Multi-messenger Astronomy

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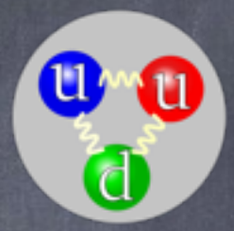
What's it all about?

~50 g
30-50 Joule

proton

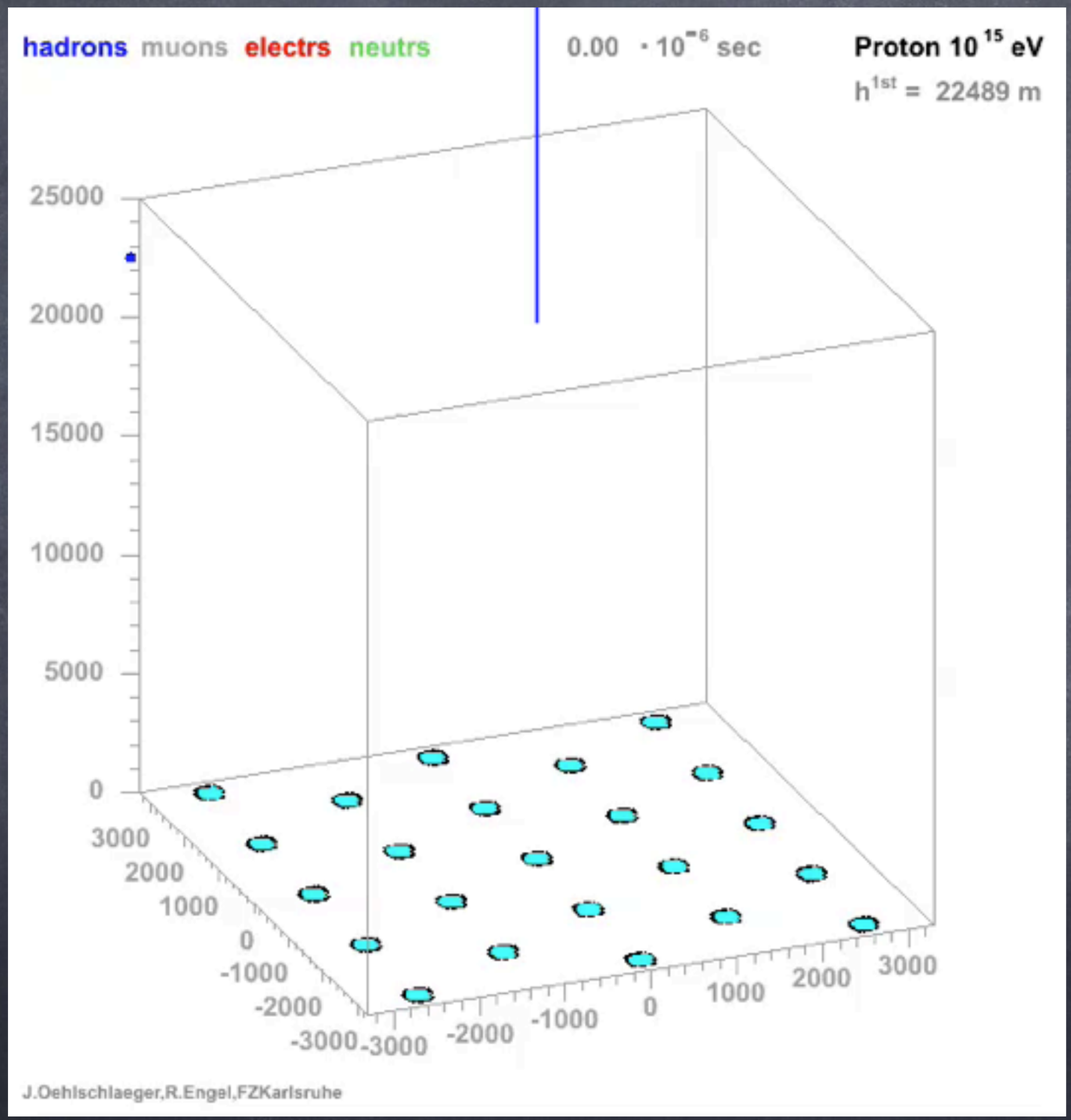


1.7×10^{-27} kg
$\sim 10^{20}$ eV

1eV = 1.6×10^{-19} joules = $1{,}6 \times 10^{-12}$ erg

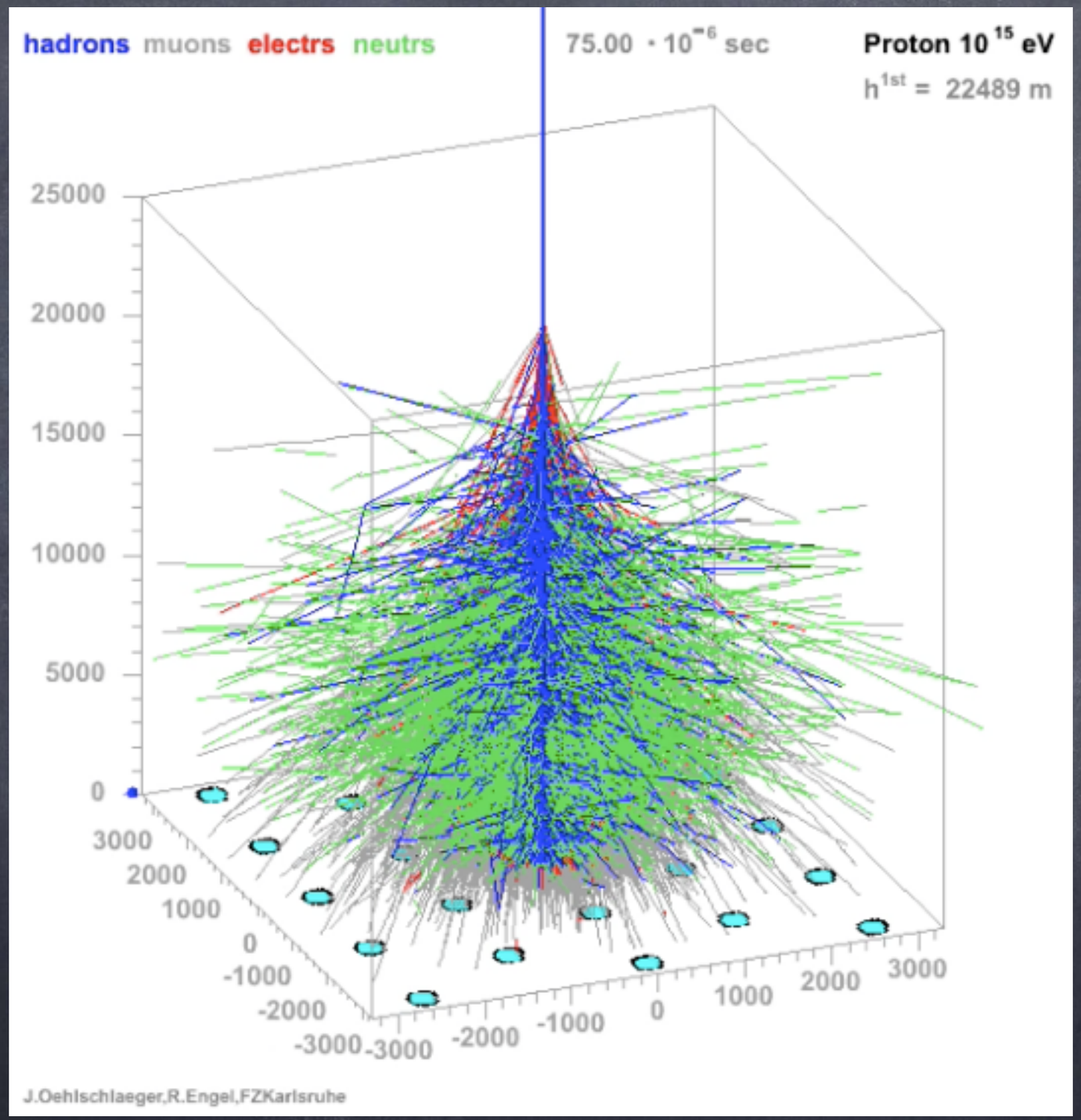
Cosmic Particles up to ~10^{20} eV

Extended Air Shower



Cosmic Particles up to ~10^{20} eV

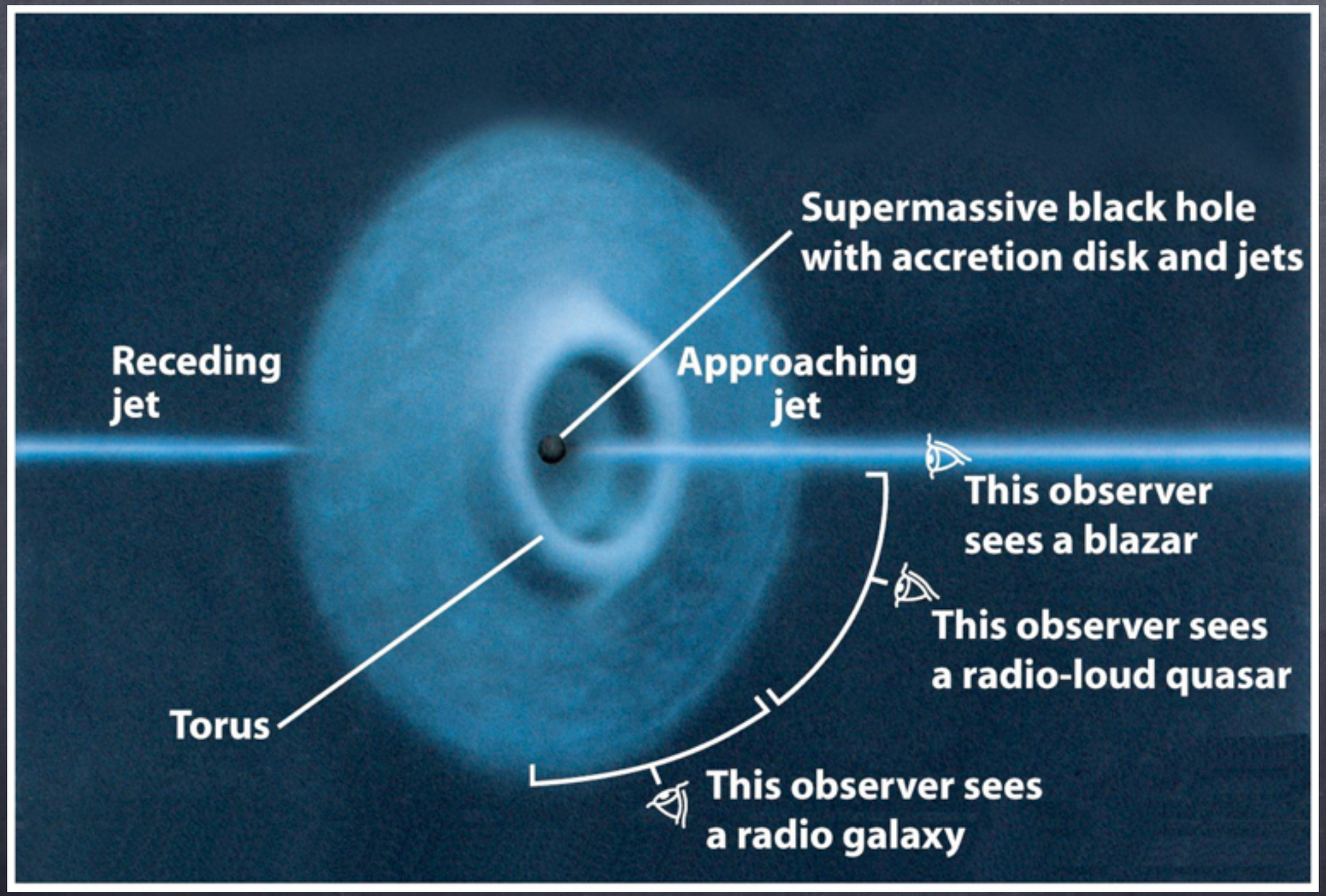
Extended Air Shower



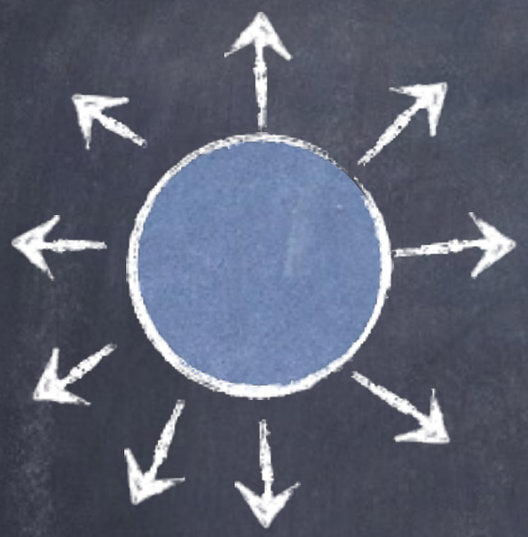
… need an accelerator

terrestrial one (up to 10^{12}eV) or …

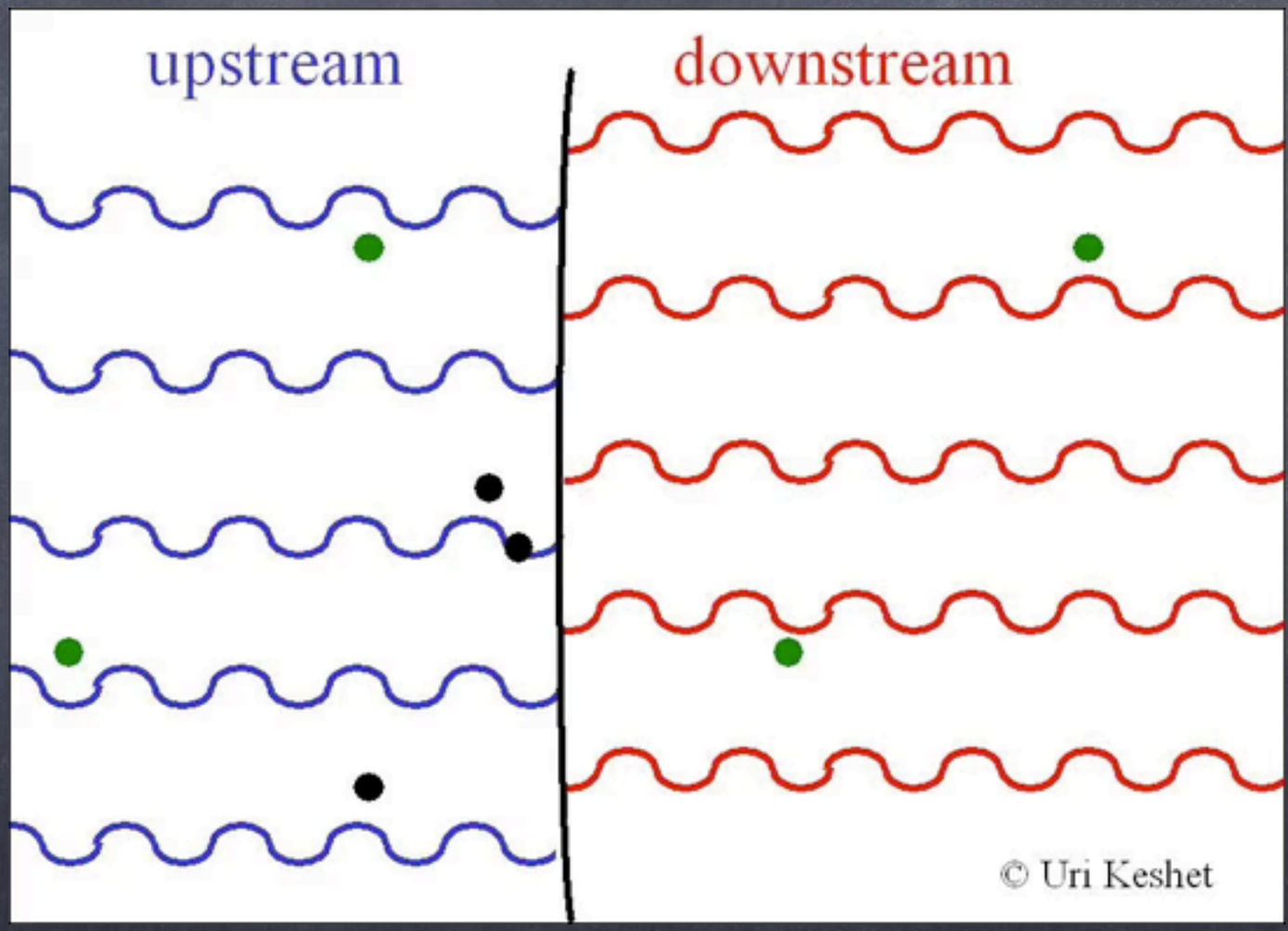
… a cosmic accelerator



Collision-less acceleration



Cosmic Accelerator



shock front

Which sources?

