The University Of Sheffield.

Coincidence reconstruction for supernova neutrino detection with gadolinium doping.

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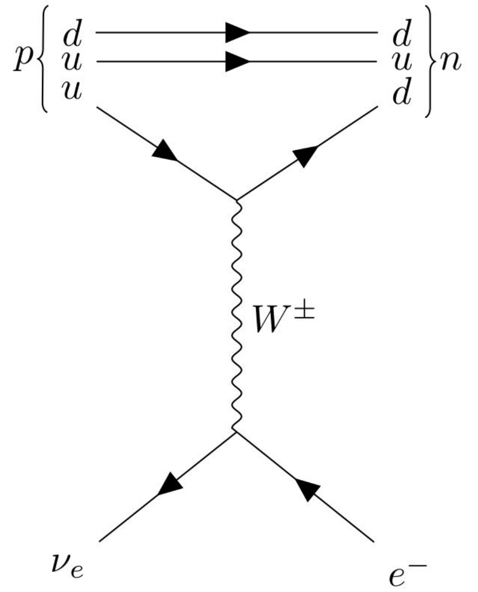
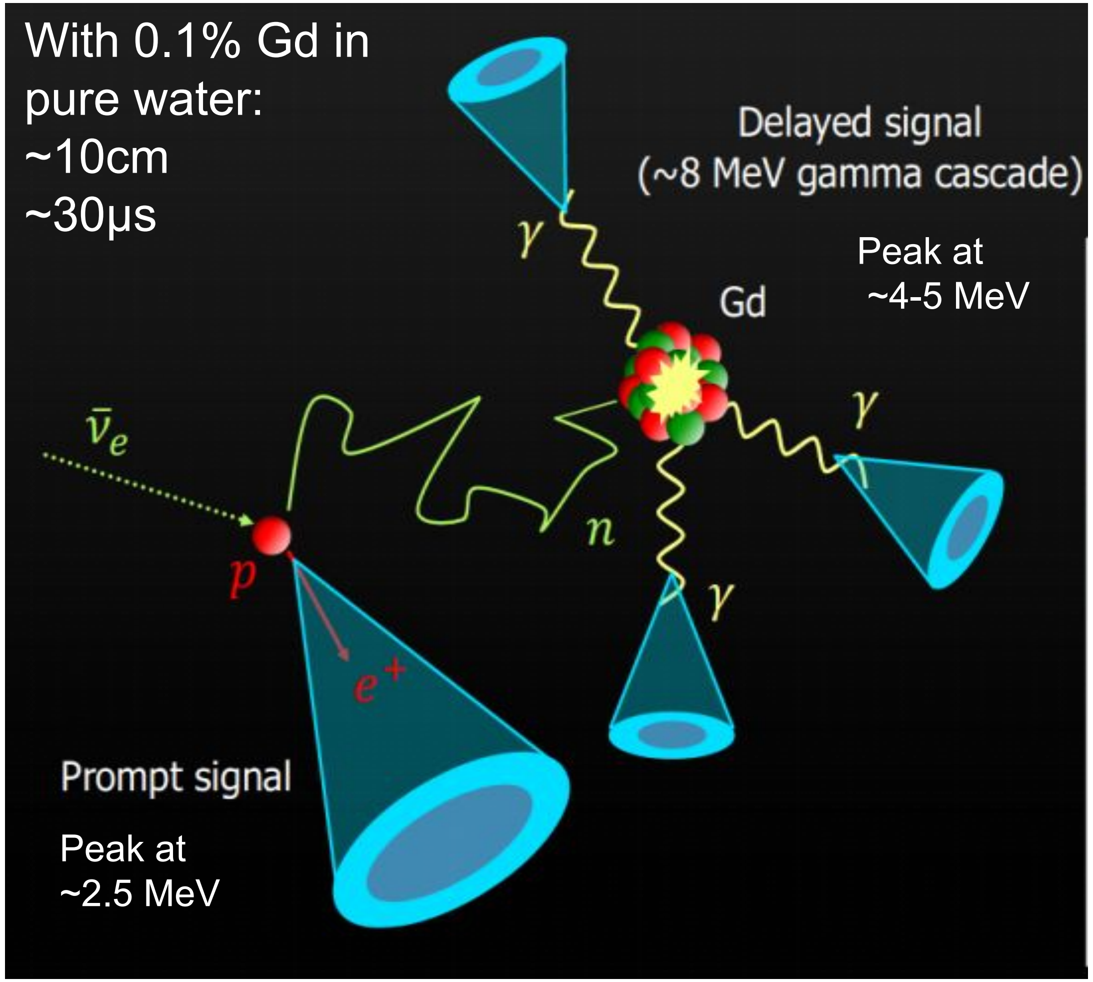
M. Weiss / Center for Astrophysics | Harvard & Smithsonian

Gd-water: advances in antineutrino detection

The anti-neutrino interacts with free protons in the detector via inverse beta decay (IBD).



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



With gadolinium (Gd) loading, we can see the IBD as a pair of interactions.

	H_2O	Gd-H_2O
σ	~0.3 b	~ 49,000 b
τ	~200 μsec	~30 μsec
E	2.2 MeV gamma	~8 MeV gamma cascade

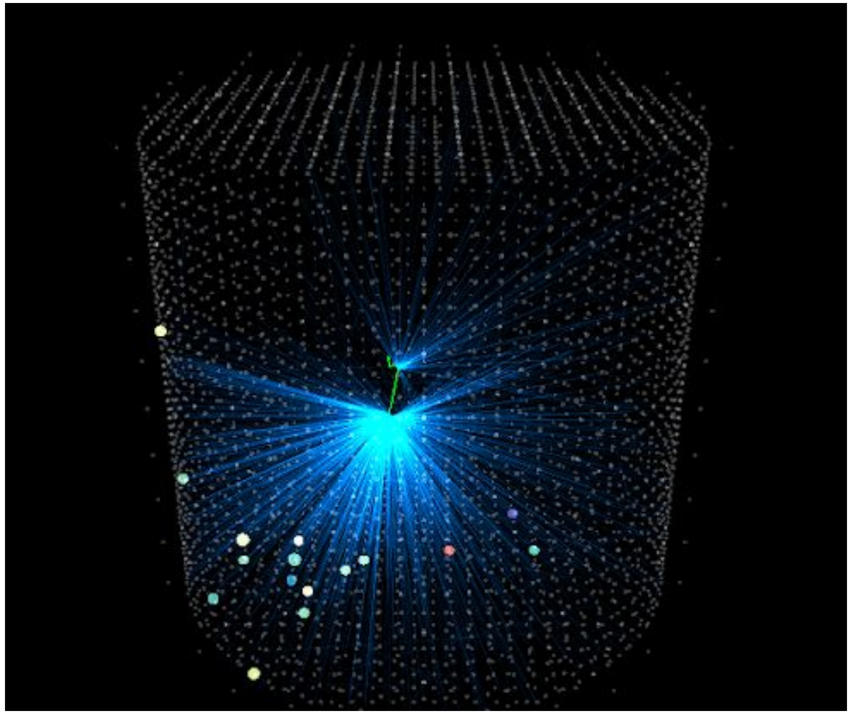
Neutron-capture on Gd > 90% with 0.1% Gd

CoRe - Coincidence Reconstruction

CoRe implementation of BONSAI[1] combined pair reconstruction uses the additional light from the neutron to improve reconstruction of IBD events.

