Looking towards the Exa-scale

EeV dark matter:
from the production to the detection

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Dark Side of the Universe 2019, Buenos-Aires, July 17th.
Some Exa-scales \((10^{18})\)

[CSI convention since 1975]

- USA energy consumption per year: 15 Exajoule
  \([=\text{energy needed in Appolo 11 mission to the moon}]\)
- Age of Universe: 0.43 Exasecond
- 1 Exameter = 110 light-years
- Gmail: 1 Exabyte
- 57 Exahashes per second: calculation rate of bitcoin network
- Proton mass = \(10^{-9}\) Exaelectronvolt (!)
Other motivations range from..
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Cosmic ray production of EeV neutrino (GZK cut= 50 EeV)
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Intermediate sectors in SO(10) unified models
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Reheating temperature:

\[ T_{RH} = \sqrt{\Gamma_{\text{inflaton}} \times M_{\text{Planck}}} \approx EeV \]
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EeV Majorana mass \( M_R \) => natural see-saw (\( y_\nu = 1 \))
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Higgs (meta)stability
Producing EeV dark matter in the early Universe
Temperature

mixed universe
\[ H \propto T^4 \]
\[ T = \beta a^{-3/8} \]

Radiative universe
\[ H \propto T^2 \]
\[ T = \beta a^{-1} \]

mixed universe

\[ H \alpha T^4 \]
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Radiative universe

\[ H \alpha T^2 \]
\[ T = \beta a^{-1} \]

\[ \langle \sigma v \rangle \sim T^n / \Lambda^{n+2} \]

DM

DM

\[ T_{RH} \]

Temperature

mixed universe

$H \propto T^4$

$T = \beta a^{-3/8}$

DM production

10% if $\langle \sigma v \rangle \sim T^2/\Lambda^4$

50% if $\langle \sigma v \rangle \sim T^4/\Lambda^6$

99.996% if $\langle \sigma v \rangle \sim T^6/\Lambda^8$

Radiative universe

$H \propto T^2$

$T = \beta a^{-1}$

\[ \Omega h^2 \propto 0.1 \frac{\frac{T_{RH}^{n+1} M_P}{\Lambda^{n+2}}}{\left( \frac{M_{DM}}{0.1 \text{ EeV}} \right)} \]
Some examples...
The abundance of particles in the thermal bath, considered the heavy fermions generating the GCS couplings in the unitary gauge, the term related to the evolution of dark matter, and the SM. In section III, we discuss our computation of the SM which includes (in addition to the massless vectorial Abelian gauge bosons appearing in Eq. (4) and define the derivative vertex can be extracted from Eq. (3) as a spin-2 particle.

The evolution of dark matter number density with the correct relic abundance. This means that only axial coupling is present for the fermionic dark matter. The correct amount of dark matter is generated in a regime in which the abundance of dark matter is much smaller than the abundance of particles in the thermal bath, considering the heavy fermions generating the GCS couplings.
A concrete example:
Supergravity
High scale supergravity

\[ \psi_\mu \frac{1}{M_{Pl}} \rightarrow \psi \frac{\partial_\mu}{M_{Pl}} \]

\[ R(T) = \frac{T^{12}}{M_{SUSY}^4 M_{Pl}^4} \]


High scale supergravity

\[
\frac{\psi_\mu}{M_{Pl}} \rightarrow \psi \frac{\partial_\mu}{M_{Pl}}
\]

\[
\begin{align*}
G & \quad \tilde{g} \\
M_{SUSY} & \quad \tilde{G} \\
G & \quad \tilde{g}
\end{align*}
\]

\[
R(T) = \frac{T^{12}}{M_{SUSY}^4 M_{Pl}^4}
\]

\[
\Omega_{3/2} h^2 \simeq 0.11 \left( \frac{0.1 \text{ EeV}}{m_{3/2}} \right)^3 \left( \frac{T_{RH}}{2 \times 10^{10}} \right)^7 \times \frac{56}{5} \ln \left( \frac{T_{\text{max}}}{T_{RH}} \right)
\]


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And what is the signature of such models?

A smoking gun signal
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A smoking gun signal

Gravitino DM

\[ \nu \quad \text{EeV (10}^9 \text{ GeV)} \]

\[ g^\sim \]

\[ \gamma \quad \text{EeV} \]
« And what is the signature of such models? »

A smoking gun signal

Gravitino DM

\( \tilde{g} \rightarrow \nu \rightarrow \gamma \rightarrow EeV (10^9 \text{ GeV}) \)

Scalar DM

\( \nu_R \rightarrow \nu_R \rightarrow \gamma \rightarrow EeV \)
EeV events?
The ANITA experiment
IceCube and ANITA introduce some additional power into the pulse tail.

