Physics of the Mysterious ANITA events

Invisibles19 Workshop

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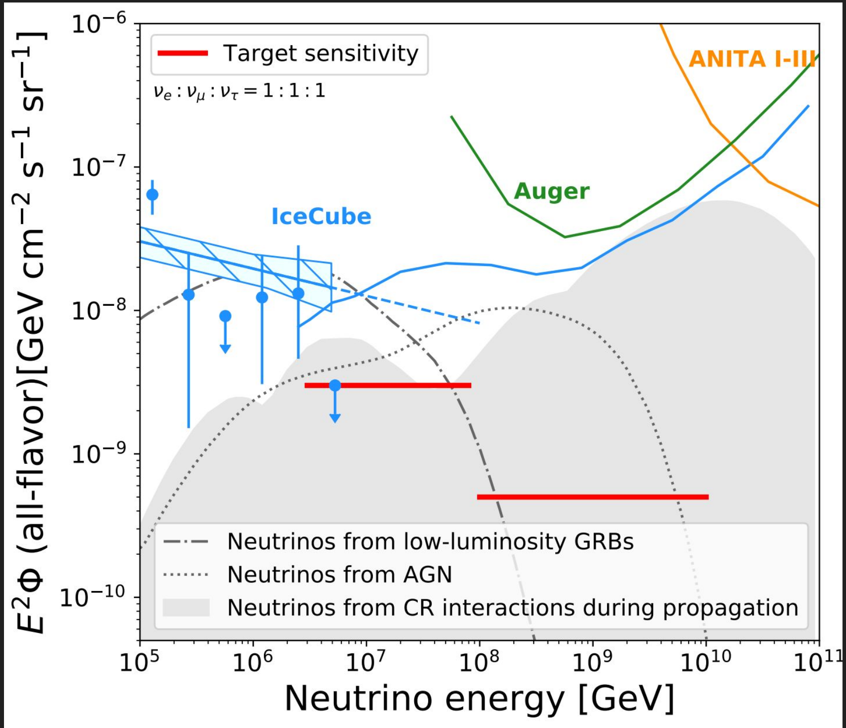
arXiv:1905.10372

Motivation: searching astrophysical neutrinos

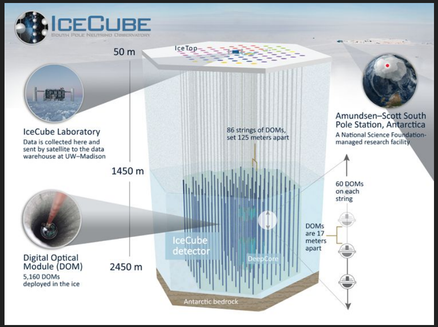


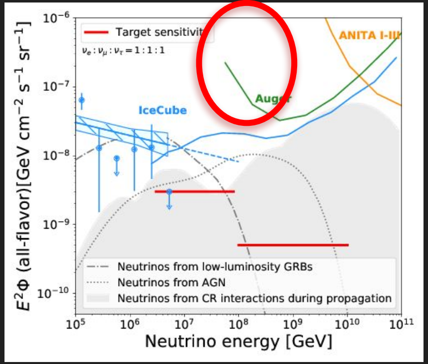
- IceCube is already seeing the universe with Neutrinos.
- The highest energy events are huge in size and energy!
- ANITA is intended to go to the highest energies expected using even larger volumes.

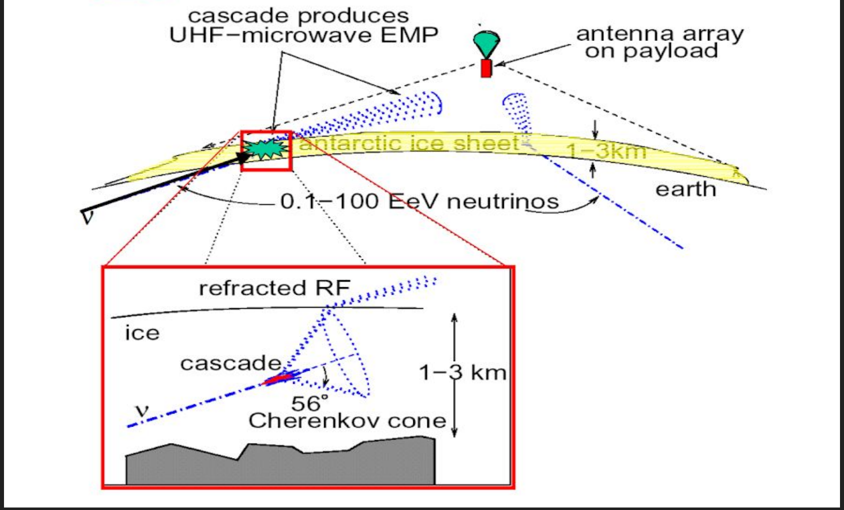
Fig. from: arXiv:1903.04334 Markus Ackermann, et.al.

