Future Observatories and Techniques

Partial list of projects (UHECR/ν)

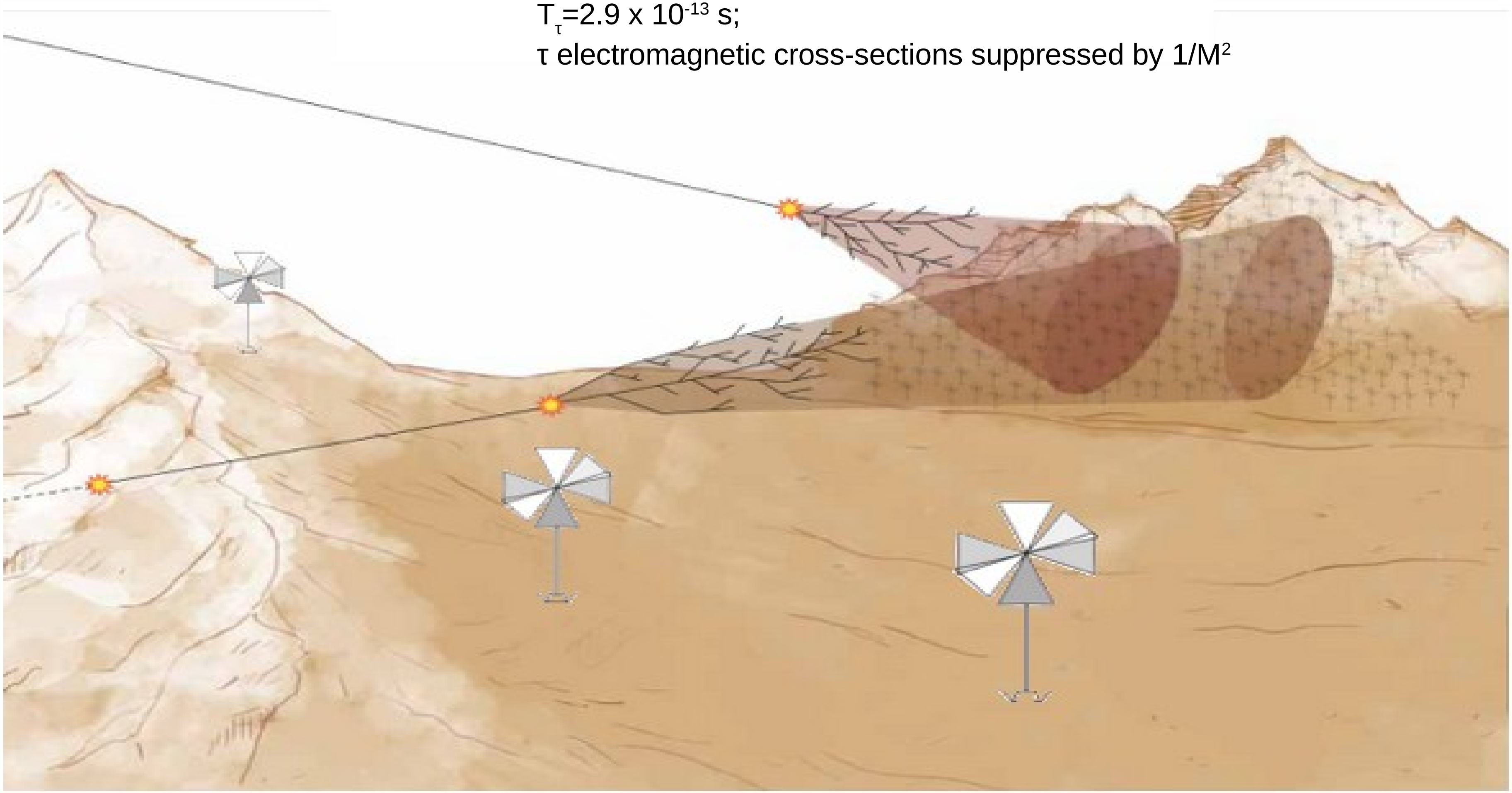
- IceCube-Gen2: (South Pole, Antarctica)
  - In-ice photomultipliers + surface radio array (geomagnetic UHECR detection) + in-ice radio array (Askaryan UHE ν detection)
- ARIANNA-200: (Moore’s Bay, Antarctica)
  - 200 radio antenna stations; 8 Rx/station
- RNO-G: (Summit Station, Greenland)
  - 30 in-ice stations (100 m deep); 16 Rx/station
- RET-CR and RET-nu (Taylor Dome, Antarctica)
  - RADAR radio technique, prototyping at Taylor Dome, Antarctica
- GRAND-200K (China)
  - BEACON & Deep Valley (tau neutrinos only)
- POEMMA (Space-based [JEM/EUSO heritage)

Grand designs: the Giant Array for Neutrino Detection project aims to detect ultrahigh-energy neutrinos originating from deep space using 200,000 antennas spread across mountainous regions around the world. (Courtesy: GRAND)

Science and Design

$T_\tau = 2.9 \times 10^{-13}$ s;

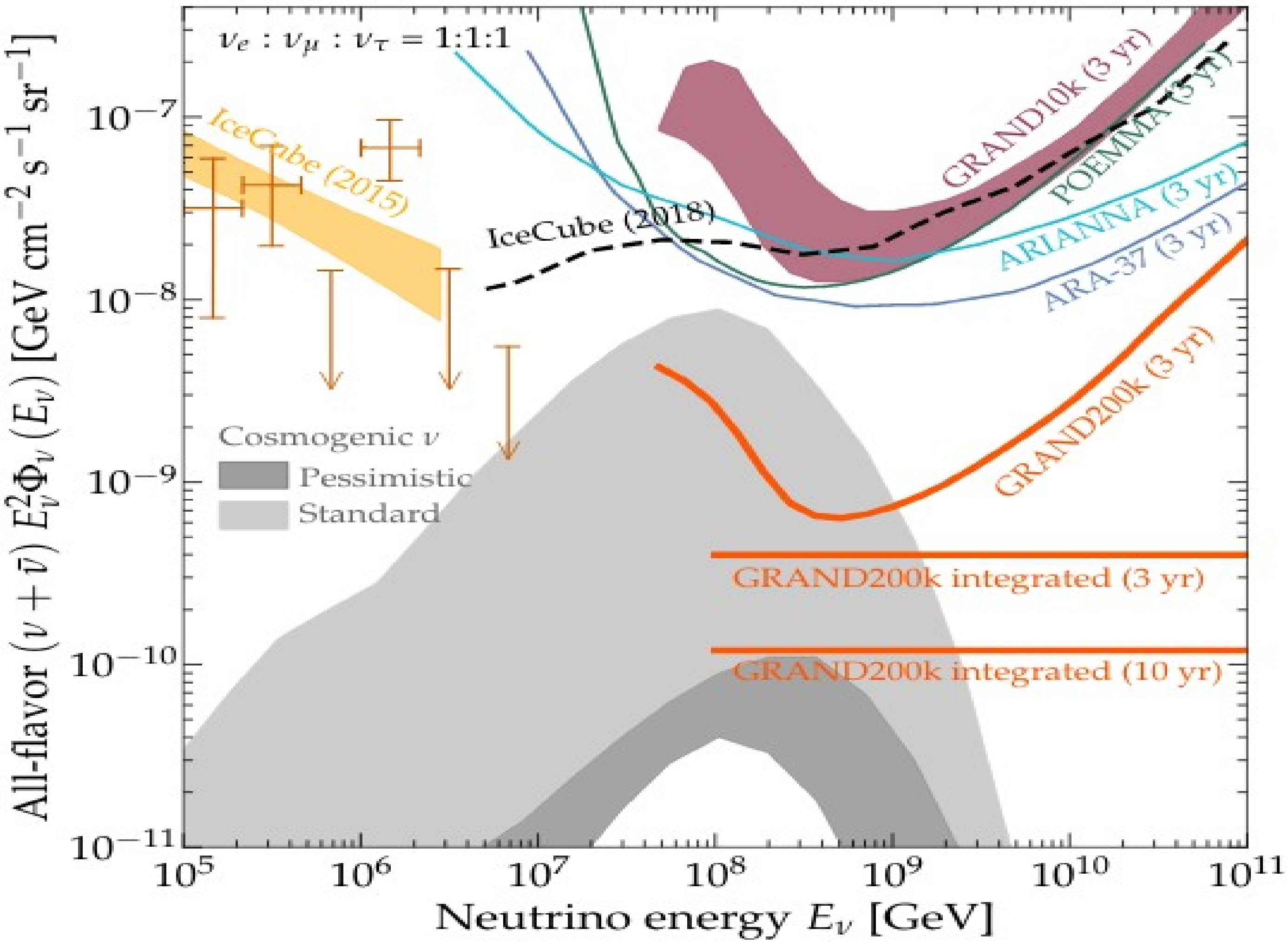
τ electromagnetic cross-sections suppressed by $1/M^2$



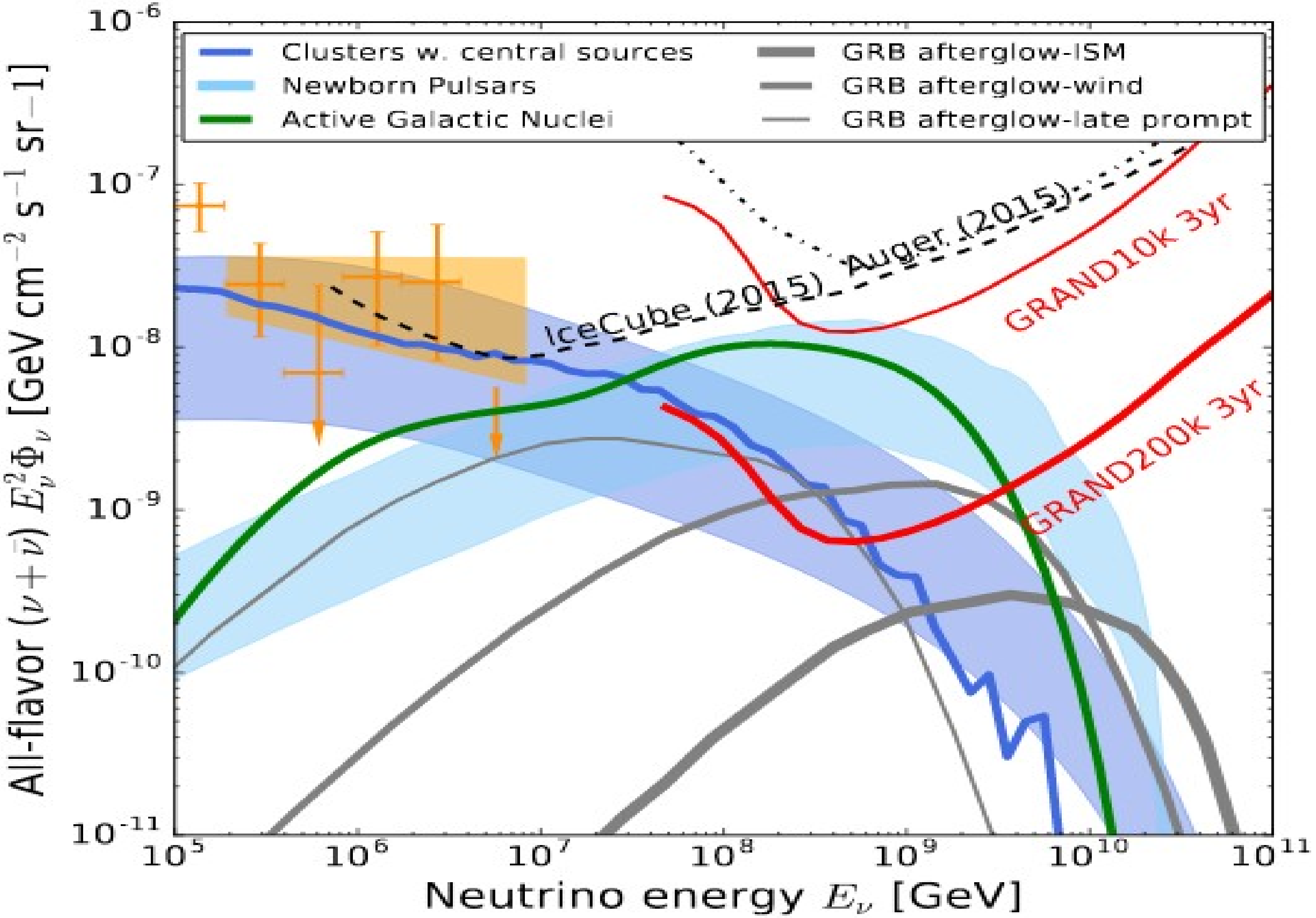
Why would CN consider $1B GRAND?

