21-Sep-2018 @TMEX2018WCP

SUPERNOVA PHYSICS WITH SK / SK-GD / HK

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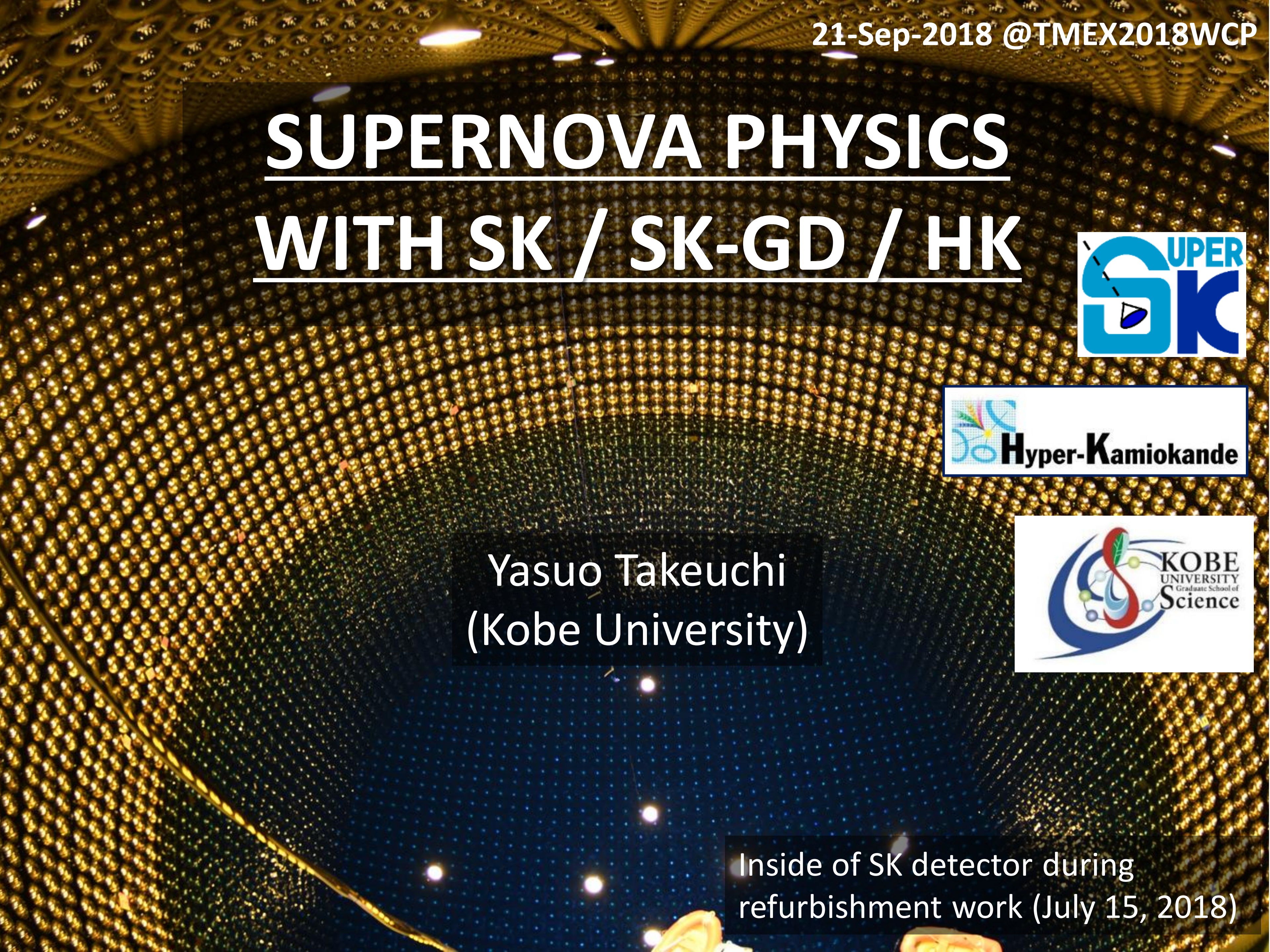
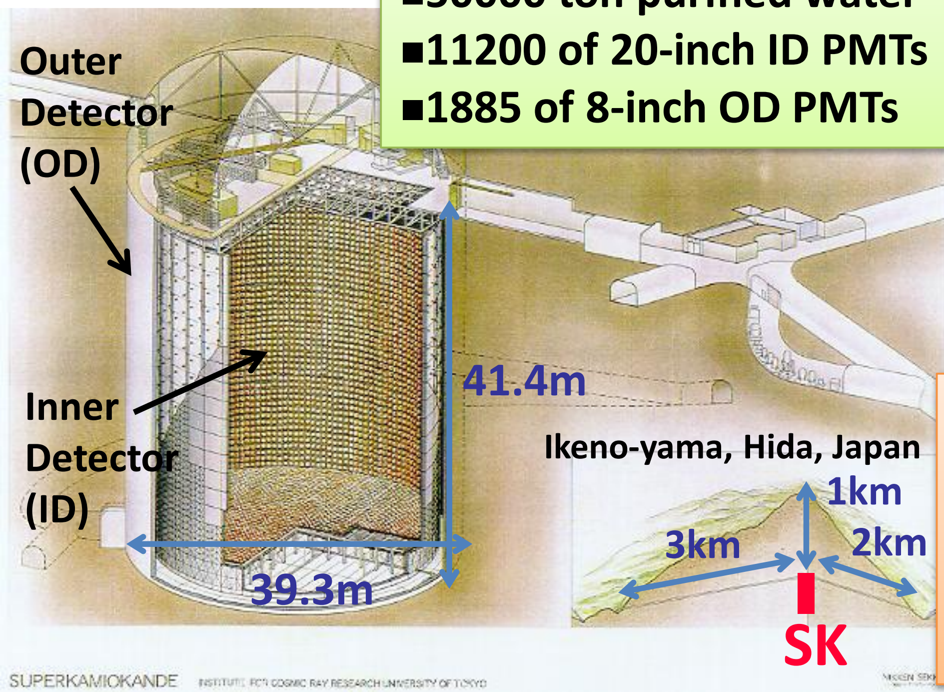


Inside of SK detector during refurbishment work (July 15, 2018)

Super-Kamiokande(SK) / SK-Gd



- 1 km underground in Japan
- 50000 ton purified water
- 11200 of 20-inch ID PMTs
- 1885 of 8-inch OD PMTs

Physics targets:

- Nucleon decay search
- Neutrino oscillation study
  - Solar ν, Atm. ν, Accel. ν (as T2K)
- Astrophysical neutrino search
  - Supernova (burst, relic), Dark matter (Galactic, Sun, Earth), GRB, etc.

Achievements:

- Discovery of atmospheric ν oscillation (1998)
- Discovery of solar ν oscillation w/ SNO (2001)
- Nobel prize in Physics (2015)
  - Discovery of ν oscillations

NOW

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19

SK-I	SK-II	SK-III	SK-IV	
11146 ID PMTs 4.5 MeV 1496 days	5182 ID PMTs 6.5 MeV 791 days	11129 ID PMTs 4.5 MeV 548 days	Electronics Upgrade 3.5 MeV 2860 days	Start upgrade for SK-Gd Neutron tagging with Gd

■ Analysis energy threshold (recoil electron kinetic energy) ■ Live time (for solar neutrino analysis)

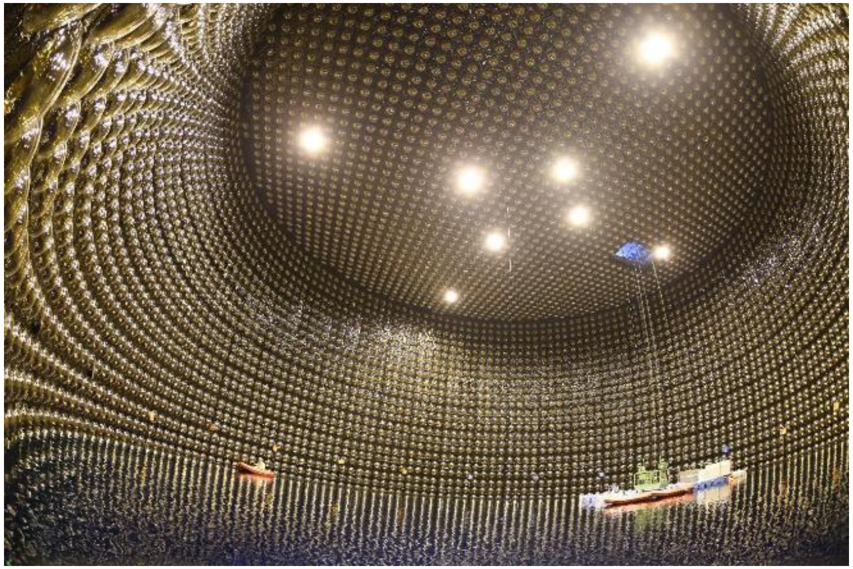
Next step: SK-Gd Phase

Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

Physics targets:
- Detect the world's first supernova relic neutrinos (SRN or DSNB)
- Improve pointing accuracy for supernova
- Early warning of nearby supernova from pre-burst signal
- Enhance ν or anti-ν discrimination in atm. ν & T2K analysis
- Reduce backgrounds in proton decay search

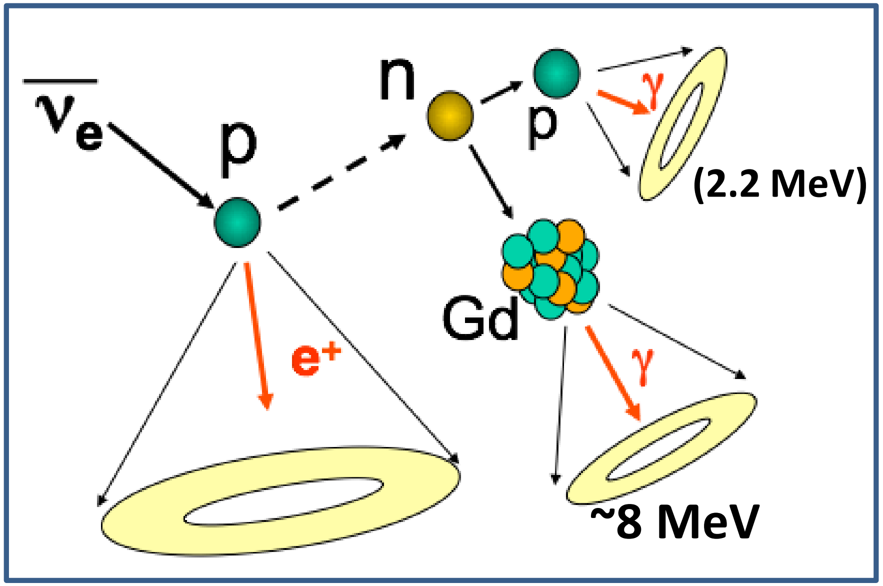
SK refurbishment is ongoing since June 2018
- Fix water leakage
- Replace dead PMTs
- Improve water piping in the SK detector

