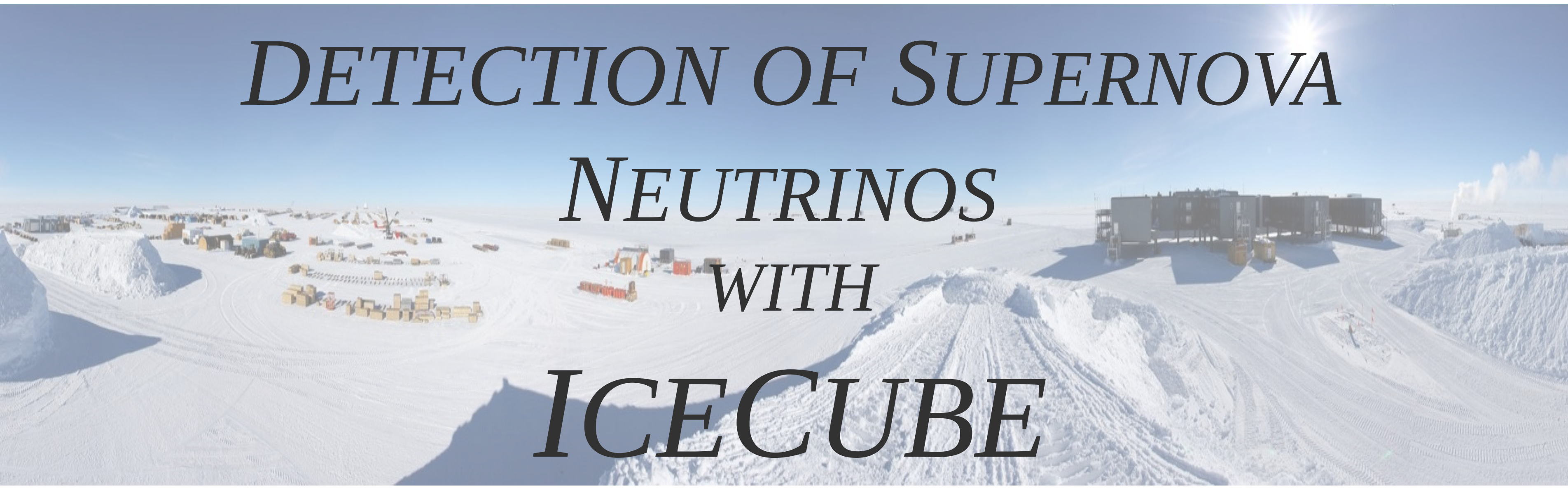
DETECTION OF SUPERNOVA NEUTRINOS WITH ICECUBE



David Heereman for the IceCube Collaboration
IIHE Internal Seminar

Outline

Supernovae & Neutrinos

The IceCube Detector

Noise Properties

SN Neutrino Interactions in Ice

Detection of Cerenkov Photons in IceCube

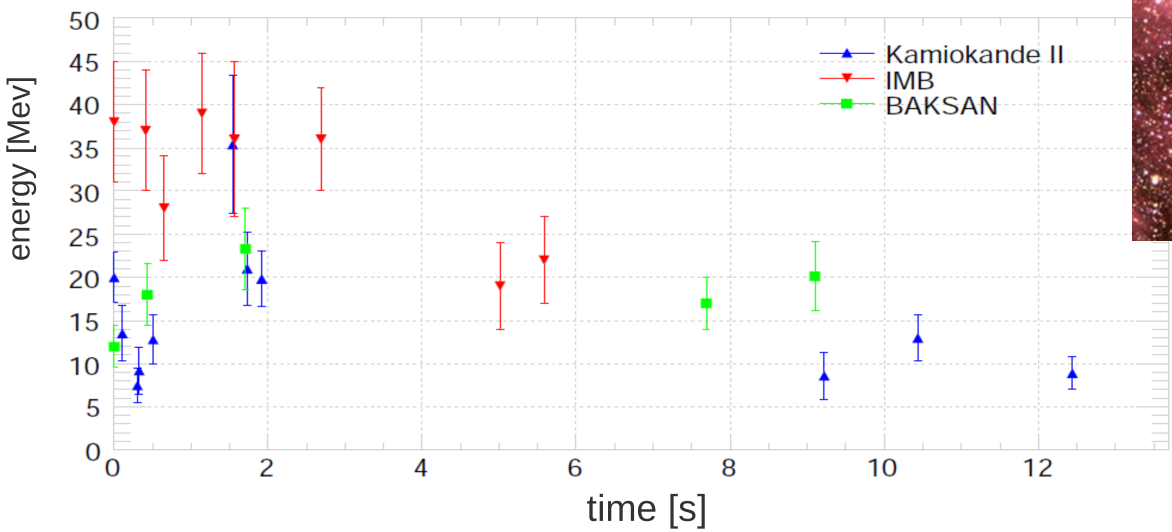
Analysis Method

Detector Performance and its Simulation

Improving IceCube's Supernova system

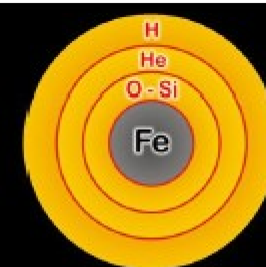
Supernova

- Supernova: F. Zwicky & W. Baade (Proceedings of the National Academy of Science 20 (5) 1934)
  "The phenomenon of a super-nova represents the transition of an ordinary star into a body of considerable smaller mass"
- Predicting Neutrinos from core-collapse SN: G. Gamow & M. Schoenberg (Phys. Rev. 58:1117 (1940)) "These neutrinos […] must carry away very large amounts of energy […] [and] must cause a rapid contraction of the stellar body […] resulting in a catastrophic collapse"
- SN1987A



Thermonuclear vs. Core-Collapse

Thermo-nuclear (Type Ia)	Core collapse (Type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface



Chandrasekhar limit is reached — $M_{Ch} \approx 1.5\ M_{sun}$

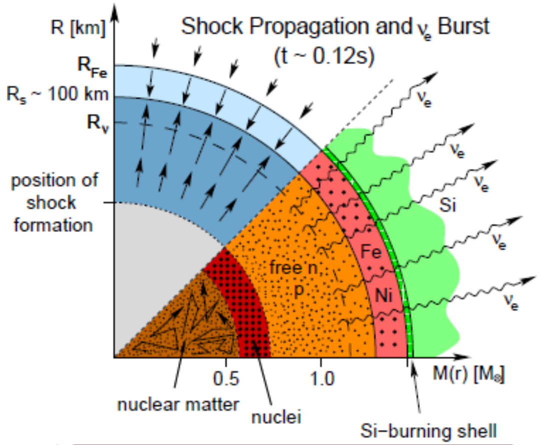
COLLAPSE SETS IN

Thermo-nuclear (Type Ia)	Core collapse (Type II, Ib/c)
Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy 1 MeV per nucleon	Gain of gravitational binding energy 100 MeV per nucleon 99% into neutrinos

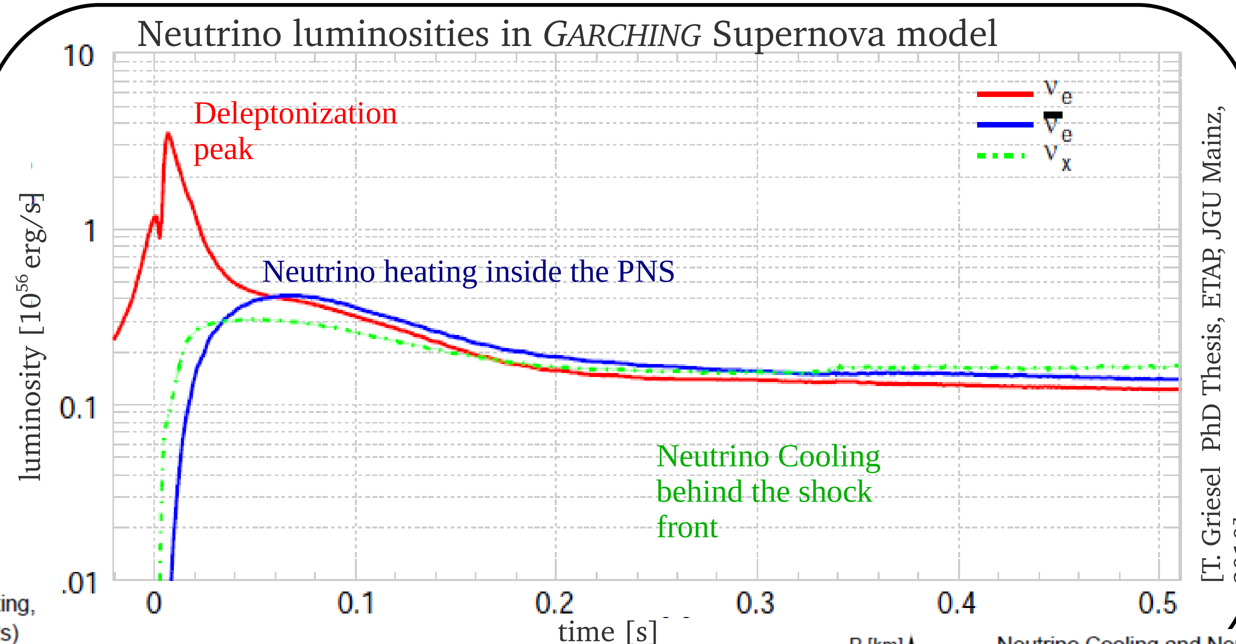
Comparable "visible" energy release of $\sim 3 \times 10^{51}$ erg

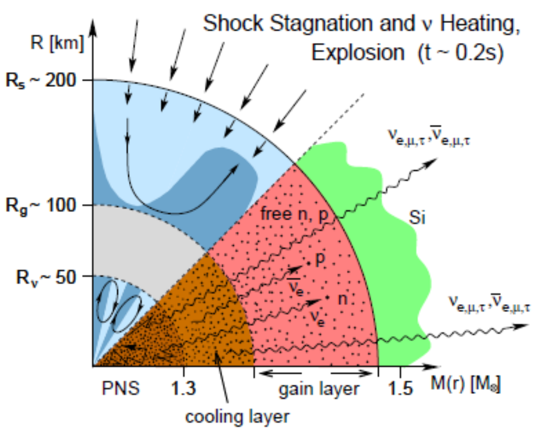
[Georg Raffelt, MPI Phsics, Munich - Lecture "Supernova Neutrinos" at ISAPP 2011, Varenna Italy]

Neutrino Luminosity & Energy



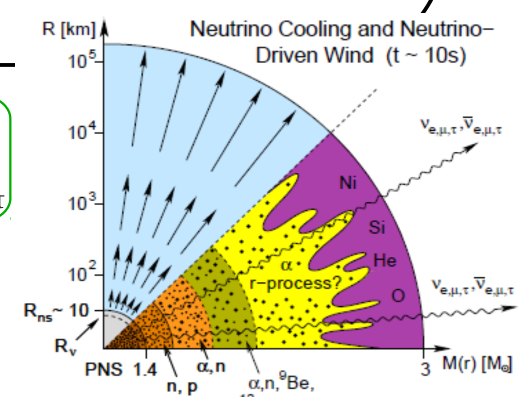
$$e^- + p \rightarrow n + \nu_e$$
$$e^- + N(Z,A) \rightarrow N(Z-1,A) + \nu_e$$