The group delay variation of the passband edges of the bandpass filters, but most of the energy arrives within a fraction of a nanosecond, as determined in previous measurements of the bandpass filters, but most of the energy arrives within the group delay of the edge response. The apparent “ringing” artifact of the raw impulse response. The apparent “ringing” artifact of the raw impulse response. The apparent “ringing” artifact of the raw impulse response.

The ANITA receiver system. Bottom: Pulse received during the experiment in an upper-ring antenna near the peak of the Cherenkov cone, also showing the raw pulse, and partially partially deconvolved.

FIG. 3: Top: Raw, and partially-deconvolved impulse response of the ANITA receiver system. Bottom: Pulse received during the experiment in an upper-ring antenna near the peak of the Cherenkov cone, also showing the raw pulse, and partially partially deconvolved.

FIG. 4: Left: Field strength vs. frequency of radio Cherenkov emission at several energies. The data are consistent with the theoretical expectation for a shower in ice at this energy. Right: Quadratic dependence in the T486 experiment. The curve is the theoretical expectation of quadratically scaling over the energy range we probed, indicating that the radiation is coherent over the entire frequency range over which the RF transmissivity of ice is at its highest.

FIG. 5 shows the measured and predicted angular dependence of the radiation. The Cherenkov emission refracts into the forward direction out of the ice, and is clearly delineated by providing pulse-phase interferometry. The uncertainty in the T486 experiment is taken from Fig. 4. We scale these data by providing pulse-phase interferometry. The uncertainty in the T486 experiment is taken from Fig. 4. We scale these data by providing pulse-phase interferometry. The uncertainty in the T486 experiment is taken from Fig. 4. We scale these data by providing pulse-phase interferometry. The uncertainty in the T486 experiment is taken from Fig. 4. We scale these data by providing pulse-phase interferometry.

The ice was contained in a 10 cm thick insulating foam-lined box, and a 10 cm foam lid was used during operation, along with a freezer unit, to maintain temperatures of between -5 and -20°C. Such temperatures are adequate to avoid significant RF absorption over the several m pathlengths of the radiation and are dominated by a combination of the 1-2dB uncertainty in the gain calibration of the antennas, and by comparable uncalibrated antenna gains.

In Figure 4 (left) we display measurements of the absorption coefficient for a shower in ice at this energy. The coefficient is given approximately by the requirement that the absorption of the Cherenkov emission obtains is given approximately by the requirement that the absorption of the Cherenkov emission.

The field strengths are compared to a parameterization based on shower+electrodynamics simulations for ice [10, 11], and the agreement is well within our systematic errors to match the peak of the theoretical expectation. We scale these data by providing pulse-phase interferometry. The uncertainty in the T486 experiment is taken from Fig. 4. We scale these data by providing pulse-phase interferometry. The uncertainty in the T486 experiment is taken from Fig. 4. We scale these data by providing pulse-phase interferometry. The uncertainty in the T486 experiment is taken from Fig. 4. We scale these data by providing pulse-phase interferometry.
Horizon

Icecube

ANITA

6° introduce some additional power into the pulse tail.

and railing near the target, as well as the payload structure

form of Fig. 3 (bottom), later-time reflections from shieldi

ments of the Askaryan effect [7]. In the measured T486 wave-

fraction of a nanosecond, as determined in previous measure

of the bandpass filters, but most of the energy arrives within

ceiving system is due to the group delay of the edge response

peak of the Cherenkov cone. The apparent "ringing" of the re-

system (top), and one of the measured waveforms near the

antenna signals simultaneously at 2.6 Gsamples/sec.

digitizer modules [22], 9 of which are used to record all 72

signals are digitized by custom compact-PCI-based 8-chann

the bicone/discones) to sample the arriving wavefront. The

nal directed along their nearest neighbors' boresights. Th

lower and upper payload sections respond well even to a sig-

antennas are arranged so that adjacent antennas in both the

to complement the suite of horn antennas. The ANITA horn

monitor antennas (four bicones and four discones) are used

highest [9]. Eight additional vertically polarized broadb

quency range over which the RF transmissivity of ice is at its

the target, as shown in Fig. 2. The antenna frequency range

emission at a location about 15 m away from the center of

polarization quad-ridged horn antennas was used to receive

through the ice [9].

