An Overview of Atomic Dark Matter in Mirror Twin Higgs

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Introduction

The Twin Higgs framework is a promising approach to the naturalness problem of the Standard Model (SM).

In Mirror Twin Higgs models, the SM is extended to include a complete mirror ("twin") copy of the SM, with its own particle content and gauge groups.

The SM and its twin counterpart are related by a discrete Z_2 "twin" symmetry.

$$\mathrm{SM_A} \xleftrightarrow{\quad Z_2 \quad} \mathrm{SM_B}$$

The mirror particles are completely neutral under the SM strong, weak and electromagnetic forces. Only feel gravity.

In Mirror Twin Higgs models, the one loop quadratic divergences that contribute to the Higgs mass are cancelled by twin sector states that carry no charge under the SM gauge groups.

Discovery of these states at LHC is therefore difficult. May explain null results.

The SM and twin SM primarily interact through the Higgs portal.

$$|H_A|^2|H_B|^2$$

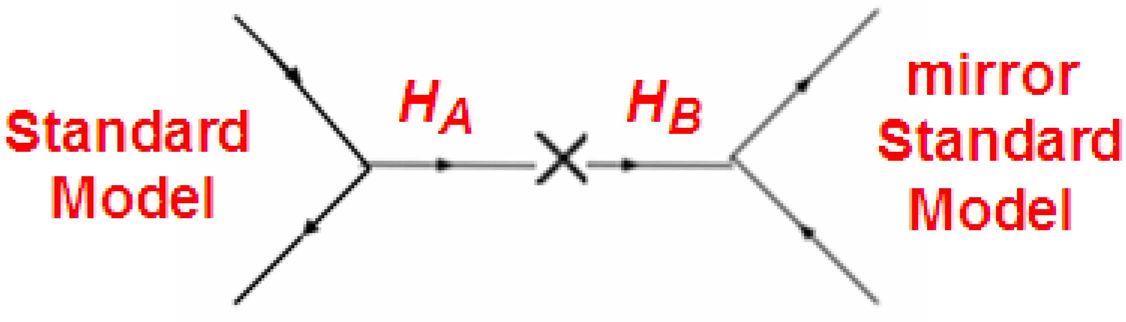
This interaction is needed for cancellation of quadratic divergences and gives rise to mixing between the Higgs and twin Higgs.

A soft breaking of the Z_2 twin symmetry ensures that v_B, the VEV of the twin Higgs, is greater than v_A, the VEV of the SM Higgs.

Twin fermions are heavier than SM fermions by a factor of v_B/v_A .

Higgs measurements $\Rightarrow v_B/v_A \gtrsim 3$. Naturalness $\Longrightarrow v_B/v_A \lesssim 5$.

Interactions mediated by the Higgs keep the SM and twin sectors in thermal equilibrium until temperatures of order a few GeV.



Then the twin photon and twin neutrinos contribute significantly to the energy density in radiation. The model is disfavored by BBN and CMB.

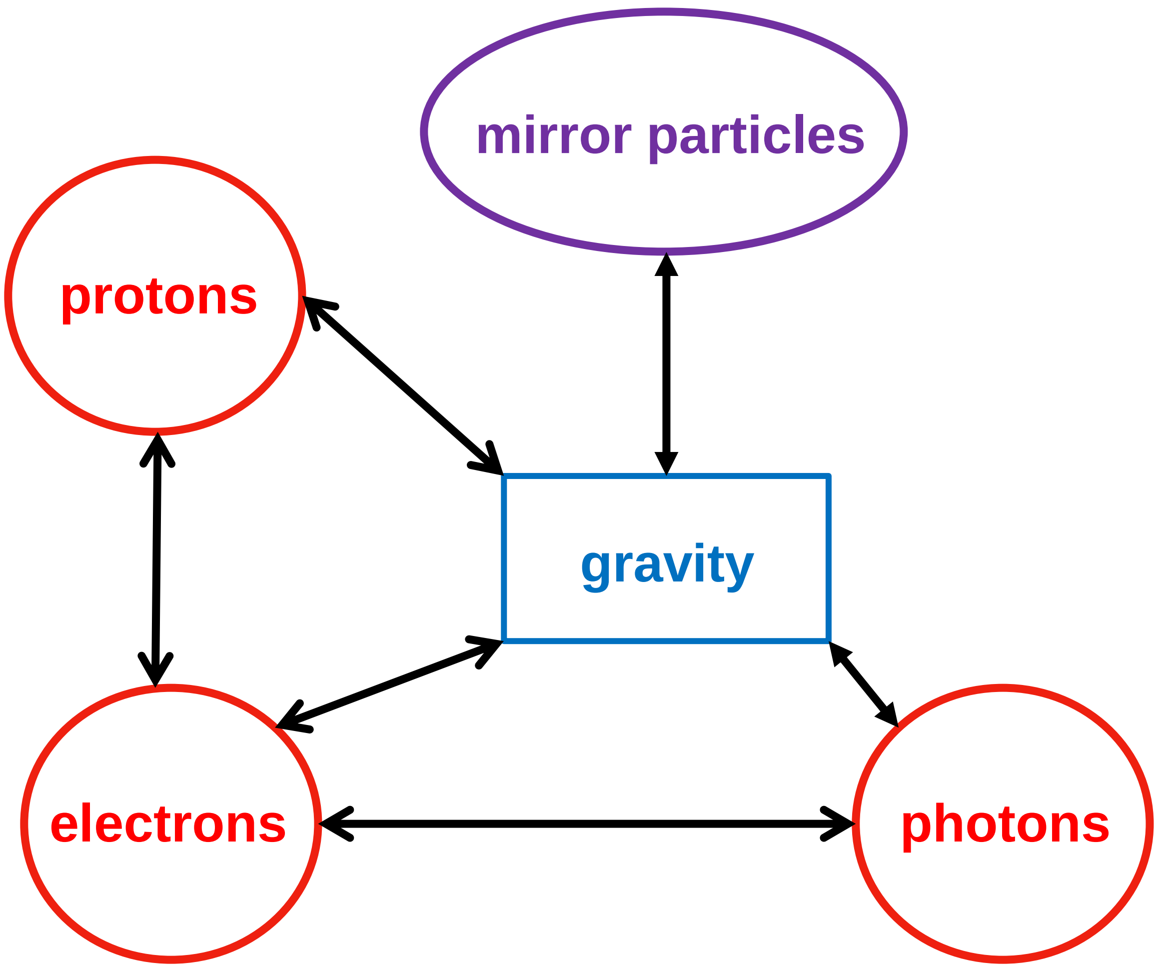
Introduce new dynamics that preferentially heats up the SM sector after the two sectors have decoupled. Does not require further Z_2 breaking.

