CoEPP

ARC Centre of Excellence for
Particle Physics at the Terascale

THE UNIVERSITY OF MELBOURNE

WHAT I THINK ABOUT WHEN I THINK ABOUT DARK MATTER

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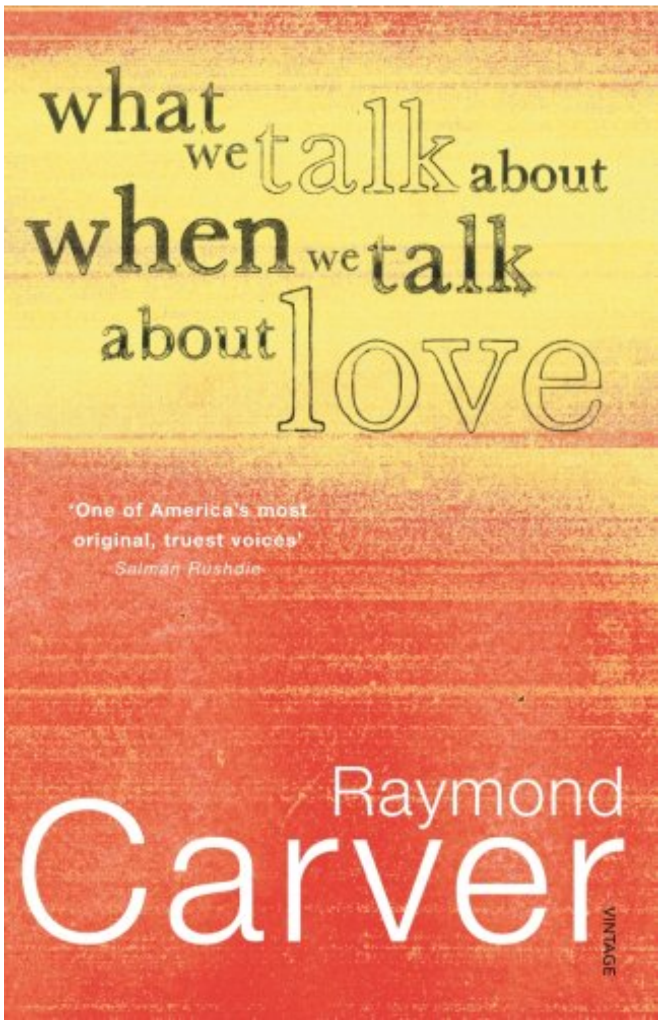
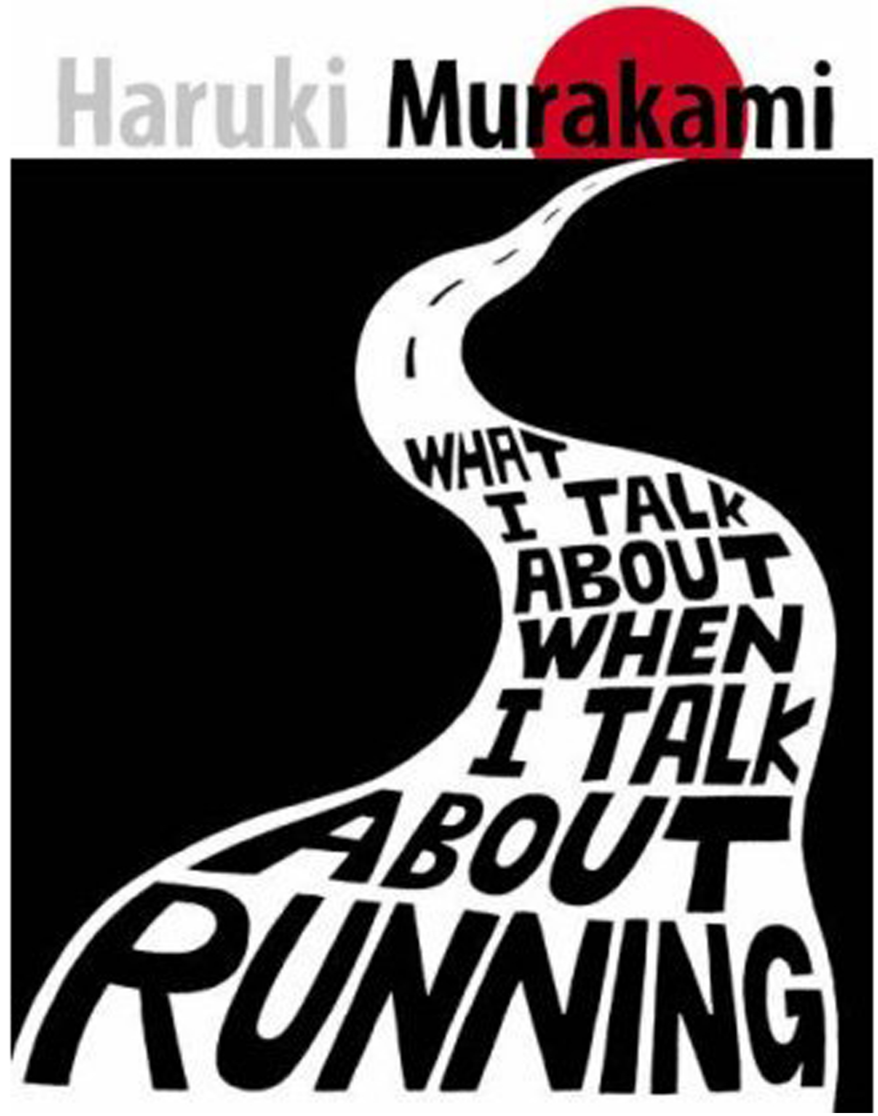
Apologies to Raymond Carver and Haruki Murakami ☺





