Can the DAMA/LIBRA annual modulation signal be explained by Dark Matter?

Thomas Schwetz
Dark Matter in a Milkyway-like Galaxy

Via Lactea N-body DM simulation Diemand, Kuhlen, Madau, astro-ph/0611370
"standard halo model": Maxwellian velocity distribution

$$f_{\text{gal}}(\vec{v}) \approx \begin{cases} \frac{N}{\sqrt{2\pi}} \exp \left( -\frac{v^2}{\bar{v}^2} \right) & v < v_{\text{esc}} \\ 0 & v > v_{\text{esc}} \end{cases}$$

with $\bar{v} \approx 220$ km/s and $v_{\text{esc}} \approx 650$ km/s
DM direct detection

Look for recoil of DM-nucleus scattering:

\[ \chi + N \rightarrow \chi + N \]

cnts / keV recoil energy \( E_R \):

\[
\frac{dN}{dE_R}(t) \propto \frac{\rho_\chi}{m_\chi} \int_{v>v_{\text{min}}} d^3v \frac{d\sigma}{dE_R} \, v \, f_\oplus(\vec{v}, t)
\]

- \( \rho_\chi \): DM energy density, default: 0.3 GeV cm\(^{-3}\)
- \( v_{\text{min}} \): minimal DM velocity required to produce recoil energy \( E_R \)

ex.: SI scattering:

\[ v_{\text{min}} = \sqrt{\frac{M E_R}{2 \mu_\chi^2}} \]
Annual modulation

\[ f_{\oplus}(\vec{v}, t) = f_{\text{gal}}(\vec{v} + \vec{v}_\odot + \vec{v}_{\oplus}(t)) \]

sun velocity: \[ \vec{v}_\odot = (0, 220, 0) + (10, 13, 7) \text{ km/s} \]
earth velocity: \[ \vec{v}_{\oplus}(t) \text{ with } v_{\oplus} \approx 30 \text{ km/s} \]
Annual modulation

\[ f_\oplus (\vec{v}, t) = f_{\text{gal}} (\vec{v} + \vec{v}_\odot + \vec{v}_\oplus (t)) \]

sun velocity: \( \vec{v}_\odot = (0, 220, 0) + (10, 13, 7) \text{ km/s} \)

earth velocity: \( \vec{v}_\oplus (t) \) with \( v_\oplus \approx 30 \text{ km/s} \)

annual modulation is a few % effect
DAMA/LIBRA results
DAMA/LIBRA annual modulation signal

Scintillation light in NaI detector, 0.82 t yr exposure

\[ \sim 1 \text{ cnts/d/kg/keV} \rightarrow \sim 2 \times 10^5 \text{ events/keV in DAMA/LIBRA} \]

8.2\( \sigma \) evidence for an annual modulation of the count rate with maximum at day \( 144 \pm 8 \) (June 2nd: 152)

---

2-6 keV

<table>
<thead>
<tr>
<th>Time (day)</th>
<th>Residuals (cpd/kg/keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>3500</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>4500</td>
<td></td>
</tr>
</tbody>
</table>

Bernabei et al., 0804.2741
Energy dependence of the modulation signal

Modulation signal at 2 – 6 keV above 6 keV consistent with no modulation
Can this be explained by DM?
Can this be explained by DM?

- Yes, the DAMA signal can be explained, spin-independent, spin-dependent, inelastic scattering, …

- but it is difficult to reconcile it with constraints from other experiments.
DAMA and spin-indep. elast. scattering

Fairbairn, Schwetz, 0808.0704
DAMA and spin-indep. elast. scattering

- Best fit: $m_{\chi} = 12$ GeV, $\chi^2_{\text{min}} = 36.8 / 34$ dof
- Local minimum: $m_{\chi} = 51$ GeV, $\chi^2_{\text{min}} = 47.9 / 34$ dof ($\Delta\chi^2 = 11.1$)

Energy shape of the modulation is important

Chang, Pierce, Weiner, 0808.0196
Fairbairn, TS, 0808.0704

Not included e.g., in

Gondolo, Gelmini, hep-ph/0504010
Petriello, Zurek, 0806.3989

(Only two bins: 2-6 keV and 6-14 keV)
Energy spectrum of the modulation

- 12 GeV, 1.3e-41 cm$^2$
- 51 GeV, 7.8e-42 cm$^2$
- 6 GeV, 2.8e-41 cm$^2$
DAMA and spin-indep. elast. scattering

