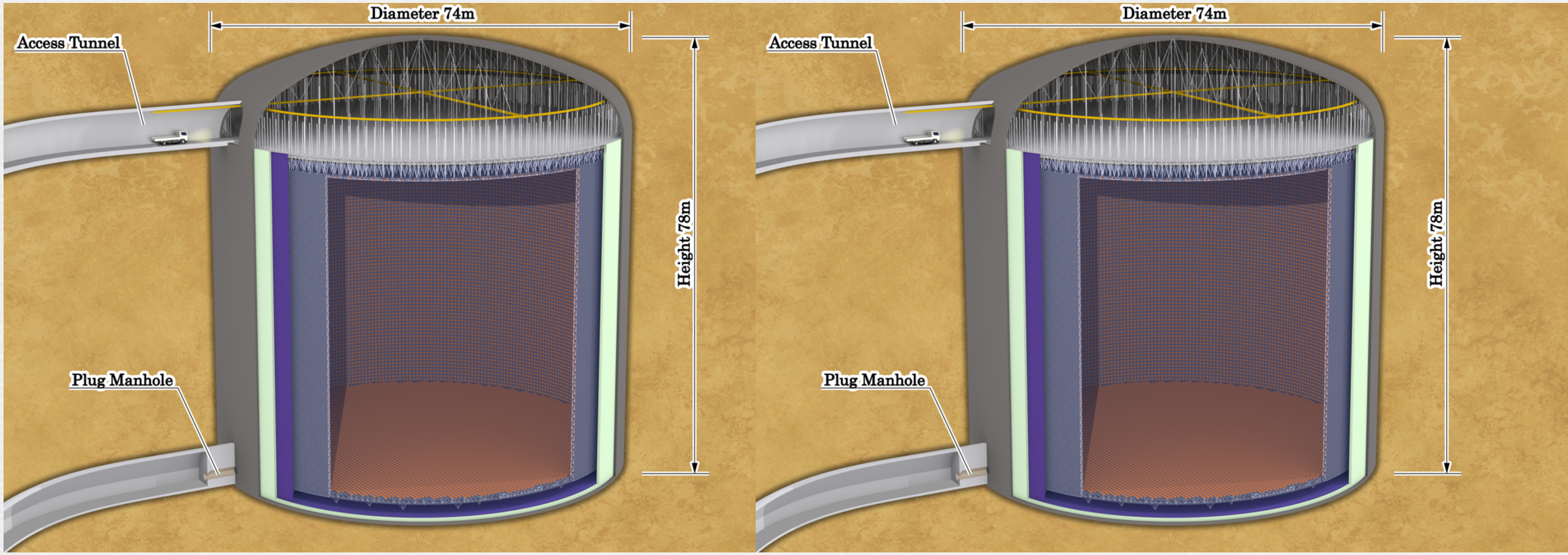
DETECTING SUPERNOVA NEUTRINOS IN HYPER-KAMIOKANDE

Erin O'Sullivan,
on behalf of and with contributions from the HK astrophysics group
Duke University
SN@DUNE Workshop
March 12, 2016

THE HYPER-K DETECTOR

HK DETECTOR TANKS



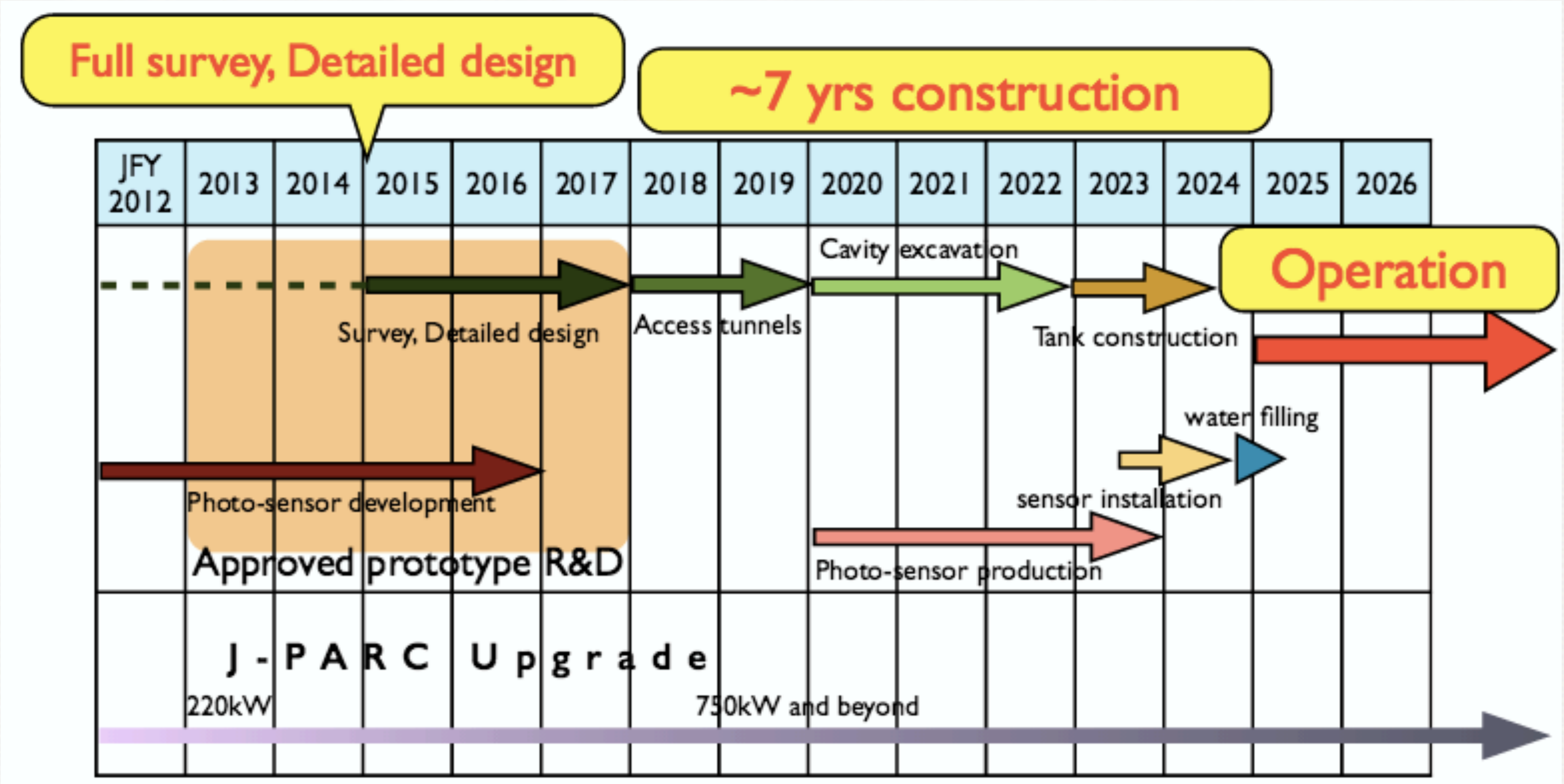
Two 74m (D) x 60m (H) tanks

- Total (fiducial) volume of two tanks: 516 kT (374 kT).

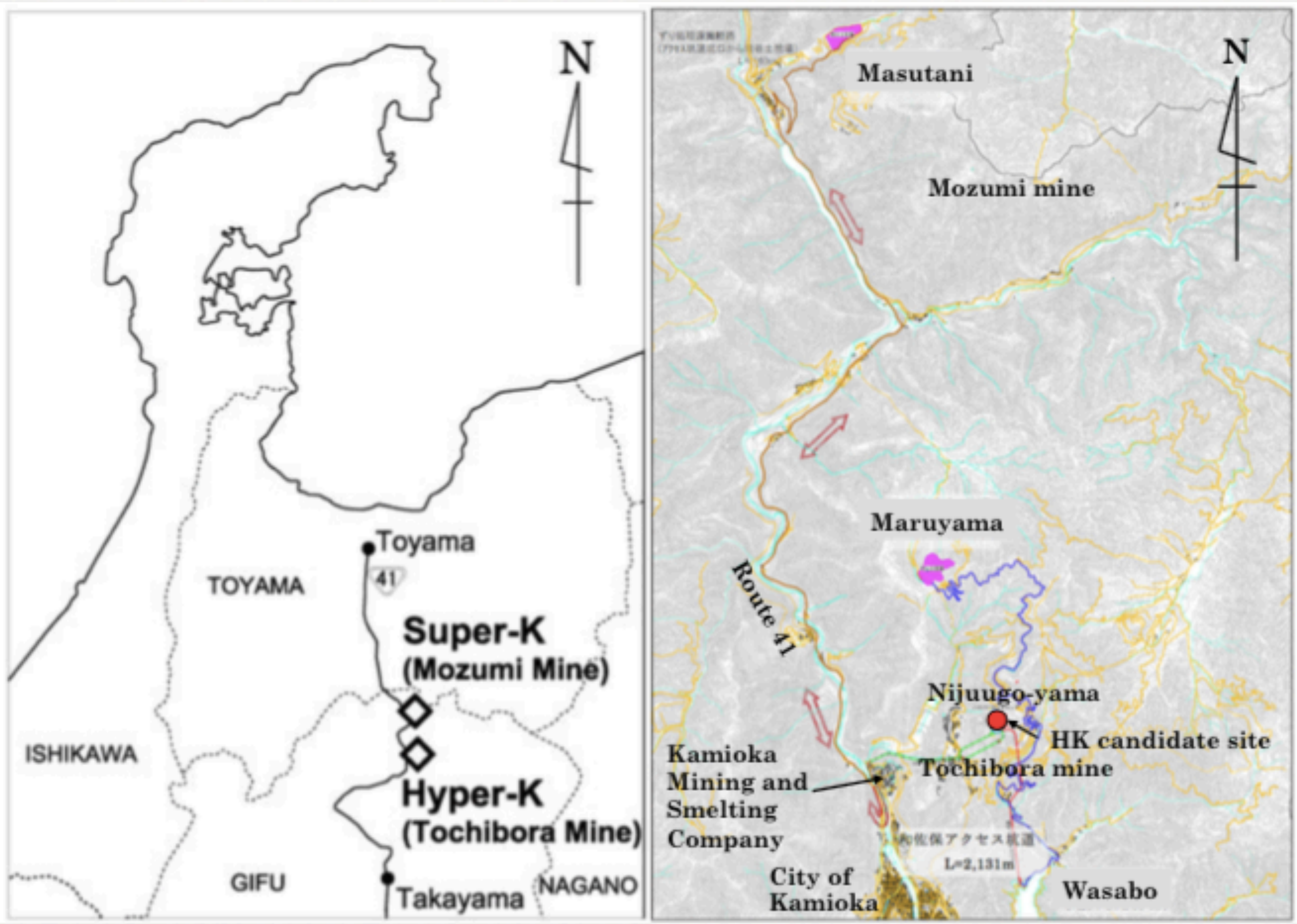
In the nearby SN analysis, we use the volume of the full inner detector (440 kT).

- Staged design: second tank will come online 6 years after the first.