Current schedule:
- Jun. ~ Dec. 2018: refurbishment & water filling
- Jan. 2019 ~: pure water run
- 20XX(T_1): add 0.02% of $Gd_2(SO_4)_3$ (50% eff.)
- 20XX(T_2): add 0.2% of $Gd_2(SO_4)_3$ (90% eff.)
  - First possible T_1 is late 2019 (will be decided w/ T2K)



Inner detector during refurbishment
July 15, 2018 (around half water level)

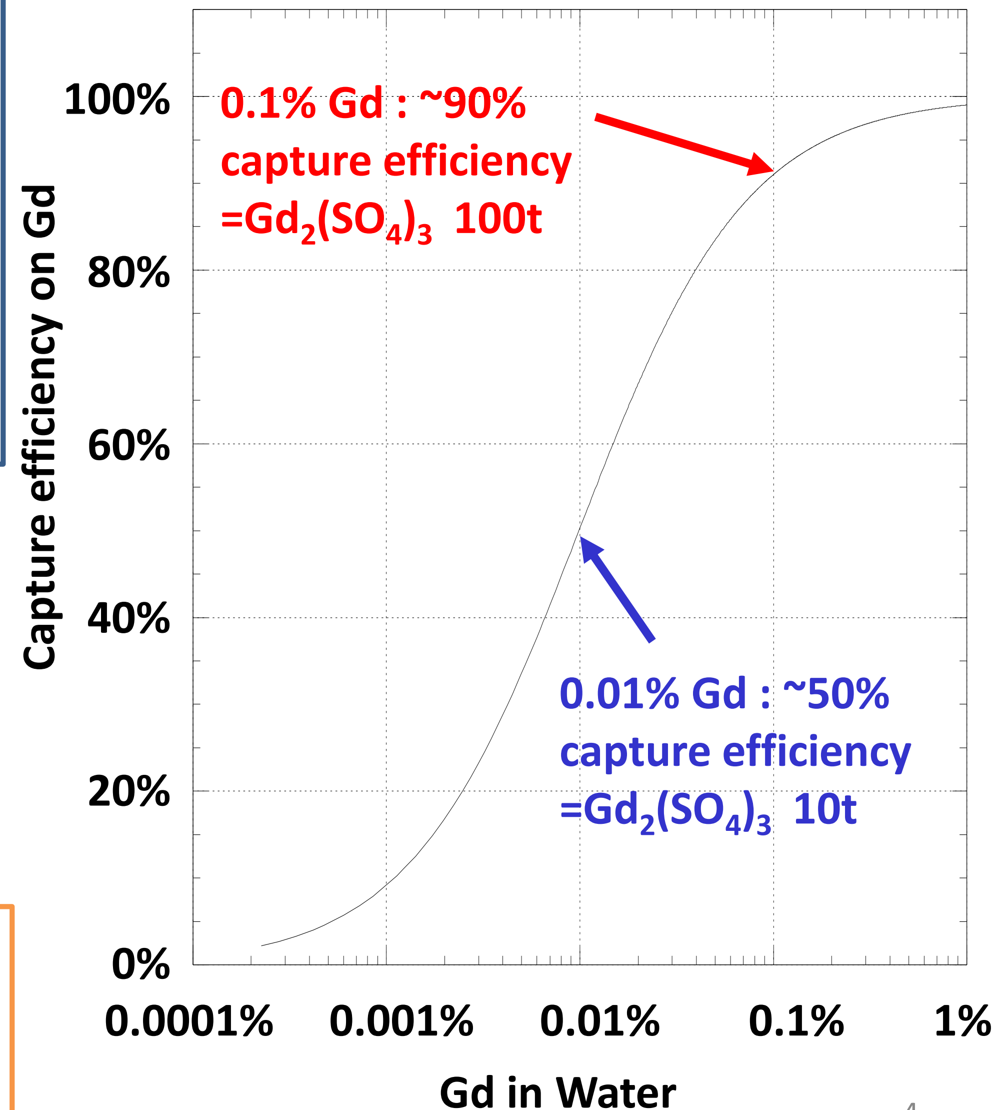
SK-Gd



- Reduce BG of $\overline{\nu}_e$ signal
  - Delayed coincidence
  - ΔT ~ 30 μs
  - Vertices within ~ 50 cm

- Note: Neutron tag with proton for limited events (> ~8 MeV, no OD hits) is possible in SK-IV due to electronics & DAQ upgrades.

Dissolve Gadolinium into SK
J. Beacom and M. Vagins, PRL93, 171101 (2004)

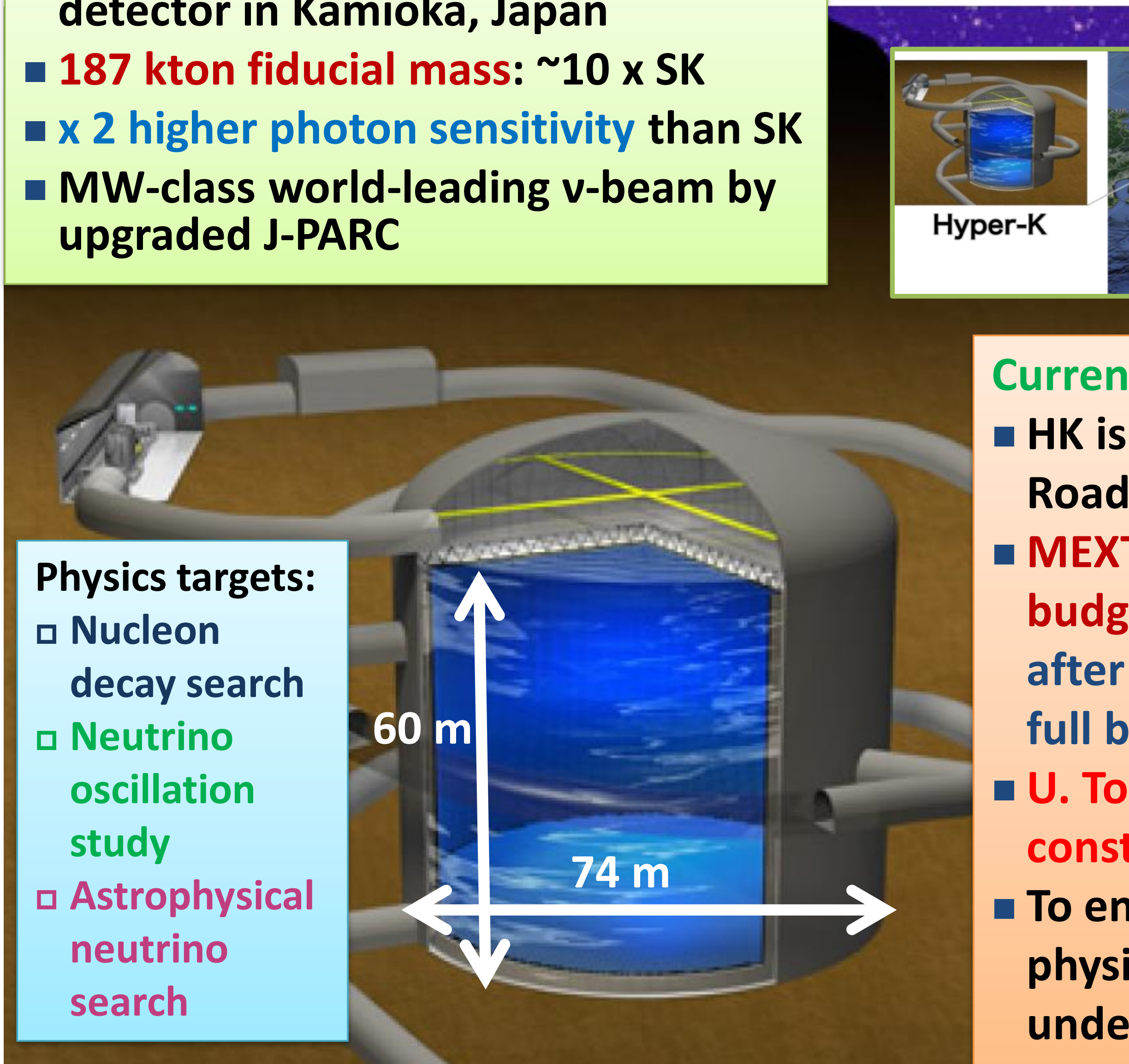


Hyper-Kamiokande (HK)

Hyper-Kamiokande

Design Report 2018: arXiv:1805.04163

- Gigantic neutrino and nucleon decay detector in Kamioka, Japan
- 187 kton fiducial mass: ~10 x SK
- x 2 higher photon sensitivity than SK
- MW-class world-leading ν-beam by upgraded J-PARC



Physics targets:
- Nucleon decay search
- Neutrino oscillation study
- Astrophysical neutrino search

Current status:
- HK is a priority project by MEXT's Roadmap 2017
- MEXT decided to request a seed budget of HK in FY2019. (In SK, after the one-year seed budget, full budget was allocated)
- U. Tokyo decided to start HK constriction in April 2020.
- To enhance neutrino oscillation physics, a 2nd detector in Korea is under study

