Supernova detection in IceCube
Status and Future

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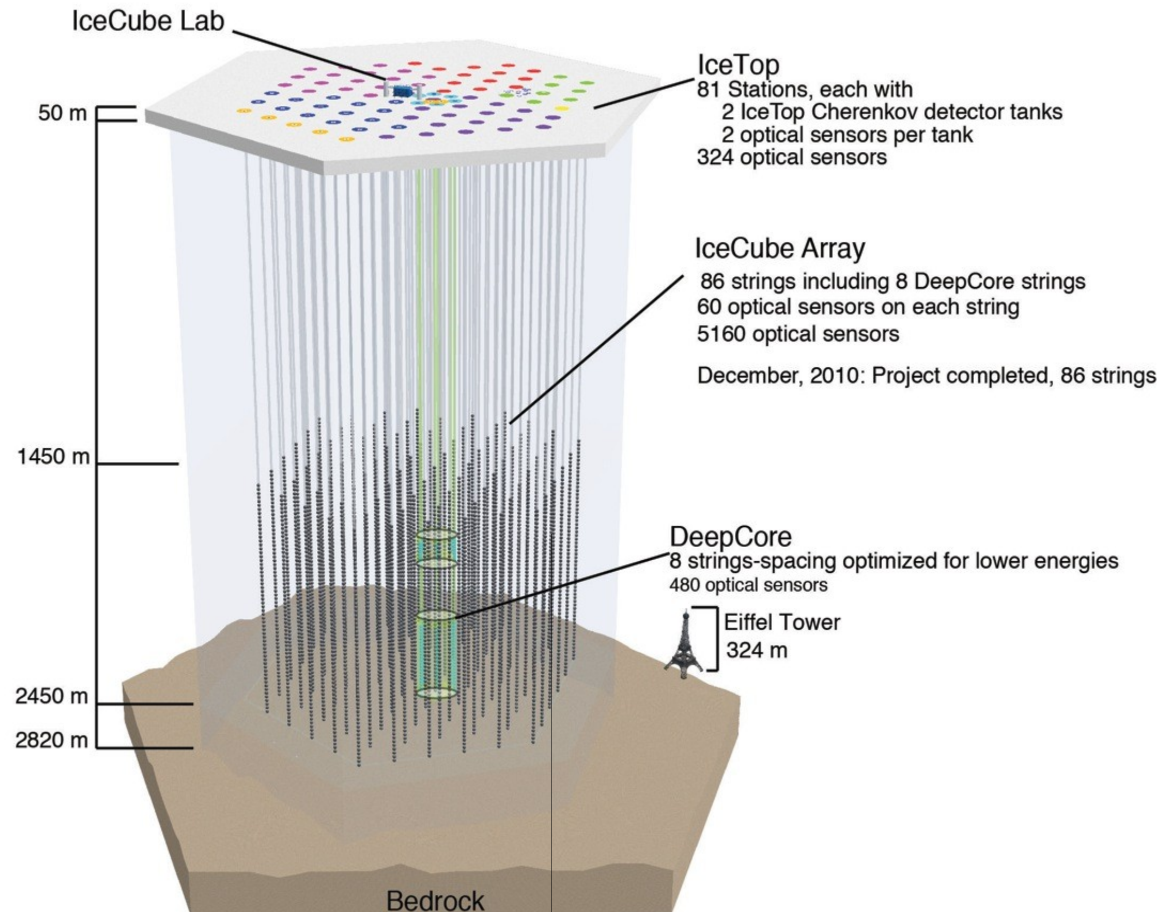
ICECUBE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

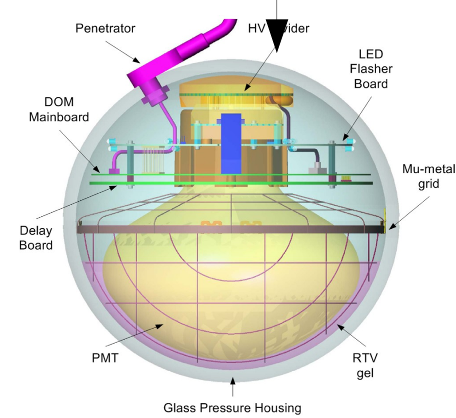
IceCube

- Km^3 instrumented in the Antarctic Ice at the South Pole
- Sensors : 10” photomultipliers housed in pressure resistant spheres: DOMs
- 86 strings total
- 5160 DOMs
- DeepCore:
  - Optimized for lower energies



- Physics programme:
  - Neutrino point sources
  - Gamma ray bursts
  - Cosmic-ray anisotropy
  - Neutrino oscillations
  - ...

DOM:



See IceCube talks at this conference for more details

Main detection channel/events in IceCube

Cherenkov light from the products of the interaction of an individual primary

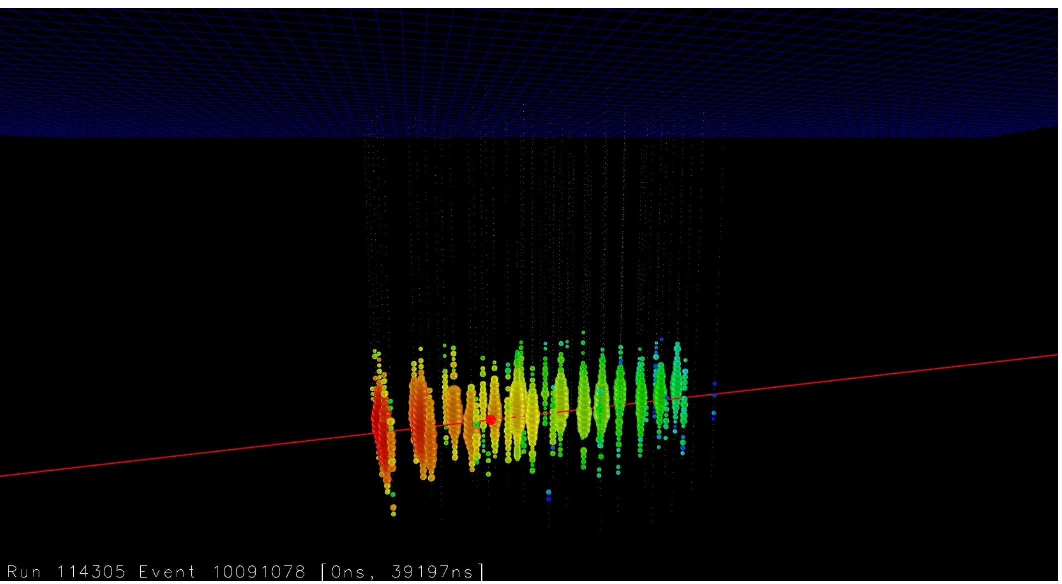
Different primary and interaction types lead to different hit patterns (hit: recorded photon(s))

Primaries carry enough energy to create a significant number of hits

The large number of hits allows for reconstruction of event (direction, energy, type)

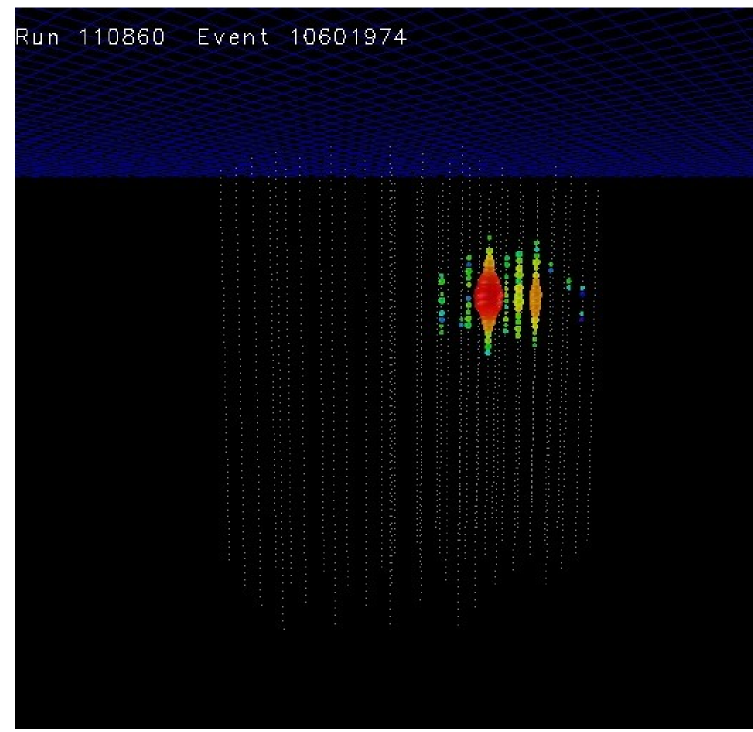
Examples:

Tracks



Up-going (~TeV) muon track from a muon neutrino interaction

Cascades



Sensitive to all neutrino types through neutral current

Supernova detection in IceCube

In contrast, the interaction of a supernova neutrino (~10 MeV) does not produce enough photons to derive the properties

- Main interaction channel (~93%) :
    - Inverse beta decay (anti-nue)
- Detection: Cherenkov light from positrons
    - Number of photons proportional to *E*
    - <u>Very small photon detection probability per interaction</u>

Need a large number of interactions to have significant signal !

Supernova within our Galaxy (at 10kpc):

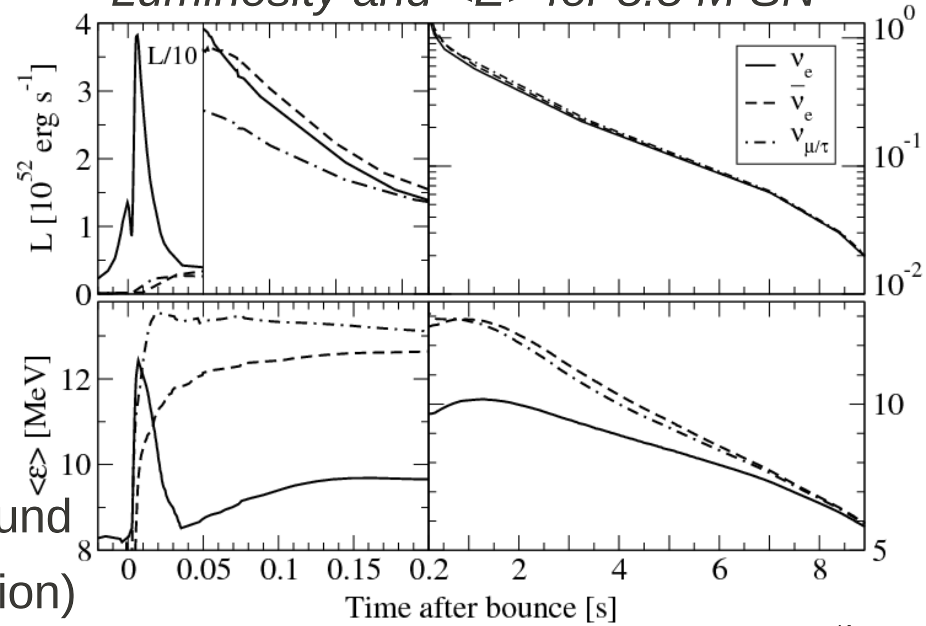
~0.3 neutrino interactions/m^3/10 seconds uniformly distributed

~$3x10^8$ interactions in IceCube volume

Detection by increase of noise rate on top of background

No information on individual interaction (energy/direction)