RF absorption over the several m pathlengths of the radiatio

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box, and a 10 cm foam lid was used during operation, along

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cone, also showing the raw pulse, and partially partially-d

FIG. 3: Top: Raw, and partially-deconvolved impulse respon

se is due

partially deconvolved

raw impulse response

raw RF Cherenkov

es is due

partially deconvolved

partially deconvolved

FIG. 4: Left: Field strength vs. frequency of radio Cherenko

4 kms

35 kms

6° horizon

35 kms

4 kms

Icecube

Horizon

Ice
The anomalous CR 15717147. The inversion of the normal reflected for an inverted UHECR that had an upcoming angle close to that of the ice sheet. For a shower initiated at a height of 4 km above the parameters could be directly compared and scaled. The errors here are statistical, based on the root-mean-square against 12 of the 16 ANITA-I cosmic ray events for which the PSD can thus be introduced some additional power into the pulse tail. In the measured T486 waveform the group delay of the edge response is due to the group delay of the edge response of Fig. 3 (bottom), later-time reflections from shieldings of the Askaryan effect [7]. In the measured T486 waveform (top), and one of the measured waveforms near the experiment in an upper-ring antenna near the peak of the Cher discone and bicone antennas were used to receive through the ice [9].

FIG. 4: Left: Field strength vs. frequency of radio Cherenkov pulses for a shower in ice at this energy. Right: Quadratic dependence of the pulse power with shower energy. The dependence is linearly polarized, without consideration of correlation experimental errors. Figure 4 (right) shows results of the parameterization based on shower + electrodynamics simulation including data from the ANITA Low Frequency Antenna (ALFA). A amplitude spectral density (ASD) for the event, from 50-800 MHz, allows multiple antennas (typically 4 to 6 horns and 3 to 4 of the antennas are arranged so that adjacent antennas in both the polarization quad-ridged horn antennas was used to receive. In Figure 4 (left) we display measurements of the absolute

\[ E_{\nu} \propto \frac{n_1 - n_2}{n_1 + n_2} \]

\[ H_{\text{pol}} : \quad E = v_y B_z - v_x B_z \]

\[ V_{\text{pol}} : \quad E = \frac{n_1 - n_2}{n_1 + n_2} \]

Horizon

Icecube

ice
of the cross-check sample. The errors here are statistical, based on the root-mean-square

For a shower initiated at a height of 4 km above

the ice sheet. For a shower initiated close to the event's projected position on

the parameters could be directly compared and scaled. The

results are quite consistent, yielding an estimated shower en-

against 12 of the 16 ANITA-I cosmic ray events for which

only an upper limit to the background,

-1

0

1

-10 0 10 20 30 40 50

-10 0 10 20 30 40 50

for an inverted UHECR that had an upcoming angle close to that of

as the above-horizon events B and C. Panel D shows the waveform

A,B,C. Panel A shows the anomalous event, with the same polarity

field strength, mV/m

1

0

-1

1

-10 0 10 20 30 40 50

-10 0 10 20 30 40 50

the anomalous CR 15717147. Detailed simulations of the UHECR radio emis-

15717147. The inversion of the normal reflected

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1

0

-1

1

-10 0 10 20 30 40 50

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for the entire 20 UHECR sample. Thus by all indications the

-1

0

1

-10 0 10 20 30 40 50

-10 0 10 20 30 40 50

upward air shower

anomalous

°

°

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0

1

-10 0 10 20 30 40 50

-10 0 10 20 30 40 50

Radio signal is dependent on the observer's viewing angle rel-

sion process find that the power spectral density (PSD) of the

15717147. Econvolved

-1

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-10 0 10 20 30 40 50

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quency range over which the RF transmissivity of ice is at its

10

40

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20

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-2

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0

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-10 0 10 20 30 40 50

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-1

0

1

-10 0 10 20 30 40 50

-10 0 10 20 30 40 50

to verify that the beamforming solution is unique.

3d B ) . T h e s e

depth

beams

To verify that the beamforming solution is unique.

