SUPERNOVA NEUTRINO SIGNAL IN ICECUBE

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HAνSE Workshop 2011

Overview

- IceCube in a nutshell
- IceCube's low energy ν detection principle
- Detector performance for low energy ν searches
- Physics performance studies
- Conclusion and outlook

IceCube Collaboration

Canada:
University of Alberta, Edmonton

USA:
Bartol Research Institute, Delaware
University of California, Berkeley
University of California, Irvine
Pennsylvania State University
Clark-Atlanta University
Ohio State University
Georgia Tech
University of Maryland
University of Alabama, Tuscaloosa
University of Wisconsin-Madison
University of Wisconsin-River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University and
A&M College, Baton Rouge
University of Alaska, Anchorage

Barbados:
University of the West Indies

UK:
Oxford University

Belgium:
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

Switzerland:
EPFL, Lausanne

Sweden:
Uppsala Universitet
Stockholm Universitet

Germany:
DESY-Zeuthen
Universität Mainz
Universität Bochum
Universität Bonn
Universität Dortmund
Universität Wuppertal
Humboldt Universität
MPI Heidelberg
RWTH Aachen

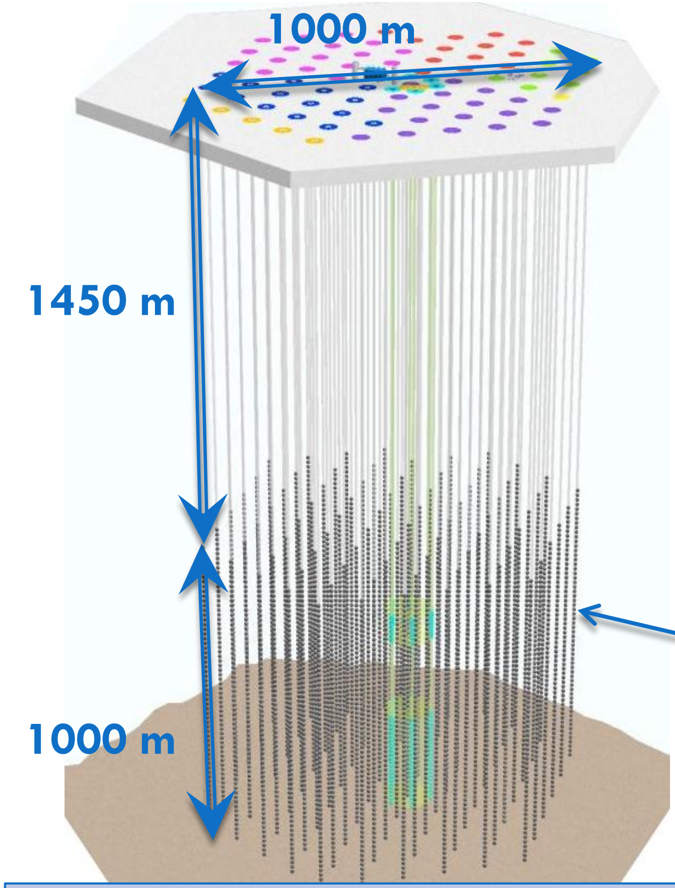
Japan:
Chiba University

New Zealand:
University of Canterbury

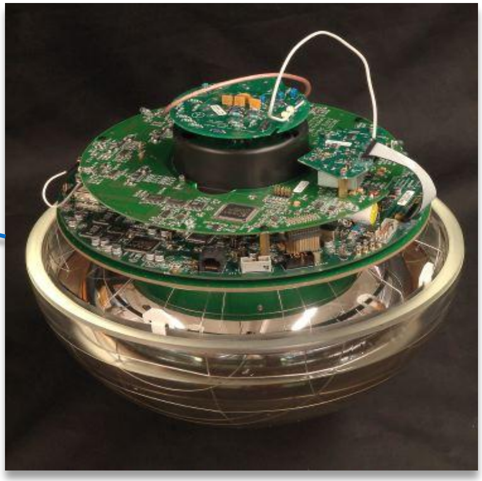
36 institutions, ~250 members

http://icecube.wisc.edu

The IceCube Observatory



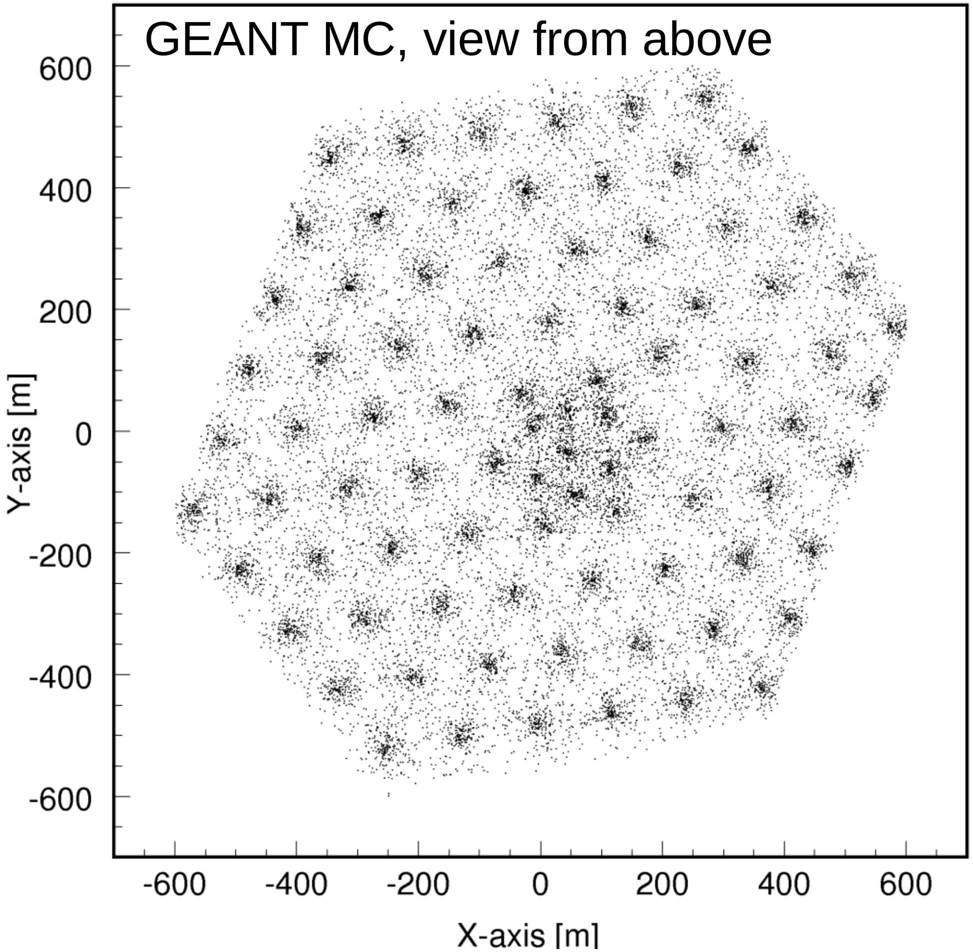
- 78 sparsely instrumented strings
  - ⇨ 17 m vertical sensor distance
  - ⇨ 125 m horizontal string distance
- 8 densely instrumented strings
  - ⇨7-10 m sensor distance
  - ⇨ 60 m horizontal string distance
- 5160 sensors + autonomous DAQ in ice



Status:

- last string deployed on 2010-12-18
- Full 86-string DAQ started on 2011-05-13

Interaction vertices in IceCube



define effective positron volume:

$$N_{\gamma}^{detected} = V_{e^+}^{eff} \times n_{\nu}$$

Simulation:

$$V_{e^+}^{eff} = 29.0 \times E_{e^+}/\mathrm{MeV}$$

$\overline{E_{e^+}} = 20\ \mathrm{MeV}$

Corresponds to:

$\overline{V_{e^+}^{eff}} = 580\ \mathrm{m}^3 \Leftrightarrow r_{eff} = 5.2\ \mathrm{m}$