HYPER-K TIMELINE



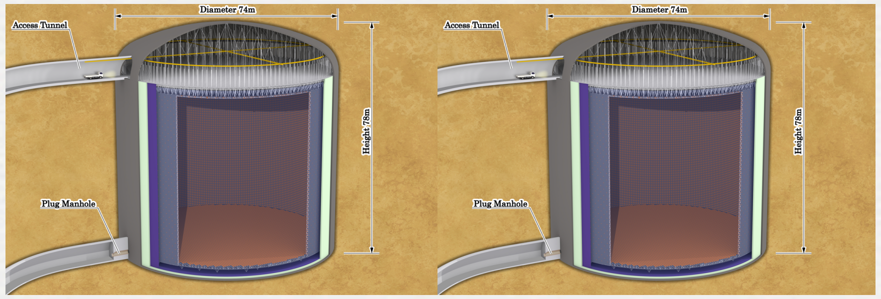
HK DETECTOR CANDIDATE SITE



SUPER-KAMIOKANDE TO HYPER-KAMIOKANDE

Super-K

Hyper-K

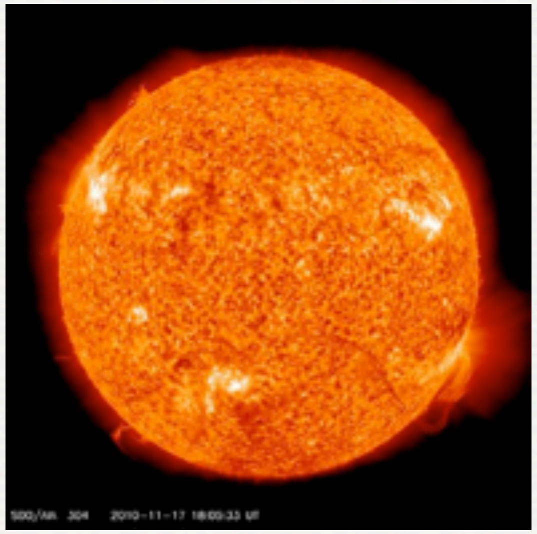


- Fiducial volume 22.5 kT
- 11,000 20" PMTs (40% coverage)
- 2-3 ns timing resolution

- Fiducial volume 374 kT (16x bigger)
- 80,000 20" Box and line (still 40% coverage, but 2x more efficient)
- 1 ns timing resolution

Bigger volume, higher detection efficiency, better resolution

HK PHYSICS GOALS

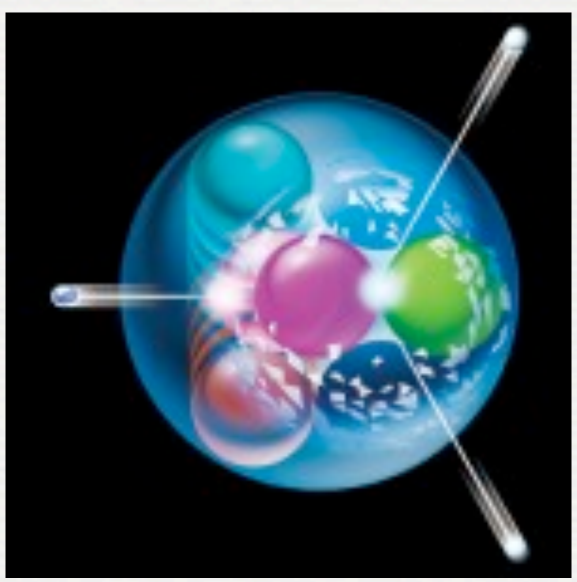


Solar neutrinos

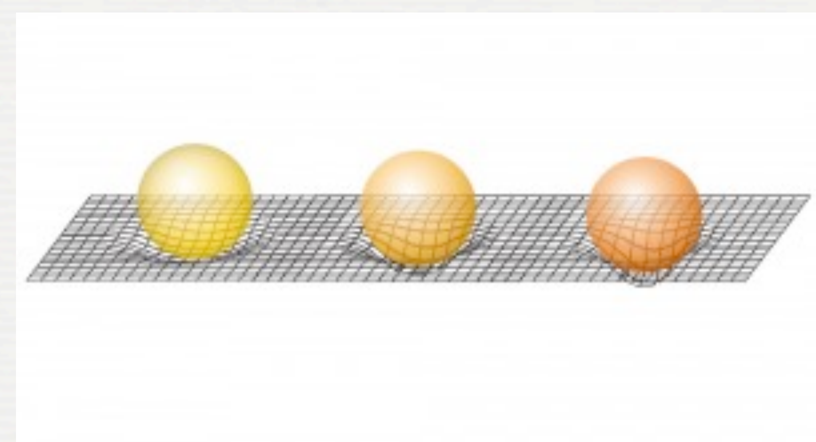
CP violation

Supernova neutrinos

Focus of today's talk



Proton decay



Mass hierarchy

SUPERNOVA NEUTRINO BURST OBSERVATIONS IN HK

A WORD ON FLUX MODELS...

- livermore: older model, predicts higher neutrino temperatures and therefore higher number of observed events. Historically used in neutrino experiments. See Astrophys J. 496.216, 1998.
- gkvm: includes collective oscillations and shock wave effects. See Phys. Rev. Lett.103.071101, 2009.
- garching: more recent model, uses 8.8 $M_{\odot}$ progenitor. See PhysRevLett.104.251101, 2010.

SN NEUTRINO INTERACTIONS WITH WATER

$$\bar{\nu}_e + p \to e^+ + n$$ **IBD**

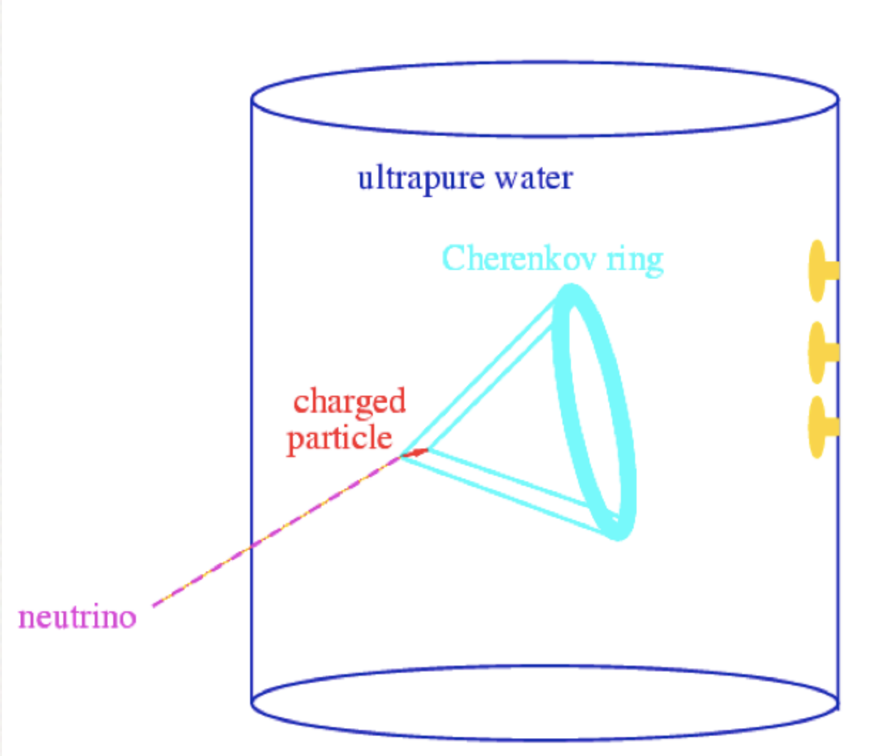
Other Reactions

$$\nu_x + e^- \to \nu_x + e^-$$ **ES**

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

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

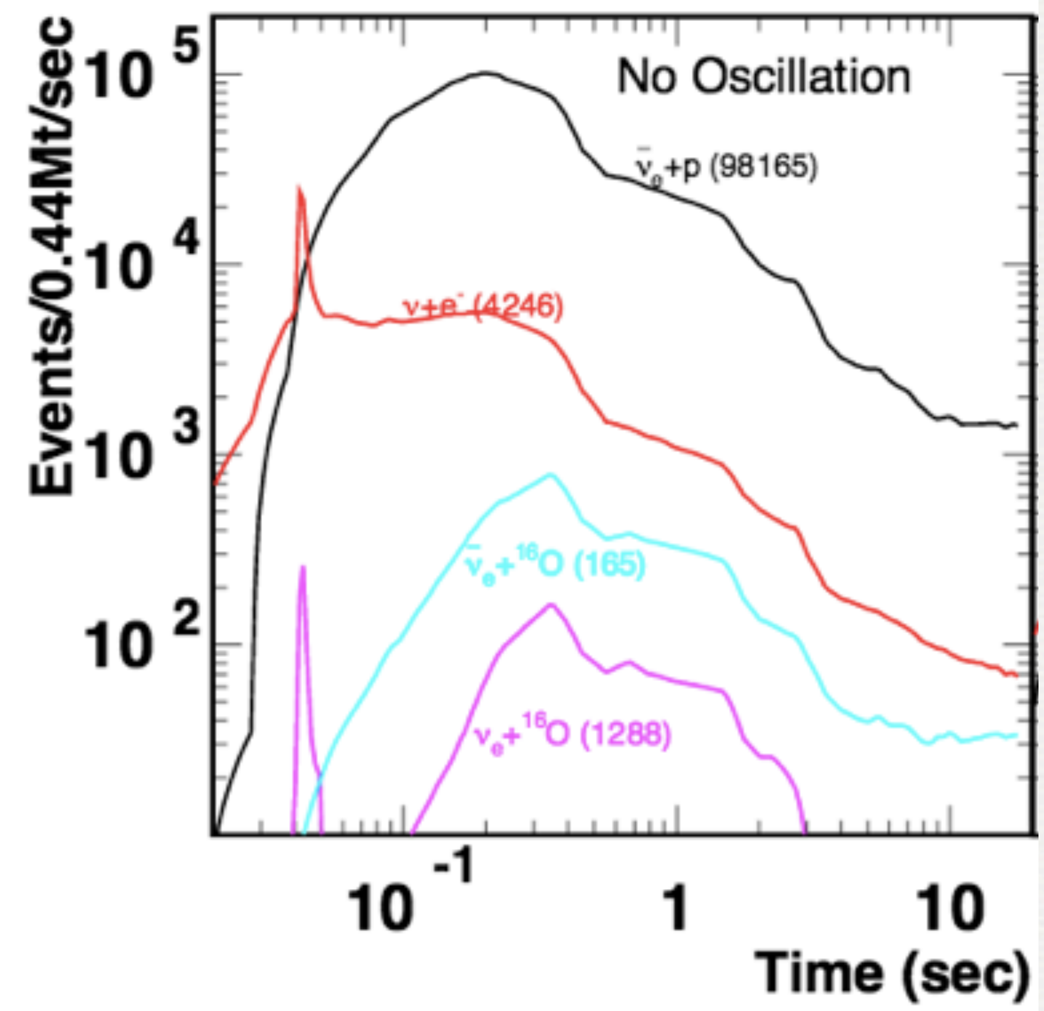
$$\nu_x + {}^{16}\mathrm{O} \to \nu_x + {}^{16}\mathrm{O}^*$$ **NC**