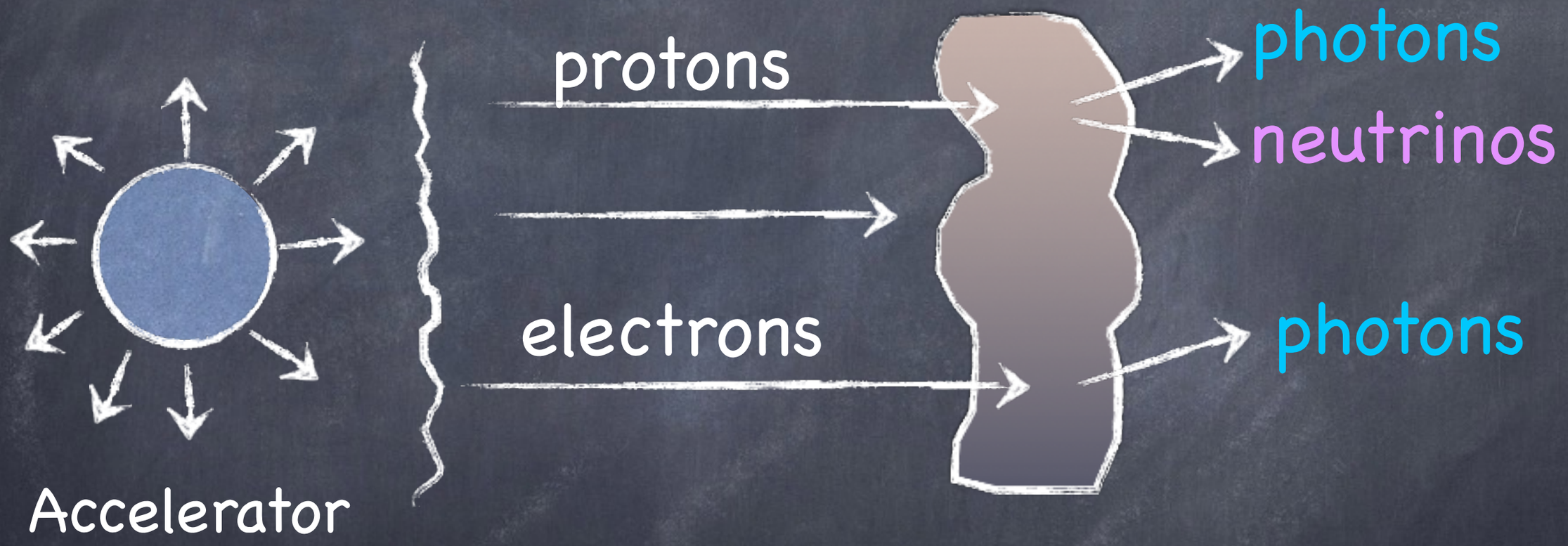
Can we do astronomy with particles?

With charged particles NO (magnetic fields)

Use NEUTRAL particles:

photons and neutrinos

Use NEUTRAL particles:
photons and neutrinos



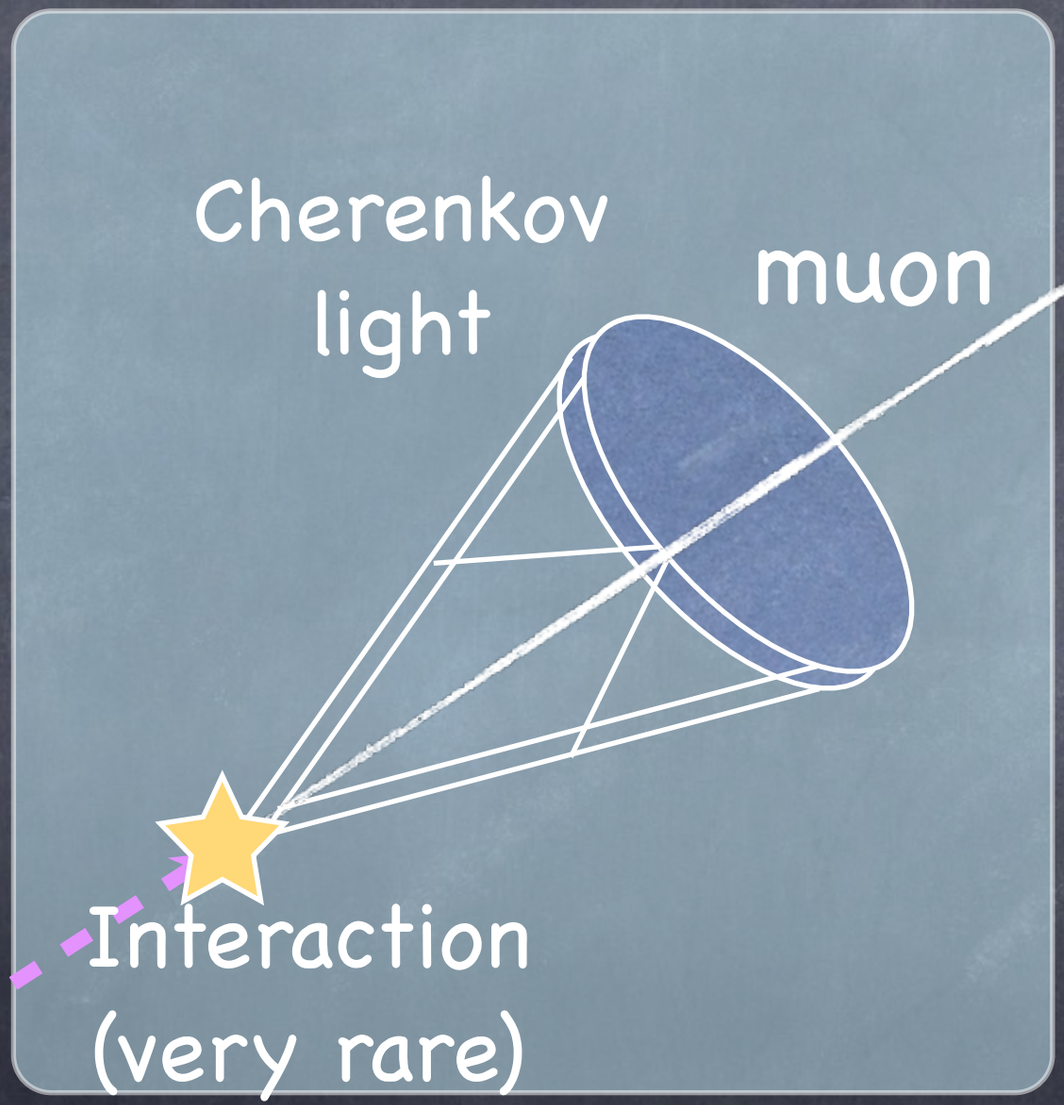
Cosmic Accelerator → protons → neutrinos

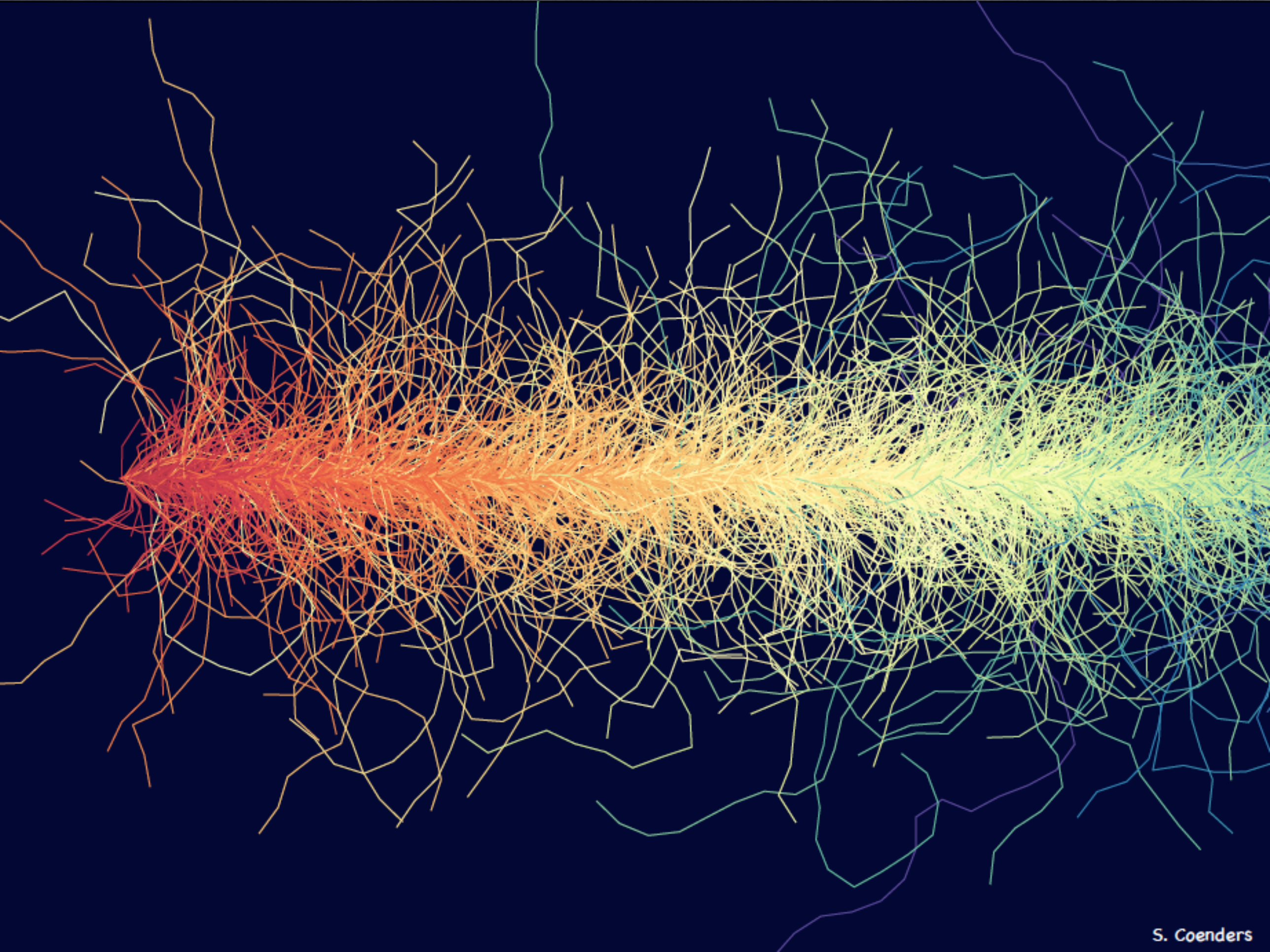
use neutrinos as cosmic messenger
but neutrinos are "invisible"

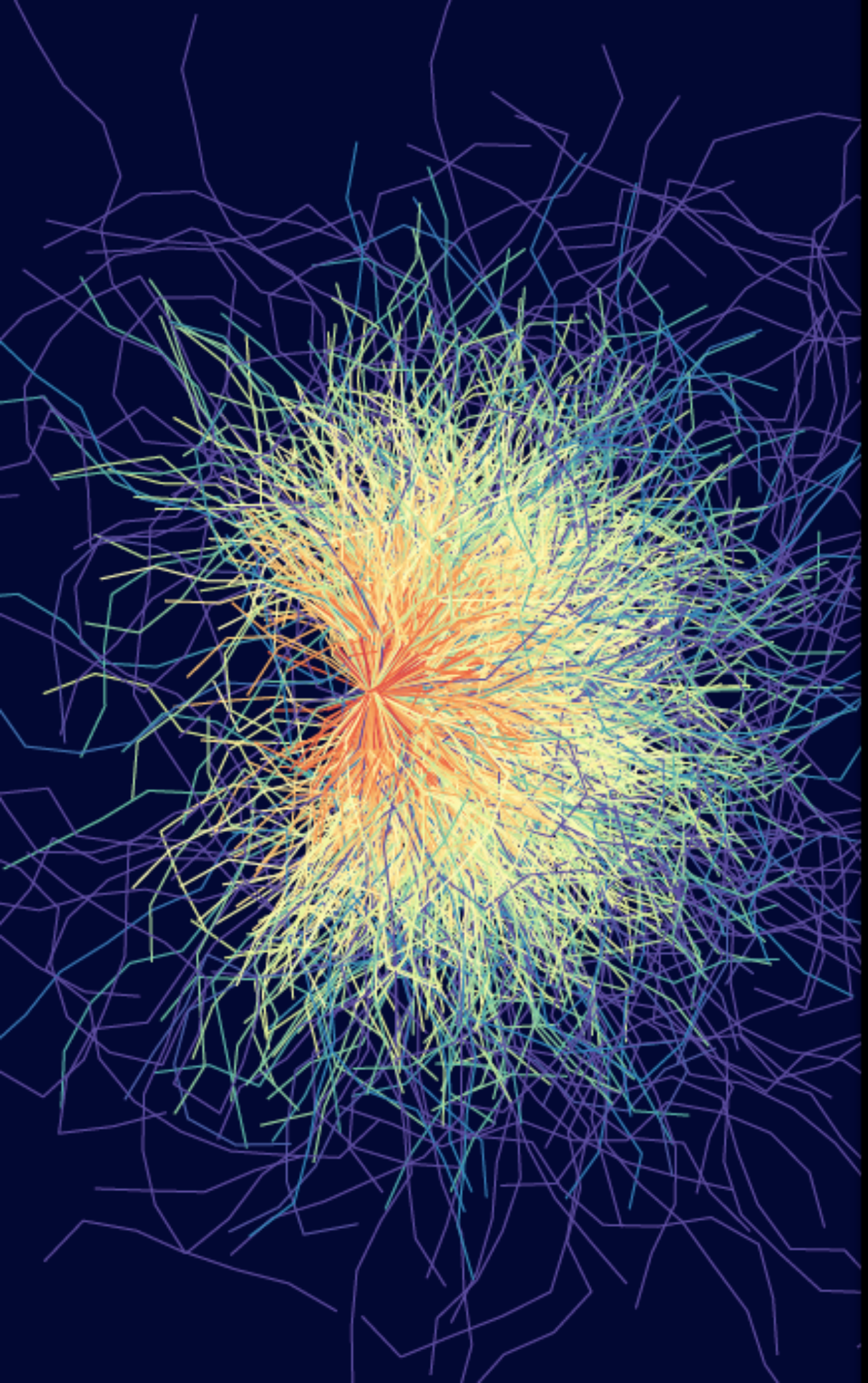
My mission: make the "invisible" "visible"

