Asymmetric Dark Matter and Cold Dark Sectors

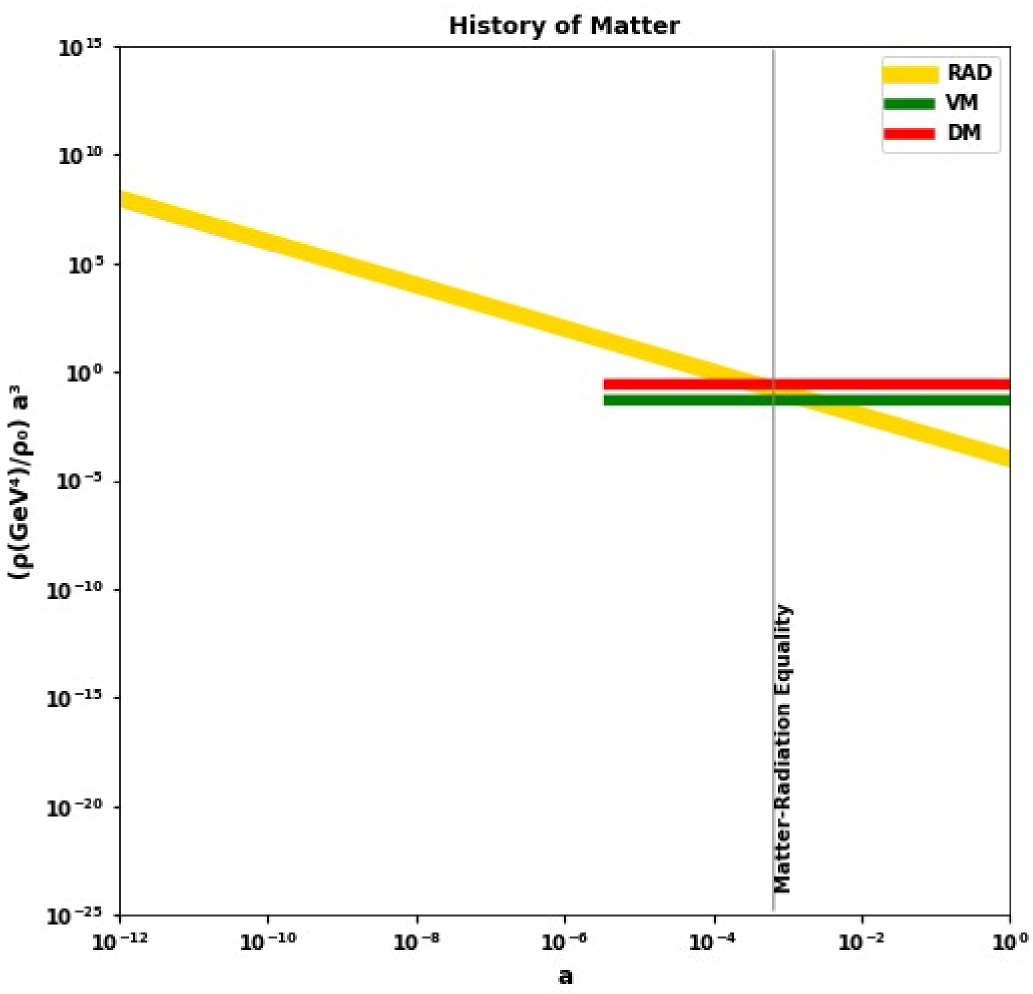
IBS-MultiDark-IPPP Workshop 2019

Stephen J. Lonsdale (IBS-CTPU)

Outline

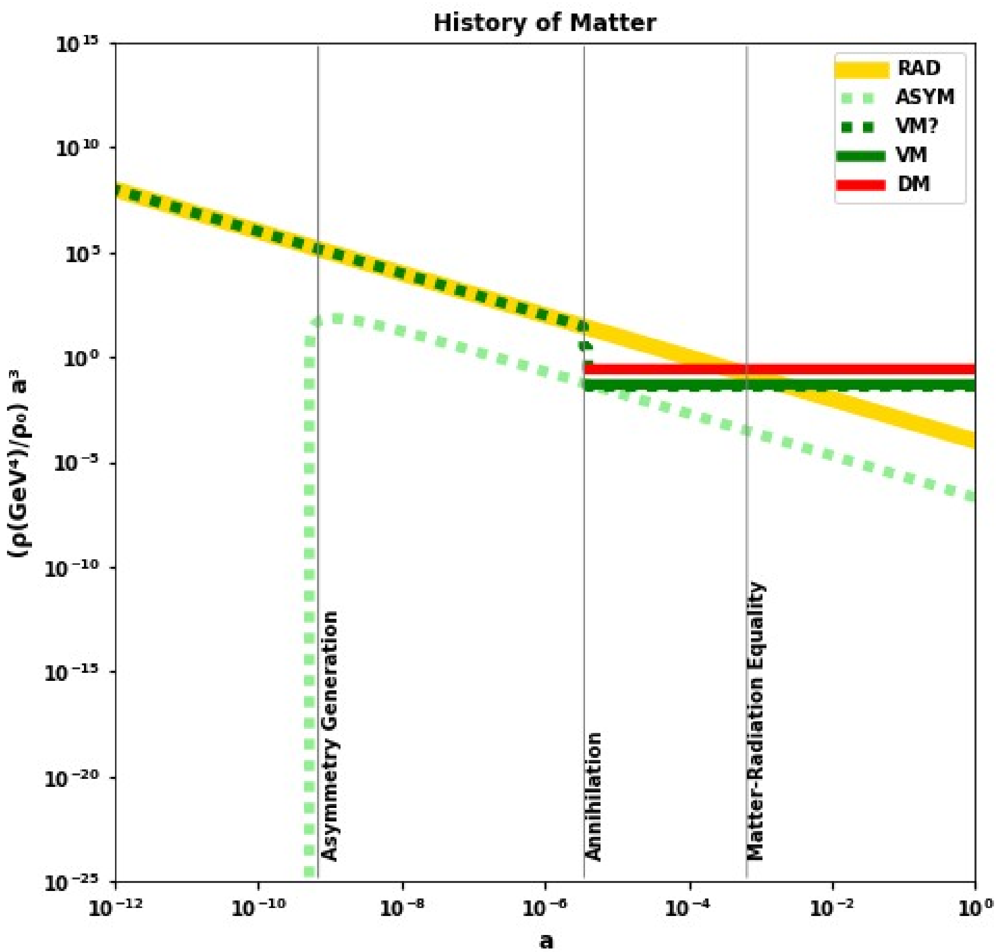
- Review Asymmetric Dark Matter
- Bounds on ADM from the early universe
- Cold Dark Sectors from model building
- Phenomenology of Dark Sectors

