Protons in Perspective

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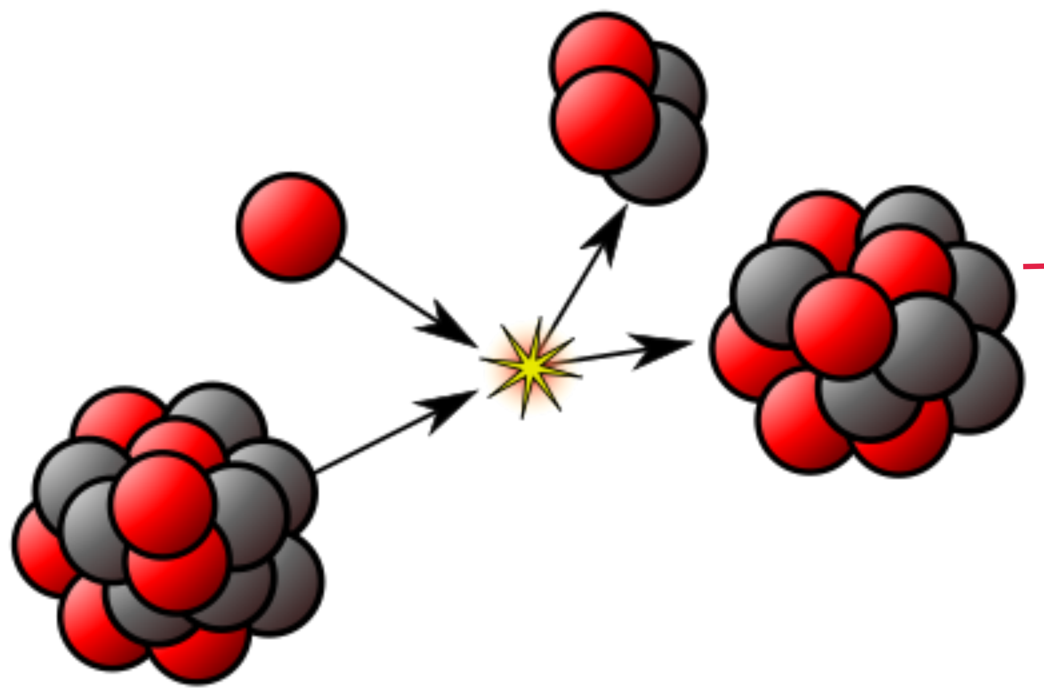
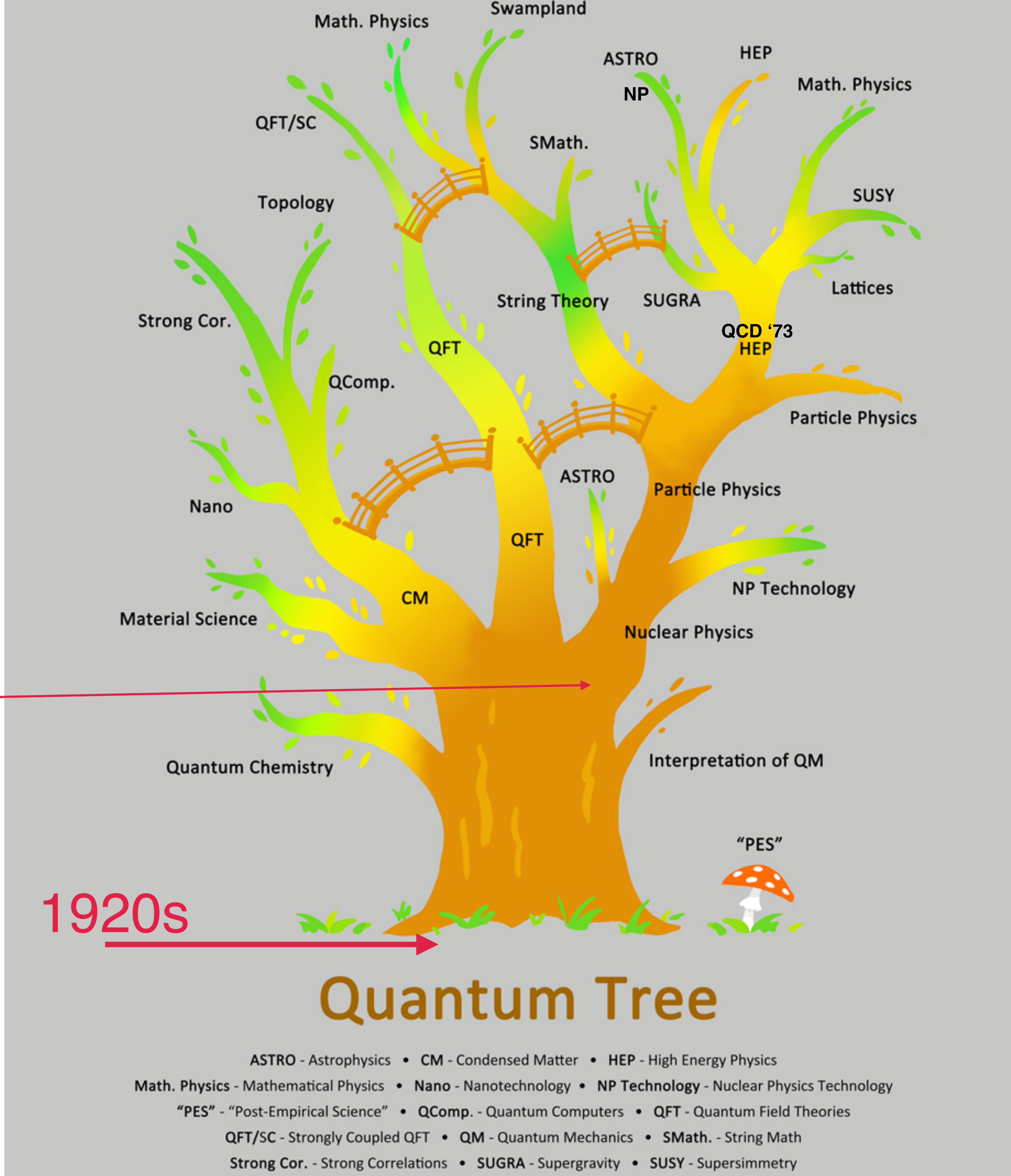


