Radar detection of high-energy neutrino induced particle cascades in ice

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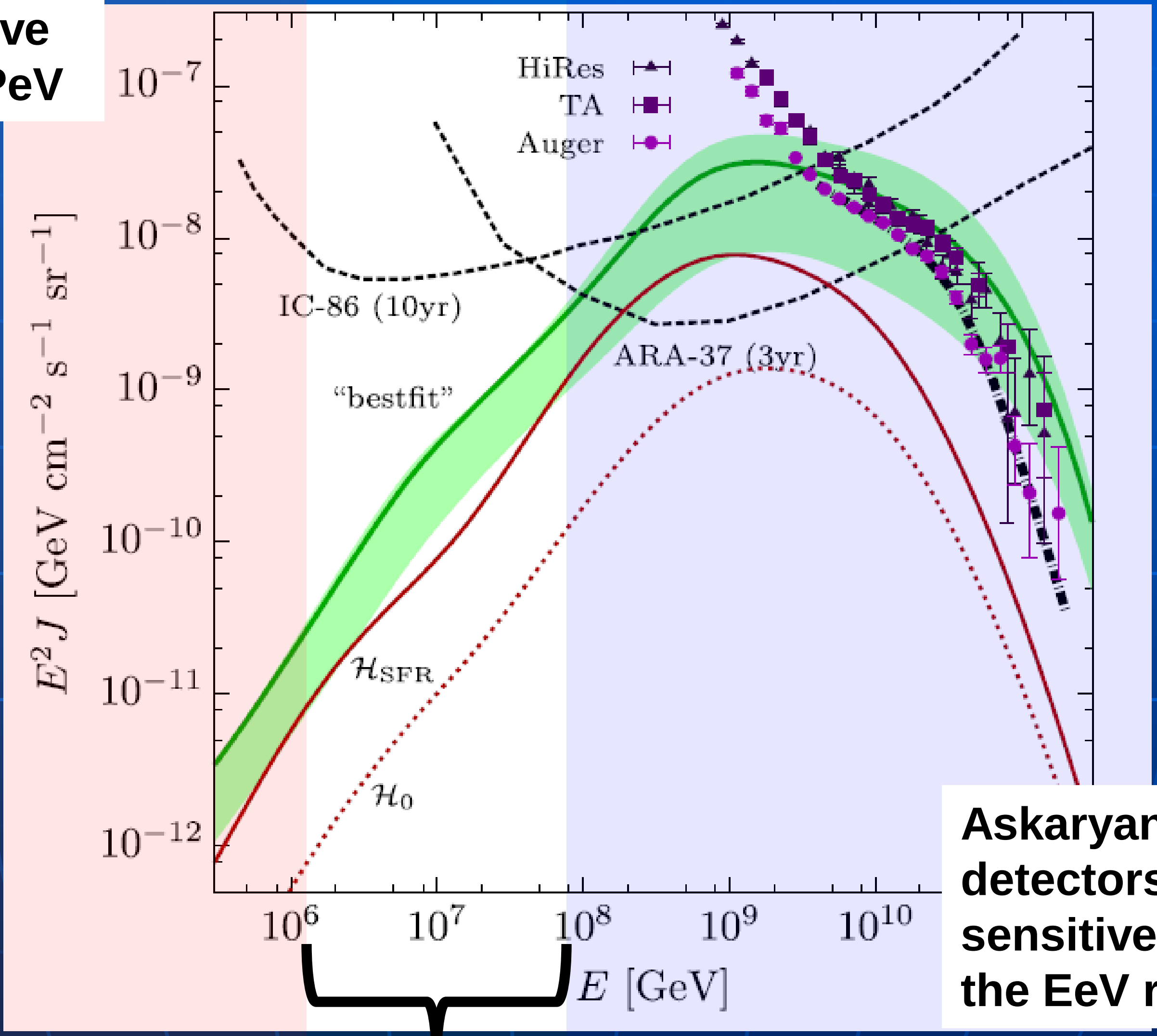
Motivation

IceCube sensitive below several PeV

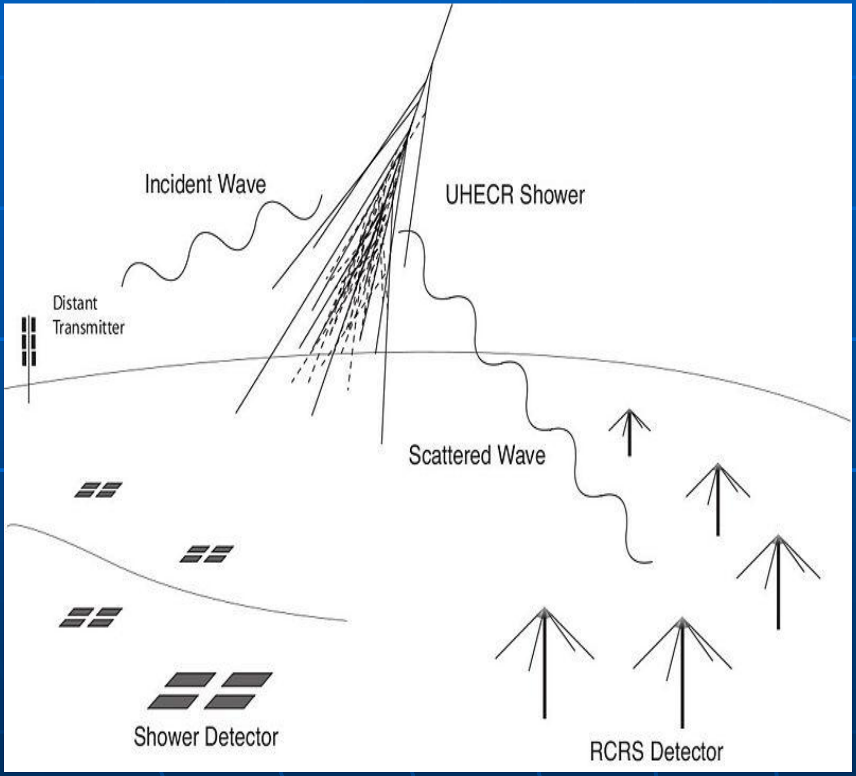


Sensitivity Gap in PeV – EeV region

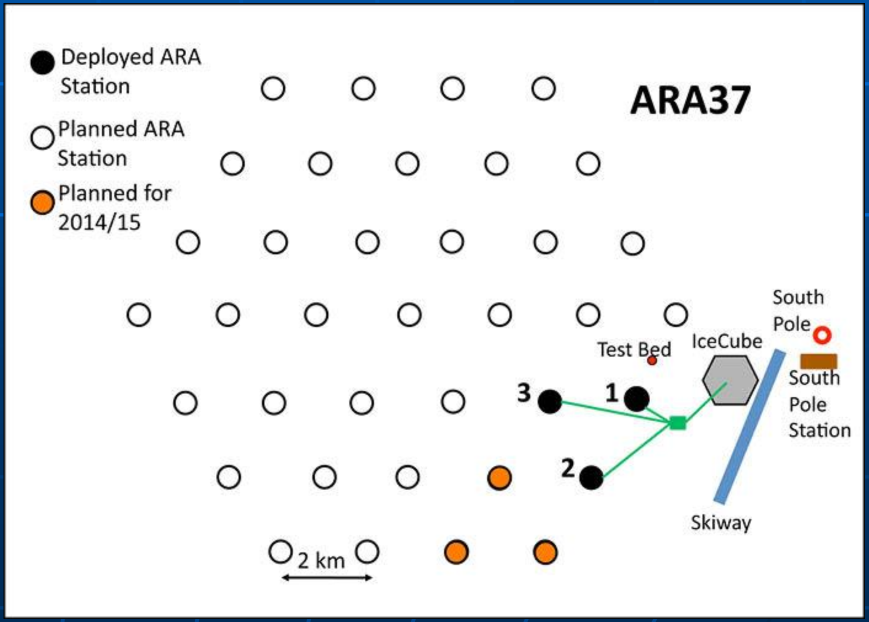
Askaryan Radio detectors become sensitive close to the EeV region

New detection method

If a RADAR signal can be bounced off of a neutrino induced cascade in ice, we have control over the signal strength!



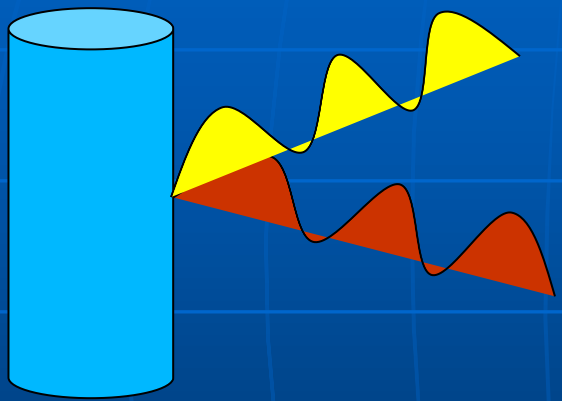
Infrastructure already available!



