Low Energy Physics

International Workshop on Next Generation Nucleon Decay
and Neutrino Detectors (NNN18)
Satellite open HyperK workshop

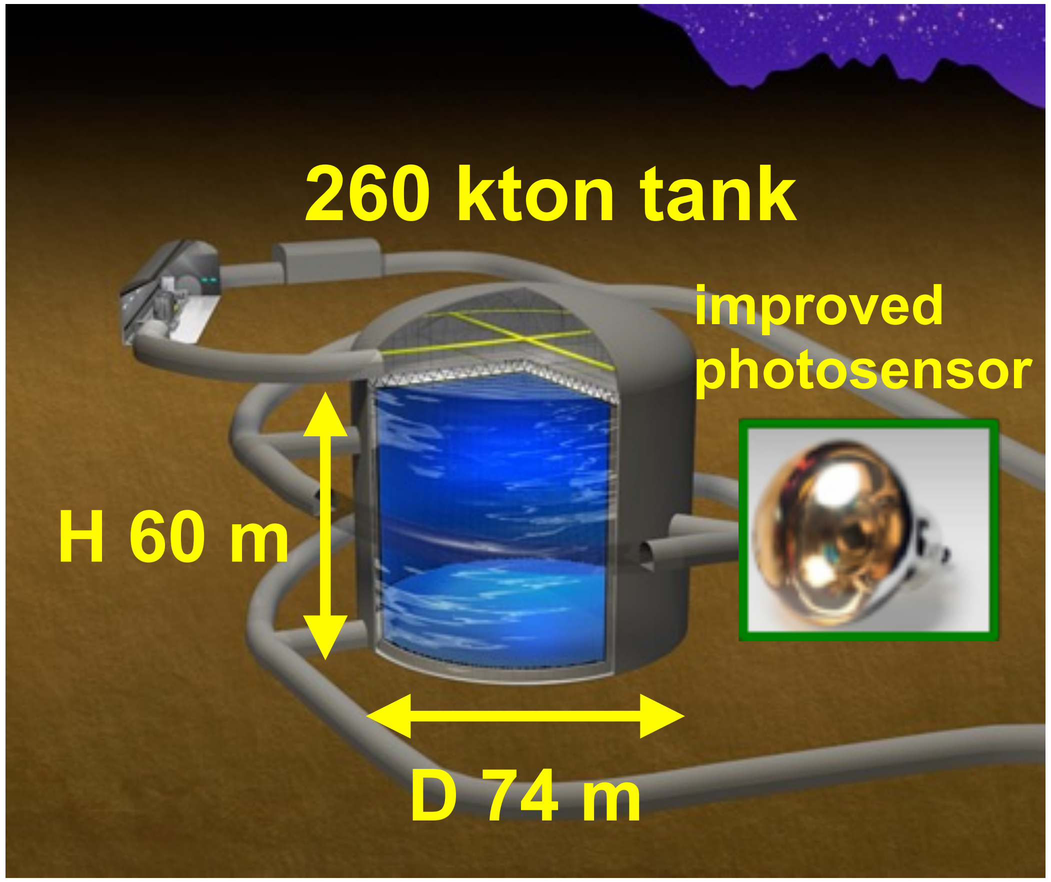
October 31, 2018

Hyper-K Detector

Next generation of large-scale water Cherenkov detectors

	Super-K	**Hyper-K** (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**40,000**
Photo-coverage	40%	40% (**×2 sensitivity**)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

- High statistics (**~10 × Super-K**) keeping low energy threshold and low background will significantly enhance the physics sensitivities
- Construction start in 2020
- Data taking start in 2027



Event Reconstruction in Hyper-K

Light attenuation ☹️

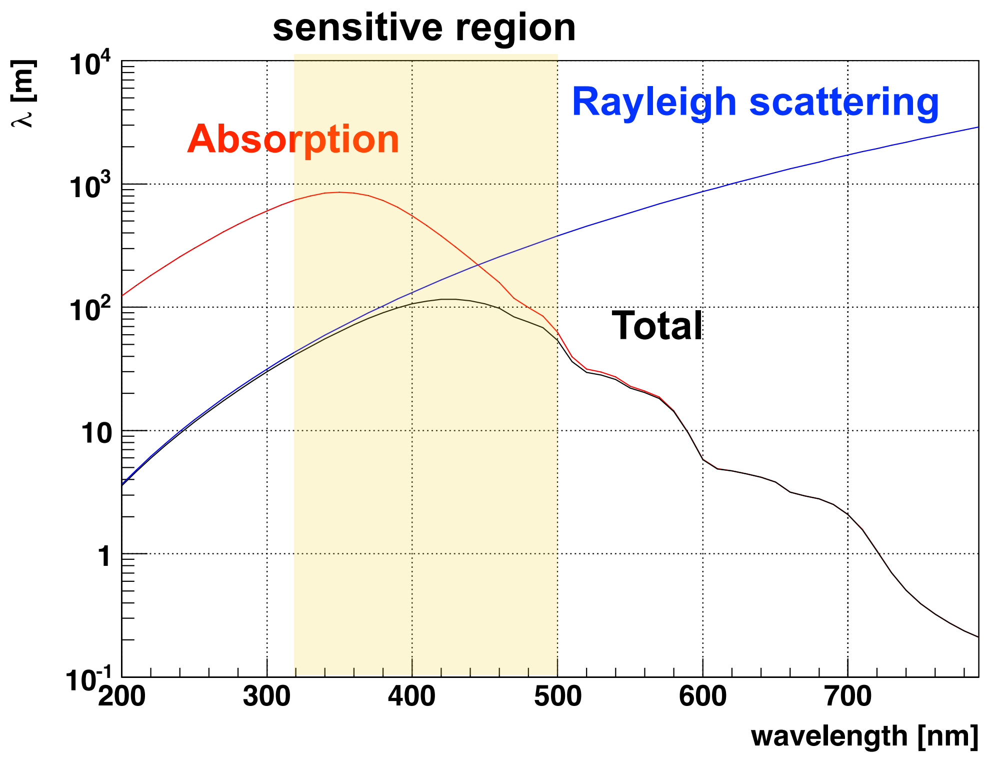
Attenuation length is ~60 m @ 350 nm

↓

Increase Rayleigh scattering photon
for a large size HK detector

Fraction of direct photon hits will decrease

worse angular/vertex resolution



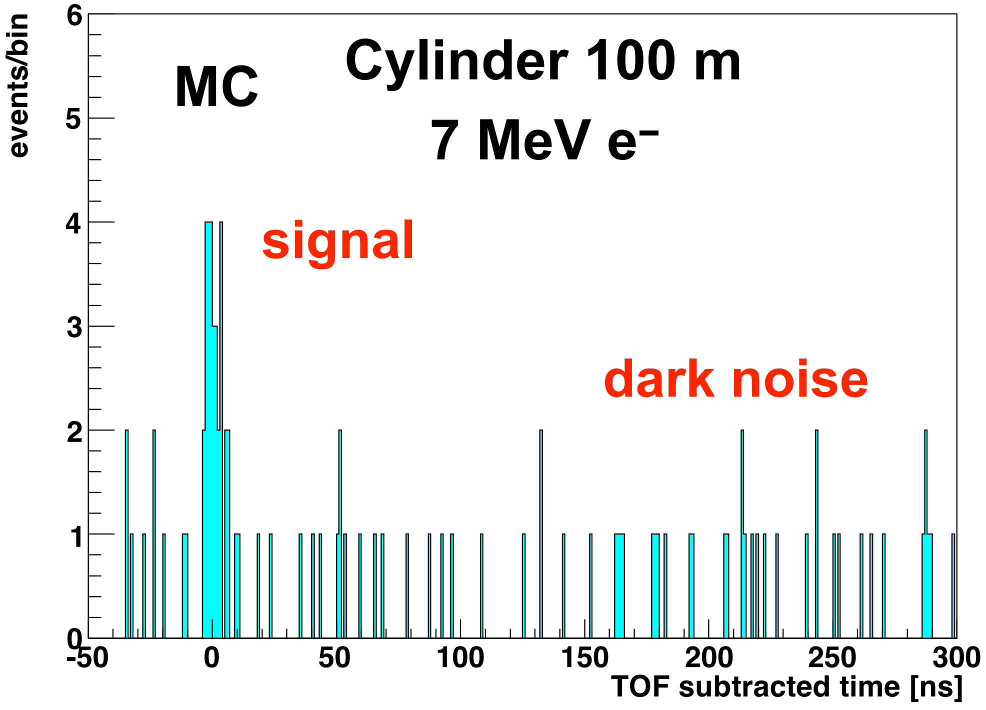
Higher dark-rate ☹️

Number of photo-sensor needs to be increased
to compensate the total photo-coverage

(#photo-sensor) ~ (dark rate) ~ (detector size)^2

dark-hit : HK ~ SK x 4

larger miss-fit



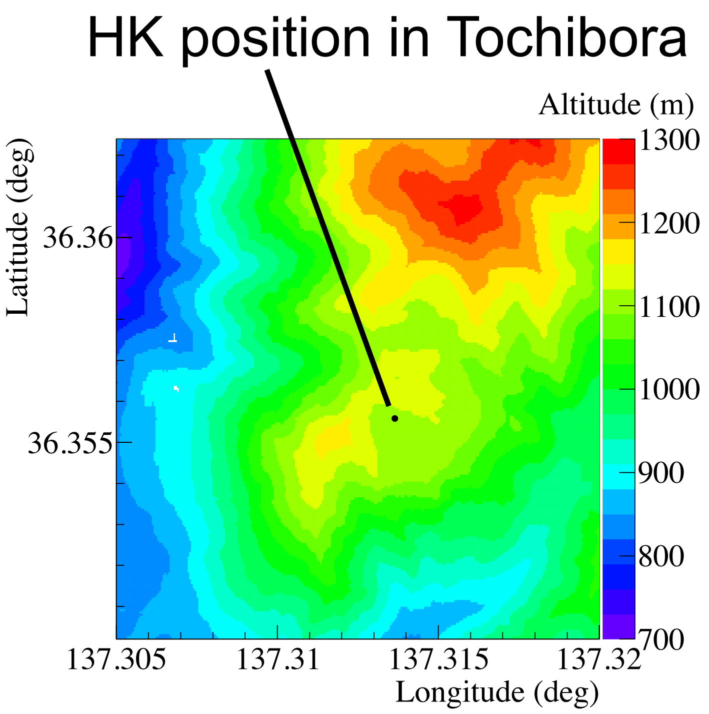
Better timing resolution 😀

Option of better timing resolution with Box-and-Line PMT

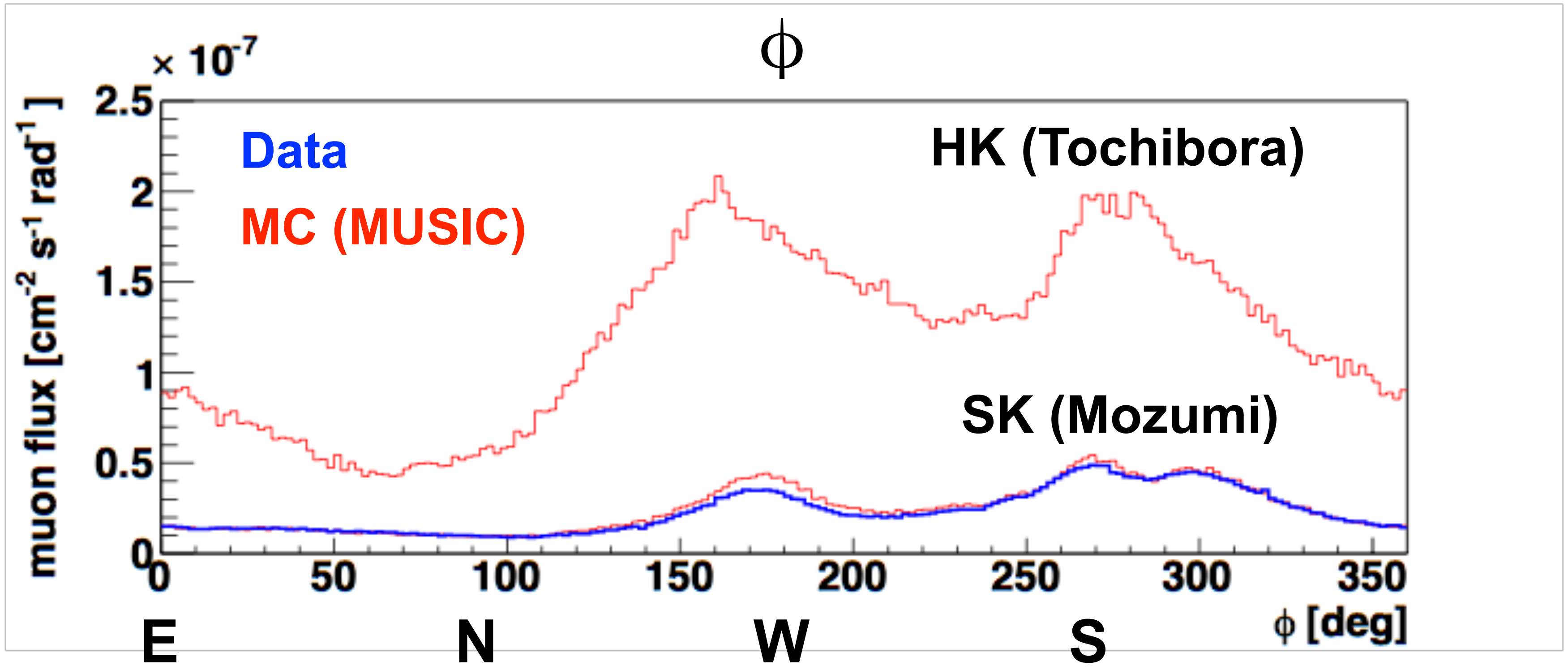
TTS (time transit spread in FWHM) SK PMT : 5.5 ns B&L PMT : 2.7 ns

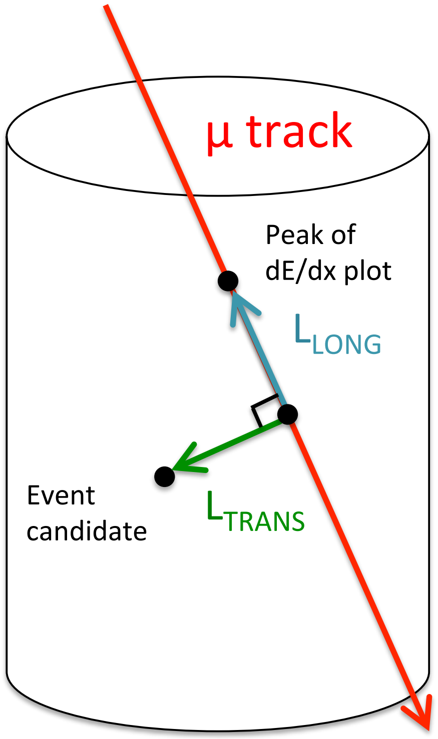
better vertex resolution

Spallation Background in Hyper-K



vertical depth ~ 600 m
(Super-K: 1,000 m)





Spallation BG from simulation study

Muon flux : Hyper-K = **~5** × Super-K ☹

larger muon spallation background

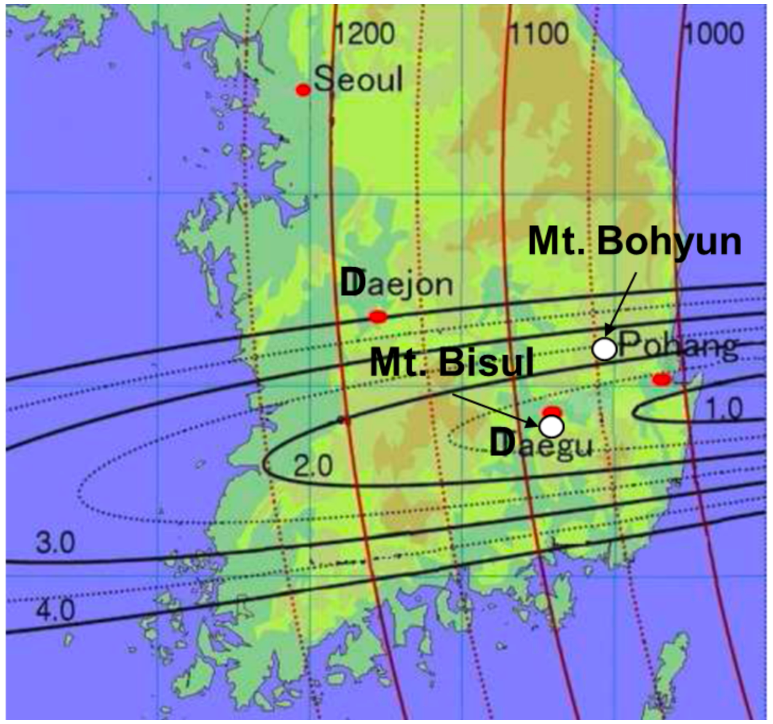
Spallation product : Hyper-K = **~4** × Super-K

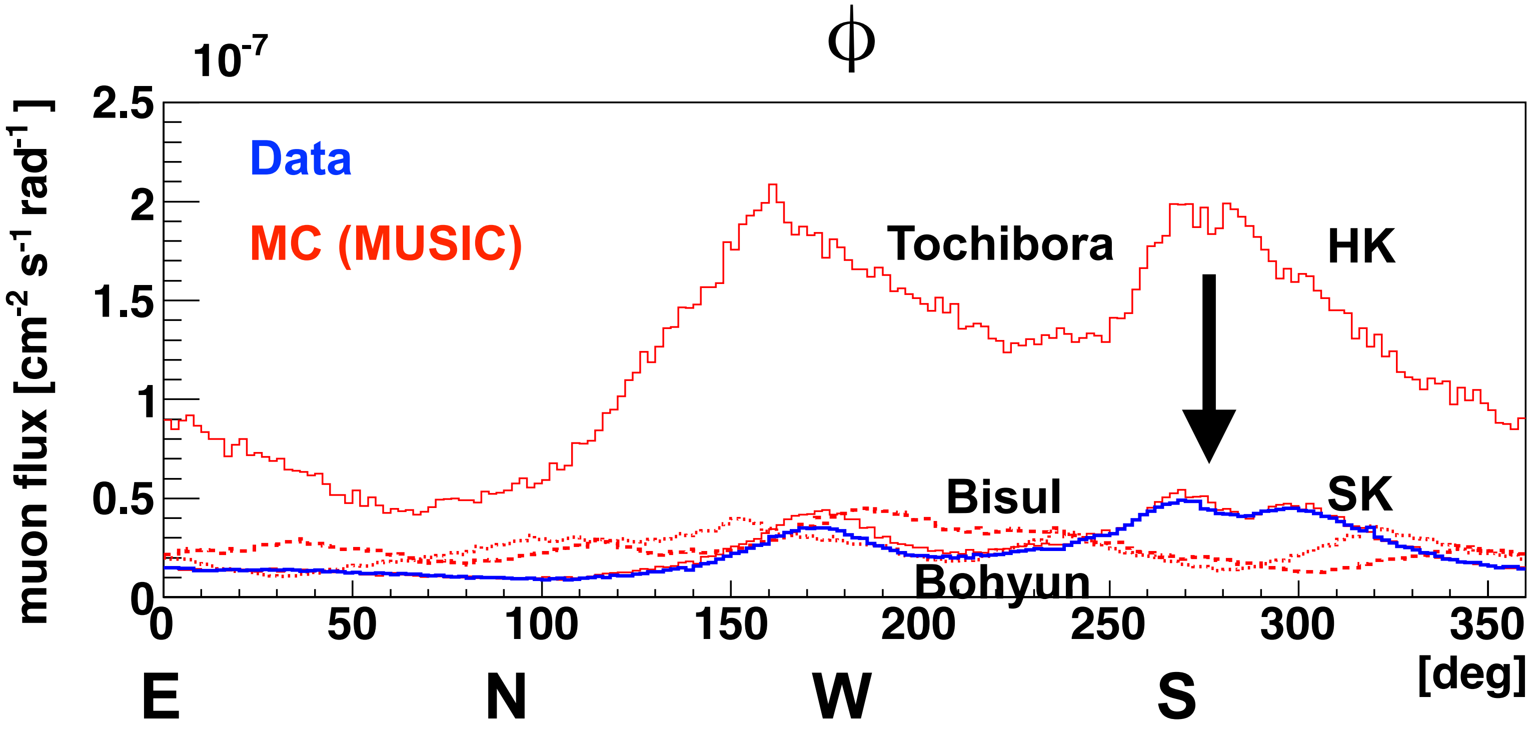
new likelihood cut ↓

~2.7 × Super-K

Improved spallation cut will mitigate the BG increase caused by the higher muon flux

2nd Hyper-K Detector in Korea (HKK)





HKK candidate sites

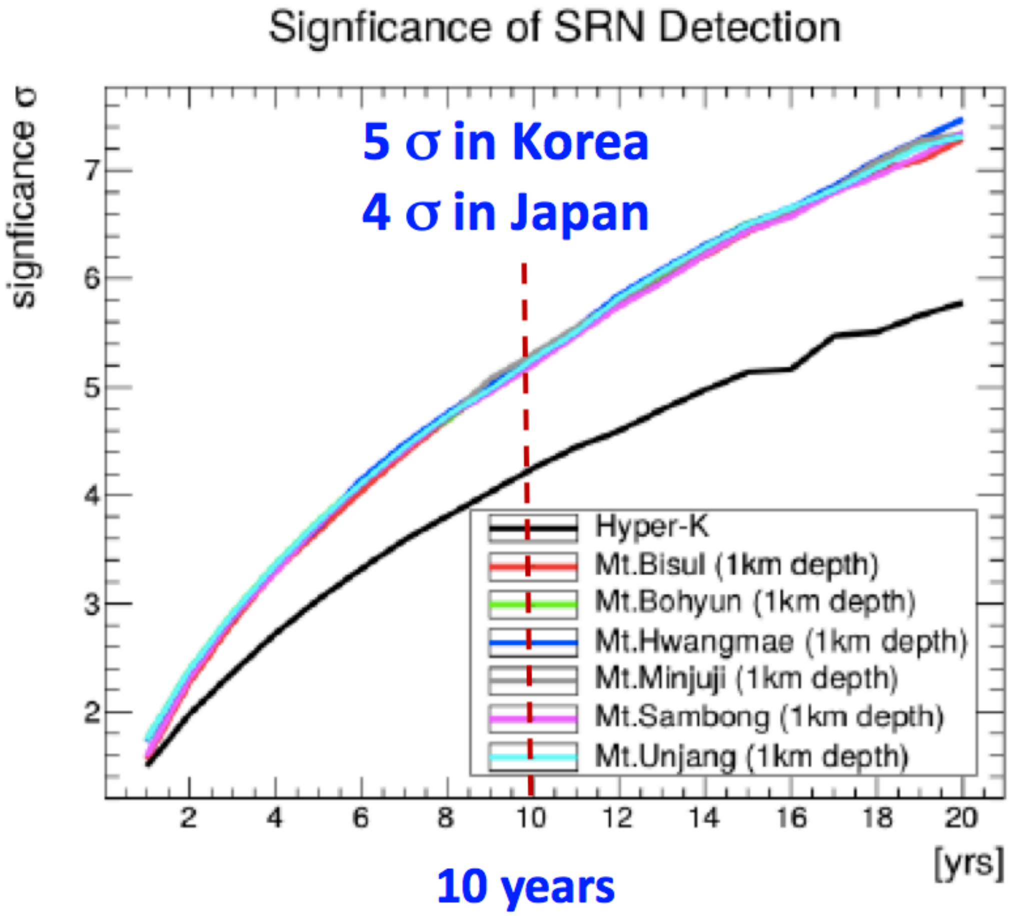
Underground of **Mt. Bisul, Mt. Bohyun**

1,000 m overburden

expect enhanced shield against muon

Benefits in low energy physics owing to lower muon spallation BG (~1/4)

→ Better sensitivity in solar and supernova relic neutrino studies



Nuclear Spallation Background in Water (Michael's Comment)

- mechanism: muon occasionally starts showers,
- some showers contain hadrons; e.g. neutrons or, $\pi^{\pm}$
- these break up the oxygen nucleus and change them to radioactive elements: ^{16}N, ^{12}B, and many others
- after some msec's to sec's, these elements βγ decay and make background
- the decay locations are close to the muon tracks, but directly correlate with the volume covered by the shower

★^{16}O

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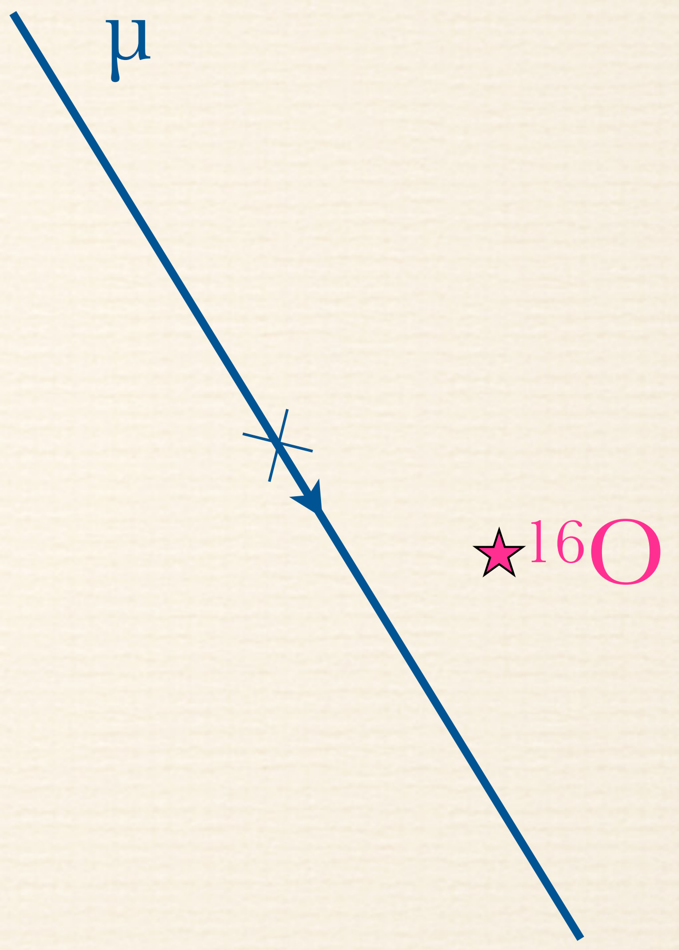

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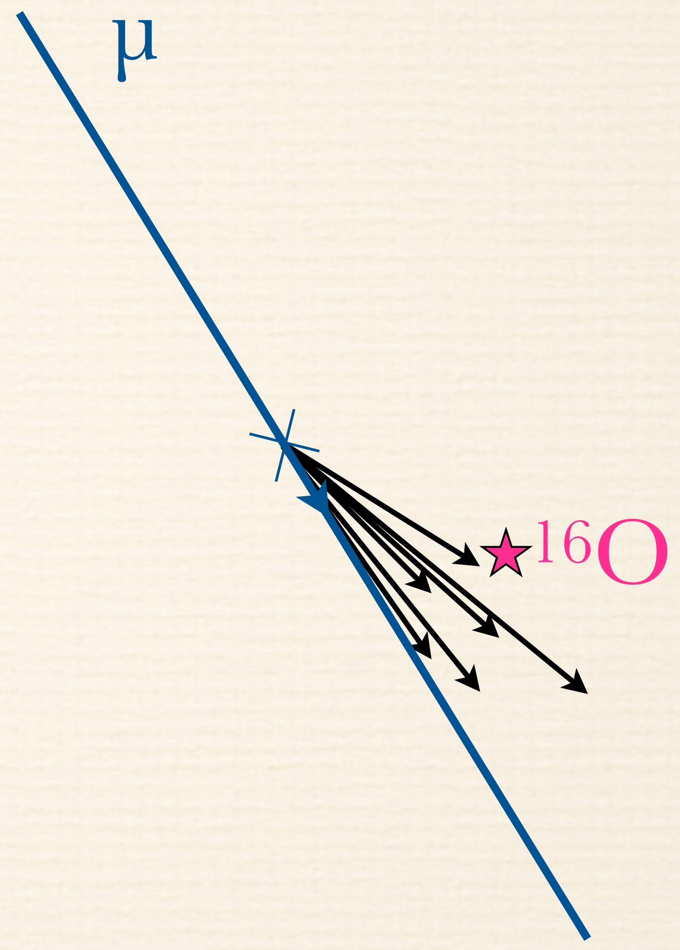