The "theory space" for DM is still huge.

It is not humanly possible to survey it!

Instead, I will follow one line of thinking that makes sense to me.

What do we know about DM?

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

It looks “cold”, but may be a little bit “warm” or just “chilled”. Galactic and sub-galactic anomalies exist (core vs cusp, satellites, “too big to fail”).

Effectively collisionless on extra-galactic scales.

Forms spheroidal haloes.

What DM is not: ordinary neutrinos.

What DM does not do:

- Accumulate in neutron stars, form BHs and eat the stars.
- Affect stellar evolution in any obvious way.
- Get produced at 7&8 TeV pp collisions.
- Etc.

How DM teases us:

DAMA, CoGeNT, SuperCDMS, LUX, etc.
130 GeV line, 3.5 keV line, PAMELA, Hooperon.
Probably will think of new and unusual ways in the future. ☺

Let me obsess about: $\Omega_{\rm DM} \simeq 5\Omega_{\rm VM}$

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

proton mass

$\Lambda_{\rm QCD}$

Baryon-antibaryon asymmetry

$$\frac{n_{\rm B} - n_{\overline{\rm B}}}{n_s} \sim 10^{-10}$$

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

Obvious hint:

$$n_{\rm D} \sim n_{\rm V}$$

$$m_{\rm D} \sim m_{\rm V} = m_p \simeq \mathrm{GeV}$$

The WIMP miracle, by contrast, has (usually)

$$m_{\rm D} \gg m_{\rm V} = m_p \simeq \mathrm{GeV}$$

$$n_{\rm D} \ll n_{\rm V}$$

The "miracle" is that this works for non-rel, thermal freeze-out with weak-scale DM annihilation cross-section.

One person's miracle may be another's coincidence!

Anybody's BSM theory.
Includes WIMP theories.
Includes my theories.
Includes your theories.

Theory built on the foundations of reality.
Unique example: Standard Model.

Look at $n_{\rm D} \sim n_{\rm V}$ first.

Only sensible choice: asymmetric DM.

Review: K.Petraki and RV, IJMP A28 (2013) 1330028; 1305.4939

Dark "baryons", dark "antibaryons".

Dark "baryo"genesis.

Conserved baryon-number-like quantum number during chemical equilibrium between visible and dark sectors => the related number densities.

Allows, not mandates, DM to be: multi-component, self-interacting, come with dark radiation, …

I spoke about this at the previous joint workshop.

There are many models, many variations, many possible phenomenological and observational consequences.

Here I want to focus on the second issue: the origin of mass.

No, not the Higgs …

Origin of visible (i.e. nucleon) mass is QCD. The up and down quark masses, from the Higgs, are a few MeV; nothing to do with proton mass.