- Inexpensive
  - construction of a horn antenna ~ $20 in raw material
  - TUNKA-REX (~6 publications) based on $30K hardware budget
- Optimal frequency regime for geomagnetic detection of air showers: 30-200 MHz
  - Can program 200 MHz bandwidth digital scopes @$100/channel
- Physics: dN/dE, composition, lightning discharge
- Simulations of radio signals from UHECR are mature!
  - CoREAS / ZHSAireS: Uncertainty in radio signal yield~uncertainty in UHECR simulations (ergo, radio now part of ‘standard’ hybrid)

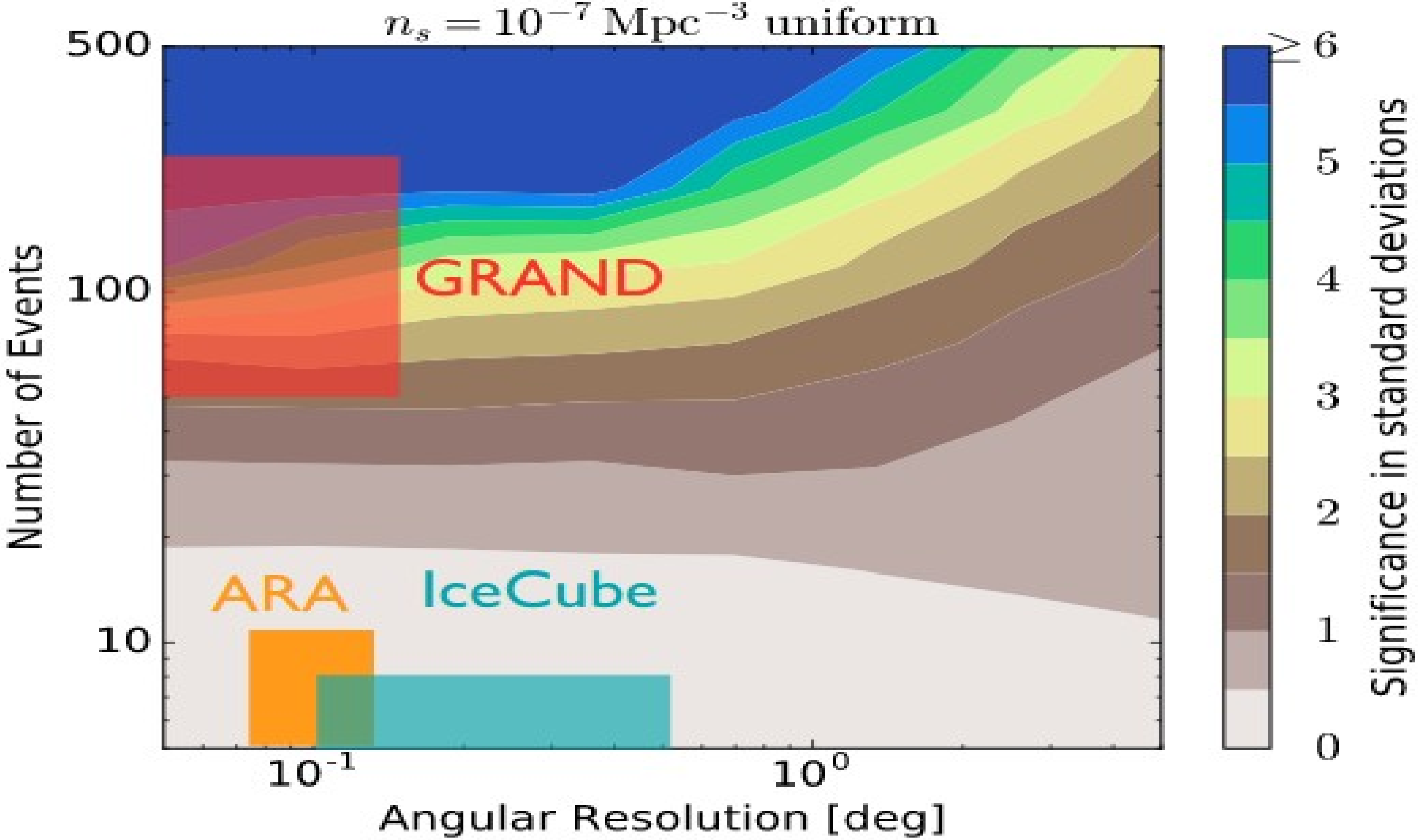
Science comparison

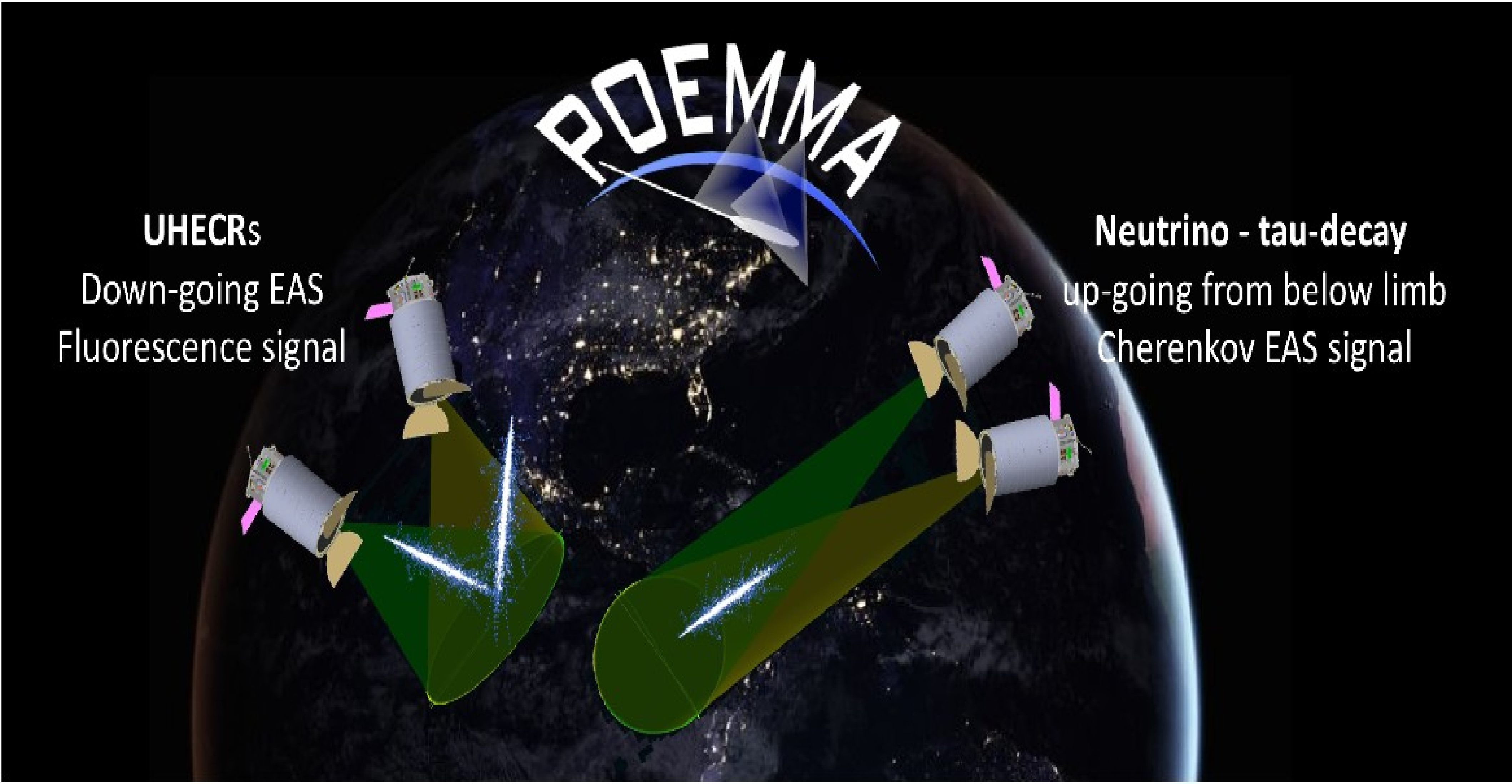


Variety of sources

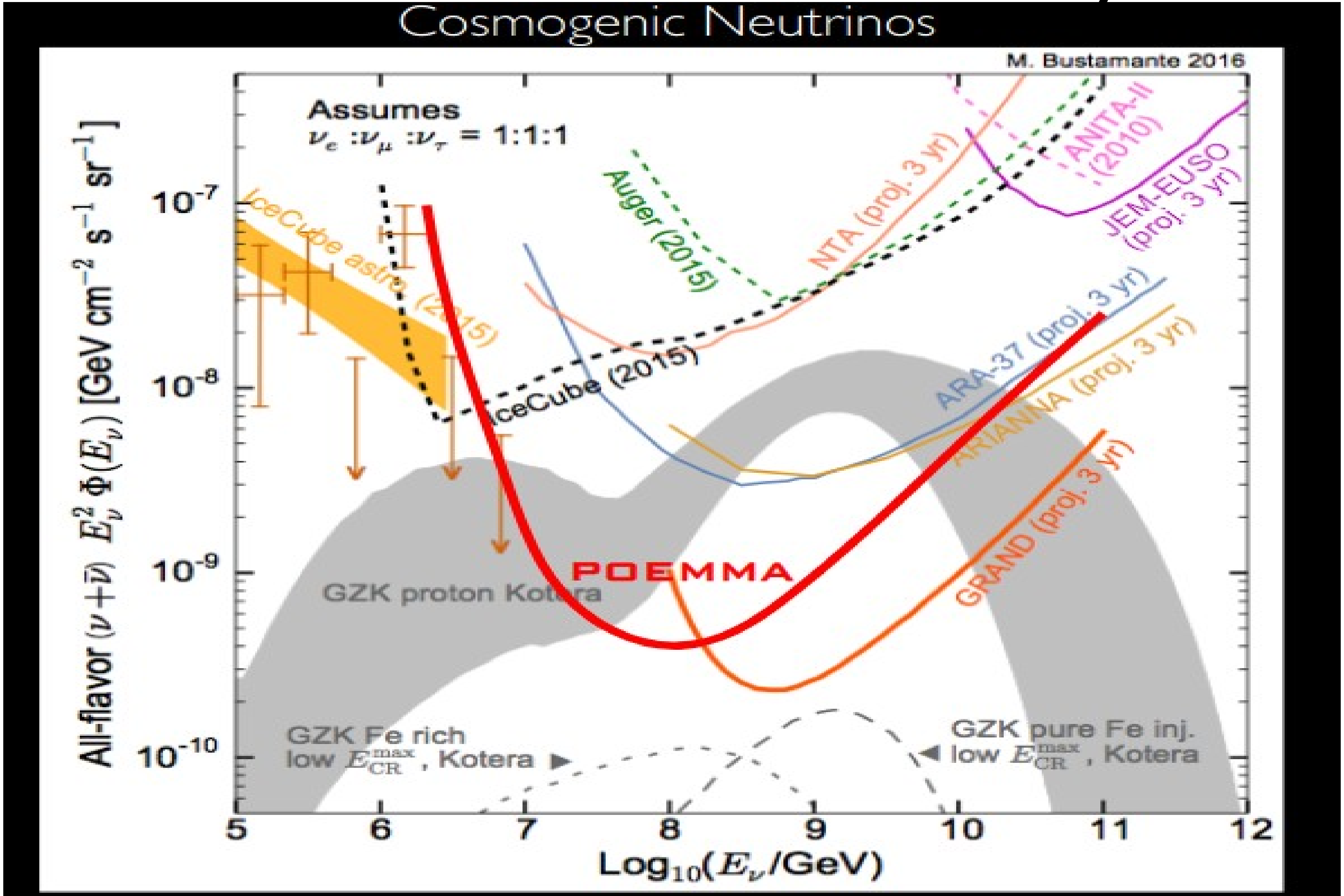


Neutrino pointing

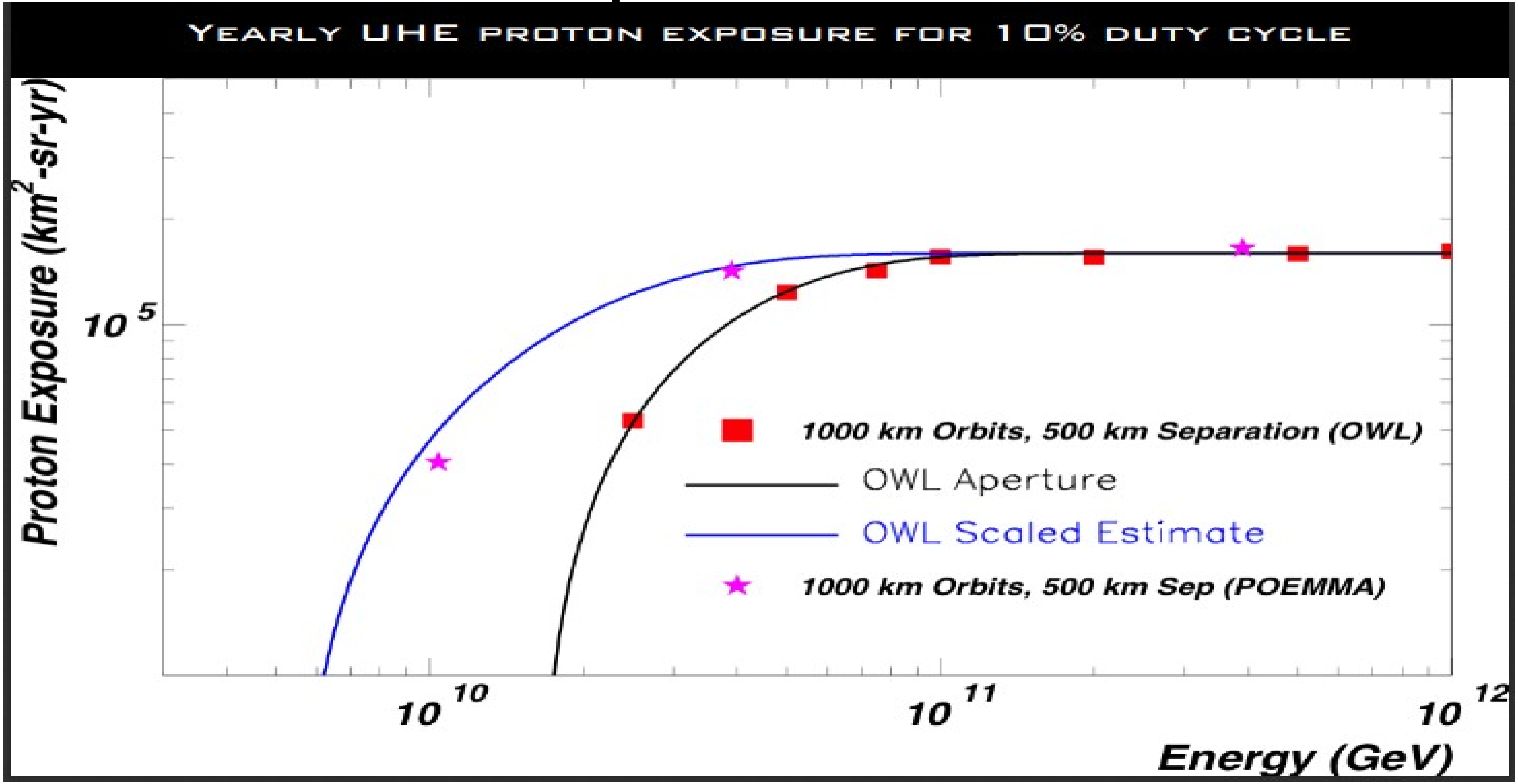



POEMMA
UHECRs
Down-going EAS
Fluorescence signal
Neutrino - tau-decay
up-going from below limb
Cherenkov EAS signal

POEMMA sensitivity



POEMMA exposure vis-a-vis GZK



TARA (Utah, USA)

- радиолокационный метод обнаружения частоты космических лучей
  - космические лучи с энергией теннисного мяча