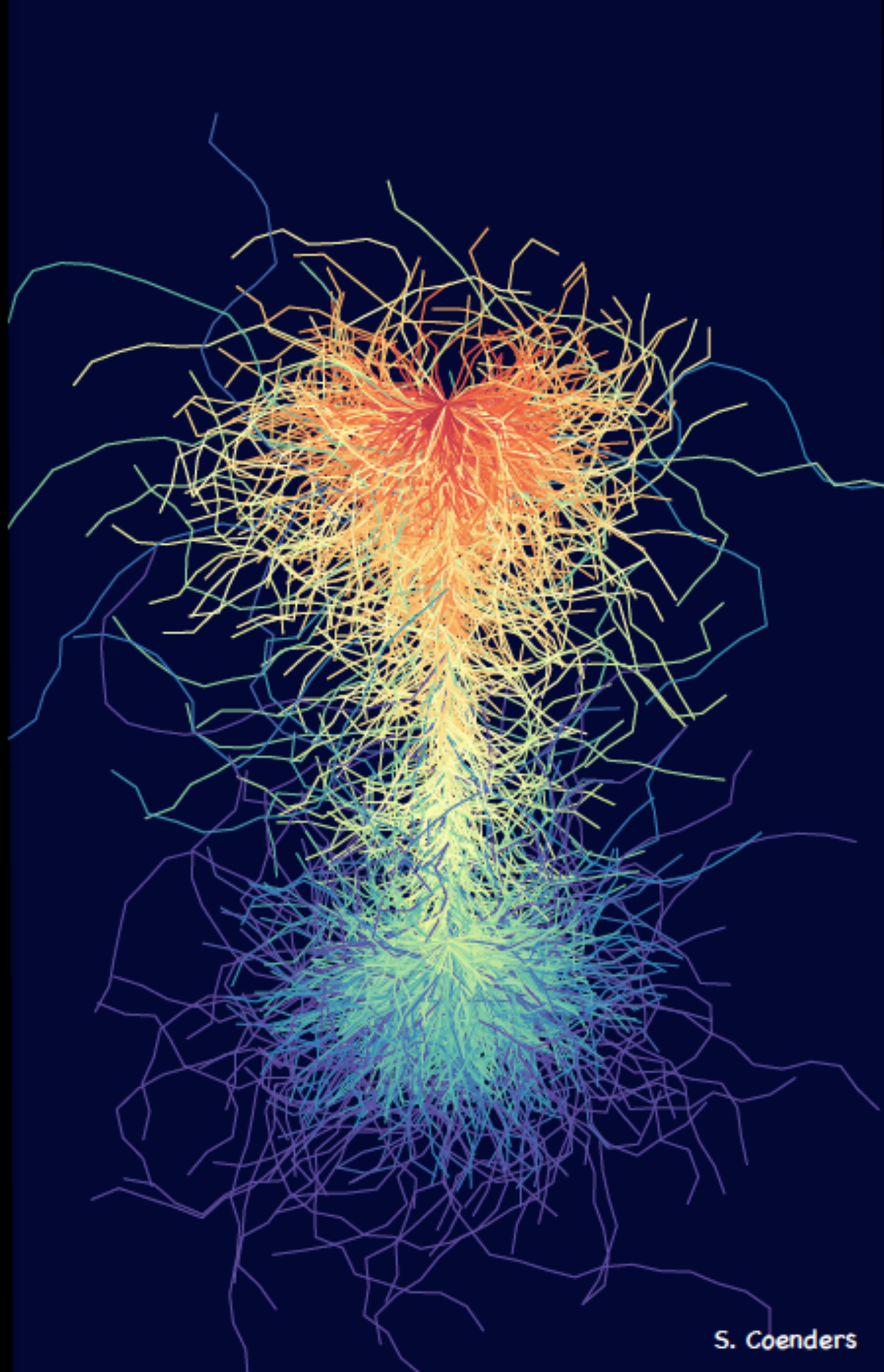
@ TUM:
"Experimental Physics with Cosmic Particles"
http://www.cosmic-particles.ph.tum.de

