Title: Particle/Astro Observations

Speakers:

Collection: TRISEP 2023

Date: June 30, 2023 - 11:00 AM

URL: https://pirsa.org/23060087

Particle Astrophysics
High Energy Neutrinos

TRISEP - June 2023

Many thanks to the broad particle astrophysics community for sharing materials online!

Content from: Jordan Goodman - U.Maryland; Francis Halzen - UW-Madison; Jörg R. Hörandel - RU Nijmegen, Nikhef, VU Brussel; Athina Meli - Univ. Athens; Elisa Resconi - TUM; Christian Stegmann - DESY; Yajie Yuan -Flatiron Institute

Jordan Goodman - Gamma ray astronomy with extensive air showers (https://agenda.astro.ru.nl/event/12/contributions/192/)
Jordan Goodman - Recent results from HAWC (https://agenda.astro.ru.nl/event/12/contributions/190/)
Jordan Goodman - Recent results from LHAASO and future arrays (https://agenda.astro.ru.nl/event/12/contributions/189/)
Francis Halzen - https://user-web.icecube.wisc.edu/~halzen/presentations/Olomouc22_Halzen.pptx
Jörg R. Hörandel - Historical introduction and basic properties of cosmic rays (https://agenda.astro.ru.nl/event/12/contributions/197/)
Athina Meli - http://wwwiexp.desy.de/groups/astroparticle/de/lehre/guest_seminar/meli.pdf
Elisa Resconi - https://campus.tum.de/tumonline/wblvangebot.wbshowlvoffer?ppersonnr=275352
Christian Stegmann - Ground-based gamma-ray astronomy with imaging air Cherenkov telescopes (3 lectures - https://agenda.astro.ru.nl/event/12/contributions/236/; https://agenda.astro.ru.nl/event/12/contributions/202/; https://agenda.astro.ru.nl/event/12/contributions/210/)
Yajie Yuan - https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjAxO-a7-P_AhWVFlkFHTvhDoAQFnoECBAQAQ&url=https://confluence.slac.stanford.edu/download/attachments/223229391/ParticleAcceleration1.pdf?version=1&modificationDate=1496672393000&api=v2&usg=AOvVaw0BcCvH_wJNVD0UZyDbPVHP&opi=89978449

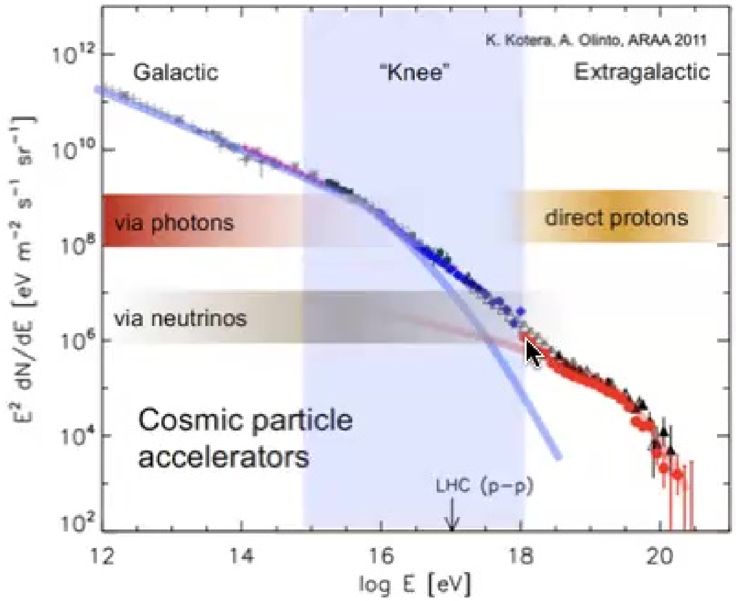
Christian Stegmann, Erice 2022

Cosmic particle production

Protons
- Directly produced in the sources

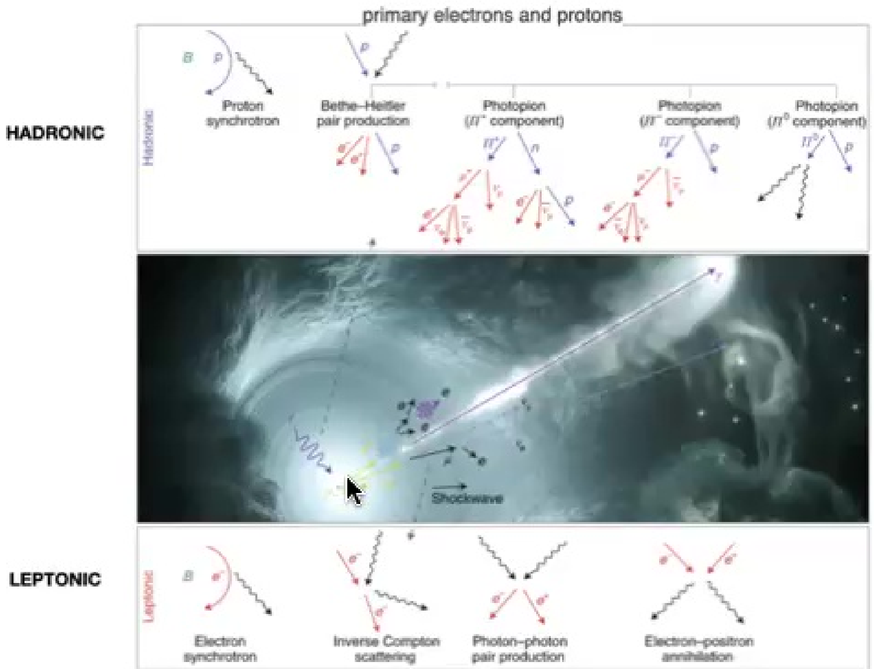
Photons
- From protons via pion decay
- From electrons via inverse Compton scattering

Neutrinos
- From protons via pion decay



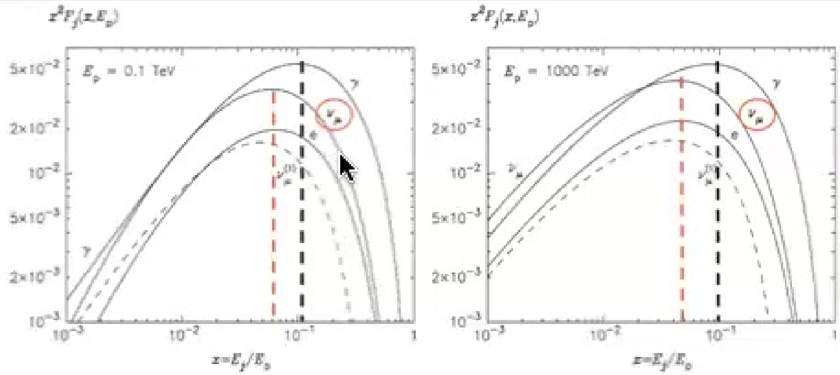
Ellisa Resconi TUM

Cosmic ray “standard” scenario (hadronic and leptonic processes)



Cosmic ray ‘standard’ scenario: the secondary products from hadronic mechanisms

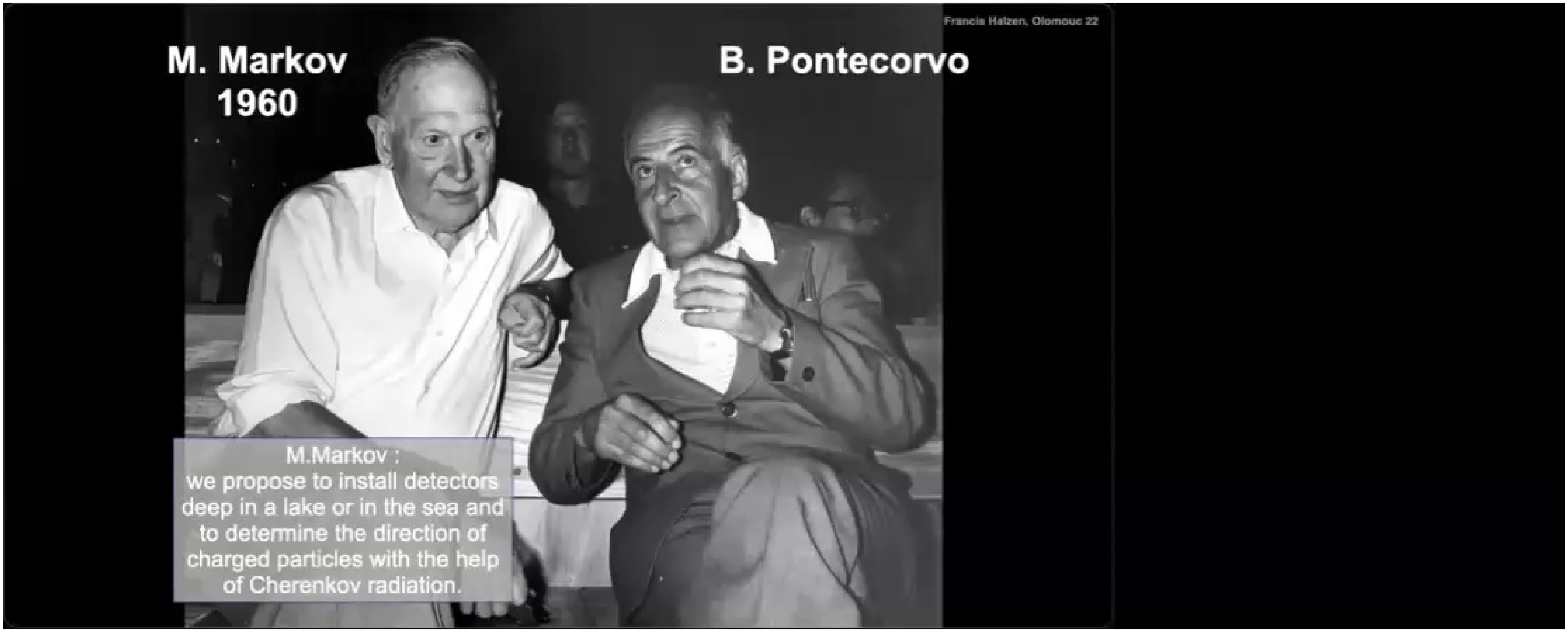
- Reference:
- pp Interaction (S.R. Kelner, F. A. Aharonian,V.V. Bugayov, Phys.Rev.D74:034018,2006)
- pγ Interaction (S.R. Kelner, F.A. Aharonian, Phys.Rev.D78:034013,2008)
- A. Reimer et al., SOPHIA MonteCarlo, http://ebl.stanford.edu/

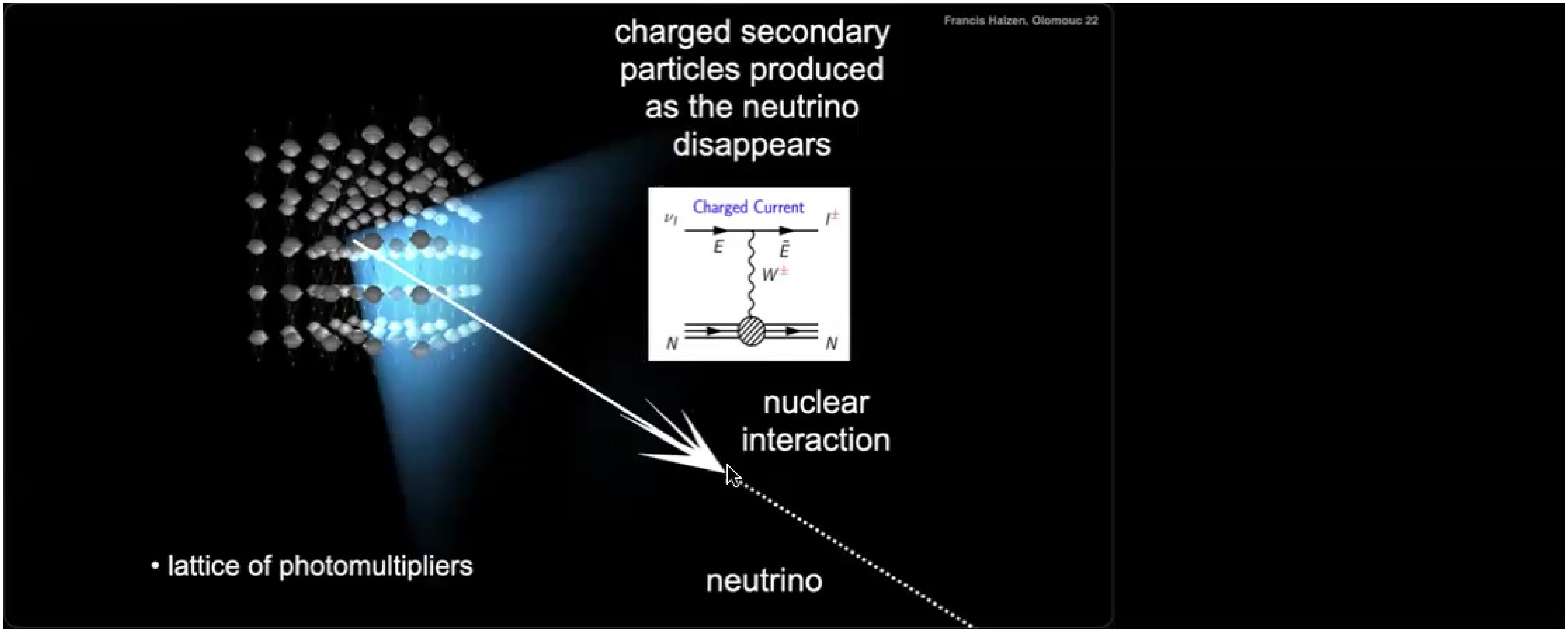


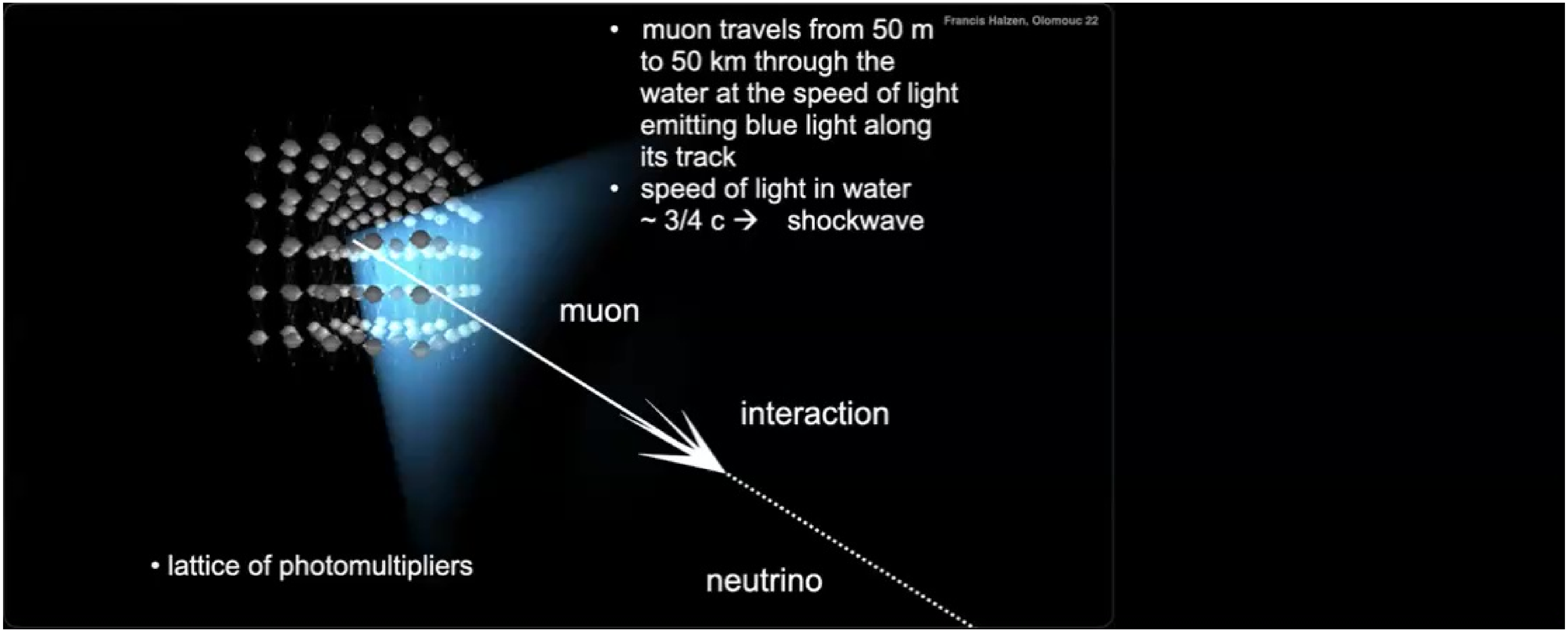
$E_p:E_\gamma:E_\nu$ = 1: 0.1: 0.05

Interaction of accelerated CR naturally leads to production of neutrinos and gamma rays.

