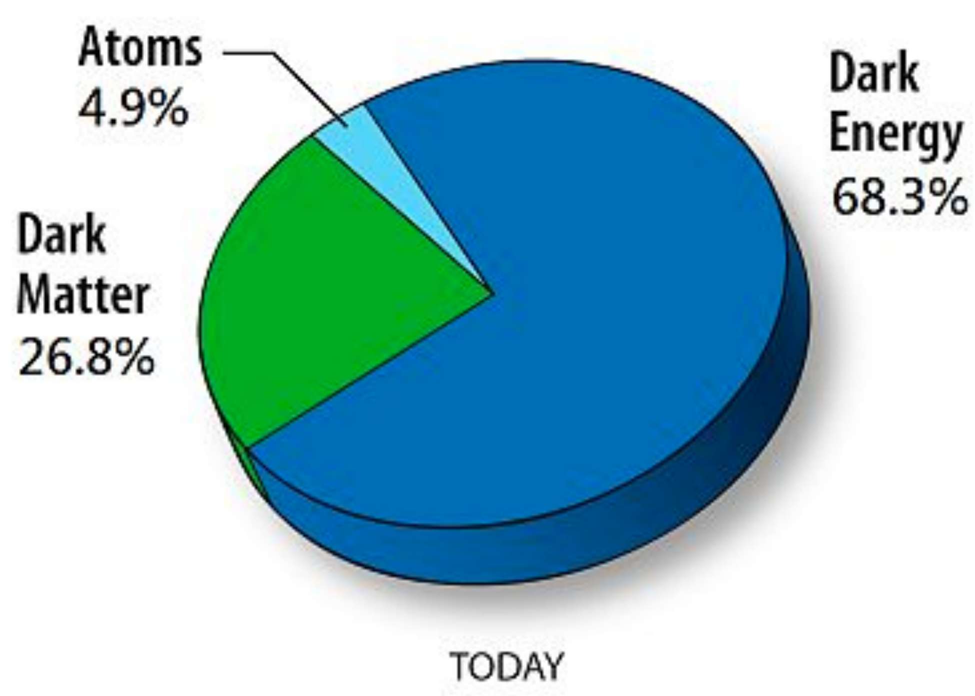

Actually we are even less ambitious than that

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We want to understand the proton mass

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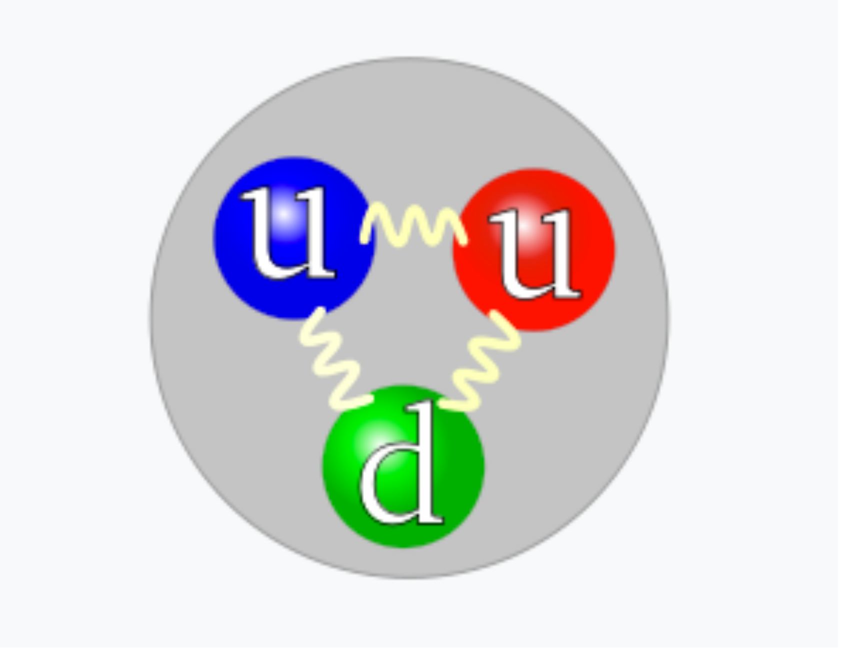


Starting point ?

Seems to be

Q C D

Quantum Chromodynamics

Trace anomaly
— classical theory

Take $m_q = 0$ & $m_Q = \infty$

$$x^\mu \to x'^\mu = \lambda\, x^\mu \quad \begin{cases} q(x) \to q'(x) = \lambda^{3/2} q(\lambda x) \\ A_\mu(x) \to A'_\mu(x) = \lambda\, A_\mu(\lambda x) \end{cases}$$

Action is invariant: $S'_{\rm QCD} = \int d^4x\, \lambda^4\, \mathcal{L}_{\rm QCD}(\lambda x) = \int d^4x'\, \mathcal{L}_{\rm QCD}(x') = S_{\rm QCD}$

Noether theorem: $J^\mu_{\rm dilat}(x) = T^{\mu\nu}(x)\, x_\nu \longrightarrow \partial_\mu J^\mu_{\rm dilat}(x) = T^\mu_\mu(x) = 0$

$$\boxed{\langle h|T^\mu_\mu|h\rangle = m_h \to 0}$$

$|h\rangle$: hadron state

Trace anomaly
— quantum theory

$$\boxed{g = g(\mu)}$$

$$T^{\mu}_{\mu}(x) \;=\; \frac{2\beta(\alpha_s)}{\alpha_s}\frac{1}{4}G^a_{\mu\nu}(x)G^{a\mu\nu}(x) = -\frac{1}{2}b_0\alpha_s\, G^a_{\mu\nu}(x)G^{a\mu\nu}(x)$$

$$= \;-\frac{9}{32\pi^2}\, g^2 G^a_{\mu\nu}(x)G^{a\mu\nu}(x)$$

$$\boxed{m_h = -\frac{9}{32\pi^2}\,\langle h|g^2 G^a_{\mu\nu}G^{a\mu\nu}|h\rangle}$$

The entire mass comes from gluons

Contribution from quark masses

$$m_h = \frac{\beta(\alpha_s)}{2\alpha_s} G^a_{\mu\nu}(x) G^{a\mu\nu}(x) + \langle h | \bar{q}\, m_q\, q | h \rangle$$

small

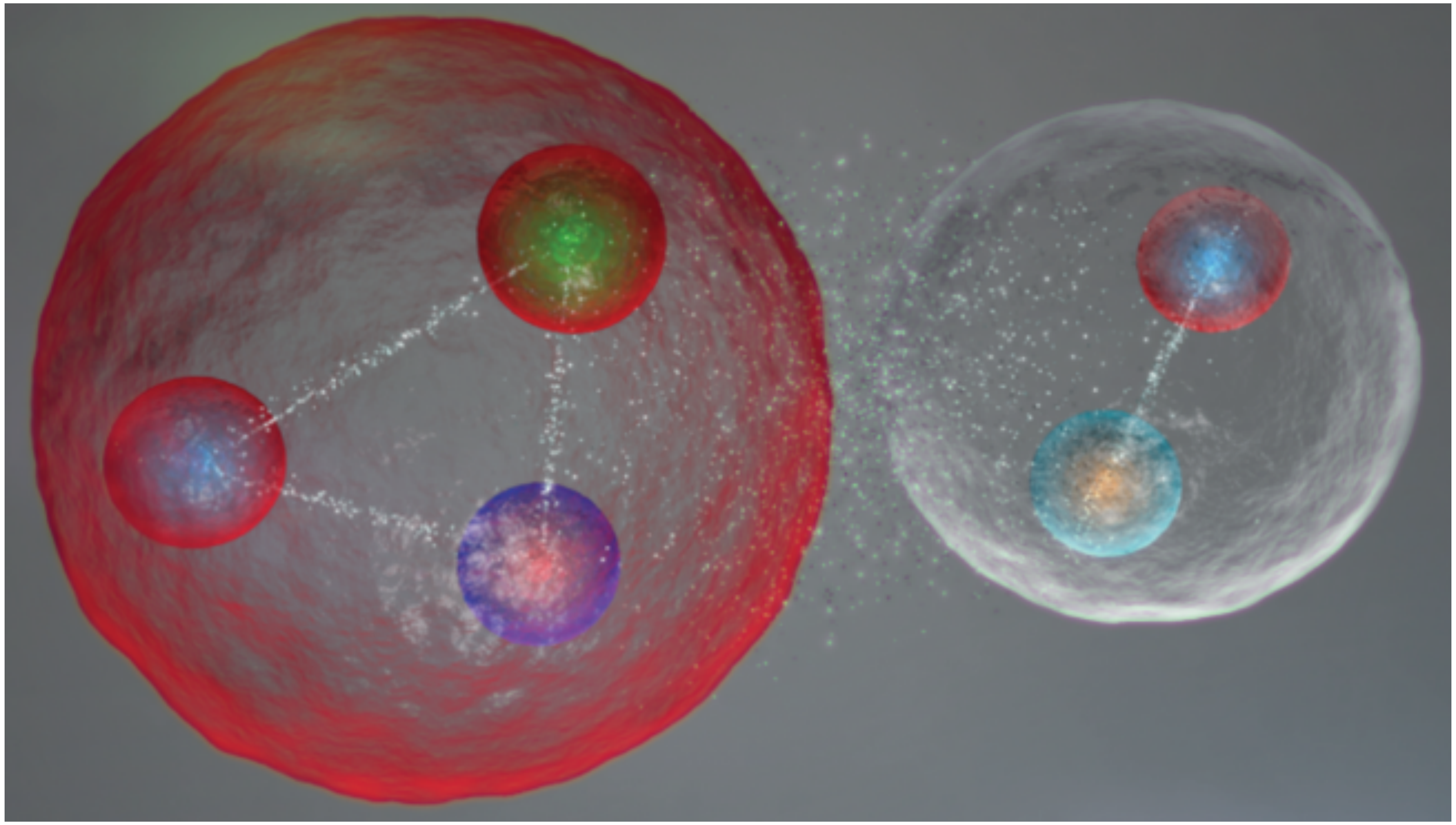
Why is this interesting ?

