GeV-scale Physics in the South Pole Icecap

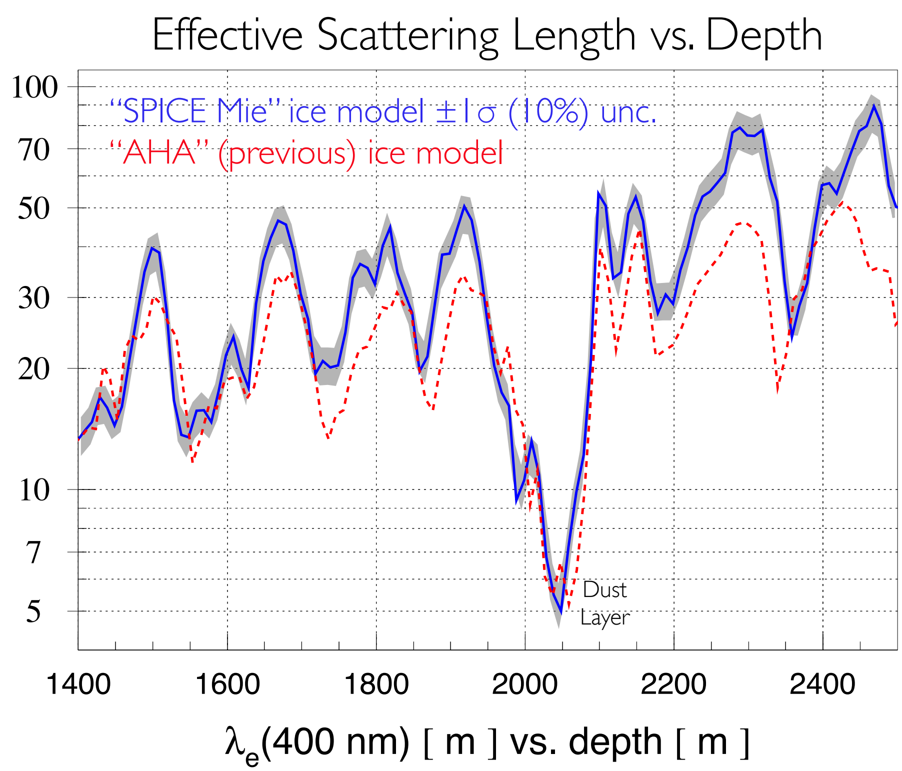
Baryon Number Violation Workshop
Intensity Frontier
Argonne National Laboratory
25-27 April, 2013
Doug Cowen

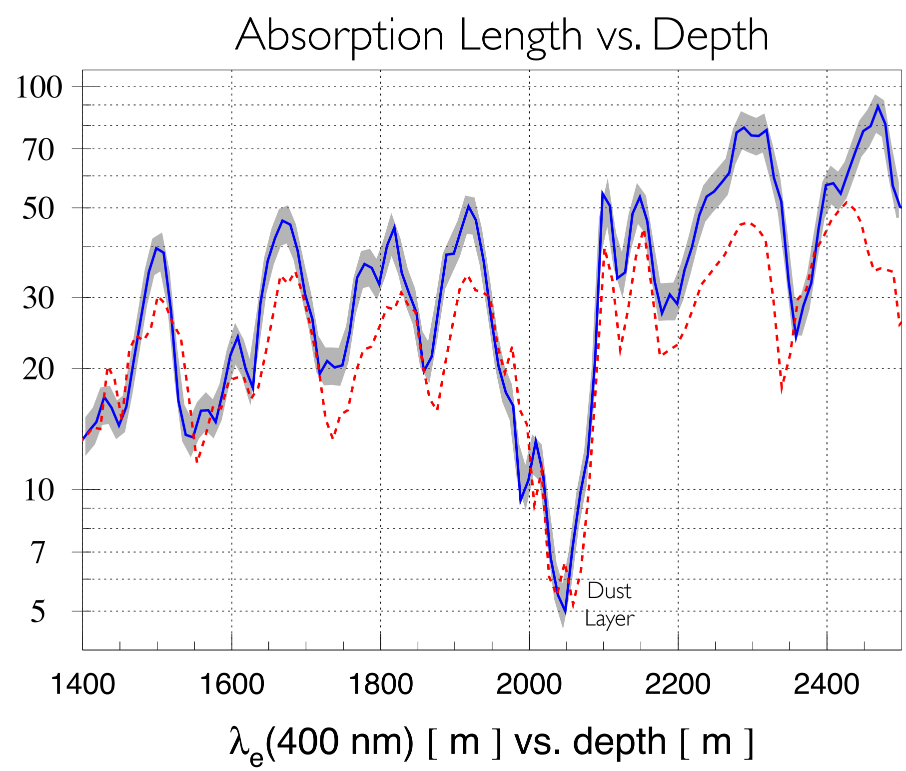
Outline

- Advantages of South Pole ice
- IceCube and its low-energy extensions
- Very preliminary ideas for MICA (Megaton-scale Ice Cherenkov Array)
  - possible geometries, photon detectors
  - very crude time scale and cost estimates
  - proton decay
  - supernova neutrino burst detection

Advantages of South Pole Ice

- Extremely clear medium for Cherenkov light
- No cavities to carve out of rock: big cost savings
- Melting deep holes is well understood technology
- Excellent infrastructure at South Pole

