SK-Gd実験における
超新星背景ニュートリノ探索

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新学術「地下宇宙」 第６回超新星ニュートリノ研究会

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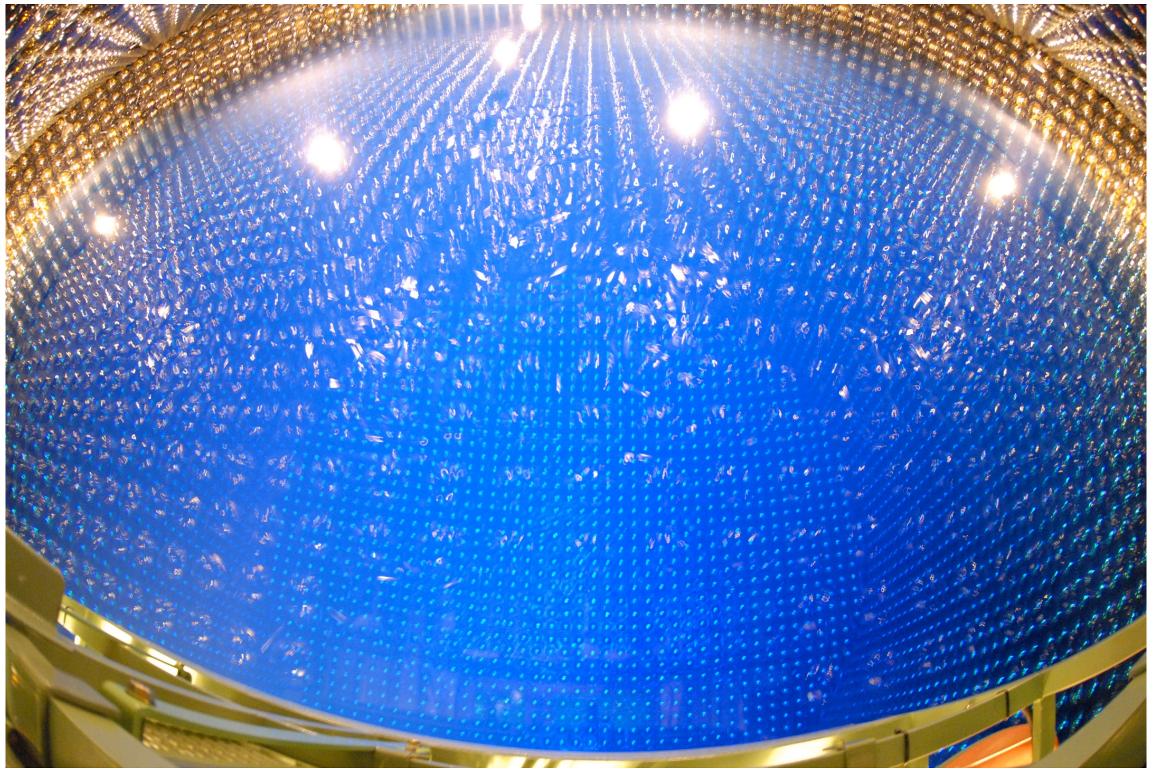
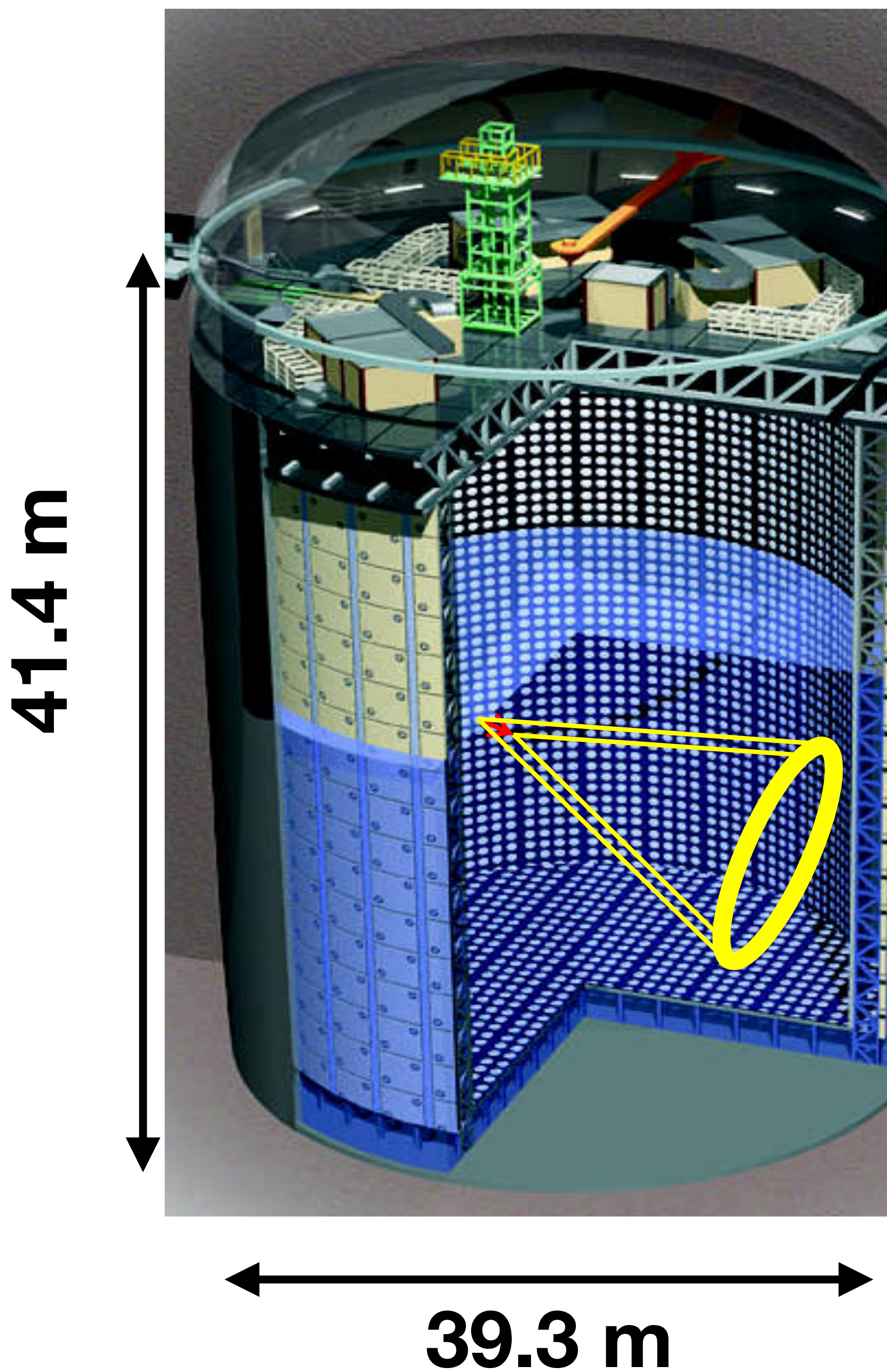


Super-Kamiokande



- 50-kton water Cherenkov detector located at Kamioka, Japan
    - Overburden: 2700 mwe
    - Inner Detector covered by > 11000 20-inch PMTs
- Can detect neutrinos for wide energy rage
    - Solar neutrinos
    - Supernova neutrinos
    - Atmospheric/Accelerator neutrinos

~ MeV

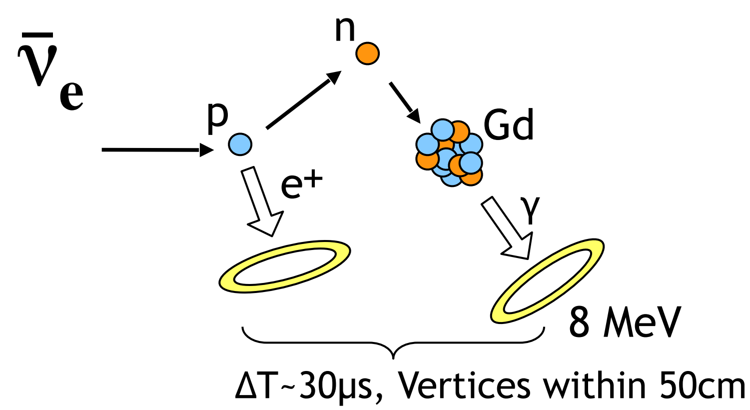
~ GeV

- Operational since 1996

SK-Gd project

- Dissolving Gd to Super-Kamiokande to significantly enhance detection capability of neutrons from ν interactions
- Idea first proposed in:

J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. 93 (2004) 17110



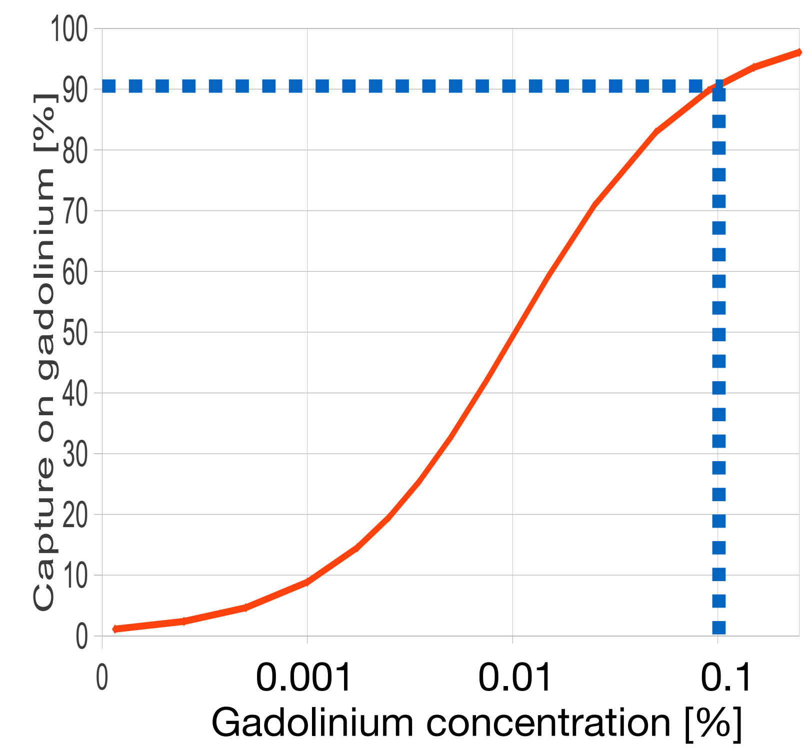
Goals of SK-Gd:

- **First observation of Diffuse Supernova Neutrino Background (DSNB)**
- Improve pointing accuracy for galactic supernova
- Precursor of nearby supernova by Si-burning neutrinos
- Reduce proton decay background
- Neutrino/anti-neutrino discrimination (Long-baseline and atmospheric neutrinos)
- Reactor neutrinos