Because

$$\boxed{\langle h | g^2 G^a_{\mu\nu} G^{a\mu\nu} | h \rangle}$$

accessed through threshold
quarkonium-nucleon scattering

Quarkonium-nucleon



Quarkonium: $\phi(s\bar{s}), \;\; \eta_c(c\bar{c}), \;\; J/\Psi(c\bar{c}), \;\; \eta_b(b\bar{b}), \;\; \Upsilon(b\bar{b})$

Quarkonium-nucleon scattering

$$\varphi = \phi(s\bar{s}), \quad \eta_c(c\bar{c}), \quad J/\Psi(c\bar{c}), \quad \eta_b(b\bar{b}), \quad \Upsilon(b\bar{b})$$

Forward amplitude

$$\mathcal{A}_{\varphi N} = \frac{1}{2}\alpha_\varphi \langle N| \left(g\vec{E}\right)^2 |N\rangle$$

α_φ : color polarizability

Chromopolarizability & color van der Waals forces
— an EFT perspective

Interactions between color neutral objects:

Via creation of instantaneous color dipole moments &
gluon transitions in virtual color-octet intermediate state

— Polarizability—

N. Brambilla, GK, J. Tarrús-Castellà, A. Vairo, PRD 93, 054002 (2016)

EFT approach

— Chromopolarizability of quarkonium

use pNRQC (potential Nonrelativistic QCD)

— van der Waals force

use QCD trace anomaly to match pNRQC to a chiral EFT

QCD $\longrightarrow$ NRQCD $\longrightarrow$ pNRQCD

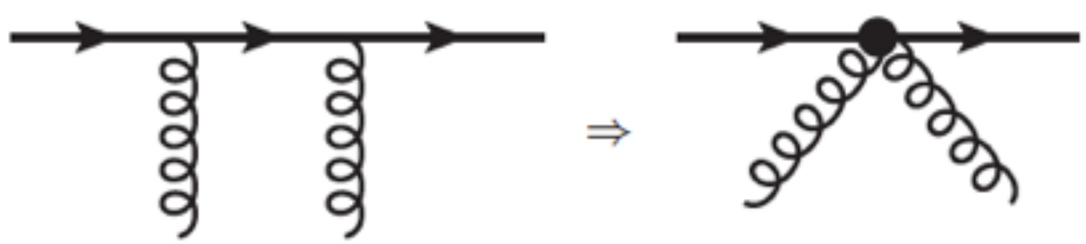
$\downarrow$

gWEFT $\longrightarrow$ χEFT $\longrightarrow$ WEFT

Polarizability

van der Waals

Chromopolarizability



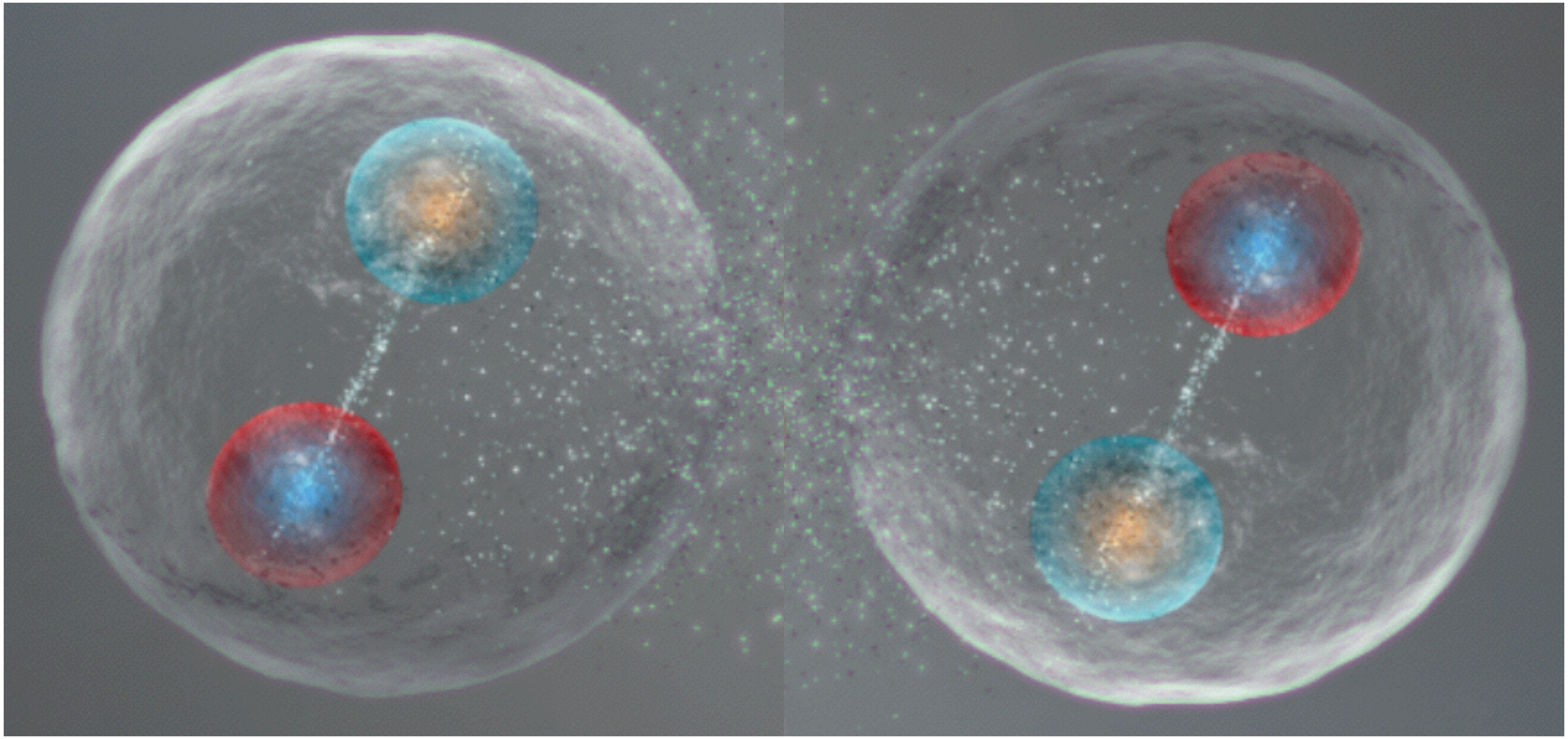
pNRQCD $\longrightarrow$ gWEFT

$$\mathcal{L}_{\mathrm{gWEFT}} = \mathcal{L}_{\mathrm{light}} + \varphi^\dagger(t,\vec{R})\left(i\partial_0 - E_\varphi + \frac{\nabla^2_{\vec{R}}}{4m} + \frac{1}{2}\alpha_\varphi g^2 \vec{E}^2 + \cdots\right)\varphi(t,\vec{R})$$

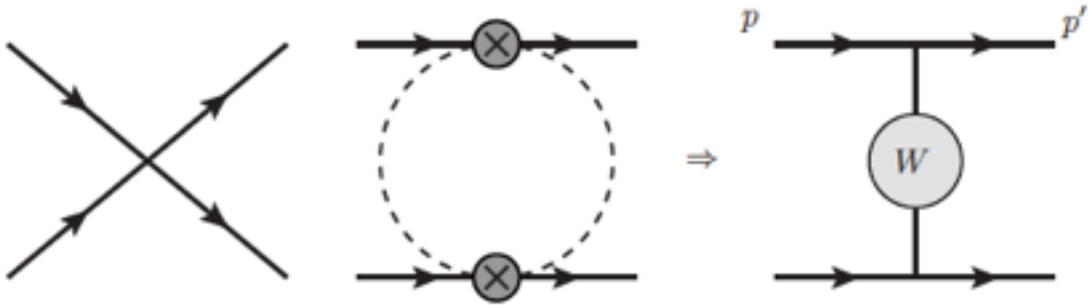
Chromopolarizability

$$\alpha_\varphi = -\frac{2V_A^2 T_F}{3N_c}\langle\varphi|r^i\frac{1}{E_\varphi - h_o}r^i|\varphi\rangle$$

$$\eta_b - \eta_b$$



vdW potential



$$\boxed{\eta_b - \eta_b}$$

$$W(r) \sim -\frac{3(3+\kappa_2)^2 \pi^{3/2} \beta^2}{4b^2} \frac{m_\pi^{9/2}}{r^{5/2}} e^{-2m_\pi r}$$