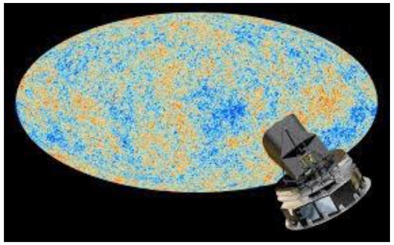
The light degrees of freedom at CMB include the twin photon plus the 3 (massless) twin neutrinos. Treat $\Delta N_{\rm eff}$ as a free parameter.

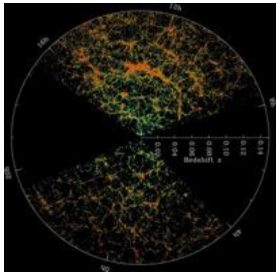
If there is a baryon asymmetry in the mirror sector, the bath will also contain twin baryons and electrons. Atomic dark matter!

In the cosmological framework, the twin baryons, electrons, photons and neutrinos lead to distinctive signals that can distinguish this class of models.

The mirror particles affect the dynamics of the visible sector through gravity.







This scenario gives rise to some characteristic signals.

- Twin photons and twin neutrinos constitute distinct forms of dark radiation that have different effects on the CMB and can be distinguished.
  - The twin neutrinos free stream, suppressing inhomogeneities.
  - The twin photons scatter of dark baryons. Do not free stream till late.

Fraction of dark radiation that free streams is fixed by the model. A prediction!

- The twin baryons constitute an acoustic subcomponent of dark matter.

The presence of both twin hydrogen and twin helium components leads to characteristic features in the matter power spectrum.

- The mirror particles can scatter of ordinary matter through the hypercharge portal, giving rise to direct detection signals.

Twin hydrogen, twin helium and twin electrons each give rise to distinct signals. The mirror nature of the theory can potentially be distinguished!

Parametrizing Mirror Cosmology

To describe Mirror Twin Higgs cosmology, we need 3 (additional) parameters,

$$\Delta N_{eff}, \qquad v_B/v_A, \qquad r_{\rm all} = \Omega_{\rm all\ mirror\ baryons}/\Omega_{\rm DM}$$

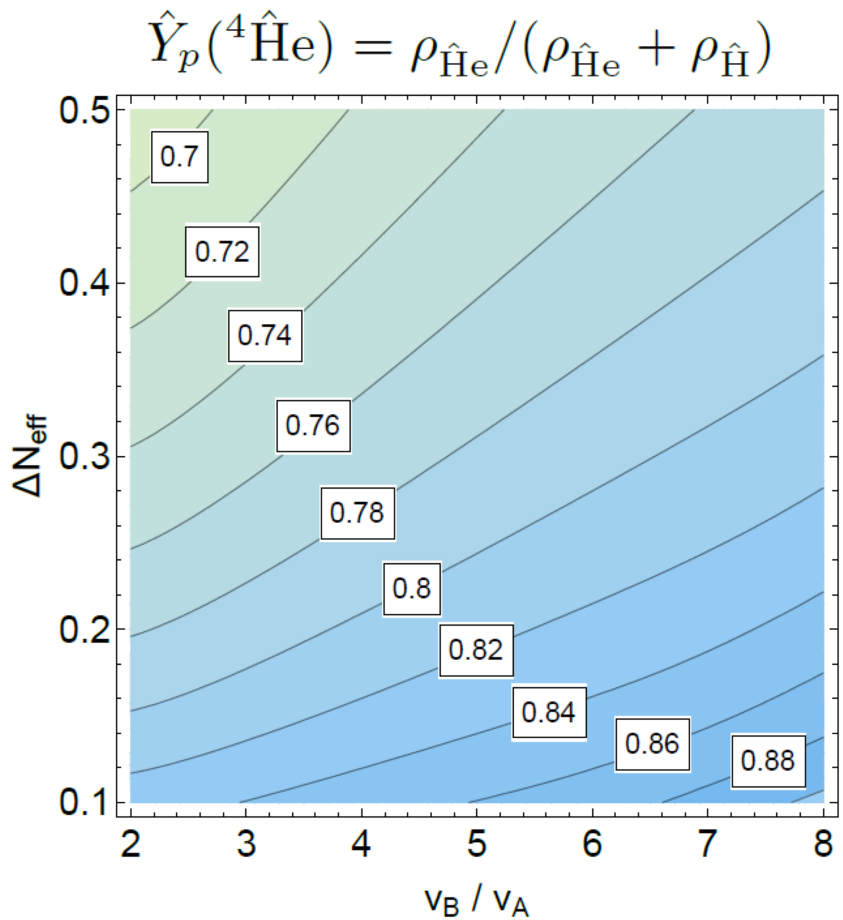
- ΔN_{eff} represents the energy density in dark radiation, expressed in terms of the effective number of neutrinos.
- The ratio of Higgs VEVs v_B/v_A fixes the masses of the mirror particles.
- The parameter $r_{\rm all}$ represents the fractional contribution of mirror matter to the total energy density in dark matter.