90%, 99.73% CL (2 dof)

best fit: $m_\chi = 12$ GeV
$\chi^2_{\text{min}} = 36.8 / 34$ dof

local minimum: $m_\chi = 51$ GeV
$\chi^2_{\text{min}} = 47.9 / 34$ dof ($\Delta \chi^2 = 11.1$)

prediction for total rate must not exceed the observed number of events

Chang, Pierce, Weiner, 0808.0196
Fairbairn, TS, 0808.0704
Prediction for total rate

\[ R(E_R) = B(E_R) + R_{\text{DM}}(E_R; m_\chi, \sigma_p) + A(E_R; m_\chi, \sigma_p) \cos \omega(t - t_0) \]

in a given model \( R_{\text{DM}} \) and \( A \) are not independent
Constraints from other experiments

- **CDMS:**

<table>
<thead>
<tr>
<th></th>
<th>exposure</th>
<th>threshold</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDMS-Si (2005)</td>
<td>12 kg day</td>
<td>7 keV</td>
<td>26 GeV</td>
</tr>
<tr>
<td>CDMS-Ge (2008)</td>
<td>121.3 kg day</td>
<td>10 keV</td>
<td>67 GeV</td>
</tr>
</tbody>
</table>

Both CDMS-Si and CDMS-Ge observe zero events

- **XENON10:**

7 bins from 4.6 to 26.9 keV, 316 kg day exposure
10 candidate events: (1, 0, 0, 0, 3, 2, 4)
DAMA vs CDMS/XENON

DAMA 90% CL region excluded by 90% CL XENON, CDMS bounds

\[ \chi^2_{\text{min, glob}} = \frac{59.3}{45 - 2} \]

(P \approx 5\%)

consistency check:

\[ P_{PG} = 1.2 \times 10^{-5} \]
The Channeling effect

Quenching:
DAMA observes scintillation light ⇒ measures energy in “electron equivalent” (keVee) only a fraction $q$ of nuclear recoil energy $E_R$ is observable as scintillation signal in DAMA:

$$E_{\text{obs}} = q \times E_R$$

with $q_{\text{Na}} = 0.3$, $q_{\text{I}} = 0.09$

⇒ the energy threshold of 2 keVee implies a threshold in $E_R$ of 6.7 keV for Na and 22 keV for I.
The Channeling effect

Drobyshevski, 0706.3095; Bernabei et al., 0710.0288

with a certain probability a recoiling nucleus will not interact with the crystal but loose its energy only electro-magnetically for such “channeled” events $q \approx 1$
The Channeling effect

fraction of nuclear recoil events with $q \approx 1$

Bernabei et al., 0710.0288

channeling is important for low energy recoils
Channeling is very relevant

\[
\begin{align*}
10^1 & \quad 10^2 & \quad 10^3 & \quad 10^4 \\
10^{-39} & \quad 10^{-40} & \quad 10^{-41} & \quad 10^{-42}
\end{align*}
\]

\[
\begin{align*}
m_\chi \text{ [GeV]} & \\
1 & \quad 10 & \quad 100
\end{align*}
\]

90\%, 99.73\% CL (2 dof)

DAMA

CDMS-Ge

CoGeNT

no channeling

DAMA

CDMS-Si

XENON
Beyond spin-independent elastic DM scattering

- spin-dependent scattering
- inelastic scattering
- DM scattering only on electrons
in general there is a spin-independent and spin-dependent contribution to the DM nucleon scattering cross section:

\[ \sigma = \sigma_{\text{SI}} + \sigma_{\text{SD}} \]

with

\[ \sigma_{\text{SI}} = \sigma_p \left( \frac{\mu_\chi}{\mu_p} \right)^2 A^2 |F(q)|^2 \rightarrow A^2\text{-enhancement} \]

\[ \sigma_{\text{SD}} = \frac{32 \mu_\chi^2 G_F^2}{2J + 1} \left[ a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q) \right] \]

\[ a_p, a_n : \text{ couplings to proton and neutron} \]
 \[ S_{pp}(q), S_{pn}(q), S_{nn}(q) : \text{ nuclear structure functions} \]
Spin-dependent scattering

coupling mainly to an un-paired nucleon:

<table>
<thead>
<tr>
<th></th>
<th>neutron</th>
<th>proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}_{11}\text{Na}$</td>
<td>even</td>
<td>odd</td>
</tr>
<tr>
<td>$^{127}_{53}\text{I}$</td>
<td>even</td>
<td>odd</td>
</tr>
<tr>
<td>$^{129}<em>{54}\text{Xe}$, $^{131}</em>{54}\text{Xe}$</td>
<td>odd</td>
<td>even</td>
</tr>
<tr>
<td>$^{73}_{32}\text{Ge}$</td>
<td>odd</td>
<td>even</td>
</tr>
</tbody>
</table>

coupling with proton promising for DAMA vs CDMS/XENON

**BUT:** severe bounds from other experiments

(\text{COUPP, KIMS, PICASSO})
Spin-dependent scattering

coupling mainly to an un-paired nucleon:

<table>
<thead>
<tr>
<th></th>
<th>neutron</th>
<th>proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}_{11}$Na</td>
<td>even</td>
<td>odd</td>
</tr>
<tr>
<td>$^{127}_{53}$I</td>
<td>even</td>
<td>odd</td>
</tr>
<tr>
<td>$^{129}<em>{54}$Xe, $^{131}</em>{54}$Xe</td>
<td>odd</td>
<td>even</td>
</tr>
<tr>
<td>$^{73}_{32}$Ge</td>
<td>odd</td>
<td>even</td>
</tr>
</tbody>
</table>

coupling with proton promising for DAMA vs CDMS/XENON

BUT: strong constraint from Super-Kamiokande / IceCube bounds on neutrinos from DM annihilations in the sun

Savage, Gelmini, Gondolo, Freese, 0808.3607
Hooper, Petriello, Zurek, Kamionkowski, 0808.2464
SD scattering: proton-only coupling

S. Archambault et al., 0907.0307
Inelastic DM scattering


• in addition to the DM $\chi$ there exists an excited state $\chi^*$, with a mass splitting

\[ m_{\chi^*} - m_\chi = \delta \simeq 100 \text{ keV} \sim 10^{-6} m_\chi \]

• elastic scattering $\chi + N \rightarrow \chi + N$ is suppressed with respect to inelastic scattering

\[ \chi + N \rightarrow \chi^* + N \]
Inelastic DM scattering

\[ v_{\text{min}}^{\text{inel}} = \frac{1}{\sqrt{2} M_E R} \left( \frac{M_E R}{\mu \chi} + \delta \right) \]

\[ v_{\text{min}}^{\text{el}} = \sqrt{\frac{M_E R}{2} \frac{1}{\mu \chi}} \]

- sampling only high-velocity tail of velocity distribution
- no events at low recoil energies
- targets with high mass are favoured

\( m_\chi = 120 \text{ GeV}, \delta = 100 \text{ keV} \)
Inelastic DM scattering

Chang, Kribs, Tucker-Smith, Weiner, 0807.2250

### Table I

<table>
<thead>
<tr>
<th>#</th>
<th>$m_X$ (GeV)</th>
<th>$\sigma_n$ ($10^{-40}$ cm$^2$)</th>
<th>$\delta$ (keV)</th>
<th>DAMA 2-6 keV</th>
<th>XENON 5.5-45 keV</th>
<th>CDMS 10-100 keV</th>
<th>ZEPLIN 5-20 keV</th>
<th>KIMS 3-8 keV</th>
<th>CRESST 12-60 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>expt</td>
<td></td>
<td></td>
<td></td>
<td>(counts)</td>
<td>(counts)</td>
<td>(counts)</td>
<td>(counts)</td>
<td>(counts)</td>
<td>(counts)</td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>11.85</td>
<td>119</td>
<td>0.93</td>
<td>1.39</td>
<td>0</td>
<td>8.81</td>
<td>0.77</td>
<td>8.92</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>5.75</td>
<td>123</td>
<td>1.25</td>
<td>5.52</td>
<td>0</td>
<td>14.87</td>
<td>1.62</td>
<td>9.38</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>3.63</td>
<td>125</td>
<td>1.24</td>
<td>9.06</td>
<td>0.26</td>
<td>18.61</td>
<td>2.27</td>
<td>9.64</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>2.92</td>
<td>126</td>
<td>1.21</td>
<td>11.17</td>
<td>1.19</td>
<td>20.55</td>
<td>2.63</td>
<td>9.82</td>
</tr>
<tr>
<td>5</td>
<td>180</td>
<td>2.67</td>
<td>126</td>
<td>1.18</td>
<td>12.46</td>
<td>2.22</td>
<td>21.09</td>
<td>2.85</td>
<td>9.93</td>
</tr>
<tr>
<td>6</td>
<td>250</td>
<td>2.62</td>
<td>127</td>
<td>1.14</td>
<td>14.01</td>
<td>3.95</td>
<td>23.03</td>
<td>3.12</td>
<td>10.02</td>
</tr>
</tbody>
</table>

