IBS CTPU Focus Meeting on Composite Dynamics & Phenomenology 2019

Asymmetric dark matter and dark QCD

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OUTLINE

Asymmetric dark matter

Dark QCD via effective potentials

Exotic QCD

Asymmetric Dark Matter

Motivating principle of ADM is the similarity of visible matter and dark matter mass densities

$$\Omega_D \simeq 5\Omega_V$$

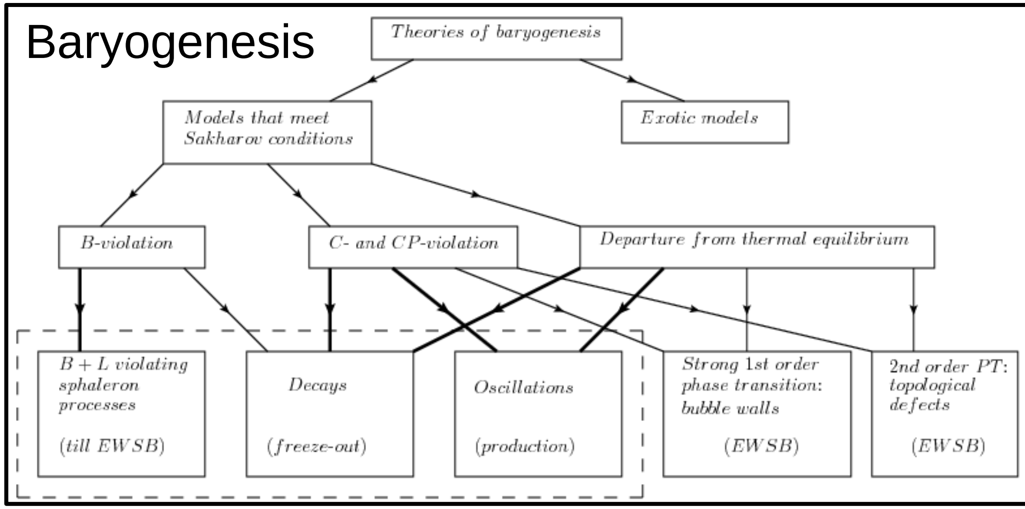
?

Protons, Neutrons

Λ_{QCD}

+

Baryogenesis



arXiv:1604.07740
Zhuridov, Dmitry

Asymmetric Dark Matter

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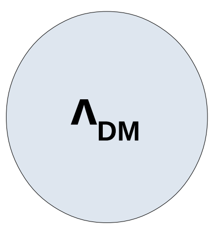
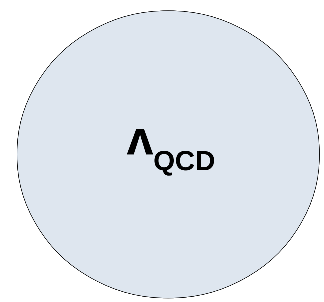
$$\Omega_D \simeq 5\Omega_V$$

Composite dark matter



Protons, Neutrons



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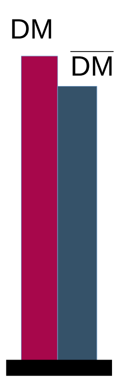
Asymmetric Dark Matter



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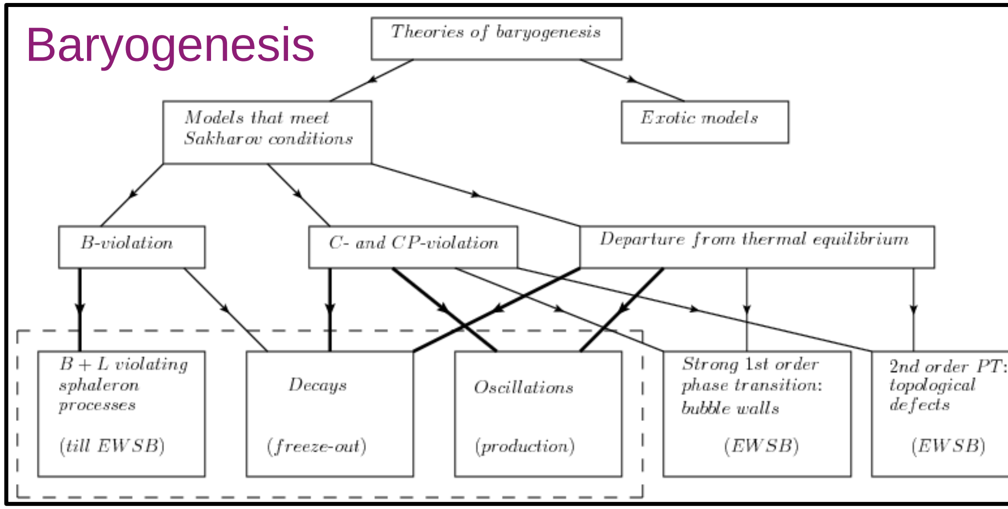
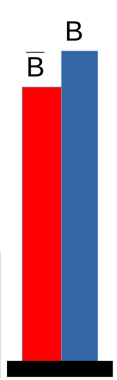
Baryogenesis





