THE UNIVERSITY of WISCONSIN MADISON

Supernova Neutrino Detection with IceCube

Overview and Outlook

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for the IceCube Collaboration
Institute for Nuclear Theory - University of Washington
Special Workshop: Probing the Supernova Mechanism by Observations
July 20th, 2012

IceCube

Outline

Overview of IceCube

Detection Method

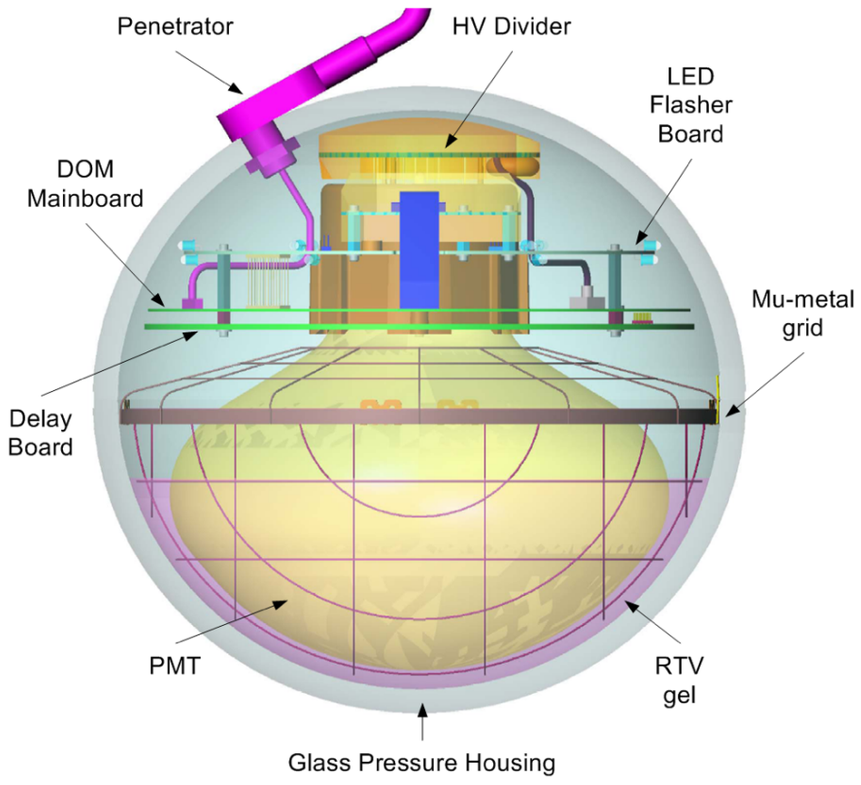
Detector Performance

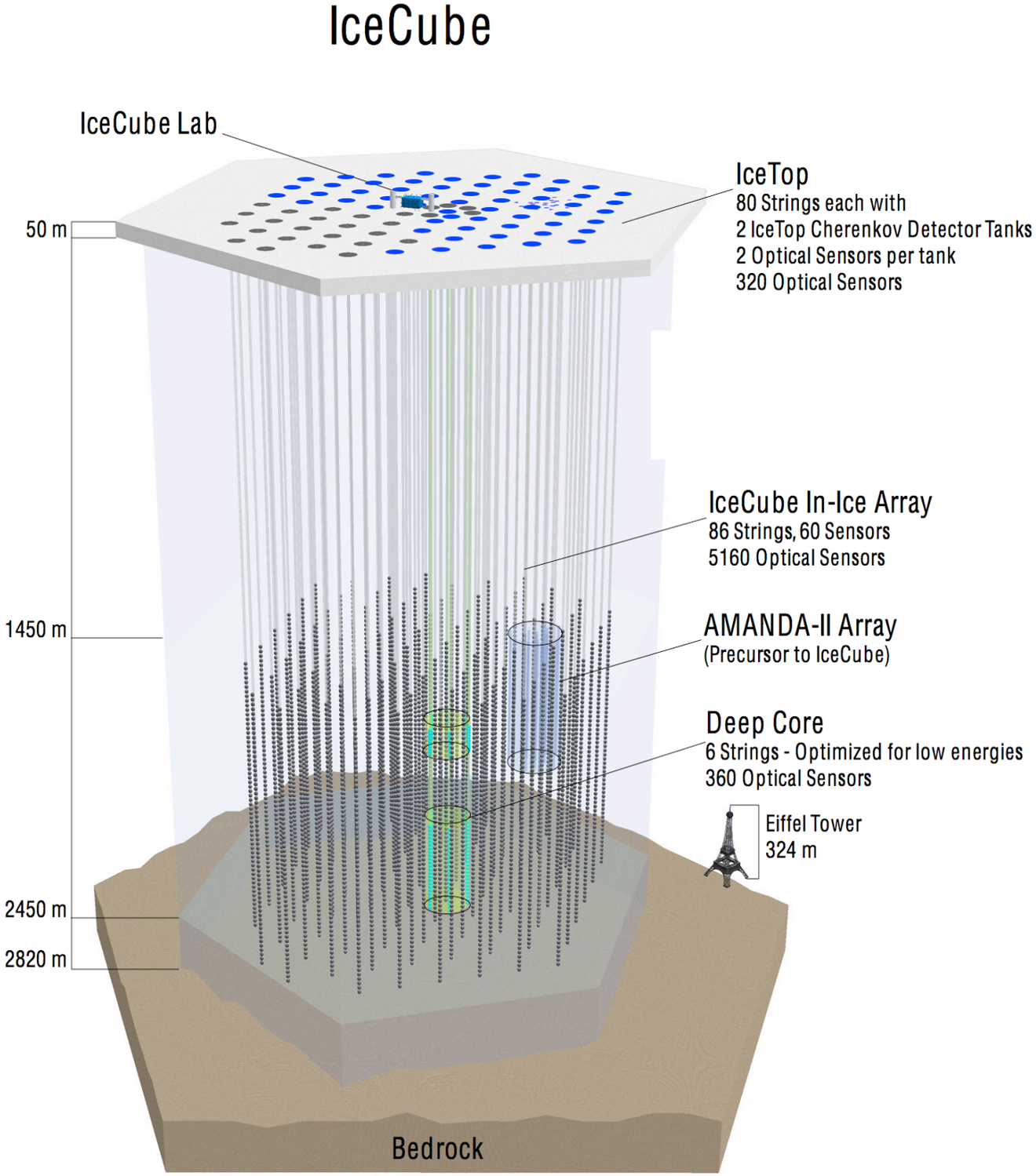
Physics Capabilities

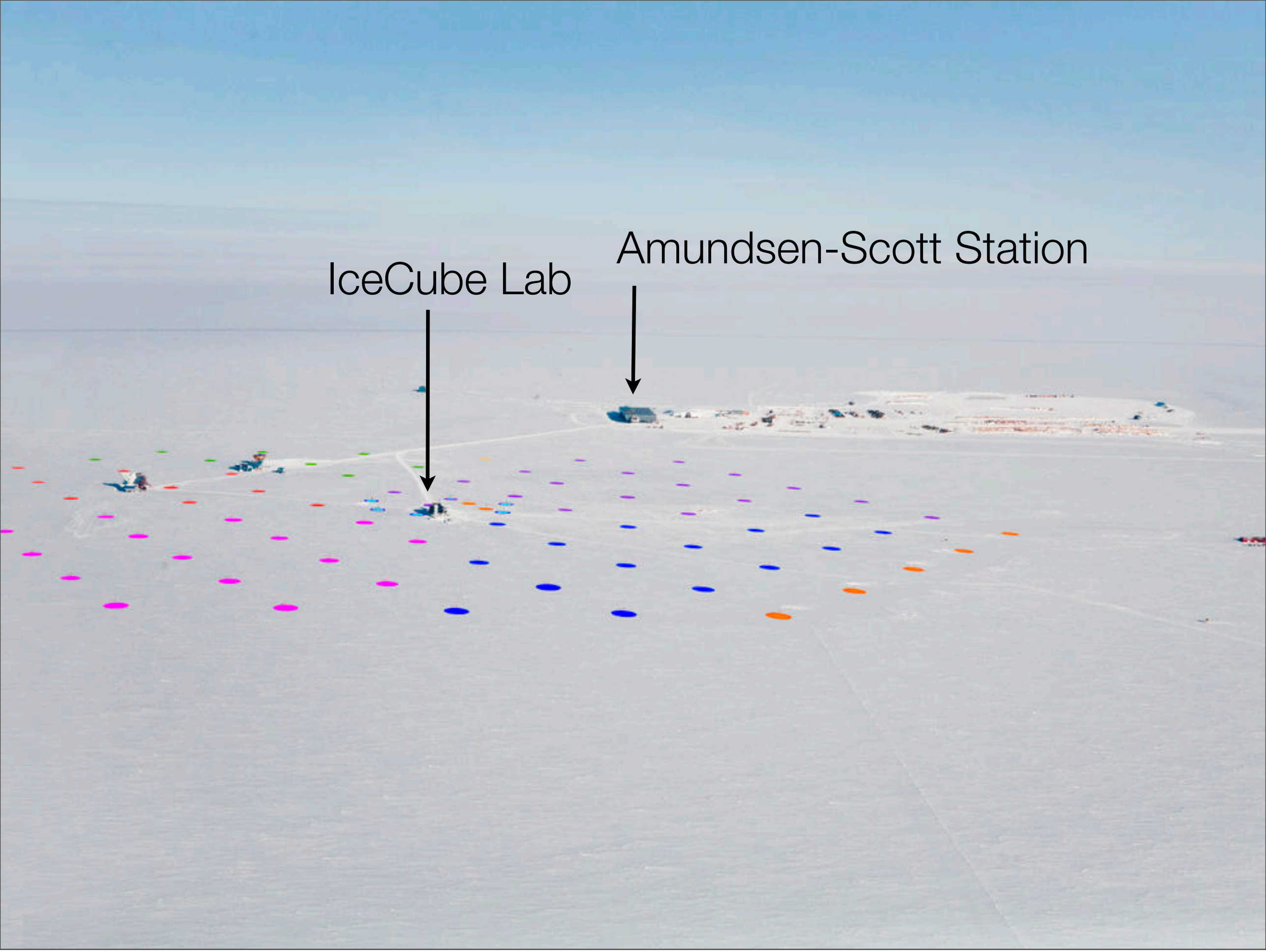
Future Improvements

IceCube Detector

- 1km^3 instrumental volume
- 86 Strings
  - 80 strings ~125 m apart
  - 60 Digital Optical Modules (DOM)/ string at 17 m vertical spacing
  - 6 special strings, 62 m apart, 7 m vertical spacing (high QE PMTs)
- 5160 DOMs in total
- DeepCore: 6 high-QE + 7 nearest standard strings







Thursday, July 19, 2012

IceCube Collaboration

The IceCube Collaboration

Stockholm University
Uppsala Universitet

University of Alberta

University of Oxford

Deutsches Elektronen-Synchrotron
Humboldt Universität
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität München
Universität Bonn
Universität Dortmund
Universität Mainz
Universität Wuppertal

Ecole Polytechnique
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University of Geneva

Chiba University

Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls

Université Libre de Bruxelles
Université de Mons
University of Gent
Vrije Universiteit Brussel

University of the West Indies

University of Adelaide

University of Canterbury

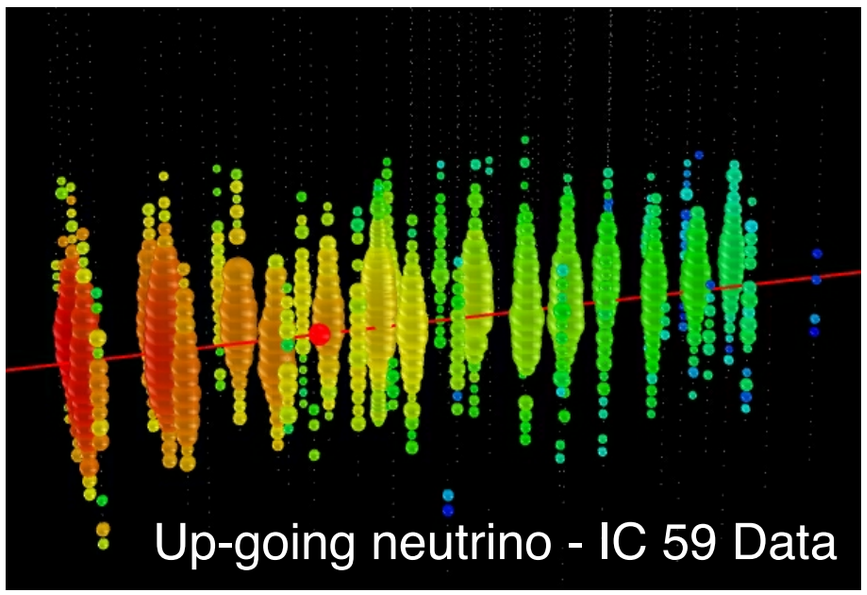
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

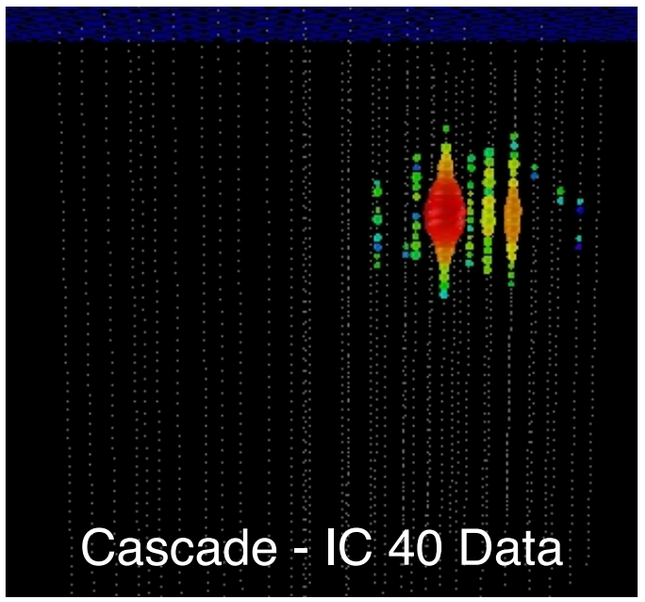
Typical IceCube Events

Multiple DOMs form a distinctive pattern to make a detection

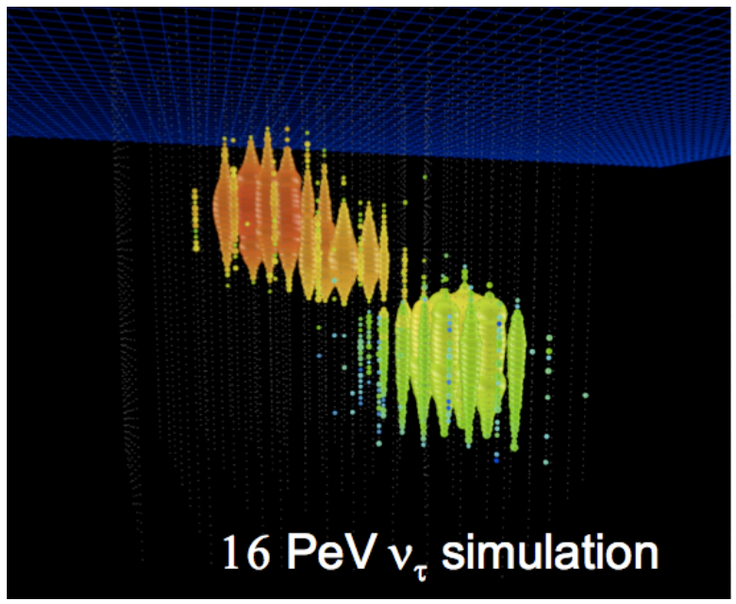
Tracks:
- ~TeV through-going muons
- Pointing resolution ~1°



Cascades:
- ~100 GeV - 100 TeV
- Neutral current for all flavors



Composites:
- Starting tracks
- high-E ν_τ (Double Bangs)



With an order of ~10^6 lower energies this is not what we are looking for with supernovae!

