Dark QCD and asymmetric dark matter

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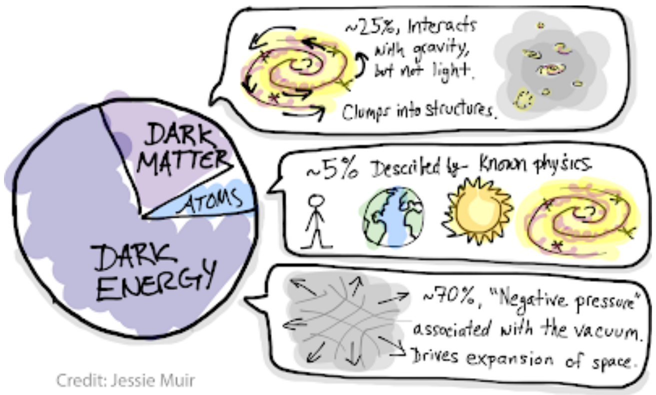
Observationally, it is now very well established that



$$\Omega_{\rm DM} \simeq 5\Omega_{\rm VM}$$

dark matter — visible matter

This cosmological connection may be a clue to the particle nature of DM.

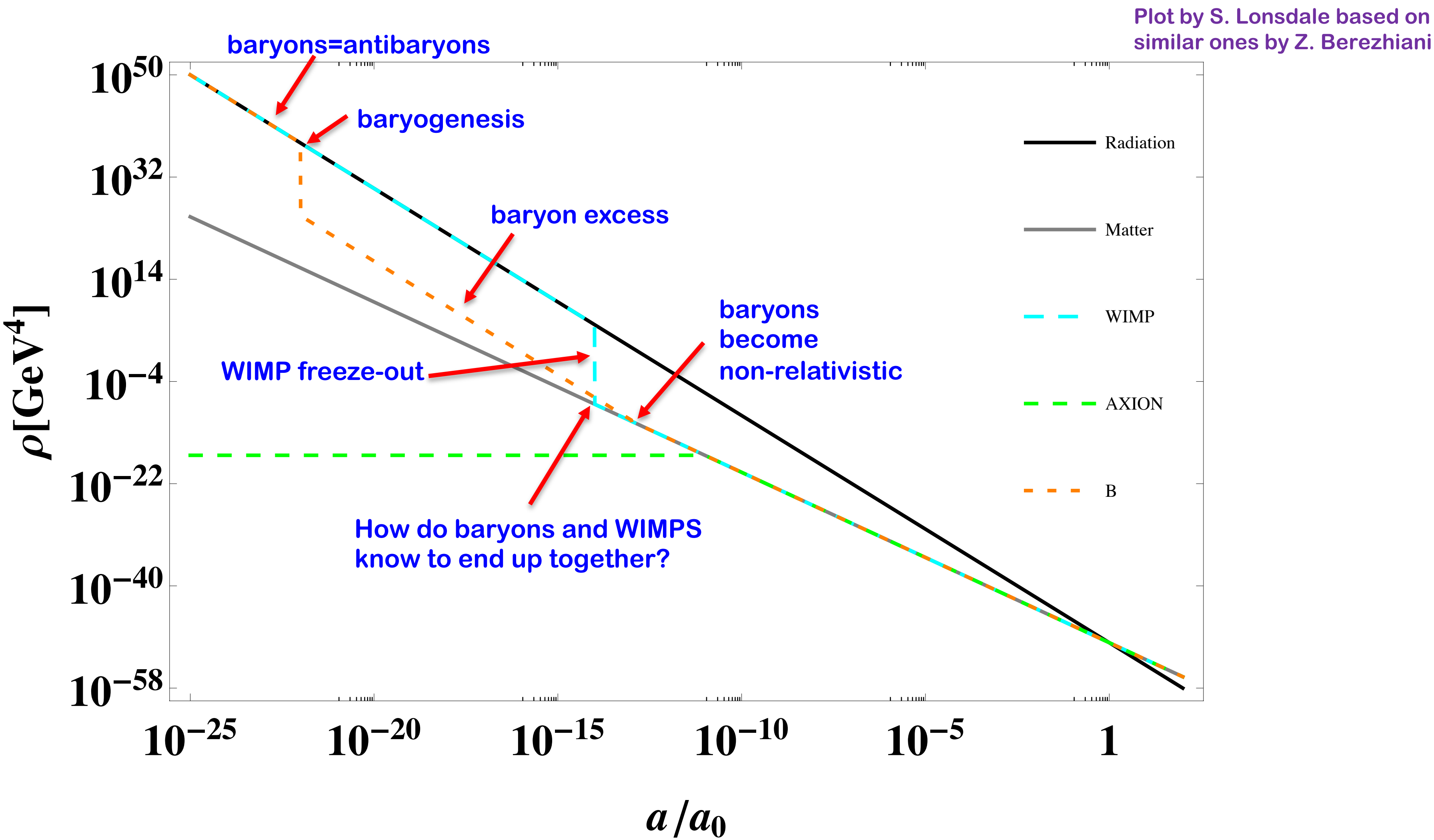
The origin of VM has been identified, if not dynamically understood.

It is the baryon asymmetry of the universe:

$$\Omega_{\rm VM} \equiv \frac{\rho_p - \rho_{\bar{p}}}{\rho_c} \simeq \frac{\rho_p}{\rho_c}$$

p = proton/neutron
c = critical

In almost all DM theories, the DM/VM~5 relation has to be largely coincidental.



Can we make DM naturally track the thermal history of VM?

Yes.

The idea is called "asymmetric dark matter".

DM may be the stable component of a "dark sector" whose relic density is determined by a dark matter-antimatter asymmetry that is related to the visible matter-antimatter asymmetry.

The idea can be traced back in history to early mirror matter studies (Blinnikov and Khlopov, 1982-1983).
Technicolour realisation (Nussinov, 1985; Barr, Chivukula and Farhi, 1990).
The "asymmetric DM" name (Hooper, March-Russell and West, 2005; Kaplan, Luty, Zurek, 2009).
Review article (Petraki and RV, 2013).

Physical requirements for asymmetry generation

$$\eta_p \simeq \frac{n_p}{n_\gamma} \sim 10^{-10}$$

Sakharov's conditions:

1. Baryon number violation

2. C and CP violation

3. Out-of-equilibrium

Common general mechanisms:

Out-of-equilibrium decays of heavy particles:

$$\Gamma(\psi \to x_1 \; x_2 \ldots) \neq \Gamma(\psi \to x_1^* \; x_2^* \ldots)$$

Affleck-Dine: production of charged scalar condensate through time-dep. phase.
Supersymmetry, uses flat directions.

First-order phase transition: nucleation of bubbles of true vacuum, sphalerons,
CP-violating collisions with bubble walls.

Out-of-equilibrium scattering: DM particles scatter/coannihilate with SM
particles at a different rate from DM antiparticles.