History of Matter



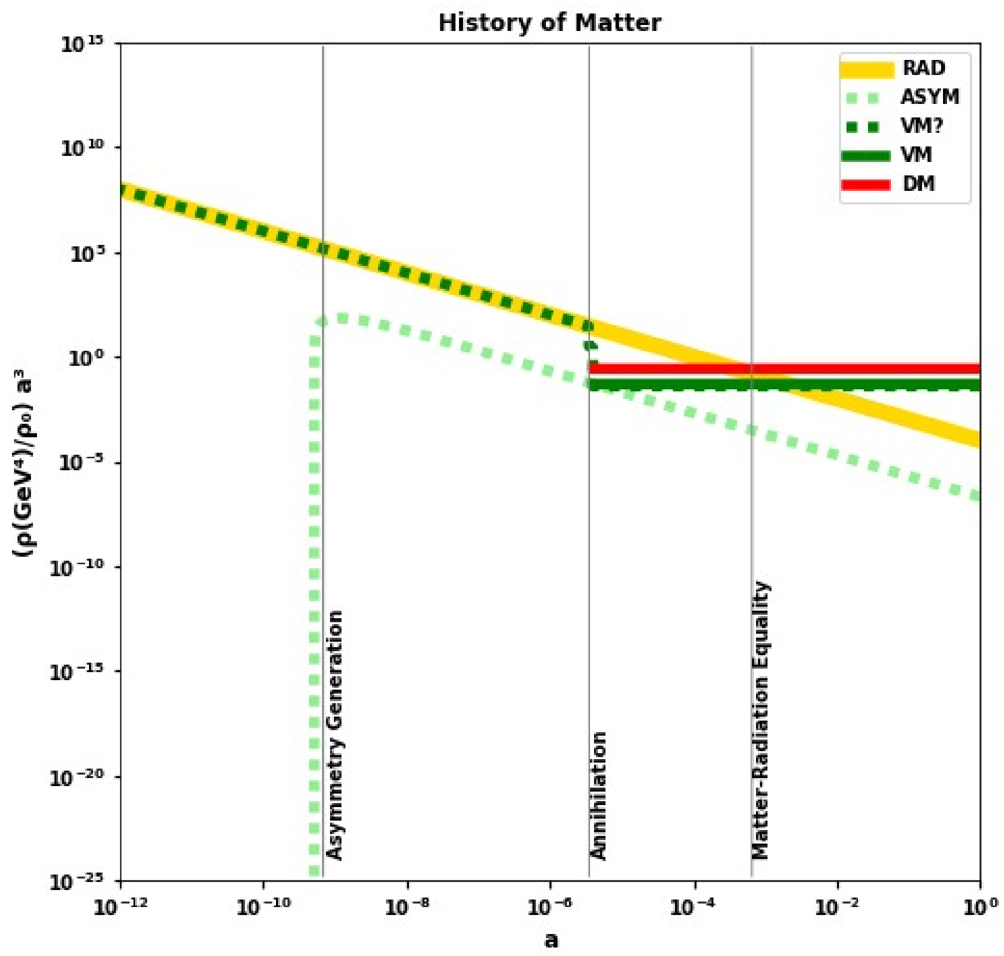
- We can start with scaling back the mass densities as measured.
- The ratios among matter, radiation, dark energy change over the history of the universe.
- But the matter and dark matter tracks will stick together forever into the future.
- Matter-Dark matter ratio known to be approximately 5.

History of Matter



- What do we know about the origin of the baryon density?
- Baryon asymmetry of the universe not fully explained but well measured.
- Models of baryogenesis generally seek to satisfy the Sakharov conditions (violate B, CP and depart thermal equilibrium).
- Generate a sufficient asymmetry in early universe between baryons and antibaryons.

