Design of a Robust Fiber Optic Communications System for Future Giga-scale Neutrino Detectors

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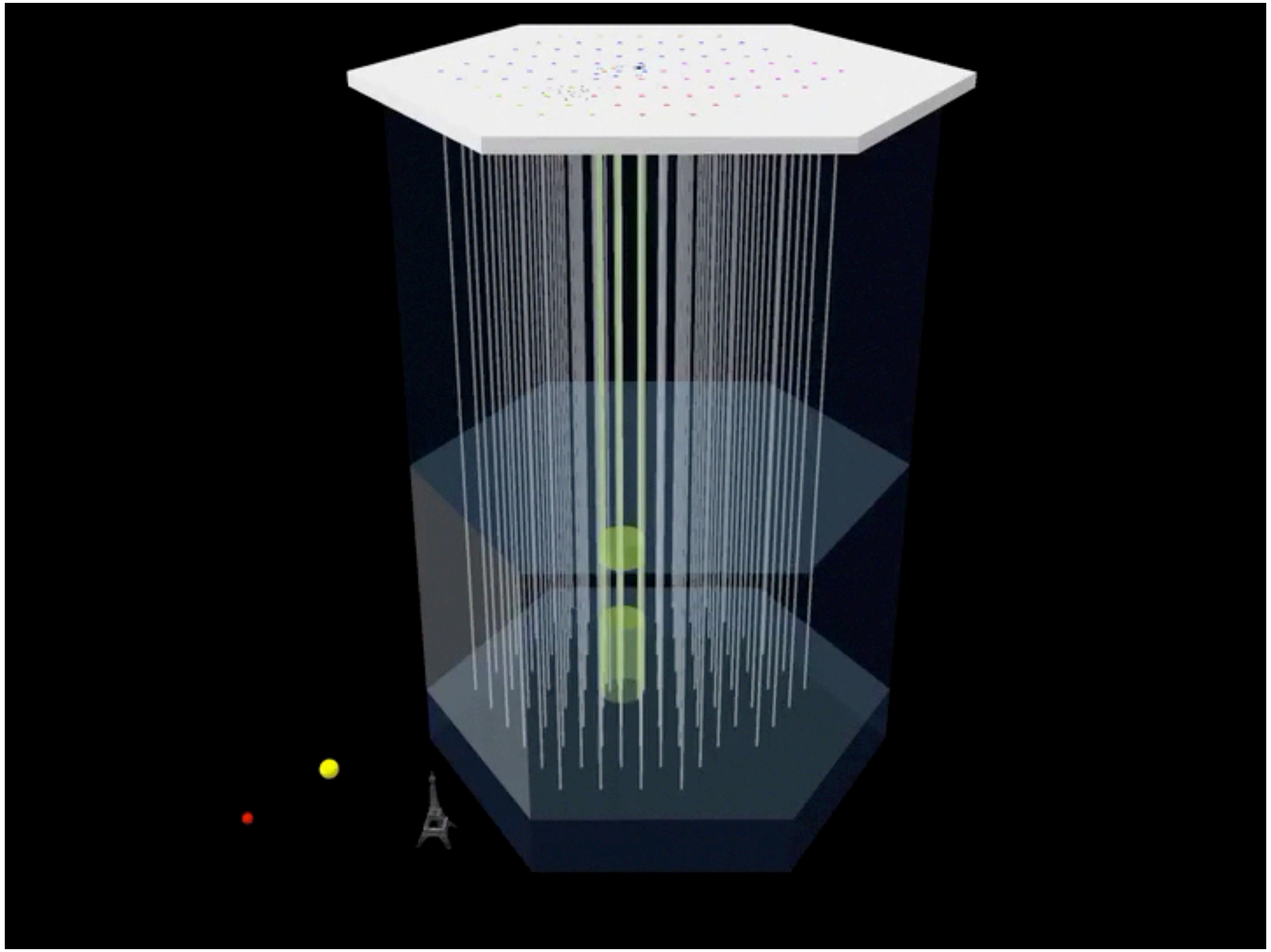
IceCube South Pole Neutrino Observatory

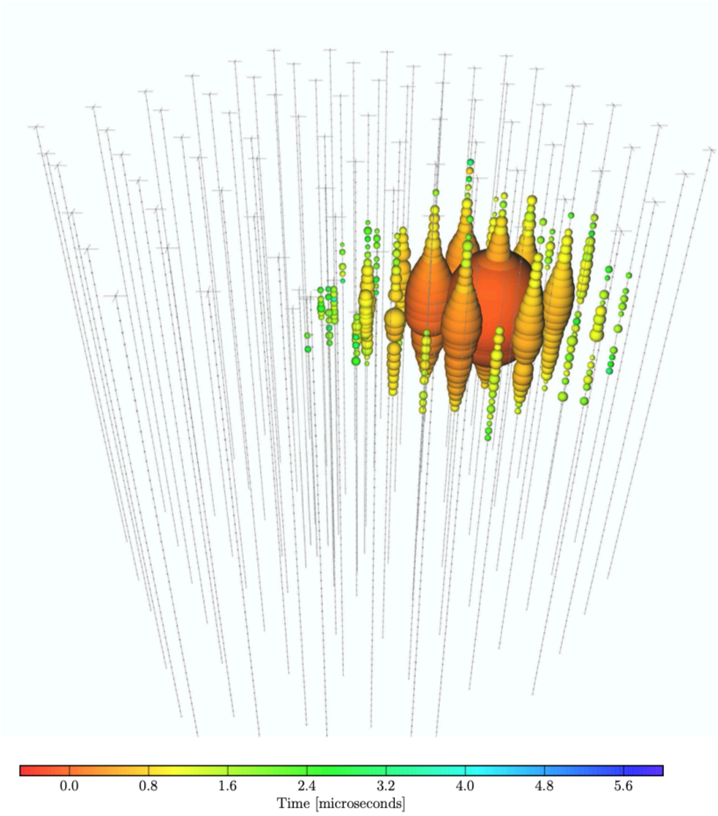


- Uses >5k 10” PMTs frozen into the Antarctic Glacier
- Detects muons and neutrinos from ~4Gev to ~10PeV
- Signals are digitized in the optical modules and sent to surface

