Cosmic-ray observations with in-ice radio detectors

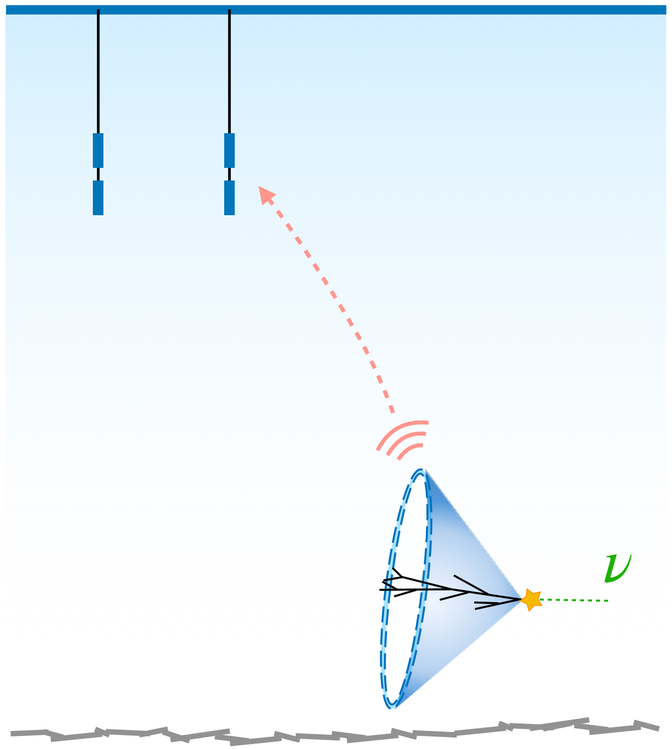
Can we make a mass-sensitive measurement?

Nathaniel Alden *(University of Chicago)*

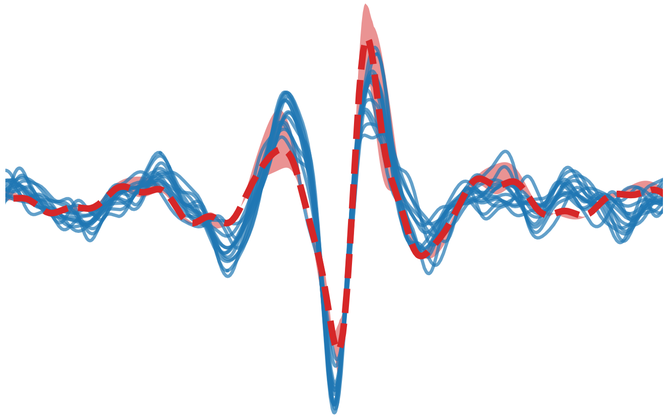
IPA, October 2026



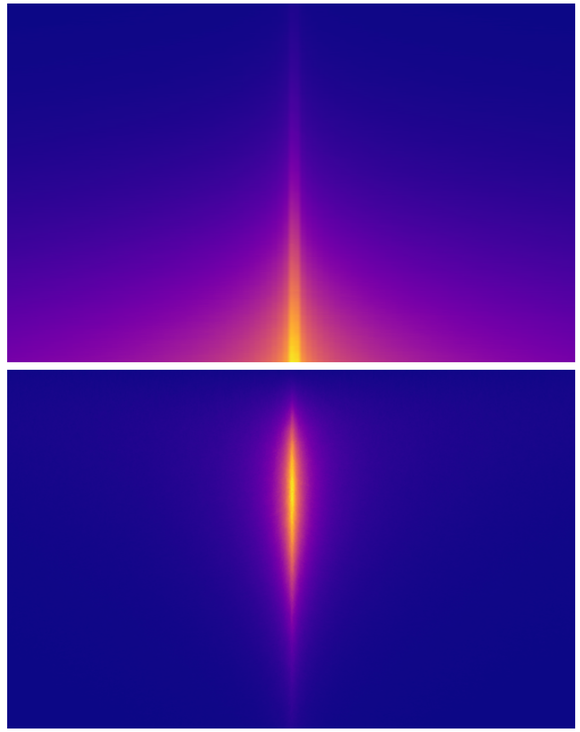
For today



In-ice radio detectors:
Why and how?



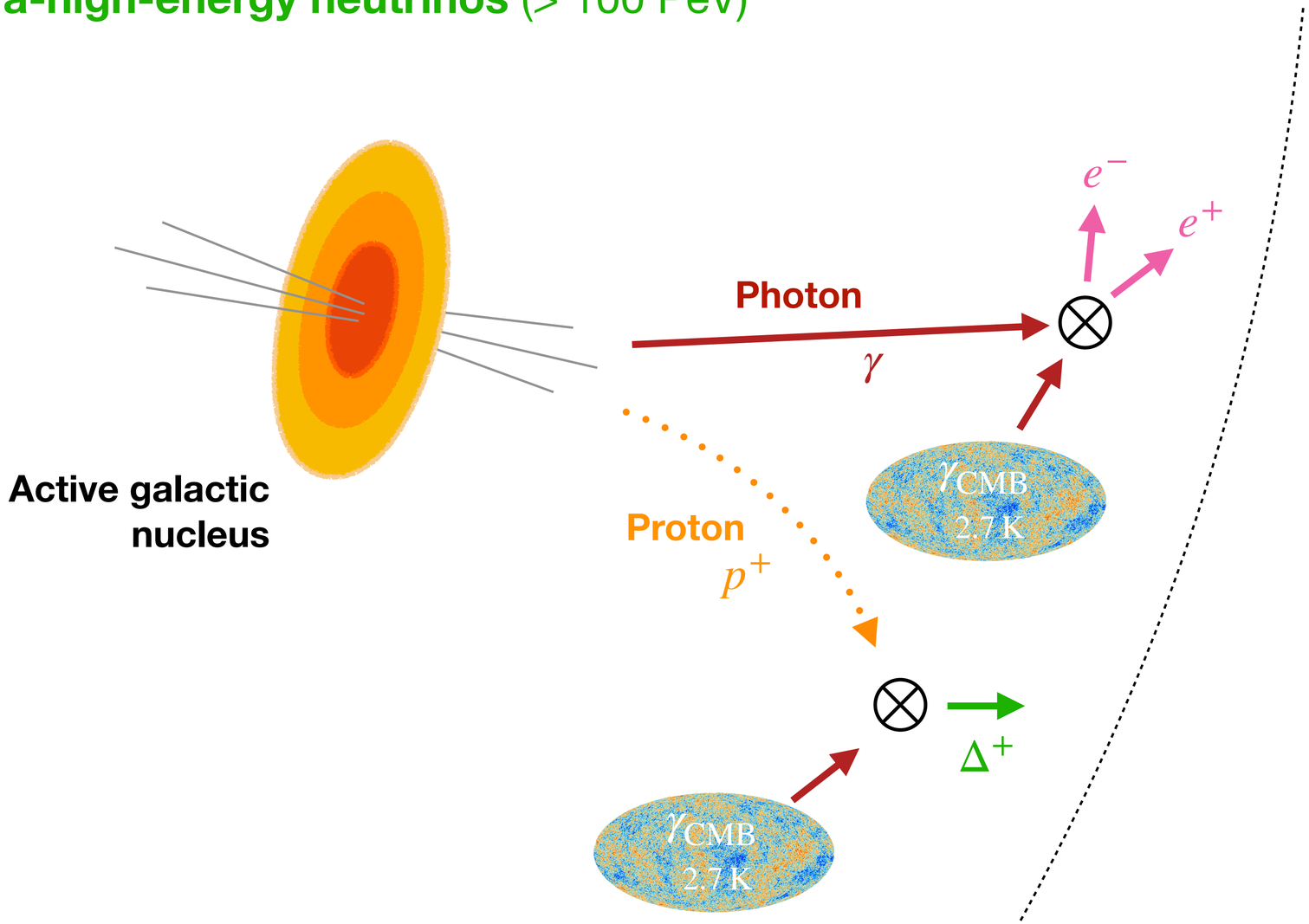
The first in-ice
cosmic ray detection



Contributing to
cosmic ray physics?

In-ice radio detectors: why and how?

The universe should contain a tiny flux of ultra-high-energy neutrinos (> 100 PeV)



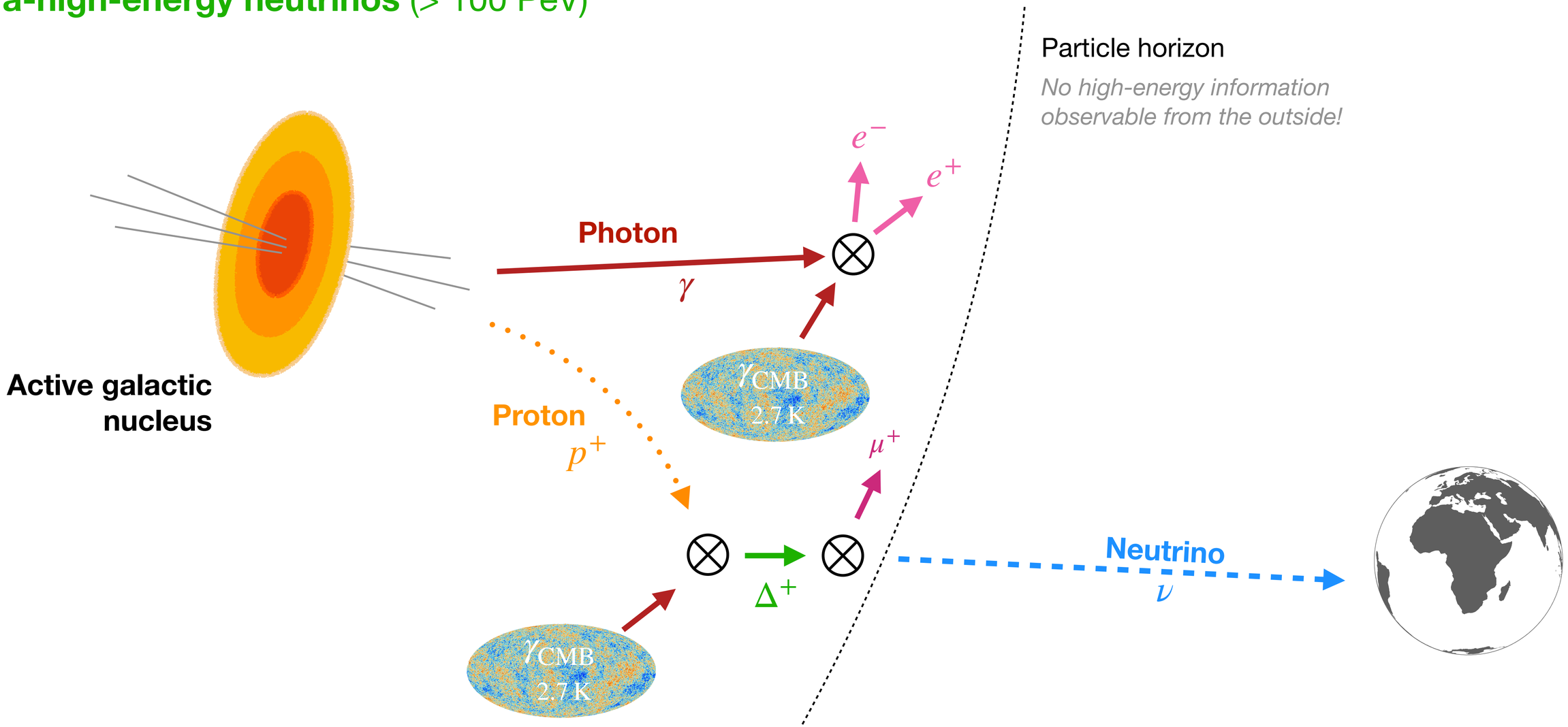
Particle horizon

No high-energy information observable from the outside!