Luminosity and <E> for 8.8 M SN



L. Hüdepohl, B. Müller, H. -T. Janka,
A. Marek, G. G. Raffelt, Phys. Rev. Lett. 104, 251101 (2010).

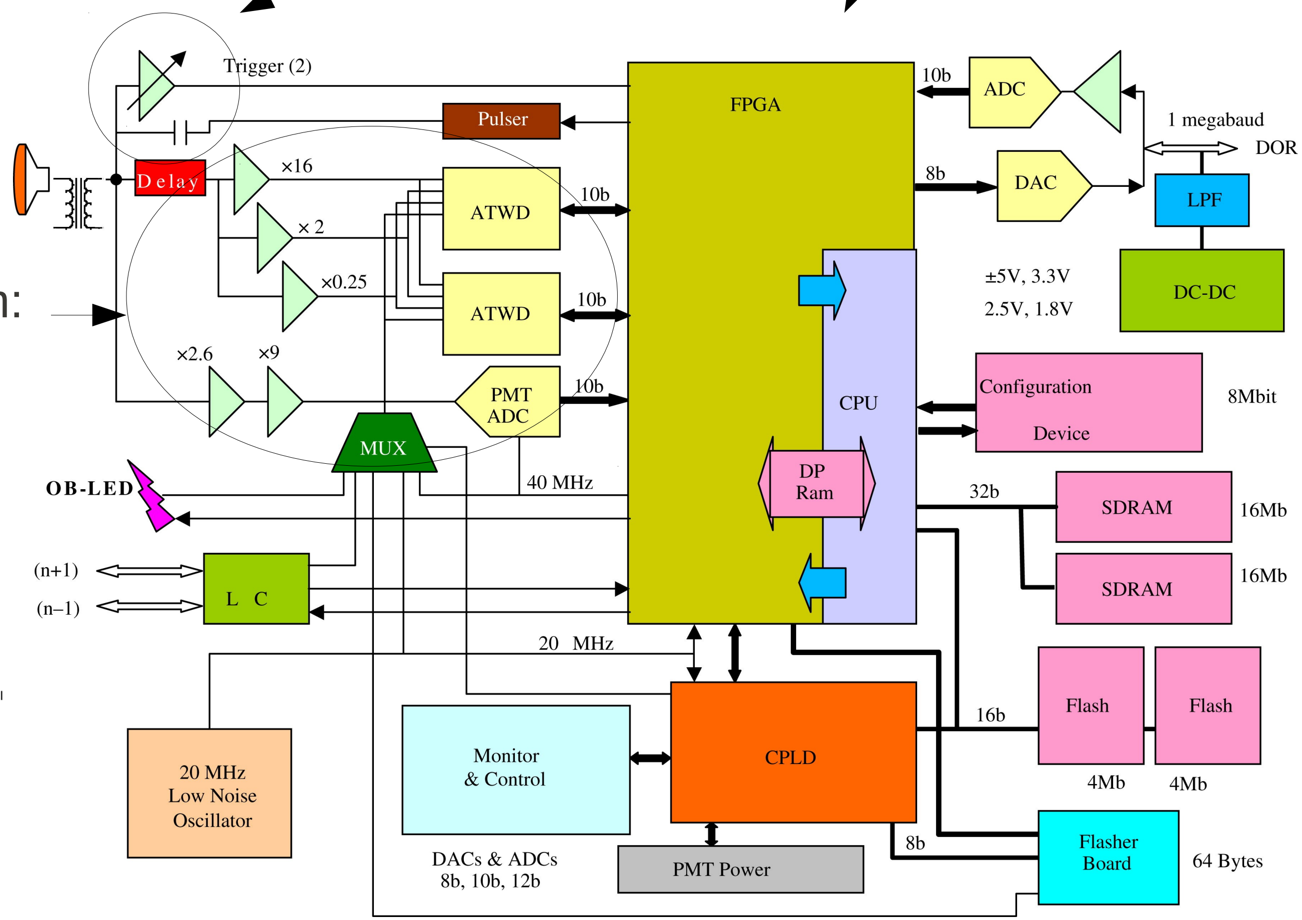
Standard Supernova detection: SNdaq

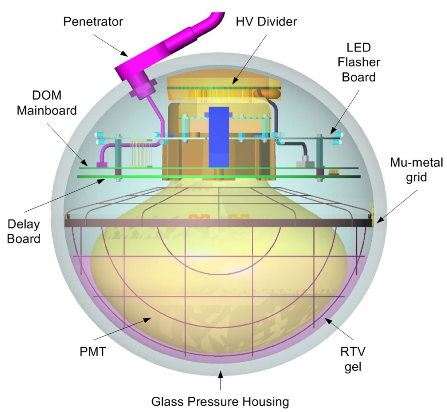
The supernova datastream is separate from the primary datastream
- Scaler format
- Discriminator threshold: 0.25 p.e.
- Binning: 1.6384 ms

Scaler

Software counter

Primary data stream: Waveforms

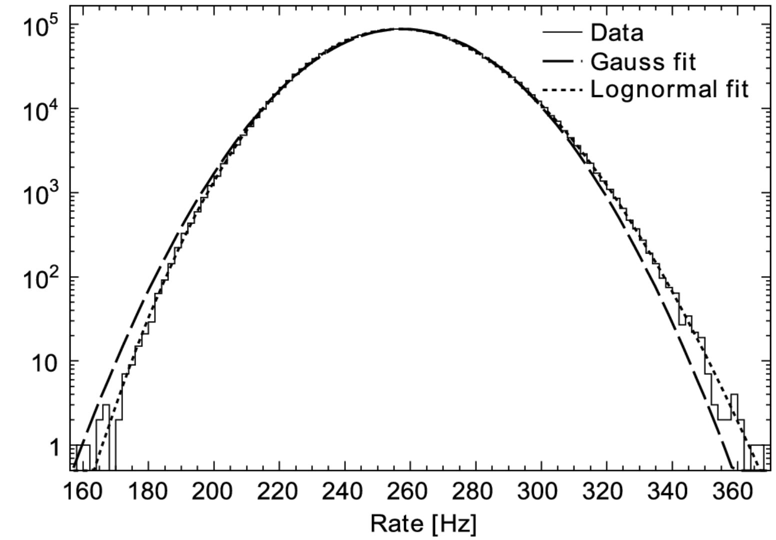




Nucl.Instrum.Meth. A601 (2009) 294-316 arXiv:0810.4930

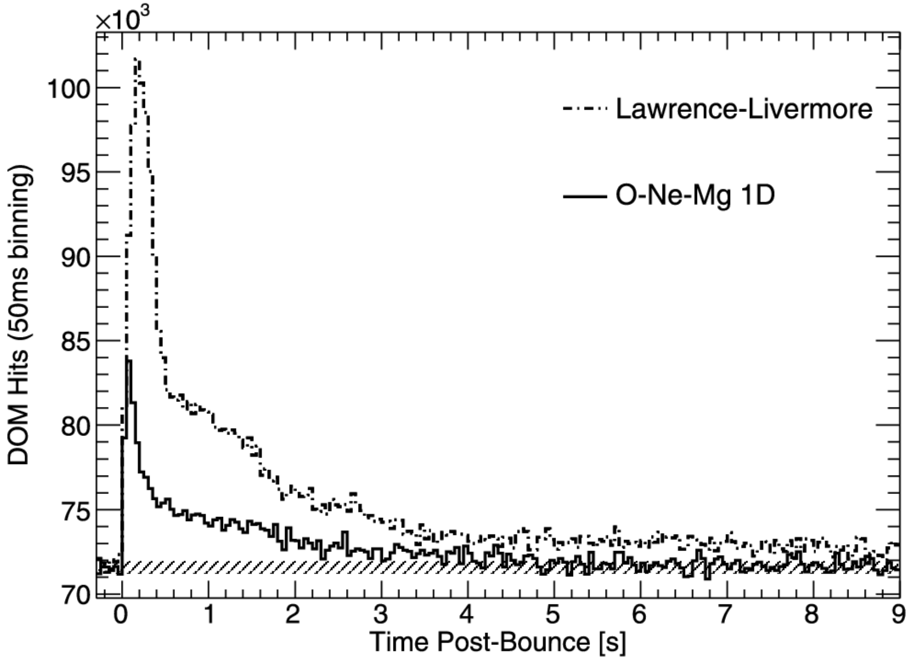
Standard supernova detection: background and signal

- DOM noise rates are log-normally distributed
- Rate: 265+-26 Hz after deadtime
- Stable, with 6% seasonal variation
- Re-binned and synchronized in 2ms bins



Supernova detection :

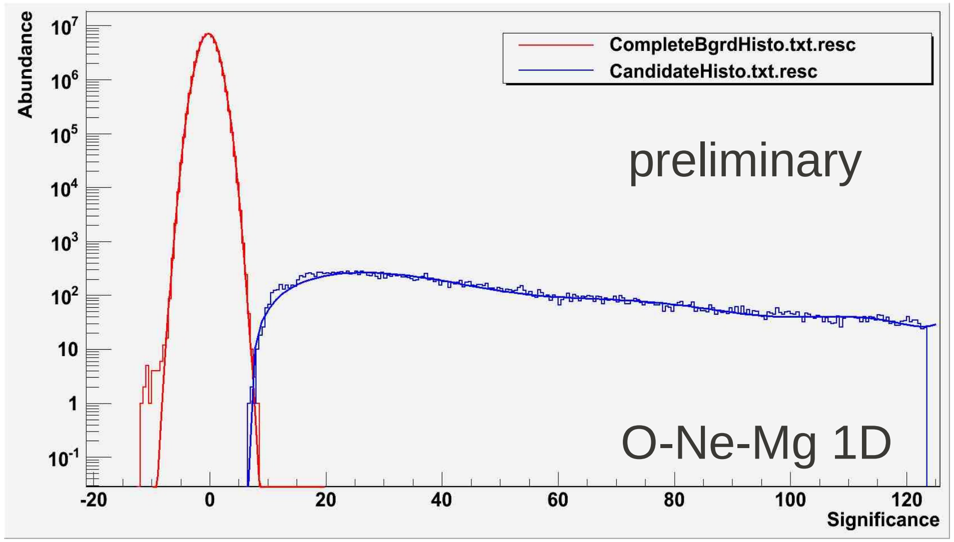
- Search for <u>collective</u> rise over all DOMs in noise ($\Delta\mu$)
  - Rate estimate in 300 s bins
  - Likelihood analysis estimates $\Delta\mu$ and error $\sigma_{\Delta\mu}$
  - Correction for individual DOM characteristics
  - Several bin sizes: 0.5 , 1.5,4 and 10 s



IceCube Collaboration: R. Abbasi et al (Journal) Astronomy and Astrophysics 535 (2011) A109

Standard Supernova detection

- Significance: $\xi=\Delta\mu/\sigma_{\Delta\mu}$
- Atmospheric muon background widens significance distribution and is corrected



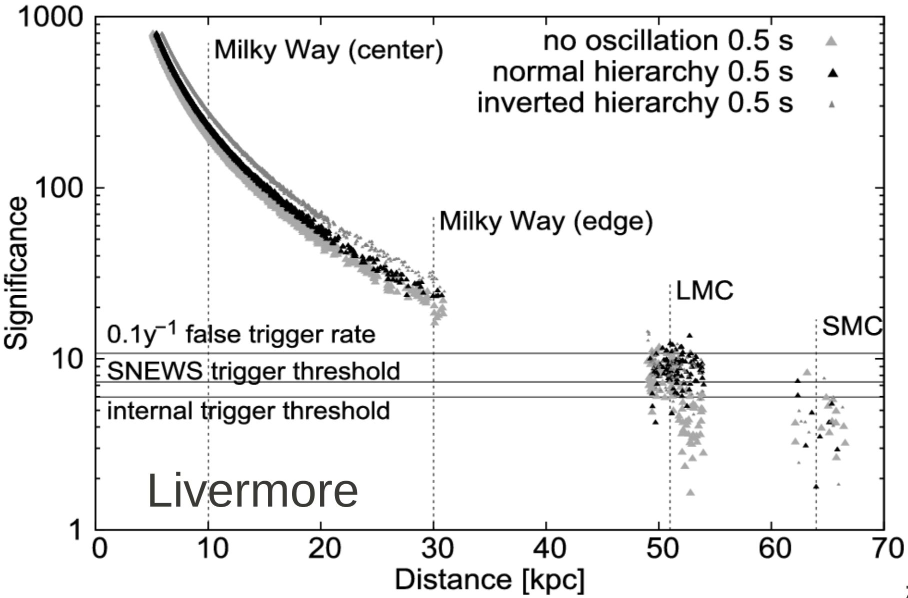
Supernova triggers :

