School and Workshop on Dark Matter and Neutrino Detection

Dark Matter — Direct Detection

Lecture 3

Enectalí Figueroa-Feliciano
Northwestern
Outline

- Lecture 1:
  - The dark matter problem
  - WIMP and WIMP-like DM detection
- Lecture 2:
  - WIMP detection technologies
  - Current and future limits
- Lecture 3:
  - More DM detection technologies
  - To the Neutrino Floor, and beyond!
- Lecture 4:
  - The SuperCDMS Experiment
  - meV - 1GeV direct detection
- Lecture 5:
  - Indirect sterile neutrino detection
Last Time: Low Mass Region

Dark Matter Mass $[\text{GeV}/c^2]$ vs. Dark Matter–nucleon $\sigma_{\text{SI}}$ $[\text{cm}^2]$

- NEWS–G
- DAMIC
- CDMSlite R2
- CDEX
- CYGNUS
- HD
- \textbf{Color Center (H)}
- \textbf{Color Center (O)}
- \textbf{Si HV}
- \textbf{Ge HV}
- BubWat

Data from:
- DAMIC–1
- DAMIC–1K
- CDMSlite R2
- CRESST–II
- EDELWEISS
- CDEX
- HD–10
- He–10
- HV–10

Excluded regions for low mass regions.
PICO Bubble Chamber: Superheated Liquids!

-2012 COUPP

2013-17 PICO-2L

See next talk by Andrew Sonnenschein 2018-

PICO-60

PICO-40L

PICO-500

PICASSO
PICO Bubble Chamber: SD and SI limits!

PICO-60 CF3I  PandaX-II
PICO-2L  IceCube
PICASSO  SuperK
SIMPLE

See next talk by Andrew Sonnenschein
CCD-based DM Search

- Silicon CCD technology highly advanced thanks to utility in astronomical and satellite-based imaging
- WIMPs scatter coherently off of Si nuclei, which recoil and yield detectable ionization signals
- CCDs are “exposed”, i.e. collect charge, for \( \delta(1 \text{ day}) \) and images are then read out for analysis

16 Mpix CCD
LBNL designed
6 cm x 6 cm
15-\( \mu \text{m} \) pixel pitch
675-\( \mu \text{m} \) thick
CCD-based DM Search

WIMP nuclear-recoil search

Hidden-photon search

See talks by Juan Estrada
Directional Detection

- Measure WIMP-induced recoil directions with efficient electron-recoil discrimination even at low energy (<20 keV).
- Discriminate and measure Solar neutrino coherent scattering with directionality ($^8$B)
- Probe for WIMPs below neutrino floor.
Directional Detection

- Measure WIMP-induced recoil directions with efficient electron-recoil discrimination even at low energy (<20 keV).
- Discriminate and measure Solar neutrino coherent scattering with directionality ($^8$B).
- Probe for WIMPs below neutrino floor.

Sky map in galactic coordinates of recoils from 100 GeV WIMPs on $^{19}$F, $E>50$ keV

Galactic dipole: - strongest predicted direct detection signature - unambiguous proof of cosmological origin
Directional Detection: Non-TPC

From Kentaro Miuchi’s talk at IDM

**NonTPC**

- **NEWSdm**
  - Astroparticle Physics 80 (2016) 16-21
  - SEE Umemoto’s talk

- **ZnWO₄**
  - [Italy, Japan]
  - R. Cerulli
  - INFN-LNGS
  - α/β ratio
  - “anisotropic” scintillator
  - large mass
  - need to confirm in low energy

- **DeCANT**
  - Double brush
  - CNT brush
  - Silicon substrate
  - WIMP “wind”
  - • Carbon nano tube
  - • large mass
  - • “Channeling” needs to be proven

**PTOLEMY-G3**

- • Graphene
  - • large mass
  - • Proof of concept is ongoing

From Kentaro Miuchi’s talk at IDM
Directional Detection: TPC

Experimental concept
Recoil nuclear track detection < 100keV
challenge: short track
a few mm in low pressure gas
a few 100 nm in solid

Typical approach:
low pressure gas TPC
(time projection chamber)