$E_\nu \approx 0.05 \cdot E_{nucleon} = 0.05 \cdot \frac{E_{CR}}{A}$


Francis Halzen, Olomouc 22
M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

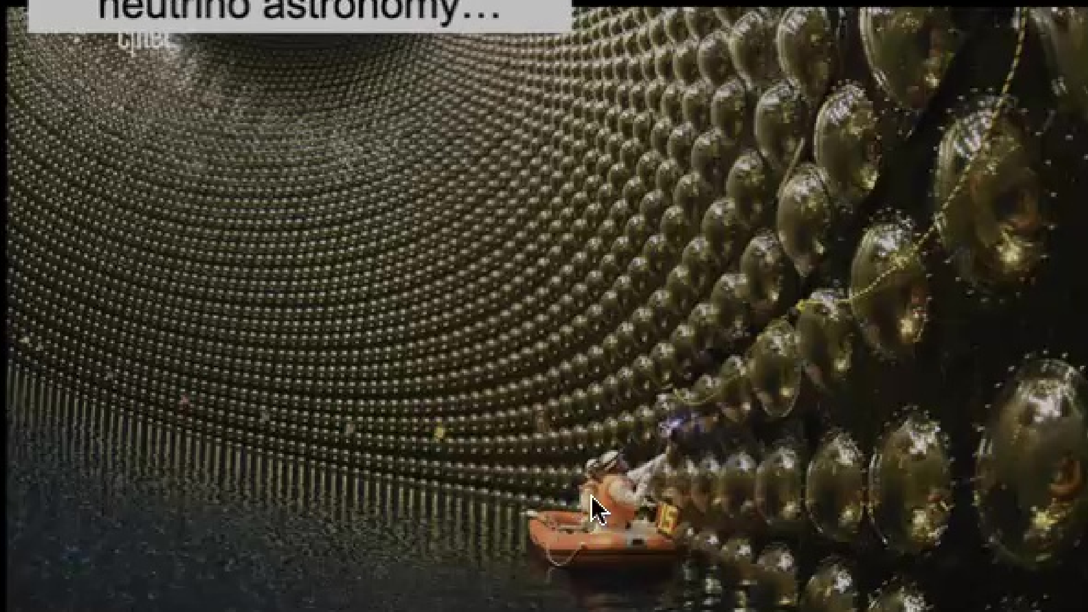

Francis Halzen, Olomouc 22
charged secondary particles produced as the neutrino disappears
Charged Current
ν_l
$l^{\pm}$
E
$\bar{E}$
$W^{\pm}$
N
N
nuclear interaction
• lattice of photomultipliers
neutrino



Francis Halzen, Olomouc 22
• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
• speed of light in water ~ 3/4 c → shockwave
muon
interaction
neutrino
• lattice of photomultipliers

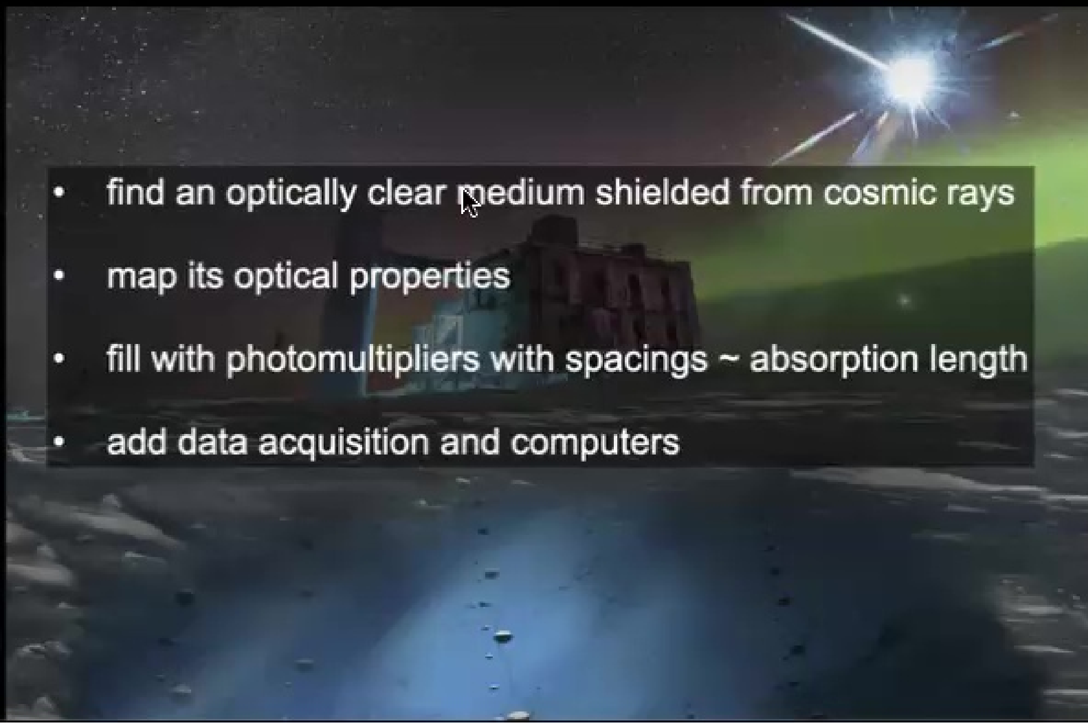
Francis Halzen, Olomouc 22

10,000 times too small to do neutrino astronomy…



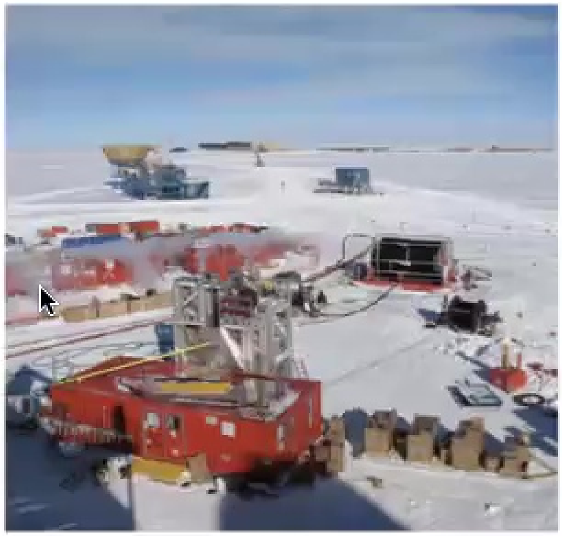
Francis Halzen, Olomouc 22

ice 1.4 kilometers below geographic South Pole



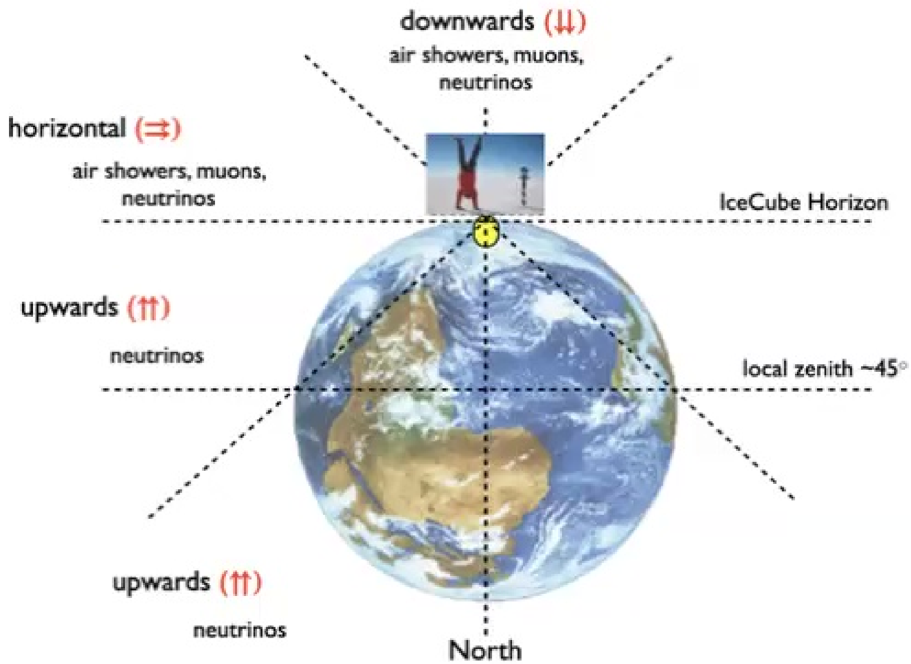
- find an optically clear medium shielded from cosmic rays
- map its optical properties
- fill with photomultipliers with spacings ~ absorption length
- add data acquisition and computers

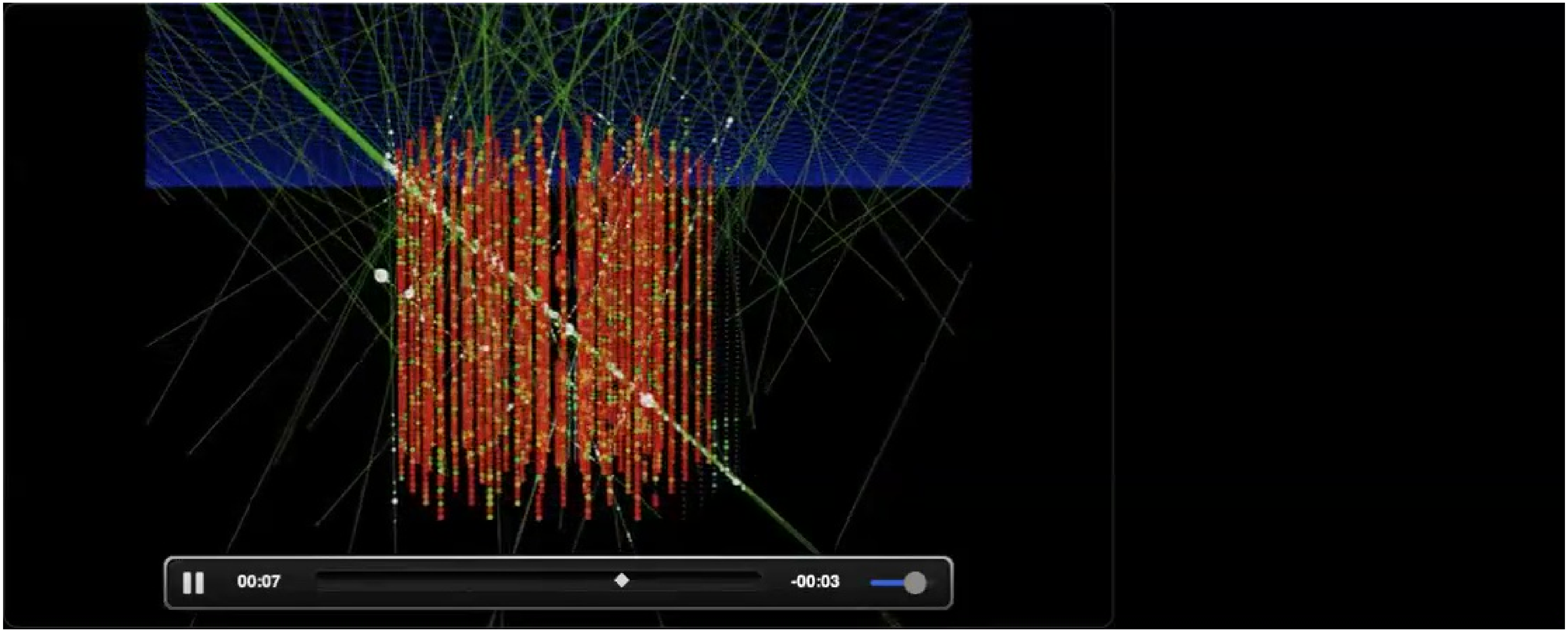

Francis Halzen, Olomouc 22
• 3 km deep South Pole glacier
• ultra-transparent ice below 1.35 km
• absorption length: 100 ~ 250+ m



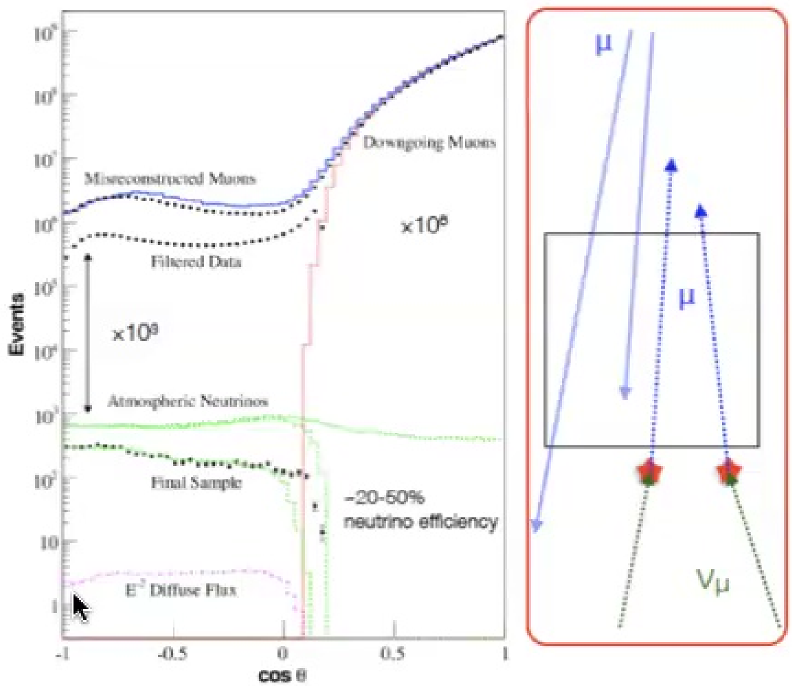
IceCube Drill-Camp, South Pole Station Antarctica

High-energy neutrinos - background considerations



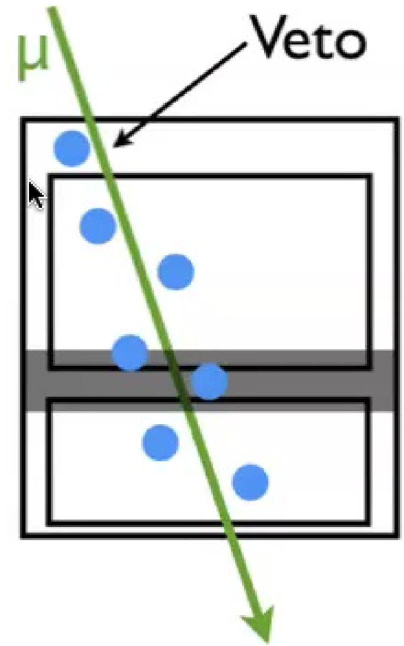

00:07
-00:03

through-going (tracks)

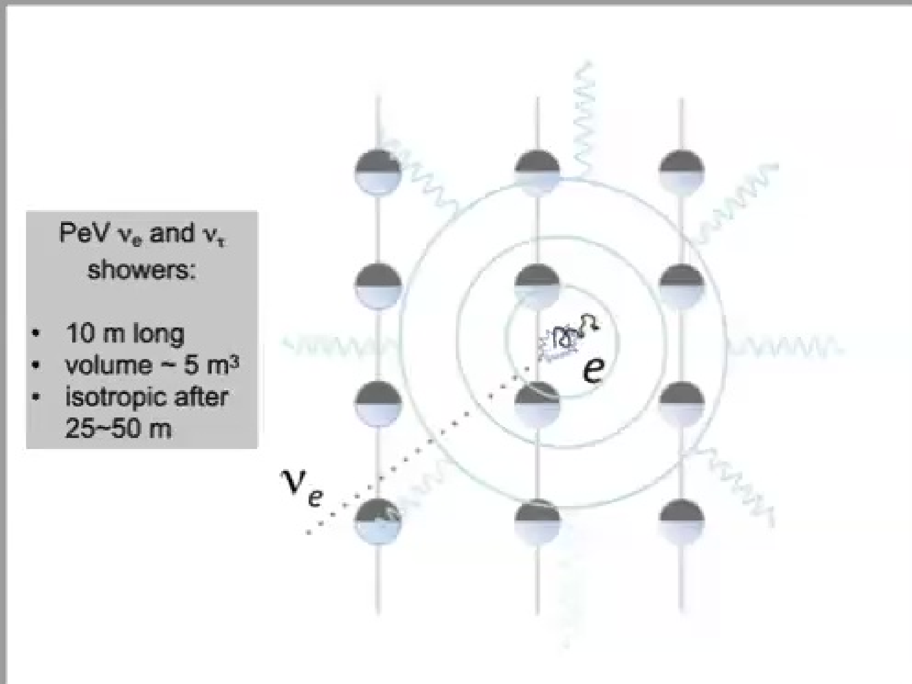


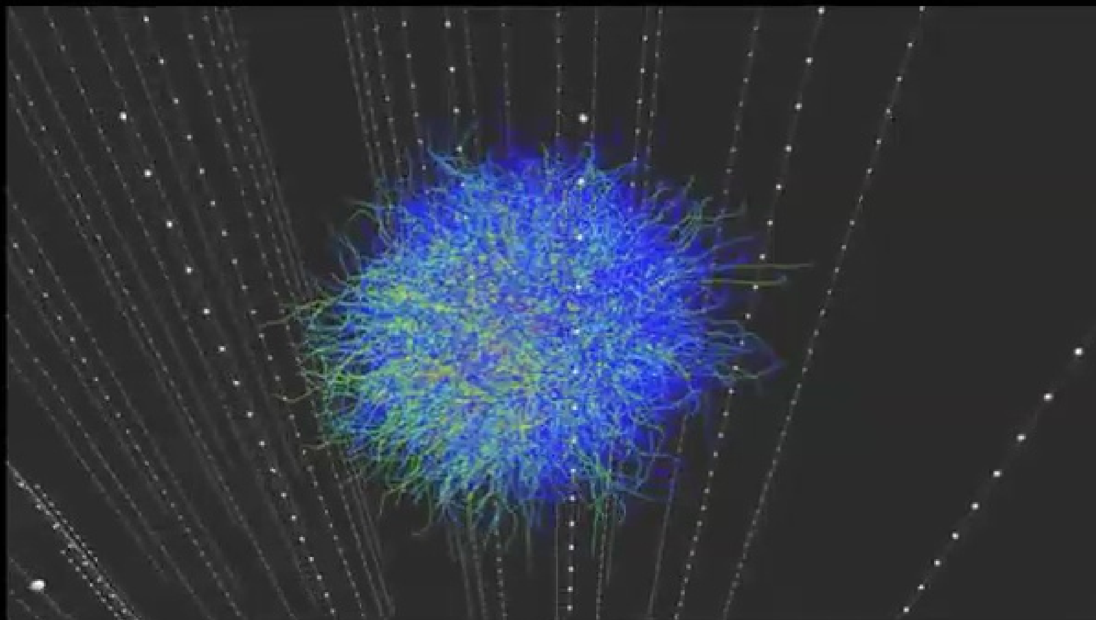
IceCube high energy starting events search