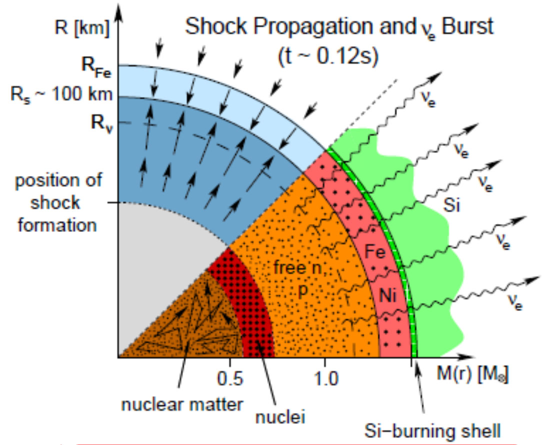


$$e^- + e^+ \rightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$
$$N + N' \rightarrow N + N' + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$$

$$e^+ + n \longrightarrow p + \bar{\nu}_e$$
$$e^- + p \longrightarrow n + \nu_e$$



Neutrino Luminosity & Energy



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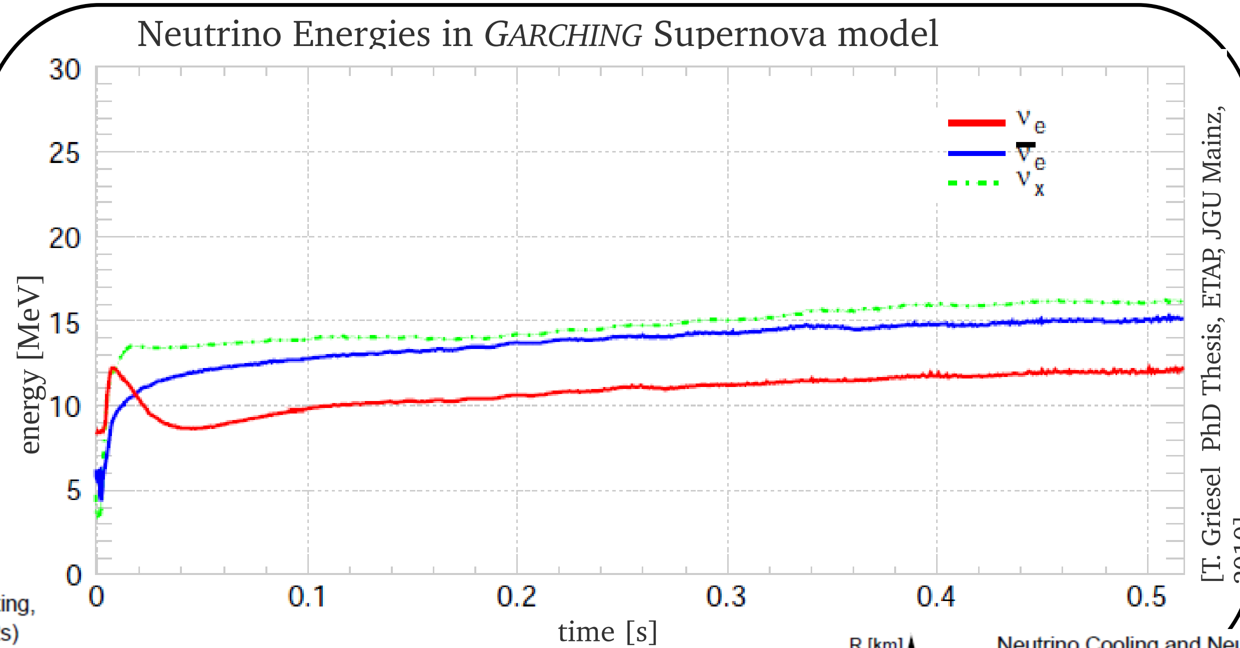

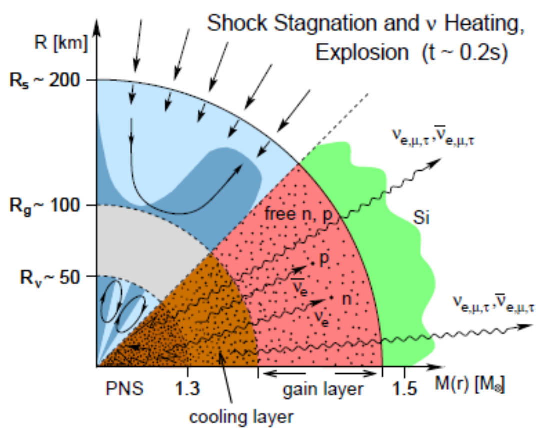

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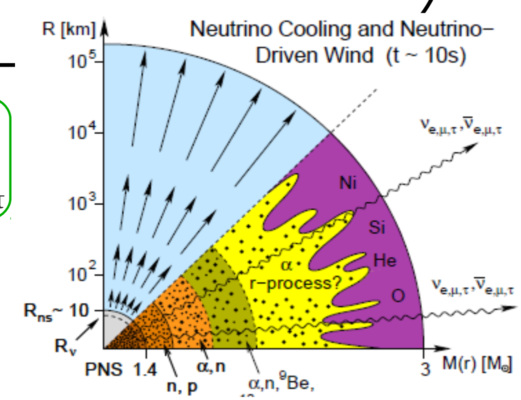
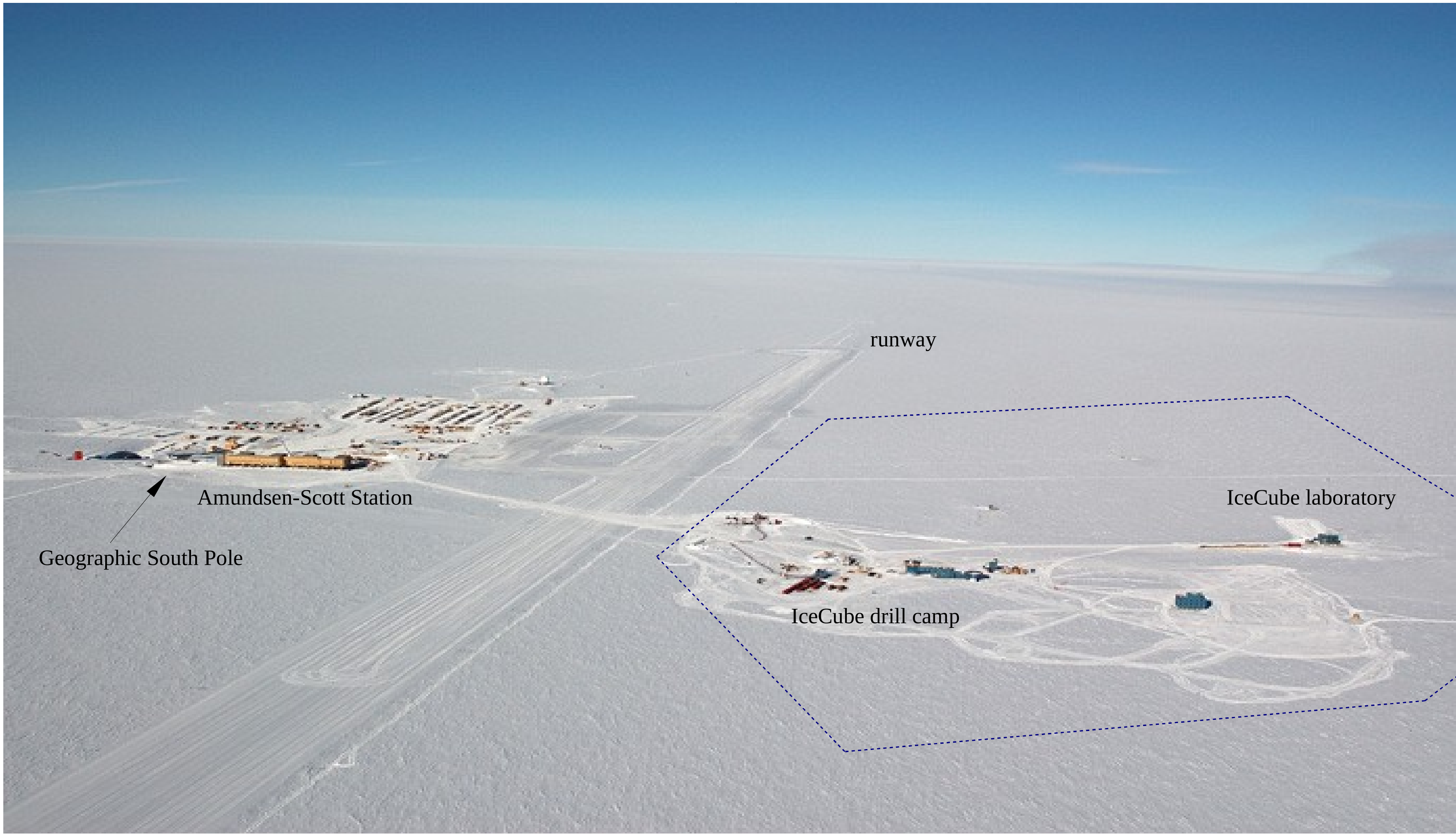
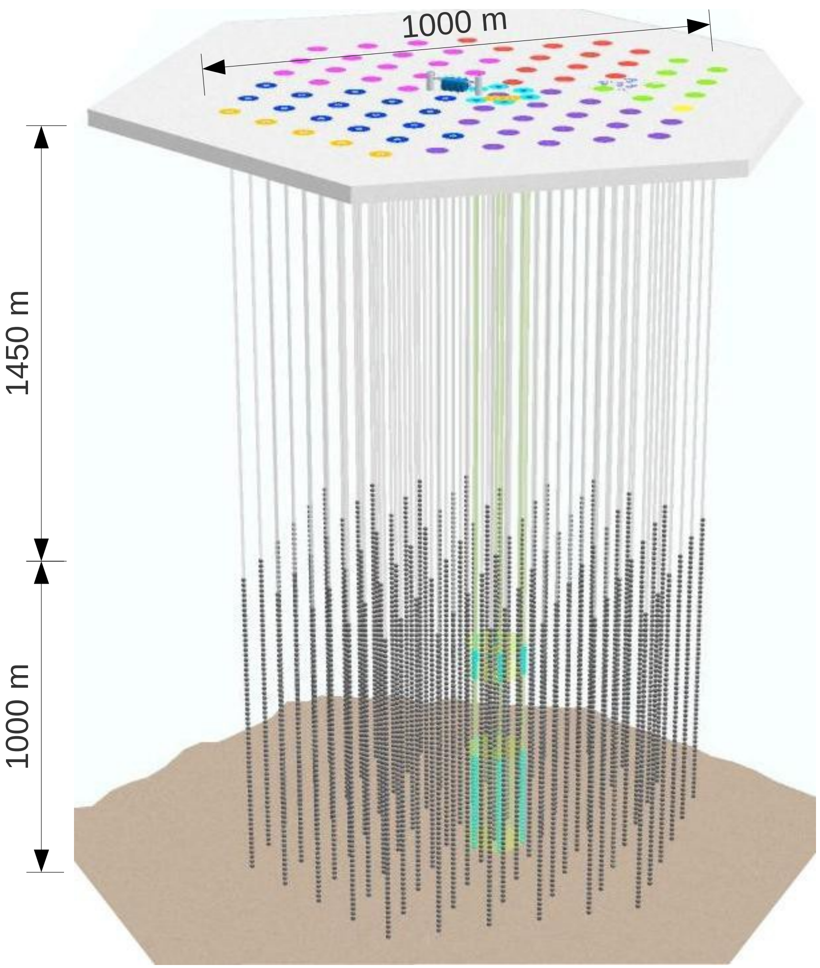


South Pole


runway
Amundsen-Scott Station
Geographic South Pole
IceCube laboratory
IceCube drill camp

The IceCube Neutrino Observatory



Scientific goals:

- Neutrino point source searches
- Atmospheric fluxes of neutrinos & muons
- WIMPs & magnetic Monopoles
- Diffuse neutrino flux
- ***Supernova search***

Detection principle:

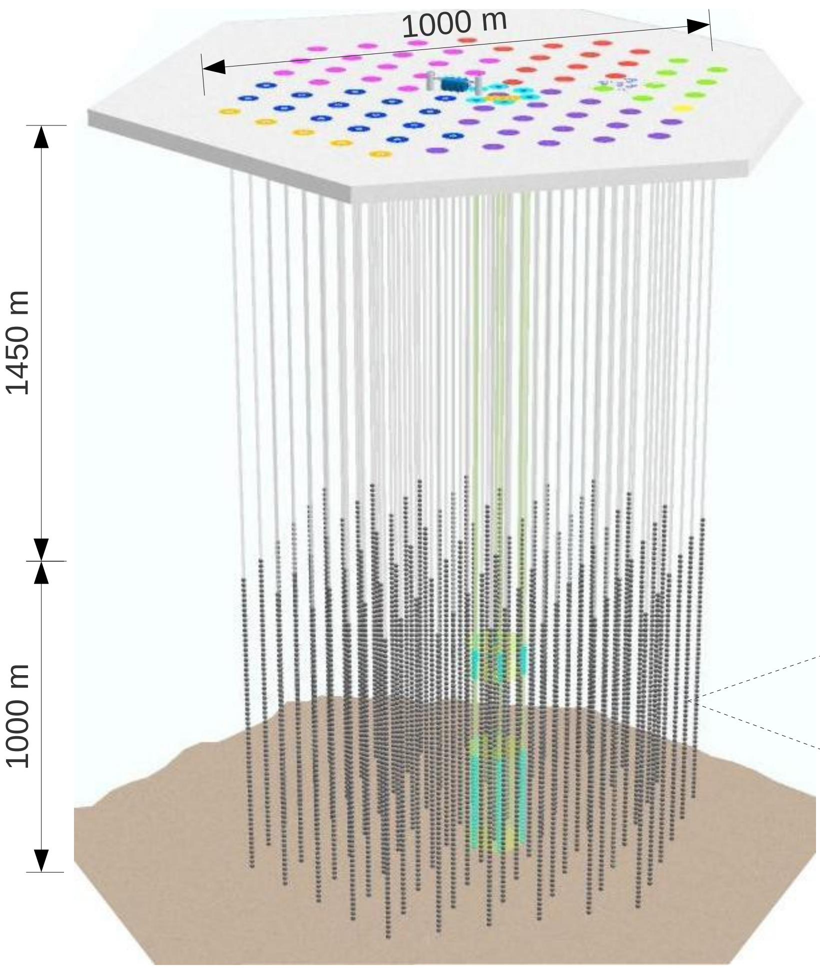
- Cerenkov radiation emission from charged by-products of neutrino interaction in the ice

Advantages of Ice:

- Clear : Long absorption length (~96 m)
- No radioactivity, nor bio-luminescence

Perfect for detection of Cerenkov light !

The IceCube Neutrino Observatory

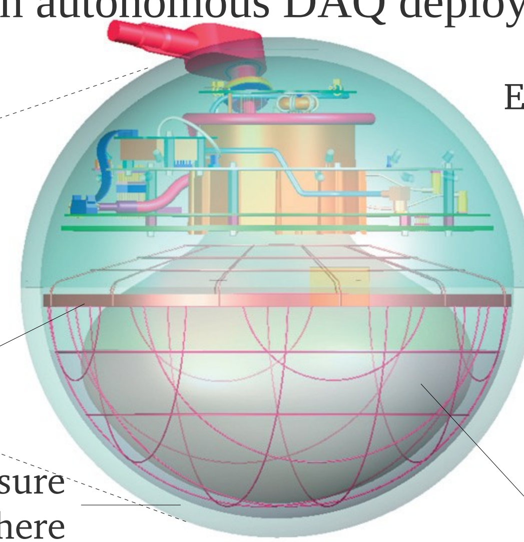


IceCube Array:

86 strings with 60 optical sensors on each string

- 78 sparsely instrumented strings:
  17 m between sensors
  125 m between strings
- 8 densely instrumented strings (DeepCore)
  7 m between sensors with high efficiency PMT
  60 m between strings

5160 DOMs with autonomous DAQ deployed in ice



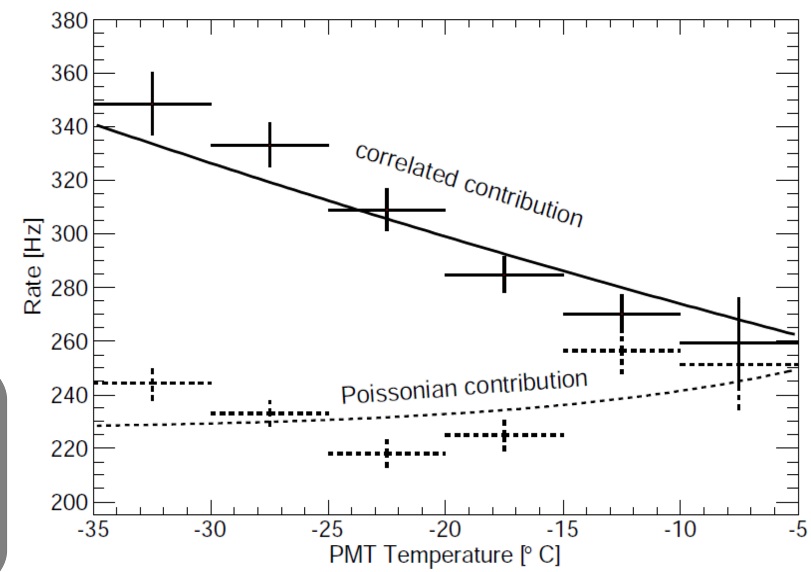
Noise Properties of the DOM

SN Detection Method: Counting single DOM hit rates on top of low noise background

- Poissonian noise (≈ 225 Hz)
- Atmospheric muons (≈ 16 Hz)
- Thermal emission from photo-cathode (< 10 Hz)
- PMT induced after-pulses (≈ 30 Hz)
- Correlated noise from Cerenkov radiation and scintillation in the glass of the photomultiplier and the surrounding sphere (radioactive decays)

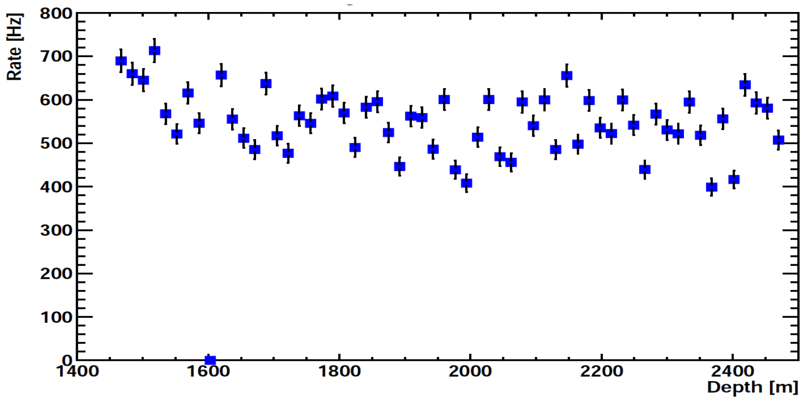
standard DOM (4800): **~ 540 Hz**
high quantum efficiency DOMs (360) ~ 680 Hz

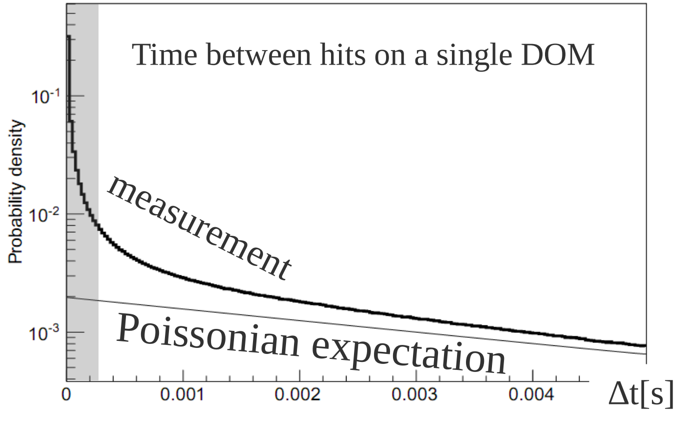
- Bursts increase in rate and size as the PMT gets colder: $r(T) = G \cdot A_C \cdot e^{-\frac{T}{T_r}}$
- Uncorrelated part follows Richardson's Law: $r(T) = A \cdot T^2 \cdot e^{-\frac{W}{kT}} + C$



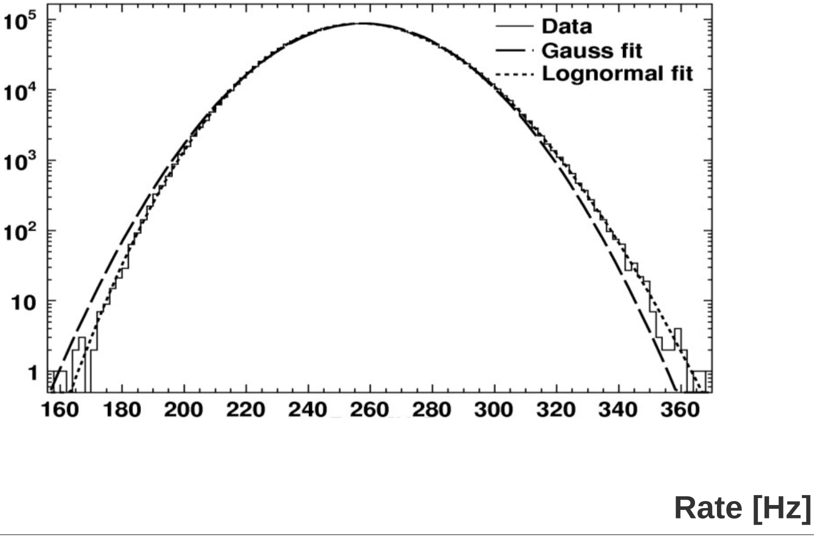
Noise Studies for SN DAQ

- Analysis of raw data sets





- Artificial dead-time (250µs) to reduce correlated noise
- With applied dead-time: 285 ± 25 Hz



SN Neutrino Reactions in Ice

- Inverse β – decay accounts for ~ 94% of all interactions:

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

- Reaction with the Oxygen-core makes up 1% and $\propto E_\nu^{3/2}$:

$$\nu_e + \mathrm{O} \rightarrow \mathrm{F} + e^+ \;\&\; \bar{\nu}_e + \mathrm{O} \rightarrow \mathrm{N} + e^+$$

- Scattering on Electrons (3% and $\propto E_\nu$):

$$\nu_l + e^- \rightarrow \nu_l + e^-$$ with l= e, μ, τ

- Electrons/Positrons in MeV – Range: $E_{e+} \approx 22$ MeV

No single reconstruction possible due to short track length (~ 0.56cm*E_{e+}(MeV))

