My Projects in Two Parts

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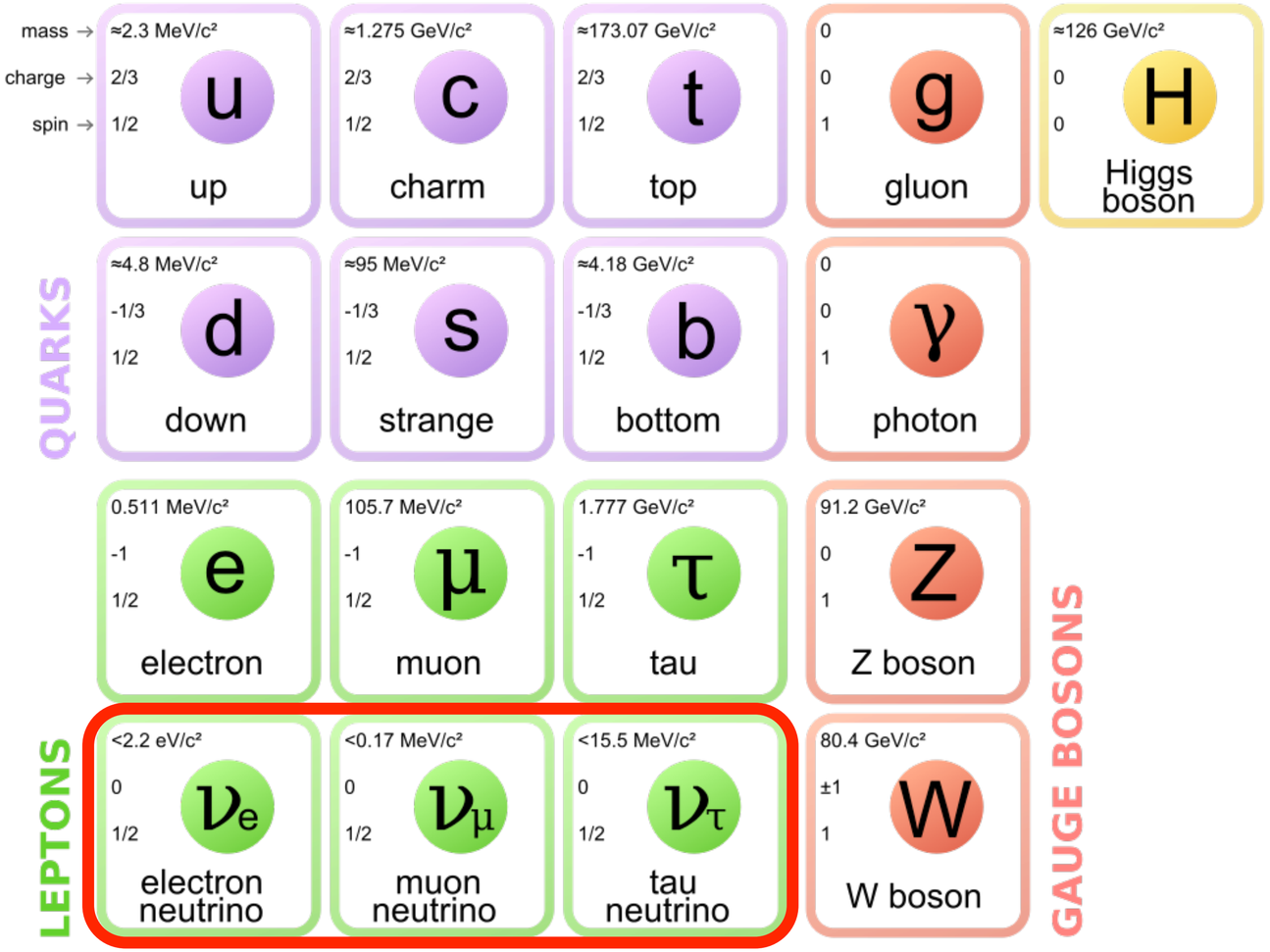
TRIUMF

Queen's University

Part 1 - Neutrinos

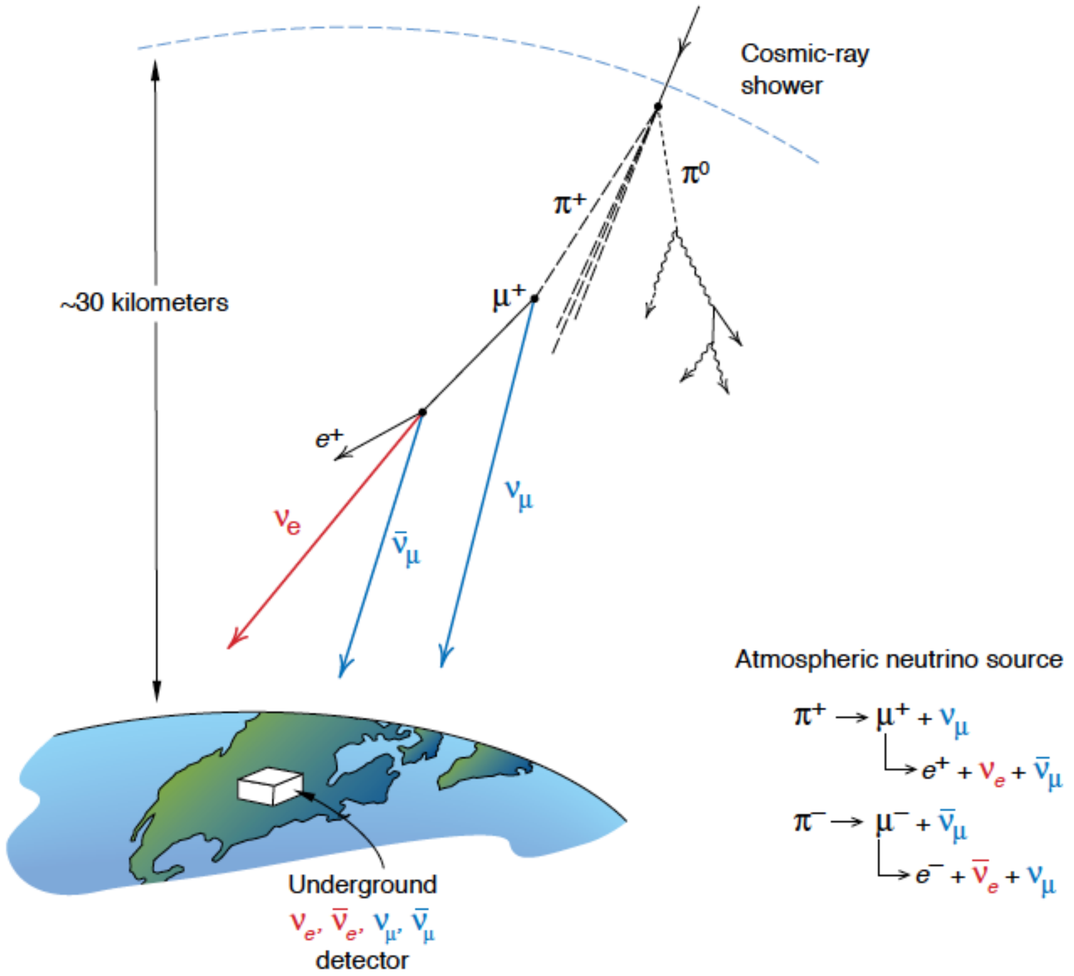
- Neutrinos have already been introduced here
- VERY light, neutral particles
- Only interact very weakly
- Very prevalent in the universe
- Three flavours



Sources of Neutrinos

- Experiments study neutrinos from different sources
  - Solar neutrinos (Homestake, Borexino, SNO)
  - Reactor neutrinos (KamLAND, Daya Bay, RENO)
  - Neutrino Beams (MINOS, T2K, OPERA)
  - Atmospheric Neutrinos (SuperK, Antares, IceCube)

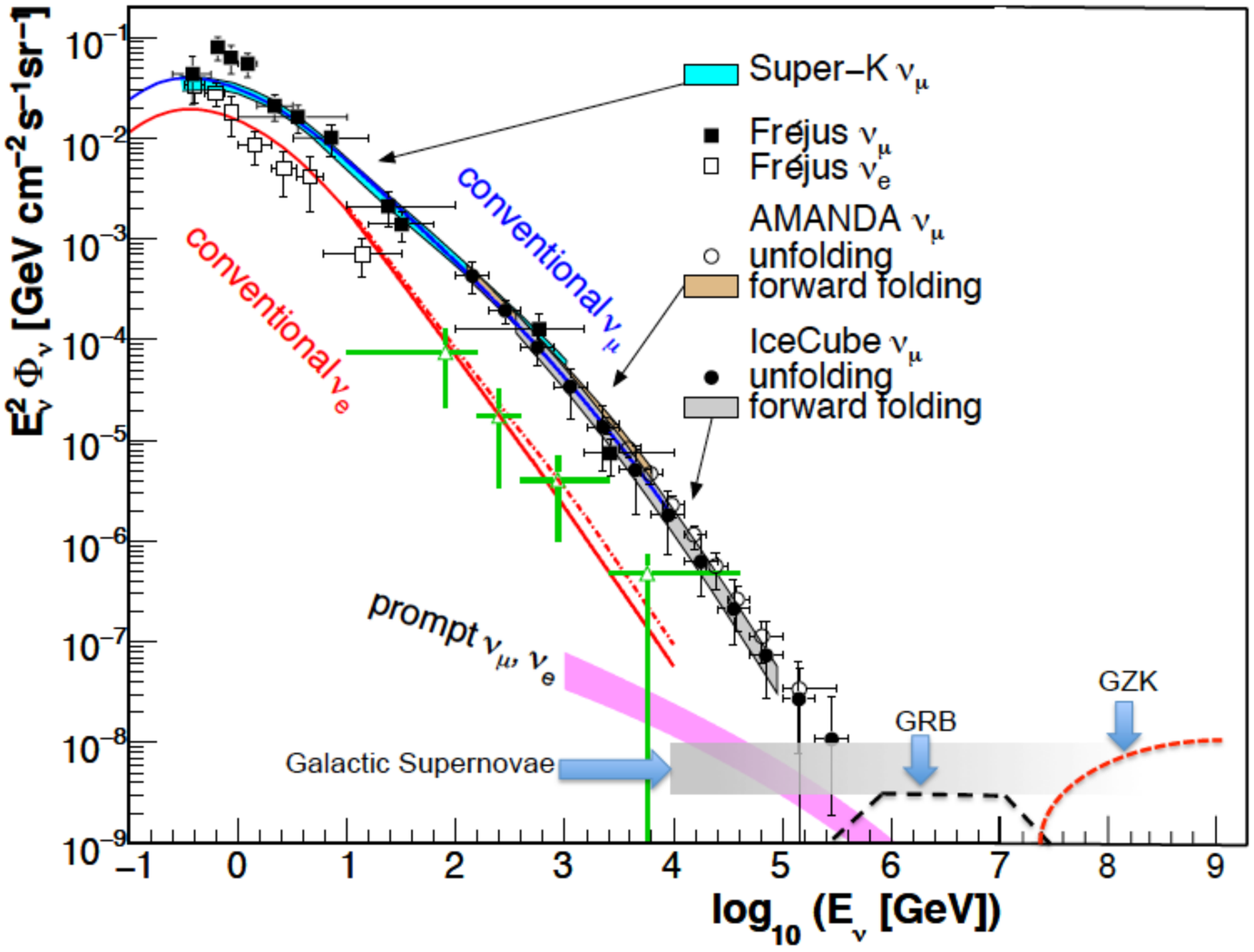
Atmospheric Neutrinos



- Source of neutrinos is the interaction of particles in the atmosphere
- These interactions produce neutrinos with an understood flux and flavour content

Neutrino Energy Spectrum

- Studying neutrinos at high energies was the motivation
- Success with intermediate IceCube configurations



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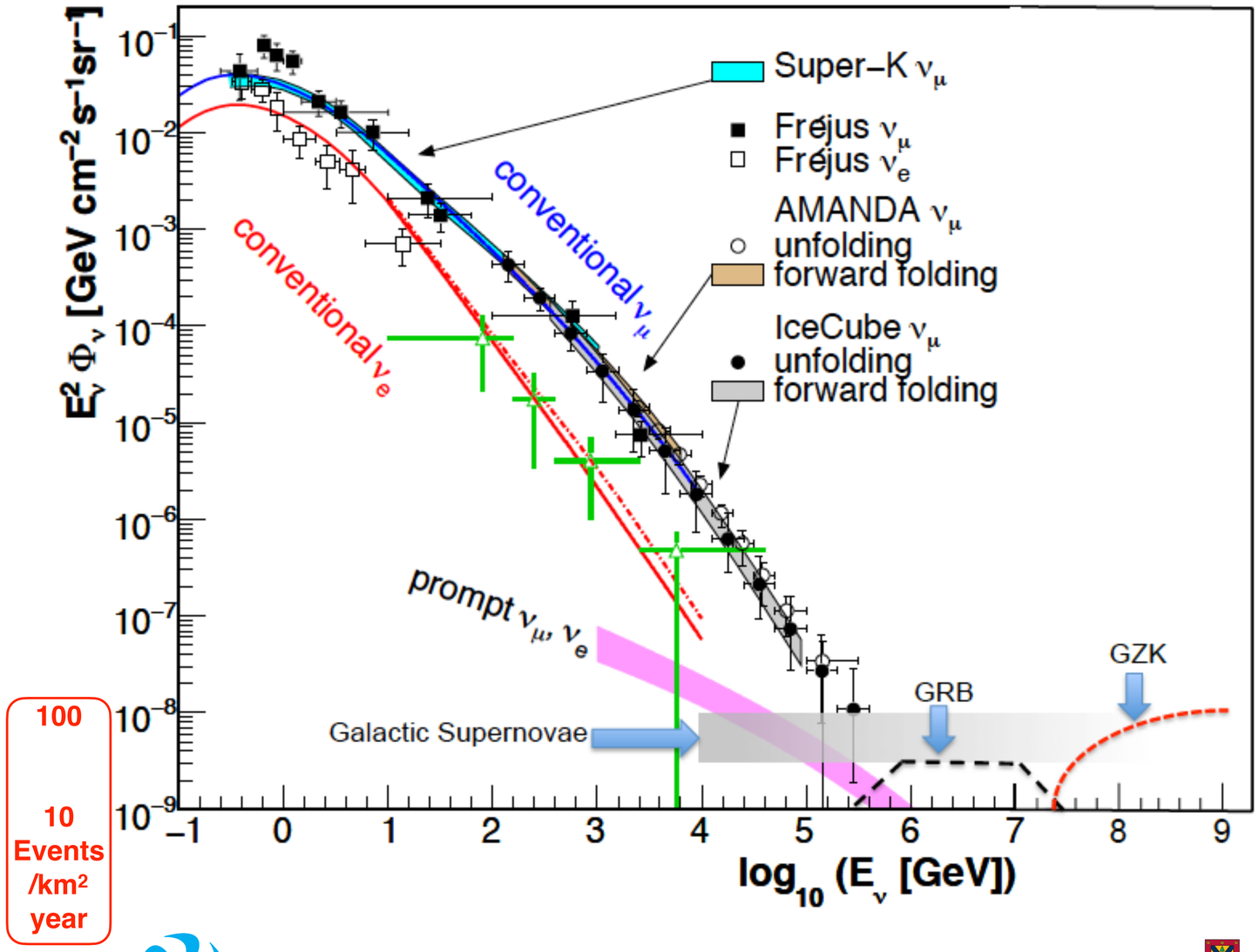
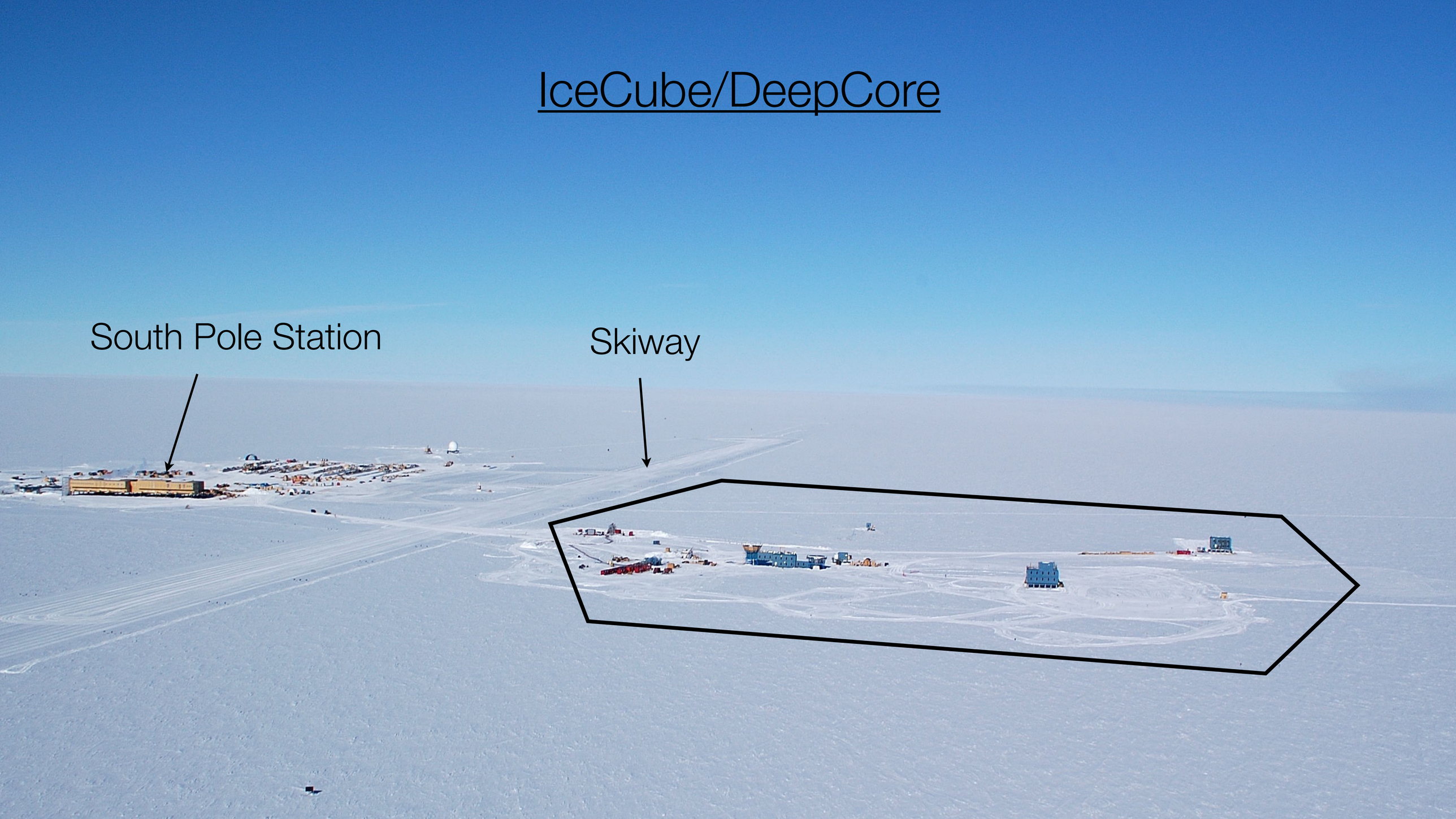