Given $r_{\rm all}$ the fractional contributions of mirror hydrogen and helium to the dark matter density are determined by twin Big Bang nucleosynthesis (TBBN).

$$r_{\hat{\rm H}} = \Omega_{\hat{\rm H}}/\Omega_{\rm DM}, \qquad r_{\hat{\rm He}} = \Omega_{\hat{\rm He}}/\Omega_{\rm DM}$$

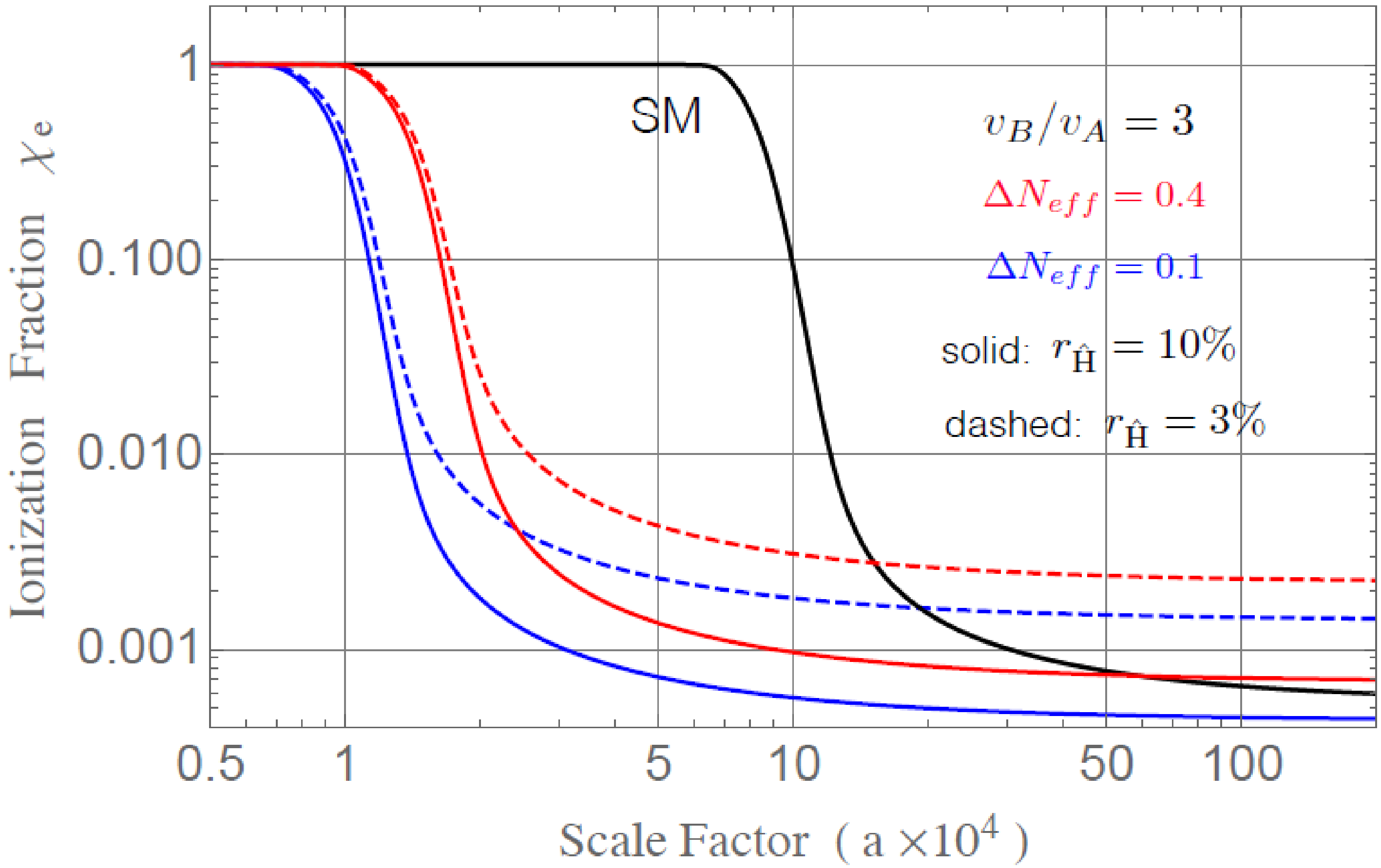
The signals are sensitive to the relative fractions of hydrogen and helium.