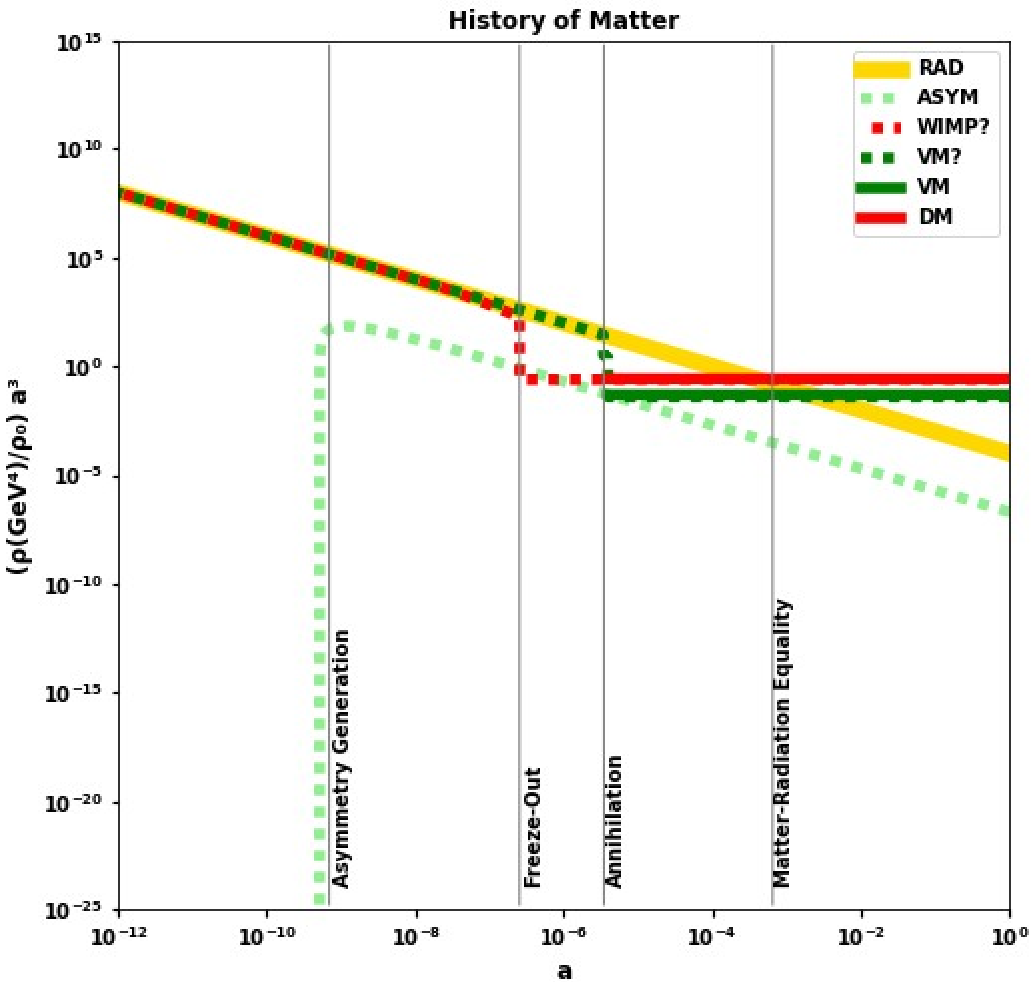
History of Matter



- Once the asymmetry floor is generated, ready to generate the relic density of baryons following annihilation.
- History of visible matter still has much uncertainty.
- Which model of baryogenesis is correct?
- Many models:

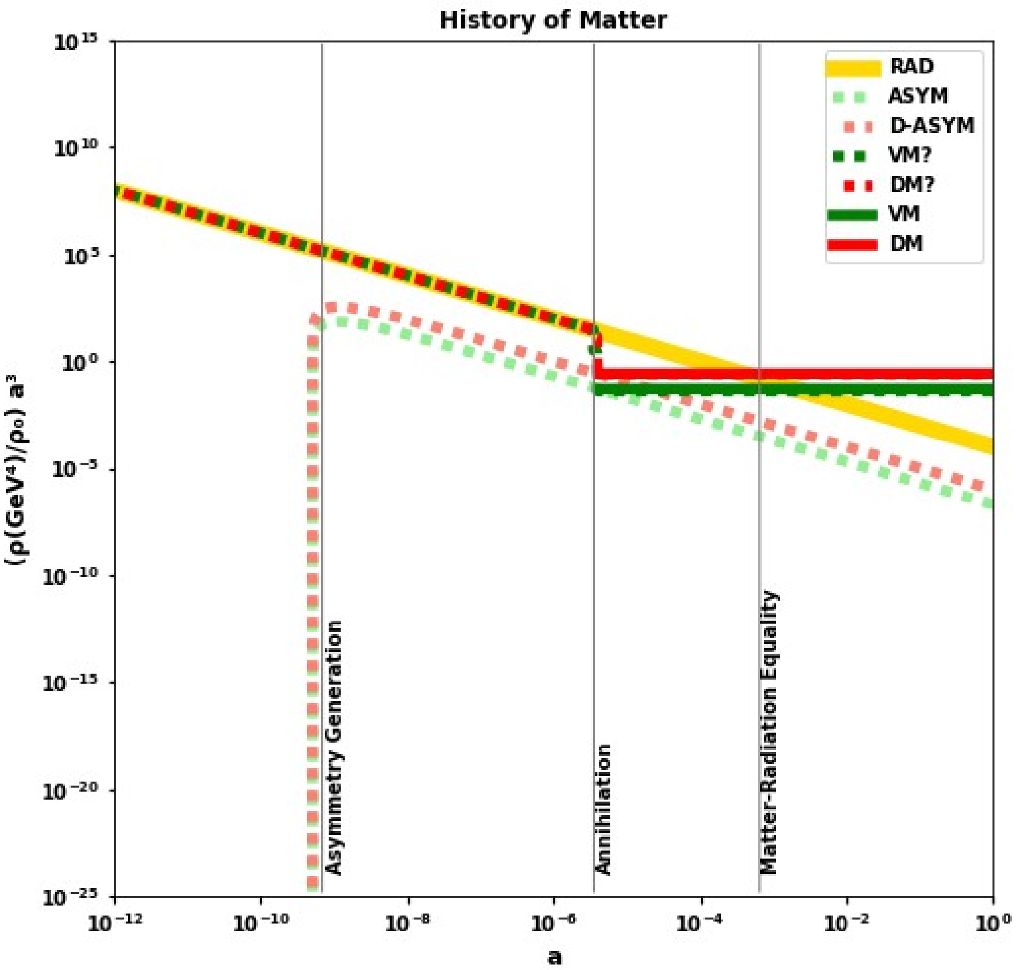
  EW baryogenesis, baryogenesis via leptogenesis, Affleck-Dine, GUT baryogenesis…

History of Matter



- Move onto Dark Matter, we know even less.
- Take a WIMP scenario, with weak freeze out.
- Nicely generates the correct DM mass density.
- DM/M ratio is a curious coincidence, but we can’t argue with results.
- WIMPS are a good idea. Very well motivated.

Asymmetric dark Matter



- Another possible scenario is quite obvious and can give similar mass densities.
- Share the asymmetry in the early universe between the sectors. This gives us a dark asymmetry of similar magnitude, assuming thermal equilibrium during asymmetry formation.
- If DM mass is near the proton, matter tracks end up together forever.
- Annihilation of DM requires radiation candidate (SM or DS?)

Asymmetric Dark Matter

- Many models of ADM (Reviews: Petraki arxiv:1305.4939, Zurek arxiv:1308.0338)
- Tied directly or indirectly to the cause of the Baryon asymmetry.
- Common models include generalized B-L shared between sectors, asymmetry generated in DS/VS and shared to VS/DS, mirror sectors.
- If annihilation is to visible sector, (possibly via mediator), highly constrained for GeV scale DM.
- If annihilation is to pure dark sector species, we are faced with a number of problems...

What do we look for?

How to explain N_{eff}, a critical probe of hidden sectors from CMB and BBN?

