Indirect Searches for Dark Matter

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• Motivation

• Search for self-annihilating dark matter

• Search for dark matter decay

• Dark matter captured in the Sun and Earth

• Anomalies

• Outlook & Conclusions
Motivation
Synergy

Indirect

Annihilation / Decay

\[ \tilde{\chi} \Rightarrow e^\pm, \nu, \gamma, p, D, \ldots \]

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Scattering

Direct

Collider

Production

\[ W^+, Z, \tau^+, b, \ldots \Rightarrow e^\pm, \nu, \gamma, p, D, \ldots \]

\[ W^-, Z, \tau^-, \bar{b}, \ldots \Rightarrow e^\pm, \nu, \gamma, p, D, \ldots \]
Evidence for Dark Matter

Dark Matter already gravitationally “observed”, but ...

- What is it?
- What are its properties?

Some of us like WIMPs $<\sigma v> \sim 3 \times 10^{-26} \text{cm}^3\text{s}^{-1}$

“Indirect Targets”

Pick a target that is well defined and that has low or understood astrophysical backgrounds.
Indirect Dark Matter Searches
Dark Matter Signals

- Identify overdense regions of dark matter
  ⇒ self-annihilation can occur at significant rates
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds

Annihilation Products
\[ \tilde{\chi} \rightarrow W^+, Z, \tau^+, b, \ldots \Rightarrow e^\pm, \nu, \gamma, p, D, \ldots \]

Decay
\[ \tilde{\chi} \rightarrow W^-, Z, \tau^-, \bar{b}, \ldots \Rightarrow e^\mp, \nu, \gamma, \bar{p}, D, \ldots \]

Messengers

Annihilation Rate \( \sim \rho^2 \)
(Decay Rate \( \sim \rho \))

\[ \chi \approx m_\chi \]

Beacom, Bell, Mack (2006)

Identify overdense regions of dark matter
- self-annihilation can occur at significant rates

Pick prominent Dark Matter target

Understand / predict backgrounds

Exploit features in the signal to better distinguish against backgrounds

\[
\begin{align*}
\text{MW Halo + Atm.} \\
\text{Cosmic + Atm.} \\
\text{Atmospheric Neutrinos}
\end{align*}
\]

Beacom, Bell, Mack (2006)
Targets - Dark Matter Annihilations


Milky Way Halo: Large DM content, nearby source, $O(10)$ larger flux than extra-galactic. Anisotropy.

Galactic Center: Very dense DM accumulation, nearby source. Extended Source. Relatively independent from DM halo profile.


Clusters of Galaxies: Large DM content, high boost factors from sub structure. Extended source.

For discovery observations at multiple sources with different observatories (Multiwavelength !) that yield a consistent picture.
Dark Matter Distributions / Halo Profiles

\[ \rho_{\text{NFW}}(r) = \frac{\rho_s}{r} \left(1 + \frac{r}{r_s}\right)^{-2} \]

\[ \rho_{\text{Ein}}(r) = \rho_s \exp \left\{ -\frac{2}{\alpha} \left[ \left( \frac{r}{r_s} \right)^{\alpha} - 1 \right] \right\} \]

\[ \rho_{\text{Iso}}(r) = \frac{\rho_s}{1 + (r/r_s)^2} \]

\[ \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1 + r/r_s)(1 + (r/r_s)^2)} \]

\[ \rho_{\text{Moo}}(r) = \rho_s \left( \frac{r_s}{r} \right)^{1.16} \left( 1 + \frac{r}{r_s} \right)^{-1.84} \]

<table>
<thead>
<tr>
<th>DM halo</th>
<th>( \alpha )</th>
<th>( r_s ) [kpc]</th>
<th>( \rho_s ) [GeV/cm(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFW</td>
<td>—</td>
<td>24.42</td>
<td>0.184</td>
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<td>Einasto</td>
<td>0.17</td>
<td>28.44</td>
<td>0.033</td>
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<td>EinastoB</td>
<td>0.11</td>
<td>35.24</td>
<td>0.021</td>
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<tr>
<td>Isothermal</td>
<td>—</td>
<td>4.38</td>
<td>1.387</td>
</tr>
<tr>
<td>Burkert</td>
<td>—</td>
<td>12.67</td>
<td>0.712</td>
</tr>
<tr>
<td>Moore</td>
<td>—</td>
<td>30.28</td>
<td>0.105</td>
</tr>
</tbody>
</table>