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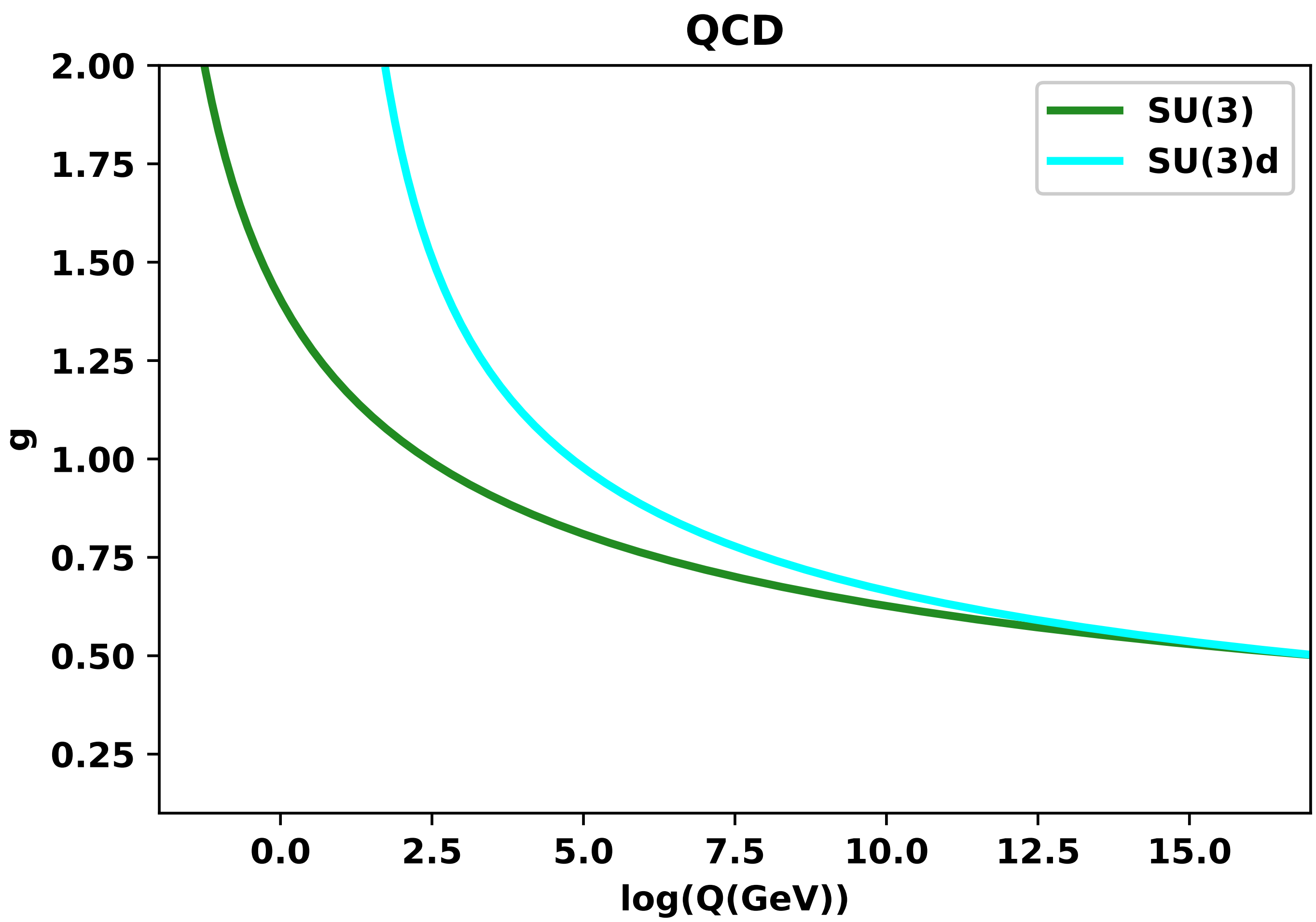
Dimensional Transmutation

Confining non-abelian gauge groups are a common feature of hidden sectors.



Mass scale for proton and mass scale for Dark Matter could share a common origin.

Consider RGEs at 1 loop with gauge couplings governed by 1 loop beta function,

$$\beta = \frac{-g^3}{16\pi^2}\left(\frac{11}{3}N - \frac{4}{3}\frac{n_f}{2}\right)$$

$$\frac{\partial g}{\partial \ln\mu} = \beta$$

Connections at the GUT scale

Composite Asymmetric Dark matter

- In order to explain the near 1:5 ratio of matter to DM however, we need the dark confinement scale to be close to the QCD scale and a reason for similar asymmetry in visible and dark sector.
- Two model building perspectives:

  Asymmetric dark matter in search of composites or dimensional transmutation DM in search of asymmetric dark matter.

- A number of solutions, immediate solution is some GUT scale connection in gauge coupling constants $g_{SU(3)}$ and a dark $g_{SU(3)}$.
- Story of baryogenesis can be connected to dark matter asymmetry in order to explain the similar number densities.

Composite ADM

- At low energy dark matter made of stable dark baryons, analogues of protons and neutrons with mass proportional to Λ_{DM}.
- Interested in cases where mass is dominated by confinement scale and not dark quark mass.

  Need some form of dark radiation in the theory to annihilate the symmetric component of DM.

Mirror Matter

- Such models of composite ADM have a history within mirror matter models.
- Early model of restoring parity to SM Lagrangian.
- Exchange fields with mirror partners under parity. Gauge structure

$$[\,\mathrm{SU}(3)\times SU(2)\times U(1)]\times[SU(3)'\times SU(2)'\times U(1)']$$

- Can also consider mirror GUTs: GxG with spontaneous breaking of mirror symmetry $\rightarrow$ Visible sector X Dark sector.

