Towards Neutrino Astronomy: the IceCube Experiment at the South Pole

Stefan Westerhoff

University of Wisconsin-Madison

June 11, 2012

IceCube: An Unusual Telescope

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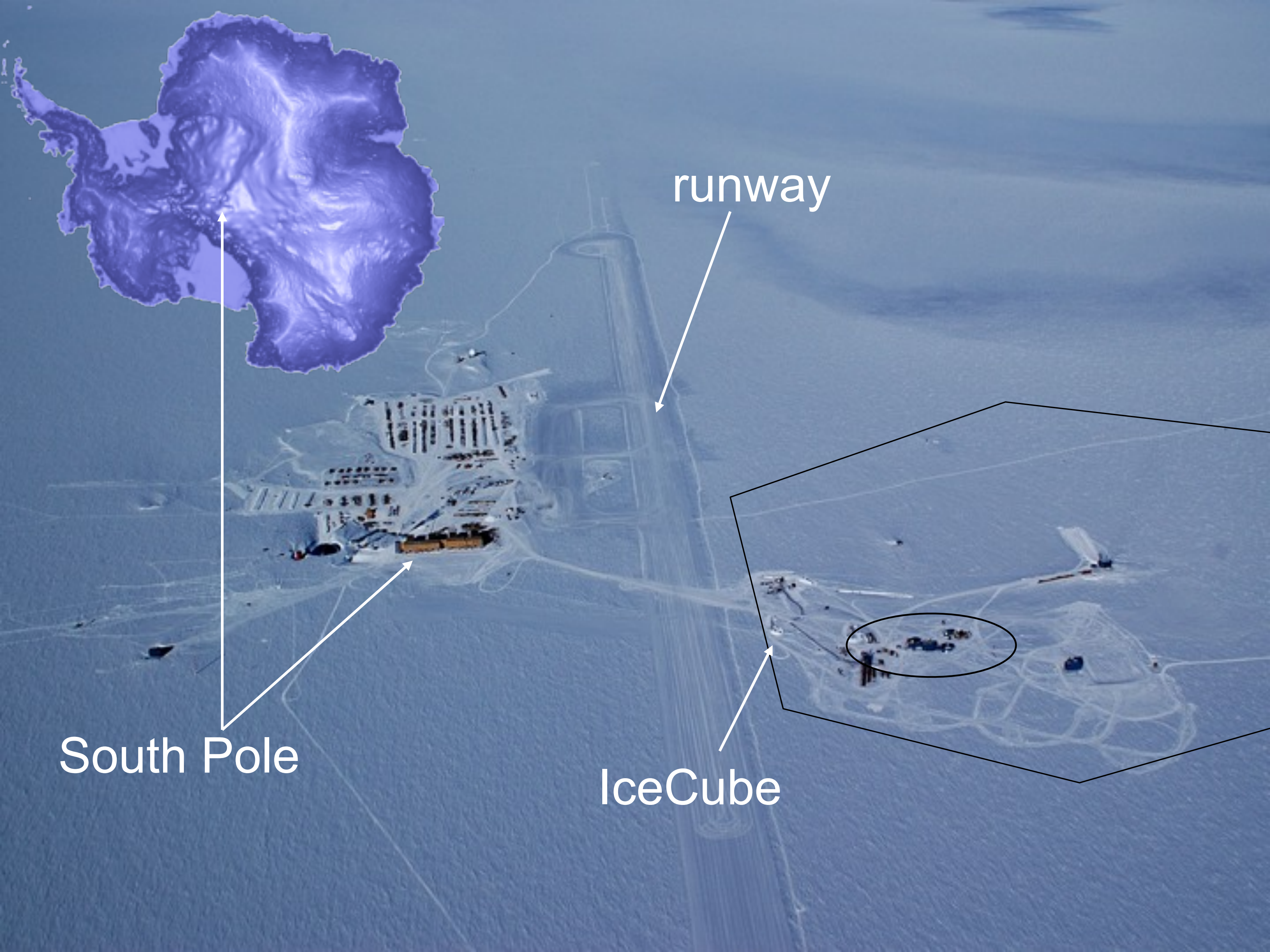
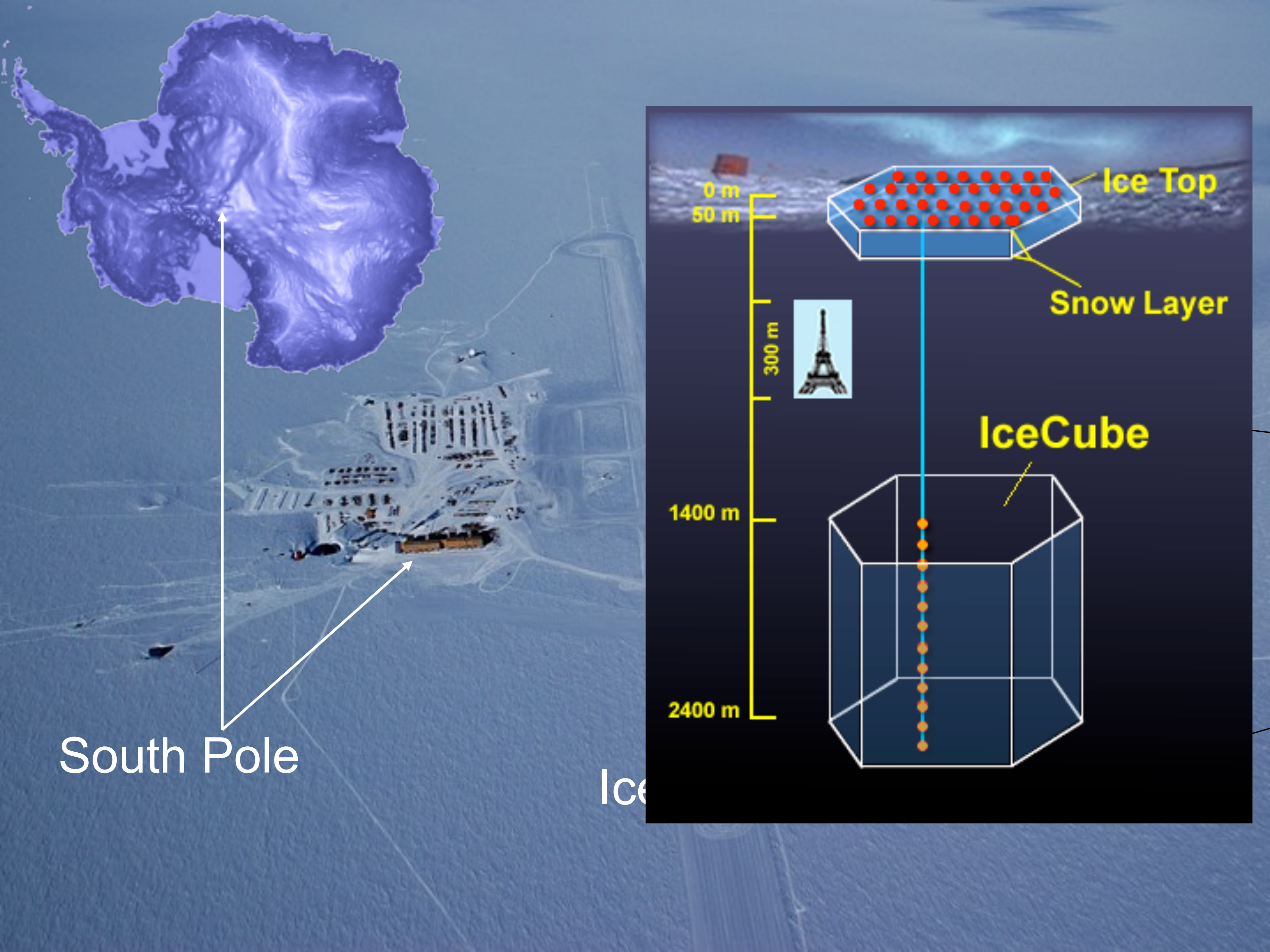
- The detector volume is about a billion tons of ice, instrumented with more than 5000 light detectors.

Amundsen-Scott South Pole Station


runway
South Pole
IceCube


South Pole
0 m
50 m
300 m
1400 m
2400 m
Ice Top
Snow Layer
IceCube


Why?

Outline

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- Particle Astrophysics - Searching for the Most Energetic Sources of the Universe

Particle Astrophysics

- "Classical" Astronomy – electromagnetic spectrum from radio to X-rays.

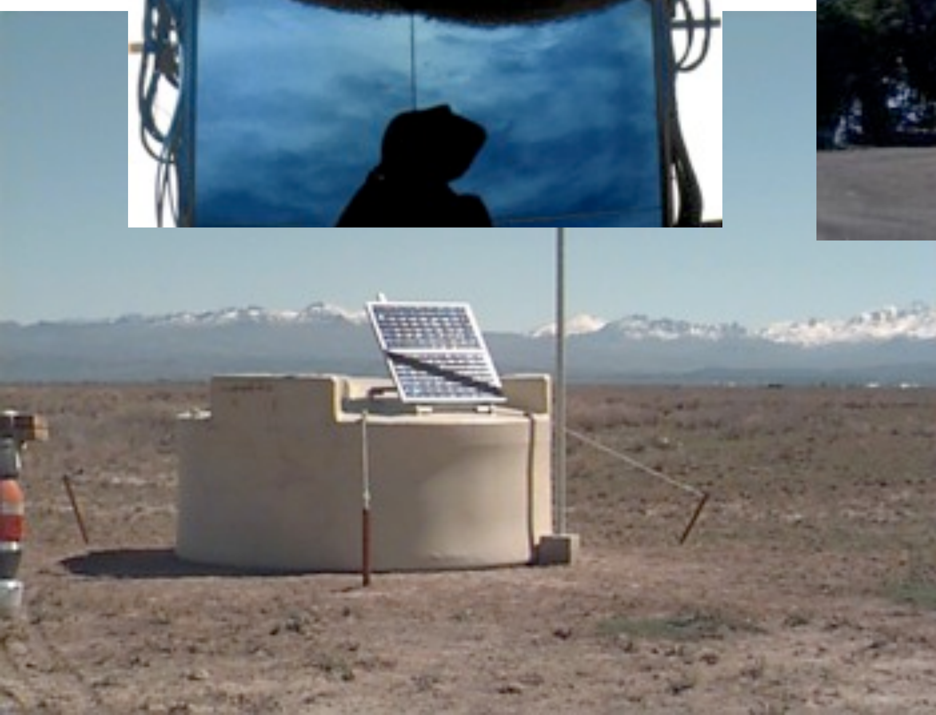
- Gamma-ray Astronomy – photons (light particles) with energies 10^{10} larger than optical light.

- Cosmic Rays – protons and heavier nuclei with energies up to several Joule, the highest particle energies observed in the Universe.

- Neutrinos – tightly connected to cosmic rays and their sources, but neutral and not subject to deflection in magnetic fields (= easier for "astronomy").

energy

Particle Astrophysics "Telescopes"

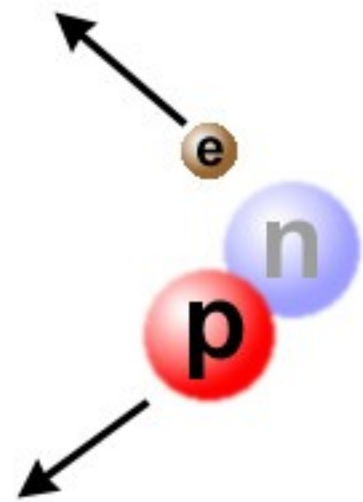


Neutrinos

- The fundamental building blocks of atoms (and therefore of the world we know) are…
  - Neutrons
  - Protons
  - Electrons

- In nuclear reactions, neutrons can turn into protons and vice versa by emitting an electron (β decay).

- Something is missing… or total momentum is not conserved!



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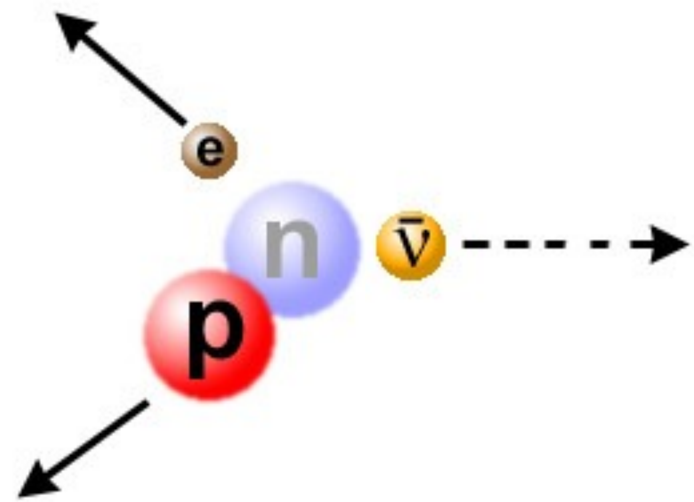


Neutrinos

- To “fix” the picture, Wolfgang Pauli invented a new particle that is very light and has no charge - the neutrino (the “small neutral one”).

- Neutrinos usually escape unseen - they interact very little with anything, move almost at the speed of light and are difficult to catch.

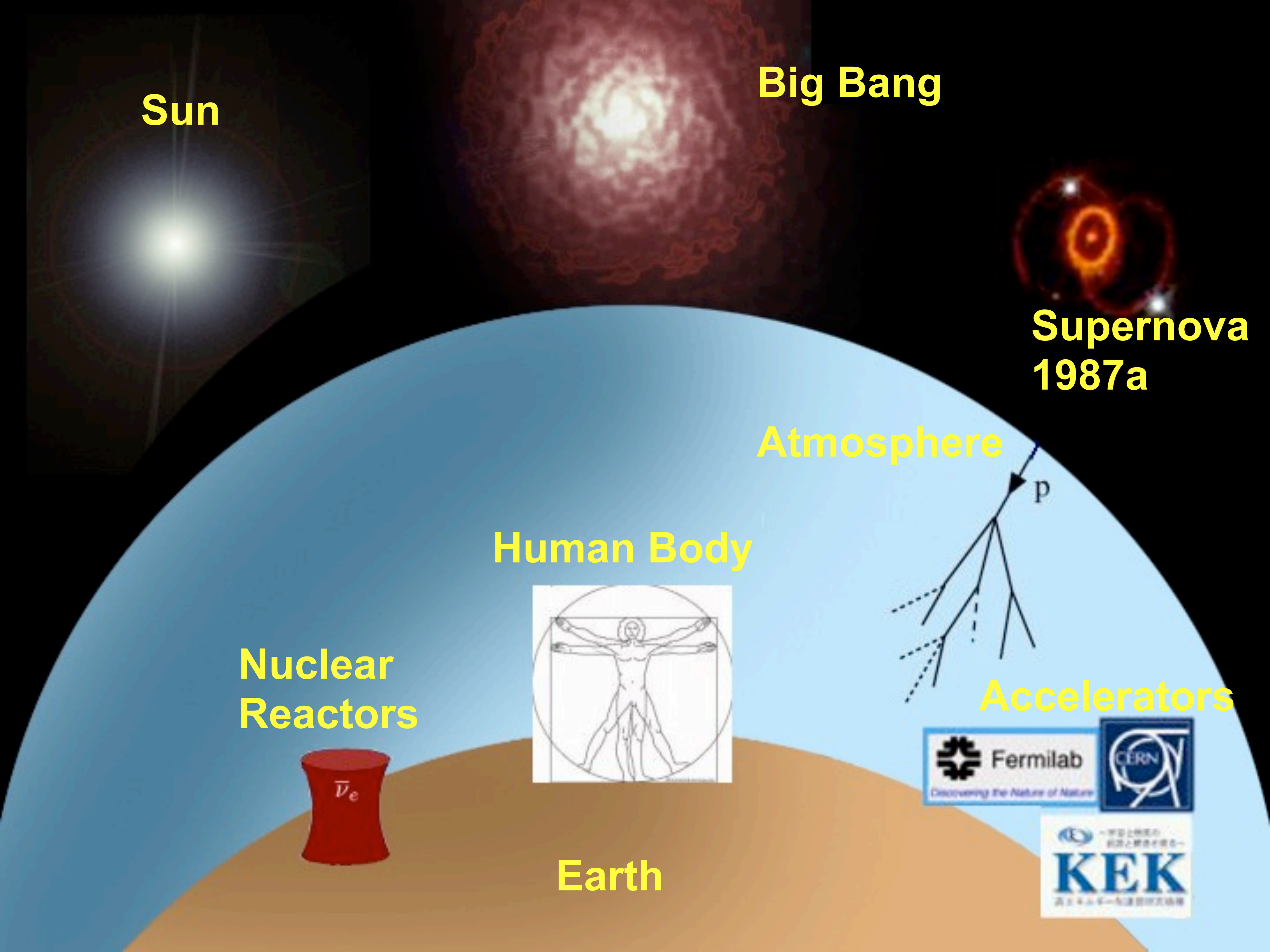
- *“I have done a terrible thing, I have postulated a particle that cannot be detected.”*

Wolfgang Pauli (1900-1958)

Neutrinos

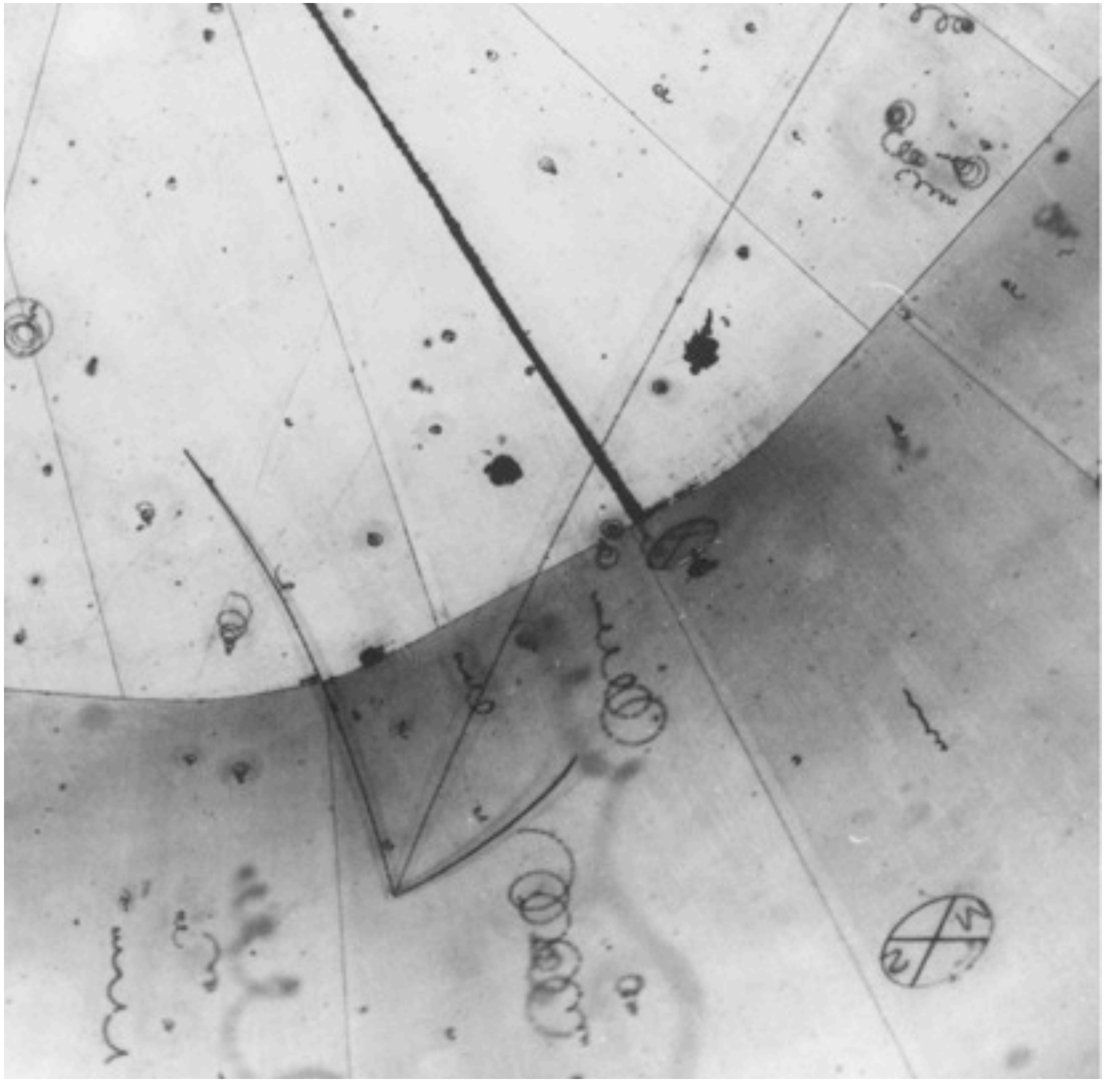
- The neutrino *was* eventually detected by Reines and Cowan in 1956 in a nuclear reactor, three years before Pauli's death.
- *Pauli's response: "Everything comes to him who knows how to wait."*
- Neutrinos are produced wherever there are nuclear reactions, for example in the Sun. More than 50 trillion (50×10^{12}) solar neutrinos pass through your body every second.

Wolfgang Pauli (1900-1958)


Sun
Big Bang
Supernova
1987a
Atmosphere
p
Human Body
Nuclear
Reactors
$\overline{\nu}_e$
Accelerators
Fermilab
CERN
KEK
Earth

The Thing About Neutrinos

- Neutrinos rarely interact - they just zip through almost everything - and are therefore hard to detect!



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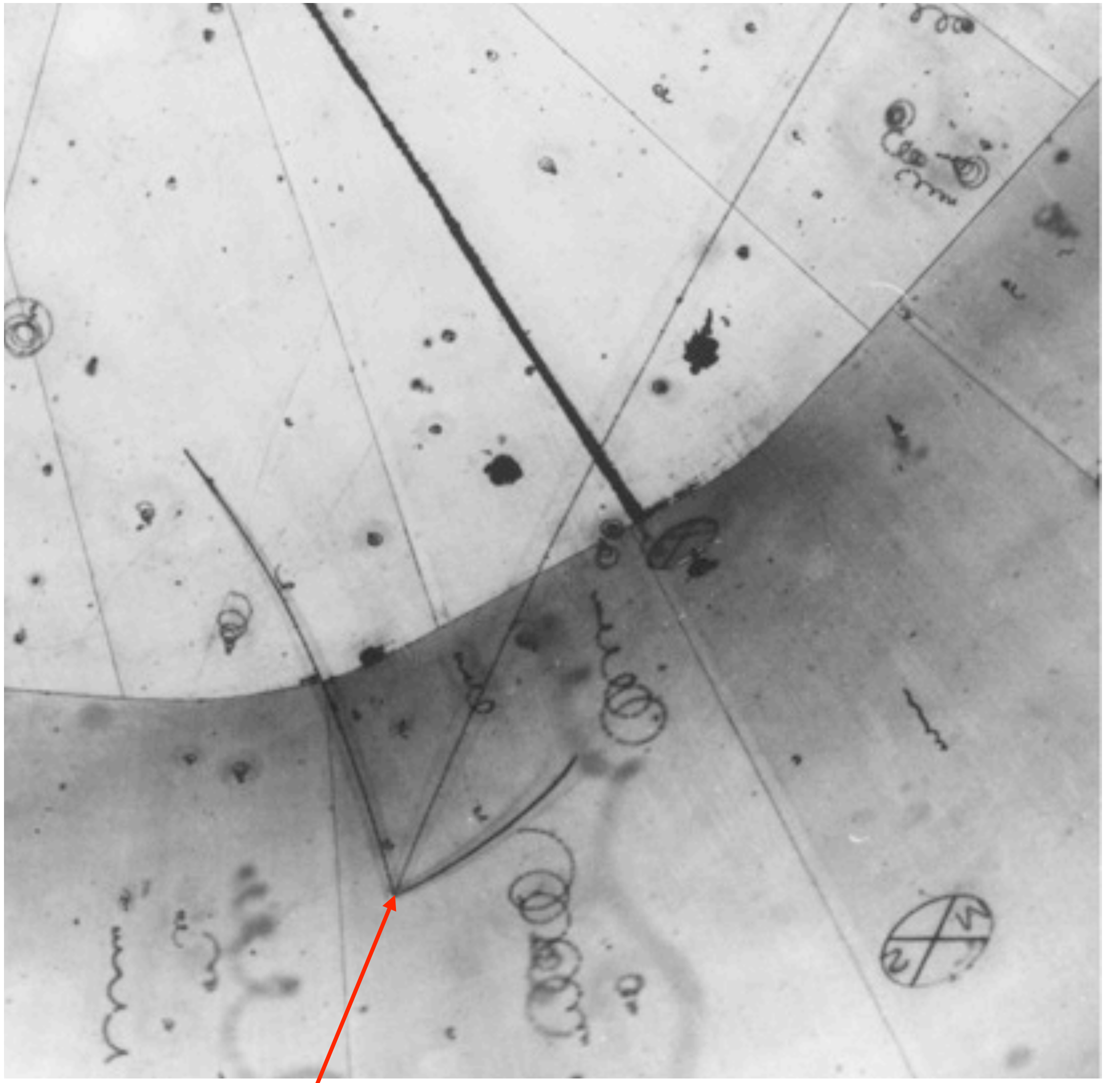

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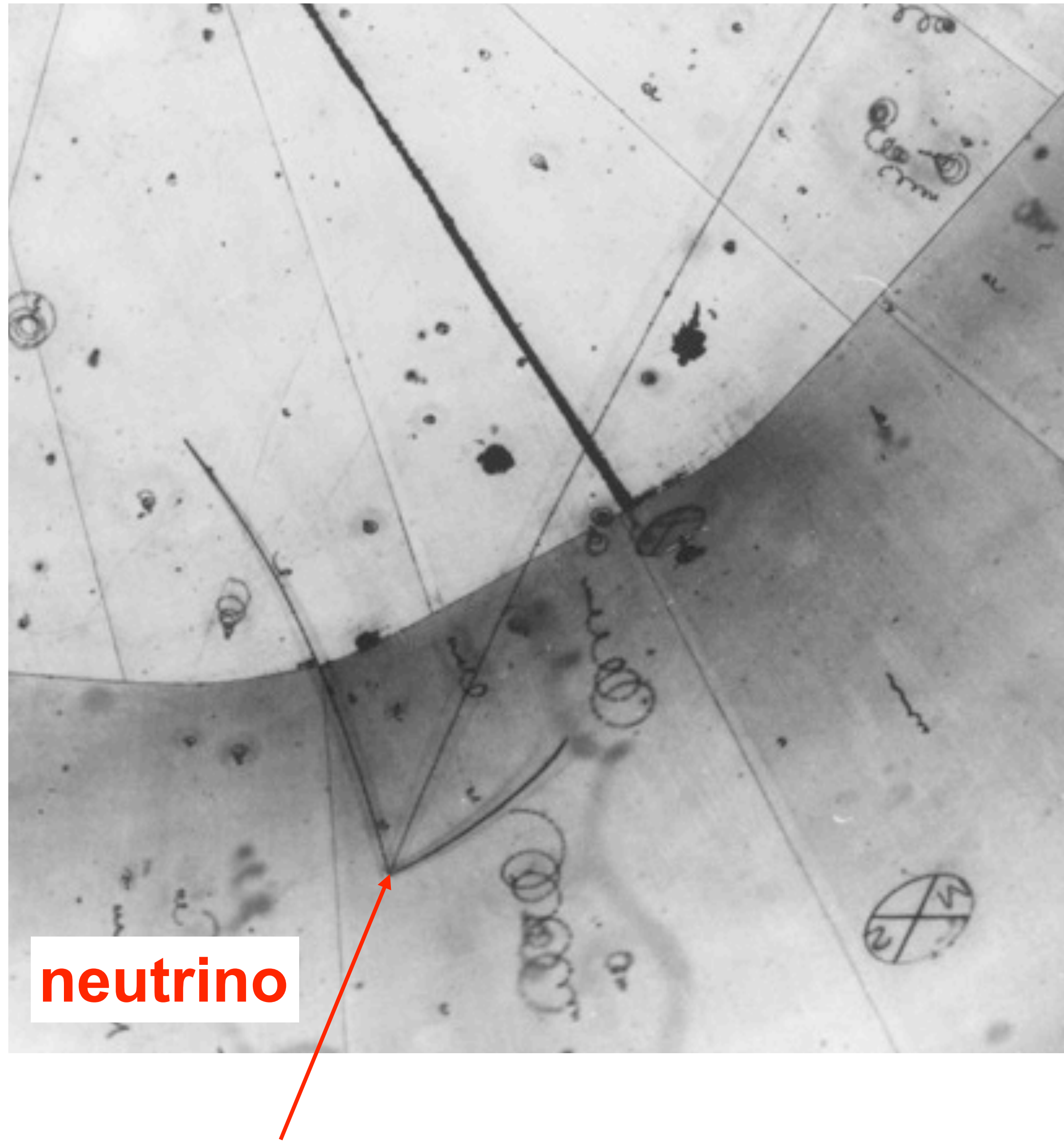

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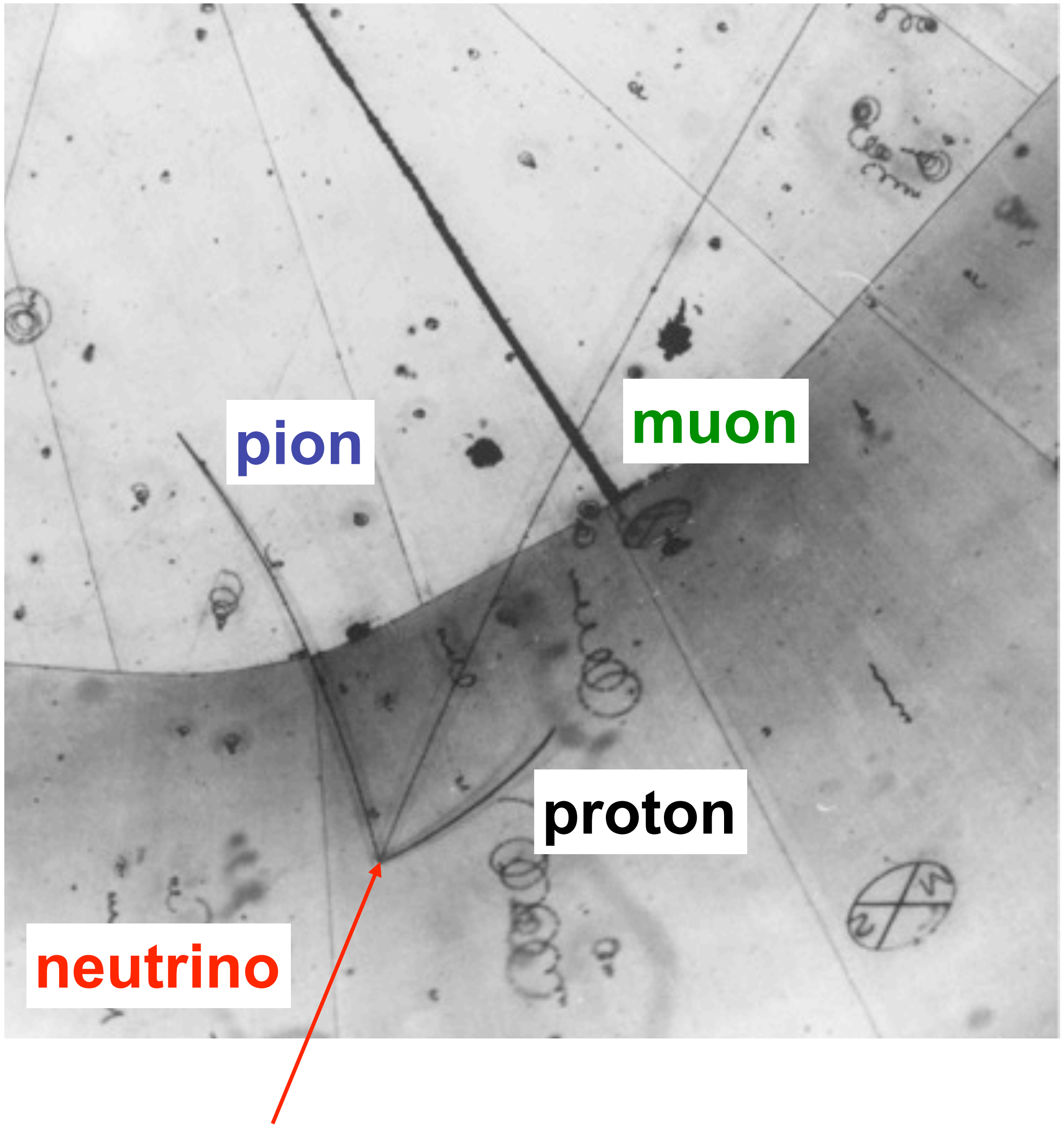

Why do we expect to see neutrinos from astrophysical sources?

Cosmic Rays -
a 100-year old mystery

Cosmic Rays -
a 100-year old mystery

Victor Hess, 1912

- Electroscopes discharge slowly even if no radioactive material is around - does the Earth radiate?

Victor Hess (1883-1964)

Balloon Data

7. Fahrt (7. August 1912).

Ballon: „Böhmen“ (1680 cbm Wasserstoff). Führer: Hauptmann W. Hoffory.
Meteorolog. Beobachter: E. Wolf. Luftelektr. Beobachter: V. F. Hess.

Nr.	Zeit	Mittlere Höhe absolut m	Mittlere Höhe relativ m	Beobachtete Strahlung Apparat 1 q_1	Beobachtete Strahlung Apparat 2 q_2	Beobachtete Strahlung Apparat 3 q_3	Beobachtete Strahlung Apparat 3 reduz. q_3	Temp.	Relat. Feucht. Proz.
1	15^h 15—16^h 15	156	0	17,3	12,9	—	—	—	—
2	16^h 15—17^h 15	156	0	15,9	11,0	18,4	18,4	1½ Tag vor dem Aufstiege (in Wien)	
3	17^h 15—18^h 15	156	0	15,8	11,2	17,5	17,5		
4	6^h 45—7^h 45	1700	1400	15,8	[illegible],4	21,1	25,3	+6,4°	60
5	7^h 45—8^h 45	2750	2500	17,3	12,3	22,5	31,2	+1,4°	41
6	8^h 45—9^h 45	3850	3600	19,8	16,5	21,8	35,2	−6,8°	64
7	9^h 45—10^h 45	4800 (4400—5350)	4700	40,7	31,8	—	—	−9,8°	40
8	10^h 45—11^h 15	4400	4200	28,1	22,7	—	—	—	—
9	11^h 15—11^h 45	1300	1200	(9,7)	11,5	—	—	—	—
10	11^h 45—12^h 10	250	150	11,9	10,7	—	—	+16,0°	68
11	12^h 25—13^h 12	140	0	15,0	11,6	—	—	(nach der Landung in Pieskow, Brandenburg)	

IceCube

Balloon Data

7. Fahrt (7. August 1912).

Ballon: … …uptmann W. Hoffory.
Meteoro… …eobachter: V. F. Hess.

- Going up as high as 17,500 feet, Hess showed that the radiation level *increases* with altitude!

Nr.	Zeit	absolut m	relativ m	Apparat 1 q_1	Apparat 2 q_2	Apparat 3 q_3	reduz. q_3	Temp.	Relat. Feucht. Proz.
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Cosmic "Rays?"

- Nuclei? Electrons? Photons?
- After their discovery, the chemical nature of cosmic "radiation" was unclear for some time.
- The name "cosmic rays" reflects Robert Millikan's belief that they were gamma rays from space.
- In the 1930s, it became clear that cosmic rays are mainly energetic particles.
- Most ultra-high-energy cosmic rays are protons and heavier nuclei.

Robert A. Millikan (1868-1953)

Arthur H. Compton (1892-1962)

The New York Times

The New York Times

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THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

PROF. RUSSELL ELECTED

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MILLIKAN'S DATA CONFIRM COMPTON

Results of Cosmic Ray Study at Panama Tend to Back Rival's Ideas.

RAY INTENSITY VARIES

Strength Is Greater at the Poles—Equatorial Tests Are Now Projected.

PASADENA, Cal., Feb. 4 (AP).—The stratosphere above equatorial regions of the earth should be the next scene of exploration in the quest of the secrets of the cosmic ray, Dr. Robert A. Millikan said here today.

Announcing that observations of his co-workers at Panama confirmed the earlier reports of Dr. Arthur H. Compton of Chicago that the rays from interstellar space showed latitude effects, Dr. Millikan disclosed that the variance was as high as 8 per cent.

The New York Times

COSMIC RAY TO OPEN PLANETARIUM TONIGHT

Caught by Delicate Apparatus, It Will Switch On Stars in 'Artificial Heaven.'

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So far as is known, this will be the first time that a cosmic ray, most powerful "electrical bullets" found in nature, will be made to perform a useful task at the bidding of man.

The cosmic ray will be trapped by delicate electrical apparatus and made to provide the impulse that will switch on the great planetarium projector with its 9,000 stars. This was announced yesterday by Dr. Clyde Fisher, curator of New York's "Theatre of the Stars."

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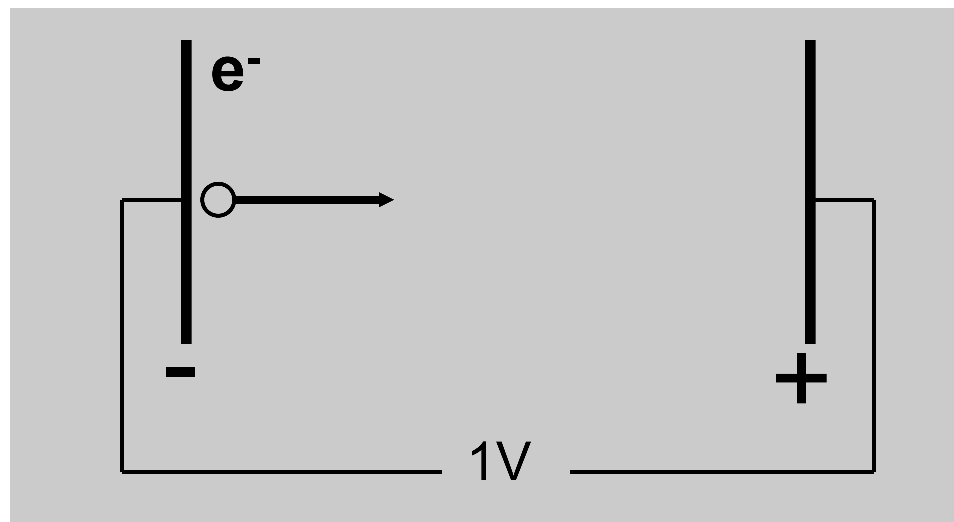
- Cosmic rays are charged particles (protons or heavier nuclei) that continuously rain down on Earth from outer space.
- A small fraction of them have energies in excess of several Joules, which makes them the highest energy particles in the known Universe.
- Where do they come from? Do they point back to their sources? Can we do *astronomy* with these particles?