2D readout + timing → 3D tracking

From Kentaro Miuchi’s talk at IDM
Directional Detection: TPC

From Kentaro Miuchi’s talk at IDM

- MWPC (2mm pitch)
- First started direction-sensitive method
  - Underground
  - Low background
  - Large size (1m³)

- Pixel readout (ATLAS FE-I4) chip
- R&D in the surface lab

- Micromegas (~400μm pitch)
  - Quenching factor measurement
  - Underground

- µ-PIC (400μm pitch)
  - Direction-sensitive limit
  - Underground

Baracchini Friday afternoon

MIMAC [France]

NEWAGE [Kobe+]

D3 [Hawaii]

NITEC/CYGNO [Italy]
Review of other Nuclear Detection Technologies

- Silicon CCDs: DAMIC & Sensei
  - Excellent SD Sensitivity
  - (currently running at SNOLAB)
- Bubble Chamber Experiments
  - PICO and COUPP
- Xenon Bubble Chamber
- Directional Detection Experiments
  - DRIFT, DMTPC, NEWAGE, MIMAC
- New Ideas
  - DNA and/or organic detectors?
  - Molecular dissociation / inelastic collisions?
Neutrino Backgrounds
Low-energy $\nu$ Interactions

<table>
<thead>
<tr>
<th>Charged Current</th>
<th>Quasi-Elastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>IBD $\nu_\mu, \nu_\tau$ not low-E</td>
</tr>
<tr>
<td>For $\nu_e$ and $\bar{\nu}_e$</td>
<td></td>
</tr>
<tr>
<td>Neutral Current</td>
<td></td>
</tr>
<tr>
<td>For all $\nu$ flavors</td>
<td></td>
</tr>
</tbody>
</table>

For all $\nu$ flavors, $\nu_\mu, \nu_\tau$ not low-$E$
Low-Energy Neutrino Cross Sections

Cross Section [cm\(^{-2}\)]

Neutrino Energy [MeV]

\(\bar{\nu}_e N \rightarrow \bar{\nu}_e N\)
\(\nu_e p \rightarrow e^+ n\)
\(\nu_e n \rightarrow e^- p\)
\(\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-\)
\(\nu_\mu e^- \rightarrow \nu_\mu e^-\)
\(\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-\)
\(\mu_\gamma = 10^{-10} \mu_B\)
Neutrino Sources for Dark Matter Detectors

- Solar ($\nu_e$)
- Diffuse Supernova Neutrino Background (all flavors)
- Atmospheric (all flavors)
- Geothermal ($\bar{\nu}_e$)
- Reactor ($\bar{\nu}_e$)
- Internal ($\beta\beta$ decays, $\bar{\nu}_e$)
- Supernova (burst, so not really a background, all flavors)
Solar Neutrino pp Chain

\[ p^+ + p^+ \rightarrow ^2H + e^+ + \nu_e \quad 99.77\% \]

\[ ^2H + p^+ \rightarrow ^3He + \gamma \]

\[ ^3He + ^4He \rightarrow ^7Be + \gamma \]

\[ ^7Be + e^- \rightarrow ^7Li \quad \nu_e \]

\[ ^7Li + p^+ \rightarrow ^4He + ^4He \quad \text{pplII} \]

\[ ^8B \rightarrow ^8Be^* + e^- + \nu_e \]

\[ ^8Be^* \rightarrow ^4He + ^4He \quad \text{pplIII} \]
Diffuse Supernova Background

- Mostly from Core Collapse Supernovae

Horiuchi 2009
Atmospheric Neutrinos

- From Cosmic Ray interaction in atmosphere.

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping $\mu$ decay</td>
<td>0.078</td>
<td>0.070</td>
<td>0.124</td>
<td>0.148</td>
</tr>
<tr>
<td>$\mu$ decay in flight</td>
<td>0.378</td>
<td>0.470</td>
<td>0.876</td>
<td>0.852</td>
</tr>
<tr>
<td>Stopping $\pi$ decay</td>
<td>0.003</td>
<td>0.007</td>
<td>0.00002</td>
<td>$\sim$0</td>
</tr>
<tr>
<td>$\pi$ decay in flight</td>
<td>0.541</td>
<td>0.453</td>
<td>0.00003</td>
<td>0.00005</td>
</tr>
<tr>
<td>$K$ decay in flight</td>
<td>0.0005</td>
<td>0.0003</td>
<td>0.0007</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Total fraction of each flavor

Total fraction and contribution by the different production channels are given.