Results in:

1. Better vertex resolution and lower reconstruction threshold.
2. Direction and energy resolution improved at lower energies.
3. Better rejection of backgrounds due to 'accidental coincidences'.



[1] **B**ranch **O**ptimization **N**avigating **S**uccessive **A**nnealing **I**terations
M. Smy. *Low energy event reconstruction and selection in Super-Kamiokande-III*: 30th International Cosmic Ray Conference, (2007)

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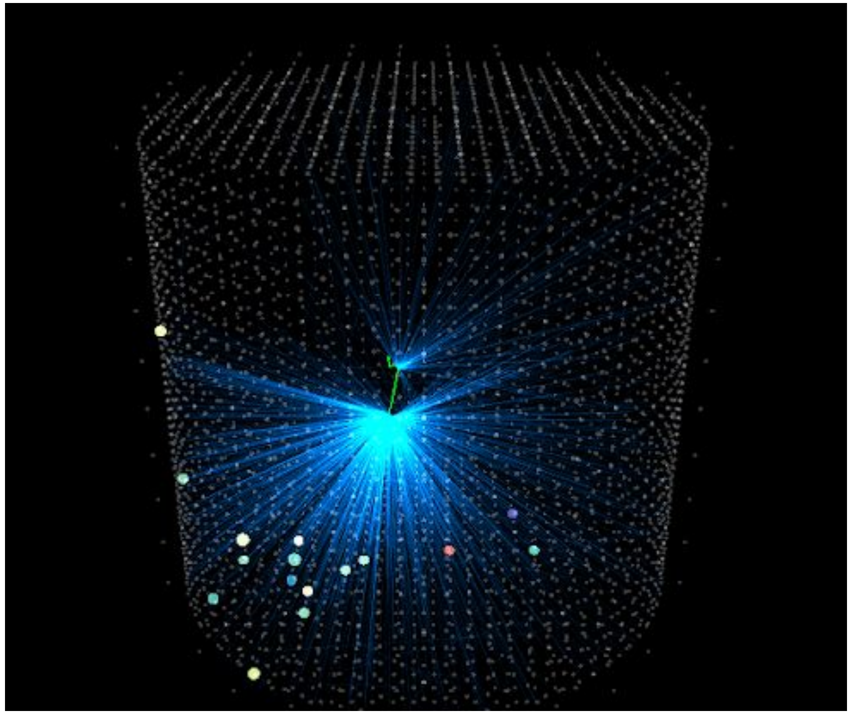

Results in:

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CoRe - BONSAI combined likelihood

Likelihood maximisation using all hits from both the prompt and delayed events

$$ln\mathcal{L}_{combined}(\mathbf{x}, t_0) = ln\mathcal{L}_p(\mathbf{x}, t_0) + ln\mathcal{L}_d(\mathbf{x}, t_0)$$

$$ln\mathcal{L}(\mathbf{x}, t_0) = ln(\prod_{i=1}^{N} P(\Delta t_i(\mathbf{x})))$$

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Difference between the actual hit time and expected hit time from a given vertex ***x***

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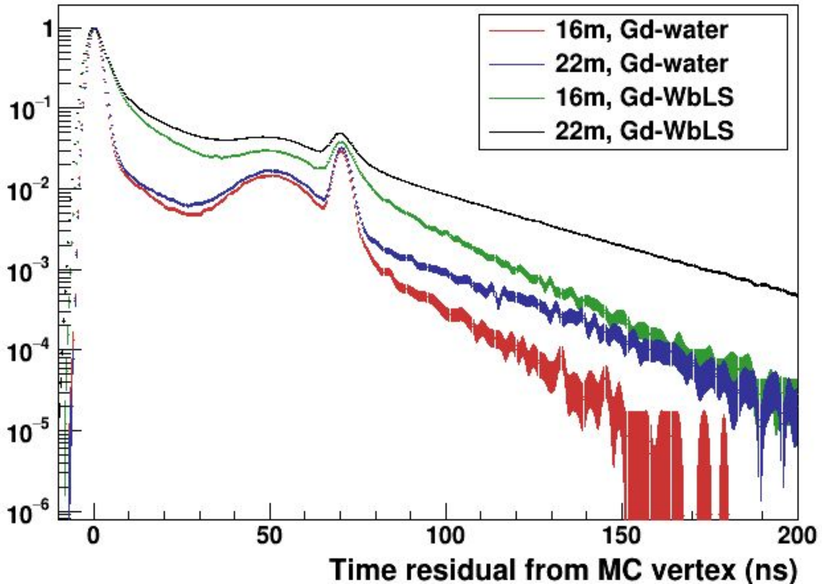