Supernova burst neutrinos

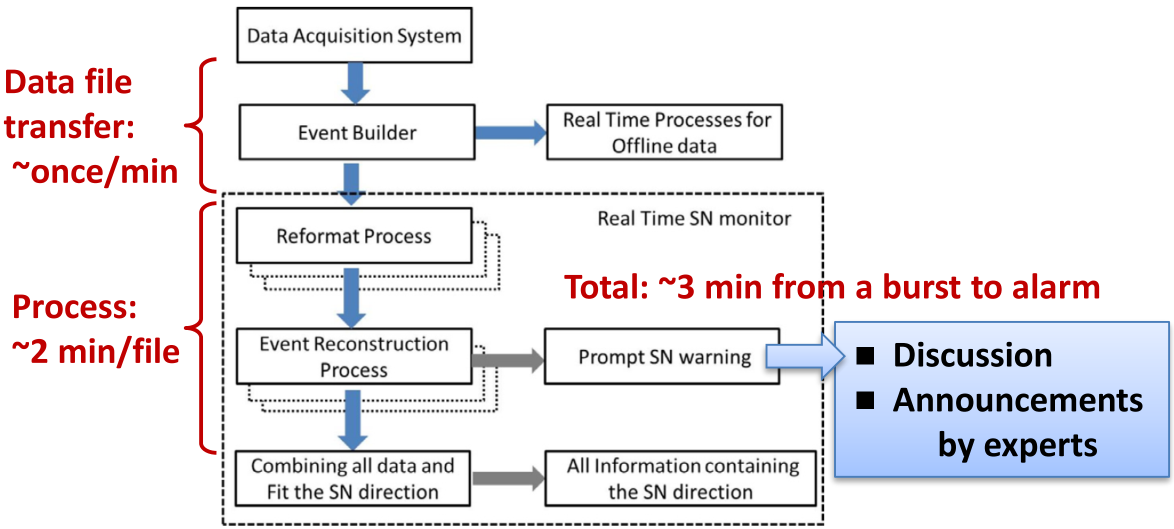
Supernova burst neutrinos

- SN burst ν was observed from SN1987A.
  - KAMIOKANDE-II (2.1 kton): 11 events / 13 sec.
  - @LMC (~50 kpc)
  - Consistent with standard core-collapse scenario.
    - Total energy in ν : 2.2×10^{53} erg. (Astropart. Phys. 31 (2009) 163-176)
  - To study explosion models in detail, more ν are necessary.
- A galactic SN burst (at 10 kpc) will provides:
  - SK / SK-Gd (32 kt): ~10,000 events ($E_{e,\ kinetic}$ > 4.5 MeV)
    HK (0.22 Mt): ~70,000 events
    - Livermore simulation (ApJ. 496, 216 (1998)), normal mass hierarchy (NH) neutrino oscillation
  - Nakazato simulation (ApJ. Suppl. 205:2 (2013)): ~50% less flux
  - Detail discussions of explosion models would be possible
- A real-time burst monitor is implemented at SK
  - burst alarm → discussion → send announcements (< 1hour)

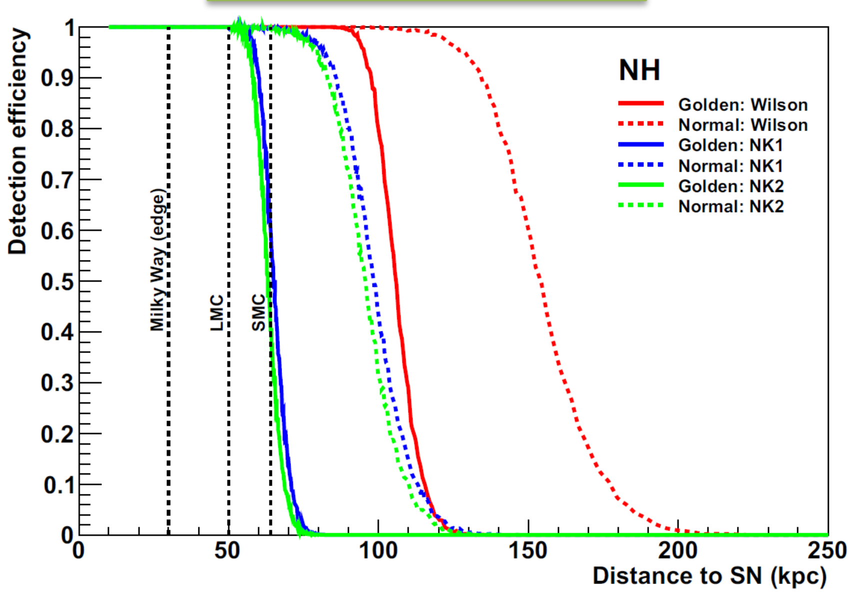
Real-time SN burst monitor at SK

Astropart. Phys. 81 (2016) 39-48

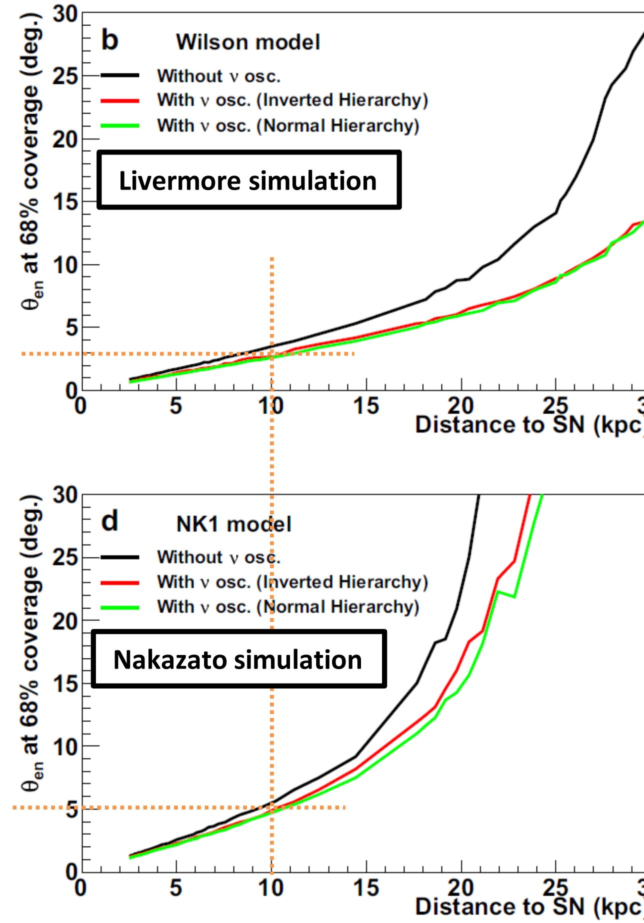
Flow diagram



Detection efficiency



Pointing accuracy



- Reviewed announcements: < ~1 hour
- ~100% detection for a galactic SN
- Pointing accuracy: 3~5 degree at 10 kpc

Expected supernova burst ν at HK:1

Design Report 2018: arXiv:1805.04163

- **Precise measurement of time & energy profile is important**
  → Dynamics of SN central engine, explosion mechanism, neutron star / black hole (BH) formation, …

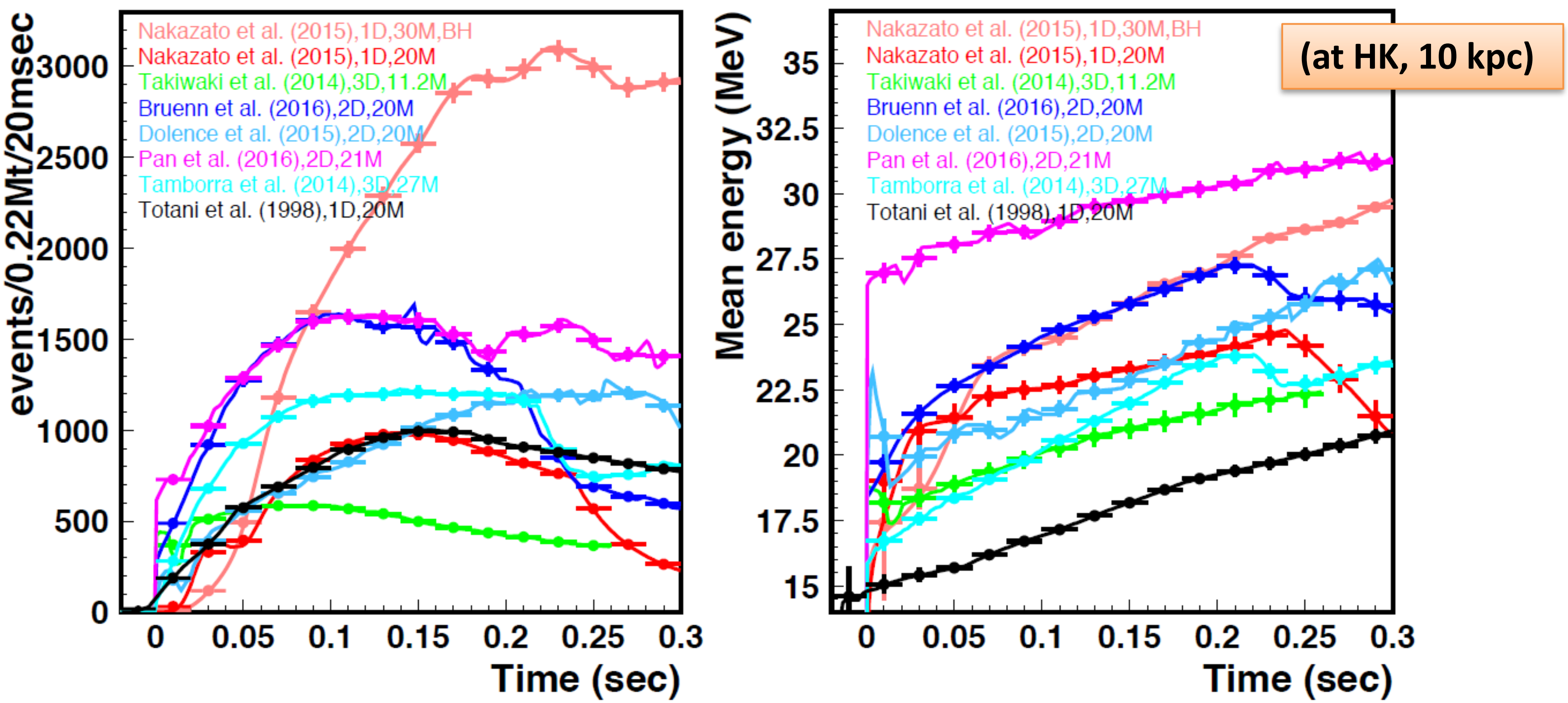
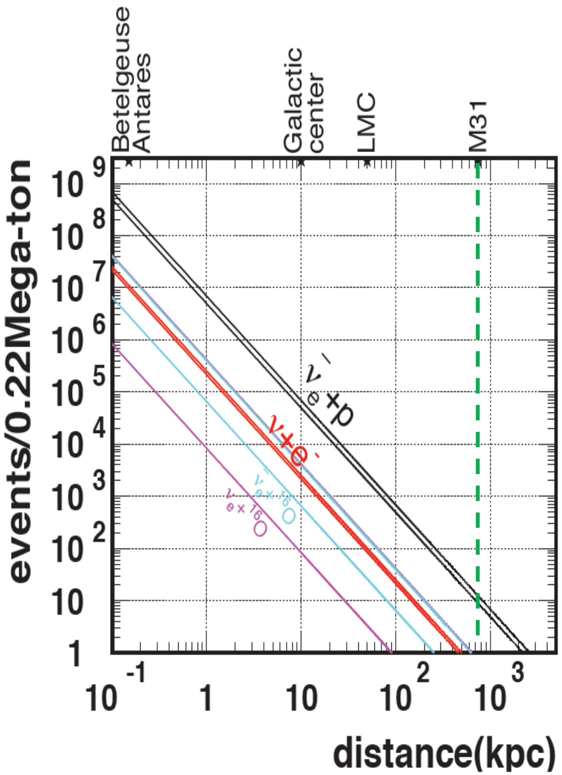


FIG. 181. Time profiles of the observed inverse beta decay event rate (left) and mean energy of these events, predicted by supernova simulations [250, 253–258] for the first 0.3 seconds after the onset of a 10 kpc distant burst with Hyper-K 1 tank.

