Inelastic Dark Matter and DAMA/Libra: An *Experimentum Crucis*

Tongyan Lin

w/ Doug Finkbeiner, Neal Weiner 0906.0002
Direct detection of dark matter

- Velocity $\sim 220$ km/s, $10^3$
- Energy $\sim 100$ keV (if WIMPs)
Spin-independent scattering

\[
\frac{dR}{dE_R d \cos \gamma} = N_T \frac{\rho_X}{m_\chi} \int d^3v \, v \, f(\vec{v} + \vec{v}_E) \frac{d\sigma}{dE_R d \cos \gamma} F^2(E_R)
\]

- Local dark matter density \(0.3 \text{ GeV/cm}^3\)
- Local dark matter velocity distribution
- Scattering cross section
- Nuclear form factor
DAMA

- NaI scintillator
- 260,000 kg day
DAMA Spectrum

$S_m$ (cpd/kg/keV)

Energy (keV)
Constraints from other direct detection experiments?

DATA listed top to bottom on plot
CDMS (Soudan) 2005 Si (7 keV threshold)
Edelweiss I final limit, 62 kg-days Ge 2000+2002+2003 limit
WARP 2.3L 96.5 kg-days 55 keV threshold
DAMA/LIBRA 2008 5sigma, no ion channeling
ZEPLIN II (Jan 2007) result
CRESST 2007 60 kg-day CaWO4
CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
ZEPLIN III (yr 1) Proj. Sens.
ZEPLIN III (Dec 2008) result
CDMS: 2004+2005 (reanalysis) +2008 Ge
XENON10 2007 (Net 136 kg-d)
XENON100 projected sensitivity: 6000 kg-d, 5-30 keV, 45% eff.
LUX 300 kg LXe Projection (Jul 2007)
09081-060901
Explanations of DAMA?

- Dark Matter
  - Inelastic dark matter
  - Light dark matter (channeling)
  - DM-Electron scattering

- Systematics
  - Bananas
  - ??

- Other??
Inelastic Dark Matter

\[ \beta_{\text{min}} = \sqrt{\frac{1}{2m_N E_R}} \left( \frac{m_N E_R}{\mu} + \delta \right), \]

\[ m_{\chi^*} = m_\chi + \delta \]

Models of iDM?
- Composite States
- Neutrinos/Sneutrinos
- Neal's talk tomorrow?
- ...
Inelastic Dark Matter

- Enhanced annual modulation
- Scattering off heavy nuclei preferred
- Low energy recoil events suppressed

\[
\frac{dR}{dE_R d\cos \gamma} = N_T \frac{\rho_X}{m_\chi} \int d^3v \; v \; f(\vec{v} + \vec{v}_E) \frac{d\sigma}{dE_R d\cos \gamma} F^2(E_R)
\]

- Local dark matter density
- Local dark matter velocity distribution
- Scattering cross section
- Nuclear form factor

![Graph showing function behavior](image-url)
Inelastic dark matter & DAMA

\[ \delta \sim 120 \text{ keV} \]
Inelastic dark matter & DAMA

\[ m_\chi = 150 \text{ GeV} \]
Inelastic Dark Matter Benchmarks

- Uncertainties
  - Halo model
  - Astro parameters
  - Form factors
  - Quenching factors

<table>
<thead>
<tr>
<th>#</th>
<th>$m_\chi$ (GeV)</th>
<th>$\sigma_n$ ($10^{-40}$ cm$^2$)</th>
<th>$\delta$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>11.85</td>
<td>119</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>5.75</td>
<td>123</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>3.63</td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>2.92</td>
<td>126</td>
</tr>
<tr>
<td>5</td>
<td>180</td>
<td>2.67</td>
<td>126</td>
</tr>
<tr>
<td>6</td>
<td>250</td>
<td>2.62</td>
<td>127</td>
</tr>
</tbody>
</table>
Directional Detection

- Advantages
  - Daily modulation
  - Sidereal day – out of phase with solar day
  - Enhanced modulation
Directional Detection / DM-TPC
Directional Detection / DM-TPC

Recoil Track Length

\[ e^- \quad \alpha \quad C \quad F \]

\[ E \text{ (keV)} \]

\[ dE/dx \]

15.5 cm

100 Torr

500

300

200

100

0

0

500

1000

Range (mm)

15.5 cm
Spectrum (in angle/energy) for elastic dark matter

\[ M_\chi = 150 \text{ GeV} \quad \delta = 0 \text{ keV} \quad v_0 = 220 \text{ km/s} \]

Scattering angle relative to earth velocity

Nuclear Recoil Energy
Spectrum for inelastic dark matter

Scattering angle relative to earth velocity

Nuclear Recoil Energy
Directional Detection

- Advantages
  - Daily modulation
  - Sidereal day – out of phase with solar day
  - Enhanced modulation

- Advantages for inelastic dark matter
  - Even more enhanced modulation
  - Enhanced cross section at higher energies
Exposure to achieve 3$\sigma$ result 95% of the time

\[ E_R = [50,80] \text{ keV}, \text{ angular resolution 15 degrees} \]
\[ V_e = 225 \text{ km/s}, \ v_{esc} = 500 \text{ km/s} \]
Lowering the energy threshold is more important than improving angular resolution.
Parameter Estimation from 1000 kg day

\[ \log \left( \frac{m}{\sigma} \right) \]

FIG. 9: Confidence levels for determining \( \delta \) and \( m_\chi/\sigma_n \), where \( m_\chi \) is unknown, with an exposure of 1000 kg \cdot day, taking \( \sigma_0 = 10^{-40} \text{ cm}^2 \). Over most of the parameter space, some value of \( m_\chi \) (and therefore \( \sigma_n \)) can be found to produce enough events for the given \( \delta \). However, in the case of large \( \delta \) and large \( m_\chi/\sigma_n \), no solution is possible in some cases.
Conclusions

- **iDM can explain DAMA and other experiments**
  - Mass $\sim 100$-$1000$ GeV, $\delta \sim 120$ keV
- DAMA+iDM will be tested by LUX, XENON, etc, very soon
- **Direct Detection**
  - Daily modulation
  - Enhanced modulation
  - if DAMA/iDM is correct, clear signal of WIMP detection with few hundred, $\sim 1000$ kg day
Exposure to achieve $3\sigma$ result 95% of the time

- WINTER:
  - ~40 WIMP events, ~150 Background
  - ~11 events

- SUMMER:
  - ~16 WIMP events, ~6 Background
  - ~40 WIMP events, ~140 Background