Extra relativistic species

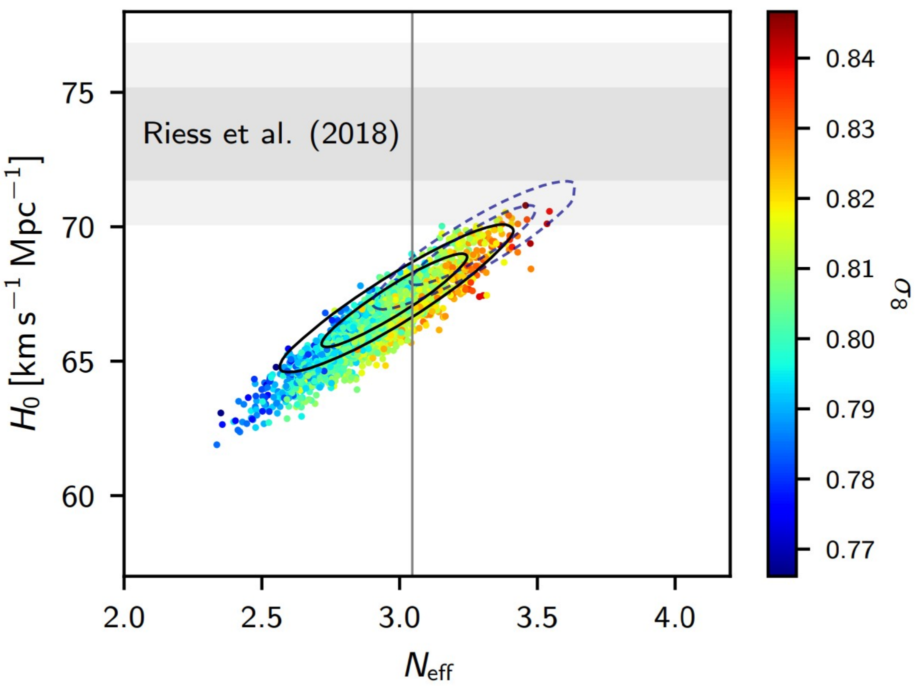
Any contribution to the radiation density in the early universe will in principle contribute to expansion and hence dark radiation can be measured as an additional contribution to the measured number of neutrino species, N_{eff} measurement (SM:N_{eff} ~3.046).

Additional degrees of freedom beyond the SM ruled out for anything with comparable temperature to photons.

Colder degrees of freedom still allowed. Are there cold dark sectors?

$$N_{eff} = 3.00^{+0.57}_{-0.53}\ 95\%,\ \text{Planck TT+low E}$$

$$N_{eff} = 2.99^{+0.34}_{-0.33}\ 95\%,\ \text{Planck TT, TE, EE+low E+lensing+BAO}$$



PLANCK(2018)

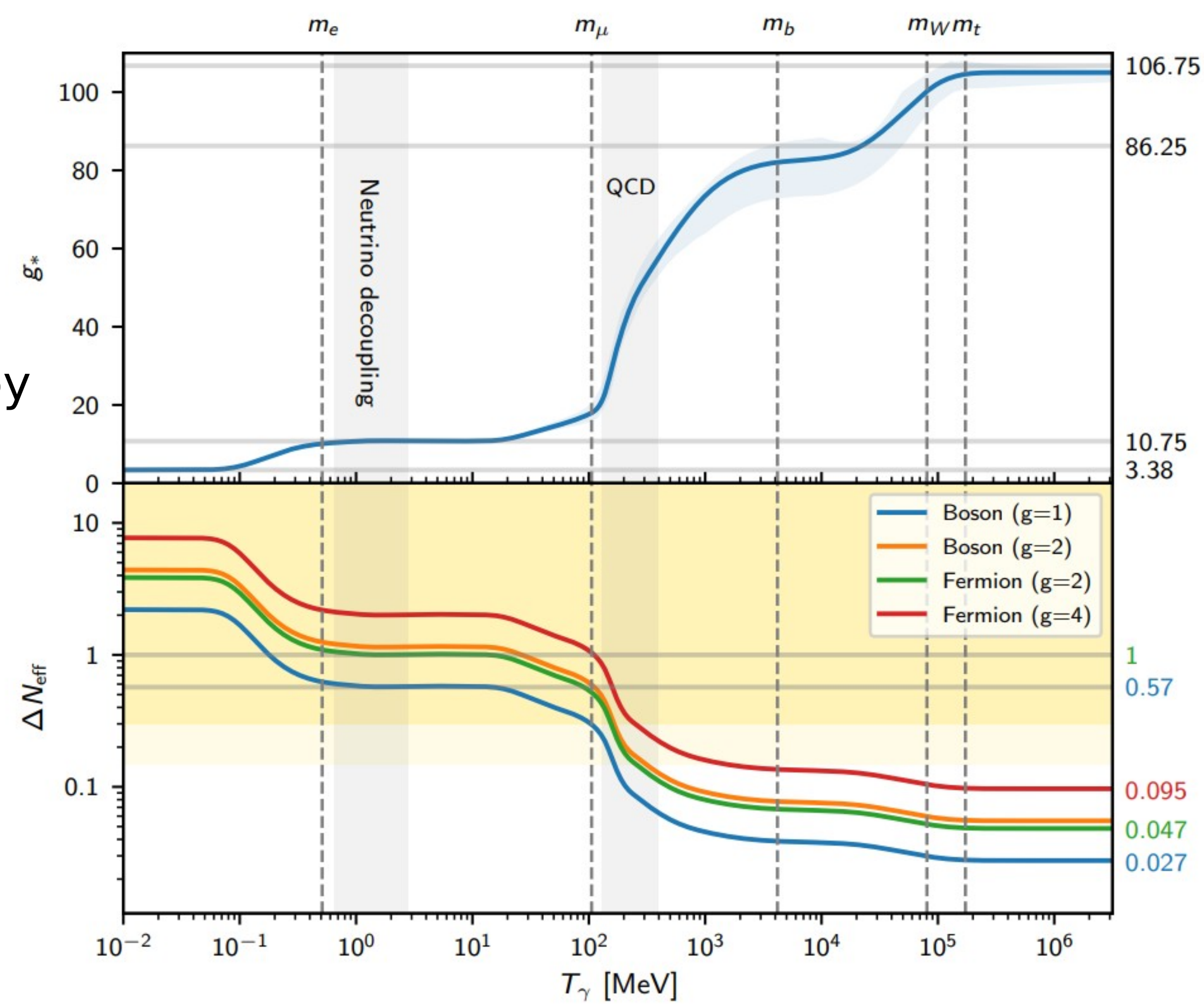
Neff

Express ΔN_{eff} in terms of temperature ratio and dark degrees of freedom

$$\Delta N_{eff} = \left(\frac{T_d}{T_v}\right)^4 \frac{4}{7} \left(\frac{11}{4}\right)^{4/3} g_{*,d}$$

For decoupling of sectors at earlier times, if the visible sector photons receive entropy injections from Boltzmann suppressed species, the temperature ratio drops.