NEWish! Baldes, Bell, Petraki, RV (2014) and Baldes, Bell, Millar, Petraki, RV (2014)

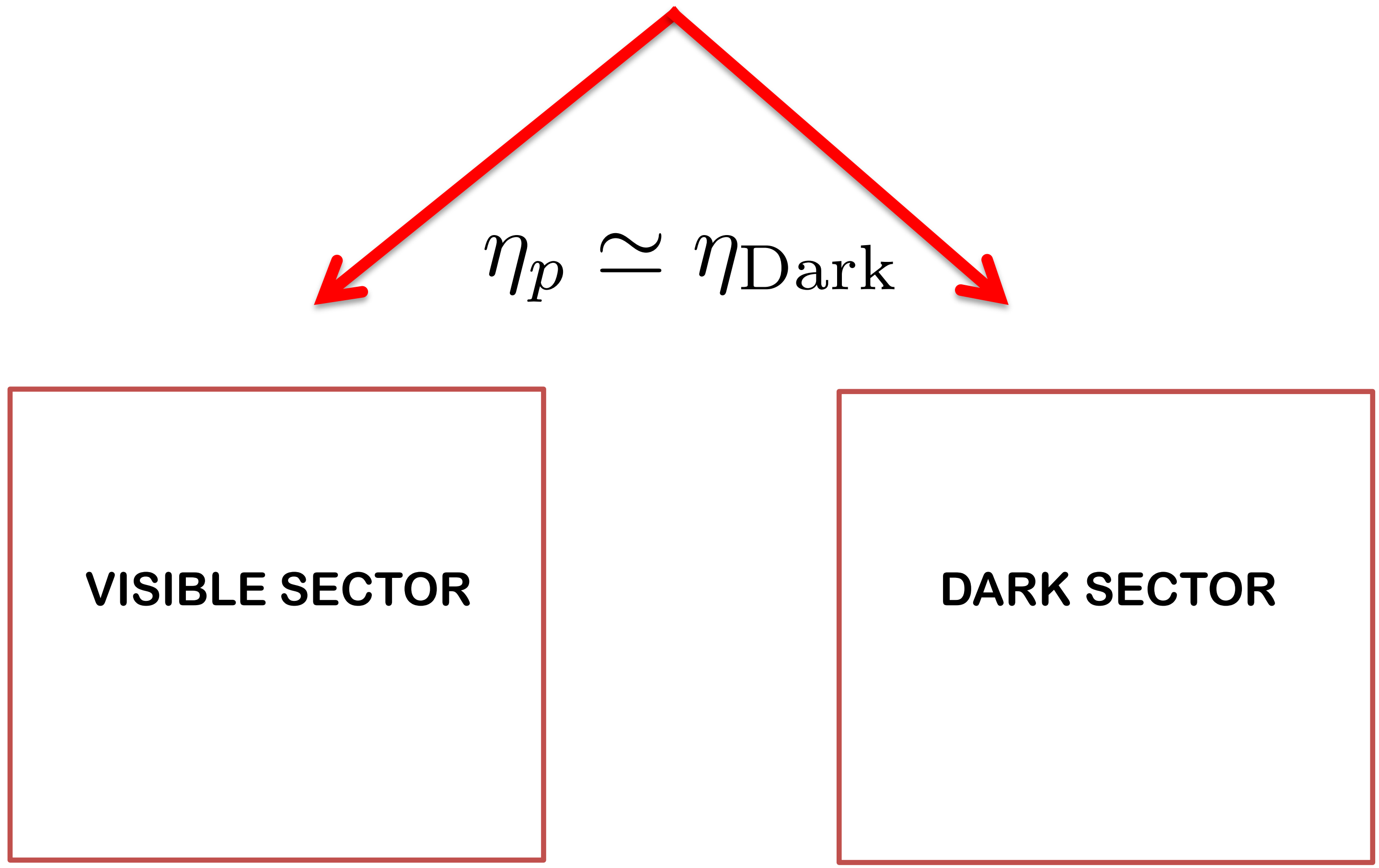
Asymmetric thermal production (asymmetric freeze-in): DM and anti-DM
never in thermal equilibrium; slowly produced at different rates.

Spontaneous genesis: Sakharov conditions presuppose CPT invariance.
Expanding universe induces effective CPT violation.
Asymmetry generation in eq. without C, CP violation.

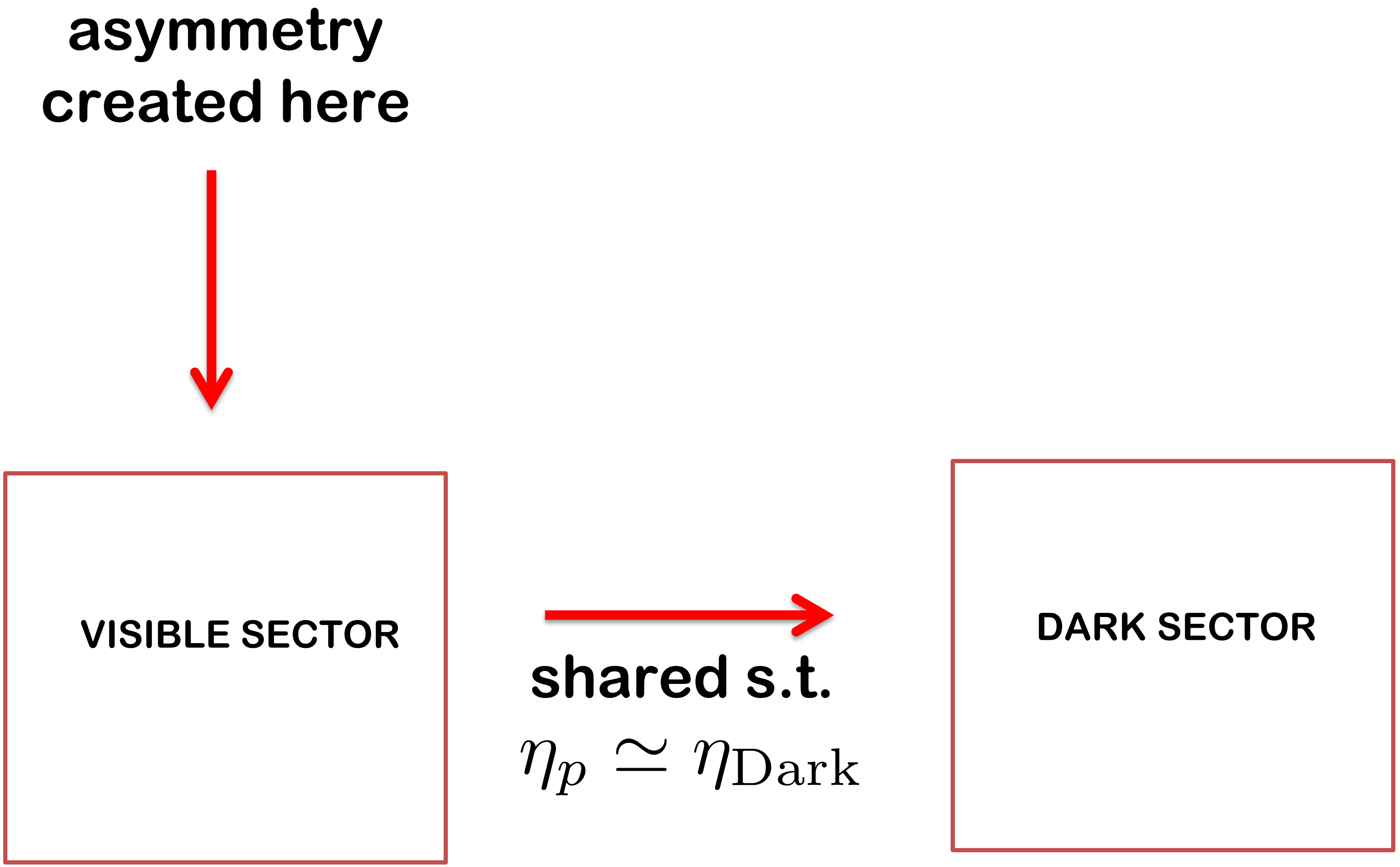
Steps in the construction of an ADM model:

- **Decide if VM is described by the SM or an extension**
- **Specify the dark sector gauge group and particle content**
- **Sometimes there is a third sector that connects the VM and DM sectors**
- **Choose an asymmetry generation mechanism**
- **Specify the dynamics that relates the VM and DM number-density asymmetries**
- **Make the symmetric part of the dark plasma annihilate into phenomenologically acceptable radiation**
- ***Connect the number-density asymmetries to mass-densities …***

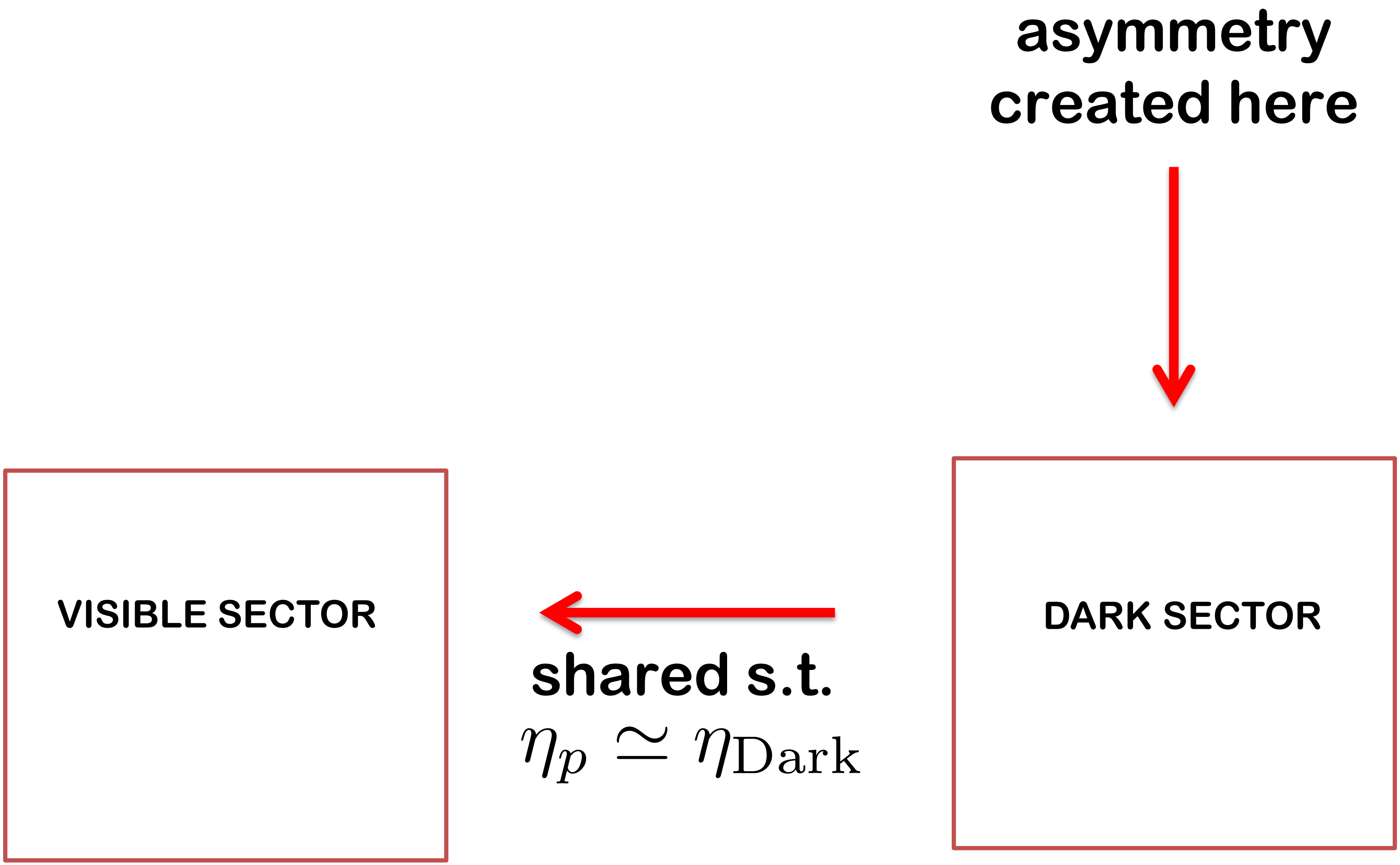
Simultaneous creation of correlated asymmetries.
“Pangenesis” “Cogenesis”



Or: visible to dark reprocessing



Or: dark to visible reprocessing



- …
- *connect the number-density asymmetries to mass-densities …*

Back to: $\Omega_{\rm DM} \simeq 5\Omega_{\rm VM}$

which is: $m_{\rm D}\, n_{\rm D} \simeq 5\, m_{\rm V}\, n_{\rm V}$

proton mass: $\Lambda_{\rm QCD}$

Baryon-antibaryon asymmetry

$$\eta_p \simeq \frac{n_p}{n_\gamma} \sim 10^{-10}$$

Obtaining number density relation, $n_D \sim n_p$,
is a staple of the asymmetric DM literature.

$$\boxed{\text{But why } m_D \sim m_p\text{?}}$$

This is a very neglected topic in the ADM literature.

Could the DM particle be, for example, a “dark neutron”?

The lightest, stable fermionic bound state of “dark QCD”?

This is an example of “composite dark matter”.

