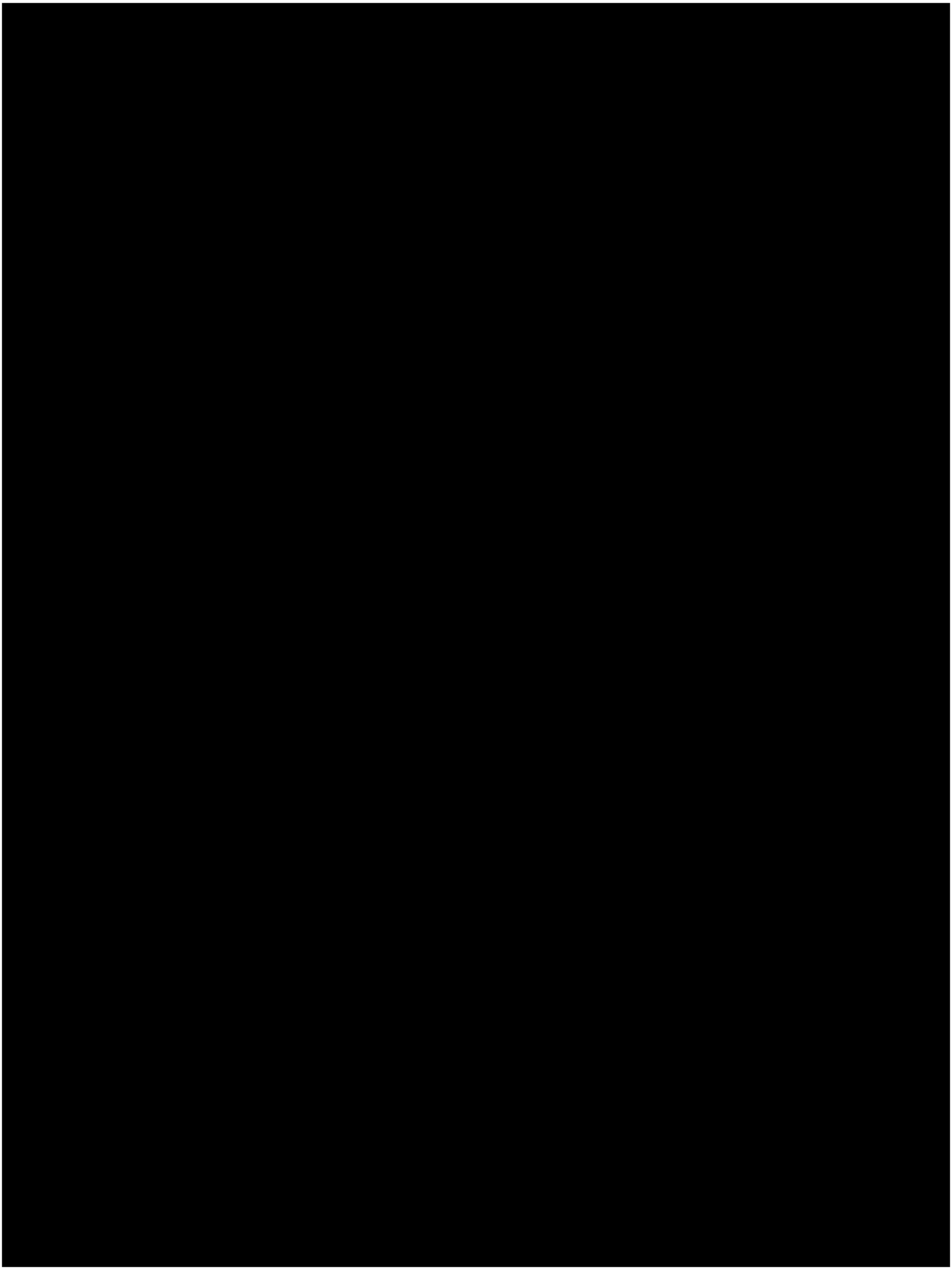
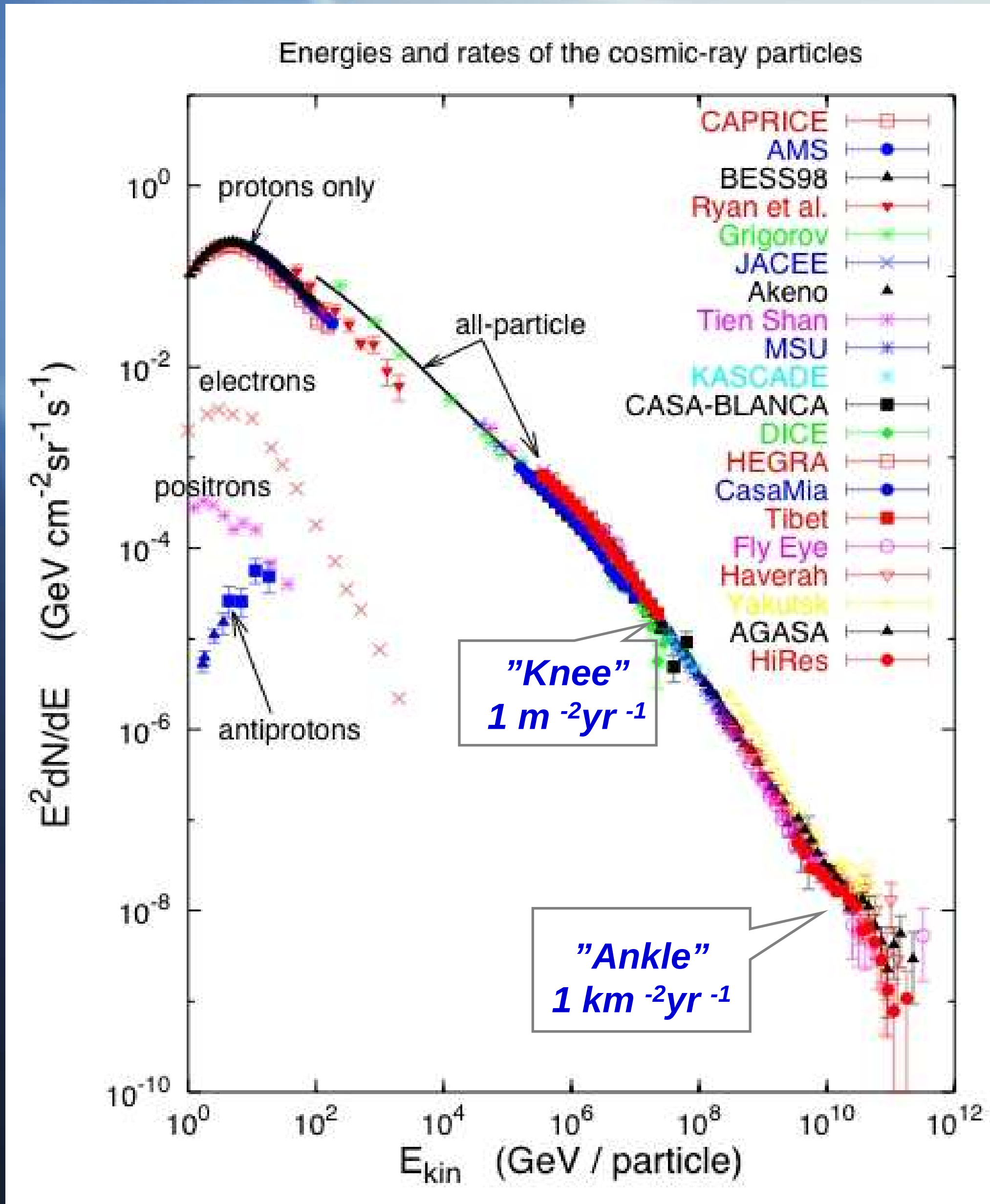


Neutrino: the "little neutral one" - from sub-eV mass to PeV energies

Two fields on the brink of discovery:

High-energy neutrino astronomy

Neutrino-less double-beta decay

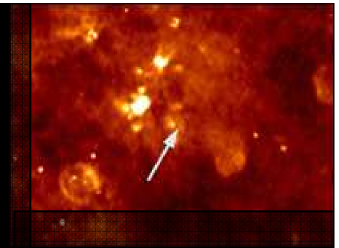


Cosmic Rays

- What are they?
- How do the CR particles reach high energies?
- Where do they come from?
- What does the spectrum tell us?
- What about neutral particles?

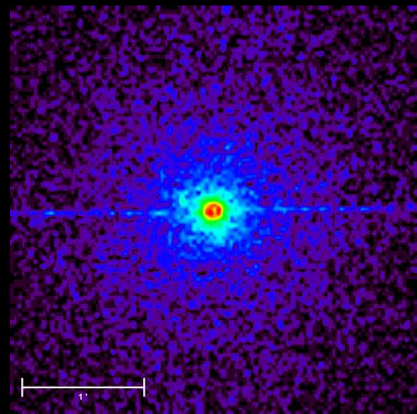
Many Possible Sources

nearby AGN M87 (HST)

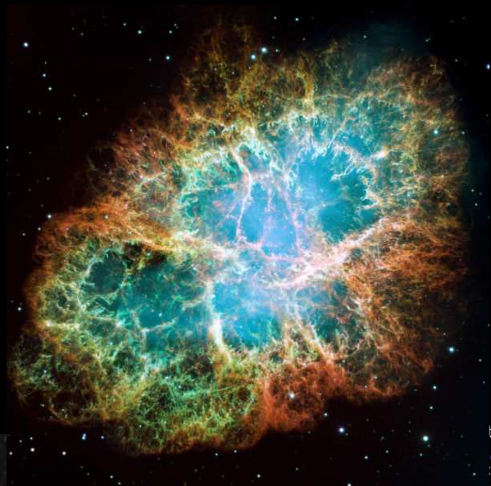


Magnetar SGR 1806-20

Quasar 3C273 Kitt Peak

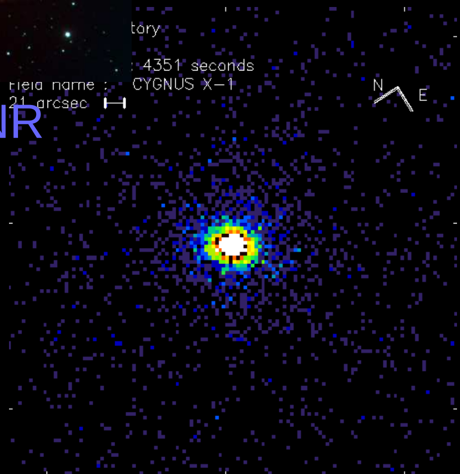


Cygnus X-3 x-ray (Chandra)



Crab nebula SNR

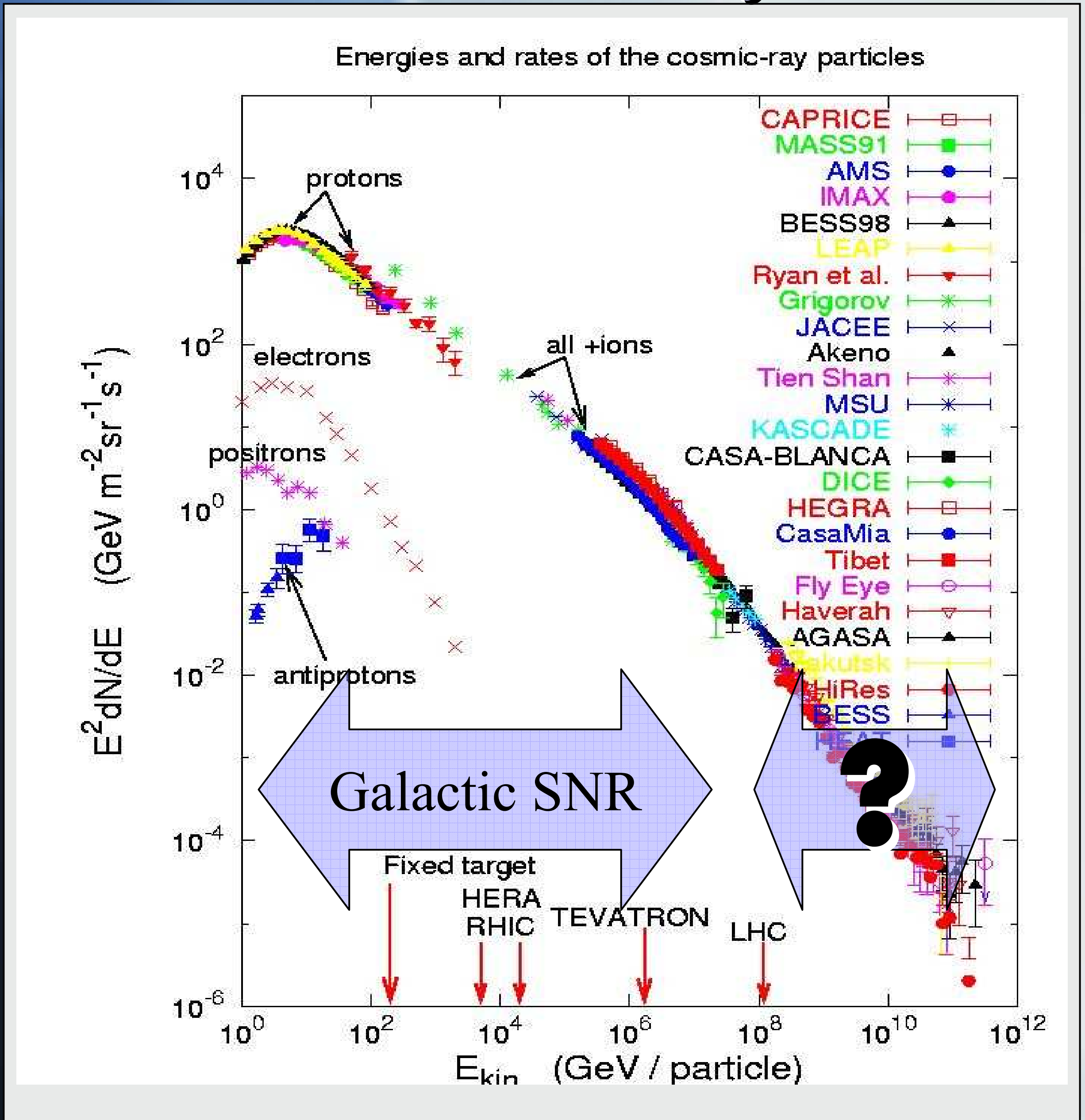
BL Lac Markarian 421



Cygnus X-1

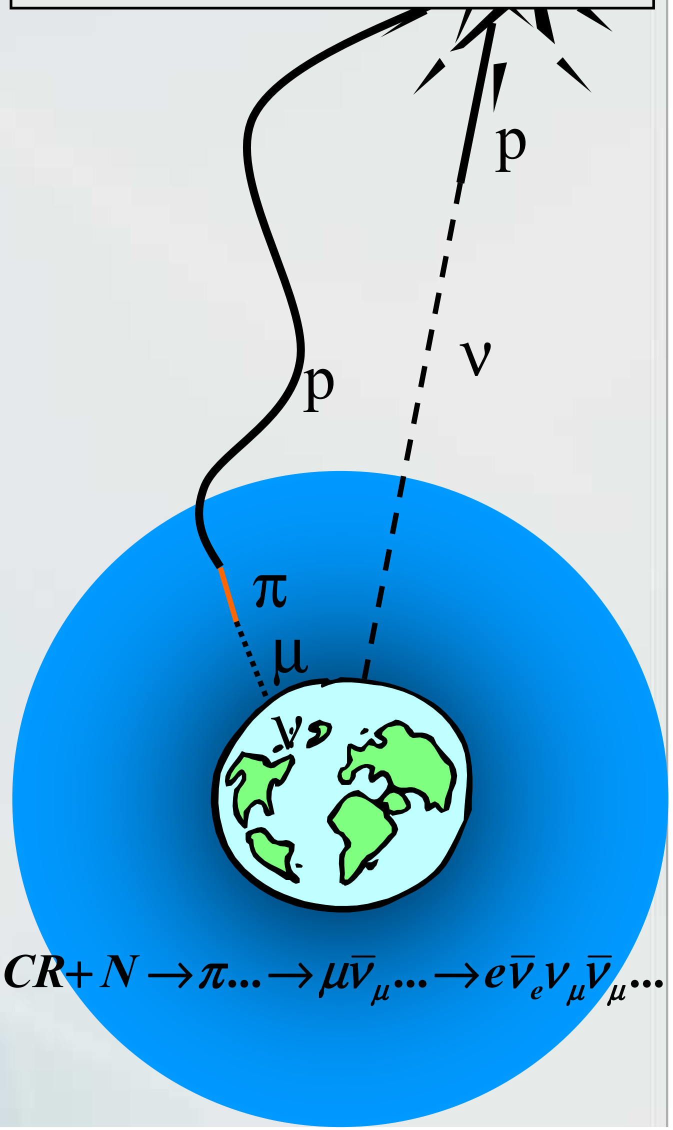
Microquasar SS433 (VLBA)

Cosmic Rays & Neutrinos



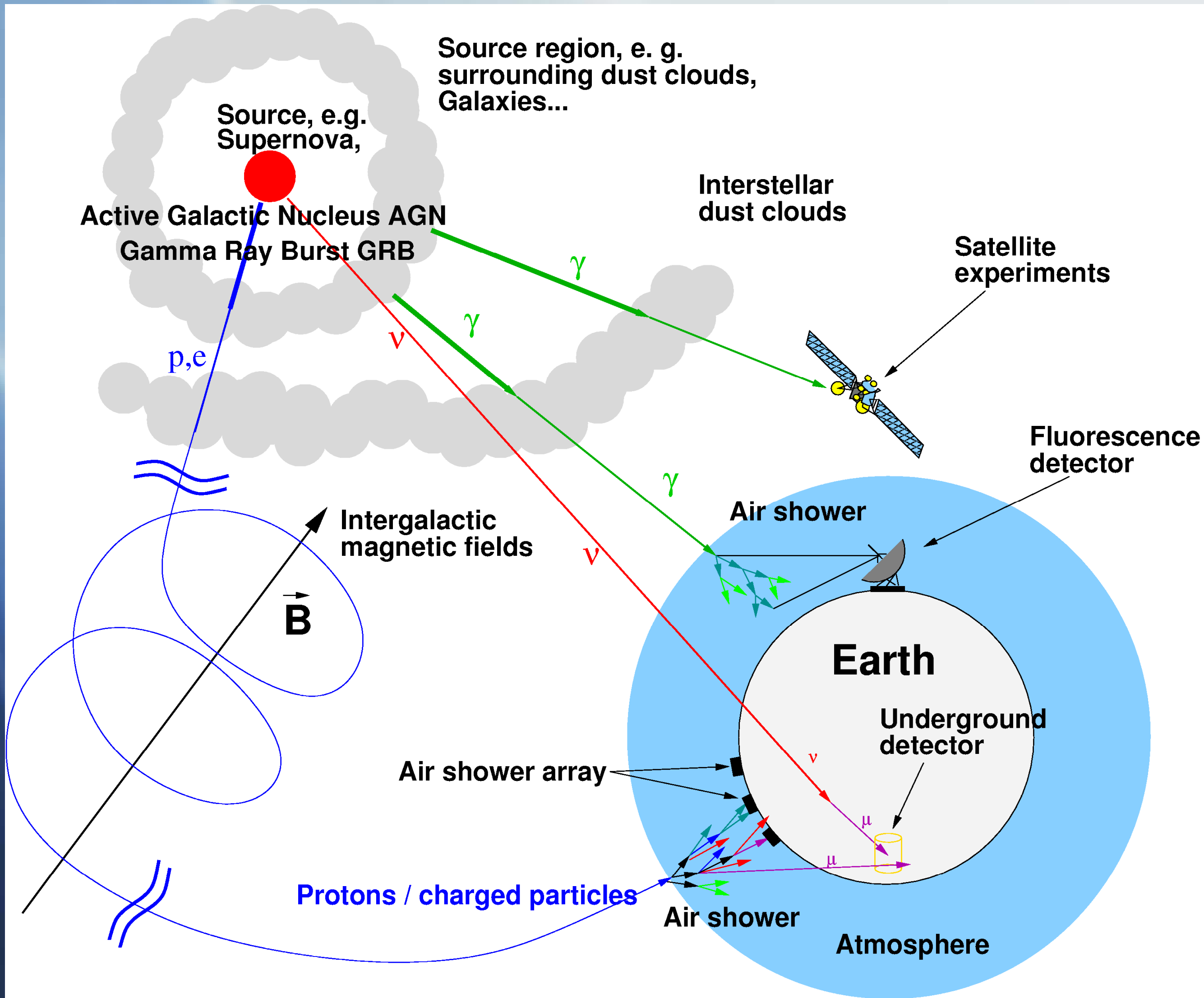
$p+p \rightarrow \pi+\ldots \rightarrow \nu+\ldots$ **or**

$p+\gamma \rightarrow \Delta \rightarrow \pi+n \rightarrow \nu+\ldots$

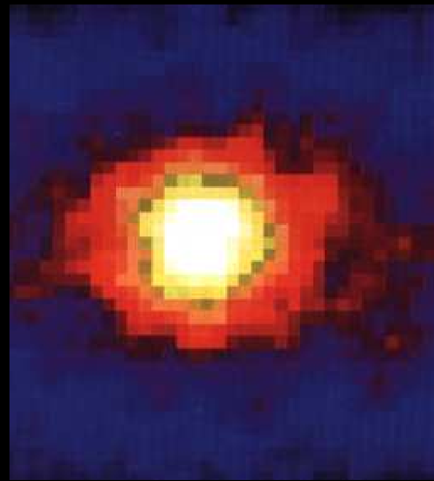


$CR+N \rightarrow \pi\ldots \rightarrow \mu\bar{\nu}_\mu\ldots \rightarrow e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu\ldots$

Astroparticle physics



The observed neutrino sky - so far



MeV
- SUN (Kamiokande, SuperK, SNO)
- SN 1987A (few neutrino events)
  Kamiokande & IMB,…
- The neutrino "ground": Geo-ν's in Kamland

GeV
- Atmospheric neutrinos: Kamiokande, SuperK, MACRO,…

TeV-
- AMANDA, Baikal, now — Soon: IceCube, & "km3NeT"