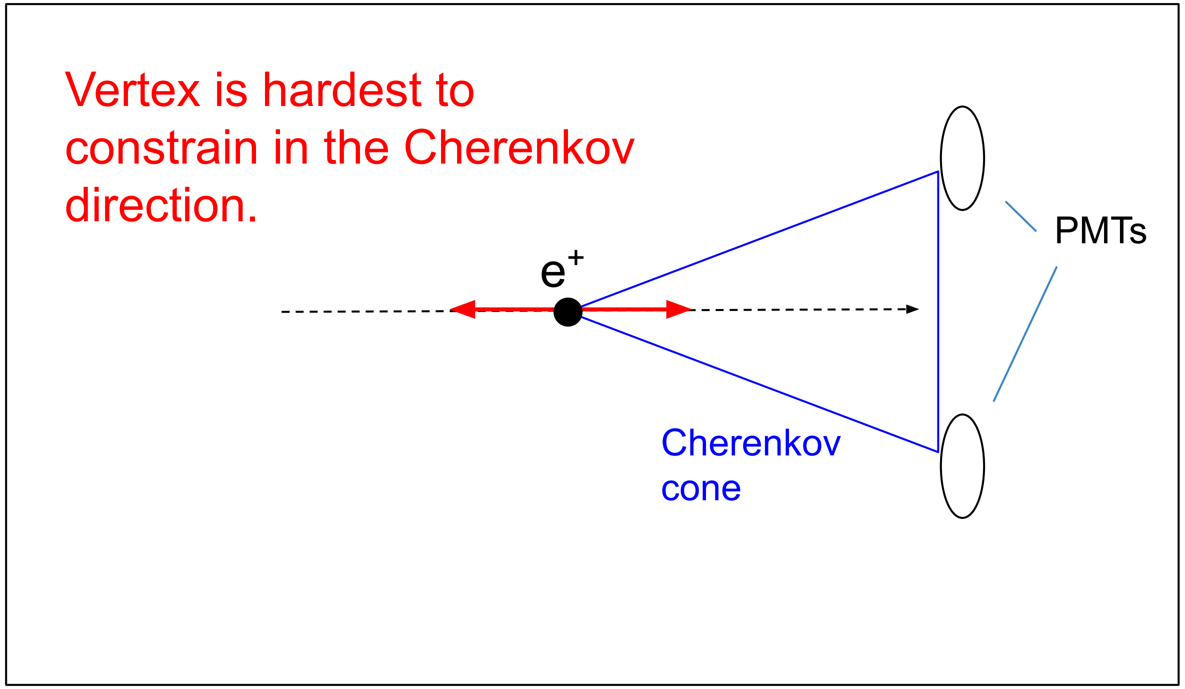
$$P(\Delta t)$$

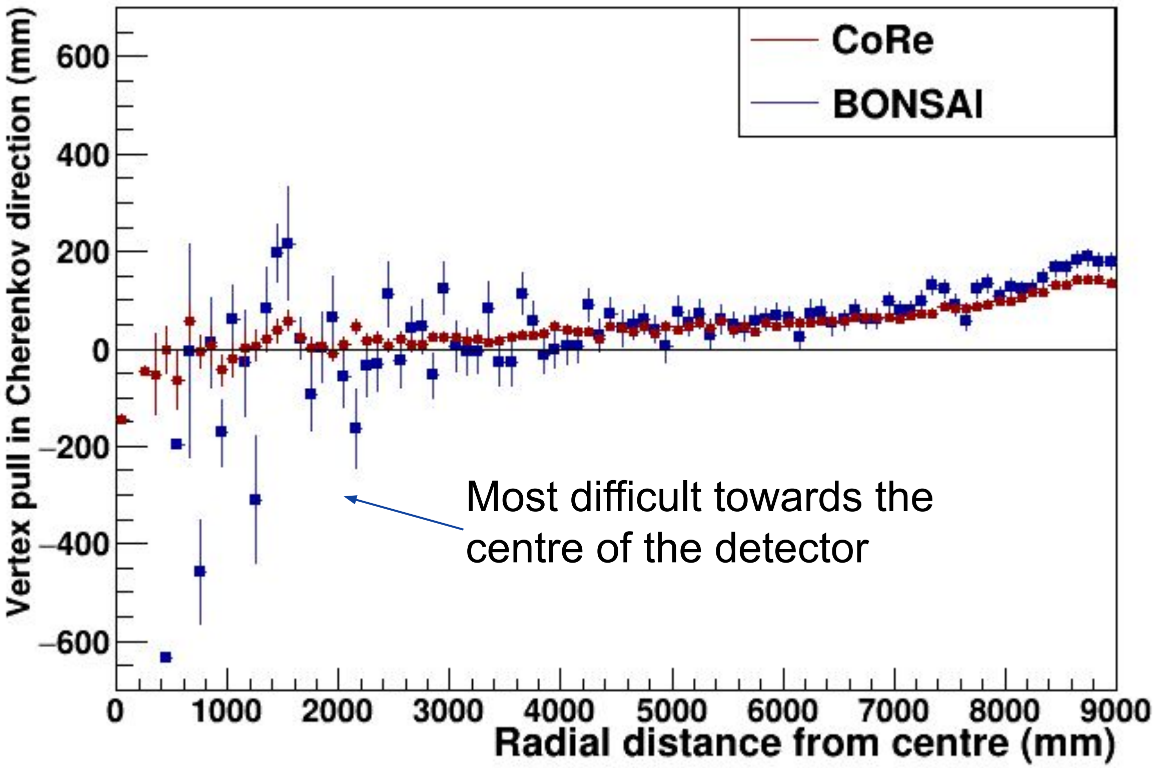
PDFs of hit-time residuals from true vertices.

$$\Delta t_i = t_i - t.o.f. - t_0$$

Difference between the actual hit time and expected hit time from a given vertex ***x*.**

CoRe - stability at the centre of the detector





Difficulty reconstructing events close to the centre of the detector increases with detector size.

22m Gd-water

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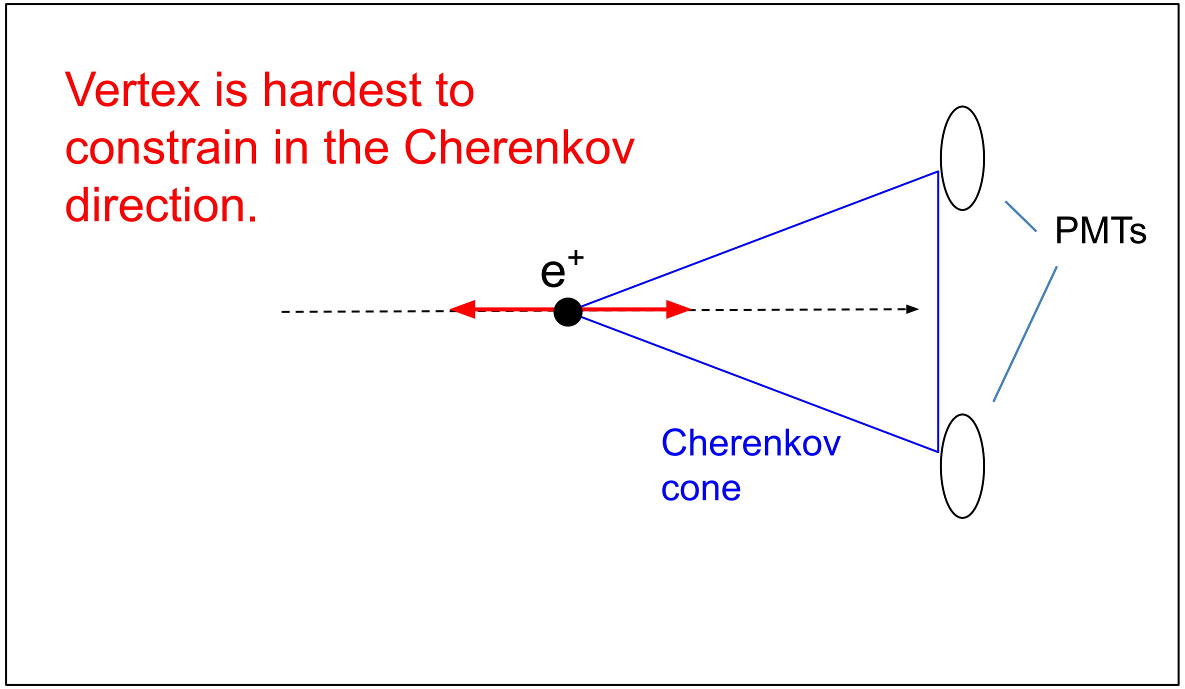

