From Particle Dark Matter to Quantum Chromodynamics

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A brief academic history…

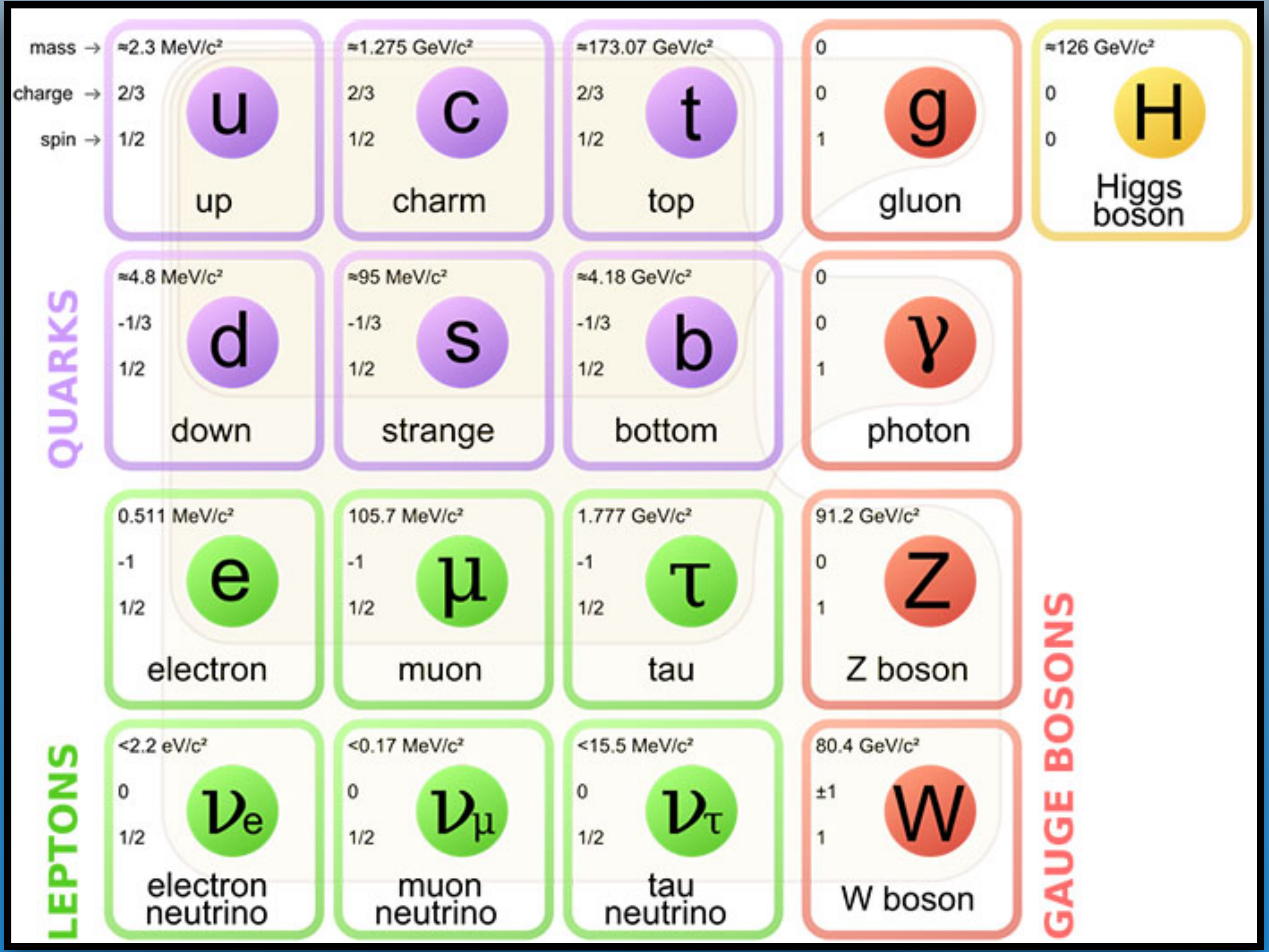
Degrees from:
University of California Santa Barbara…
University of California Davis…
University of California Irvine

First postdoctoral fellowship at Berkeley Lab (paycheck from University of California Berkeley)

Standard Model of Particle Physics

"Symmetries, Dark Matter and Minicharged Particles"
December 2019 PhD from University of California, Irvine

- Early Universe (~2 ns post-Big Bang) interactions:
  $SU(3)_{color} \otimes SU(2)_L \otimes U(1)_Y$
- Higgs field broke early symmetry structure down to Standard Model of today:
  $SU(3)_{color} \otimes U(1)_{EM}$
- Past?
- Future?



