Physics Beyond the Standard Model in the Early Universe

June 7, 2004

- The Standard Model has been very successful at describing particle physics

- It clearly cannot be the final theory since it fails to explain many observations (Dark matter, dark energy, weak gravity, three SM generations...)

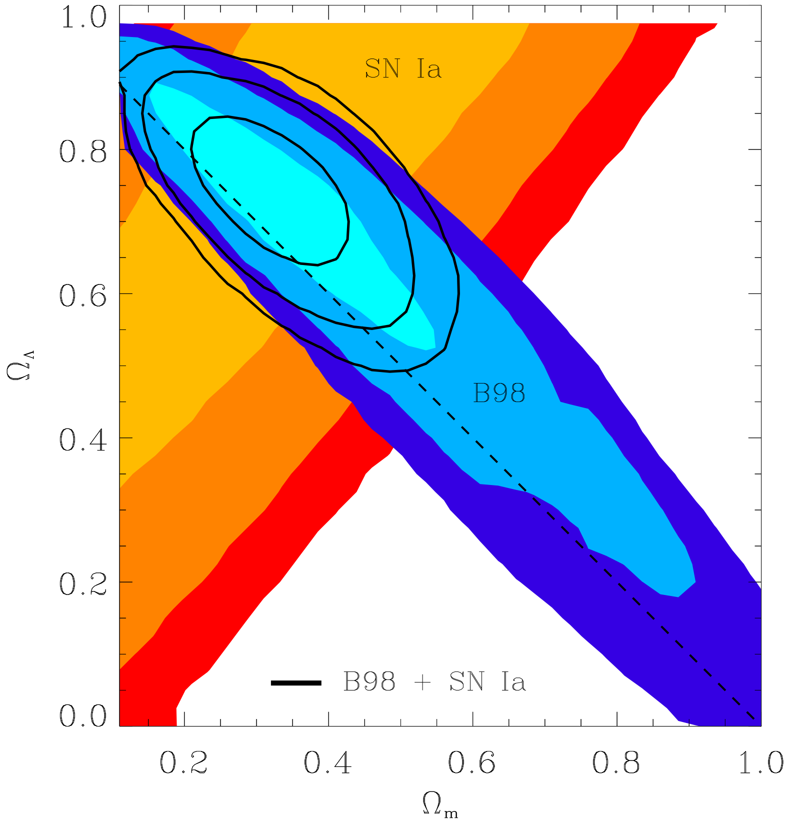
- There are numerous theories which can solve these problems, but no effects have been detected in collider experiments.

- Technological and economical constraints limit the energies that can be probed in terrestrial experiments.

- There are no limits on the energies accesible in the early Universe.

- It is possible that extensions of the Standard Model will leave some signature that is stable, and can be observed.

> Eg. Distortions of the nuclei abundance predicted by BBN, changes in the gamma ray background, stable relic particles...



-The most recent data gives

$$\Omega_M h^2 = 0.135 \pm 0.008 \qquad \Omega_b h^2 = 0.0224 \pm 0.0008$$

which results in a dark matter component

$$\Omega_{DM} h^2 = \Omega_M h^2 - \Omega_b h^2 = 0.113$$

- For the remaining energy, $\Omega_{DE} \approx 0.73$ and the equation of state is

$$\rho = wp \qquad -1 < w < -0.78$$

I. Dark Matter

- We propose to explore models with a single additional field, and simple interactions:
  * A scalar field with a Higgs coupling
  * A field with gravitational interactions in a warped background.