Battistoni 2009
Geoneutrinos and Reactor Neutrinos

• Geoneutrinos are plentiful, but too low energy and are thus subdominant to the Solar $\nu$ flux.

• Reactors vs can are only important if physically close to a reactor, so we can safely ignore them.
Neutrino Sources: Solar, Atm, DSNB

$\frac{dN}{dE_{\nu}}$ [cm$^{-2}$.s$^{-1}$.MeV$^{-1}$]

Neutrino Energy [MeV]

Bahcall 2005
Keil 2003
Honda 2011

Bahcall 2005
Keil 2003
Honda 2011

$\nu$ type
$E_{\nu \max}$ (MeV)
$E_{\nu \max}$ (keV)
$\nu$ flux ($\text{cm}^{-2}.\text{s}^{-1}$)

pp
7Be, pep
8B
13N
15O
17F
AtmNu$_e$
AtmNu$_{\bar{e}}$
AtmNu$_{\mu}$
AtmNu$_{\mu \bar{e}}$

dsnbflux

 Bahcall 2005
 Keil 2003
 Honda 2011

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 Bahcall 2005
 Keil 2003
 Honda 2011

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7Be, pep
8B
13N
15O
17F
AtmNu$_e$
AtmNu$_{\bar{e}}$
AtmNu$_{\mu}$
AtmNu$_{\mu \bar{e}}$

dsnbflux
Coherent Elastic $\nu$-Nucleus Scattering (CE$\nu$NS)

$$\sigma_o \approx \frac{4m_r^2}{\pi} f A^2$$

atomic mass
coupling constant

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N} = \text{"reduced mass"}$$

- Same type of process occurs with neutrinos:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} \left[ N - Z(1 - 4 \sin^2 \theta_W) \right]^2 \left( 1 - \frac{M_{AT}}{2E_\nu^2} \right) F(Q^2)^2$$

Dark Matter detectors are getting good enough to be sensitive to this signal!
CEνNS Cross Sections

\[ \frac{d\sigma}{dT} \left[ \text{cm}^{-2} \text{eVnr}^{-1} \right] \]

Recoil Energy [keVnr]

\[ E_\nu : 7 \text{ MeV} \quad 40 \text{ MeV} \quad 200 \text{ MeV} \]

- Xe, \( E_\nu = 7 \text{ MeV} \)
- Ge, \( E_\nu = 7 \text{ MeV} \)
- Ar, \( E_\nu = 7 \text{ MeV} \)
- Xe, \( E_\nu = 40 \text{ MeV} \)
- Ge, \( E_\nu = 40 \text{ MeV} \)
- Ar, \( E_\nu = 40 \text{ MeV} \)
- Xe, \( E_\nu = 200 \text{ MeV} \)
- Ge, \( E_\nu = 200 \text{ MeV} \)
- Ar, \( E_\nu = 200 \text{ MeV} \)
Neutrino CEνNS Recoil Spectrum

\[
\frac{dR_{\nu}}{dT} = \int_{E'_{\nu}}^{E_{\nu}} \frac{dN}{dE_{\nu}} \frac{d\sigma}{dT} dE_{\nu}
\]

WIMP signal: \( m_\chi = 6 \text{ GeV/c}^2 \), \( \sigma_{\chi\text{-n}} = 4.4 \times 10^{-45} \text{ cm}^2 \)

Event rate \([\text{ton.year.keV}]^{-1}\)

Recoil energy \([\text{keV}]\)

- 8B
- 13N
- 15O
- 17F
- dsnbflux_8
- dsnbflux_5
- dsnbflux_3
- AtmNu_e
- AtmNu_ebar
- AtmNu_mu
- AtmNu_mubar
- total

\( 7\text{Be}_{384.3\text{keV}} \)
\( 7\text{Be}_{861.3\text{keV}} \)
\( 8\text{B} \)
\( 13\text{N} \)
\( 15\text{O} \)
\( 17\text{F} \)
\( \text{dsnbf} \)
\( \text{AtmNu} \)
\( \text{total} \)
Fitting the 8B CEνNS Signal As Dark Matter