TABLE I: Parameter values and predicted experimental signals for $v_{\text{esc}} = 500$ km/s. Note that 1 dru = 1 cpd/kg/keV. In the second row, experimental observed rates and number of events are given. These counts listed are without any background subtraction. In parentheses are the 90% Poisson confidence upper limits on the expected number of signal events.

**XENON, ZEPLIN, and CRESST have seen already DM!**
Inelastic DM scattering

quenched events

Schmidt-Hoberg, Winkler, 0907.3940
Inelastic DM scattering

channeled events

Schmidt-Hoberg, Winkler, 0907.3940
DM scattering off electrons

• DAMA looks for the annual modulation of their (relat. large) count rate from scintillation light
  ⇒ pure electron events fully contribute

• CDMS, XENON10, CRESST, KIMS, ZEPLIN, . . . reject electron events to perform a low background search for nuclear recoils.
DM scattering off electrons

- DAMA looks for the annual modulation of their (relat. large) count rate from scintillation light ⇒ pure electron events fully contribute

- CDMS, XENON10, CRESST, KIMS, ZEPLIN,... reject electron events to perform a low background search for nuclear recoils.

- PAMELA, ATIC, FERMI see an anomaly in cosmic electrons/positrons, but not in anti-protons ⇒ Has DM a special affinity to leptons?

- simple model for “leptophilic DM” Fox, Poppitz, 0811.0399
DM scattering off electrons

DM scattering off electrons at rest: recoils of order $m_e v^2 \sim eV$ cannot account for the DAMA signal at few keV

⇒ bound electrons with $p \sim $ MeV, Bernabei et al., 0712.0562

wave function suppression of count rate $\sim 10^{-6}$
Loop induced DM-nucleus scattering

suppose an effective interaction of DM with electrons:

this will induce DM-nucleus interactions at loop level:

Kopp, Niro, Schwetz, Zupan, 0907.3159
count rate $R$:

DM-electron: \[ R_e \propto m_e \epsilon_{WF} \]

DM-nucleus @ $n$-loop: \[ R_N^{(n)} \propto m_N (\alpha Z / \pi)^{2n} \]

\[ \Rightarrow \quad R_e : R_N^{(n)} \sim 10^{-10} : 1 \]

Whenever loop-induced DM-nucleon scattering is present it will dominate over scattering off electrons (at 1 and 2-loop)
Electron vs Loop scattering

Have to forbid loop diagrams!

example: fermionic DM with axial-vector coupling

\[ \mathcal{L}_{\text{eff}} = G \left( \bar{\chi} \gamma_\mu \gamma_5 \chi \right) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right) \]

with

\[ G = \frac{1}{\Lambda^2} \]
Axial coupling without loop

Best fit prediction for the modulated and unmodulated spectrum in DAMA from DM-electron scattering

⇒ disfavoured by spectral shape and constraint from unmodulated event rate
Axial coupling without loop

very “large” cross sec: \( \sigma^{0}_{\chi e} \sim 10^{-31} \text{ cm}^2 \times \left( \frac{m_{\chi}}{100 \text{ GeV}} \right) \)

requires \( \Lambda \lesssim 0.1 \text{ GeV} \)
Axial coupling without loop

Kopp, Niro, Schwetz, Zupan, 0907.3159

excluded by SuperK constraints on neutrinos from DM annihilations in the sun
Concluding remarks
Concluding remarks

• DAMA observes an annual modulation of their count rate at a significance of $8.2\sigma$. The phase is in agreement with DM scattering.
Concluding remarks

- DAMA observes an annual modulation of their count rate at a significance of 8.2σ. The phase is in agreement with DM scattering.