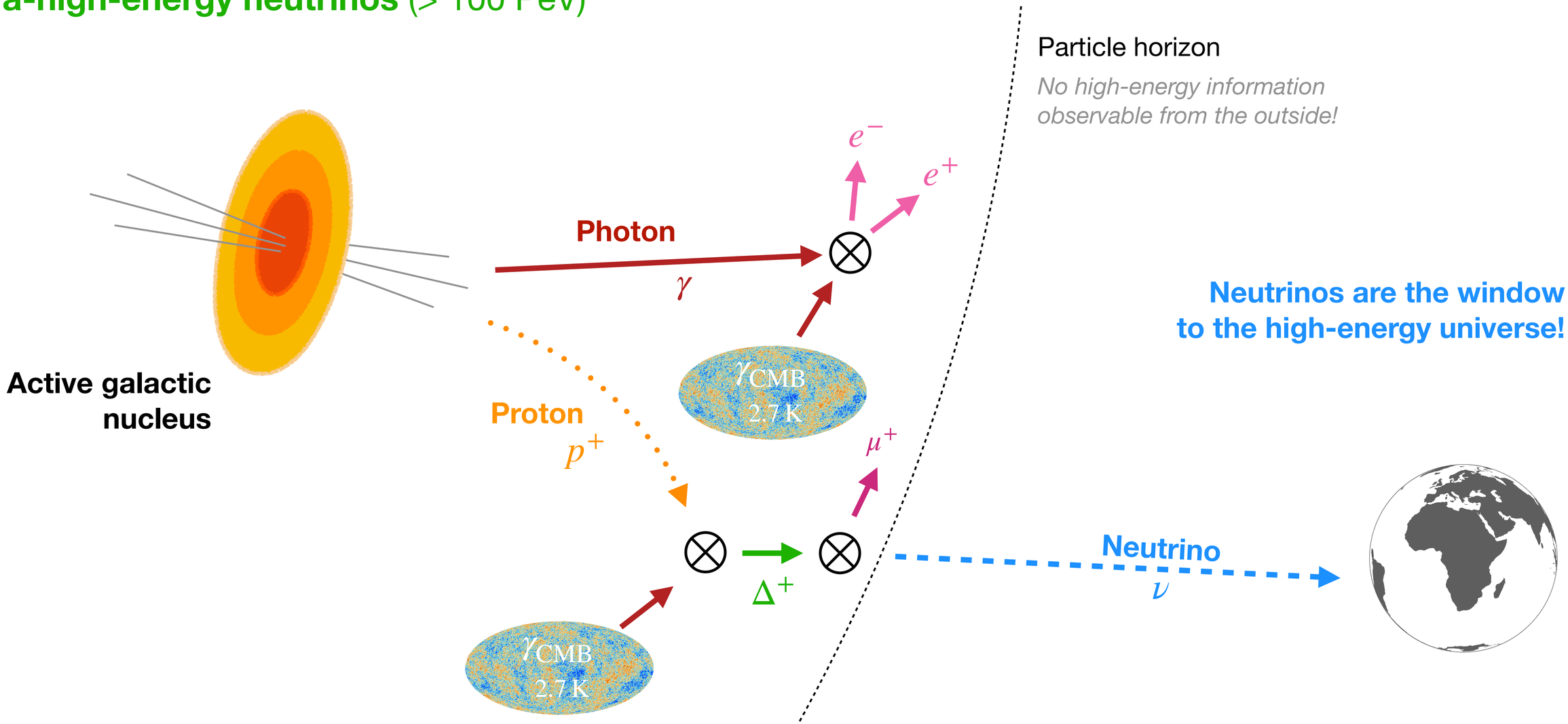
In-ice radio detectors: why and how?

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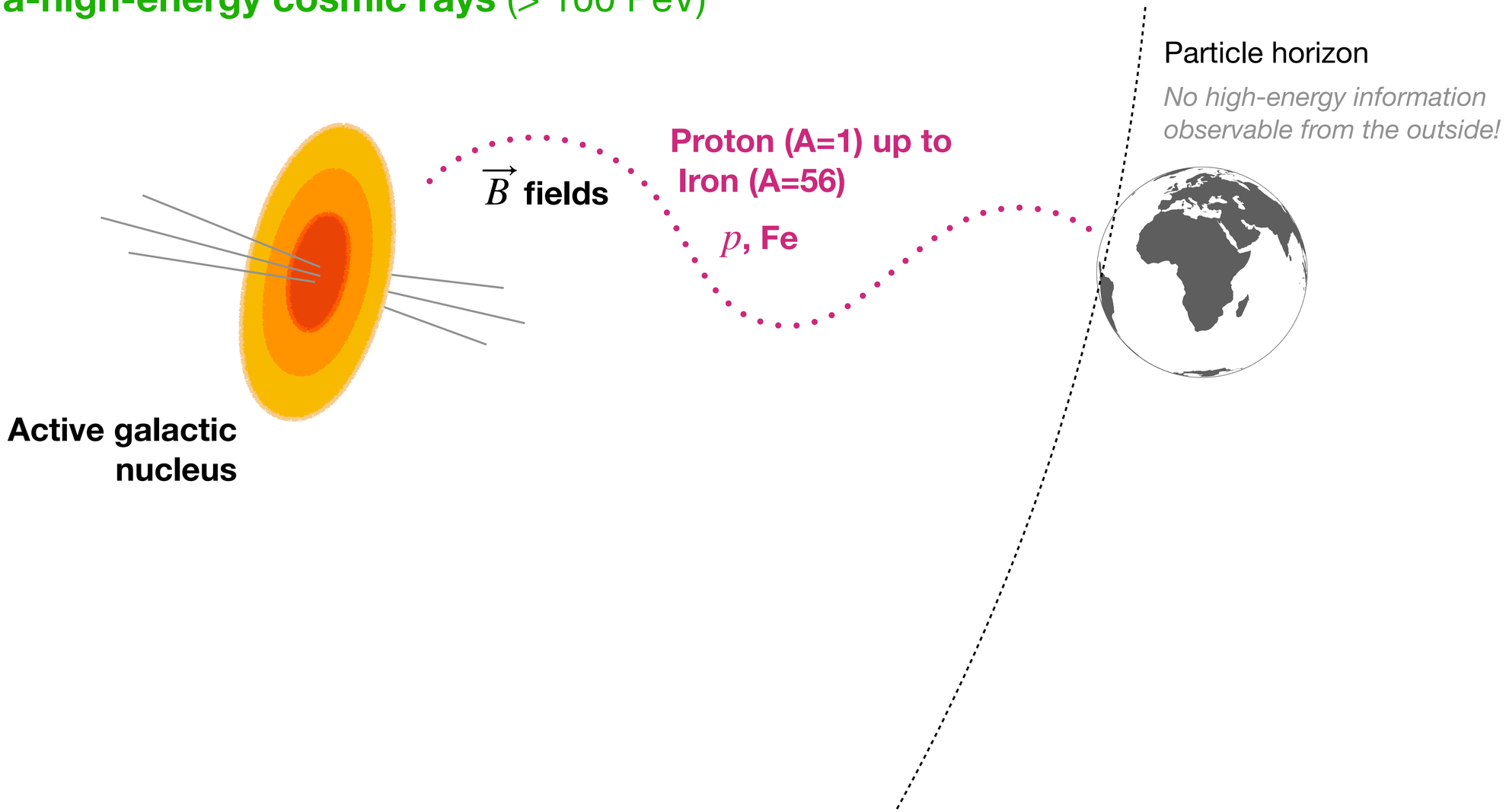
In-ice radio detectors: why and how?

The universe should contain a tiny flux of ultra-high-energy neutrinos (> 100 PeV)



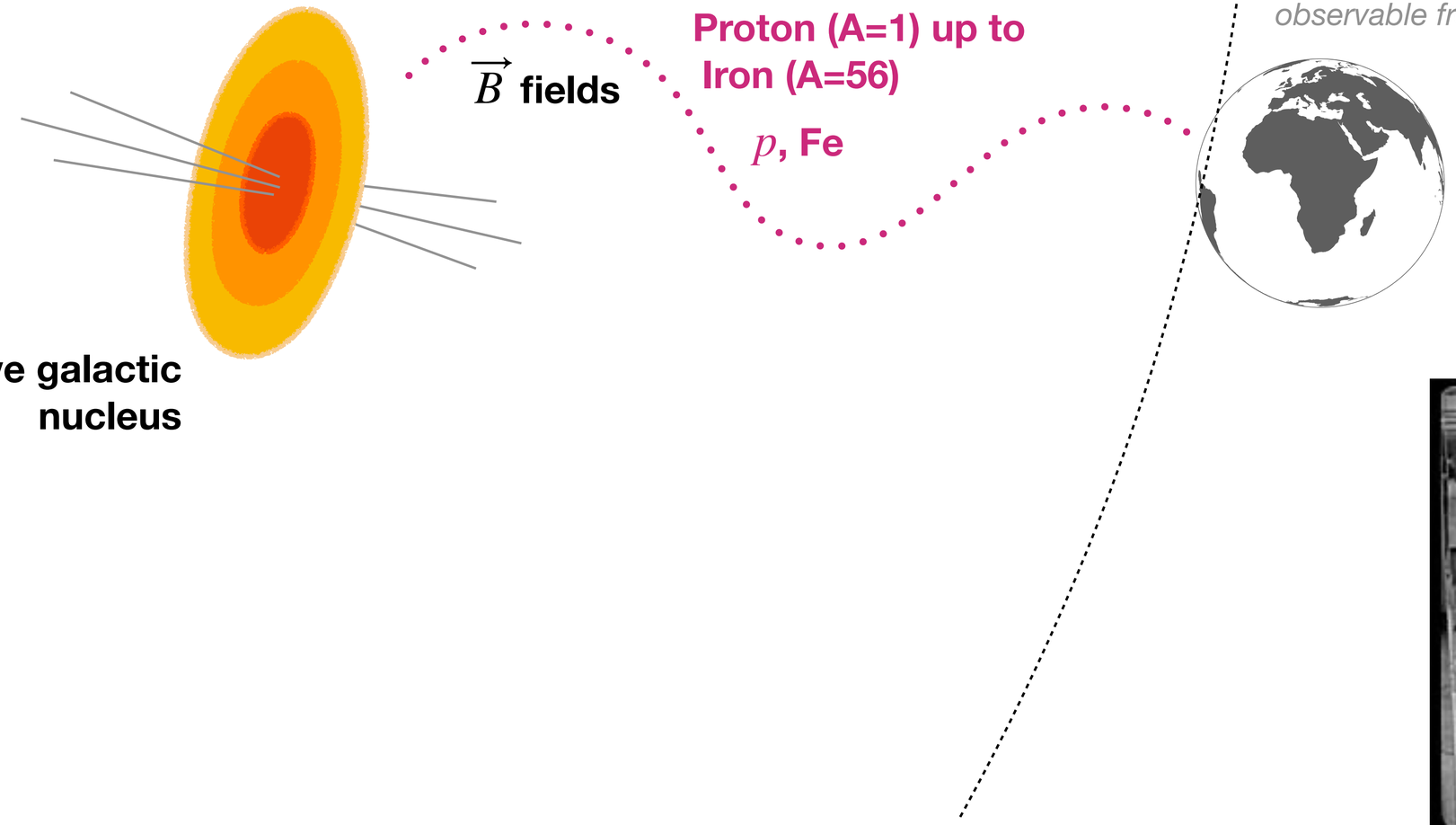
In-ice radio detectors: why and how?

And the universe does contain a less-tiny flux of ultra-high-energy cosmic rays (> 100 PeV)



In-ice radio detectors: why and how?