- The reconstructed parameters are target dependent

\[ \sigma_o \simeq \frac{4 m_r^2}{\pi} f A^2 \]

SI: coupling constant with atomic mass
Fitting the 8B CEνNS Signal As Dark Matter

- The reconstructed parameters are target dependent
- They also depend on the assumed interaction mechanism

\[
\sigma_o = \frac{32(J + 1)}{\pi J} G_F^2 m_r^2 \left( a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2
\]

Nuclear Angular Momentum
Fermi constant
Coupling constant
Spin

<table>
<thead>
<tr>
<th>Target number of nucleons (A)</th>
<th>WIMP-nucleon cross section [cm(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>(10^{-36})</td>
</tr>
<tr>
<td>40</td>
<td>(10^{-38})</td>
</tr>
<tr>
<td>60</td>
<td>(10^{-40})</td>
</tr>
<tr>
<td>80</td>
<td>(10^{-42})</td>
</tr>
<tr>
<td>100</td>
<td>(10^{-44})</td>
</tr>
</tbody>
</table>

SD: The reconstructed parameters are target dependent. They also depend on the assumed interaction mechanism.
We can map where each neutrino component would land on the WIMP SI cross section - mass plane

Individual Fits for a Xe Target with Zero Treshold

Nuclear form factor prevents WIMP mass determination for at high masses
Fits to the Entire Neutrino Background as WIMPs

Event rate [(ton.year.keV)^{-1}]

Recoil energy [keV]

- Total neutrino background
- Threshold: 1 eV
- Threshold: 10 eV
- Threshold: 100 eV
- Threshold: 1 keV
- Threshold: 2.5 keV
- Threshold: 5 keV
- Threshold: 7.5 keV
- Threshold: 10 keV
The “Neutrino Floor”

Dark Matter Mass [GeV/c²]

Dark Matter–nucleon $\sigma_{SI}$ \textit{[cm}^2\textit{]}

Dark Matter–nucleon $\sigma_{SI}$ \textit{[pb]}

Neutrino Background

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581
WIMP Discovery Limit

- To assess the discovery potential of WIMP searches, we define the WIMP Discovery Limit.

- Definition of WIMP Discovery Limit: If the true WIMP model lies above this limit, then a given experiment has a 90% probability to obtain at least a $3\sigma$ detection of the signal.

- We want to gauge the significance of an excess in our data from the expected neutrino background, so we define a likelihood function:

  $$\mathcal{L}(\sigma_{\chi} - \bar{n}, \bar{\phi}) = \frac{e^{-(\mu_{\chi} + \sum_{j=1}^{n_{\nu}} \frac{\mu_{\nu}^j}{\mu_{\nu}})}}{N!} \times \prod_{i=1}^{N} \left[ \mu_{\chi} f_{\chi}(E_{R_i}) + \sum_{j=1}^{n_{\nu}} \mu_{\nu}^j f_{\nu}^j(E_{R_i}) \right] \times \prod_{i=1}^{n_{\nu}} L_i(\phi_i)$$

- Using a likelihood ratio test, we determine what cross section of WIMPs would be detected at $3\sigma$ or better 90% of the time.
Formally, there is no Neutrino Floor
Saturation around 6 GeV WIMP Mass from $^8\text{B} \nu$

SI discovery limit at 6 GeV/c$^2$ [cm$^2$]

Threshold and Efficiency Dependent $\rightarrow$ Number of expected $^8\text{B}$ neutrino events

$\propto 1/\sqrt{MT}$

SuperCDMS SNOLAB

Saturation Regime

Precision Regime

Uncertainty in Neutrino Fluxes

1% $\times$ 10% $\times$
2% $\times$ 15% $\times$
5% $\times$ 20% $\times$
Formally, there is no Neutrino Floor.
Saturation above 100 GeV WIMP Masses from Atm $\nu$

Saturation will happen for all WIMP masses above about 100 GeV

Threshold and Efficiency Dependent

\[ \propto \frac{1}{\sqrt{M T}} \]

\[ \propto \frac{1}{M T} \]

Number of expected atmospheric neutrino events

Exposure (ton-year)

Uncertainty in Neutrino Fluxes

Saturation above 100 GeV WIMP Masses from Atm $\nu$

LZ

“G3”

“G4?”