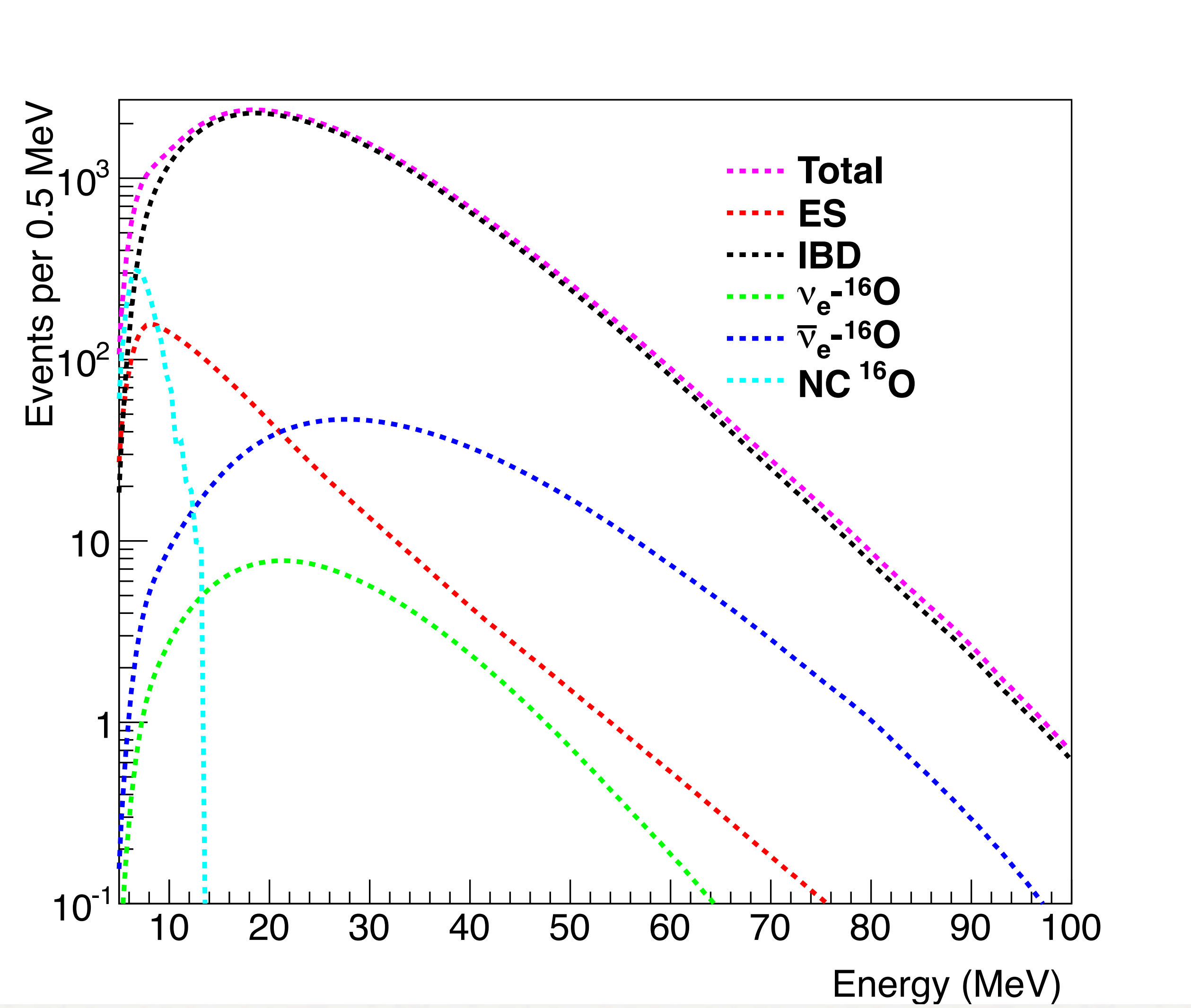
Main channel is inverse beta decay (IBD)
Elastic scattering (ES) channel has directionality
Neutral current (NC) channel gives overall flux info (without oscillation complications)

WHAT DOES A SN LOOK LIKE IN HK?

Timing spectrum



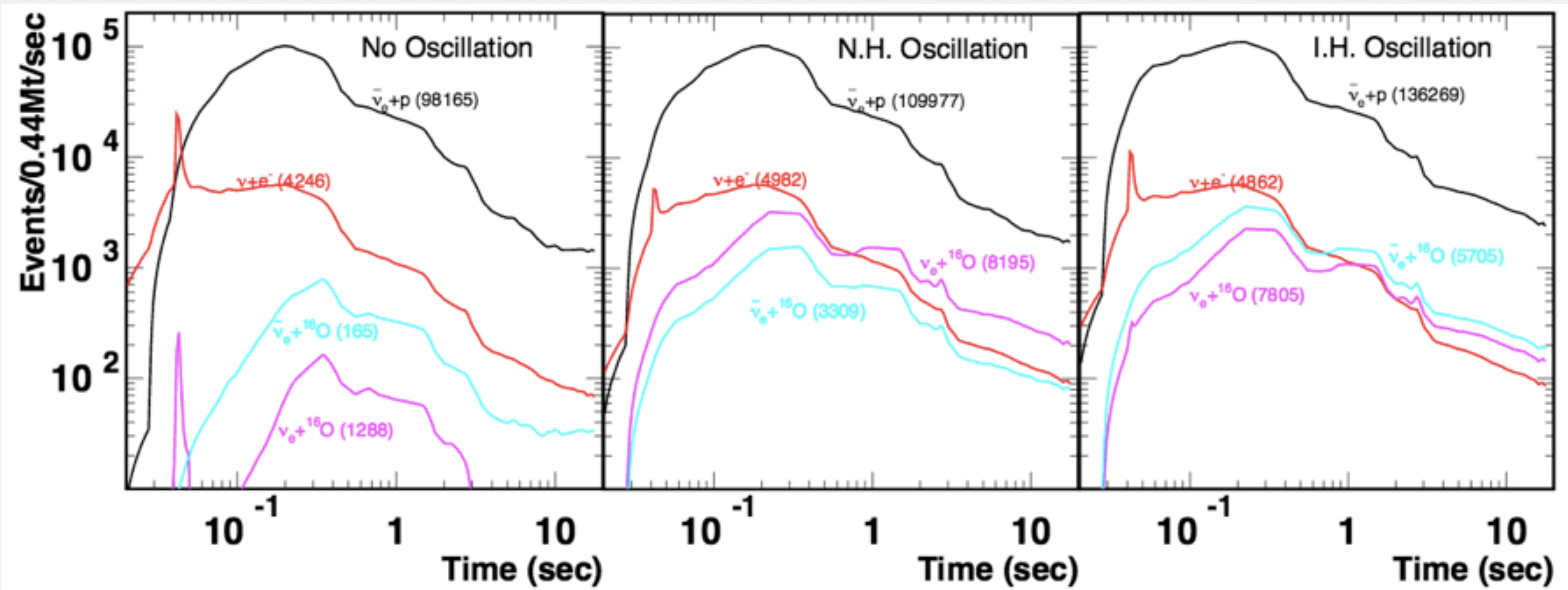
Energy spectrum



Livermore, 10kpc

WHAT HAPPENS IF YOU CONSIDER (MSW) OSCILLATIONS?

Livermore, 10kpc



Oscillations mix flavour spectra ($\nu_e \rightleftarrows \nu_x, \overline{\nu_e} \rightleftarrows \overline{\nu_x}$), suppresses the elastic scattering channel, changes expected amounts in other channels

NUMBER OF NEUTRINOS IN EACH INTERACTION CHANNEL (10KPC SN)

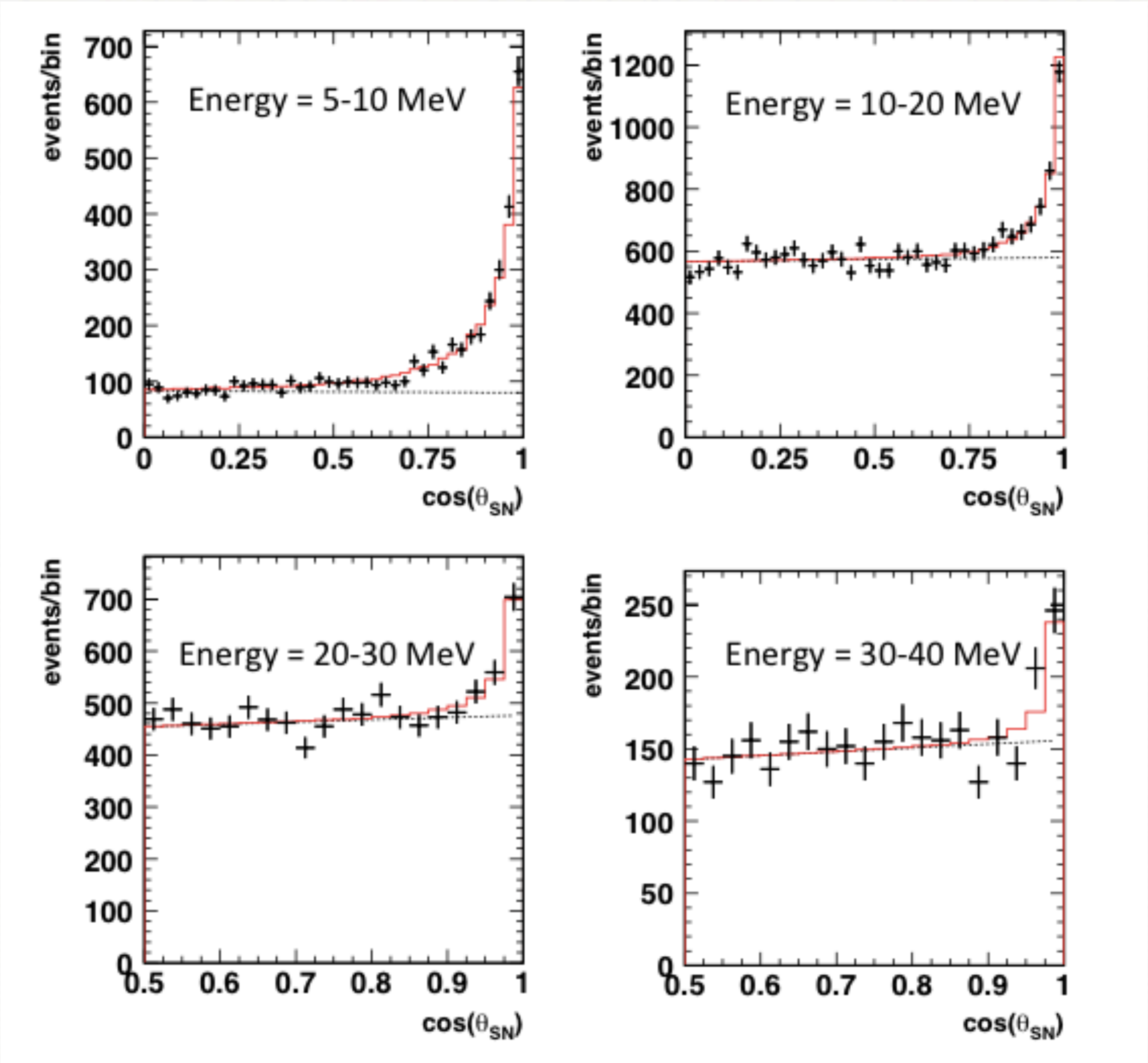
Livermore, 10kpc, expected range from oscillation effects

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.