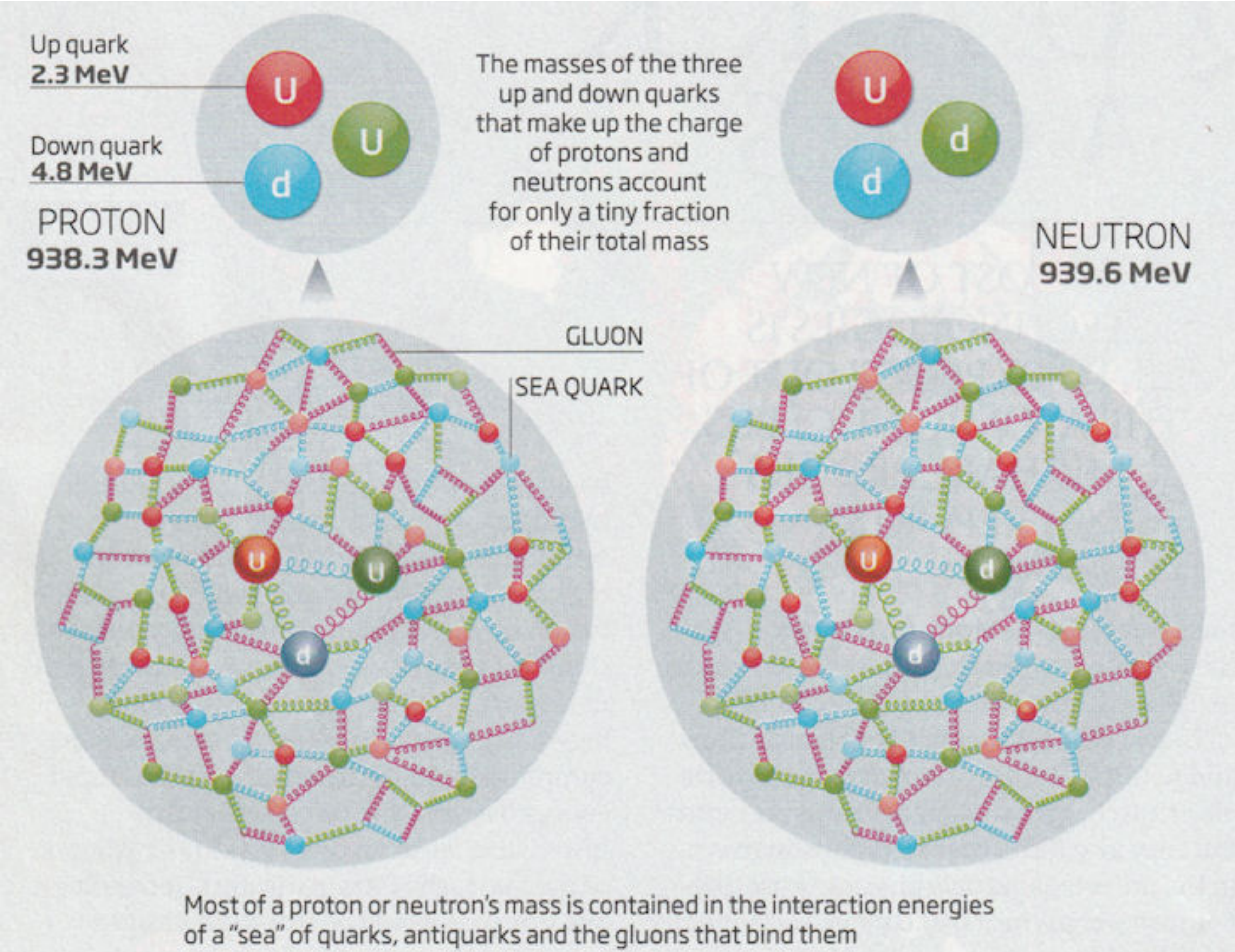


Image credit: universe-review.ca

Origin of dark QCD?

Probably some version of a broken or unbroken mirror matter model:

Gauge group: $G_{VM} \times G_{DM}$ with $G_{VM} \cong G_{DM}$ and discrete Z_2: $G_{VM} \leftrightarrow G_{DM}$

$$G = SU(3) \times SU(2) \times U(1), \quad SU(5), \quad SO(10), \quad \ldots$$

Pre-modern: Lee+Yang (1956), Kobzarev+Okun+Pomeranchuk (1966), Blinnikov+Khlopov (1982-1983), …
Modern: Foot+Lew+RV (1991), Berezhiani et al, Mohapatra et al, H.-J. He et al, …

R. Foot (recent years): *heroic analyses of unbroken mirror dark matter.*

We pursue broken mirror models in this talk.

Spontaneously broken mirror models of ADM: PhD thesis (2018) of Stephen J. Lonsdale.

S.J. Lonsdale, RV: PRD90 (2014) 083501
(E) PRD91 (2015) 129906

S.J. Lonsdale: PRD91 (2015) 125019

parameter space for $\Lambda_D \gtrsim \Lambda$

S.J. Lonsdale, M. Schroor, RV: PRD96 (2017) 055027

dark hadron spectra from "hyperspherical constituent quark model"

S.J. Lonsdale, RV: PRD97 (2018) 103510

example of a comprehensive theory

What are the requirements for such a theory?

- Way to spontaneously break G_{VM} and G_{DM} differently despite the Z_2
- Preservation of $SU(3)_{DM}$ as exact subgroup
- Strong coupling constant running so that $\Lambda_D \gtrsim \Lambda$
- Dark hadron spectrum with viable DM candidate
- A full theory: renormalisable
  correlated visible and dark baryogenesis
  acceptable way to annihilate symmetric part of dark sector
  neutrino masses
  fully specified and viable cosmological history

Way to spontaneously break G_{VM} and G_{DM} differently despite the Z_2

Asymmetric symmetry breaking:

$$\phi_1 \leftrightarrow \phi_2, \qquad \chi_1 \leftrightarrow \chi_2$$ **1=visible, 2=dark**

$$V = \lambda_\phi(\phi_1^2 + \phi_2^2 - v_\phi^2)^2$$ **Φ sector nonzero**

$$+\lambda_\chi(\chi_1^2 + \chi_2^2 - v_\chi^2)^2$$ **χ sector nonzero**

$$+\kappa_\phi \phi_1^2 \phi_2^2$$ **either Φ_1 or Φ_2 zero**

$$+\kappa_\chi \chi_1^2 \chi_2^2$$ **either χ_1 or χ_2 zero**

$$+\sigma\left(\phi_1^2\chi_1^2 + \phi_2^2\chi_2^2\right)$$ **If $\Phi_1 \neq 0$ then $\chi_1 = 0$ etc.**

$$+\rho(\phi_1^2 + \phi_2^2 + \chi_1^2 + \chi_2^2 - v_\phi^2 - v_\chi^2)^2$$

$$\lambda_\phi,\ \lambda_\chi,\ \kappa_\phi,\ \kappa_\chi,\ \sigma,\ \rho > 0$$

$$\boxed{\begin{array}{l}\langle\phi_1\rangle = v_\phi, \quad \langle\phi_2\rangle = 0 \\ \langle\chi_1\rangle = 0, \quad \langle\chi_2\rangle = v_\chi\end{array}}$$

Asymmetric symmetry breaking can cascade:

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

such that

$$\boxed{\begin{array}{ll} \langle\phi_1\rangle = v_\phi, & \langle\phi_2\rangle = 0 \\ \langle\chi_1\rangle = 0, & \langle\chi_2\rangle = v_\chi \end{array}}$$

can through coupling induce

$$\Omega_1 \leftrightarrow \Omega_2, \qquad \eta_1 \leftrightarrow \eta_2$$

such that

$$\boxed{\begin{array}{ll} \langle\Omega_1\rangle = v_\Omega, & \langle\Omega_2\rangle = 0 \\ \langle\eta_1\rangle = 0, & \langle\eta_2\rangle = v_\eta \end{array}}$$

That's the basic idea. Any realistic implementation will have extra complications that have to be worked through.

