The hard problem in DM model building

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CDMPP Annual Workshop, 26 Nov. 2020

1. A cosmological coincidence? Motivation for asymmetric dark matter.

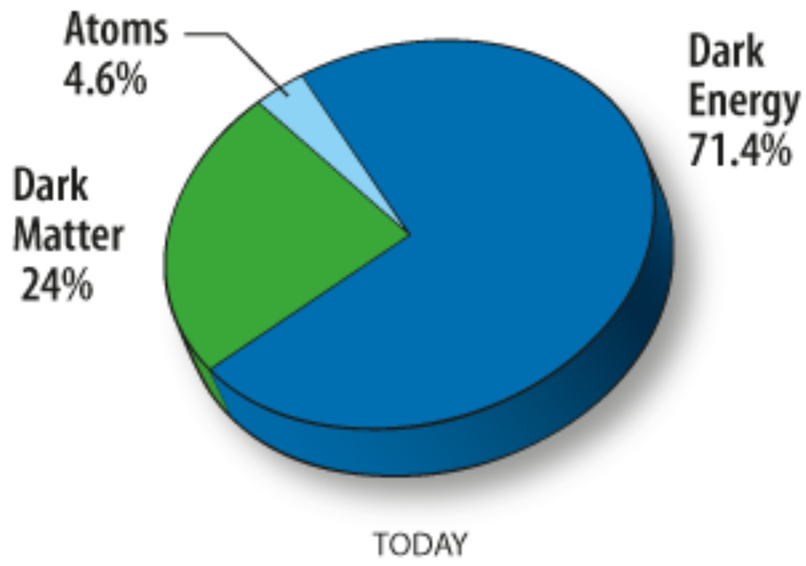
2. Fully satisfactory theory? Framework and challenges.

3. Final remarks.

1. A cosmological coincidence? Motivation for asymmetric dark matter.

Observationally, it is now very well established that

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