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

$$| + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma(s)$$ **(8 MeV)**

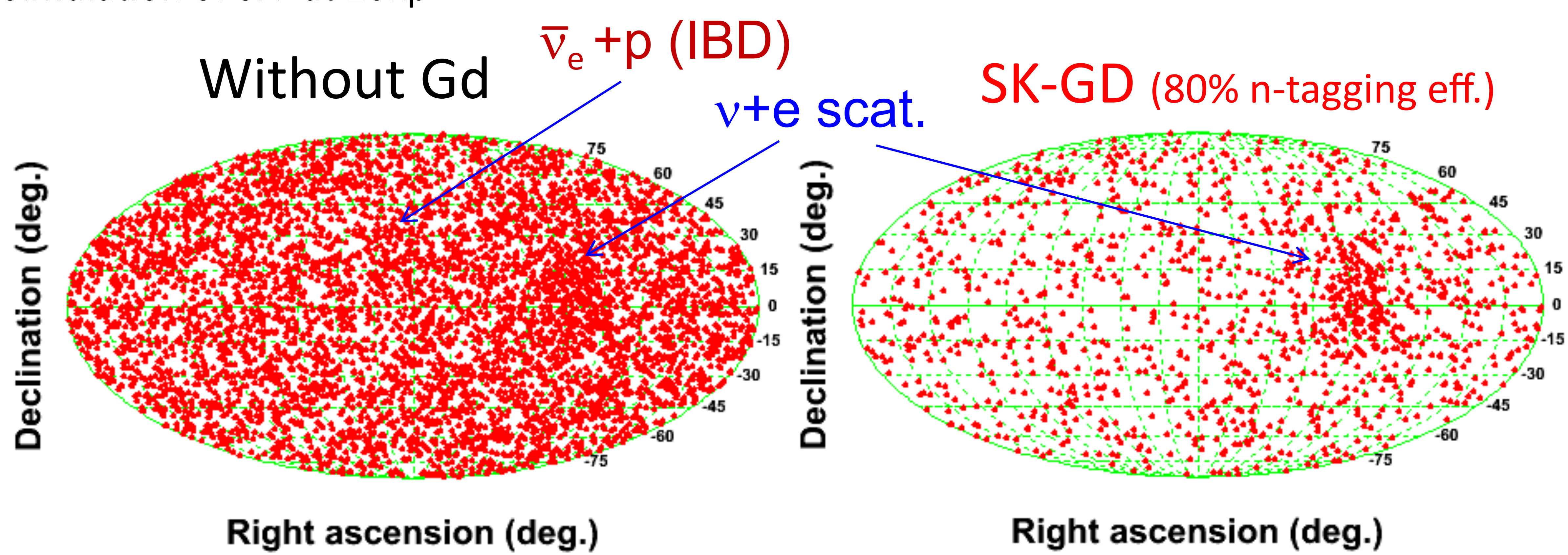
$$| + H \rightarrow D + \gamma$$ **(2.2 MeV)**



Improving pointing accuracy for supernova burst neutrinos

- By tagging IBD events with Gd (which does not have directional information), extract ν+e elastic scattering events from SN burst
- Pointing accuracy for SN at 10 kpc: **4~5° → 3° (90%CL)**
  - Helps finding coincidence with optical observations

Simulation of SN at 10kp



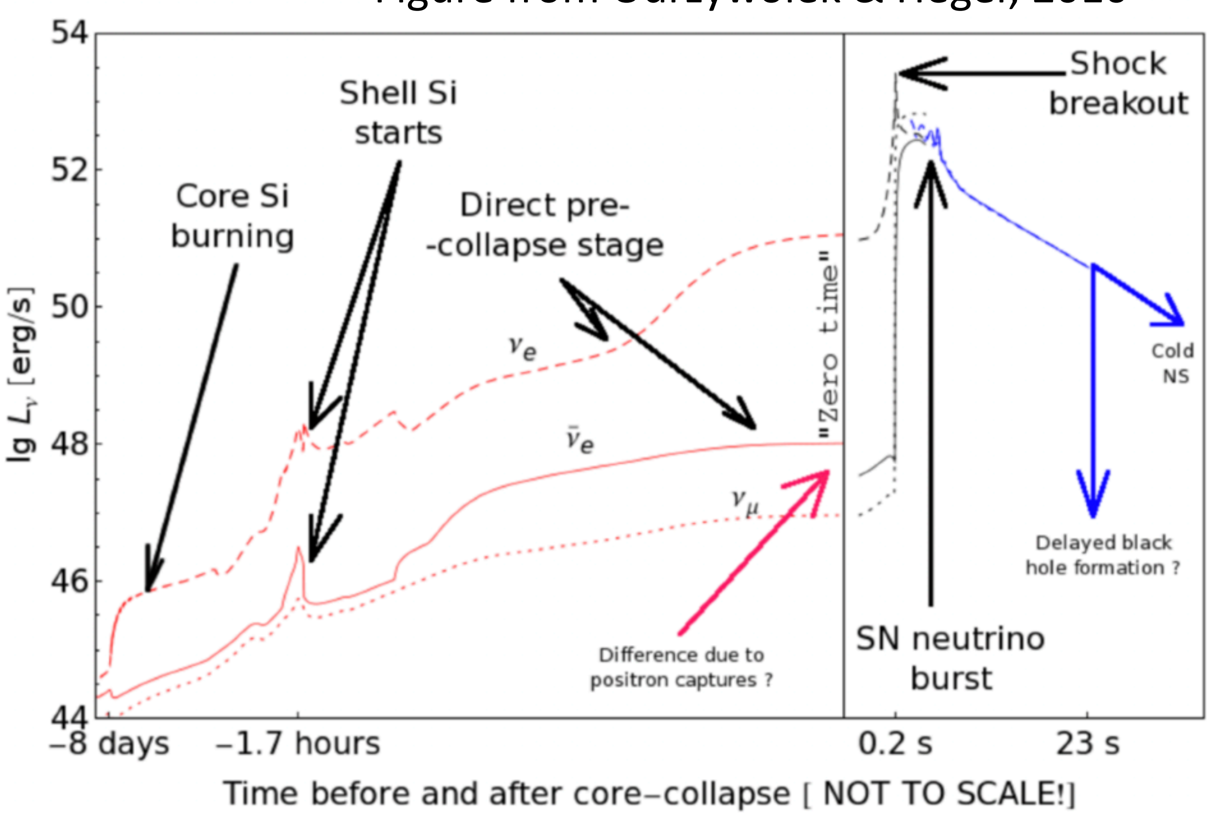
Pre-supernova signals

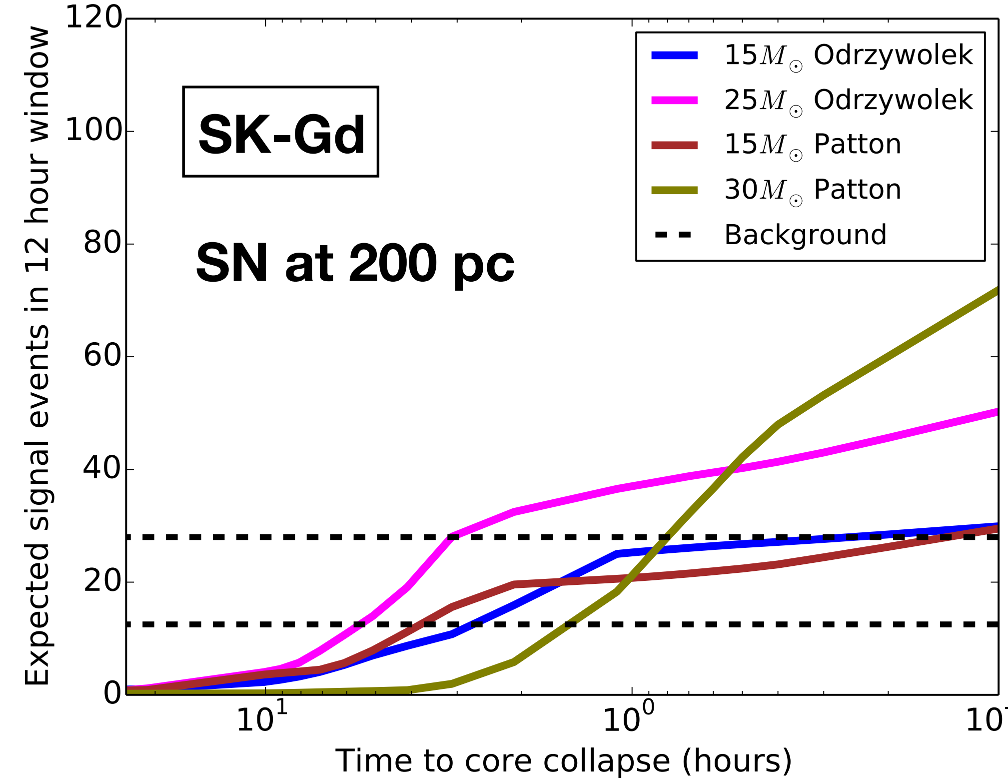
- Precursor signal from Si-burning can also be detectable for nearby SN bursts.
    - eg. Betelgeuse at ~200 pc
- KamLAND warning system have been implemented and running

    KamLAND, Astrophys. J. **818**, 91 (2016)
- SK-Gd will also have sensitivity

    C. Simpson et al [Super-Kamiokande Collaboration]
    Astrophys. J. **885**, 133 (2019)

Figure from Odrzywolek & Heger, 2010





(b) DC expected signal rate

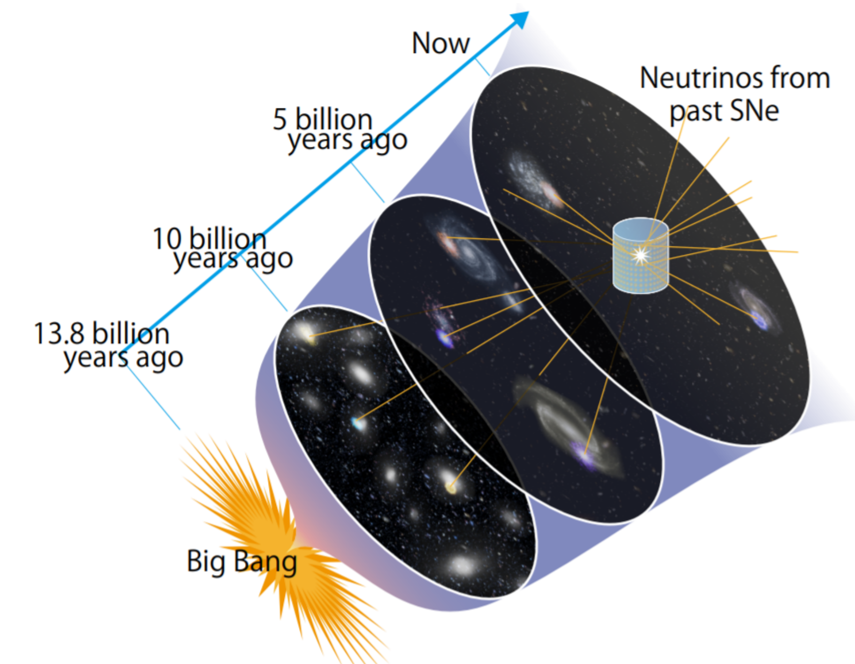
Diffuse Supernova Neutrino Background

- Diffuse Supernova Neutrino Background (DSNB): Neutrinos produced from the past SN bursts and diffused in the current universe.

