Axionic Origin of the Mysterious ANITA Events

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In collaboration with:

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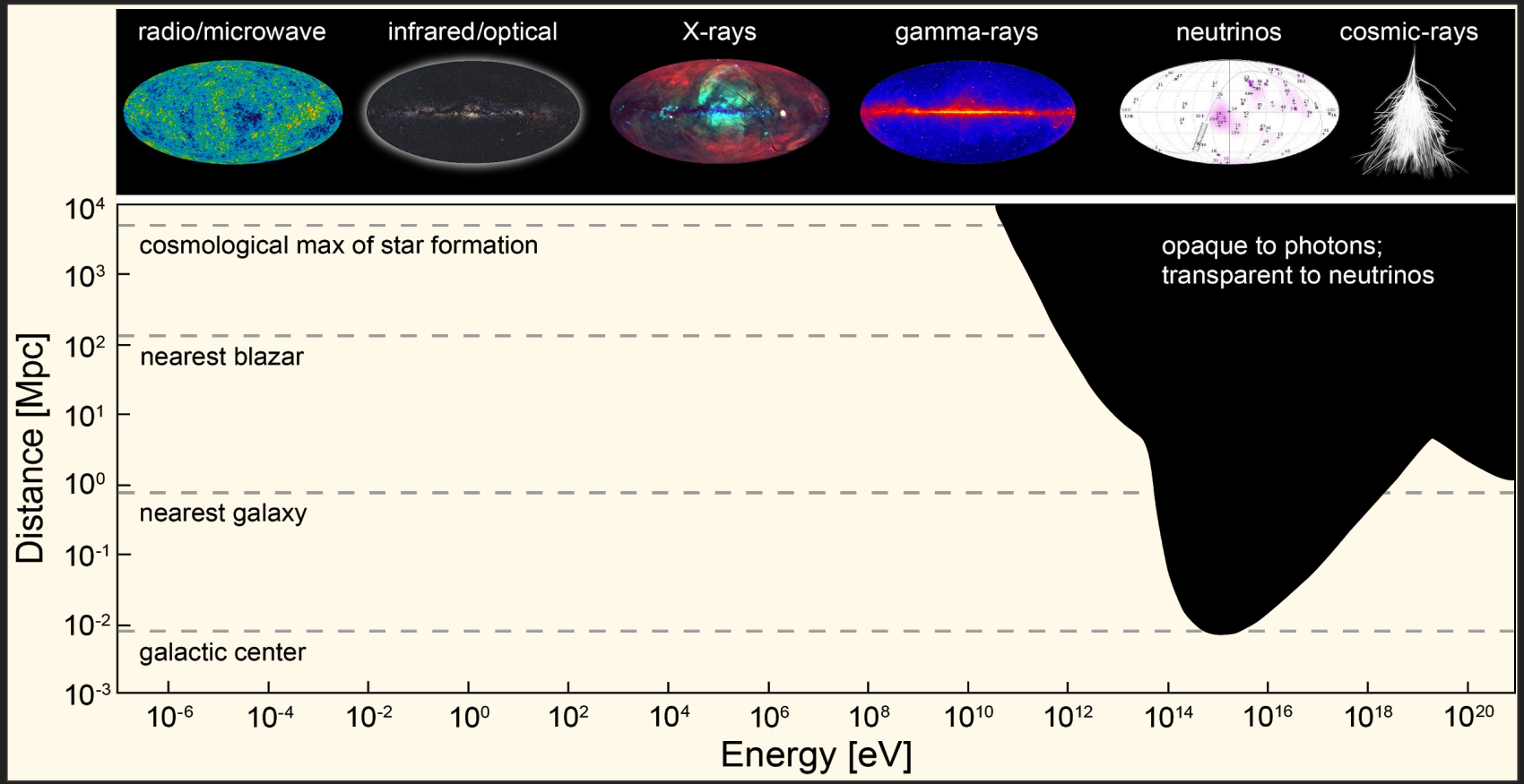
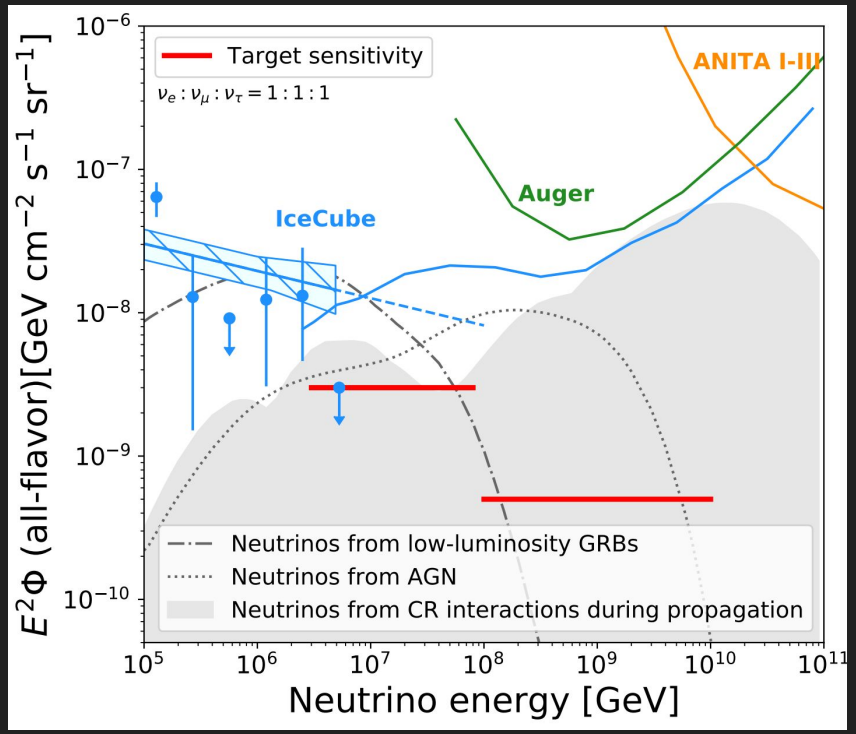
arXiv:1905.10372

Why Neutrino Telescopes



Motivation: searching astrophysical neutrinos

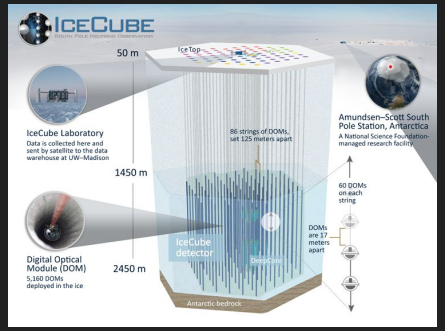


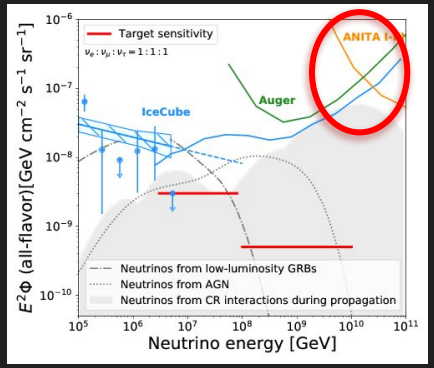
- IceCube is already seeing the universe with Neutrinos.
- The highest energy events are huge in size and energy!
- ANITA is intended to go to the highest energies expected using even larger volumes.

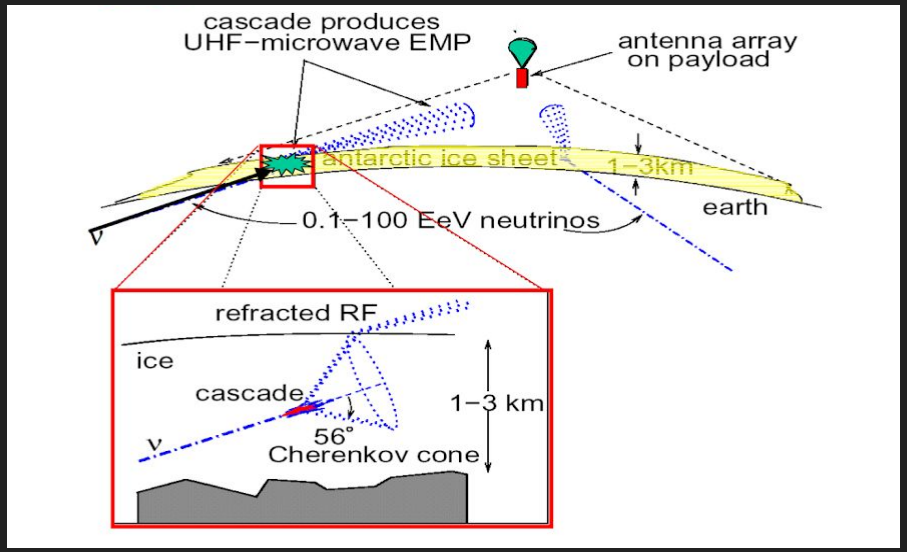
Fig. from: arXiv:1903.04334 Markus Ackermann, et.al.