Twin Big Bang Nucleosynthesis



The fraction of helium is about 75% by weight, as compared to just 25% in the visible sector! The effects of mirror helium on cosmology cannot be neglected.

Recombination

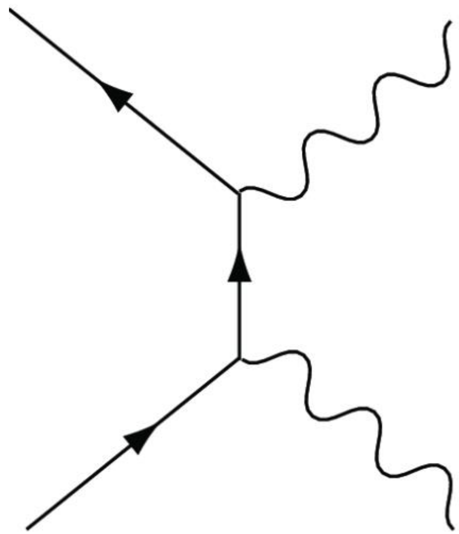


Since the mirror sector is colder than the visible sector, and the atomic binding energies larger, recombination occurs earlier!

CMB Signals of a Mirror Twin Higgs

The CMB signals of dark radiation partly depend on whether it free streams (like neutrinos), or scatters with a short mean free path (like a fluid).

While the twin neutrinos free stream, the twin photons are prevented from free streaming by Compton scattering off twin electrons.



At later times, after recombination happens in the twin sector, the twin photons also free stream. Since the twin electron is heavier, this happens during the CMB epoch, when the SM temperature is of order an eV.

The size of these effects depends on the free streaming fraction, f_ν.

This is defined as the total energy in free streaming radiation expressed as a fraction of the total energy in radiation.

$$f_\nu \equiv \frac{\rho_{\text{all free rad}}}{\rho_{\text{all rad}}} = \frac{3\rho_{1\nu} + \rho_{\text{DR}}^{\text{free}}}{3\rho_{1\nu} + \rho_\gamma + \rho_{\text{DR}}^{\text{free}} + \rho_{\text{DR}}^{\text{scatt}}}$$

In the limit that ΔN_{eff} is small, free streaming dark radiation and scattering dark radiation contribute to f_ν with opposite sign!

$$f_\nu - f_\nu\big|_{\text{SM}} = \frac{0.41}{3}\left(0.59\Delta N_{\text{eff}}^{\text{free}} - 0.41\Delta N_{\text{eff}}^{\text{scatt}}\right)$$

Their effects on the CMB are different!

The amplitudes of the CMB modes depend on f_ν.

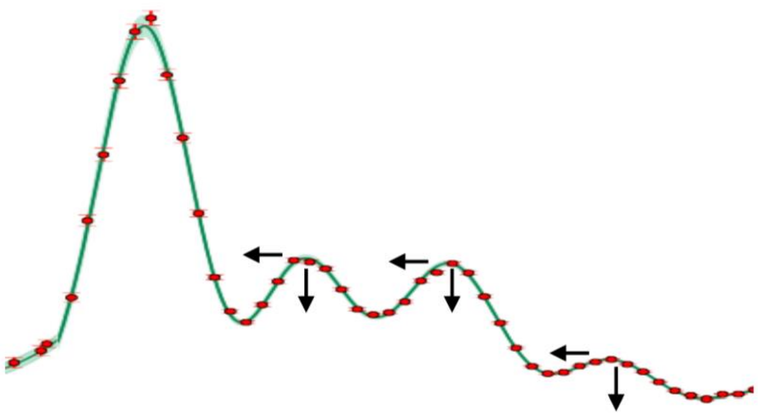
$$\frac{\delta C_\ell}{C_\ell} = -\frac{8}{15} f_\nu$$

Peebles
Hu & Sugiyama

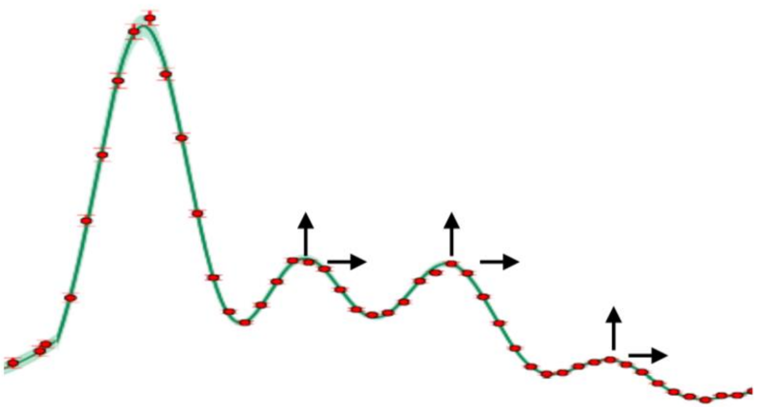
The locations of the CMB peaks also depend on f_ν. For higher *l*,

$$\delta\ell \simeq -57\, f_\nu \, \frac{\ell_A}{300}$$

Bashinsky & Seljak



Free Streaming DR



Scattering DR

The sign of the effect is different in the two cases! Distinguishable!