~ a few SN explosions every second

O(10^{18}) SNe so far in this universe

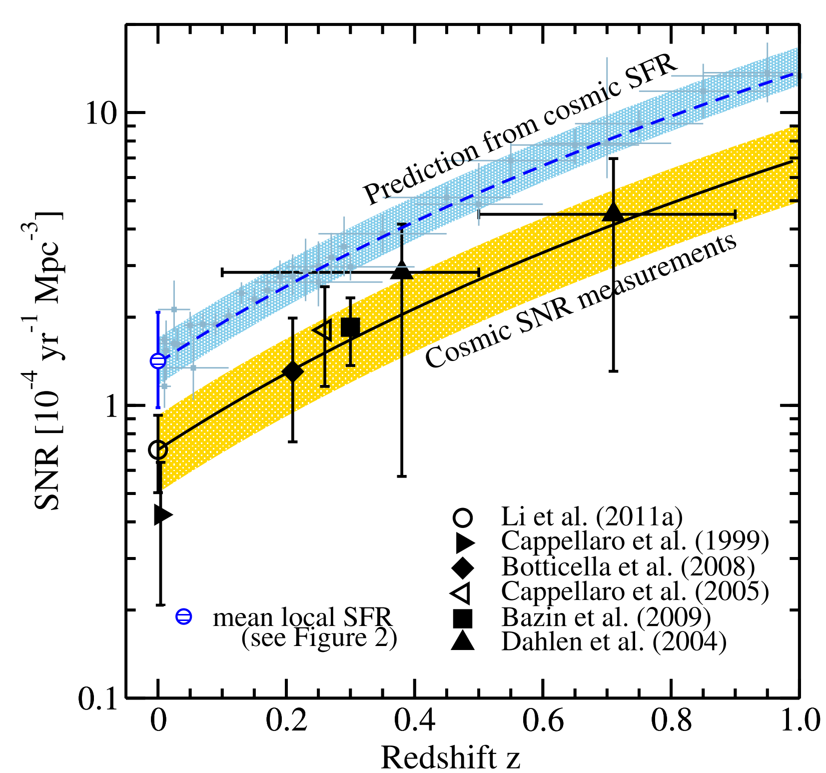
- Can study history of SN bursts with neutrinos



- **SN rate problem**: Observed SN burst rate lower than prediction from cosmic star formation rate
  - Invisible dim supernova?
  - Black-hole formation?
  - Something blocking optical light?

DSNB signal will help resolving the puzzle

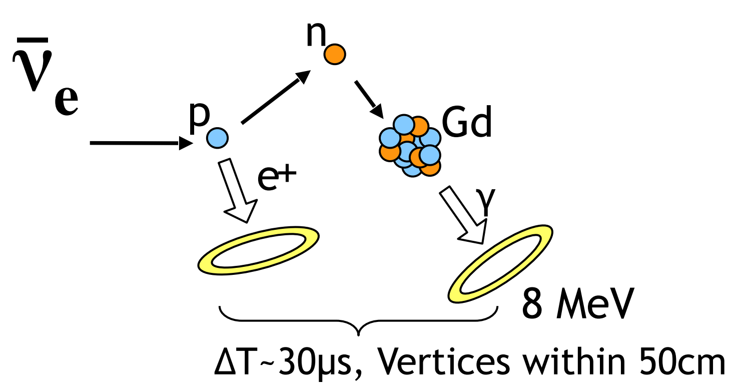
H. Horiuchi et al, Astrophys. J. **738**, 154 (2011)



Current status of DSNB searches

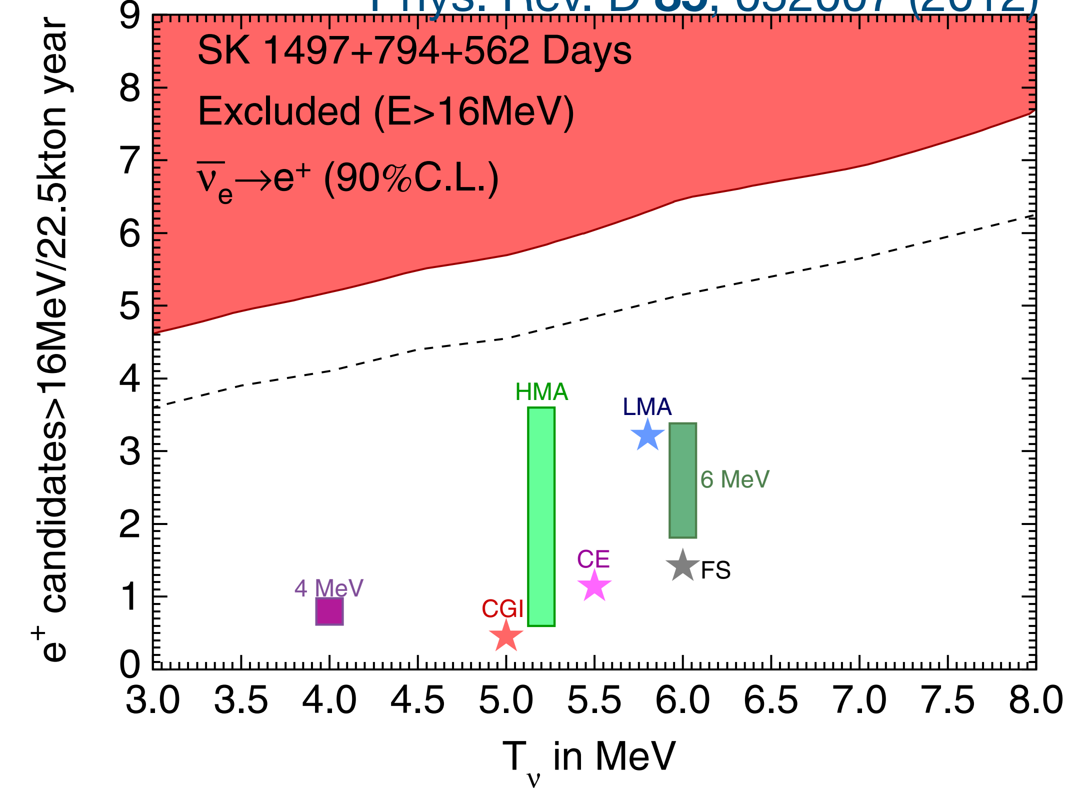
- Current most stringent limit by SK within one order of magnitude from most of the models.
- Experimental sensitivity limited by backgrounds
- Reducing backgrounds is the key for the first observation of DSNB

→Neutron tagging in SK-Gd

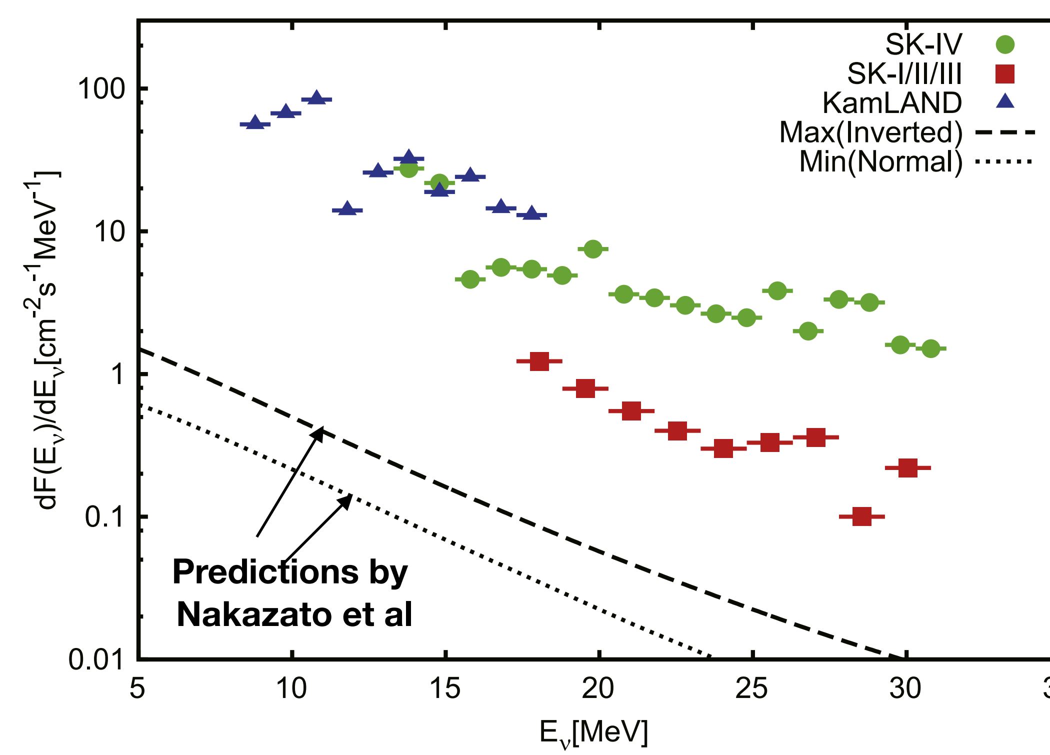


- First observation within reach of **SK-Gd**

[Super-Kamiokande Collaboration]
Phys. Rev. D **85**, 052007 (2012)