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

In almost all DM theories, this relation has to be ascribed as a coincidence.

There is an important exception: asymmetric DM.

Reviews: K. Petraki and RV, arXiv:1305.4939
K. Zurek, arXiv:1308.0338

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

It is the baryon asymmetry of the universe:

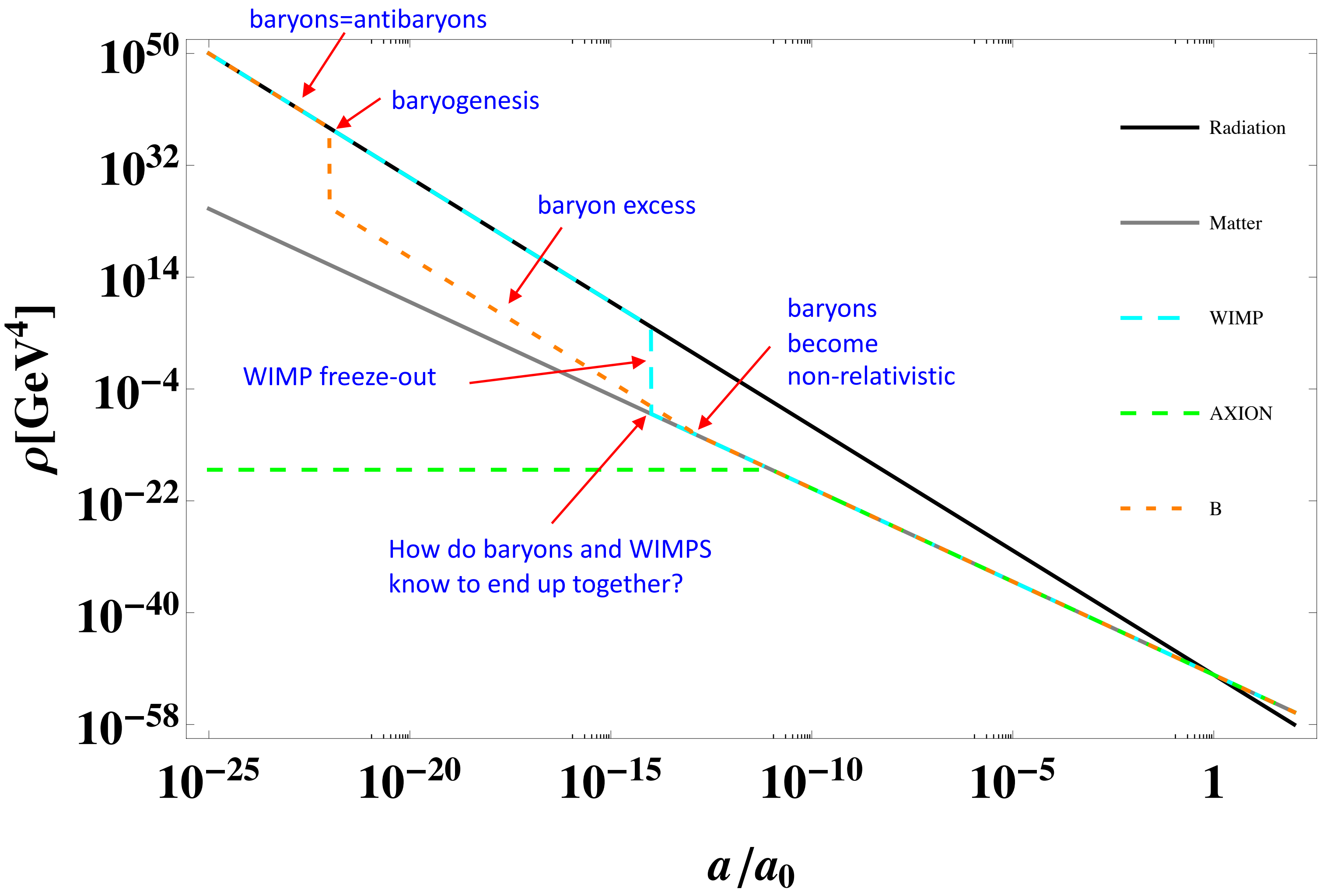
$$\Omega_{\mathrm{VM}} \equiv \frac{\rho_p - \rho_{\bar{p}}}{\rho_c} \simeq \frac{\rho_p}{\rho_c}$$