Saturation Regime

Precision Regime

5% 20% 10% 25% 15% 30%
Formally, there is no Neutrino Floor
The WIMP Discovery Limit

- The curve we publish in our papers is constructed from two separate calculations, one at low mass and one at high mass.
- The low mass threshold is set to get no pp neutrino events.
- The high mass threshold is set to get no $^8\text{B}$ events.
- The curve is not a sensitivity curve! Reiterating the definition:

> If the true WIMP model lies above this limit, then a given experiment has a 90% probability to obtain at least a $3\sigma$ detection of the signal.

<table>
<thead>
<tr>
<th>Target</th>
<th>Sample Experiment</th>
<th>$E_{\text{th, low}}$ (eV)</th>
<th>$E_{\text{th, high}}$ (keV)</th>
<th>Exposure$_{\text{low}}$ (ton-yr)</th>
<th>Exposure$_{\text{high}}$ ($\times 10^3$ ton-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>LZ/XENON1T</td>
<td>3</td>
<td>4</td>
<td>0.19</td>
<td>9.3</td>
</tr>
<tr>
<td>Ge</td>
<td>SuperCDMS/CoGeNT</td>
<td>5.3</td>
<td>7.9</td>
<td>0.38</td>
<td>15.6</td>
</tr>
<tr>
<td>Si</td>
<td>SuperCDMS/DAMIC</td>
<td>14</td>
<td>20</td>
<td>1.26</td>
<td>73.1</td>
</tr>
<tr>
<td>Ar</td>
<td>DEAP/DarkSide</td>
<td>9.6</td>
<td>14.4</td>
<td>0.72</td>
<td>32.5</td>
</tr>
<tr>
<td>CaWO$_4$</td>
<td>CRESST</td>
<td>25</td>
<td>35</td>
<td>1.48</td>
<td>24.4</td>
</tr>
<tr>
<td>$\text{C}_3\text{F}_8$</td>
<td>PICO</td>
<td>33</td>
<td>47.7</td>
<td>2.02</td>
<td>25.1</td>
</tr>
<tr>
<td>CF$_4$</td>
<td>MIMAC/DMTPC</td>
<td>33</td>
<td>47.7</td>
<td>2.39</td>
<td>22.9</td>
</tr>
<tr>
<td>CF$_3$I</td>
<td>PICO/COUPP</td>
<td>33</td>
<td>47.7</td>
<td>2.42</td>
<td>23.8</td>
</tr>
</tbody>
</table>

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581
WIMP Discovery Limit for Different Targets

Spin Independent Interaction

SI WIMP-nucleon cross section [cm$^2$] vs. WIMP mass [GeV/c$^2$]

- Xe
- Ge
- Ar
- Si

Xenon100 (2012)
CDMS SI (2013)
DAMIC
DAMAPA
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
SIMPLE (2012)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)

WIMP-nucleon cross section [pb]
WIMP Discovery Limit for Different Targets

![Graph showing WIMP mass vs. SI WIMP-nucleon cross section for different targets.]

- **CaWO₄**
- **CF₃I**
- **CF₃I with energy**
- **C₃F₈**
- **C₃F₈ with energy**

**Target Examples:**
- LUX (2013)
- Xenon100 (2012)
- CDMS II Ge (2009)
- ZEPLIN-III (2012)
- COUPP (2012)
- SIMPLE (2012)
- DAMA
- CRESST
- EDELWEISS (2011)
- DAMIC
- CDMS Lite (2013)
- CDMS Si (2013)
- EDELWEISS (2011)
- SuperCDMS-LT (2014)
- CRESST
- LUX (2013)

**Legend:**
- Spin Independent Interaction

**Units:**
- WIMP mass [GeV/c²]
- SI WIMP-nucleon cross section [cm²]
- WIMP-nucleon cross section [pb]
WIMP Discovery Limit for Different Targets

Spin Dependent Interaction

SD (proton) WIMP-nucleon cross section [cm²]

WIMP mass [GeV/c²]

Xenon100 (2013)
CDMS II Ge (2004-2008)
PICASSO (2009)
COUPP (2011)
SIMPLE (2011)