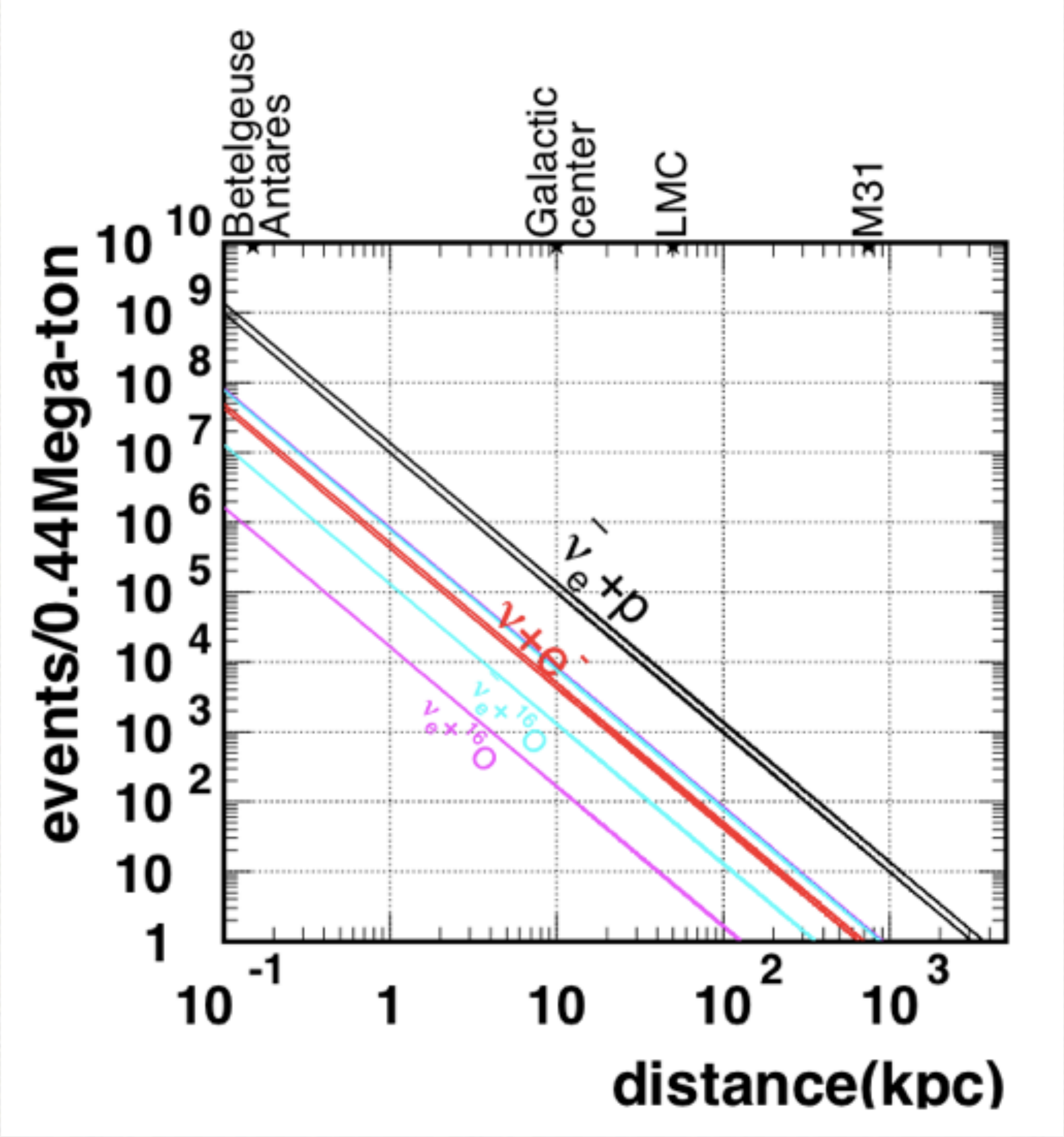
DIRECTIONALITY OF SN NEUTRINOS IN HK

- Most directional info comes from lower energy bins where ES is highest
- HK can reconstruct direction to within 2° for livermore, 10kpc



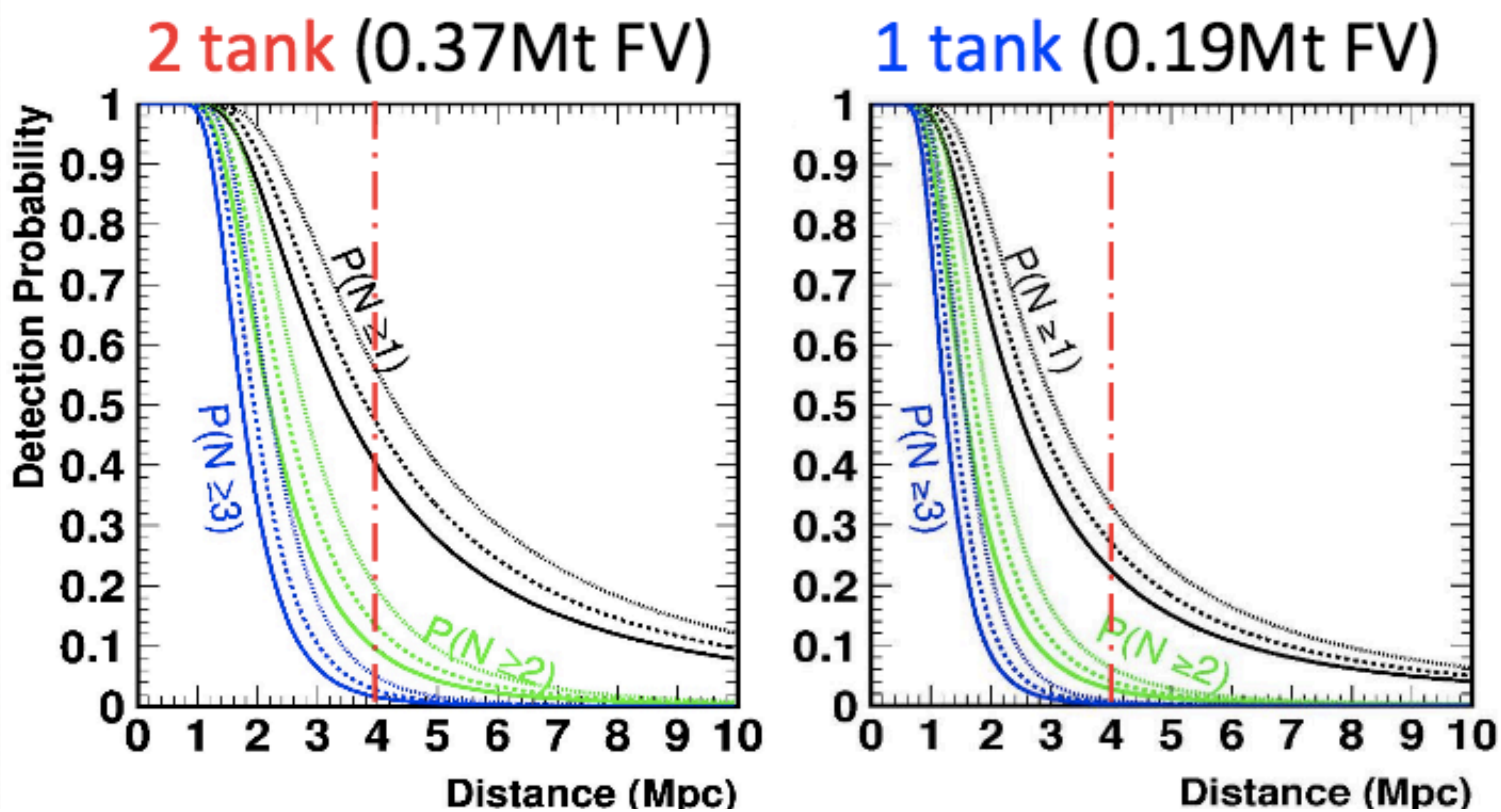
HOW MANY NEUTRINOS AS A FUNCTION OF SN DISTANCE

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



Livermore, expectation range from oscillation effects

DETECTION PROBABILITY FOR MPC SN



For 4Mpc supernova

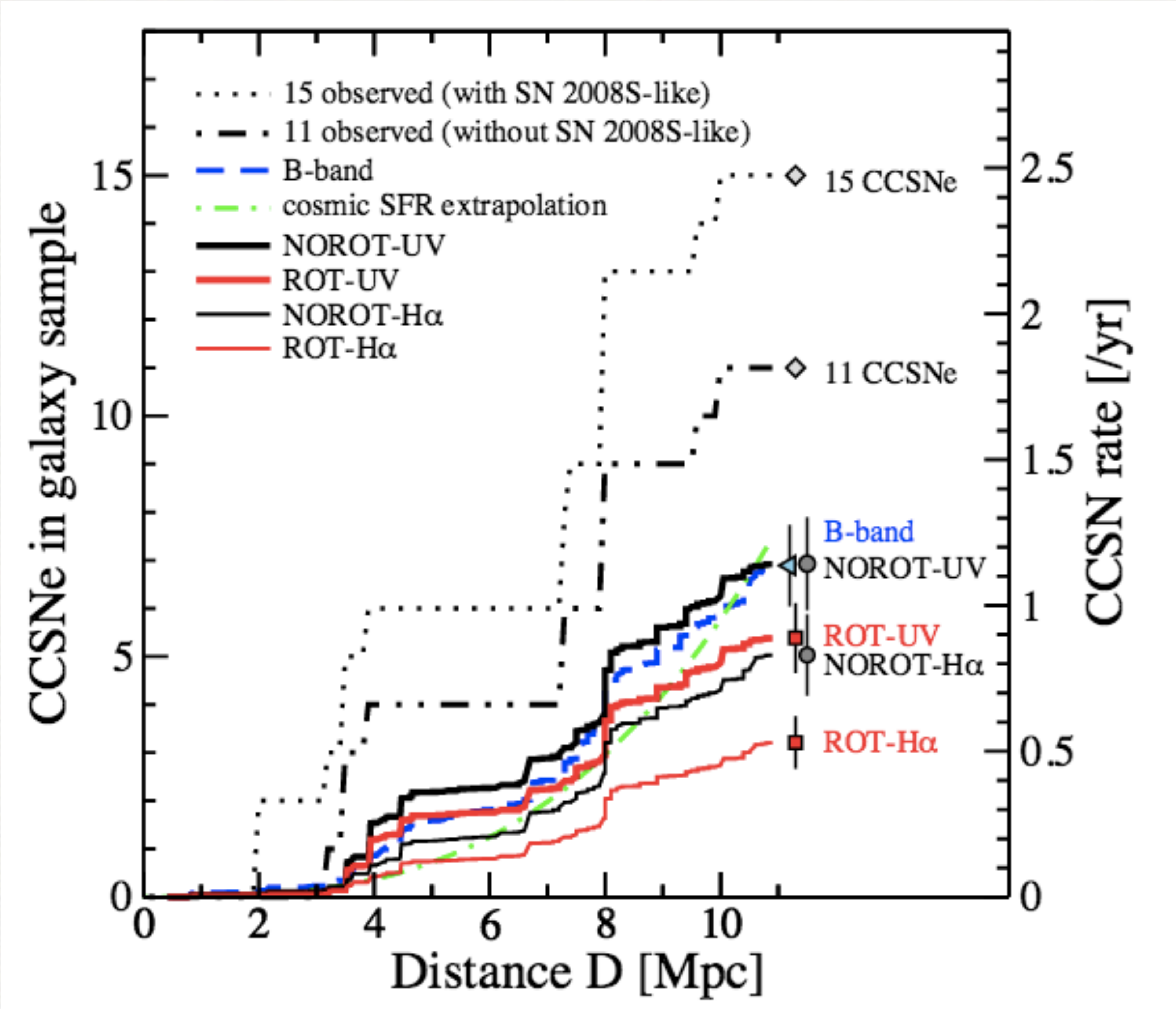
10-20 % for P(N >= 2)

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

Livermore, 10 MeV threshold, expectation range from oscillation effects

HOW MANY SNE MIGHT THERE BE IN HK'S LIFETIME WITHIN 10 MPC?