Earlier decoupling leads to greater allowed number of species in the dark sector.



PLANCK(2018)

Dark Sectors

More generally consider 2 sectors, visible and dark, initially in thermal equilibrium.
Let sectors decouple and conserve entropy density separately in each sector after decoupling.

$$a(t)^3 g_{*,d}(t) T_d(t)^3 = a(t_{dec})^3 g_{*,d}(t_{dec}) T_d(t_{dec})^3$$
$$a(t)^3 g_{*,v}(t) T_v(t)^3 = a(t_{dec})^3 g_{*,v}(t_{dec}) T_v(t_{dec})^3$$

Ratio of temperatures following decoupling governed by

$$\left(\frac{T}{T}\right)^{1/3} = \frac{g_{*,v}(t)}{g_{*,v}(t_{dec})} \frac{g_{*,d}(t_{dec})}{g_{*,d}(t)}$$

Are there additional species beyond the EW scale in the visible sector? How large and complex could the dark sector be?

Dark matter mass

- Of course we need more than just asymmetry connection in ADM. The mass of DM also needs to be similar to the proton mass.
- This makes composite DM candidates a natural complement to asymmetric dark matter models.
- Models of Hidden/Dark SU(N) gauge theory in the dark sector, confining at low energy.
- Past work on GUTs + Broken discrete symmetries→ UV connection limits difference in confinement scales, similar asymmetry generation in visible and dark sector.

Comprehensive ADM

- Assume the SM gauge couplings unify at high energy and at the GUT scale the couplings of two sectors are the same with a discrete Z2 symmetry. Then the confinement scales at low energy are related.

$$\mathrm{G}_V \times \mathrm{G}_D$$

- The QCD confinement scale can be expressed (at one loop) as a function of GUT scale and the mass of quarks between the two scales. Spontaneous symmetry breaking breaks discrete symmetry and can break each sector to different subgroups.

  But the dark confinement scale can end up far away even if a dark SU(3) coupling is the same at such high energy.

- However if total number of quarks in each sector are the same, as in the case of a complete Z2 symmetry, then each SU(3) coupling constant will evolve the same until the first mass threshold following Z2 symmetry breaking.

- Use thermal leptogenesis, for example, at an intermediate scale where sectors are in thermal equilibrium and identical abundances are generated. DM mass and proton mass are constrained to be similar by connection in gauge couplings.

Asymmetric Symmetry Breaking

SU(5) X SU(5)

Consider a mirror symmetric SU(5) GUT, with 4 scalars in representations (1,R),(R,1) and (1, R'), (R',1).

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

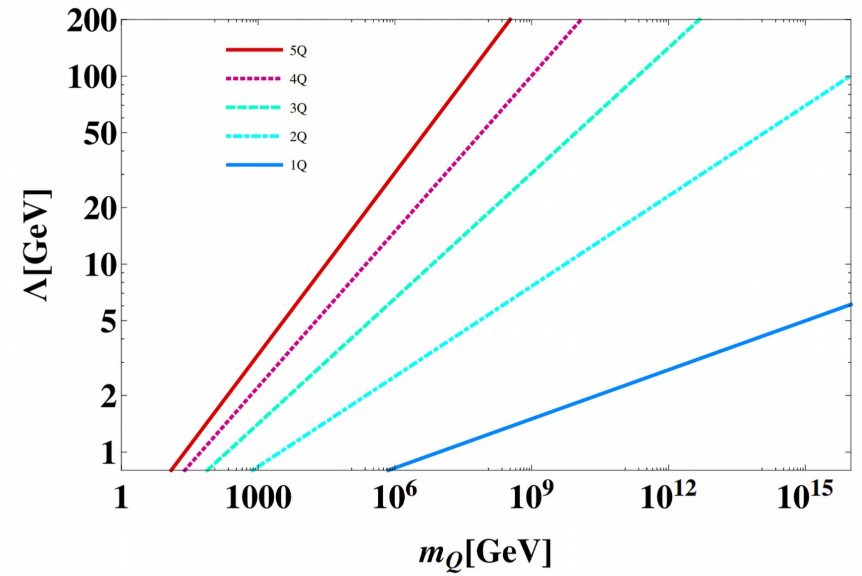
Build symmetric potentials for which the vacuum breaks the discrete symmetry.

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

By choice of R and R', the GUTs of each sector can break completely differently.

