$$\mu c^2 = \underset{\uparrow \; m_e c^2}{0.5110} \times (\underset{\uparrow \text{ smaller by } 1/2000}{0.99946})$$

$$a_0 = \frac{\hbar}{\mu e^2} = \frac{\hbar c}{\mu c^2} \cdot \frac{\hbar c}{e^2}$$

$$= \frac{\hbar c}{m_e c^2} \cdot \frac{\hbar c}{e^2} \cdot \left(\frac{m_e}{\mu}\right)$$

$$= 0.5292 \text{ nm} \times \left(1 + \frac{m_e c^2}{m_p c^2}\right)$$

$$\boxed{a_0 = \underset{\uparrow \; a_{0\infty}}{0.5292 \text{ nm}} \times (\underset{\uparrow \text{ bigger by } 1/2000}{1.00055})}$$

also $Ry = Ry_\infty \cdot (0.99946) = 13.6$ eV

How about e^+ e^-

$$\frac{1}{\mu} = \frac{1}{m_e} + \frac{1}{m_e} = \frac{2}{m_e}, \quad \mu = \frac{1}{2} m_e \, !$$

$$a_p = \frac{\hbar}{\left(\frac{m_e}{2}\right) e^2} = 2 a_{0\infty} \cong 1.06 \text{ nm}$$

$$Ry_p = \frac{1}{2}\alpha^2 \left[\frac{m_e}{2} c^2\right] = \frac{1}{2} \cdot Ry_\infty \simeq 6.8 \text{ eV}$$

On to quarkonium, deuterium next lecture.

Quarkonium

Six quarks: $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$ ← electric charge $+2/3$ ← $-1/3$

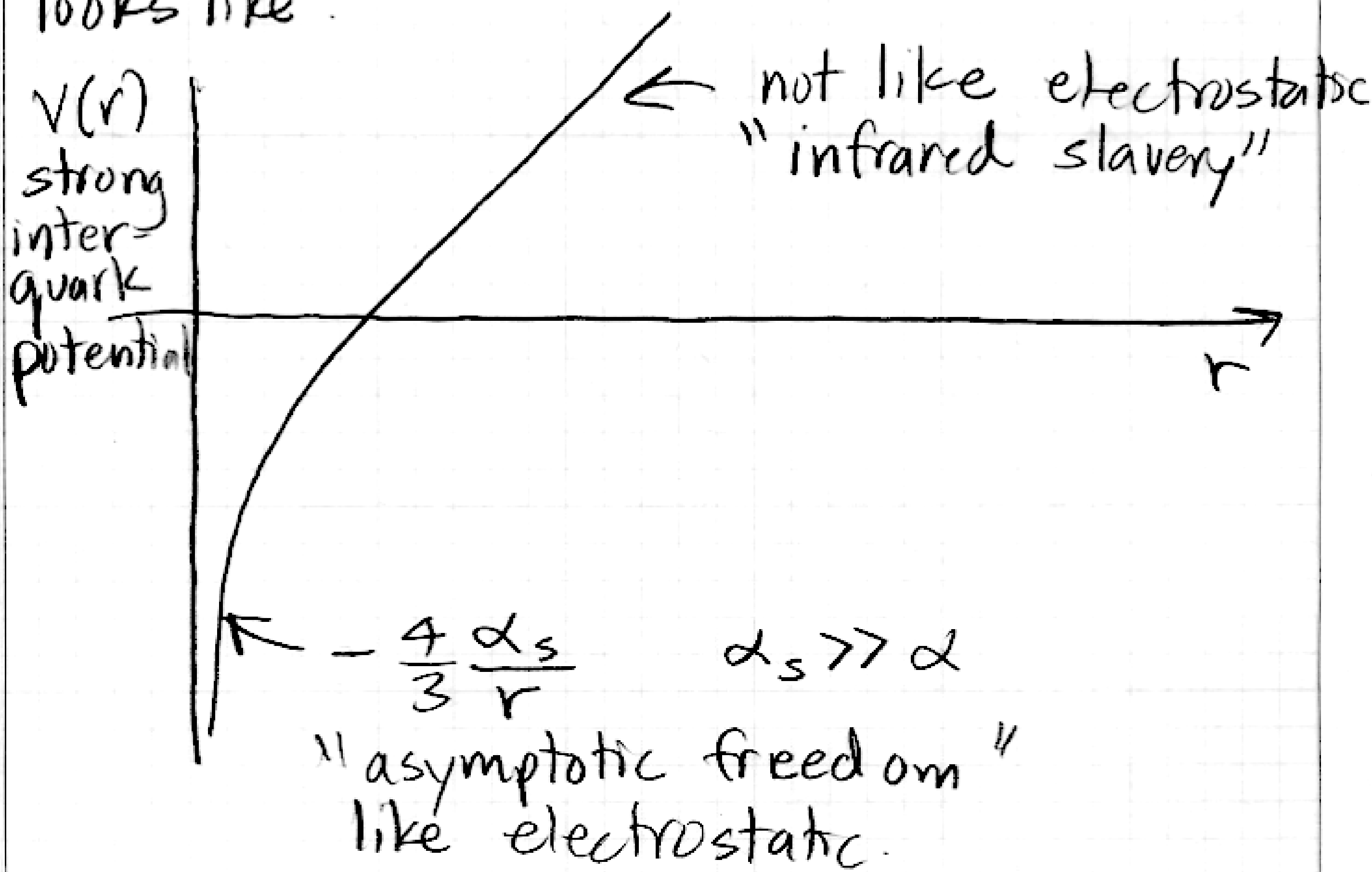
$m_u c^2 = m_d c^2 = 310$ MeV ("constituent")

