RADAR DETECTION OF HIGH-ENERGY NEUTRINO-INDUCED PARTICLE CASCADES

Krijn D. de Vries

VRIJE UNIVERSITEIT BRUSSEL

Research Foundation Flanders
Opening new horizons

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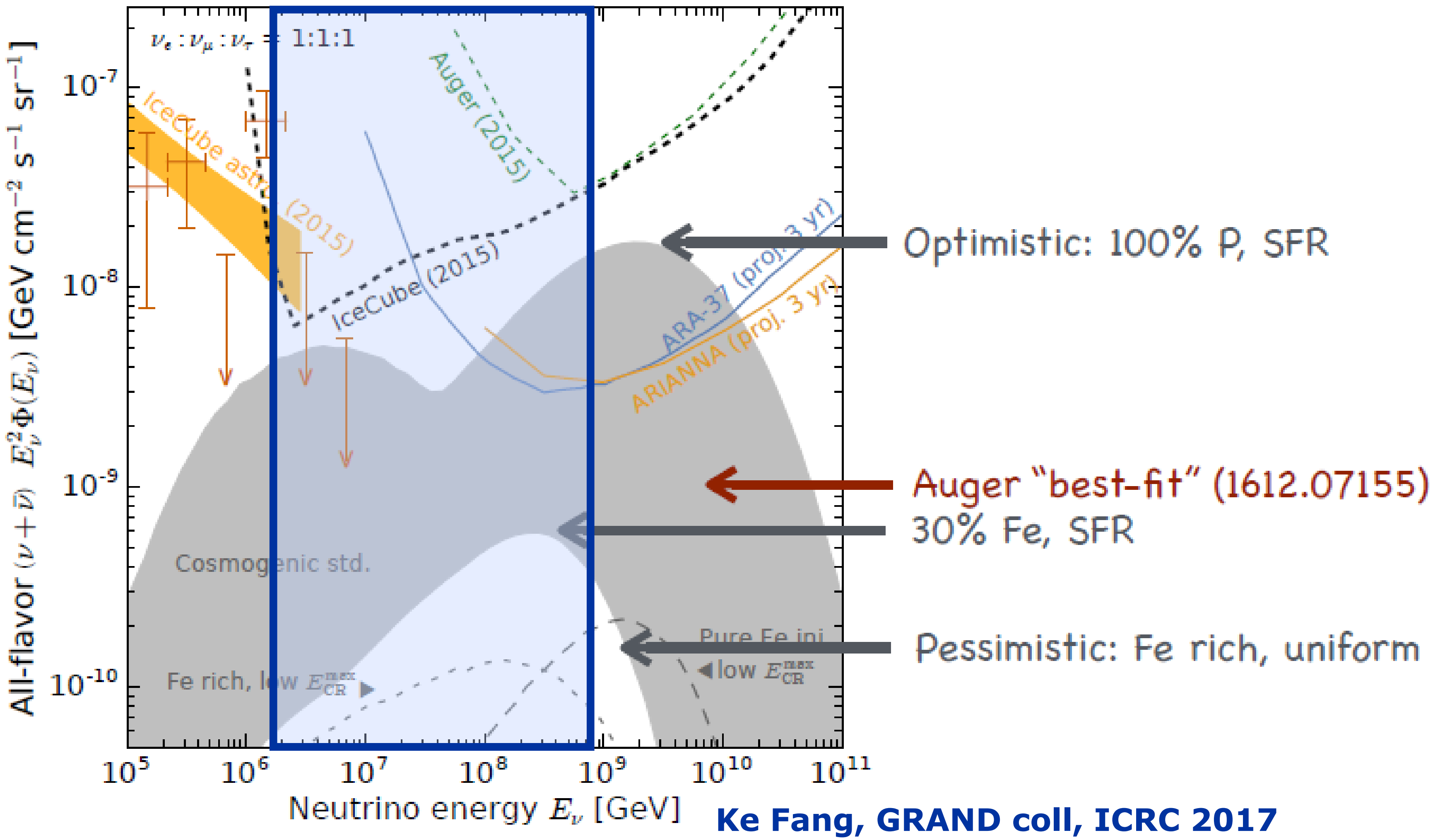
WHY RADAR?

NEUTRINO ASTRONOMY



Ke Fang, GRAND coll, ICRC 2017

https://history.nasa.gov/SP-4217/ch3.htm

- Radar detection used widely since the 1940's of the previous century.

- In 1941 Blackett and Lovell propose to use the radar detection technique to probe high-energy cosmic-ray induced air showers:

- Method tested at Jodrell Bank Research Station. Attention shifted to meteor research after its first detection in 1946.

- The method was revived in the beginning of this century:

On the possibility of radar echo detection of ultra-high energy cosmic ray- and neutrino-induced extensive air showers

Peter W. Gorham

Jet Propulsion Laboratory, Calif. Inst. of Technology
4800 Oak Grove, Drive, Pasadena, CA, 91109 USA

- Several experiments performed to search for an in-air scatter. So-far no detection.

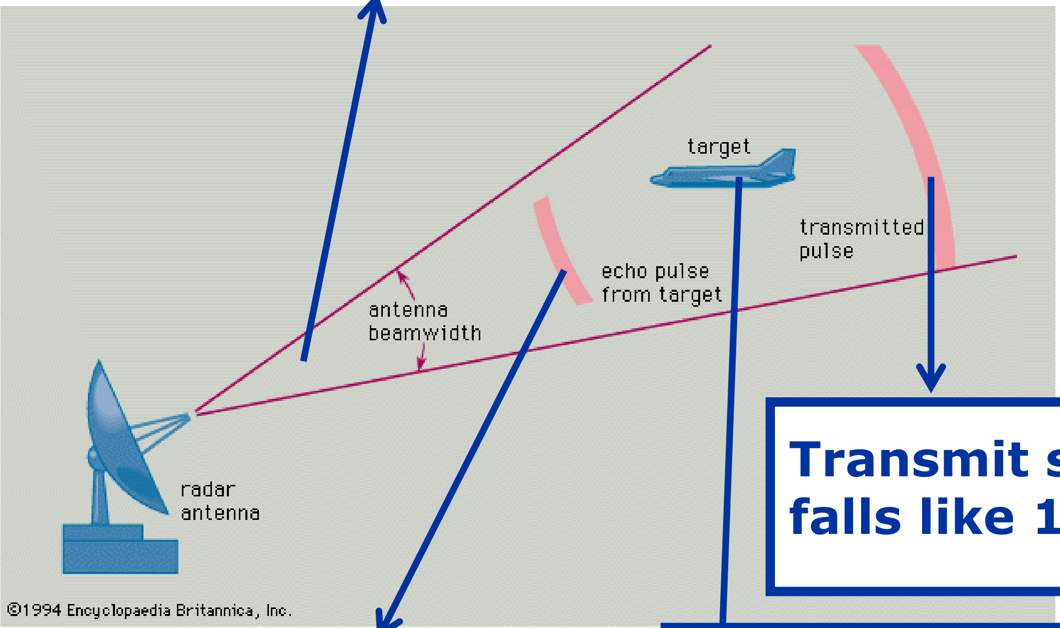
Sir Bernard Lovell

P.M.S. Blackett and A.C. Bernard Lovell, "Radio Echoes and Cosmic Ray Showers," Proceedings of the Royal Society of London, ser. A, vol. 177 (1941): 183-86

RADAR

HOW DOES RADAR WORK?

Beamed emission = larger gain (G), smaller aperture



Transmit signal falls like $1/R^2$

Return signal falls like $1/R^2$

Scatter over surface area(radar cross-section)

Directly probe the object by searching for a <u>scattered</u> radio wave

RADAR DETECTION OF HIGH-ENERGY NEUTRINO INDUCED PARTICLE CASCADES

OUTLOOK

- The feasibility of the radar detection technique to probe high-energy neutrino-induced particle cascades in ice (arXiv:1312.4331, Astrop. Phys. 60,2015,25-31).

On the feasibility of RADAR detection of high-energy neutrino-induced showers in ice

Krijn D. de Vries[a], Kael Hanson[b], Thomas Meures[b]

[a] Vrije Universiteit Brussel, Dienst ELEM, B-1050 Brussels, Belgium
[b] Université Libre de Bruxelles, Department of Physics, B-1050 Brussels, Belgium

- From radar cross-section to sensitivity (to be submitted):

On the Radar detection of high-energy neutrino-induced cascades in ice; From Radar cross-section to sensitivity

Krijn D. de Vries[a], Paul Coppin[a], Aongus Ó Murchadha[b], Olaf Scholten[a,c], Simona Toscano[a], Nick van Eindhoven[a]

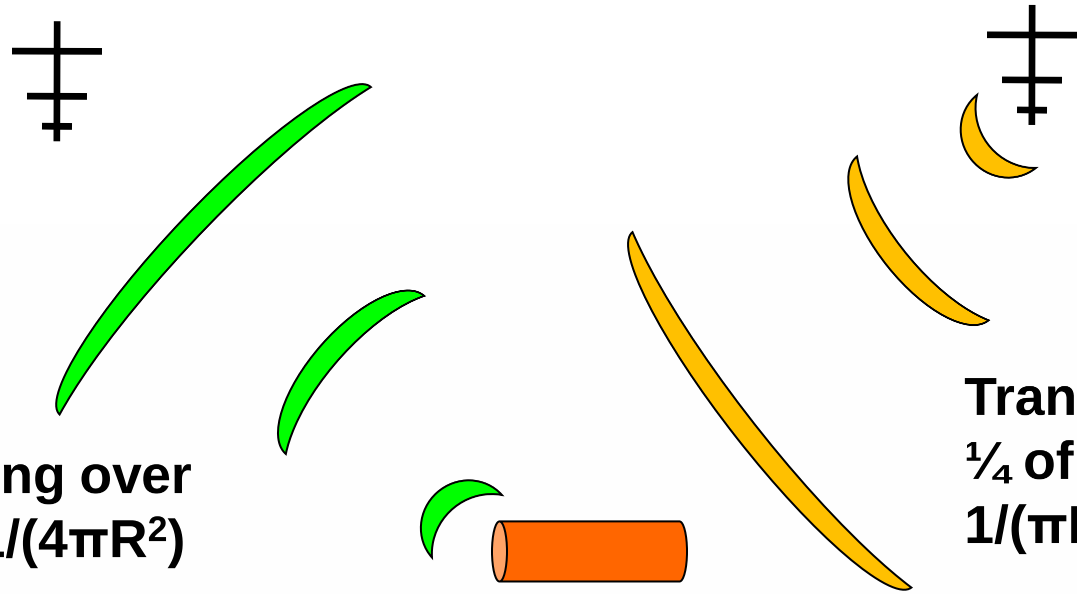
- Experimental verification of the radar detection technique at the Telescope Array Electron Light Source facility (PoS(ICRC2017)1049 PoS(ICRC2017)391).