M. Abou Bakr Othman et al, Proceedings 32nd ICRC, Beijing 2011

RADAR scattering

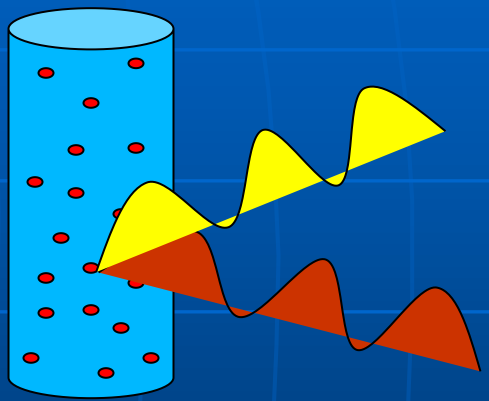
- Over-dense scattering:



Radar frequency < Plasma Frequency

Reflection from the surface of the plasma tube

- Under-dense scattering:



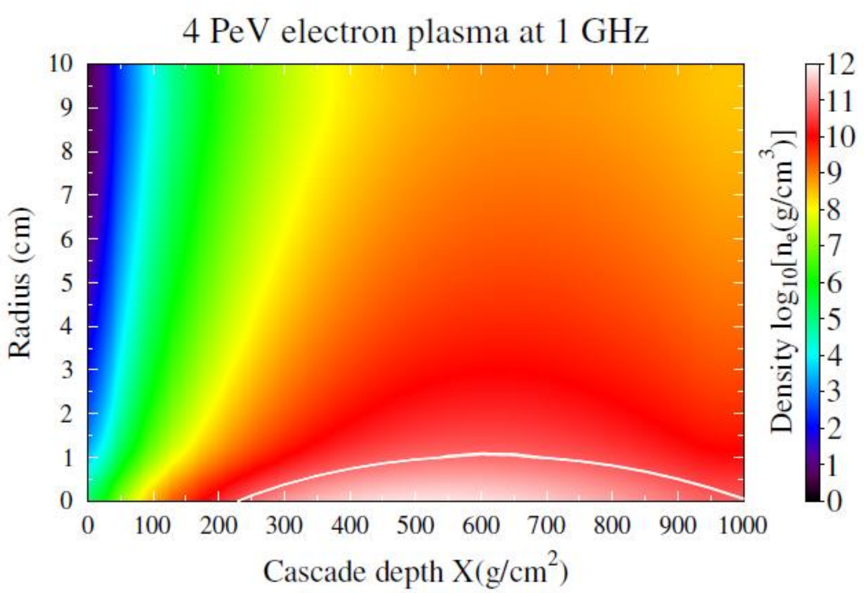
Radar frequency > Plasma Frequency

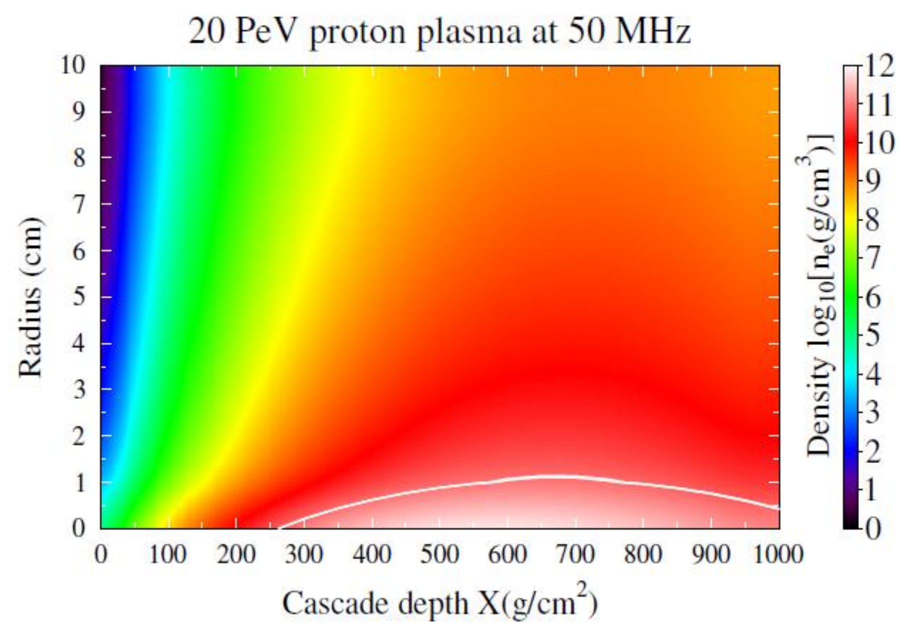
Scattering off of the individual charges in the plasma

Over-dense scattering

$$\upsilon_{Plasma} > \upsilon_{Radar} > \begin{cases} 1/\tau_{Plasma} & c_{med}\tau_{e} < l_{c} \\ c_{med}/l_{c} & c_{med}\tau_{e} > l_{c} \end{cases}$$

$$\upsilon_{Plasma} \propto \sqrt{n_{Plasma}} \propto \sqrt{E_{primary}}$$



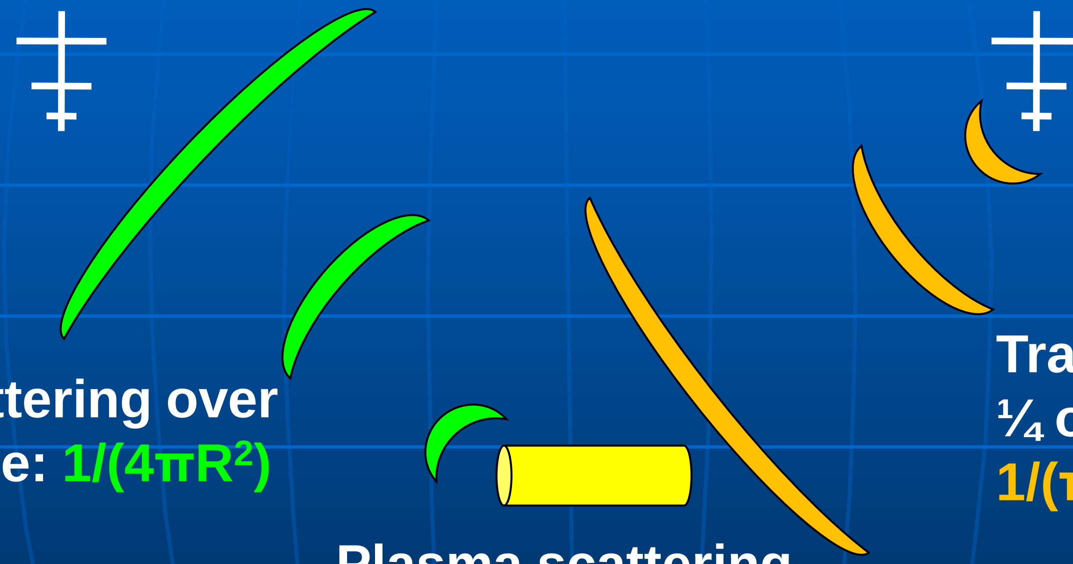


RADAR return power estimation

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 return power estimation (single antenna)

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

$\lambda = 0.18\,\mathrm{m}$

$\sigma_{eff}^{\max} = 0.11\,\mathrm{m}^2$

$\sigma_{eff}(\theta = 60^0, \phi = 60^0) = 1.6 \cdot 10^{-4}\,\mathrm{m}^2$

$L_\alpha = 1\,\mathrm{km}$

$\mathrm{P}_{\mathrm{noise}} = k_b T_{sys} \Delta \nu$

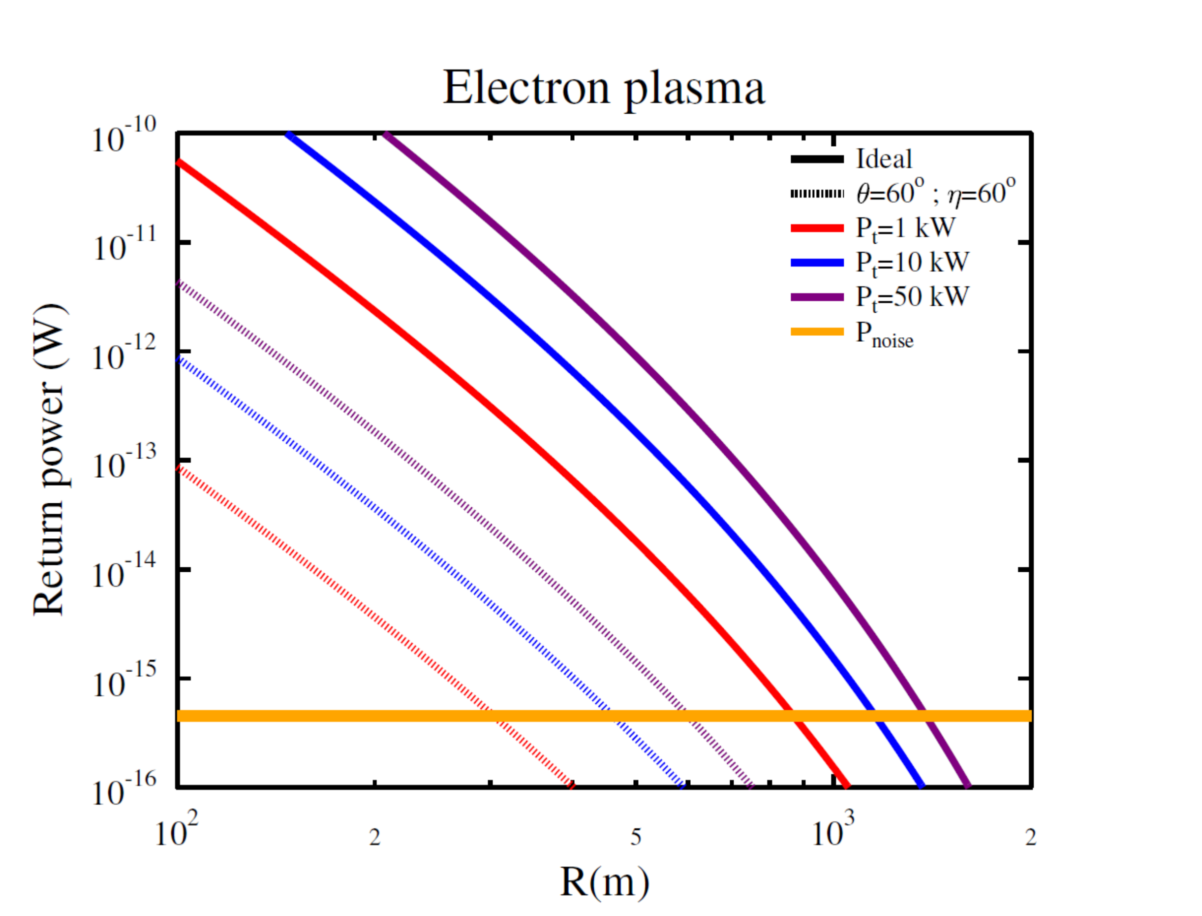
$T_{sys} = 325\,\mathrm{K}$

$\Delta \nu = 100\,\mathrm{kHz}$

N antennas :

