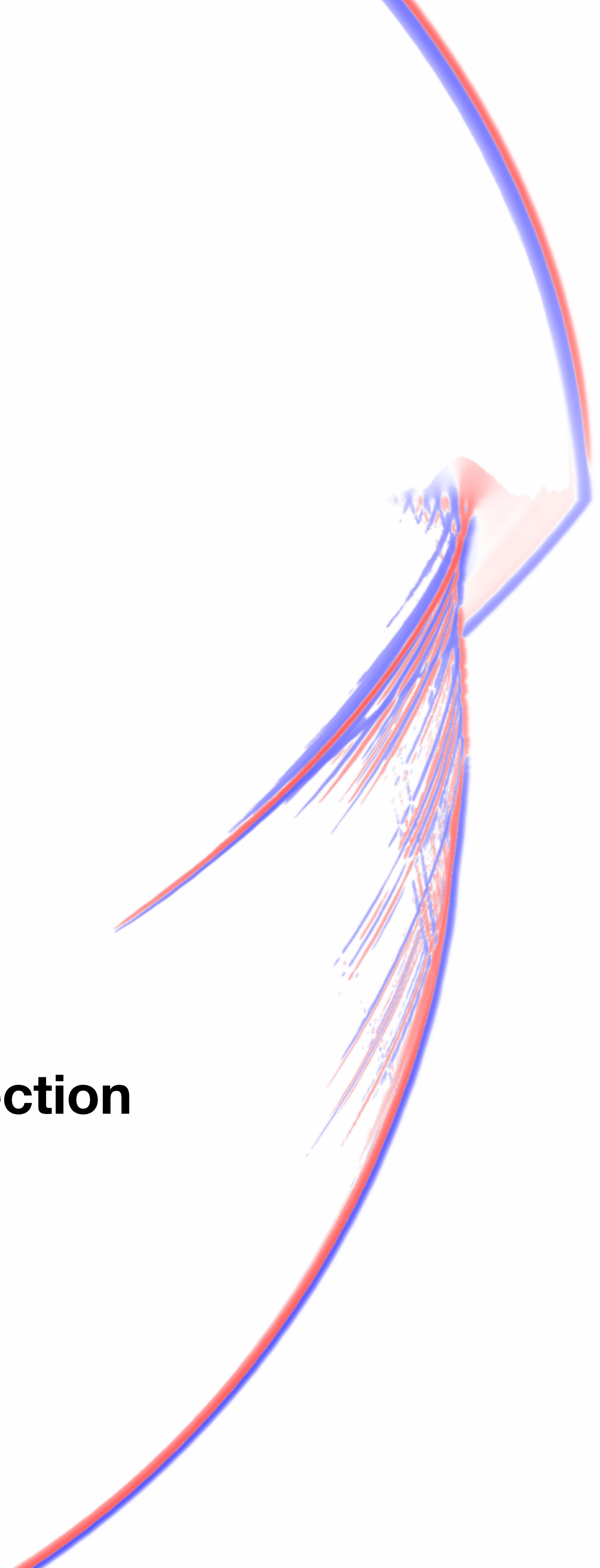
Detectors for physics and physics for detectors

Challenges and opportunities in radio neutrino detection

DESY Zeuthen, May 24, 2024

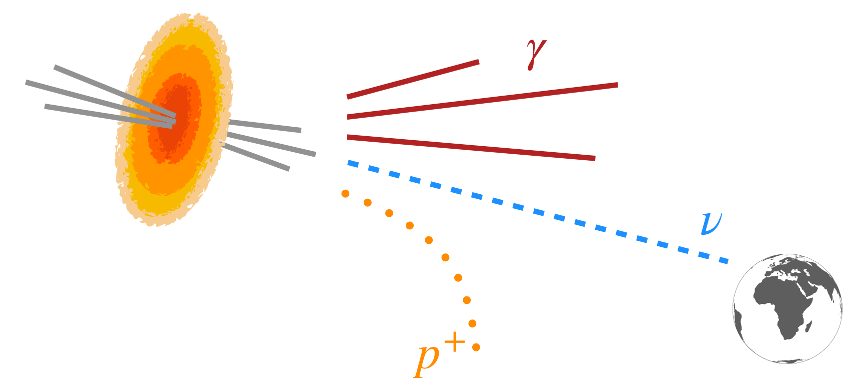


Philipp Windischhofer
University of Chicago

What can you expect?

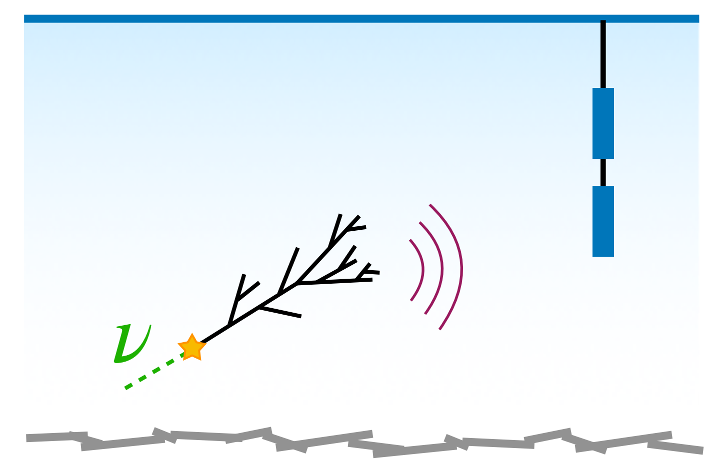
An overview of ultra-high energy neutrino astronomy

High-energy phenomena in the universe, cosmic accelerators, and messenger particles



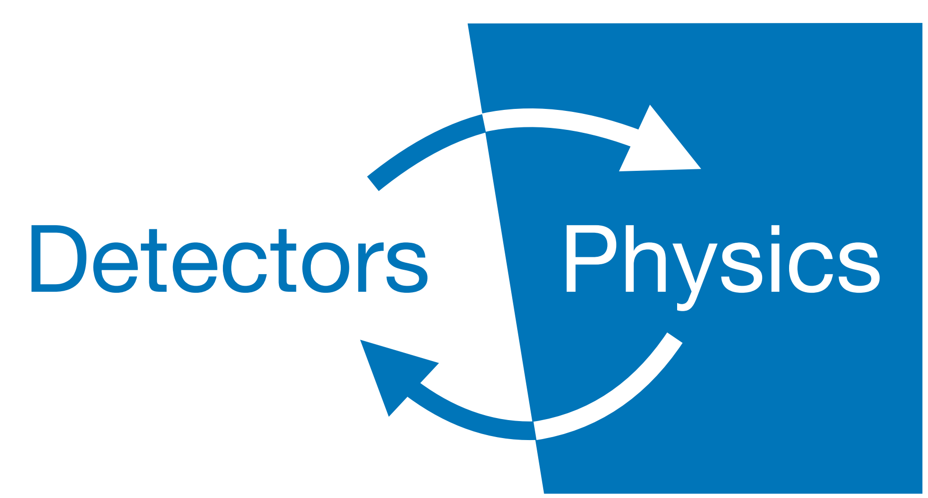
A summary of current experimental strategies …

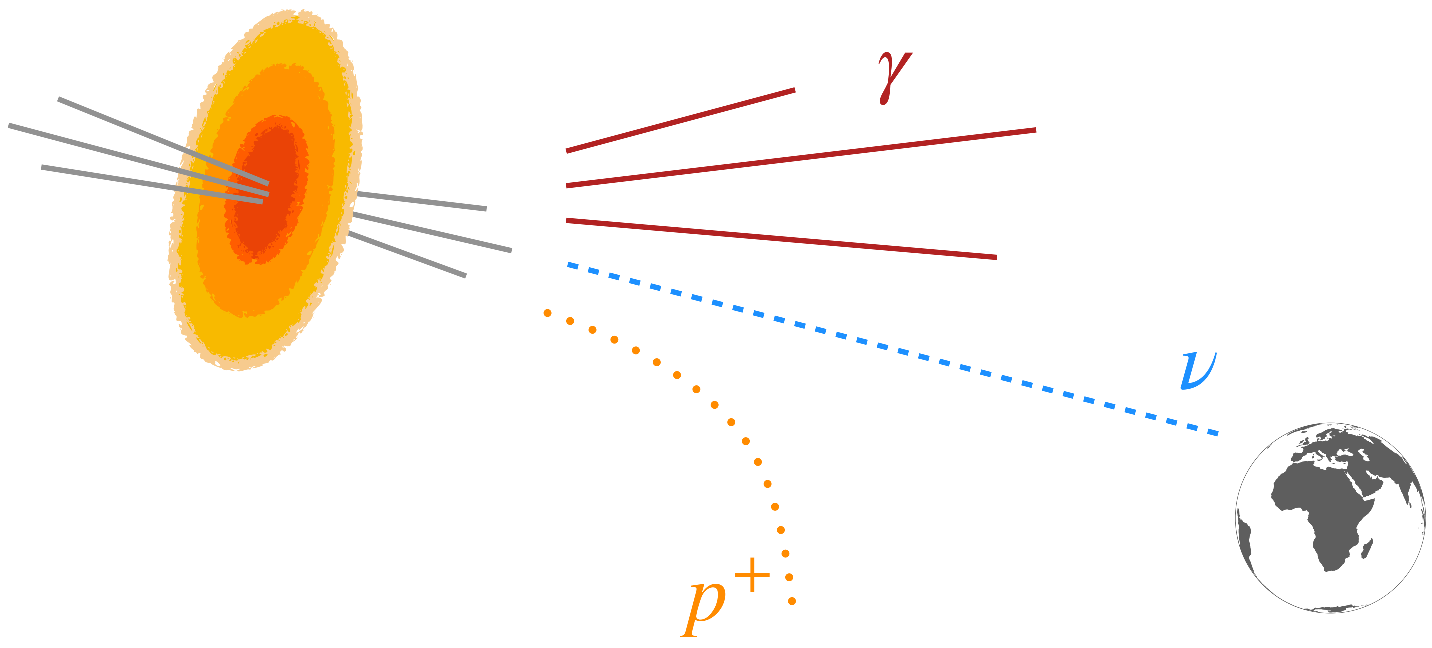
Neutrino-induced radio emissions in polar ice



… and some of their challenges

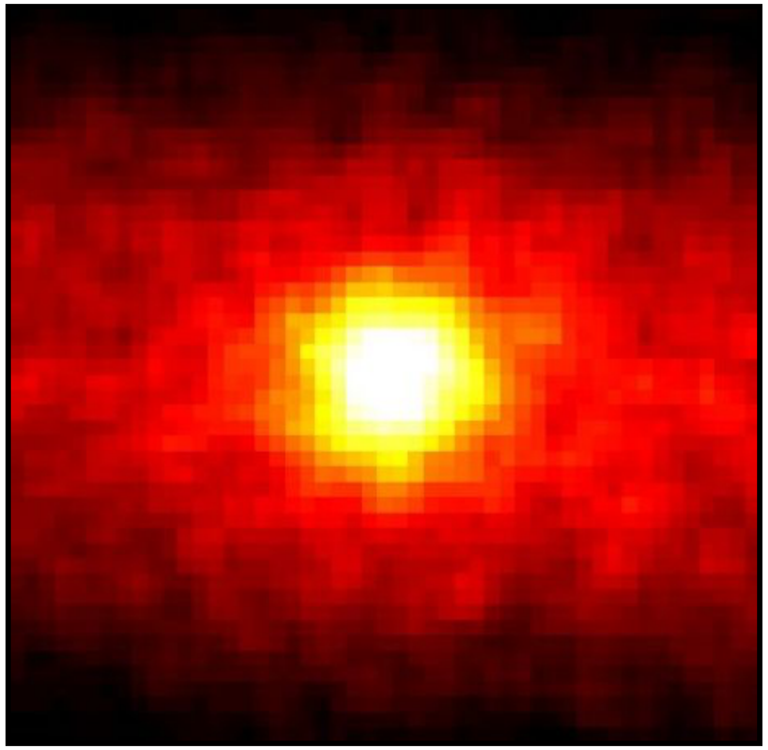
Use established ("old") physics to understand and improve our detectors





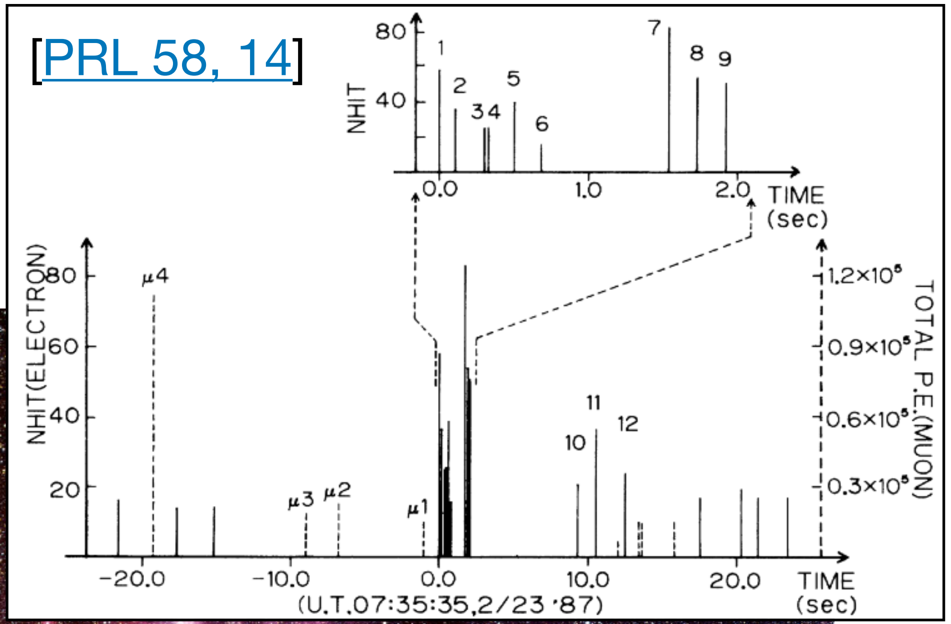
Ultra-high energy neutrino astronomy

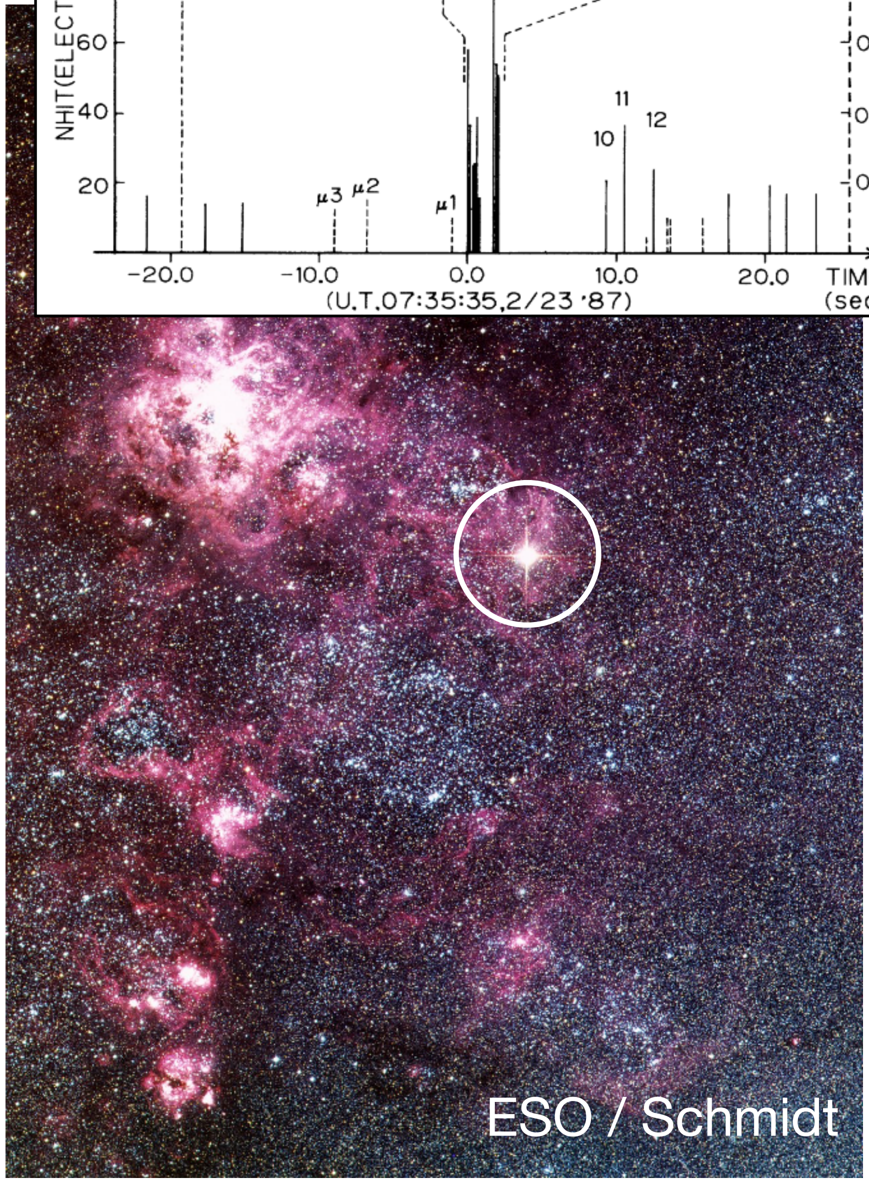
40 years of neutrino astronomy



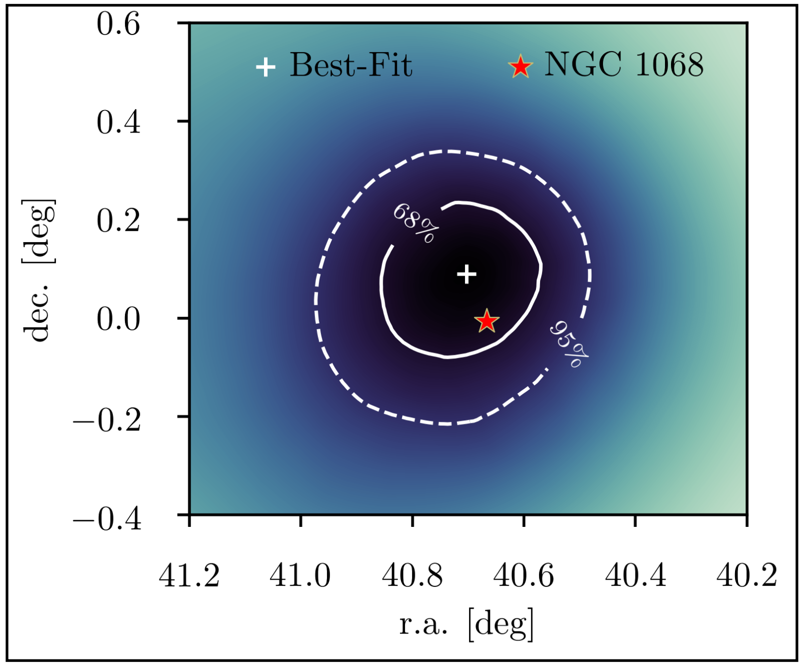
The sun in neutrinos
Super-Kamiokande,
[1996-2018]

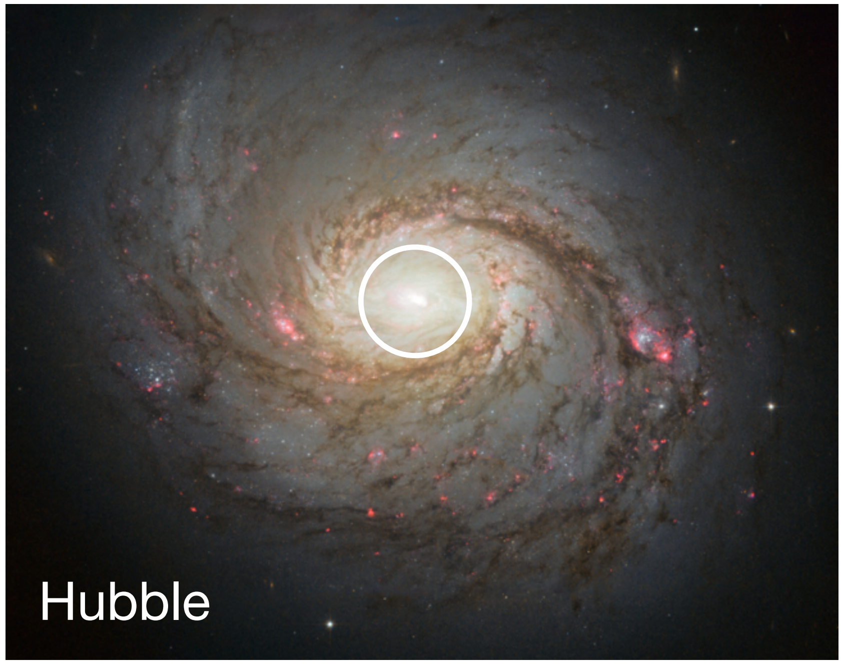
SN 1987A, Kamiokande-II





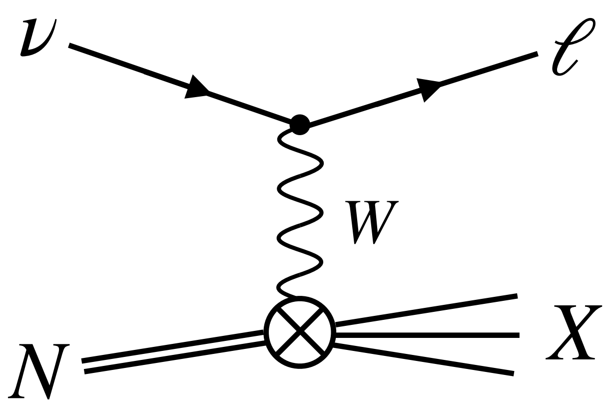
NGC 1068, IceCube 2024
[arXiv:2211.09972]



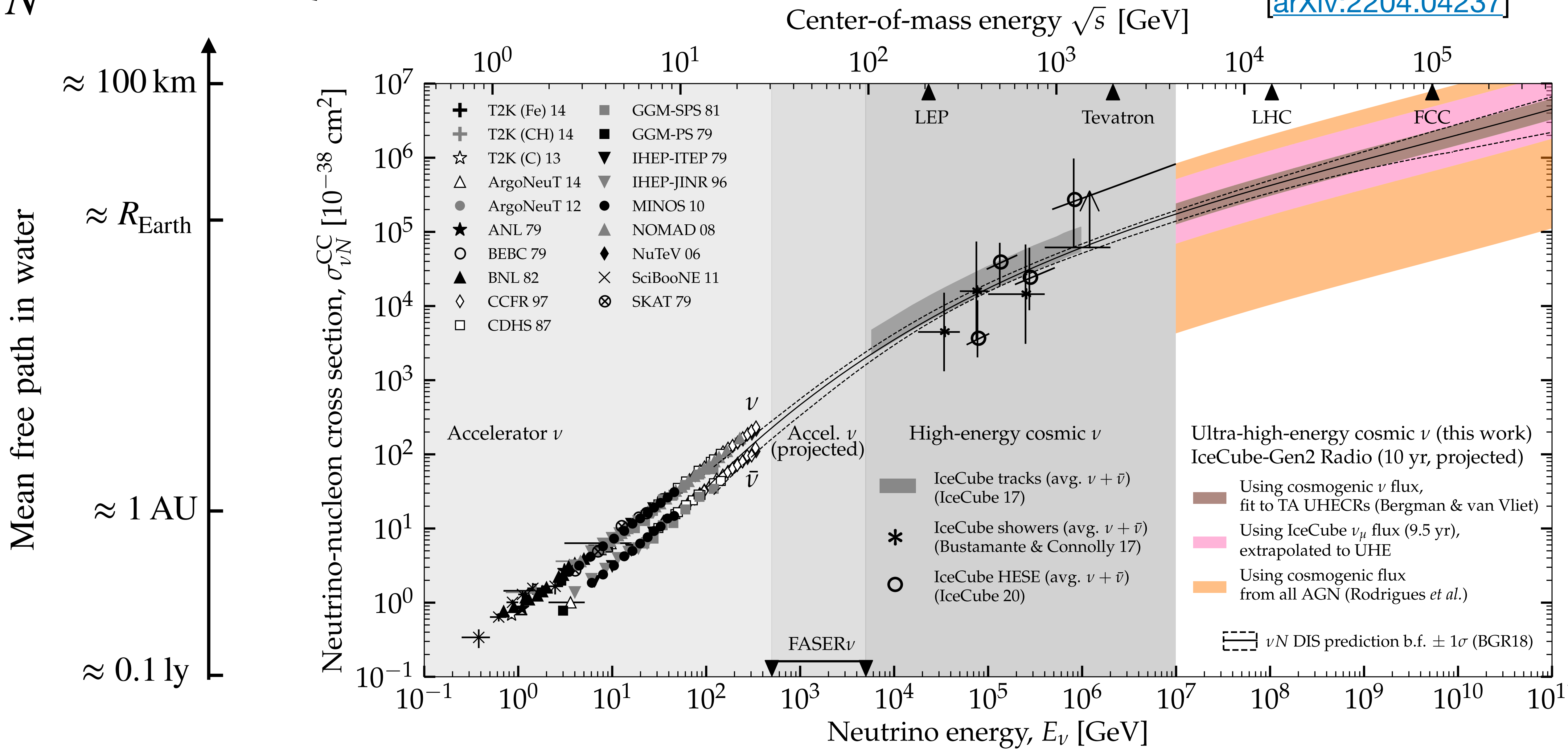


Fundamental physics with cosmic neutrinos

Neutrino-nucleon charged-current scattering

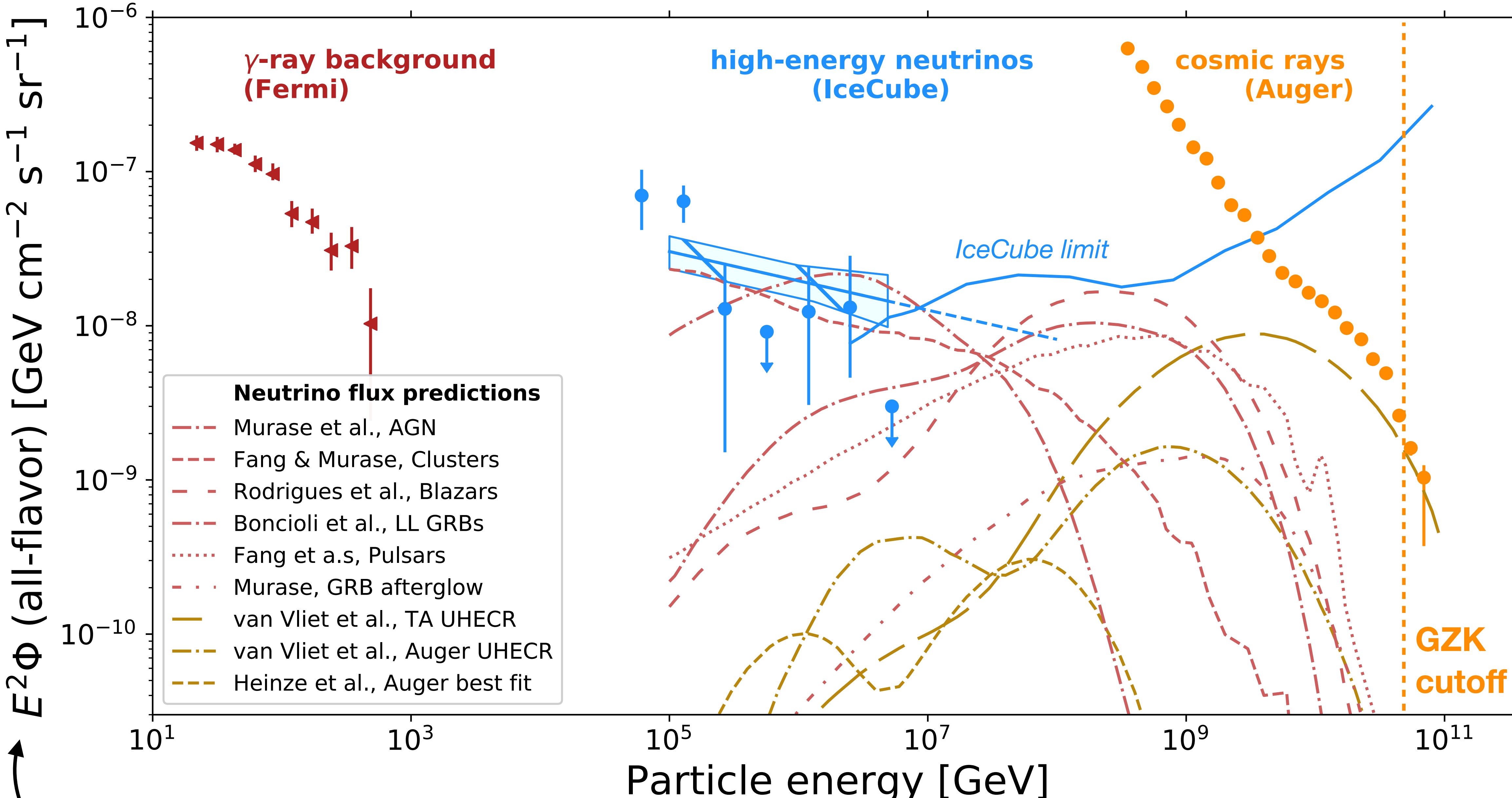


[arXiv:2204.04237]



The high-energy landscape of our universe

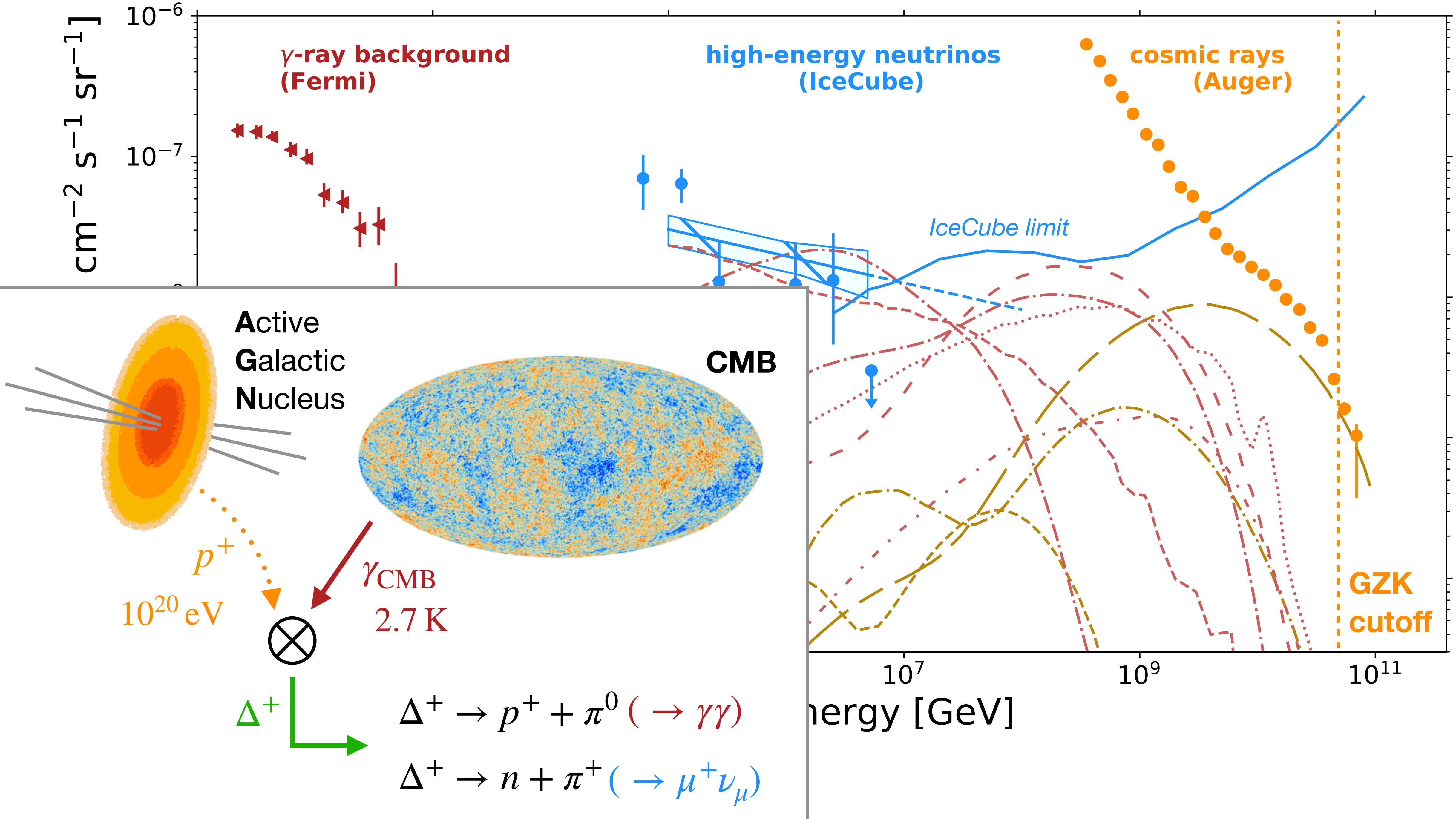
[arXiv:2010.12279]



"Energy flux"

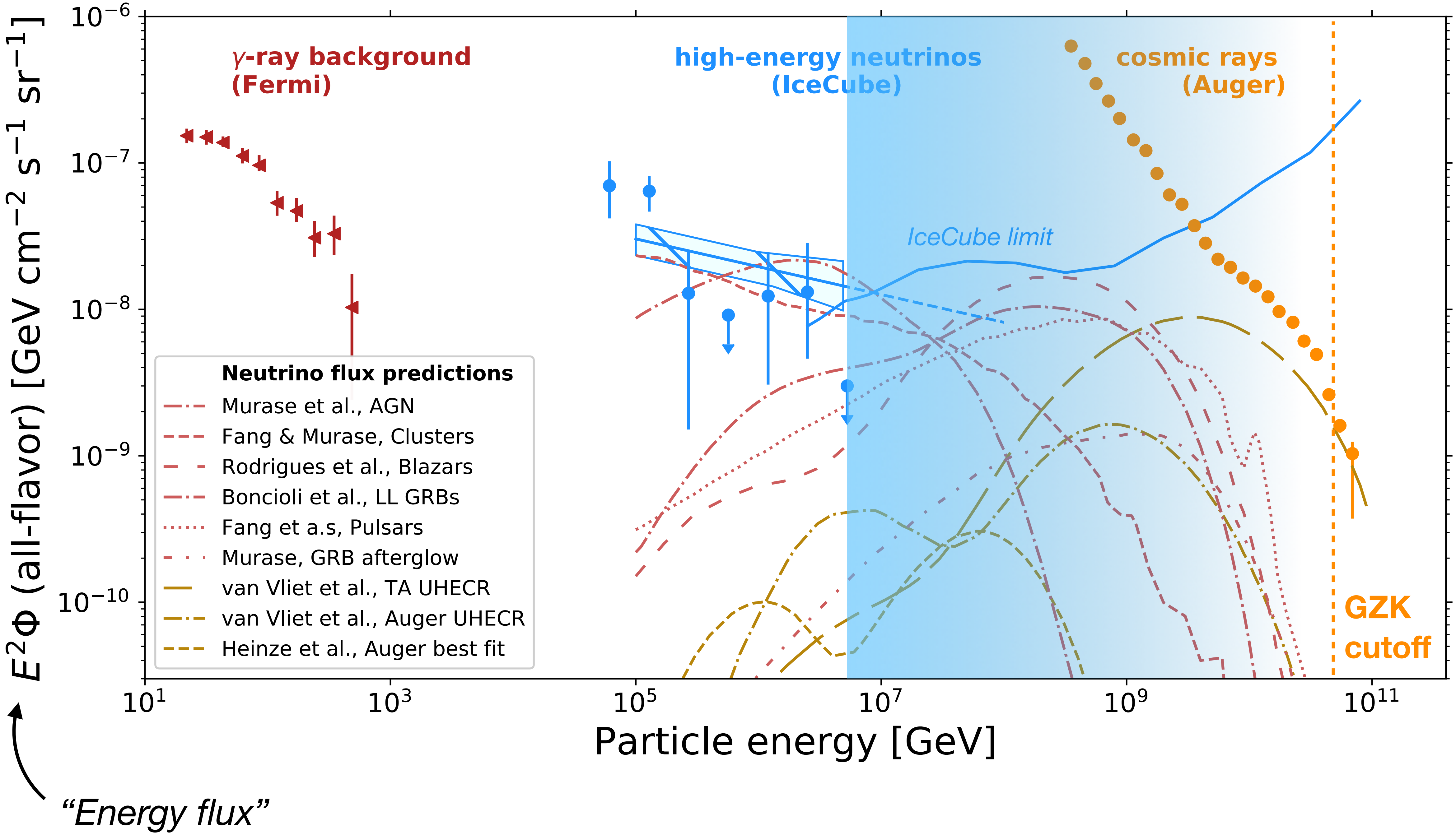
The high-energy landscape of our universe

[arXiv:2010.12279]



Textbook physics → neutrinos with energies of 10s of PeV must exist!

