New strong dynamics beyond the standard model

Lecture 7 12 December 2017

Last time

- Lattice results for the electroweak S parameter (an LEC of low-energy EFT) from computing the transverse vacuum polarization function $\Pi_{V-A}(Q^2)$
- Consistent gravitational evidence for dark matter (DM) from all accessible scales
  Spiral galaxy rotation curves ($\sim$kpc)
  Galaxy motion and lensing within galaxy clusters ($\sim$Mpc)
  Formation of large-scale structure ($\sim$Gpc)
  Cosmic microwave background power spectrum
- Resulting features of dark matter: Stable, non-relativistic ($w = 0$), non-dissipative (Long-range dark U(1) may be possible — "effectively collisionless" if $\alpha_{\text{dark}} \lesssim 10^{-4}$)
- Motivations for composite dark matter: Natural scale, stable particles, balancing DM–SM interactions in early-universe production vs. ongoing searches

Overview of dark matter production in early universe

- $O(1)$ ratio $\frac{\Omega_{DM}}{\Omega_B} \approx 5$ motivates non-gravitational DM–SM interactions
- **Thermal** relic freeze-out relies on DM–SM interactions, in three stages:
  At early times, high $T \gtrsim M_{DM}$ allows DM $\longleftrightarrow$ SM in thermal equilibrium
  (can be strong $2 \to 2$ dark sector production of states that decay to SM)
  Once $T \lesssim M_{DM}$, DM $\longrightarrow$ SM annihilation rapidly depletes DM density
  Expansion of universe further dilutes DM number density
  $\longrightarrow$ DM particles no longer find each other to annihilate $\longrightarrow$ freeze-out
- Stronger couplings $\alpha \longrightarrow$ more efficient depletion leaving fewer DM particles $\longrightarrow$ must have larger mass to produce observed relic density Ω_{DM}
- Calculating the numerical factors (for $2 \to 2$ processes) gives $200\alpha \simeq \dfrac{M_{DM}}{100\text{ GeV}}$
  WIMP 'miracle': $\alpha \sim \alpha_{EW} \sim 0.01 \Longrightarrow M_{DM} \sim 200$ GeV $\sim v_{EW}$
  Composite DM: $\alpha \sim 4\pi \Longrightarrow M_{DM} \sim 100$ TeV (smaller for $2 \to n$ processes)
- **Asymmetric** production relies on DM–SM interactions to distribute net baryon/lepton/DM number asymmetries among those sectors
- Many models have $n_{DM} \sim n_B \Longrightarrow M_{DM} \sim 5M_B \approx 5$ GeV
  integrate out direct coupling at Λ_{UV} scale $\longrightarrow$ high-dim. interactions in EFT
- Alternately DM–Higgs couplings allow $n_{DM} \sim n_B e^{-M_{DM}/T_s} \Longrightarrow M_{DM} \sim$ TeV from EW sphaleron processes above $T_s \sim 200$ GeV

Overview of searches for dark matter

- **Direct** detection uses large underground detectors to reduce backgrounds
  Tightest constraints from searches for nuclear recoil
  $\longrightarrow$ sensitive to DM–nucleon cross section $\sigma \simeq 10^{-10}$ pb for $M_{DM} \simeq 50$ GeV
- Weaker bounds for lighter DM since not enough energy to produce visible signals
  $\longrightarrow$ can probe by looking for scattered electrons or using cryogenic crystals
  Weaker bounds for heavier DM since smaller number of heavier particles
- Approaching "neutrino floor" where irreducible background present
  from coherent ν scattering $\longrightarrow$ directional detection may help to address
- **Indirect** detection looks for SM products of DM annihilation or decay
  Many observations, all potentially just complicated astrophysical backgrounds
  Examples: XMM-Newton 3.55-keV X-rays
  Fermi-LAT ~GeV γ-rays from galactic center
  AMS-02 e^+ and $\overline{p}$ excesses up to $O(100\text{ GeV})$ (Kfir Blum seminar)
  DAMPE $e^\pm$ spectral break ~0.9 TeV and potential excess ~1.4 TeV
- **Collider** searches for missing E_T may be difficult to identify as definitely DM
  So far more powerful constraints on related predictions,
  for example the 'R parity' that can stabilize susy WIMP DM

Overview of composite dark matter candidates

- Gauge–fermion dynamics $\longrightarrow$ analogs of glueballs, mesons or baryons
  as typical composite DM candidates
  More exotic possibilities if elementary fermions in higher rep(s)
  adjoint $\longrightarrow$ fermionic 'glueballino' (fermion–gluon composite, susy not needed)
- Cosmological stability $\longrightarrow$ candidate is lightest state carrying conserved quantity
- Stability easiest for lightest **baryon** due to accidental symmetry as in QCD,
  can also have stable **nuclei**
  Baryon can be fermionic or bosonic depending on odd vs. even number of colors
- Small elementary fermion masses (vs. dark confinement scale, $m_f \ll \Lambda_{DM}$)
  $\longrightarrow$ light **PNGBs** can be DM candidates if decays suppressed
  Can study through low-energy EFT, like composite Higgs or χPT
- Large $m_f \gg \Lambda_{DM} \longrightarrow$ analog of **quarkonium** if decays suppressed,
  or possibly stable **glueballs** as lightest dark-sector particles