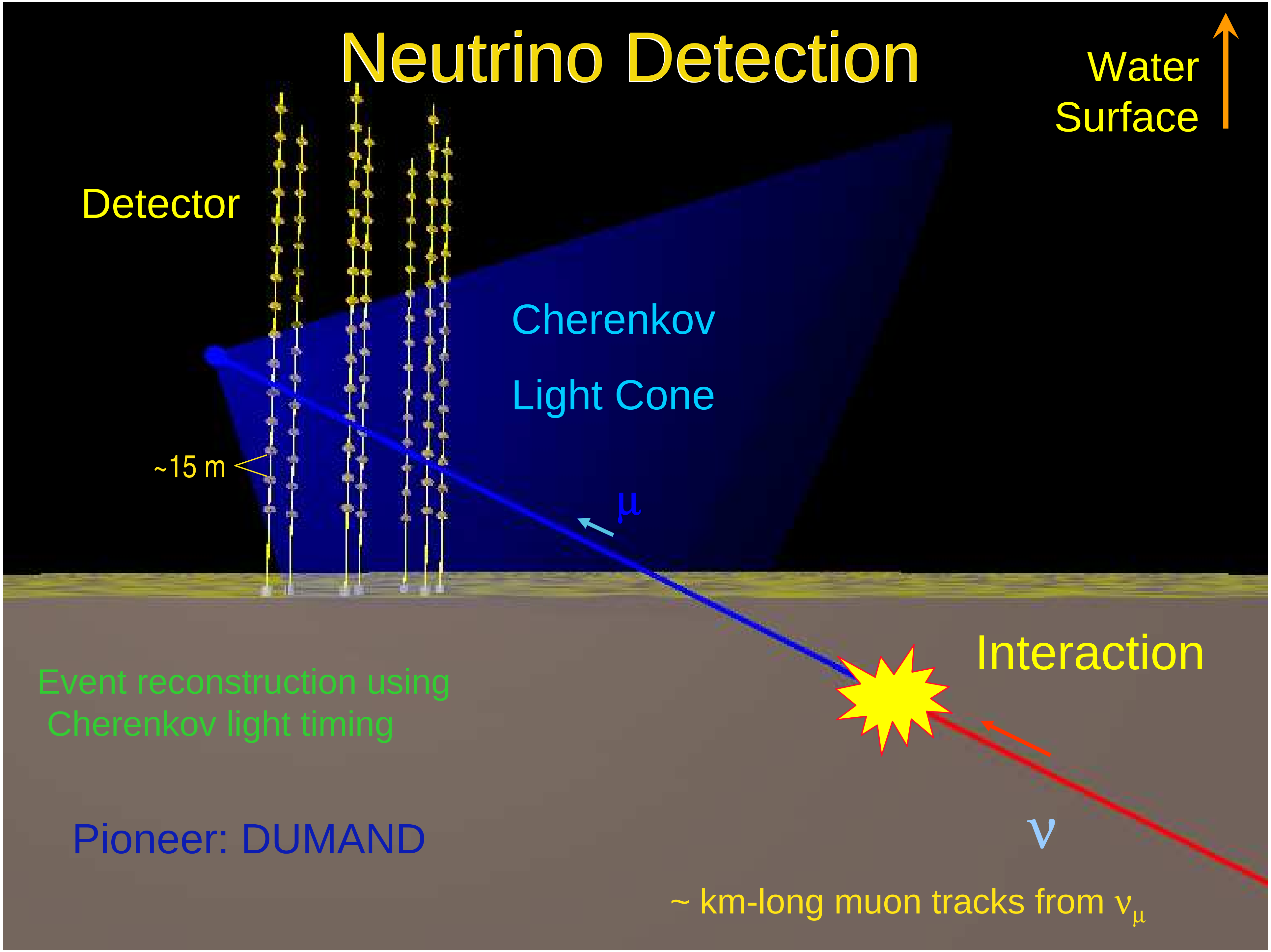
PeV-

?

$$p + p \rightarrow \pi + ... \rightarrow \nu + ... \quad \text{or}$$
$$p + \gamma \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + ...$$

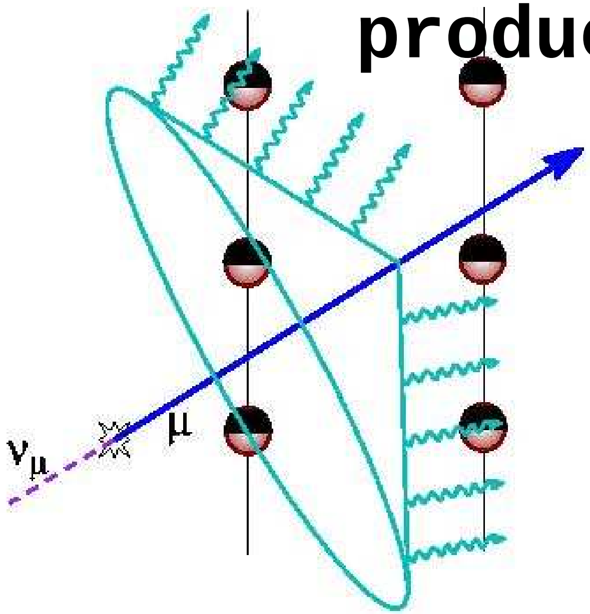
Basic Scientific Goal:
To map the UHE neutrino sky

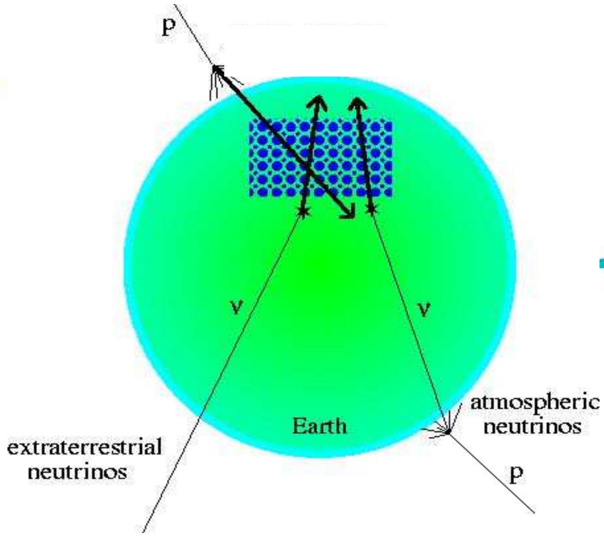
- Sensitivity adequate to confront estimates for
  - Point sources - AGNs, SNR, μquasars,…
  - Diffuse fluxes - all types
  - Transient events - GRBs, SN, …
  - Energy spectra - atm. neutrinos + …
- Adequate control of systematic effects
  - Confidence in data for unexpected signals

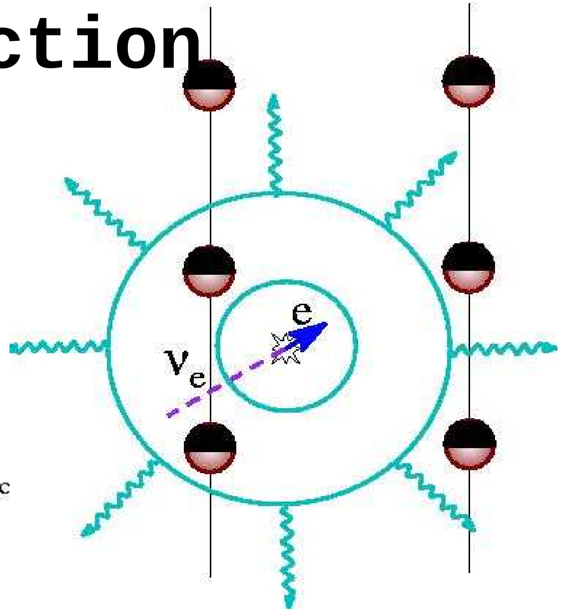


Neutrino Detection
Water
Surface
Detector
Cherenkov
Light Cone
~15 m
μ
Interaction
Event reconstruction using
Cherenkov light timing
Pioneer: DUMAND
ν
~ km-long muon tracks from ν_μ

Neutrino Detection: Cherenkov light from charged products of interaction







Up-going μ tracks (ν_μ)

Cascades ($\nu_{e,\mu,\tau}$ NC, $\nu_{e,\tau}$ CC)

Requires:

Large volumes (small interaction cross sections)

Natural medium (cost)

Very transparent medium (cannot instrument very densely)

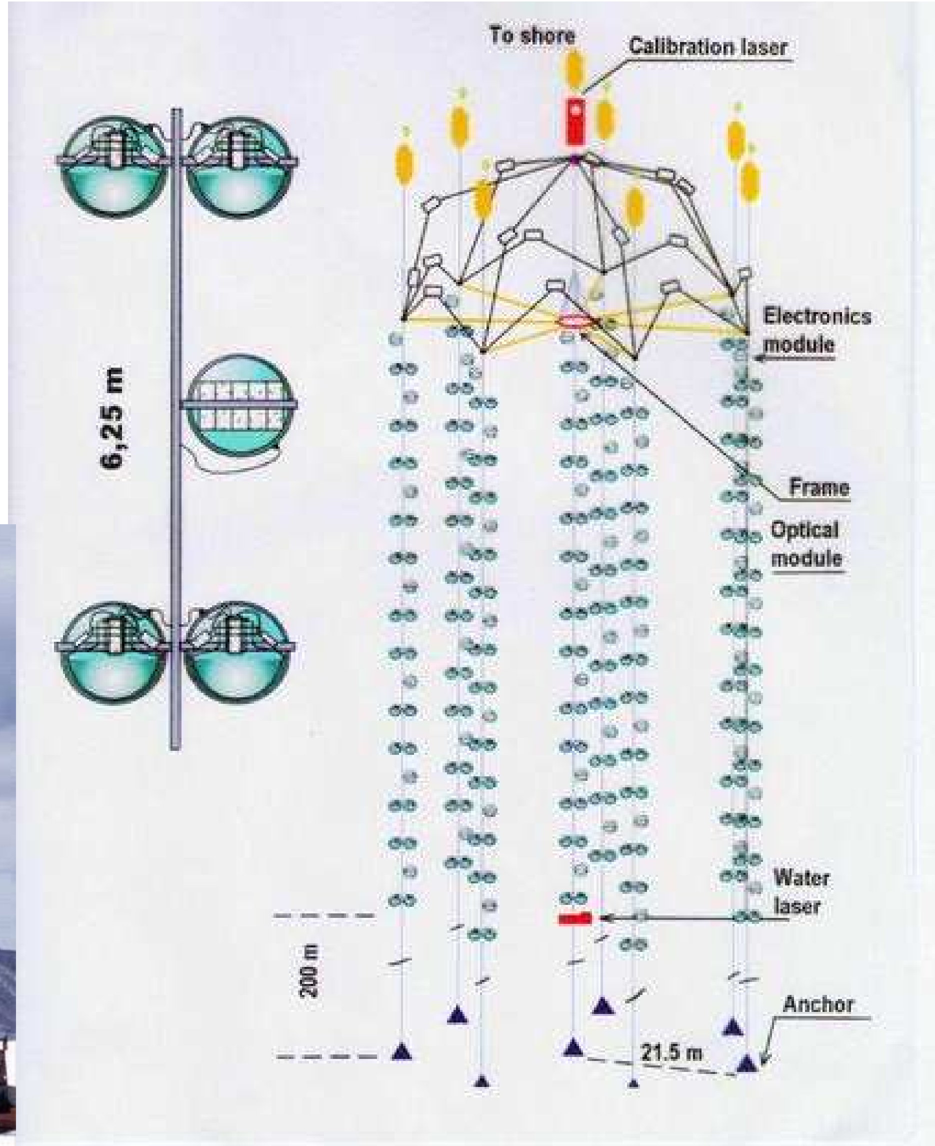
Neutrino Telescopes

BAIKAL NT-200

Baikal NT-200

Location: Lake Baikal

Commissioned:	1997
No. of Strings:	8
Optical Sensors:	192
Depth:	1100m
Instrum. Volume/km3:	10^{-4}
μ-Effective area (1 TeV):	≈2000 m^2
Angular resolution (1 TeV):	3°



Neutrino Telescopes

ANTARES

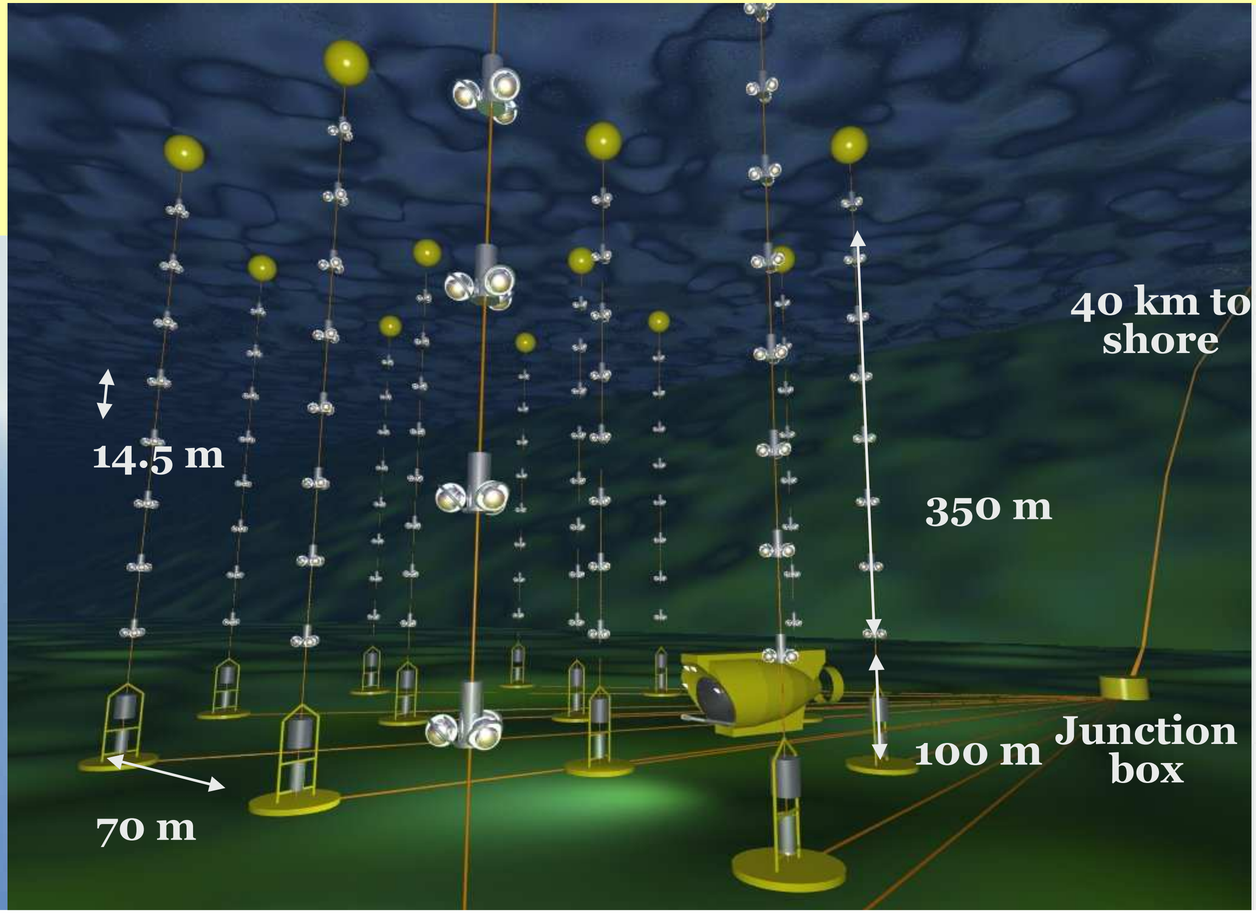
Location: Mediterranean Sea, 40 km off shore

Construction schedule:	2005 - 2007
No. of Strings:	12
Optical Sensors:	900
Depth:	2100-2400m
Instrum. Volume/km3:	0.011

μ-Effective area (1 TeV): 0.016 km^2

Angular resolution (>10 TeV): <0.3°

Architecture: local digitization, transmission of all data to shore.



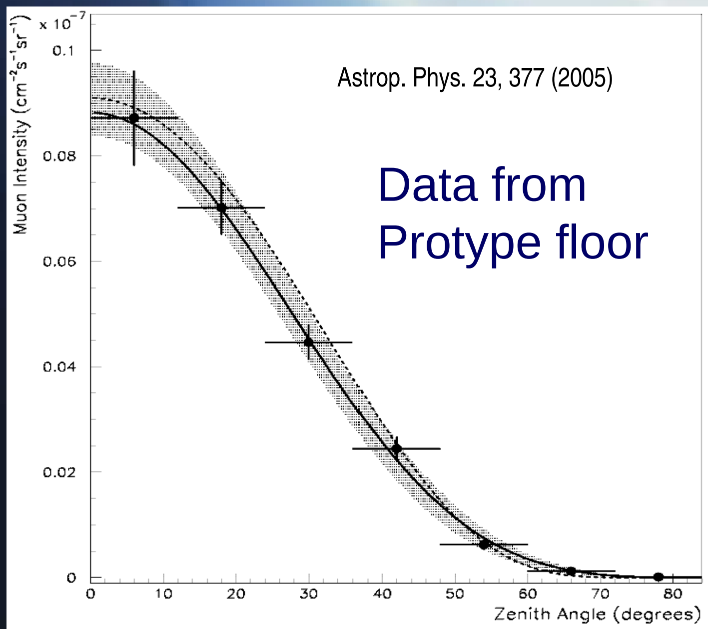
Neutrino Telescopes NESTOR

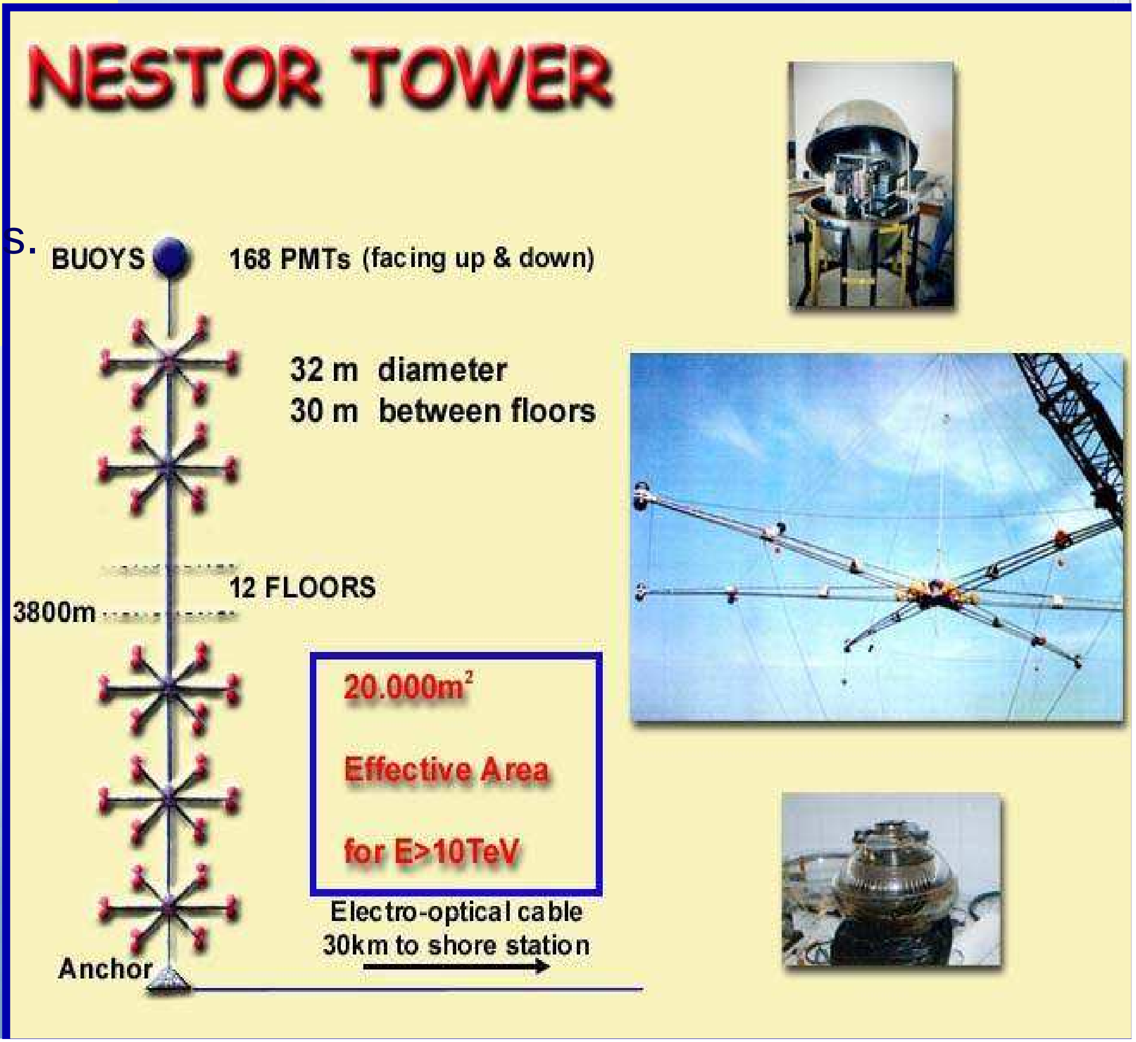
Location: Mediterranean Sea, Pylos
Construction schedule: 2005 - 2007
No. of sensors/floor: 12
Optical Sensors: 168
Pairs facing up and down

Depth (sea floor): 5200 m

Measured very good water properties.
Reconstructed events.

First floor (reduced size) with 12 PMTs deployed and operated in 2003
Goal to deploy 4 more floors in spring 2006.