[arXiv:2010.12279]



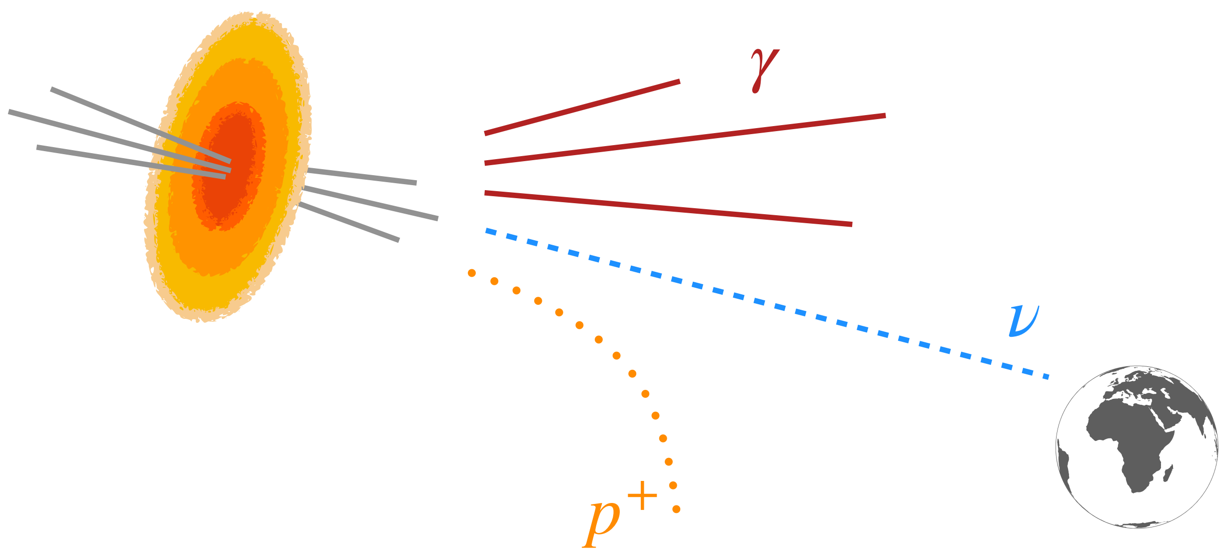
Neutrinos above IceCube energies <u>must</u> exist!

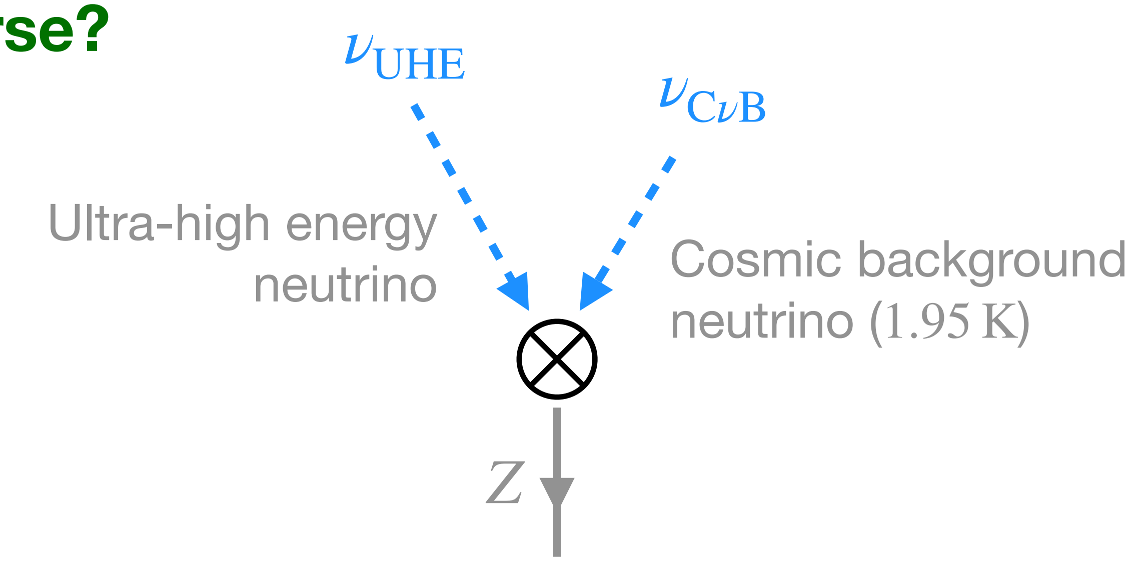
Detecting them is an experimental problem!

The opportunity: probe the universe with neutrinos

What is the real high-energy cutoff in the universe?

10 PeV? 100 PeV?

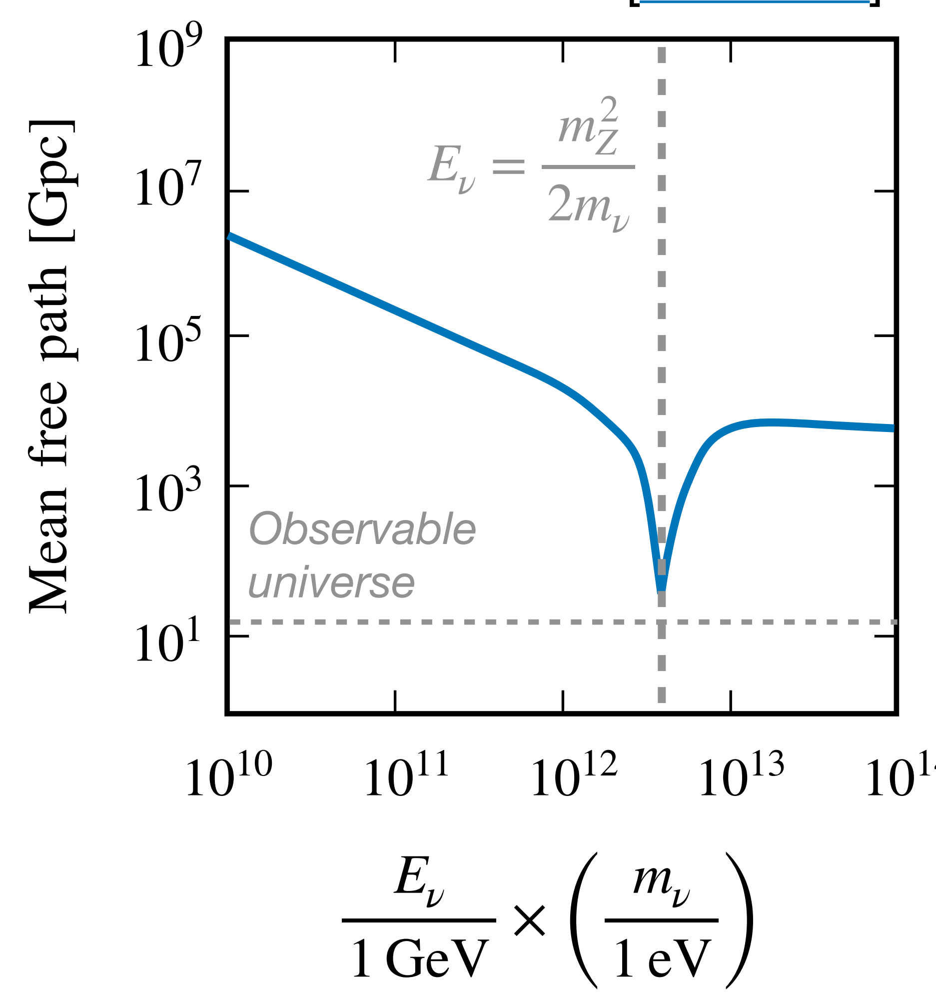




Which kind of sources saturate the cutoff, and where are they?

Mean free path $\gtrsim$ observable universe!

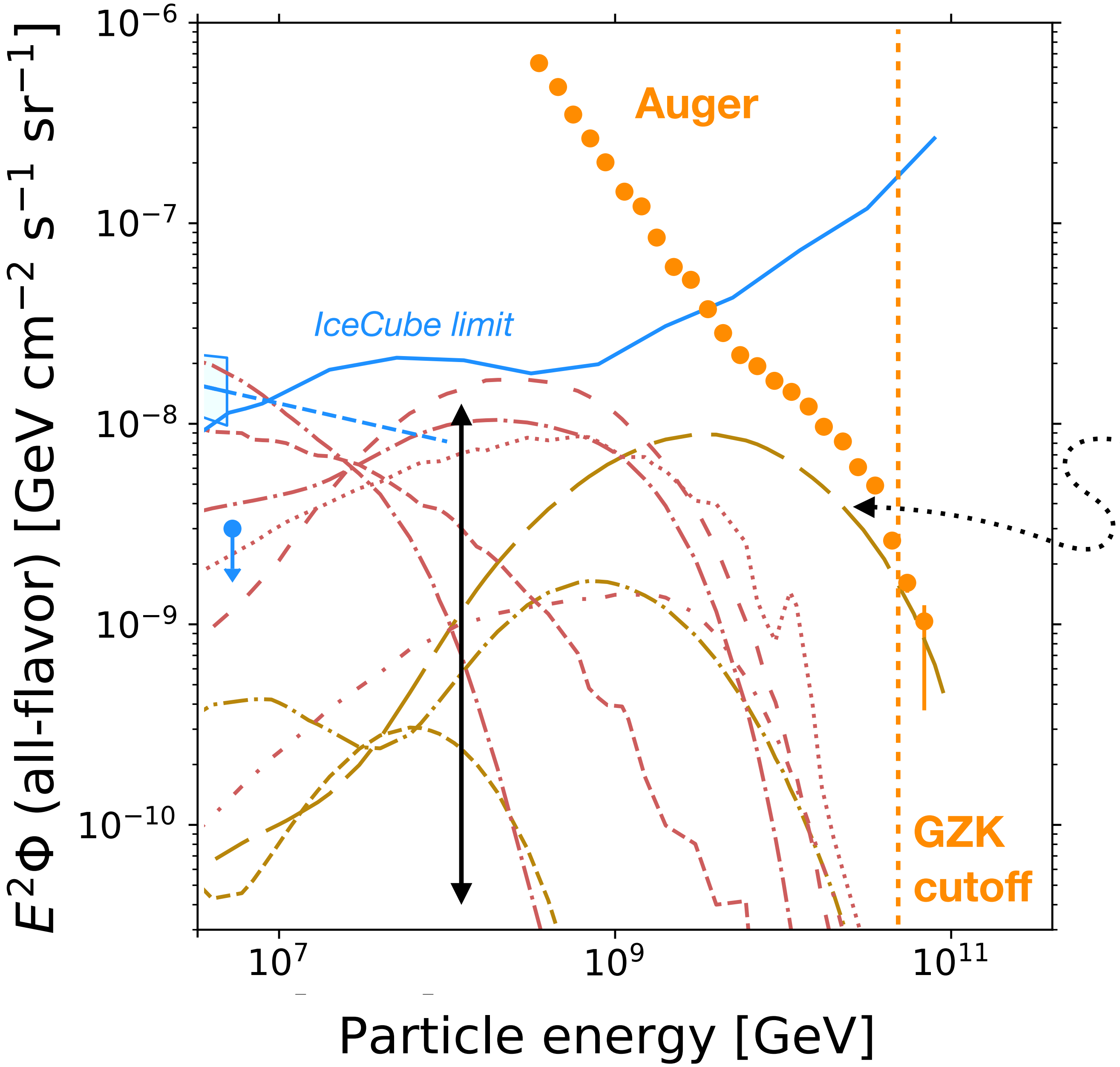
From [APJ 1997]



What are the fundamental properties and interactions of neutrinos at these energies?

Neutrino oscillation experiments over cosmological baselines?

An experimental challenge



Predicted ultra-high energy neutrino flux very uncertain *(and also tiny)*

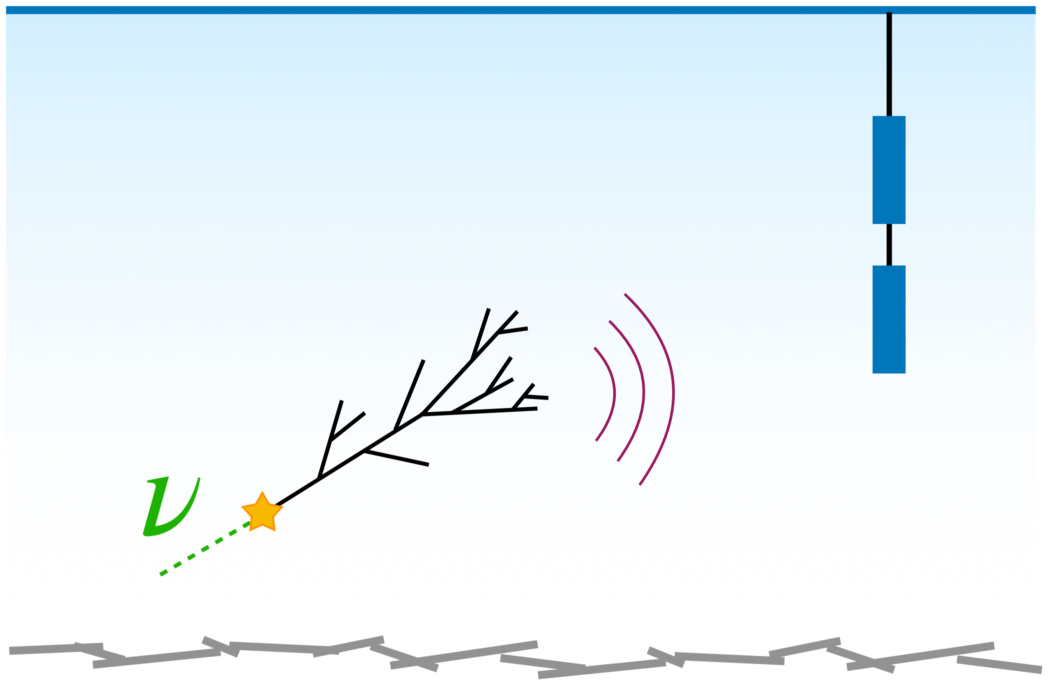
Back-of-the-envelope estimate:

Assumed flux:
O(1) GZK-scale neutrino / km^2 / year

Interaction length: O(100) km

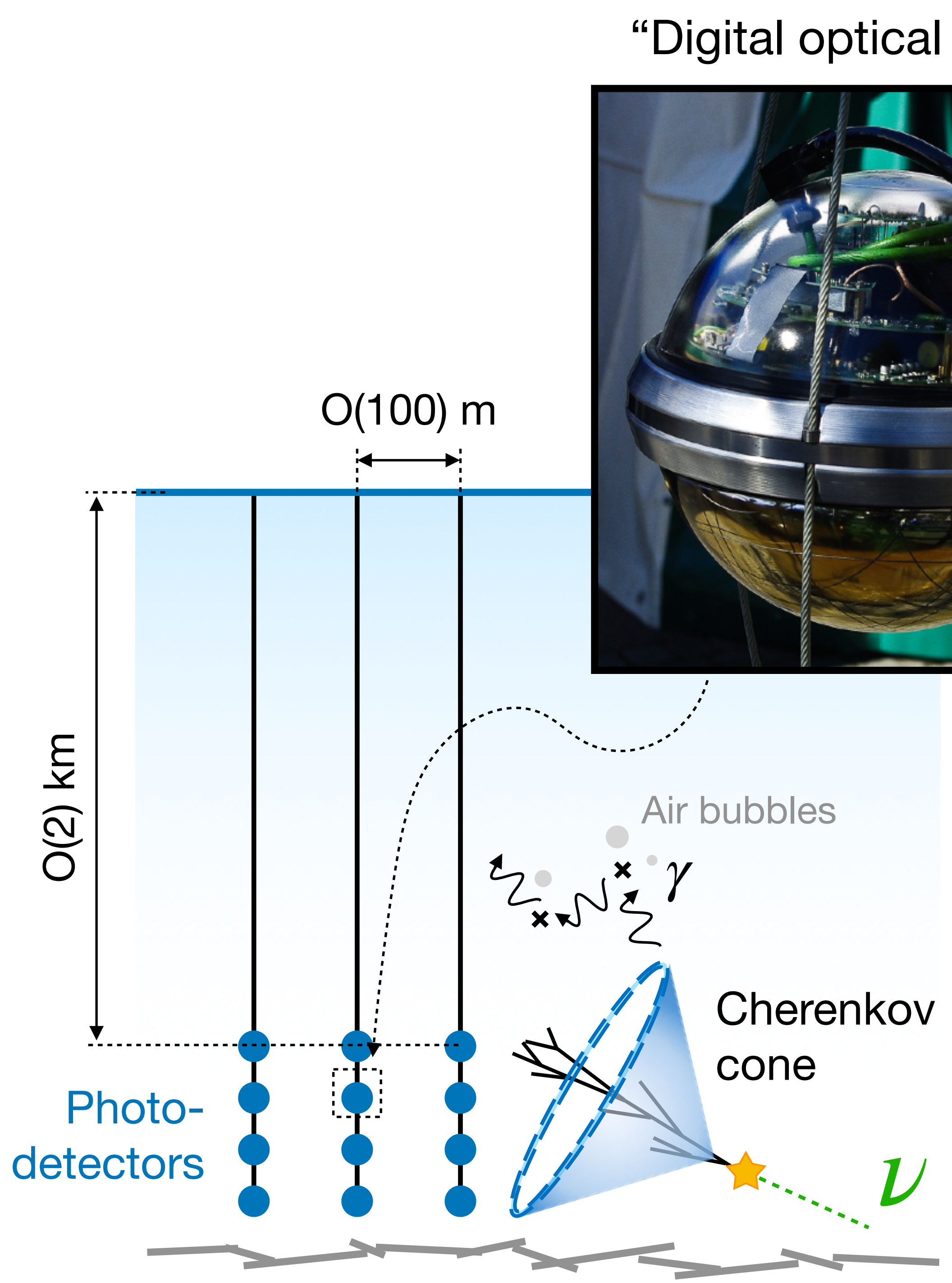
→ **0.01 interactions / km^3 / year**

Need to build a detector with sensitive volume of O(100) km^3!



Experimental techniques

From IceCube to radio



IceCube

Peak sensitivity at $\lambda \sim 400\,\mathrm{nm}$

Neutrino interaction in glacial ice

→ Charged-particle cascade

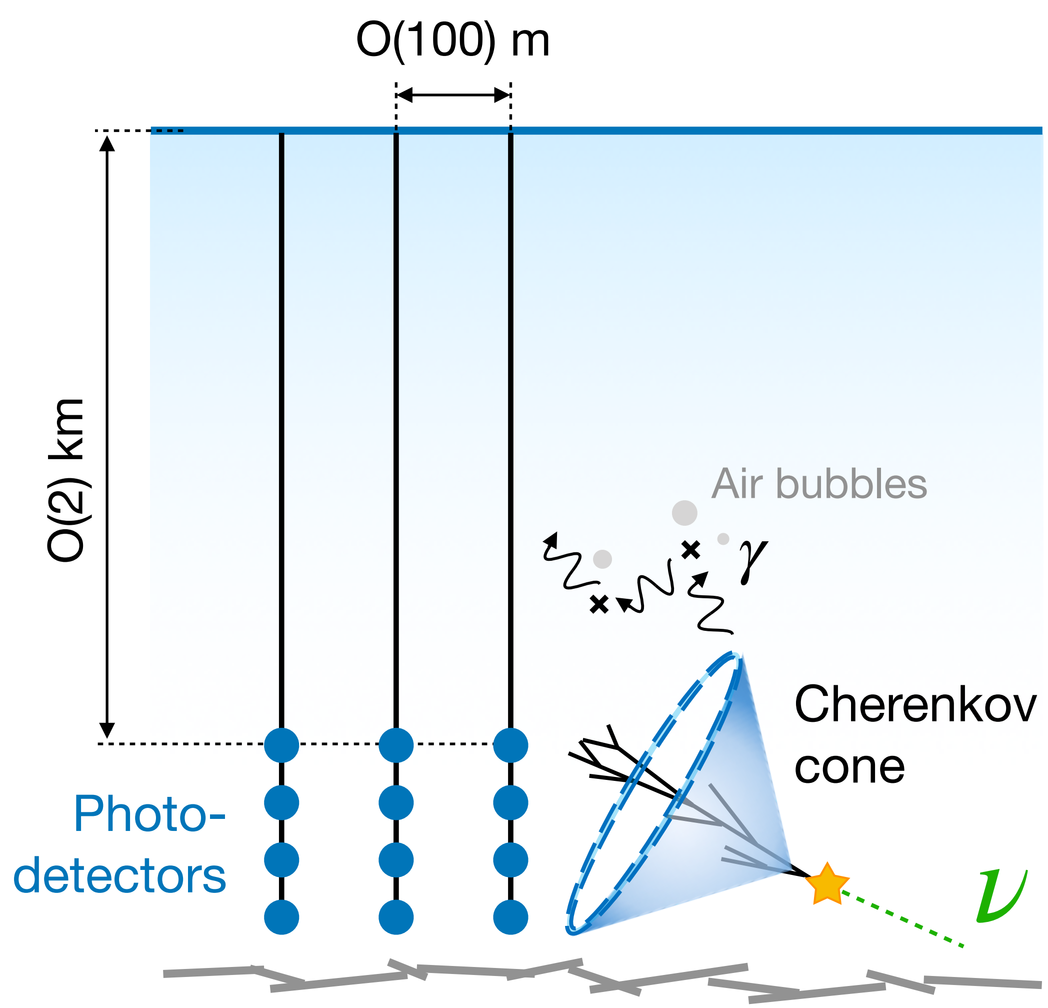
IceCube:

Cherenkov photons scatter in the ice

Scattering length ~ O(100) m ~ distance between adjacent photodetectors

Can **instrument O(1) km³**, but **difficult** to go **significantly beyond**

From IceCube to radio



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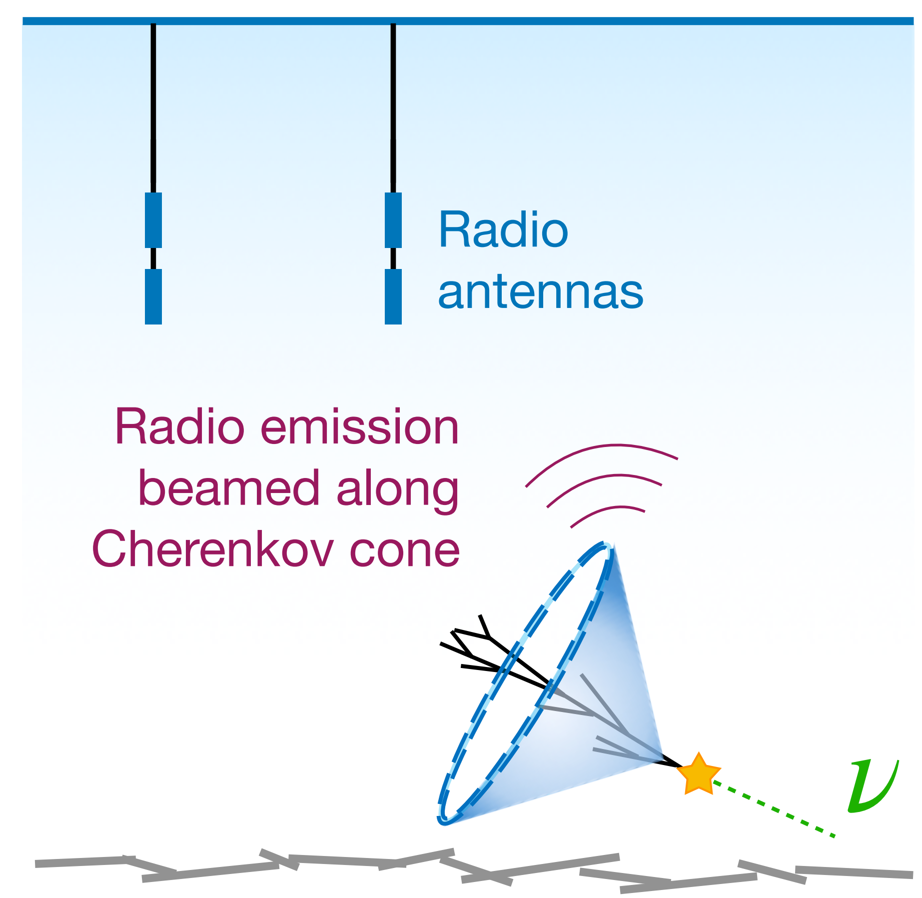


Radio neutrino detector

$\lambda \sim 0.4\,\mathrm{m} \leftrightarrow f \sim 500\,\mathrm{MHz}$

From IceCube to radio

Clean & cold ice is very transparent to radiation in the MHz - GHz band!

Attenuation length ~ O(km)

Ice is dense!

Emitting particle cascade is smaller than wavelength

Coherent emission:

Signal amplitude $\sim E_\nu$

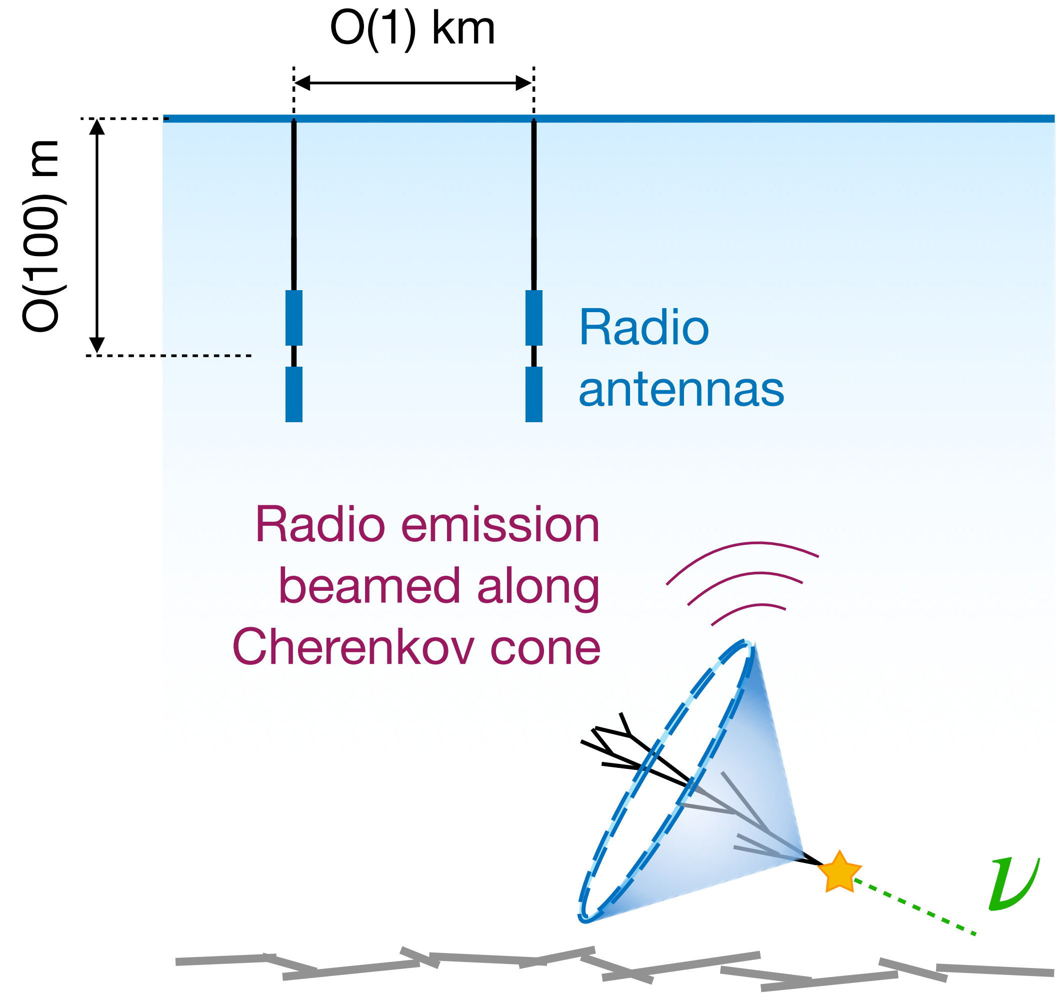
"Askaryan effect" dominates: similar, but distinct from Cherenkov emission

Expect **strong signals** at high energies, **detectable over long distances**

O(100) km^3 instrumented volume not unreasonable

Neutrino interaction in glacial ice

→ Charged-particle cascade



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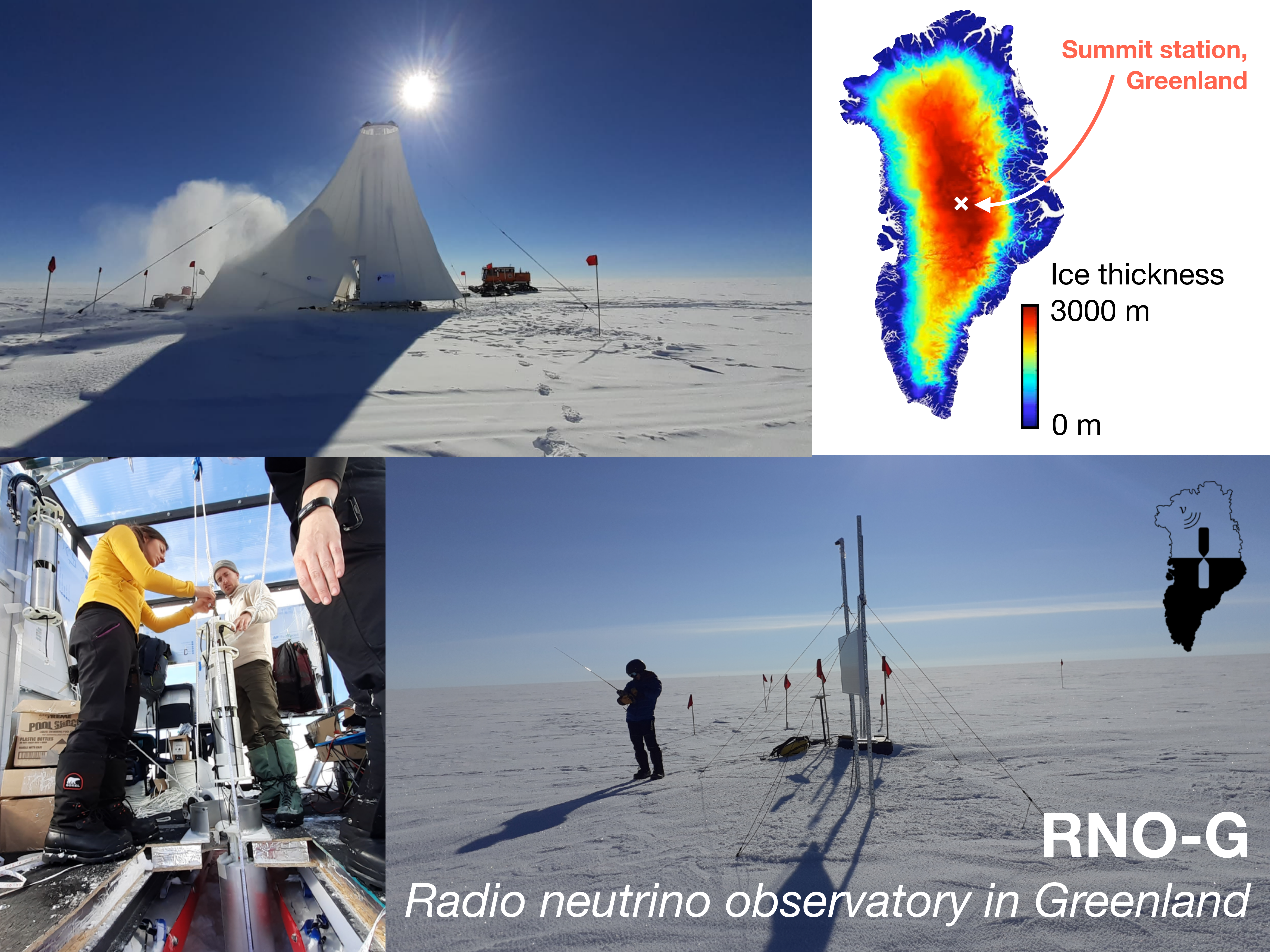
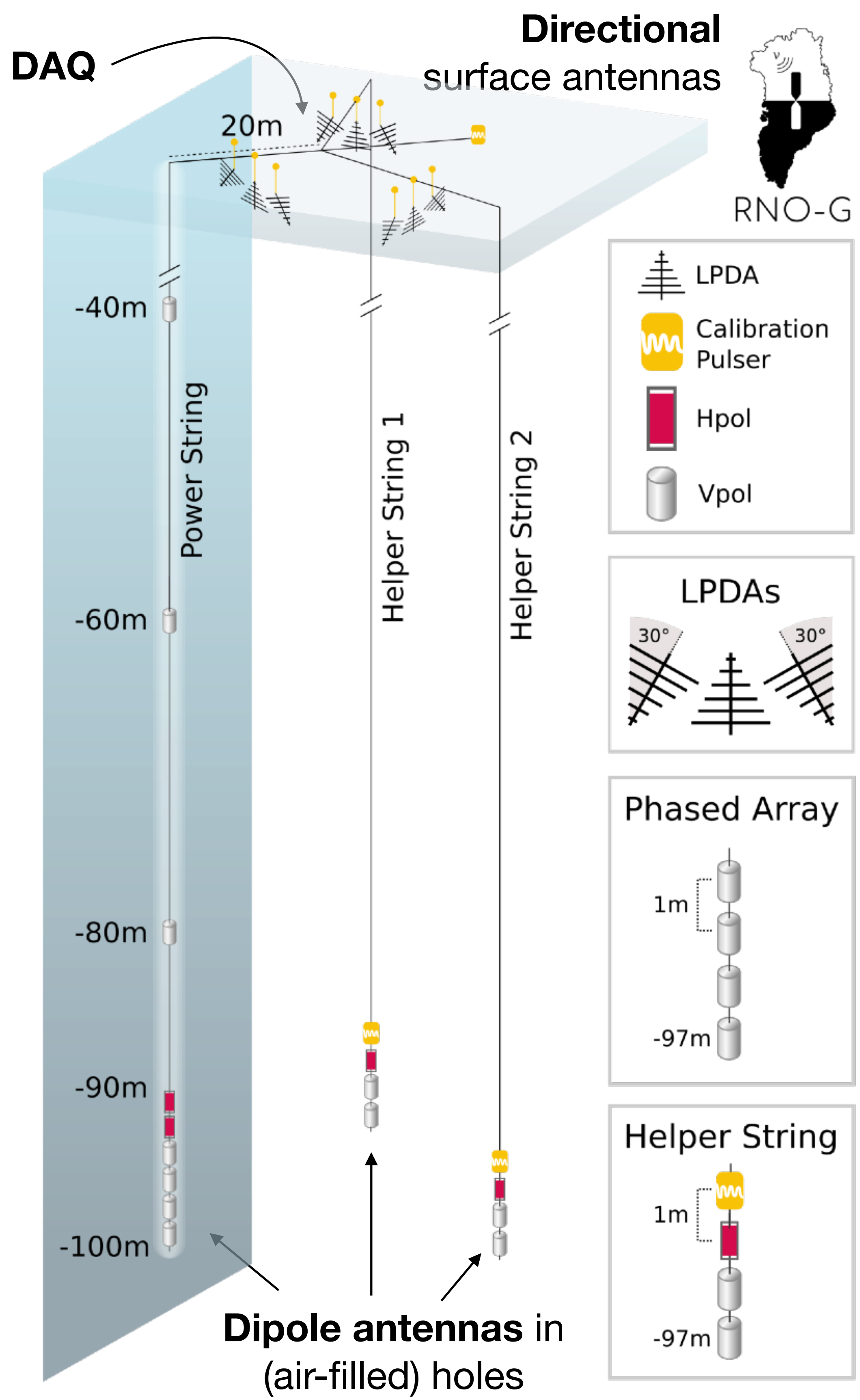

Summit station,
Greenland
Ice thickness
3000 m
0 m
RNO-G
Radio neutrino observatory in Greenland

