Detection of Supernova Neutrinos at Hyper-K

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SN at HK Workshop

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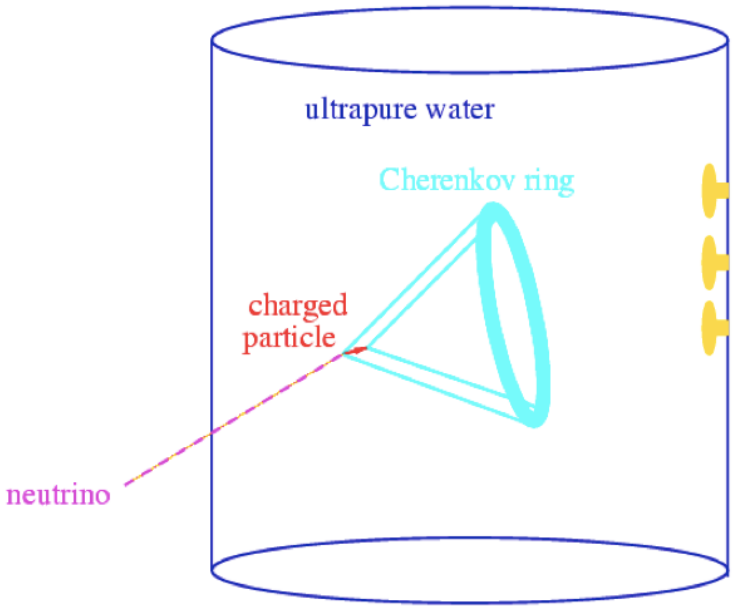
Detecting supernova neutrinos in water

Dominant Reaction

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

Main detection channel is inverse beta decay.

- Sensitive only to electron anti-neutrinos



Detecting supernova neutrinos in water

Dominant Reaction

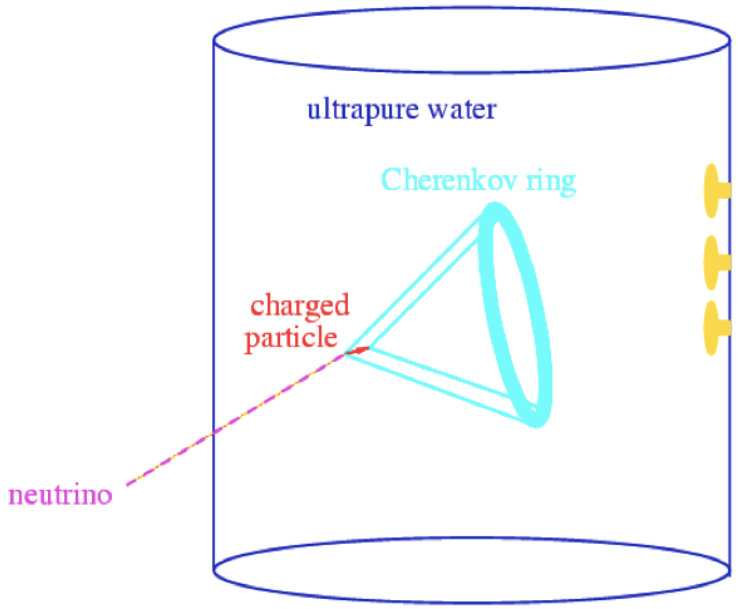
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Other Reactions

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Elastic scattering:

- Sensitive all neutrino flavours, although has a higher cross-section for $\boldsymbol{\nu}_e$
- Has direction information for the incoming neutrino



Detecting supernova neutrinos in water

Dominant Reaction

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

Other Reactions

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

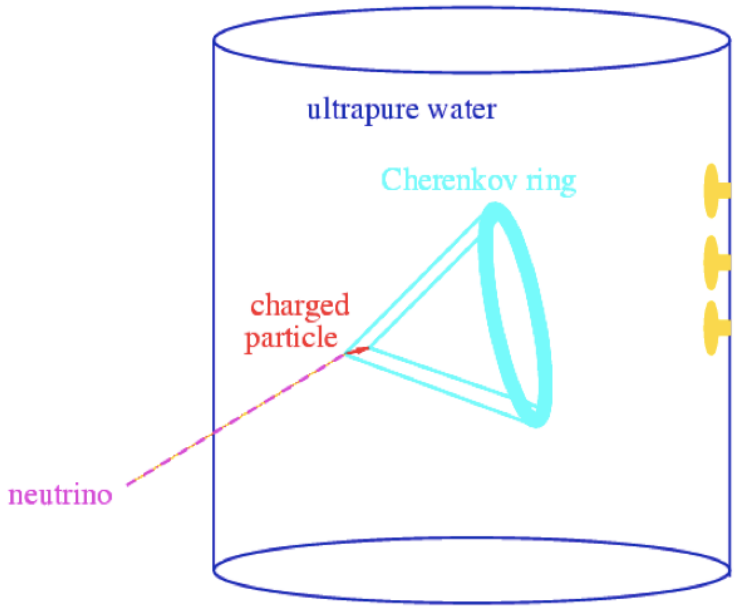
$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$$

$$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$$

$$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + {}^{16}\mathrm{O}^*$$

Reactions with ^{16}O:

- These are low in energy and will be subdominant to the other channels



Detecting supernova neutrinos in water

Dominant Reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n$$ **(CC)**

Other Reactions

$$\nu_x + e^- \rightarrow \nu_x + e^-$$ **(ES) (CC, NC)**

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$$ **(CC)**

$$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$$ **(CC)**

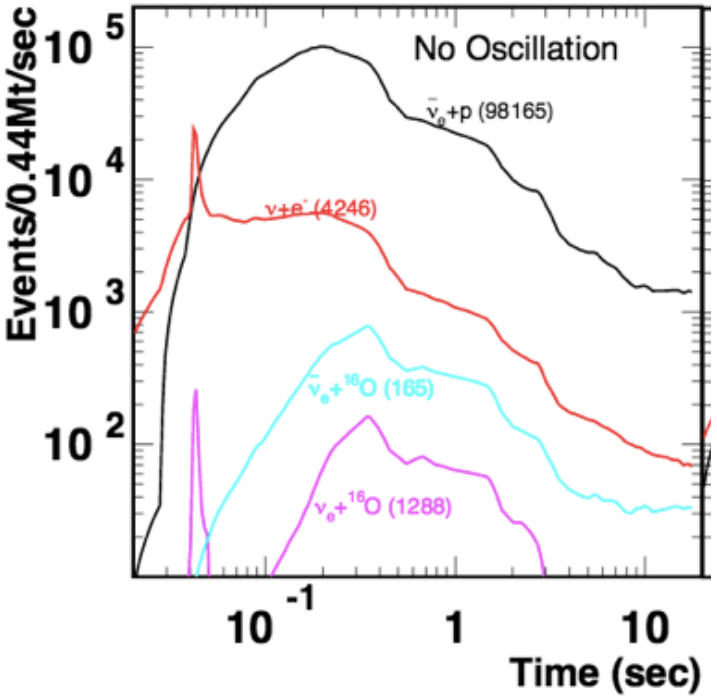
$$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + {}^{16}\mathrm{O}^{*}$$ **(NC)**

- Charged current (CC) channels give us flavour information
- Neutral current (NC) channels give us total flux information
- Elastic scattering (ES) channel gives us directionality information

Supernova Bursts

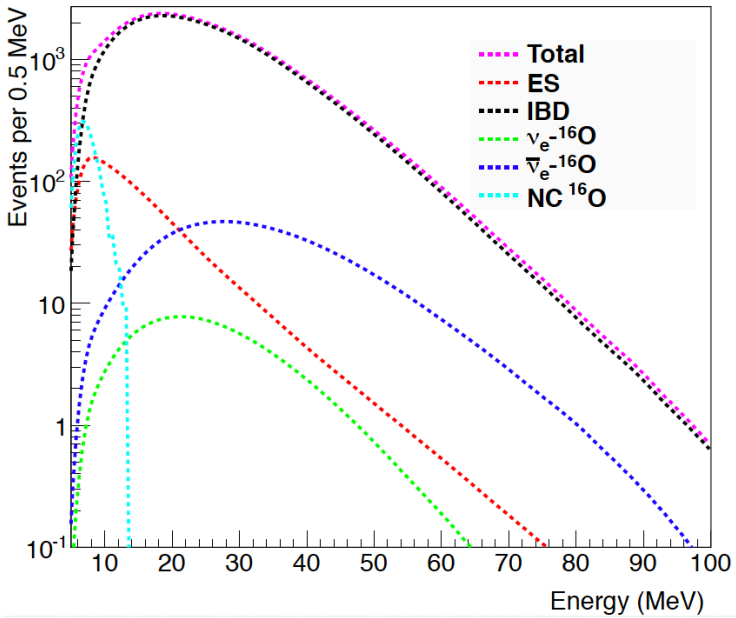
What does a signal look like in HK?