And the universe does contain a less-tiny flux of ultra-high-energy cosmic rays (> 100 PeV)



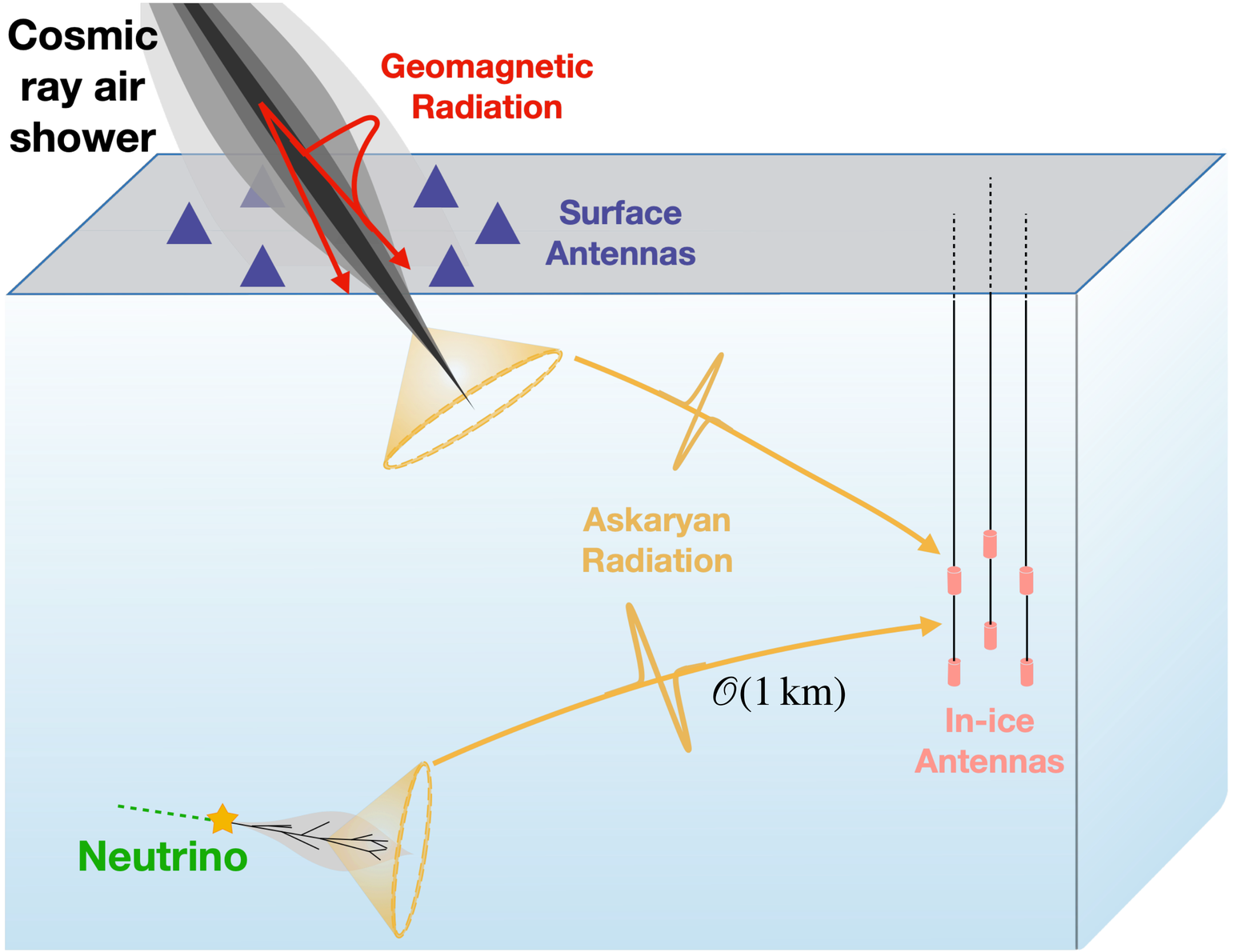
… And cosmic rays are the funhouse mirror to the (closer) high-energy universe



Askaryan radiation

Like neutrinos, cosmic ray air showers can enter the ice and make detectable Askaryan emission

Higher flux than neutrinos- but can be discriminated based on their arrival direction



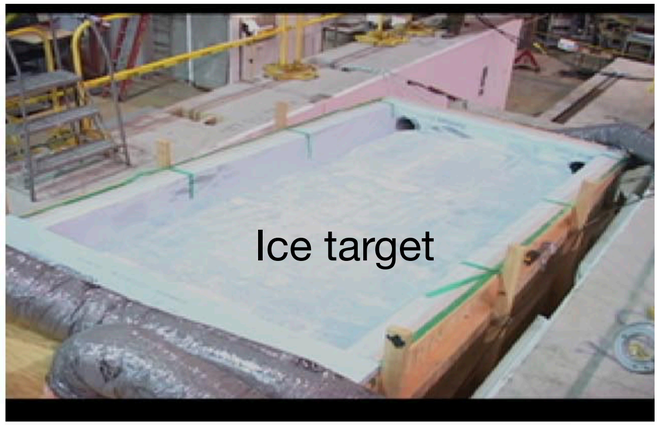
Askaryan radiation

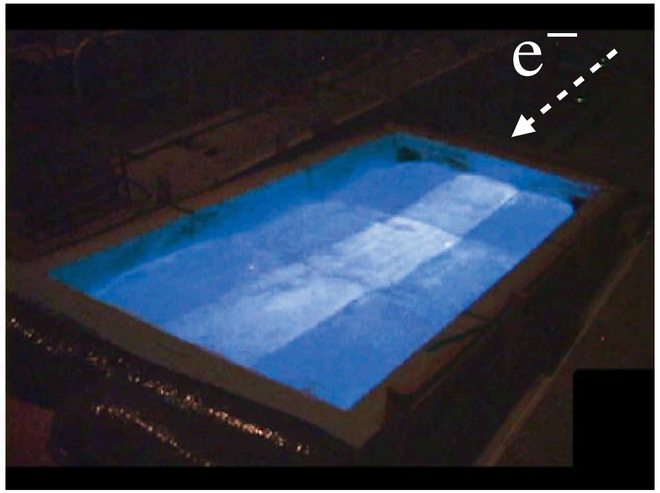
Like neu
air show
ice and
Aska

Higher f
but car
base

First observed in ice during laboratory measurements in the 2000s ↓

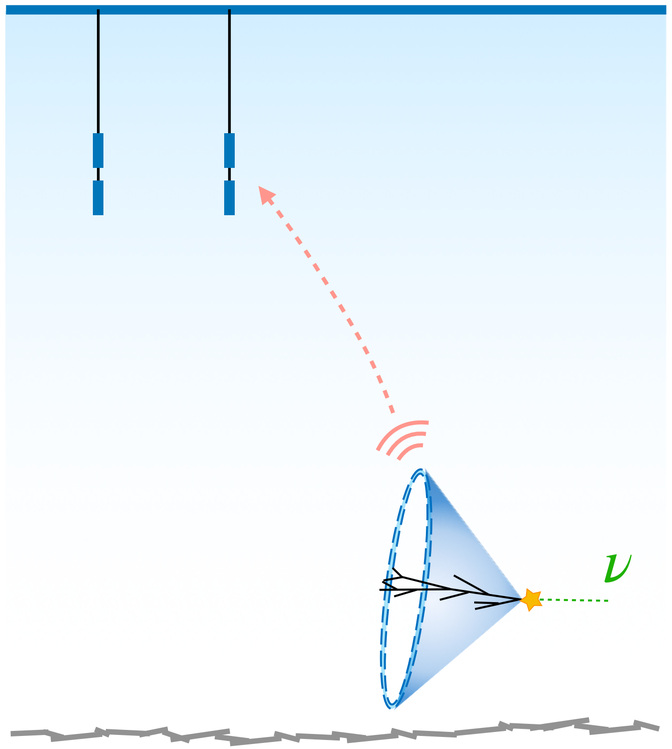




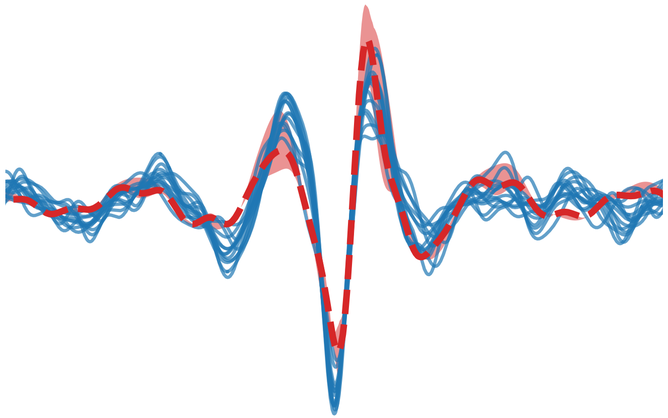


*Gorham et. al, PRL **99,** 171101 (2007)—annotated*

For today

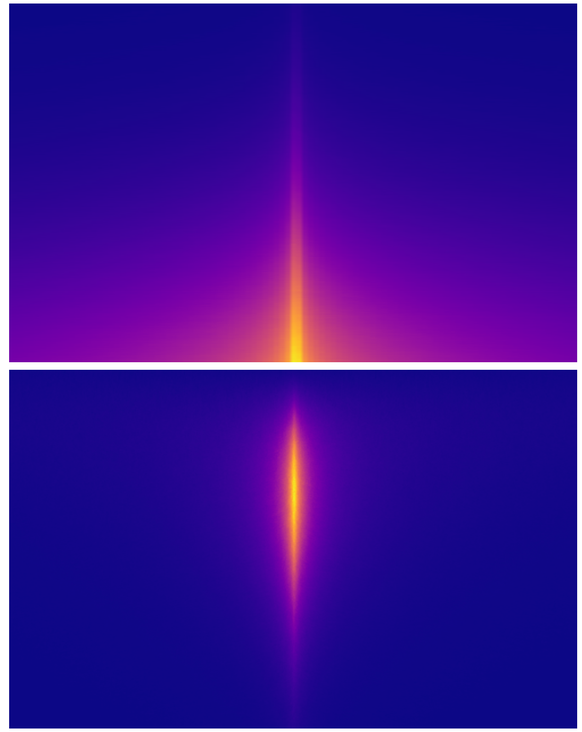


In-ice radio detectors:
Why and how?



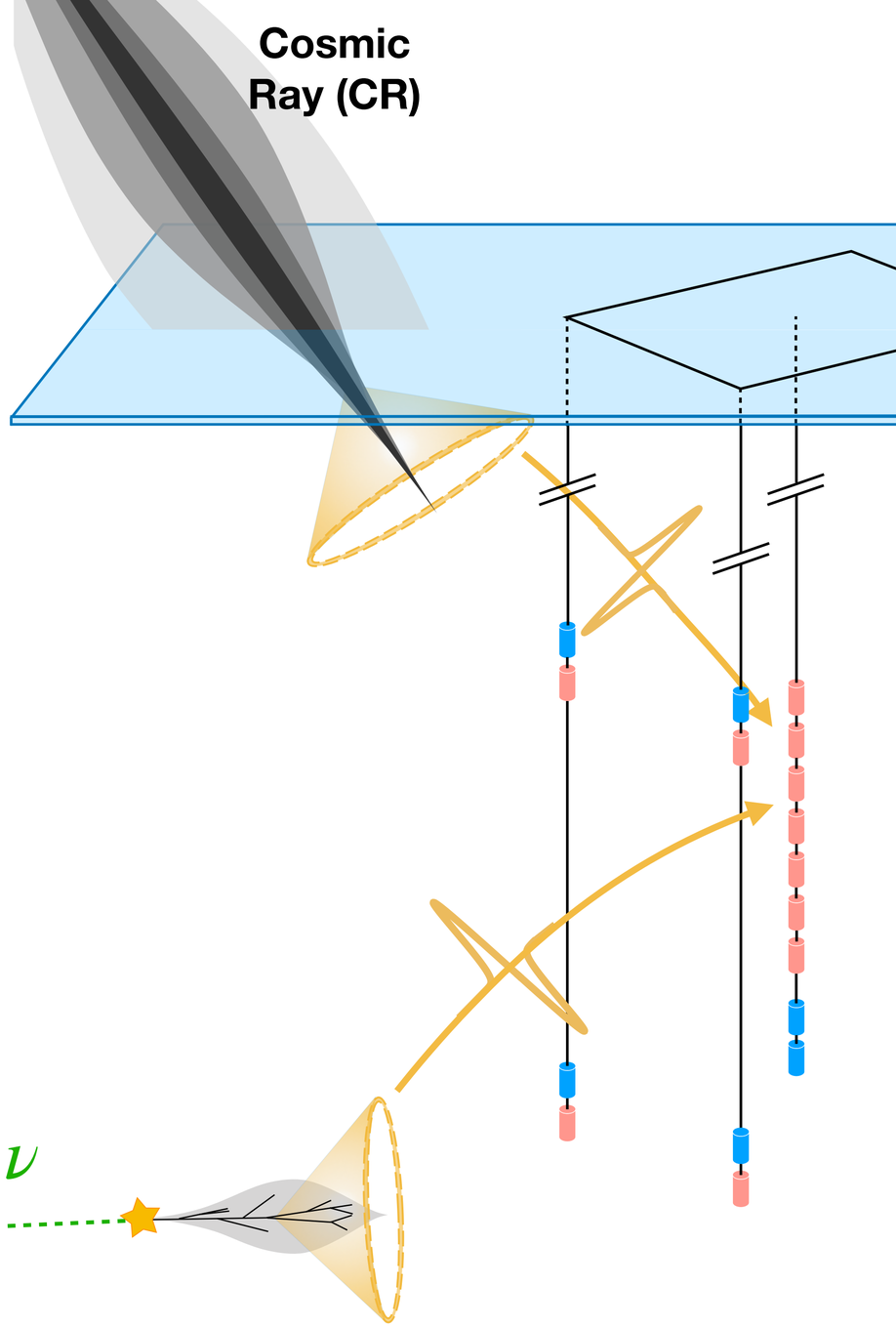
The first in-ice
cosmic ray detection

NA + ARA coll., PRL **136**, 151003 (2026)



Contributing to
cosmic ray physics?