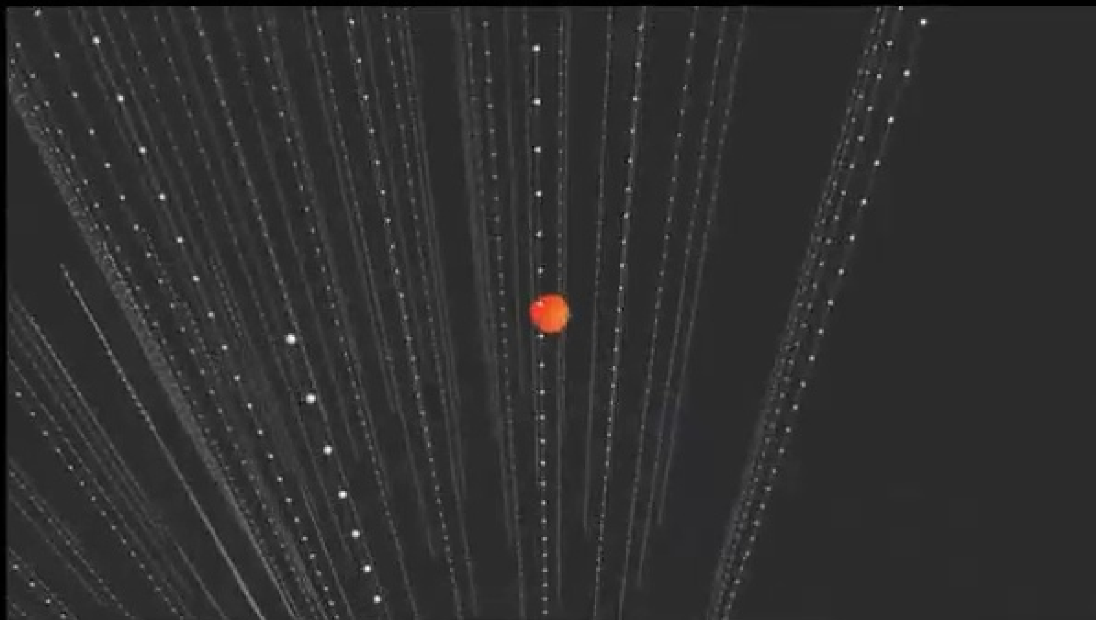
- Identify starting events in the detector by applying an active veto to remove the down-going backgrounds:
  - atmospheric muons identified by using part of the detector in anti-coincidence; can estimate potential contamination by using subsequent detector regions to measure number of muons that evade the other veto layer
  - atmospheric neutrinos: starting outside the detector see above; starting inside the detector tag with a parent atmospheric muon



electron showers …

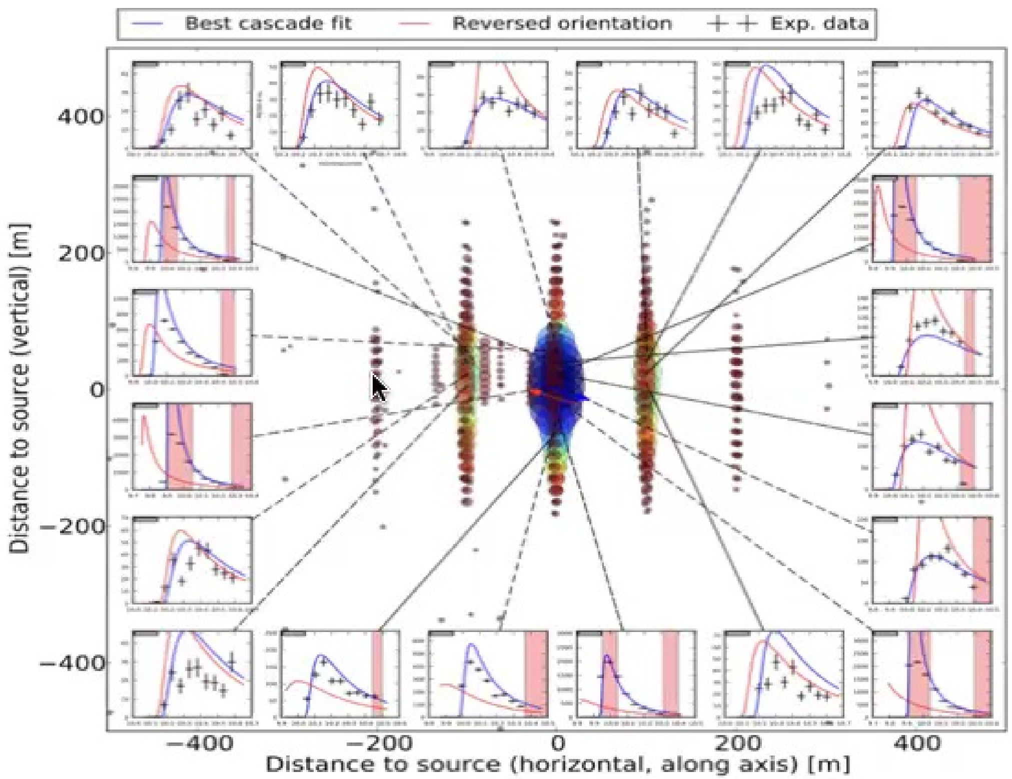



size = energy
color = time = direction



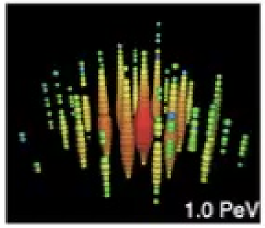
size = energy

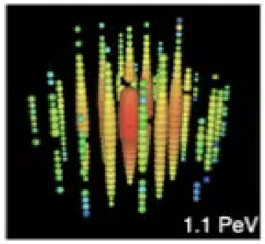
color = time = direction

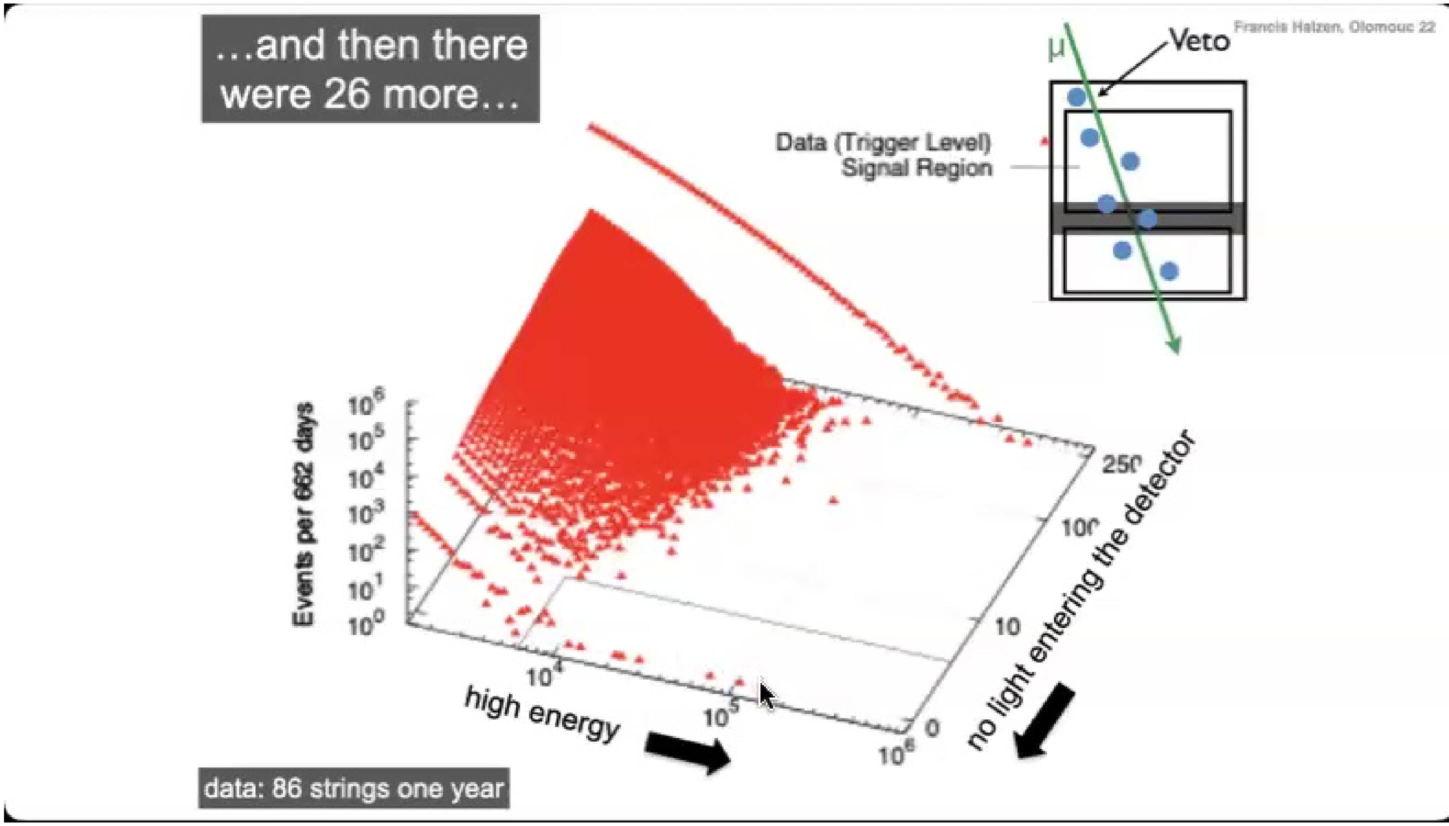


Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400

IceCube high energy starting events search

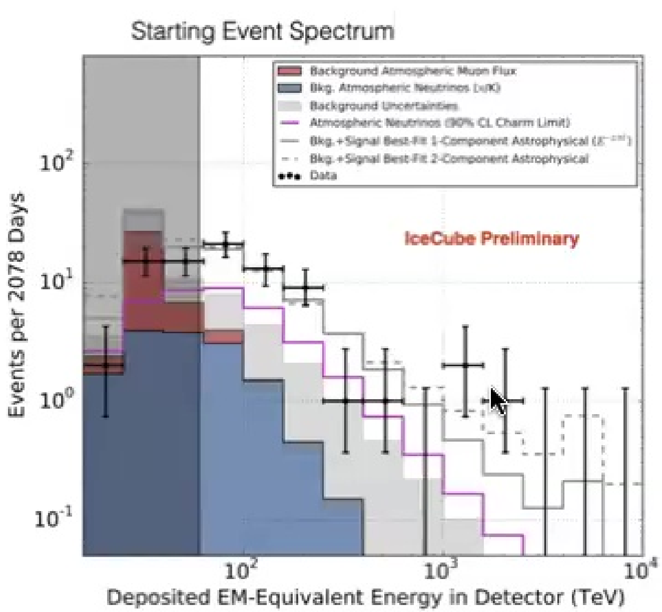


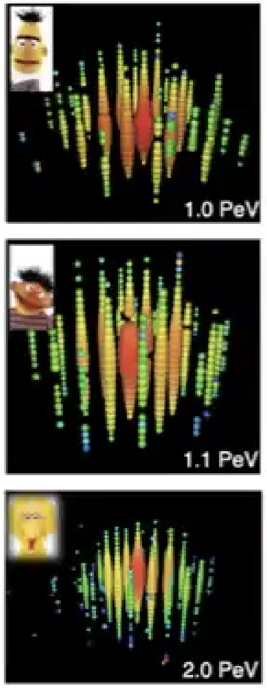


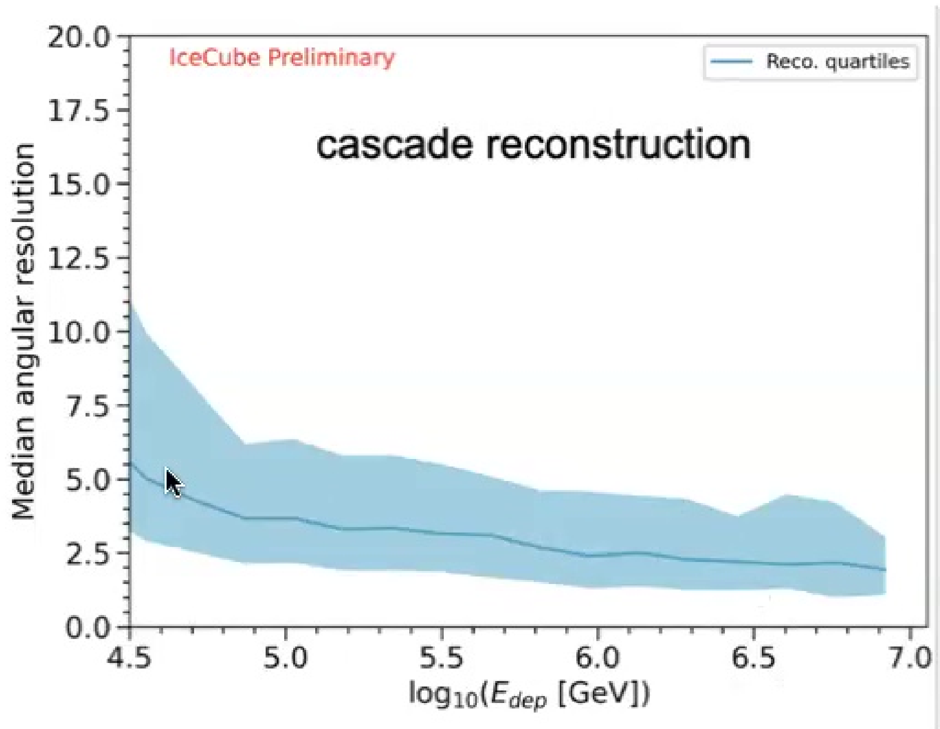


...and then there were 26 more...
Francis Halzen, Olomouc 22
Veto
μ
Data (Trigger Level)
Signal Region
Events per 662 days
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^4
10^5
10^6
high energy
0
10
100
250
no light entering the detector
data: 86 strings one year

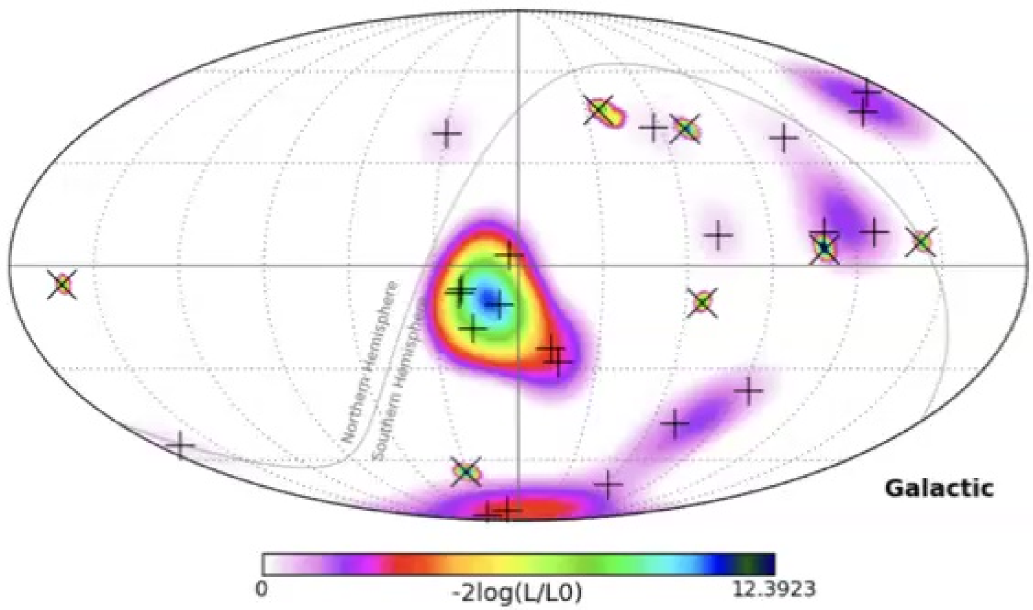
IceCube high energy starting events search






Francis Halzen, Olomouc 22
IceCube Preliminary
Reco. quartiles
cascade reconstruction
Median angular resolution
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
4.5
5.0
5.5
6.0
6.5
7.0
log10(E_dep [GeV])