„full efficient sphere“

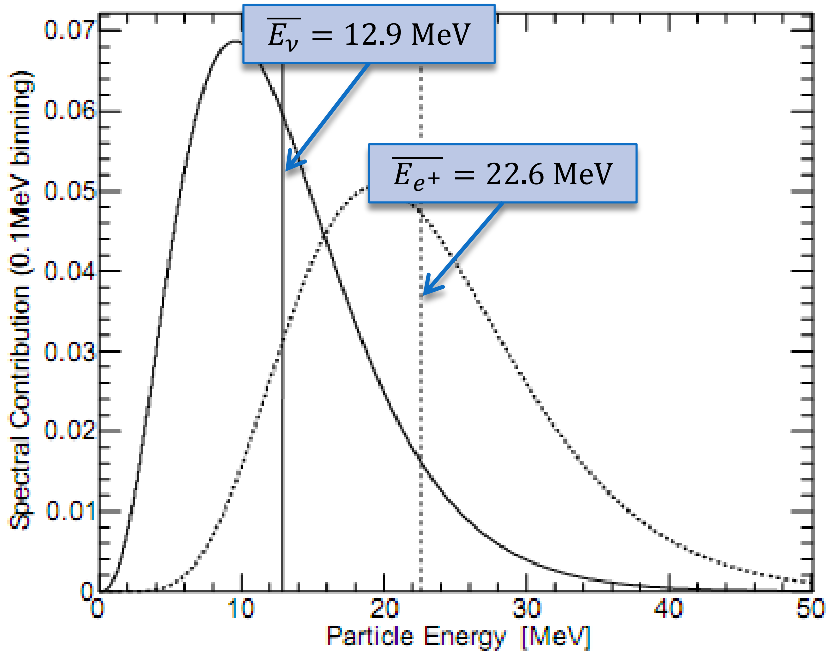
Coincidence probability: $\mathcal{O}(1\%)$

→ small overlap of effective volumes

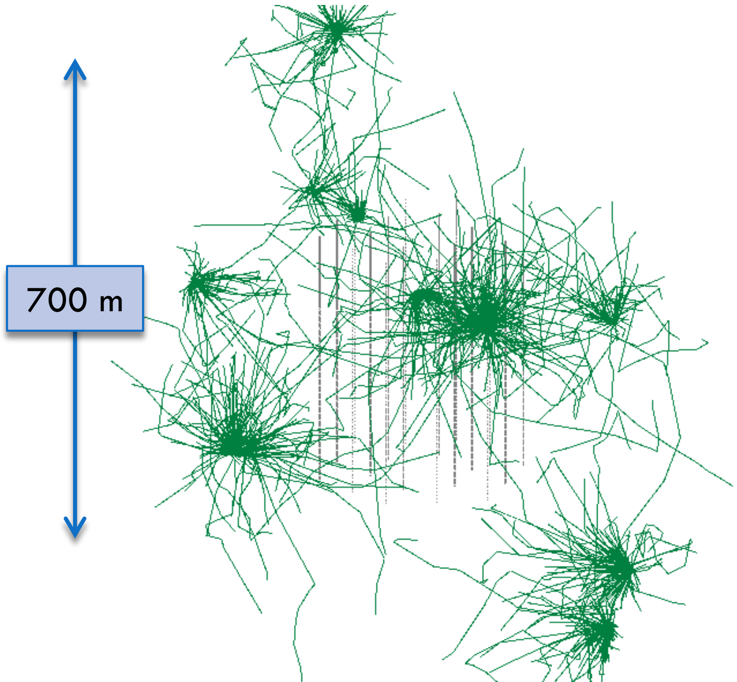
Idea: count single rates on top of low noise background

Detection Principle

Low energy neutrino interactions dominated by inverse beta decay (typical e^+ energy 25 MeV, rate ~ E^3)



Cherenkov photons radiated by 10 e^+ (Avg. Energy 15 MeV, thinned out)



Track length ~ $0.56\ \text{cm} \times E_{e^+}(\text{MeV})$ $\quad N_\gamma^{300-600nm} \sim 178 \times E_{e^+}(\text{MeV})$

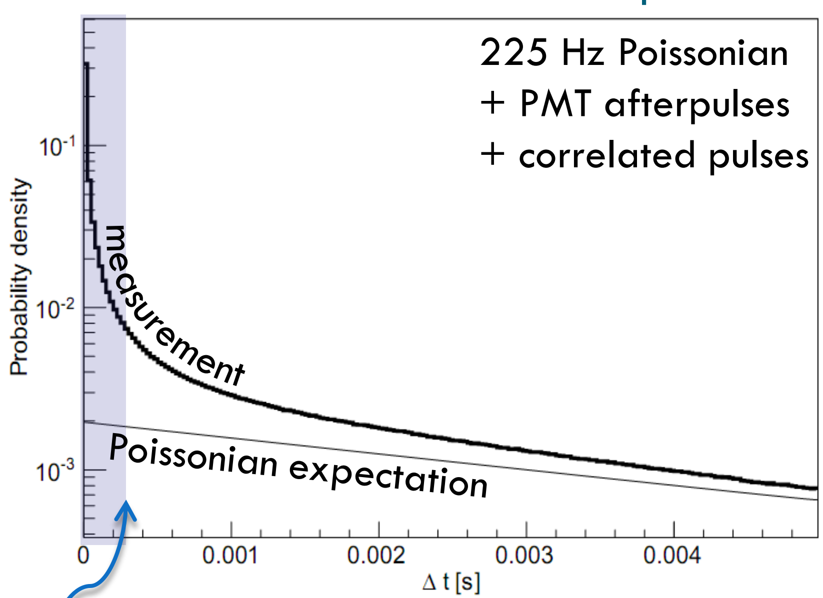
directional dependence and correlations due to Cherenkov ring

→ unimportant for inverse beta decay, max. 20% rate variation ν_e elastic cross section

IceCube background noise

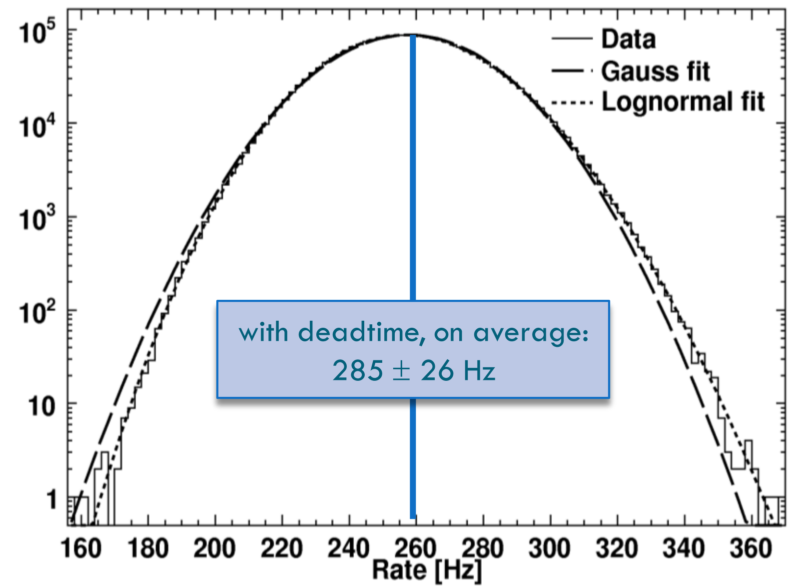
standard DOMs (4800):	**540 Hz**
high quantum efficiency DOMs (360):	680 Hz

time difference between pulses



artificial deadtime to reduce correlated noise (250 μs, non paralyzing)