Movie I

59 String Configuration

Up-going neutrino event

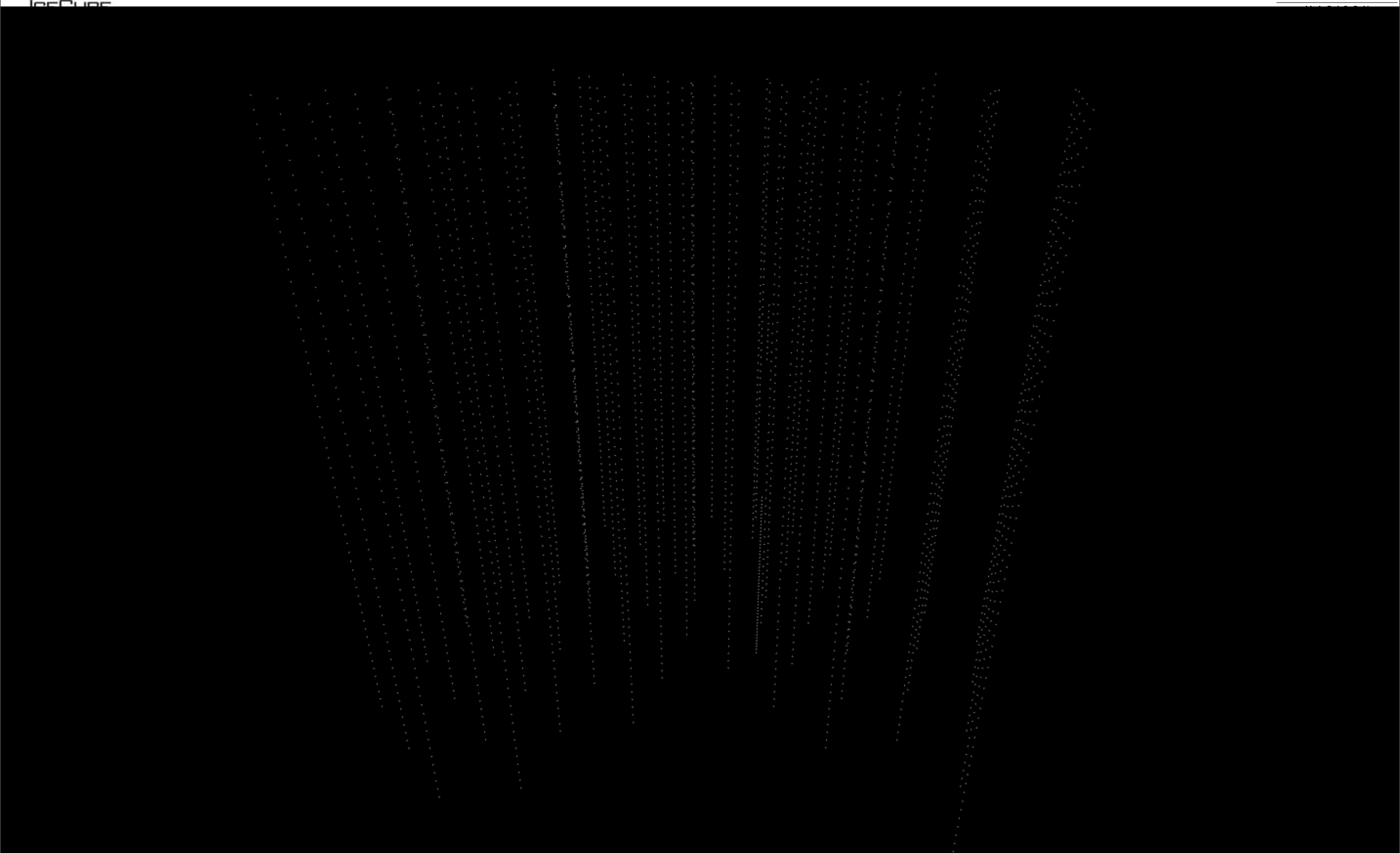
DOM Colors represent arrival times

Red - Early

Green/Blue - Later

DOM Size represents amount of deposited charge

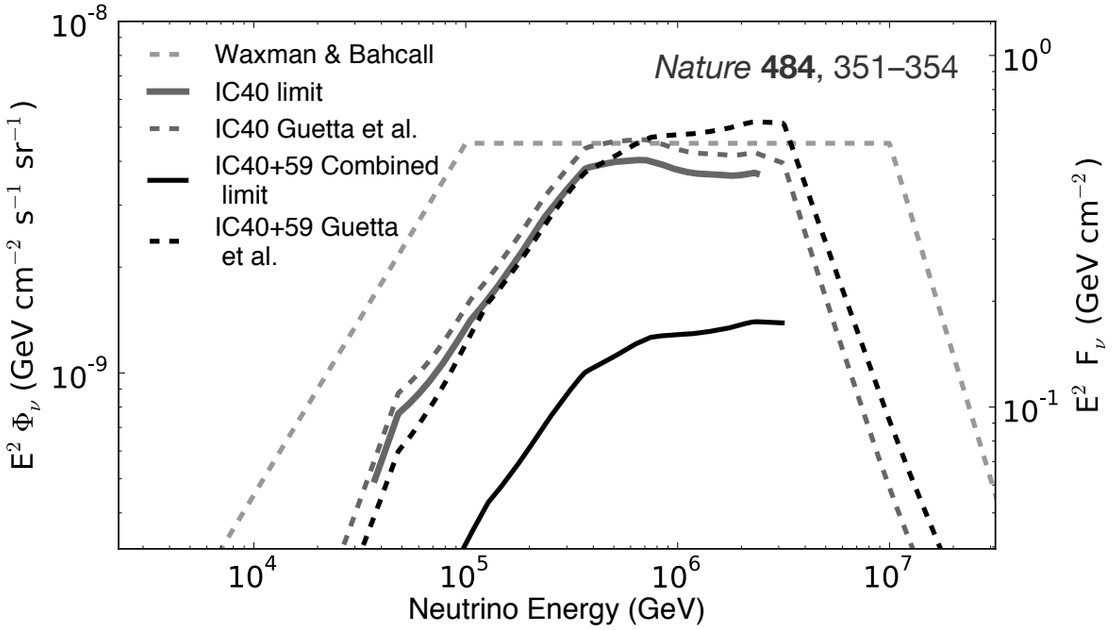
Courtesy of A. Schuhkraft



Courtesy of A. Schuhkraft

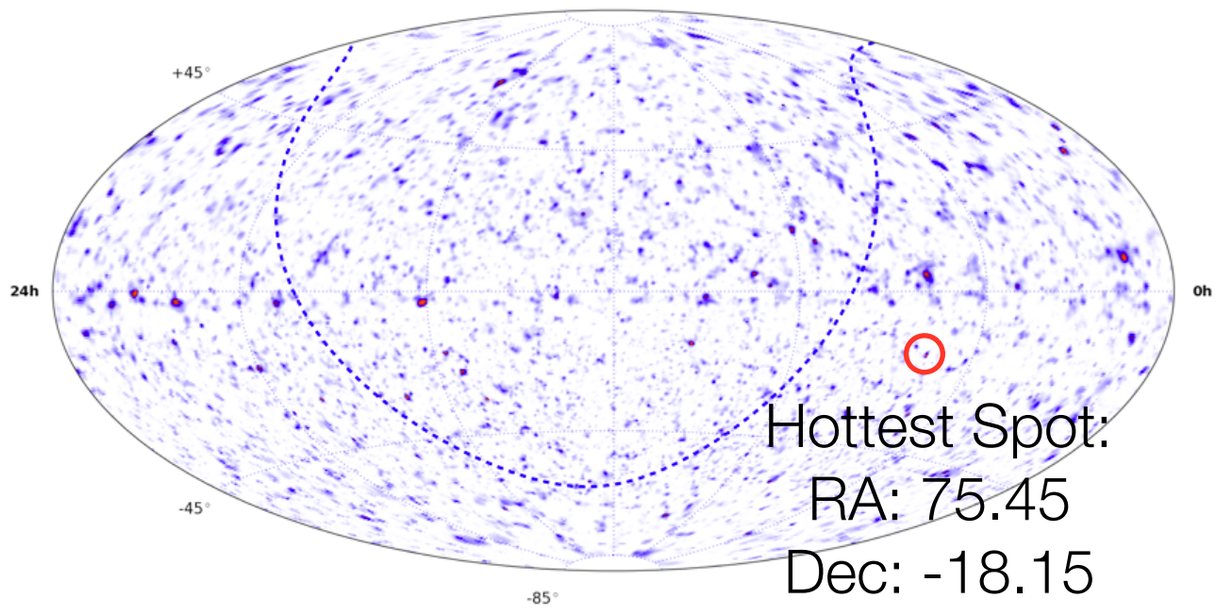
IceCube Science

GRB

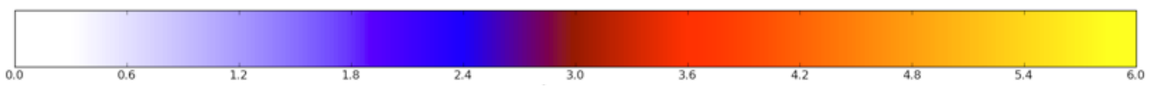


Neutrino Flux factor 3.7 below expected!

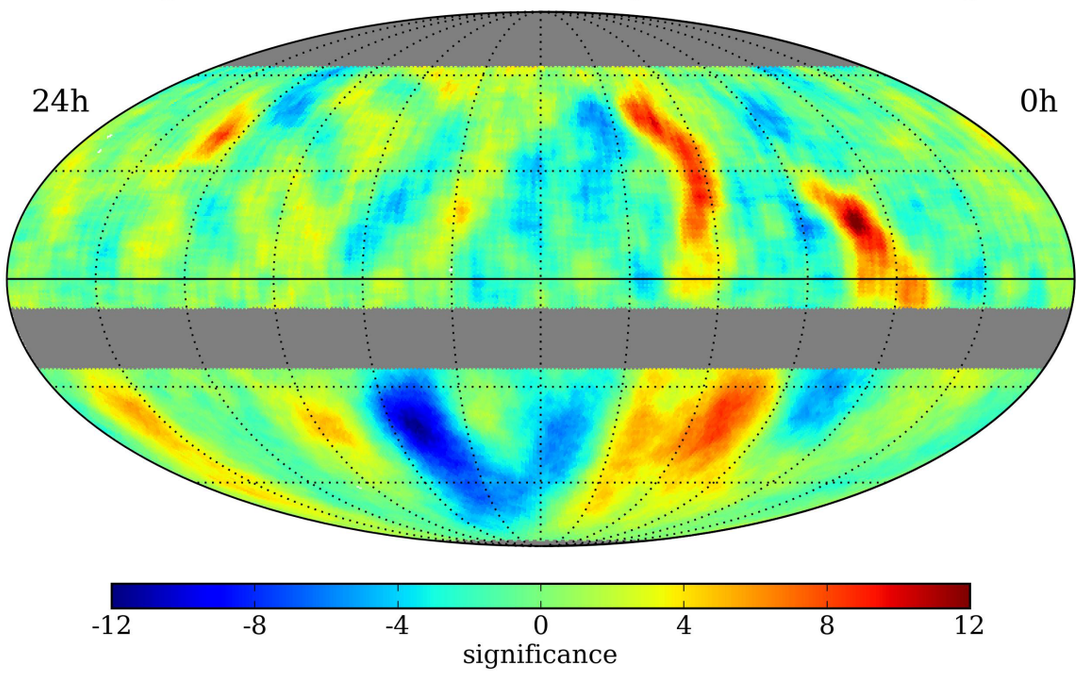
Neutrino Point-Sources



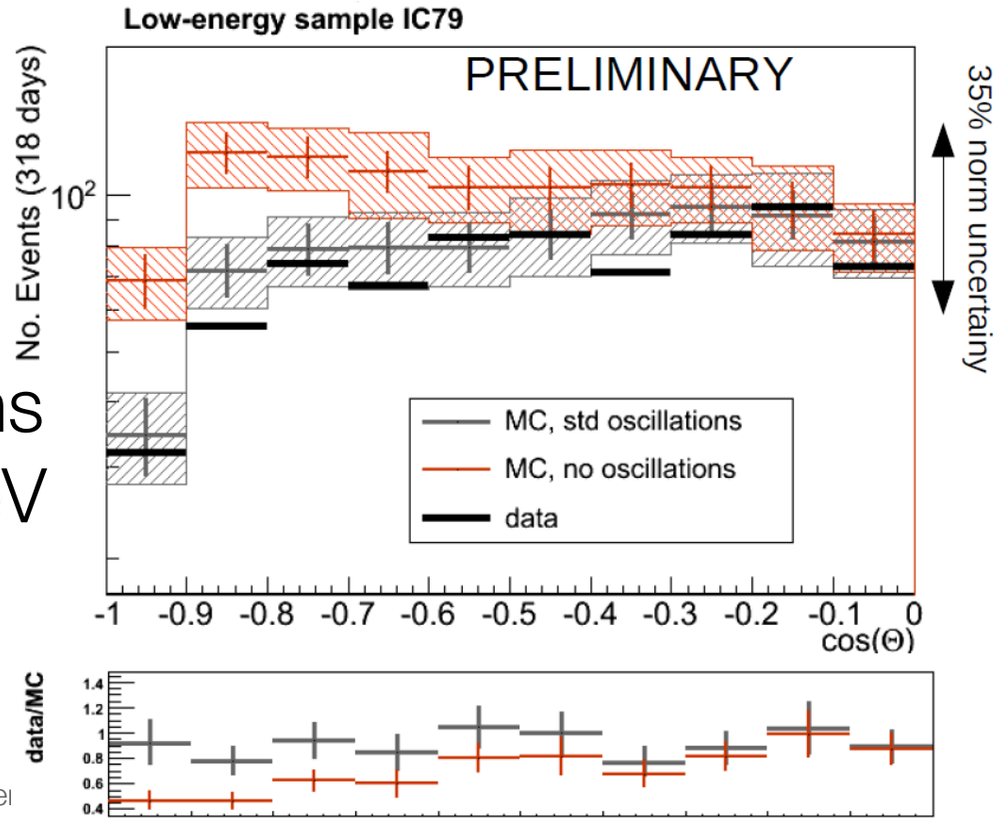
Hottest Spot:
RA: 75.45
Dec: -18.15
-log$_{10}$(p-value) = 4.65