In addition to the targeted search for UHECR events, we

anomalous CR 15717147. Bottom: ANITA combined

FIG. 4:
Fig. 3 shows the incident field strength waveforms for all UHECR samples. Pulse heights for event 15717147, -3.6

The apparent "ringing" artifact of the raw impulse response is due to partially deconvolved signals. For detected radio impulses, the large fields-of-view for the antennas are arranged so that adjacent antennas in both the horizontal and vertical planes are directed along their nearest neighbors' boresights. The ANITA payload, consisting of an array of 32 dual-quad-ridged horns used in ANITA allow up to 15 antennas, to be drawn from up to 5 azimuthal sectors of the payload, to be used for coherent beam forming. Pulse-phase interferometry allows blind analyses of all events, favoring impulsive, highly-directional, and the azimuthal angle of the radio impulse to typical precisions of 0.5°.

The gain calibration of the antennas, and by comparable un-calibrated, corrects for the gain variation of the horn antennas. A microsecond time delay in the receiving electronics corrects for the propagation delay of the radio signal, further introduction of power into the pulse tail. The ANITA Low Frequency Antenna (ALFA) was used to verify that the beamforming solution is unique.

The ANITA Low Frequency Antenna (ALFA) was used to verify that the beamforming solution is unique. In addition to the targeted search for UHECR events, we performed two completely independent optimized multivariate analyses, complete isolation from any anthropogenic source or background estimates for both 15717147 and for any other events was a stringent requirement, and event 15717147 passed in both cases. These two analyses confirm that event 15717147 is unique, impulsive, and isolated even with respect to the "normal" UHECR events, chosen because its arrival angle was close to that of the above-horizon events B and C. Panel D shows the waveform resulting selection of events represents a very pure sample of the "normal" UHECR events, chosen because its arrival angle was close to that of the above-horizon events B and C.

In addition to the targeted search for UHECR events, we also introduce some additional power into the pulse tail. The background level. There is thus significant evidence for a physical mechanism not considered. The rate of actual UHECR events is such that event 15717147 is unique, impulsive, and isolated, even with respect to the "normal" UHECR events, chosen because its arrival angle was close to that of the above-horizon events B and C. Panel D shows the waveform resulting selection of events represents a very pure sample of the "normal" UHECR events, chosen because its arrival angle was close to that of the above-horizon events B and C.

The errors here are statistical, based on the root-mean-square method. The radio signal is dependent on the observer's viewing angle relative to the point of shower initiation, and the azimuthal angle of the radio impulse to typical precisions of 0.5°. The three non-inverted polarity events are shown in panels A, B, and C. The ANITA payload, consisting of an array of 32 dual-quad-ridged horns used in ANITA allow up to 15 antennas, to be drawn from up to 5 azimuthal sectors of the payload, to be used for coherent beam forming. Pulse-phase interferometry allows blind analyses of all events, favoring impulsive, highly-directional, and the azimuthal angle of the radio impulse to typical precisions of 0.5°.
A CR event is clearly evident.

FIG. 3: The incident field strength waveforms for all ANITA-III UHECR Air Showers A,B,C. Panel A shows the anomalous event, with the same polarity as the above-horizon events B and C. Panel D shows the waveform of the cross-check sample.

The parameter could be directly compared and scaled. The results are quite consistent, yielding an estimated shower energy of 3.6 x 10^18 eV for this event, assuming that 0.5 of the cross-check sample.

The radio signal is dependent on the observer's viewing angle relative to the event.

For detected radio impulses, the large fields-of-view for the quad-ridged horns used in ANITA allow up to 15 antennas, each with a map signal from 50-800 MHz, including data from the ANITA Low Frequency Antenna (ALFA). A spectral-density curve is overlain.

FIG. 4: Top: ANITA combined analysis of the event, from 50-800 MHz, for detected radio impulses. Bottom: ANITA combined analysis of the event, from 50-800 MHz, for detected radio impulses.

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ANITA-III events have polarizations V and H, and the azimuthal angle is measured relative to the payload. Mapping is done for 360° in elevation and azimuth, respectively [9]. Fig. 4 shows the map signal from 50-800 MHz, including data from the ANITA Low Frequency Antenna (ALFA). A spectral-density curve is overlain.

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unknown cosmic-ray neutrino flux. Finally upward-propagating cosmic rays though most of these events featured a phase reversal searching for radio pulses produced during their propagation.

Our model in section II and compute the galactic production of these EeV neutrino produced resonantly in the rock a long-lived into sterile neutrinos mutating into active ones through 

Decaying Dark Matter hypothesis ANITA I = 25.4 ± 0.56 days, both assumed to be SM sin-

constraint processes find that the power spectral density (PSD) of the 

15717147. Detailed simulations of the UHECR radio emission process that leads to direct upward-moving cosmic-ray-like showers above the ice surface.