- We have shown that light dark matter can be probed in heavy particle decays, and will extend this to include several models

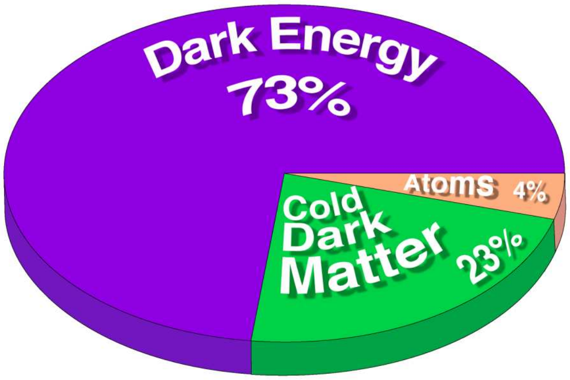
II. Luminous Matter as a Probe of New Physics

- We have already shown that the abundance of light nuclei can be use to place an upper bound on the size of extra dimensions

- We intend to use the $511 keV$ γ-ray flux to further constrain extra dimensions and models of light dark matter

III. Extra Dimensions

- We intend to develop general conditions under which extra dimensions can form and can be stable



Dark Matter

- Dark matter is measured through gravitational effects, which can determine abundances but not other properties

- Most research into dark matter has focused on four candidates:

(1) *Axions*

(2) *Sterile Neutrinos*

(3) *Neutralinos*

(4) *WIMPs* - A class of massive particles which have weak interactions. These particles have lifetimes comparable to the age of the Universe, and can thus be present in large abundance.

GeV and Sub-GeV WIMPs

- Dark matter candidates are usually assumed to have $M_{DM} \gtrsim 10\ GeV$ to prevent overabundance.
(Lee & Weinberg, 1977)

- DAMA has recently claimed a detection using dark matter nuclei scattering, while CDMS and other experiments have not

    - This is consistent with a WIMP with $M_{DM} < 10\ GeV$
    (Gelmini & Gondolo, 2004)

- Scalar dark matter can be even lighter, with $M_{DM} \lesssim 1\ GeV$
(Boehm & Fayet, 2003)

    - This also may explain the 511 keV flux from the galactic center

-The low mass range has not been well explored in theories or experiments, but could be probed in colliders.