Representative models of mesonic composite DM

- Tempting to start with the $(1,1)$ PNGB in the SO(6)/SO(5) Next-to-MCHM
  corresponding to SU(2) gauge theory with $F=2$ fermions in fundamental rep

  However, this generically decays too quickly
  for example through dim-5 operators like $\frac{1}{\Lambda_{UV}}\overline{Q}QH^\dagger H, \;\; \frac{1}{\Lambda_{UV}}\overline{Q}\sigma_{\mu\nu}QB_{\mu\nu}$

  Try to suppress decays with more elaborate model building...

- Strongly Interacting Massive Particle (SIMP) models use SM-singlet fermions

  Connect to SM by gauging and Higgsing U(1) flavor symmetry
  $\longrightarrow$ massive 'dark photon' A_μ kinetically mixes with hypercharge

  $$\mathcal{L} \supset -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} + \frac{1}{2}M_A A_\mu A^\mu - \epsilon B_{\mu\nu}A^{\mu\nu} \qquad \text{with} \quad \epsilon \ll 1$$

- PNGB SIMP DM candidates π mainly analyzed through EFT

  Thermal freeze-out through $3 \to 2$ DM process via WZW 5-PNGB interaction
  $\sim \frac{1}{f^5}\epsilon^{\mu\nu\rho\sigma}\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi \quad \longrightarrow$ very light $M_\pi \sim 100$ MeV possible

- 'Quirky' DM is example of heavy meson/diquark DM candidate

  Two-flavor SU(2) gauge theory with $m_f \gg \Lambda$,
  global U(1) 'quirky baryon number' symmetry imposed to stabilize diquark DM

  Asymmetric production via electroweak sphalerons $\longrightarrow$ fermions in chiral EW rep
  $\longrightarrow$ ruled out by (**light**) Higgs exchange in direct detection experiments