- An interpretation of this signal in terms of SI elastic DM scattering is in conflict with bounds from XENON and CDMS at the level of 3σ.
Concluding remarks

• DAMA observes an annual modulation of their count rate at a significance of 8.2σ. The phase is in agreement with DM scattering.

• An interpretation of this signal in terms of SI elastic DM scattering is in conflict with bounds from XENON and CDMS at the level of 3σ.

• To my knowledge, so-far no convincing model which works “out of the box”
Concluding remarks

• DAMA observes an **annual modulation** of their count rate at a significance of 8.2\(\sigma\). The phase is in agreement with DM scattering.

• An interpretation of this signal in terms of SI elastic DM scattering is **in conflict with bounds from XENON and CDMS** at the level of 3\(\sigma\).

• To my knowledge, so-far **no convincing model** which works “out of the box”

• In some cases the problems in the fit depend on
  - exper. subtleties (channeling, energy scale/threshold)
  - assumptions on the DM halo model
Additional slides
The DAMA annual modulation signal

fitting count rate with $S_0 + A \cos \omega(t - t_0)$:

<table>
<thead>
<tr>
<th></th>
<th>$A \text{ (cpd/kg/keV)}$</th>
<th>$T = \frac{2\pi}{\omega} \text{ (yr)}$</th>
<th>$t_0 \text{ (day)}$</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DAMA/NaI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2–4) keV</td>
<td>0.0252 ± 0.0050</td>
<td>1.01 ± 0.02</td>
<td>125 ± 30</td>
<td>5.0σ</td>
</tr>
<tr>
<td>(2–5) keV</td>
<td>0.0215 ± 0.0039</td>
<td>1.01 ± 0.02</td>
<td>140 ± 30</td>
<td>5.5σ</td>
</tr>
<tr>
<td>(2–6) keV</td>
<td>0.0200 ± 0.0032</td>
<td>1.00 ± 0.01</td>
<td>140 ± 22</td>
<td>6.3σ</td>
</tr>
<tr>
<td><strong>DAMA/LIBRA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2–4) keV</td>
<td>0.0213 ± 0.0032</td>
<td>0.997 ± 0.002</td>
<td>139 ± 10</td>
<td>6.7σ</td>
</tr>
<tr>
<td>(2–5) keV</td>
<td>0.0165 ± 0.0024</td>
<td>0.998 ± 0.002</td>
<td>143 ± 9</td>
<td>6.9σ</td>
</tr>
<tr>
<td>(2–6) keV</td>
<td>0.0107 ± 0.0019</td>
<td>0.998 ± 0.003</td>
<td>144 ± 11</td>
<td>5.6σ</td>
</tr>
<tr>
<td><strong>DAMA/NaI+ DAMA/LIBRA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2–4) keV</td>
<td>0.0223 ± 0.0027</td>
<td>0.996 ± 0.002</td>
<td>138 ± 7</td>
<td>8.3σ</td>
</tr>
<tr>
<td>(2–5) keV</td>
<td>0.0178 ± 0.0020</td>
<td>0.998 ± 0.002</td>
<td>145 ± 7</td>
<td>8.9σ</td>
</tr>
<tr>
<td>(2–6) keV</td>
<td>0.0131 ± 0.0016</td>
<td>0.998 ± 0.003</td>
<td>144 ± 8</td>
<td>8.2σ</td>
</tr>
</tbody>
</table>

expectation for DM: $T = 1 \text{ yr}, t_0 = 152 \text{ (2nd June)}$
The DAMA annual modulation signal

fitting count rate with $S_0 + A \cos \omega(t - t_0)$:

<table>
<thead>
<tr>
<th></th>
<th>$A$ (cpd/kg/keV)</th>
<th>$T = \frac{2\pi}{\omega}$ (yr)</th>
<th>$t_0$ (day)</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DAMA/NaI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2–4) keV</td>
<td>0.0252 ± 0.0050</td>
<td>1.01 ± 0.02</td>
<td>125 ± 30</td>
<td>5.0σ</td>
</tr>
<tr>
<td>(2–5) keV</td>
<td>0.0215 ± 0.0039</td>
<td>1.01 ± 0.02</td>
<td>140 ± 30</td>
<td>5.5σ</td>
</tr>
<tr>
<td>(2–6) keV</td>
<td>0.0200 ± 0.0032</td>
<td>1.00 ± 0.01</td>
<td>140 ± 22</td>
<td>6.3σ</td>
</tr>
<tr>
<td><strong>DAMA/LIBRA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2–4) keV</td>
<td>0.0213 ± 0.0032</td>
<td>0.997 ± 0.002</td>
<td>139 ± 10</td>
<td>6.7σ</td>
</tr>
<tr>
<td>(2–5) keV</td>
<td>0.0165 ± 0.0024</td>
<td>0.998 ± 0.002</td>
<td>143 ± 9</td>
<td>6.9σ</td>
</tr>
<tr>
<td>(2–6) keV</td>
<td>0.0107 ± 0.0019</td>
<td>0.998 ± 0.003</td>
<td>144 ± 11</td>
<td>5.6σ</td>
</tr>
<tr>
<td><strong>DAMA/NaI+ DAMA/LIBRA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2–4) keV</td>
<td>0.0223 ± 0.0027</td>
<td>0.996 ± 0.002</td>
<td>138 ± 7</td>
<td>8.3σ</td>
</tr>
<tr>
<td>(2–5) keV</td>
<td>0.0170 ± 0.0020</td>
<td>0.998 ± 0.002</td>
<td>145 ± 7</td>
<td>8.9σ</td>
</tr>
<tr>
<td>(2–6) keV</td>
<td>0.0131 ± 0.0016</td>
<td>0.998 ± 0.003</td>
<td>144 ± 8</td>
<td>8.2σ</td>
</tr>
</tbody>
</table>

expectation for DM: $T = 1$ yr, $t_0 = 152$ (2nd June)

8.2σ evidence for annual modulation
Dropping the first energy bin

- Counts/kg/day/keVee
- 12 GeV, 1.3e-41 cm²
- 51 GeV, 7.8e-42 cm²
- 6 GeV, 2.8e-41 cm²

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2_{\text{DAMA},\text{min}}$</th>
<th>$m_{\chi,\text{best}}$</th>
<th>$\chi^2_{\text{glob},\text{min}}$</th>
<th>GOF</th>
<th>$\chi^2_{\text{PG}}$</th>
<th>PG</th>
<th>$m_{\chi,\text{best}}^{\text{glob}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>default</td>
<td>36.8</td>
<td>12</td>
<td>62.9</td>
<td>0.02</td>
<td>26.1</td>
<td>$2 \times 10^{-6}$</td>
<td>8.6</td>
</tr>
<tr>
<td>w/o 1st bin</td>
<td>30.3</td>
<td>10</td>
<td>40.4</td>
<td>0.50</td>
<td>10.1</td>
<td>$6 \times 10^{-3}$</td>
<td>3.9</td>
</tr>
</tbody>
</table>
Exclusion curves depend on energy threshold

ex.: new evaluation of $L_{\text{eff}}$ in XENON:
“scintillation yield of Xe for nuclear recoils, relative to the zero-field scintillation yield for electron recoils at 122 keVee.”

$$E_R = \frac{S_1}{L_y L_{\text{eff}} \frac{S_e}{S_n}}$$

$L_{\text{eff}} \approx 0.15$ instead of 0.19 at low energies moves the threshold of 4.6 keV to about 6 keV

Sorensen et al., 0807.0459
Exclusion curves depend on energy threshold

ex.: new evaluation of $L_{\text{eff}}$ in XENON:
“scintillation yield of Xe for nuclear recoils, relative to the zero-field scintillation yield for electron recoils at 122 keVee.”

\[
E_R = \frac{S_1}{L_y L_{\text{eff}}} \frac{S_e}{S_n}
\]

$L_{\text{eff}} \approx 0.15$ instead of 0.19 at low energies moves the threshold of 4.6 keV to about 6 keV

E. Aprile @ idm2008, Stockholm