ANtarctic Impulsive Transient Antenna

ANITA concept:







APS meeting 2003 Steve Barwick, UC Irvine

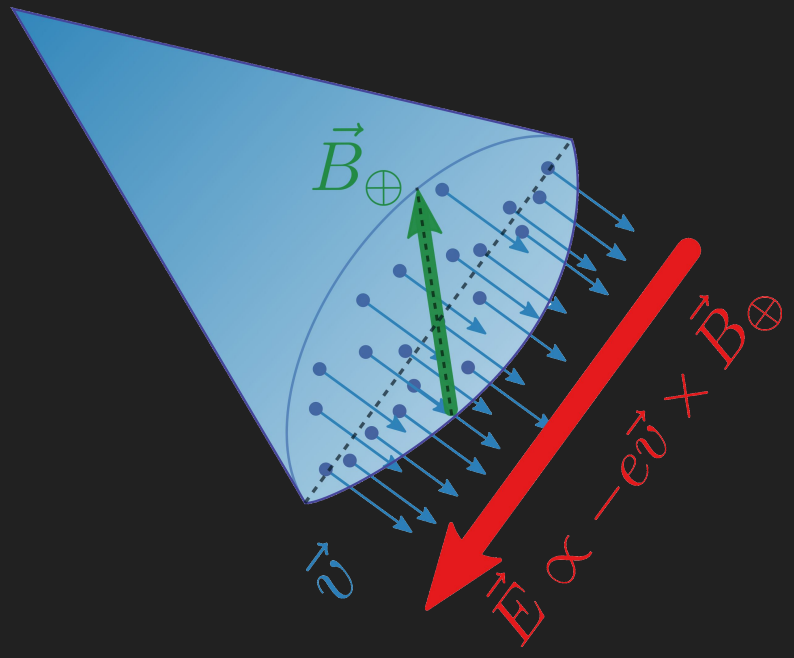
- IceCube has a kilometer cube of instrumented volume.
- ANITA has a much larger target mass but only one detection point measuring a secondary product of the cascade (radio pulse)
- The events need to be HUGE!

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

Physical properties of the expected events:

- Space and Time localization. (Isolated and Impulsive)
- Polarization. (Direction and degree of polarization).
- Phase or Polarity(name used in ANITA papers) or also initial sign of the E field.
- Coherence (Small relative phases of the different modes)

Radio from High E events:



- The B field in Antarctica produces H-pol(geocorr) 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.
- Coherent and isolated radio pulses are expected.

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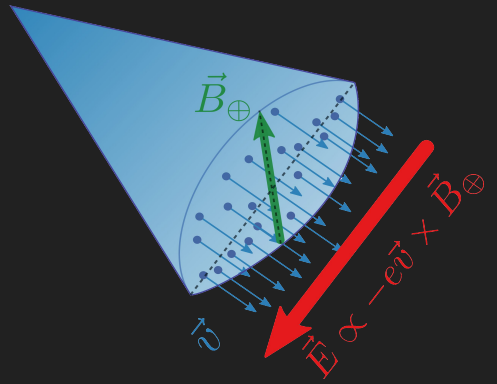

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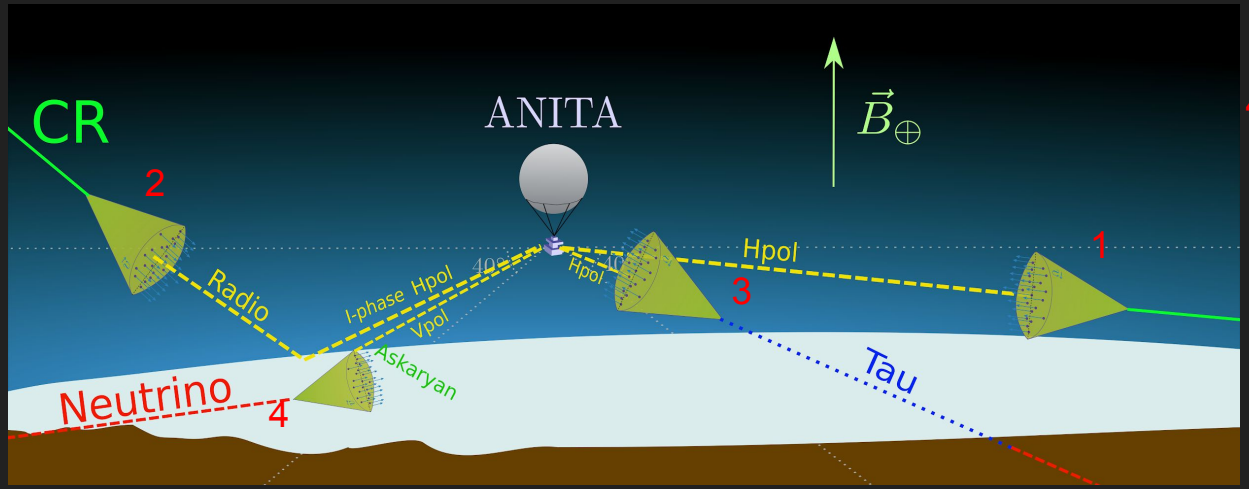
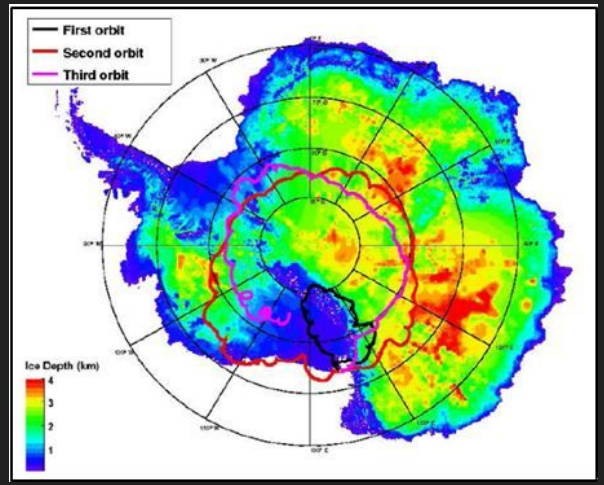
Expected Event types:

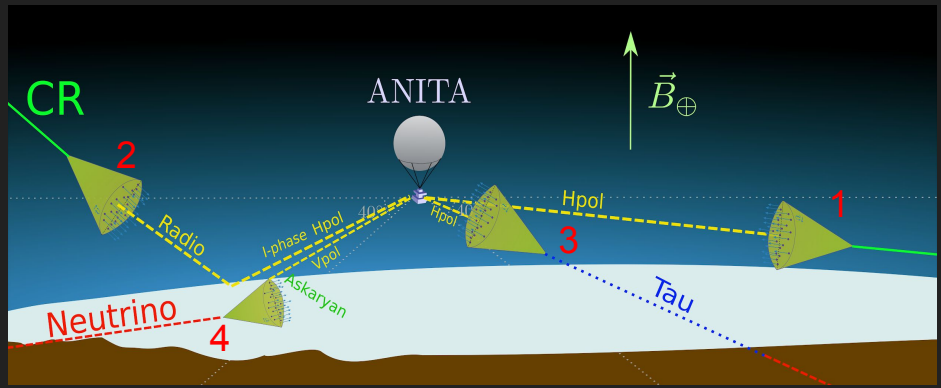
1. Direct CR: H-pol, direct phase, above horizon.
2. Reflected CR: H-pol, inverted phase, below horizon.
3. Tau event type: Direct CR like below the horizon. (created by tau neutrino)
4. In ice high energy cascade: Askarian radiation, V-polarized.