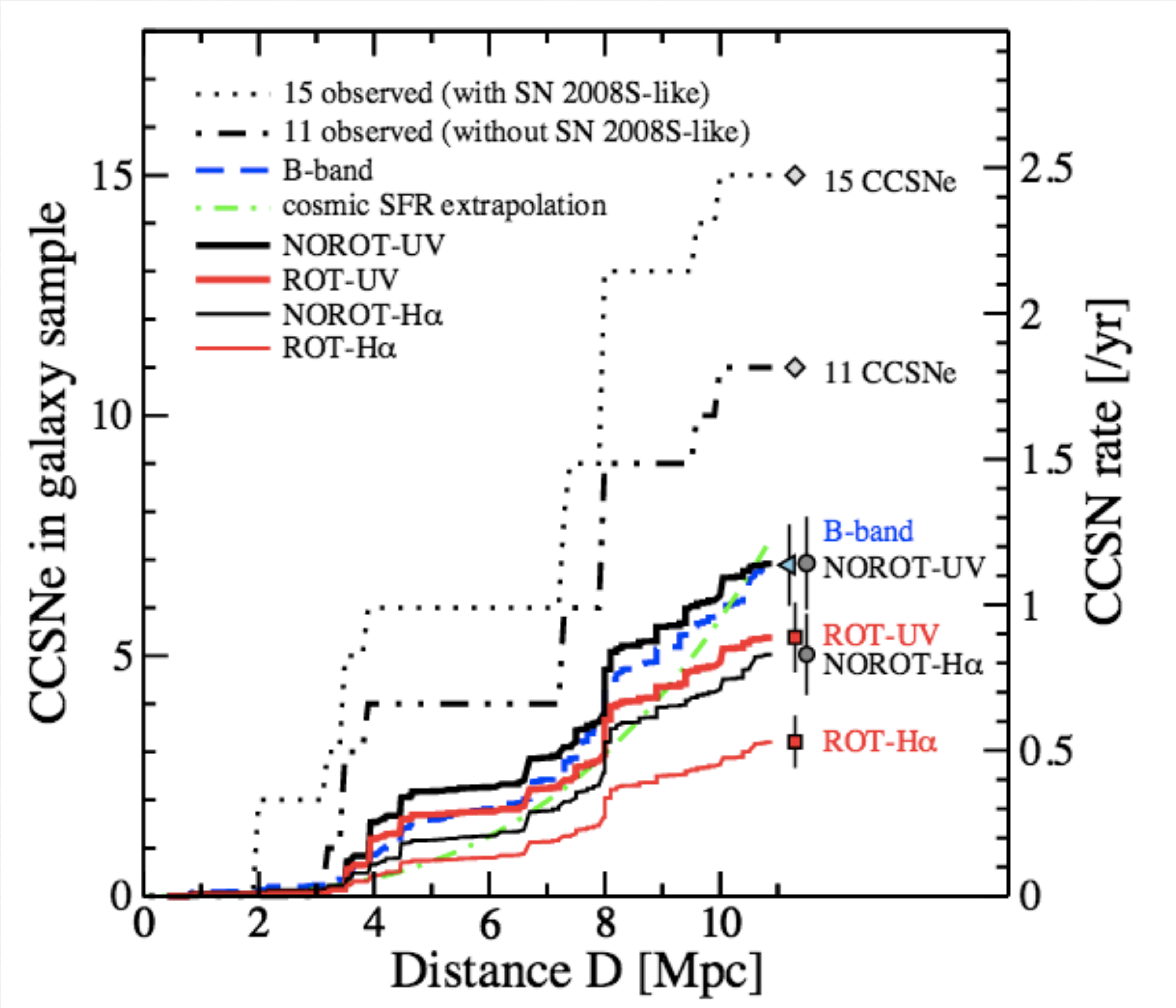
- **17.5 SNe/20y** (theoretical, ROT-UV)
- **36.4 SNe/20y** (observation, without SN 2008s-like)
- **49.6 SNe/20y** (observation, with SN 2008s-like)



Shunsaku Horiuchi, John F. Beacom, Matt S. Bothwell, Todd A. Thompson
Astrophys.J.769:113,2013

WHAT INFORMATION CAN WE GET?

- < 1Mpc: SN alarm, coincidence with gravitational wave, many neutrino events
- 1-4 Mpc: possible SN alarm, coincidence with optical signal
- >> 4 Mpc: Supernova relic neutrino background



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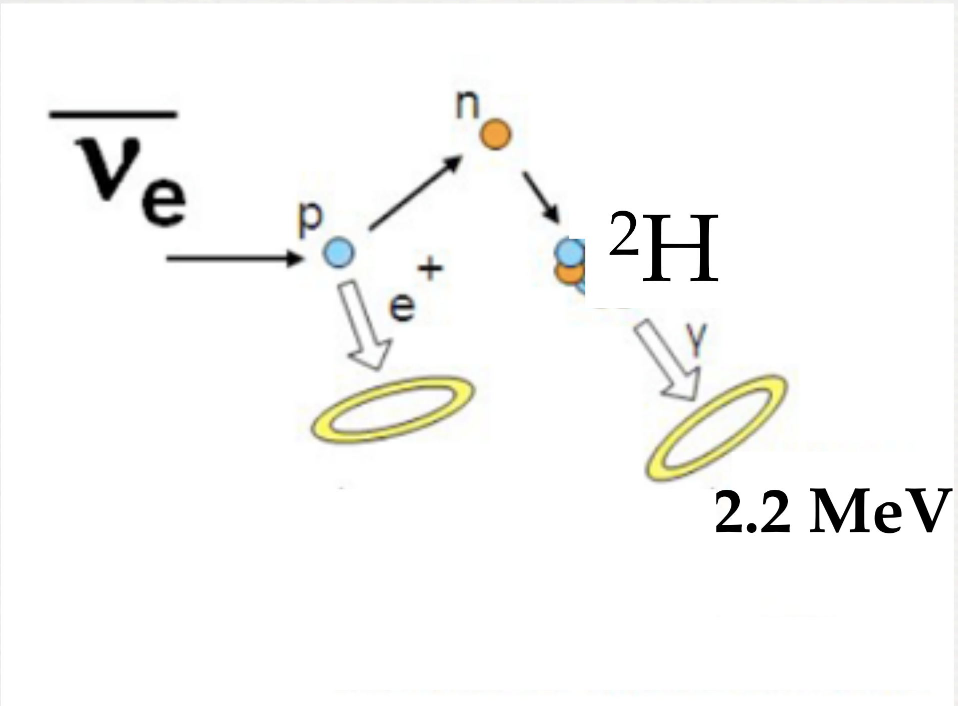
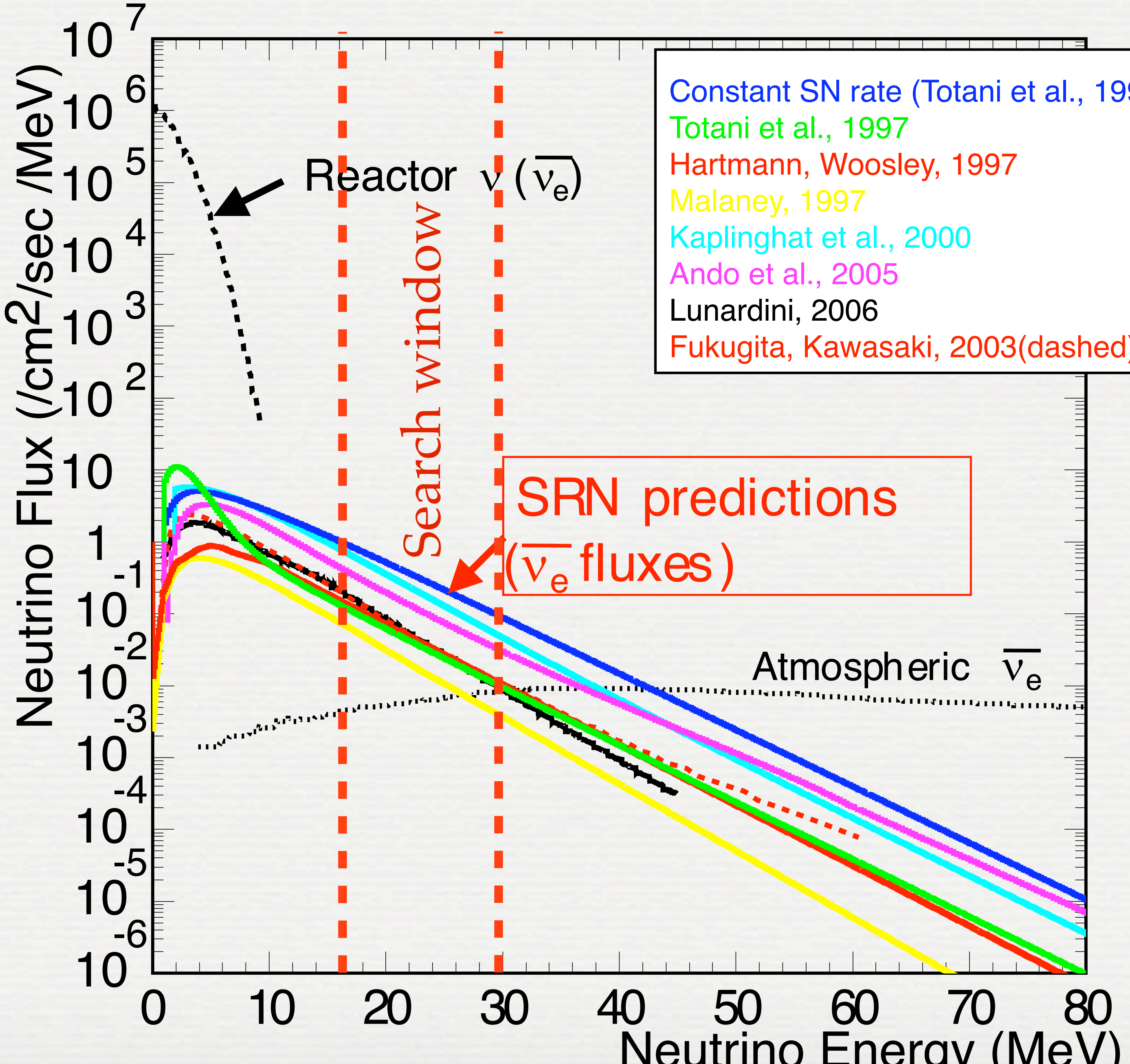
SUPERNOVA RELIC NEUTRINOS