N. Brambilla, GK, J. Tarrús-Castellà, A. Vairo, PRD 93, 054002 (2016)

H. Fujii and D. Kharzeev, PRD 60, 114039 (1999)

Quarkonium-nucleon

Natural staring point: gWEFT

$$\mathcal{L}_{\mathrm{gWEFT}} = \mathcal{L}_{\mathrm{light}} + \varphi^\dagger(t,\vec{r})\left(i\partial_0 - E_\varphi + \frac{\nabla^2}{4m_\varphi} + \frac{1}{2}\alpha_\varphi g^2 \vec{E}^2 + \cdots\right)\varphi(t,\vec{r})$$

$$\alpha_\varphi = -\frac{2V_A^2 T_F}{3N_c}\langle\varphi|r^i\frac{1}{E_\varphi - h_o}r^i|\varphi\rangle$$

$\varphi(t,\vec{r})$: quarkonium field

Embed this into a
nuclear many-body framework

GK, A. W. Thomas, K. Tsushima, arXiv:1706.02688

Quarkonium in nuclei

$$H = H_N + H_{\varphi N}$$

$$\begin{aligned} H_{\varphi N} \;&=\; \int d^3r\, \varphi^\dagger(t,\vec{r}) \left(-\frac{1}{2m_\varphi}\nabla^2\right) \varphi(t,\vec{r}) \\ &+ \int d^3r d^3r'\, N^\dagger(t,\vec{r})\varphi^\dagger(t,\vec{r}\,')\, W_{\varphi N}(\vec{r}-\vec{r}\,')\, \varphi(t,\vec{r}\,')N(t,\vec{r}) \end{aligned}$$

Quarkonium-nucleon potential
— from EFT, lattice, ….

Hartree-Fock equation

$$\boxed{-\frac{1}{2m_\varphi}\nabla^2\varphi_\alpha(\vec{r}) + W_{\varphi A}(\vec{r})\varphi_\alpha(\vec{r}) = \epsilon_\alpha\varphi_\alpha(\vec{r})}$$

$$W_{\varphi A}(\vec{r}) = \int d^3r'\, W_{\varphi N}(\vec{r}-\vec{r}\,')\,\rho_A(\vec{r}\,')$$

$$\rho_A(\vec{r}) = \langle A|N^\dagger(\vec{r})N(\vec{r})|A\rangle = \sum_{n=1}^{A} N_n^*(\vec{r})N_n(\vec{r})$$

From experiment or a model

Need quarkonium-nucleon

$$\mathcal{A}_{\varphi N} = \frac{1}{2}\alpha_\varphi \langle N| \left(g\vec{E}\right)^2 |N\rangle$$

Trace anomaly: $\langle N| \left[\left(g\vec{E}\right)^2 - \left(g\vec{B}\right)^2\right] |N\rangle = -\frac{1}{2}\langle N|g^2 G^a_{\mu\nu} G^{a\mu\nu}|N\rangle = \frac{16\pi^2}{9} m_N \leq \langle N| \left(g\vec{E}\right)^2 |N\rangle$

Scattering length: $a_{\varphi N} = -\left(\frac{\mu_{\varphi N}}{2\pi}\right) \mathcal{A}_{\varphi N} = -\left(\frac{\mu_{\varphi N}}{4\pi}\right) \alpha_\varphi \langle N| \left(g\vec{E}\right)^2 |N\rangle$

$$\boxed{a_{\varphi N} \leq -\left(\frac{\mu_{\varphi N}}{4\pi}\right) \frac{16\pi^2}{9} m_N \alpha_\varphi = -\frac{4\pi m_N}{9} \mu_{\varphi N} \alpha_\varphi}$$

Quarkonium in nuclei

$$W_{\varphi A}(\vec{r}) = \int d^3r'\, W_{\varphi N}(\vec{r}-\vec{r}')\, \rho_A(\vec{r}')$$

From the forward amplitude:

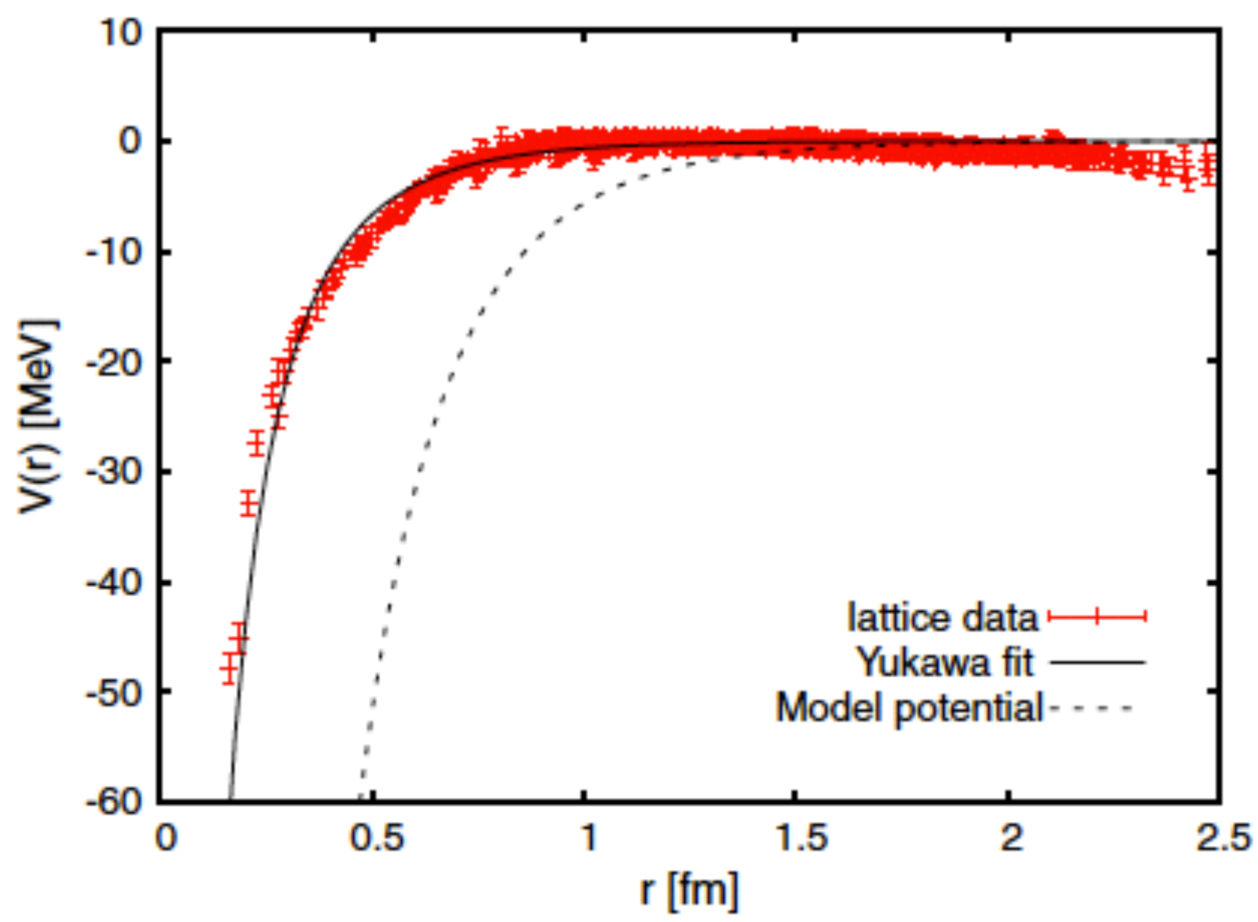
$$W^{\rm pol}_{\varphi N}(\vec{r}) = \frac{4\pi}{2\mu_{\varphi N}}\, a_{\varphi N}\, \delta(\vec{r}) = -\frac{8\pi^2}{9} m_N \alpha_\varphi\, \delta(\vec{r})$$

$$\boxed{W^{\rm pol}_{\varphi A}(\vec{r}) = \frac{4\pi}{2\mu_{\varphi N}}\, a_{\varphi N}\, \rho_A(\vec{r}) = -\frac{8\pi^2}{9} m_N \alpha_\varphi\, \rho_A(\vec{r})}$$