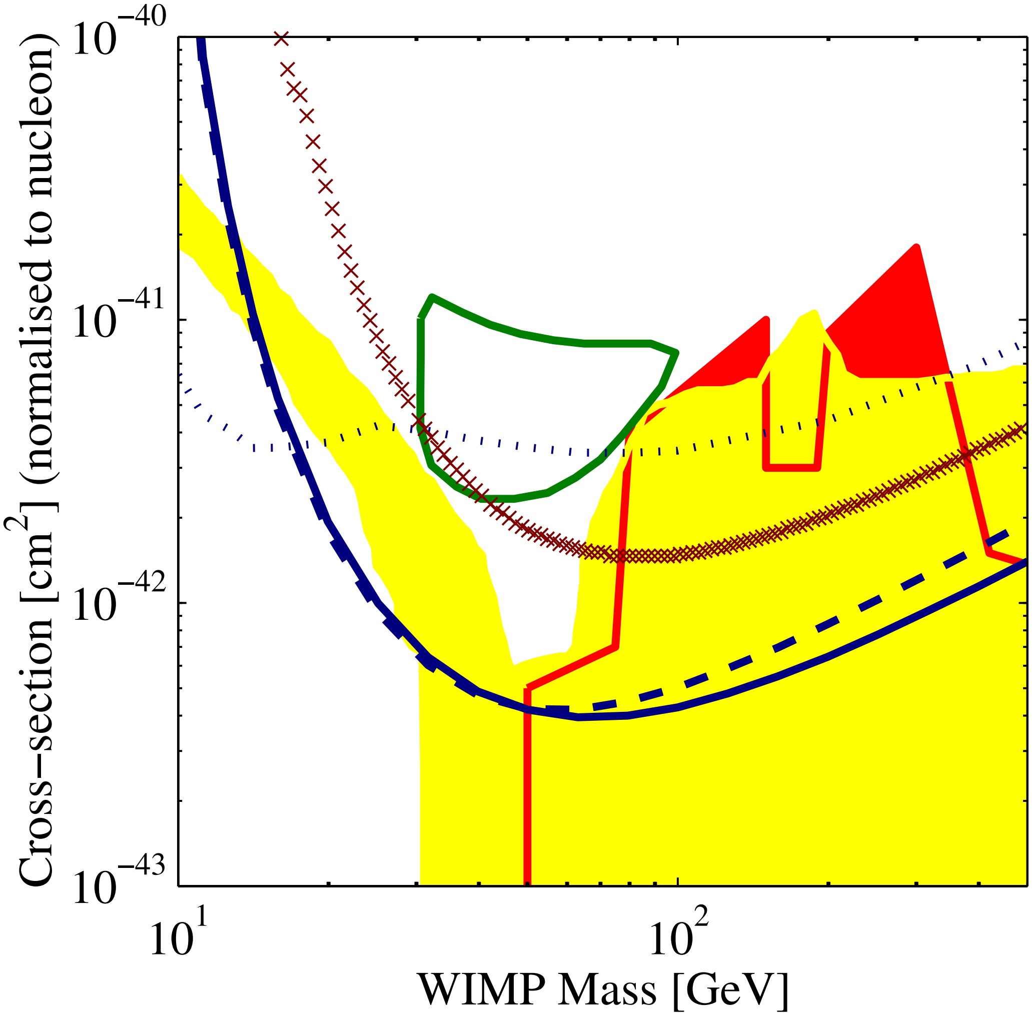


Figure 1: Results from CDMS, astro-ph/0405033

The Minimal Model of Dark Matter

- The minimum extension of the Standard Model is a single scalar, with Higgs interactions:

$$-L_S = \frac{1}{2} m_S^2 S^2 + \frac{\lambda_S}{4} S^4 + \lambda v_{EW} S^2 h + \frac{\lambda}{2} S^2 h^2$$

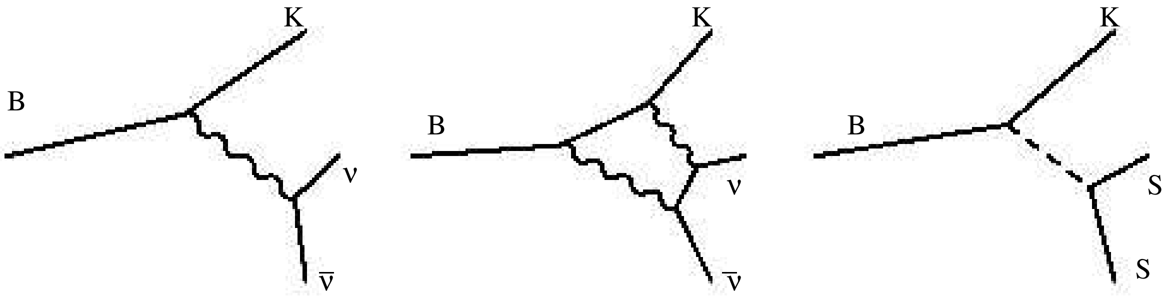
- In the minimal model, the important processes (WIMP annihilation, pair production, nuclei scattering) depend only on the two paramters m_S and $\kappa \equiv \lambda(100GeV/m_h)^2$.

- From WMAP observations, the annihilation cross section for dark matter must be

$$< \sigma_{ann} v/c > \approx 0.7pb$$

which can be used to fix one parameter of the model.

- This model has, in effect, only one free parameter (m_S)



Dark Matter in B-Decays (Bird, Jackson, Kowalewski, & Pospelov,hep-ph/0401195)

- The existence of light dark matter will increase the widths for heavy mesons decaying to missing energy.