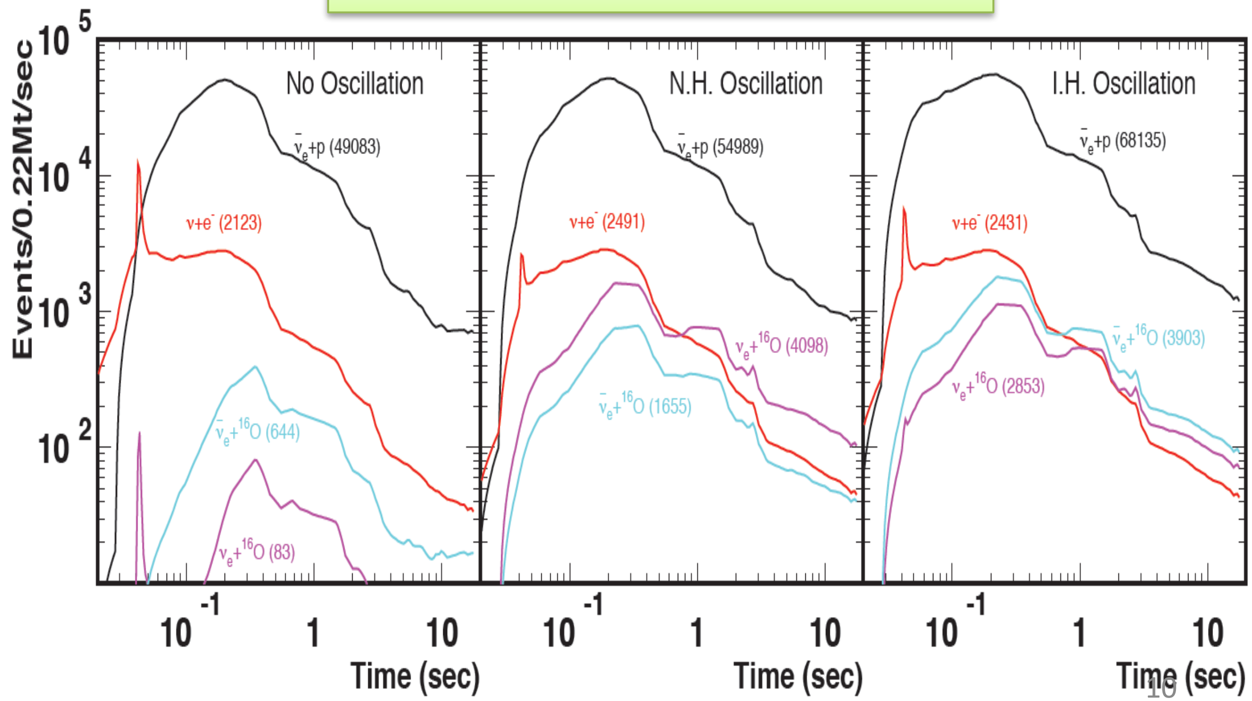
Expected supernova burst ν at HK:2

Design Report 2018: arXiv:1805.04163

- 52-79 k events / SN at 10 kpc (in 0.22 Mt)
  - ~10 events / SN in Andromeda galaxy (M31)
- Time profile would depend on ν oscillation and ν mass hierarchy, however the actual ν behavior during SN burst is not obvious due to possible other effects (matter effect, collective effect (PRL97, 241101 (2006)), …)
  - Cf. Livermore simulation (ApJ. 496, 216 (1998))



Time profile and ν mass hierarchy

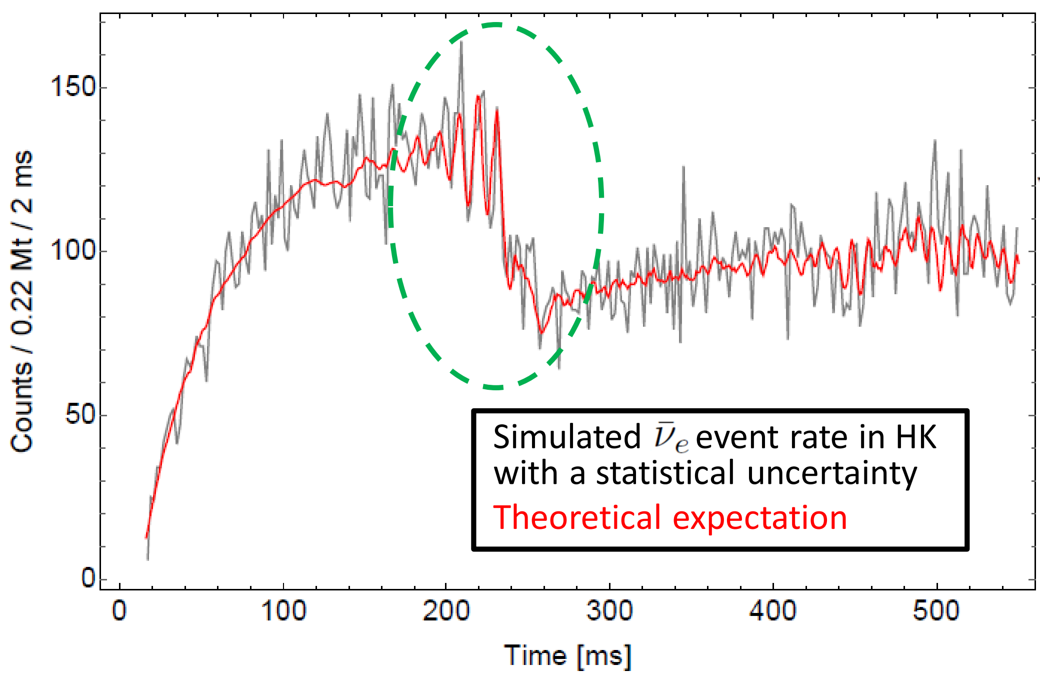


Expected supernova burst ν at HK:3

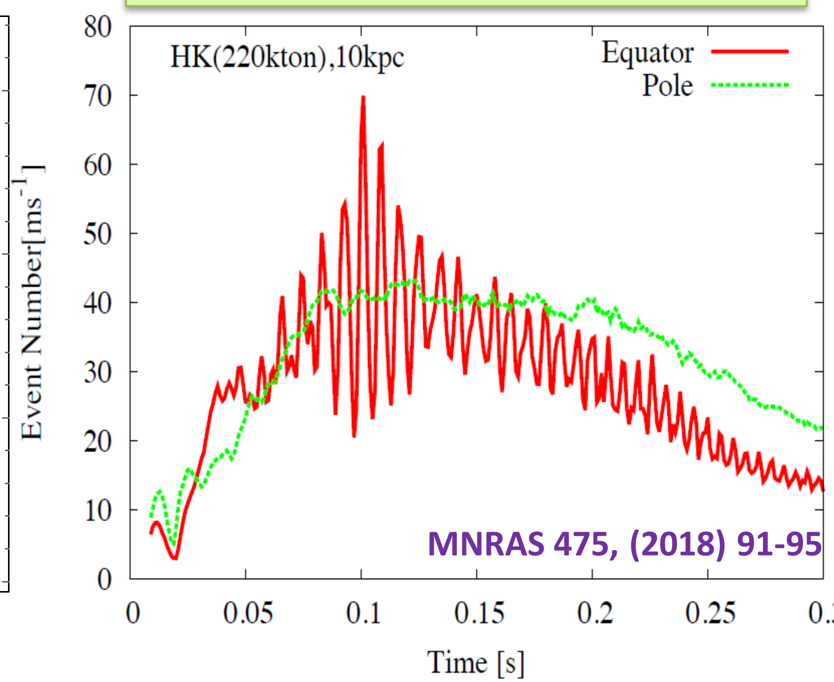
Design Report 2018: arXiv:1805.04163

- Detection rate modulations could be observed
  - ~3% level SASI (Standing Accretion Shock Instability) could be detected from 90% of a galactic SN (PRL 111, 121104 (2013))
  - A rotating supernova explosion model (MNRAS 475, (2018) 91-95)

Detection rate modulation induced by SASI



Detection rate modulation induced by a rotating model



Supernova burst ν: Multi messenger performance

- **Multi messenger performance:**
  - **HK: ~1 degree (opening angle) determination of direction of SN at 10 kpc**