$\xi=6.0$: internal trigger

$\xi=7.65$: SNEWS trigger

(SNEWS: Supernova Early Warning System)

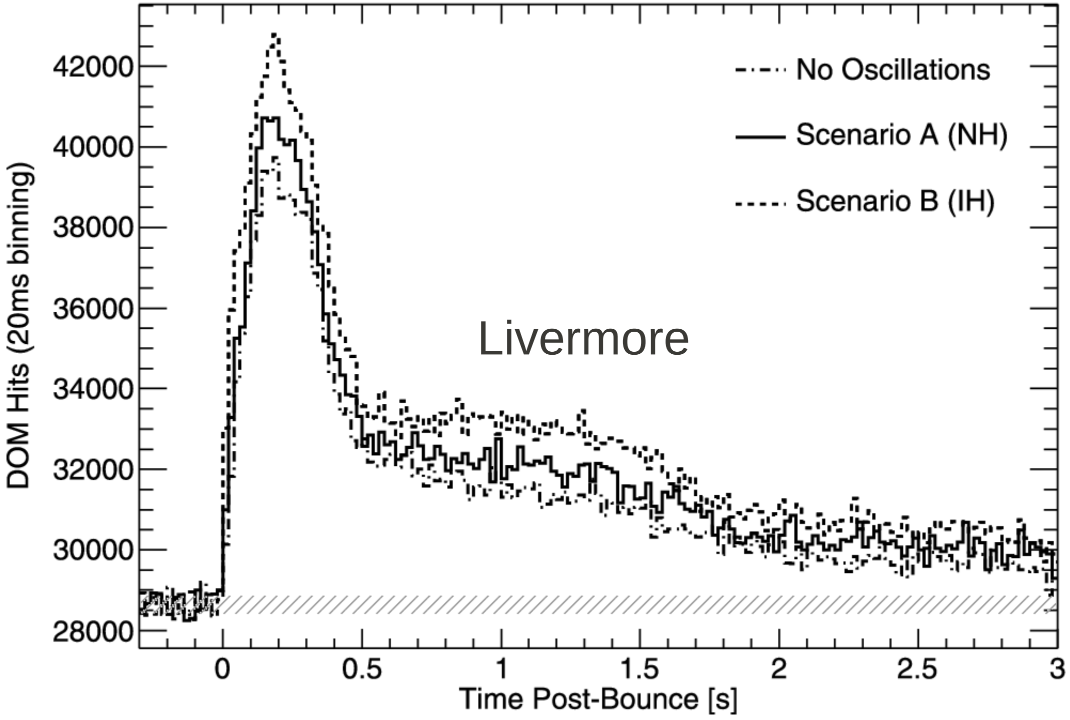
- High significance within Milky Way
- Triggers up to Small Magellanic cloud

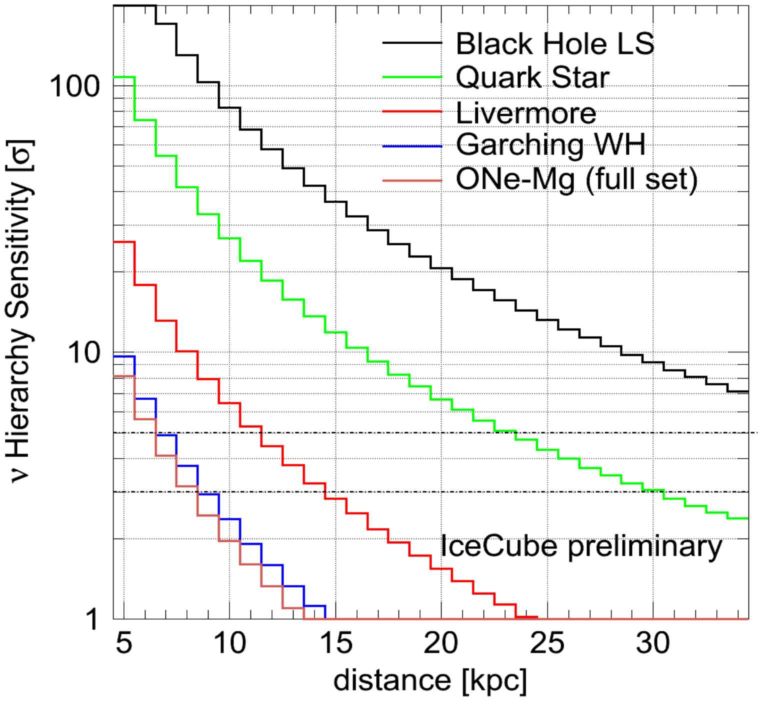


Standard Supernova detection: Neutrino Oscillations/Hierarchy

Different neutrino hierarchies lead to different detected rates for a given model

<u>If the emission model is known</u>, hierarchy can be determined for close supernovae





Beyond Standard SN detection: coincident hits

The luminosity and average energy are entangled, and cannot be distinguished by just measuring the rate !

Luminosity

Flux at detector
$$\frac{d\tilde{\Phi}_{\bar{\nu}_e}}{dE_\nu}(E_\nu, d) = \frac{1}{4\pi d^2}\int_0^{\tilde{t}} \frac{L(t)}{\langle E\rangle(t)} f_{\alpha(t),\langle E\rangle(t)}\, dt$$

Average energy

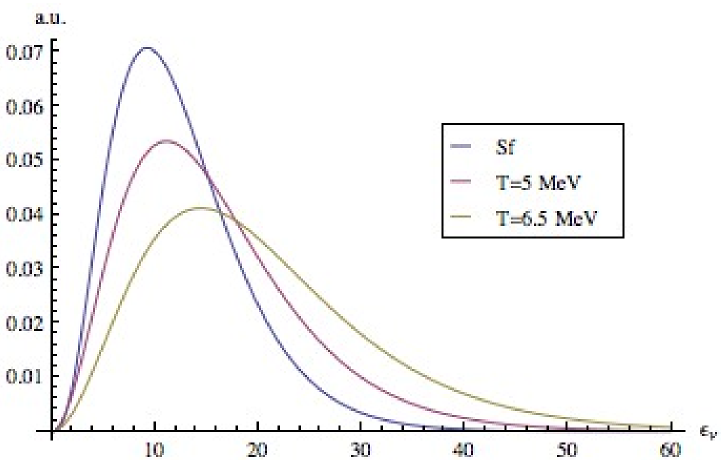
Spectral shape
In this talk we use:
$$f_{\alpha,\langle E_\nu\rangle}(E_\nu) = \frac{(1+\alpha)^{1+\alpha}}{\langle E_\nu\rangle \Gamma(1+\alpha)} \left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{\langle E_\nu\rangle}}$$

Average energy

'Shape'

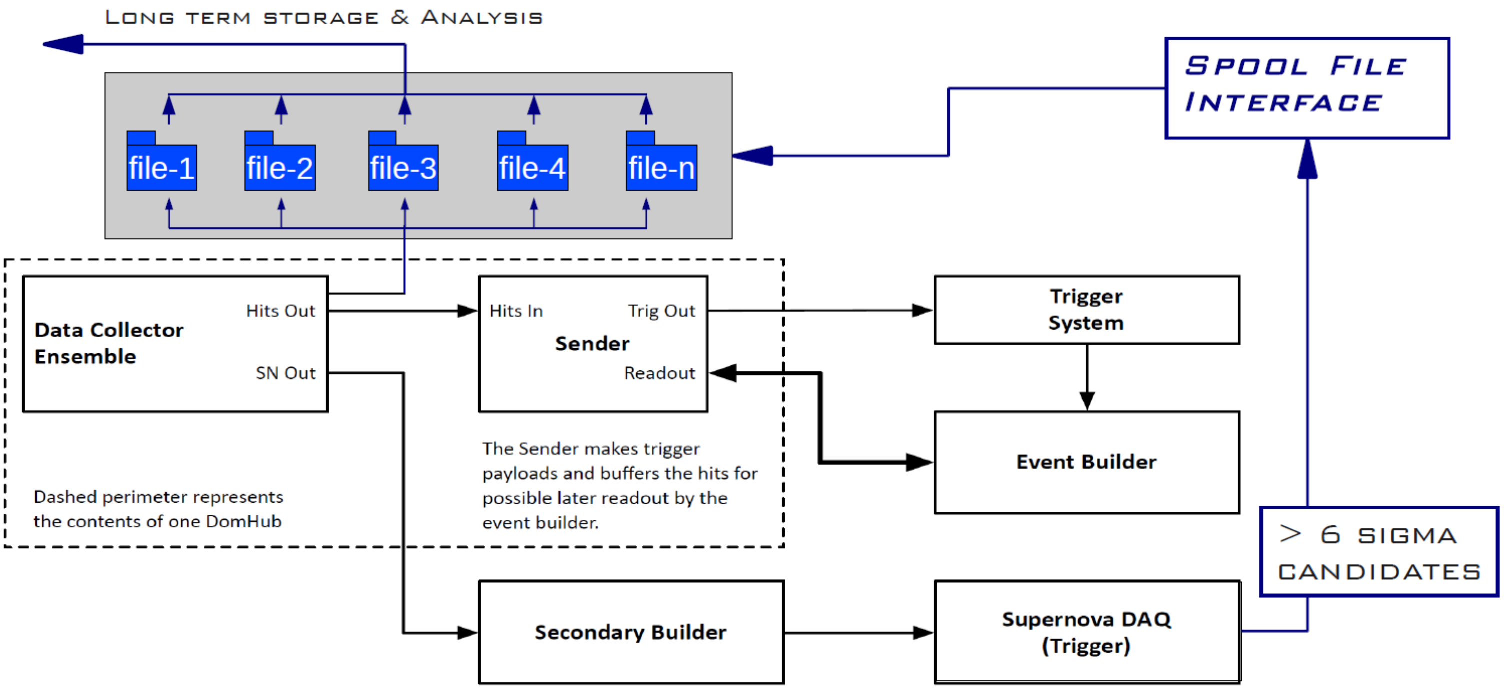
Coincident hits from individual interaction can provide additional information

- Coincidences are sensitive to different parts of the spectrum
    - Probability of coincidence increases with energy
- The more dense the detector, the more powerful this technique



Coincident Hits: Future DAQ improvement: Hit-Spooling

- An improvement to the SNdaq is foreseen : Hit-Spooling
  - All photon hits are stored in a rotating file system
  - Written to permanent storage in case of a SN trigger
- Advantages :
  - Improved timing resolution
  - Additional information can be obtained from coincident hits
  - Background monitoring and reduction



Coincident Hits: Hit modes

Photon hits *i* and *j*, at times t_i and t_j are coincident when $|t_i - t_j| < \delta t$

Several hit modes :