Creating Uncanny Sectors

With Z2 discrete symmetry, start with 2 scalar fields in each sector transforming as

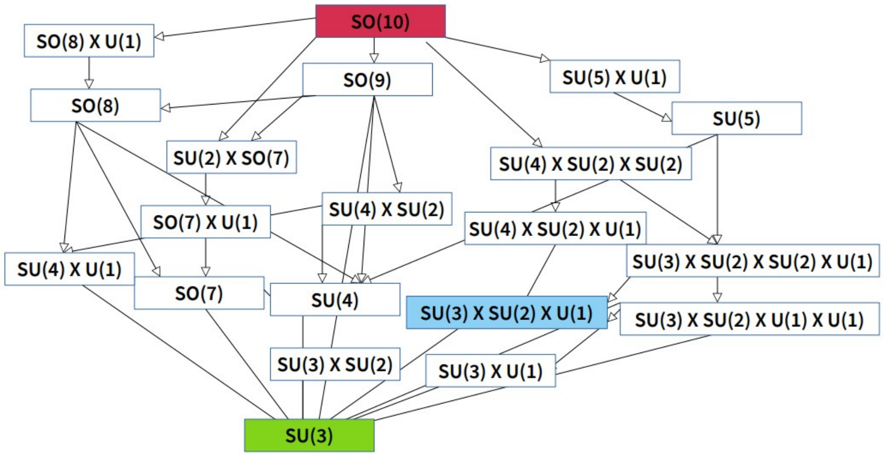
$$\phi_1 \leftrightarrow \phi_2, \qquad \chi_1 \leftrightarrow \chi_2.$$

$$\begin{aligned} V = &+ \lambda_\phi(\phi_1^2 + \phi_2^2 - v_\phi^2)^2 \\ &+ \lambda_\chi(\chi_1^2 + \chi_2^2 - v_\chi^2)^2 \\ &+ \kappa_\phi(\phi_1^2\phi_2^2) \\ &+ \kappa_\chi(\chi_1^2\chi_2^2) \\ &+ \sigma(\phi_1^2\chi_1^2 + \phi_2^2\chi_2^2) \\ &+ \rho(\phi_1^2 + \chi_1^2 + \phi_2^2 + \chi_2^2 - v_\phi^2 - v_\chi^2)^2. \end{aligned}$$

$$\phi_1 = v_\phi, \qquad \chi_1 = 0,$$
$$\phi_2 = 0, \qquad \chi_2 = v_\chi.$$

SO(10)XSO(10)

Choose different representations for fields not connected by symmetries. Result is 'Asymetric Symmetry Breaking'.



UV scale mirror gut becomes visible sector and dark sector with different gauge breaking chains

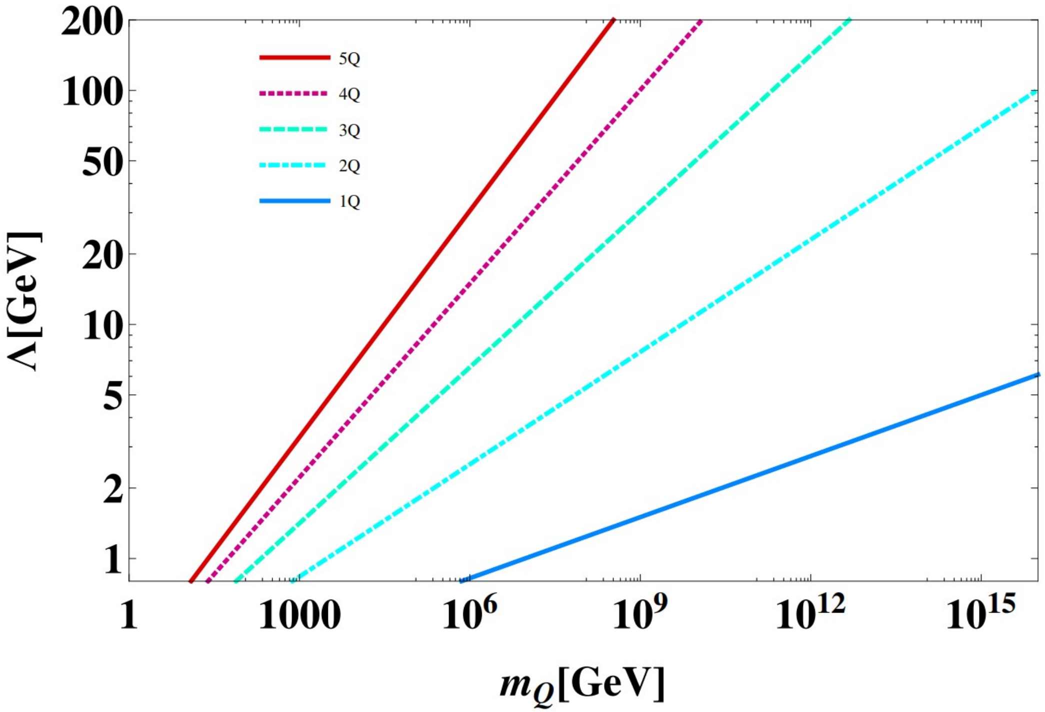
SJL, R. Volkas *arXiv :* 1407.4192
SJL *arXiv :* 1412.1894
SJL, R. Volkas *arXiv :1801.05561*

Broken Discrete Symmetries

Compare two SU(3) theories at one loop level.

If the number of fermions is the same as QCD, then the difference in scale at which confinement occurs is proportional to the mass scale where differences between the two gauge theories arise.

Depending on the theory this could be the top quark mass or a larger mass scale for n/6 dark fermions.



Confinement scale is remarkably insensitive to the larger mass scale of dark fermions.