p = proton/neutron
c = critical

DM may similarly be the stable component of a “dark sector” whose relic density is determined by a dark matter-antimatter asymmetry.

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

Plot by S. Lonsdale PhD thesis (2018)
based on similar ones by Z. Berezhiani



We can make asymmetric DM naturally track the thermal history of VM.

Sakharov's conditions:

1. Baryon number violation

2. C and CP violation

3. Out-of-equilibrium

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

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: PRL 113 (2014) 18, 181601 and Baldes, Bell, Millar, Petraki, RV: JCAP 1411 (2014) 11, 041

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.

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

$$m_{\rm DM}\, n_{\rm DM} \simeq 5\, m_{\rm VM}\, n_{\rm VM}$$

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

Baryon-antibaryon asymmetry

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

Obtaining number density relation, $n_{DM} \sim n_{proton}$, is a staple of the ADM literature.

But why $m_{DM} \sim m_p$?

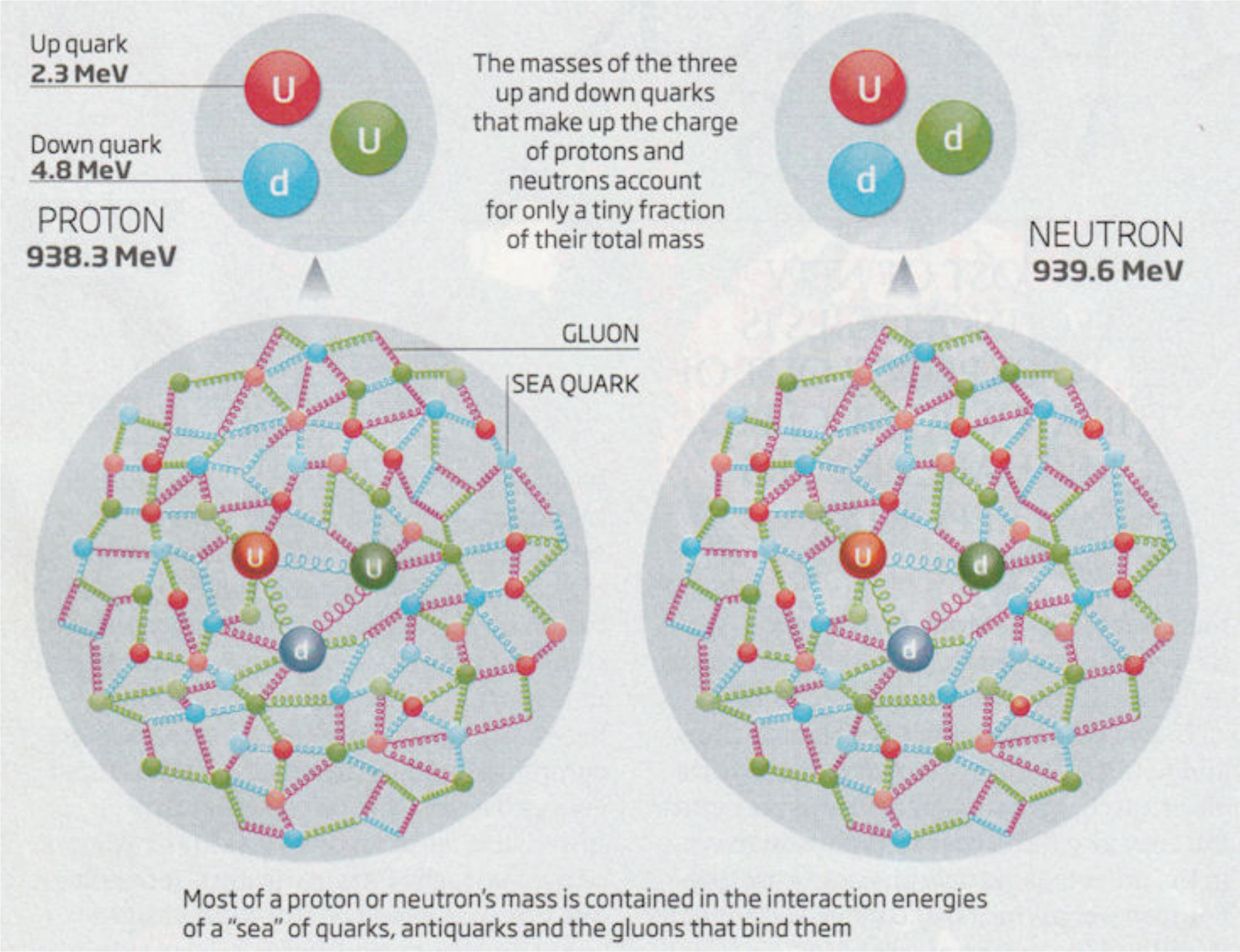
Asymmetric DM needs a good answer to this question to be truly successful.

Need a theory that relates DM and proton masses without introducing other fine-tunings or coincidences.

3. Fully satisfactory theory? Framework and challenges.

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 …*



Could the DM particle be a "dark neutron"?

The lightest, stable fermionic bound state of "dark QCD"?

Origin of dark QCD?

Probably some version of a (probably) broken "mirror matter" model:

Gauge group: $G_{VM} \times G_{DM}$ with $G_{VM} \cong G_{DM}$

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

Pre-modern: Lee+Yang, Kobzarev+Okun+Pomeranchuk, Blinnikov+Khlopov, …
Modern: Foot+Lew+RV, Berezhiani+, H.-J. He+, ...

In order to focus on DM and not get distracted by GUT-related problems we choose, for now, G = SU(3) x SU(2) x U(1).

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

S.J. Lonsdale: PRD91 (2015) 125019

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

Out-of-equilibrium decay ⟶ S.J. Lonsdale, RV: PRD97 (2018) 103510

1st-order phase transition ⟶ A. Ritter, RV: manuscript in preparation

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
  no fine-tunings that spoil the motivation for the theory

The details are very complicated. I'll just touch on a few key points here.

Ordinary hadron mass spectrum depends on:

Confinement scale $\Lambda \simeq$ 300 MeV.

