Theory Workshop

Dark Matter and DUSEL

April 5, 2008 – Ohio State University
Our **audience:** Non-physics scientists, Congressmen, Senators

Our **goal:**

- Argue that the quest for **Dark Matter** is crucial for our understanding of the Universe
- Argue that **DUSEL** is fundamental to this quest
Direct Detection

- WIMP Direct Detection: **steady progress** in recent years

- If WIMPs are produced thermally we generically expect
  (“crossing symmetry” between pair annihilation and WIMP-nucleon scattering) **cross sections close to experimental sens.**

- Quantitatively, experiments are exploring the **parameter space** where theoretically well motivated WIMP models predict **signals**

- Several **uncertainties** in the experimental reach
  (e.g. s-content of nucleons, local DM density, DM velocity distribution, ...)


Direct Detection

- For a Majorana fermion, in the non-relativistic limit, the most general possible interaction with nuclei is a coherent spin-independent coupling ($\sim A^2$, the de Broglie wavelength of the momentum transfer is of nuclear dimensions) plus a spin-dependent coupling.

- In general, spin-independent scattering on large $A$ nuclei are favored.

- Models exist, however, where SD searches are more promising (cancellations, pure higgsinos or gaugino states, …)

- Main figure of merit: (WIMP mass; Cross Section with Nuclei)
Direct Detection as of 4/2008
Experimental Timeline

Several Exp. Techniques in advanced R&D phase

- Final target: reach the $10^{-46}$ cm$^2$ sensitivity level with ton-sized expt’s
- How does this compare with theoretical predictions?
Theoretical Predictions

- See Pran’s and Howie’s talks!
- Narrowing the theory landscape sets lower limits
Monte Carlo Markov Chain PS Scans

- Is this approach theoretically motivated?
- What are the theoretical “systematics”?
- Which prior probability distribution should one use?
- Which phenomenological constraints should be used?

Roszkowski et al, 2007

DUSEL 7400 and 4850 level!
Beyond SUSY: the case of UED
Beyond SUSY: the case of UED
Bottom Line: Theory Predictions

- Need for **ton-sized detectors**

- Although there are **loopholes** (cancellations, SuperWIMPs), the theory expectation is that there is a generic “**lower limit**” on the scattering of WIMP Dark Matter off nuclei

- Even in the absence of a signal, **non-detection** can yield dramatic discoveries and **implications**
  
  *(ruling out WIMP theories; ruling out the stability of candidate long-lived neutral particles discovered at the LHC, …)*
Role of DUSEL for Dark Matter Searches

Other underground laboratories exist

Why is **DUSEL** important - if not fundamental - for DM searches?

1. **Redundancy** with other facilities
2. Need for **Large Underground Laboratory Space**
   - Host multiple experimental setups
   - Spin Dependent searches
   - Go beyond the WIMP paradigm
   - Neutrinos from the Sun
3. Post-detection **WIMP astronomy** (see Paolo’s talk)
4. **A Center** for Theory
Redundancy with other facilities

- If a signal is detected anywhere in the world, one will need to confirm and reproduce the result.
- As the DAMA saga taught us, systematics and backgrounds are difficult to control in this field – and they may depend on environment: it will be essential to run experiments in more than one facility.

- It will be essential to also confirm the signal with multiple nuclear targets.
- Bottom line: more than one deep underground laboratory will be needed for direct detection.

Bernabei et al. 2007
Need for Space: A multi-pronged approach

- A statistically significant detection from one detector would require **confirmation** of (1) signal rate, (2) recoil spectral shape and (3) scaling with nuclear number.

- Present technology has this capability built into it via the use of **several target materials** (e.g., Ge, Si, Ne, Ar, Xe and CF$_3$I).

- Combinations of experiments based on these materials could provide **essential information**, including (1) measure of X-sec, (2) its A dependence, (3) from the shape of the latter, an estimate of the WIMP mass.

- Any claim of **periodicity** (day-night and/or seasonal) will benefit from simultaneous operation of two or more detectors.
Need for Space: Spin Dependent Searches

- Even if disfavored in vanilla models, a **SD WIMP-nucleon** program is essential, and will be possible if enough space is available.
- WIMP models exist where **SD is more competitive** than SI.
- **Complementary information** – greater understanding in case of 2 det’s.