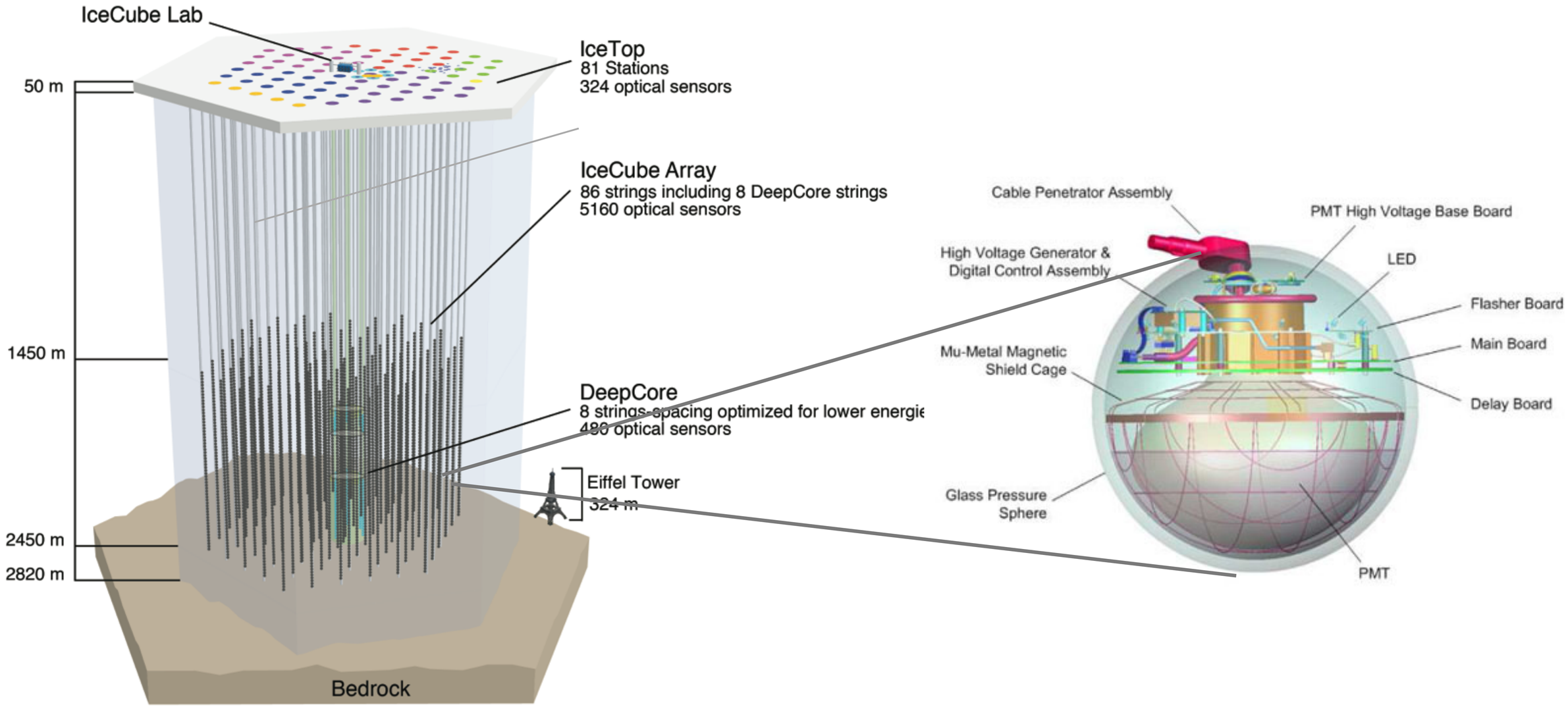
Detector Wish List

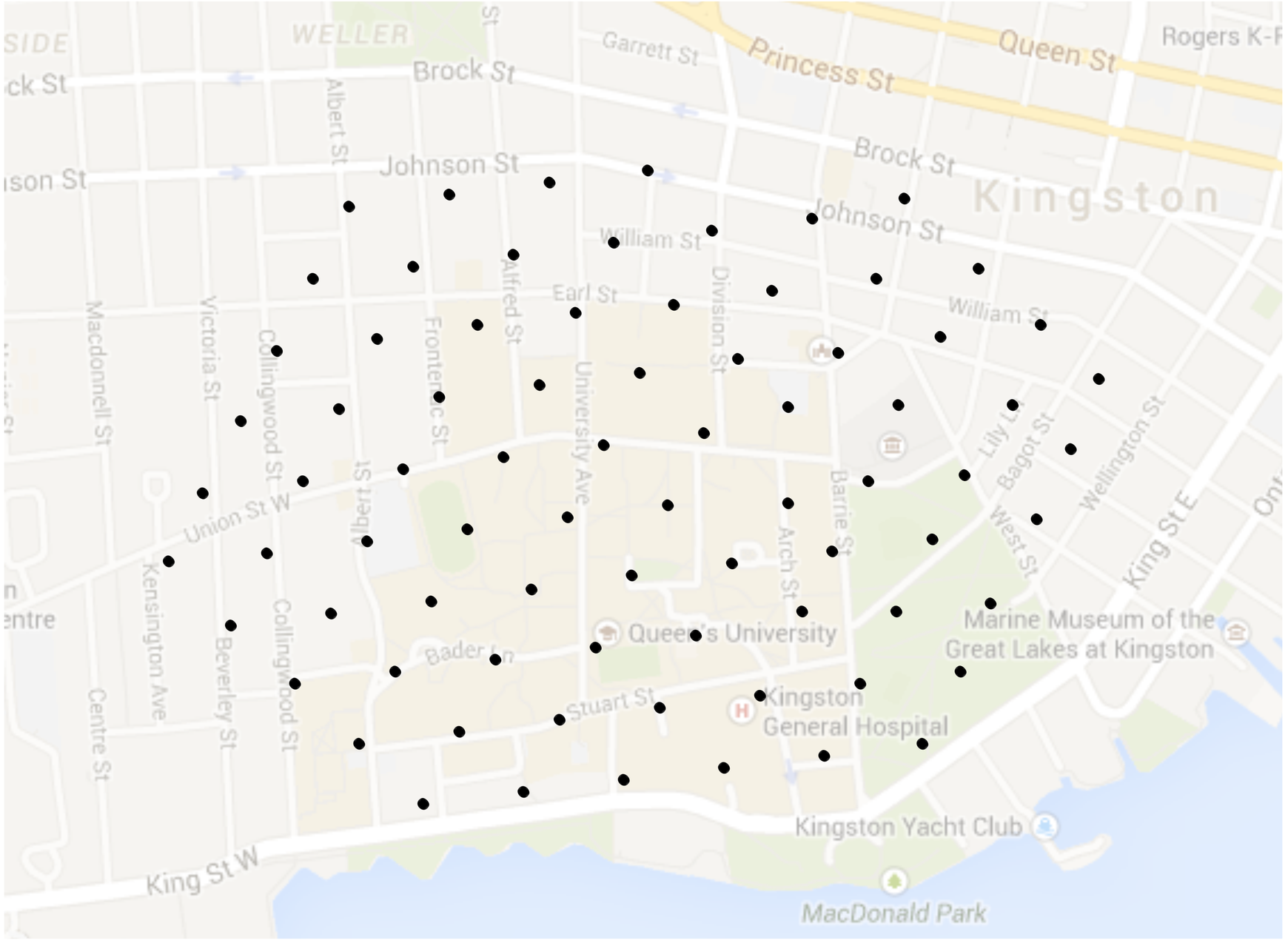
- In order to detect these neutrinos, a detector was needed which would:
  1. Have a large target mass
  2. Provide a very clear medium so that light can be detected
  3. Be at least somewhat shielded from outside radiation

IceCube/DeepCore

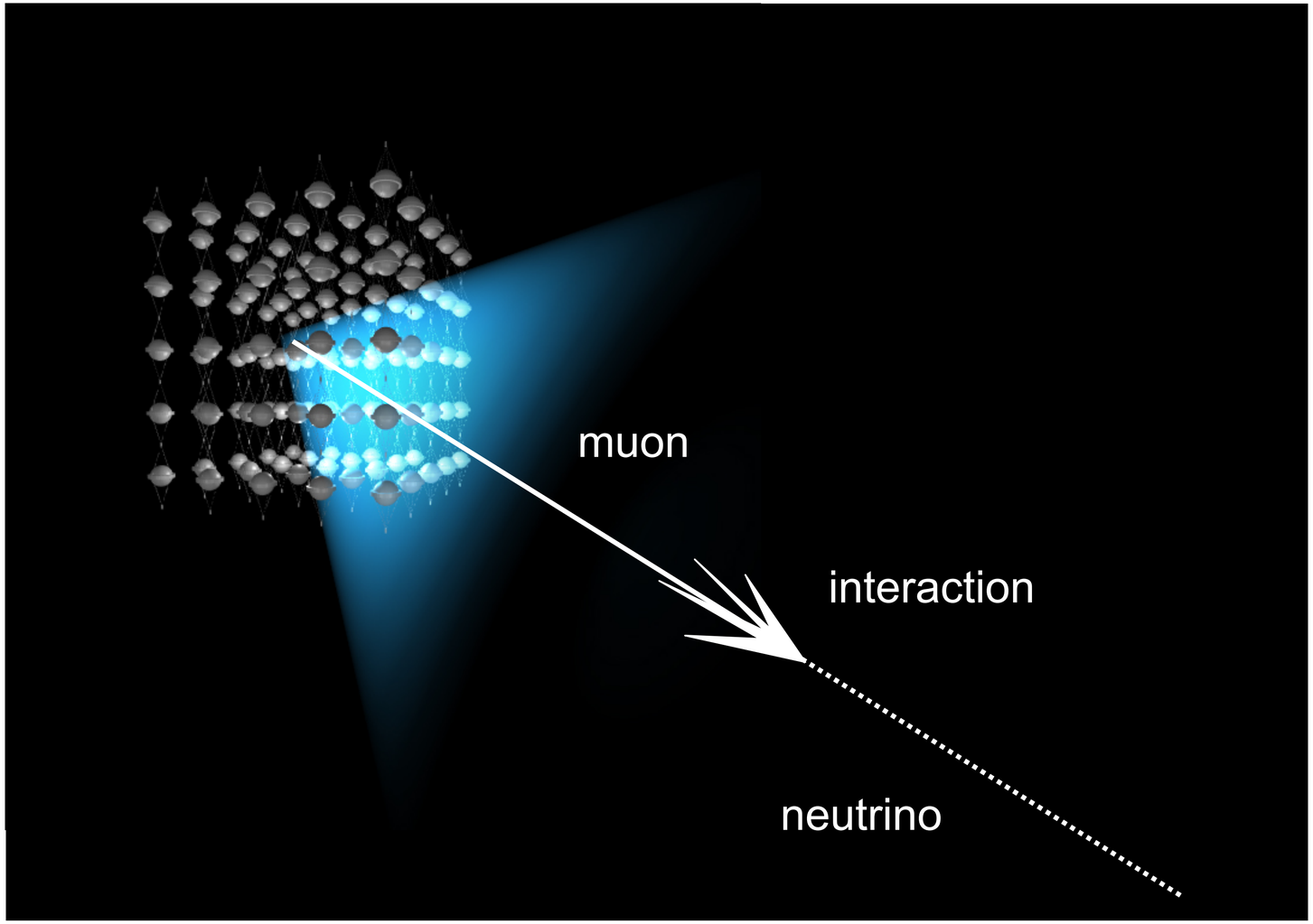


The IceCube Neutrino Telescope

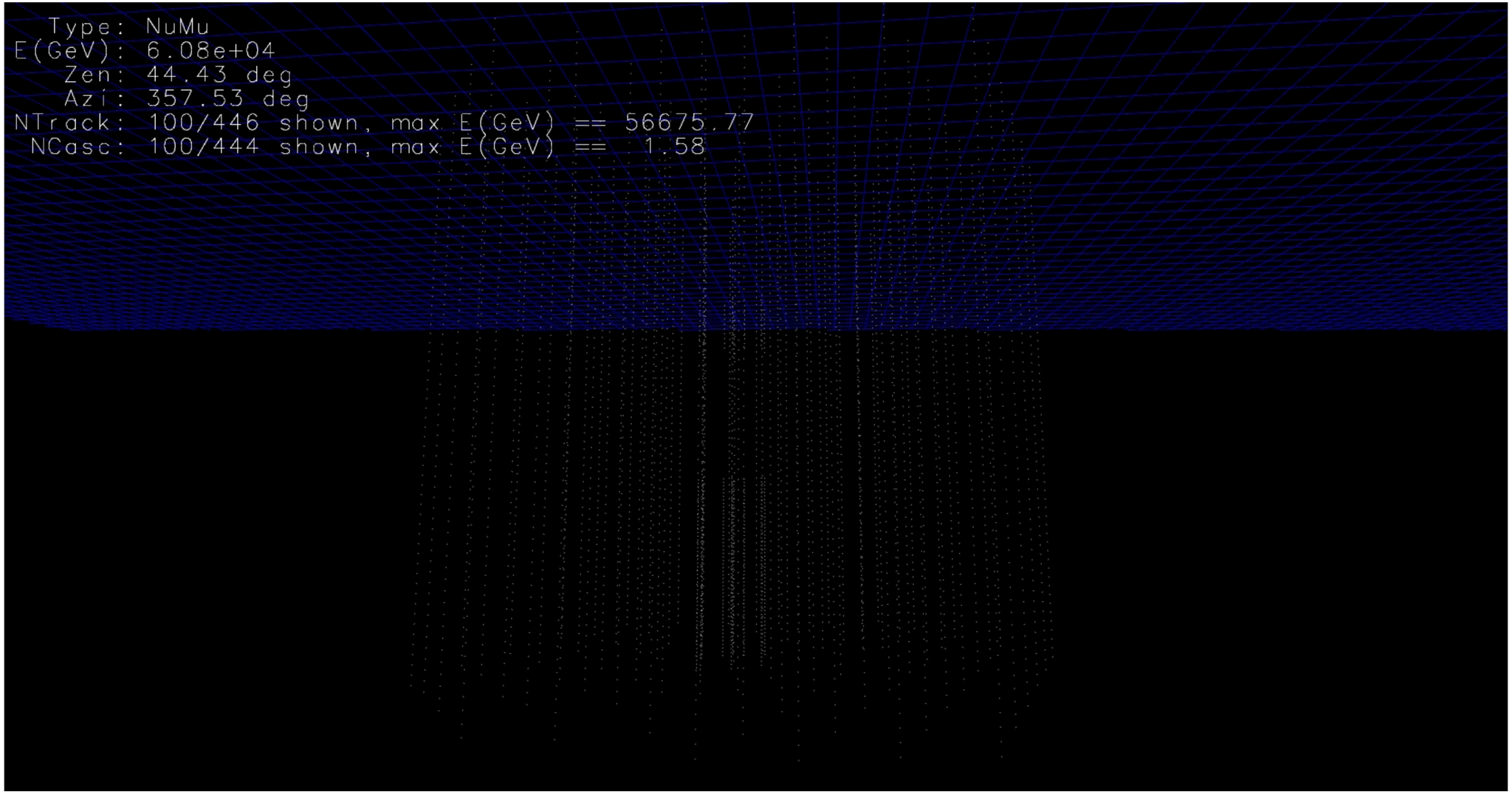



Brock St
Princess St
Queen St
Johnson St
Kingston
William St
Earl St
Division St
Alfred St
Frontenac St
University Ave
Albert St
Union St W
Victoria St
Collingwood St
Macdonnell St
Kensington Ave
Beverley St
Centre St
Barrie St
Arch St
West St
Lily St
Bagot St
Wellington St
King St E
Queen's University
Bader Ln
Stuart St
Kingston General Hospital
Marine Museum of the Great Lakes at Kingston
Kingston Yacht Club
King St W
MacDonald Park
Garrett St
Albert St
WELLER

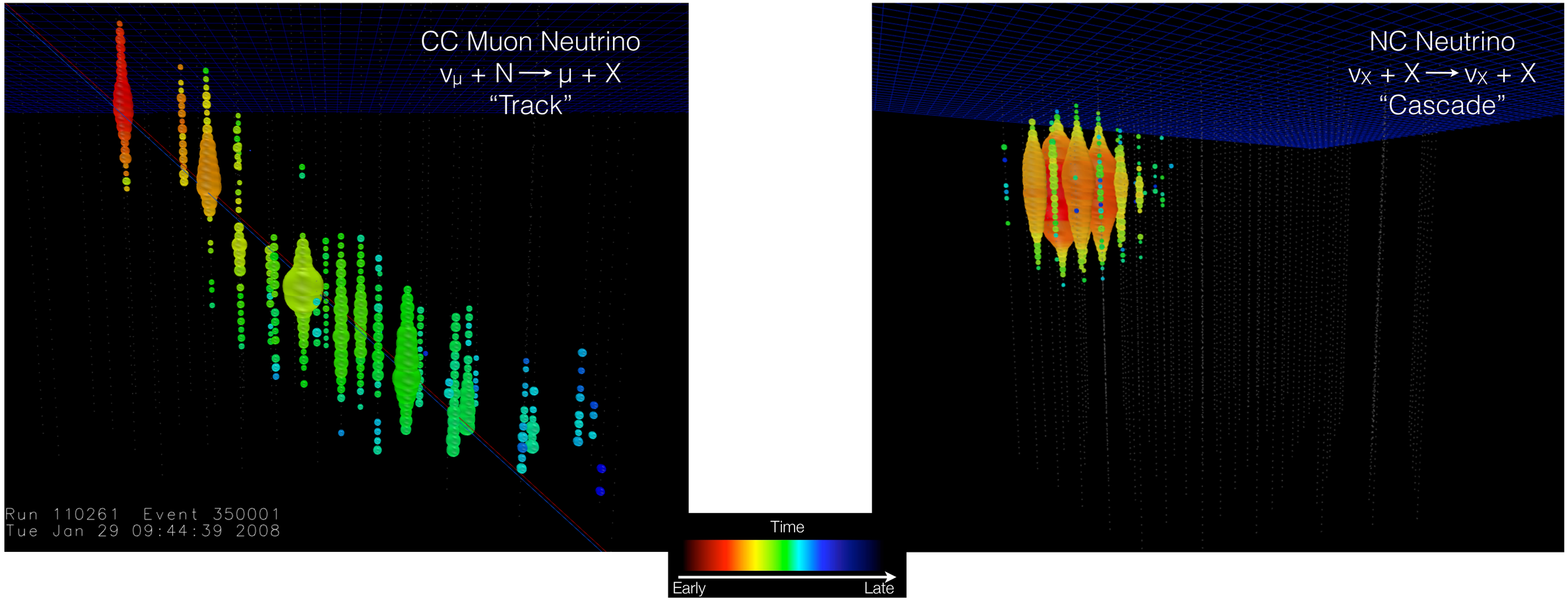
Detection Method



Detection of Events



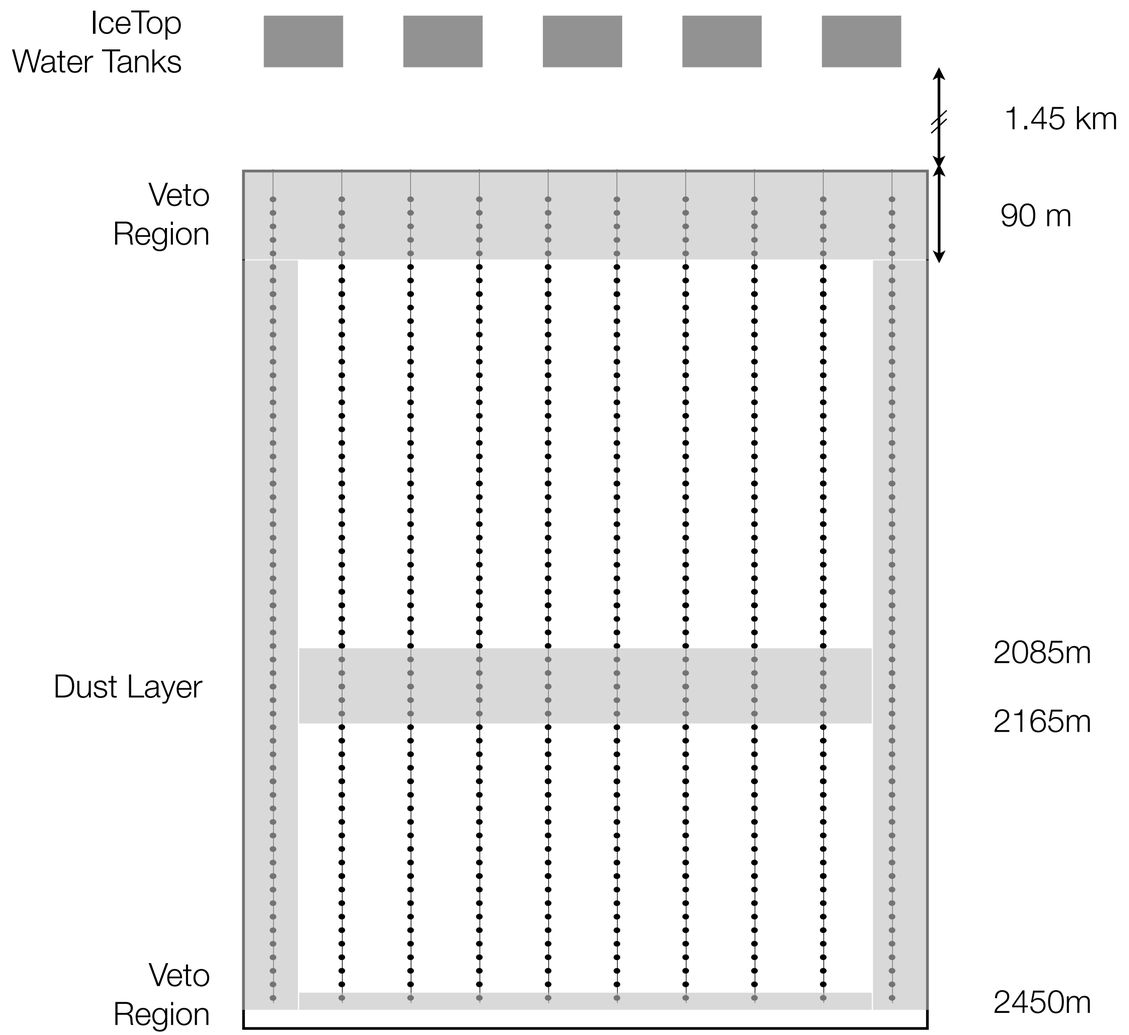
Events in the Detector



- Events are separable using their signature in the detector

Event Selection

- Use an extensive veto to remove specific classes of events
- Want to retain only events which have their first interaction inside the detector