For detected radio impulses, the large fields-of-view for the 

In addition to the targeted search for UHECR events, we

35° (+27°)

35 km

7000 km

4 km

Vτ

ANITA II ANITA III ANITA IV
Duration 35 days 28.5 days 22 days 29 days
Events #308526 - #1571714 TBA
Energy 0.6±0.4EeV - 0.56±0.3EeV -
θem 95.4±1° - 85.5±1° -

18° 6°

A, B, C. Panel A shows the anomalous event, with the same polarity of the cross-check sample. Results are quite consistent, yielding an estimated shower en-

C and D show field strength vs. time for an inverted UHECR that had an upcoming angle close to that of the ice, the energy is reduced by about 30% to 

the atmosphere-skimming air shower was initiated close to the event’s projected position on the map. Elevation is with respect to the payload horizon-

For detected radio impulses, the large fields-of-view for the 

15717147 passed in both cases. These two analyses confirm that event 15717147 is unique, impulsive, and isolated, even when not selected by its UHECR-related properties. The 

background estimates for both 15717147 and for 

the parameters could be directly compared and scaled. The 

only an upper limit to the background,

that some inevitably do get included (and therefore lost to the 

In addition to the targeted search for UHECR events, we
2 Anomalous events at 0.5 EeV

- Mean free path for an EeV neutrino in the earth crust is \( \sim 100 \text{ kms} \)
- Probability \( p \sim 10^{-6} \) of crossing 7000 kms

![Graph showing cumulative histograms and residuals](image)

3 events left from 100 million generated
How genius are our theoretical physicists..

“Along with ‘Antimatter,’ and ‘Dark Matter,’ we’ve recently discovered the existence of ‘Doesn’t Matter,’ which appears to have no effect on the universe whatsoever.”
$\nu$ (1 EeV)

$\theta_{em}$

prob = $10^{-6}$
The neutrino cross section saturates at a certain energy due to gluon recombination (Color Glass Condensate)

\[ \text{prob} = 10^{-6} \]

\[
\begin{align*}
\sigma_{\text{SM}} &- \text{Standard Model} \\
\sigma_{\text{GGC}} &- \text{Color Glass Condensate} \\
\epsilon_{\nu} = 0.1 &- \text{Small neutrino transmission probability}
\end{align*}
\]
The neutrino cross section saturates at a certain energy due to gluon recombination (Color Glass Condensate) 

\[ \text{prob} = 10^{-6} \]
\( \nu \) (1 EeV) \( \theta_{em} \) prob = \( 10^{-6} \)
Metastable superheavy RHN decaying inside the earth

$M_R = 500 \text{ PeV}$

Problem: the required mass is 5 orders of magnitude greater than the amount of dark matter that could be trapped inside the earth

Cline, Gross and Xue; 1904.13396.
$\nu$ (1 EeV)
\[ \text{gravitino} \]

\[ \tau \]

\[ \theta_{\text{em}} \]

\[ \text{prob} = 10^{-6} \]

\[ \tilde{\tau}_R \]

\[ \nu \]

(1 EeV)

\( \nu \) (1 EeV)

\[ \theta_{em} \]

\[ \text{prob} = 10^{-6} \]
$\nu$, $\nu_{\text{em}}$ prob $= 10^{-6}$

ν
(1 EeV)

θ_{em}

prob = 10^{-6}
Figure 1: The evolution of the EeV neutrino survival probability with respect to the travelling distance, corresponding to the ANITA event 15717147. The active-sterile mixing angle is chosen as $\theta_{14} = 0.1$, and the mass of $\nu_4$ could be 2 keV, 0.5 keV, or 0.2 keV. The dashed curves show the evolution of the standard $\nu_\tau$ flux. The solid blue curve stands for the survival probability of the sterile component, while the solid red curves stand for that of the $\nu_\tau$ component in the context of active-sterile mixing.

The fraction of electrons and $n$ the nucleon number density of the matter, and $L$ is the local attenuation length of the neutrino. $L_{\text{atten}}$ depends on the nucleon density and the neutrino energy through $L_{\text{atten}} = \left[\frac{(E_{\nu_4})_\text{v}}{n}\right]^{-1}$. The number density profile of the Earth can be found in the PREM model [39]. The NC and CC cross sections are referred to [40], and we note that both the CC and NC interactions contribute to the attenuation effect. We have neglected the regeneration effect for simplicity. The $\nu_\tau$-lepton produced by the CC can decay back to $\nu_4$. For the NC interaction, the produced neutrino carries averagely 80% of the initial energy, but not removed from the flux. Thus our simulation will be more conservative than the realistic case. The initial conditions for the evolution read $c_\tau(0) = \sin \theta_{14}$, $c_s(0) = \cos \theta_{14}$ before the $\nu_4$ flux entering the Earth.