Dataset and event selection



Dataset and event selection

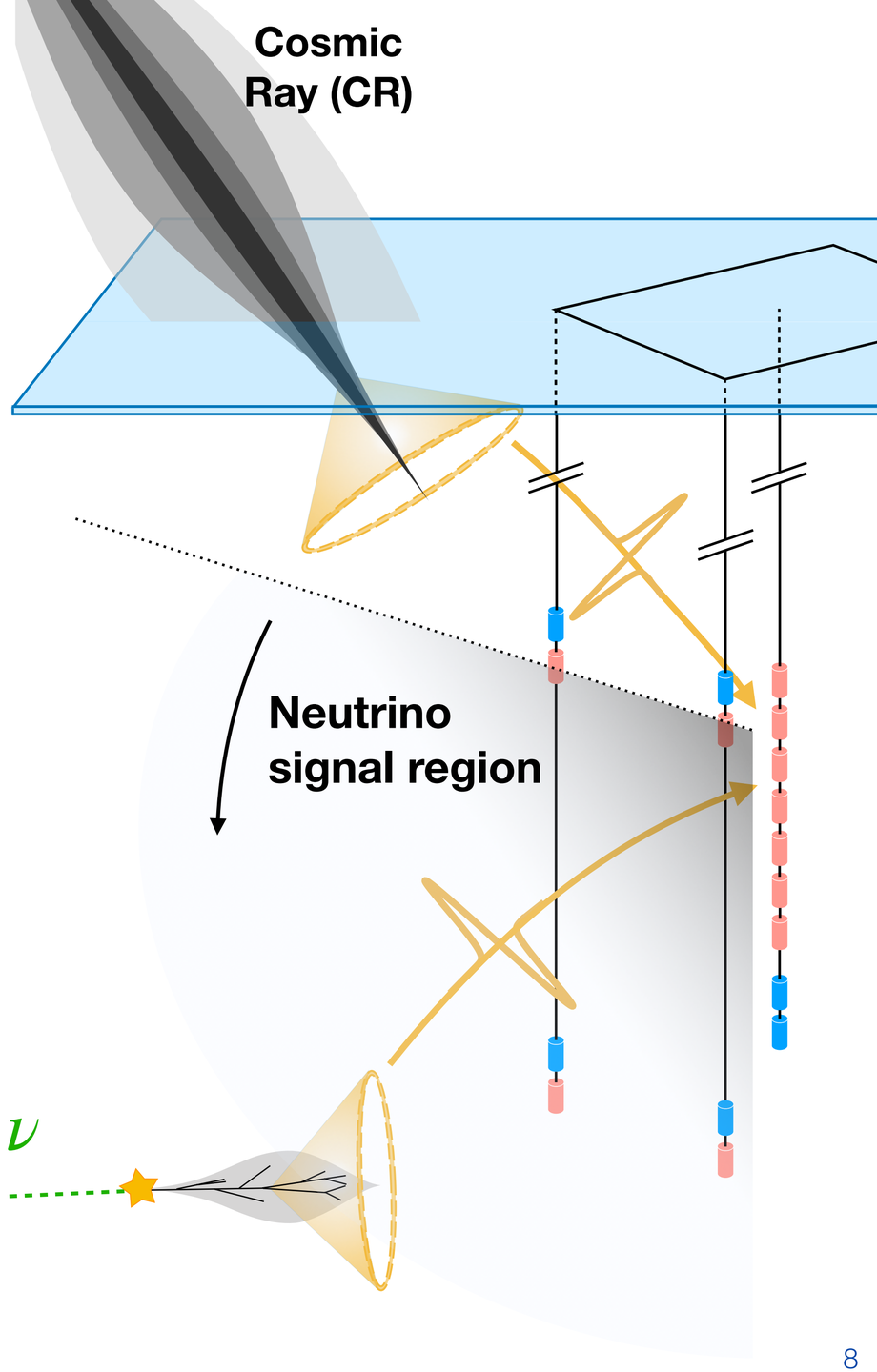
Study events observed in sideband of neutrino search
[Phys. Rev. D 105, 122006 (2022)]

Neutrino signal region:

→ Non-thermal events selected by *multivariate discriminant*

→ Upgoing or mildly-downgoing radiation

(avoids contamination from surface sources)



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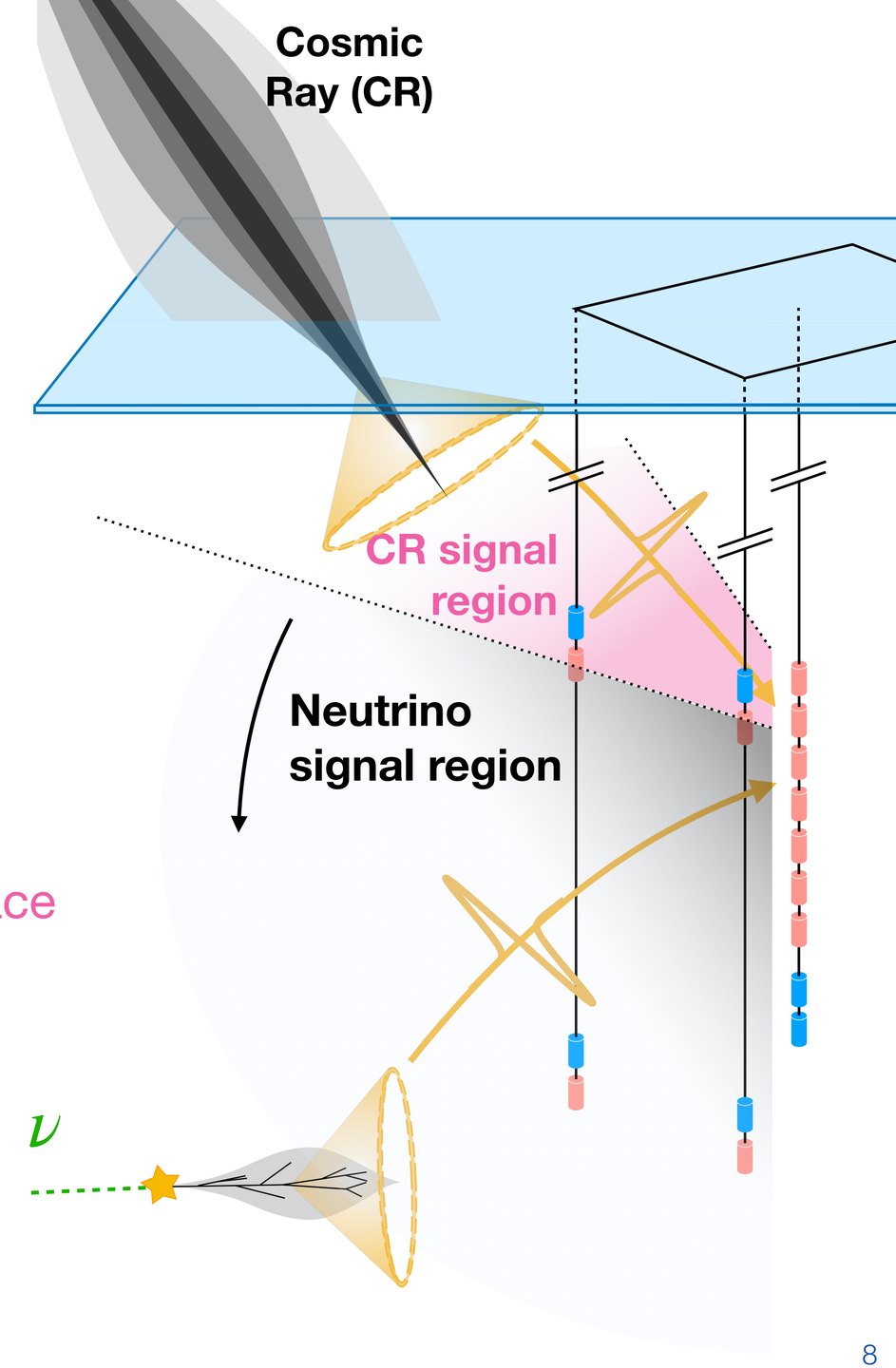
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Here: study events observed in sideband, arriving shallower than angle of total internal reflection at air-ice interface

Select signals that arrive steeper than neutrino signal region …



Dataset and event selection

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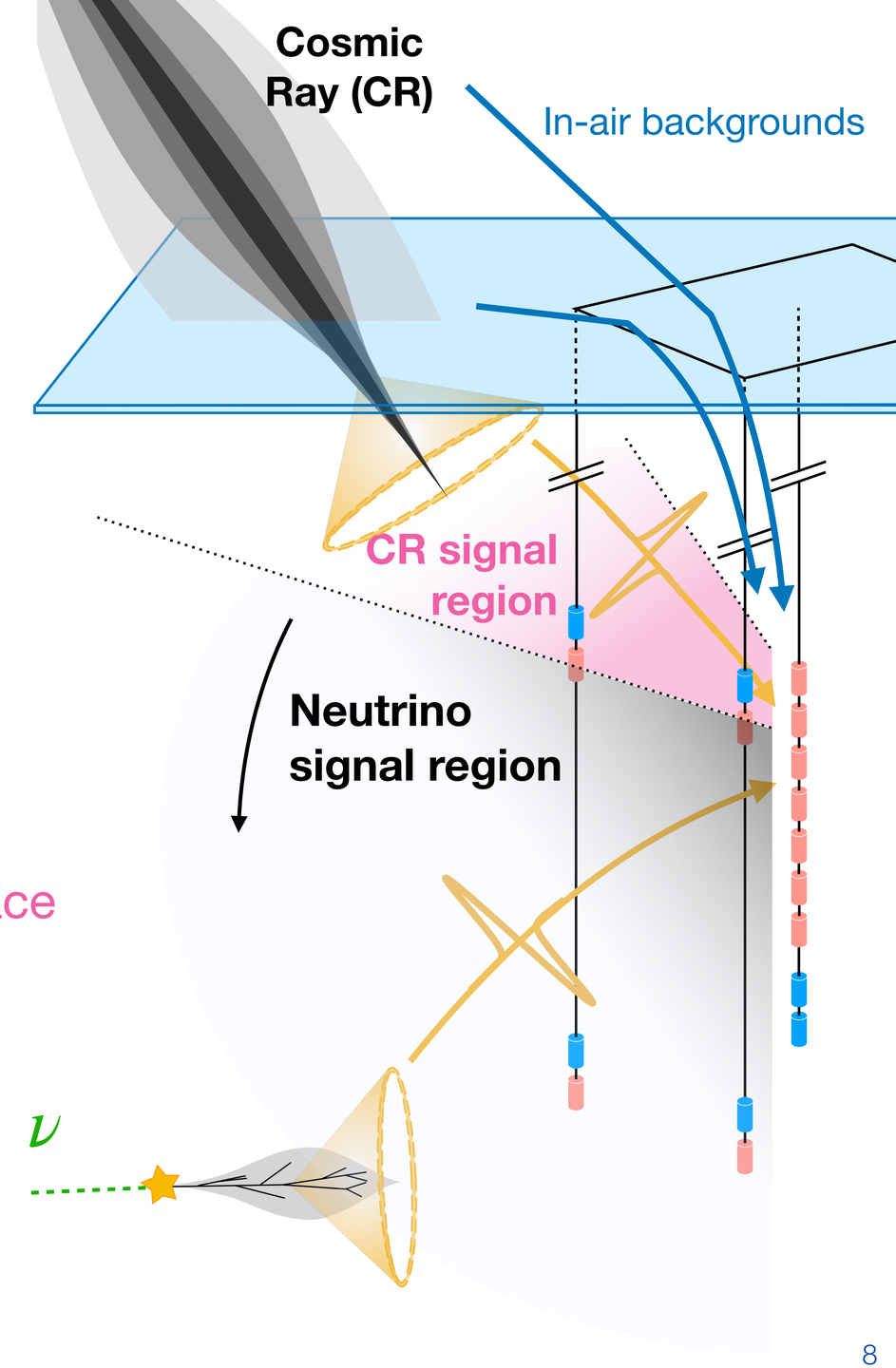
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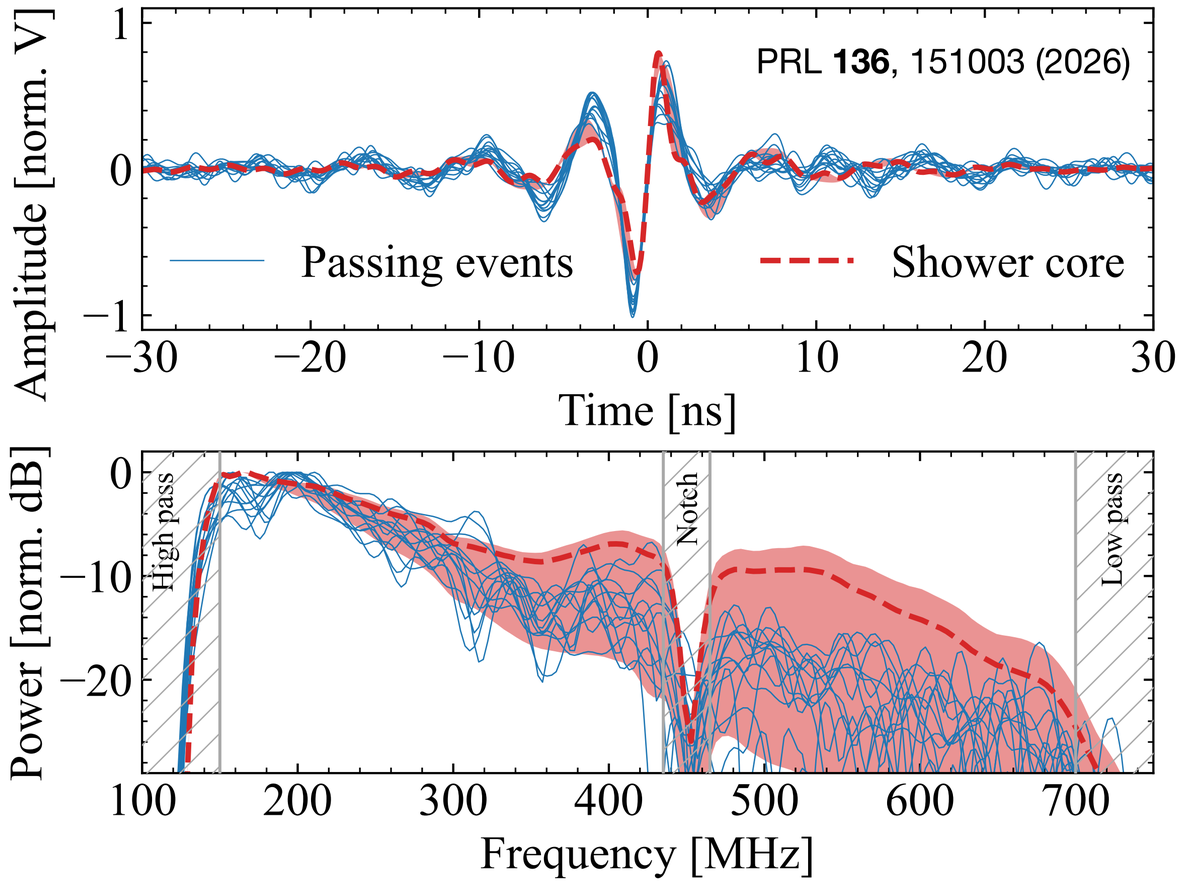
… but shallower than in-air backgrounds