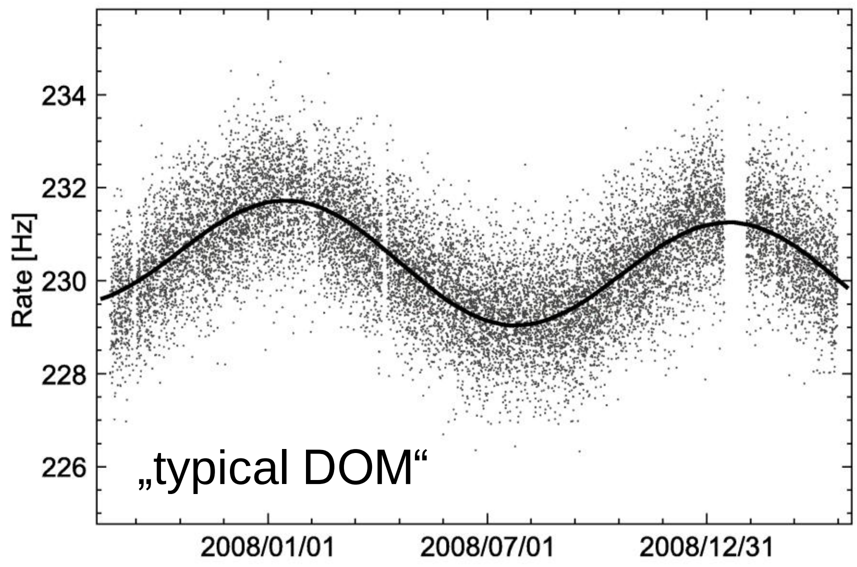
single DOM rate distribution



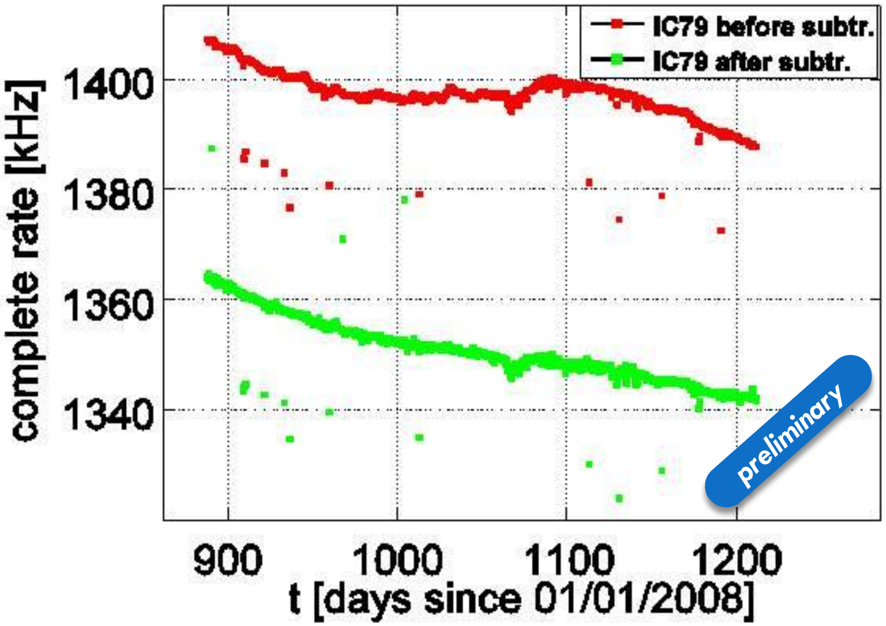
very stable rates, slight depth (=temperature) dependence

Atmospheric muon influence

Seasonal change of noise rate
due to atmospheric pressure (~6%)



Freezing effects still visible
after μ-subtraction



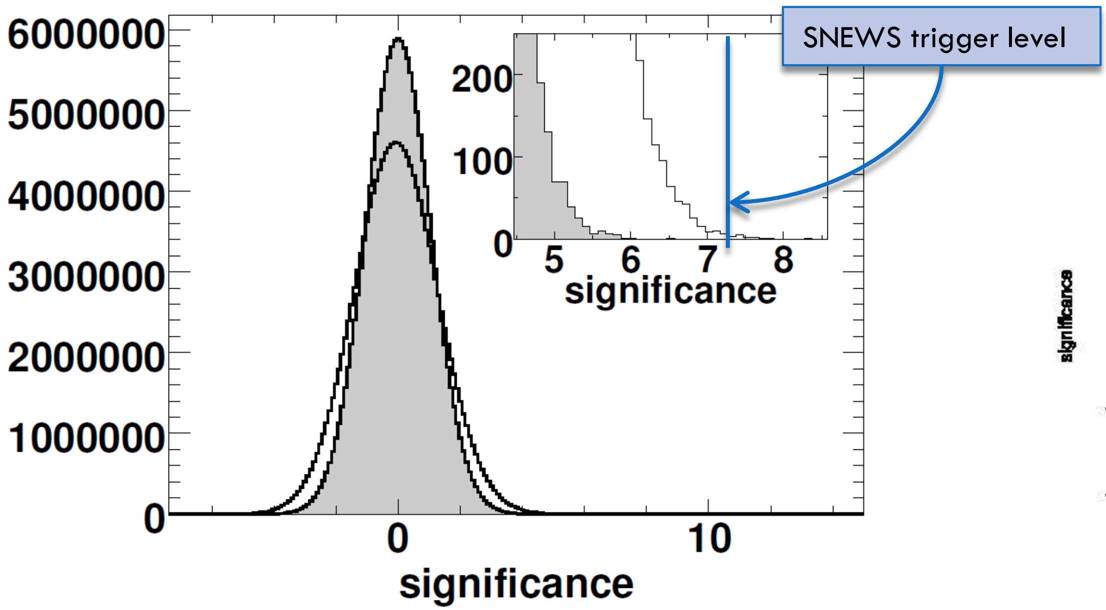
Small contribution which increases significance due to non-Poissoninan correlations
Has been corrected for by subtracting hits associated to a muon track

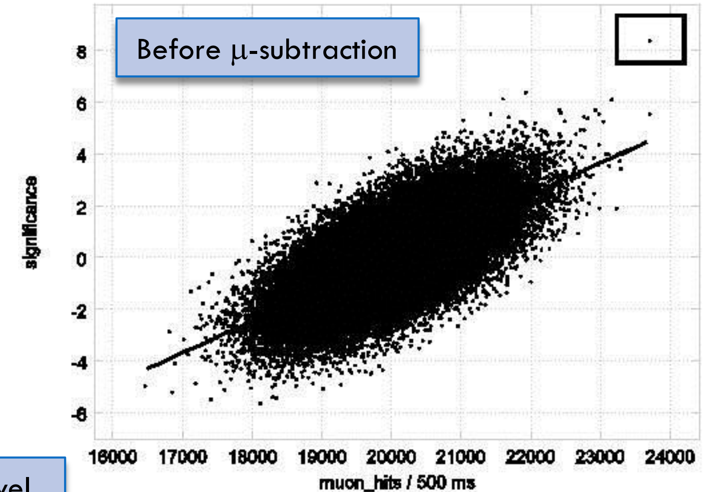
Significance distribution

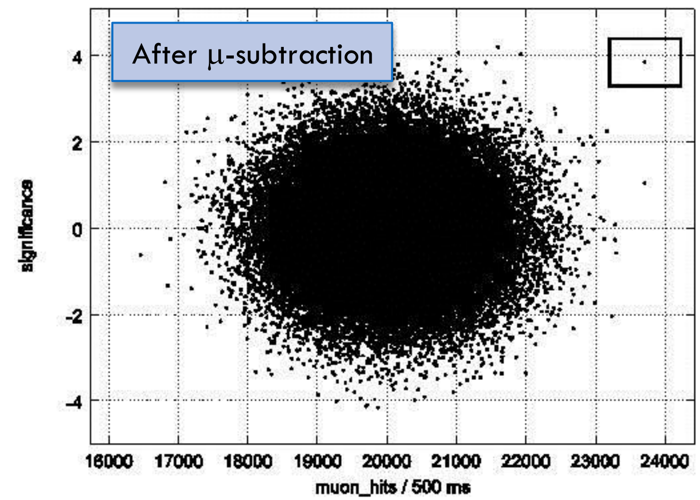
Significance:

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

Overall improvement after subtracting muon hits:

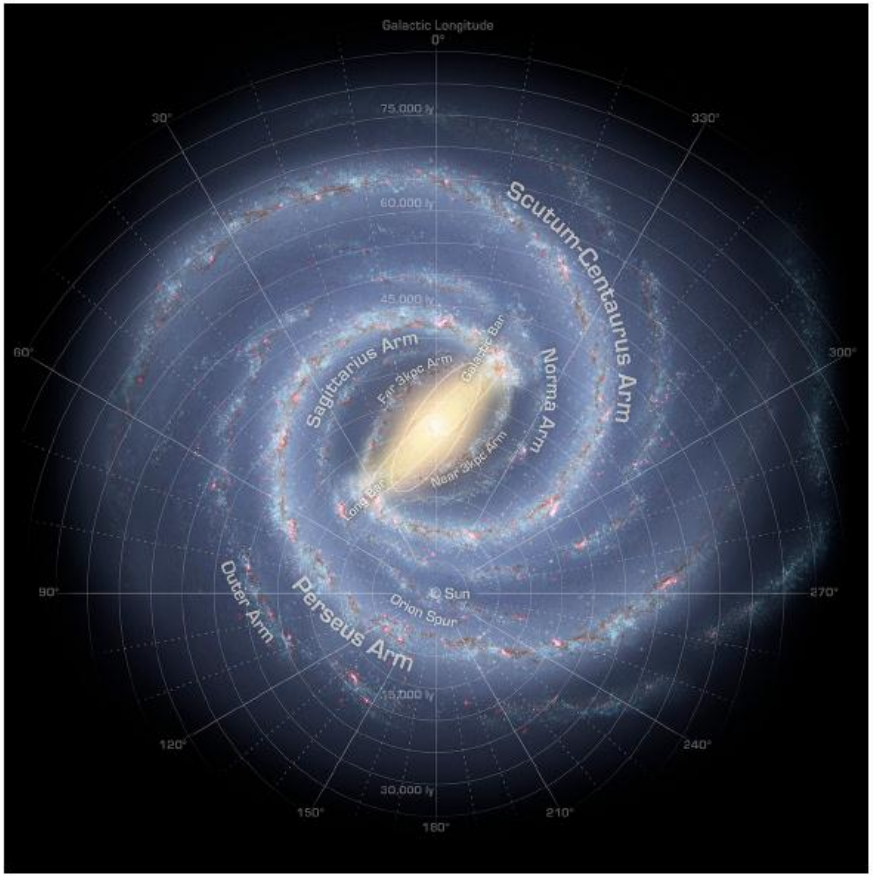




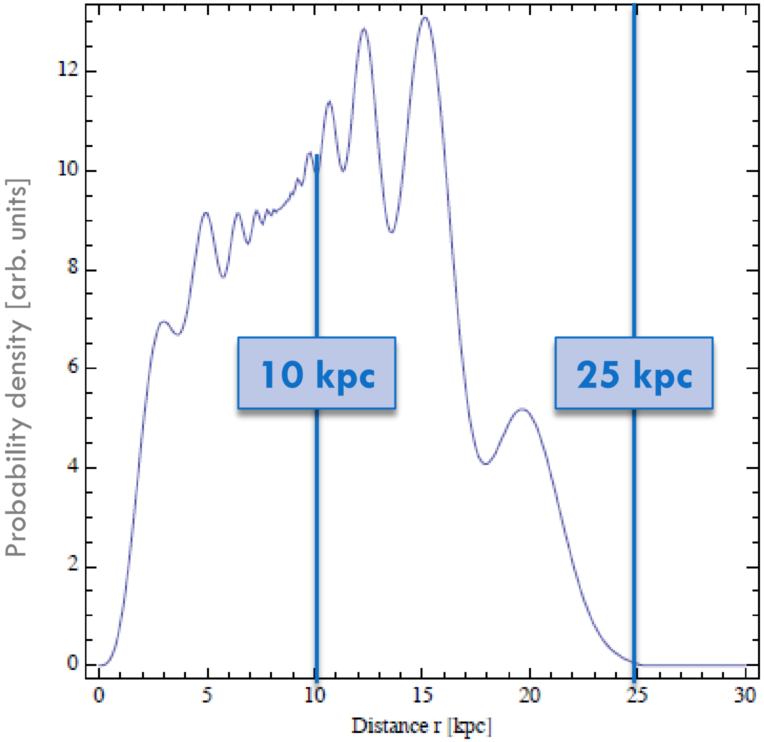


Supernova progenitors in Milky-Way

unclear how candidates follow star distribution …



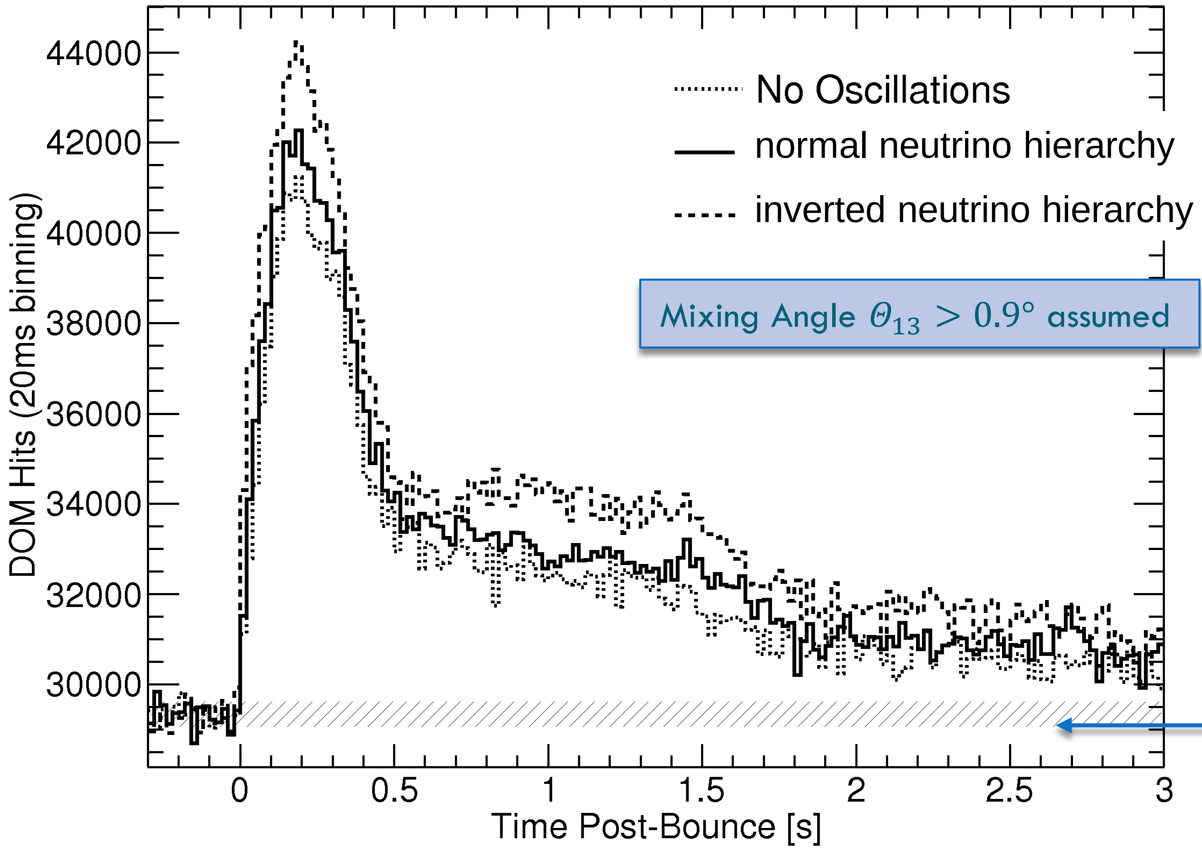
probability distribution for
SN progenitors



PR D80:123017,2009 Ahlers, Mertsch Sarkar

Expected time signal

Lawrence Livermore model, 10 kpc distance (~ distance to center)
IceCube Monte Carlo with time dependent energy spectra incorporated



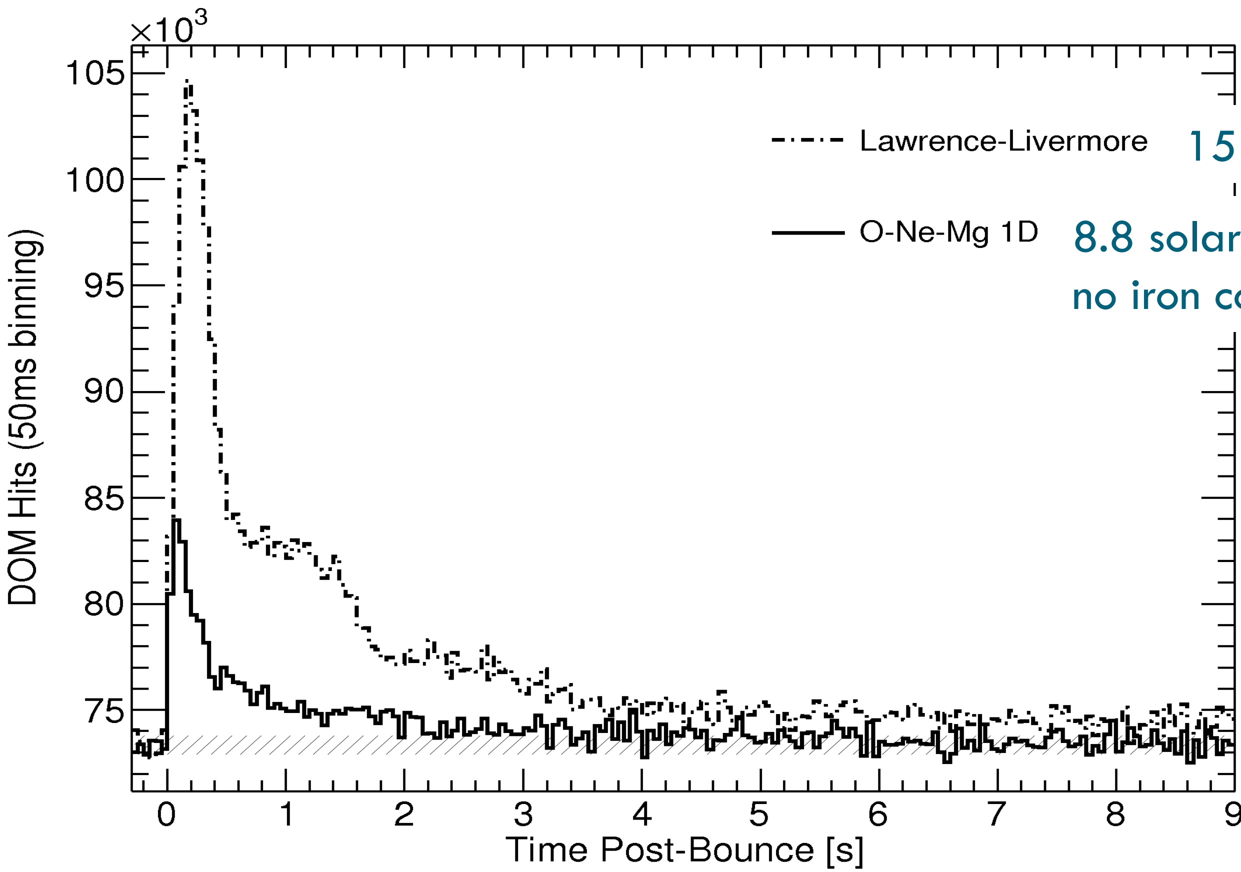
clear differences in model shapes for normal and inverted hierarchy!