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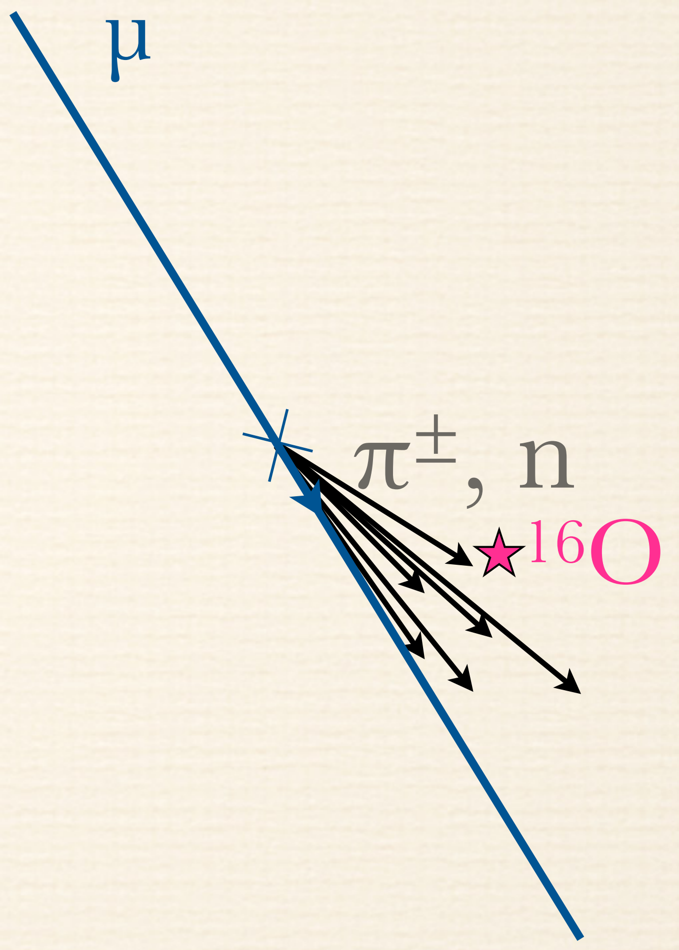

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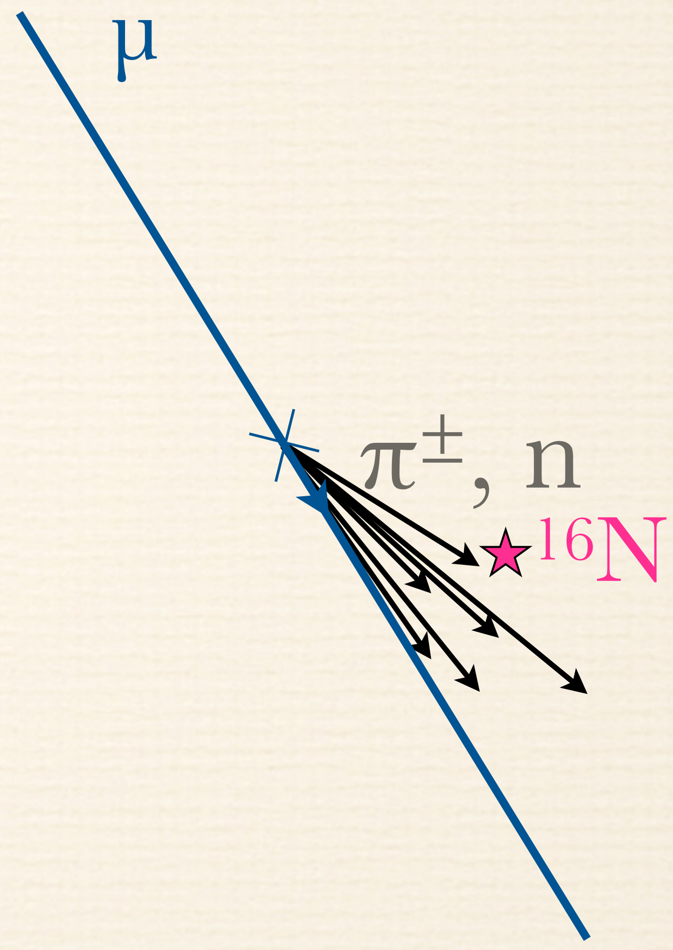

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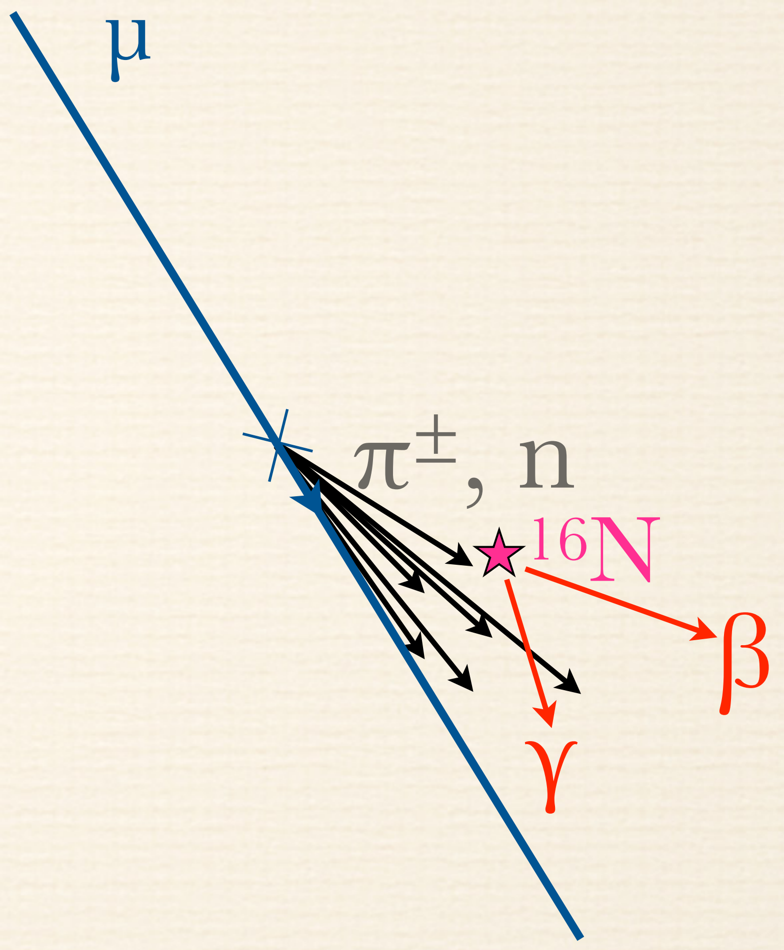
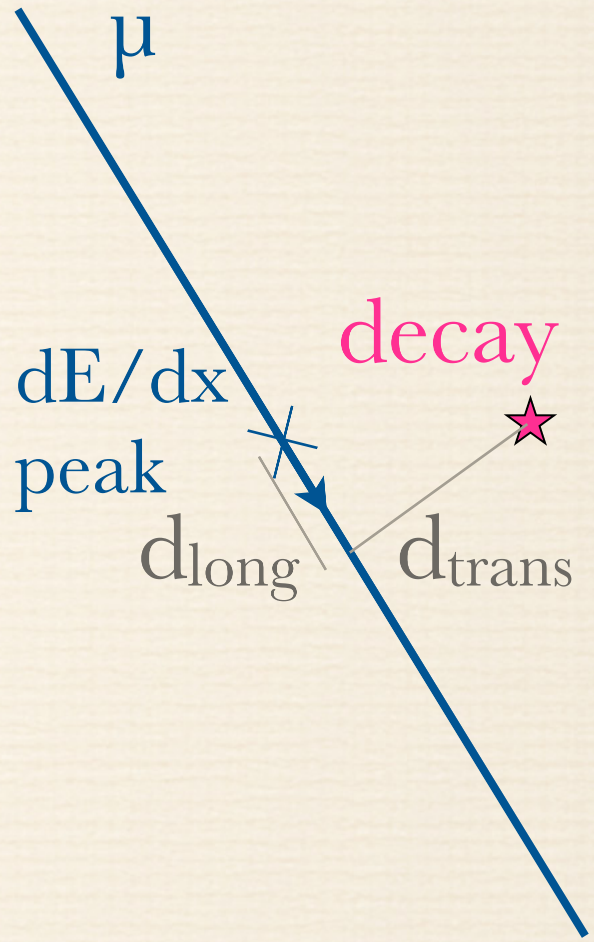


Nuclear Spallation Tagging (Michael's Comment)

- traditionally, form likelihood based on time difference to muon, distance to muon track, and excess light of the muon above the MIP expectation (from electromagnetic component of the showers)
- in 2012, we invented a new method for the distant supernova neutrino search: the muon dE/dx profile (using water Cherenkov detectors as a TPC) points out the spallation location



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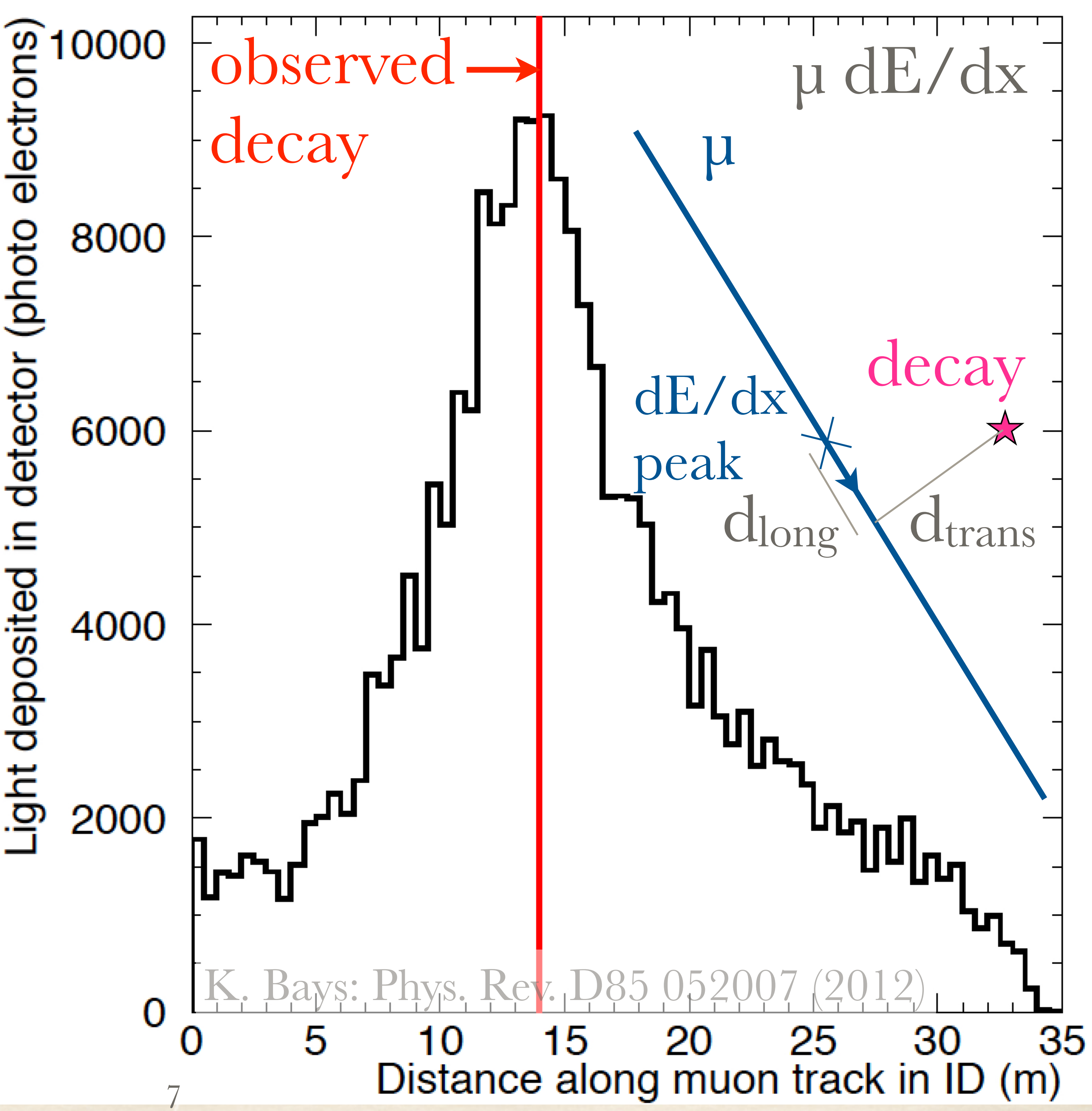
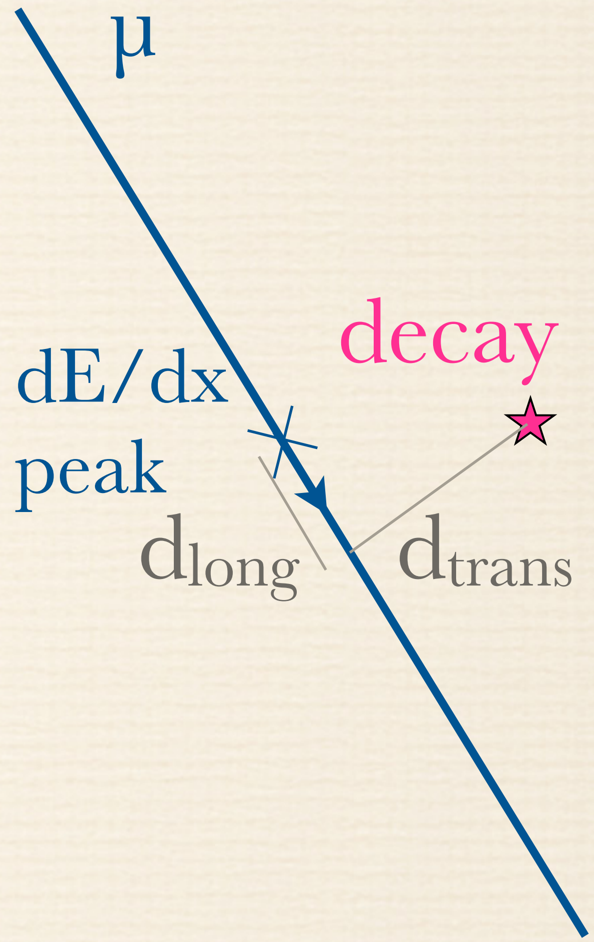
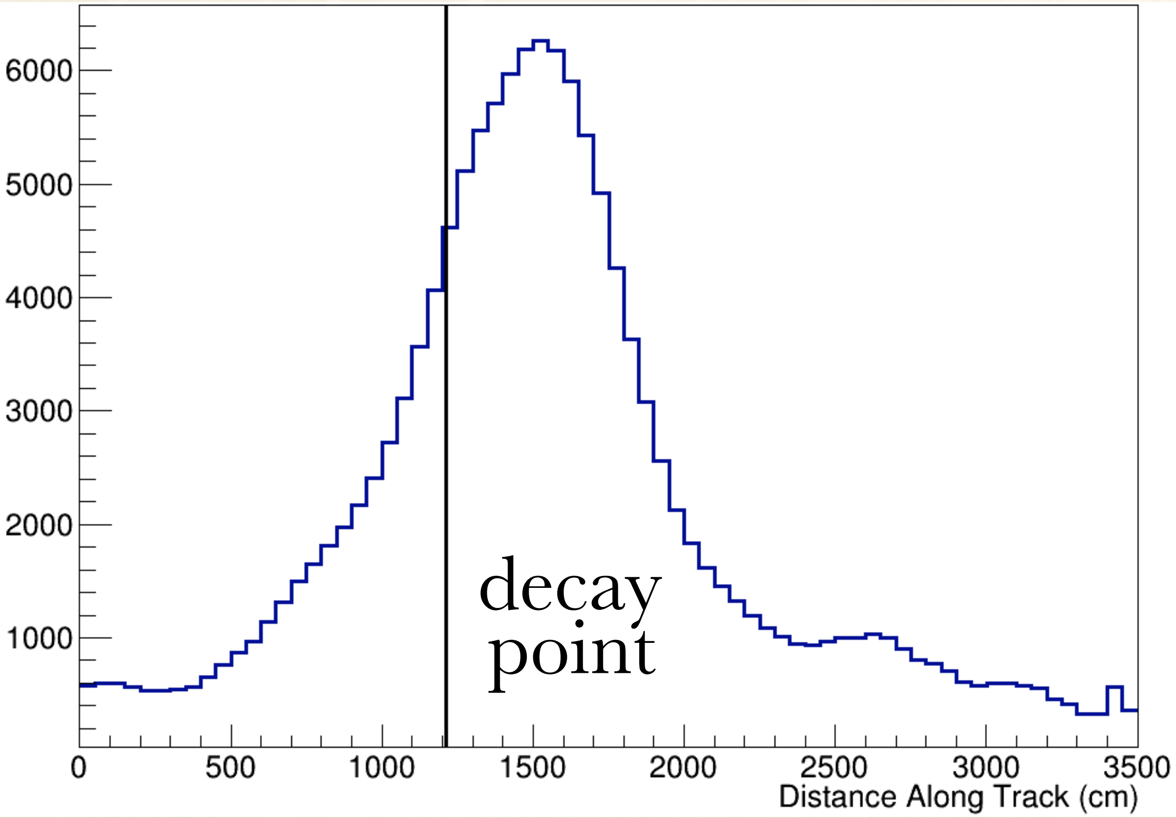


K. Bays: Phys. Rev. D85 052007 (2012)

Tagging Improvements (Scott Locke and Michael)

- since then improved dE/dx style EM shower reconstruction by weighing PMT hit times according to their timing resolution
- automatically takes into account "geometrical effects": how well a PMT constrains the shower position depends on its location wrt the μ
- observe neutrons to tag hadronic showers
- tag multiple spallation without neutrons





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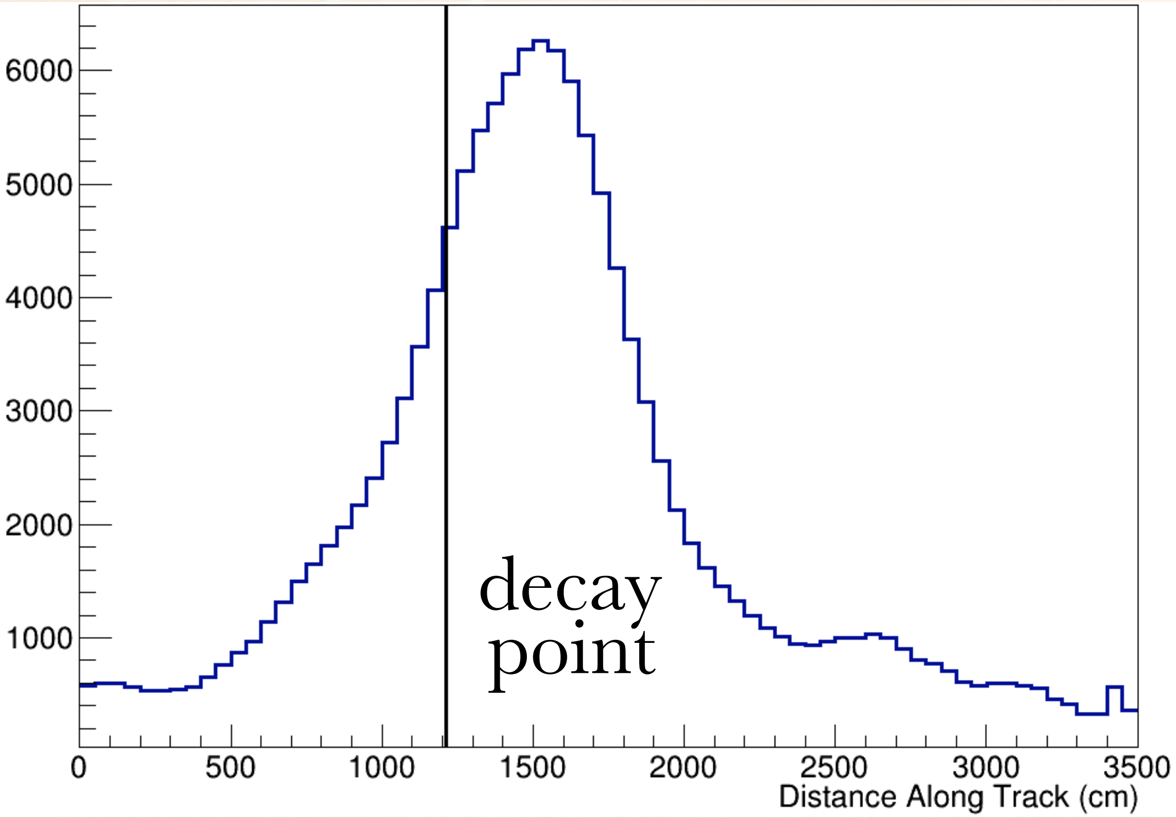
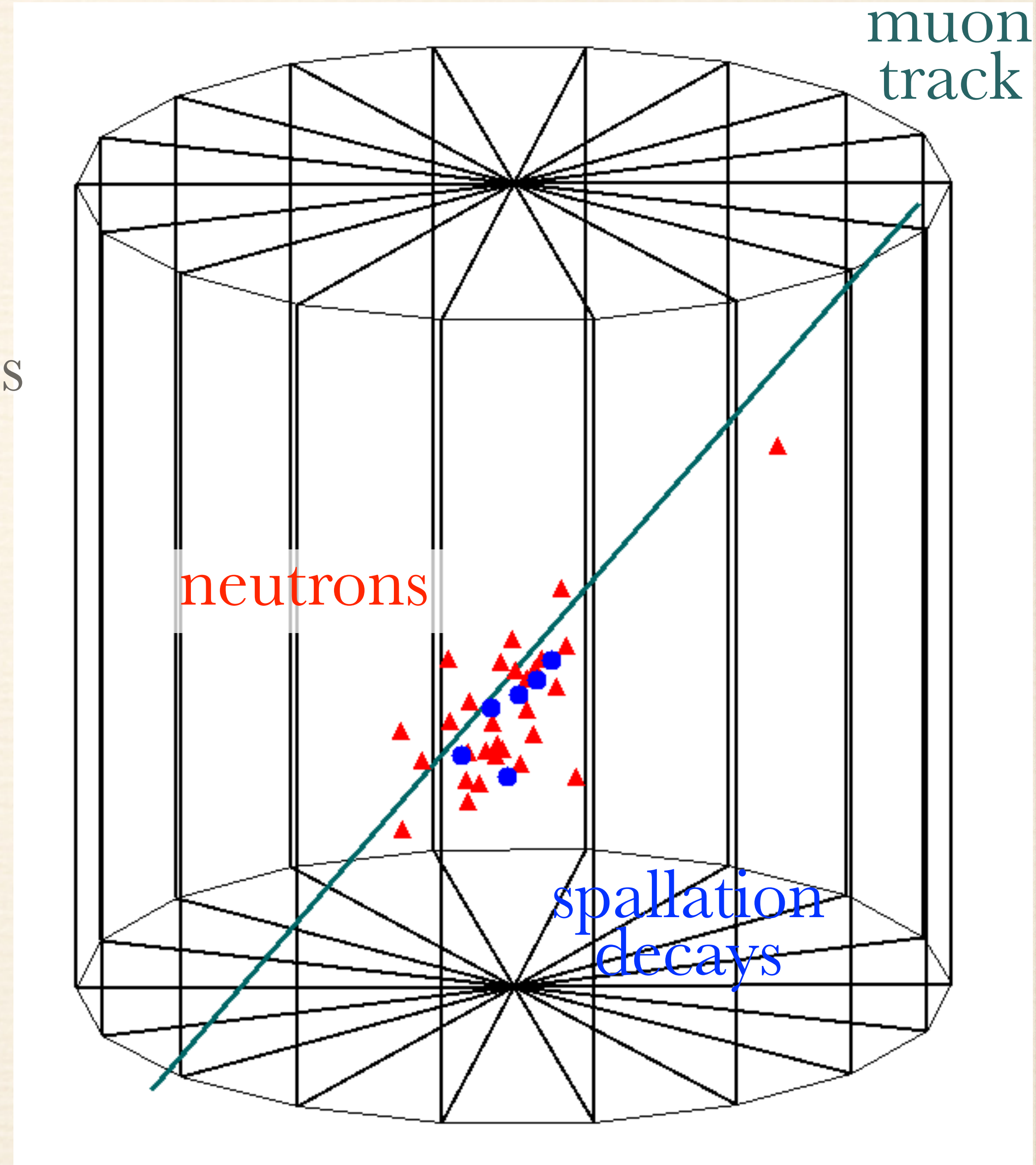
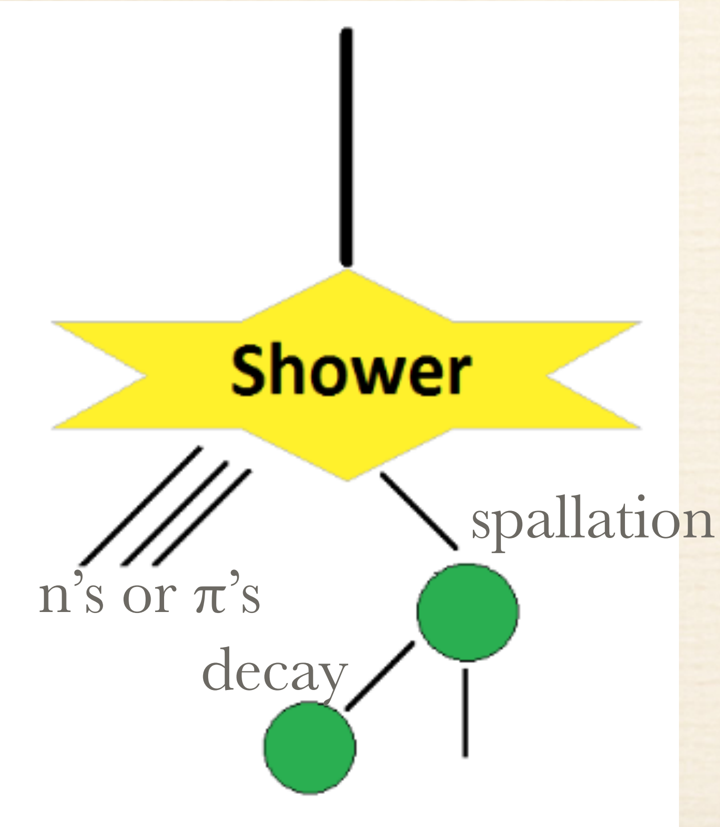