Timing information

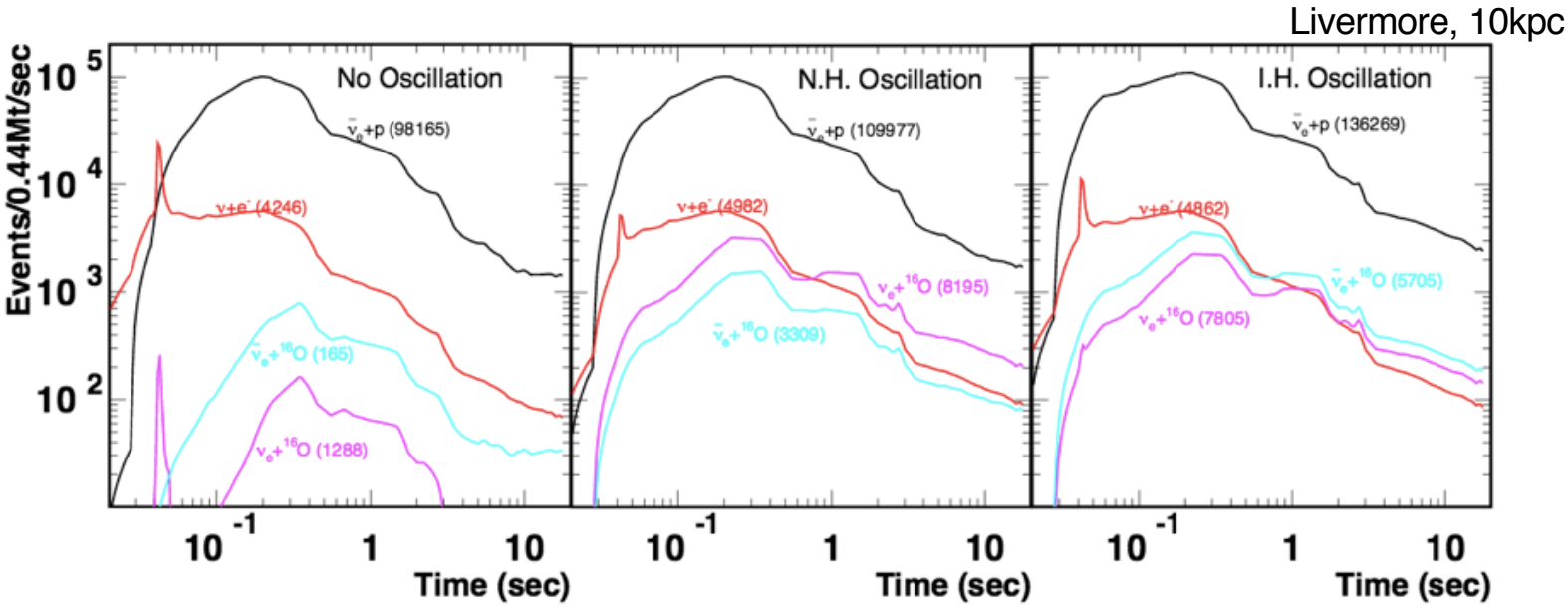


Livermore, 10kpc

Energy information

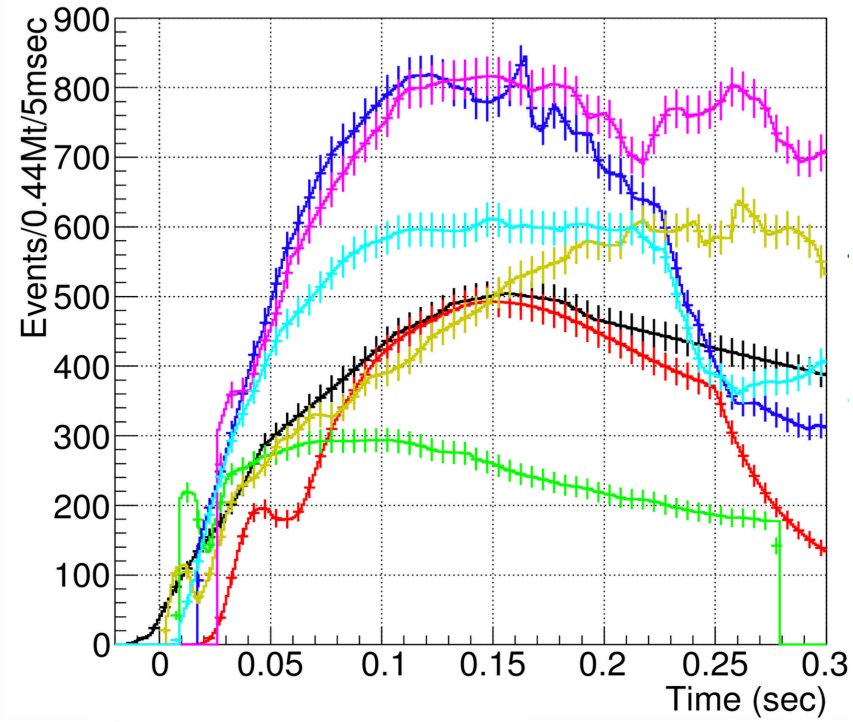


How does (MSW) oscillation affect the HK signal?



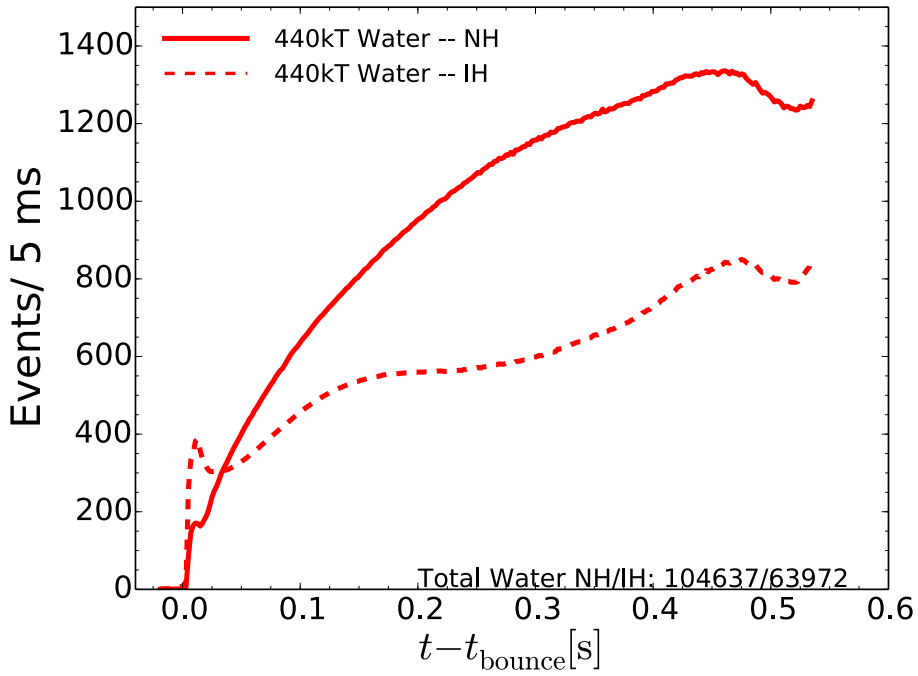
Oscillations mix flavour spectra ($\nu_e \rightleftarrows \nu_x$, $\bar{\nu}_e \rightleftarrows \bar{\nu}_x$), suppresses the neutronization burst, changes expected amounts in other channels

What different SN models look like in HK



Livermore, 11.2M (1D)
Nakazato, 20M (1D)
Takiwaki, 11.2M (3D)
BRUENN(OakRidge), 20M (2D)
DOLENCE(Princeton), 20M (2D)
K.C.PAN(Basel), 21M (2D)
TAMBORRA(Max-Plank), 27M (3D)

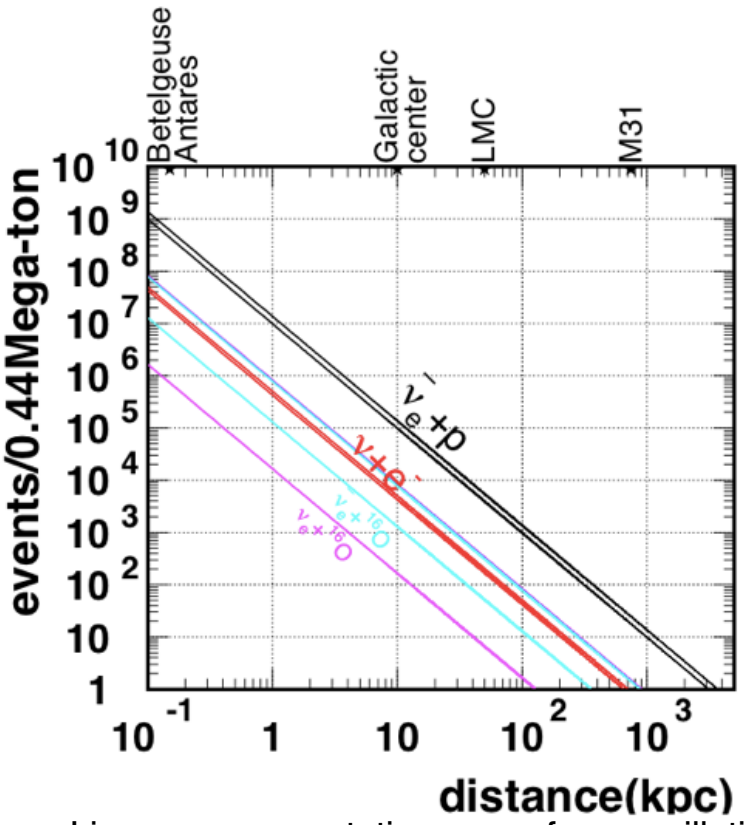
Failed SN (black hole formed)