- Single sensor hit: mode 10 (or “1+0”)
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- A single hit in two sensors : 11 (or “1+1”)
  - Nearest-neighbour (NN)
  - Next-to-nearest-neighbour (NNN)
  - Even farther distance (...)
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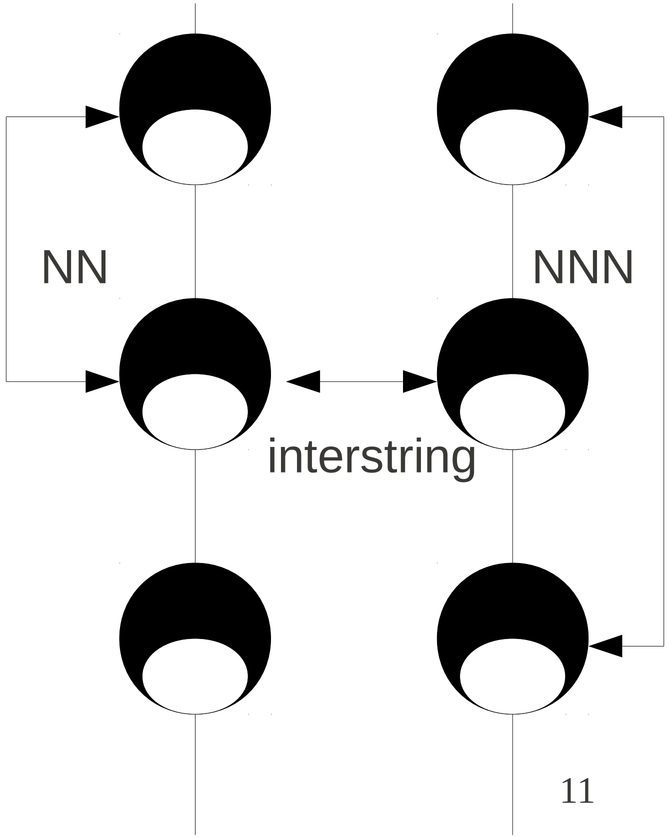
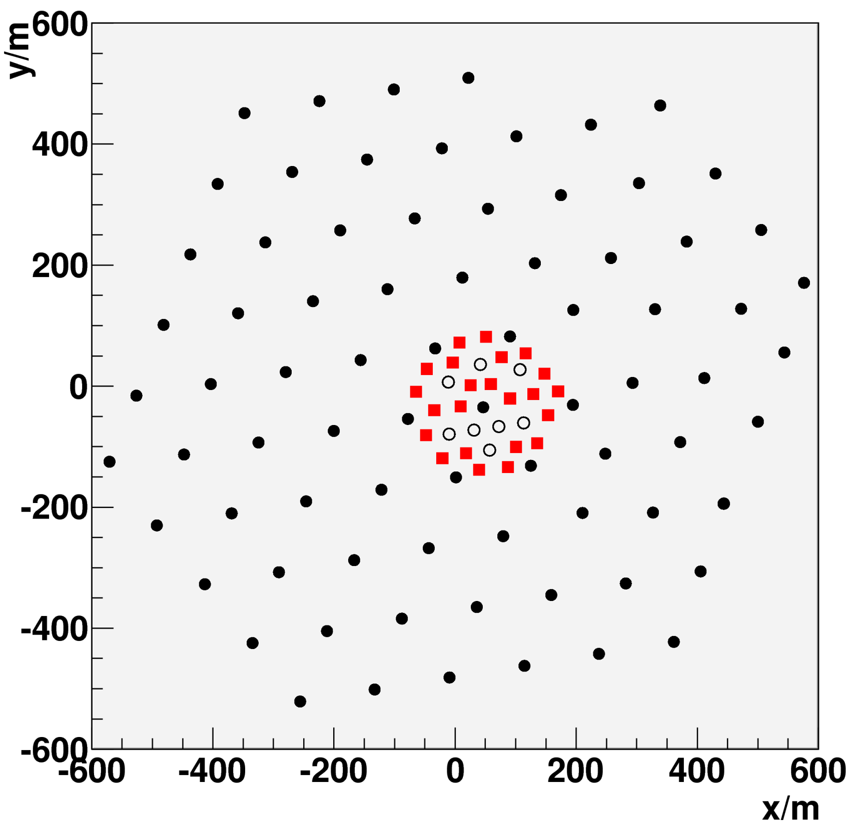
  - Same string, NN, NNN or farther
  - Different strings (2 or 3 strings)
- And more ...

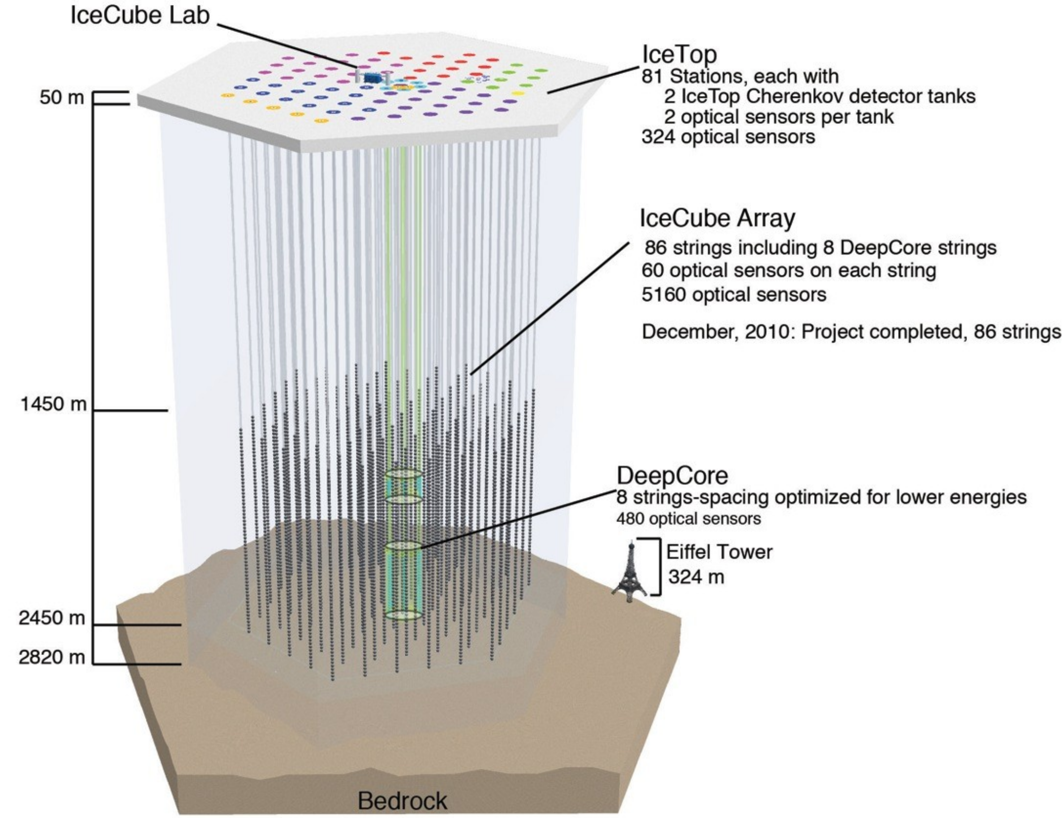


Coincident Hits: Denser detector

IceCube : 17 m between sensors
DeepCore : 7 m between sensors



● : IceCube
○ : DeepCore
■ : Deep and Dense



PINGU: projected dense enhancement
The final configuration is not settled,
here we assume the particular geometry
from ApP 35, 485 (2012) which we call:

Deep and Dense

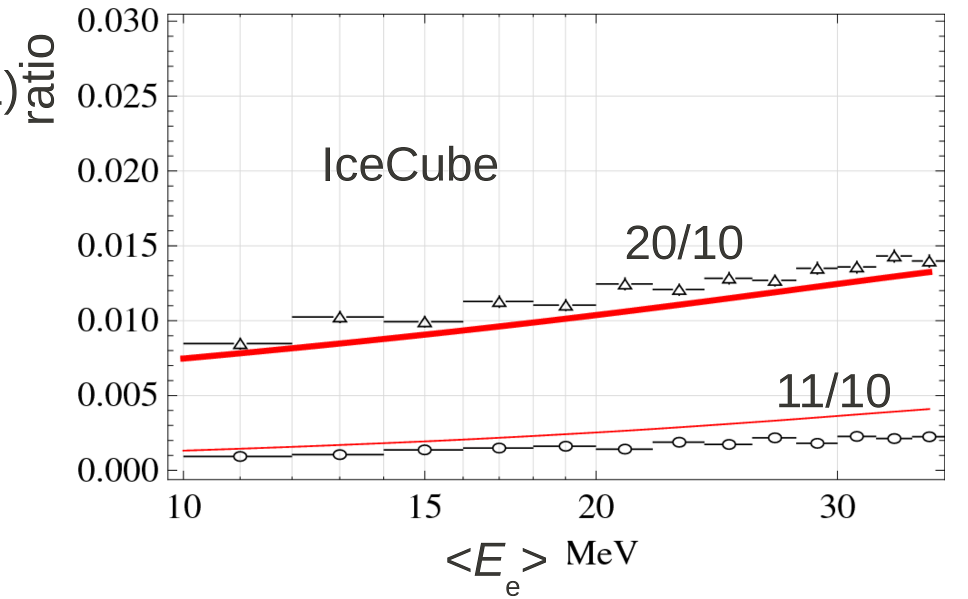
20 strings
120 sensors/string
3 meter between sensors
4π sensitive sensors

Coincident Hits: Energy

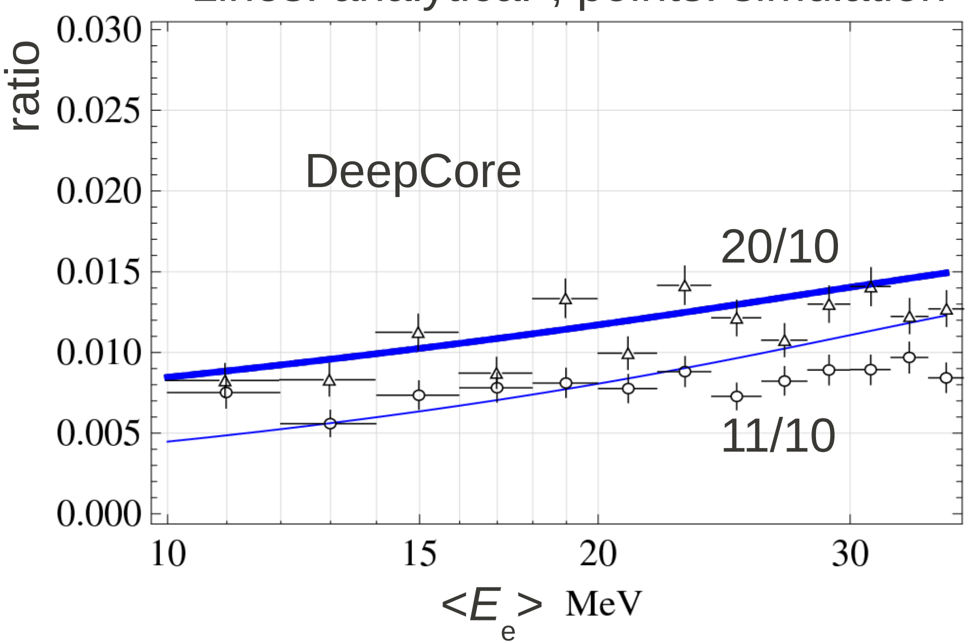
The ratios of the different hit modes (rate2/rate1) show a sensitivity to the average energy