Neutrino detection



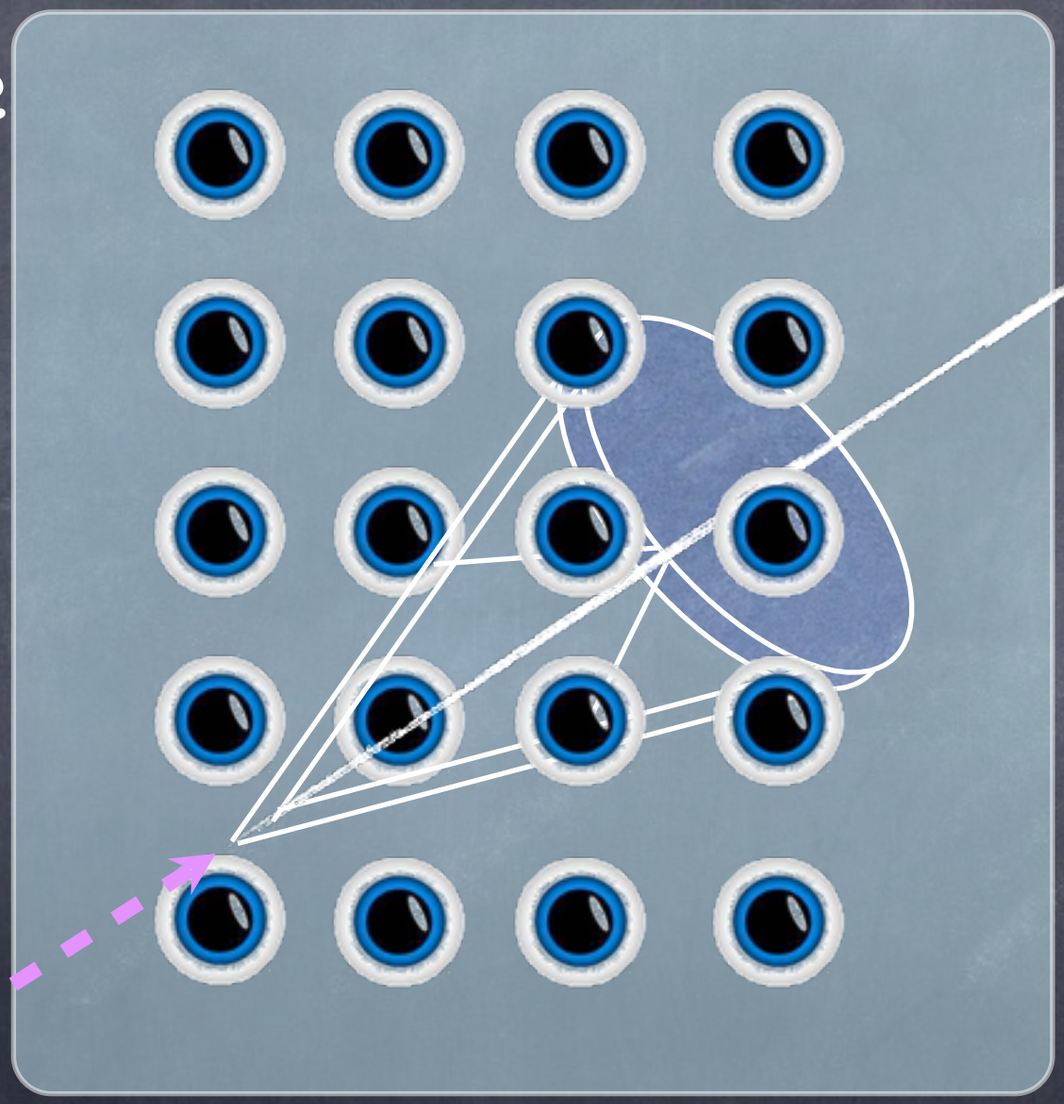

S. Coenders




S. Coenders

Neutrino detection

Let's "see" the Cherenkov photons



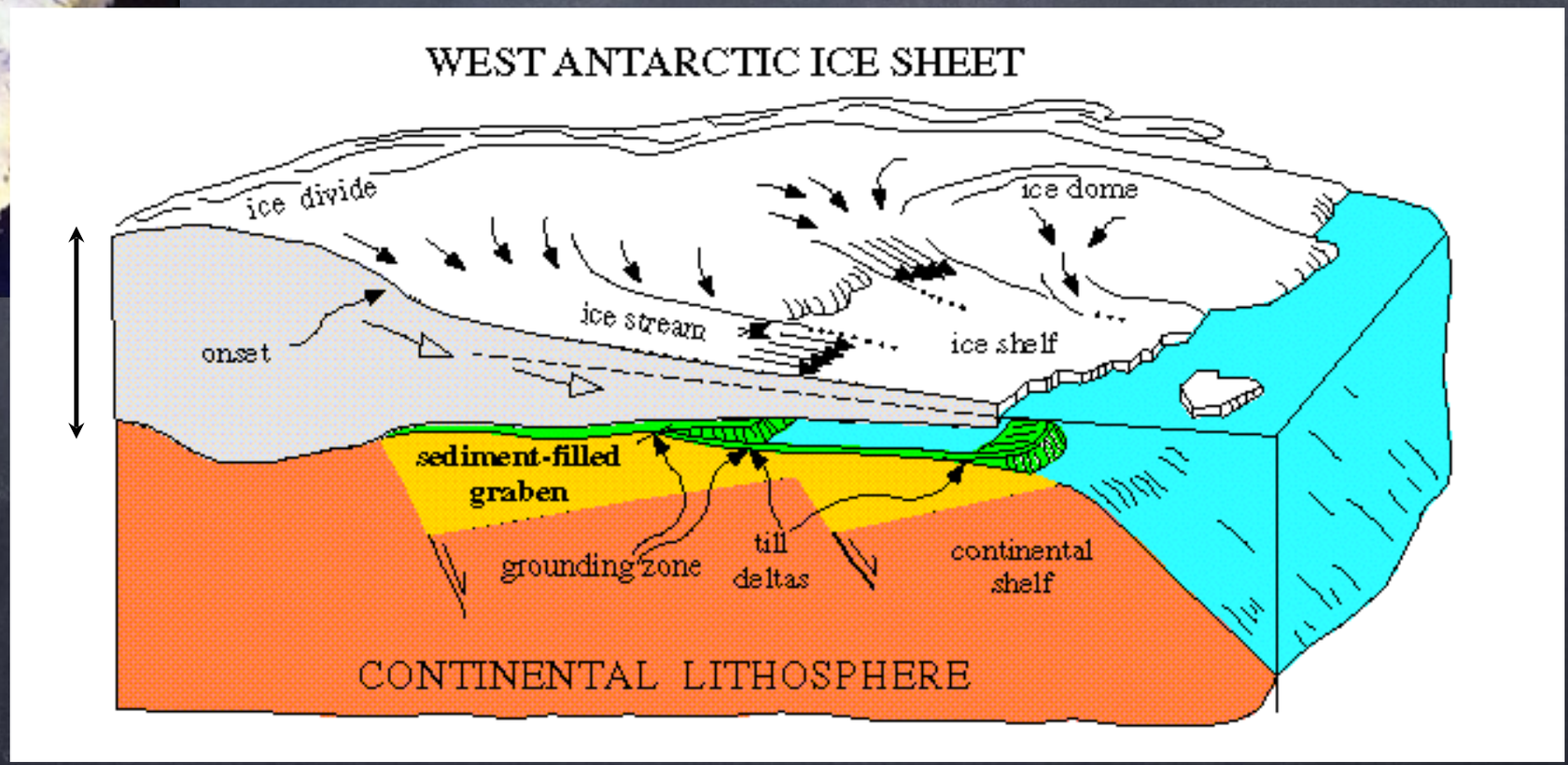
Target Mass needed: >1km^3

Neutrino muon-type

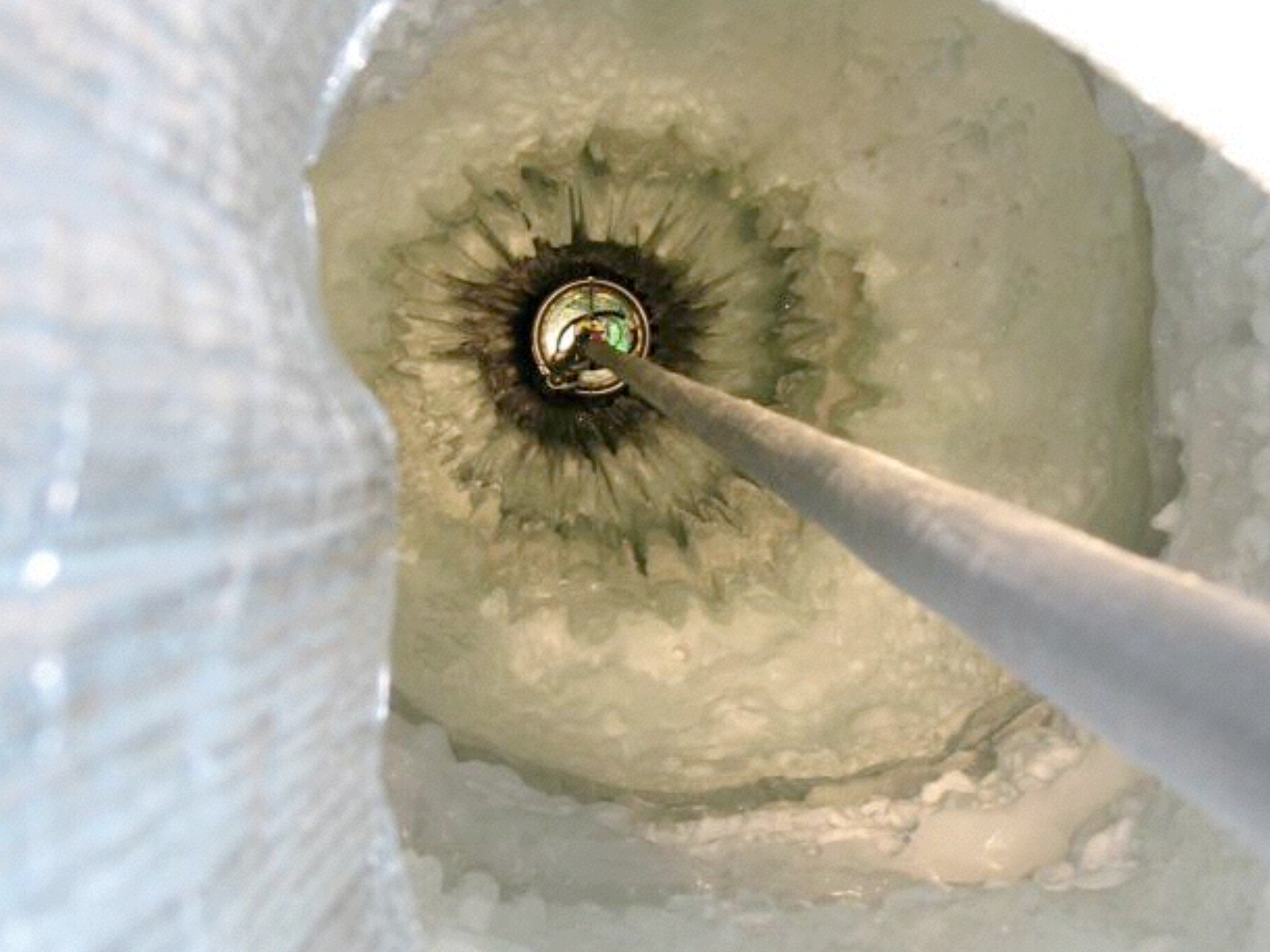
IceCube @ South Pole

Huge volume of transparent material

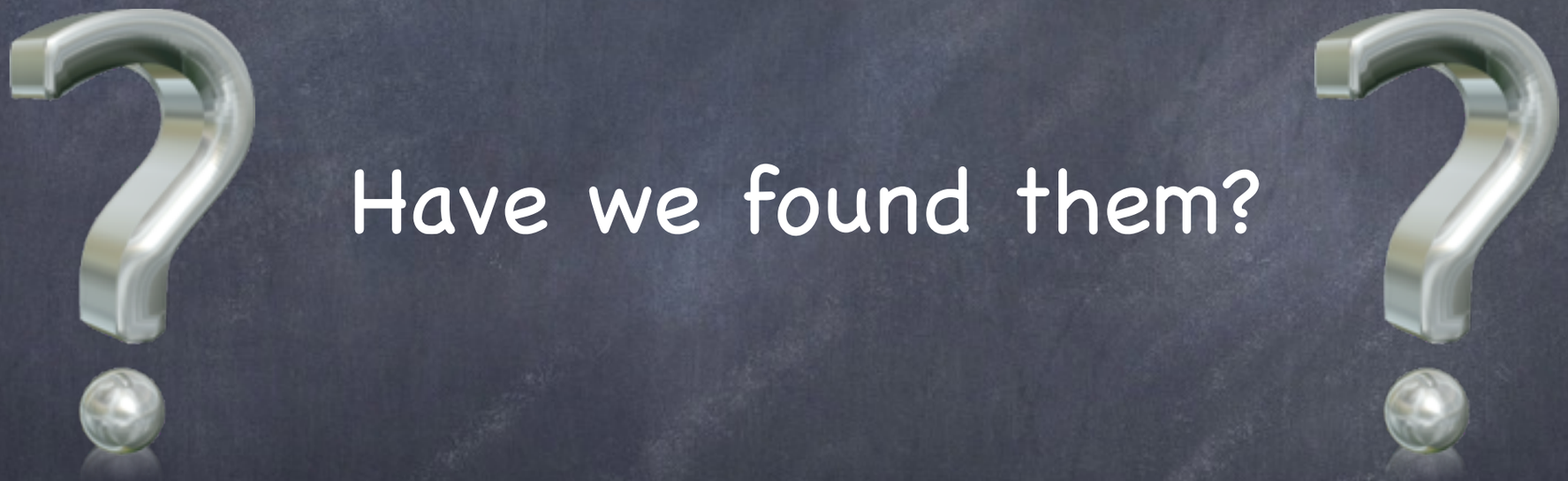
3 km thick glacier



IceCube @ South Pole



Cosmic Neutrinos



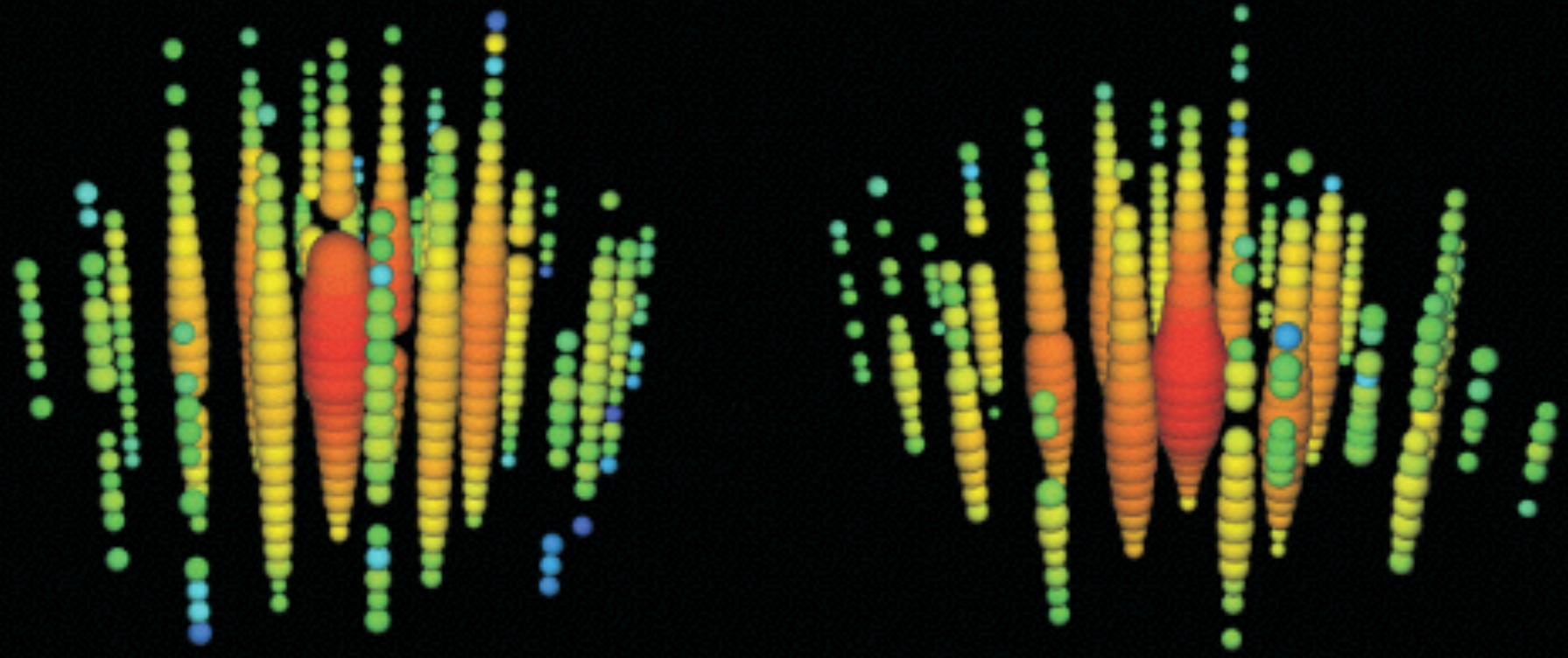
Have we found them?

YES!

The IceCube Coll., Phys. Rev. Lett. 111, 021103 (20

Bert

Ernie



1041^{+132}_{-144} TeV

MJD 55783

Dec -27.9 deg, R.A. 265.6

Median Angular error 13.2 deg

1141^{+143}_{-133} TeV

MJD 55929

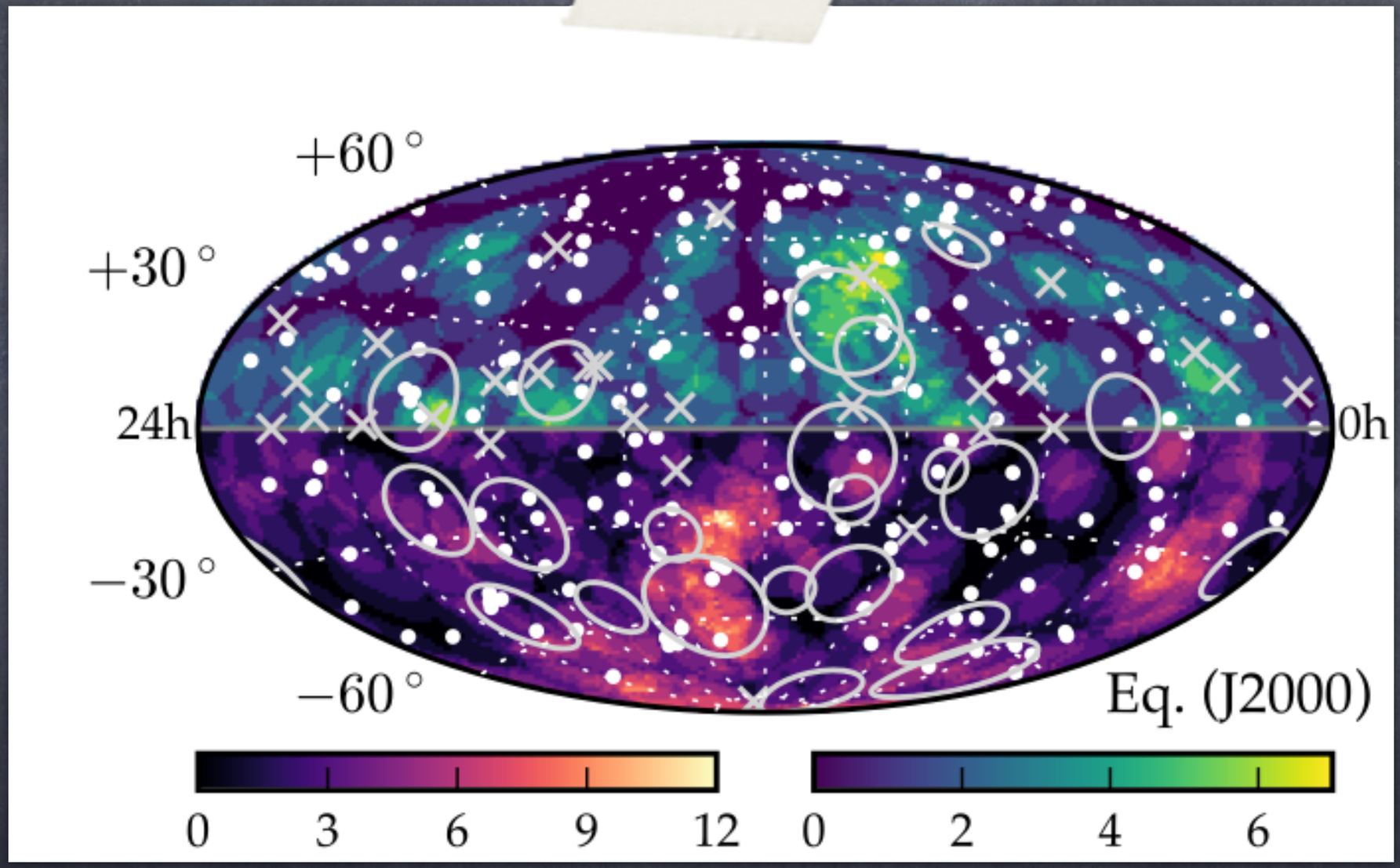
Dec -67.2 deg, R.A. 38.3

Median Angular error 10.7 deg

Cosmic Neutrinos

Are they connected to the origin of cosmic rays?

maybe ...

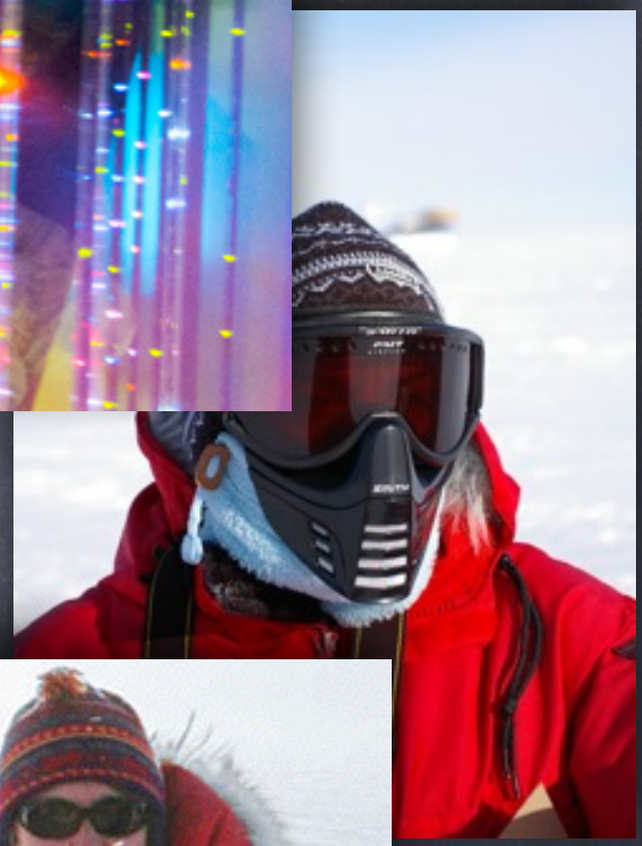


E.R, S. Coenders, P. Padovani, P. Giommi, L. Caccianiga, submitted (2016)

we are moving the first steps into multi-messenger astronomy

the IceCube Collaboration

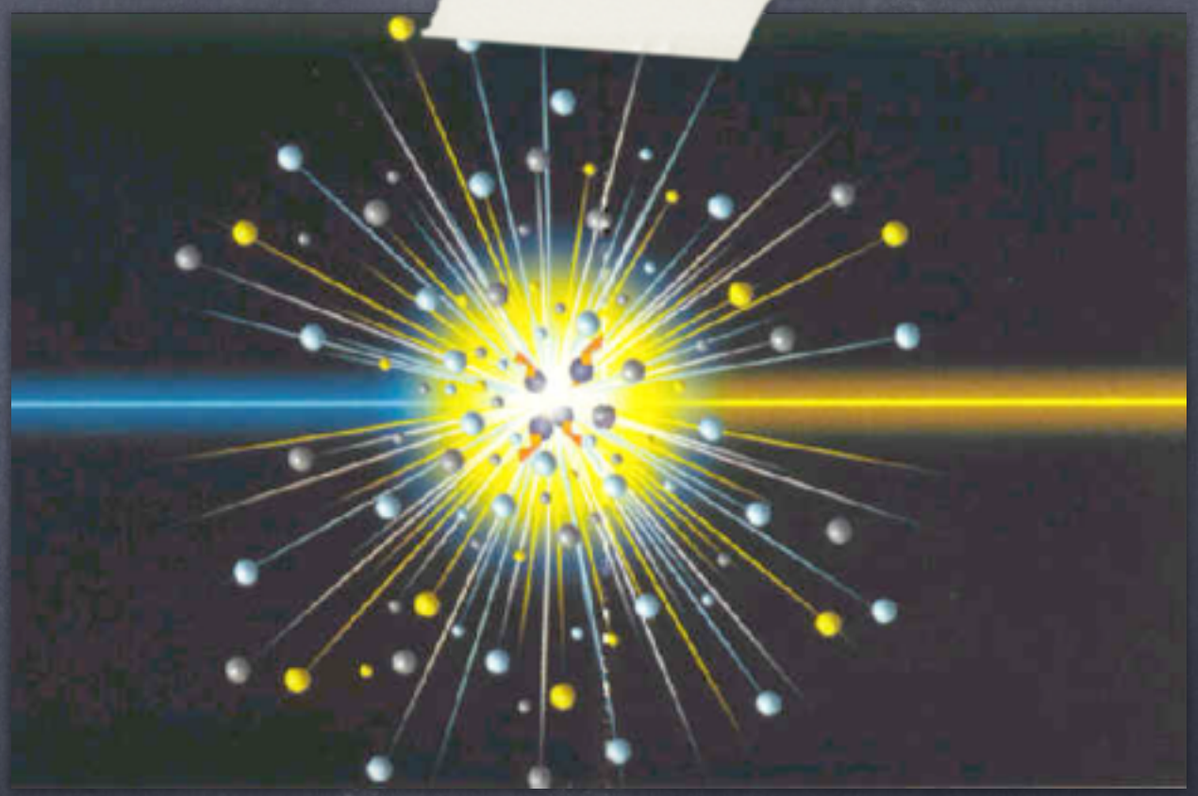
South Pole IceCube "girls"



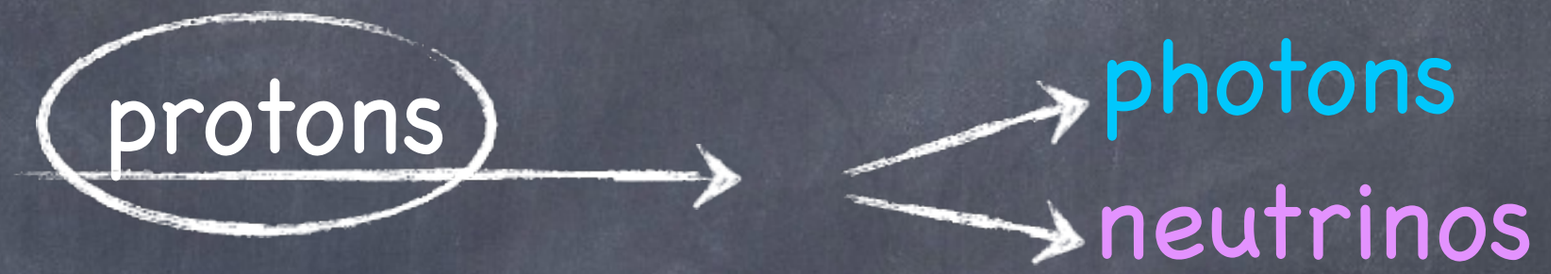
...but it is not like this everywhere
...IceCube is still an exception
...multiple issues call for multiple actions

(1) support of young parents,
(2) female role model in schools,
(3) support of young female students,
(4) bridge funds for dual career,
(5) gender-awareness training in recruitment

Astro & Partile Physics



photons are produced in both protons (CR) and electrons -> ambiguous interpretation



neutrinos are produced ONLY in proton interactions -> un-ambiguous interpretation

WHAT are neutrinos ?