Cosmic Ray Anisotropy

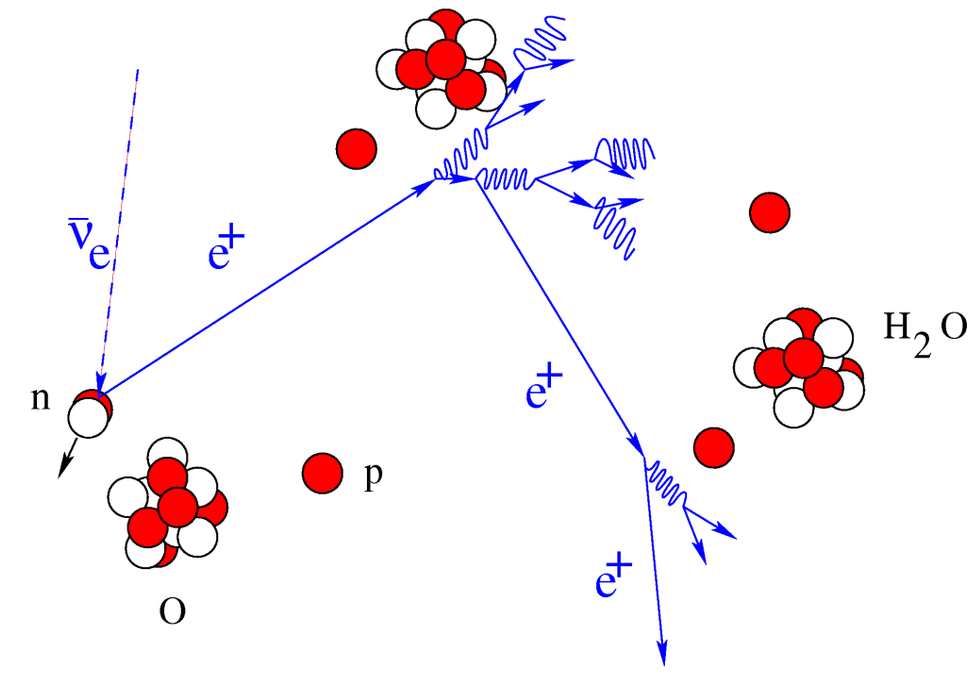


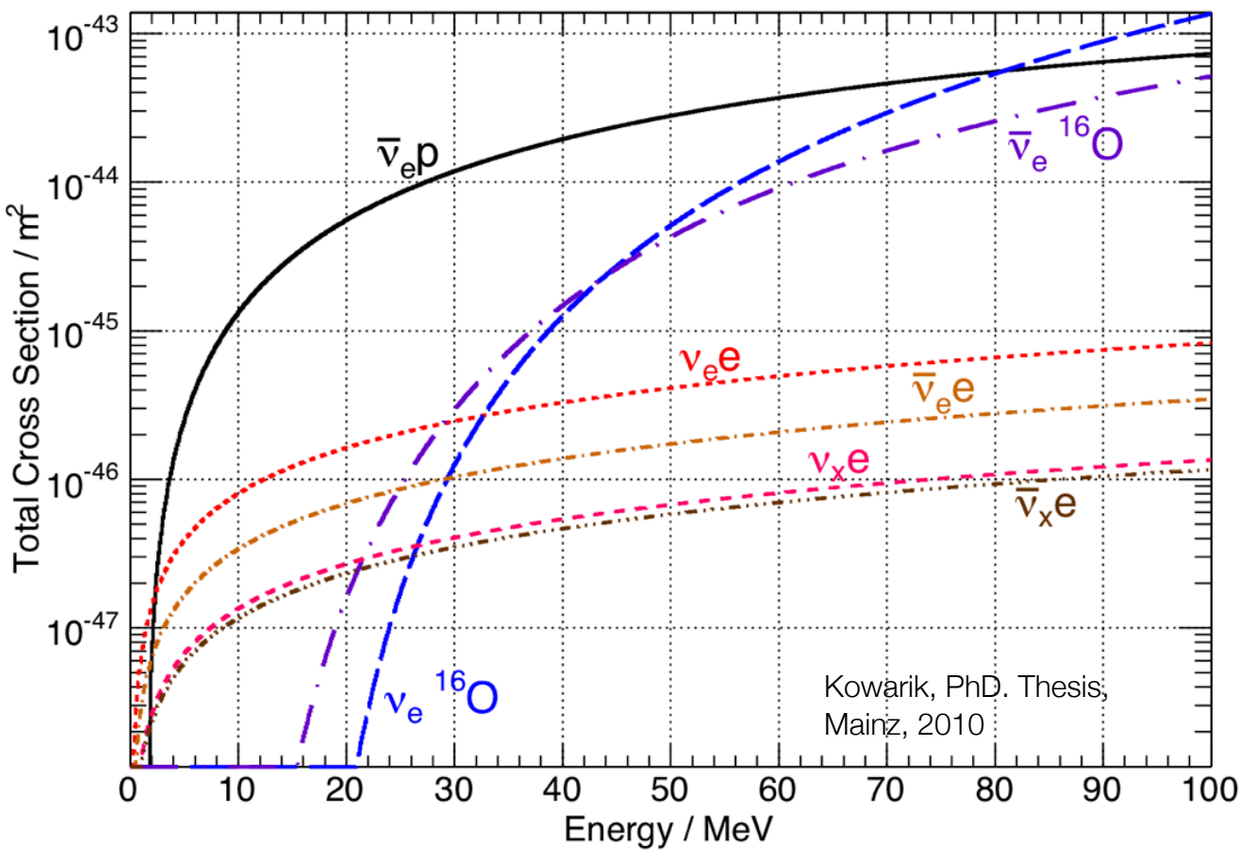
Neutrino Oscillations at ~50 GeV



MeV Neutrinos in IceCube

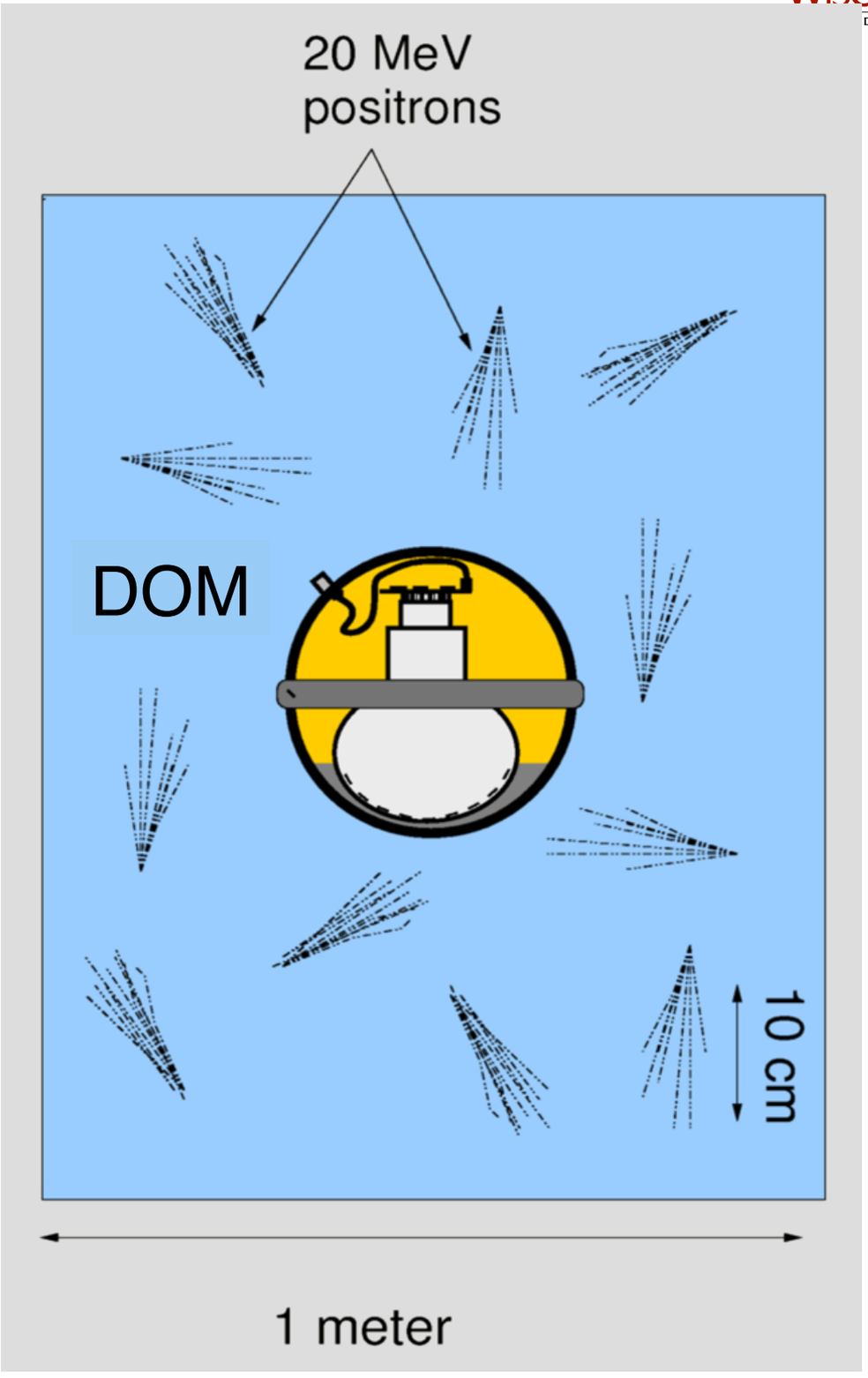
- For every MeV neutrino that interacts generally 0-1 photons are detected
  - Coincident hit probability on *O*(1%)
  - Need a large flux!
- Interaction Channels
  - Inverse β-decay is main interaction channel (~93-94%)
  - Nucleon and electron scattering processes account for the remainder (~6-7%)





MeV Positrons in IceCube

- Supernova
  - Uniform illumination in the ice
  - ~0.5 to 1×10^6 events in 10 seconds
  - Significant increase in detector rate on top of background
- Capabilities
  - Low DOM noise - ~500-600 Hz
  - High statistics due to large volume
  - Time resolution limited to 2 ms at present
  - No pointing
  - No individual events
  - No energy information



Movie II

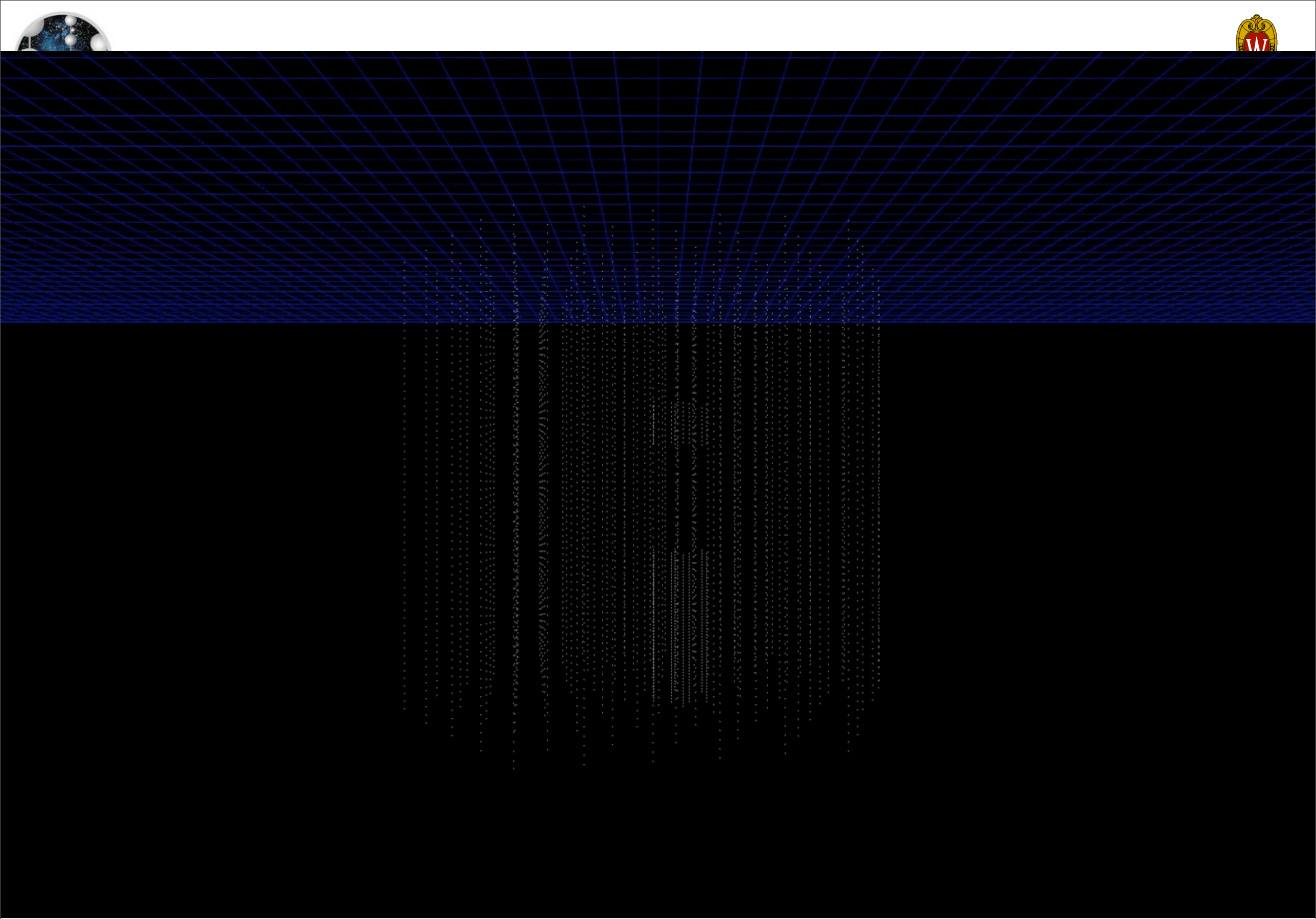
DISCLAIMER

THIS IS A TOY MODEL OF 100000 O(10 MeV) POSITRONS INJECTED AT THE SAME TIME

ABOUT A TENTH OF THE TOTAL NUMBER EXPECTED EVENTS

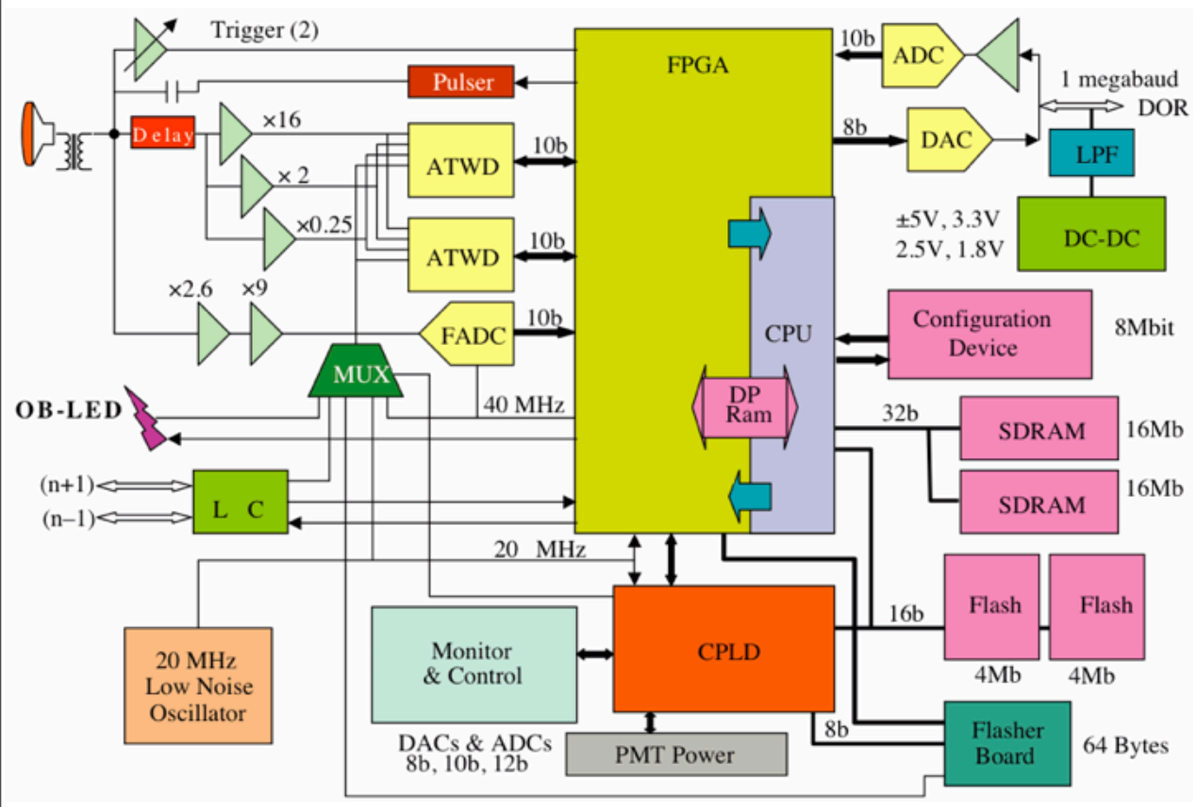
NO REAL PHYSICS!