$$k\ \mathrm{cotan}\,\delta(k) = -\frac{1}{a} + \frac{1}{2} r_e k^2 + \cdots$$

Lattice*

— quenched, m_π = 640 MeV



Yukawa fit

$$V_{N\eta_c} = -\gamma \frac{e^{-\alpha r}}{r}$$

$$\gamma = 0.1$$
$$\alpha = 3 \text{ fm}^{-1}$$

T. Kawanay & S. Sasaki, PRD 82, 091501 (2010)

Pion mass dependence
— quenched x unquenched

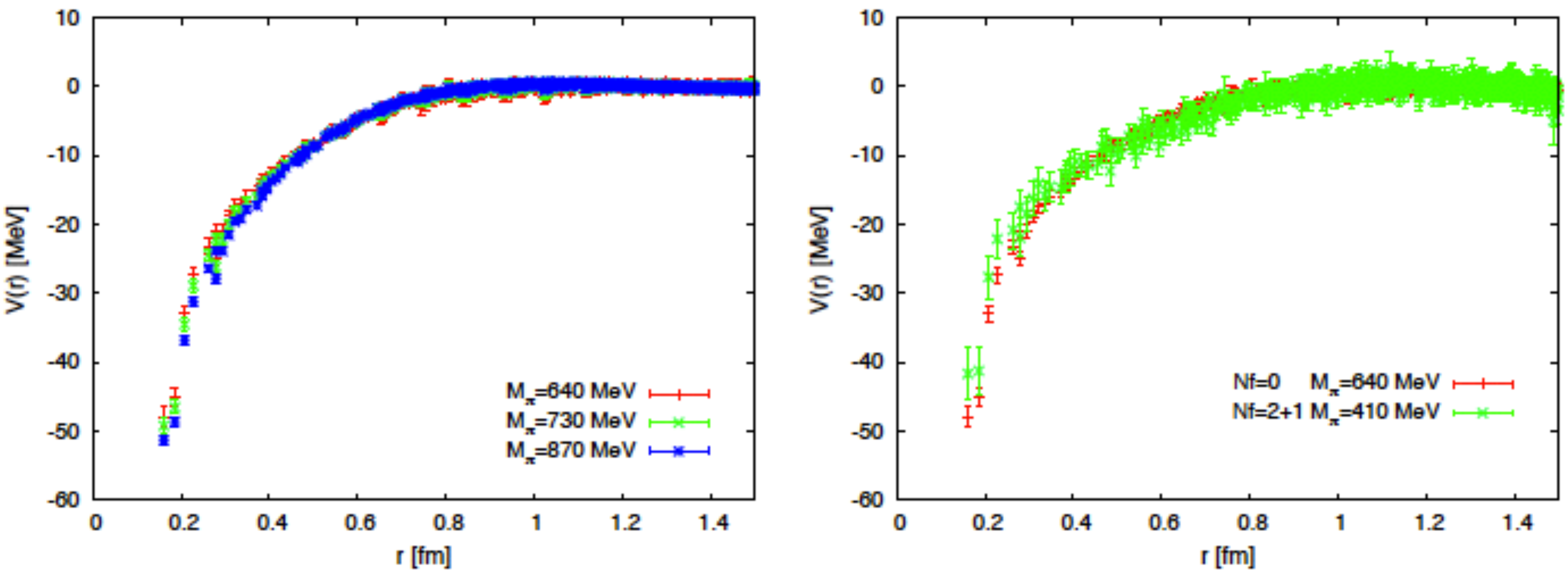


Figure 2: The quark-mass dependence of the η_c-N potential (left) and a comparison between quenched and dynamical simulations (right)

T. Kawanay & S. Sasaki, Pos (Lattice) 2010, 156 (2010)

Fit to lattice results

Reproduce scattering length

$$W^{\rm latt}_{\varphi N}(r) = -W_0\,[1 - f(r, r_{\rm vdW})] + V^{\rm fit}_{\eta_c N}(r)\, f(r, r_{\rm vdW})$$

$$f(r, r_{\rm vdW}) = \frac{1}{1 + (r_{\rm vdW}/r)^{10}}.$$

$$\boxed{W^{\rm latt}_{\varphi A}(\vec{r}) = \int d^3r'\, W^{\rm latt}_{\varphi N}(\vec{r} - \vec{r}\,')\rho_A(\vec{r}\,')}$$

Fit to lattice results

$$(a_{J/\Psi N})_{\rm SAV} \sim 0.35 \text{ fm} > a_{\eta_c N} \sim 0.25 \text{ fm}$$

$$r_e \sim 1.0 \text{ fm}$$

	$\eta_c N$		$J/\Psi N$	
$r_{\rm vdW}$	W_0	r_e	W_0	r_e
0.3	252	1.4	288	1.2
0.5	74	1.7	95	1.4

Quarkonium in nuclei

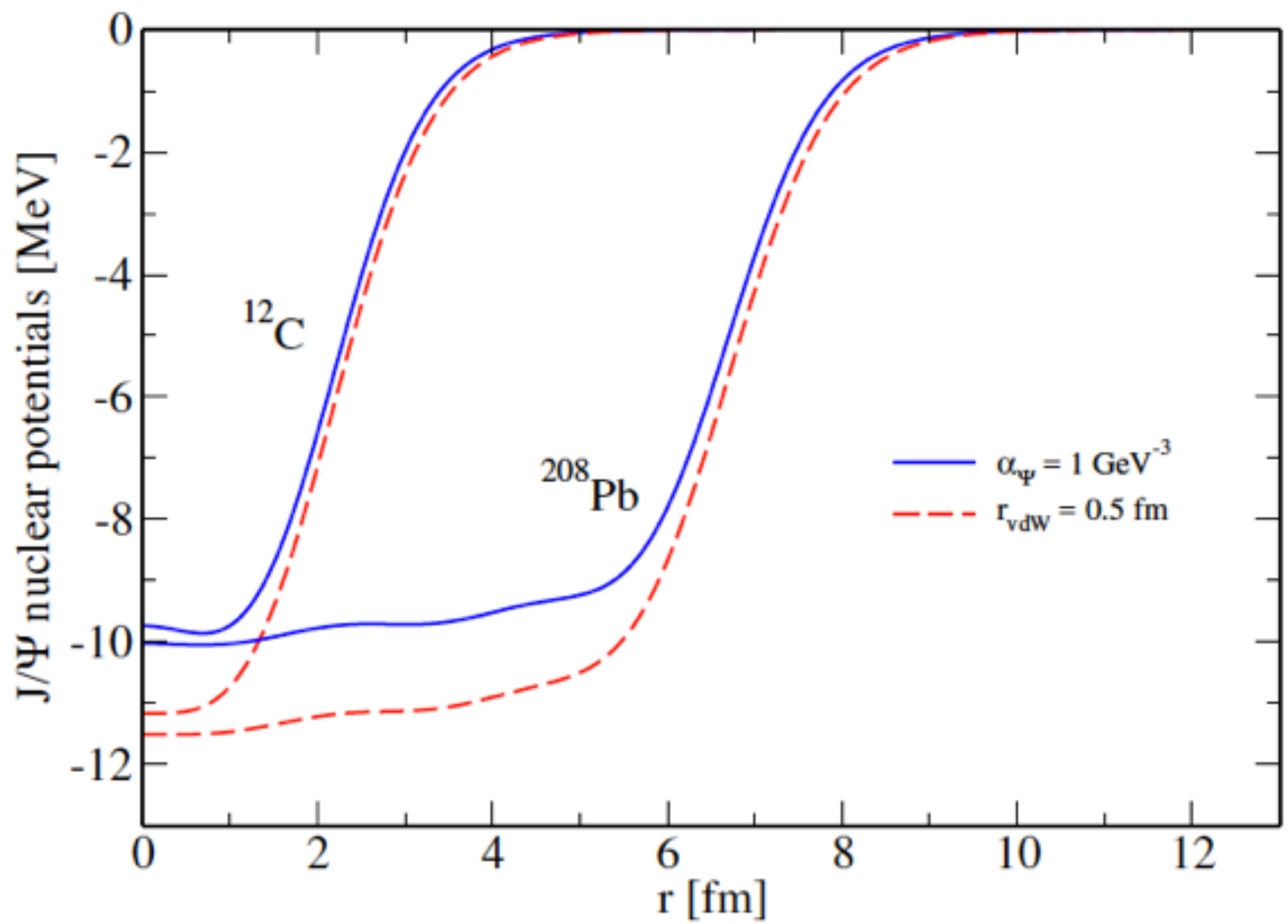


Figure 8: J/Ψ nuclear potentials $W^{\text{pol}}_{J/\Psi A}(\vec{r})$ (solid line) for a polarizability $\alpha_{J/\Psi} = 1\ \text{GeV}^{-3}$ and $W^{\text{latt}}_{J/\Psi A}(\vec{r})$ (dashed line) from a fit to the lattice data with a cutoff $r_{\text{vdW}} = 0.5$ fm.

Quarkonium in nuclei

Table 7: Predictions for J/Ψ single-particle energies in several nuclei obtained with the polarization potential $W^{\rm pol}_{J/\Psi A}(\vec{r})$, defined in Eq. (105).