MNRAS 461 (2016) 3296-3313

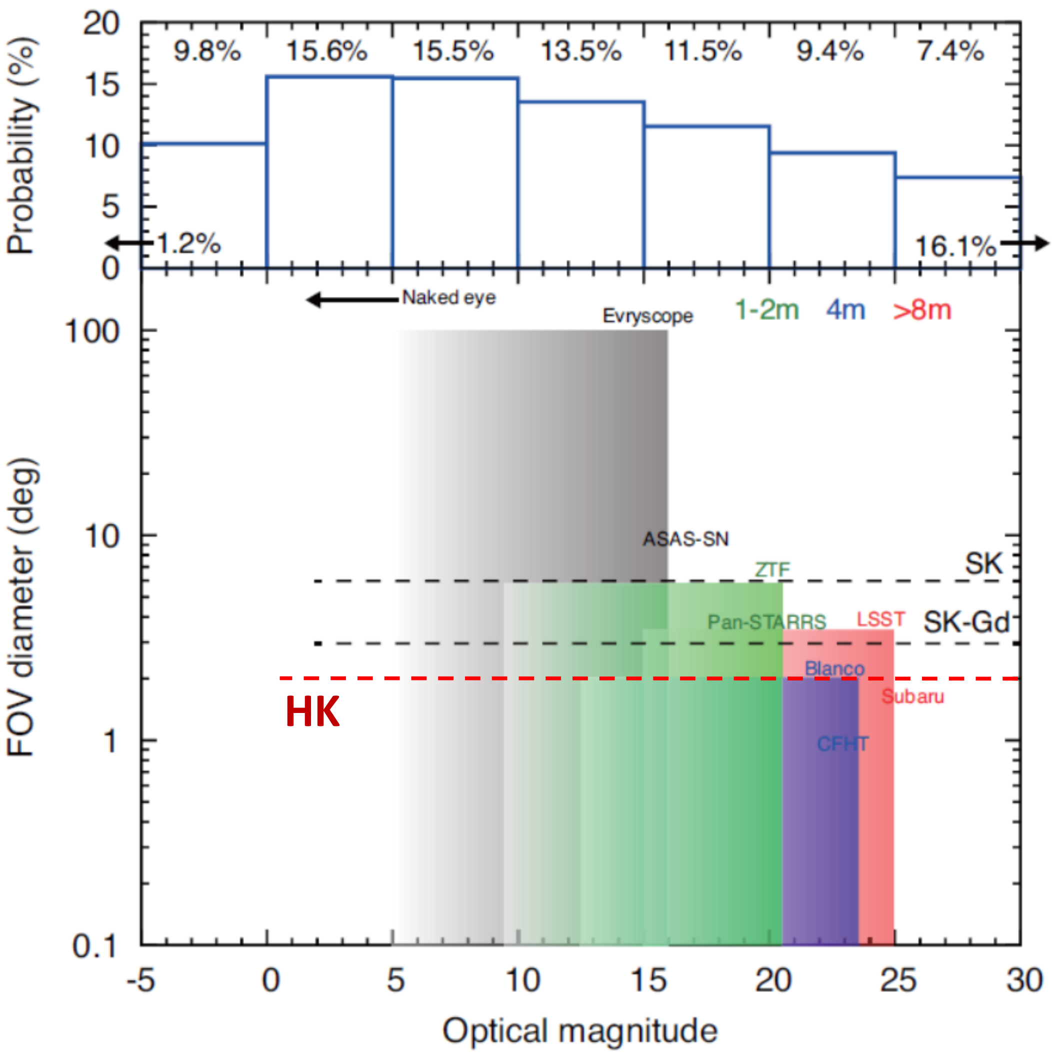
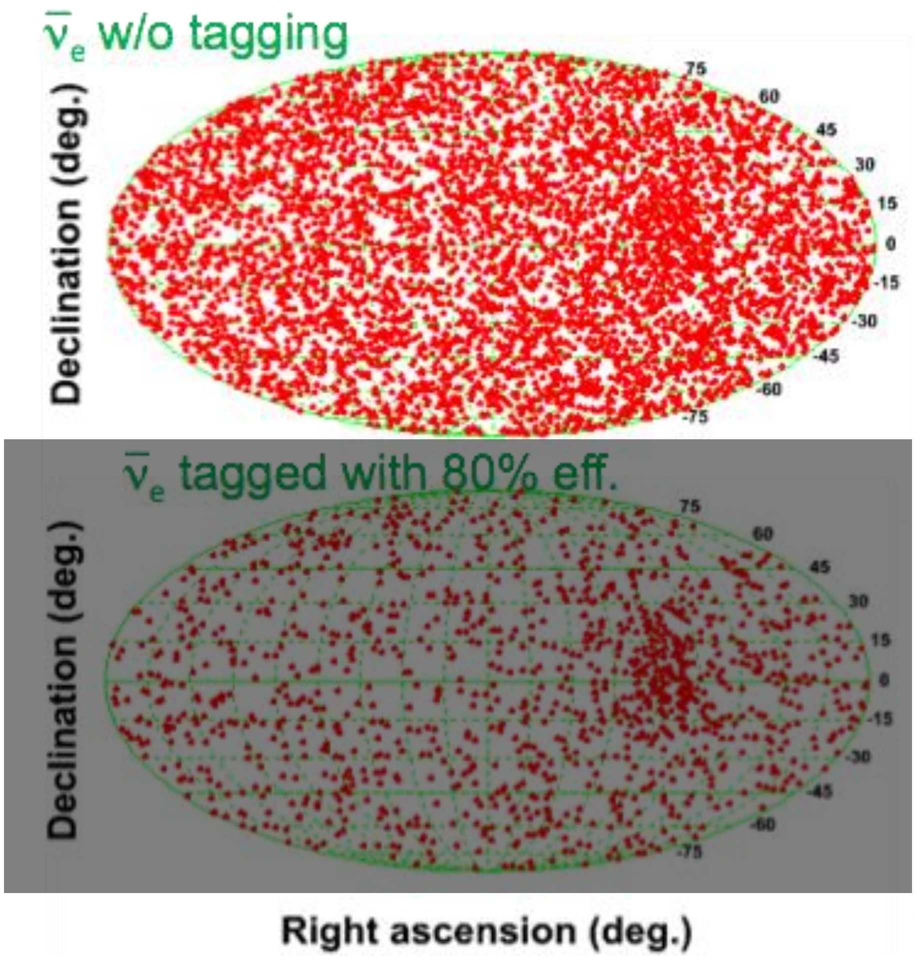


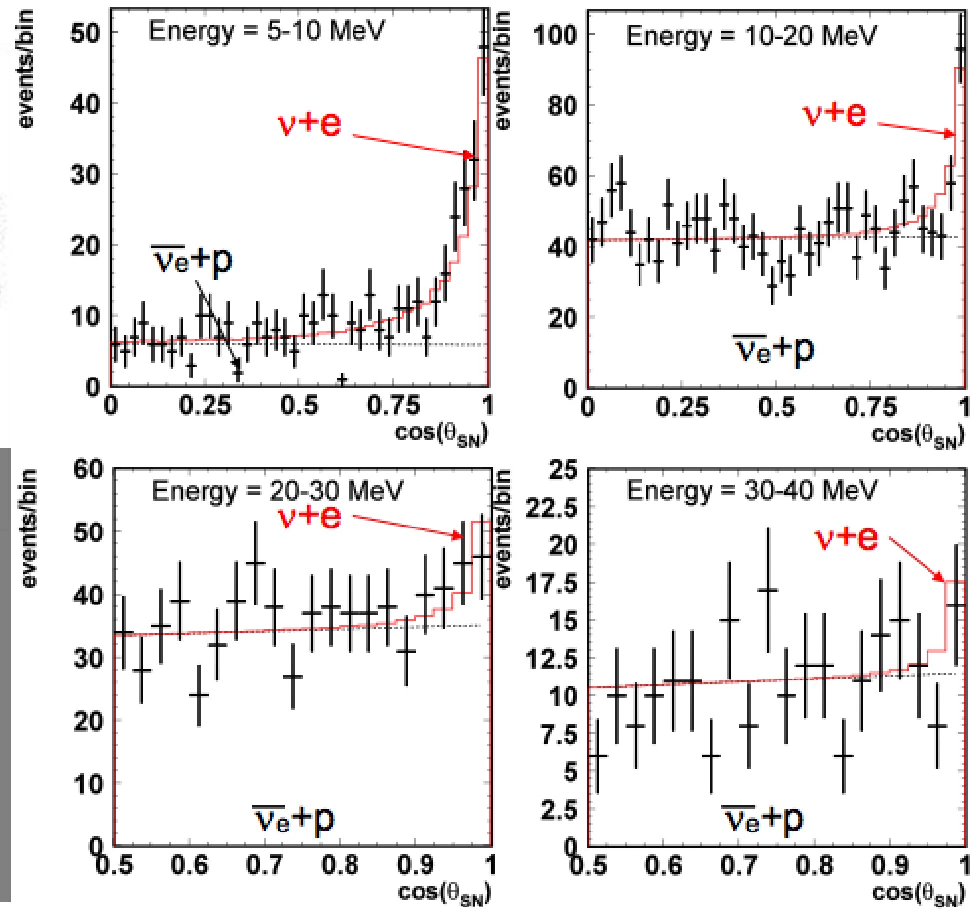
Figure 9. Detection prospects and strategies of the plateau signal of Galactic CCSNe. The top histogram shows the dust-attenuated plateau magnitudes with their respective percentage of the total CCSNe; 1.2% and 24.5% fall beyond the magnitude range shown. The optical magnitudes of the SBO emission are also similar to the plateau magnitudes (the SBO emission is likely to be fainter by about 1 mag, Tominaga et al. 2011). The bottom panel shows the typical magnitude ranges and fields of view (FOV) of various optical telescopes: ASAS-SN, Blanco, CFHT, Evryscope, LSST, Pan-STARRS, Subaru, and ZTF (shaded rectangles), as well as the naked eye (left-pointing arrow). See text for details. The error circle in CCSN pointing from the CCSN neutrino burst, for Super-K with and without Gadolinium, are represented by the horizontal dashed lines and labeled.