arXiv:1612.05093

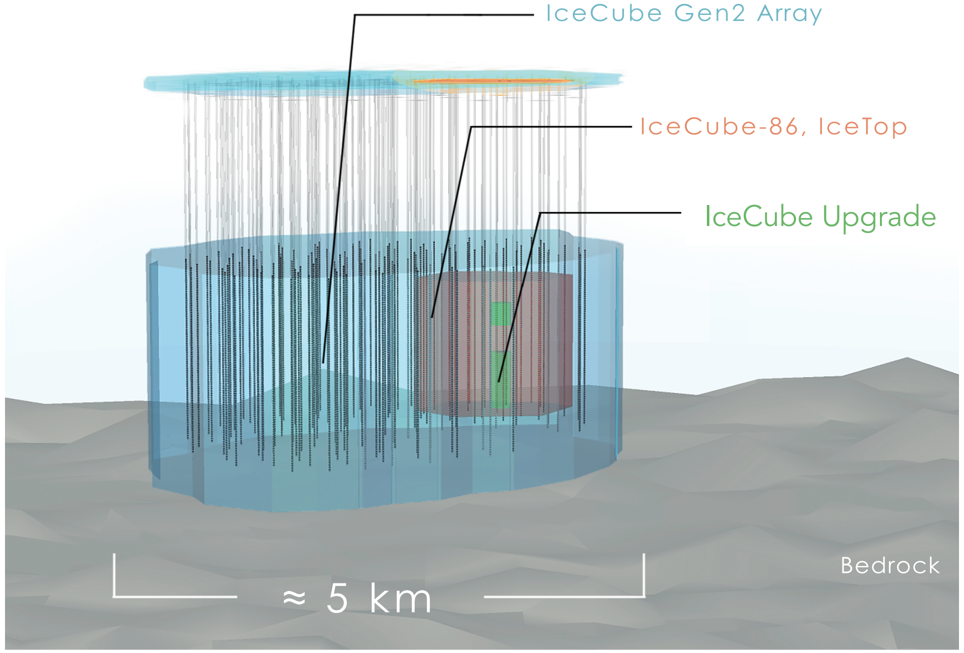
IceCube Science

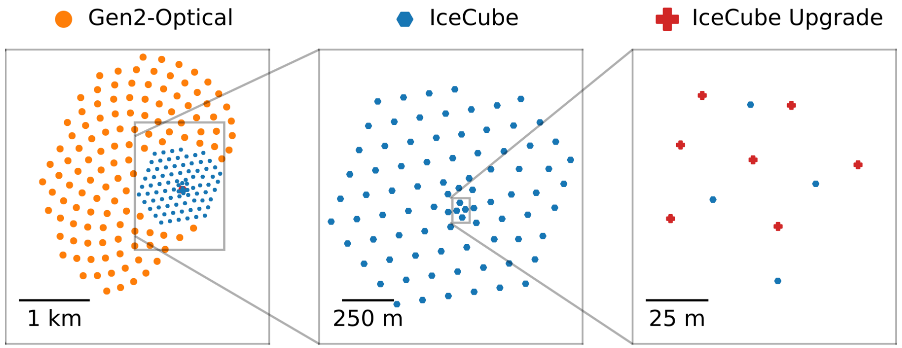
1 PeV Cascade from HESE



- HESE discovery of astrophysical neutrino flux (arXiv:2011.03545)
- High Precision oscillations measurement (arXiv:1707.07081)
- TXS0506+056 Blazar correlation – first neutrino source (arXiv:1807.08816)

Future Detectors





- IceCube-Gen2 will expand detection volume to 8km^3 for high energy astrophysics
- IceCube Upgrade infill for science at lower energies + testbed for Gen2 devices + ice calibration

Future Detectors

mDOM

D-Egg

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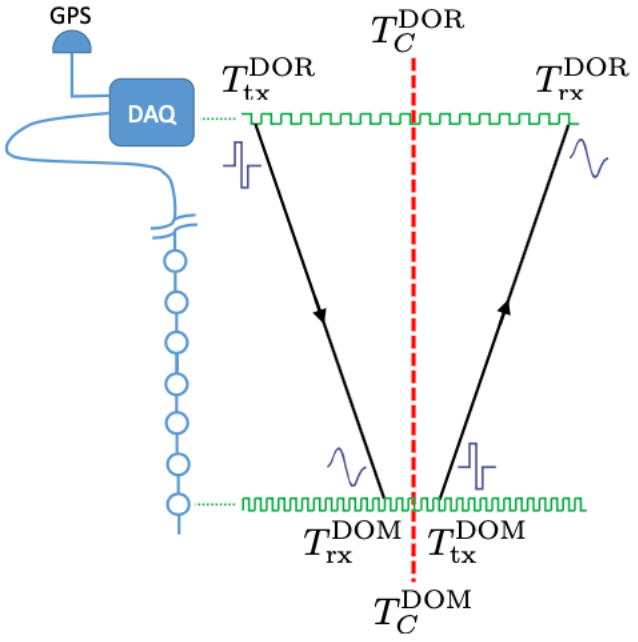
Requirements: Comms and Timing in IC and IC-Gen2

IceCube: Communications over long run copper

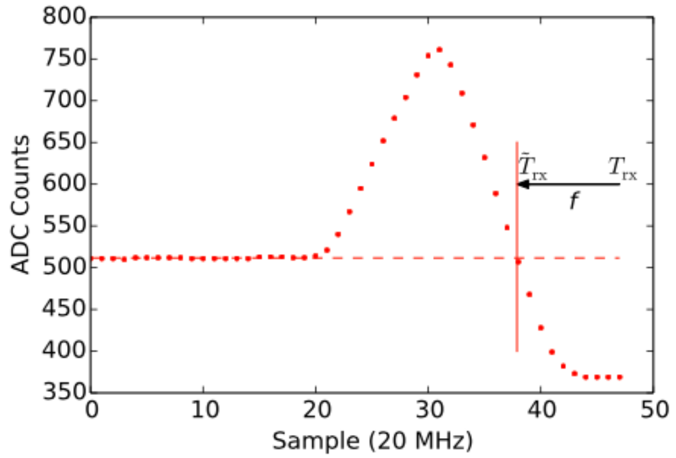
- Custom ASK Signaling protocol @ 0.72 Mbits/s per pair bandwidth capacity
- Reciprocal timing translation @1.6ns time resolution
- Stringent cross-talk requirements drive design

Gen2:

- New multi-PMT sensors means **1.5Mbits/s** per pair capacity
- Timing will also need to be O(~**1ns**)