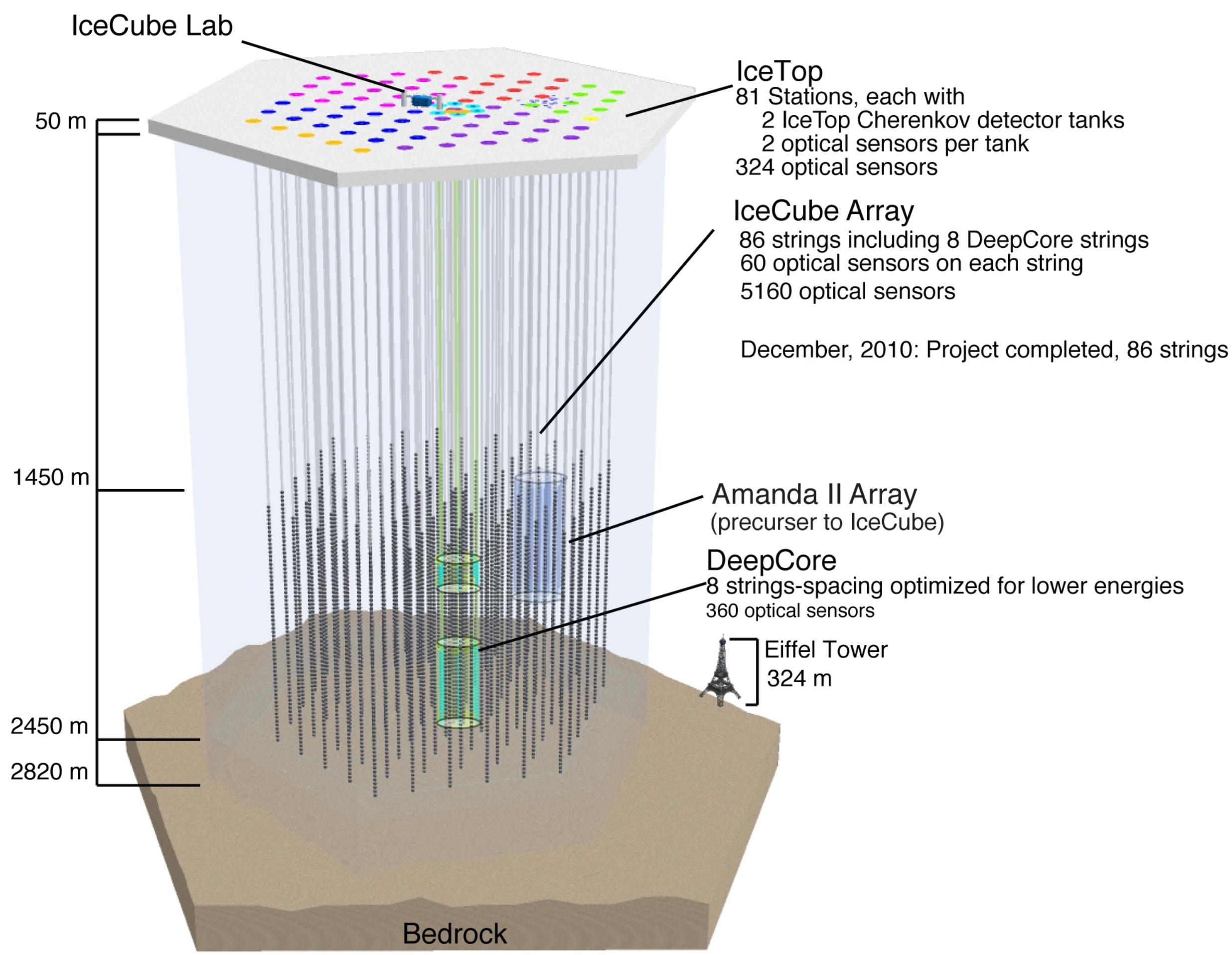




arXiv:1301.5361

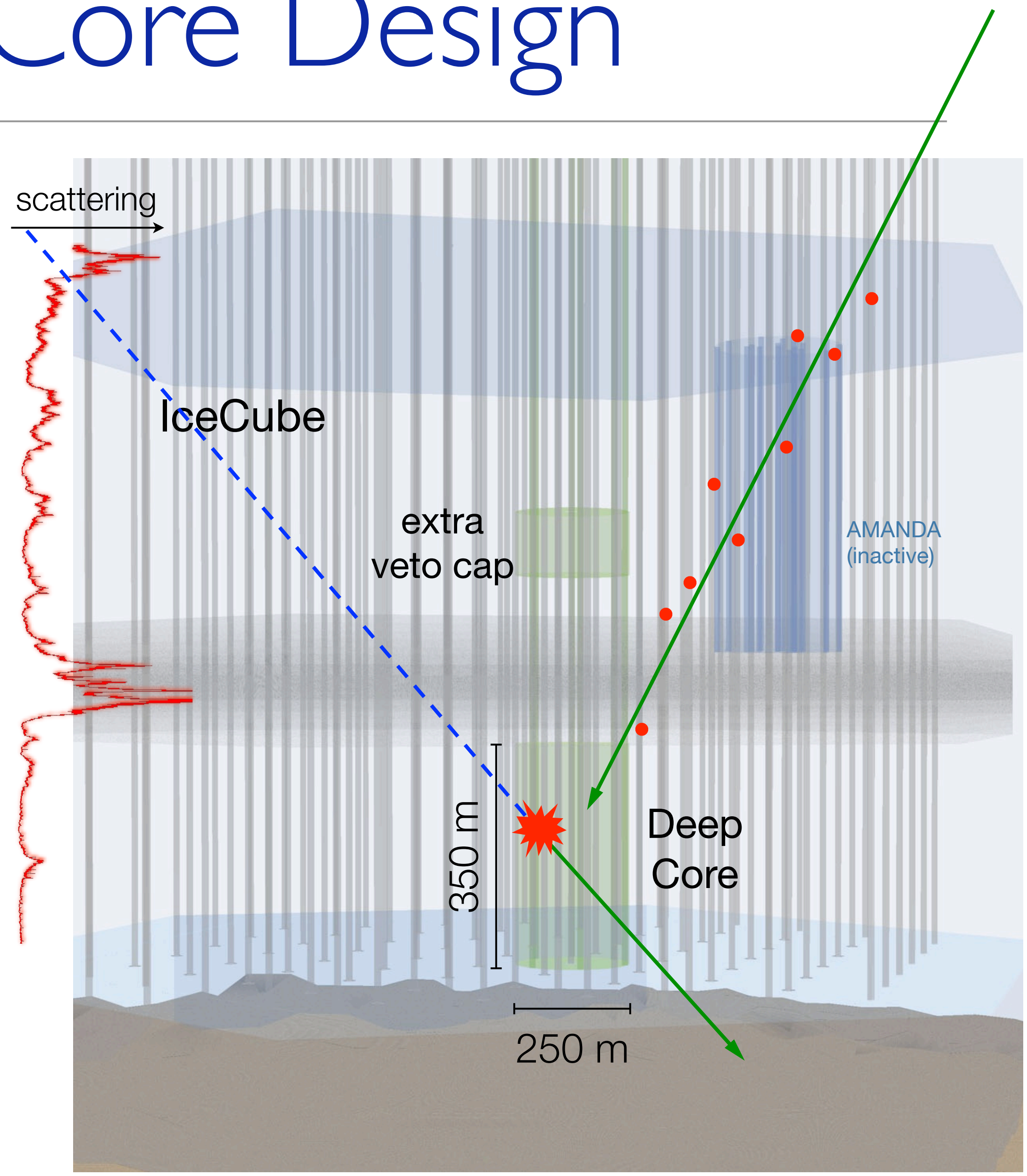
IceCube/DeepCore

- Original IceCube design focused on threshold of $E_\nu >$ few 100 GeV
- DeepCore has lower threshold ($E_\nu > \sim 10$ GeV)
  - in a reduced volume
- Expect $\mathcal{O}(10^5)$ atm. ν triggers per year
  - big increase at low E_ν



IceCube/DeepCore Design

- High module density region at bottom center of IceCube
  - in very clear ice
    - λ_{eff} ~50m
    - λ_{abs} ~150m
  - surrounding IceCube employed as an active veto against downward-going cosmic ray muons
    - Note: any future detector situated in this region can also use DeepCore as a veto