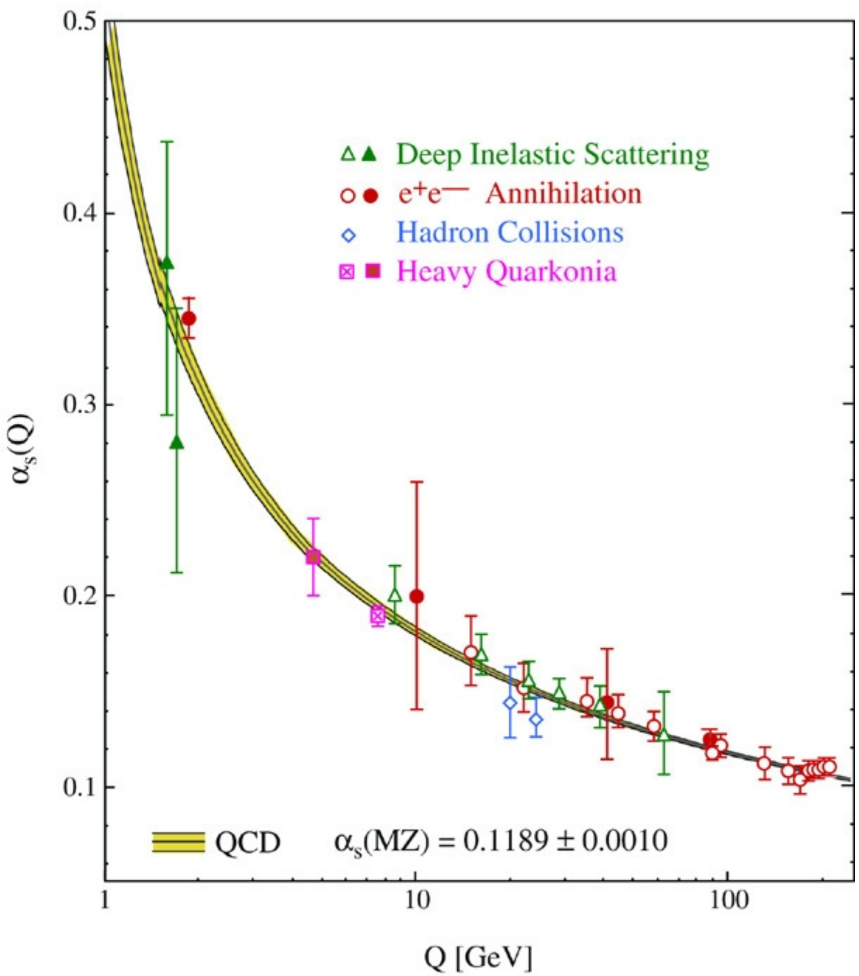
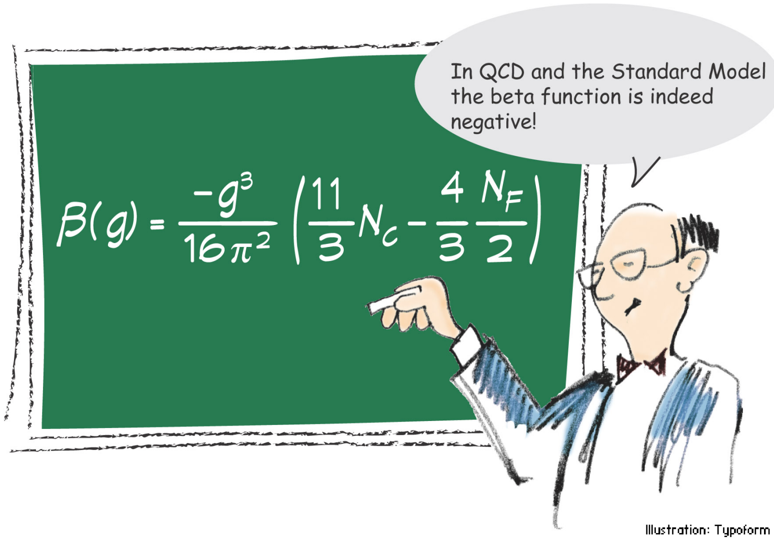