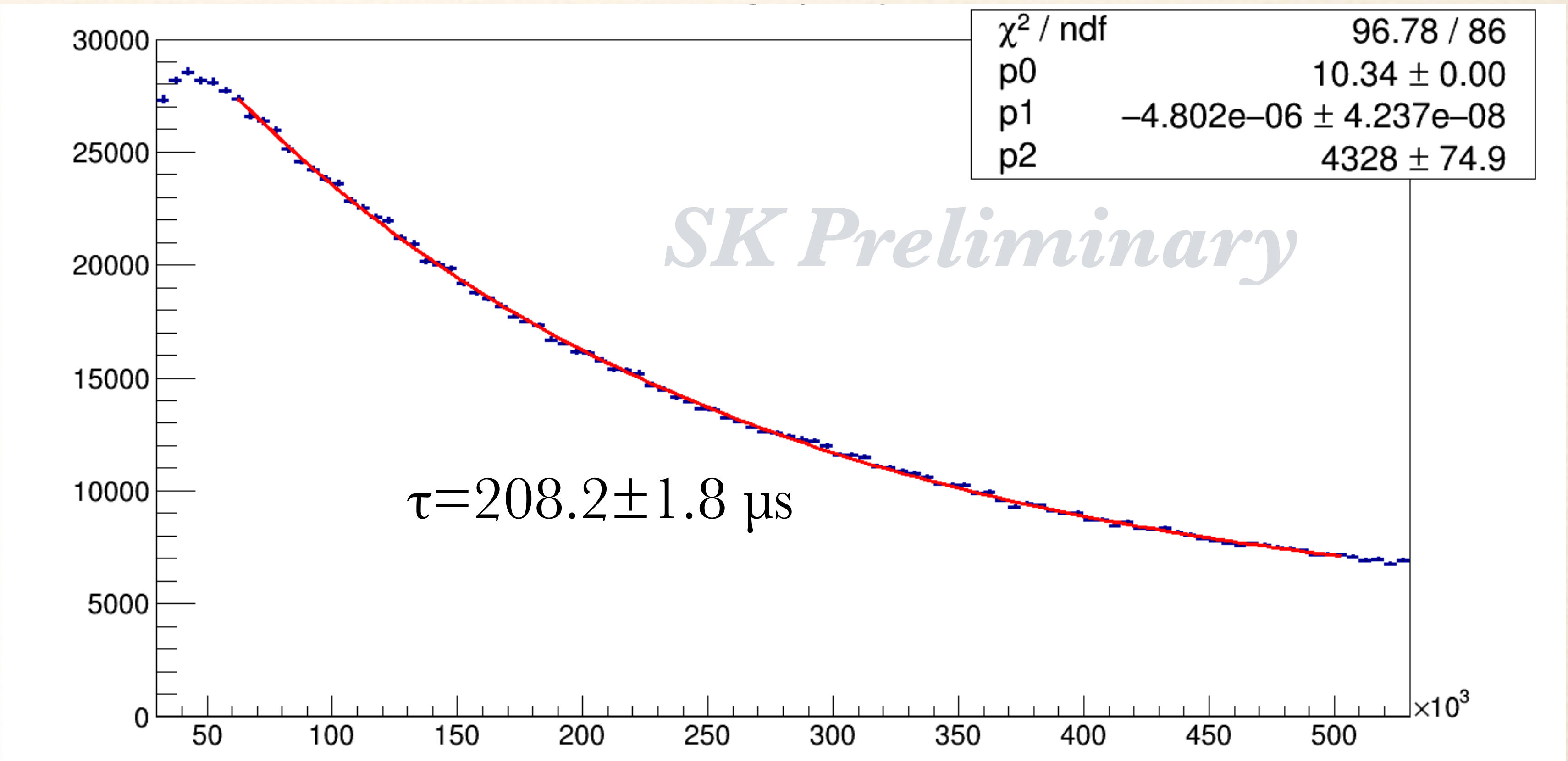


Detecting Hadronic Showers (Scott Locke and Michael)

- J. Beacom, S. Li (Phys. Rev. C 89, 045801, 2014): investigate how spallation nuclei are produced in hadronic showers
- S. Locke (TeVPA 2017): observed 2.2 MeV γ's from many neutron captures on hydrogen after muons using Super-K's new software trigger (threshold ~2.5 MeV kinetic electron energy; 2.2 MeV γ efficiency ~13%)

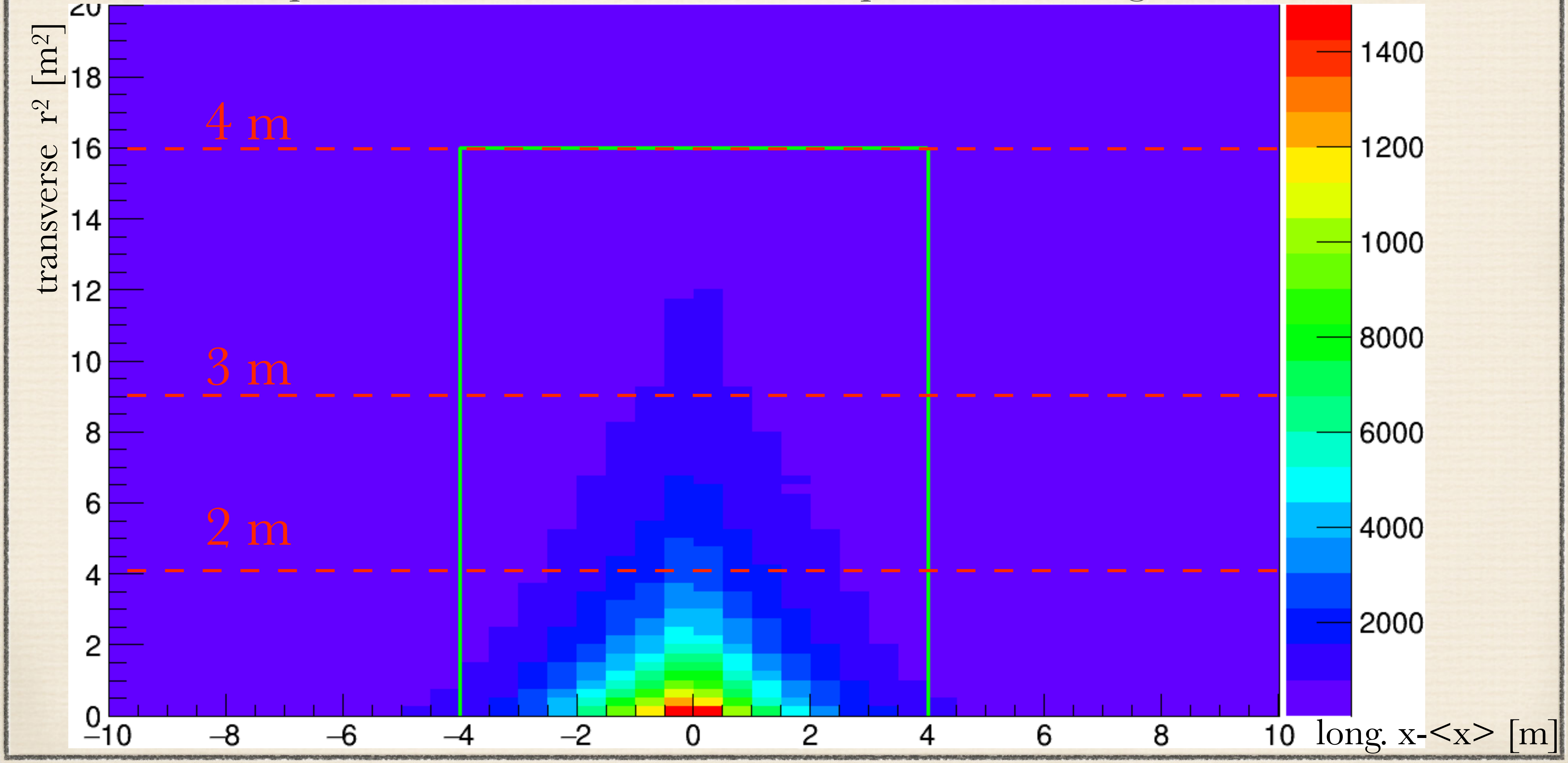
time difference





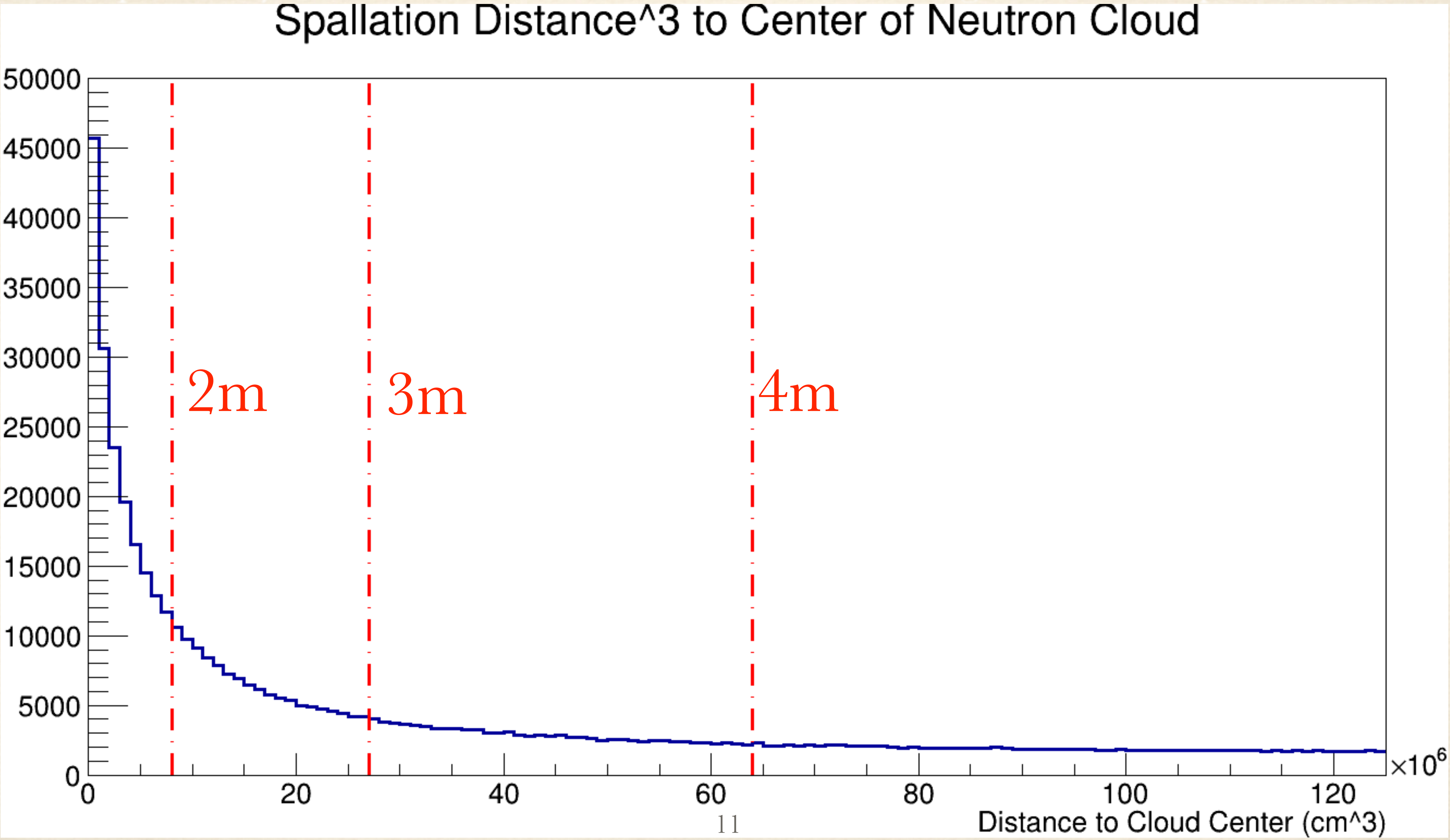
Hadronic Showers (Scott Locke and Michael)

- neutrons after muons are spatially correlated with the μ track and each other: neutrons tag ^{16}N production as well as indicate the 3D location of the decay
- reduce Super-Kamiokande's dominant spallation background



Finding Spallation Decays (Scott Locke and Michael)

- simplest way: events within 1 minute near the average neutron capture vertices



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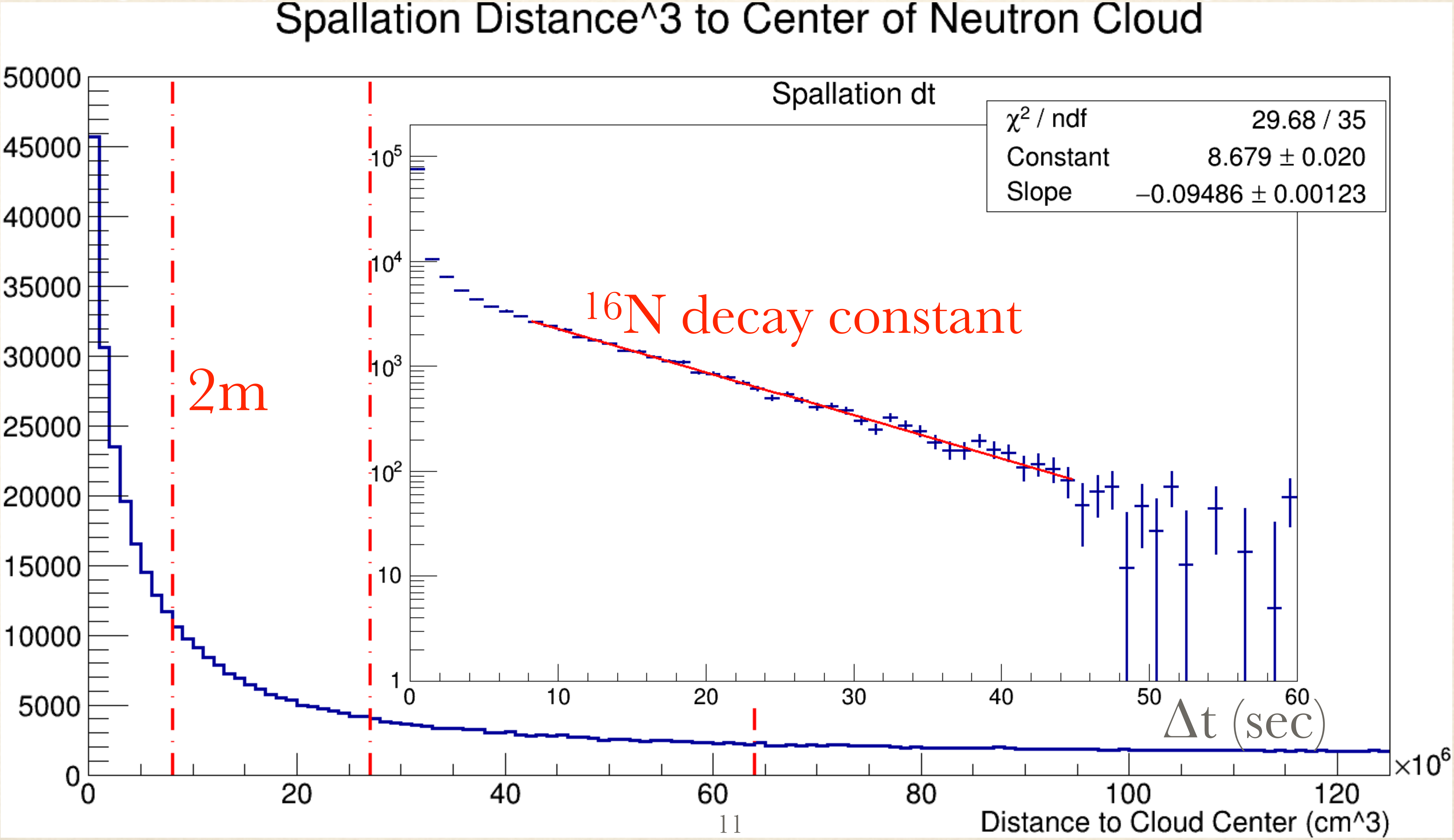
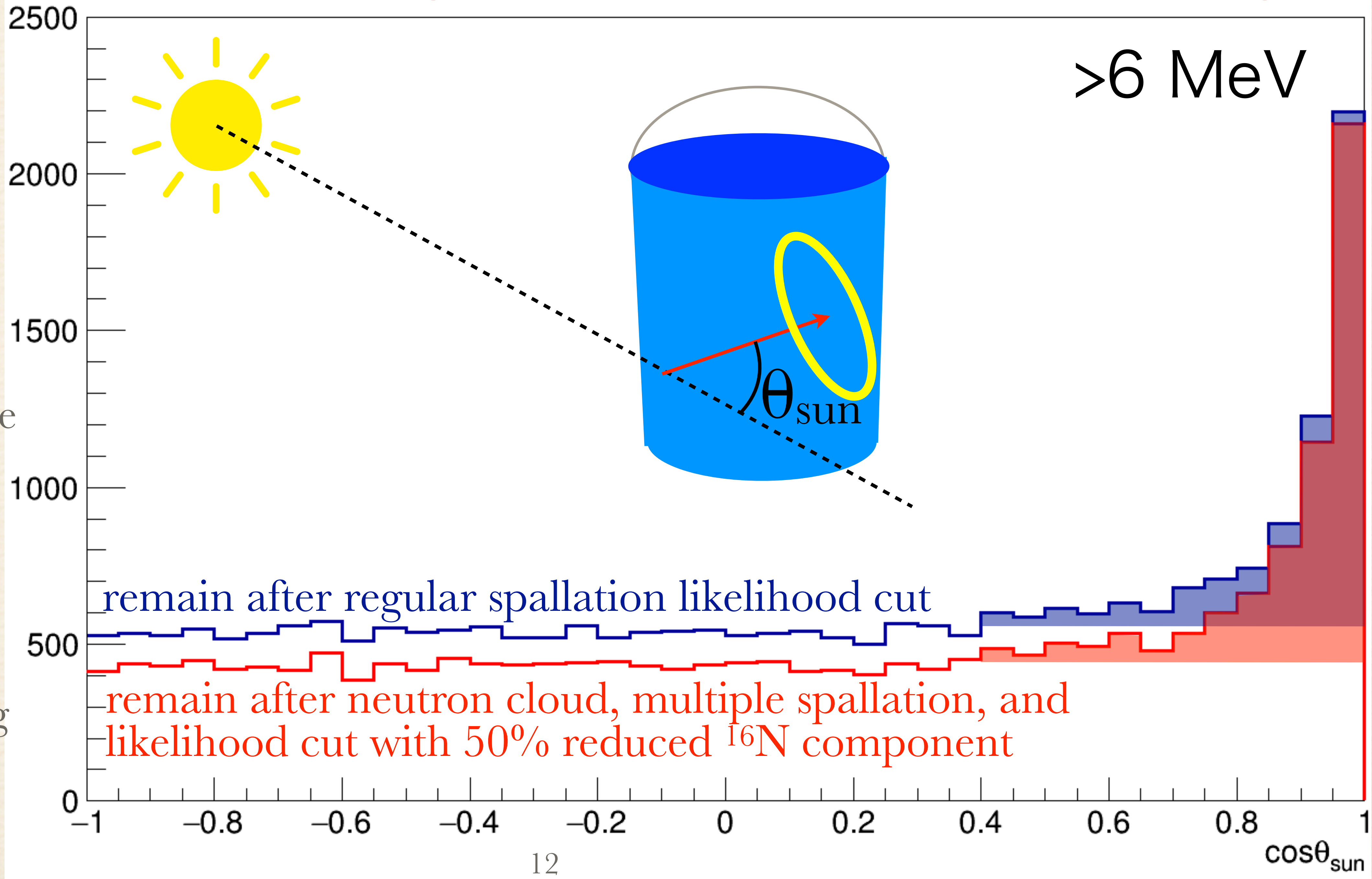


Impact on Solar Neutrino Detection (Scott Locke and Michael)

multiple spallation:

- account for 35-40% of spallation nuclei decays observed in Super-K
- “tag each other”: remove event clusters within 1min., 4m above ~6 MeV
- no need for muon tracking (or even triggering)

Super-K Solar Neutrino Sample: ~10% less signal loss, ~20% more background suppression without tuning!



Low Energy Challenges

Larger detector : larger dark hit (= larger miss-fit)

Shallower detector site : higher muon spallation background

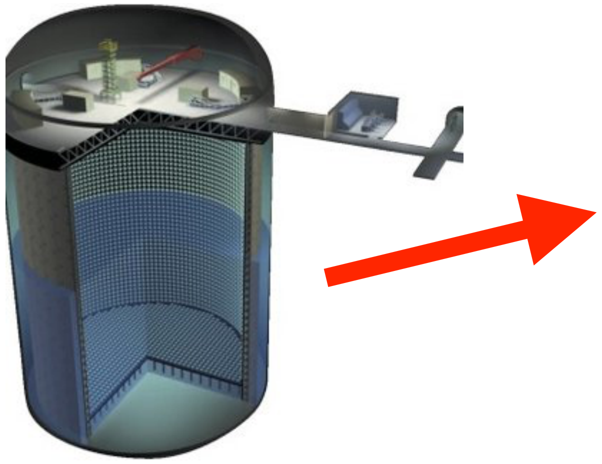
Analysis challenges

- Improvement of vertex / angular reconstruction
- Optimization of muon spallation cut

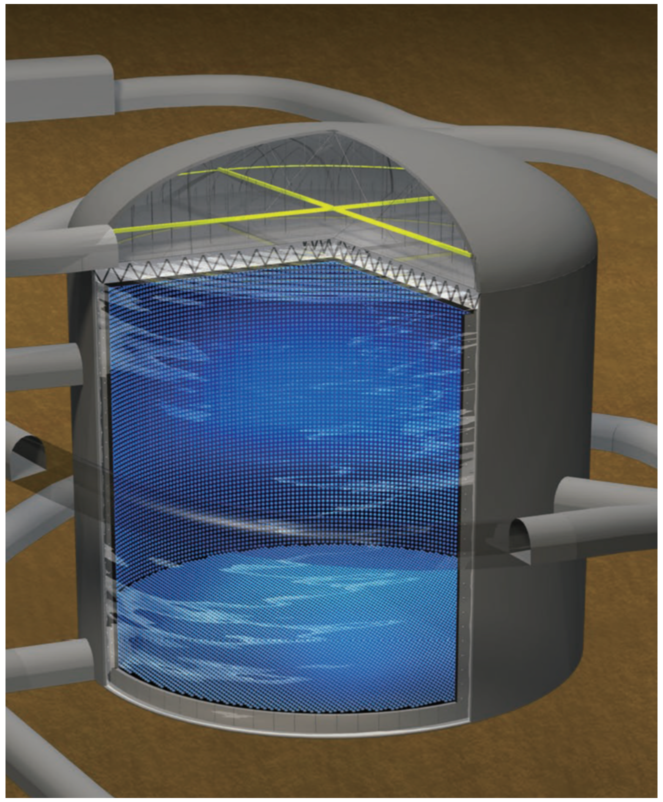
Hardware challenges

- PMT / light collection
- Gd loading
- Radon reduction
- Energy calibration
- Intelligent trigger

various new technique will be required in Hyper-K



Super-K



Hyper-K

Analysis Challenges

- Improvement of vertex / angular reconstruction
    - Likelihood fit maximization in (x, y, z, t) with more efficient method
    - Identification of Cherenkov ring with machine learning

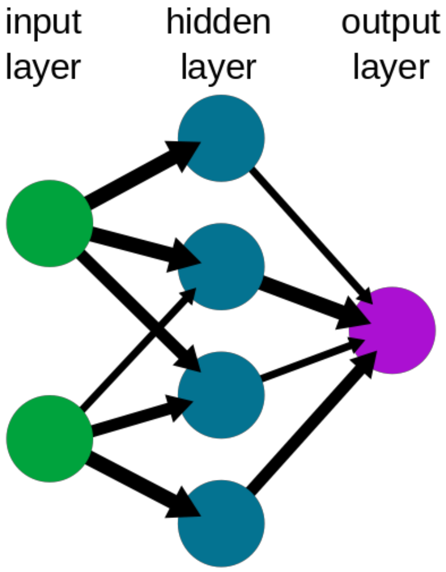
better reconstruction competing with **larger dark hit**

- Optimization of muon spallation cut
    - Muon shower / multi-track ID, muon induced neutron tagging
    - Particle ID (e/gamma) with machine learning

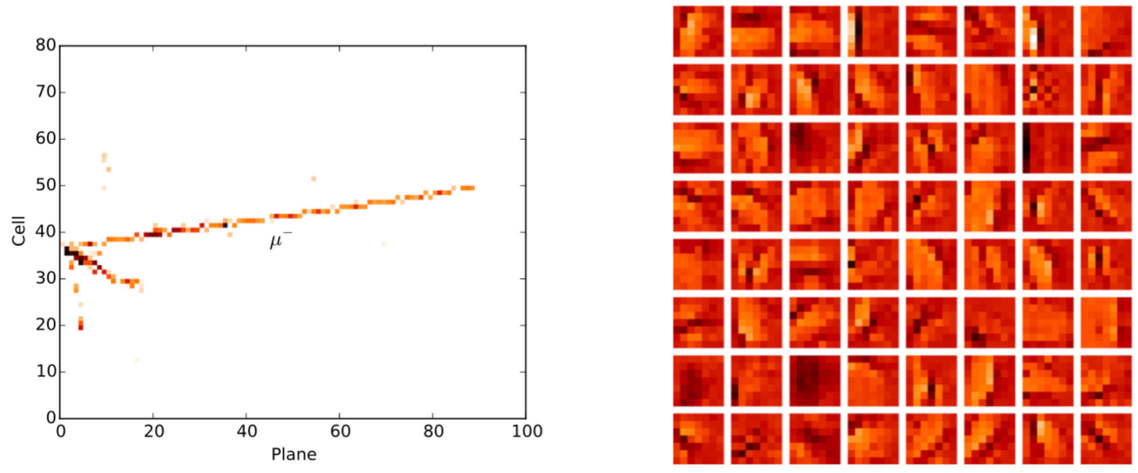
better rejection competing with **higher muon spallation background**

Machine learning applications

A simple neural network

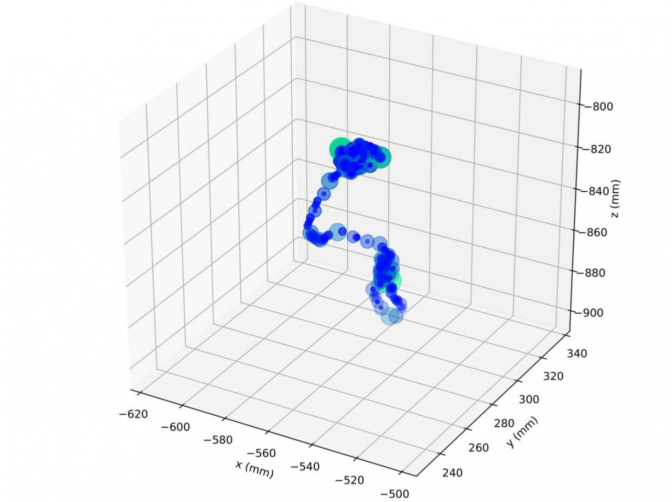


ν_μ CC classification



A. Aurisano, et al. J. of Instr.

$0\nu\beta\beta$ identification



H. Qiao, et al. Sci. China-Phys. Mech. Astron.

Event Reconstruction with Machine Learning (Michael's Point of View)

my (naive) understanding of CNNs

- solve pattern recognition problems
- idea is a deep neural network with several hidden layers of neurons to relate input (e.g. CCD pixels) to output (is it a face or is it not?)
- uses a small "receptive field" (subset of the CCD) for each neuron and sum in a convolution integral (overlap thereceptive fields)
- application in particle physics: recognize particle tracks, vertices, etc.

