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Dark quark nuggets 1810.04360

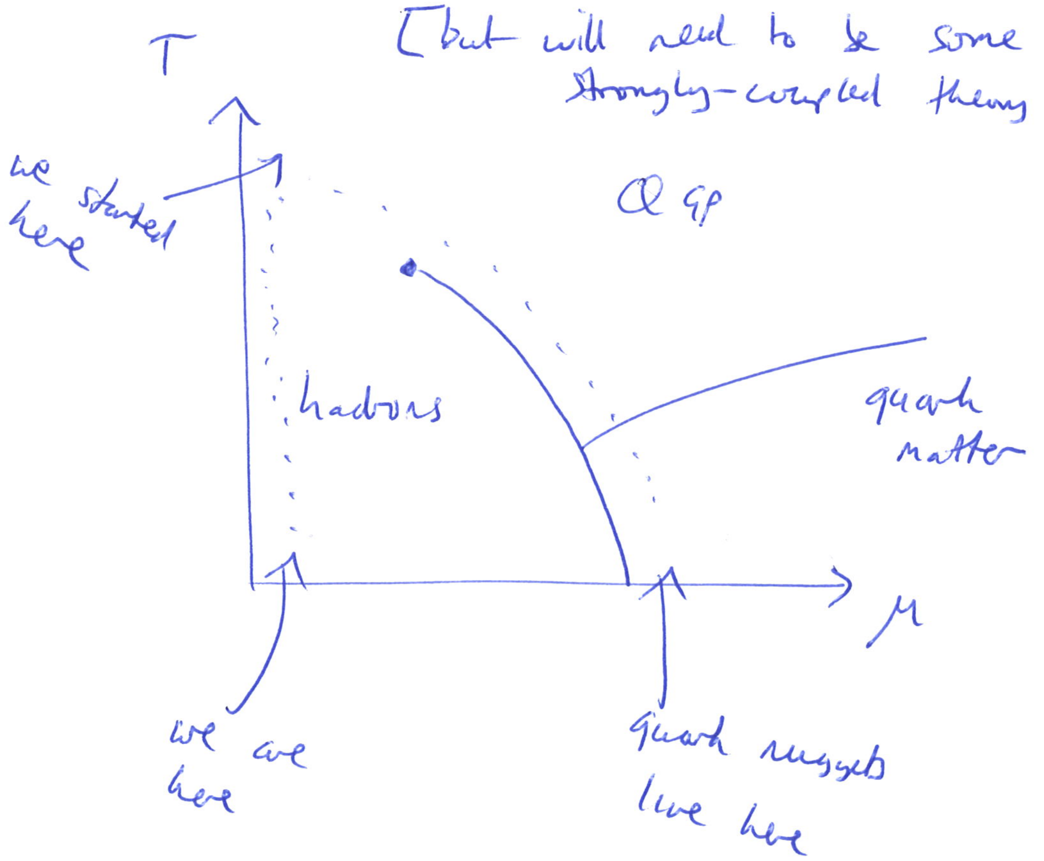
Inspired by Witten's 1984 "Cosmic separation of phases"

Quark nuggets:

- Macroscopic nucleons, $N_B > 10^{30}$, $r \lesssim 1\,cm$
- Formed when (most of) the universe undergoes FOPT (χSB + confining)

  [not viable in SM]
- Could survive as DM candidate.

  [but will need to be some other strongly-coupled theory besides QCD].



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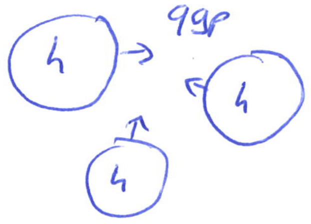
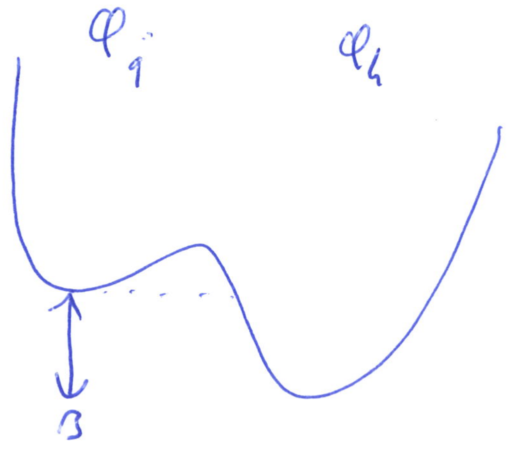
What do nuggets need?

1) First order PT





2) Conserved global charge, like baryon number

3) Cosmological excess of matter over antimatter.

$\Downarrow$

quark nuggets form & stick around

How?