Planck constant $\mathscr{E} = \hbar\omega$

1900



Ernest Rutherford, 1871-1937

James Chadwick, 1891-1974

1932: neutron discovery in nucleus

Cylinder containing a polonium source and beryllium target/ protons deflected/ 2 weeks

1935 Nobel Prize

$\alpha\ (\mathrm{He}_4)$ и $\beta\ (e^{\pm})$ decays

1908 Nobel Prize

1911 Discovery of nuclei

gold foil experiment

Frédéric and Irène Joliot-Curie "managed" to knock protons out of paraffin wax using Polonium as a source for "γ" radiation. Chadwick said NO. (Majorana came to similar conclusion): The Joliot-Curies saw a neutron but did not understand

"father of nuclear physics"

Radioactivity is caused by process inside nuclei

- What determines the QCD scale?
- What does QCD dynamics predict about the proton mass if the scale is just a parameter?
- How would the physical world (condensed matter, chemistry, and biology) change if Λ_{QCD} is increased or decreased by a factor of 2?
- What is the interplay between the Higgs and QCD mass generation mechanisms?
- What is the role of the trace anomaly in QCD? Does it reflect both color confinement and dimensional transmutation?

Trace anomaly is EXACT, reflects everything

- What is the role of chiral symmetry breaking (χSB) in determining the nucleon mass? What is the interplay between the CSB and color confinement?