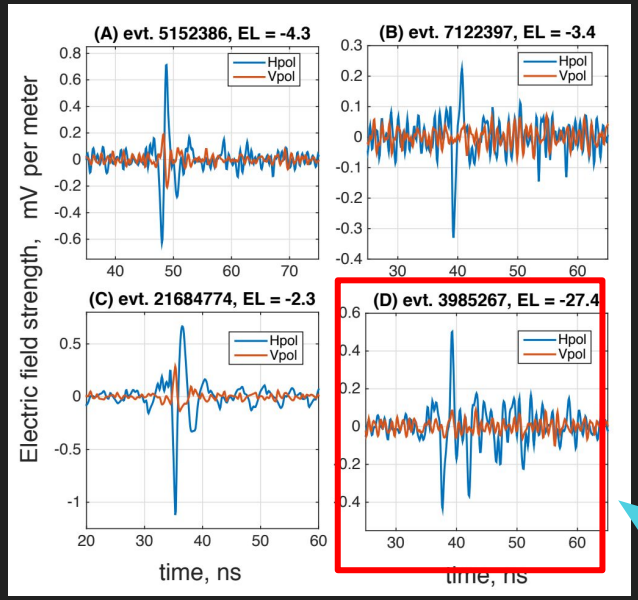
ANITA flights:

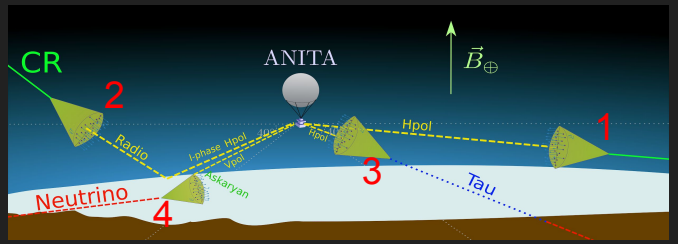
- ANITA-I:
  a. Search: Isolated, impulsive, geocorr signals.
  b. No Askarian neutrino events.
  c. 2 type (1) and 14 type (2) found.
  d. One non inverted phase upgoing CR like (3).
- ANITA-II:
  a. Search: Askarian neutrino events.
  b. Different polarization from UHECR (no CR like events expected).
  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. One non inverted phase upgoing CR like (3).



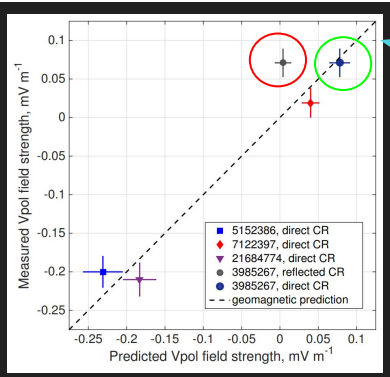


ANITA-I anomalous event



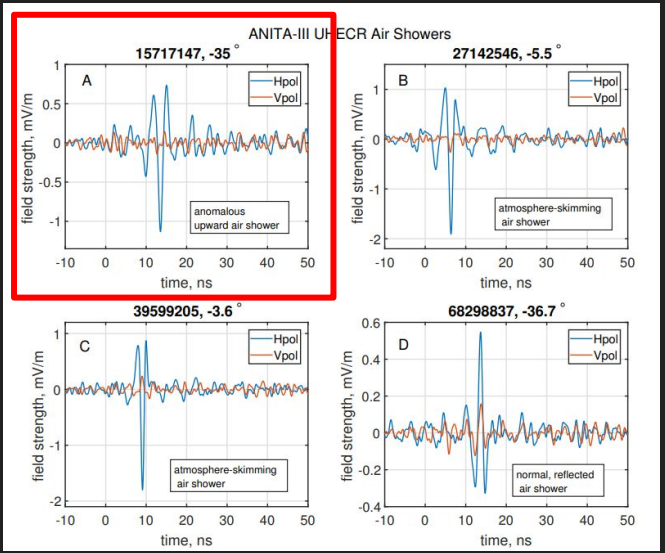


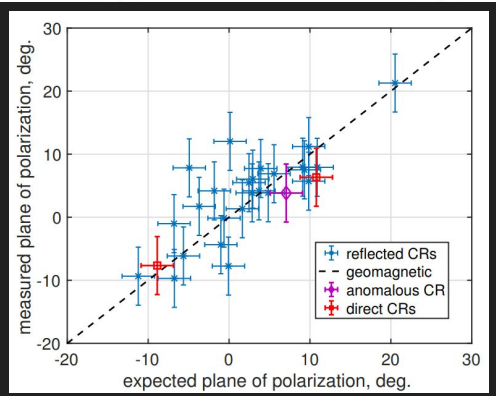
- Events A, B, C are type (1) [2 ANITA-I 1 ANITA-II].
- Event D at -27.4 degrees below the horizon can only be type (2) or (3) since is geocorrelated (~Hpol).
- The phase is consistent with a direct event.
- The small V-pol after reflection is too large before to be type (2).

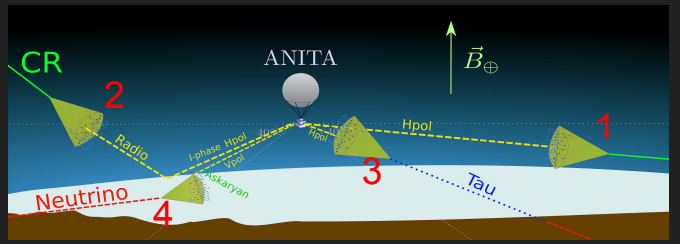


Phys.Rev.Lett. 117 (2016) no.7, 071101 ANITA collaboration

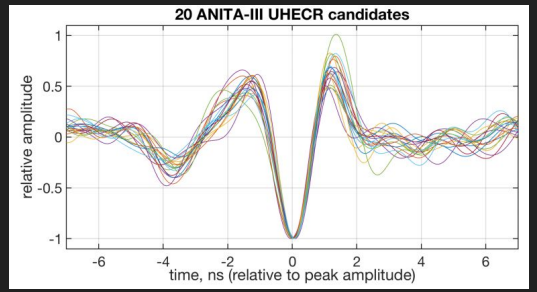
ANITA-III anomalous event







- 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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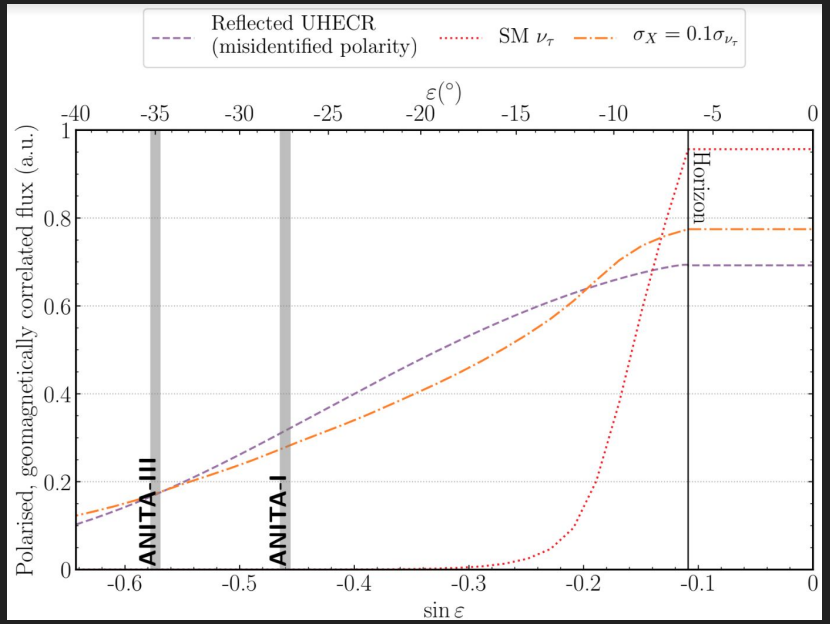
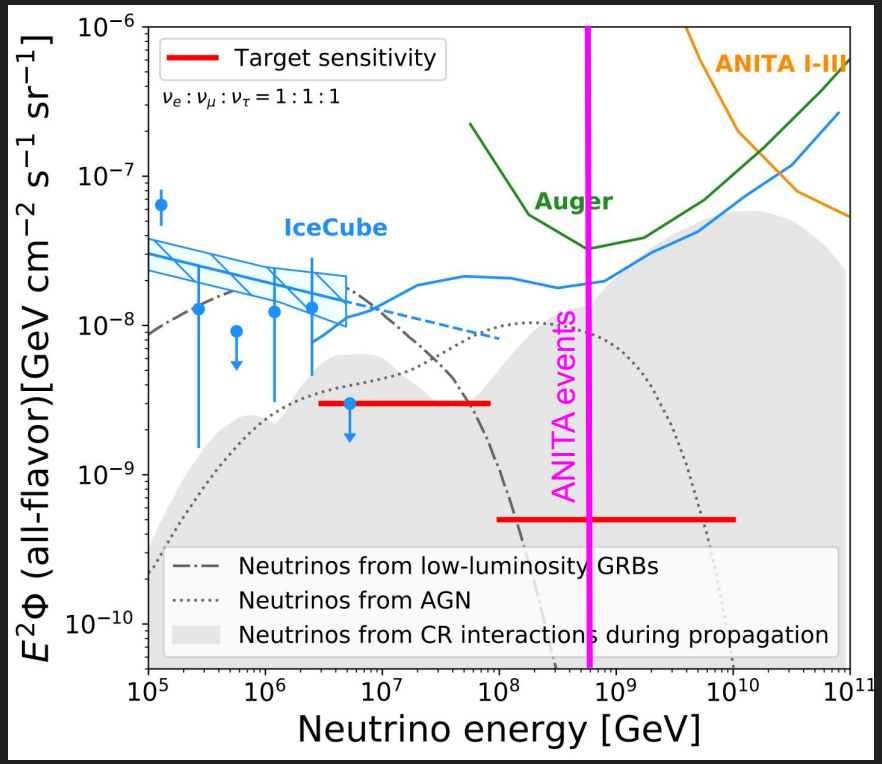
Are these Tau events?