	${}^{4}_{J/\Psi}$He	${}^{12}_{J/\Psi}$C	${}^{16}_{J/\Psi}$O	${}^{40}_{J/\Psi}$Ca	${}^{48}_{J/\Psi}$Ca	${}^{90}_{J/\Psi}$Zr	${}^{208}_{J/\Psi}$Pb
			$\alpha_{J/\Psi} = 1$ GeV^{-3}				
1s	n	-3.36	-4.41	-6.77	-6.84	-7.91	-8.38
1p	n	n	-0.39	-3.47	-3.95	-5.71	-7.05
2s	n	n	n	-0.26	-0.59	-2.70	-5.01
2p	n	n	n	n	n	-0.21	-2.94
3s	n	n	n	n	n	n	-0.70
			$\alpha_{J/\Psi} = 2$ GeV^{-3}				
1s	-4.49	-10.76	-12.62	-16.41	-16.16	-17.70	-17.27
1p	n	-3.98	-6.54	-11.95	-12.44	-14.95	-16.30
2s	n	n	-0.54	-6.74	-7.50	-11.07	-13.95
2p	n	n	n	-1.62	-2.52	-7.33	-11.41
3s	n	n	n	n	n	-2.71	-8.28

GK, A. W. Thomas, K. Tsushima, arXiv:1706.02688

Quarkonium in nuclei

Table 8: Single-particle energies of η_c and J/Ψ in selected nuclei. The $\eta_c N$ and $J/\Psi N$ potentials fit the lattice scattering lengths and incorporate the Yuakwa tail from the fit from lattice data.

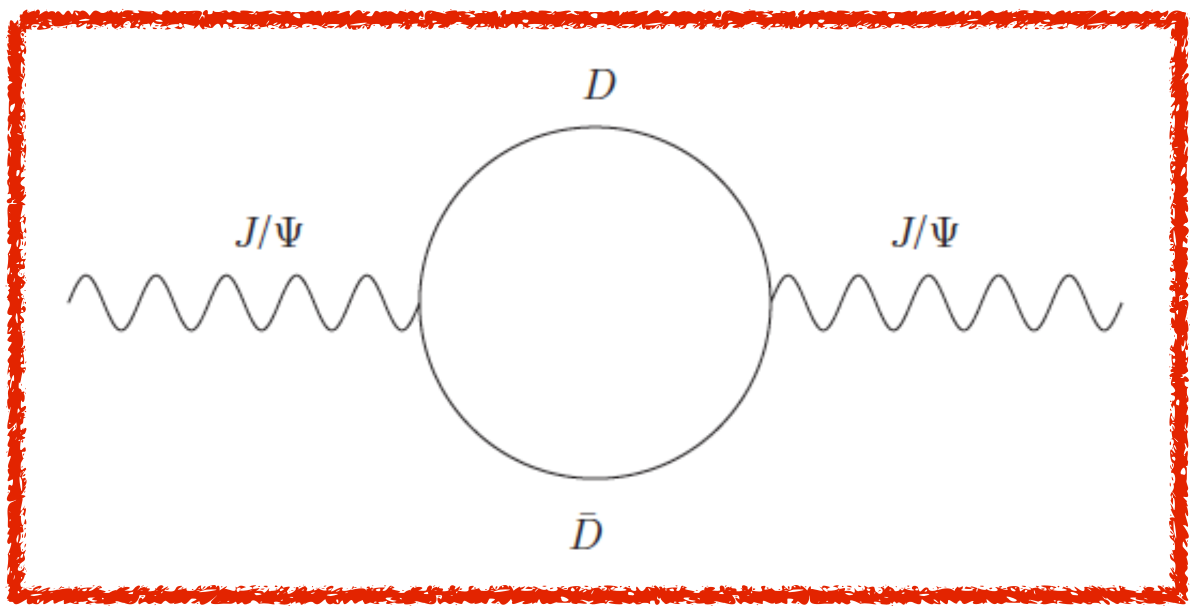
	$^{16}_{\eta_c}$O	$^{40}_{\eta_c}$Ca	$^{90}_{\eta_c}$Zr	$^{290}_{\eta_c}$Pb	$^{16}_{J/\Psi}$O	$^{40}_{J/\Psi}$Ca	$^{90}_{J/\Psi}$Zr	$^{290}_{J/\Psi}$Pb
				$r_{\mathrm{vdW}} = 0.3$ fm				
1s	-2.92	-5.15	-6.32	-6.88	-3.62	-5.92	-7.10	-7.62
1p	n	-2.06	-4.17	-5.55	n	-2.74	-4.93	-6.29
2s	n	n	-1.40	-3.53	n	n	-2.06	-4.29
2p	n	n	n	-1.50	n	n	n	-2.30
				$r_{\mathrm{vdW}} = 0.5$ fm				
1s	-3.62	-5.99	-7.23	-7.79	-5.23	-7.95	-9.24	-9.74
1p	n	-2.72	-4.99	-6.41	-0.87	-4.41	-6.90	-8.33
2s	n	n	-2.04	-4.33	n	-0.82	-3.71	-6.20
2p	n	n	n	-2.28	n	n	-0.92	-4.03

GK, A. W. Thomas, K. Tsushima, arXiv:1706.02688

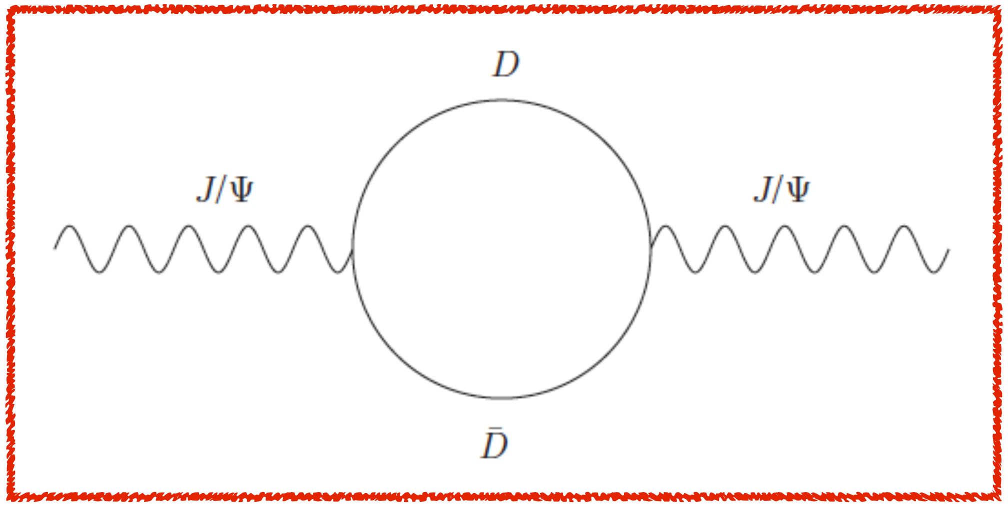
Another mechanism ?

D,D* meson-loop

D mesons interact with the nuclear mean fields



D,D*-meson loops



Calculate loop with effective Lagrangians

– need coupling constants & form factors

– need medium dependence of D masses

D,D* in medium

Light quarks in D mesons

— quark condensate changes for nonzero temperature and baryon density

— quark-model: masses of the D mesons change

Quark condensate at finite T

— model independent result*

For low temperatures:

$$\frac{\langle \bar{q}q \rangle_T}{\langle \bar{q}q \rangle} = 1 - \frac{\Sigma_\pi}{m_\pi^2 f_\pi^2}\, \rho_s^\pi(T)$$

$$\simeq 1 - \frac{T^2}{8 f_\pi^2}$$

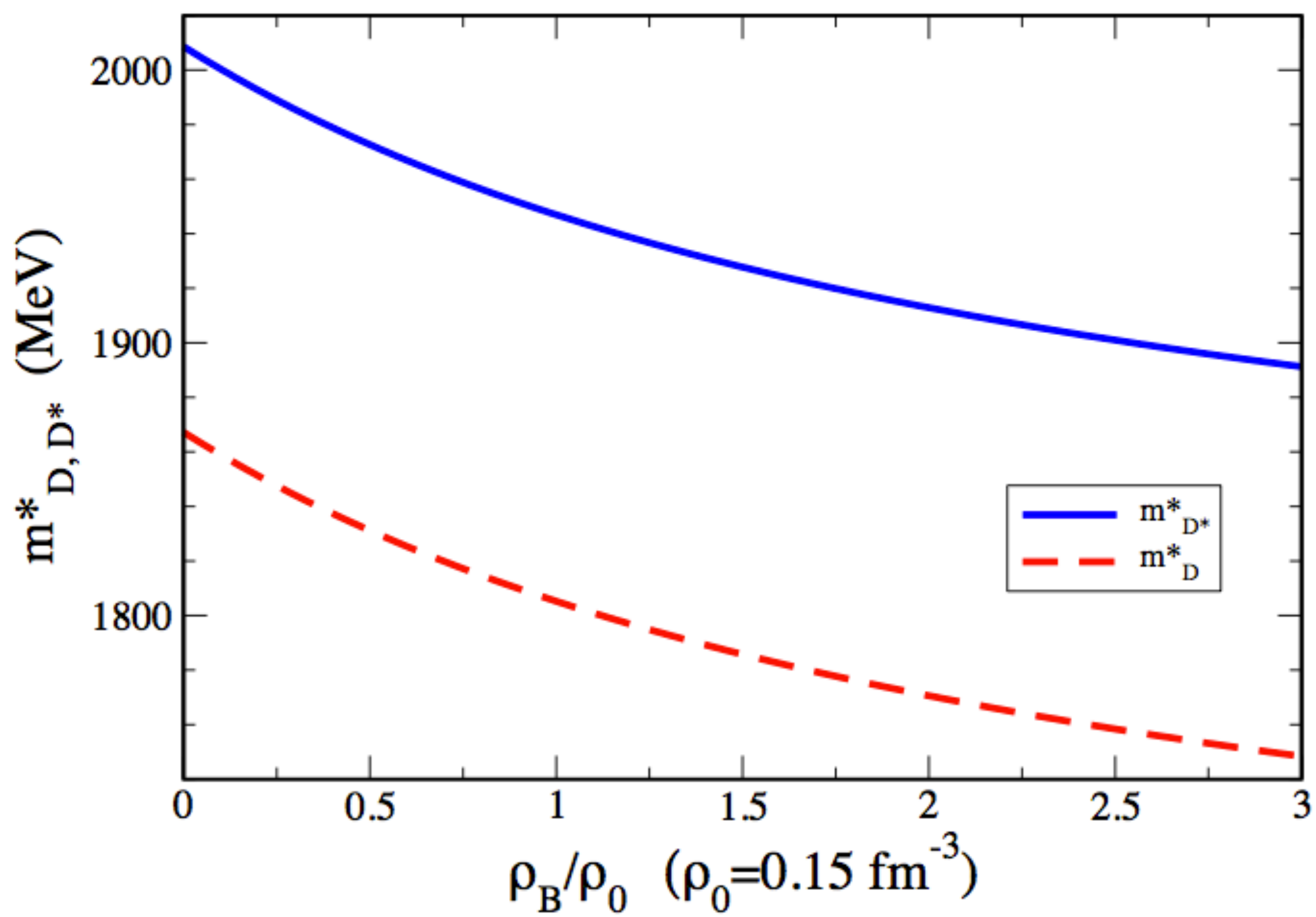
$$\Sigma_\pi = m_q \frac{dm_\pi}{dm_q}$$