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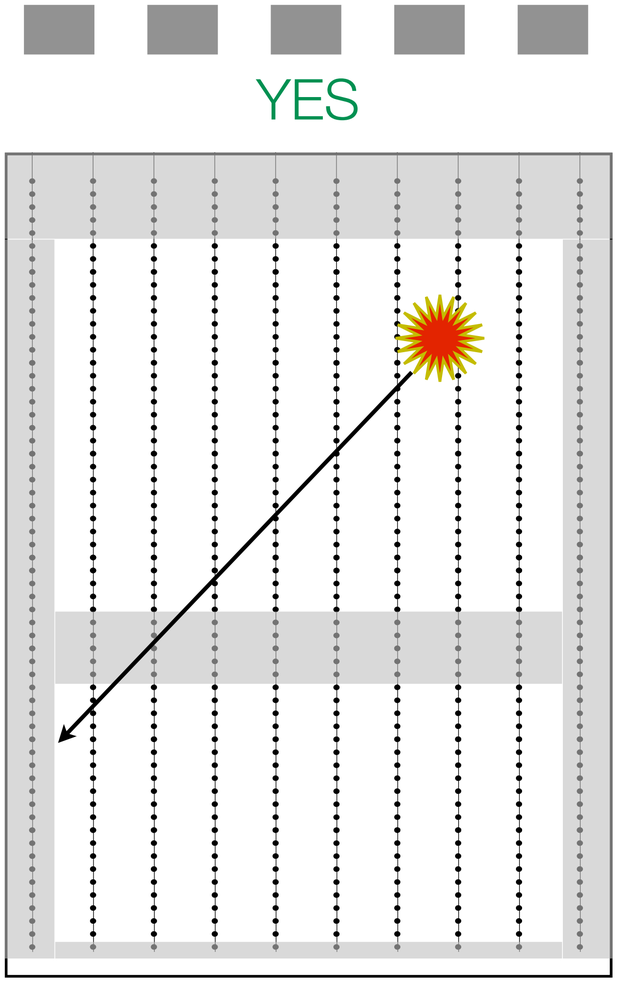
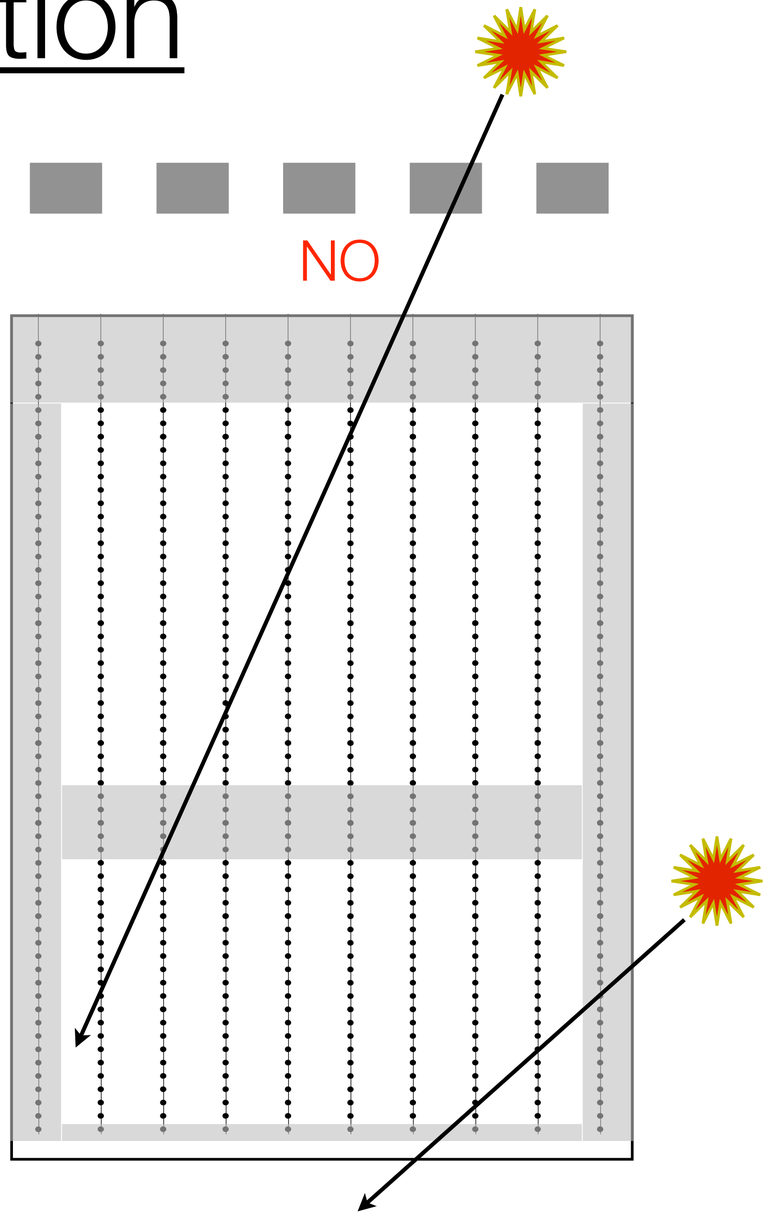
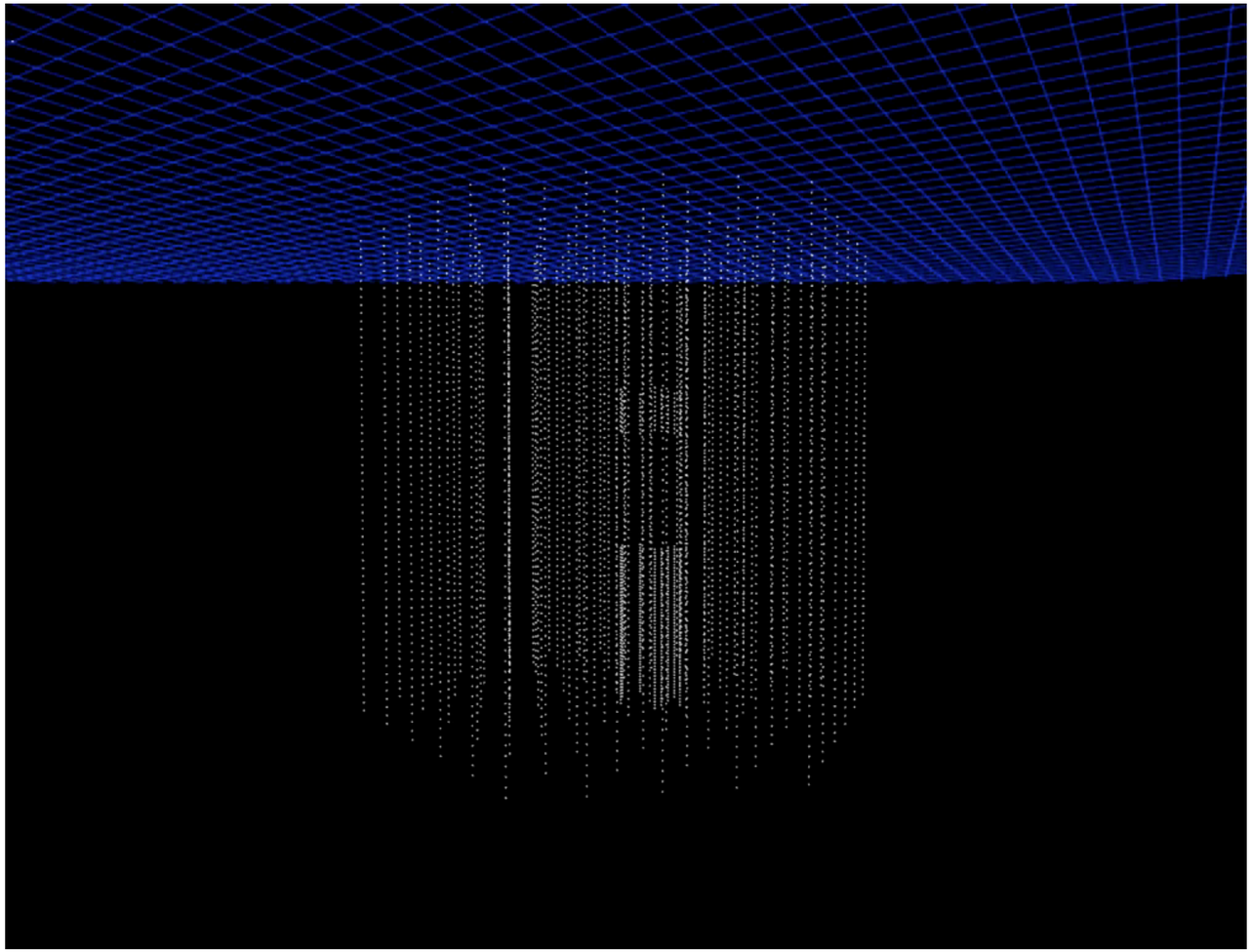




Why so strict?



- This is 10 **ms** of data
- In one year IceCube will detect:

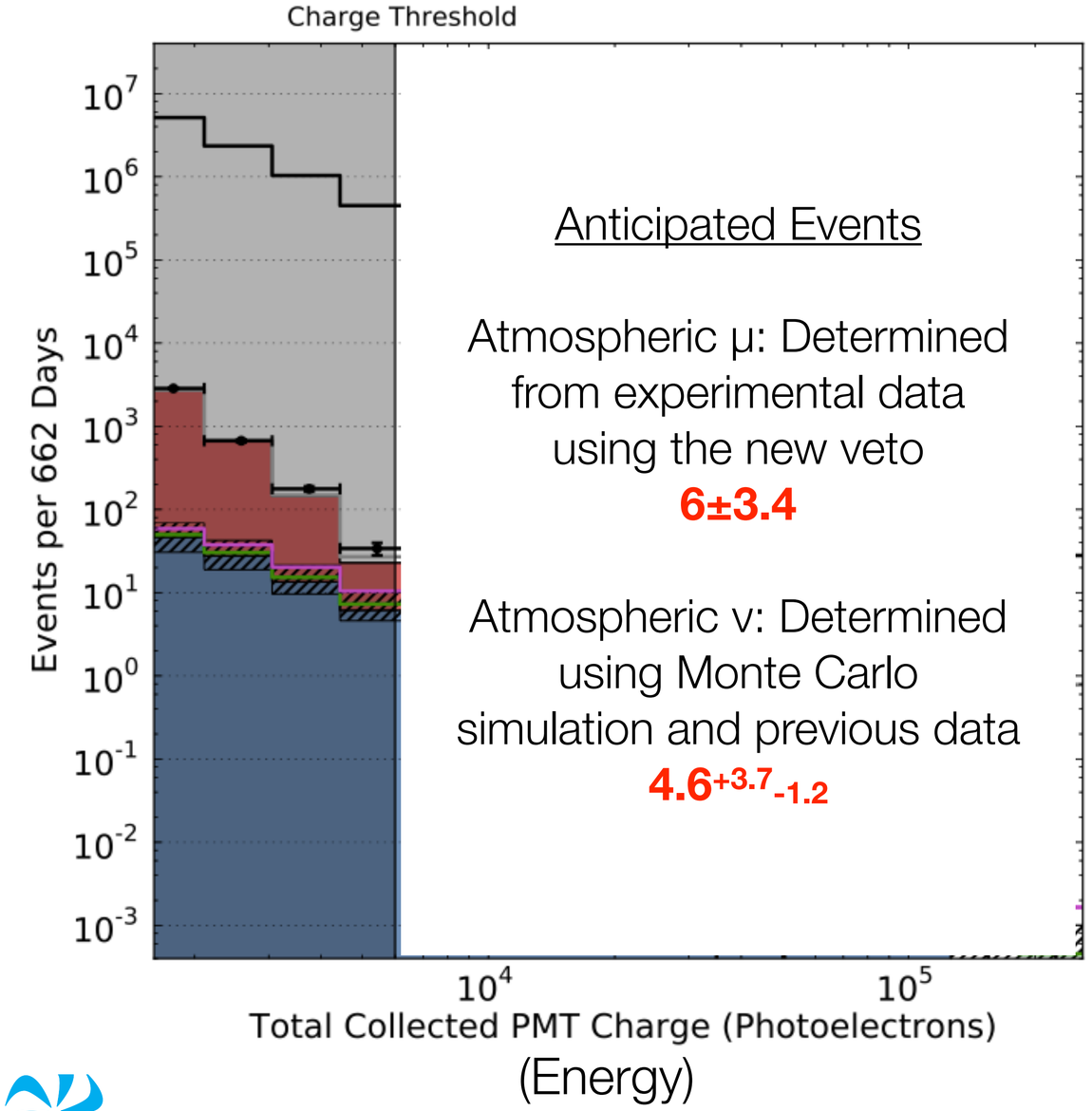
~10^{11} atmospheric muons (3000 per second)

~10^{5} atmospheric ν->μ (1 every 6 minutes)

~10 cosmic ν->μ

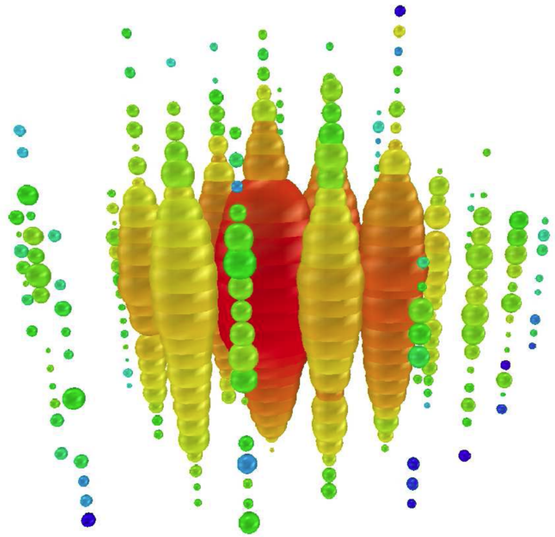
Analysis Preparation

- Several aspects required to prepare for the full analysis of the high energy events
- Need to determine the number of neutrinos expected and their energy spectrum
- Need to verify the veto procedure with existing data/ Monte Carlo

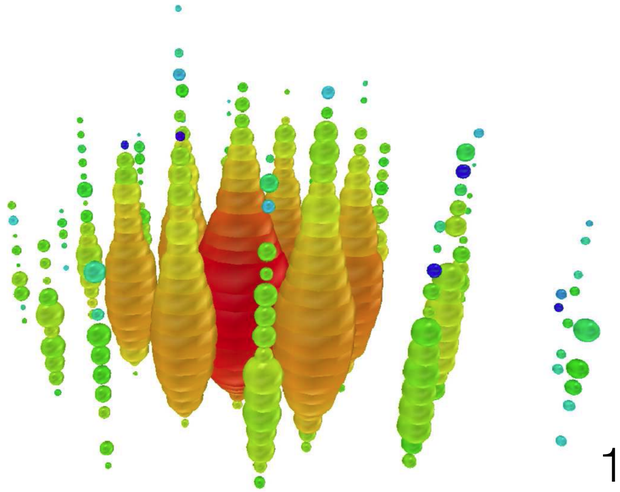


IceCube Results

- Try out these new methods on a subsample of the IceCube data
- Completely unexpectedly, two very high energy events were found



1.04±0.16 PeV



1.14±0.17 PeV

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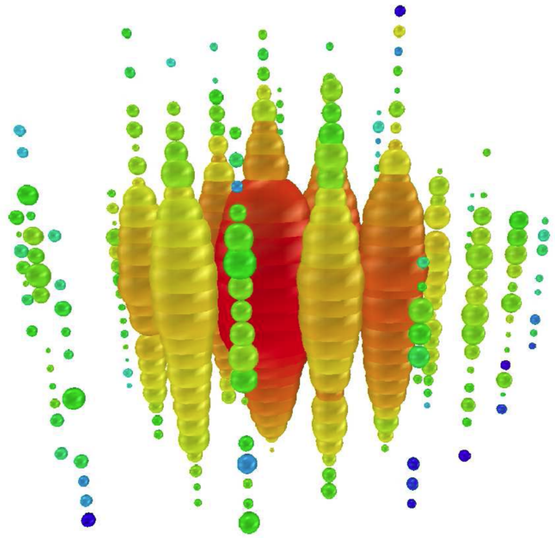

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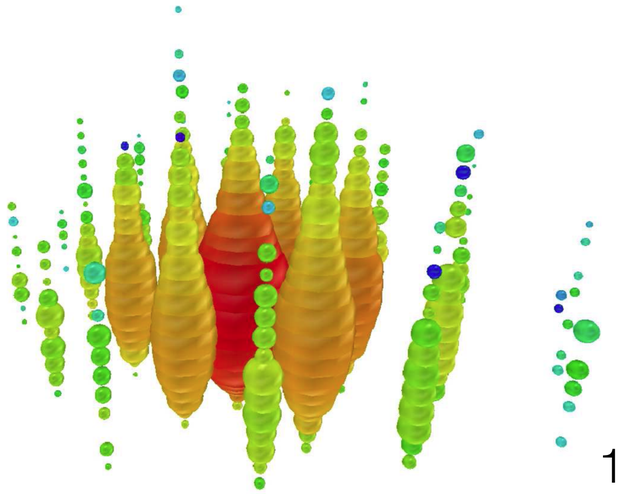


1.14±0.17 PeV

Predicted Results

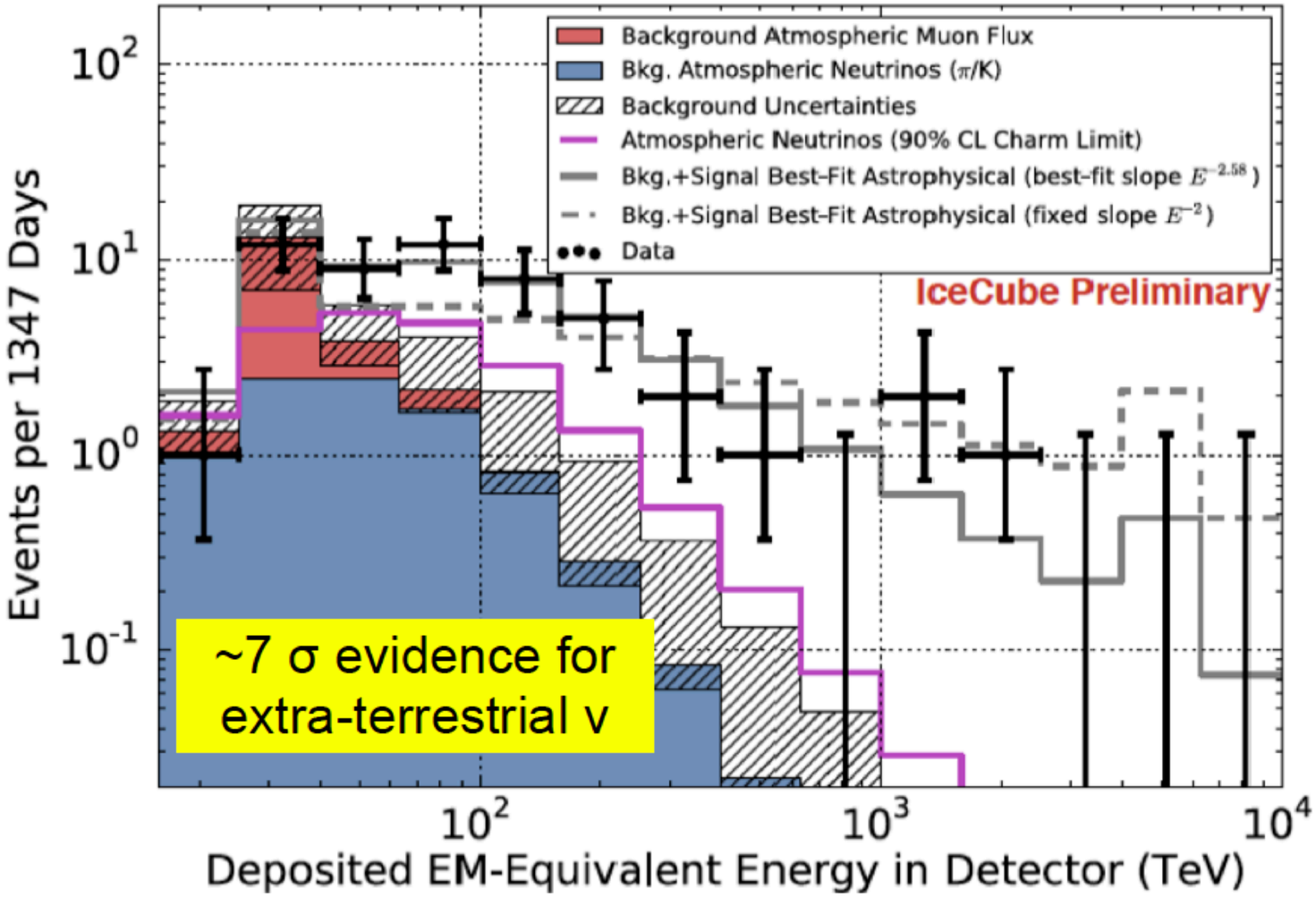
Expected to see $10.6^{+5.0}_{-3.6}$ in two years