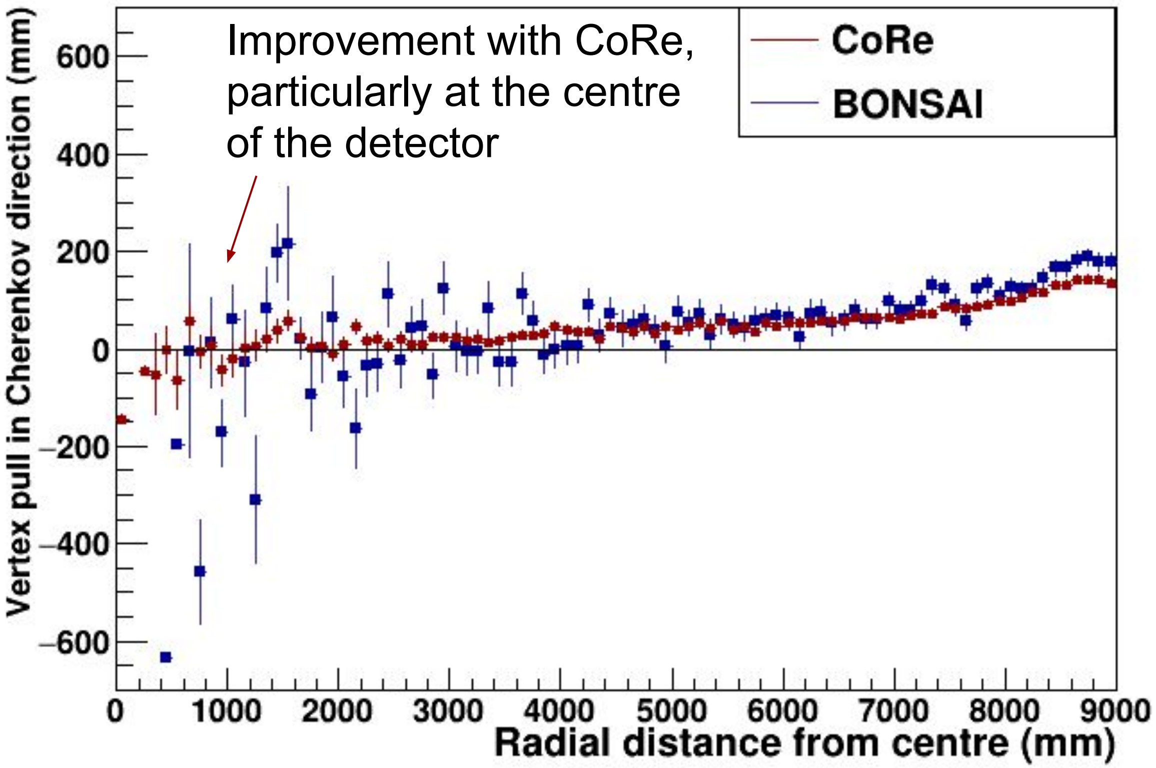

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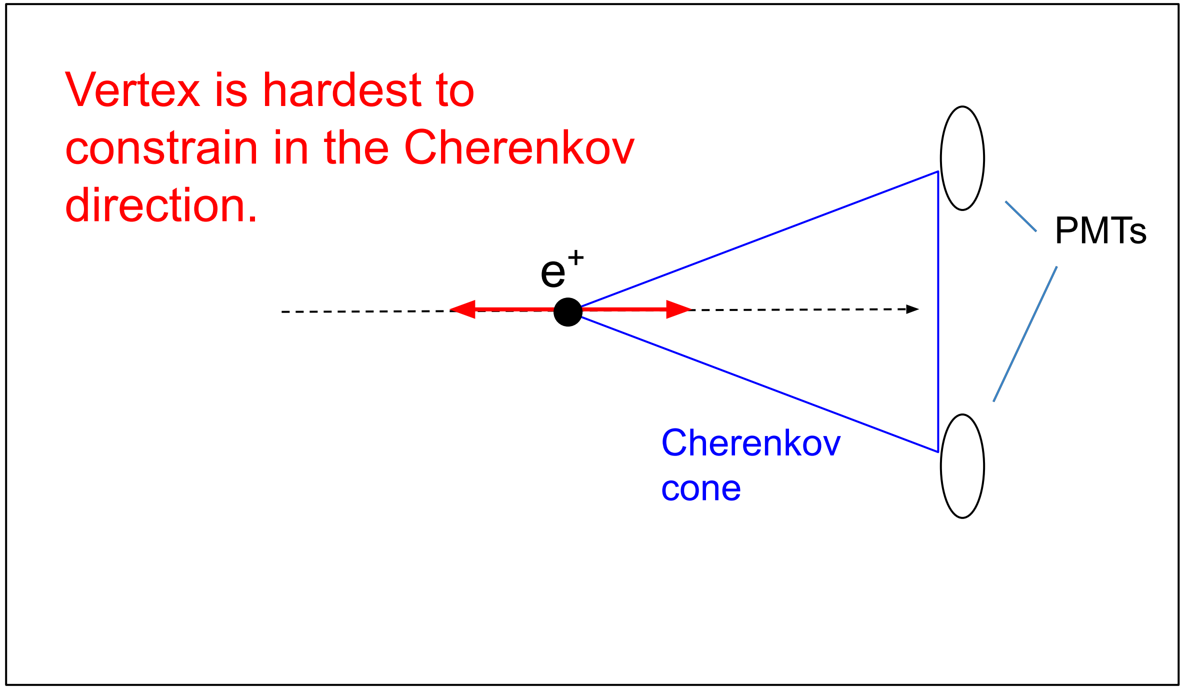
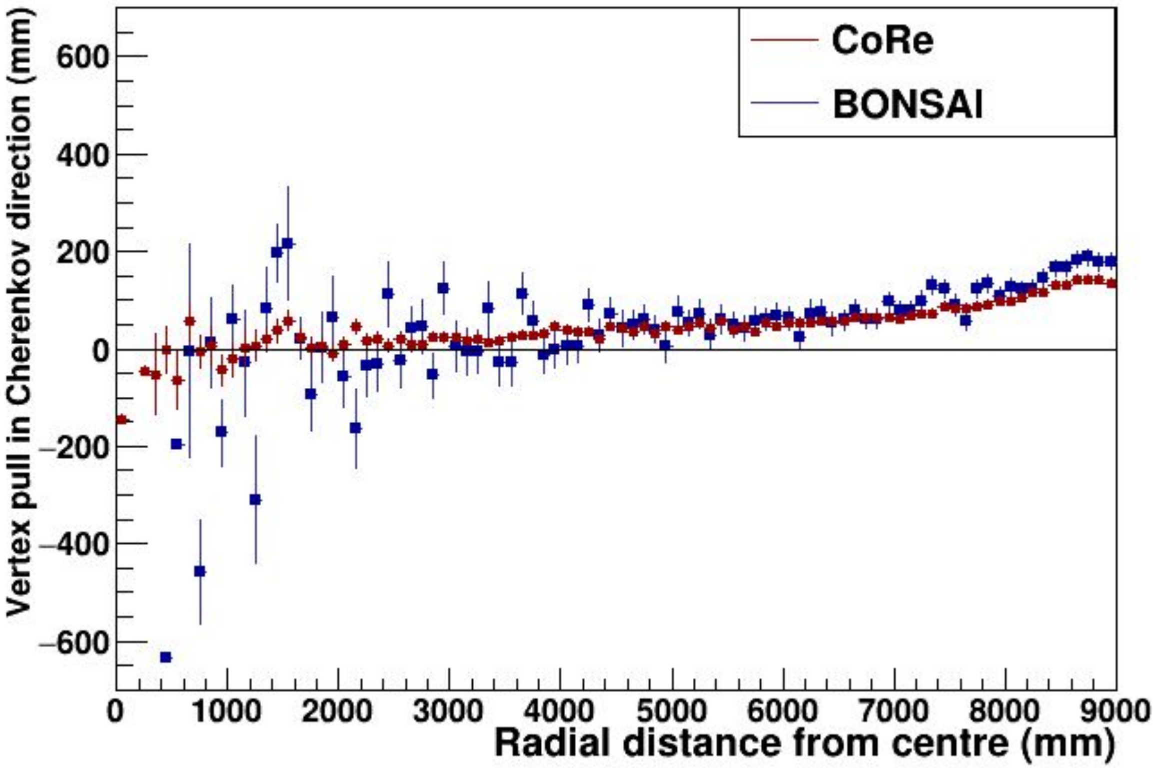