Past: Dark Matter & Beyond the Standard Model Physics

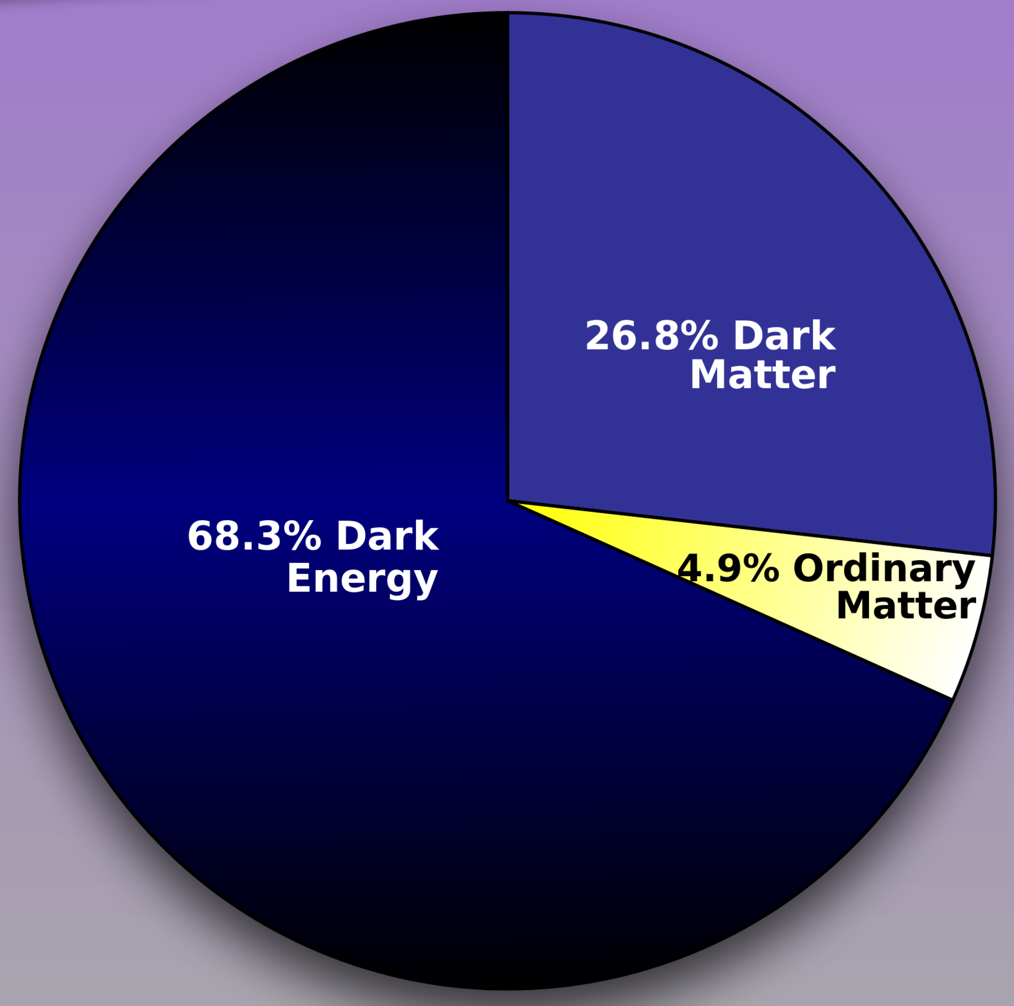
"Asymmetric Dark Matter & Baryogenesis from $SU(2)_\ell$"
Fornal et al. with JRW, PRD 2017

<u>A Recipe for Beyond the Standard Model Physics</u>

- Begin with Standard Model:
  $SU(3)_{color} \otimes SU(2)_L \otimes U(1)_Y$
- Increase gauge symmetries in the early universe, either unify or enlarge:
  $SU(3)_{color} \otimes SU(3)_{L'} \otimes U(1)_Y$
- Break it down to the SM with a new scalar field
- Sort through debris - search for dark matter, baryogenesis, dark energy, inflation…
- Our model:
  $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes SU(2)_\ell$

Beyond the Standard Model (BSM) Motivation:

- Gravity! search for spin-2 gauge boson
- Dark energy - expansion of universe speeds up - could be new fields/particles, or the Cosmological Constant
- Matter/antimatter asymmetry
- Neutrino masses
- Dark matter - invisible matter with gravitational effects