Signal shape

13 observed events: all are band-filling, have common polarity, and similar signal shape

Time-aligned and summed waveforms from phased-array receivers



Good agreement with ab-initio simulation of impacting air shower core (shown in red)

CORSIKA 8: microscopic simulation of cross-media shower

Eisvogel: full-electrodynamics radio emission + propagation

(Shown here: 10^{17} eV vertical proton shower)

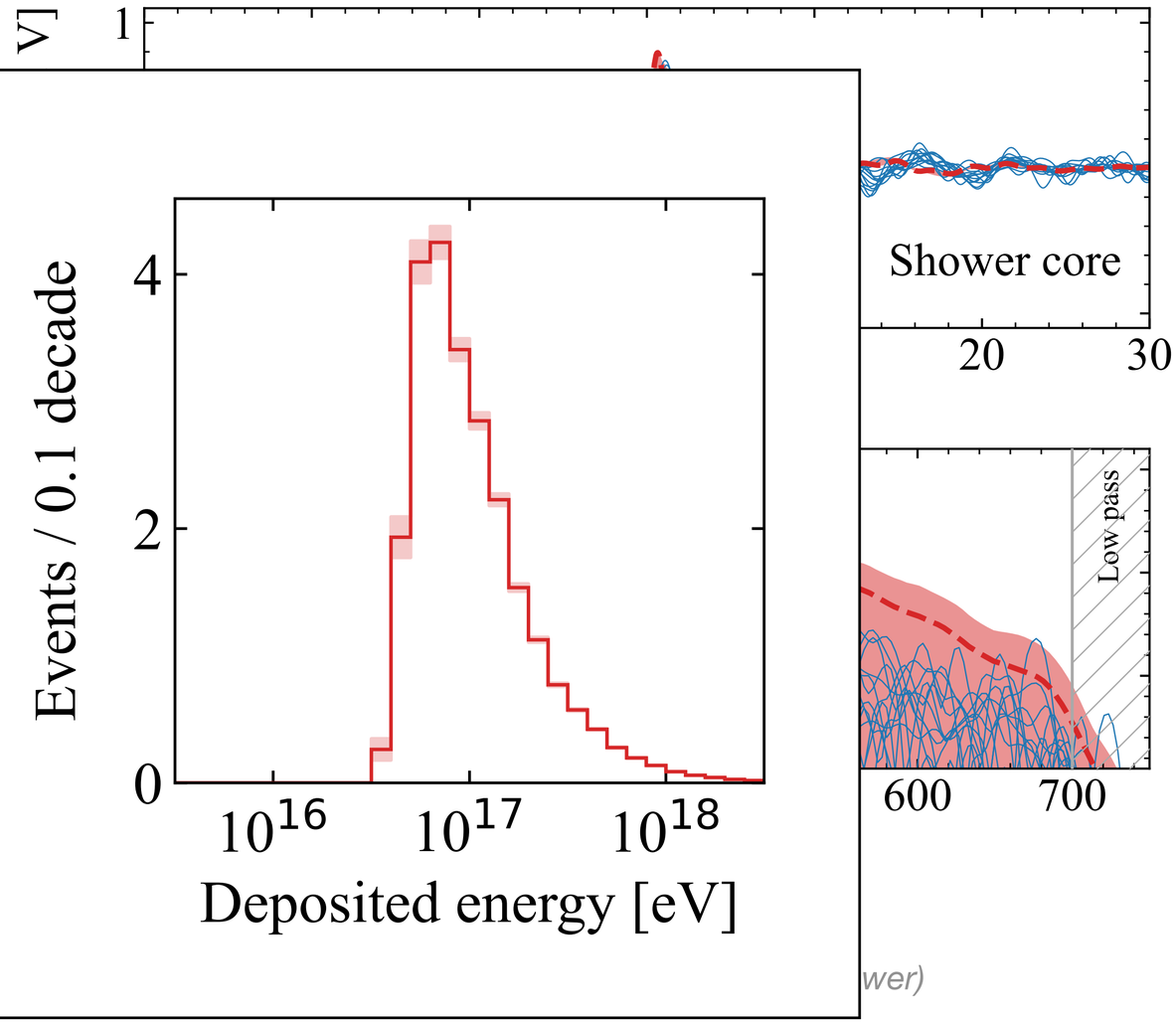
Signal shape

13 observed events: all are band-filling, have common polarity, and similar signal shape

No per-event energy reconstruction performed

Simulation indicates energy scale: 10^{17}–10^{18} eV

Atmospheric depth at South Pole: ~700g/cm^2 *(~2800m above sea level)*



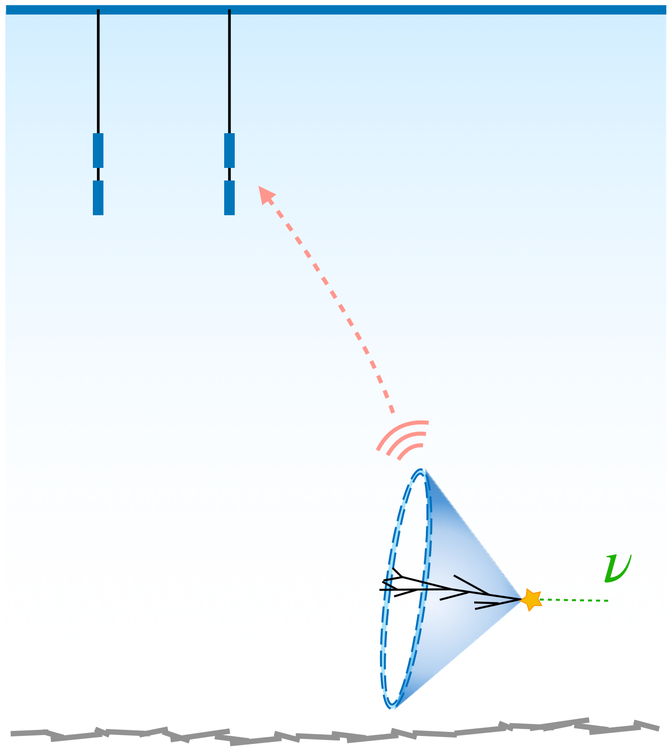
Good agre
impacting

CORSIKA

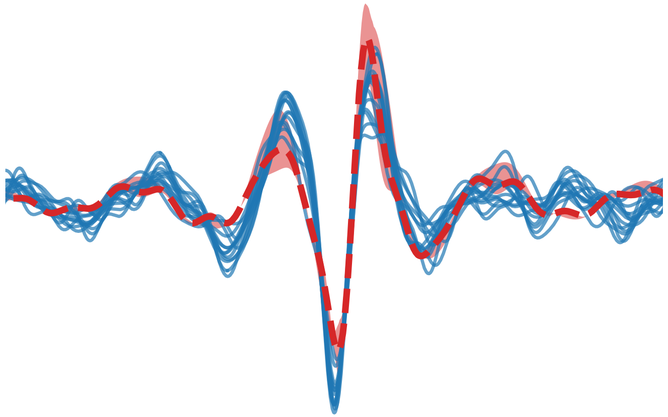
Eisvogel: f

wer)

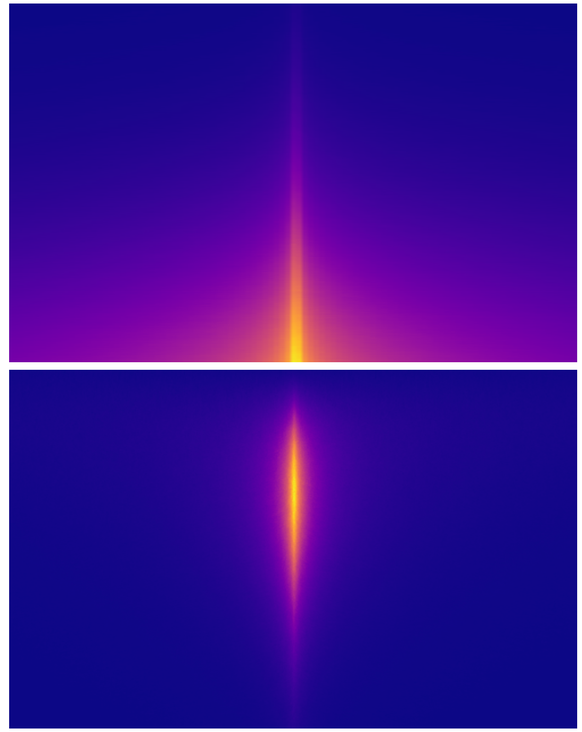
For today



In-ice radio detectors:
Why and how?