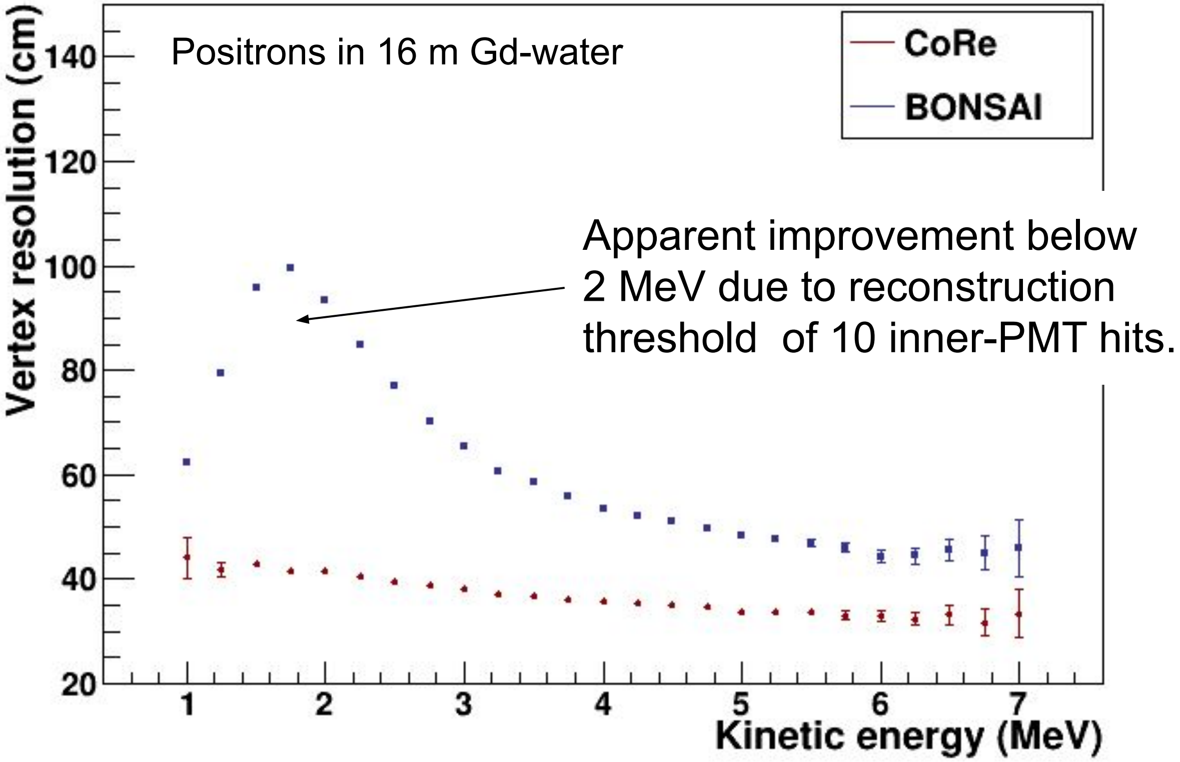
Difficulty reconstructing events close to the centre of the detector increases with detector size.

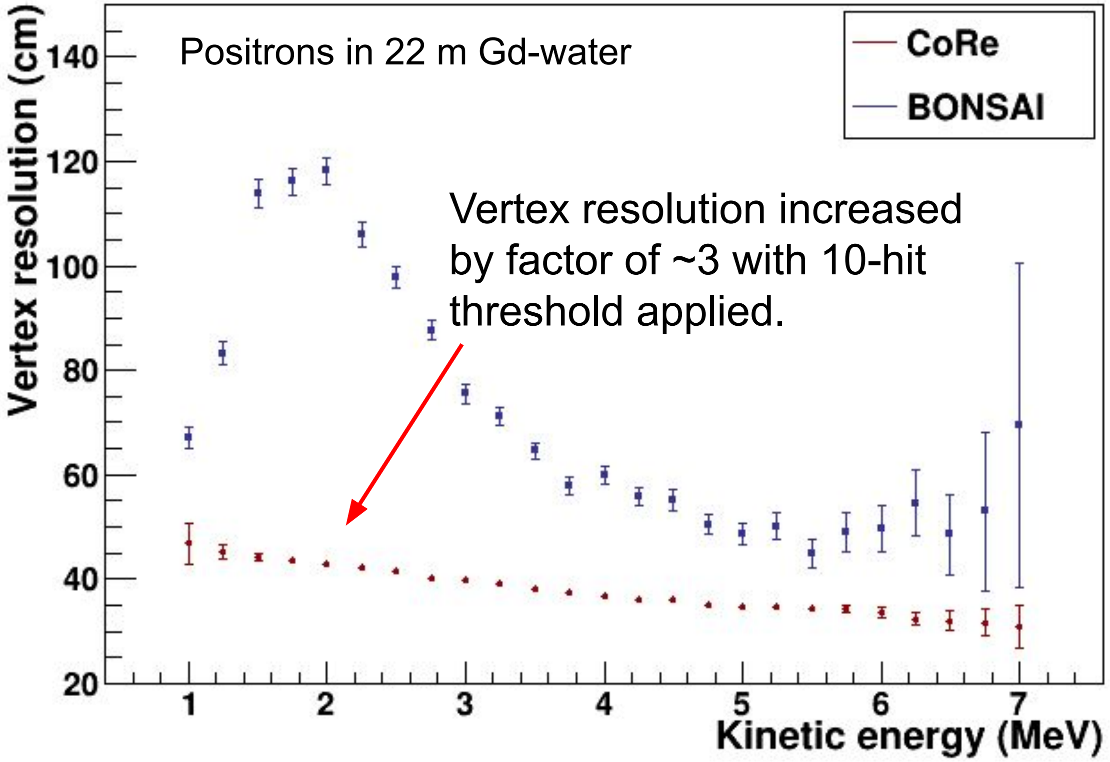
22m Gd-water

Expect this improvement to have more significance in a larger detector.