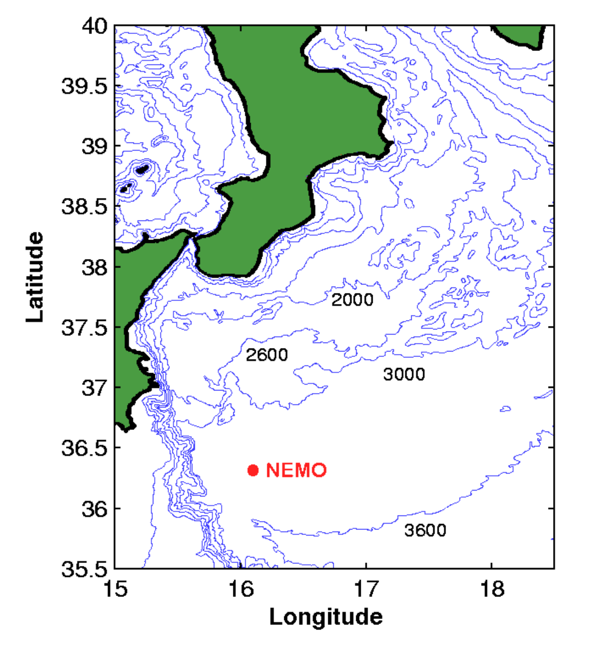
Neutrino Telescopes — NEMO

NEMO in R & D, Phase 1 (to 2006)
Location: (≈80 km) off the coast of Sicily (Capo Passero)

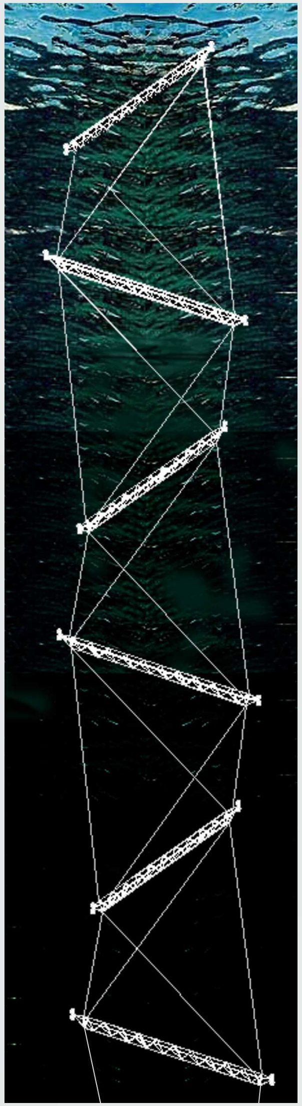
Optical Sensors:	5600
Depth:	≈2800 m - 3400 m
Instrum. Volume/km3:	1

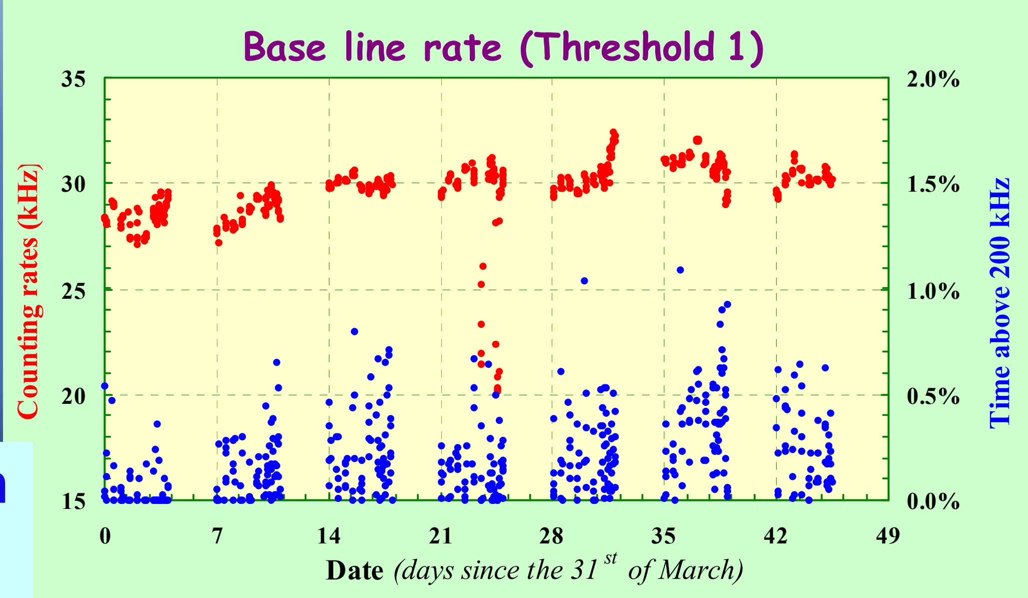
Detailed measurements and studies of water and other site parameters.

Medium is found excellent.



Tower structure

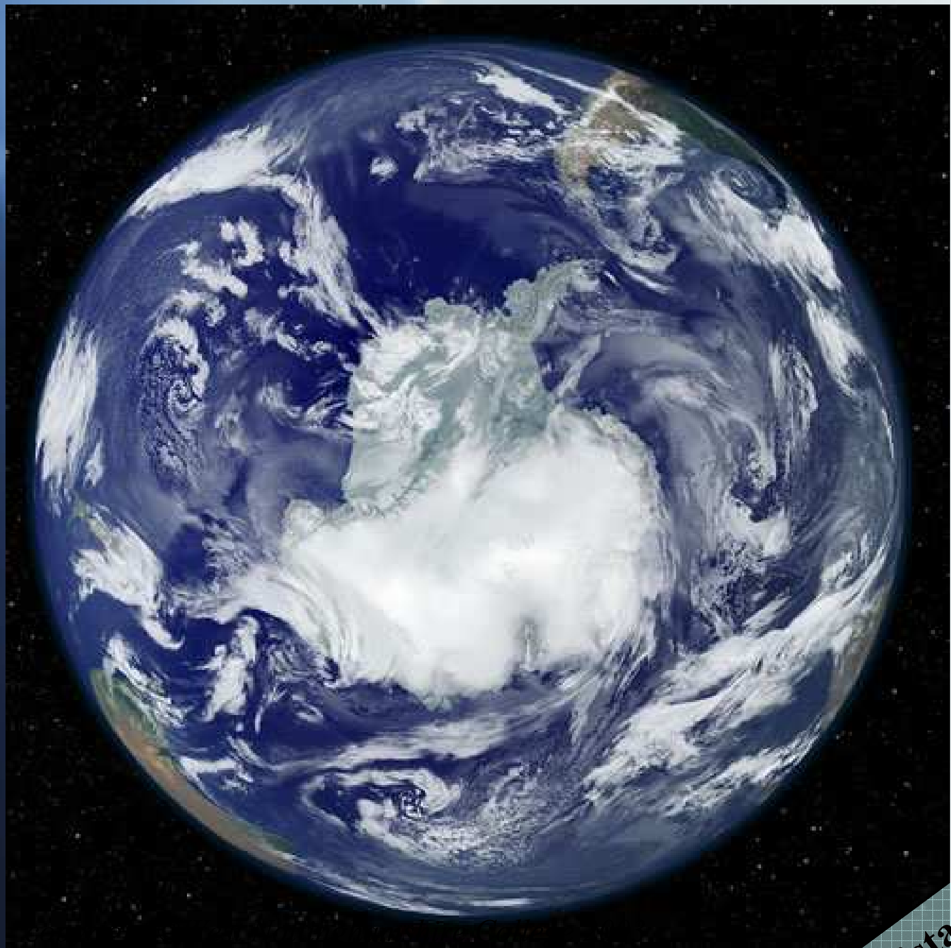




Baseline rate ~ 30 kHz

Burst fraction ~ 0.2 %

IceCube - at the bottom of the world



Distance from Paris 15440 km

9 May 2007 Valencia

David Nygren

Getting There…

Fuel flown to
South Pole:
To run electrical power plants,
Vehicles, and airplanes

LC-130 Hercules

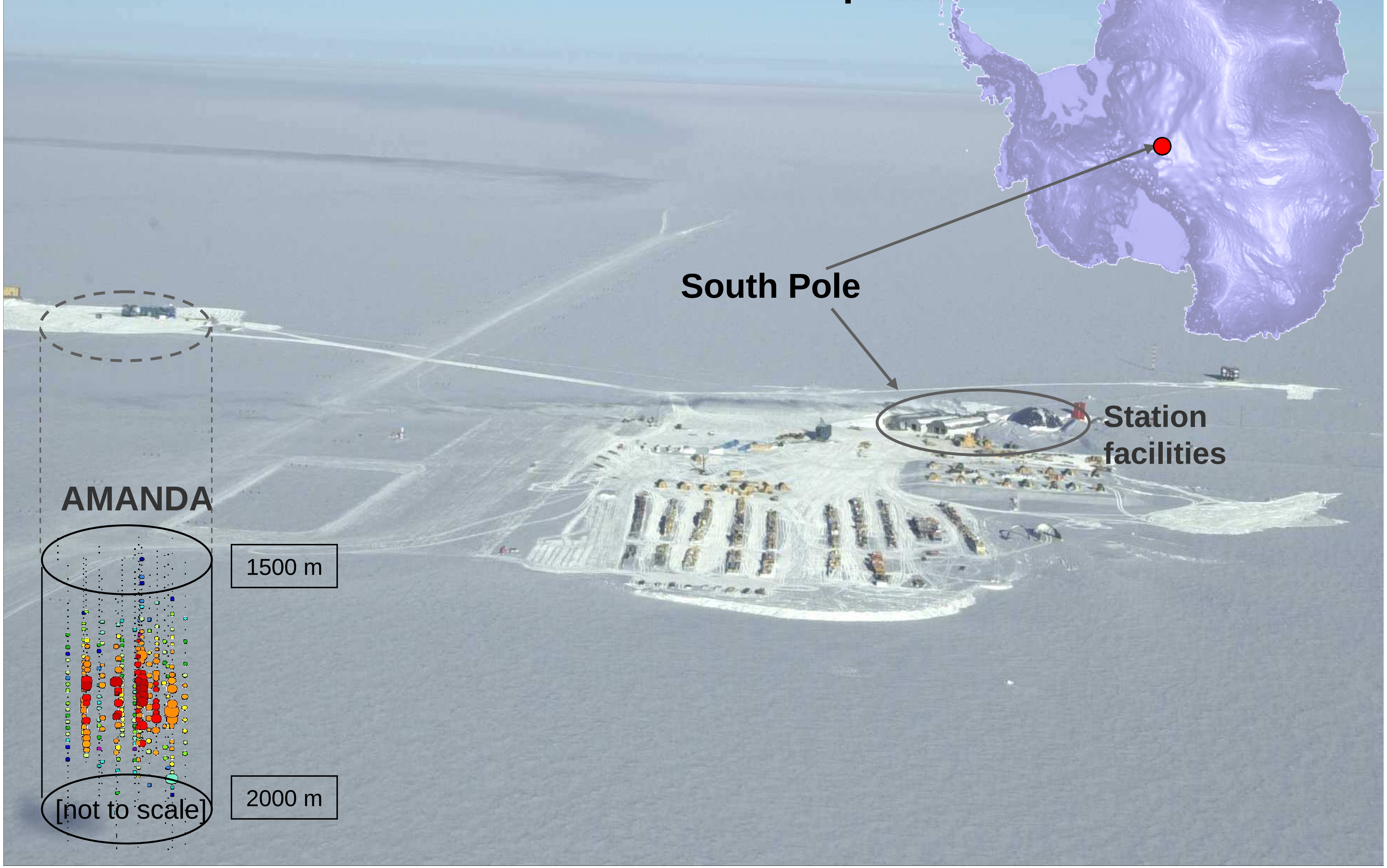
Fuel ship delivers
~7 million Gallons of fuel

LC-130: Cargo from McMurdo to
The Pole. 3 ½ hr for ~ 800 miles

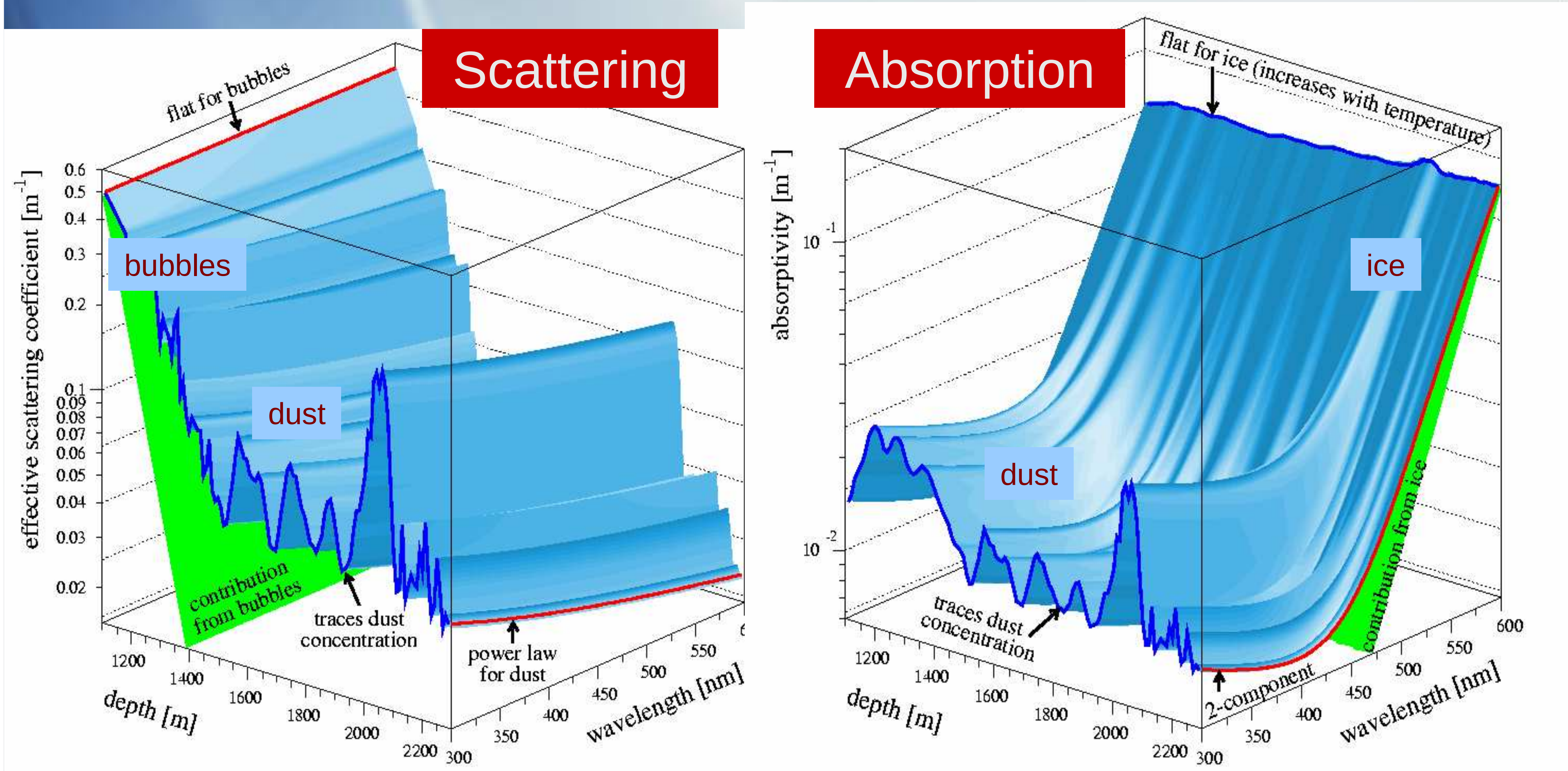
A Hercules plane ready to transport people and goods to Antarctica.

Photo: S. Barwick, UCI

Amundsen-Scott South Pole Station as of 2000: AMANDA completed



Detector medium: ice optical properties



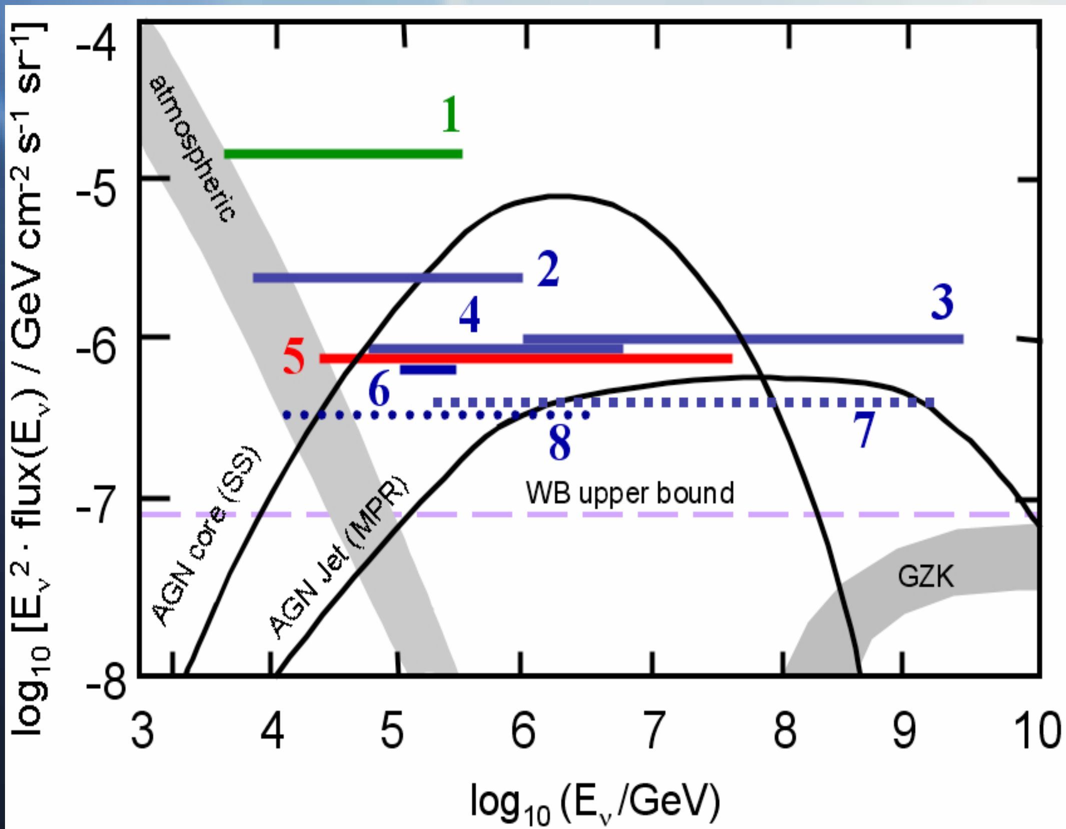
Measurements:
- ► in-situ light sources
- ► atmospheric muons

Average optical ice parameters:

λ_{abs} ~ 110 m @ 400 nm

λ_{sca} ~ 20 m @ 400 nm (eff λ)

Diffuse neutrino flux limits



1. MACRO
2. AMANDA B10 ν_μ (1997)
3. AMANDA-B10 UHE (1997)
4. AMANDA-II cascades (2000)
5. Baikal cascades 1998-2002
6. AMANDA-II ν_μ-analysis (2000)
7. AMANDA-II UHE sensitivity !!
8. AMANDA ν_μ-analysis (2000-2003) sensitivity

Preliminary!

All limits multiplied by 3 for oscillations!!

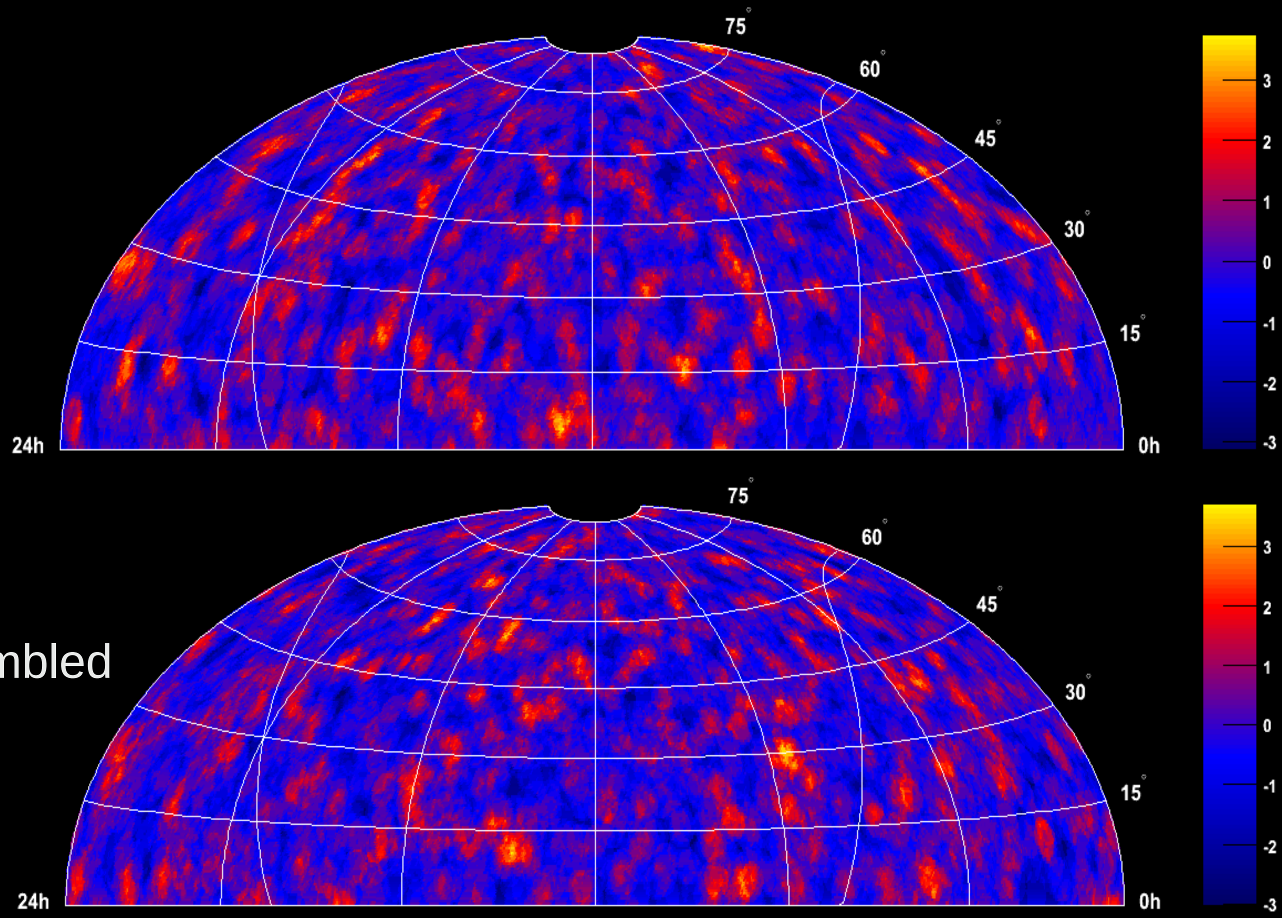
Search for neutrino clusters in the northern sky

event selection optimized for both $dN/dE \sim E^{-2}$ and E^{-3} spectra

significance map

Data

Time scrambled Data



AMANDA II data from 2000-2004 (1001 live days)