- 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.

For isotropic flux

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!

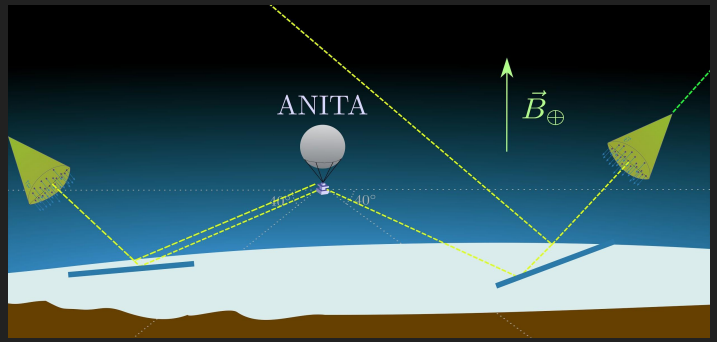
[1809.09615, 1802.01611, 1803.11554, 1804.05362, 1810.08479, 1902.04584, 1904.12865, 1904.13396]

Non-BSM explanations

ICE structures:

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

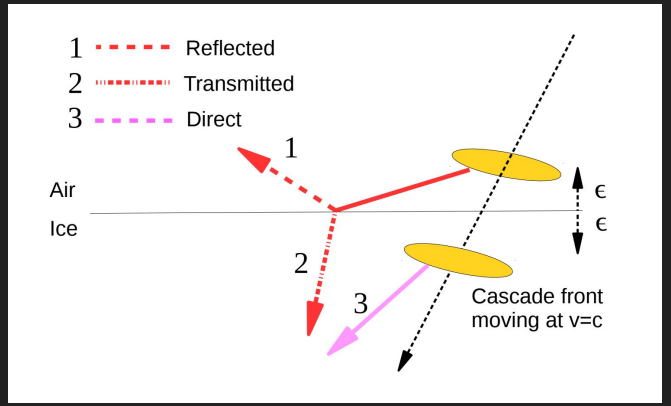
- A layer with smaller refraction index may produce a second reflection with the right phase.
- >7% of antarctica needs to have this structures.
- The structures should be always tilted to avoid production of rare double events.
- HiCal calibration doesn't seem to agree, it produces CR like pulses for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



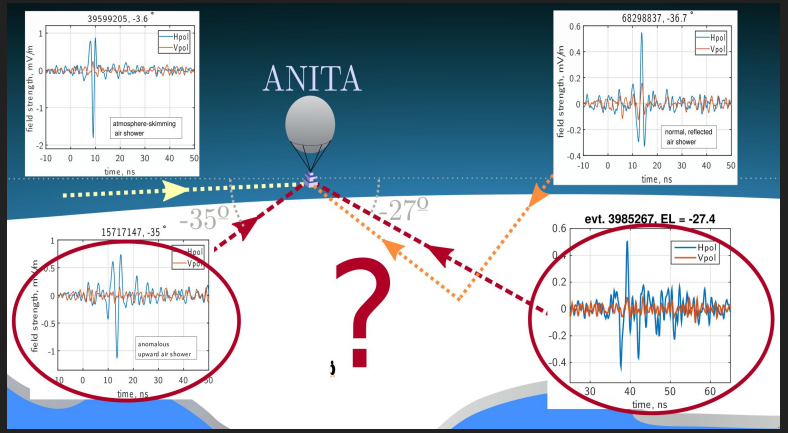
Let's summarize:

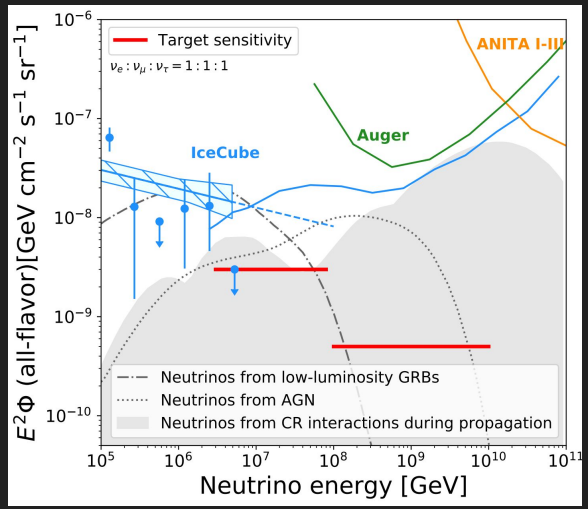
Facts:

1. ANITA saw two mysterious events.

2. Direction + IceCube and Auger bounds: strong tension with SM.

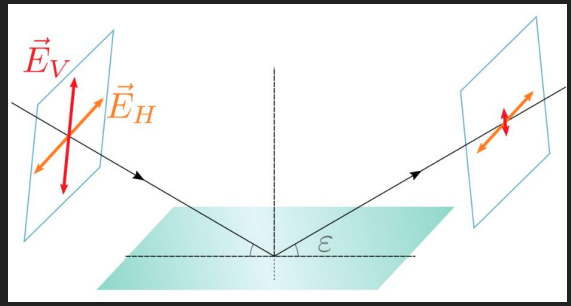
3. BSM high energy, O(EeV), explanations disfavored by IceCube and Auger. (arXiv:1909.10487, arXiv:1907.06308)

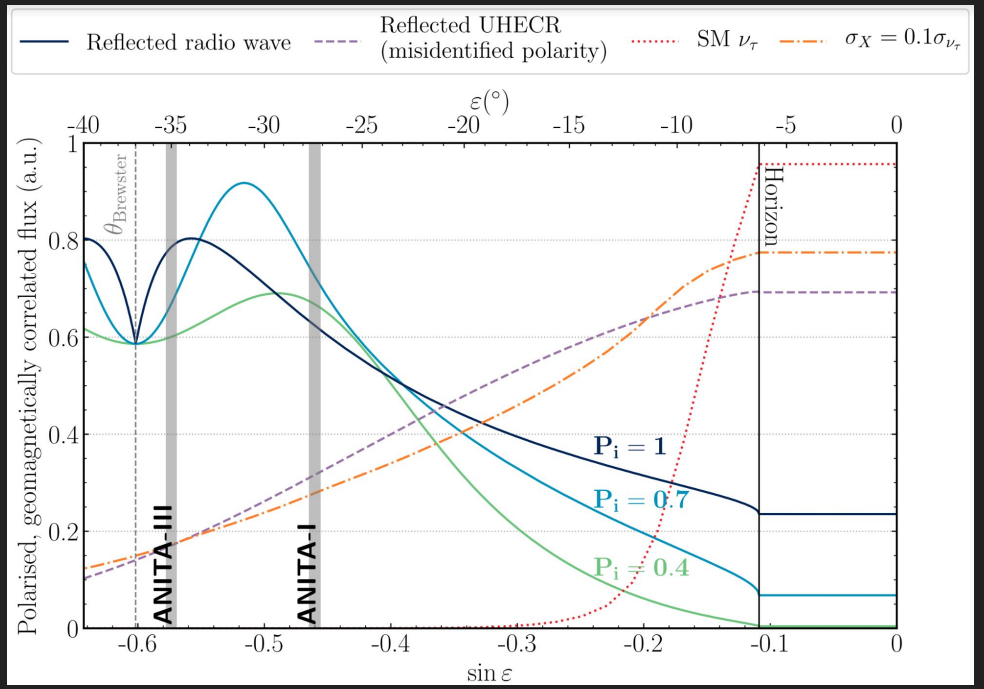




Relevant Observation:

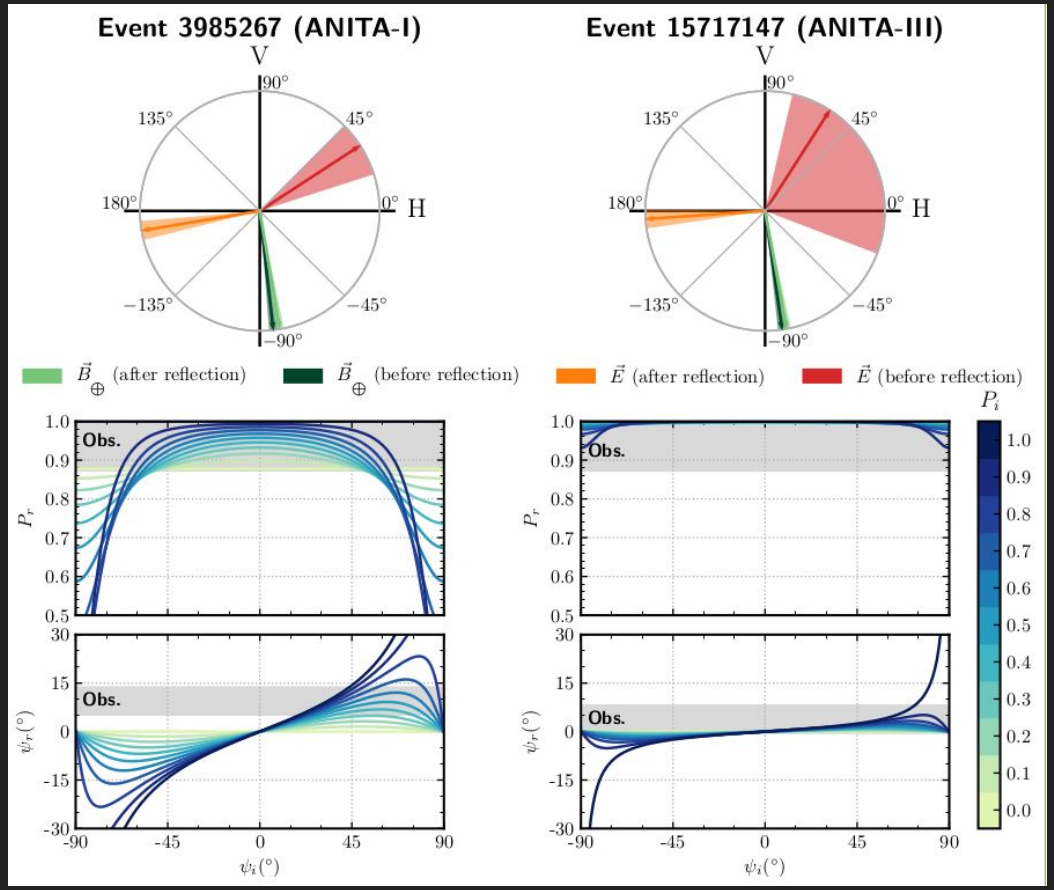
- Any pulse with arbitrary polarization direction will look Hpol ~ geocor ~ CR like at elevations closer to the Brewster angle (-37 degrees) (2).





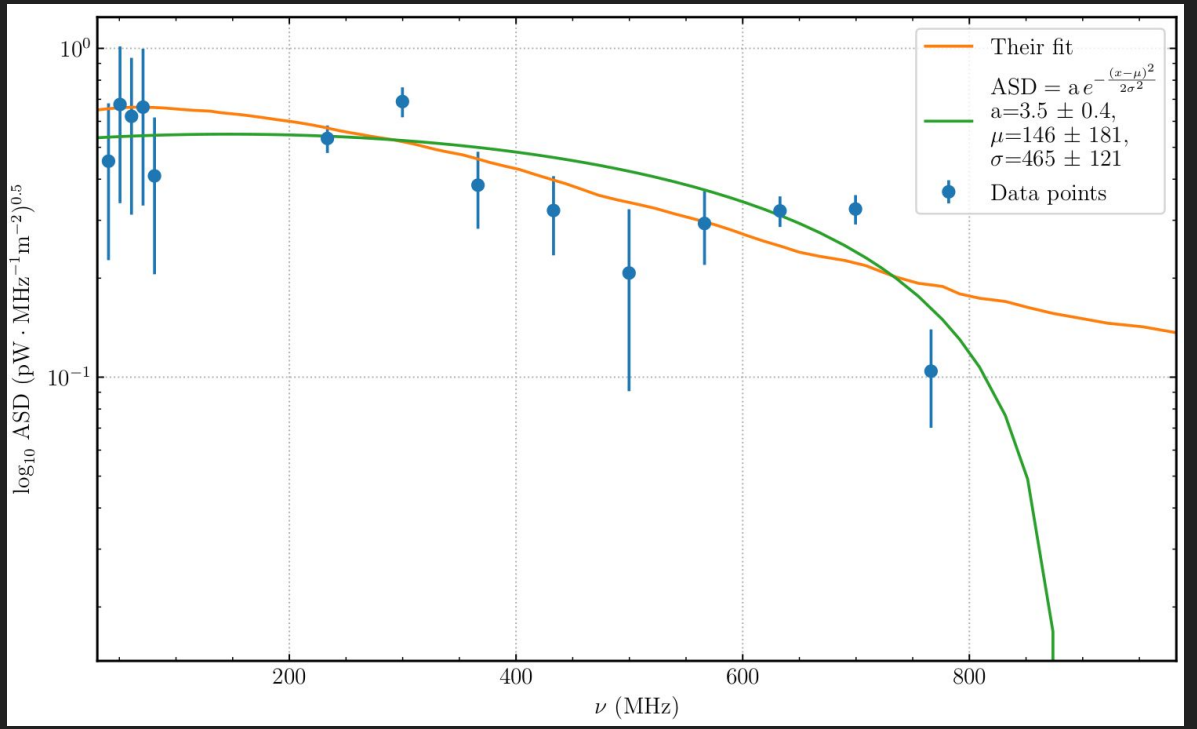
Undoing Reflection

- (Event I) has too much vertical component of polarization.
- (Event II) still compatible with the measured polarization.
- Both have the wrong phase to be reflected CR.



Spectrum and phase

- The spectral part is relatively easy to fit.
- Fitting a gaussian pulse gives large range for the fitting parameters.



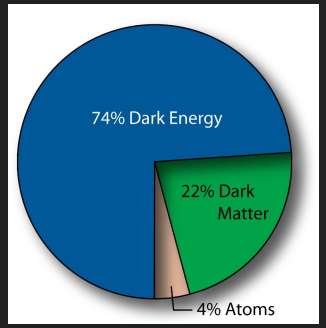
Axion Hypothesis

- Can we produce a Radio Pulse with not CR like polarization and phase, NOT involving High E physics?

- In the presence of a magnetic field and for “radio” frequencies, Axions are a classical candidate. We still need high occupation number.

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 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 very far!! below IceCube & Auger energy threshold.

D. G. Levkov, A. G. Panin and I. I. Tkachev, "Relativistic axions from collapsing Bose stars," Phys. Rev. Lett. **118**, no. 1, 011301 (2017) doi:10.1103/PhysRevLett.118.011301 [arXiv:1609.03611 [astro-ph.CO]].

INR-TH-2016-034

Relativistic axions from collapsing Bose stars

D.G. Levkov,[1,*] A.G. Panin,[1,2] and I.I. Tkachev[1]

[1] *Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary prospect 7a, Moscow 117312, Russia*

[2] *Moscow Institute of Physics and Technology, 141700, Dolgoprudny, Russia*

The substructures of light bosonic (axion-like) dark matter may condense into compact Bose stars. We study collapses of the critical-mass stars caused by attractive self-interaction of the axion-like particles and find that these processes proceed in an unexpected universal way. First, nonlinear self-similar evolution (called "wave collapse" in condensed matter physics) forces the particles to fall into the star center. Second, interactions in the dense center create an outgoing stream of mildly relativistic particles which carries away an essential part of the star mass. The collapse stops when the star remnant is no longer able to support the self-similar infall feeding the collisions. We shortly discuss possible astrophysical and cosmological implications of these phenomena.

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

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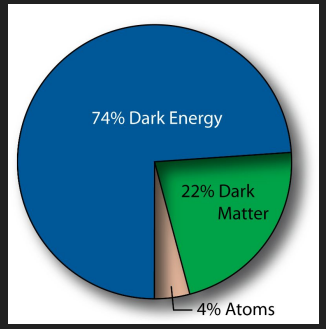

AXIONS?