Before turning to numerical demonstration of the evolution, we can first have some analytical observations. If we ignore the oscillation terms, i.e. the first two terms in the right-hand side of Eq. (1), the evolution is trivial. The active and sterile components will evolve independently such that the active component is quickly absorbed by the Earth with only the unobservable sterile component left, and there will be null signal in the detector as in the standard case. However, the sterile and active neutrinos are actually mixed, and can oscillate from one to the other if the propagation length covers the oscillation length of $L_{\text{osc}} = \frac{\nu_{14}}{E_{\nu_4}}/m^2_{\nu_4}$. For the ANITA events 3985267 and 15717147 with emitting zenith angles of 63° and 55°, the corresponding chord lengths are 5785 km and 7309 km.
$\nu_{\text{em}}$ 

$\text{prob} = 10^{-6}$

$\nu$ (1 EeV)
\[ \nu \theta \]

The Antarctic Impulsive Transient Antenna (ANITA) work is beyond the scope of this paper.

The evolution of this integrated flux with the declination is negligible in our analysis. Since the ANITA experiment observes events emerging below ANITA is 12 millions of events [15, 16, 24].

We give the example of a real scalar dark matter, but considering our approach is valid on average here as the ANITA observation.

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_\nu + \frac{y_\phi}{\sqrt{2}} \tilde{\nu}_R \nu_R - \frac{1}{2} m_{\text{DM}} \phi^2
\]

\[
\rho_{\text{DM}}(r) \propto \frac{1}{\left( \frac{r}{r_s} \right) \left[ 1 + \left( \frac{r}{r_s} \right)^2 \right]}
\]

L. Heurtier, Y.M., M. Pierre; arXiv:1902.xxxxx
Taking into account constraints from $N_{\text{eff}} + \text{BAO} + \text{relic abundance} + \text{CHARM} + \text{mean free path}$.  
2 regions are left: $\nu_R < 50 \text{ eV}$ and $10 \text{ MeV} < \nu_R < 0.5 \text{ GeV}$

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_\nu + \frac{y_\phi}{\sqrt{2}} \phi \nu_R^c \nu_R - \frac{1}{2} m_{\text{DM}}^2 \phi^2
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\rho_{\text{DM}}(r) \propto \frac{1}{\left( \frac{r}{r_s} \right) \left[ 1 + \left( \frac{r}{r_s} \right)^2 \right]}
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The Minimal and Simplest Extension One Can Imagine

\[
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\]

\[
\rho_{\text{DM}}(r) \propto \frac{1}{(r/r_s)} \left[ 1 + \left( \frac{r}{r_s} \right)^2 \right]
\]

\[
N_{\text{tot}} \simeq 2.5 \times \left( \frac{\theta_R}{0.01} \right)^2 \left( \frac{10^{23}}{\tau_{\text{DM}}} \right) \left( \frac{T_{\text{exp}}}{85.5 \text{ days}} \right) \left( \frac{20 \text{ EeV}}{m_{\text{DM}}} \right)^{2/3}
\]
Even if the exposure of IceCube is larger than ANITA, a 20 PeV $\tau$ has a mean free path > 1 km: difficult to distinguish it from a $\mu$ (just a track, no decay).

For this reason it has been shown by Fox et al. [1809.09615] that the 2 ~PeV down-going events observed by IceCube can be misinterpreted as ~ 0.07 EeV upgoing events. Which is also the number of events we predict...

Generic problem

- Source for such a flux

- Tensions with ICECUBE:

\[ N_{\text{events}} = \Phi \times \text{Exposure} \times \text{Probability} \leq 6 \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1} \times 2.4 \text{ km}^{2} \text{ sr yr} \times P \]

\[ \Phi_{\text{limit ICECUBE/AUGER}} \]

Exposure ANITA
Generic problem

- Source for such a flux

- Tensions with ICECUBE:

  \[ N_{\text{events}} = \Phi x \text{Exposure} x \text{Probability} \]
  \[
  < 6 \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1} \times 2.4 \text{ km}^2 \text{ sr yr} \times P
  \]

  This implies \( P > 10^{-1} \) to observe 1 event in ANITA
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  Hooper et al. [1904.12865] proposed Askaryan radiation (which has better transmission probability) from dark matter decay
Standard Model solution?