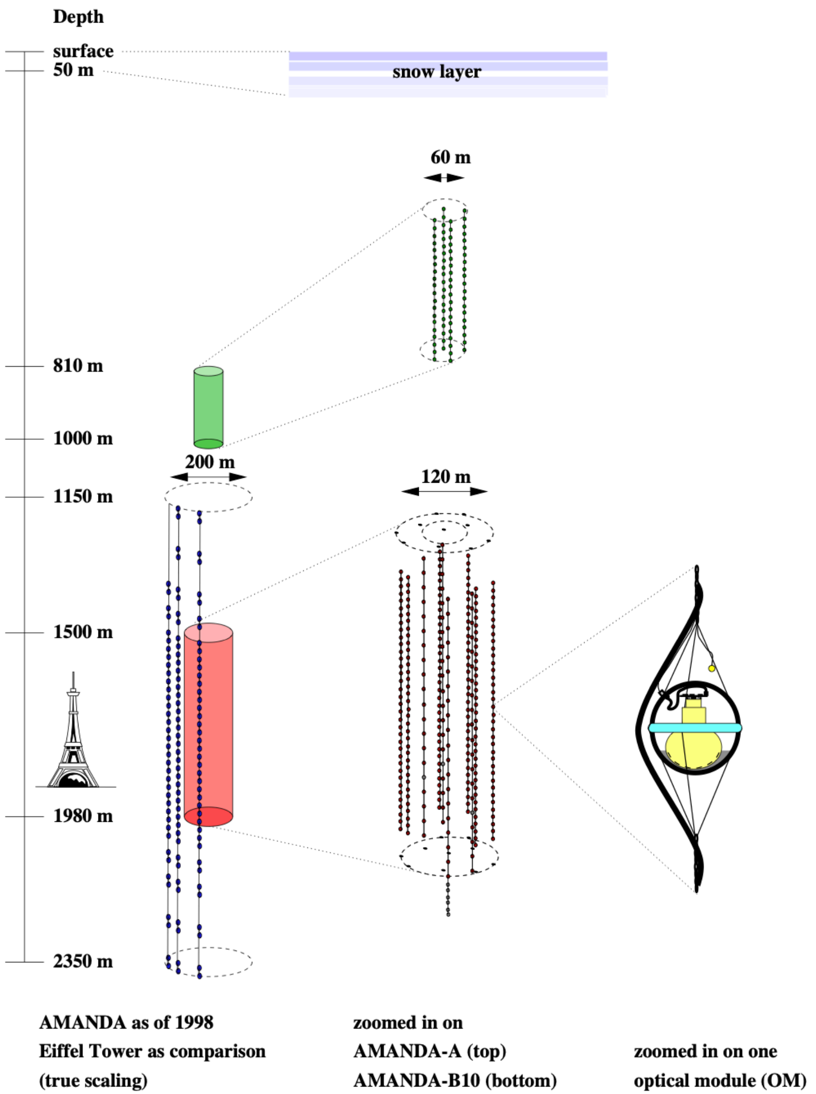
Reciprocal Active Pulsing Calibration (RAPCAL) for timing



Recorded RAPCAL Pulse

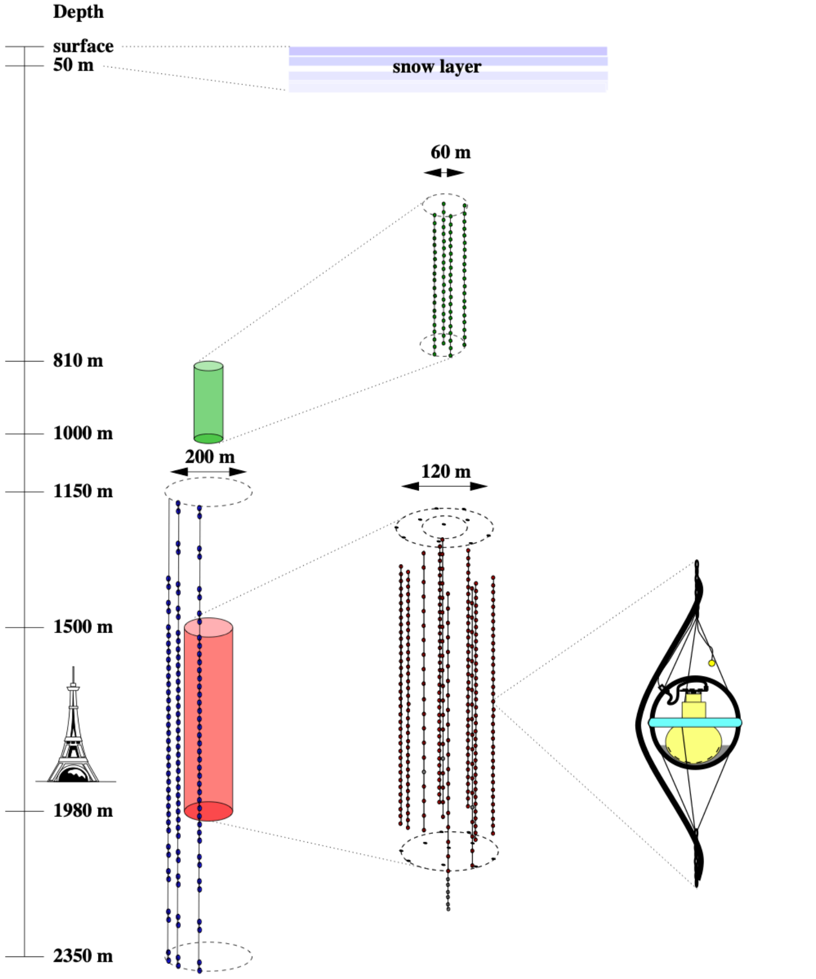
IceCube JINST paper: arXiv:1612.05093

Lessons from AMANDA



- Antarctic Muon And Neutrino Detector Array (AMANDA) is IceCube's most recent predecessor
- During 1999/2000 season, 6 strings of fiber optics were deployed
  - Loose tube fibers were deployed for signal collection from PMTs (undigitized)
- Of the 5 strings with "standard" fiber feed throughs (penetrators), 94.6% survived freeze-in.

Lessons from AMANDA



AMANDA as of 1998
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

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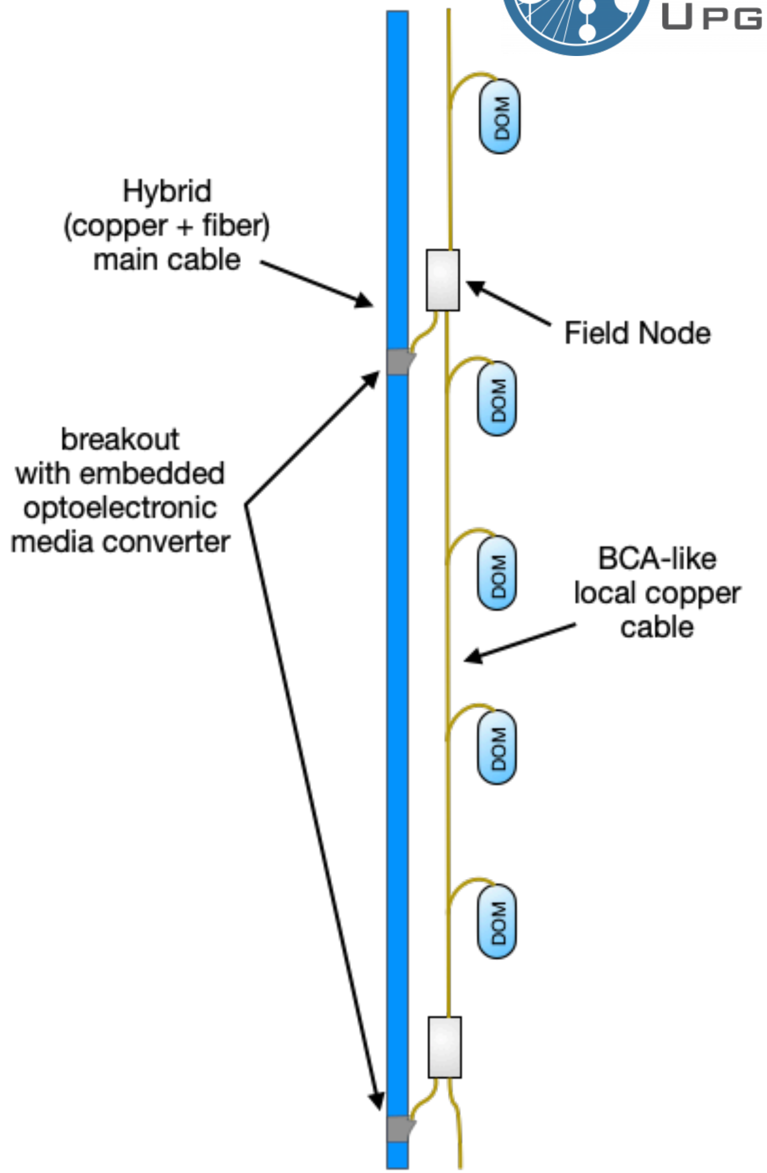
Two takeaway requirements:

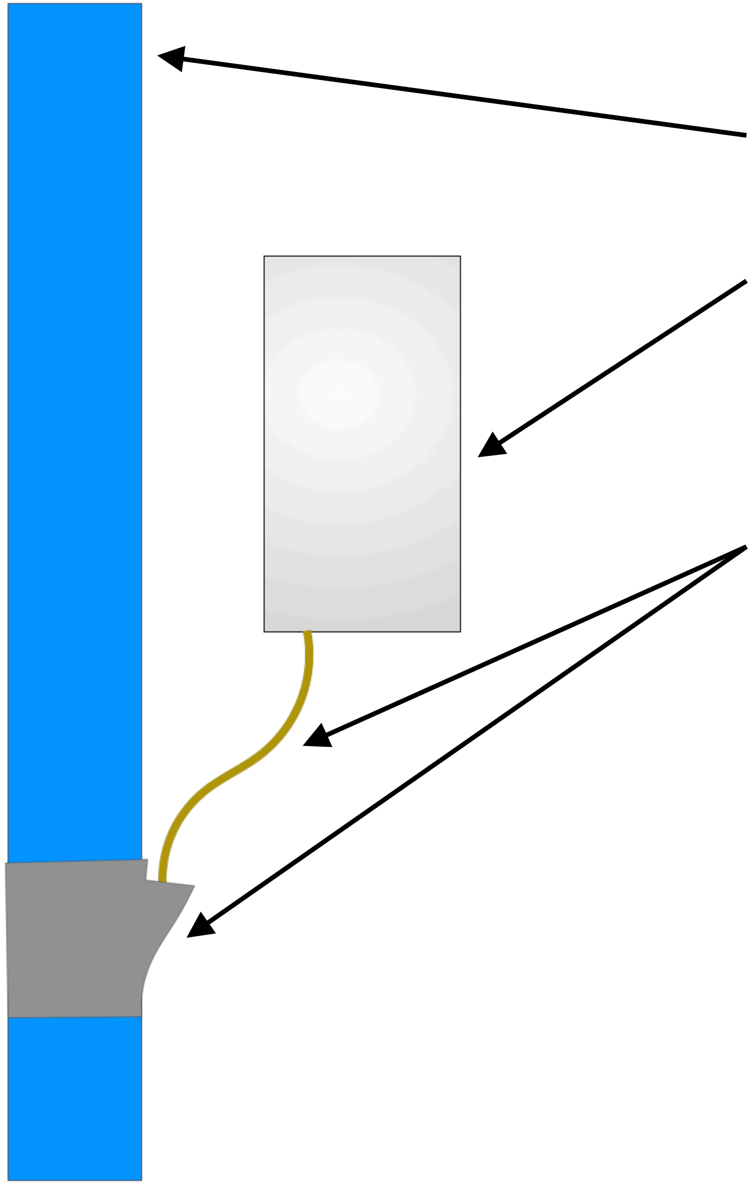
- **We need to either use a more robust fiber-penetrator combo and/or,**
- **We need to be failure tolerant to >5.4%**

Gen2 Fiber Option

- Hybrid main cable with fiber data path and copper power delivery
- Main cable feeds fiber data to Field Nodes
- Field Nodes distribute power and timing and communicate with DOMs over local copper
  - Redundant up and downgoing copper connections