CoRe - stable down to lowest energies

Vertex resolution stable down to the positron Cherenkov threshold with CoRe





Improvement increases with size →

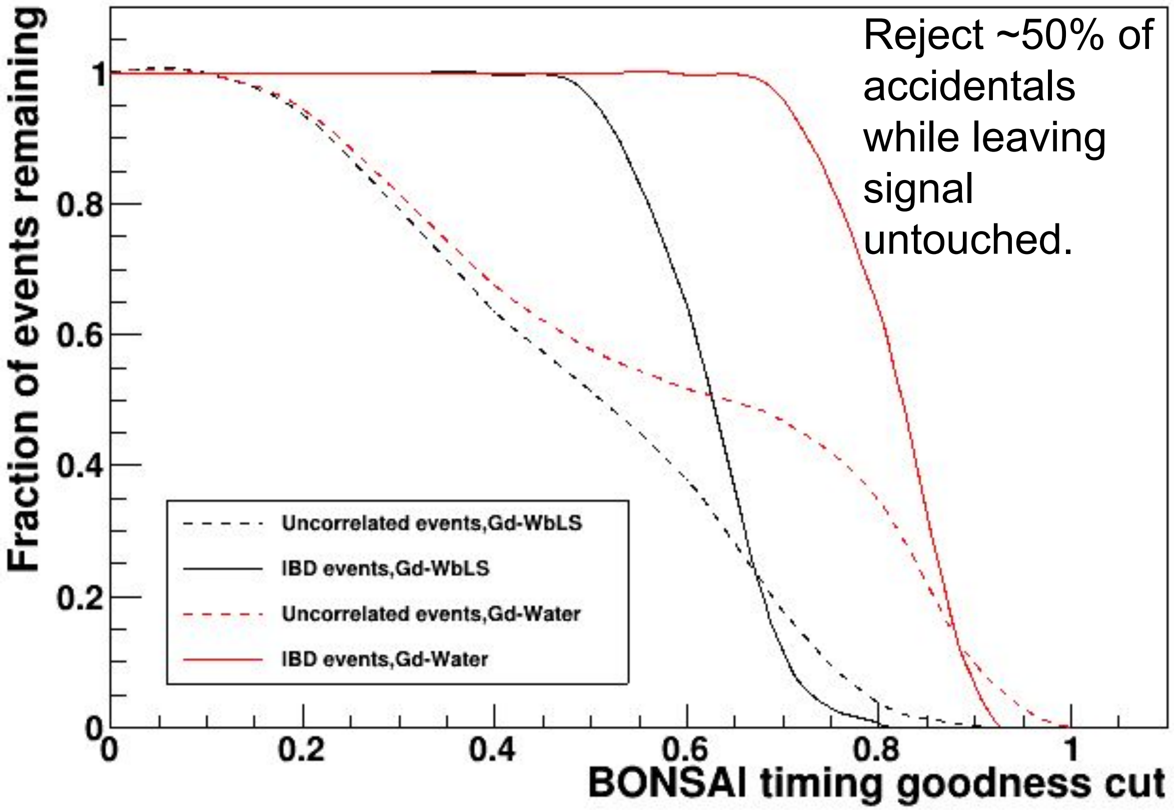
Power to reject accidental coincidences

Fit quality threshold offers powerful rejection of accidental coincidences.

Uncorrelated events can occur in accidental coincidence with each other and mimic the IBD signal pair.

Thanks to better reconstruction of IBD events in CoRe:

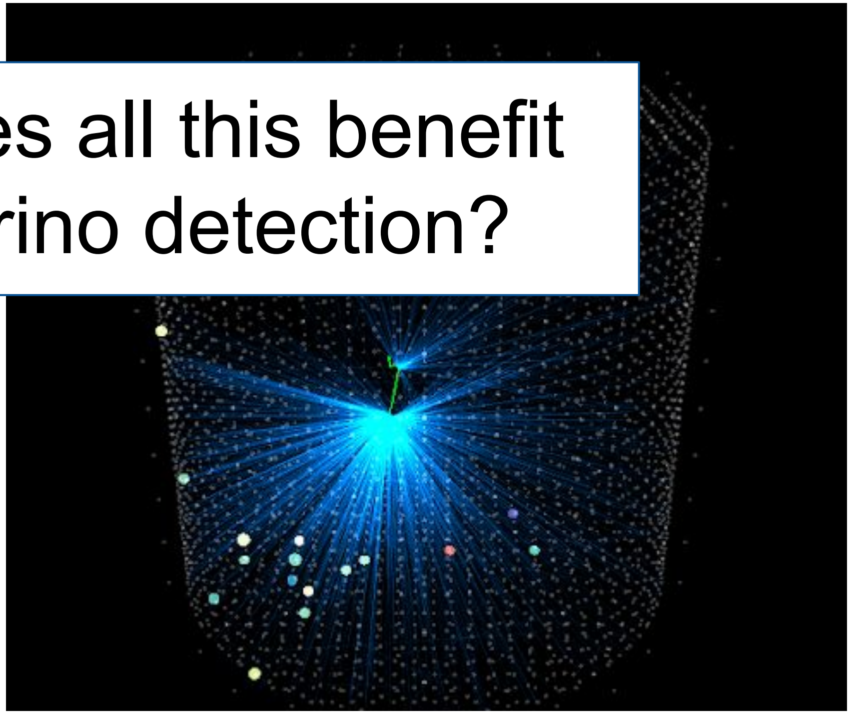
a measure of fit quality can be used to help select true IBD events and reject false pairs.



CoRe - Coincidence Reconstruction

CoRe implementation of BONSAI[1] combined pair reconstruction uses the additional light from the neutron to improve reconstruction of IBD events.

How does all this benefit SN neutrino detection?