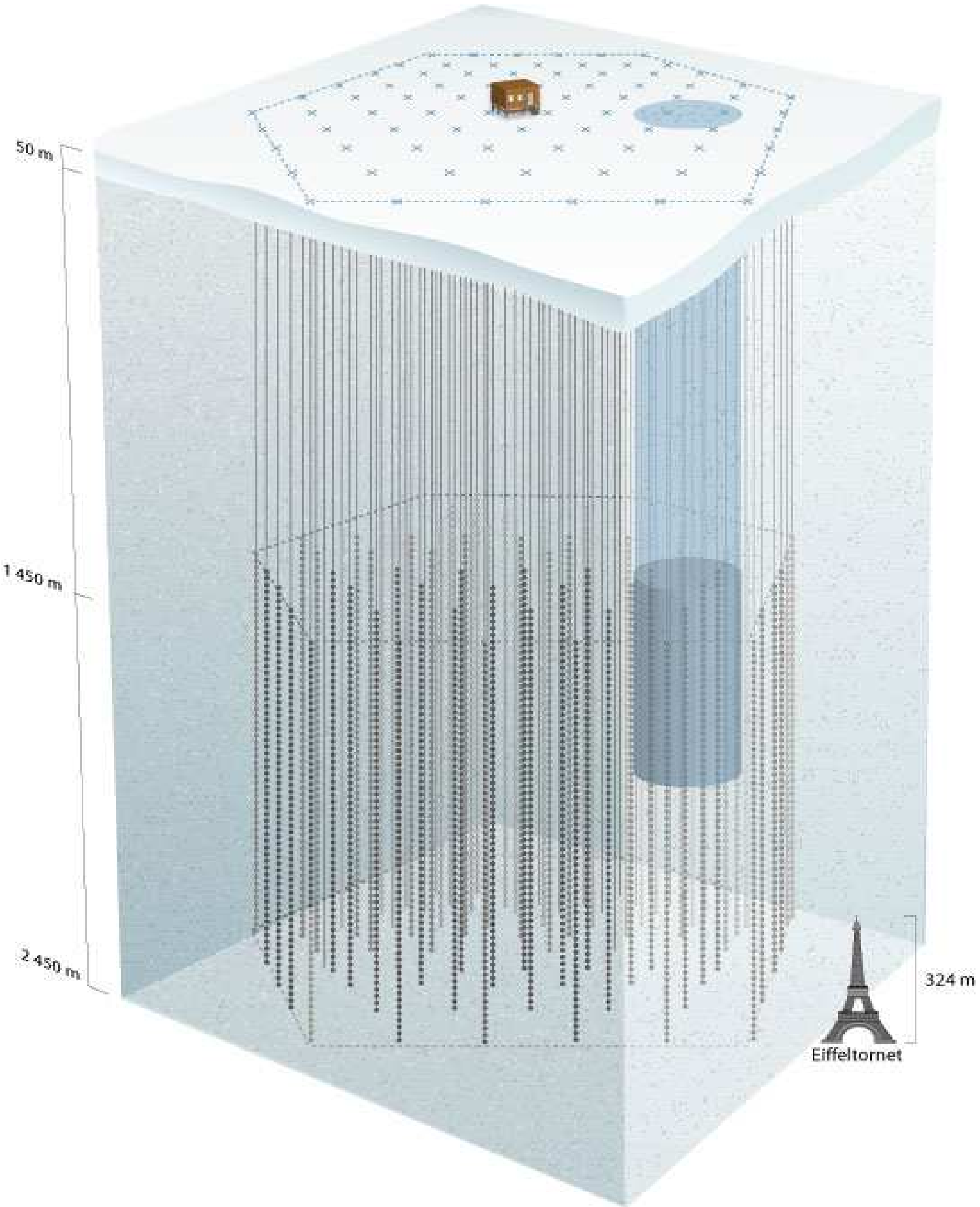
4282 ν from northern hemisphere

No signal observed

The IceCube collaboration

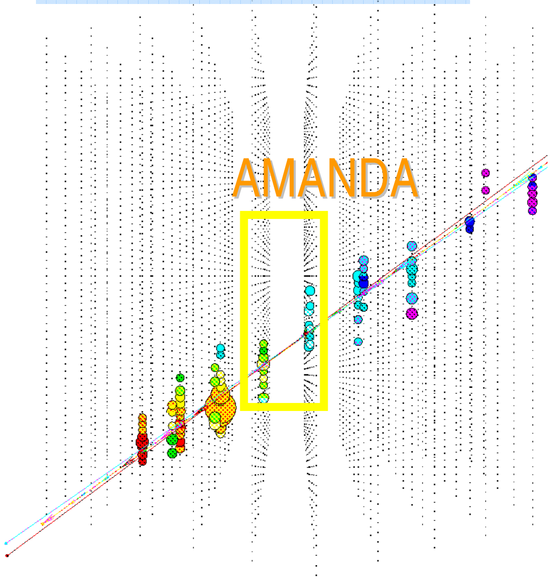
IceCube

- 1 km^3 of Antarctic Ice - ~1 gigaton detector
- 4800 Digital Optical modules on 80 strings
- 160 Ice-Cherenkov tank surface array (**IceTop**)
- Surrounding exisiting AMANDA detector
  - 677 Optical Modules
- Just completed 3rd construction season

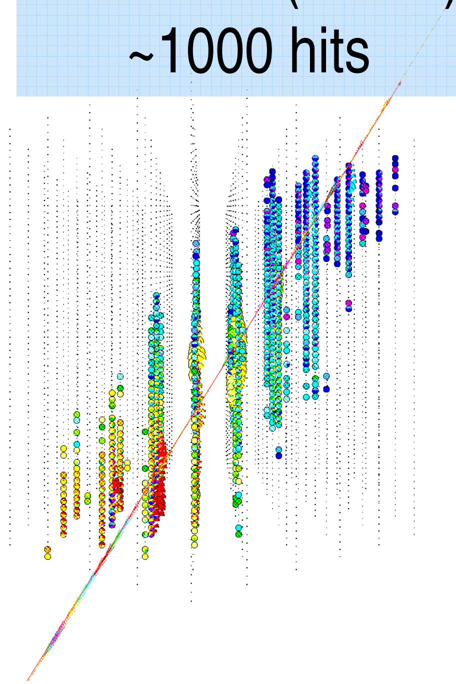


Event Signatures in IceCube

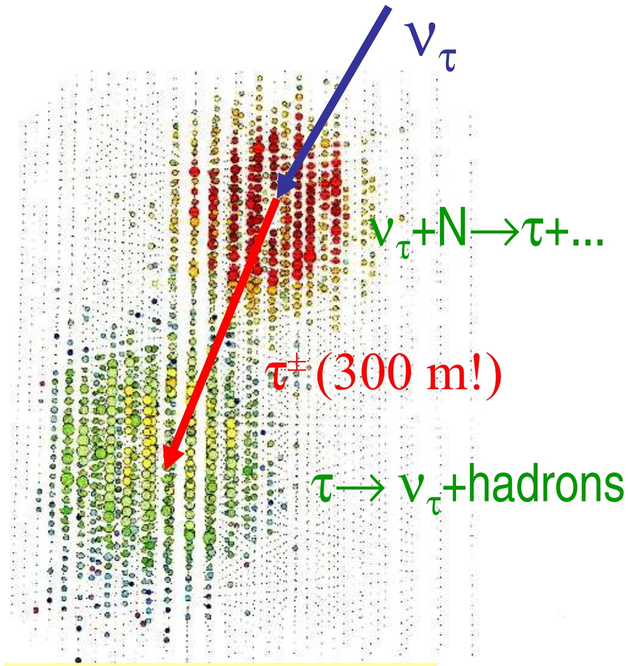
10^{13} eV (10 TeV)
~90 hits



6×10^{15} eV (6 PeV)
~1000 hits



Multi-PeV

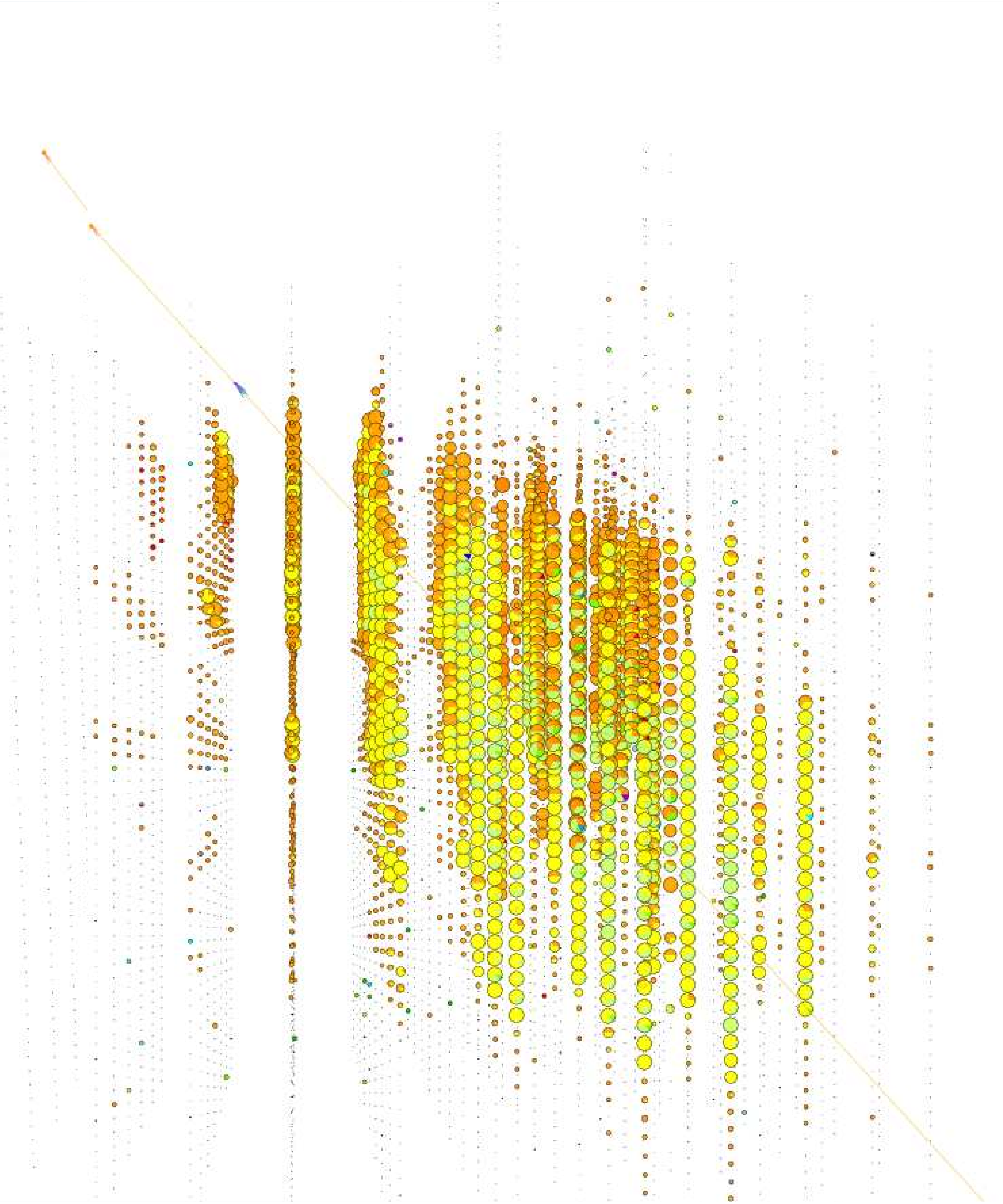


ν_μ signature

ν_τ signature

Expect about 100,000 events/yr

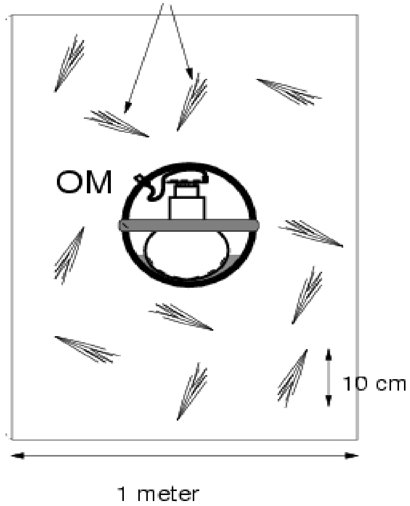
UHE ν in AMANDA And IceCube



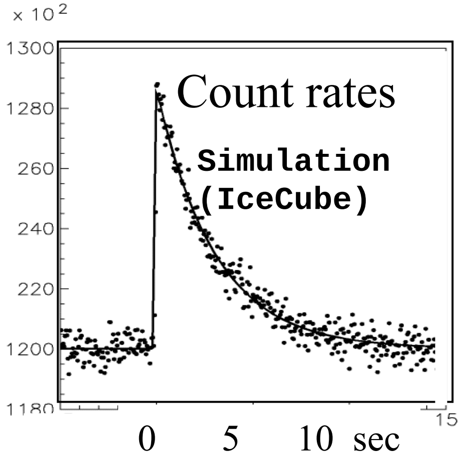
Searches for SN neutrinos

Look for collective rate increase in all PMT's on top of dark noise

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

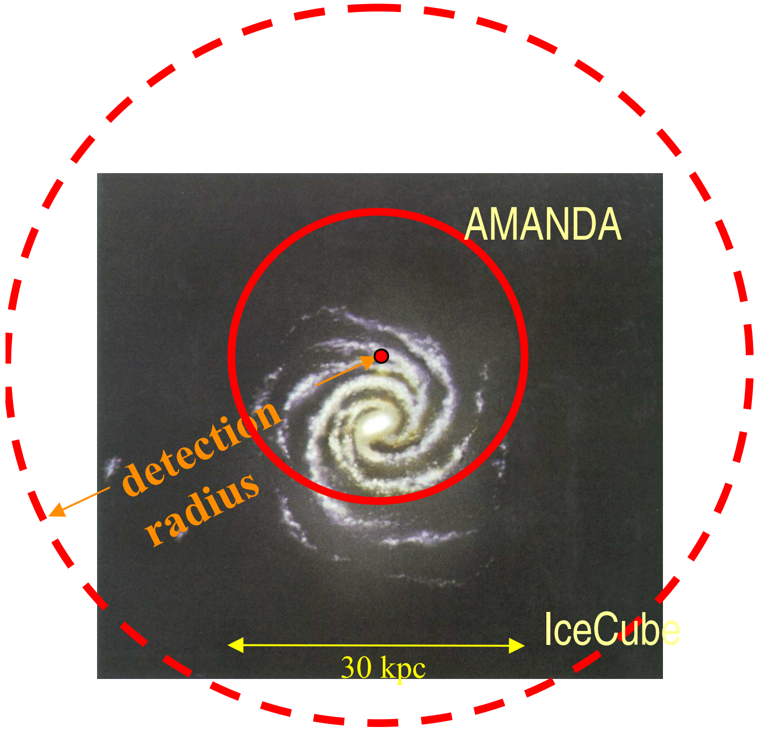


O(10cm) long tracks



Coverage of our galaxy
B10: 70%
A-II: 95%
IceCube: to LMC

- published 215 live days (AM-B10) ⇒ no candidate events
- prel. limit 2000-03 < 2.6 SN/year



SNEWS (SuperNova Early Warning System) includes Super-K, SNO, LVD, KamLAND, AMANDA/IceCube, BooNE
http://snews.bnl.gov/

The South Pole

- Agency: NSF
- Access: ~ 3 - 4 summer months
- Altitude: ~ 3000 m (Ice thickness!)
- Temperature: - 30º C (summer)
- Wind: Significant
- Major Activity: Station Modernization
- Population: Limited

⇒ Intense working conditions

IceCube: Technology Transition

Decision

- Digital Optical Module (DOM)
- All-digital copper network: twisted pairs
  - Supplies power to DOM
  - Transmits commands to DOM
  - Transmits timing signal to DOM
  - Receives data from DOM

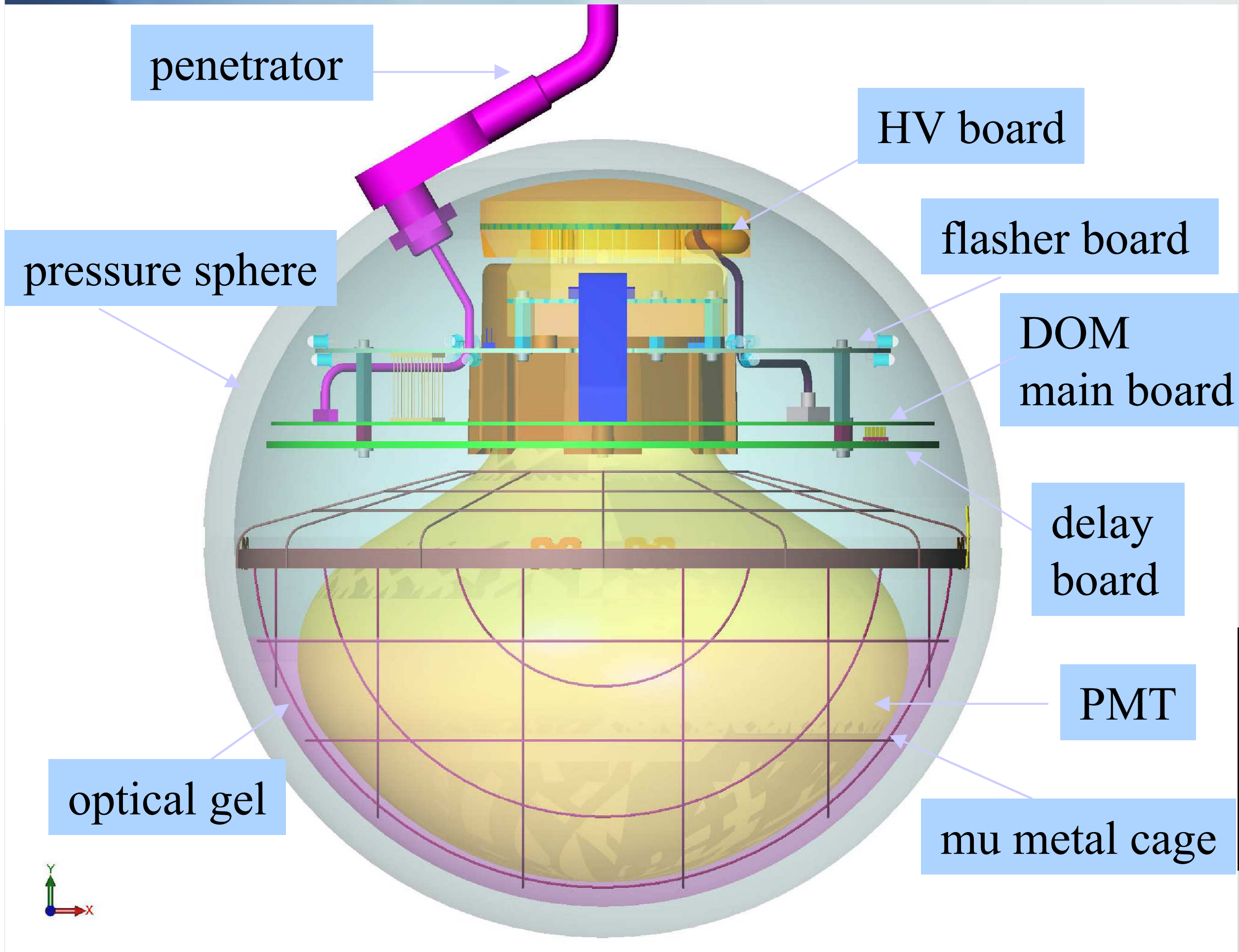
No low-level signals outside of DOM

Fully differential signaling in network

Fully automated calibration, NH operation

Digital Optical module (DOM)

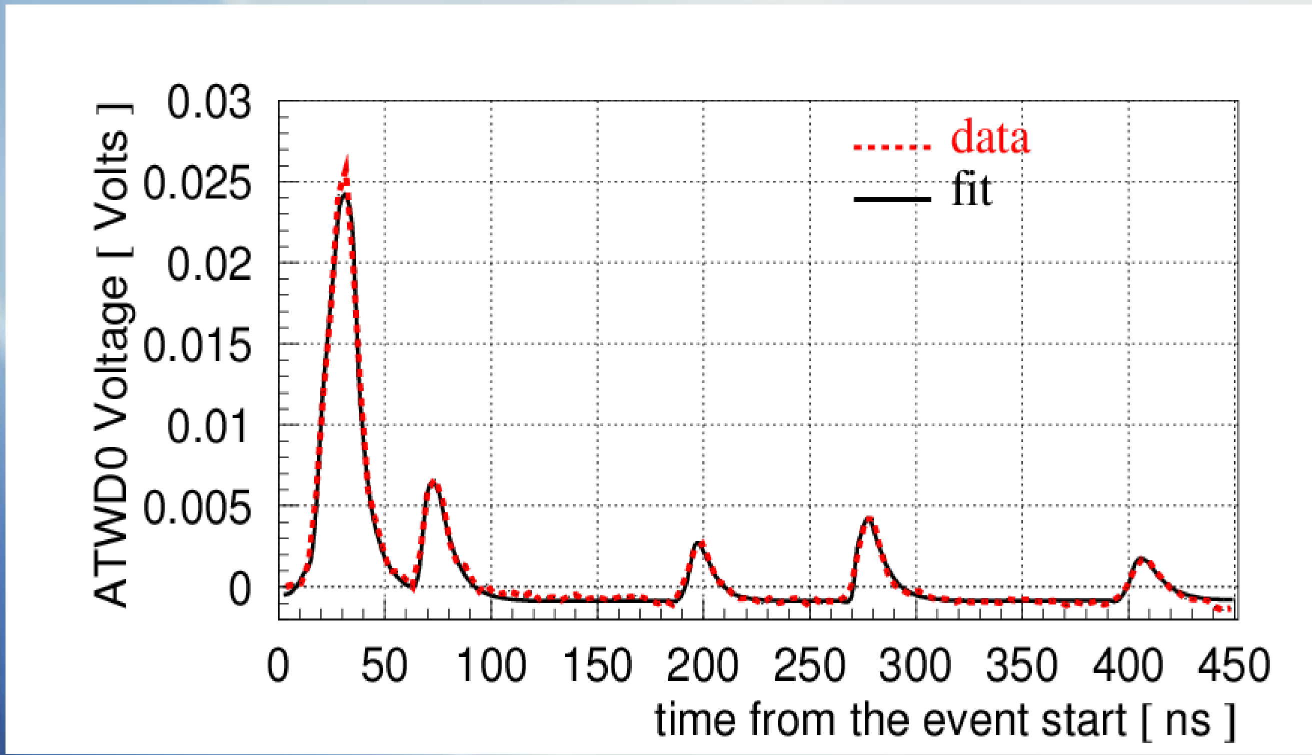
- an optical sensor
10 inch Hamamatsu R-7081