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- 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.
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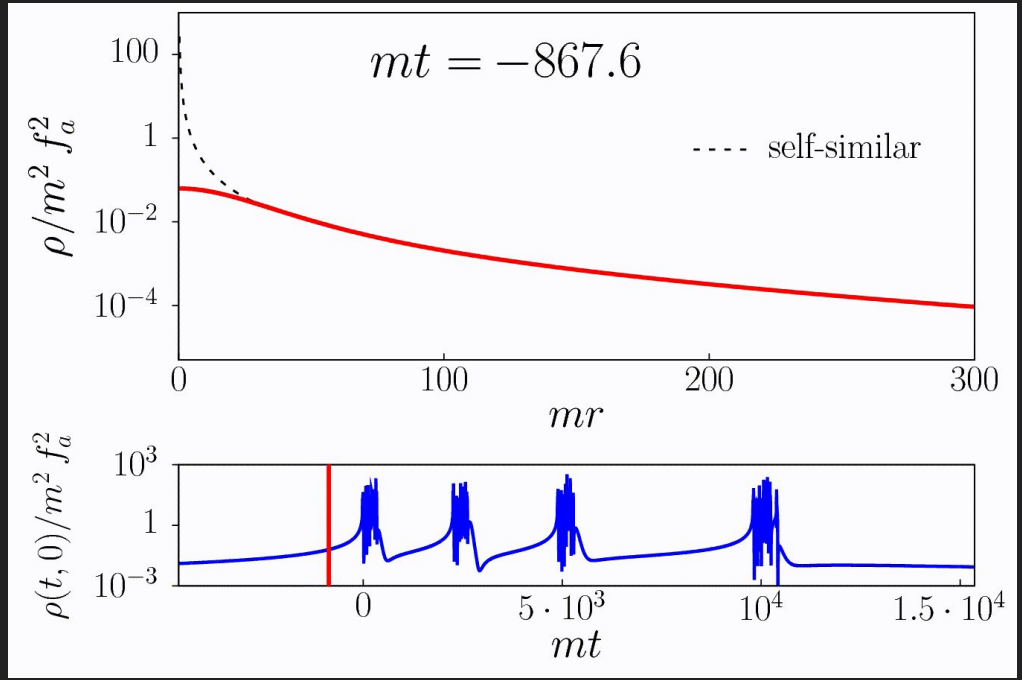
Numerical evolution of the AXION instability



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Phys.Lett.B 777 (2018) 64-72 L. Visinelli, S. Baum, J. Redondo, K. Freese, F. Wilczek

Assumption to test:

Ignoring the motivating complexity of the last two slides.

What happens if:

A pulse of Axion DM field with similar temporal, spatial and spectral properties of the measured events arrives to the Earth.

Axion to photon equation of motion

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

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

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

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

Characteristic frequencies:

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

If the conversion happens in a region with free electrons

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

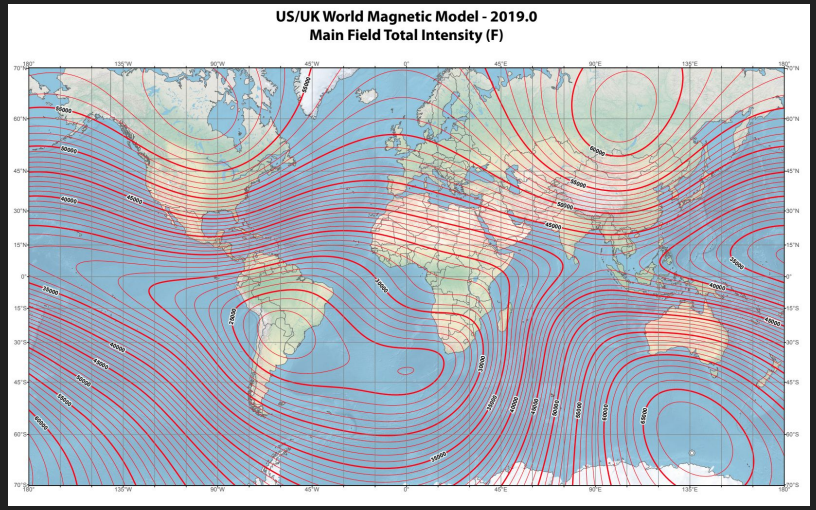
$$\Omega_z = \frac{eB_z^{\oplus}}{m_e}$$

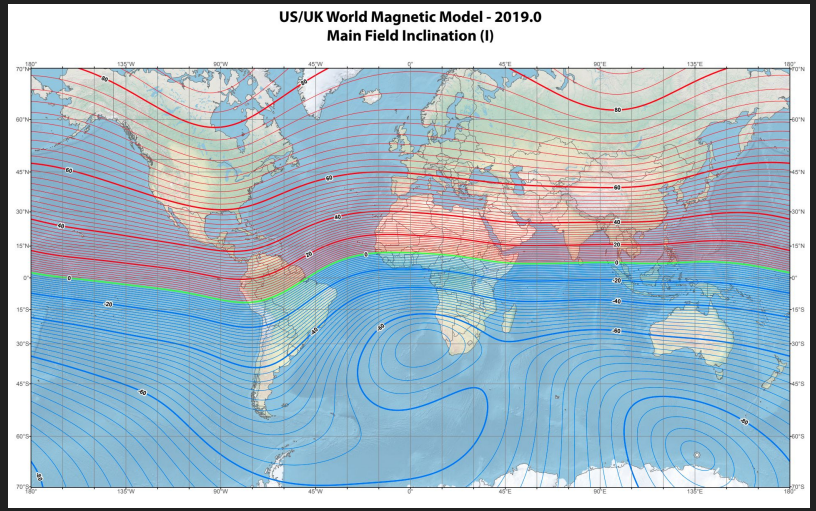
Small coupling terms:

- Axion to photon conversion.
- Faraday rotation therms.

We have a magnetic field

- Pretty well measured by the National Centers for Environmental Information
- In Antartica between 70 and 90 degrees inclination.
- Around 6500nT of intensity

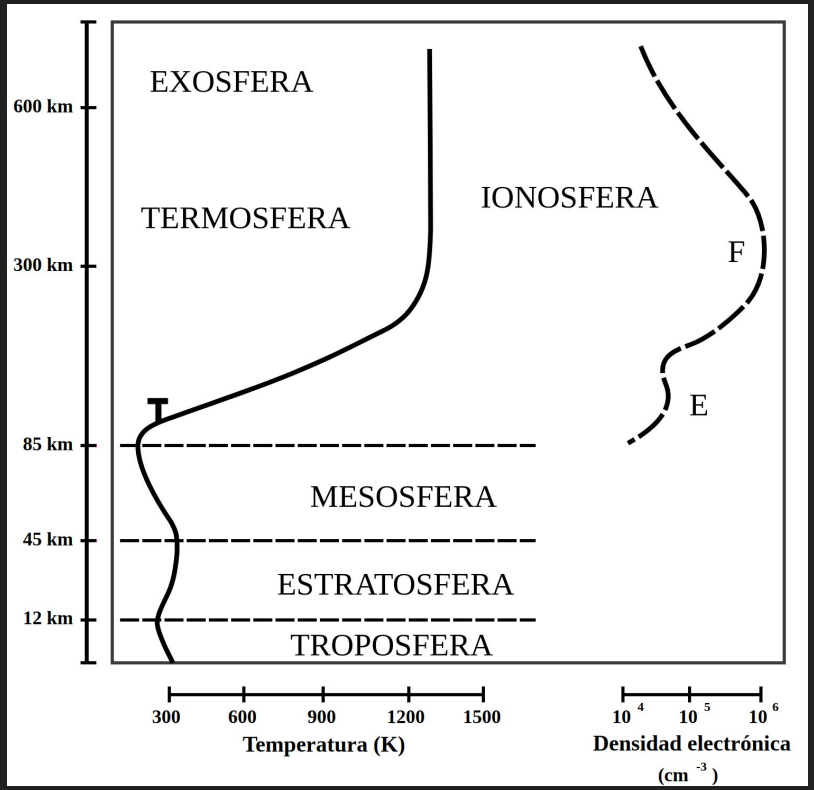




From: https://www.ngdc.noaa.gov

Are there free electrons?

- Yes, in the Ionosphere!
- Ionosphere has between 10^4 to a few 10^6 free electrons per cm^3
- It extends hundreds of km.
- Time variations are very Large, day/night and solar activity.