- The small neutral ones
- Elementary particles
- Very small mass ≠ 0 (not yet measured)
- Probably stable (don't decay, but oscillate)
- Interact very sporadically (weakly)
  - travel undisturbed cosmological distances (+)
  - difficult to be detected (-)

Cosmic Rays

The Universe routinely produces very high energies (higher then LHC)

How does it work?

Cosmic Accelerators

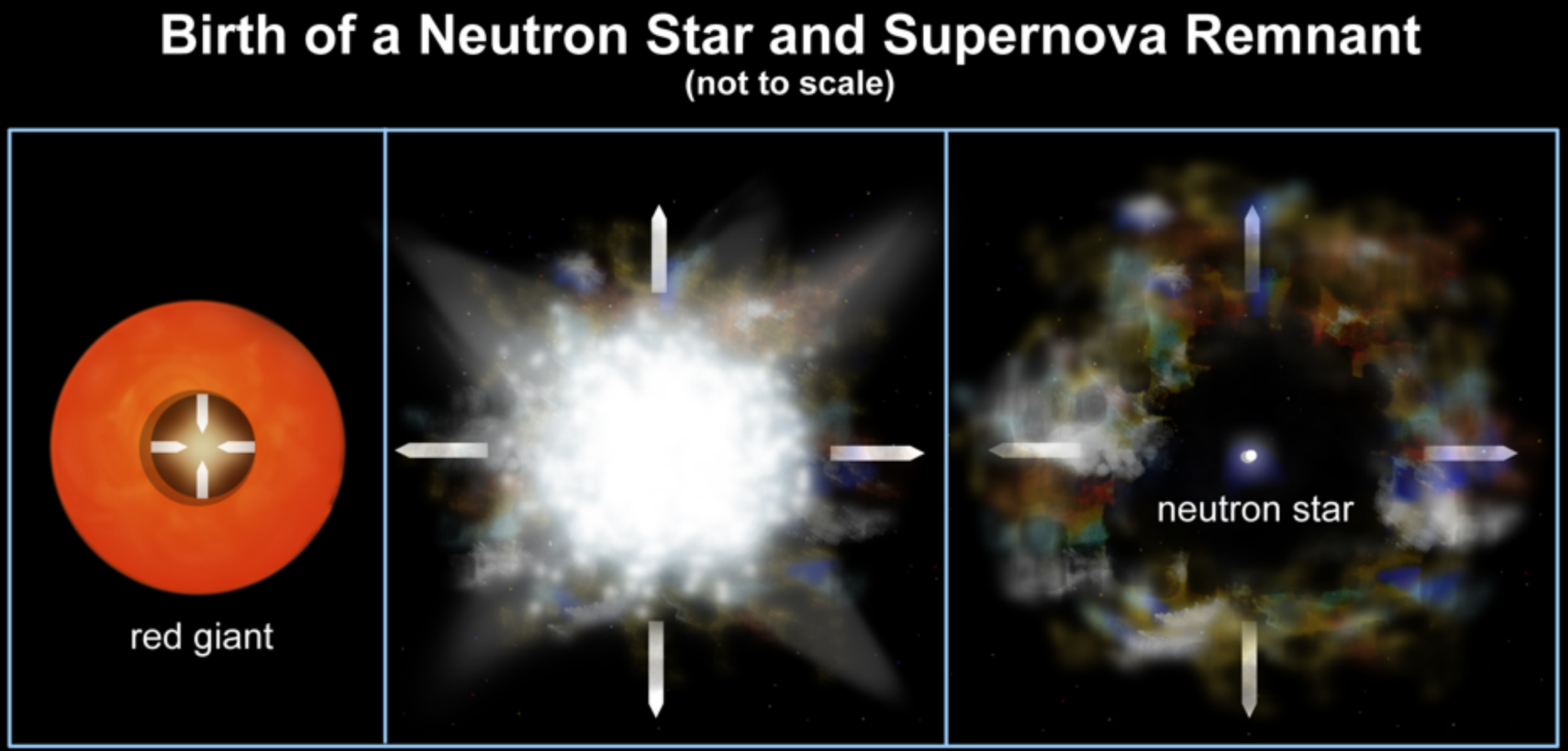
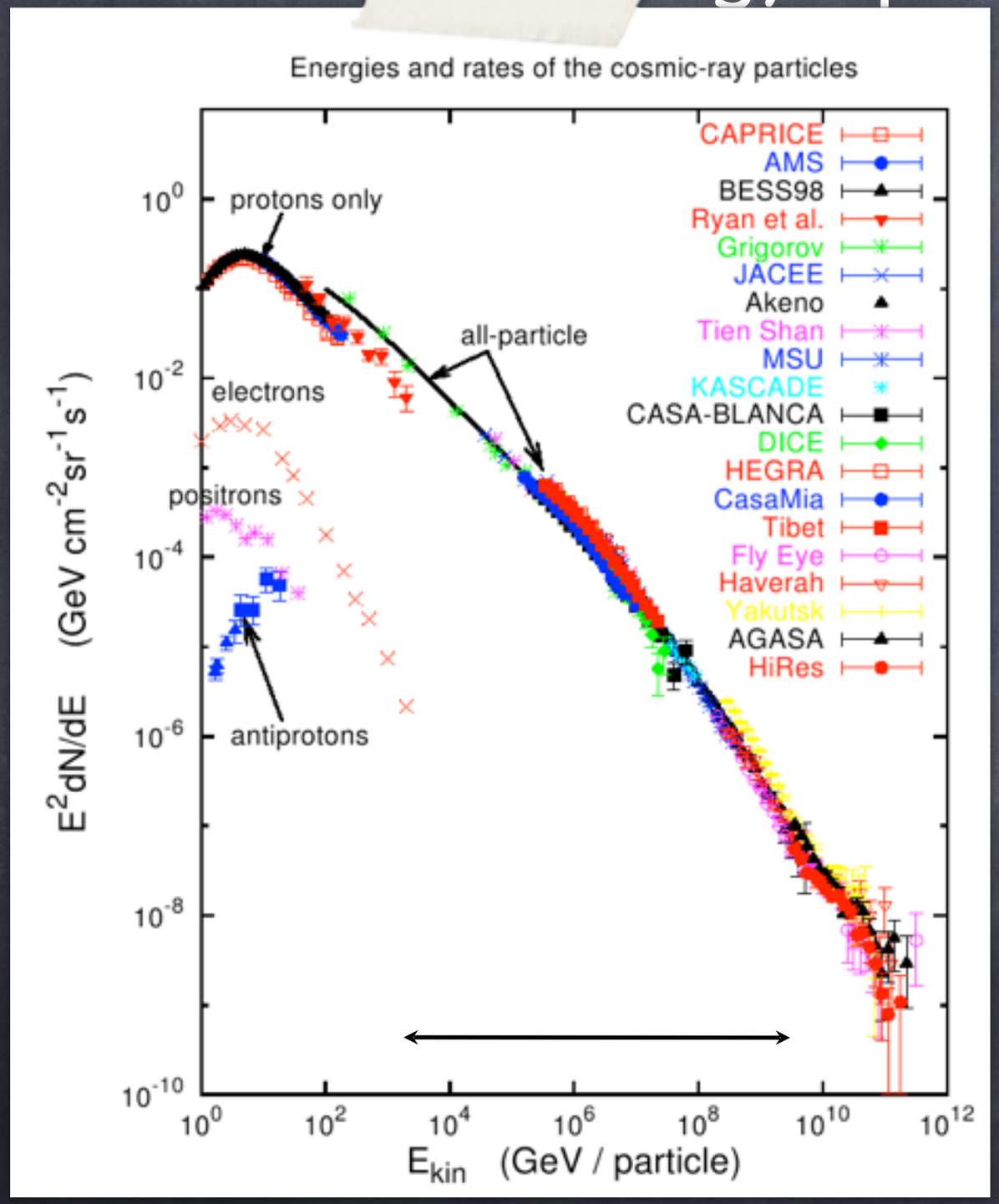
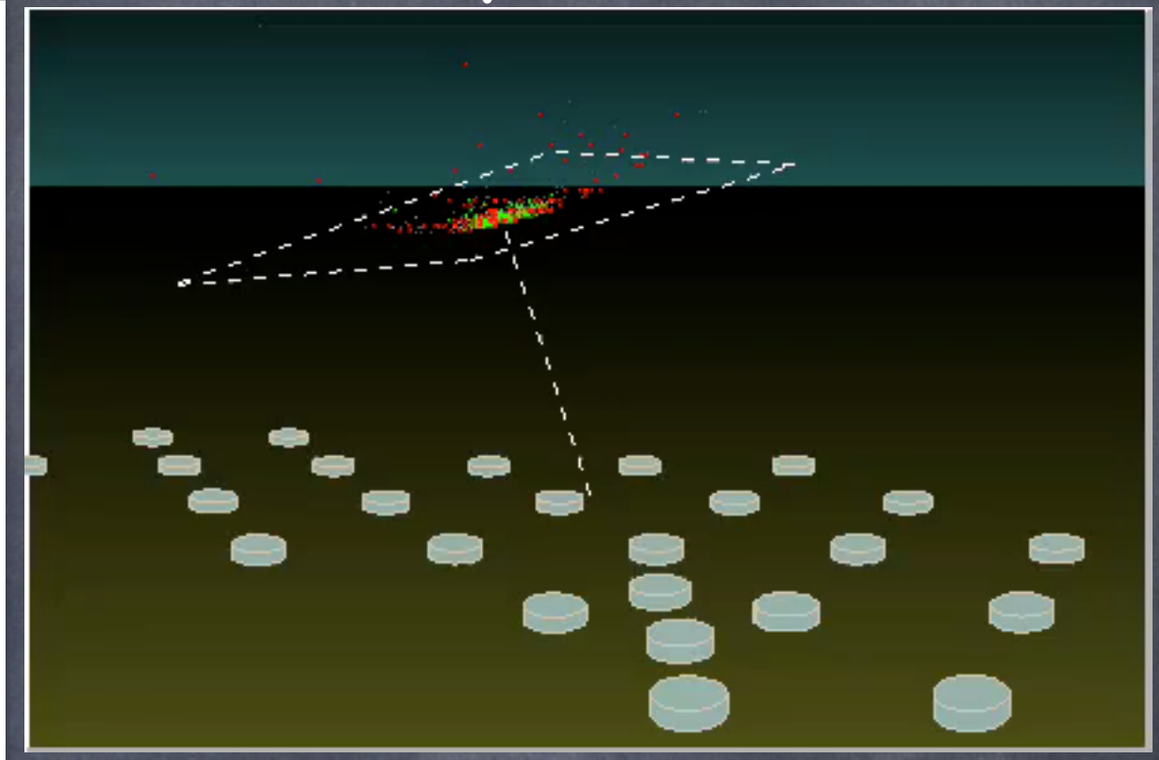


Illustration: NASA/CXC/M.Weiss

Let's prove this idea ...

Observable: Energy spectrum of (primary) CRs





Heat in the source is not enough!
Acceleration is happening in sources.

Neutrinos
as astronomical messenger

- From the atmosphere (MeV-TeV energies)

Extra-terrestrial:

- From the SUN (keV-MeV energies)
- From core collapse SuperNovae, 1987A (MeV energies)
- From cosmic accelerators: the search for TeV neutrinos still on-going

Neutrinos as astronomical messenger

- From the Atmosphere
- From the SUN (keV-MeV energies)

Observation of neutrino oscillations

Mass of neutrinos ≠ 0

First "evidence" of atmospheric muon neutrinos disappearance

[SuperKamiokande Collaboration, **Phys. Rev. Lett. 81, 1562–1567 (1998)**]

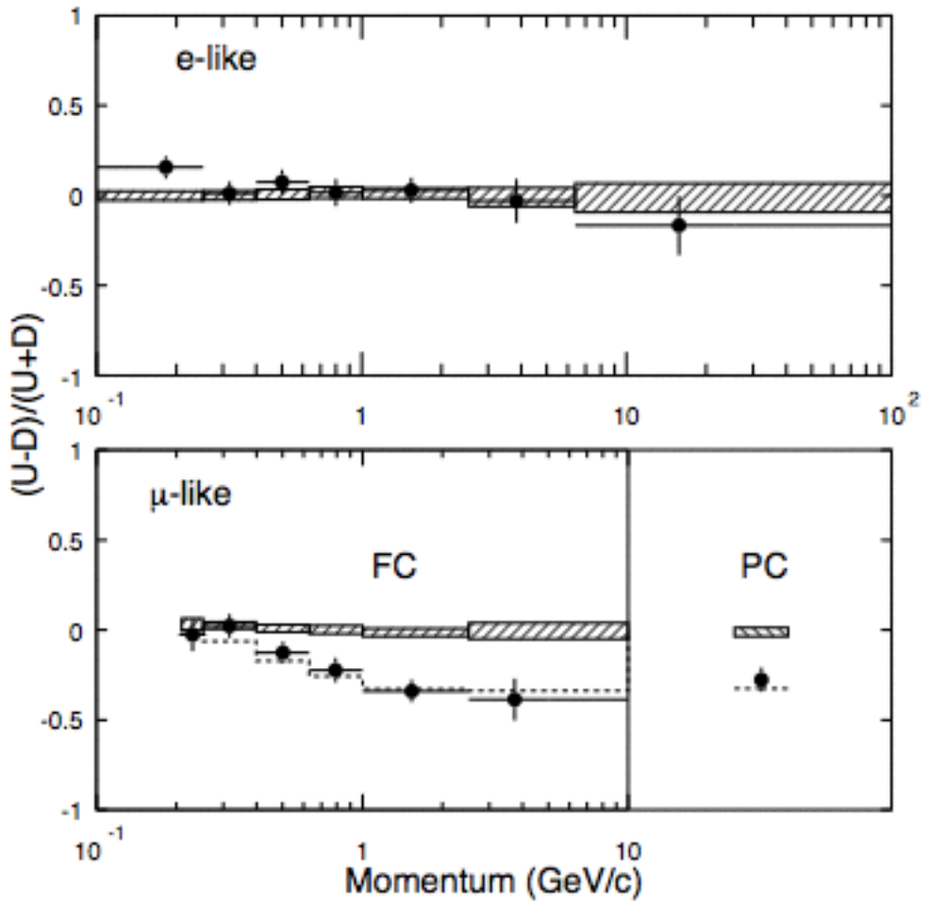


FIG. 1. The $(U - D)/(U + D)$ asymmetry as a function of momentum for FC e-like and μ-like events and PC events. While it is not possible to assign a momentum to a PC event, the PC sample is estimated to have a mean neutrino energy of 15 GeV. The Monte Carlo expectation without neutrino oscillations is shown in the hatched region with statistical and systematic errors added in quadrature. The dashed line for μ-like is the expectation for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $(\sin^2 2\theta = 1.0, \Delta m^2 = 2.2 \times 10^{-3}\ \mathrm{eV}^2)$.