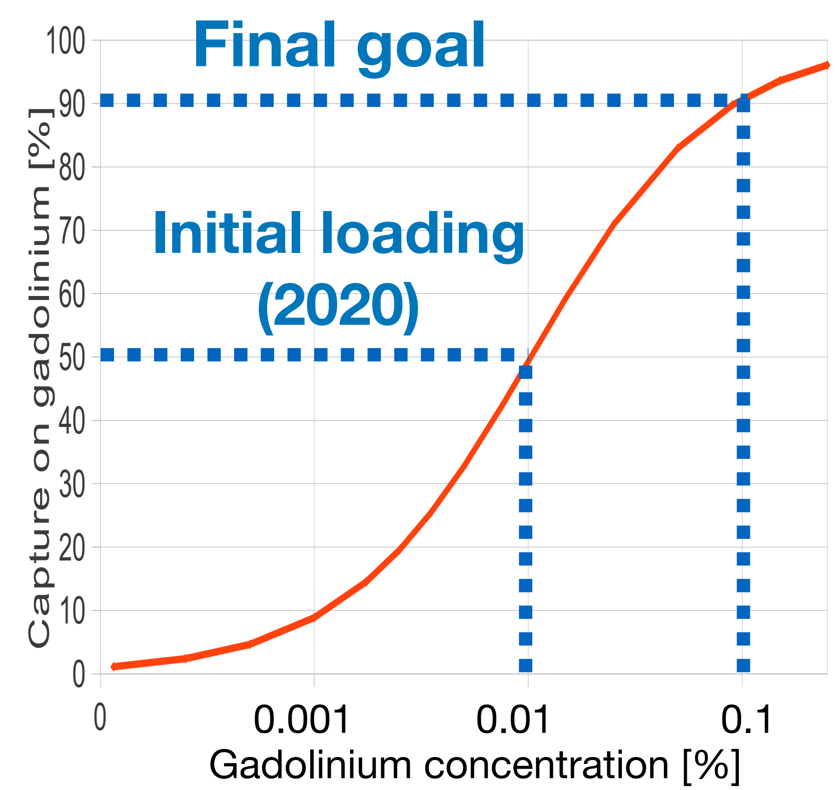


K. Nakazato et al, Astrophys. J. **804**, 75 (2015)



Towards first Gd loading to SK

- As the first step, we will load 10 tons of $Gd_2(SO_4)_3$ (0.01% Gd concentration) in 2020 (1/10 of the final goal)
  - 50% of neutron would be captured by Gd
  - x2 - x3 enhancement of n-tagging efficiency
- Many preparation works towards the first Gd loading:
  - Fixing leak from the SK tank
  - Production of ultra-pure $Gd_2(SO_4)_3$ powder
  - Construction of a dedicated purification/ recirculation system for Gd-water



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

$| + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma(s)$ (8 MeV)

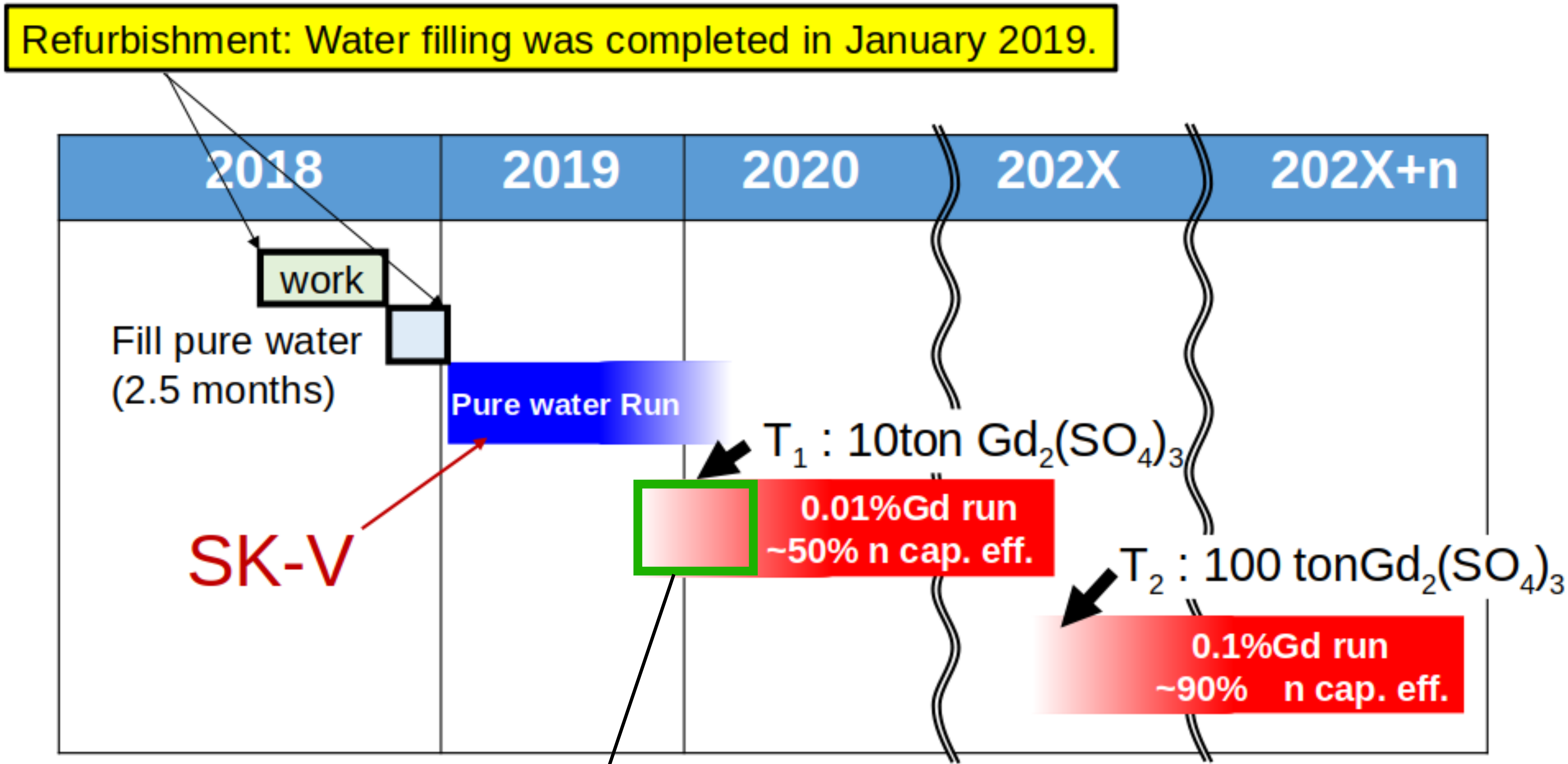
$| + H \rightarrow D + \gamma$ (2.2 MeV)

n-Gd detection efficiency: ~0.9

n-H detection efficiency: ~0.25

Details of the preparation works in the next talk by Ito-san

Timeline

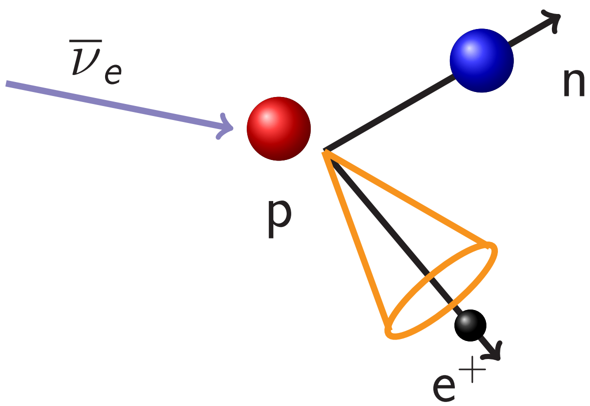


Step 1: **Preparation of the new Gd-water system**
Step 2: **SK pure water recirculation w/ the new water system (*Started on Dec. 24, 2019*)**
Step 3: **Gd loading to 0.01% (*This spring!*)**

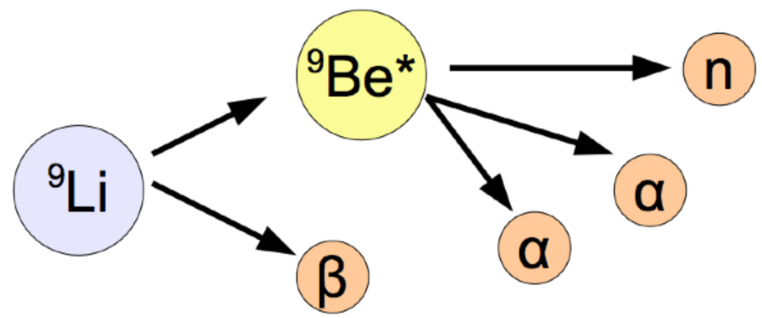
DSNB search at SK(-Gd)
- Current and Future -

DSNB signal and backgrounds
(after requiring neutrons)

Signal

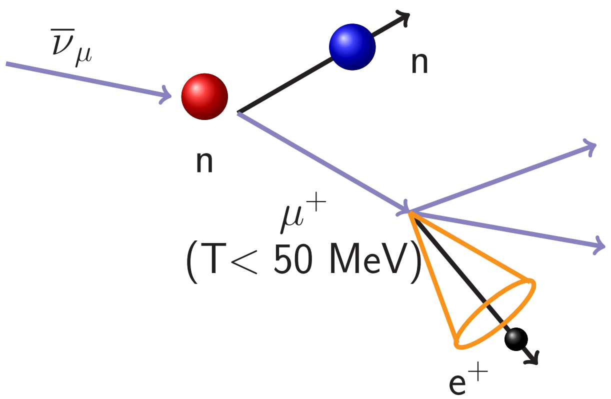


^{9}Li (from cosmic muon spallation)

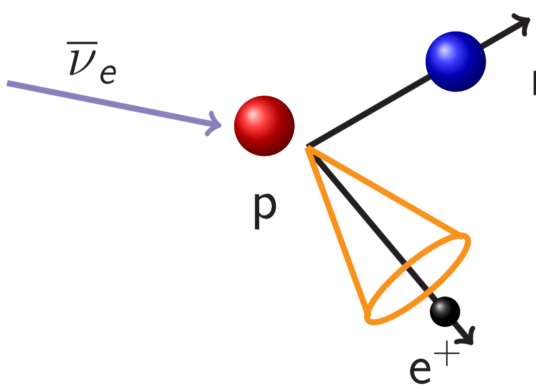


Atmospheric neutrinos

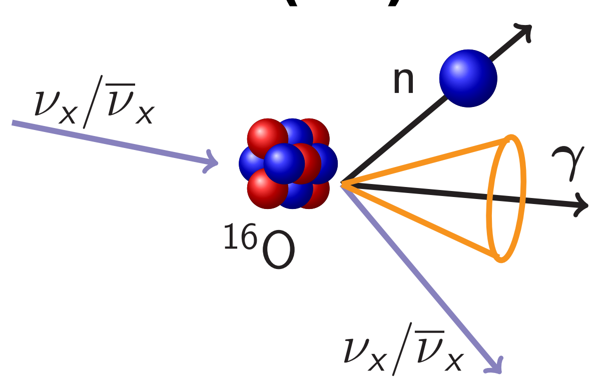
ν_μ CC



ν_e CC



NC(QE)