RNO-G layout

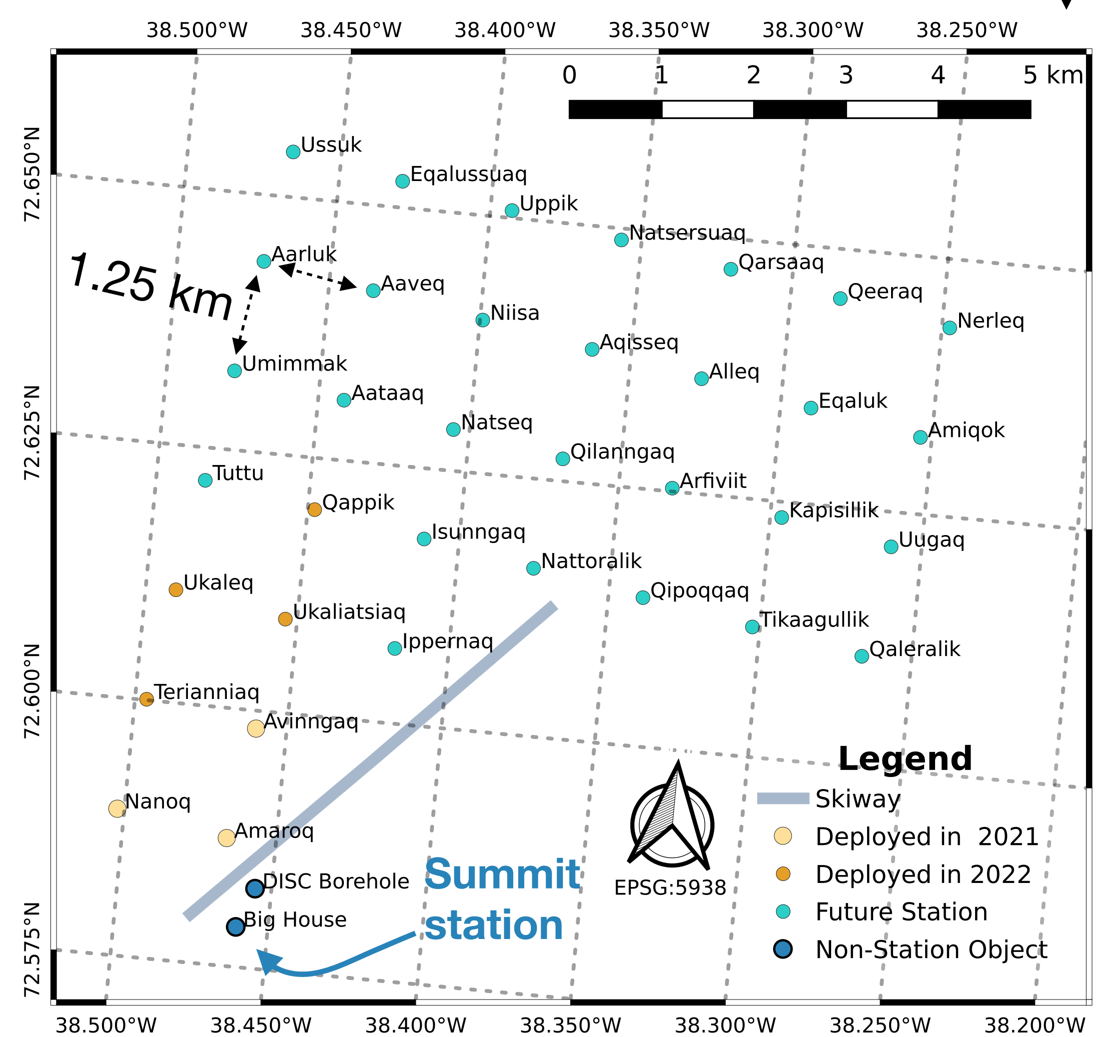


Triangular station layout with vertically- and horizontally-polarized dipole antennas

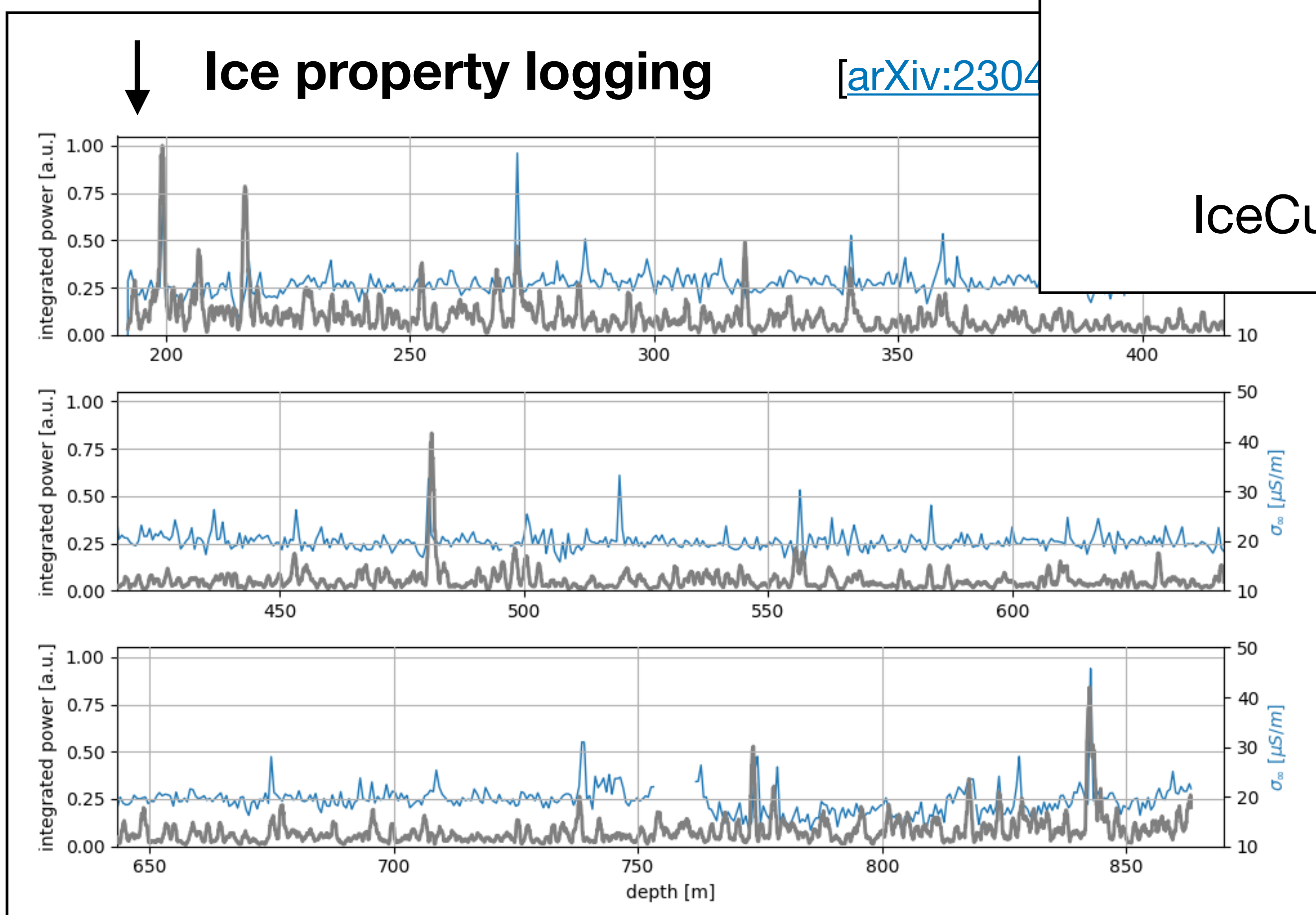
→ synthesize higher-gain antennas through phasing

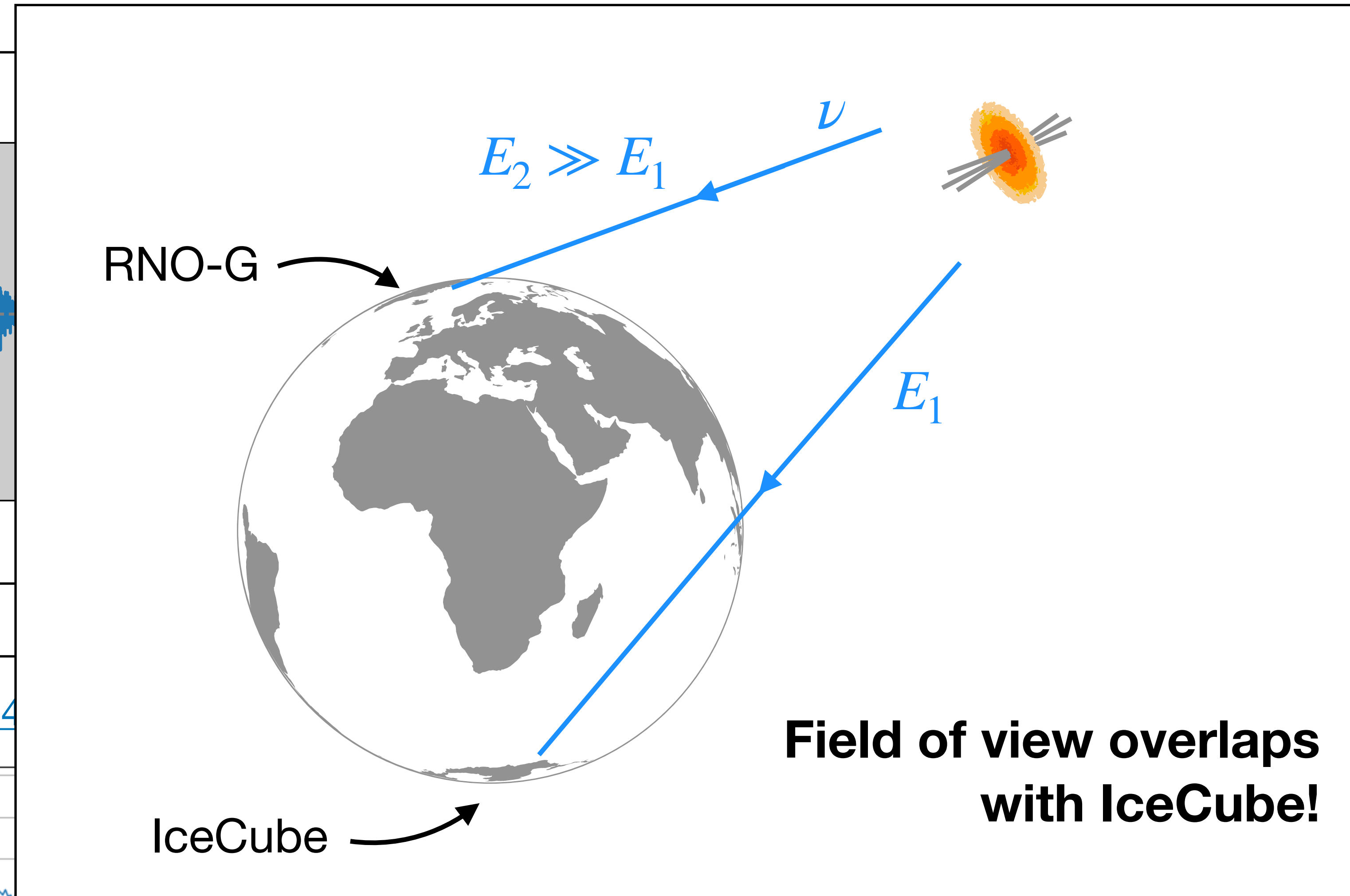
→ seek out more-homogeneous "deep" ice (~100 m depth)

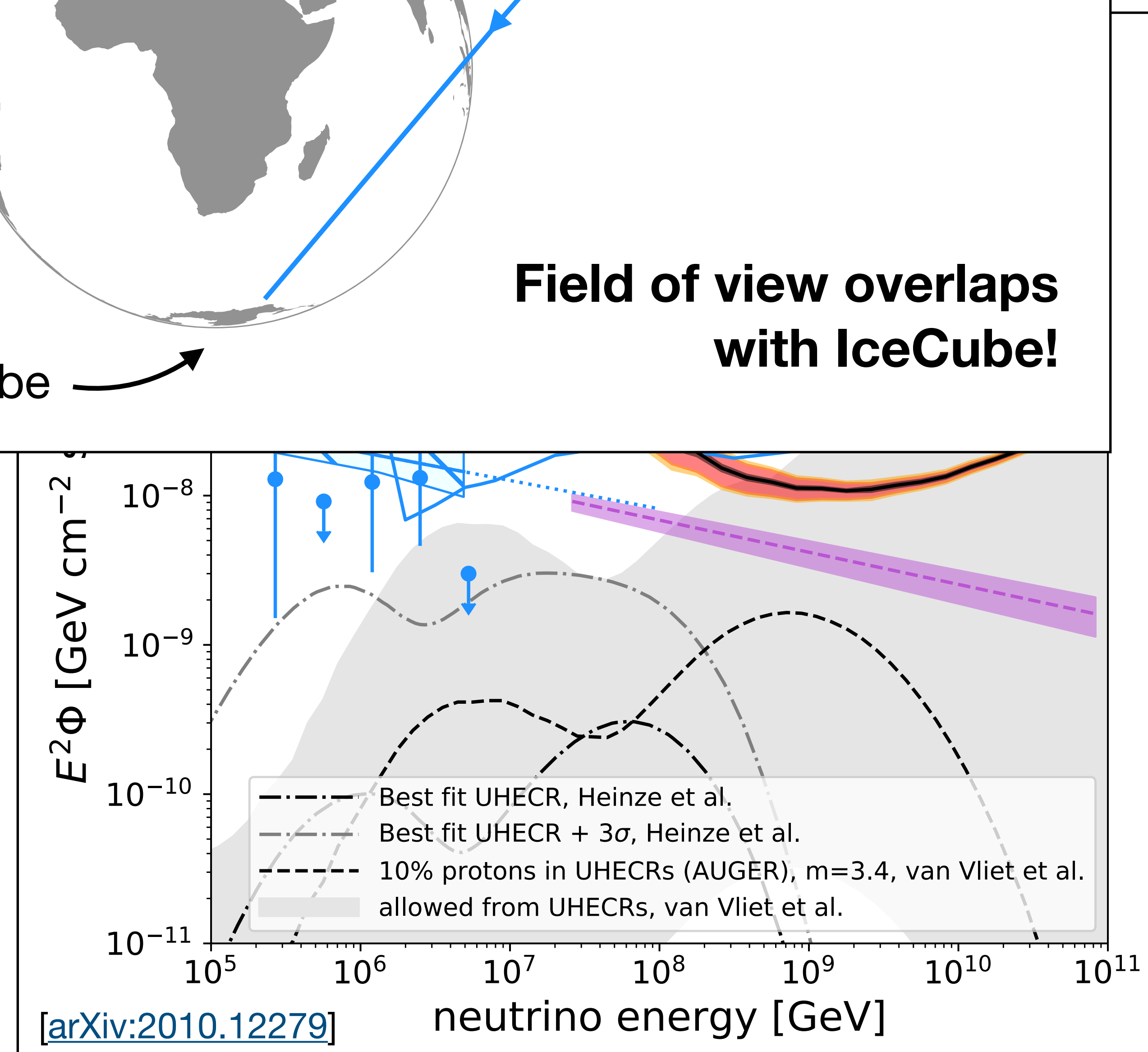
7 stations deployed and taking data, 28 more to come!

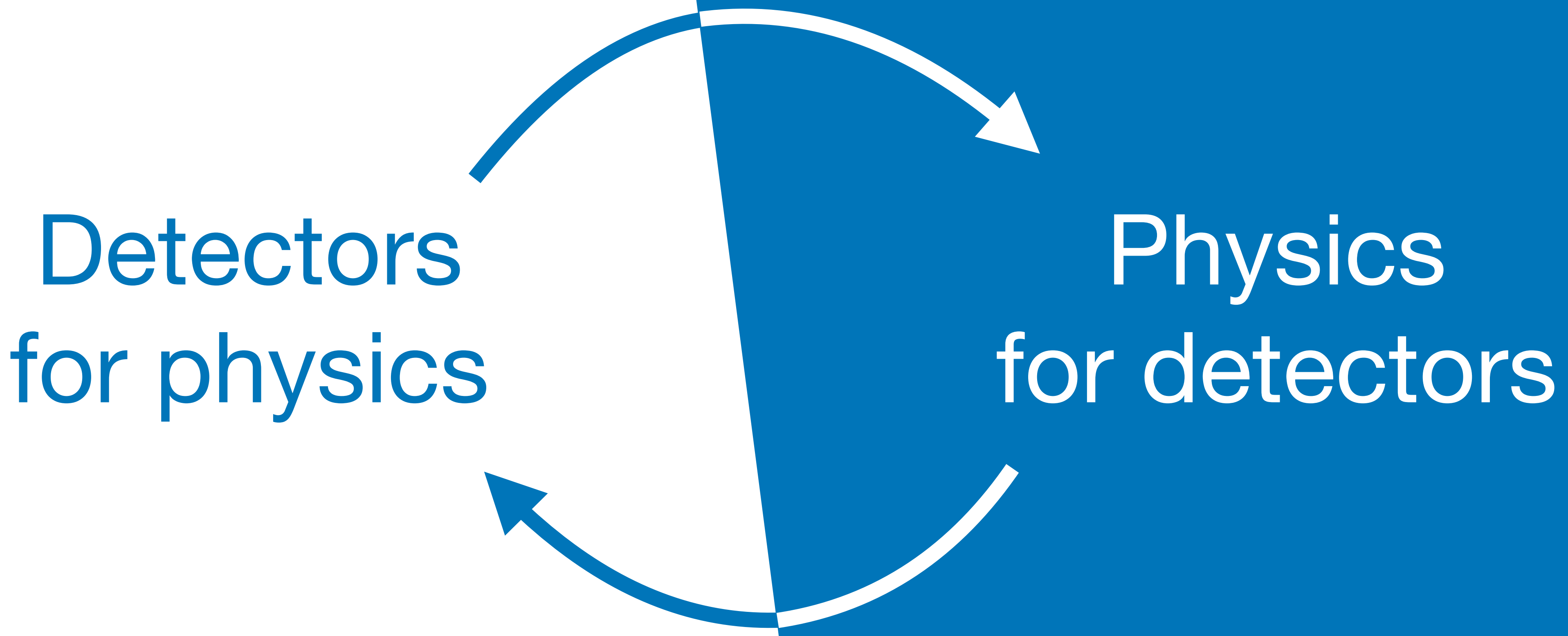


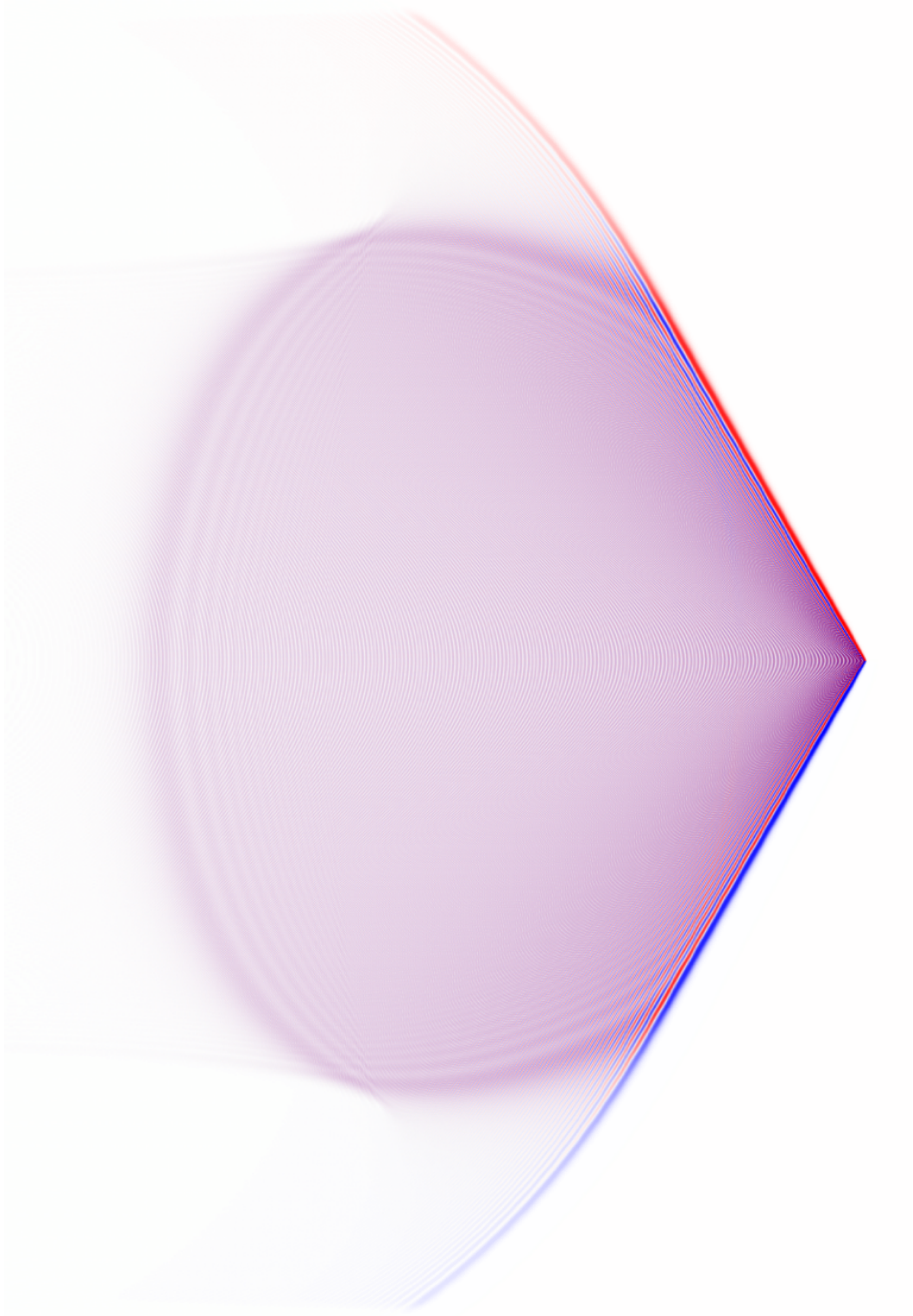
Challenges and opportunities







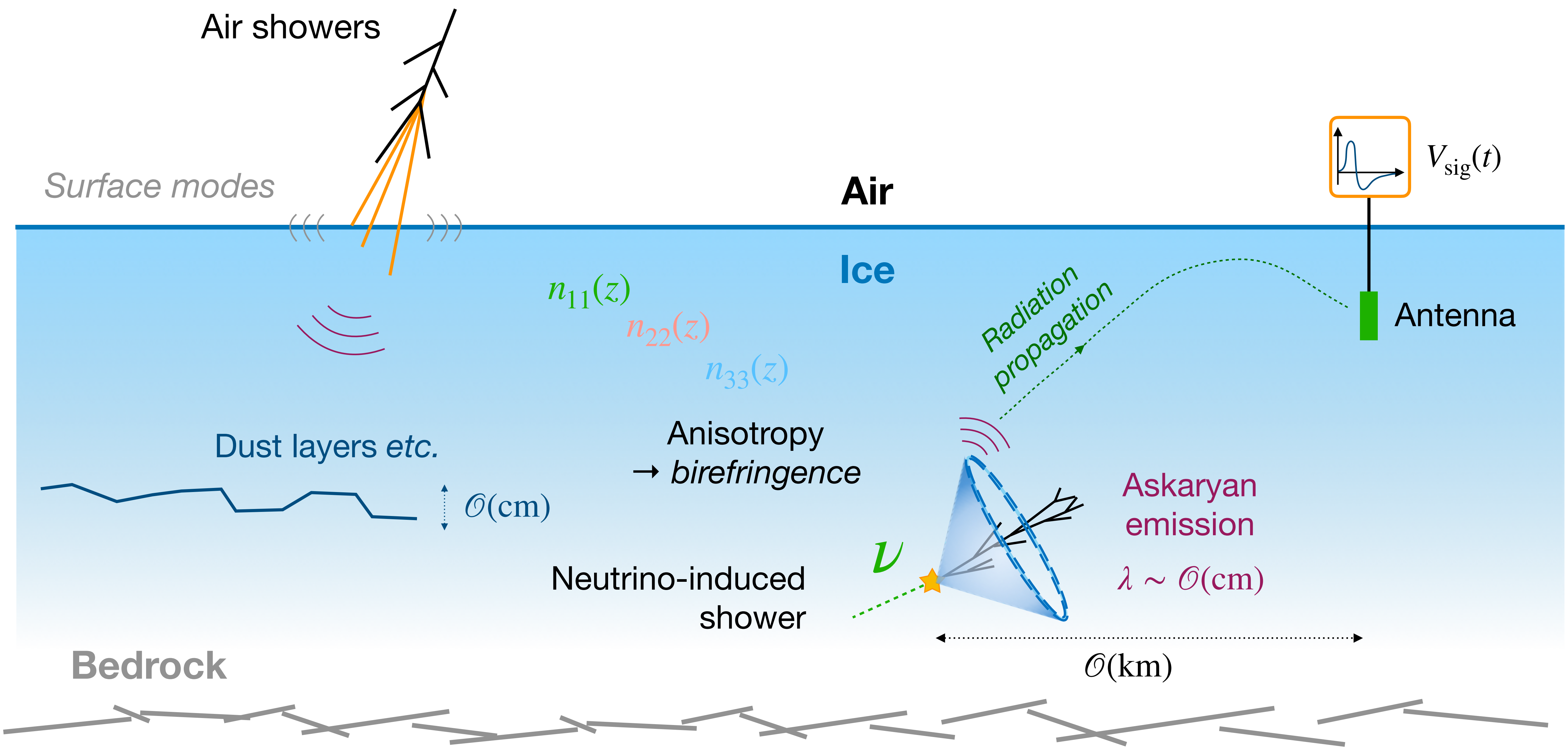

Detectors
for physics
Physics
for detectors



Electrodynamics of antenna signal formation

The problem

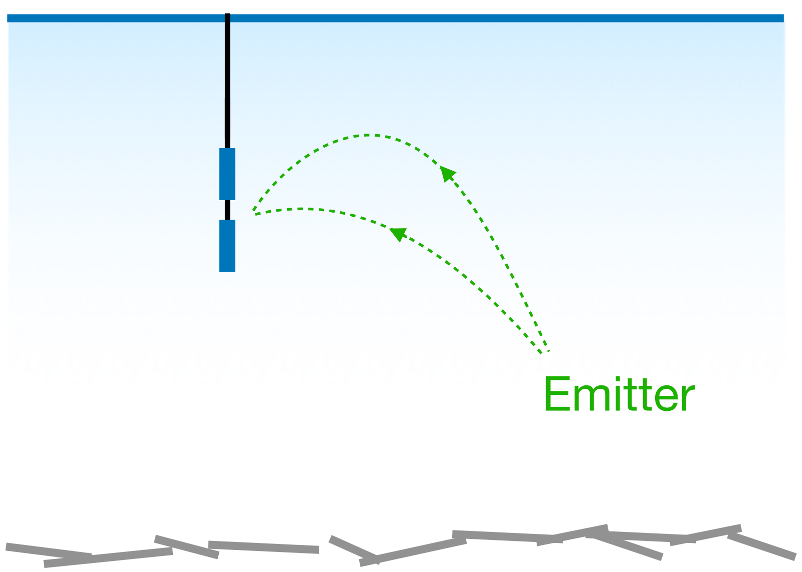
Ice is complicated!



Simulations: a question of granularity

Raytracing

Geometric optics:
$\lambda \to 0$

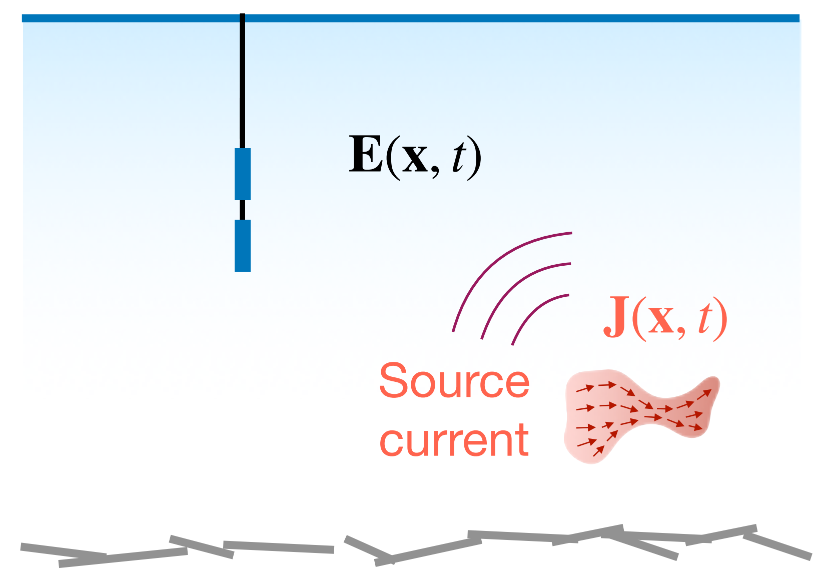


Radiation travels along "rays", curved in environment with varying index of refraction
(Snell's law)

Long-time workhorse, but known to be incomplete!

Maxwell's equations

All wave-optics effects included



$$\nabla \times \mathbf{E} = -\partial_t \hat{\mu} \mathbf{H}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \hat{\sigma} \mathbf{E} + \partial_t \hat{\epsilon} \mathbf{E}$$

"There is no new physics in electromagnetism"

cm-scale voxels over *km*-scale volume, no symmetries → **intractable in practice!**

The idea: reciprocity

Alice

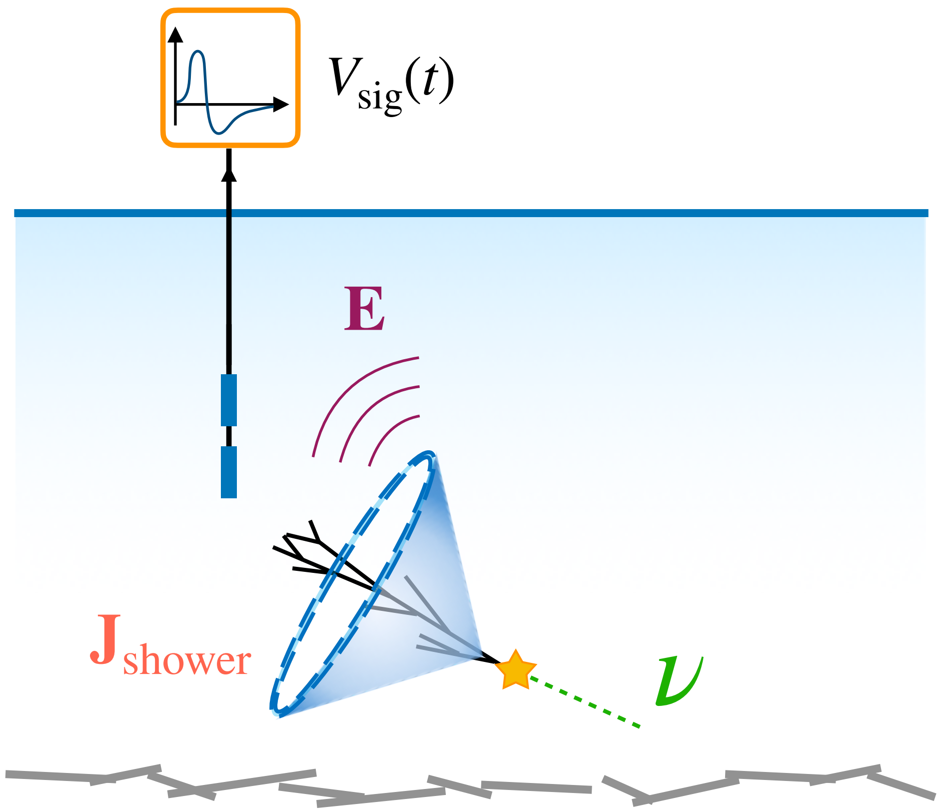
Alice can see Bob …

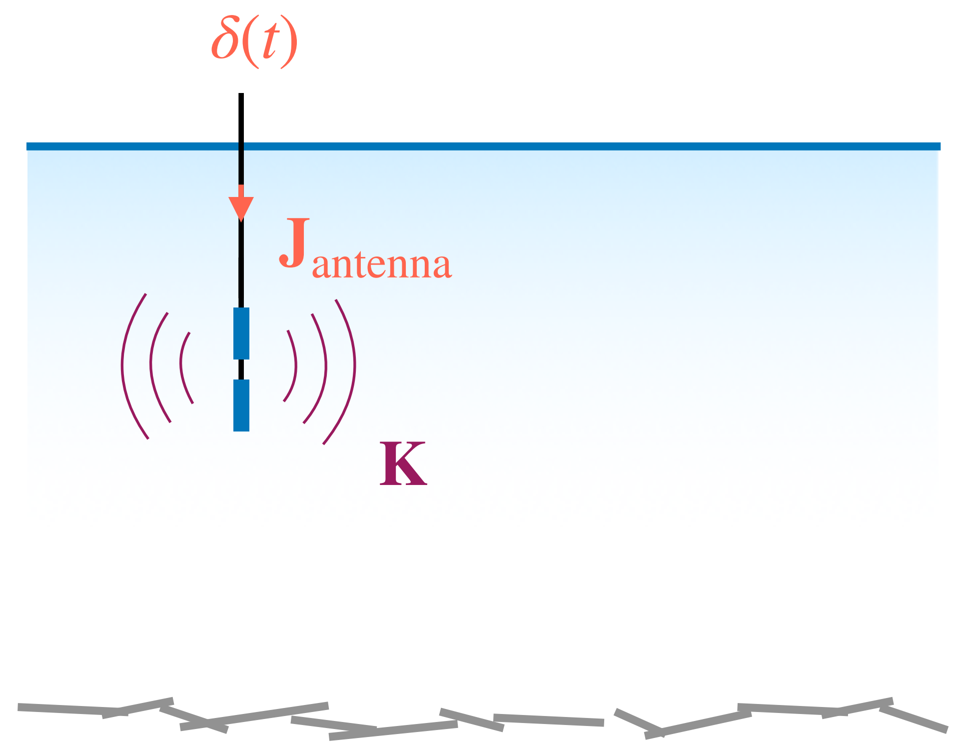
… if and only if
Bob can see Alice

Bob

The idea: reciprocity

Electromagnetic "communication channels" are symmetric





Antenna is receiver, produces voltage signal

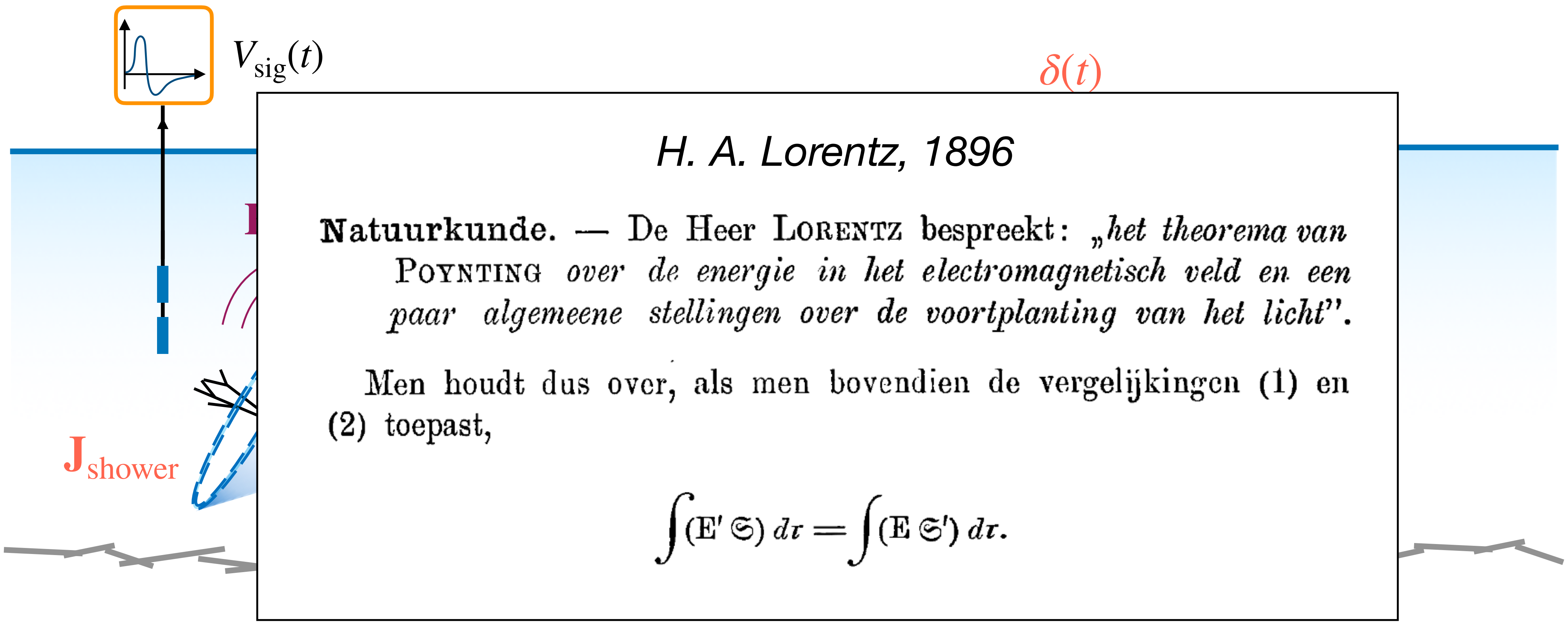
Feed delta-like signal into antenna, is transmitter

Antenna "sees" shower ⟷ *Shower "sees" antenna*

Reciprocity

The idea: reciprocity

Electromagnetic "communication channels" are symmetric



H. A. Lorentz, 1896

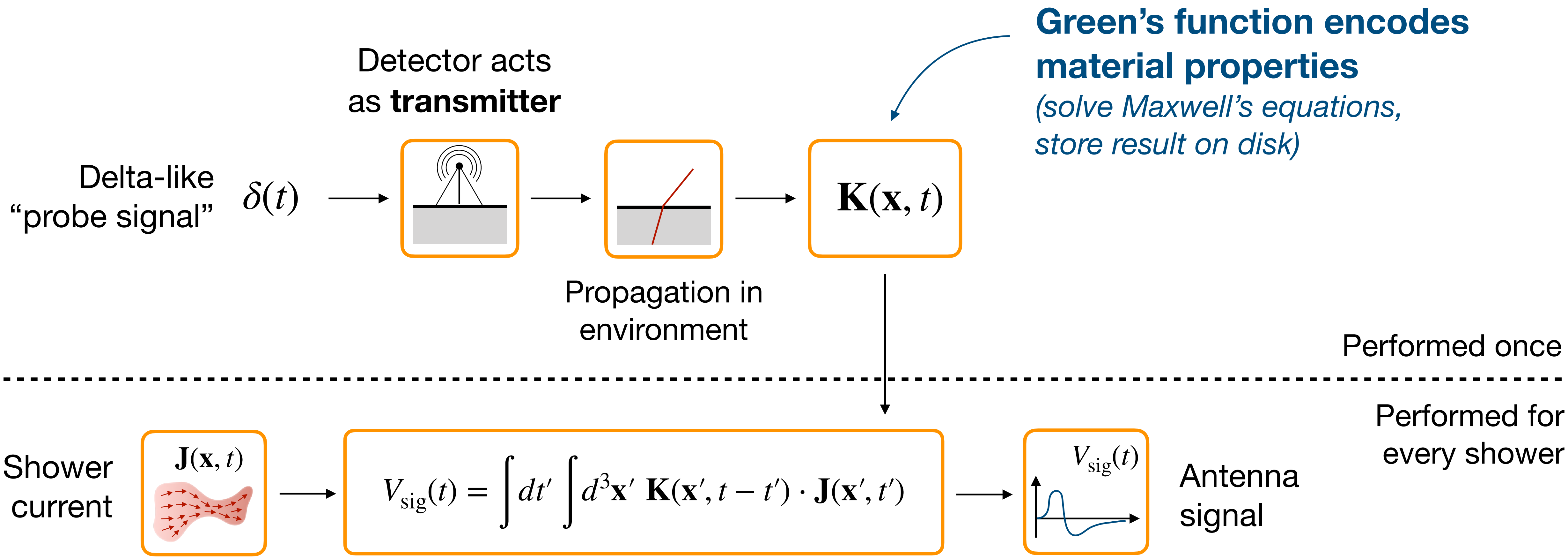
> **Natuurkunde.** — De Heer LORENTZ bespreekt: *„het theorema van* POYNTING *over de energie in het electromagnetisch veld en een paar algemeene stellingen over de voortplanting van het licht".*
>
> Men houdt dus over, als men bovendien de vergelijkingen (1) en (2) toepast,
>
> $$\int (\mathrm{E}' \mathfrak{S})\, d\tau = \int (\mathrm{E}\, \mathfrak{S}')\, d\tau.$$

$$V_{\text{sig}}(t) = \int dt' d^3x' \;\; \mathbf{K}(\mathbf{x}', t - t') \cdot \mathbf{J}_{\text{shower}}(\mathbf{x}', t')$$

"The electric field transmitted by the antenna is a Green's function for the received signal"

A detector-centric calculation

This makes fully-electrodynamic signal calculations possible!