- *Way to spontaneously break G_{VM} and G_{DM} differently despite the Z_2*
- *Preservation of $SU(3)_{DM}$ as exact subgroup*
- *Strong coupling constant running so that $\Lambda_D \gtrsim \Lambda$*

One example: $SU(5)_V \times SU(5)_D$

broken by

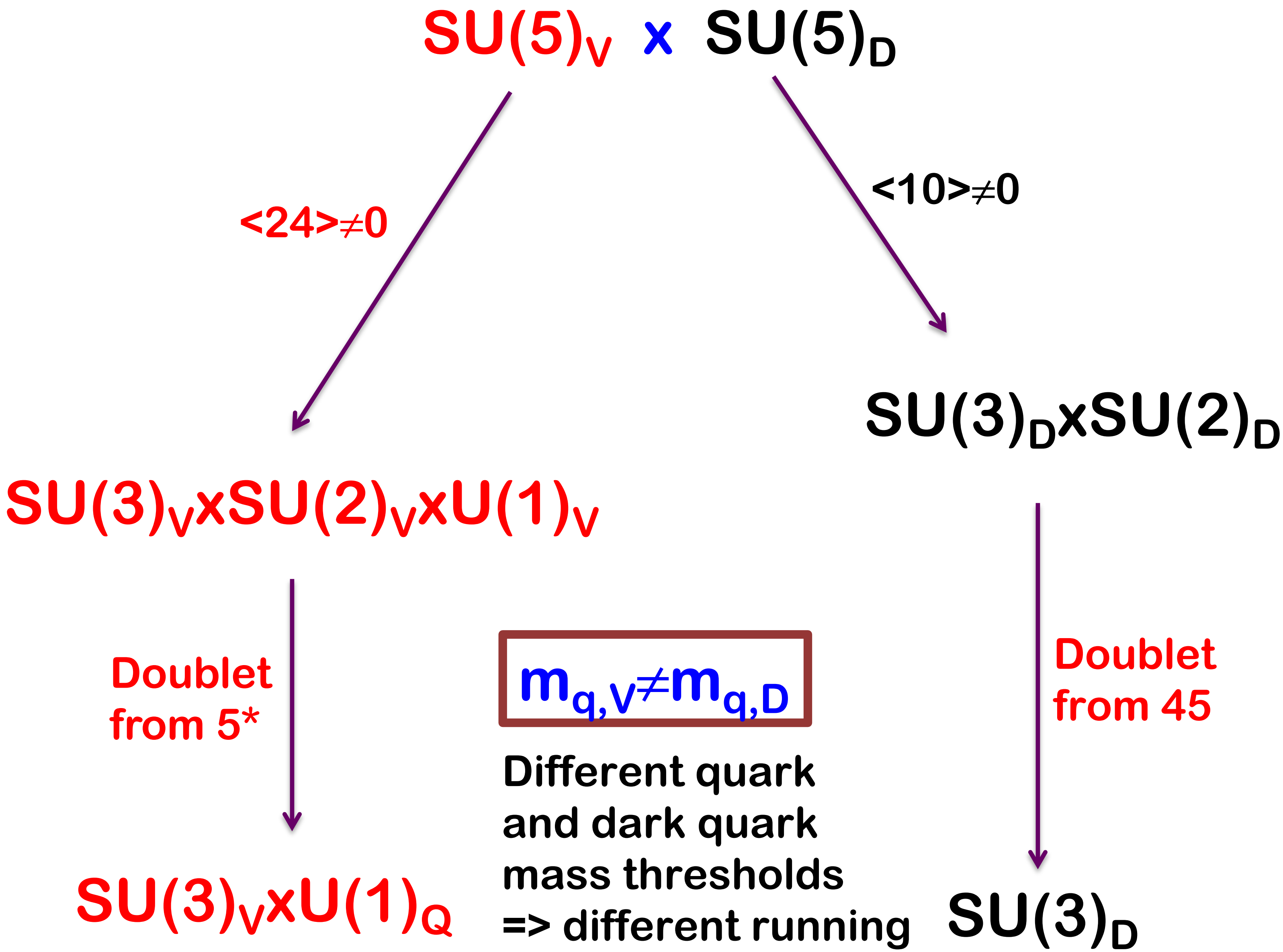
$$(24,1) \leftrightarrow (1,24), \qquad (10,1) \leftrightarrow (1,10)$$

nonzero zero zero nonzero

Fermion masses generated by

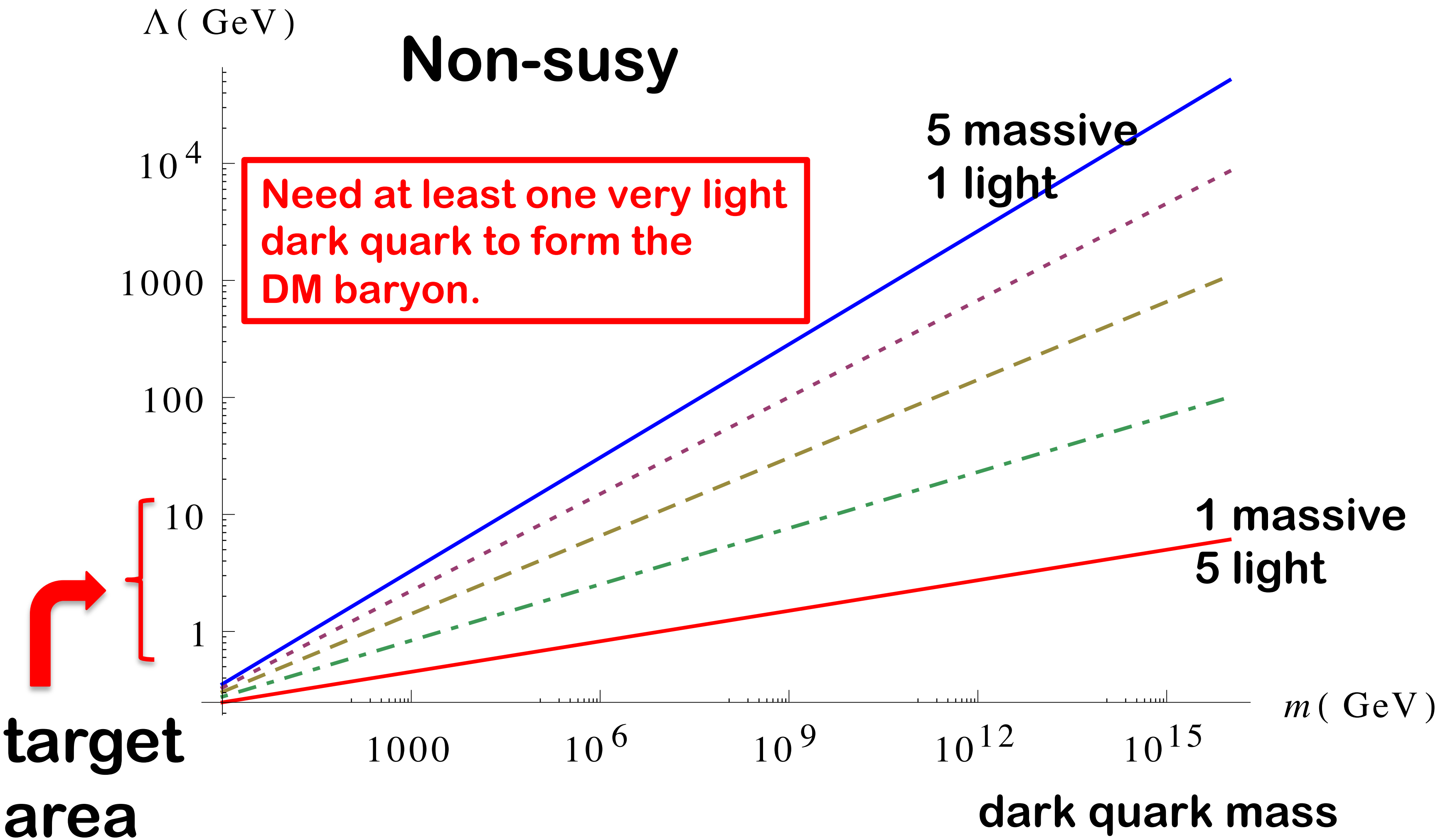
$$(5^*,1) \leftrightarrow (1,5^*), \qquad (45,1) \leftrightarrow (1,45)$$

nonzero zero zero nonzero



$SU(5)_V \times SU(5)_D$
$\langle 24 \rangle \neq 0$
$\langle 10 \rangle \neq 0$
$SU(3)_D \times SU(2)_D$
$SU(3)_V \times SU(2)_V \times U(1)_V$
Doublet from 5*
$m_{q,V} \neq m_{q,D}$
Doublet from 45
Different quark and dark quark mass thresholds => different running
$SU(3)_V \times U(1)_Q$
$SU(3)_D$