Krijn D. de Vries*[a], Masaki Fukushima[b], Romain Gaior[cd], Kael Hanson[e], Daisuke Ikeda[b], Yusuke Inome[f], Aya Ishihara[c], Takao Kuwabara[c], Keiichi Mase[c], John Matthews[g], Thomas Meures[e], Pavel Motloch[h], Izumi S. Ohota[f], Aongus O'Murchadha[e], Florian Partous[a], Matthew Relich[c], Hiroyuki Sagawa[b], Tatsunobu Shibata[i], Bokkyun Shin[j], Gordon Thomson[g], Shunsuke Ueyama[c], Tokonatsu Yamamoto[f], Shigeru Yoshida[c]

Bi-static RADAR configuration

Effective area of receiver: A_{eff}

Transmitted power: P_t



Re-scattering over a sphere: $1/(4\pi R^2)$

Transmission over ¼ of a sphere: $1/(\pi R^2)$

Plasma scattering surface: σ_{eff}

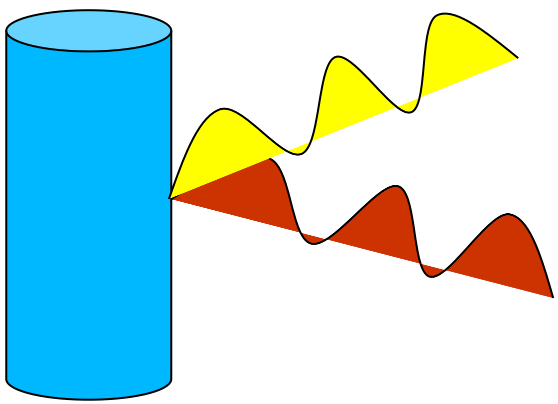
Attenuation by the medium

$$P_r = P_t \eta \frac{\sigma_{eff}}{\pi R^2} \frac{A_{eff}}{4\pi R^2} e^{-4R/L_\alpha}$$

RADAR

HOW DO WE SCATTER?

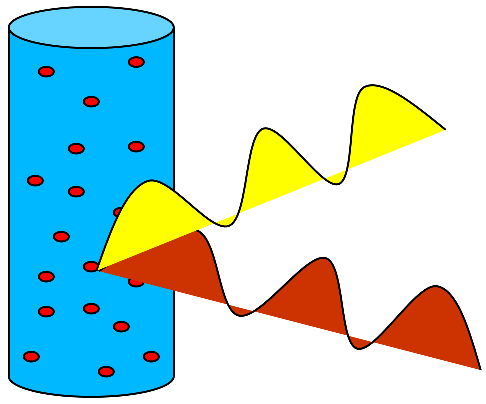
Over-dense scattering:



Radar frequency < Plasma Frequency

Reflection from the surface of the plasma tube

Under-dense scattering:



Radar frequency > Plasma Frequency

Scattering off of the individual charges in the plasma

We need free charges!

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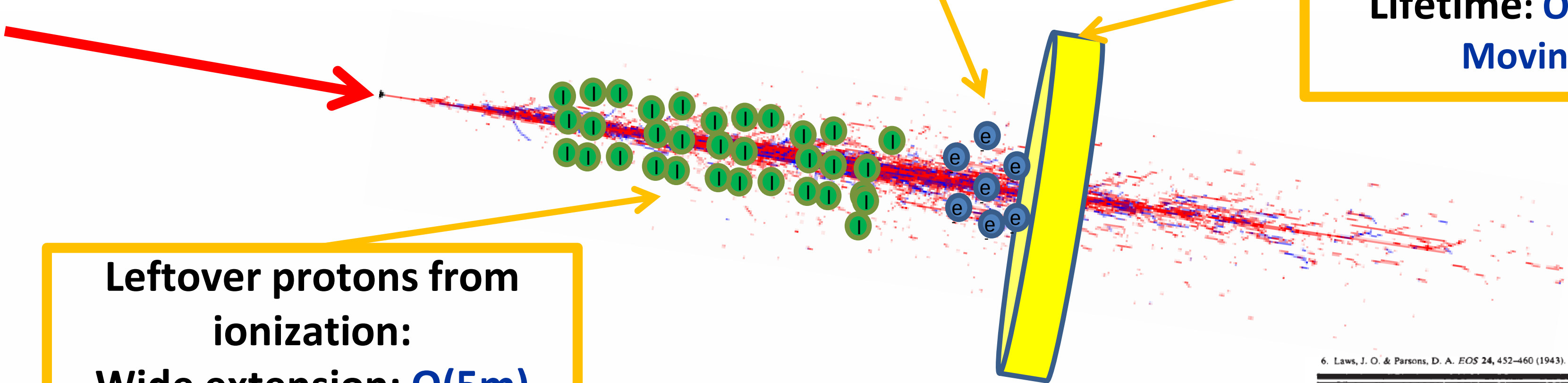
DO WE SCATTER? PLASMA LIFETIME

Leftover electrons from ionization:
Extension: O(30 cm)
Lifetime: O(1-20 ns)

Shower front electrons:
Extension: R_L = O(10 cm)
Lifetime: O(100ns)
Moving!



Leftover protons from ionization:
Wide extension: O(5m)
Lifetime: O(10-1000 ns)

Ionization numbers come from Physical Chemistry research!

6. Laws, J. O. & Parsons, D. A. *EOS* **24**, 452–460 (1943).

Proton mobility in ice

Marinus Kunst & John M. Warman

Interuniversitair Reactor Instituut, Mekelweg 15, 2629 JB Delft, The Netherlands

Ice is frequently taken as a model when factors controlling proton transport in hydrogen-bonded molecular networks are discussed. Such discussions have increased with the acknowledgement that proton transfer across cell membranes may play a significant part in energy conversion and storage in biological systems[1–4] and that this transfer may involve hydrogen-bonded chains spanning the membrane[5,6]. However, there is still much

Figure from arXiv:1210.5140v2

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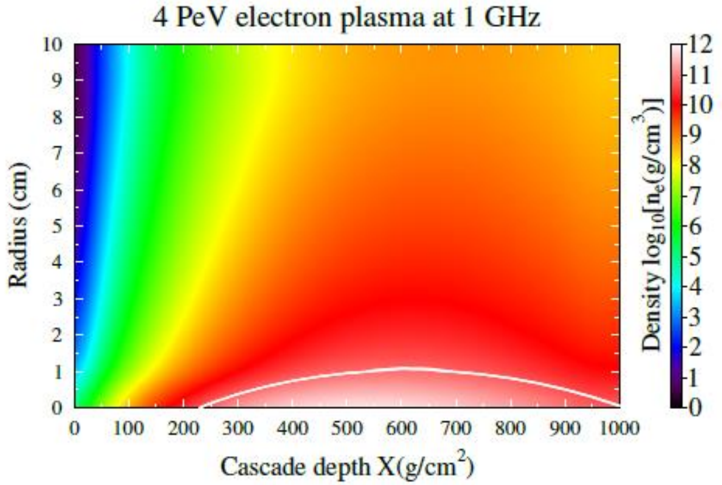
DO WE SCATTER? OVERDENSE VS UNDERDENSE



1 GHz vs 50 MHz:
Free electron lifetime: 1-20 ns
Free proton lifetime: 10-1000 ns

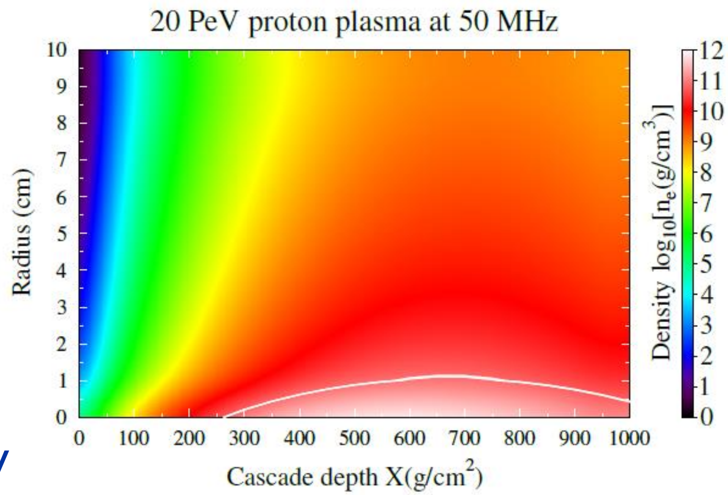
$$\omega_p = 8980\sqrt{\frac{m_p}{m_e} n_e}$$

Plasma modeling through NKG functions:

$$N(X) = \frac{0.31\ \exp[(X/X_0)(1 - 1.5\ln s)]}{\sqrt{\ln(E/E_{crit})}}$$

$$w(r) = \frac{\Gamma(4.5 - s)}{\Gamma(s)\Gamma(4.5 - 2s)} \left(\frac{r}{r_0}\right)^{s-1} \left(\frac{r}{r_0} + 1\right)^{s-4.5}$$

Assume 20eV ionization energy, 2MeV/g/cm^2 energy deposit for high-energy cascade particles.



(b)

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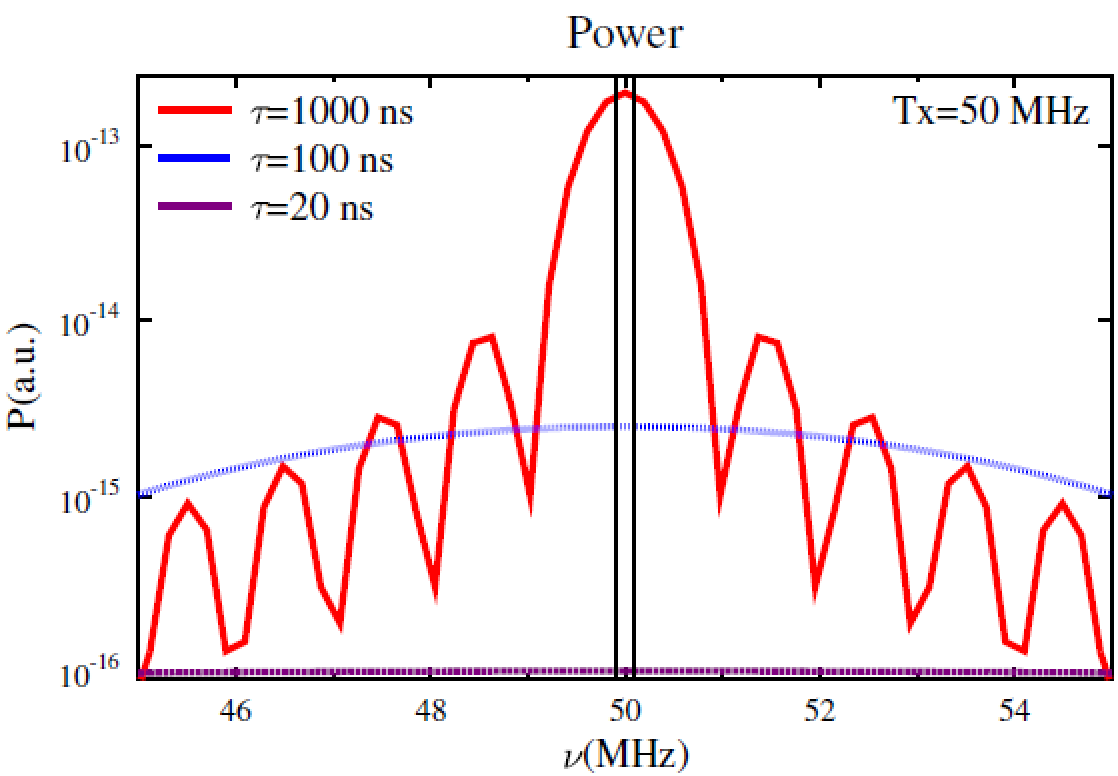
SO WHAT ABOUT THE LIFETIME?



Noise power:

$$P_n = k_b T \Delta\nu$$

Return signal gets dispersed for small lifetimes -> S/N ratio drops.