The first in-ice
cosmic ray detection



Contributing to
cosmic ray physics?

arXiv:2608.28536, ARENA proceedings

Cosmic ray properties

To contribute to cosmic ray science, we need to be able to reconstruct three quantities:

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Arrival direction

Can be reconstructed from
particle / radio footprint
of the shower on the ground

[S. Bouma thesis]

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Primary energy

Primary mass



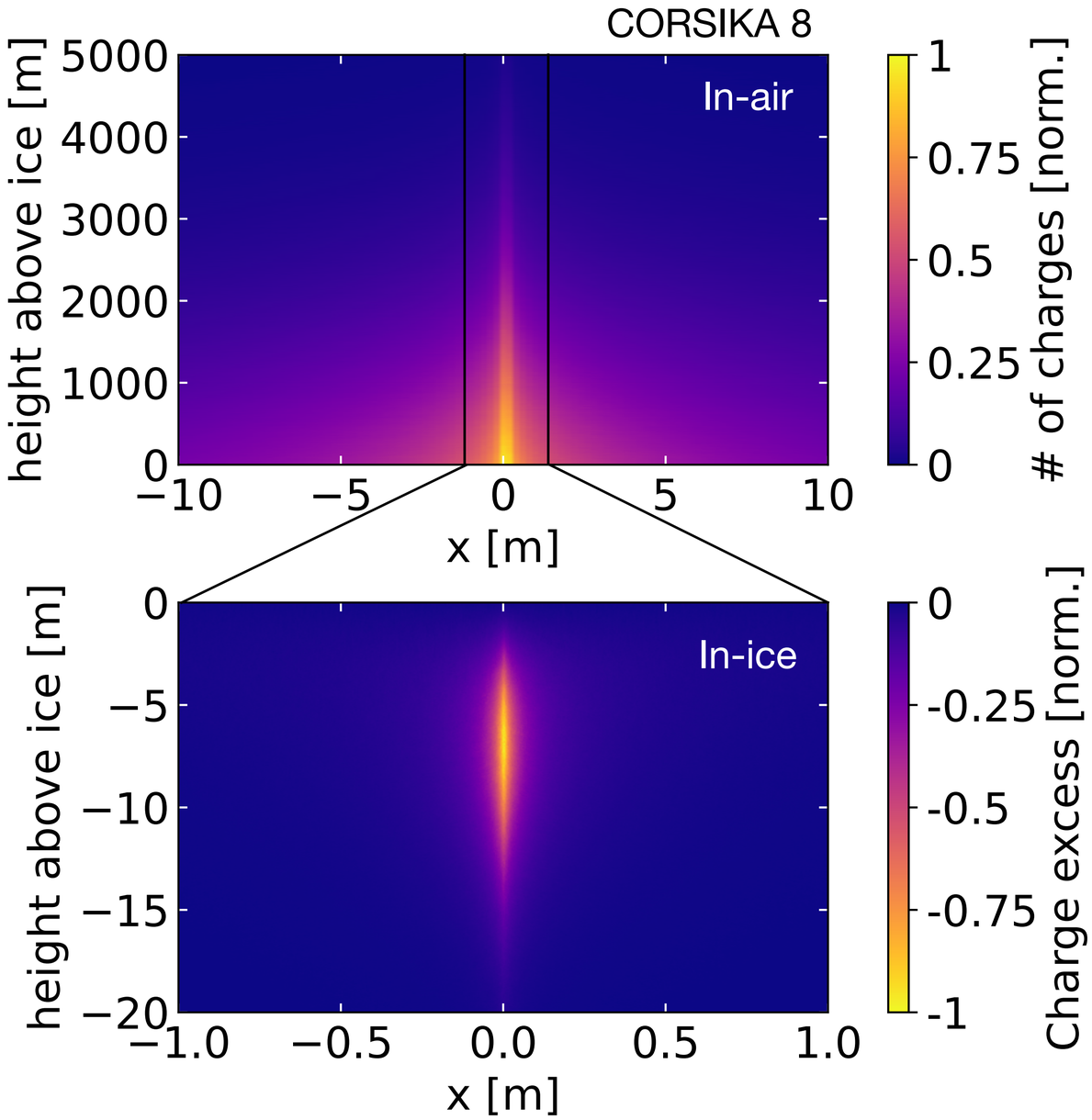
Focus on these

Observing shower cores

CR-induced in-ice cascade probes the high-energy core of the air shower

Transfer of information from *(see next few slides!)*

Air shower core → in-ice cascade → Askaryan emission



Observing shower cores

CR-induced high-energy

Transfer of i

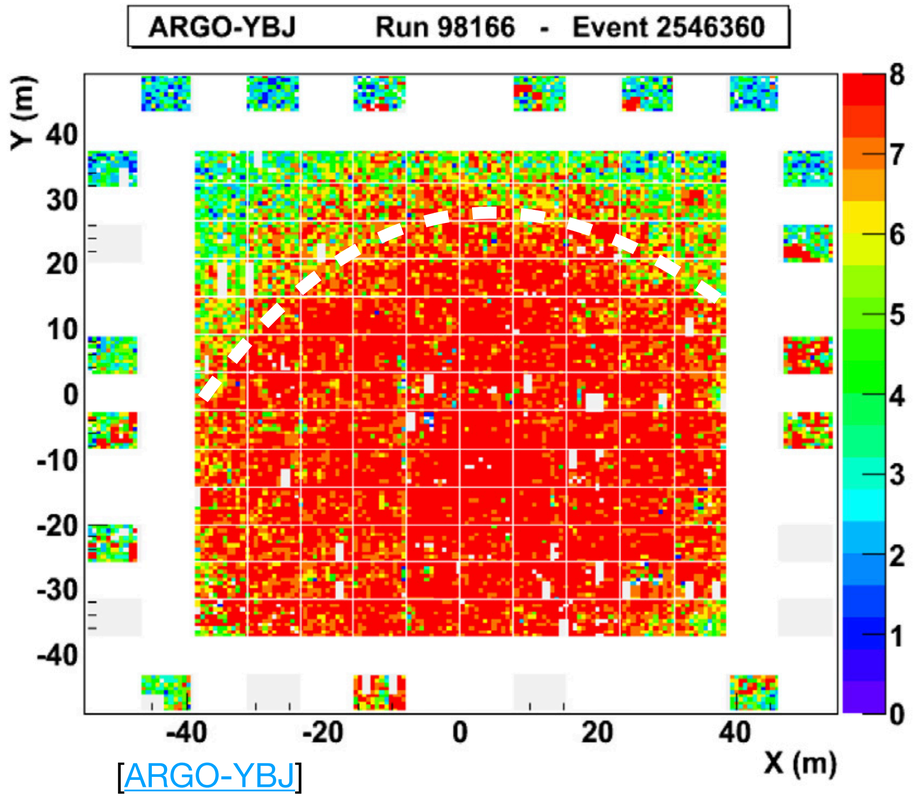
Air showe

Similar in spirit to dedicated air-shower core experiments

But through radio observation instead of dense instrumentation

e.g. ARGO-YBJ extracts the **shower age** and energy from

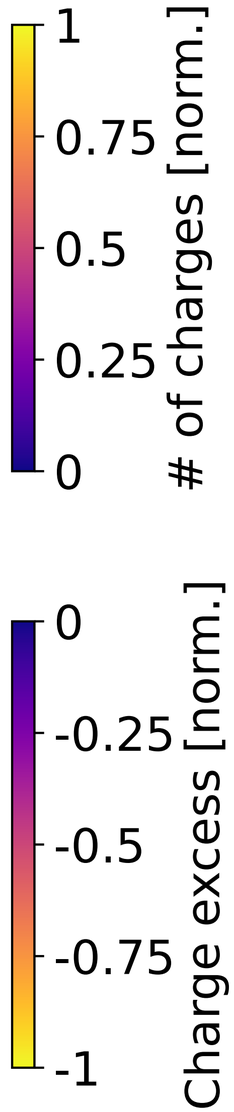
direct measurements of the air shower core size → use to reconstruct primary mass+energy



[ARGO-YBJ]



ARGO-YBJ+LHAASO



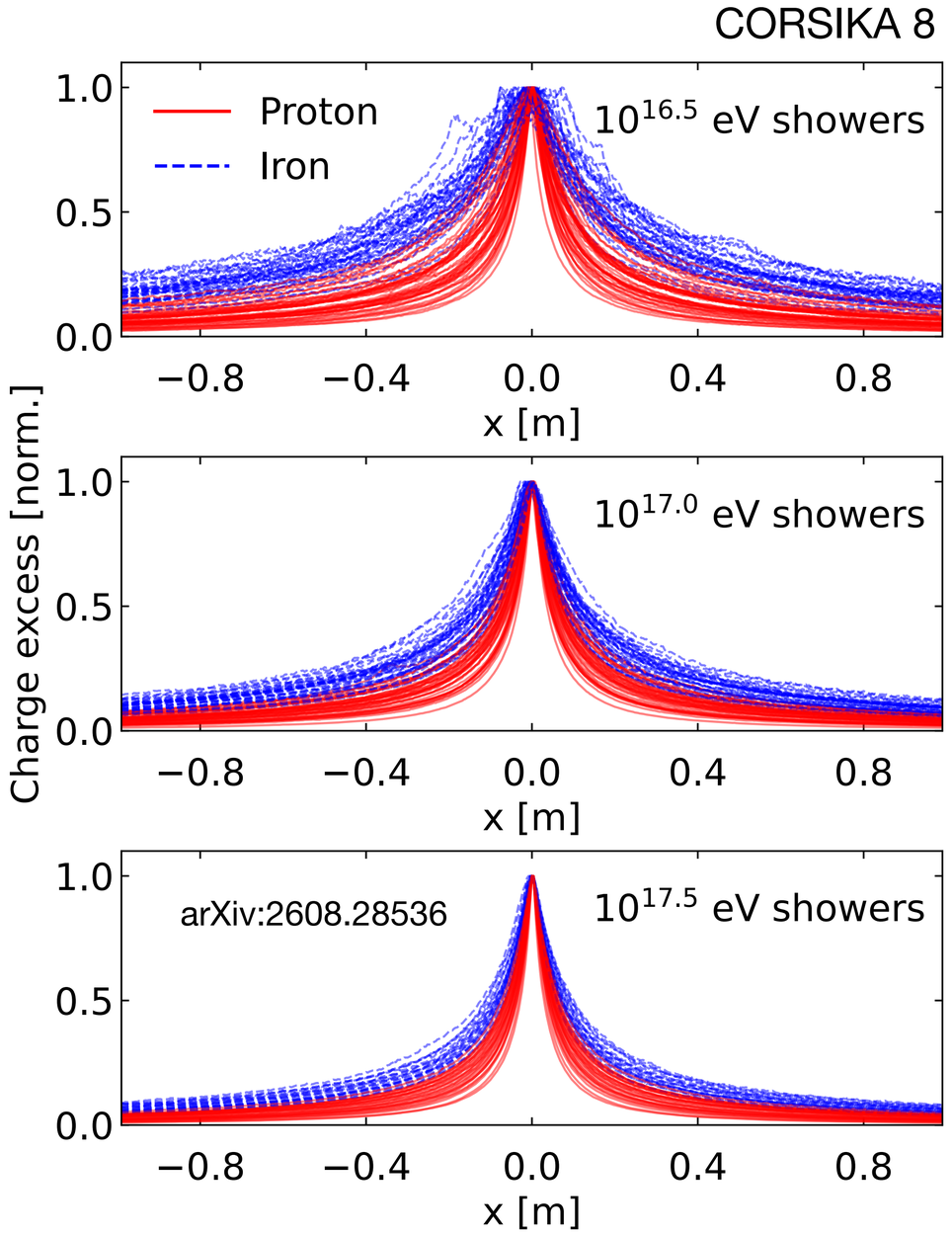
Steeply falling flux ⟹ direct observation of cores impractical above 10 PeV

Studying the in-ice shower core

Air shower core → **in-ice cascade** → Askaryan emission

We find that the lateral shape of the in-ice charge excess is also sensitive to primary mass

(But the longitudinal shape is not)



Note: shape is degenerate in mass and energy

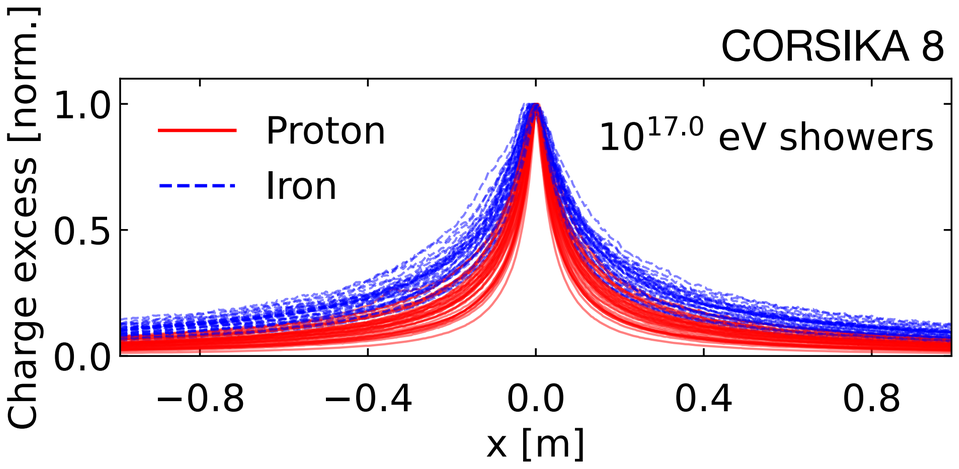
Askaryan emission = shower core tomography

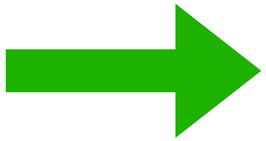
Air shower core → in-ice cascade → **Askaryan emission**