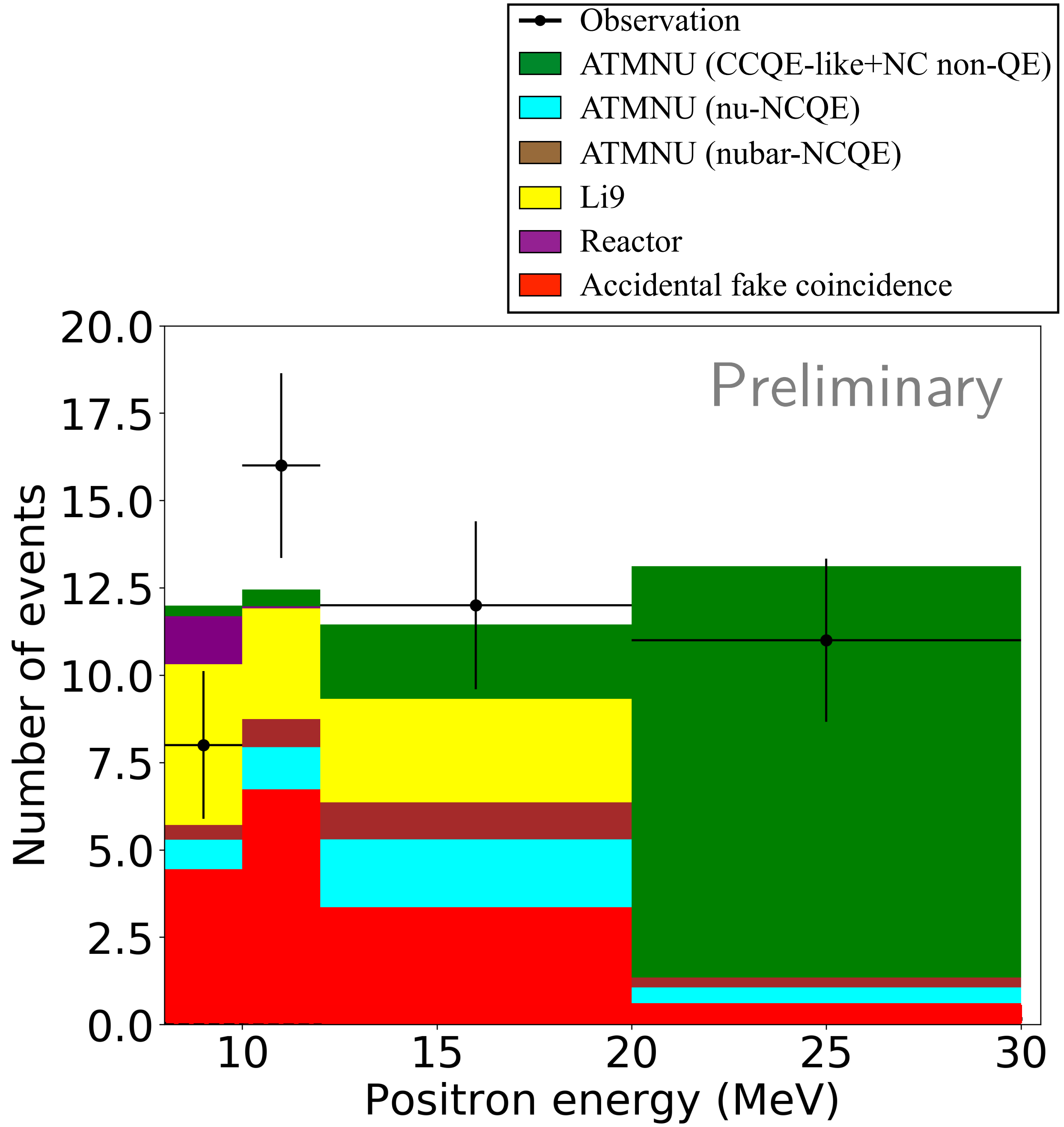
+ Accidental coincidence (mostly spallation products + fake-neutrons)

+ Reactor neutrons

DSNB search with the full SK-IV data

- Analysis using the full SK-IV data (2970 live days) in progress
- Utilize neutron tag with H-capture
- Signal efficiency: ~10% (dominated by poor n-tag efficiency)
- Major backgrounds:
  - Accidental coincidence
  - ^{9}Li
  - Atmospheric neutrino NCQE and CC interactions
- Sensitivity limited by backgrounds

Total backgrounds:
~50 evts/22.5kton/2970days (> 8 MeV)
→ ~6 evts/22.5kton/year

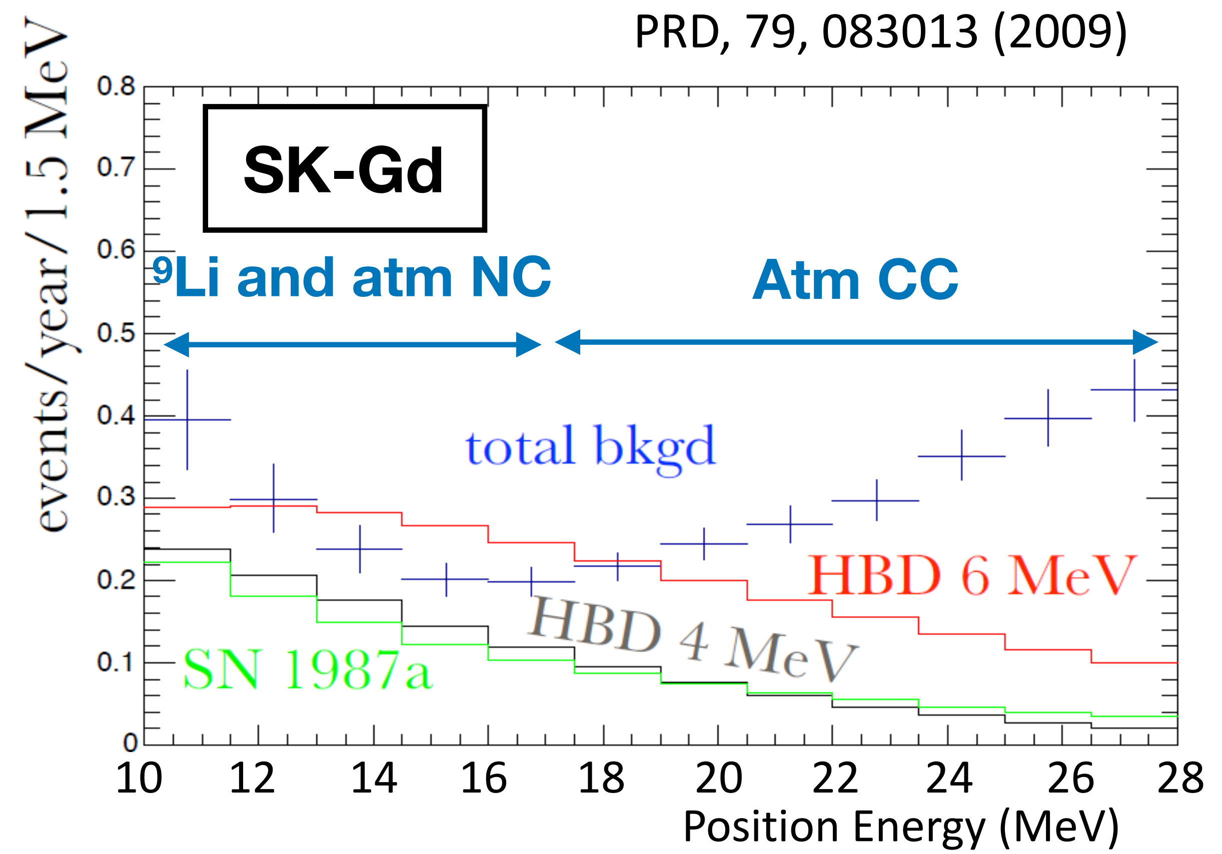


What we expect with SK-Gd

Expected change from the latest analysis w/ n-tag

- Signal efficiency:
  - Increase w/ n-tag efficiency:
    ~20% → ~50% (0.01% Gd)
    → >70%?(>0.03% Gd)
- Backgrounds
  - Accidental: significantly reduced
    - Shorter neutron capture time
    - Less fake neutron signal due to larger n-capture signal (8 MeV vs 2 MeV)
  - ^{9}Li and atmospheric neutrino backgrounds expected to remain similar to SK-IV n-tag analysis
    - Increase w/ n-tag efficiency
    - ^{9}Li reduction w/ re-optimization of spallation neutron cut
    - Atmospheric event reduction w/ n-multiplicity cut

SRN flux;
Horiuchi, Beacom and Dwek,
PRD, 79, 083013 (2009)



SK-Gd: FV = 22.5 kton, 10 year observation, 0.1%Gd

Model	10-16MeV	16-28MeV	Total
HBD 8MeV	11.3	19.9	31.2
HBD 6MeV	11.3	13.5	24.8
HBD 4MeV	7.7	4.8	12.5
HBD SN1987a	5.1	6.8	11.9
BG	10	24	34

Impact of backgrounds

- Current background uncertainty: >40%
- Toy sensitivity estimation:
  - ε_{prompt} = 64% (based on current SK-IV analysis)
  - $\varepsilon_{neutron}$ = 50% (first two years)
    70% (From the third year)
  - Background sys error = 40%
  - Significance = N_{sig} / σ_{bkg}(stat+sys)
- *Can only reach 1-1.5σ for DSNB at 4 int/22.5kton/year*
- *Reducing backgrounds and its systematic uncertainty are both critical for DSNB observation*

Most problematic background:
Atmospheric ν NCQE interactions

- Spectrum shape similar to DSNB
- Suffered by large uncertainty from
  - Atmospheric nu flux (~15%)
  - NCQE cross-section (~30%)
  - Neutron multiplicity (~40%)