2 year HESE


Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

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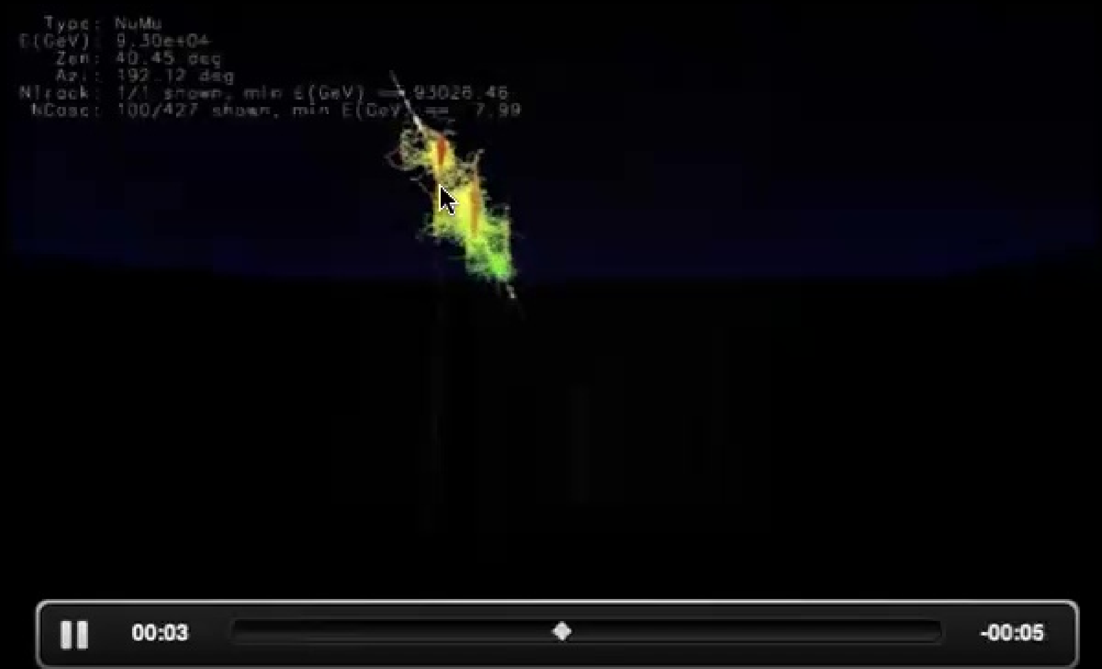
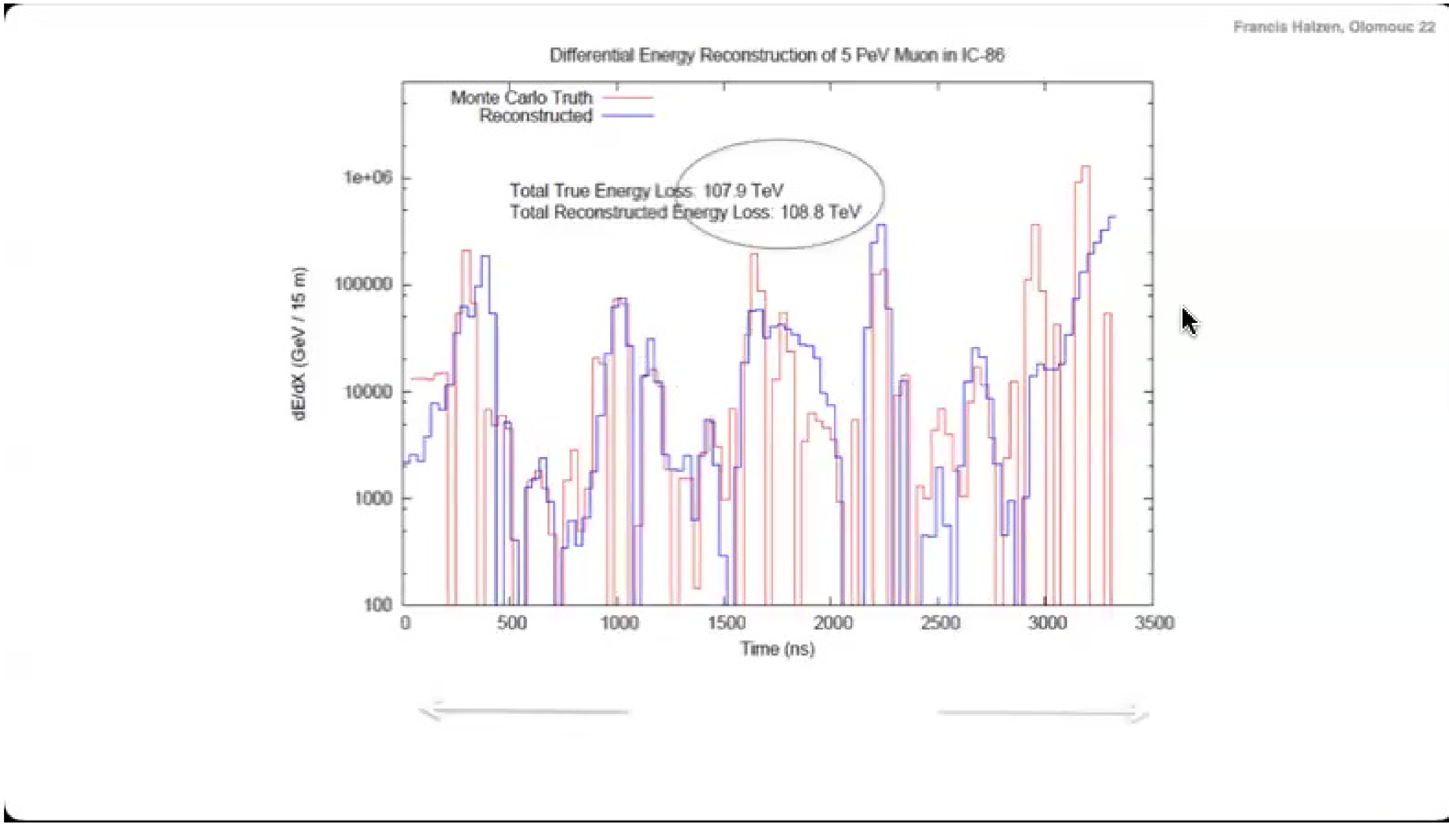
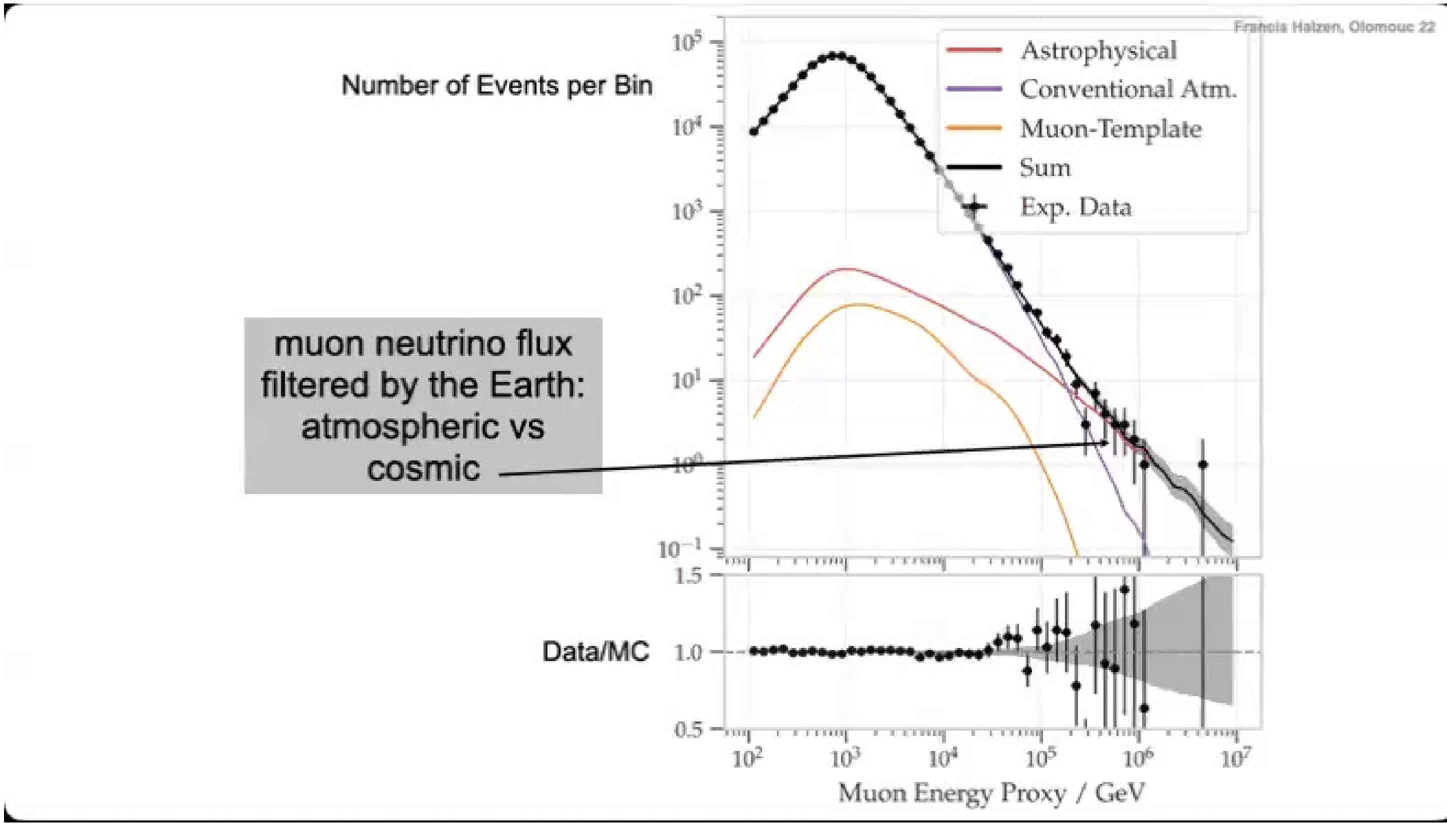
93 TeV muon: light ~ energy




Francis Halzen, Olomouc 22
Differential Energy Reconstruction of 5 PeV Muon in IC-86
Monte Carlo Truth
Reconstructed
Total True Energy Loss: 107.9 TeV
Total Reconstructed Energy Loss: 108.8 TeV
dE/dX (GeV / 15 m)
1e+06
100000
10000
1000
100
0
500
1000
1500
2000
2500
3000
3500
Time (ns)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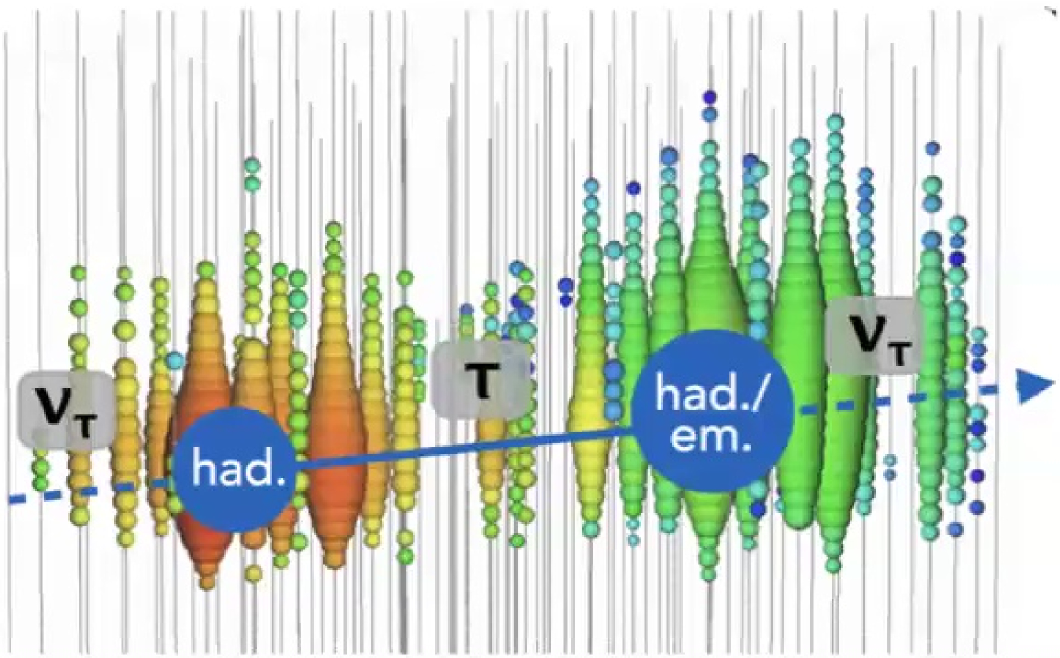
Number of Events per Bin
Astrophysical
Conventional Atm.
Muon-Template
Sum
Exp. Data
muon neutrino flux filtered by the Earth: atmospheric vs cosmic
Data/MC
Muon Energy Proxy / GeV

tau neutrino production and decay

tau decay length:
$\gamma c \tau$ = 50m per PeV



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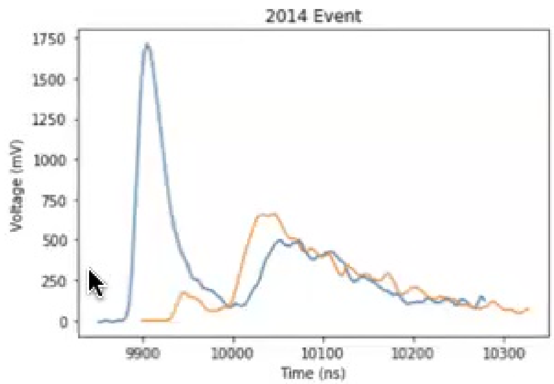
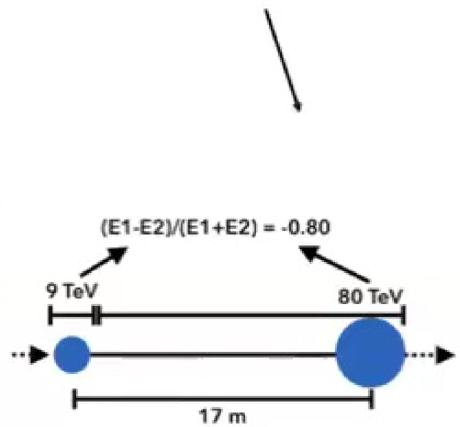
tau decay length:
50m per PeV





event found in 3 different analyses

a cosmic tau neutrino with 17m lifetime

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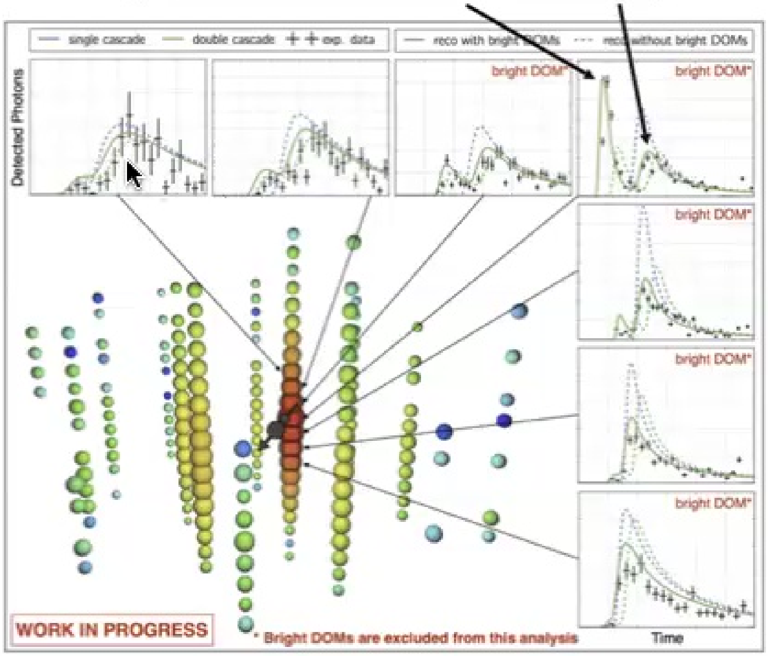
light from nutau interaction and tau decay



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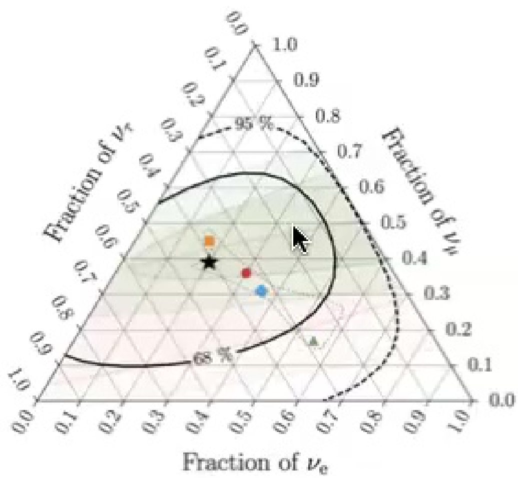
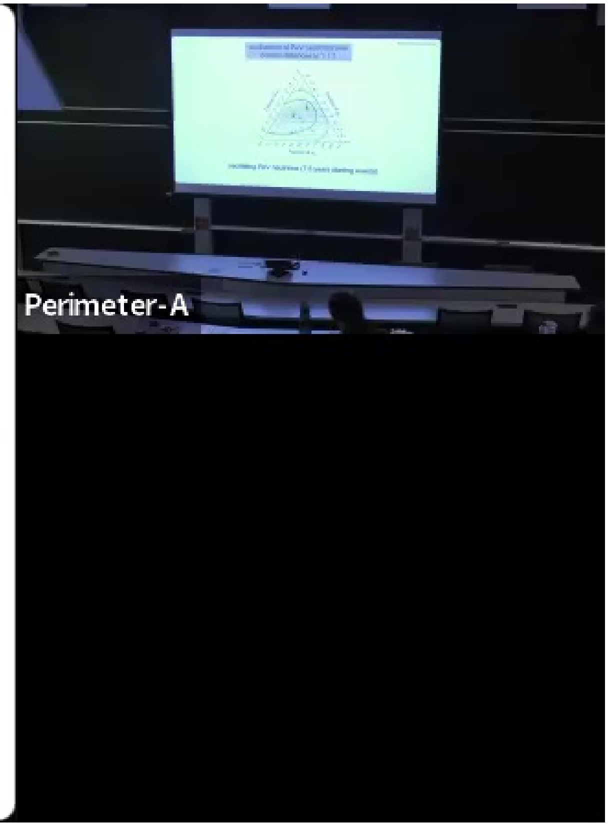
oscillations of PeV neutrinos over cosmic distances to 1:1:1

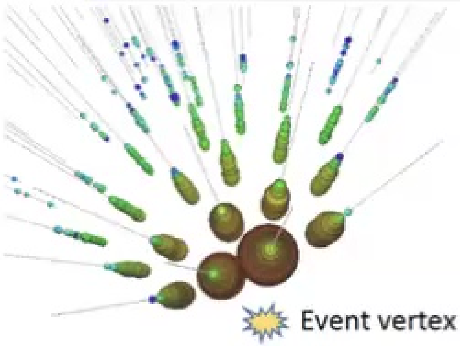


oscillating PeV neutrinos (7.5 years starting events)

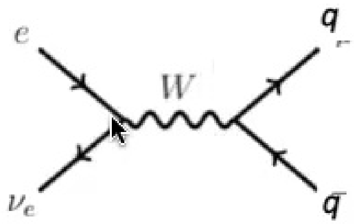


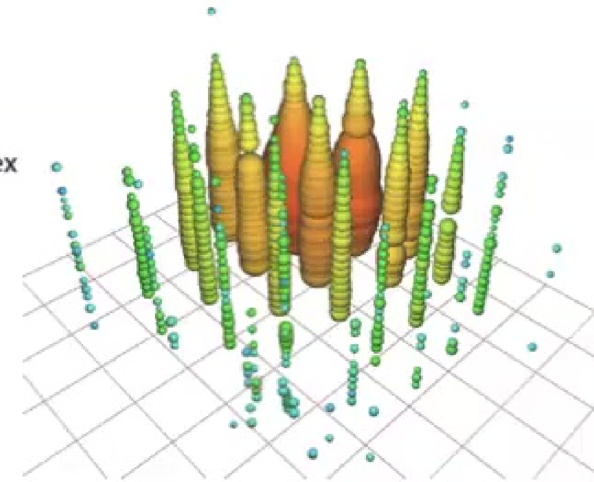
First observation of a Glashow Resonance Event

partially contained event with energy 6.3 PeV



resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron





First observation of a Glashow Resonance Event

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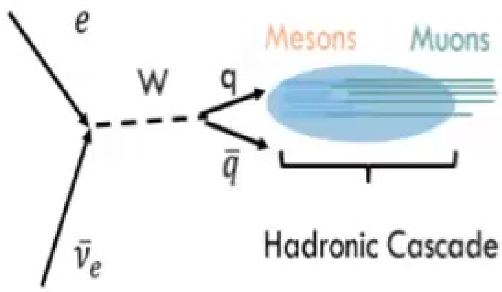
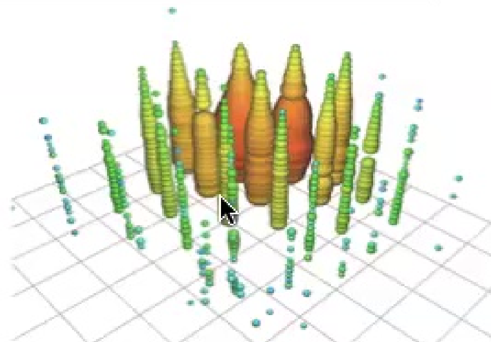
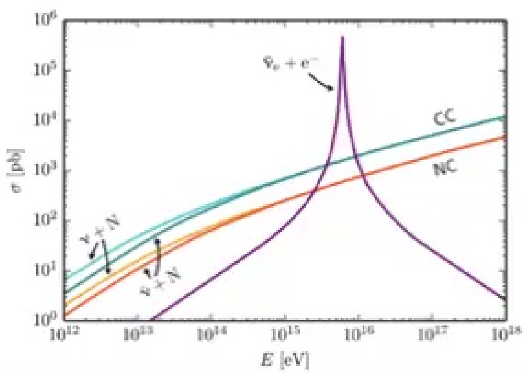
Glashow resonance: anti-ν_e + atomic electron → real W