ANtarctic Impulse Transient Antenna

ANITA concept:





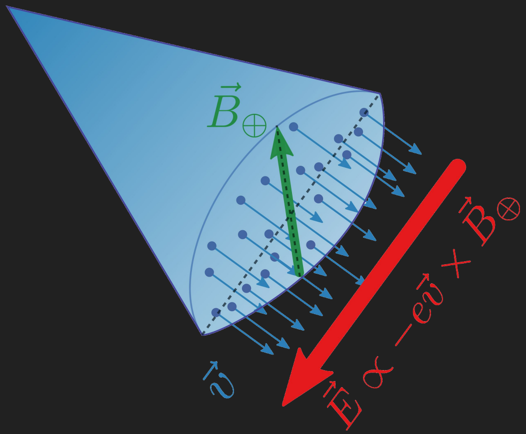


APS meeting 2003 Steve Barwick, UC Irvine

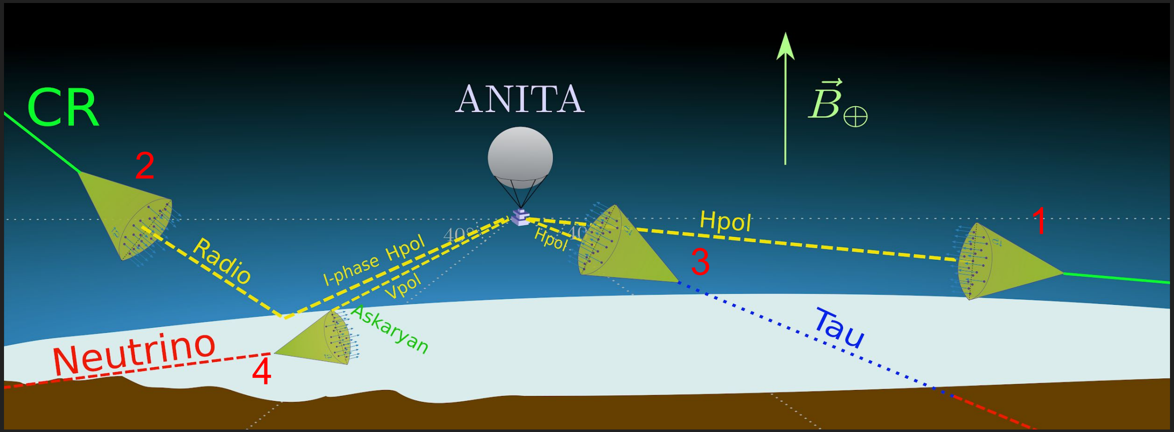
- IceCube has a kilometer cube of instrumented volume.
- ANITA has a much larger target mass but only one detection point measuring a secondary product of the cascade (radio pulse)
- The events need to be HUGE!

$\boxed{10^{19}eV}$ to compare with IceCube

Radio from High E events:



- The B field in Antarctica produces H-pol pulses in the atm-cascades due to the Lorentz force.
- The phase is well determined.
- A cascade in the ice produces V-pol pulse, Askarian radiation (not observed)
- In the reflection process the phase changes sign, and any V component gets suppressed depending on the elevation.
- Coherent and isolated radio pulses are expected.

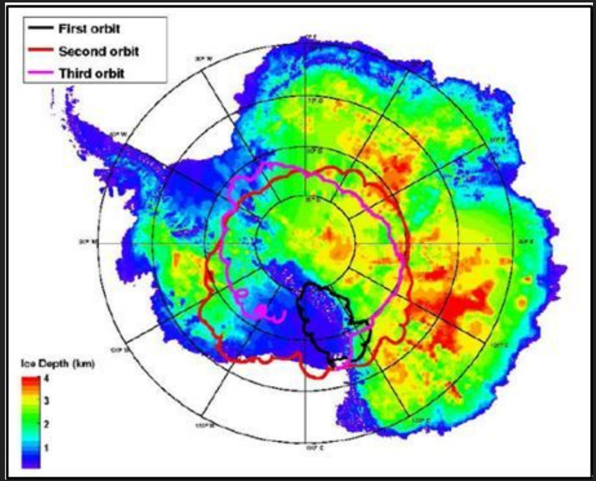


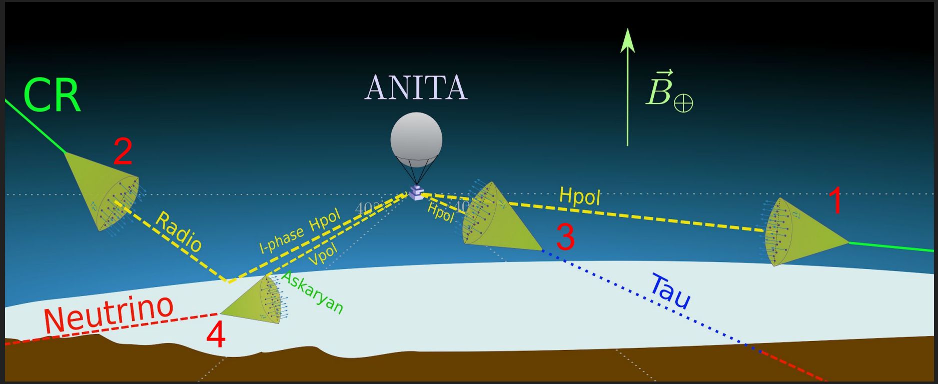
Expected Event types:

1. Direct CR: H-pol, direct phase, above horizon.
2. Reflected CR: H-pol, inverted phase, below horizon.
3. Tau event type: Direct CR like below the horizon. (created by tau neutrino)
4. In ice high energy cascade: Askarian radiation, V-polarized.

