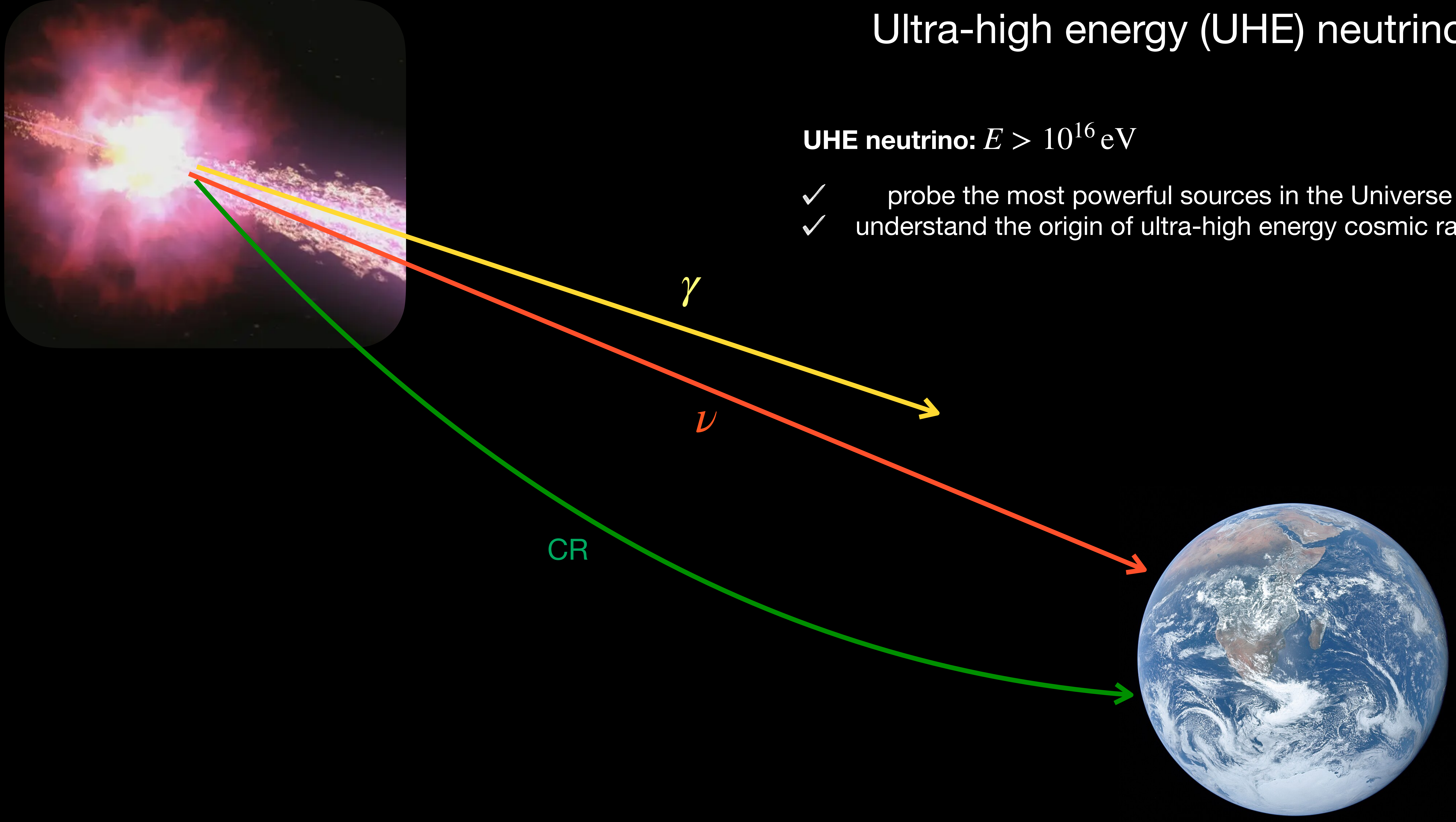
Modeling in-ice radio signals from cosmic ray particle cascades

***Simon Chiche**, Simona Toscano, Krijn de Vries*

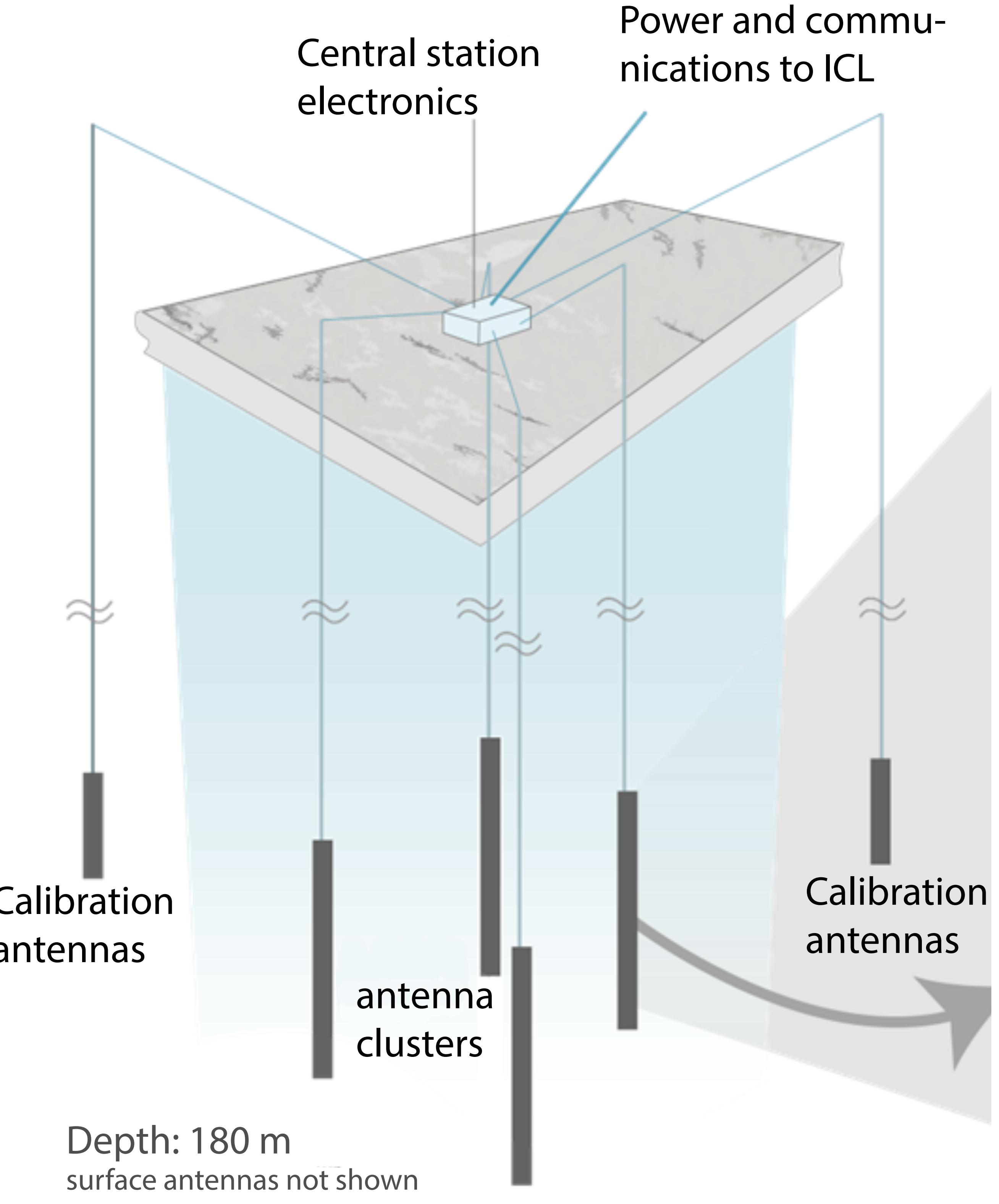
Ultra-high energy (UHE) neutrinos

UHE neutrino: $E > 10^{16}\,\mathrm{eV}$

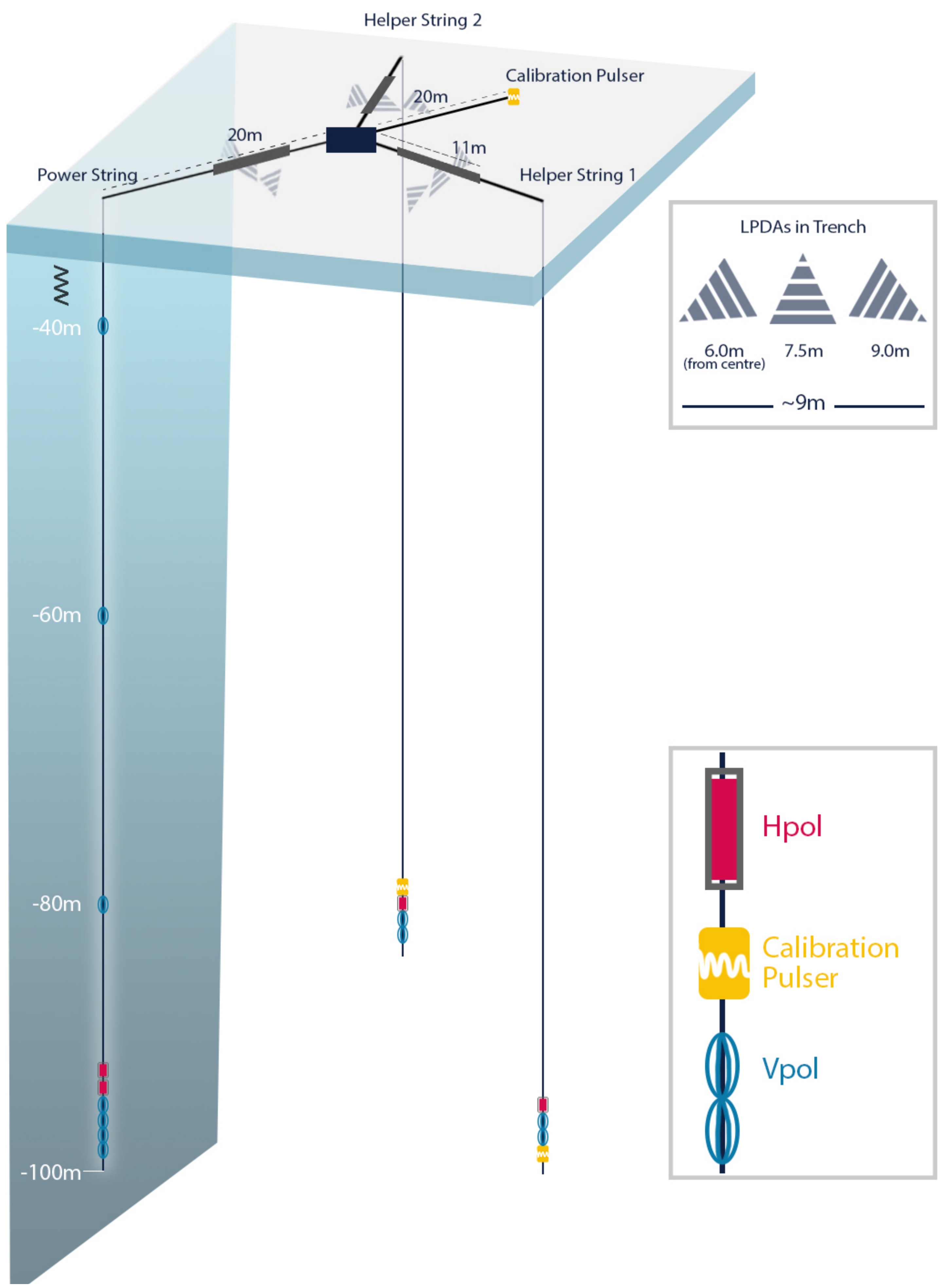
✓ probe the most powerful sources in the Universe
✓ understand the origin of ultra-high energy cosmic rays