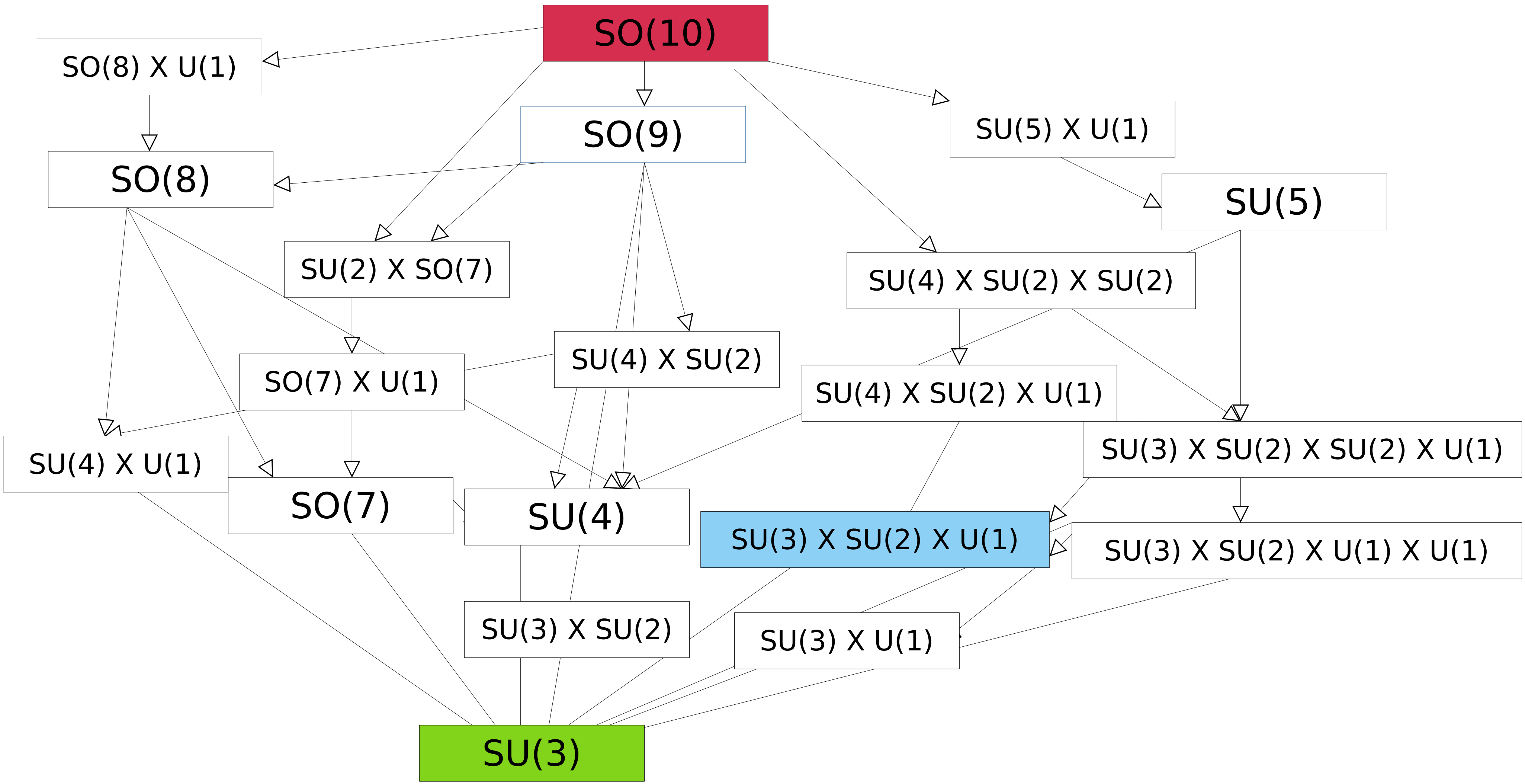
$$SU(5)_d \to SU(3) \times SU(2),$$

$$SU(5)_v \to SU(3) \times SU(2) \times U(1).$$



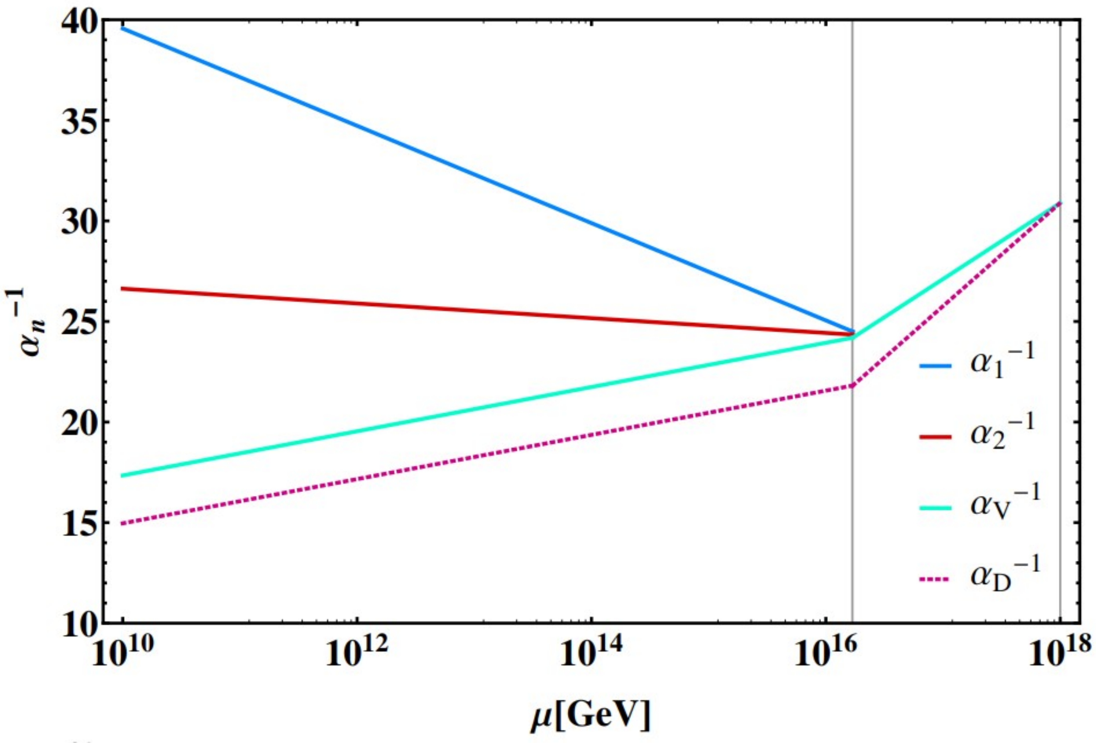
Visible and dark sectors may look almost nothing alike, but the confinement scales are remarkably insensitive to the differences that appear.

Breaking Chains of SO(10)



Unified dark matter with intermediate symmetry breaking scales. [arXiv:1412.1894]
-SJL

Asymmetric Sectors



Intermediate groups: SU(5) vs SO(8)

Select two chains from the GUT era. Proton and DM mass scales can maintain their similarity.

Add two additional features:

An asymmetry generation mechanism at an appropriate scale.

A thermal decoupling scale for the visible and dark sectors.

Comprehensive ADM

Consider a low to intermediate scale model with gauge groups the same at the thermal leptogenesis era.