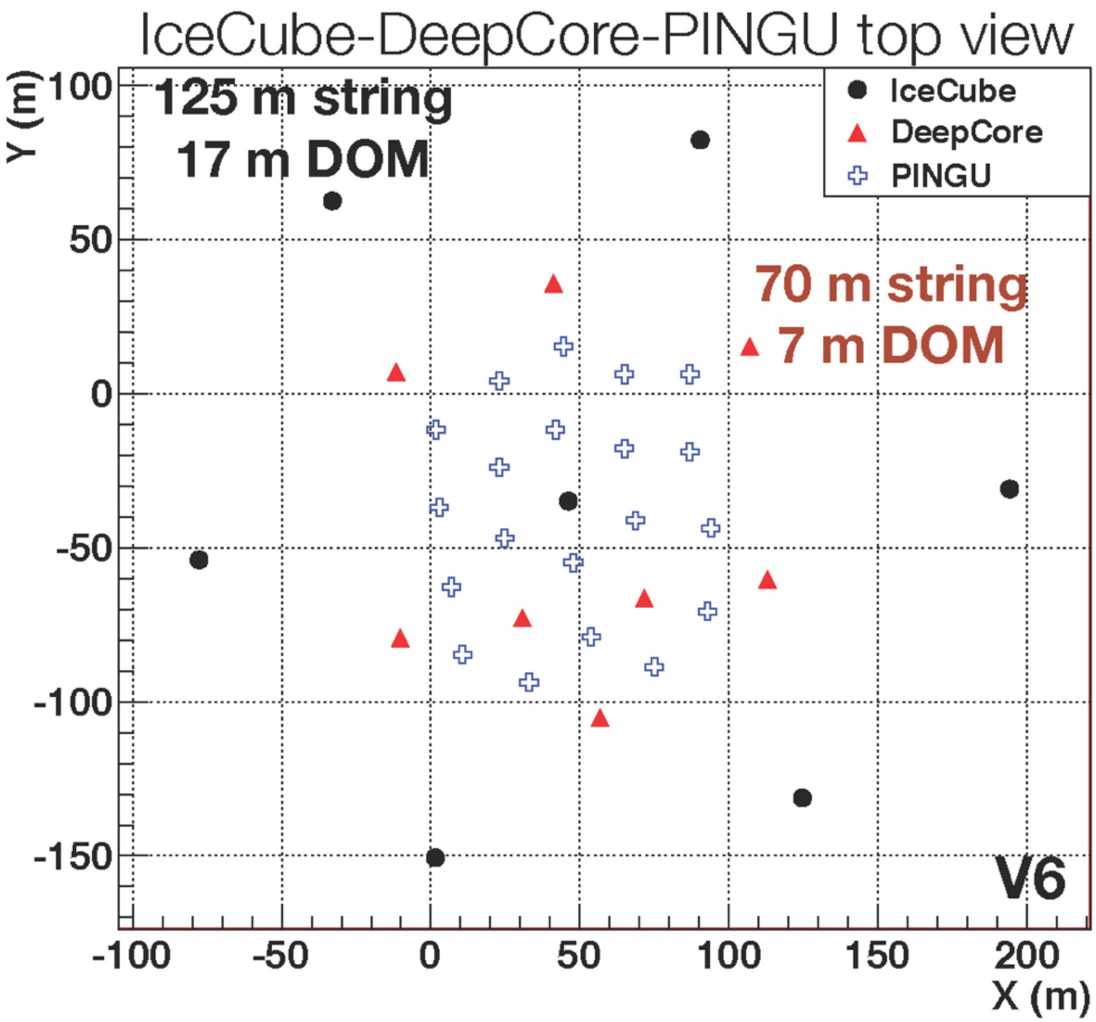


IceCube/PINGU

- Precision IceCube Next Generation Upgrade (PINGU; to be proposed)
  - in-fill array within DeepCore
    - reach few-GeV E_ν threshold
    - standard IceCube Digital Optical Modules (DOMs) for light collection
  - primary goal
    - measure neutrino mass hierarchy with atmospheric neutrinos
  - secondary goals
    - WIMP searches, neutrino oscillations, earth tomography...
  - tertiary goal
    - pathfinder for new detector technology for MICA

IceCube/PINGU

- Geometries being studied
  - 20 strings, 60 modules @ 5m vertical (see fig.)
  - 20, 100@3
  - 40, 60@5
  - 40, 100@3
- Timescale
  - 2yr prep., 2(3)yr deployment, start data taking early 2018(2019)



MICA: Megaton-scale Ice Cherenkov Array

A Possible MeV-GeV Detector in the Ice

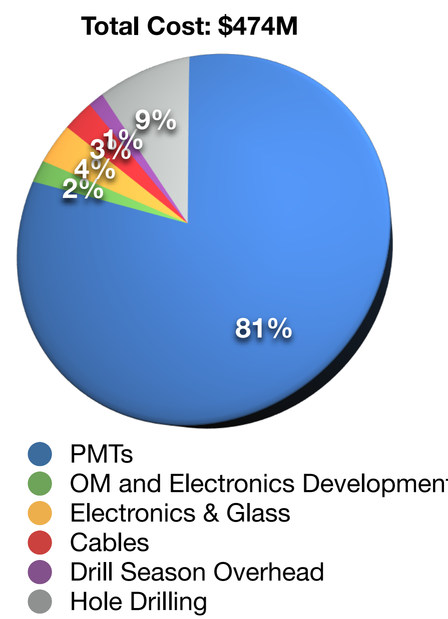
- We present here *plausibility* arguments, not detailed simulation results
  - Construction, Logistics, Schedule:
    - IceCube has demonstrated high-speed hot water drill capable of 20 holes per season & managed challenging South Pole logistics
  - Cost:
    - Detection medium is the support structure
    - Driver is photocathode, not civil engineering
- Fundamental question: How much information can we extract from the ice? Ballpark numbers:
  - For EM showers, expect ~100,000γ/GeV → ~1000γ/GeV @ 1% coverage
  - Reduced by ~5x due to glass, QE, etc. → ~200p.e./GeV
    - Further reduced by impact of scattering
    - Super-K sees 5p.e./MeV @ 40% (5,000p.e. for $p \rightarrow e\pi^0$, and scattering is less of an issue)
  - (We make no claims about being able to reconstruct events @1% coverage!)