Event Reconstruction with Machine Learning (Michael's Point of View)

limitations of standard CNNs for low E water Č

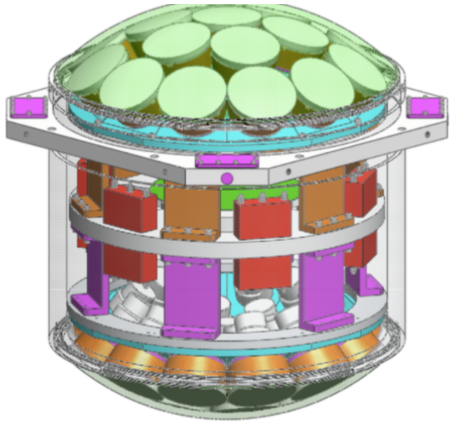
- the small receptive field implies good signal correlations of neighbors
- looks for spatial patterns only, space-time signature is dominant in low E water Č, as multiple scattering obscures the ring
- assumes finite, open surface topology (not true for water Č detector)

… but a deep, fully-connected NN can't handle 40,000 PMTs with hit pattern, times and charges (too many parameters)

possible adaptation of the CNN concept

- use causality constraint (proven to work well for SK low energy reconstruction) to define a receptive field: $\Delta t_{ij} < \Delta x_{ij}$ for direct light: requires variable-sized receptive fields, in principle up to entire detector!
- this also solves closed surface problem as receptive fields are not defined by spatial geometry alone
- possibly can't handle PMT individual characteristics (e.g. its noisiness), but only by external parameters (location, orientation, dark rate) to make training feasible

Hardware Challenges



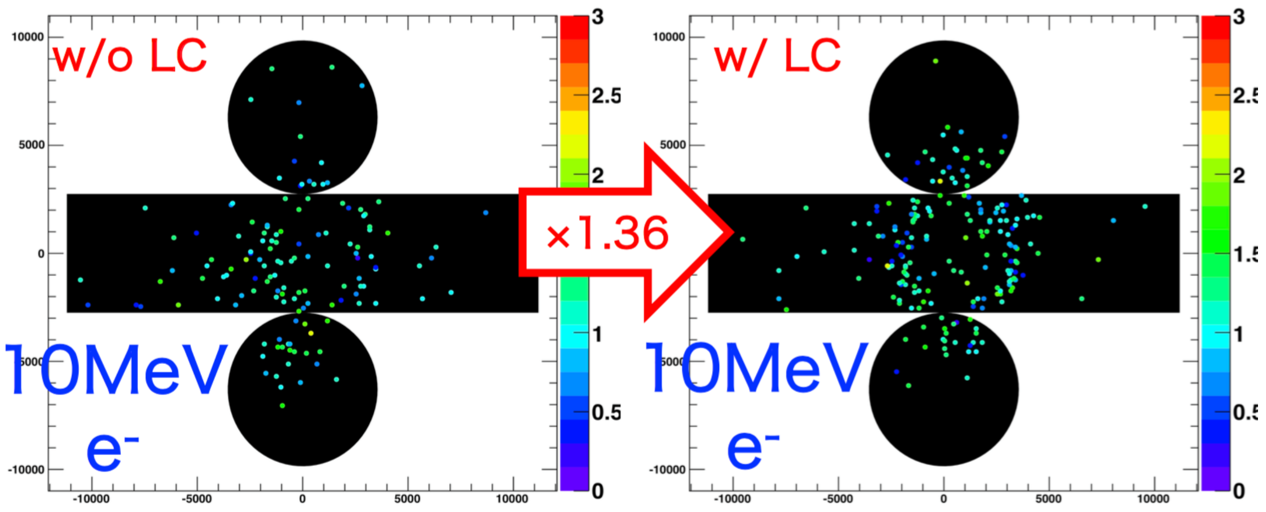
- PMT / light collection
  - Dark rate reduction of 20” PMT from 8 kHz to 4 kHz
  - Additional high performance PMTs (mPMT, MCP-PMT, …)
  - Light collection by mirror or wavelength shifting plate

higher light yield or better time resolution competing with **larger dark hit**

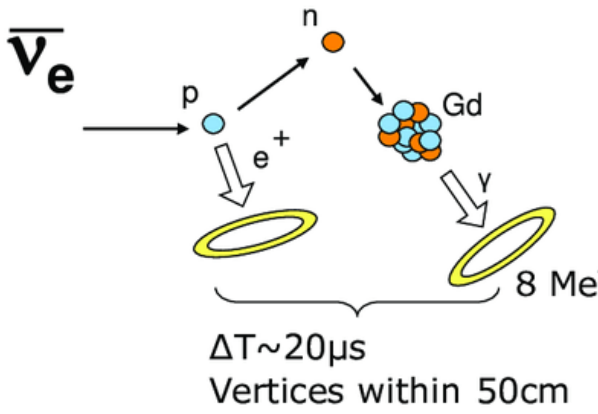
- Gd loading
  - Neutron tagging without accidental BG by adding Gd (~0.01wt%)
  - Hermetic detector (ID/OD separation, balloon / acrylic vessel)

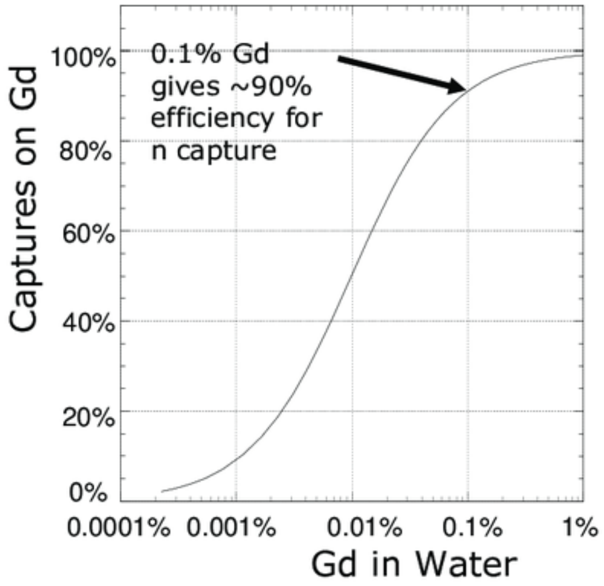
better rejection competing with **higher muon spallation background**

higher light yield by light collector

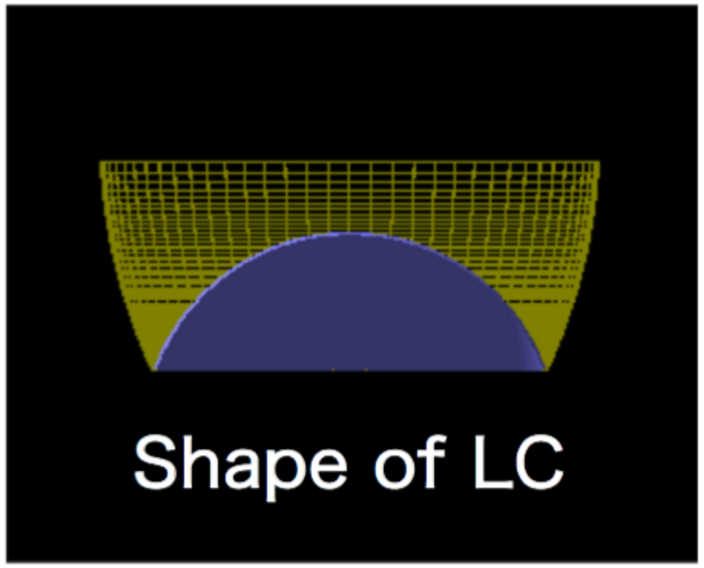


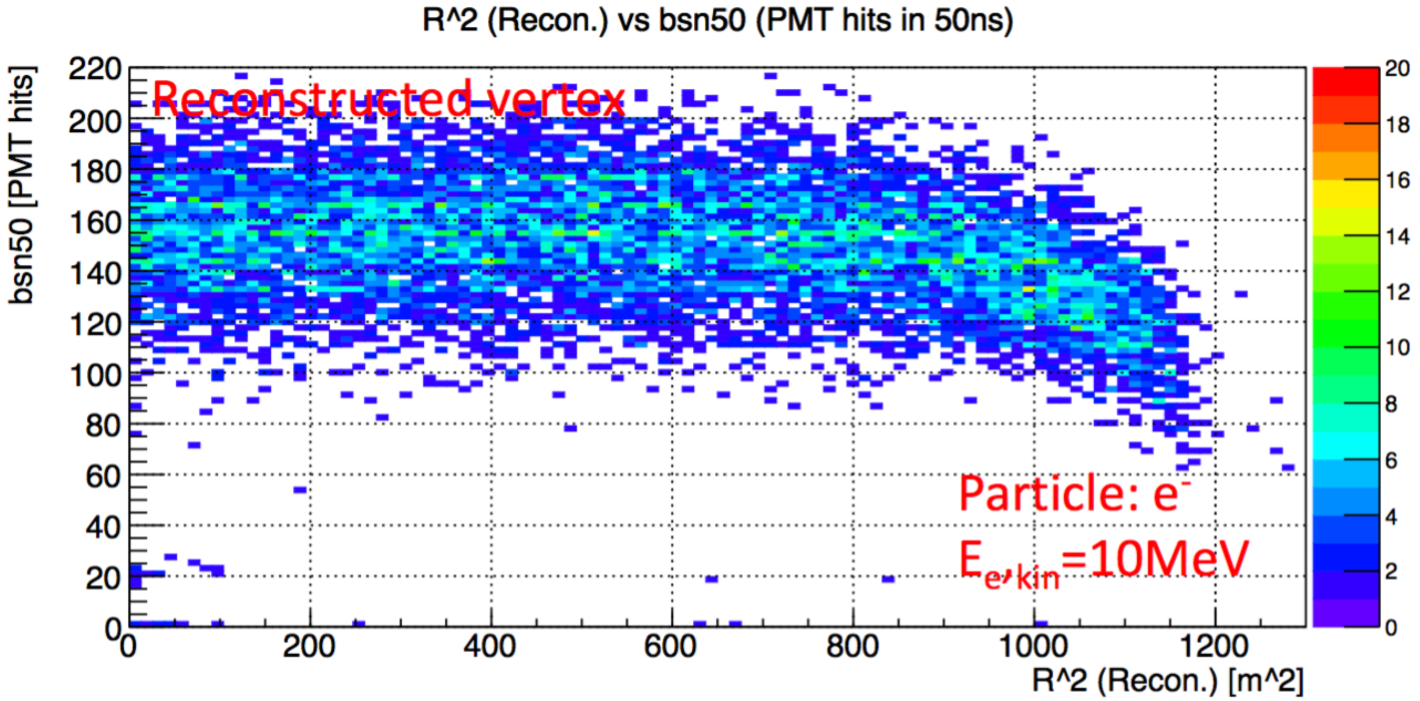
clear neutron identification



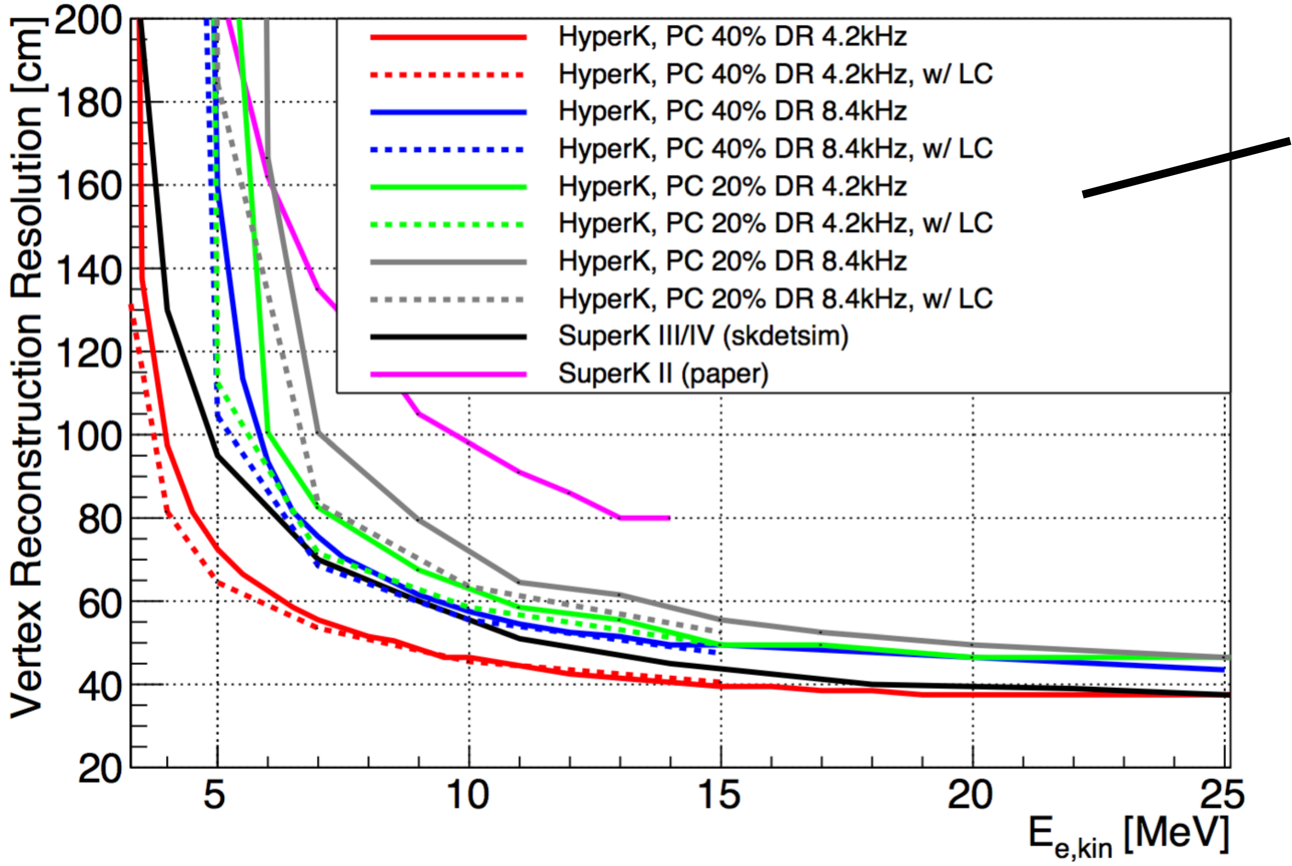


Effect of Light Collection





vertex resolution v.s. kinetic energy



light collection ~ ×1.3

20% or 40% photo-coverage

4.2 kHz or 8.2 kHz dark rate

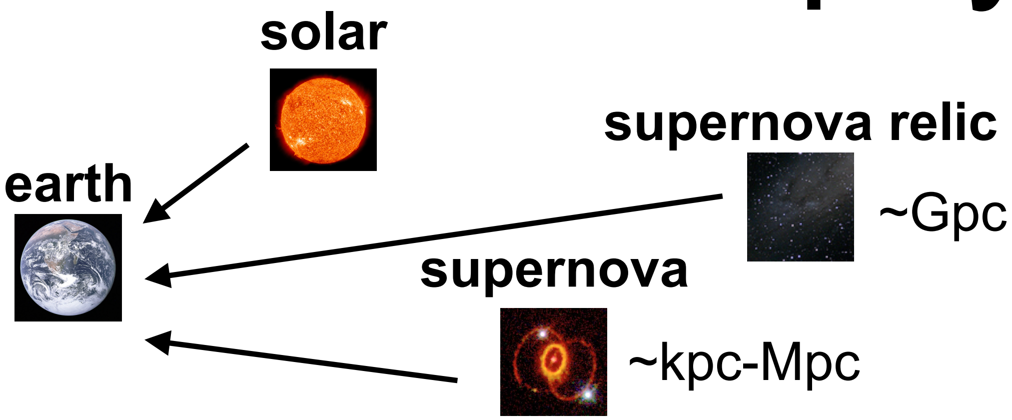
E threshold depends on light yield and dark rate

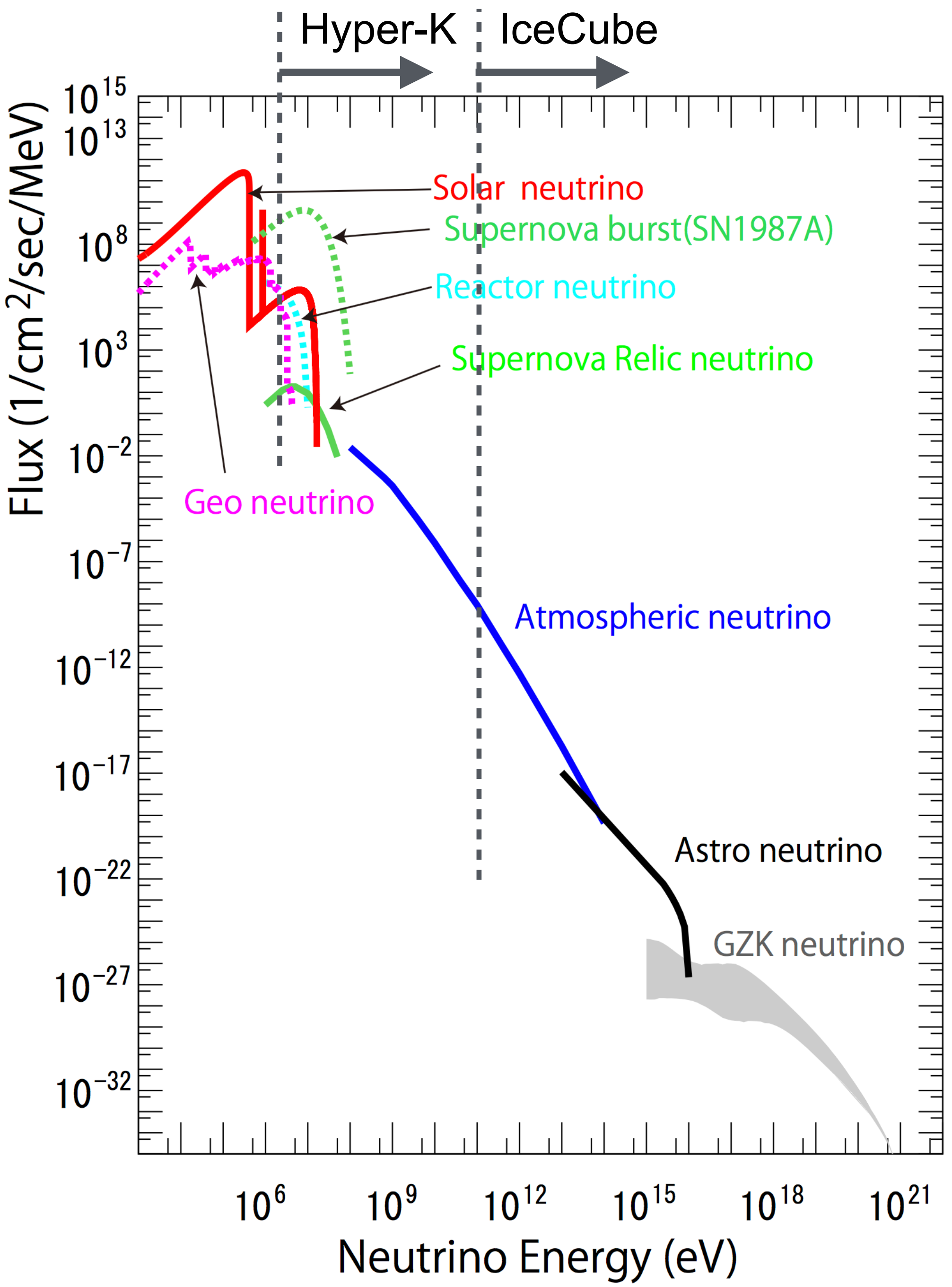
→ critical for solar neutrino study

5 MeV energy threshold is possible even for 20% photo-coverage w/ LC

worse resolution → large miss-fit contributions

Astrophysical Neutrinos





Hyper-K (187 kton H_2O)

^{8}B solar neutrino	130 events / day
Supernova neutrino	~50,000 events / burst
Supernova relic neutrino	~18 events / year

highest statistics / directional information

DUNE (40 kton Ar)

Supernova neutrino	~3,000 events / burst

sensitive to only electron neutrinos

no directional information

JUNO (17 kton LS)

Supernova neutrino	~5,000 events / burst
Supernova relic neutrino	~3 events / year

no directional information

IceCube (2,400 kton H_2O)

Supernova neutrino	~300,000 events / burst

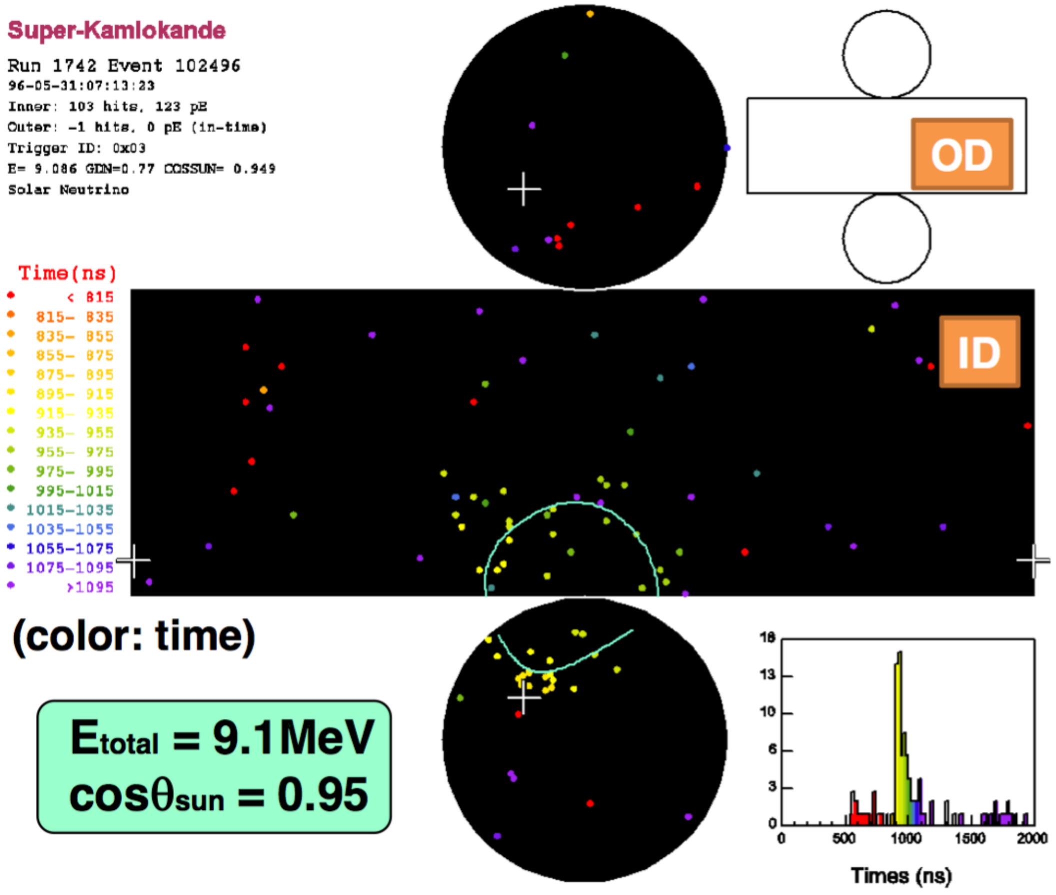
no energy / directional information

Solar Neutrino

Real time measurement allowing solar neutrino spectroscopy

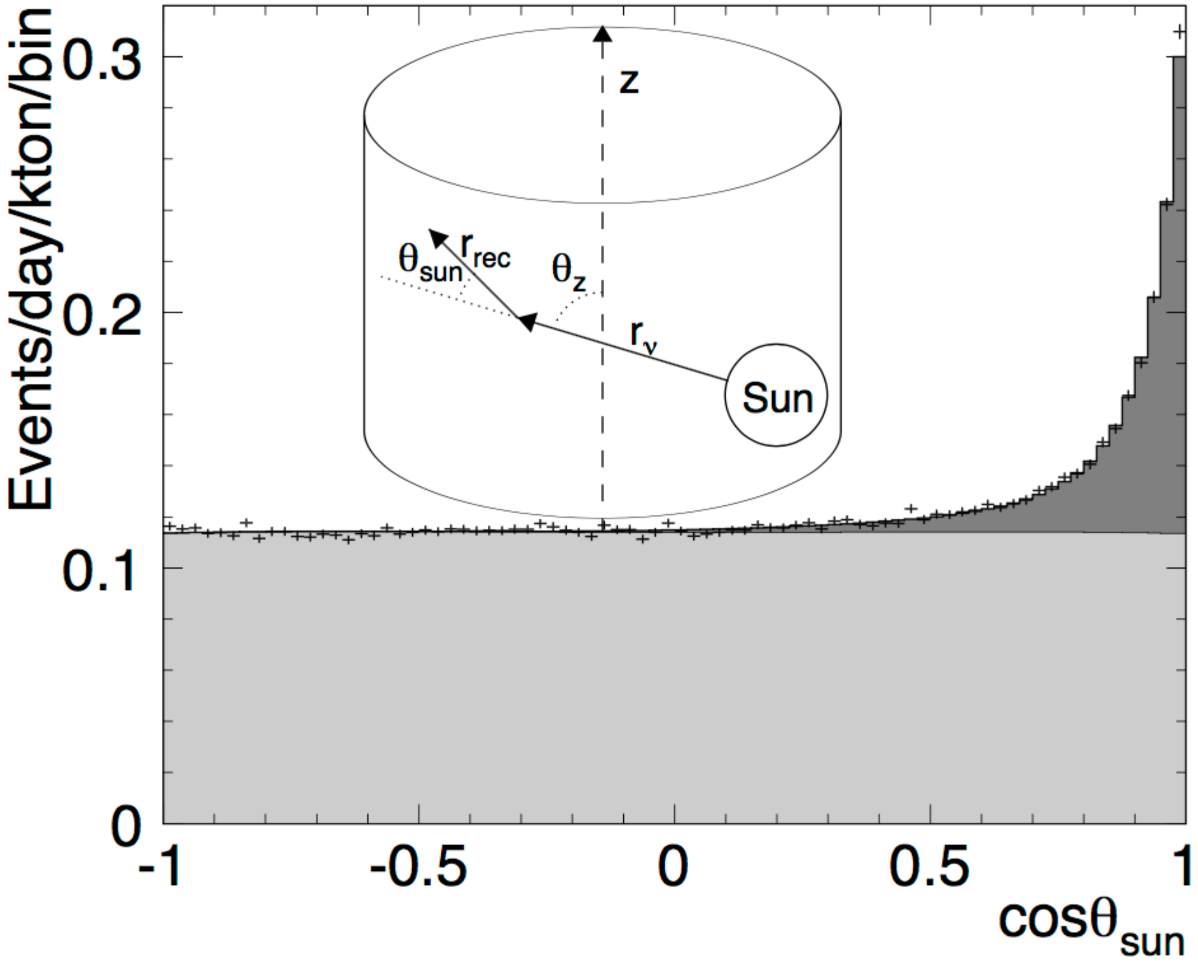
Cherenkov ring image in Super-K

$$\nu + e^- \rightarrow \nu + e^-$$



(color: time)

E_{total} = 9.1MeV
$\cos\theta_{sun}$ = 0.95



Prospect in future solar neutrino

MSW matter effect of the neutrino oscillations in the Sun

Neutrino regeneration in the Earth (Day-Night effect)