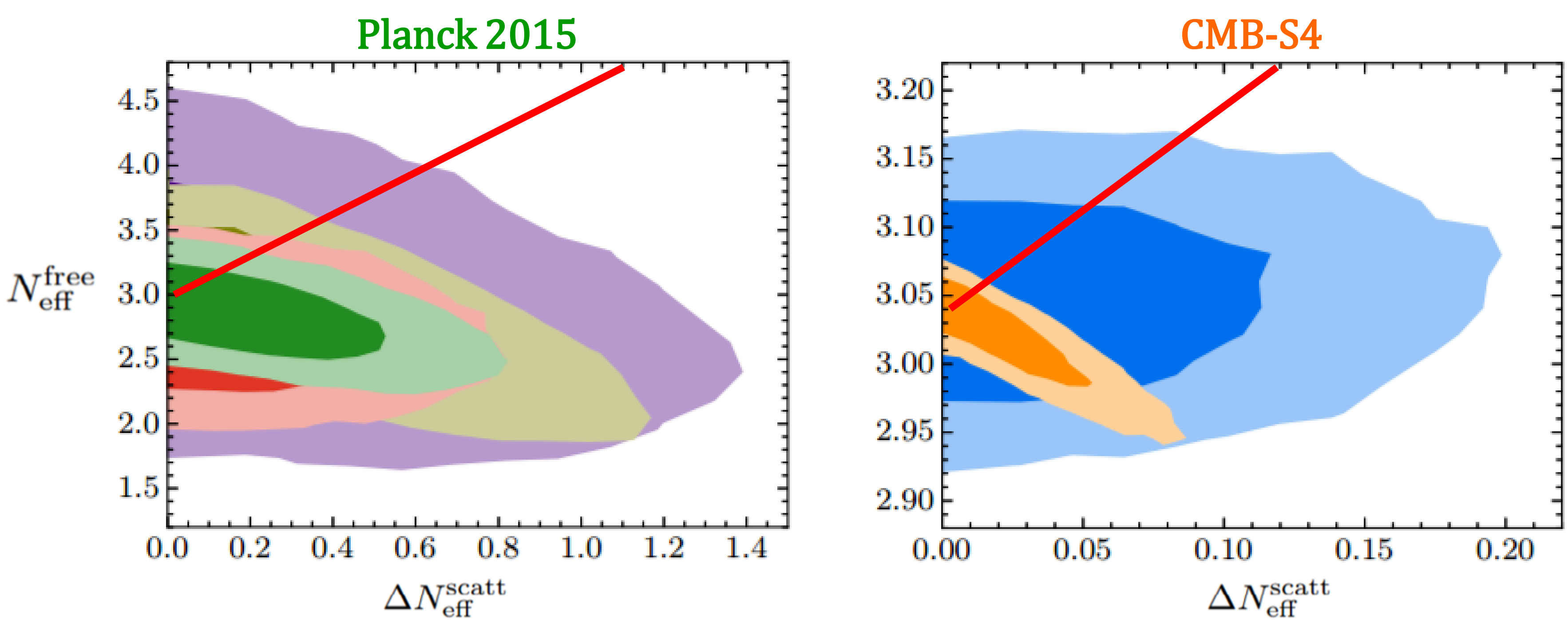
The Mirror Twin Higgs predicts the ratio

$$\frac{\Delta N_{\rm eff}^{\rm scatt}}{\Delta N_{\rm eff}^{\rm free}} = \frac{4.4}{3.0}$$

How well can current and future CMB experiments distinguish this?

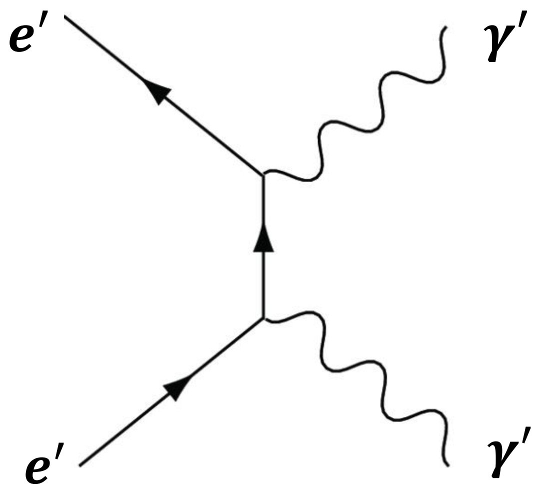
The current 2σ bounds on $\Delta N_{\rm eff}^{\rm free}$ and $\Delta N_{\rm eff}^{\rm scatt}$ stand at 0.5 and 0.6 respectively. The sensitivity is expected to improve by an order of magnitude in CMB-S4.