Kusenko et al. had a nice proposition: the Antarctic subsurface.
Standard Model solution?

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\frac{E_r}{E_i} = \frac{n_1 - n_2}{n_1 + n_2}
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Conclusions

**EeV dark matter** thermally as natural as WIMP

Motivated constructions (High scale SUSY, spin-2, Moduli) lead to **EeV DM**

**PeV/EeV DM** observable (observed?) by Icecube and/or ANITA
The FIMP:
Freeze-In Massive Particle
Freeze out

Infrared freeze in

(FIMP)

Observed abundance

Equilibrium abundance

abundance

time = 1/T

« Infrared » freeze out (neutralino)

« Ultraviolet » freeze out (neutrino)

Ultraviolet freeze in (gravitino)

Infrared freeze in (FIMP)
DM production

- 10% if $<\sigma v> \sim T^2 / \Lambda^4$
- 50% if $<\sigma v> \sim T^4 / \Lambda^6$
- 99.996% if $<\sigma v> \sim T^6 / \Lambda^8$

mixed universe

$$H \propto T^4$$
$$T = \beta a^{-3/8}$$

Radiative universe

$$H \propto T^2$$
$$T = \beta a^{-1}$$

Instantaneous reheating

Non-instantaneous reheating
Example of rates

\[ R(T) = \frac{T^8}{M_{\phi}^4} \]

\[ R(T) = \frac{T^{10}}{M_{\phi}^4 \Lambda^2} \]

\[ R(T) = \frac{T^{12}}{M_{\phi}^4 \Lambda^4} \]
Non-instantaneous reheating: introducing the inflaton
Before the end of the reheating process, while the Universe was still dominated by the matter (inflaton), but temperature was higher than $T_{RH}$
Before the end of the reheating process, while the Universe was still dominated by the matter (inflaton), but temperature was higher than $T_{RH}$.

In other words, one should compare the total DM production releasing the hypothesis of instantaneous reheating.
\[
\frac{dY_\chi}{dT} = -\frac{8}{3} \frac{R(T)}{H T^9} \quad \text{with} \quad Y_\chi = \frac{n_\chi}{T^8}
\]

\[
R(T) = \frac{T^{6+n}}{\Lambda n+2}
\]
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\[ B^n_F = \frac{\Omega_{\text{non instantaneous}}}{\Omega_{\text{instantaneous}}} = \frac{\int_{T_{\text{max}}}^{T_{RH}} dn}{\int_{T_{RH}}^{0} dn} \]
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\[
B_F^n = \frac{\Omega_{\text{non instantaneous}}}{\Omega_{\text{instantaneous}}} = \frac{\int_{T_{\text{RH}}}^{T_{\text{max}}} dn}{\int_{T_{\text{RH}}}^{0} dn}
\]

\[
B_{F}^{n<6} = \frac{8}{5} \left( \frac{n + 1}{6 - n} \right)
\]

\[
B_{F}^{6} = \frac{56}{5} \ln \left( \frac{T_{\text{max}}}{T_{\text{RH}}} \right)
\]

\[
B_{F}^{n>6} = \frac{8}{5} \left( \frac{n + 1}{n - 6} \right) \left( \frac{T_{\text{max}}}{T_{\text{RH}}} \right)^{n-6}
\]
Conclusion:

3 sources of production:

1) From thermal equilibrium (freeze out)
[Higgs-portal, Z/Z’-portal]

2) Out of equilibrium (freeze in)
[gravitino, FIMP]

3) During reheating due to large temperature
[Planck/String interactions]

4) and…
Other models where care should be taken proceeding with early Universe computation
SO(10)


Massive spin 2


« string inspired » moduli fields

Ellis, Kim and Nanopoulos (84) then considered for the first time the dominant process (in fact, they listed 10 processes).
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\[ \mathcal{L} = \frac{1}{4M_{Pl}} \bar{\psi}^\alpha \gamma_\alpha [\gamma^\mu, \gamma^\nu] \tilde{G} G_{\mu\nu} \]