As long as one dark fermion exists at low energy to form dark baryons, such dark QCD models are a good fit for ADM.

$$SU(3) \times SU(2) \times U(1) \times SU(3)_D \times \ldots$$

Fermion Masses with broken discrete symmetries

The spontaneous symmetry breaking of discrete symmetries can create dark sectors very different to the SM while maintaining connection of confinement scales and asymmetric number densities.

$$[\,\mathrm{SU}(3)\times SU(2)\times U(1)]\times[SU(3)'\times SU(2)'\times U(1)']$$

Take two Higgs doublets in each sector with vevs v_1, v_2, w_1, w_2.
Symmetry breaking can break gauge symmetry asymmetrically.

$$v_1 >> v_2, \;\; w_2 >> w_1, \;\; w_2 >> v_1.$$

While Lagrangian is Z2 symmetric the Higgs responsible for giving mass to fermions in each sector is a different mixture of states in each sector.

$$H_1 = \frac{v_1^*\Phi_1 + v_2^*\Phi_2}{v}, \qquad H_2 = \frac{-v_2\Phi_1 + v_1\Phi_2}{v}.$$

$$H_1' = \frac{w_1^*\Phi_1 + w_2^*\Phi_2}{w}, \qquad H_2' = \frac{-w_2\Phi_1 + w_1\Phi_2}{w}.$$

Independent fermion masses for visible and dark SU(3) theories.

Dark QCD

- For a general model of dark QCD, consider SU(3) with confinement scale and quark mass scales as all free parameters.
- What is the phenomenology of the dark sector?
- Can consider SM limit where masses, confinement are identical and SU(2)XU(1) charges are switched on. This is our only test case for experimental comparison.

Dark QCD models and candidates

Dark baryons as analogues of visible sector matter density. Mass dominated by confinement scale and abundance can be created from asymmetry.	Dark mesons such as dark pion DM. Can behave like WIMP particle or SIMP. Kribs, Neil 1604.04627	Dark quark nuggets as very large stable 'nuclei' from dark 1st order phase transitions. Yang Bai et al 1810.04360
Dark neutron stars and other compact object formation in complex or mirror like sectors with possibly very strong self interactions. Addazi Marciano, Alexander 1603.01853	Dark Glueballs from pure hidden yang mills theories. Soni, Zhang 1602.00714	Dark Nuclei and dark atoms. Dark BBN in early universe depends on dark quark content and additional dark species Detmold, McCullough, Pochinsky 1406.2276

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HyperSpherical QCD

1704.05213 SJL, Schroor, Volkas

Consider the hyperspherical approach to quantum three-body problem with three dressed valence quarks per baryon. Single Hyper-Radius and 5 angles.

$$\vec{\rho} = \vec{r_2} + \vec{r_1}$$

$$\vec{\lambda} = \frac{1}{\sqrt{3}}(2\vec{r_3} - \vec{r_1} - \vec{r_2})$$

$$\vec{R} = \frac{1}{3}(\vec{r_1} + \vec{r_2} + \vec{r_3})$$

$$x = \sqrt{\rho^2 + \lambda^2}$$

$$\phi = tan^{-1}(\frac{\rho}{\lambda})$$

Hypercentral approach to ground states takes the first order solution, separable into hyper-radius and angular function.

Then consider separable Schrodinger equation for hyper-radial wavefunction and use phenomenological potentials that shift between coulomb and linear scaling.