Non-susy



Greater # of massive dark quarks => faster running of dark QCD coupling => higher dark confinement scale

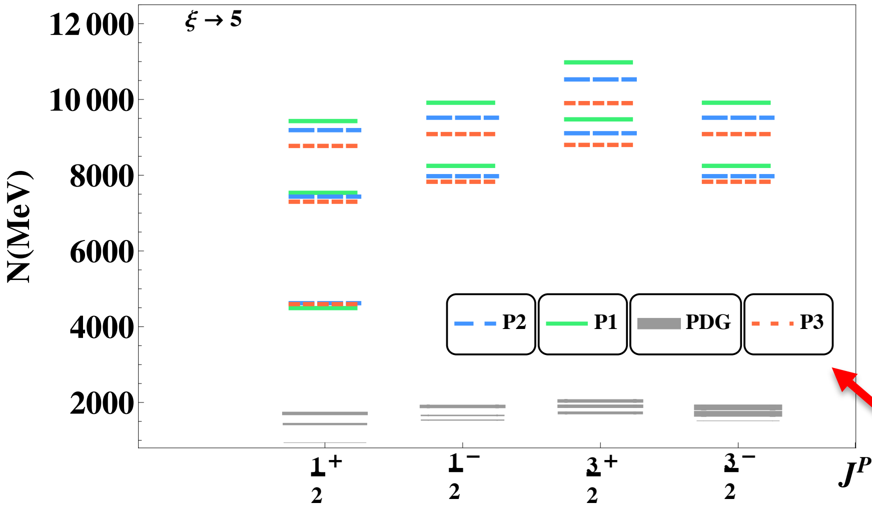
- Way to spontaneously break G_{VM} and G_{DM} differently despite the Z_2
- Preservation of $SU(3)_{DM}$ as exact subgroup
- Strong coupling constant running so that $\Lambda_D \gtrsim \Lambda$
- *Dark hadron spectrum with viable DM candidate*

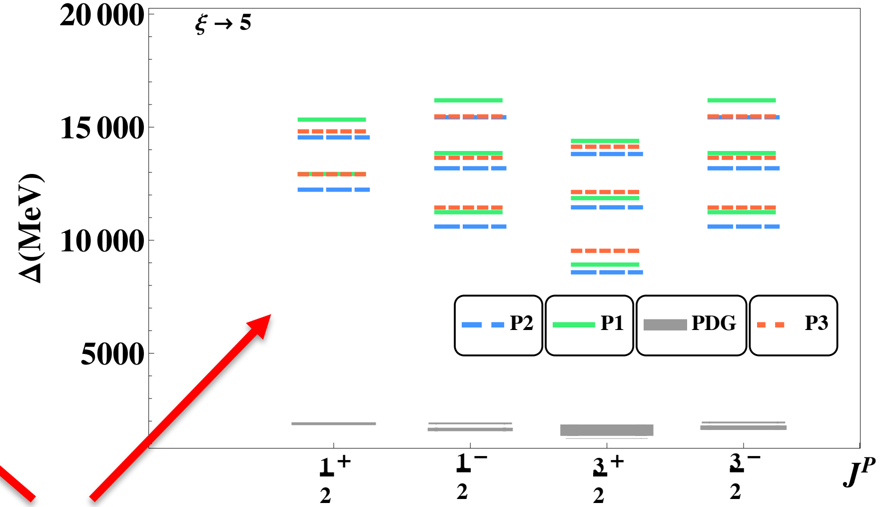
Ordinary hadron mass spectrum depends on:

Confinement scale $\Lambda \simeq$ 300 MeV.

$m_q \ll \Lambda$ (true for q = up, down)
$m_q \simeq \Lambda$ (true for q = strange)
$m_q \gg \Lambda$ (true for q = charm, bottom, top)

For dark QCD, want dark hadron spectrum as function of $\Lambda_D \gtrsim \Lambda$ and the dark quark mass spectrum.

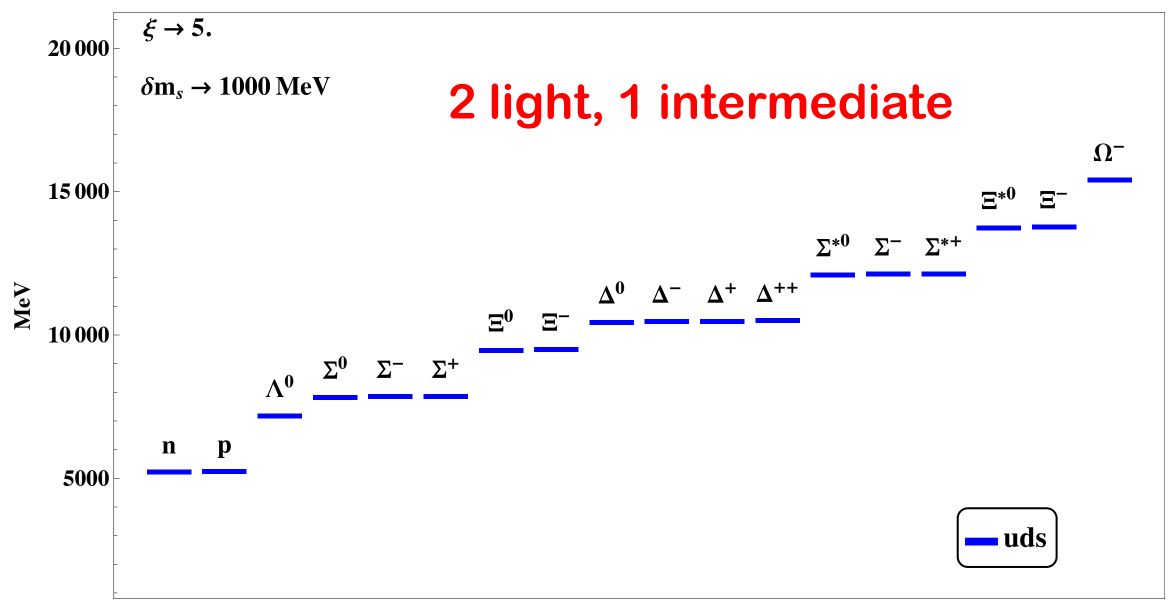




3 light dark quarks

Examples of dark baryon spectra plots produced using the hyperspherical constituent quark model formalism.

$$\xi = \Lambda_D/\Lambda$$



2 light, 1 intermediate

- Way to spontaneously break G_{VM} and G_{DM} differently despite the Z_2
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  acceptable way to annihilate symmetric part of dark sector
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S.J. Lonsdale, RV: PRD97 (2018) 103510 presents what we have called a "comprehensive" theory.