Electronvolt eV

- **Our usual unit of energy, the Joule, is inconvenient when dealing with sub-atomic particles. Particle physicists therefore usually use of different unit, the *electronVolt.***

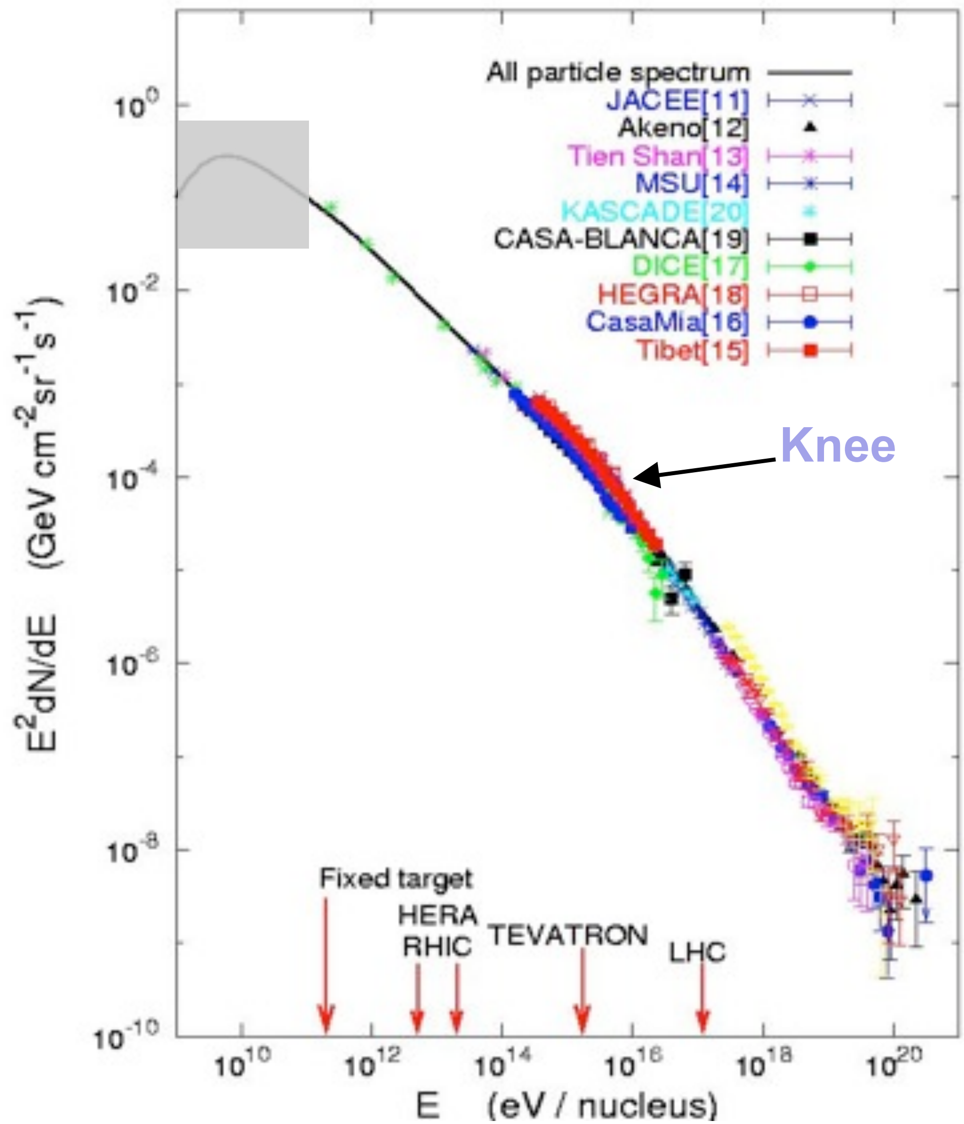
- **1 electronVolt (eV) is the amount of energy gained by an electron (or a particle with the same charge) when it is accelerated through an electrostatic potential difference of 1 Volt.**

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ Joule}$$



Cosmic Rays Energy Spectrum

- Cosmic ray energy spectrum is *nonthermal:*
  - Energy distribution has *no characteristic temperature.*
  - Source energy is given to a relatively small number of particles.
- Energies of the nonthermal Universe (up to 10^{20} eV) are well beyond the capabilities of thermal emission processes.
- The origin of cosmic rays at energies above GeV is unknown *- no astrophysical object has ever been definitively identified as an accelerator of high energy nucleons.*

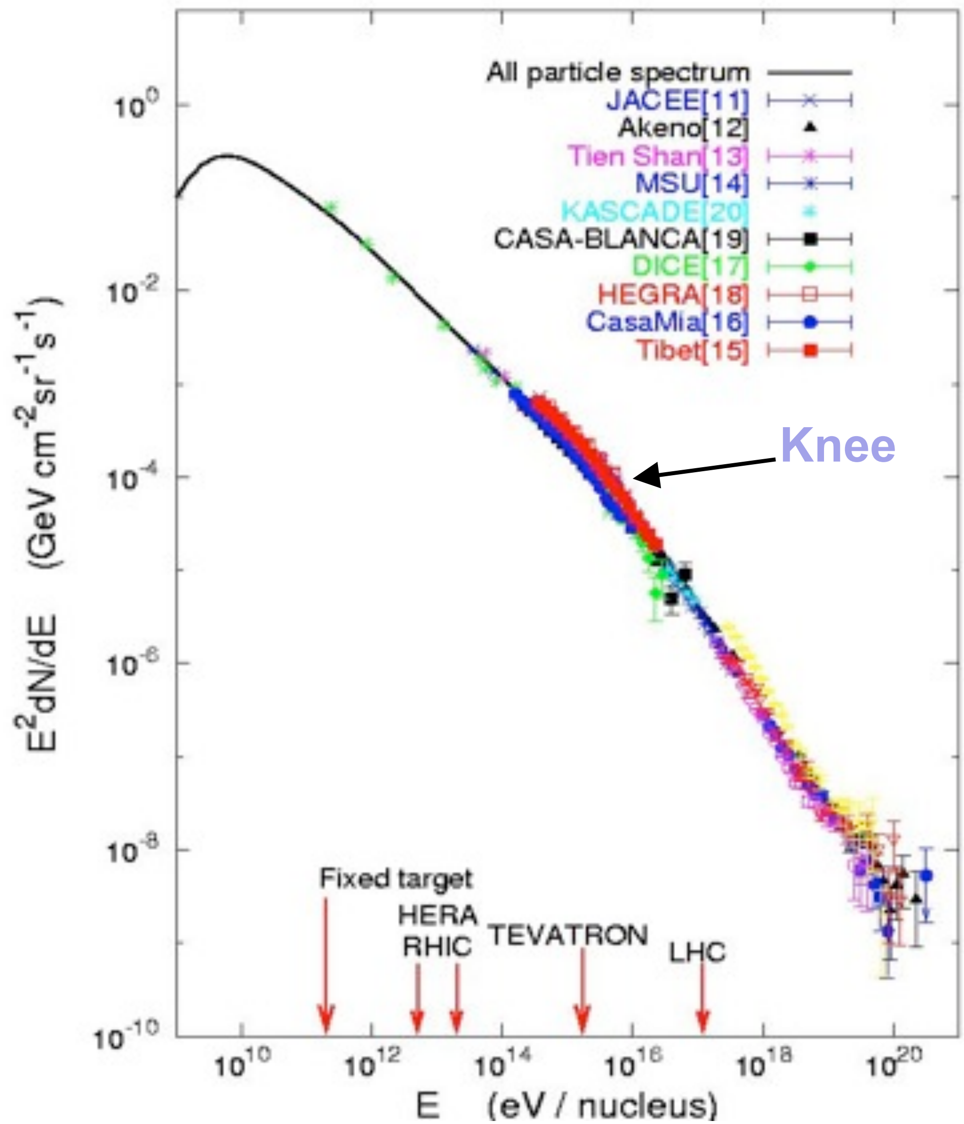


Cosmic Rays Energy Spectrum

- Accessible to experiment:
  - Energy spectrum.
  - Chemical composition.
  - *Arrival directions.*

- *Astronomy* with charged particles?
  - Protons and nuclei are *charged* and therefore subject to deflection in Galactic and intergalactic magnetic fields (of unknown strength)!

$$R \cong 1\,\mathrm{kpc}\ \frac{E_{EeV}}{B_{\mu G}}$$



Acceleration Mechanism

- A possible acceleration mechanism was suggested in 1949 by Enrico Fermi.
- Particles are accelerated “by collisions against moving magnetic fields.”

Enrico Fermi (1901-1954)

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PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

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I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept relatively near the sun by the action of magnetic

where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

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Power Law

- How can we get a power law? $N(>E) \propto E^{-\gamma}$

- Assume particles are not accelerated in one single step, but little by little in a process that repeats *n* times, with an energy gain *per step* of

$$\Delta E = \xi E$$

- After *n* steps, the energy is $E_n = E_0 (1+\xi)^n$

- … so the number of steps needed to reach energy E is

$$n = \frac{\ln(E/E_0)}{\ln(1+\xi)}$$

Power Law

- Complication: after every step, the particle can escape from the acceleration region with some probability P_{esc}. Once it escapes, its energies does not increase any more.

- The probability P_n that the particle reaches energy E_n is equal to the probability that the particle has *not* escaped for n encounters:

$$P_n = \left(1 - P_{esc}\right)^n$$

- The number N of particles with energy > E_n is proportional to the number of particles that remain in the acceleration region for more than n steps:

$$N(\geq E) \propto \sum_{m=n}^{\infty} \left(1 - P_{esc}\right)^m$$

$$= \frac{\left(1 - P_{esc}\right)^n}{P_{esc}}$$

Power Law

- This can be re-written as

$$N(\geq E) \propto \frac{E}{E_0} \qquad \textbf{with} \qquad \gamma = \frac{\ln\left[1/\left(1 - P_{esc}\right)\right]}{\ln\left(1 + \xi\right)}$$

$\Rightarrow$ **a process with a repeated energy increase $\Delta E = \xi E$ per step naturally gives a power law.**

- Note:

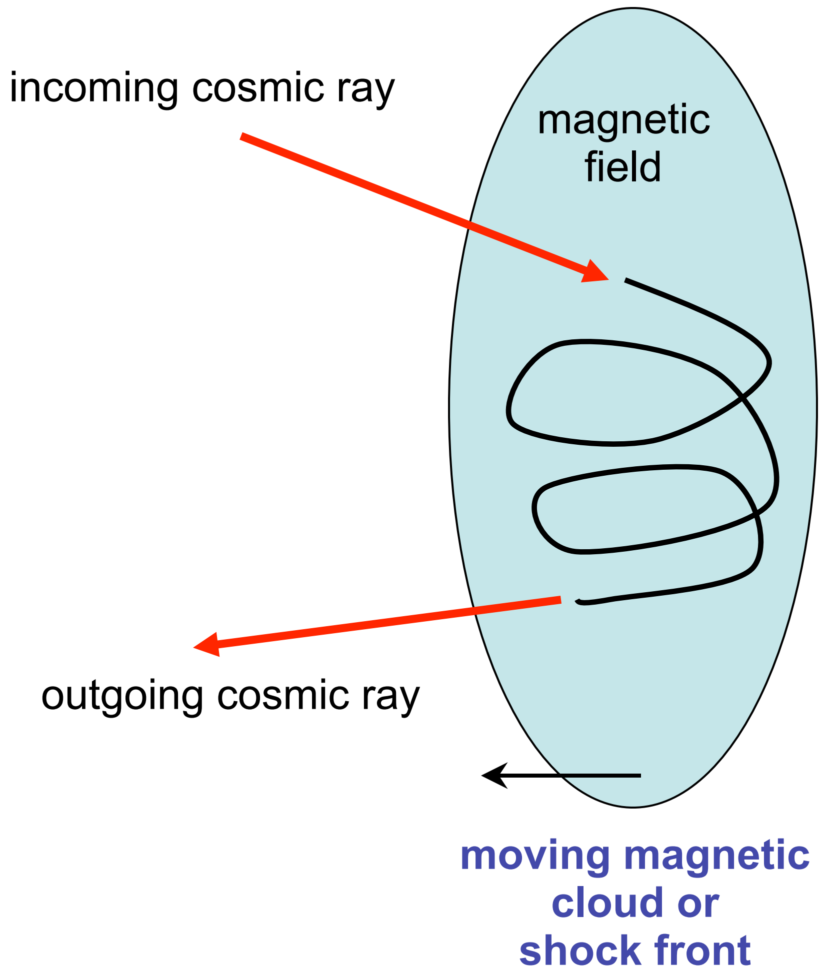
$$\frac{dE}{dt}$$

ν = frequency of acceleration
T = characteristic time of process

$\Rightarrow$ **reaching higher energies takes longer; if the accelerator has a limited lifetime, only some characteristic maximum energy can be reached.**

Source Candidates?

- In Fermi's cosmic ray shock accelerator, protons speed up by bouncing off moving magnetic clouds in space - just like a tennis ball is faster after it bounces off a wall moving towards the observer.
- Shock acceleration is a tedious process - the particles gain energy over many (10^7 or more) collisions.
- This is not the correct model, but the model can be improved: replace magnetic clouds by shock fronts…



Fermi Acceleration

- Second order Fermi acceleration (charged particle interactions with clouds containing turbulent magnetic fields):

$$\frac{\Delta E}{E}$$

β = velocity of cloud (typically $\beta < 10^{-4}$)

$\Rightarrow$ **power law guaranteed!**

- First order Fermi acceleration (1977) (replace cloud by shock front)

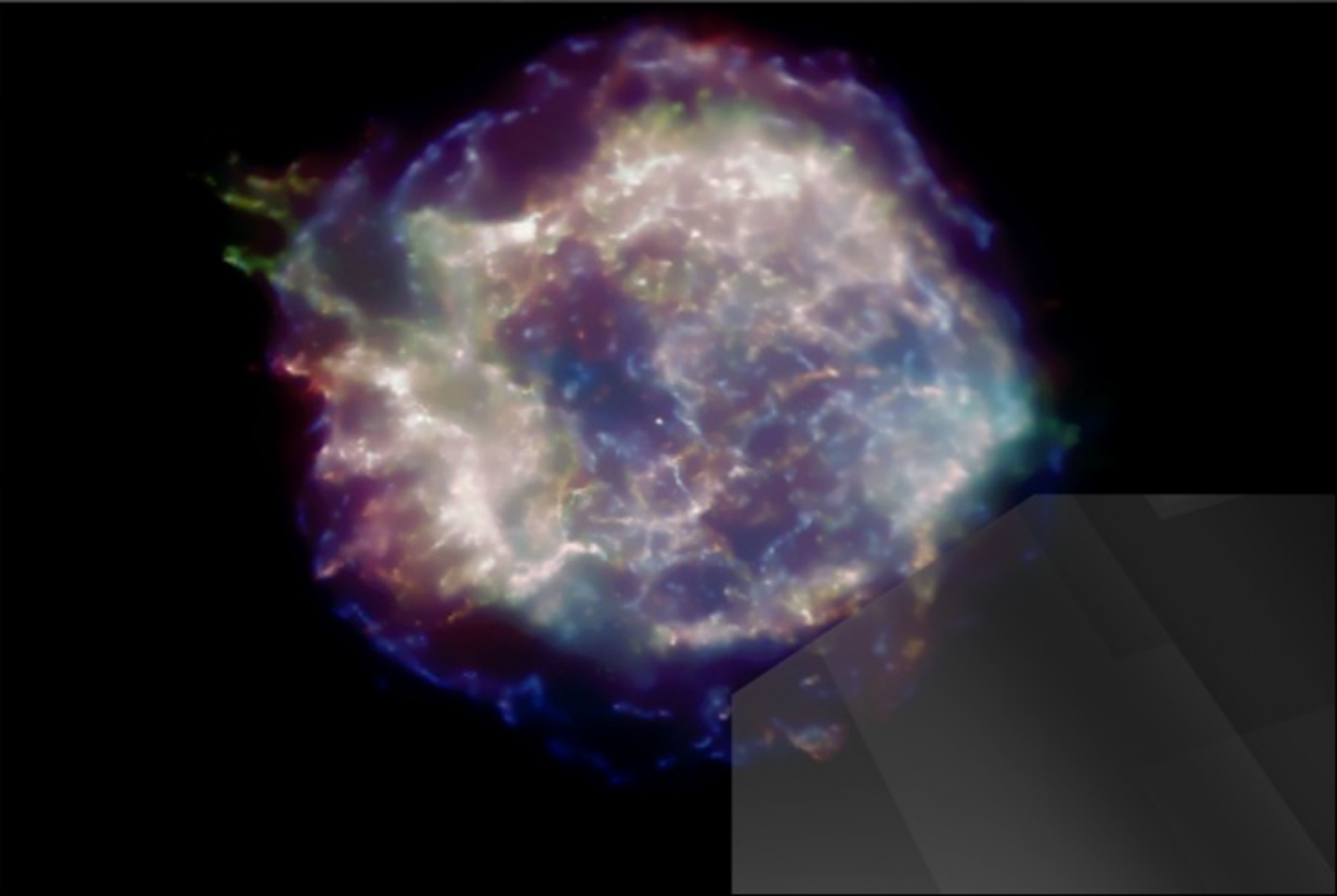
$$\frac{\Delta E}{E}$$

β = velocity of shocked gas relative to the unshocked gas (typically $\beta c \cong 10^4$ km/s)

$\Rightarrow$ **power law guaranteed *plus* the spectral index is independent of the properties of the shock wave and depends only on the ratio of upstream to downstream velocities.**

$\Rightarrow$ **predicts a *unique* spectral index for diverse environments.**

Cas A supernova remnant in X-rays



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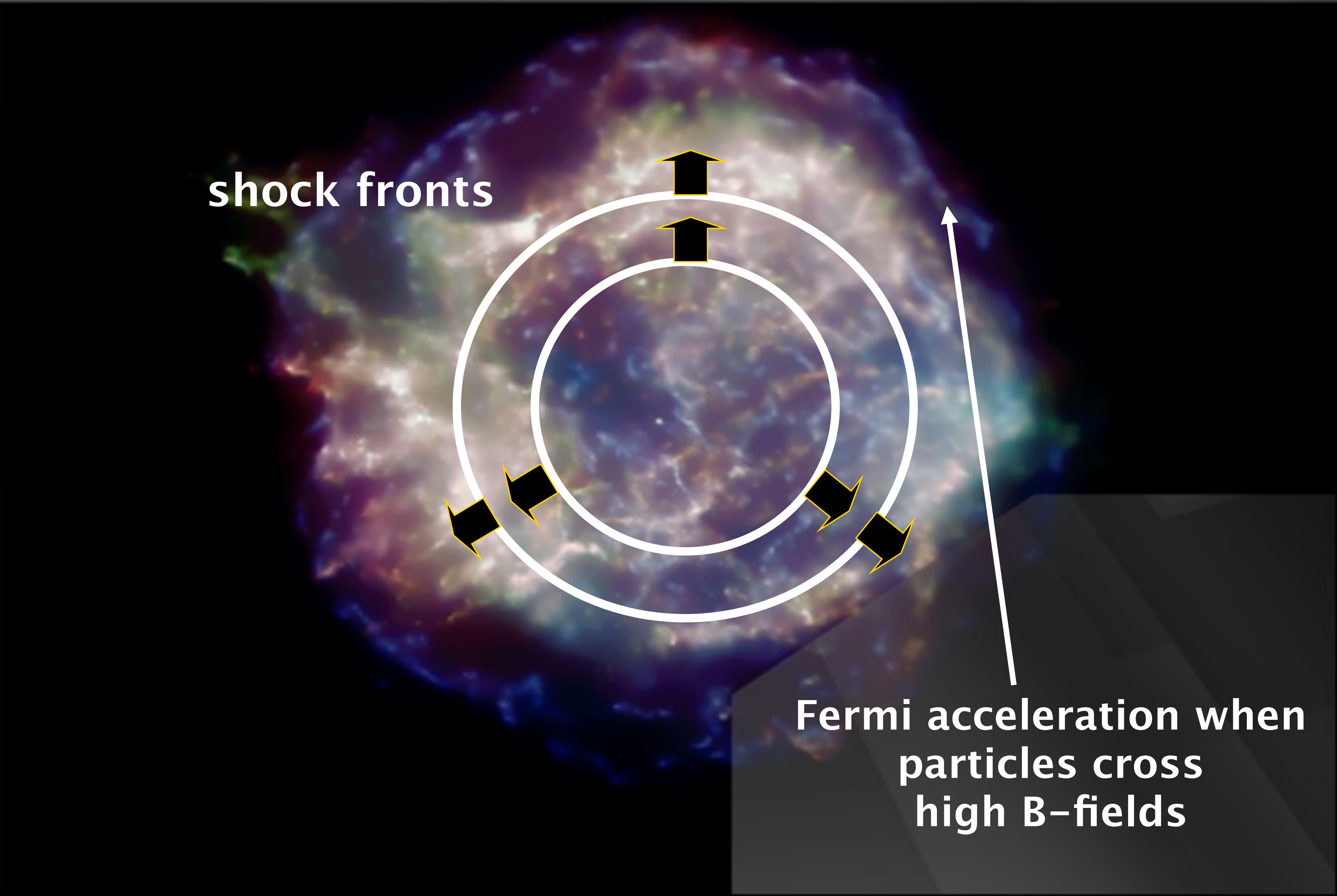
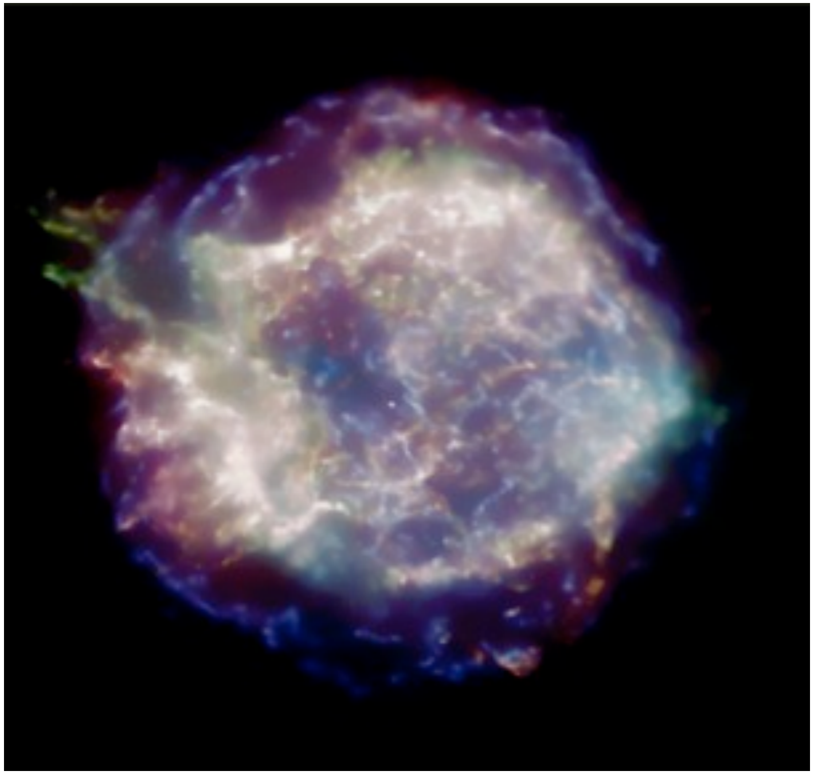


Cosmic Particle Accelerators

- Baade and Zwicky suggested in 1934 that *supernova remnants* could be the sources of Galactic cosmic rays.
- Particles are accelerated in diffuse shocks associated with young (~1000 year old) supernova remnants expanding into the interstellar medium.
- The shock sweeps up the ~1 proton/cm^3 density of hydrogen in the Galactic plane.
- Fermi acceleration occurs in the high magnetic fields in the outer reaches of the shock.



Cas A, courtesy Chandra (NASA)

Cosmic Particle Accelerators

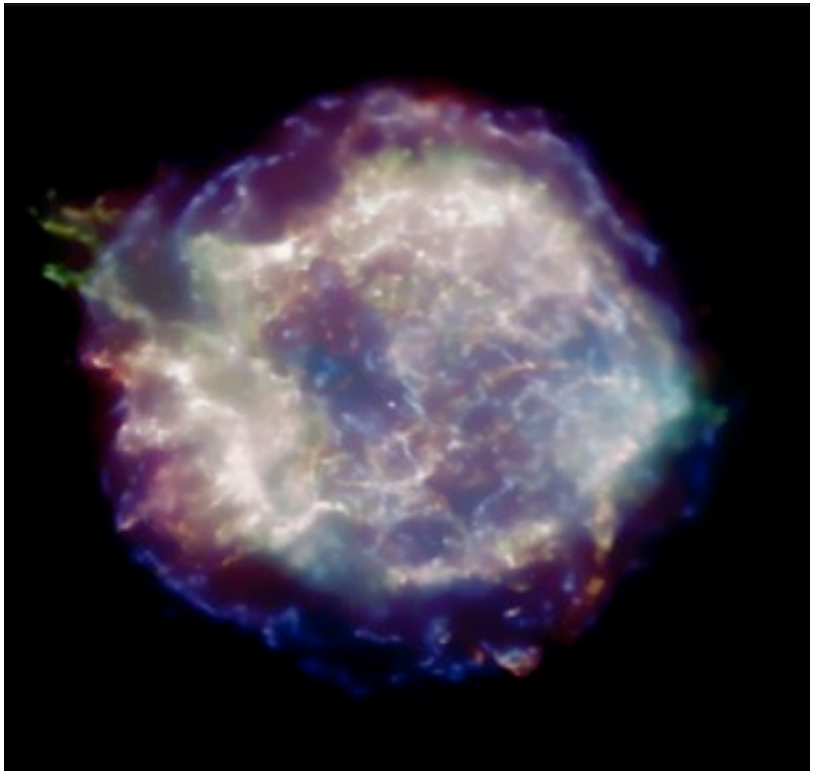
- *Supernovae* can account for cosmic rays with energies up to $\sim 10^{16}$ eV.

- The strongest argument for this scenario is based on energy considerations:

  - Observed energy density of galactic cosmic rays: $\sim 10^{-12}$ erg/cm^3

  - Supernova remnants: 10^{51} erg every 30 years: $\sim 10^{-12}$ erg/cm^3

- Supernova remnants provide the *environment* and *energy* to explain the galactic cosmic rays.



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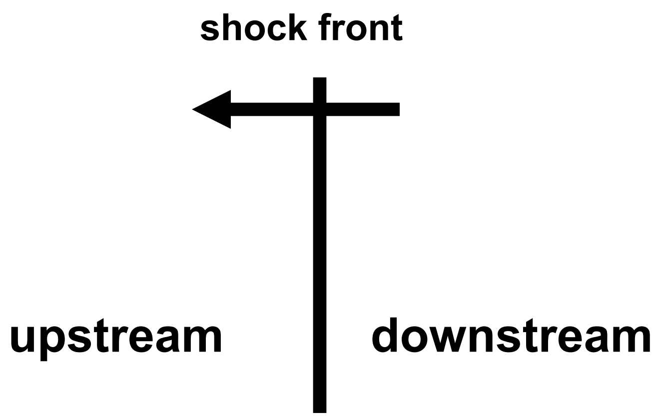
Spectral Index

A.R. Bell,
MNRAS 182 (1978) 147



$$\gamma = \frac{\ln\left[1/\left(1 - P_{esc}\right)\right]}{\ln\left(1+\xi\right)}$$

with

$$\xi = \frac{4}{3}$$

For a strong shock wave, the ratio of the upstream to downstream velocities depends only on the ratio of specific heats of the gas:

for a fully ionized gas

$$u_1\rho_1 = u_2\rho_2 \quad \Leftrightarrow \quad \frac{u_1}{u_2}$$

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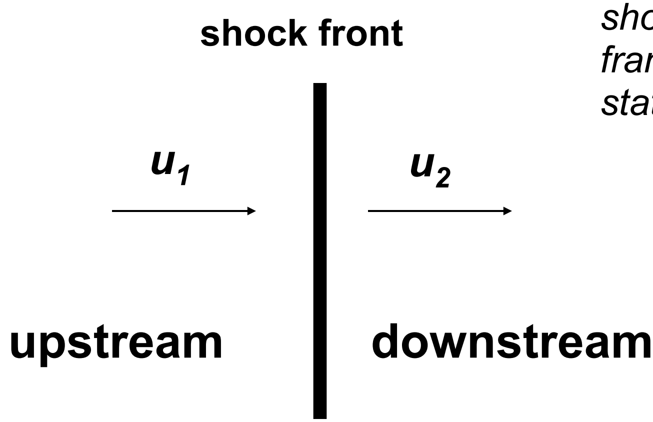


shock viewed in the frame in which it is stationary

$$\gamma = \frac{\ln\left[1/\left(1 - P_{esc}\right)\right]}{\ln\left(1 + \xi\right)}$$ **with** $$\xi = \frac{4}{3}$$

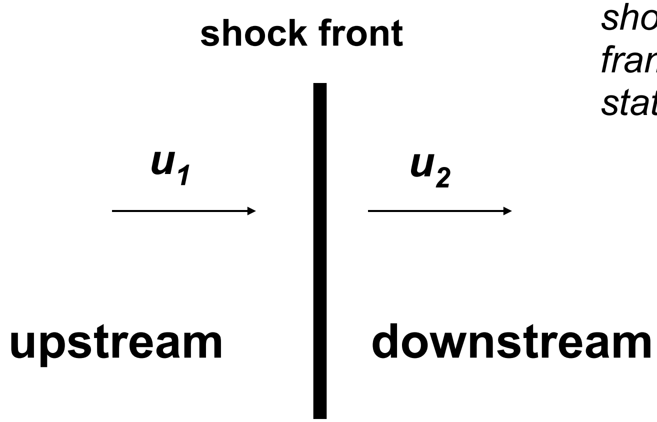
For a strong shock wave, the ratio of the upstream to downstream velocities depends only on the ratio of specific heats of the gas:

for a fully ionized gas

$$u_1\rho_1 = u_2\rho_2 \quad \Leftrightarrow \quad \frac{u_1}{u_2}$$

Spectral Index

A.R. Bell,
MNRAS 182 (1978) 147



shock viewed in the frame in which it is stationary

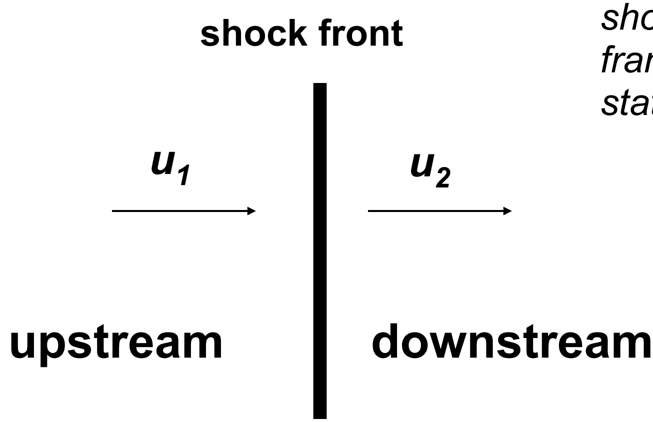
$$\Rightarrow \quad \frac{u_1}{u_2}$$

The escape probability is the ratio

$$P_{esc} = \frac{\text{escape rate (through convection downstream)}}{\text{rate of shock encouters}}$$

Spectral Index

A.R. Bell,
MNRAS 182 (1978) 147



shock viewed in the frame in which it is stationary

Final result: $\gamma = -2 \quad \rightarrow \quad N(E)dE \propto E^{-2}dE$

- The spectral index is independent of the absolute magnitude of the velocity of the plasma - it depends only on the ratio of upstream to downstream velocities.
- The spectral index is "universal" and its value comes close to what is needed to explain the cosmic ray energy spectrum.

Fermi Acceleration

- First order Fermi acceleration is faster than second order, but it is by no means fast.

- The time scale of a typical SN blast wave is roughly the time it takes the expanding shell to sweep through its own mass of the interstellar medium - after that, it slows down.
  - *Example:*

$$10\ M_{sun}\ \text{ expanding at } 5\times 10^{8}\ \text{cm/s into a medium}$$
$$\text{of average density } 1\ \frac{\text{proton}}{\text{cm}^3}$$

  - This means that of order 30 SN actively accelerate cosmic rays at any given time.

Fermi Acceleration

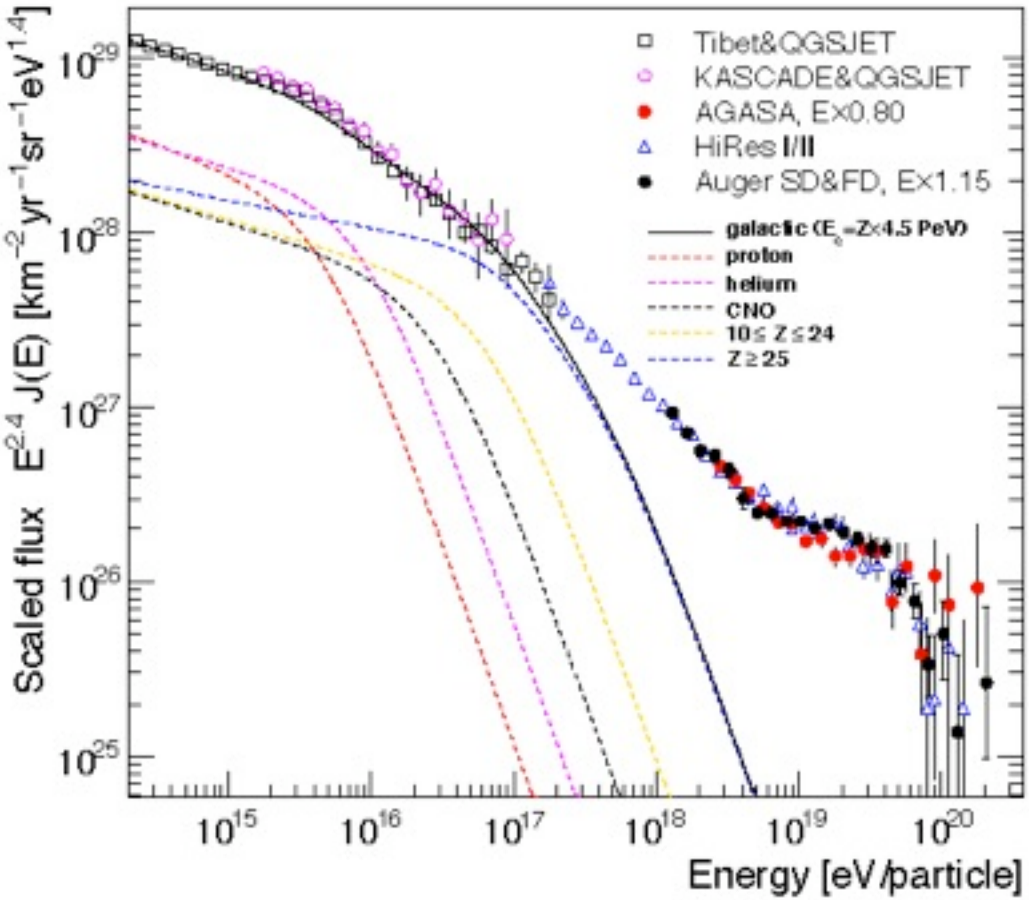
- The finite lifetime of the SN blast wave as a strong shock limits the maximum energy per particle that can be achieved with Fermi acceleration:

$$E_{\max} \leq Z \times 3 \times 10^{4}\ \mathrm{GeV}$$

- The cosmic ray energy spectrum extends well beyond E_{max}, so acceleration in SNRs cannot account for the full spectrum!

- This limit can be raised if the SN does *not* explode into the average interstellar medium, but into an environment formed by the wind of its progenitor (stellar wind SN). This raises the limit for E_{max} by about two orders of magnitude (Völk & Biermann, 1988).

Polygonato Model



('polygonato' model, Hörandel, APP (2003))

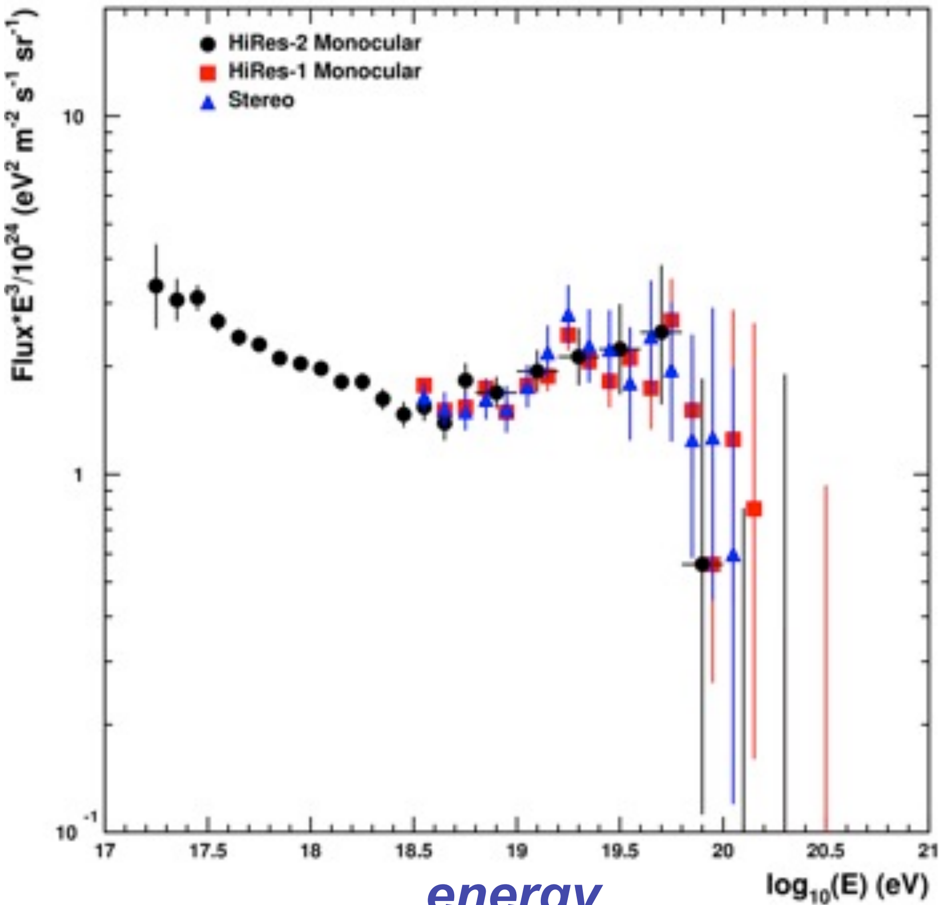
- Standard Model of "knee:"
  - Maximum energy $\propto Z \times E$
  - Leakage from Galaxy $\propto Z \times E$
- Between 10^{17} and 10^{19} eV transition from Galactic to extragalactic sources

Cosmic Particle Accelerators

- Above ~10^{18} eV, the gyroradius of a proton in Galactic magnetic fields exceeds the size of the Galaxy, so cosmic rays above this energy must be *extragalactic* all the way to the highest observed energies ~10^{20} eV.

- Direct support for this scenario comes from the observation of the *absorption of the particle flux by the microwave background* ("GZK cutoff") by the HiRes and Pierre Auger cosmic ray experiments.

Flux × E^3



energy

HiRes Collaboration,
PRL 100 (2008) 101101

GZK Suppression

- Cosmic rays interact with the 2.7 K microwave background.
- Protons above ~ 6×10^{19} eV suffer severe energy loss from photopion production.

$$
\begin{aligned}
p\,\gamma_{3\mathrm{K}} &\rightarrow e^{+}e^{-}\,p \\
&\rightarrow \pi^{+}\,n \\
&\rightarrow \pi^{0}\,p
\end{aligned}
$$

- Proton (or neutron) emerges with reduced energy, and further interaction occurs until the energy is below the cutoff energy.
- Greisen-Zatsepin-Kuz'min Suppression

VOLUME 16, NUMBER 17 PHYSICAL REVIEW LETTERS 25 APRIL 1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

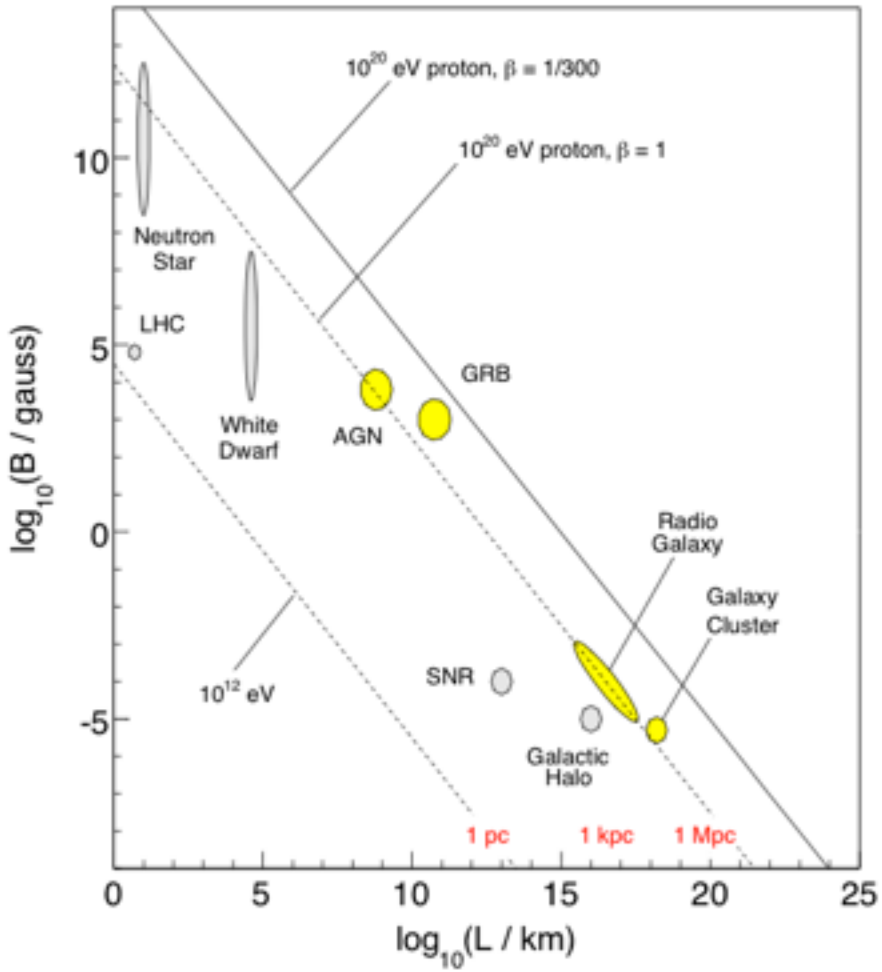
Cornell University, Ithaca, New York

(Received 1 April 1966)

The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under de-

Penzias and Wilson[3] at 4080 Mc/sec (7.35 cm) and now confirmed as thermal in character by measurements of Roll and Wilkinson[4] at 3.2

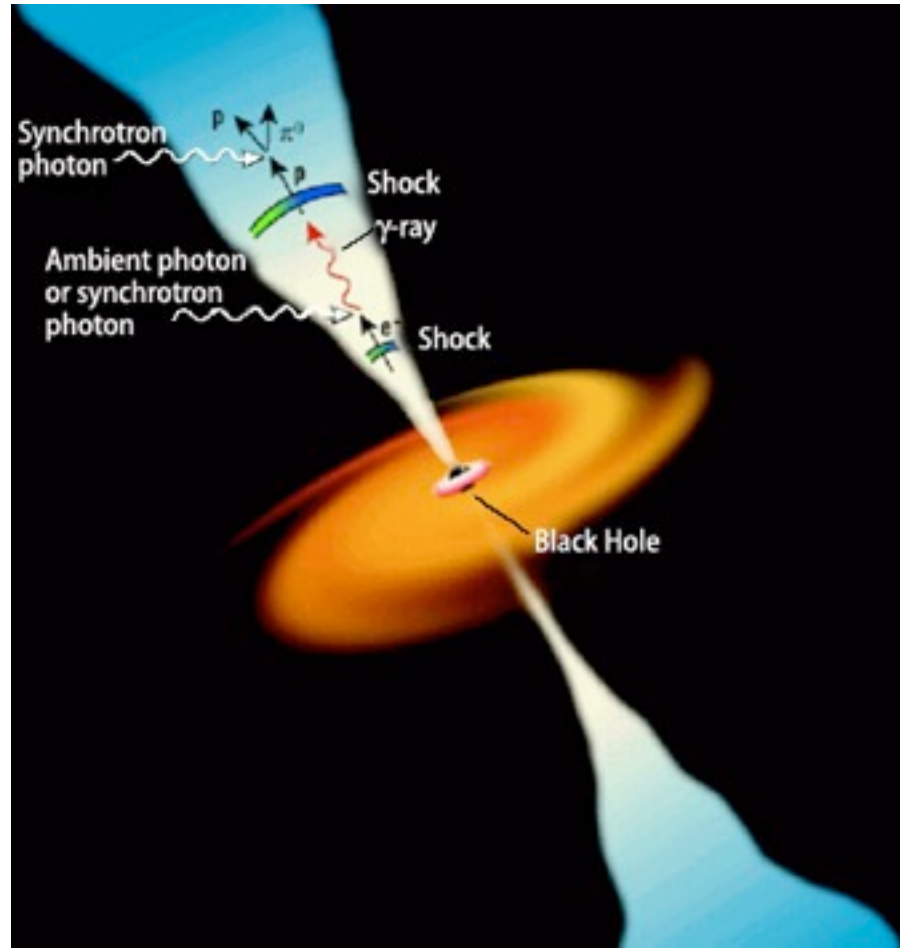
Extragalactic Sources?