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

Add a second Higgs doublet and right handed N and associated dark sector copies.

$$L_{yukawa} = \lambda_{1ij}\bar{l}^i_L e^j_R \Phi_1 + \lambda_{1ij}\bar{l'}^i_R e'^j_L \Phi'_1 + h_{1ij}\bar{l}^i_L N^j_R \tilde{\Phi}_1 + h_{1ij}\bar{l'}^i_R N'^j_L \tilde{\Phi}'_1 +$$
$$\lambda_{2ij}\bar{l}^i_L e^j_R \Phi_2 + \lambda_{2ij}\bar{l'}^i_R e'^j_L \Phi'_2 + h_{2ij}\bar{l}^i_L N^j_R \tilde{\Phi}_2 + h_{2ij}\bar{l'}^i_R N'^j_L \tilde{\Phi}'_2 +$$
$$f_{1ij}\bar{l}^i_L (N'^j_L)^c \tilde{\Phi}_1 + f_{1ij}\bar{l'}^i_R (N^j_R)^c \tilde{\Phi}'_1 + f_{2ij}\bar{l}^i_L (N'^j_L)^c \tilde{\Phi}_2 + f_{2ij}\bar{l'}^i_R (N^j_R)^c \tilde{\Phi}'_2.$$

Thermal leptogenesis creates the same B-L asymmetry in each sector but at low energy after EWSB the vacuum makes the sectors look very different.

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

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

$$H'_1 = \frac{w_1^*\Phi_1 + w_2^*\Phi_2}{w}, \qquad H'_2 = \frac{-w_2\Phi_1 + w_1\Phi_2}{w}.$$

Comprehensive asymmetric dark matter model.[arXiv:1801.05561]
-SJL and Raymond R. Volkas

Naturally Cold DS

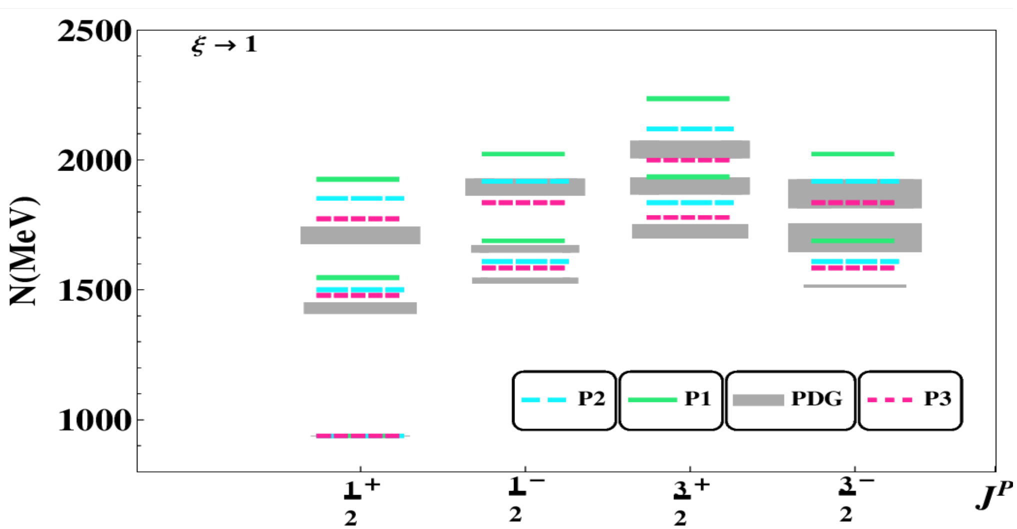
- Similar to a number of models, the thermal decoupling of sectors takes place between the visible and dark confinement scales.(Farina 1506.03520, Bai, Long, Lu 1810.04360)
- Most natural way to do this is a model where the first PT triggers decoupling...
- Dark matter is a mixture of dark neutrons and dark hydrogen atoms. Depending on Majorana neutrino mass, dark H can decay with long lifetimes into dark N + SM species as source of indirect detection.
- Dark neutron self-interaction: $\sigma/m \sim 3cm^2/g \times \left(\frac{\Lambda_{\mathrm{D}M}}{m_N}\right)\left(\frac{\Lambda_{\mathrm{D}M}}{a^{-1}}\right)^2\left(\frac{100\mathrm{M}eV}{\Lambda_{\mathrm{D}M}}\right)^3$
- In general many cross-sector terms can be included:U(1) kinetic mixing, neutrino Portal, Higgs portal, scalar mediators...

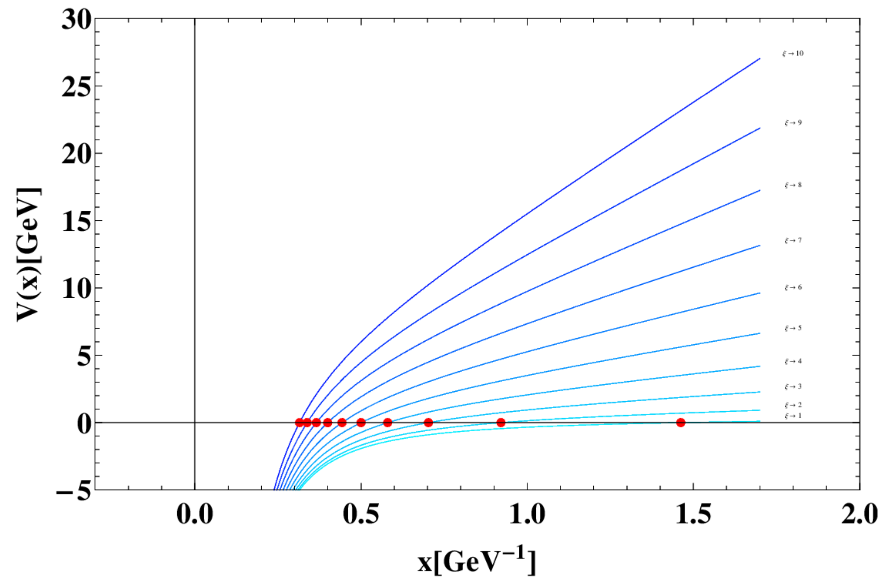
Composite ADM

Composite hidden sectors can also have a rich structure compared to regular QCD.