IceCube Results

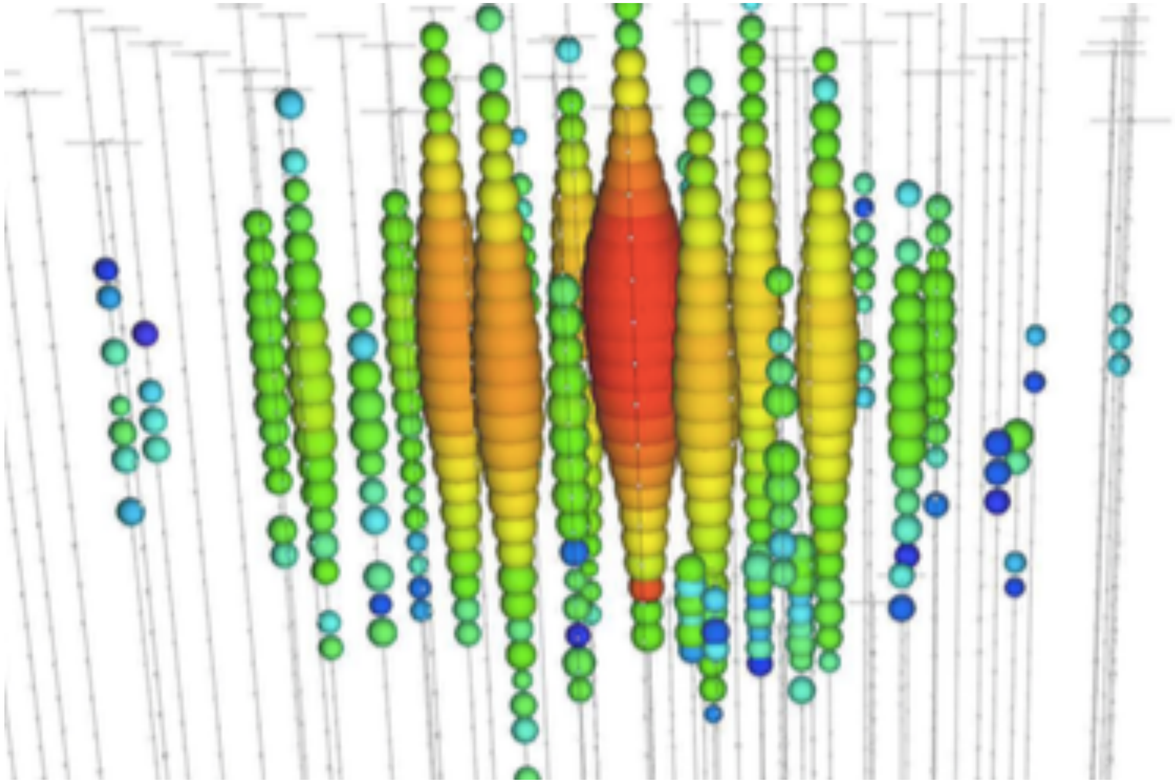
Actually saw 28 (in the first two years of data)

IceCube Results

54 events observed with 20±6 expected from atmosphere



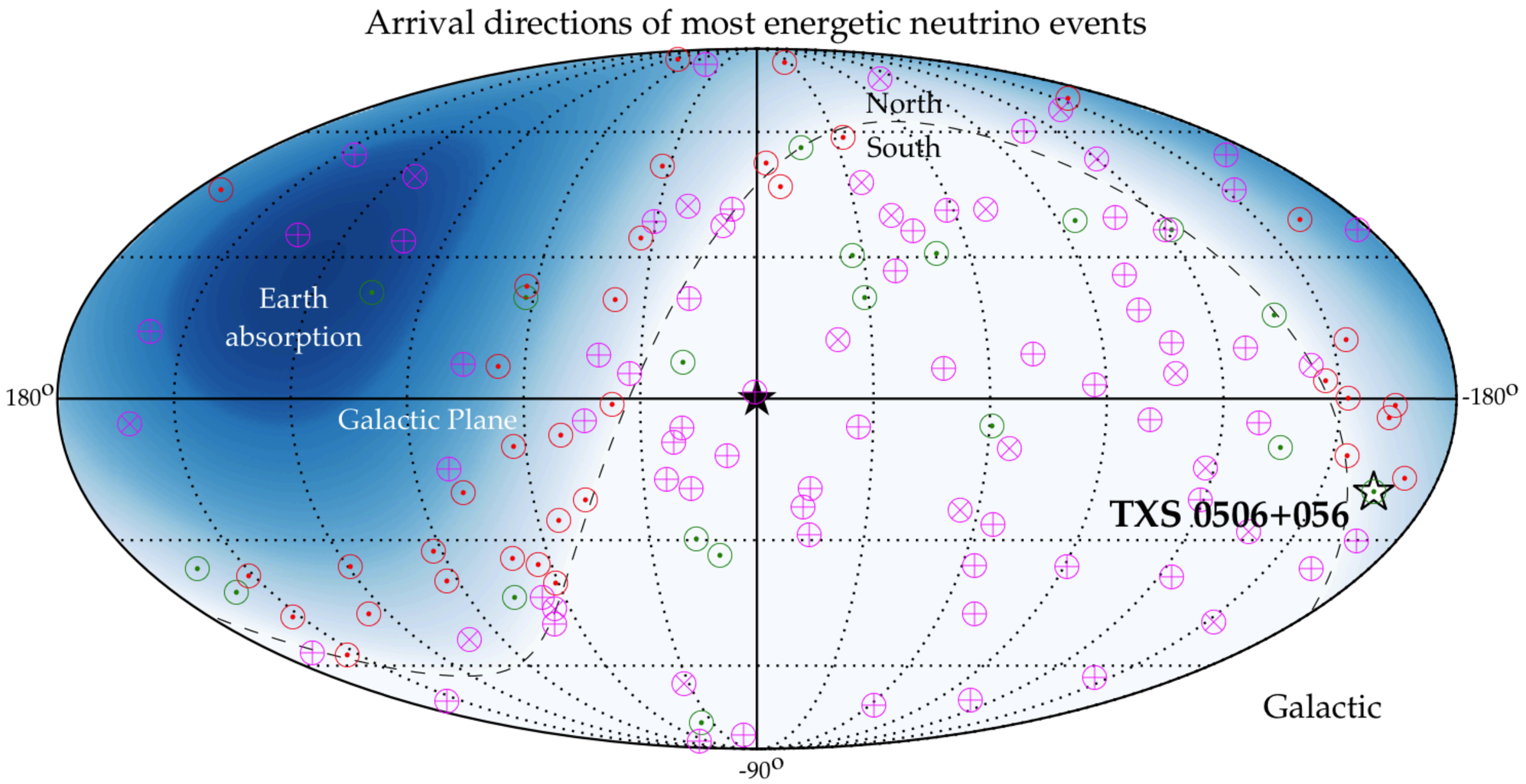
Highest Energy



2.2 PeV

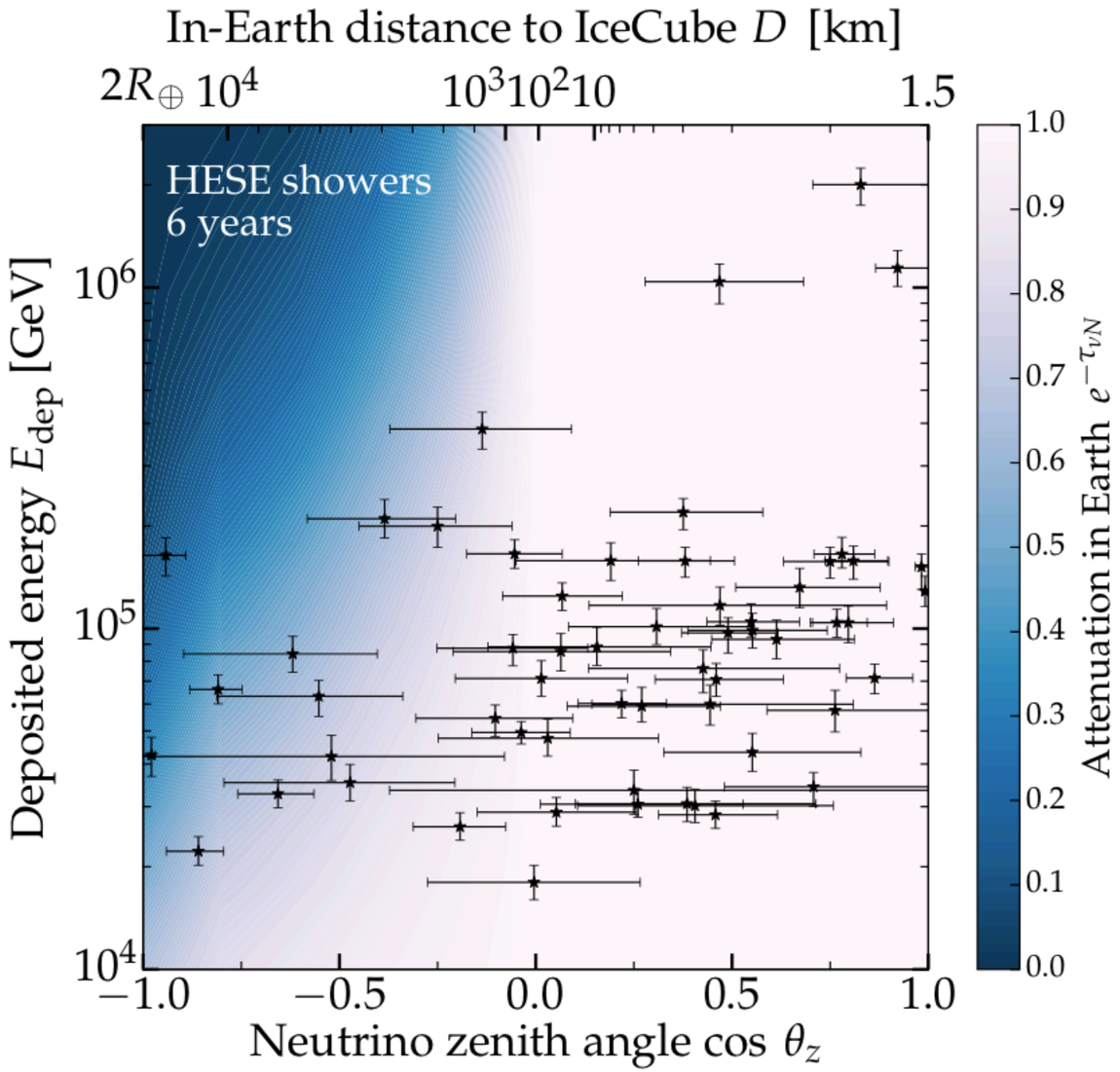
- Ernie & Bert stood as the highest energy events for some time
- During the full analysis, a new record-setting event was found

Source?


Arrival directions of most energetic neutrino events
North
South
Earth
absorption
Galactic Plane
180°
-180°
-90°
TXS 0506+056
Galactic

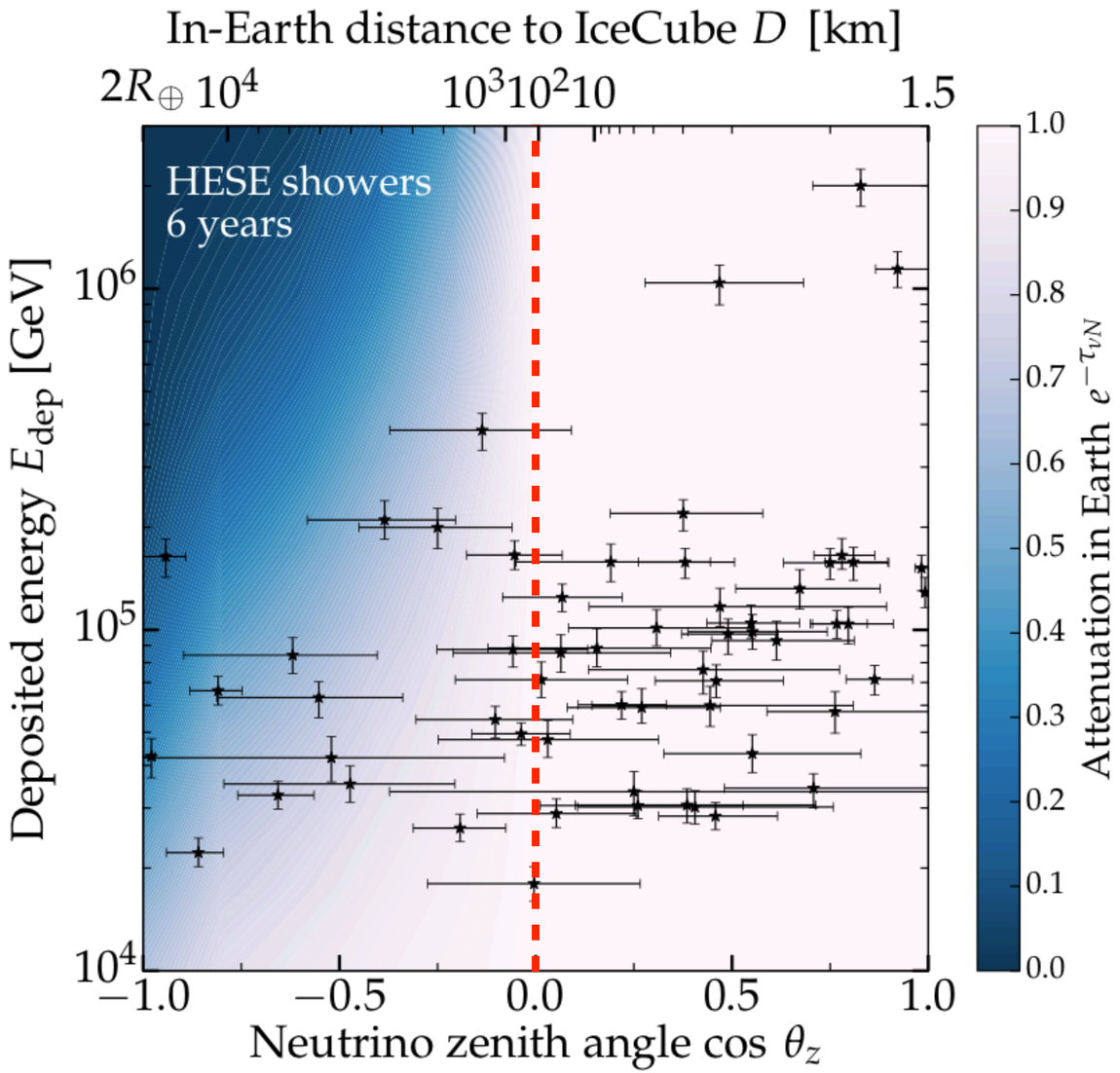
Energy Isn't Everything…

- Problem is the Earth becomes opaque to ν on the PeV scale
- We need a solution that doesn't traverse the entire Earth

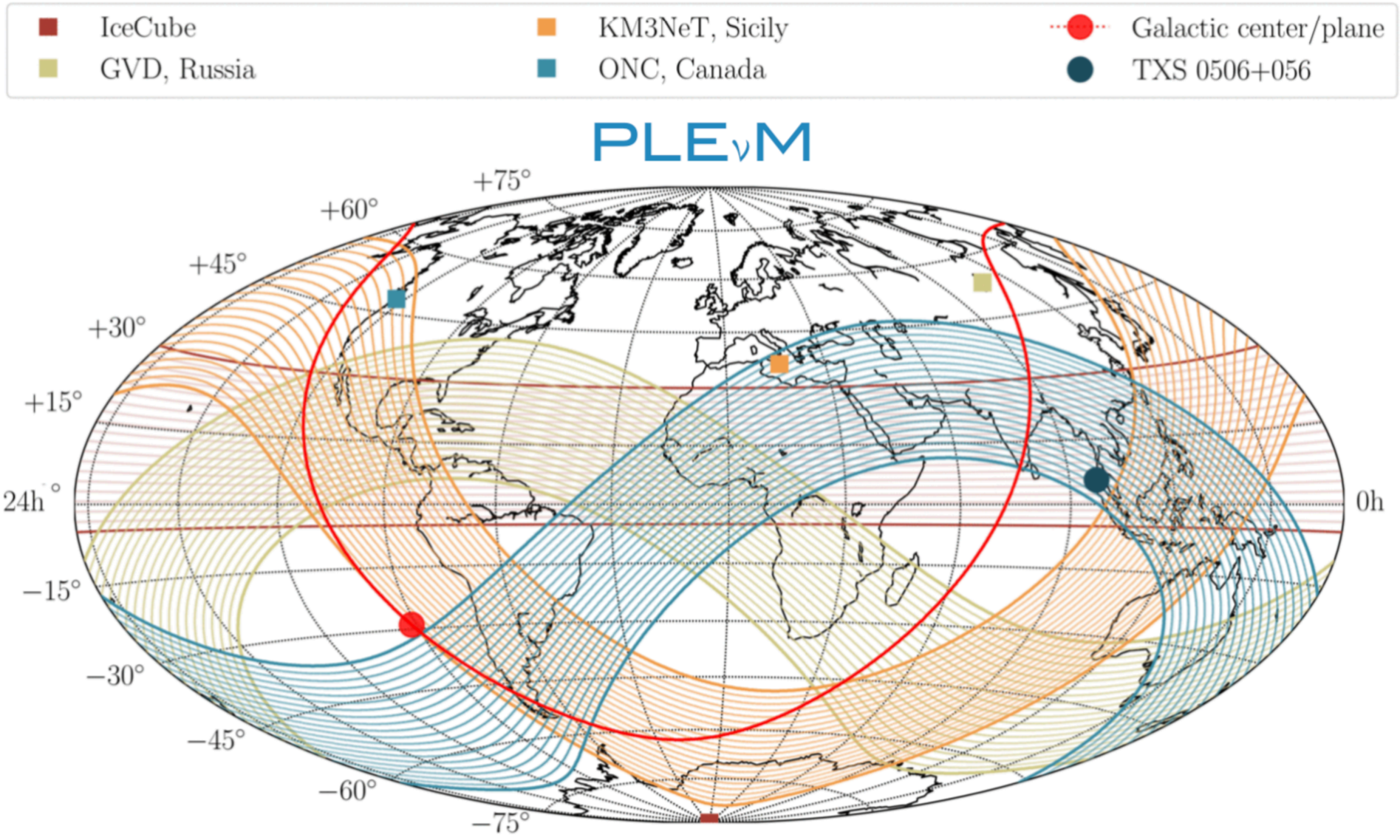


Energy Isn't Everything…

- Problem is the Earth becomes opaque to ν on the PeV scale
- We need a solution that doesn't traverse the entire Earth
- Focus on the horizon

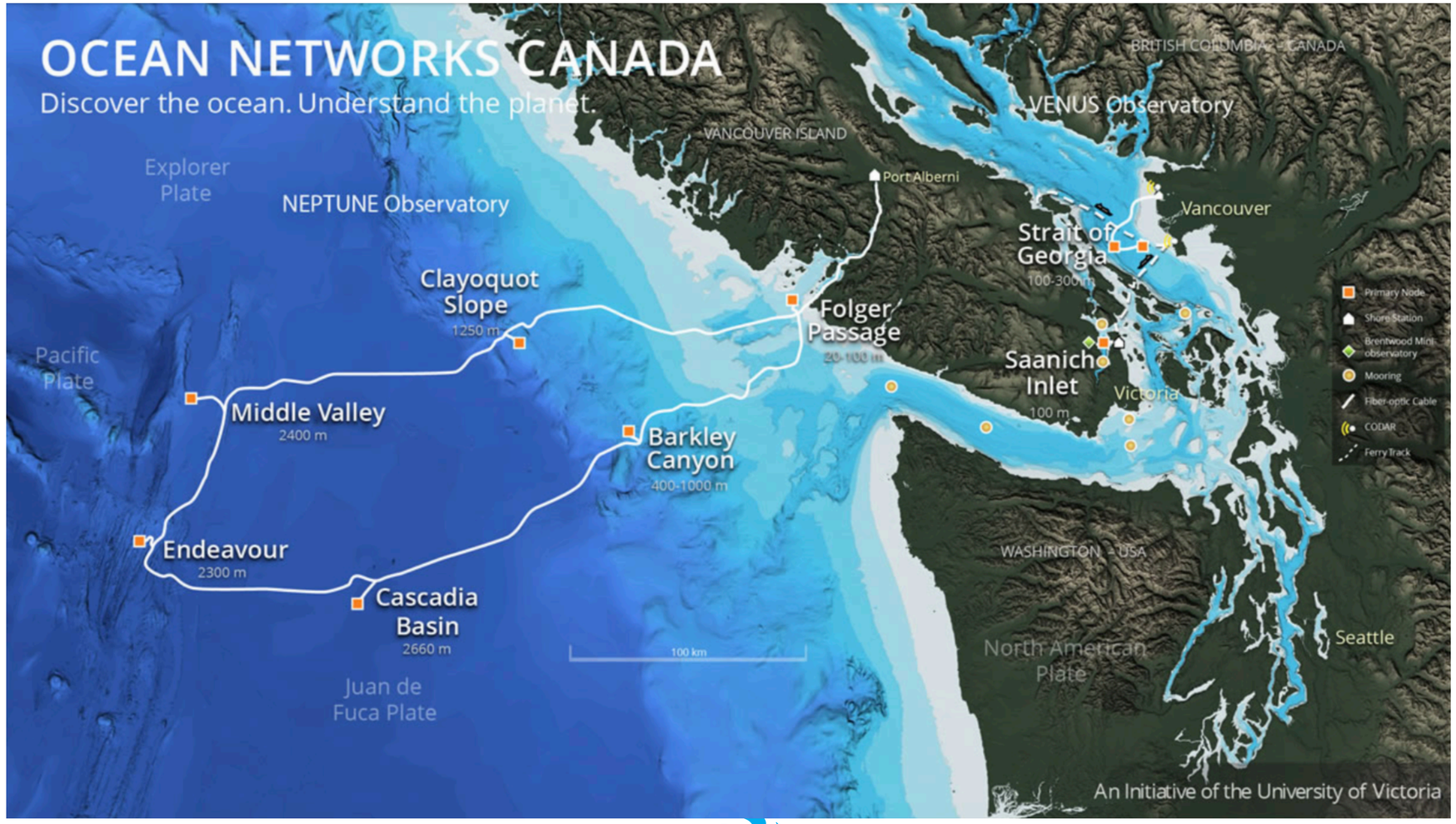


But… coverage?