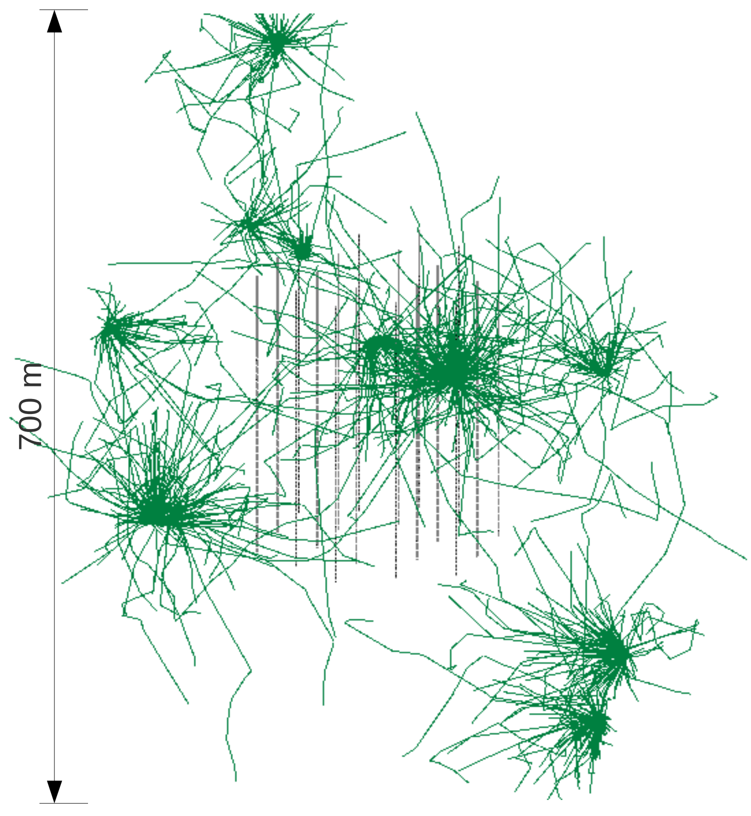
But: low noise and high statistics lead to a collective increase of the hit rate in the whole detector in case of a Supernova

Cerenkov Photon Signal in IceCube

- Low energy neutrinos interact mainly via inverse beta decay
- $E_{e+} \approx 22$ MeV
- N_γ rises with $\sim E_\nu^3$

  (cross-section $\sim E_\nu^2$ & Cherenkov light production directly proportional to track length)

- Simulation of Cherenkov photons radiated by 10 e^+ (15 Mev avg. Energy, thinned out)



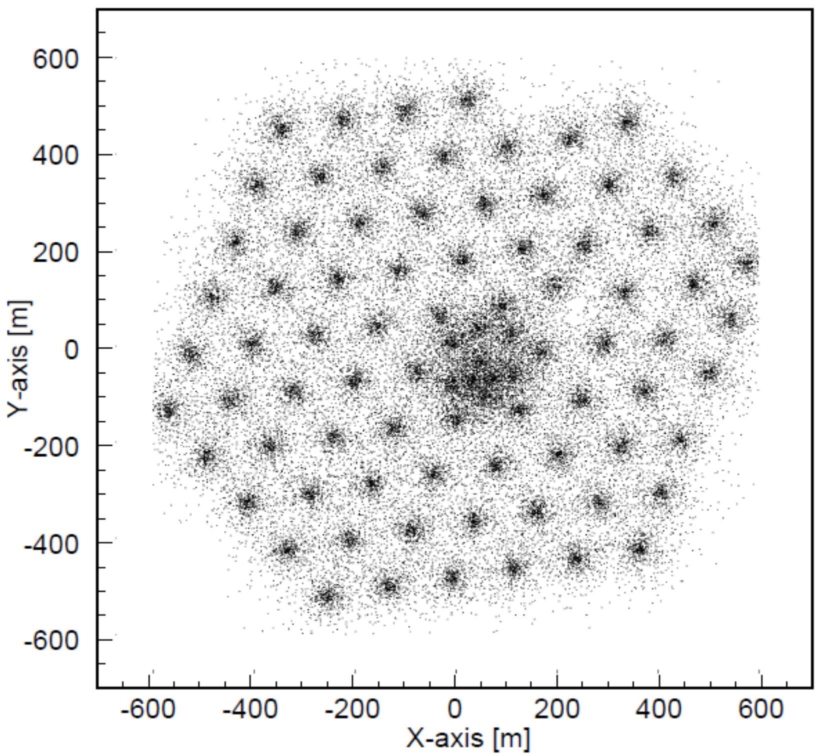
Track length: ~ 0.56 cm $\cdot$ E_{e+} (MeV) (GEANT4)

$N_\gamma^{300\text{-}600nm} \sim 178 \cdot E_{e+}$(MeV) (Frank-Tamm)

Cerenkov Photon Signal in IceCube

Determing # of detected signal hits N_{γ}^{detect} from # of neutrinos crossing the detector:

Approach: GEANT-3.21 GCALOR based simulation of individual events:

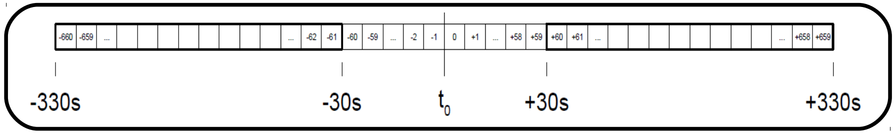


- SN ν_e & $\bar{\nu}_e$ on protons, electrons and oxygen
- e^+ annihilation
- neutron capture
- photon propagation in the ice including dust layer effects
- detector geometry & DOM response
- *10^7 neutrino interactions simulated.* Projected on horizontal plane
- 180.000 … 3.600.000 ν induced PMT hits from SN @ 10kpc distance

Analysis Method

SN system in IceCube is based on counting noise rate increase (per DOM) on top of background

Individual DOM's rate expectation values $\langle r_i \rangle$ calculated in moving 300s window: ±30s around t0 excluded for the case of wide signals' impact on mean reates



Most likely ***collective rate deviation <Δμ>*** of all DOM noise rates r_i from their individual rates $\langle r_i \rangle$: maximized Likelihood:

$$\mathcal{L}(\Delta\mu) = \prod_{i=1}^{N_{\mathrm{DOM}}} \frac{1}{\sqrt{2\pi}\langle\sigma_i\rangle} \exp\left(-\frac{(r_i - (\langle r_i\rangle + \epsilon_i \Delta\mu))^2}{2\langle\sigma_i\rangle^2}\right) .$$

$$\Delta\mu = \sigma_{\Delta\mu}^2 \sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i (r_i - \langle r_i\rangle)}{\langle\sigma_i\rangle^2} \quad \text{with} \quad \sigma_{\Delta\mu}^2 = \left(\sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i^2}{\langle\sigma_i\rangle^2}\right)^{-1} .$$

Indicator for strength and homogeneity of the illumination of the ice: ***significance ξ***

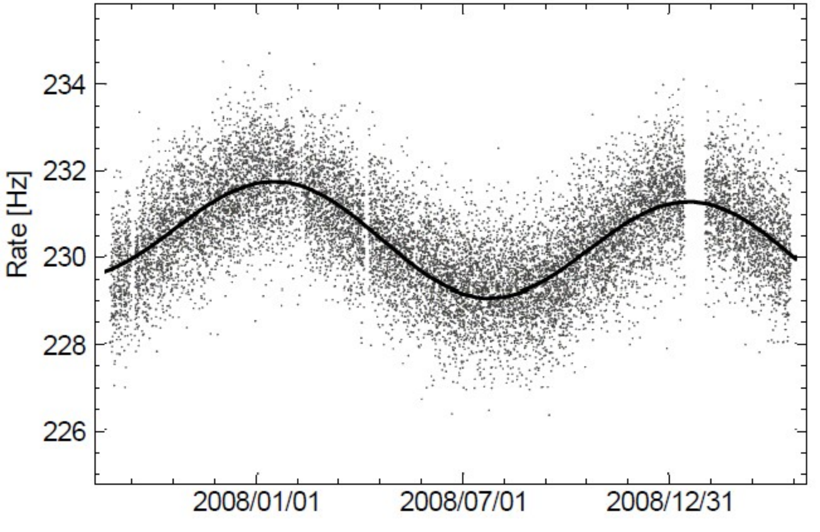
$$\xi = \frac{\text{deviation from sliding average}}{\text{uncertainty of deviation}} = \frac{\Delta\mu}{\sigma_{\Delta\mu}}$$

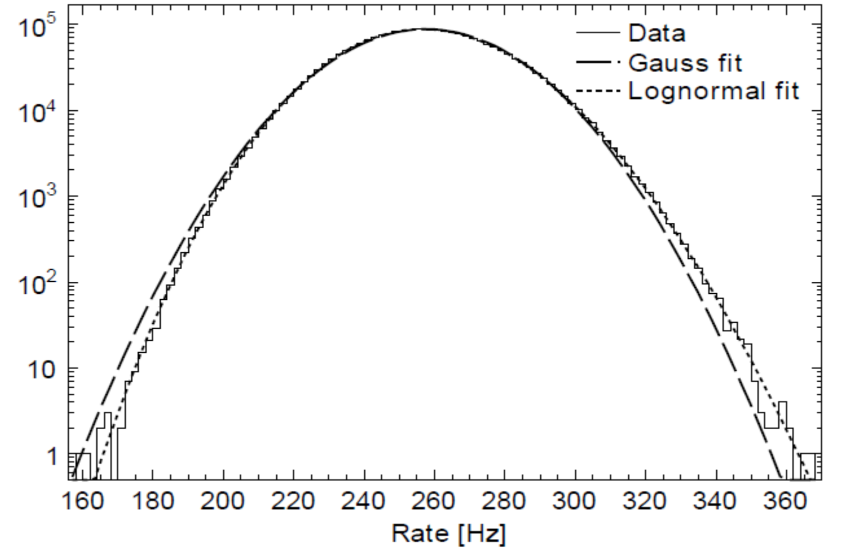
Detector Performance

- Long term DOM rate behavior characterized by

$$r(t) = r_0 + c_1 e^{-t/\tau} + c_2 \sin(2\pi(t/\text{year}))$$

- Seasonal variation due to atmospheric muons (internal report 201107001)



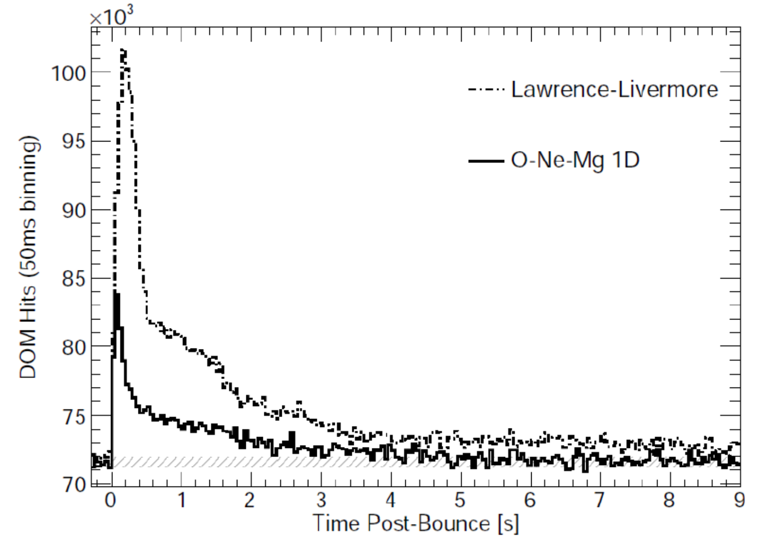


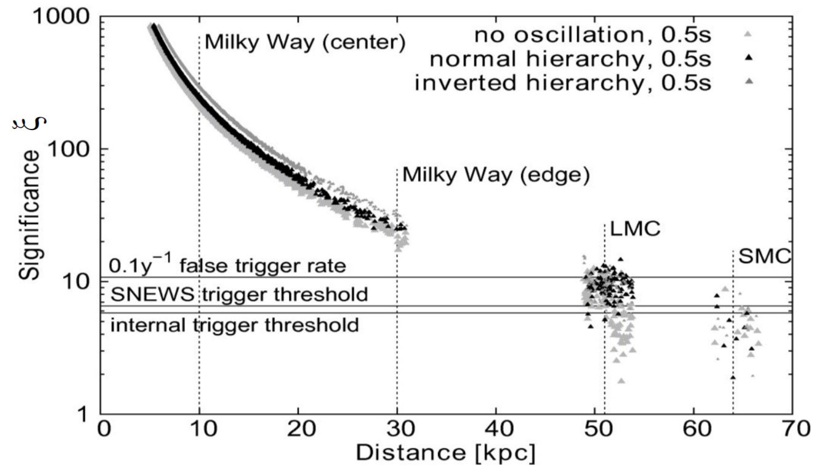
- DOM rates distribution (after dead-time) better described by lognormal than by Gaussian