Effective scattering condition:

$$\nu_{coll} \ll {}^{1}/_{\tau} < \nu_d < \nu_p$$

Since ν_p scales with $n_e \sim E$ (energy), this conditions leads to an energy threshold. Calculations show E_{th}~PeV energies.

The big unknown:
The free charge collision rate!! Linked to lifetime??

TOWARDS THE SENSITIVITY: OVERDENSE SCATTERING CROSS SECTION

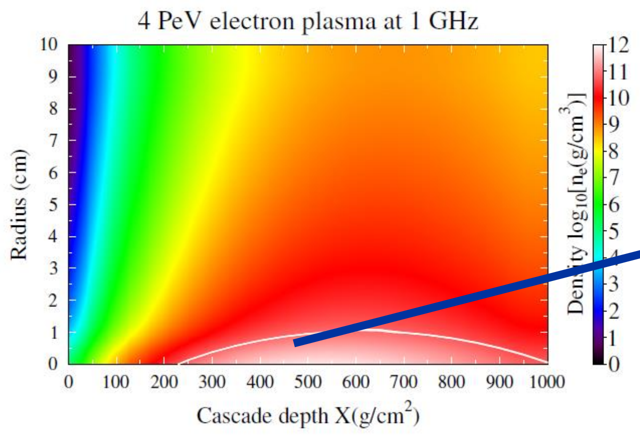
$$\sigma_{od} = \sum_{i=1}^{N} A_c^i \times f_{geom} \times f_{skin}^i$$

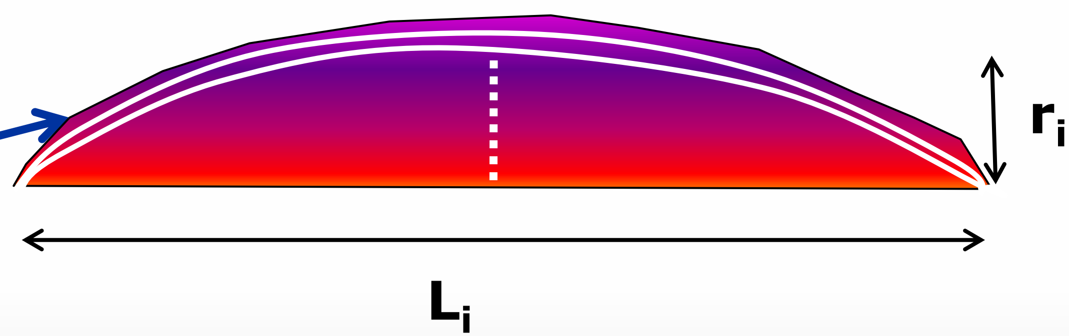
Amount of reflected power determined by skin depth:

$$\delta = c/2w_p \longrightarrow P_{sc}(x) = P_0(1 - e^{-x/\delta})$$

Plasma frequency ω_p ~ electron density: Integrate over layers of equal density:

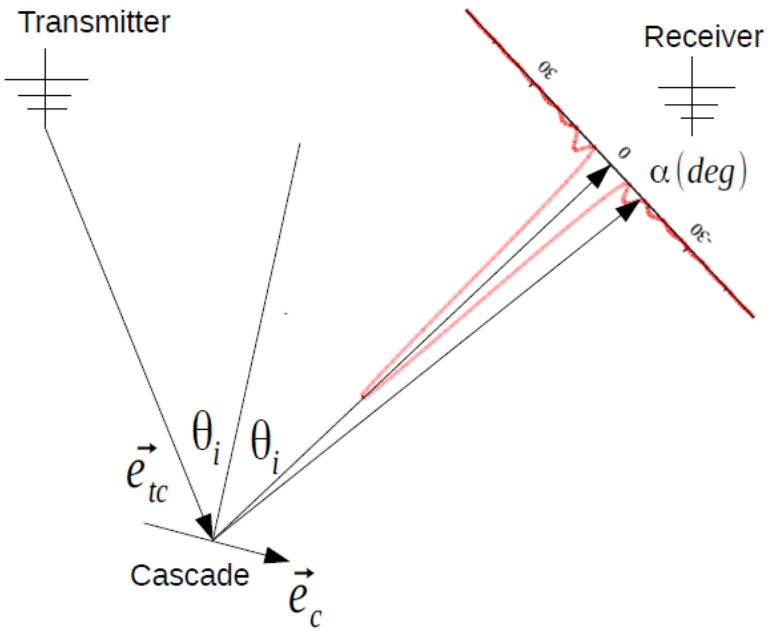
$$A_{Plasma}^i \approx L_i r_i$$





TOWARDS THE SENSITIVITY: POLARIZATION AND DIFFRACTION

$$\sigma_{od} = \sum_{i=1}^{N} A_c^i \times f_{geom} \times f_{skin}^i$$



Cascade dimensions of the order of the wavelength: Diffraction!!

Model as single slit diffraction.

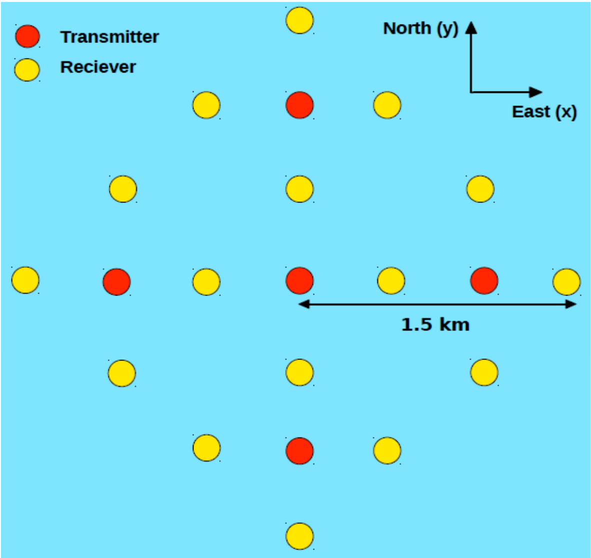
$$f_{geom} = (1 - \vec{e}_{tc} \cdot \vec{e}_c)(\vec{e}_t \cdot \vec{e}_c) f_{dif}$$

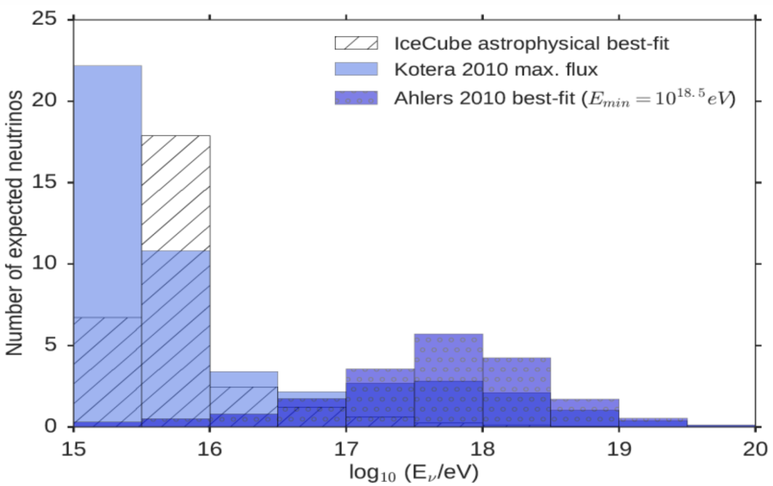
$$f_{dif} = \frac{I(\alpha)}{< I(\alpha) >}$$

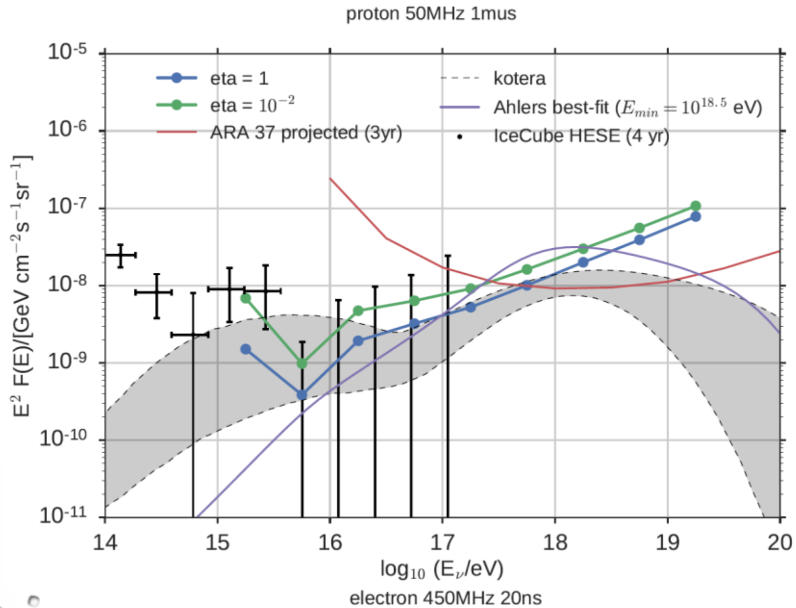
RADAR

RADAR SENSITIVITY

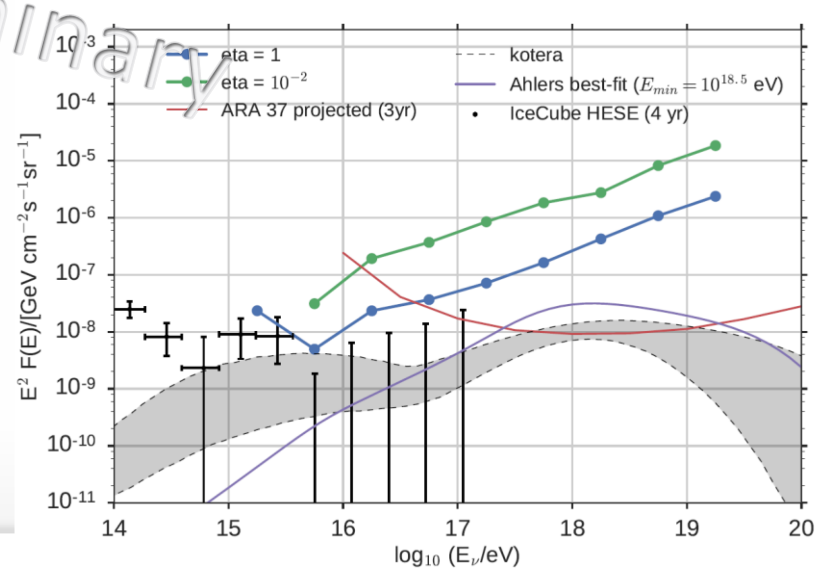
Credit: Simona Toscano, Paul Coppin







Preliminary



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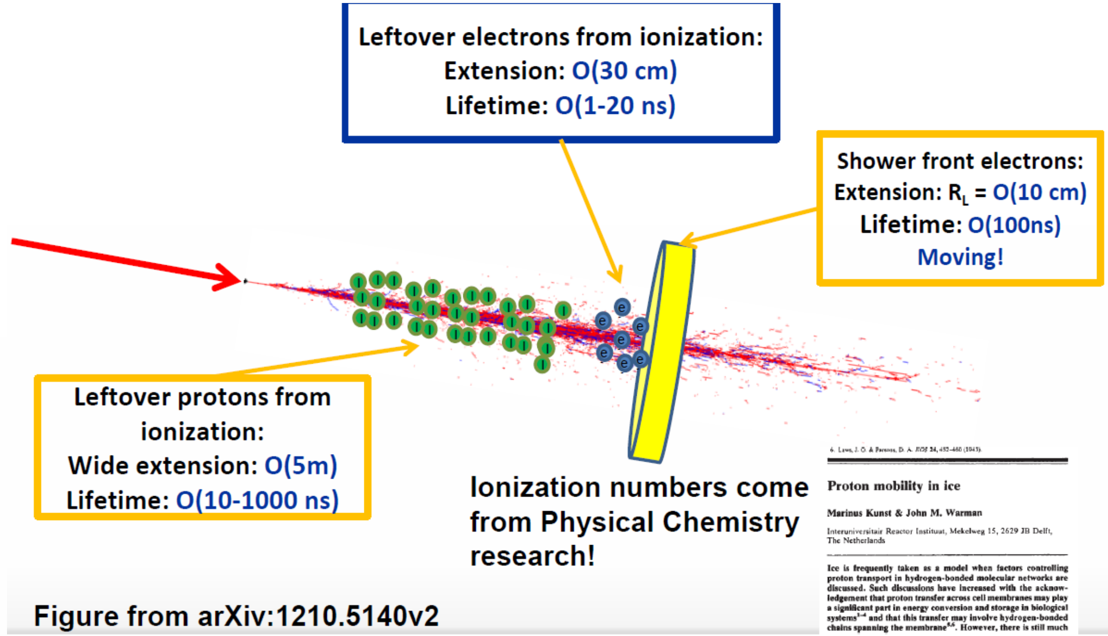
OPEN QUESTIONS: MODEL PARAMETERS/ASSUMPTIONS?