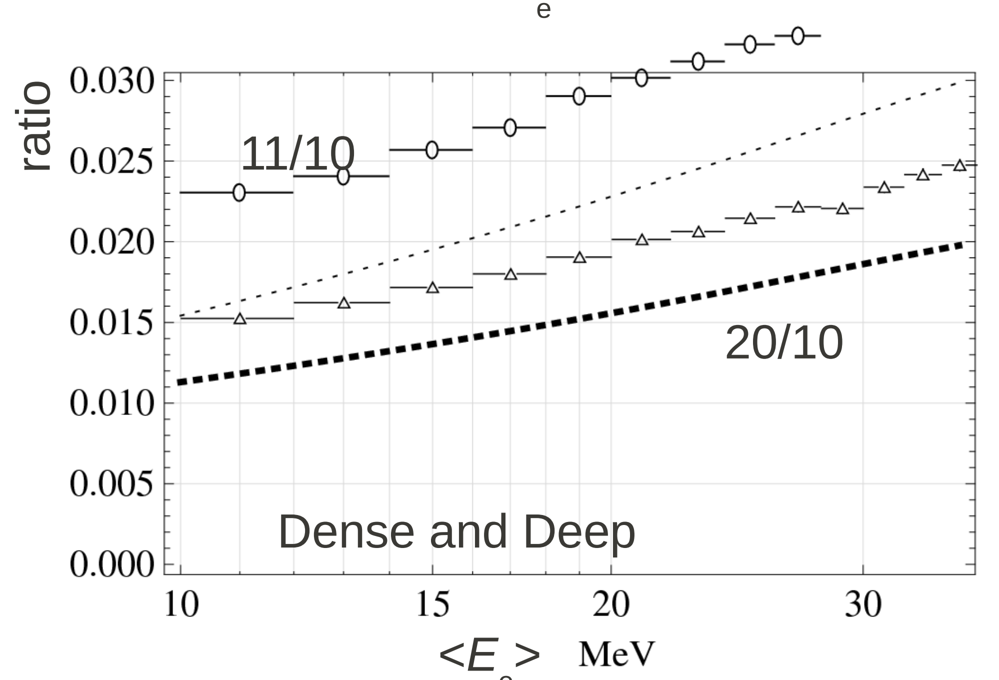
Plots show the ratios as function of average positron energy, using the Garching model.

Thus, the average energy and luminosity can be disentangled for a given model



Lines: analytical*, points: simulation



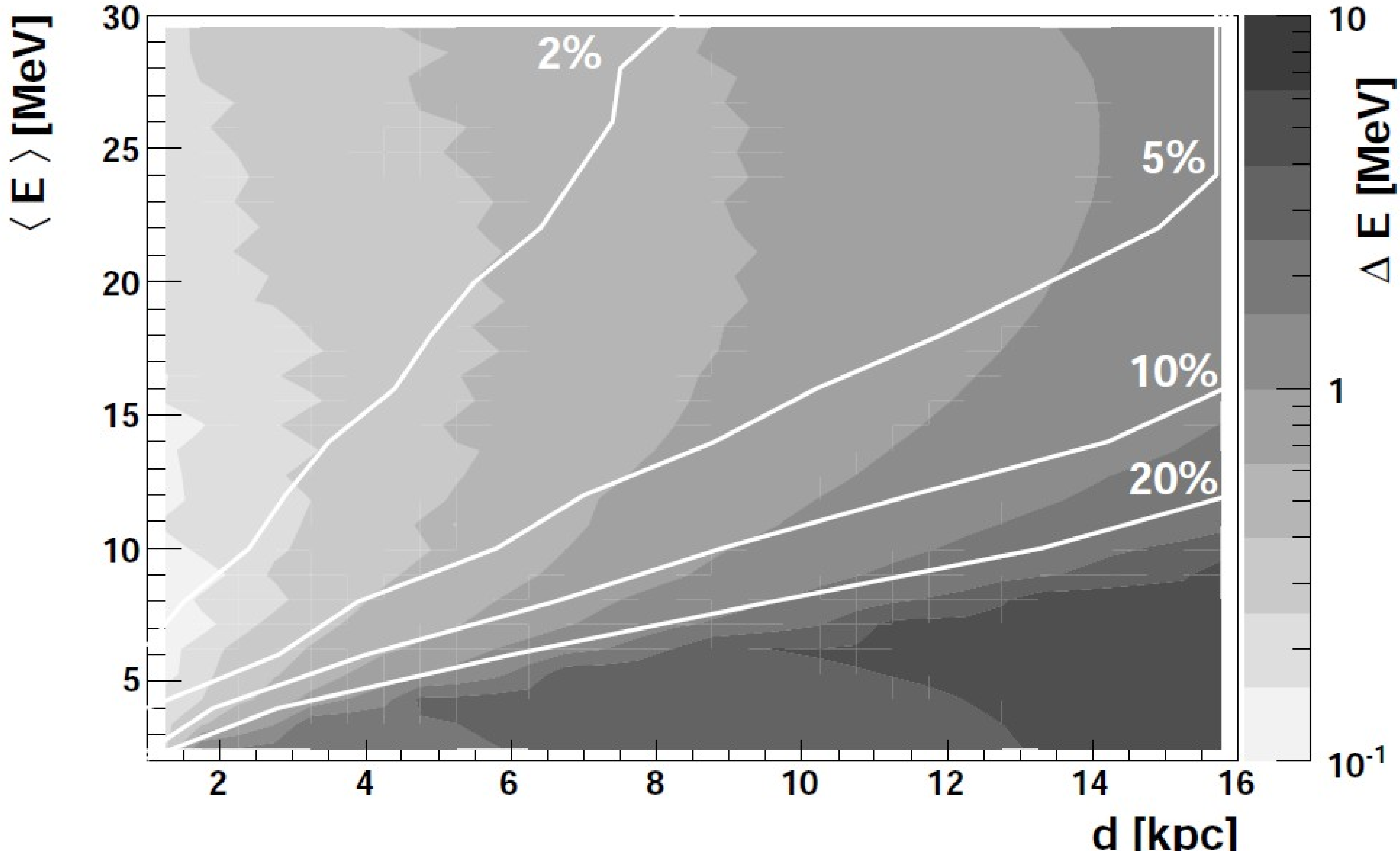


Analytical calculation breaks down for 4π sensitive modules

*: M. Salathe, M. Ribordy, L. Demirörs, Astropart. Phys. 35, 485 (2012), see also M. Ribordy, arXiv:1205.4965

Coincident Hits: Energy resolution

The average energy can be determined from the ratios of hit rates for different modes
Below, the energy resolution obtained for DeepCore and the 11/10 hit ratio using the Garching model.
The resolution is determined by the mode with the lowest statistics, thus 11.



Energy resolution as function distance and average energy

L. Demirörs, M. Ribordy, Supernova detection with IceCube and beyond, ICRC 2011

Can we determine shape parameters ?

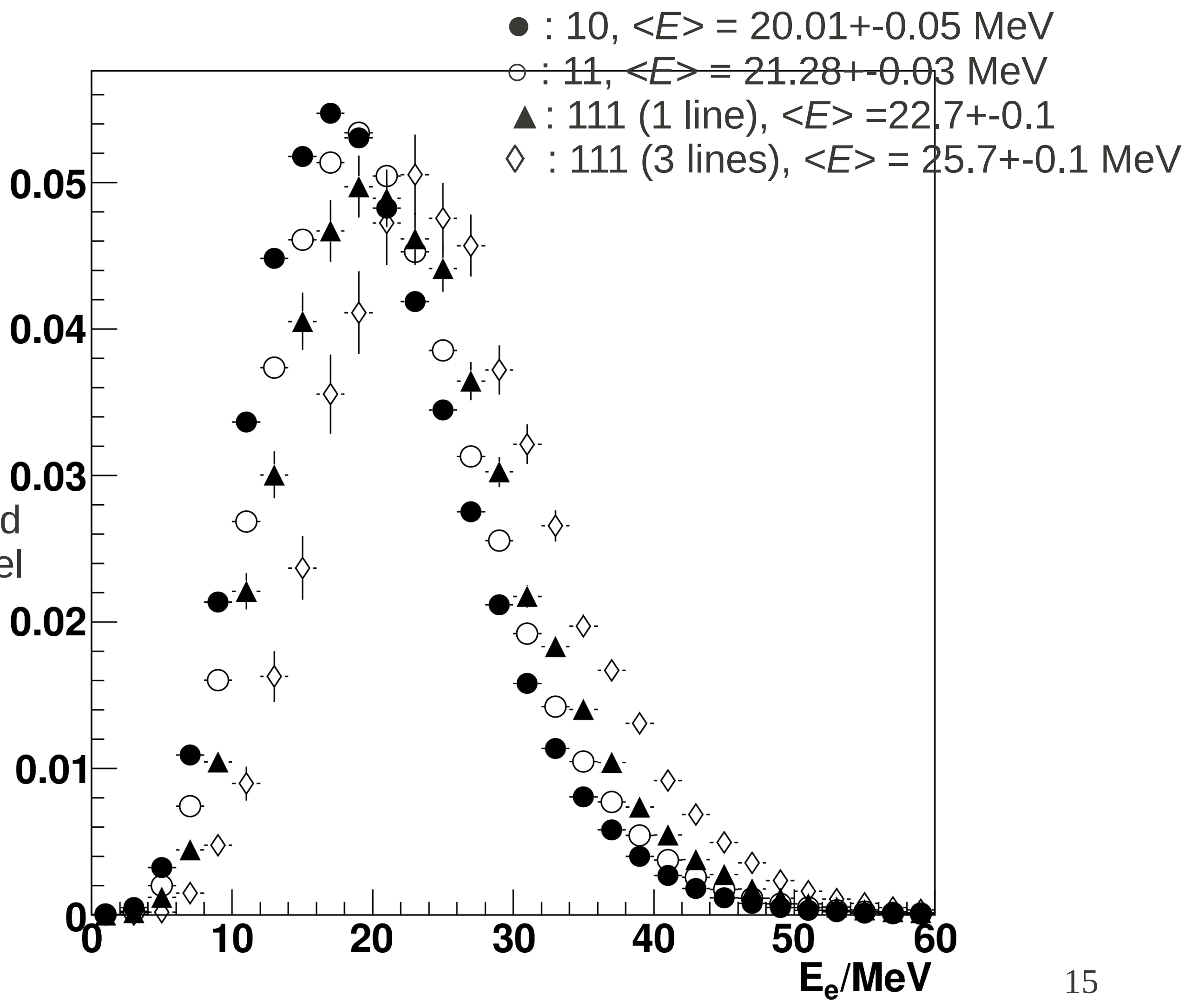
Different modes probe different parts of the spectra

They depend differently on energy

Thresholds for higher order coincidences are at higher energies

In an envisaged dense detector, the coincidence rates are sufficiently high to also look at triple coincidences

The following plot is made for the Deep and Dense configuration for the Garching model