Thanks to C. Kopper



Thanks to C. Kopper

Data Stream


Trigger (2)
Pulser
Delay
×16
× 2
×0.25
ATWD
ATWD
FADC
10b
10b
10b
×2.6
×9
MUX
OB-LED
40 MHz
(n+1)
(n–1)
L C
20 MHz
20 MHz
Low Noise
Oscillator
Monitor
& Control
CPLD
DACs & ADCs
8b, 10b, 12b
PMT Power
FPGA
CPU
DP
Ram
10b
ADC
8b
DAC
1 megabaud
DOR
LPF
±5V, 3.3V
2.5V, 1.8V
DC-DC
Configuration
Device
8Mbit
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SDRAM
16Mb
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16Mb
16b
Flash
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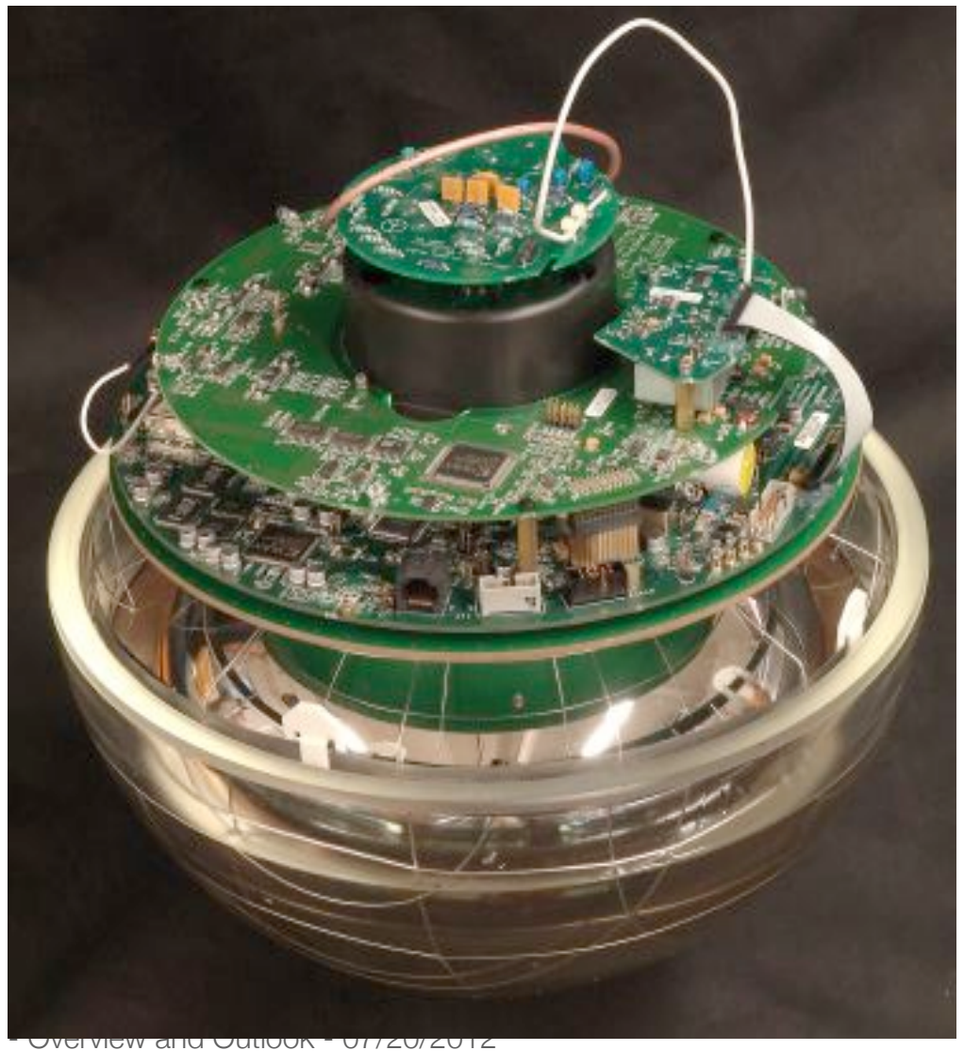
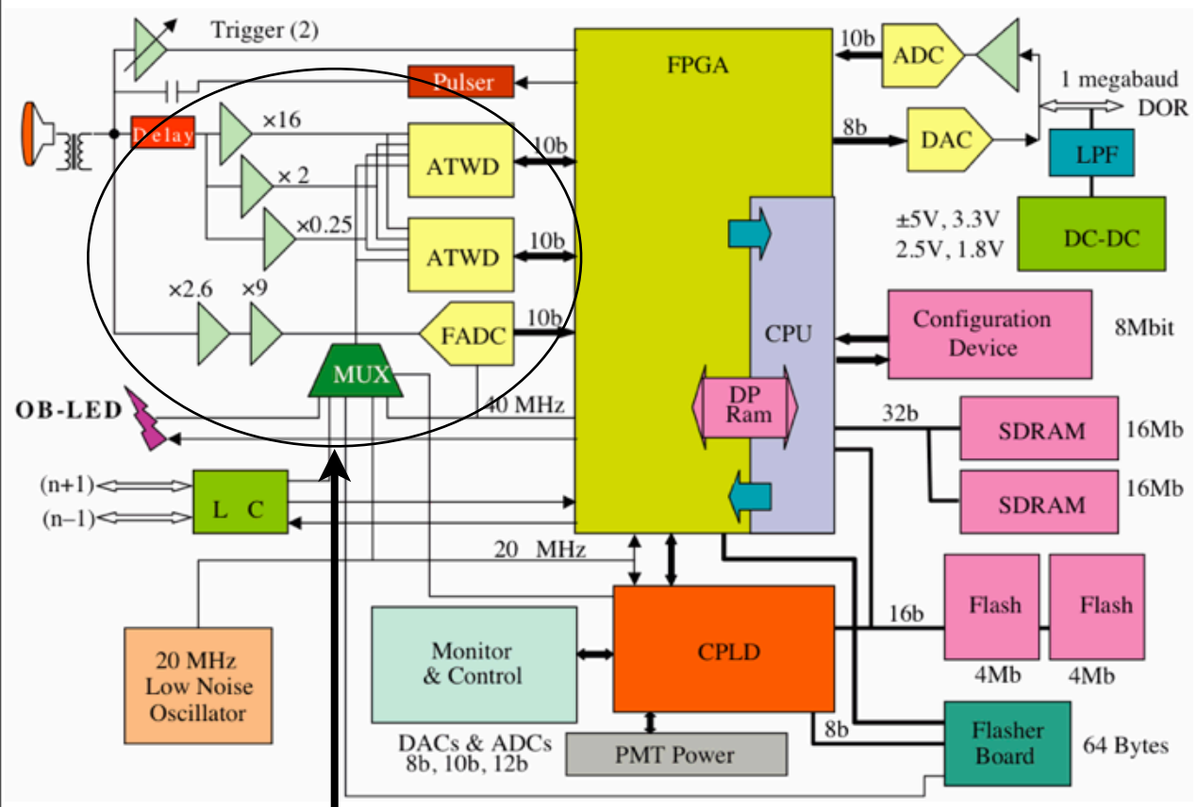
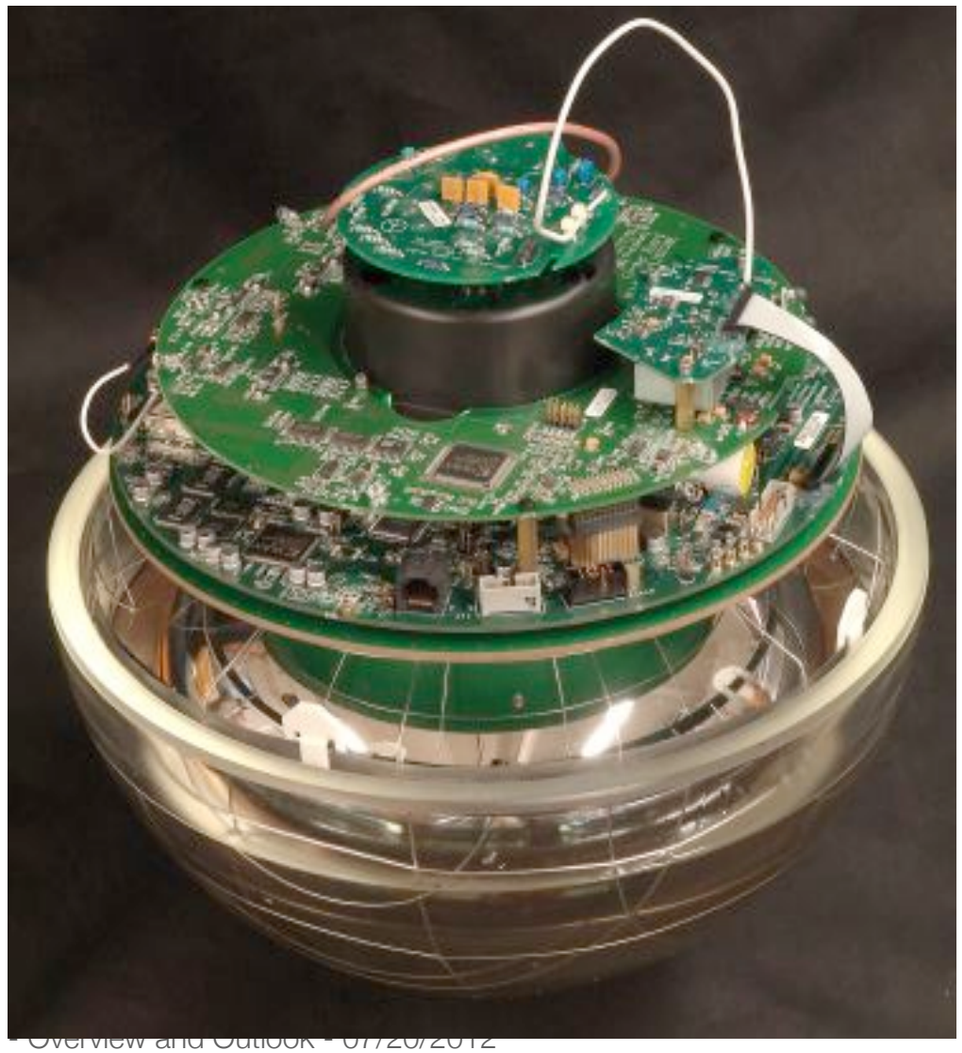
4Mb
8b
Flasher
Board
64 Bytes