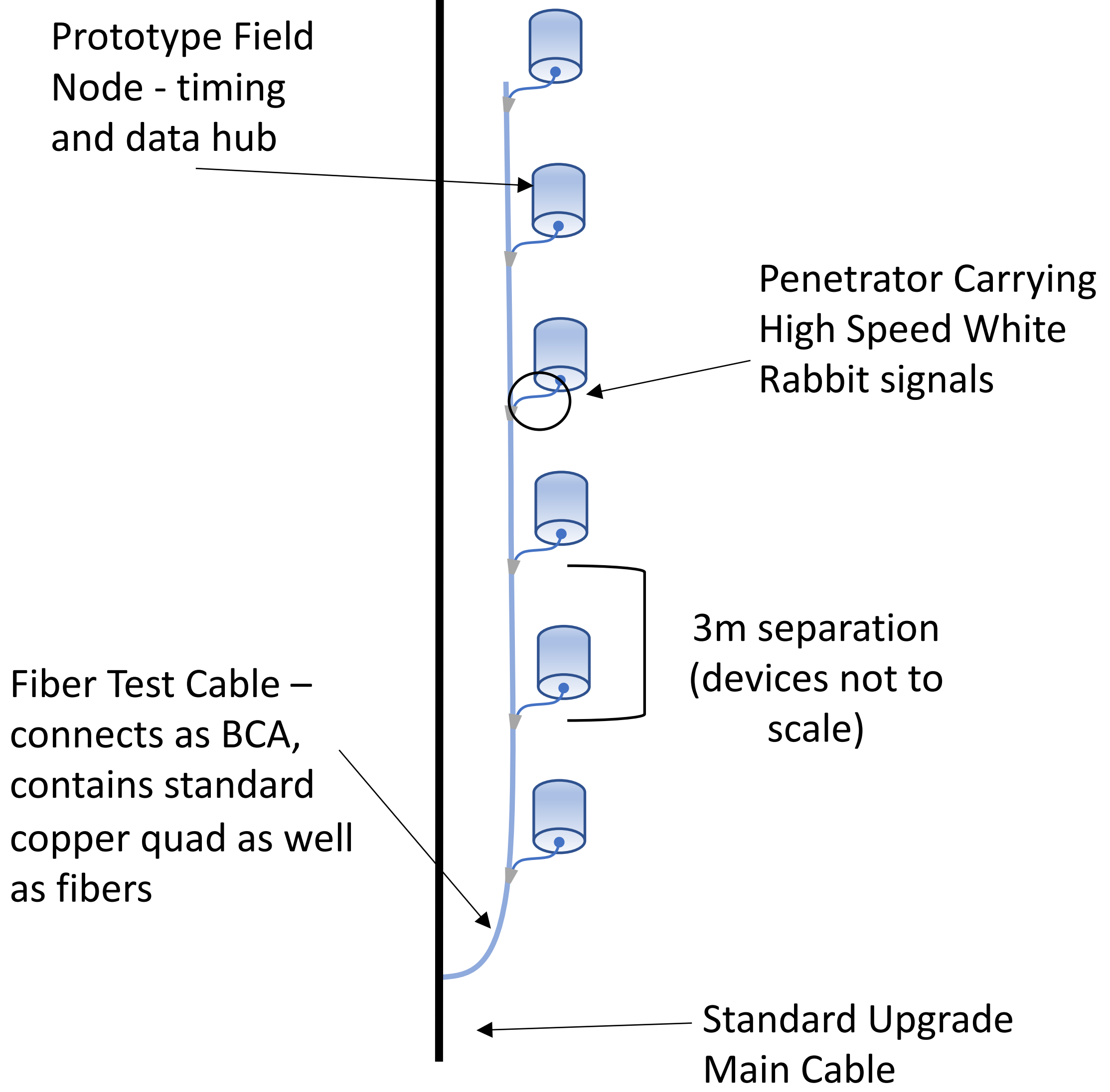
Fundamental Building Blocks



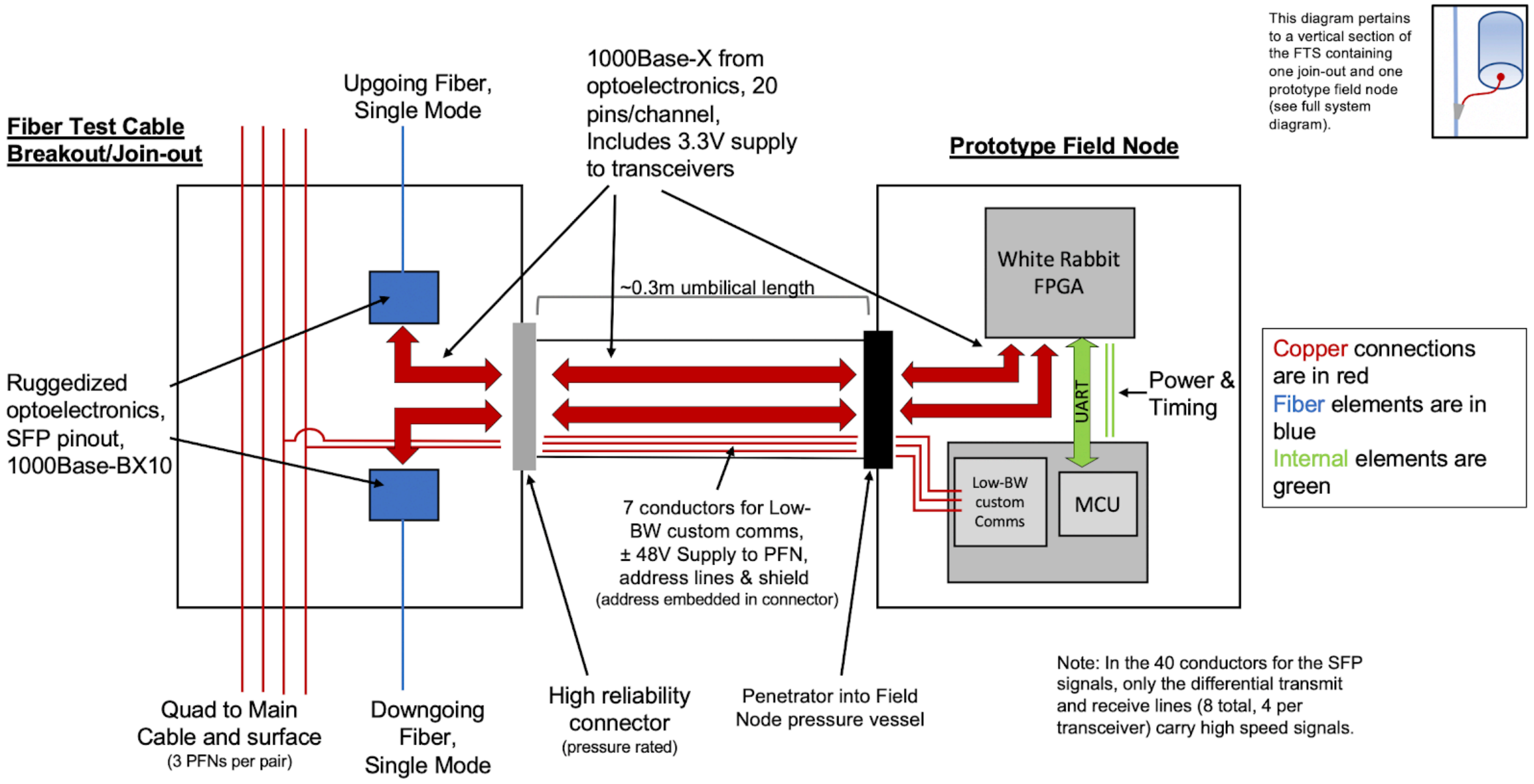
- Hybrid Copper + Fiber Main Cable
- Field Node Computing Bundle w/ White Rabbit PTP Core (WR "brain")
- Breakout and penetrator combination that can
  - Withstand freeze-in pressures
  - Deliver White Rabbit data and timing signals (Copper/Hybrid Fiber, i.e. 1000Base-X/-BX)

Demonstrating the Building Blocks – the Fiber Test System

- Deploying the Fiber Test System in the IceCube Upgrade
- 6 Prototype Field Nodes communicate via White Rabbit and with the surface via standard comms
- System connectorized drop in for standard IC-Upgrade breakout cable
    - 4 DOM equivalent

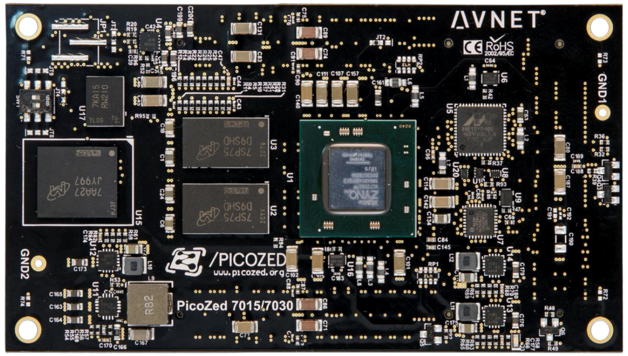


FTS Block Diagram

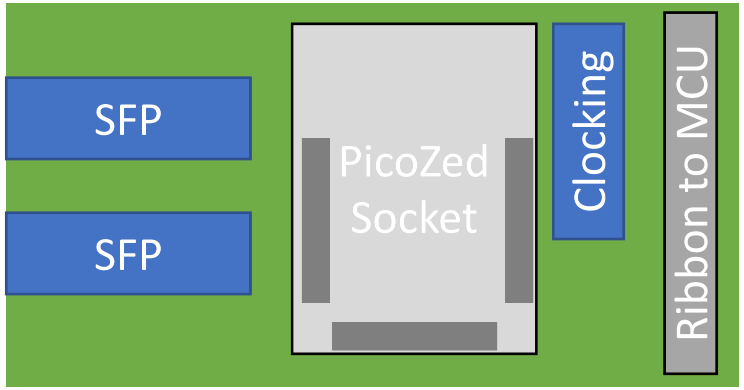


IceCube White Rabbit Node

- Targeting PicoZed SOM + daughter board for White Rabbit FPGA package
  - SOM design simplifies daughter board
  - Includes WR Clocking resources and SFPs
- Optimizing for low power consumption and high reliability
  - Using Glenair Ruggedized SFPs