Measure Flux

\[
\frac{d\Phi}{dE}(E, \phi, \theta) = \frac{1}{4\pi} \frac{\langle \sigma_A v \rangle}{2m^2} \sum_f \frac{dN}{dE} B_f \times \int_{\Delta \Omega(\phi, \theta)} d\Omega' \int_{\text{los}} \rho^2(r(l, \phi')) dl(r, \phi')
\]
Neutrino Telescopes / Detectors

- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon.
- Consists **885 10”PMTs** on 12 lines with 25 storeys each.
- Detector was competed in May 2008. **Depth: 850 hg/cm²**
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using **3,150 liquid scintillation counters**.
- Operating since Dec 1978; More than 34 years of continuous operation.

- **Lake Baikal**, Siberia, at a depth 1.1 km NT36 in 1993.
- NT200 (since Apr 1998) consists of one central and seven peripheral strings of 70m length.

- **IceCube** at the Geographic South Pole
- **5160 10”PMTs in Digital optical modules** distributed over 86 strings instrumenting ~1km³.
- Physics data taking since 2007; Completed in December 2010, including **DeepCore** low-energy extension.

- **Super-Kamiokande** at Kamioka uses **11K 20” PMTs**.
- 50kt pure water (22.5kt fiducial) water-cherenkov detector.
- Operating since 1996.
INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES

Galactic Halo DM annihilation searches cover 10 GeV - 300 TeV Dark Matter masses with 4 analyses:

- ANTARES GC 2007 to 2015
- IceCube Galactic Halo Cascades 2yrs
- IceCube Galactic Center Tracks 4yrs (incl. 3yr MESE)
- IceCube Galactic Center Track 3yrs (low-energy)
  - IceCube [arXiv:1705.08103]

- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

see talks from Vincent Bertine and Morten Medici
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High Altitude Water Cherenkov (HAWC)

- Located at 97.5° W, 18.9° N (Parque Nacional Pico de Orizaba) at 4100m
- 300x 7.3 m diameter, 5 m height tanks,
  - 3x 8" R5912 PMTs and 1x 10" R7081-HQE PMT
- In total: 55kT of water
- Covers 22000 m²
- Completed in 2016
- Trigger rate: 24kHz
- Data rate: 2TB of data per day, 95% livetime

507 days of HAWC data analyzed

Targets:
- Dwarf spheroidal (dSph) galaxies
  - Combined results were computed for 15 dSph
- Galaxies / Galaxy clusters
  - Virgo cluster and M31

Future improvements:
- include more dSph
- extended source analysis
- more data …

Also measurements on:
- TeV γ emission from pulsars
- Dark Matter Decay
Dark Matter Annihilation Search with VERITAS

Array of four IACTs in Southern AZ, USA
- Energy Range: 85 GeV to > 30 TeV
- Energy Resolution: 15-25%
- Pointed observation (FOV~3.5°)

Targets
- Dwarf Spheriodal Galaxies
- Fermi-LAT unidentified sources
- Galactic Center (soon)
- Galactic Center region does not transit above 30° elevation at VERITAS site

Five dSphs observed by VERITAS between 2007 and 2013
- Total of 230 hours after data quality selection
- 92 hours for Segue 1

see also Archambault et al. [VERITAS] Phys. Rev. D 95, 082001
### Line Searches

Peak in the $\gamma$ energy distribution at the WIMP mass ("$\gamma$-ray line") would be clear signal for DM annihilations.

**Dwarf Spheroidal Galaxies (dSphs)**
- Low/no gas, dust or recent star formation
- DM dominated
- Several large datasets already recorded

**Significance Map**

- **Fornax**
  - 2.6 hours livetime
  - Signal significance: $-2.4\sigma$

- **Peak in the $\gamma$ energy distribution** at the WIMP mass would be clear signal for DM annihilations.

- **Limit on $\langle \sigma v \rangle$** of $3 \times 10^{-25}$ cm$^3$s$^{-1}$ reached for $M_X$ range 0.4-1.0 TeV
- **First H.E.S.S. DM line search from dwarf galaxies and first combined DM line search**
- **More complex line-like models to be included for upcoming paper**
• Sensitivity only \((2 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \text{ @1TeV})\), unblinding in progress ... expect results soon

• Lower energy threshold thanks to the improved raw data analysis: best limit shifted down to lower masses

• Fermi-LAT limits surpassed of a factor about 6 @300 GeV
Dark Matter Decay
Could the observed neutrino flux be due to only dark matter decaying into multiple channels?