Without χSB proton would have to be massless

What determines the QCD scale?

$$b = 4N\left(1 - \frac{1}{12}\right) - \frac{2n_f}{3}$$

$$\Lambda = \text{const} \times M_{\text{uv}} \exp\left\{ -\frac{2\pi}{b(\alpha_s)_{\text{uv}}} \right\}$$

Can be calculated more accurately

UV scale

Modern perspective: Standard Model is an effective field theory obtained from "something else" at a high UV scale

Λ is not a directly measurable quantity; it depends on definition

For any physical quantity of dim [mass], $\mathrm{M} = \text{const}\,\Lambda + EW$

Most results for Λ are in the 200 to 300 MeV range, e.g. $\Lambda_{\text{MS}} = 332 \pm 17\,\text{MeV}$ for three "active" quark flavors

QCD scale is determined by UV parameters and some details of evolution to IR. Why $(\alpha_s)_{\text{uv}}$ is small? $\longrightarrow$ NOBODY KNOWS (nature's grand design or accident or anthropic)

Constants contain $O(m_q^2, \Lambda^2)$ corrections

$$\boxed{M_{\rm p} = \text{const} \times \Lambda + \sum_{i=1}^{3} c_i m_i}$$

u, d, s quark masses

σ term in pion proton scattering

$\sim 50 - 60$ MeV

$$\boxed{M_{\rm p}\, \bar{p}p = \left\langle p \left| -\frac{b}{4}\frac{\alpha_s}{2\pi} G^{\mu\nu\, a} G^a_{\mu\nu} + \sum_{u,d,s} m_q \bar{q}q + \sum_{c,b,t} O\left(m_h^{-2}\right) \right| p \right\rangle}$$

1978

$b = 9$ for $\mathrm{SU}(3)_{\rm color}$

This is RG invariant because represents trace of energy-momentum T_μ^μ

938.272 **MeV**

939.565 **MeV**

1.293 MeV

$$\frac{1}{2}\left(M_{\rm p} + M_{\rm n}\right) = M_0 - 4c_1 m_\pi^2 - \frac{3g_A^2 m_\pi^3}{32\pi F_\pi^2} \approx 938.9 \text{ MeV}$$

m_q

$(m_q)^{3/2}$

$$\frac{1}{2}\left(M_{\mathrm{p}} + M_{\mathrm{n}}\right) = M_0 - 4c_1 m_\pi^2 - \frac{3g_A^2 m_\pi^3}{32\pi F_\pi^2} \approx 938.9\ \mathrm{MeV}$$