$$V(x) = -\frac{\tau}{x} + kx^{\rho}$$

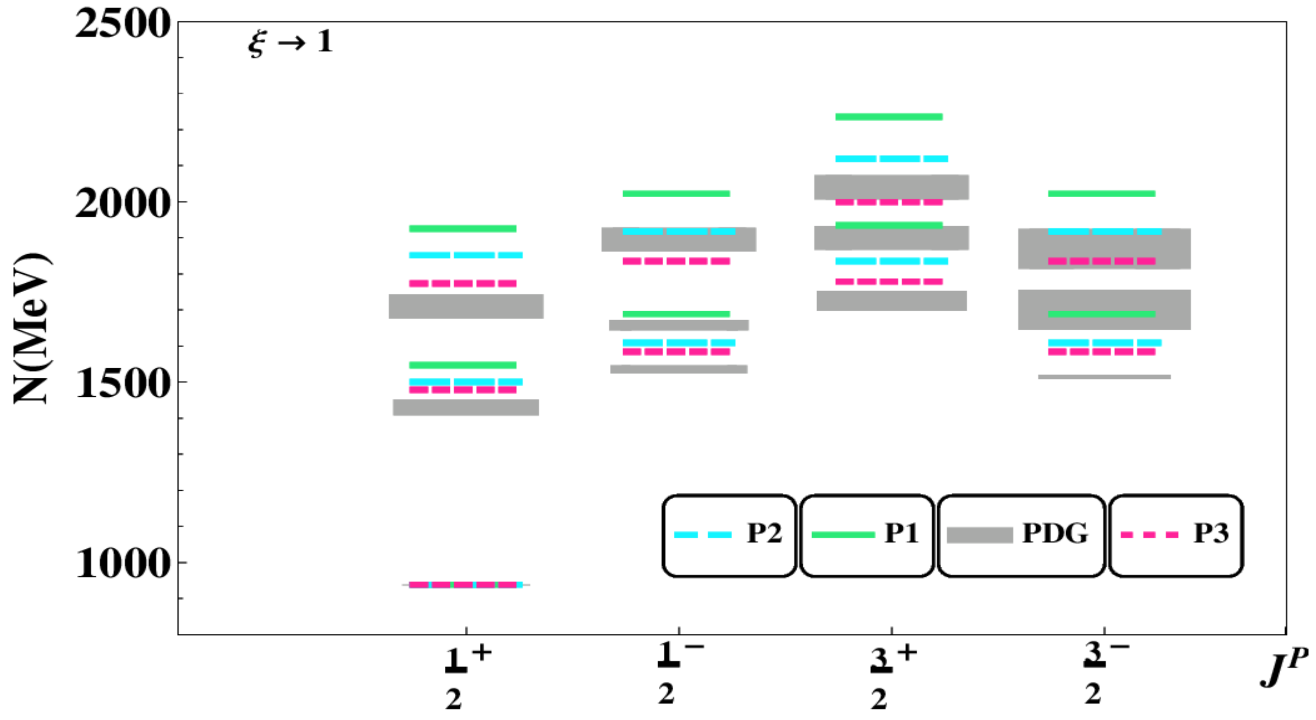
Modeling DQCD Spectra

Effective potentials from QCD studies. Will use these as starting point.

Extend to dark modeling by scaling dimensional parameters per dark sector model.

Focus on fit to ground state baryons where spatial wavefuction is symmetric.

$$\left[\frac{d^2}{dx^2} + \frac{5}{x}\frac{d}{dx} - \frac{\gamma(\gamma+4)}{x}\right]\psi_{N,[\gamma]} = -2m\left[E - V(x)\right]\psi_{N,[\gamma]}$$