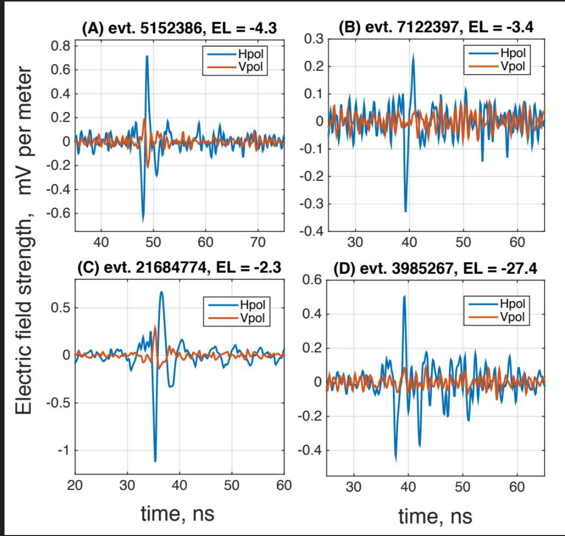
ANITA flights:

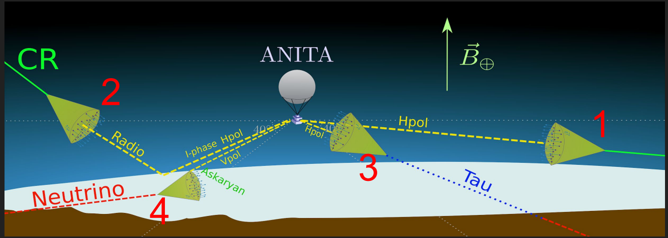
- ANITA-I:
  a. Search: Isolated, impulsive, geocorr signals.
  b. No Askarian neutrino events.
  c. 2 type (1) and 14 type (2) found.
  d. <u>One non inverted phase upgoing CR like</u> (3).
- ANITA-II:
  a. Search: Askarian neutrino events.
  b. Different polarization from UHECR (no CR like events expected).
  c. Some CR of high intensity detected.
- ANITA-III
  a. Search: Isolated, impulsive, signal shape selected.
  b. No Askarian neutrino events.
  c. 3 type (1) and 17 type (2) found.
  d. <u>One non inverted phase upgoing CR like</u> (3).



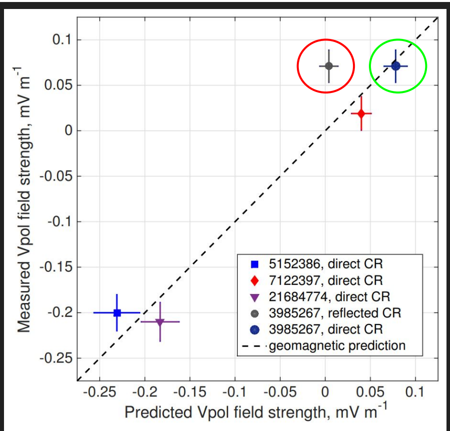


ANITA-I anomalous event



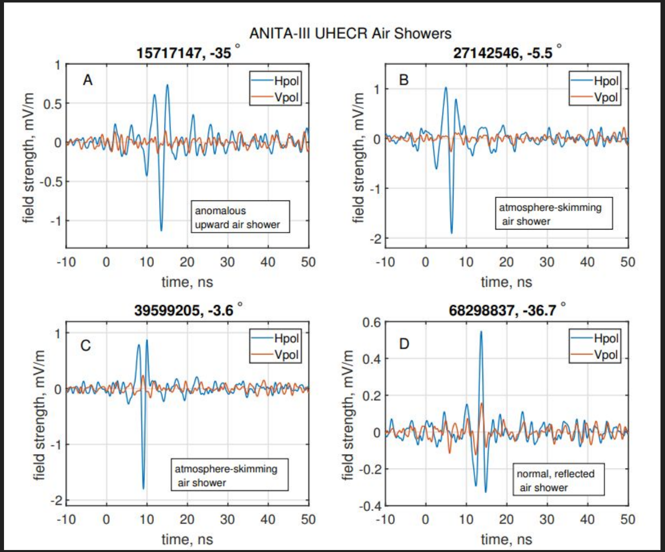


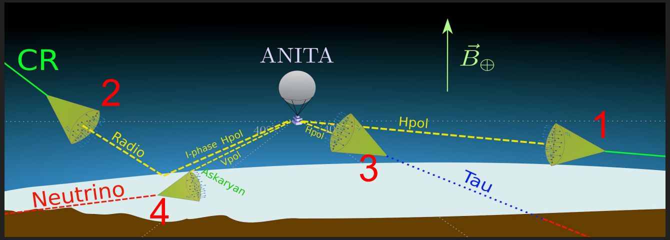
- Events A, B, C are type (1) [2 ANITA-I 1 ANITA-II].
- Event D at -27.4 degrees below the horizon can only be type (2) or (3) since is geocorrelated (~Hpol).
- The phase is consistent with a direct event.
- The small V-pol after reflection is too large before to be type (2).