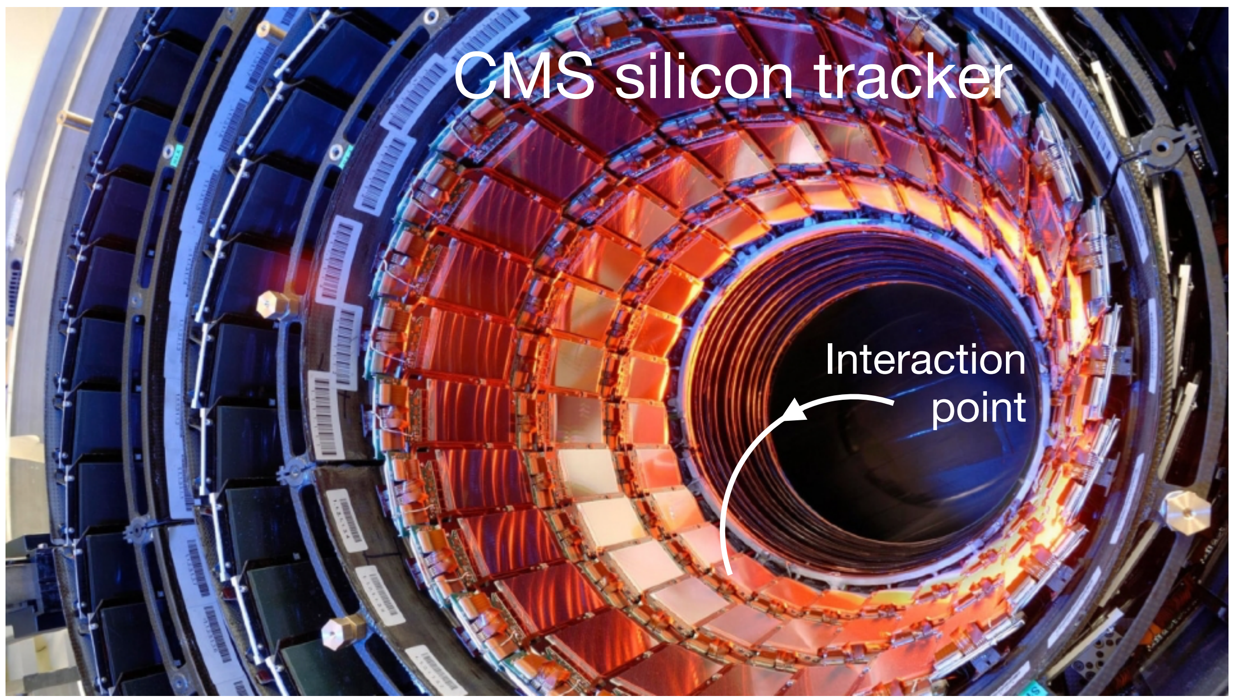
Convolution with shower is *fast*!

Calculation of complicated radiation propagation amortized into Green's function

A detector-centric calculation

This is the electrodynamic generalization of the Ramo-Shockley theorem!

~90 years old; widely used by collider detector builders

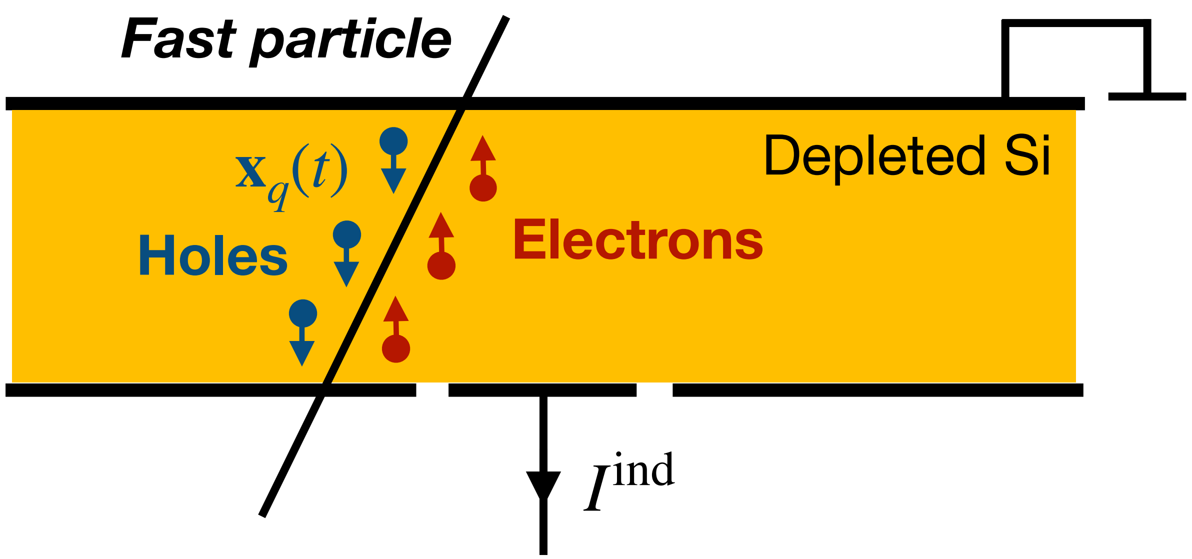


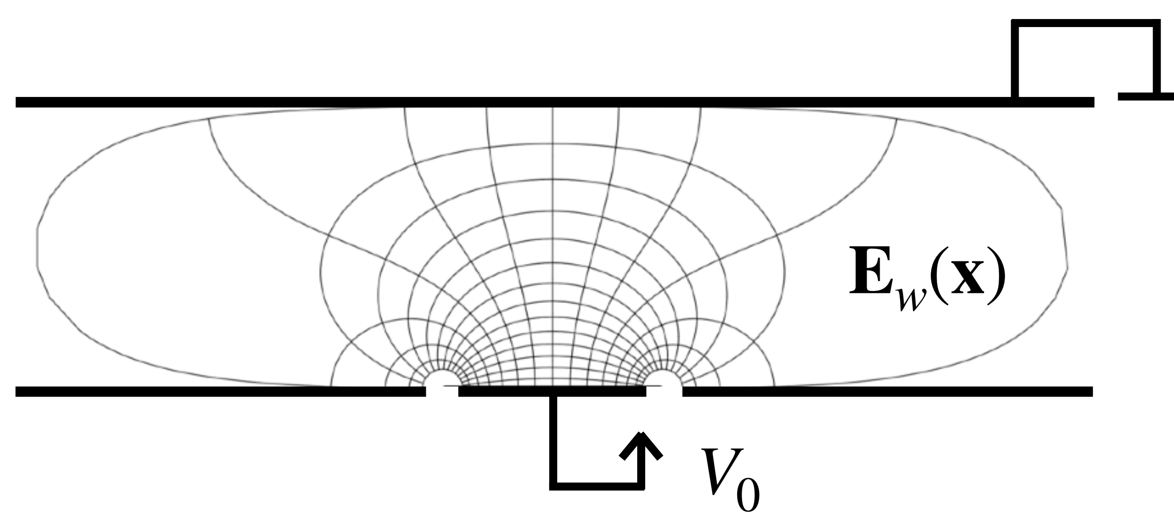
How to calculate current induced by slowly-drifting charges on detector electrodes?

$$I^{\text{ind}}(t) = -\,q\,\boxed{\mathbf{E}_w(\mathbf{x}_q(t))}\cdot\boxed{\dot{\mathbf{x}}_q(t)}$$

"Weighting field" ↕ Green's function

Particle trajectory ↕ Shower current





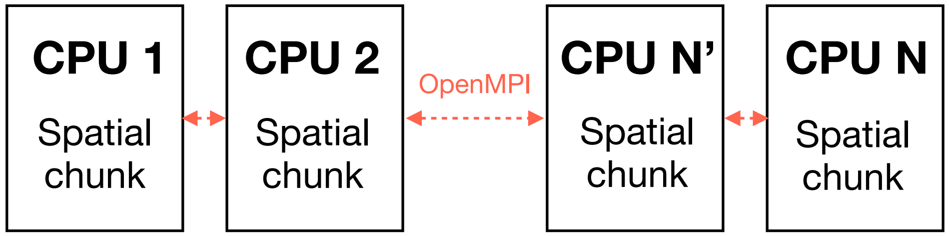
Into practice

This makes fully-electrodynamic signal calculations possible!

… but still not entirely trivial from a computing perspective

Developed by the Nanostructures and Computation Group (MIT)
[homepage] [code]

Off-the-shelf numerical solvers for Maxwell's equations apply to large-scale geometries



Distributed-memory parallelism

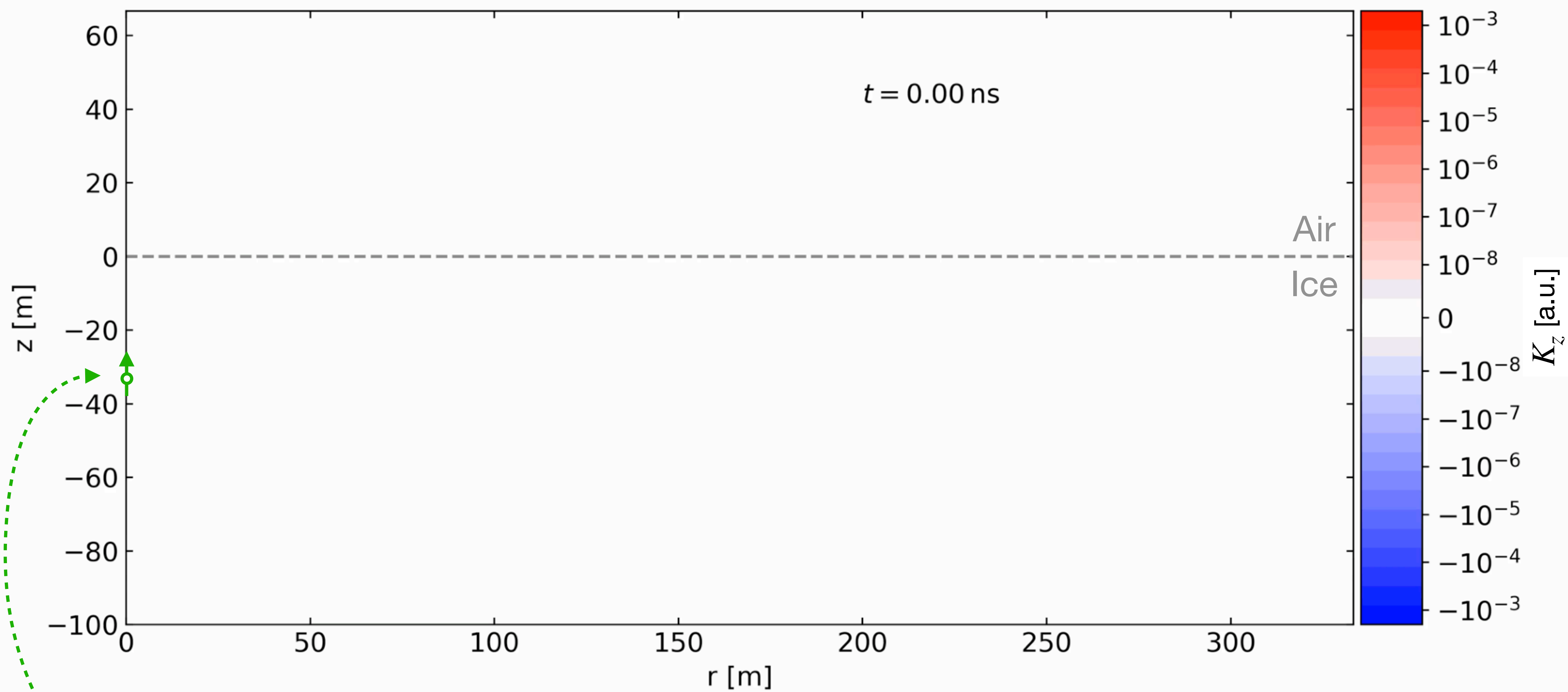
Real **problem: how to store Green's function on disk in an efficient manner?**

300m cylindrical geometry, 2.5cm voxel size
→ **O(10) TB if stored naively!**

But: Green's function is **sparse** in the time domain!
→ *efficient compression is possible*

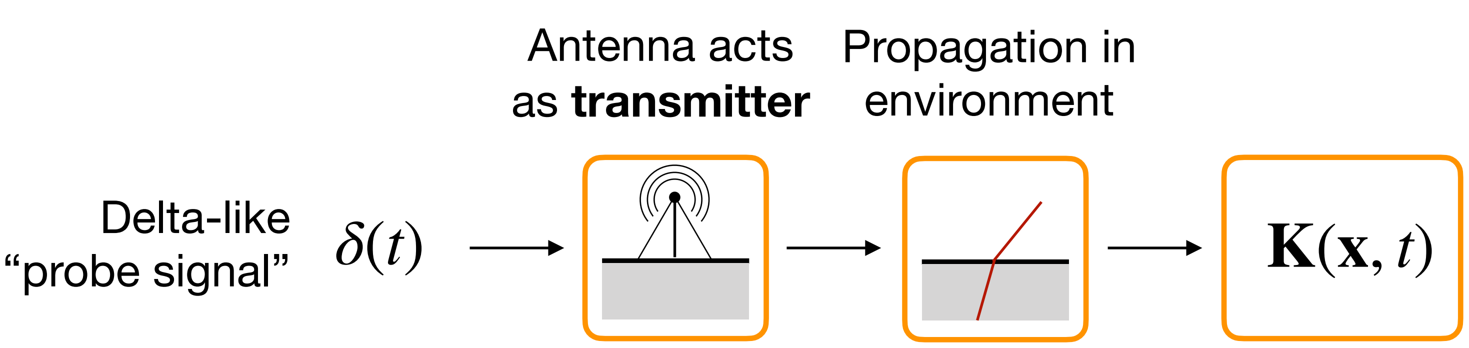
https://github.com/eisvogel-project/Eisvogel

Green's functions are pretty!



Vertically-polarized
dipole antenna

Takes 100 GB of disk space
(instead of ~10 TB when stored naively)



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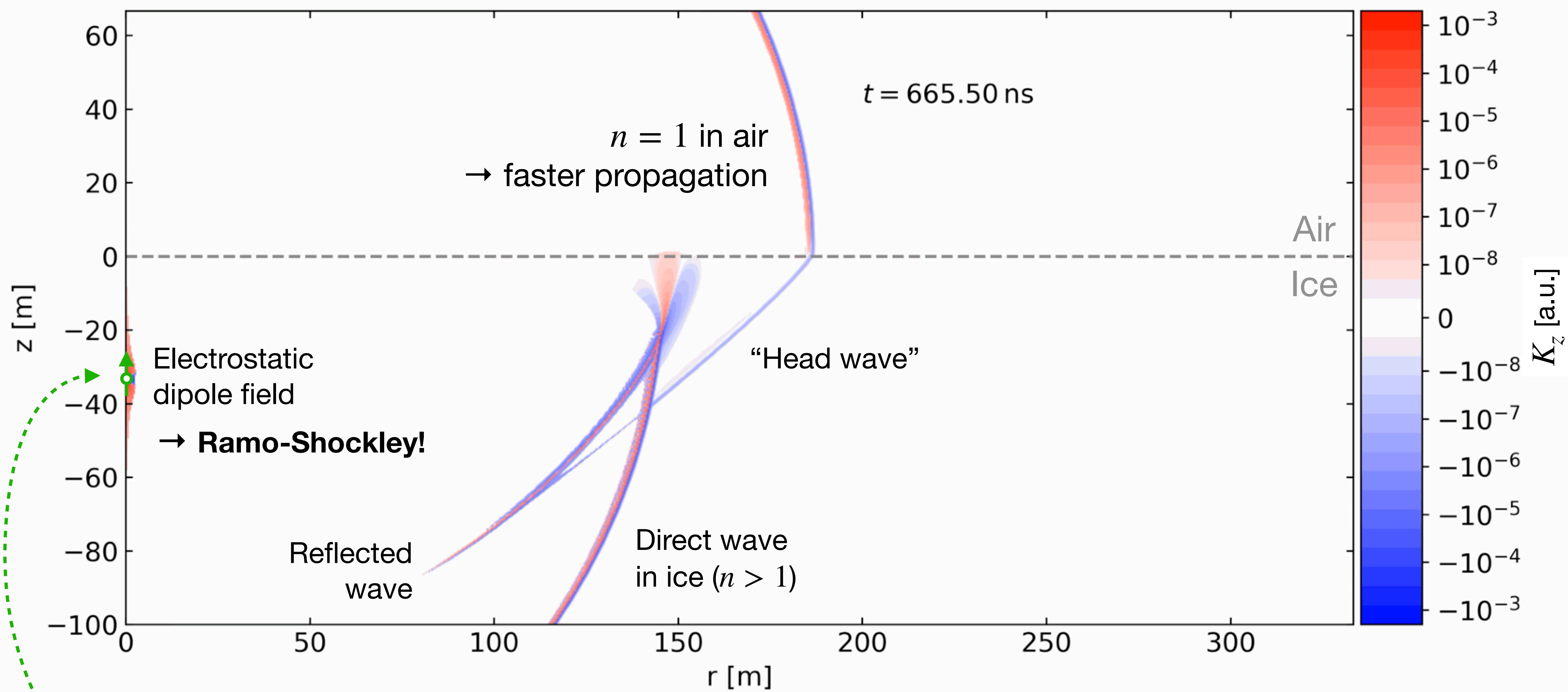

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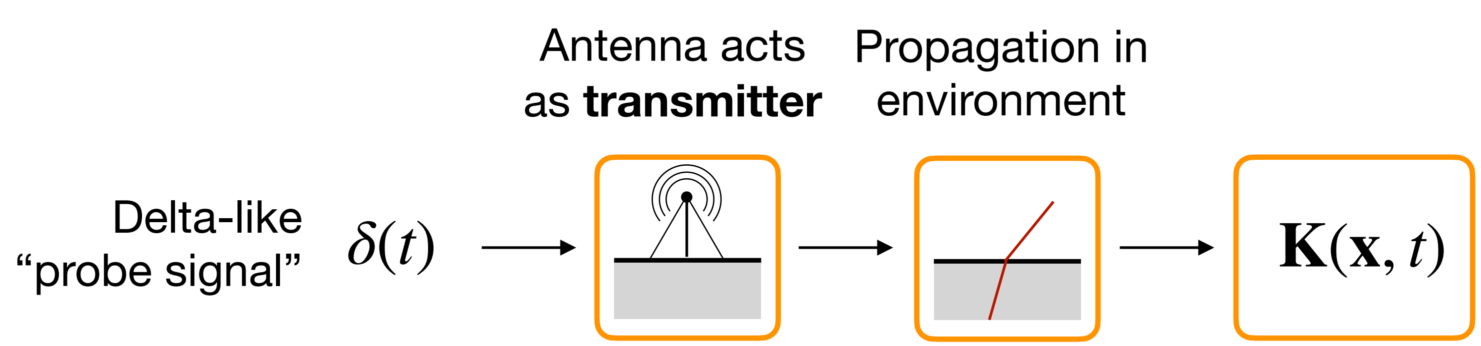
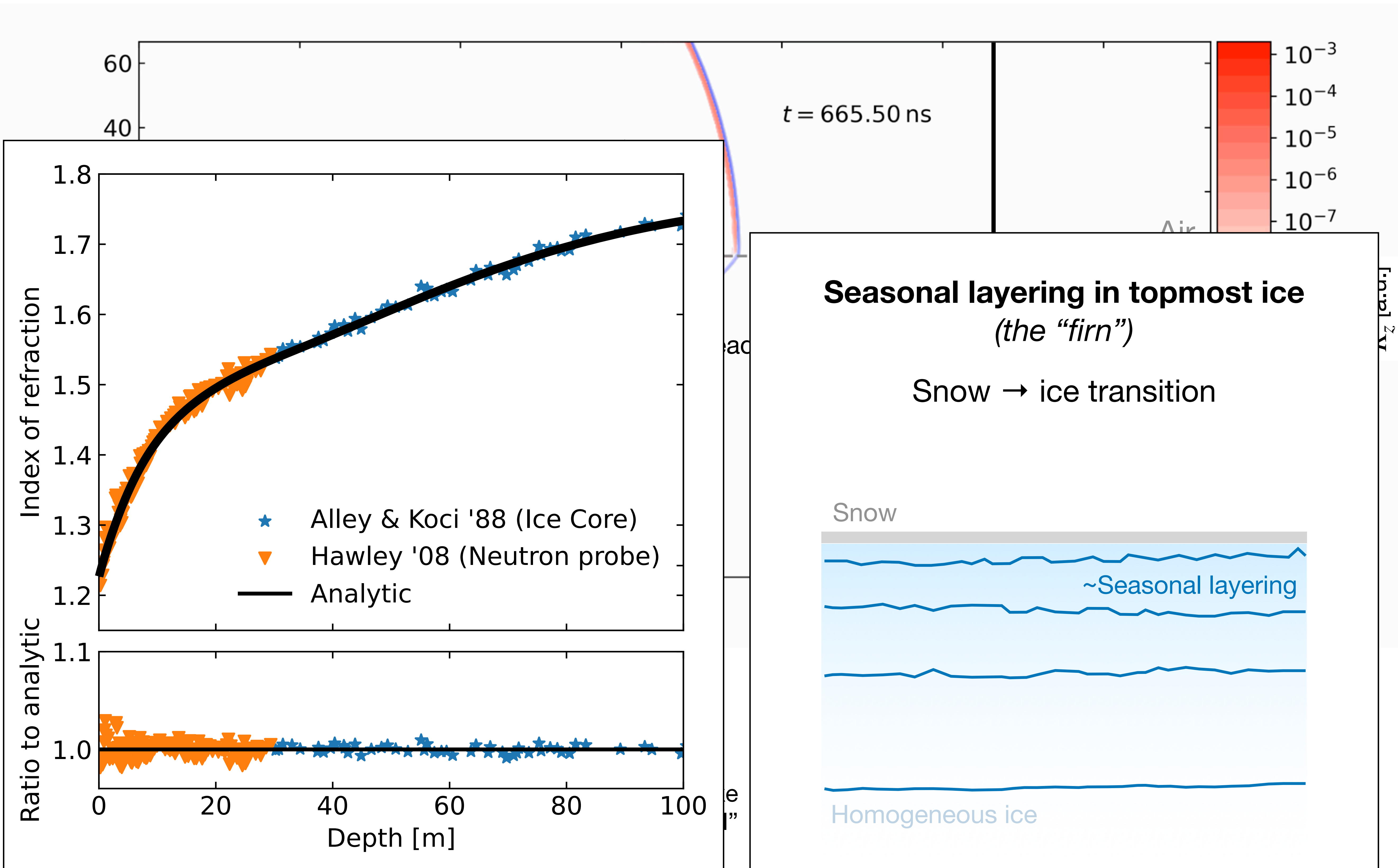
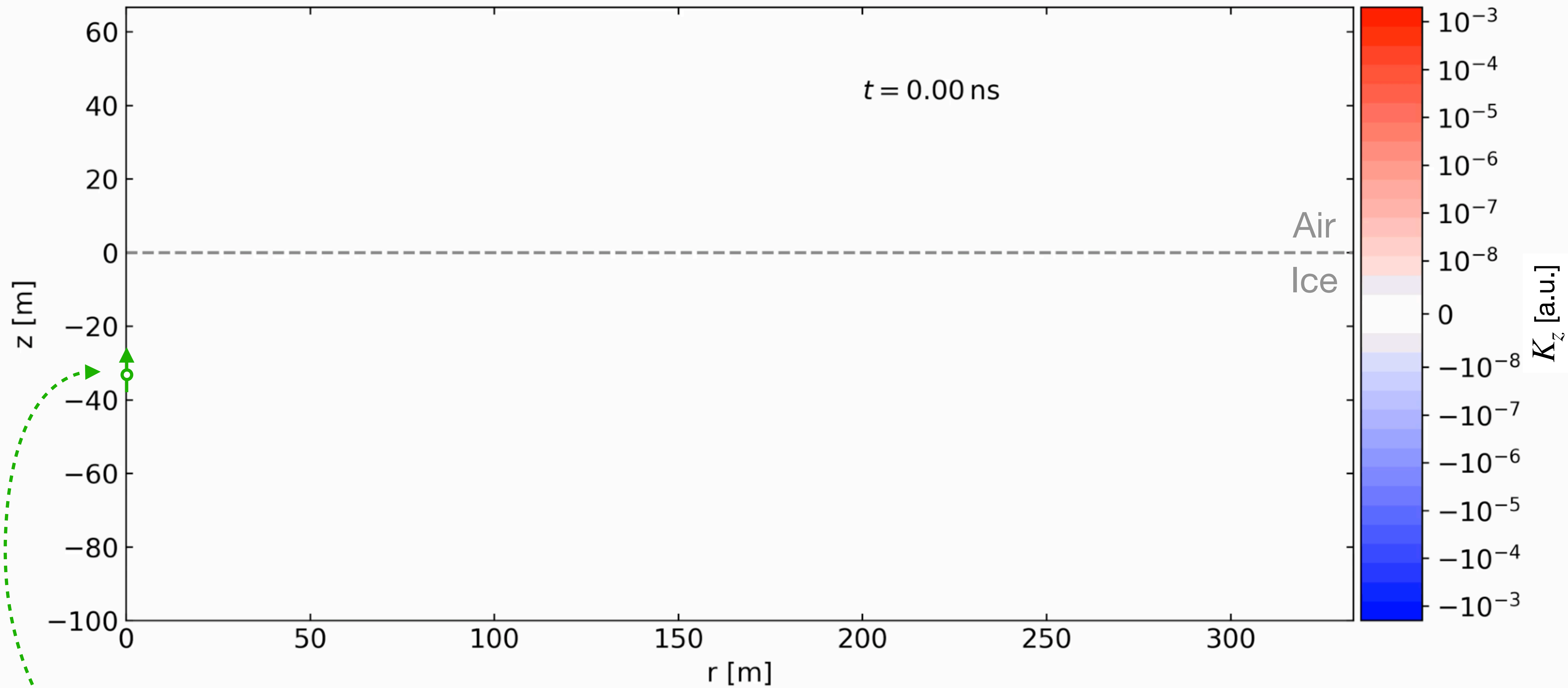


Glacial ice in Greenland



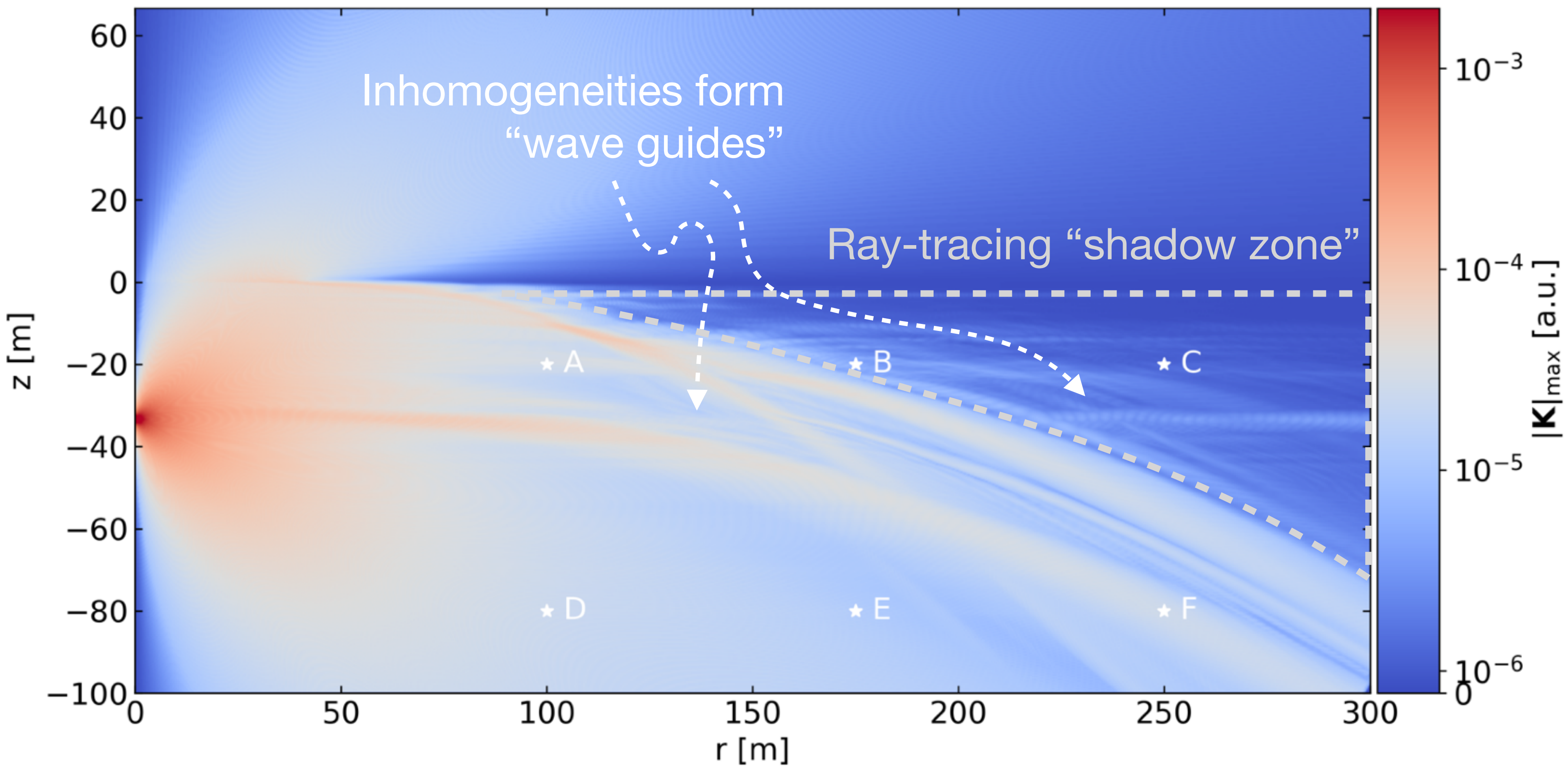
A more realistic Green's function



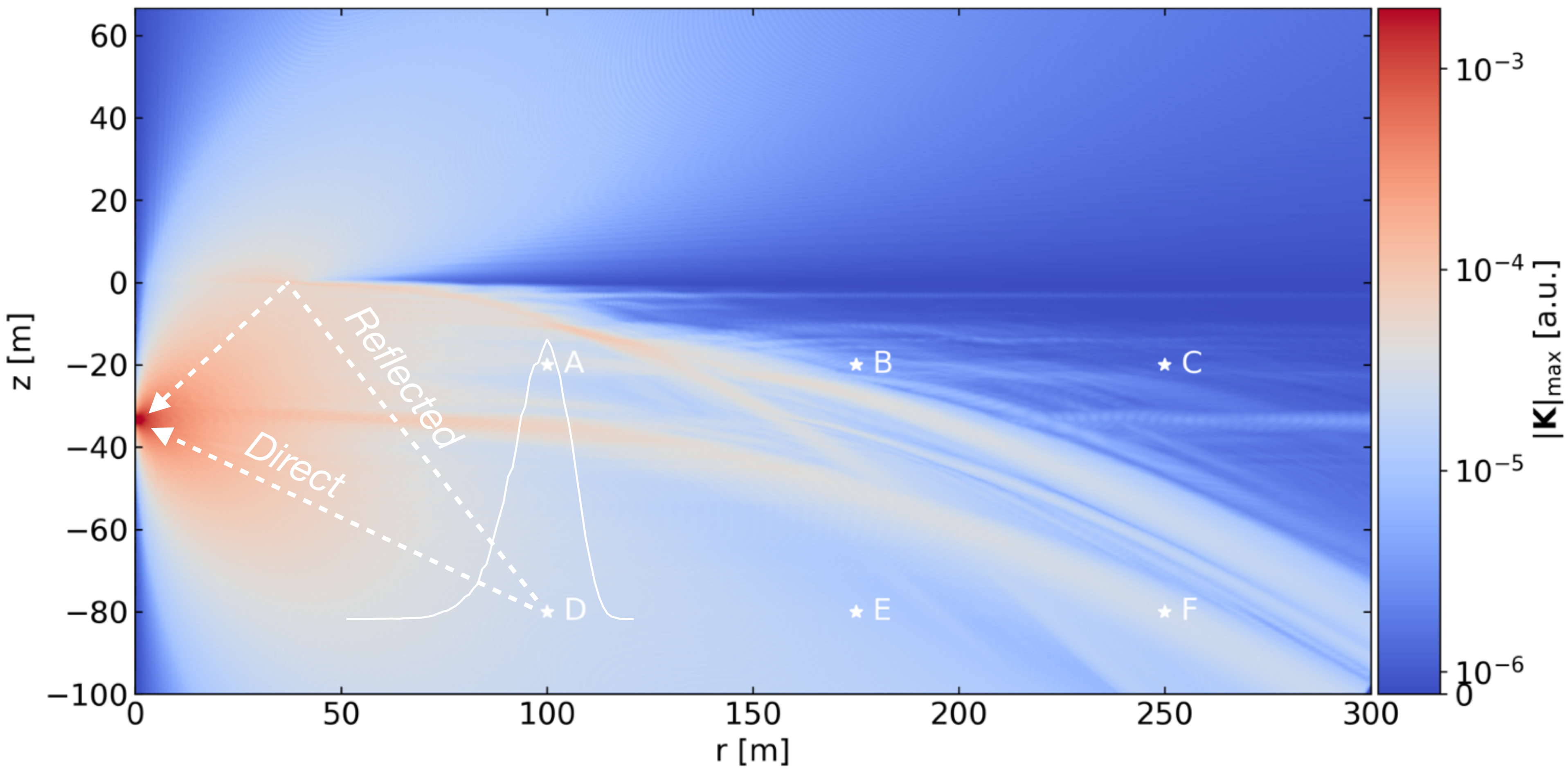
Vertically-polarized
dipole antenna

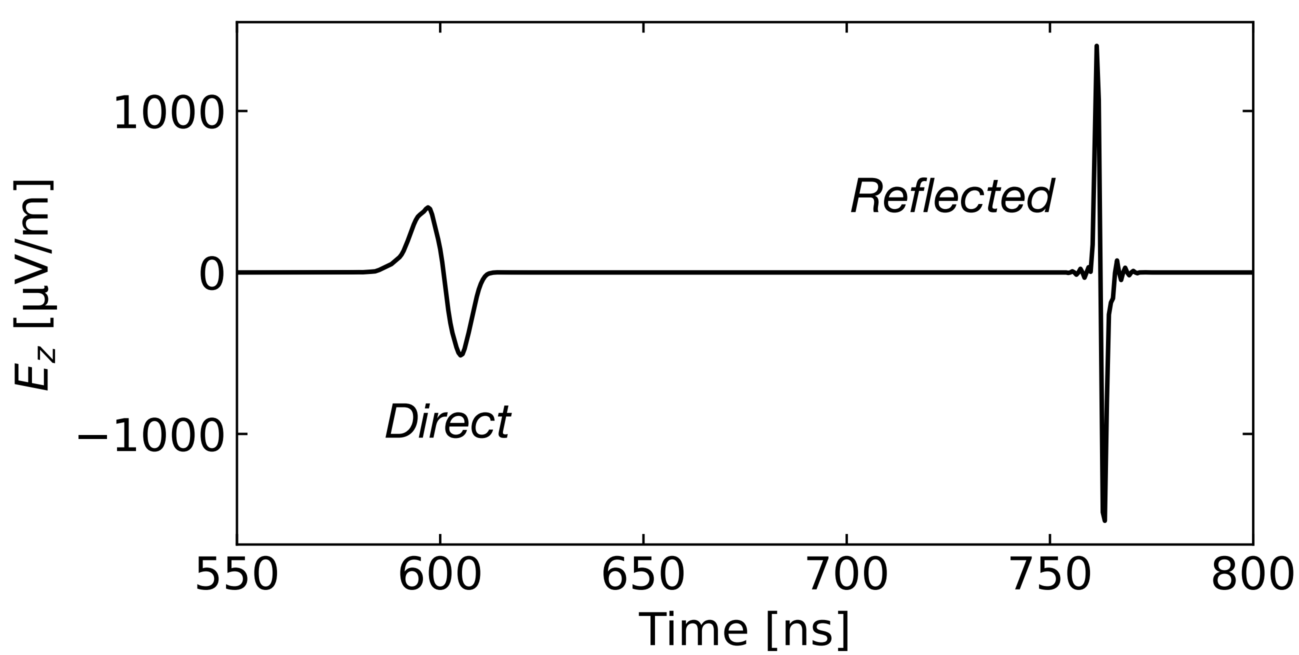
Wavefront in the **topmost part of the ice** *(the "firn")* becomes **extremely complicated!**