Strawman MICA: Photocathode Coverage

- Run some numbers to set the scale for possible detectors
- Back-of-the-envelope sub-sub-optimal strawman using existing technology, IceCube-like effort (~5 yrs deployment) & expense (~$200M, exclusive of personnel):
  - 60 strings each with 120 IceCube 10" PMT DOMs
    - 3 m vertical DOM spacing: 360 m long strings
    - 5 m horizontal string spacing
  - r = 50 m cylindrical geometry
    - N.B.: no top or bottom caps
  - surrounds ~3 MTon of ice
- Gives ~0.3% photocathode coverage ($A_{photocathode}/A_{cylinder}$)

Strawman MICA: Photocathode Coverage

- "Anything worth doing is worth overdoing."
- Could reach ~10% coverage over 1Mt with
  - 140 strings
    - 6.8m horizontal spacing
    - r(array) = 40m, h(array) = 221m
    - ~7 year deployment timescale
  - 130 modules per string
    - basically a continuous line of photodetectors
  - 60 3" PMTs per module ($330/PMT)
    - 1 MegaPMT
- Cost: ~$500M
  - *strongly* dominated by cost of photocathode



MICA Photon Detectors

- Back to the real world...sort of...
- Co-deploy few R&D modules with PINGU
  - composite multi-PMT DOMs
    - see next slides
  - wavelength shifter optical modules (WOMs)
    - see next slides
  - hybrid PMTs?
    - standard Hamamatsu PMT with silicon replacing dynode structure
    - substantial cost savings, but is performance adequate?
  - LAPPDs? (LANPDs???)
    - Large Area Pico(Nano*)second Photon Detectors
    - Consortium headquartered at Argonne
- Ideally, want a continuous line of detectors in each drilled hole
- *New, cheaper photon detectors would be a game-changer*

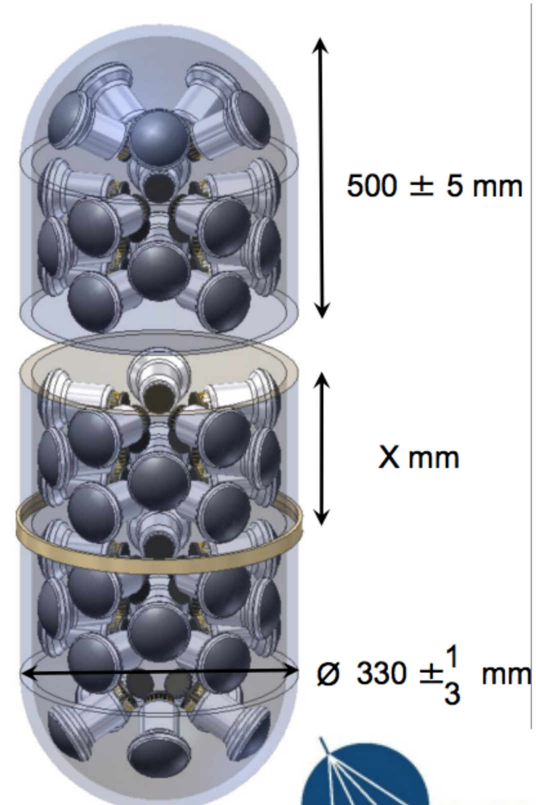
*MICA would be happy with ns resolutions

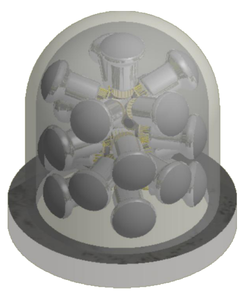
Composite DOM

- Cylinder with ~60 3'' PMTs and electronics; single connector
  - Effective photocathode area >6x that of a 10'' PMT
  - Diameter comparable to IceCube DOM so drilling requirement would be similar
  - Design study underway (NIKHEF and Erlangen)


Existing KM3NeT Design

P. Kooijman, NIM A567 (2006), S. Kuch NIM A567 (2006), KM3NeT TDR



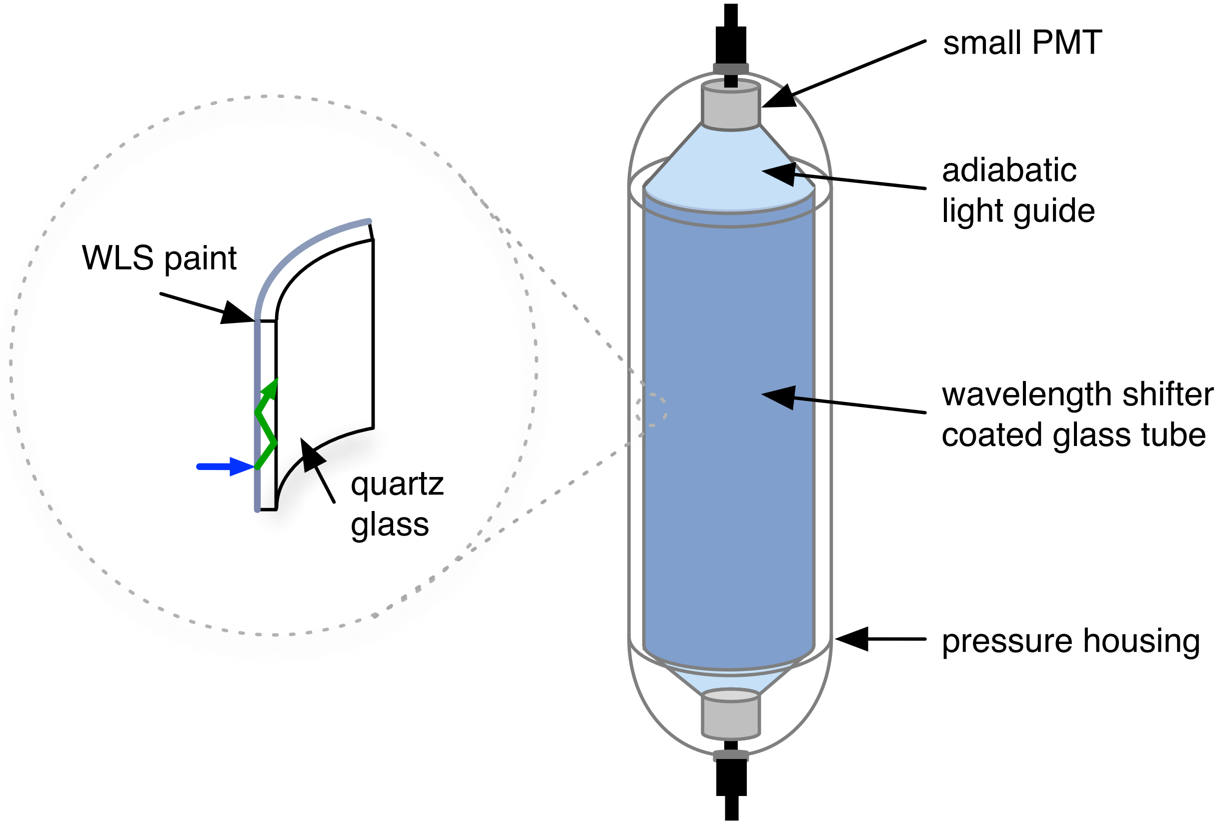



Prototype cylinder

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Wavelength-shifter Optical Module

- WOM
  - large collection area
  - low noise rate (few Hz)
    - big advantage for SNe
  - better UV sensitivity
  - cost effective
  - but: somewhat slower response time
- Prototype under development at U. Bonn