It is complicated, so I will only sketch the scenario.

There are two loose ends, hence "comprehensive" rather than "full".

Gauge group is that of the minimal mirror matter model:

$$SU(3) \times SU(2) \times U(1) \times SU(3)' \times SU(2)' \times U(1)'$$

Discrete Z_2 symmetry:

$$G^{\mu} \leftrightarrow G'_{\mu}, \qquad f_L \leftrightarrow f'_R, \qquad \phi \leftrightarrow \phi'$$

This is needed to equate the QCD and dark QCD coupling constants at the scale of Z_2 breaking.

Non-minimal Higgs sector, two doublets per gauge sector:

$$\phi_1 \leftrightarrow \phi'_1, \qquad \phi_2 \leftrightarrow \phi'_2$$

This is needed so that dark quark masses are unrelated to ordinary quark masses. Each sector is Type-3 2HDM.

Use asymmetric symmetry breaking to arrange:

$$\langle\phi_1\rangle \gg \langle\phi_1'\rangle, \qquad \langle\phi_2\rangle \ll \langle\phi_2'\rangle$$

Notice that this generalises the basic pattern, because the small VEVs are not exactly zero. This arises because of additional terms in the Higgs potential.

We want some dark quark masses to be well above the top quark mass so that the SU(3) running is changed and we get $\Lambda_D > \Lambda$. Thus:

$$v = \sqrt{\langle\phi_1\rangle^2 + \langle\phi_2\rangle^2} \ll w = \sqrt{\langle\phi_1'\rangle^2 + \langle\phi_2'\rangle^2}$$

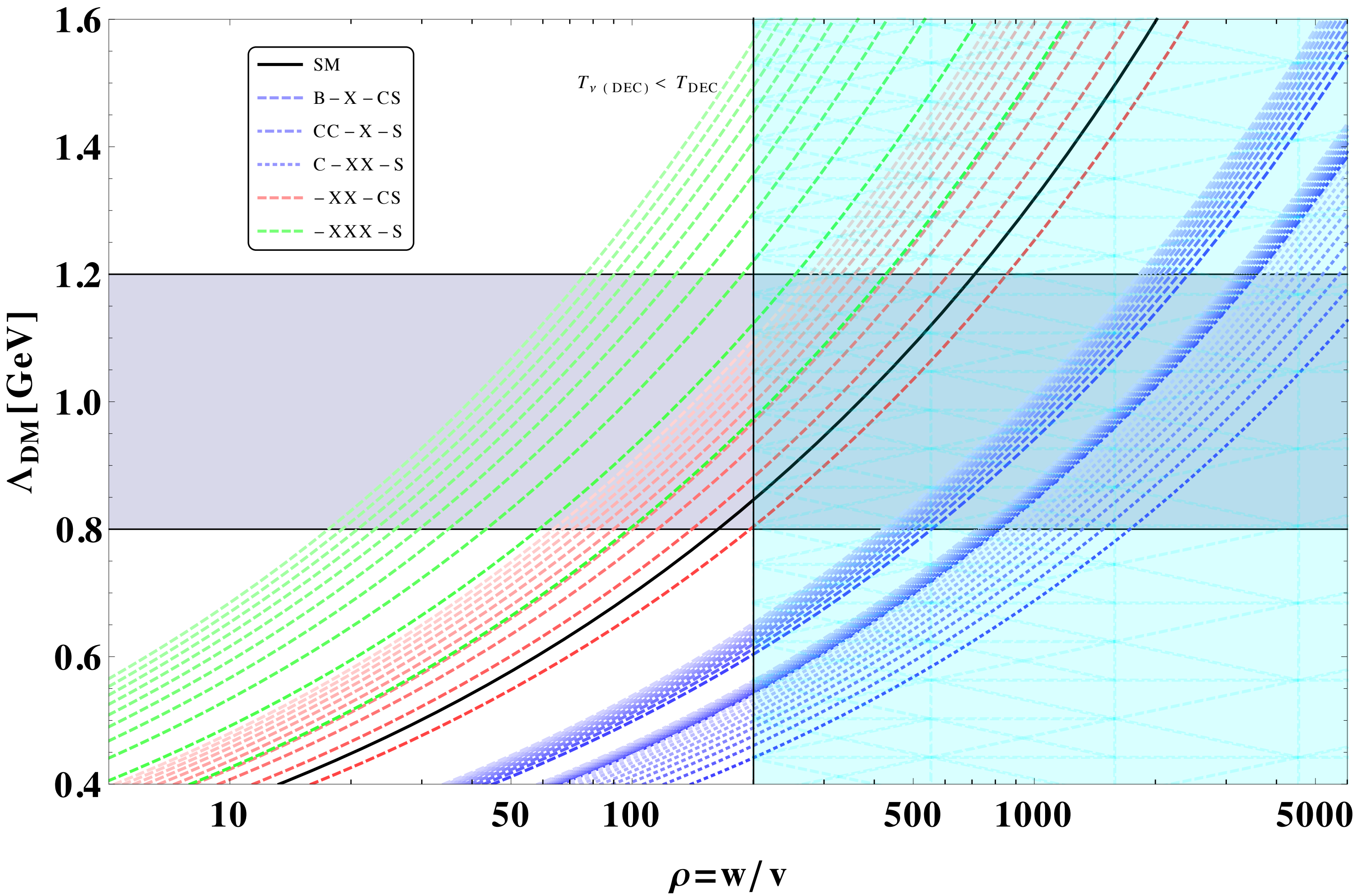
i.e. EW scale << dark EW scale.

Neatly, this also suppresses Higgs-induced FCNCs.

Some cross-sector couplings in the Higgs potential need to be small. This is probably technically natural, but needs to be checked.

Λ_D as a function of w/v for different dark quark mass spectra.

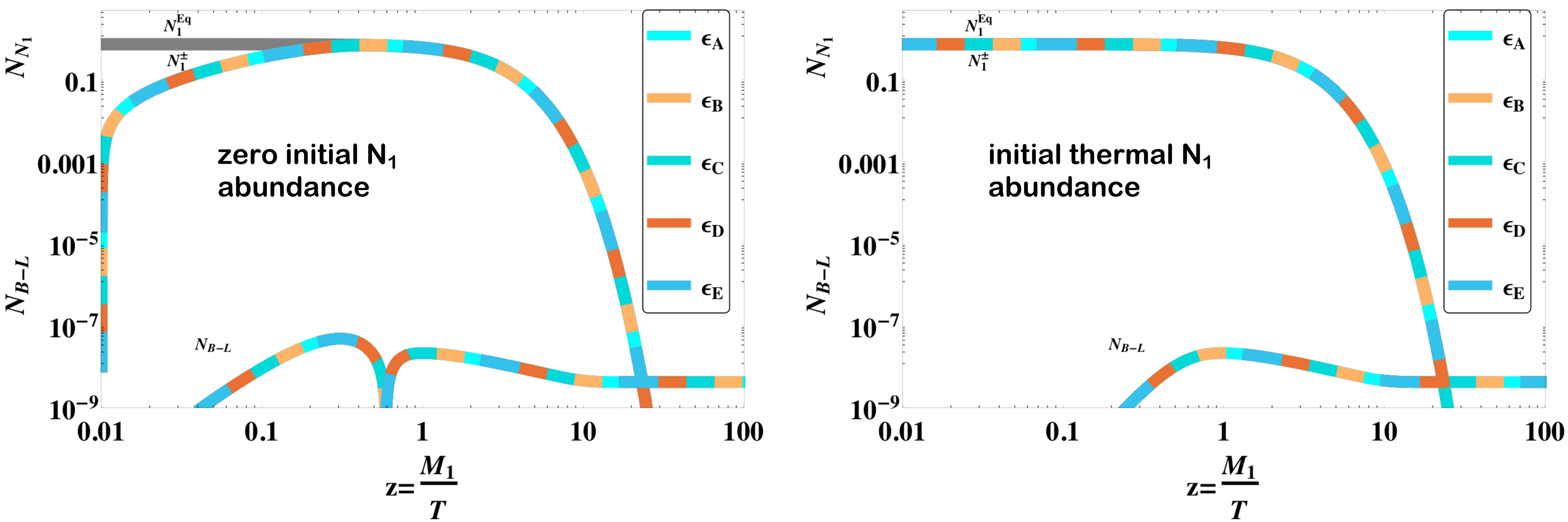
These cases all feature two light dark quarks.
The different curves are for different Yukawa coupling ranges.