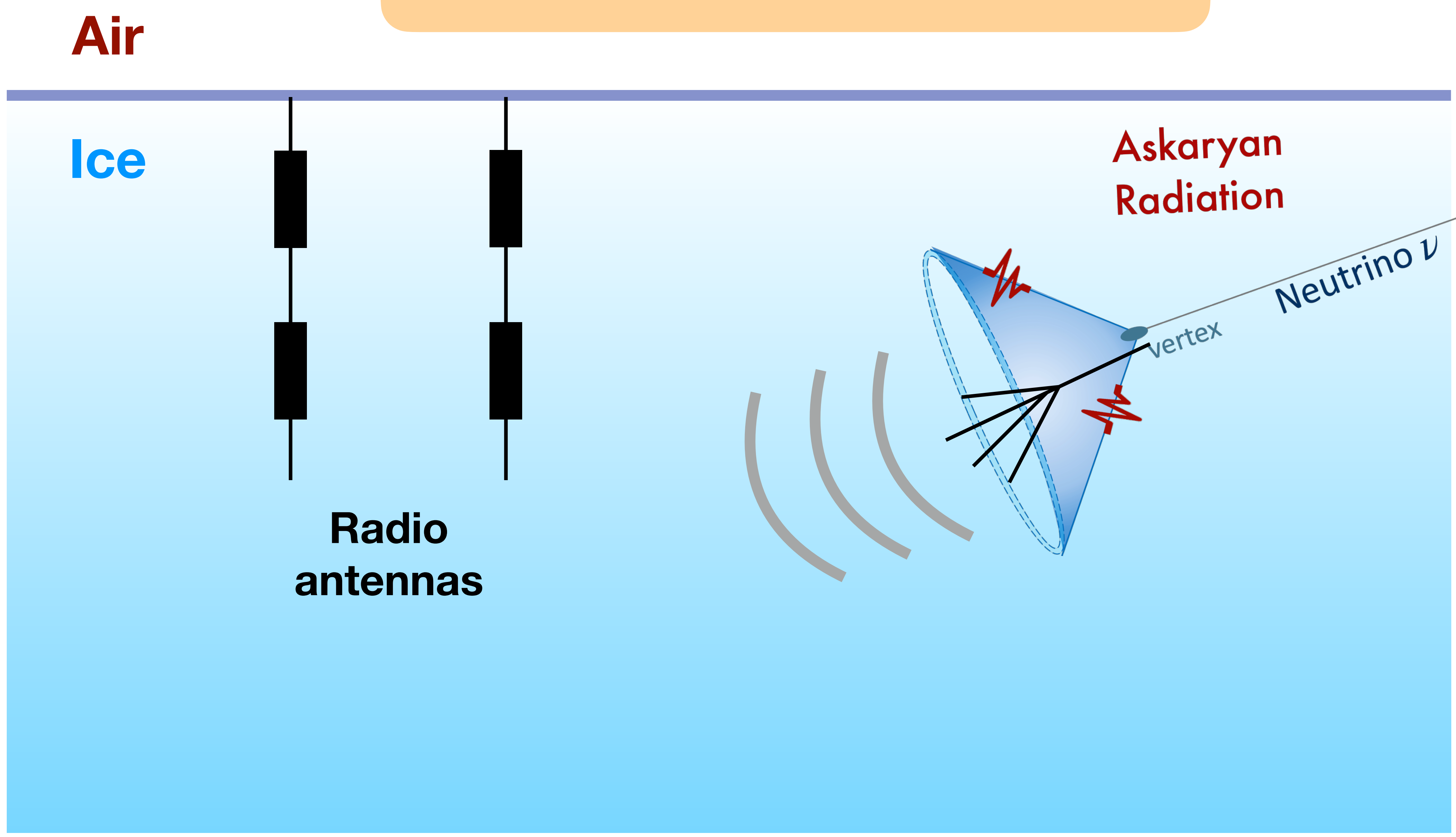
ARA



RNO-G

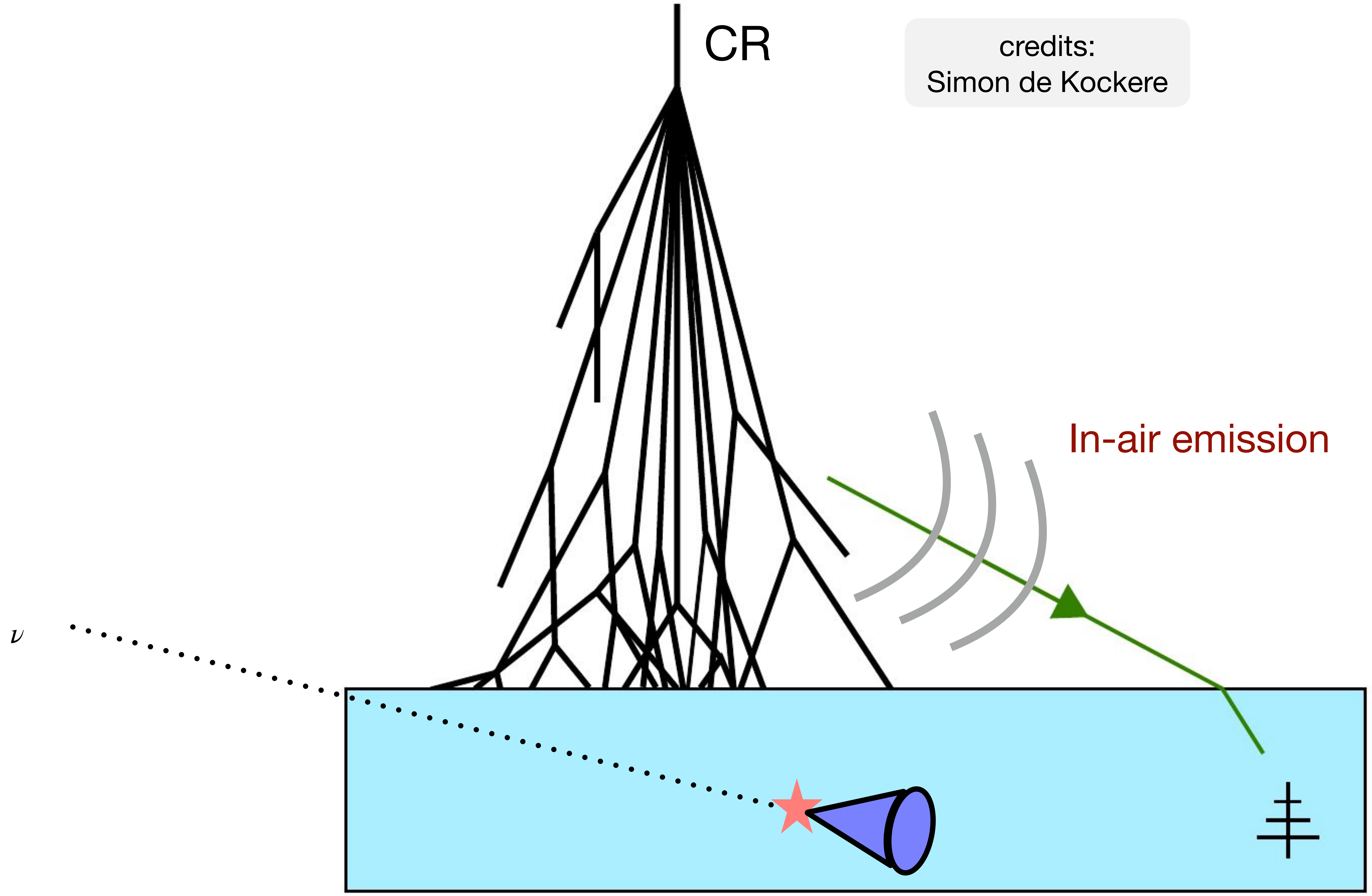


Radio detection of ultra-high energy neutrinos



In-ice radio detection: promising technique to detect ultra-high energy neutrinos

Radio emission of cosmic-ray air showers can also reach the deep antennas



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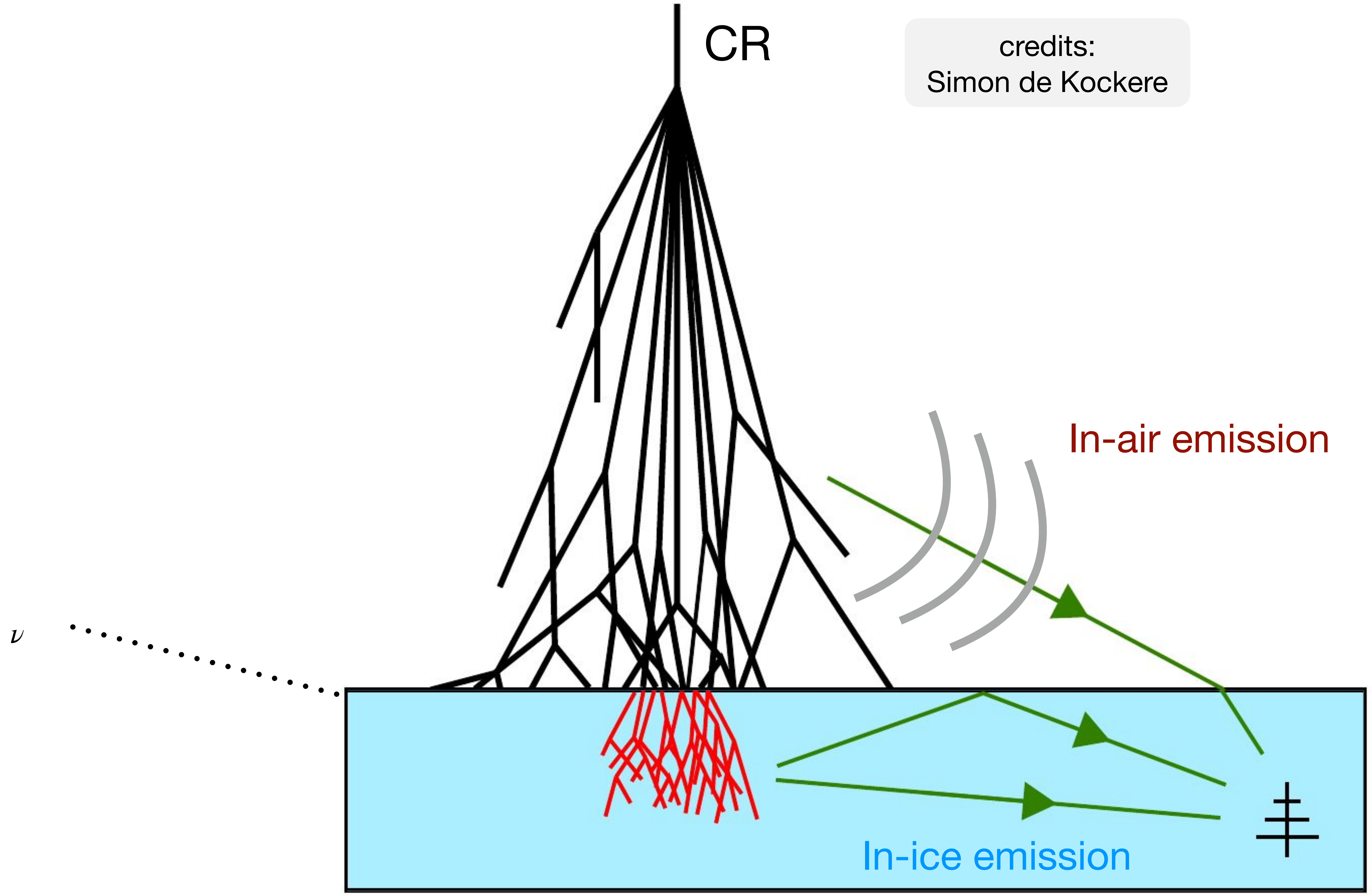

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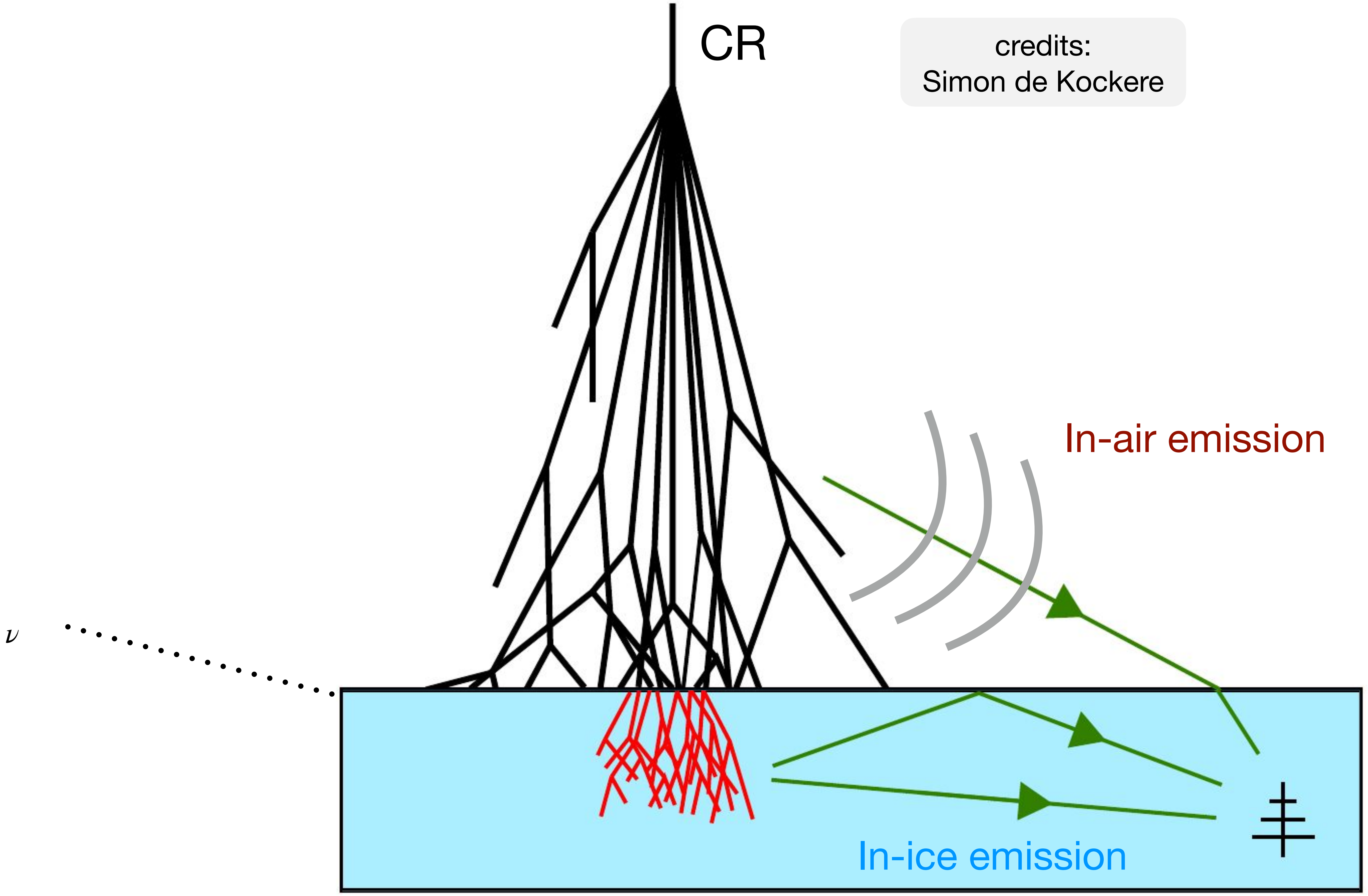
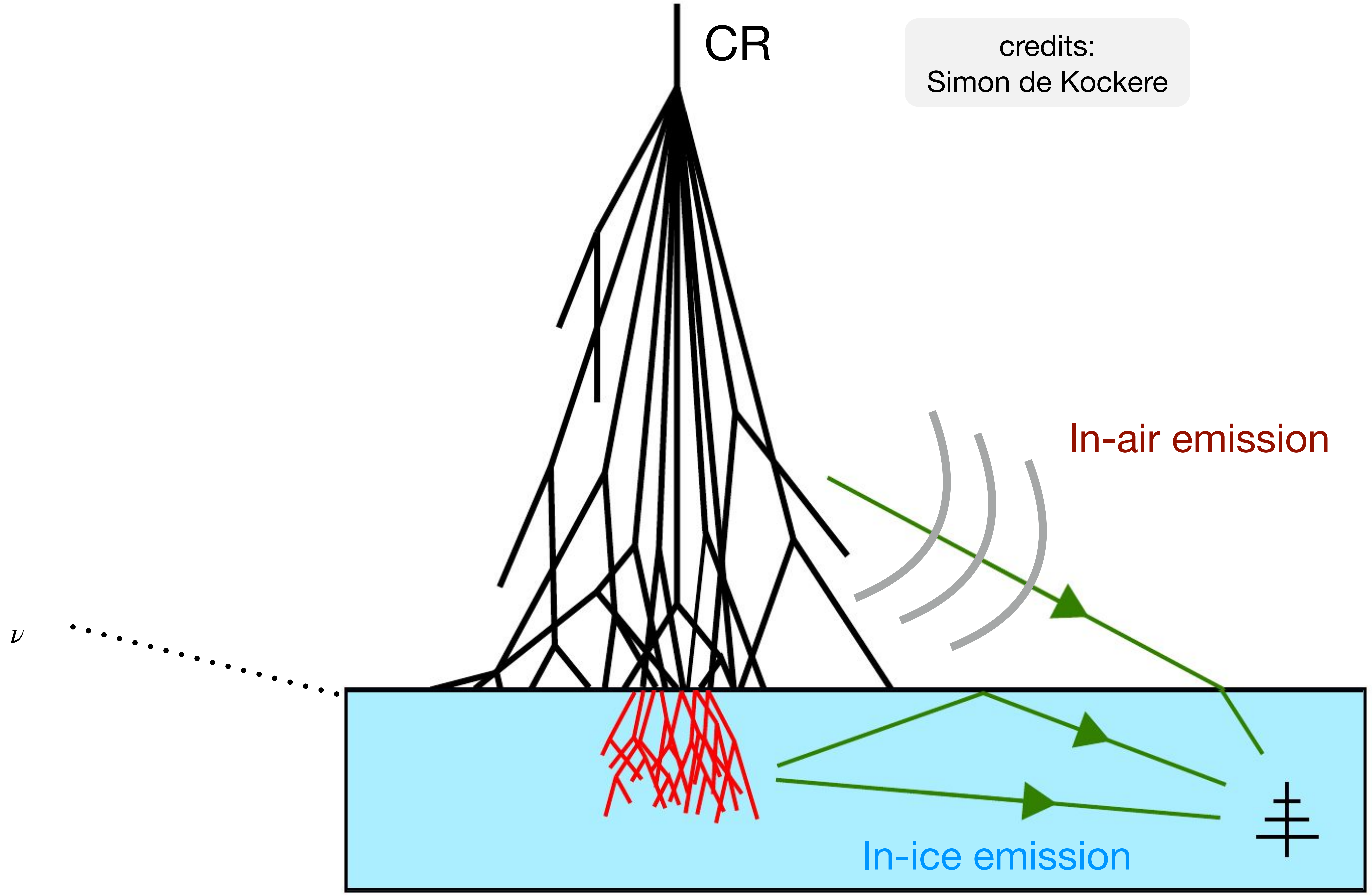


The cosmic-ray flux should be much larger than the neutrino flux:

In-ice radio emission from cosmic-ray air showers

Radio emission of cosmic-ray air showers can also reach the deep antennas

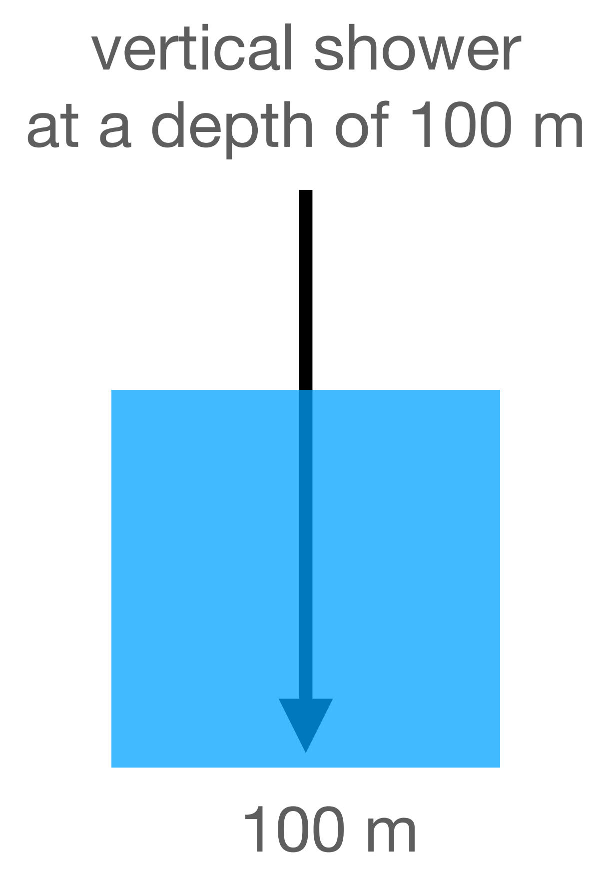


The cosmic-ray flux should be much larger than the neutrino flux:

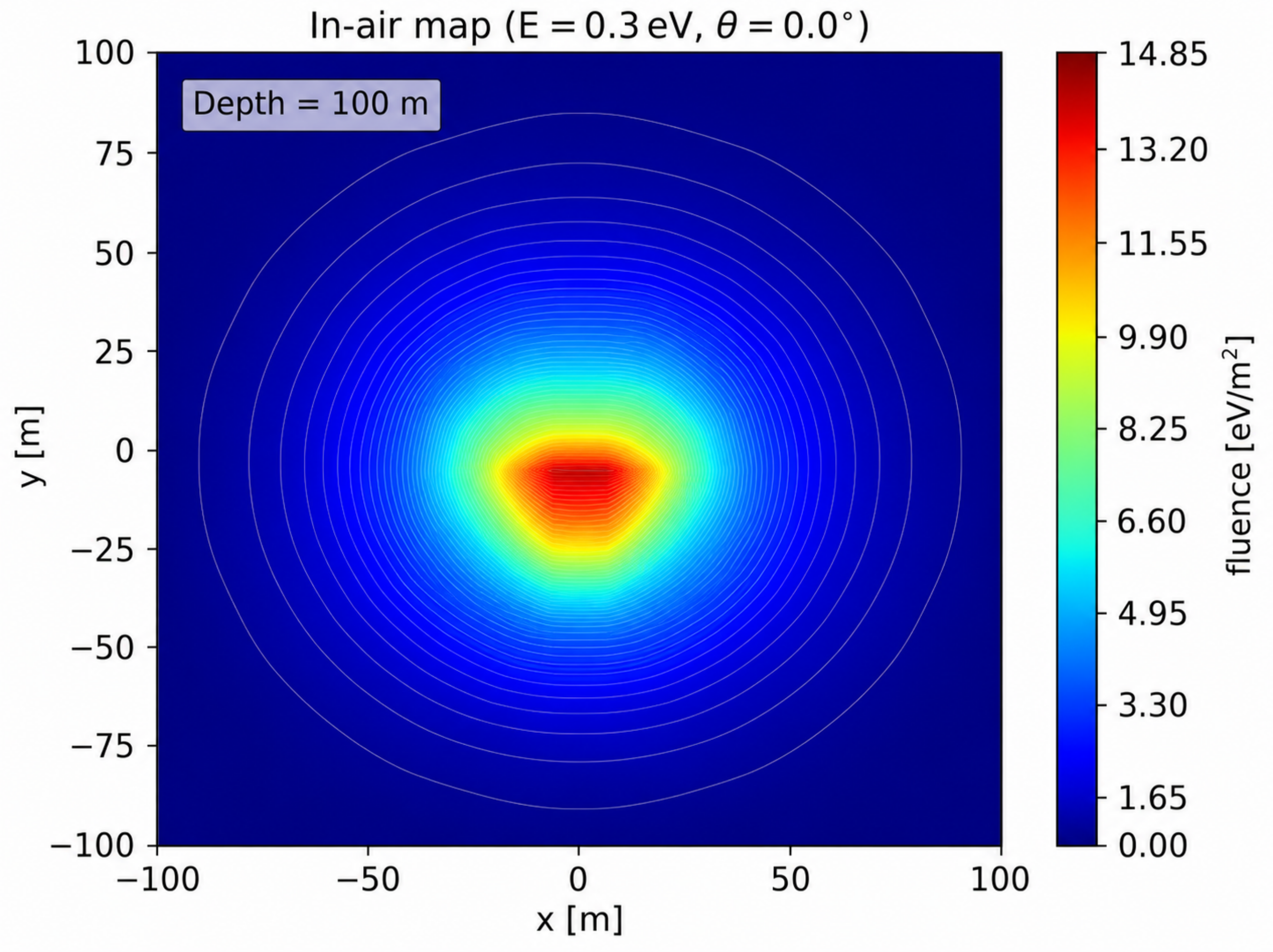
- Cosmic-ray detection would validate in-ice radio detection principle
- Cosmic-ray/neutrino discrimination is needed to ensure successful neutrino detection

Simon Chiche
(IIHE)

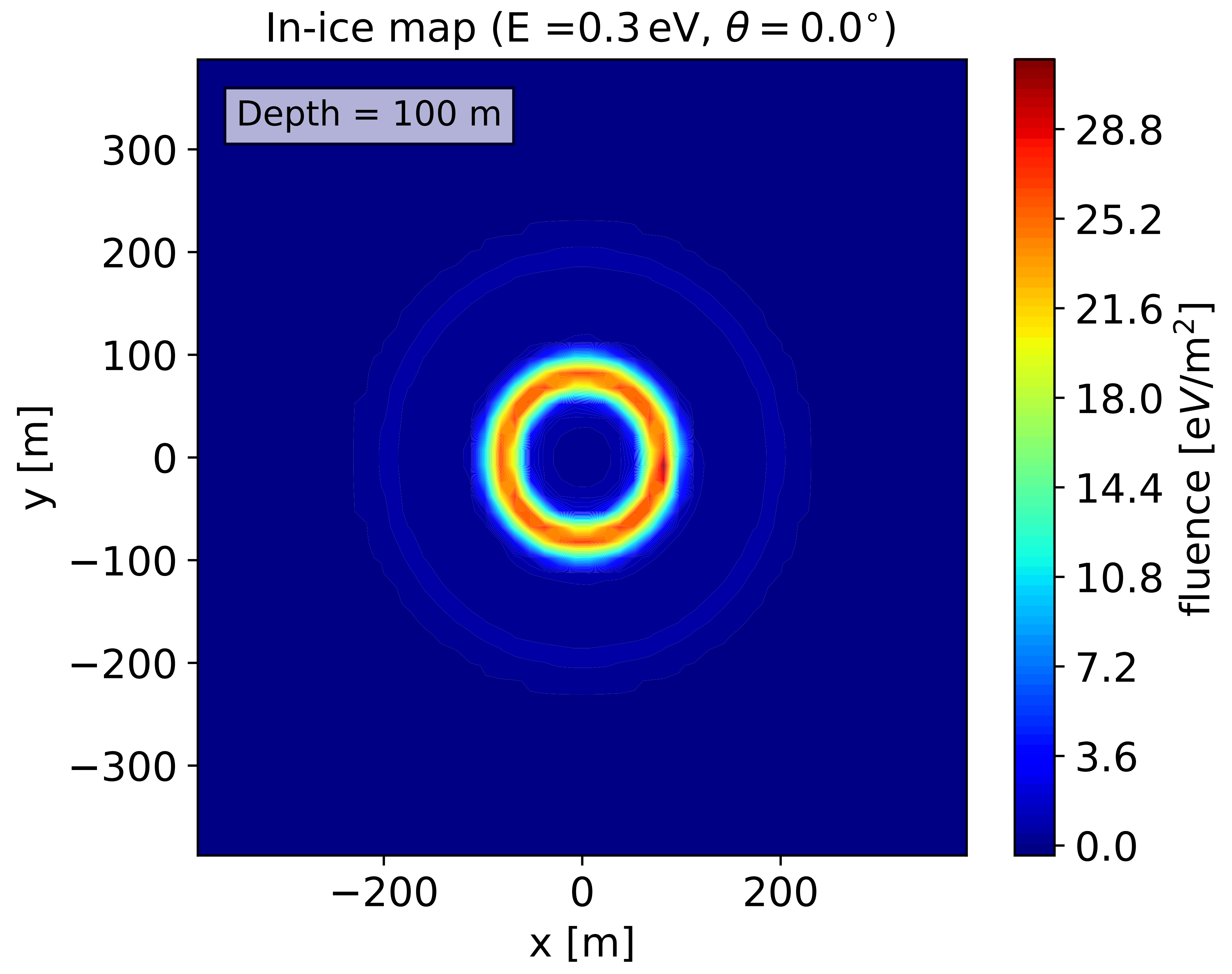
We can simulate cosmic ray radio emission at deep in-ice antennas using FAERIE



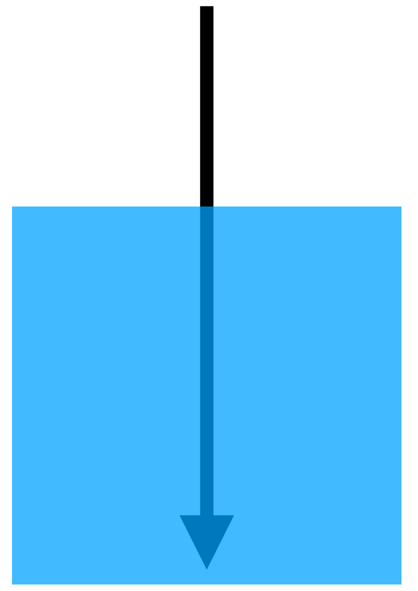
In-air



In-ice



(S. Chiche et al.,
Astropart. Phys., 2026)

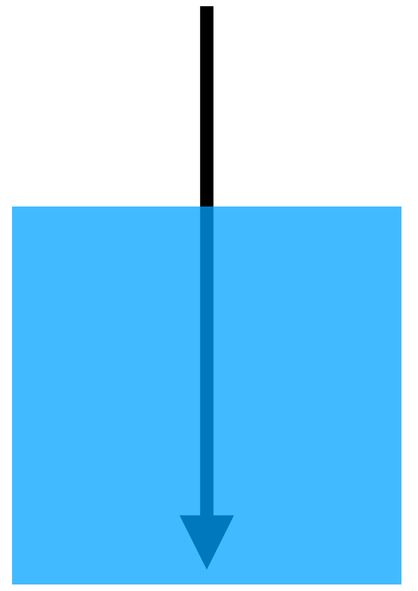


FAERIE-simulated cosmic ray library

Energy [eV]	$10^{16.5}$; 10^{17}; $10^{17.5}$
Zenith [°]	0; 20; 28; 34; 39; 43; 47; 50
Depth [m]	0; 60; 100

Monte-Carlo simulations are extremely expensive… we need a fast and precise alternative

Simon Chiche (IIHE)



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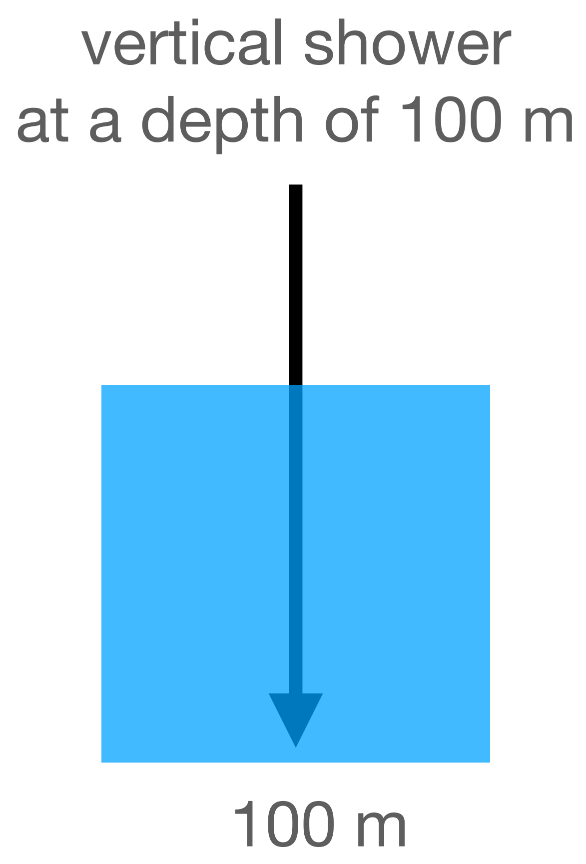
Semi-analytical modeling

Motivation



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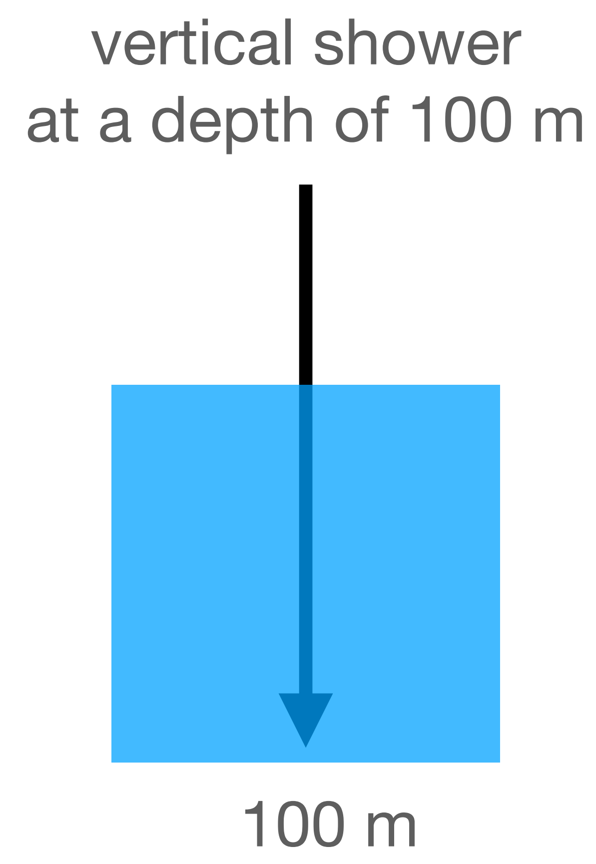

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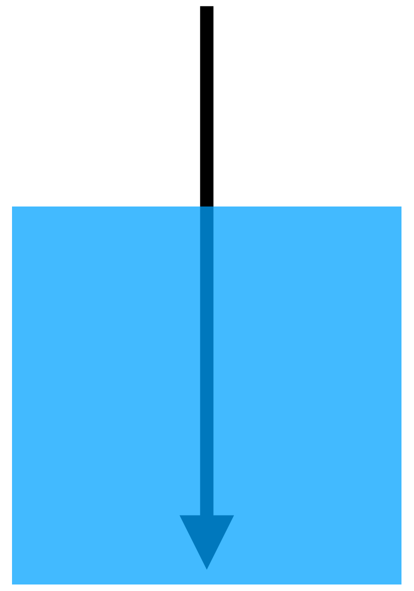
Semi-analytical modeling

FAERIE-simulated library

+

Scaling laws

vertical shower
at a depth of 100 m



100 m

FAERIE-simulated cosmic ray library

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Monte-Carlo simulations are extremely expensive… we need a fast and precise alternative