$\mathrm{P}_{Noise}(N) = N \cdot P(N=1)$

$\mathrm{P}_{Signal}(N) = N^2 \cdot P(N=1)$



RADAR return power estimation (single antenna)

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

$\lambda = 3.6\,\mathrm{m}$

$\sigma_{eff}^{\max} = 5.5\,\mathrm{m}^2$

$\sigma_{eff}(\theta = 60^0, \phi = 60^0) = 1.2 \cdot 10^{-2}\,\mathrm{m}^2$

$L_\alpha = 1.4\,\mathrm{km}$

$\mathrm{P}_{\mathrm{noise}} = k_b T_{sys} \Delta\nu$

$T_{sys} = 325\,\mathrm{K}$

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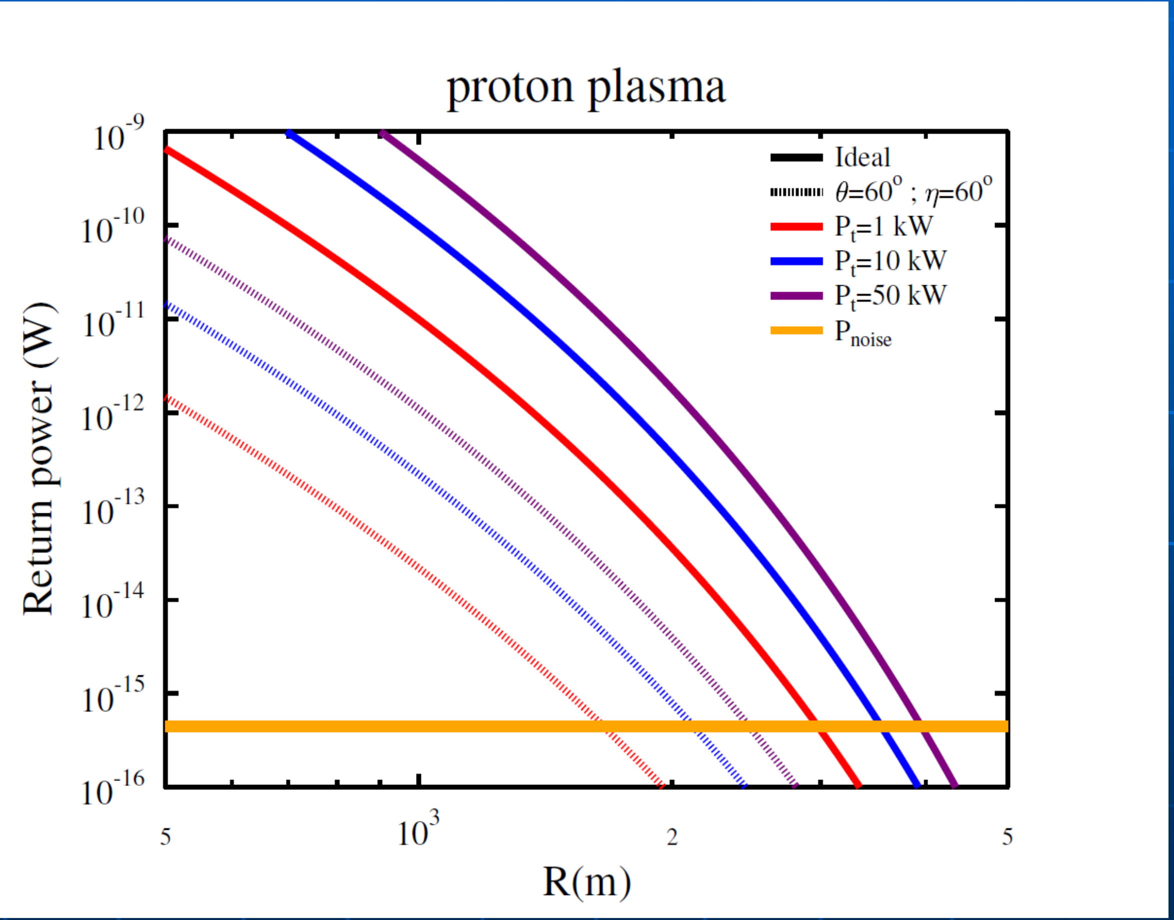

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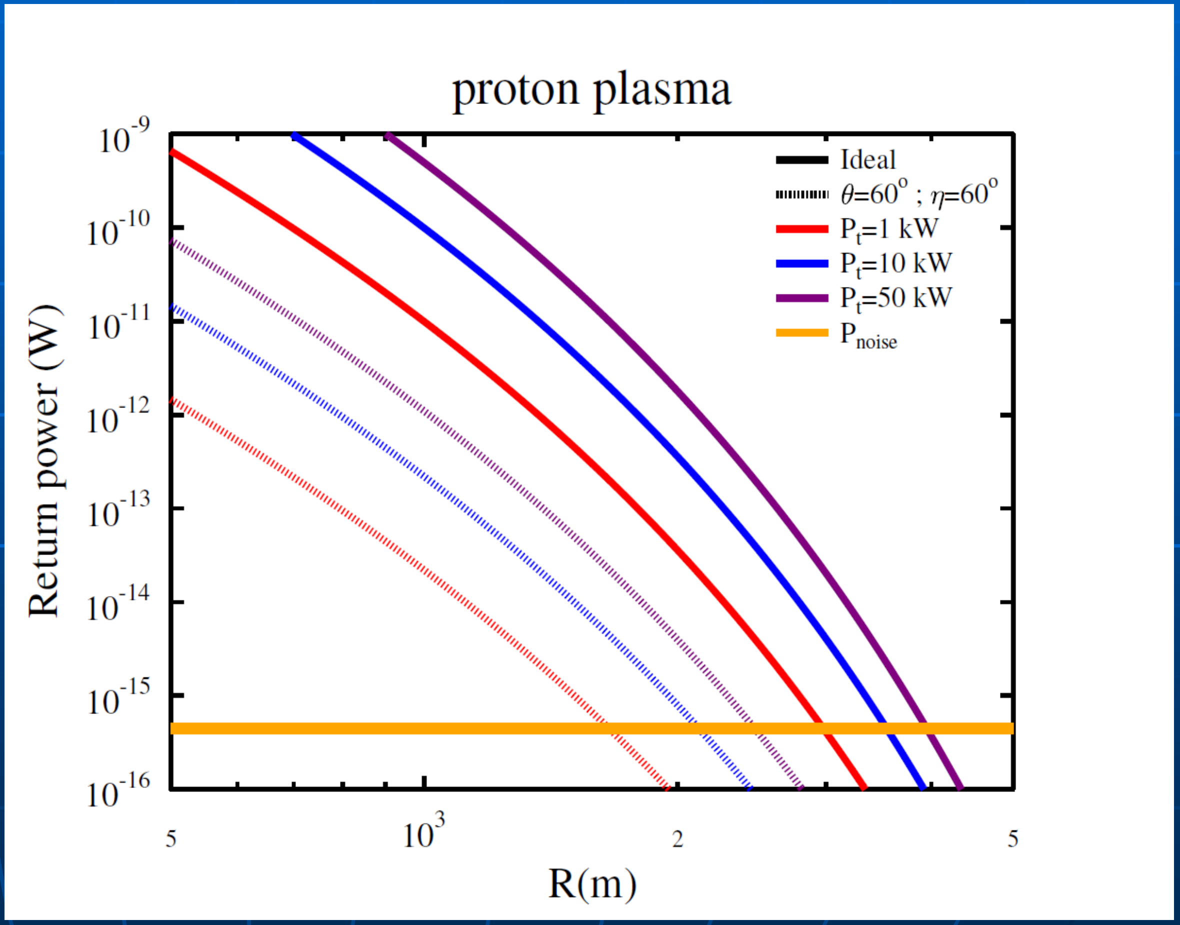


Open questions: The Plasma

- How large is the over-dense plasma?

- What is the influence of skin-effects?

- What is the lifetime of the plasma?