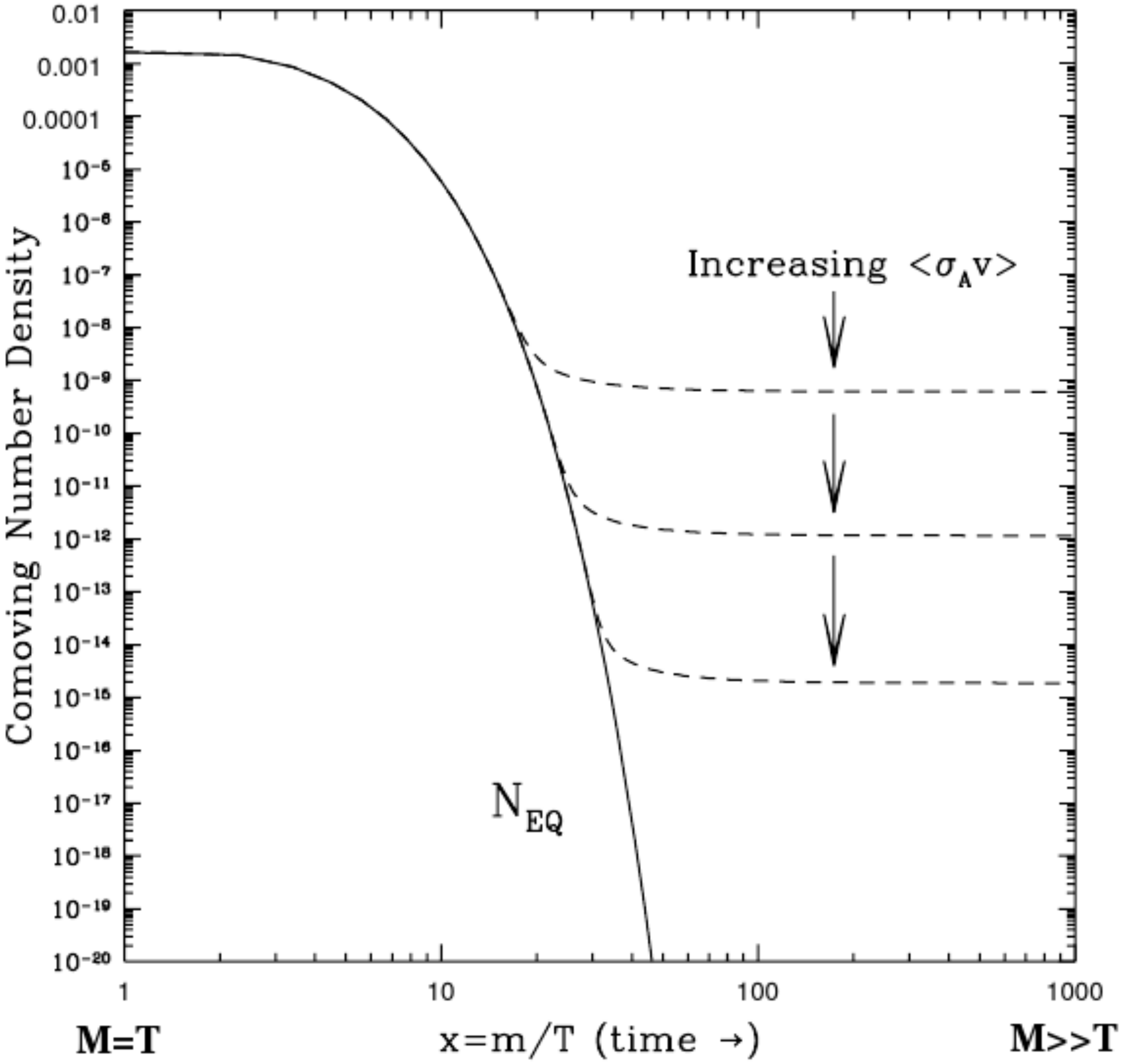

Figure 1: The standard picture of thermal relic freeze-out, from *The Early Universe* by Kolb and Turner. At early times (high temperatures) non-gravitational DM–SM interactions allow DM $\longleftrightarrow$ SM in thermal equilibrium (corresponding to the solid line). Once the temperature of the universe falls below the dark matter mass, DM $\longrightarrow$ SM annihilation rapidly depletes the dark matter density. At the same time the expansion of the universe further depletes the dark matter number density, which eventually becomes low enough that dark matter particles can no longer 'find each other' to annihilate and instead freeze out (dashed lines). As the coupling (and hence the velocity-averaged DM annihilation rate $\langle \sigma_A v \rangle$) increases the depletion is more efficient, leading to a smaller number density after freeze-out. Reproducing the observed mass density from this smaller number density requires more massive dark matter particles.

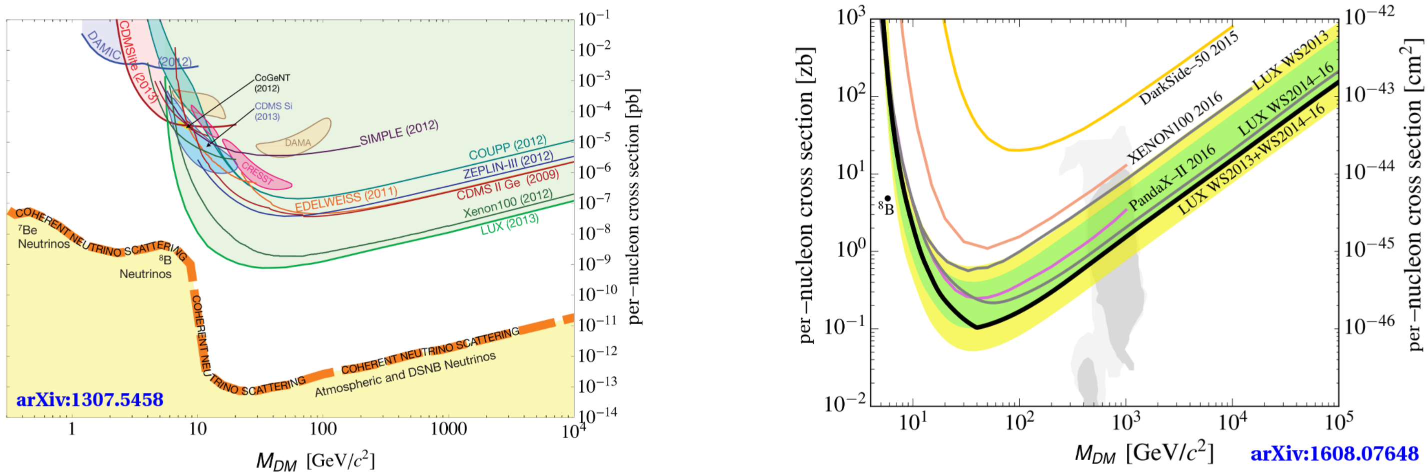

Figure 2: Constraints on DM–nucleon cross sections vs. the dark matter mass from direct detection experiments. **Left:** The status of searches in 2013, compared to the "neutrino floor" where coherent ν scattering introduces an irreducible background. **Right:** Zooming in on more recent final results from the Large Underground Xenon (LUX) experiment, which reach $\sigma \simeq 10^{-46}$ cm^2 $= 10^{-10}$ pb for $M_{DM} \simeq 50$ GeV. The ^{8}B label should be in the same place in both plots. The grey blob is favored by the constrained minimal supersymmetric standard model (CMSSM, largely ruled out by LHC experiments).