Outline

- **Overview of dark matter searches**
- **Cosmological history of DM: How to explain the dark matter density?**
- **Composite DM scenarios**
Overview

Measurement from CMB + supernovae
+LSS indicates 23% of our universe is composed of DM;

Three ways to detect DM:

Direct detection  Indirect detection  Collider production

CERN
Direct detection:

XENON 100 rules out DM-nucleon cross section of order $10^{-45}$ cm$^2$ for DM mass ~ 100 GeV!
Direct detection implications:

Elastic DM scattering off nucleons through Z-exchange leads to a cross section $10^{-40}$ cm$^2$!
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Elastic DM scattering off nucleons through $Z$-exchange leads to a cross section $10^{-40}$ cm$^2$!

Unless the elastic scattering is shut off, e.g., due to a mass splitting between $\chi$ and $\chi'$; Inelastic DM scenarios
Direct detection implications:

DM scatters off nuclei through Higgs exchange when DM gets part of its mass from the Higgs

For instance, a scalar $S$ with a quartic coupling $\lambda |S|^2 |H|^2$

$$\sigma \sim \lambda^2 10^{-44} \text{cm}^2 \left( \frac{100 \text{ GeV}}{m_{DM}} \right)^2$$

The range current direct detections probe

An important quantity for understanding the limits of direction detection is the nucleon form factor which lattice calculations already contribute a lot!
Eg. $<N|qq|N>$ J. Giedt; A. Thomas and R. Young; Toussaint and Freeman ‘09
indirect signal:

It was often claimed that: “smoking-gun” signal of annihilating DM would be a monochromatic gamma-ray line (lines) in a region of high DM density, e.g., our Galactic center!

Presently DM is non-relativistic: \( DM + DM \rightarrow \gamma \gamma \)

\[ E_{\gamma} = M_{DM} \]
Recently, an observation of such a line at around 128 GeV is reported: Bringman, Huang, Ibarra, Vogl and Weniger; Weniger;

\[ \langle \sigma v \rangle_{DM + DM \rightarrow 2\gamma} \sim 10^{-27} \text{cm}^3/\text{s} \]

Subsequent studies suggest a second line with energy of about 111 GeV: Rajaraman, Tait and Whiteson; Su, Finkbeiner; Consider \( DM + DM \rightarrow \Upsilon \Upsilon, \Upsilon Z \); for \( DM + DM \rightarrow \Upsilon Z \)

\[ E_\gamma = M_{DM} - \frac{m_Z^2}{4m_{DM}} = 111 \text{GeV} \]

It is also reported that both lines show up in unassociated photon sources in the Fermi-LAT catalogue: Su, Finkbeiner
Recently, an observation of such a line at around 128 GeV is reported:

\[ \langle \sigma v \rangle_{DM+DM \rightarrow 2\gamma} \sim 10^{-27} \text{ cm}^3/\text{s} \]

Not easy to explain this line:

a. Continuum constraint; \textbf{(almost) rule out MSSM neutralino as an explanation)

\textbf{charged matter loop (W, ...)}

\[ \Rightarrow \]

\[ \text{Charged matter can decay to showers of hadrons, } \pi_0 \]

b. Strong couplings and mass coincidences to boost the cross section of the loop process:

large coupling between DM + charged matter running in the loop (e.g, \sim 10);

charged matter running in the loop has to be light with mass \sim 100 \text{ GeV}.

\textbf{Something to watch out: Fermi symposium October 28 - November 2}
Cosmological history of DM: How to explain $\Omega h^2 \approx 0.11$

- Thermal freezeout: DM in thermal equilibrium with the SM until Hubble expansion is faster than the interactions

The annihilation cross section in the early Universe is not necessarily the same as today’s.
\[ \langle \sigma v \rangle = \frac{1}{8\pi} \frac{\kappa^4}{m^2_{DM}} \]

\( \kappa: \) DM coupling

Only the ratio is fixed to get a right thermal relic

\( m_{DM} \quad \leftarrow \quad (100 \, GeV - 1 \, TeV) \quad \rightarrow \quad (10 - 100 \, TeV) \)

\( \kappa \quad \leftarrow \quad (0.1 - 1) \quad \rightarrow \quad (\sqrt{4\pi} - 4\pi) \)

\( WIMP \quad ? \)
Thermal history is not the only choice. For example,

Asymmetric DM: Nussinov ‘85; Barr, Chivukula and Farhi, ‘90; B. Kaplan ‘92; E. Kaplan, Luty and Zurek ‘09...