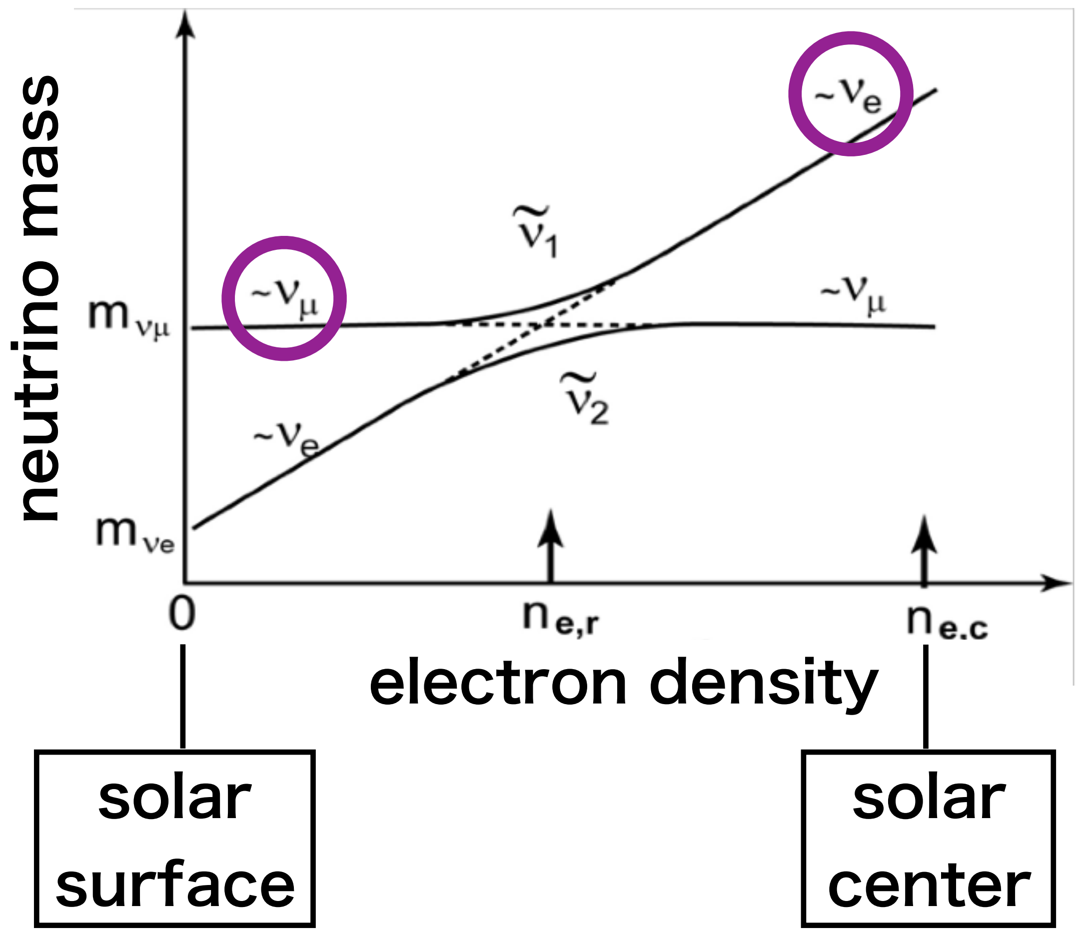
Temporal flux variation / relation with solar activities

Branching ratio of nuclear fusion reactions

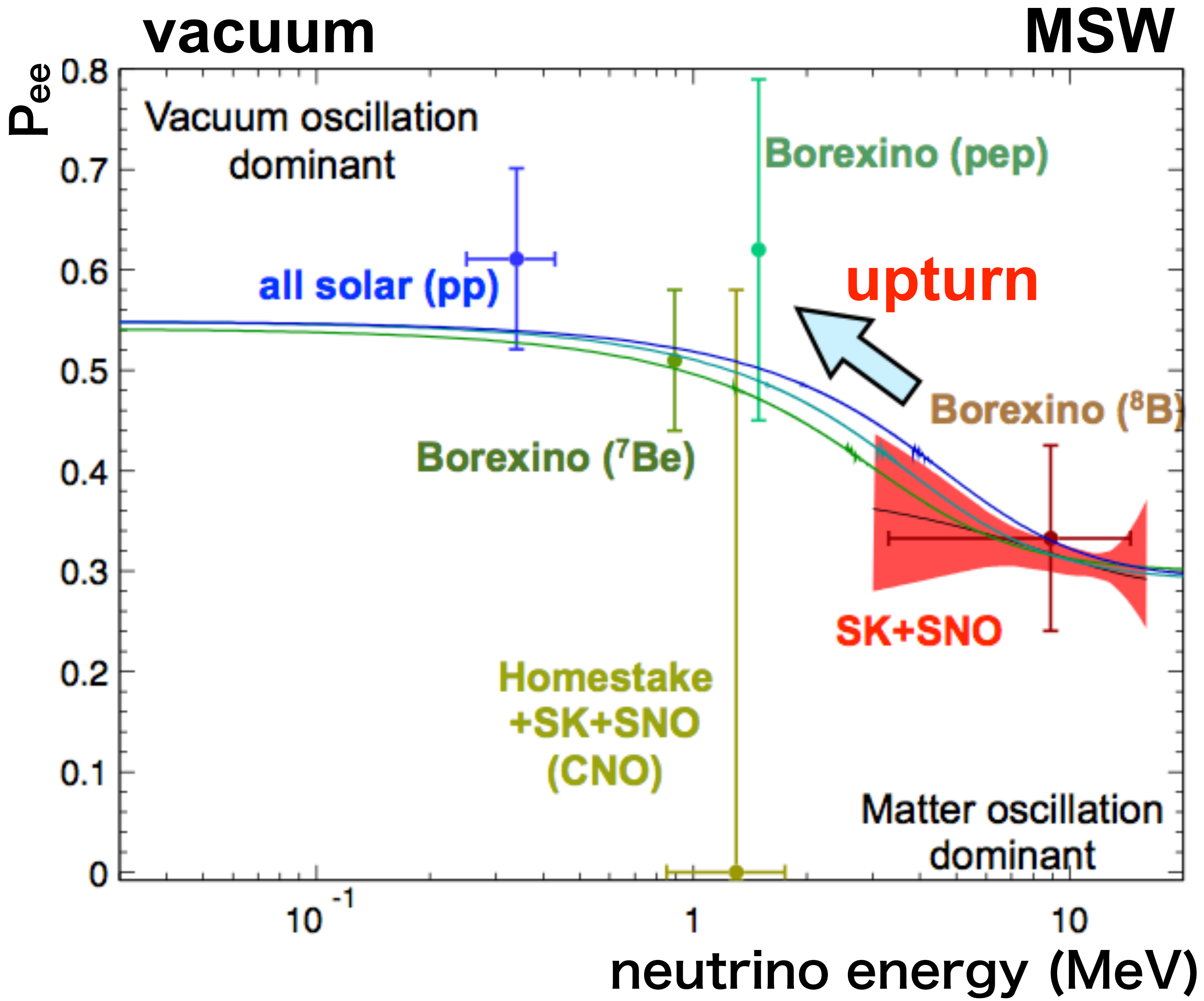
Hyper-K can address the issues

MSW Matter Effect

Required by observed energy dependence of survival probability (P_{ee})



MSW resonance oscillation



Energy dependence of survival probability

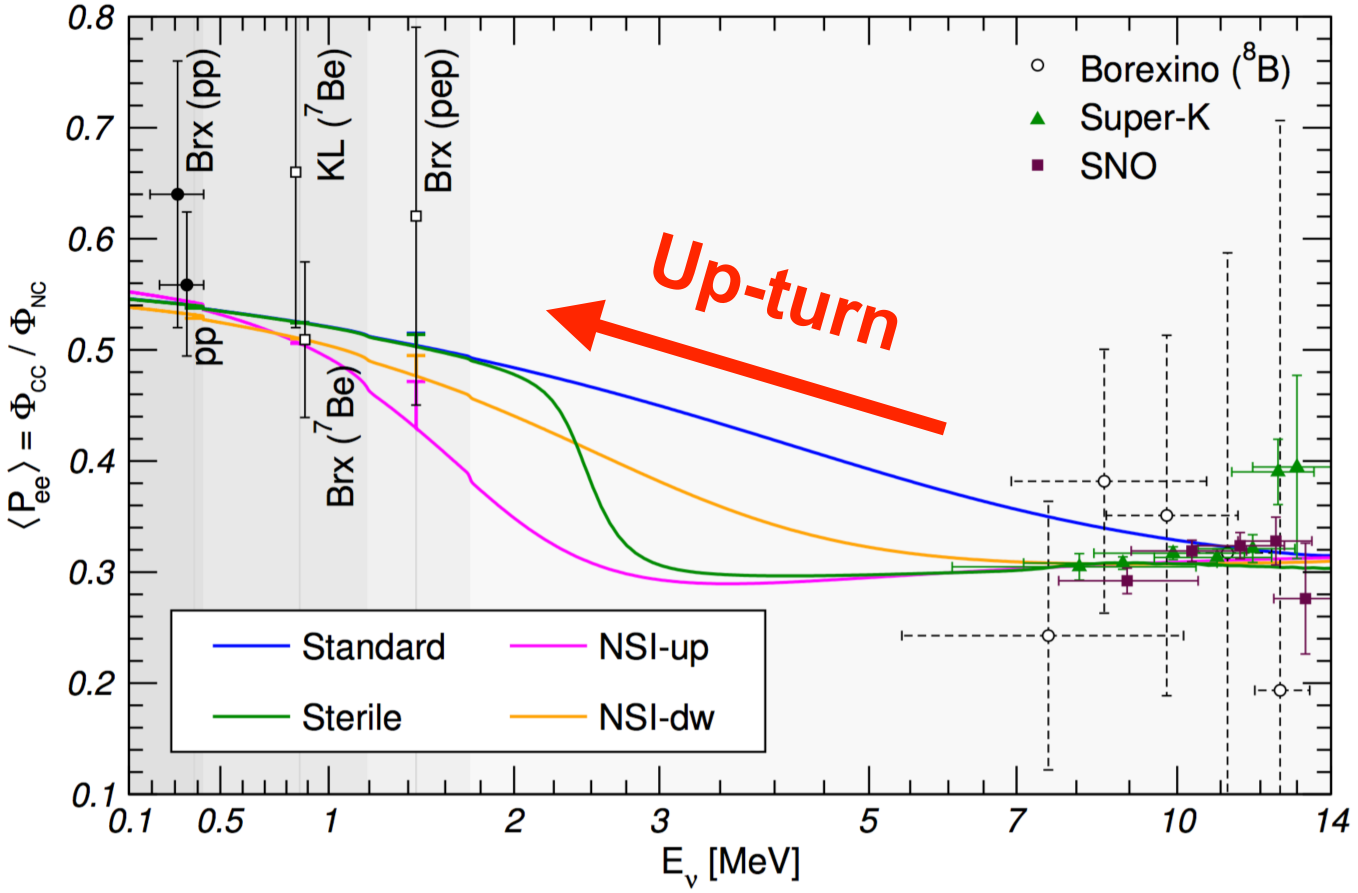
$$P_{\mathrm{ee}} = \sin^2\theta_{12} \;\; (\beta > 1,\; \mathrm{MSW}) \qquad \beta = \frac{2\sqrt{2}G_F n_e E_\nu}{\Delta m^2}$$

$$P_{\mathrm{ee}} = 1 - \frac{1}{2}\sin^2 2\theta_{12} \;\; (\beta < \cos 2\theta_{12},\; \mathrm{vacuum})$$

Spectrum Up-turn

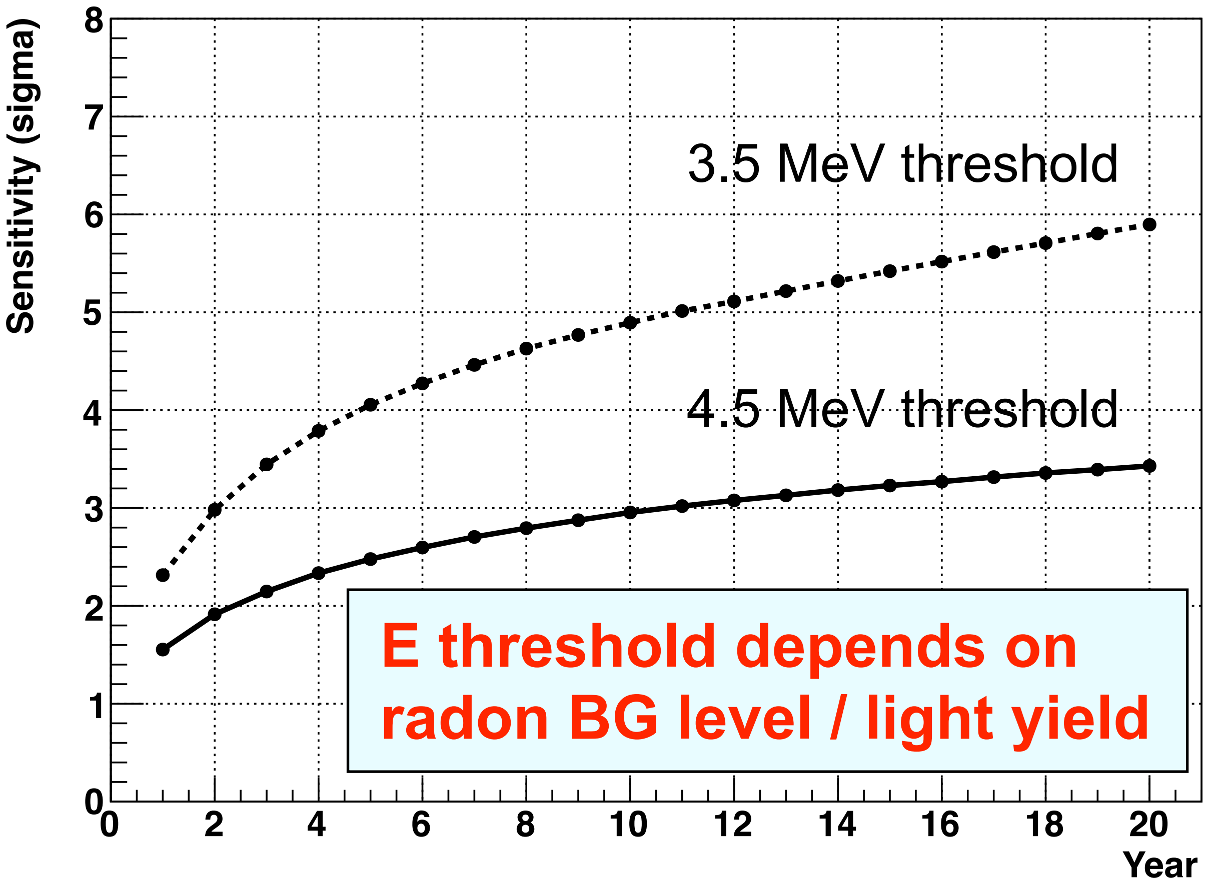
Intermediate energy region between vacuum and MSW oscillation (up-turn) can be measured more precisely in Hyper-K

survival probability of electron solar neutrinos



M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)

sensitivity of energy spectrum up-turn



E threshold depends on radon BG level / light yield

~40% photo-coverage is necessary

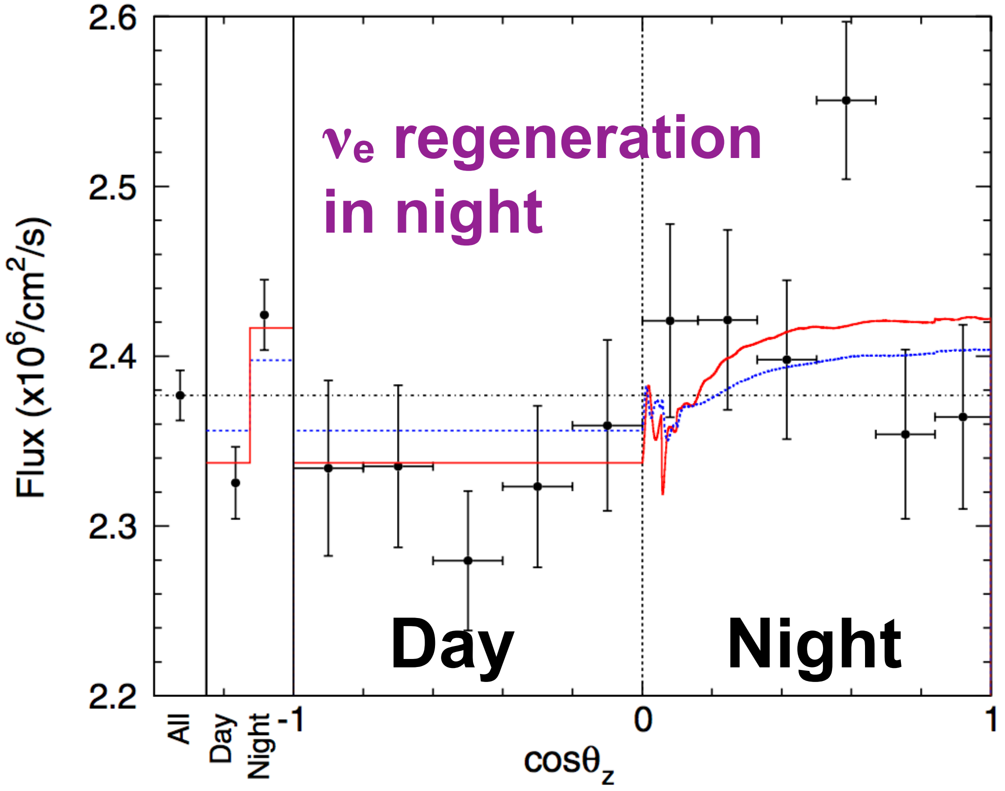
>3σ sensitivity

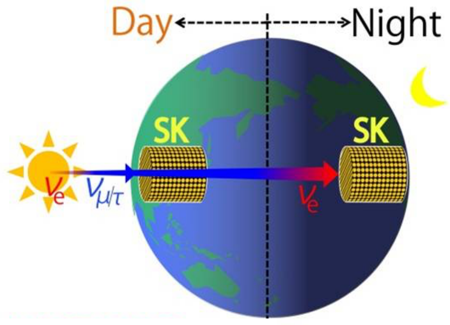
Observation of MSW oscillation with single neutrino source (^{8}B)

Test exotic scenario (non-standard interaction, sterile neutrino)

Day-Night Effect

zenith angle dependence of flux in Super-K



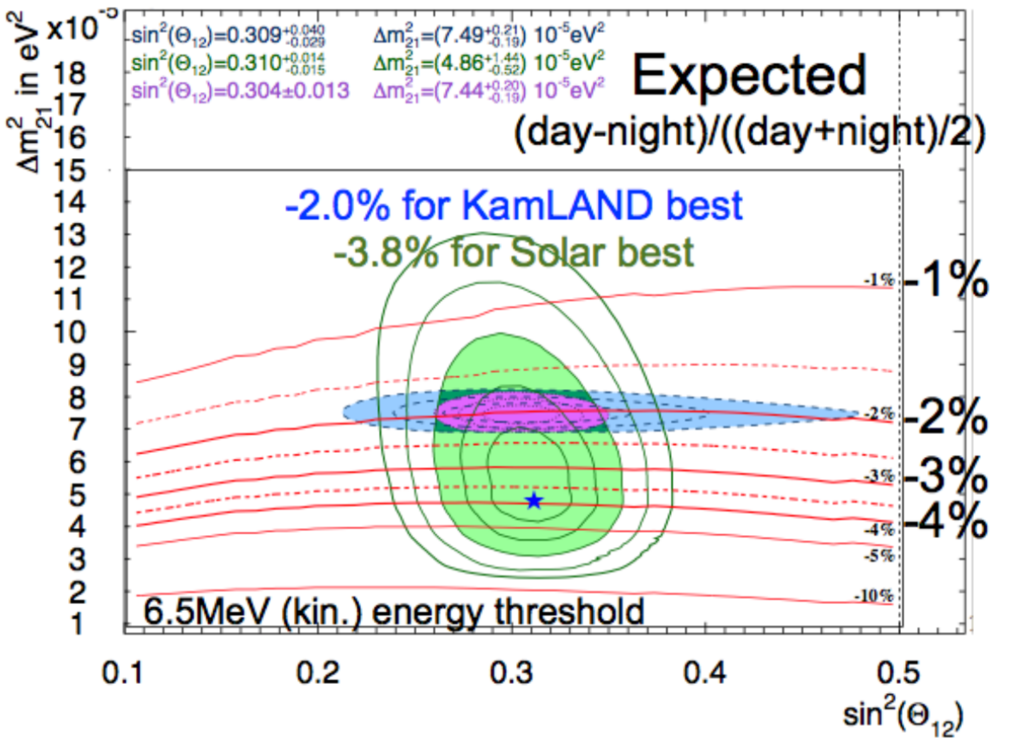


Super-K best

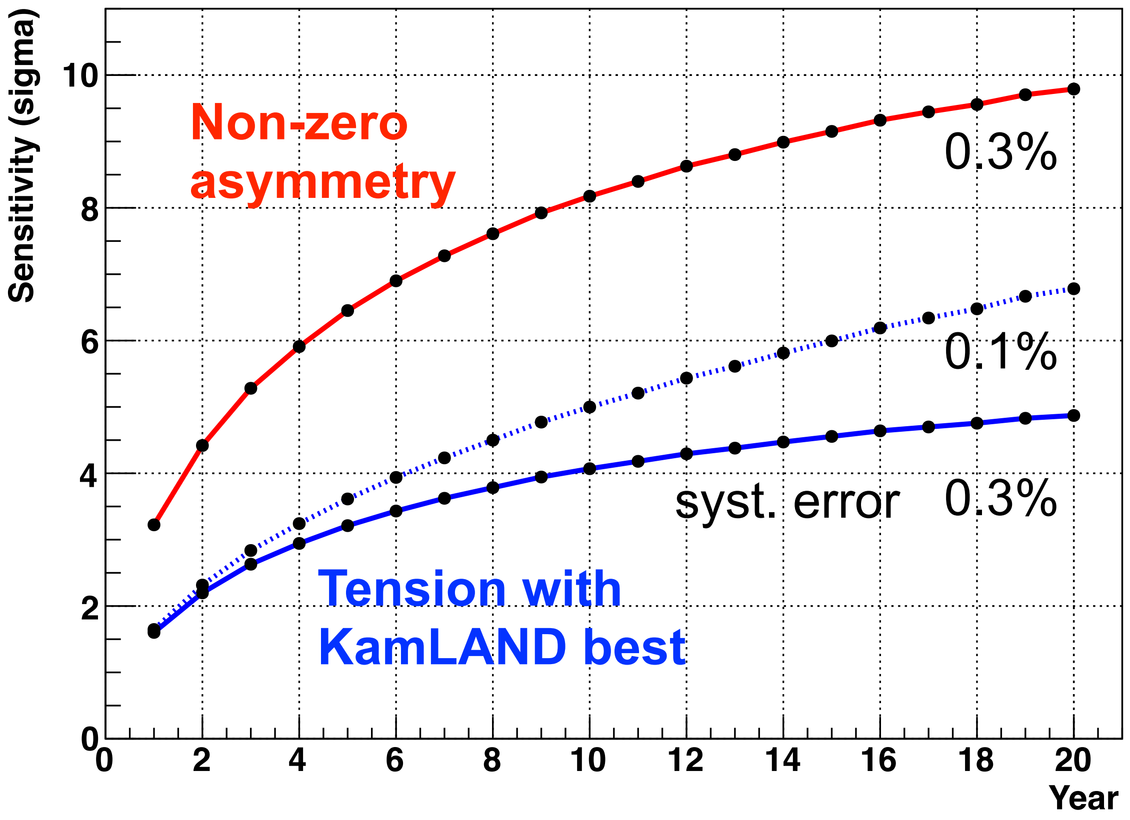
Solar + KamLAND

A. Renshaw et al.,
Phys. Rev. Lett. 112,
091805 (2014)

oscillation parameters : Solar and KamLAND



sensitivity from Day-Night in Hyper-K



Super-K $A_{\mathrm{DN}}^{\mathrm{fit}} = [-3.2 \pm 1.1(\mathrm{stat}) \pm 0.5(\mathrm{syst})]\%$

