Title: Dark matter from the Fraternal Twin Higgs

Date: Oct 06, 2015 01:00 PM

URL: http://pirsa.org/15100069

Abstract: Twin Higgs theories attempt to solve the little hierarchy problem - why has the LHC not yet observed new states stabilising the EW scale? - by introducing a SM-neutral twin sector, related to the SM by an approximate Z_2 symmetry. The physical Higgs is then a PNGB mixture from both sectors, and acts as a portal between them. In this talk, I will discuss the cosmology of minimal (â€œfraternalâ€•) Twin Higgs models. Higgs portal interactions establish thermal equilibrium between the SM and twin sector at high temperatures, giving a thermal history with possibilities for both symmetric dark matter (through a â€œtwin WIMP miracleâ€•), and asymmetric dark matter (from twin QCD states which naturally have GeV-scale masses). More generally, relic abundances of cosmologically stable states place constraints on the parameters of the theory, and twin sector phase transitions need to be considered.

Dark Matter from the Fraternal Twin Higgs

Robert Lasenby, Perimeter Institute

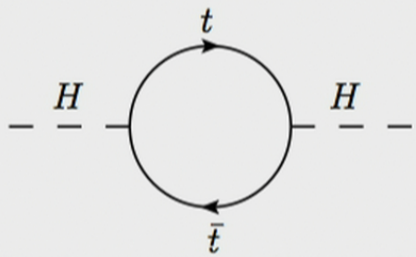
Work with J. March-Russell, I. García García
arXiv 1505.07109 and 1505.07110

October 6th 2015

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

The (little) Hierachy Problem

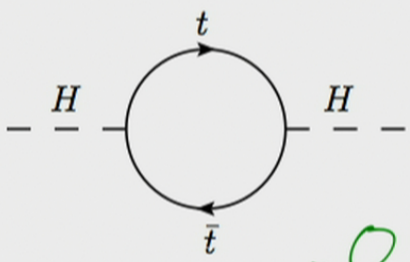
- Quadratic divergence of Higgs mass squared:

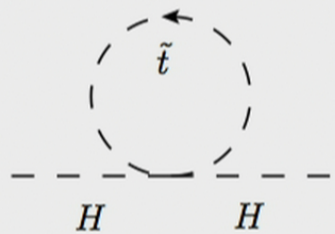


$$\delta m_H^2 \sim -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

(viewing y_t as adjustable parameter, parametric correction from compositeness at scale Λ)

- SUSY solution:





$$\delta m_H^2 \sim \frac{3}{8\pi^2}\left((\lambda_t - y_t^2)\Lambda^2 + \#(m_{\tilde{t}}^2 - m_t^2)\log\frac{\Lambda}{v} + \dots\right)$$

0

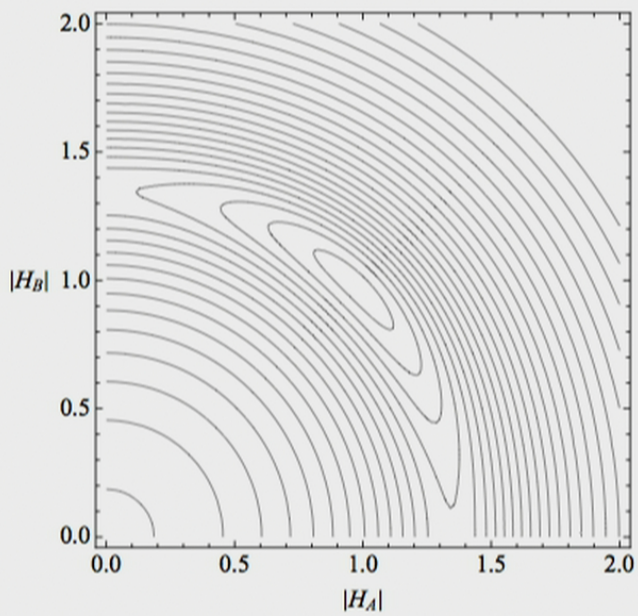
The Twin Higgs

- *Problem*: SM-charged (especially coloured) top partners should've been seen already!
- *Possible solution*: make partners SM-neutral
- *Example*: Twin Higgs theories. Goal is *not* to remove all $\#\Lambda^2$ contributions, but just to make $|\#| < 3y_t^2/(8\pi^2)$, so that a few-TeV cutoff gives acceptable tuning.

The Twin Higgs

- *Idea*: introduce two Higgs doublets, H_A, H_B. Imposing Z_2 exchange symmetry,

$$V(H_A, H_B) = \lambda(|H_A|^2 + |H_B|^2 - f^2/2)^2 + \kappa(|H_A|^4 + |H_B|^4)$$



The Twin Higgs

- *Idea*: introduce two Higgs doublets, H_A, H_B. Imposing Z_2 exchange symmetry,

$$V(H_A, H_B) = \lambda(|H_A|^2 + |H_B|^2 - f^2/2)^2 + \kappa(|H_A|^4 + |H_B|^4)$$