$\rho_s^\pi(T)$: scalar density of pions in medium

* Gerber & Leutwyler (1989)

D,D* in medium

— QMC model

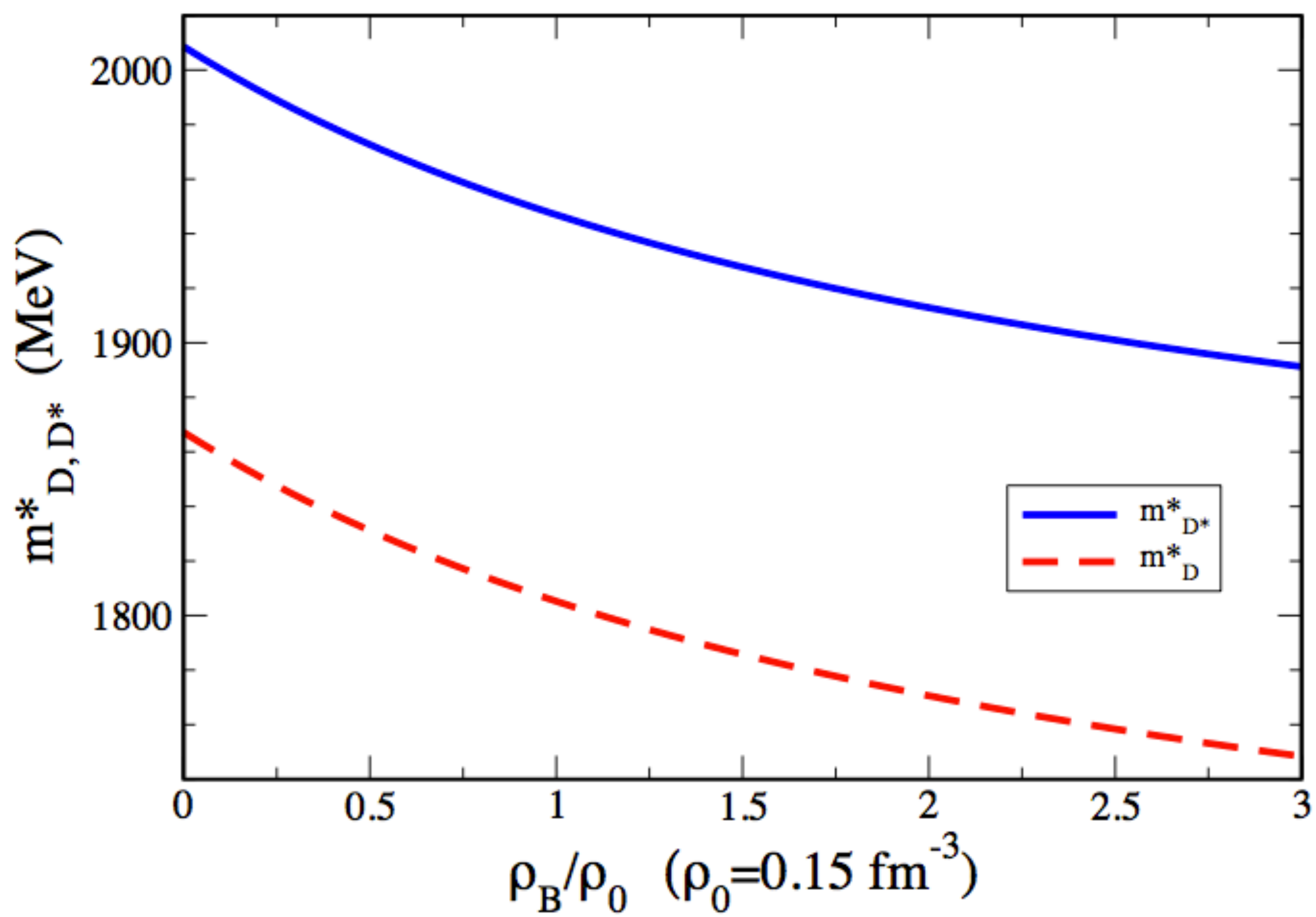


Low temperature and density:

K. Saito, K. Tsushima & A.W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

D,D* in medium

— QMC model



Low temperature and density:

$$\langle \bar{q}q \rangle \simeq \left(1 - \frac{T^2}{8f_\pi^2} - 0.3\frac{\rho}{\rho_0}\right) \langle \bar{q}q \rangle_{\rm vac}$$

K. Saito, K. Tsushima & A.W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

Effective Lagrangians

– SU(4) flavor symmetry for coupplings

$$\mathcal{L}_{\psi DD} = i g_{\psi DD}\, \psi^\mu \left[\bar{D} \left(\partial_\mu D \right) - \left(\partial_\mu \bar{D} \right) D \right]$$

$$\mathcal{L}_{\psi DD^*} = \frac{g_{\psi DD^*}}{m_\psi}\, \varepsilon_{\alpha\beta\mu\nu} \left(\partial^\alpha \psi^\beta \right) \left[\left(\partial_\mu \bar{D}^{*\nu} \right) D + \bar{D} \left(\partial_\mu D^{*\nu} \right) \right]$$

$$\begin{aligned} \mathcal{L}_{\psi D^* D^*} &= i g_{\psi D^* D^*} \left\{ \psi^\mu \left[\left(\partial_\mu \bar{D}^{*\nu} \right) D^*_\nu - \bar{D}^{*\nu} \left(\partial_\mu D^*_\nu \right) \right] \right. \\ &+ \left[\left(\partial_\mu \psi^\nu \right) \bar{D}^*_\nu - \psi^\nu \left(\partial_\mu \bar{D}^*_\nu \right) \right] D^{*\mu} \\ &+ \left. \bar{D}^{*\mu} \left[\psi^\nu \left(\partial_\mu D^*_\nu \right) - \left(\partial_\mu \psi^\nu \right) D^*_\nu \right] \right\} \end{aligned}$$

J/Ψ in nuclear matter

J/Ψ self-energy:

$$i\Sigma_{\psi}^{D\bar{D}}(k^2) = -\frac{8}{3} g_{\psi D\bar{D}}^2 \int \frac{d^4 q}{(2\pi)^4} F(q^2) \Delta_D(q) \Delta_{\bar{D}}(k-q)$$

$\Delta_D, \Delta_{\bar{D}}$: propagators

$F(q^2)$: form factors, extension of the mesons

Effective potential:

$$U_{\psi}(\rho_B) \equiv m_{\psi}^* - m_{\psi}$$

$$\boxed{\begin{aligned} m_{\psi}^2 &= \left(m_{\psi}^{(0)}\right)^2 + \Sigma_{\psi}^{D\bar{D}}(k^2 = m_{\psi}^2) \\ m_{\psi}^{*2} &= \left(m_{\psi}^{(0)}\right)^2 + \Sigma_{\psi}^{*D\bar{D}}(k^2 = m_{\psi}^2) \end{aligned}}$$