\[
\frac{d\Phi_{DM,\nu}}{dE_\nu} = \frac{d\Phi_{G,\nu}}{dE_\nu} + \frac{d\Phi_{EG,\nu}}{dE_\nu}
\]

Take Galactic and Extra galactic contributions into account

Find that HESE data can be best described with the combination of the astrophysical neutrino flux and the dark matter decay

Caution when interpreting HESE events:
- Earth absorption needs to be considered
- Outcome strongly depends on background assumption
Dark Matter Decay with IceCube

- Two expected flux contributions:
  - Dark Matter decaying in the Galactic Halo (Anisotropic flux + decay spectrum)
    \[
    \frac{d\Phi^G}{dE_\nu} = \frac{1}{4\pi m_{DM} \tau_{DM}} dN_\nu \int_0^\infty \rho(r(s, l, b)) \, ds
    \]
  - Dark Matter decaying at cosmological distances (Isotropic flux + red-shifted spectrum)
    \[
    \frac{d\Phi^{EG}}{dE} = \frac{\Omega_{DM} \rho_c}{4\pi m_{DM} \tau_{DM}} \int_0^\infty \frac{1}{H(z)} dN_\nu \frac{(1 + z)E_\nu}{(1 + z)E_\nu^*} \, dz
    \]

Bound on DM lifetime up to $10^{27.5}$s obtained with IceCube data for $m_{DM} > 100$ TeV.
Results from 270h of good quality data (from 2009-2017)

No evidence of dark matter decay observed
Obtain limit on DM life times of $\sim 8 \cdot 10^{25}$ s for $bb$ and $\tau \tau$
Dark Matter Decay with HAWC

Results for 15 dSph, Virgo Cluster and M31
Dark Matter Decay Bounds

- IceCube 90% C.L.
- Magic Perseus (270hrs) 95% C.L.
- Veritas Segue1
- HAWC (15 Dwarfs w/o Trill) 95% C.L.
- Fermi-LAT (Galactic Halo)

see also Fermi-LAT Astrophys. J. 761 (2012) 91
Dark Matter Decay Bounds

Dark matter lifetime limit comparison

$\log_{10}(\text{Dark matter mass [GeV]})$

$\log_{10}(\text{Dark matter lifetime [s]})$
Solar Dark Matter Searches
Solar Dark Matter

- $\rho_\chi$ (velocity distribution)
- $\chi$ (interactions)
- $\nu$ oscillations
- Detector

Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86
Solar Dark Matter - IceCube/ANTARES

- Search for an excess in direction of the Sun
- Off source region used to reliably predict backgrounds from data
Solar Dark Matter - IceCube/ANTARES

- Convert neutrino flux limit into limit on WIMP-nucleon scattering cross section

Solar WIMPs
- S. In and K. Wiebe [IceCube] ICRC2017 (912)
Solar Dark Matter Summary

Spin-dependent scattering

Spin-independent scattering

Dark Matter Mass (log(m_{DM}/GeV))

log_{10}(\sigma_{SIDP}/cm^2)

\sigma_{SIDP} [cm^2] vs. m_{\chi} [GeV]

\sigma_{SIDP} [cm^2] vs. m_{\chi} [GeV]
Availability of data

Spin-dependent scattering

- IceCube data released
- Nulike part of GAMBIT (see Talk Thursday afternoon Jonathan Cornell)

software to test your own model (cross section/branching ratios)
  - Likelihood includes:
    - energy and directional information

http://nulike.hepforge.org/
Solar Atmospheric Neutrino Floor
Cosmic ray interactions with the Sun

- CR interaction in the Solar atmosphere result produce gamma-rays and neutrinos
- Background to dark matter search from the Sun, that soon will be relevant (and first high-energy neutrino point source ??)

Leptonic
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadroncic
- Seckel, Stanev, Gaisser (1991)
- Moskalenko, Karakula (1993)
- Ingelman & Thunman (1996)

see talk by Kenny Ng
• Natural background to Solar Dark Matter Searches!