→**Many efforts to tackle NCQE backgrounds ongoing**

SK-Gd: FV = 22.5 kton, 10 year observation, 0.1%Gd

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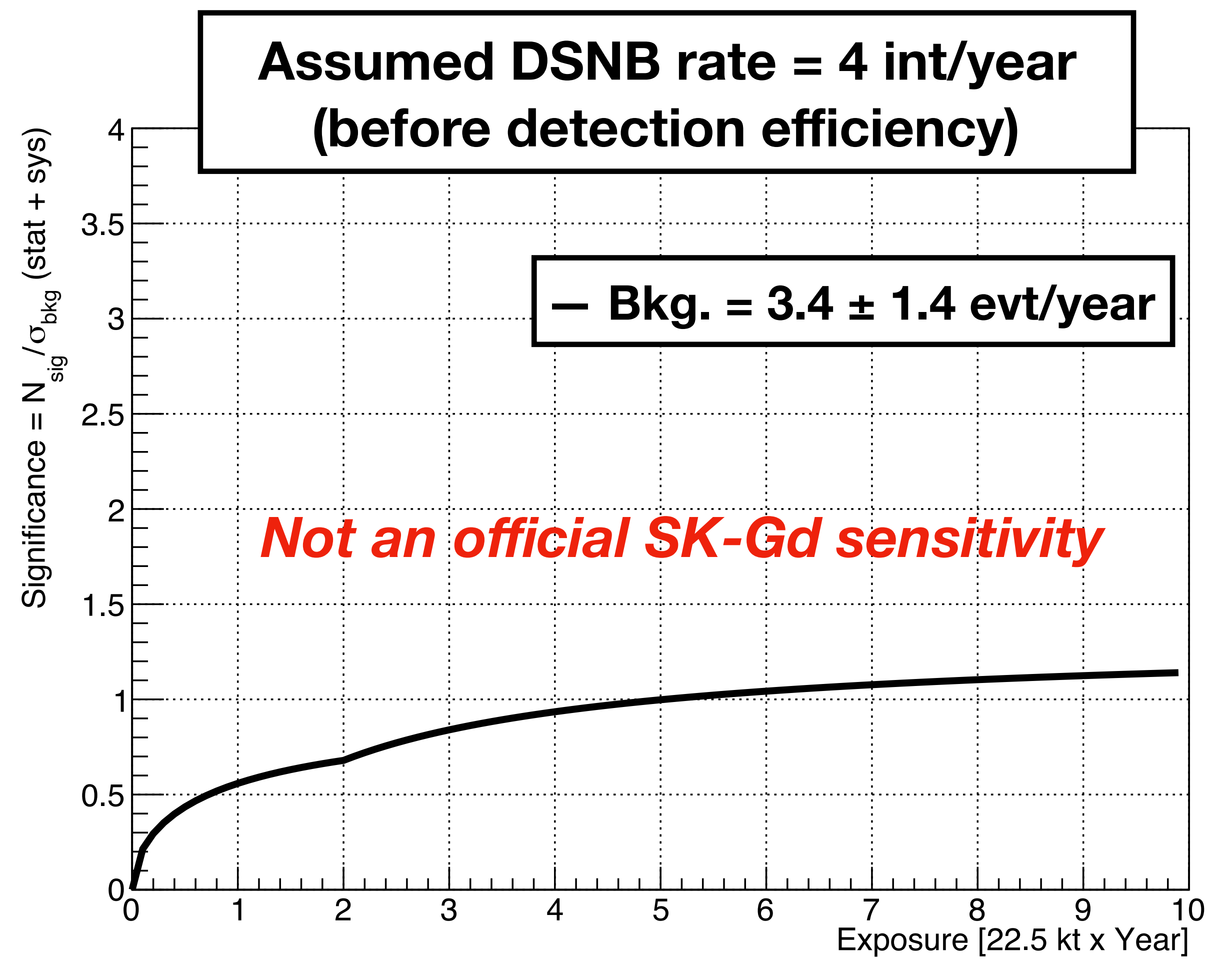
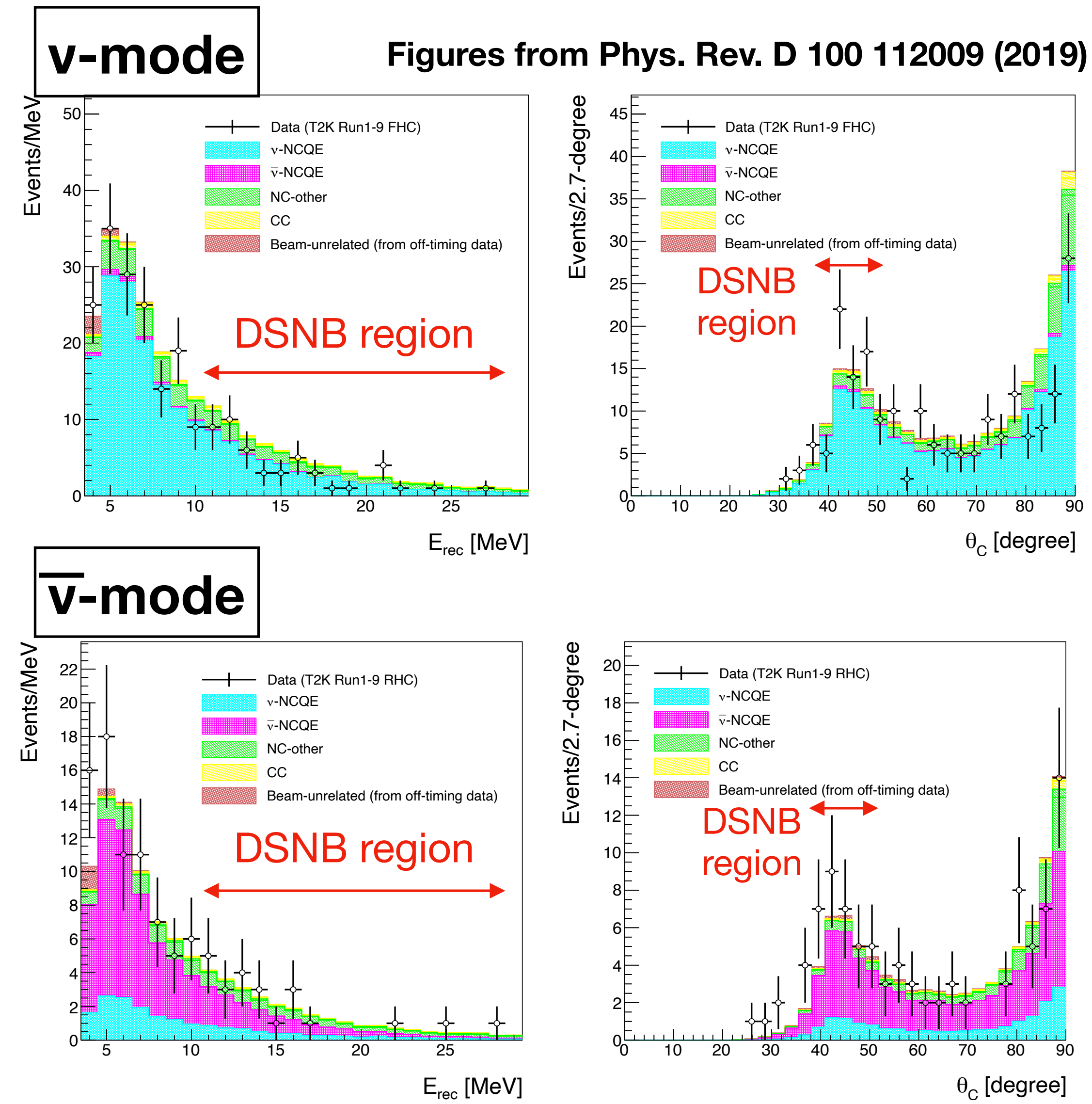
Background ~ 3.4 events / 22.5 kton / year



NCQE measurement with accelerator neutrino beam

- Unique feature for SK-Gd (and HK): control sample of NCQE interactions w/ accelerator neutrino beam from J-PARC
- Large part of beam energy spectrum overlaps with atmospheric neutrinos
- [NEW!] Just released new results at SK with the T2K beam: Phys. Rev. D **100** 112009 (2019)
- Still statistics is poor in the region of interest. Precision will be improved with more data

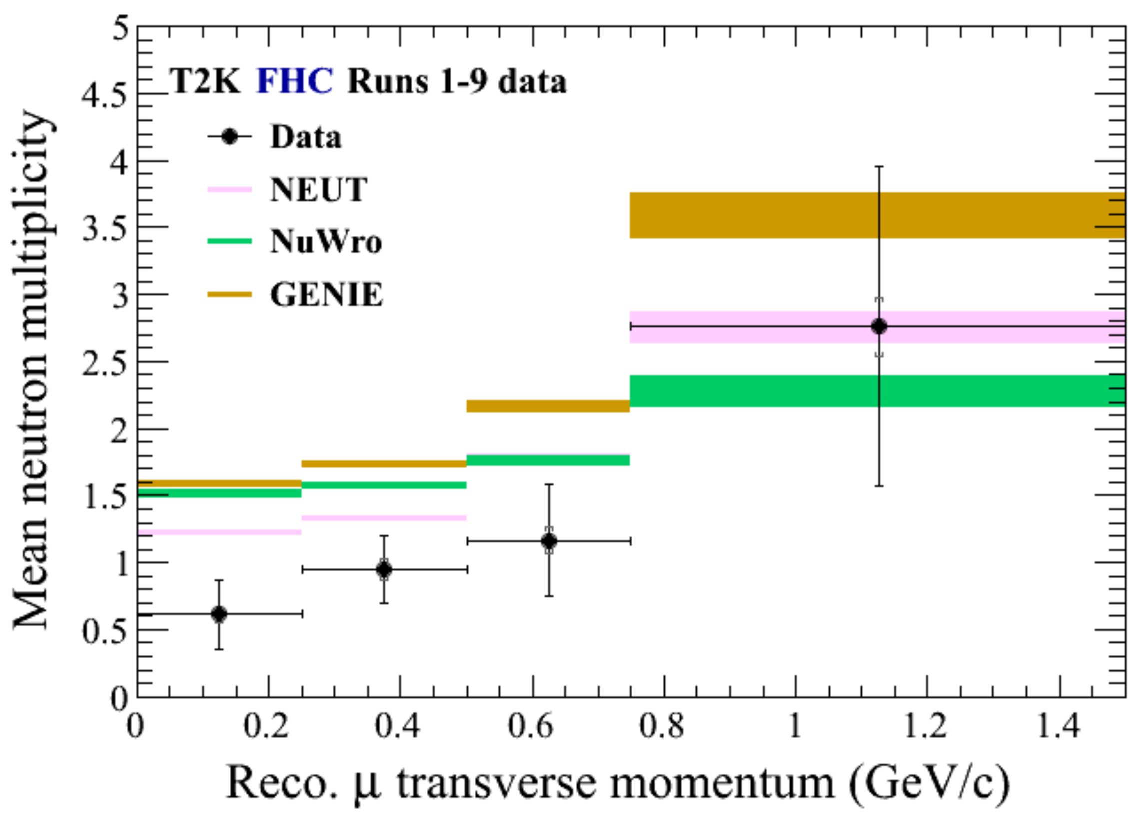
Figures from Phys. Rev. D 100 112009 (2019)



