Cold Dark Matter: Theory

- Most favored candidate is the WIMP. WIMPS are massive, weakly interacting and freeze-out when non-relativistic.
- Free-streaming length is small. Structure all the way to "earth mass halos".
- Phase space density is large.

\[
Q \equiv \frac{\rho}{\langle v^2 \rangle^{3/2}}
\]

\[
Q_{\text{CDM}} = 10^{14} \frac{M_{\odot}}{pc^3} \left( \frac{\text{km}}{\text{s}} \right)^{-3} \left( \frac{M}{100\text{GeV}} \right)^{3/2}
\]

[Dalcanton and Hogan, 2000]
Dark Matter Particles from Decay

- What if the dark matter today was created by the decay of another massive particle in the early universe?

- This is the case in a large region of supersymmetric parameter space where the gravitino is the lightest supersymmetric particle. *Super-WIMPs.*

  [Feng, Rajaraman and Takayama, PRL 2003]

- Example: sneutrino NLSP. sneutrino decays to gravitino with a lifetime $\sim 1/(8\pi G M_{\text{weak}}^3) \sim$ month.
Abundance of Dark Matter from Early Decays

WIMP

$\Gamma \sim M_w^3/m_{pl}^2$

Dark Matter

- WIMPs have the right abundance because of their weak interactions

- $\rho_{DM} = \rho_{WIMP} \frac{m_{DM}}{m_{WIMP}}$

- If $m_{DM} \sim m_{WIMP}$, then the dark matter abundance today is naturally in the correct range.

- Example: In super-gravity models, all super-partners have similar masses.
The Case for Dark matter from Early Decays

- Theoretically compelling.
- Strong theoretical hints that new physics (particles) may be lurking at the 100 GeV scale.
- Weak cross-section and $G_N$ naturally leads to the right dark matter abundance.
- Successful cosmological predictions on large (greater than about a Mpc) scales.
- Differences on small scales. May alleviate some "problems" with CDM.

Same as CDM
Recap

• Weak scale mass gravitinos

• Not completely cold

• Not thermal (unlike the gravitino considered as dark matter by Pagels and Primack, 1982)

• Super-WIMP framework more general
Distinguishing from WIMPs

- Accelerator searches
  - Look for signatures of long-lived charged particles at LHC [Hamaguchi et al. 2004, Feng and Smith 2004]

- Cosmology
  - Early Universe
    - Big Bang Nucleosynthesis
    - Cosmic Microwave Background black body
  - Late Universe
    - Small scale structure formation
Cosmological consequences: Early Universe

• Late entropy injection distorts CMB blackbody spectrum.
  [Feng, Su and Takayama, 2004; Austri and Roszkowski, 2004; Lamon and Durrer, 2005]


• Bound states of Helium-4 with charged NLSP
  [Pospelov 2006, Kohri and Takayama 2006, Kaplinghat and Rajaraman, 2006]
Cosmological consequences: Late Universe

• Growth of small scale structure modified [Kaplinghat 2005]
  • Larger free streaming scale
    • Produces lesser power on small scales; cuts off the power spectrum like warm dark matter models
  • Smaller phase space density
    • Creates lower concentration (less dense) halos and perhaps those with observable flat density cores even though the phase space density does not have a FD form
    
    \[ Q = 10^{-3} \frac{M_\odot}{pc^3} \left( \frac{km}{s} \right)^{-3} \left( \frac{m}{pcm} \right)^3 \left( \frac{10^{-7}}{a_{\text{decay}}} \right)^3 \]

• Natural Super-WIMP parameter space [Cembranos et al 2005]
Small-scale structures

- Lesser power on small scales means less substructure on small scales.
- Lower concentration or cored small mass halos are more easily destroyed.
- Lower concentration small mass halos are more consistent with 2-d rotation curves. [Bullock]

- Constant density cores in small galaxies? Need more accurate velocity dispersion and rotation velocity measurements.
BBN with negatively charged dark matter

- Atoms!
- He4 is the electron.
- Charged NLSP is the proton.

- Binding energy = 0.3 MeV
- “Bohr radius” = 3.6 fm

- When does “recombination” happen?
Recombination

![Graph showing recombination process with bound fraction on the y-axis and temperature on the x-axis.](image)
Bound Decays

- Once in a while, the decay product (tau) will destroy the helium nucleus.
- The photo-disintegration occurs through a one-photon exchange diagram. This can occur as long as the energy transferred to the hadronic system, is larger than the binding energy, 28.8 MeV.
- Probability for photo-disintegration of helium: $f_p=10^{-6}$
- The decay products Helium-3 and T will impinge on background Helium-4 and produce Lithium-6
- Include energy loss and destruction by non-thermal photons
Li$^6$ abundance
Li$^6$ abundance

Enhancement due to E field of X$^{-}$ (Pospelov 06)
We include destruction by non-thermal photons

He$_4$(D,$\gamma$)Li$^6$

He$_4$(He$_3$,p)Li$^6$

Work in progress
Models which give Q values needed for large cores are in marginal conflict with Ly-α power spectrum.

Is the relation between power spectrum suppression and Q fixed?
Free-streaming

- Closed set of equations including DDM and DM?
  \[ \delta T_{\mu,\nu}^{\nu} = 0 \]

- We need isotropic and anisotropic perturbations to the pressure.

\[ c_s\eta \propto \frac{1}{Q^{1/3}} \quad (RD) \]
\[ \propto \frac{1}{Q^{1/3}\tau^{1/3}} \quad (MD) \]

Late decays will give rise to large phase space cores in dark matter halos that have formed hierarchically!

Strigari, Kaplinghat and Bullock 2006

June 11, 2006
Dark matter today is born from the (non-relativistic) decay of a neutral NLSP at $z \sim 1000$ or lower

$$\text{NLSP} \rightarrow m\text{CDM} + \text{SM particle}$$

Energy of decay products $\sim \text{GeV}$

Imparted momentum/mass $\sim 10^{-3}$

Can we get a phase-space density, $Q$ of order $10^{-6}$ and have a power spectrum that looks like CDM?

[Strigari, Kaplinghat, Bullock 2006]
For early decays ($M^2_{pl}/M^3_{\text{weak}}$):

cutoff scale $\sim Q^{-1/3}$

For late decays (10^5 yrs.):

cutoff scale given by

$$0.2 \left(\frac{\tau}{10^{12} \text{ s}}\right)^{1/3} \left(\frac{Q}{10^{-6}}\right)^{-1/3} \text{ Mpc}$$

Linear power spectrum like that of CDM.
But small dark matter halos have cores!
Summary

Rich phenomenology of dark matter from decays

WIMP

$\Gamma \sim \frac{M_w^3}{m_{pl}^2}$

Dark Matter

Constraints
Free-streaming cut-off
Phase space limits
Adequate reionization
Non-linear small scale structure
CMB black body
BBN

Probes
LHC, BBN, CMB,
Weak lensing, Reionization,
21 cm, Ly-\(\alpha\) forest, …