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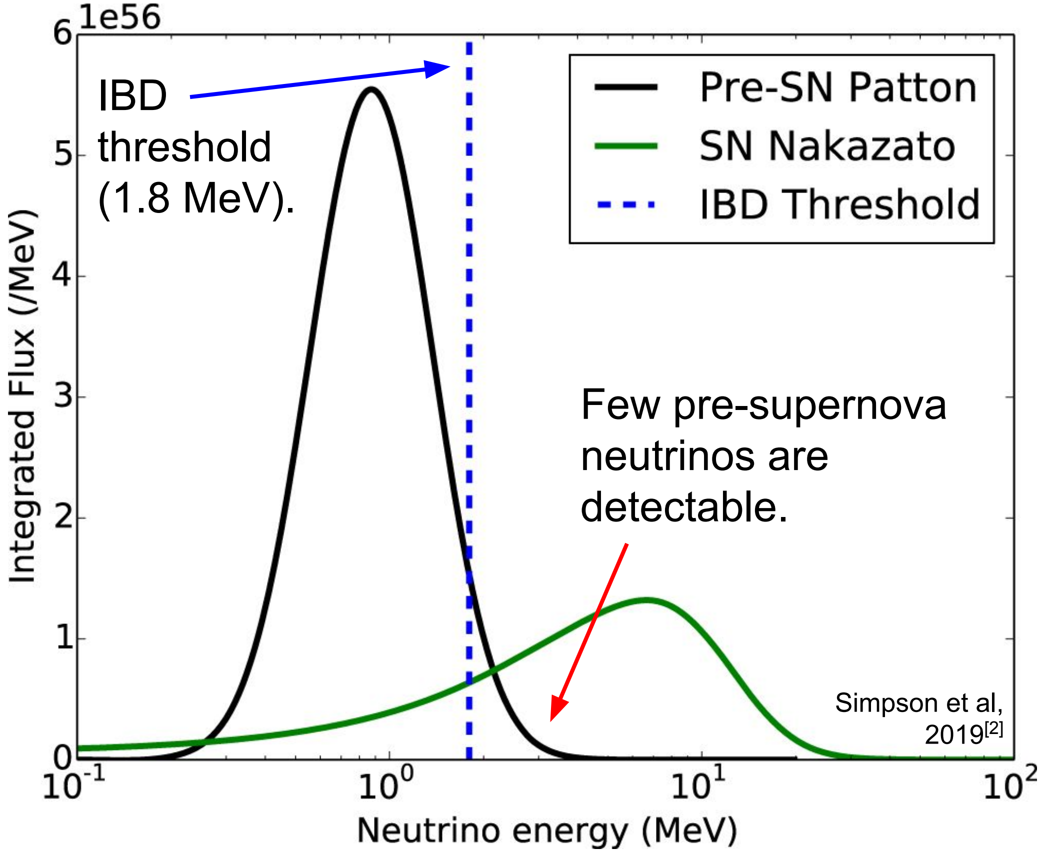
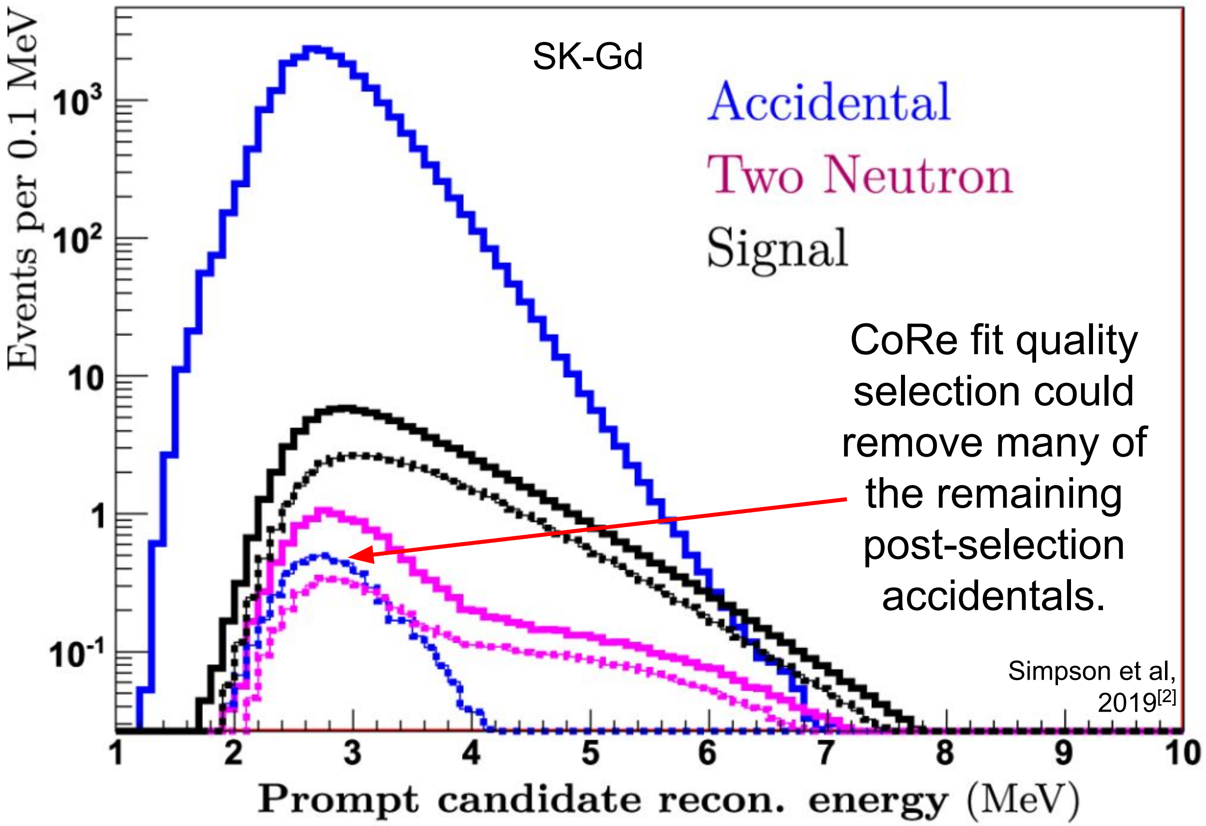
Pre-supernova antineutrinos