- What are the plasma constituents?
- What is the lifetime of these constituents?
- Is the free charge collision rate low enough?



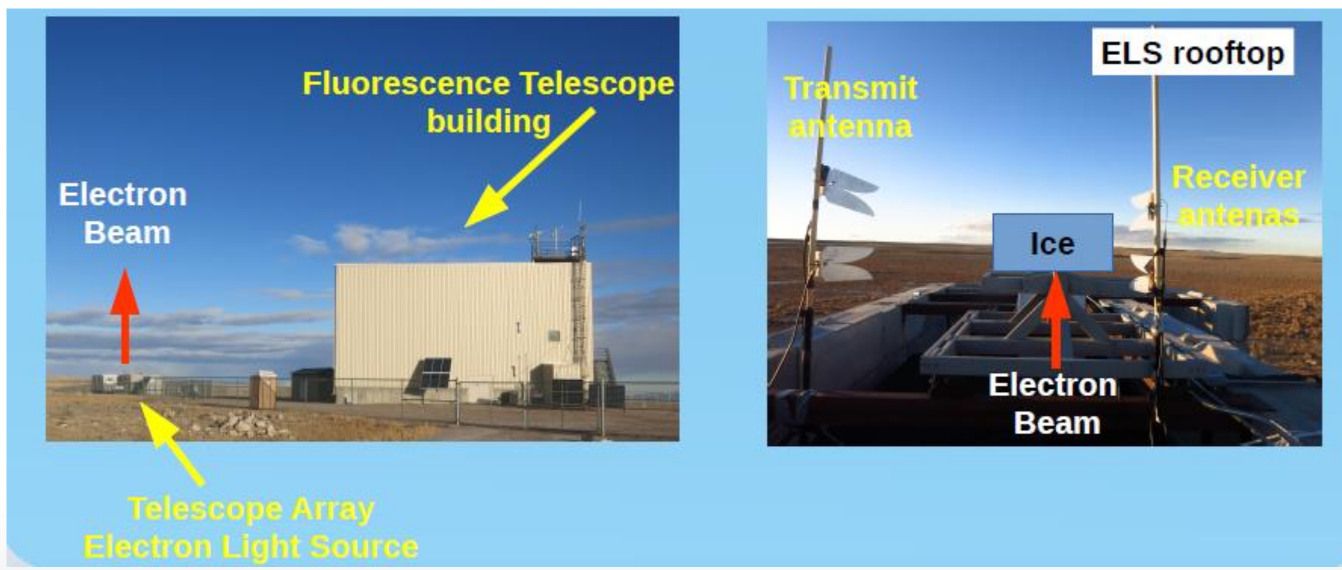
⇒ Experimental verification needed!!!!

RADAR

EXPERIMENTAL VERIFICATION AT THE TELESCOPE ARRAY ELECTRON LIGHT SOURCE FACILITY

Krijn D. de Vries[*a], Masaki Fukushima[b], Romain Gaior[cd], Kael Hanson[e], Daisuke Ikeda[b], Yusuke Inome[f], Aya Ishihara[c], Takao Kuwabara[c], Keiichi Mase[c], John Matthews[g], Thomas Meures[e], Pavel Motloch[h], Izumi S. Ohota[f], Aongus O'Murchadha[e], Florian Partous[a], Matthew Relich[c], Hiroyuki Sagawa[b], Tatsunobu Shibata[i], Bokkyun Shin[j], Gordon Thomson[g], Shunsuke Ueyama[c], Tokonatsu Yamamoto[f], Shigeru Yoshida[c]

Many thanks to the TA collaboration!!



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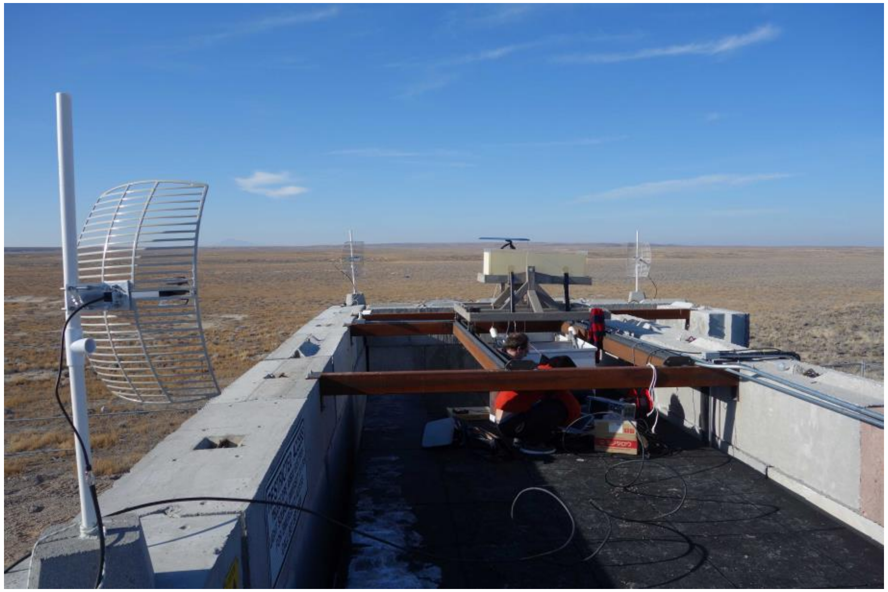
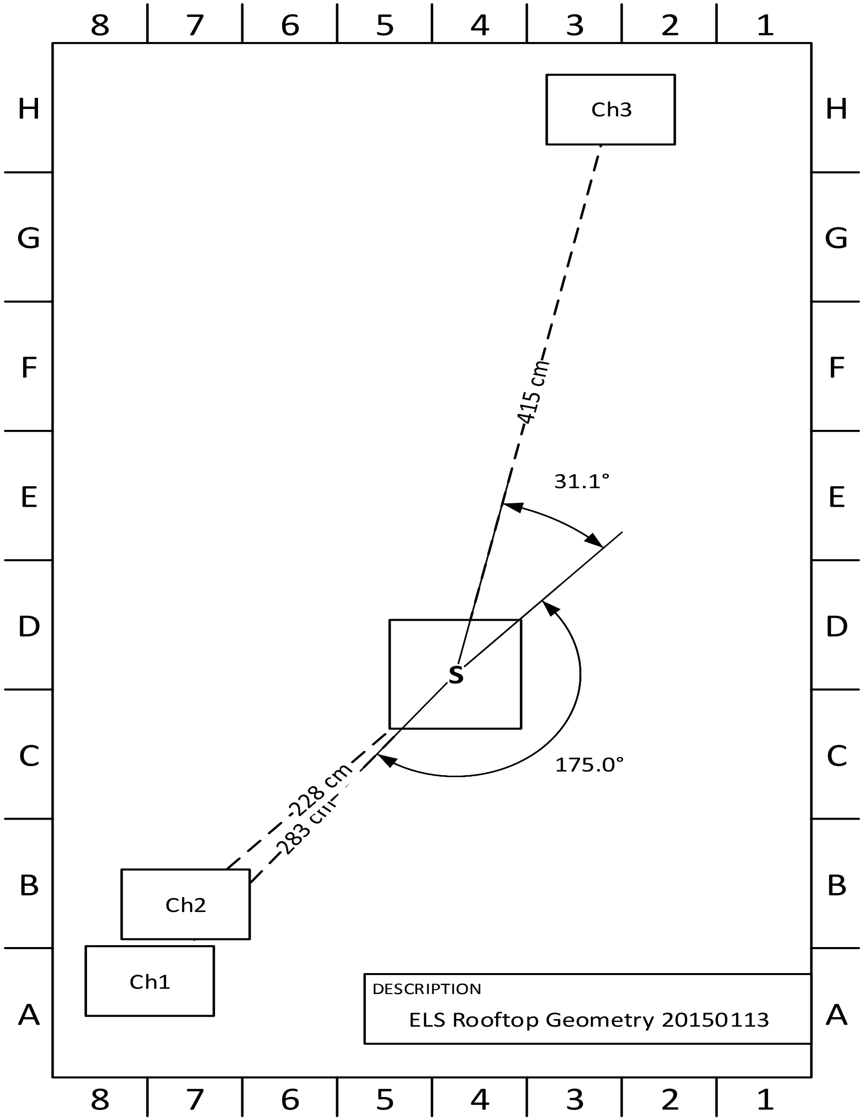
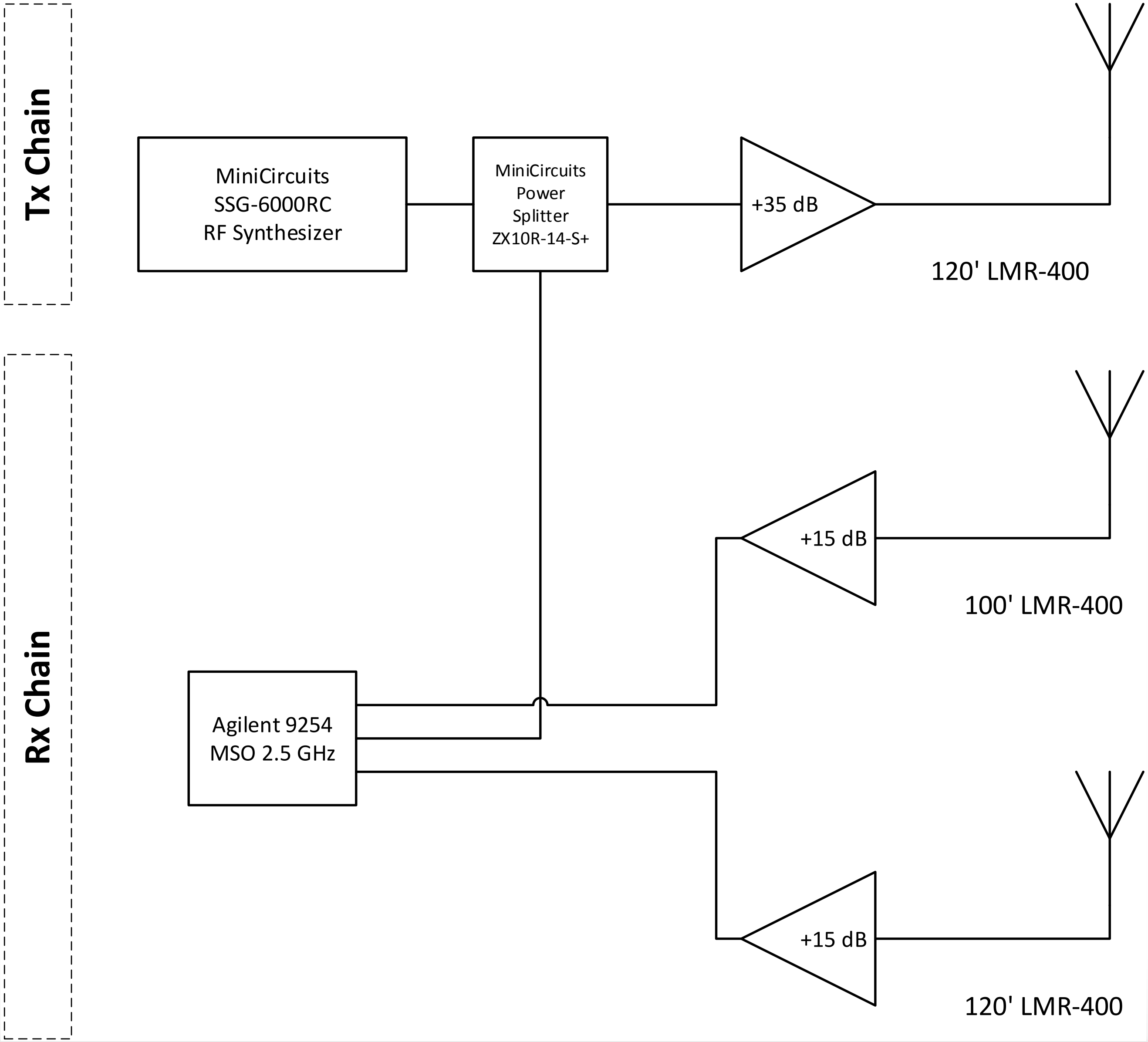
EXPERIMENTAL SETUP