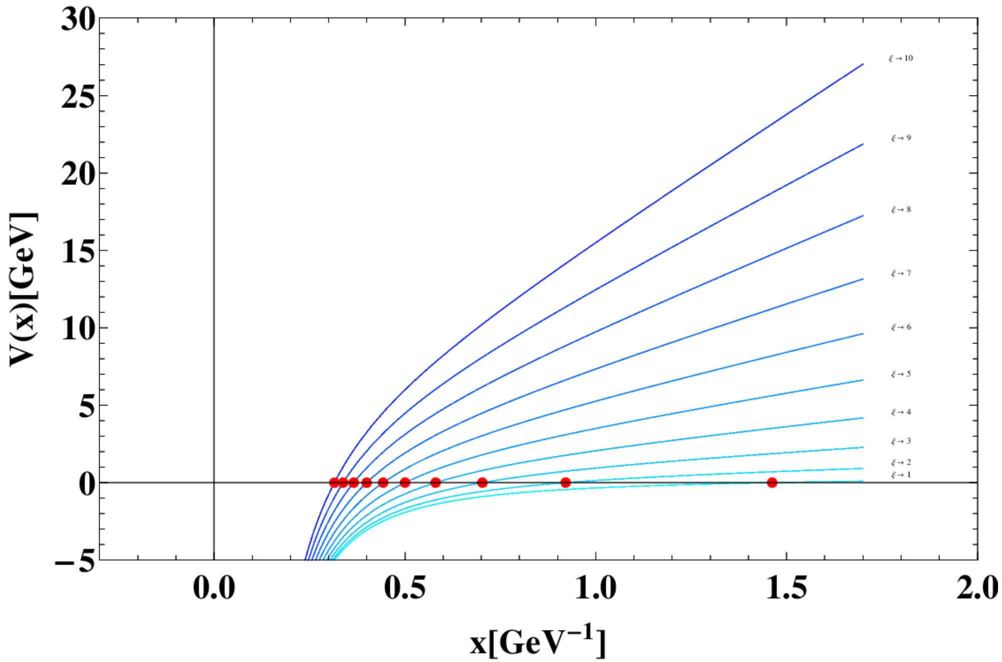


Define the ratio of confinement scales

$$\xi = \frac{\Lambda_{DM}}{\Lambda_{QCD}}$$

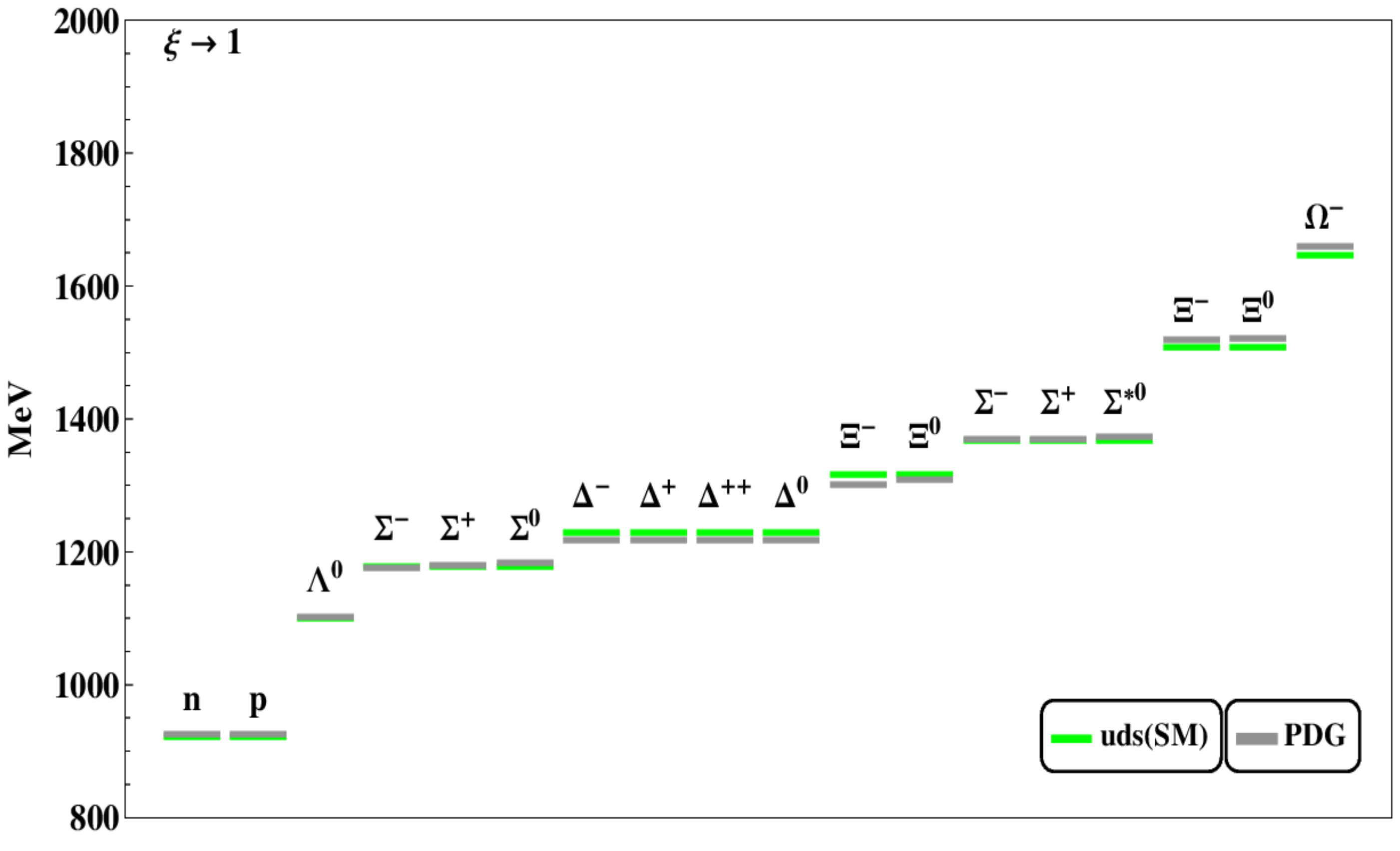
Starting with potentials for SM QCD, scale dimensional parameters in potential with the ratio.

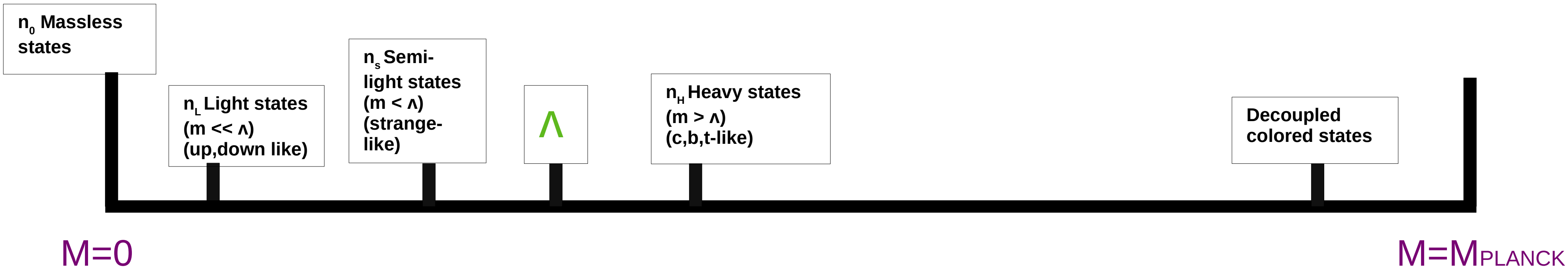
Crossing radius scales as expected, similar to bag model of QCD.



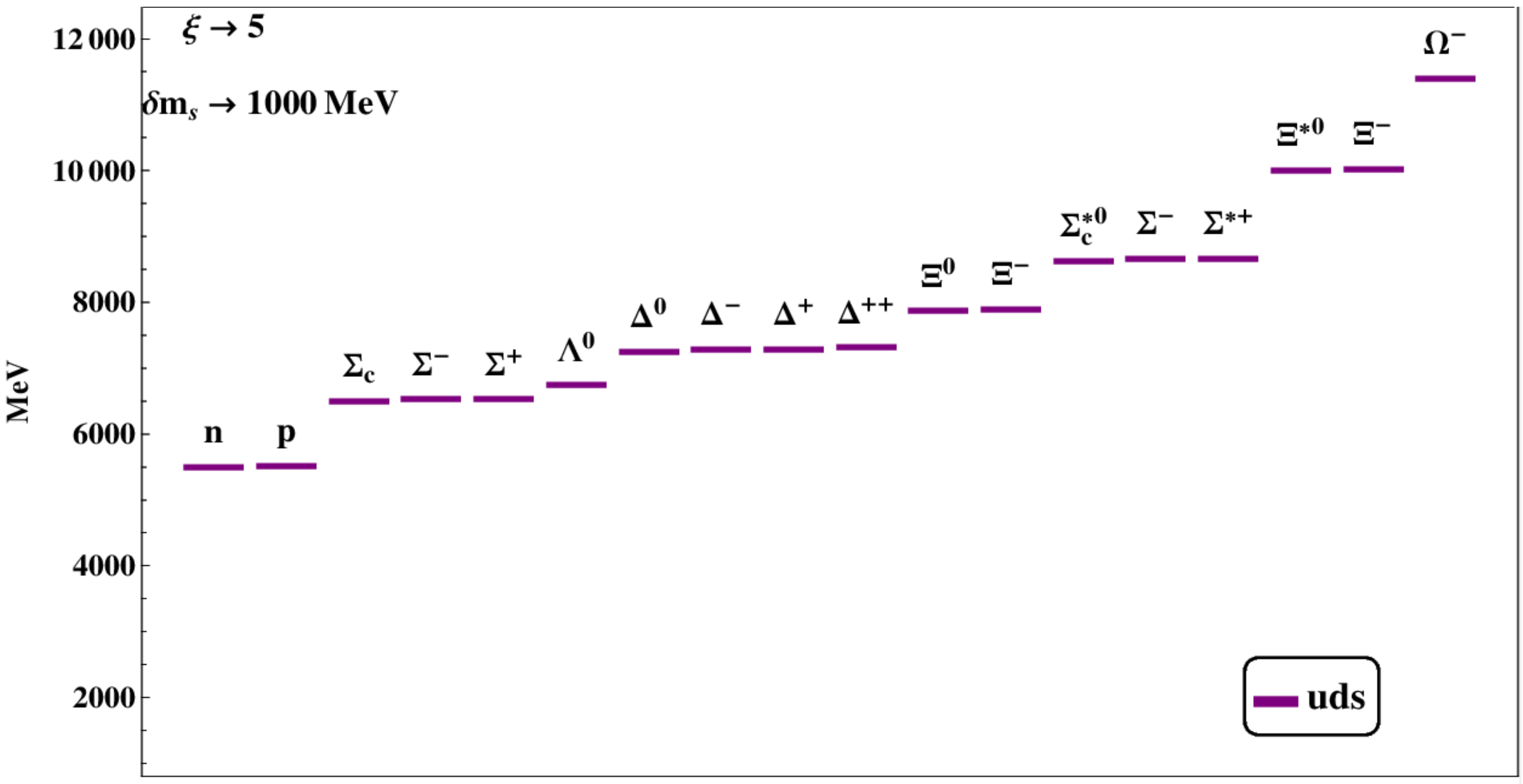
Spin-flavour symmetries of ground state baryons