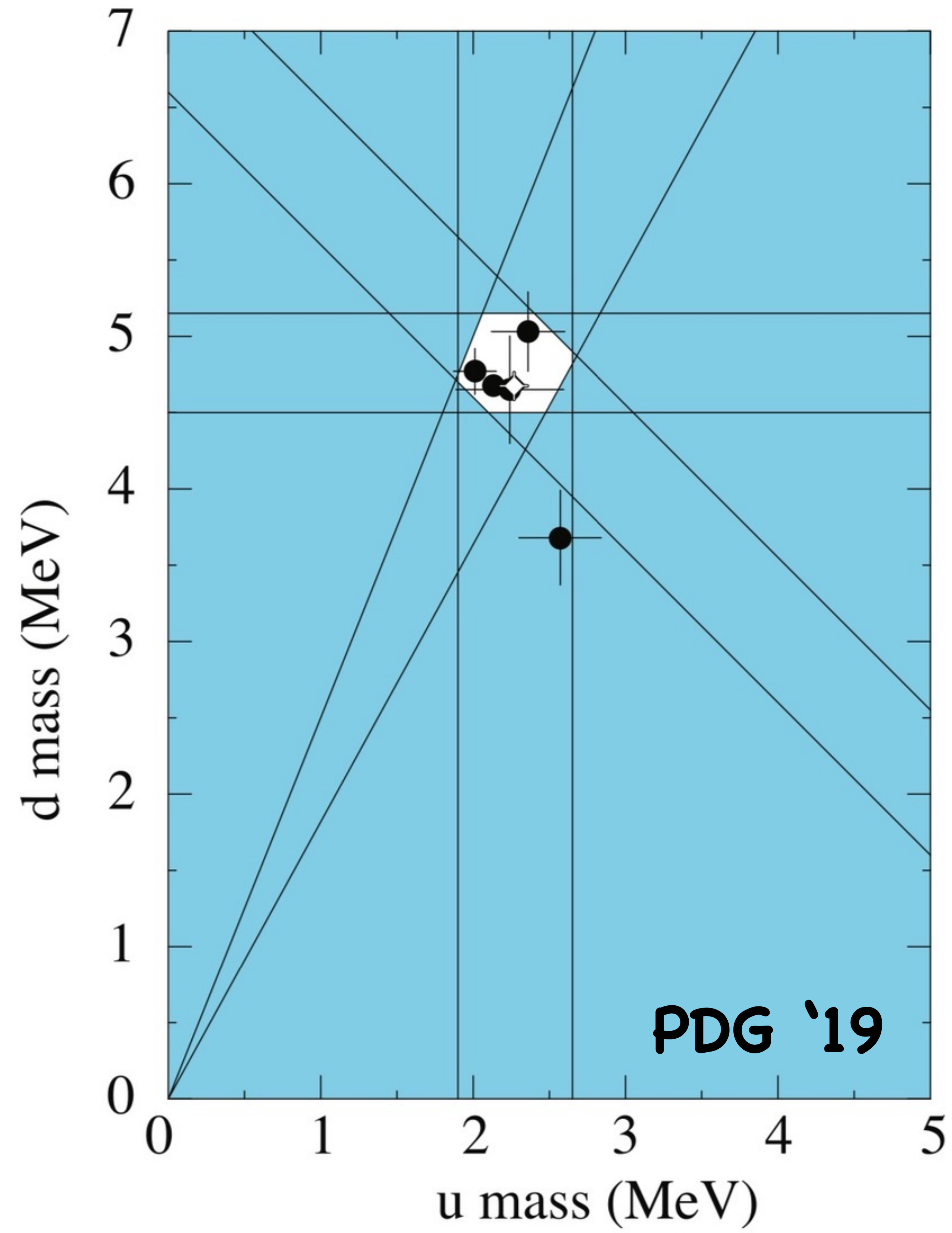
CPT: 865 MeV 86 MeV -12 MeV

$c_1 = -1.1\ \mathrm{GeV}^{-1}$

(Hoferichter et al; Meissner et al., ...)

$M_{\mathrm{n}} - M_{\mathrm{p}} \approx 1.29\ \mathrm{MeV}$

$\left(M_{\mathrm{n}} - M_{\mathrm{p}}\right)_{\mathrm{QCD}} \approx 1.87\ \mathrm{MeV}$



u and d quark masses

A. Kronfeld

Lattices: $m_u \approx 2.2\ \mathrm{MeV},\ m_d \approx 4.7\ \mathrm{MeV}\ [\mu_{\mathrm{MS}} = 2\ \ \mathrm{GeV}],\quad \frac{m_u}{m_d} \approx 0.5\ ;$

CPT: $\frac{m_u}{m_d} \approx 0.56$

How the physical world (condensed matter, chemistry, and biology) would change if Λ_{QCD} is increased or decreased by a factor of 2?

Λ is a dimensional parameter. What matters is the ratio m_q/Λ or m_q/M_{p} and m_e/Λ

Chemistry is determined by electromagnetic interactions, typical scale is from 0.1 eV (in organic chemistry) to 100 eV.