Better angular resolution would help optical telescope's multi messenger observations

SK-Gd: Supernova burst neutrinos



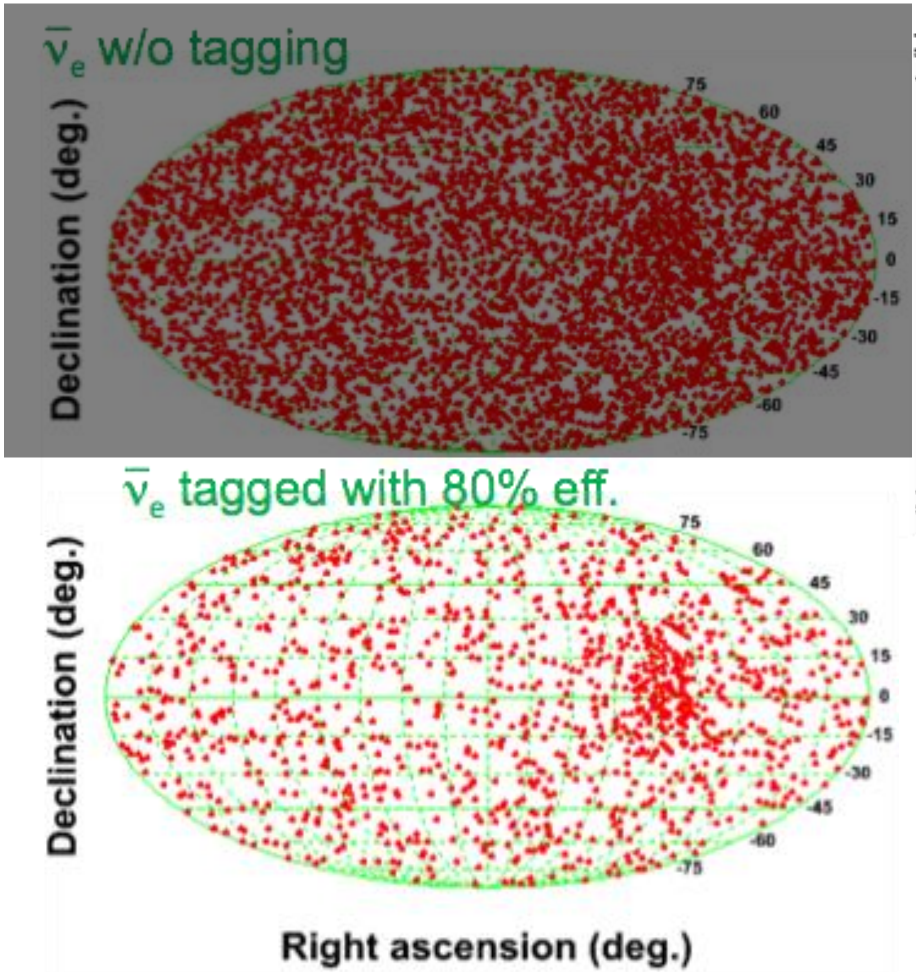
Without neutron tagging

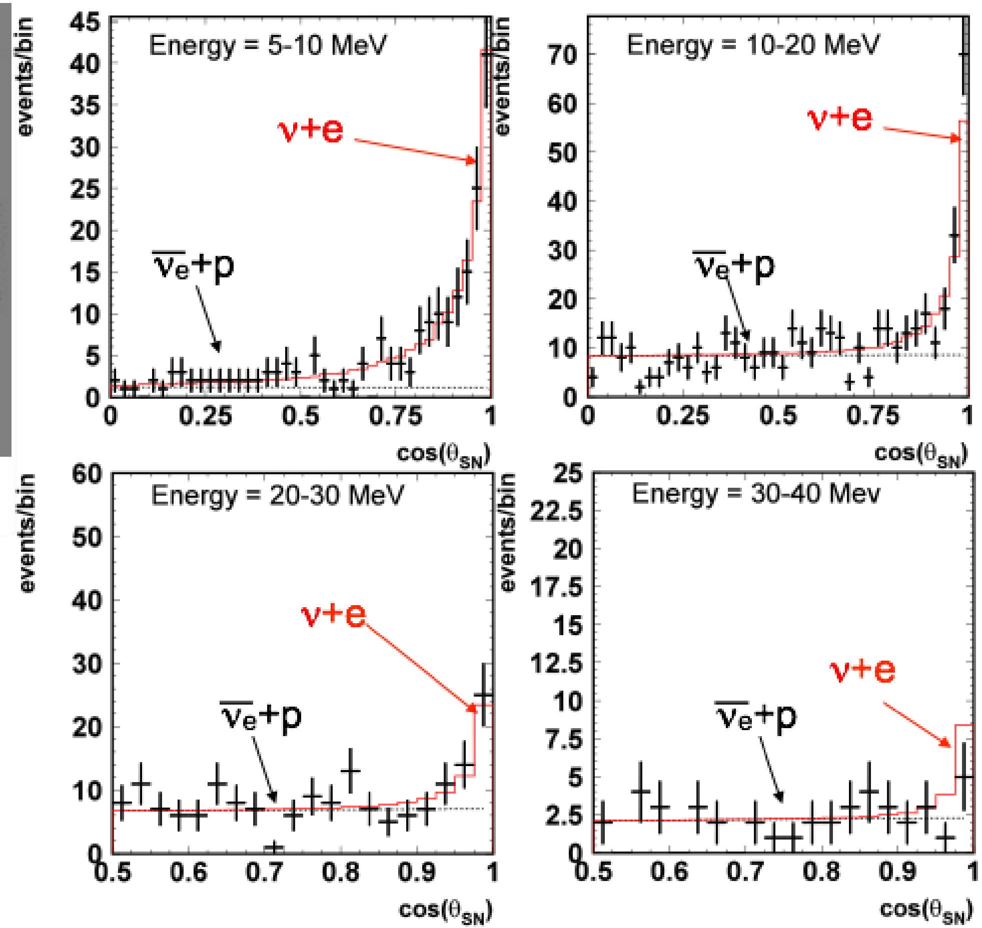


4~5 degree resolution @10kpc

SK-Gd: Supernova burst neutrinos

With neutron tagging (to remove $\bar{\nu}_e$+p)



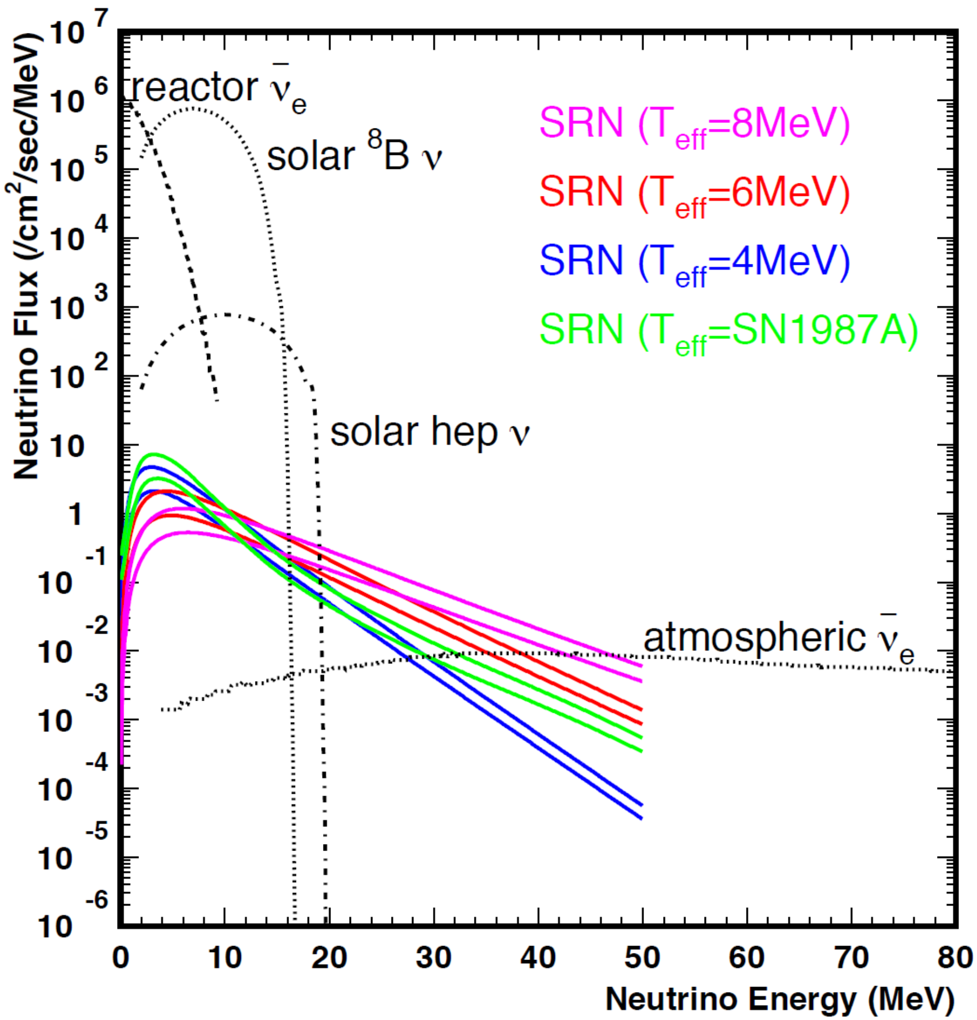


~3 degree resolution @10kpc

Supernova relic neutrinos

Supernova relic neutrinos

HK Design Report 2018: arXiv:1805.04163



- **Supernova relic neutrino (SRN) or Diffuse supernova neutrino background (DSNB)**
- **Accumulation of past SN bursts**
- **Spectrum depends on the time of the burst**
  - **Early time → larger red shift → low temperature**
  - **History of star/Black hole (BH) formation could be studied**
- **SK-Gd is expected to discover SRN**
- **HK is expected to measure energy spectrum**

SRN analysis in SK-I~III

PRD 85, 052007 (2012)

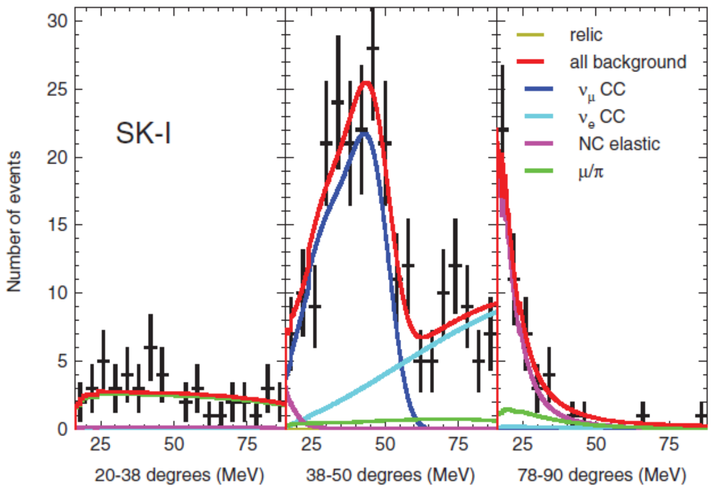
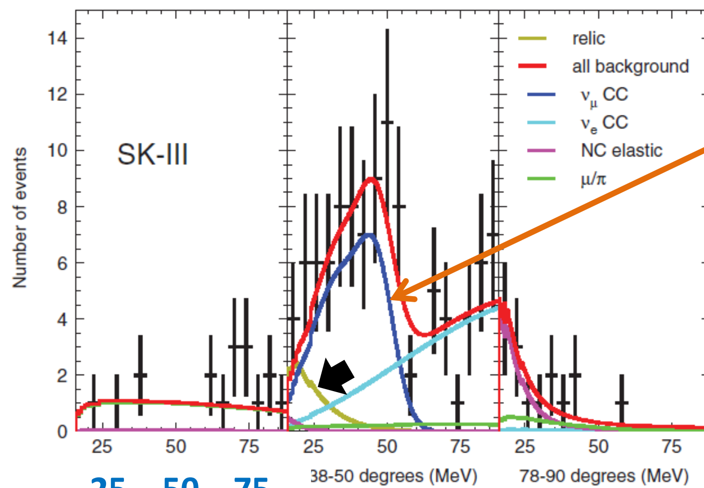


FIG. 14 (color). SK-I LMA best fit result. The relic best fit is negative, so a relic fit of $\boxed{0}$ is shown.