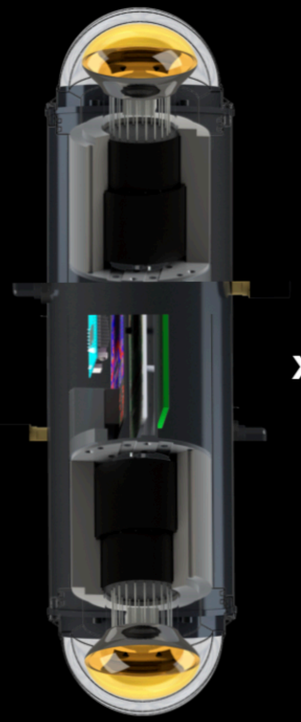
Location

- So this thing should be in the northern hemisphere, somewhere with deep enough water



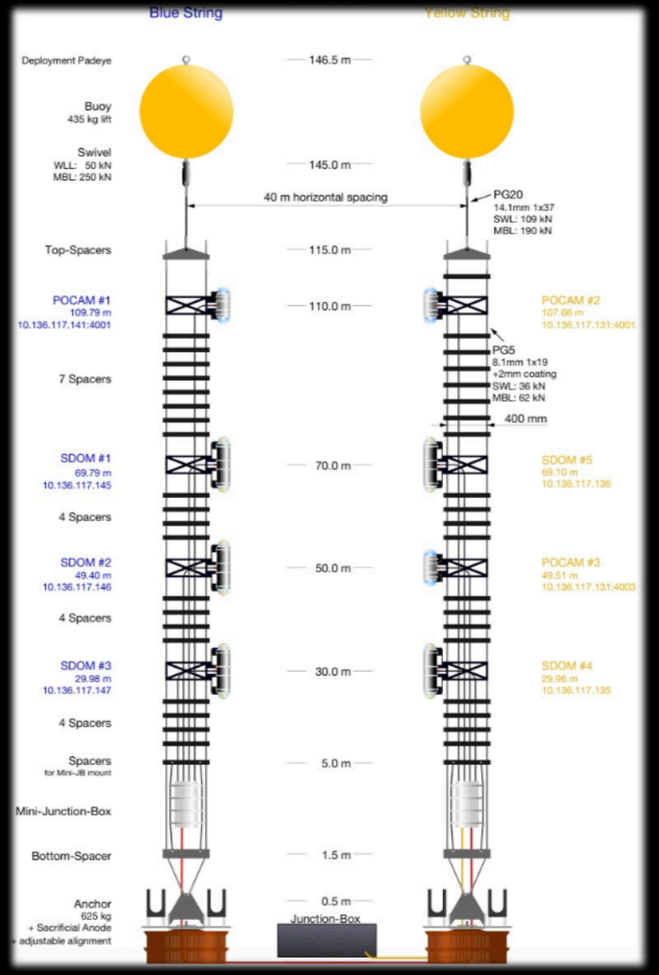
STRAW — Strings for absorption length in water

mid 2017	09/17	05/18	06/18	06/18	11/18
STRAW Idea	Construction	Shipment / Test on site	Deployment	Commissioning	Data Taken

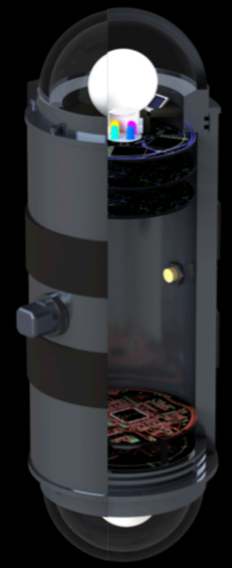


x5

sDOM
(STRAW Digital Optical Module)



x3



POCAM
(Precision Optical Calibration Module)

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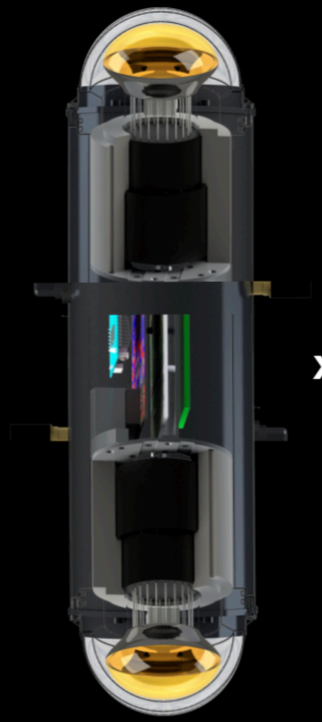

x5

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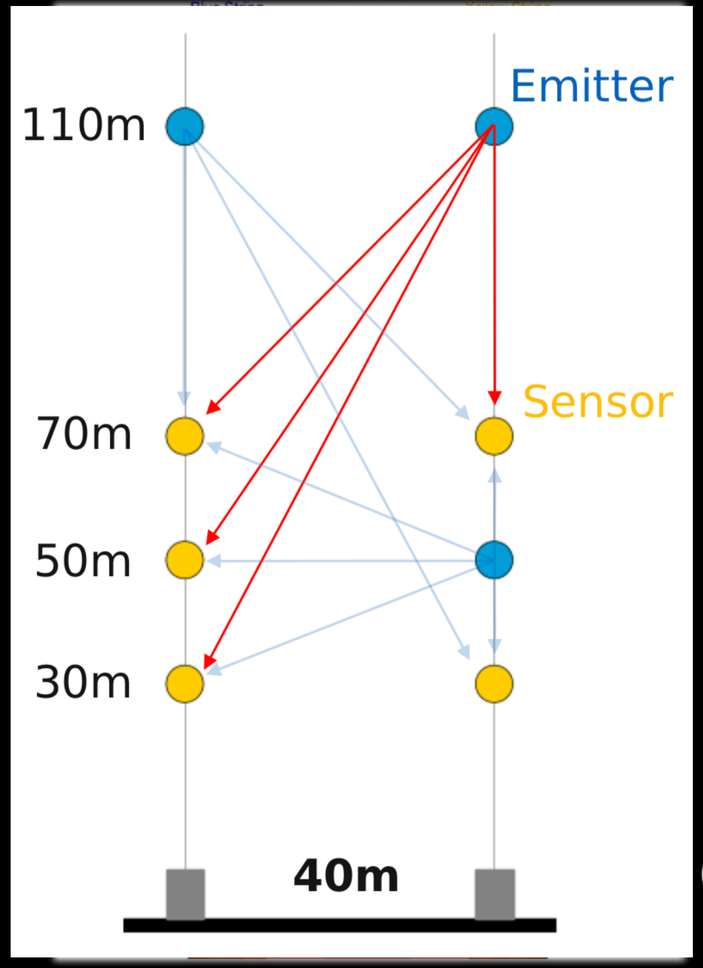
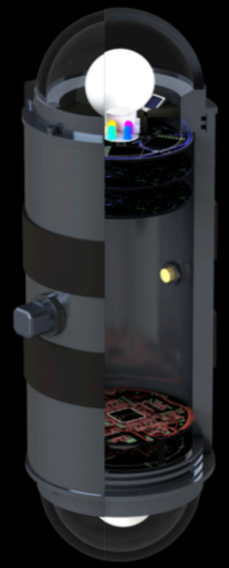


x3



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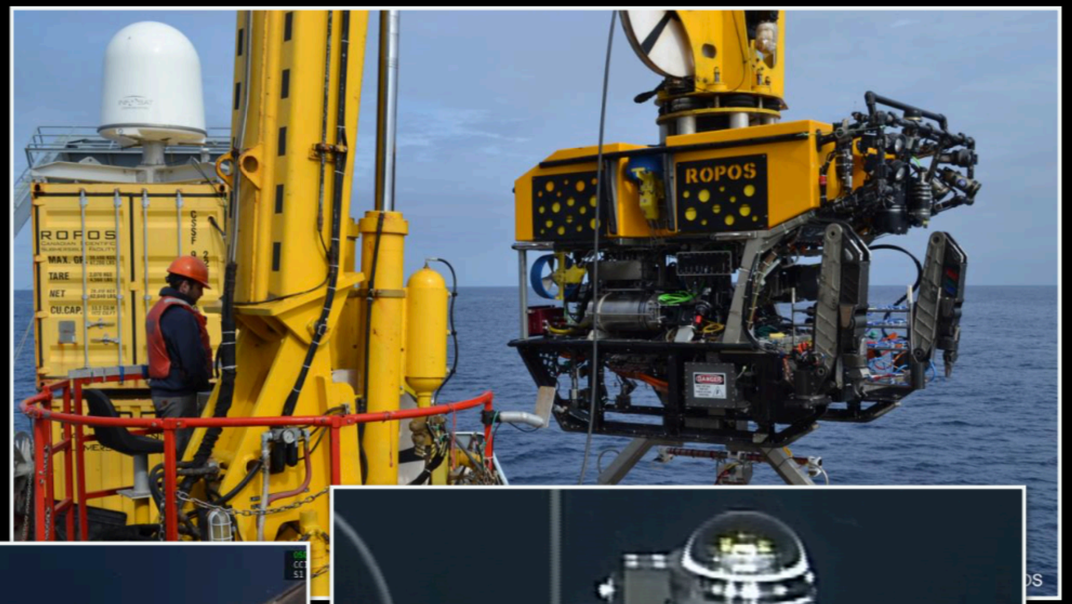
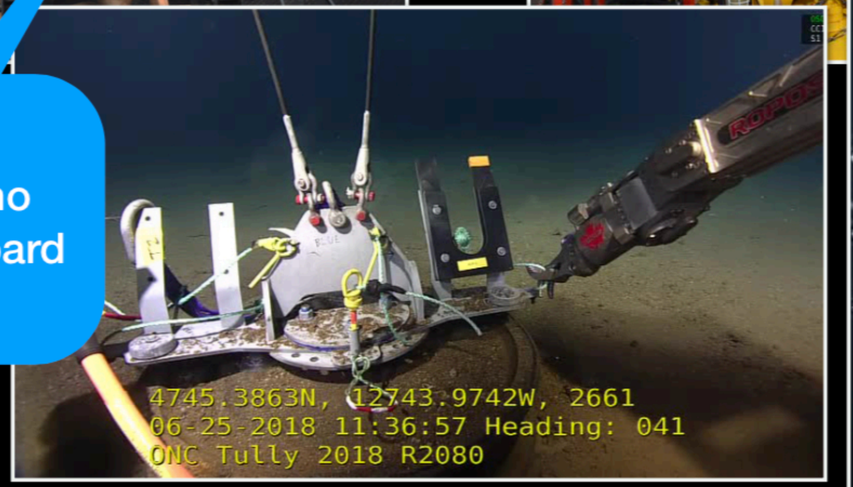
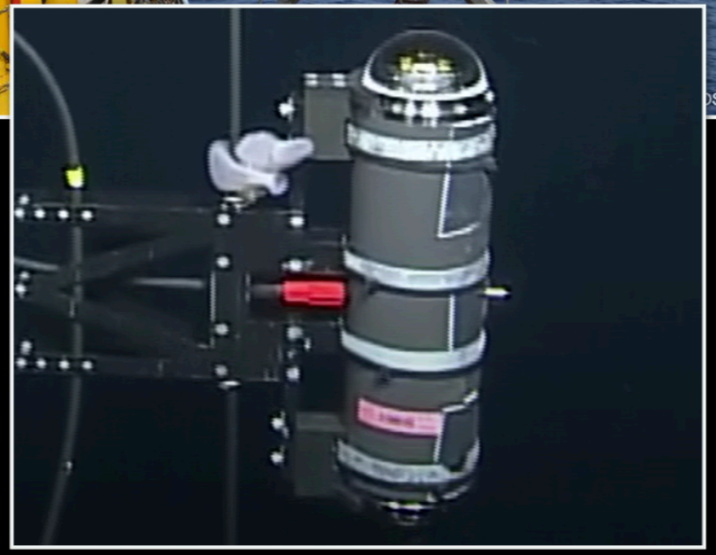
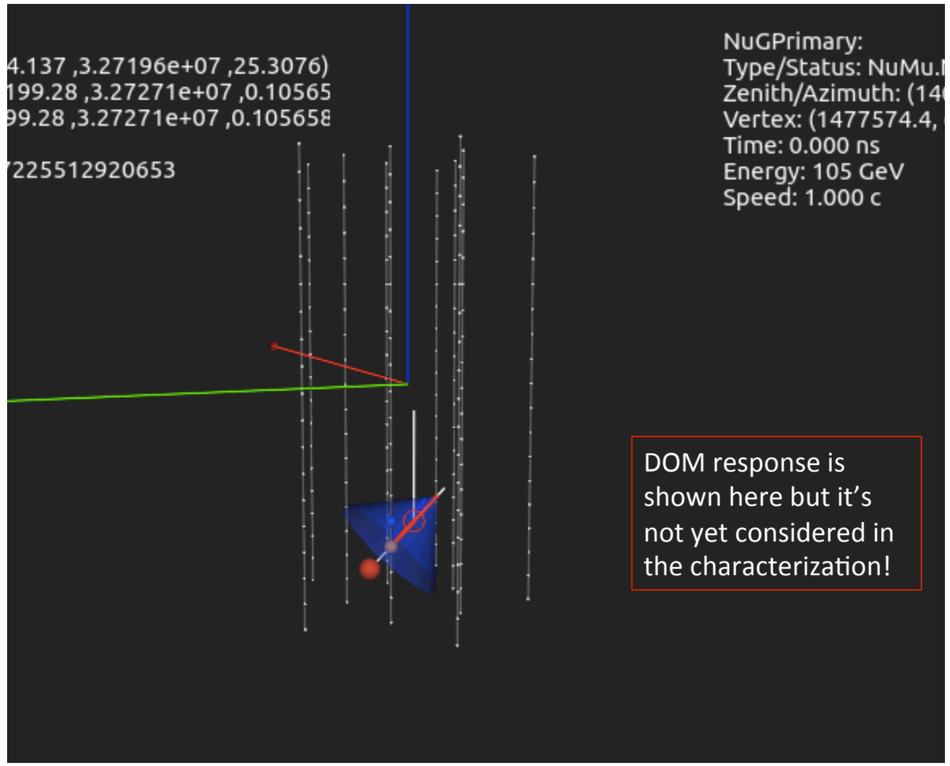