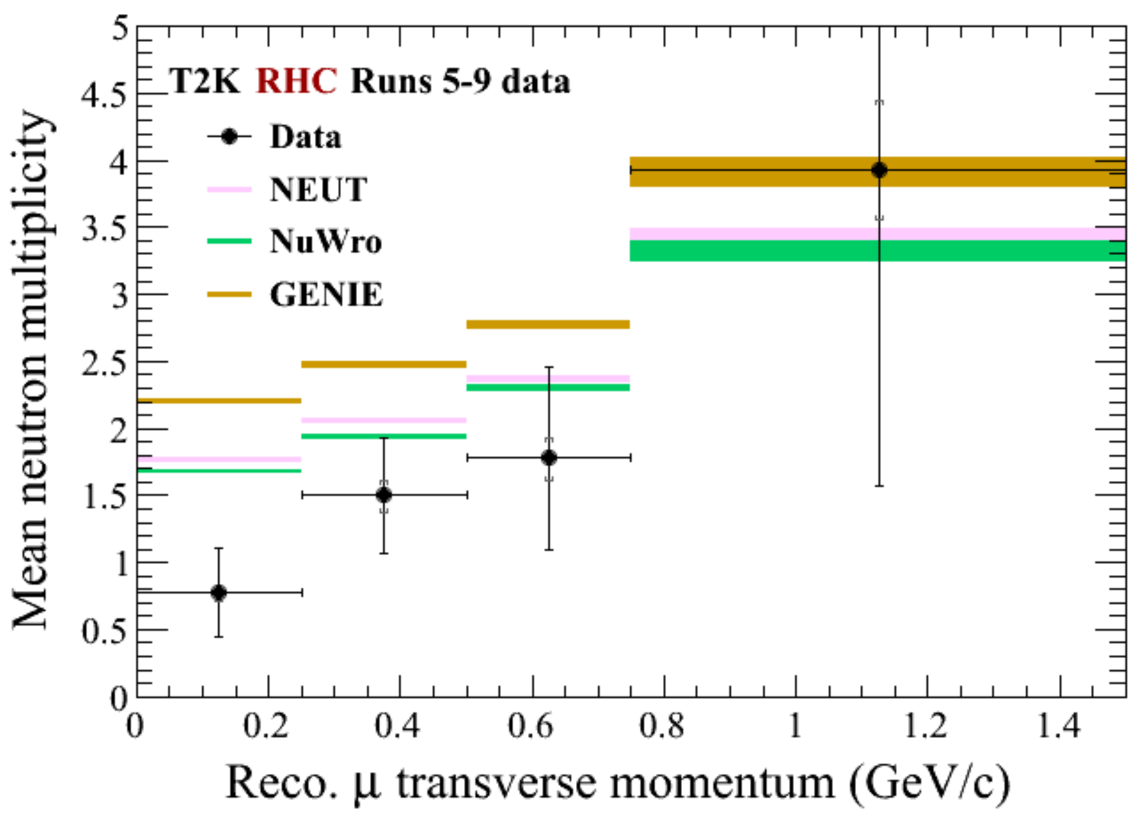
Neutron multiplicity measurement with accelerator neutrino beam

- [NEW!] Measurement of neutron multiplicity by CC interactions from the T2K neutrino beam
- Used neutron captures on Hydrogen
- Revealed significant discrepancy from the predictions
- Awaiting for improved measurement with Gd-capture neutrons

ν-mode

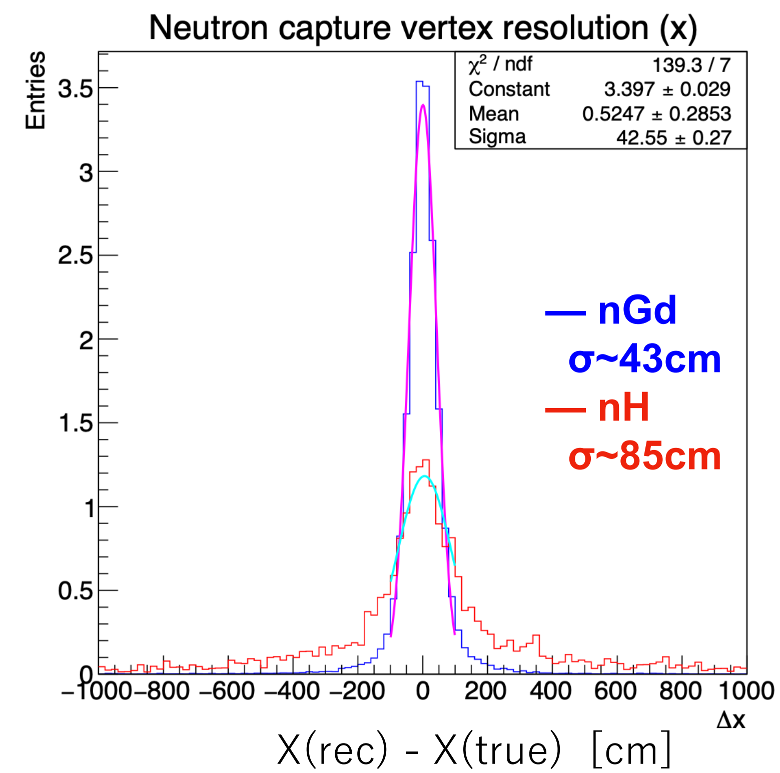


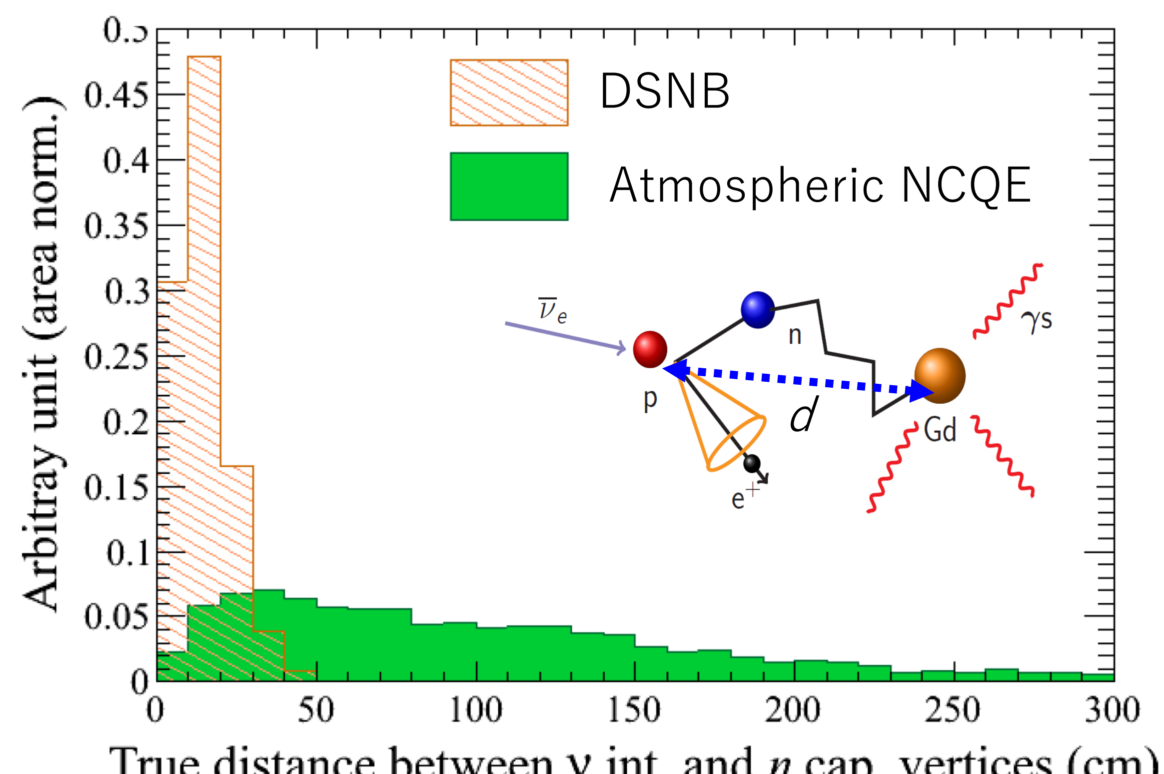
$\bar{\nu}$-mode



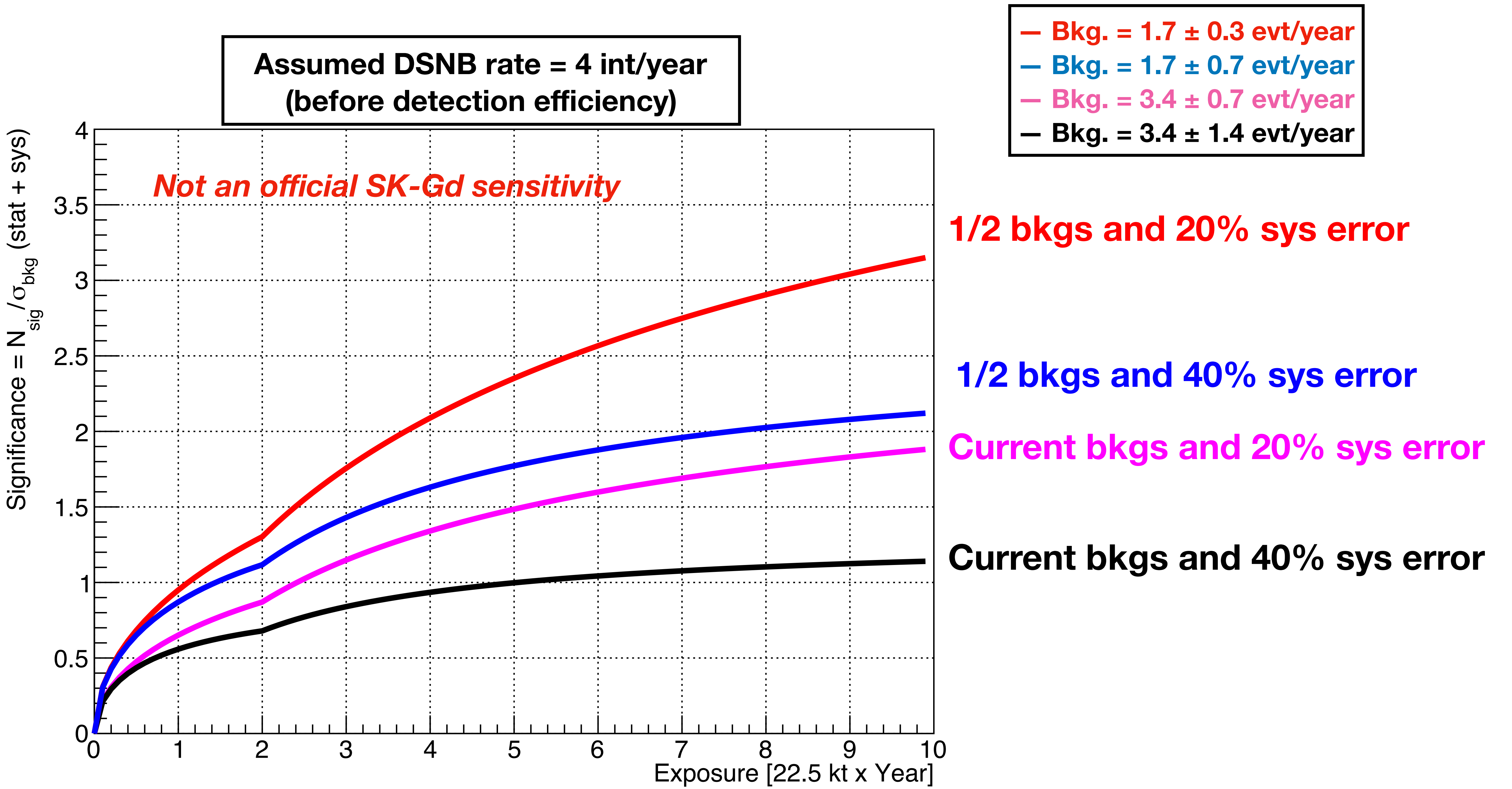
Further background reduction w/ event topology