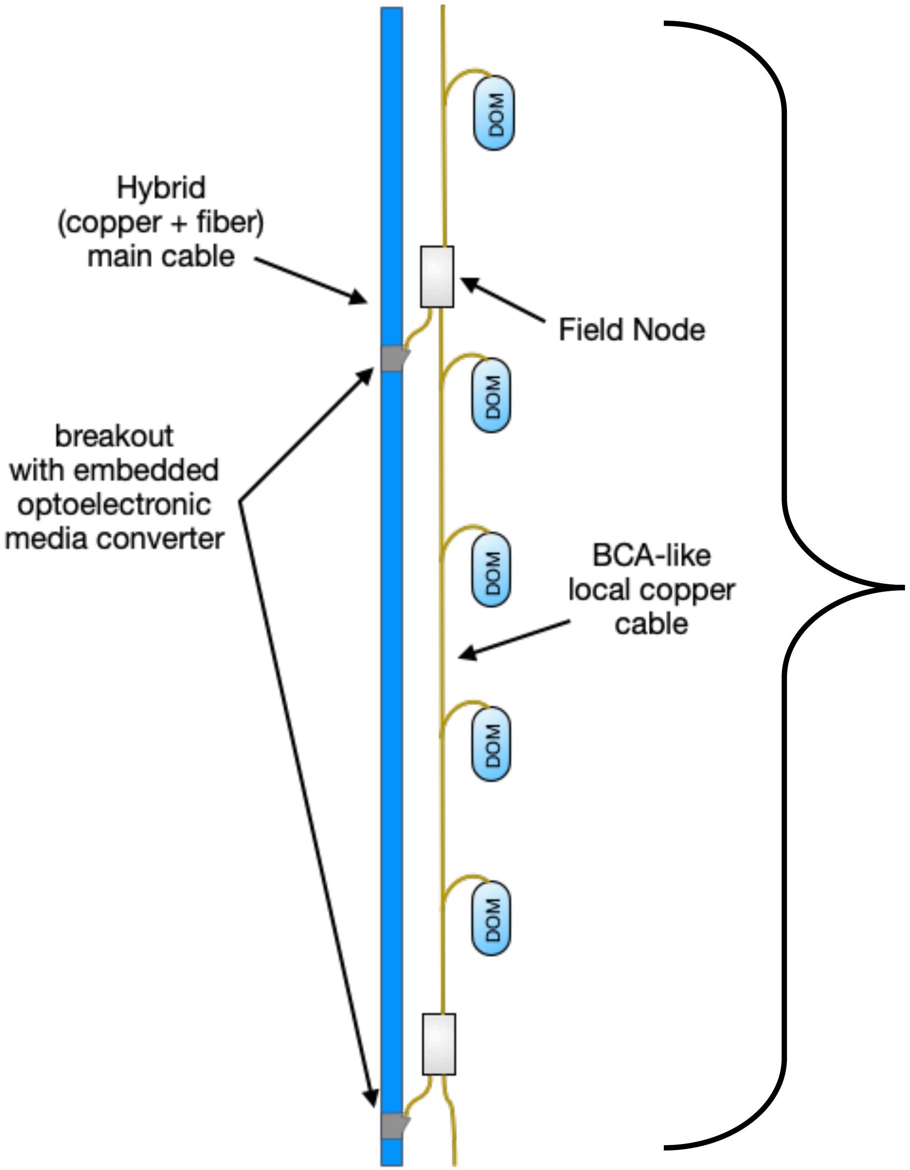


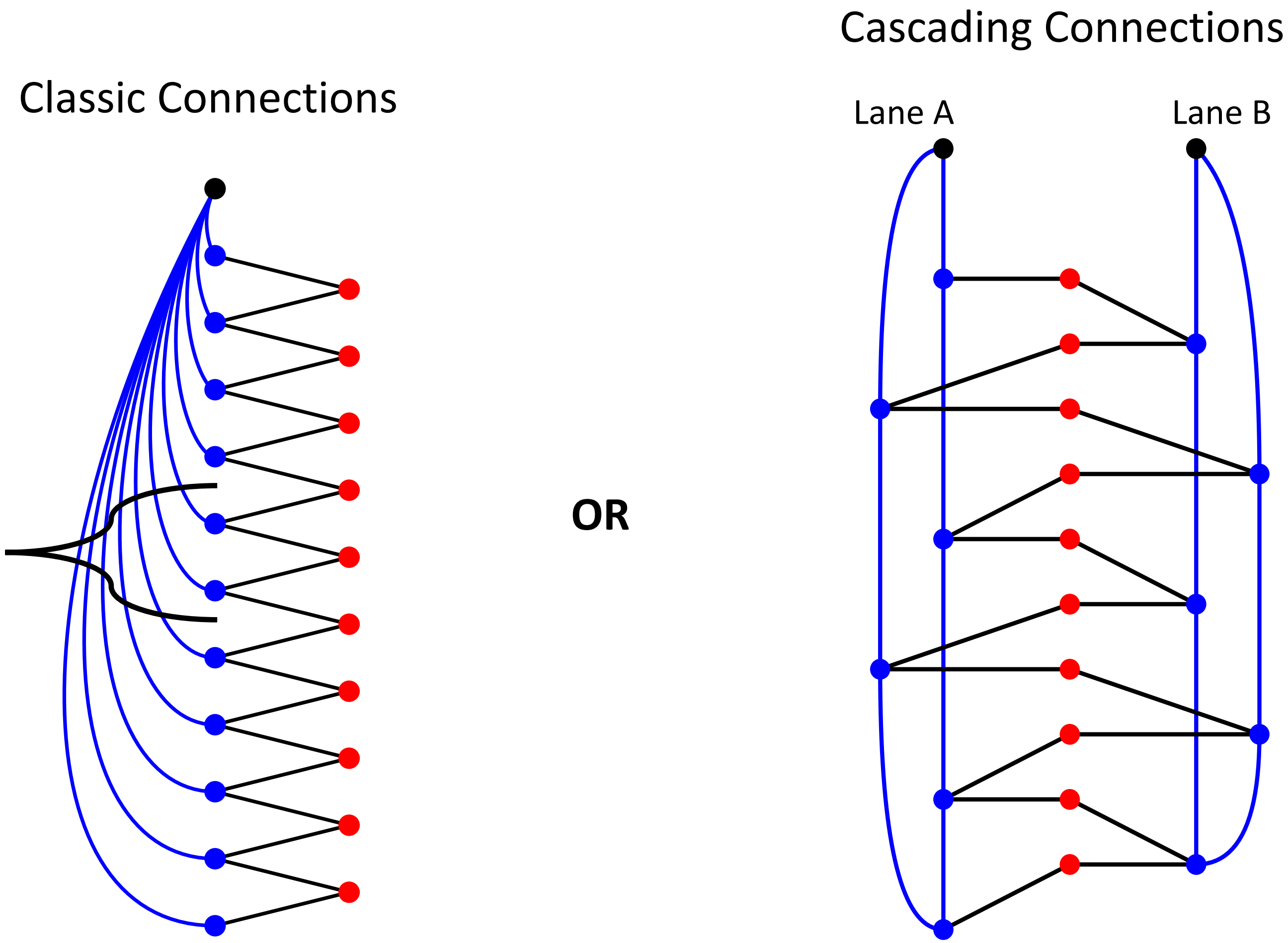
PicoZed SOM



WR Daughter Board

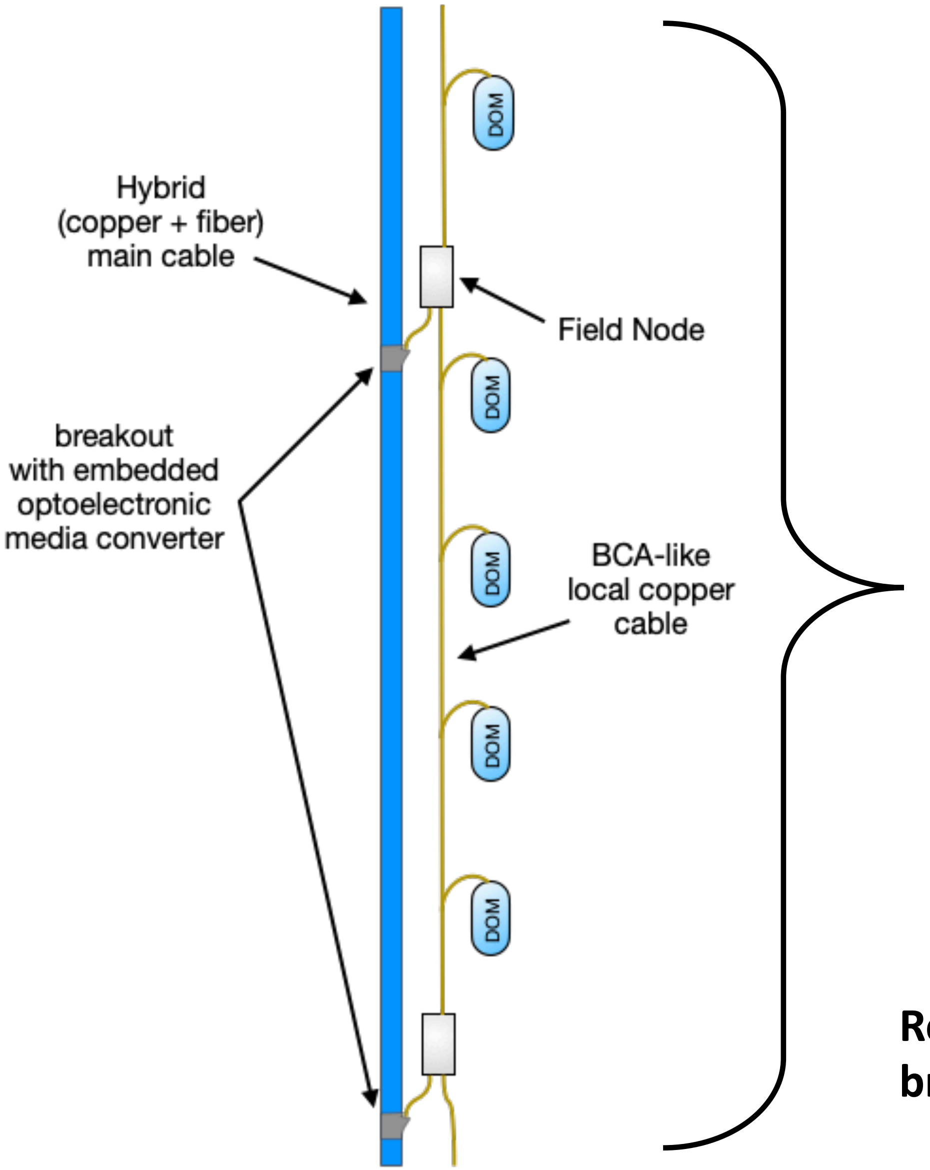
The last requirement – Redundancy



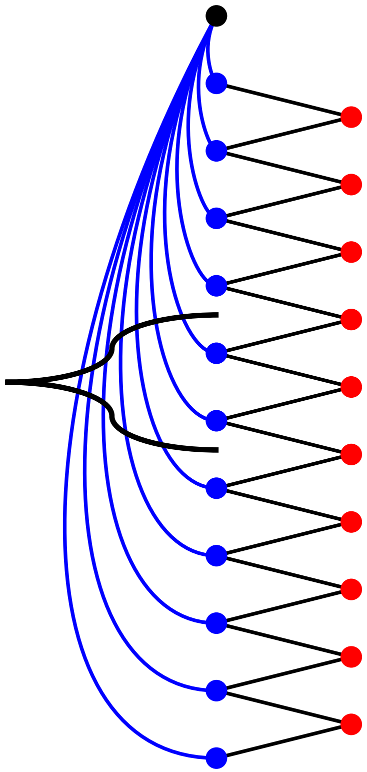


- Endpoint Node (Surface)