Baryogenesis proceeds through thermal leptogenesis.

Because this happens above the Z_2 breaking scale, equal asymmetries are generated in each sector.

Outcomes for w/v=30 and $M_1 = 10^9$ GeV with light dark neutrinos:



The different colours are for different dark neutrino mass choices and varying Casas-Ibarra parameters.

Annihilating the symmetric part of the dark plasma with acceptable relic dark radiation:

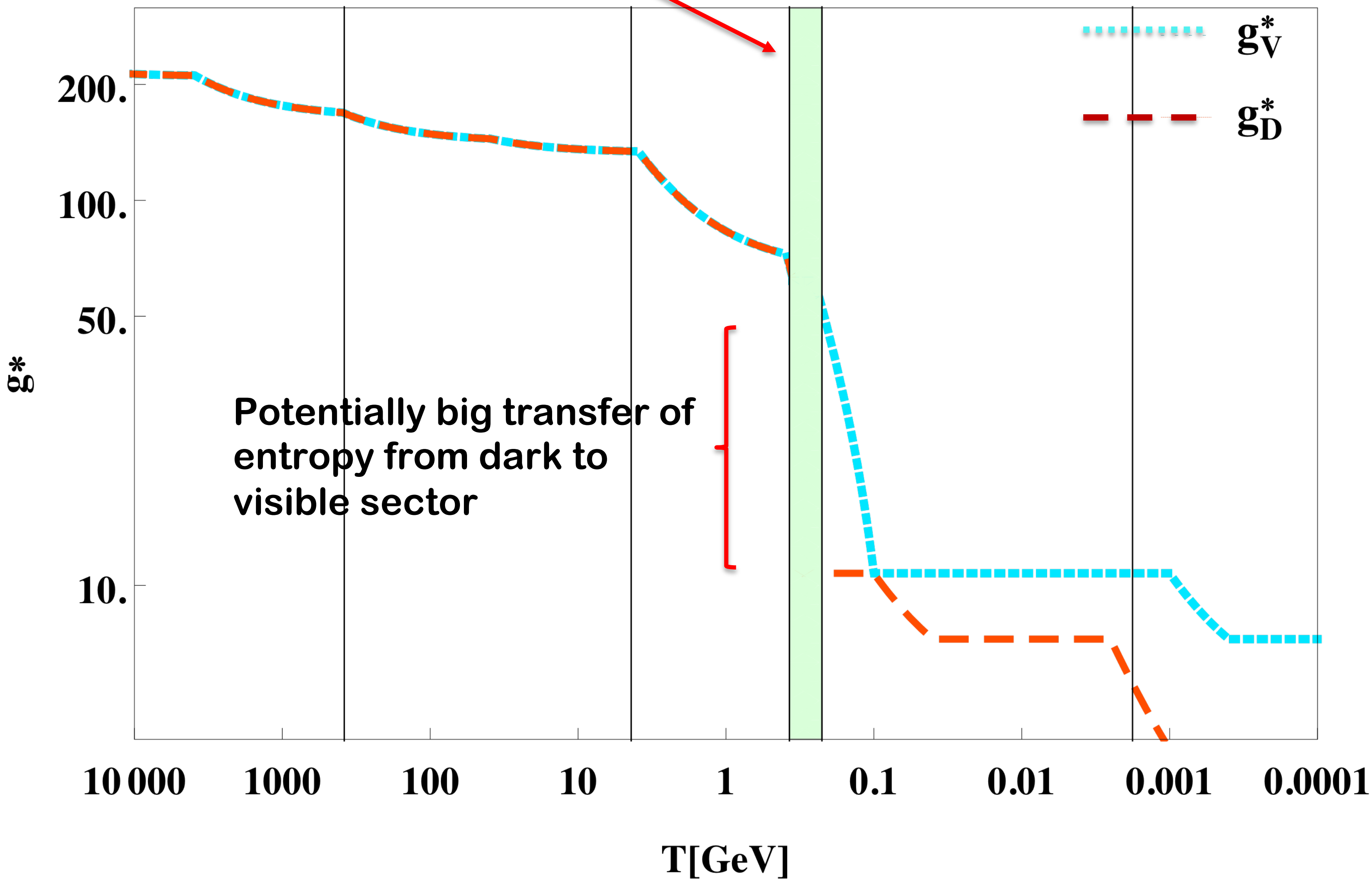
Using conservation of entropy density, it is evident that the temperature ratio of visible and dark radiation after the sectors thermally decouple is given by:

$$\frac{g_V^* T_V^3}{g_D^* T_D^3} = \left(\frac{g_V^*}{g_D^*}\right)_{\mathrm{Dec}}$$

At thermal decoupling, we want $g_V^*(\mathrm{Dec}) \gg g_D^*(\mathrm{Dec})$ so that most of the energy density is <u>not</u> in dark radiation.

Can this come about in a natural way?

There is an interesting epoch: between the dark quark-hadron PT and the visible quark-hadron PT.



Could thermal decoupling occur during this epoch without the need for fine-tuning?

Maybe! Postulate some new physics that induces what one may call a neutron-lambda portal:

$$\frac{1}{M^5}\,\bar{u}\,\bar{d}\,\bar{d}\,u'd's' + h.c.$$

Let this interaction be what maintains thermal equilibrium between the sectors at the lowest temperatures.

The dark QHPT occurs first. Dark lambdas form, decay through portal to SM quarks, transferring entropy.

Also, dark baryons immediately become Boltzmann suppressed after the dark QHPT. By the time the visible QHPT occurs, the suppression may be sufficient for thermal decoupling to have occurred.

Speculative because not calculable, but interesting I think. Also, we have not attempted to UV complete this operator.

Final remarks

Is the DM mass density deeply related to baryon mass density?

If so ⇒ asymmetric DM with dark neutrons or dark atoms or nuclei.

What would be evidence for this scenario?

No WIMPs (sorry world!), axions as DM subcomponents, no keV sterile neutrinos

Few-GeV DM mass.

Need for self-interactions (sub-Galactic CDM issues).

DM bound states.

Compact DM objects (exist in some scenarios).

Loose ends in our "comprehensive" theory: thermal decoupling, rigorous check of technical naturalness.