- a semi-autonomous DAQ platform:
  - ✓ records
  - ✓ timestamps
  - ✓ digitizes
  - ✓ stores data
  - ✓ transmits to surface at request

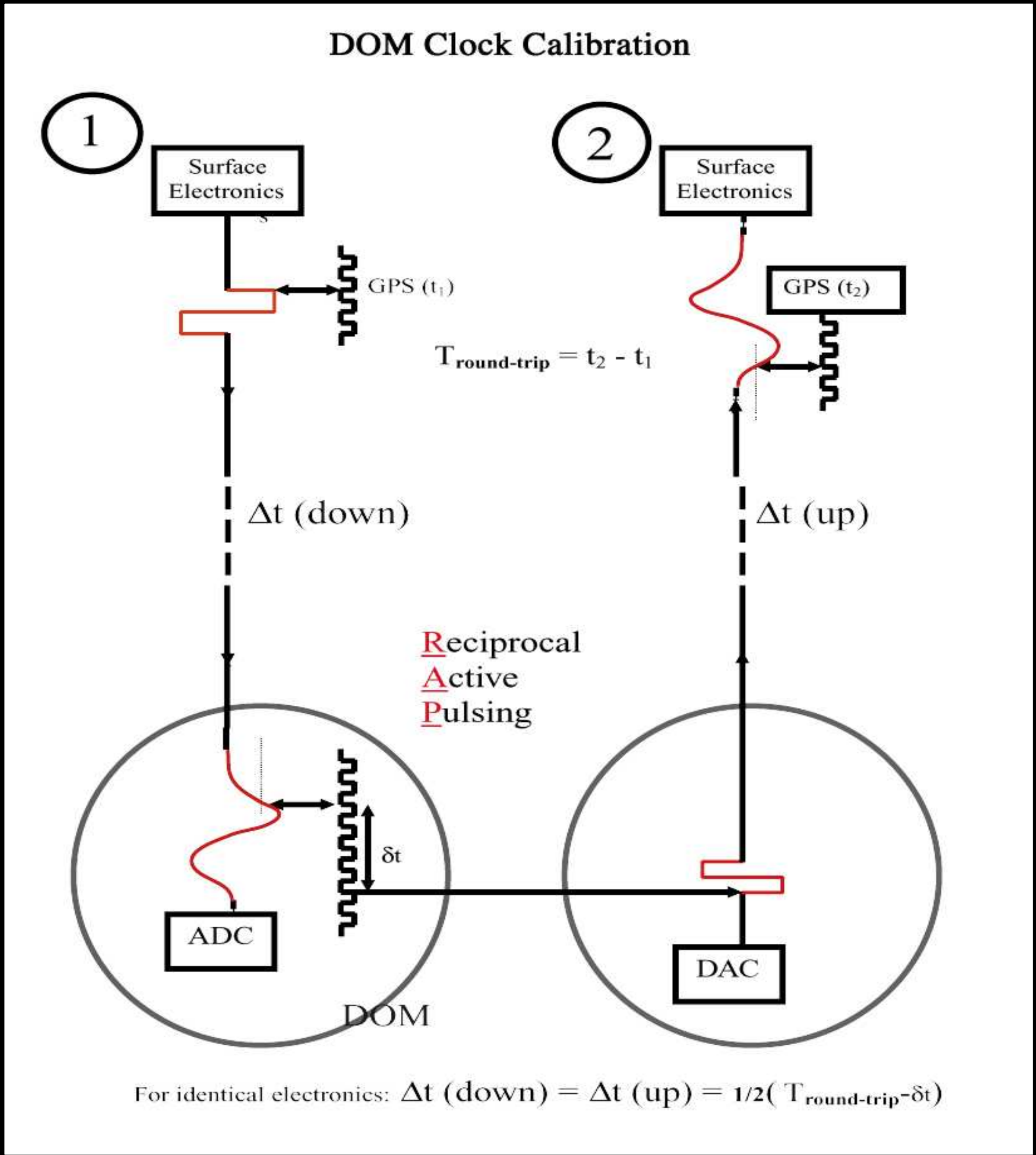
Noise rate ~600 Hz:
Excellent SN monitoring
within our Galaxy

Example of the trace in one DOM, caused by a triggering muon



Acquired and reconstructed waveform

Performance: Reciprocal Active Pulsing

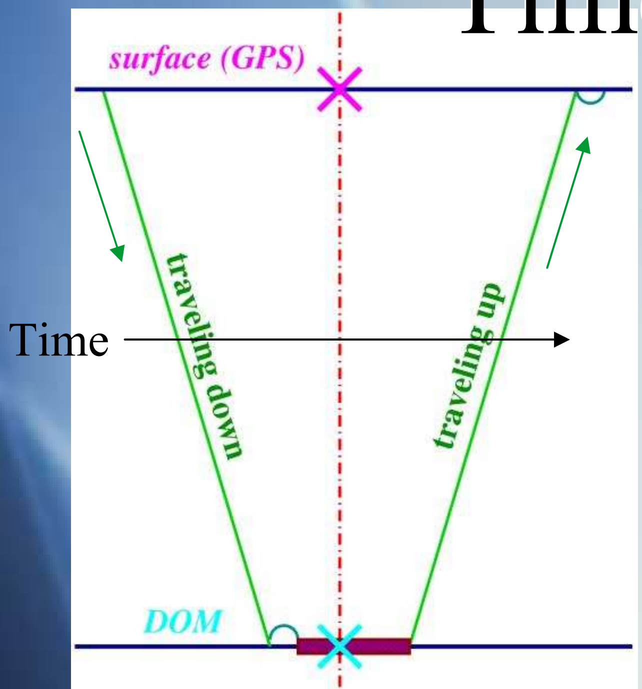


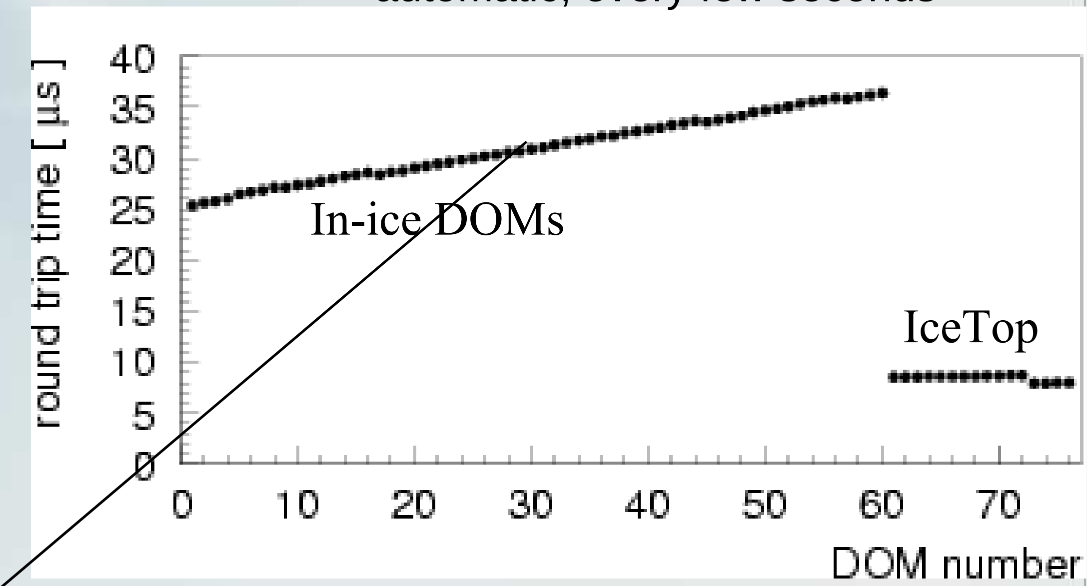
Relates the local free running DOM oscillators to the Universal Time Code standard transmitted by GPS satellites

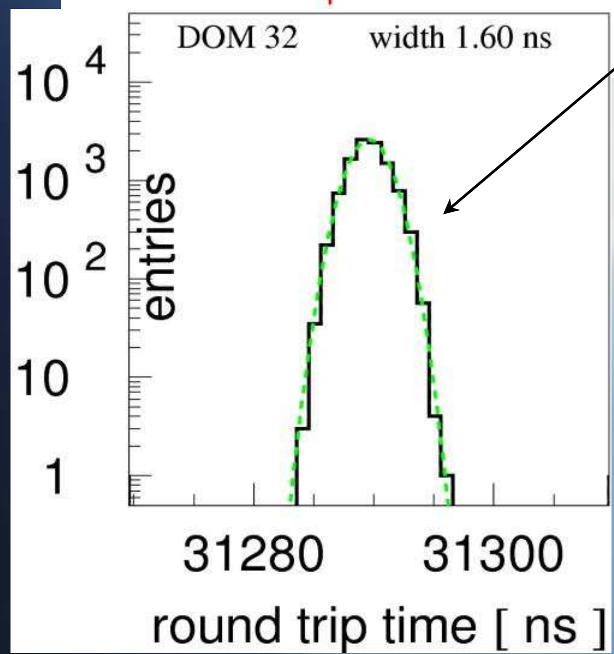
Makes the 5000 DOMs in the detector and AMANDA look like they are running from a single common clock

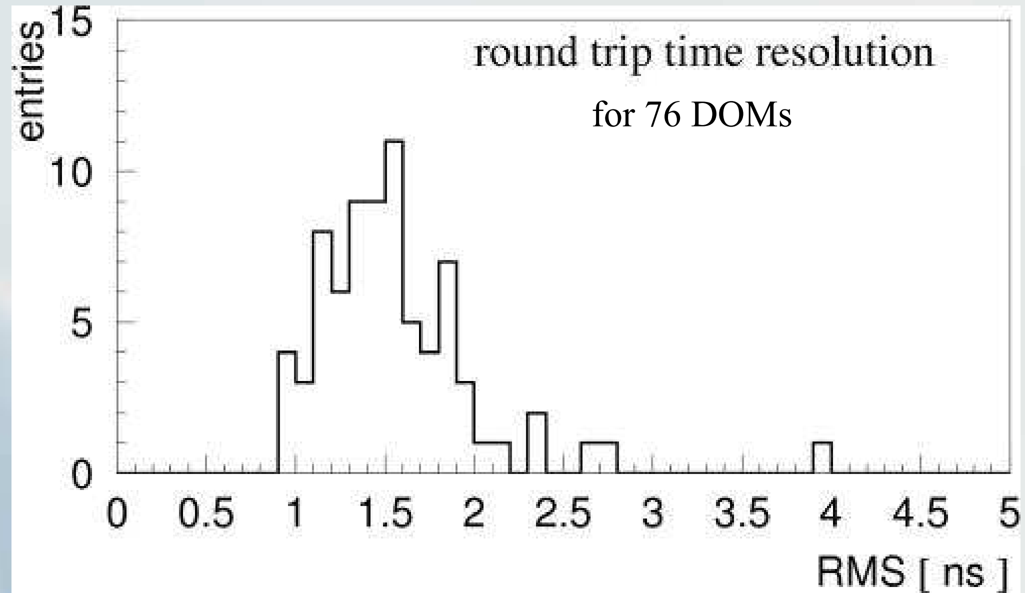
Time Calibration

automatic, every few seconds



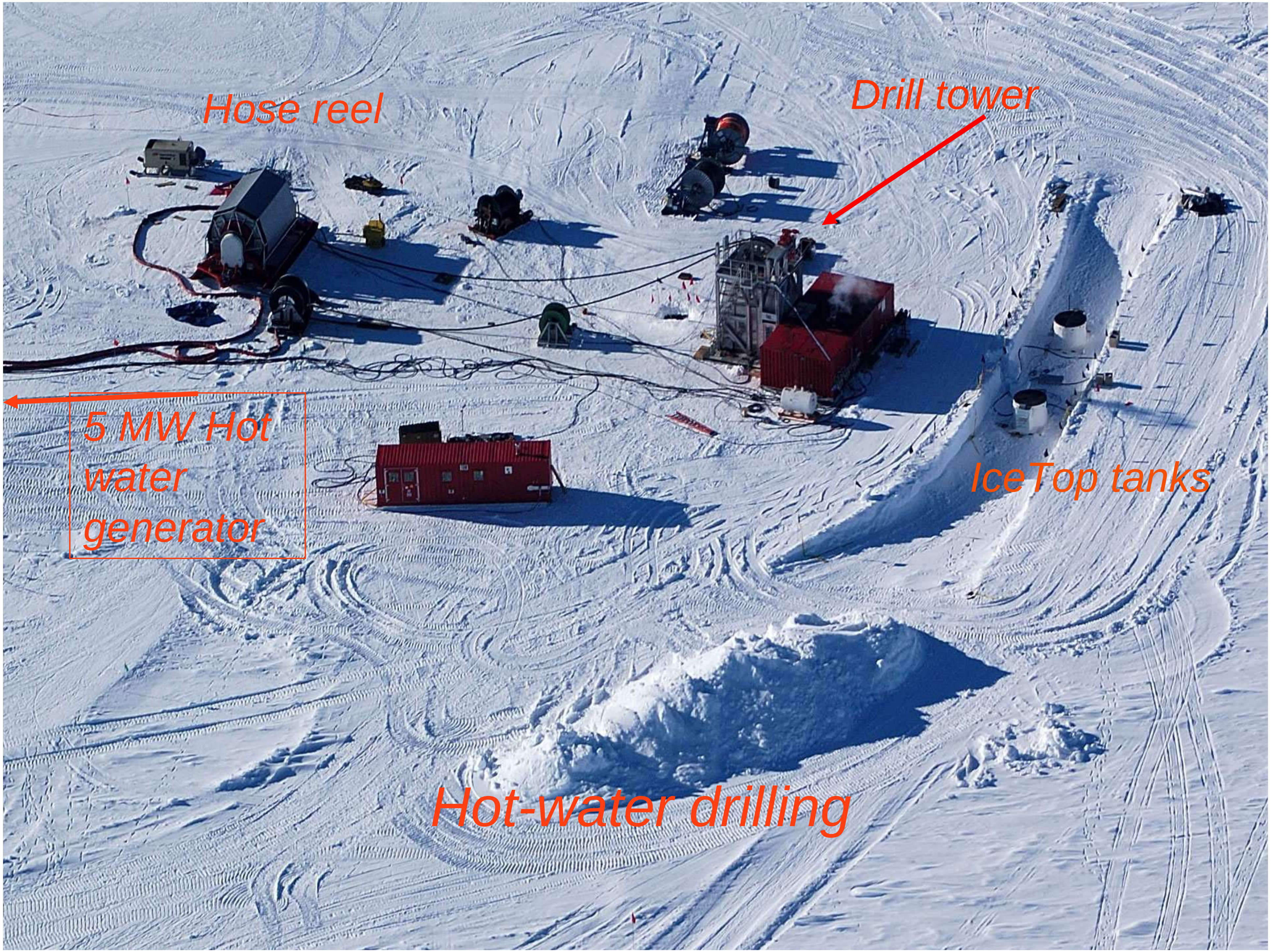




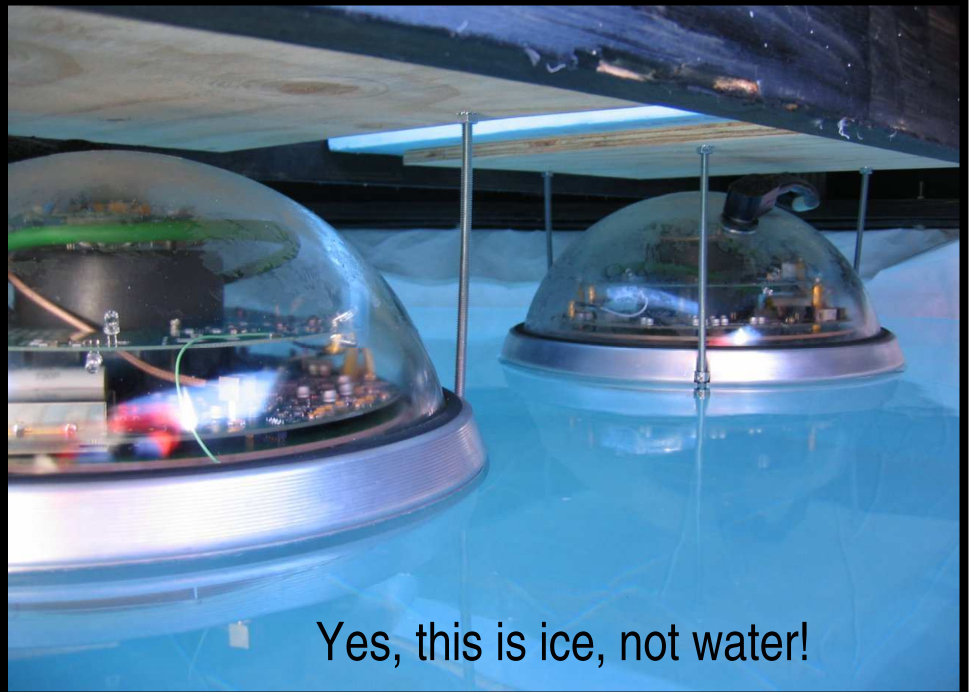


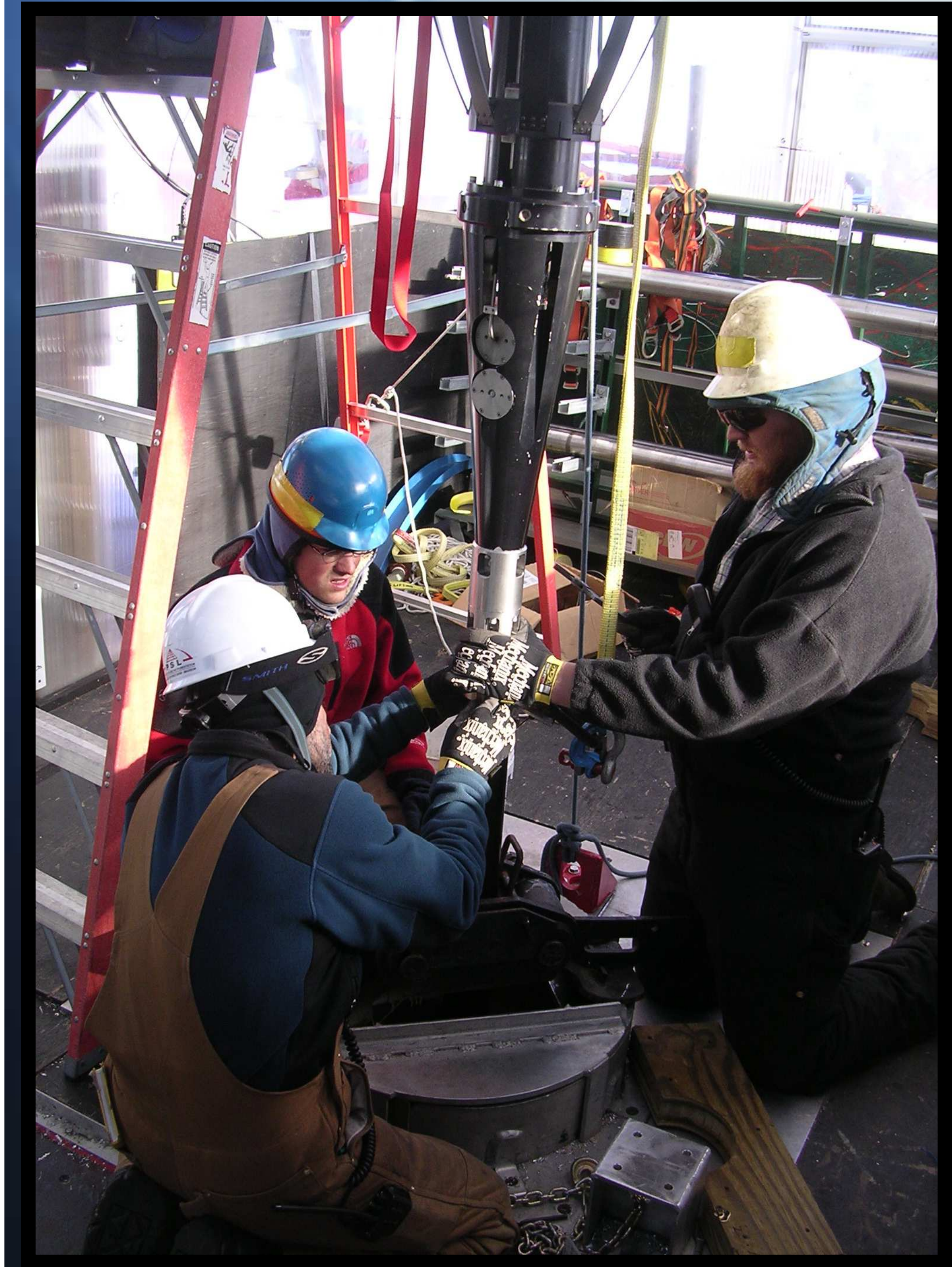
Summary of Technology Impact

- Decentralized architecture preserves data quality through digital messaging
- Innovative timing scheme has negligible impact on bandwidth of network
- Self-calibrating and autonomous behavior permits minimum on-site personnel
- Goals: effective control of systematics and high confidence in physics content of data