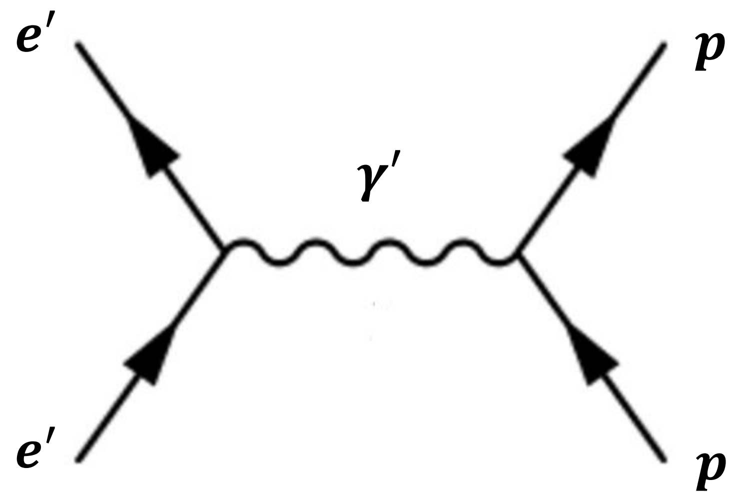
Baumann, Green, Meyers & Wallisch
Brust, Cui & Sigurdson



Signals in Large Scale Structure

The interactions of twin baryons with twin photons at early times suppresses the growth of density perturbations in the twin sector.



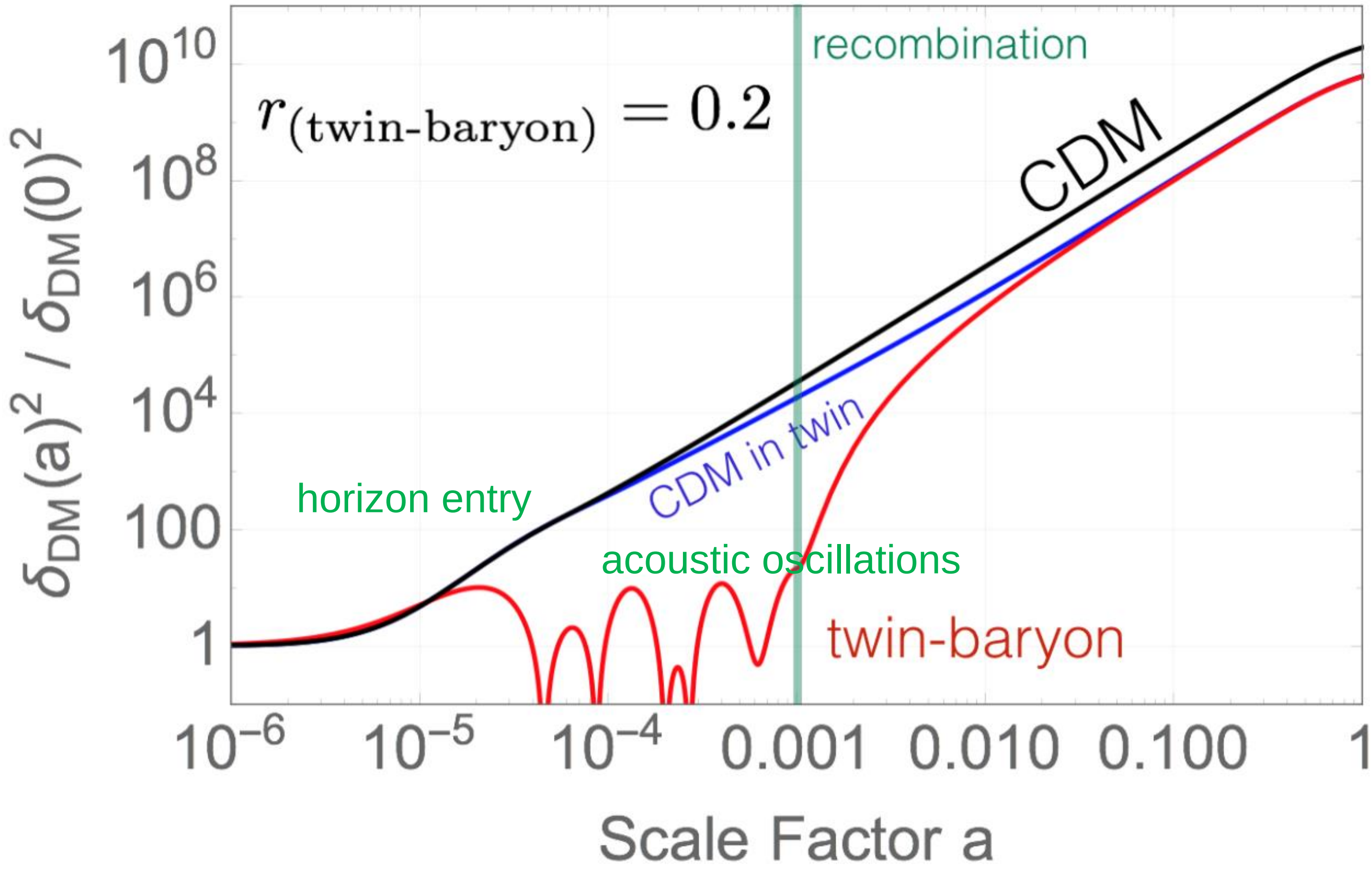


The size of these effects is determined by Γ, the rate of momentum transfer between twin photons and twin baryons,

$$\Gamma \equiv \frac{1}{\langle p^2 \rangle} \frac{\mathrm{d}\langle \delta p^2 \rangle}{\mathrm{d}t}$$

Since $\Gamma > H$ at early times, these effects are large and suppress the growth of structure in the twin sector till recombination occurs (at around an eV).