background level

Totani et al. Astrop. Phys. 496, 216 (1998)

Strong model dependence

… two available models that make long term predictions



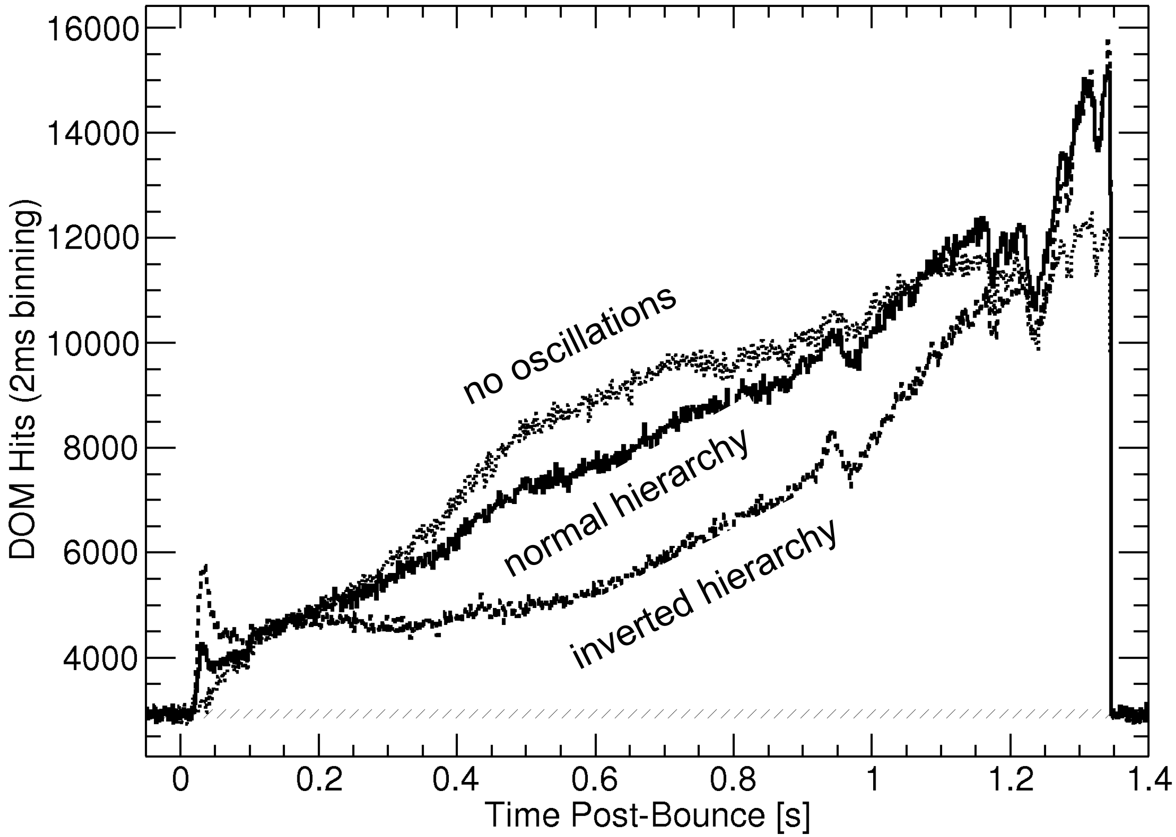
15 solar masses

8.8 solar masses
no iron core

Hüdepohl et al., Phys. Rev. Lett. 104, 251101 (2010)

Exotic Signals

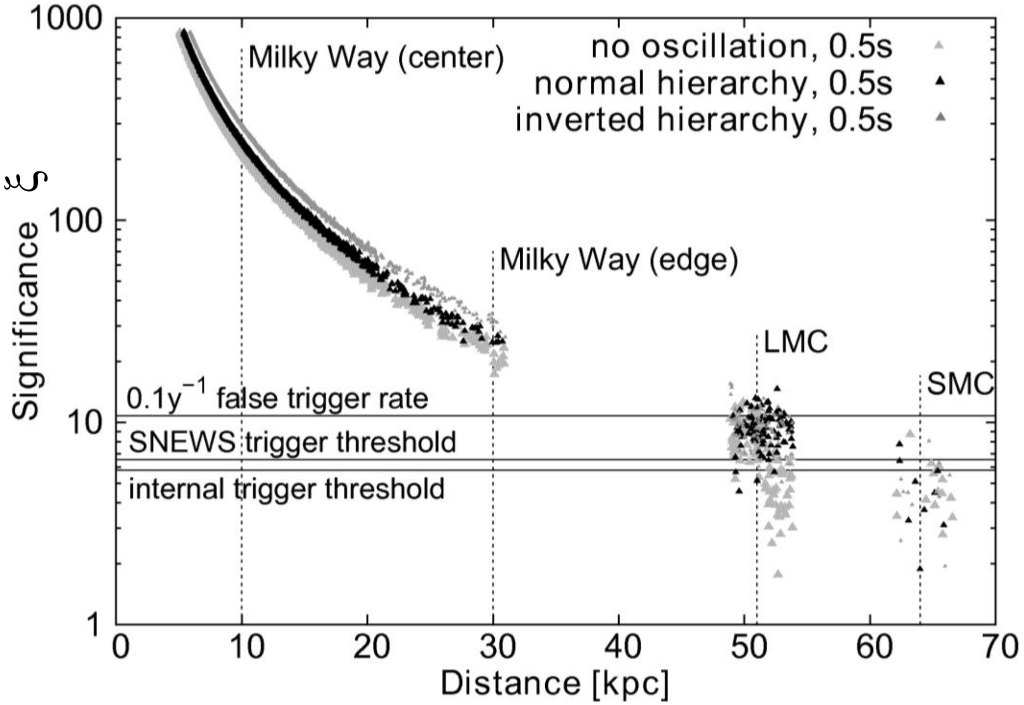
Black hole formation (>40 solar mass progenitor) → no explosion!

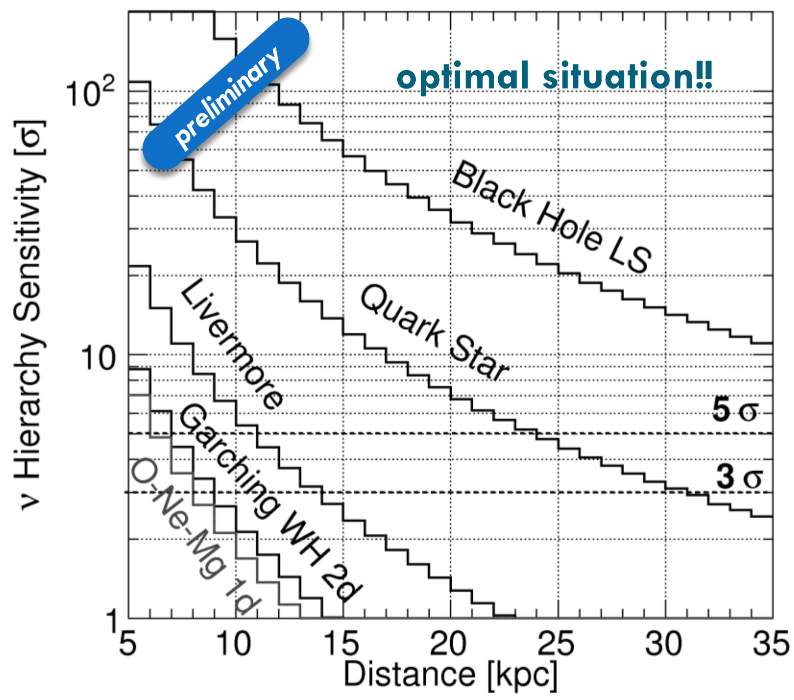


- neutrino emission stops when black hole is formed
- strong hierarchy dependence
- very high statistics!