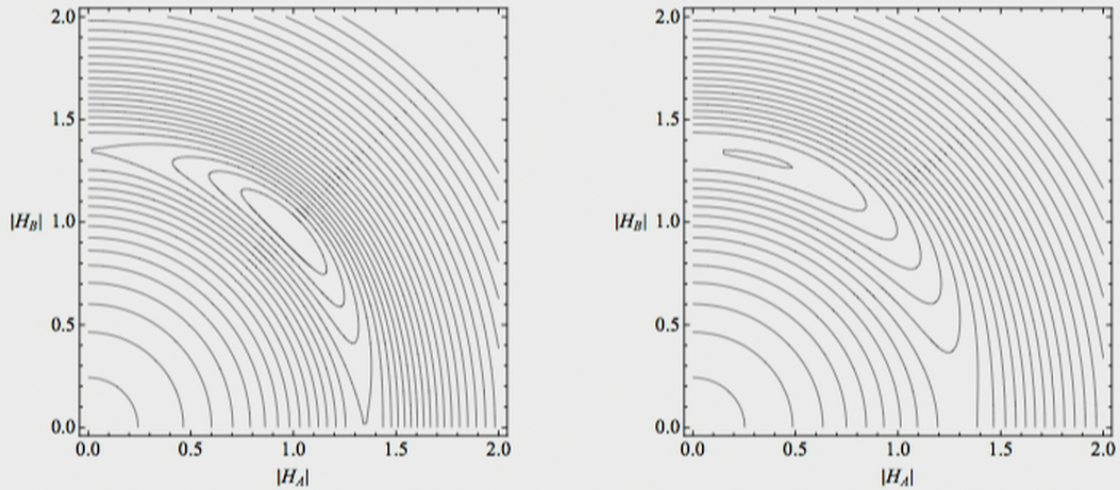
- If H_A, H_B couple to separate t, t', corrections are

$$\delta V = -\frac{3y_t^2}{8\pi^2}|H_A|^2\Lambda^2 - \frac{3y_t'^2}{8\pi^2}|H_B|^2\Lambda^2 + \frac{6y_t^4}{16\pi^2}|H_A|^4 \log\frac{\Lambda}{y_t|H_A|} + \frac{6y_t'^4}{16\pi^2}|H_B|^4 \log\frac{\Lambda}{y_t'|H_B|} + \dots$$

- If $y_t = y_t'$, quadratic part of V is still $SO(8)$-symmetric. For κ small, have PNGBs from $SO(8) \to SO(7)$, with $m^2 \sim \kappa f^2$.
- Correction to λf^2 is $\sim \frac{3y_t^2}{8\pi^2}\Lambda^2$, so f can naturally be smaller than Λ.

The Twin Higgs

- Identify A sector with SM, B with SM-neutral twin sector.
- Get 7 PNGBS: 3 eaten by $SU(2)_A$, 3 by $SU(2)_B$, 1 as physical light Higgs.
- Observed Higgs is SM-like — doesn't have large couplings to another sector.
- So, need to tune Z_2-breaking H_A, H_B potential to make light Higgs mostly in A direction, $v_A \ll v_B$.

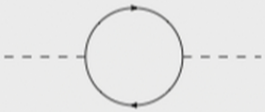


The Twin Higgs

- Identify A sector with SM, B with SM-neutral twin sector.
- Get 7 PNGBS: 3 eaten by $SU(2)_A$, 3 by $SU(2)_B$, 1 as physical light Higgs.
- Observed Higgs is SM-like — doesn't have large couplings to another sector.
- So, need to tune Z_2-breaking H_A, H_B potential to make light Higgs mostly in A direction, $v_A \ll v_B$.
- Requires tuning of $\sim 2v^2/f^2$. Higgs couplings measurements $\Rightarrow f \gtrsim 3v$, so tuning $\lesssim 20\%$.
- SM couplings to physical Higgs modified by $\cos(v/f)$, couplings to twin sector by $\sin(v/f)$.

The Fraternal Twin Higgs

- Top loop corrections:



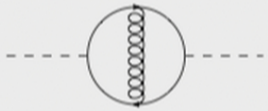
$$\delta m_h^2 \simeq \frac{3\Lambda^2}{4\pi^2}(y_t^2 - y_t'^2) \lesssim (125\,\mathrm{GeV})^2 \quad \Rightarrow \quad \left|\frac{y_t' - y_t}{y_t}\right| \lesssim 0.01$$

(at $\Lambda \sim 5\,\mathrm{TeV}$).

- $SU(2)_A$ and $SU(2)_B$ loop corrections:

$$\delta m_h^2 \simeq \frac{9\Lambda^2}{32\pi^2}(g_2^2 - g_2'^2) \lesssim (125\,\mathrm{GeV})^2 \quad \Rightarrow \quad \left|\frac{g_2' - g_2}{g_2}\right| \lesssim 0.1$$

- 2-loop QCD corrections:



$$\delta m_h^2 \simeq \frac{3y_t^2\Lambda^2}{4\pi^4}(g_3^2 - g_3'^2) \lesssim (125\,\mathrm{GeV})^2 \quad \Rightarrow \quad \left|\frac{g_3' - g_3}{g_3}\right| \lesssim 0.15$$

- $U(1)_Y$ loop corrections: $\sim m_h^2$ for $\Lambda \sim 5\,\mathrm{TeV}$, so not necessary to cancel with $U(1)'$.