RADAR
SIGNAL CHAIN



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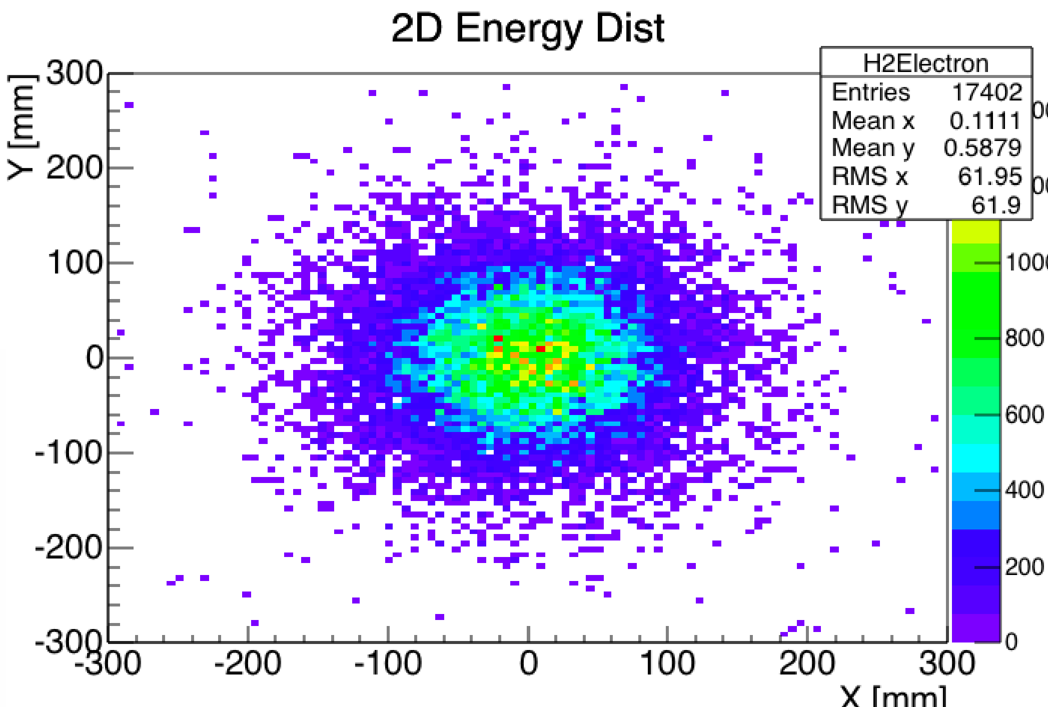
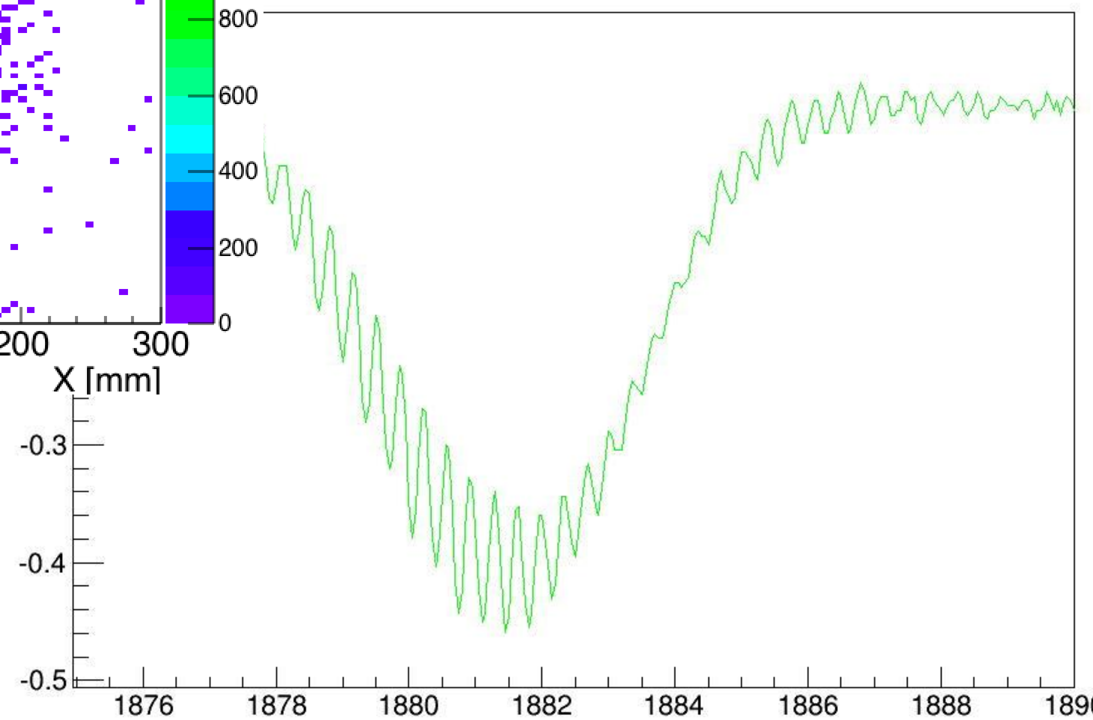
ELECTRON BEAM



~10^9 (40 MeV) electrons

~ 40 PeV



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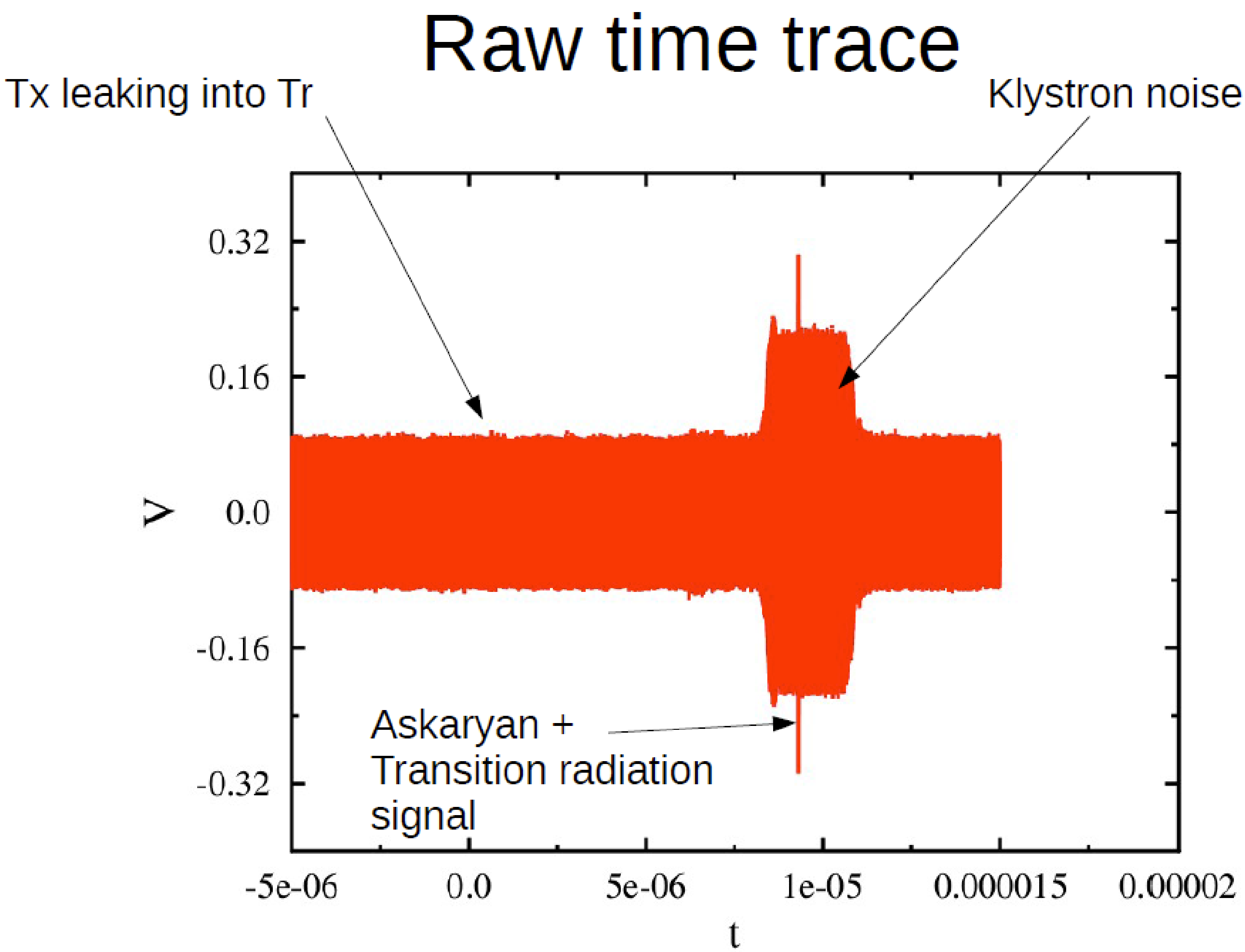
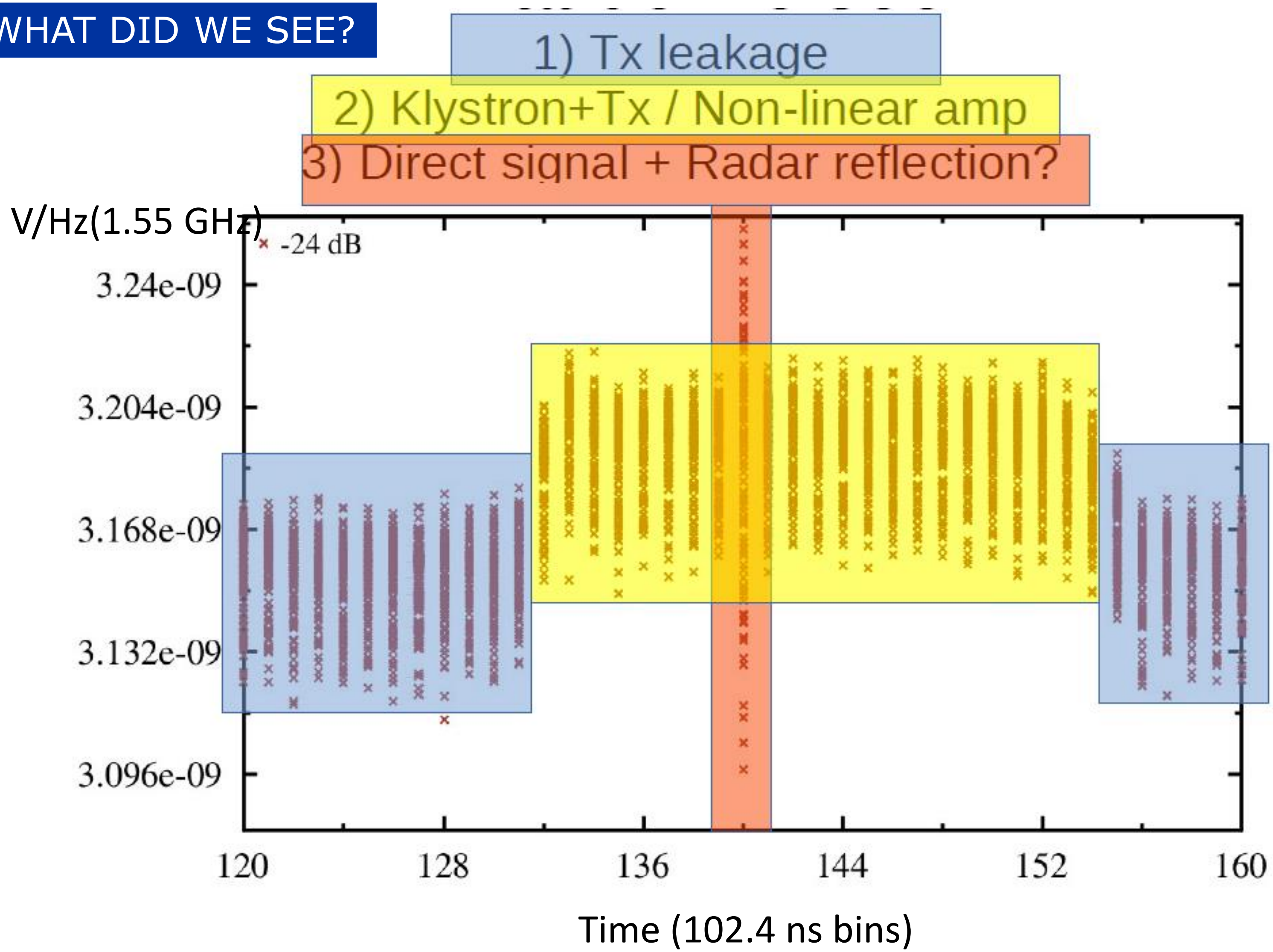
WHAT DID WE SEE?