-We have calculated the decay width for

$$B \to KSS$$

and shown that the increased decay width for B-mesons could be detected in the decay $B \to K$+missing energy.

$$BR_{B \to K+E} = 4 * 10^{-6} + 2.8 * 10^{-4} \kappa^2 F(m_S)$$

($0 < F(m_S) < 1$ is a measure of available phase space)

-For scalars with $m_S \sim 100 MeV$, $\kappa \sim 1$ and the decay rate is ~ 50 times larger than SM predictions

- Existing data from BaBar and CLEO restricts the allowed masses

- A similiar method can be applied to other dark matter models

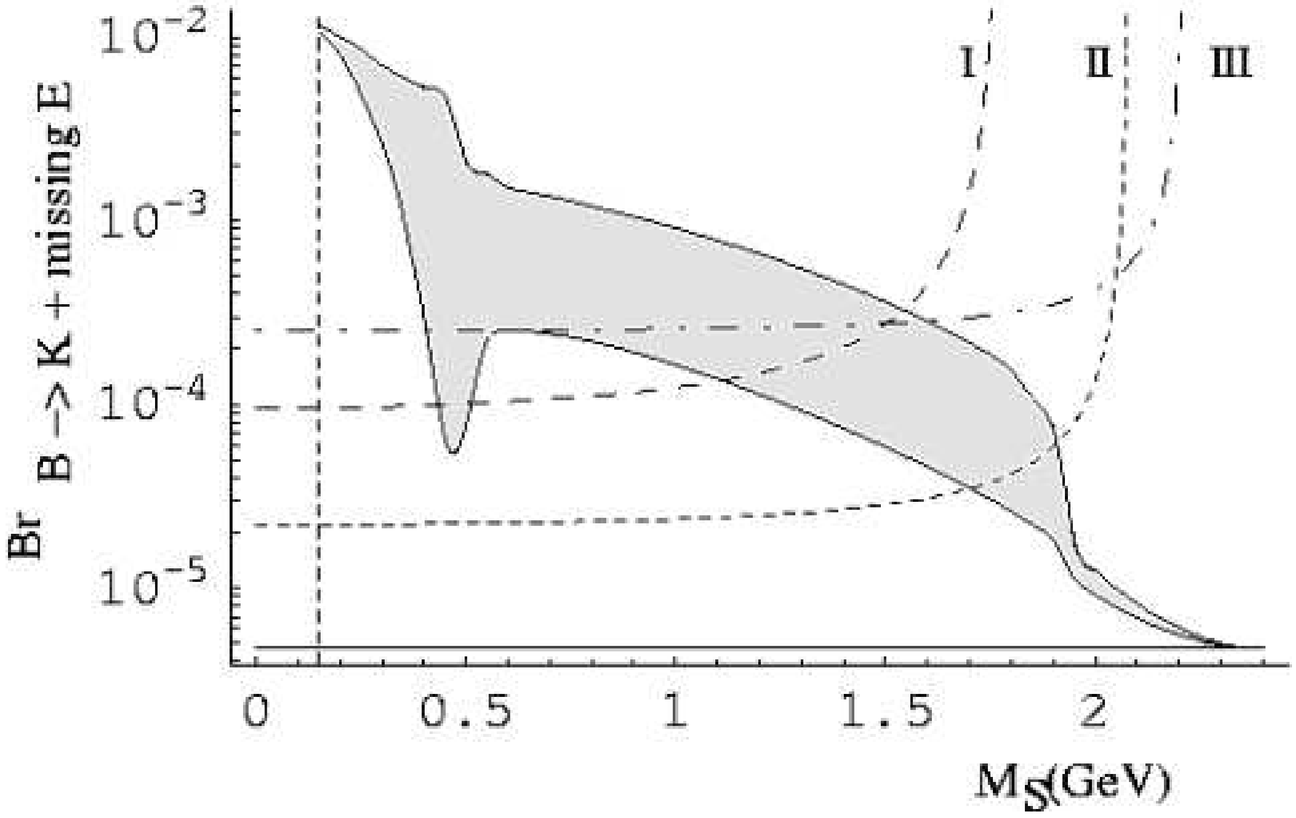


Figure 2: Predicted branching ratios for the decay $B \to K+$ *missing energy* with dark matter (shaded region) and with only SM neutrinos (solid line). Current limits from Babar (I), CLEO (III) and predicted results from BaBar (II) are also indicated. Masses less than $\sim 150\ MeV$ are excluded by kaon decays.