Data Stream

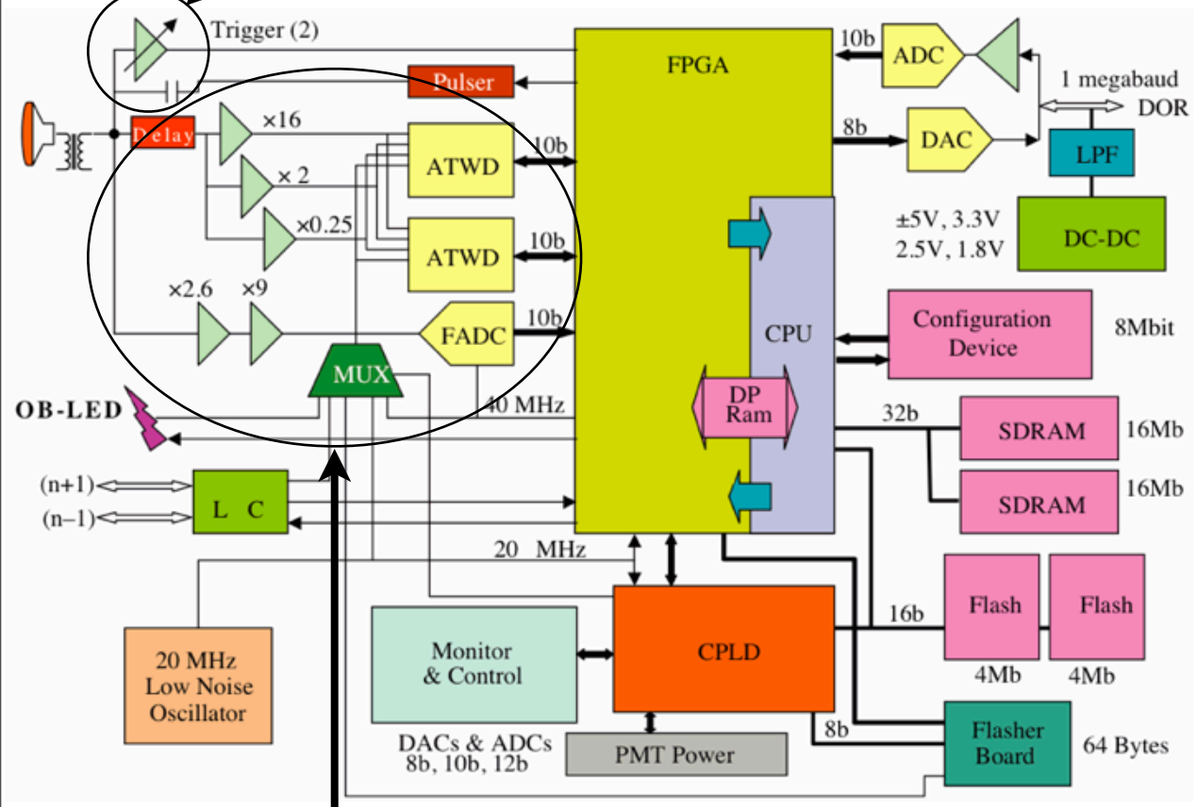


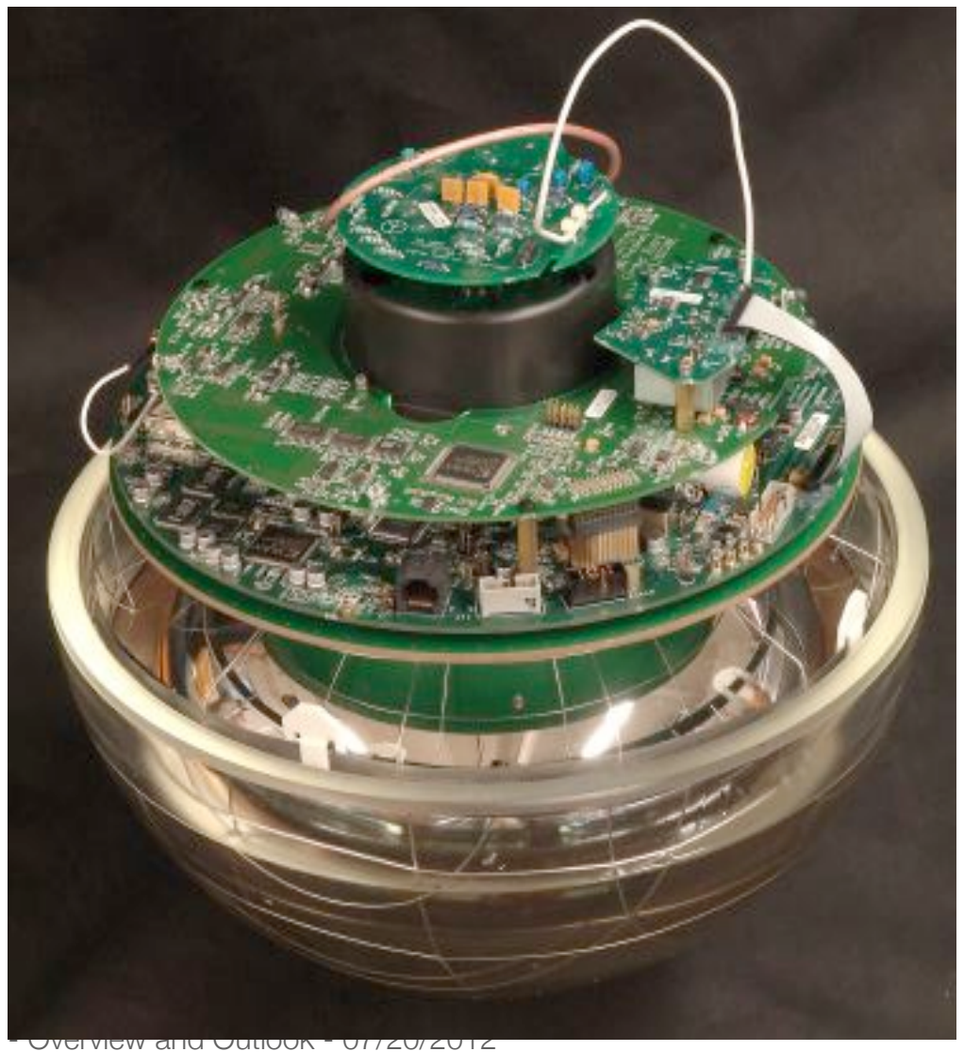
Primary Data Stream is waveforms



Data Stream

Supernova channel uses a scaler data format



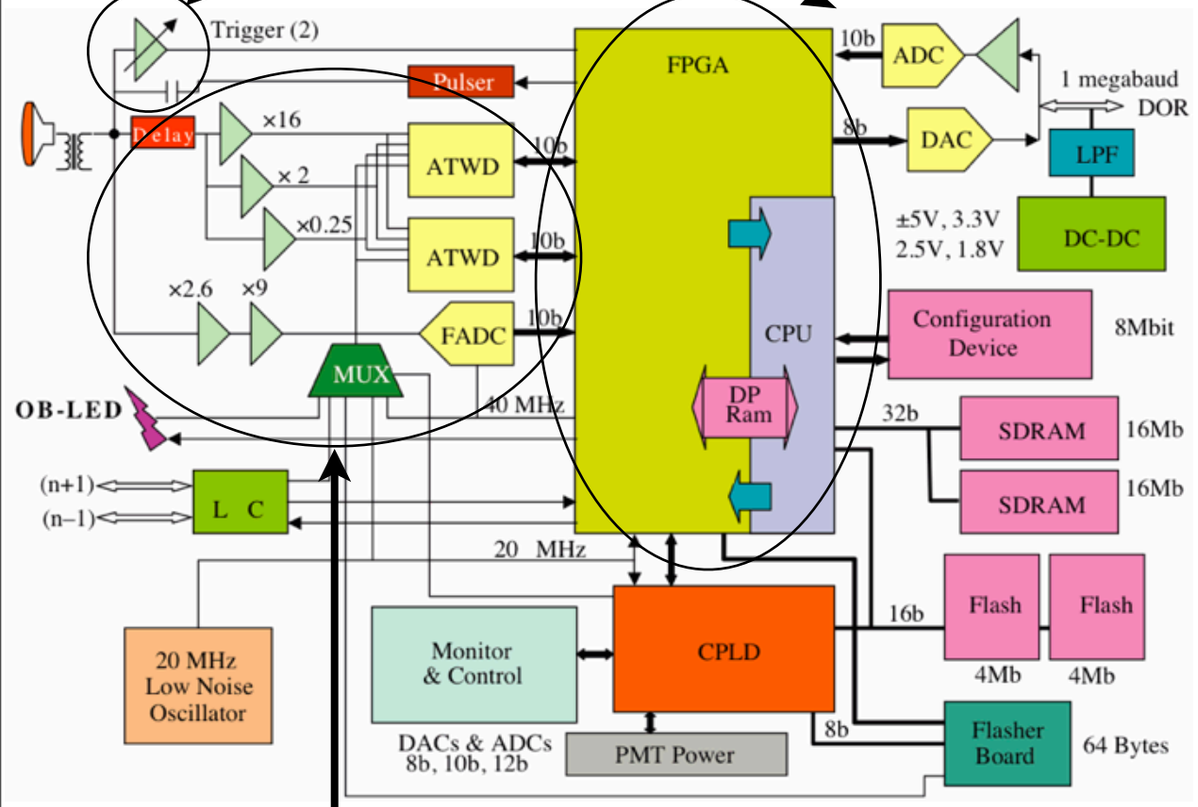


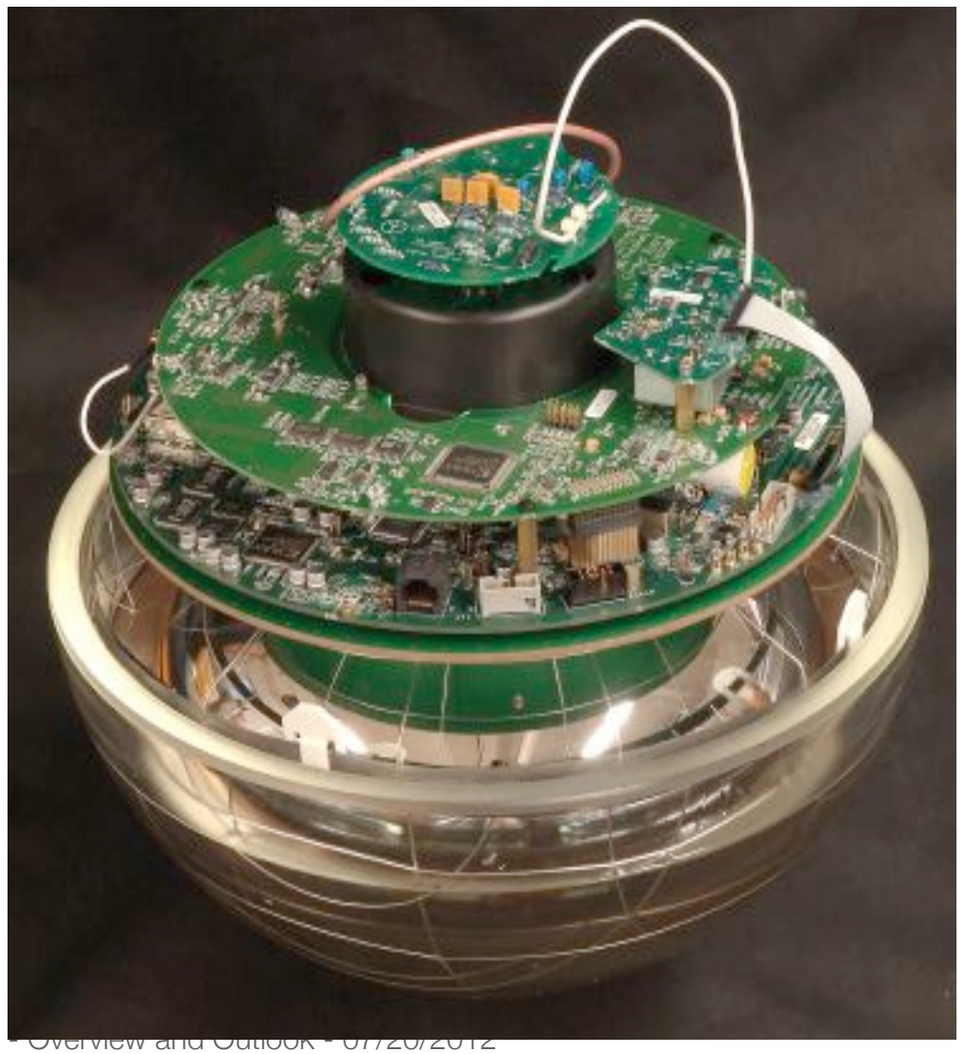
Primary Data Stream is waveforms

Data Stream

Supernova channel uses a scaler data format

- On-board Software Counter
  - Count discriminator crossings (0.25 PE) in 1.6384 ms
  - Artificial deadtime of 250 μs for background reduction

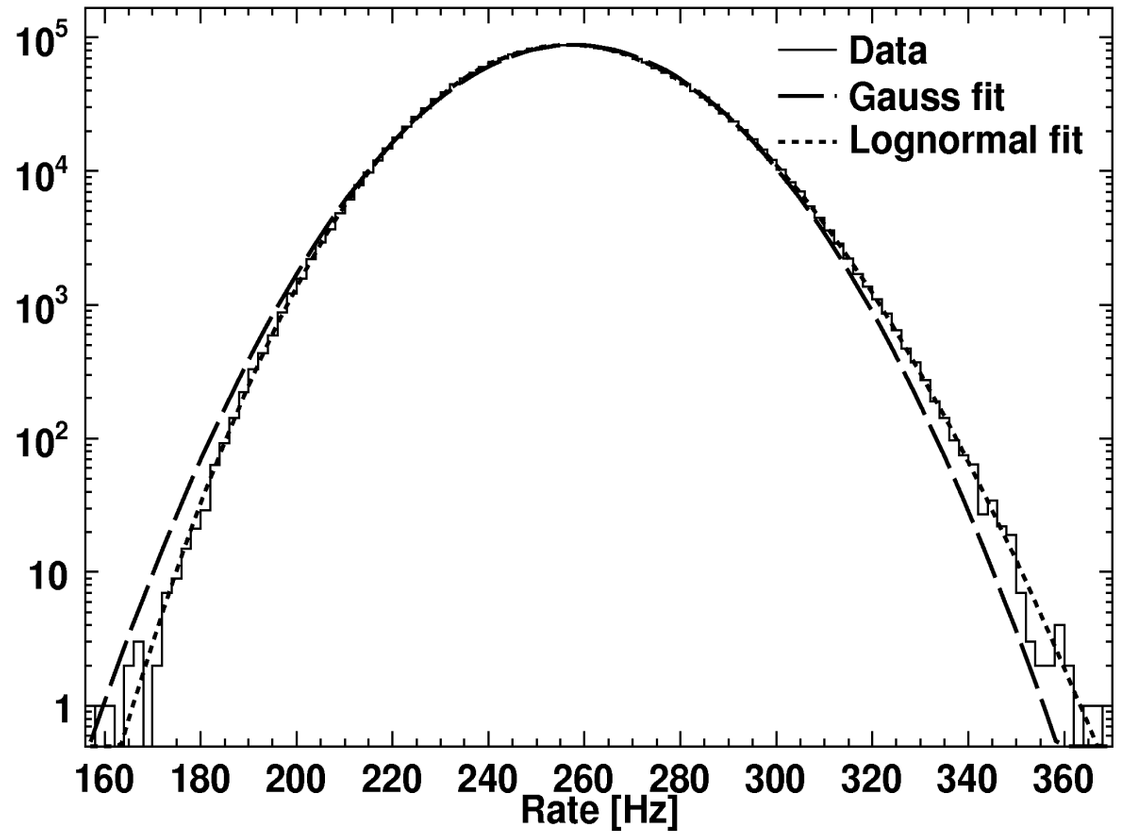


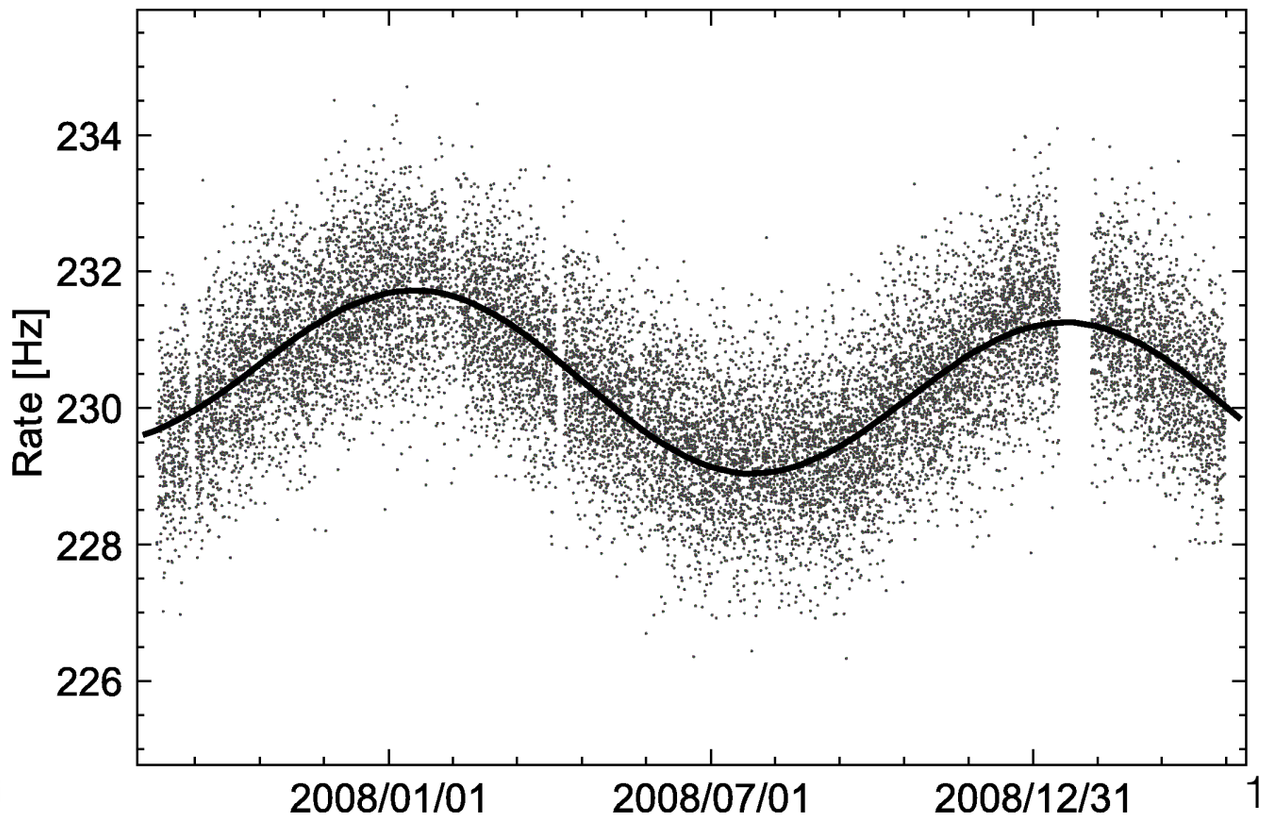


Primary Data Stream is waveforms

Detector Performance

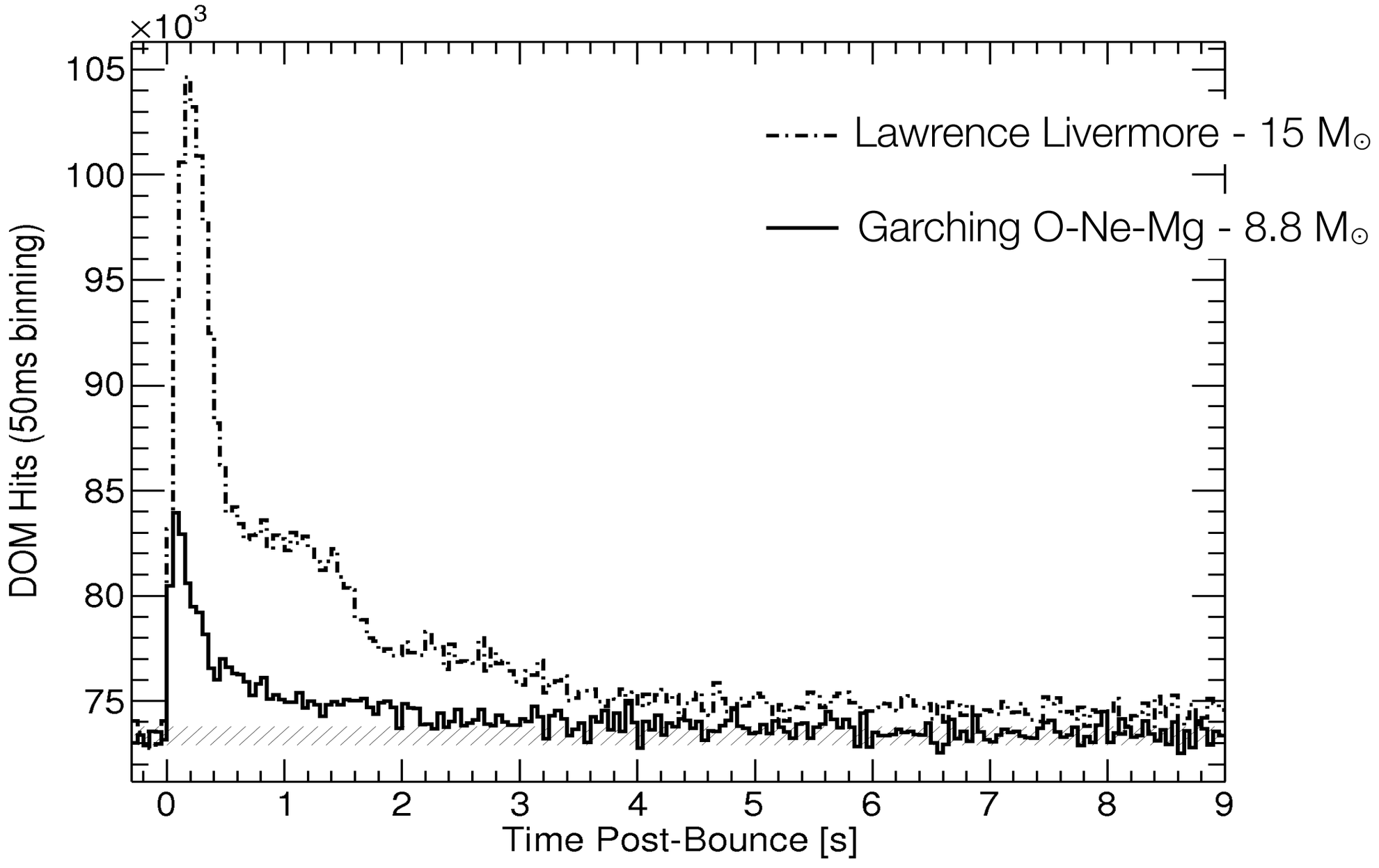
- Individual DOM noise log-nomally distributed
  - Post deadtime average: 265 ± 26 Hz
  - Lower temperature environment
    - 240 - 265 K (depth dependence)
- Stable rate
  - ~6% variation due to atmospheric changes