Sumiyoshi et al., ApJ 667, 382 (2007)

Expected significance





ξ > 25 in Galaxy
ξ ~ 3-10 in Magellanic clouds

depends on detection technique as well as model and neutrino properties …

Conclusion

Advantages:

- **World's best detector for fine details in ν flux of close supernova**
- Good prospects to test ν properties
  $\rightarrow$ distinction of hierarchies
- Observation of exotic phenomena
  $\rightarrow$ black hole formation, maybe even quark gluon plasma transition
- Location far from other SN detectors
  $\rightarrow$ triangulation, earth effect …

Disadvantages:

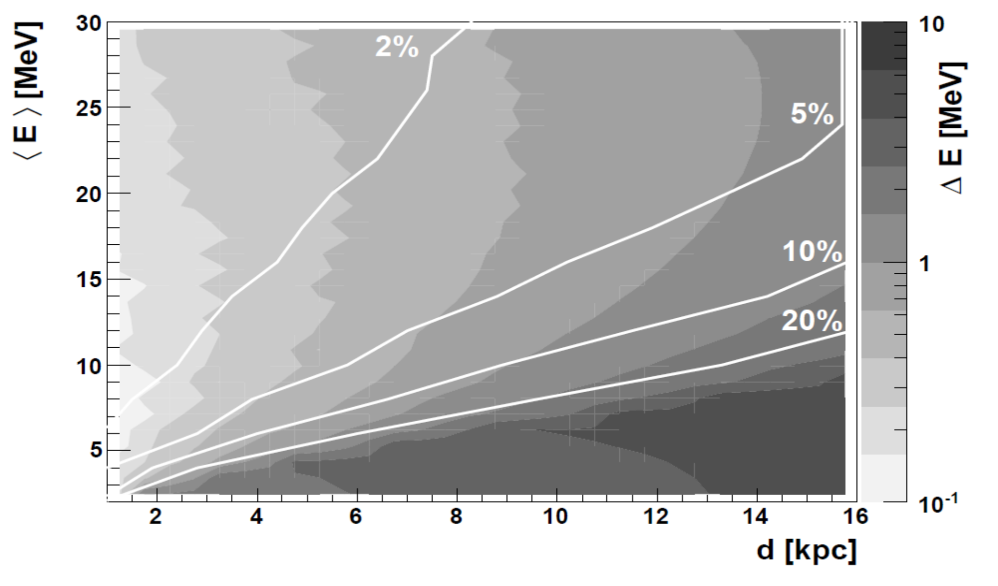
- No information on type, direction and energy of individual neutrino
- Reach limited to 50 kpc
- Limited sensitivity to ν_e (H_2O target)
- Limited time resolution of 2 ms (subject to change…)

…IceCube is a Mton scale detector for supernova neutrinos …

Outlook

- Major low level SnDAQ improvements:
  - Buffer all hit information (including non-SN systems) and dump complete set of individual DOM-hits in case of SN
    - Easier muon subtraction
    - Access to unbinned data, timestamps w. ns precision per hit
    - No overflow for super close SN's (<1 kPc)
  - Shorter delay for trigger system (esp. for SNEWS)

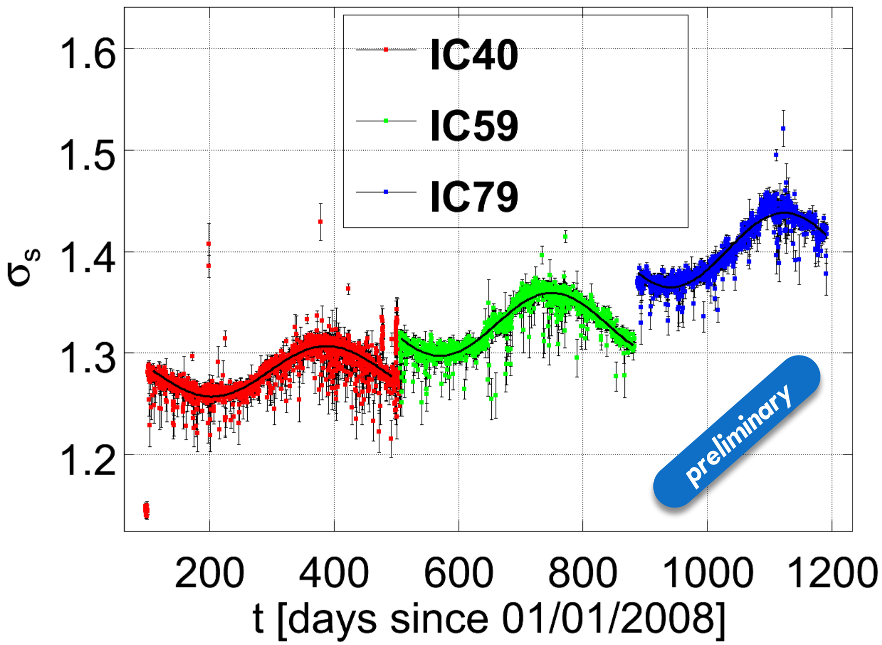
- Using coincidence hits for SN-detection:
  - Background reduction
  - Possible average energy estimator



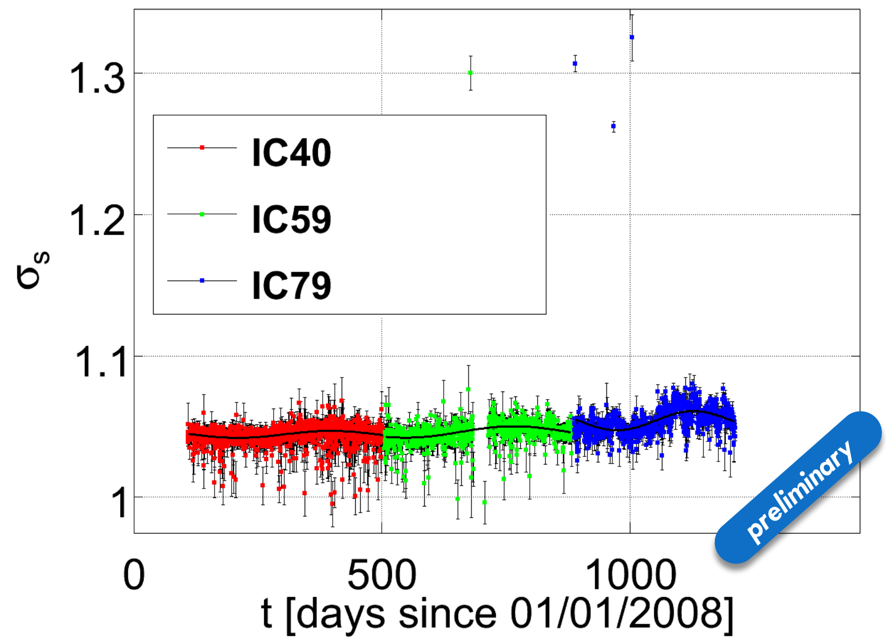

Thank you!