O'Connor 2015 (GR1D), 40M (1D)

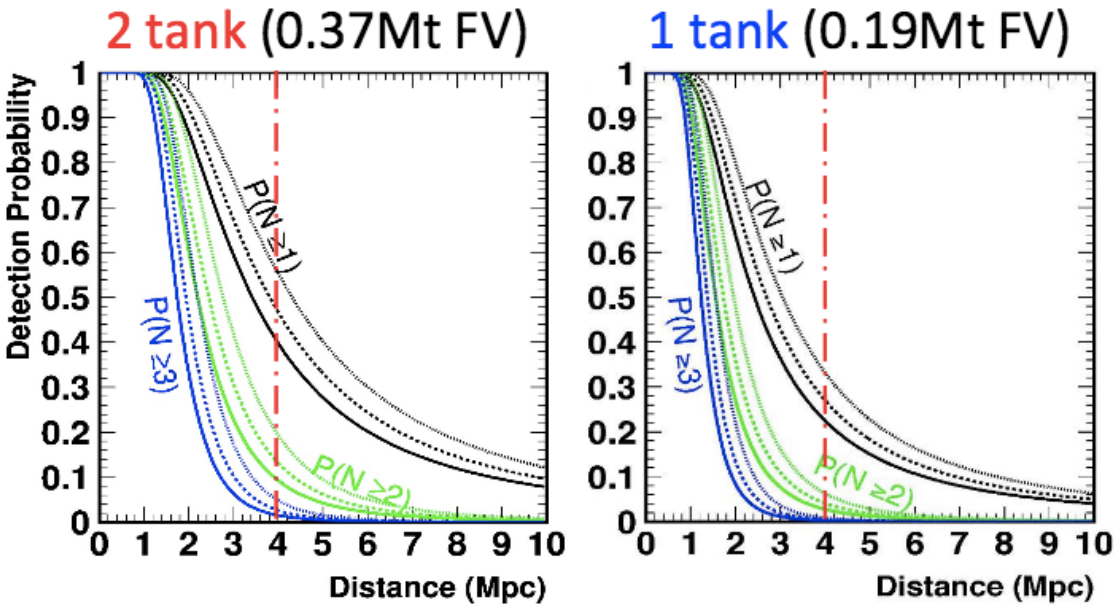
Number of neutrinos as a function of distance

Expect big statistics out to kpc range, a handful of events out to Mpc range



Livermore, expectation range from oscillation effects

Detection Probability for a MPc SN



For 4Mpc supernova

10-20 % for P(N >= 2) 3-6% for P(N >= 2)

Livermore, 10 MeV threshold, expectation range from oscillation effects

Number of events in HK

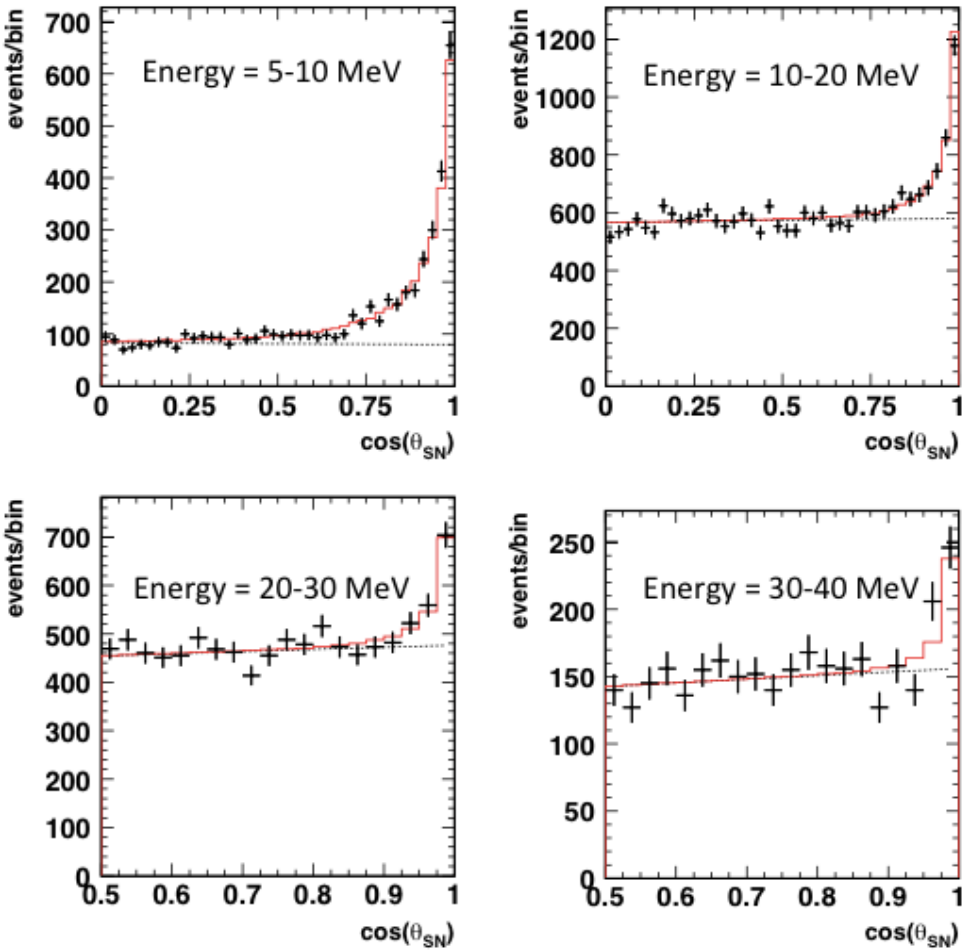
Livermore, 10kpc, expectation range from oscillation effects