- Avg rate: 285 Hz (QE DOM)
  359 Hz (HQE DOM)

Performance Simulation

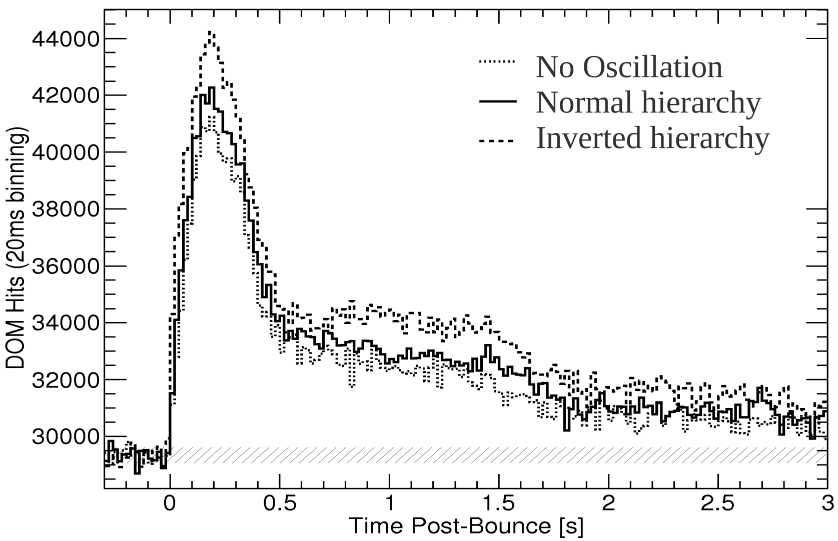
- For SN explosion at 10 kpc distance, different models applied
  - 20 solar mass progenitor (Lawrence-Livermore: SN1987A modeled)
  - 8.8 solar mass progenitor O-Ne-Mg core modeled
- Significance & Galaxy Coverage:
  - # likely progenitors in Galaxy as fct of distance to Earth is important for simulation
    - Detection ability for SN in LMC with significance $\xi \sim 6$, in SMC ~ 3 (no SNEWS alarm!)
    - For Milky Way: observation of at least 25 ξ at 30 kpc!

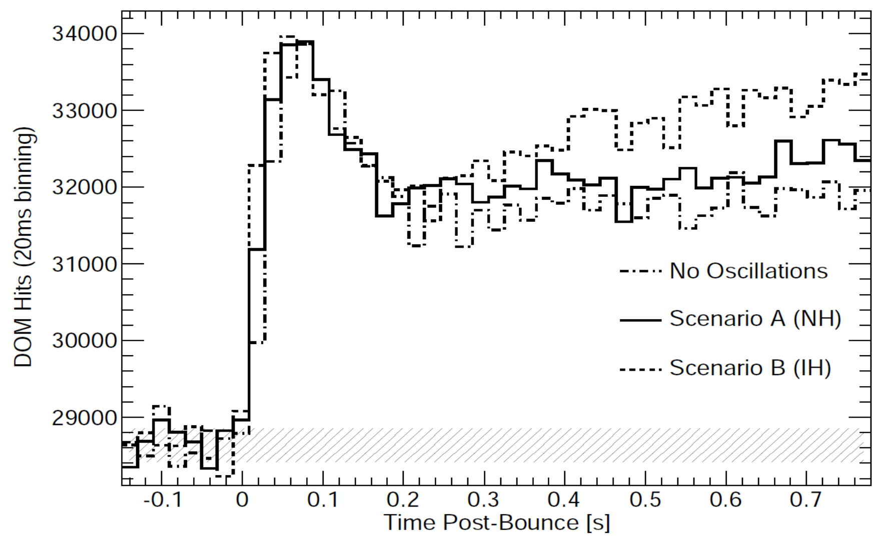




Expected Signal

- Simulation of SuperNova at 10 kpc distance following LL & Garching models
- IceCube MC simulation with time dependent energy spectra





Clearly visible differences for normal and inverted hierarchy in LL model!

Improving SN detection for IceCube

- Gain as much information as possible in case of a SN
  - Buffering of Hit Spooling Data at Pole
- So far IceCube has two parallel DAQ system
  - Slow stream: Hit rates recording for SN system (sni3daq)
  - Fast stream: PMT pulses' data stream (pdaq)
- Improvement: Combining the two systems
  - Implementation of an Interface
  - Implementation of raw data stream recording

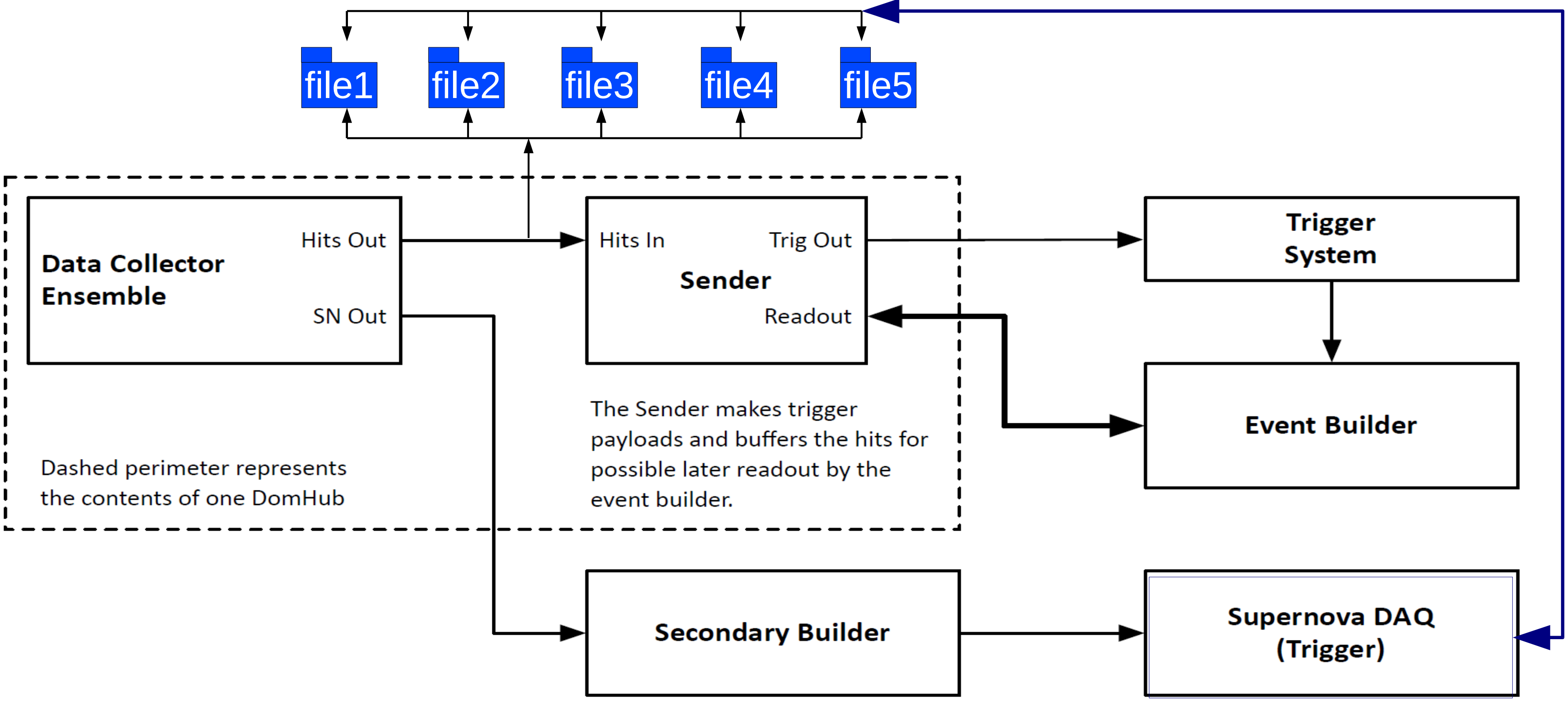
Improving SN detection for IceCube

- My current work: **Improving SN detection for IceCube**
  - Improving Supernova DAQ
    - Development, testing & implementation of Interface and actual hit spooling at pole
  - SN Data Analysis (Hit Spooling)
    - Low level analysis of raw data
      - Development of standard procedures for raw data: on-line code
      - Optimal atmospheric muon rejection
- Efforts by others Groups
  - Noise Generation for new Noise Maker, after-pulse parametrization (Madison)
  - Study of optimal correlated noise rejection, muon rejection (Mainz)
  - …

Improving SN detection for IceCube

Current system: early separation of Sn DAQ and physical Hit data

Improvement: Hit spool file system to store raw data and access it at any time later

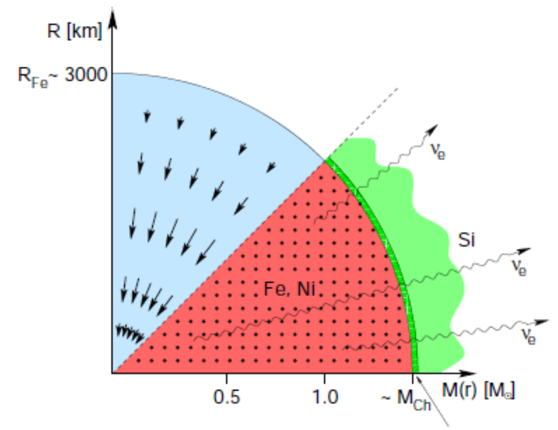


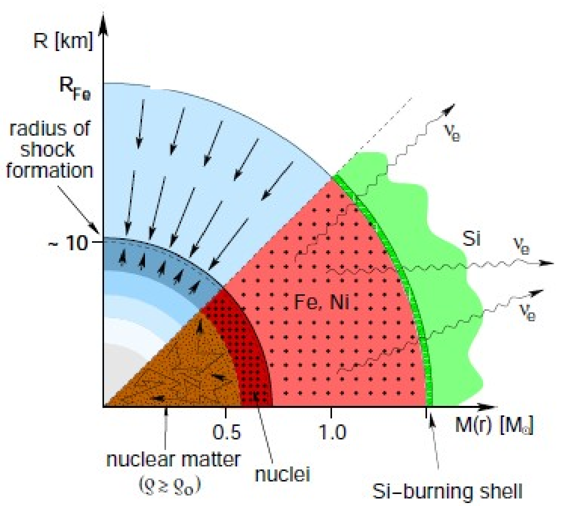
Summary

- ***World's best detector for fine details in ν flux of close supernovae***
- No single track reconstruction but overall noise-rate increase detection
- Possible due to low noise (well understood with ongoing investigation)
- SN signal strong model dependent
- Distinction of neutrino mass hierarchy possible
- Improvements of the SN DAQ to gain information about type, direction & energy of individual neutrino
- Let's have a galactic Supernova!