The Green's function landscape



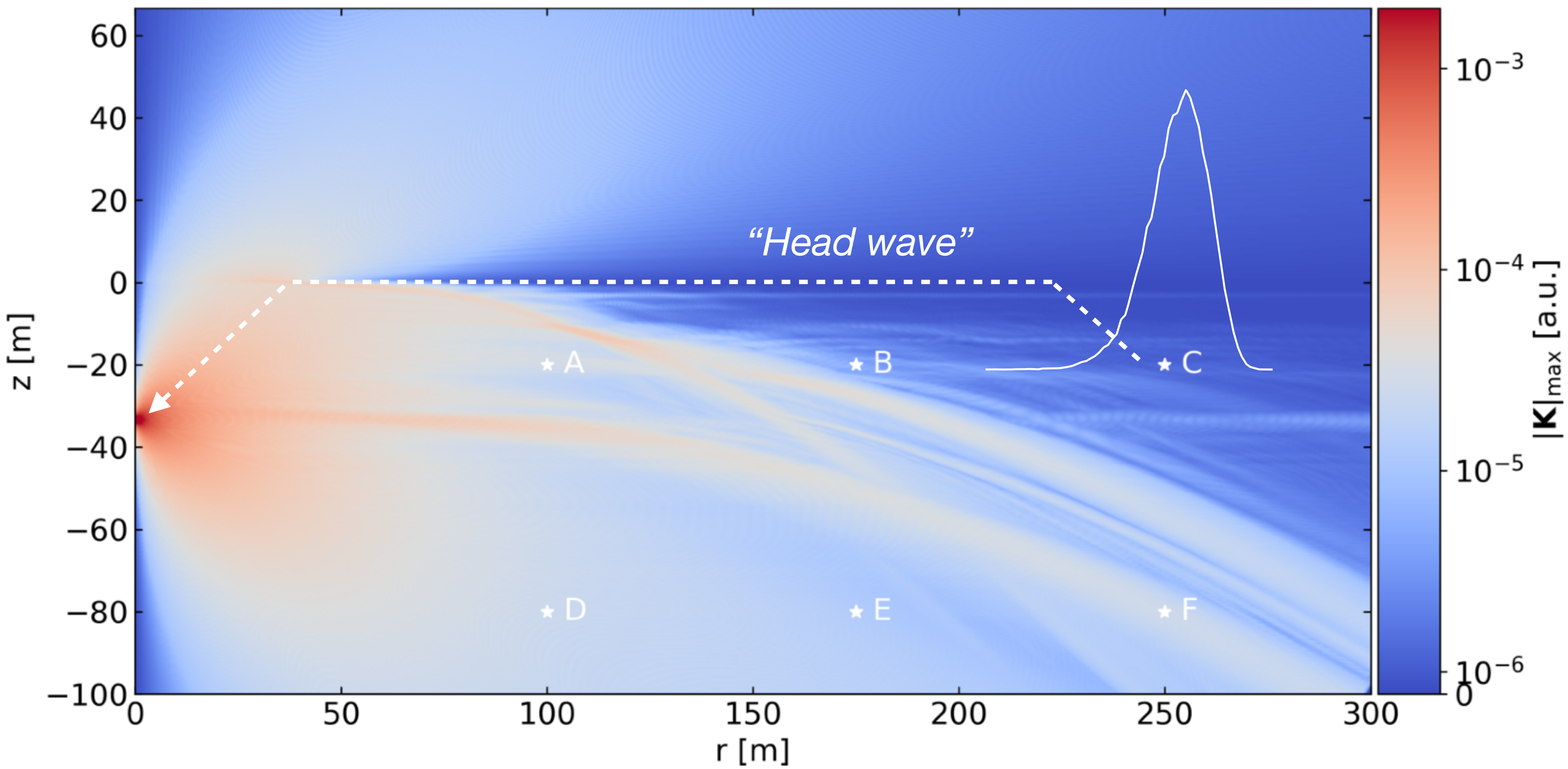
Signals from neutrino-induced showers

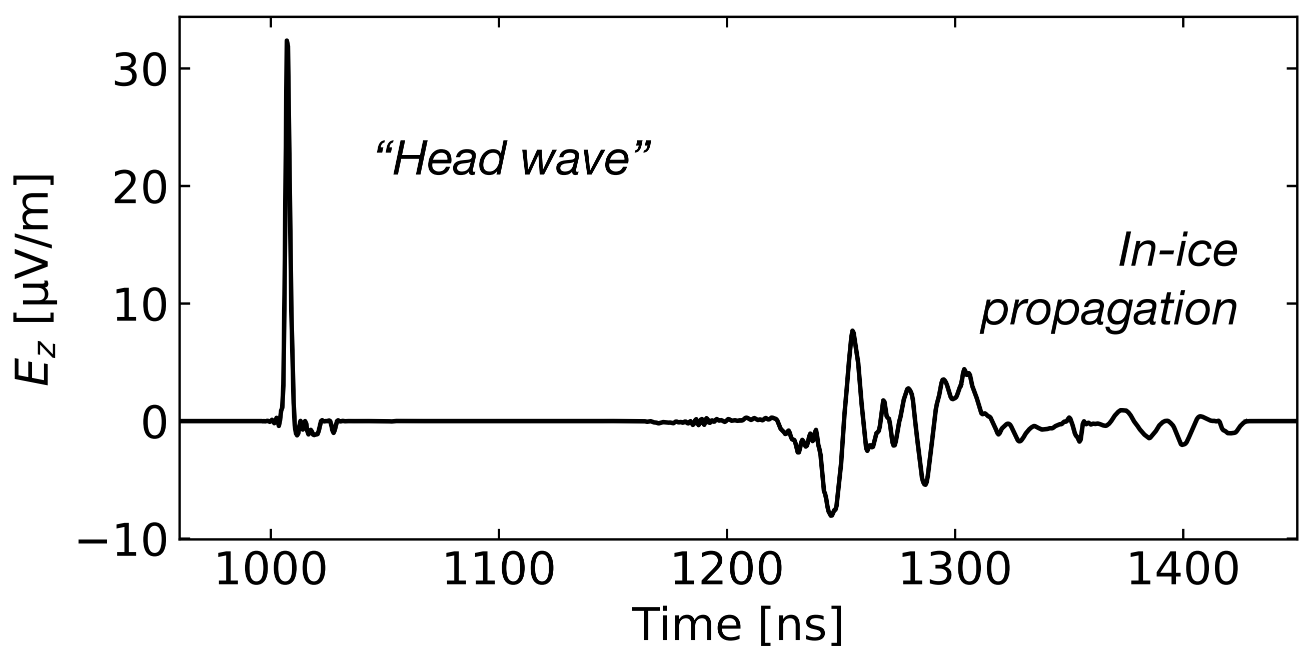




10^{18} eV hadronic shower, 1-dim profile

Signals from neutrino-induced showers

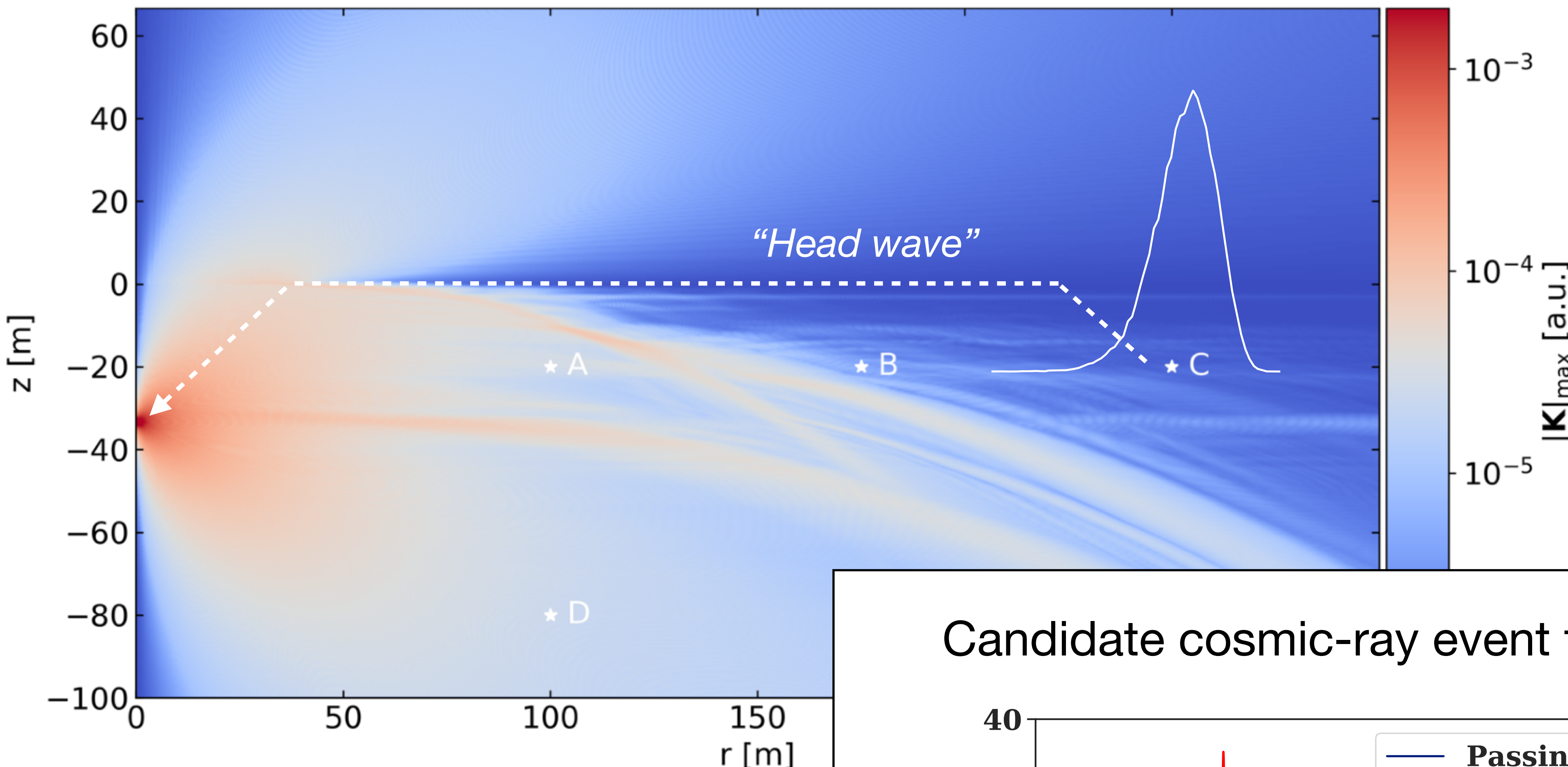


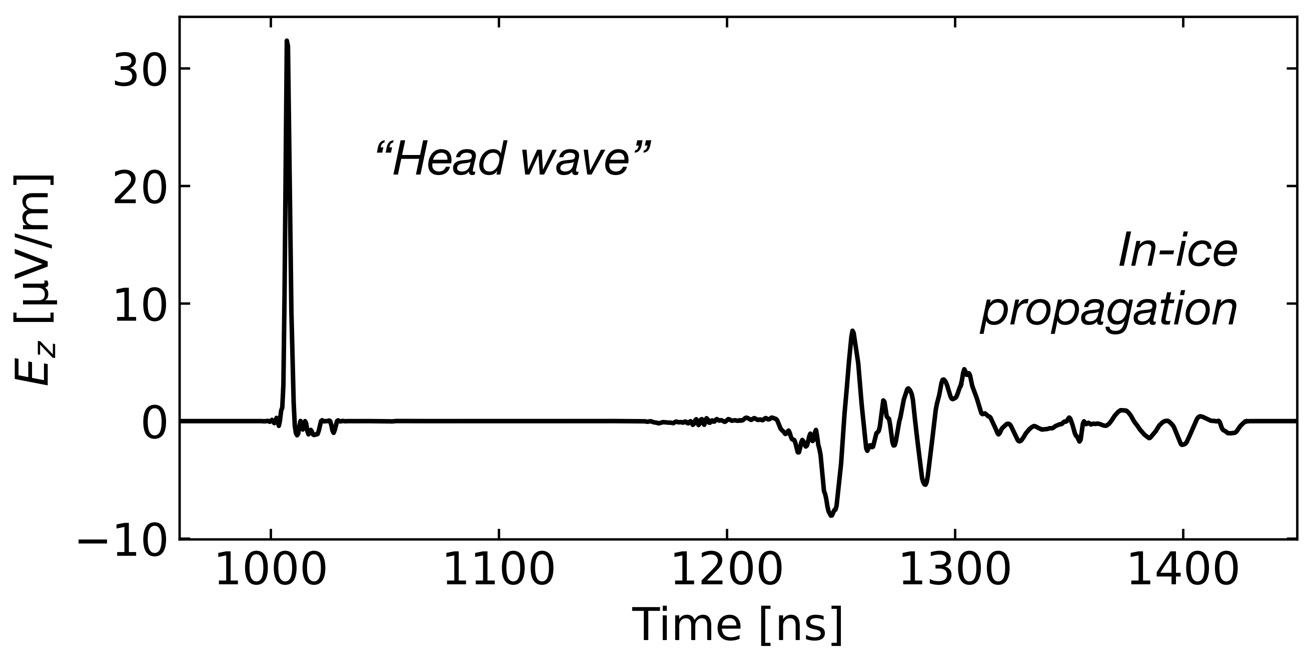


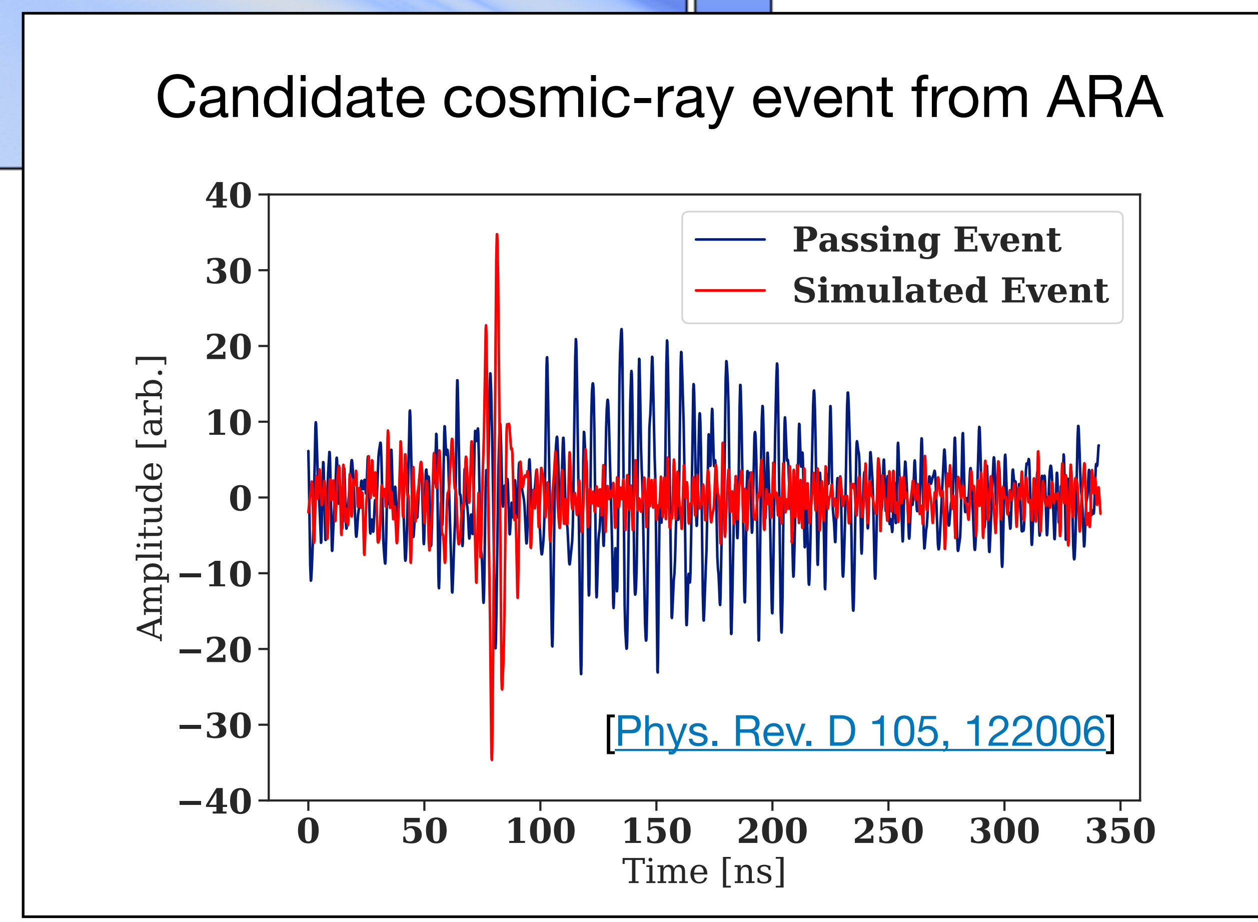
Expect **very complicated and dispersed** signals from **cosmic-ray air showers** impacting in **shadow zone**

10^{18} eV hadronic shower, 1-dim profile

Signals from neutrino-induced showers







10^{18} eV hadronic shower, 1-dim profile

Eisvogel

https://github.com/eisvogel-project/Eisvogel

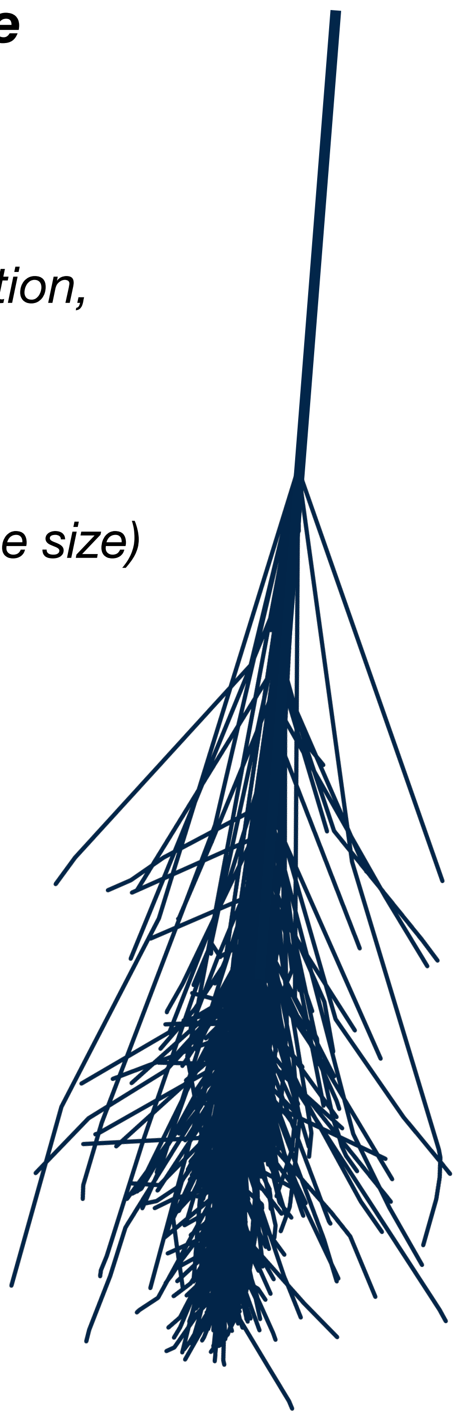
Designed to be a useful community tool, developed in the open

Development mostly done, already ***applicable to real-world scenarios***

O(5) hours for calculation of Green's function
(300m cylindrical geometry, 1.2cm resolution, 128 cores)

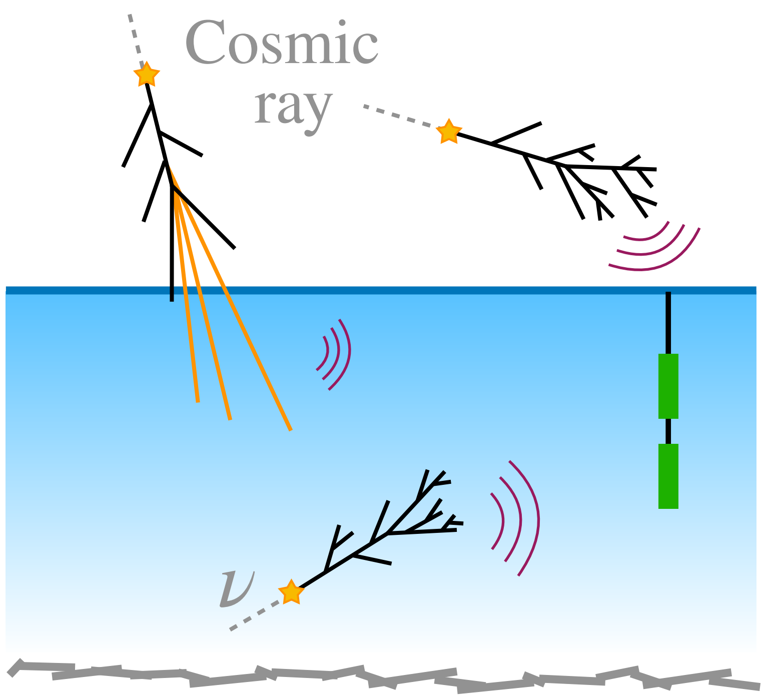
O(50) μs / particle track for signal calculation
(some dependence on track length / cache size)

Only started to scratch the surface, full phenomenology waiting to be explored

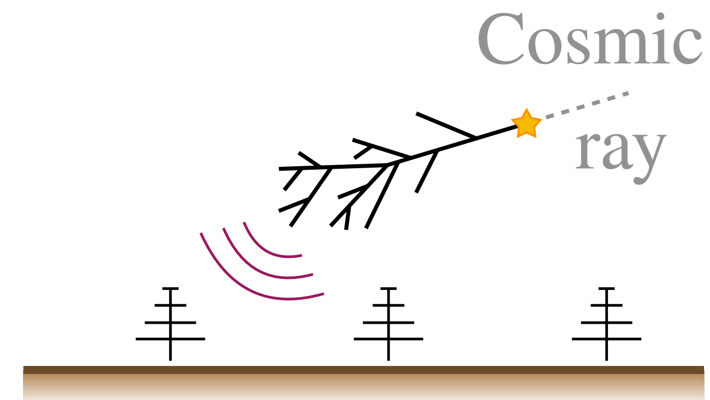


Integration into CORSIKA 8 in progress
→ enables **fully-microscopic simulations** of **showers in complex media**

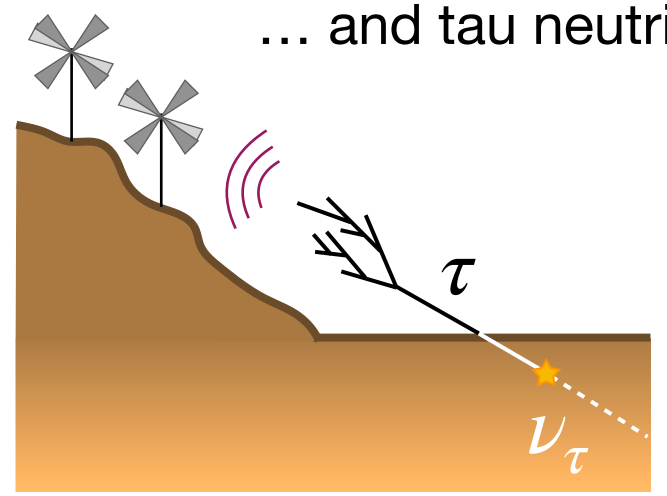
Other potential applications (?)



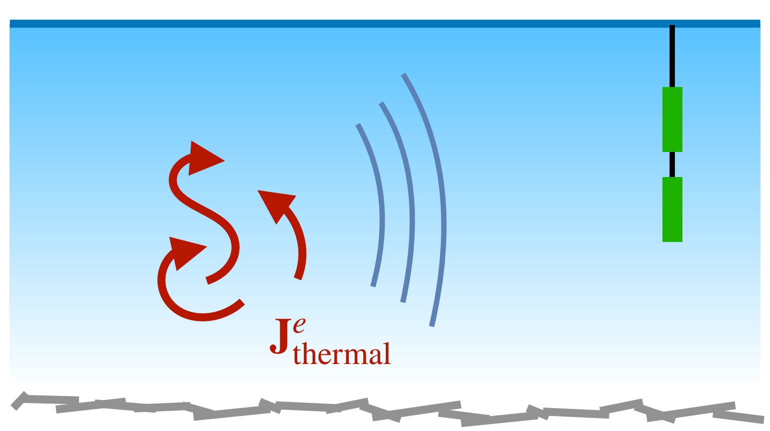
Radio detection of inclined air showers …



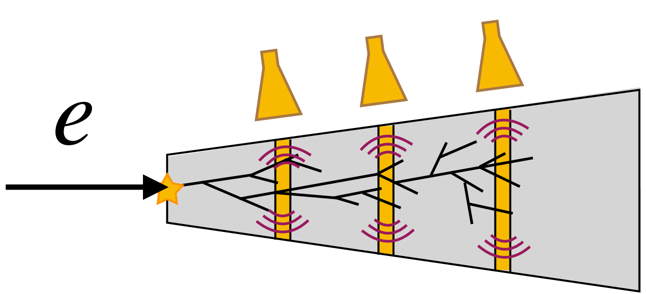
… and tau neutrinos



Antenna noise temperature

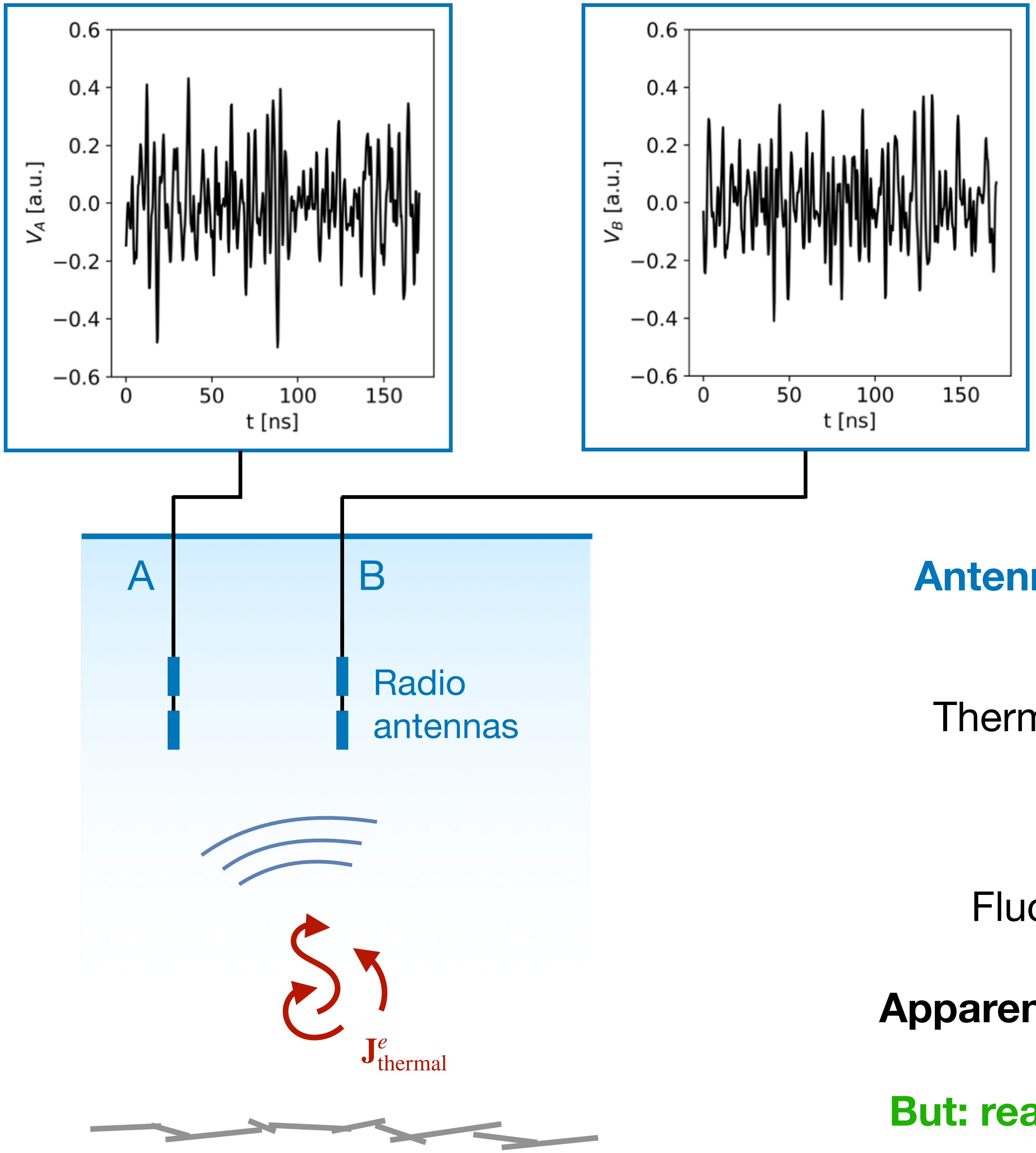


Radio calorimeters for future colliders



Extracting information from thermal noise

Thermal noise is pervasive



Can we use the noise to learn something about the antenna geometry or the environment?

Antennas embedded in thermal bath of surrounding ice

Thermally excited, stochastic motion of electrons

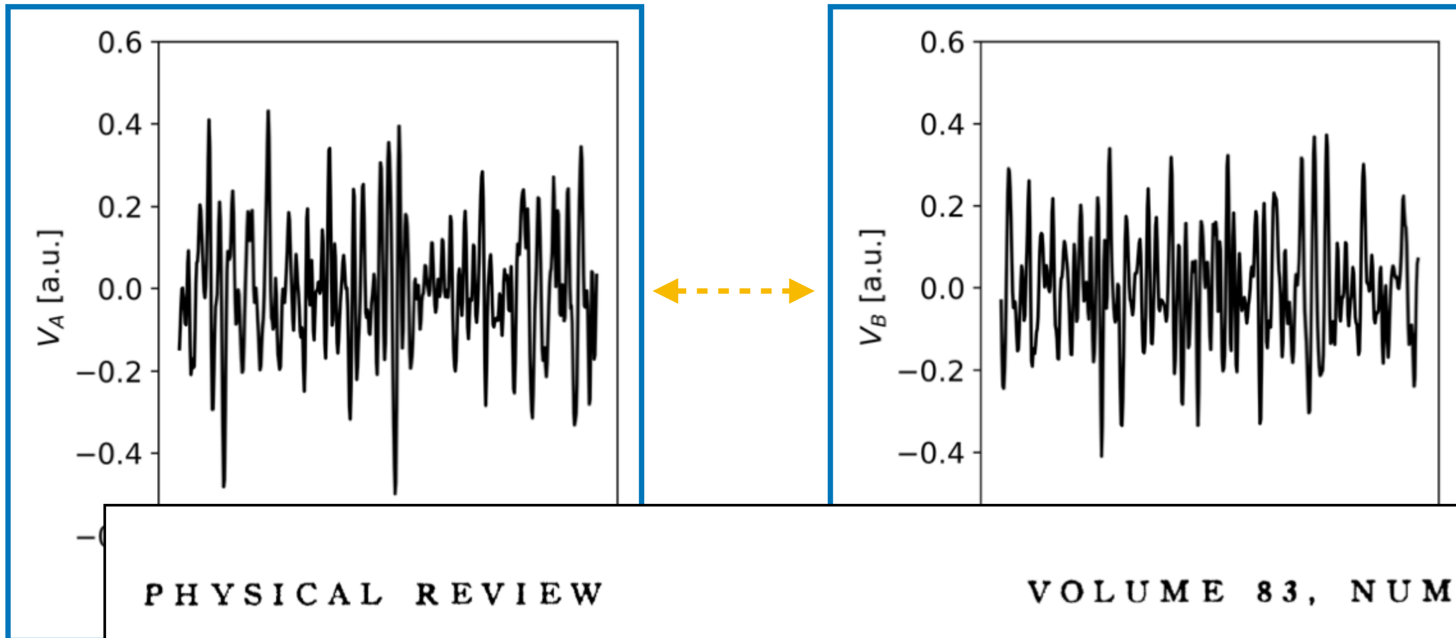
↓

Fluctuating electromagnetic field

Apparently random and non-informative

But: real radiation propagating through real environment!

Thermal noise is informative



Noise signals are not independent, but <u>correlated</u>

PHYSICAL REVIEW VOLUME 83, NUMBER 1 JULY 1, 1951

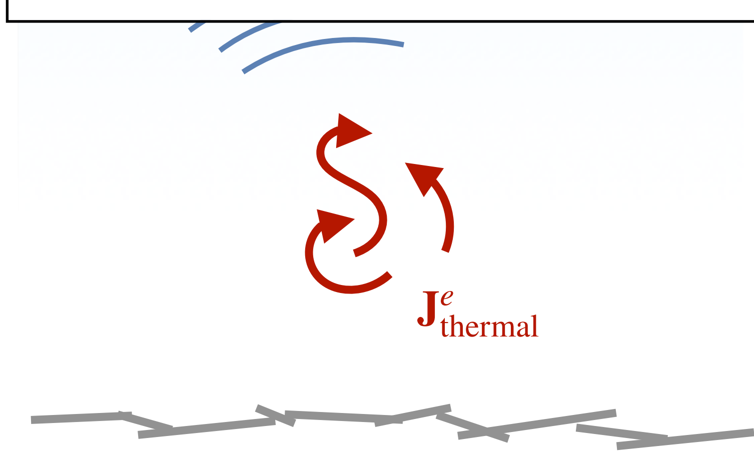
Irreversibility and Generalized Noise*

HERBERT B. CALLEN AND THEODORE A. WELTON†
Randal Morgan Laboratory of Physics, University of Pennsylvania, Philadelphia, Pennsylvania

(Received January 11, 1951)

A relation is obtained between the generalized resistance and the fluctuations of the generalized forces in linear dissipative systems. This relation forms the extension of the Nyquist relation for the voltage fluctuations in electrical impedances. The general formalism is illustrated by applications to several particular types of systems, including Brownian motion, electric field fluctuations in the vacuum, and pressure fluctuations in a gas.