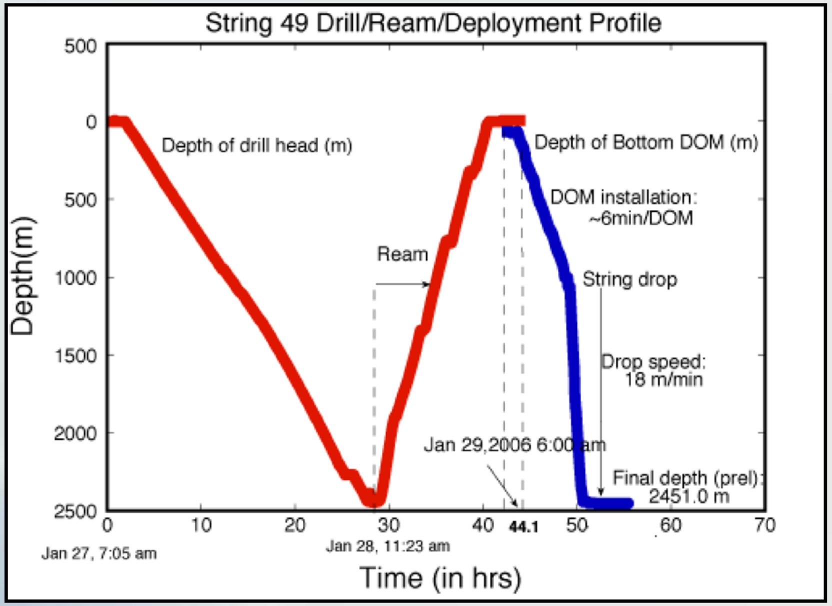

Hose reel
Drill tower
5 MW Hot water generator
IceTop tanks
Hot-water drilling

IceTop Tanks

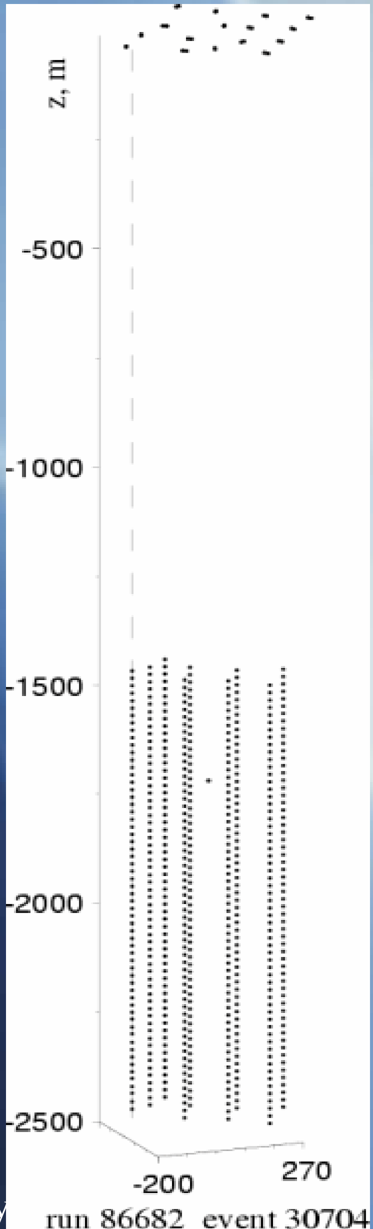


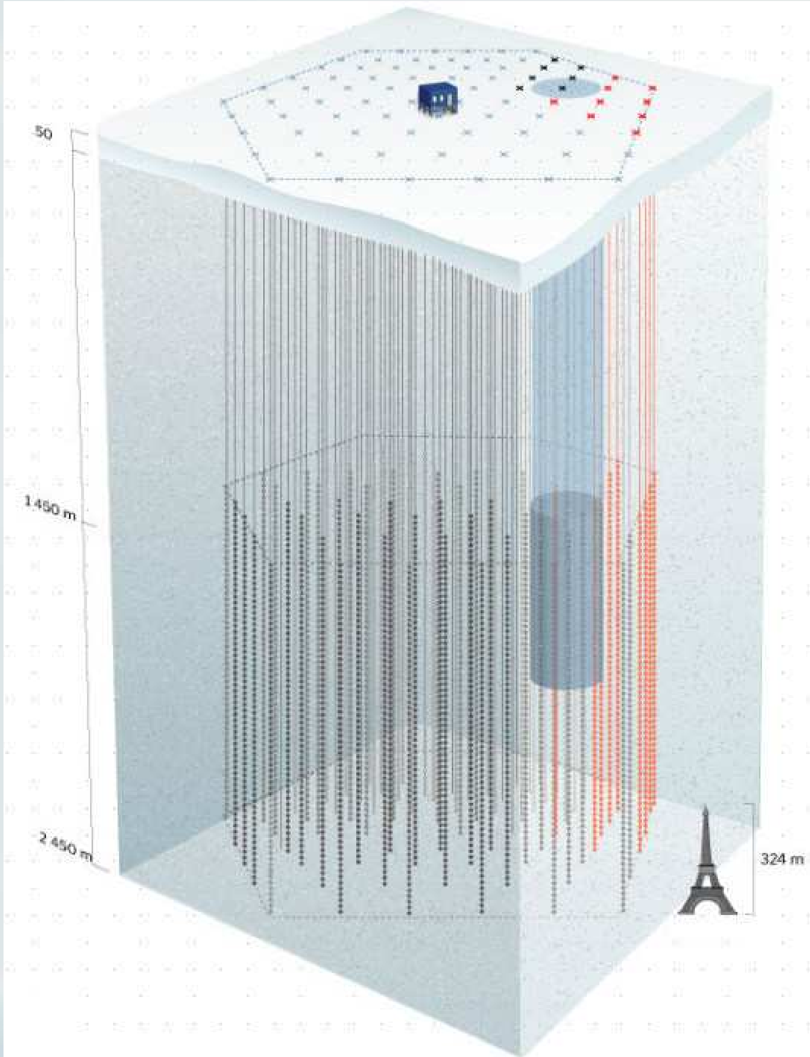


Drilling and Deployment

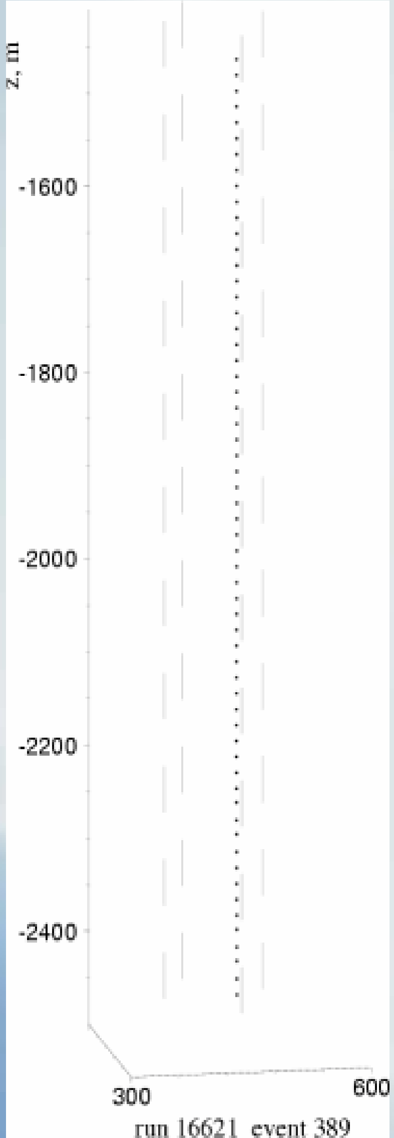


an IceCube-IceTop event



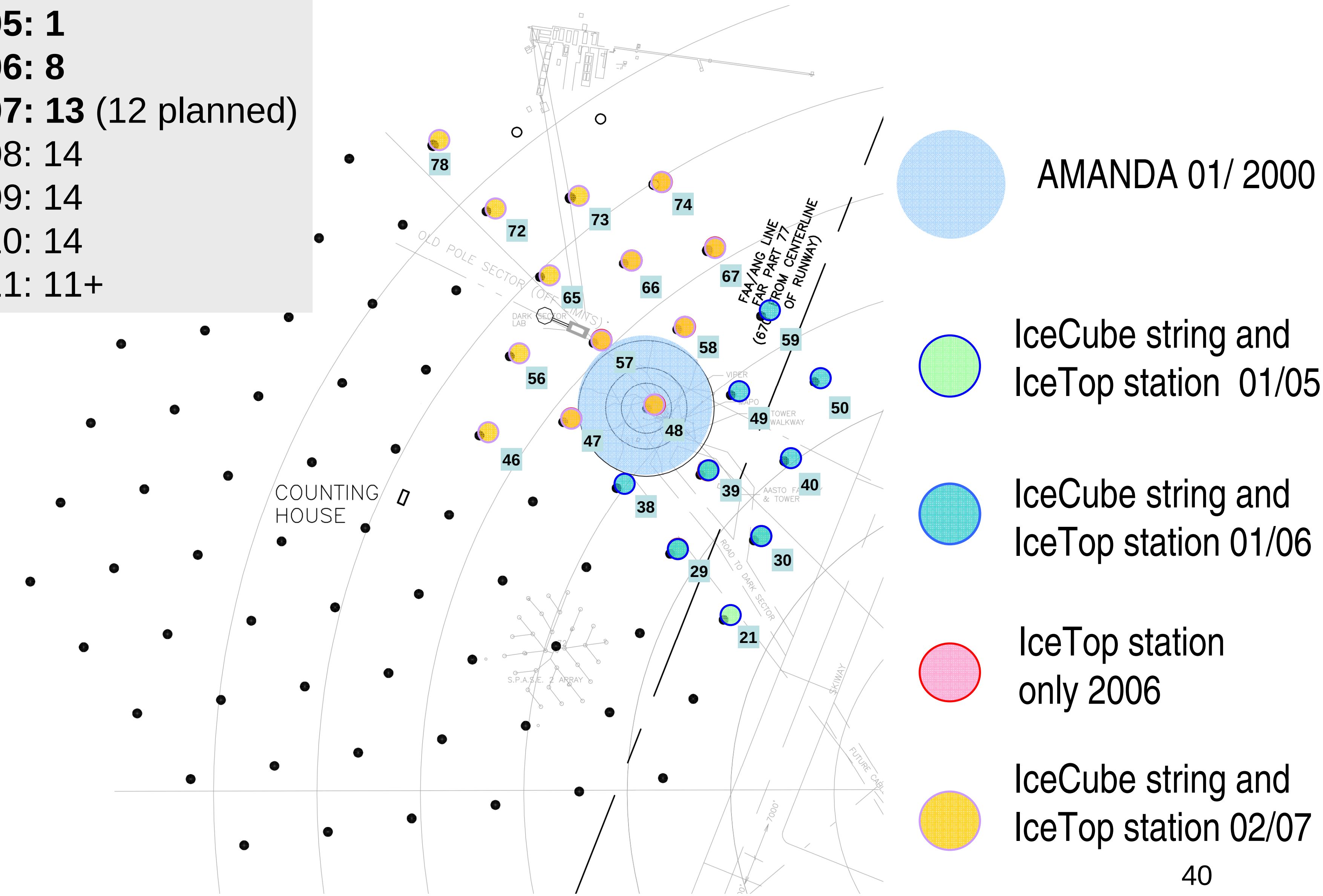


an IceCube (1 string) neutrino event

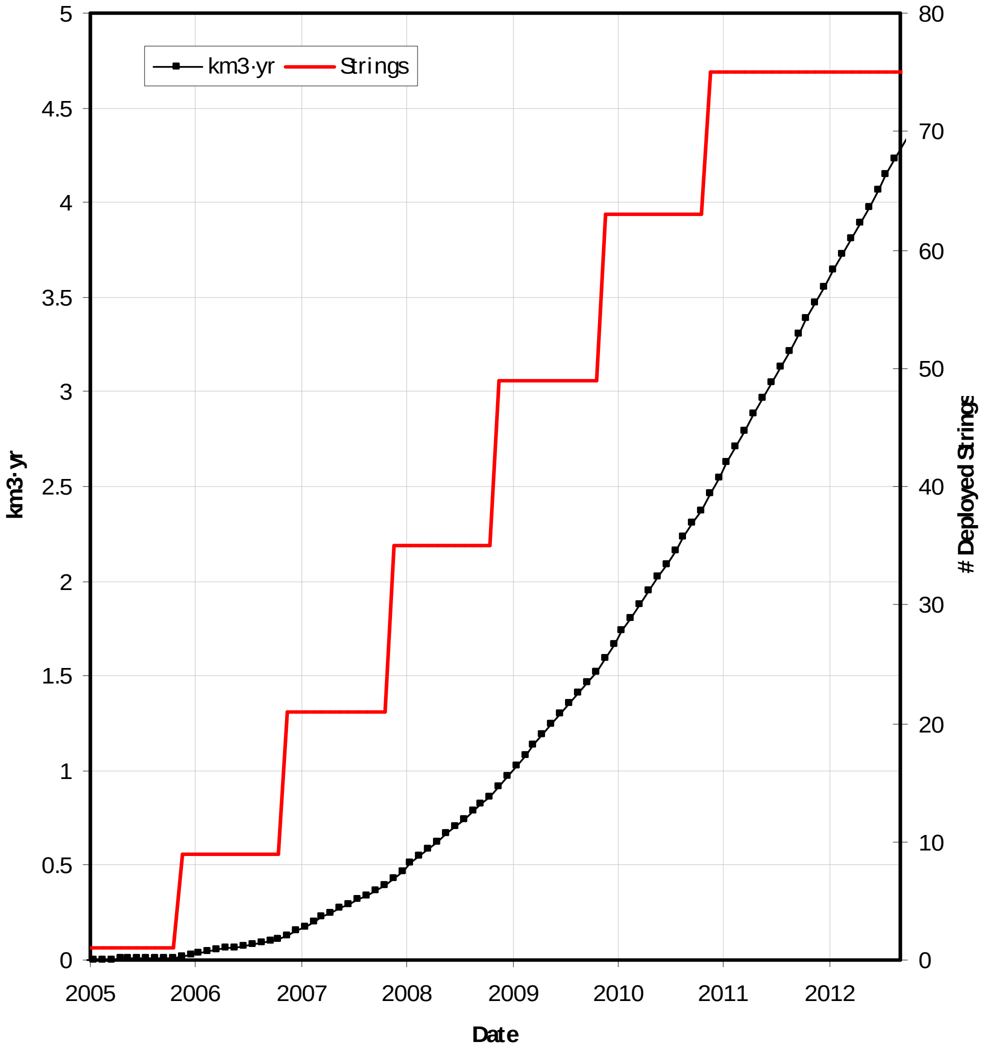


Deployments

2005: 1
2006: 8
2007: 13 (12 planned)
2008: 14
2009: 14
2010: 14
2011: 11+



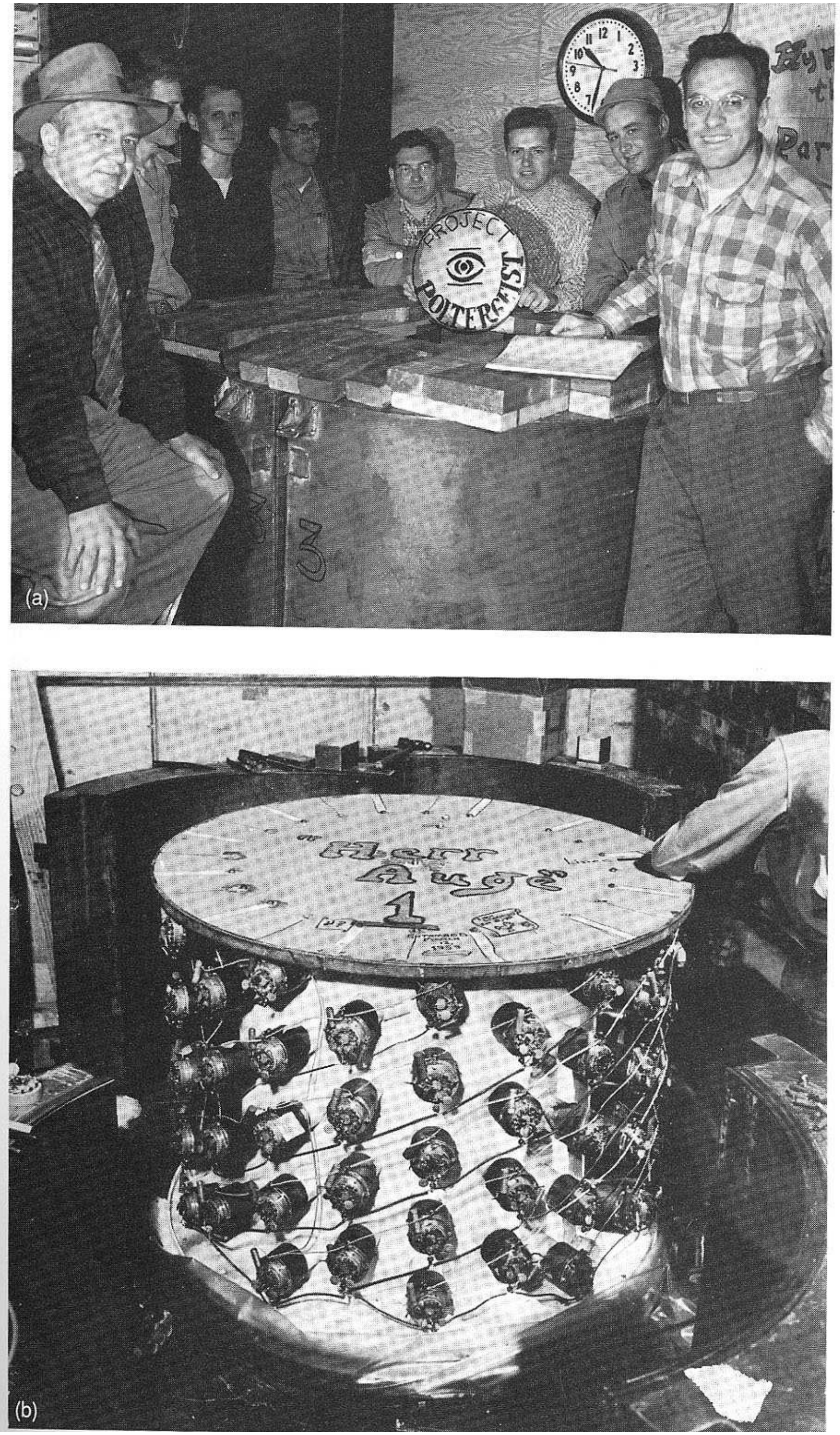
The Future



- Graph shows *cumulative* km^3·yr of exposure volume
- 1 km^3·yr reached 2 years *before* detector is completed
- Close to 4 km^3·yr at the beginning of 2nd year of full array operation.

Perspective: in ~50 years, the physical scale & energy scale have increased by 10^9

From an "undetectable particle" to a messenger from distant galaxies!



Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

New Window on Universe?
Expect Surprises

IceCube: Summary

- IceCube will reach a sensitivity where signals beyond the atmospheric *v* spectrum can be reasonably expected
- ...

IceCube: Summary

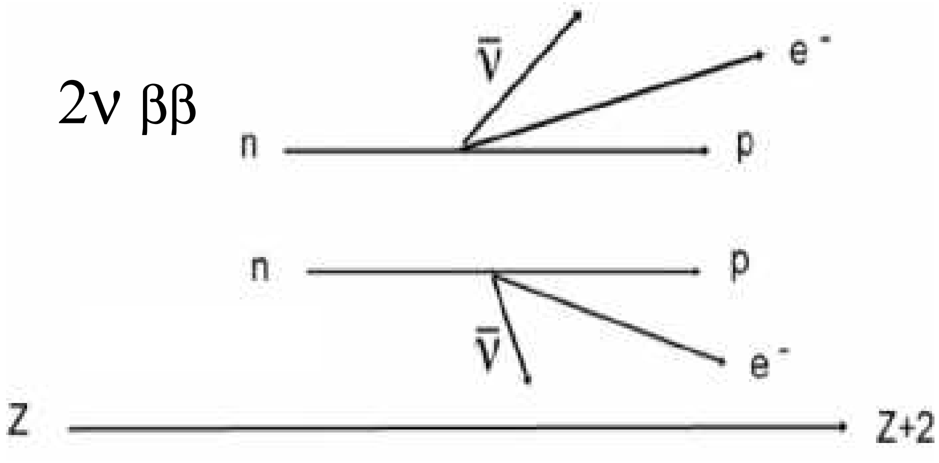
- IceCube will reach a sensitivity where signals beyond the atmospheric *v* spectrum can be reasonably expected
- High quality data will aid in the perception of new unexpected signals
- …

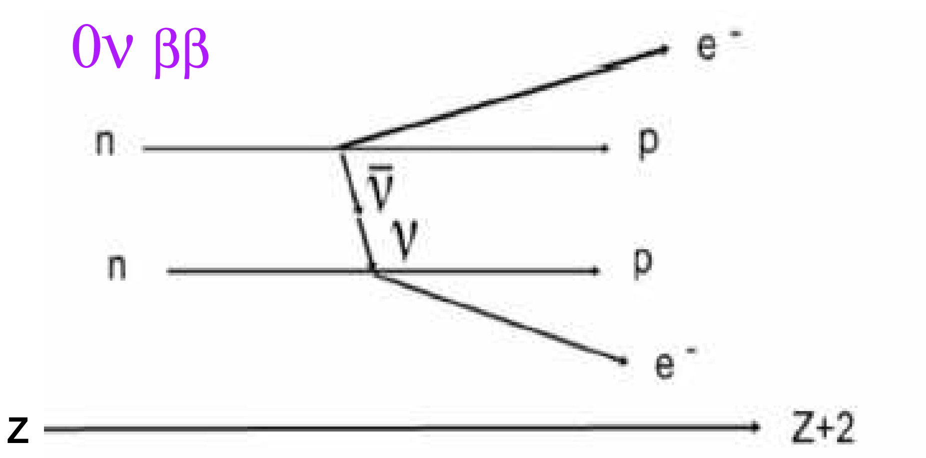
IceCube: Summary

- IceCube will reach a sensitivity where signals beyond the atmospheric *v* spectrum can be reasonably expected
- High quality data will aid in the perception of new, unexpected signals
- If so, IceCube will open, for the first time, a **new tunnel** into the universe.


And now…A process
where no neutrinos may
tell us something new!

Two Types of Double Beta Decay





Neutrinoless double beta decay.

A known standard model process and an important calibration tool

$$T_{\frac{1}{2}} \approx 10^{19}\ yrs.$$

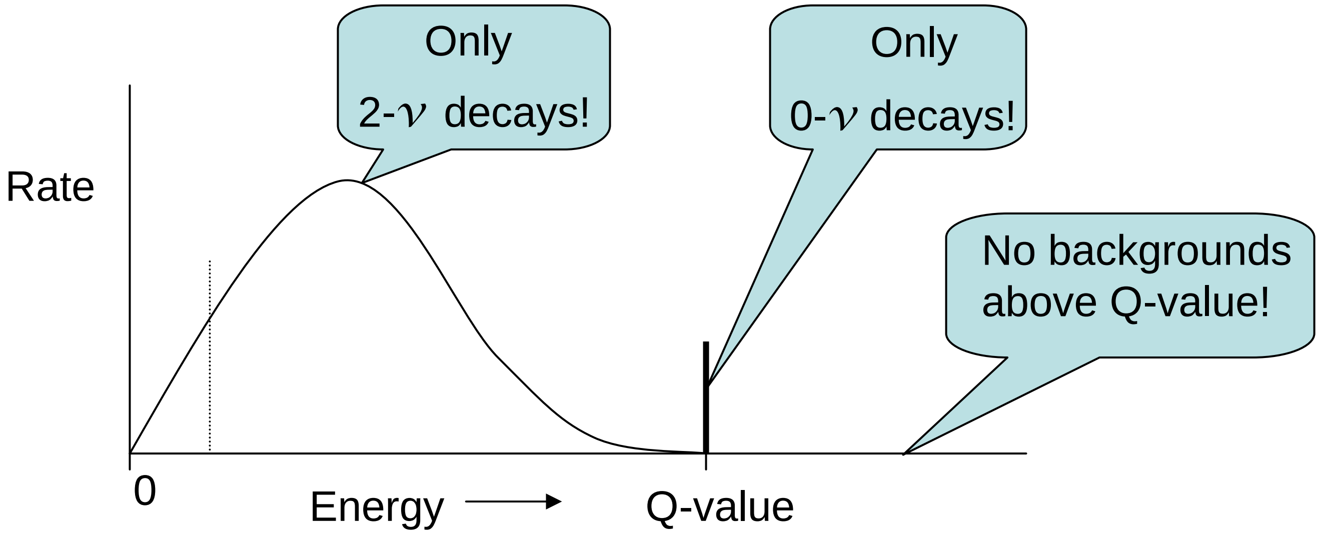
If this process is observed:
Neutrino = Anti-neutrino!
Neutrino mass ≠ 0
Lepton number is not conserved!

$$\frac{1}{T_{\frac{1}{2}}} = G \times \|\mathbf{M}\|^2 \times m_{\bar{\nu}}^{\ 2}$$

Neutrinoless double beta decay lifetime

Neutrino effective mass

A “robust” experimental result:



The experimental result is a spectrum of all ββ events, with very small or negligible backgrounds.