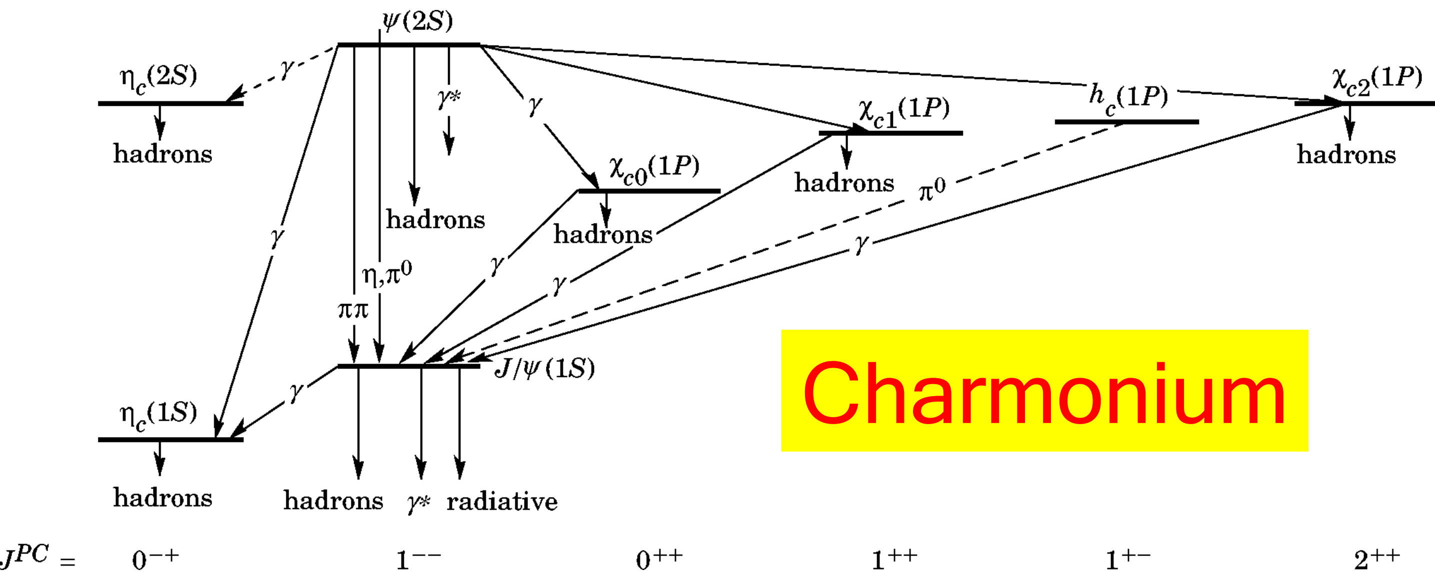
$m_s c^2 = 480$ MeV $m_t c^2 = 174{,}000$ MeV