The Fraternal Twin Higgs

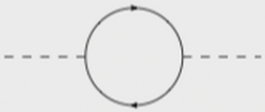
Required particle content is

- Twin top t', with $y'_t \simeq y_t$
- Twin $SU(2)'$ gauge bosons W'^i, with $g'_2 \simeq g_2$
  - $\Rightarrow$ b'_L quark as doublet partner of t'_L
  - $\Rightarrow$ Additional 'twin lepton' doublet (τ'_L, ν'_L) to cancel Witten anomaly
- Twin $SU(3)'$ gauge bosons, with twin confinement scale $\Lambda'_3 \simeq 0.5\,\mathrm{GeV} - 20\,\mathrm{GeV}$
  - $\Rightarrow$ b_R quark to cancel $SU(3)$ anomaly

As long as $y'_b \ll y_t$, it is unconstrained by tuning. Can introduce right-handed leptons, but not required.

The Fraternal Twin Higgs

- Top loop corrections:



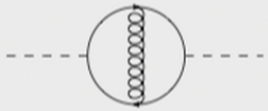
$$\delta m_h^2 \simeq \frac{3\Lambda^2}{4\pi^2}(y_t^2 - y_t'^2) \lesssim (125\,\mathrm{GeV})^2 \quad \Rightarrow \quad \left|\frac{y_t' - y_t}{y_t}\right| \lesssim 0.01$$

(at $\Lambda \sim 5\,\mathrm{TeV}$).

- $SU(2)_A$ and $SU(2)_B$ loop corrections:

$$\delta m_h^2 \simeq \frac{9\Lambda^2}{32\pi^2}(g_2^2 - g_2'^2) \lesssim (125\,\mathrm{GeV})^2 \quad \Rightarrow \quad \left|\frac{g_2' - g_2}{g_2}\right| \lesssim 0.1$$

- 2-loop QCD corrections:



$$\delta m_h^2 \simeq \frac{3y_t^2\Lambda^2}{4\pi^4}(g_3^2 - g_3'^2) \lesssim (125\,\mathrm{GeV})^2 \quad \Rightarrow \quad \left|\frac{g_3' - g_3}{g_3}\right| \lesssim 0.15$$

- $U(1)_Y$ loop corrections: $\sim m_h^2$ for $\Lambda \sim 5\,\mathrm{TeV}$, so not necessary to cancel with $U(1)'$.

The Fraternal Twin Higgs

Required particle content is

- Twin top t', with $y'_t \simeq y_t$
- Twin $SU(2)'$ gauge bosons W'^i, with $g'_2 \simeq g_2$
  - $\Rightarrow$ b'_L quark as doublet partner of t'_L
  - $\Rightarrow$ Additional 'twin lepton' doublet (τ'_L, ν'_L) to cancel Witten anomaly
- Twin $SU(3)'$ gauge bosons, with twin confinement scale $\Lambda'_3 \simeq 0.5\,\mathrm{GeV} - 20\,\mathrm{GeV}$
  - $\Rightarrow$ b_R quark to cancel $SU(3)$ anomaly

As long as $y'_b \ll y_t$, it is unconstrained by tuning. Can introduce right-handed leptons, but not required.

The Fraternal Twin Higgs

- Twin states are SM-neutral, so LHC production rate is low
- Signatures: Higgs couplings modifications, possibly displaced decays of twin glueballs/mesons (hidden valley phenomenology)
- We'll investigate cosmological consequences

Cosmologically stable states

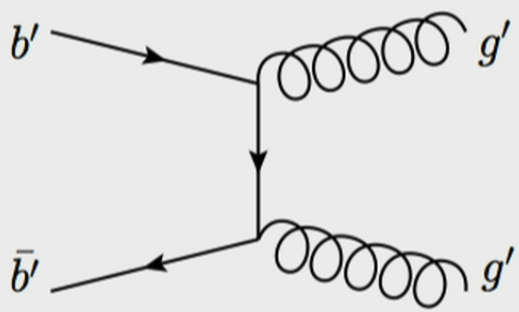
- Symmetries:
  - Twin baryon number B' is an accidental symmetry. Lightest B'-carrying state is spin-3/2, $\Delta' = b'b'b'$
  - For simplicity, suppose that twin 'charge' Q' is a good symmetry, even if $U(1)'$ not gauged. Assuming $m_{\nu'} + m_{\tau'} < m_{W'}$, the lightest L'-carrying state is τ'
  - Q' also implies that twin lepton number L' is an accidental symmetry. If $m_{\nu'} < m_{\tau'}$, then ν' is lightest L'-carrying state.
- No quark flavour symmetry, so no light twin QCD states — mesons/glueballs decay via h or $SU(2)'$.
- Decay timescales depend on the UV completion. For example, if this links B' and SM baryon number B, then Δ' decay operators will be of the form

$$(q'q'q')(qqq)\ldots$$

so will necessarily be of high dimension.

Thermal history — Δ'

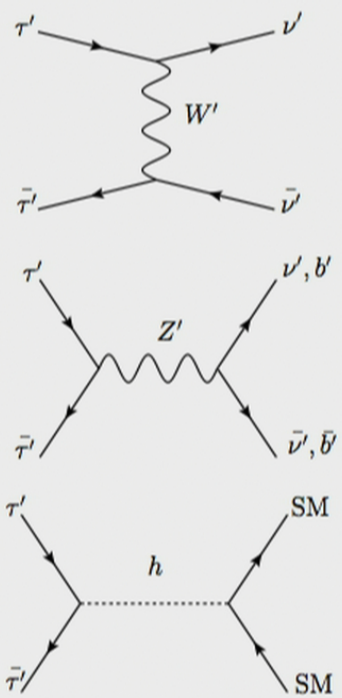
- Higgs portal interactions mean that SM and twin sector are in thermal equilibrium until temperatures well below the EFT cutoff $\Rightarrow$ thermal freeze-out scenario.
- $b'\bar{b}' \to gg$ annihilation cross section not far from unitarity bound, so unless $m_{b'} \gtrsim \mathrm{TeV}$, b' is well below DM abundance.