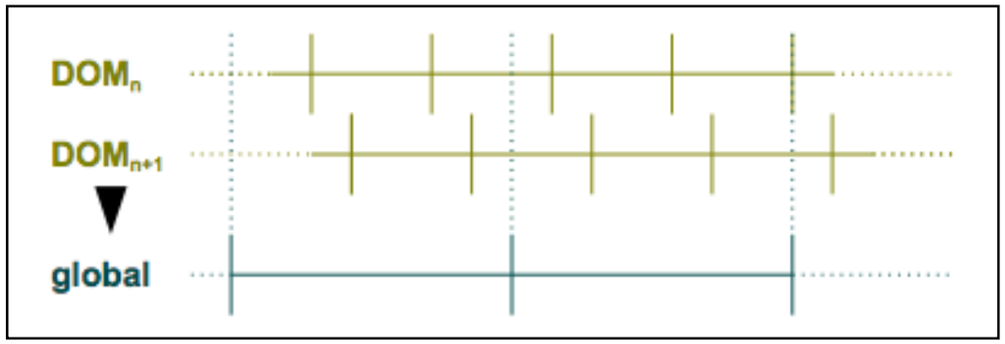
Supernova in IceCube - Motivation

- Looking for subtle changes in background rate
- Need to understand detector properties as well as we possible

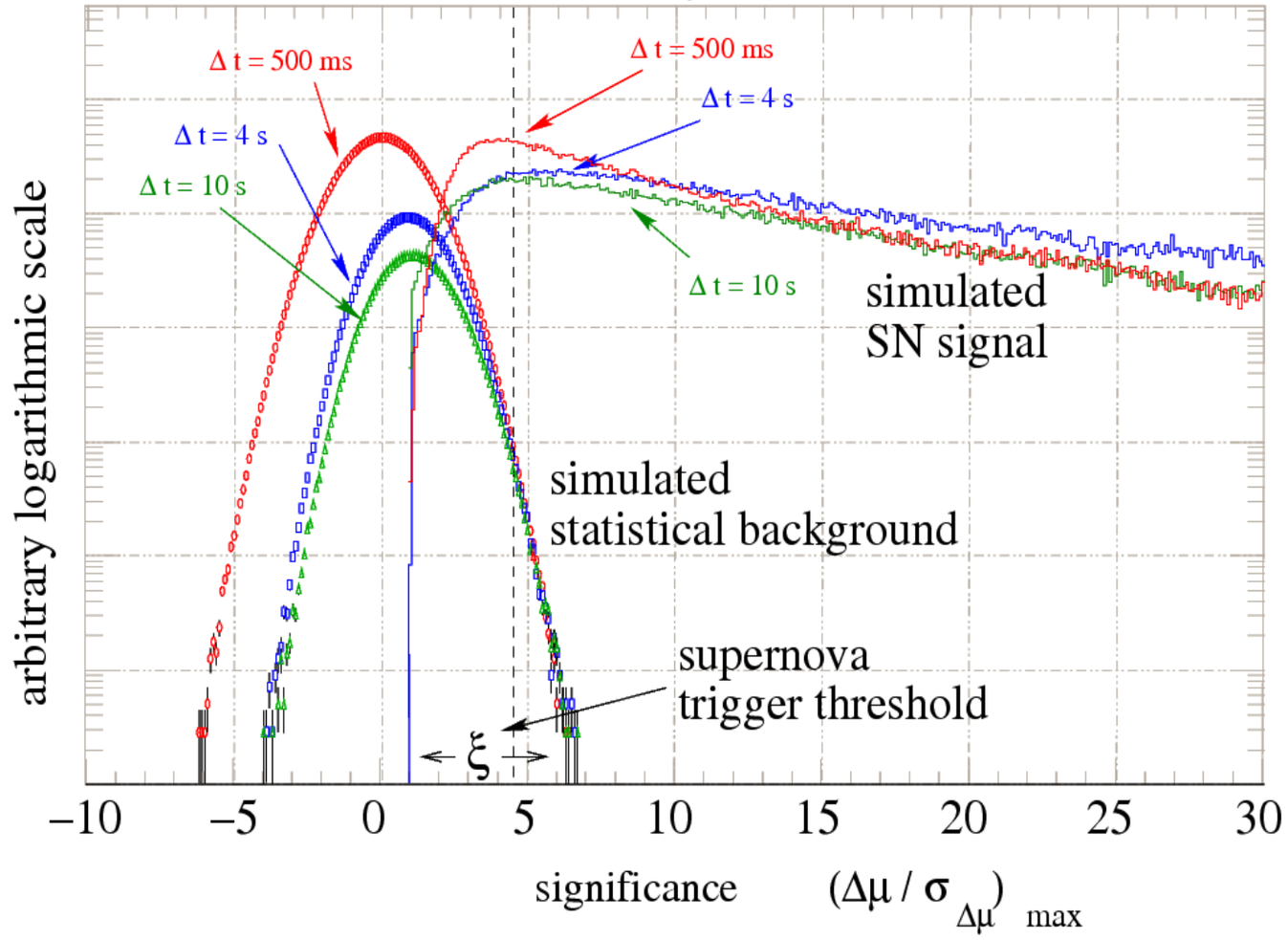


Supernova in IceCube - SNDAQ

- Rebinning individual 1.6384 ms bins into global 2 ms
  - Time synchronizing
- Search for collective increase in noise ($\Delta\mu$) and error ($\sigma_{\Delta\mu}$) in 0.5, 1.5, 4, and 10 s bins



Note: AMANDA case without muon subtraction, better separation in IceCube



Supernova in IceCube - SNDAQ - II

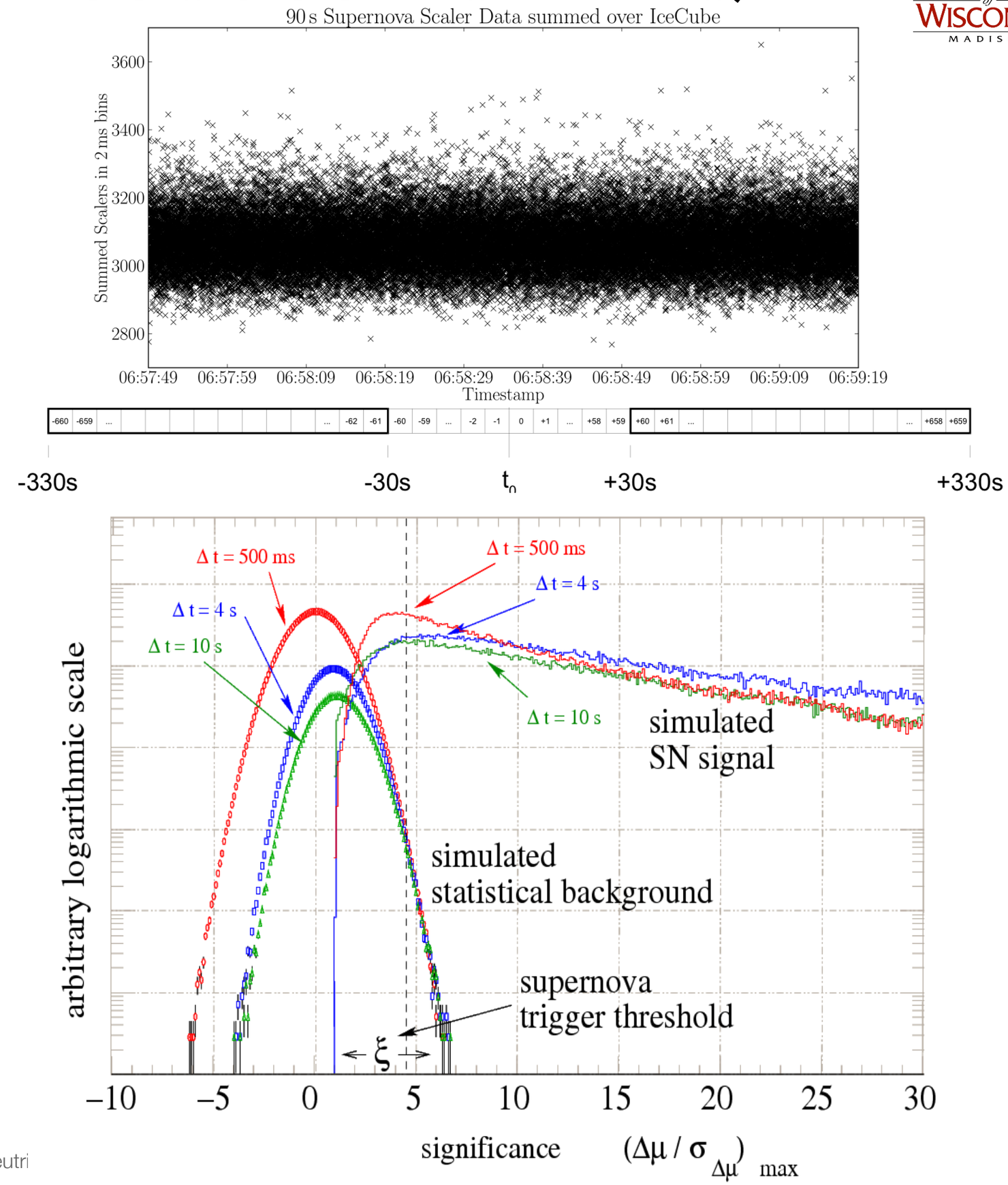
- 60 s central window and ±300 s window for rate estimates
- Log-Likelihood analysis to find $\Delta\mu$ and $\sigma_{\Delta\mu}$ from individual DOM rates (r_i) and their averages ($\langle r_i \rangle$) and errors ($\langle \sigma_i \rangle$)

$$\sigma^2_{\Delta\mu} = \left(\sum_{i=1}^{N_{DOM}} \frac{\epsilon_i^2}{\langle \sigma_i \rangle^2} \right)^{-1}$$

$$\Delta\mu = \sigma^2_{\Delta\mu} \sum_{i=1}^{N_{DOM}} \frac{\epsilon_i (r_i - \langle r_i \rangle)}{\langle \sigma_i \rangle^2}$$

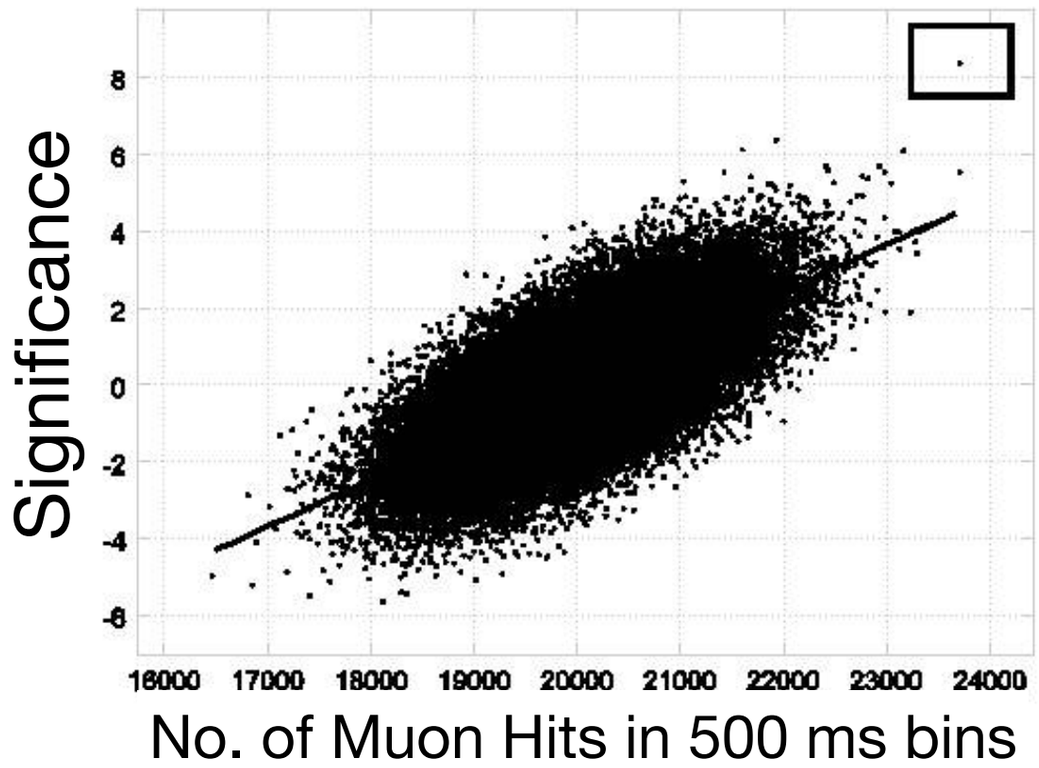
ε - DOM efficiency parameter

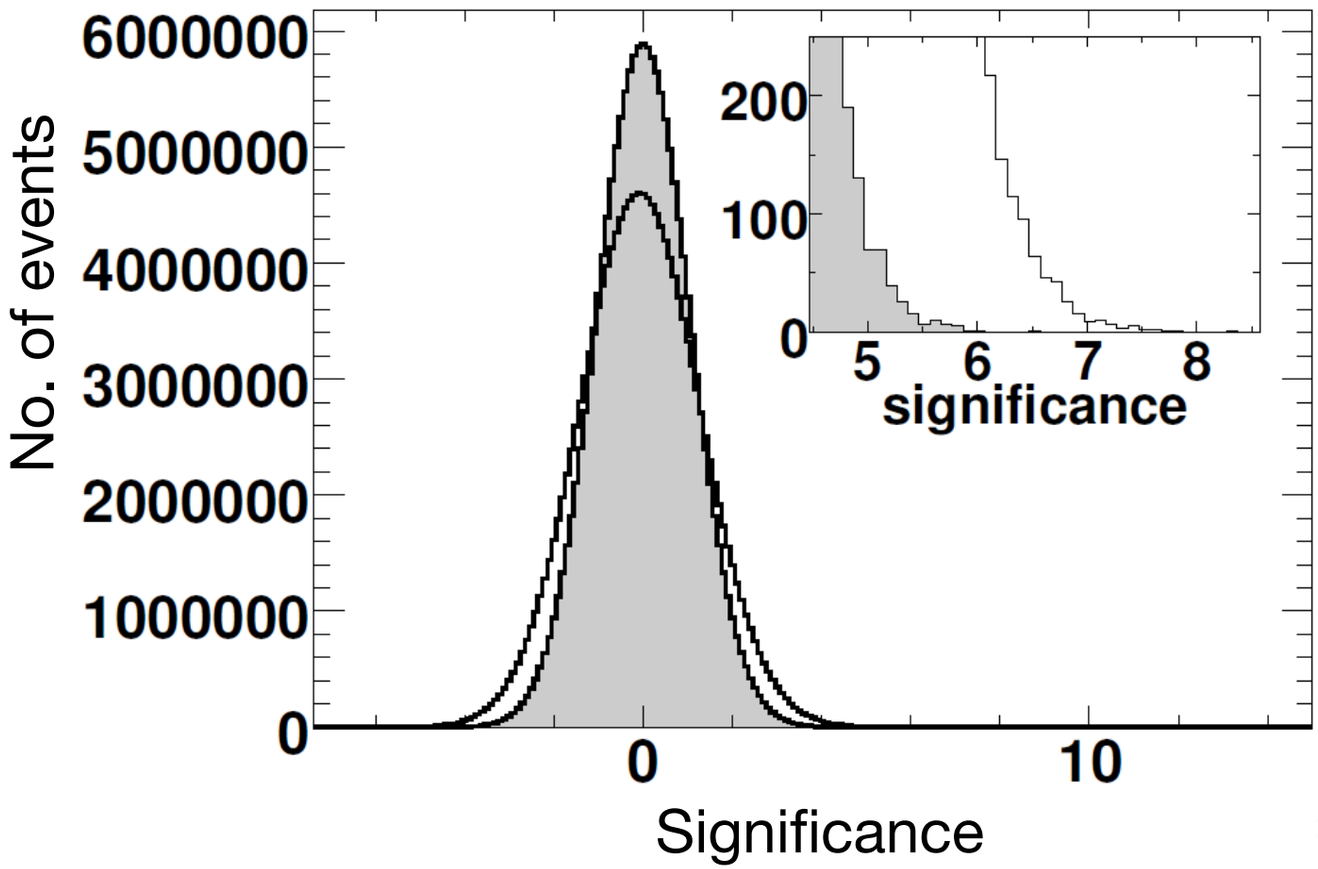
- Significance (ξ) = $\dfrac{\Delta\mu}{\sigma_{\Delta\mu}}$