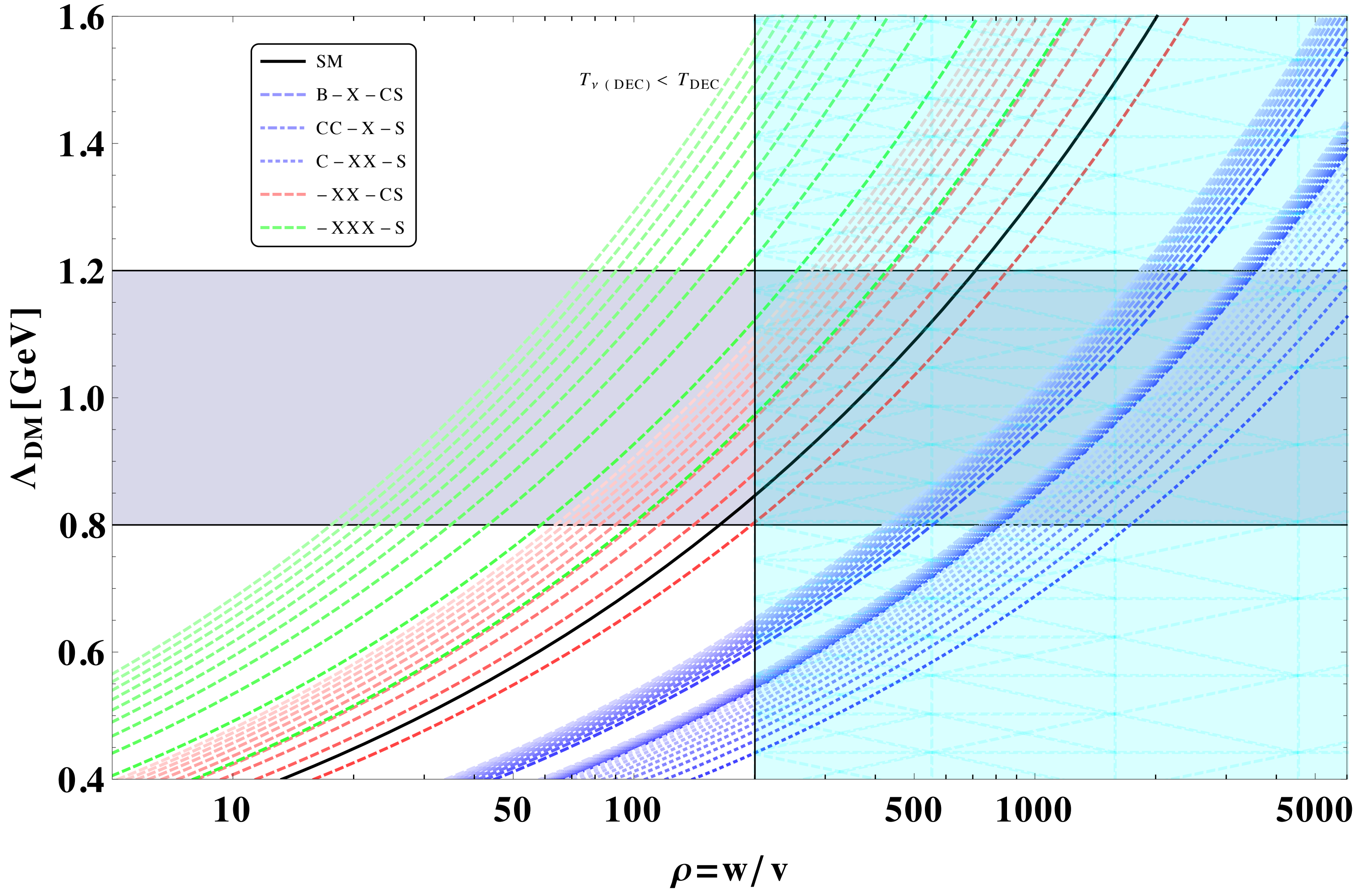
$m_q \ll \Lambda$ (true for q = up, down)
$m_q \simeq \Lambda$ (true for q = strange)
$m_q \gg \Lambda$ (true for q = charm, bottom, top)

For dark QCD want: $\Lambda_D \gtrsim \Lambda$.
The dark quark mass spectrum is model dependent.

Λ_D as a function of (dark EW scale)/(visible EW scale) for different dark quark mass spectra.

These cases all feature two light dark quarks.
The dark QCD coupling constant runs more quickly => $\Lambda_D \gtrsim \Lambda$.
The different curves are for different Yukawa coupling ranges.