SUPERNOVA RELIC NEUTRINOS

Search for the diffuse flux of neutrinos from distant, past SNe



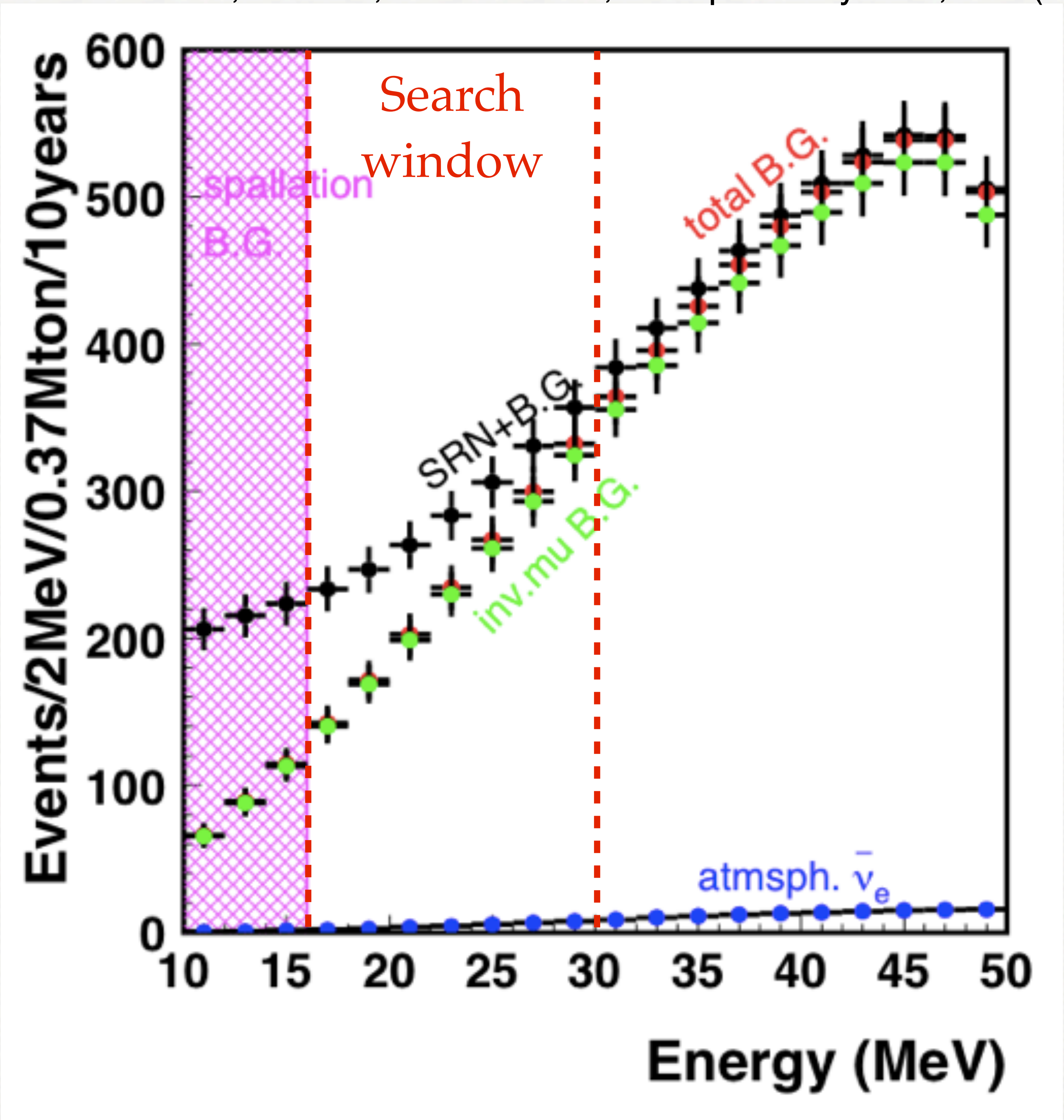


BACKGROUNDS TO THE SRN SEARCH

- With no neutron tagging, invisible muons are the primary background in the search window
- Neutron tagging significantly reduces invisible muons. SK tagging eff is ~20% (~70% with Gd)[1,2]. The higher photodetector efficiency could improve HK's ability to tag neutrons (details still under investigation).

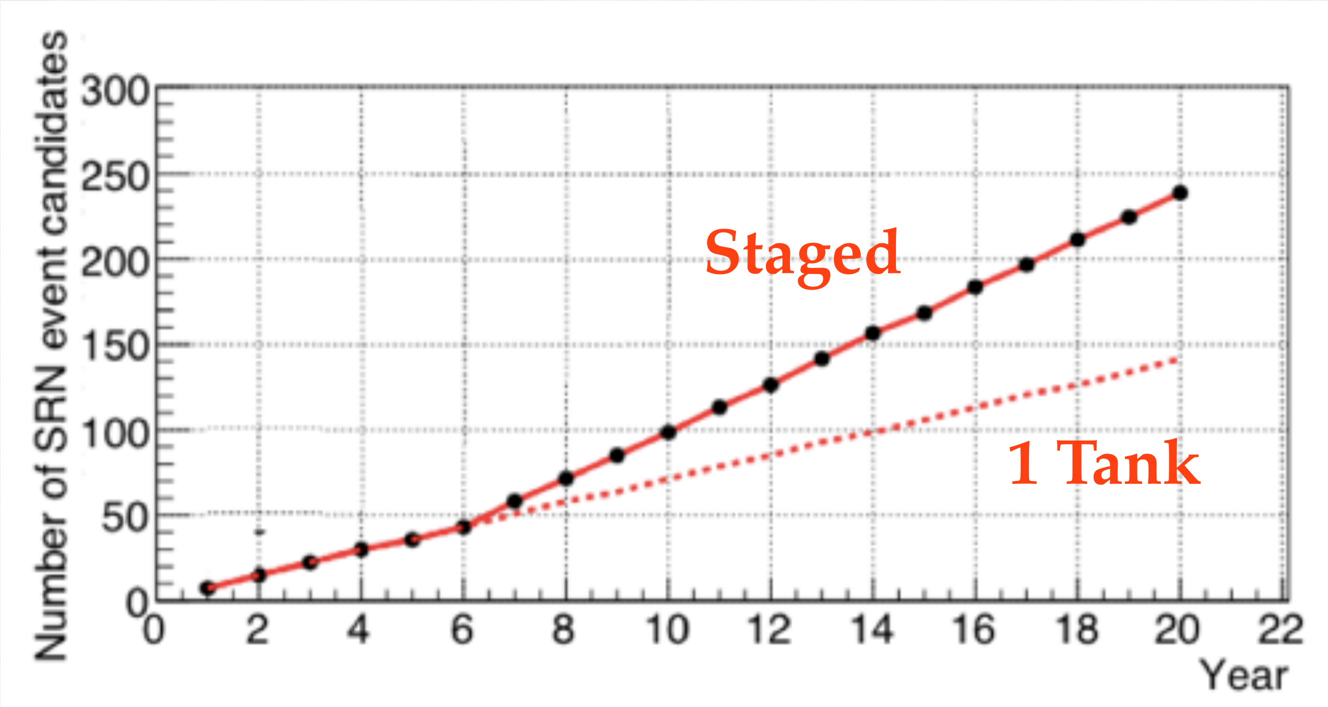
1. Watanabe et al Astropart.Phys. 31 (2009) 320-328
2. J .F. Beacom and M. R. Vagins, Phys. Rev. Lett., 93:171101, 2004

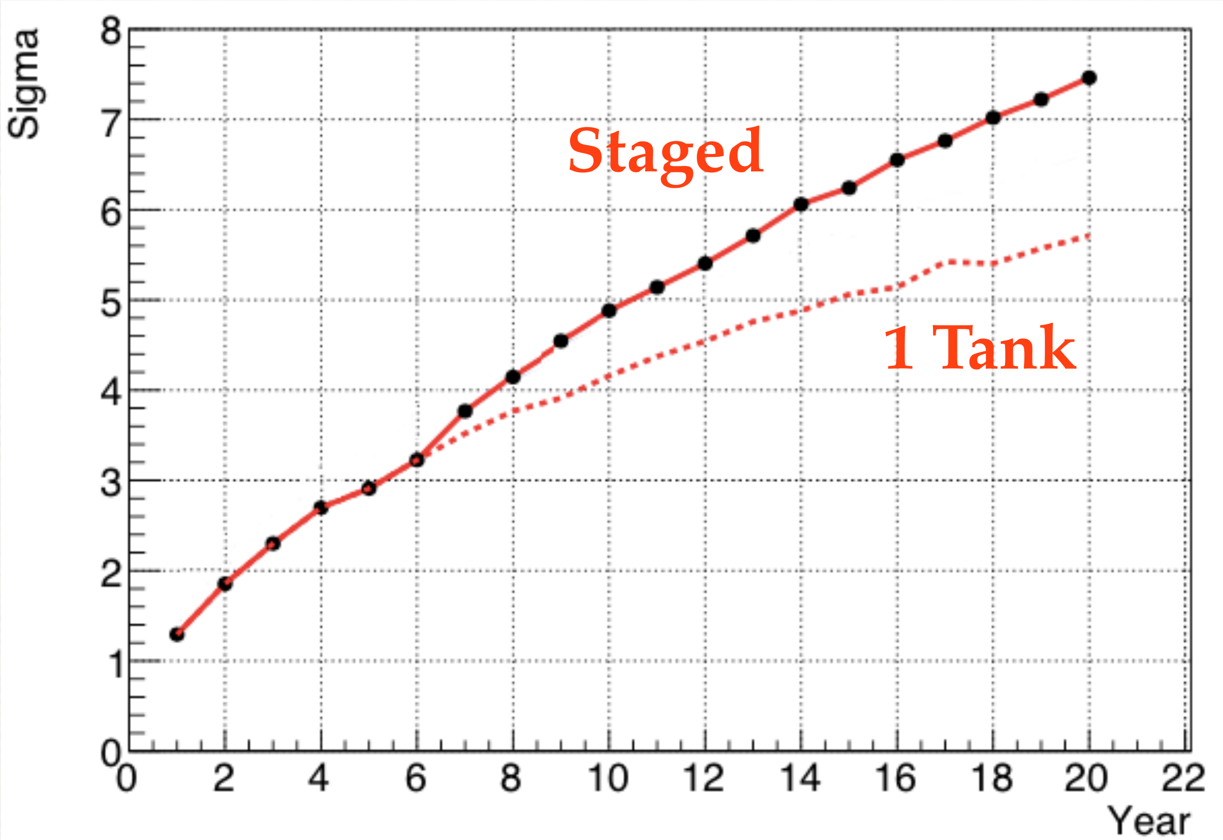
Flux: S. Ando, K. Sato, and T. Totani, Astropart. Phys. 18, 307 (2003)



HOW MANY SRNS WILL WE MEASURE?