Gravitino

Gluino

Gluon

COSMOLOGICAL GRAVITINO REGENERATION AND DECAY

John Ellis, Jihn E. Kim* and D.V. Nanopoulos

CERN - Geneva

Careful analyses of their decay products' disruptive effects on light nuclei and on the microwave background radiation suggest \( T_{\text{max}} < 10^9 \sim 10^{10} \text{ GeV} \).
Ellis, Kim and Nanopoulos (84) then considered for the first time the dominant process (in fact, they listed 10 processes)

\[ \mathcal{L} = \frac{1}{4 M_{Pl}} \overline{\psi}^\alpha \gamma^\alpha \left[ \gamma^\mu, \gamma^\nu \right] \tilde{G} G_{\mu\nu} \]

gravitino

\[ \text{gluino} \quad \text{gluon} \]

\[ \Omega_{3/2} h^2 \sim 0.3 \left( \frac{1 \text{ GeV}}{m_{3/2}} \right) \left( \frac{T_{RH}}{10^{10} \text{ GeV}} \right) \sum \left( \frac{m_{\tilde{G}}}{100 \text{ GeV}} \right)^2 \]
High-scale supersymmetry: \( \mathcal{M}_{\text{SUSY}} \gg T_{\text{max}} \)
High-scale supersymmetry: 
\[ M_{\text{SUSY}} \gg T_{\text{max}} \]
Adding the contribution from radiative decay of the inflaton
The direct decay of the inflaton. For example, in no-scale models, one can then extract the maximum reheating temperature shown as the horizontal dashed line in the Figure 1. We can immediately see the linear increase in the Yukawa coupling in the region allowed by PLANCK [32]. The black (solid) and green (dashed) lines represent the relic abundance. Then, as one can see from Eq.(11), the condition \( y_\Phi \) corresponding to the changing in the slope for larger value of \( m_{3/2} \) is increased. Finally, we point out that in models with so-called stabilized field [52, 53], this coupling may change.

Using the result from [41] for the gravitino abundance constraints [32] in the plane (\( m_{3/2}, y_\Phi \)). It is also possible to produce gravitinos through the inflaton decay, both the branching ratio or the gravitino mass is increased. The cosmological constraint is strengthened as the gravitino production, our limit to the coupling is improved when either the branching ratio or the gravitino mass is increased.

\[
\frac{d\rho_\Phi}{dt} + 3H \rho_\Phi = -\Gamma_\Phi \rho_\Phi \quad \text{[inflaton \( \Phi \)]}
\]
\[
\frac{d\rho_R}{dt} + 4H \rho_R = +\Gamma_\Phi \rho_\Phi \quad \text{[radiation \( R \)]}
\]
\[
\frac{dn_\chi}{dt} + 3H n_\chi = R(T) \quad \text{[dark matter \( \chi \)]}
\]
\[
H^2 = \frac{\rho_\Phi}{3M_P^2} + \frac{\rho_R}{3M_P^2} \quad \text{[scale \( a \)]}
\]
\[
\Rightarrow T = \beta a^{-3/8} \quad (H = \frac{\dot{a}}{a})
\]
\[
[T = \beta a^{-1} \text{ in radiation dominated universe}]
\]
\[
\Rightarrow H(T) = \frac{5}{6} \frac{\alpha}{\Gamma_1 M_P^2} T^4
\]
\[
[H(T) = \frac{\alpha}{3M_P} T^2 \text{ in radiation dominated universe}]
\]
\[
\frac{dY_\chi}{dT} = -\frac{8}{3H T^9} \quad \text{with} \quad Y_\chi = \frac{n_\chi}{T^8}
\]
Another DM source: The inflaton decay

\[ T_{RH} = \left( \frac{10}{g_s} \right)^{1/4} \left( \frac{2\Gamma_\phi M_P}{\pi c} \right)^{1/2} = 0.55 \frac{y_\phi}{2\pi} \left( \frac{m_\phi M_P}{c} \right)^{1/2} \]

\[ \Omega_{3/2} h^2 \simeq 0.11 \left( \frac{0.1 \text{ EeV}}{m_{3/2}} \right)^3 \left( \frac{m_\phi}{3 \times 10^{13} \text{ GeV}} \right)^{7/2} \left( \frac{y_\phi}{2.9 \times 10^{-5}} \right)^7 \]

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\[ \Omega h^2 = \left( \frac{B_R}{2.0 \times 10^{-9}} \right) \left( \frac{T_{RH}}{M_\Phi} \right) \left( \frac{M_{DM}}{10^{10} \text{GeV}} \right) \]

\[ B_R = \frac{\Gamma_{\Phi \rightarrow DM} \cdot DM}{\Gamma_\Phi} \]