Design, Construction and Operation of a Low-Power, Autonomous Radio-Frequency Data-Acquisition Station for the TARA Experiment

S. Kunwar[b,*], R. Abbasi[a], C. Allen[b], L. Beard[c], J. Belz[a], D. Besson[b,g], M. Byrne[a], B. Farhang-Boroujeny[a], A. Gardner[a], W.H. Gillman[d], W. Hanlon[a], J. Hanson[b], S.L. Larson[e], T. Myers[a], A. Novikov[g], S. Prohira[b], K. Ratzlaff[b], A. Shustov[g], M. Smirnova[g], P. Sokolsky[a], H. Takai[f], G.B. Thomson[a], D. von Maluski[a], R. Young[b]

[a] *University of Utah, Salt Lake City, UT 84112 U.S.A.*
[b] *University of Kansas, Lawrence, KS 66045 U.S.A.*
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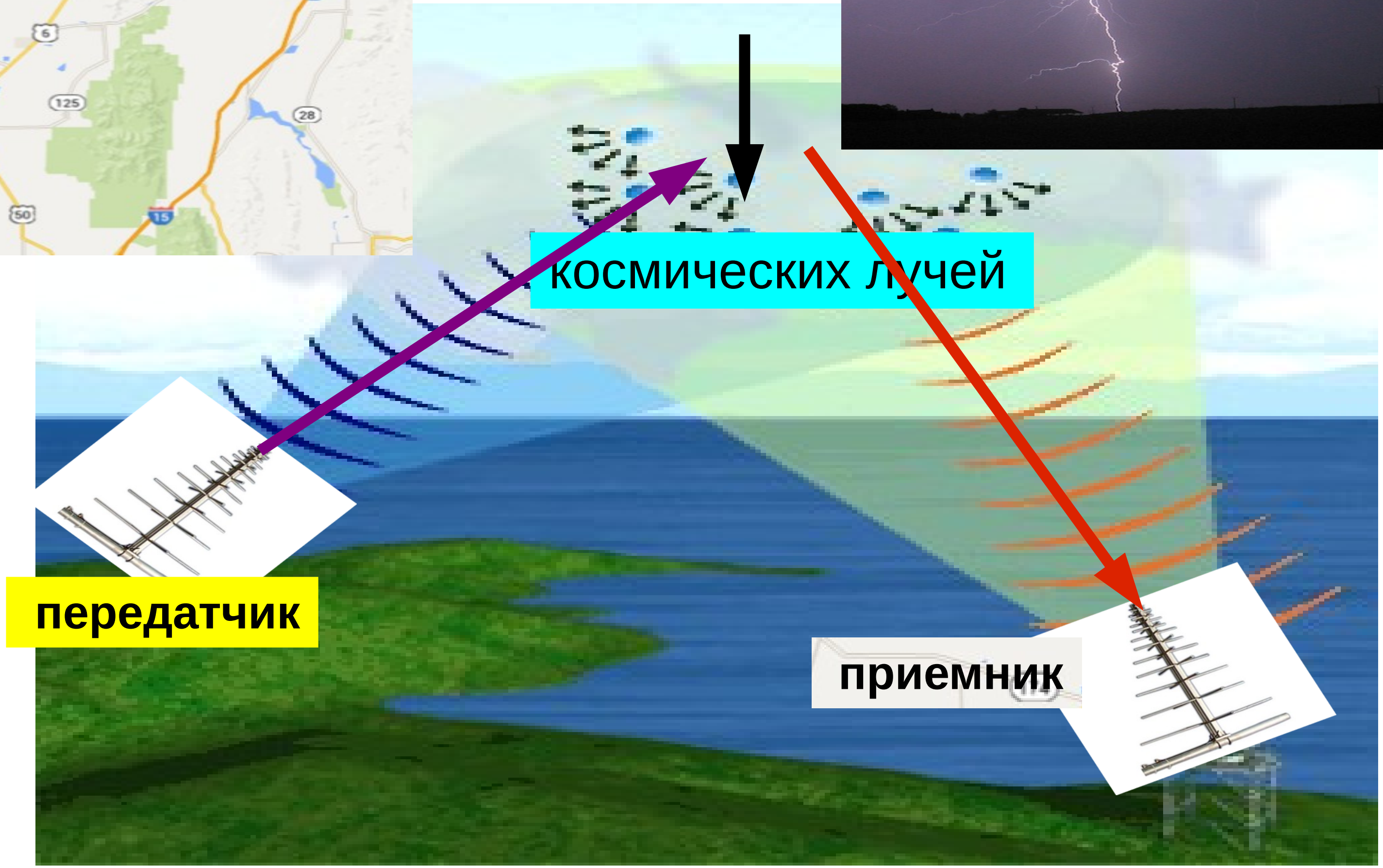
[e] *Utah State University, Logan, Utah 84322 U.S.A.*
[f] *Brookhaven National Laboratory, Upton, NY 11973 U.S.A.*
[g] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409 Russia*

Чем работает?



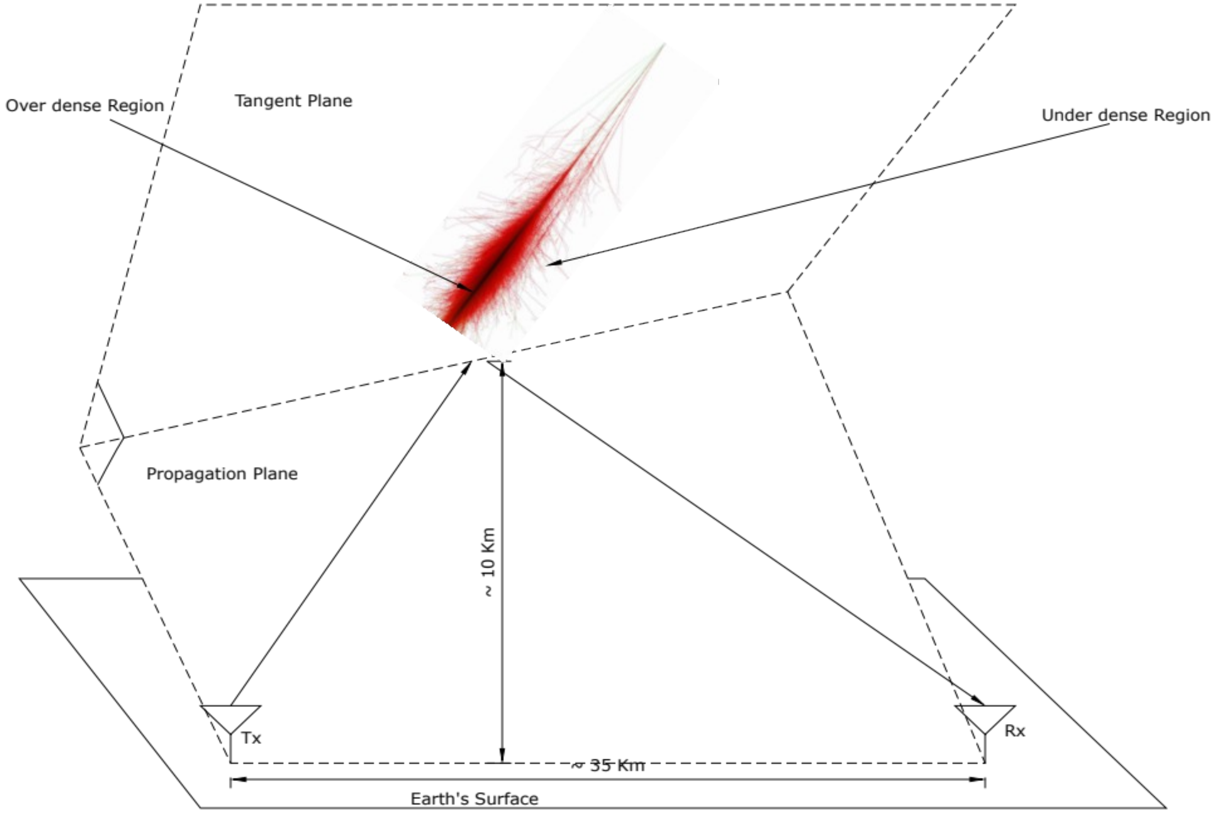
Given the diagram on the right, sketch the expected spectrogram of V(t)

Bi – Static Radar

Cross – section?

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_{Tx}^2 R_{Rx}^2} = P_t G_t G_r \left[\frac{\sigma c^2}{(4\pi)^3 f^2 R_{Tx}^2 R_{Rx}^2} \right]$$

~~Under – dense($\nu > \nu_e$)~~
Fatal!



$$\nu_e = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}} \frac{1}{2\pi}$$

Over - dense ($\nu < \nu_e$)
Thin Wire approximation!

Physics

Plasma trail from EAS tail

Let the electrons experience transmitter E-field with CW *sounding frequency* $\omega = 2\pi\nu$:

$$m_e(\ddot{\vec{x}} + \gamma\dot{\vec{x}} + \omega_0^2\vec{x}) = -e\vec{E}\exp(-i\omega t) \tag{4}$$

$$\vec{p} = -e\vec{x} = \frac{e^2}{m}(\omega_0^2 - \omega^2 - i\omega\gamma)^{-1}\vec{E} \tag{5}$$

$$\frac{\vec{P}}{\epsilon_0\vec{E}} = \chi_e, \quad N, \quad \sum_i f_i = Z \tag{6}$$

$$\frac{\epsilon}{\epsilon_0} = 1 + \frac{Ne^2}{\epsilon_0 m_e}\sum_j f_j(\omega_0^2 - \omega^2 - i\omega\gamma)^{-1} \tag{7}$$

High-frequency limit

Let $\omega \gg \omega_j$. We have

$$\frac{\epsilon}{\epsilon_0} = 1 - \frac{ZNe^2}{\epsilon_0 m_e}\omega^{-2} \tag{8}$$

$$\omega_p^2 = \frac{ZNe^2}{\epsilon_0 m_e} \tag{9}$$

$$n_e = NZ \tag{10}$$

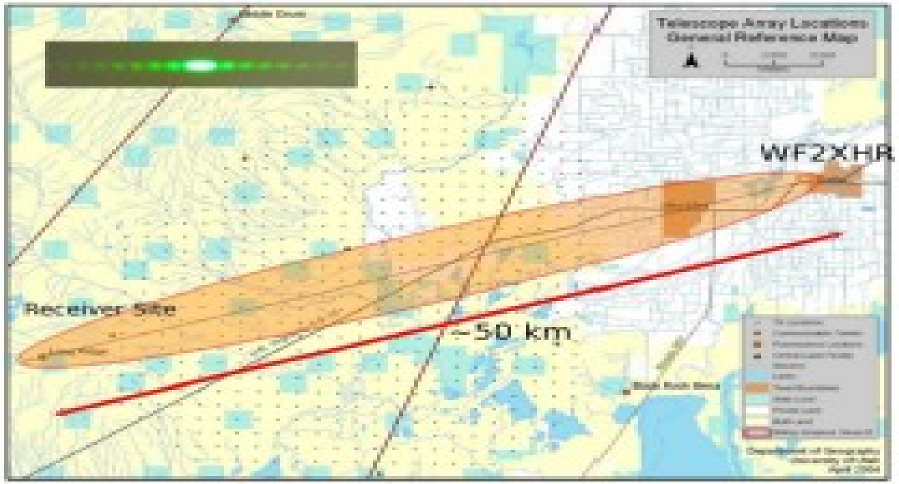
$$\boxed{\nu_p = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}} \tag{11}$$

Terminology:

If $\nu < \nu_p$, the shower trail is over-dense. If $\nu > \nu_p$, then the shower trail is under-dense.

Goal of TARA

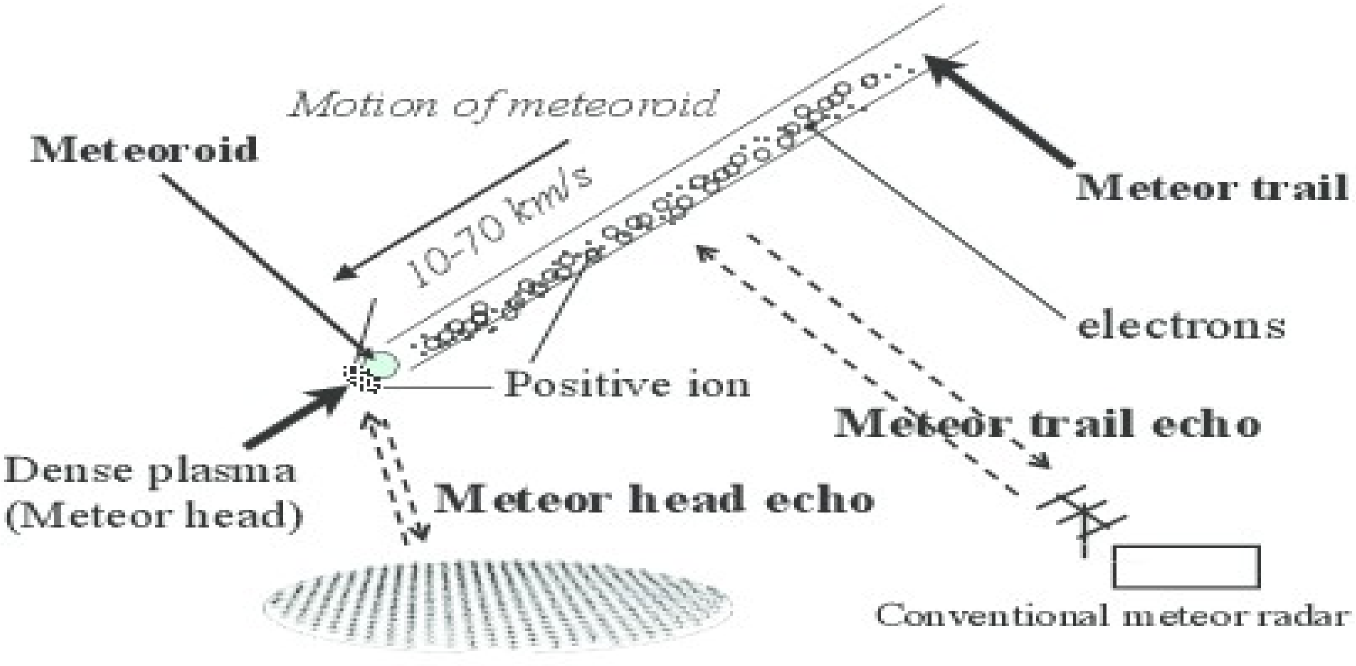
- TARA aims to reduce costs of detecting the highest energy cosmic rays
- Bi-static radar system situated above Telescope Array (TA) surface detector (SD)
- Receiver co-located with Long-ridge fluorescence detector (FD)
- Situated to allow for coincidence studies