target area



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

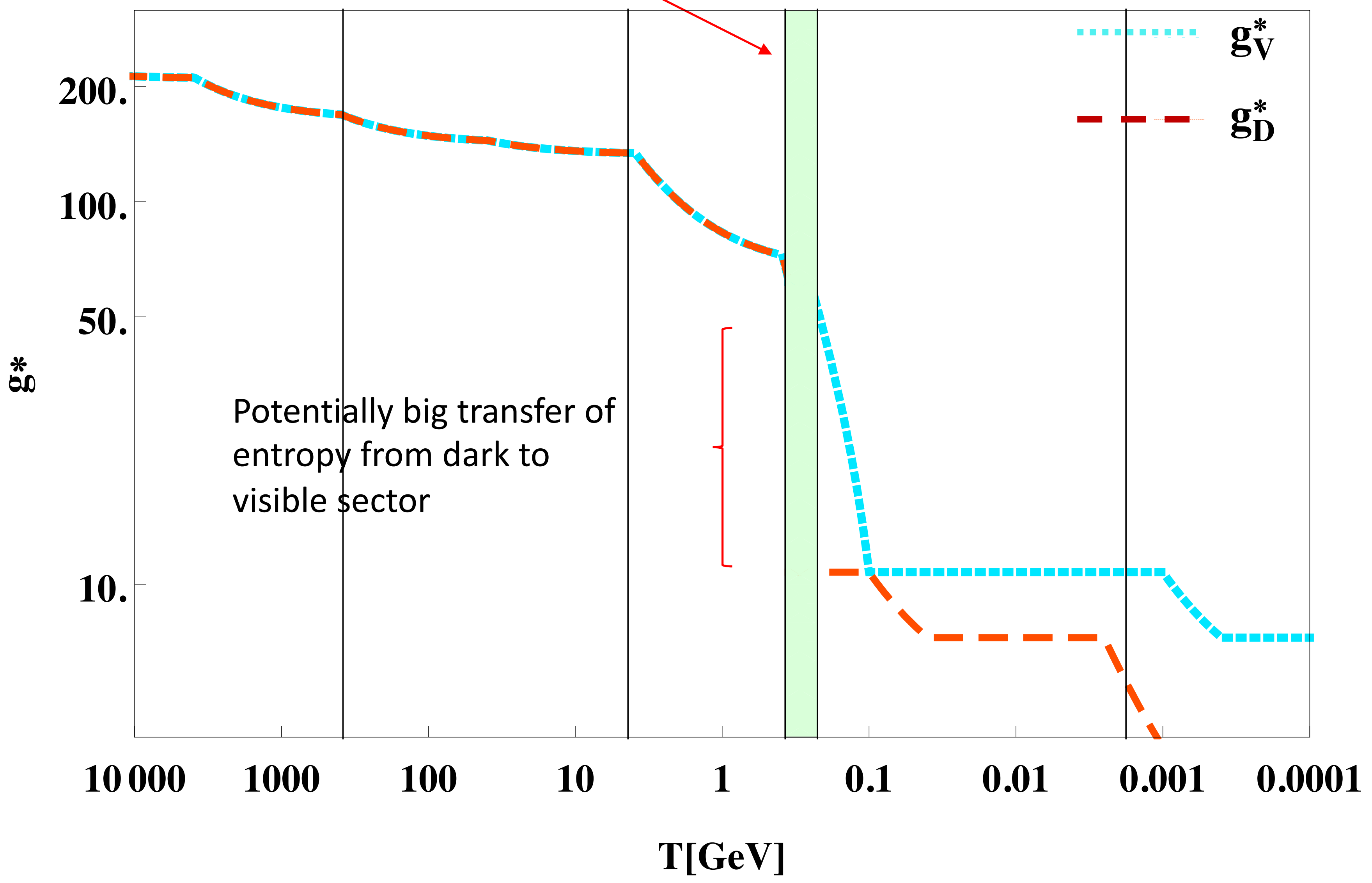
Using conservation of entropy density, it is evident that the temperature ratio of visible and dark radiation after the sectors thermally decouple is given by:

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

At thermal decoupling, we want $g_V^*(\rm Dec) \gg g_D^*(\rm Dec)$
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 potentially interesting.

A. Ritter and I have looked in more detail at this and have identified some challenges:

* The scale M has to be quite low, which causes pheno problems.
* While the flavour structure of the operator preserves DM stability at leading order, the situation at higher order is a concern.

At this stage, it looks to us like the dark radiation bound presents the most serious obstacle to constructing a fully satisfactory theory.

4. Final remarks

- The dark matter problem remains one of the deepest mysteries in physics.
- The cosmological “coincidence” between dark & visible mass densities is a serious issue that most DM theories ignore.
- Asymmetric dark matter is motivated as a possible solution.
- But … need to relate the DM mass to the proton mass, which is not easy.
- The search for a fully satisfactory theory continues.