Opening angle (degree):
20-38 38-50 78-90



25 50 75
Electron total energy (MeV)

Dominant BG: Invisible muon decays
→could be reduced by neutron tagging

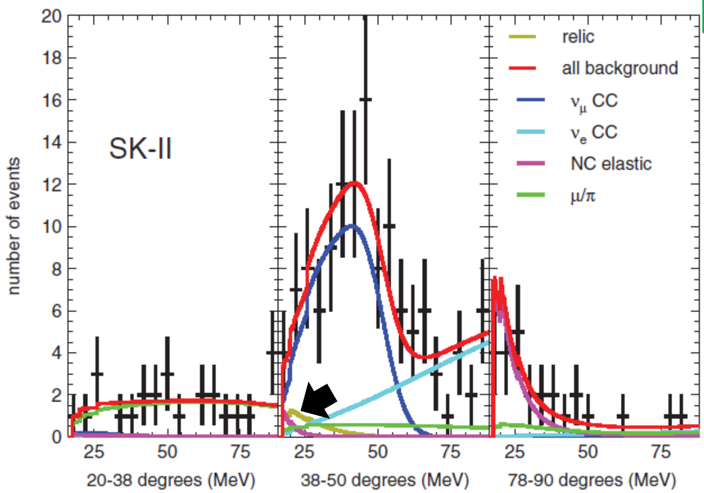
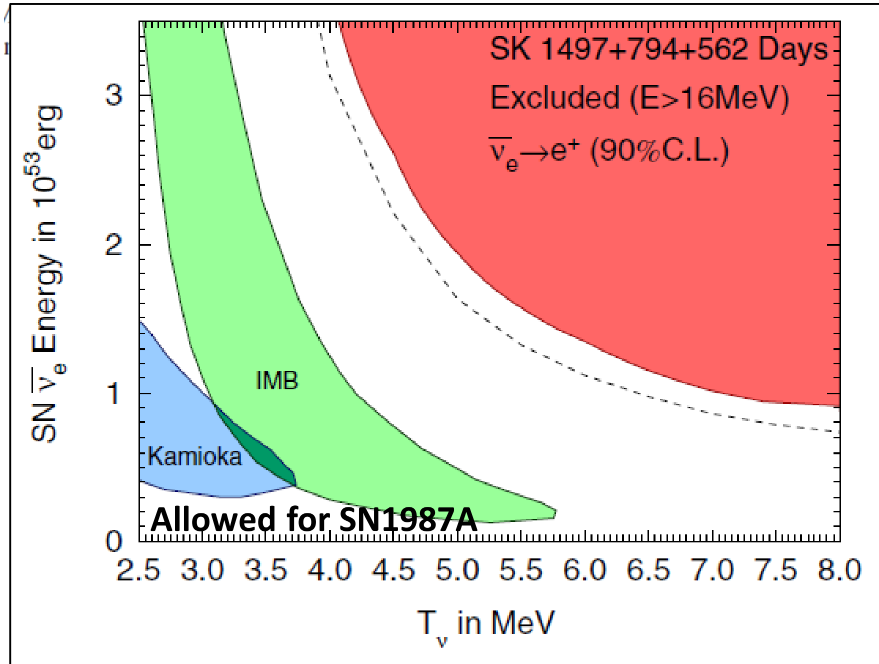
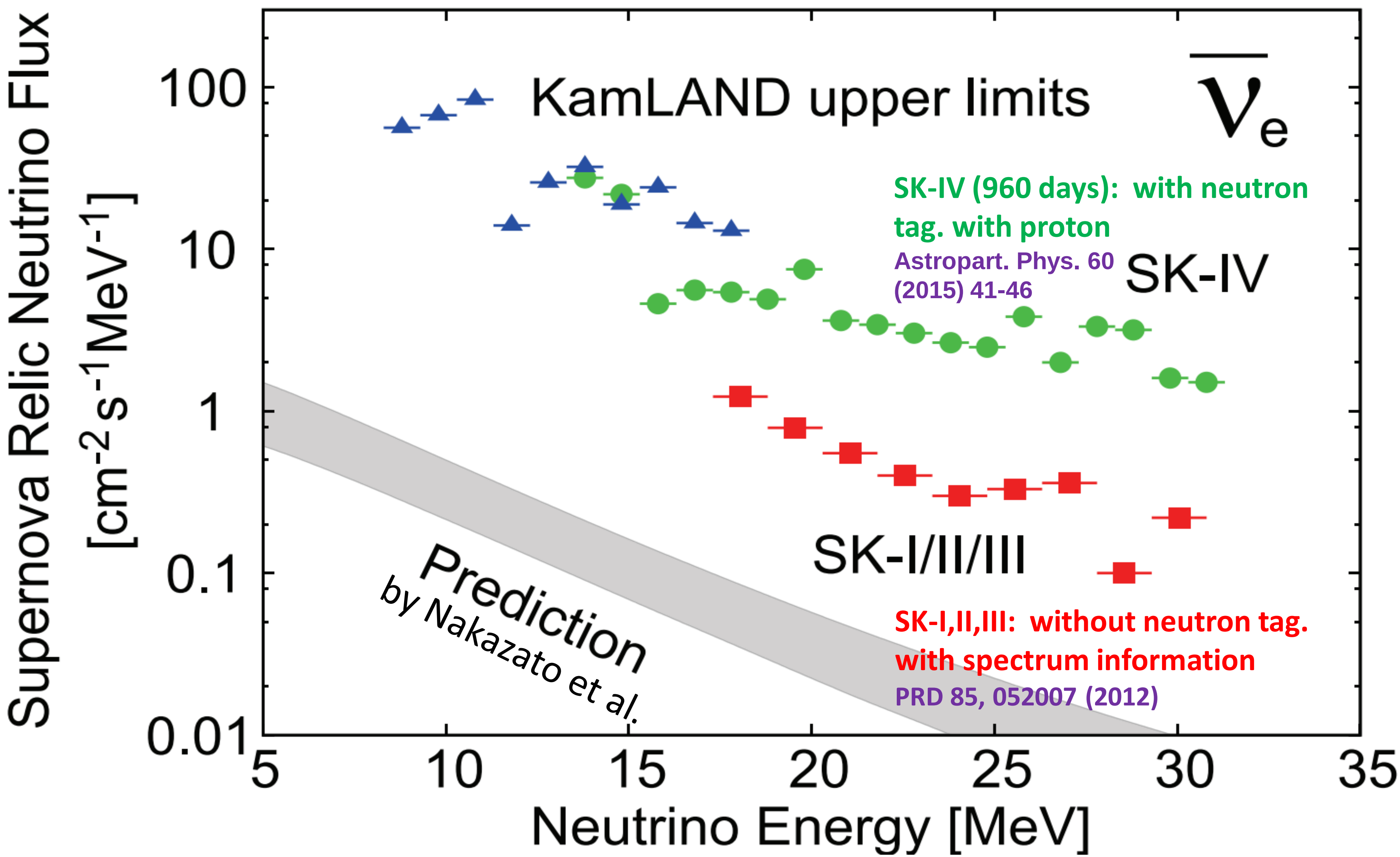


FIG. 15 (color). SK-II LMA best fit result. The relic best fit is $\boxed{3.05}$ events per year interacting in the detector (before reduction efficiencies).