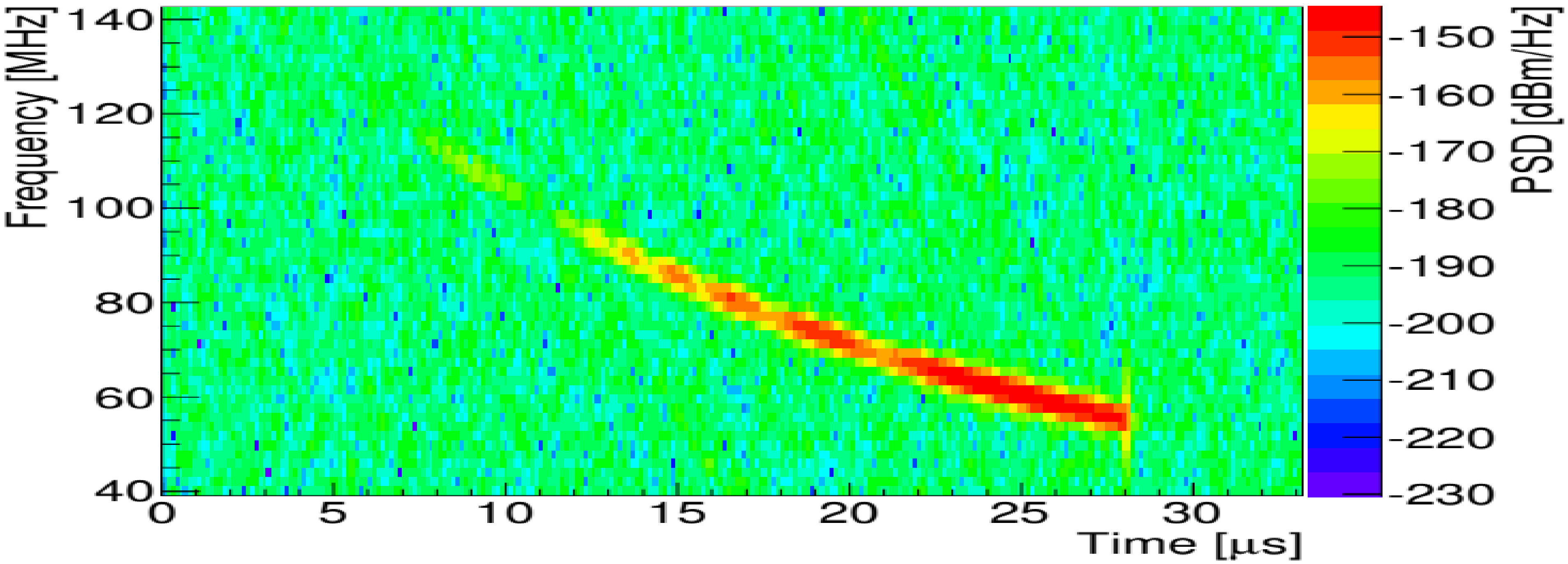
Ballpark figures.

Exp.	TA	PAO	TARA
Cost (Mill. USD)	50	150	1.5
Stations/Units	500	1600	2
Energy Threshold (EeV)	10 (excluding TALE)	1 (hybrid)	10
Surface Area (km^2)	800	3000	200
(km^2)/(Mill. USD)	20	20	100

Anatomy of a reflector

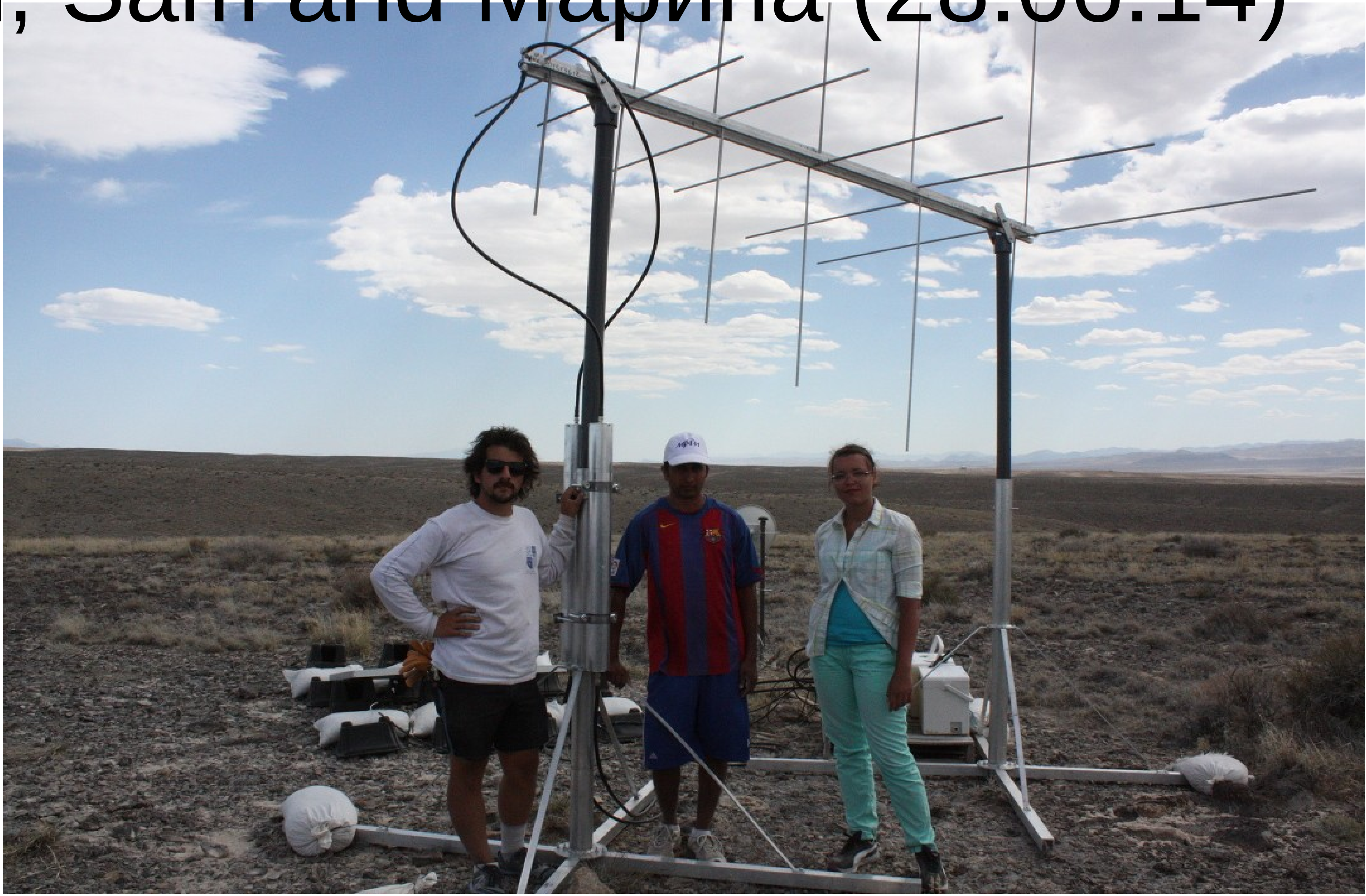


Chirps!



Frequency [MHz]
140
120
100
80
60
40
0
5
10
15
20
25
30
Time [µs]
-150
-160
-170
-180
-190
-200
-210
-220
-230
PSD [dBm/Hz]

Steven, Sam and Марина (28.06.14)

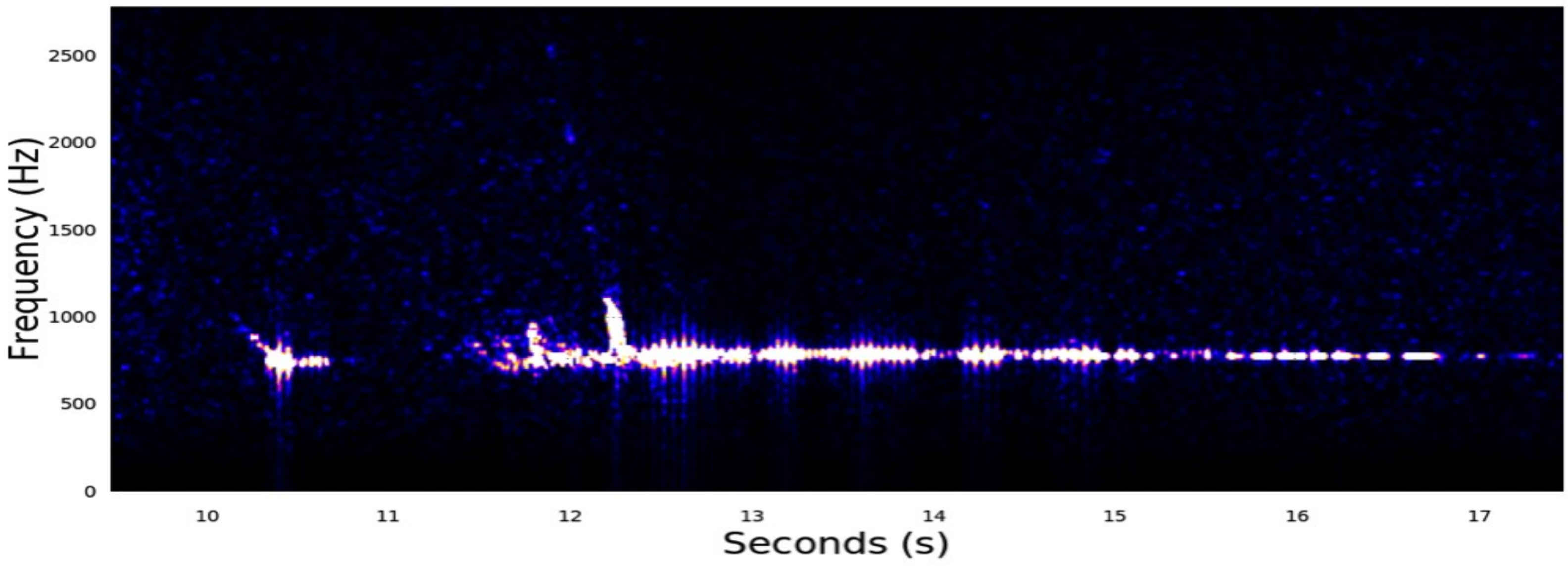


Саша (18.08.14) (ремонт)

TARA Meteorite (80 km elevation; no LOS)

Head Echo (~ Shower Front)

Trail Echo (~ Ionization Trail)



Tx : TARA Utah Back lobe

Rx : Lawrence, KS

1600 km

Plasmas and critical frequencies

Free ionization trail ~ coupled harmonic oscillators

$F=ma=qE(\omega,t)$ + damping-term (dissipative collisions)

$d^2x/dt^2=q\omega E(\omega,t)/(\omega+i*f_{collisions})$

Resonant (plasma frequency): $\omega_P \sim (q^2/m)^{1/2}$ (cf: $\omega=\text{sqrt}(k/m)$)

Derive equivalent of complex refractive index

imaginary component: attenuation ($\rightarrow$ in absence of damping)

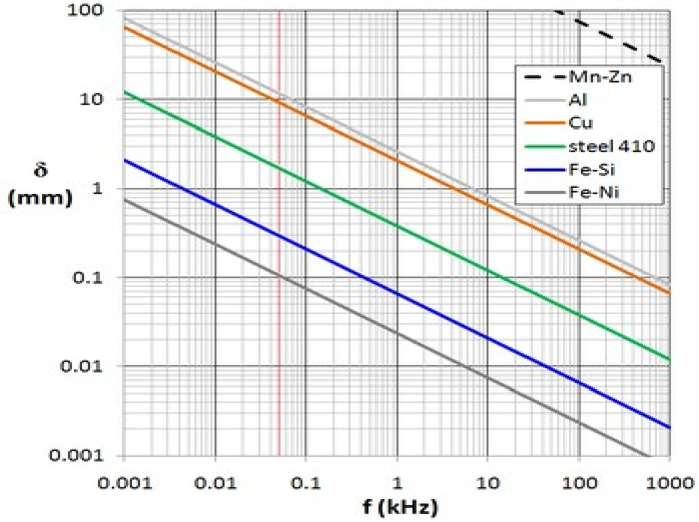
real component: $c \rightarrow c/n$

Qualitatively, in coupled harmonic oscillator model, expect maximum absorption at high or low frequencies?

Quick primer on plasma frequencies!