① Possible in (e.g.) dark QCD and similar theories with $N_f \geq 3$ light fermions (QCD doesn't work because strange isn't very light)

② Dark baryon # (or technibaryon/twin baryon/etc)

③ Assume that visible baryon asymmetry is n_B/n_γ shared with dark sector (assume same [illegible])

③

Dark QCD

$$\left.\begin{array}{ll} N_d & \text{colours} \\ N_f & \text{light flavours} \end{array}\right\} \rightarrow \begin{array}{l} N_d^2-1 \text{ dark gluons} \\ N_f \text{ dark } q/\bar{q} \end{array}$$

Need a theory with a dark colour continuity phase transition + χSB

$$\underline{\text{at}}\quad \underset{\substack{\nearrow \\ \text{critical} \\ \text{temp}}}{T_c} \sim \underset{\substack{\uparrow \\ \text{dark} \\ \text{confinement scale.}}}{\Lambda_d}$$

If quark masses are light ($m_i \ll \Lambda_d$) and

1/ $N_f \geq 3$, "Pisarski - Wilczek" argument says get FOPT & (with χSB)

2/ $N_f \lesssim 2N_d + 4$ get confinement (ie need to be below the conformal window)

④

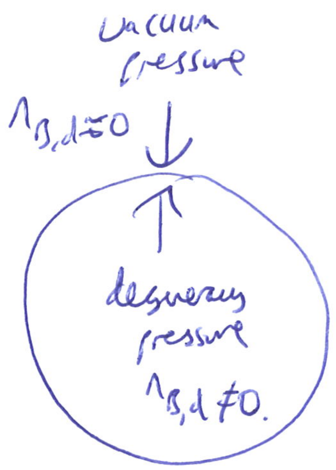
The $T=0$, high density region possesses a dark quark matter phase.

Assume temperature T, thermal eq^m

nonzero $n_{B,d}$.

$m_i \ll T \ll \mu$

relativistic degenerate Fermi gas.



$$\downarrow$$

$\epsilon_{dQM} = 4B$ energy density

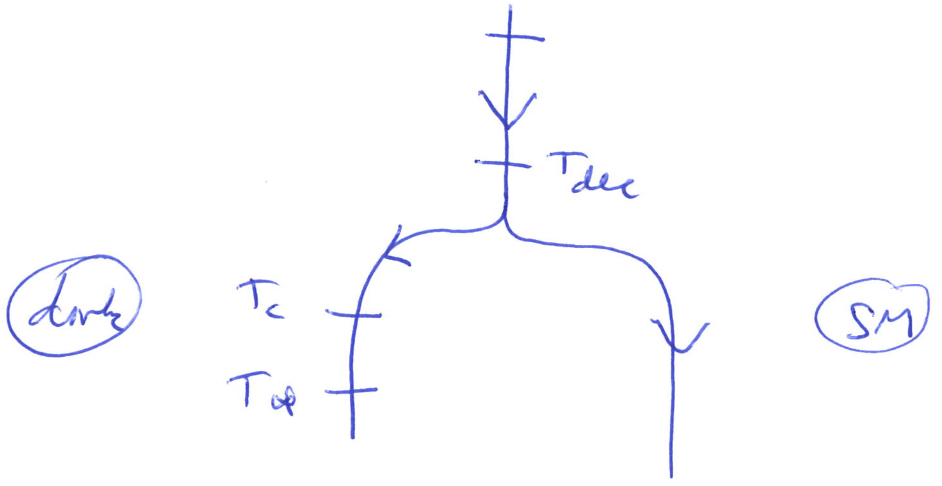
$$n_{Bd,dQM} = \left(\frac{64 N_f}{3\pi^2 N_d^3}\right)^{1/4} B^{3/4}$$ density of dark BN

$$\text{if} \quad \frac{\epsilon_{dQM}}{n_{Bd,dQM}} < \underset{\substack{\uparrow \\ \text{lightest stable} \\ \text{dark baryons}}}{m_{Bd}} \Rightarrow \text{stable}$$

How to make them

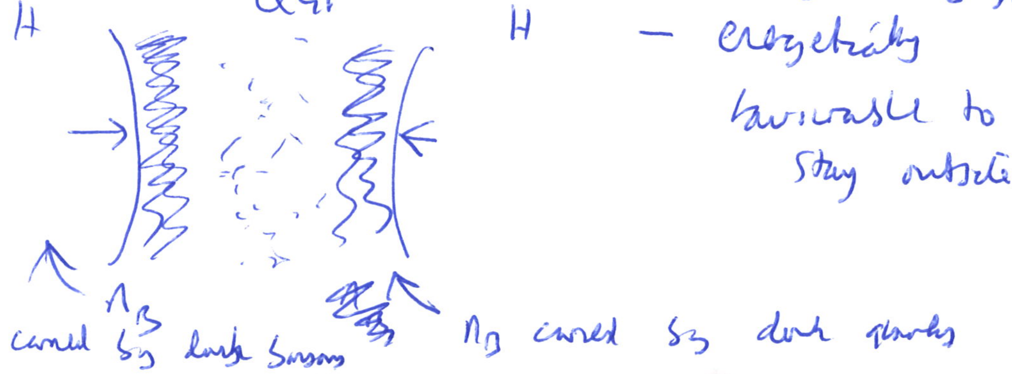
(TL,DR: Same as ordinary quark nuggets)

① Dark sector $\overset{\text{thermal}}{\Longleftrightarrow}$ SM sector until T_{dec}



② At $T_\phi \lesssim T_c$ (Small supercooling)
[→ not actually sure why this is necessary]
bubbles of dark hadron phase form and grow ~~[illegible]~~ at a [nonrelativistic] terminal speed ?