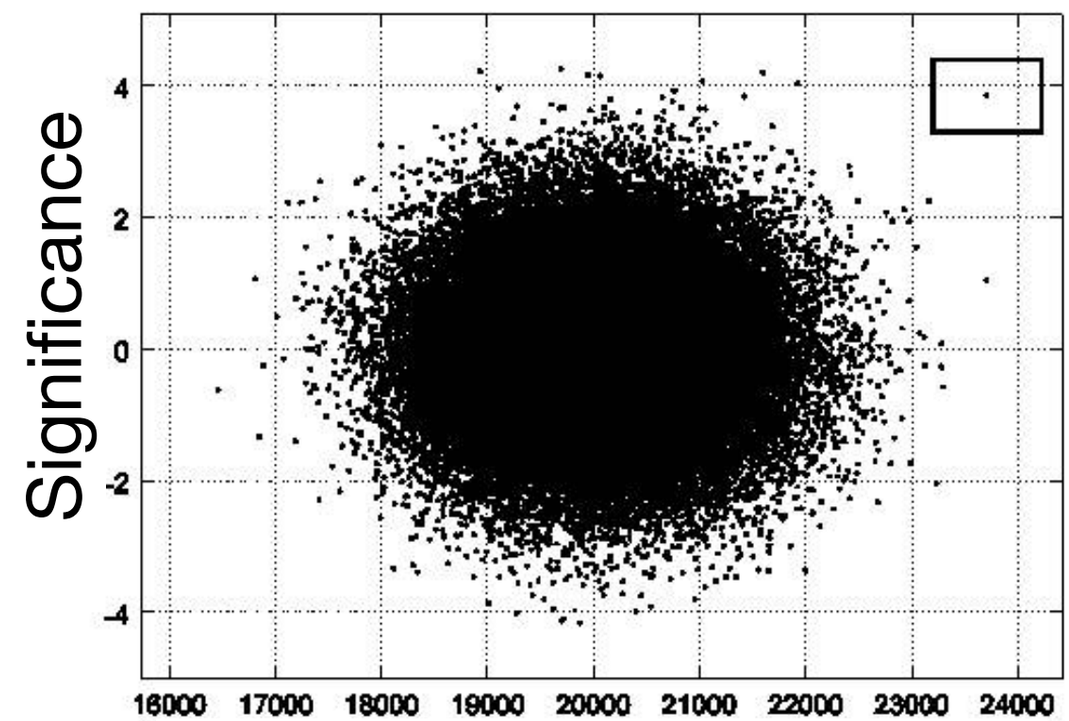


Background - Atmospheric Muons

- DOM-to-DOM correlated noise
- Atmospheric Muons widen the significance distribution
- Example Supernova events with large significance

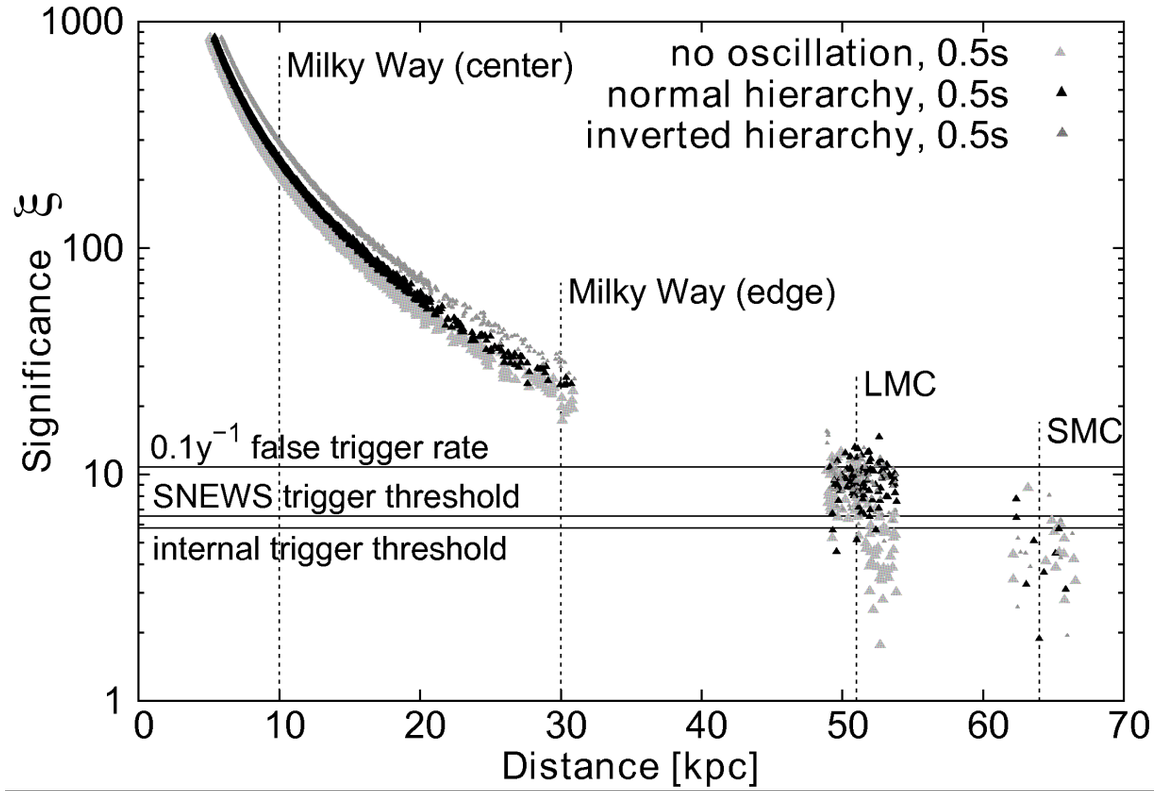


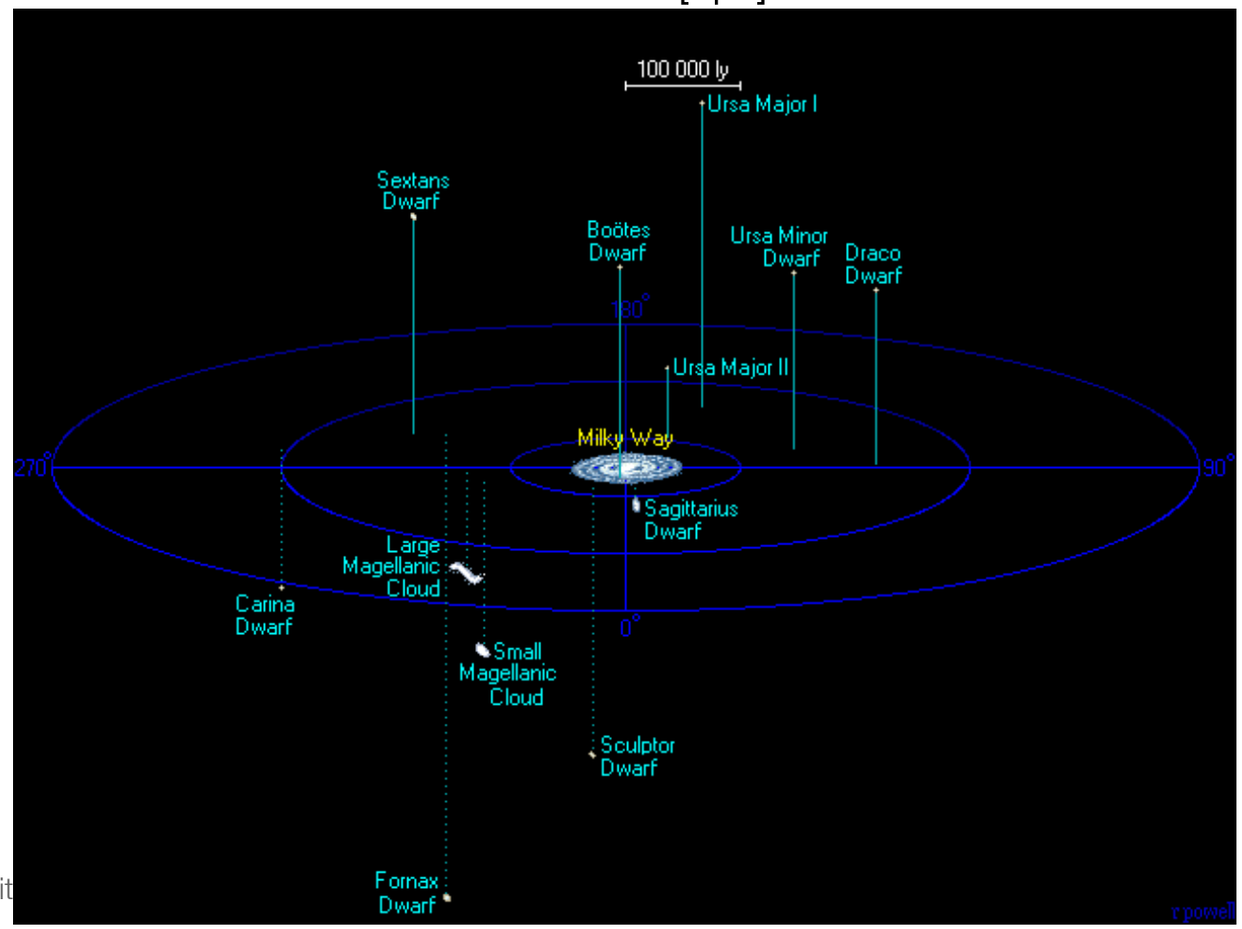




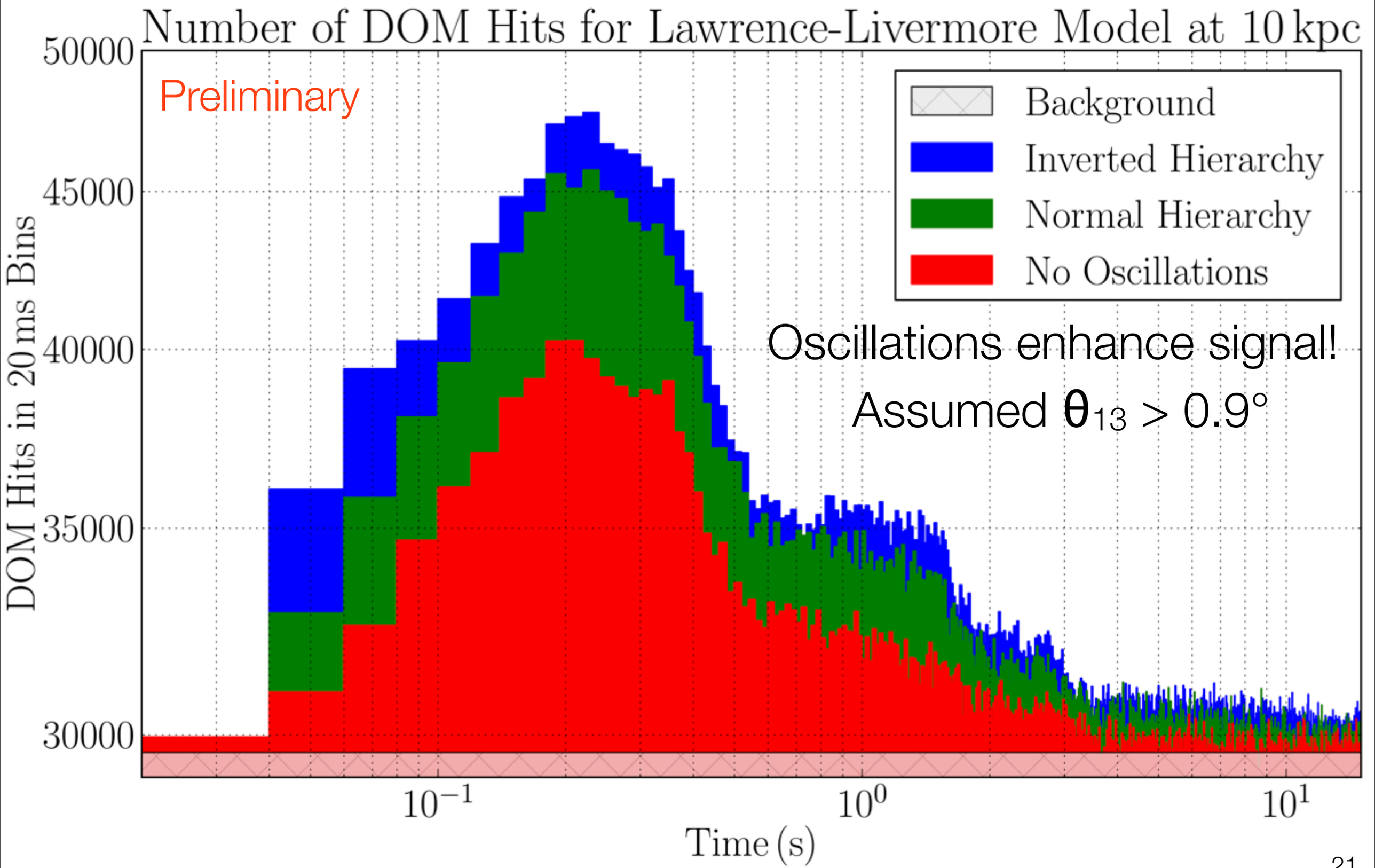
Physics Capabilities - Big Picture

- High detection significance up to edge of Milky Way
  - Detection of “hidden” SN possible
- Significant detection up to the Small Magelanic Cloud possible - ~65 kpc
- SNEWS alerts being generated up to Large Magelanic Cloud - ~ 50 kpc