Structure of the mesons
— form factors

$^3P_0$ — model

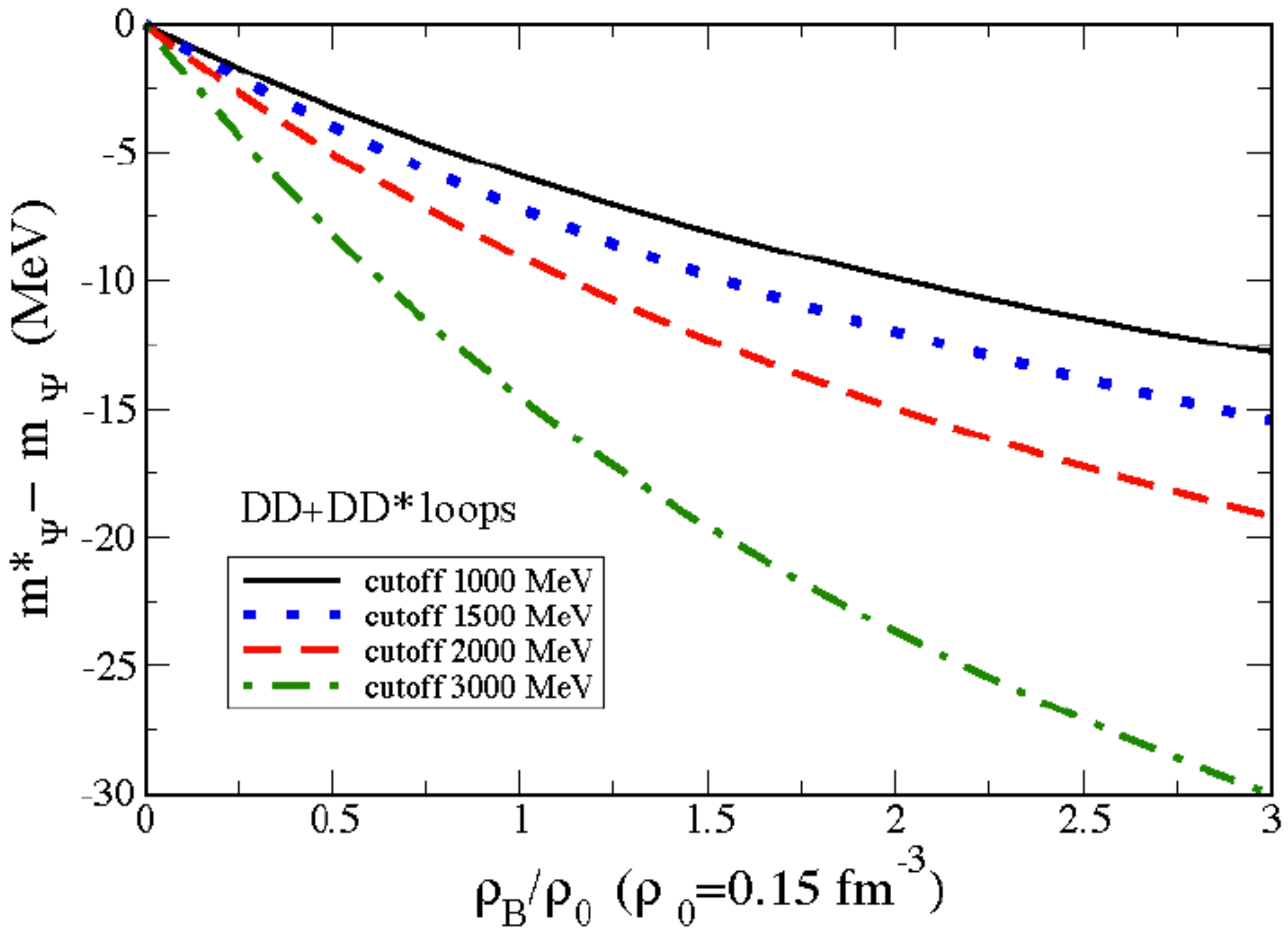
(E. Swanson)

$$F(q^2) = \gamma^2 \pi^{3/2} \frac{m_\psi^3}{\beta^3} \frac{2^6 r^3 (1+r^2)^2}{(1+2r^2)^5} e^{-q^2/2\beta_D^2(1+2r^2)}, \qquad r = \frac{\beta_\psi}{\beta_D}$$

Phenomenological

$$F(q^2) = \left[\frac{\Lambda^2 + m_\psi^2}{\Lambda^2 + 4(q^2 + m_D^2)} \right]^2, \quad g_{\psi D\bar{D}} = 7.7$$

J/Ψ in nuclear matter



GK, A. W. Thomas & K. Tsushima PLB 697, 136 (2011)

J/Ψ single-particle energies in nuclei

— from Klein-Gordon equation

		$\Lambda_{D,D^*} = 1500$ MeV	$\Lambda_{D,D^*} = 2000$ MeV
		E (MeV)	E (MeV)
$^{4}_{\Psi}$He	1s	−4.19	−5.74
$^{12}_{\Psi}$C	1s	−9.33	−11.21
	1p	−2.58	−3.94
$^{16}_{\Psi}$O	1s	−11.23	−13.26
	1p	−5.11	−6.81
$^{40}_{\Psi}$Ca	1s	−14.96	−17.24
	1p	−10.81	−12.92
	1d	−6.29	−8.21
	2s	−5.63	−7.48
$^{90}_{\Psi}$Zr	1s	−16.38	−18.69
	1p	−13.84	−16.07
	1d	−10.92	−13.06
	2s	−10.11	−12.22
$^{208}_{\Psi}$Pb	1s	−16.83	−19.10
	1p	−15.36	−17.59
	1d	−13.61	−15.81
	2s	−13.07	−15.26

K. Tsushima, D. Lu, GK & A.W. Thomas PRC 83, 065208 (2011)

PHYSICAL REVIEW D **91,** 114503 (2015)

Quarkonium-nucleus bound states from lattice QCD

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Quarkonium-nucleus systems are composed of two interacting hadronic states without common valence quarks, which interact primarily through multigluon exchanges, realizing a color van der Waals force. We present lattice QCD calculations of the interactions of strange and charm quarkonia with light nuclei. Both the strangeonium-nucleus and charmonium-nucleus systems are found to be relatively deeply bound when the masses of the three light quarks are set equal to that of the physical strange quark. Extrapolation of these results to the physical light-quark masses suggests that the binding energy of charmonium to nuclear matter is $\boxed{B^{\mathrm{NM}}_{\mathrm{phys}} \lesssim 40\ \mathrm{MeV}}$.

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Models

TABLE I. Estimates for the binding energies of charmonium to light nuclei and nuclear matter (in MeV) from selected models. A "$*$" indicates the system is predicted to be unbound, while entries with center dots indicate that the system was not addressed.

	Binding energy (MeV)			Binding energy (MeV)	
Ref.	^{3}He η_c	^{4}He η_c	NM η_c	^{4}He J/ψ	NM J/ψ
[1]	19	140	$*$		
[2]	0.8	5	27		
[3]			10		10
[5]	$*$	$*$	9		
[6]					5
[7]				5	18
[8]				15.7	

NPLQCD

TABLE V. The binding energies (in MeV) of charmonium-nucleus systems calculated on the $L = 24$ and 32 ensembles. The rightmost column shows the infinite-volume estimate, which, without results on the $L = 48$ ensemble, is taken to be the binding calculated on the $L = 32$ ensemble. The first and second sets of parentheses shows the statistical and quadrature-combined statistical plus systematic uncertainties, respectively.

System	$24^3 \times 64$	$32^3 \times 64$	$L = \infty$
$N\eta_c$	17.9(0.4)(1.5)	19.8(0.7)(2.6)	19.8(2.6)
$d\eta_c$	39.3(1.3)(4.8)	42.4(1.1)(7.9)	42.4(7.9)
$pp\eta_c$	37.8(1.1)(4.5)	41.5(1.0)(7.5)	41.5(7.6)
^{3}Heη_c	57.2(1.3)(8.3)	56.7(2.0)(9.4)	56.7(9.6)
^{4}Heη_c	70(02)(13)	56(06)(17)	56(18)
^{4}HeJ/ψ	75.7(1.9)(9.4)	53(07)(18)	53(19)

Phenomenological implications

Mass/Mass difference	$1S\,[\mathrm{MeV}]$	$1P\,[\mathrm{MeV}]$	$2S\,[\mathrm{MeV}]$
M_{nL} (experiment)	3068.6	3525.3	3674.4
$M_{nL}^{(0)}$ (Schrödinger)	3068.6	3483.3	3674.4
$\Delta M^{(\pi)}$	-1.7	-3.1	-4.0
$\Delta M^{(K)}$	-1.5	-2.9	-3.8
$\Delta M^{(\rho)}$	-2.5	-4.9	-6.5
$\Delta M^{(K^*)}$	-1.6	-3.2	-4.2
$\Delta M^{(\phi)}$	-1.6	-3.2	-4.3
$\Delta M^{(N)}$	-2.4	-4.3	-5.5
$\Delta M^{(\Xi)}$	-2.0	-3.9	-5.1
$\Delta M^{(\Delta)}$	-0.9	-1.0	-1.0
$\Delta M^{(\Xi^*)}$	-2.6	-4.8	-6.3

We find $\Delta M^{(H)} < 0 \Rightarrow$ charmonium "within" a hadron H is energetically favourable.