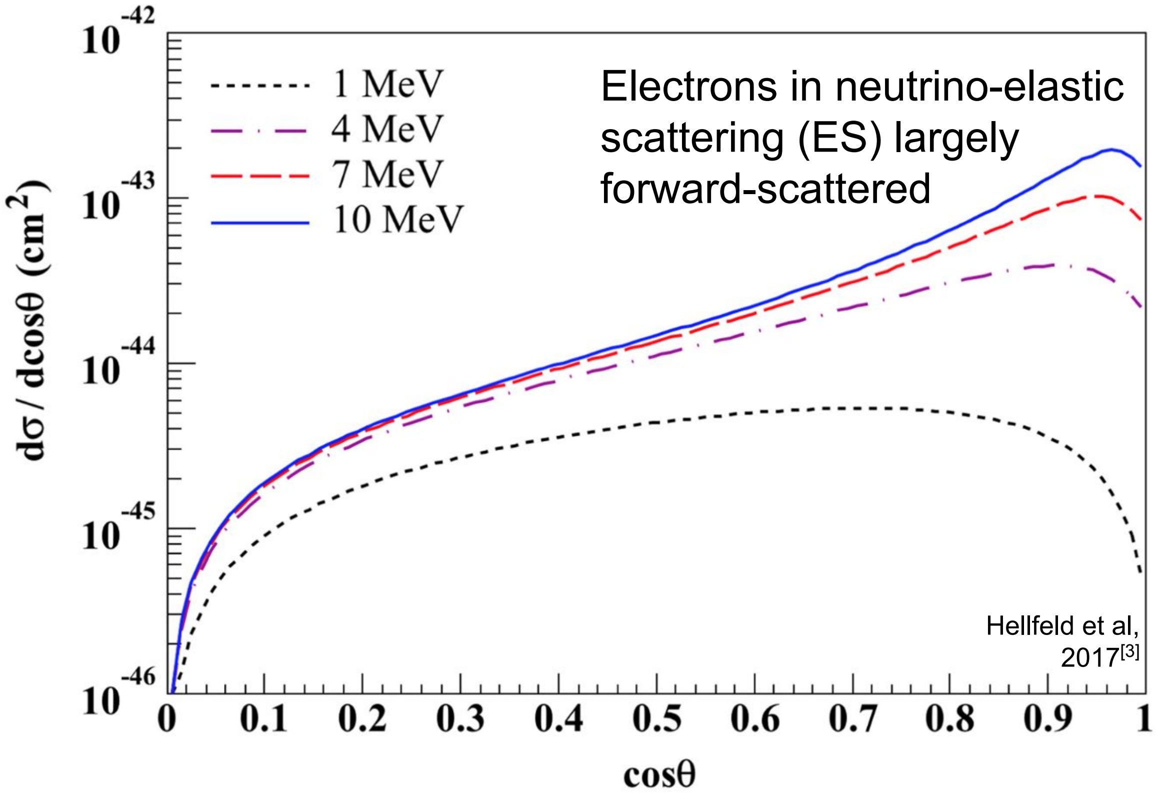


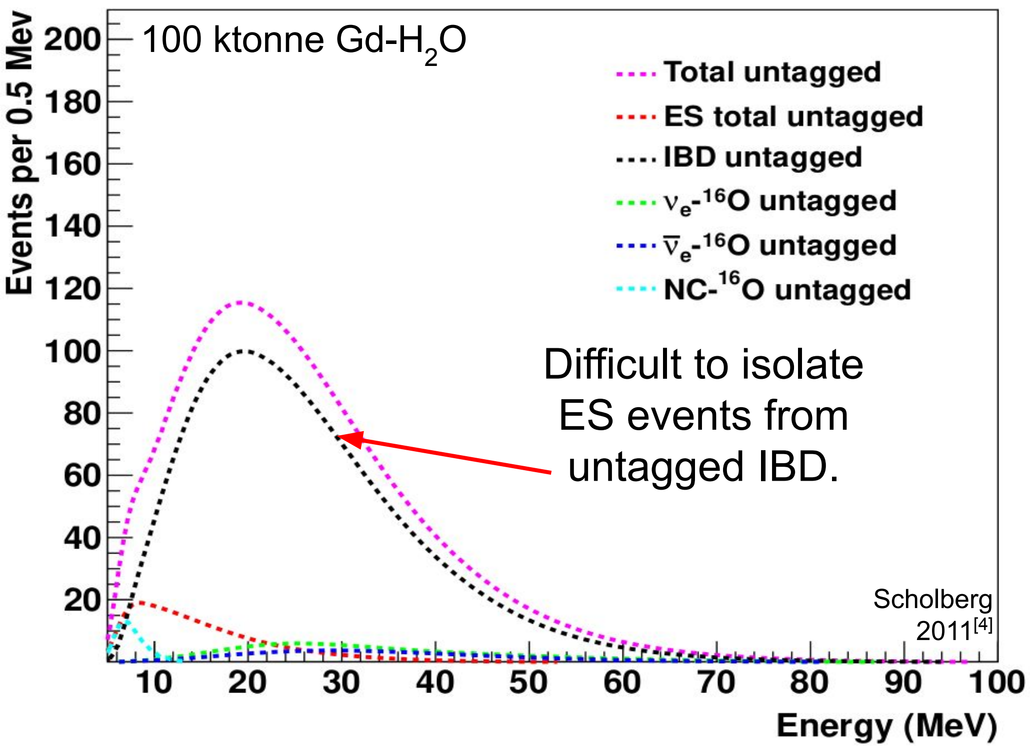
Stability at lowest energies with CoRe could take sensitivity down below the current reconstruction threshold.

Accidental background rejection power of CoRe could reduce this major background.

[2] C. Simpson et al. *Sensitivity of Super-Kamiokande with Gadolinium to Low Energy Antineutrinos from Pre-supernova Emission*, The Astrophysical Journal, Volume 885, Number 2 (2019).

Disentangle νe^- scattering to point to SN





Elastic scattering (ES) interactions point back in the direction of the supernova.

Use the ability to discriminate IBD pairs from single events to disentangle the ES.

[3] Hellfeld et al. *Reconstructing the direction of reactor antineutrinos via electron scattering in Gd-doped water Cherenkov detectors*, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 841:130–138 (2017)
[4] K. Scholberg. *Supernova Neutrino Detection in Water Cherenkov Detectors,* Journal of Physics: Conference Series 309 (2011) 012028 (2011)

CoRe - for the future of SN antineutrino detection

- **Combined reconstruction/neutron-tagging algorithm.**
- **Stable vertex resolution right down to the IBD threshold.**
- **Rejection of accidentals via fit quality selection.**
- **Potential application to pre-SN and directional detection of supernovae.**

- **CoRe now to be re-factored for open-source use - please contact me for future access.**

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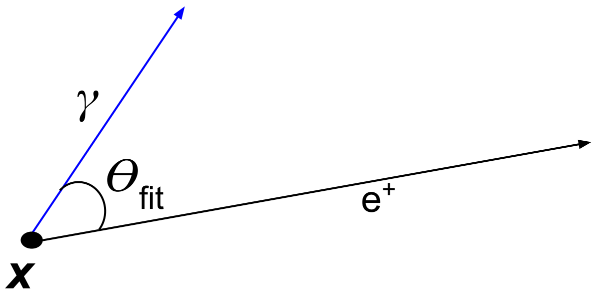
BACKUPS

CoRe - implementation

BONSAI uses a constraining angle of $\theta_c = 44.75°$ to create a likelihood which gives preference to vertices which give a Cherenkov light distribution:

$$ln\mathcal{L}'(\mathbf{x}, t_0, \lambda) = ln\mathcal{L}(\mathbf{x}, t_0) - \lambda\Delta\theta(\mathbf{x})^2$$



where the value of λ depends on whether or not $\Delta\theta(\mathbf{x}) = \theta_c - \theta_{fit}$ is greater than zero.

Constraining angle was optimised in CoRe for positrons and neutrons in all configurations:

Detector size	Detector medium	Optimal constraining angle
16 m	Gd-water	80°
22 m	Gd-water	90°
16 m and 22 m	Gd-WbLS	None

CoRe - background rejection power

Uncorrelated events can occur in accidental coincidence with each other and mimic the IBD signal pair.

Thanks to better reconstruction of IBD events:

a measure of fit quality can be used to help select true correlated events and reject false pairs.

BONSAI fit quality (*timing goodness*)

$$g(\boldsymbol{x}) = \frac{\sum_{\mathrm{hits}} \mathrm{w_i} \mathrm{e}^{-0.5\left(\frac{\Delta \mathrm{t_i}(\boldsymbol{x})}{\sigma}\right)^2}}{\sum_{\mathrm{hits}} \mathrm{w_i}}$$

where w_i are weights calculated using a wider Gaussian distribution.

(σ = 4 ns and σ_w = 50 ns)