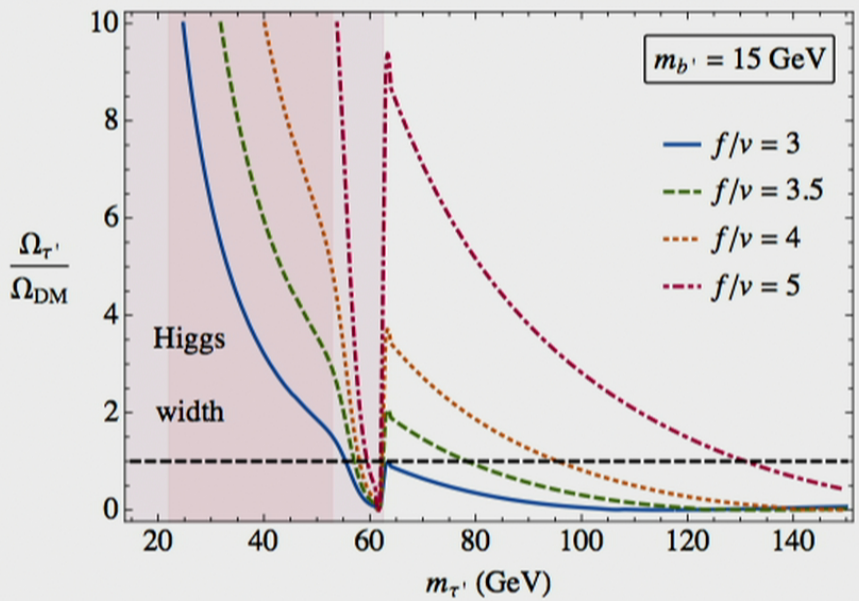


- If $m_{b'}$ light compared to Λ', then Δ' annihilate efficiently to mesons / glueballs, so have sub-DM abundance.
- So, in absence of B' asymmetry, relic abundance of Δ' is very low.

Thermal history — τ'

- $\tau'\bar{\tau}'$ annihilation via twin weak interactions, and h portal
- 'Twin WIMP miracle': $\Omega h^2 \simeq 0.1\,\mathrm{pb}/\langle\sigma v\rangle$





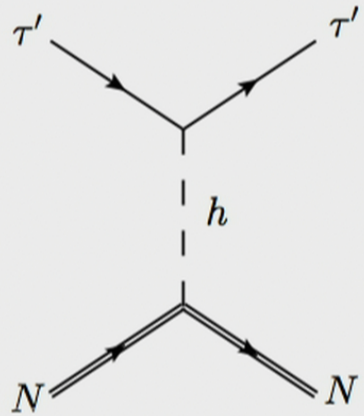
- Light $\tau' \Rightarrow$ over-production

Thermal history — ν'

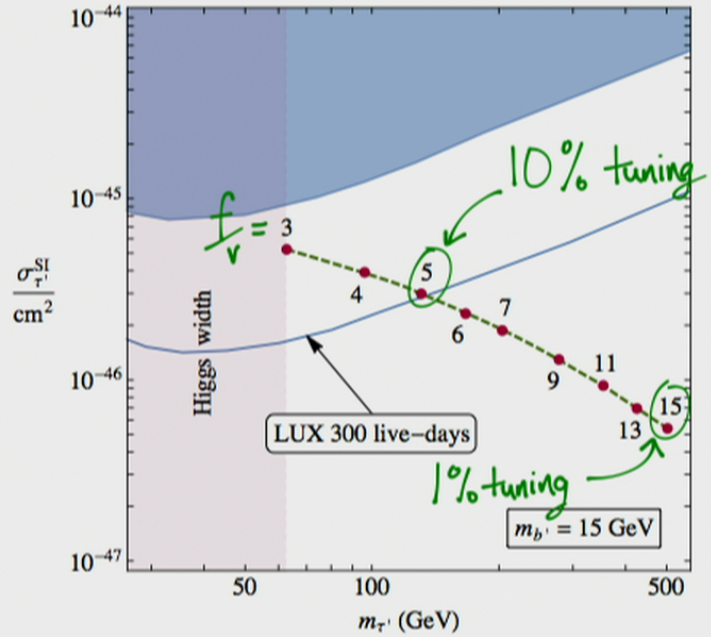
- If ν' gets a heavy Dirac mass, it behaves like heavy τ' (difference only in labelling) $\Rightarrow$ twin WIMP
- If $m_{\nu'}$ lighter, and $\gtrsim \mathrm{few\,eV}$, then abundance is too large
- So, either require DM (or sub-DM) twin WIMP abundance, or $m_{\nu'} \lesssim \mathrm{few\,eV}$, giving dark radiation relic abundance
- Dark radiation abundance constrained by effective number of extra neutrino species ΔN_{eff}.