DM, like ordinary baryons, also has an inherent asymmetry; both asymmetries related by e.g., high-dimensional operators that violate both baryon and DM numbers;

Rough features of original proposals:

\[ n_{DM} \sim n_{baryon}, m_{DM} \sim m_{baryon} \rightarrow \rho_{DM} \approx 5\rho_{baryon} \]
Non-thermal history e.g.: axion DM; more later

Late-decaying scalar field populates SM radiation, that annihilate into DM  
Chung, Kolb, Riotto `98

\[ \Omega h^2 = M_{DM}^2 \langle \sigma v \rangle \left( \frac{2000 T_{RH}}{M_{DM}} \right)^7 \]

DM density is proportional to the annihilation cross section!
Composite DM Theories
Thermal composite DM scenarios:

a. Strongly-interaction heavy DM

\[ m_{DM} \leftarrow (100 \text{ GeV} - 1 \text{ TeV}) \rightarrow (10 - 100 \text{ TeV}) \]

\[ \kappa \leftarrow (0.1 - 1) \rightarrow (\sqrt{4\pi} - 4\pi) \]

WIMP ?

Constraints on self-interaction from dark matter halos and bullet cluster are weak:

\[ \frac{\sigma}{m_{DM}} \leq 0.1 \text{ cm}^2/g \approx 500 \text{ GeV}^{-3} \]

In the SUSY context, such composites could naturally reside in dynamical SUSY breaking sector: Dimopoulos, Giudice and Pomarol ‘98; Fan, Thaler, Wang (indirect signals) ‘10.
b. Light thermal DM: pNGB of the flavor group

A confining sector: $\Lambda$

$$m_{DM} \ll \Lambda$$

$$f \sim \frac{\Lambda}{4\pi}$$

$$m_{DM}^2 f^2 = m_q \Lambda^3 \rightarrow m_{DM} \sim 4\pi \sqrt{m_q \Lambda}$$

$$\sigma \sim \frac{m_{DM}^2}{4\pi f^4} \sim \frac{(4\pi)^5 m_q}{\Lambda^3}$$

By choosing small explicit flavor symmetry breaking parameter $m_q \ll \Lambda$, one can get the right relic;

Buckley, Neil ‘12; In the SUSY context: Ibe, Nakayama, Murayama, Yanagida ‘09..
Asymmetric heavy composite DM scenarios: technibaryon, quirk...

Nussinov ‘85; Barr, Chivukula and Farhi, ‘90; Kribs, Roy, Terning and Zurek ‘09; Del Bobile, Gudnason, Kouvaris, Ryttov and Sannino ;

Non-perturbative effect such as electroweak sphalerons intermix baryon, lepton and the composite DM numbers. The heavy mass of the composite DM also lead to a Boltzmann suppression of their relic \( \exp \left[ -\frac{m_{DM}}{T} \right] \), where \( T \) is the temperature where sphalerons shut off.
Non-thermal composite DM scenarios: Fan, Reece '12;

\[ \frac{1}{2} \left( m_{DM} - \sqrt{m_{DM}^2 - m_{\pi}^2} \right) < E_\gamma < \frac{1}{2} \left( m_{DM} + \sqrt{m_{DM}^2 - m_{\pi}^2} \right) \]

The gamma rays are no longer monochromatic but rather box-shaped!

In the limit \( m_\pi \) close to DM mass ~ 260 GeV, the box mimics a line! For example:

\[ m_{DM} - m_\pi \approx 50 \text{ MeV}, \ \delta E_\gamma \approx 5 \text{ GeV} \]

The mass degeneracy could arise from symmetry

Current Fermi resolution is ~ 10 GeV
Simple possibility exists: scale up QCD

\[ \pi^+ \pi^- \rightarrow \pi^0 \pi^0, \quad \pi^0 \rightarrow \gamma \gamma, \quad \gamma Z. \]

Doesn’t determine relic as it doesn’t change the pion numbers

\[ \sigma v (\pi^+ \pi^- \rightarrow \pi^0 a) \quad \text{is too small to generate a right thermal relic;} \]

Have to reply on non-thermal history to get the right relic!
Direct detection signal:
a. If composite DM scatters off nucleons through Z/h exchange, the constraints before apply;

b. composite DM itself is SM neutral; yet if its constituents are charged, it could interact through EM moments such as charge radius and polarizability.
Pospelov, ter Veldhuis ‘00

In most models above, two important physical quantities:
a. Annihilation cross section for determining the relic;
b. Composite DM moments;
They need to be calculated either by \( \chi \)PT or lattice.
Axions: solution to the strong CP problem

\[ 10^9 \text{ GeV} \leq f_a \leq 10^{15} \text{ GeV} \]

Relic Abundance:
Allowing late-time decaying particle to dilute the relic
Kawasaki, Moroi, Yanagida ‘95;
Axion detections:

Lower end of $f_a$ could be probed by ADMX: resonant cavity axion search; looking for axions converting into photons in a magnetic field;

Higher end of $f_a$ could be probed by rapidly time-varying neutron EDM
Graham and Rajedran ‘11;
The time-dependence (MHz) could be detected by atom-interferometry.
Conclusion

There have been interesting progresses in DM detections that might give us clues of DM properties;

For composite DM scenarios, the annihilation cross sections and its couplings to SM (through higher order moments) are important quantities for its cosmological history and direct detections.