Subtracting muon background

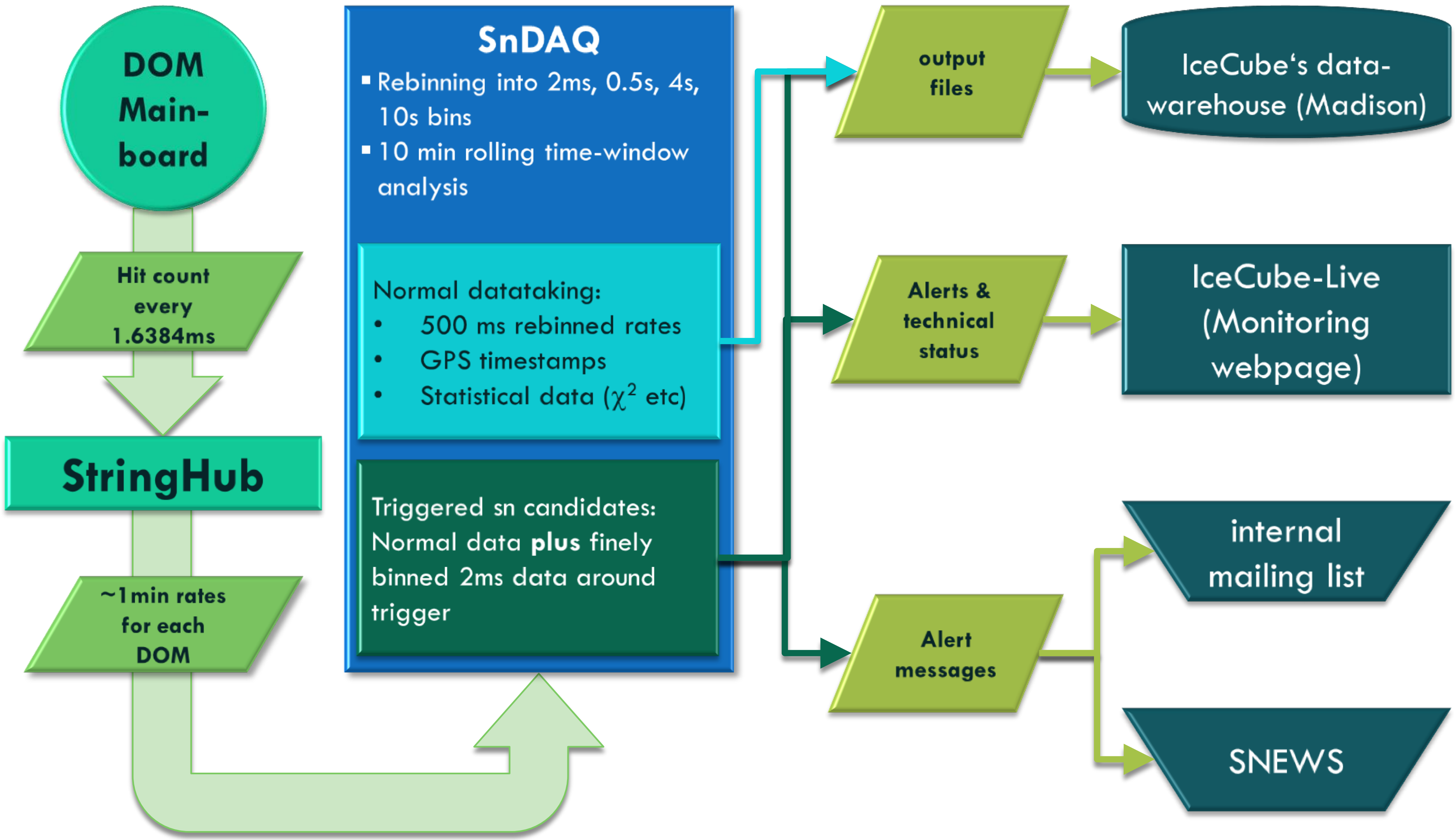
width of significance distribution over three years of construction



Same with muon background subtracted



Supernova-DAQ



Contributing neutrino reactions

Reaction	# Targets	# Signal Hits	Signal Fraction	Reference
$\bar{\nu}_e + p \to e^+ + n$	$6 \cdot 10^{37}$	134 k (157 k)	93.8 % (94.4 %)	Strumia & Vissani (2003)
$\nu_e + e^- \to \nu_e + e^-$	$3 \cdot 10^{38}$	2.35 k (2.25 k)	1.7 % (1.4 %)	Marciano & Parsa (2003)
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	$3 \cdot 10^{38}$	660 (720)	0.5 % (0.4 %)	Marciano & Parsa (2003)
$\nu_{\mu+\tau} + e^- \to \nu_{\mu+\tau} + e^-$	$3 \cdot 10^{38}$	700 (720)	0.5 % (0.4 %)	Marciano & Parsa (2003)
$\bar{\nu}_{\mu+\tau} + e^- \to \bar{\nu}_{\nu+\tau} + e^-$	$3 \cdot 10^{38}$	600 (570)	0.4 % (0.4 %)	Marciano & Parsa (2003)
$\nu_e + {}^{16}O \to e^- + X$	$3 \cdot 10^{37}$	2.15 k (1.50 k)	1.5 % (0.9 %)	Kolbe et al. (2002)
$\bar{\nu}_e + {}^{16}O \to e^+ + X$	$3 \cdot 10^{37}$	1.90 k (2.80 k)	1.3 % (1.7 %)	Kolbe et al. (2002)
$\nu_{all} + {}^{16}O \to \nu_{all} + X$	$3 \cdot 10^{37}$	430 (410)	0.3 % (0.3 %)	Kolbe et al. (2002)
$\nu_e + {}^{17/18}O/{}^2_1H \to e^- + X$	$6 \cdot 10^{34}$	270 (245)	0.2 % (0.2 %)	Haxton (1999)

Expected rates

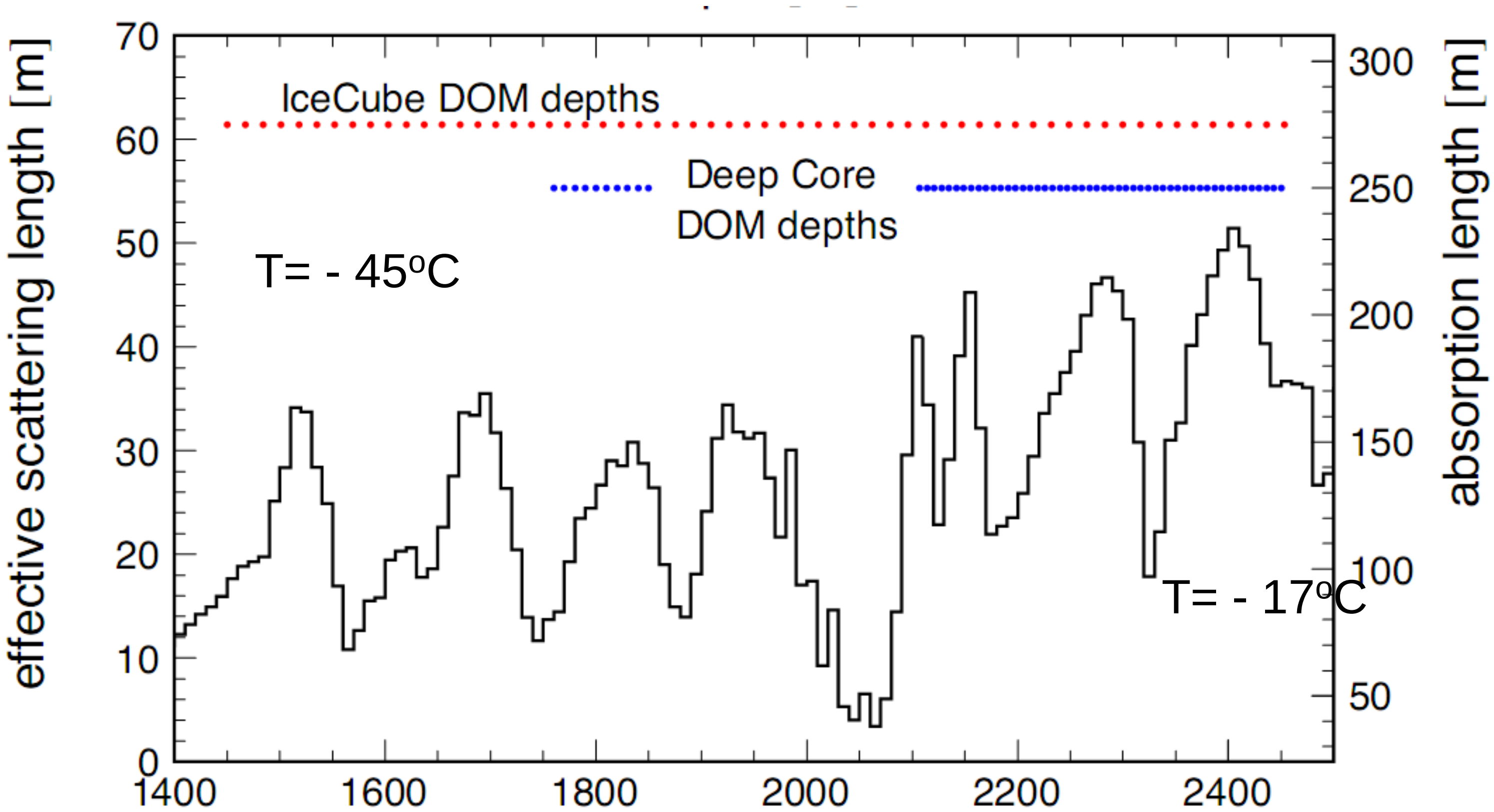
… for various models …

Expected rates

Model	Reference	Progenitor mass ($M_\odot$)	#ν's $t < 380$ ms	#ν'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 …