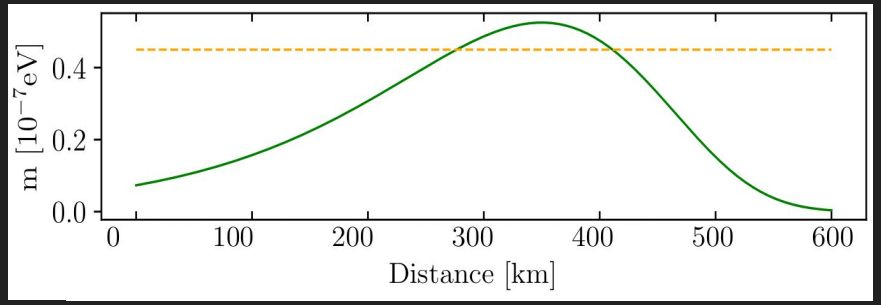
Chapman-layer [Chapman 1931, Kelley:2009]

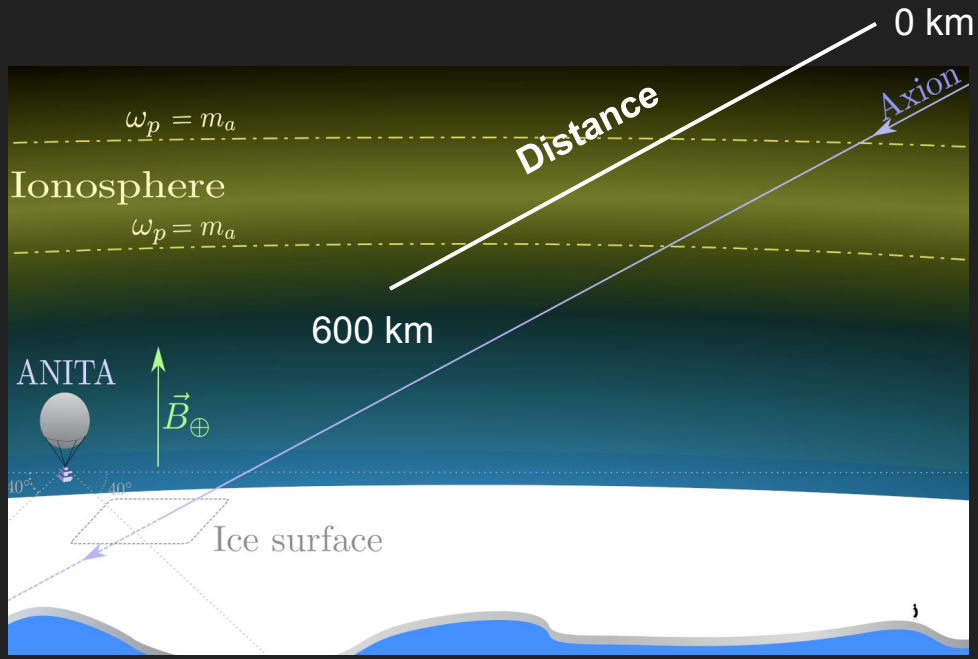
$$n_e(z) = n_e^{\max} \exp\left\{\frac{1}{\alpha}\left[1 - \frac{\mu - z}{\sigma} - \exp\left(-\frac{\mu - z}{\sigma}\right)\right]\right\}$$

Ionosphere effect: Resonance

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

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





Resonance for typical free electron densities of the ionosphere:

Plasma frequency ~ Axion mass ~ ANITA frequencies !!!

Ionosphere: Solution

Both resonant production points can be treated separately.

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

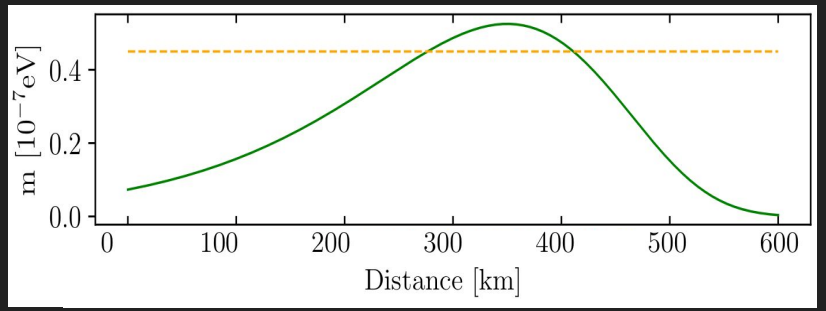
$$|E|^2 = |a_0|^2 \left(\frac{2 g_{a\gamma\gamma} B_y^{\oplus} \omega^2}{m_a^2} \right)^2 \left[\frac{\pi}{4} \frac{m_a^2/k^2}{\left. \frac{\mathrm{d}\omega_p^2/m_a^2}{k\,\mathrm{d}z} \right|_{\mathrm{res}}} \right]$$

Derivative of plasma frequency at resonance.

Enhancement of the transition

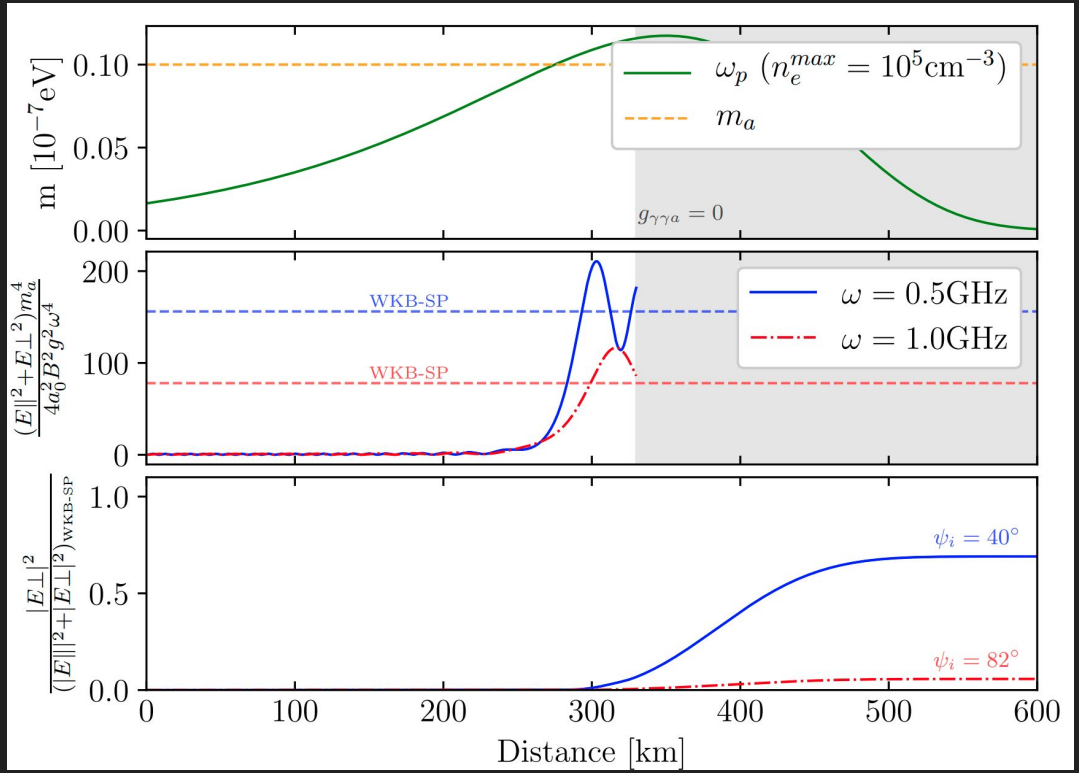
O(1000)

The localization of the process helps to keep it coherent.



Numerical Solution (First resonance)

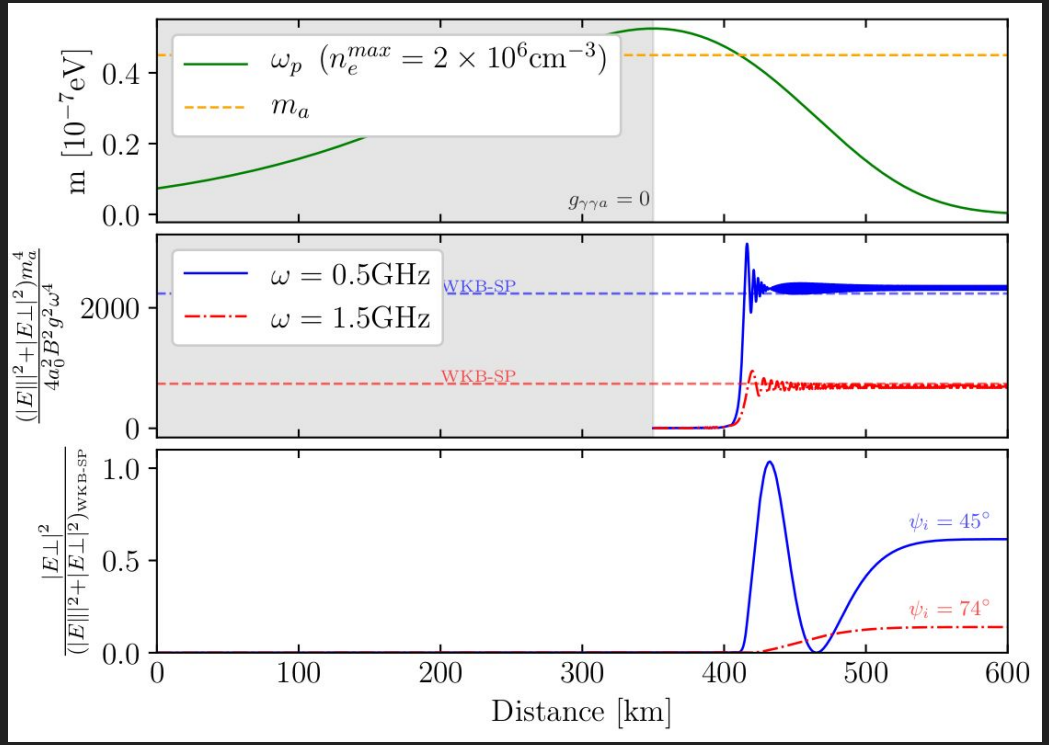
- For relatively low ionization the first resonant may produce a signal:
  - Enough Faraday rotation
  - Still coherent after crossing the remaining ionosphere.
- Second resonance would be:
  - Too vertical -> triggered out by the searches.
  - Also suppressed by reflection.