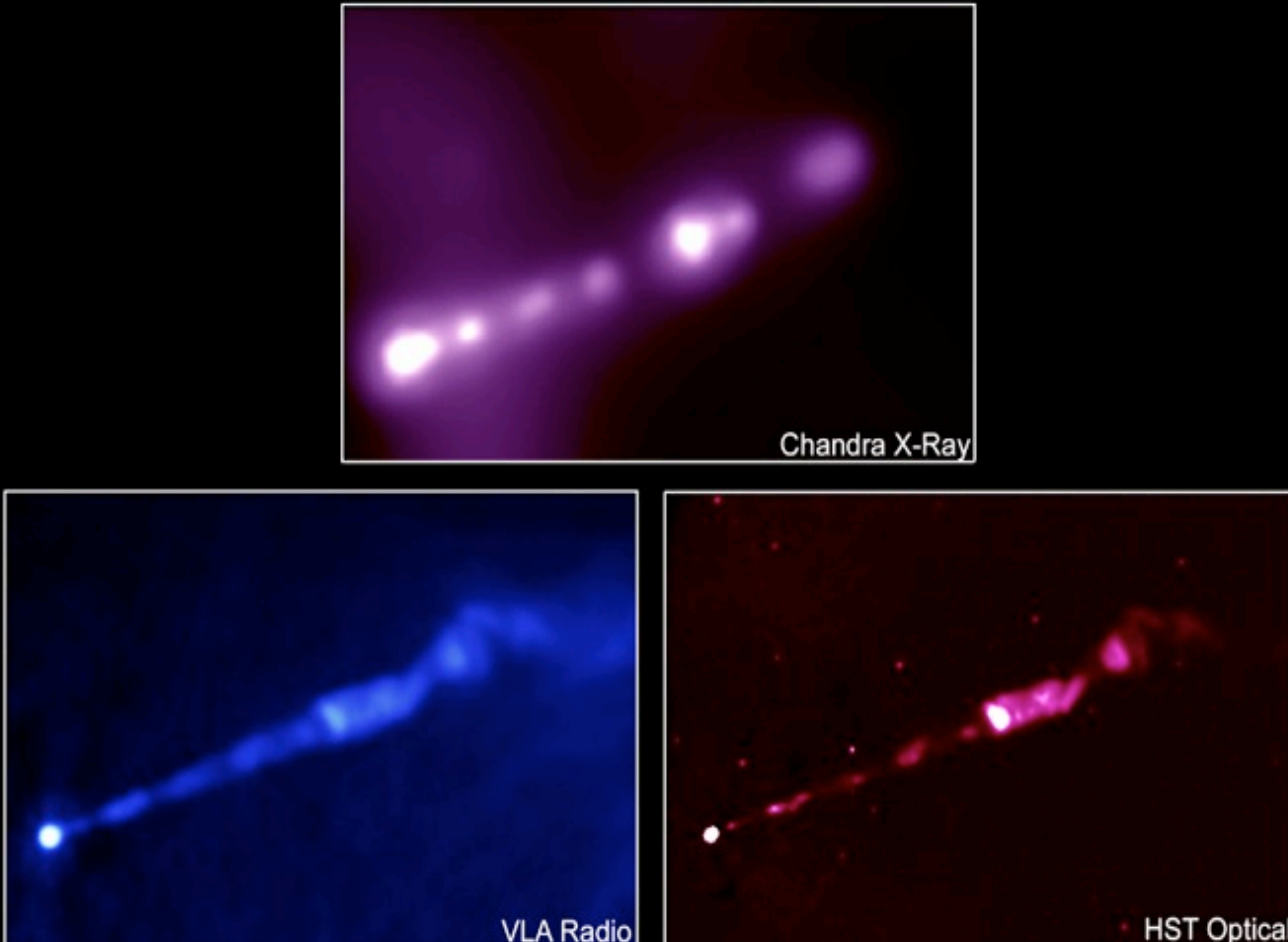


A. M. Hillas, Ann. Rev. Astron. Astrophys. 22, 425 (1984)

Cosmic Particle Accelerators

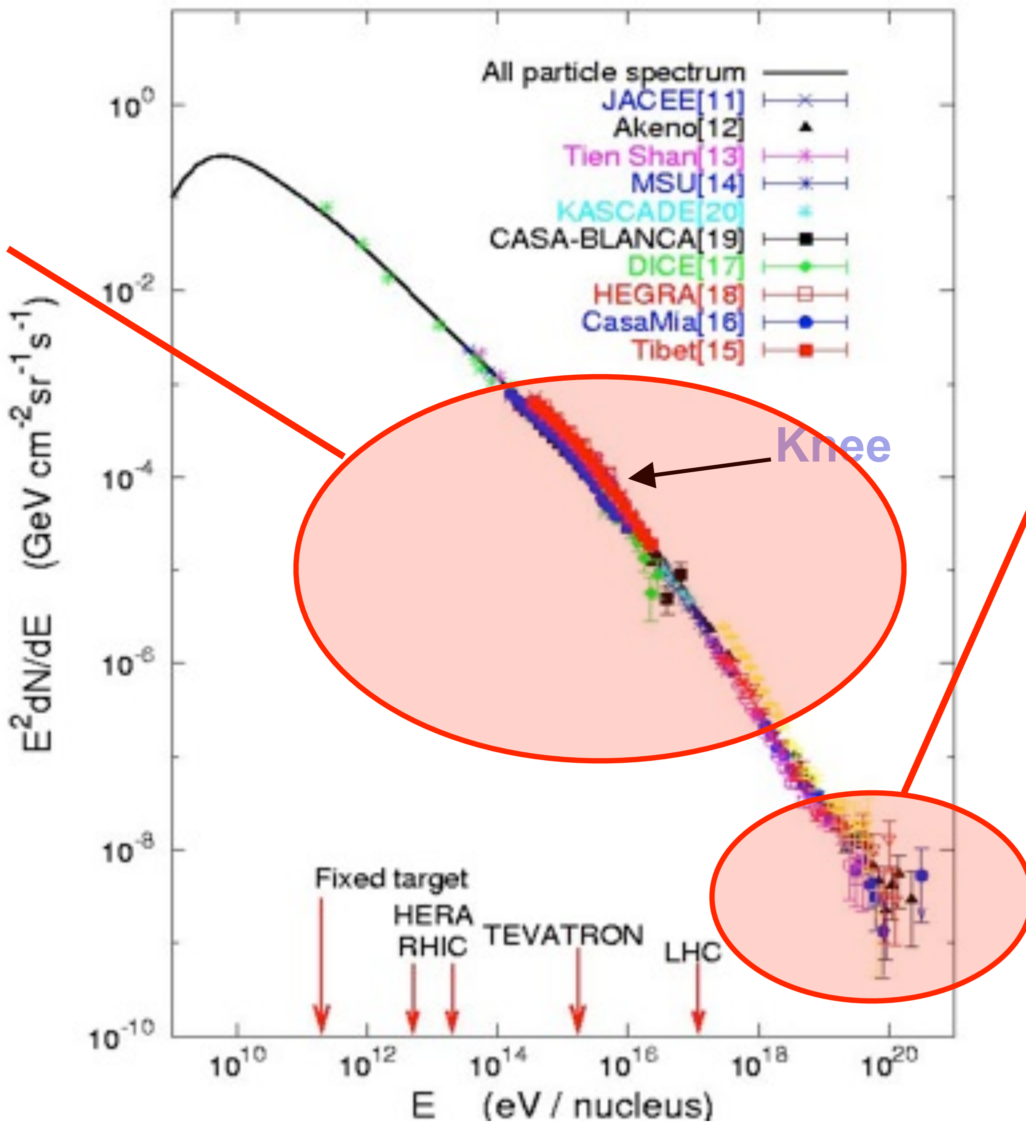
- *Active Galactic Nuclei* (AGN) are possible sources: they consist of a supermassive black hole, an accretion disk, and two jets in which shocks move outward.
- Energy considerations work out for AGN …
- … but also for *Gamma Ray Bursts* (GRBs), so both AGN and GRBs are leading candidates.
- But again, *no extragalactic object has been unambiguously identified as a source of cosmic rays…*




Chandra X-Ray
VLA Radio
HST Optical

Origin of Cosmic Rays

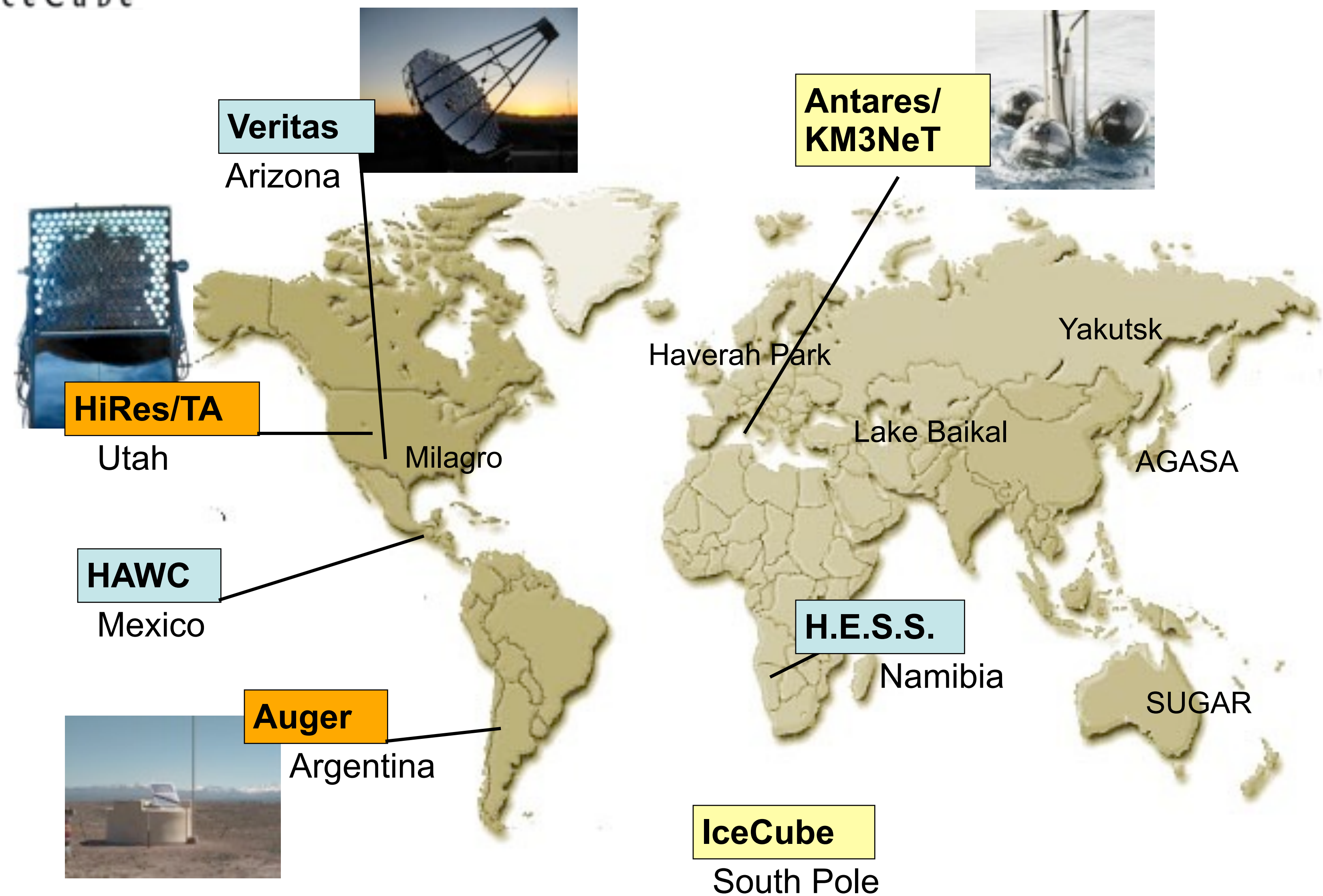
Galactic origin
- Supernovae
- …



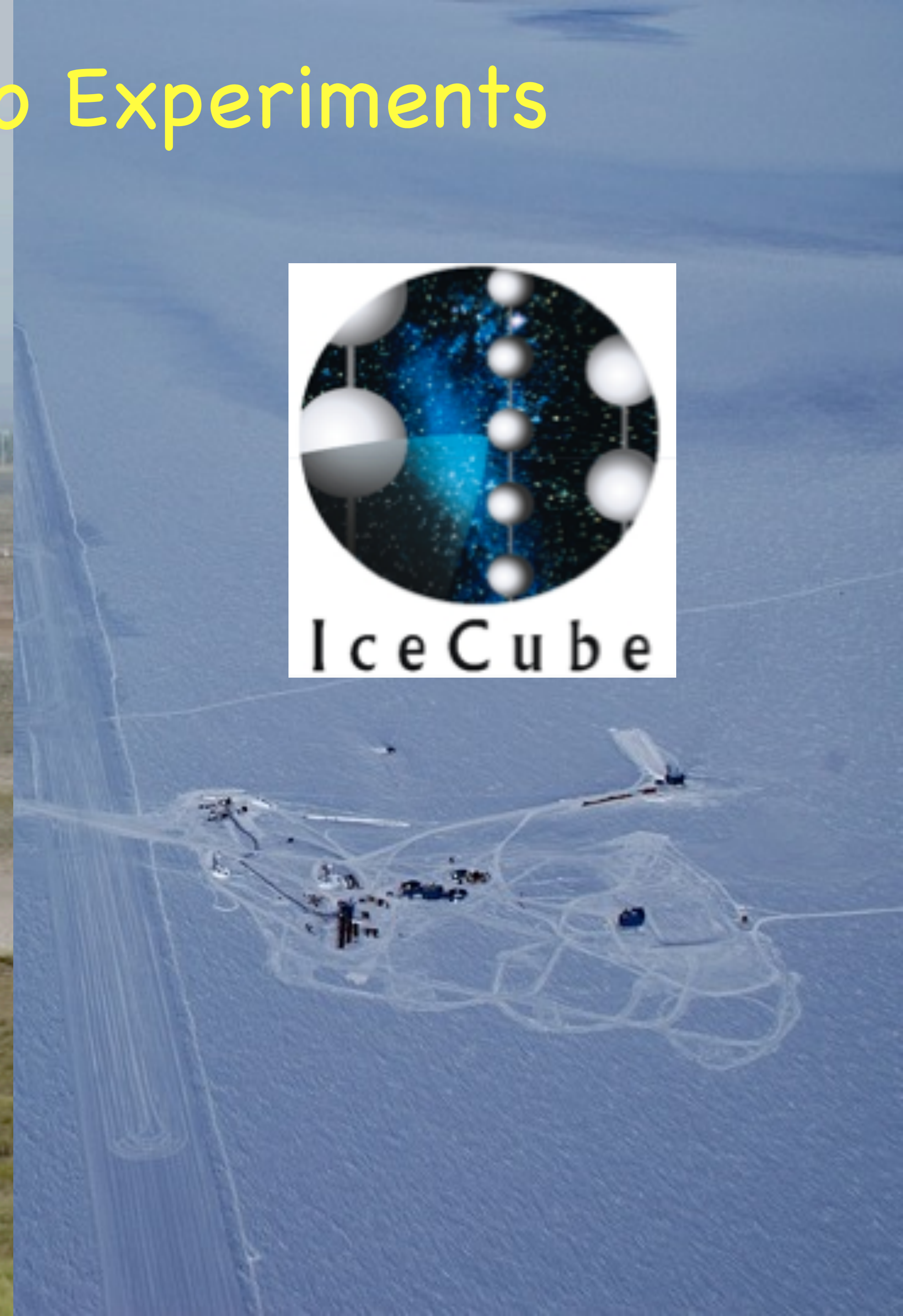
Extragalactic origin
- Active Galactic Nuclei
- …

- How can we find the sources of cosmic rays?
- Do cosmic rays point back to their sources?
- Is astronomy with (charged) particles possible?

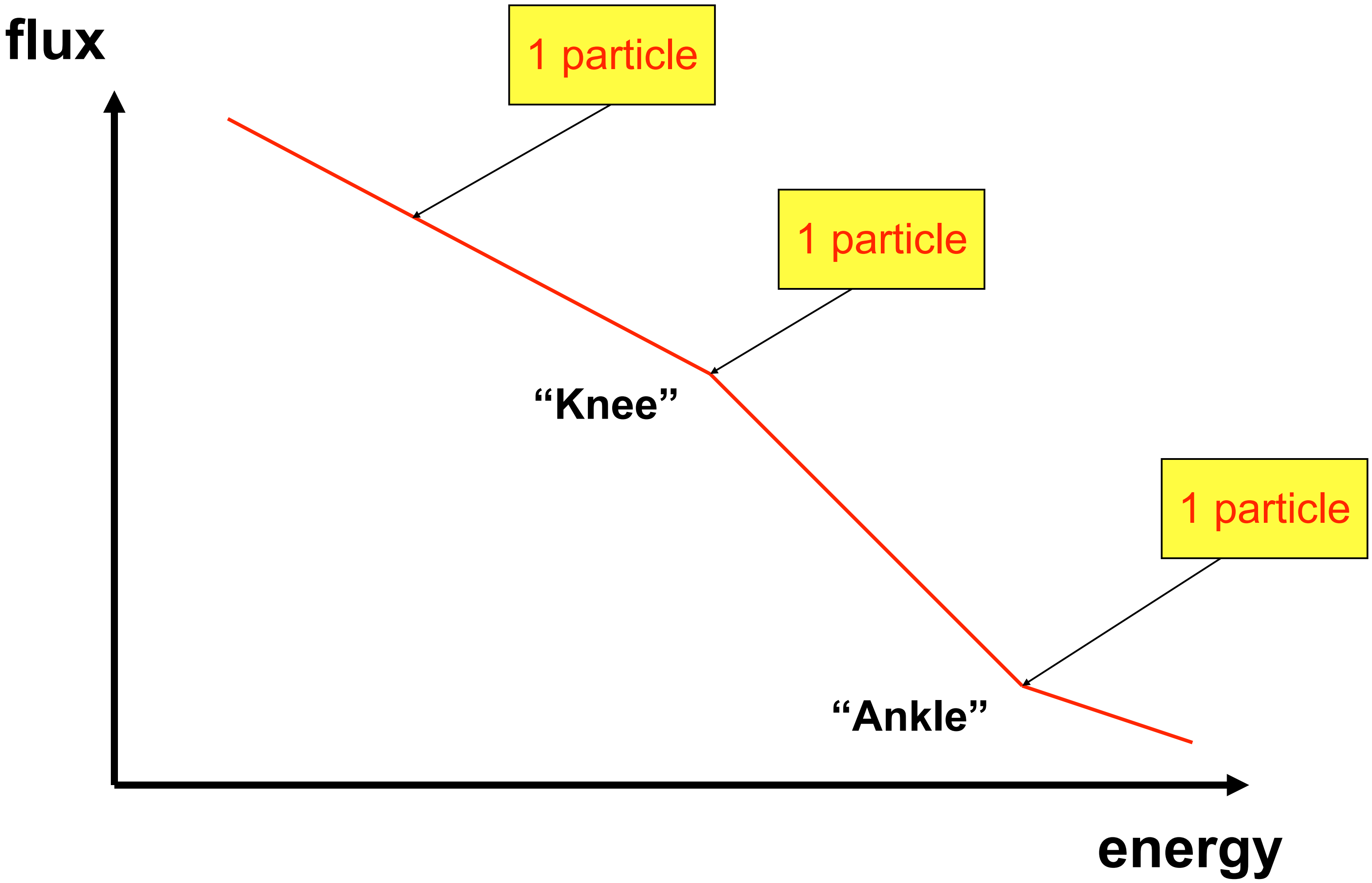
A World-Wide Effort



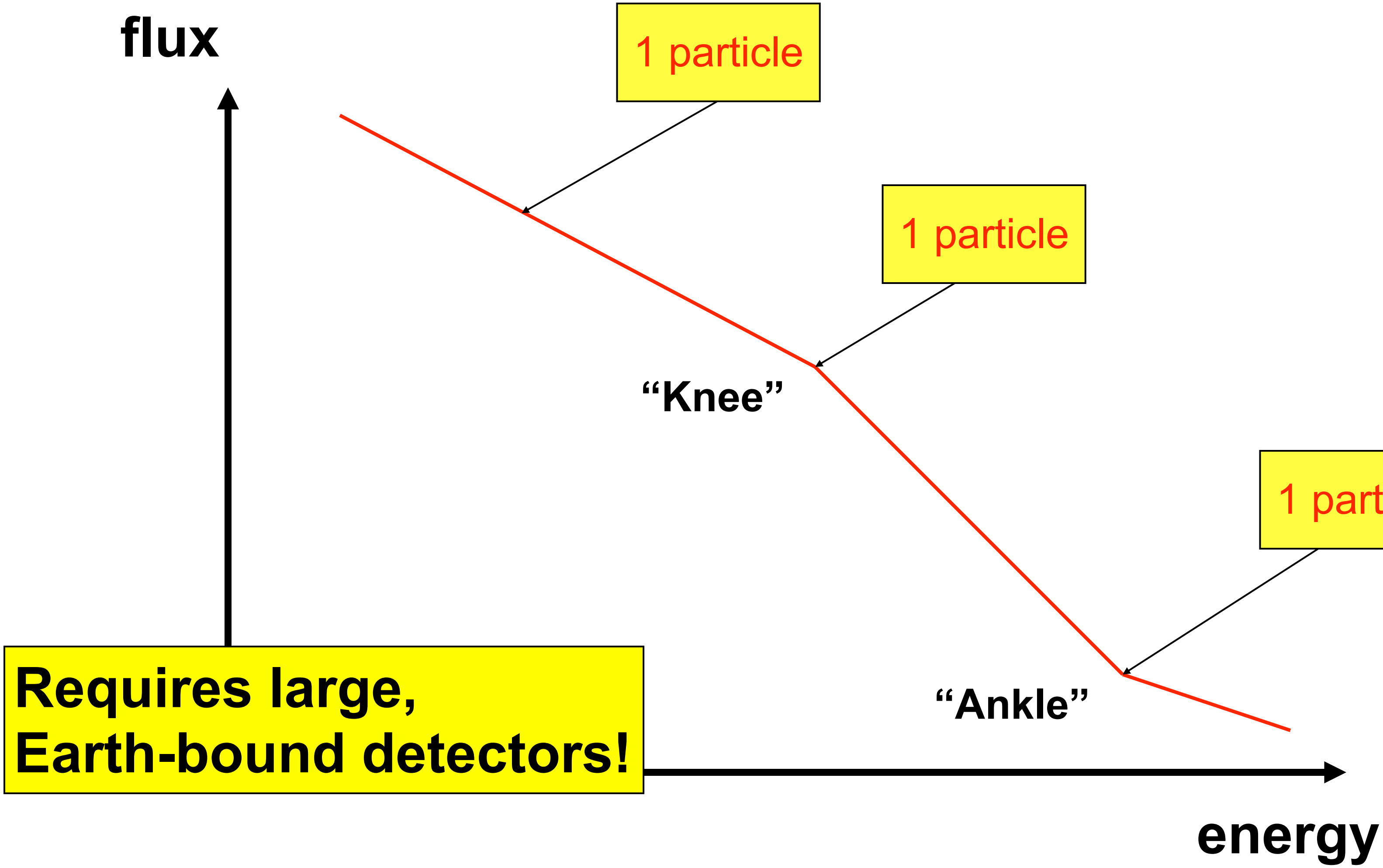
A Tale of Two Experiments

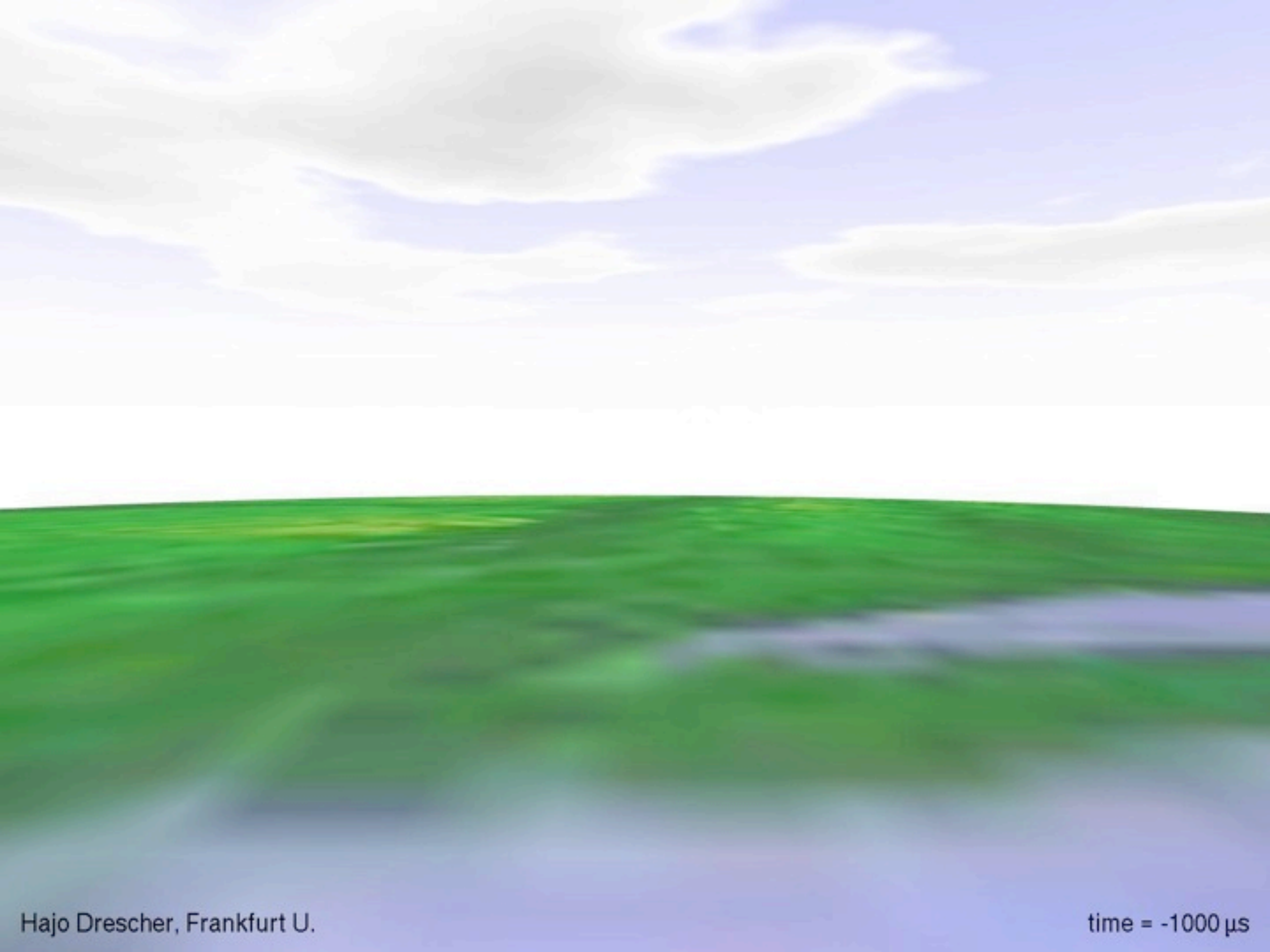


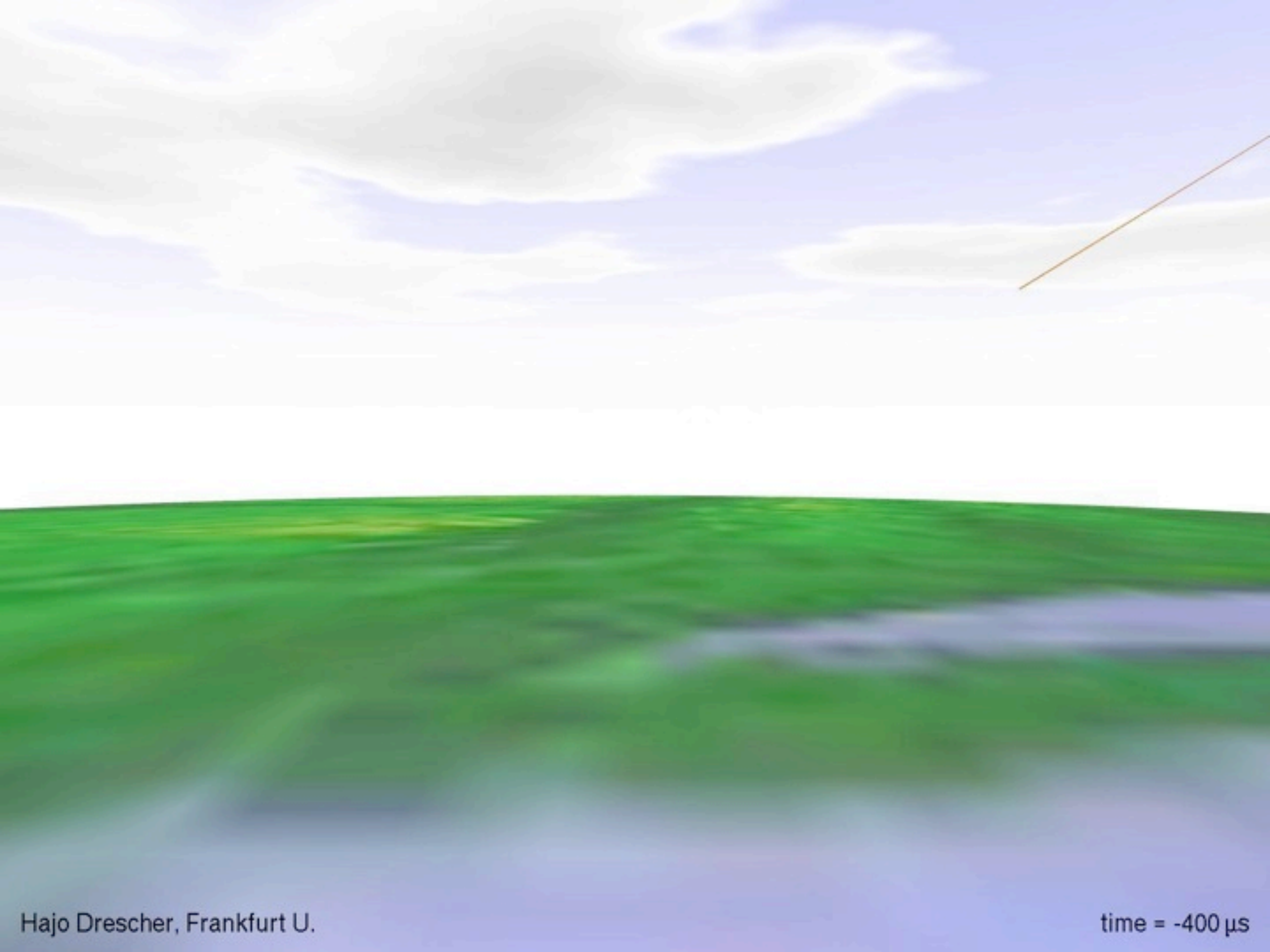
Integral Flux



Integral Flux




Hajo Drescher, Frankfurt U.
time = -1000 μs


Hajo Drescher, Frankfurt U.
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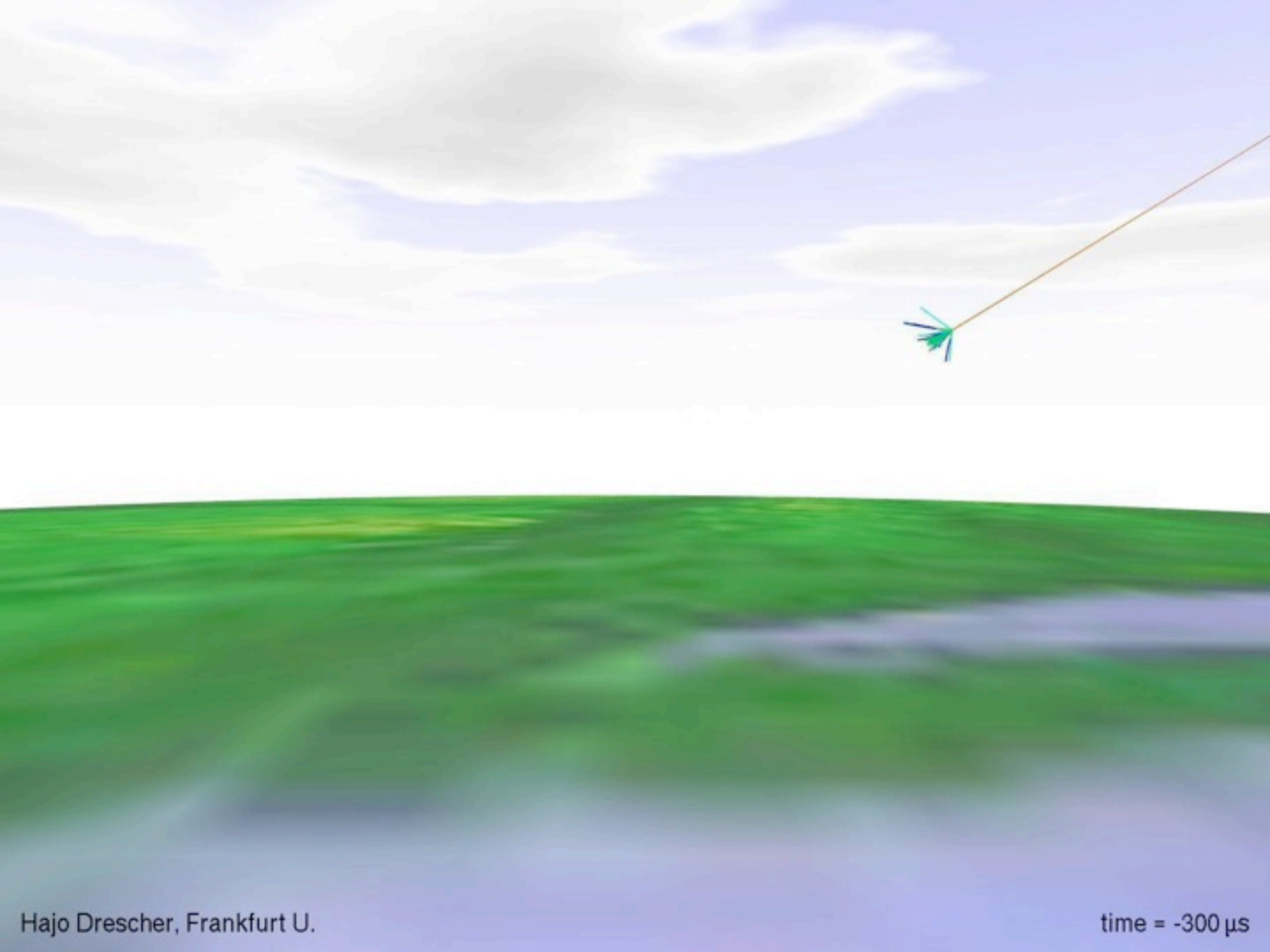
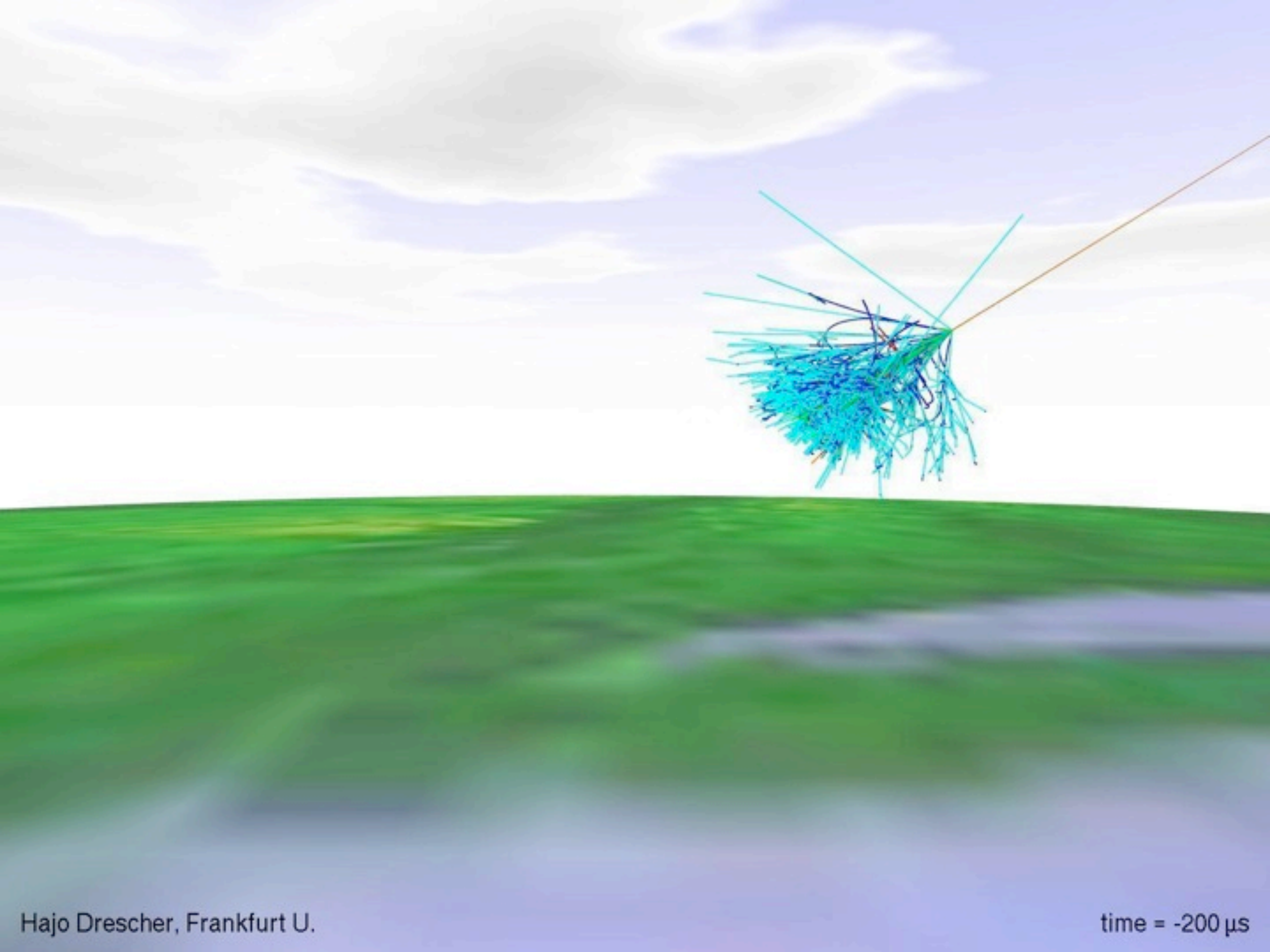