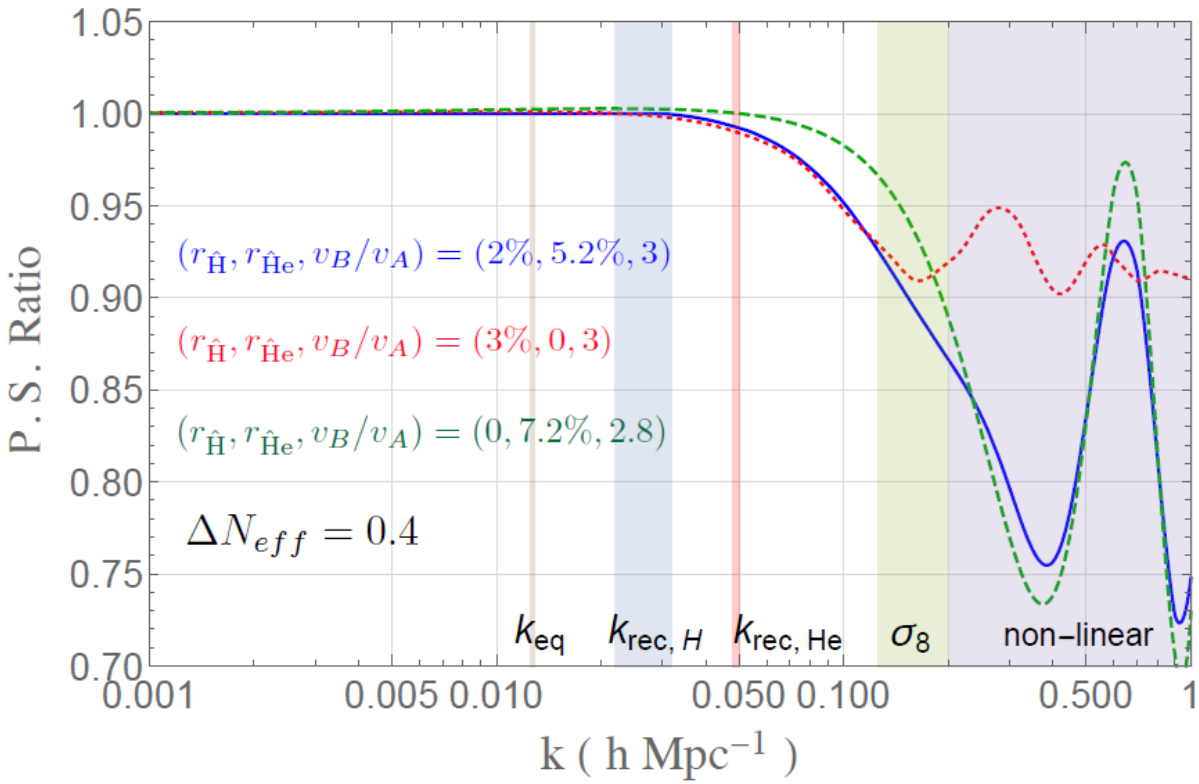
Consider a mode that enters the horizon well before recombination. Acoustic oscillations in the twin sector suppress growth of structure relative to ΛCDM.



Modes which enter after twin recombination are relatively unaffected.

For a given ΔN_{eff} , it does not appear possible to reproduce all the features of the matter power spectrum with just a single species of atom.

Since hydrogen recombines later, its oscillations determine the power spectrum at lower k. At higher k, the effects of helium begin to dominate.



A distinctive feature of the MTH framework!

Galaxy surveys, CMB lensing and 21 cm measurements may be able to test this.

Direct Detection of Mirror Matter

Can the twin baryons and electrons be discovered in direct detection experiments?

The Higgs portal cross sections are too small to generate a viable signal.

However, there can also be renormalizable interactions between the SM and twin sectors through the hypercharge portal.

$$\frac{\epsilon}{2\cos\,\theta_W} B_{\mu\nu} B'^{\mu\nu}$$

The bounds on dark radiation constrain $\epsilon \lesssim 10^{\wedge}(-9)$.

In the Mirror Twin Higgs, this interaction is not generated through three loop order, so this bound is satisfied.

Gravity loops are expected to generate this coupling with $\epsilon \sim 10^{\wedge}(-13)$. Potentially large enough to be detected!

Direct detection signals depend on distribution of mirror matter in the galaxy.

Part of the visible matter in our galaxy has collapsed into a disc. Is the mirror matter in the neighborhood of earth in the form of a halo or a disc?

When halo formation occurs at $z \sim 10$, the mirror atoms fall into gravitational wells. Their collisions result in a shock wave that heats up the mirror sector.

If the resulting temperature is high enough, the mirror atoms will be ionized!

The ionized mirror particles lose energy in collisions with background mirror photons, and by emitting radiation after colliding with each other.

If the time scale for this energy loss is less than the convection timescale, the ionized halo may have collapsed into a disc!

There are several processes that play a role in energy loss.

- Compton scattering off background mirror photons.
- Bremsstrahlung radiation arising from mirror electron-proton collisions.
- Atomic cooling processes such as recombination and collisional excitation.

Since these processes require collisions between mirror particles, the cooling rate is lowered if the energy density in mirror matter r_{all} is reduced.

For $r_{all} \lesssim 0.01$, cooling rate is small, and distribution remains an ionized halo.

For larger values of r_{all}, the result is less clear. Cooling is less efficient than in the SM, and the model lives close to the boundary line that separates the disc regime from the halo regime.