Luminous Matter as a Probe of New Physics

-New physics can have an effect on luminous matter as well

(1) Particle decays to gamma rays after $\sim 10^{12}$ s will contribute to the gamma ray background. Measurements by EGRET & COMPTEL restrict new physics.

- For extra dimensions, this gives a lower bound on the Planck mass and an upper limit on the size of the dimensions:

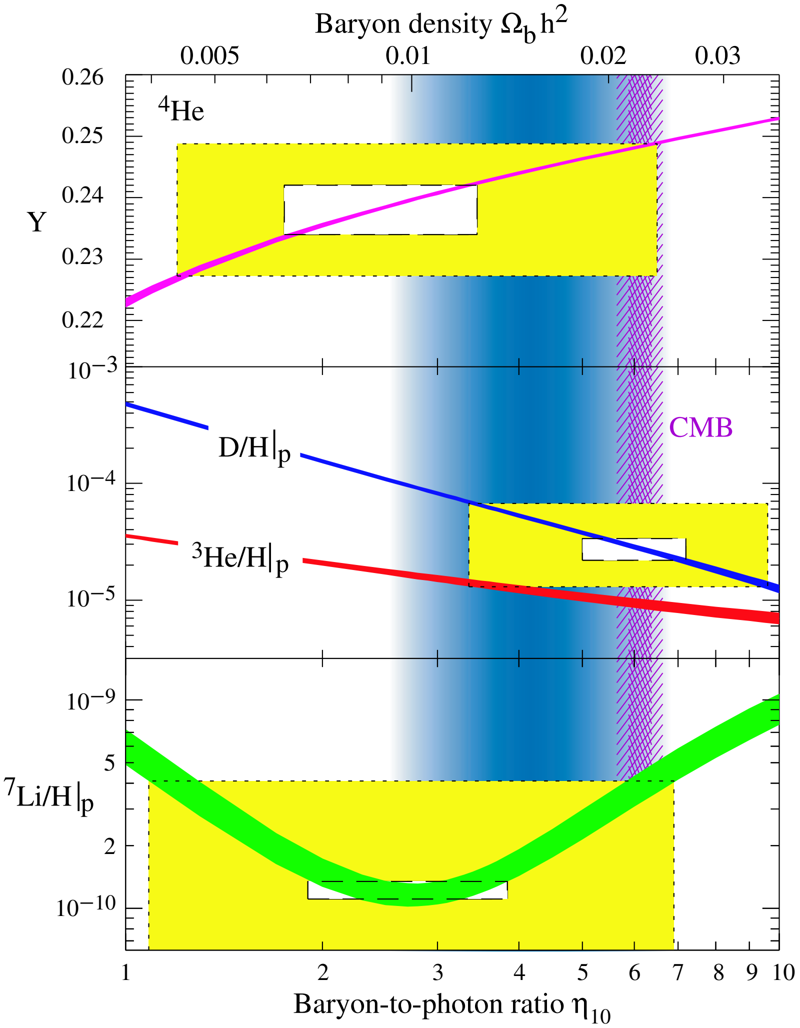
	$d = 2$	$d = 3$	$d = 4$	$d = 5$	$d = 6$
M_*	167 TeV	21.7 TeV	4.75 TeV	1.55 TeV	< 1 TeV
R	0.022 μm	2.5×10^{-5} μm	1.1×10^{-6} μm	1.7×10^{-7} μm	$> 2.9 \times 10^{-8}$ μm