• However, energy spectrum expected to be different

• DM annihilation neutrinos significantly attenuated above a few 100GeV

Expect ~2 events per year at cubic kilometer detector

Recent works on the Solar Atmospheric Neutrino Floor

• Argüelles et al. [astro-ph/1703.07798]
• Ng et al. [astro-ph/1703.10280]
• M. Masip (2017), [hep-ph/1706.01290]
ANTARES Secluded Dark Matter

- Dark matter annihilates into meta-stable particle
  - $\chi\chi$ annihilates into mediator $\phi$
    - $\phi \rightarrow \nu\nu$ or $\mu\mu$
  - Livetime of 1321 days (Jan 2007 to Oct 2012)

![Di-Muon decay into Neutrino](image1)

![Di-Muon decay into Neutrino](image2)

![Mediator decay into Neutrino](image3)

![Mediator decay into Neutrino](image4)

Annihilation of DM in the Sun x Branching ratio

$M_\chi = 0.5 \text{ TeV, } m_\phi = 1 \text{ GeV}$

 Allowed Region

 Excluded

 $L = \gamma \tau [\text{km}]$

 $\Gamma [\text{s}^{-1}]$

 $1 \text{ AU}$

 Di-muons

 Di-muons to neutrino

 Into $\nu$

 $\log_{10} [\sigma v] \text{ [pb]}$

 $M_\chi [\text{GeV}]$

 $10^1$ $10^2$ $10^3$ $10^4$

 $\text{ANTARES Di-}\mu; \gamma \tau = 1.5 \times 10^8 \text{ km}$

 $\text{ANTARES Di-}\mu; \gamma \tau = 2.8 \times 10^7 \text{ km}$

 $\text{ANTARES } \phi \text{ into } \nu; \gamma \tau = 1.5 \times 10^8 \text{ km}$

 $\text{ANTARES } \phi \text{ into } \nu; \gamma \tau = 2.8 \times 10^7 \text{ km}$

 $\text{PICO-2L}$

 $\text{XENON100}$

 $\text{TAUP2017}$
Super-K Dark Matter Searches

Galactic Center

90% CL UPPER LIMIT

SK preliminary

Earth WIMPs

natural scale – expectation for DM as thermal relic

\( \frac{\langle v \rangle}{c^2} \mathrm{[cm}^3\mathrm{s}^{-1}] \)

\( M_\chi \mathrm{[GeV/c^2]} \)

\( \cos \theta_{GC} \)

\( \cos \theta_{ZHENTH} \)

\( \cos \theta_{SUN} \)

SK preliminary

6 GeV WIMP into bb

\( \mu^+ \mu^- \mathrm{IC} \)

\( b\bar{b} \mathrm{IC} \)

\( b\bar{b} \mathrm{SK} \)

\( \mu^+ \mu^- \mathrm{SK} \)

\( W^+W^- \mathrm{SK} \)

\( \nu\bar{\nu} \mathrm{IC} \)

\( \nu\bar{\nu} \mathrm{SK} \)

\( \mathrm{WIMP-nucleon SI Cross section [cm}^2\mathrm{]} \)

\( M_\chi \mathrm{[GeV/c^2]} \)

\( \text{SK preliminary} \)

\( \text{SK I-IV, } b\bar{b} \)

\( \text{SK I-IV, } \tau^+\tau^- \)

\( \text{DAMA/LIBRA (2008)} \)

\( \text{ANTARES, 2007-2012, } b\bar{b} \)

\( \text{ANTARES, 2007-2012, } \tau^+\tau^- \)

\( \text{IceCube, 2011-2012, } \tau^+\tau^- \)

\( \mathrm{[h}^+\mathrm{ep}^{-}] \)}
Anomalies?
The GeV excess @ Galactic Center

- First claimed in 2009 with Fermi data (arXiv:0910.2998)
  - If interpreted as dark matter, it points to \( O(10-100) \) GeV DM
  - DM claim is in tension with bounds from dwarf spheroidal galaxies
- Fermi-LAT collaboration finds that
  - The spectrum and morphology is sensitive to the assumed diffuse emission model. However the excess is still statistically significant under all models tested. (Astrophys.J. 819 (2016) no.1, 44 & arXiv: 1704.03910)
3.5 keV line

3.5 keV x-ray line may indicate the existence of 7 keV sterile neutrino
- Bulbil et al., arXiv:1402.2301 (APJ) (Stacked galaxy clusters, Perseus)

“smooking gun” line signal

Has been proposed as sterile neutrino signal
3.5keV line

3.5 keV x-ray line may indicate the existence of 7 keV sterile neutrino
- Bulbil et al., arXiv:1402.2301 (APJ) (Stacked galaxy clusters, Perseus)

What could it be?
- X-ray lines also from atomic transitions of highly-ionized Z ~ 16-20 atoms
  - Example K XVIII has lines near 3.5 keV
  - To predicted the brightness based on other lines we need the relative elemental abundance and plasma temperature

Why we should be skeptical:

Final word …
- Future observations ATHENA, HERD, Micro-X, …
- Dark matter velocity spectroscopy (Speckhard, Ng, Beacom, Laha Phys. Rev. Lett. 116 (2016) 031301)
- Look where no background is expected …
Dark matter velocity spectroscopy is a promising tool to distinguish signal and background in dark matter indirect detection.