Image credit: Siegfried Bethke

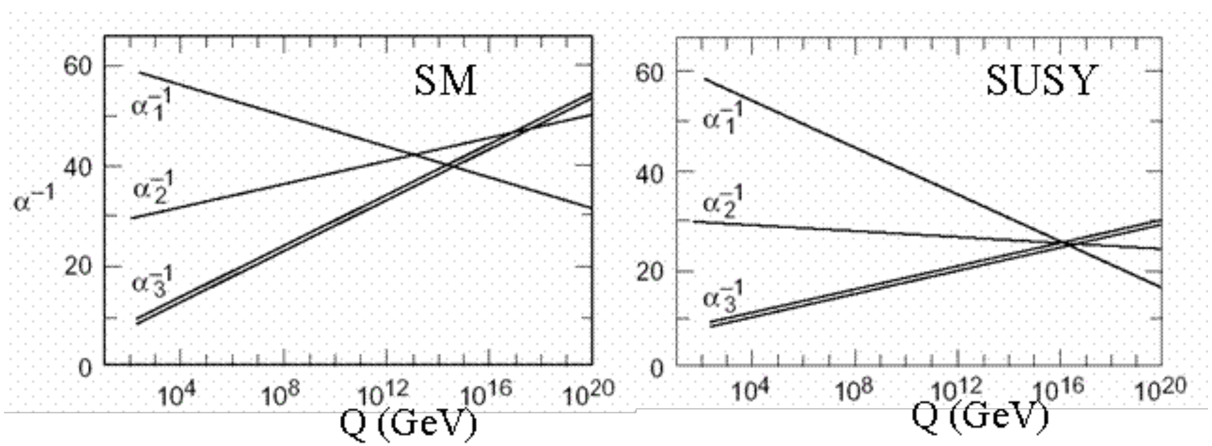
The strong coupling constant becomes large at about 200 MeV: the QCD confinement scale, Λ_{QCD}.

If the DM mass scale is really similar to the proton mass, then the reason may be a “dark QCD”.

Why might there be a dark QCD with a similar confinement scale to visible QCD?



$$\alpha_s\left(\mu_1^2\right) = \frac{4\pi}{\left(11 - \frac{2n_f}{3}\right)\ln\left(\frac{\mu_1^2}{\Lambda^2}\right)}$$



Maybe dark matter is grand unified with ordinary matter.

Robert Foot will be happy to tell you that the most elegant way to achieve this is through the "mirror matter model".

$$[\,SU(3)\times SU(2)\times U(1)\,]_{\rm V} \quad\times\quad [\,SU(3)\times SU(2)\times U(1)\,]_{\rm D}$$

V←→D discrete symmetry

$SU(3)_V$ and $SU(3)_D$ running couplings exactly the same, so $m_D = m_V = m_p$ (mirror nuclei).

Need $n_D \approx 5n_V$.

Symmetric microphysics,

asymmetric macrophysics.

Follow similar starting point but different development here.

$G_V \times G_D$

with V←→D and $G_V = G_D = SU(5)$, $SO(10)$, …

"Grand-unified hidden-sector dark matter"