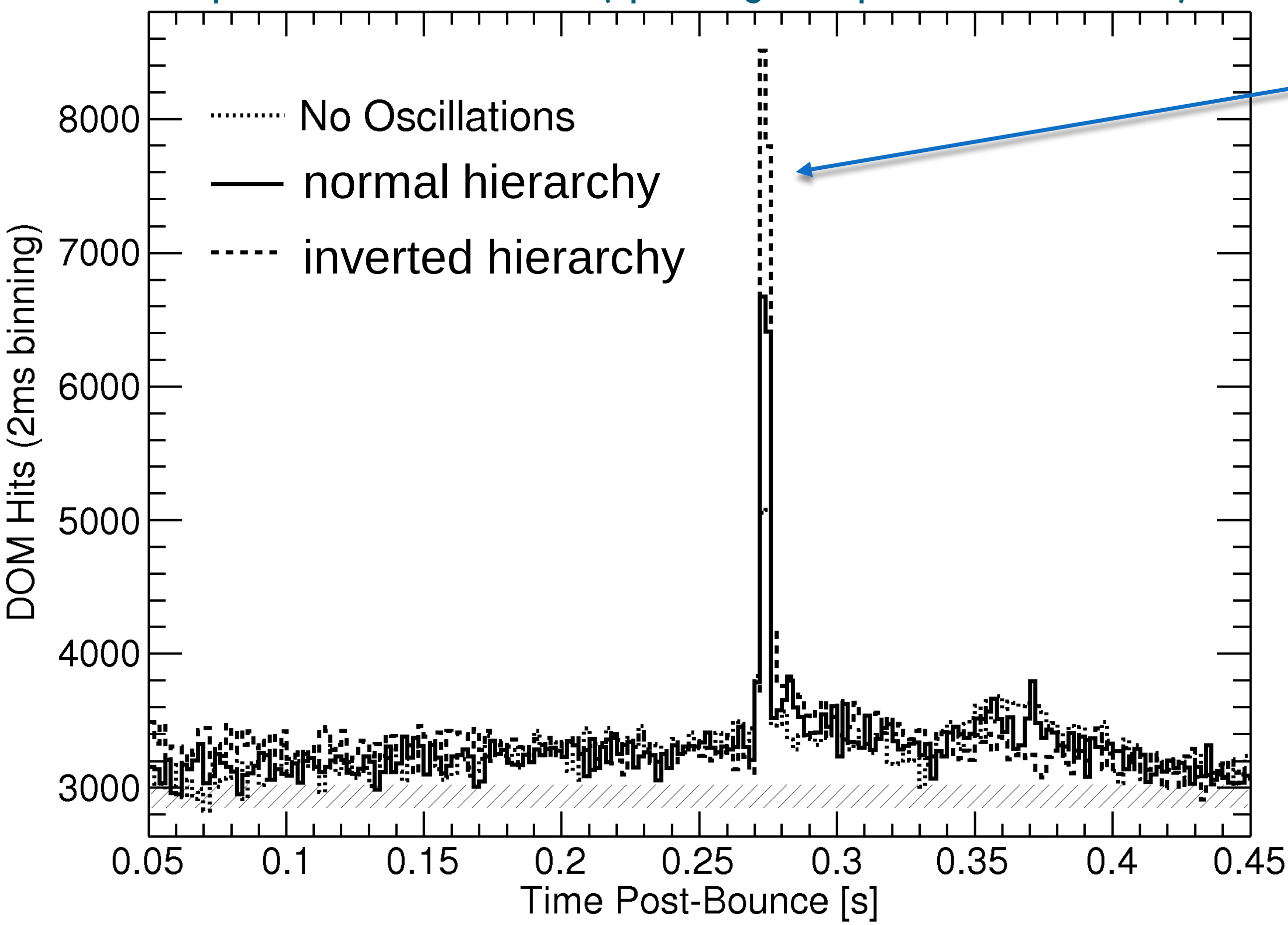
Ice Properties



- Long absorption lengths (>100 m)
- **Low temperature,** dark and inert ice
- Very **low radioactivity** !

…even more exotic signals

quark star formation (quark-gluon plasma transition)

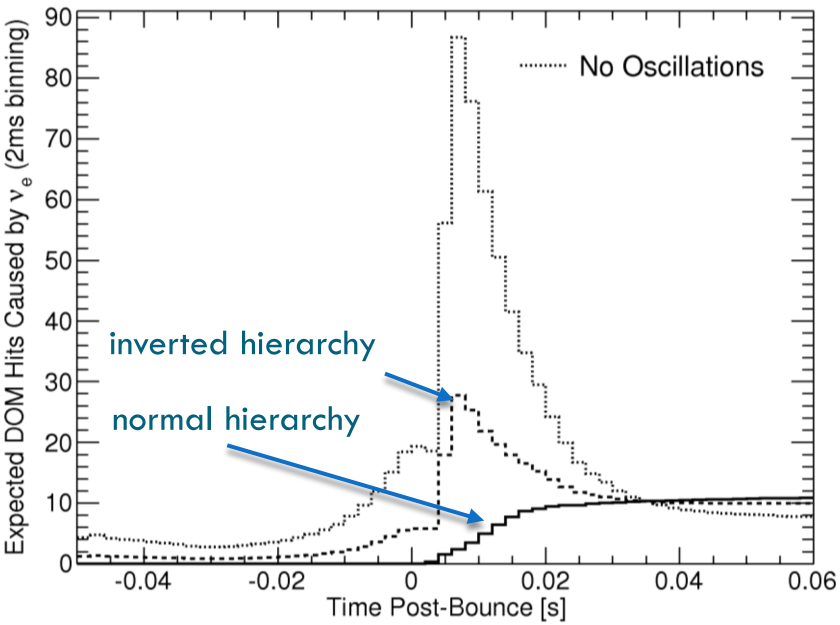


clear anti-υ peak!
… hierarchy dependence

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

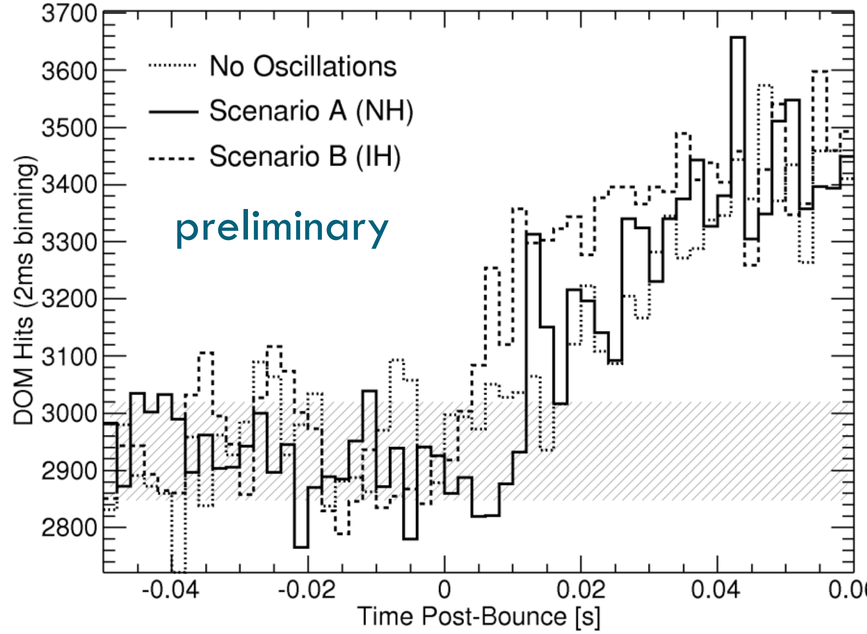
Onset of neutrino production

no background, only υ_e



„deleptonization peak"

with backgrounds, all υ's



very much dependent on neutrino properties and oscillations

→ difficult to observe …

Kachelriess et al., Phys. Rev. D 71, 063003 (2005)