Dependence through nuclear structure (whether or not they exist)

Lee, Meissner, Olive, Shifman, Vonk (2020): Nuclear Physics versus θ

Nuclear Physics versus m_q/Λ : General tendencies

Reducing m_q/Λ by a factor of ~ 2 we dramatically decrease neutron-proton mass difference down to ~ 0.5 MeV, isolated neutron becomes stable, nucleon attraction in nuclei becomes stronger.

Scaling the ratio m_q/Λ up by a factor of ≤ 2 we dramatically increase neutron-proton mass difference and decrease nucleon binding in nuclei down from its current value ~ 9 MeV.

Hoyle resonance, stellar evolution, nuclei stability, BBN, ...

Does diquark $[qq]$ has a role in nucleon physics?

- "Good" diquarks $(u_{\alpha\, i}\, d_j^{\alpha})\varepsilon^{ijk}$ have spin zero, isospin zero, and color index the same as antiquark

- Discussion of diquarks started in the late 1970s, and was revitalized by works of Jaffe&Wilczek and Selem&Wilczek in the early 2000s.

- Strong attraction in the spin-$0^{\pm}$ qq channel was noted in QCD SR in 1981 and later by Shuryak et al. in instanton liquid model.

Hypothesis: "good" (isospin 1/2) baryons $\longrightarrow [ud]^k q_k$

$$E \approx \sqrt{\sigma L} + \kappa L^{-\frac{1}{4}} \mu^{\frac{3}{2}}$$

Selem and Wilczek, 2006: Extensive baryon phenomenology based on Chew-Frautschi formula:

$$\kappa \equiv \frac{2}{3}\frac{\pi^{\frac{1}{2}}}{\sigma^{\frac{1}{4}}}$$

$q_k(m_1)$ $[ud]^k(m_2)$

Larger than Casimir correction

$$\mu^{\frac{3}{2}} \equiv m_1^{\frac{3}{2}} + m_2^{\frac{3}{2}}$$

Our [SW] hypotheses are quite different from of nonrelativistic quark model. The observation that good diquark configurations have mass comparable to that of a single quark, which appears strikingly in the L = 2 data, is a qualitative challenge to the foundation of such models.

Importance of diquarks as building blocks of baryons is difficult to accommodate within large N paradigm. Specifically, the approximate degeneracy between mesons

and baryons with good diquarks, which is a striking feature of the (moderately) large L data inconsistent with large N limit. [Other arguments see NSVZ 1981]

BIG PROBLEM : Diquarks, being color-antitriplets, is hard to relate to first principle in much the same way as nonrelativistic quark model.

If N=3 is not large, why not try N=2. A dramatic change

→ color – singlet good diquarks, uniquely and fully defined

Shifman Vainshtein 2005

SU(2) Yang-Mills with two flavors

$$\chi^i = \begin{pmatrix} u_L \\ d_L \\ \bar{d}_R \\ -\bar{u}_R \end{pmatrix},$$

Chiral symmetry is SU(4), not SU(2)xSU(2)