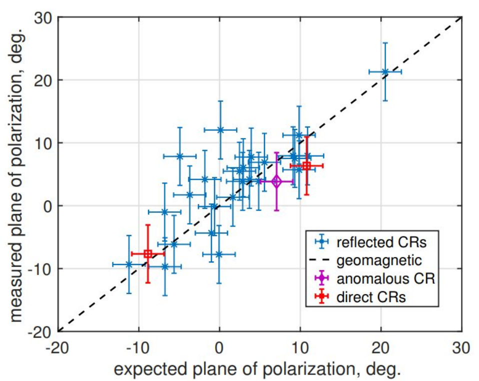
Phys.Rev.Lett. 117 (2016) no.7, 071101 ANITA collaboration

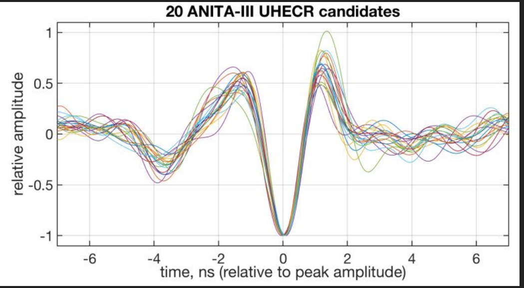
ANITA-III anomalous event





- Events B and C are type (1)
- Event D is type (2), inverted phase at a similar direction.
- Event A seams to be again type (3), direct phase and consistent polarization.
- The shape used to trigger in ANITA-III also seems consistent.





Phys.Rev.Lett. 121 (2018) no.16, 161102
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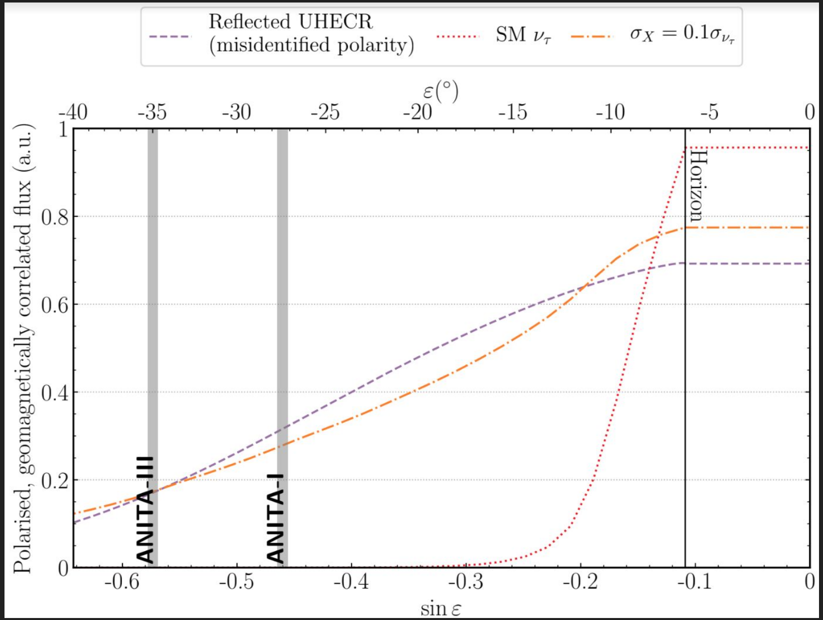
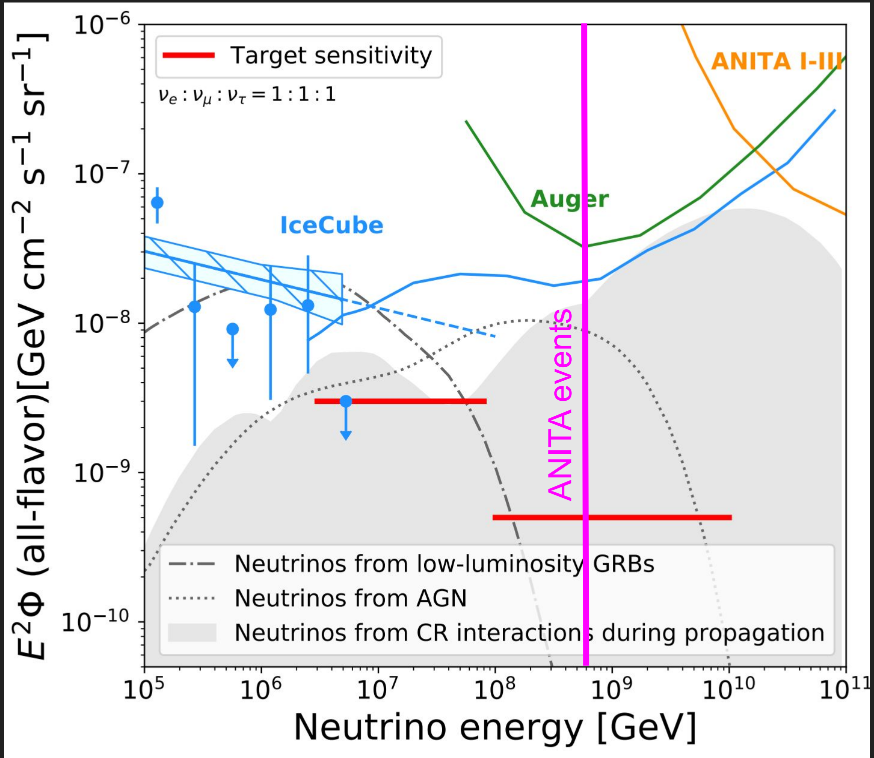
Are these Tau events?