Hajo Drescher, Frankfurt U.
time = -300 µs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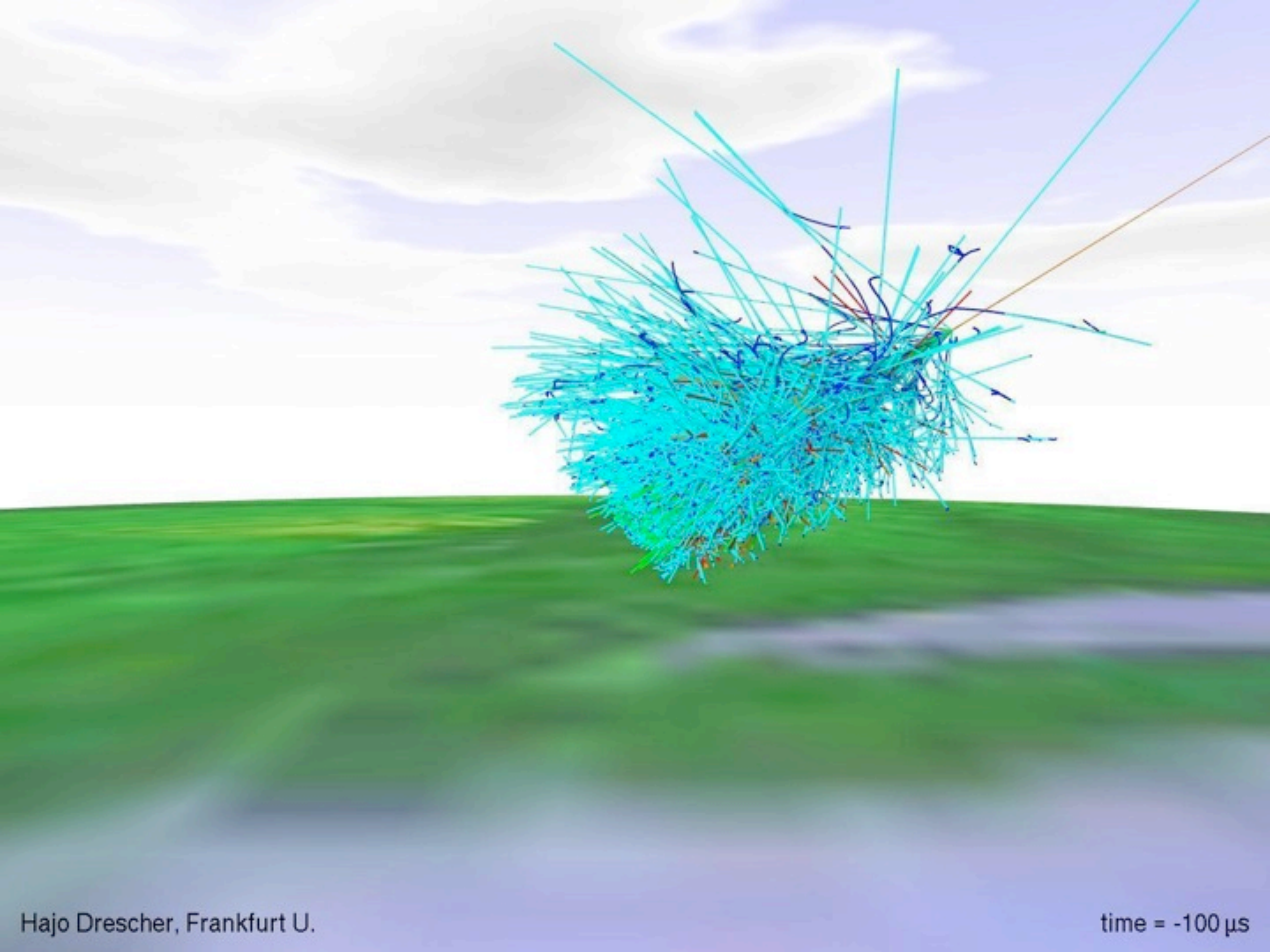
Hajo Drescher, Frankfurt U.
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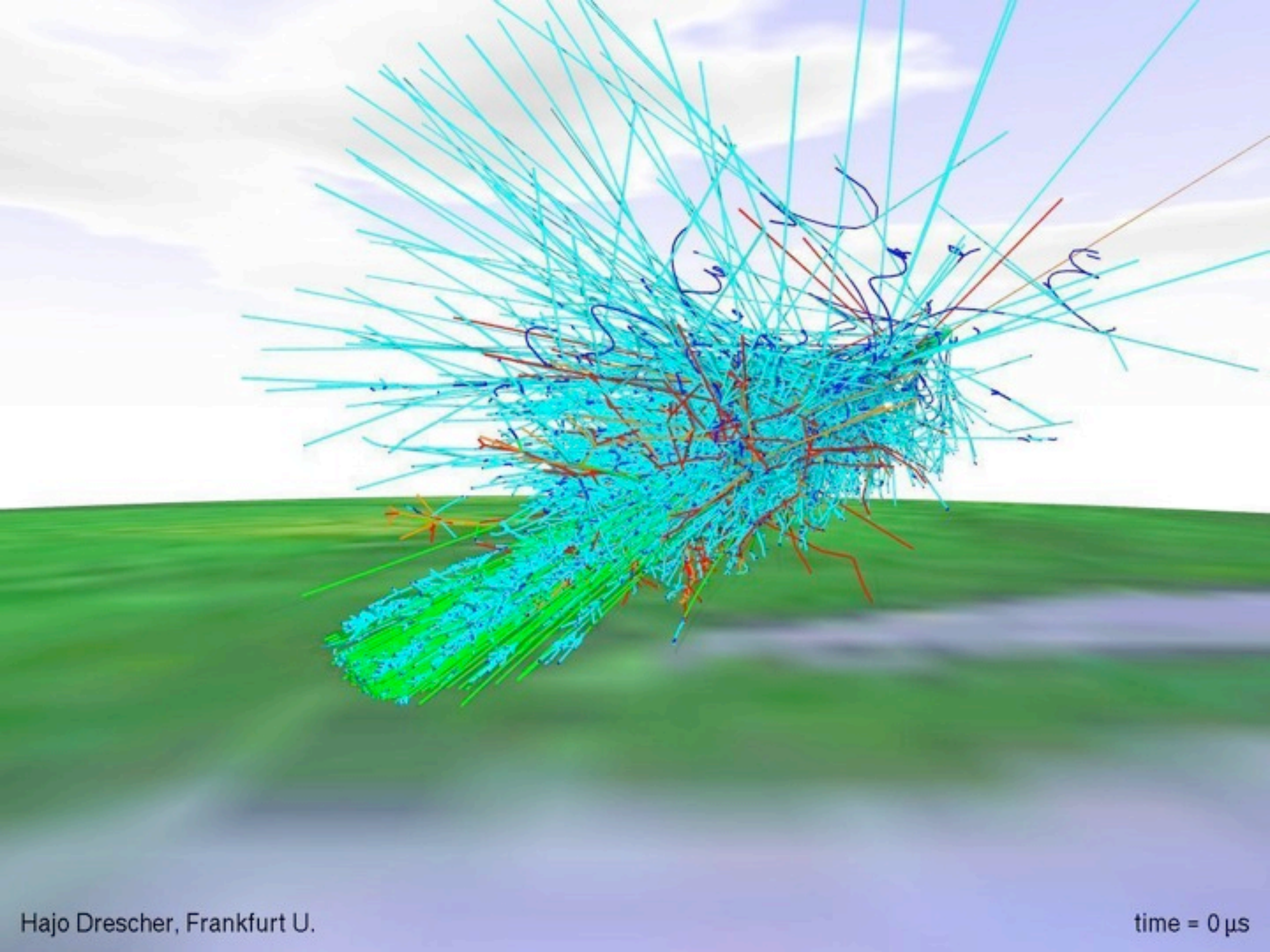
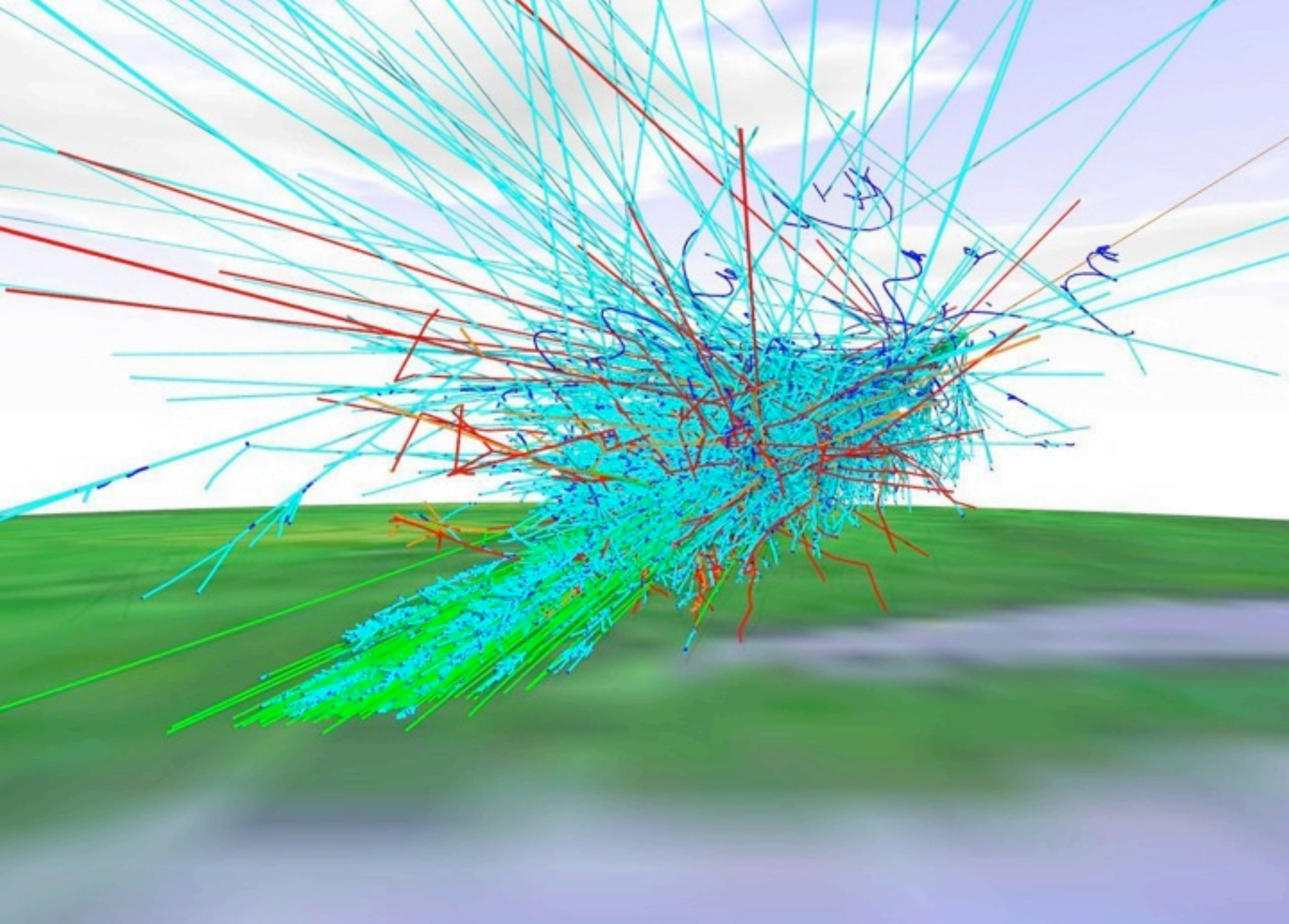
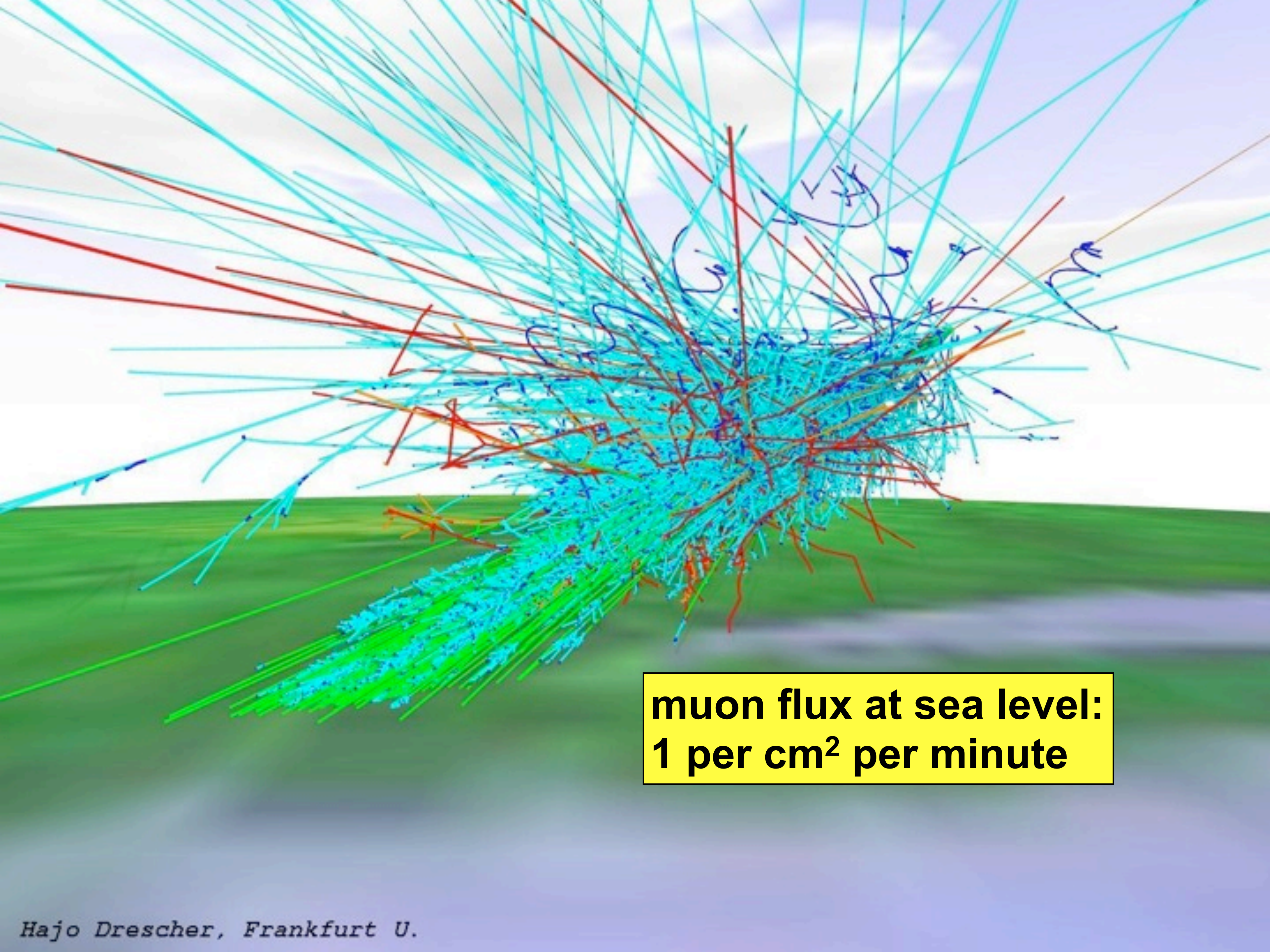
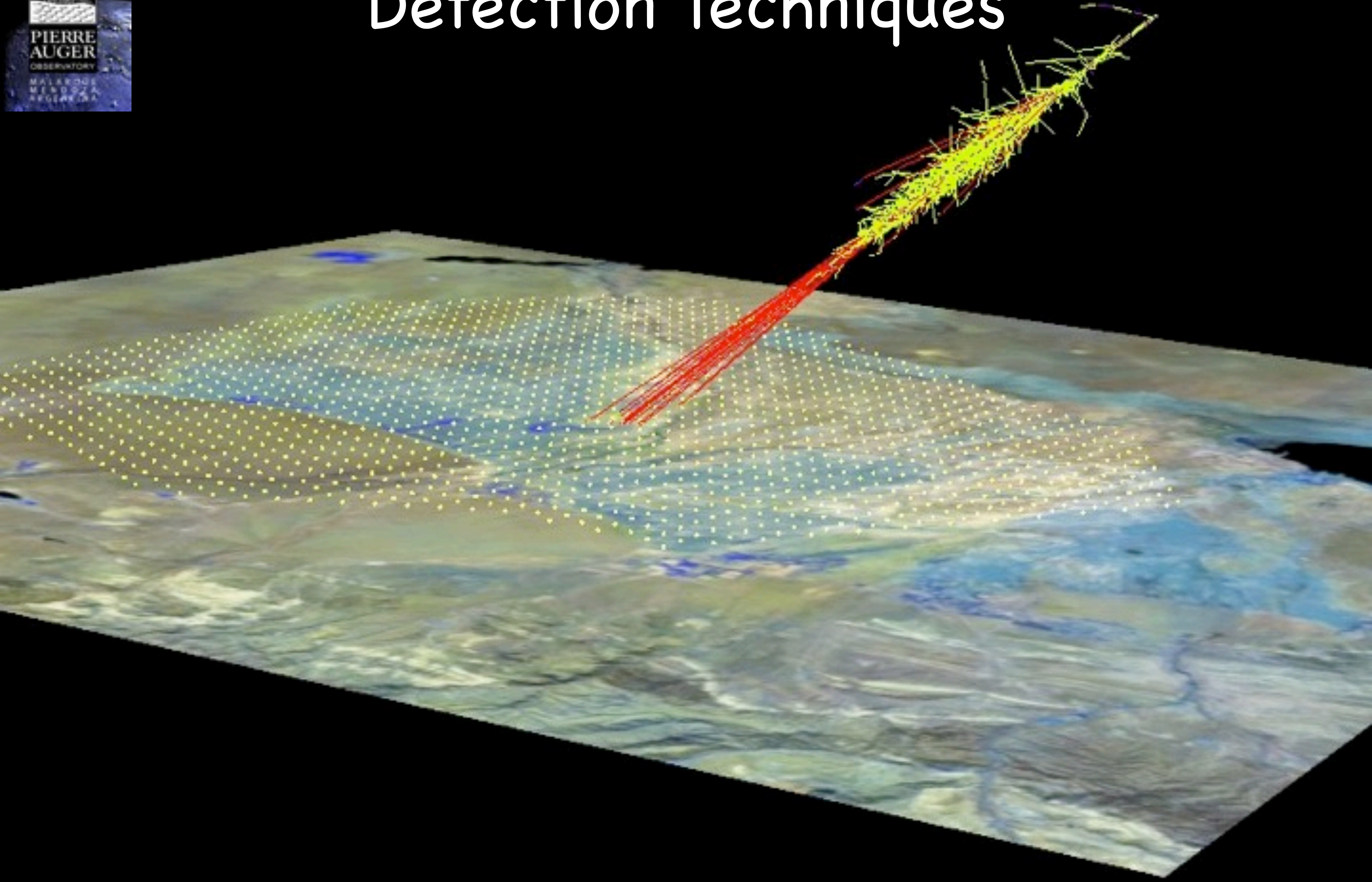

Hajo Drescher, Frankfurt U.
time = 0 µs



Hajo Drescher, Frankfurt U.

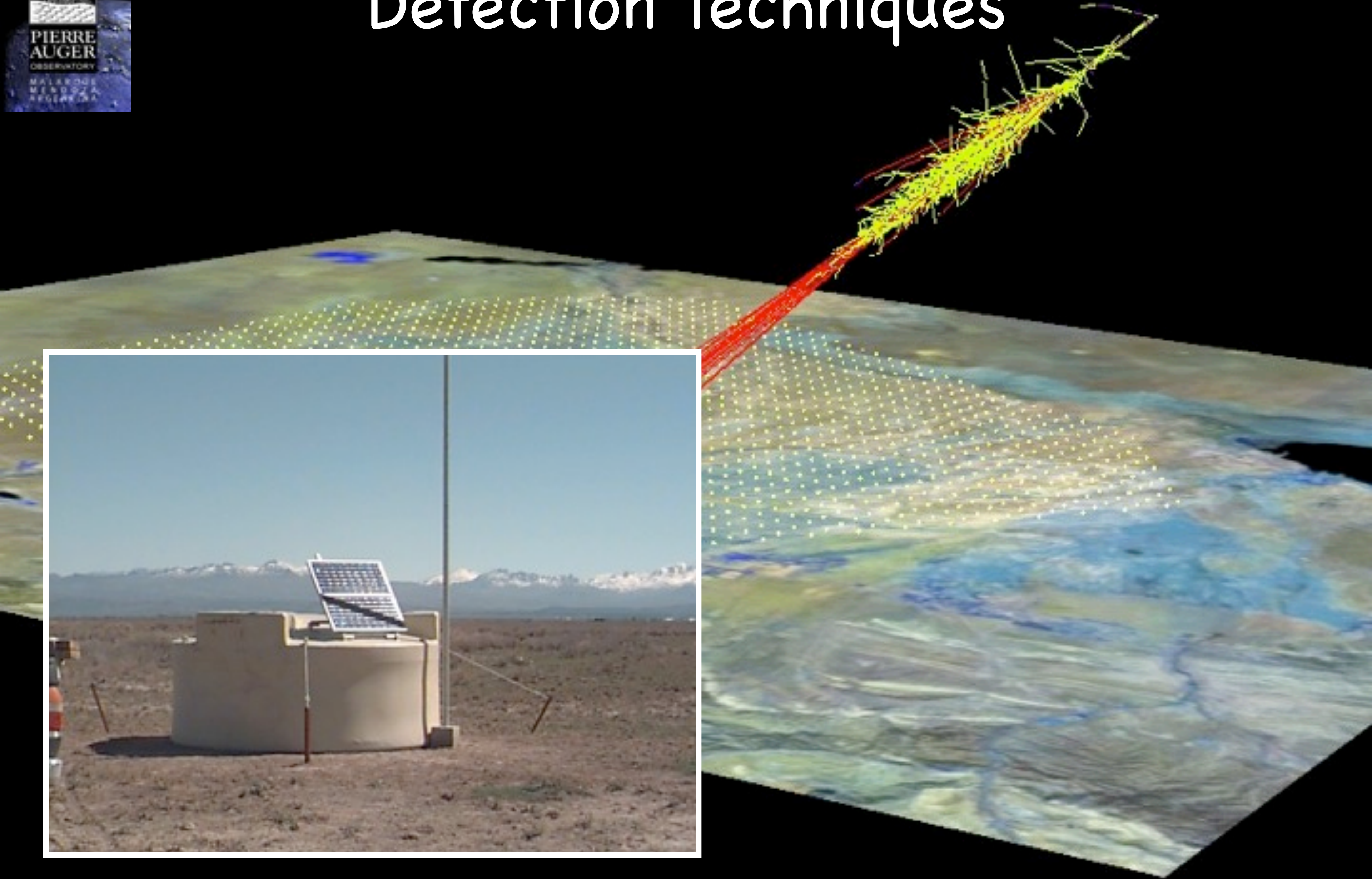

muon flux at sea level:
1 per cm^2 per minute
Hajo Drescher, Frankfurt U.

Detection Techniques

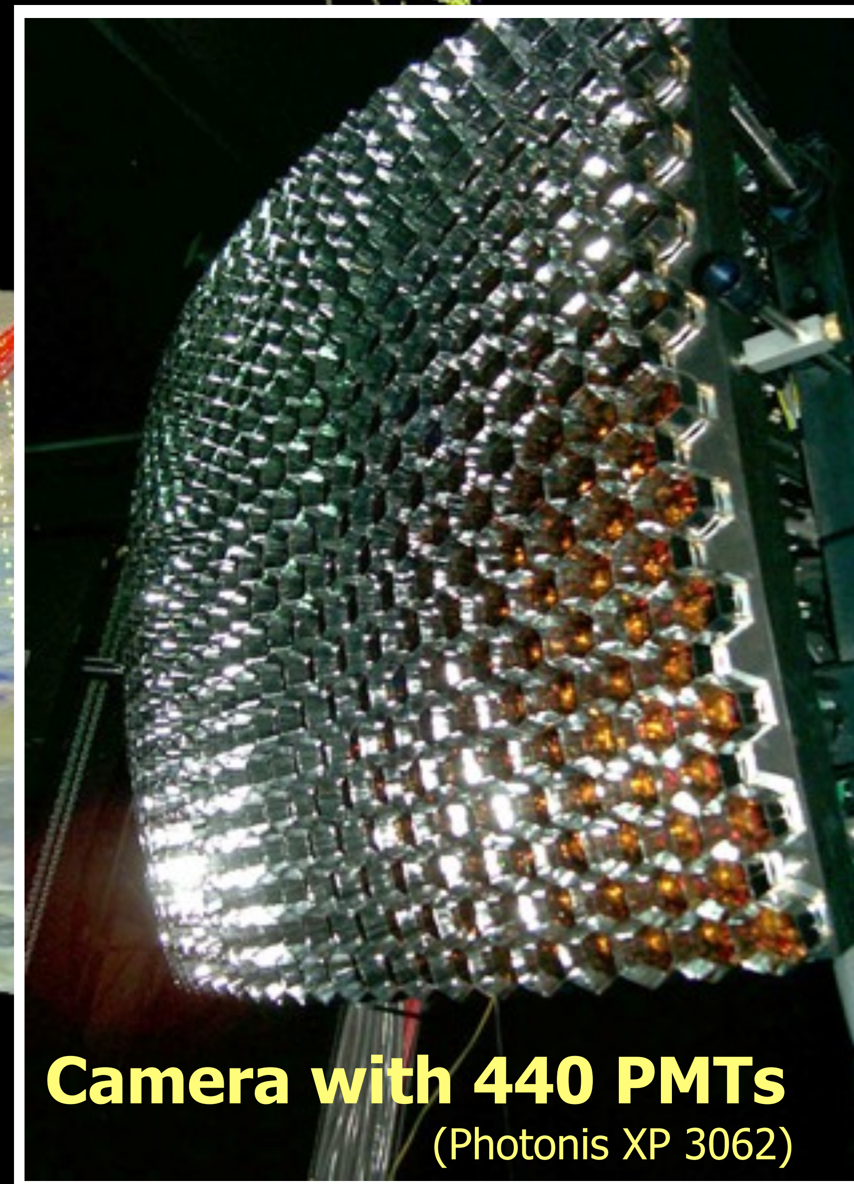


PIERRE AUGER OBSERVATORY

Detection Techniques



Detection Techniques



Pierre Auger Collaboration

- *International effort involving more than 350 scientists at 72 institutions in 18 countries:*
  - Argentina, Australia, Bolivia, Brazil, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Slovenia, Spain, United Kingdom, USA, Vietnam

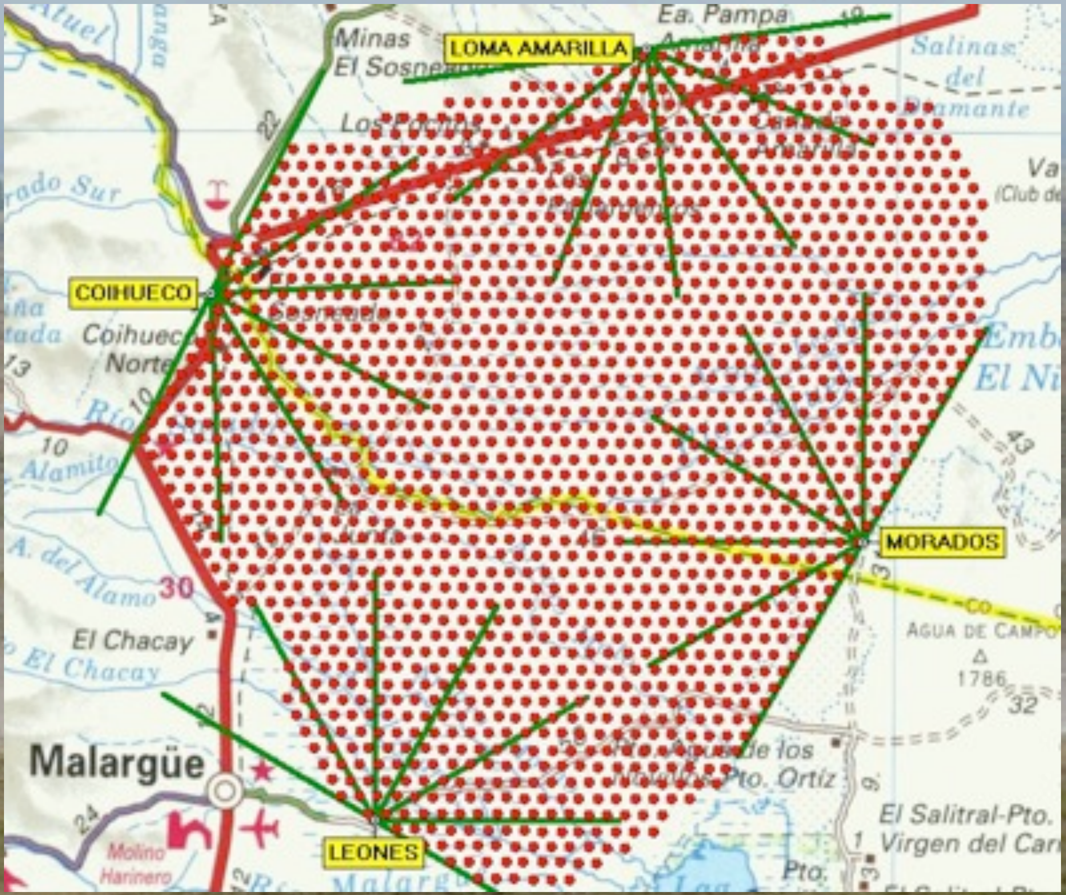
www.auger.org

auger.physics.wisc.edu

Surface Detector

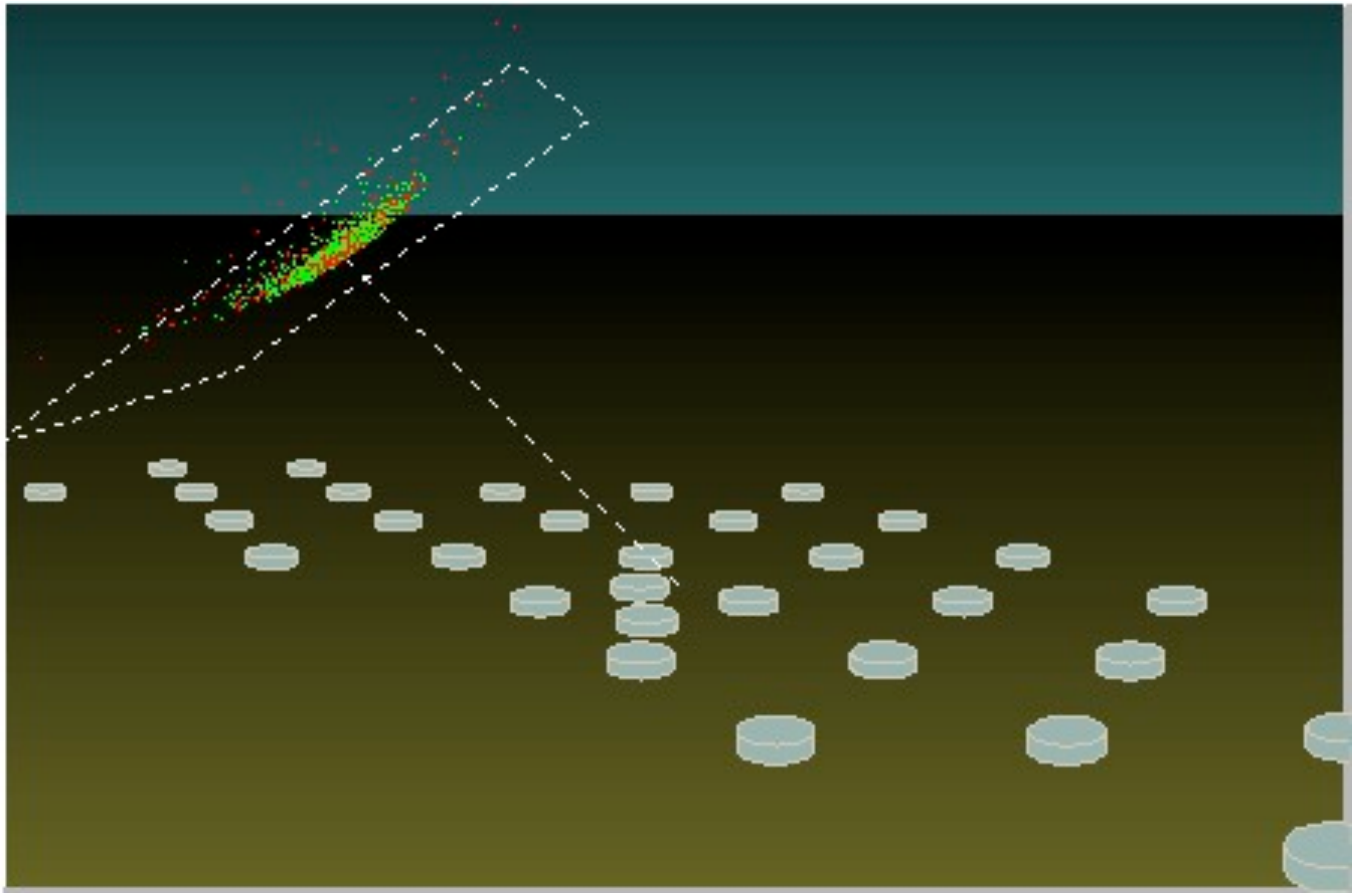
Surface Detector

3000 km^2 area



Surface Detector

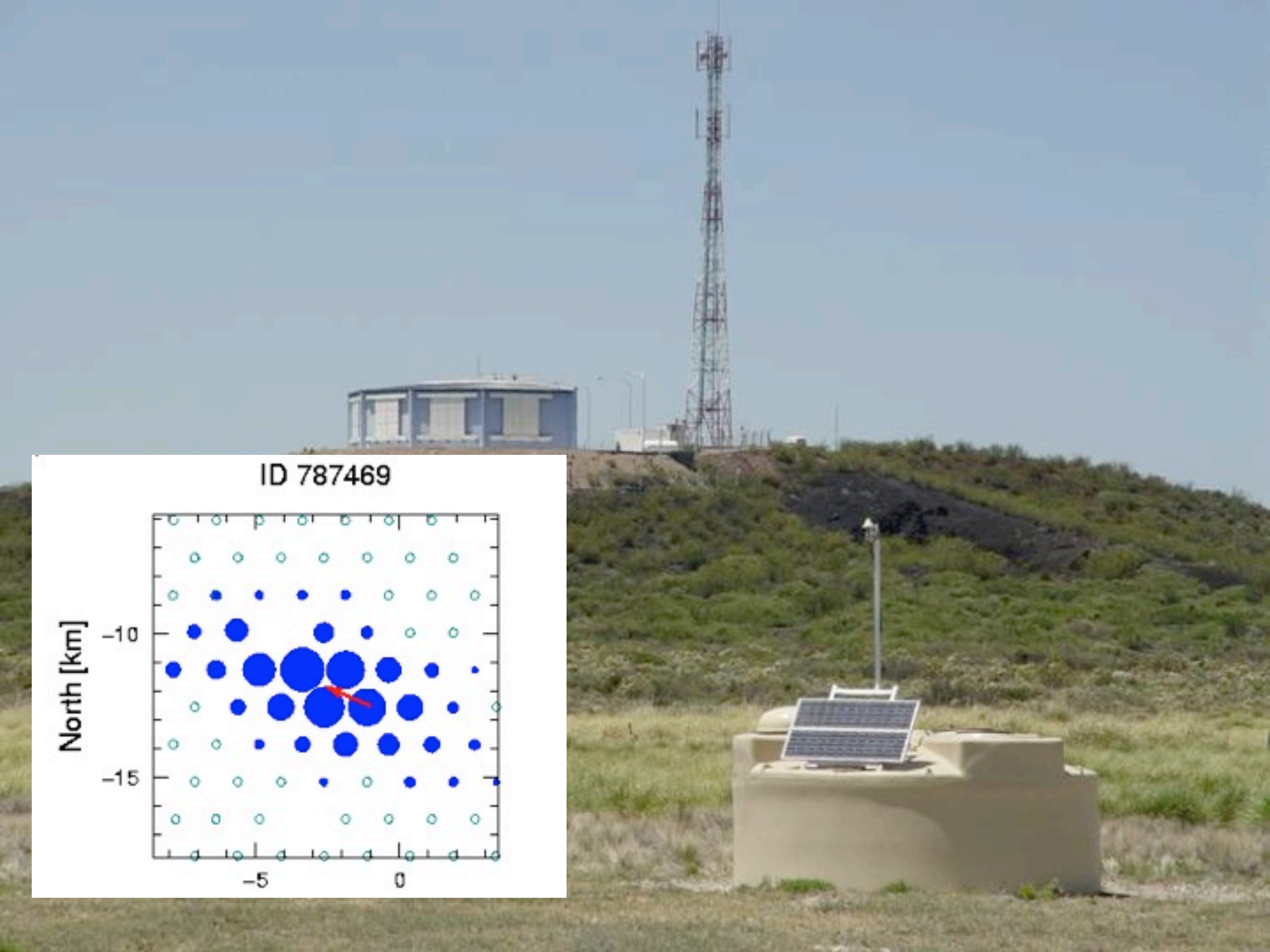
3000 km^2 area

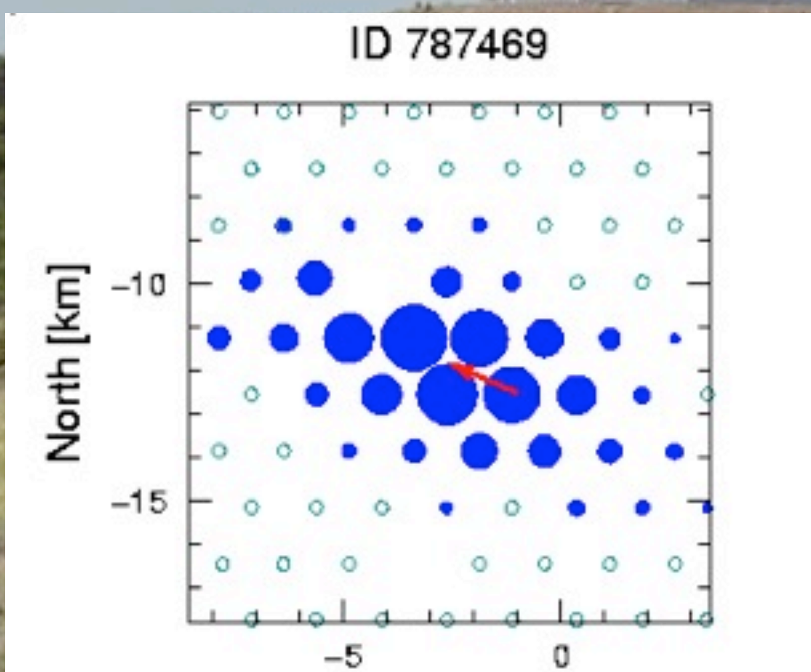


Fluorescence Detector

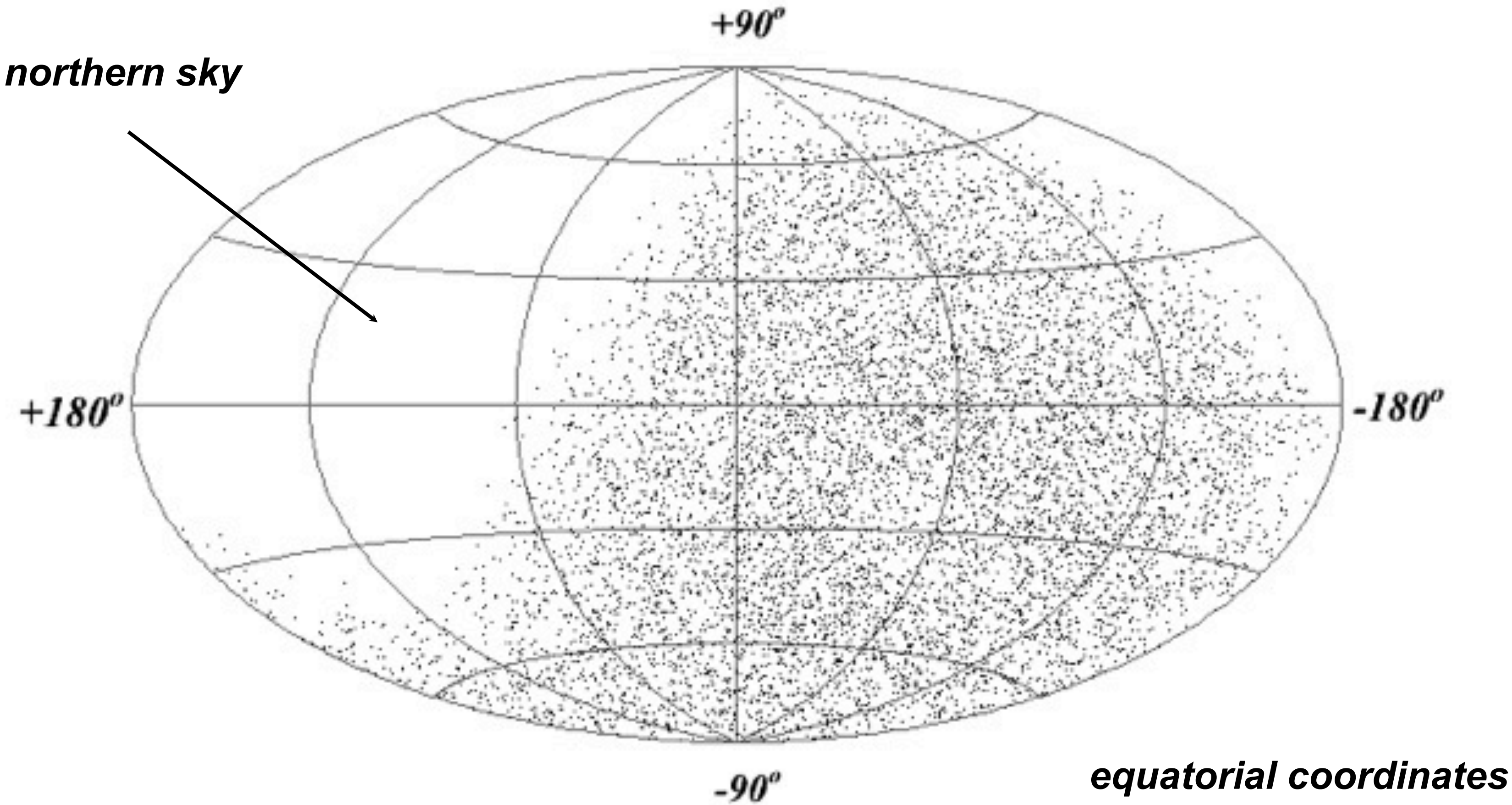
Fluorescence Detector

Fluorescence Detector


ID 787469
North [km]
−10
−15
−5
0

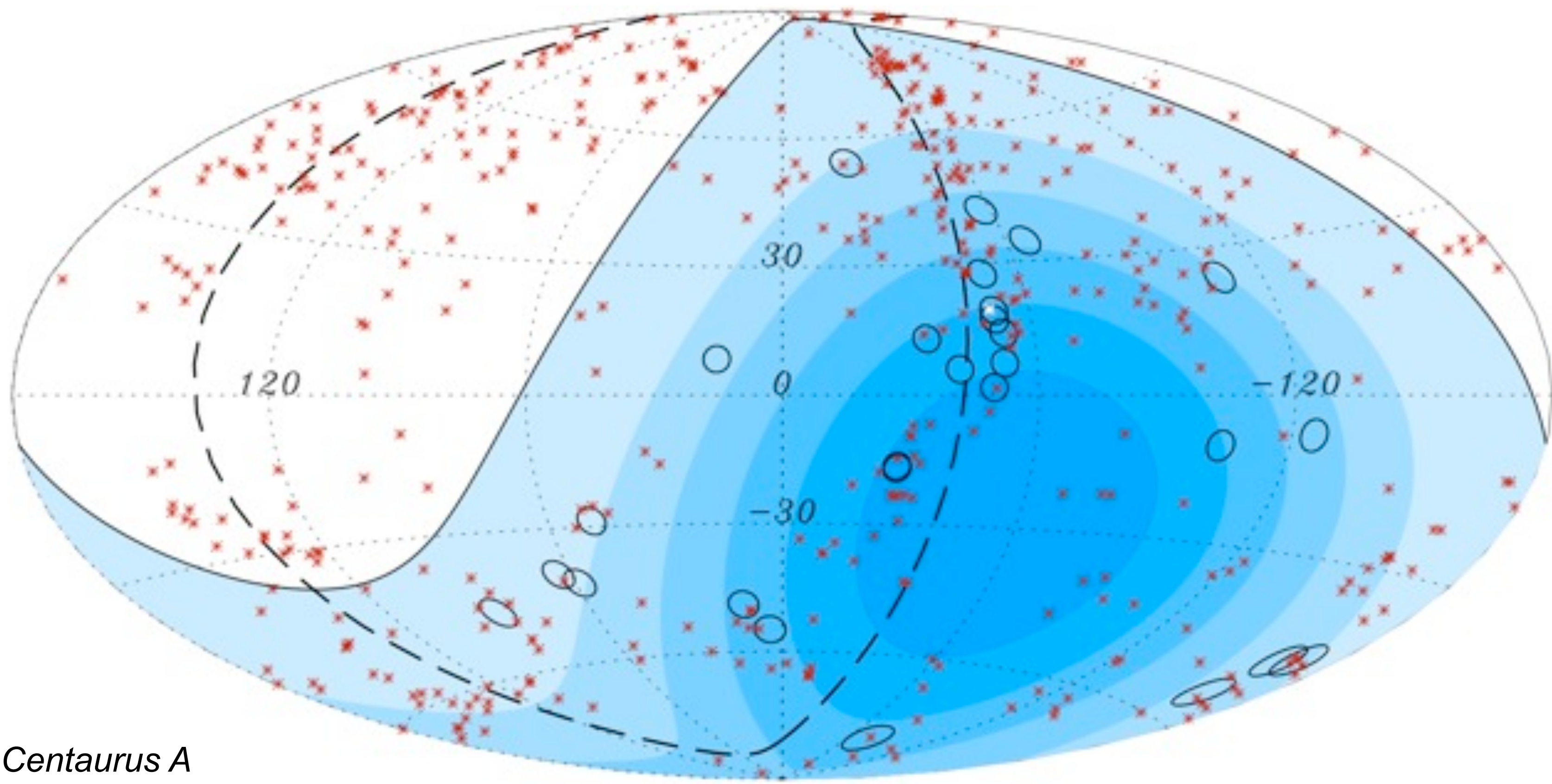

ID 787469
North [km]
−10
−15
−5
0

Arrival Directions



Skymap at the Highest Energies

- 472 AGN with $z < 0.018$ (red crosses), 27 cosmic ray arrival directions with 3.1º circle, color indicates relative exposure, position of CenA (white cross).