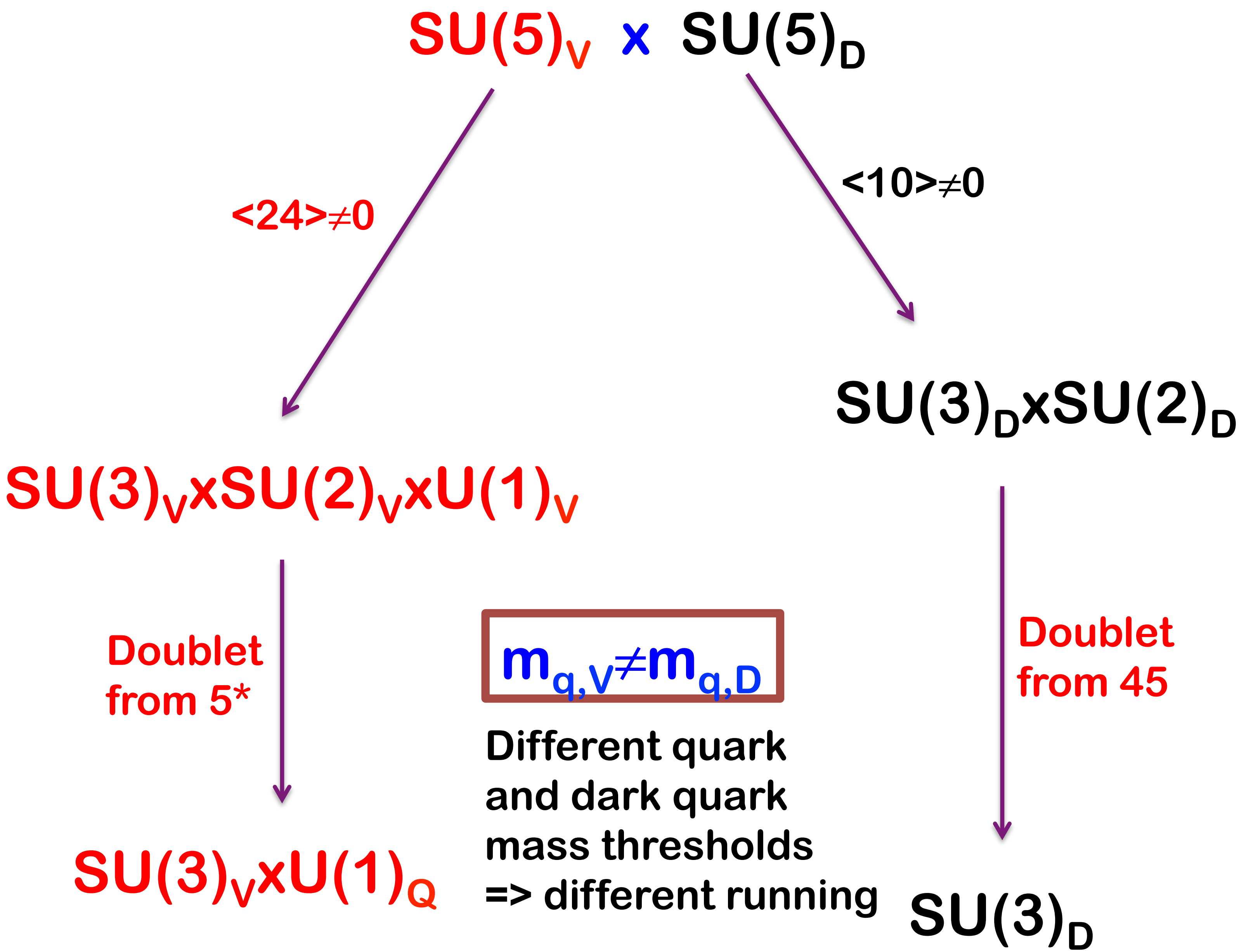
S.J. Lonsdale and RRV, arXiv:1407.4192, PRD (in press)

G_V breaks to the SM.

Have G_D break differently, but contain an unbroken $SU(3)_D$.

"Asymmetric symmetry breaking"

One example:



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

Asymmetric symmetry breaking

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

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

Φ sector nonzero

χ sector nonzero

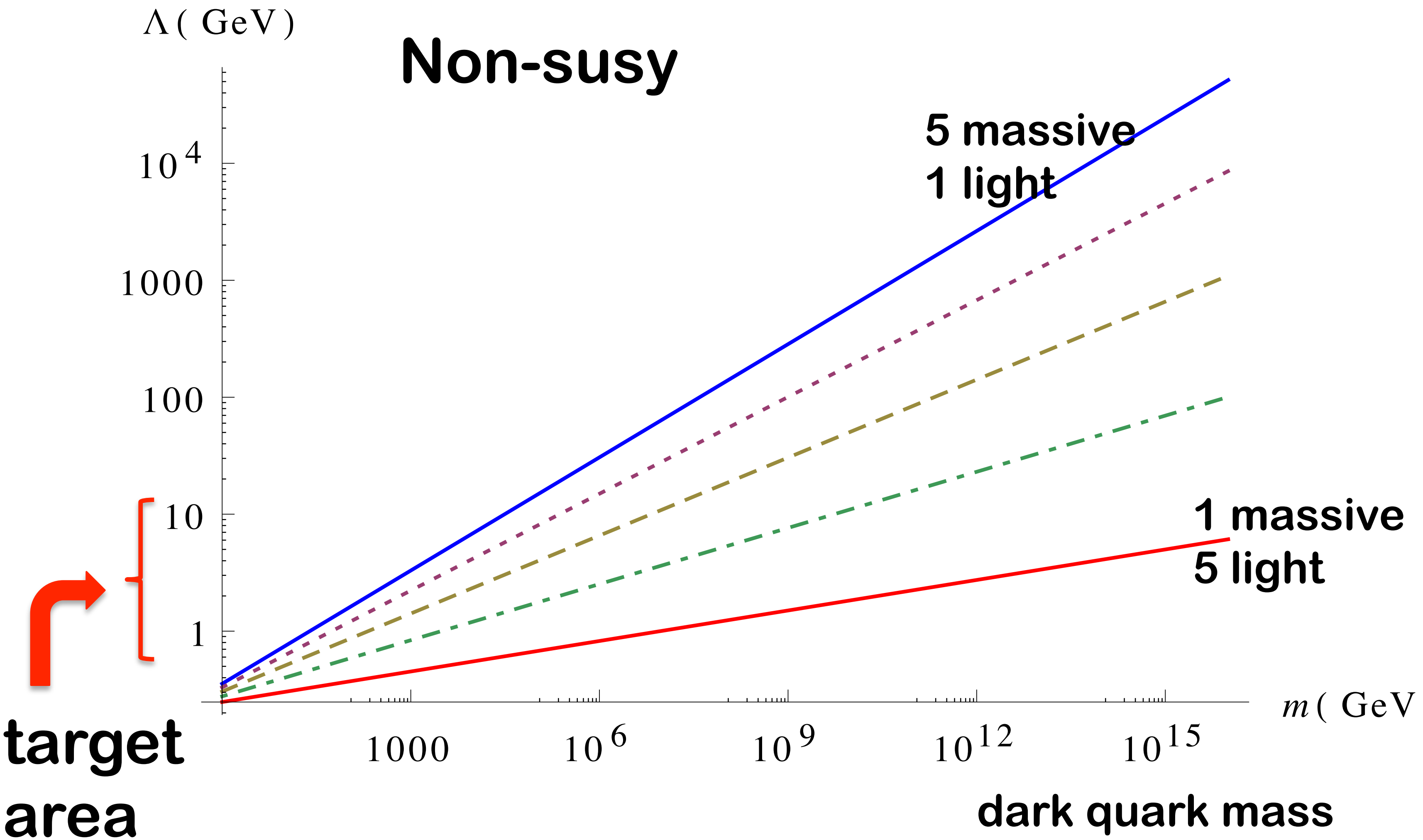
either Φ_1 or Φ_2 zero

either χ_1 or χ_2 zero

If $\Phi_1 \neq 0$ then $\chi_2 = 0$ etc.