A ↔ B

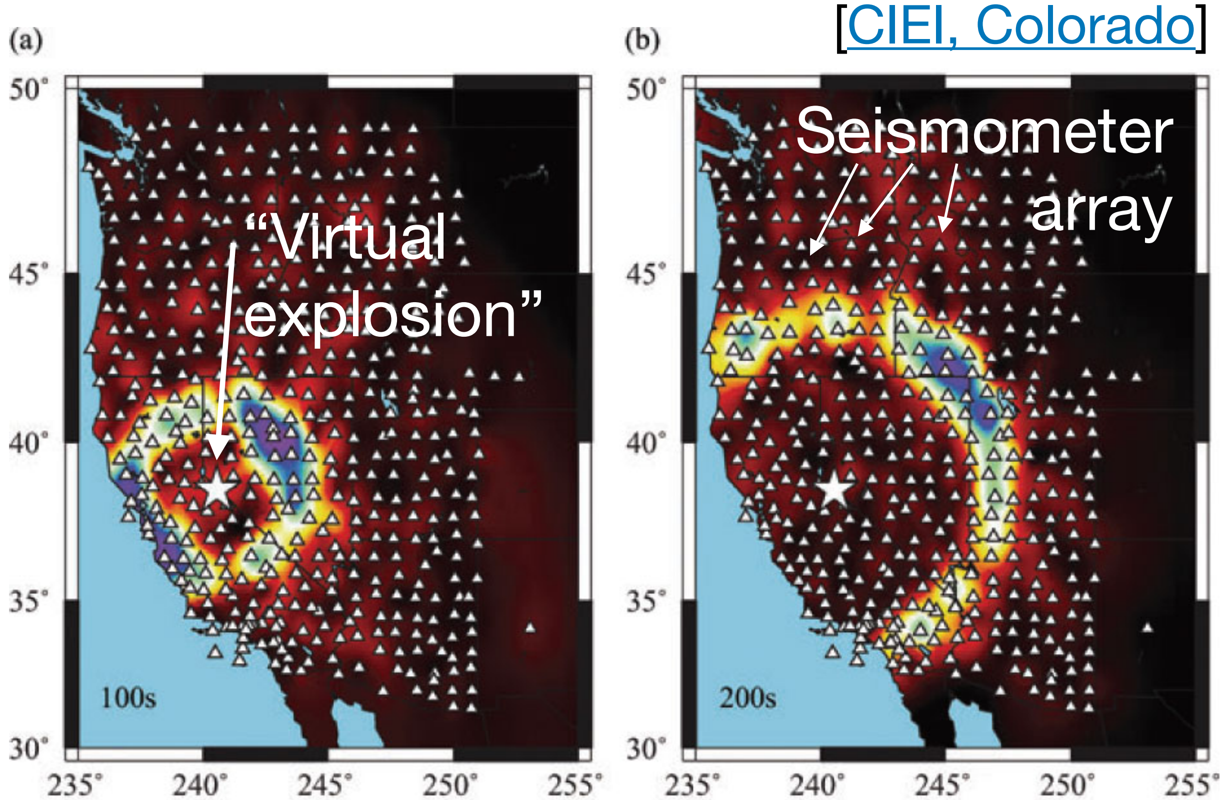


This is a <u>very</u> general fact; exists beyond electrodynamics

"Fluctuation-dissipation theorem"

Different manifestations

[CIEI, Colorado]



Ambient noise correlations in seismology

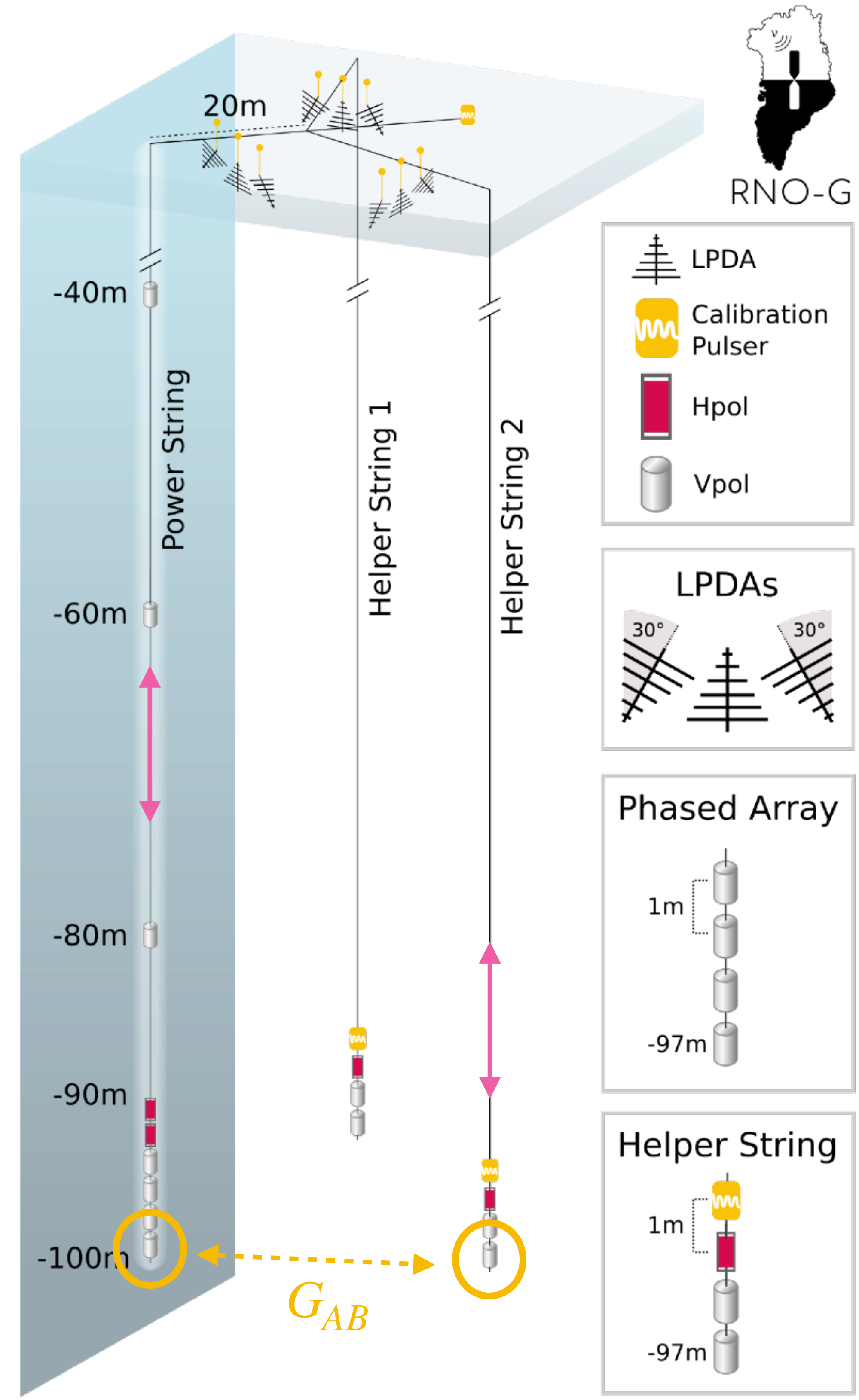
Constant “background rumble” of the Earth’s crust

→ *Information about propagation of elastic waves*

Ambient noise correlations in ice

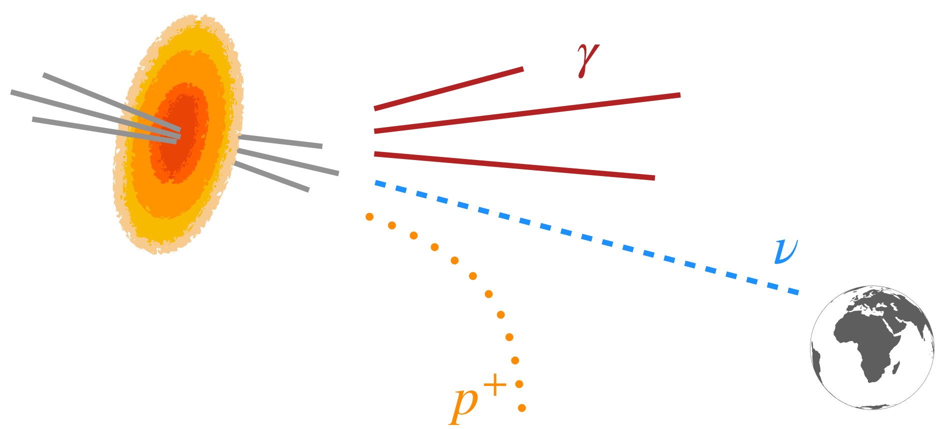
Constant thermal emissions from surrounding ice

→ *Information about propagation of electromagnetic waves for **detector calibration***



Summary

Very exciting times for radio neutrino astronomy!



Current generation of instruments will **significantly improve** our **knowledge** of **high-energy phenomena** in the universe

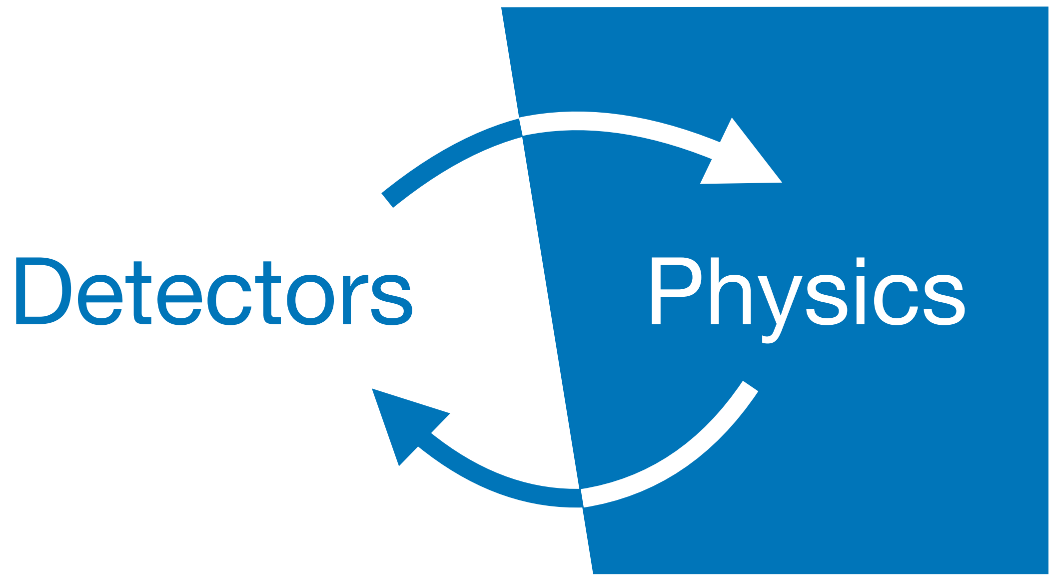
(In deployment!)

Detector performance rests on our ability to exploit textbook electromagnetism!

Large-scale **Green's functions** make **high-fidelity** signal **simulations efficient**

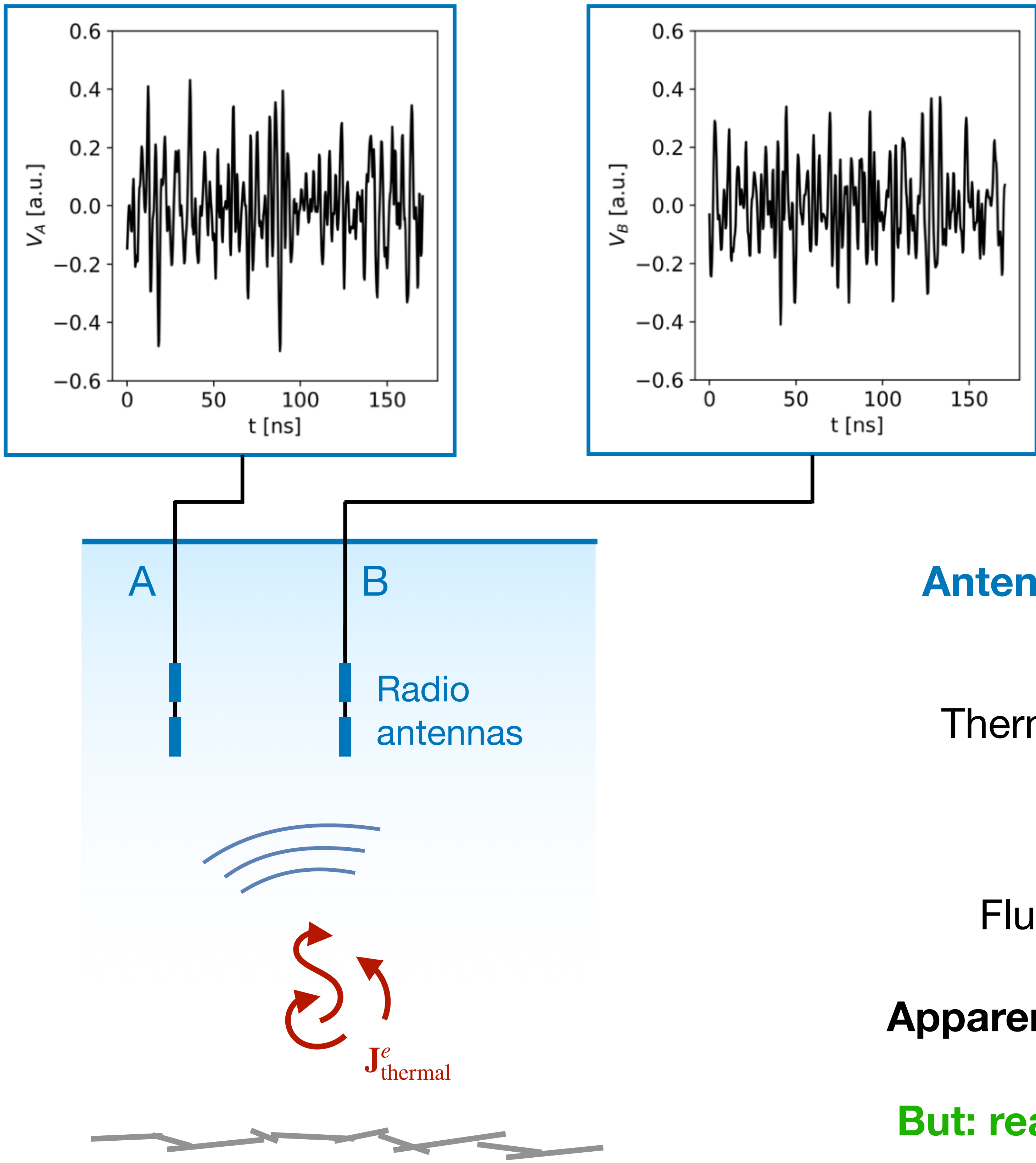
Pervasive **thermal noise** informs **detector calibration**

Exciting times ahead!



Backup

Thermal noise is pervasive



Can we use the noise to learn something about the antenna geometry or the environment?

Antennas embedded in thermal bath of surrounding ice

Thermally excited, stochastic motion of electrons

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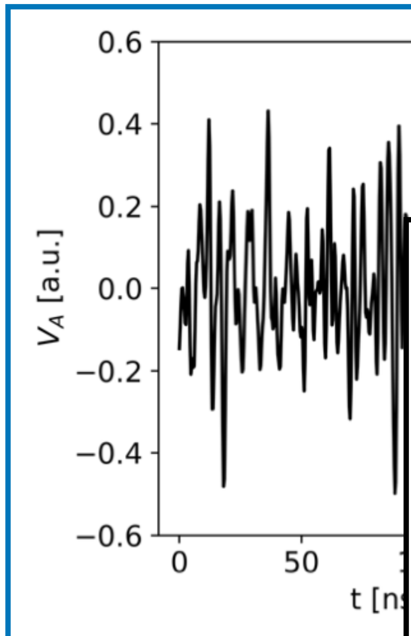
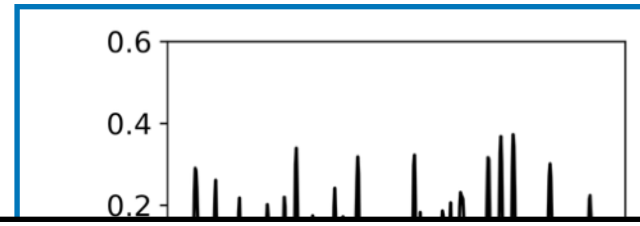
Fluctuating electromagnetic field

Apparently random and non-informative

But: real radiation propagating through real environment!

Thermal noise is pervasive



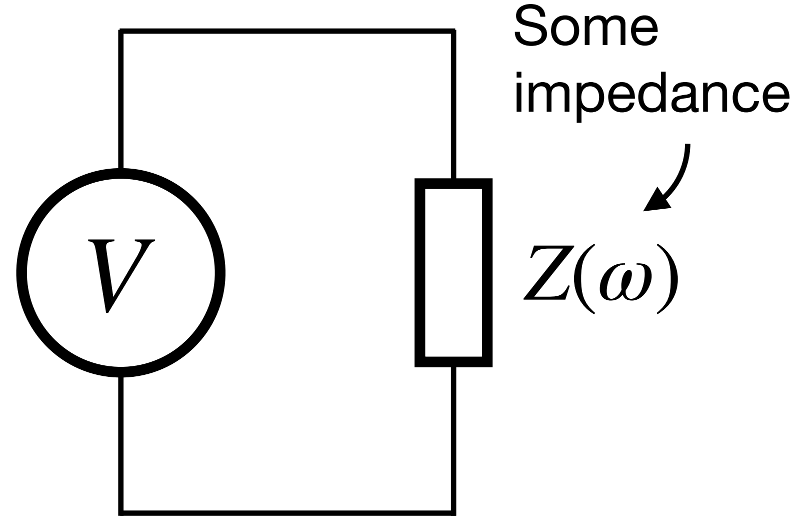


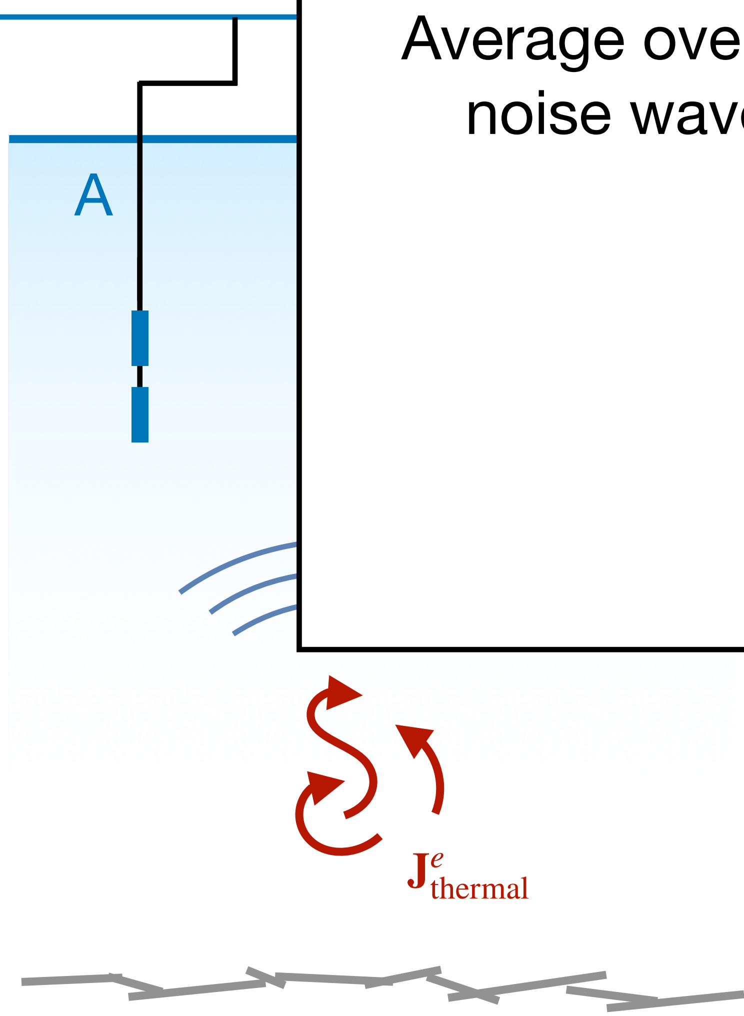
Can we use the noise to ... g about the ... etry or the ... ent?

$$\langle |V|^2(\omega) \rangle \sim k_B T \, \mathrm{Re}\left[Z(\omega)\right]$$

RMS voltage:
Average over many noise waveforms

Impedance





mal bath

motion

Fluctuating electromagnetic field

Apparently random and non-informative

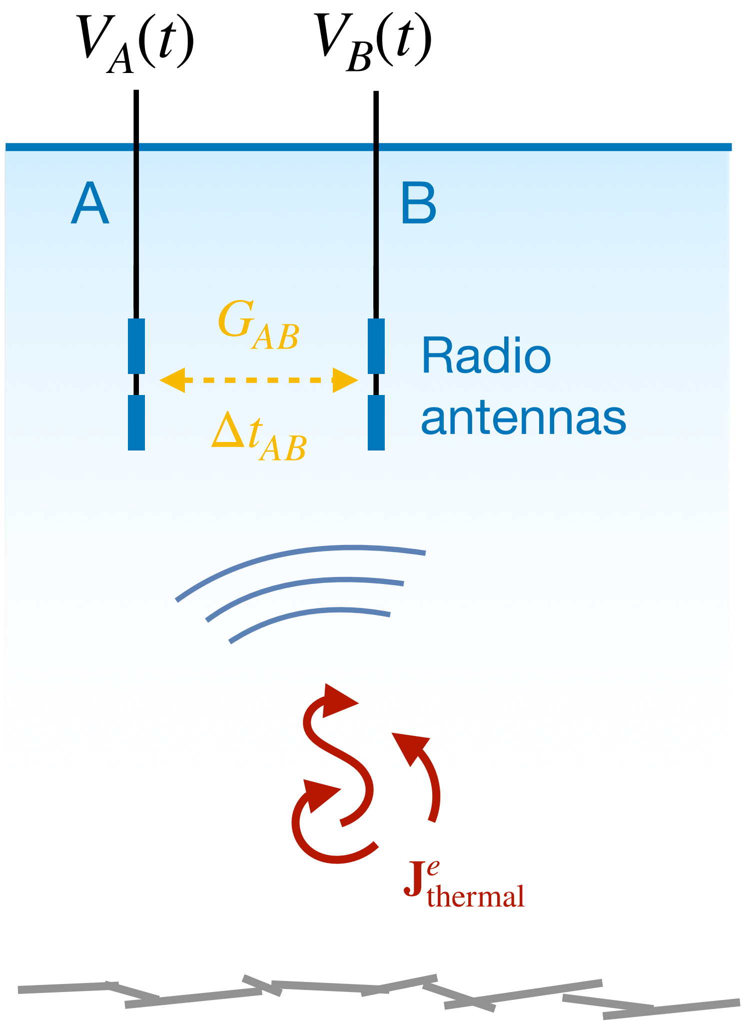
But: real radiation propagating through real environment!

Thermal noise is informative

Idea: each thermal noise waveform *("noise realization")* is random, but its statistical properties are deterministic (and informative!)

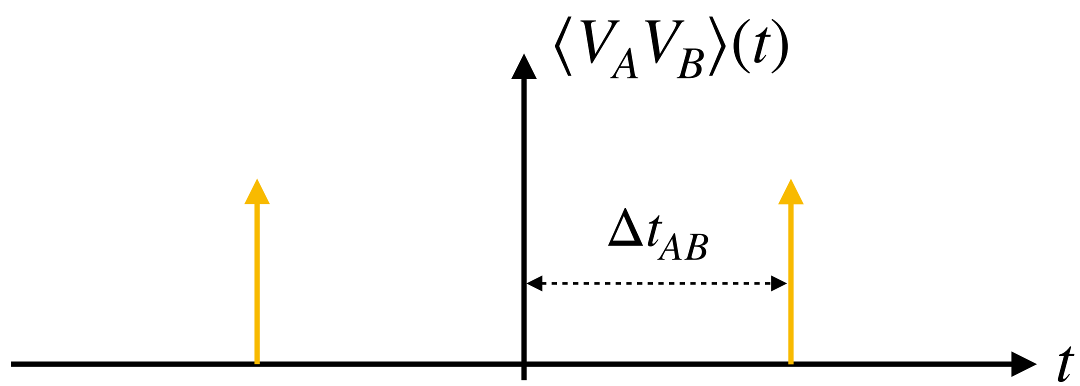
In particular: **noise recorded in two spatially separated channels** is not independent, but **weakly correlated**!

→ *Averages over many noise events expose "hidden" correlations*



"2-point correlator" of noise waveforms is proportional to the Green's function between A and B!

$$\langle V_A(\omega) V_B^*(\omega) \rangle \sim k_B T \,\mathrm{Re}\left[G_{AB}(\omega)\right]$$



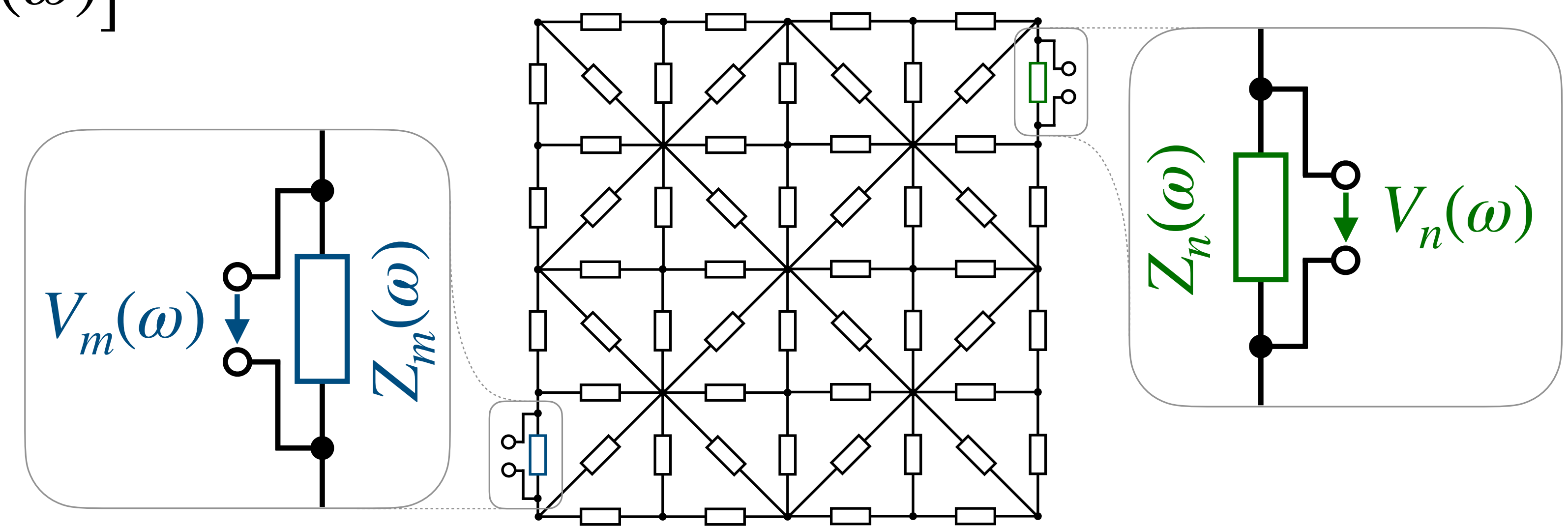
This is not surprising!

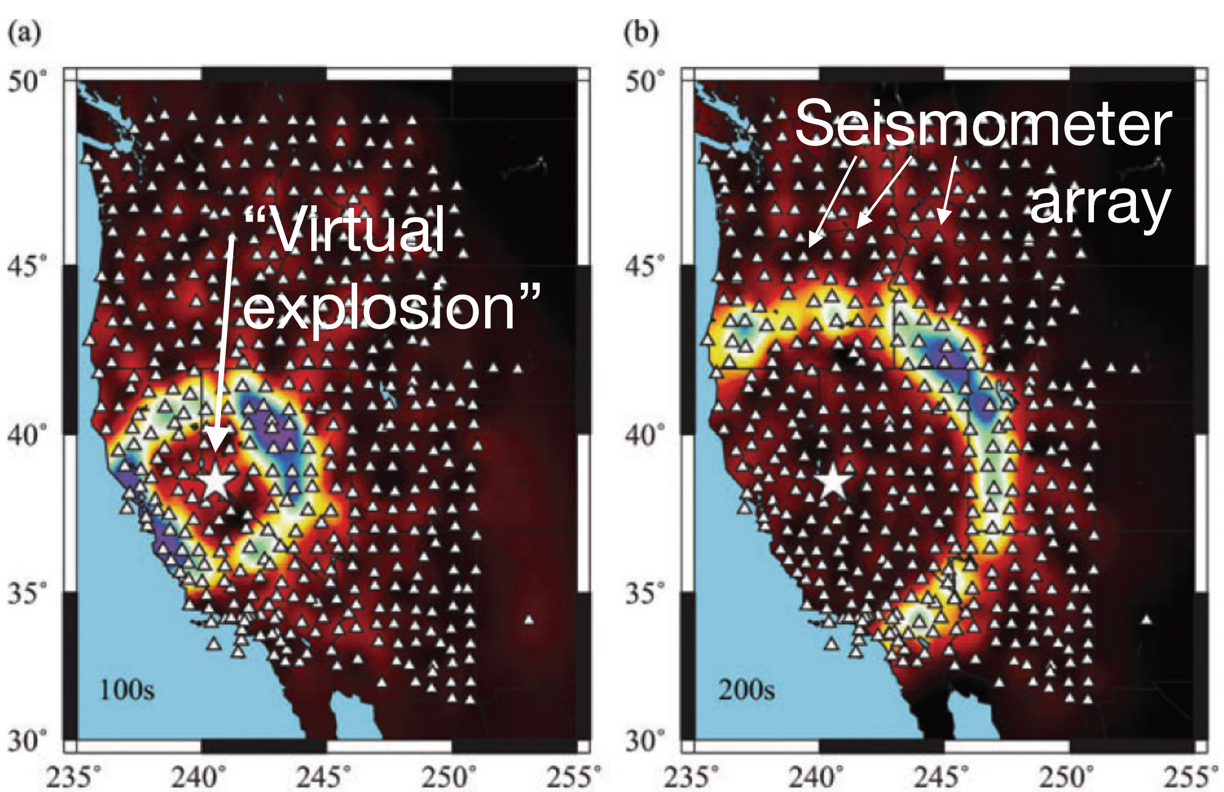
Thermal noise correlations in an impedance network:

$$\langle V_n(\omega) V_m^*(\omega) \rangle \sim k_B T \,\mathrm{Re}\left[T_{mn}(\omega)\right]$$

Transfer function T_{mn}:

Current at n → voltage at m





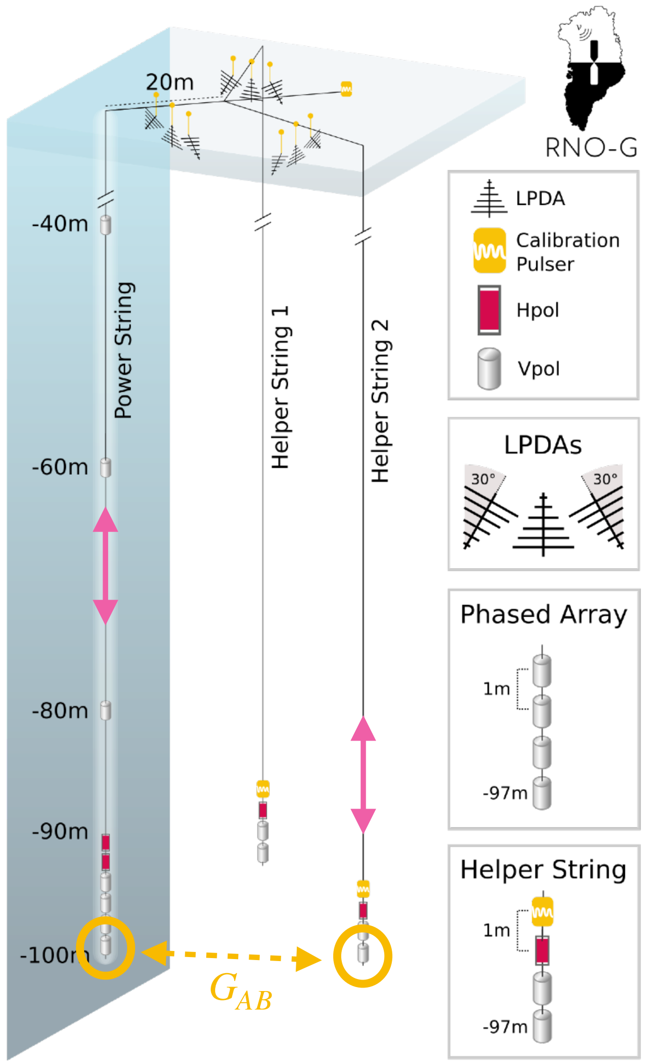
Ambient noise correlations in seismology:

Constant "background rumble" of the Earth's crust

↕

Information about propagation of elastic waves

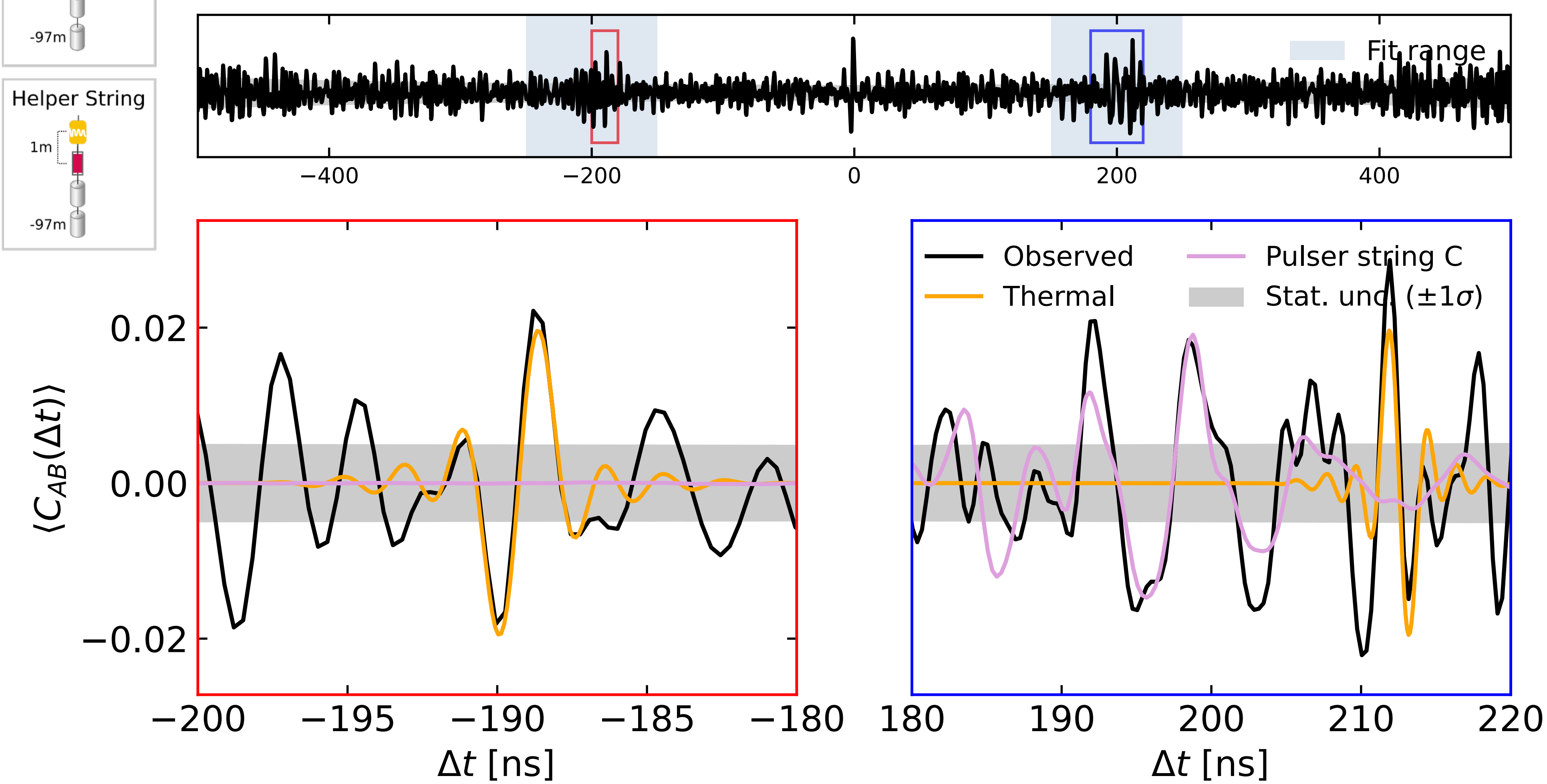
Noise correlations in use at RNO-g



Correlation signature present in long-term average of RNO-g noise data

Also see “noisy” point sources nearby …

Used for in-situ calibration of antenna geometry
(in combination with other data sets)