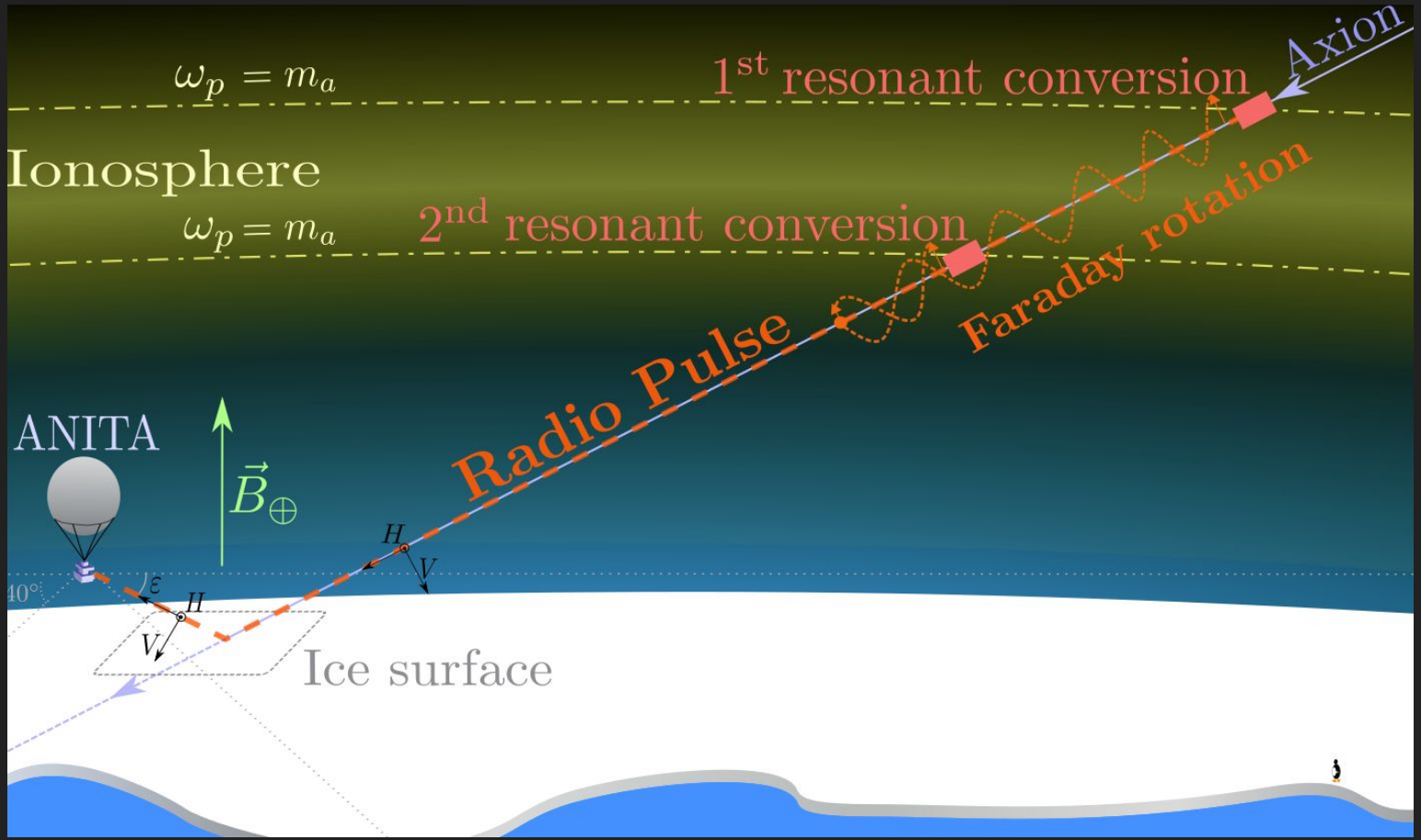
Numerical Solution (Second resonance):

- For relatively high ionization the second resonant may produce a signal:
  - Enough Faraday rotation
  - Still coherent after crossing the remaining ionosphere.

- First resonant would be:
  - Unpolarized.
  - Non coherent radio pulse (frequency). Always triggered out.



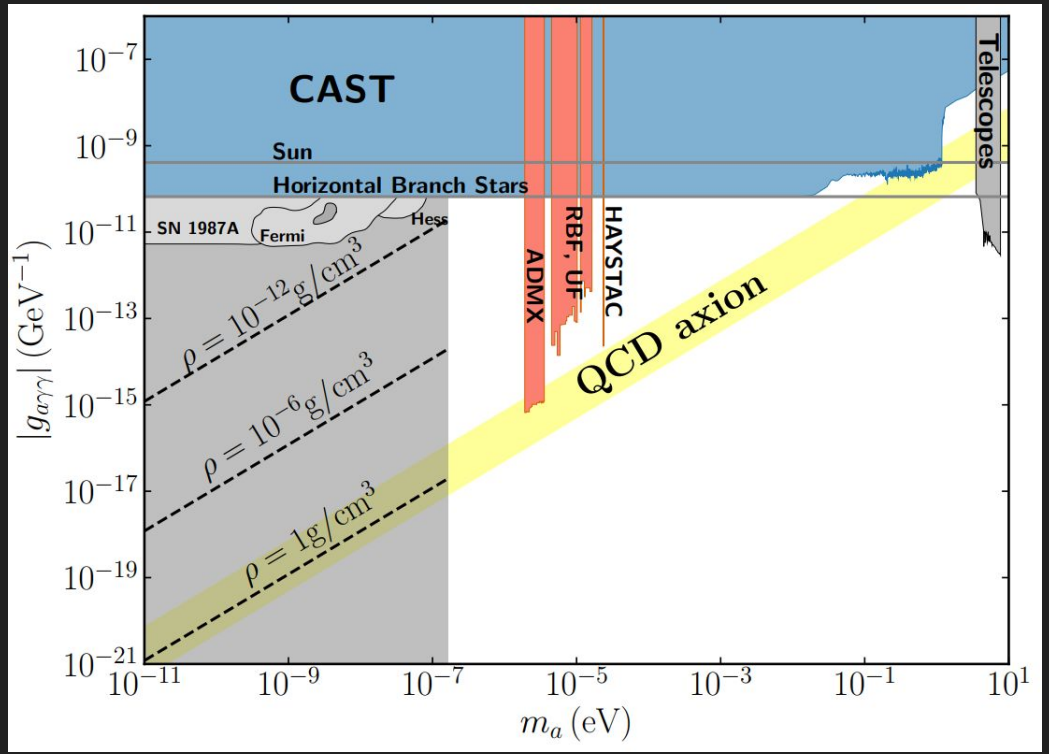
Global picture



Axion Parameter Space

- To reach the amplitude needed for the measured EM field the axion over densities are comparable to the ones predicted by Axion mini clusters.

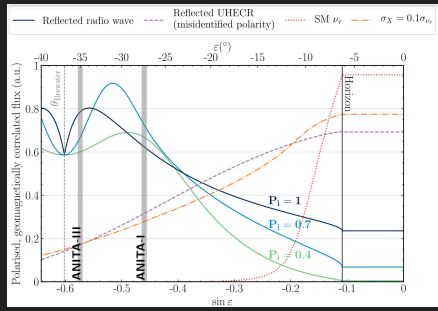
- Still some complex dynamics is needed to produce this marginally relativistic localized pulses.



Discriminating Different Explanations and Signatures

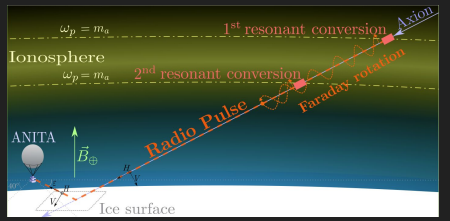
Reflection hypothesis (direction):

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



Axion hypothesis (Energy):

- 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 excluded by IceCube and Auger.
- Not looking at the phase, the direction favors the reflection Hypothesis.
- Classical dark sector Axion pulse origin can not be constrained by IceCube and Auger, and can produce the right signal due to the enhancement in the resonant regions in the Ionosphere.
- The localized production keeps enough coherence.
- Already taken data can be easily reanalyzed to look test both hypothesis.
- The **fourth ANITA flight** is being analyzed.

Thanks!