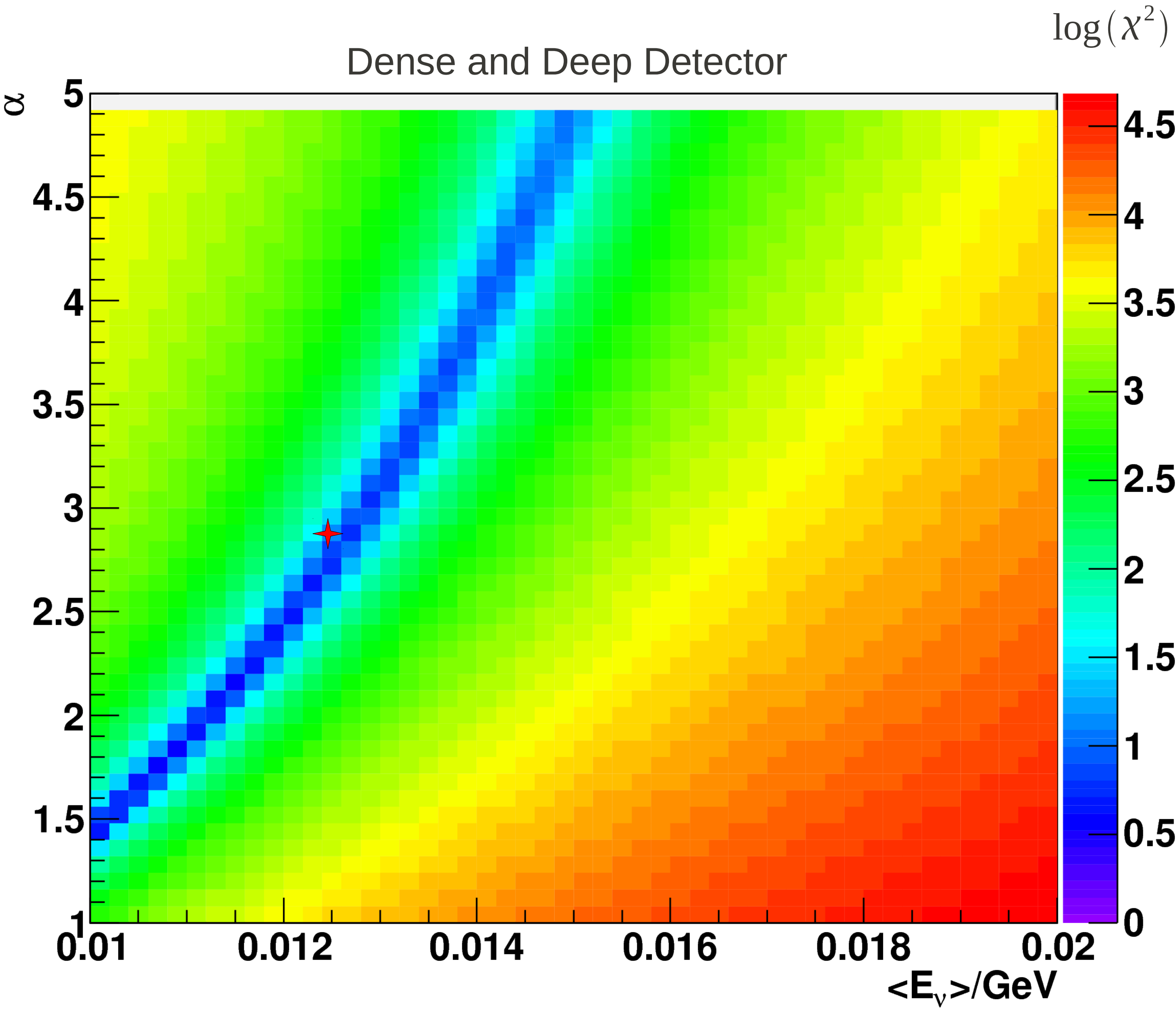
Can we determine shape parameters ?

$$\chi^2 = (\overline{r_{meas}} - \overline{r_{model}})^T \boldsymbol{V}^{-1} (\overline{r_{meas}} - \overline{r_{model}})$$

with $$r = \begin{pmatrix} \left(\frac{rate^{11}}{rate^{10}}\right) \\ \left(\frac{rate^{111}}{rate^{10}}\right) \\ \dots \end{pmatrix}$$

A scan over *α* and <*E*> assuming the Garching model at 10 kpc

Degeneracy between *α* and <*E*>
Multiple minima scattered in a narrow 'valley'



true <*E*> : 0.01247 GeV
true *α* : 2.84

Summary/Outlook

- IceCube/DeepCore is a capable supernova detector
- Coincident hits can provide additional information on galactic supernova properties
  - Average energy and luminosity can be disentangled with IceCube when hitspooling is commissioned
- In dense detectors there is potential for studying finer spectral features

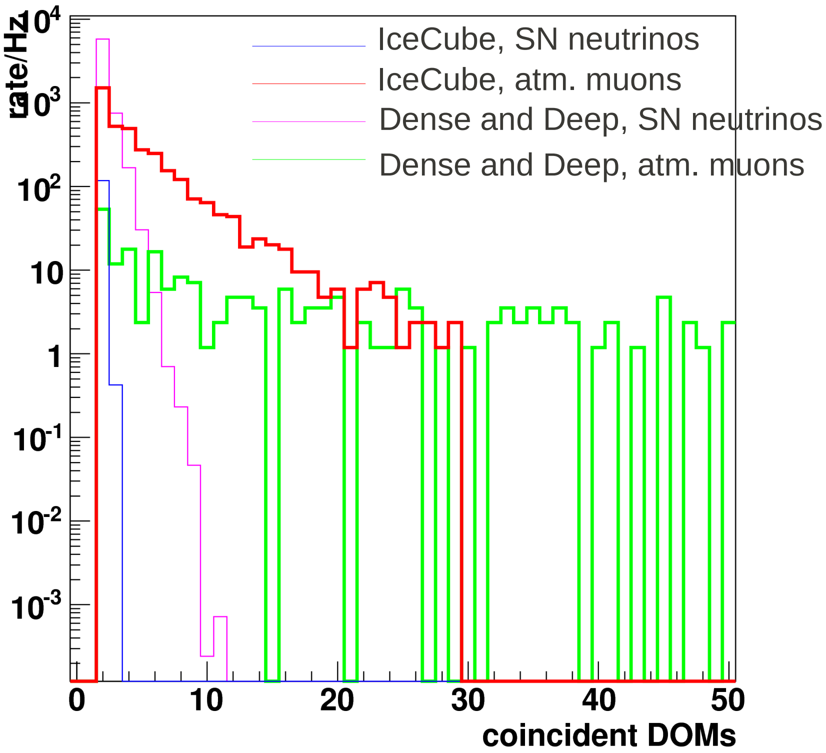
Backup slides

Sources of background

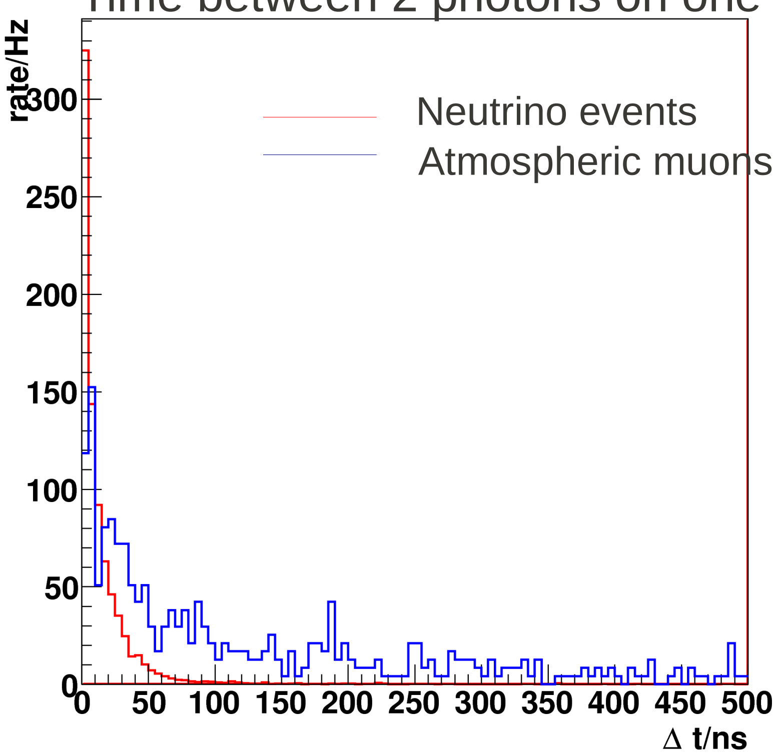
While the coincidental rate is reduced by requiring multiple hits, sources of correlated noise form a background which can be reduced by offline analysis

- Cosmic-ray induced muons
- Sensor correlated noise (afterpulses*, radioactive decays)
    - Suppressed by narrow time window

Number of coincident DOMs



Time between 2 photons on one DOM

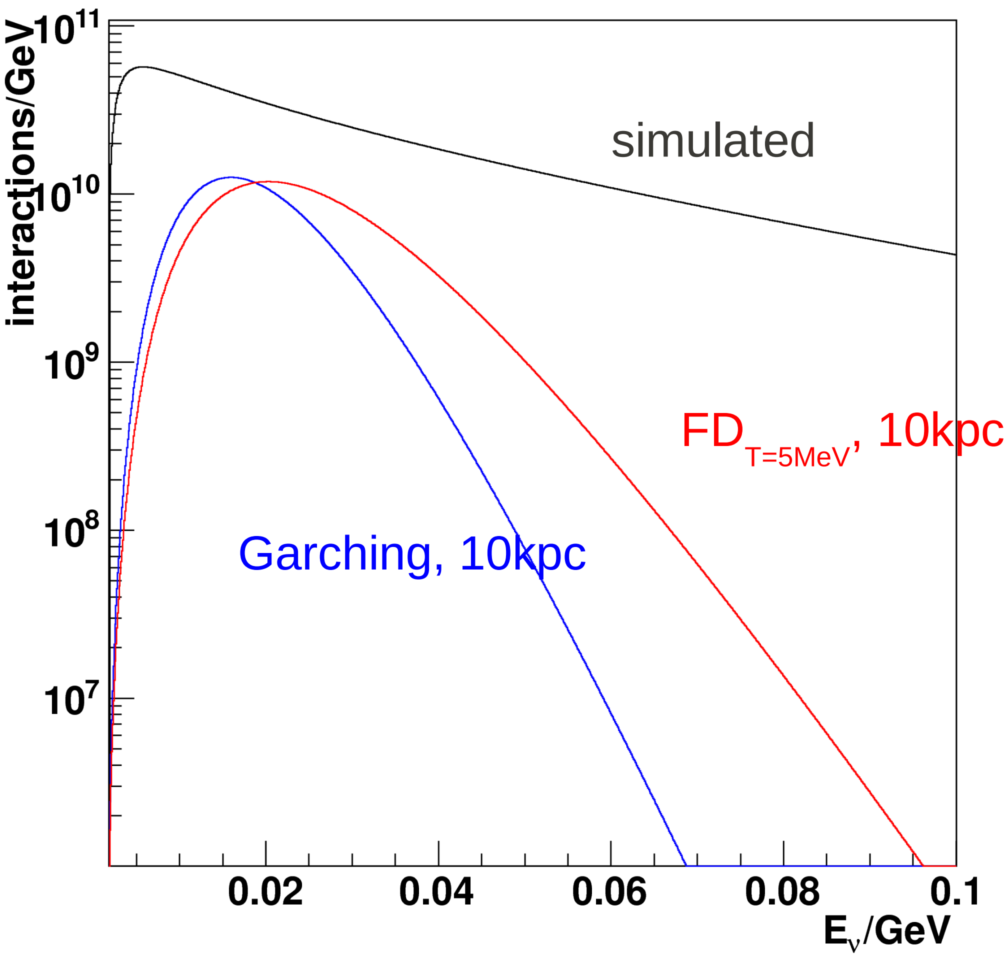


Cuts on the number of coincidences and time distribution can reduce atmospheric muon background (under study)