dominant error

mainly from BG shape

non-zero significance : 2.7σ

Hyper-K

Goal of systematic error : 0.3%

Systematic error depends on quality of energy calibration

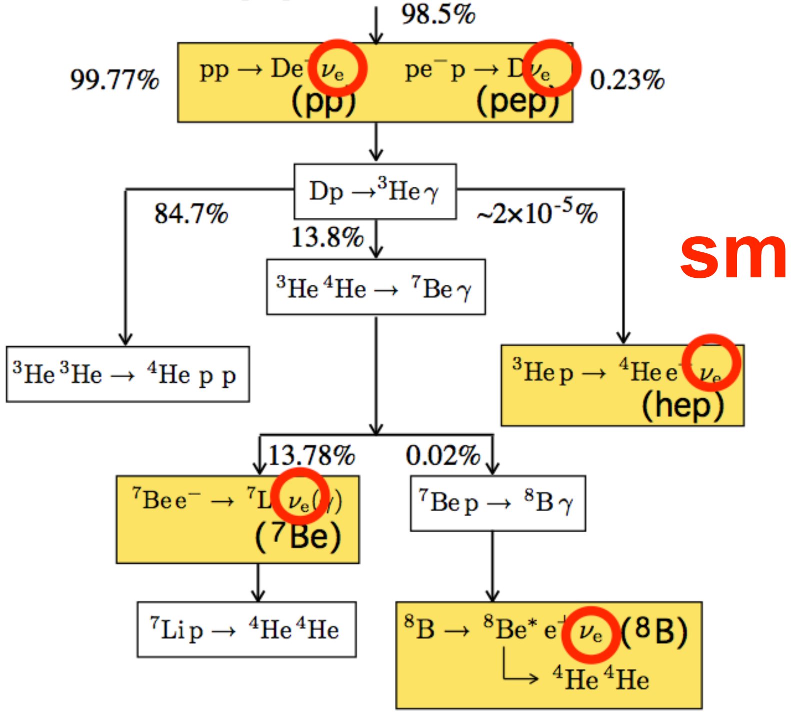
>4σ for non-zero asymmetry

& CPT invariance ($P_\nu = P_{\bar{\nu}}$) test

Hep Solar Neutrino

Three orders of magnitudes smaller than ^{8}B solar neutrino flux

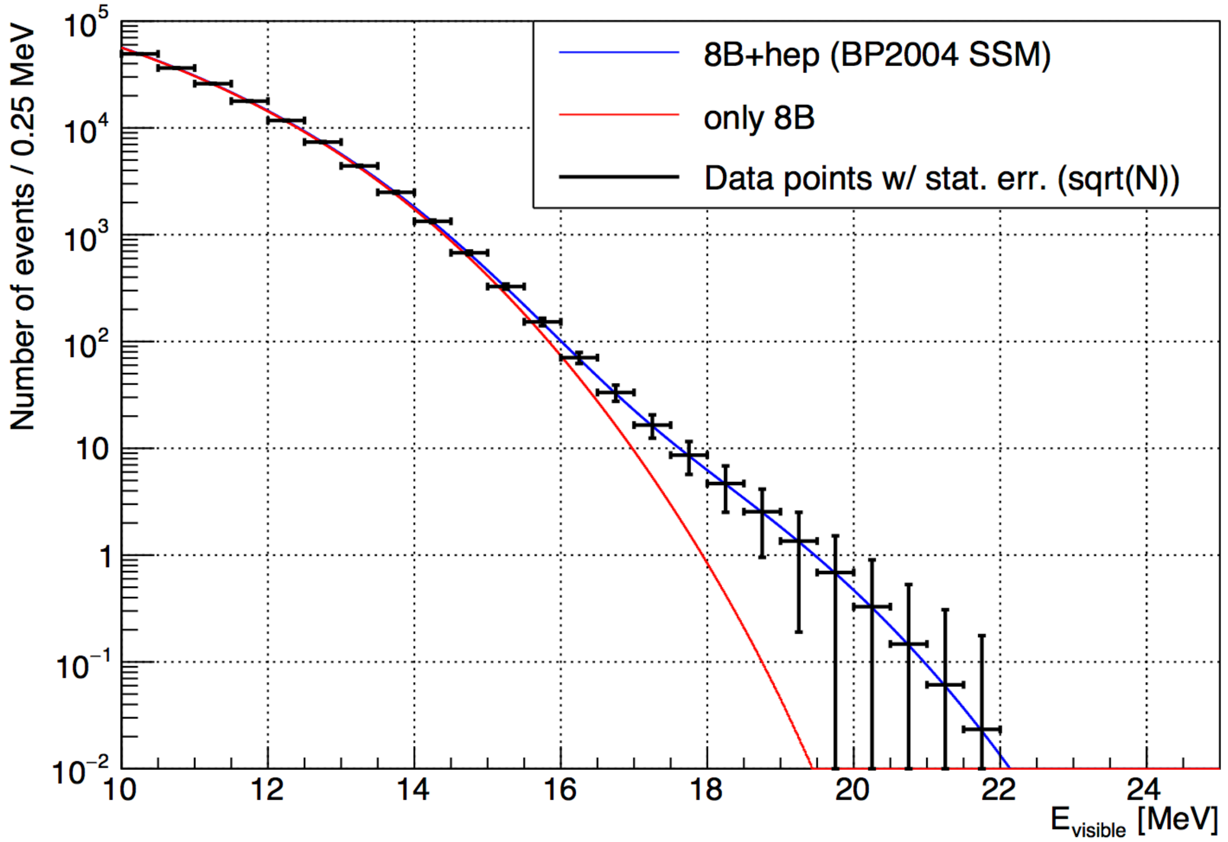
pp chain

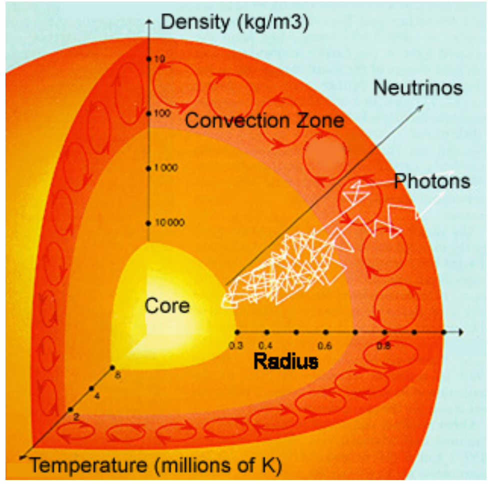


small branch

not detected yet

expected energy spectrum in 10 years





convection may enhance hep ν production at the high temperature core

$$^3\mathrm{He}\ p \rightarrow {}^4\mathrm{He}\ e^+\ \nu_e$$

sensitivity is limited by E resolution

Energy resolution depends light yield and calibration

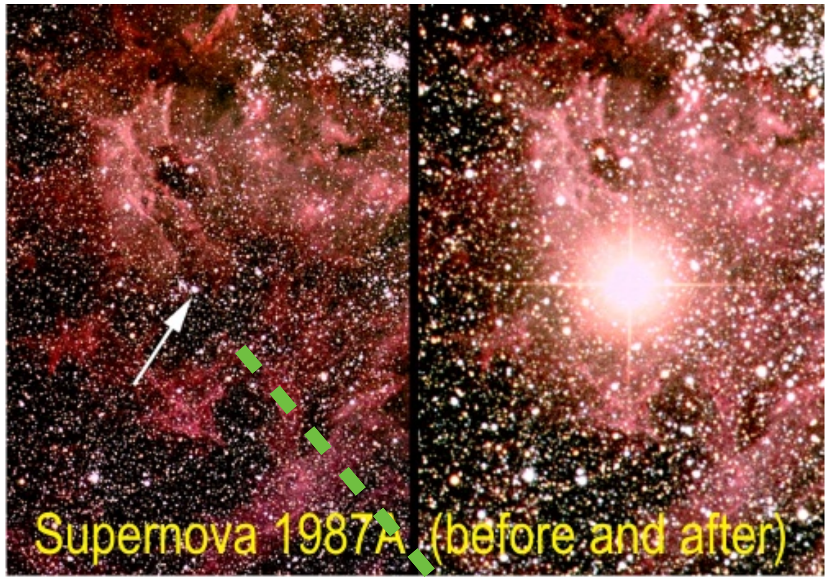
~40% photo-coverage is necessary

First measurement of hep solar neutrinos at ~2σ

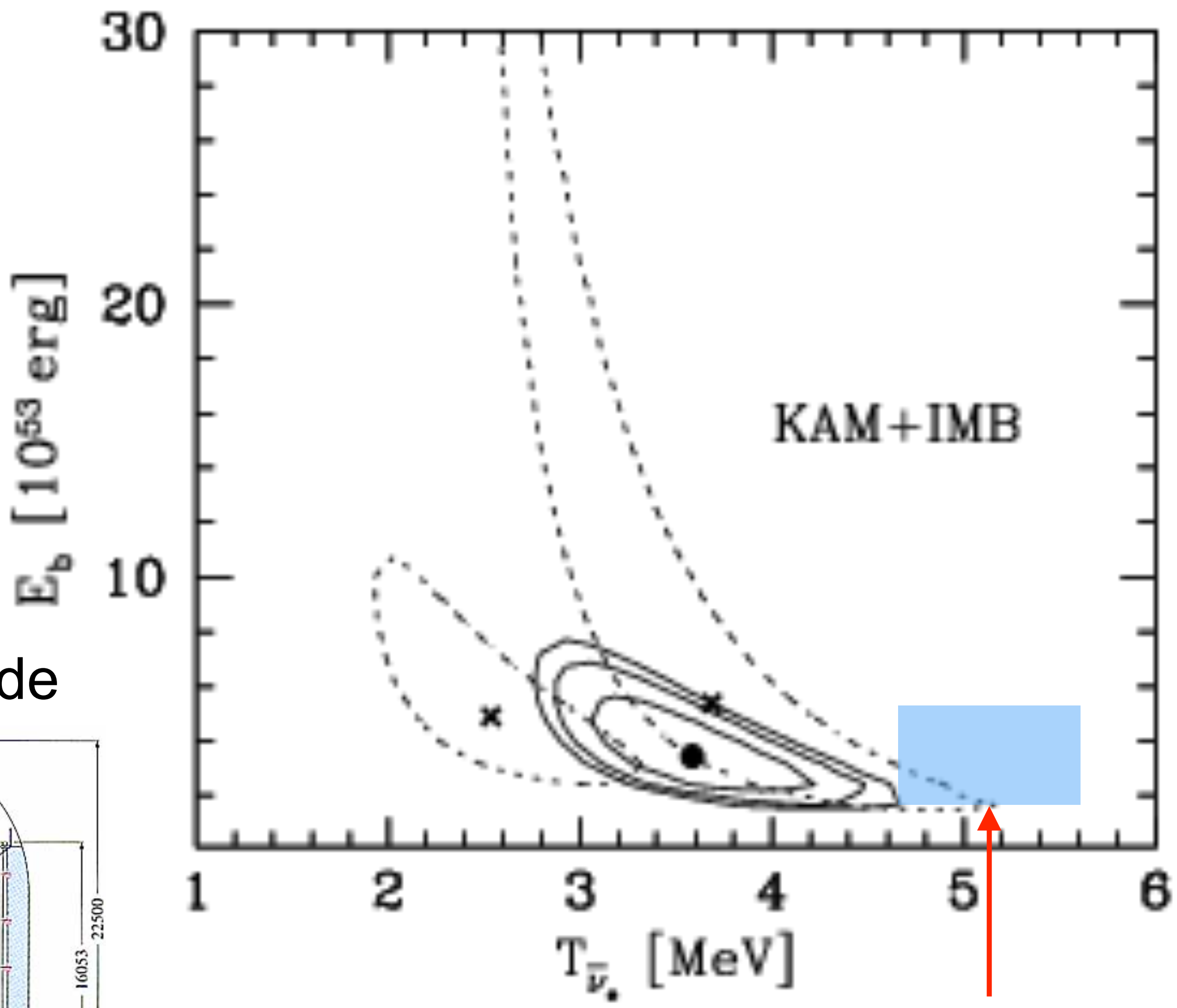
Test cross-section of He + p fusion, convection (non-standard SSM)

Supernova Neutrino

SN1987A at 50 kpc : first detection of supernova burst neutrino

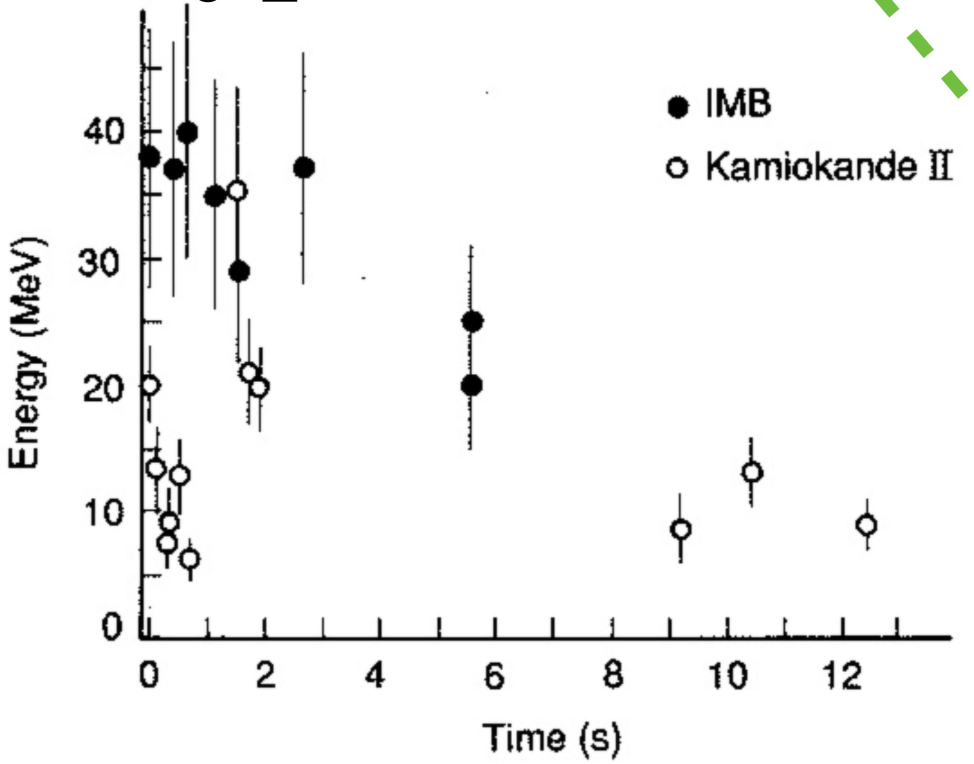


binding energy v.s. neutrino temperature

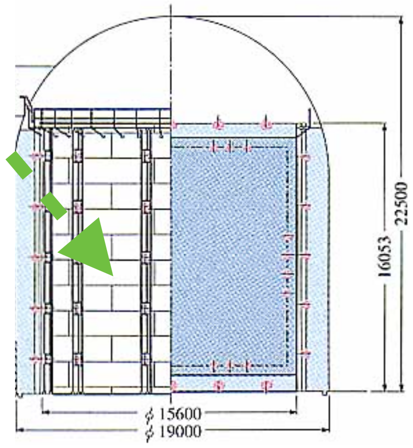


main reaction

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



Kamiokande

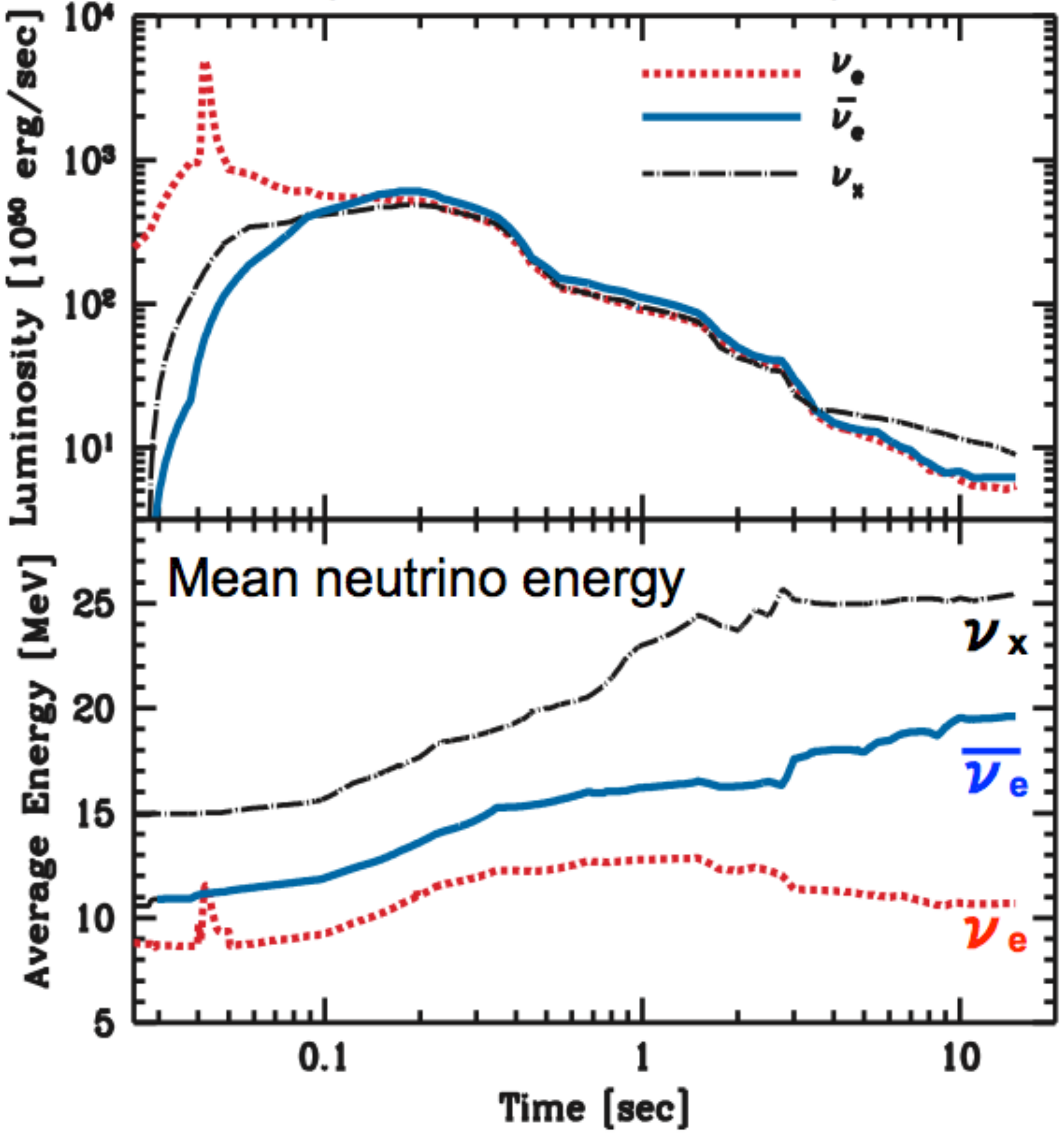


theoretical prediction

Confirmed that neutrinos bring most of the burst energy only in 10 sec

Prospect in Future Supernova

Expected time profile
(Livermore simulation)



Time modulation of neutrino luminosity and average energy

Normal Hierarchy (NH)

$$\frac{\mathrm{d}N_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} = |U_{\mathrm{e}1}|^2 \frac{\mathrm{d}N_{\bar{\nu}_1}}{\mathrm{d}E_{\bar{\nu}_1}} + |U_{\mathrm{e}2}|^2 \frac{\mathrm{d}N_{\bar{\nu}_2}}{\mathrm{d}E_{\bar{\nu}_2}} + |U_{\mathrm{e}3}|^2 \frac{\mathrm{d}N_{\bar{\nu}_3}}{\mathrm{d}E_{\bar{\nu}_3}}$$

$$= |U_{\mathrm{e}1}|^2 \frac{\mathrm{d}N^0_{\bar{\nu}_\mathrm{e}}}{dE_{\bar{\nu}_\mathrm{e}}} + \left(1 - |U_{\mathrm{e}1}|^2\right) \frac{dN^0_{\nu_\mathrm{x}}}{dE_{\nu_\mathrm{x}}},$$

Inverted Hierarchy (IH)

$$\frac{\mathrm{d}N_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} = |U_{\mathrm{e}3}|^2 \frac{\mathrm{d}N^0_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} + \left(1 - |U_{\mathrm{e}3}|^2\right) \frac{\mathrm{d}N^0_{\nu_\mathrm{x}}}{\mathrm{d}E_{\nu_\mathrm{x}}} \simeq \frac{\mathrm{d}N^0_{\nu_\mathrm{x}}}{\mathrm{d}E_{\nu_\mathrm{x}}}$$

Neutrino oscillation
Mass hierarchy

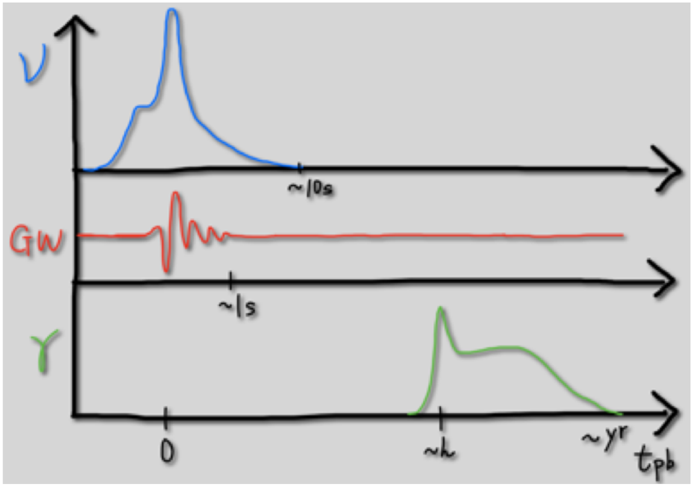
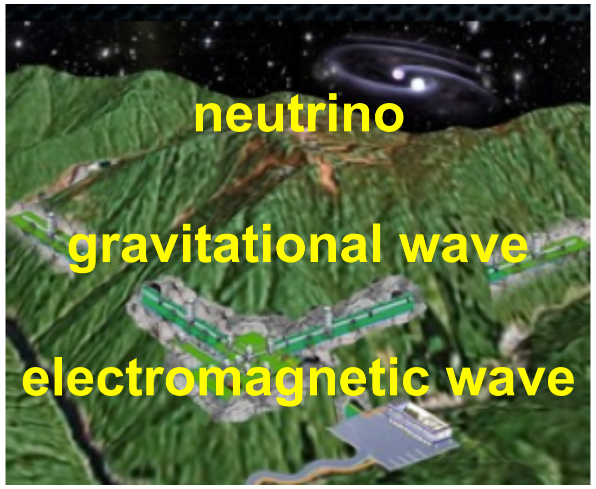


Fig. by Y. Suwa

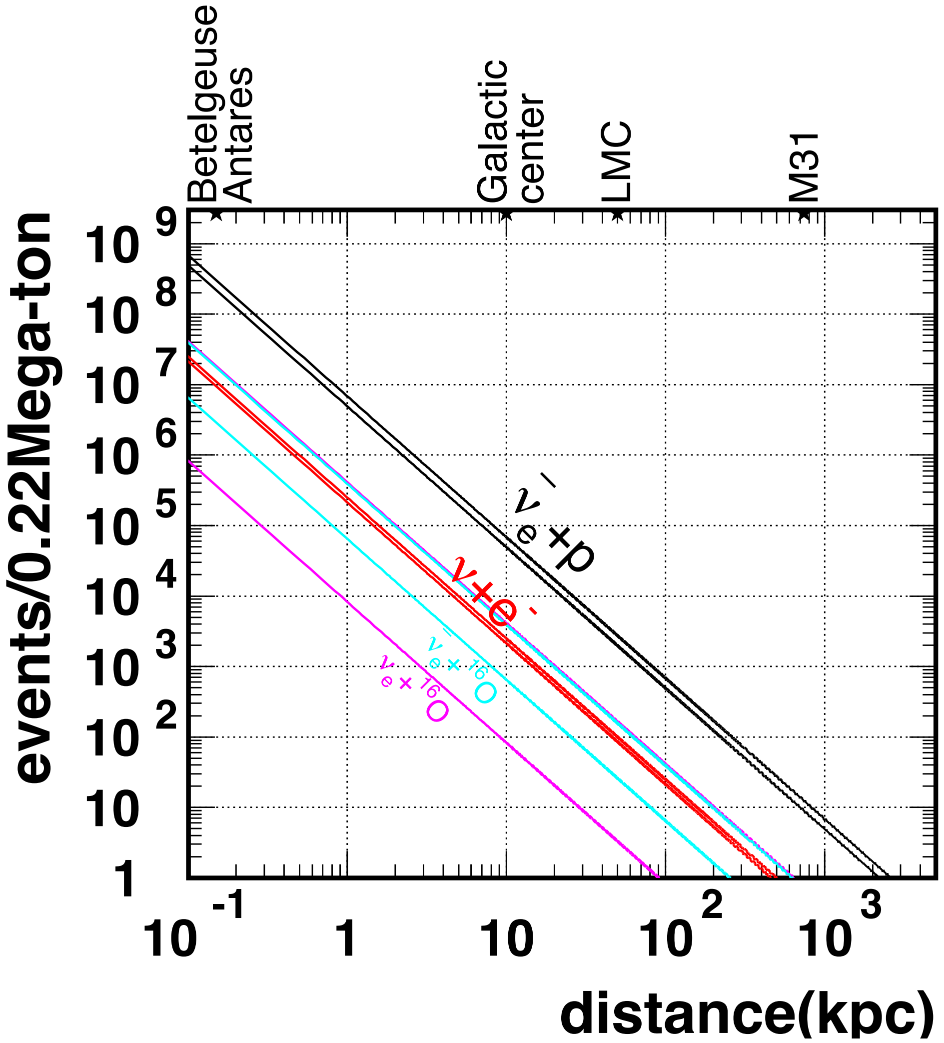


Multi-messenger astronomy

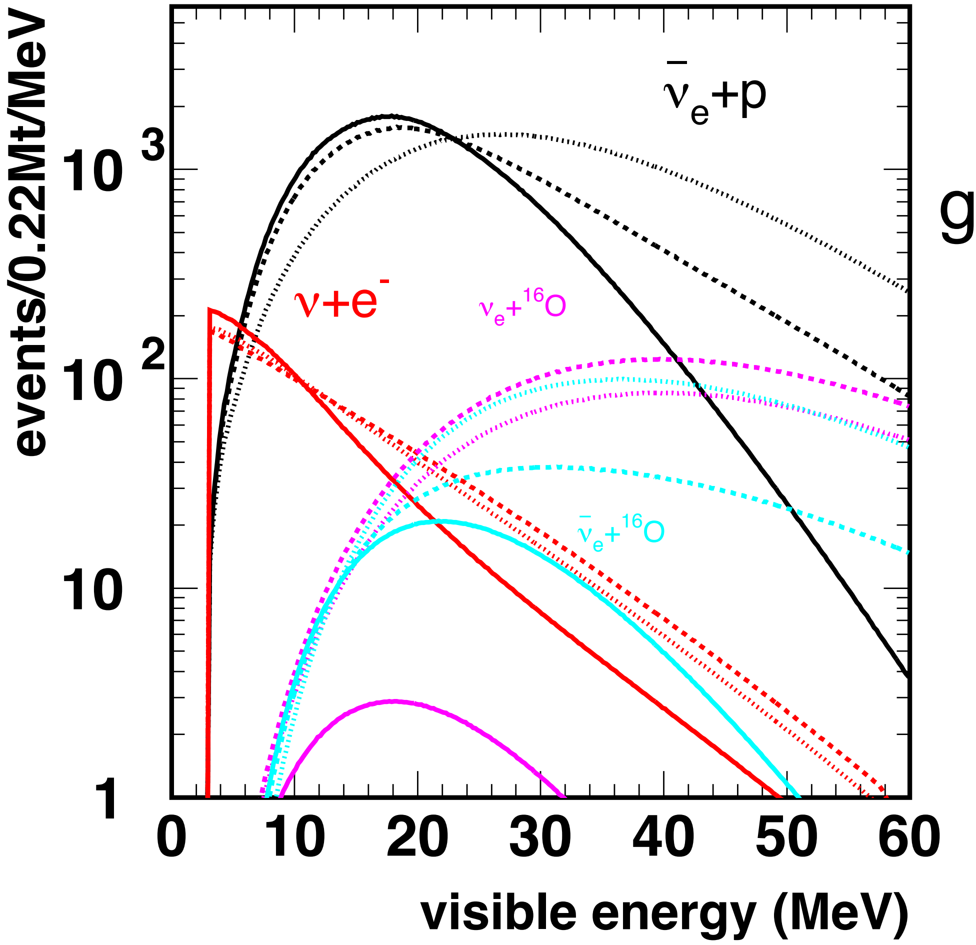
Supernova Neutrino in Hyper-K

Main detection channels

Inverse beta decay	$\overline{\nu}_e + p \rightarrow e^+ + n$	E > 1.8 MeV
ν-e scattering	$\nu + e^- \rightarrow \nu + e^-$	
ν_e ^{16}O CC	$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$	E > 15 MeV
$\overline{\nu}_e$ ^{16}O CC	$\overline{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$	E > 11 MeV



Total energy spectrum



galactic supernova
at 10 kpc

54,000-90,000
events in total

high statistics

Time Modulation w/ Neutrino Oscillation

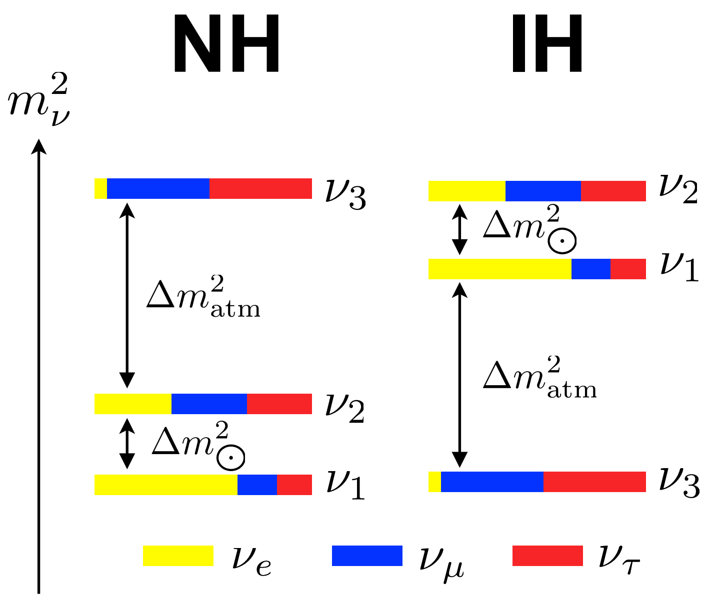
Normal Hierarchy (NH)

$$\frac{\mathrm{d}N_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} = |U_{\mathrm{e}1}|^2 \frac{\mathrm{d}N_{\bar{\nu}_1}}{\mathrm{d}E_{\bar{\nu}_1}} + |U_{\mathrm{e}2}|^2 \frac{\mathrm{d}N_{\bar{\nu}_2}}{\mathrm{d}E_{\bar{\nu}_2}} + |U_{\mathrm{e}3}|^2 \frac{\mathrm{d}N_{\bar{\nu}_3}}{\mathrm{d}E_{\bar{\nu}_3}}$$