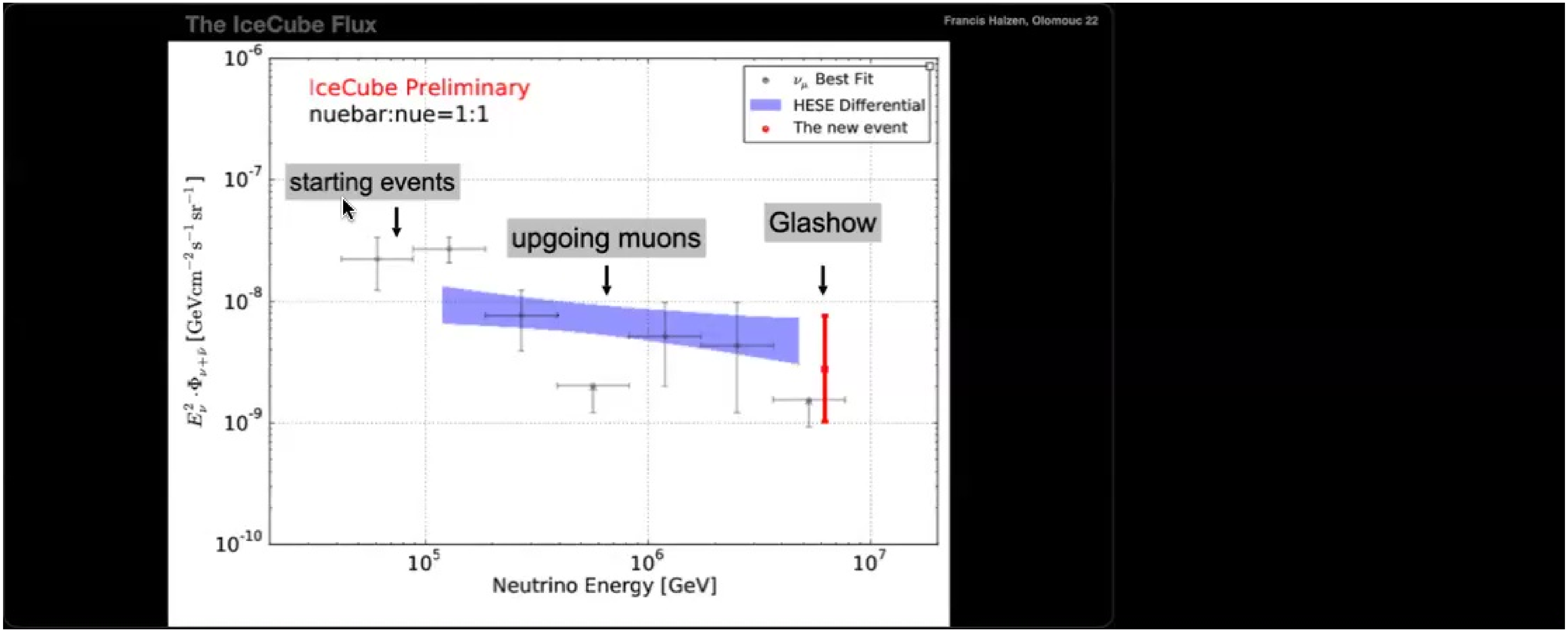




- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

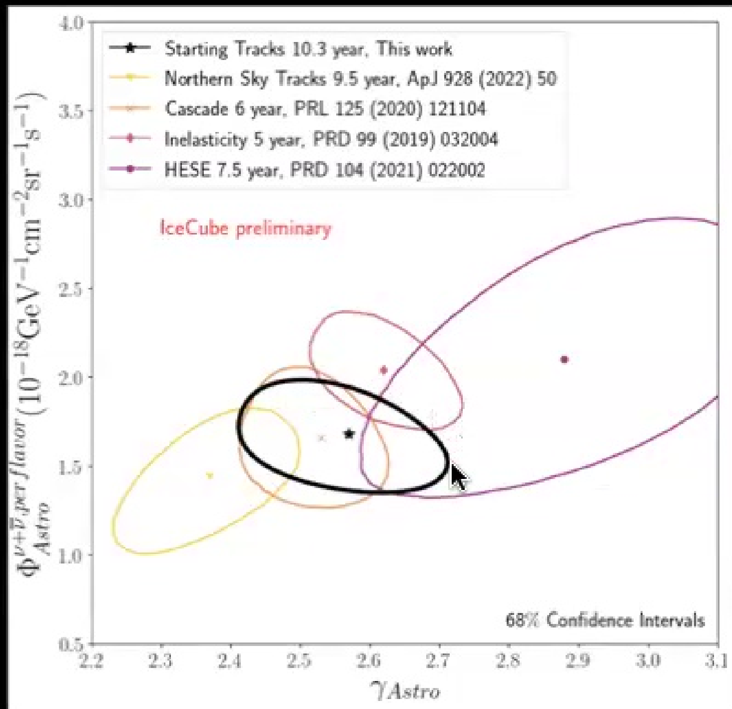
- → resonance: E_ν = 6.3 PeV

work on-going



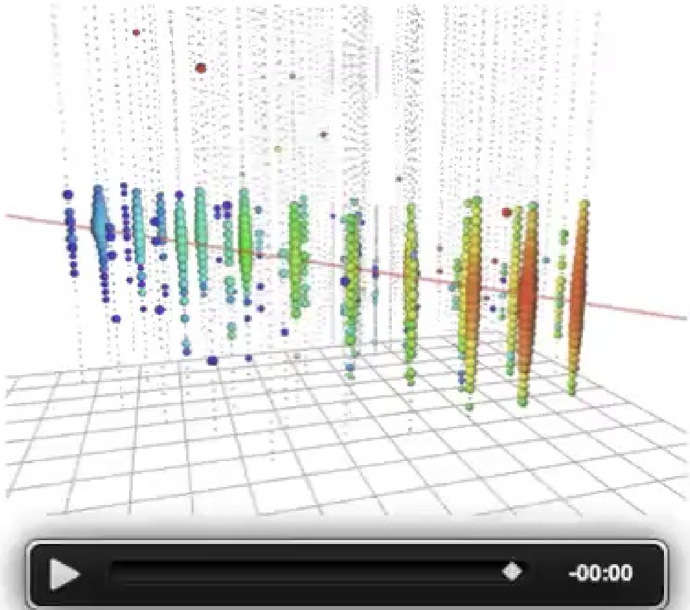
The IceCube Flux
Francis Halzen, Olomouc 22
IceCube Preliminary
nuebar:nue=1:1
starting events
upgoing muons
Glashow
ν_μ Best Fit
HESE Differential
The new event
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]

The IceCube Flux



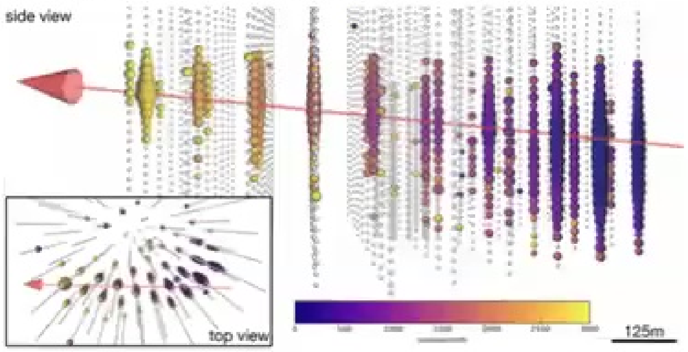
September 22, 2017

IceCube-170922A

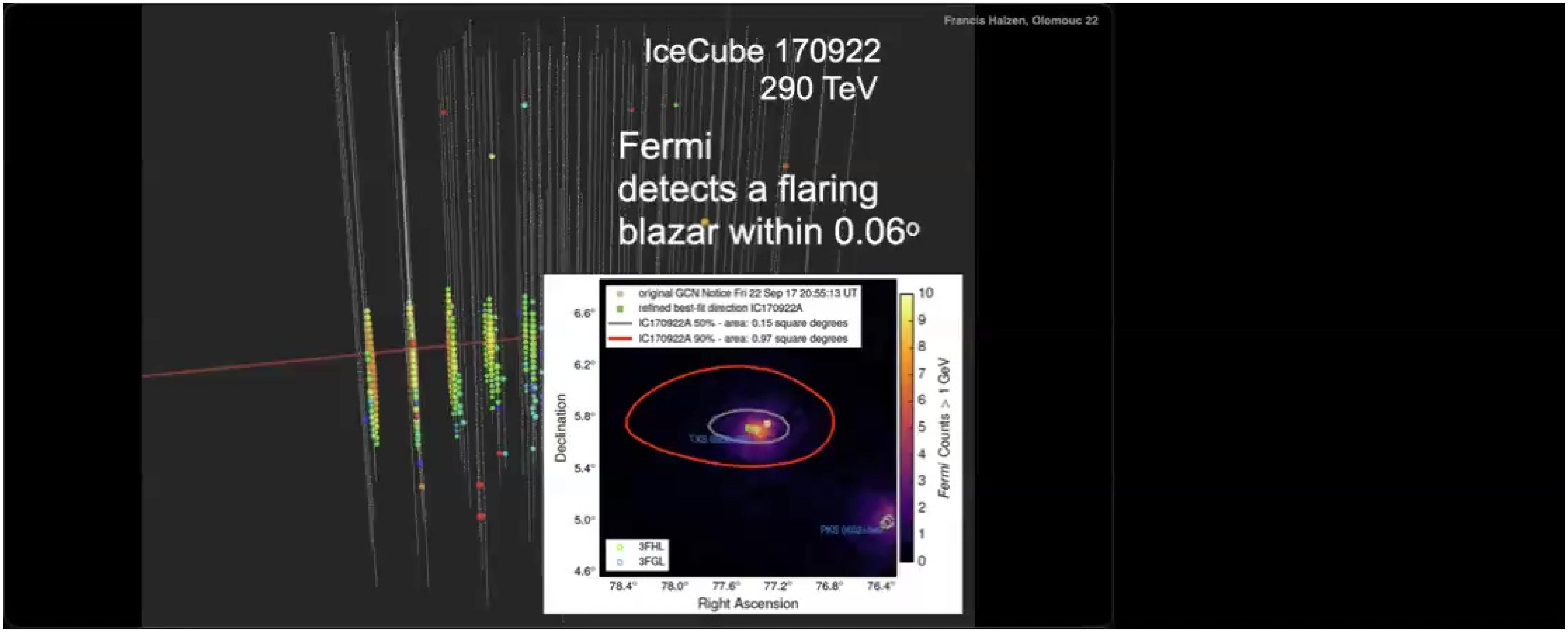


The story of a neutrino…

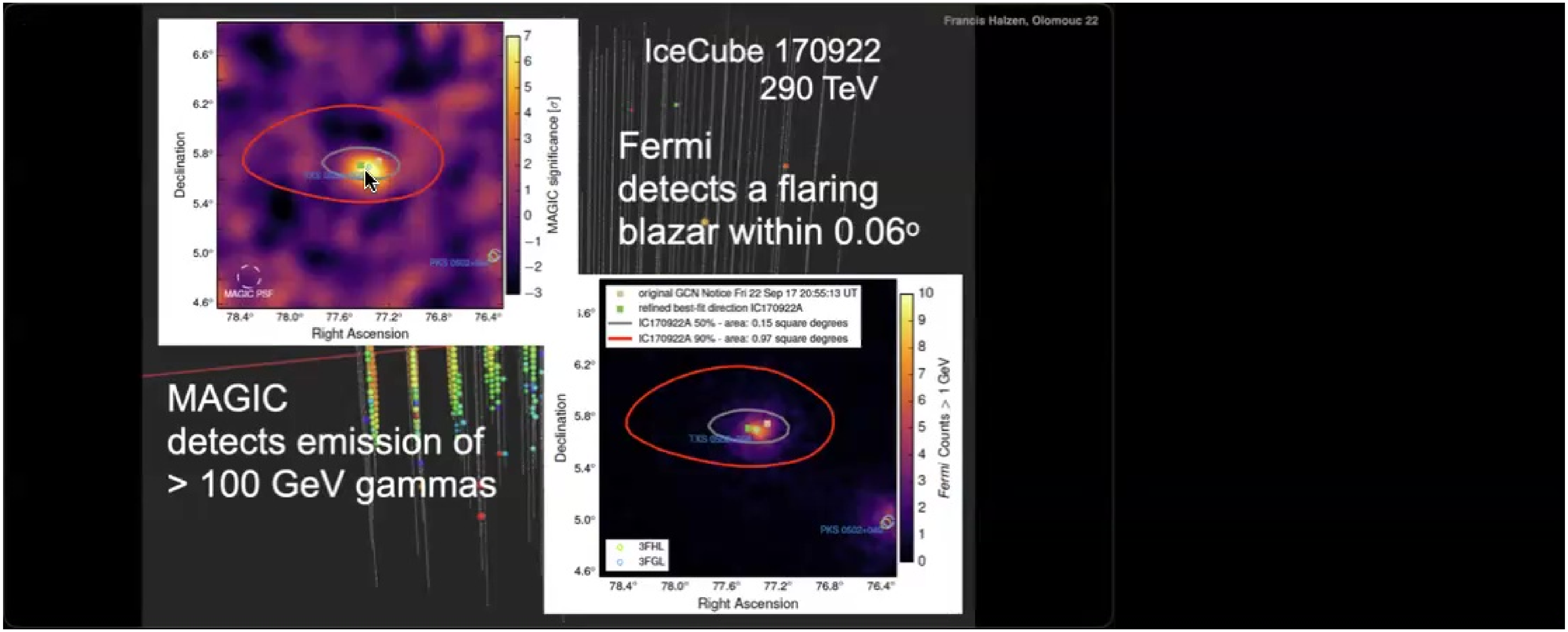
IceCube-170922A and TXS 0506+056



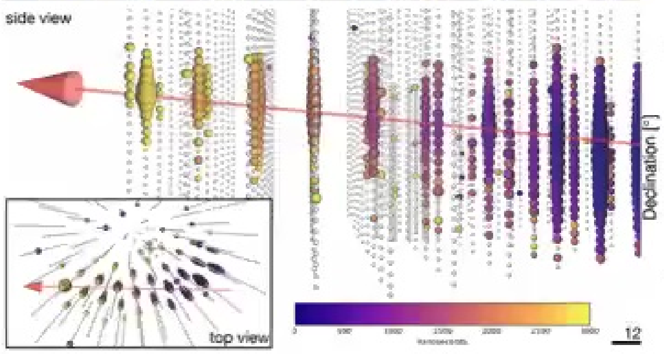
TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
[…]
On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state.[…]

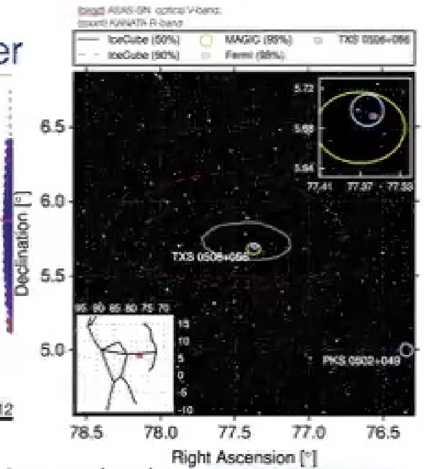


Francis Halzen, Olomouc 22
IceCube 170922
290 TeV
Fermi
detects a flaring
blazar within 0.06°
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
3FHL
3FGL
Declination
Right Ascension
Fermi Counts > 1 GeV
6.6°
6.2°
5.8°
5.4°
5.0°
4.6°
78.4°
78.0°
77.6°
77.2°
76.8°
76.4°
10
9
8
7
6
5
4
3
2
1
0


Francis Halzen, Olomouc 22
IceCube 170922
290 TeV
Fermi
detects a flaring
blazar within 0.06°
MAGIC
detects emission of
> 100 GeV gammas
Declination
Right Ascension
MAGIC significance [σ]
MAGIC PSF
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
Fermi Counts > 1 GeV
3FHL
3FGL

The story of a neutrino…and a blazer





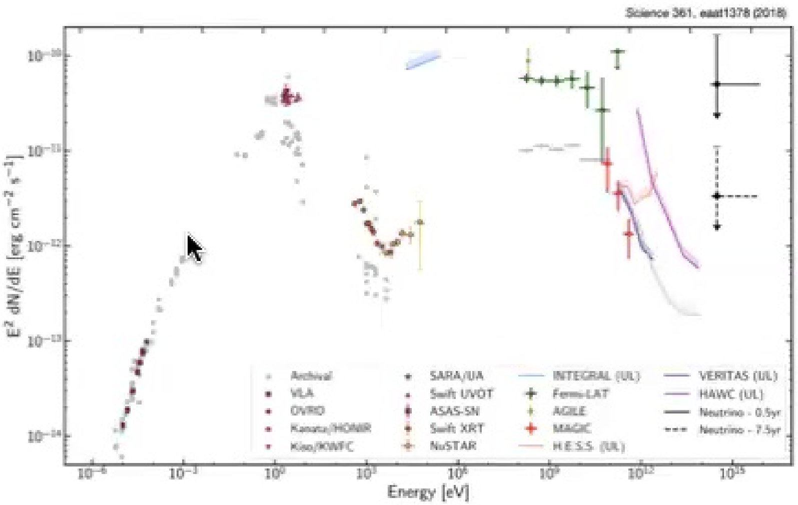
Following the direction of this neutrino 4 billion light years back into the distant sky we found an active supermassive black hole (blazar); the first compelling source for high energy neutrinos, and hence cosmic rays!