*: NIM, A618 (2010),139-152

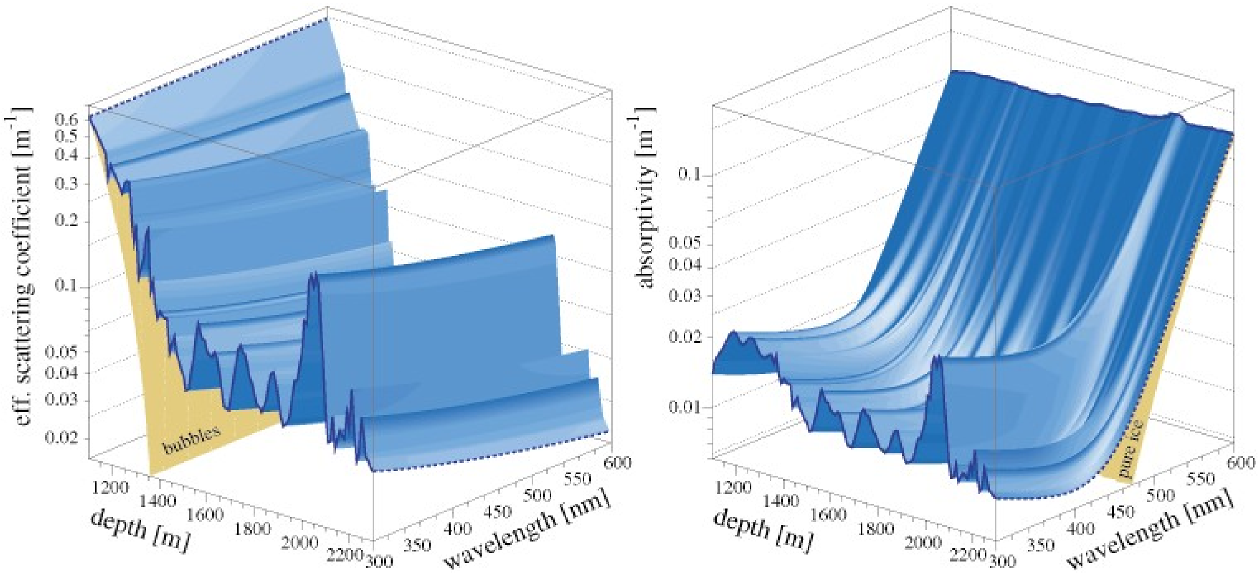
Simulated sample

- Generated ~2x10^9 positron interactions
- Non-physical spectrum folded with cross-section



Simulation

- Geant4 based simulation
  - Extends analytic calculation to a full detector
  - All hit modes
- Custom photon tracking
  - Depth dependent ice properties
- Now, only inverse beta decay on protons
  - Other neutrino cross-sections are already implemented



M. Ackermann et al.(2006), Optical properties of deep glacial ice at the South Pole, J. Geophys. Res., 111, D13203

Supernova emission models

8.8 solar mass electron capture supernova (Garching*)

$$\frac{d\tilde{\Phi}_{\bar{\nu}_e}}{dE_\nu}(E_\nu, d) = \frac{1}{4\pi d^2}\int_0^{\tilde{t}} \frac{L(t)}{\langle E\rangle(t)} f_{\alpha(t),\langle E\rangle(t)}\, dt \qquad f_{\alpha,\langle E_\nu\rangle}(E_\nu) = \frac{(1+\alpha)^{1+\alpha}}{\langle E_\nu\rangle \Gamma(1+\alpha)}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{\langle E_\nu\rangle}}$$

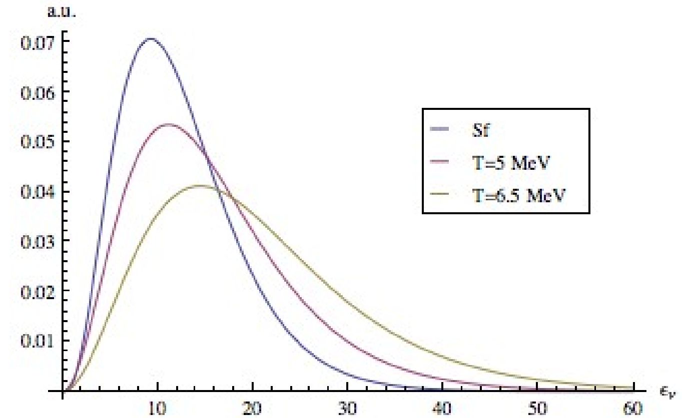
Throughout this work, we use an effective spectrum integrated over $\tilde{t} = 2.95\, s$
Obtained by optimizing signal over noise with an exponential luminosity decrease and τ=2.35 s. This is conservative as the spectrum is steeper a shorter times.

The integrated luminosity : $\tilde{L} = 2.13\cdot 10^{52}\, erg$
The average energy : $\langle \tilde{E}_{\bar{\nu}_e}\rangle = 12.5\, MeV$ and $\alpha = 2.84$

We use as a benchmark distance 10 kpc : $\tilde{\Phi} = 0.89\cdot 10^{15}\, m^{-2}$

Also neutrino spectra with a Fermi-Dirac ("FD") distribution are considered, normalized to have the same luminosity as Garching.

$$f_{\eta,T}(E_\nu) = N(\eta, T)\frac{(E_\nu/T)^2}{1+e^{E_\nu/T-\eta}} \qquad N(\eta, T) = -(2\mathrm{TLi}_3(-e^{\eta}))^{-1}$$



Used values:

$$\eta = 0 \quad \langle \tilde{E}_{\bar{\nu}_e}\rangle_{T=5\mathrm{MeV}} = 15.8\, MeV$$

$$\langle \tilde{E}_{\bar{\nu}_e}\rangle_{T=6.5\mathrm{MeV}} = 20.5\, MeV$$

*: L. Hüdepohl, B. Müller, H. -T. Janka, A. Marek, G. G. Raffelt, Phys. Rev. Lett. 104, 251101 (2010).

Effective volume calculation (analytical) I

M. Salathe, M. Ribordy, L. Demirörs, Astropart. Phys. 35, 485 (2012)

Effective volume* for model M (e.g. Garching, FD) and hit mode kk' (k hits in one sensor and k' in another) :

$$V_{eff}^{M,kk'} = \frac{1}{\rho_e^M(d)} \int \frac{d\rho_e^M}{dE_e}(E_e, d)\, V_{eff}^{kk'}(E_e)\, dE_e$$

Positron effective volume

Positron energy distribution

(M dropped, implicit from now on)

$$\frac{d\rho_e}{dE_e}(E_e, d) = \rho_p \int \frac{d\sigma}{dE_e}(E_\nu, E_e) \frac{d\Phi_{\bar{\nu}_e}}{dE_\nu} dE_\nu \longrightarrow \rho_e(10\text{kpc}) =$$

0.074 m^{-3},Garching
0.096 m^{-3}, $T_{FD=5\ MeV}$
0.12 m^{-3}, $T_{FD=6.5\ MeV}$

A. Strumia, F. Vissani, Phys. Lett. B564, 42-54 (2003)

Interactions per m^3

*Effective volume =
(protons in detection volume)*(detected positrons)/(generated positrons)

Effective volume calculation (analytical) II

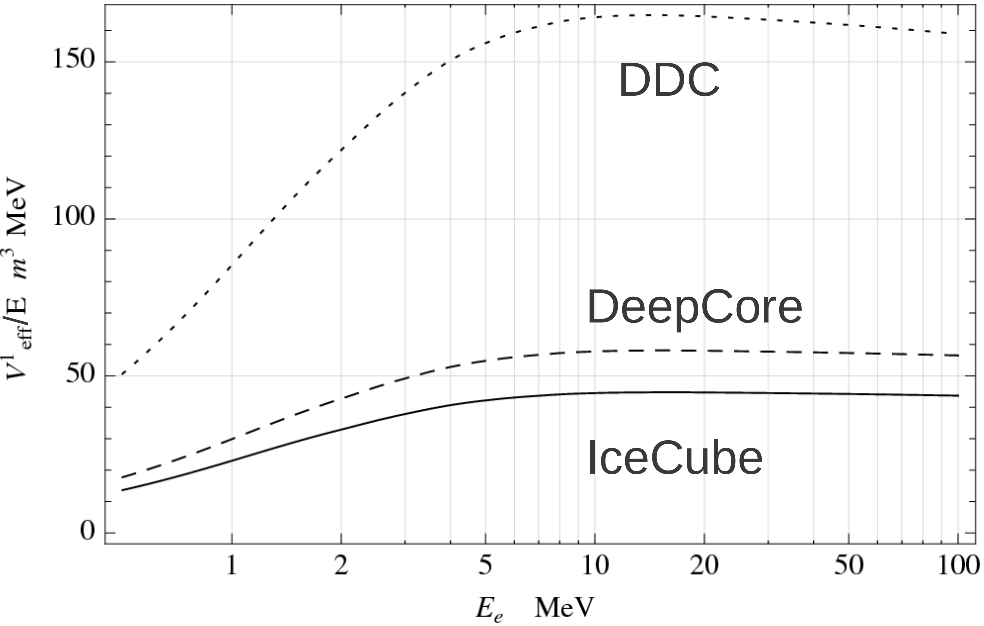
Now, the positron effective volume :

$$V_{\mathrm{eff}}^{kk'}(E_{\mathrm{e}}) = 2\pi \int_R^\infty r^2 \mathrm{d}r \int_{-1}^{1} \mathrm{d}\cos\theta \times 4 f(k, r, \theta, E_{\mathrm{e}}) f(k', r', \theta', E_{\mathrm{e}})$$

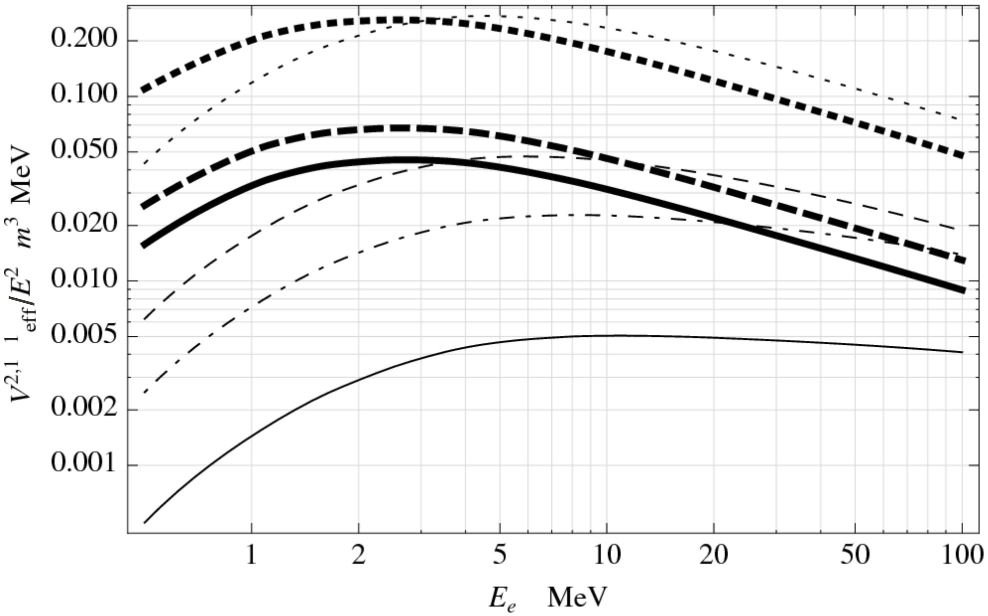
Probability density of detecting k hits or more
Contains :

- Number of detectable Cherenkov photons emitted by a positron (quantum efficiency taken into account)
- Fraction of sensitive area viewed under angle theta at distance r