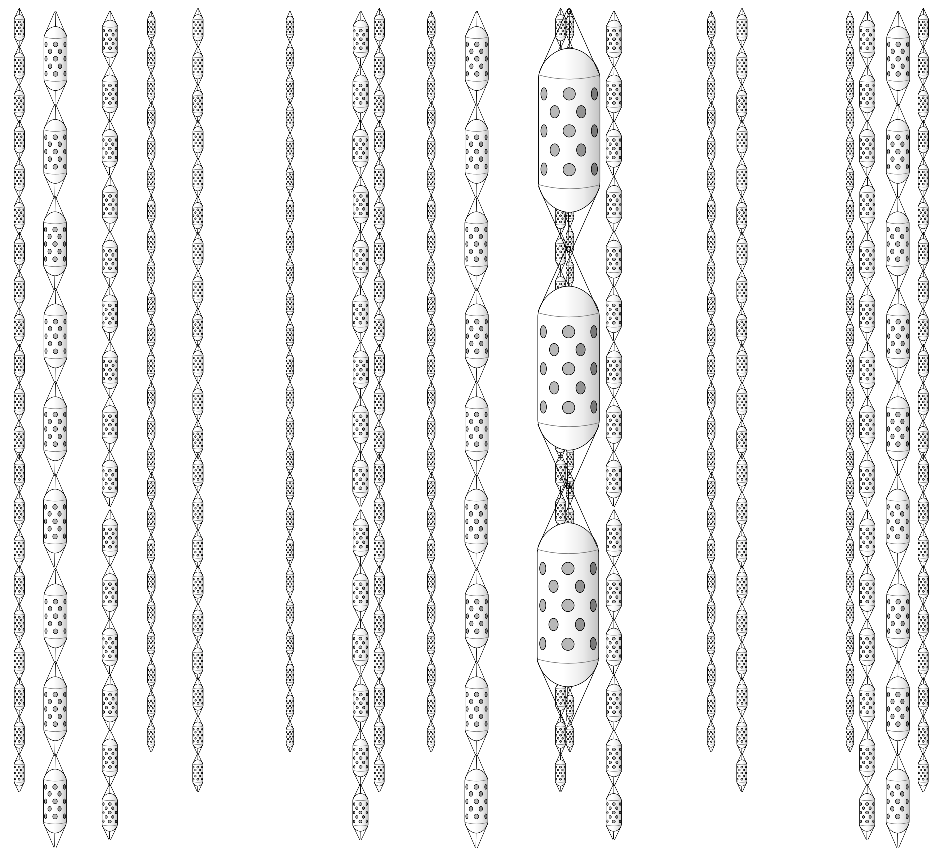


Module	Mean QE [%]	λ_{peak}[nm]	Aeff [cm^2]*	Noise [Hz]
WOM	1.5	370	100-150	~10
IceCube DOM	7.10	420	18	800

*Includes glass transmission, ang. acceptance, and PMT eff.; λ>300nm

Continuous Line Detectors for MICA

- Composite DOMs might be rather pricey
- WOMs alone have nice price point but timing resolution may be inadequate (for proton decay)
  - needs simulation studies
- Combine the two as a hybrid detector?



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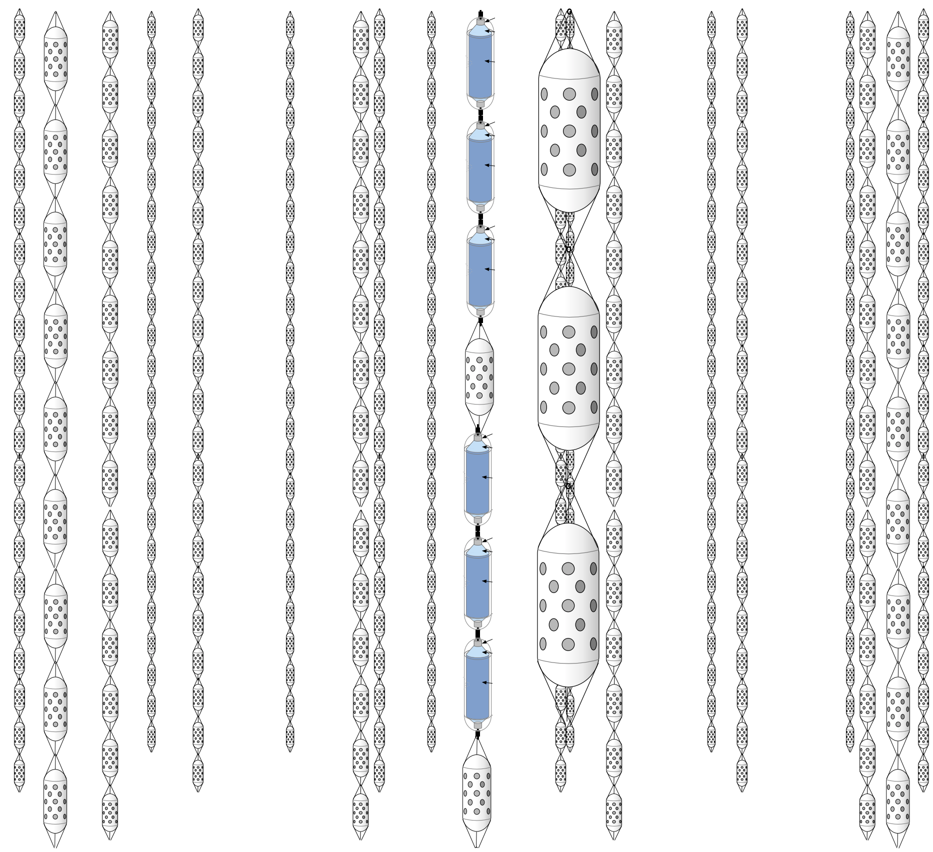