THANK YOU !
In (galactic) Supernova we trust

Dynamics of the Collapse





t~0s: initial phase of collapse

- Inactive iron core continuously growing due to in-falling matter from outer shells
- Electron-pressure reduced: $e^- + p \rightarrow n + \nu_e$

➡ M_{CH} is exceeded

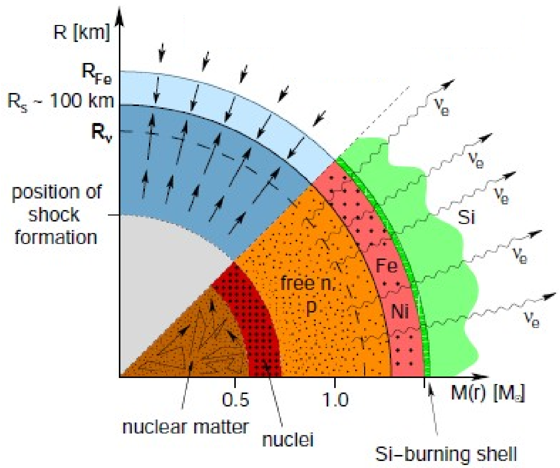
➡ core gets gravitationally unstable & collapses

- ν are captured for density $\rho_{core} \approx 10^{11}$ g/cm³

t~0.1s: bounce & shock formation

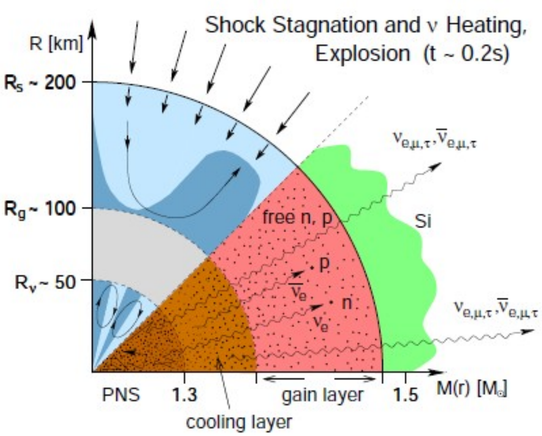
- $\rho_{core} \approx 3 \cdot 10^{11}$ g/cm³, degeneration pressure stops collapse → PNS
- In-falling matter bounces back from incompressible core → shock formation
- ν_e captured and thermalized

Dynamics of the Collapse



t~0.12 s: shock propagation & ν_e burst

- Shock wave propagates and dissociates iron → neutronization: $e^- + N(Z,A) \rightarrow N(Z-1,A) + \nu_e$
- density decreases → ν_e escaping
- deleptonization peak (~ 5 ms)



t~0.2 s: stagnation, ν heating & explosion

- Energy loss due to deleptonization & dissociation shock stagnation
- Matter accretion on PNS → E_ν & L_ν ↗
- PNS cooling via neutrino pair-production (~10 s)
- Neutrinos deposing energy (heating) in layer between PNS and shock front
- explosion

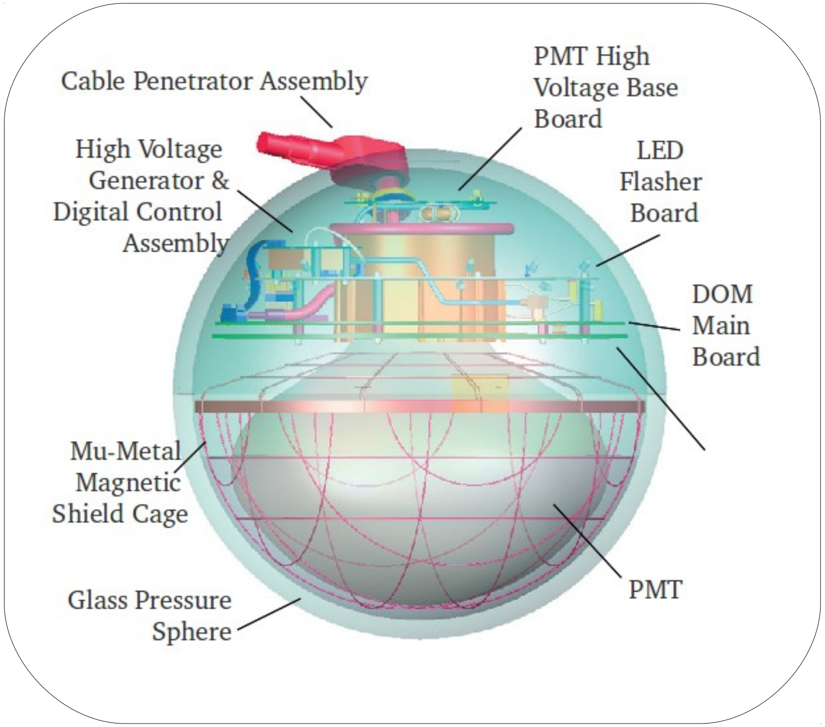
2d & 3d SN simulations

- Visualization of 2D & 3D models:
    - Garching 2D Sim short & Hallmark Filaments
    - Garching Group 15Msolar 2DSim long
    - Garching 3D sim

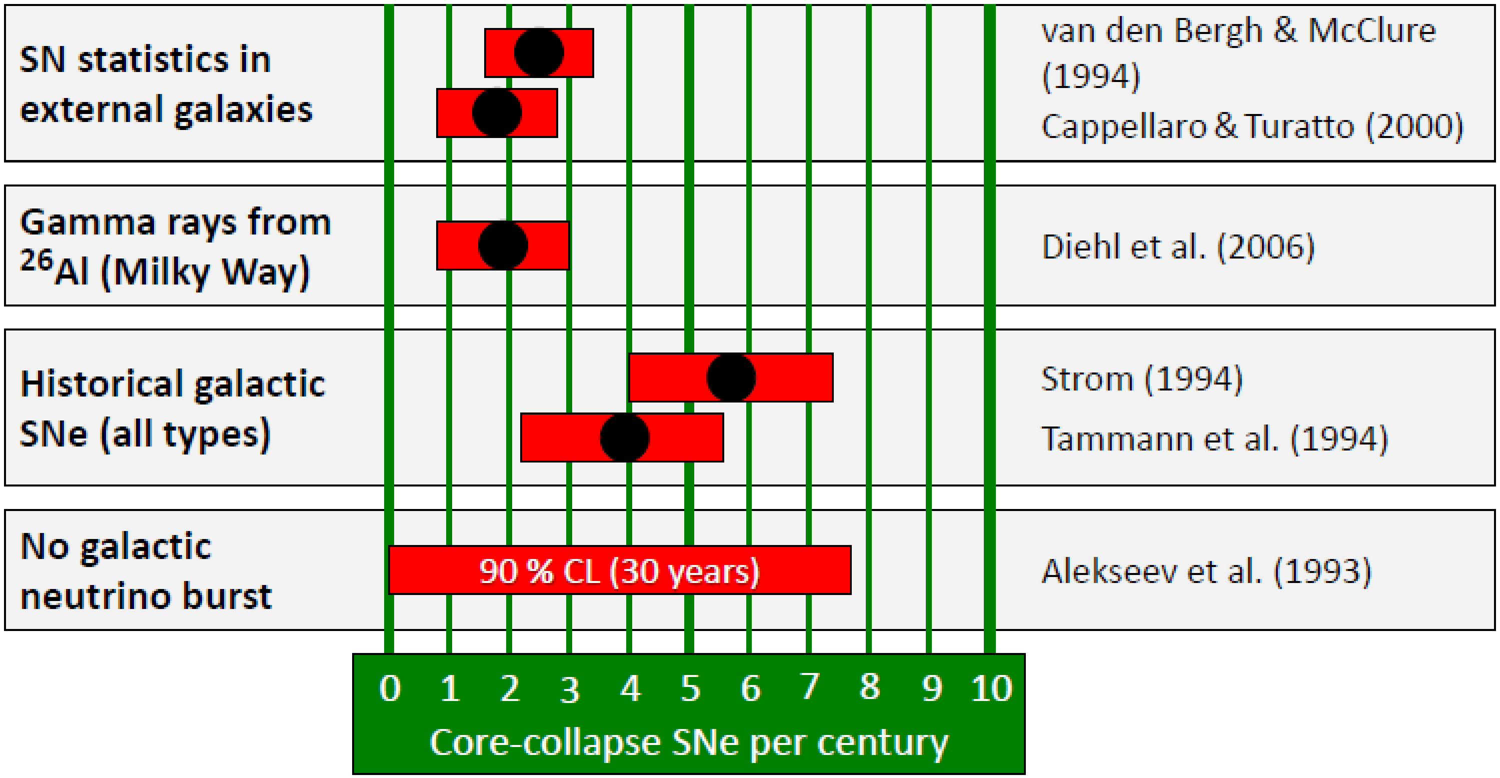
The DOM

- Spectral response : 300 nm – 600 nm wavelength
- Peak Quantum Efficiency of 25% at 420 nm → well-matching Cerenkov-signal spectrum & optical properties of the glacial ice

- QE of HighQE DOMs ~ 1.35 times higher with noise increase of 25%
- Dark count noise rate ***~ 540 Hz*** for Temperatures between -43°C (1450m) and -20°C (2450m)
- Most PMTs operating at gain = 10^7
- SPE-pulses with ~ 8 mV amplitude and 10 ns length
- Threshold of front end pulse discriminator set to 2 mV (= 10 · RMS noise level)
- 85% of all SPE pulses pass the threshold
- **Full on-board digitization of the data!**



SN rate



References: van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455. Diehl et al., Nature 439 (2006) 45. Strom, Astron. Astrophys. 288 (1994) L1. Tammann et al., ApJ 92 (1994) 487. Alekseev et al., JETP 77 (1993) 339 and my update.