- We see a smoking gun in motion
- Immediate application to the 3.5 keV line
- Future improvements in the energy resolution of telescopes at various energies will result in this technique being widely adopted

**Instruments with $\mathcal{O}(0.1)\%$ energy resolution**

**Past**
- Hitomi/ Astro-H
  - $\frac{\sigma_E}{E} \approx \frac{1.7 \text{ eV}}{3.5 \text{ keV}}$

**Present**
- INTEGRAL/ SPI
  - 2.2 keV (FWHM) at 1.33 MeV
  - [http://www.cosmos.esa.int/web/integral/instruments-spi](http://www.cosmos.esa.int/web/integral/instruments-spi)

**Future**
- Micro-X
  - FWHM of 3 eV at 3.5 keV
- ATHENA
  - [ATHENA X-IFU](http://www.cosmos.esa.int/esapub/20000/20015/2001520015.pdf)

**HERD: High Energy Cosmic Radiation Detection**
- Energy resolution for electrons and gamma will be < 1% at 200 GeV
  - Wang & Xu Progress of the HERD detector
Positron Excess

- Large excess of positrons above 10GeV inconsistent with secondary production expectations (PAMELA / Fermi-LAT / AMS-02)
- Dark matter interpretation for decay or annihilation in tension with other indirected bounds
- Astrophysical sources (pulsars) potentially provide large signal contributions

... not every bump in the data is from DM
What to expect in the future with Indirect Searches
DAMPE detector, consists of 4 subsystems:

- the plastic scintillator strips detector (PSD),
- the silicon-tungsten tracker-converter (STK),
- the BGO imaging calorimeter (BGO), and
- the neutron detector (NUD).

Dark Matter Particle Explorer successfully launched on December 17, 2015

Sensitivity with 3 yrs of data DAMPE

CTA - Cherenko Telescope Array

CTA sites and example telescope layouts different deployment strategies

Northern Site
4 Large-size telescopes
15 Medium-size telescopes

Southern Site
4 Large-size telescopes
25 Medium-size telescopes
70 Small-size telescopes

[Image of maps showing the locations of Northern and Southern Sites]
Dark Matter improvement estimate by 2023

CTA sensitivity curve from Carr et al. 2015 500 hr, statistical only, NFW, 30 GeV threshold arXiv:1508.06128

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section
The GAPS Experiment to Search for Dark Matter using Low-energy Antimatter

Anti-D’s production

essentially background free (secondary production)

Timeline & Summary

GAPS Sensitivity (35days) T. Aramaki et al., Astroparticle Phys. 74, 6 (2016).
Next generation neutrino detectors

IceCube-Gen2 (PINGU fill in)

• ORCA and IceCube-Gen2 (PINGU infill) have unique capability to explore DM between 4-50GeV in indirect solar wimp searches
  • This will also be an interesting region for Hyper-K / T2HKK / DUNE
• KM3NeT and IceCube-Gen2 extremely competitive for high-mass DM decay

At TAUP2017 see also
• Jason Kumar (Friday morning)
• Claudio Kopper (Tuesday morning)
• Hidekazu Tanaka (Wednesday afternoon)
• Takatomi Yano (Wednesday afternoon)
• Sunny Seo (Wednesday afternoon)

ORCA

• C. Tönnis [ANTARES] ICRC2017 (913)

S. In [IceCube] ICRC2017 (912)
Conclusions

• Dark Matter exists
• Multiwavelength campaigns needed to identify it
• Anomalies remain of high interest, but alternative explanations becoming more compelling
• Vibrant field with many new results
• New strong bounds on dark matter decay and annihilations
• Solar Atmospheric neutrinos new background to solar dark matter searches
• Taking searches beyond the WIMP paradigm - still useful framework for result interpretation
Backup
Unexpected Result: The Rigidity Dependence of Elementary Particles $e^+$, $\bar{p}$, $p$ are identical from 60-500 GV.

$e^-$ has a different rigidity dependence.