Neutrino source	2TankHD (440 kt Full Volume)	1TankHD (220 kt Full Volume)
$\bar{\nu}_e + p$	98,000~136,000 events	49,000~68,000 events
$\nu_e + e^-$	4,200~5,000 events	2,100~2,500 events
$\nu_e + {}^{16}O$ CC	160~8,200 events	80~4,100 events
$\bar{\nu}_e + {}^{16}O$ CC	1,300~7,800 events	650~3,900 events
$\nu_e + e^-$ (Neutronization)	12~80 events	6~40 events
Total	104,000~158,000 events	52,000~79,000 events

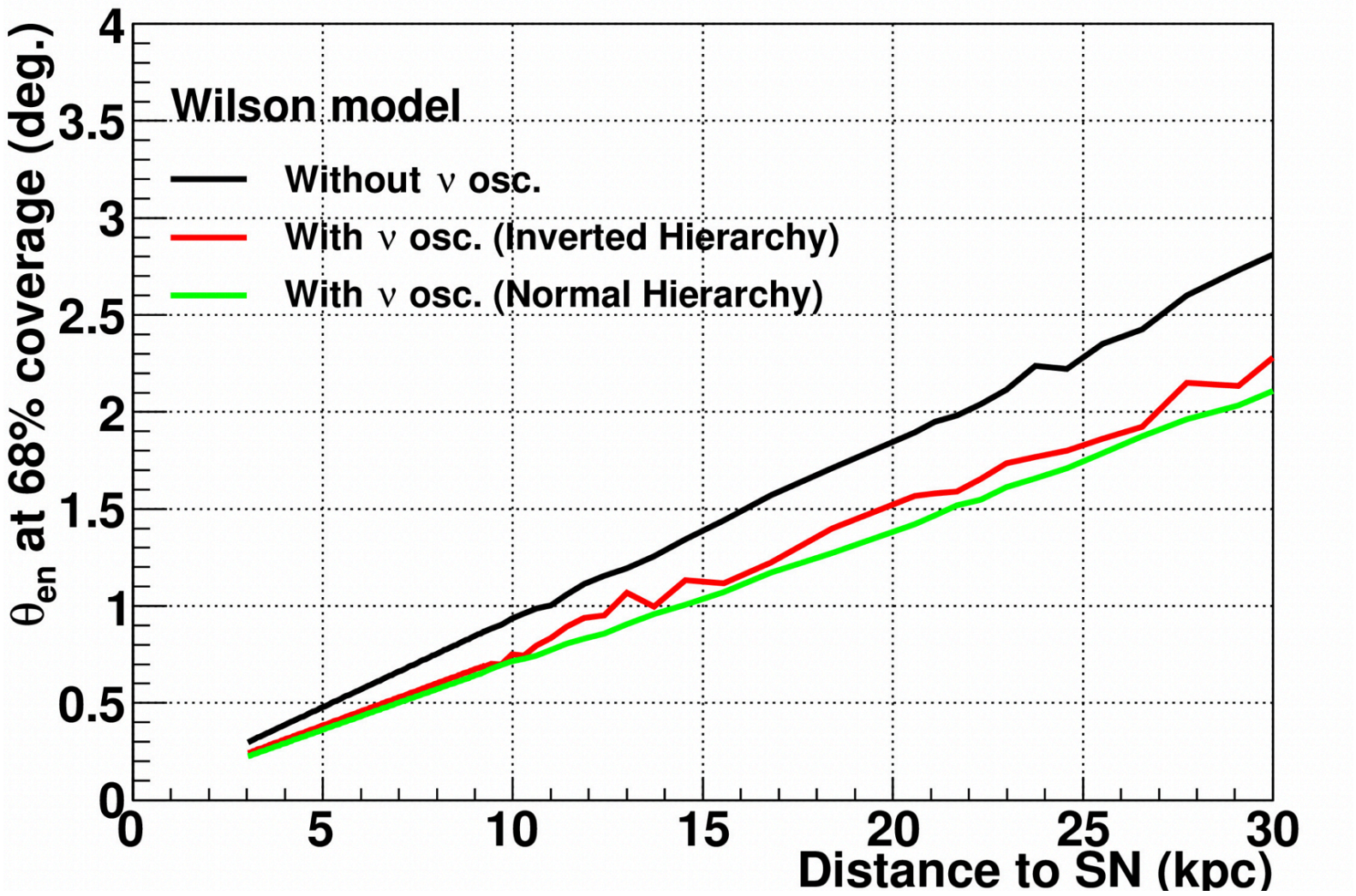
+ potentially hundreds of events in the ^{16}O NC channel.
With high photocoverage, we might be able to see these.

What information can we extract?