Current Status

- Present status (partial list):
  - Heidelberg-Moscow (^{76}Ge) result: $\langle m_\nu \rangle$ = **0.44** $^{+0.14}_{-0.20}$ eV - *disputed!*
  - Cuoricino (^{130}Te): taking data, but - background limited...
  - EXO (^{136}Xe): under construction, but - δE/E shape/resolution issue...
  - GERDA (^{76}Ge): under construction at LNGS
  - Majorana (^{76}Ge): proposal & R&D stage
  - NEMO $\rightarrow$ Super-NEMO (foils): proposal & R&D stage
- Global synthesis: Σm_i < 0.17 eV (95% CL)*

  $\Rightarrow$ 100's to 1000's of kg active mass likely to be necessary!
  - Rejection of internal/external backgrounds in ~10^{28} atoms!
  - Excellent energy resolution: δE/E <10 x 10^{-3} FWHM - at least!
- Target (from oscillations): $\langle m_{\beta\beta} \rangle$ ~0.05 eV

*Mohapatra & Smirnov 2006 *Ann. Rev. Nucl. Sci.* **56** - (other analyses give higher values)

Perils of backgrounds

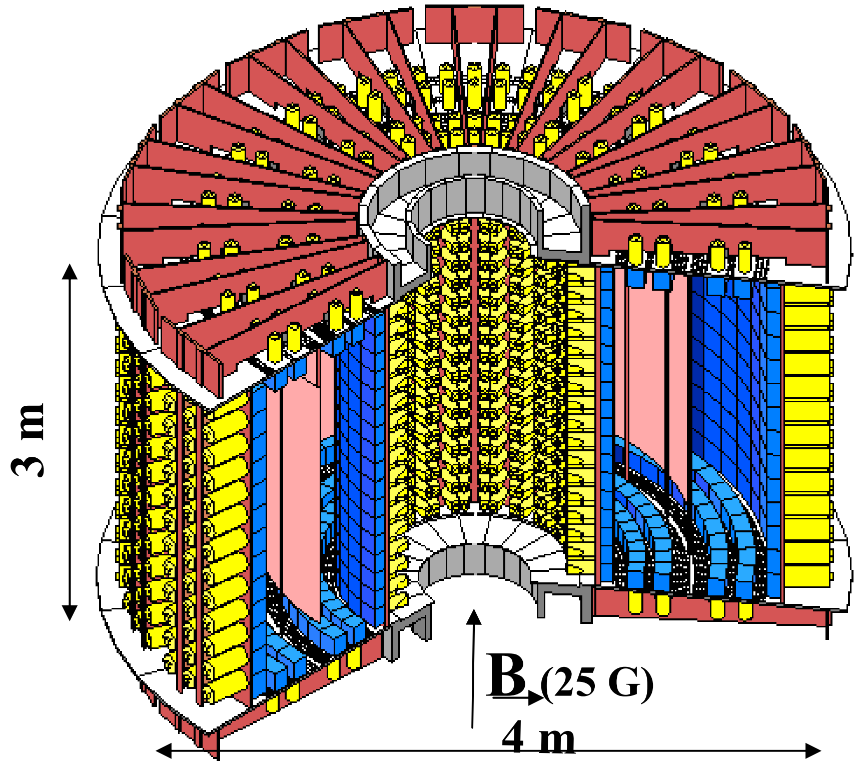
- Sensitivity to mass changes if backgrounds begin to appear:
  - $m_\nu \sim \{1/MT\}^{1/2}$
  - $m_\nu \sim \{(b\delta E)/MT\}^{1/4}$

Ouch!

    - b = number of background events/unit energy
    - δE = energy resolution of detector system

NEMO

20 sectors



Fréjus Underground Laboratory : 4800 m.w.e.

Source: foils (10 kg of ββ isotopes)

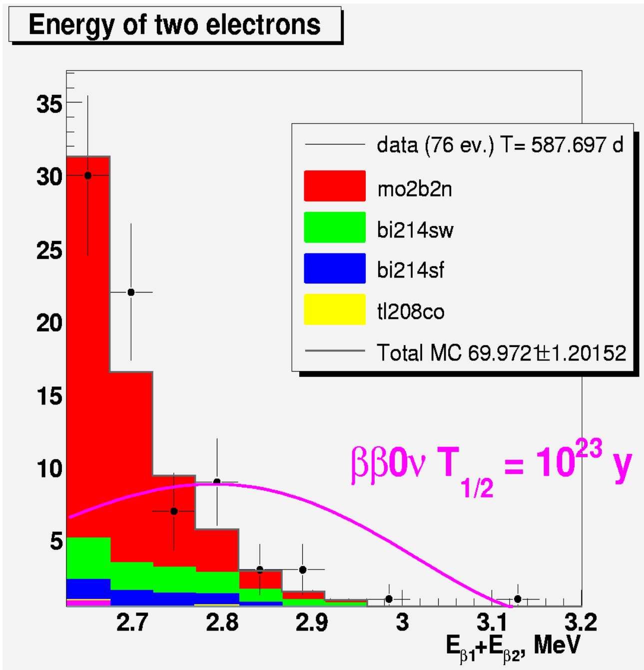
cylindrical, S = 20 m², 60 mg/cm²

Tracking detector:

drift wire chamber operating in Geiger mode (6180 cells)

Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

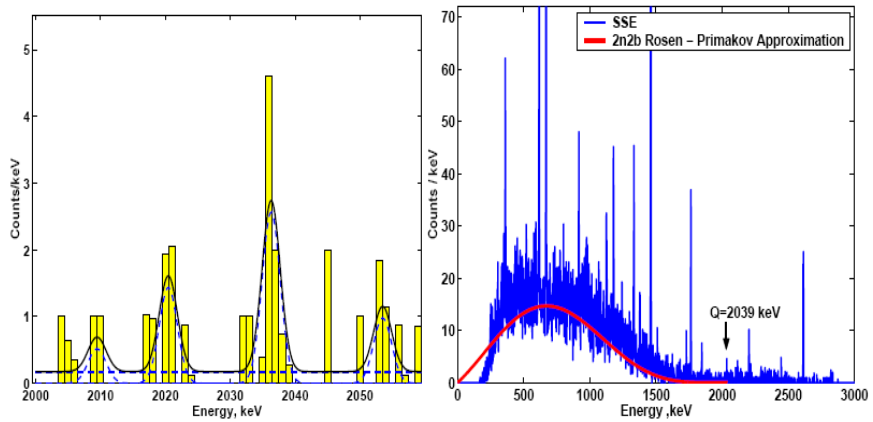


Germanium - Ion chambers

The Gold Standard: Germanium diodes

$\delta E/E \sim$ 1.25 x 10^{-3} FWHM (at 2.6 MeV)

- Only claimed evidence of $0\nu\beta\beta$ detection with 11 kg of 86% enriched ^{76}Ge for 13 years



$T_{1/2}$~1.19×10^{25}y
<m> ~ 0.44 eV

•Klapdor-Kleingrothaus et al **Phys.Lett.B586:198-212,2004**.

- New experiments Majorana/GERDA planned with better background rejection and larger mass (20-500 kg)

Majorana

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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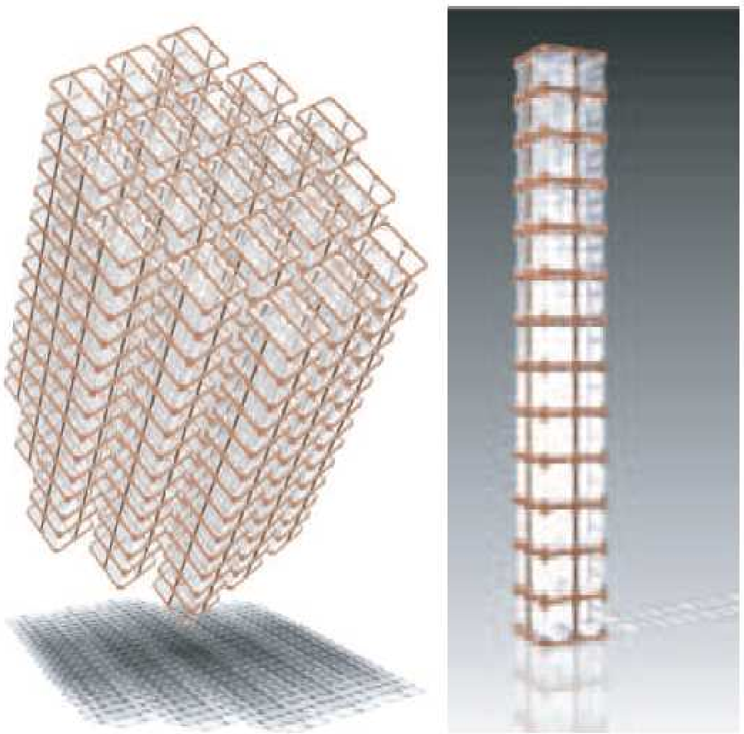
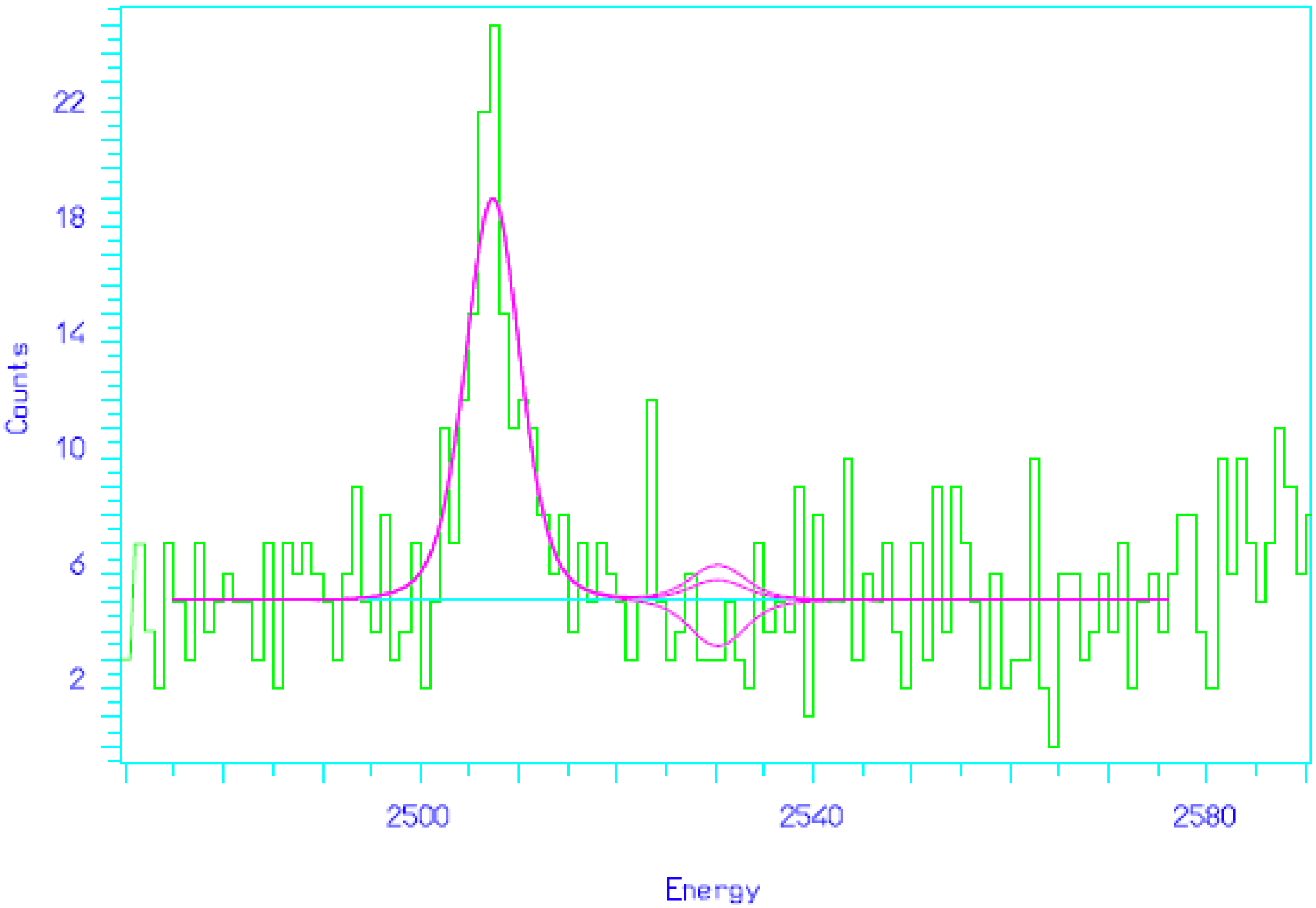
Cuore - Cuoricino



- Cryogenic “calorimeters”
  - 34% ^{130}Te natural abundancy
- CUORE ~1000 crystals, 720 kg
  - Construction underway
  - $10M - relatively cheap
- CUORICINO: 40.7kg TeO_2
  - Running now!
  - $T^{0\nu}_{1/2} \geq 2.4 \times 10^{24}$ yr (90% C.L.)
  - $<m_\nu> \leq 0.2 – 0.9$ eV
  - $\delta E/E$ ~5keV FWHM at 2.5 MeV
  - Backgrounds present in data…

Cuoricino Data!



EXO-200

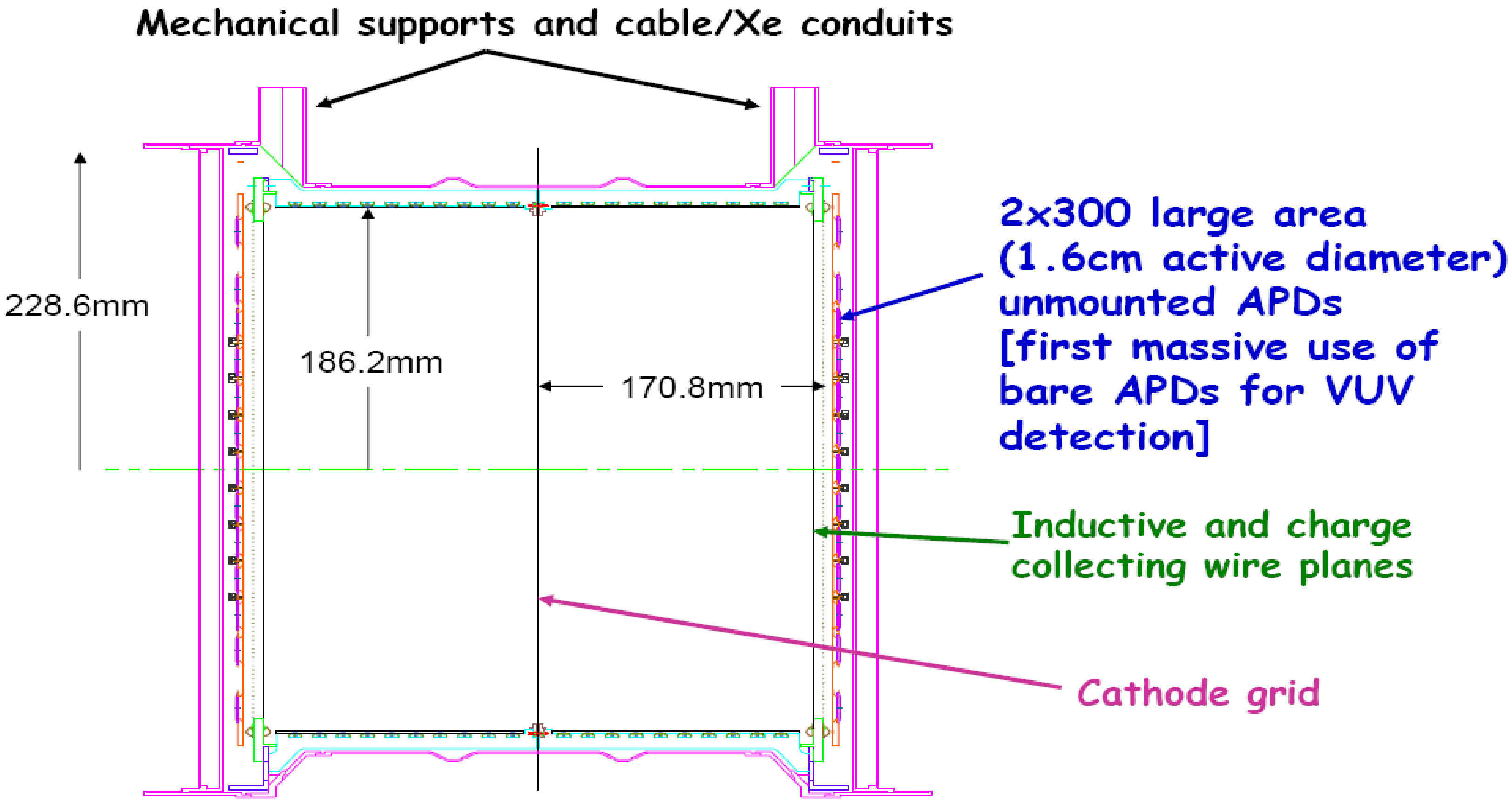
Underway **now**, at WIPP:

- 200kg of 80% enriched ^{136}Xe
- Liquid xenon TPC
- Localization of the event in x,y,z
  (using scintillation for T_0)
- Scintillation & Ionization anti-correlated
- Expect s(*E*)/*E* = 1.4% for 0nbb

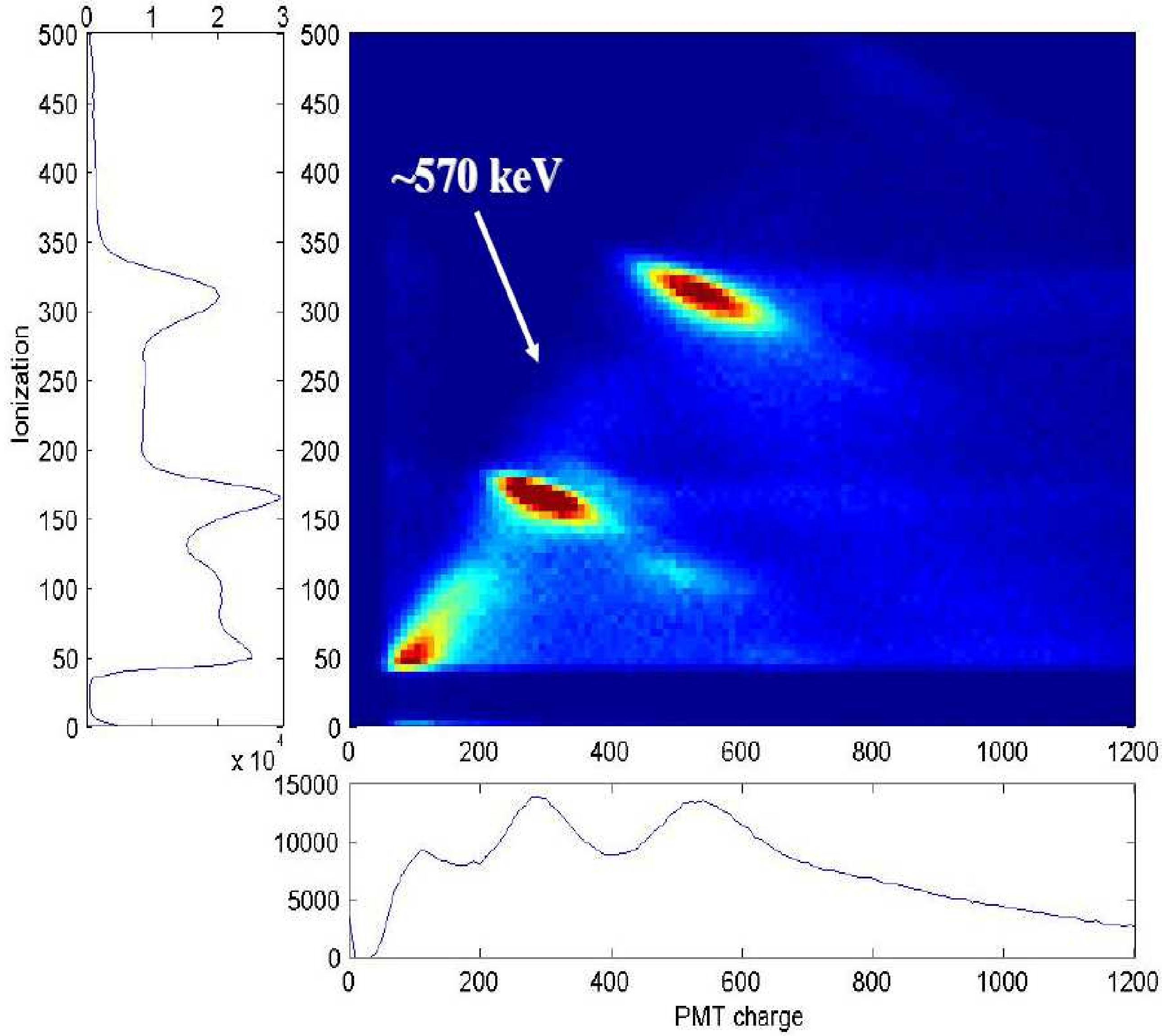
For a subsequent phase of experiment:

- Barium daughter tagging by
  optical spectroscopy
  (for future full EXO detector)

EXO Experimental Design



EXO:
Strong anti-Correlation observed between scintillation and ionization



Energy resolution in xenon shows complexity: ionization/scintillation

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

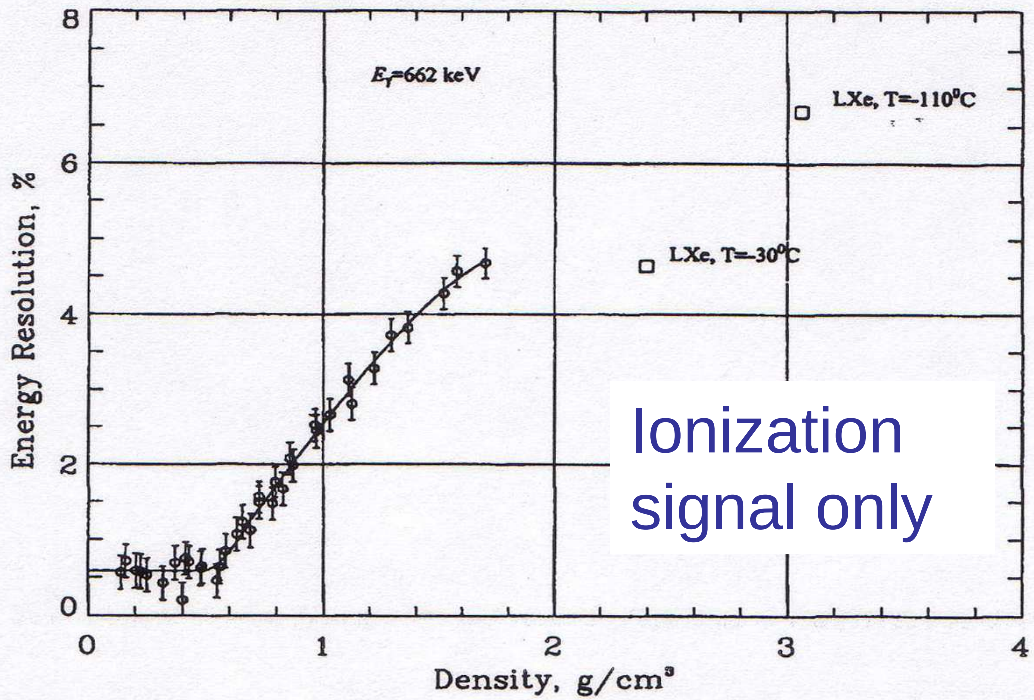


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For $\rho > 0.55$ g/cm^3, a strong anti-correlation appears!