Semi-analytical modeling

FAERIE-simulated library

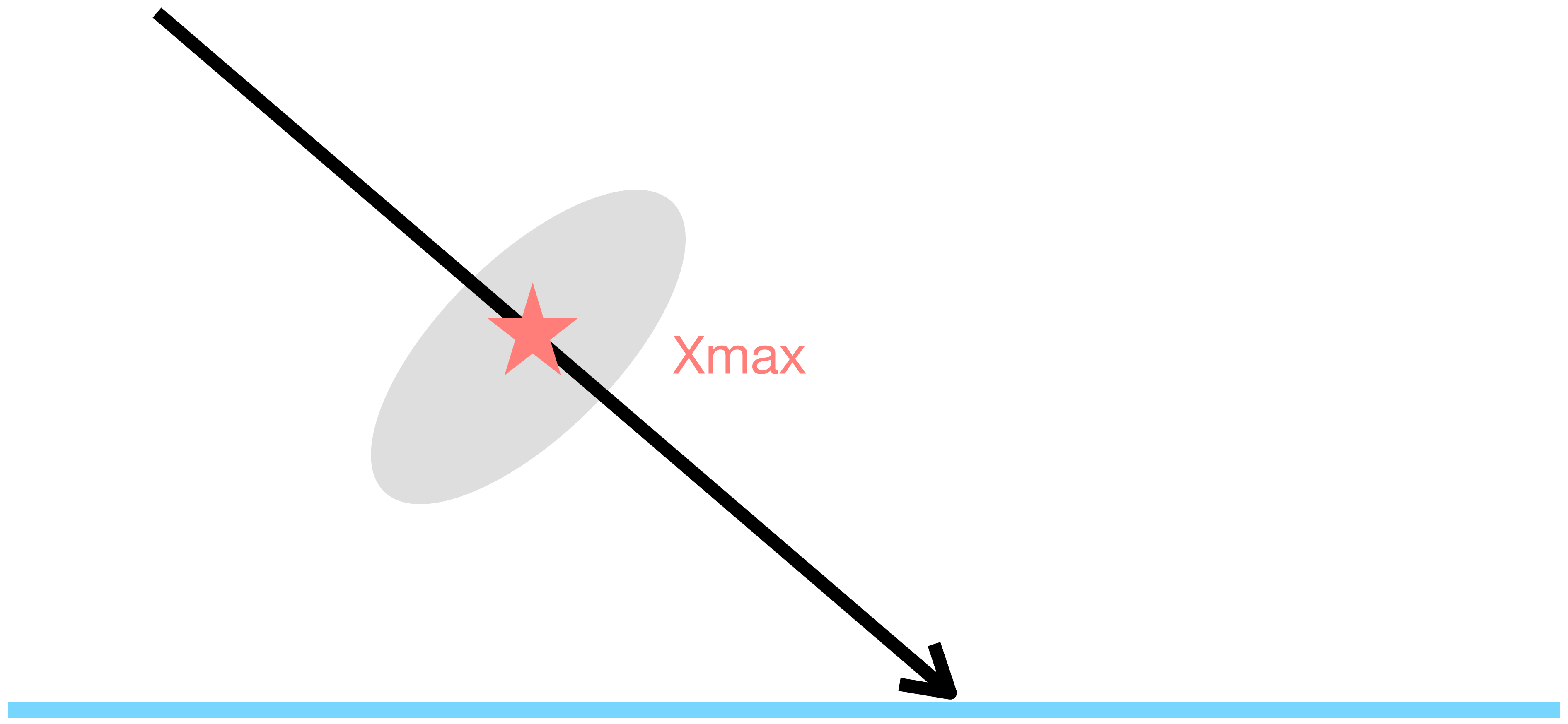
+

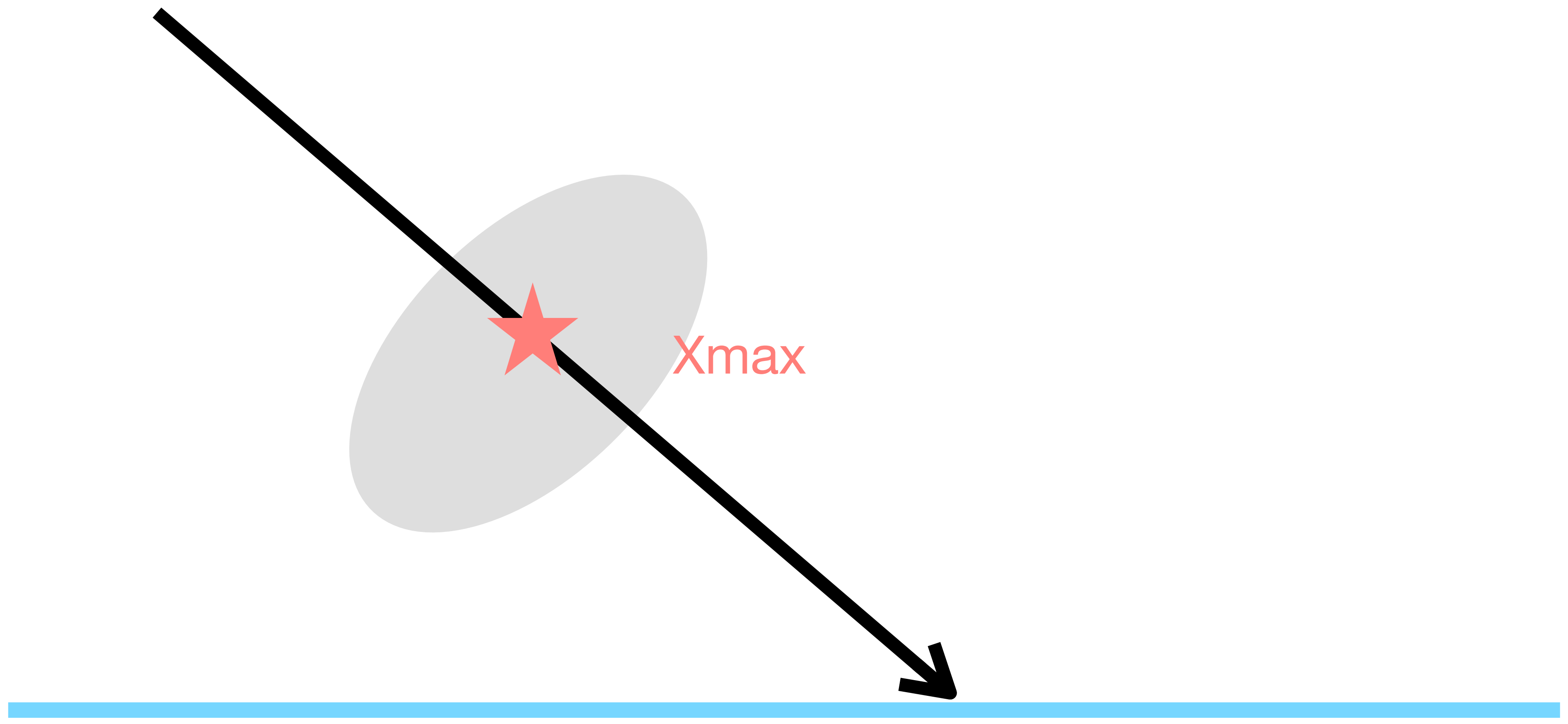
Scaling laws

Radiation energy:

$$E_{\text{rad}} = K \times f(\mathcal{E}_p) \times f(\theta) \times f(\varphi) \times f(Z)$$

In-air scaling


Xmax



$N_{\mathrm{EM}} \propto \mathscr{E}_p$ & $E_{\mathrm{rad}}^{\mathrm{air}} \propto N_{\mathrm{EM}}^2$

$$\boxed{E_{\mathrm{rad}}^{\mathrm{air}} \propto \mathscr{E}_p^2}$$

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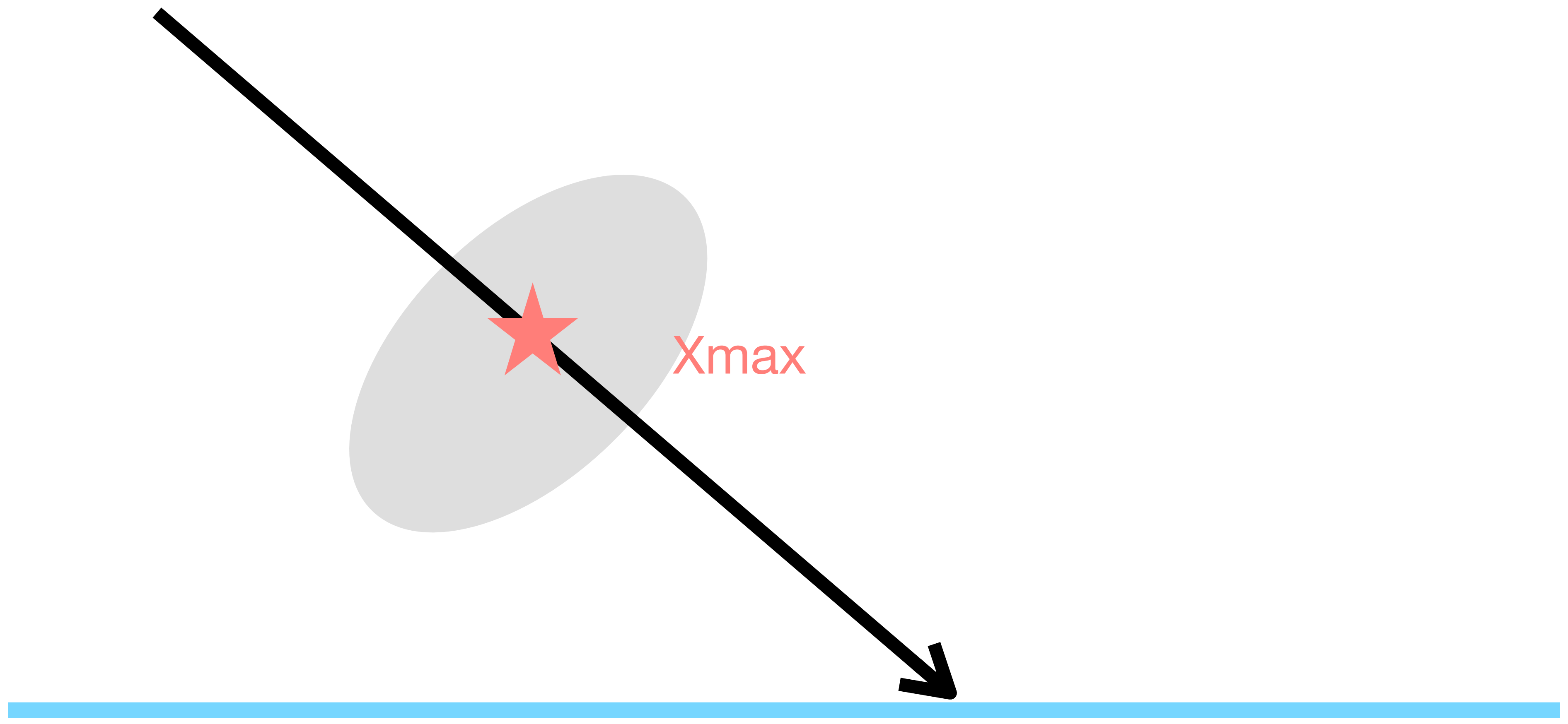

$$N_{\mathrm{EM}} \propto \mathscr{E}_p \quad \& \quad E_{\mathrm{rad}}^{\mathrm{air}} \propto N_{\mathrm{EM}}^2$$

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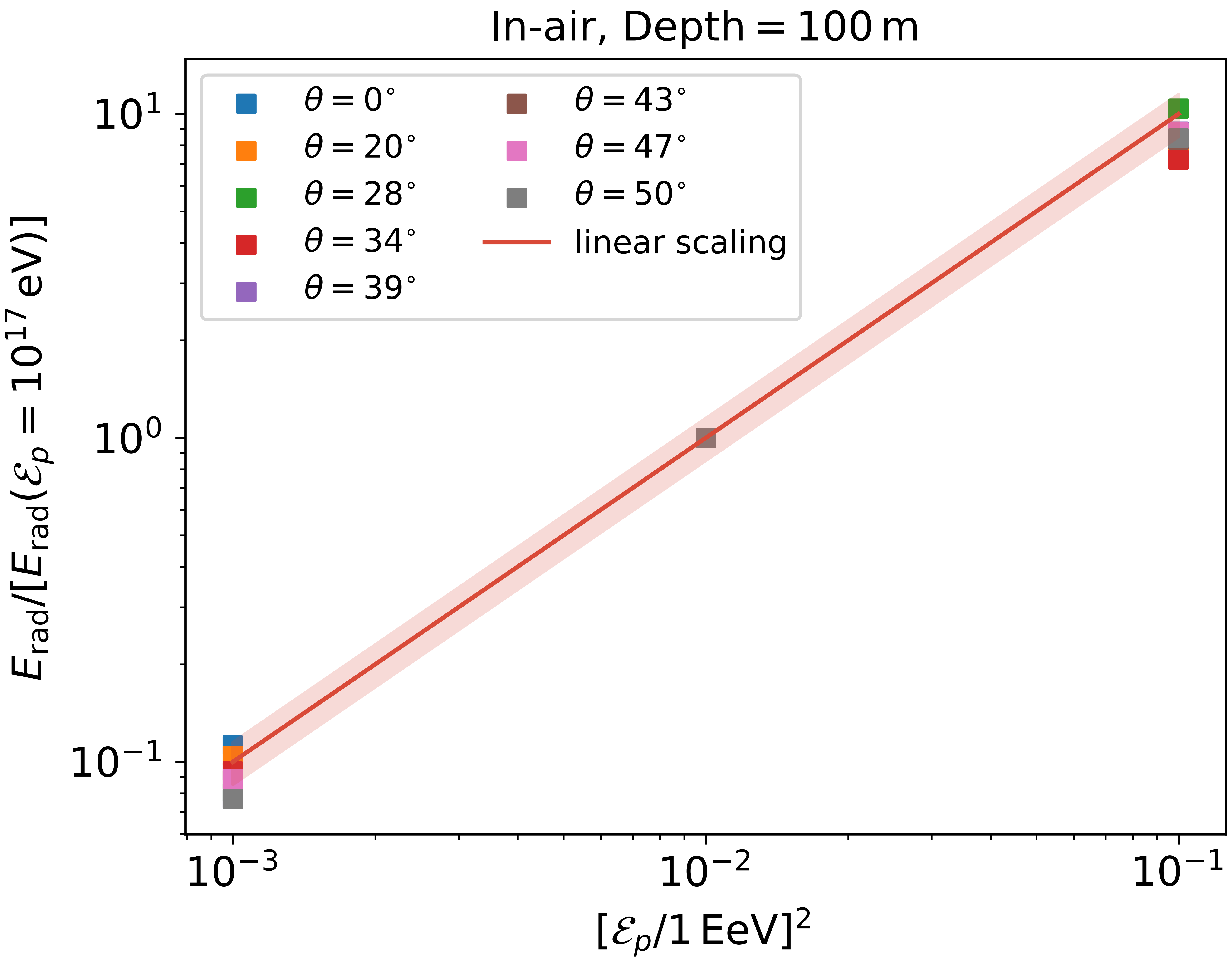