Today we know:

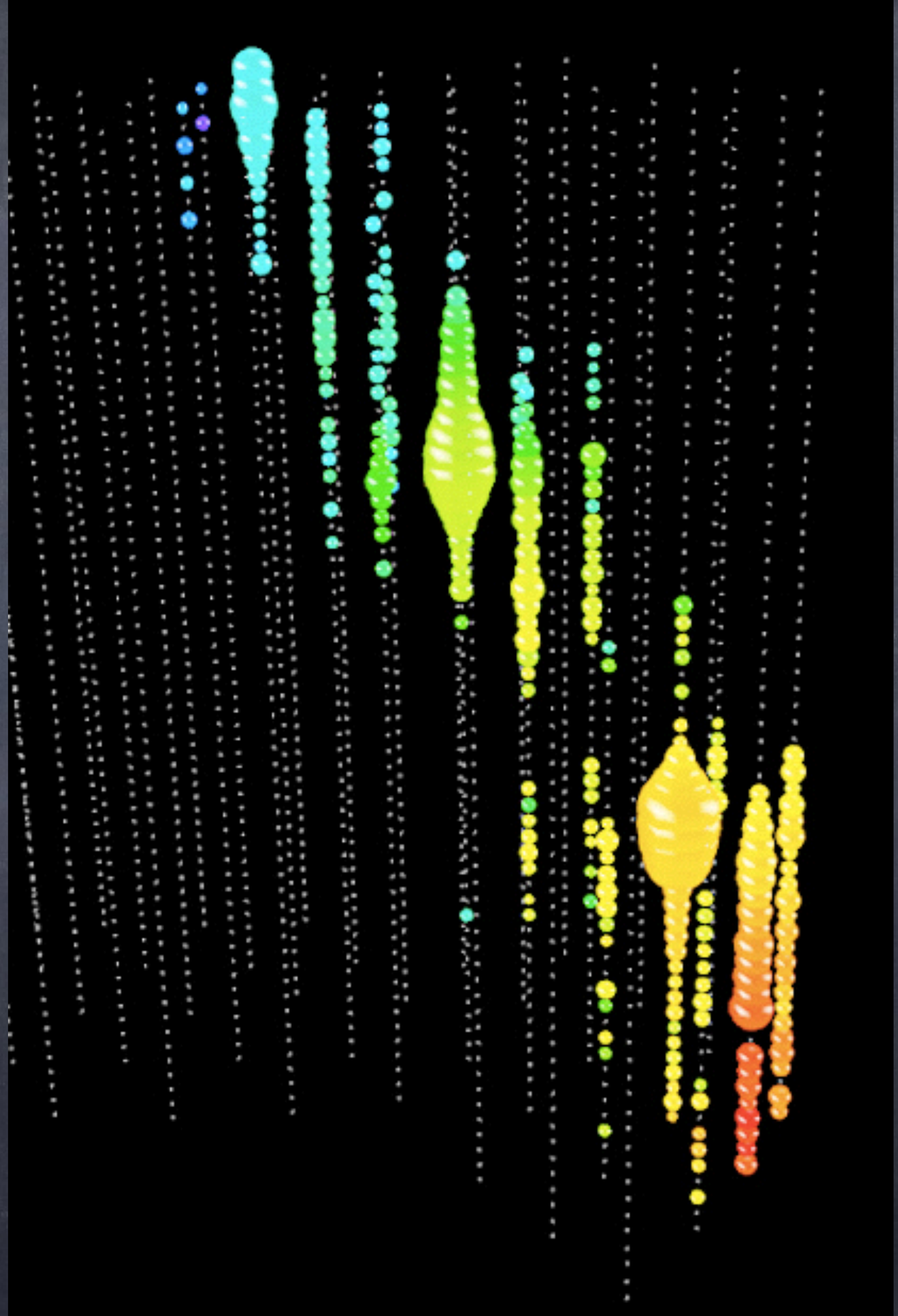
- three neutrinos type
- neutrinos are mixed (in quantum mechanical sense)
- most of mixing parameters measured
- is this picture enough? sterile/ superluminal neutrinos ???

$$V = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

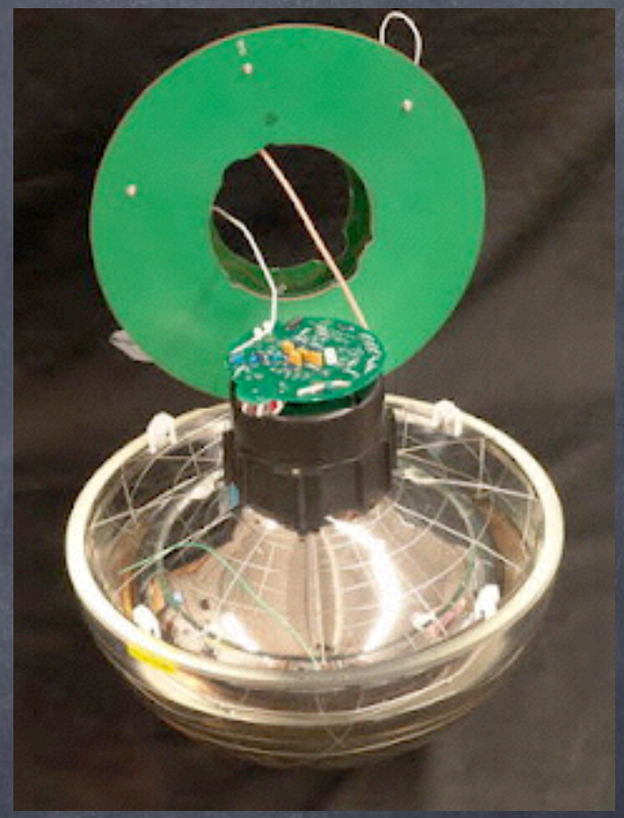
Neutrino detection

- In water or liquid scintillators
- Detection of induced particles
- In underground: shield from atmospheric background (underground laboratory)
- Very large masses

IceCube
(South Pole)
PeV muon
neutrino



The "eyes" of a neutrino telescope

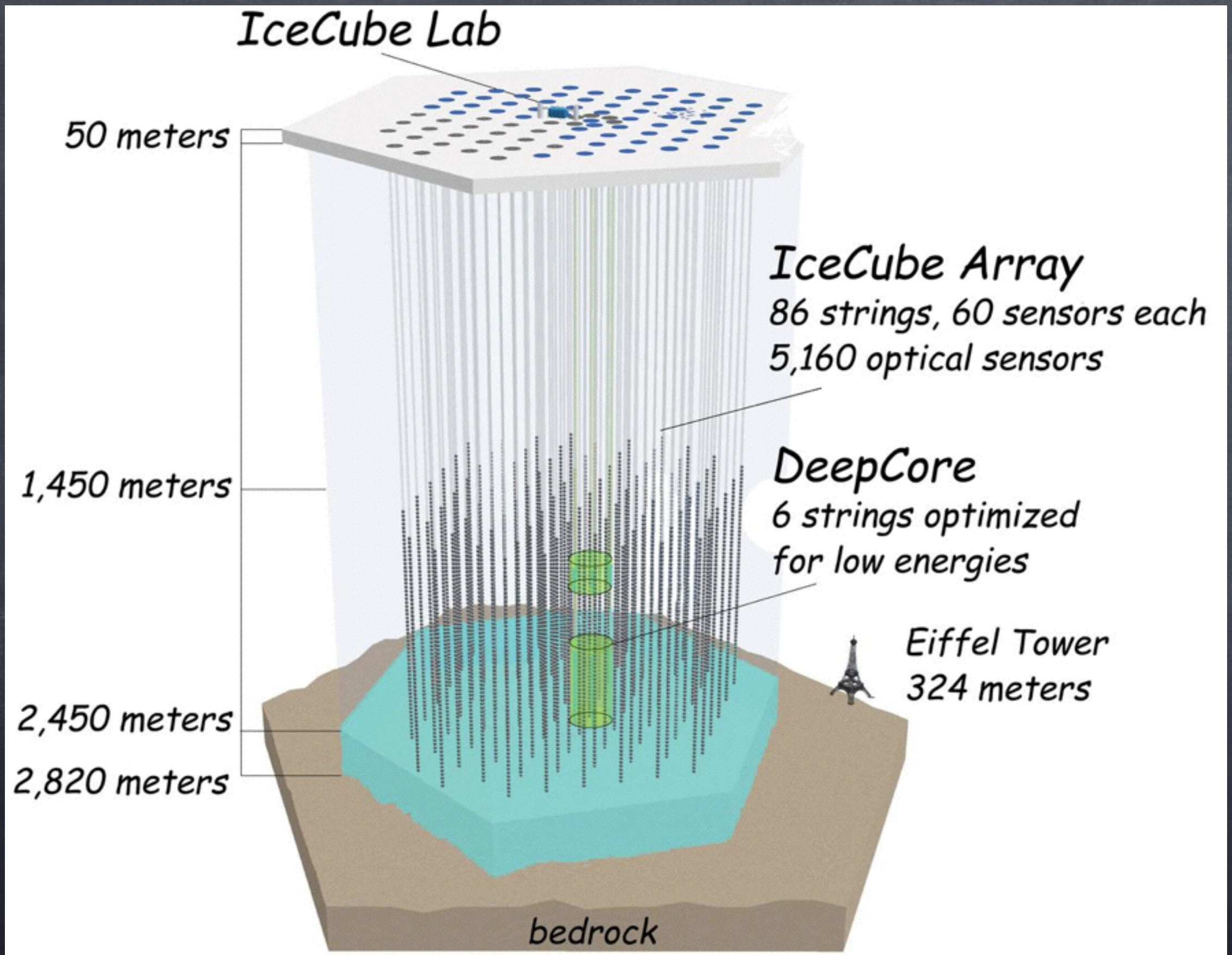


In summary:
Shopping list for a neutrino telescope

- Huge volume of transparent material (km^3)
  - No laboratory can host such an experiment
  - Check natural materials

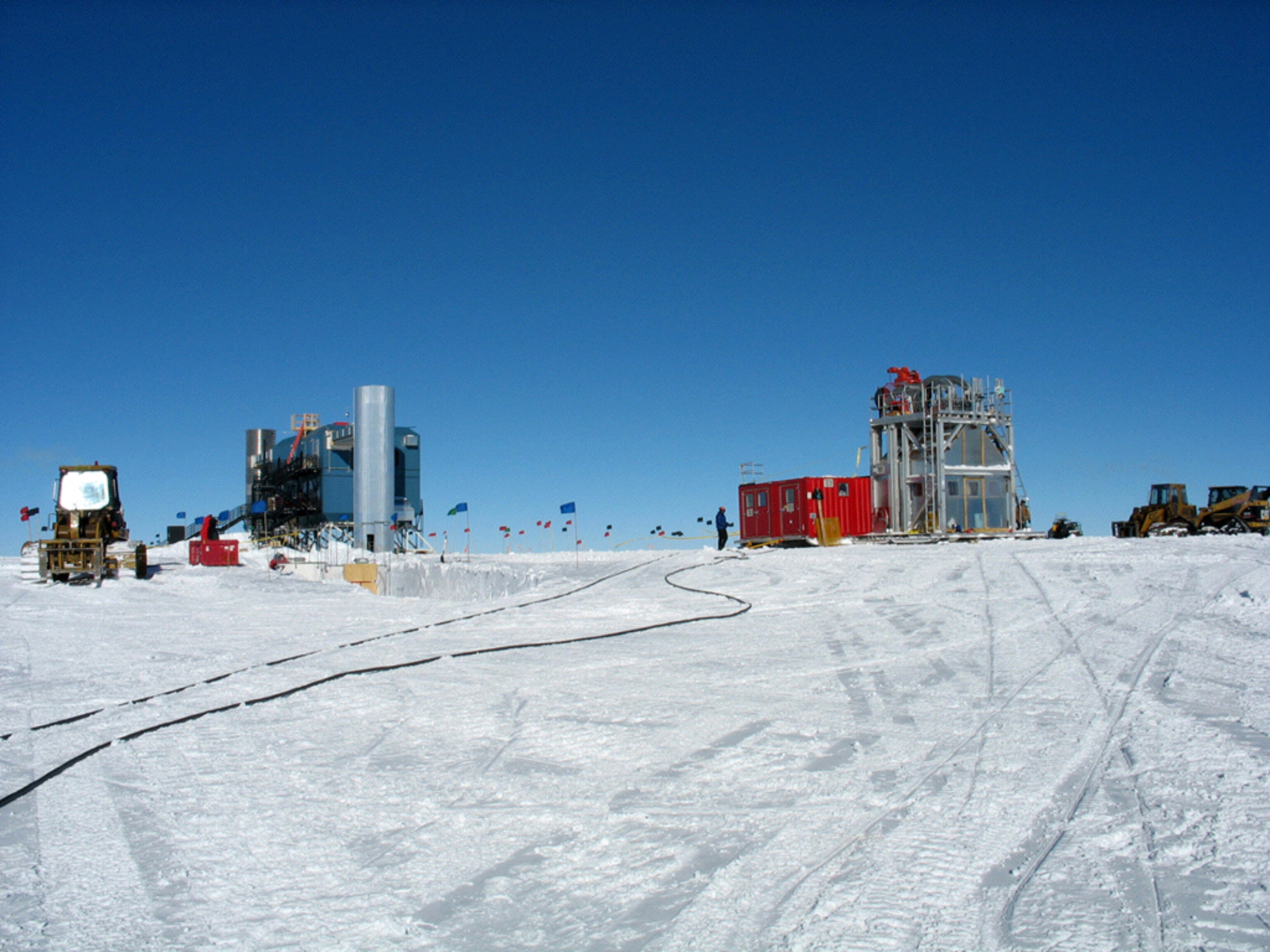
- A lot of "eyes"
  - This will be expensive!

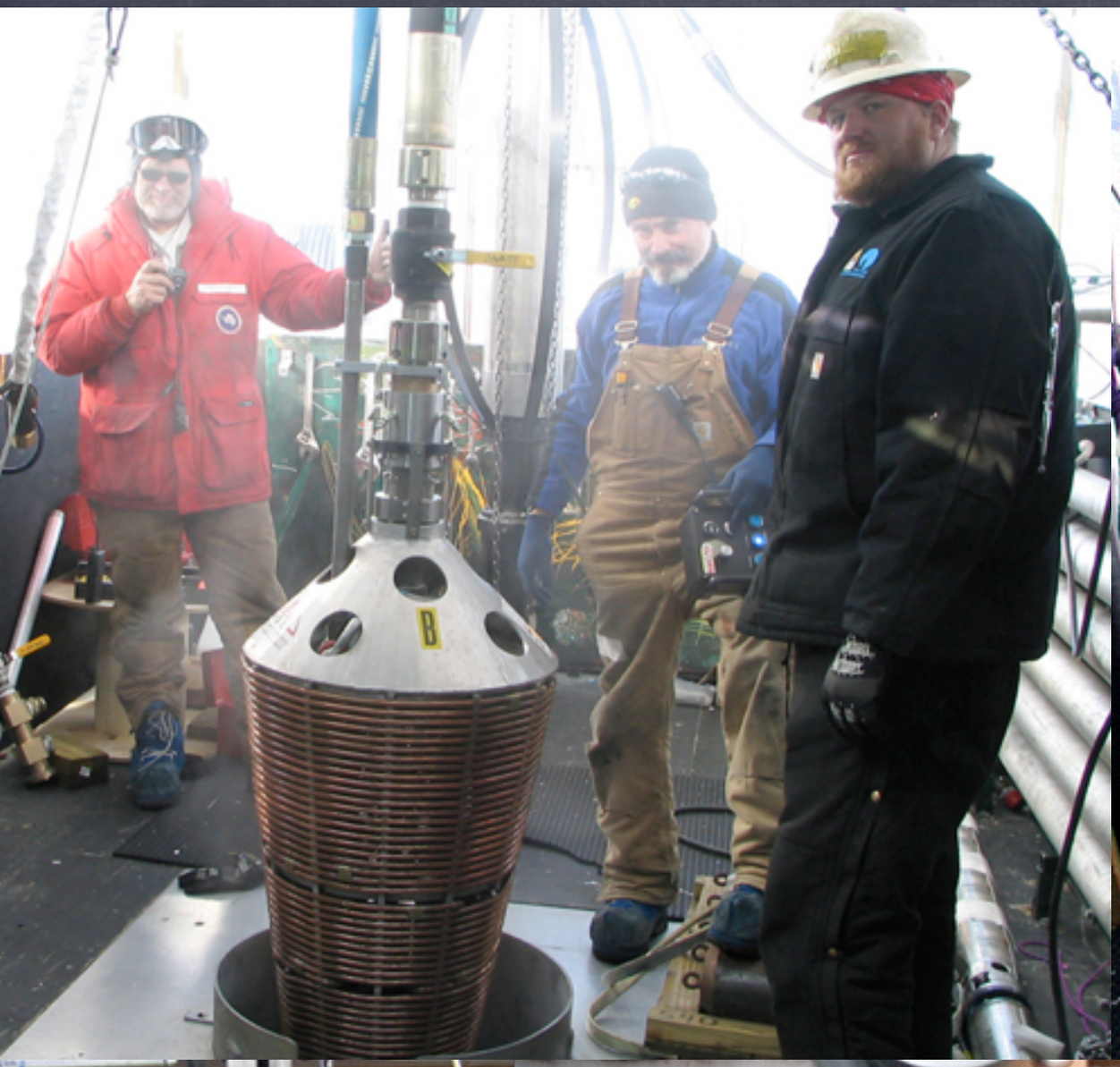
IceCube @ South Pole


IceCube Lab
50 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
1,450 meters
DeepCore
6 strings optimized
for low energies
Eiffel Tower
324 meters
2,450 meters
2,820 meters
bedrock

The drill of 3 km holes in the ice ??

we have a better system ....