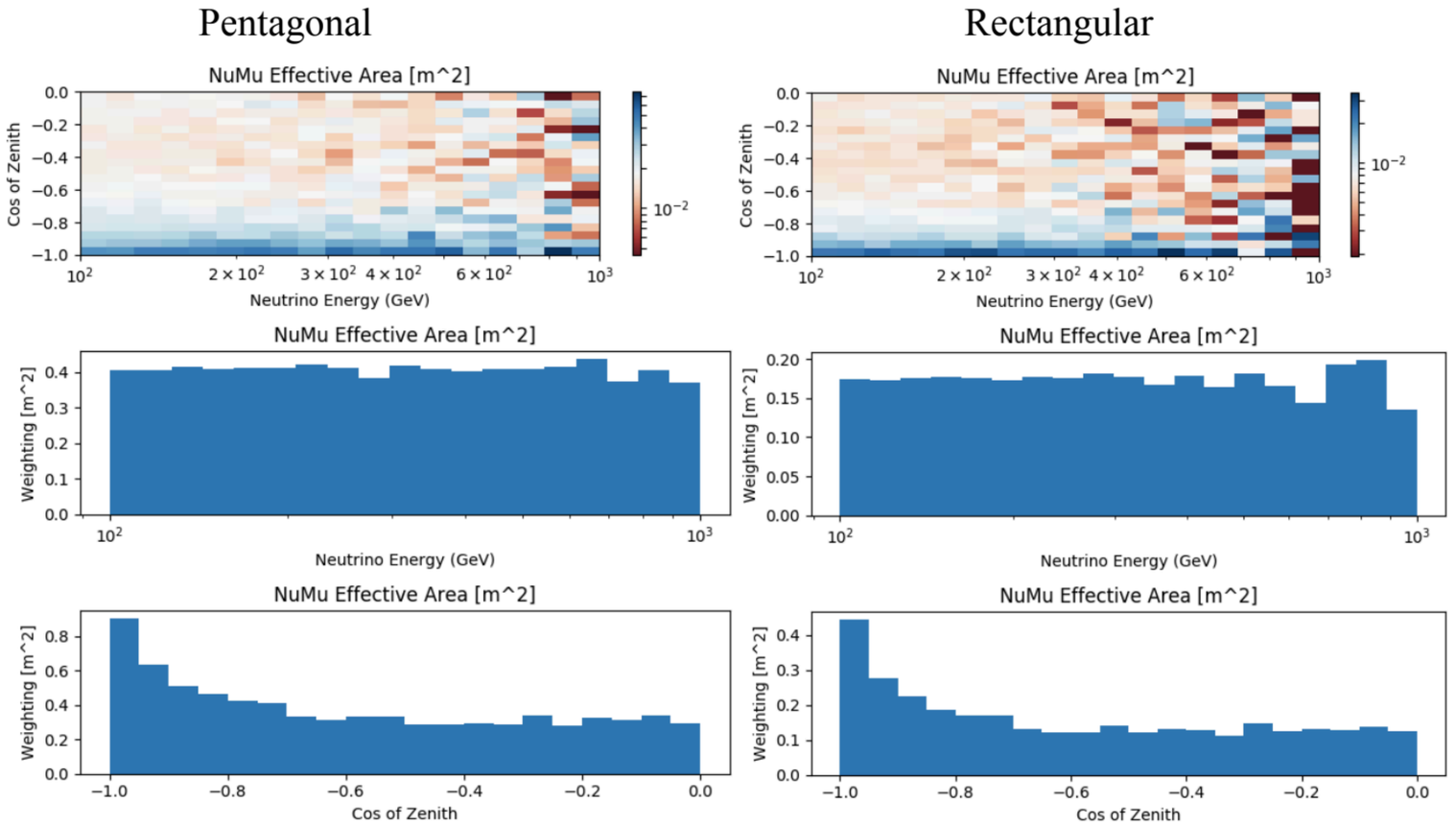




ONC team - no physicist on board

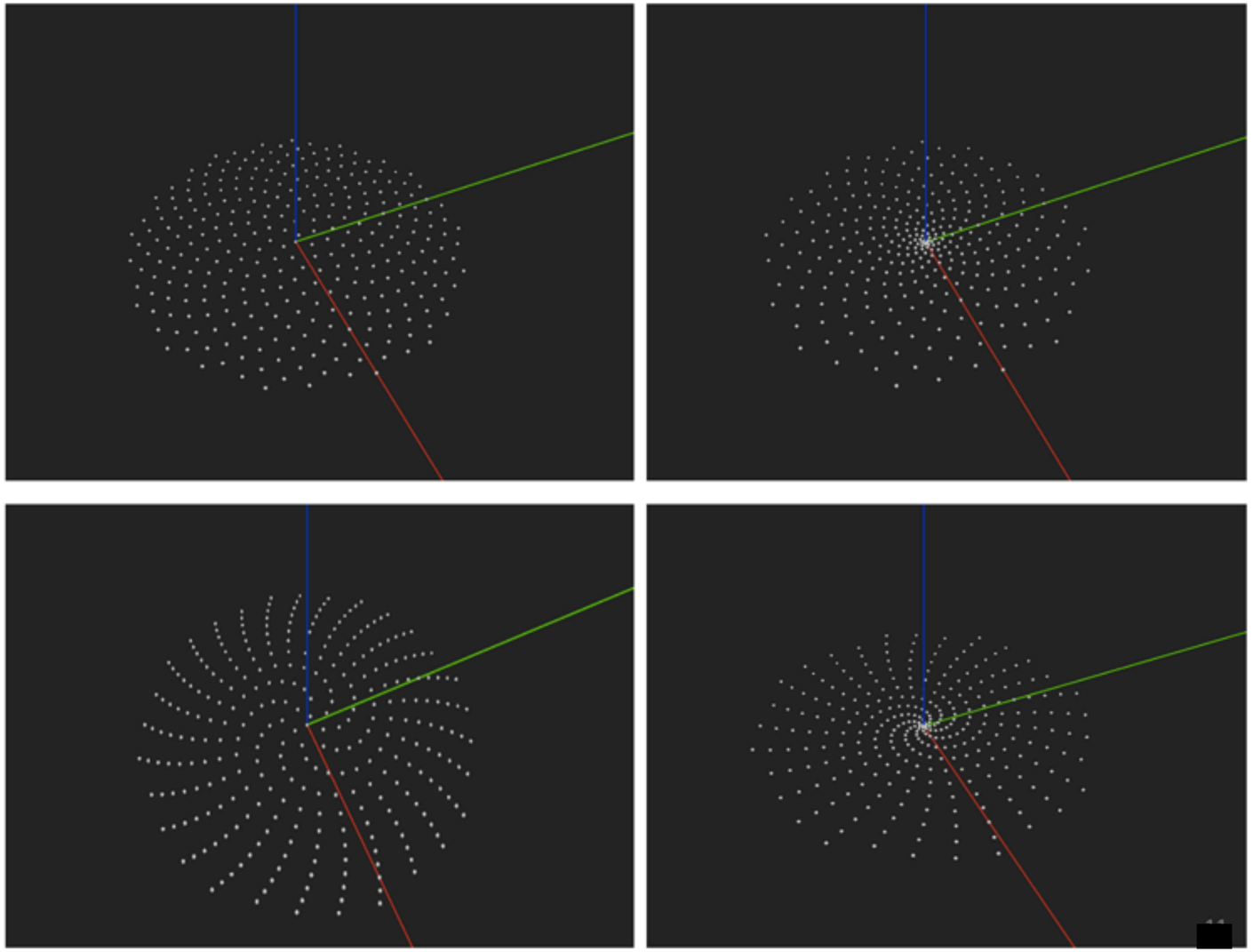
Geometry Studies





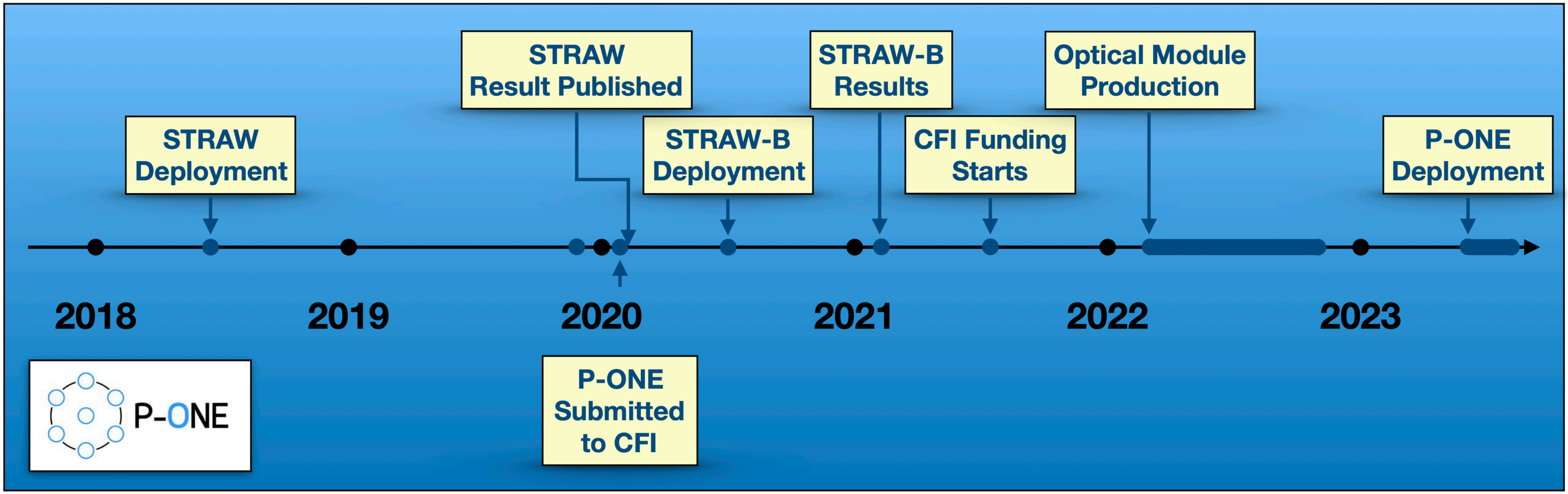
Fletcher Barrett, Co-op student at Queen's

Even more creative



Fletcher Barrett

Timeline

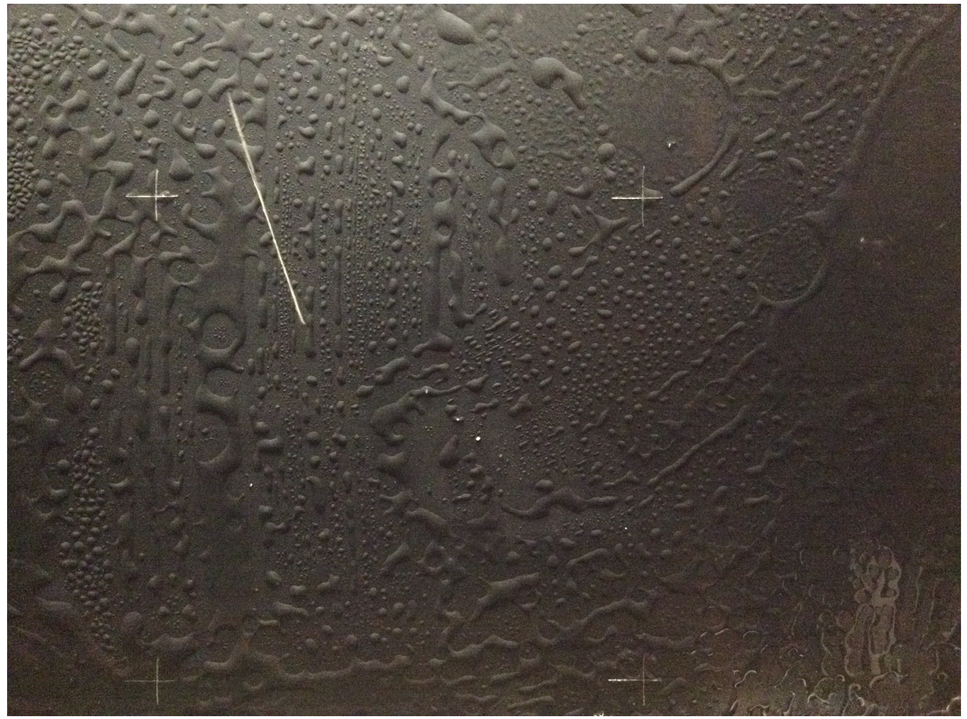

STRAW Result Published
STRAW-B Results
Optical Module Production
STRAW Deployment
STRAW-B Deployment
CFI Funding Starts
P-ONE Deployment
2018
2019
2020
2021
2022
2023
P-ONE
P-ONE Submitted to CFI

Part 2 - Dark Matter (…& Neutrinos)

How did this start?

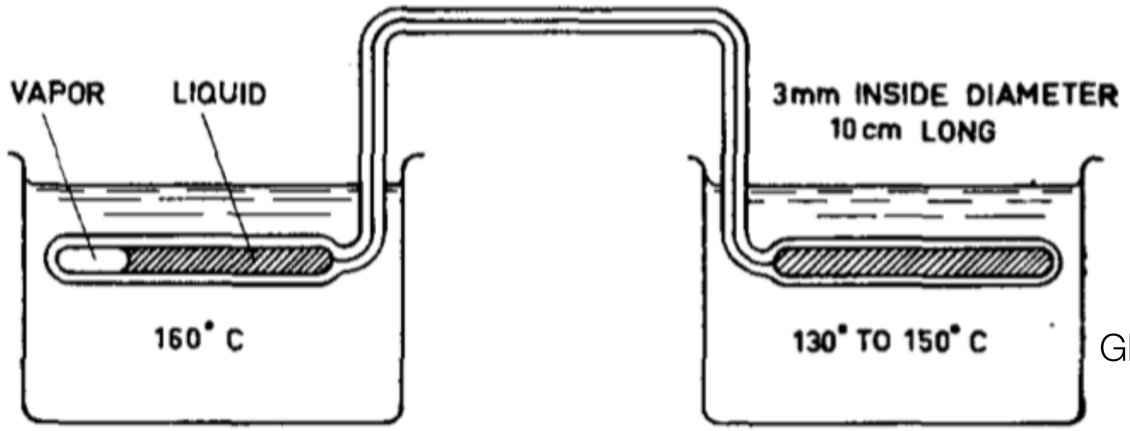
- Physicists needed to detect particles
  - Kind of one of the main things we do, or did…
- Cloud chambers existed, but had some issues:
  - low density
  - low rate

Accelerators started to outstrip the detection using these chambers



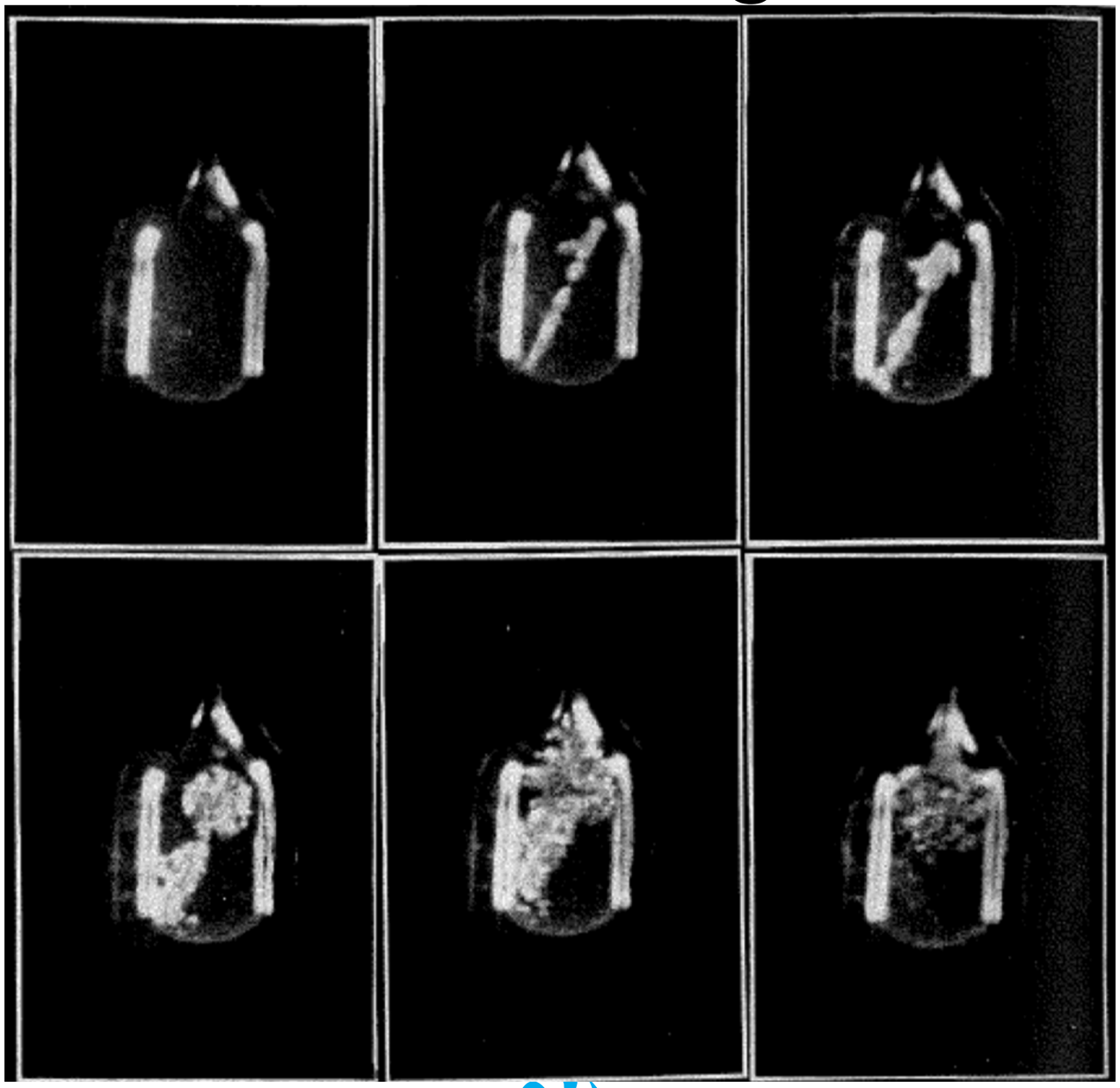
Glaser was inspired

- Donald Glaser saw these problems and worked on a solution
- He used superheated liquid to show the tracks
    - This allowed for a clear view and quick “reset” of the detector
- He has denied that he was inspired to do this by beer, but apparently did try it as an active fluid



Glaser, Nuovo Cimento 11 (1954) 361

Glaser Images



Enter the bubble chamber

Many bubble chambers were constructed

Table 1
Major bubble chambers used in high-energy physics[a].

	H_2	D_2	Ne/H_2	C_3H_8, Freon, LXe
US chambers (total > 50)				
Berkeley	2″, 4″, 6″, 10″, 15″, 25″, 72″			UM LXe LRL 50 cm, 10″
SLAC	15″, 40″			
BNL	30/31″, 80″, 84″, 7′ (3.9 Mpx)			15 cm, 170 l
Argonne	30″ (4.7 Mpx), 12′ (7 Mpx)		30″, 12′	UM 40″
Fermilab	15′ (2.9 Mpx) UW 30″ [Scotchlite]	15′	15′	Tohoku (Holographic)
European chambers (total > 50)				
German	85 cm (6.3 Mpx)	85 cm	85 cm	
French	80 cm (16 Mpx)			BP3, Gargamelle (4.7 M)
British	150 cm			Oxford He
Russian	Ludmilla		Ludmilla?	1 m, 2 m, SKAT ITEP He, 700 l LXe
CERN	Mirabelle (3.3 Mpx) 30 cm, 2 m (40 Mpx) BEBC (6.3 Mpx) LEBC (5.2 Mpx triggered)	2 m BEBC	Mirabelle? BEBC	HOBC

BEBC: Big European Bubble Chamber; LEBC: Lexan Bubble Chamber; HOBC: Holographic Bubble Chamber; Gargamelle: Heavy Liquid Bubble Chamber; *Ludmilla*: Russian Heavy Liquid Bubble Chamber; *Mirabelle*: Bubble Chamber built in Saclay/France; Mpx: million pictures, UM: U. Michigan Heavy Liquid and Liquid Xe Bubble Chambers. Data in round brackets () give the number of pictures taken with a chamber, those in straight brackets special features of the chambers.

[a] Adopted from Gert G. Harigel, in "30 Years of Bubble Chamber Physics" (Bologna 2003); Ref. [38].

History of the bubble chamber and related active- and internal-target nuclear tracking detectors, F.D. Becchetti, NIMA 784 (2015) 518-523

Queen's University

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CERN	Mirabelle (3.3 Mpx) 30 cm, 2 m (40 Mpx) BEBC (6.3 Mpx) LEBC (5.2 Mpx triggered)	2 m BEBC	Mirabelle? BEBC	HOBC

BEBC: Big European Bubble Chamber; LEBC: Lexan Bubble Chamber; HOBC: Holographic Bubble Chamber; Gargamelle: Heavy Liquid Bubble Chamber; *Ludmilla*: Russian Heavy Liquid Bubble Chamber; *Mirabelle*: Bubble Chamber built in Saclay/France; Mpx: million pictures, UM: U. Michigan Heavy Liquid and Liquid Xe Bubble Chambers. Data in round brackets () give the number of pictures taken with a chamber, those in straight brackets special features of the chambers.

[a] Adopted from Gert G. Harigel, in "30 Years of Bubble Chamber Physics" (Bologna 2003); Ref. [38].

We'll come back to this one…

History of the bubble chamber and related active- and internal-target nuclear tracking detectors, F.D. Becchetti, NIMA 784 (2015) 518-523

Queen's University

Enter the bubble chamber

- Using this technology, many discoveries were made

Particle	Source of Radiation	Instrument
e^+	Cosmic ray	Cloud chamber
$\mu^\pm$	Cosmic ray	Cloud chamber
$\pi^\pm$	Cosmic ray	Nuclear emulsion
π^0	Accelerator	Counters
$K^\pm$	Cosmic ray	Nuclear emulsion
K^0	Cosmic ray	Cloud chamber
Λ^0	Cosmic ray	Cloud chamber
Σ^+	Cosmic ray	Nuclear emulsion
		Cloud chamber
Σ^-	Accelerator	Cloud chamber
Σ^0	Accelerator	*Bubble chamber*
Ξ^-	Cosmic ray	Cloud chamber
Ξ^0	Accelerator	*Bubble chamber*
Ω^-	Accelerator	*Bubble chamber*
Λ_c^+	Accelerator	*Bubble chamber*
p, n	Accelerator	Counters
B (Σ^+, Ξ^+, Ω^+)	Accelerator	*Bubble chamber*

Gert G. Harigel, *Bubble Chambers, Technology and Impact on High Energy Physics*

There was a real boom in bubble chamber physics for many years

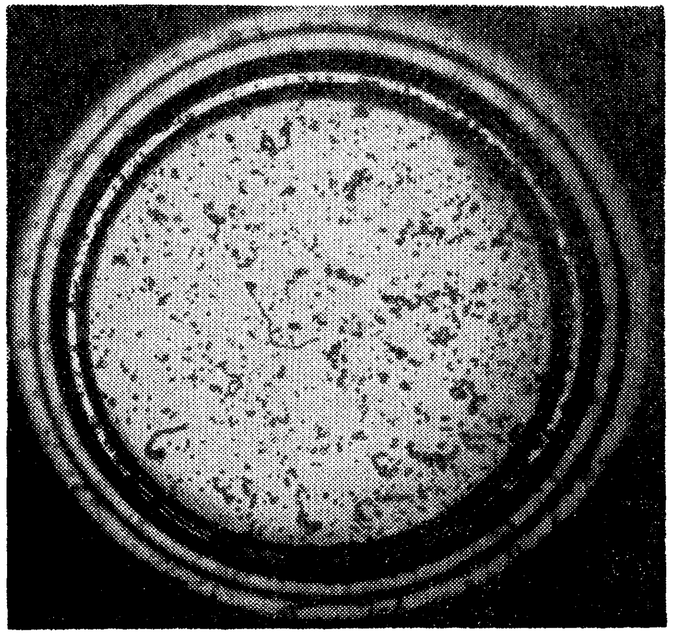
Exit the bubble chamber

- This technology worked solidly for decades, making lots of contributions to physics
- Unfortunately the use of hydrogen as a target had some associated dangers
- New detectors with more convenient readout started to supplant the bubble chamber, at least for some uses

15’ bubble chamber at Fermilab

- But these are all building on the same technology…

Revisit a bit of history

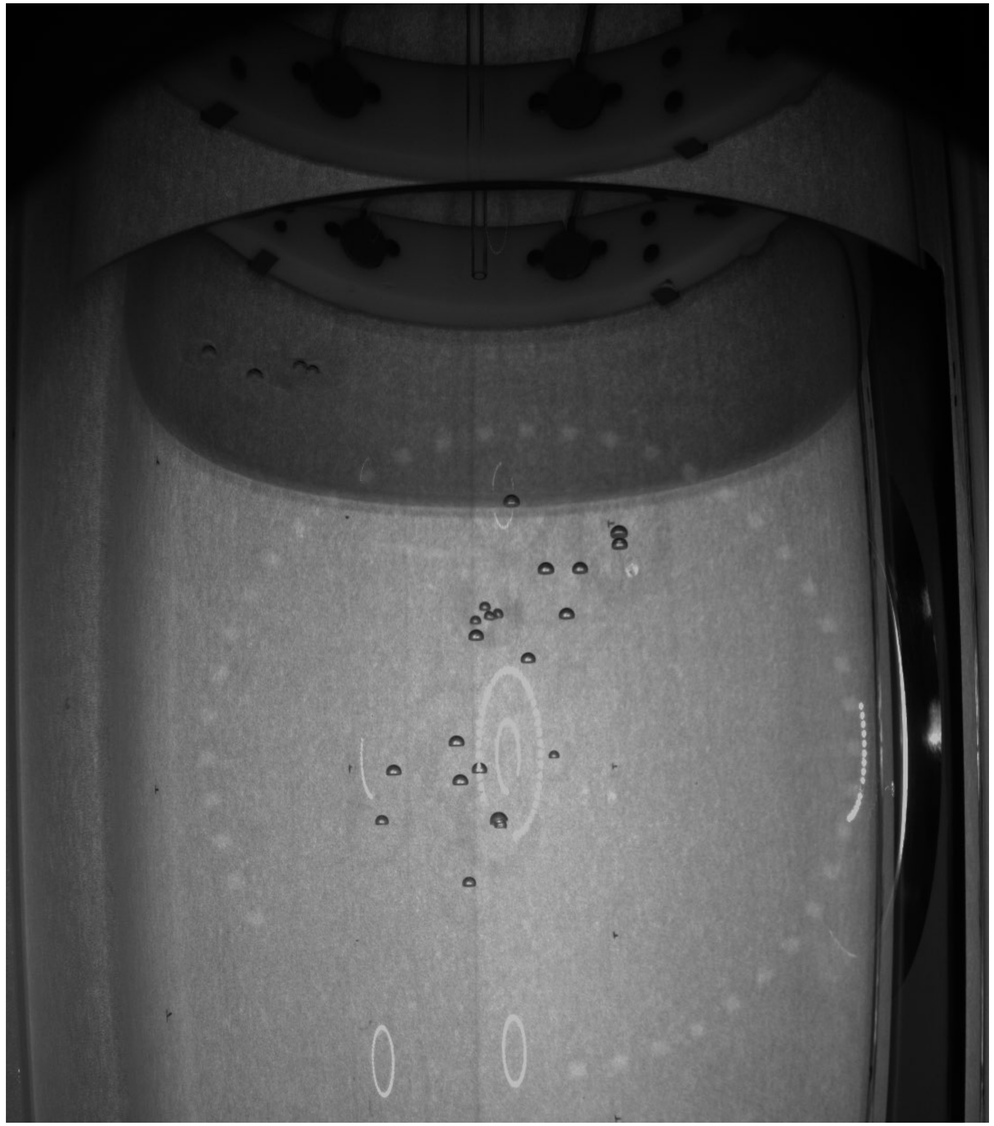


Phys. Rev. 102, 586 (1956)

- In 1956, Glaser made a xenon bubble chamber
  - No bubbles in pure xenon even at 1keV threshold with gamma source
  - Normal production in 98% xenon + 2% ethylene (scintillation completely quenched)
- Scintillation suppresses bubble nucleation (?)