- 3 major press conference (US, Germany, Japan)
- more than 2,000 articles, videos and radio/podcasts to date, including major news (BBC, CNN, FoxNews, Frankfurt Allgemaine, NYtimes, Washington Post,…), specialized, and children's programming

Vox 10 science stories in 2018 that made us go, "Whoa, that's awesome"

The story of a neutrino…and a blazer

Spectral Energy Distribution — Sept/Oct 2017



- Extensive broad-band follow-up measurements
- Inferred ~300 TeV neutrino emission has νF_ν of same order as HE / VHE gamma rays
- NB: observations not strictly contemporaneous

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global robotic network of optical telescopes connects TXS 0506+056 to IC170922A in the time domain

"MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level"

Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

V.M. Lipunov[1,2], V.G. Kornilov [1,2], K.Zhirkov[1], E. Gorbovskoy[2], N.M. Budnev[4], D.A.H.Buckley[3], R. Rebolo[5], M. Serra-Ricart[5], R. Podesta[9,10], N .Tyurina [2], O. Gress[4,2], Yu.Sergienko[8], V. Yurkov[8], A. Gabovich[8], P.Balanutsa[2], I.Gorbunov[2], D.Vlasenko[1,2], F.Balakin[1,2], V.Topolev[1], A.Pozdnyakov[1], A.Kuznetsov[2], V.Vladimirov[2], A. Chasovnikov[1], D. Kuvshinov[1,2], V.Grinshpun[1,2], E.Minkina [1,2], V.B.Petkov [7], S.I.Svertilov[2,6], C. Lopez[9], F. Podesta[9], H.Levato[10], A. Tlatov[11], B. Van Soelen[12], S. Razzaque[13], M. Böttcher[14]

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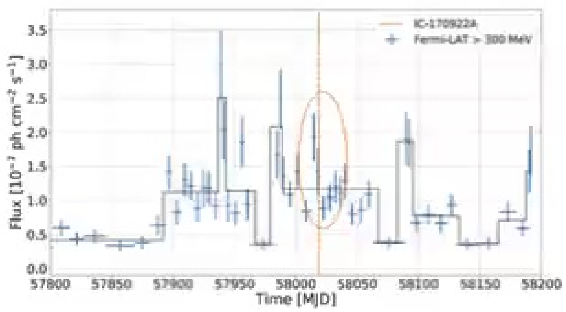
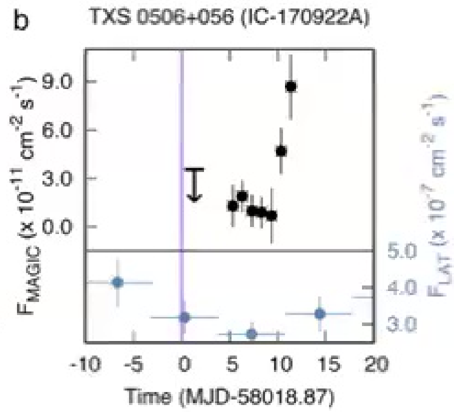
gamma rays in 2017 at the time the neutrino is produced ?
consistent with an obscured source, not a blazar

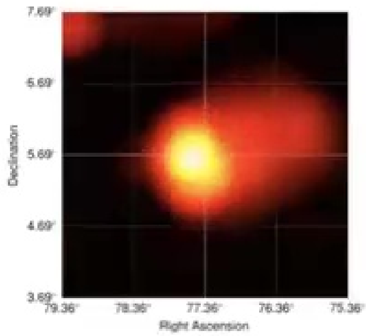


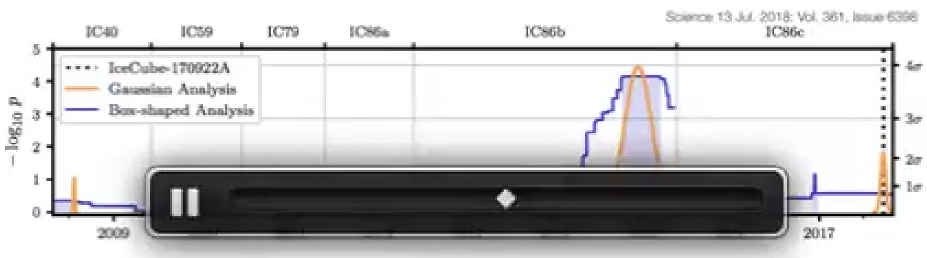


- MAGIC, HESS and VERITAS: TeV flux is highly variable and there is no TeV gamma ray emission at the time the neutrino is produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

The story of a number of neutrinos and a blazar…

IceCube-170922A and TXS 0506+056





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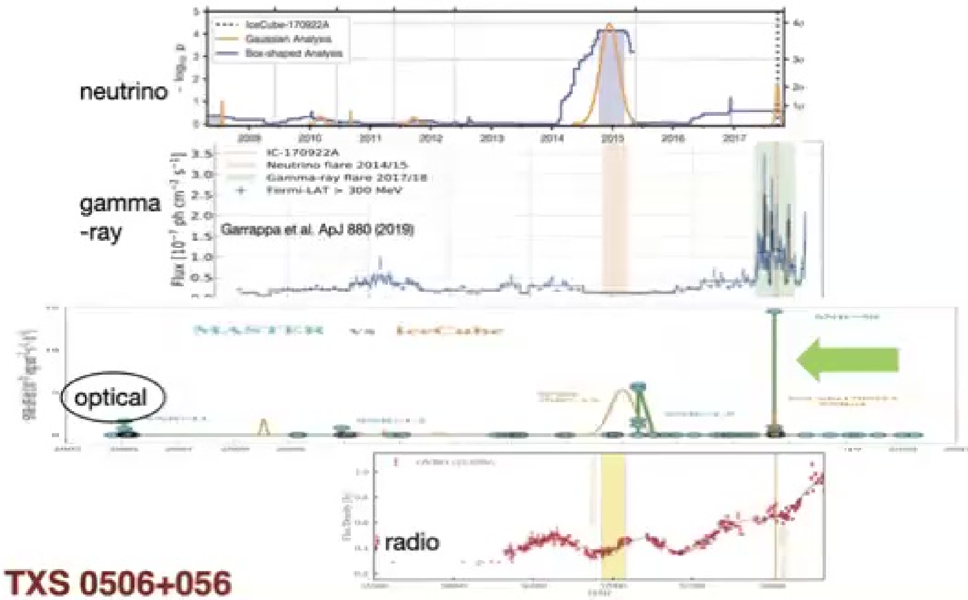
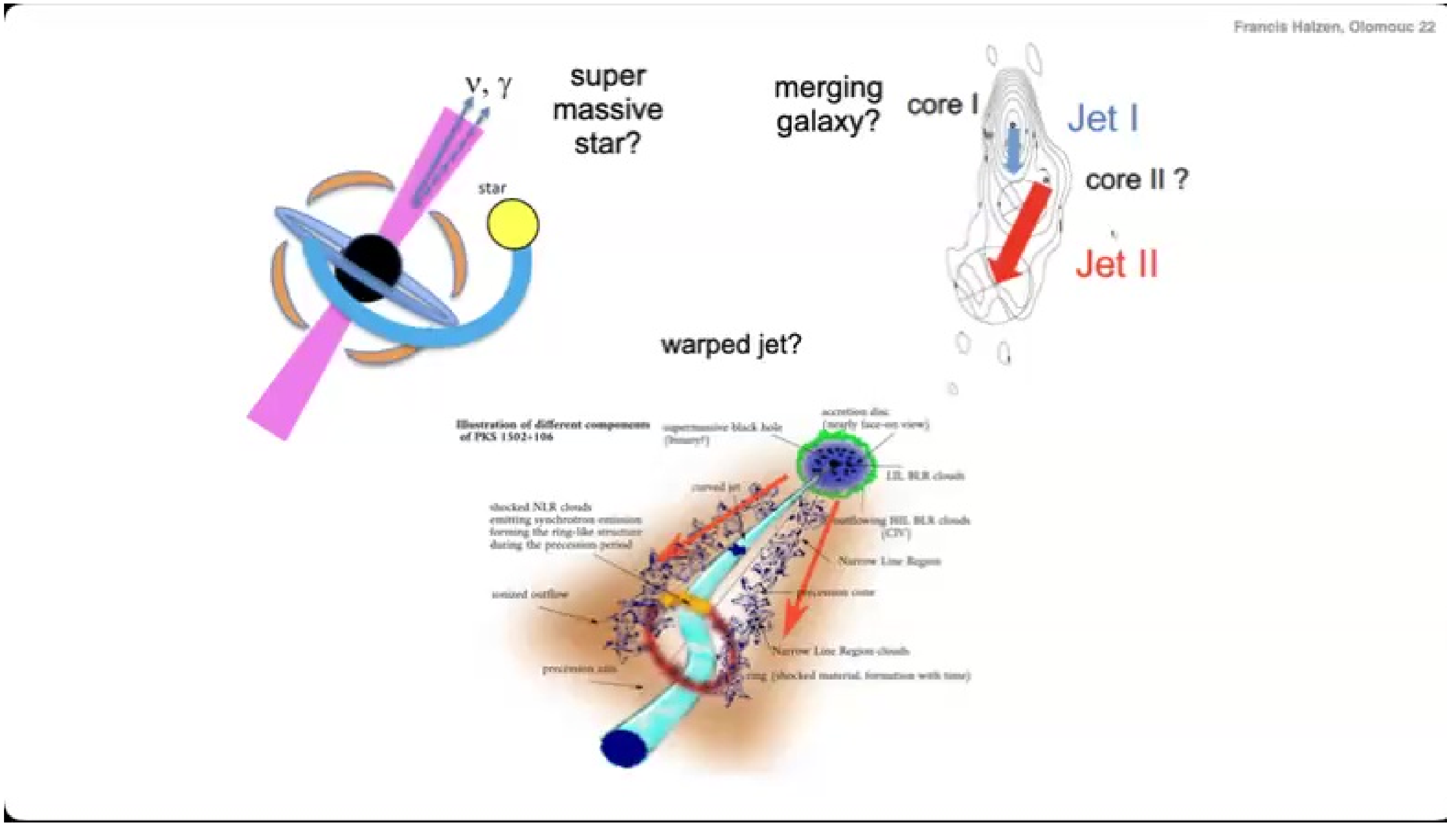


TXS 0506+056

- multimessenger observations in the time domain
- change of flux 2 hours after 170922 neutrino
- source is quiet 10 previous and 3 following years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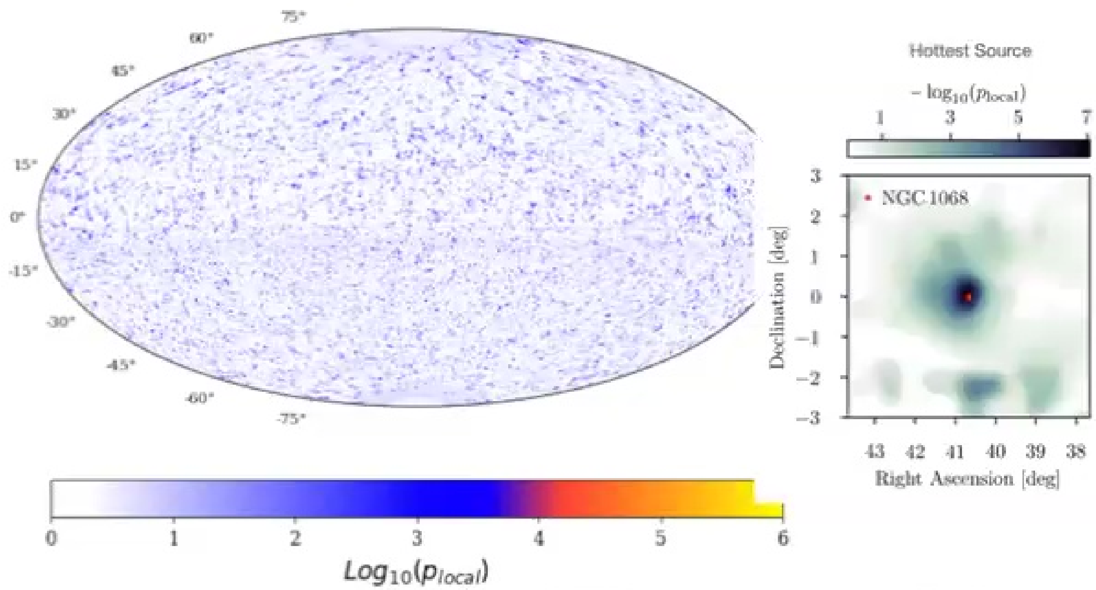
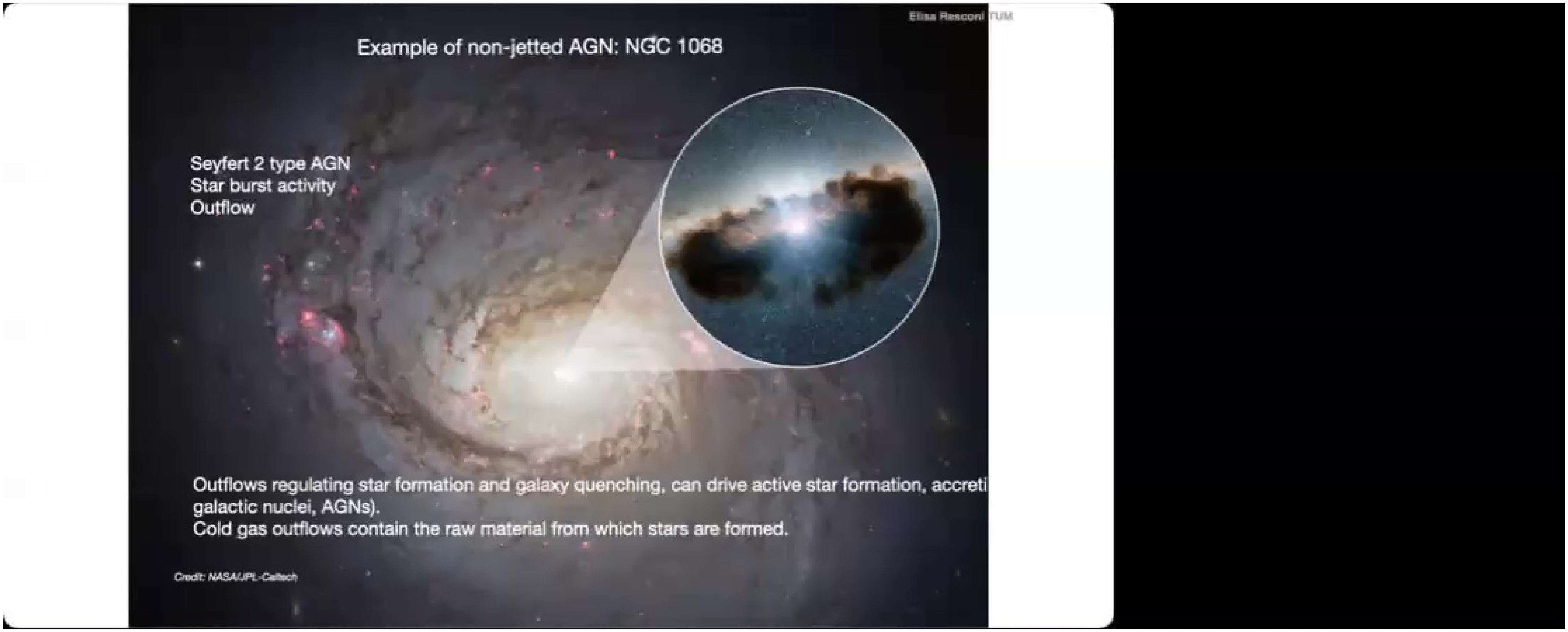
ν, γ
star
super
massive
star?
merging
galaxy?
core I
Jet I
core II ?
Jet II
warped jet?
Illustration of different components
of PKS 1502+106
supermassive black hole
accretion disc
shocked NLR clouds
Narrow Line Region
Narrow Line Region clouds
ring (shocked material, formation with time)

Sources of high-energy astrophysical neutrinos…



evidence for non-uniform sky map in 10 years of IceCube data : mostly resulting from 4 extragalactic source candidates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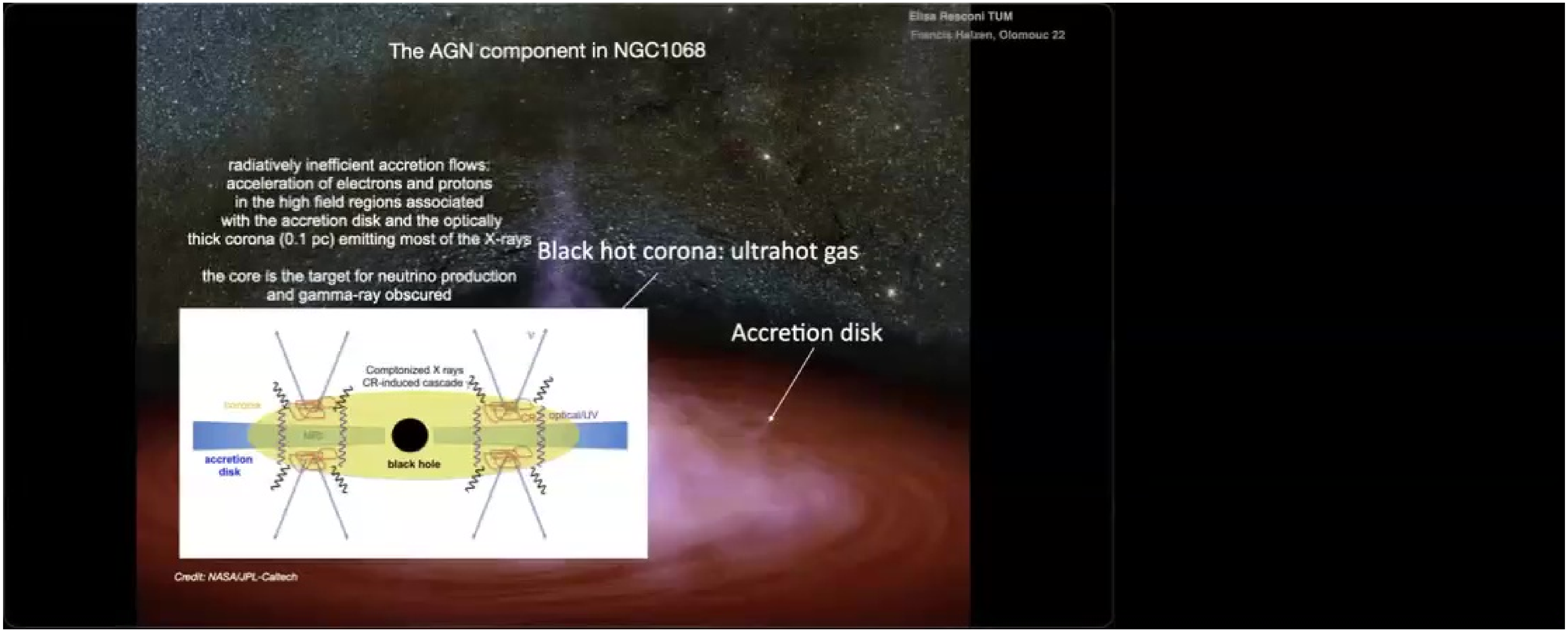
Example of non-jetted AGN: NGC 1068
Seyfert 2 type AGN
Star burst activity
Outflow
Outflows regulating star formation and galaxy quenching, can drive active star formation, accreti
galactic nuclei, AGNs).
Cold gas outflows contain the raw material from which stars are formed.
Credit: NASA/JPL-Caltech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The AGN component in NGC1068
radiatively inefficient accretion flows:
acceleration of electrons and protons
in the high field regions associated
with the accretion disk and the optically
thick corona (0.1 pc) emitting most of the X-rays
the core is the target for neutrino production
and gamma-ray obscured
Black hot corona: ultrahot gas
Accretion disk
Comptonized X rays
CR-induced cascade
optical/UV
accretion
disk
black hole
Credit: NASA/JPL-Caltech

Sources of high-energy astrophysical neutrinos… coming next?