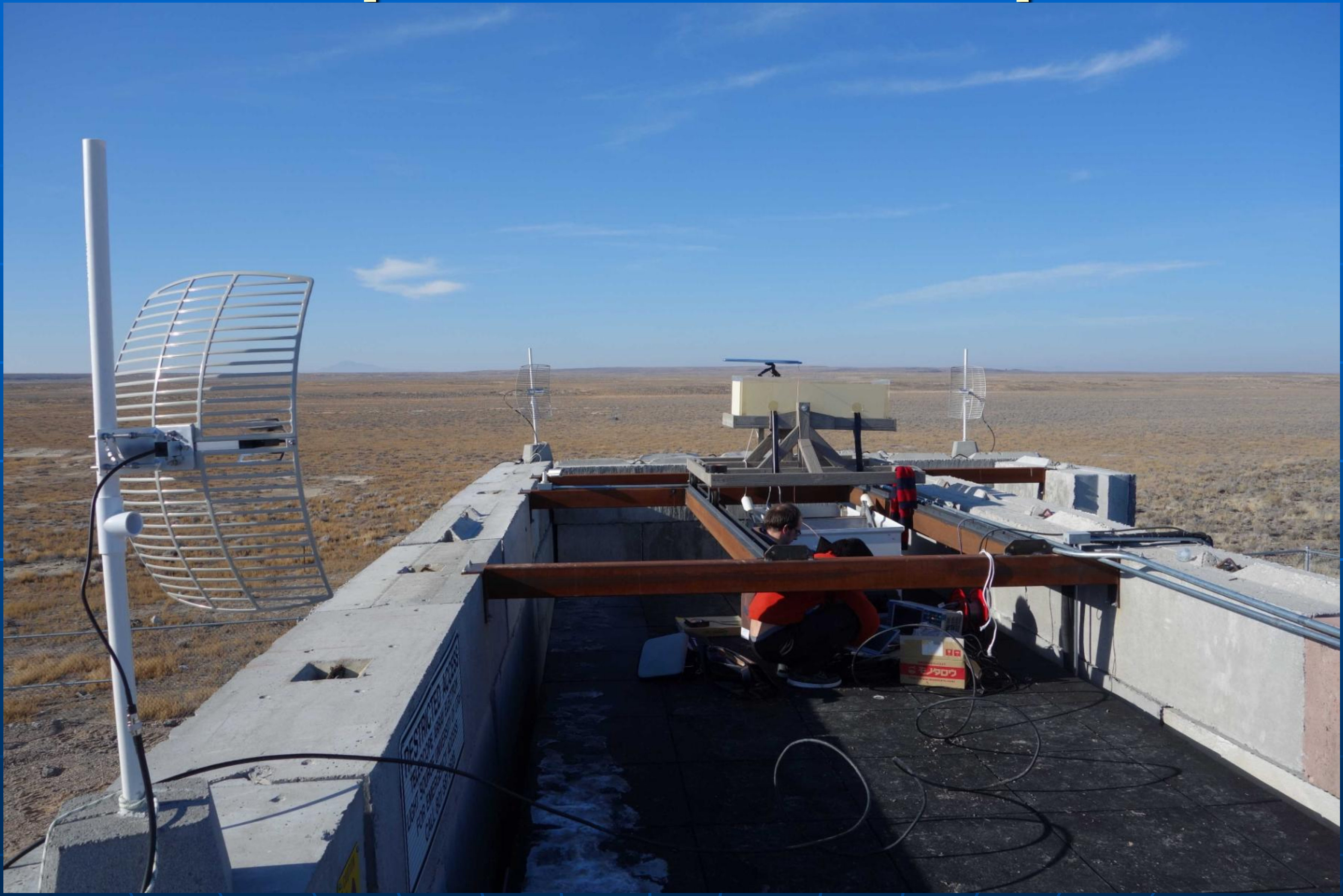
- Is the plasma collision frequency low enough?

→ **Experimental verification needed!**

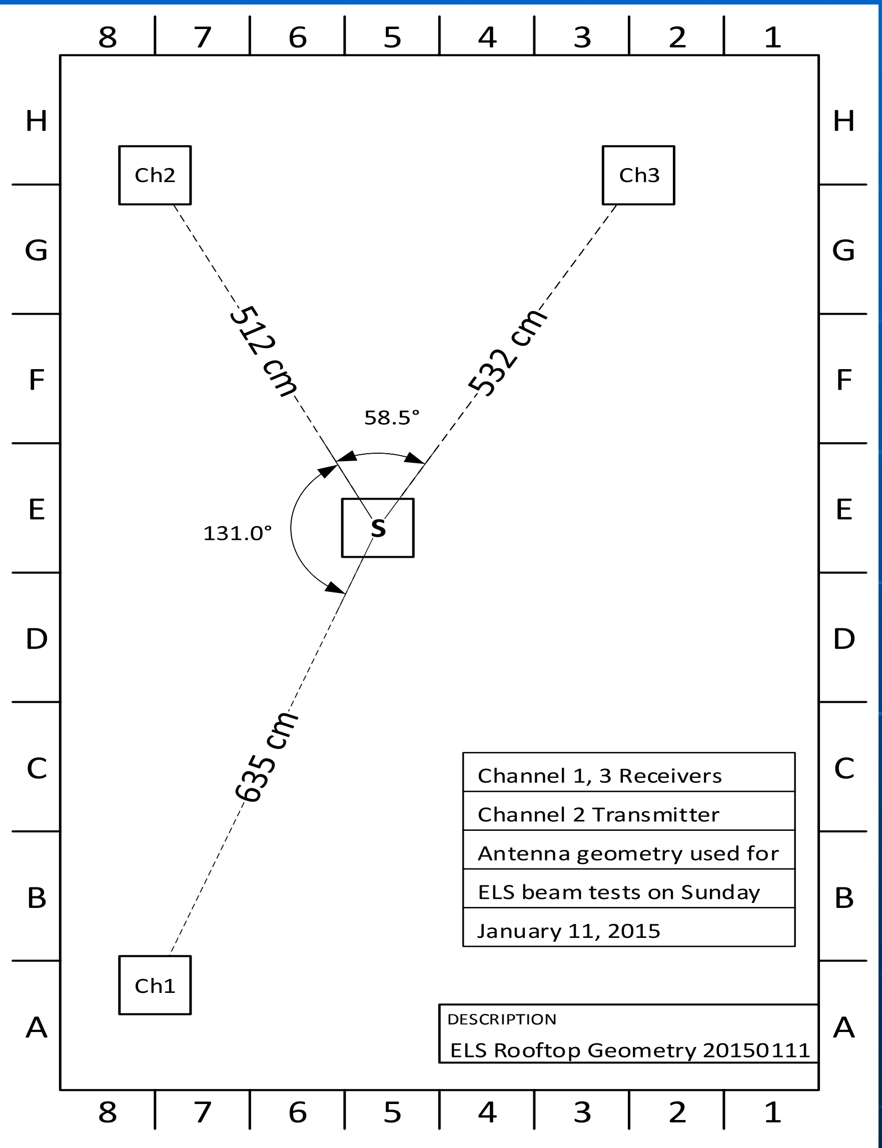
Radar scattering experiment at TA-ELS

Many thanks to the Chiba group and the Telescope Array Collaboration !