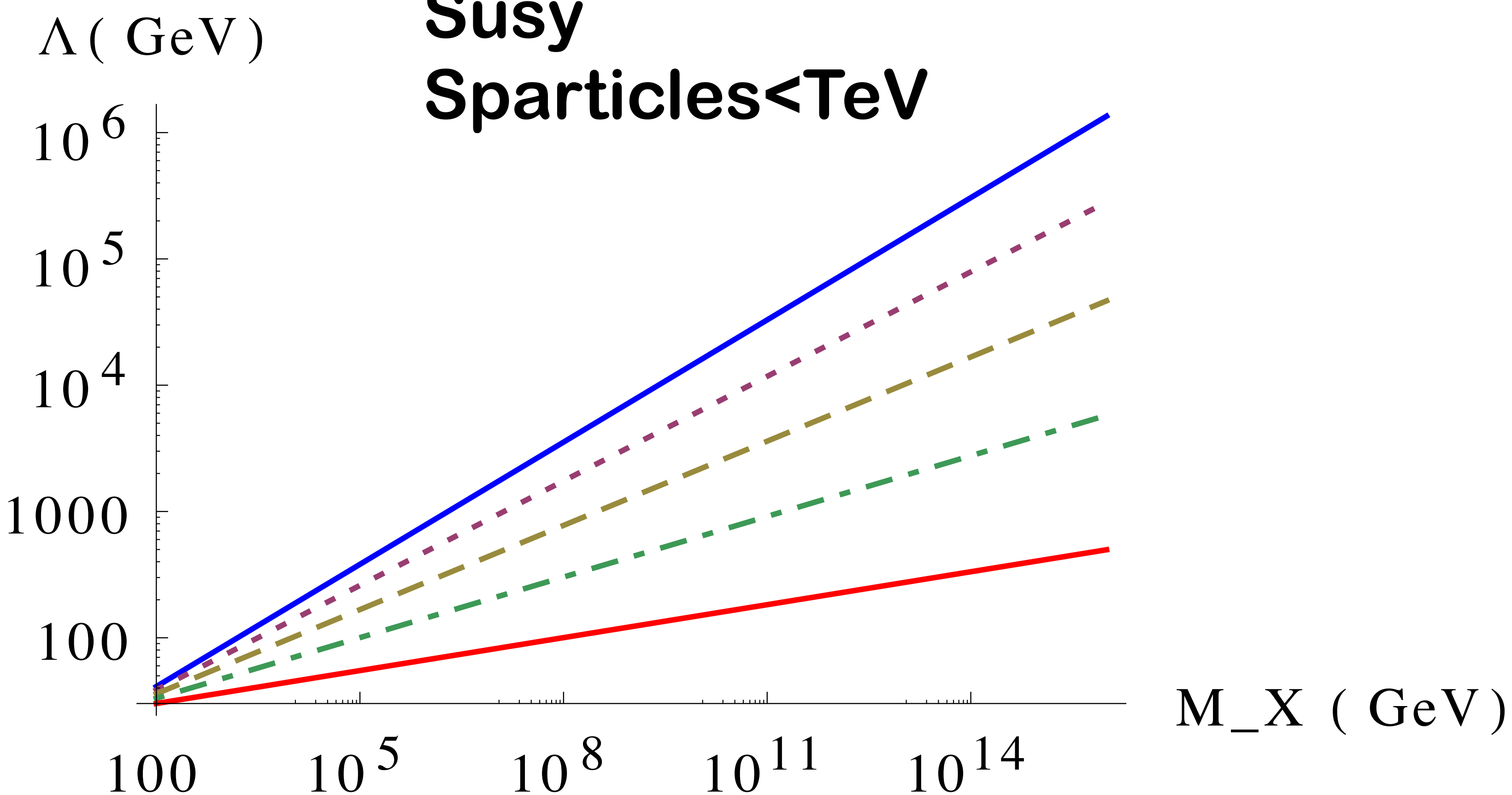
$$\lambda_\phi,\ \lambda_\chi,\ \kappa_\phi,\ \kappa_\chi,\ \sigma,\ \rho > 0$$

$$\langle\phi_1\rangle = v_\phi, \quad \langle\phi_2\rangle = 0$$
$$\langle\chi_1\rangle = 0, \quad \langle\chi_2\rangle = v_\chi$$



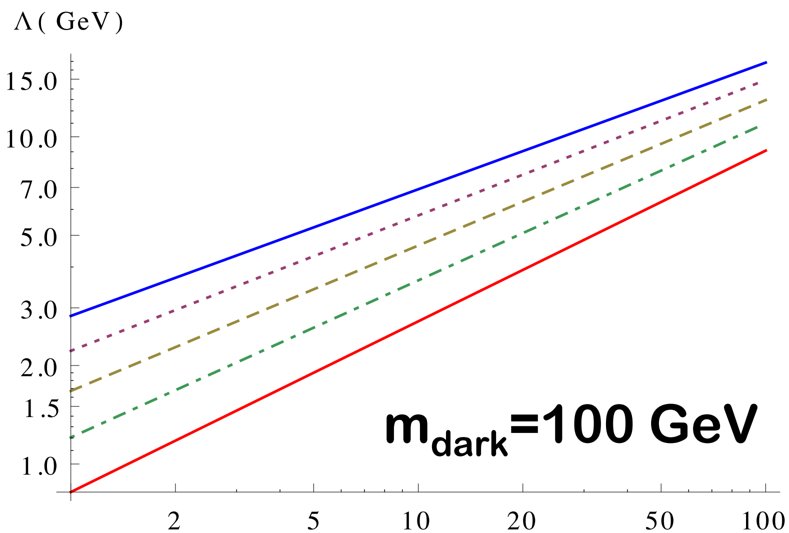
Greater # of massive dark quarks => faster running of dark QCD coupling => higher dark confinement scale