→ $m_c c^2 = 1500$ MeV $m_b c^2 = 4700$ MeV

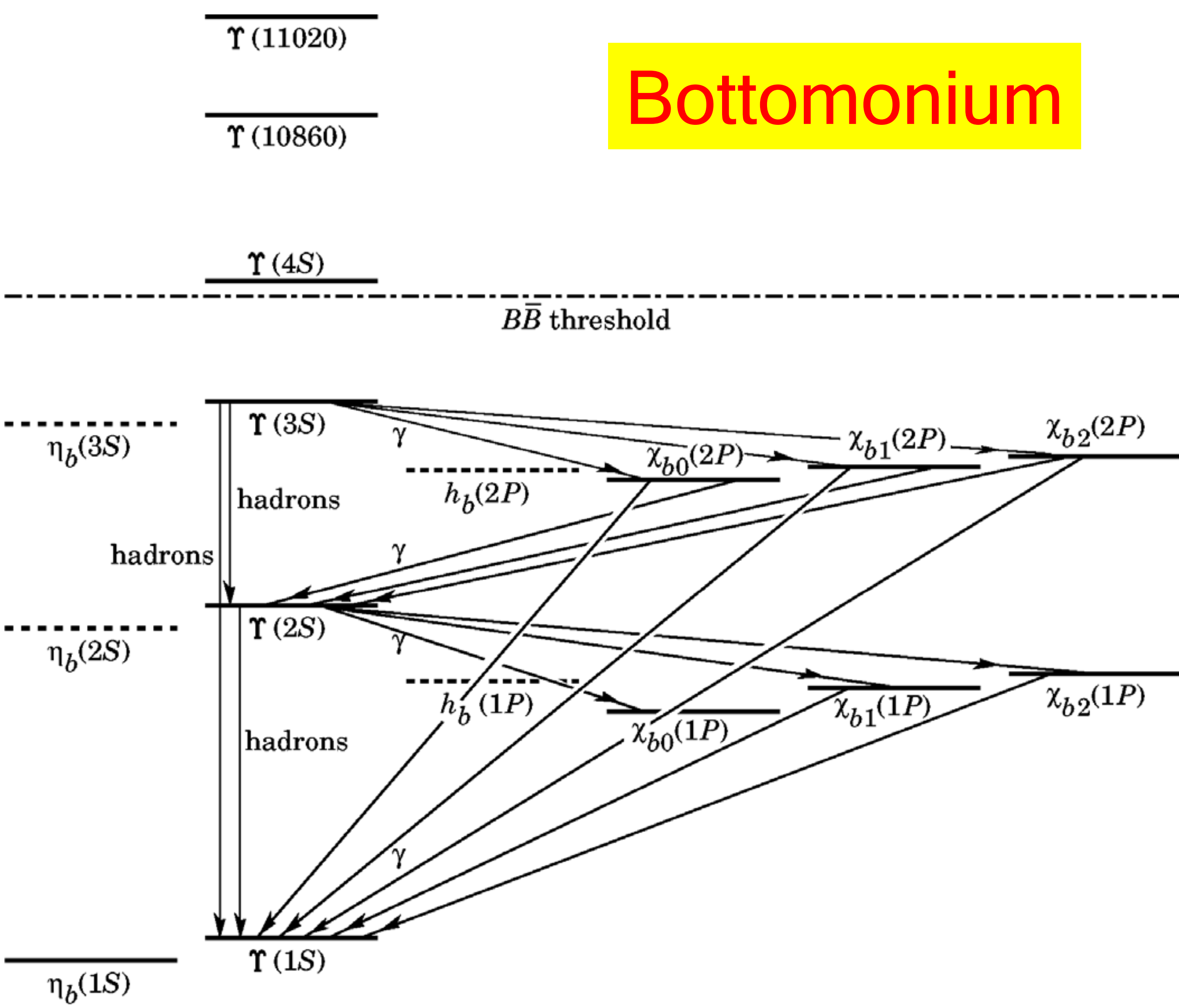
conditions are right for these quarks to form "quarkonium"

$V(r)$ is not due to the electrostatic interaction $\left(\propto -\frac{e^2}{r} \propto -\frac{\alpha}{r}\right)$, but is due to the strong interaction. That $V(r)$ looks like:





Charmonium
ψ(2S)
η_c(2S)
χ_c0(1P)
χ_c1(1P)
h_c(1P)
χ_c2(1P)
J/ψ(1S)
η_c(1S)
hadrons
γ
γ*
η,π0
ππ
π0
radiative
JPC = 0−+ 1−− 0++ 1++ 1+− 2++



Bottomonium
ϒ(11020)
ϒ(10860)
ϒ(4S)
BB̄ threshold
ϒ(3S)
η_b(3S)
χ_b0(2P)
χ_b1(2P)
χ_b2(2P)
h_b(2P)
ϒ(2S)
η_b(2S)
h_b(1P)
χ_b0(1P)
χ_b1(1P)
χ_b2(1P)
ϒ(1S)
η_b(1S)
hadrons
γ

Quarkonium exhibits a phenomena hidden in hydrogen, positronium: <u>spin</u> of the quarks matter.

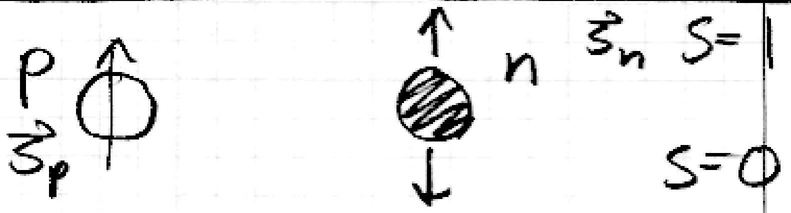
η_c, η_b : $\vec{s}_1 \uparrow$ $\quad \downarrow \vec{s}_2$ $\quad J=0$

$L=0$

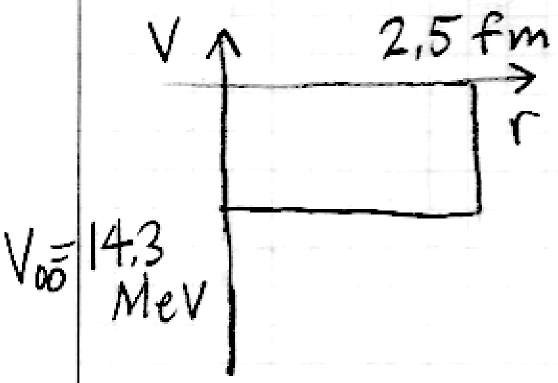
$J/\psi, \Upsilon$: $\vec{s}_1 \uparrow$ $\quad \uparrow \vec{s}_2$ $\quad J=1$

$L=1$

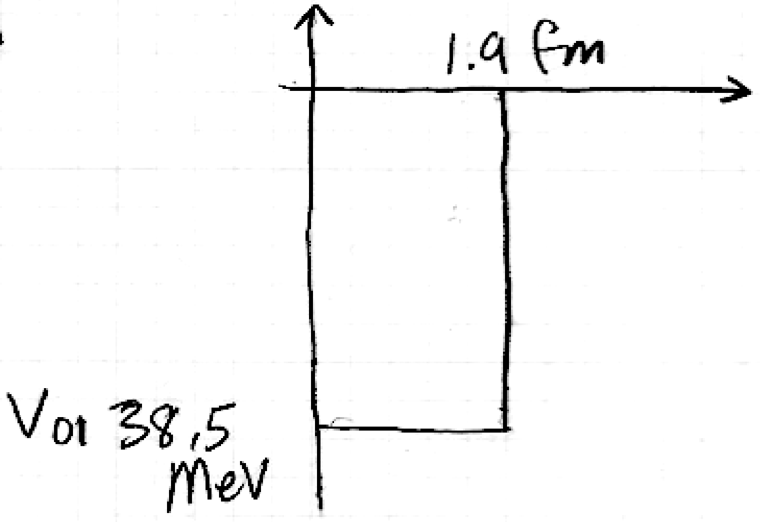
Deuteron
(from Martin Savage)
U. Wash



S=0:



S=1



$$\mu c^2 = \frac{(m_n c^2)(m_p c^2)}{(m_n c^2 + m_p c^2)} = \frac{939.57 \cdot 938.27}{939.57 + 938.27} = 469.46 \text{ MeV}$$