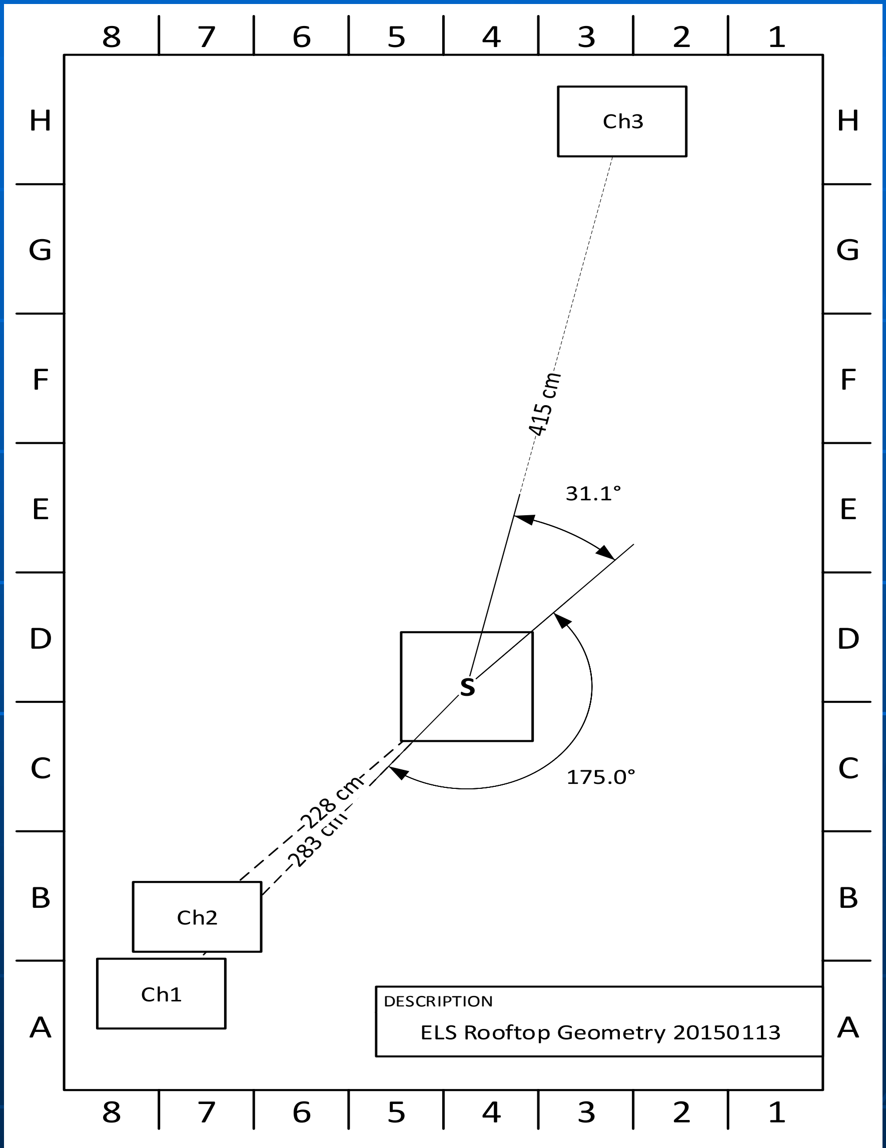
Experimental setup



Experimental setup

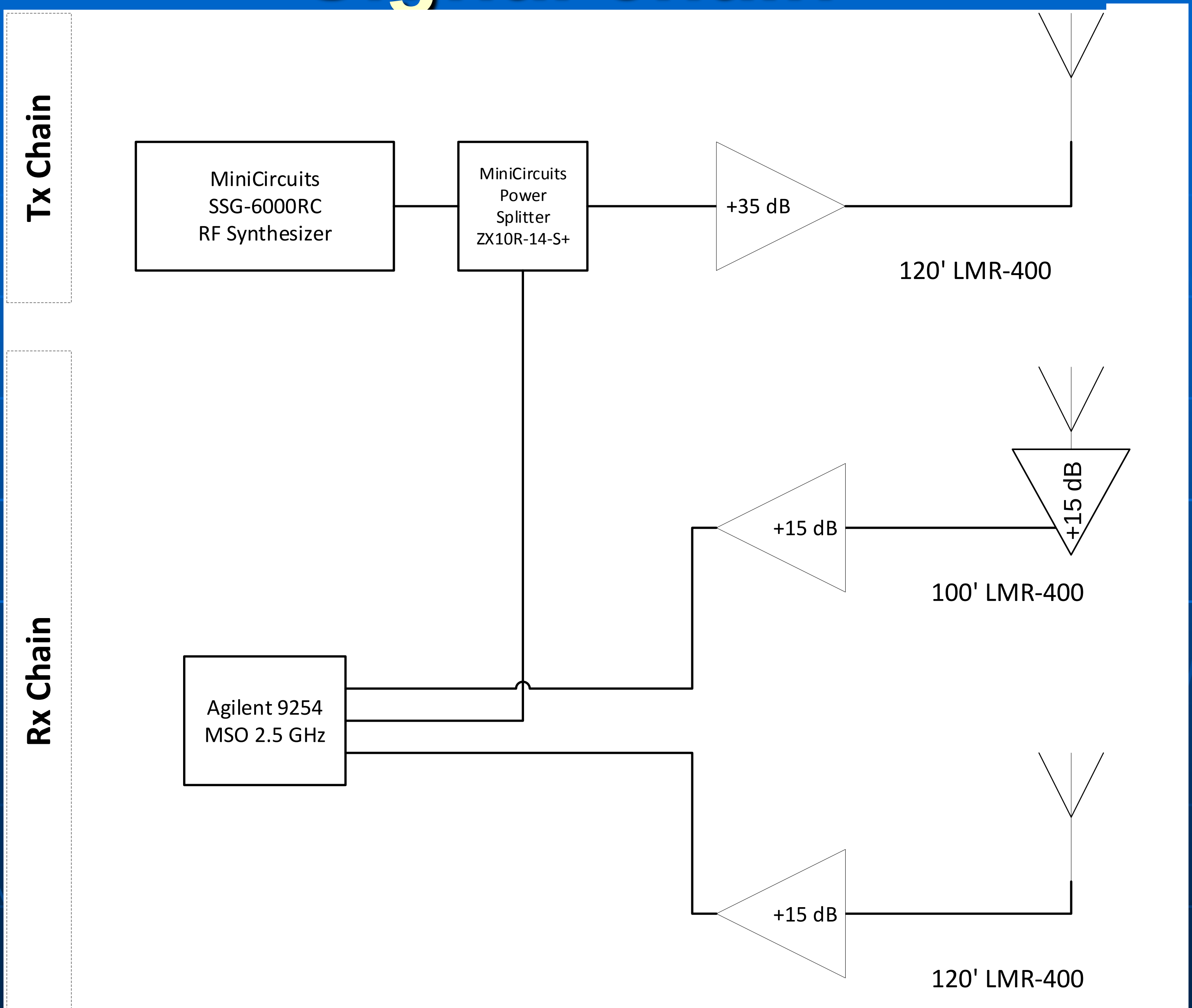


Early Configuration

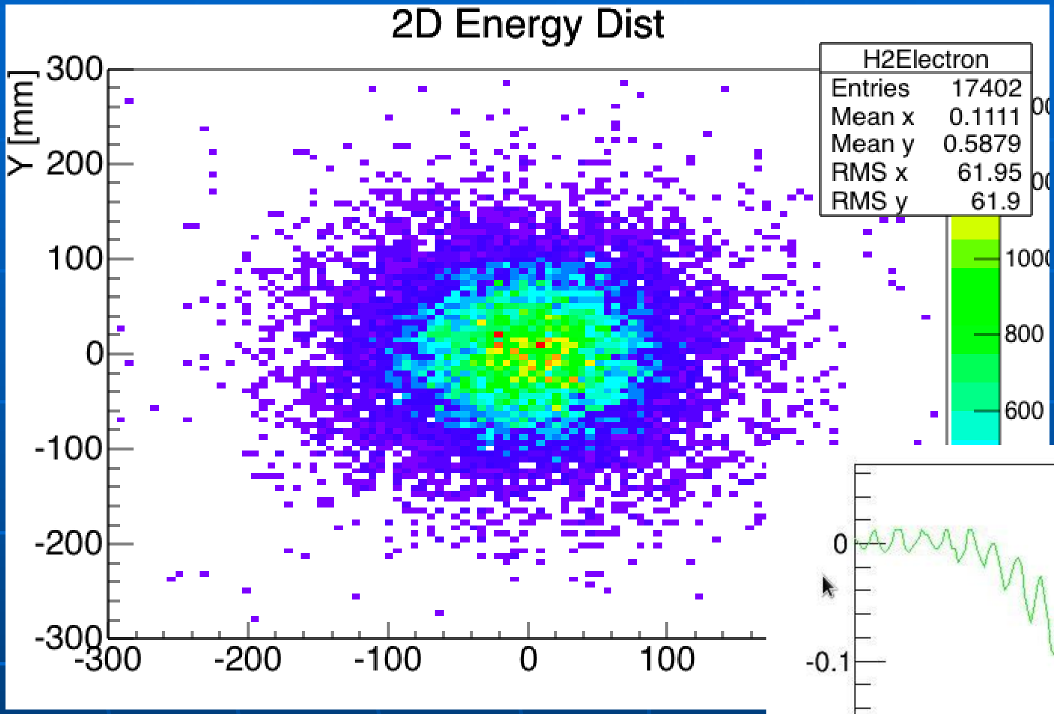


Later Configuration

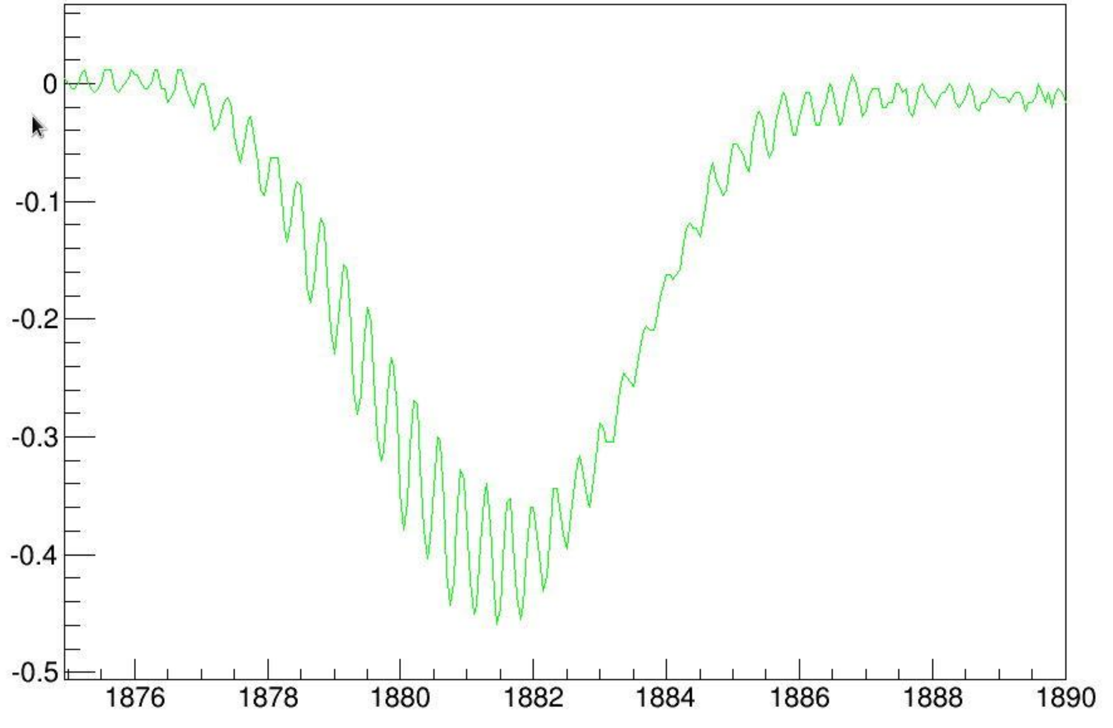
Signal chain