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

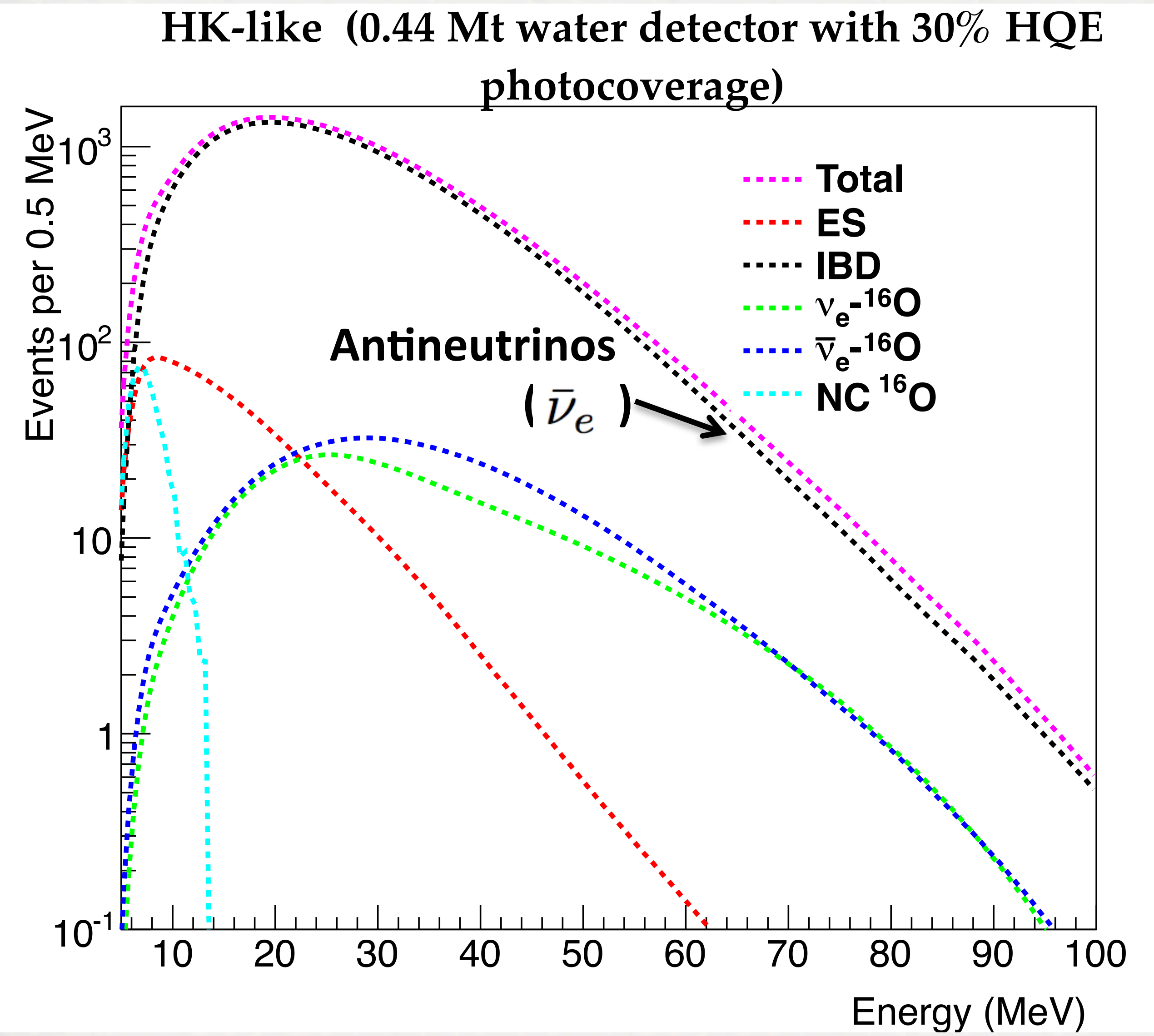


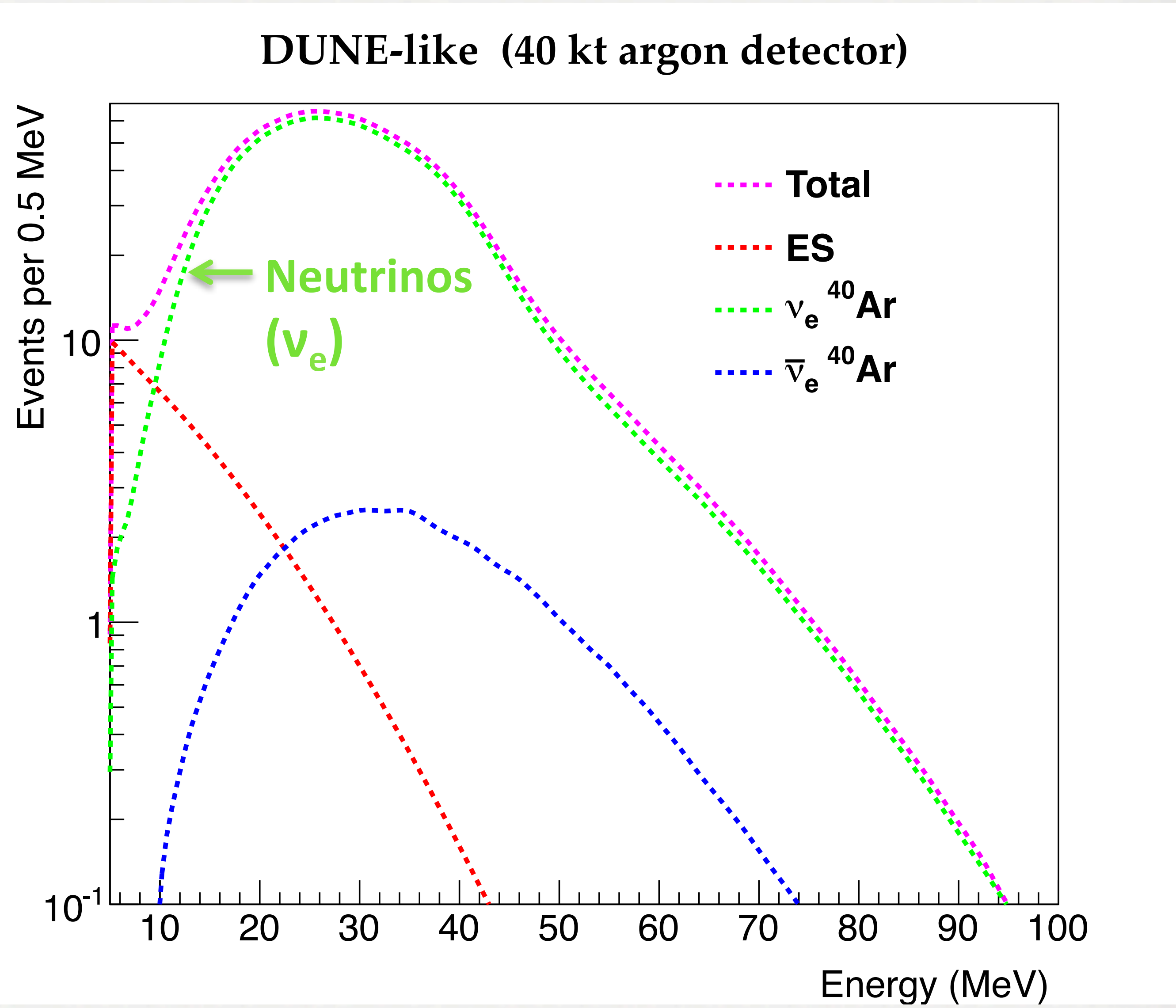


HK has a high discovery potential for the presence of SRNs

HK COMPLEMENTARITY WITH DUNE

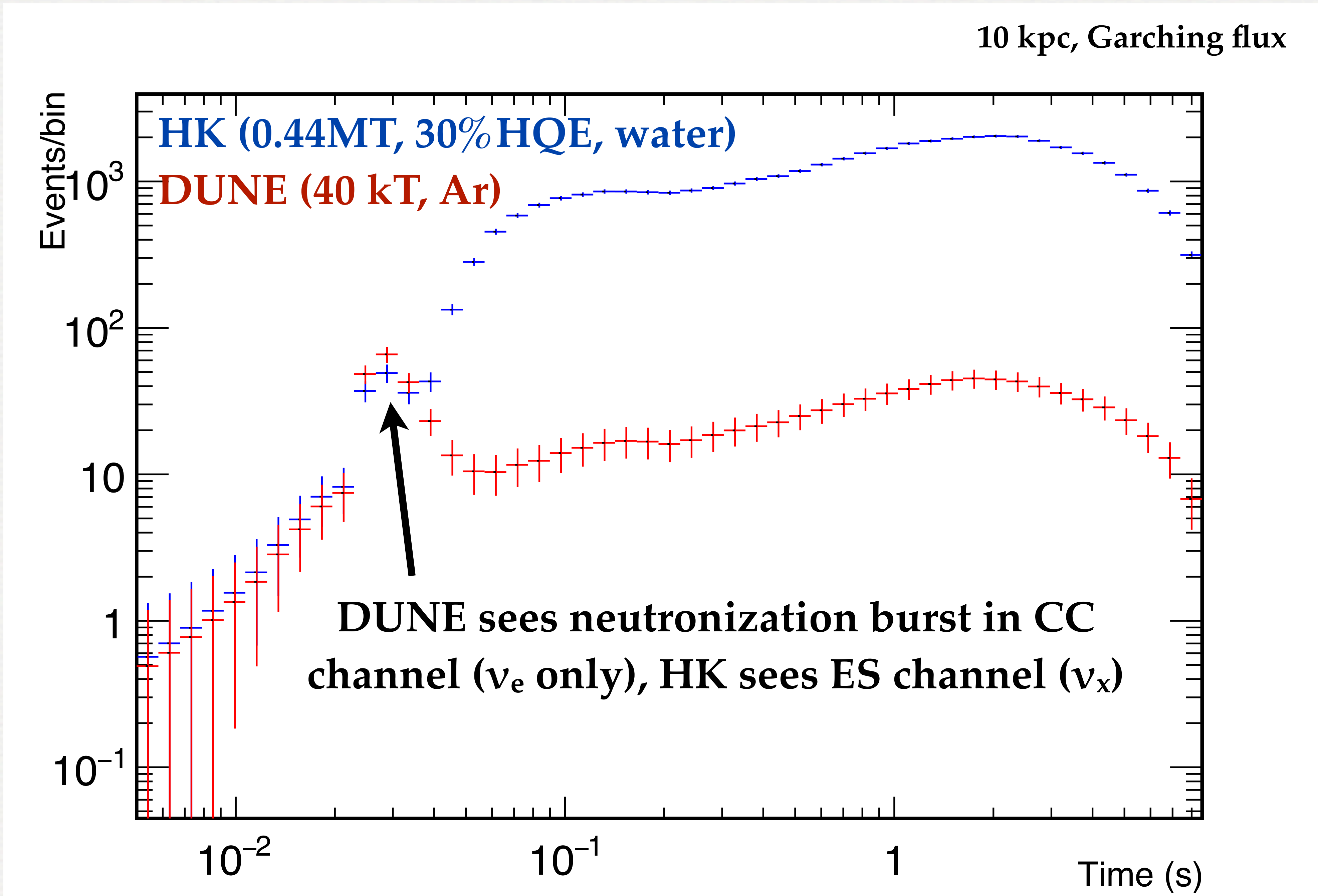
HK SEES ANTI-NEUTRINOS, DUNE SEES NEUTRINOS





10 kpc, GKVM flux
plots made using SNOwGLoBES
(http://www.phy.duke.edu/~schol/snowglobes/)