Future: Cosmological Fate of $\mathrm{SU}(3)_{\mathrm{color}} \otimes \mathrm{U}(1)_{\mathrm{EM}}$

"Millicharged scalar fields, massive photons and the breaking of $\mathrm{SU}(3)_{\mathrm{color}} \otimes \mathrm{U}(1)_{\mathrm{EM}}$"
JRW, PRD 2019

We know one spontaneous symmetry breaking occurred in the past, via the Higgs ϕ_H:

$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \rightarrow \mathrm{SU}(3)_C \otimes \mathrm{U}(1)_{\mathrm{EM}}$$

Will there be one in the future?

The **ELECTRIC HIGGS**:

$$\mathrm{SU}(3)_{\mathrm{color}} \otimes \mathrm{U}(1)_{\mathrm{EM}} + \Phi_{\mathrm{EM}}$$

$$\Phi_{\mathrm{EM}} \text{ electric charge : } \quad 10^{-1} > \frac{q}{e} > 10^{-7}$$

EDGES Millicharged Dark Matter
Future Constraints from LDMX

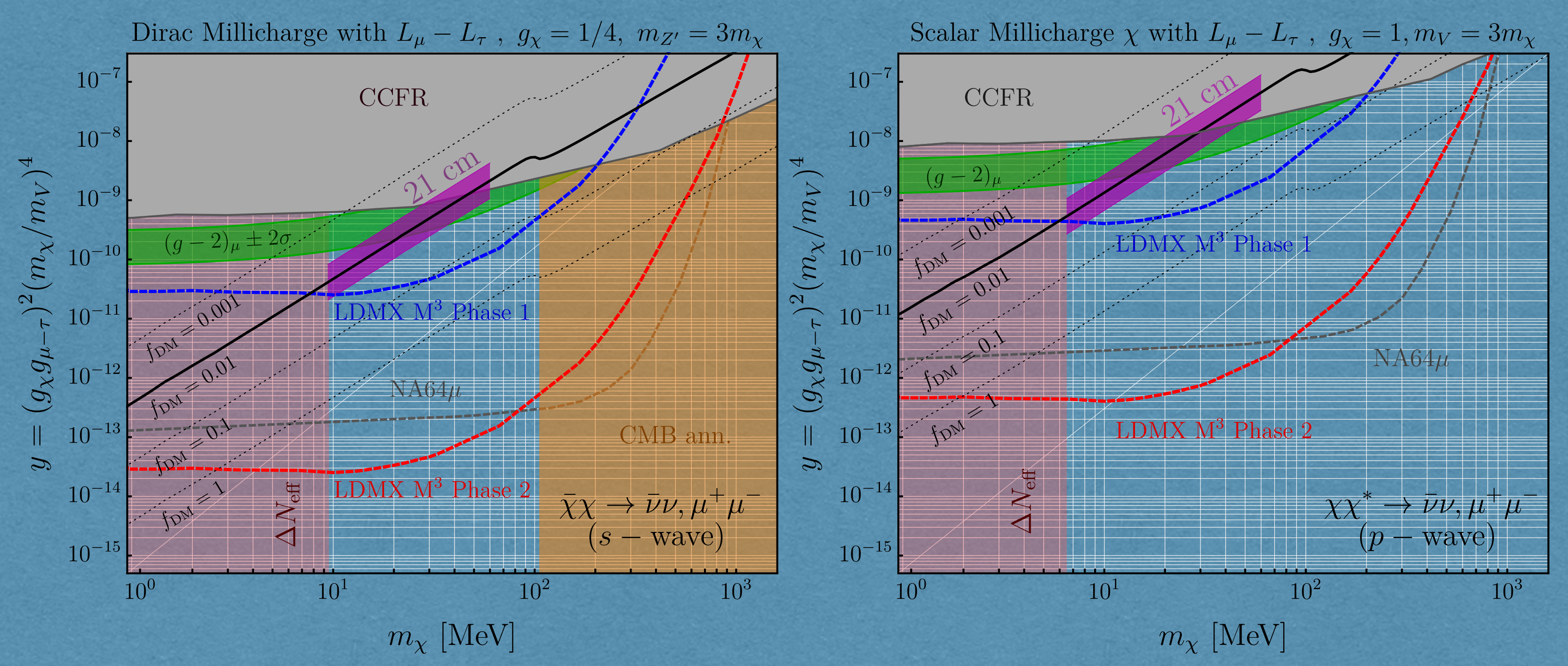


FIG. 10: Constraints on fermion (left) and scalar (right) dark matter which carries *both* a QED millicharge and additional charge under a gauged $L_\mu - L_\tau$ force. This combination of interactions is motivated by the dark matter interpretation of the EDGES 21-cm excess, which requires the millicharge to explain the anomaly and the