RADAR

WHAT DID WE SEE?



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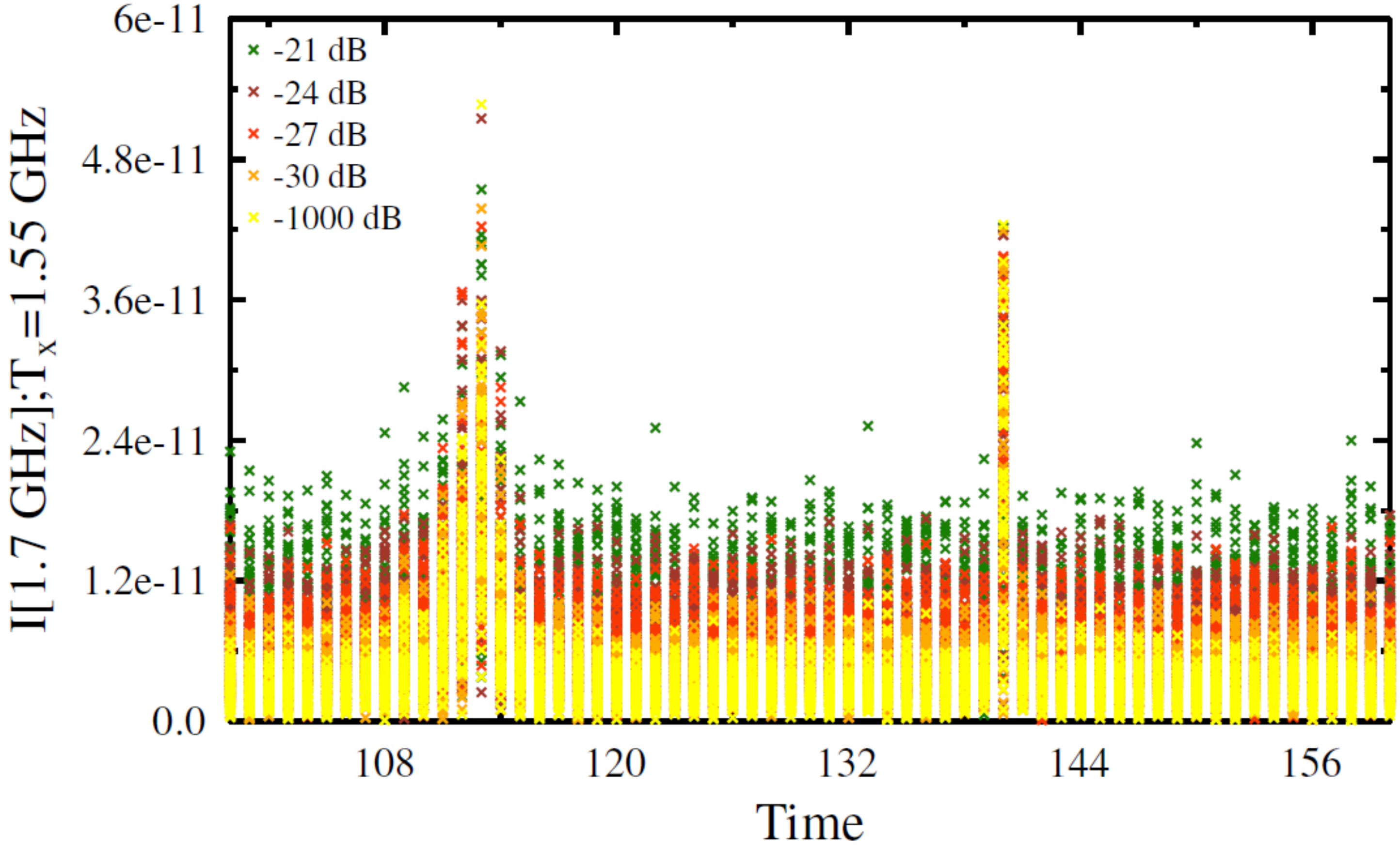
WHAT DID WE SEE?

- Accelerator noise interferes with our transmit signal
- Non-linear amplifier response
- Signal can be mimicked by these effects!
- What if we look at a different frequency than our transmit frequency?

RADAR

NO ICE CONFIGURATION: AIR!!



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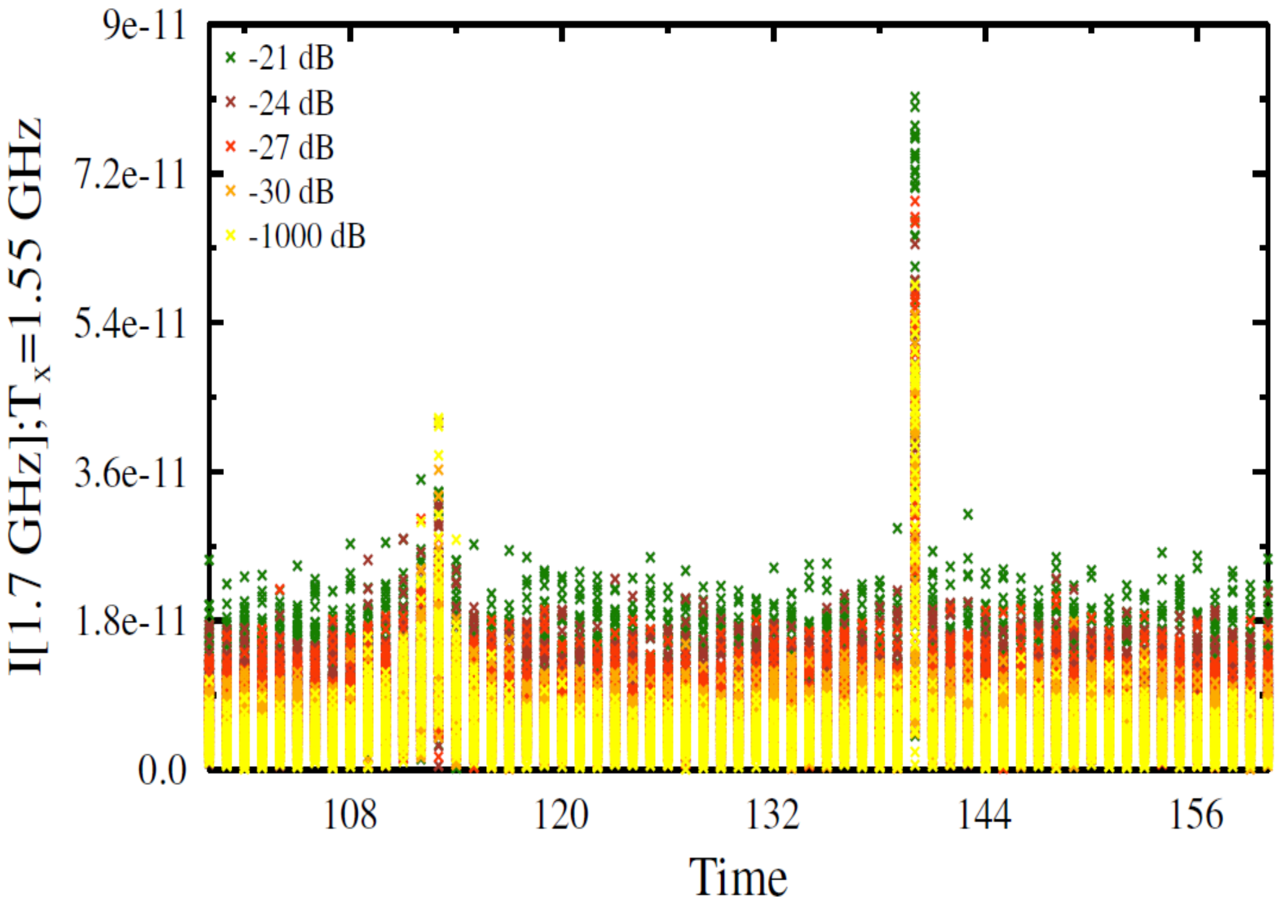
ICE CONFIGURATION



Unfortunately data at other frequencies was less clear

⇩

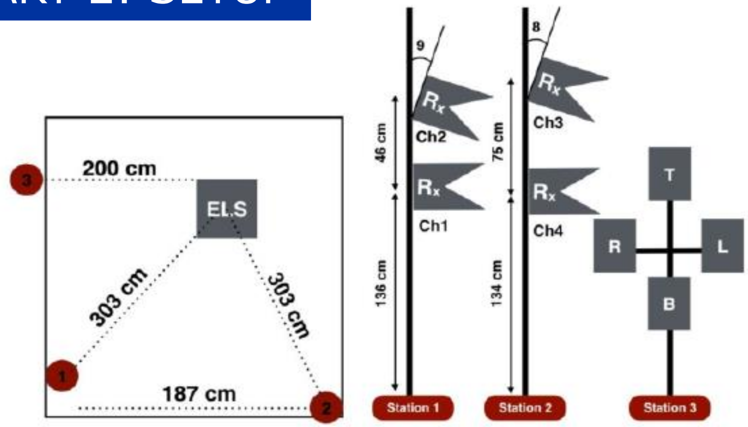
Redo experiment!