Recall Prof. Pravata's slide on particle number vs. radial distance from core.
For small particle number density, scattering is at individual-particle level; for large particle number density, can have coherent response

Q: To get coherent return signal, want ω_{radar} > or < ω_{plasma} ?



re-radiation happens within the skin depth,

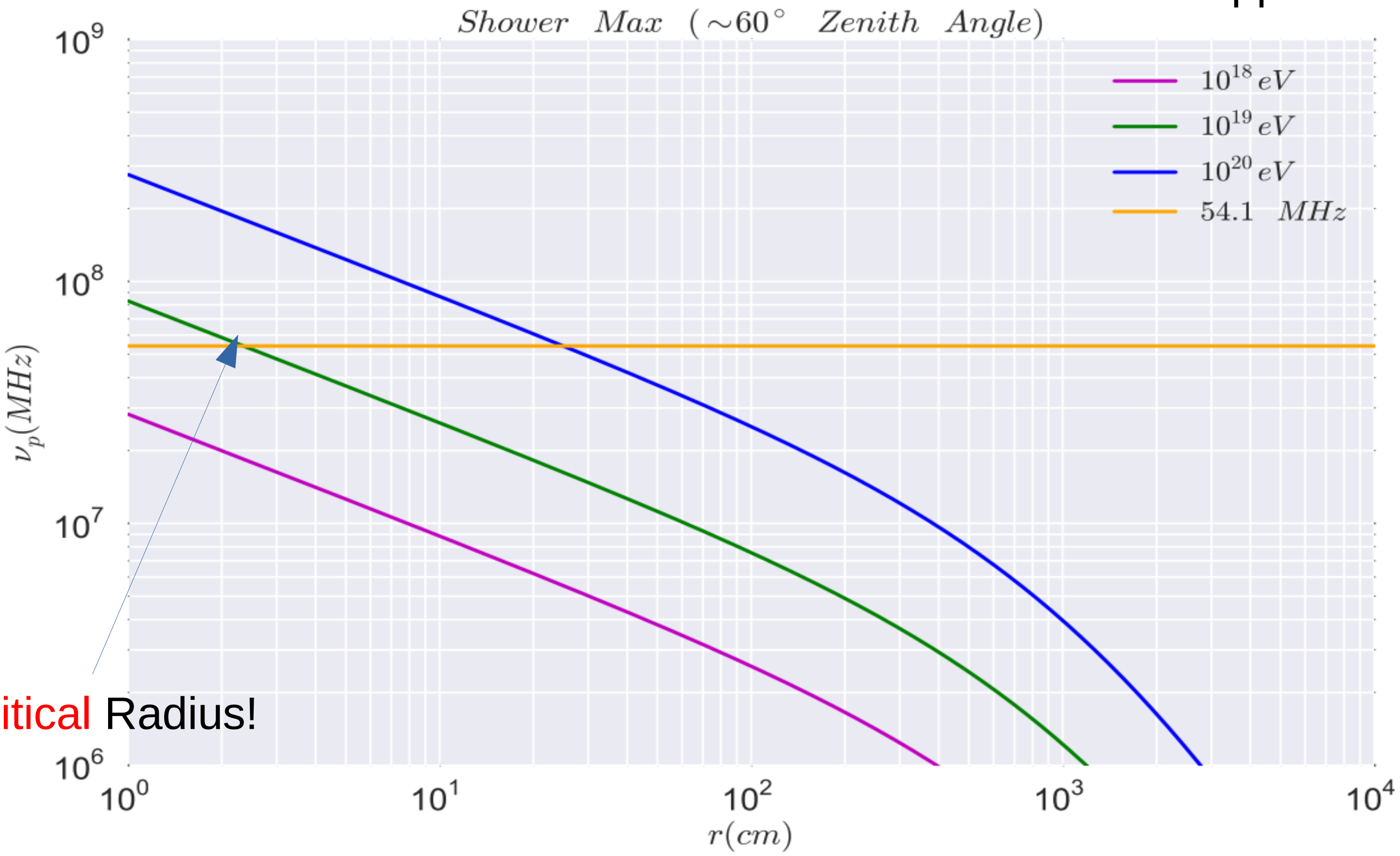
beyond the skin depth the external field cannot penetrate, so that is where there is energy transfer to the free electrons

beyond that the field is damped so the electrons are there but they don't see any external field

Need plasma frequency above 54.1 MHz carrier

~~Under – dense($\nu > \nu_e$)~~
Fatal!

Over - dense ($\nu < \nu_e$)
Thin Wire approximation!



Critical Radius!

Transmitter

~ 20 – 40 KW at *54.1 MHz*

Phased Yagi Array

20 ft.

10 ft.

20 ft.

39 km to receiver

Power Amplifier

Filters

100 ft.

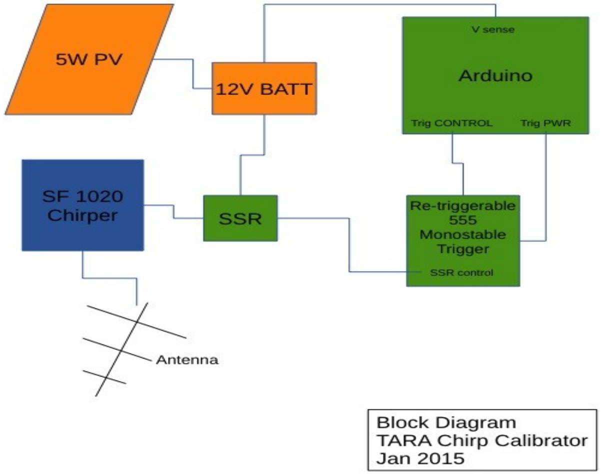
Forward *Gain* : *22.6 dBi*
Horizontal Beam Width : *12°*
Vertical Beam Width : *10°*

KUTV(20 KW)

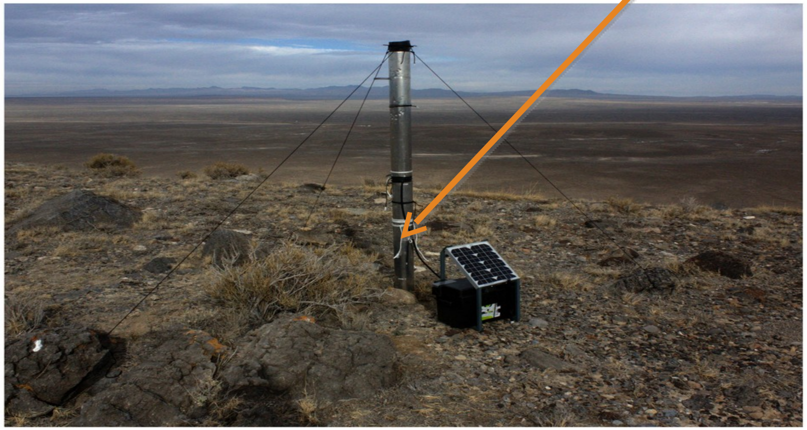
KTVN (20KW)

Chirp Calibration Unit (CCU)

Deployed Jan 19th 2015

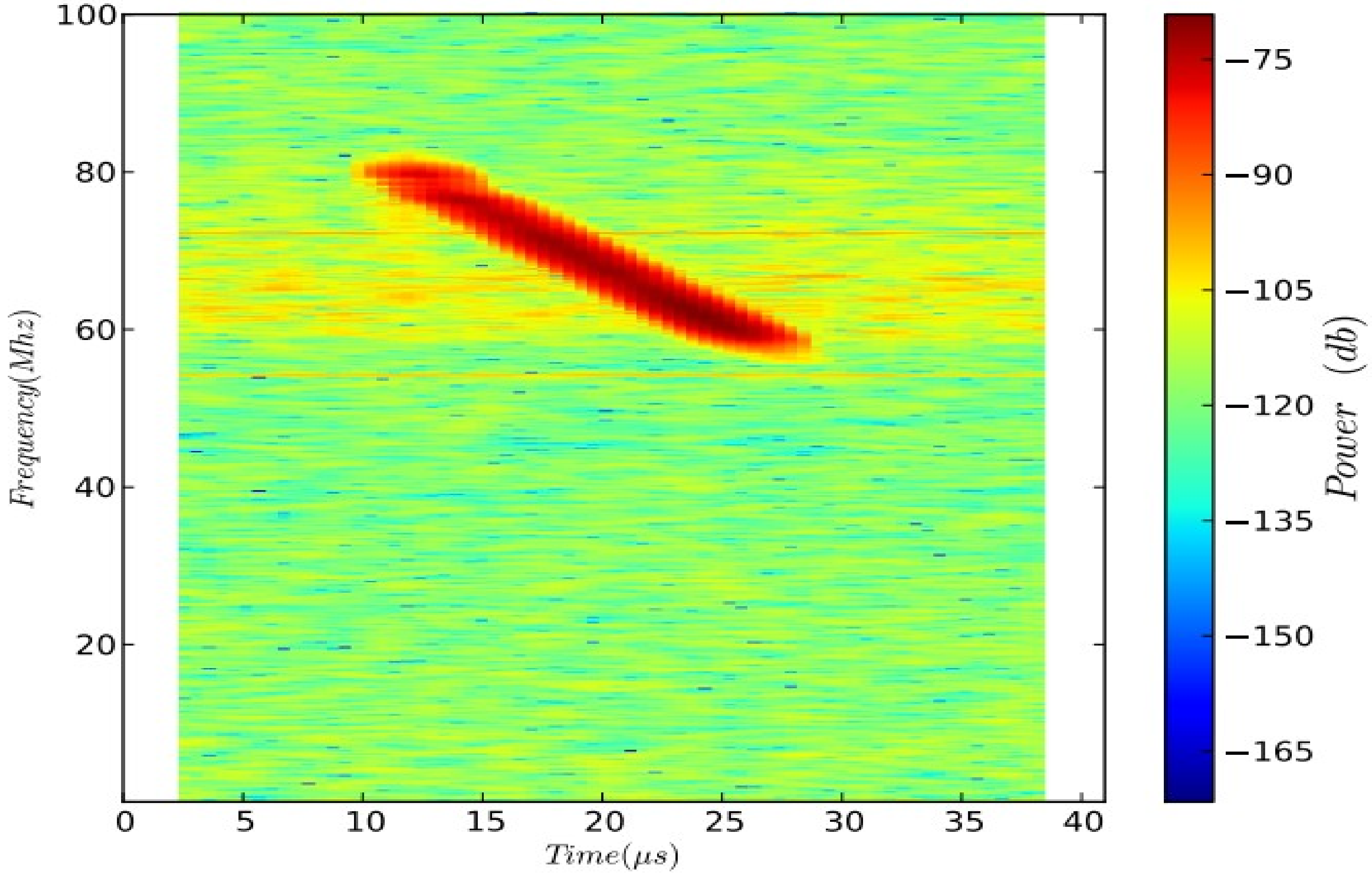


Fat dipole

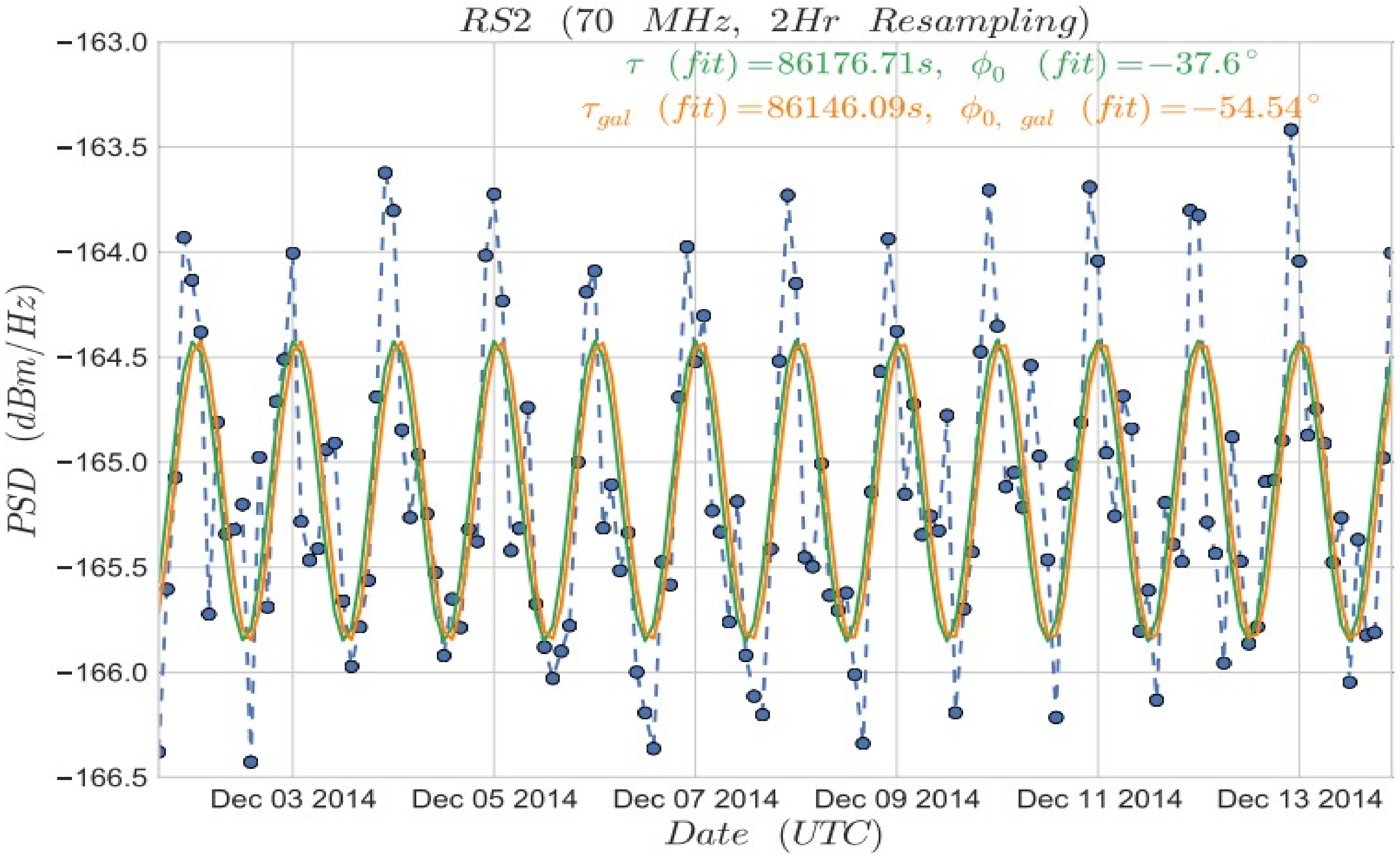


PV

Field Calibration Chirp



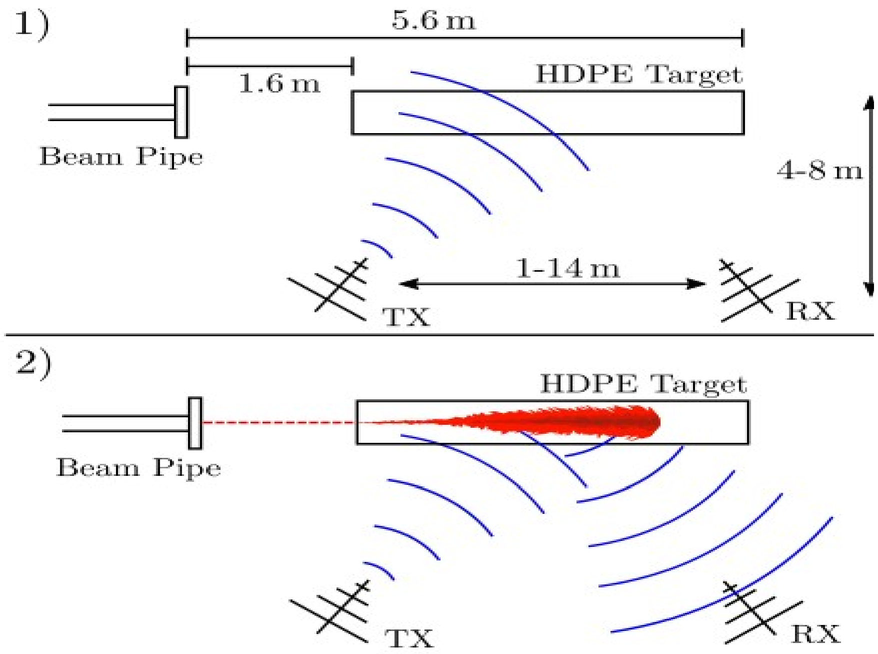
Sidereal Variation (wrt Sagittarius A*)