Directionality

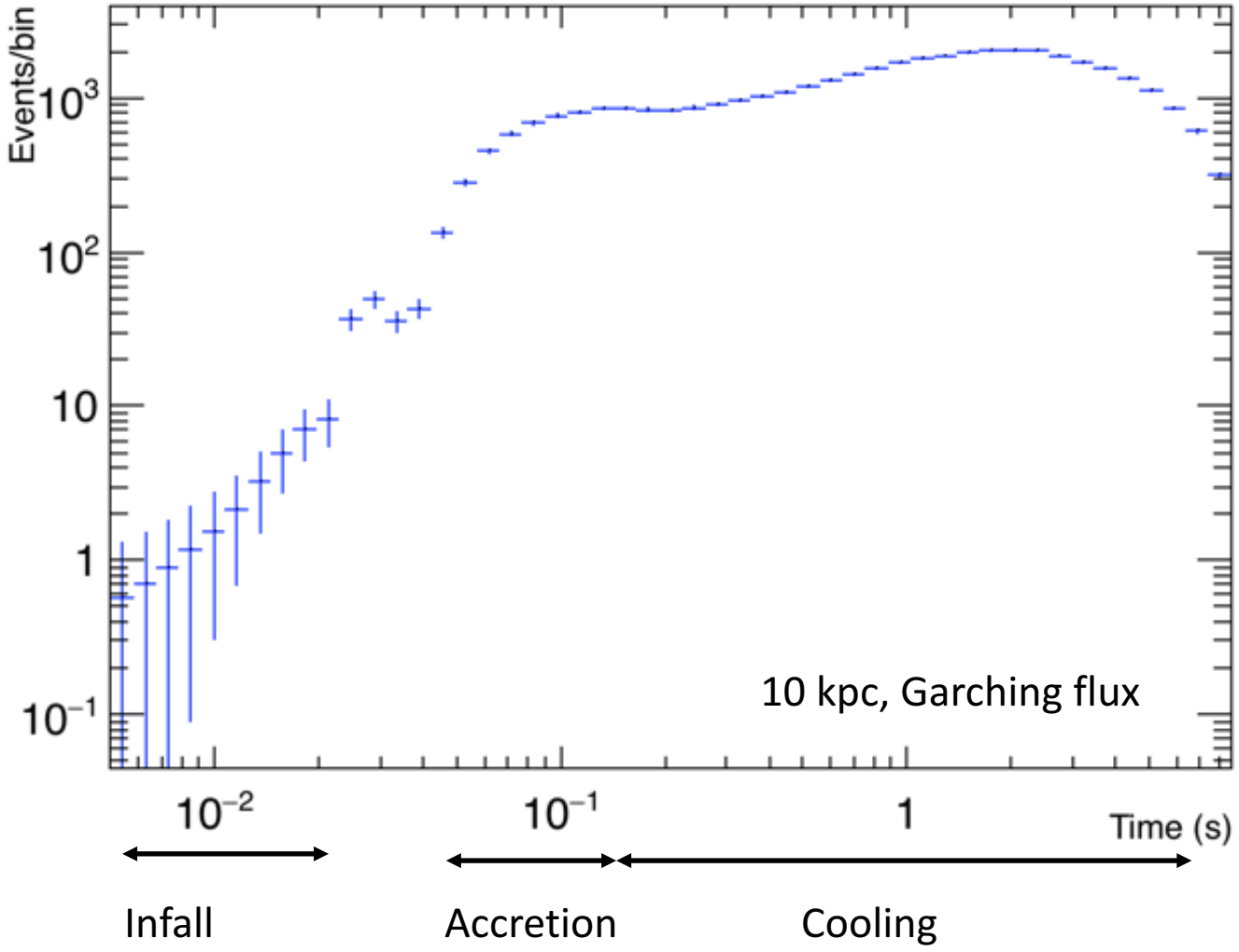


What information can we extract?



HK points to ~1° for a 10 kpc SN

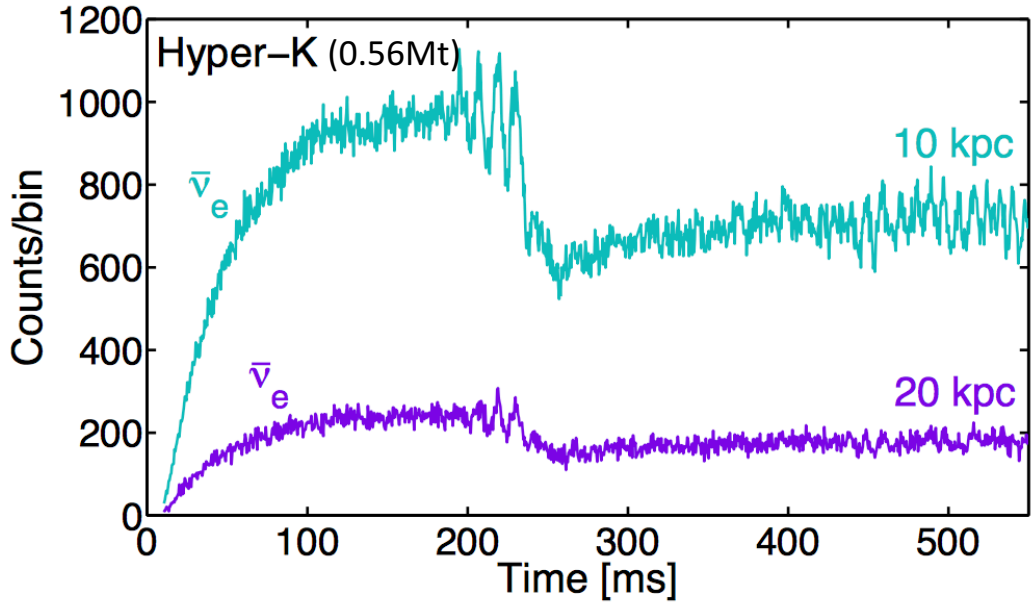
What information can we extract?



Neutrinos are a way to probe the inner dynamics of the explosion

What information can we extract?

Standing Accretion Shock Instability (SASI)