Light quarkonium in nuclei

$$\boxed{\phi}$$

J.J. Cobos-Martínez, K. Tsushima, G. Krein, A.W. Thomas

— Phys. Lett. B771, 113 (2017)

— Phys. Rev. C 96, 035201 (2017)

Mass and width in medium

$$\boxed{\begin{gathered} m_\phi^2 = \left(m_\phi^0\right)^2 + \Re\Pi_\phi(m_\phi^2) \\ \Gamma_\phi = -\frac{1}{m_\phi}\Im\Pi_\phi \end{gathered}}$$

$$\Re\Pi_\phi = -\frac{2}{3}g_\phi^2\,\mathcal{P}\!\int\frac{\mathrm{d}^3q}{(2\pi)^3}\,\vec{q}^{\,2}\frac{1}{E_K(E_K^2 - m_\phi^2/4)}$$

$$\Im\Pi_\phi = -\frac{g_\phi^2}{24\pi}m_\phi^2\left(1 - \frac{4m_K^2}{m_\phi^2}\right)^{3/2}$$

ϕ-nucleus bound states

		E	$\Gamma/2$	E	$\Gamma/2$
^{4}He	1s	-1.39	0	n	
^{12}C	1s	-7.70	0	-6.47	11.00
^{208}Pb	1s	-21.22	0	-21.06	16.25
	1p	-17.69	0	-17.35	15.76
	1d	-13.34	0	-12.78	15.06
	2s	-11.68	0	-10.97	14.67

Binding energy ~ width

Perspectives

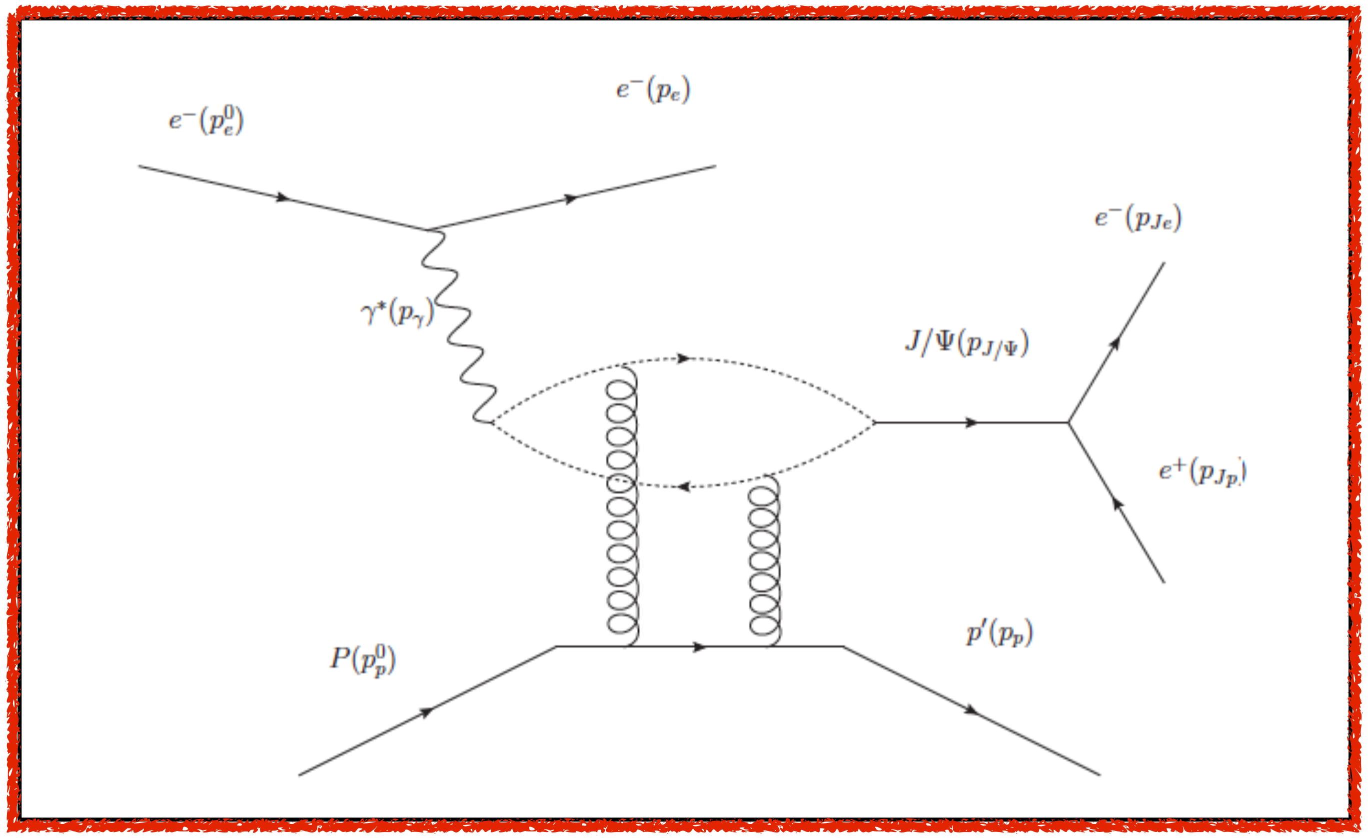
— EFT: nonperturbative input from the lattice

— Phenomenology: need experiments, e.g. DN

— J/Ψ electroproduction on nuclei (JLab)

— ϕ large width, challenging

JLab @ 12 GeV



Need crucial input

— DN interaction

Need crucial input

— DN interaction

$\overline{\mathrm{P}}$ANDA @ FAIR

Need crucial input
— DN interaction

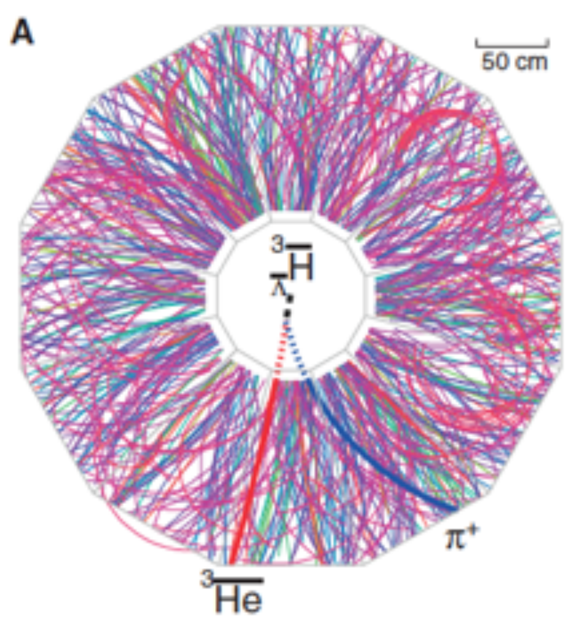
P̄ANDA @ FAIR

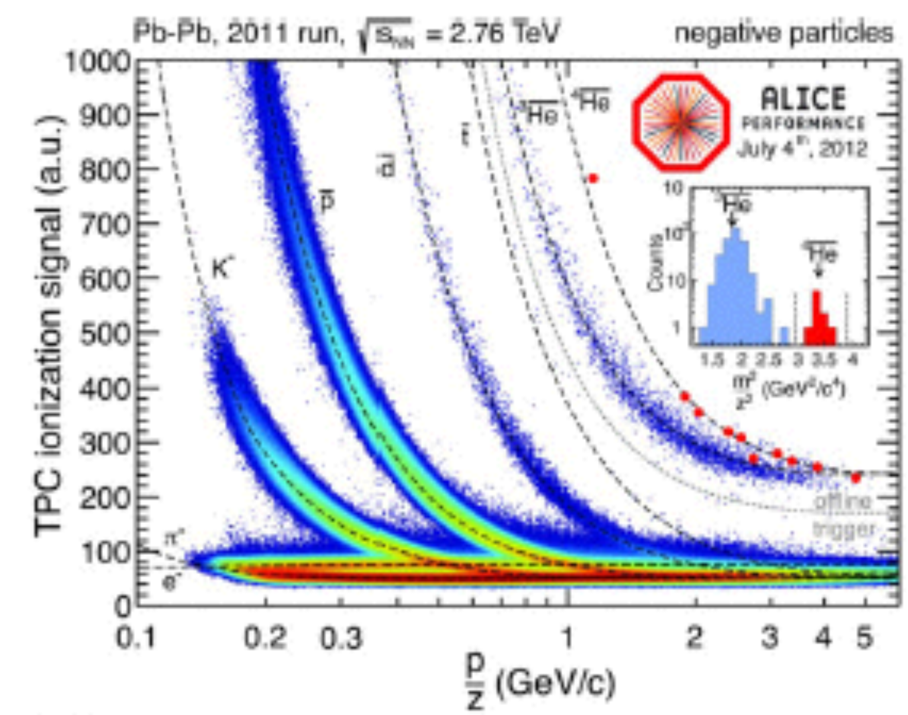
How About coalescence at the LHC?

— Chances of a charmed hadron meeting one or two nucleons not smaller than of two antinucleons and one antihyperon meeting to form an antihypernucleus

Science AAAS

Observation of an Antimatter Hypernucleus
The STAR Collaboration
Science **328**, 58 (2010);
DOI: 10.1126/science.1183980





Need to detect in coincidence the decay products

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