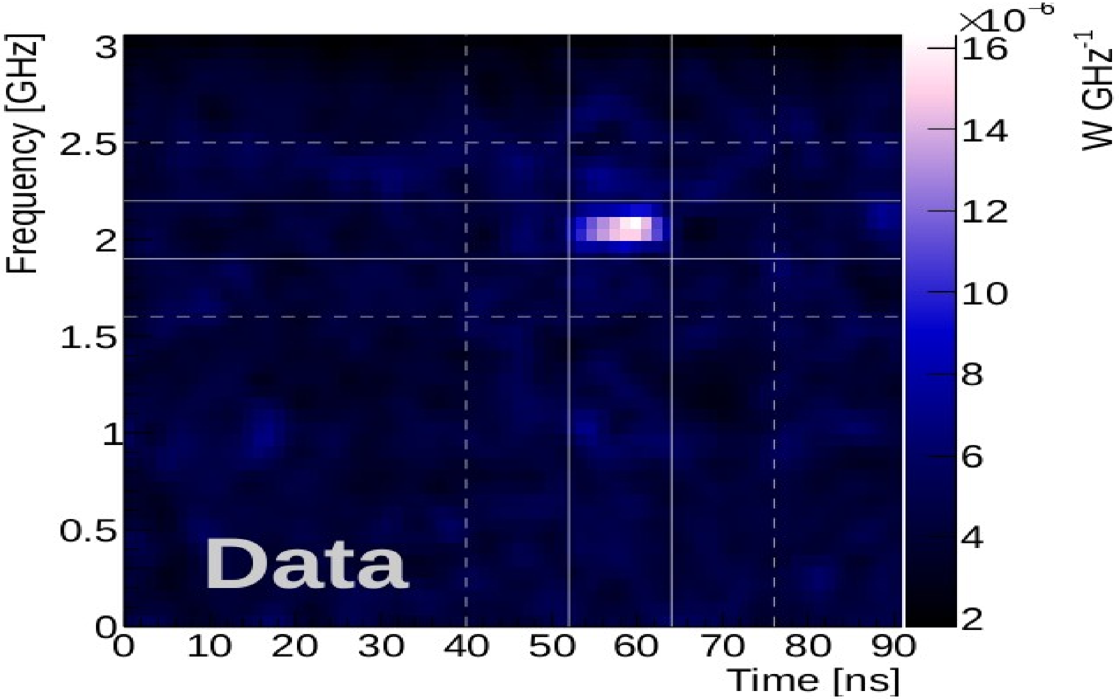


In-air Radio reflection techique

- But-No signals yet!
- In-air may be limited by
  - Molecular damping
  - Recombination with Oxygen
- Deployment in-ice can avoid these
  - But requires a ~10 kW transmitter buried into ice.

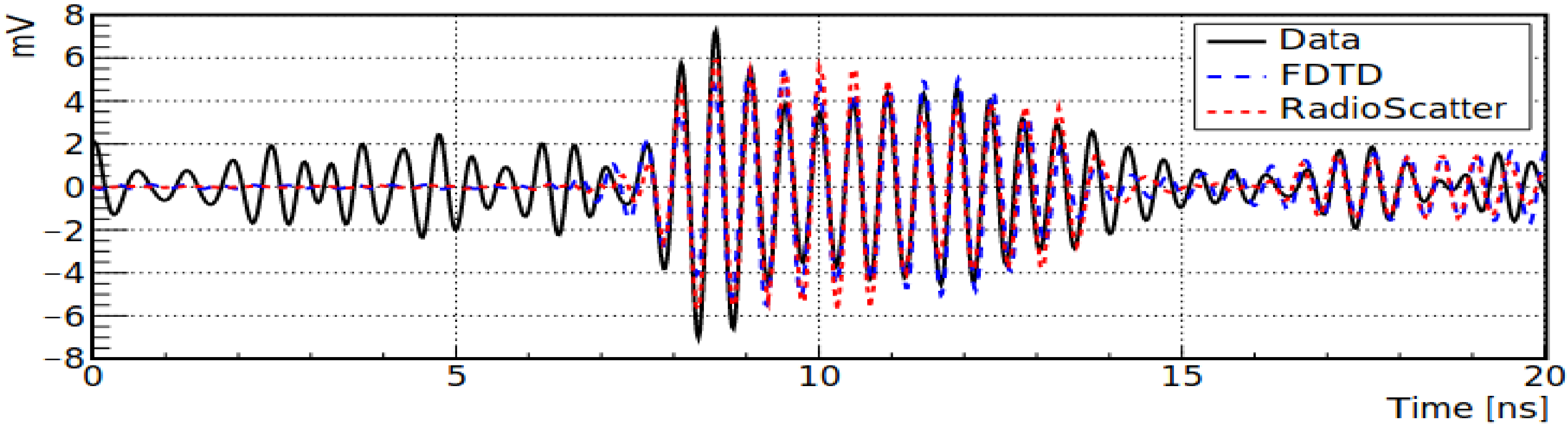
T-576 → RET-CR and RET-NU





Comparison to Askaryan:
2pi coverage rather than limited C-cone;
distinctive chirp-pattern recognition;
Arbitrarily high transmitter strength

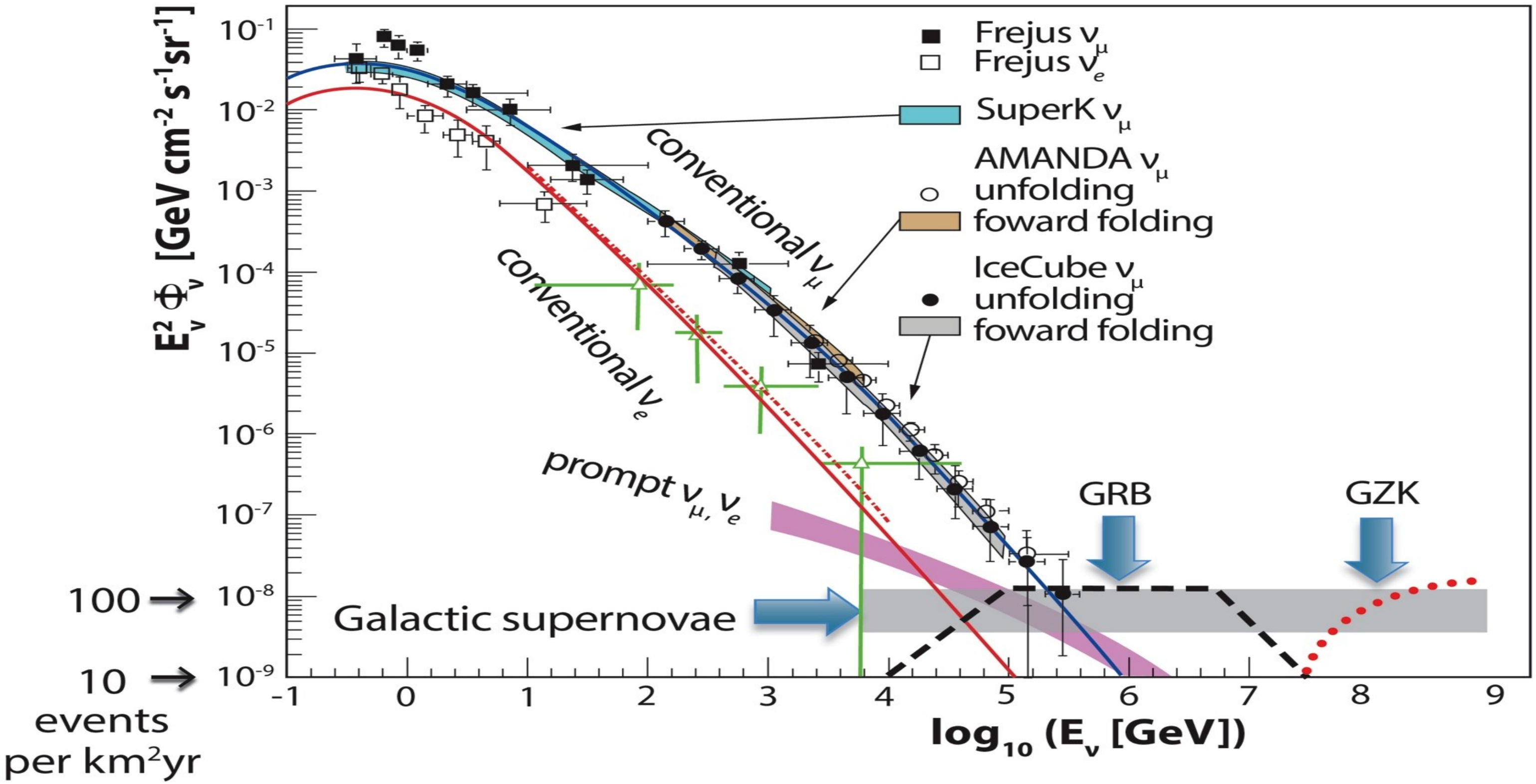
Comparison with prediction



Current Status: Proposal submitted to install transmitter and receiver at Taylor Dome, Antarctica for proto-typing...

- Sample spectrum
  - (IceCube)
- cosmic neutrinos: energy > 60 TeV

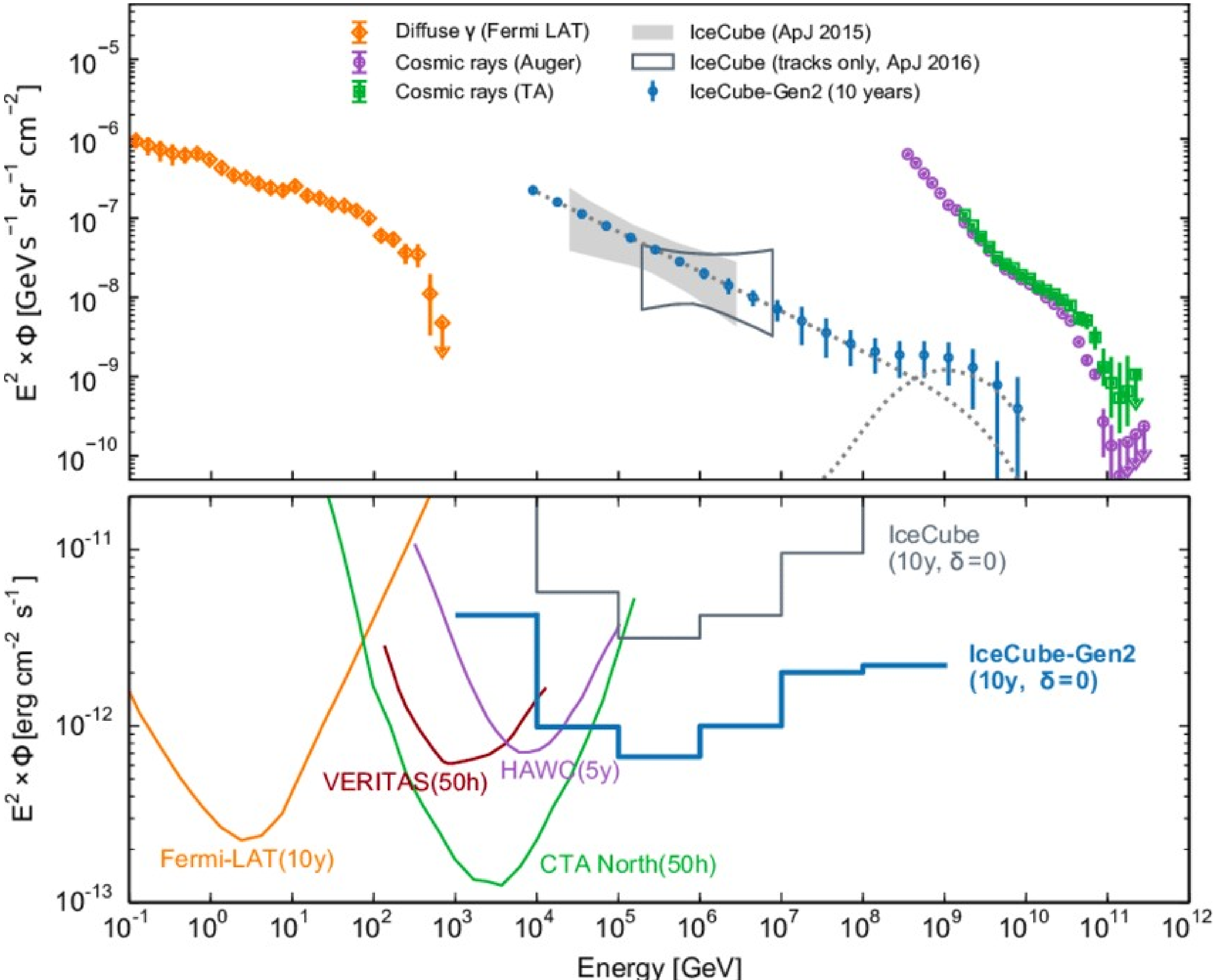
- atmospheric background: 1~2 events per year