Continuous Line Detectors for MICA

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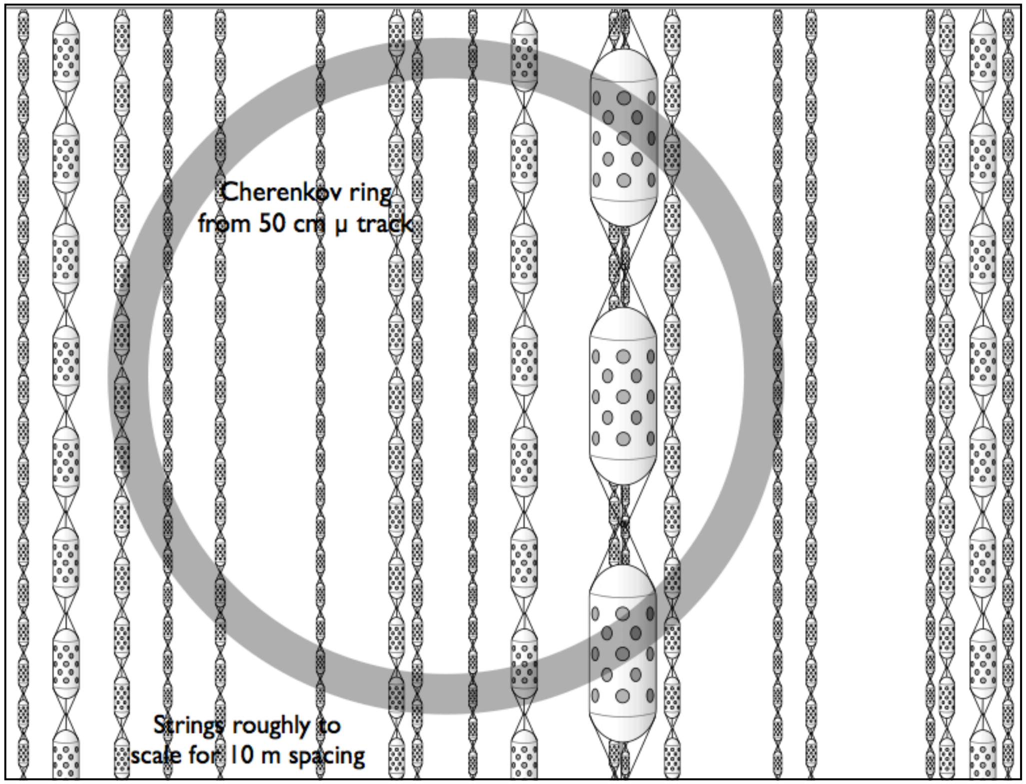
- Combine the two as a hybrid detector?
  - timing from composite DOM
  - calorimetric energy measurement from WOM



MICA Physics

- Proton Decay
  - Need to move to the Mton scale to reach $\tau_p \sim 10^{35\text{-}36}$ yr
- Simulation work has only scratched the surface
  - IceCube's low energy contingent is focused on PINGU now
  - Interested parties are welcome to contribute to MICA simulation studies!
    - With IceCube "Associate Membership," gain access to all our software and you'll produce interesting results in no time!

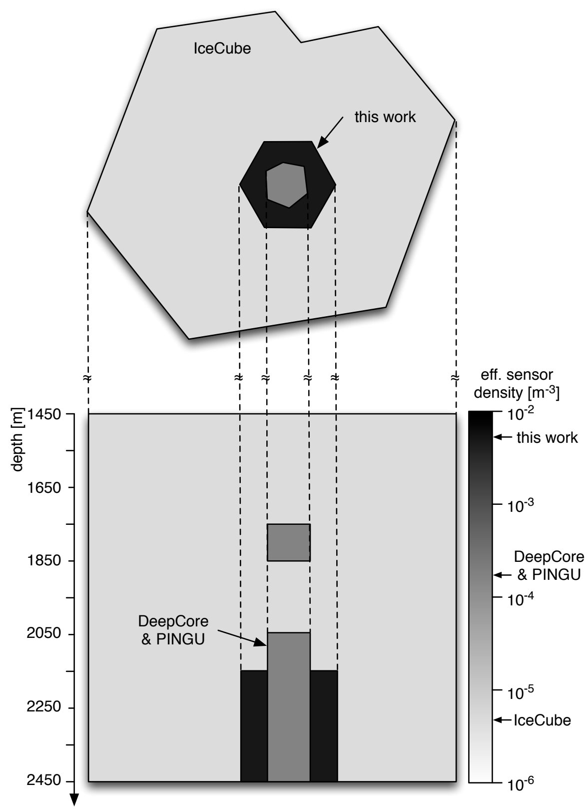
MICA' Physics

- Supernova neutrino burst detection
  - Current detectors sensitive to galactic SNe (1-2 per century)
  - To reach >1 SNe/yr need
    - ~5 Mton fiducial volume
      - Bigger than what we described earlier
    - ~10 MeV threshold
  - To beat down noise from solar & atm. ν, Michel e^-, intrinsic PMT, require:
    - >= 5 hits per event
    - >= 3 events in 10 seconds
    - ~30° directional resolution (reject solar ν)

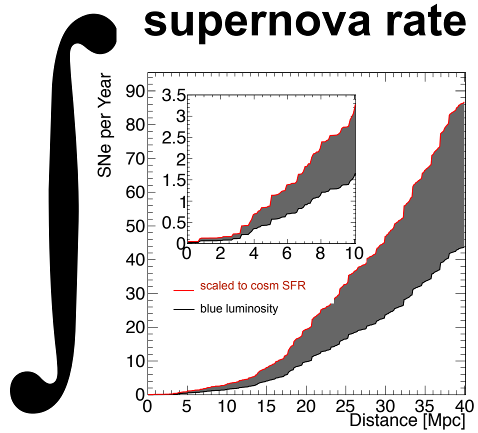
[S.Boeser et al., arxiv:1304.2553]

MICA' Physics

Rough idea of 10 MTon detector layout

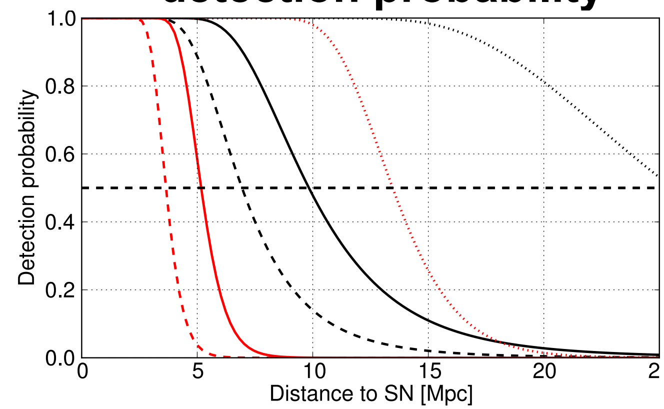


supernova rate



$\otimes$

detection probability



d[Mpc]

=

observed SNe / year

Model	$N_\nu \geq 3$	$N_\nu \geq 10$
LL	2.34	0.55
TBP	1.13	0.26
Dark SNe*	2.03	0.34
Sum**	1.5 - 8.6	0.6 - 1.8