Problem 12.6.9: p. 349:

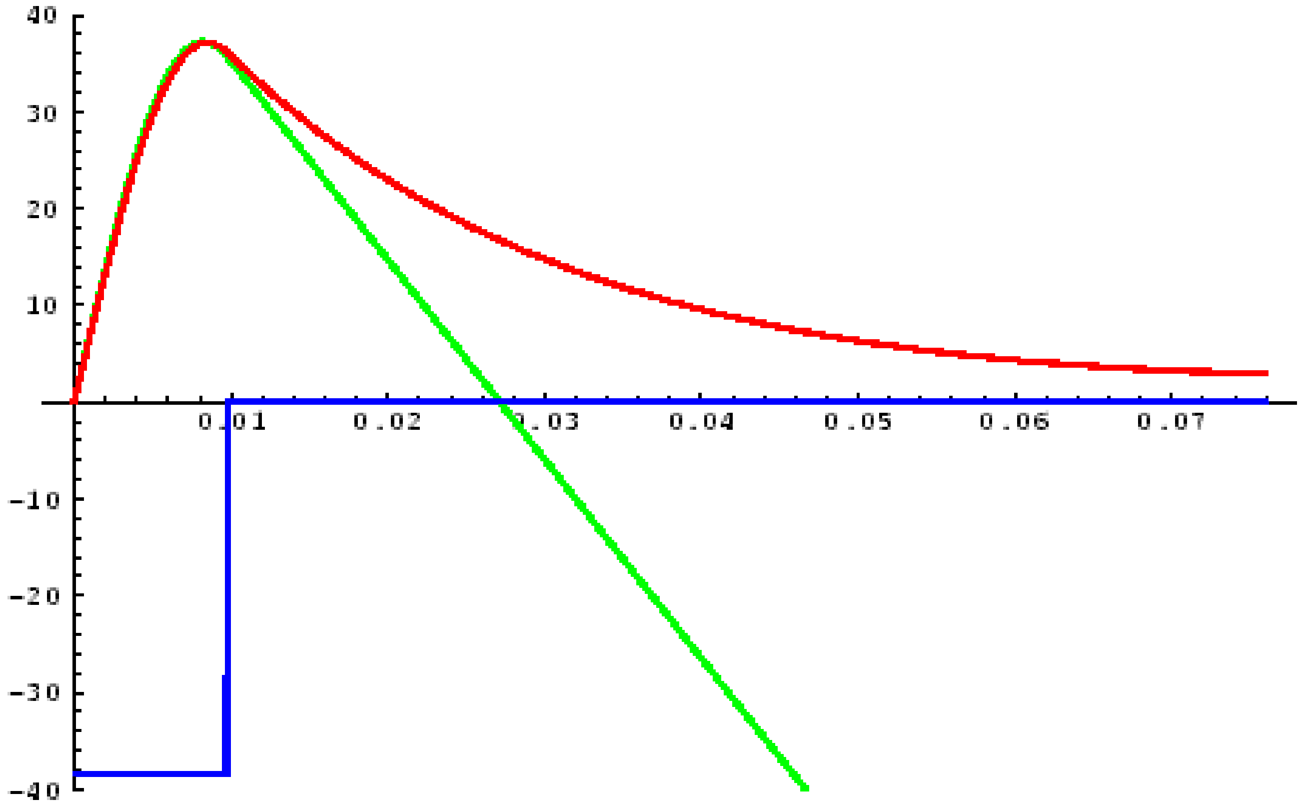
$$\frac{\pi^2 (\hbar c)^2}{8 \mu c^2 r_0^2} = \frac{\pi^2 \cdot (197.3)^2}{8 \cdot 469.46 \cdot 2.5^2} = 16.4 \text{ MeV}$$

$$\frac{\pi^2 (\hbar c)^2}{8 \mu c^2 r_0^2} = \frac{\pi^2 (197.3)^2}{8 \cdot 469.46 \cdot 1.9^2} = 27.5 \text{ MeV}$$

$V_{00} = 14.3 \text{ MeV} < 16.4 \text{ MeV}$
no bound state

$V_{01} = 38.5 \text{ MeV} > 27.5 \text{ MeV}$
at least 1 bound state

Deuteron Wave Function



From M. Savage, U.Wash.