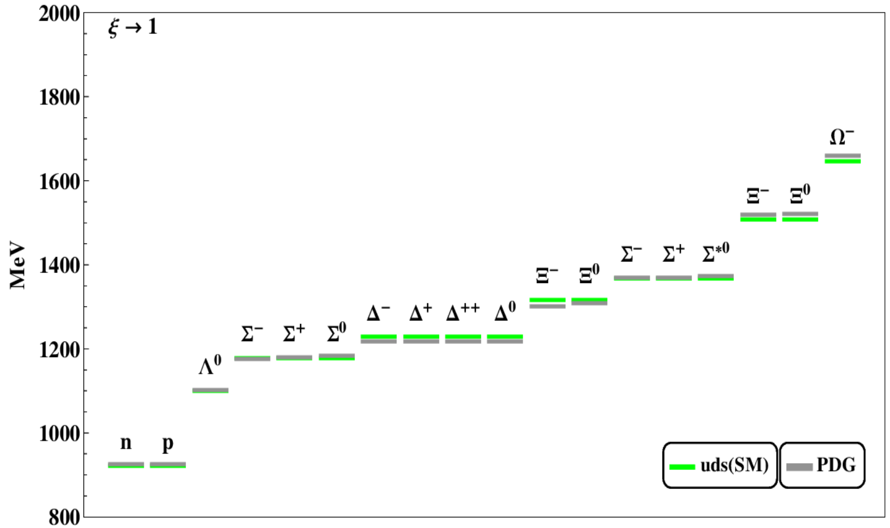
$$\left[\frac{d^2}{dx^2} + \frac{5}{x}\frac{d}{dx} - \frac{\gamma(\gamma+4)}{x}\right]\psi_{N,[\gamma]} = -2m\left[E - V(x)\right]\psi_{N,[\gamma]}$$

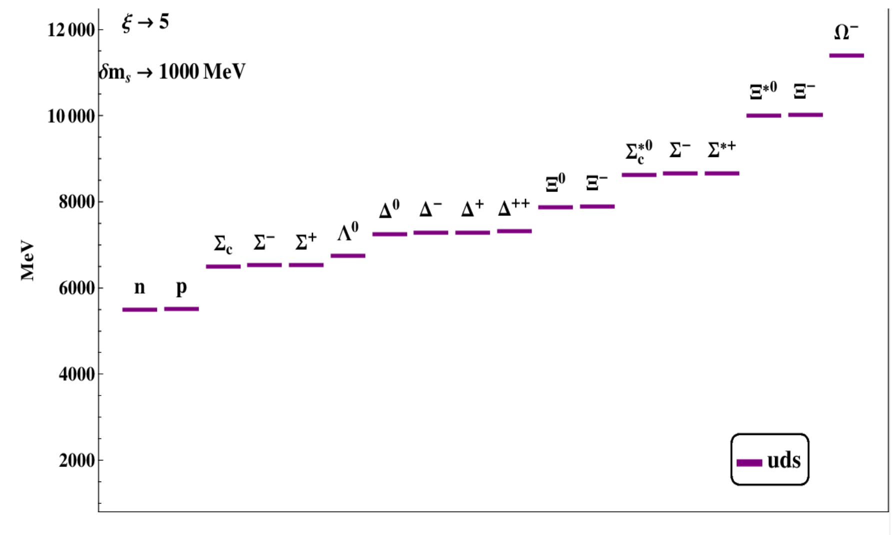
Take a simple model of QCD and explore hadronic spectra for variable confinement scale and quark masses.

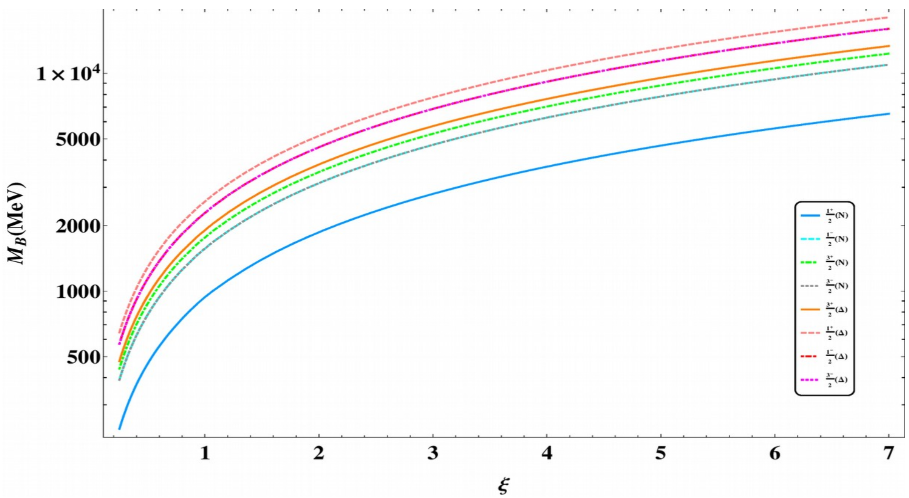




Composite ADM







Baryon Spectra

We can obtain spectra for a mix of light quarks and semi-light quarks.

Limited parameter space for meson spectra to examine range of nuclear forces.

Asymmetric dark matter and the hadronic spectra of hidden QCD. [arxiv:1704.05213]
-SJL, Martine Schroor and Raymond R. Volkas

Composite ADM

- Such hidden confining theories are as likely to produce complex systems of many different particles as a single dark matter candidate.
- The exploration of these dark QCD theories will benefit from more exploration and in particular lattice studies are better suited to map the more extreme ranges of parameter space.
- Compact object formation such as dark neutron stars.
- Other exotic confined states such as ‘Dark quark nuggets’, ‘dark glueballs’.
- Within complex dark sectors, composite ADM states often accompanied by lighter dark sector states…as in the visible sector.

Summary

- Comprehensive models of asymmetric dark matter can form naturally using asymmetric symmetry breaking. Mirror or mirror GUT theories at high energy can spontaneously break to form the standard model and a dark sector which solves the dark matter question in a satisfying way.
- Dark sectors can be naturally cold, feature composite DM.
- Confining non-abelian gauge theories of the two sectors are constrained to have similar confinement scales by high scale mirror symmetry even when significant differences in the visible and dark sectors arise.
- The search for ADM is tied to the field of baryogenesis - understanding sources of CP violation, origin of neutrino mass...