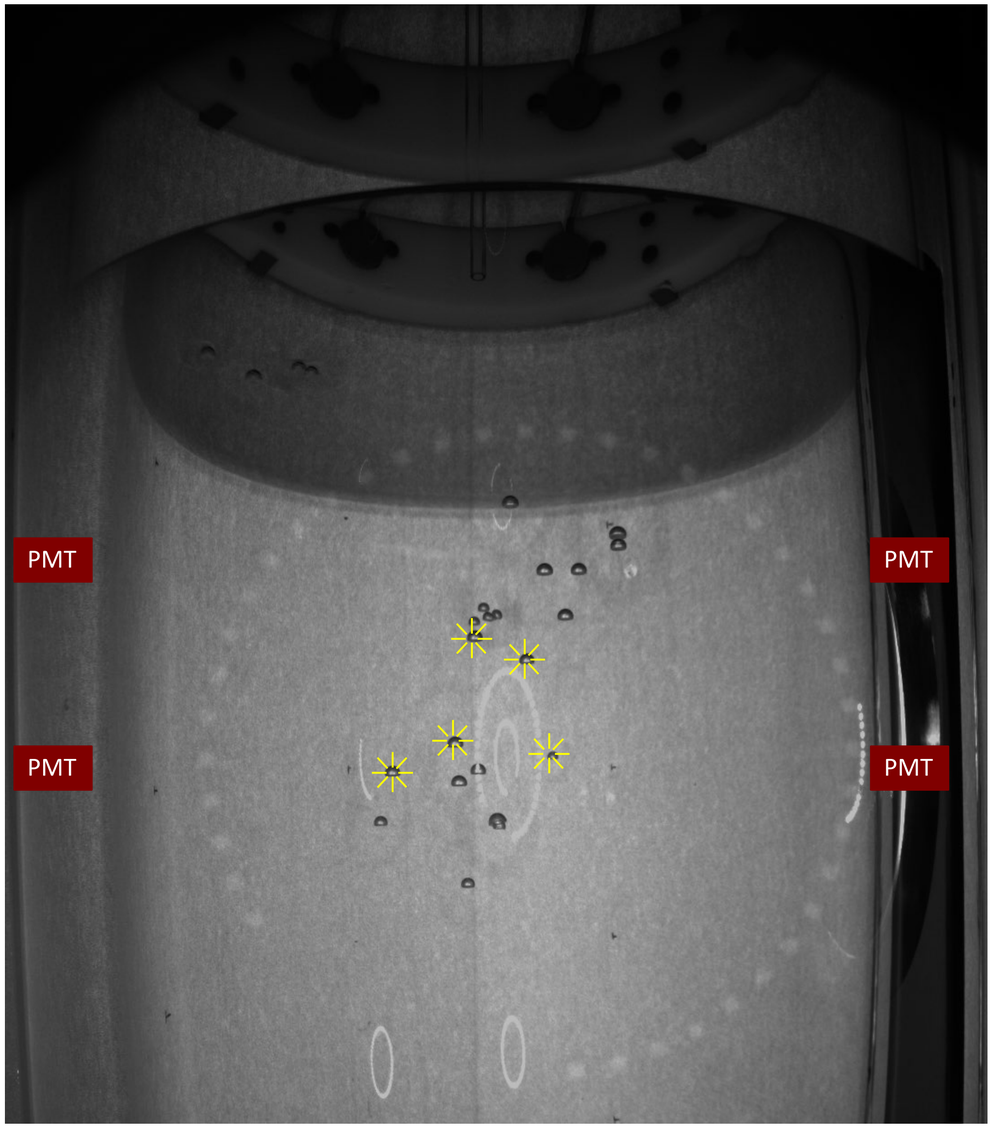
The “traditional” bubble chamber

- Superheated target (C_3F_8, CF_3I…)
- Particle interactions nucleate bubbles
- Cameras and acoustic sensors capture signals
- Chamber recompresses after each event



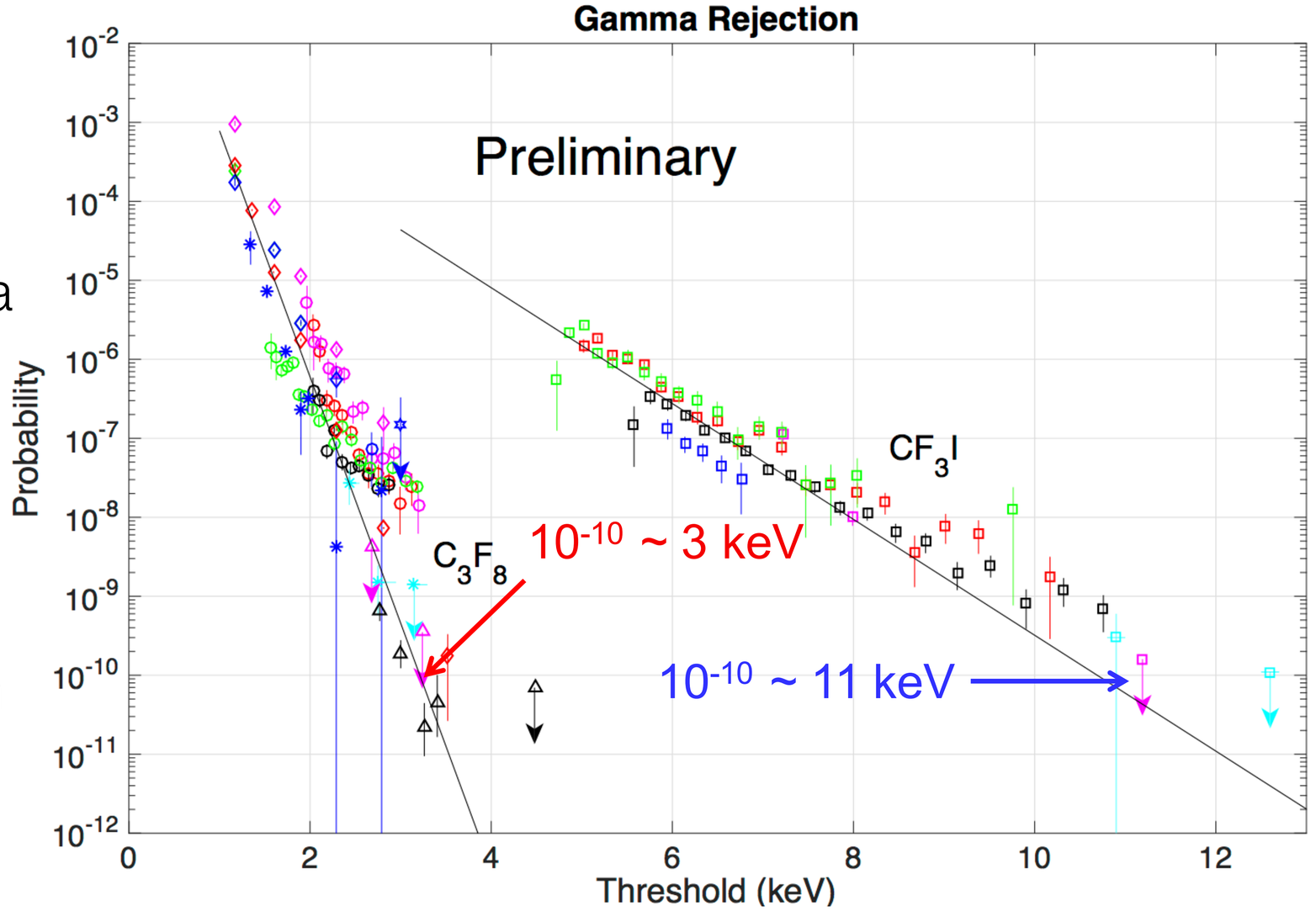
The “scintillating” bubble chamber

- Superheated scintillator (Xe, Ar…)
- Particle interactions nucleate bubbles and cause scintillation
- Cameras and acoustic sensors capture signals, photodetectors collect scintillation light
- Chamber recompresses after each event



Bubble Chamber Advantages

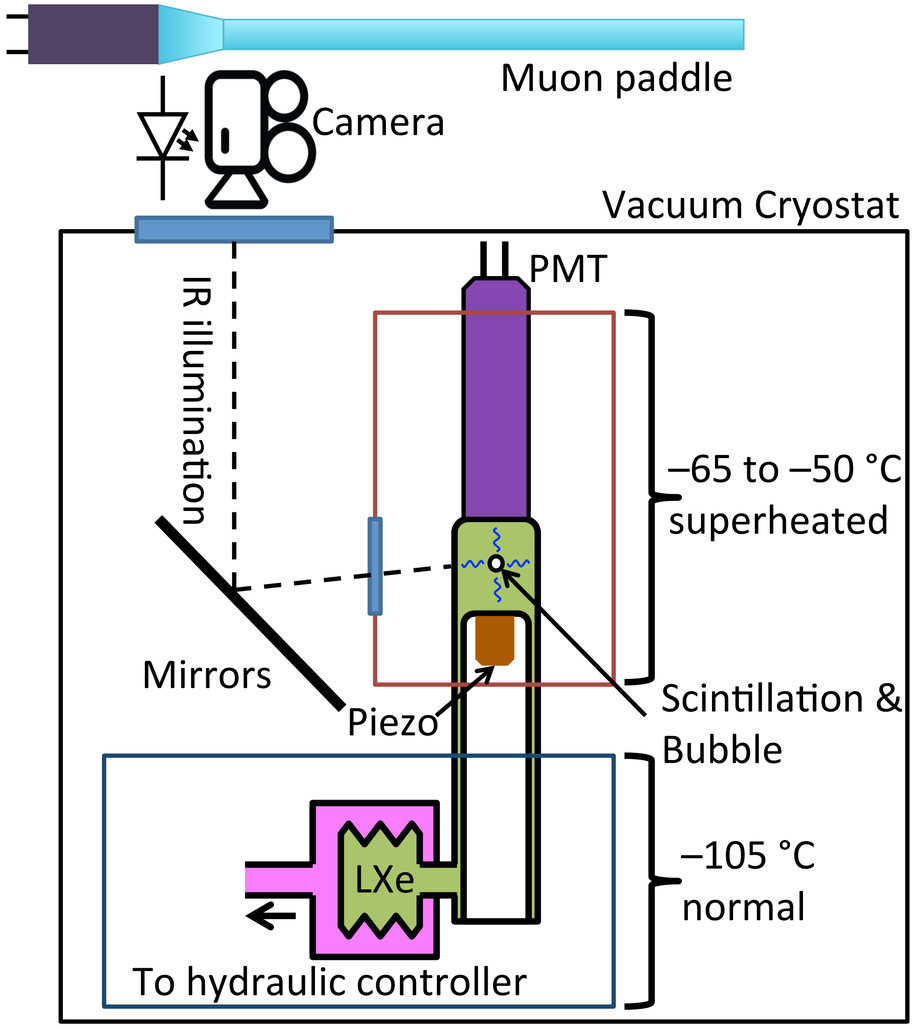
- Better background rejection compared to PICO
    - Improve on 10^{10} gamma rejection
- Improved information for rejection compared to usual xenon detectors
- Good position reconstruction from cameras



Questions to be answered

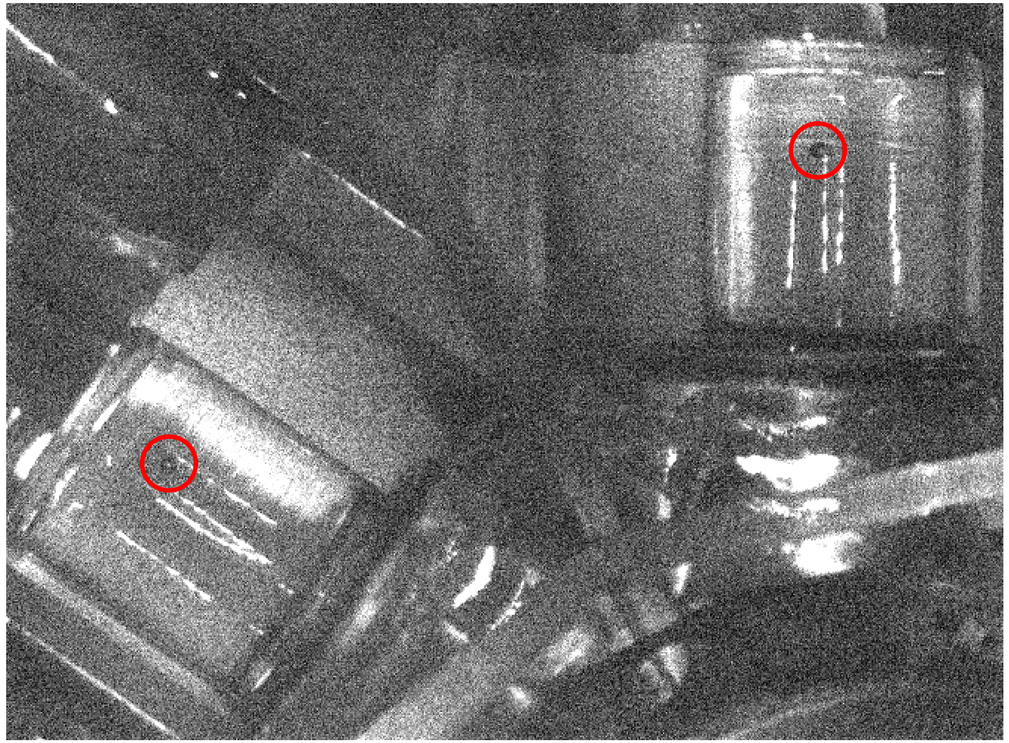
- Can this style detector be operated for a DM search?
- Can the ~1keV threshold be reached in xenon?
  - What's the nuclear recoil efficiency at that threshold?
  - What is the low threshold behaviour?

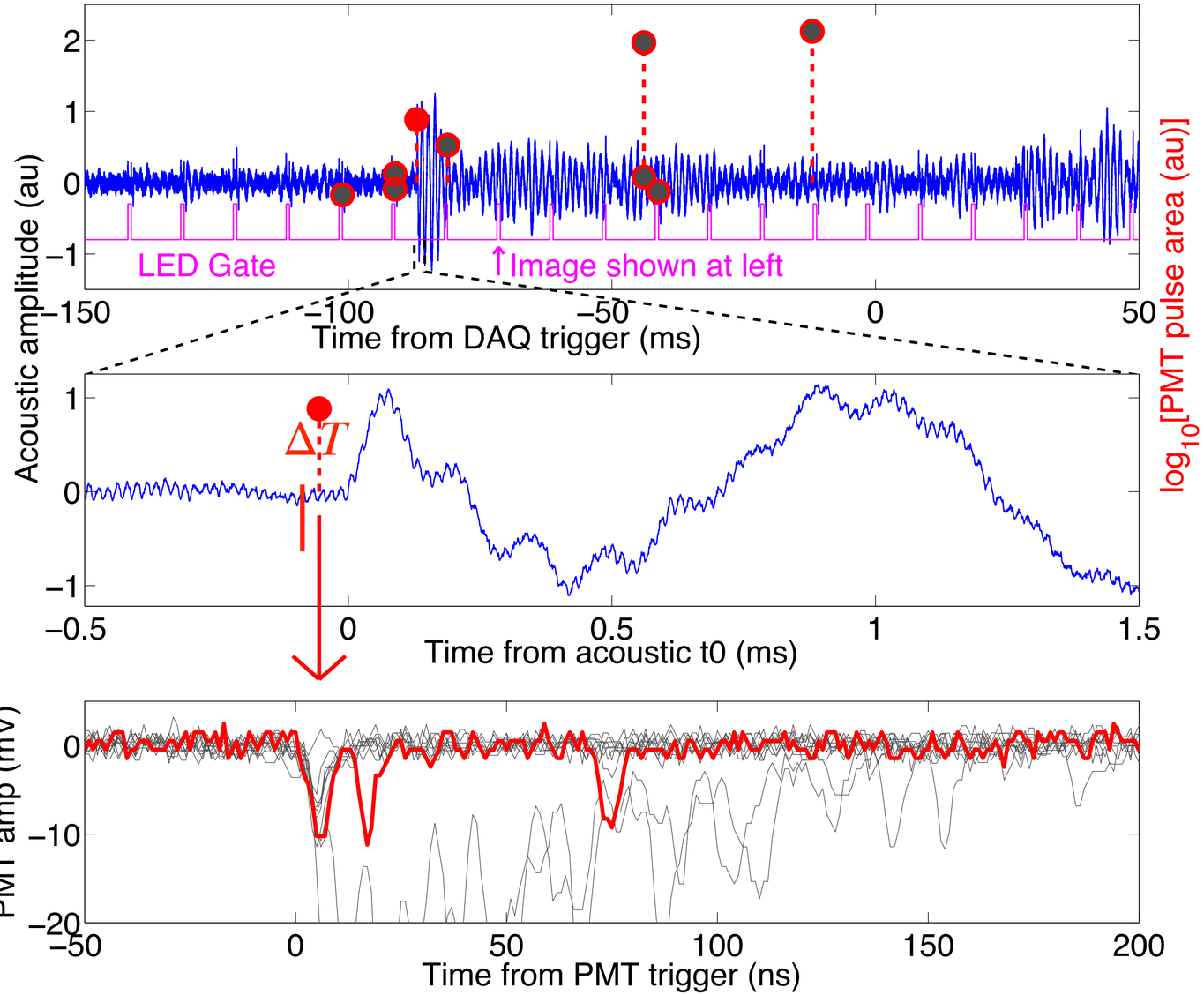
Northwestern Chamber

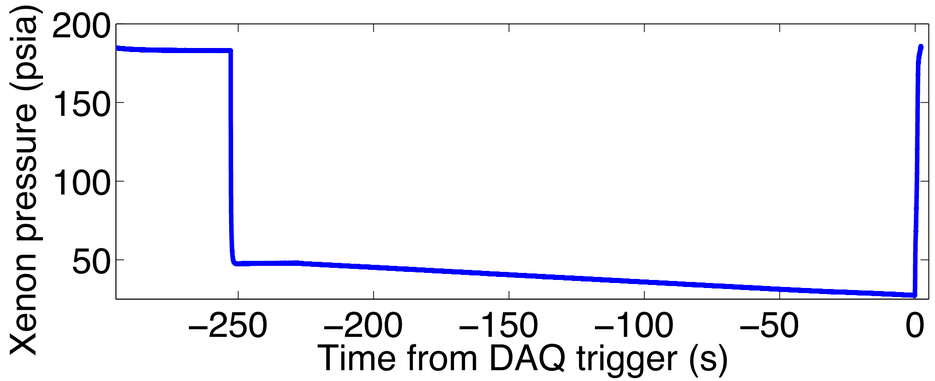


- Operated at 4keV threshold
- Camera ported through sapphire window
- Mirrors allow two angles on the bubble