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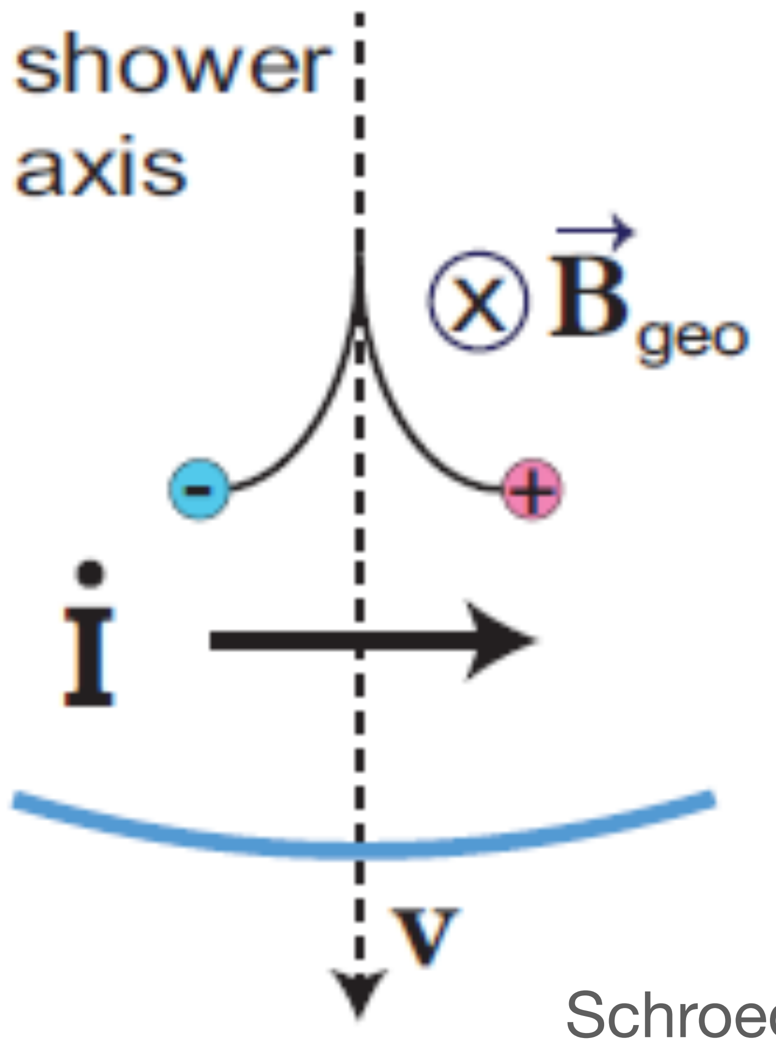
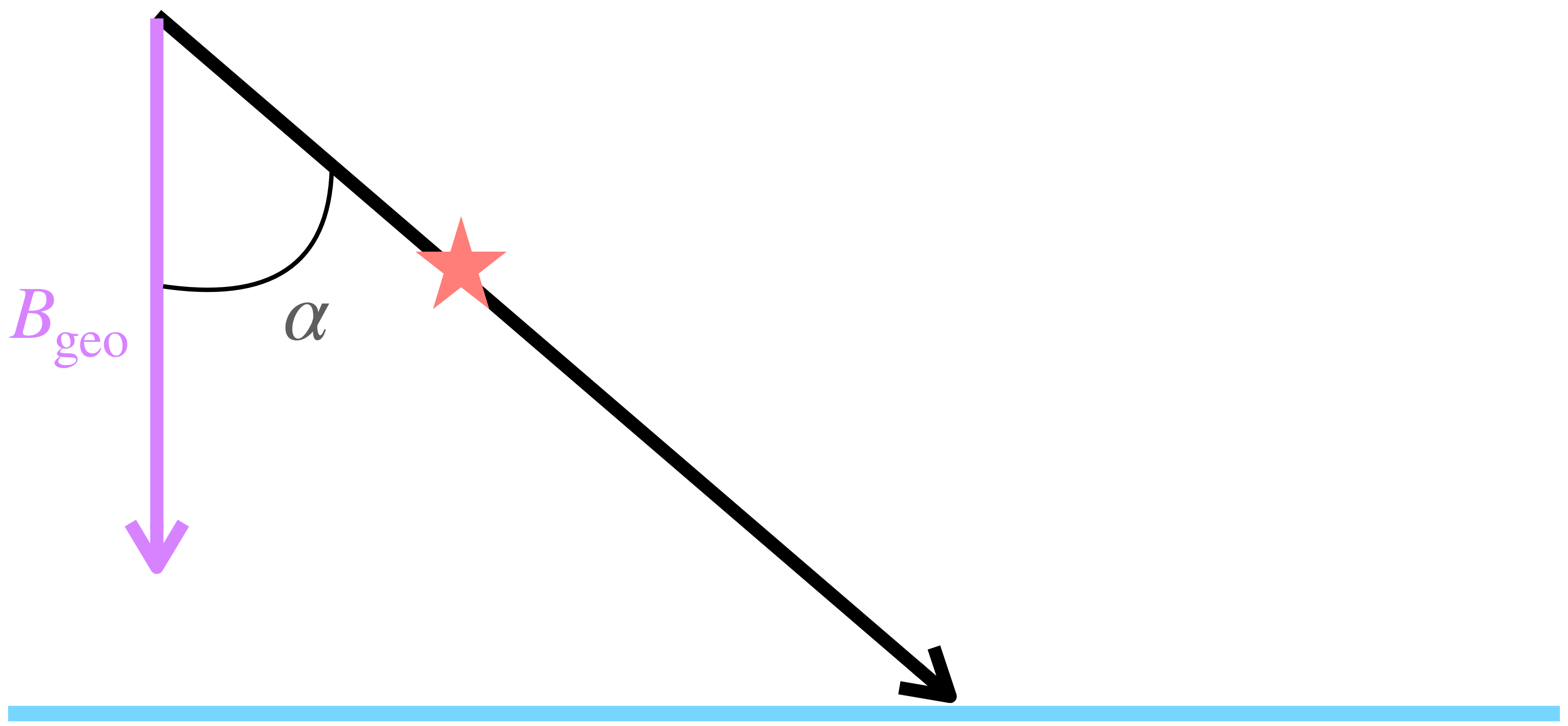
Geomagnetic mechanism:
Transverse current emission



Schroeder (2017)



Geomagnetic angle

$$\vec{E}_{geo} \propto \vec{F}_L = qvB\sin\alpha \quad \& \quad E_{rad}^{air} \propto E_{geo}^2$$

$$\boxed{E_{rad}^{air} \propto \sin^2\alpha}$$

(We neglect in-air charge excess)

Scaling with the air density

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Air density

$$\rho_{\mathrm{xmax}} = f(E, \theta, Z)$$

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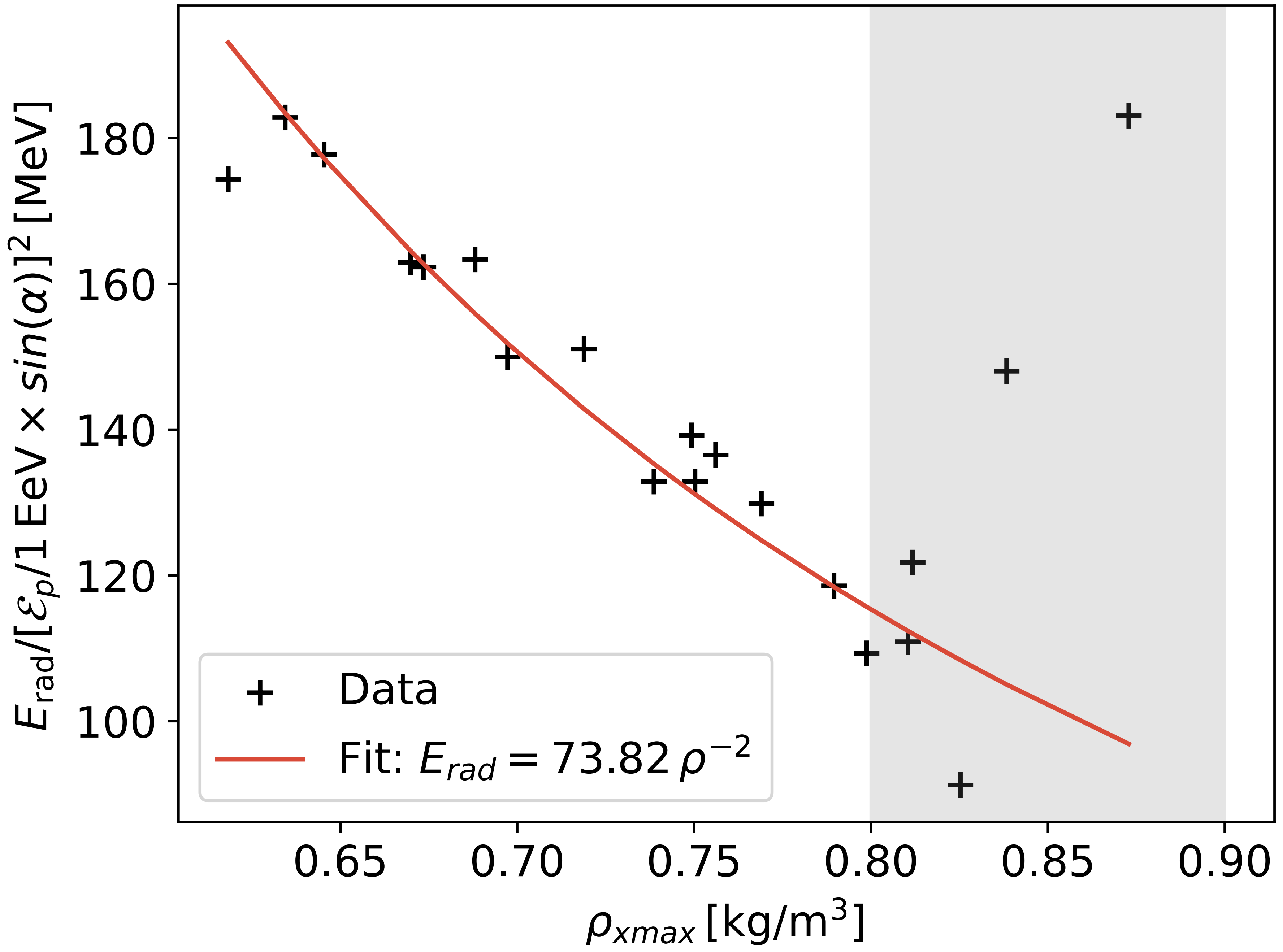
$$\boxed{E_{\mathrm{rad}}^{\mathrm{air}}/(\mathscr{E}_p \times \sin\alpha)^2 \propto \rho^{-2}}$$



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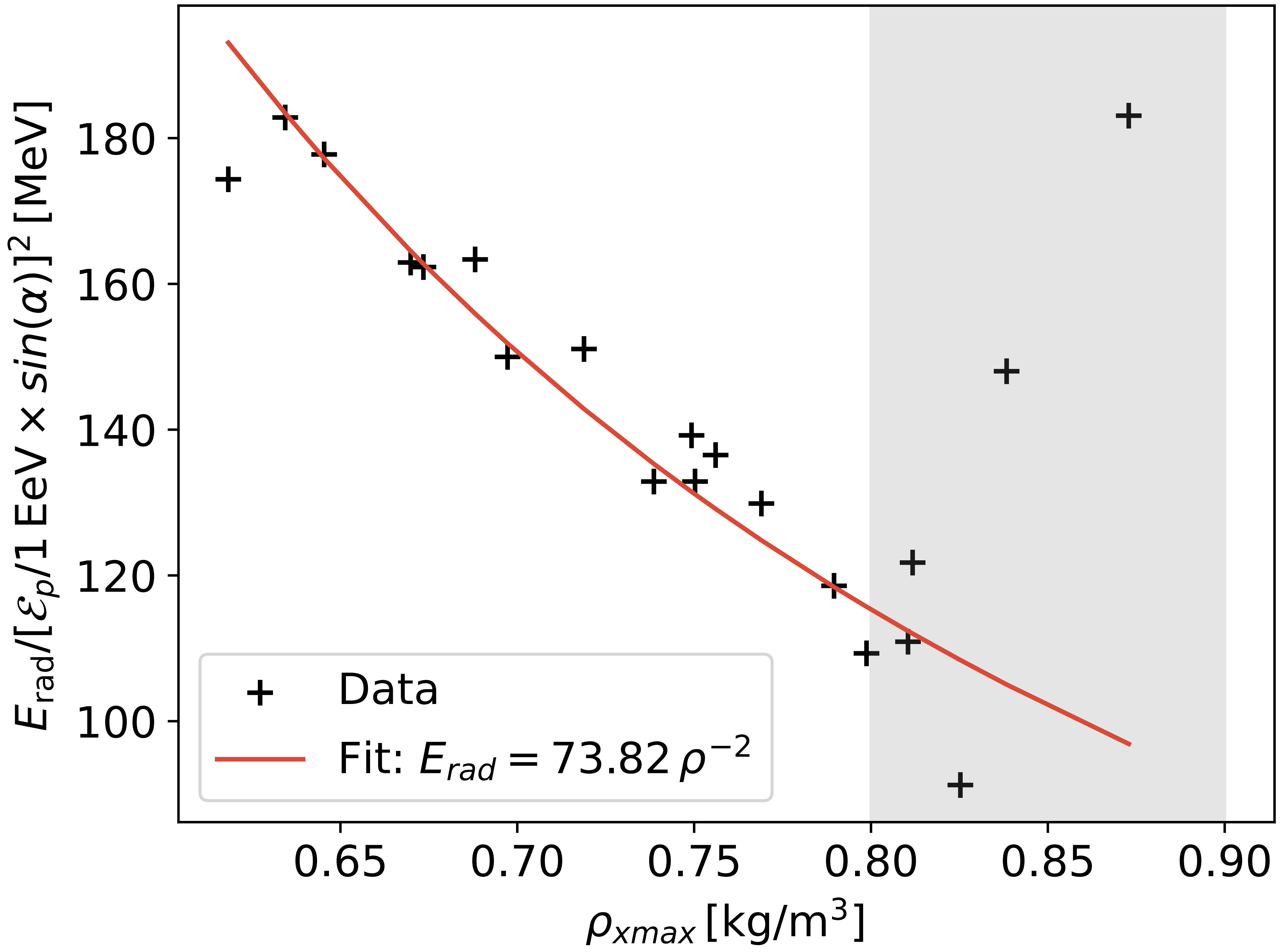
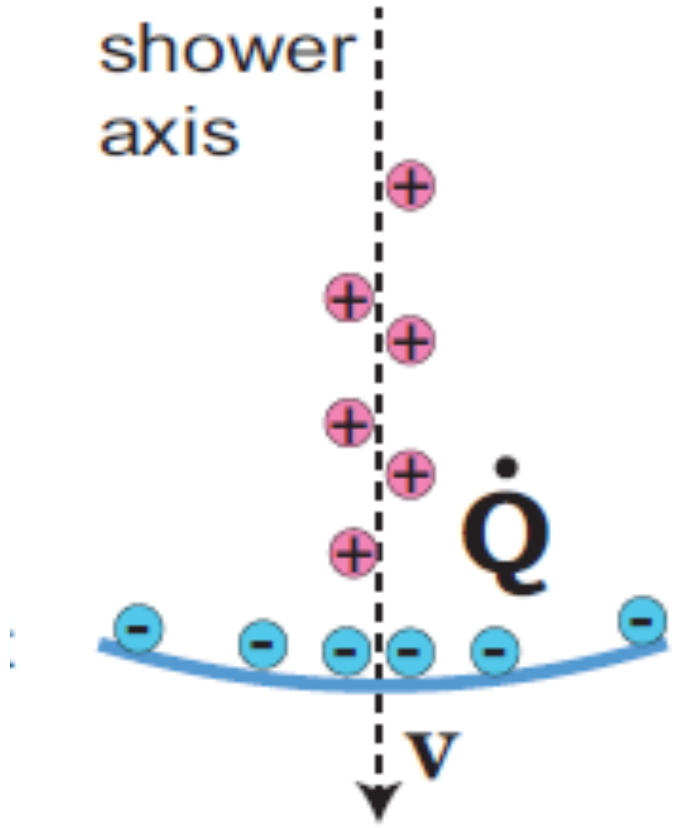
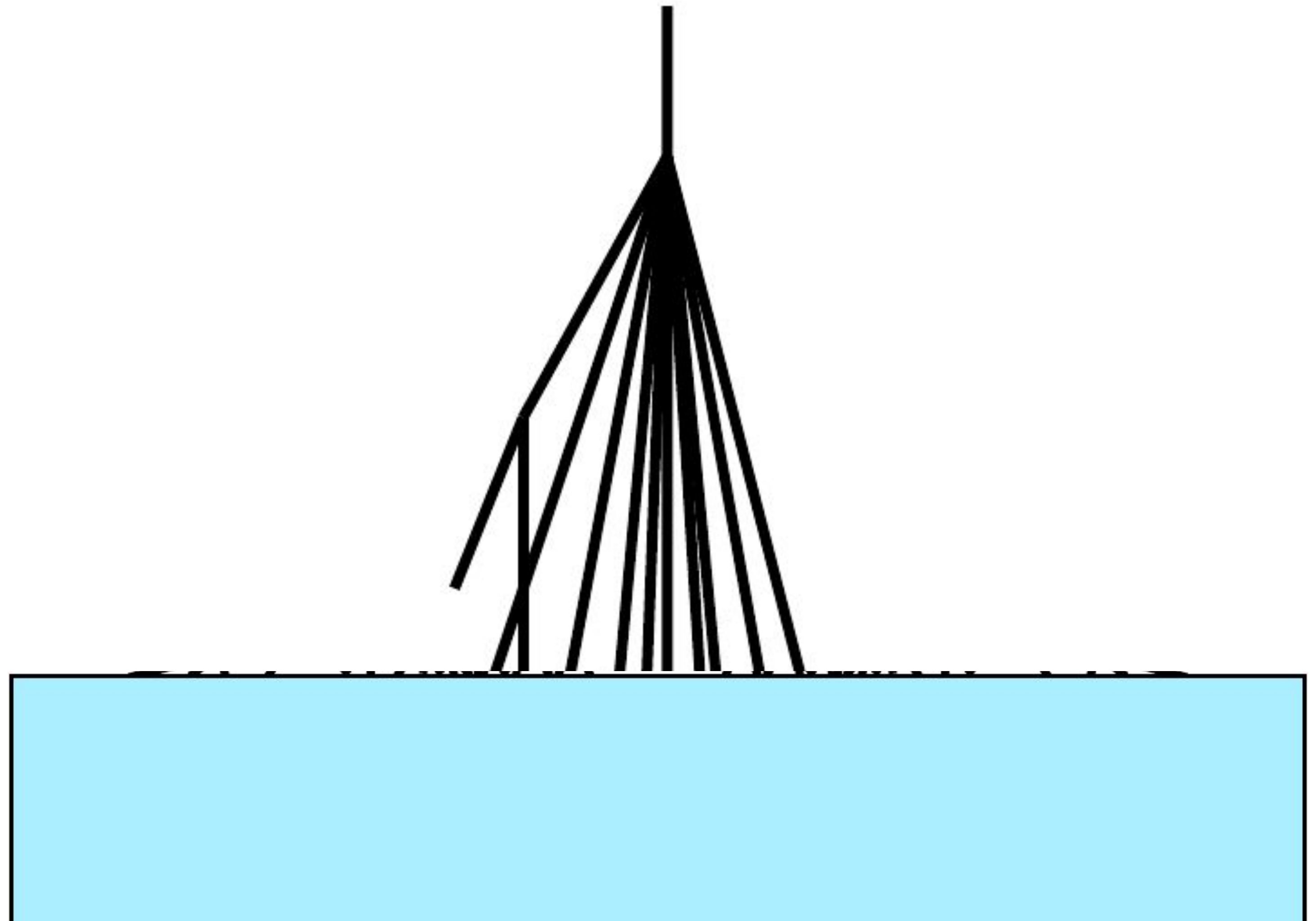