Current SRN upper limits

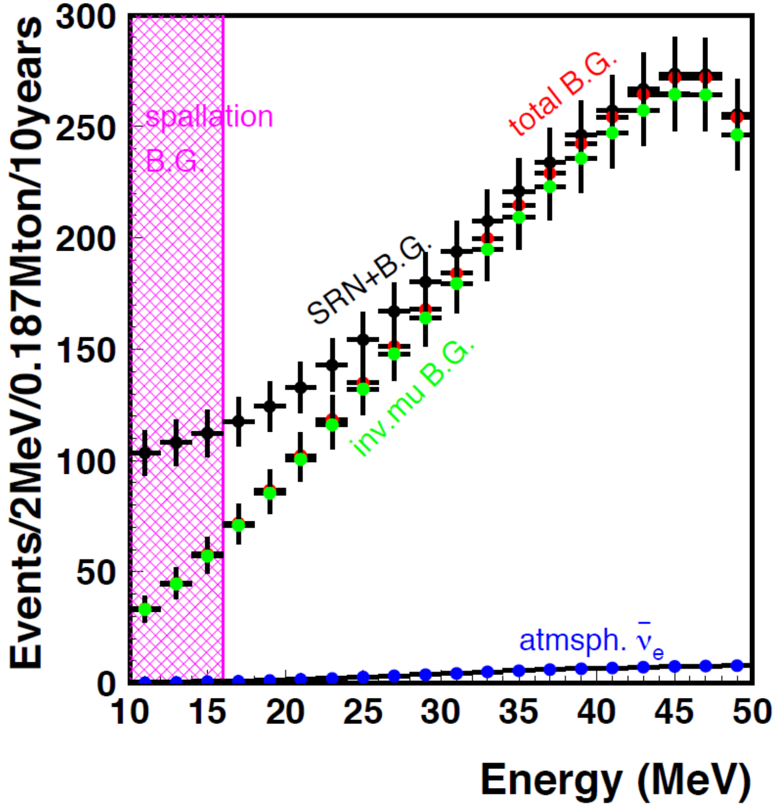


Expected SRN signal & BG in HK

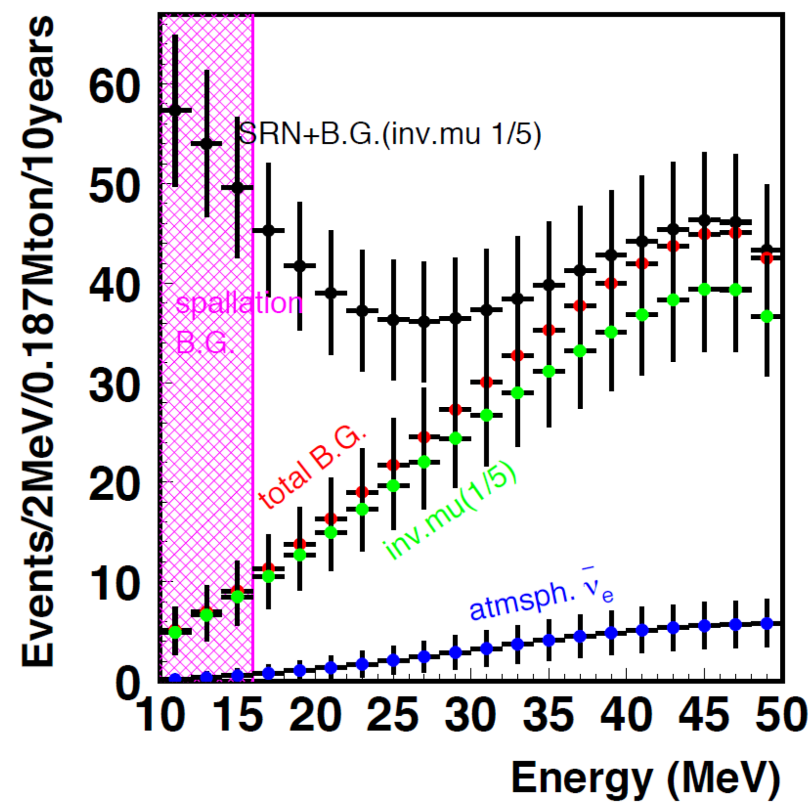
SRN flux: S. Ando et. al, Astropart. Phys. 18 (2003) 307-432, NNN05, T_{eff} = 6 MeV

HK Design Report 2018: arXiv:1805.04163

Without neutron tagging (only signal 90% eff.)

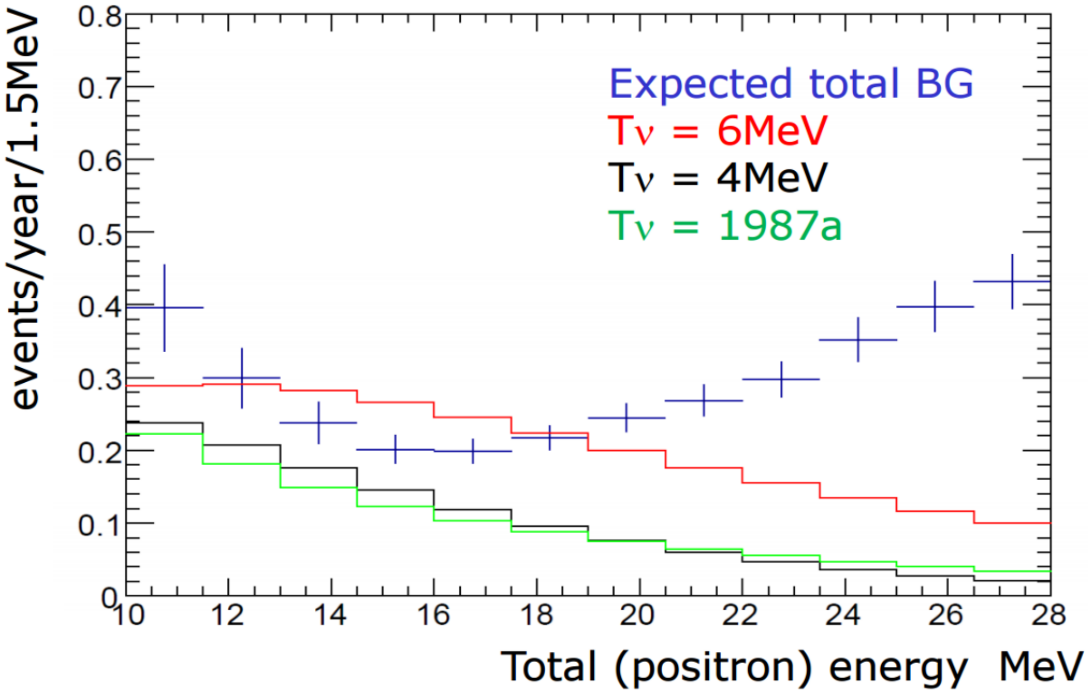


With neutron tagging w/ Gd (only n-tag 70% eff.)



- **~70 events / 16-30 MeV / 10 year (without Gd, n-tag eff. ~70% (w/ proton), lower signal efficiency due to spallation cut, especially in 16-18 MeV, etc.)**
- **~280 events / 10-30 MeV / 10 year (with Gd option, only n-tag eff. ~70%)**

Expected SRN sensitivity in SK-Gd



SRN flux:
Horiuchi et. al, PRD 79, 083013 (2009)

- **Number of SRN signal depends on effective temperature of $\overline{\nu}_e$ (T_ν, T_{eff})**
- **With ~10 years observation in SK-Gd, the 1^{st} detection of SRN would be possible**

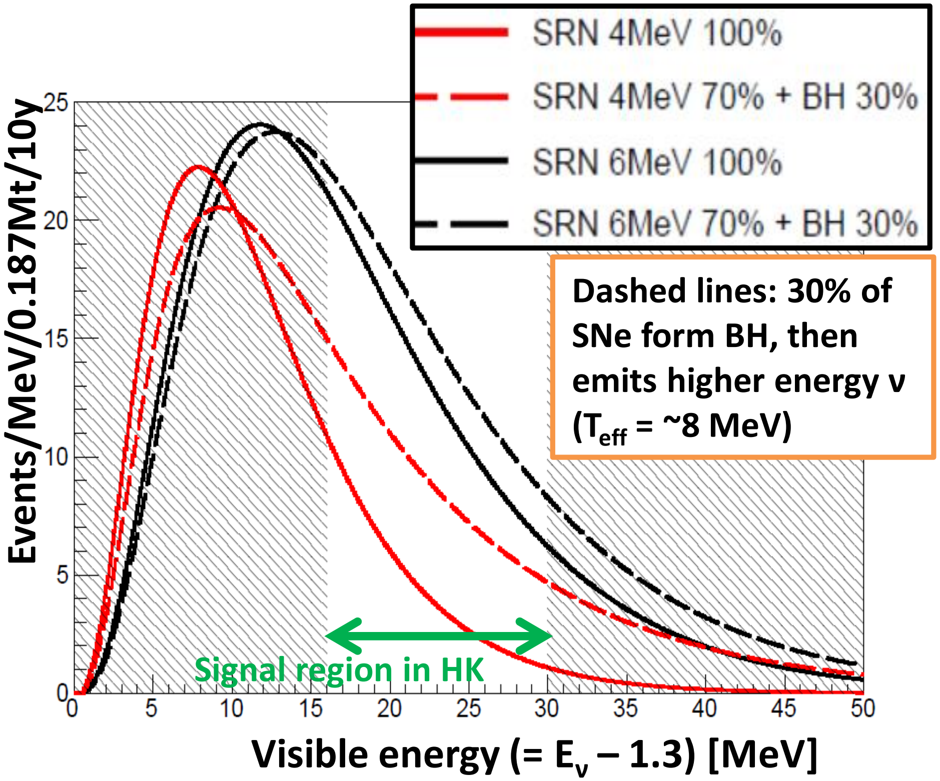
Expected SRN events in SK-Gd, 10 years

HBD models	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV)	significance (2 energy bin)
T_{eff} 8MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

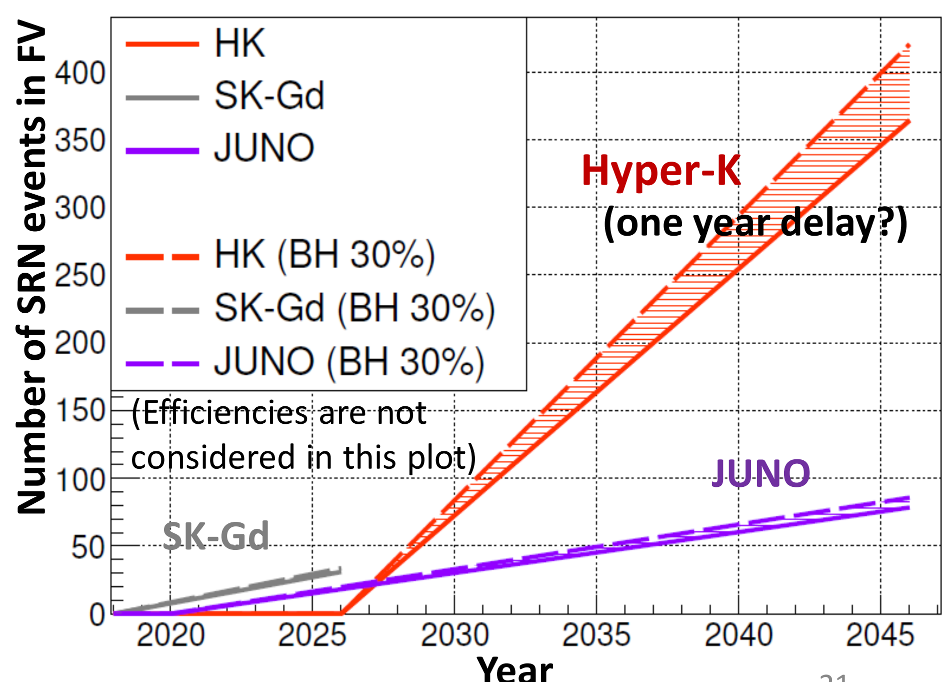
Expected SRN observation in HK

Goal of HK: measure energy spectrum of SRN

- Study history of star formation / black hole (BH) formation
- Expected 70+/-17 events in HK 10 years, in 16-30 MeV (4 σ to non-zero)
  - 5 years (15 years) → 3 σ (5 σ)



HK Design Report 2018: arXiv:1805.04163



Summary

- Measurement of a galactic supernova burst with SK/SK-Gd/HK will provide us a lot of information.
  - SK/SK-Gd: ~10,000 events / SN at 10 kpc
  - HK: ~70,000 events / SN at 10 kpc
- A real-time burst monitor is implemented in SK, and a quick announcement will be done.
  - Pointing accuracy: SK/SK-Gd: 3~5 deg., HK: ~1 deg.
- The main physics target in SK-Gd phase is the first observation of SRN/DSNB.
  - Expected: SK-Gd: 10~30 events / 10-28 MeV / 10 year
- A goal at HK is to measure SRN/DSNB spectrum
  - Expected: HK: ~70 events / 16-30 MeV / 10 year