- SM neutrino very unlikely for an isotropic flux, negligible number of events below -15 degrees.
- Smaller cross section may help, but BSM is needed.
- A reflected CR origin is only possible if ANITA misidentified the phase.

High energy origin



- Measuring these events at this energies is also in strong tension with IceCube and Auger.
- Previous BSM(steriles, CPT, HeavyDM,...) explanations involve an initial high energy vertex originating a particle cascade. Strong tension with IceCube and Auger due to the energy and larger exposure.

No isotropic flux assumed!

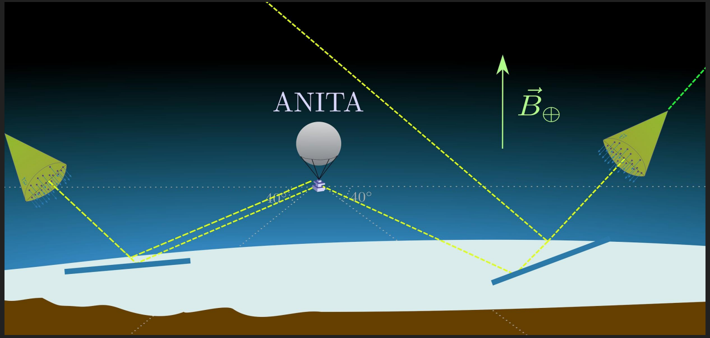
[1809.09615, 1802.01611, 1803.11554, 1804.05362, 1810.08479, 1902.04584, 1904.12865, 1904.13396]

Recent non-BSM explanations

ICE structures:

[1905.02846, Ian M. Shoemaker et. al.]

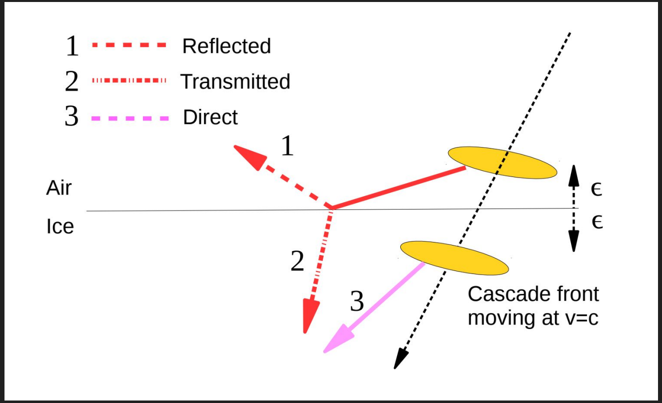
- A layer with smaller refraction index may produce a second reflection with the right phase.
- >7% of antarctica needs to have this structures.
- The structures should be always tilted to avoid production of rare double events.
- HiCal calibration doesn't seem to agree, it produces CR like pulses for calibration during the flight [1703.00415, 1801.08909]



Transition Radiation:

[1903.08750 , K. D. de Vries and S. Prohira]

- It predicts Hpol due to the Fresnel coefficients and one of the events is already in tension at 2.5 sigma.
- ANITA has CR reflected events also at steeper angles (a priori better to see this effect) don't see it.



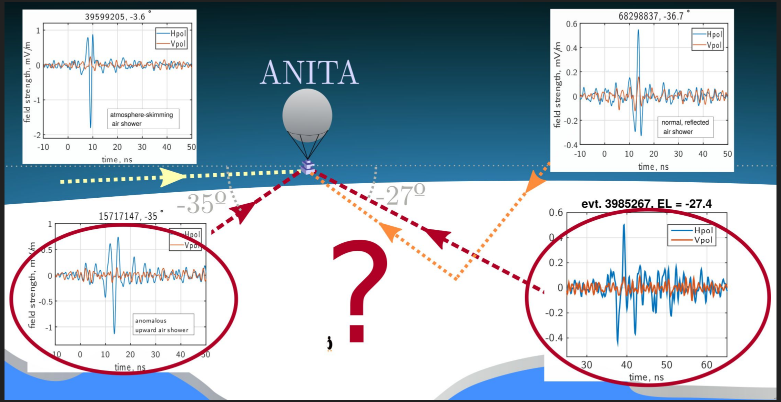
Let's summarize and try BSM again:

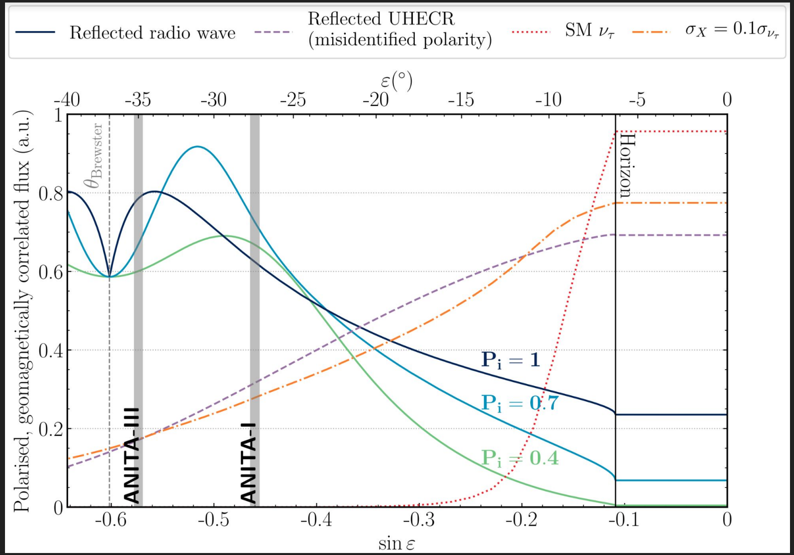
Facts:

1. ANITA saw two mysterious events.
2. Direction + IceCube and Auger bounds: strong tension with SM.
3. BSM high energy, O(EeV), explanations disfavored by IceCube and Auger.