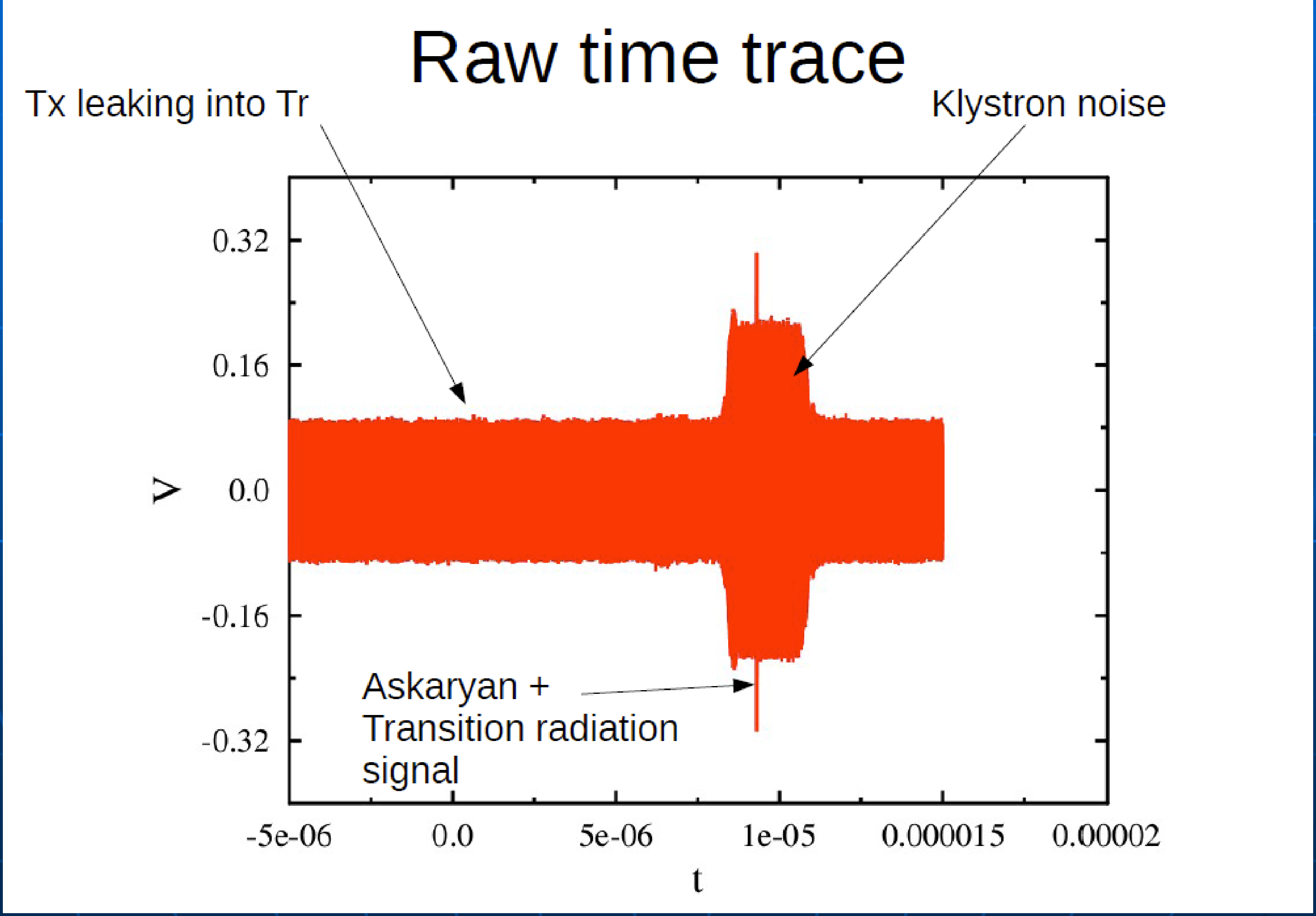
Radar scattering
Beam characteristics



- ~10^9 (40 MeV) electrons
- ~ 40 PeV



Radar scattering
What do we see?



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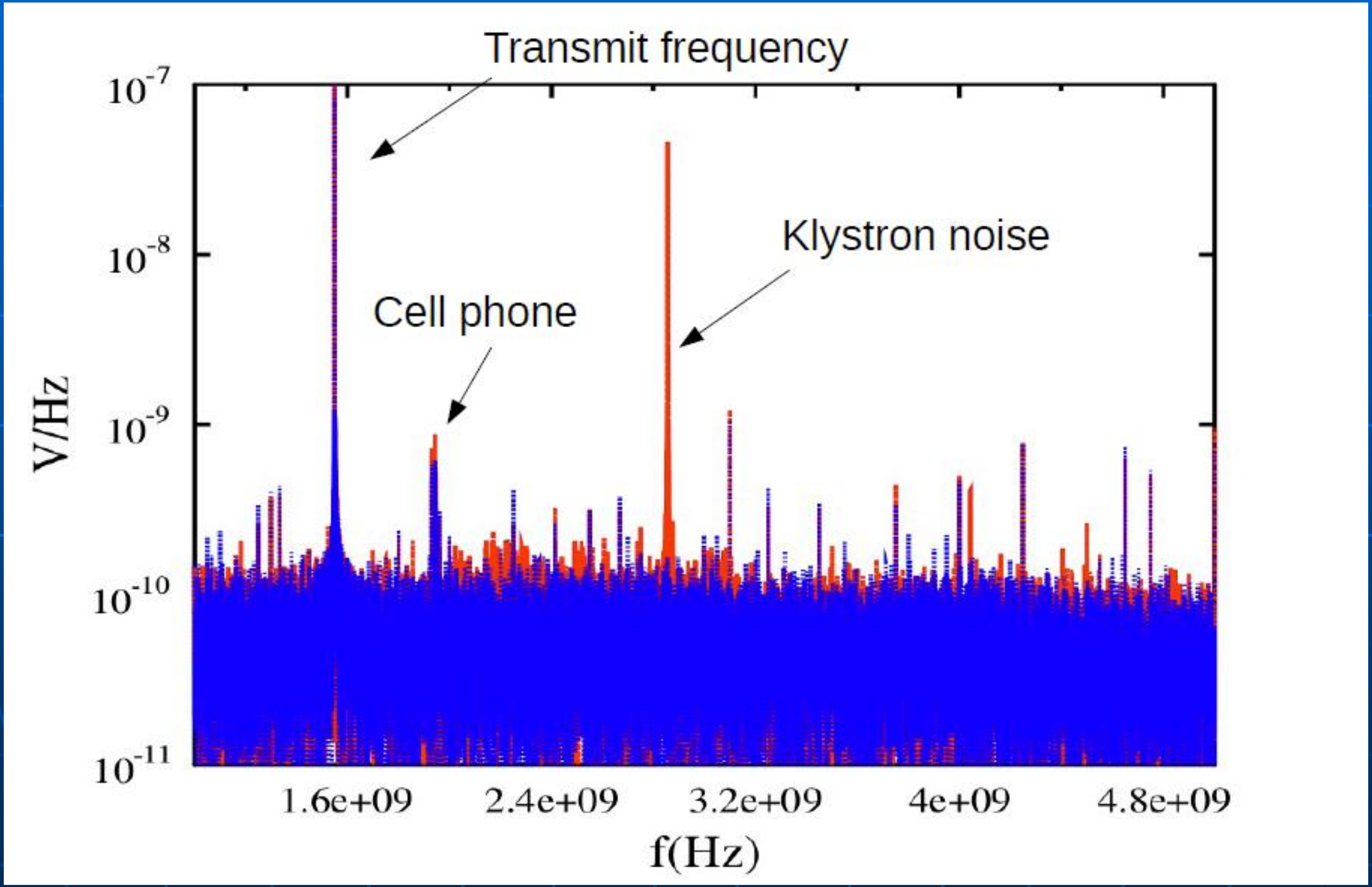
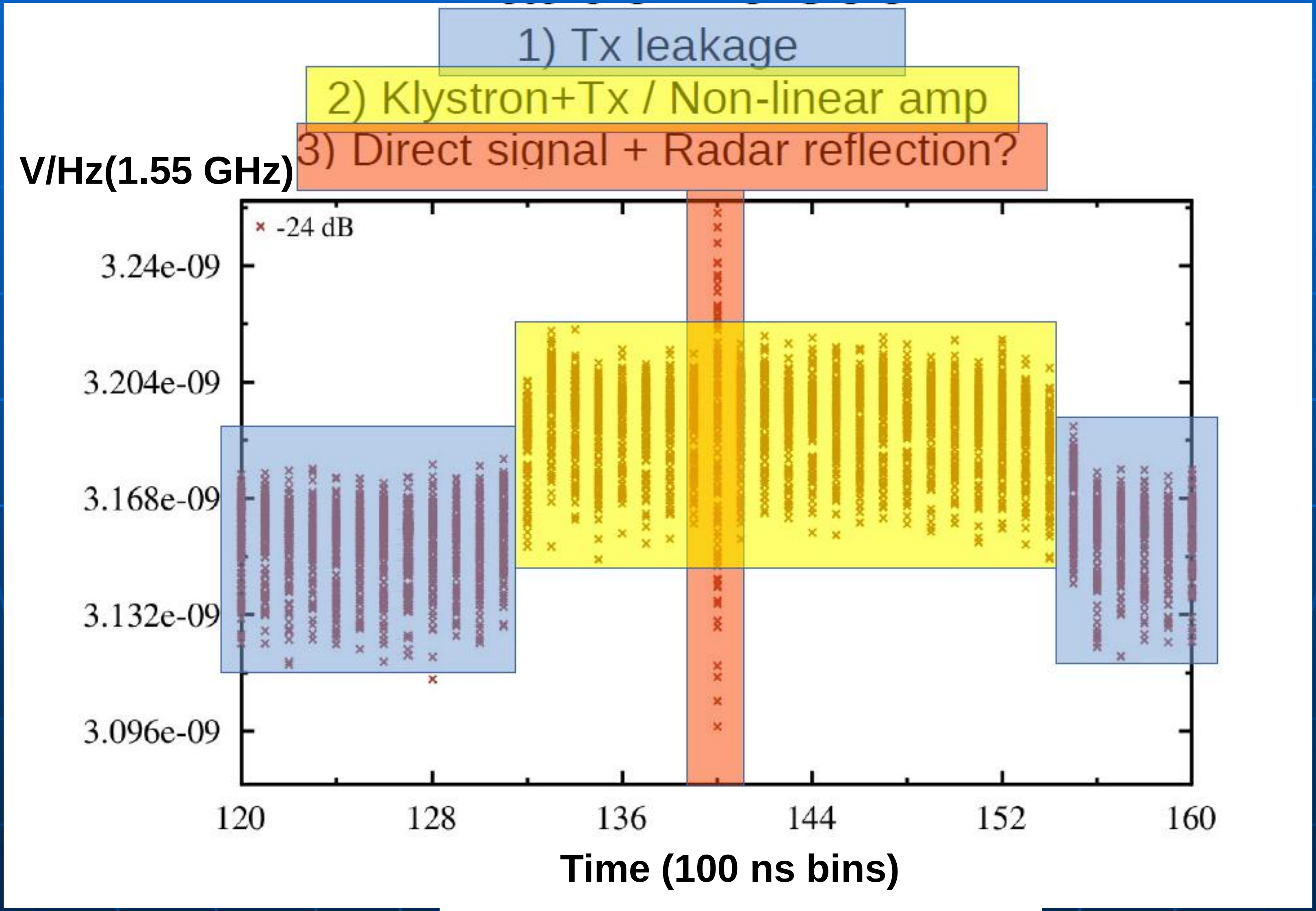