- Prototype Fiber Node
- Copper Substring (DOMs) ~8 each
- Fiber Connection
- Copper Connection

The last requirement – Redundancy



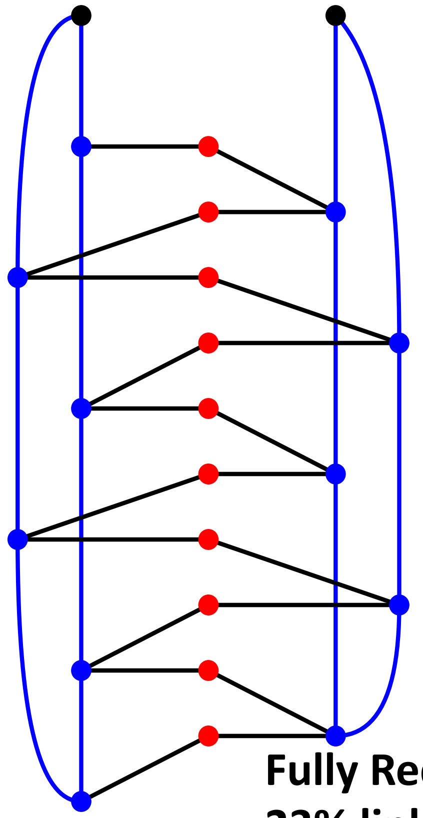
Classic Connections



Redundant to 1 link breakage (7.6% of links)