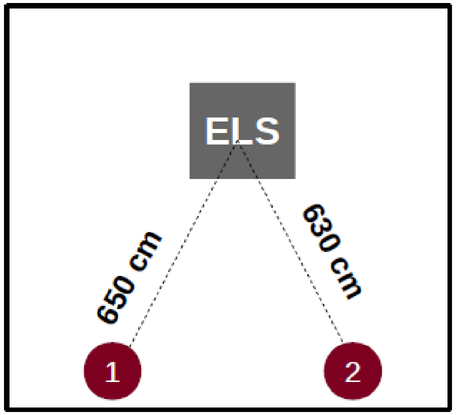
PART 2: WHAT DID WE CHANGE?

- Detect/transmit over wider band-width (50 MHz – 2.4 GHz)
- Phase out transmit leakage
- Filter out accelerator noise (S-band 2.856 GHz)
- Shield reflective materials with RF absorbers

RADAR

PART 2: SETUP





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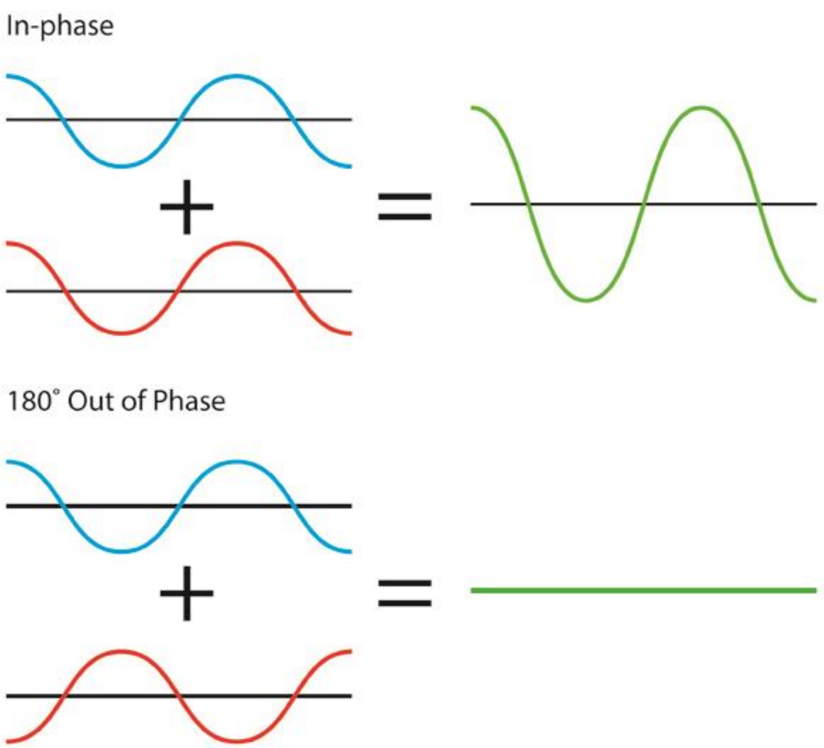
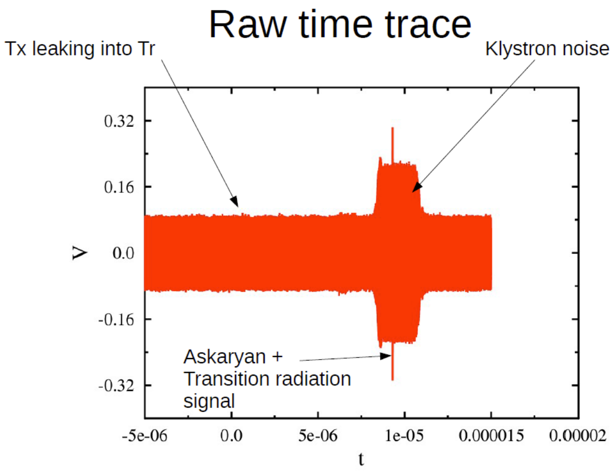
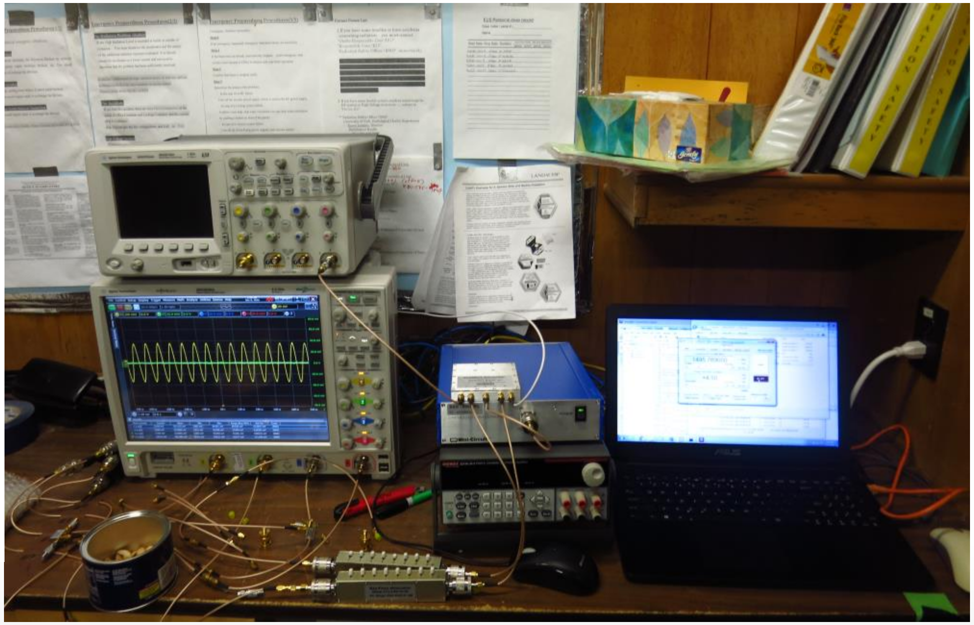
PART 2: PHASE OUT TRANSMIT LEAKAGE







What do we expect?

Background:

- Leakage of transmit signal
- Transition radiation
- Askaryan emission
- Accelerator and other noise sources

Signal

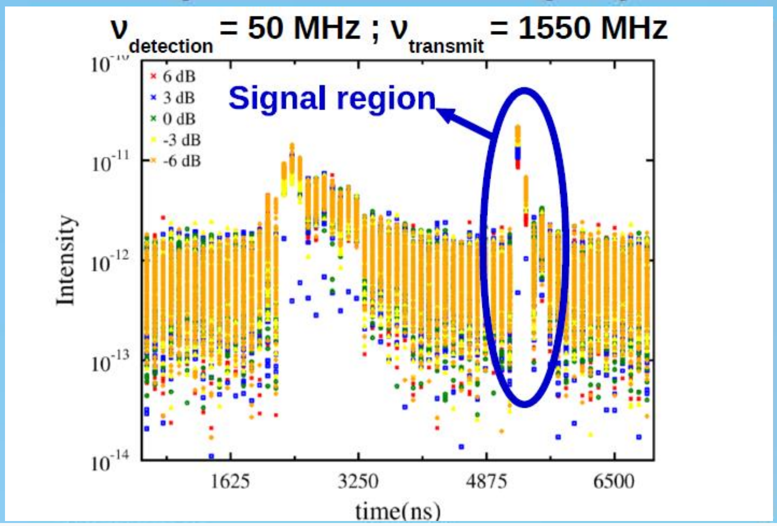
- Reflection at transmit frequency
- Direct scaling with input Power
- Signal region at ~5000 ns

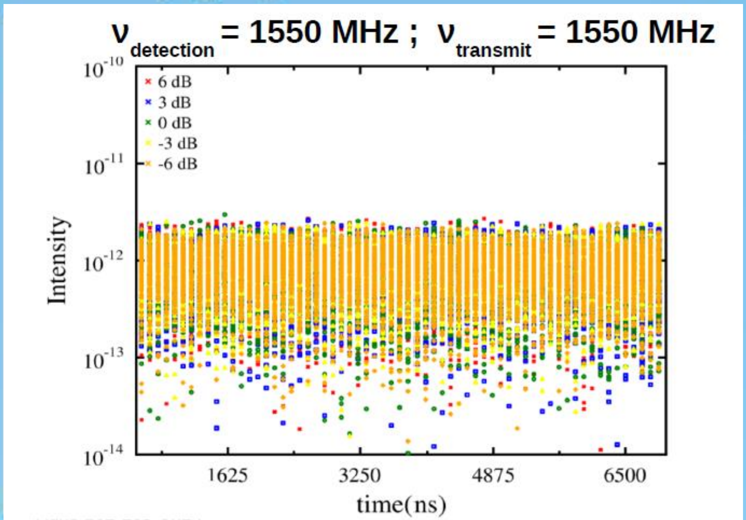
What do we show?

Radar signal transmitted at 1550 MHz

Varying transmit power: -6dB, -3dB, 0dB, 3dB, 6dB

Response at 50 MHz (left) and 1550 MHz (right) in 124ns time bins





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SUMMARY AND OUTLOOK

- We investigate the radar detection technique to probe the PeV-EeV (and above) cosmic neutrino flux.
- Radar scattering modelled in detail. Scattering cross-section modelled for the first time (previously given by empirical thin wire approximation).
- 16 (receiver) + 5 (transmit) antenna set-up is predicted to detect > 10 evts/jr in the PeV-EeV region in case of efficient scattering.
- Sensitivity strongly depends on unknown parameters due to plasma properties (lifetime, free charge collision rate).
- Two experiments performed at the TA-ELS facility. Possible signals found, data not fully understood yet.
- Higher energy beam at SLAC used for next test (early 2018).