Observations:

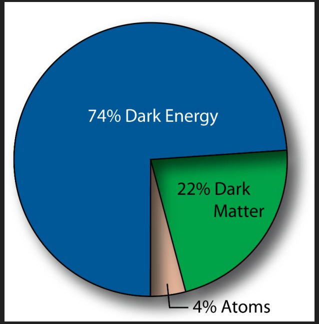
- Any pulse with arbitrary polarization will look Hpol ~ geocor ~ CR like at elevations closer to the Brewster angle (-37 degrees) (2).
- Can we produce (with BSM?) down going pulses of radio with the right phase (1) such that:
  - Do not involve high Energies (3).
  - Polarization different from CR (2).





Non trivial DM axions

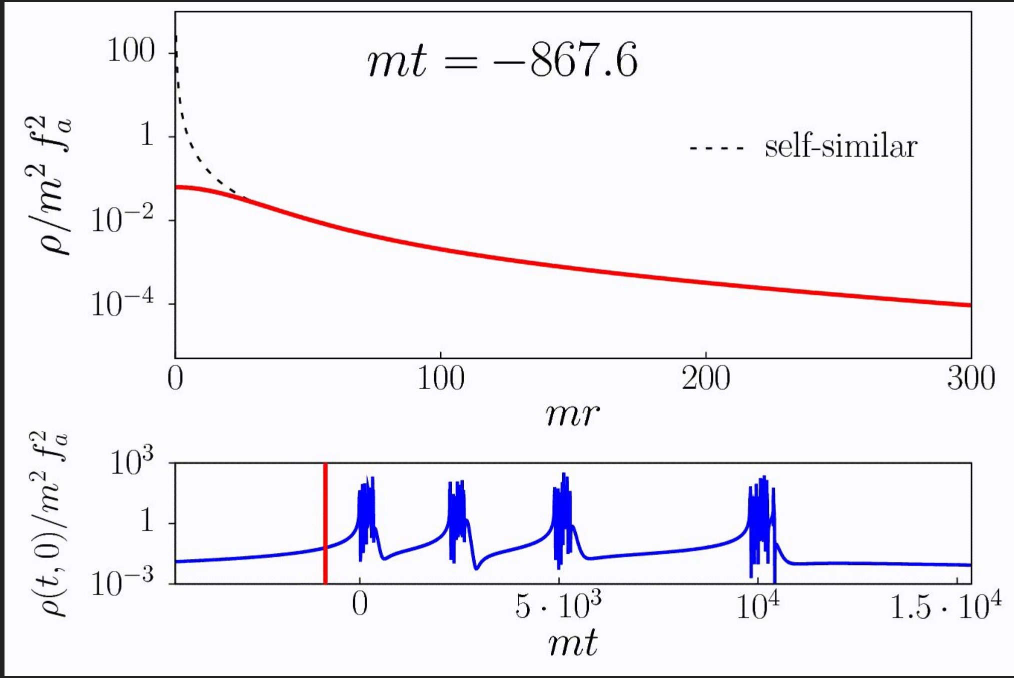
About 80% of the non relativistic content is DM in the universe!



AXIONS?

- Good DM candidate.
- They convert into photons in presence of magnetic field. Radio frequencies correspond to low axion masses.
- Non trivial behaviour due to condensation: rich dynamics in the dark sector.
- High energy not required. Large events can be generated by a classical axion DM field pulse.
- Physics far below IceCube & Auger energy threshold.

Numerical evolution of the AXION instability



Phys. Rev. Lett. 118, 011301 (2017) D.G. Levkov, A.G. Panin, I.I. Tkachev
Phys.Lett.B 777 (2018) 64-72 L. Visinelli, S. Baum, J. Redondo, K. Freese, F. Wilczek

Axion to photon equation of motion

Phys. Rev. Lett. 51, 1415 (1983). P. Sikivie.
Phys. Rev. D37, 1237 (1988). G. Raffelt , L. Stodolsky.

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a^2\right) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\left[\partial_z^2 + \omega^2 + \begin{pmatrix} \boxed{-\omega_p^2} & -i\omega_p^2\frac{\Omega_z}{\omega} & 0 \\ i\omega_p^2\frac{\Omega_z}{\omega} & \boxed{-\omega_p^2} & -g_{a\gamma\gamma}B_y^{\oplus}\omega^2 \\ 0 & -g_{a\gamma\gamma}B_y^{\oplus} & \boxed{-m_a^2} \end{pmatrix}\right]\begin{pmatrix} E_x \\ E_y \\ a \end{pmatrix} = 0$$

The two fields are described by coupled second order differential equations.

Characteristic frequencies:

- Axion mass.
- Plasma frequency (effective photon mass).

Small coupling terms:

- Axion to photon conversion.
- Faraday rotation therms.