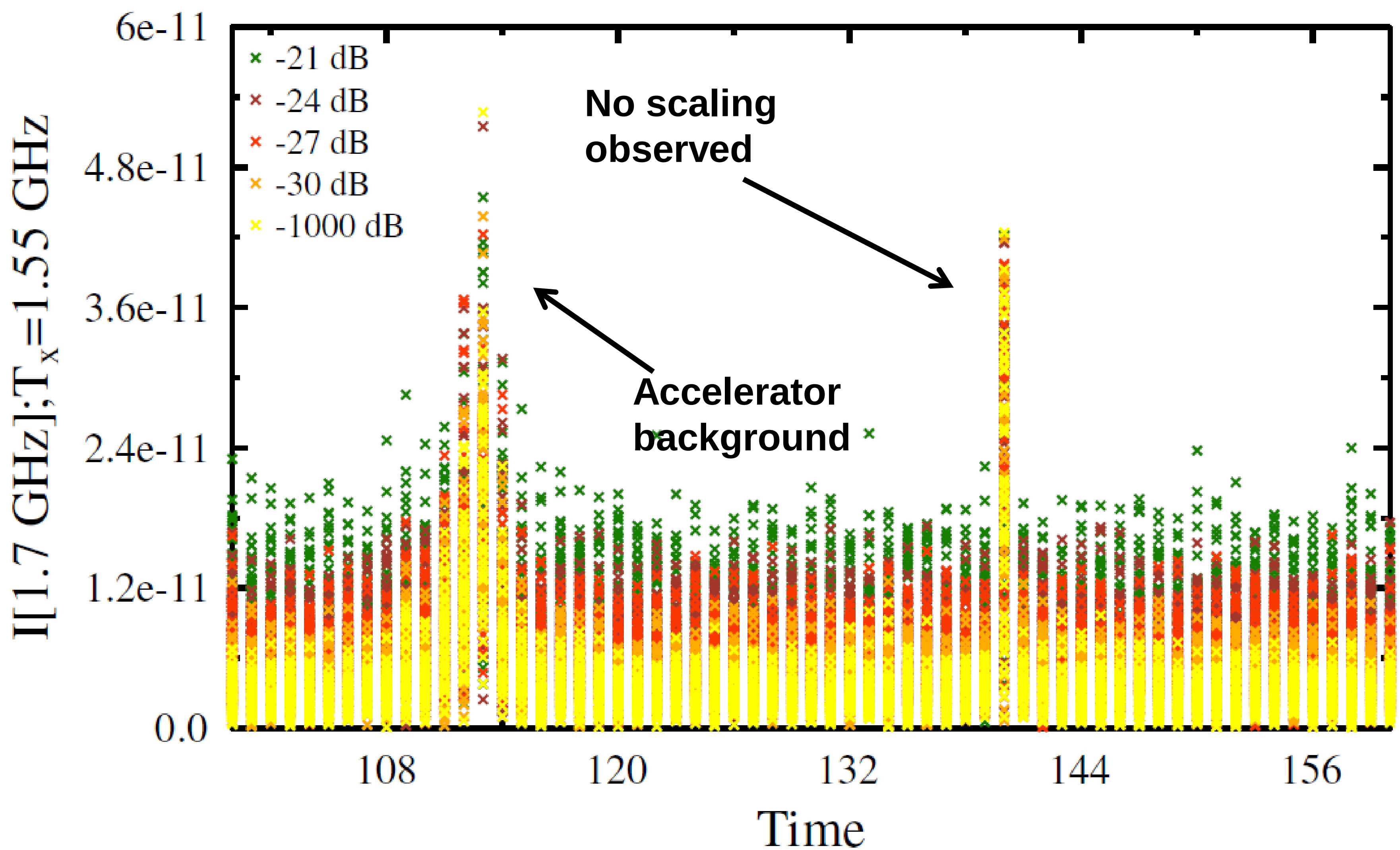
Radar scattering
What do we see?



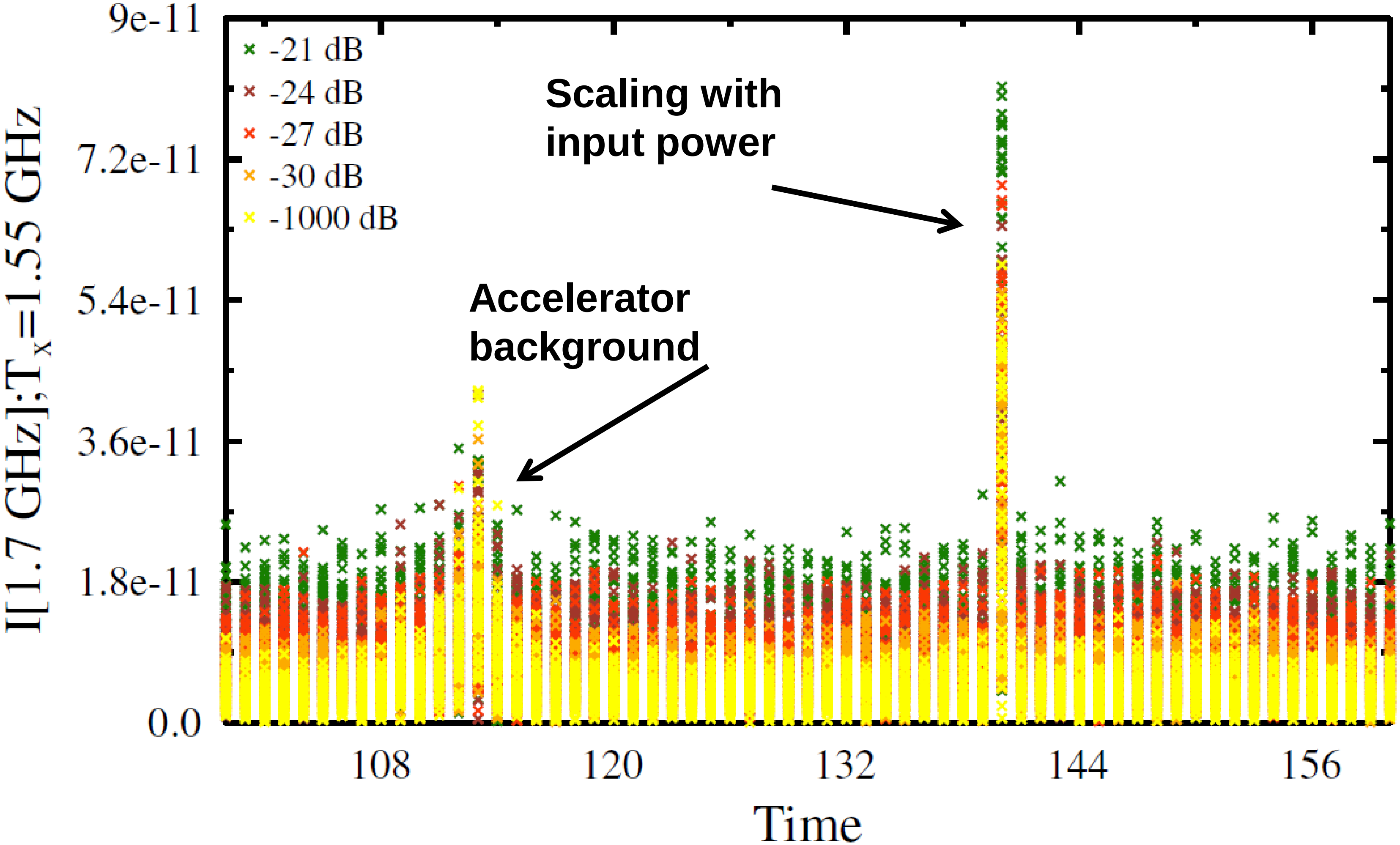
Radar scattering Interference and instrumental effects