“Intrinsic” energy resolution for HPXe ($\rho < 0.55$ g/cm^3)

Q-value of ^{136}Xe = 2.48 MeV

W = ΔE per ion/electron pair ~21.9 eV (depends on E)

N = number of ion pairs = Q/W

N $\approx$ 2.48 x 10^6 eV/21.9 eV = 113,242

σ_N^2 = FN (F = Fano factor)

F = 0.13 - 0.17 for xenon $\Longrightarrow$

σ_N = (FN)$^{1/2}$ ~ 130 electrons rms

δE/E = 2.7 x 10^{-3} FWHM (intrinsic fluctuations only)

(Ge diodes better by only a factor of ~2.2)

Energy: Loss of signal

Fluctuations in collection efficiency ε introduce another factor $L = 1 - \varepsilon$ (similar to Fano's)

- $\sigma_N = ((F + L)N)^{1/2}$
- Sources of L include:
  - Electronegative contaminants
  - Grids or meshes at the readout plane
  - Recombination
- However: L can be small! L << F seems reasonable
  - If L = 4%, then **$\delta E/E = \sim 3 \times 10^{-3}$ FWHM**

Energy: Loss of signal!

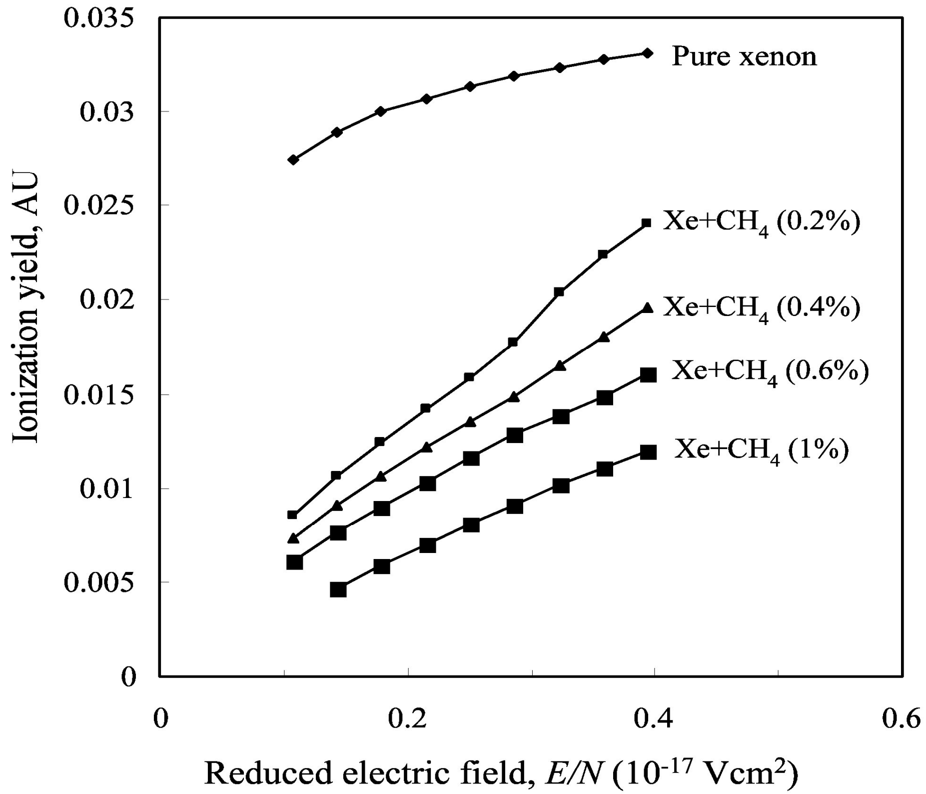


Fig.7. Dependence of ionization yield on reduced electric field (E/N) at a pressure of 2.6 MPa.

Even tiny amounts of methane leads to a big loss of primary signal!

Gotthard Xe TPC had 4% CH_4 (Ouch)

Is this really true?

Only for xenon?

Avalanche gain

– Gain fluctuations: another factor, B

- $\sigma_N = ((F + B)N)^{1/2}$ 0.7 < B < 0.9 *
- $\sigma_N = ((0.15 + 0.85)N)^{1/2} = 337$
- **δE/E = 7.0 x 10^{-3}** FWHM - not too bad, but:
- No more benefit from a small Fano factor

– Add signal losses: $\sigma_N = ((F + B + L)N)^{1/2}$

δE/E = 7.1 x 10^{-3} FWHM

Can avalanche gain be avoided?

*Alkhazov G D 1970 *Nucl. Inst. & Meth.* **89** (for cylindrical proportional counters)

“Ionization Imaging” TPC!

1. **No avalanche gain** analog readout (F + L)
    - dn/dx ~ 1.5 fC/cm: ⇒ ~9,000 (electron/ion)/cm
    - gridless pixel plane (5 mm pads)
    - **very high operational stability!**
    - ⇒ $\delta E/E = 3 \times 10^{-3}$ FWHM (F + L only)

– **but, electronic noise must be added!**
    - 50 pixels/event @ 40 e^- rms ⇒ N ~280 e^- rms
    - $\delta E/E$ = **7×10^{-3} FWHM**

⇒

“Ionization imaging” TPC: OK, but not compelling

"Negative Ion" TPC!

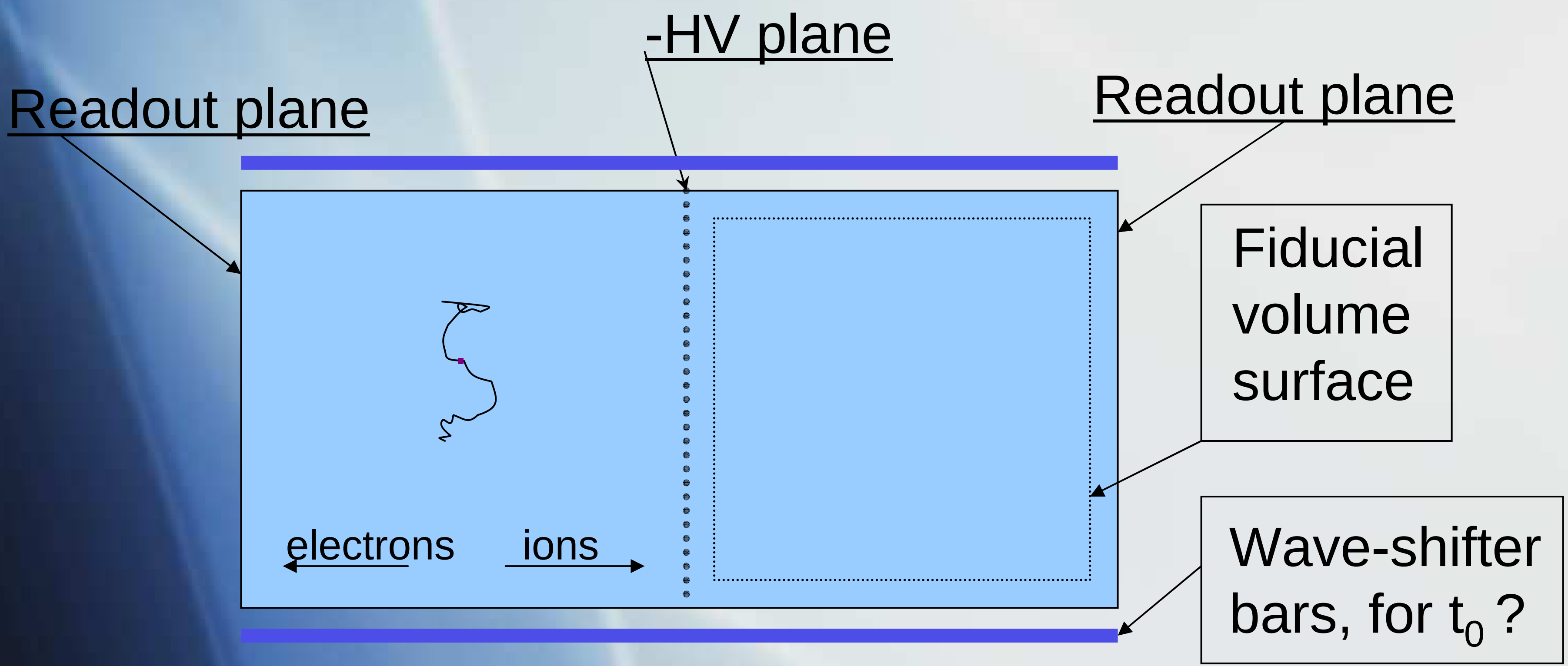
2. **"Counting mode" =** digital readout, (F + L)
- Electron capture on electronegative molecule
- Very slow drift to readout plane;
- Strip electron in high field, generate avalanche
- Count each "ion" as a separate pulse:
  - Avalanche fluctuations don't matter, and
  - Electronic noise does not enter directly, either
  - Pileup and other losses: L~ 0.04 ?
  - **$\delta E/E = \sim 3 \times 10^{-3}$ FWHM**
- Very appealing, but little experience...

“Conventional” TPC

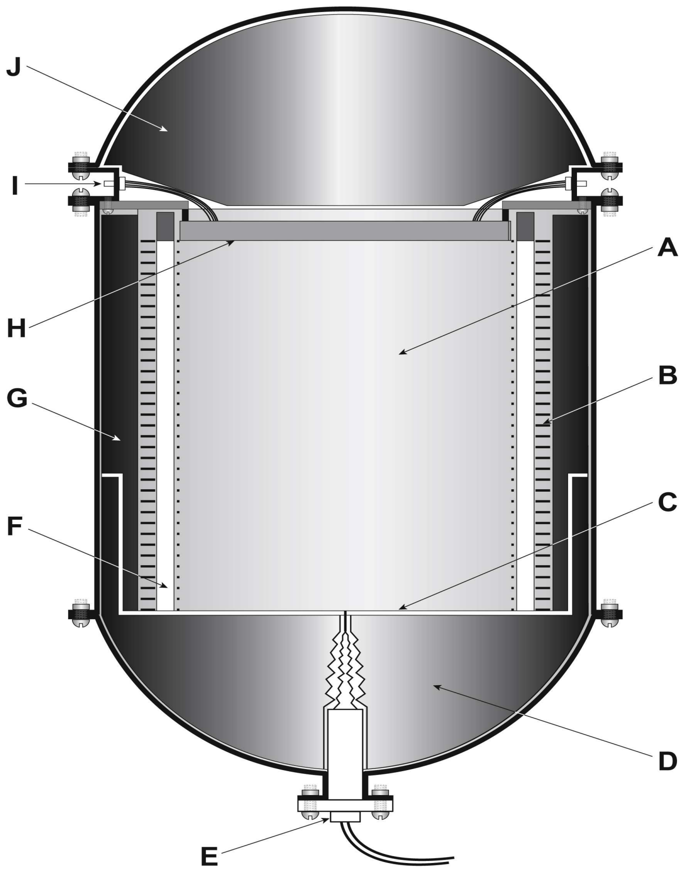
3. **<u>Avalanche gain</u>** + analog readout (F + L + B)
   - With care, electronic noise is not significant, but
   - Ballistic deficit, non-linearities, etc are important
   - Extended tracks have not been well-measured!
   - Gain stability, calibration issues challenging
   - Least R&D needed to develop large system
   - **$\delta E/E = 7.1 \times 10^{-3}$ FWHM** (F + L + B)

– realistically, maybe $\delta E/E < 10 \times 10^{-3}$ FWHM ?

Fiducial volume surface



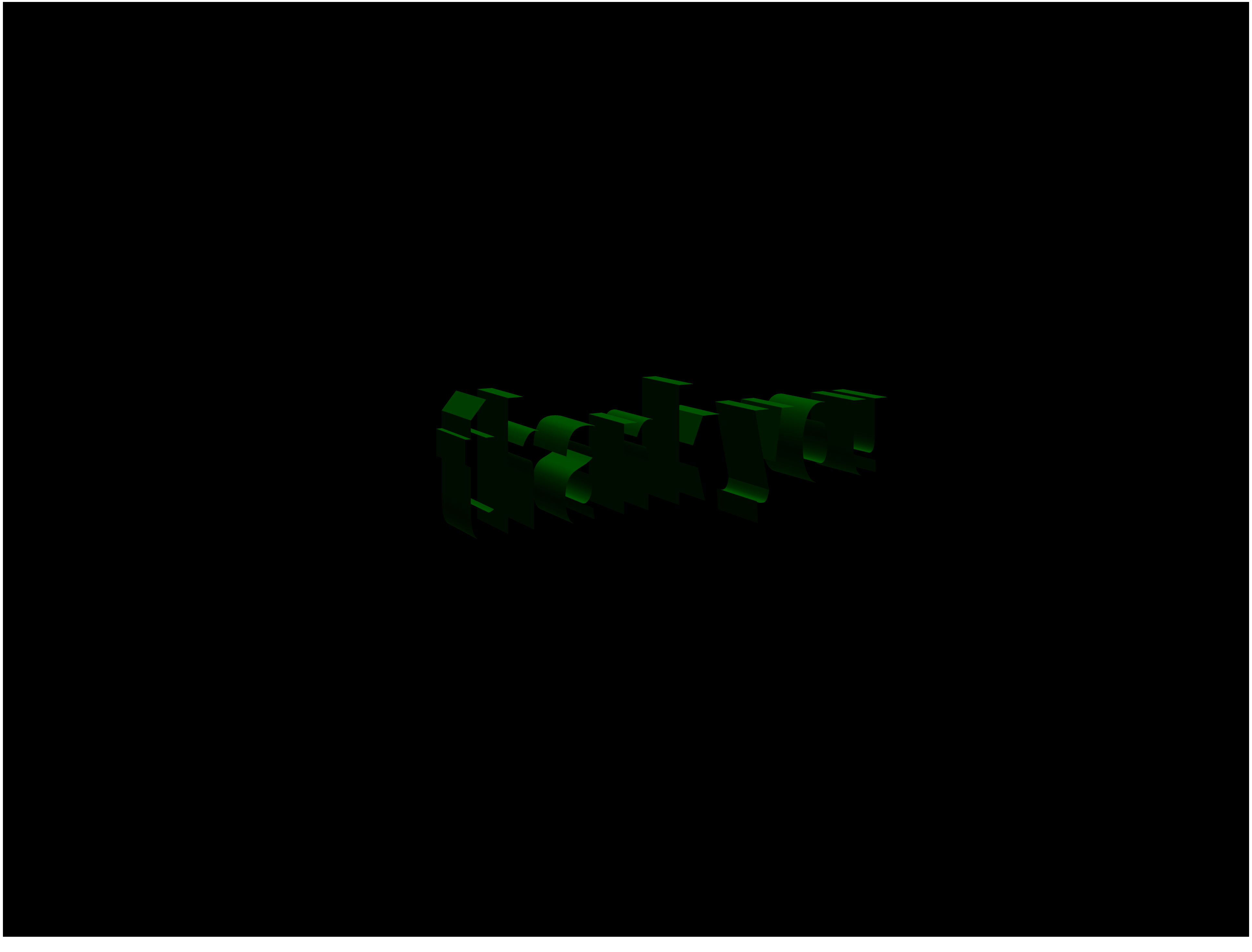
1000 kg Xe: ∅ = 225 cm, L =225 cm
ρ ~ 0.1 g/cm³ (~20 bars)



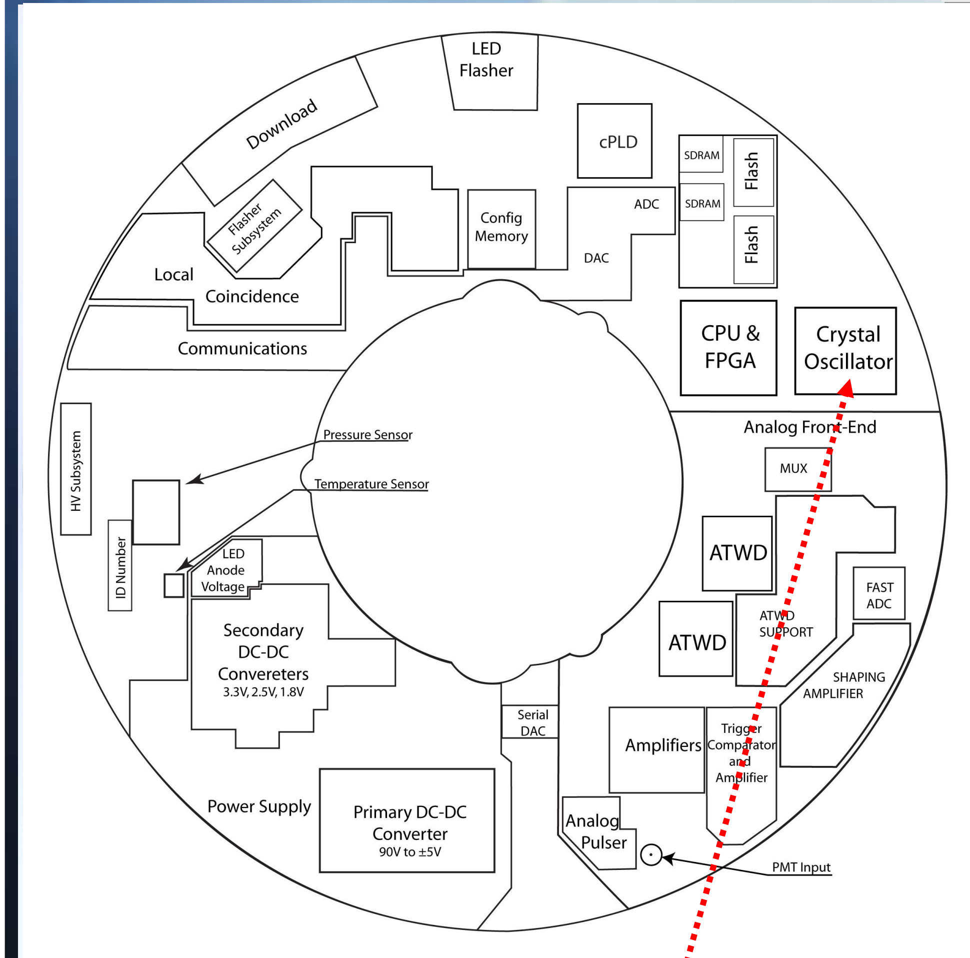
A. Sensitive volume filled with xenon at density ρ = 0.1 g/cm³ ~20 bars pressure @ 300° K
B. Field cage, comprised of rings to establish uniform equipotential surfaces;
C. Cathode plane, at negative HV;
D. Neutron absorber, HV insulator, and filler to force xenon into active volume - possibly polyethylene;
E. HV module, or feedthrough;
F. Plastic scintillator or wave-shifter bars to convert UV scintillation for event start time signal;
G. HV insulator, neutron absorber, and filler, as in d;
H. Readout plane, with front-end electronics;
I. Annular ring supporting service feedthroughs and data flow;
J. Neutron absorber, and filler.

Outlook

- Half a century of experiment has brought the search for 0-$\nu\beta\beta$ decay to the threshold of established neutrino mass: ~50 meV
- What's **NEXT**? Perhaps a **N**eutrino **E**xperiment - **X**enon **T**PC, led by a Spanish collaboration, will reach this major goal;
- The near future will be an exciting time, with neutrinos (IceCube) or without them! (0-$\nu\beta\beta$)


thank you

DOM Mainboard



20 MHz quartz oscillator
frequency stability df/f < 2×10^{-10}

- 2 four-channel ATWDs
  Analog Transient Waveform Digitizers
  low-power ASICs
  recording at 300 MHz over first 0.4μs
  signal complexity at the start of event

- 10-bit fADC
  recording at 40 MHz
  256 samples → 6.4 μs acquisition

- Dead time <<1%

Dynamic range
- 400 p.e./15 ns (trigger @0.25 p.e.)
- 2000 p.e./5 μs

energy measurement (TeV – PeV)

- a FPGA
  reads out the ATWD, fADC
  handles communications
  time stamps waveforms
  system time stamp resolution
  2 ns wrt master clock

DOM MB Block diagram