OR

Cascading Connections



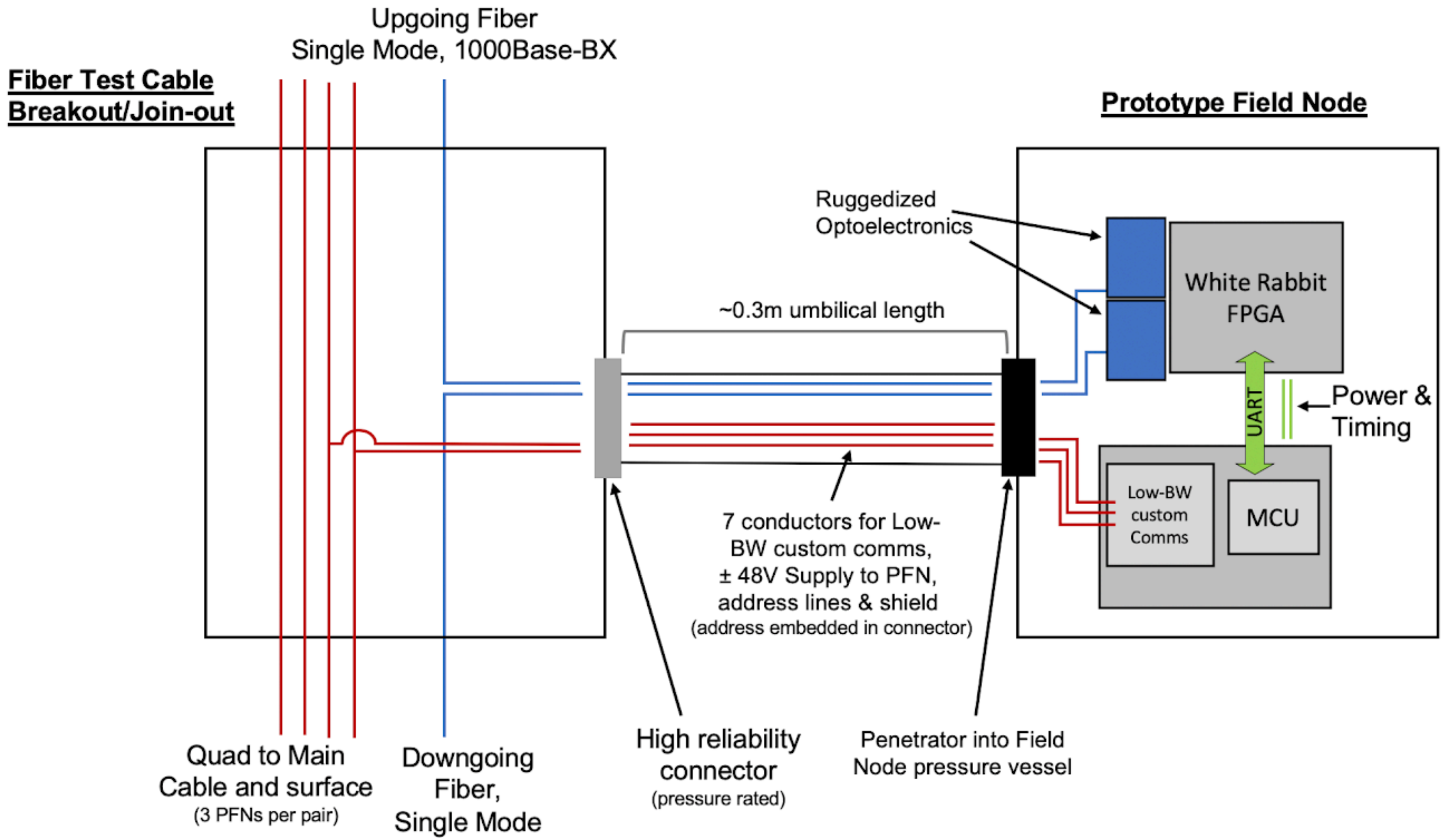
Fully Redundant to 23% link breakage and uses less fiber

- ● Endpoint Node (Surface)
- ● Prototype Fiber Node
- ● Copper Substring (DOMs) ~8 each
- ▬ Fiber Connection
- ▬ Copper Connection

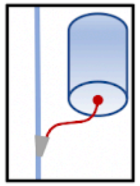
Conclusions

- Future South Pole neutrino detectors, and other large scale neutrino/astrophysics detectors will need solid, high performance data and timing transfer – fiber presents a path to provide this
- We are working towards a prototype Fiber Test System to be deployed at the South Pole as part of the IceCube Upgrade
- This system tests the building blocks of the IceCube-Gen2 Fiber option
  - Armored Fibers
  - Cascading connections (enabling redundancy)
  - White Rabbit Timing and Data transfer

Backup - Alternate Design



This diagram pertains to a vertical section of the FTS containing one join-out and one prototype field node (see full system diagram).

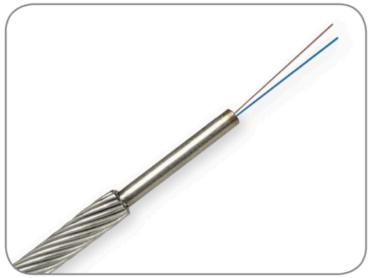


Copper connections are in red
Fiber elements are in blue
Internal elements are green

Backup – Armored Fibers

AFL

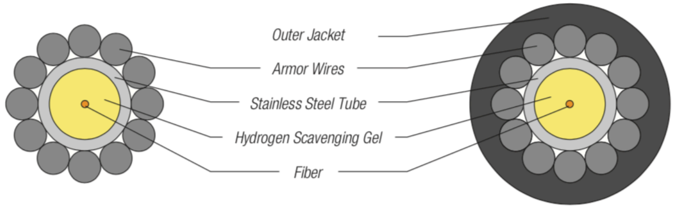
Fiber Optic Cable



Armored Stainless Steel Tubes

Armored Stainless Steel Cables from AFL are based on our patented tube technology which provides for a hermetic seal. The armor wires provide improved crush and tensile performance while maintaining good flexibility. Armored Stainless Steel Tubes can be used in a variety of applications such as temperature sensing and surface cable.

Cable Components



Features

- Hermetic Stainless Steel Tube
- High Strength Wire
- Jacket Options
- Gel Options
- Flexible
- Rugged

Options and Specifications

FIBER COUNT	TUBE O.D. (mm)	FINAL O.D. (mm)	WEIGHT (kg/km)	BREAKING STRENGTH (kg)	BEND RADIUS (mm)
4	1.32	2.12	16	222	132
6	2.00	3.20	38	526	200
12	2.40	3.60	45	619	240

Based on 200 kpsi Gips wire, gel filled tube

Encapsulation Option

PARAMETER	VALUE
Materials	Polypropylene, Nylon, PVDF, Hytrel™
Diameter	To customer specifications
Cable markings	To customer specifications