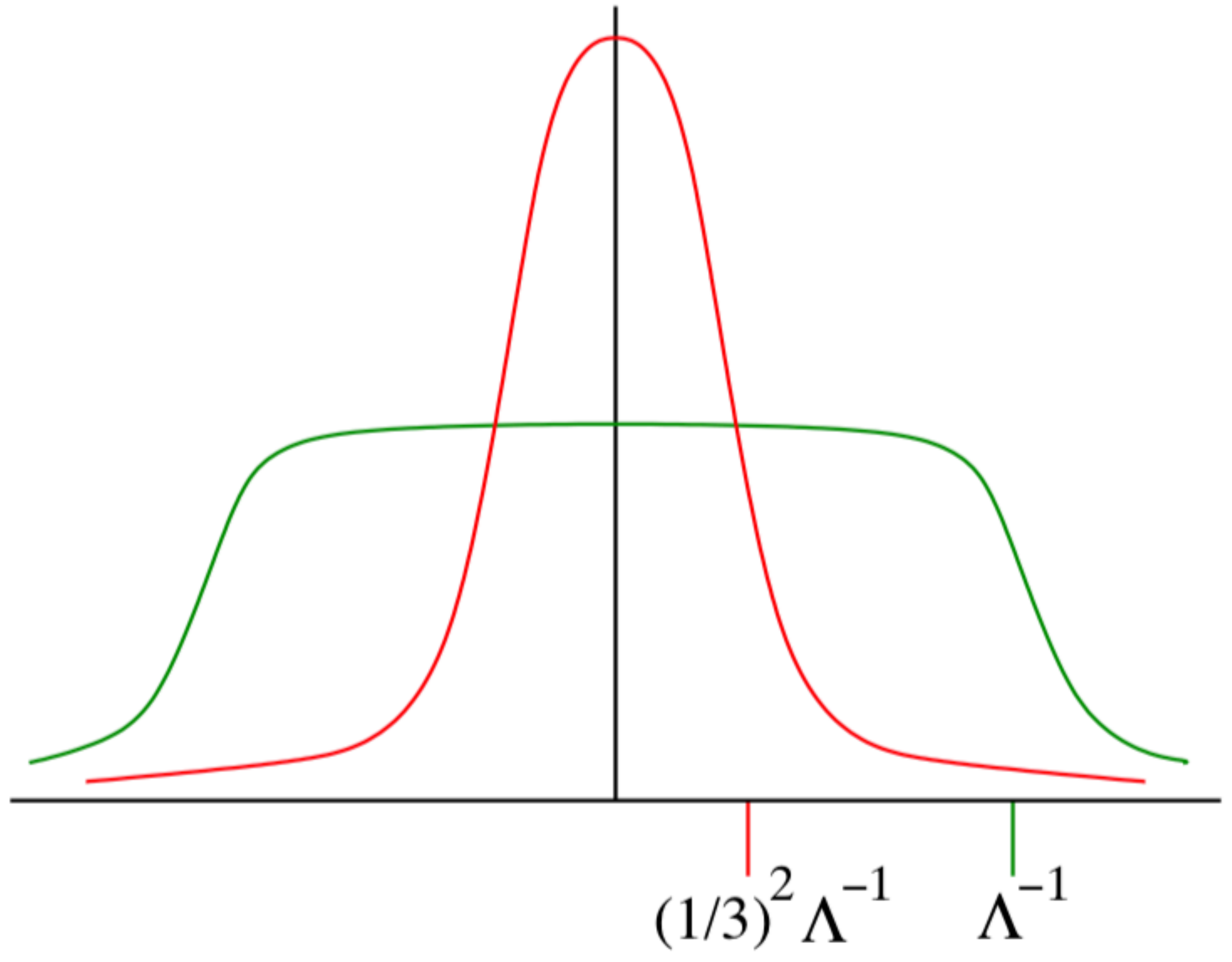
$$\Big\downarrow \chi\text{SB}$$

SO(5)

$$\Big\downarrow$$

SU(2)$_{\text{color}}$ is pseudoreal. Five (pseudo)Goldstones: three pions and two good diquarks, ud and $\bar{d}\bar{u}$, degenerate with pions and related by symmetry.

The question is, what happens to these states as we elevate the gauge group from SU(2)color to SU(3)color? It is not difficult to see that the extra states become diquarks.



Conclusions

- Λ descends to us from the UV (either Multivers or Grand Design; never know)
- Variations of m_q/Λ can significantly distort BBN, stellar nuclei synthesis, stability of nuclei;
- If variations of m_q/Λ are small enough to keep nuclei and their production intact, changes in chemistry are very small;
- Anomaly in T^μ_μ is an exact operator equality;
- Assuming that dynamics of SU(2) QCD, at least in some aspects, is not that different from SU(3) we make well defined good diquarks; They become similar to pions. (All instanton-based models will have that).