τ' dark matter - Direct detection

- Direct detection: scattering via Higgs exchange,

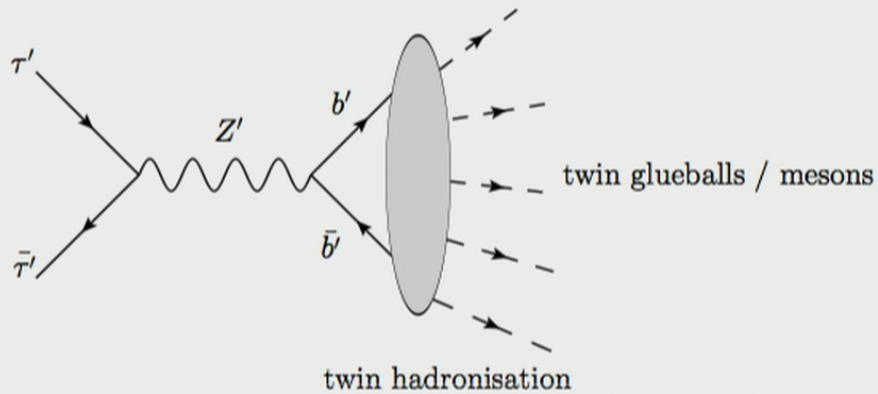


- $\sin^2(v/f)$ supppression $\Rightarrow$ below current bounds, but predict signals in next-generation experiments



τ' dark matter — Indirect detection

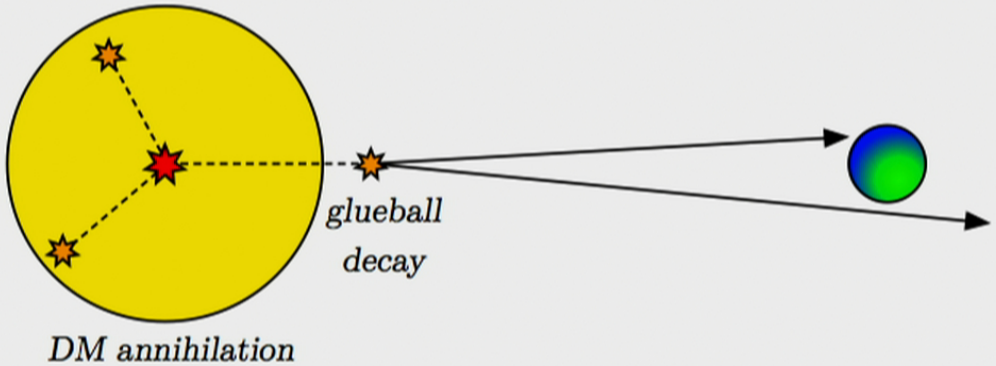
- Dominant annihilation channel is to $b'\bar{b}'$ — leads to twin QCD fragmentation



- Glueballs / mesons decay to SM via h portal (and to $\nu'\bar{\nu}'$) — get $b\bar{b}$ injection
- Produce gamma rays, and cosmic ray $\bar{p}$: softer spectrum, smaller rate than standard WIMP $\rightarrow$ SM annihilation scenario
- Safe from current constraints, but low f/v potentially within range of future observations

Indirection detection from the Sun

- If ν' are heavy, then some glueballs may be long-lived due to selection rules.
- If these have a lifetimes between a few seconds, and $\mathrm{AU}/c \sim 10^3$ sec, then products of DM annihilation in the centre of the Sun may decay outside the Sun.



- Gamma-ray signal of this kind searched for by FERMI; non-observation places constraints on rate of such processes.
- $\bar{p}$ signal also of interest (AMS-02?)

Asymmetric Dark Matter

- General idea: as occurs for SM baryons, DM relic abundance may be set by asymmetry in a conserved quantum number, with the symmetric component efficiently annihilated away.
- Hope is that, if we had some model that generated roughly comparable asymmetries and masses for SM baryons and DM, this would explain

$$\frac{m_{\rm DM}|\eta_{\rm DM}|}{m_N|\eta_B|} = \frac{\Omega_{\rm DM}}{\Omega_{\rm baryon}} \simeq 5 = \mathcal{O}(1)$$

- Here, we'll ignore question of asymmetry generation
- *Assuming* that appropriate asymmetries are generated, we will see that Δ' are a successful ADM candidate, in motivated multi-GeV mass range

Twin sector asymmetries

- Twin sector quantum numbers are B', L', Q'.
- Asymmetries in L' and Q' lead to asymmetric τ' abundance, for $m_{\tau'}$ large enough that symmetric component has low enough abundance.
- Leads to possibility of asymmetric τ' DM, for larger masses than possible in symmetric case. Similar pheno (without annihilation signals), and mass range higher than motivated region.

- If $\eta_{B'} \simeq -\eta_{Q'}$, have asymmetric Δ' relic population.
- In $m_{b'} < \Lambda'$ limit, baryon mass is set by confinment scale, $m_{\Delta'} \simeq 5\Lambda' \sim 2\,\mathrm{GeV} - 50\,\mathrm{GeV}$.