Charge-excess mechanism



(Clipping/surface effects will be further modeled)

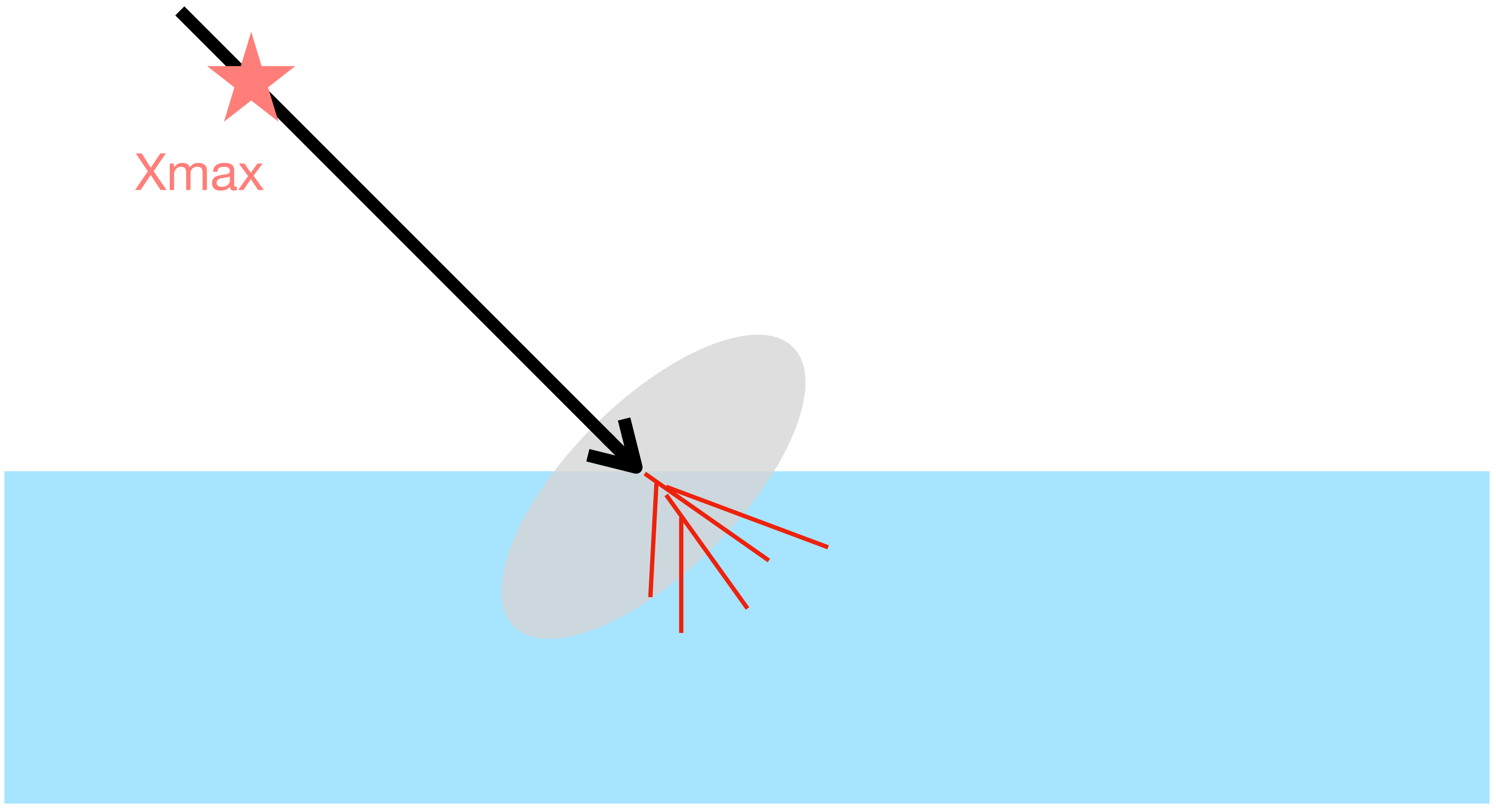
Clipping effects

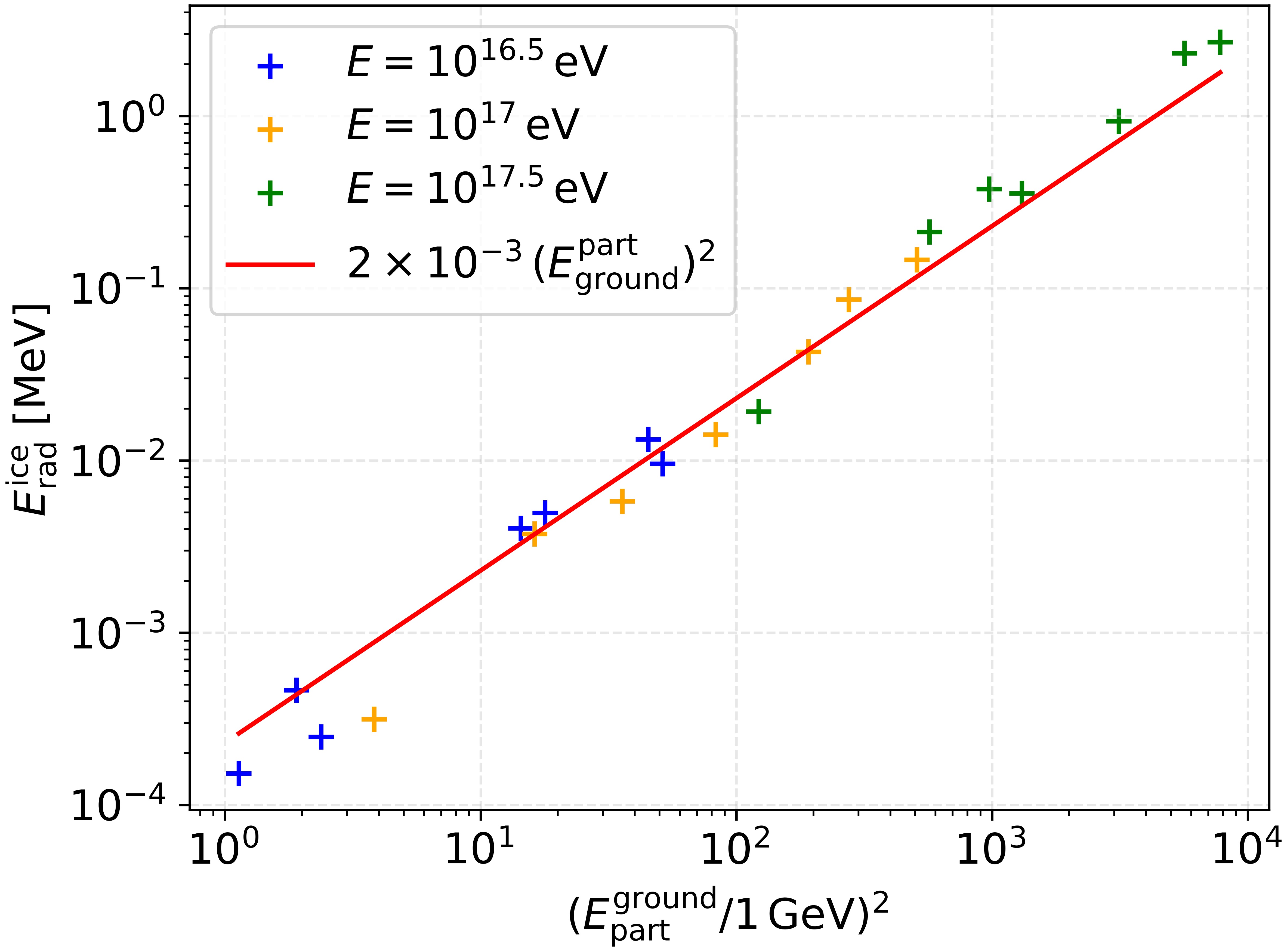


In-ice scaling

The in-ice radio emission should scale with the ground particle energy of the in-ice shower core

$$E_{\mathrm{rad}}^{\mathrm{ice}} \propto (E_{\mathrm{part}}^{\mathrm{ground}})^2$$