additional force in order to generate the requisite DM fraction $f_{\mathrm{DM}} \simeq 10^{-2}$ [118]. The purple band represents parameter space which can explain the amplitude of the observed 21-cm absorption feature. Future measurements at NA64 [119] and LDMX-M^3 [6] are expected to be sensitive to this scenario. In the green band, this model also resolves the $(g-2)_\mu$ anomaly [7, 108–110]. The shaded gray region is constrained by the CCFR experiment [113, 114]. Both plots presented here are taken from [118].

arxiv:1807.01730: Berlin, Blinov, Krnjaic, Schuster & Toro
"Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX"

Quarks as Dark Matter, then Stuck in the Nucleus

"QCD hidden-color Hexadiquark in the Core of Nuclei"

JRW, Stan Brodsky, et al. Nuc.Phys.A 2021

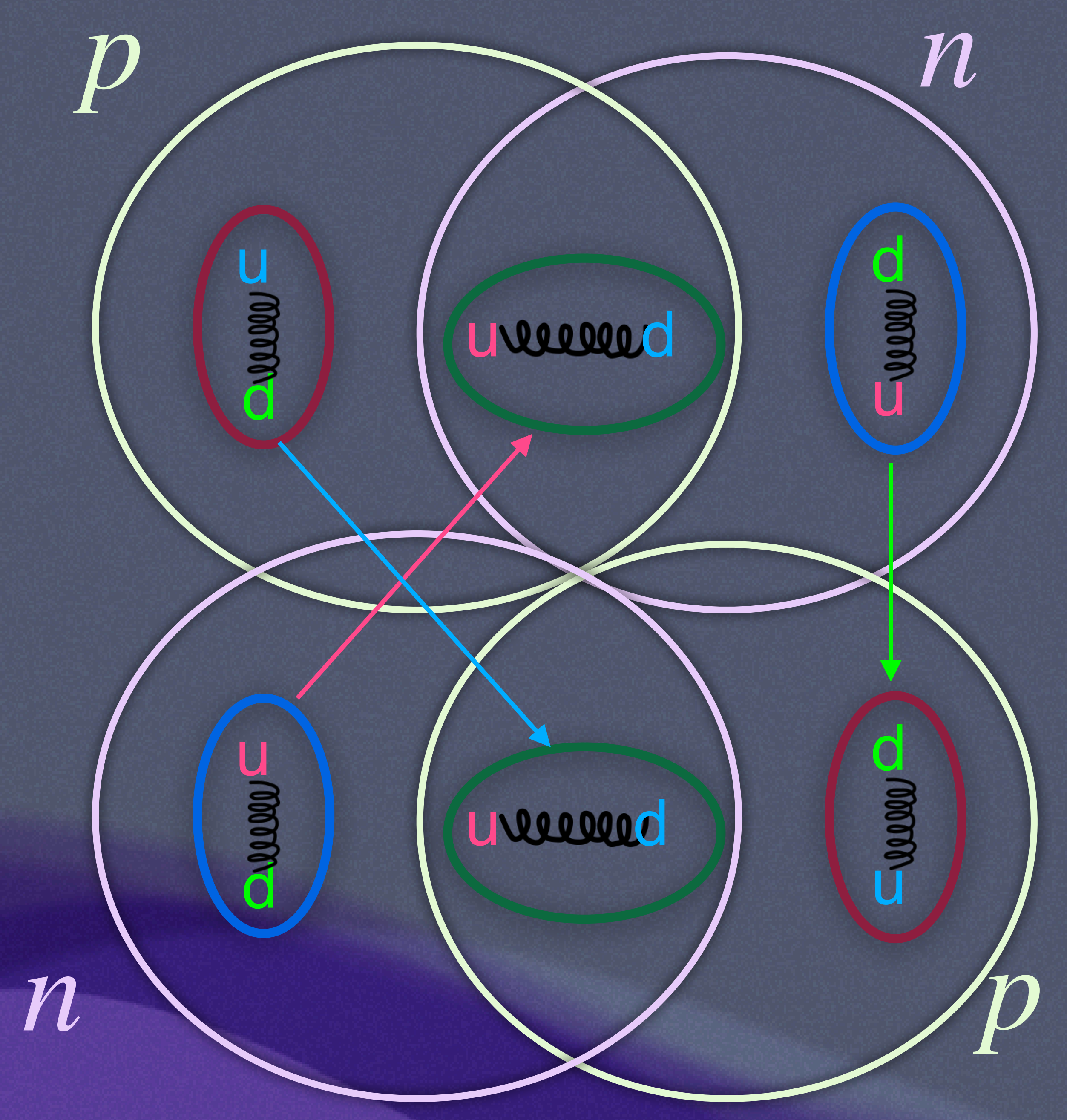
- Began with hexaquark dark matter candidate: $uuddss$
- Dark matter out the window - into the nucleus to solve the EMC effect (quark behavior in nuclei is mysterious).
- First, 6-quark hidden-color state $uuuddd$ in ^{2}H
- Too massive - but we doubled it to avoid breaking Bose statistics & it fit perfectly in ^{4}He:

$$\Psi_{\text{Hexadiquark}} \propto |[ud][ud][ud][ud][ud][ud]\rangle$$

Table 1: Effective SU(3) color factors C_F, Eqs. (A.15) and (A.19), in various formation channels from one-gluon exchange: The minus (plus) sign in the third column corresponds to short-range attraction (repulsion). The label C or NC refers to spin-statistics compliant or non-compliant cluster configurations.

Configuration	Channel	C_F	C/NC
Diquark	$\mathbf{3}\otimes\mathbf{3}\to\bar{\mathbf{3}}$	- 2/3	C
	$\mathbf{3}\otimes\mathbf{3}\to\mathbf{6}$	1/3	C
DdQ	$\bar{\mathbf{3}}\otimes\bar{\mathbf{3}}\to\mathbf{3}$	- 2/3	NC
	$\bar{\mathbf{3}}\otimes\bar{\mathbf{3}}\to\bar{\mathbf{6}}$	1/3	C
2 DdQ	$\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}\to\mathbf{6}$	- 5/3	C
HdQ	$\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}\otimes\bar{\mathbf{6}}\to\mathbf{1}$	- 5	C

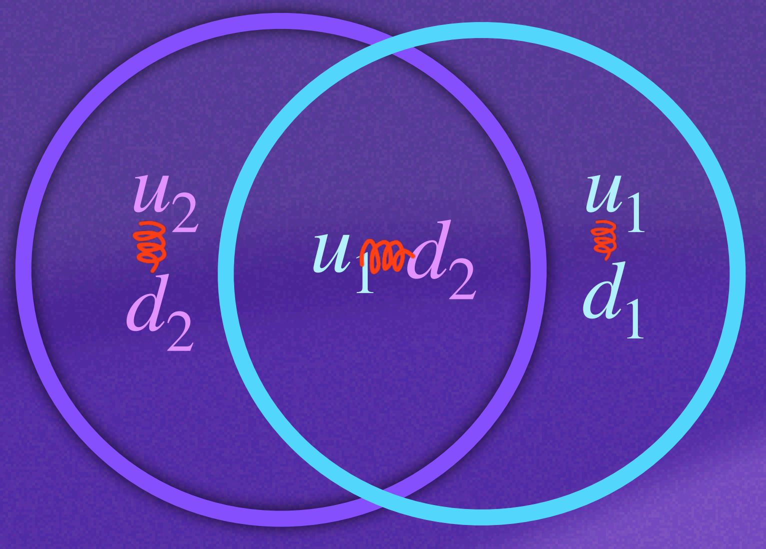
One-gluon exchange is attractive in the $\mathbf{3}_C\otimes\mathbf{3}_C\to\bar{\mathbf{3}}_C$ diquark channel; in contrast, the short-range interaction in the $\mathbf{3}_C\otimes\mathbf{3}_C\to\mathbf{6}_C$ channel is repulsive (Table 1). Likewise, the allowed DdQ formation channel $\bar{\mathbf{3}}_C\otimes\bar{\mathbf{3}}_C\to\bar{\mathbf{6}}_C$ is repulsive at short distances, but as a counter to this repulsion the DdQ will remain color confined at larger distances at a radius determined by the QCD scale. Finally,



Follow up: "Diquark induced short-range nucleon-nucleon correlations & the EMC effect"

JRW Nuc.Phys.A 2023

Breaking of the fundamental assumption of Effective Field Theories (aka scale separation)...



np SRC pair

Fin! Grazie mille…

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