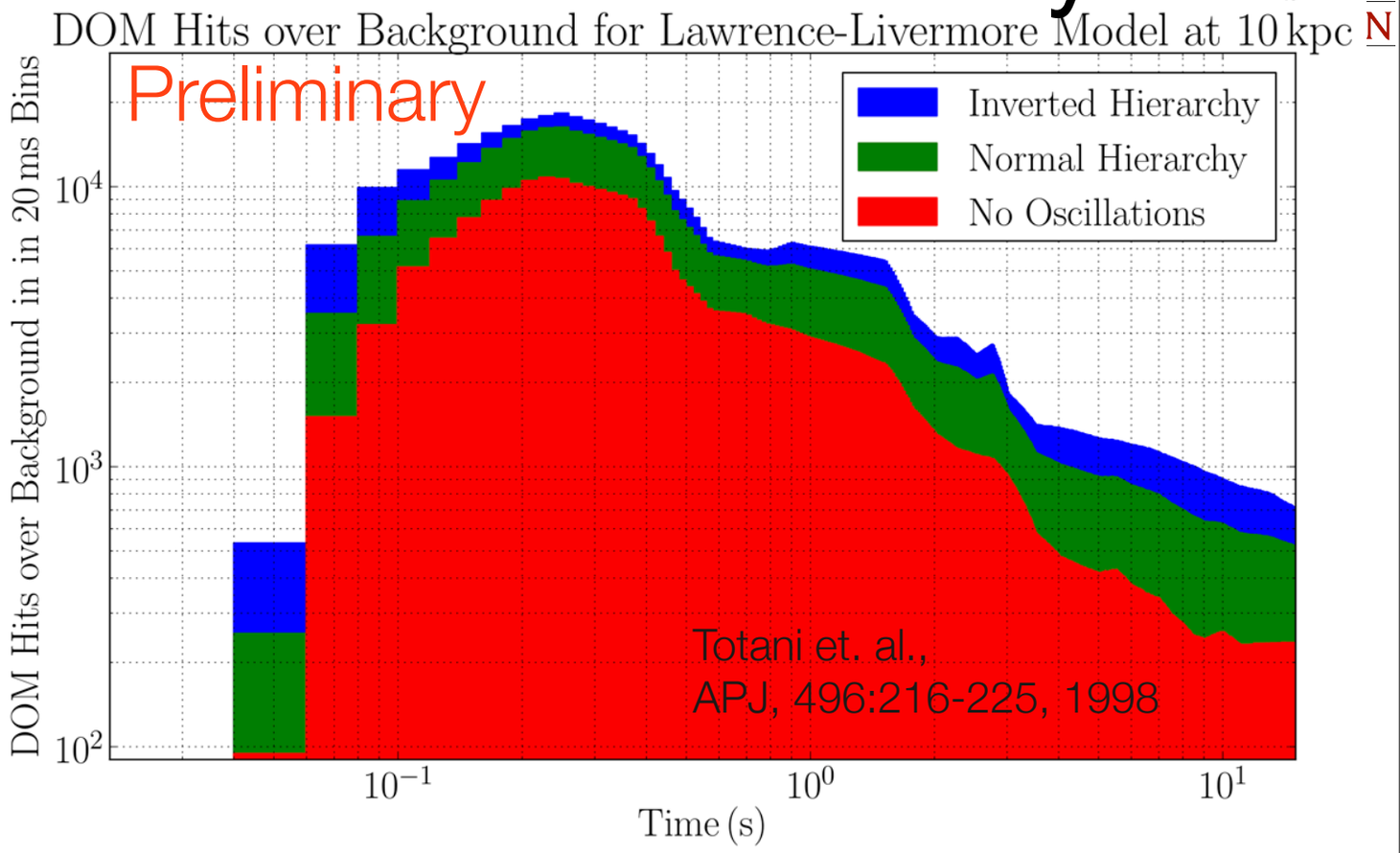


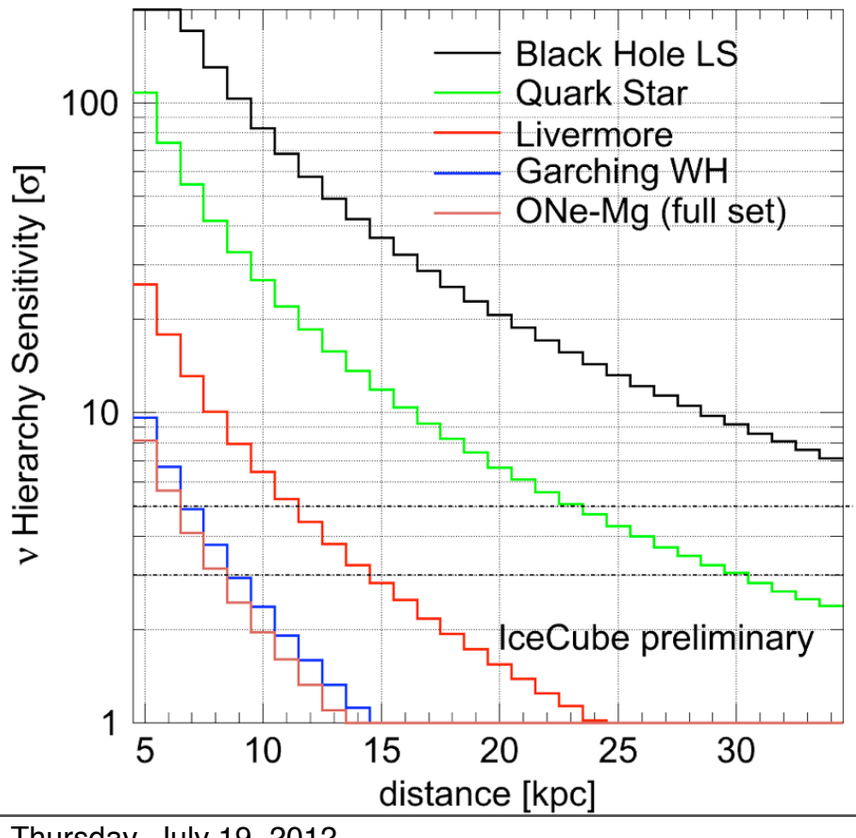
Physics Capabilities - Oscillations



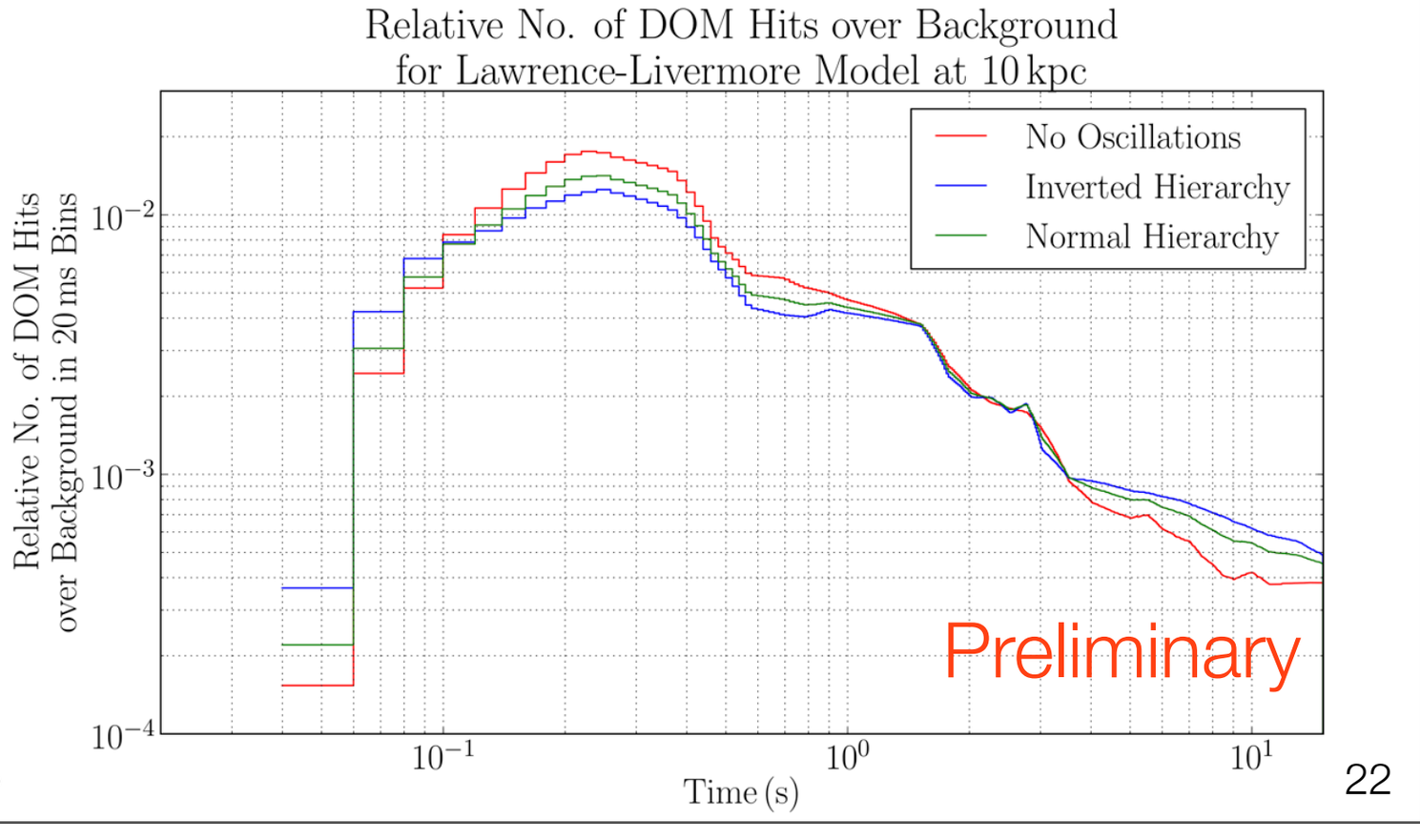
Physics Capabilities - Mass Hierarchy

- Absolute rate and shape difference for normal and inverted hierarchy
- Mass hierarchy at 5σ level is feasible given a well-known flux shape





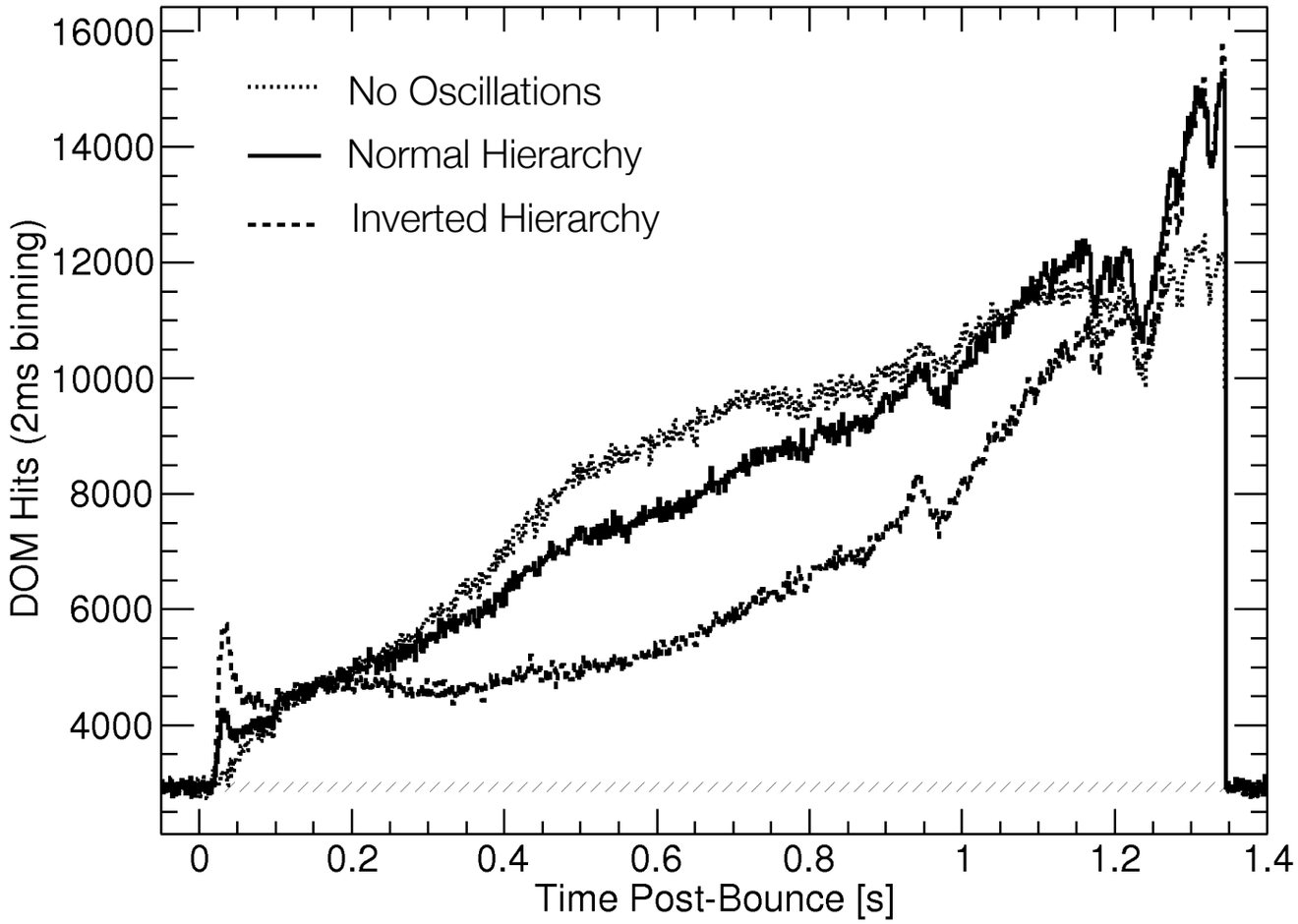
5σ
3σ



a Neutrino

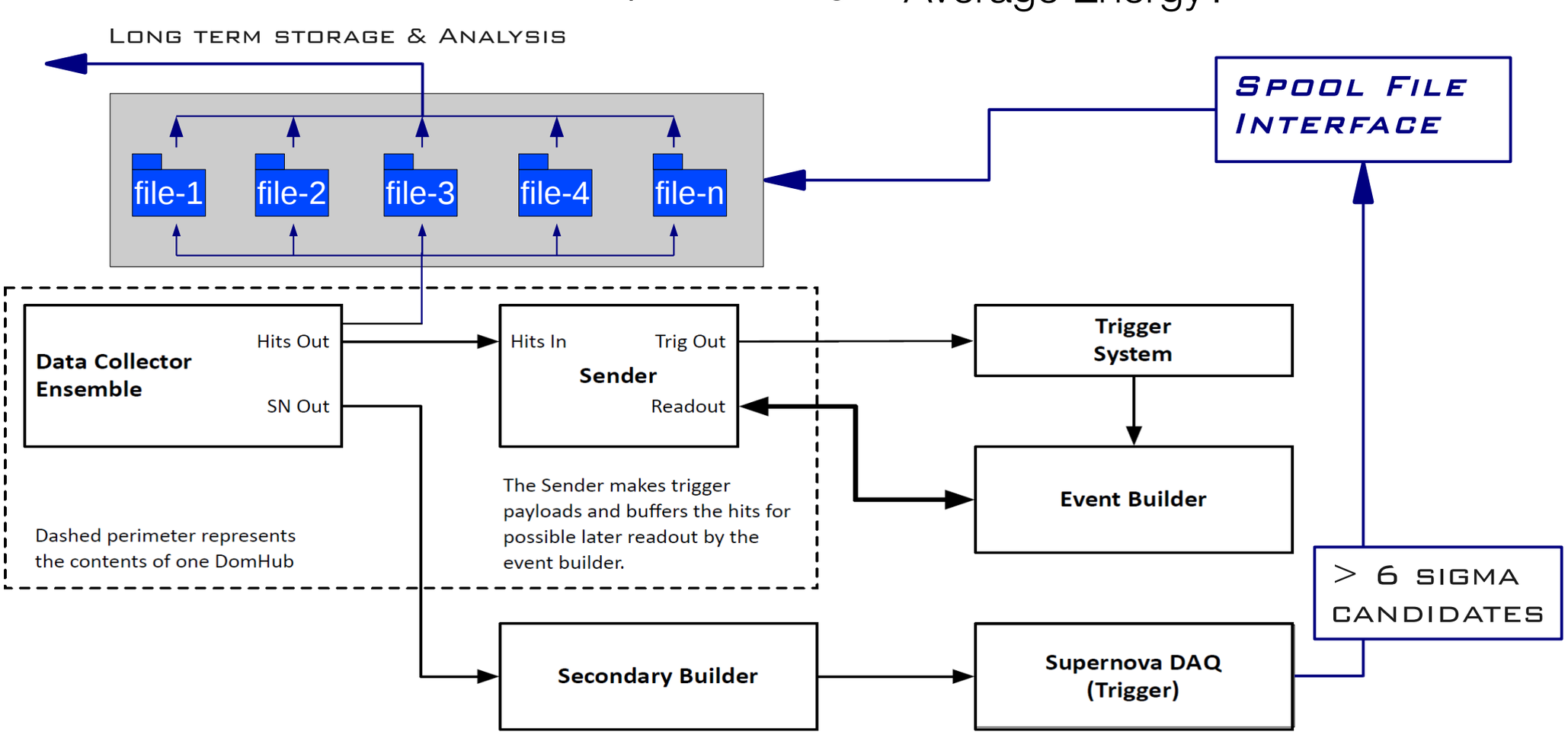
Physics Capabilities - Exotic Signal

- Black Hole formation signal
- No actual explosion
- Strong hierarchy dependence
- High statistics



Future Improvements - Hit-Spooling

- Hit-Spooling
  - All DOM output written to disk
  - DAQ independent software
    - Increase in uptime
    - Worse-case scenario backup
- Capabilities
  - Better timing resolution for some cases
  - Better detector monitoring
  - Background Monitoring and Reduction
  - Coincident Hit Method
    - See Ronald Brujin's talk
    - Average Energy?



Future Improvements - New Simulation

- Current Simulation
  - Multiple separate simulations used to parametrize the detector response
  - Advantage: Fast
  - Disadvantage
    - Can only handle supernova signal
    - Cannot model atmospheric muon background fully

Signal Simulation
+
Photon Yield per Particle
+
Photon Propagation Parametrization
+
DOM Parametrization
=
Supernova Simulation

- New Simulation
  - From scratch development
  - Better physics treatment
    - Angular distribution of interactions
    - DOM-to-DOM correlation studies
  - GEANT4-based particle propagation
  - In-house direct OpenCL-based photon propagator
  - Integrated into centrally maintained IceCube Software and Simulation Framework
  - Able to handle supernova and background signals

Signal Simulation
+
GEANT4
+
Direct Photon Propagation
+
DOM Simulation
=
New Supernova Simulation

Conclusion

- Detector is stable with 98% uptime
- Things to look forward to
  - Future improvements to detector stability and detector understanding
  - Improved simulation
  - Complete detector information available
    - Energy determination
    - Better background rejection
  - The next galactic Supernova!

Courtesy of Sven Lidstrom and Carlos Pobes

BACKUP SLIDES

Movie III

High energy neutrino induced cascade

from August 9th 2011

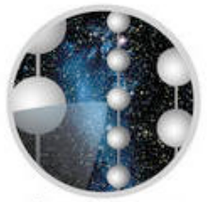
DOM Colors represent arrival times

Red - Early

Green/Blue - Later

DOM Size represents amount of deposited charge

Order of 1 PeV in Energy


IceCube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