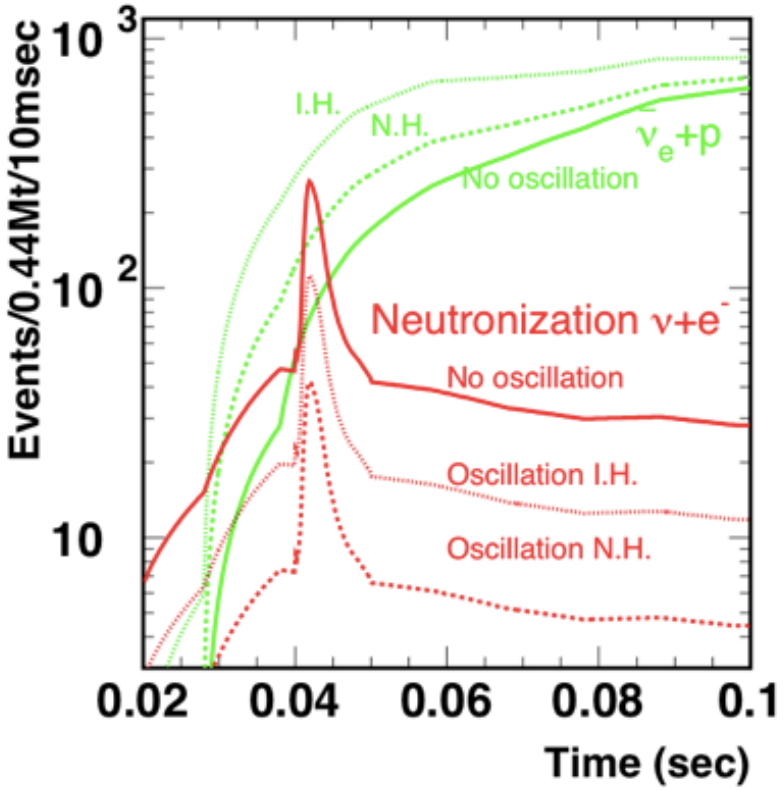


I. Tamborra, F. Hanke, B. Mueller, H.-T. Janka and G. G. Raffelt, Phys. Rev. Lett. **111** (2013) 121104, [arXiv: 1307.7936].

Neutrinos are a way to probe the inner dynamics of the explosion

What information can we extract?

Mass hierarchy: look at rise time of IBD rate

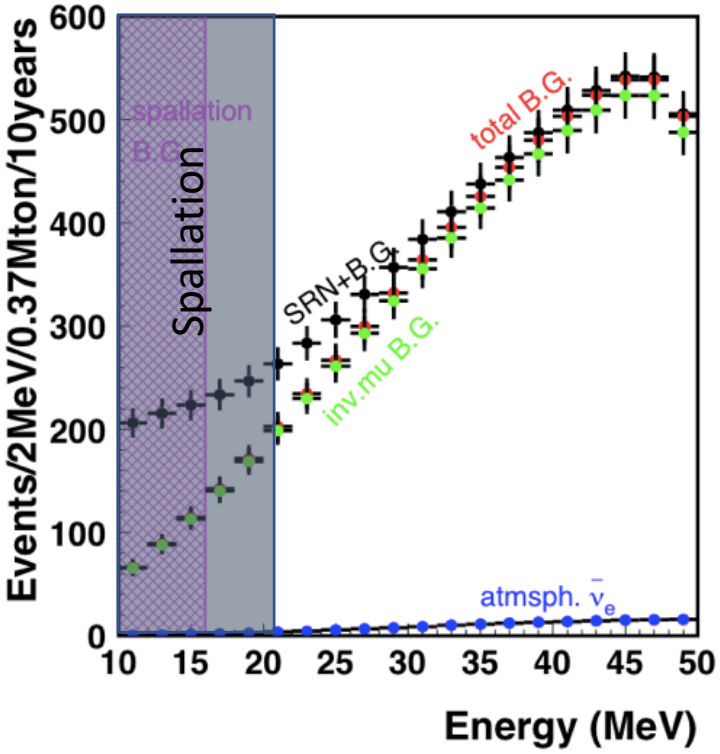


Supernova Relic Neutrinos

Backgrounds to the SRN search

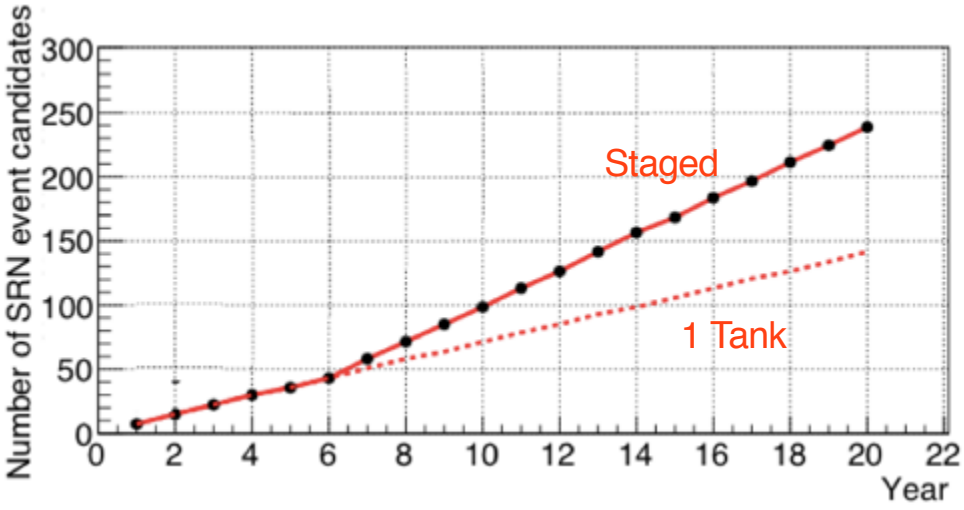
Flux: S. Ando, K. Sato, and T. Totani, Astropart. Phys. 18, 307 (2003)