Station 11

Forced triggers
2022 data
$A = CH0$
$B = CH23$

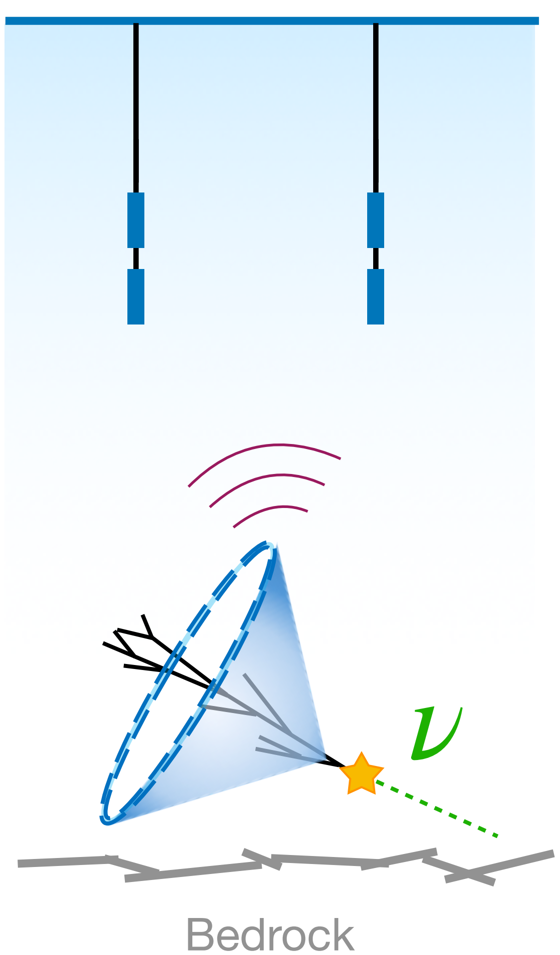
RNO-G

Work
in Progress

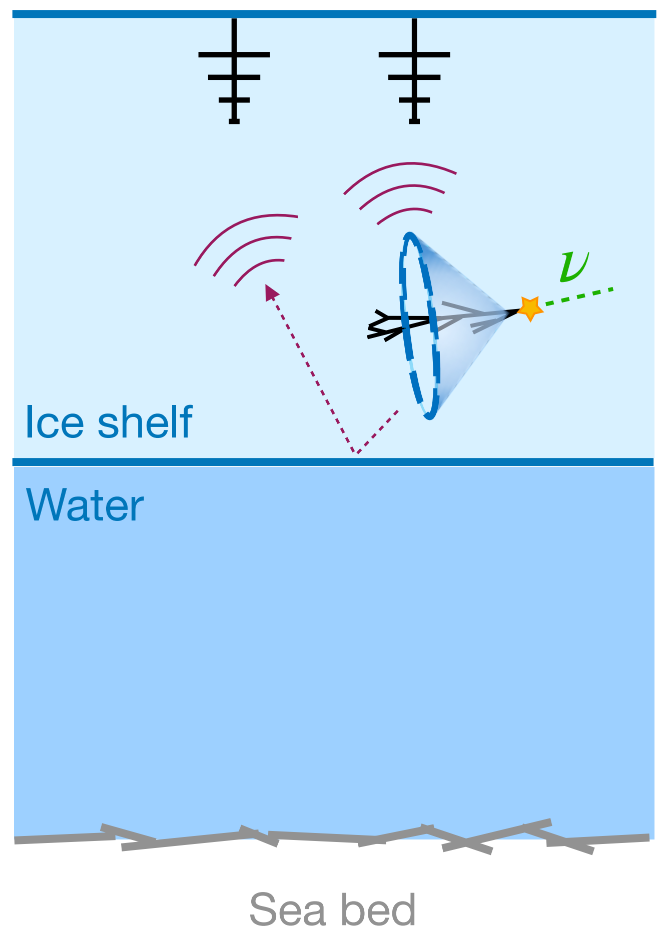
Backup

Trailblazing experiments

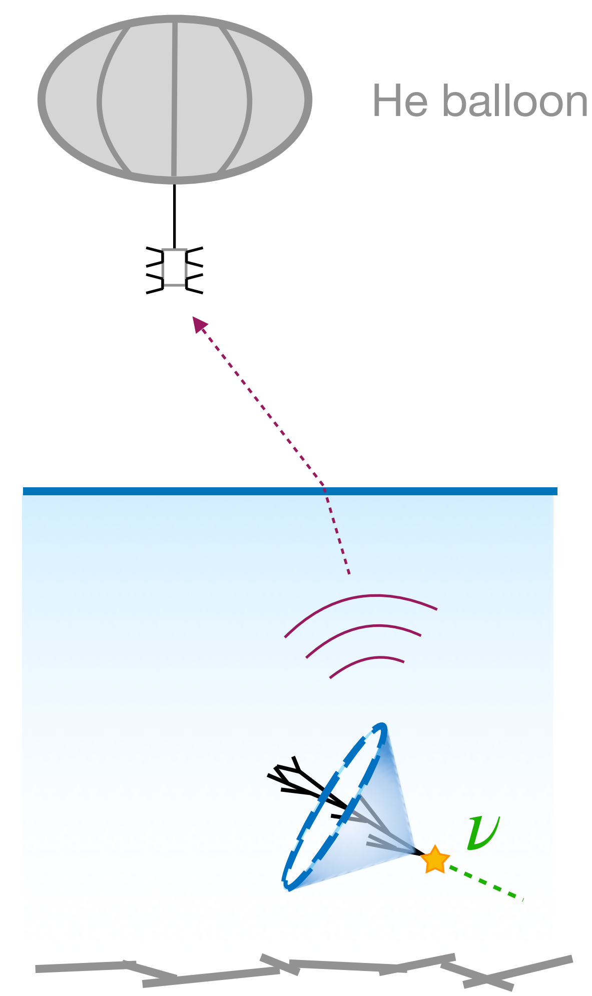
ARA
Askaryan Radio Array
(South Pole)



ARIANNA
Antarctic Ross Ice-Shelf
Antenna Neutrino Array

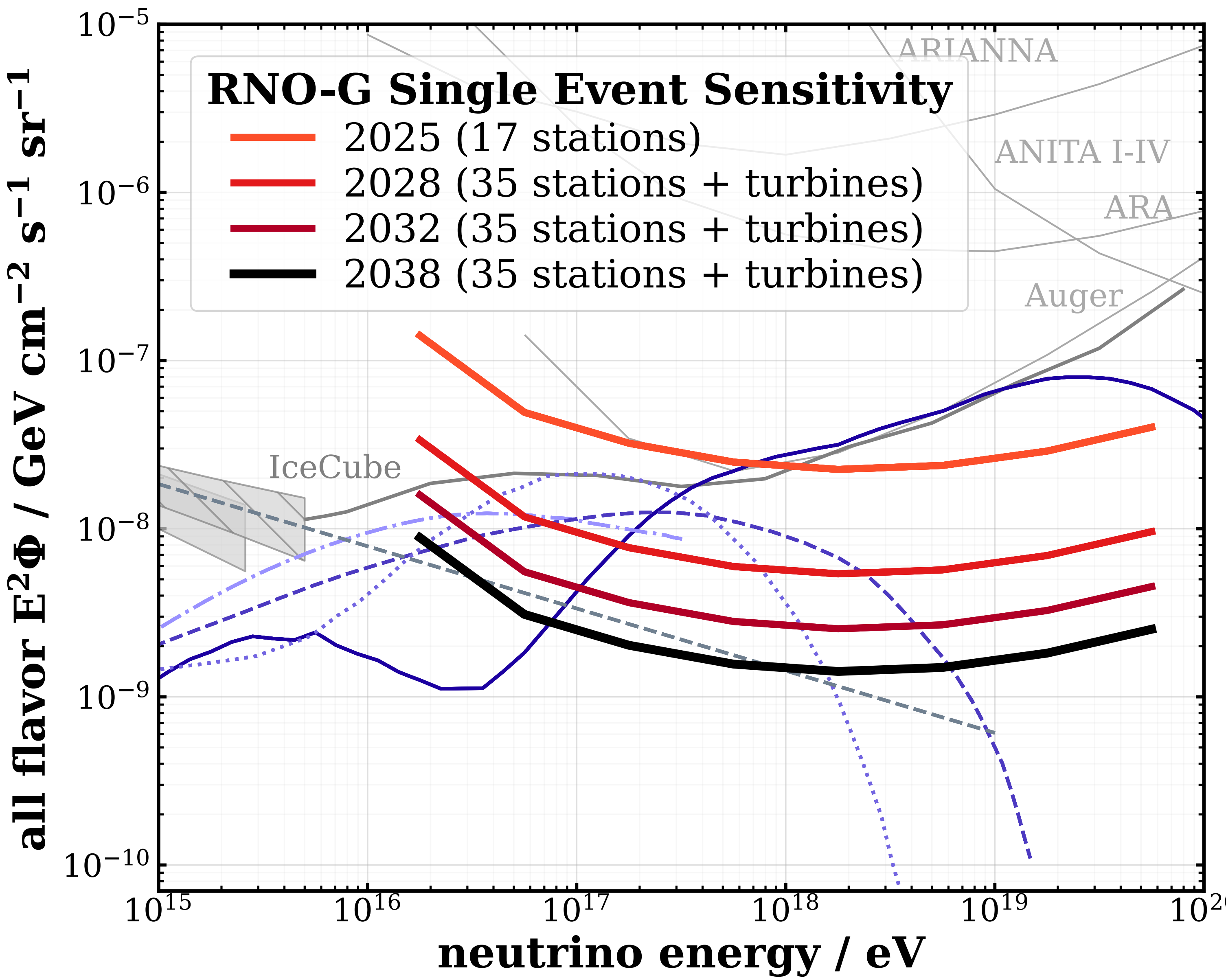


ANITA
Antarctic Impulsive
Transient Antenna

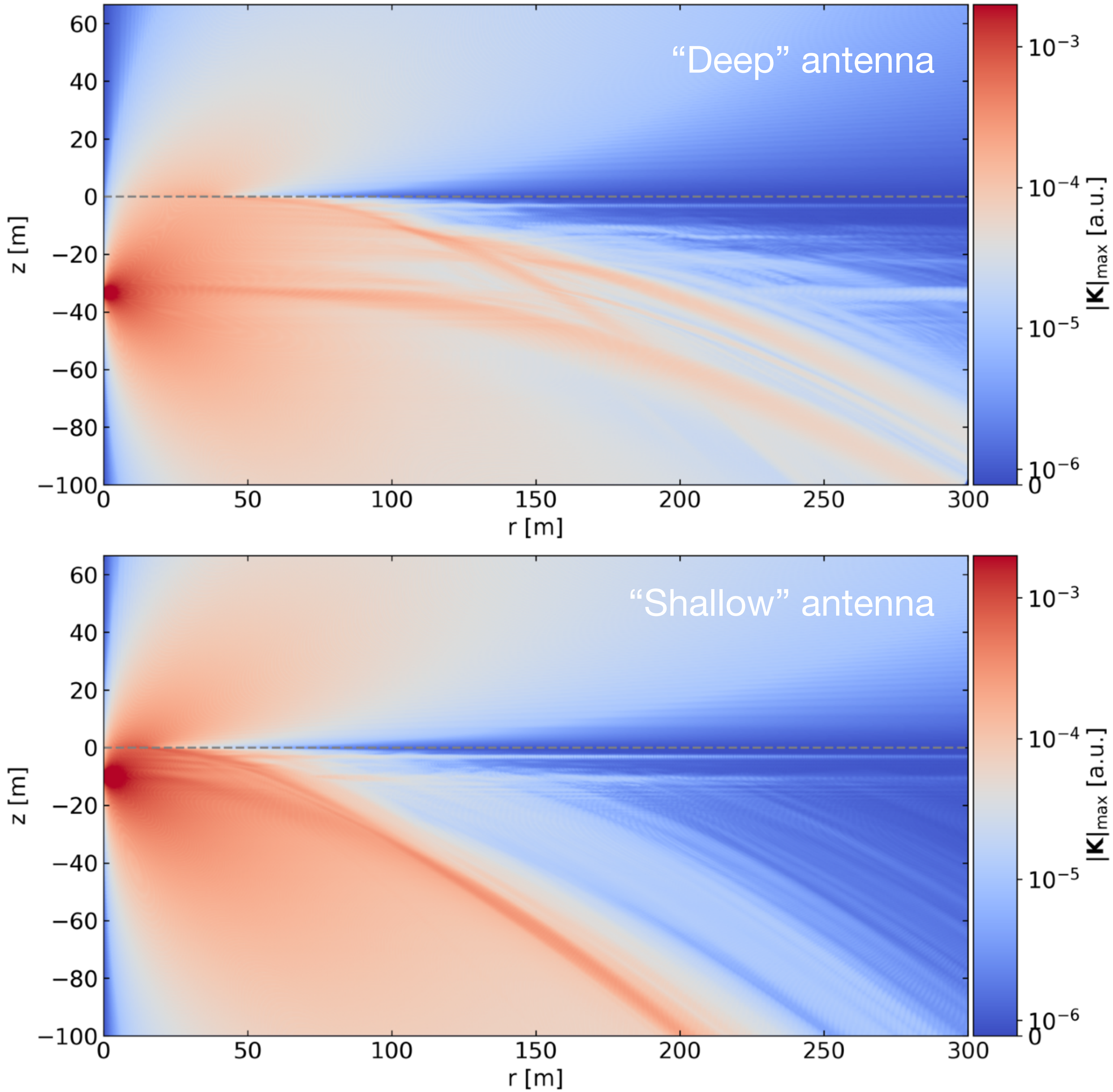


RNO-G single-event sensitivity

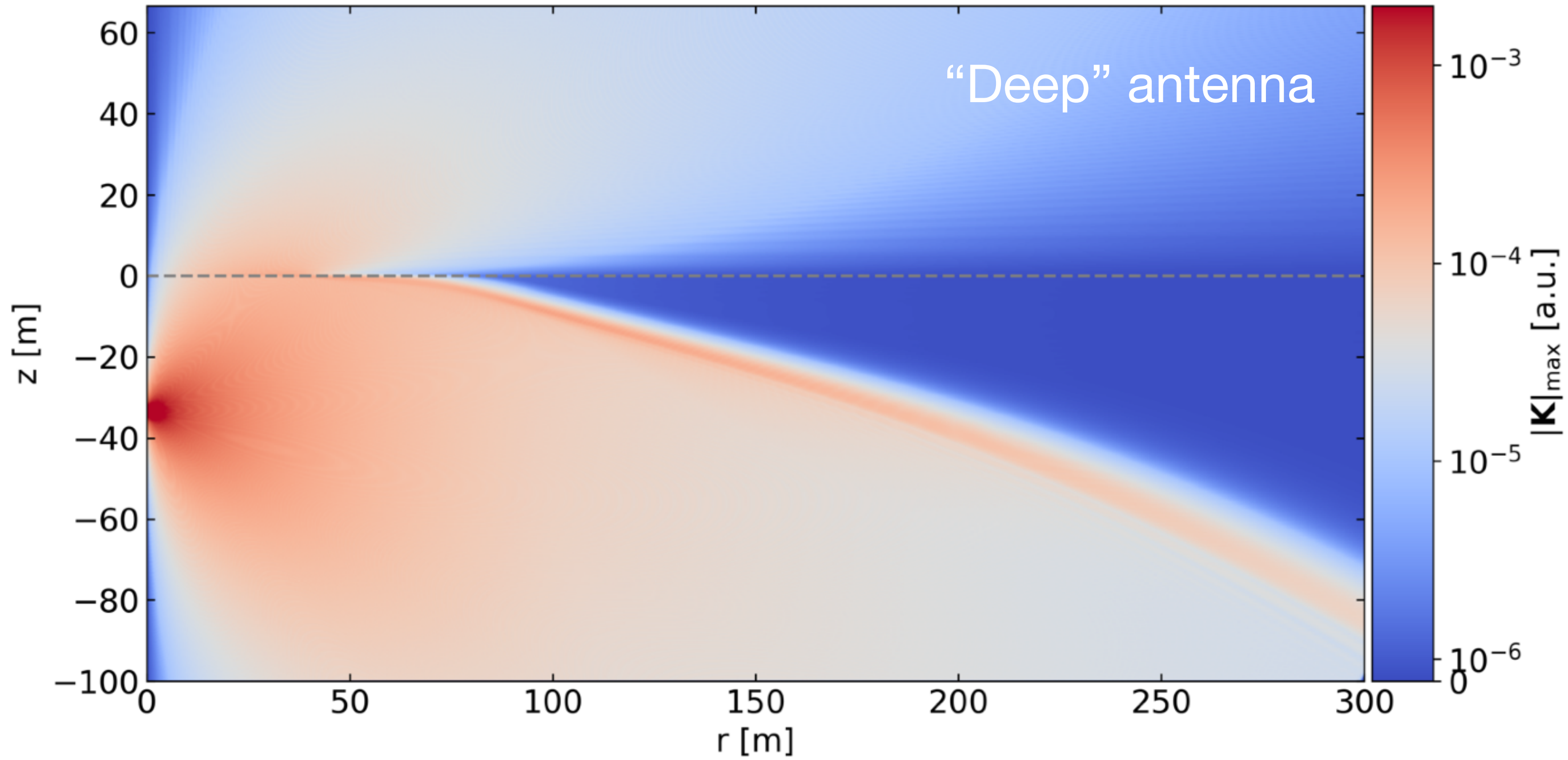
"Single-event sensitivity": flux inferred from a single observed event
(assuming no backgrounds)

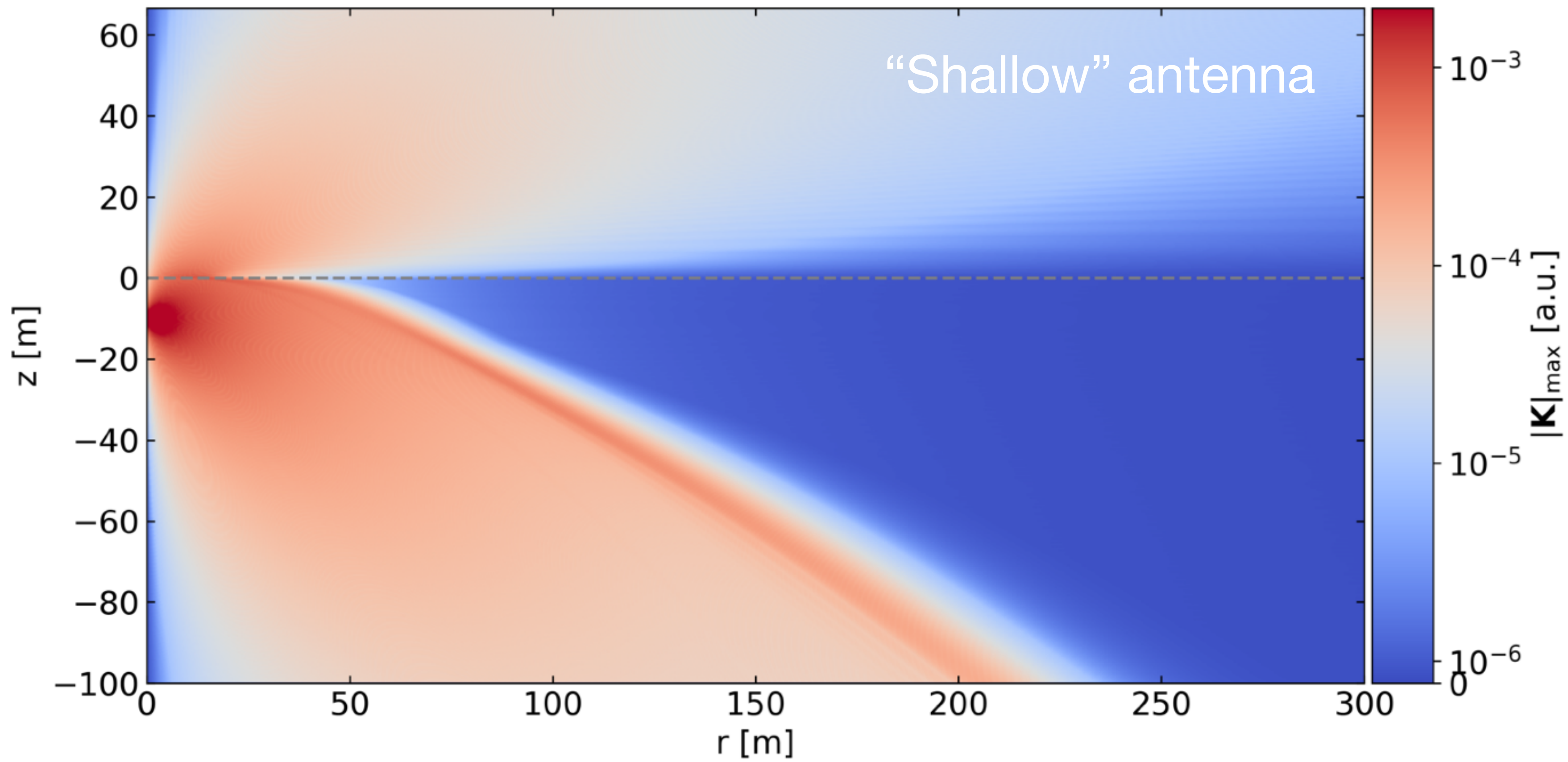


“Deep” vs “shallow” antenna placement



“Deep” vs “shallow” antenna placement

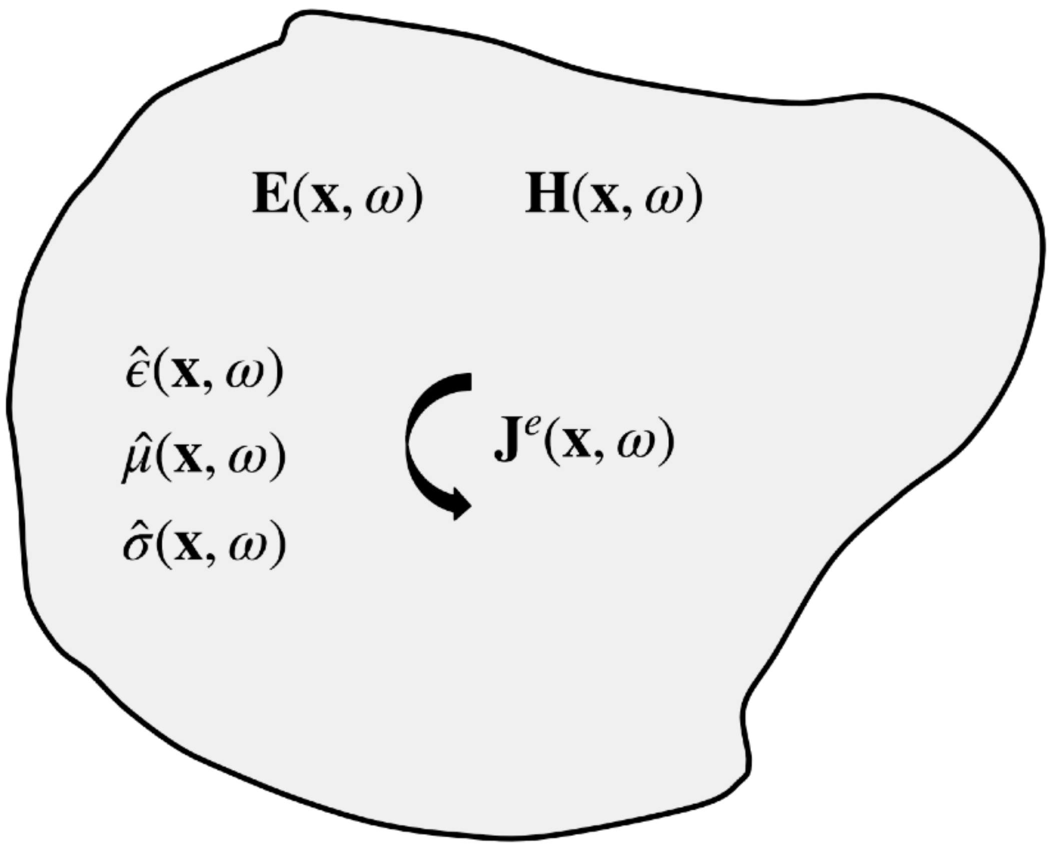


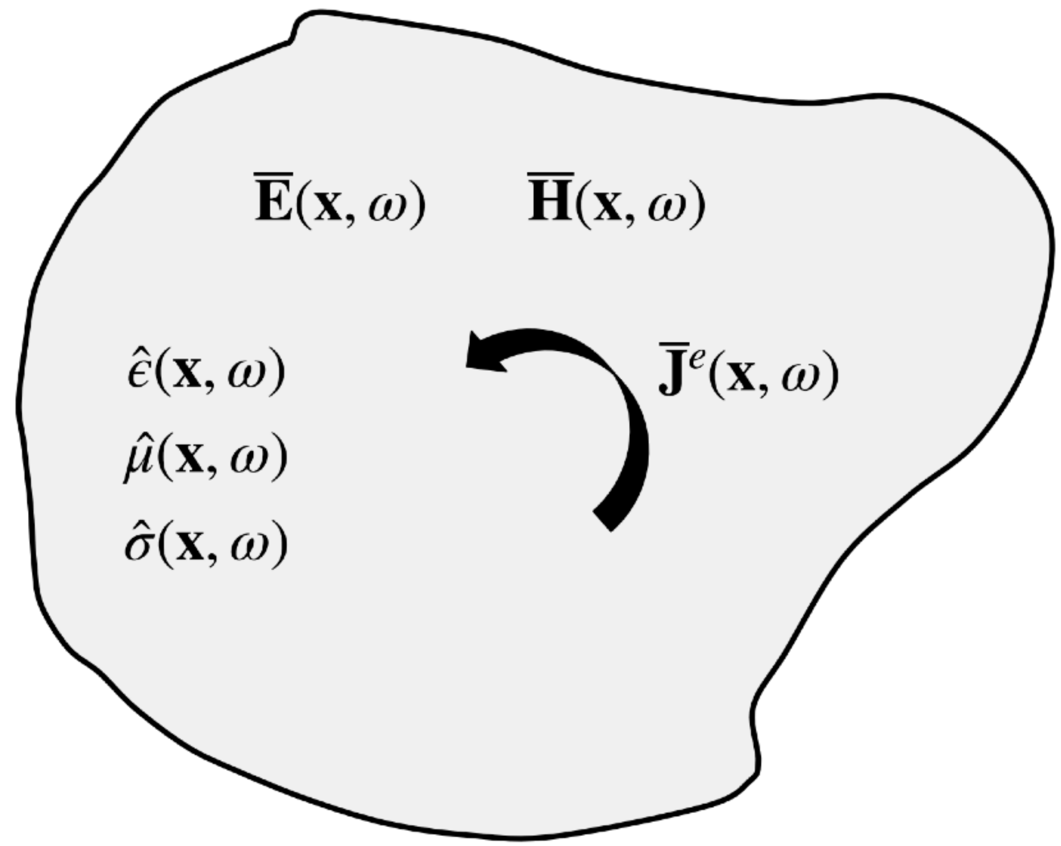


Lorentz reciprocity

Classical electrodynamics has a built-in method
to relate two different situations *(with identical geometry)*

General, linear material distribution: $\epsilon(\mathbf{x}),\ \mu(\mathbf{x}),\ \sigma(\mathbf{x})$





$$\mathbf{J}^e \xrightarrow{\text{Maxwell's eqns.}} \mathbf{E},\ \mathbf{H}$$

External current distribution → Field distributions

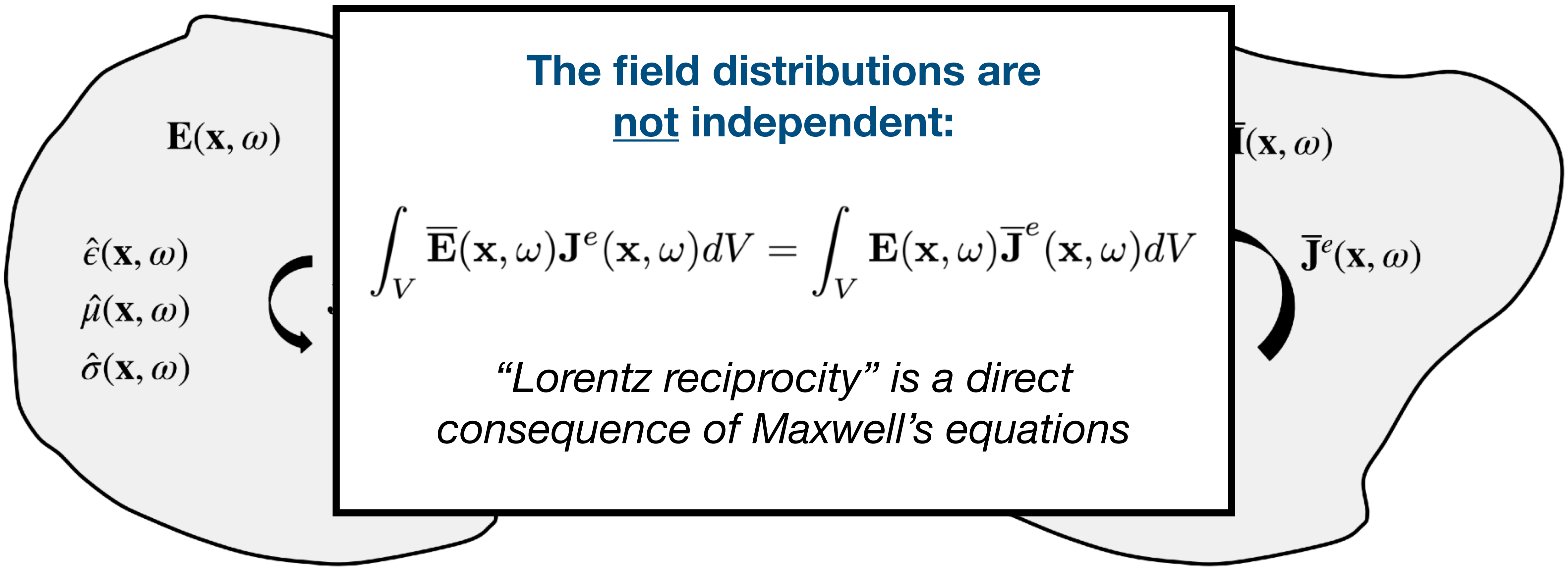
$$\bar{\mathbf{J}}^e \xrightarrow{\text{Maxwell's eqns.}} \bar{\mathbf{E}},\ \bar{\mathbf{H}}$$

External current distribution → Field distributions

Lorentz reciprocity

Classical electrodynamics has a built-in method
to relate two different situations *(with identical geometry)*

General, linear material distribution: $\epsilon(\mathbf{x}),\ \mu(\mathbf{x}),\ \sigma(\mathbf{x})$



The field distributions are
<u>not</u> independent:

$$\int_V \overline{\mathbf{E}}(\mathbf{x},\omega)\mathbf{J}^e(\mathbf{x},\omega)dV = \int_V \mathbf{E}(\mathbf{x},\omega)\overline{\mathbf{J}}^e(\mathbf{x},\omega)dV$$

"Lorentz reciprocity" is a direct consequence of Maxwell's equations

$\mathbf{J}^e \xrightarrow{\text{Maxwell's eqns.}} \mathbf{E},\ \mathbf{H}$

External current distribution — Field distributions

$\bar{\mathbf{J}}^e \xrightarrow{\text{Maxwell's eqns.}} \bar{\mathbf{E}},\ \bar{\mathbf{H}}$

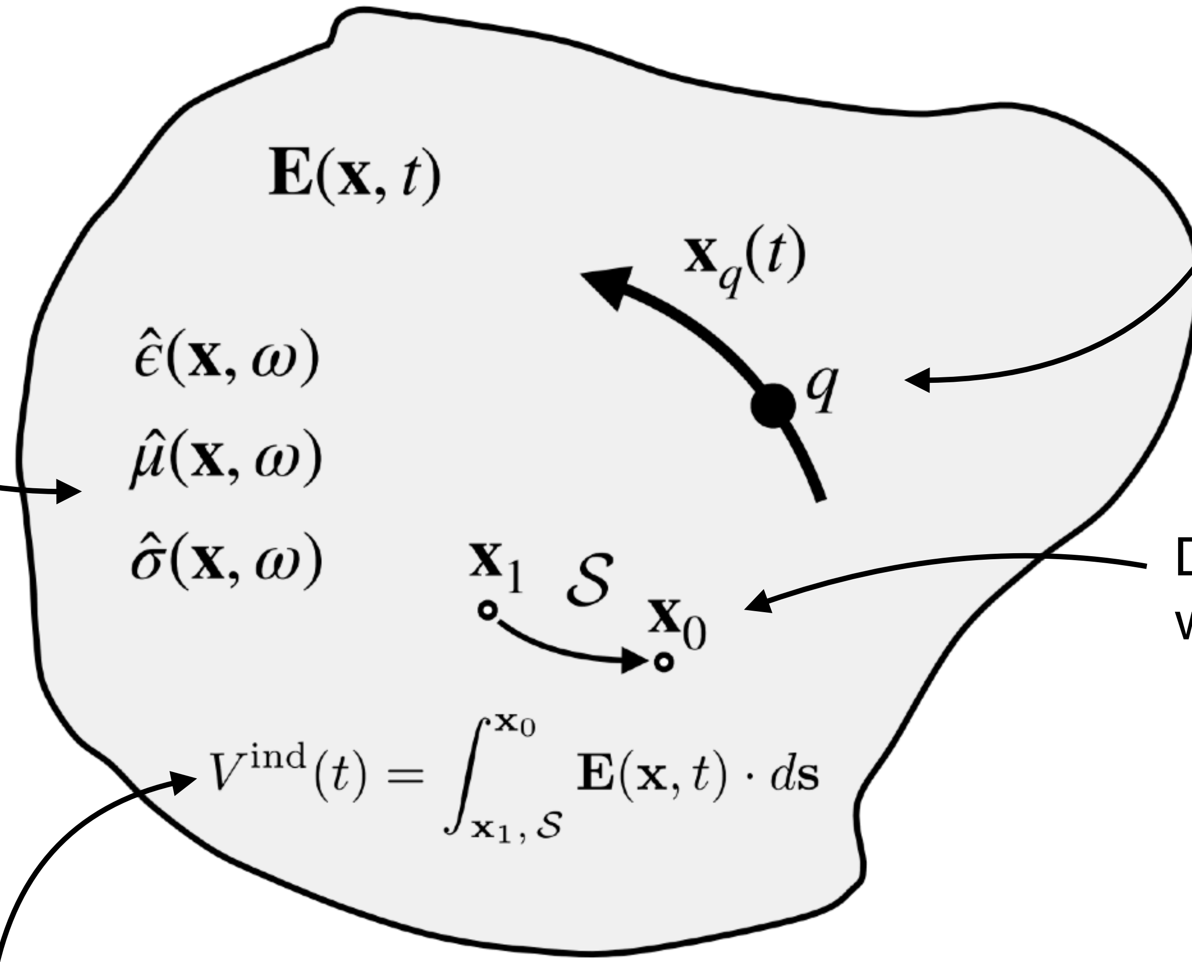
External current distribution — Field distributions

Use this "duality" to compute signal induced in detector

The "primal" situation:

Detector (antennas, cables, ...) encoded in material distribution

Charged particle



Detector "terminals" where signal is available

Detector "signal" is voltage difference across terminals
(measured along a specific path, $\nabla \times \mathbf{E} \neq 0$ *in general!)*

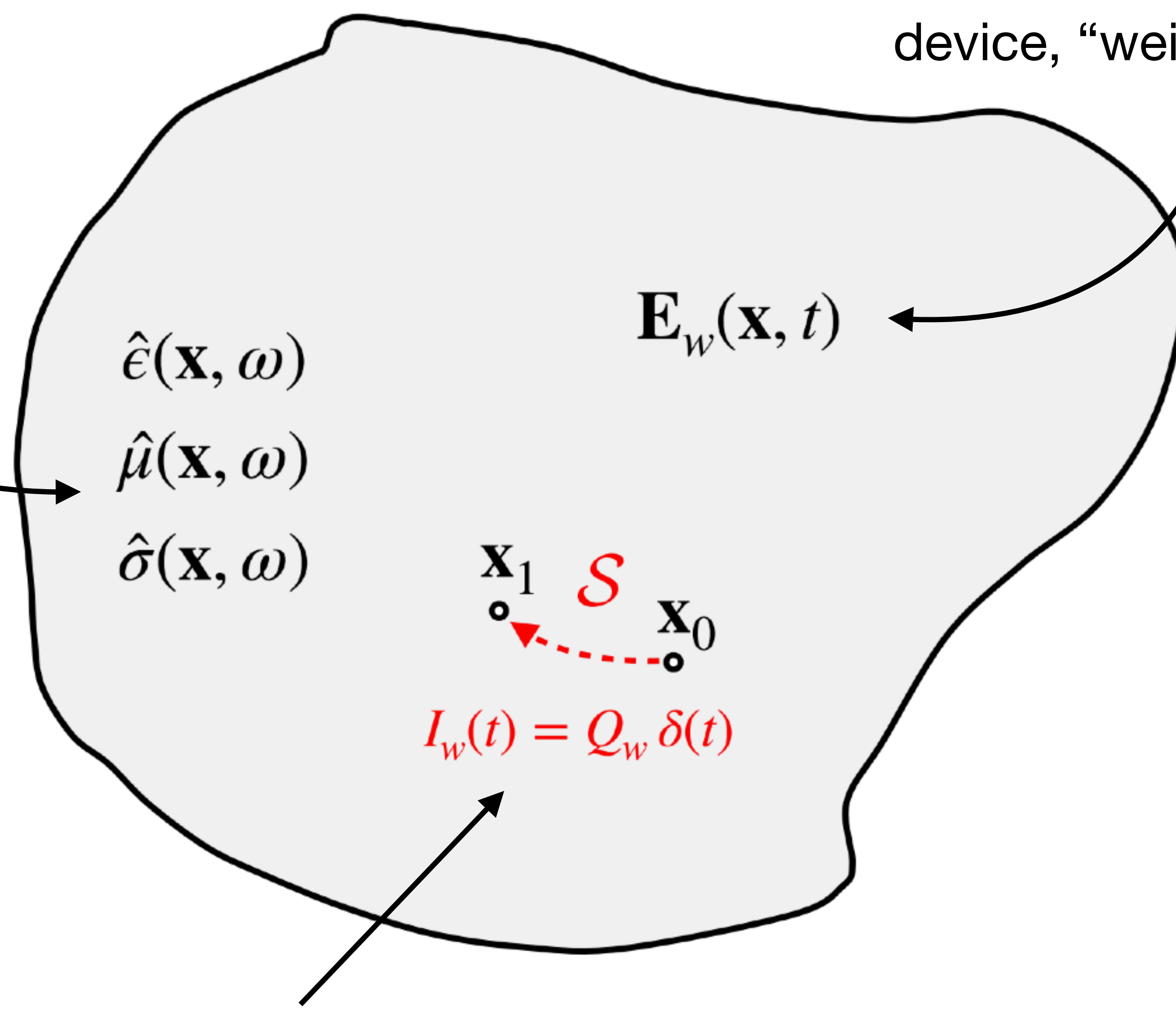
Towards a general signal theorem

Use this "duality" to compute signal induced in detector

The "dual" situation:

Detector acts as transmitting device, "weighting field distribution"