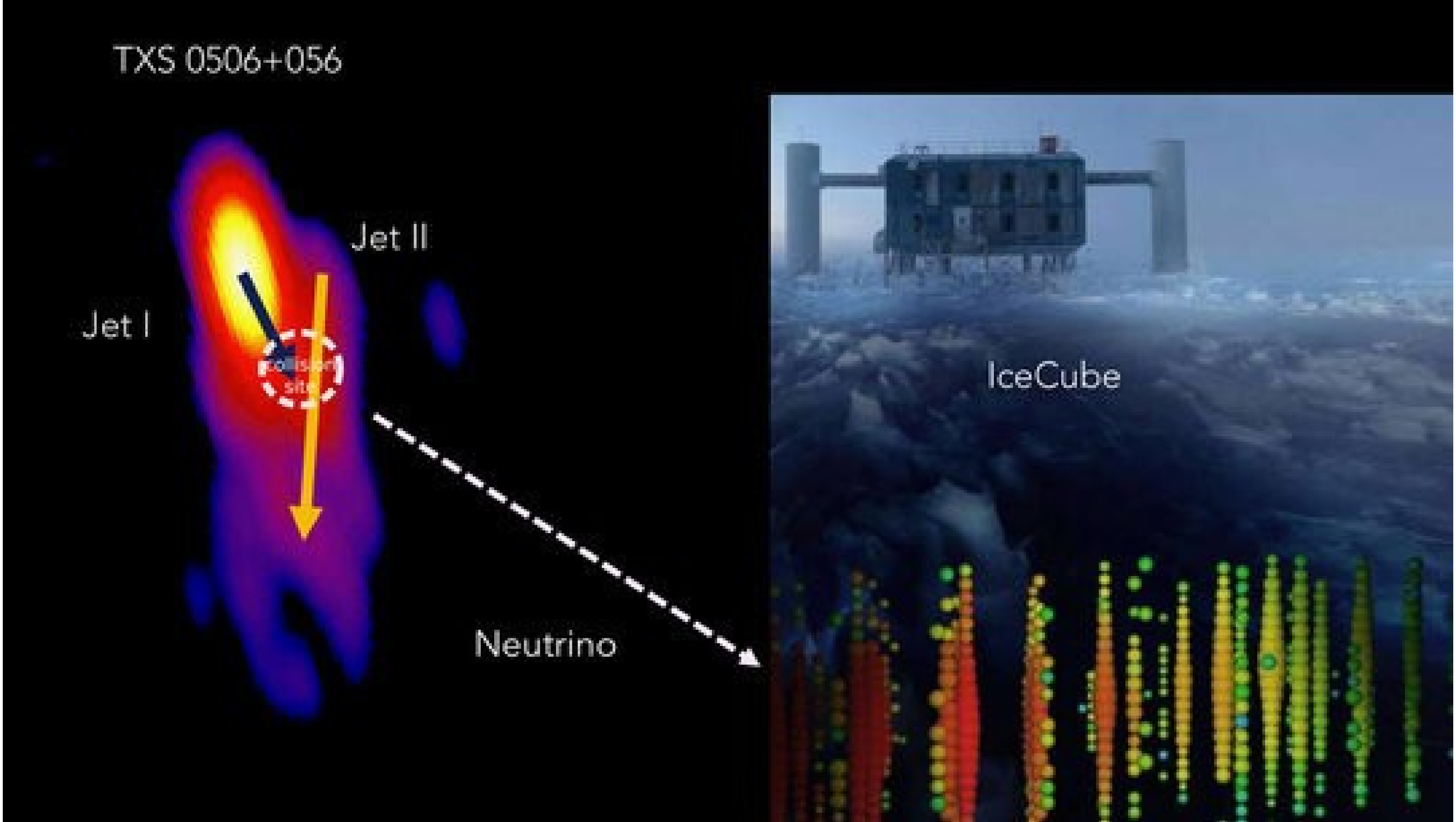


atmospheric

cosmic

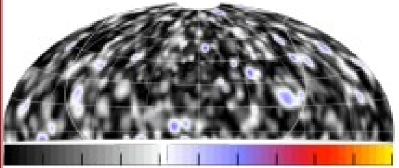
$$\Phi_\nu = \frac{dN}{dE} \approx \frac{1}{E^2}$$

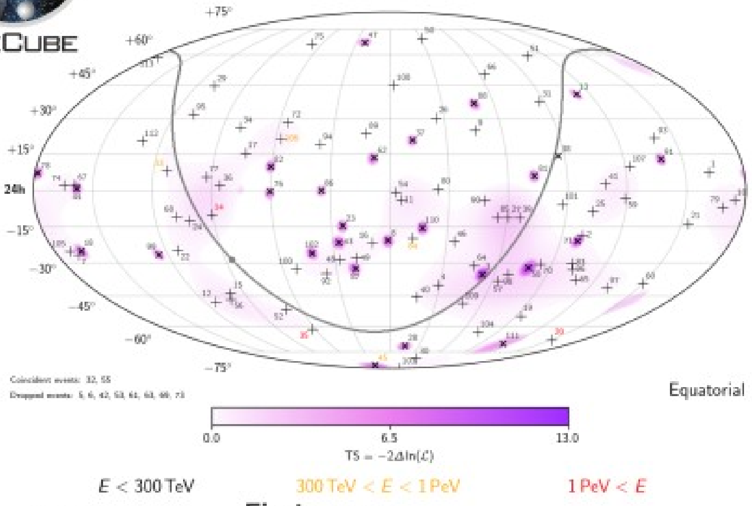

Diffuse γ (Fermi LAT)
Cosmic rays (Auger)
Cosmic rays (TA)
IceCube (ApJ 2015)
IceCube (tracks only, ApJ 2016)
IceCube-Gen2 (10 years)
E^2 × Φ [GeV s^-1 sr^-1 cm^-2]
E^2 × Φ [erg cm^-2 s^-1]
IceCube (10y, δ=0)
IceCube-Gen2 (10y, δ=0)
VERITAS(50h)
HAWC(5y)
Fermi-LAT(10y)
CTA North(50h)
Energy [GeV]


TXS 0506+056
Jet II
Jet I
IceCube
Neutrino

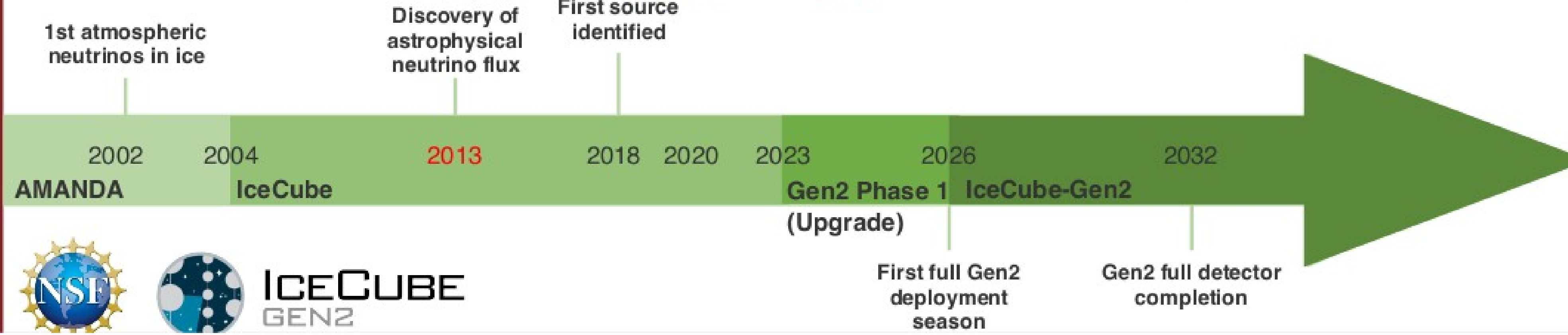
IceCube-Gen2: *From Discovery to Astronomy*

…building the future of a new field



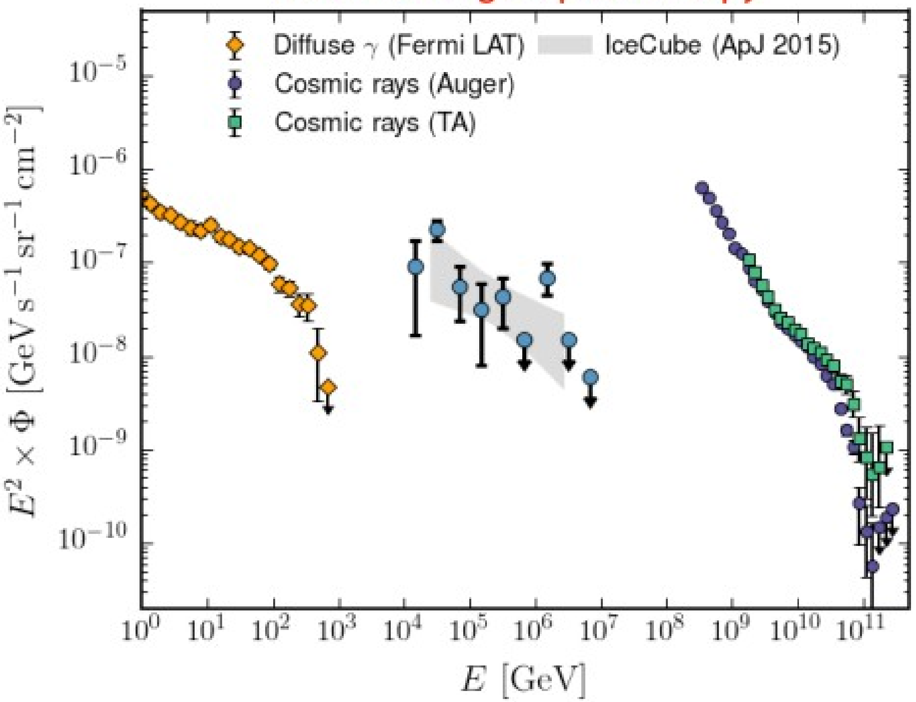


Gen2 Phase 1 (Upgrade) drill camp; January 29, 2020

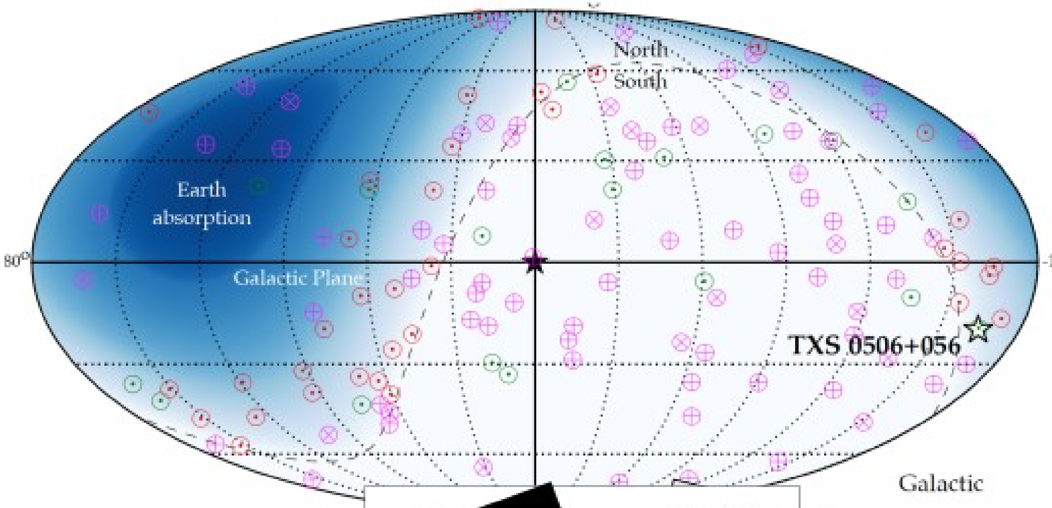


10 yrs of IceCube - a first view on the PeV Universe

Multimessenger spectroscopy



First sky map of cosmic neutrinos



Some highlights:

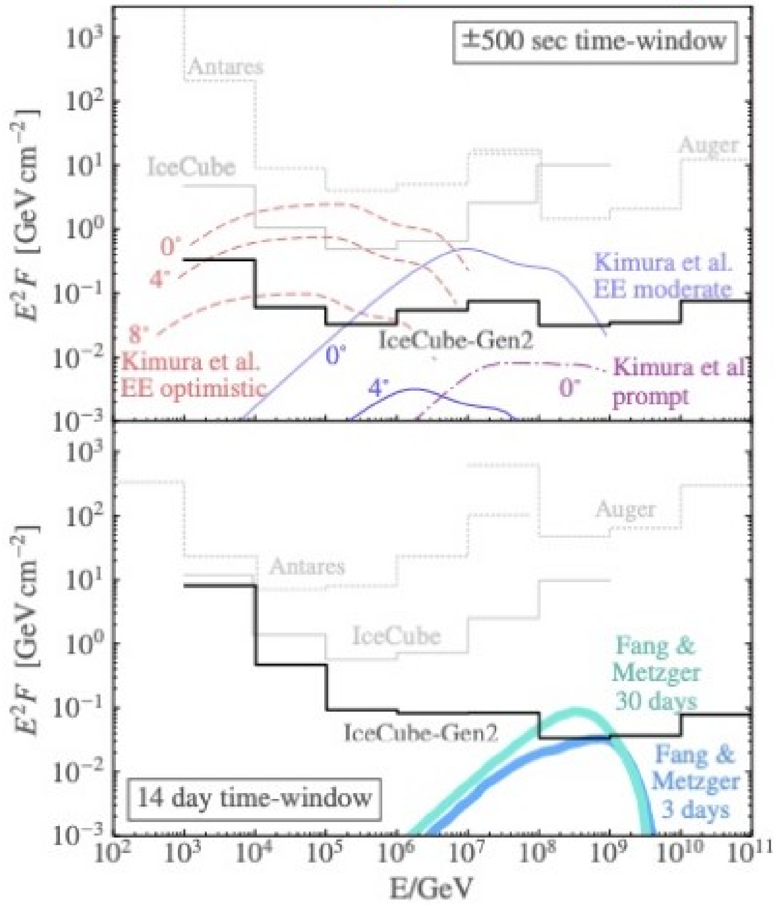
2013: Discovery of cosmic PeV neutrino flux
2018: Evidence for Blazars as neutrino sources
2019: Observation of first tau neutrino