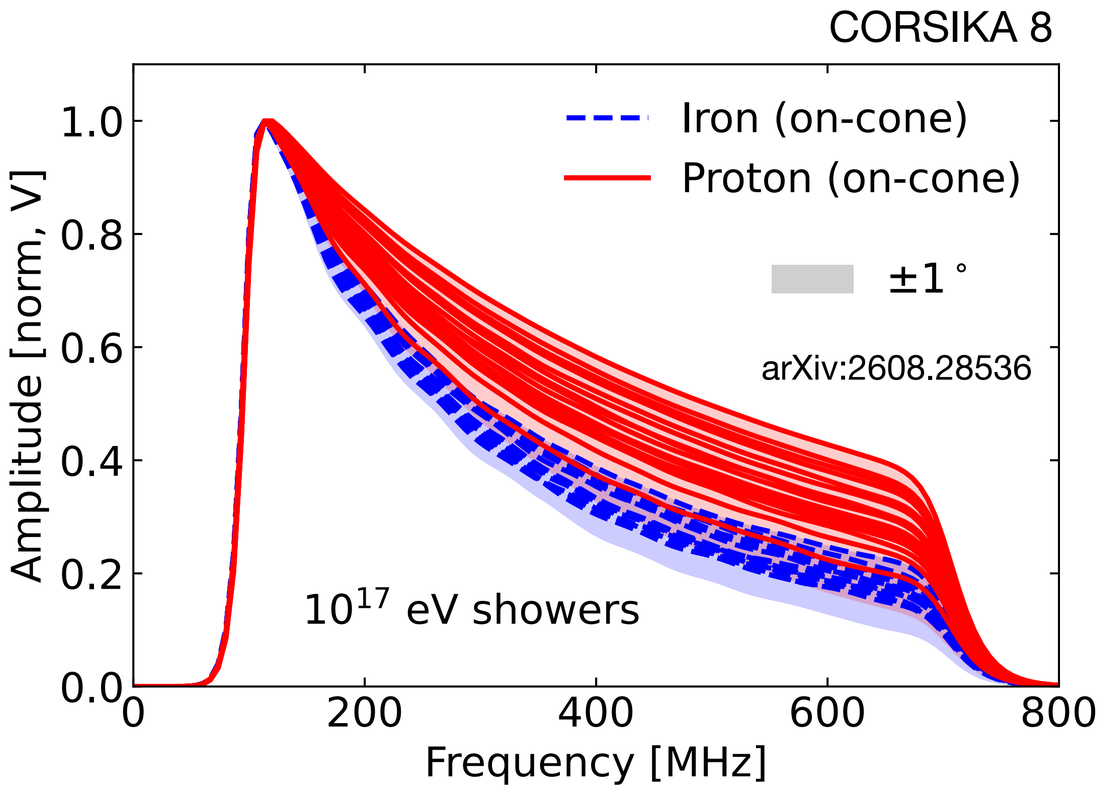
The high-energy cosmic ray flux is too small to directly observe the cores…

…But the radio signal depends on the shape of the in-ice core, and propagates over hundreds of meters

Askaryan emission = shower core tomography







Key idea: Use the <u>spectral shape</u> of the near-cone Askaryan signal to measure the lateral shape of the in-ice shower core

To simulate a realistic detector:

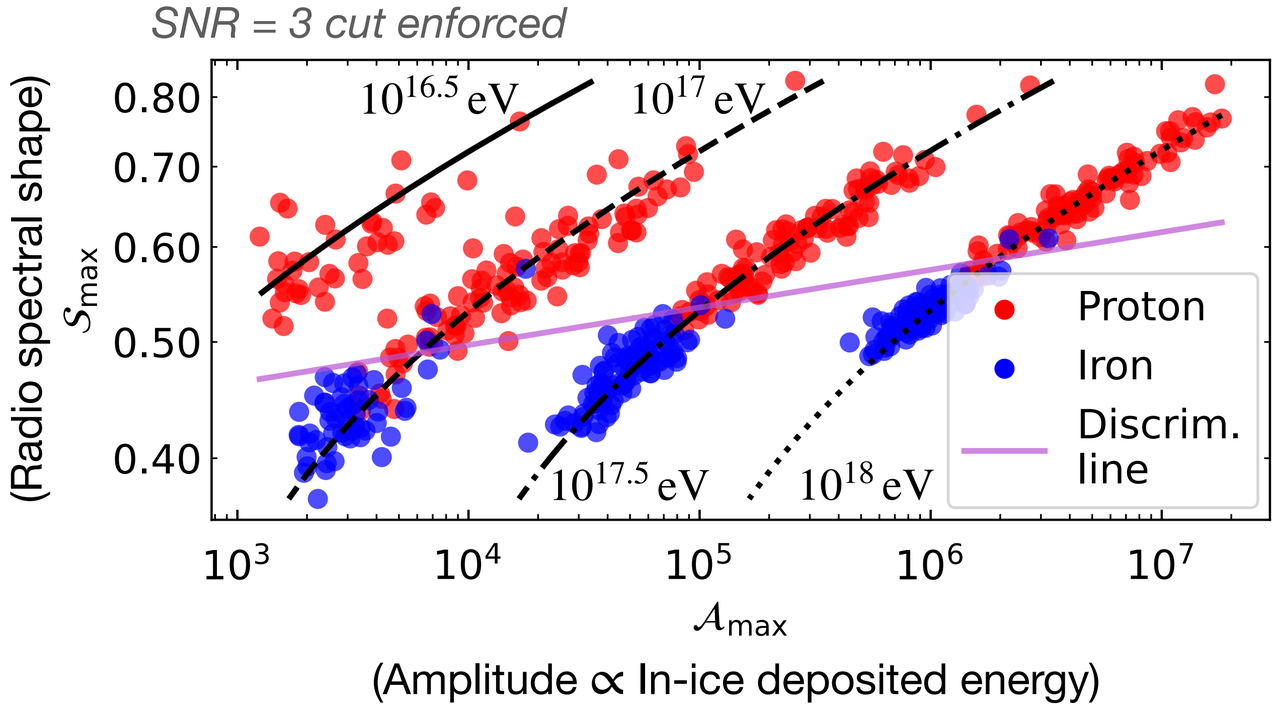
$1/f$ *antenna response*

+ RNO-G-like bandpass

Radio observables

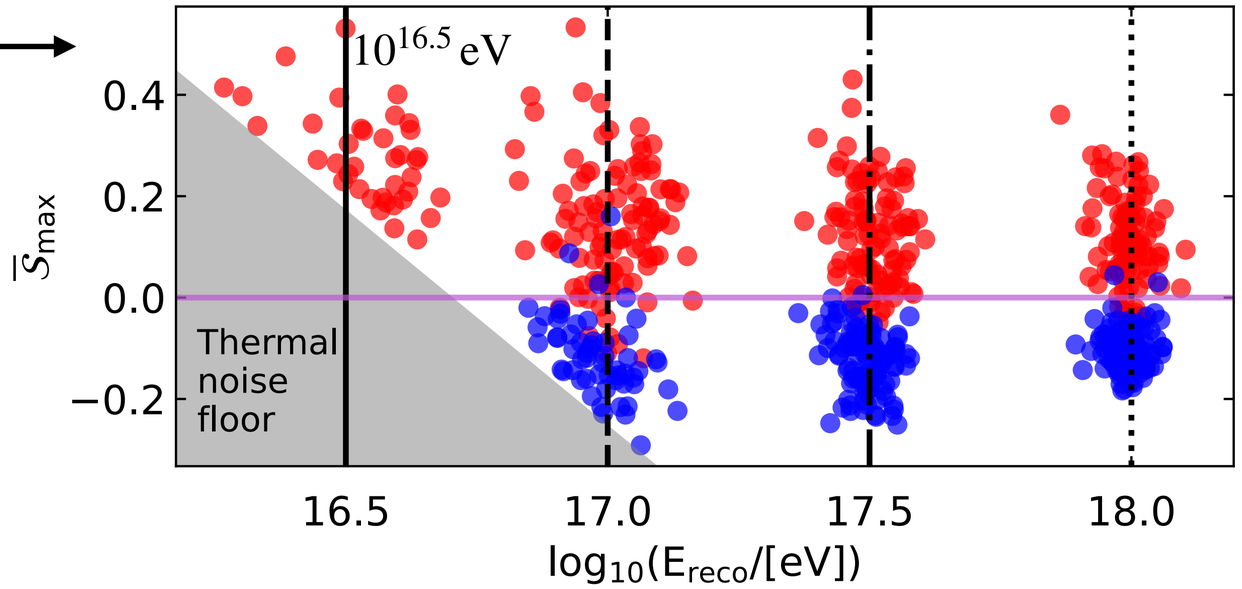
How to break the spectral shape degeneracy between mass and energy?

Add an independent observable:
Amplitude is a natural choice



Then rotate into (energy, mass) coordinates

Still to do: simulate continuous spectrum with realistic CR flux



Summary and outlook

In-ice radio detectors observe impacting cosmic-ray air shower cores

IceCube-Gen2 Radio would have >1000 CR observations per year

But: in-ice shower cores could emerge as a separate physics target

Radio observations of in-ice cores → infer primary mass and primary energy

---

Experimental capabilities will need to be pushed to make this a reality

Existing in-ice radio detectors are discovery experiments, not precision measurement devices

There are many open questions:

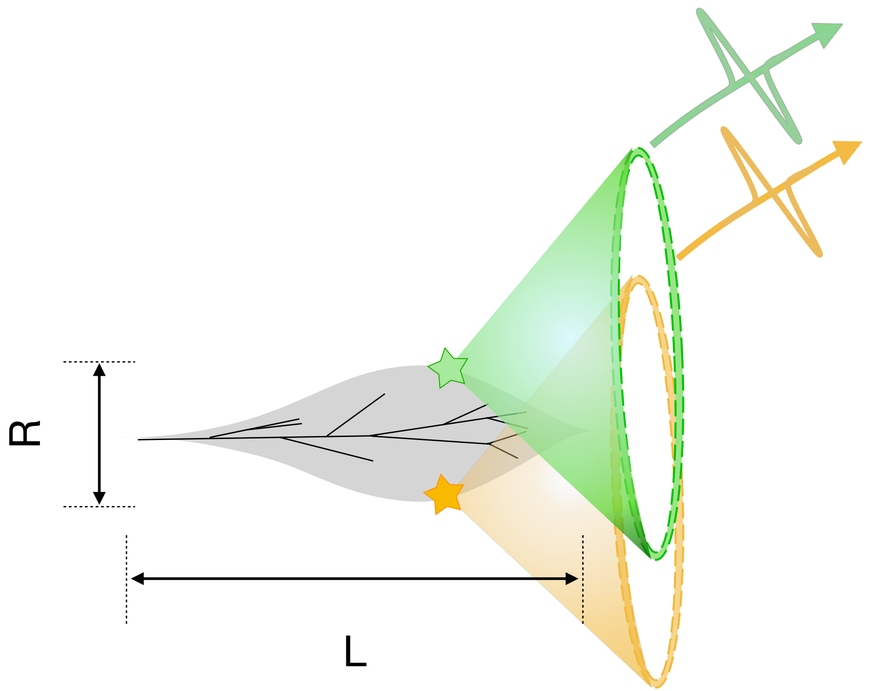
Sensitivity to hadronic model? Synergies with Auger/TA (X_{max}), KASCADE/IceTop (muon content)?

Thoughts, comments, and feedback are very welcome!