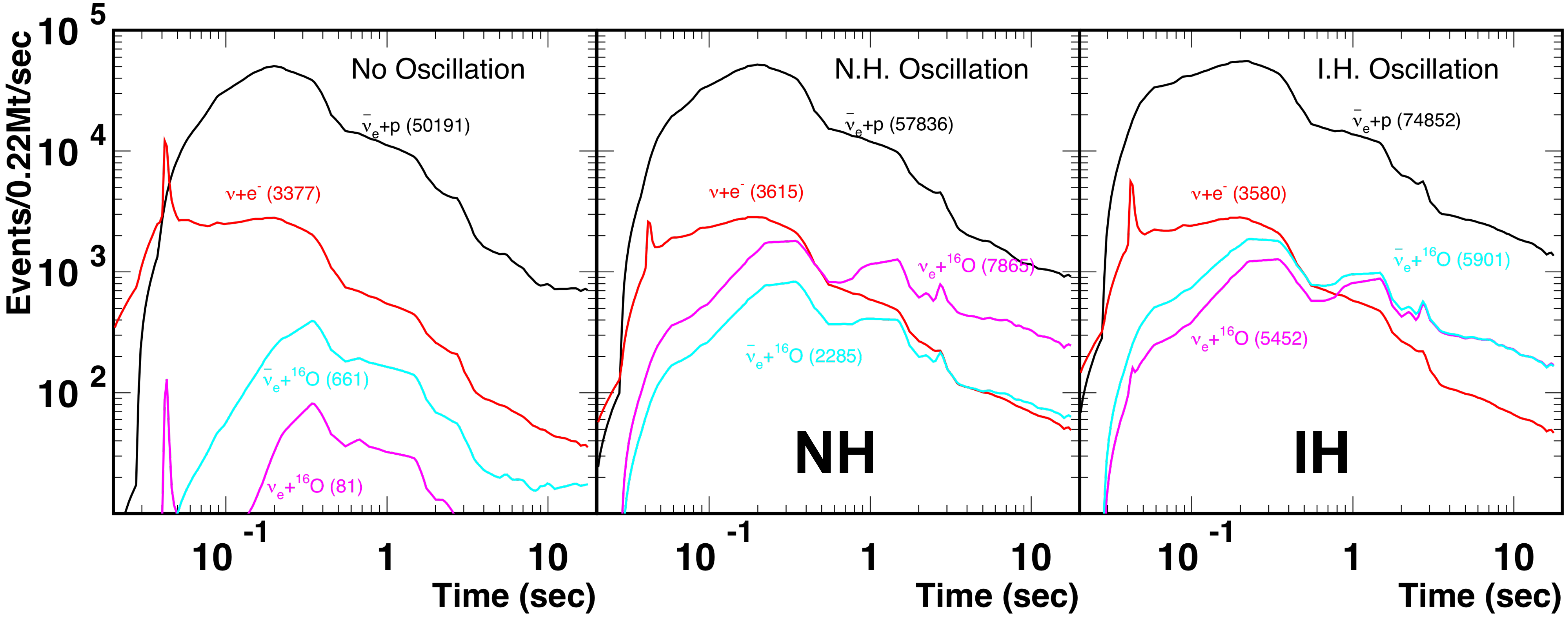
$$= |U_{\mathrm{e}1}|^2 \frac{\mathrm{d}N^0_{\bar{\nu}_\mathrm{e}}}{dE_{\bar{\nu}_\mathrm{e}}} + \left(1 - |U_{\mathrm{e}1}|^2\right) \frac{dN^0_{\nu_\mathrm{x}}}{dE_{\nu_\mathrm{x}}},$$

Inverted Hierarchy (IH)

$$\frac{\mathrm{d}N_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} = |U_{\mathrm{e}3}|^2 \frac{\mathrm{d}N^0_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} + \left(1 - |U_{\mathrm{e}3}|^2\right) \frac{\mathrm{d}N^0_{\nu_\mathrm{x}}}{\mathrm{d}E_{\nu_\mathrm{x}}} \simeq \frac{\mathrm{d}N^0_{\nu_\mathrm{x}}}{\mathrm{d}E_{\nu_\mathrm{x}}}$$



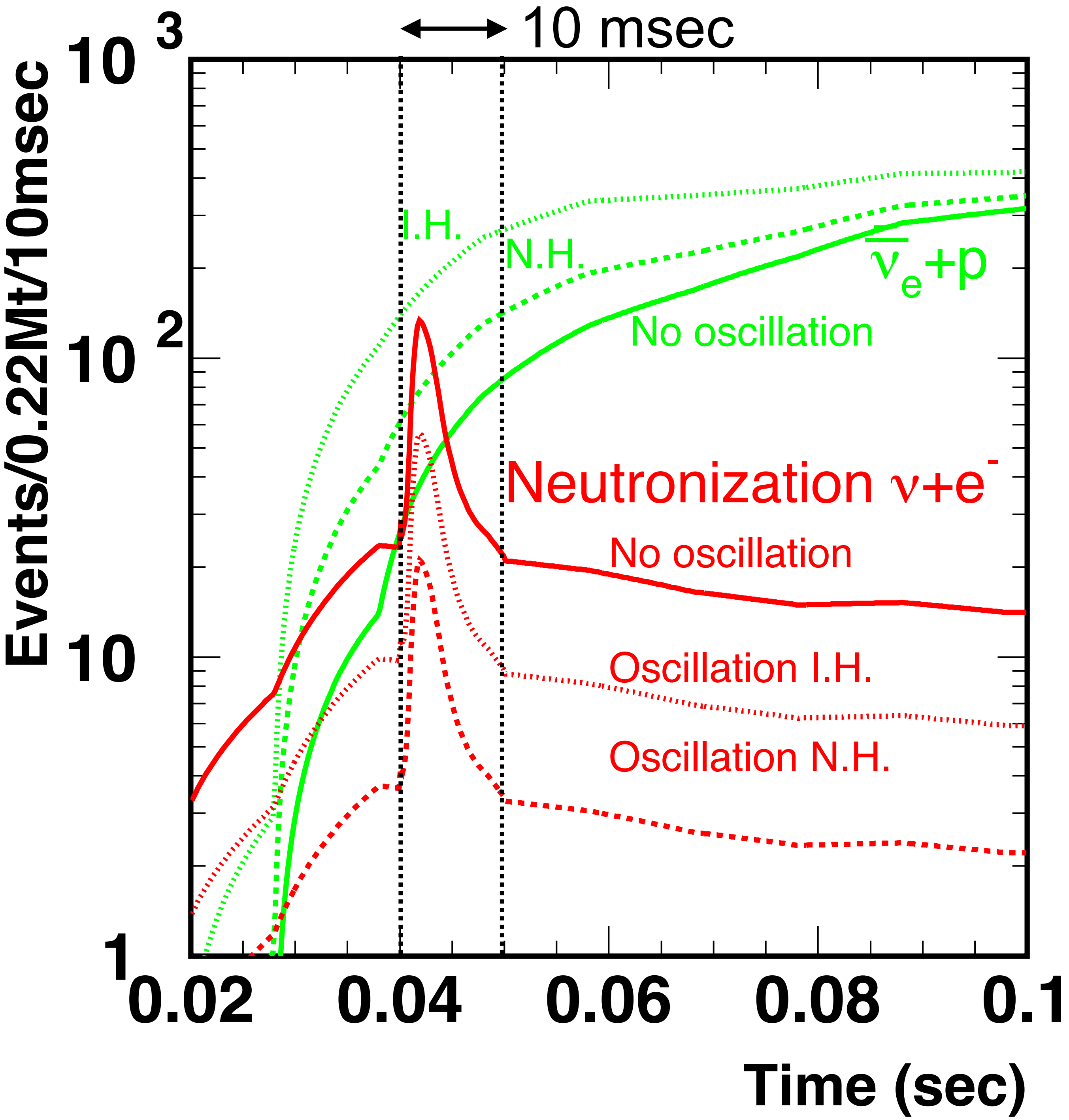
Expected time profile (Livermore simulation) of a supernova at 10 kpc



Neutralization Burst

Unique feature in ν-e scattering from neutralization burst

supernova at 10 kpc (Livermore simulation)



neutralization burst

ν_e emission for ~10 msec

shock wave propagation outward

↓

dissociation of nuclei in free nucleon which triggers $e^- p \rightarrow \nu_e n$

↓

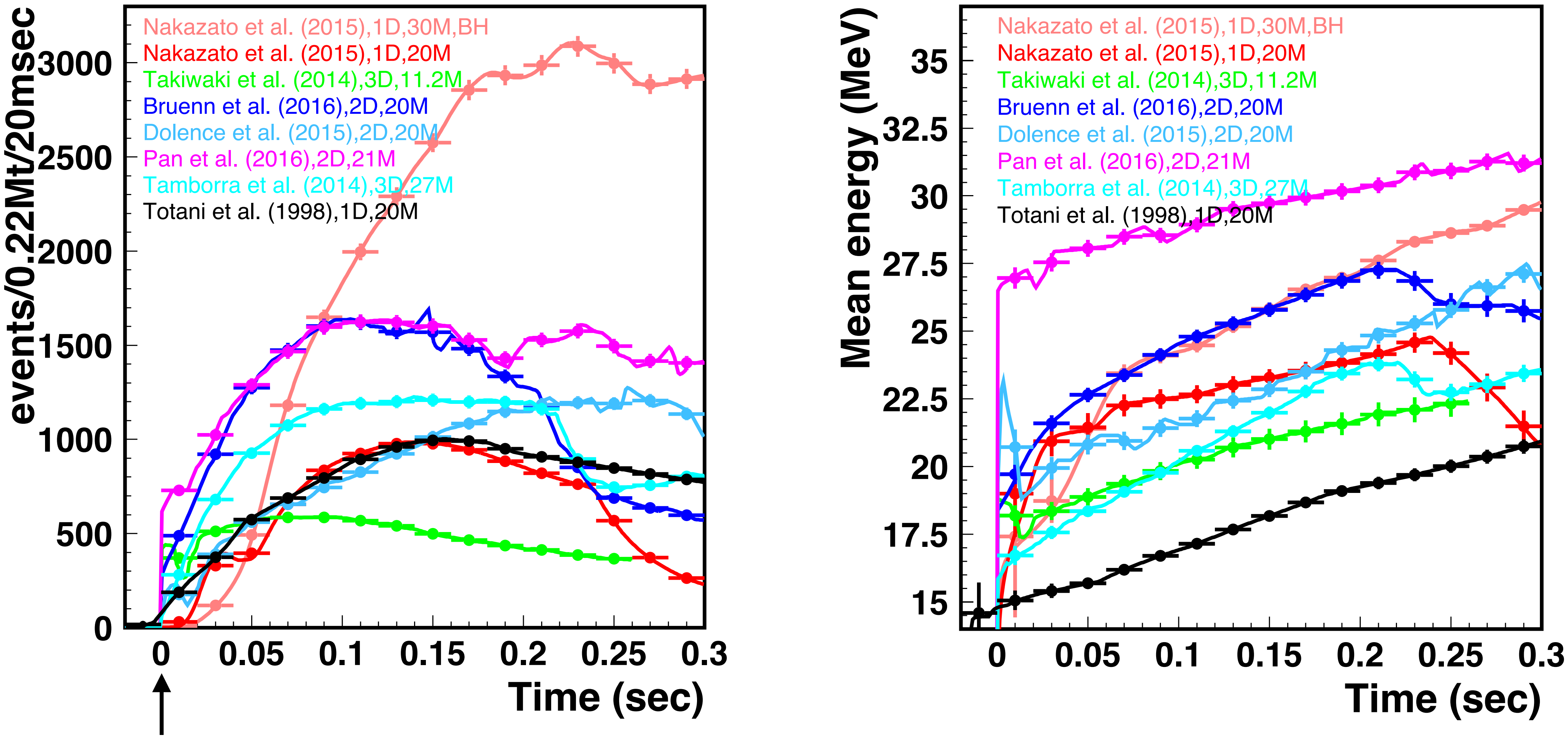
shock wave pass through neutrinosphere

Hyper-K will observe the neutralization burst

Explosion Mechanism

First 0.3 sec after the onset of supernova burst

inverse beta decay for supernova at 10 kpc



Time modulation of event rate

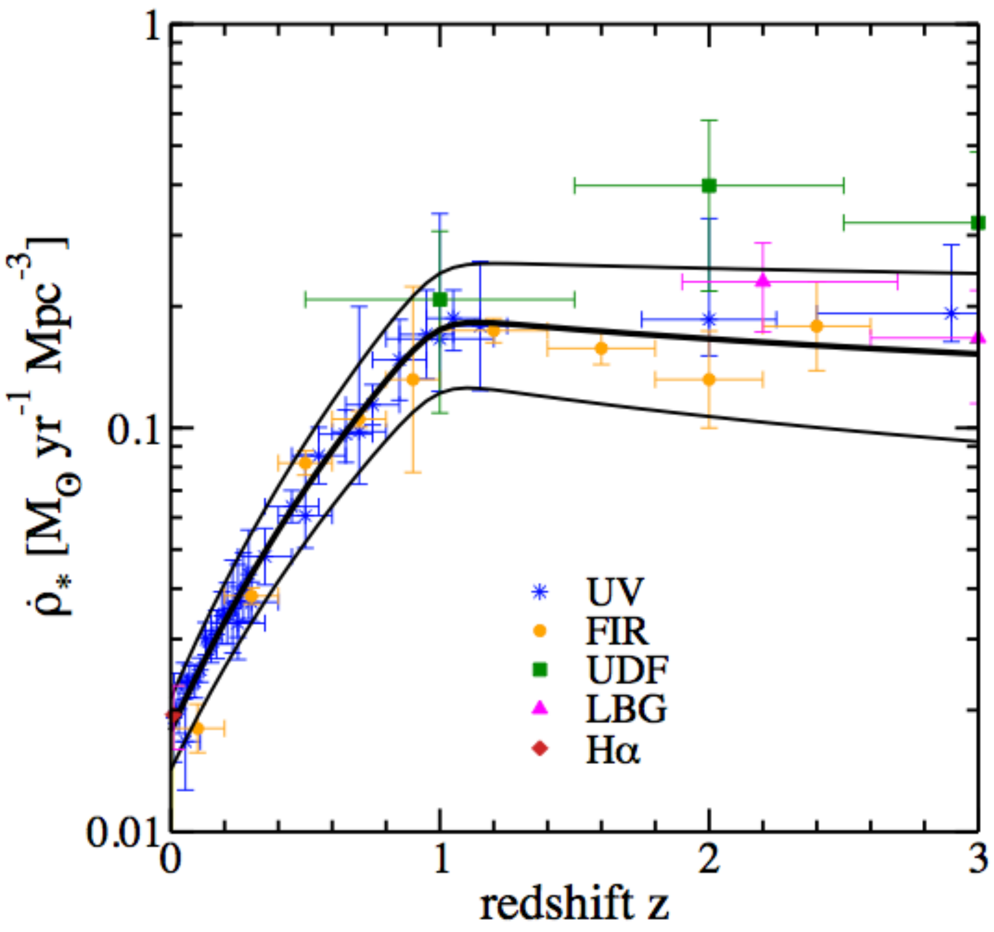
Time modulation of mean energy

onset time ~ 1 msec accuracy

Hyper-K will test the explosion mechanism, and investigate the core infall in conjunction with gravitational wave data

Supernova Relic Neutrino

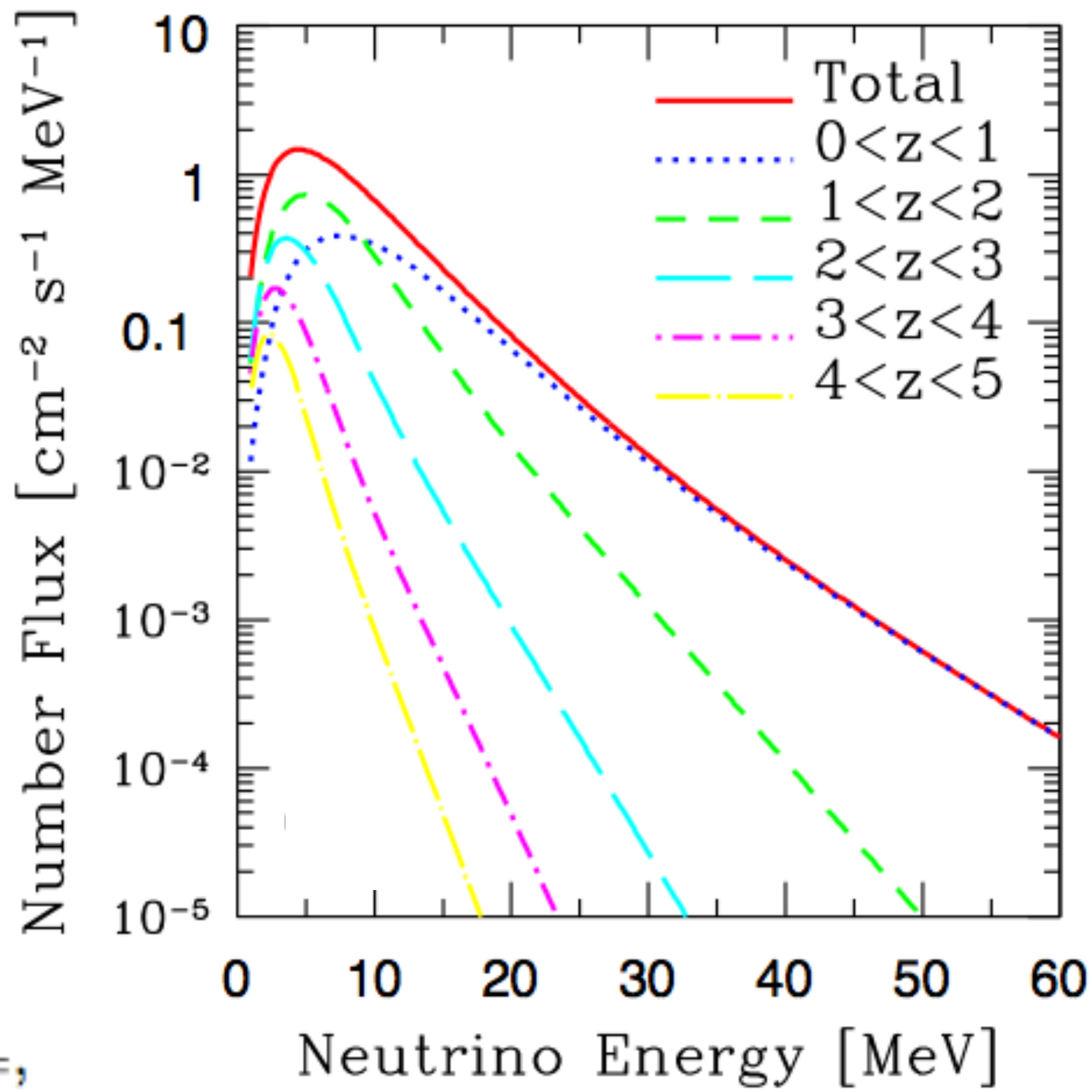
star formation rate
(= core-collapse rate)



supernova model

integrate over
past supernova
neutrinos

SRN energy spectrum
(including red shift)



S. Ando and K. Sato, New J. Phys. 6, 170 (2004)

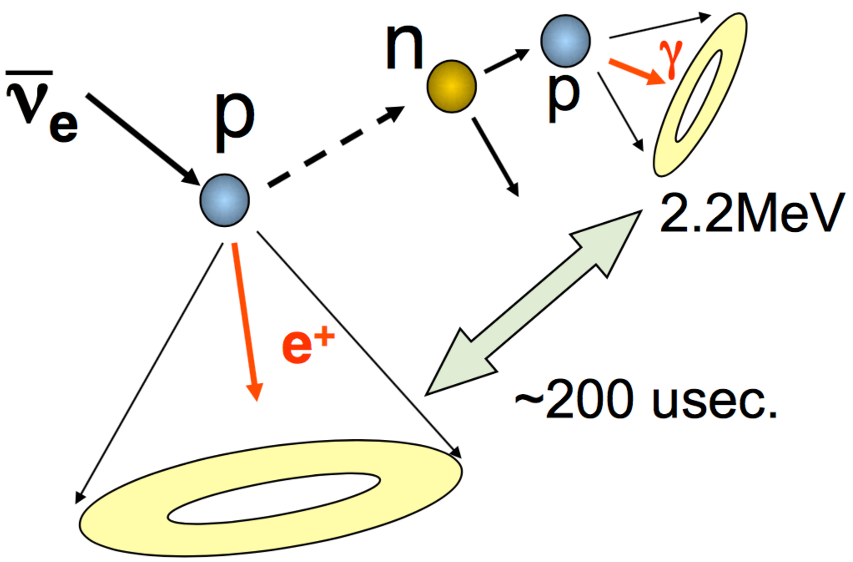
$$\frac{dF_\nu}{dE_\nu} = \frac{c}{H_0} \int_0^{z_{\max}} R_{\rm SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} \frac{dz}{\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda}},$$

Neutrinos from supernova explosions in the early universe to the present day

integrated flux ~10 cm^{-2}sec^{-1} **enough flux detectable in Hyper-K**

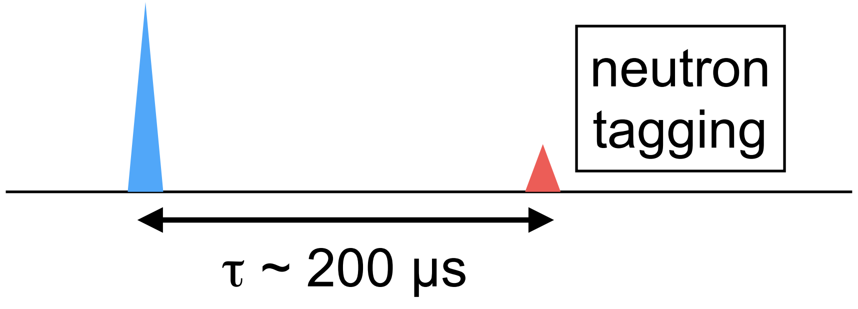
Hyper-K will measure the average flux and energy in supernovae

Signal Detection



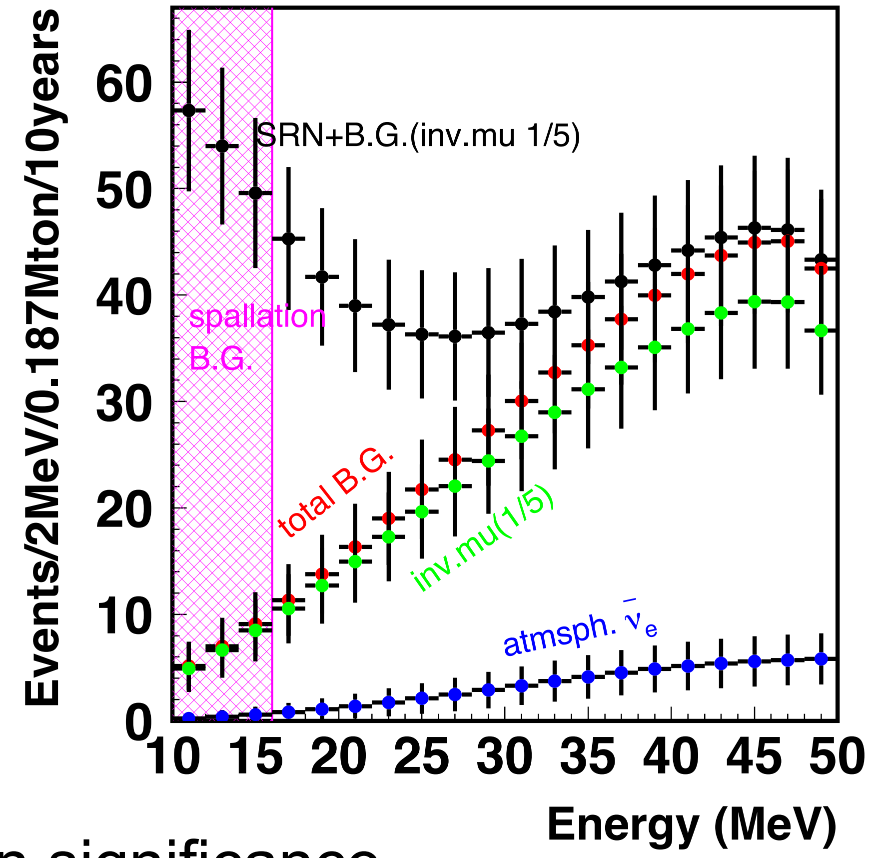
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

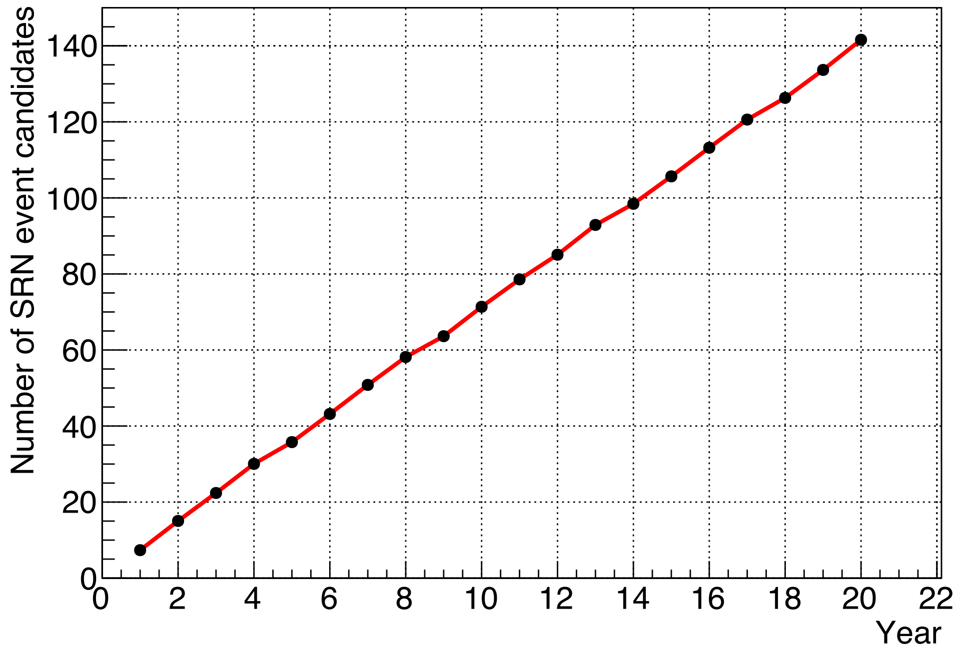


Neutron tagging effectively reduces the “invisible muon” background from atmospheric neutrinos → ×1/5