Centaurus A
4 Mpc, 11 million light years

Auger Collaboration, Science 318 (2007) 938

- There are first indications that the cosmic ray flux might not be isotropic at the highest energies, but no source has been positively identified so far.

- Maybe the particles do not point back to their sources - intergalactic and Galactic magnetic fields might scramble the arrival directions even at the highest energies!

- Cosmic rays are not the only messenger from high energy sources -where there are cosmic rays, there are also neutrinos!

Messenger Particles

- Cosmic rays are not the only messenger from high energy sources - a cosmic ray source is also a *beam-dump.*

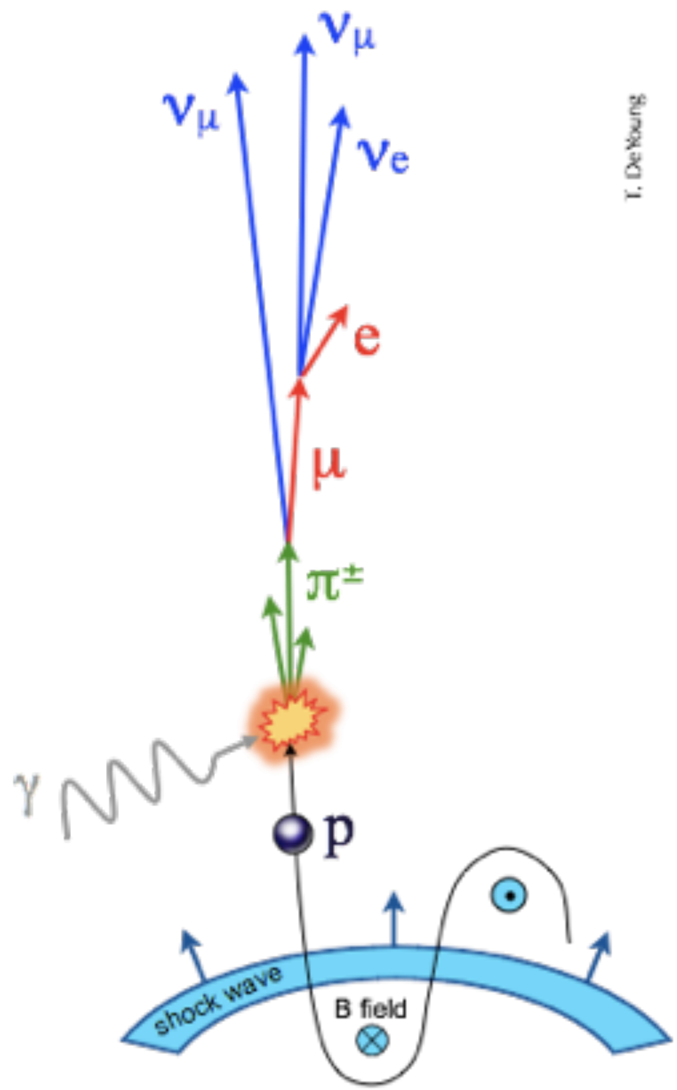
- Cosmic rays inevitably interact with radiation and gas surrounding their source, *e.g.*

$$p + \gamma \to \Delta^{+} \to \pi^{0} + p$$

$$p + \gamma \to \Delta^{+} \to \pi^{+} + n$$

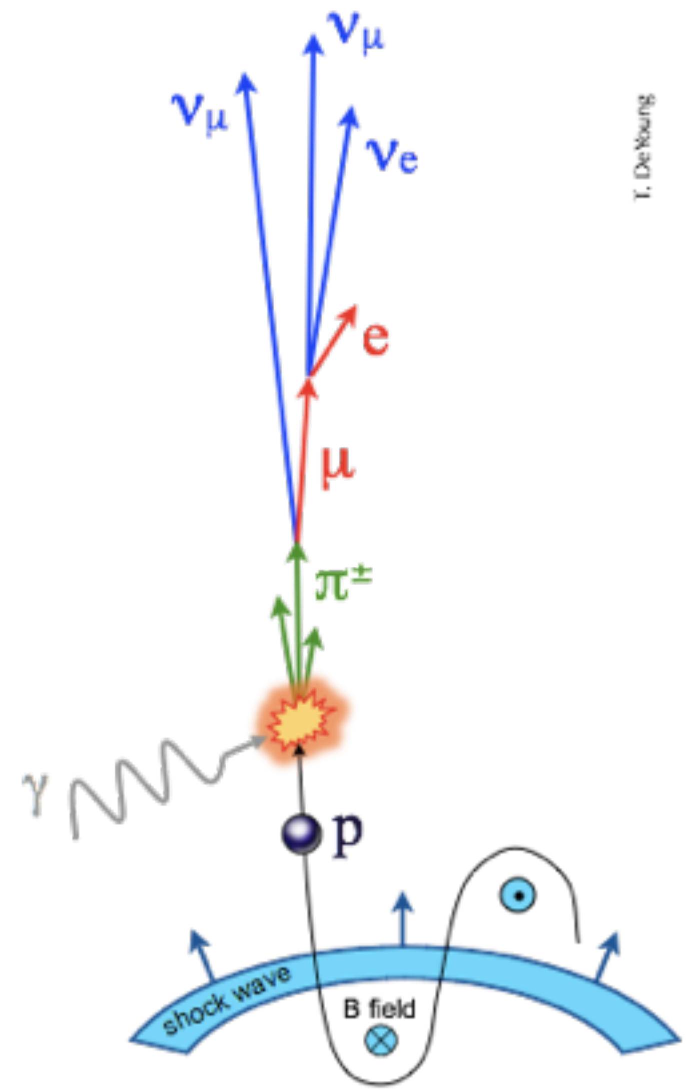
$$p + p \to N\left[\pi^{0} + \pi^{+} + \pi^{-}\right] + X$$

- Energy escaping the source is distributed among *cosmic rays*, *gamma rays*, and *neutrinos*.



Neutrino Production

- Neutrinos are the ideal “messenger particle:”
    - Neutrinos propagate in a straight line and are not easily absorbed - they can get away from the source!
    - However, they are not easily “absorbed” in detectors, either… we need km^3 size detectors!



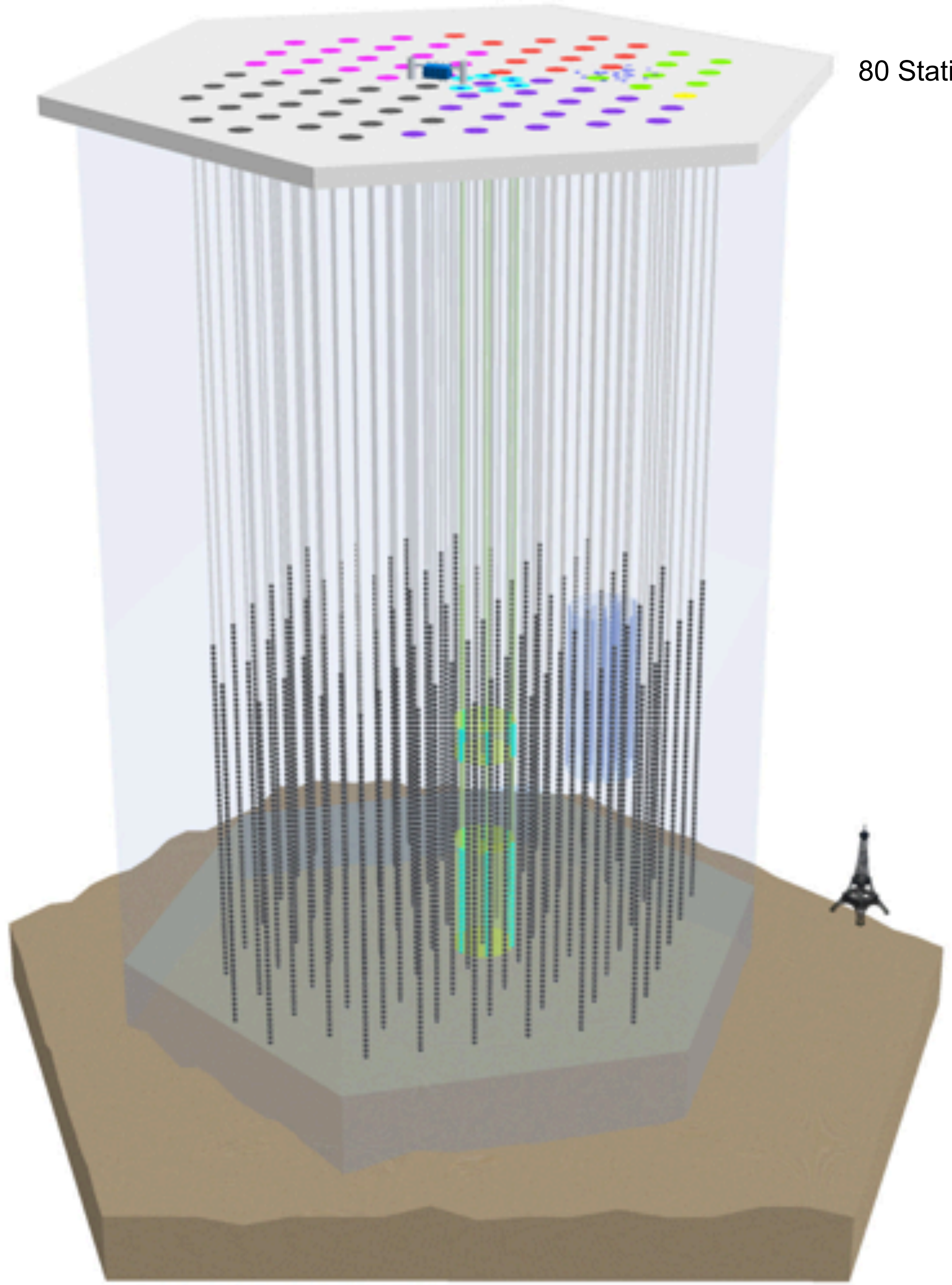
Requirements for a Neutrino Detector

- Large detector volumes - of order ~ km^3 if we want to detect a few neutrinos from astrophysical sources per year…
- Neutrinos must interact near or in the detector and produce a particle that can be detected, for example a muon.
- The detector must be shielded from the enormous background of atmospheric muons, so it needs to be deep below some absorbing material.
- At the same time, the absorbing material must allow for detection of light from particles created by neutrinos.


Blue light travels 200+ meters in ice…

IceCube

- 86 strings
- 1.5 km - 2.5 km deep
- typically 125 m spacing between strings
- 60 Modules per string
- 1 km^3 -- 1 billion tons of instrumented volume



80 Stations, each with:

IceCube Collaboration

http://icecube.wisc.edu

36 institutions, ~250 members

Canada
University of Alberta

US
Bartol Research Institute, Delaware
Pennsylvania State University
University of California - Berkeley
University of California - Irvine
Clark-Atlanta University
University of Maryland
University of Wisconsin - Madison
University of Wisconsin - River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University, Baton Rouge
University of Alaska, Anchorage
University of Alabama, Tuscaloosa
Georgia Tech
Ohio State University

Barbados
University of West Indies

Sweden
Uppsala Universitet
Stockholms Universitet

UK
Oxford University

Germany
Universität Mainz
DESY-Zeuthen
Universität Dortmund
Universität Wuppertal
Humboldt-Universität zu Berlin
MPI Heidelberg
RWTH Aachen
Universität Bonn
Ruhr-Universität Bochum

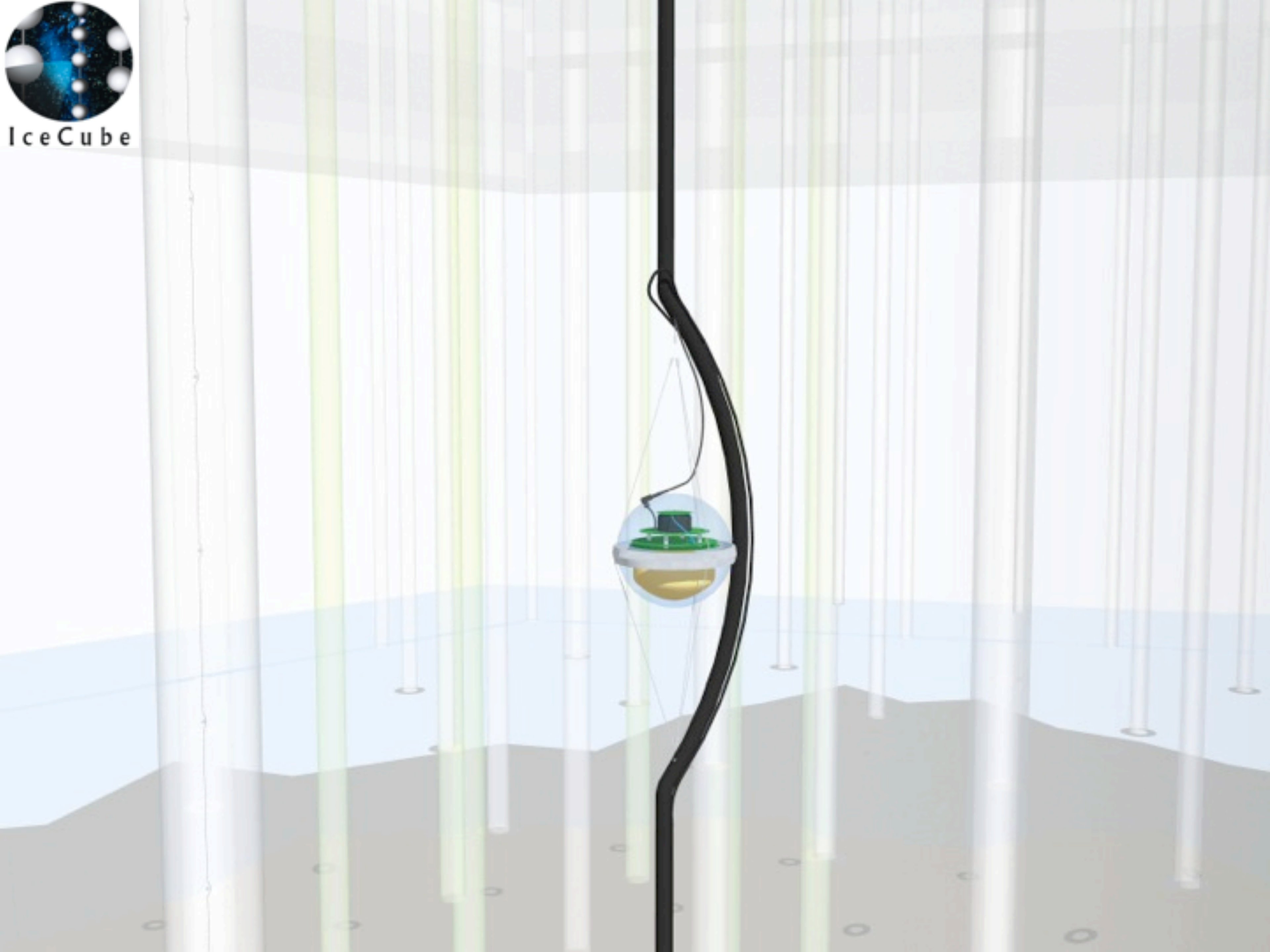
Japan
Chiba University

Belgium
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

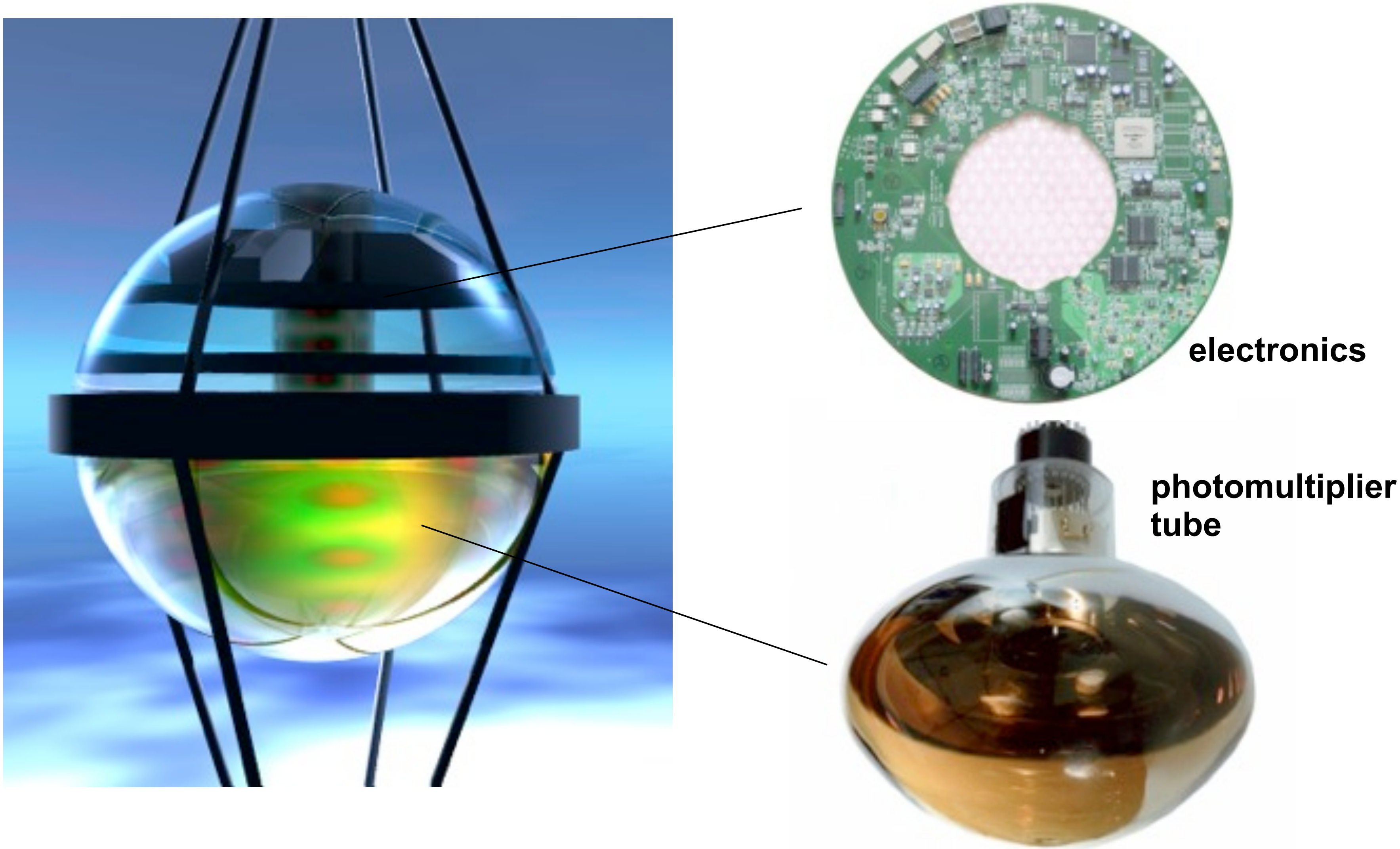
Switzerland
EPFL, Lausanne
University of Geneva

New Zealand
University of Canterbury

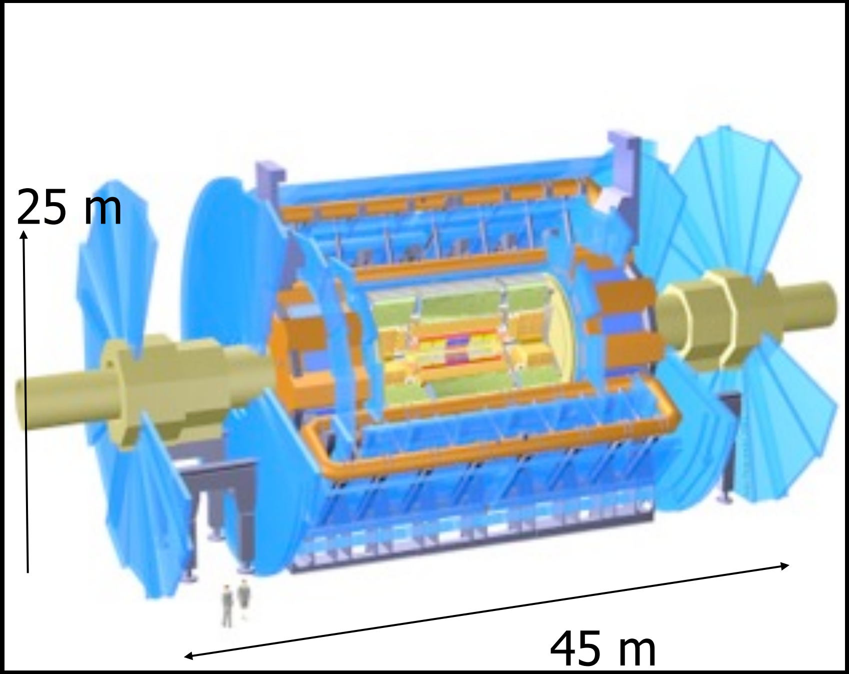
ANTARCTICA
Amundsen-Scott Station


IceCube

Digital Optical Module



IceCube



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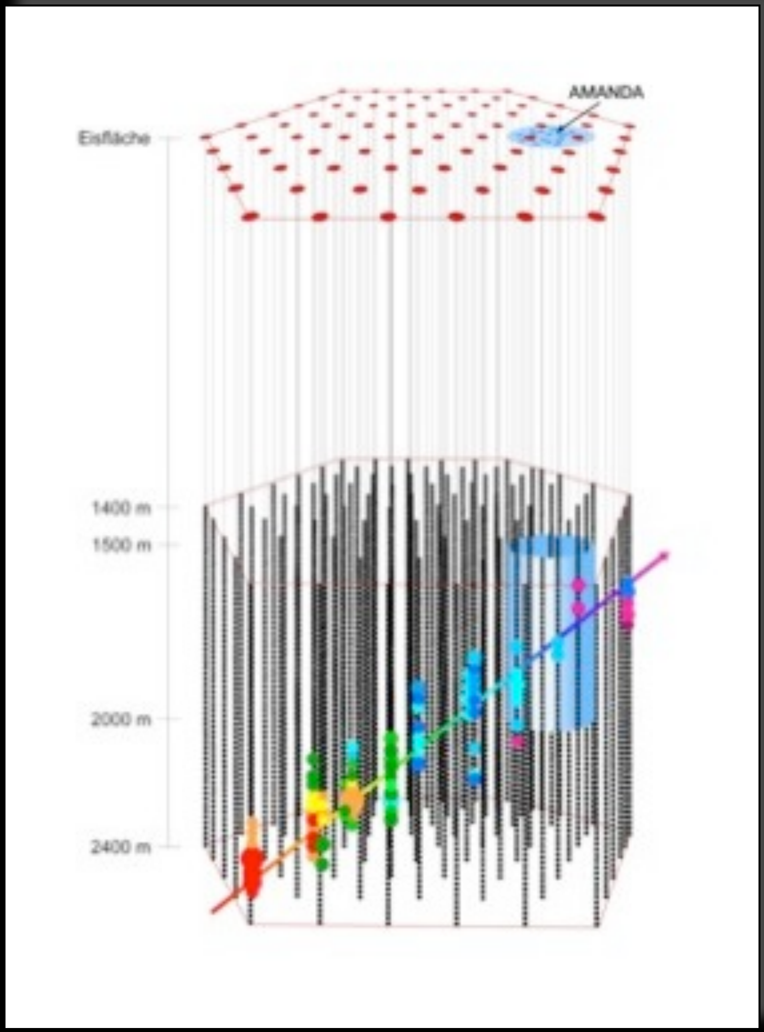

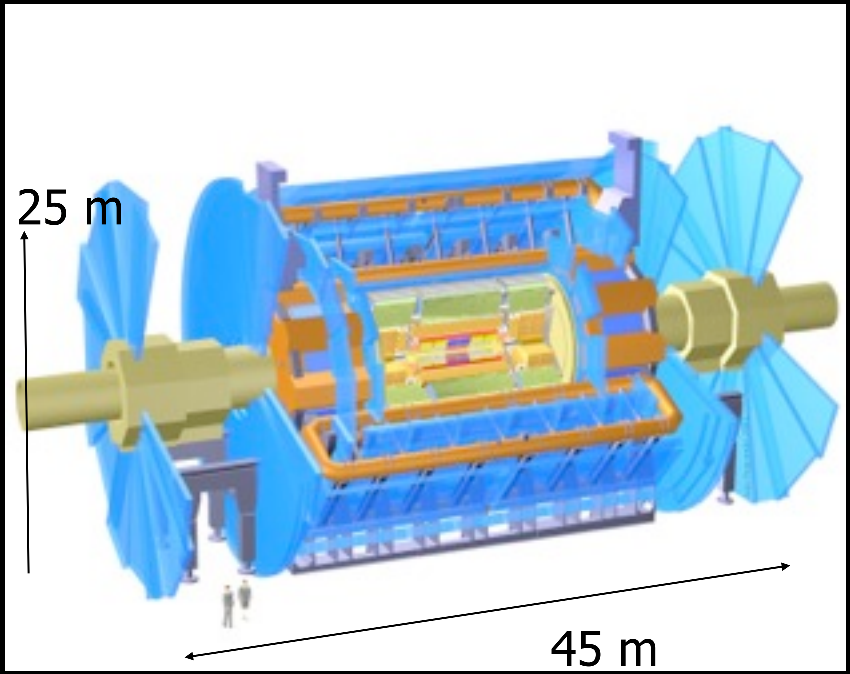

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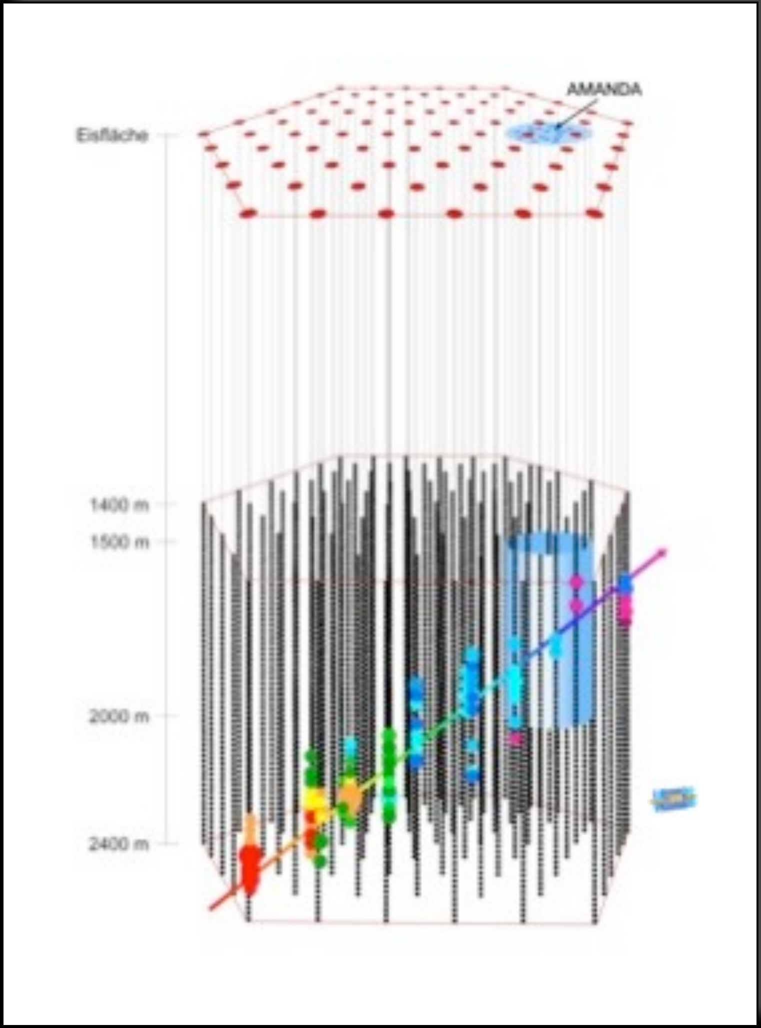
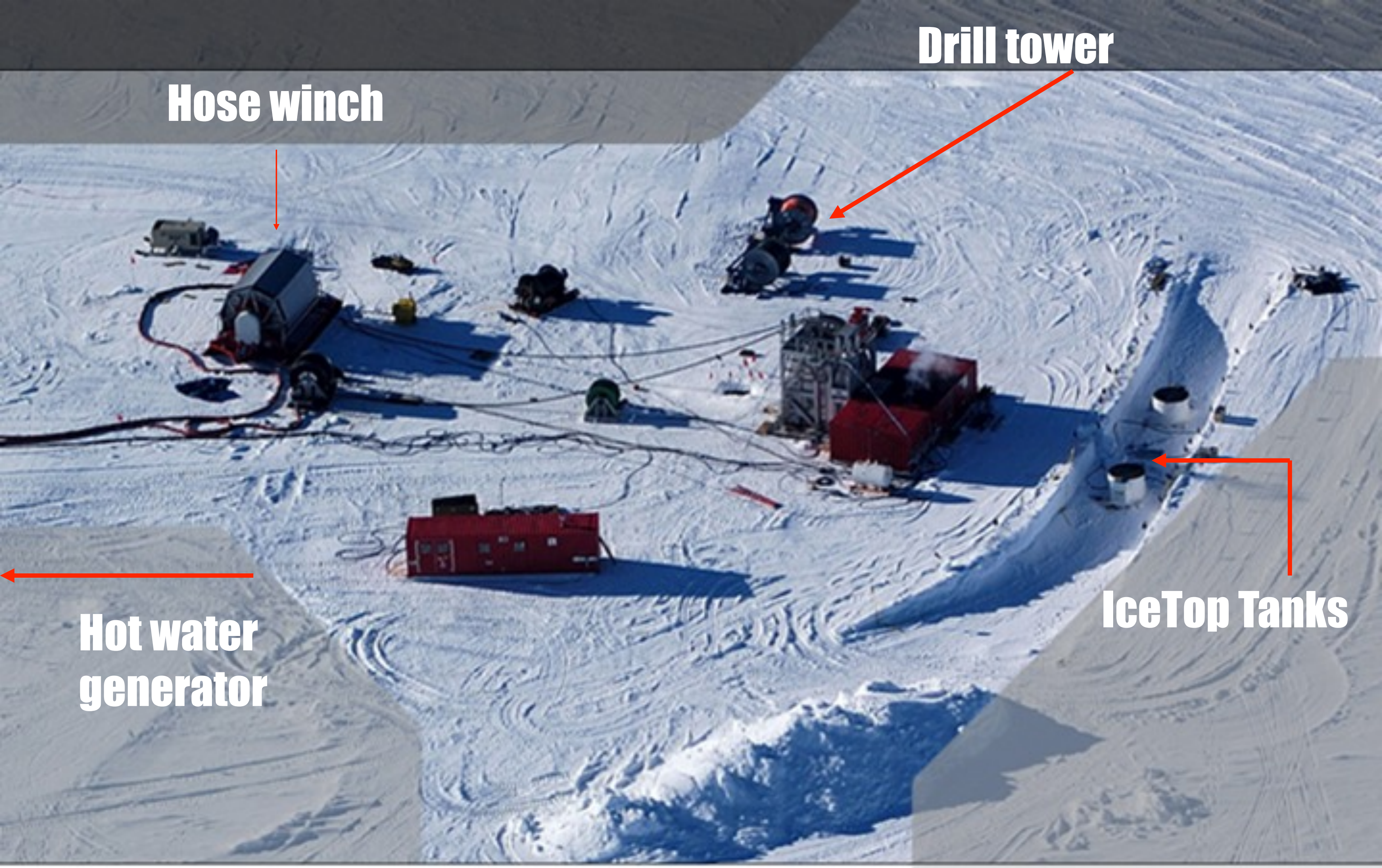
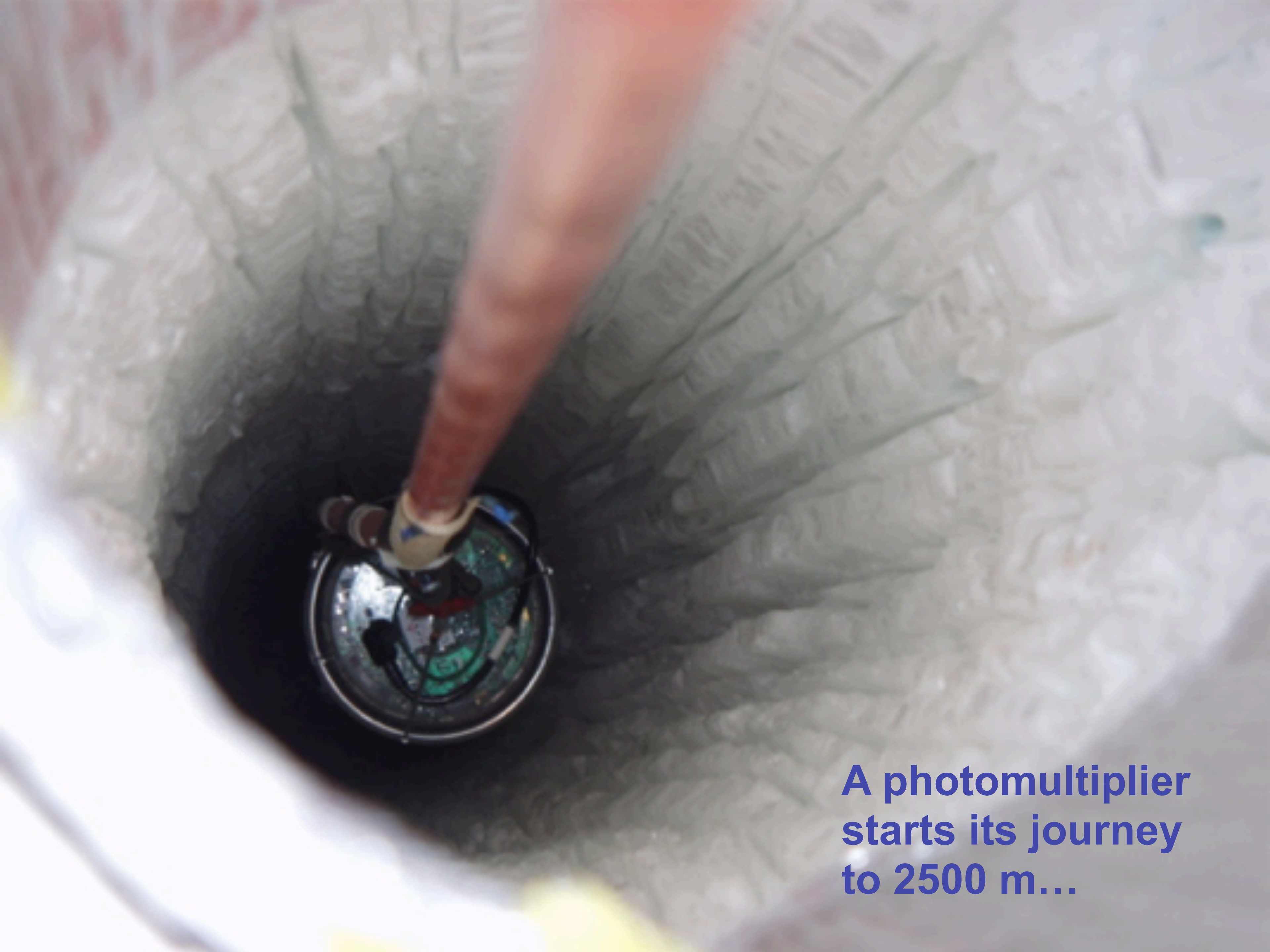
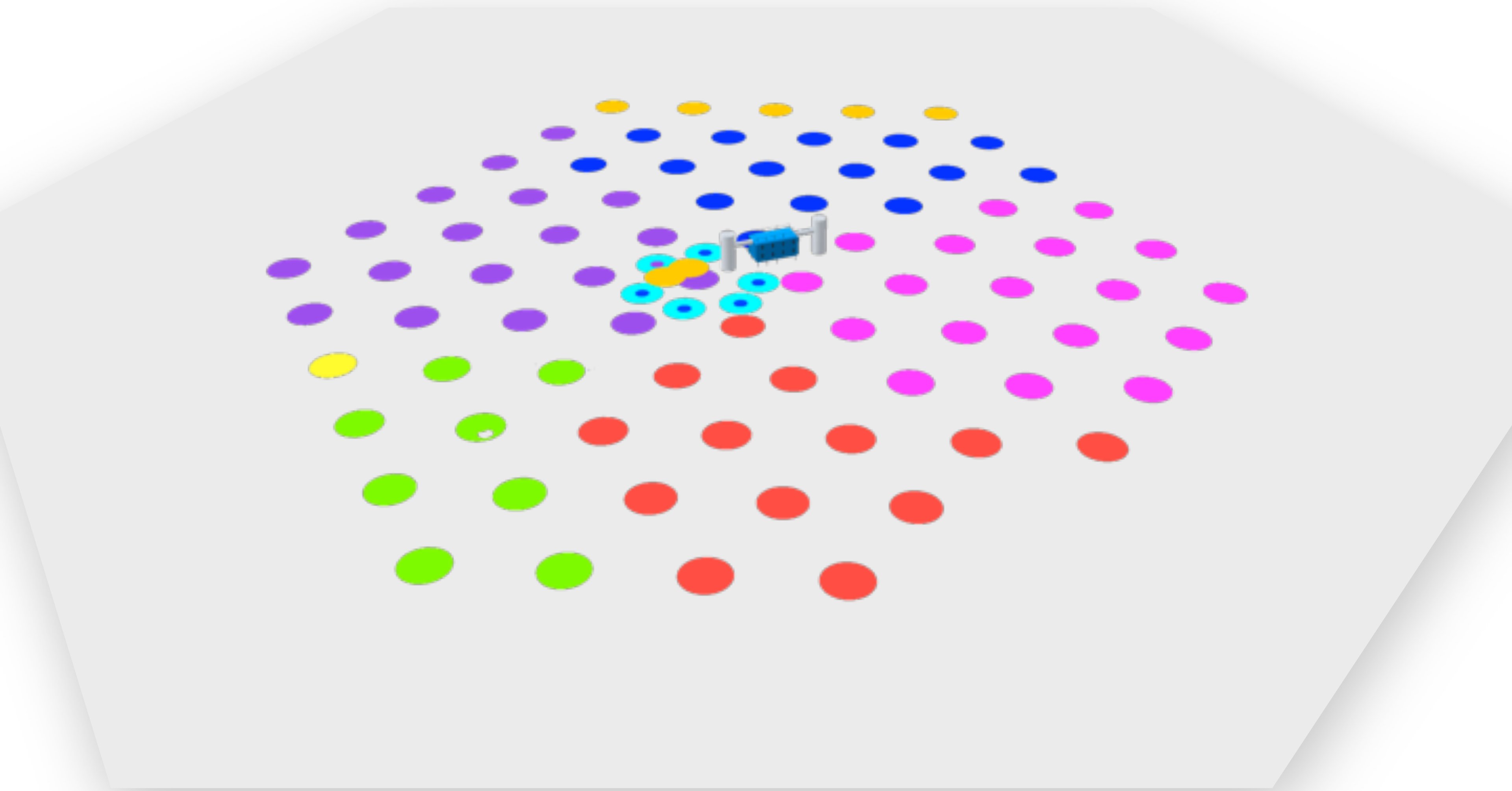