$$M = M_0 + CC_2[SU(2)_S] + DC_1[U(1)_Y] + E\left(C_2[SU(n_I)_I] - \frac{1}{4}(C_1[U(1)_Y])^2\right)$$

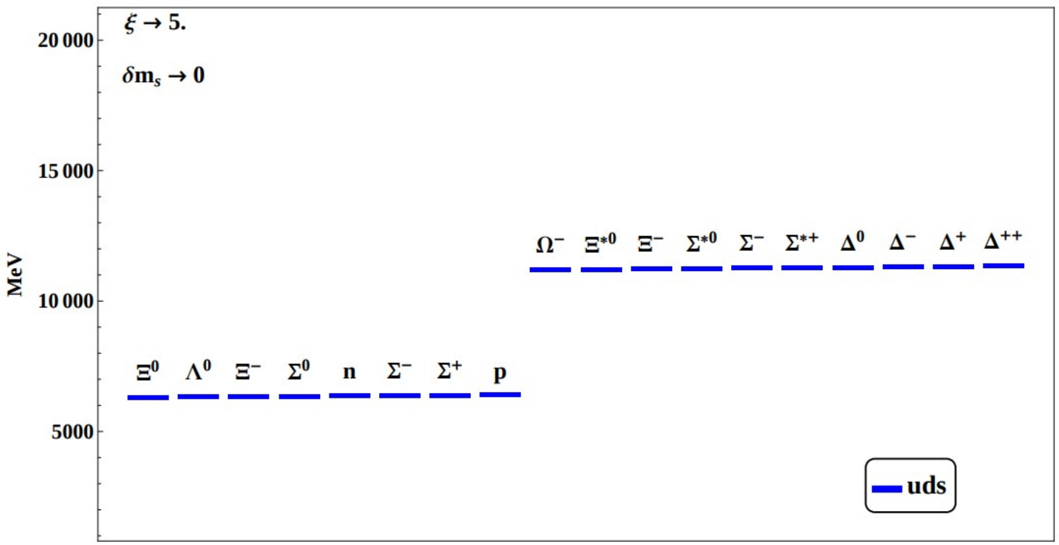




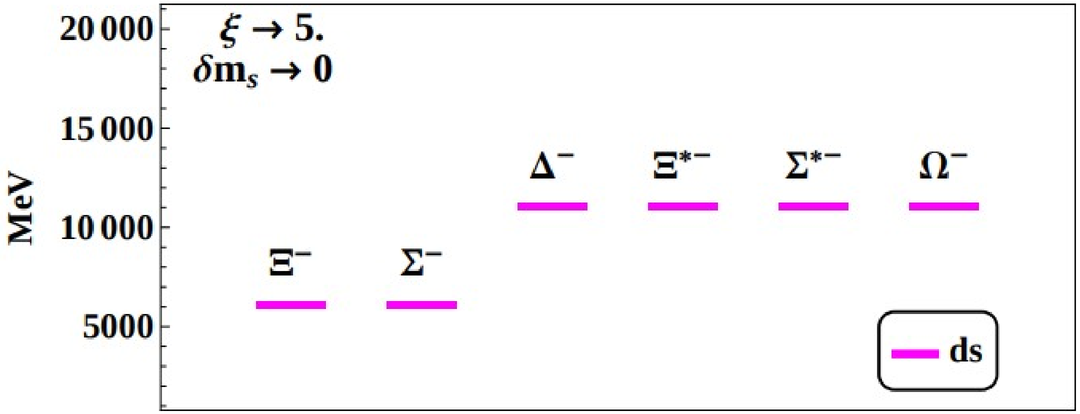
n0 Massless states
nL Light states (m << Λ) (up,down like)
ns Semi-light states (m < Λ) (strange-like)
Λ
nH Heavy states (m > Λ) (c,b,t-like)
Decoupled colored states
M=0
M=MPLANCK



$\xi \to 5$
$\delta m_s \to 1000$ MeV
MeV
12 000
10 000
8000
6000
4000
2000
n
p
Σ_c
Σ^-
Σ^+
Λ^0
Δ^0
Δ^-
Δ^+
Δ^{++}
Ξ^0
Ξ^-
Σ_c^{*0}
Σ^-
Σ^{*+}
Ξ^{*0}
Ξ^-
Ω^-
uds



Light set of dark quarks can include different choice of SU(2)XU(1) gauge charges if these are present in the theory.