10 mode

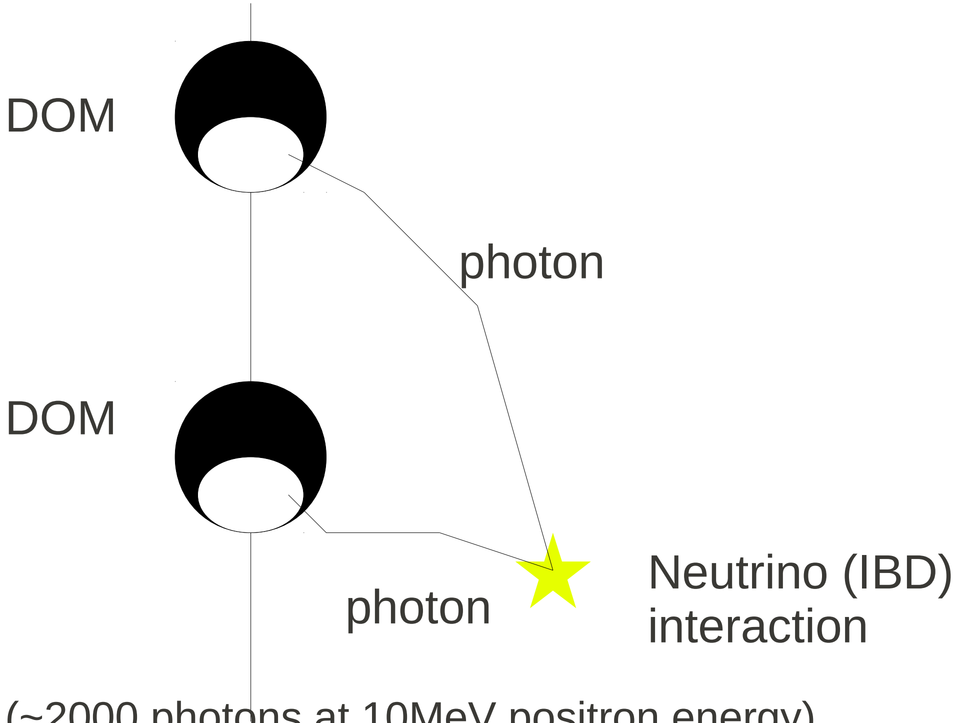


20 (Thick) and 11 (thin) modes



Making use of coincident photon hits

- Once the enhancements in the data-acquisition in IceCube/DeepCore are implemented, making <u>all photon hits</u> during a SN burst available, <u>space-time correlations</u> between hits can be used to obtain additional information
- Higher order modes (coincidental hits) have lower rates, but probe spectral features of neutrino emission at higher energies
- The more dense the detector, the more powerful this technique becomes



Combine with next

(~2000 photons at 10MeV positron energy)

Hit modes

Photon hits *i* and *j*, at times t_i and t_j are coincident when $|t_i - t_j| < \delta t$

Several hit modes :

- Single sensor hit: mode 10 (or “1+0”)
- Two photons detected in the same sensor: mode 20 (or “2+0”)
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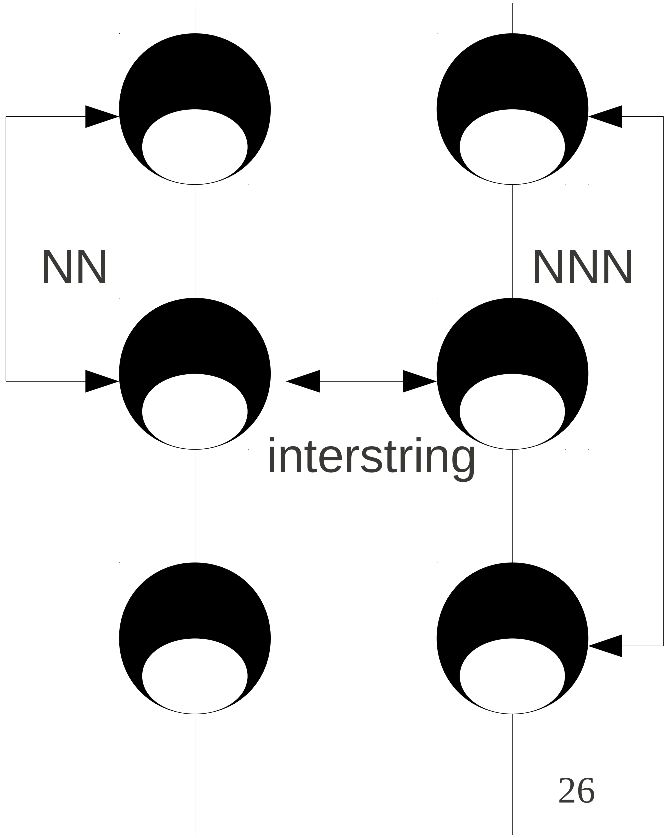


Can we determine an energy shape parameter?

<u>First simple try</u>: define a χ^2, assuming uncorrelated variables :

$$\chi^2 = \sum \frac{\left(r_{meas}^{20/10} - r_{model}^{20/10}\right)^2}{\sigma_{20/10}^2} + \frac{\left(r_{meas}^{11(NN)/10} - r_{model}^{11(NN)/10}\right)^2}{\sigma_{11(NN)/10}^2} + \frac{\left(r_{meas}^{11(NNN)/10} - r_{model}^{11(NNN)/10}\right)^2}{\sigma_{11(NNN)/10}^2} + \ldots$$

Each term is sensitive to different parts of the spectrum

Two independent data sets

1. The 'measurement' : to get the measured values for the ratios
2. The model(s) : to get the ratios for different parameters and models

Is it sensitive at all ? : Scan over parameter space, and study the sensitivity of χ^2

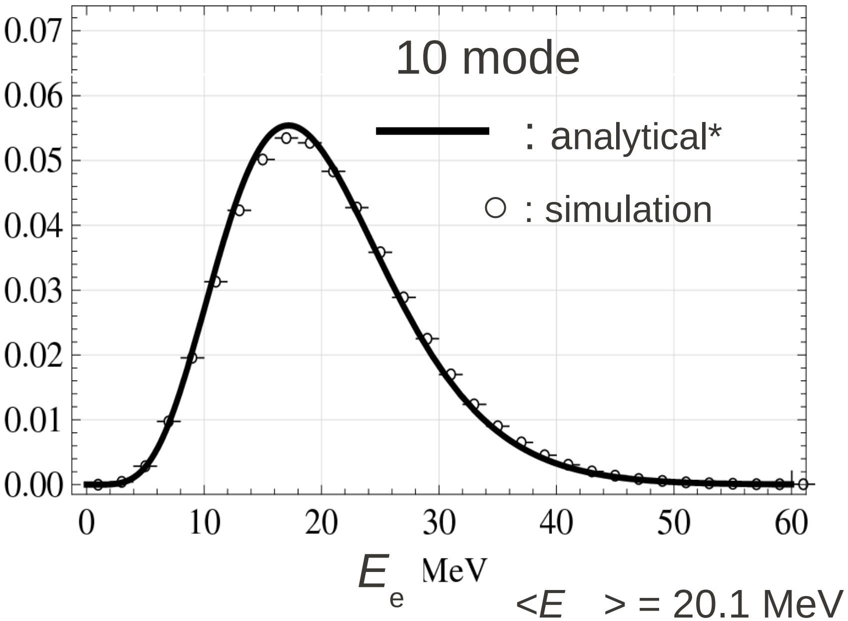
Positron spectra

Positron spectra for interactions leading to different modes

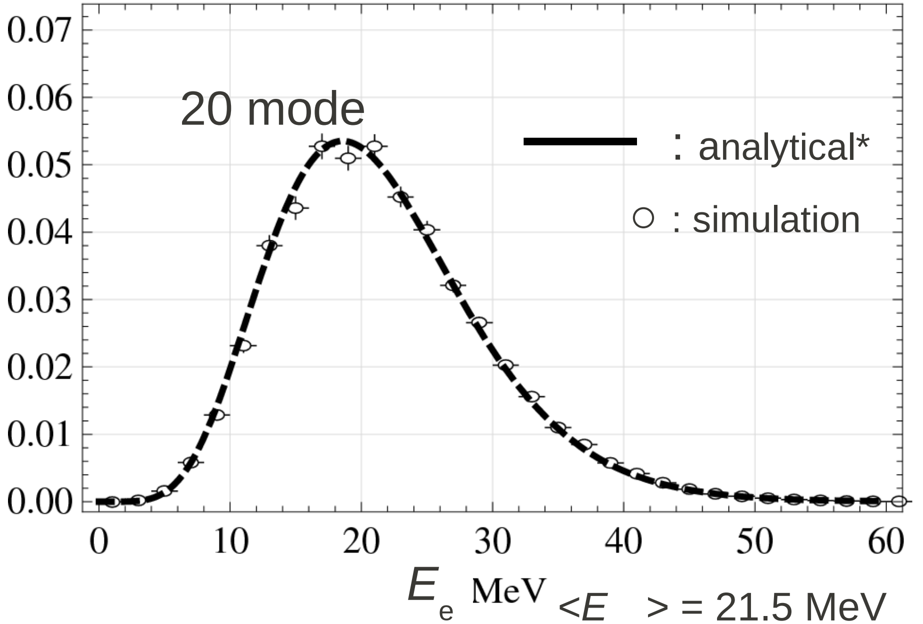
The average energy increases with higher modes

↓

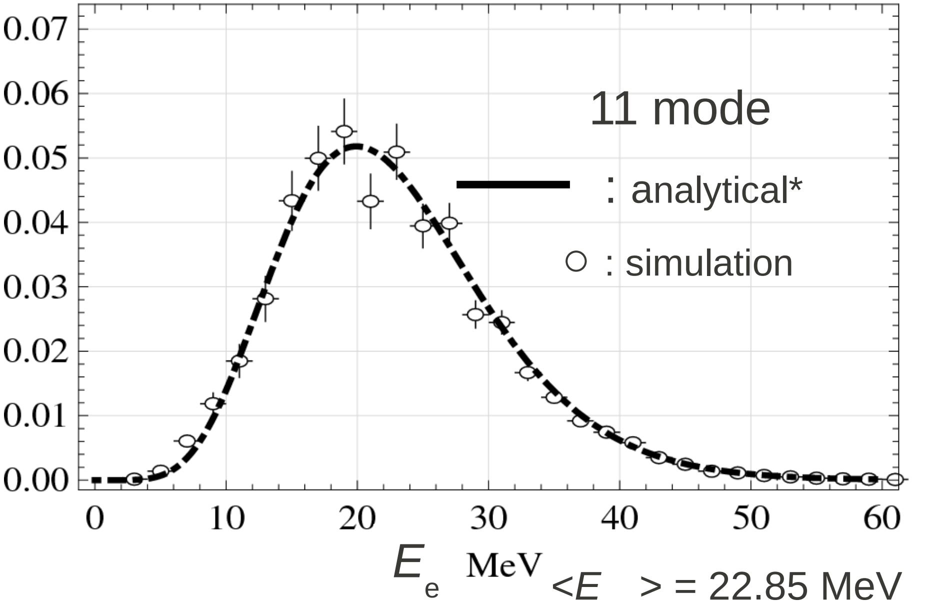
Different modes probe different parts of the spectrum



$\langle E_{ana} \rangle = 20.1$ MeV
$\langle E_{sim} \rangle = 20.46 \pm 0.01$



$\langle E_{ana} \rangle = 21.5$ MeV
$\langle E_{sim} \rangle = 21.7 \pm 0.1$



$\langle E_{ana} \rangle = 22.85$ MeV
$\langle E_{sim} \rangle = 22.5 \pm 0.2$

*: M. Salathe, M. Ribordy, L. Demirörs, Astropart. Phys. 35, 485 (2012)