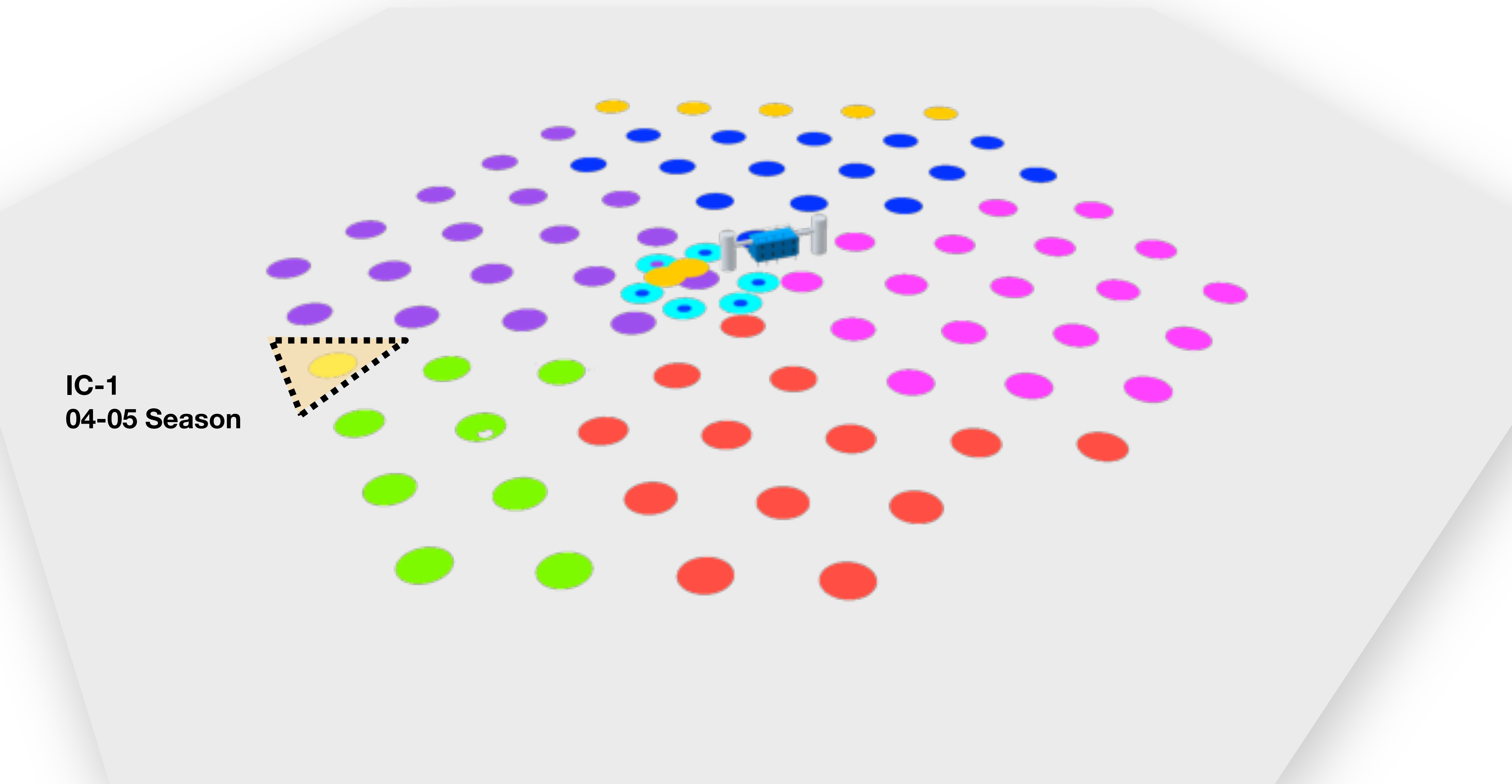
5 megawatt hot water drilling system


A photomultiplier
starts its journey
to 2500 m…

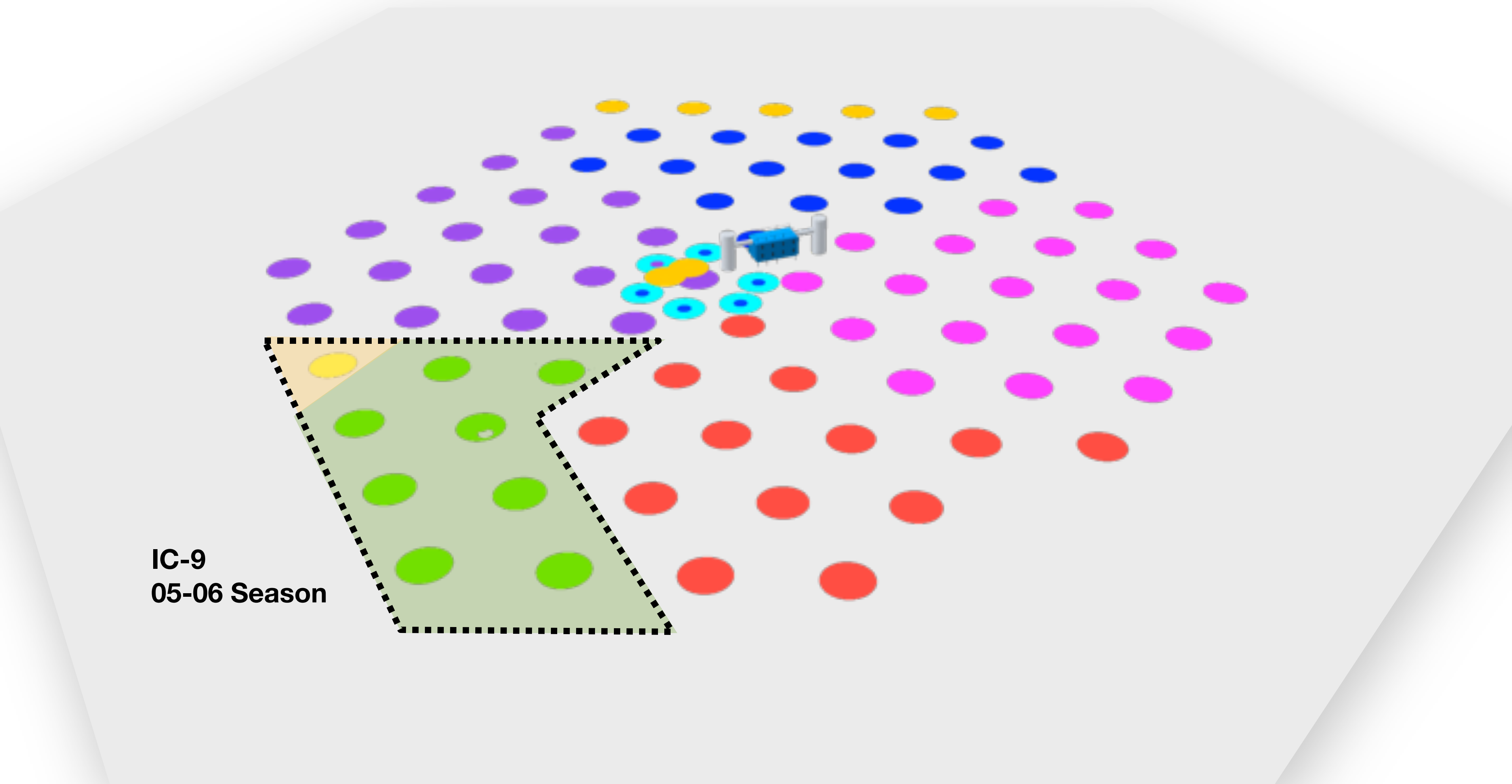
IceCube Configurations



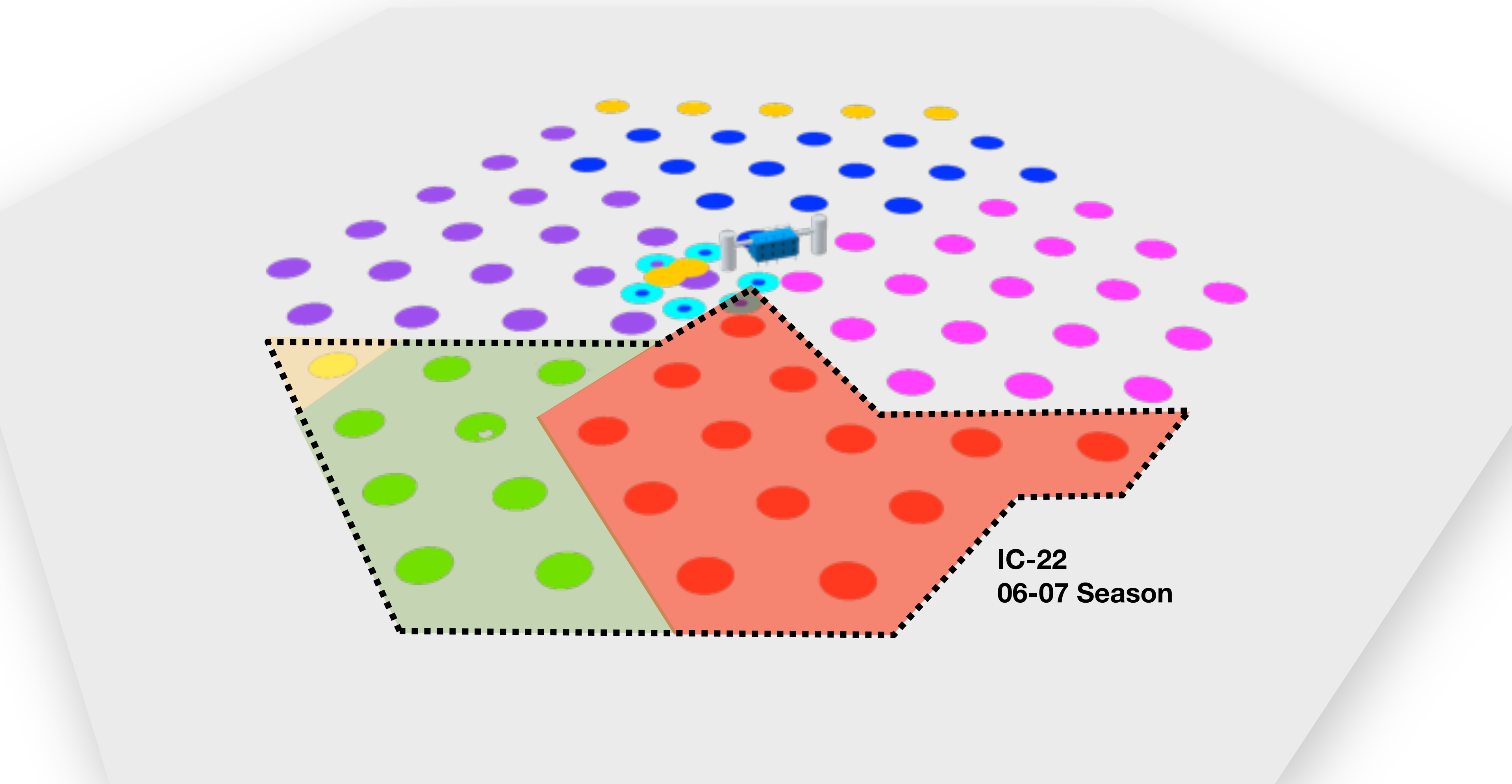
IceCube Configurations



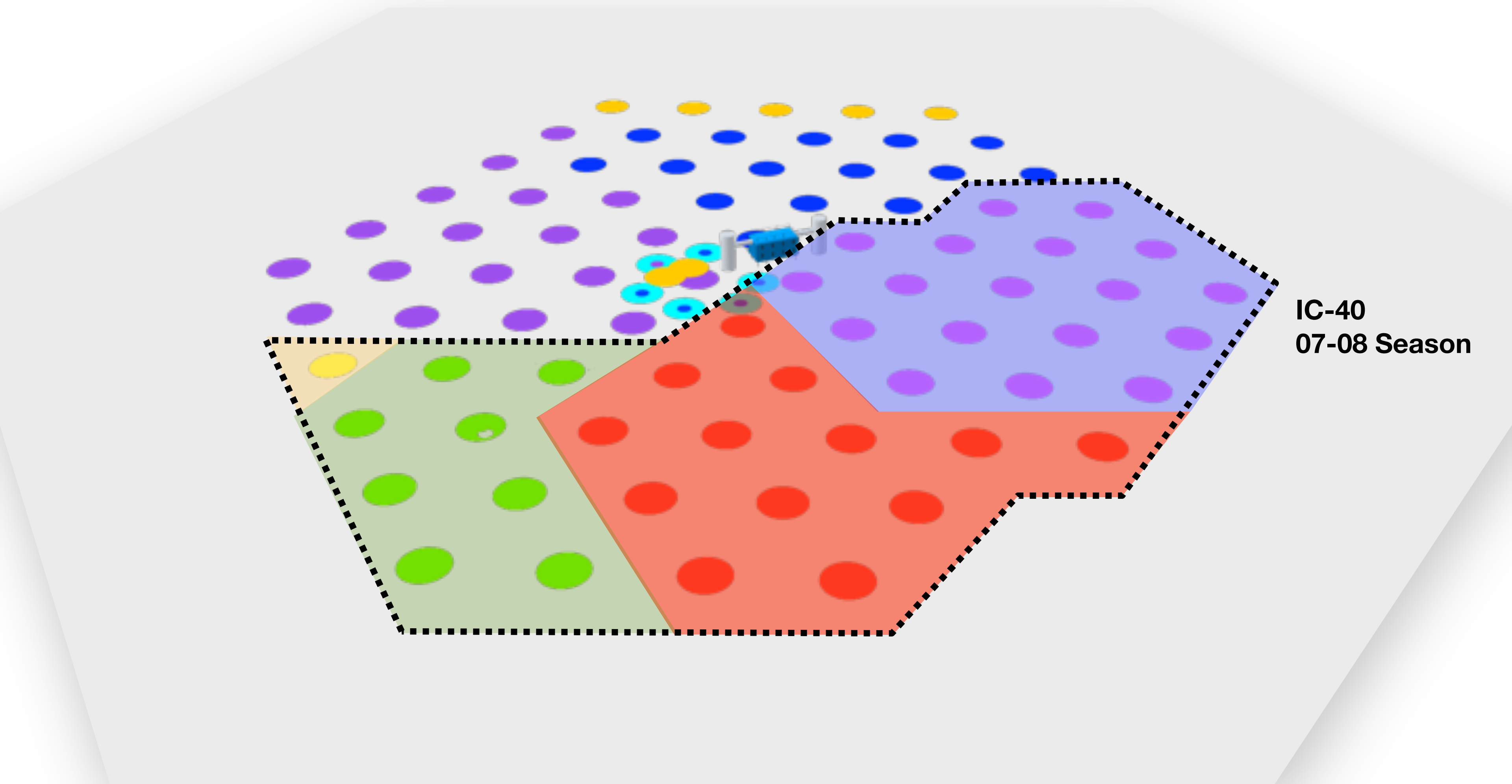
IceCube Configurations



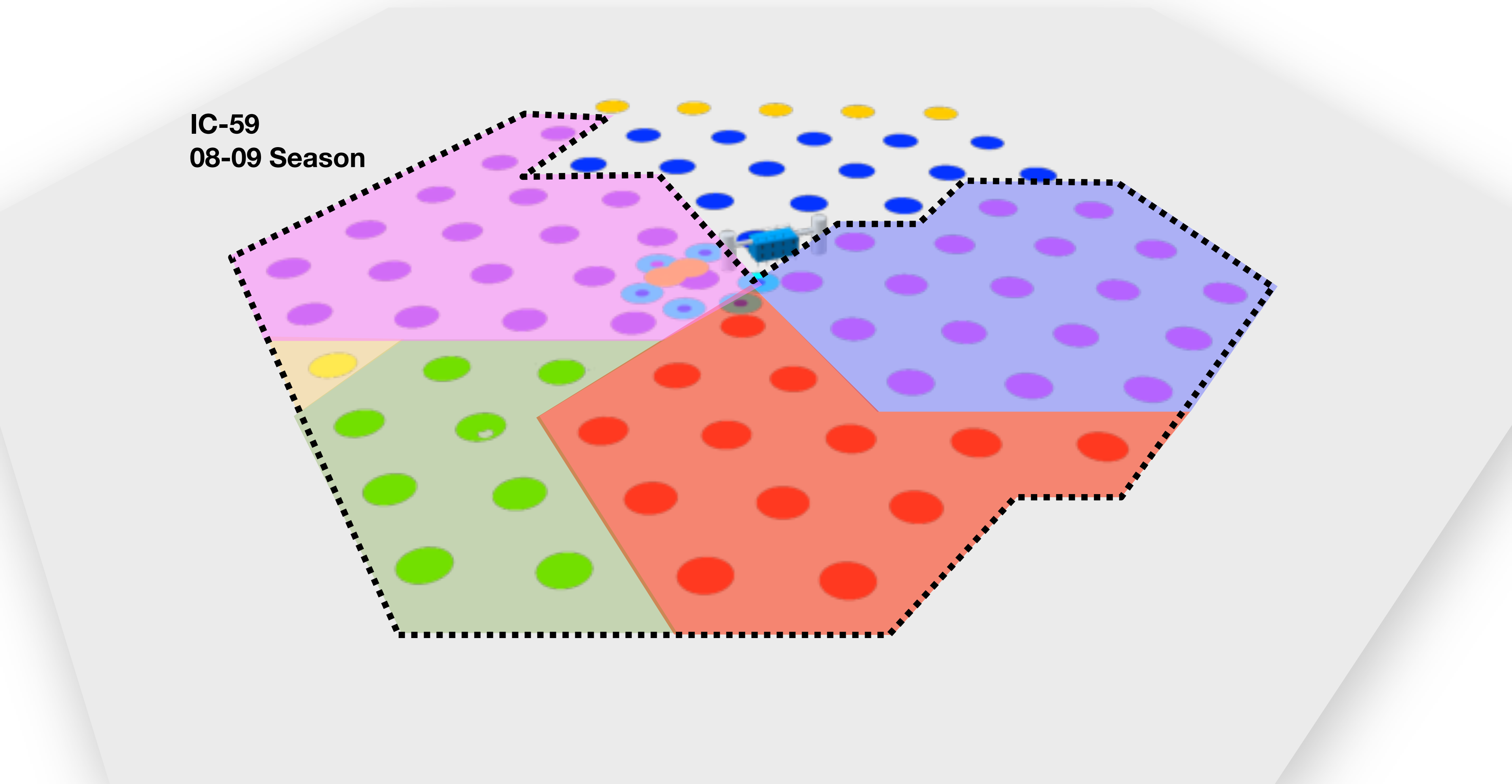
IceCube Configurations



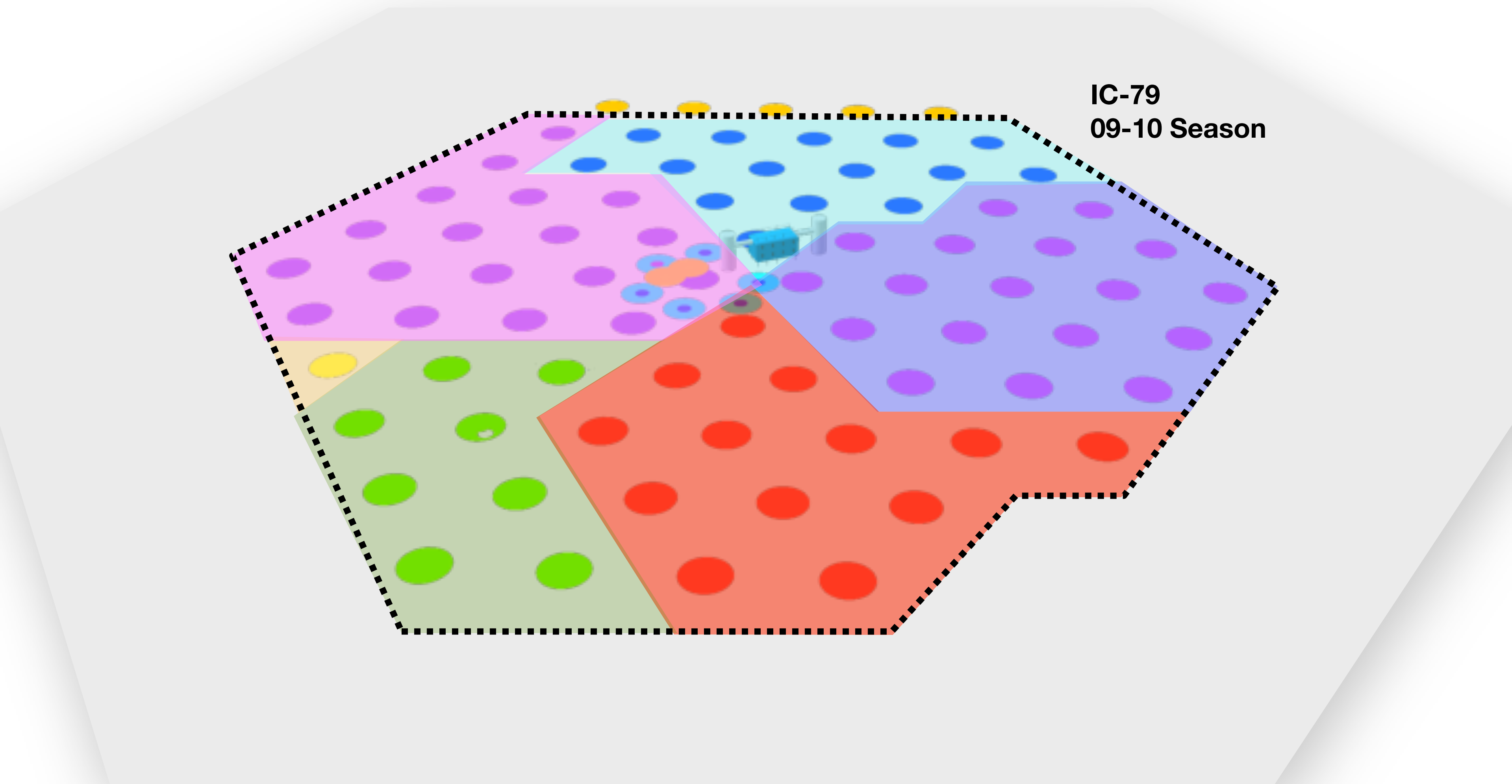
IceCube Configurations



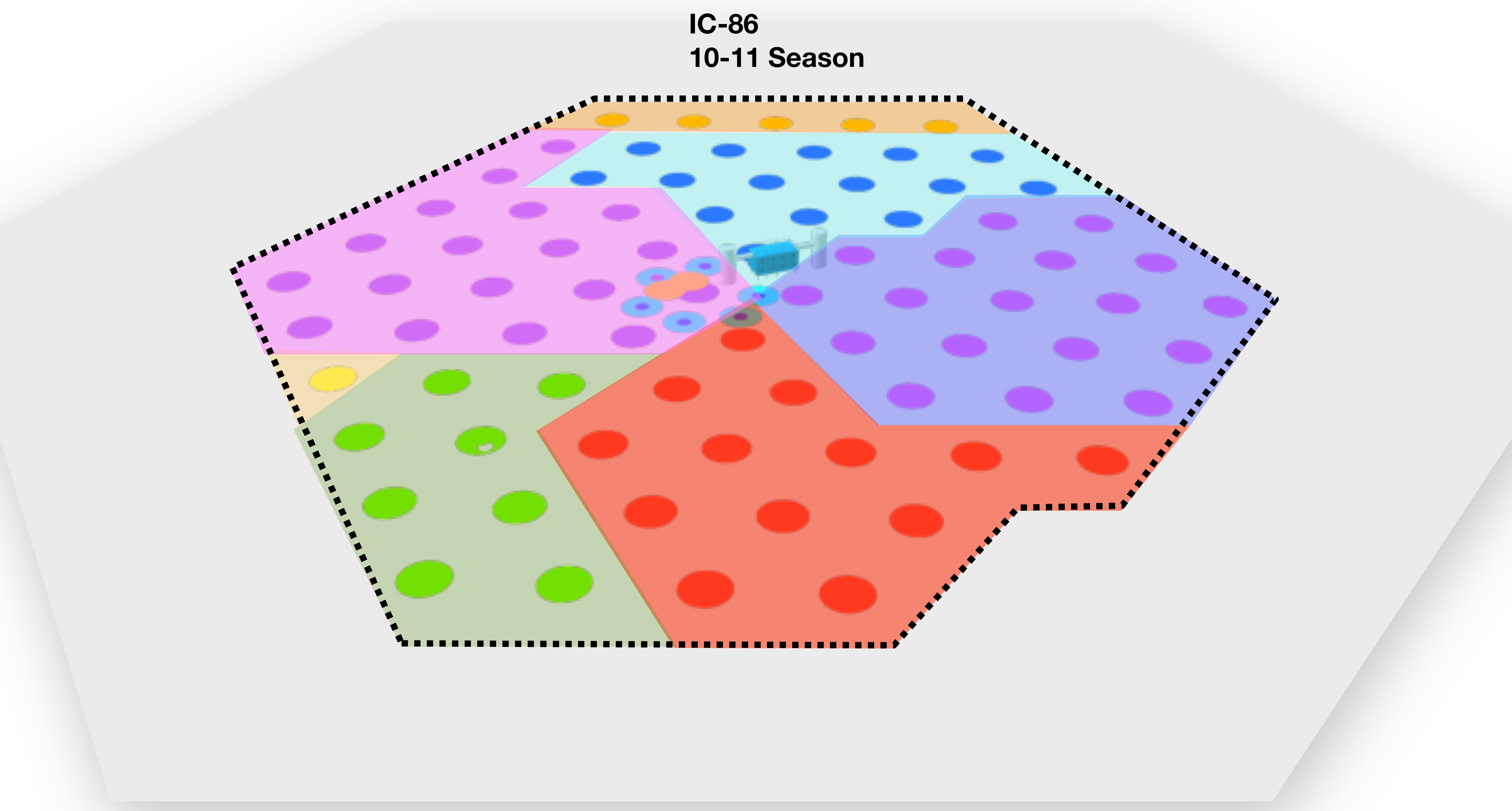
IceCube Configurations



IceCube Configurations

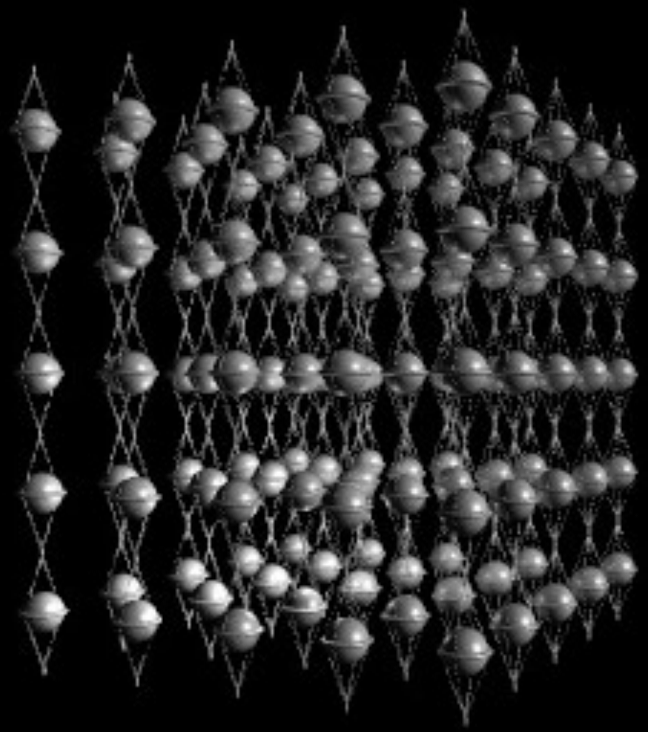


IceCube Configurations



M. Santander

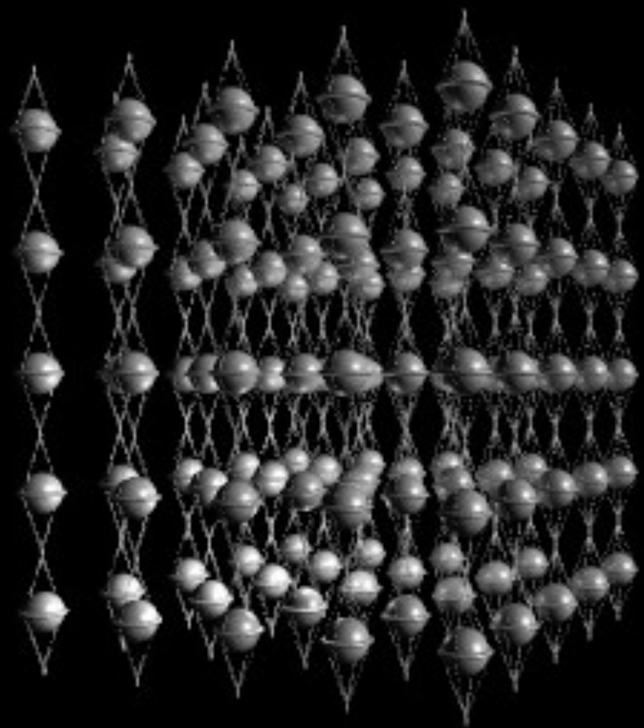
IceCube Concept



Lattice of photomultipliers

Shielded and transparent medium

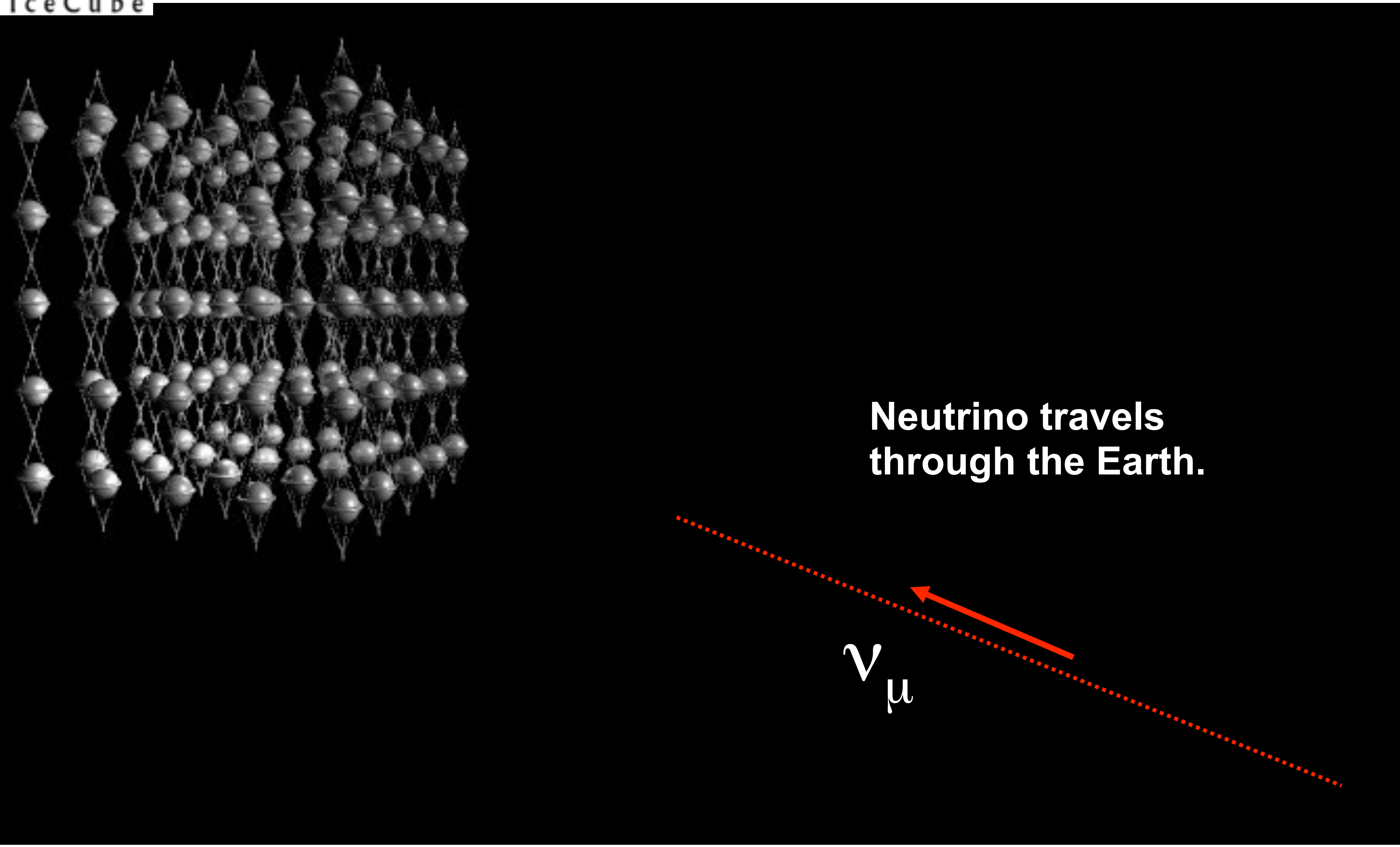
IceCube Concept



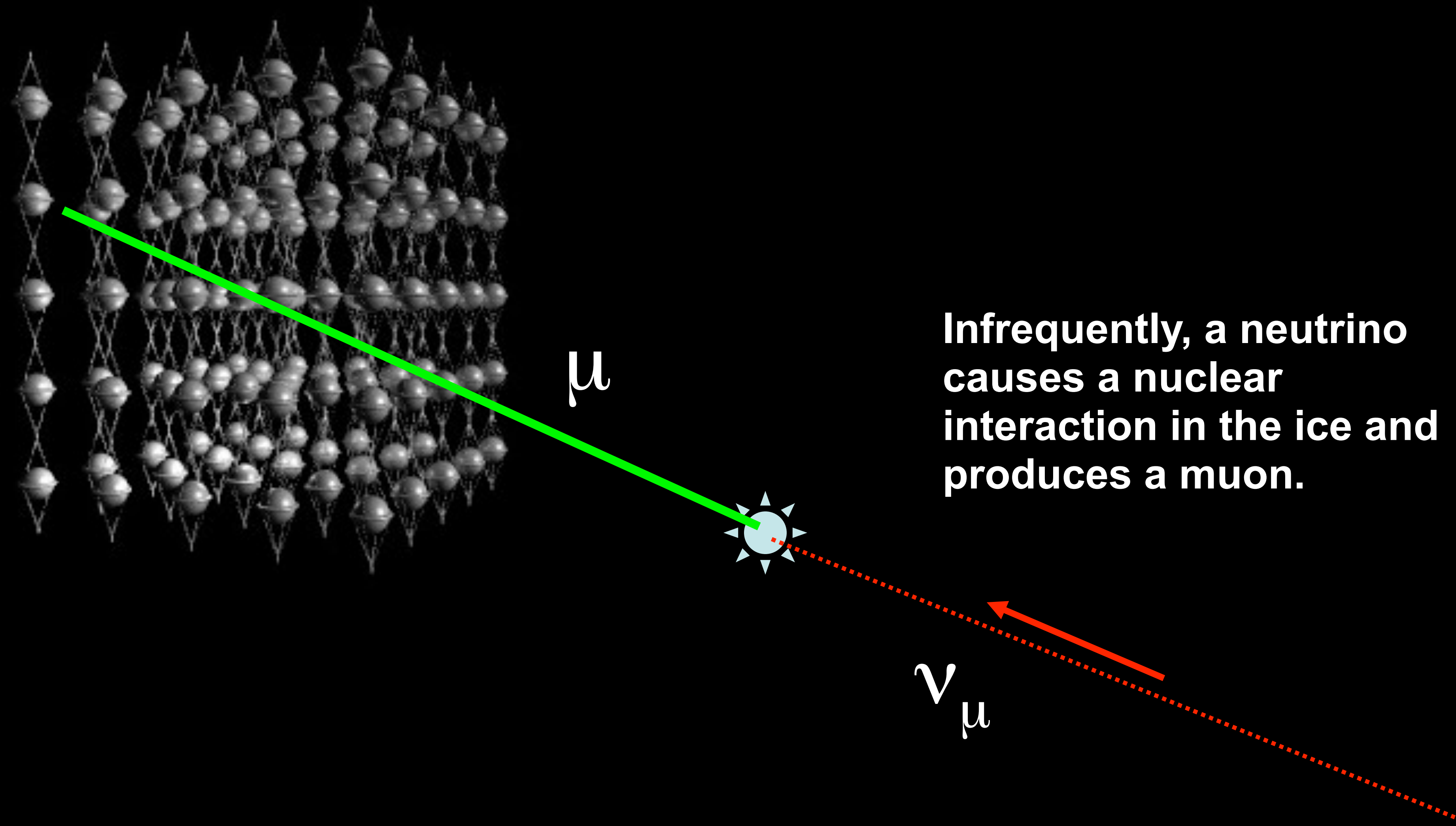
Lattice of photomultipliers

Shielded and transparent medium

IceCube Concept

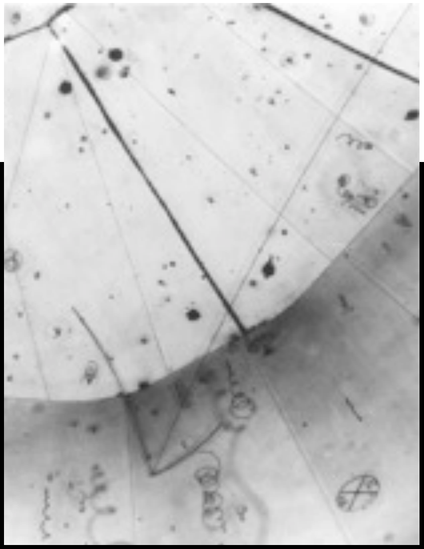


IceCube Concept



Infrequently, a neutrino causes a nuclear interaction in the ice and produces a muon.