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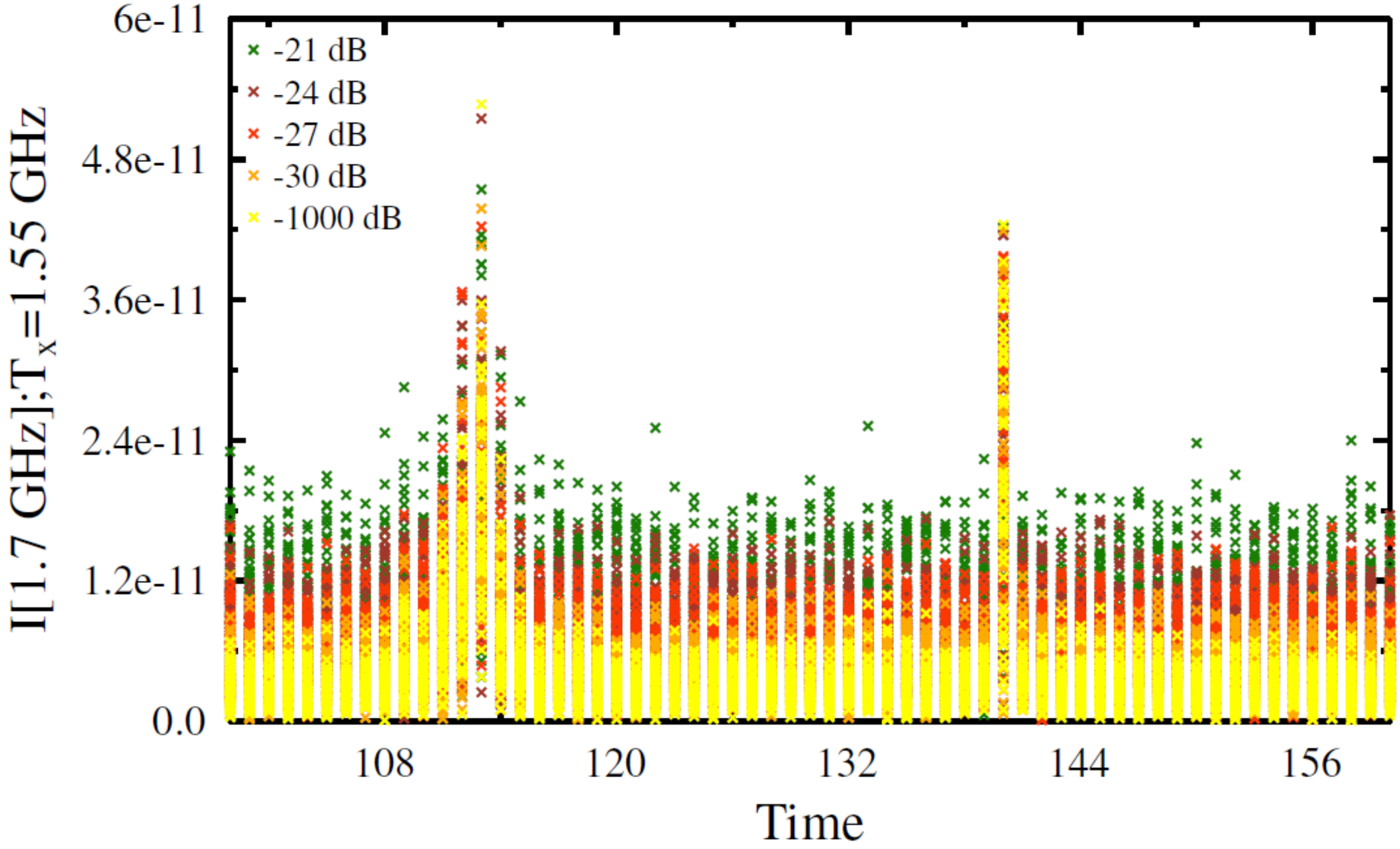
THE ELECTRON BEAM SUDDEN APPEARANCE

SIGNAL

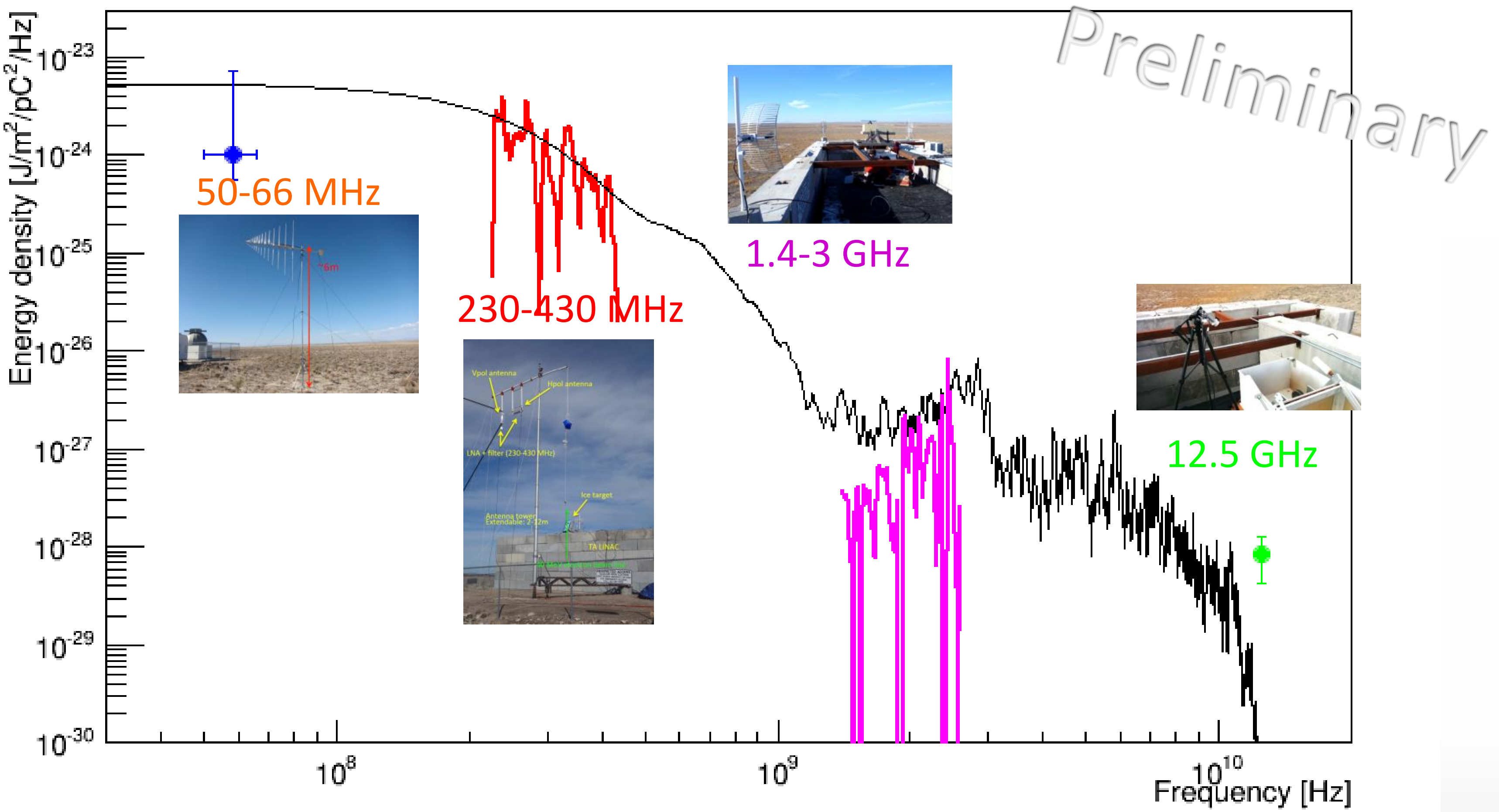
No Ice configuration, still very strong emission observed!!



THE ELECTRON BEAM SUDDEN APPEARANCE

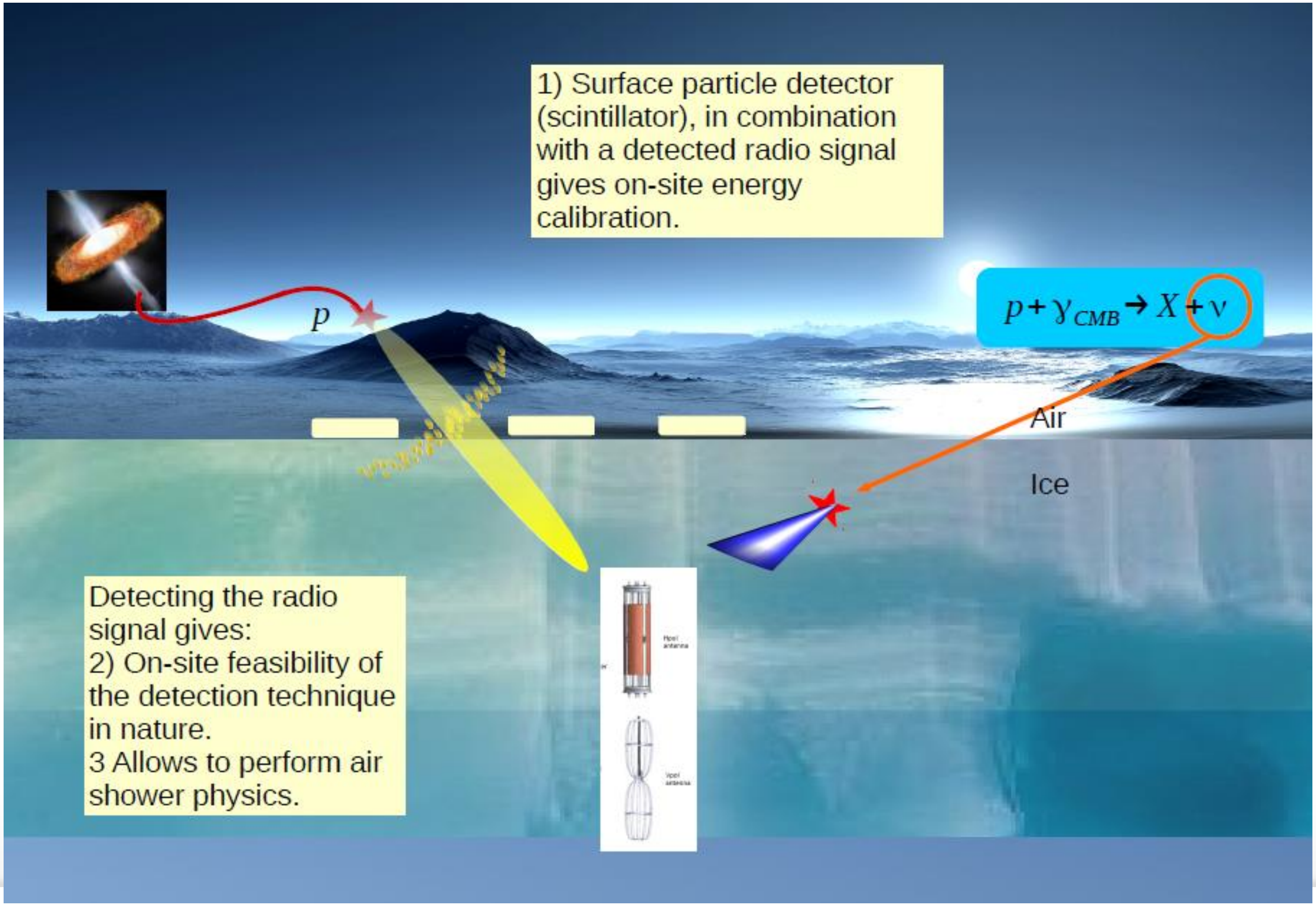
SIGNAL ANALYSED AND WELL UNDERSTOOD

Four experiments observed the sudden appearance signal in different frequency ranges



THE ELECTRON BEAM SUDDEN APPEARANCE

VERY INTERESTING APPLICATION IN NATURE:
THE COSMIC-RAY AIR SHOWER SIGNAL IN ASKARYAN RADIO DETECTORS



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