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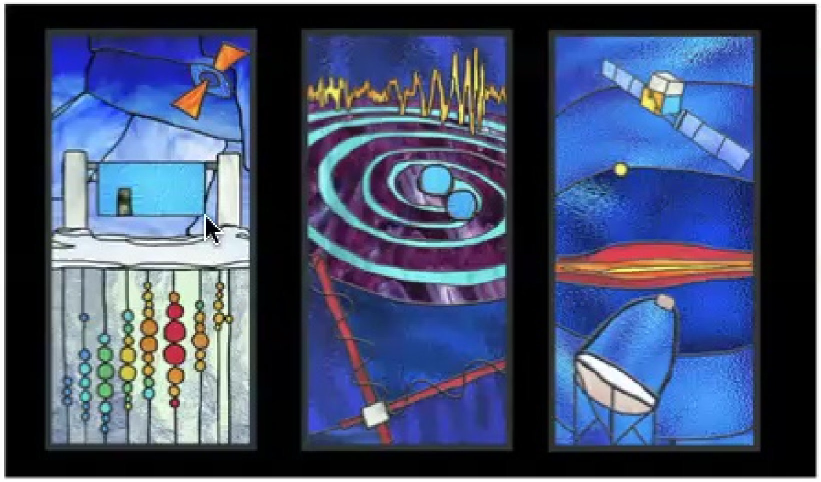

Observation of high-energy neutrinos coincident with gravitational wave events

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Sources of high-energy astrophysical neutrinos… coming next?

LIGO run O4 commenced May 2023

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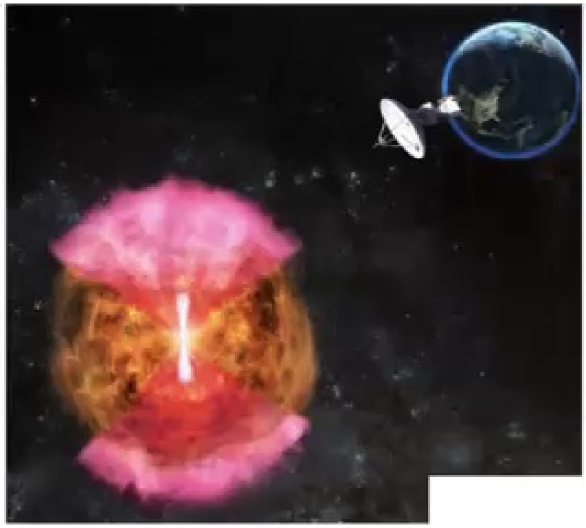
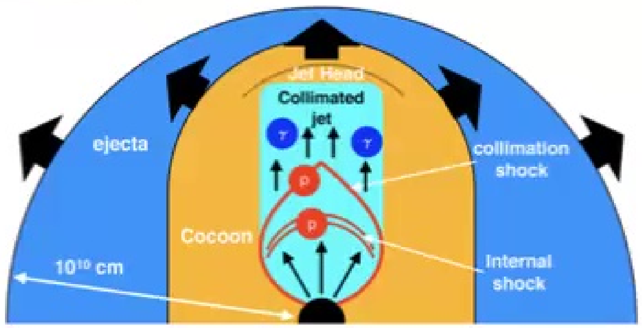


high-energy neutrinos:
from collimation (TeV) and
internal shocks (PeV):

protons photoproduce neutrinos
on photons from leakage of
the collimated jet
on synchrotron photons from
electrons (internal shock)



August 17, 2017 neutron star merger did not have the jet aligned with Earth

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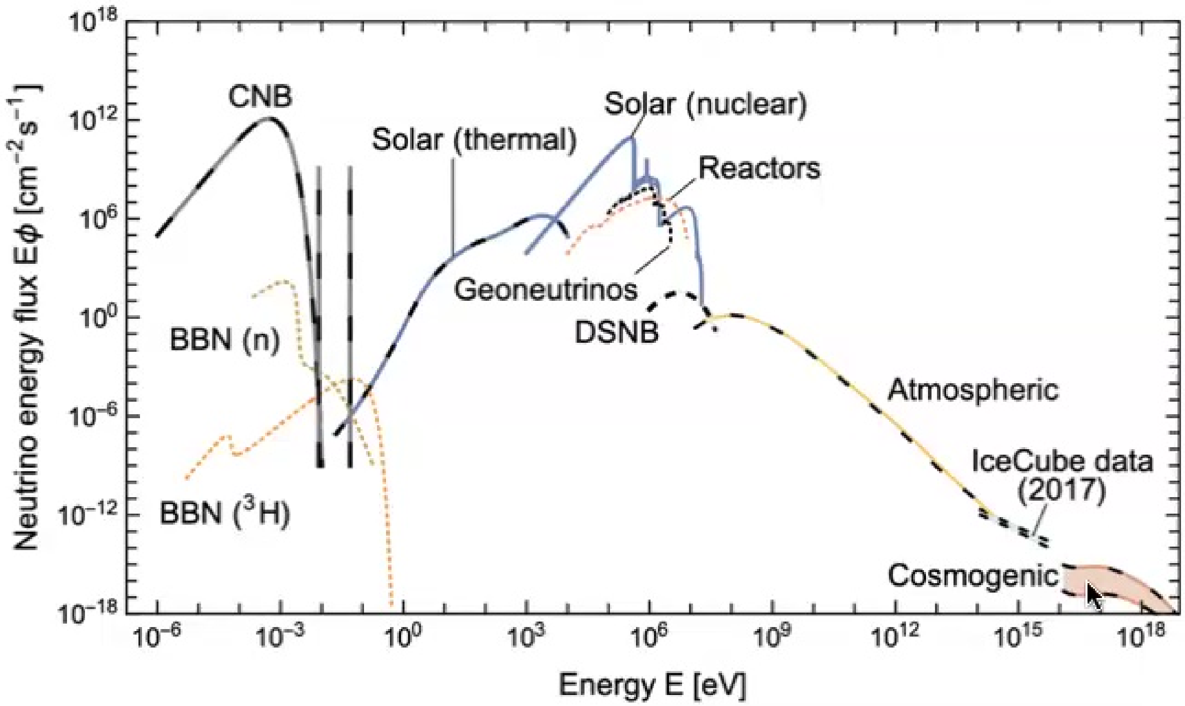
Grand unified neutrino spectrum (integrated over direction and flavour)

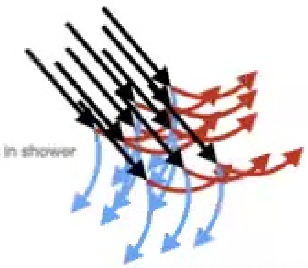


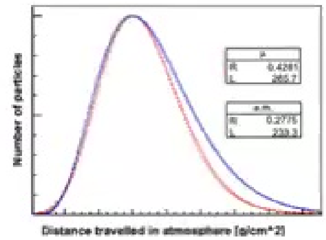
The Askaryan effect vs radio

Askar'yan, G.A., Soviet Physics JETP 14,2 441–443 (1962); 48 988–990 (1965).
https://arxiv.org/pdf/1106.6283.pdf

- In a shower: many particles
- Charge separation produces a current

- Number of particles is a function of height above ground





- The current changes as function of time/height
- A changing current causes electromagnetic emission

https://indico.e5.physik.tu-dortmund.de/event/708/attachments/616/1313/Ringvorlesung_TUDo_2021.pdf

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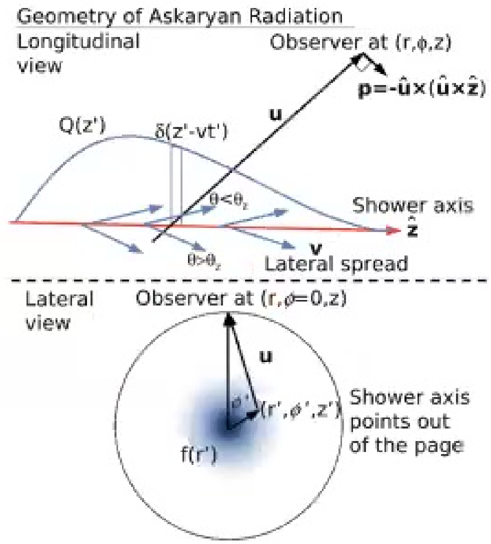
The Askaryan effect vs radio

Askar'yan, G.A., Soviet Physics JETP 14,2 441–443 (1962); 48 988–990 (1965).
https://arxiv.org/pdf/1106.6283.pdf

Ultra-High Energy (UHE) cosmic rays and neutrinos:
coherent radio pulse from the excess of electrons in a shower developing in a dense dielectric and non-absorptive medium. The signal is the radiation due to the charge excess of a shower in a linear dielectric medium such as ice, salt, or silica sand.

Emitted power goes with the square of the particle energy (experimentally confirmed in accelerators): promising idea for the detection of UHE particles.

Radio power is absorbed quickly by a small admixture of liquid water, so the natural medium should be dry, such as salt domes, or better yet, frozen to a solid state.



Geometry of a high energy particle shower.

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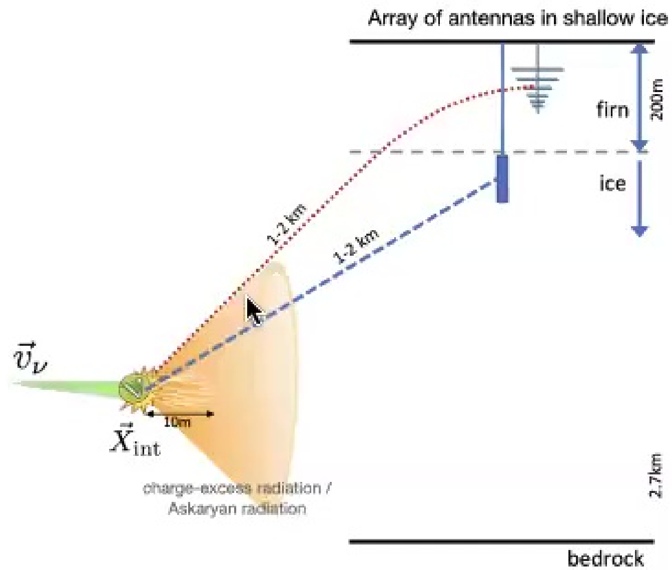
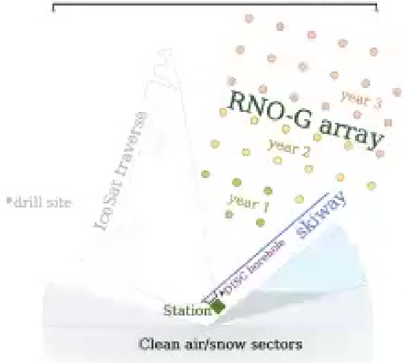
The Askaryan effect vs radio: detection via antennas in the shallow ice (South Pole, Greenland)

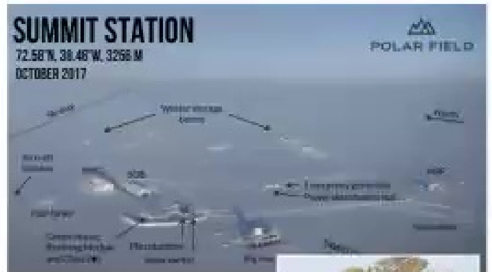
https://arxiv.org/pdf/2208.04971.pdf



The Askaryan effect vs radio: detection via antennas in the shallow ice (South Pole, Greenland)

Radio Neutrino Observatory





- After lots of proof-of principle experiments: first scale-up to large array

https://indico.e5.physik.tu-dortmund.de/event/708/attachments/616/1313/Ringvorlesung_TUDo_2021.pdf

The Askaryan effect vs radio: detection via antennas in the shallow ice (South Pole, Greenland)

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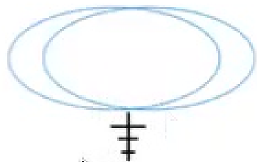
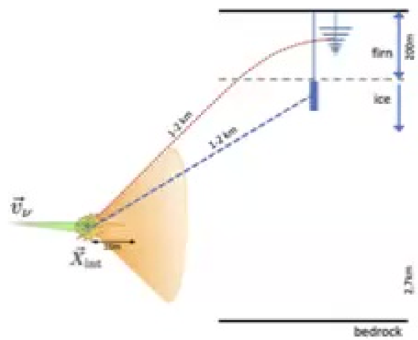


One can fly a balloon with antennas and maximize the volume observed (**ANITA** project)



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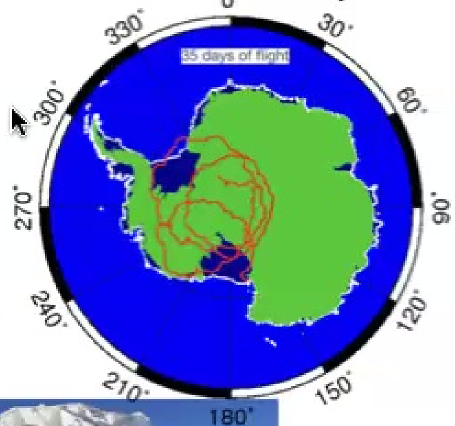
The Askaryan effect vs radio: ANITA I-IV (ANTARCTIC IMPULSE TRANSIENT ANTENNA)

Results from the last launch: https://arxiv.org/pdf/2008.05690.pdf



ANITA-I (2006-2007)

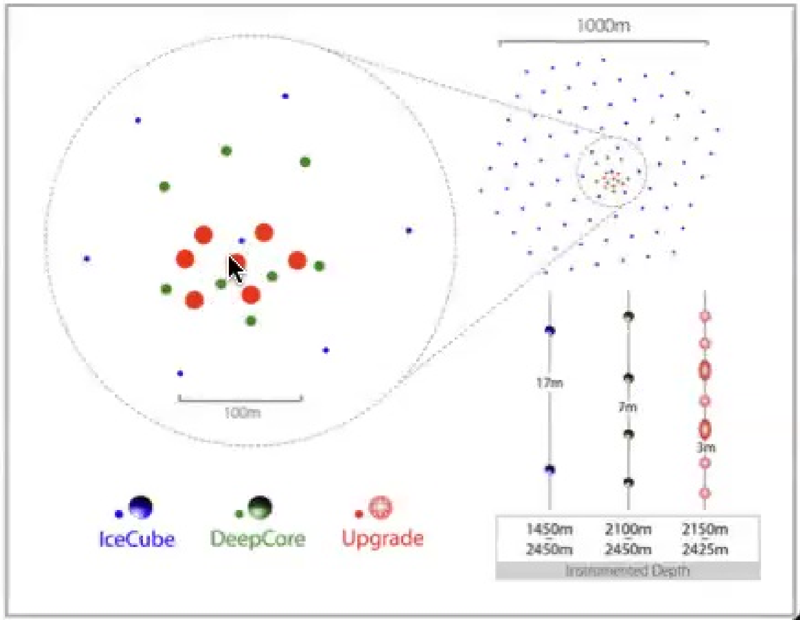
- trigger rate: 4 - 5 Hz

ANITA-II (2008-2009)

ANITA-III (2014)

ANITA-IV (2016)

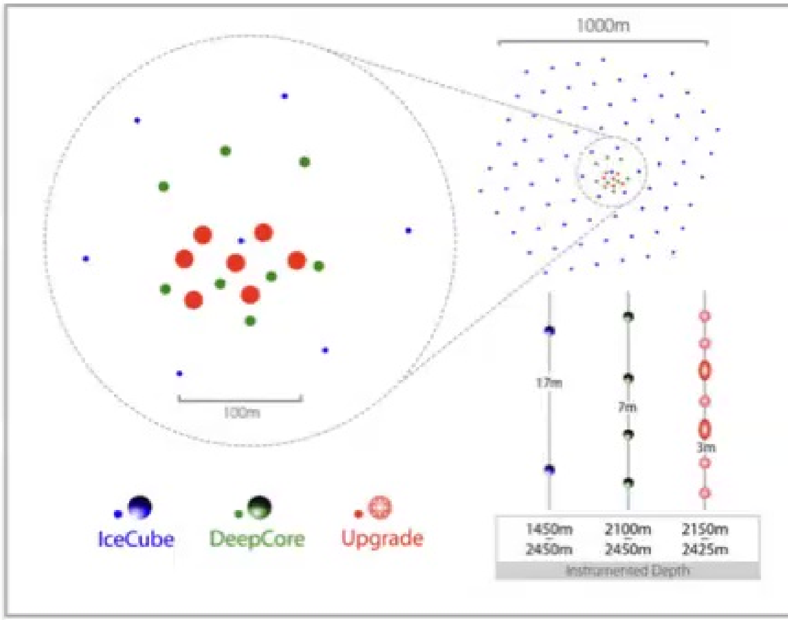
High-Energy Neutrinos ... IceCube Upgrade