- 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 scattering
Air



Radar scattering
Ice



Conclusions

- Modeling the RADAR scattering of high-energy neutrino induced cascades gives an energy threshold of several PeV.

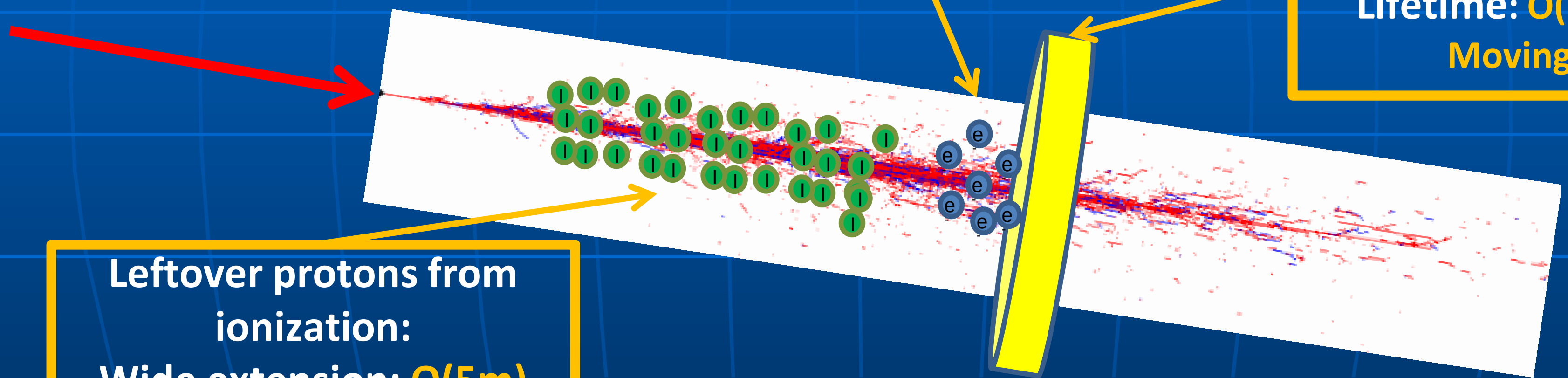
- We performed a measurement to determine the feasibility of this method.

- Obtained data hints toward a scattered signal, analysis is ongoing.

Three different types of plasma are considered

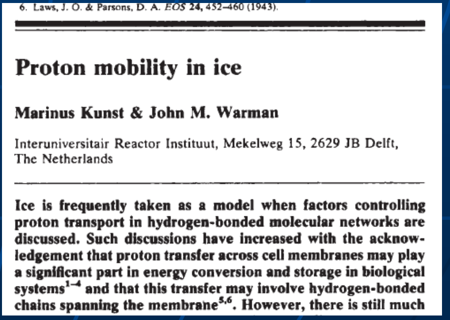
Leftover electrons from ionization:
Extension: O(30 cm)
Lifetime: O(1-20 ns)

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

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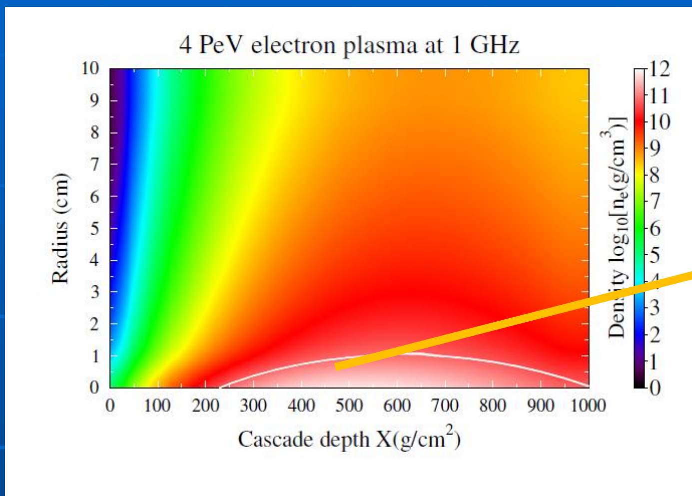
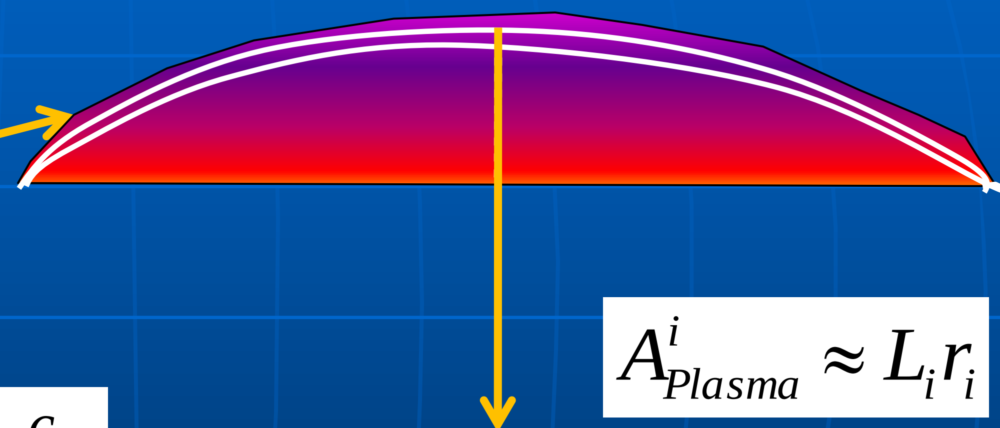
Ice is frequently taken as a model when factors controlling proton transport in hydrogen-bonded molecular networks are discussed. Such discussions have increased with the acknowledgement that proton transfer across cell membranes may play a significant part in energy conversion and storage in biological 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

Skin Effects

Model: Consider over-dense cylinders of equal density





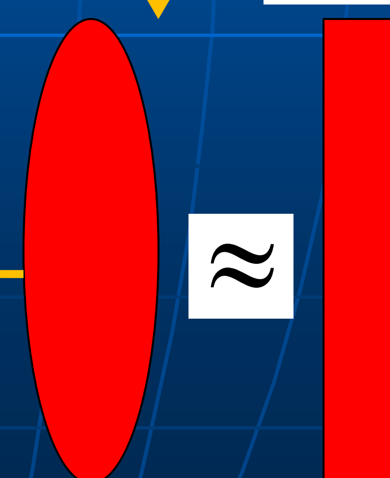
$$A^{i}_{Plasma} \approx L_i r_i$$

Calculate skin depth for a collision less plasma:

$$\delta = \frac{c}{2\omega_p}$$

Within 1 skin depth the amount of power absorbed and re-scattered equals:

$$f^{i+1}_{skin} = (1 - f^{i}_{skin})(1 - e^{-\frac{x}{\delta_i}})$$



$\approx$

The over-dense radar cross-section

This approach:

1. Include skin-effects directly into the radar cross-section.
2. Consider projected area and polarization angles for in/out-going wave

$$\sigma_{od} = A_{plasma} \times f_{skin} \times f_{geom}$$

$$A^{i}_{Plasma} \approx L_i r_i$$

$$f^{i+1}_{skin} = (1 - f^{i}_{skin})(1 - e^{-x/\delta_i})$$

$$f_{geom} = (\vec{e}_t \cdot \vec{e}_c)(\vec{e}_c \cdot \vec{e}_r)$$

$$\sigma_{od} = \sum_i L_i r_i (1 - f^{i}_{skin})(1 - e^{-x/\delta_i})(\vec{e}_t \cdot \vec{e}_c)(\vec{e}_c \cdot \vec{e}_r)$$

The under-dense radar cross-section

The wave will scatter off of the individual electron given by the Thompson cross-section

$$\sigma_T = \left(\frac{m_e}{m_p}\right)^2 0.665 \cdot 10^{-28}\ \mathrm{m}^2$$

We have to take into account for the phase lag of the individual electrons w.r.t. each other:

$$\sigma_{ud} = \sum_{i=1}^{N} \sigma_T \cos(kx)$$

$$k = \frac{2\pi}{\lambda_d}\ x = |\vec{x_1} - \vec{x_i}| + |\vec{x_2} - \vec{x_i}|$$