Bertone et al, 2007
Need for Space: Spin Dependent Searches

- **Discrimination** between WIMP scenarios (here, SUSY & UED)
- Importance of having experiments with various nuclei
  (beyond the importance of testing the SI $A^2$ coherence effect)

Bertone et al, 2007, on the COUPP experiment
The Dark Matter need not be a weak-scale particle
Having a large deep underground laboratory would allow to pursue experiments looking for particles beyond vanilla WIMP models
For instance, current experiments are not sensitive to sub-GeV (or even only sub 10-GeV) particles
A worked out example of supersymmetric models featuring super light neutralinos
Hunting the Lightest Lightest Neutralino

- The MSSM neutralino can be massless

\[
\text{det} (M_{\text{neut}}) = 0
\]

- "Split-SUSY" limit:

\[
M_1 \to 0, \ \mu \to \infty
\]

- A massless neutralino is consistent with collider data as long as its coupling to the Z is sufficiently suppressed

- Extrapolating a radiation dominated Universe prior to BBN

\[m_\chi \geq 6 \text{ GeV}\] (Lee-Weinberg limit for neutralinos)

Bottino et al., Belanger et al., Hooper & Plehn
The Lightest Lightest Neutralino

- Relaxing the assumption of radiation domination (no data prior to BBN!), arbitrarily high thermal relic neutralino abundances can be brought down to the CDM density (*). [low reheating models, late decaying species with entropy injection]

- Large scale structure data (Ly-α) and CMB anisotropies force (**) 
  \[ m_\chi \geq O(\text{keV}) \] (precise number depends on data sets and production mech.)

- Can we detect sub-GeV neutralinos?

(*) Gondolo and Gelmini, 2006; (**) Viel et al., 2005, Seljak et al, 2005
Hunting the Lightest Lightest Neutralino

- 1 MeV or 1 GeV makes no difference for LHC signatures…

- **Indirect** searches:
  \[ \chi \chi \rightarrow \gamma \gamma \]

- Hope for GLAST and future X-Ray telescopes

Profumo, 2008, in prep.
Hunting the Lightest Lightest Neutralino

- Direct Detection: designed for larger masses...

- Spin Dep.: no differences from SUSY spectrum
- Spin Dep.: very promising improvements (COUPP)
- Spin Indep.: focus also on lighter masses!!
- Spin Indep.: lighter nuclei: loose on coherence effect, but gain in sensitivity at low masses
Neutrinos from the Sun

• Search for **energetic neutrinos** produced in $\chi\chi$ pair **annihilations** in the core of nearby gravitational dips, as the center of the Sun

• **Neutrino telescopes**: rates only mildly dependent on details of DM halo profile (unlike $\gamma$-rays, antimatter…)

*Super-K*  

*IceCube*
Neutrinos from the Sun

![Graph showing the relationship between the SD pure proton cross section and WIMP mass. The graph includes data points for Xenon 10 and SuperK limit, with a shaded area representing the SUSY region.]
Neutrinos from the Sun

- Use the proton decay search facility to look for energetic $\nu$'s from the Sun or from the Earth
- Lower threshold than IceCube, competitive experiment
- Complementary to SD and SI searches
WIMP Astronomy

- See Paolo’s talk
- Carrying out post-detection WIMP astronomy will require huge statistics
- Assuming detection, what are the requirements to say something about the WIMP velocity distribution?
- What is the role of directional-sensitive detectors?

Drees et al, 2007
More on why DUSEL is good for theorists

- A laboratory always yields very fruitful **interactions** among theorists and between theorists and experimentalists

- Having a US center for DM direct detection would allow e.g.:
  - Organization of **Theory Workshops**
  - Yearly **executive summaries** of theoretical progress for experimentalists and of exp. progress for theorists

- In the era of large direct detection collaborations, it will be **strategic** to have such a laboratory in the US
Why we believe DUSEL is vital to DM searches

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3. Post-detection **WIMP astronomy**
4. A **Center** for Theory