Ground particle energy scaling

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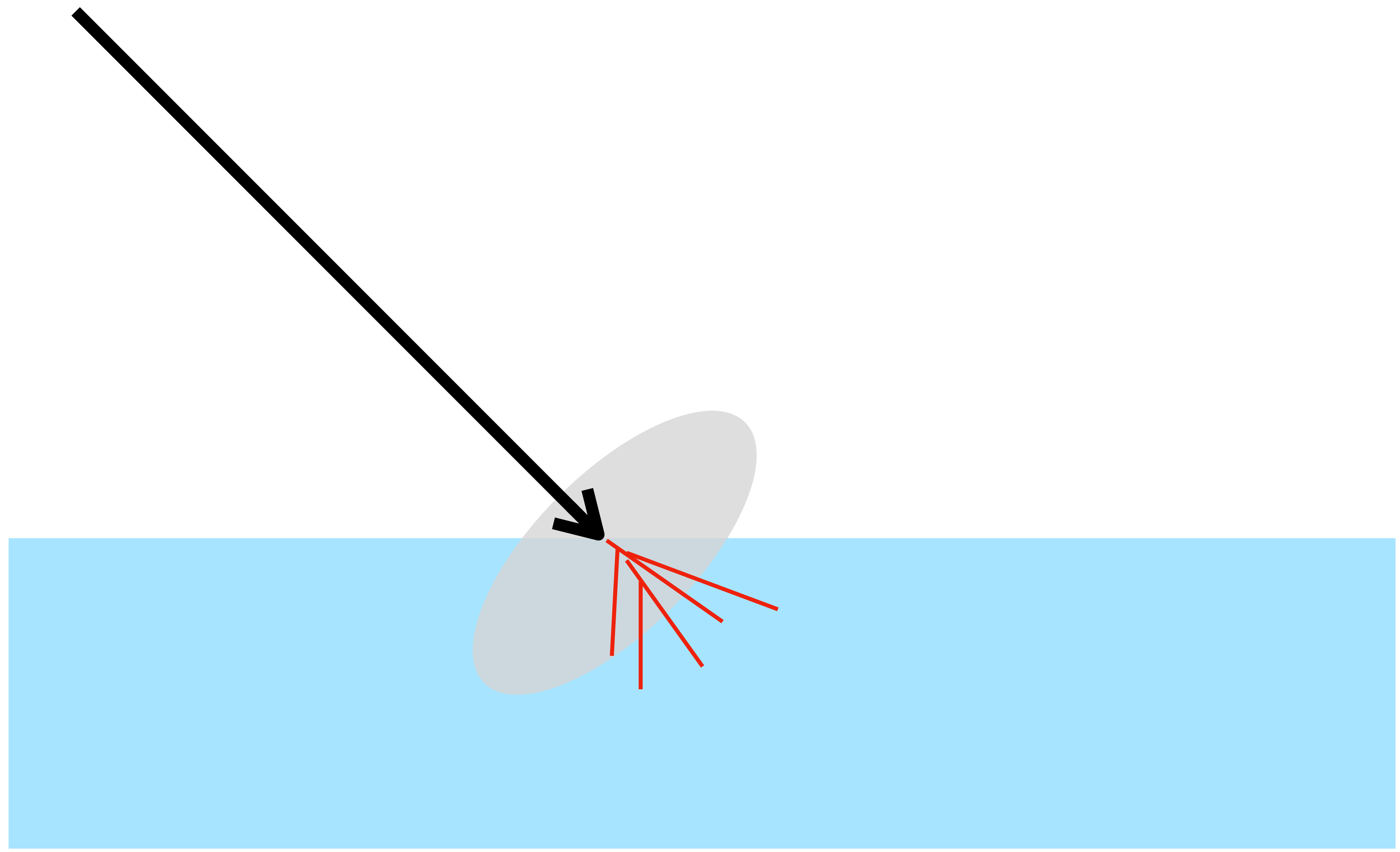
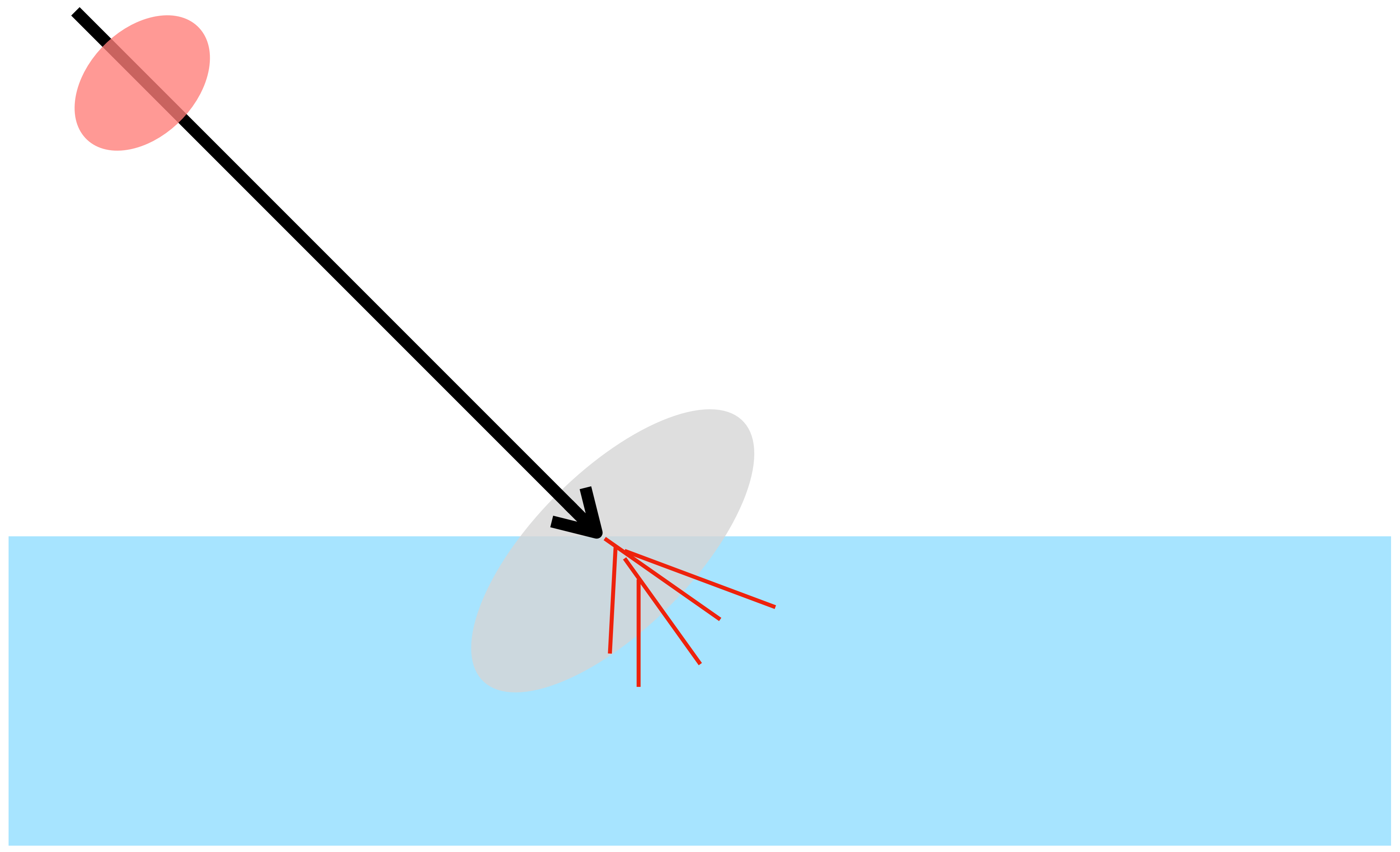
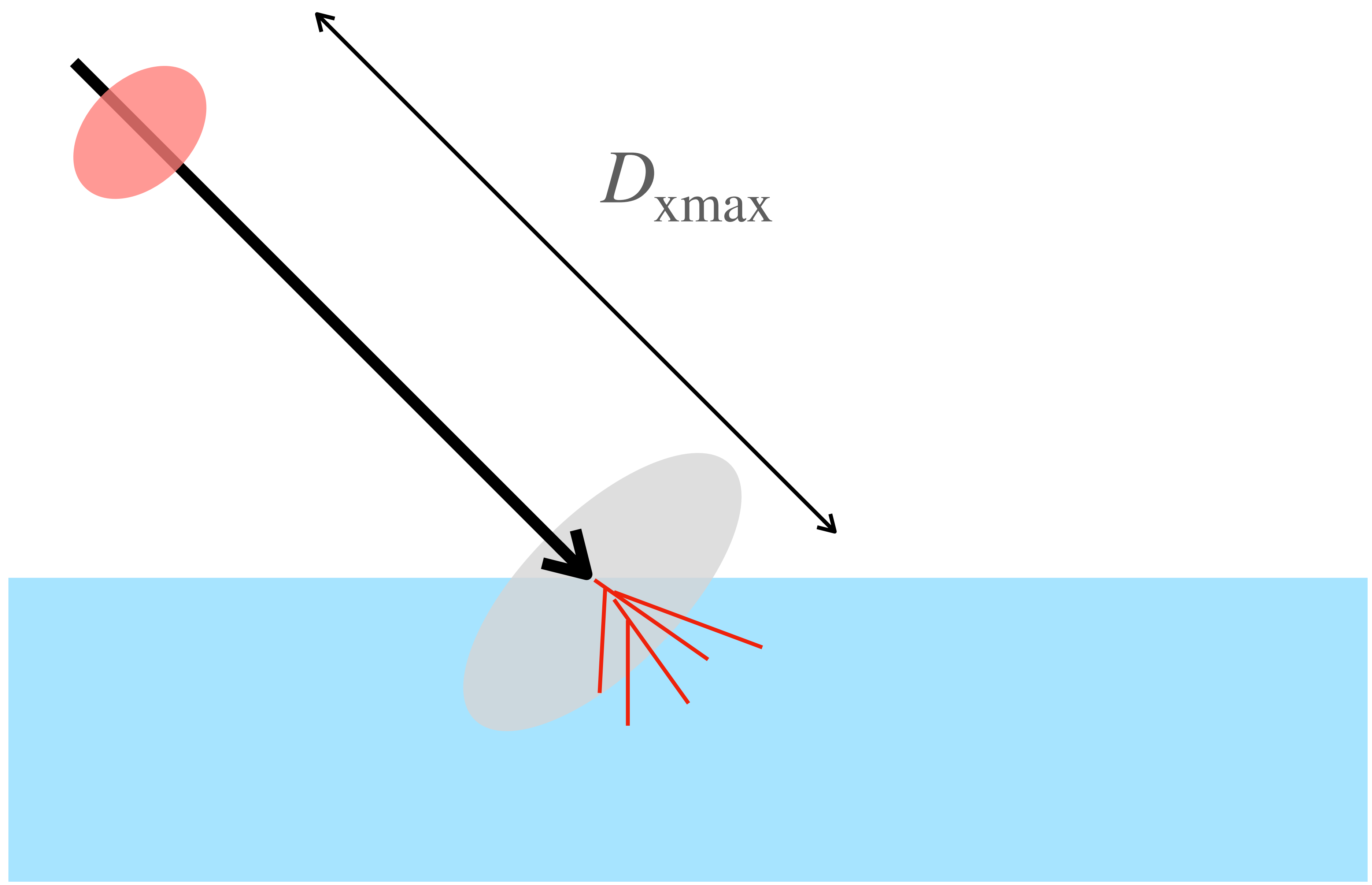
$$E^{\text{part}}_{\text{ground}}(\mathscr{E}_p, \theta, \varphi)?$$



$$E^{\text{part}}_{\text{ground}}(\mathcal{E}_p, \theta, \varphi)?$$



$E^{\mathrm{part}}_{\mathrm{ground}}(\mathscr{E}_p, \theta, \varphi)$?



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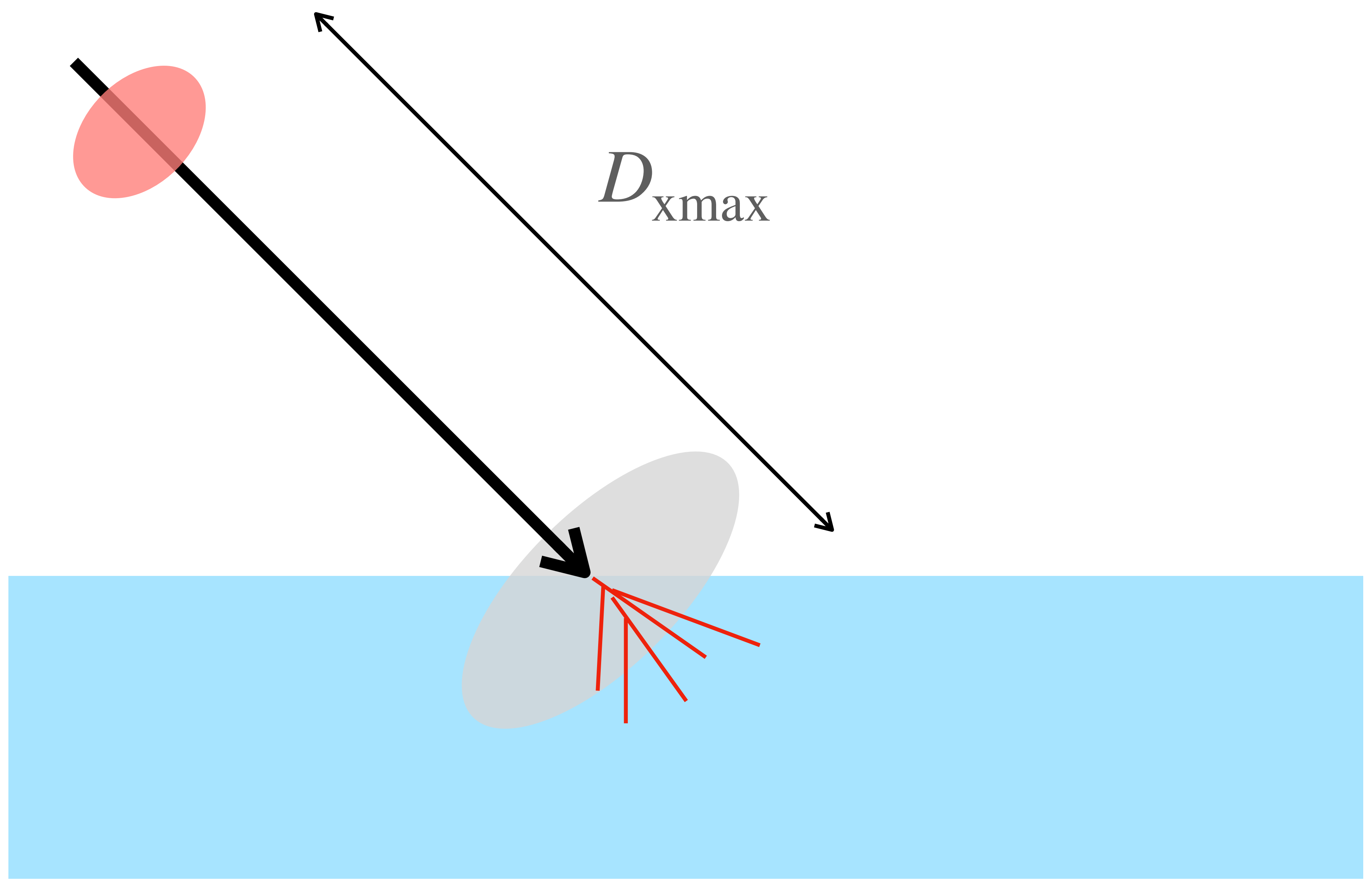
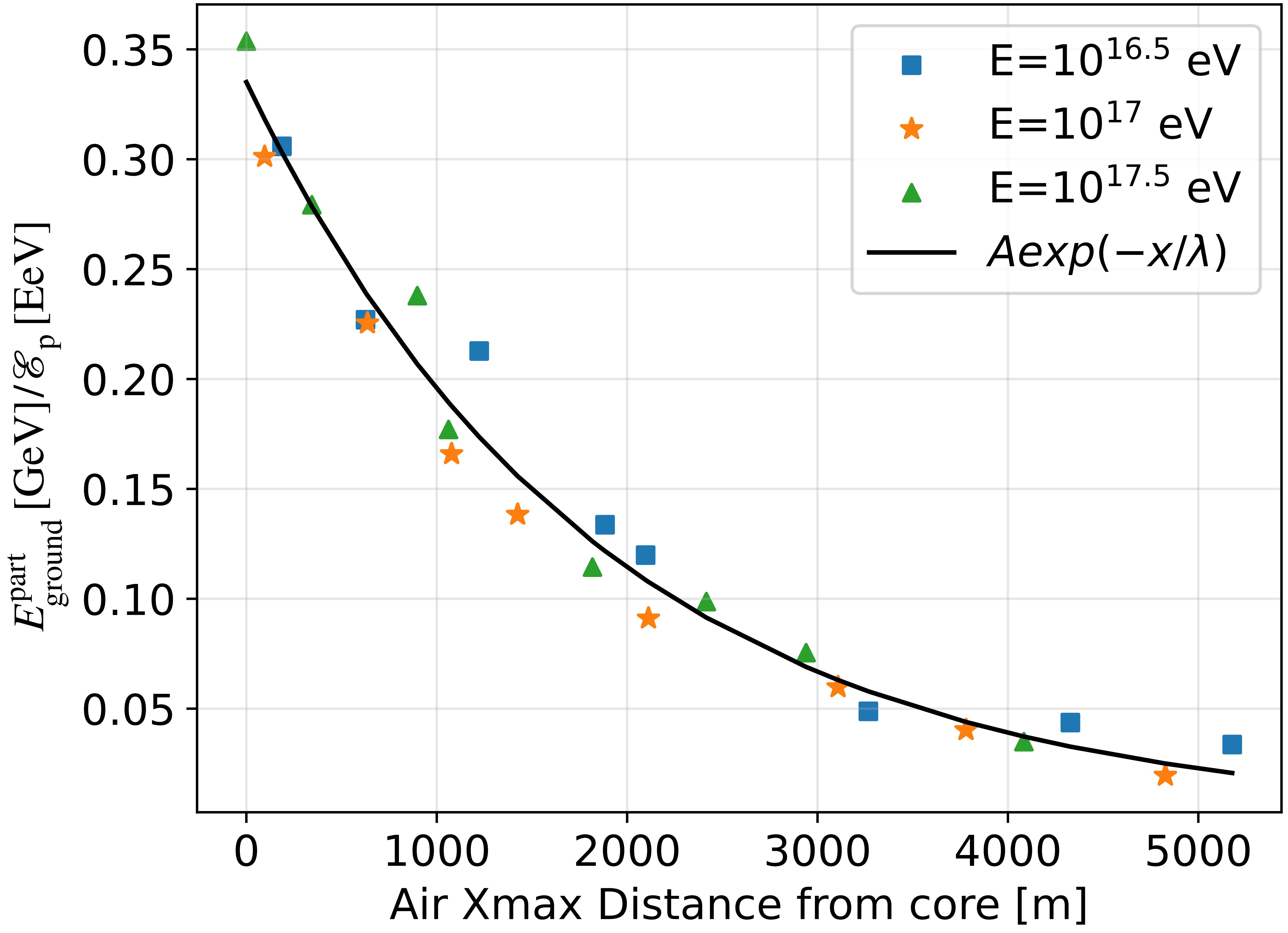
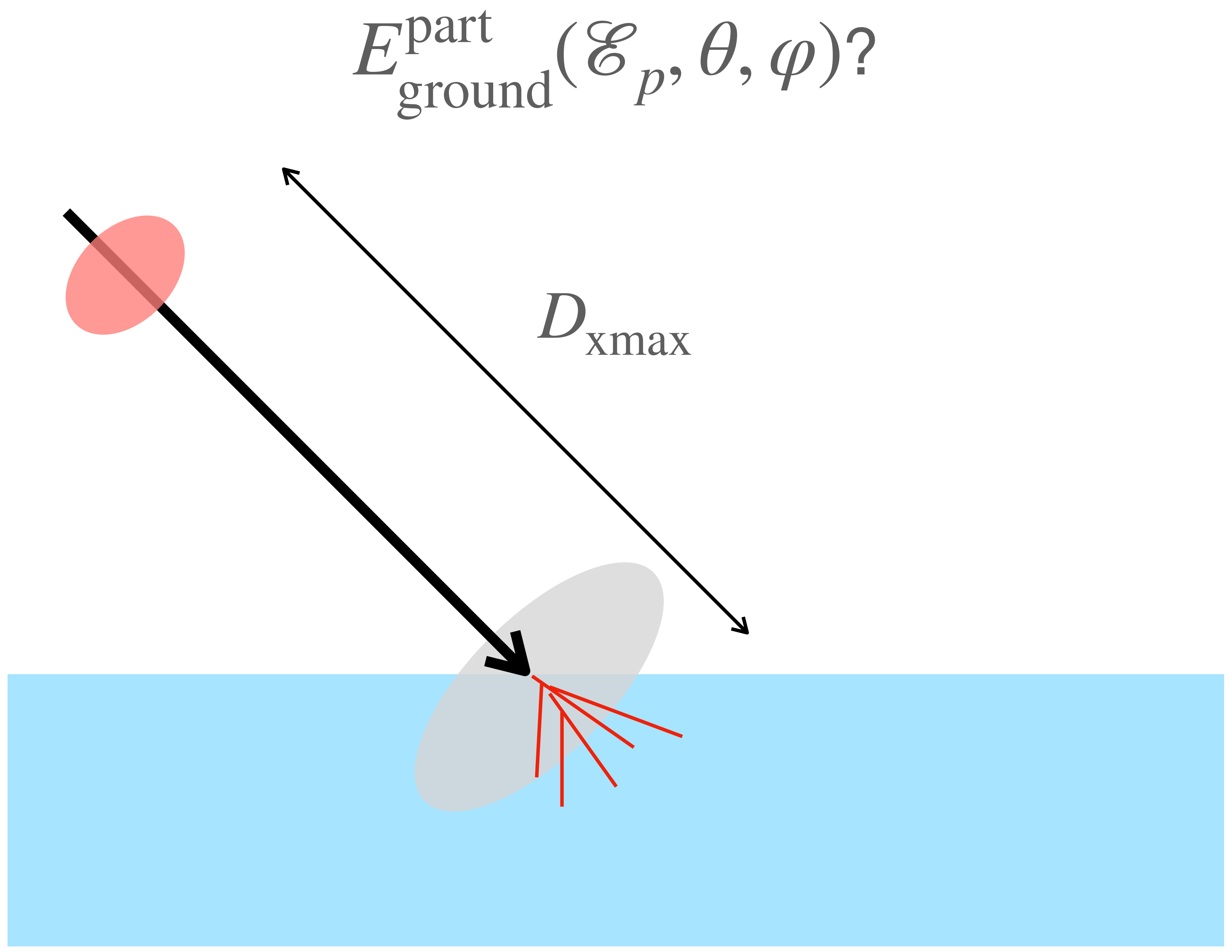
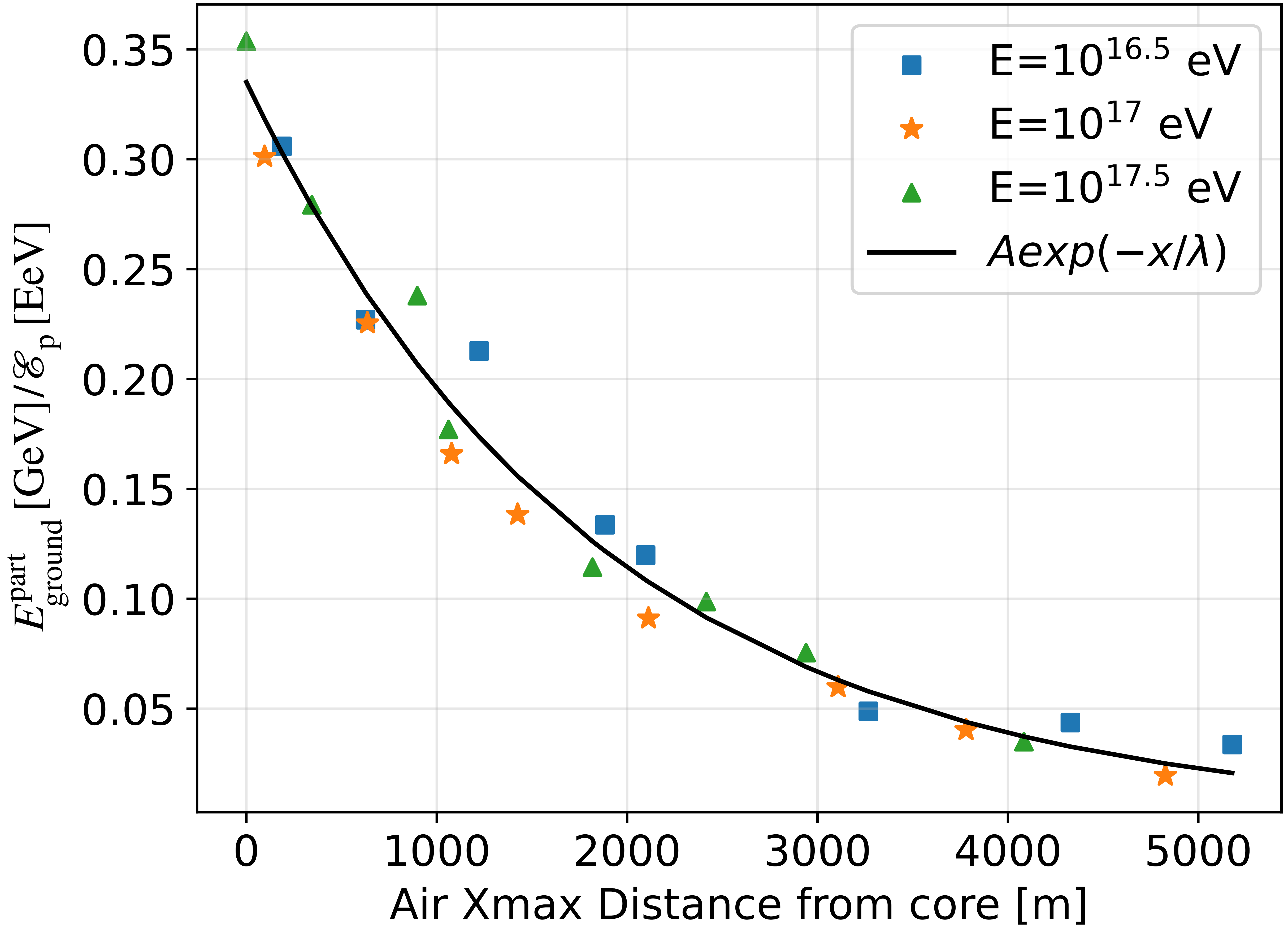