Backup

Askaryan emission = shower core tomography

Air shower core → in-ice cascade → **Askaryan emission**



Near the Cherenkov cone (where there is coherence along the longitudinal profile), the lateral spread causes destructive interference

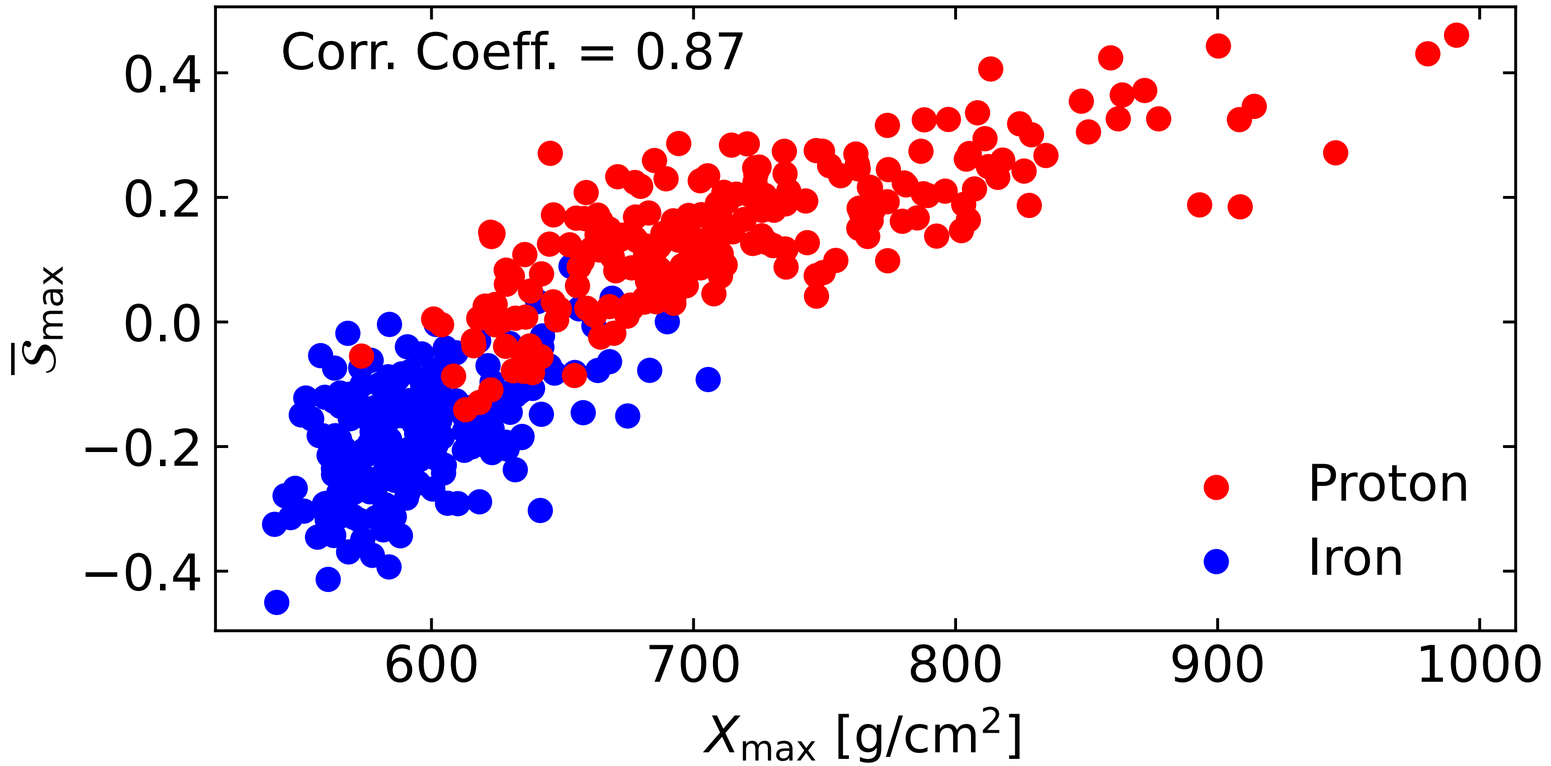
When the off-cone angle less than about $R/L \approx 1^\circ$

⇓

…The on-cone spectral shape primarily determined by lateral size of the shower

Correlation with X_{max}

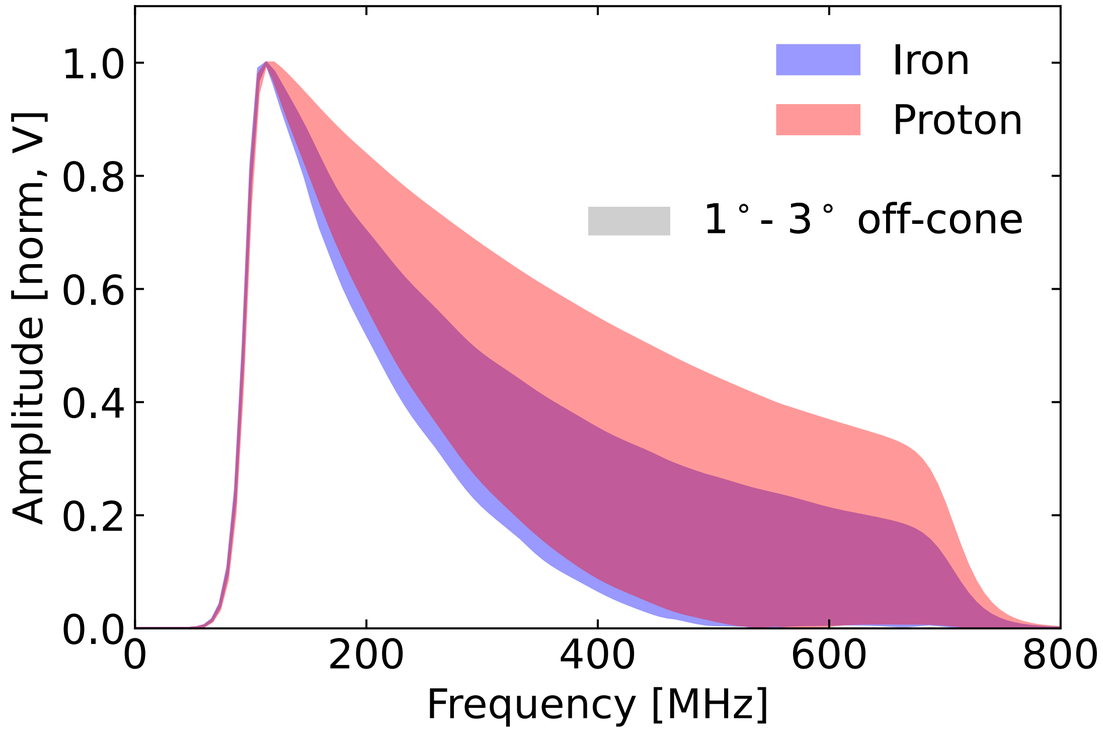
Is this "just" a different way of measuring X_{max}?



Large correlation (but not maximal!) → suggests additional / complementary information

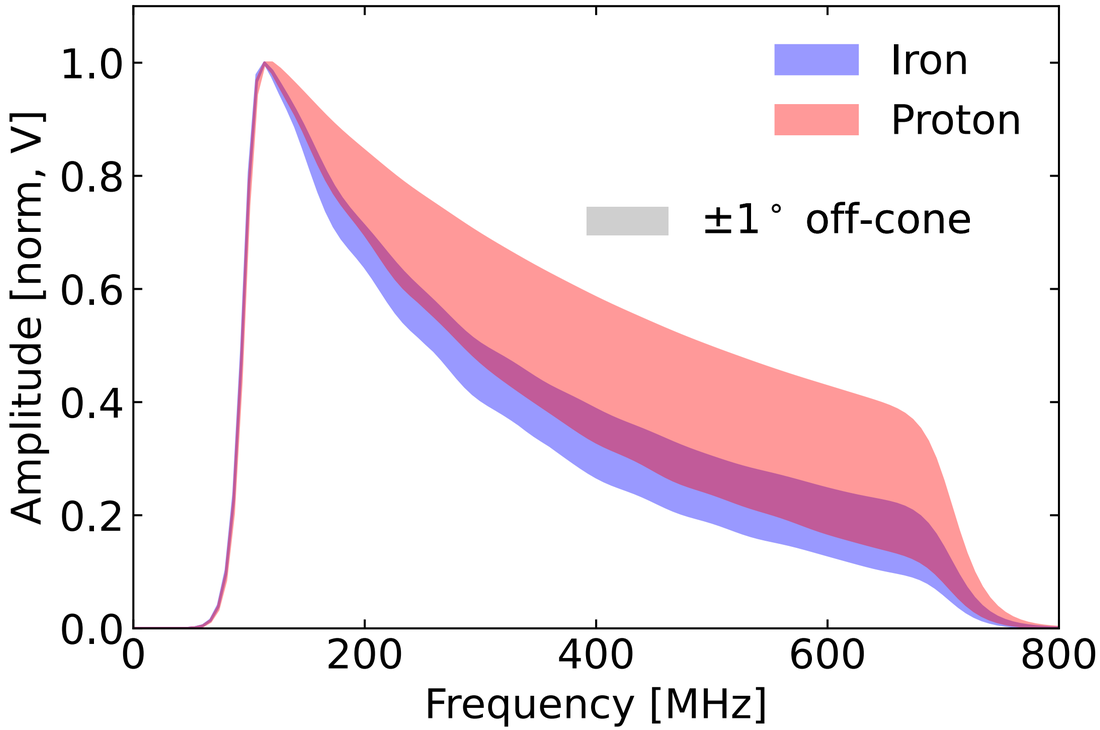
Askaryan emission = shower core tomography

What happens if you miss the cone by more?



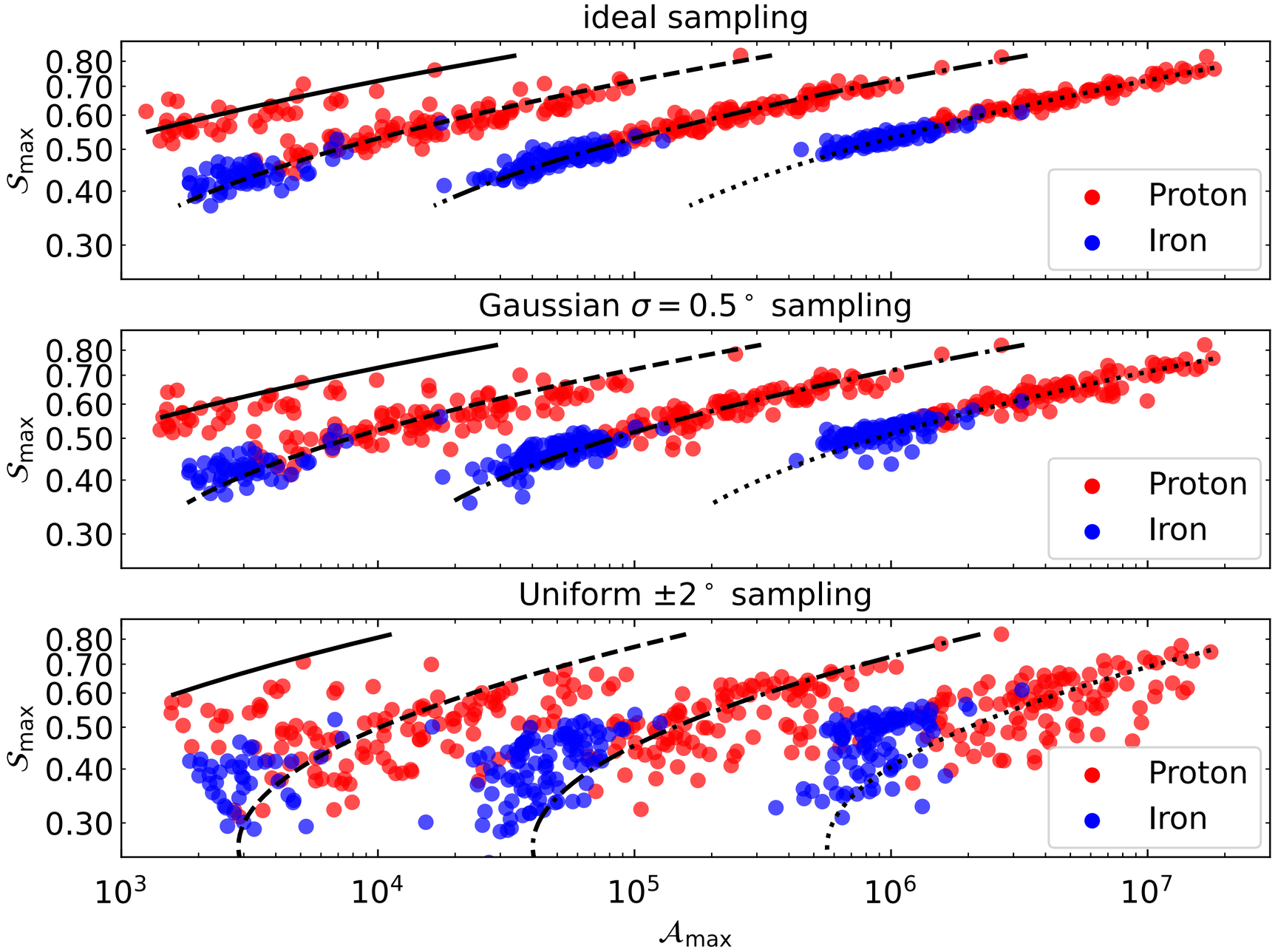
Much more overlap in proton/iron distributions!

CORSIKA 8



Discrimination power comes from separation of proton/iron lateral distributions

Three different cone samplings



Intermediate mass sensitivity

Intermediate mass showers can also be mapped to the $\overline{S}_{max}$ variable for reconstruction