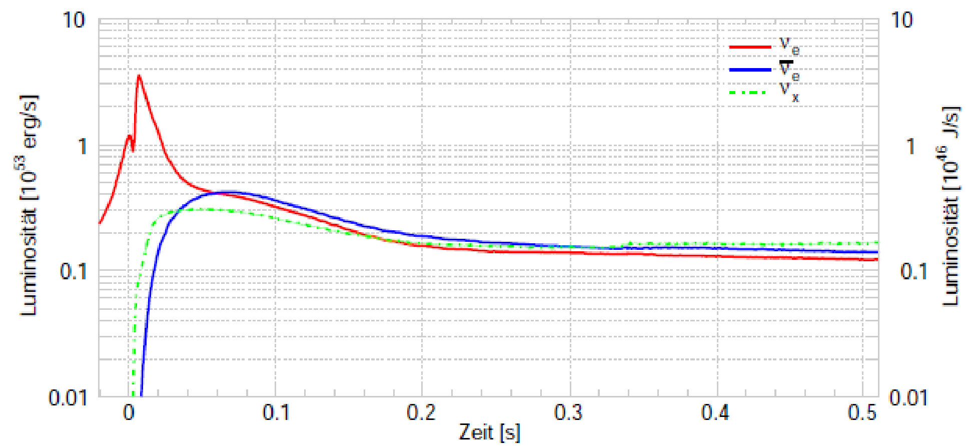
Georg Raffelt, MPI Physics, Munich — ISAPP 2011, 4/8/11, Varenna, Italy

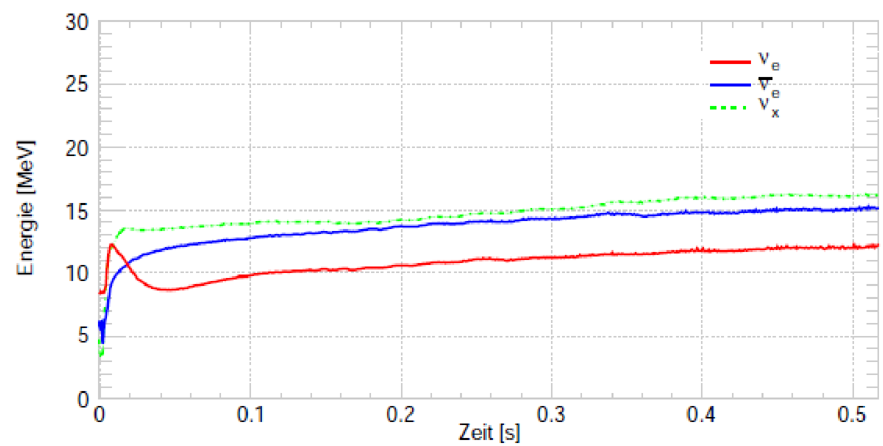
Neutrino fluxes

- Simulation of an explosion of an 8-10 $M_\odot$ progenitor star (Garching model)
- simulated till 0.8 seconds after bounce
- Flux parametrization:

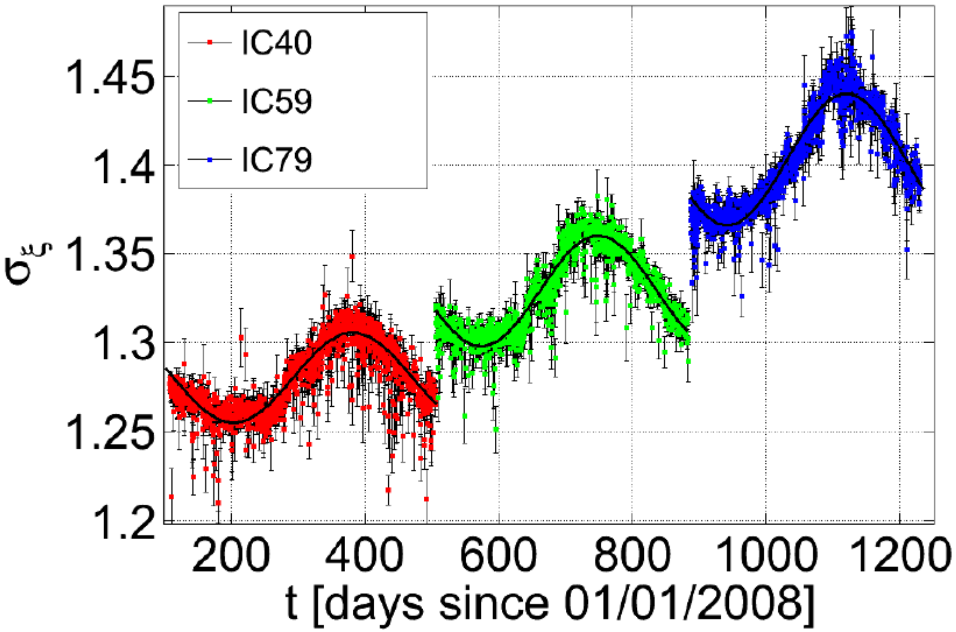
$$F^\alpha(E,\langle E\rangle,\alpha) = \frac{d\Phi(E,\langle E\rangle,\alpha)}{dE}$$

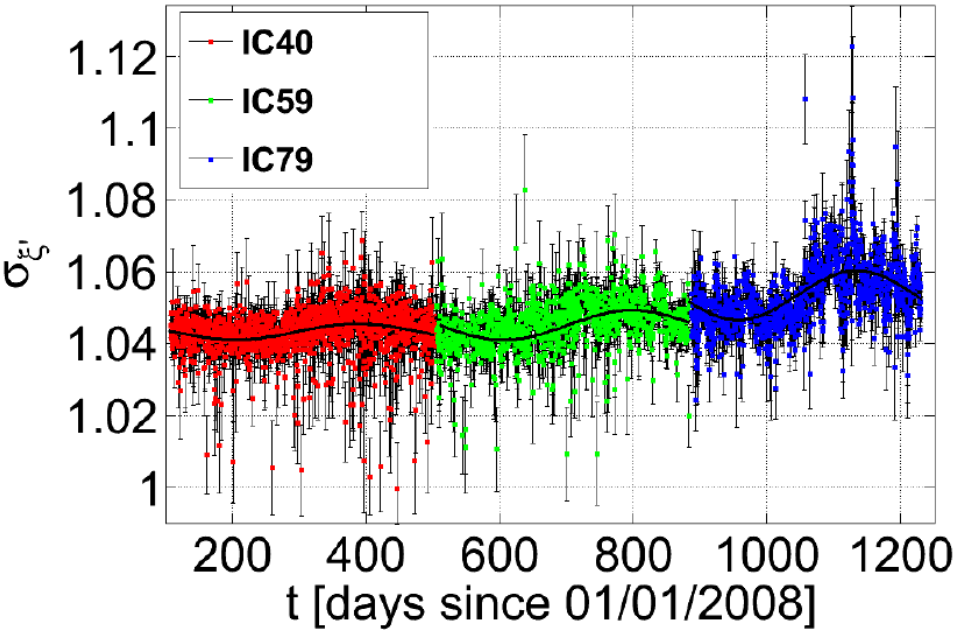
$$= \Phi_0 \frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)} \frac{E^\alpha}{\langle E\rangle^{1+\alpha}} e^{-(1+\alpha)E/\langle E\rangle}$$





Muon Background Subtraction





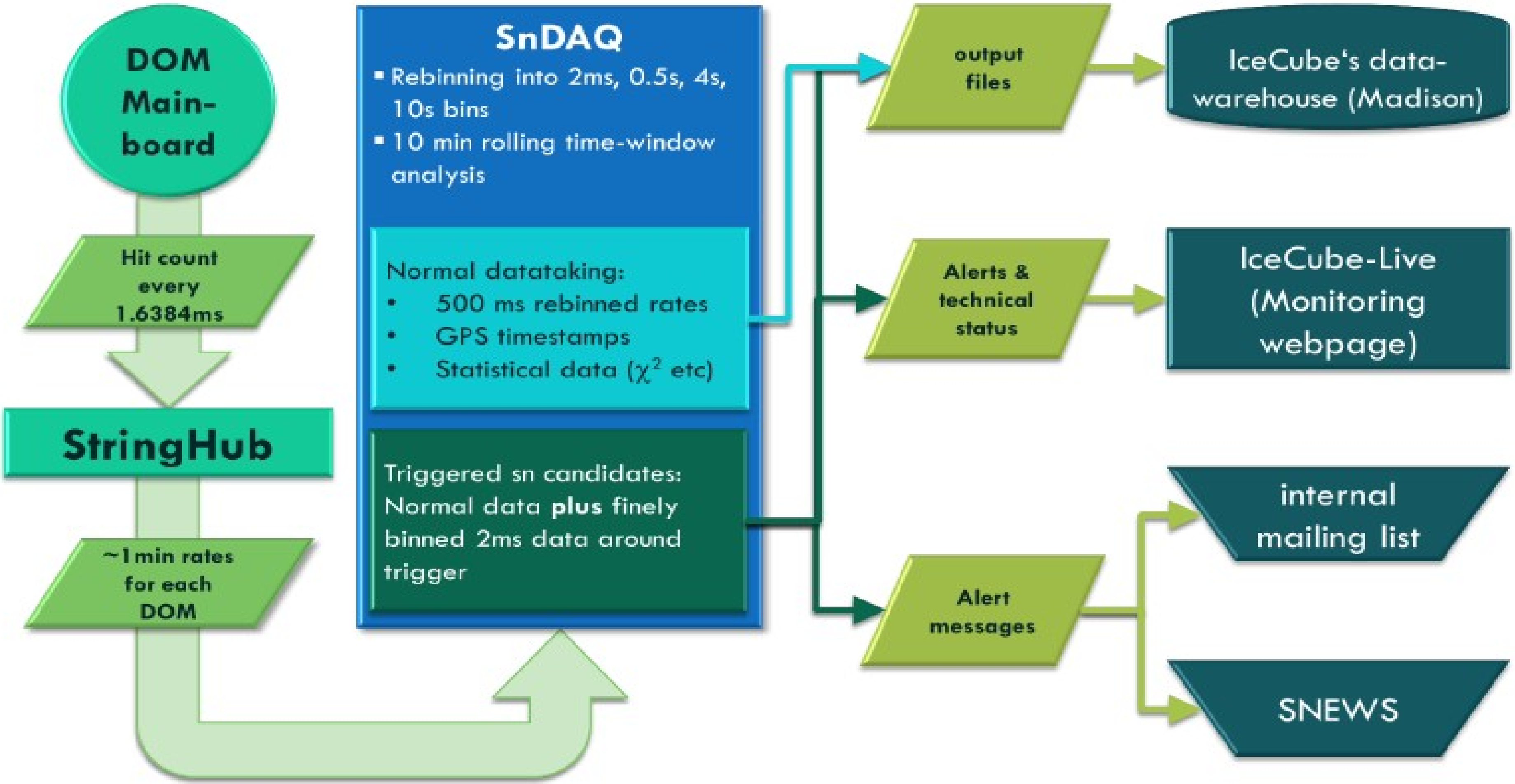
σ_s = width of significance distribution

Over three years of data taking

Same data sets with muon background subtraction

V. Baum, L. Köpke and G. Kroll 'A study of SN alarms in IC40, IC59 and IC79', IceCube Note 201107001

SuperNova DAQ



Contributing Neutrino Reactions

Reaction	# Targets	# Events	Signal Fraction	Reference
$\bar{\nu}_e + p \rightarrow e^+ + n$	$6 \cdot 10^{37}$	134 k (157 k)	93.8 % (94.4 %)	Strumia & Vissani (2003)
$\nu_e + e^- \rightarrow \nu_e + e^-$	$3 \cdot 10^{38}$	2.35 k (2.25 k)	1.7 % (1.4 %)	Marciano & Parsa (2003)
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	$3 \cdot 10^{38}$	660 (720)	0.5 % (0.4 %)	Marciano & Parsa (2003)
$\nu_{\mu+\tau} + e^- \rightarrow \nu_{\mu+\tau} + e^-$	$3 \cdot 10^{38}$	700 (720)	0.5 % (0.4 %)	Marciano & Parsa (2003)
$\bar{\nu}_{\mu+\tau} + e^- \rightarrow \bar{\nu}_{\nu+\tau} + e^-$	$3 \cdot 10^{38}$	600 (570)	0.4 % (0.4 %)	Marciano & Parsa (2003)
$\nu_e + {}^{16}O \rightarrow e^- + X$	$3 \cdot 10^{37}$	2.15 k (1.50 k)	1.5 % (0.9 %)	Kolbe et al. (2002)
$\bar{\nu}_e + {}^{16}O \rightarrow e^+ + X$	$3 \cdot 10^{37}$	1.90 k (2.80 k)	1.3 % (1.7 %)	Kolbe et al. (2002)
$\nu_{all} + {}^{16}O \rightarrow \nu_{all} + X$	$3 \cdot 10^{37}$	430 (410)	0.3 % (0.3 %)	Kolbe et al. (2002)
$\nu_e + {}^{17/18}O/{}^{2}_{1}H \rightarrow e^- + X$	$6 \cdot 10^{34}$	270 (245)	0.2 % (0.2 %)	Haxton (1999)