IceCube Concept



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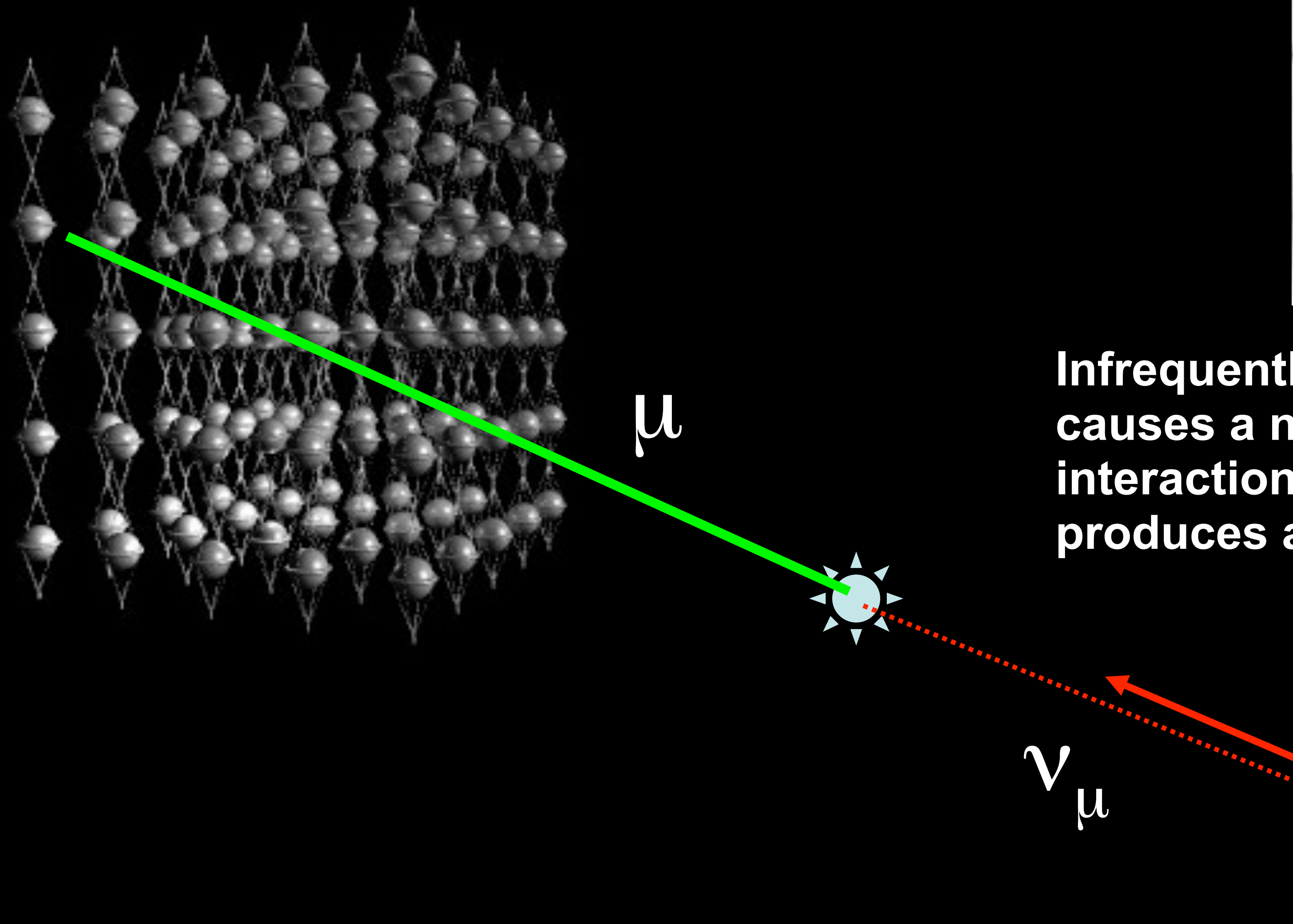
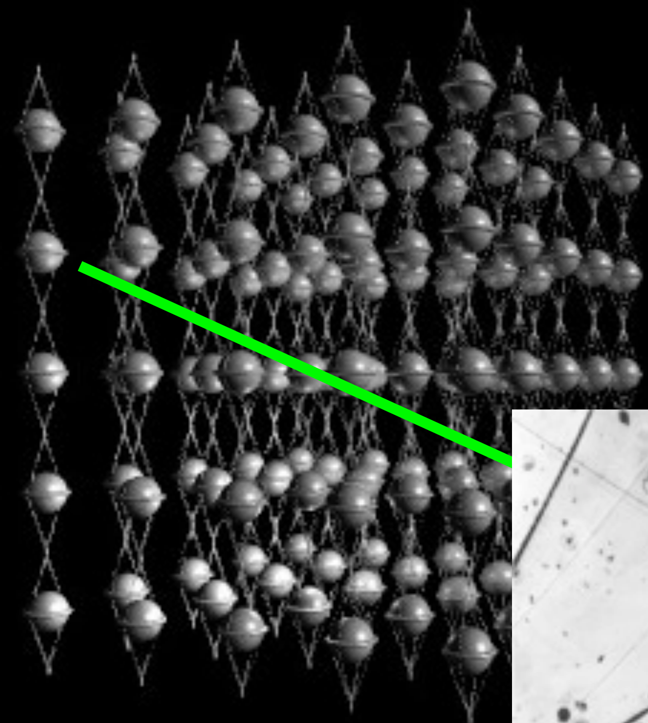
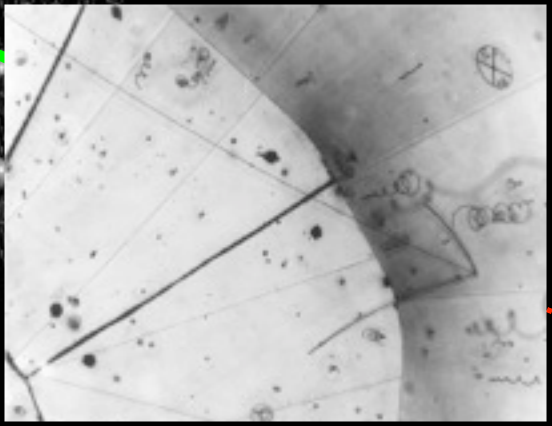
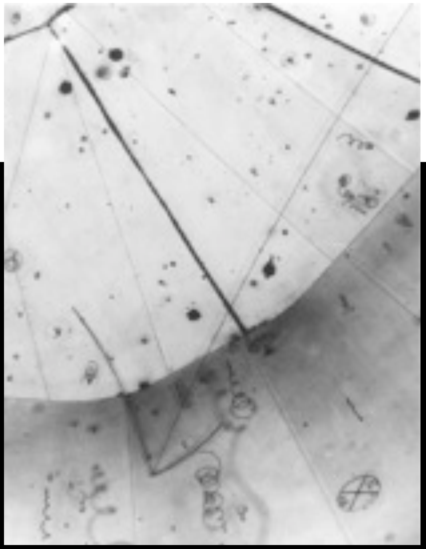


IceCube Concept



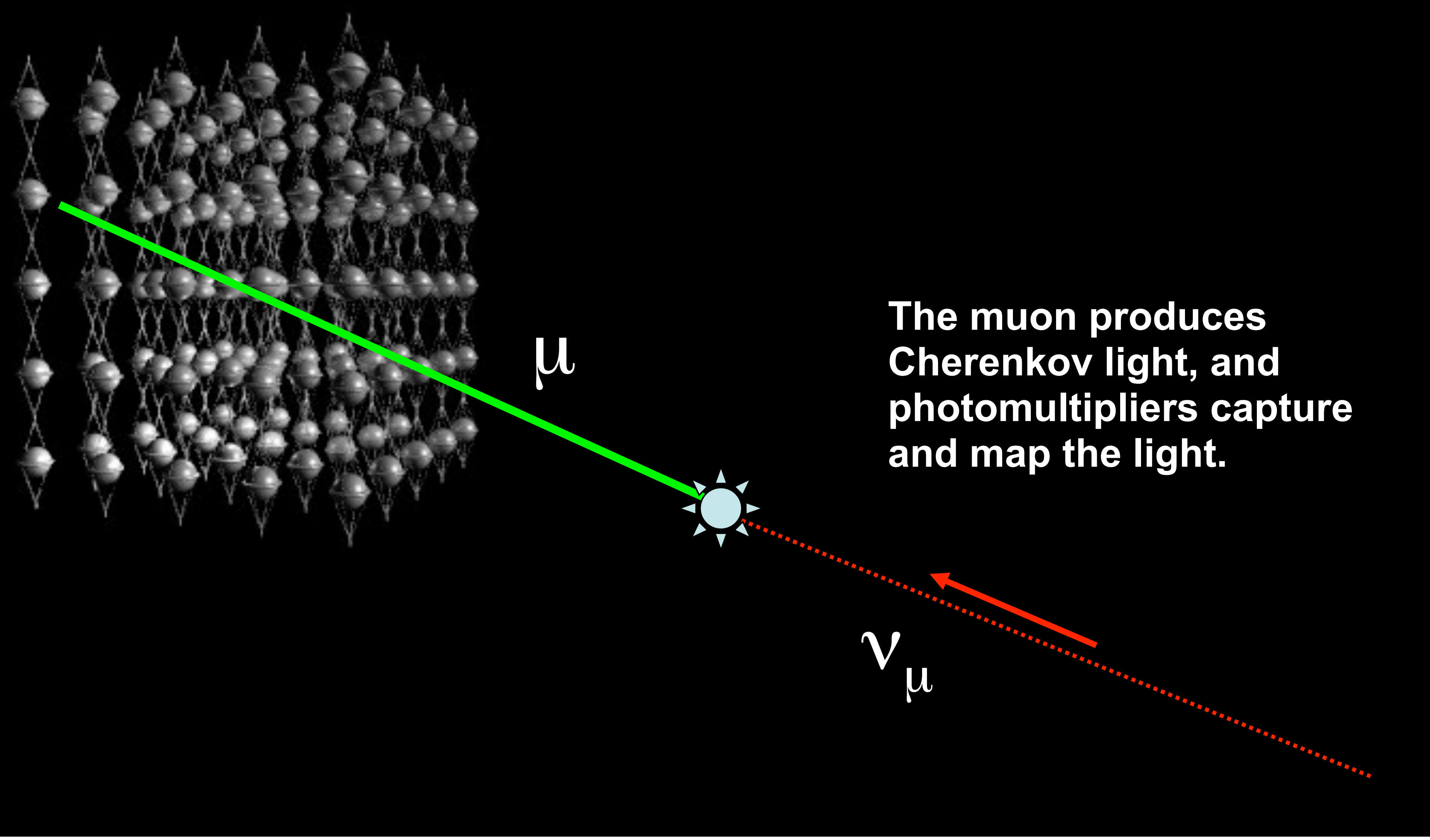




Infrequently, a neutrino causes a nuclear interaction in the ice and produces a muon.

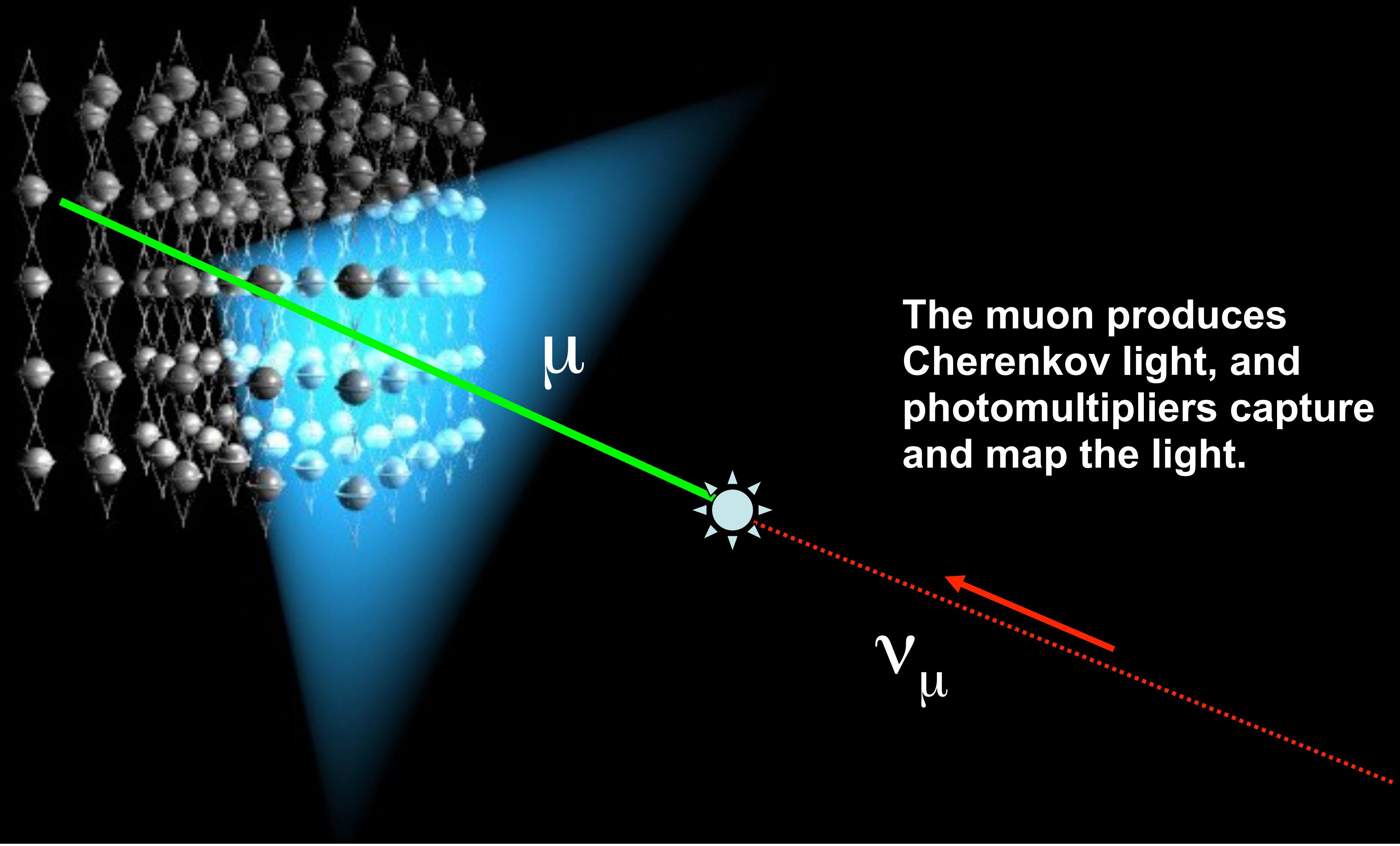
ν_μ

IceCube Concept



The muon produces Cherenkov light, and photomultipliers capture and map the light.

IceCube Concept

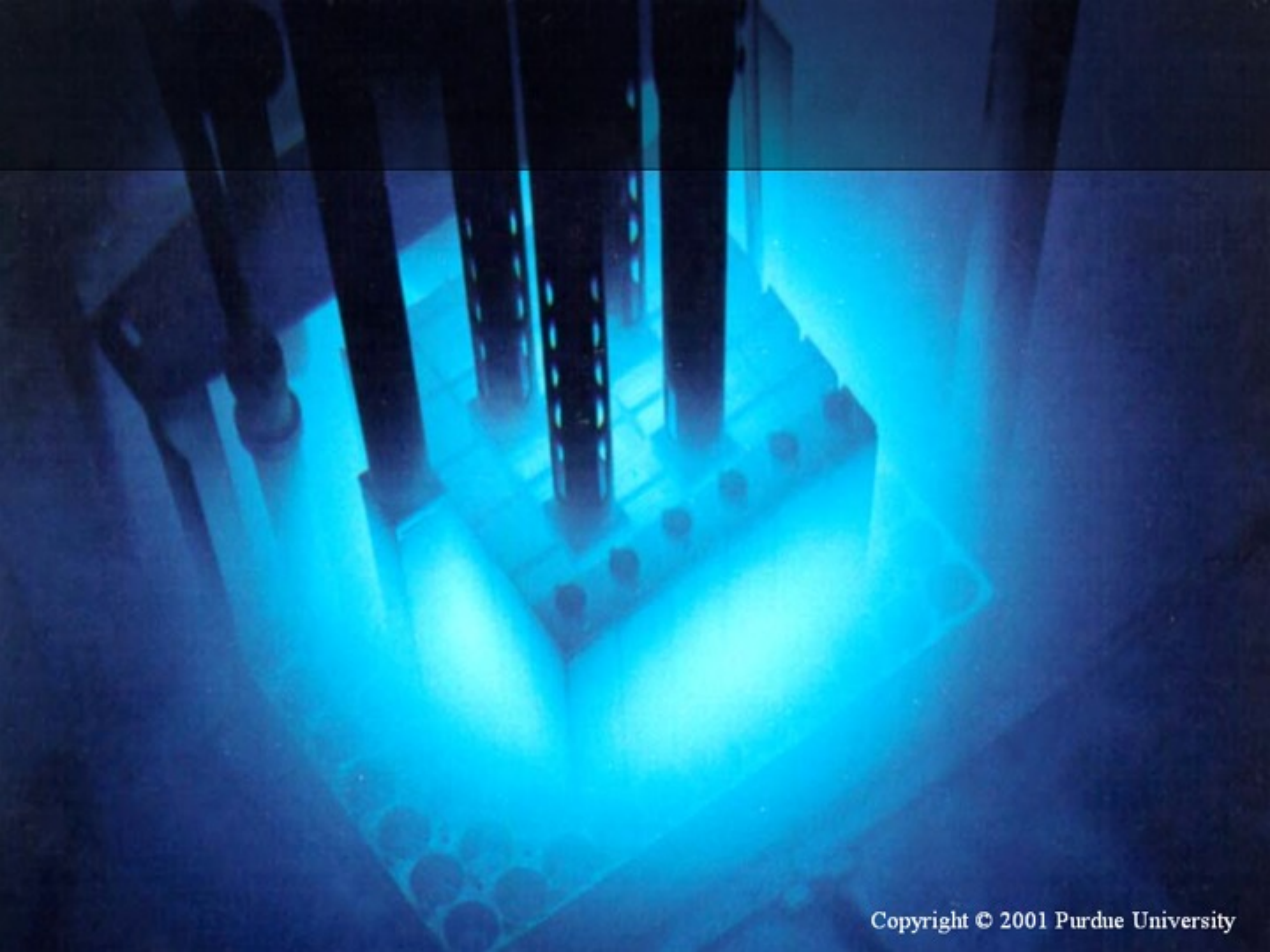


The muon produces Cherenkov light, and photomultipliers capture and map the light.

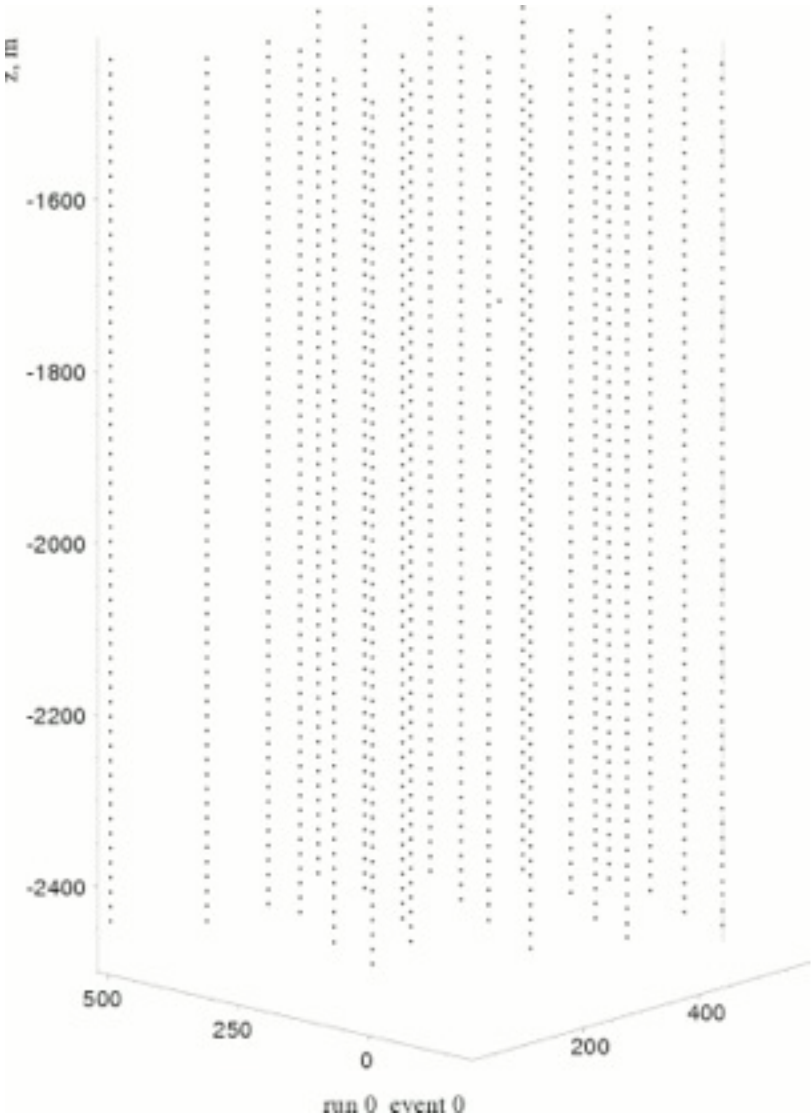
Cherenkov Light

… is produced by charged particles traveling faster than the speed of light.

optical equivalent to supersonic boost

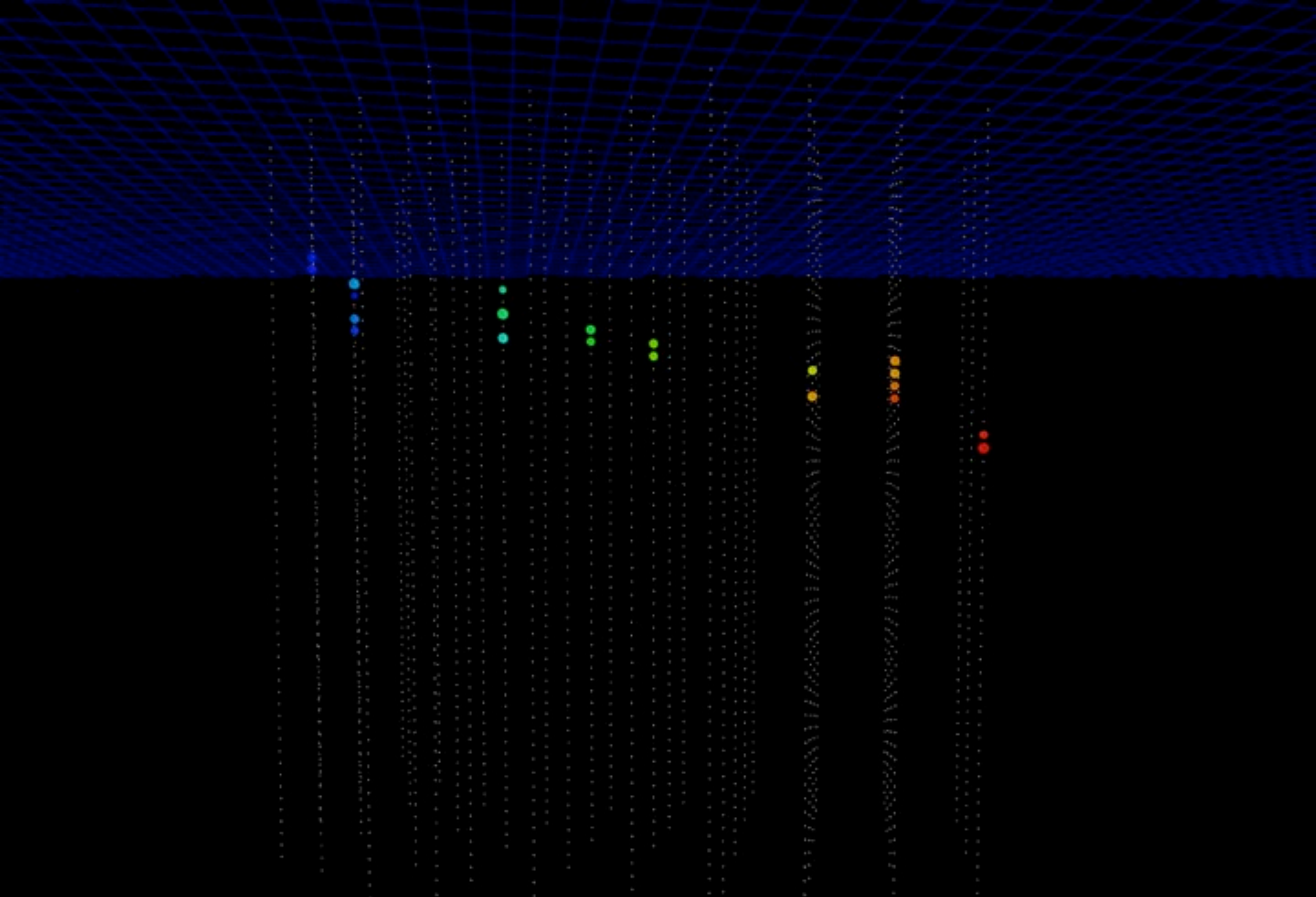


Event Display

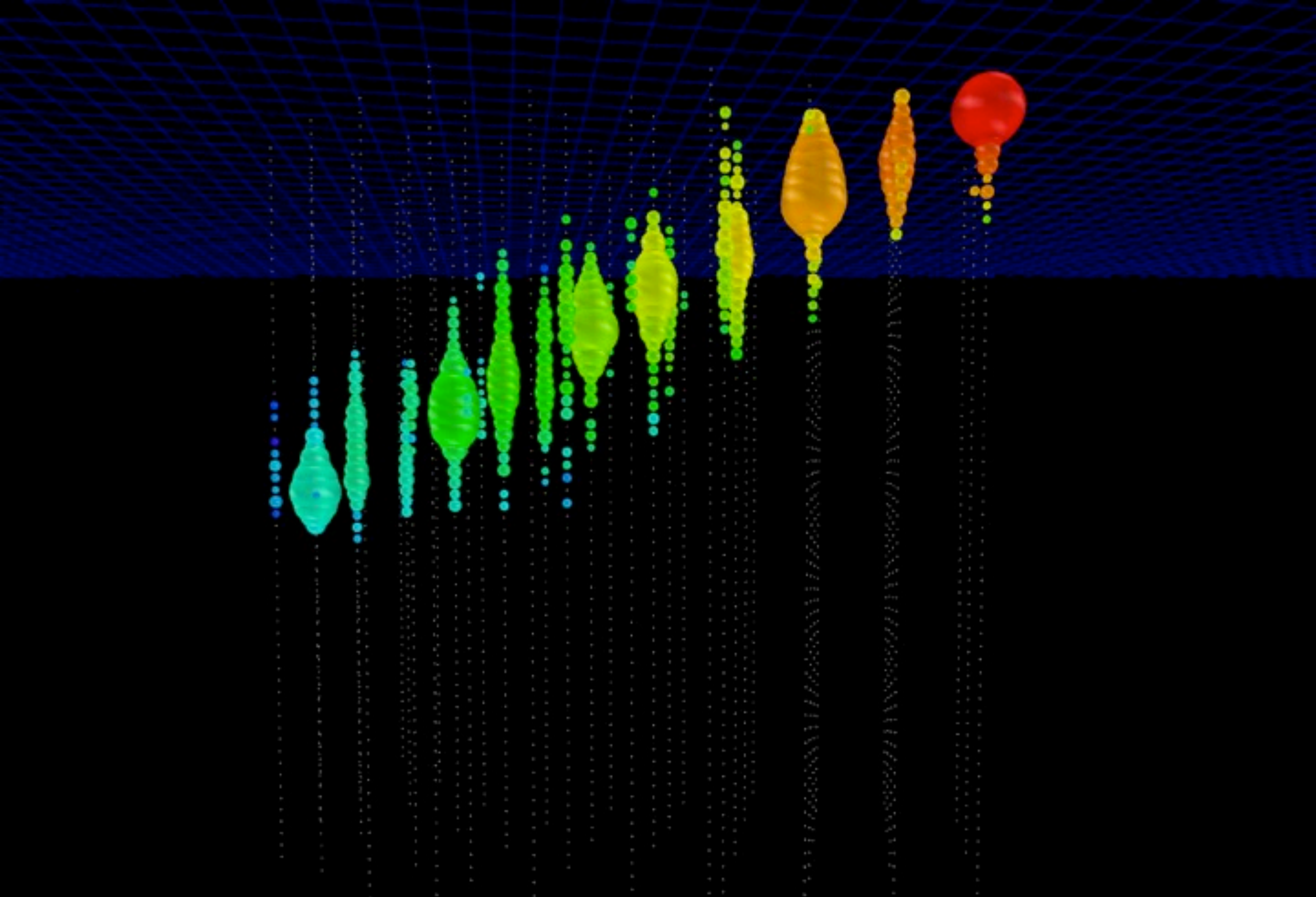


Number of hit modules: 148

est. angular error: 0.84°

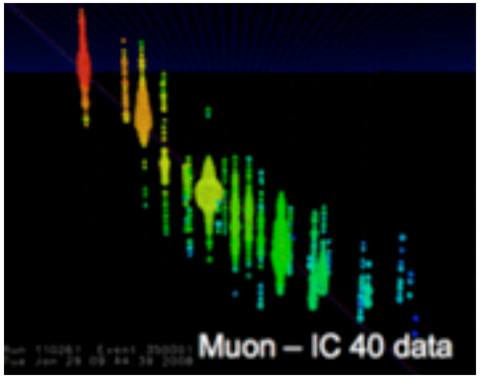


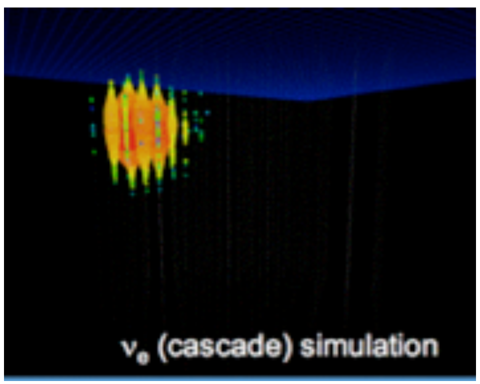
IC40 Data ~ 1 TeV neutrino-induced muon

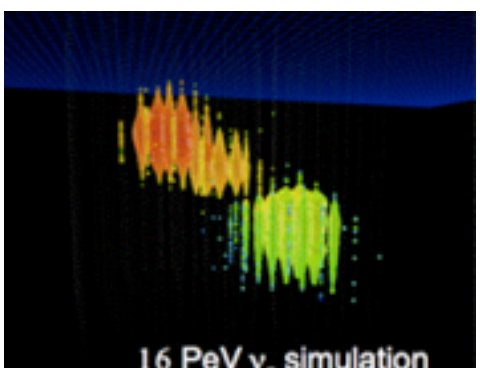


IC40 Data ~ 300 TeV cosmic ray muon bundle

Neutrino Event Signatures



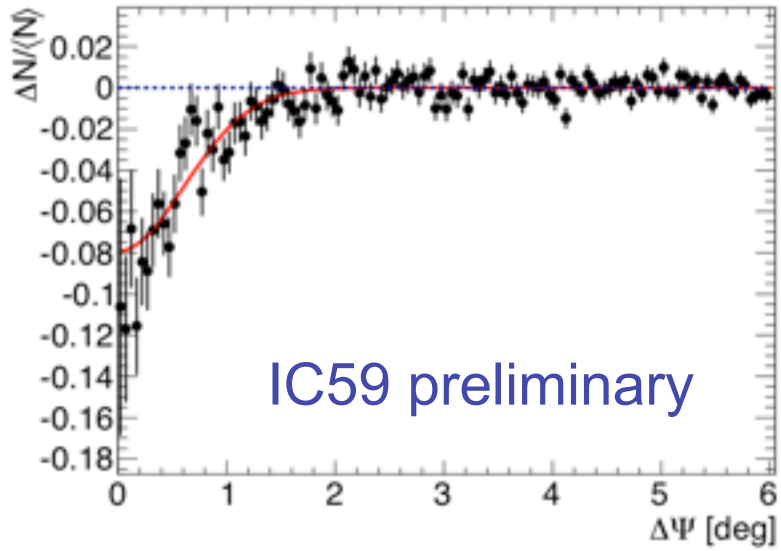


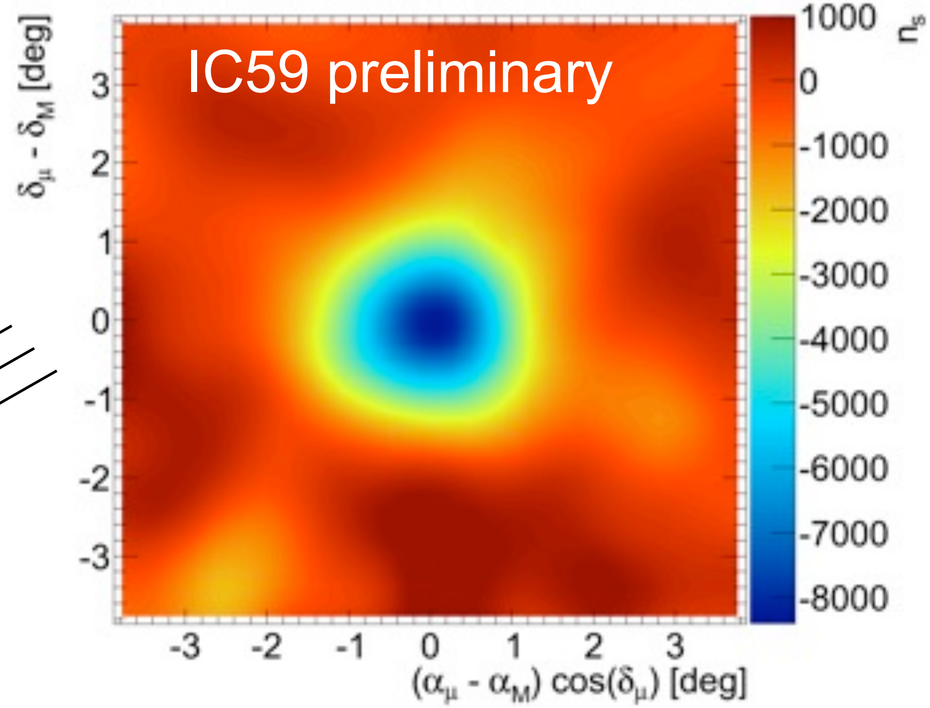


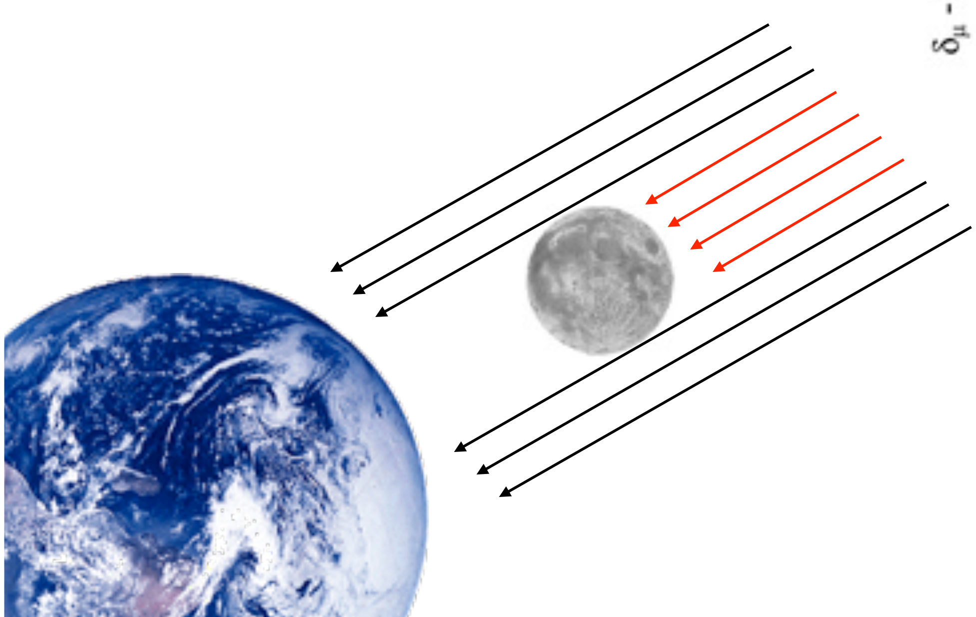
- "Tracks" from muons $\nu_\mu + N \rightarrow \mu + X$
  - Good angular resolution ~1° or less.
  - Currently the most important channel in IceCube (long tracks ⇔ large detector volume).
  - For E > TeV, muon energy loss per meter depends ~linearly on the muon energy; resolution ~0.3…0.4 in log E.
- Cascades from electrons $\nu_e + N \rightarrow e + X$
  - Showers, not track-like.
  - All energy loss inside the detector, good energy resolution ~0.1 in log E.
- "Double bang" events from taus

Moon Shadow

- Cosmic rays blocked by the moon lead to a *deficit* in the distribution of downward going muons in the detector.
- IC59 ~-12σ significance, Gaussian fit 0.61°± 0.05°, systematic pointing error < 0.1°

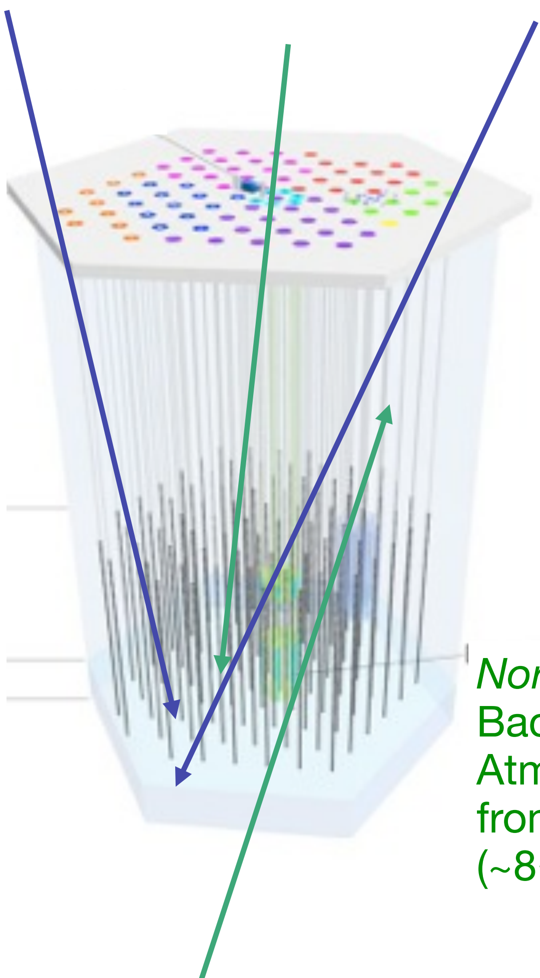






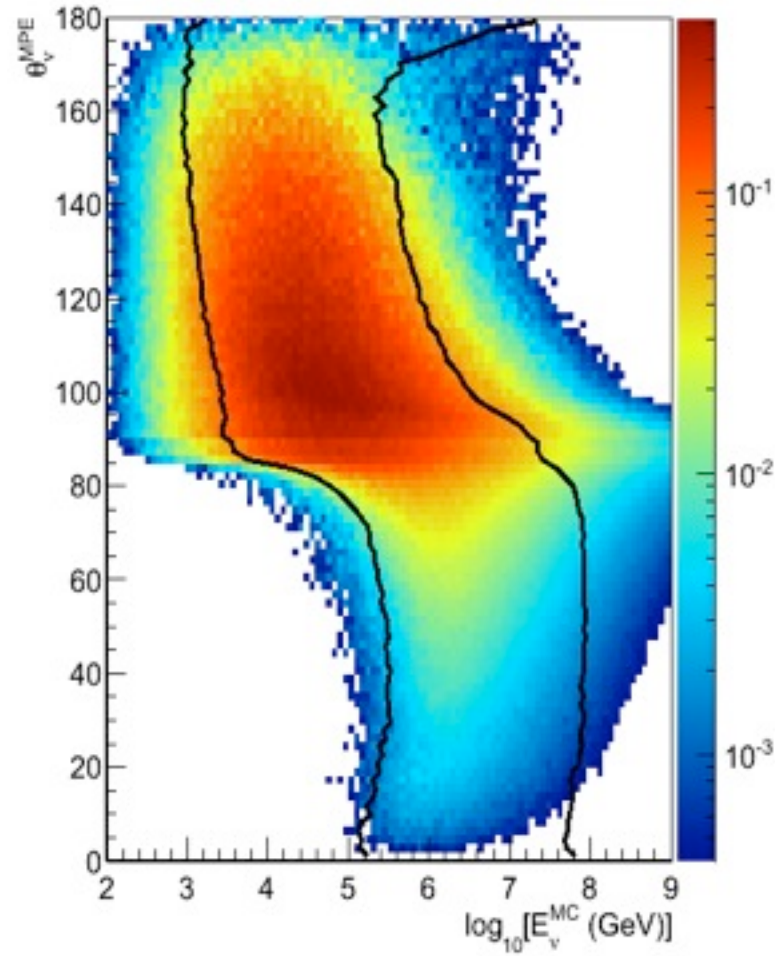
Cosmic Ray Background

- Cosmic ray air showers produce muons and neutrinos reaching the detector



Southern Sky Background: Atmospheric muons from cosmic rays ($\sim 7 \cdot 10^{10}$/year)

Northern Sky Background: Atmospheric neutrinos from cosmic rays ($\sim 8 \cdot 10^{4}$/year)



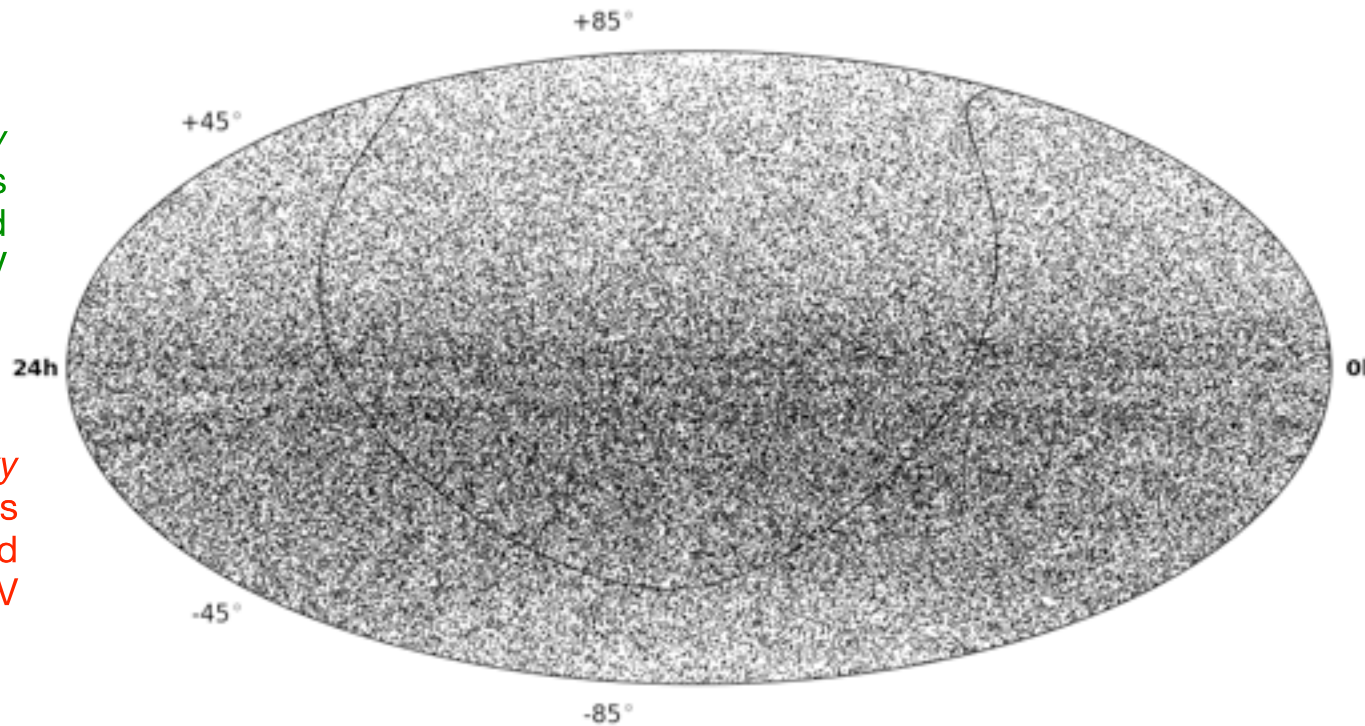
All-Sky Point Source Search

- Point source search in IC40+IC59 data sets
  - *Livetime:* 348 days (IC59) + 375 days (IC40)
  - *Data set size:* 107,00 events (43,339 upgoing + 64,230 downgoing)