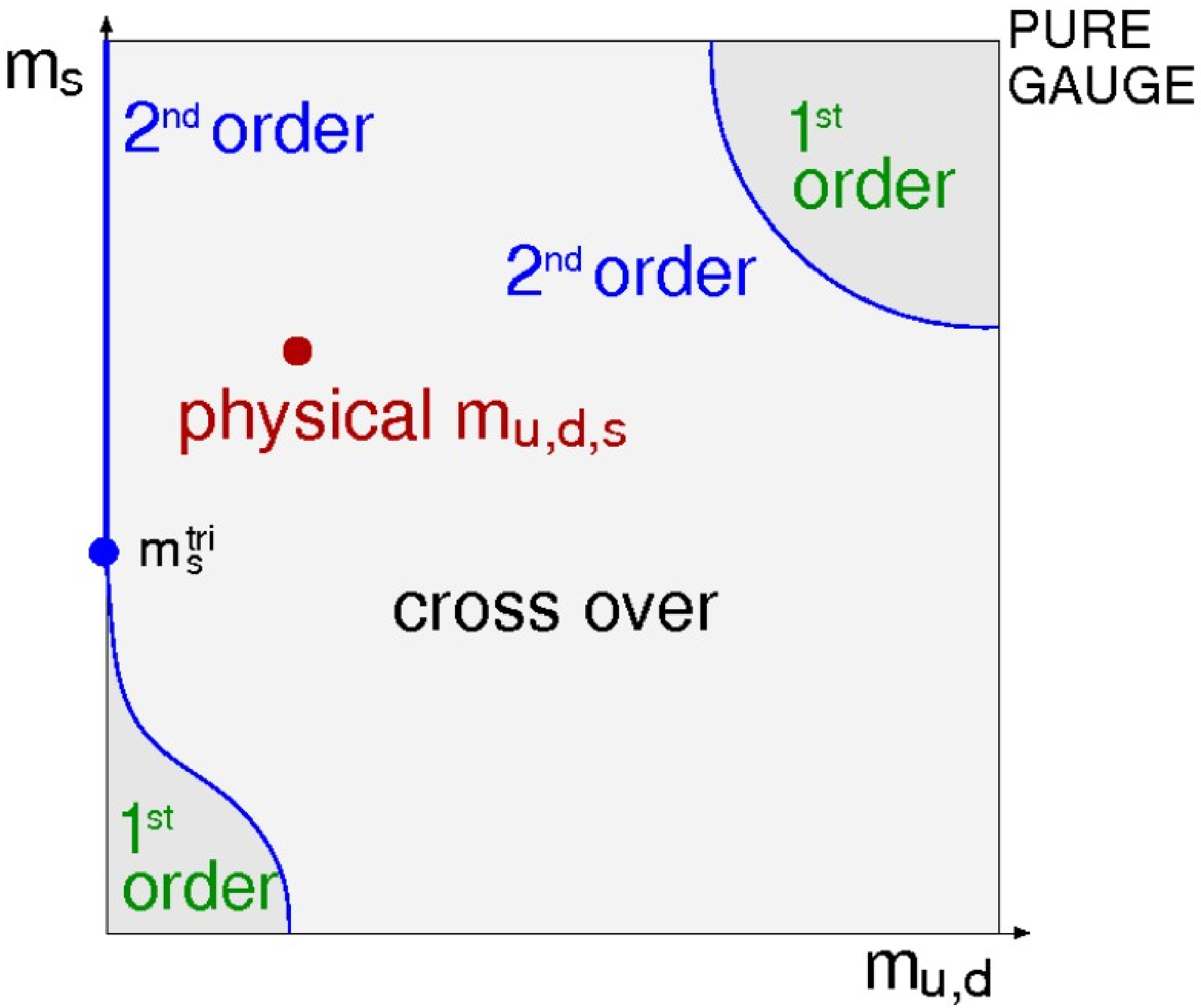
Choice of strange-like mass has strong implications for degeneracy of spectra.

PHASE TRANSITIONS

Expect that for SU(3) theory, 1st order PT if n_f=0 or $3 \leq n_f < 12$.

If ADM and we expect similar number densities form shared asymmetry, expect confinement to be near 1 GeV.

Study of GW signals of dark phase transitions and N hidden sectors
1910.02083 Archer-Smith, Linthorne, Stolarski



Schwaller PhysRevLett.115.181101
Arxiv 1810.12938 **S. Fischer**

Summary

- Hidden confining gauge theories are well motivated frameworks for dark matter.
- Combined with ADM, motivated to explore dark SU(3) with confinement near 1 GeV.
- Phenomenology of hidden QCD can be wildly different than SM, need lattice studies for extreme parameter choices.
- Future work on dark phase transitions, self interactions of composite dark matter, exotic composite dark matter objects.