If the conversion happens in a region with free electrons

$$\omega_p = \sqrt{\frac{4\pi\alpha}{m_e} n_e}$$

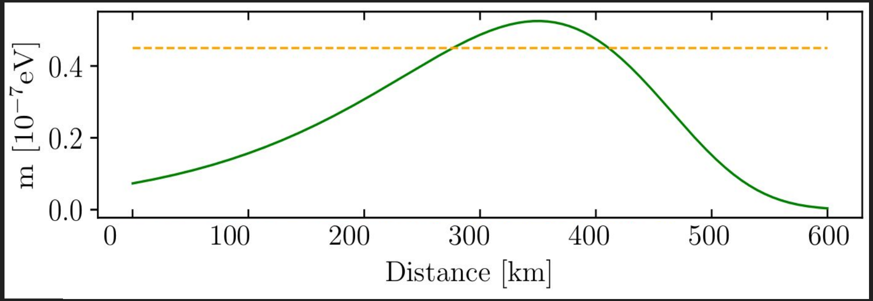
<u>See Ivan's talk and poster</u>

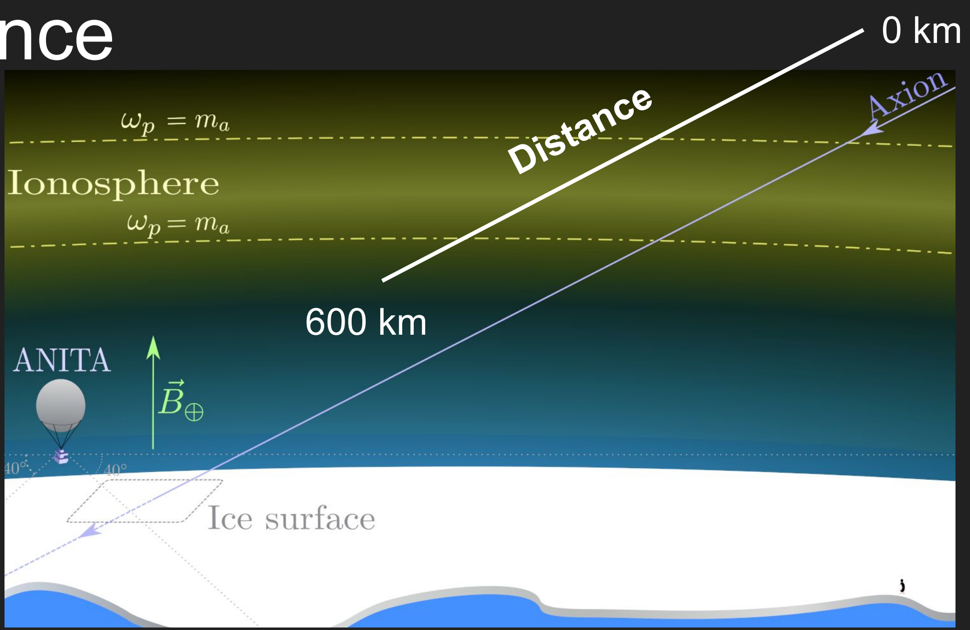
Ionosphere effect: Resonance

$$\left[\partial_z^2+\omega^2+\begin{pmatrix}-\omega_p^2 & -i\omega_p^2\frac{\Omega_z}{\omega} & 0\\ i\omega_p^2\frac{\Omega_z}{\omega} & -\omega_p^2 & -g_{a\gamma\gamma}B_y^{\oplus}\omega^2\\ 0 & -g_{a\gamma\gamma}B_y^{\oplus} & -m_a^2\end{pmatrix}\right]\begin{pmatrix}E_x\\ E_y\\ a\end{pmatrix}=0$$

$=$

Chapman-layer ionospheric profile
[Chapman 1931, Kelley:2009]





After resonance Faraday rotation occurs: more in Ivan Esteban's poster and talk.

Resonance for typical free electron densities of the ionosphere:

Plasma frequency ~ Axion mass ~ ANITA frequencies

Ionosphere: Solution

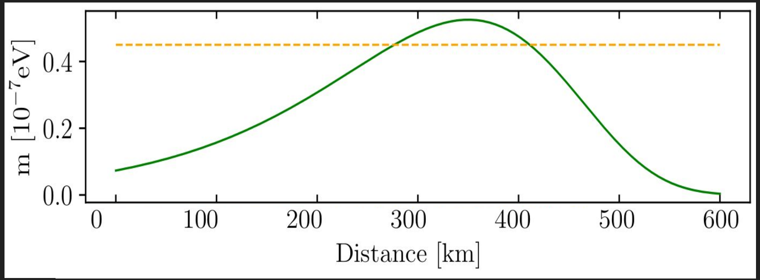
The equation can be solved analytically in the WKB stationary phase approximation:

$$|E|^2 = |a_0|^2 \left(\frac{2 g_{a\gamma\gamma} B_y^{\oplus} \omega^2}{m_a^2} \right)^2 \boxed{\left[\frac{\pi}{4} \frac{m_a^2/k^2}{\left. \frac{d\omega_p^2/m_a^2}{k\,dz} \right|_{\text{res}}} \right]}$$