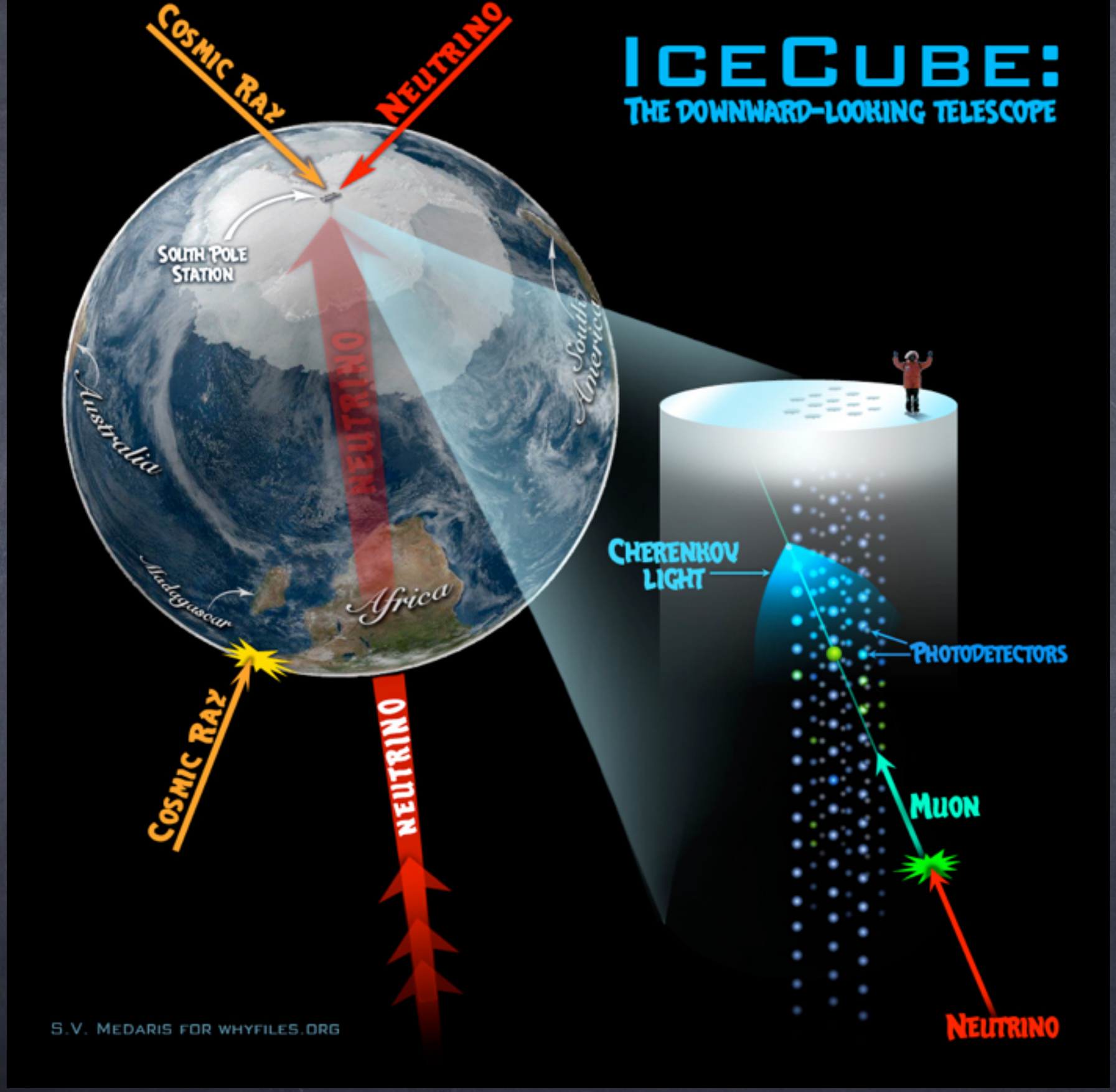




after 7 years:

260 scientists, 36 research institutions, TUM new member from 2012

IceCube:
The Downward-Looking Telescope



S.V. Medaris for whyfiles.org

IceCube: searches for neutrinos from cosmic accelerators

STEP 1:

- Collect data (monitor, calibrate, correct ...)
- Reconstruct data (clever algorithm ...)
- Filter data on-line (don't lose your signal there ...)
- Transmit them through the satellite (hope the satellites work ...)

STEP 2:

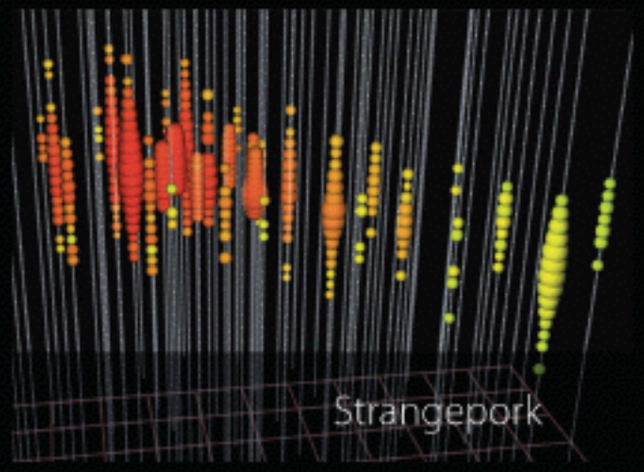
- Filter them again and again
- Realize simulated data (the model)
- Check experimental data vs simulated data and

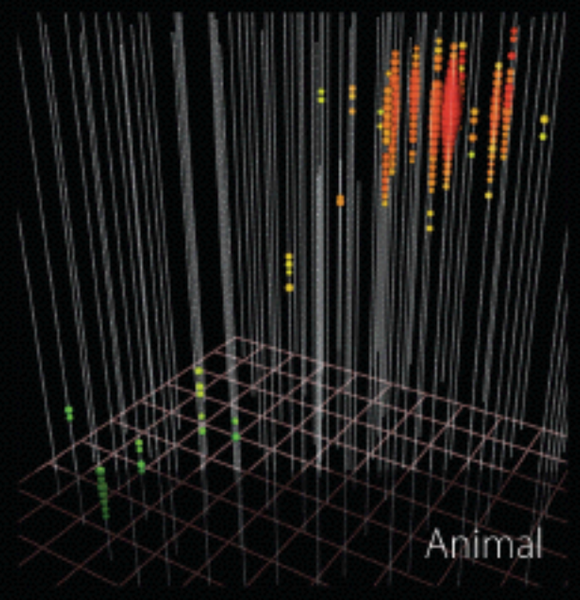
STEP 3:

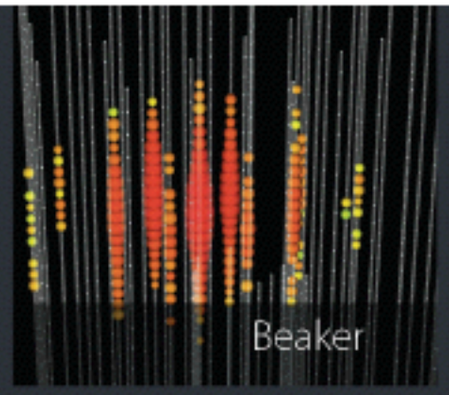
- Optimize the search for well reconstructed neutrinos
- Optimize the search for best efficiency
- Develop a good search algorithm
- Make your statistics right
- Discuss / defend your work
- with the Collaboration and ...