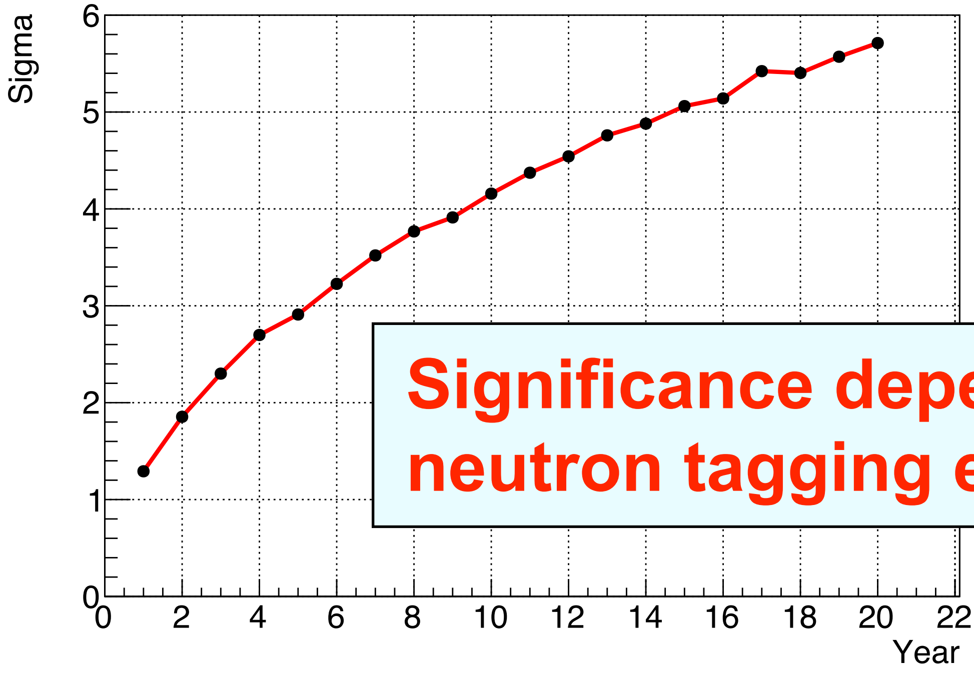
expected energy spectrum in Hyper-K (10 year)



number of SRN events



detection significance



Significance depends on neutron tagging efficiency

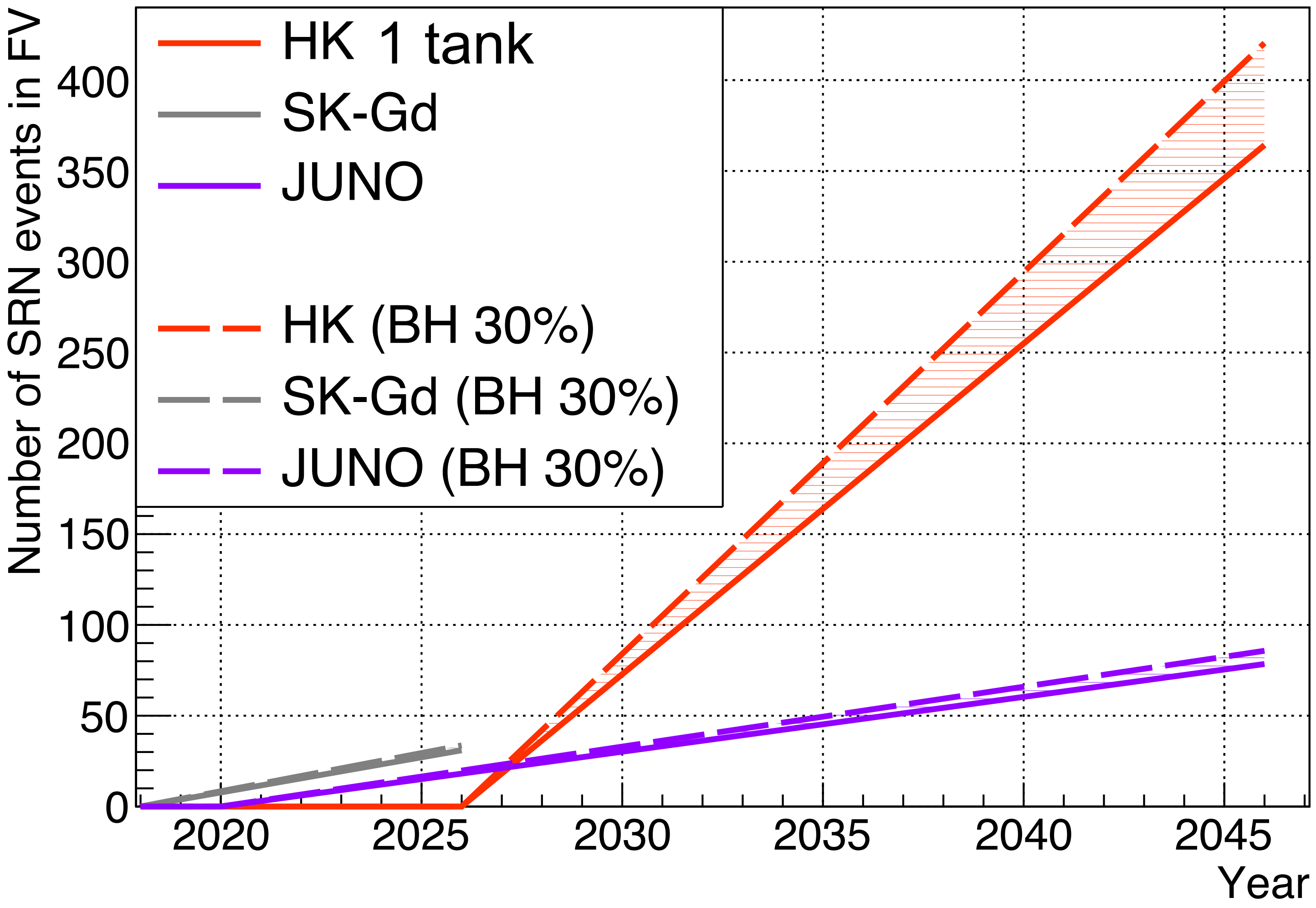
~70 events / 4σ detection significance in 10 years

Prospect

Relation with competing experiments to search for supernova relic neutrinos in the world

future projects : SK-Gd, JUNO, Hyper-K

number of SRN events in future projects



Conditions

SK-Gd (22.5 kton H_2O)

Low energy threshold : 10 MeV
neutron tagging by Gd-loading

Start data-taking in 2018

Aim for the first discovery

JUNO (17 kton LS)

Low energy threshold : 11 MeV

Start data-taking in 2020

Hyper-K (187 kton H_2O)

Energy threshold : 16 MeV

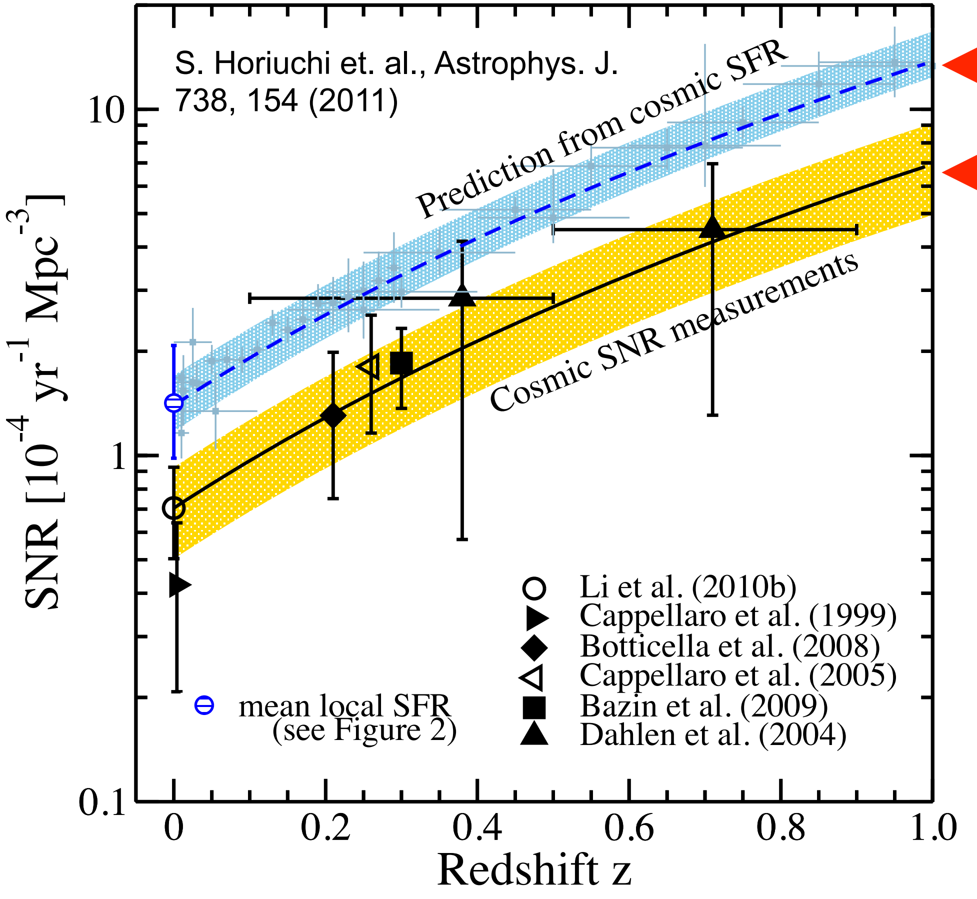
Start data-taking in 2026 → 2027

Aim for the precise flux and energy spectrum measurement

Hyper-K will be a leading experiment for supernova relic neutrinos

Star Formation History

supernova rate v.s. redshift



core-collapse rate predicted from star formation rate

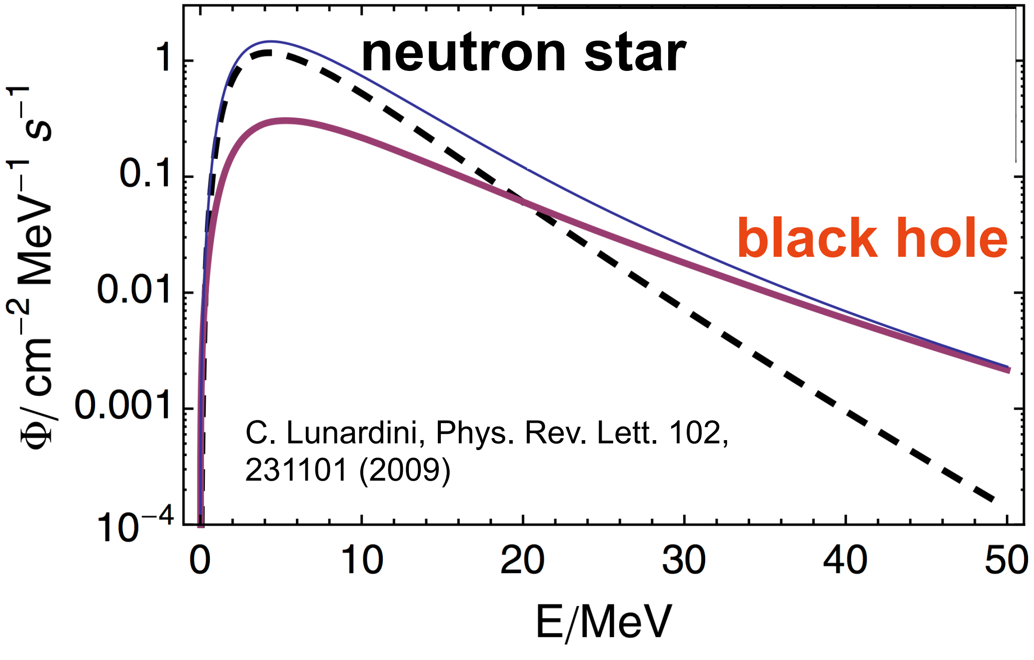
observed supernova rate visible supernovae

factor ~2 smaller than the expectation
from star formation rate

→ **invisible dim supernova or black hole formation?**

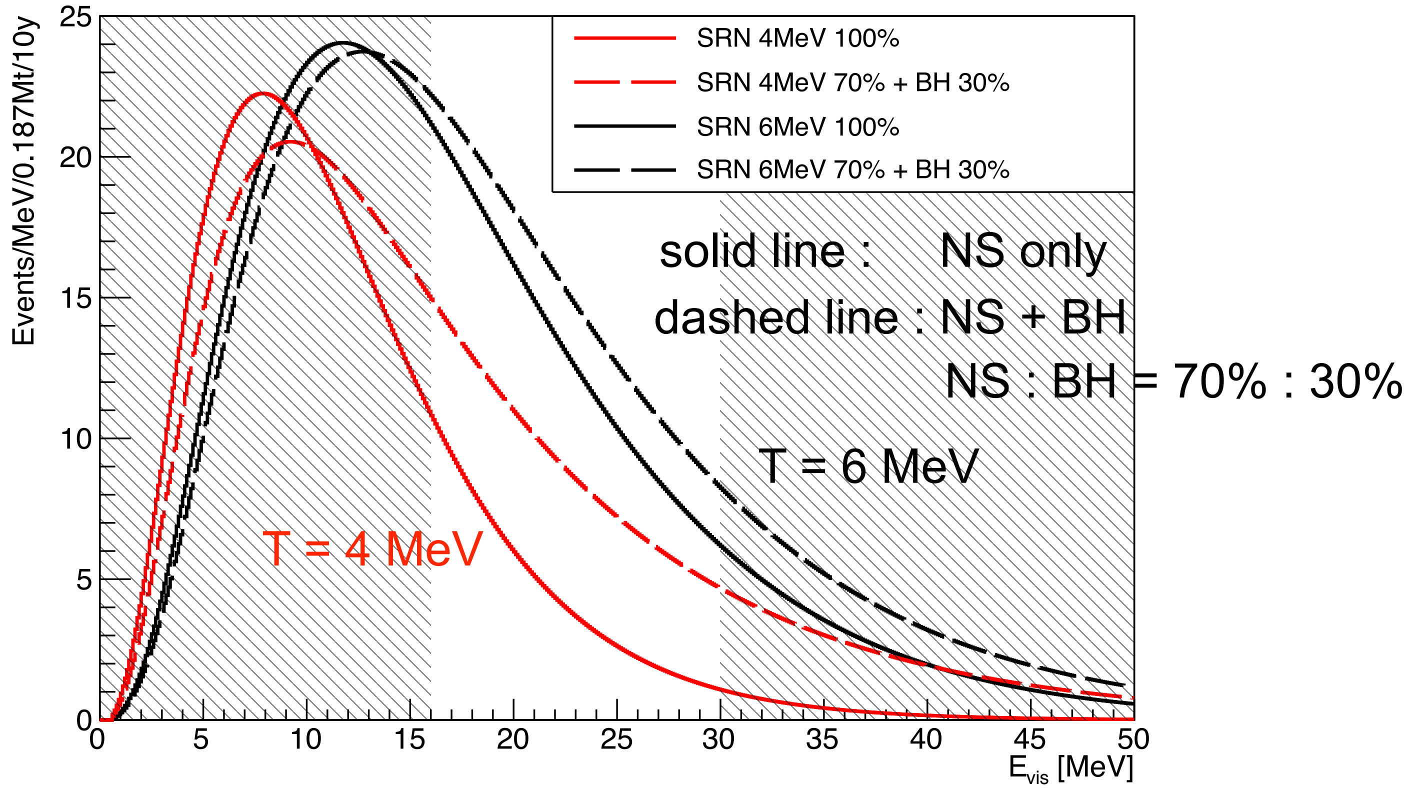
supernova explosions in massive stars (~30 solar mass)
result in **black hole formation, high E neutrino production**

neutrino flux



harder in black hole formation

expected energy spectrum in Hyper-K (10 year)

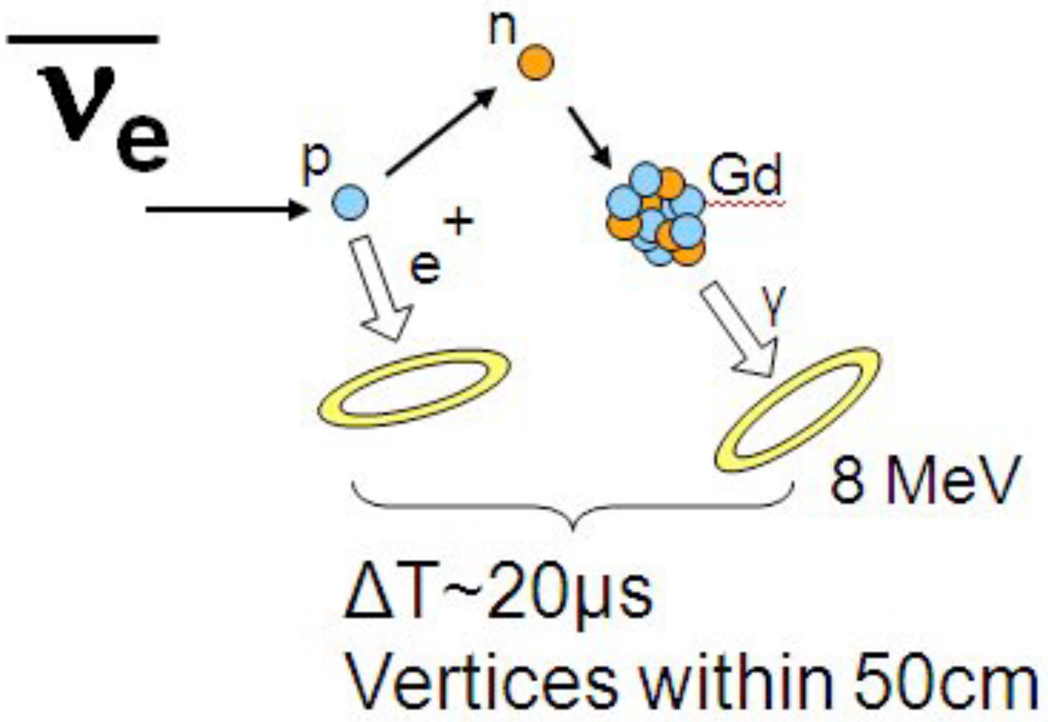


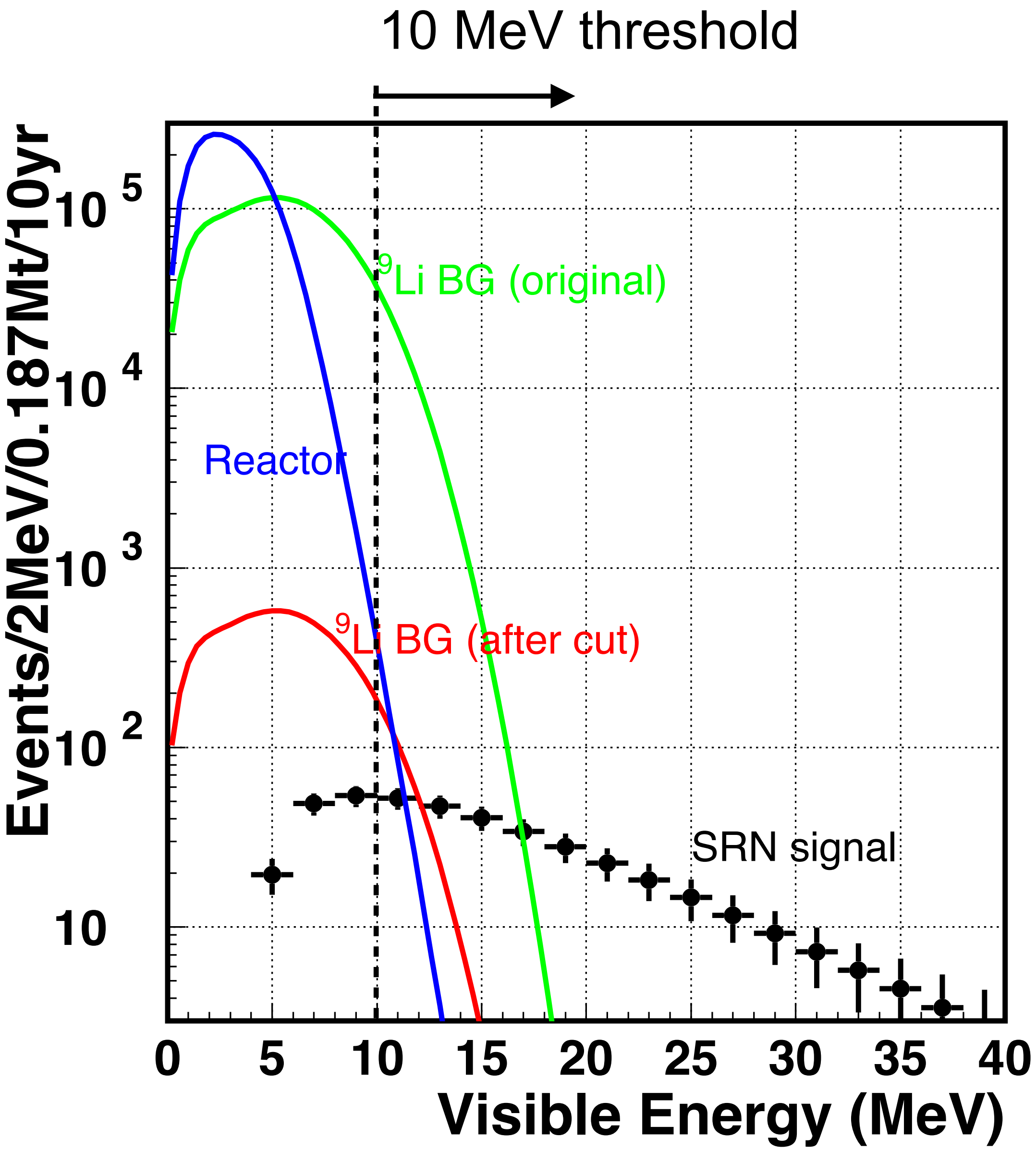
solid line : NS only
dashed line : NS + BH
NS : BH = 70% : 30%

History of black hole formation can be investigated

Hyper-K with Gd

Option to add Gd compound in Hyper-K for neutron tagging





effective tagging to reduce backgrounds

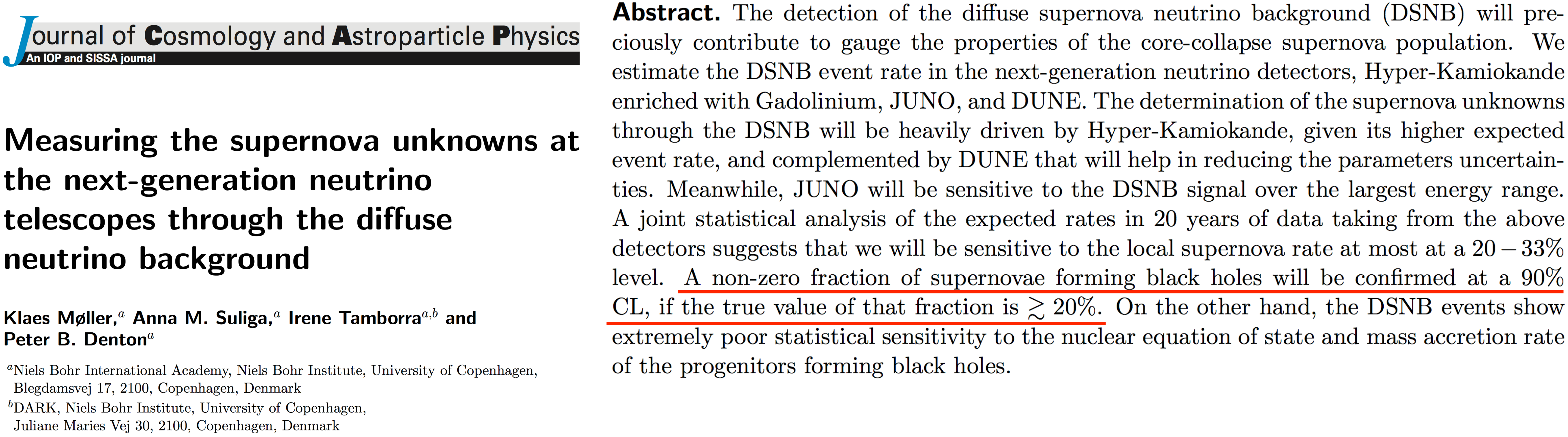
Energy threshold can be lowered from 16 MeV to 10 MeV

Explore the history of supernova burst back to red shift (z) ~ 1

Sensitivity Study for Hyper-K with Gd

recent sensitivity study for black hole formation rate using SRN spectra

K. Moller et al., J. Cosmo. Astro. Phys. 05, 066 (2018)



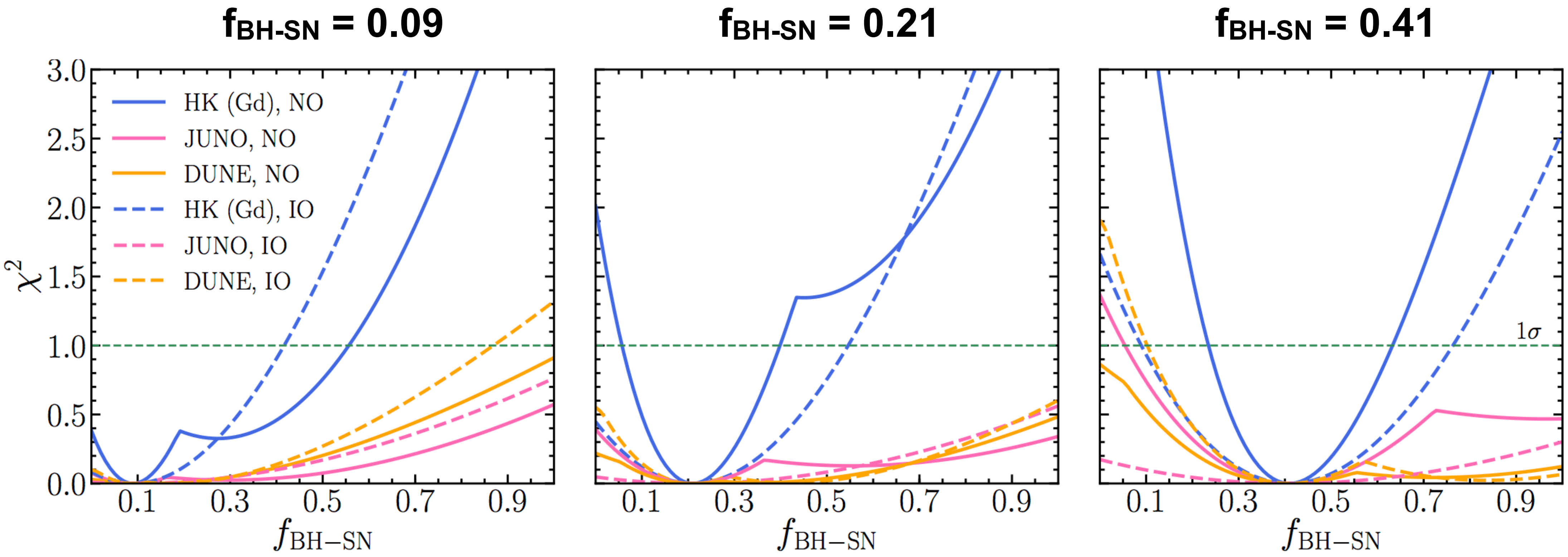
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Measuring the supernova unknowns at the next-generation neutrino telescopes through the diffuse neutrino background

Klaes Møller,[a] Anna M. Suliga,[a] Irene Tamborra[a,b] and Peter B. Denton[a]

[a]Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen,
Blegdamsvej 17, 2100, Copenhagen, Denmark
[b]DARK, Niels Bohr Institute, University of Copenhagen,
Juliane Maries Vej 30, 2100, Copenhagen, Denmark

Abstract. The detection of the diffuse supernova neutrino background (DSNB) will preciously contribute to gauge the properties of the core-collapse supernova population. We estimate the DSNB event rate in the next-generation neutrino detectors, Hyper-Kamiokande enriched with Gadolinium, JUNO, and DUNE. The determination of the supernova unknowns through the DSNB will be heavily driven by Hyper-Kamiokande, given its higher expected event rate, and complemented by DUNE that will help in reducing the parameters uncertainties. Meanwhile, JUNO will be sensitive to the DSNB signal over the largest energy range. A joint statistical analysis of the expected rates in 20 years of data taking from the above detectors suggests that we will be sensitive to the local supernova rate at most at a $20-33\%$ level. A non-zero fraction of supernovae forming black holes will be confirmed at a 90% CL, if the true value of that fraction is $\gtrsim 20\%$. On the other hand, the DSNB events show extremely poor statistical sensitivity to the nuclear equation of state and mass accretion rate of the progenitors forming black holes.



Summary

- Hyper-K will be a leading experiment in astroparticle physics research with the highest statistics and directional information

  Astroparticle physics target in Hyper-K

  - Matter effects in solar neutrinos will be confirmed
  - Neutrino flux modulation in the galactic supernova will reveal the supernova burst mechanism
  - History of black hole formation can be investigated by supernova relic neutrinos
- Various new technique for water Cherenkov detection will be required to enhance the low energy physics sensitivities
- It is time to finalize the detector design

Welcome new collaborators who join astroparticle physics research in Hyper-K!