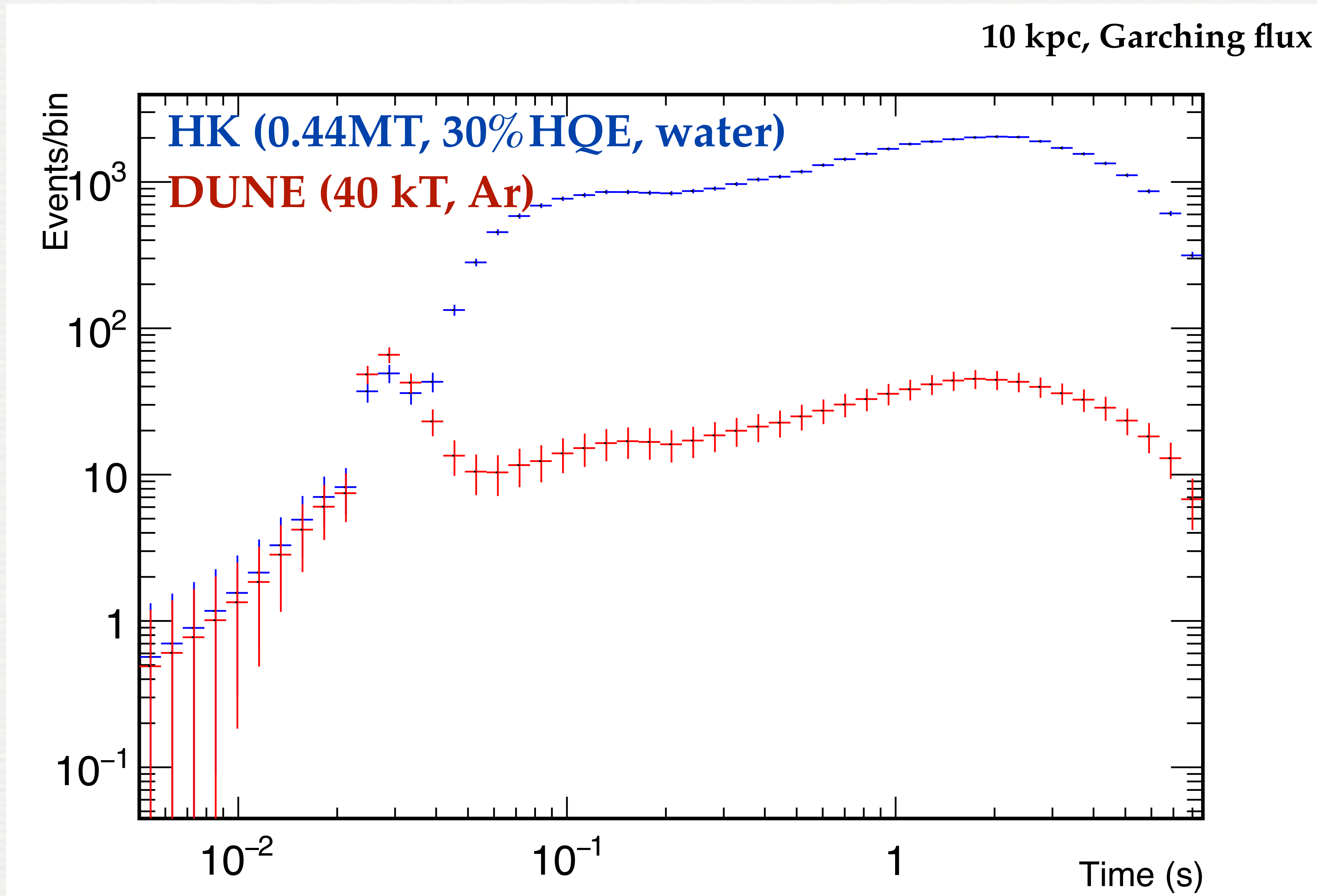
HK AND DUNE CAN USE THE NEUTRONIZATION BURST FOR FLAVOUR INFORMATION



DUNE MEASURES EARLY TIMES, HK BETTER MEASURES LATE TIMES

Early time features (infall and neutronization) are ν_e : DUNE will make a clean measurement

Late time features (accretion and cooling) : HK will make a high stats measurement



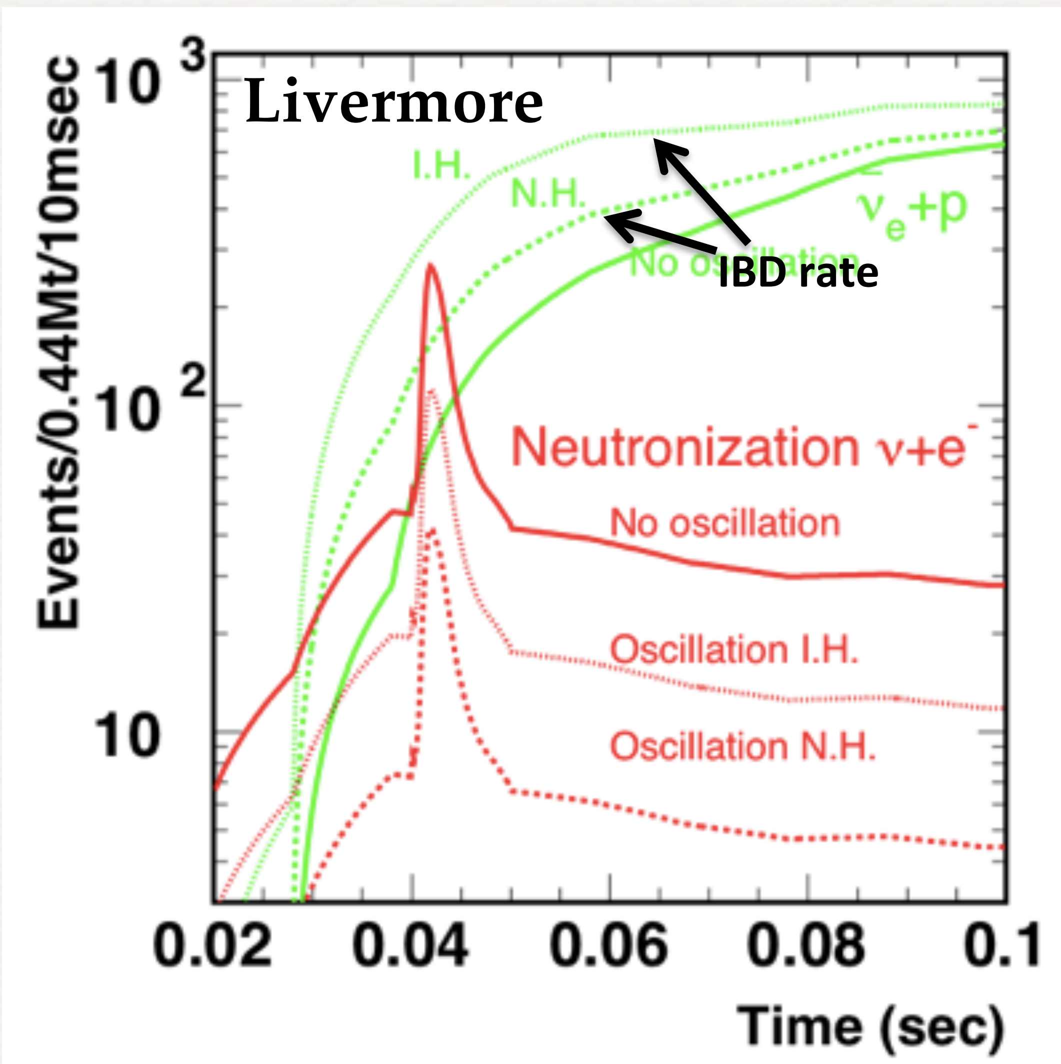
Infall

Accretion

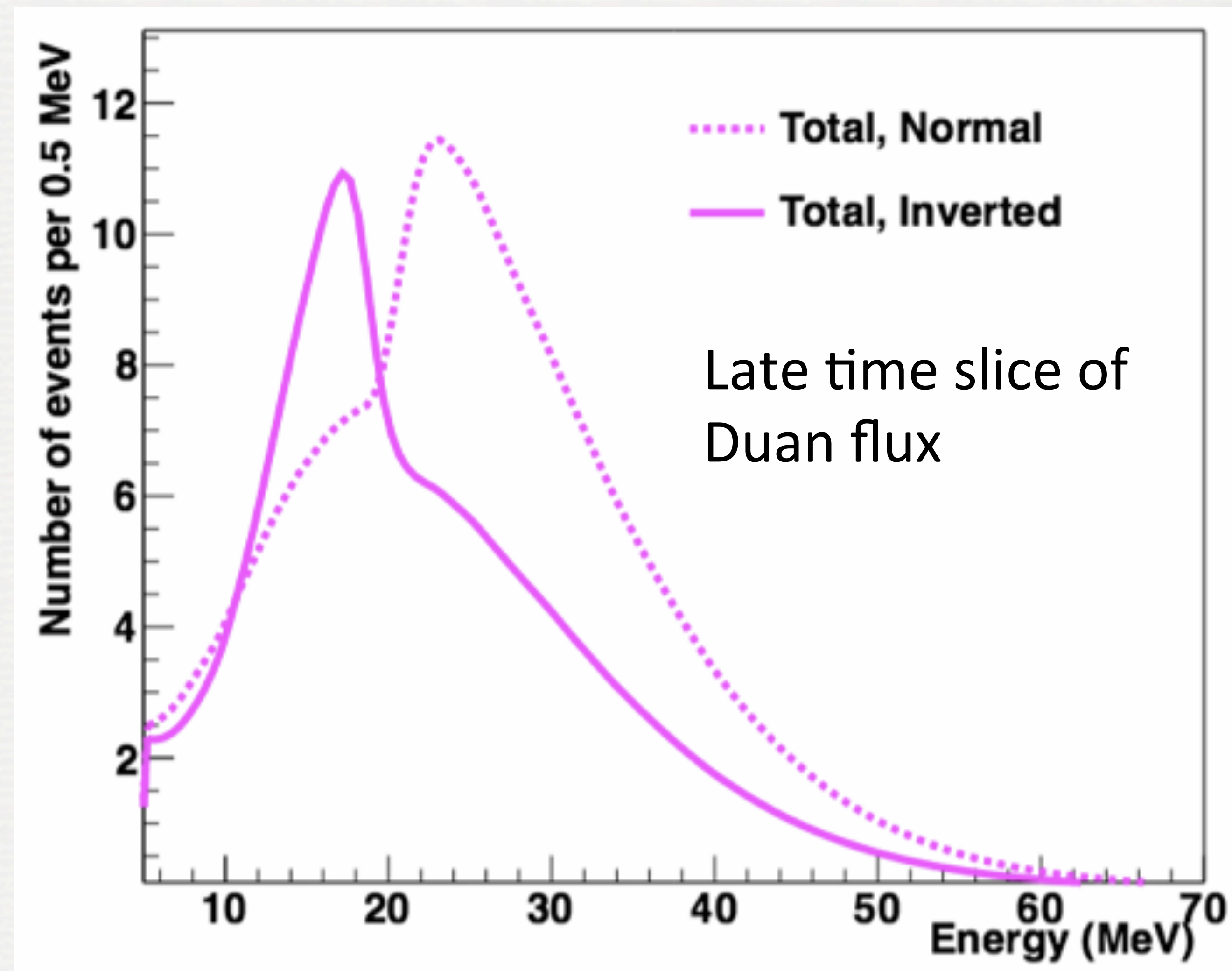
Cooling

HK AND DUNE HAVE COMPLEMENTARY WAYS TO MEASURE MASS HIERARCHY

In water: Look at the rise time in IBD rate



In argon: Look for features in the energy spectrum



LBNE Collaboration arXiv:1307.7335

CONCLUSIONS

- HK will make a high statistics measurement of the next nearby supernova. HK will also have the chance to probe neutrinos from distant supernovae.
- HK will look for relic supernova neutrinos (high discovery potential).
- HK and DUNE will make complementary measurements of many of the important topics to be learned from SN neutrinos, including oscillations, hierarchy, and neutrino behaviour at different time periods.