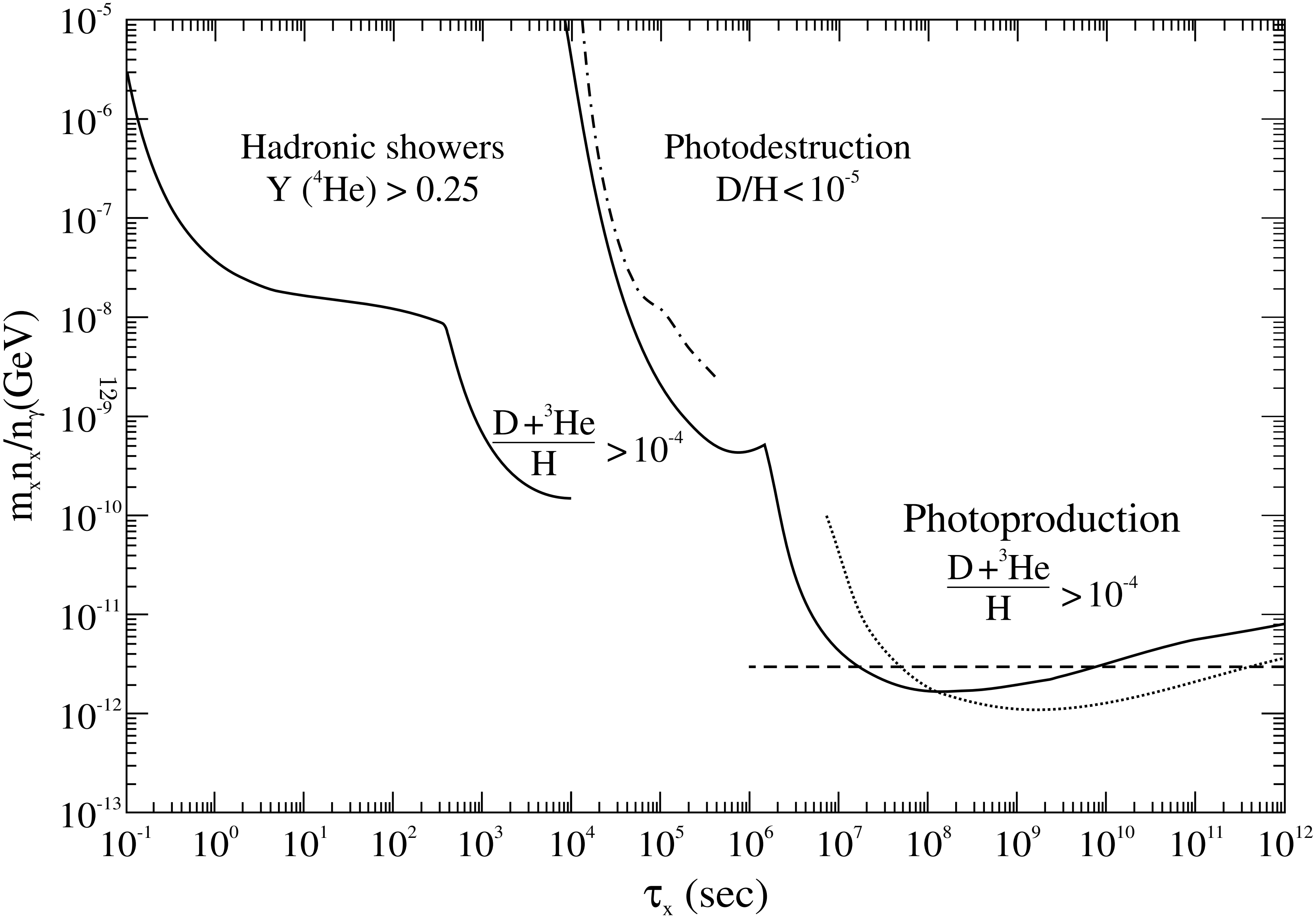
(2) The 511 keV gamma ray flux from the galactic center can be produced by annihilations or decays of new particles.

- This has been used to constrain models of sterile neutrinos (Picciotto & Pospelov, 2004)

-We intend to constrain other models of light dark matter and models of extra dimensions through KK mode decays

(3) New physics could also change the relative abundance of the nuclei in the Universe from BBN predictions.