Unexpected: The Spectra of Protons and Antiprotons:
If $\bar{p}$ are secondaries, their rigidity dependence should be different than $p$:
$p + \text{ISM} \rightarrow \bar{p} + \ldots$

Unexpectedly $\bar{p}$ and $p$ have the same rigidity dependence.
AMS-02

- **AMS Antiprotons**
  - Excess $\sim 4.5\sigma$ possibly attributed to DM \((PRL\ 118,\ 191102;\ PRL\ 118,\ 191101)\)
  - Significant uncertainties: modeling of antiproton production cross section, cosmic-ray propagation, solar modulation.

- **AMS Positrons**
  - Large excess of $e^+ > 10$ GeV inconsistent with exceptions for secondary $e^+$ from proton collisions with interstellar medium.
  - DM interpretation of signature for annihilation or decay in tension with other measurements.
  - Potential for large pulsar contribution to signal. \((arXiv:1702.08436)\)

Jodi Cooley (WIN2017)
AMS-02

AMS $\bar{p}/p$ results and modeling

AMS-02

Dark Matter

Collisions of ordinary cosmic rays

Models from Donato et al., PRL 102, 071301 (2009); $m_\chi = 1$ TeV
AMS measurements of the Electron and Positron spectra

Preliminary results. Please refer to the forthcoming AMS publication in PRL

Electron and positron spectra are significantly different in their magnitudes and energy dependences. This is a clear indication of a different origins of these two species of cosmic rays.

AMS-02

Andrei KOUNINE @ ICRC2017
Sensitivity CTA

CTA Perseus cluster
300 h, NFW profile
Statistical errors only

\[ \sigma^2 \]

DM mass (TeV)

- CTA, $b \bar{b}$
- CTA, $\tau^+ \tau^-$
- Fermi, $\tau^+ \tau^-$
- Fermi, $b \bar{b}$
MAGIC DM Decay

Results from 270h of good quality data (from 2009-2017)

Joaquim Palacio [MAGIC] ICRC2017 (920)

No evidence of dark matter decay observed
Reach sensitivities on decay life times of \(~8 \cdot 10^{25}\) s
Beyond Standard Model Physics at the PeV scale

- Intense interest in high-energy neutrino region
- Observations defy any simple explanation from a single generic source class
- Multiple sources classes?
- Hints of new physics?

- PeV Scale Right Handed Neutrino Dark Matter
- Super Heavy Dark Matter
- Neutrino Portal Dark Matter
- Right-handed neutrino mixing via Higgs portal
- Heavy right-handed neutrino dark matter
- Leptophilic Dark Matter
- PeV Scale Supersymmetric Neutrino Sector Dark Matter
- Dark matter with two- and many-body decays
- Shadow dark matter
- Boosted Dark Matter
- …
Impact of velocity distribution

- Explore the change in capture rate using different velocity distributions obtained from dark matter simulations.

A comparison of captures rates for different WIMP velocity distributions show that overall changes in the capture rate are smaller than 20%.
Boosted Dark Matter

- “Boosted Dark Matter Search”
- Following search proposed by Kopp, Liu, Wan (2015)
- using “Echo Technique” Li, Bustamante, Beacom (2016)

May sound crazy, but is just an example for exotic interactions in IceCube detectable via recoil
AMEGO - All-sky Medium Energy Gamma-ray Observatory

- **Weakly Interacting Massive Particles (WIMPs)**
  - Targets: dwarf spheroidal galaxies, Galactic Center (GC)
  - LAT: $m_\gamma \sim$500 MeV to 100 GeV, ACT: $>$1 TeV
- **Weakly Interacting Sub-eV Particles (WISPs)**
  - Targets: pulsars, galaxy clusters, SN
  - X-rays, LAT: $m_\gamma \leq 10^{-2}$, $0.5 \leq m_\gamma \leq 100$

Probe Concept: 2020 NASA Astrophysics Decadal Review

- Energy Range: 200 keV to 10 GeV
- Observing strategy: survey (80% sky/orbit, $\sim$2.5 sr FoV)

https://asd.gsfc.nasa.gov/amego/
CTA

**Galactic Halo (Einasto)**
A. Morselli [CTA] ICRC2017 (921)

**Galactic Halo (comparison)**
A. Morselli [CTA] ICRC2017 (921)

- Fermi-LAT, H.E.S.S., CTA WW
- PLANCK bb

**Dwarfs (Sculptor)**
A. Morselli [CTA] ICRC2017 (921)

**Large Magellanic Cloud**
A. Morselli [CTA] ICRC2017 (921)