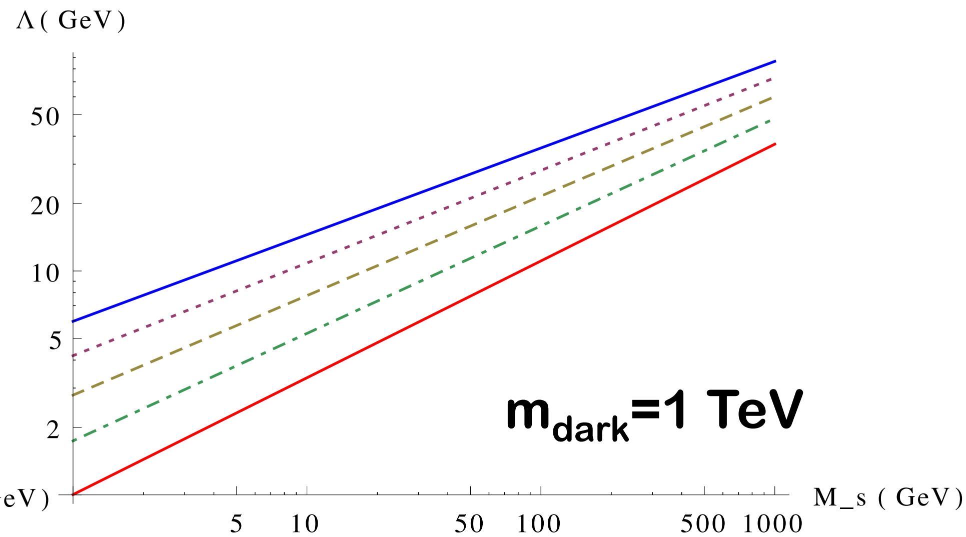
Susy
Sparticles<TeV

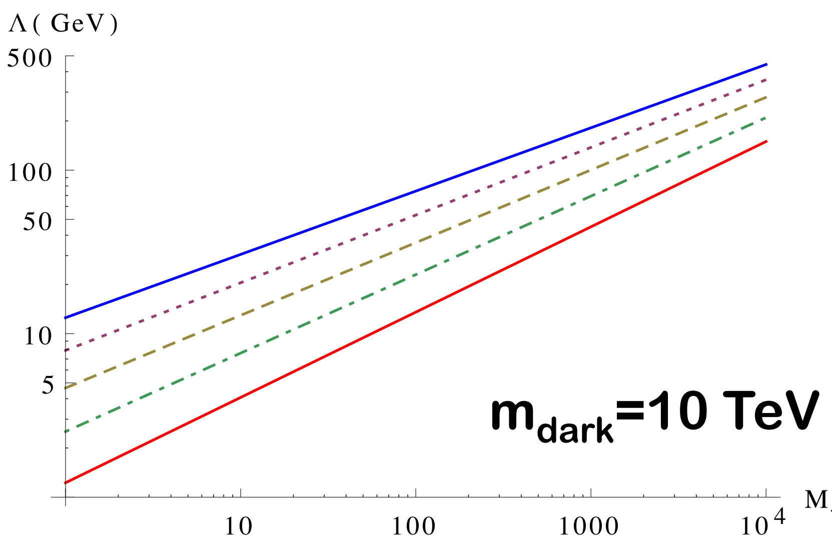


Prefers greater number of light dark quarks more strongly.

Dark confinement scale as function of dark susy scale







Preference for lighter dark quarks and lower dark susy scale.

Extension to SO(10) and larger GUT groups: dependence on intermediate symmetry-breaking scales (S. Lonsdale, in progress).

No complete model yet constructed:

- **Asymmetry generation mechanism**
- **Chemical reprocessing b/w VM and DM**
- **Annihilate symmetric part of dark plasma**
- **Solve all GUT pheno problems**

(S. Lonsdale, RV, under discussion)

Simple alternative, giving up on grand unification:
Just SM←→SM' with asymmetric sym. breaking.

- **Different quark/dark quark mass thresholds.**
- **Don't have hierarchy problem, no susy needed.**
- **No *ad hoc* elements needed as gauge coupling constant unification not required.**

Summary

DM and VM may be closely related and have a common micro- and macrophysical origin: asymmetric DM, interesting phenomenology possible.

If DM is part of a hidden gauge theory, what becomes of grand unification? One possibility is GxG with asymmetric symmetry breaking.

Successful parameter space does exist; more constrained with susy.

Of course, life is simpler without grand unification or susy.