Asymmetric Δ' — phenomenology

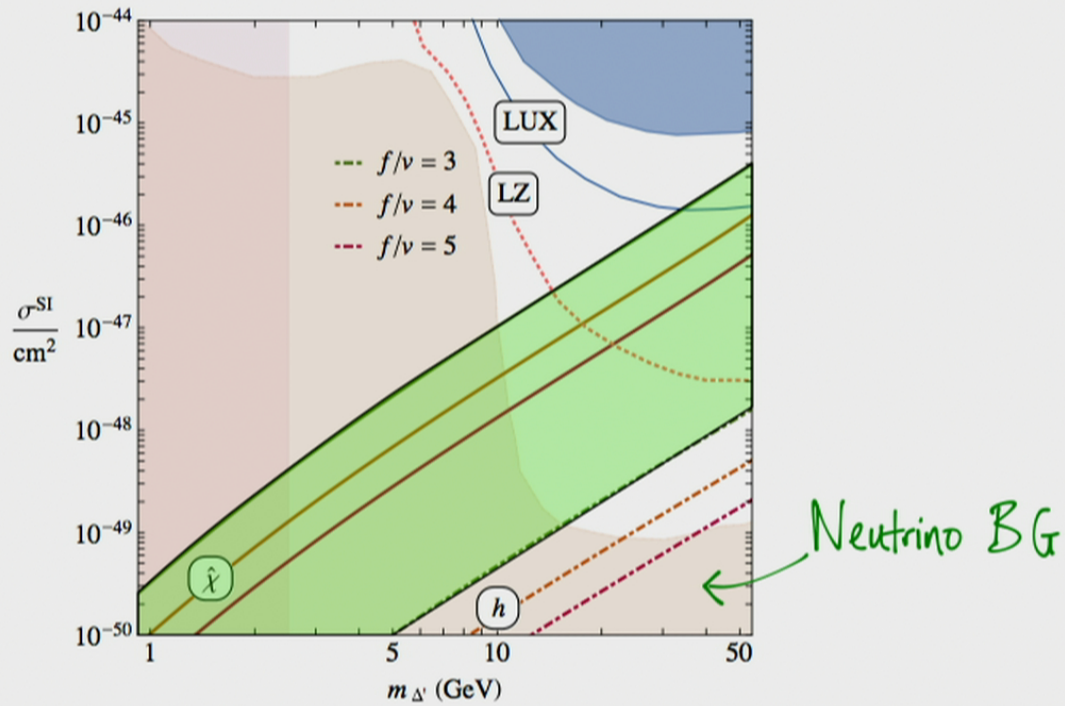
- What form will relic Δ' exist in? (c.f. SM baryons forming nuclei etc.)
- Even if bound states exist in spectrum, light states available to de-excite to are ν' and SM — both too weakly coupled for significant fusion rates in early universe. So, relic Δ' are freely-floating.
- Self-interaction cross section:

$$\sigma_{\Delta'}/m_{\Delta'} \sim \Lambda'^{-3} \sim 10^{-3} - 10^{-8}\,\mathrm{cm}^2\,\mathrm{g}^{-1}$$

Usual bound on elastic DM self-scattering;
$\sigma/m \lesssim 0.5\,\mathrm{cm}^2\,\mathrm{g}^{-1}$.

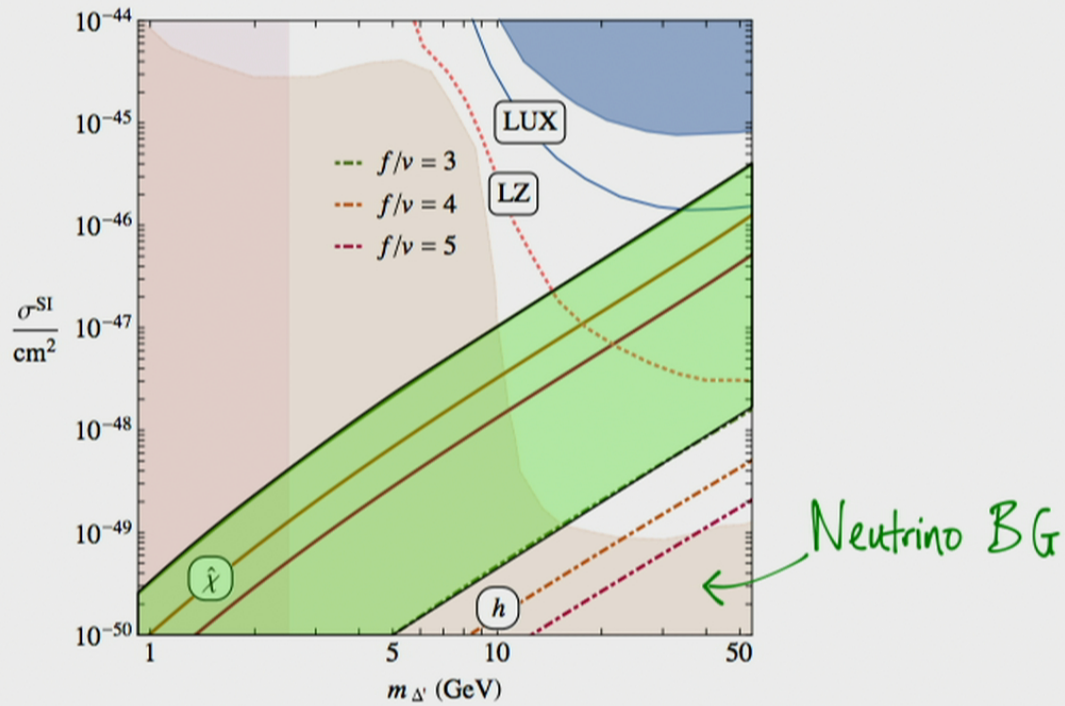
Asymmetric Δ' — direct detection

- Scattering of Δ' off SM nuclei is via h exchange, or exchange of meson/glueball that mixes with h.
- Uncertainty in h/glue mixing, and Δ'/glue coupling, gives band of plausible cross sections:



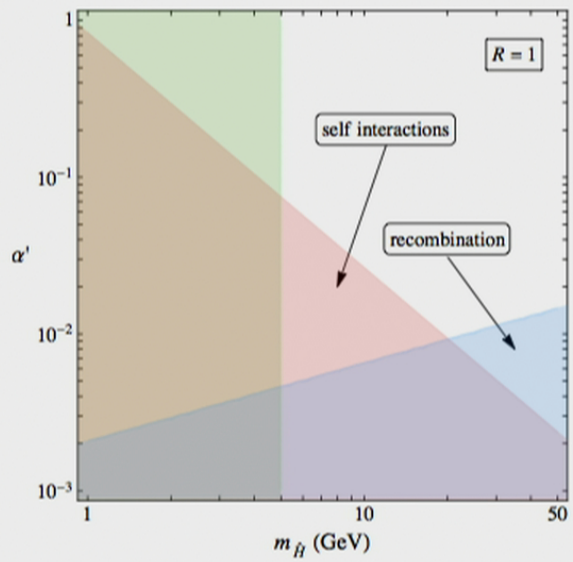
Asymmetric Δ' — direct detection

- Scattering of Δ' off SM nuclei is via h exchange, or exchange of meson/glueball that mixes with h.
- Uncertainty in h/glue mixing, and Δ'/glue coupling, gives band of plausible cross sections:



Dark atoms

- If $U(1)'$ is gauged, charge neutrality requires equal Δ', $\bar{\tau}'$ populations.
- These can form 'dark atoms': if they don't, then plasma interactions strongly affect e.g. Bullet-cluster-like collisions, unless α' extremely small.
- Self-interactions of dark atoms via EM$'$ moments impose constraints:



Dark atom physics

- Before dark recombination, Δ' and $\bar{\tau}'$ form a plasma, which will support Dark Acoustic Oscillations. For $BE \gtrsim 10\,\mathrm{keV}$, dark recombination is early enough that these aren't observationally important.
- Possibility of dark molecules? Radiative capture of neutral atoms to form molecules is very suppressed. Need abundance of charged particles to catalyse molecule formation — seems to be no suitable parameter space window.
- Dark form factor: effective size of atoms is $\sim$ SM nuclear scale, so signature possible, but not spectacular
- Various constraints on kinetic mixing between $U(1)'$ and SM $U(1)$ (twin sector charged states gain SM millicharges).

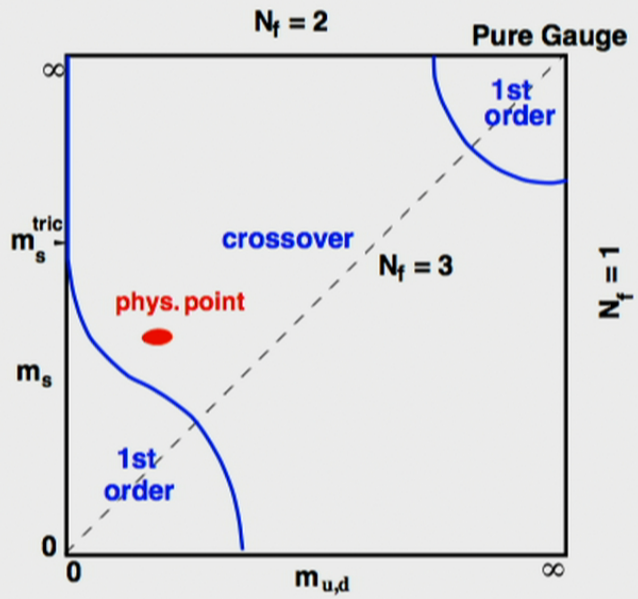
Other cosmological features

We've considered dark matter phenomenology so far. Other aspects:

- Dynamics of twin sector phase transitions: entropy production, gravitational radiation, ...
  - Twin $SU(2)$ phase transition — future work
  - Twin QCD phase transition: unlike SM QCD, may be first-order.
- Light relics (dark radiation), e.g. ν' — constraints from effective number of neutrino species $N_{\rm eff}$.

Twin QCD phase transition

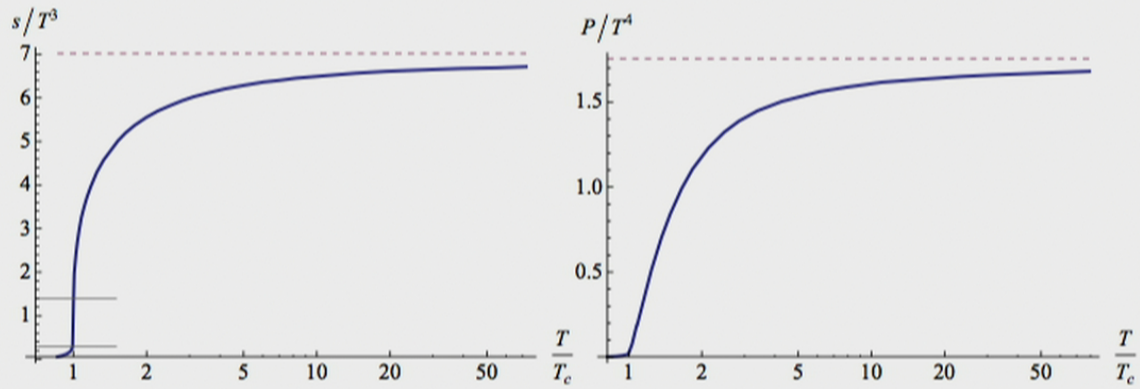
- Pure-gauge theory has first-order phase transition
- One light quark $\Rightarrow$ smooth crossover. Critical value $m_q \sim 8\Lambda'$.