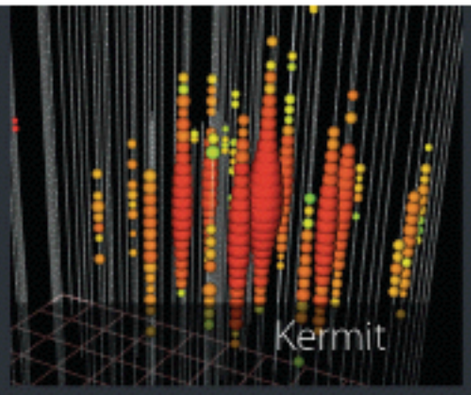
Examples of the

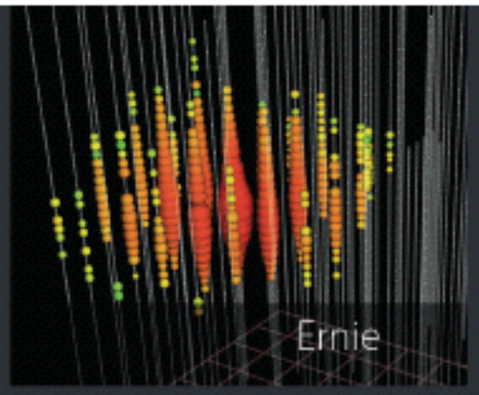
28 High Energy Events

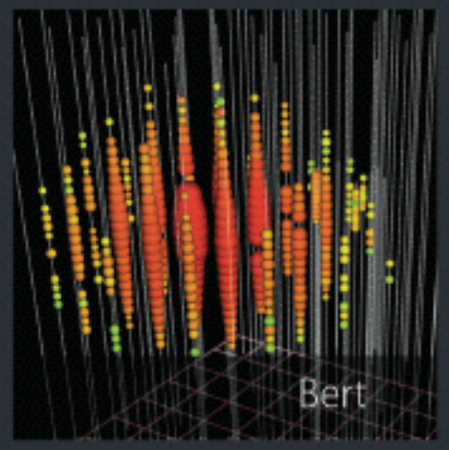


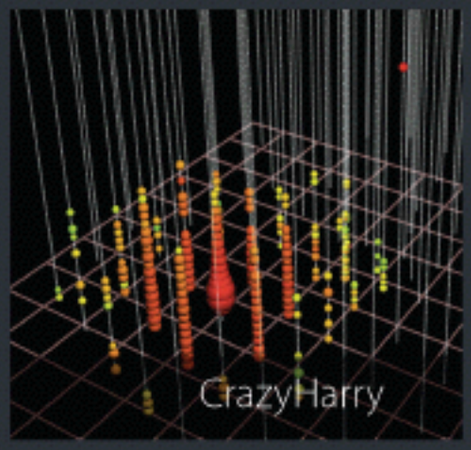


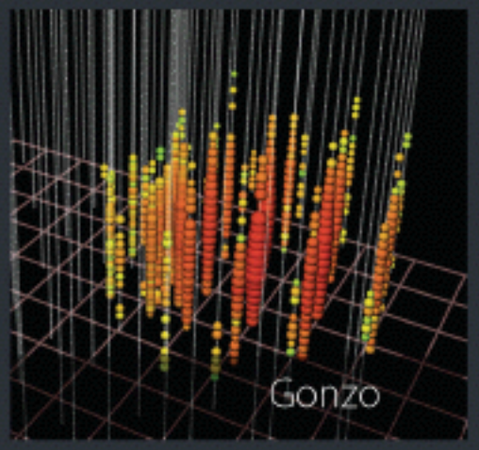


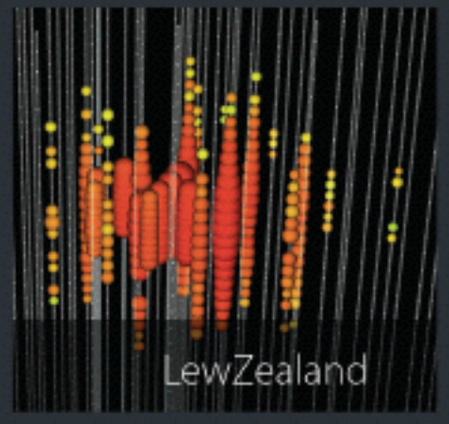


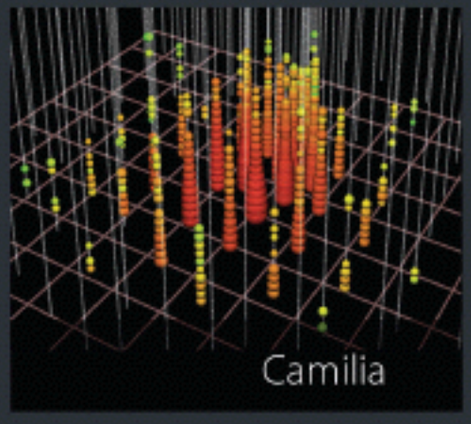


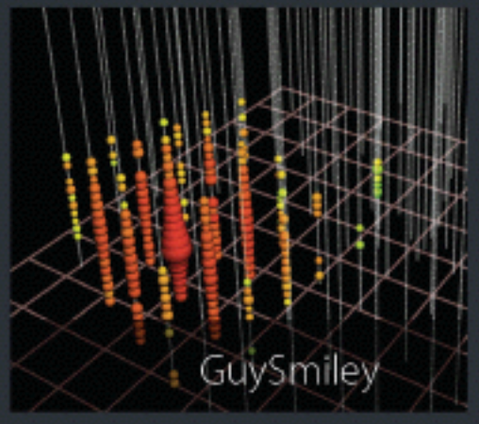


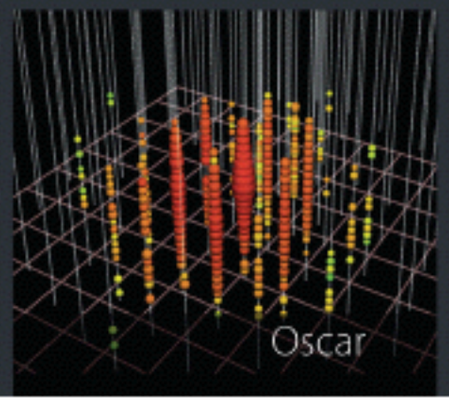


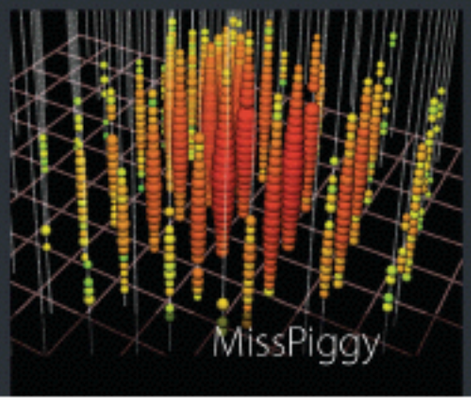


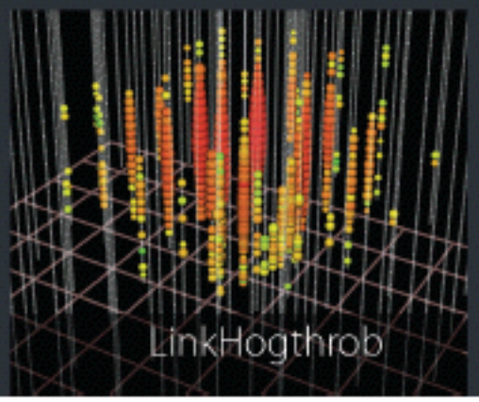






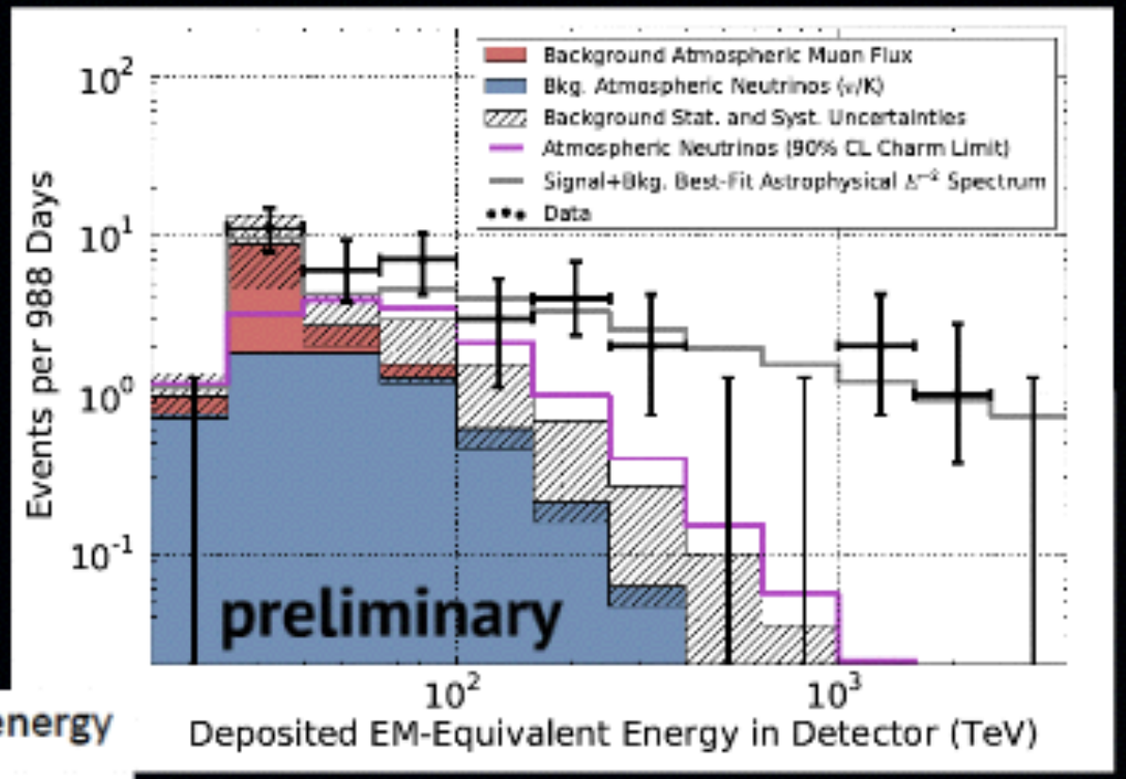






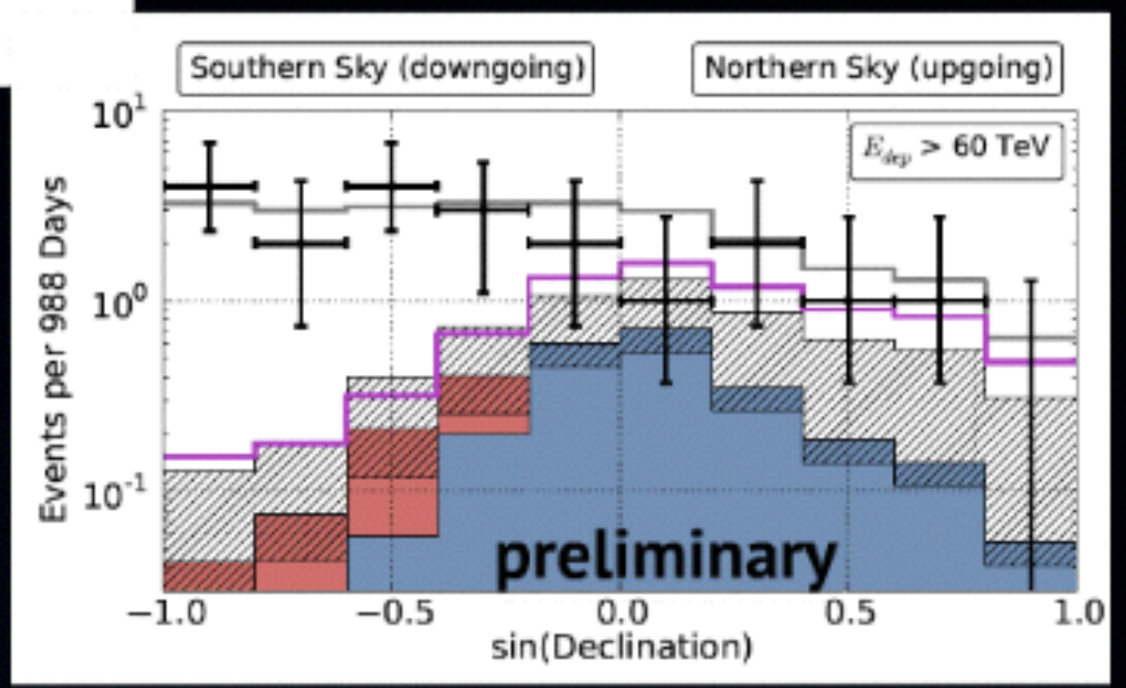
3-years sample

- confirm and strengthen
- rejection of
non-astrophysical > 5 sigma



best-fit per-flavor astrophysical (E^{-2}) flux in the energy range of 60 TeV – 3 PeV:

$$E^2\phi(E) = 0.95 \pm 0.3 \times 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



IceCube Coll, 2014 submitted to PRL, arXiv:1405.5303

physicsworld

BREAKTHROUGH OF THE YEAR

2013

IceCube

NSF

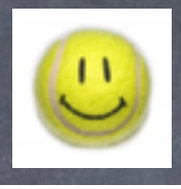
Where are these neutrinos coming from

- No idea for the moment
- Many scenarios open, the next challenge is here

What else can be searched by IceCube?

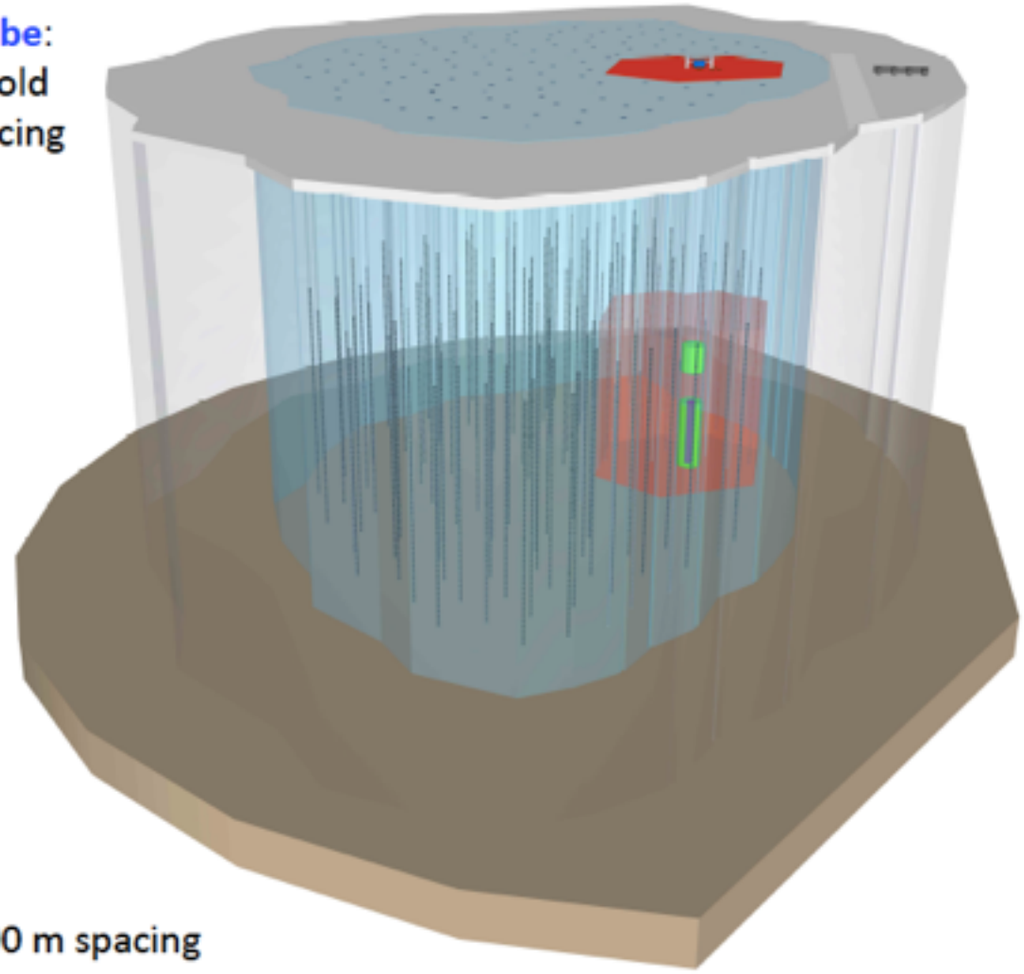
- Search for Dark Matter
- Study of Neutrino Properties
- Study of primary CR
- Search for Sn neutrinos
- Search for exotic particles

At the end of this first (big) step …
we still don't know …
where is/are the source(s) of CR!!



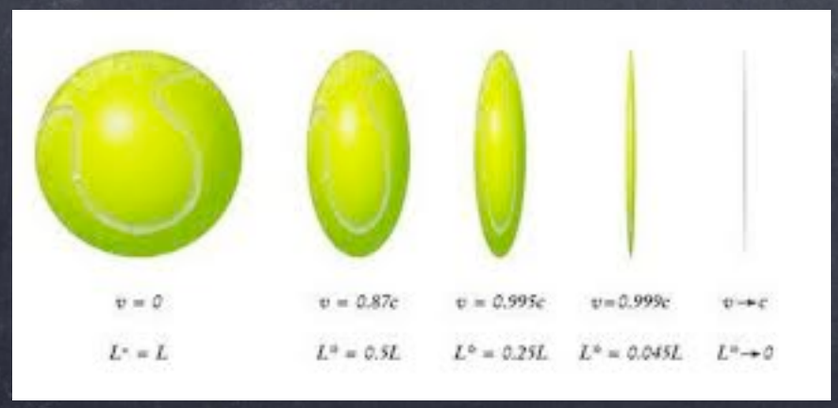
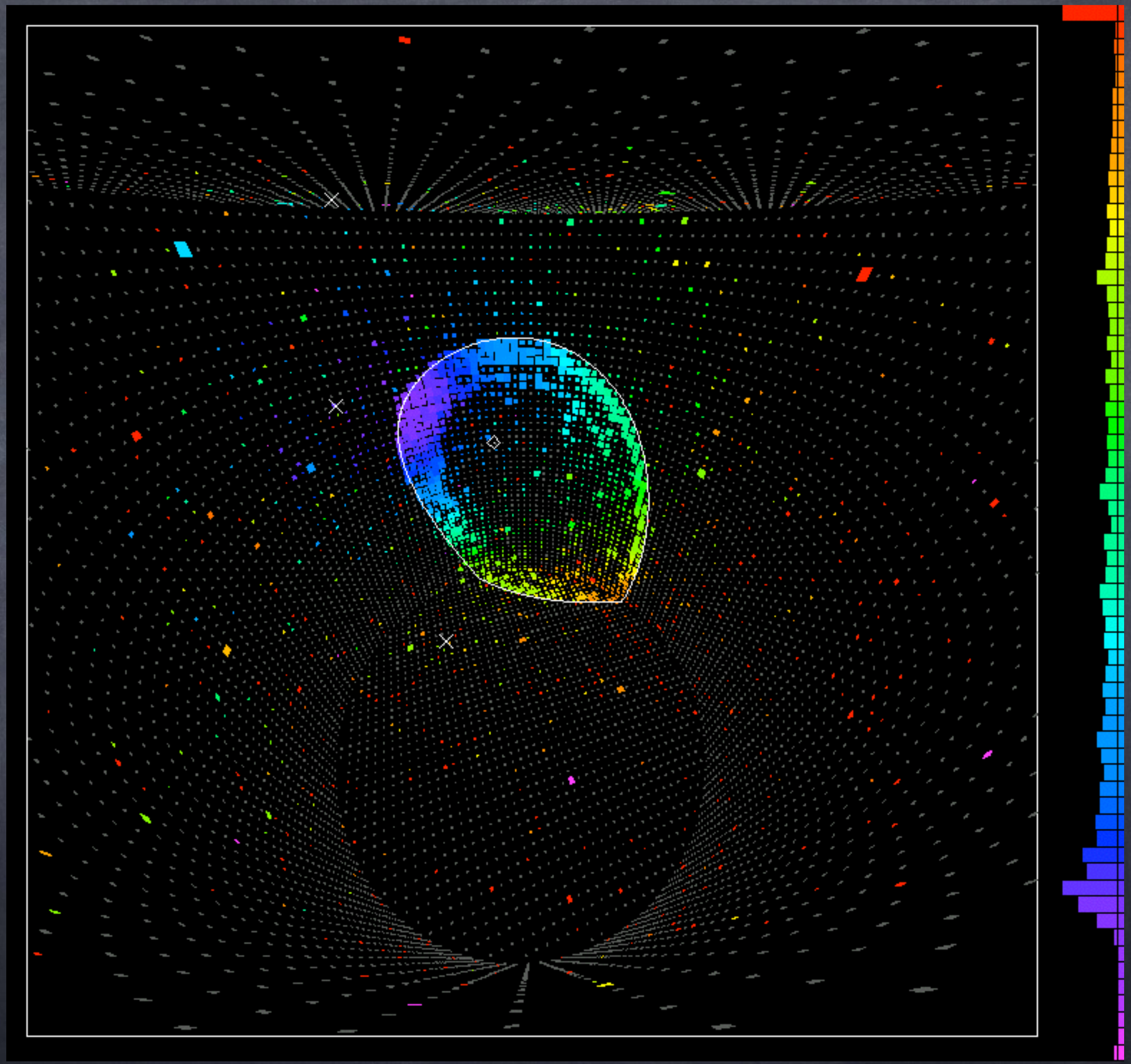
but we keep on searching …
and we are already thinking about the next generation …

Possible strategy for a
Next Generation IceCube:
Increase energy threshold
allows larger string spacing



Artist conception
Here: 120 strings at 300 m spacing

Particle Astronomy is a new emerging field with still a realistic chance of fundamental discoveries



Super-Kamiokande (Japan) GeV muon neutrino