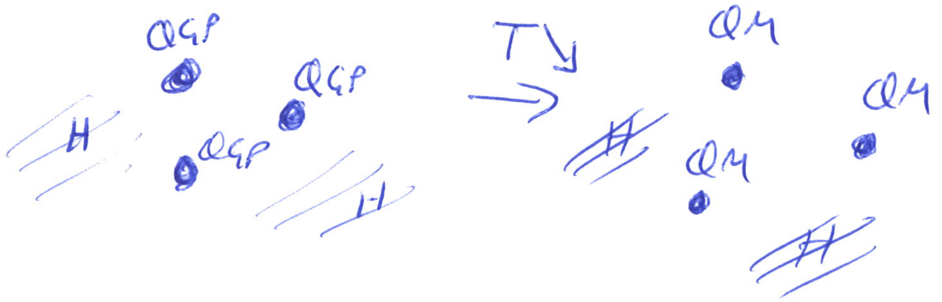
③ Dark ~~baryons~~ quarks get trapped in front of the walls – because the m_{Bd} in the hadron phase is $\gg T$, there is Boltzmann suppression preventing the dark quarks forming dark baryons.

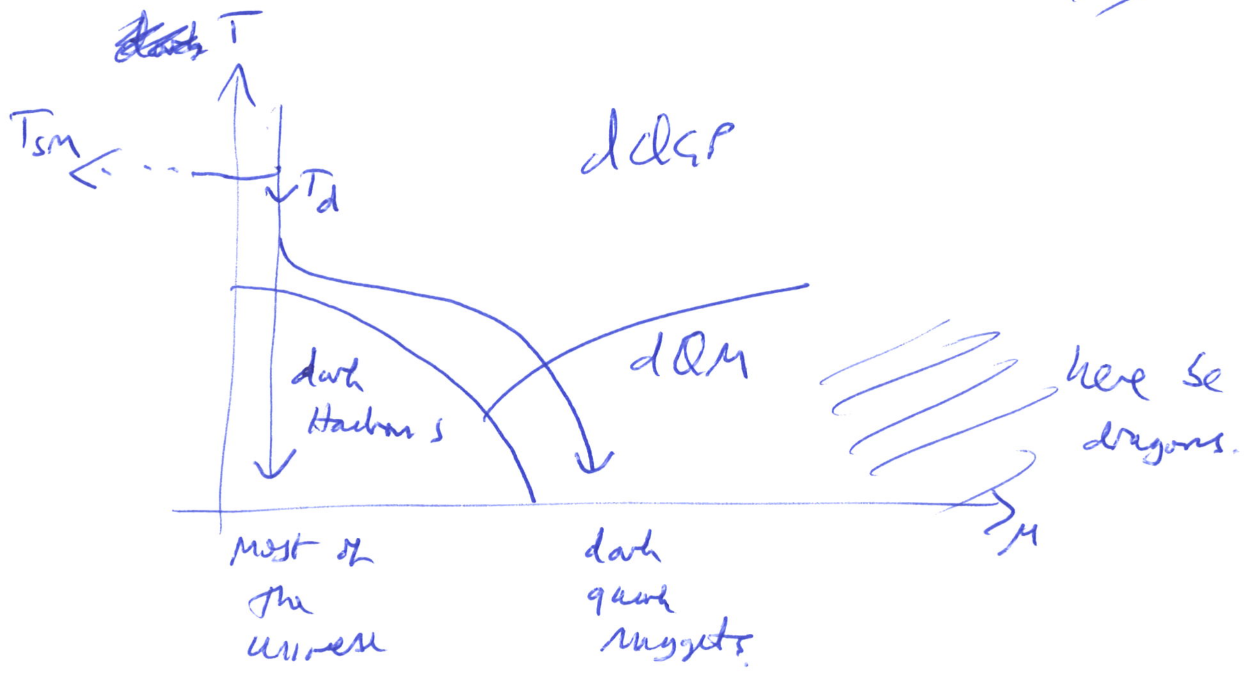


– energetically favourable to stay outside

④ Bubbles of hadron phase coalesce but there are small regions of dark QGP.

⑤ These cool to form dark quark nuggets, carrying most of the ~~dark~~ n_{Bd}.





⑦ Typical nugget size.

- Assuming they don't evaporate
- estimate 1 nugget / 1 hadron bubble
- Use χEFT to study phase transition

& obtain number of hadron bubbles nucleated

For $T_{d} = 100$ MeV, $B = 100$ MeV,

$$\frac{\Lambda_{Bd}}{\Lambda_\gamma} \simeq \frac{\Lambda_B}{\Lambda_\gamma},$$

$$M_{dQN} \sim 10^{11} g$$

$$R_{dQN} \sim 1mm.$$

& the relic abundance can explain all DM