CF₃I
CF₃I with energy
C₃F₈
C₃F₈ with energy

arXiv:1503.00008
Electron Recoil Backgrounds from Neutrinos

Baudis 2012, Schumann 2015
Low-energy $\nu$ Interactions

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Charged Current</td>
<td><img src="Image" alt="Charged Current Diagram" /></td>
<td><img src="Image" alt="Quasi-Elastic Diagram" /></td>
</tr>
<tr>
<td>For $\nu_e$ and $\bar{\nu}_e$</td>
<td>$W^+$ production</td>
<td>IBD</td>
</tr>
<tr>
<td>Neutral Current</td>
<td><img src="Image" alt="Neutral Current Diagram" /></td>
<td></td>
</tr>
<tr>
<td>For all $\nu$ flavors</td>
<td>$Z^0$ production</td>
<td>$\nu$, $\nu$ not low-E</td>
</tr>
</tbody>
</table>

For all $\nu$ flavors

$\nu_{\mu}$, $\nu_{\tau}$ not low-E
Low-Energy Neutrino Cross Sections

- Cross Section is 10,000 times smaller than CNS...
- But you get a much higher recoil due to the small mass of the electron.
- Thus pp and $^7$Be will dominate at 10 keVee recoil
Electron Recoil Backgrounds

- Lower 8.9% of the 136Xe contribution
- 99.5% rejection cut

Baudis 2012
Adding both NC and CC interactions

- S1+S2 combined (LY= 8 PE/keV)
- S1-based (LY= 8 PE/keV)
- S1+S2 combined (LY=12 PE/keV)
- S1-based (LY=12 PE/keV)
- infinite resolution
Comparison between Exposure and Sensitivity

CC Elastic Scattering changes the sensitivity, but not dramatically
Strategies to Push Beyond the Neutrino “Floor”
Target Complementarity

- The reconstructed parameters are target dependent
- Maybe we can eliminate the saturation regime using data from various targets?

\[
\text{SI: } \sigma_o \sim \frac{4m_r^2}{\pi} f A^2
\]

\[
\text{SD: } \sigma_o = \frac{32(J + 1)}{\pi J} G_F^2 m_r^2 (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2
\]

\[m_r = m_N + o' \left( 32 \left( J + 1 \right) \frac{G_2}{F_m} r^2 \left( a_p h_S p_i + a_n h_S n_i \right) \right)^2\]
For Spin Independent Interactions, there is little gain from combining different experimental results.
For Spin Dependent Interactions, there is some gain from combining different experimental results.
Directional Detectors and the Neutrino Background

- We see a “dark matter wind” in the laboratory due to the motion of the solar system in the Galaxy.
- This wind changes apparent direction in the lab frame due to the diurnal rotation of the Earth.
- The direction of the dark matter wind does not overlap with the position of the Sun in the sky, and thus the direction of solar neutrinos is always different than the dark matter wind.
- We can use this to differentiate dark matter signals from neutrino backgrounds!

Directional Detectors and the Neutrino Background

Minimum DM-Sun Separation (60°)

Time: 26th Feb. 2015 06:00
0 - 1.6667 keV

Maximum DM-Sun Separation (120°)

Time: 6th Sep. 2015 06:00
0 - 1.6667 keV

Target: Xe
1.6667 - 3.3333 keV

WIMP: \( m_x = 6 \text{ GeV}, \sigma_{x-n} = 4.9 \times 10^{-45} \text{ cm}^2 \)
3.3333 - 5 keV

\( \frac{dR_{\text{bin}}}{d\Omega} \ [\text{ton}^{-1} \text{ year}^{-1} \text{ sr}^{-1}] \)

Directional Detectors and the Neutrino Background

- Directional Detectors can keep dark matter searches “background free” from solar neutrinos (note in this study we ignored other backgrounds!)
- Atmospheric Neutrinos look isotropic to directional detectors, and thus still form an irreducible background
- The technology to perform directional detector searches at these exposures is not yet at hand, but this study motivates their continued development

The “Neutrino Floor” will be a hard wall for a while…

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581

Dark Matter Mass \( [\text{GeV}/c^2] \)

Neutrino Background
End of Lecture 3