Ground particle energy scaling





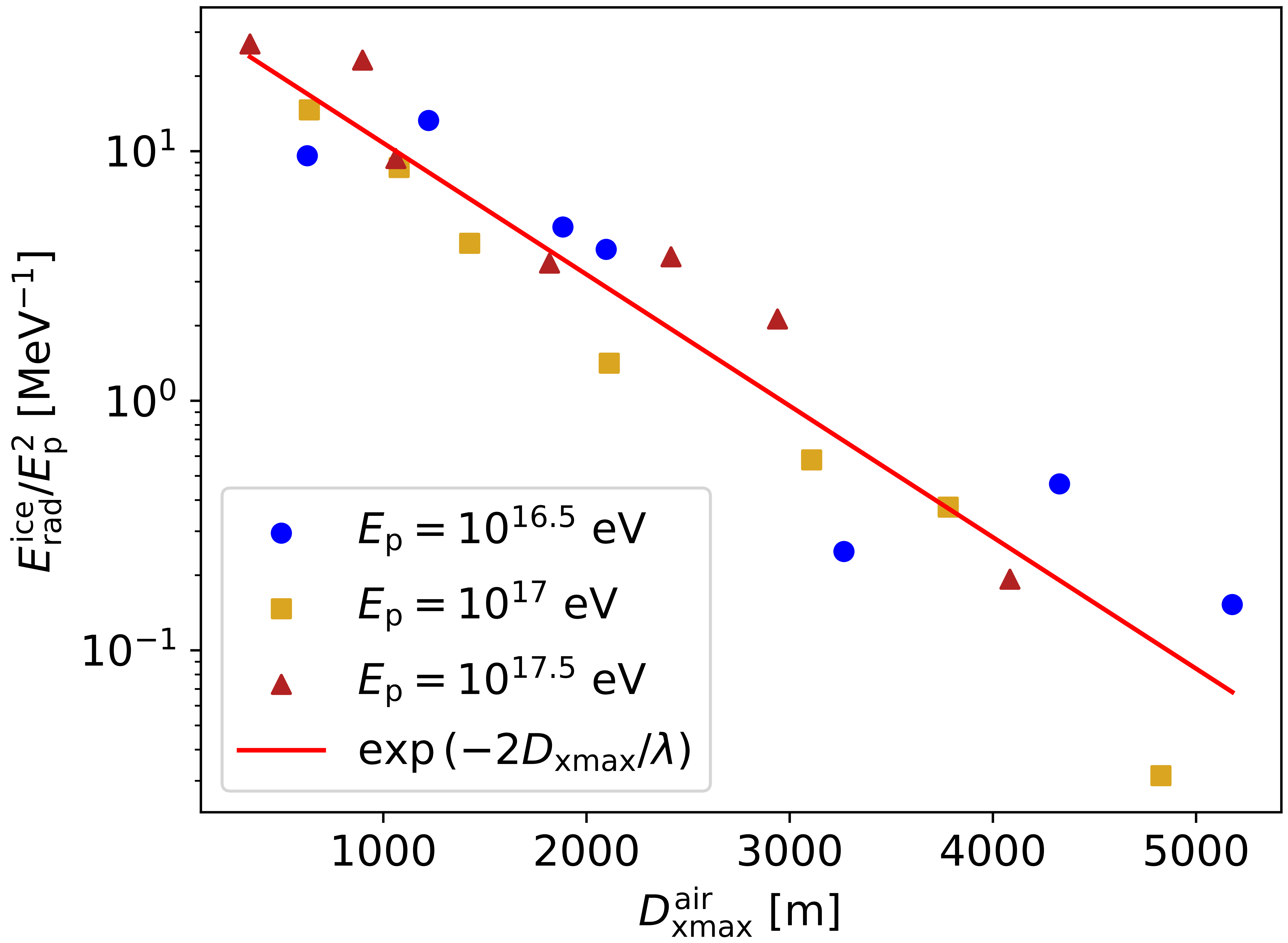
$$\boxed{E^{\rm part}_{\rm ground}(\mathscr{E}_p, \theta, \varphi) \propto \mathscr{E}_p \times \exp(-D_{\rm xmax}/\lambda)}$$

$\lambda = 1800\,\mathrm{m}$: characteristic attenuation length

In-ice radiation energy scaling

$$E_{\rm rad}^{\rm ice} \propto \mathscr{E}_p^2 \times \exp(-2D_{\rm xmax}/\lambda)$$

$D_{\rm xmax}(\mathscr{E}_p, \theta, Z)$



Reference library

Energy [eV]	$10^{16.5}$; 10^{17}; $10^{17.5}$
Zenith [°]	0; 20; 28; 34; 39; 43; 47; 50
Depth [m]	0; 60; 100

$$E_{\mathrm{rad}}^{\mathrm{air}} = K\mathcal{E}_p^2 \rho_{\mathrm{air}}^{-2} \sin^2\alpha$$

$$E_{\mathrm{rad}}^{\mathrm{ice}} = K'\mathcal{E}_p^2 \exp(-2D_{\mathrm{xmax}}/\lambda)$$

We can use scaling relations to generate new events

$$E_{\mathrm{rad}}^{\mathrm{air/ice}}(\mathcal{E}_p^{\mathrm{target}}, \theta^{\mathrm{target}}, \varphi^{\mathrm{target}}) = E_{\mathrm{rad}}^{\mathrm{air/ice}}(\mathcal{E}_p^{\mathrm{ref}}, \theta^{\mathrm{ref}}, \varphi^{\mathrm{ref}}) \times \mathcal{S}^{\mathrm{air/ice}}$$

Will be tested against an independent test library

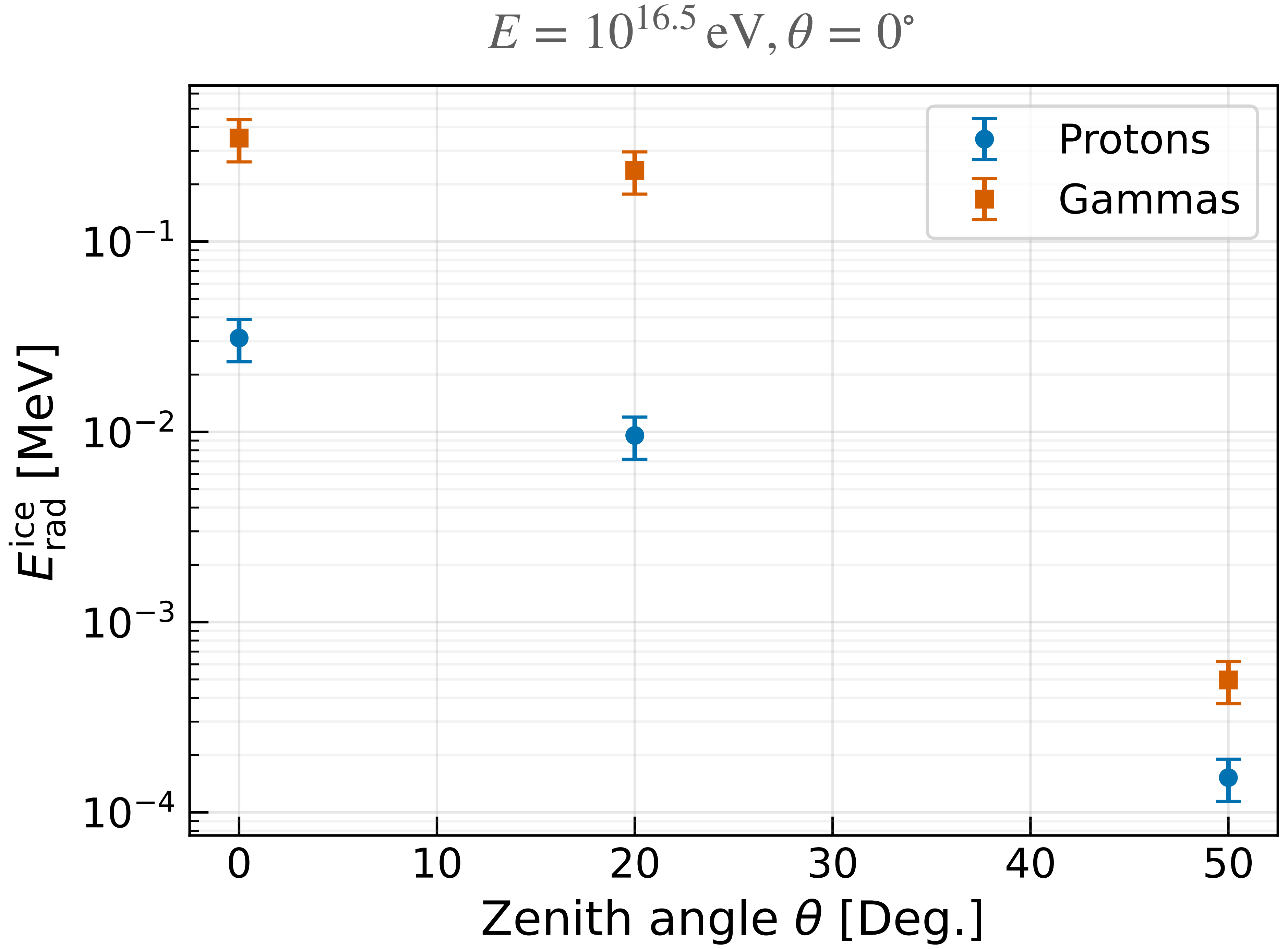
The combination of in-air and in-ice emission could potentially give a handle towards mass composition reconstruction

$$E_{\mathrm{rad}}^{\mathrm{air}} \propto \rho^{-2} \longrightarrow$$ **Increases with atomic mass**

$$E_{\mathrm{rad}}^{\mathrm{ice}} \propto \exp(-D_{\mathrm{xmax}}/\lambda) \longrightarrow$$ **Decreases with atomic mass**

The ratio $E_{\mathrm{rad}}^{\mathrm{air}}/E_{\mathrm{rad}}^{\mathrm{ice}}$ should be sensitive to the cosmic ray mass composition

We are currently investigating the discriminating power of this observable for different configurations



Summary

We have parametrized in-ice radio emission from cosmic ray particle cascades using FAERIE simulations

$$E_{\mathrm{rad}}^{\mathrm{air}} = K\mathscr{E}_p^2\rho_{\mathrm{air}}^{-2}\sin^2\alpha$$

$$E_{\mathrm{rad}}^{\mathrm{ice}} = K'\mathscr{E}_p^2\exp(-2D_{\mathrm{xmax}}/\lambda)$$

- **The accuracy of the method will be further tested and improved**
- **We can start generating cosmic ray events and estimate cosmic ray event rates using this parametrization**