- Possible cosmological consequences of first-order transition:
  - Significant entropy production?
  - Graviational radiation?

Twin QCD phase transition

- For pure-gauge $SU(3)$, phase transition is fairly weakly first-order:



- Unconfined phase supercools down to $T = (1-\delta)T_c$, until a critical bubble (pressure difference overcomes surface tension) is nucleated

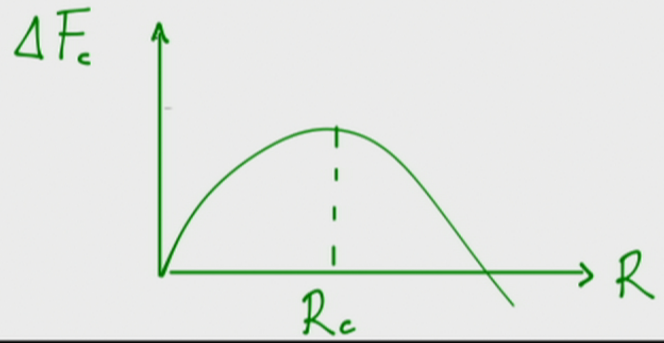
Nucleation rate

- From lattice studies, latent heat $\rho_L \simeq 1.4\,T_c^4$, bubble wall surface tension $\sigma \simeq 0.016\,T_c^3$.
- Pressure difference between phases:

$$\frac{dP}{dT} = \frac{\rho + P}{T} = s \quad \Rightarrow \quad \Delta P = P_G - P_g \simeq -\delta\rho_L$$

- Free energy cost of critical bubble ($R_c = 2\sigma/\Delta P$):

$$\Delta F_c = 4\pi R_c^2 \sigma - \frac{4}{3}\pi R_c^3 \Delta P = \frac{16\pi}{3}\frac{\sigma^3}{(\Delta P)^2} \simeq 3 \times 10^{-5}\delta^{-2} T_c$$



Phase transition dynamics

- So, either transition completes very fast, with nucleation occuring almost everywhere, or latent heat released from bubble nucleation and expansions heats the unconfined phase back above nucleation temperature.
- In either case, out-of-equilibrium processes occur at temperatures only slightly below T_c, so with a smaller pressure difference, so can only produce a small amount of entropy:

$$\Delta s \simeq \frac{\Delta P}{T_c} \sim \text{few} \times \delta \frac{\rho_L}{T_c} \sim 10^{-3} T_c$$

$\Rightarrow$ No significant dilution

- In the more likely case where bubble expansion happens above nucleation temperature, get even smaller entropy production ($\propto \delta^2$), and no significant gravitational radiation.

Light twin sector relics

- If ν' are lighter than weak scale, need to have $m_{\nu'} \lesssim \mathrm{few\,eV}$, so they form dark radiation (DR).
- Energy density of DR depends on when it decouples from SM.
- If twin sector decouples from SM after twin QCD phase transition (ν' the only twin states with significant abundance), then since $g_{\rm SM} \simeq 70$, and SM neutrios decouple at $g_{\rm SM} = 10.75$, have

$$\left(\frac{T_\nu}{T_{\nu'}}\right)^3 \simeq \frac{70}{10.75} \quad \Rightarrow \quad T_\nu \simeq 1.9\,T_{\nu'}\,,\ \Delta N_{\rm eff} \simeq 1.9^{-4} = 0.075$$

- Planck constraints: $\Delta N_{\rm eff} = 0.15 \pm 0.2$ (SM contribution: $\Delta N_{\rm eff} = 0.046$)
- Future experiments: $\sigma(N_{\rm eff}) \sim 0.05$

Early ν' decoupling

- If twin sector decouples from SM before twin QCD phase transition, then most of the entropy from the twin QCD bath (at least 16 relativistic DoF from gluons) ends up in ν'.
- This increases the temperature by a factor

$$\left(\frac{16 + 2 \times \frac{3}{4}}{2 \times \frac{3}{4}}\right)^{1/3} = 2.3$$

- Gives $\Delta N_{\rm eff} \simeq (2.3/1.9)^4 = 2.0$
- Require that $\nu' \leftrightarrow \mathrm{QCD}' \leftrightarrow \mathrm{SM}$ interactions are fast enough to bring ν' and SM almost to equilibrium
- Since e.g. glueball $\to$ SM decay rates $\propto \Lambda'^7$, and $H \propto T^2$, increasing Λ' increases Γ/H. Estimates $\Rightarrow \Lambda' \gtrsim 2.5\,\mathrm{GeV}$.

Summary

- Twin Higgs theories as examples of 'neutral naturalness' — solving the little hierarchy problem without introducing new SM-charged states
- Accidental and/or gauge symmetries may naturally give rise to cosmologically stable twin states
- 'Twin WIMP miracle', for twin leptons with reasonable Yukawa couplings
- Possibility of motivated ADM scale arising from twin confinement
- Twin sector phase transitions: possibility of out-of-equilibrium processes
- Light thermal relics: dark radiation, $\Delta N_{\rm eff}$
- We've considered the minimal ('fraternal') Twin Higgs as a motivated, predictive example of the kind of cosmology that can result from such models — many extensions!