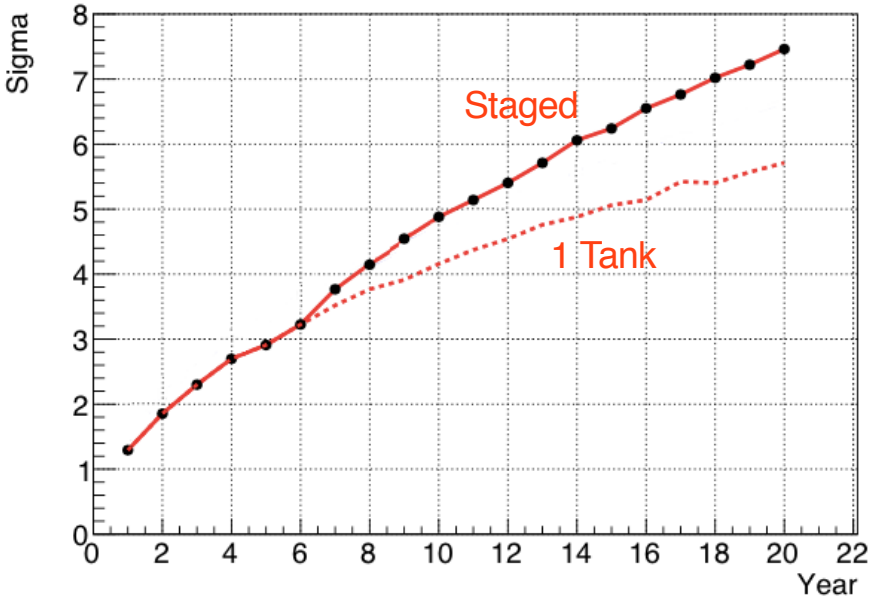
- With no neutron tagging, spallation products and invisible muons are the primary background in the search window
- Neutron tagging could significantly reduce backgrounds. This is still under investigation, but here we assume ~70%.



SRN Discovery Potential

Flux: S. Ando, K. Sato, and T. Totani, Astropart. Phys. 18, 307 (2003),
70% neutron tagging eff of 2.2 MeV gamma assumed



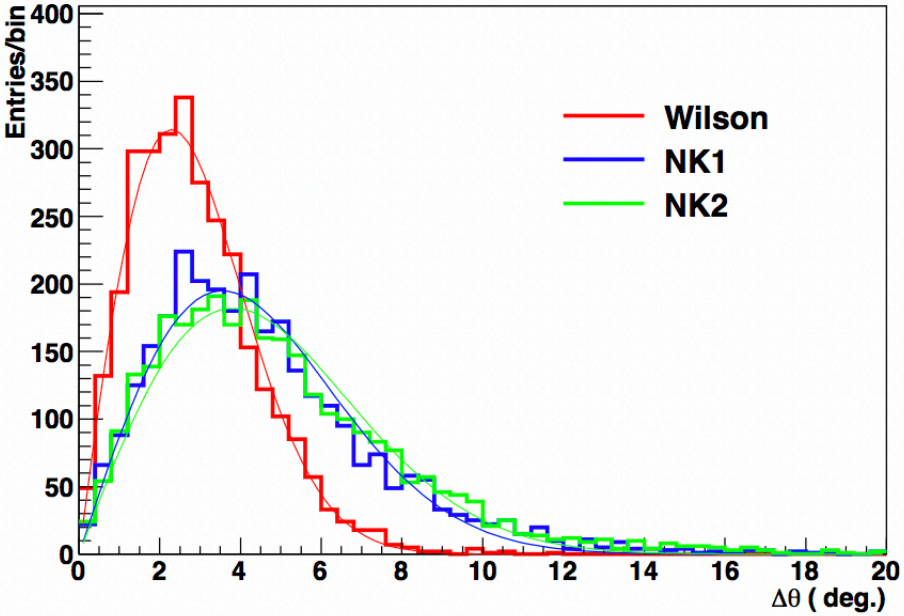


HK has a high discovery potential for the presence of SRNs

Conclusions

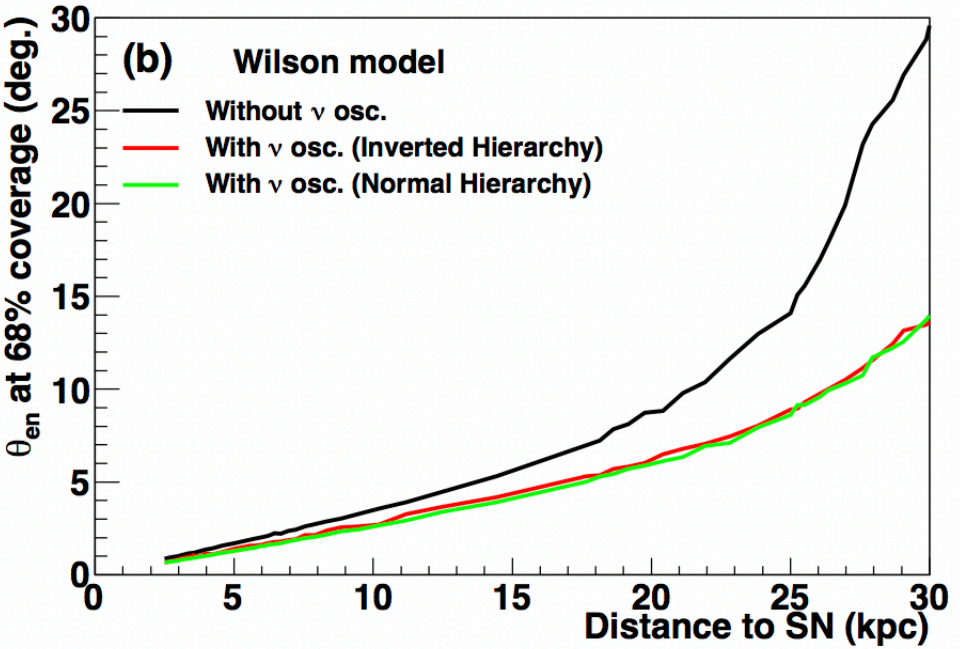
- Hyper-K will be able to measure SN neutrinos with high statistics, particularly in the IBD channel.
- The elastic scattering channel will allow us to estimate the direction of the supernova (~1° for 10 kpc).
- Features in the timing profile will allow us probe the explosion dynamics, including SASI.
- HK has a high discovery potential for SRN (> 7 $\boldsymbol{\sigma}$)

SN pointing with SK



True – Reconstructed direction distribution for 3000 SN simulations.

Wilson, NK1, NK2 are the names of SN models.



Pointing accuracy (68.3% SNe included) vs distance to SN.

~3 degrees at 10kpc.

How many supernovae will occur within 10 MPc in HK's lifetime?

- 17.5 SNe/20y (theoretical, ROTUV)
- 36.4 SNe/20y (observation, without SN 2008slike)
- 49.6 SNe/20y (observation, with SN 2008s-like)