*Dark SN rate assumed to be 10% of total

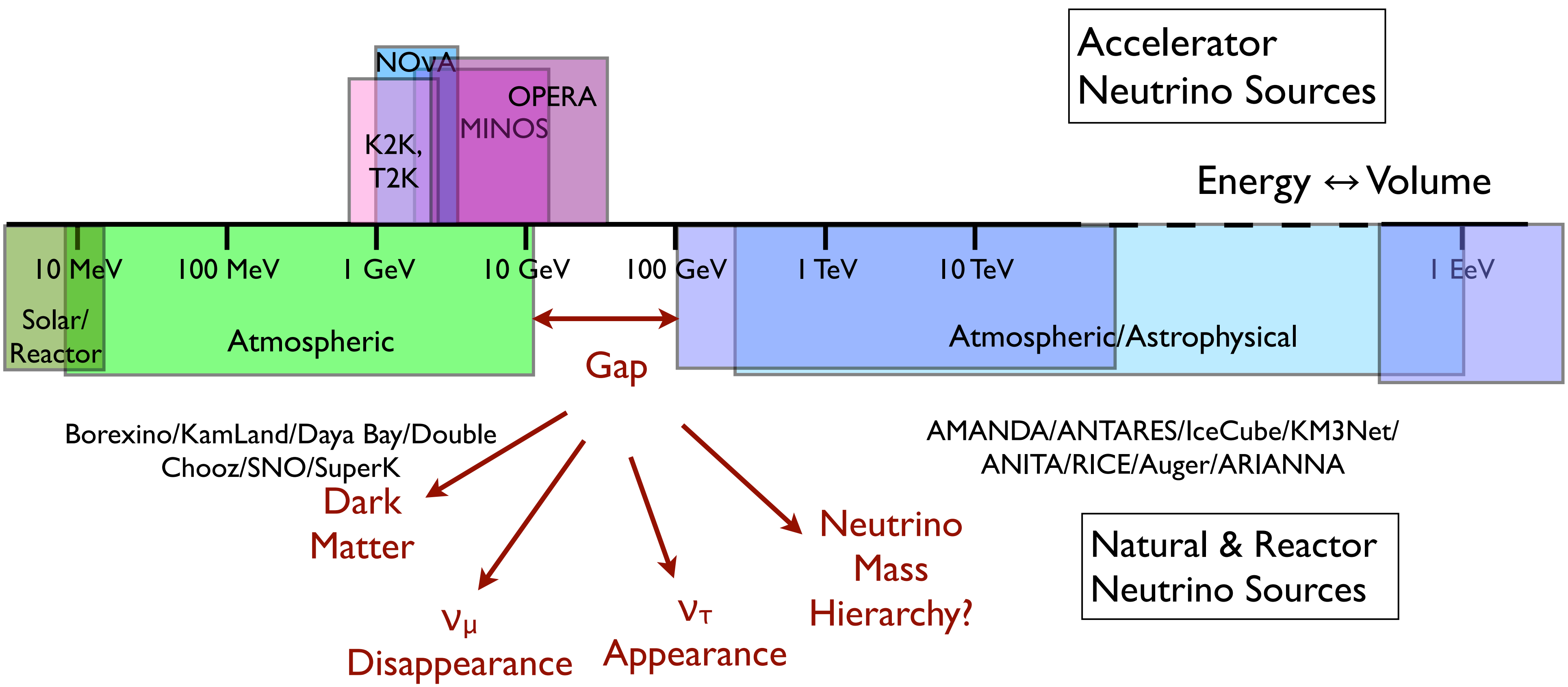
** cosmic SFR (Star Formation Rate)
2x cosmic SNR (Supernova Rate)

Conclusions

- A megaton-scale detector can be constructed in the ice at very competitive cost
  - a significantly cheaper alternative to the venerable PMT would be a real game-changer
    - for a technology at, say, 1/3 the cost of PMTs, get 1MTon for ~$250M
- Physics goals of proton decay and SNe neutrino burst detection may be attainable (but perhaps not simultaneously?)
- Much more simulation is needed to address questions such as
  - best geometry (volumetric? cylindrical? hex-cell?)
  - required photocathode coverage
  - requirements for module performance

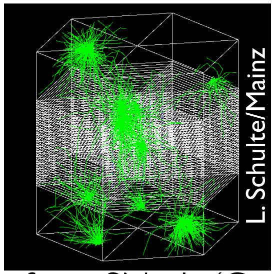
The End

The Neutrino Detector Landscape



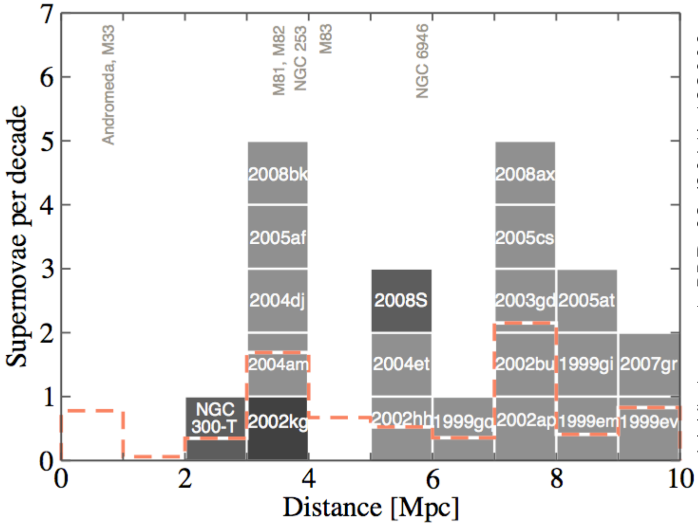
** boxes denote primary detector physics energy regimes and are not absolute limits*

MICA: Supernovae

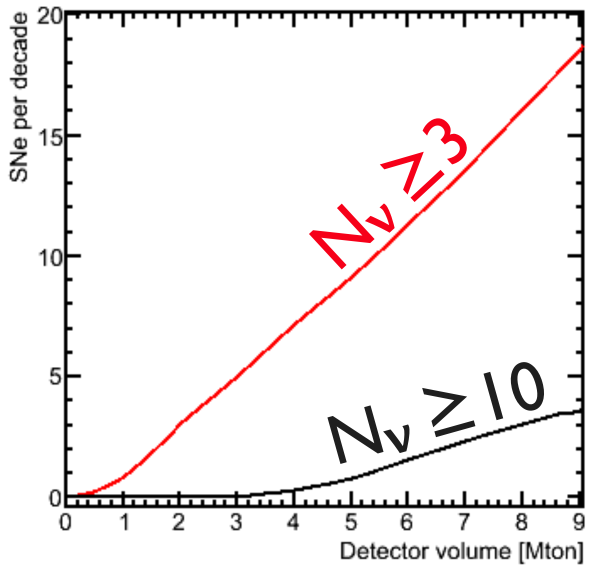


γ's from SN ν's (Geant4)

- SN neutrinos at 10-20 MeV would produce 2000-4000 Cherenkov photons:
  - Even few percent photocathode coverage enough to see a single SN neutrino
  - A burst of >=3 neutrinos in 1-10s would be above atmospheric neutrino background
    - Have not yet looked at spallation daughters
  - A ~5 MTon detector could see to ~10Mpc
    - Roughly annual supernova neutrino detection!
  - Other benefits:
    - Early triggers for optical telescopes
    - ...and gravitational wave detectors: bkgd. reduction ~10^6; signal enhancement ~1000x
  - Caveats: LOTS of uncertainties (reconstruction, particle ID, spallation rejection...)