IC40+IC59 skymap in equatorial coordinates

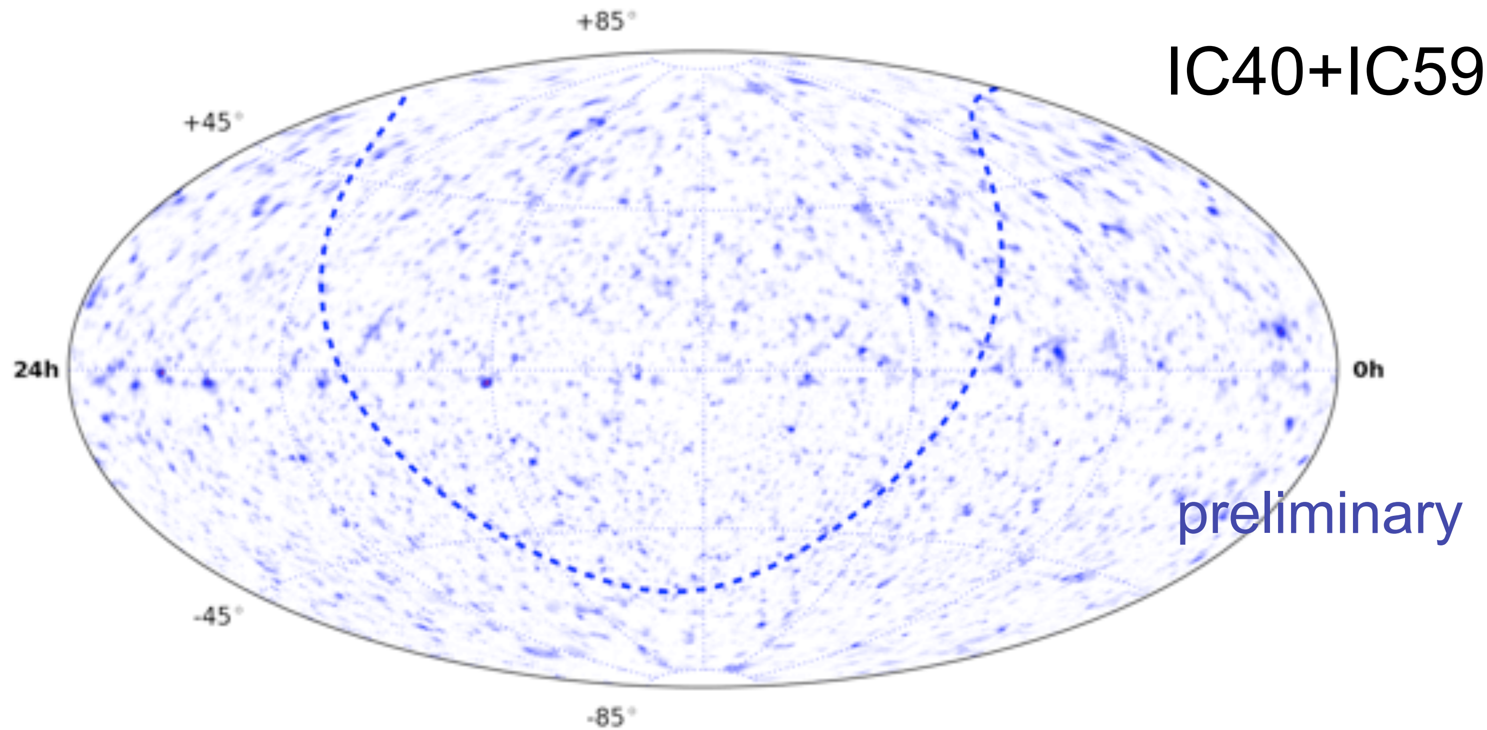
Northern Sky
Atmospheric neutrinos as dominant background
E ~ 10 to several 100 TeV

Southern Sky
Atmospheric muons as dominant background
E > PeV

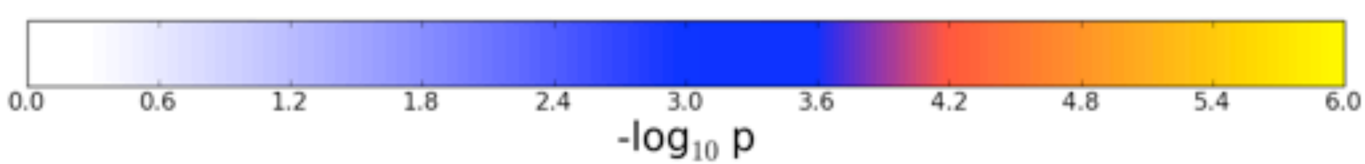


All-Sky Point Source Search

- Likelihood ratio analysis using the point-spread function and energy of events; analysis gives increased weight to high-energy events.



pre-trial probabilities

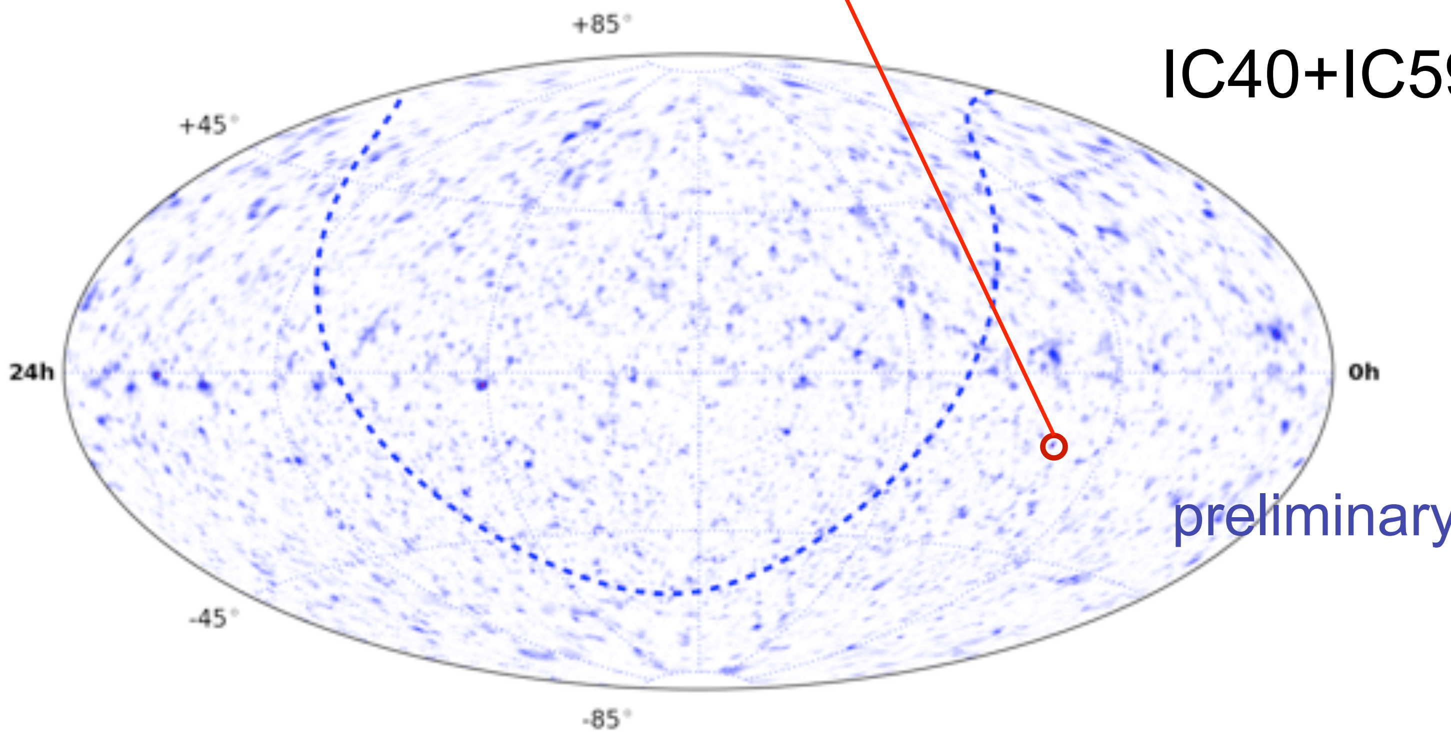


All-Sky Point Source Search

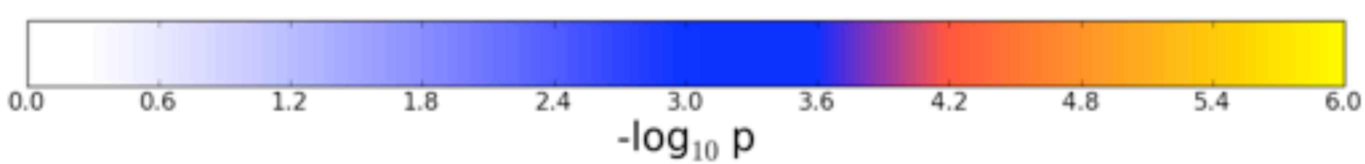
- Most "significant" excess:

(α,δ)= (74.45°,-18.15°)
n_{src}=18.3
- log *p* = 4.65

IC40+IC59



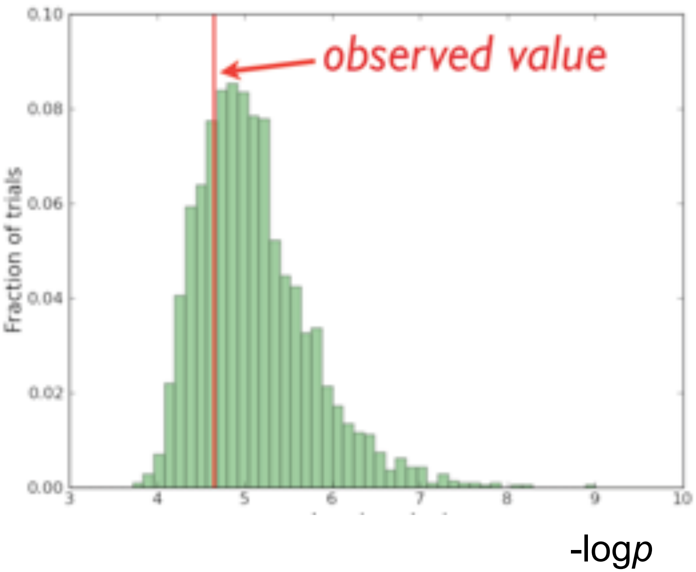
pre-trial probabilities

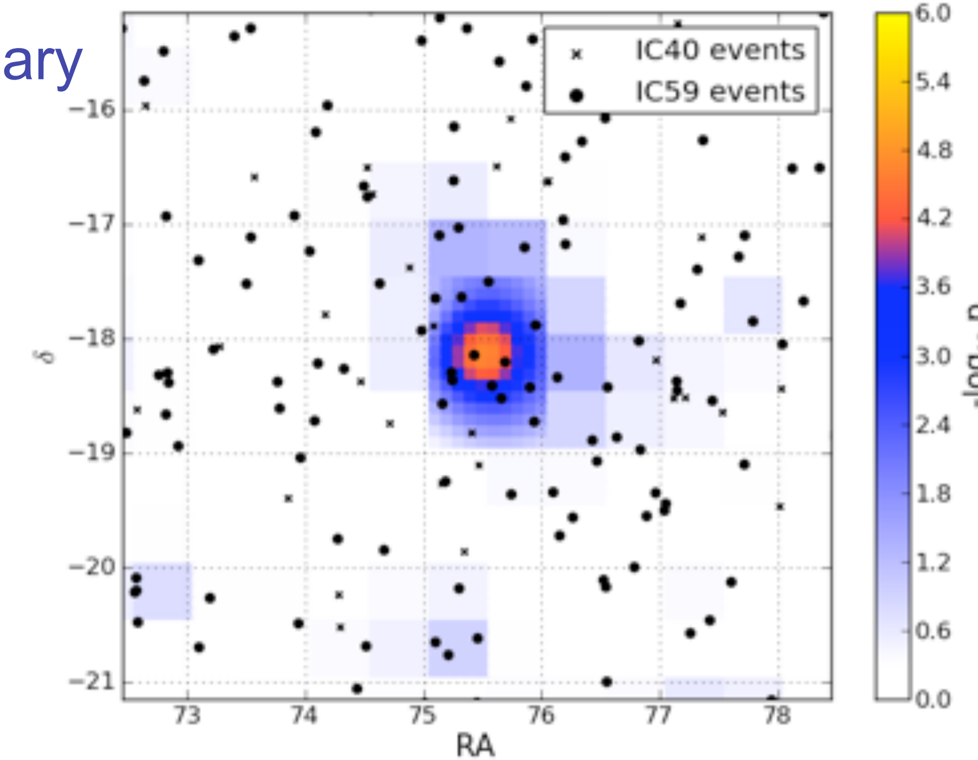


All-Sky Point Source Search

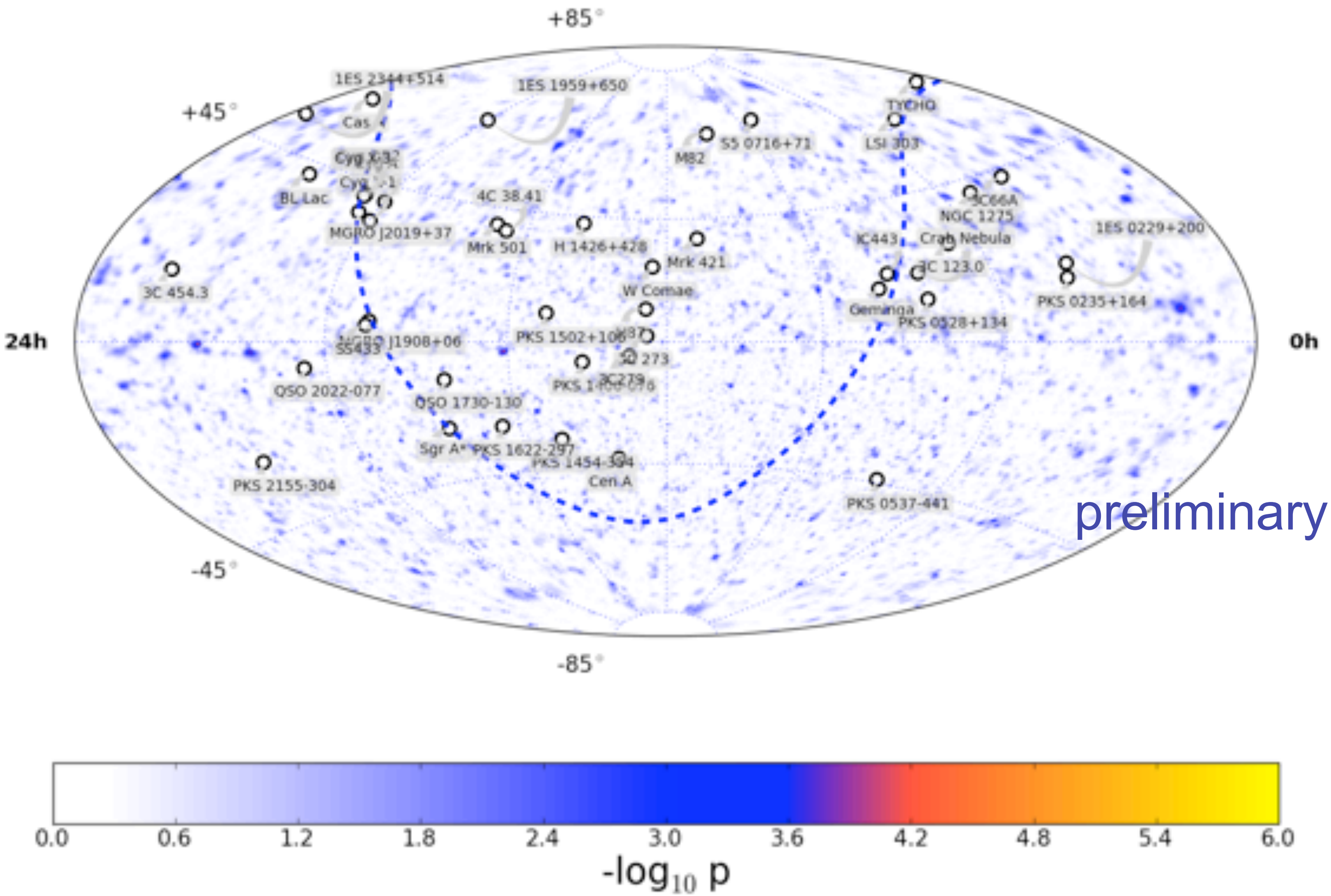
- *Post-trial* significance for the "hot spot" is estimated by applying identical analysis to scrambled data sets.
- A "hot spot" with a *pre-trial* - log p = 4.65 is found in ~74% of searches ⇒ not a significant excess

preliminary



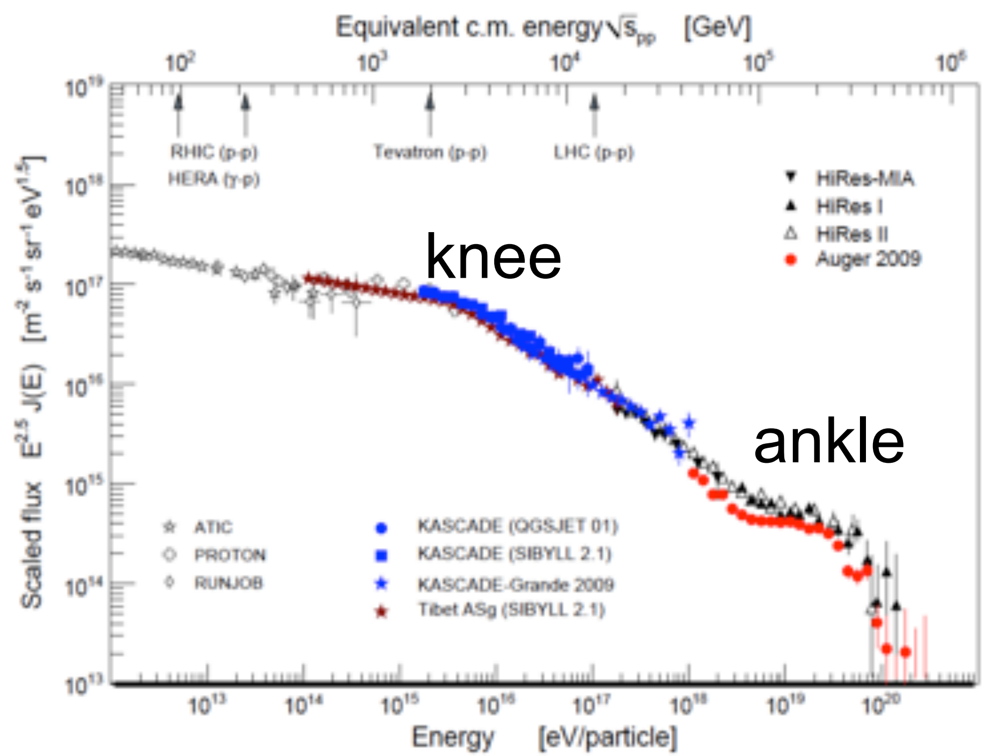


Source Lists



GRB Search

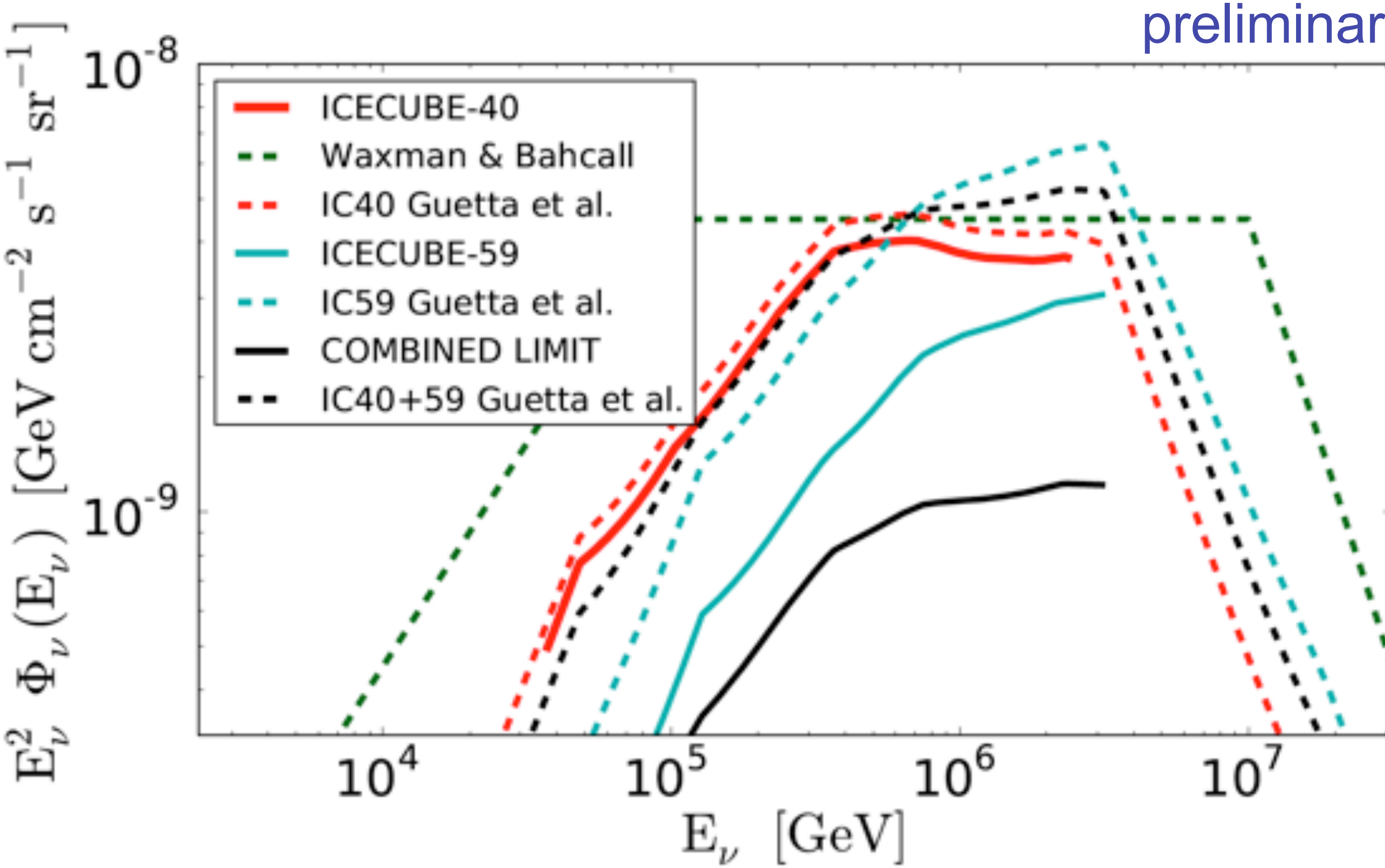
- IceCube has reached the sensitivity to test models of ultra-high energy cosmic ray (UHECR) acceleration in GRBs.
- *Model assumptions:*
  - GRBs are responsible for the flux of extragalactic cosmic rays, starting above the "knee" and dominating at the "ankle."
  - Protons escape via proton-γ interactions.
- Is expected prompt neutrino emission consistent with IceCube?



GRB Search

- Null result disfavors GRB/UHECR scenarios with their standard parameters with high significance (~12σ for IC59+IC40).

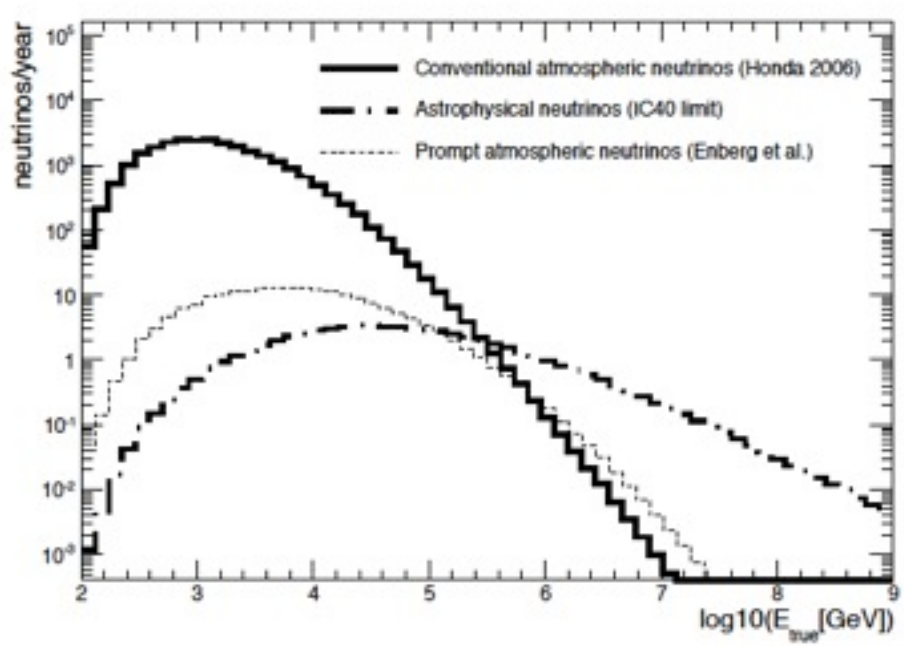
preliminary



Atmospheric Neutrinos

- Astrophysical sources of neutrinos are expected to have a harder spectrum than atmospheric neutrinos.
- “Conventional” atmospheric neutrino spectrum:

$$K^{\pm} \to \mu^{\pm} + \nu_{\mu}($$



- Critical energy for charm is 10^7 GeV, so “prompt” neutrinos from charm decay have a (harder) spectrum that reflects the primary spectrum.

  ⇒ charm contribution is expected to become dominant at higher energies

  ⇒ important and uncertain background for diffuse flux from astrophysical sources.

Atmospheric Neutrinos

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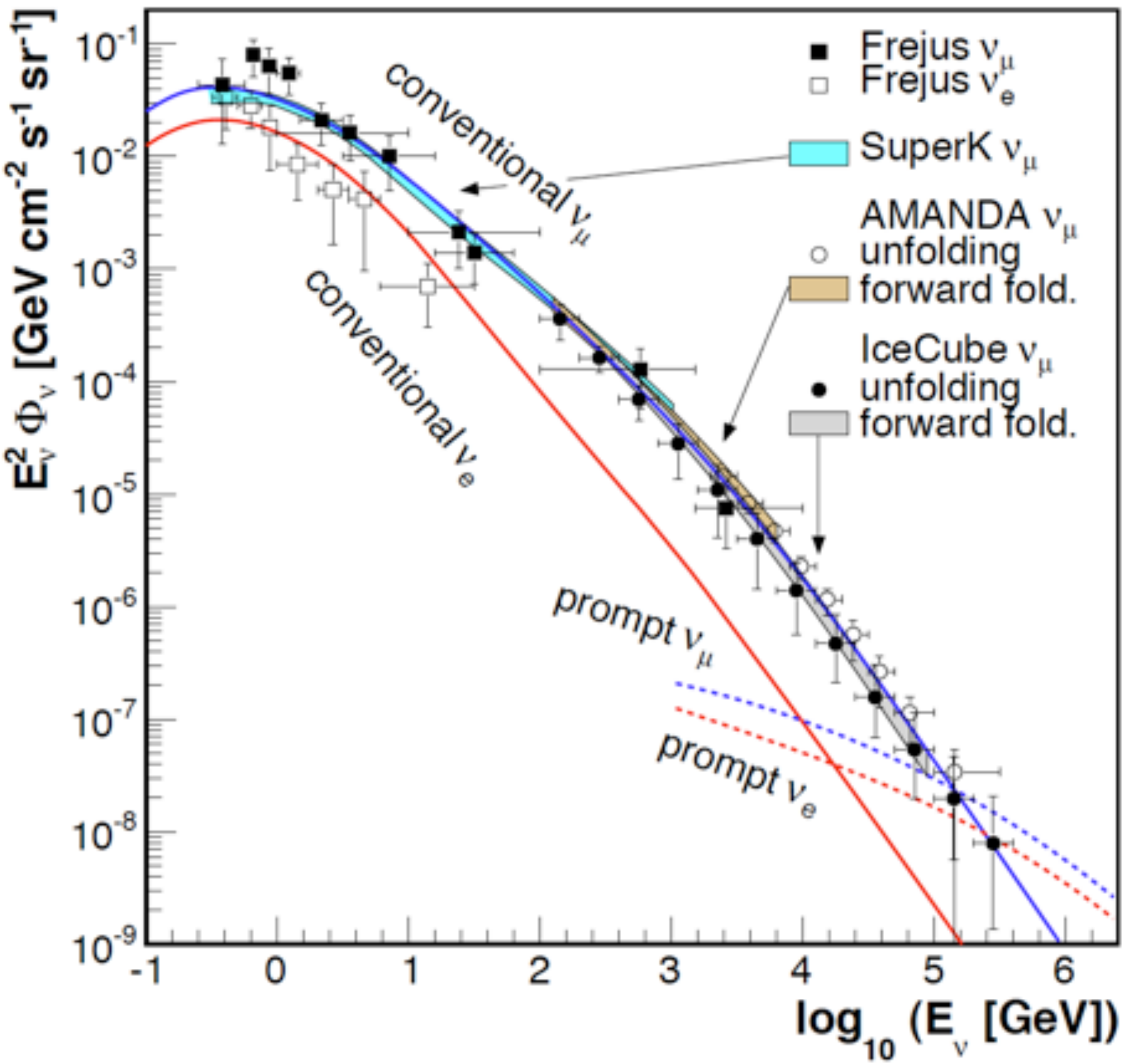
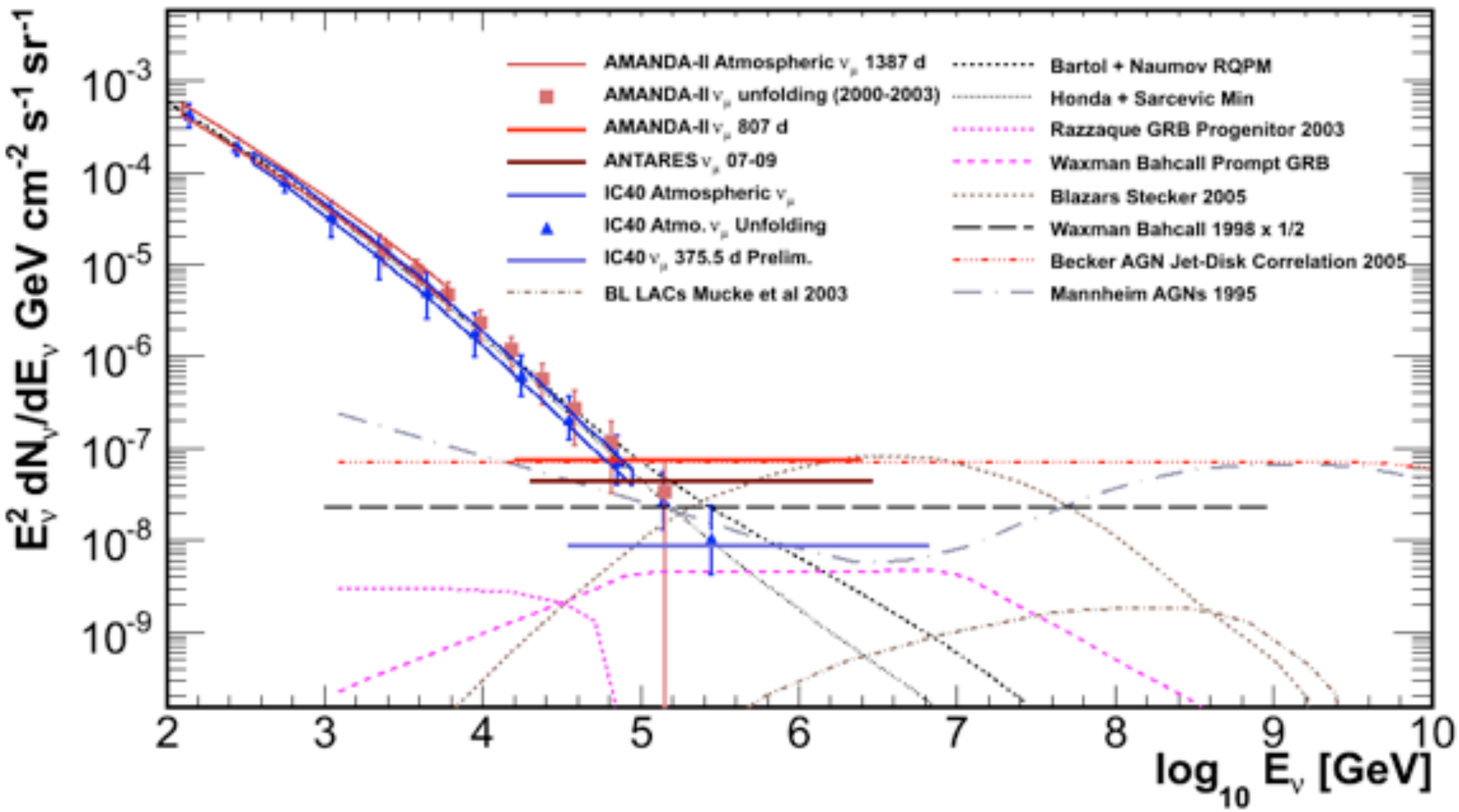


Diffuse Flux

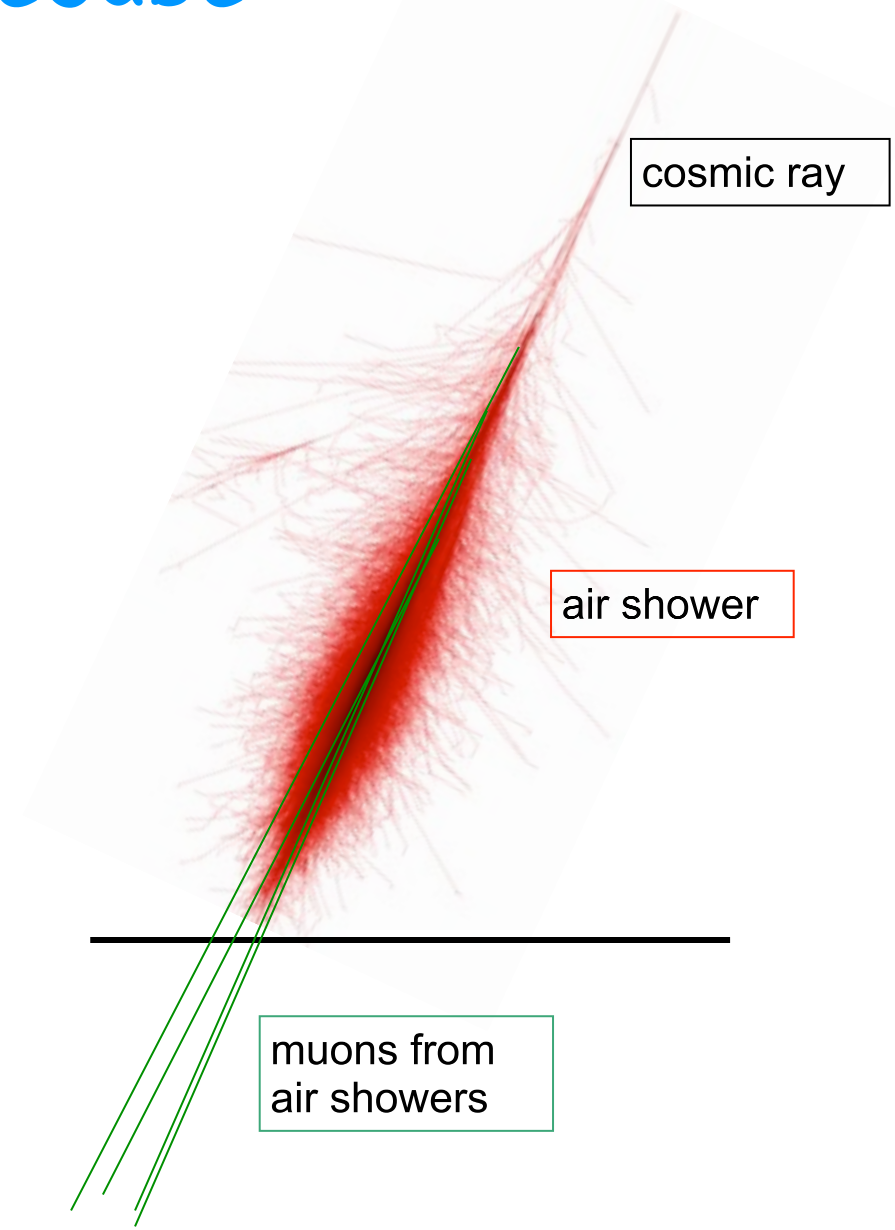
- If *individual* sources are too weak to be detected, the sum of neutrinos from all (unresolved) extragalactic sources (AGN,…) might nevertheless produce a detectable *diffuse* flux.



Cosmic Rays in IceCube

- By measuring downward going muons from air showers, IceCube can study the arrival direction distribution of cosmic rays in the energy range ~10 TeV to several 100 TeV and produce a cosmic ray sky map *of the southern sky.*

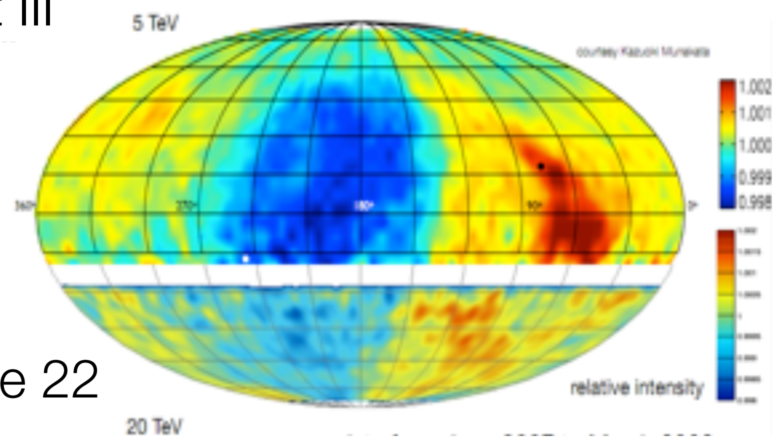
- Muons produced in downward going cosmic ray air showers are detected by IceCube at a rate of > 1000 Hz.



Cosmic Ray Anisotropies

- Anisotropies in the arrival direction distribution of >TeV cosmic rays have been observed on large scales (dipoles) and smaller scales (~10°-20°) in the northern and southern sky.
- Origin of anisotropies is unknown.

Tibet III



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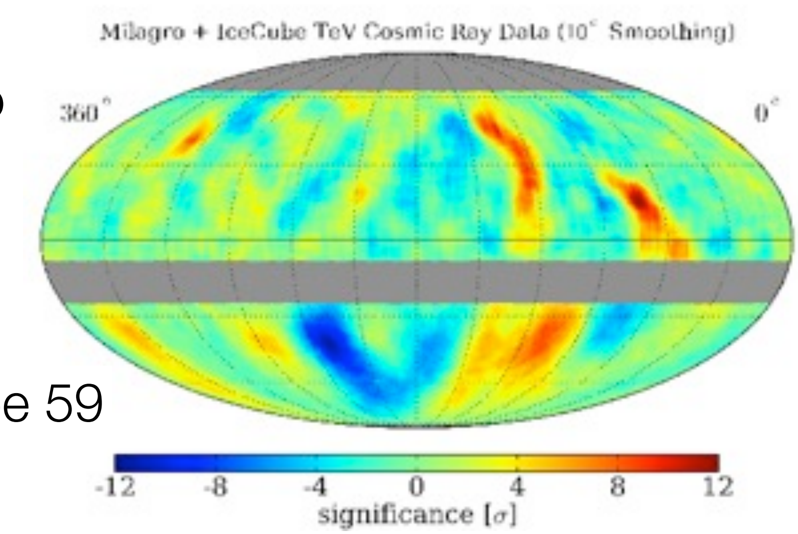
Milagro



IceCube 59

IceCube Physics

Diffuse flux from extragalactic sources. Neutrino point sources. Origin of galactic and extragalactic comic rays. Atmospheric neutrino flux. Gamma Ray Bursts and time-dependent phenomena. Supernova burst monitoring. GZK neutrinos. Atmospheric physics. Indirect WIMP searches. Relativistic monopoles and other exotic phenomena. Lorentz invariance violation. Search for non-standard model neutrino interactions. Cosmic rays with IceTop. Multimessenger approaches.

The unknown…

"If we knew what the discoveries were likely to be, it would make no sense to build such a telescope."

George Ellery Hale