Hadronic showers
Y (^{4}He) > 0.25
Photodestruction
D/H < 10^{-5}
$\frac{D+{}^3He}{H} > 10^{-4}$
Photoproduction
$\frac{D+{}^3He}{H} > 10^{-4}$
$m_x n_x/n_\gamma$(GeV)
τ_x (sec)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}

Applications to Models of Extra Dimensions (Allahverdi, Bird, Groot-Nibbelink, & Pospelov, hep-ph/0305010)

- We have used this method to place upper limits on the sizes of flat extra dimensions in inflationary cosmology.

- Inflation is usually driven by a new scalar field (the *inflaton*), which then decays to other particles

- In models with extra dimensions, this produces an abundance of KK modes with a wide range of masses

- Modes with masses $\lesssim 200 GeV$ will last long enough to distort the nuclei abundance predicted by BBN

$$\tau \approx 10^5 \text{ sec} \left(\frac{1 \text{ TeV}}{m_{KK}} \right)^3$$

-Uncertainties in the observed abundance of ${}^6Li$ provide limits on the size of the dimensions:

m_ϕ	$d = 2$	$d = 3$	$d = 4$	$d = 5$	$d = 6$
1 TeV	35 TeV $0.52 \mu m$	13 TeV $6.0 \times 10^{-5} \mu m$	7.1 TeV $5.9 \times 10^{-7} \mu m$	4.5 TeV $3.9 \times 10^{-8} \mu m$	2.8 TeV $7.4 \times 10^{-9} \mu m$
2 TeV	47 TeV $0.29 \mu m$	17 TeV $3.8 \times 10^{-5} \mu m$	9.1 TeV $4.1 \times 10^{-7} \mu m$	5.7 TeV $2.8 \times 10^{-8} \mu m$	3.4 TeV $5.7 \times 10^{-9} \mu m$
M_*	220 TeV $0.013 \mu m$	42 TeV $8.5 \times 10^{-6} \mu m$	15 TeV $1.9 \times 10^{-7} \mu m$	7.9 TeV $1.8 \times 10^{-8} \mu m$	4.0 TeV $4.6 \times 10^{-9} \mu m$

Extra Dimensions

- It has been known since 1914 that extra dimensions can be used to explain physical phenomena.

- Theories with extra dimensions can solve diverse problems such as the fermion hierarchy, dark matter, and nonsingular inflation.

- The most important use is in the *hierarchy problem.*
  * In the Standard Model, $M_{PL}/M_{EW} \approx 10^{16}$
  * The existence of extra dimensions would give an effective Planck mass

$$M_{PL} \approx M_*^{1+d/2} R^{d/2}$$

with $M_* \sim M_{EW}$.

- The Standard Model has been probed to very small distances, so the extra dimensions must either

(i)be small, $R \lesssim 10^{-16} cm$ (*Universal Extra Dimensions*),

(ii)or have all SM field trapped on a very thin brane (*Braneworlds*)

Unsolved Problems

-The size of the extra dimensions can be constrained using gravity experiments and astrophysics data.

- The number and topology of the extra dimensions have very few restrictions, even for flat dimensions.

- Any successful model must be stable against perturbations and must be quasi stable in time.

  - At present there are no general conditions which determine which models will be stable

- The extra dimensions form differently, as they clearly must have different properties.

  - It is possible that inflationary models could cause the extra dimensions to grow too large

- The conditions for stability and for compactification of extra dimensions provide constraints on possible models

Conclusions

- The Standard Model is incomplete

  -It does not explain dark matter or dark energy, which comprises $\sim 96\%$ of the energy density of the Universe, or gravity

-Collider experiments are limited as probes of new physics

- An alternative is to look for signs of new physics in the Early Universe.

- In the last two years we have completed two projects:

  (1) We have used limits on the abundance of nuclei to derive upper limits on the size of extra dimensions, leading to the strongest existing bounds on d=4,5,6.

  (2) We have shown how light dark matter can be probed in the decays of heavy mesons, and intend to extend this to other models.

- In the next two years we plan to:

  (1) Constrain extra dimensions and light dark matter using the 511 keV γ-ray flux

  (2) Develop models of dark matter in warped background

  (3) Develop general stability conditions for extra dimensions