Expected Rates

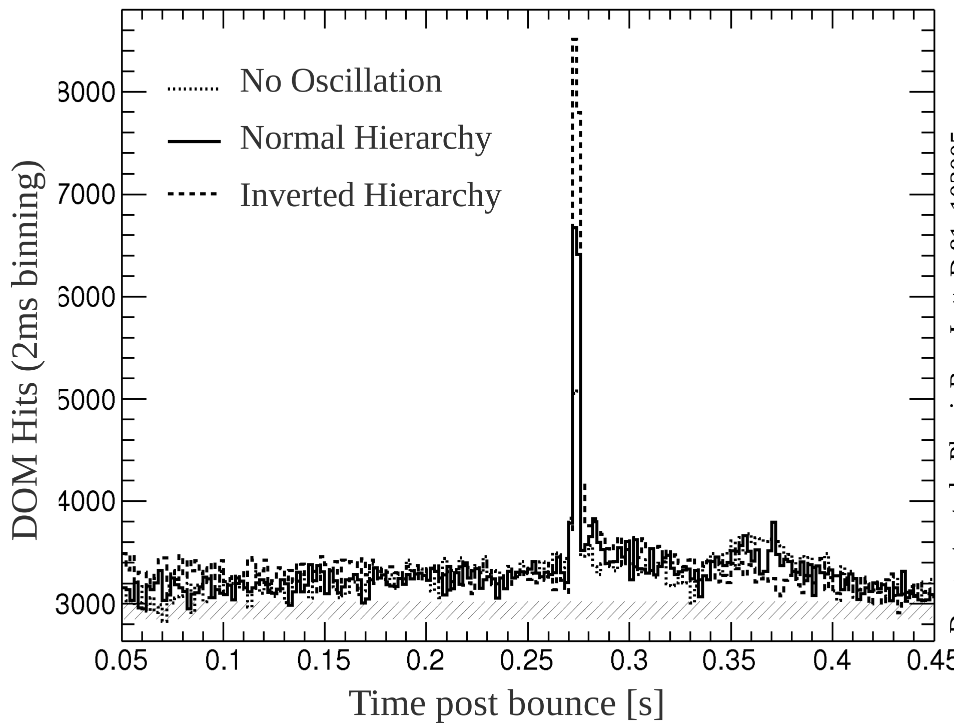
Model	Reference	Progenitor mass ($M_\odot$)	$\#\nu$'s $t < 380$ ms	$\#\nu$'s all times
"Livermore"	(Totani et al. 1997)	20	0.185×10^6	0.84×10^6
"Garching LS-EOS 1d"	(Kitaura et al. 2006)	$8 - 10$	0.073×10^6	-
"Garching WH-EOS 1d"	(Kitaura et al. 2006)	$8 - 10$	0.083×10^6	-
"Garching SASI 2d"	(Marek et al. 2009)	15	0.113×10^6	-
"Scaled 1987A"		$15 - 20$		$(0.61 \pm 0.19) \times 10^6$
"O-Ne-Mg 1d"	(Hüdepohl et al. 2010)	8.8	0.057×10^6	0.18×10^6
"Quark Star (full opacities)"	(Dasgupta et al. 2010)	10	0.071×10^6	-
"Black Hole LS-EOS"	(Sumiyoshi et al. 2007)	40	0.420×10^6	1.1×10^6
"Black Hole SH-EOS"	(Sumiyoshi et al. 2007)	40	0.355×10^6	3.6×10^6

At 10 kpc distance IceCube will see between 180.000 and 3.600.000 ν induced PMT hits!

Exotic Signals

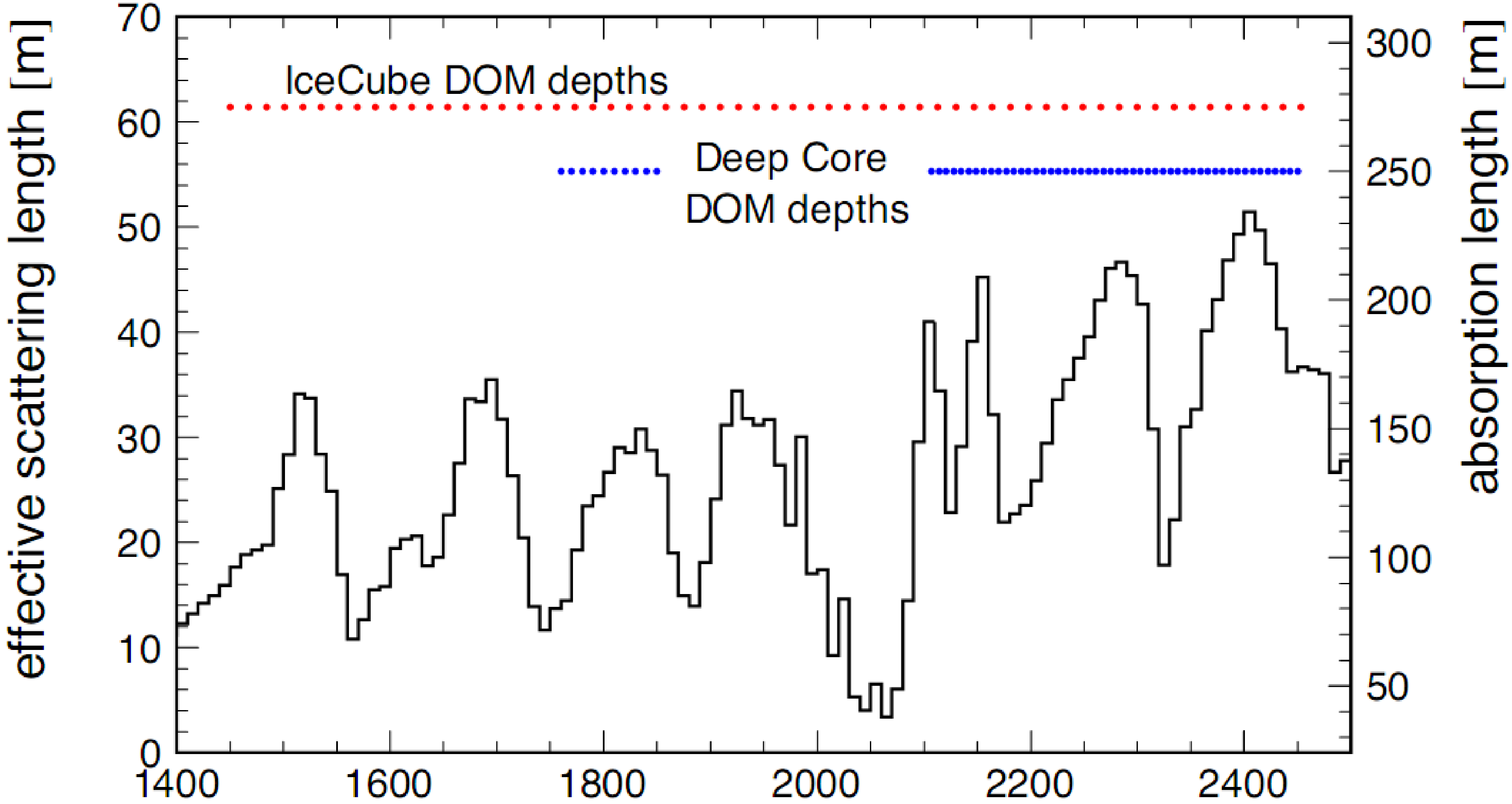
• Quark-star formation (quark-gluon plasma transition):

$\bar{\nu}$ – peak clearly visible and hierarchy dependent!

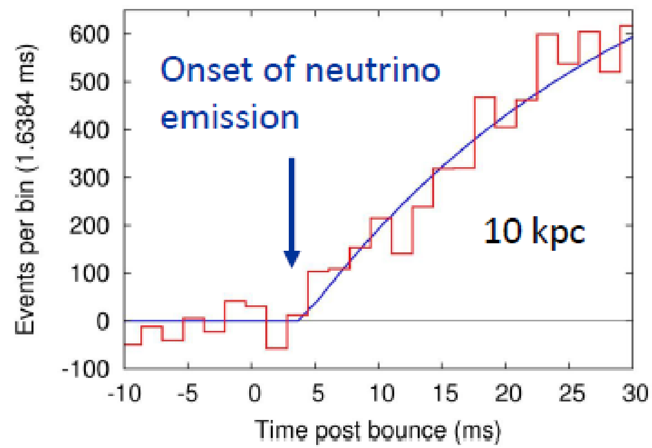


Dasgupta et al., Physi. Rev. Lett. D 81, 103005 (2010)

Ice Properties



Millisecond bounce time reconstruction

Super-Kamiokande	IceCube
• Emission model adapted to measured SN 1987A data • "Pessimistic distance" 20 kpc • Determine bounce time to a few tens of milliseconds Pagliaroli, Vissani, Coccia & Fulgione arXiv:0903.1191	 FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc. Halzen & Raffelt, arXiv:0908.2317

Georg Raffelt, MPI Physics, Munich   HANSE 2011, DESY (Hamburg), 19–23 July 2011

Cerenkov Photon Signal in IceCube

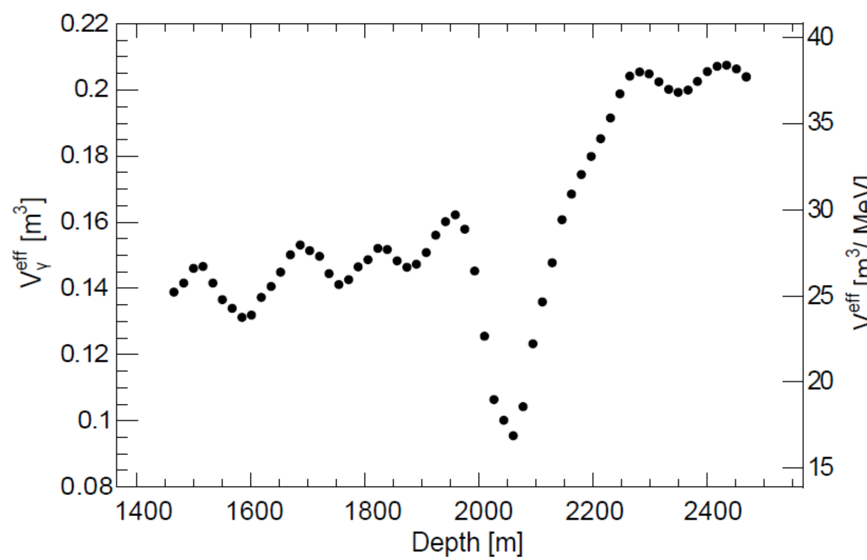
Determine # of detected signal hits N_γ^{detect} from # of neutrinos crossing the detector:

1st Approach: Simulation of interaction + γ_{Ch} creation + propagation + detection (based on tables)

$$N_\gamma^{\text{detect}} = \epsilon_{\text{deadtime}} \cdot n_\nu^{\text{interact}} \cdot \overline{V_{\text{e}}^{\text{eff}}}$$

Single photon effective Volume V_γ^{eff} determined by:

- *Cerenkov spectrum absorption length (≈ 100 m)*
- *DOM geometric cross-section (0.0856 m^2)*
- *DOM sensitivity for Cerenkov spectrum (≈ 0.071)*
- *Avg. angular sensitivity (≈ 0.32)*
- *Fraction of SP passing the DOM threshold (≈ 0.85)*



Simulated by placing 10^7 photons in a sphere of radius 250 m around each DOM

Energy dependent effective volume for detecting an e^+ or e^- : $V_e^{eff} = V_\gamma^{eff} \cdot N_\gamma(E)$