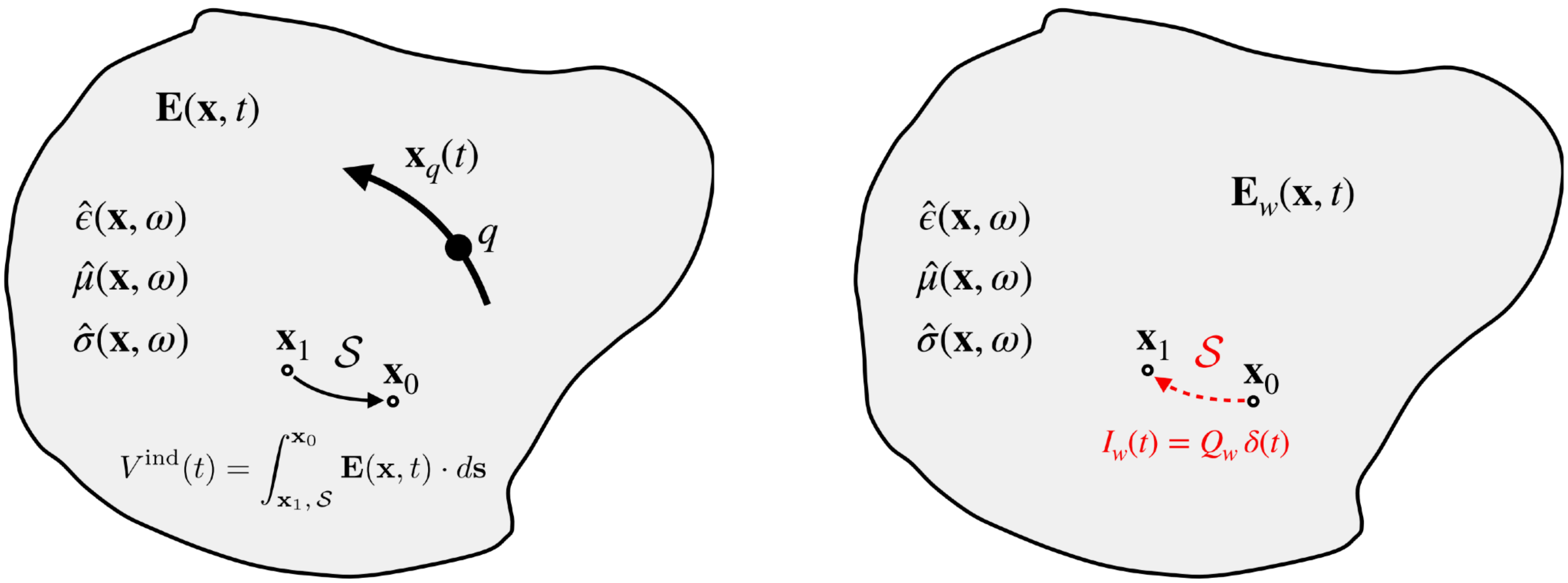
The same material distribution *(in general: the transposed response matrices)*



Current source attached to detector terminals:
delta-like current applied along the signal-defining path

Towards a general signal theorem

Use this "duality" to compute signal induced in detector



$$\int_V \overline{\mathbf{E}}(\mathbf{x}, \omega)\mathbf{J}^e(\mathbf{x}, \omega)dV = \int_V \mathbf{E}(\mathbf{x}, \omega)\overline{\mathbf{J}}^e(\mathbf{x}, \omega)dV$$

$$V^{\mathrm{ind}}(\omega) = \int_{\mathbf{x}_1, \mathcal{S}}^{\mathbf{x}_0} \mathbf{E}(\mathbf{x}, \omega)d\mathbf{s} = -\frac{1}{I_w(\omega)} \int_V \mathbf{E}_w(\mathbf{x}, \omega)\mathbf{J}^e(\mathbf{x}, \omega)dV$$

A fully general signal theorem

In the time-domain, this is

$$V^{\mathrm{ind}}(t) = -\frac{q}{Q_w}\int_{-\infty}^{\infty} \mathbf{E}_w(\mathbf{x}_q(t'), t - t')\dot{\mathbf{x}}_q(t')dt'$$

Normalising constant — Weighting field — Particle trajectory

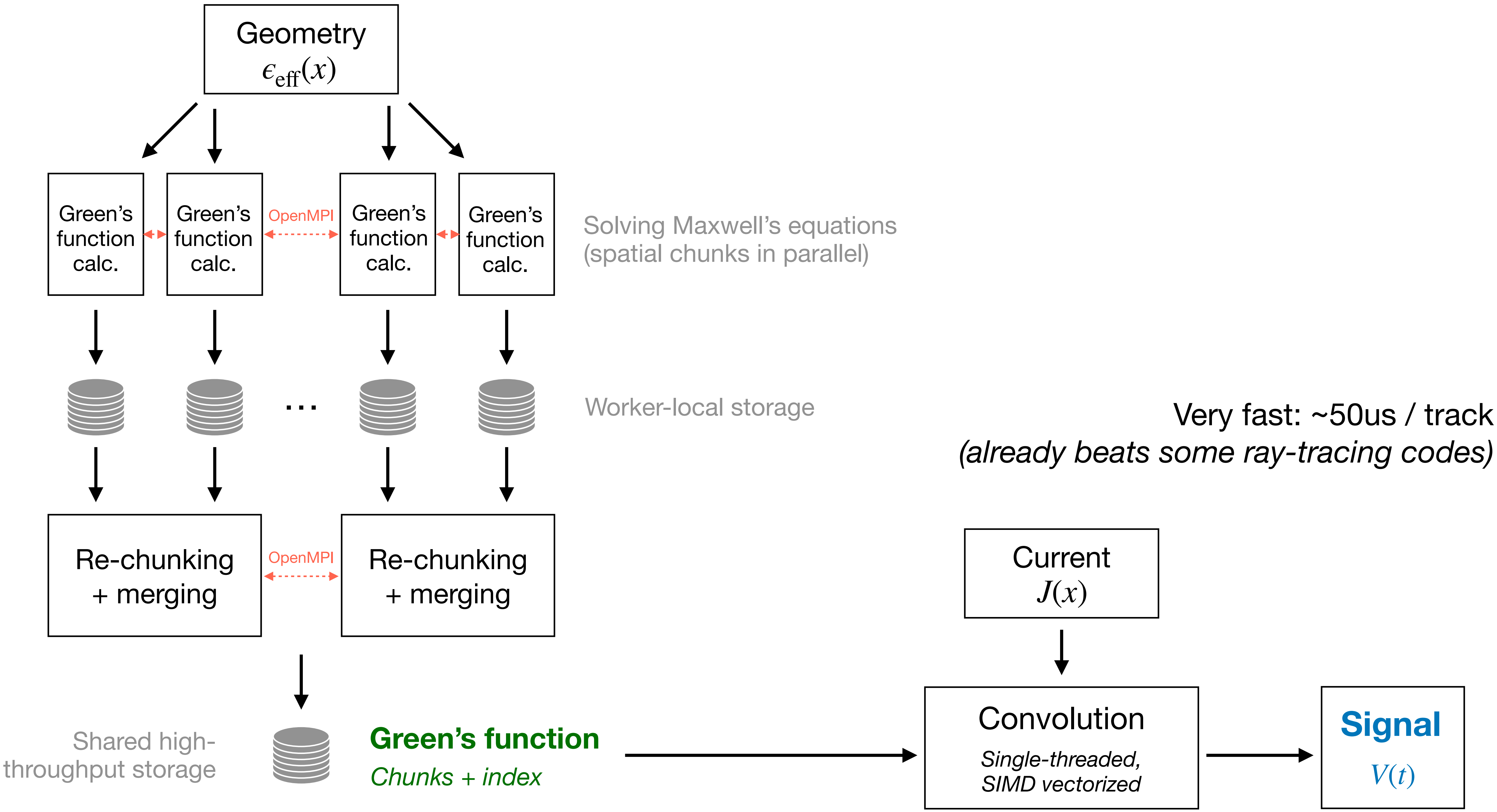
"Weighting field": Green's function for detector signal

Encodes information about detector geometry & environment; reciprocity defines concrete algorithm to compute it

Fully general, no approximations

holds exactly for all linear, anisotropic materials; approximately for nonlinear, anisotropic materials

Eisvogel internals



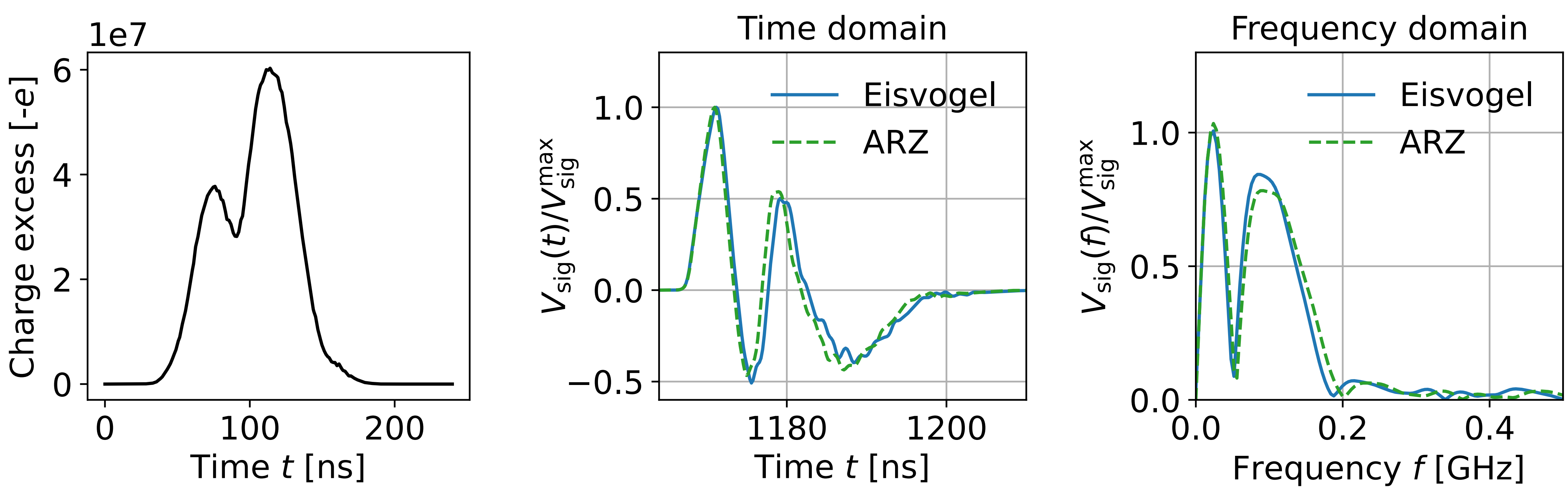
Effectively a custom, zero-suppressed distributed file system (TB → GB)

SIMD = "single instruction multiple data"

AVX512: 512-bit registers, fits 16 4-byte floating point numbers

Comparison with ARZ
(as implemented in NuRadioMC)

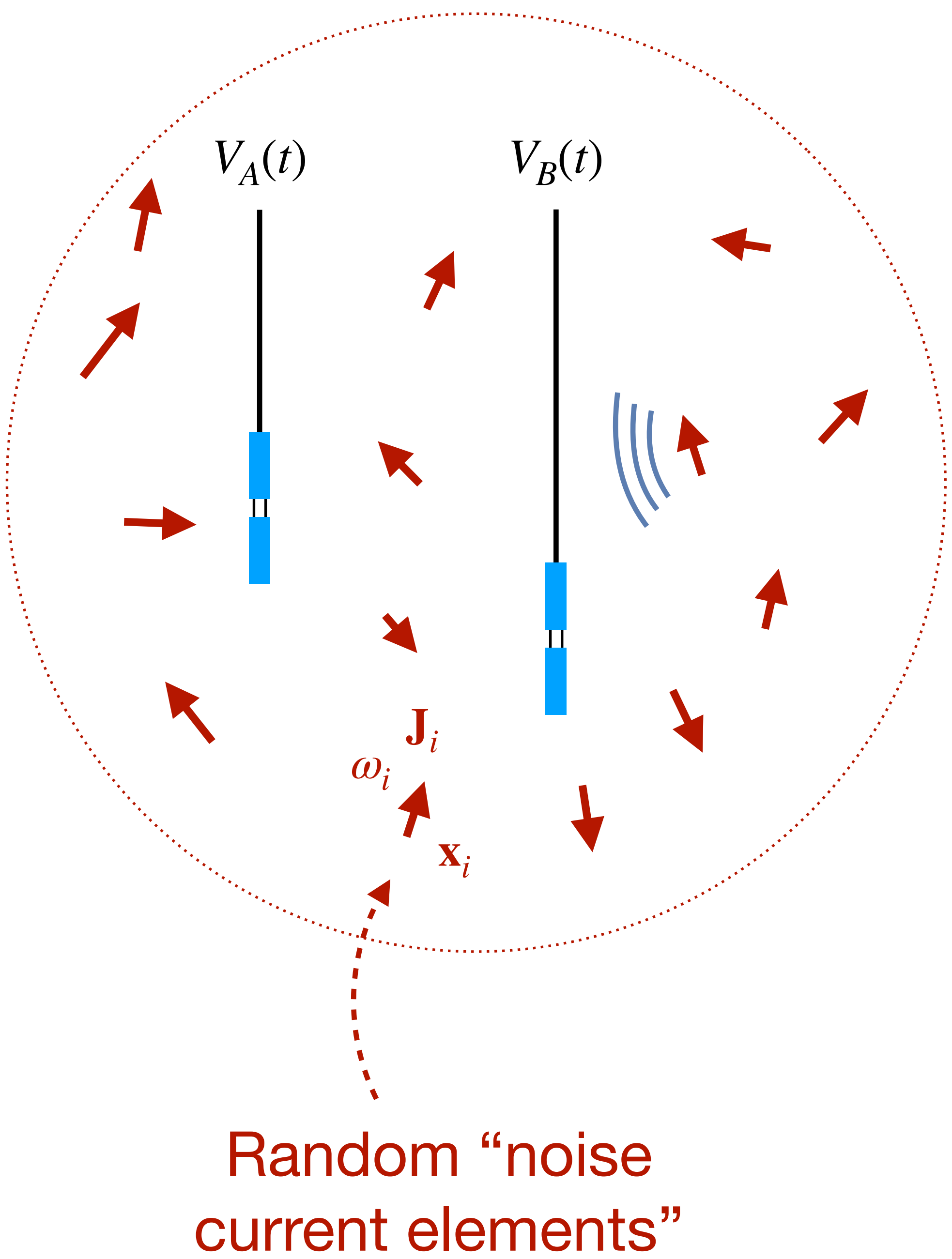
1-dim profile of electromagnetic shower developing in homogeneous medium with $n = 1.78$

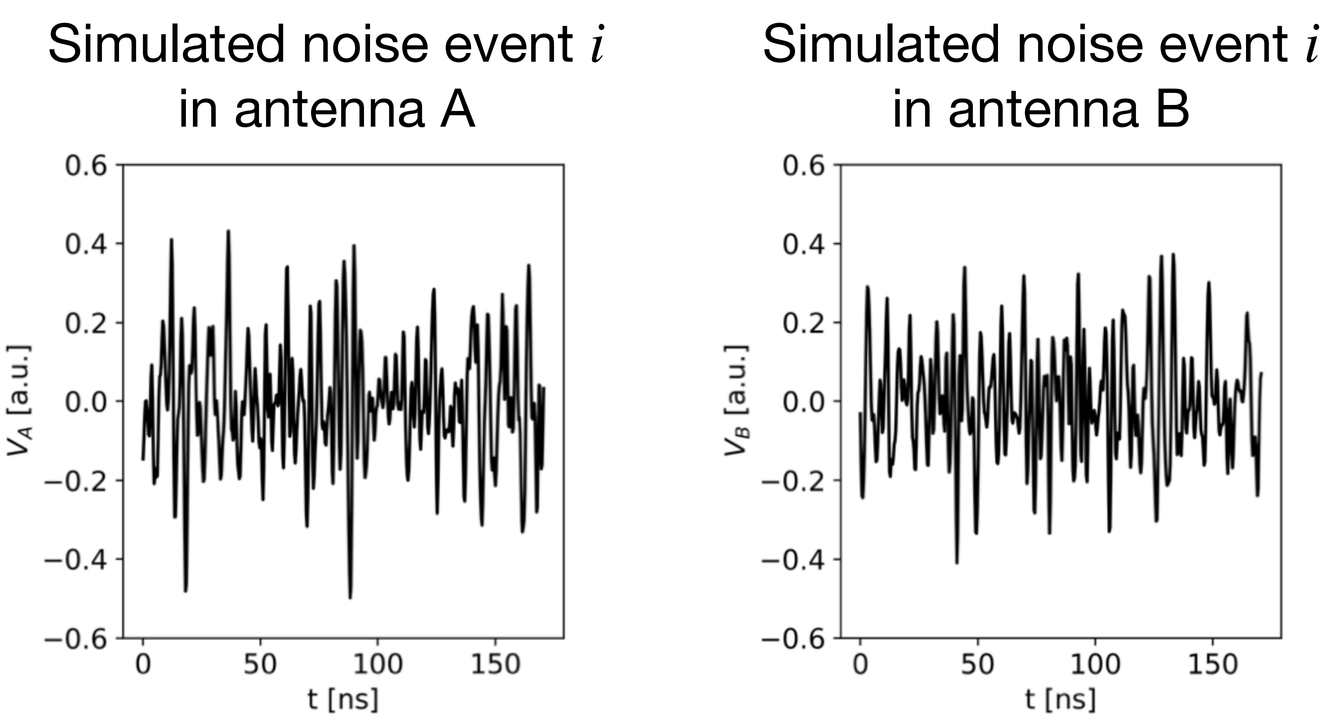


Good agreement!

How does this work?

A simple toy simulation of the procedure:





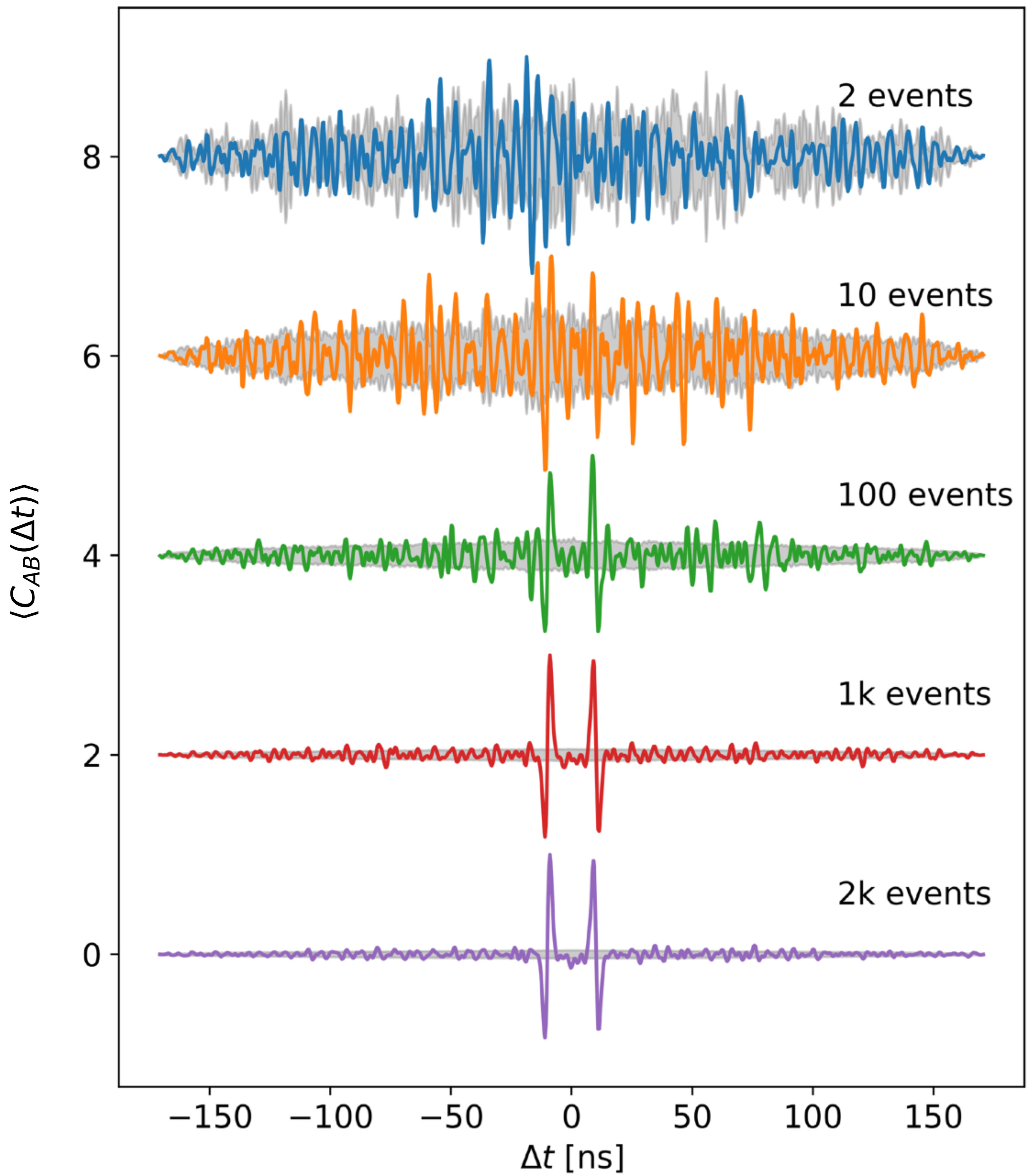
$$C_{AB}^{(i)}(\Delta t) = \int dt' \, V_A^{(i)}(\Delta t + t') V_B^{(i)}(t')$$

1) Correlate noise event-by-event

$$\langle C_{AB}(\Delta t) \rangle_N = \frac{1}{N} \sum_{i=1}^{N} C_{AB}^{(i)}(\Delta t)$$

2) Average over full data set

How does this work?

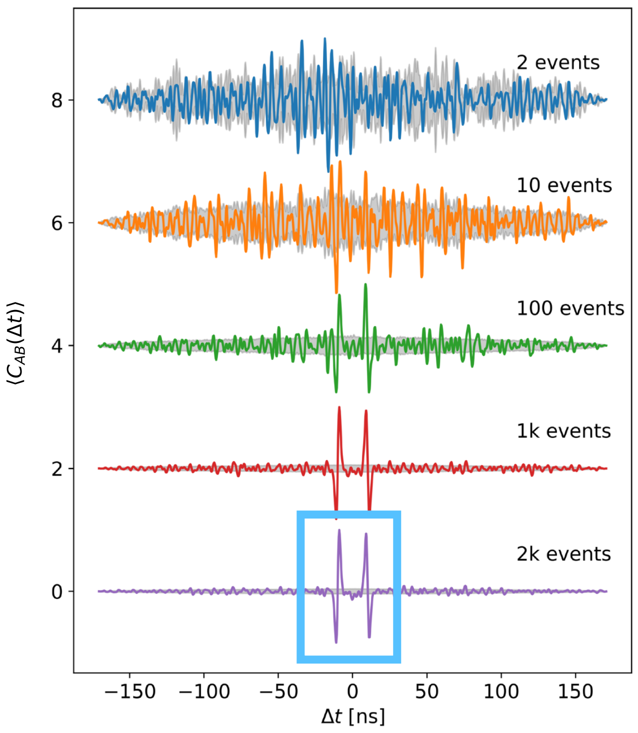


Noise correlator averaged for different N

$$\langle C_{AB}(\Delta t)\rangle_N = \frac{1}{N}\sum_{i=1}^{N} C_{AB}^{(i)}(\Delta t)$$

Noise is **uncorrelated between antennas** on a **per-event** basis

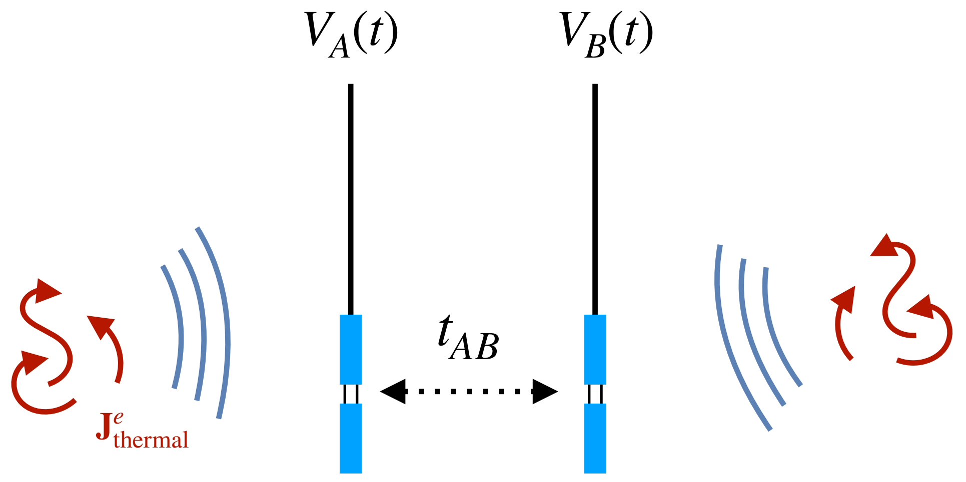
Noise is **weakly correlated** between antennas
→ *average over many events makes it visible*

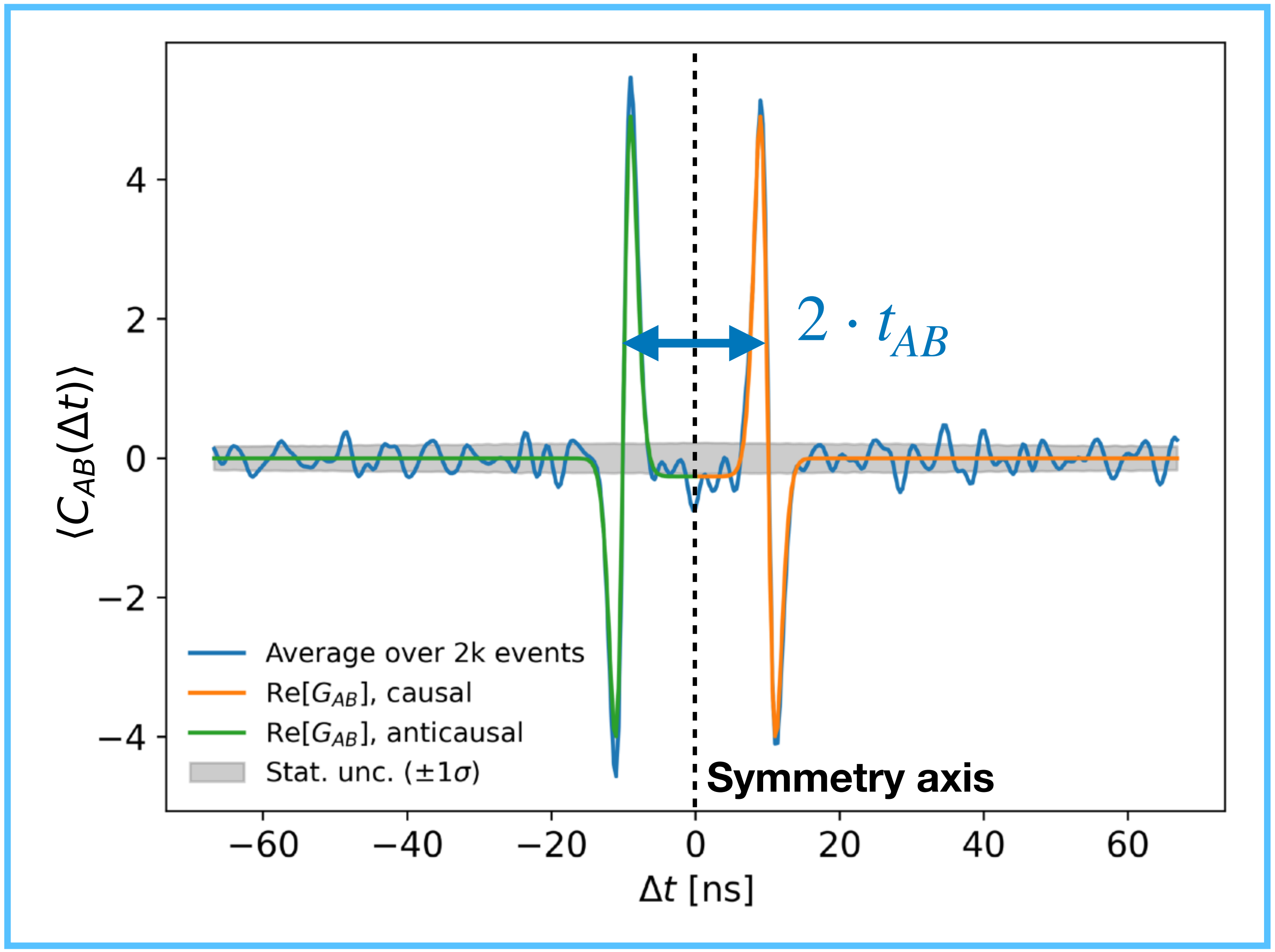


Result of averaging:

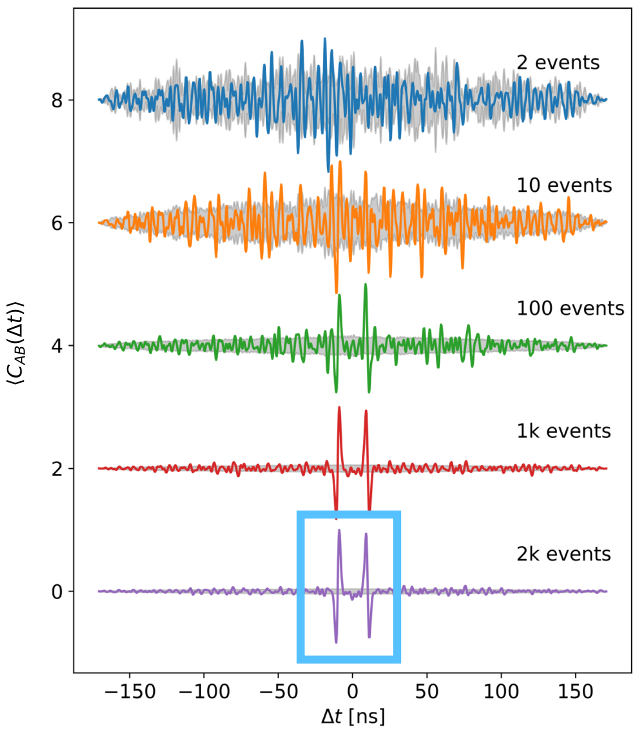
Impulse response between the two antennas (“virtual pulser”)
(Symmetry ↔ isotropy of thermal noise)

Time difference between two peaks: $2 \cdot t_{AB}$





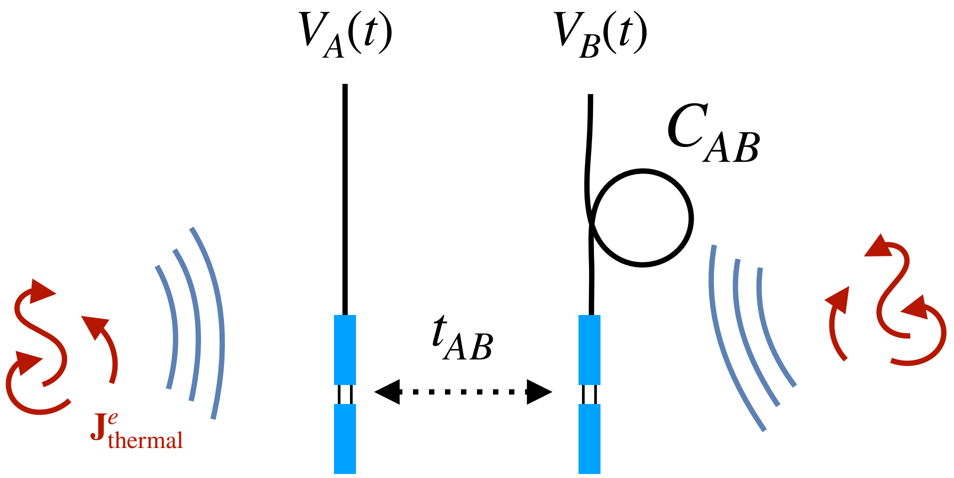
How does this work?

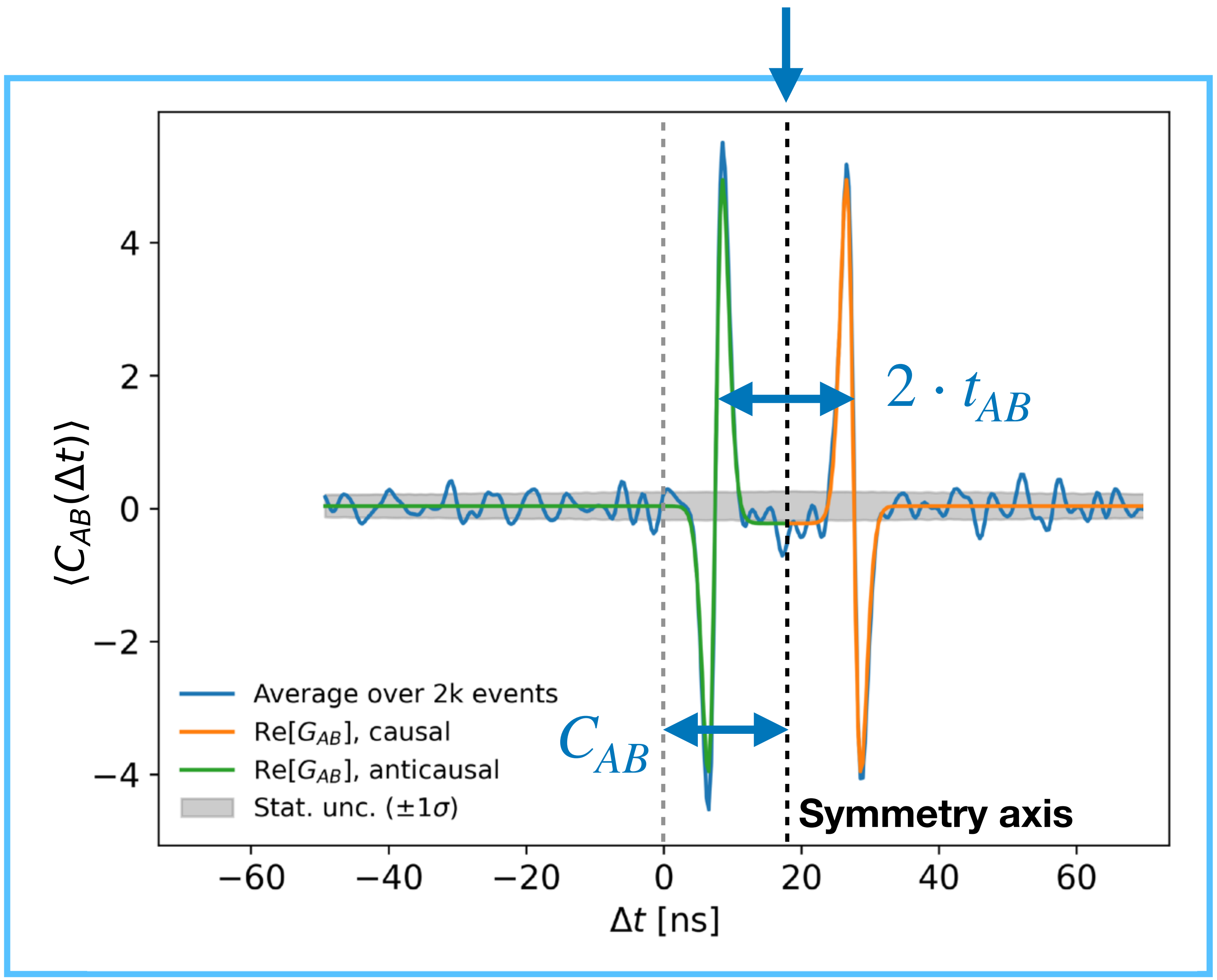


Result of averaging:

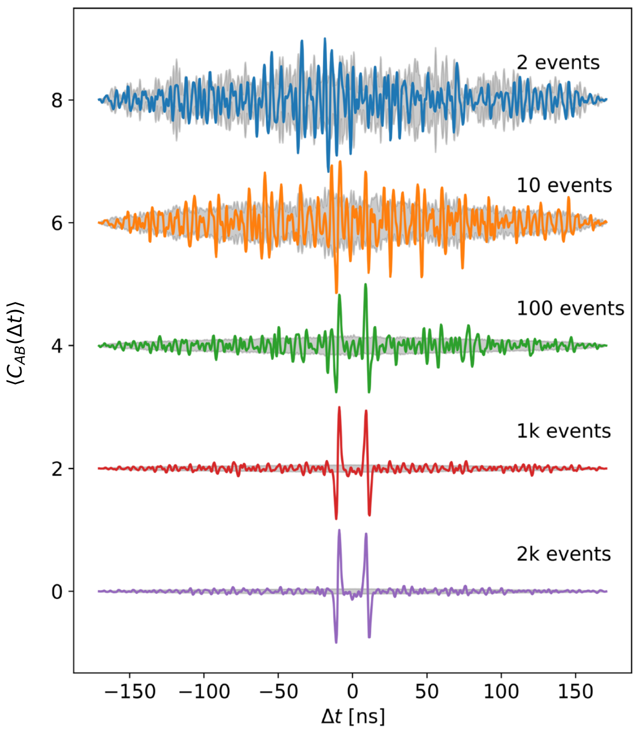
Overall shift away from $\Delta t = 0$: relative cable delay C_{AB}

→ **detectable** due to symmetric structure!





How does this work?



Far field:
Impulse response is simple;
but far-away antennas are *very weakly correlated*

Near field:
Complicated, strongly dependent on antenna geometry; but *still symmetric*