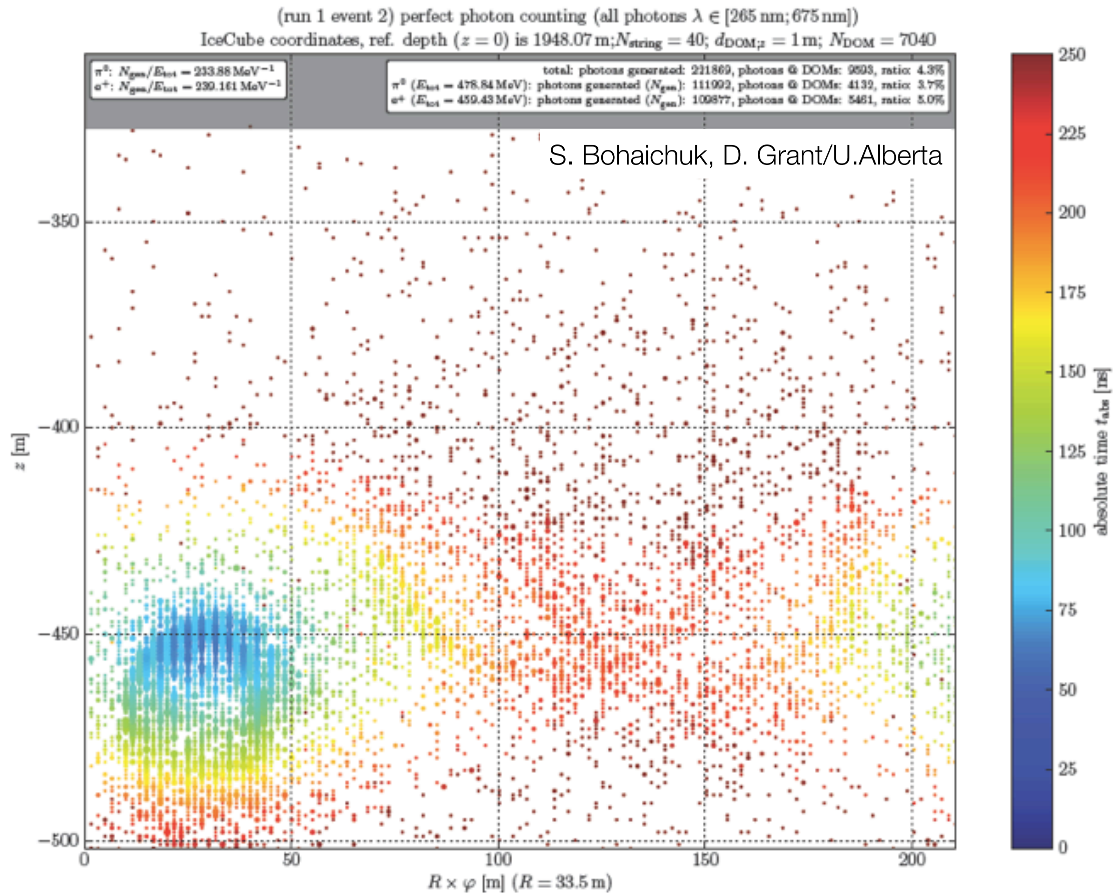
M. Kistler et al., PRD 83 (2011) 123008



M. Kowalski/Bonn

MICA: Proton Decay

- Very challenging. To beat backgrounds from atmospheric neutrinos and muon spallation products one needs:
  - energy (momentum) resolution
  - particle ID via Cherenkov ring reconstruction
  - high photocathode area
- Simulations in infancy



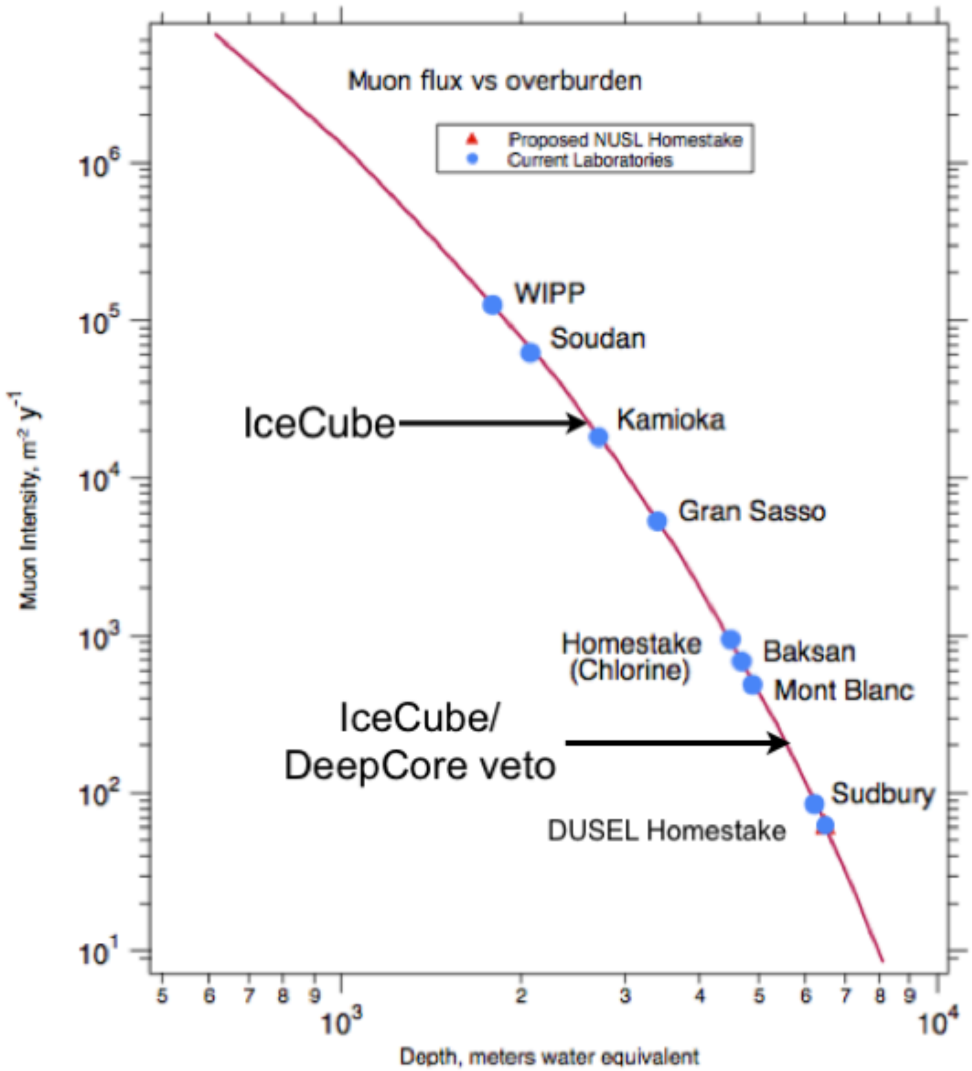
$p \rightarrow \pi^0 + e^+$

Idealized

1.5 MTon (5x10^{35} protons),
10 MeV threshold,
240 photons/MeV,
5% photons detected,
NO scattering

Muon Flux vs. Overburden

- Active veto translates to greater effective depth



Supernova Detection Probability