An event

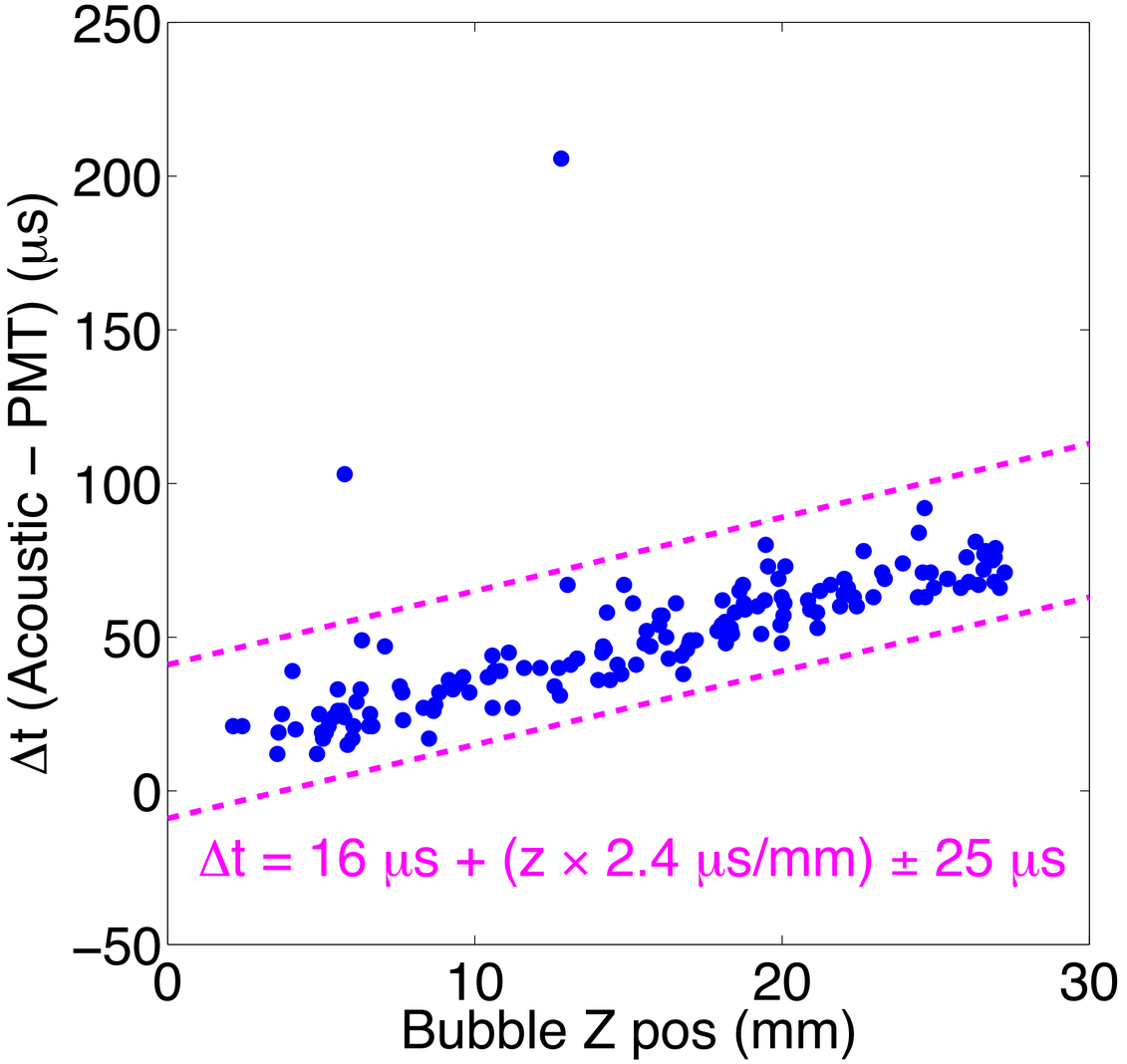



Acoustic amplitude (au)
log10[PMT pulse area (au)]
LED Gate
Image shown at left
Time from DAQ trigger (ms)
ΔT
Time from acoustic t0 (ms)
PMT amp (mV)
Time from PMT trigger (ns)

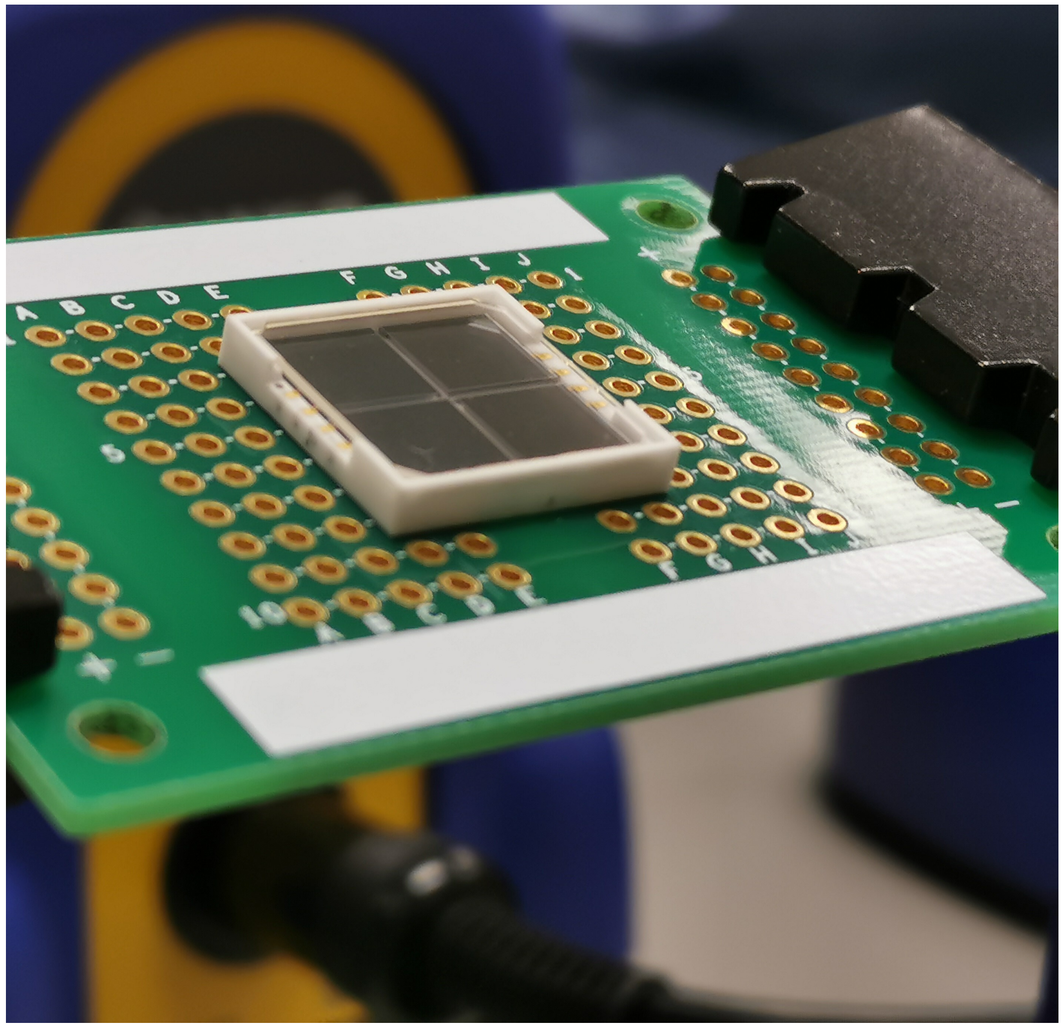

Xenon pressure (psia)
Time from DAQ trigger (s)

Timing

- Look at the time difference between scintillation and acoustics
- Derive the speed of sound in xenon (to ~20%)



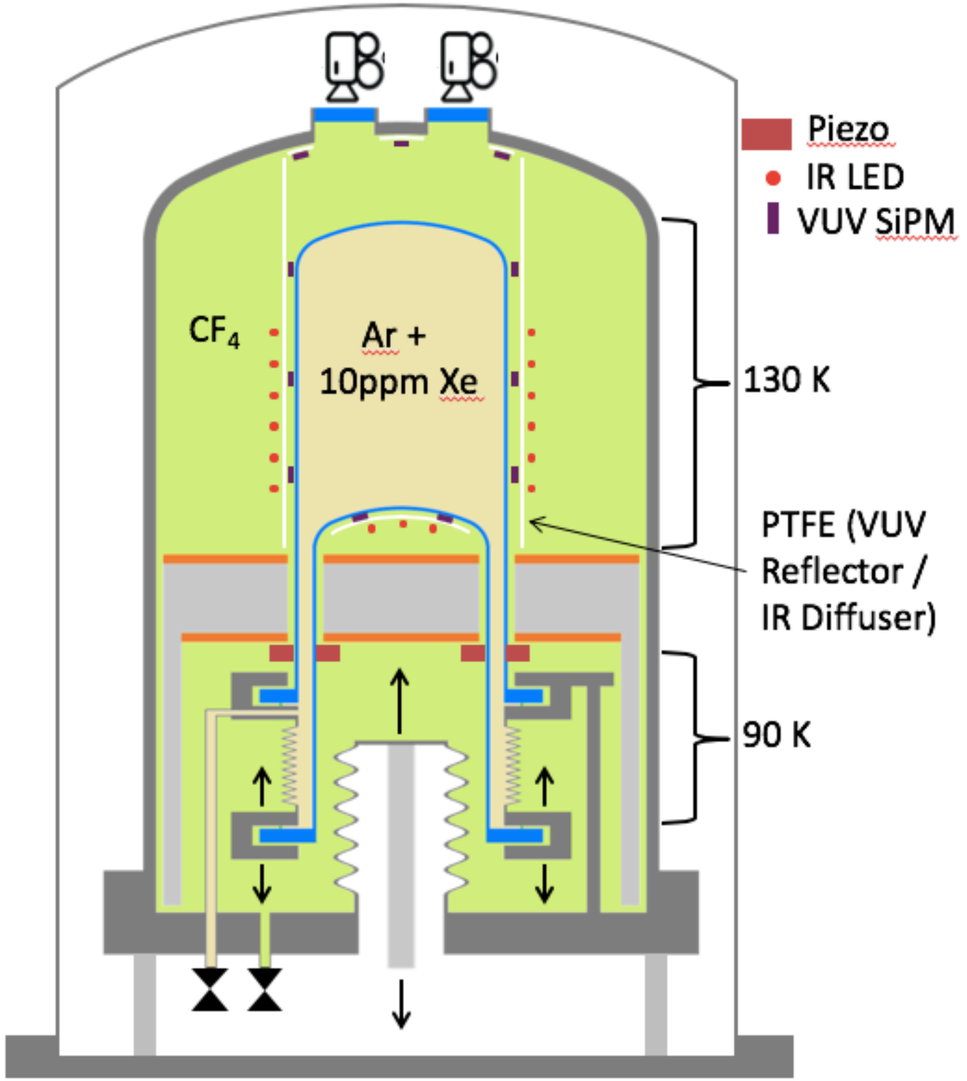
Next Questions



- What other fluids work? Could, for example, Argon be usable?
    - UV scintillation probably means spiking it with a bit of xenon
- Are there good solutions for the scintillation light collection? SiPMs?
    - Need to be pressure tolerant, operate at LAr temperatures, be compatible with camera illumination…

The SBC Detector

- Roughly 10kg of Argon
- SiPMs used for detection
- Much of the internal detail modelled on PICO 500



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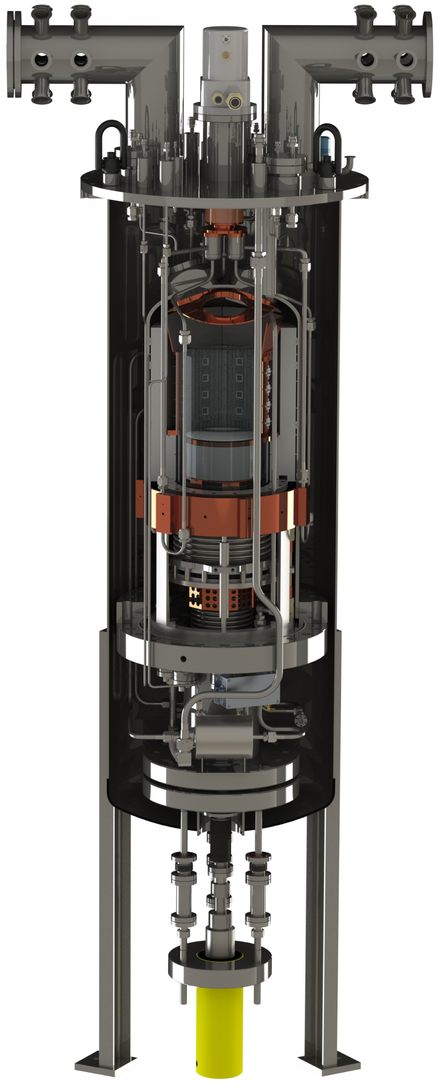
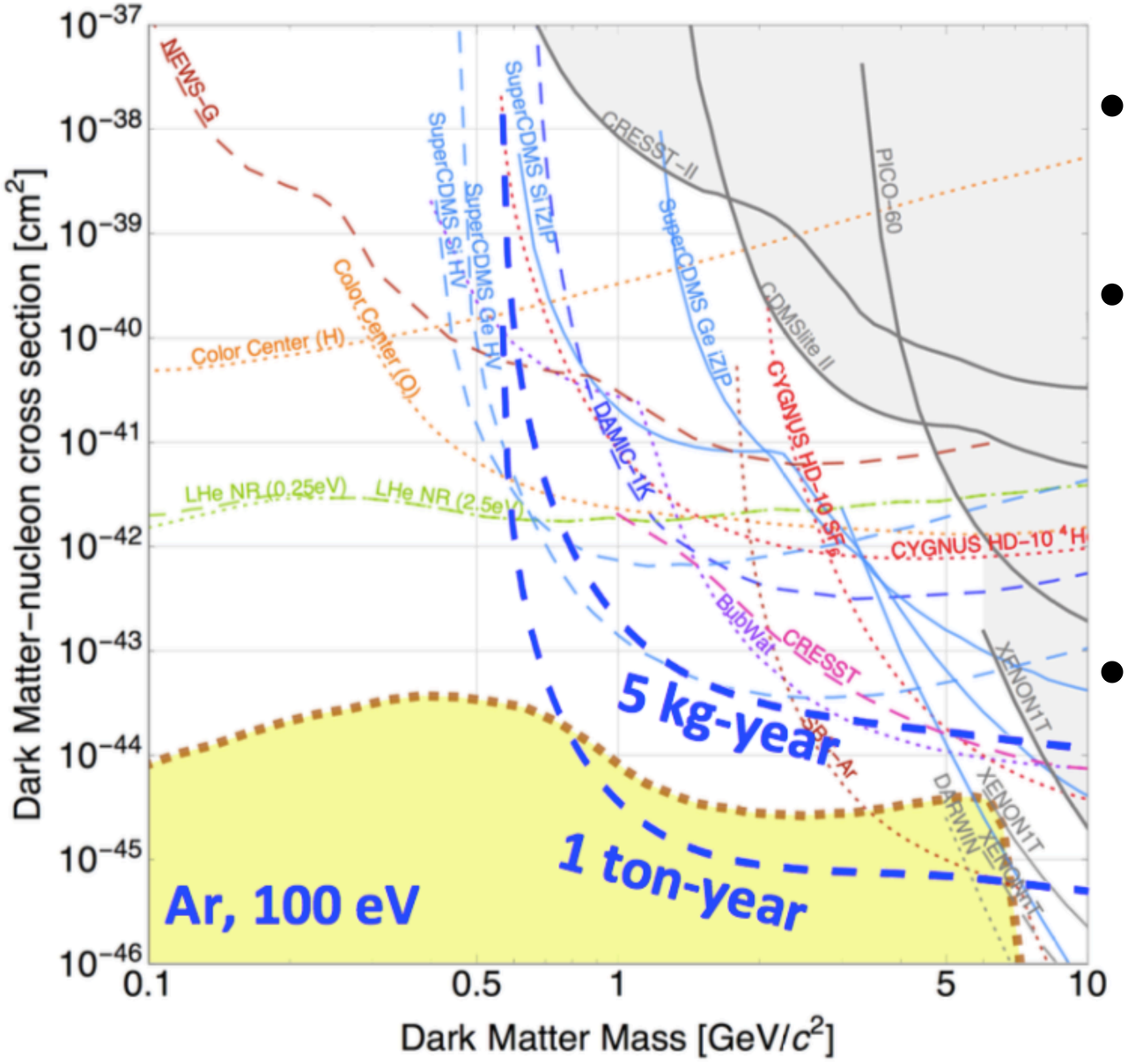


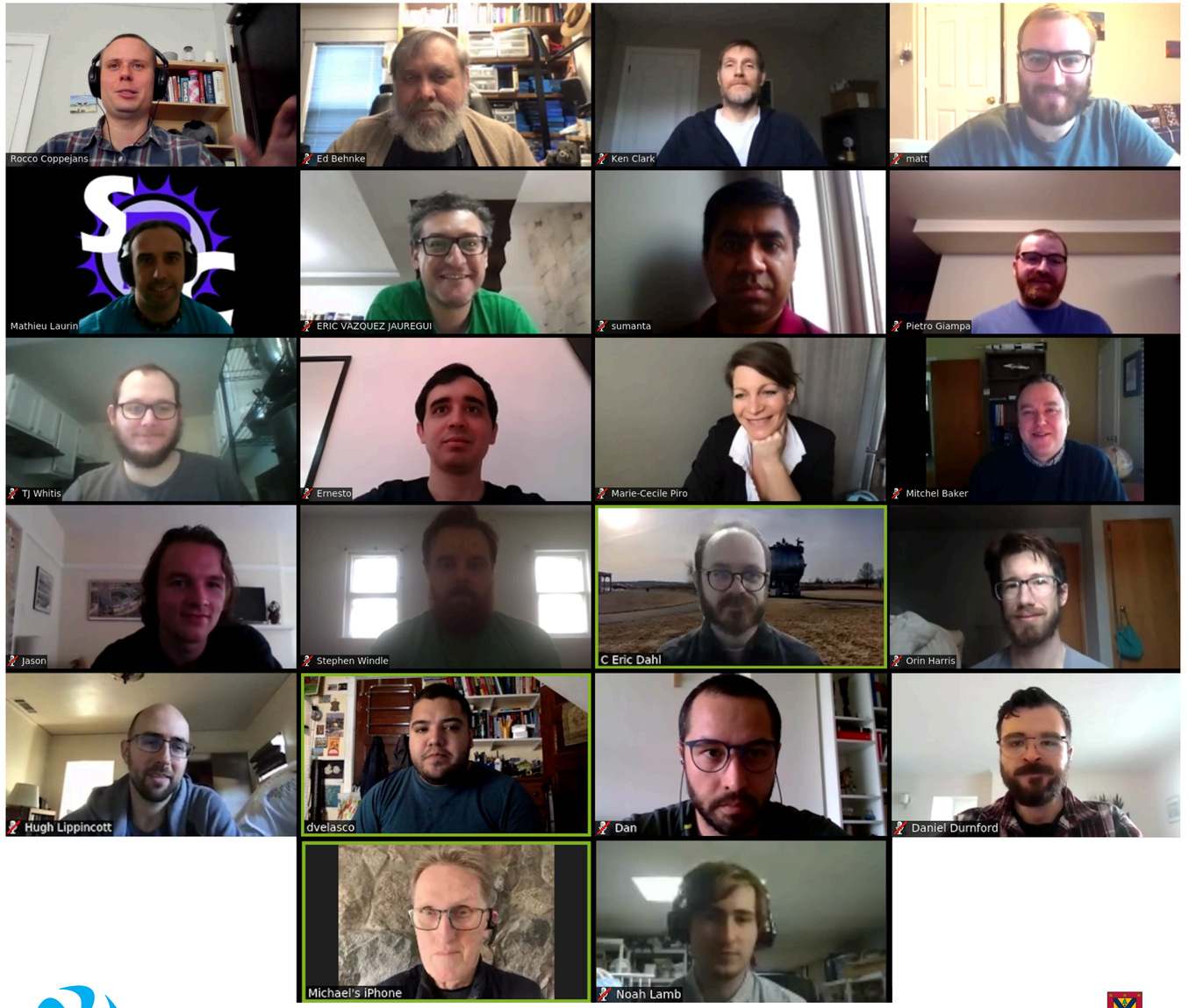
Physics Goals



- Building two detectors for two different physics goals
- One for installation at SNOLAB
  - Look into low background response and feasibility for dark matter search
- One for installation at ORNL (?)
  - Look to further study coherent neutrino scattering

Collaboration Building

- SBC Collaboration
  - U.S.: Fermilab, Northwestern, Drexel, IUSB, PNNL
  - Canada: Queen’s, Alberta, TRIUMF
  - Mexico: UNAM



Timeline

- Currently constructing first chamber to run (briefly) at Fermilab
- Expected that in 2021 we will start building at SNOLAB
  - Process should be much faster since we've done it once

Exciting times to come!