To bracket the range of possibilities, we consider the four limiting cases of an ionized halo, an ionized disc, an atomic halo and an atomic disc, and study the direct detection signals from nuclear recoil and electron recoil for each case.

The different mirror dark matter components are in thermal equilibrium. Free mirror electrons have much larger speeds than mirror hydrogen and helium.

For our study, set $r_{all} = .01$.

Focus on SuperCDMS (Ge) for nuclear recoils and SENSEI for electron recoils.

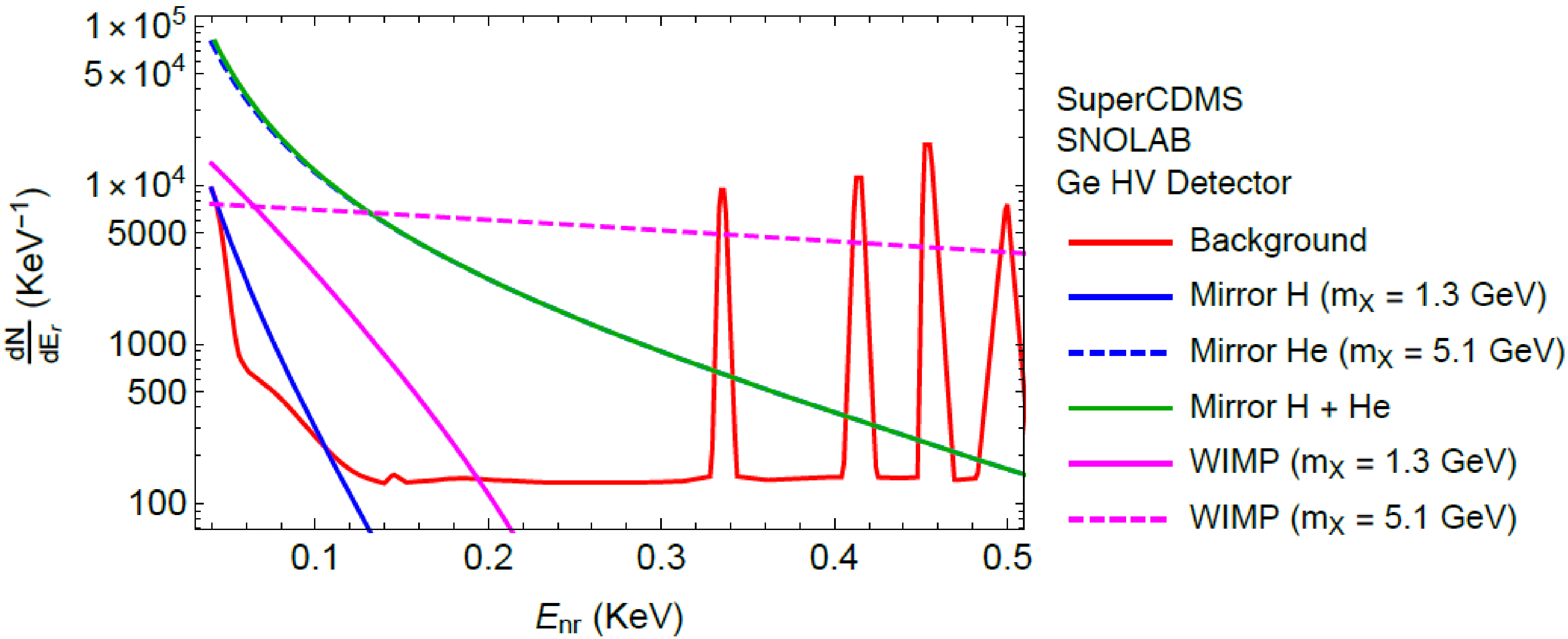
Ionized Halo: Mirror hydrogen and helium can be detected by SuperCDMS for $\epsilon \gtrsim 10^{-11}$. The reach of SENSEI is comparable. For mirror electrons, SENSEI can go all the way down to $\epsilon \sim 10^{-14}$.

Ionized Disc: Mirror baryons are now very difficult to detect, since the recoil energies are too low. For mirror electrons, SENSEI can go down to $\epsilon \sim 10^{-12}$.

Atomic Halo: Atomic hydrogen and helium can be detected by SuperCDMS for $\epsilon \gtrsim 10^{-11}$. The reach of SENSEI is slightly weaker, $\epsilon \gtrsim 10^{-10}$.

Atomic Disc: The most challenging case. Direct detection is not possible with current technology but may be possible in the future.

Direct detection experiments may be able to distinguish the mirror nature of the theory. As an example, consider an ionized halo.



Mirror hydrogen and mirror helium give rise to very different recoil spectra. Given enough events their individual contributions can be distinguished from each other, and from those of a conventional WIMP.

Conclusions

The Mirror Twin Higgs offers a simple and natural framework for atomic dark matter that makes distinctive predictions for the CMB, LSS and direct detection.

Fraction of dark radiation that free streams is a prediction of the Mirror Twin Higgs framework that can potentially be tested in future CMB experiments.

The mirror baryons constitute an acoustic subcomponent of dark matter. Baryon acoustic oscillations of mirror hydrogen and helium leave a distinctive imprint on large scale structure that can be probed in future experiments.

Apart from detecting twin baryons and electrons, direct detection experiments may be able to distinguish the mirror nature of dark matter in this framework.