NSF ICECUBE GEN2

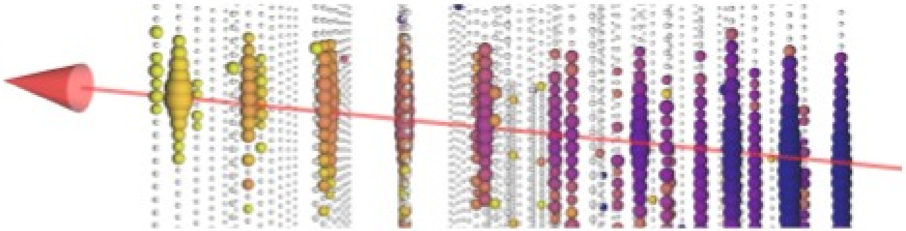
Requirements for IceCube-Gen2

1. Increase the neutrino point source sensitivity at least 5 times over the current IceCube array
2. **Enable multimessenger astronomy with individual, high-energy neutrinos**
3. Collect 10 times more neutrinos per year than the current IceCube array in the energy range 100 TeV to 10 PeV
4. Expand energy range to beyond 10^{18} eV with sensitivity improved by two orders of magnitude
5. Enhanced sensitivity to neutrino flavors and the ability for flavor identification

Gen2 sensitivity to NS-NS mergers



Neutrino alert IC170922A pointing to TXS 0506+056



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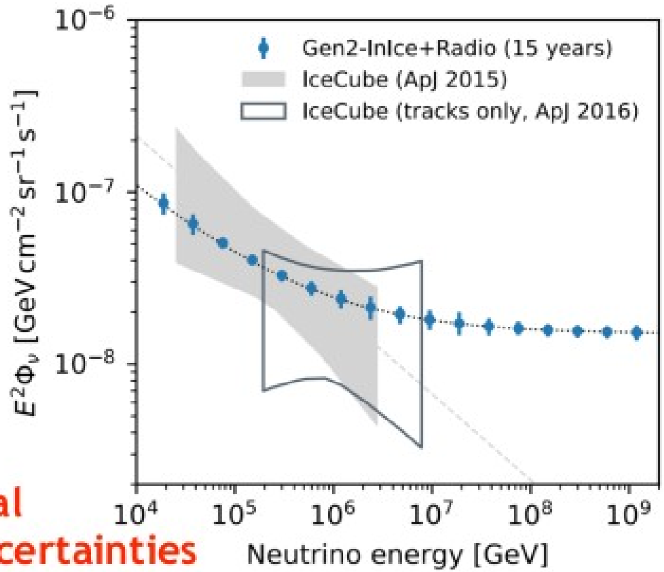
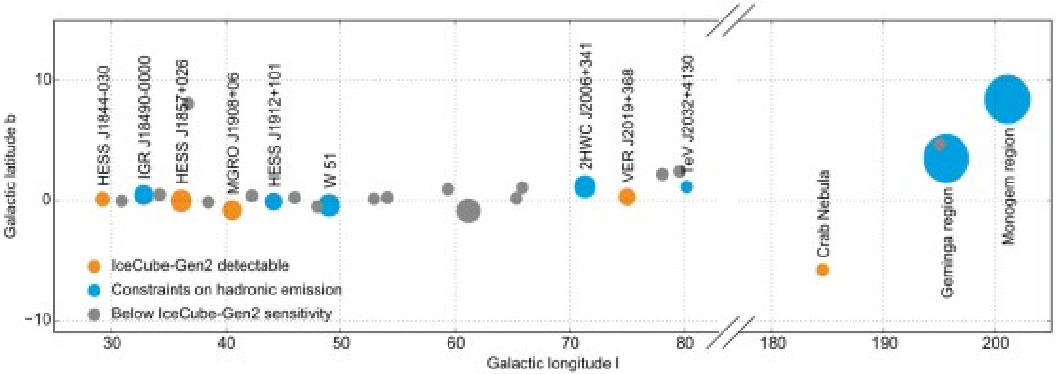


Projected spectral measurement uncertainties



Sensitivity to galactic sources

Requirements for IceCube-Gen2

1. Increase the neutrino point source sensitivity at least 5 times over the current IceCube array
2. Enable multimessenger astronomy with individual, high-energy neutrinos
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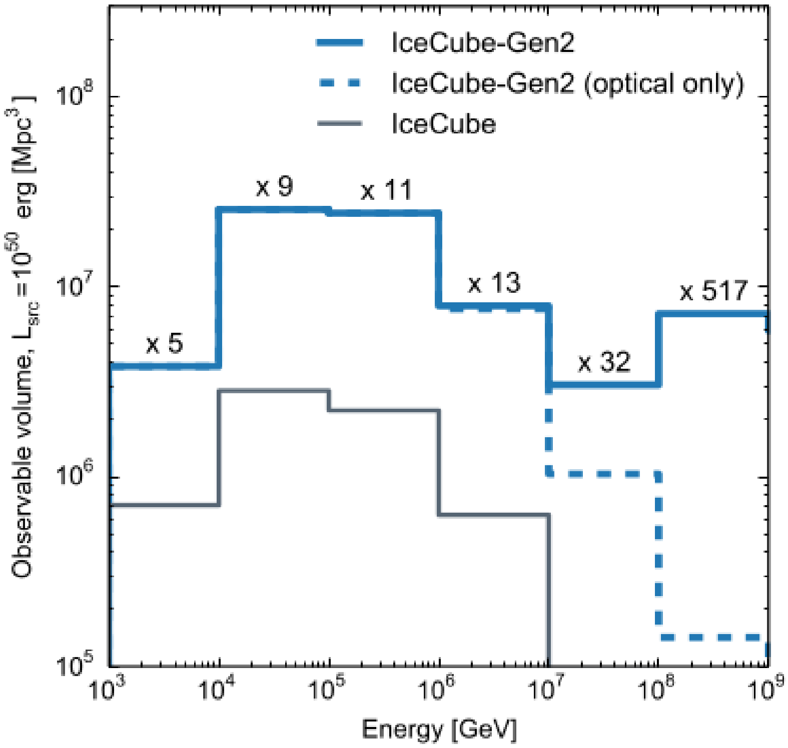
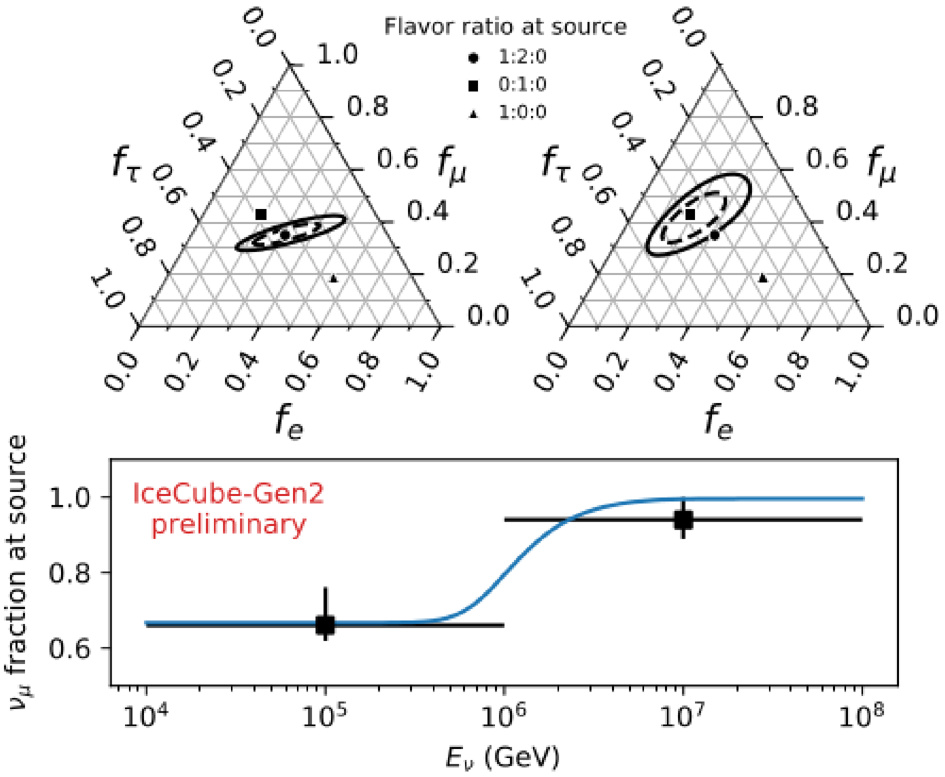


Uniform sensitivity over large energy range over more than 6 orders of mag energies.

ICECUBE GEN2

Requirements for IceCube-Gen2

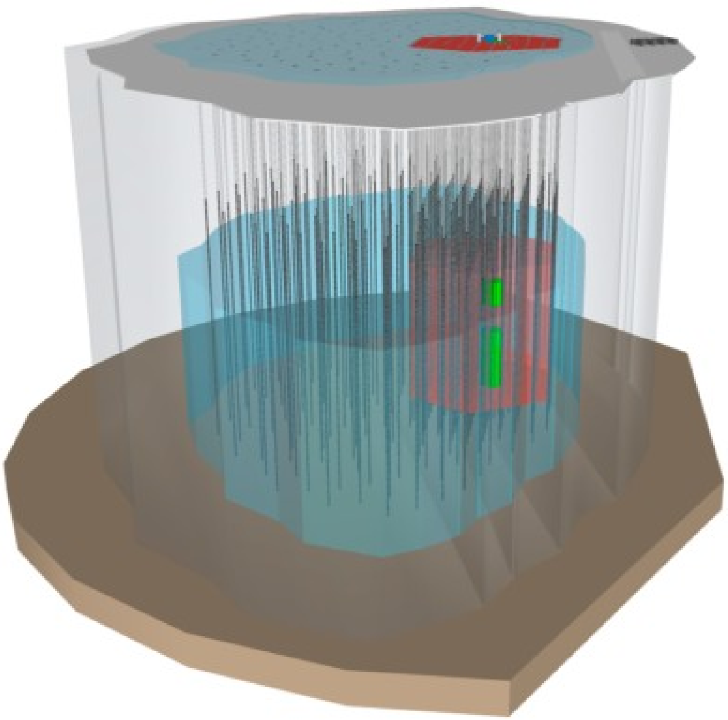
1. Increase the neutrino point source sensitivity at least 5 times over the current IceCube array
2. Enable multimessenger astronomy with individual, high-energy neutrinos
3. Collect 10 times more neutrinos per year than the current IceCube array in the energy range 100 TeV to 10 PeV
4. Expand energy range to beyond 10^{18} eV with sensitivity improved by two orders of magnitude
5. **Enhanced sensitivity to neutrino flavors and the ability for flavor identification**

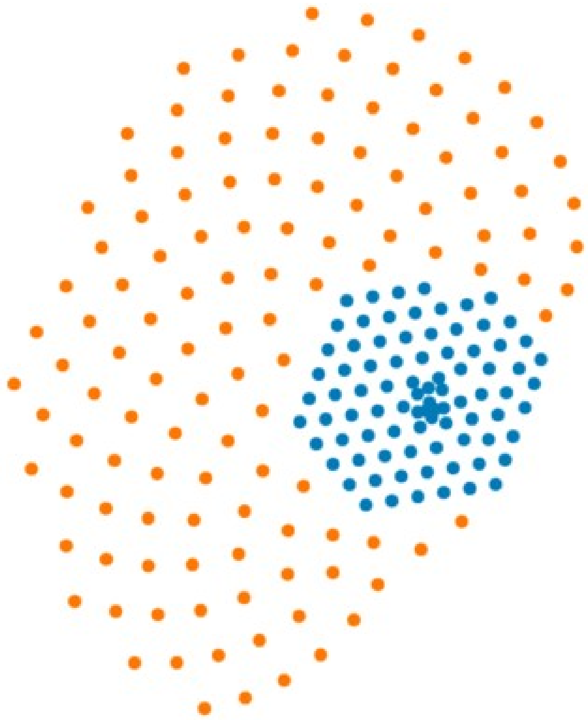


Measuring energy dependent neutrino flavor ratios (→BSM physics and nature of source)

IceCube-Gen2

A Vision for the Future of Neutrino Astronomy in Antarctica (arXiv:1412.5106)





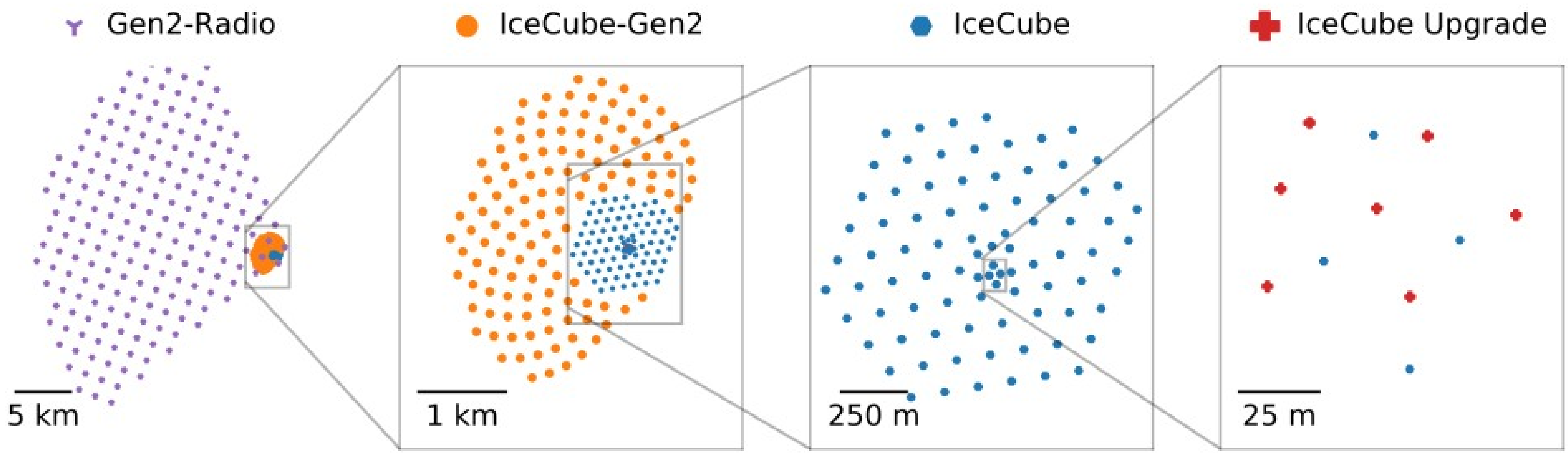
Artist's conception
120 strings at 240 m spacing

ICECUBE GEN2

The next-generation IceCube: from discovery to astronomy

IceCube-Gen2 — scope

IceCube and Gen2 on different scales reflecting different energies



10 PeV **10 TeV** **1 TeV** **few GeV**

IceCube GEN2

The only certainty is uncertainty!