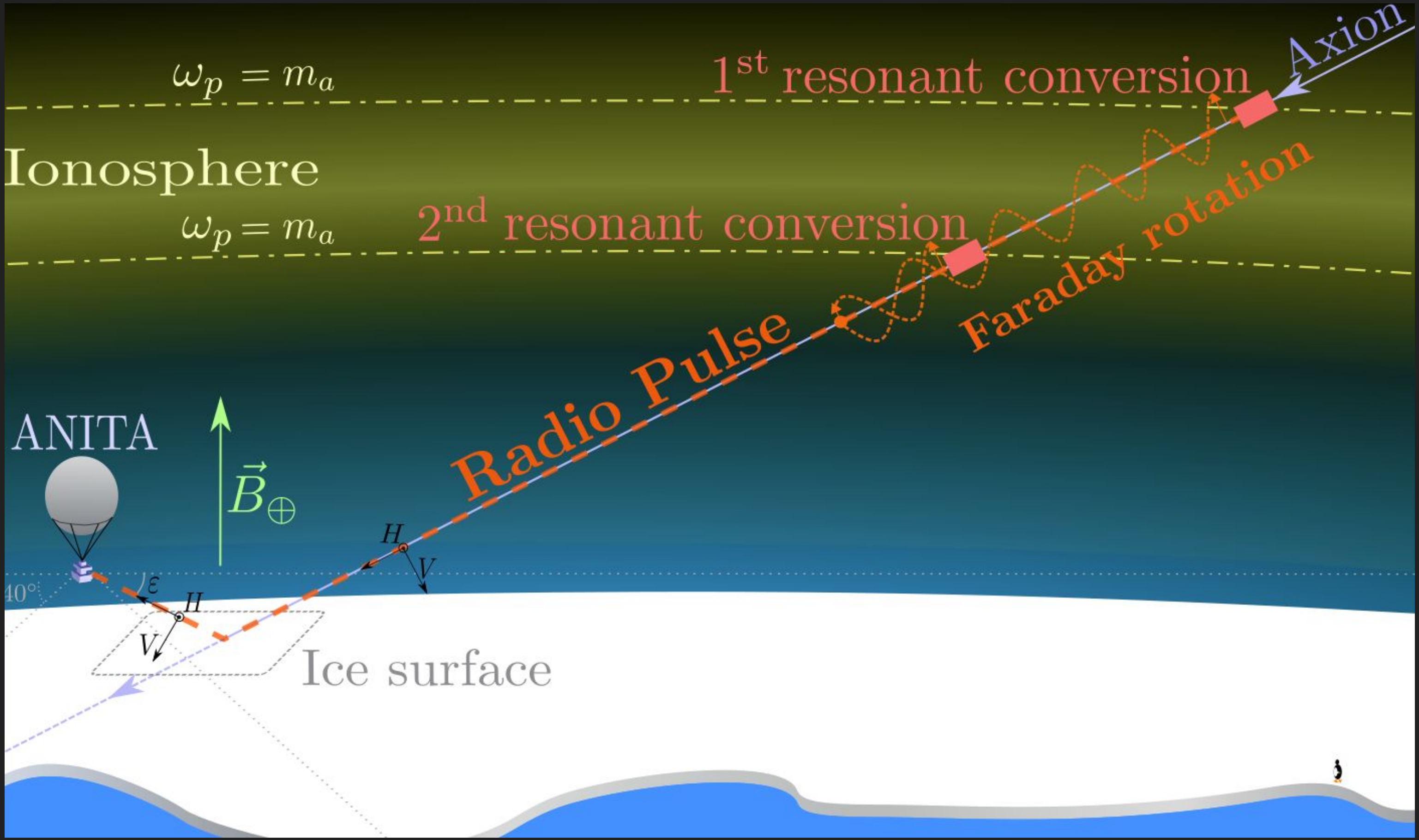
Derivative of plasma frequency at resonance.

Enhancement of the transition O(1000)

The localization of the process helps to keep it coherent.



Global picture

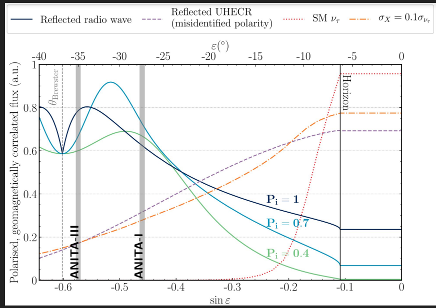


Spectrum and phase

Discriminating Different Explanations and Signatures

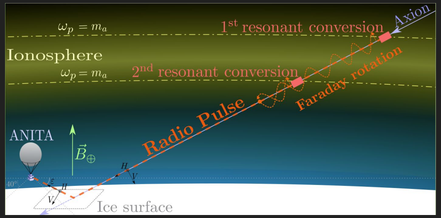
Reflection hypothesis:

- More vertically polarized events would be found closer to the horizon.
- More statistics may reveal the directional distribution.



Axion hypothesis:

- Relaxing the requirement of coherence or geocorr would reveal double impulsive events with different polarization and coherence. (not the same as double surface reflection)
- Correlation with the Ionosphere activity may be interesting.



Conclusions

- ANITA has measured 2 anomalus CR like upgoing events.
- SM explanation is challenging due to directionality and IceCube and Auger bounds.
- High energy **BSM** explanations generically disfavored by IceCube and Auger.
- The direction can be explained via reflection since the phase can not be a discriminating factor.
- Classical dark sector Axion pulse origin can not be constrained by IceCube and Auger.
- The **fourth ANITA flight** is being analysed and hopefully we will learn more.

Thanks!