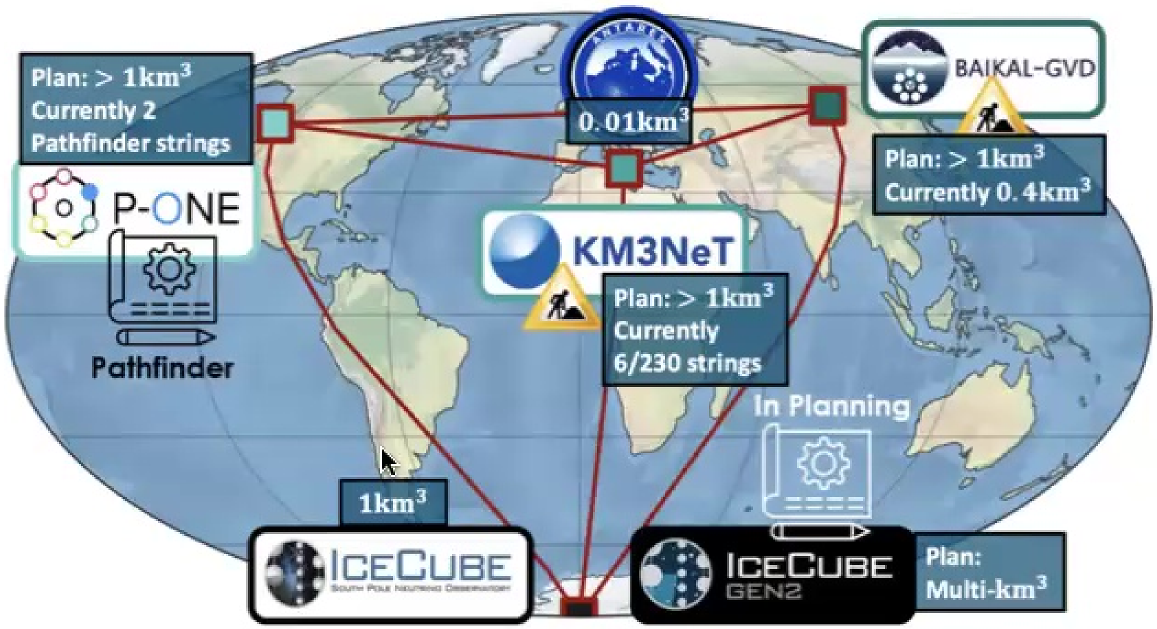
High-Energy Neutrinos ... IceCube Upgrade

Science drivers:

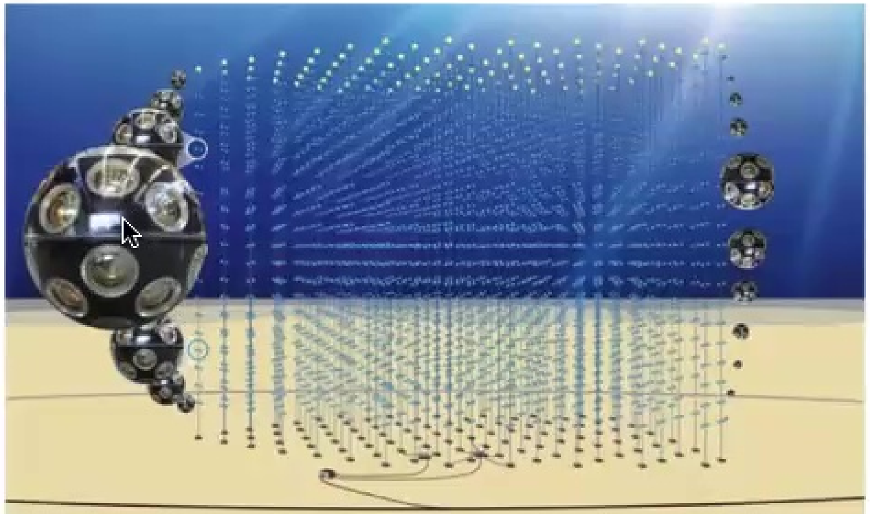
- Enhanced capability for GeV atmospheric neutrino detection at ~few GeV; world-leading measurement of tau neutrino normalization for direct text of unitarity of the PMNS mixing matrix
- Advanced calibration devices to reduce ice systematic uncertainties -> recalibration of the full array.
  - Re-analyze more than 15 years of IceCube data with substantially improved angular and energy resolutions (~factor 2 improvement)
  - Enhanced neutrino event pointing (source discovery)

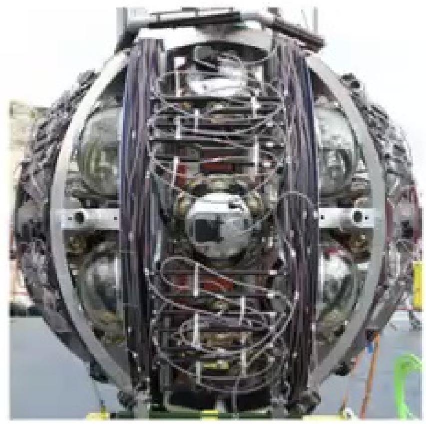


High-Energy Neutrinos ... Global View

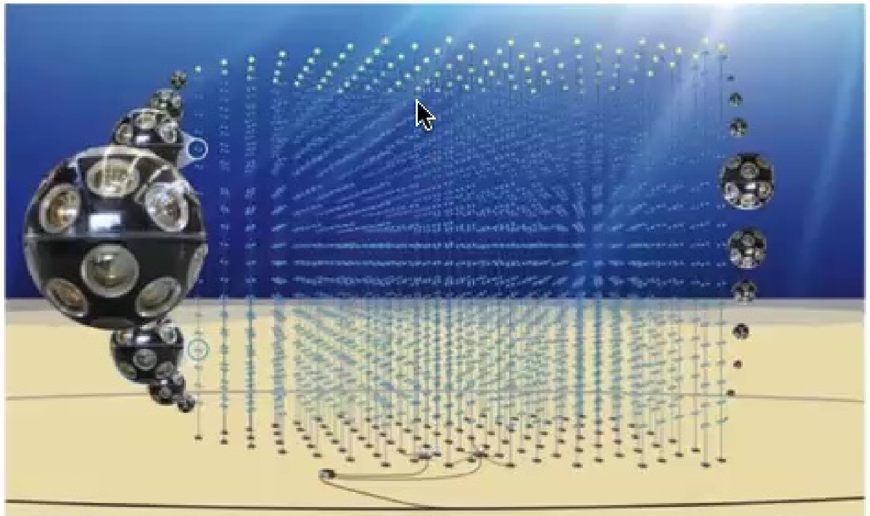


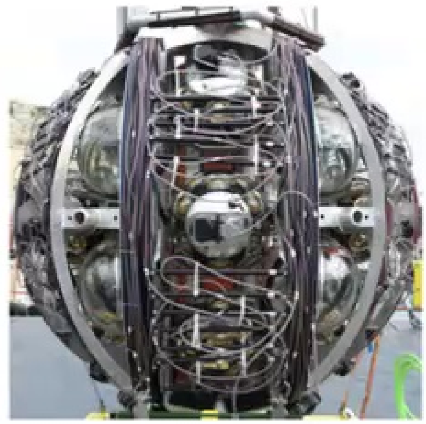
High-Energy Neutrinos … KM3NeT



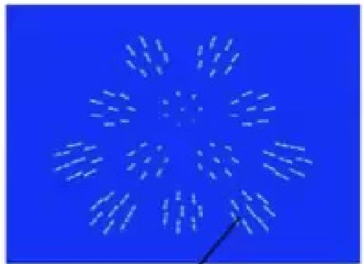


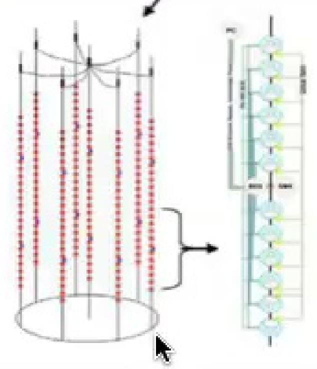
High-Energy Neutrinos … KM3NeT



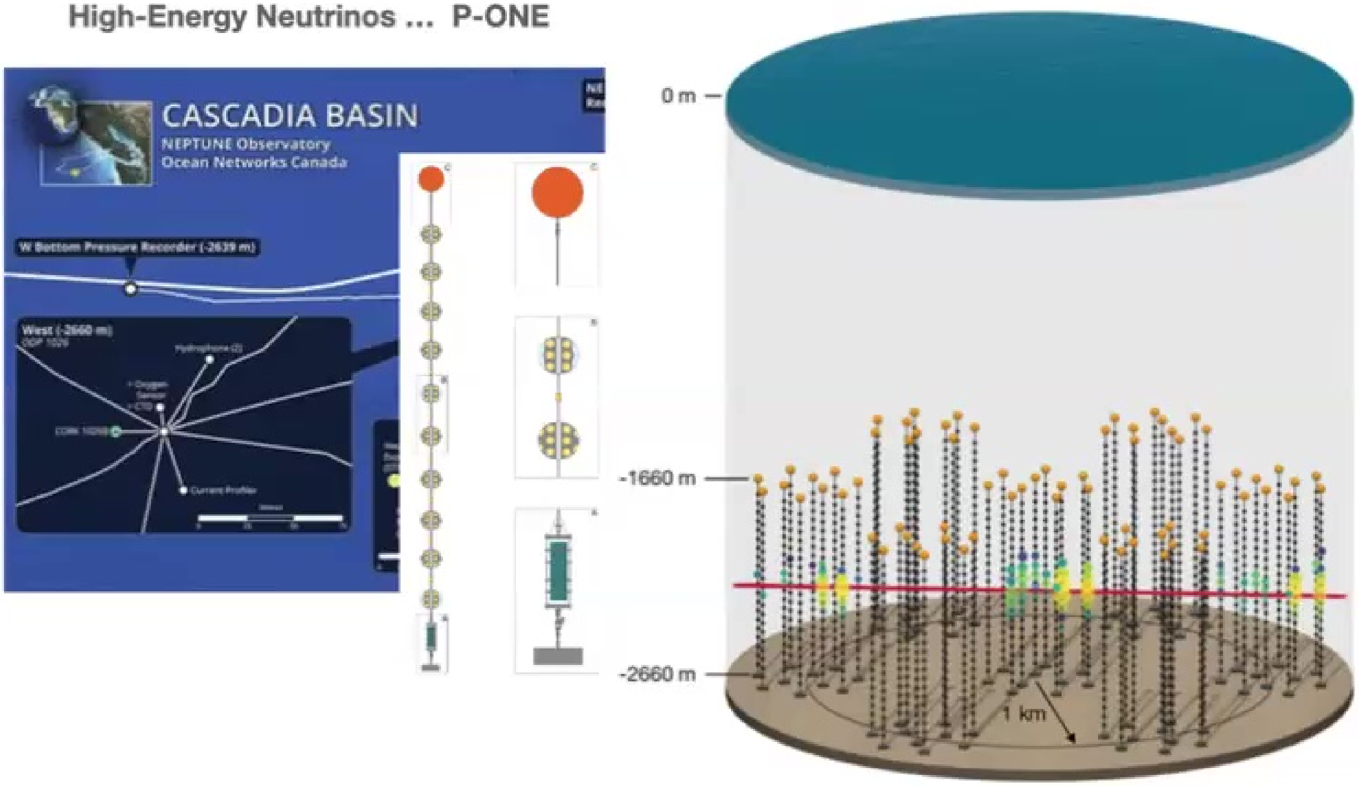


High-Energy Neutrinos … GVD

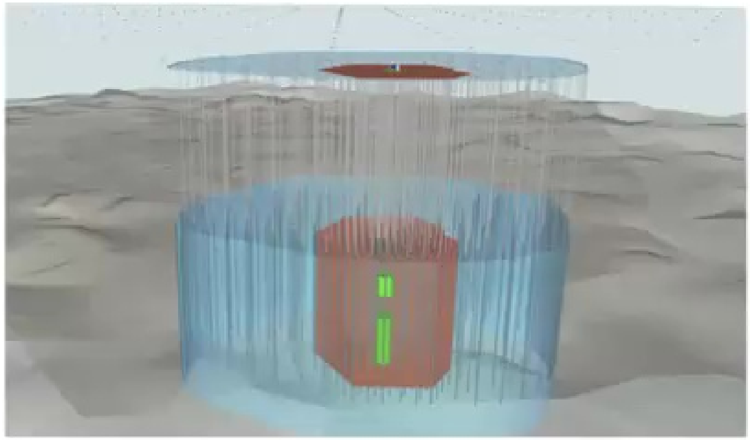


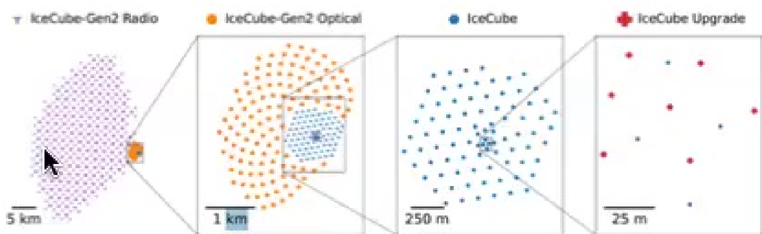


High-Energy Neutrinos … P-ONE

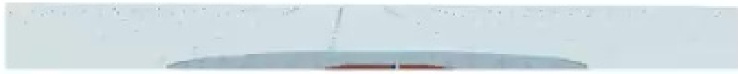


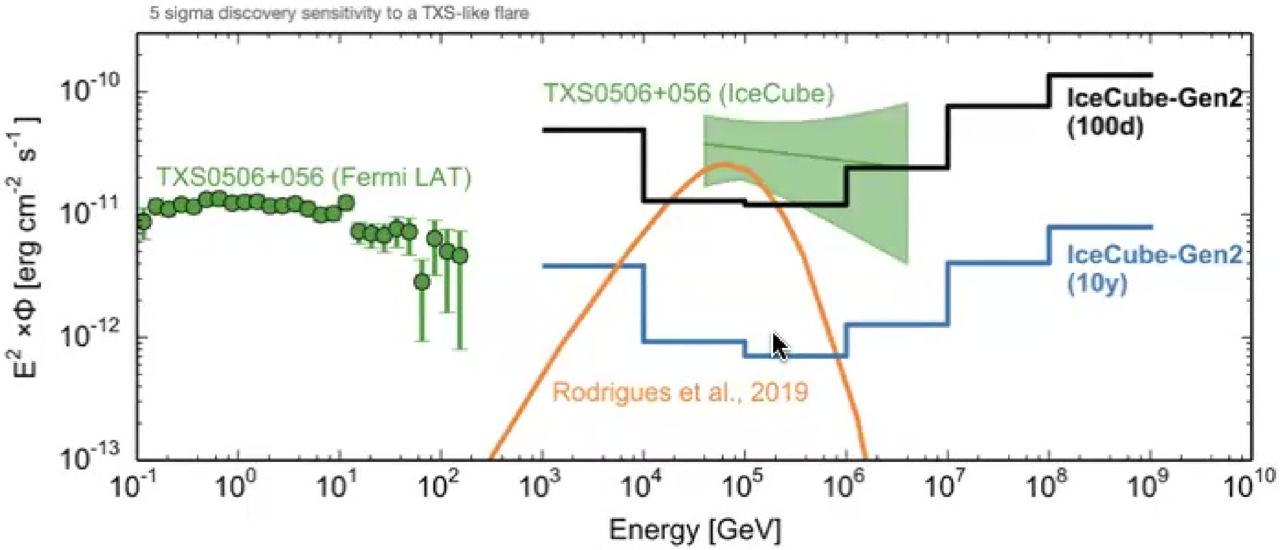
High-Energy Neutrinos ... Gen2

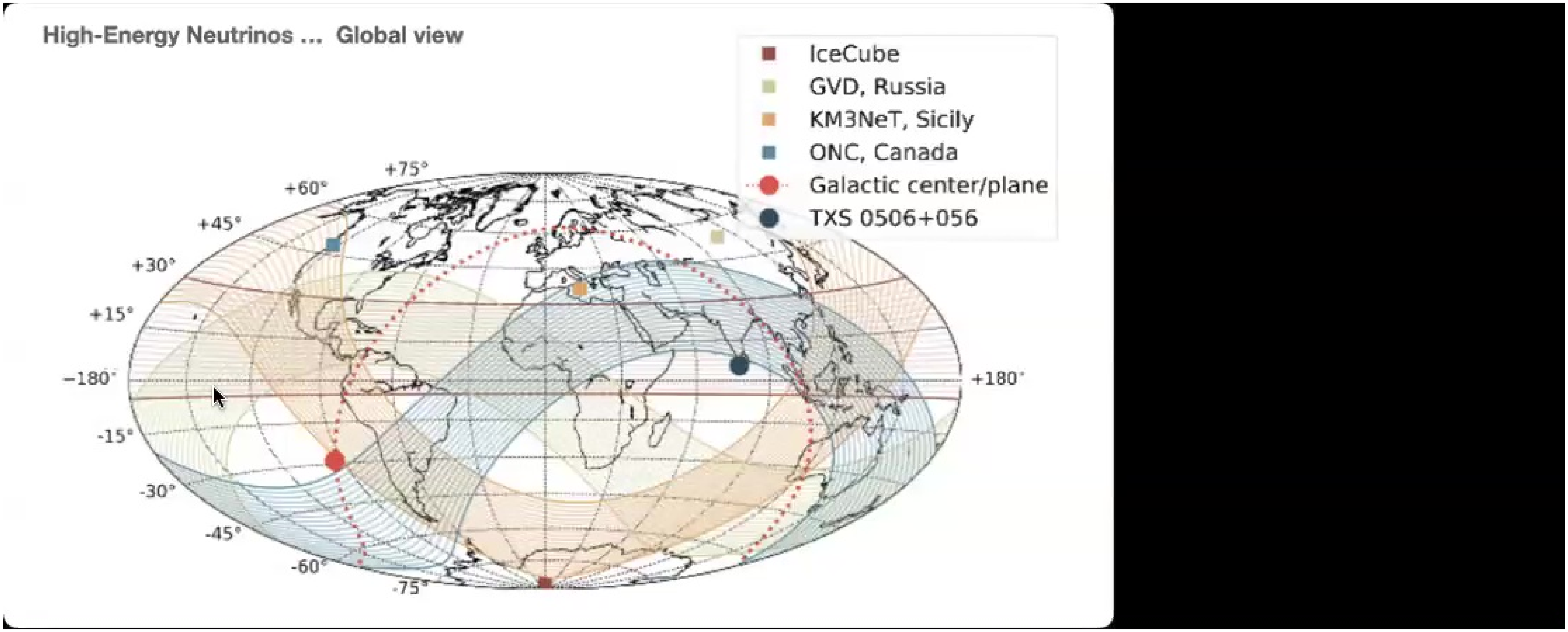




High-Energy Neutrinos … Gen2






High-Energy Neutrinos ... Global view
IceCube
GVD, Russia
KM3NeT, Sicily
ONC, Canada
Galactic center/plane
TXS 0506+056
+75°
+60°
+45°
+30°
+15°
−180°
+180°
-15°
-30°
-45°
-60°
-75°

High-Energy Neutrinos ... Global view