- x2 better vertex resolution for Gd-capture event than H-capture
- Opens the possibility of further topological cuts with neutrons
- Neutrons from atmospheric neutrino interactions tend to travel more
- Investigating possibility of further reduction w/ neutron flight distance and direction
- T2K neutrino beam would also be ideal for this study





Sensitivity scenarios



Towards first observation of DSNB signal

- Make big enough detector with low radio-impurity and efficient neutron-tagging
  →SK-Gd

But, just building SK-Gd is not enough

- Further understanding/reduction of backgrounds indispensable
  - Better understanding of atmospheric neutrino NCQE interactions:
    - Direct measurement w/ T2K beam
    - External measurement of Oxygen spectroscopic factors, neutron interactions in water etc.
  - Further topological cut w/ neutrons for atmospheric neutrinos
  - Better constraints of atmospheric neutrino flux
  - Improved cuts for spallation products

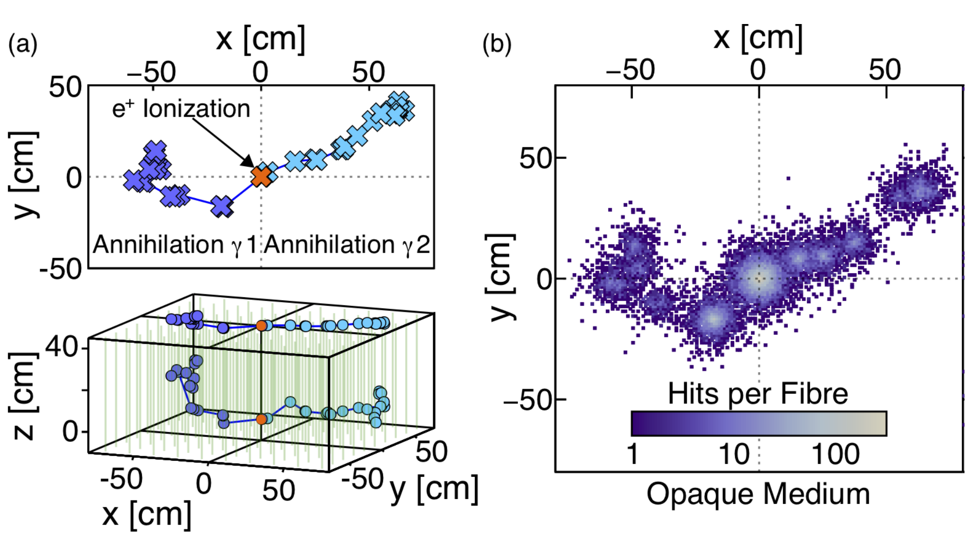
Above items can/should be realized within the time scale of SK-Gd

Dream detectors

- Can other detector technology further reduce backgrounds for DSNB?
- (Delayed) neutron signal already utilized
  → **Further topological selection for prompt positron?**
- Idea: **e+/e-/γ separation with superb position sensitivity**

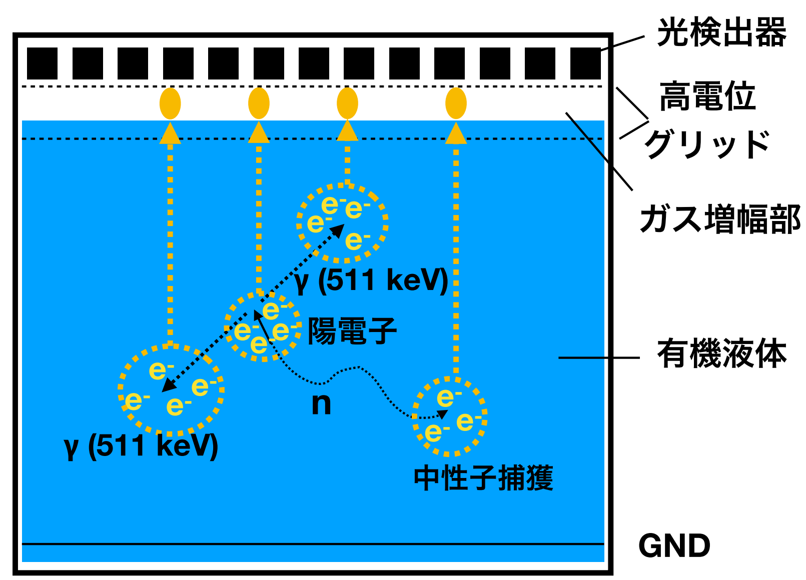
LiquidO

arXiv: 1908.02859

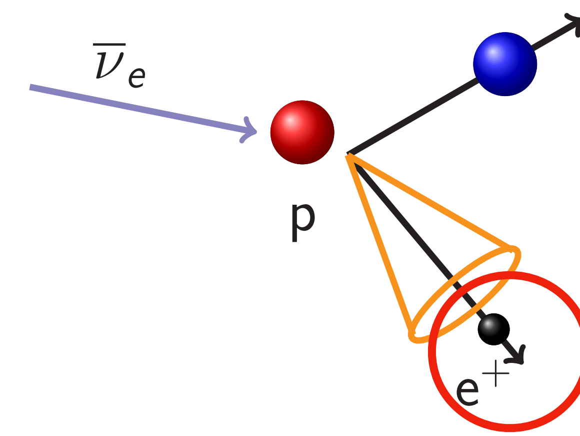


Organic liquid TPC

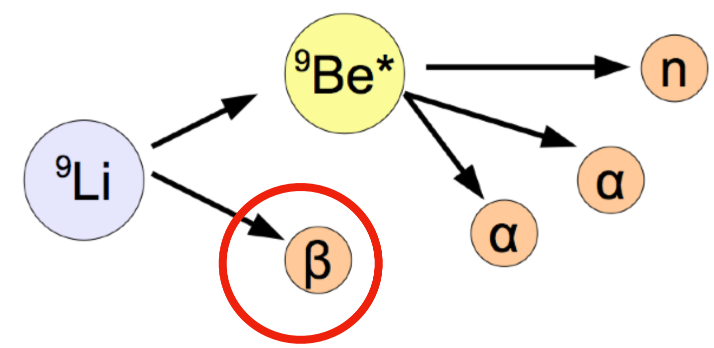
arXiv: 1405.1308 etc



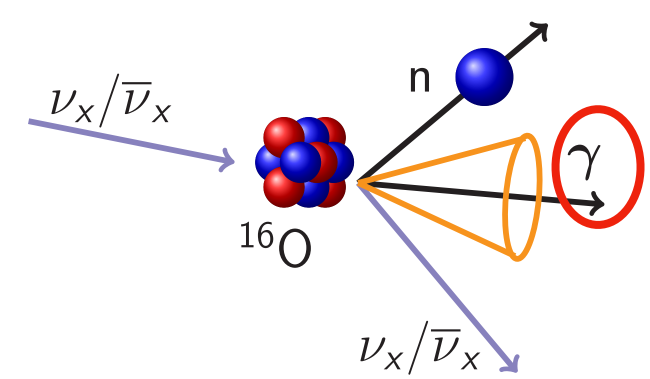
Signal (IBD)



^{9}Li

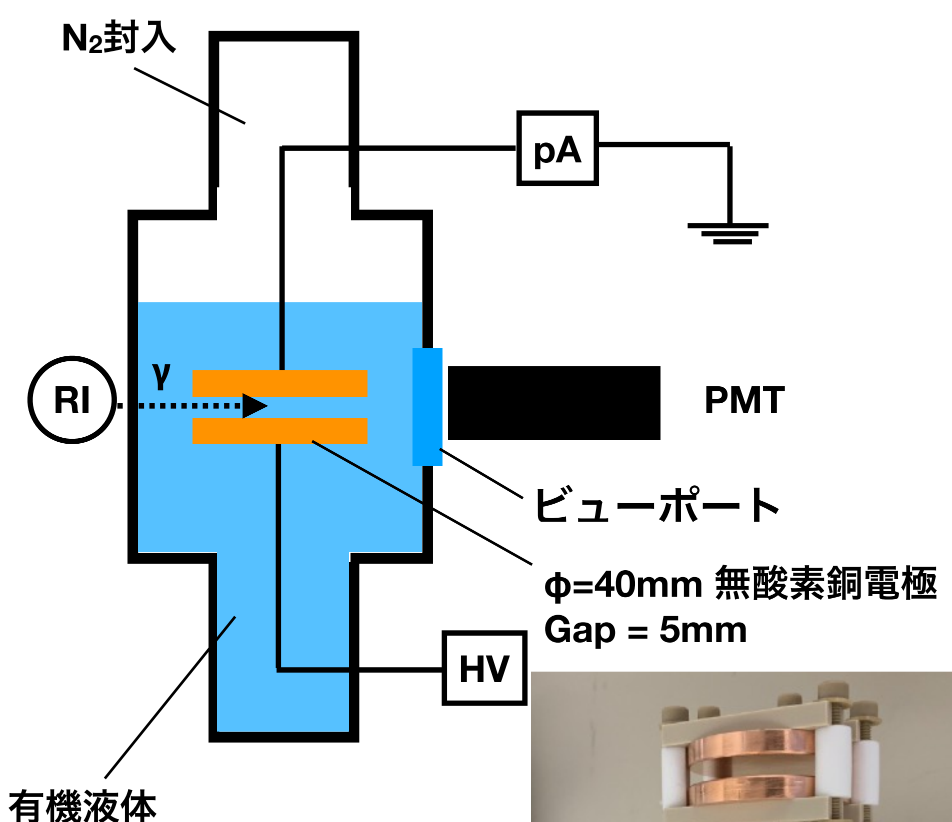


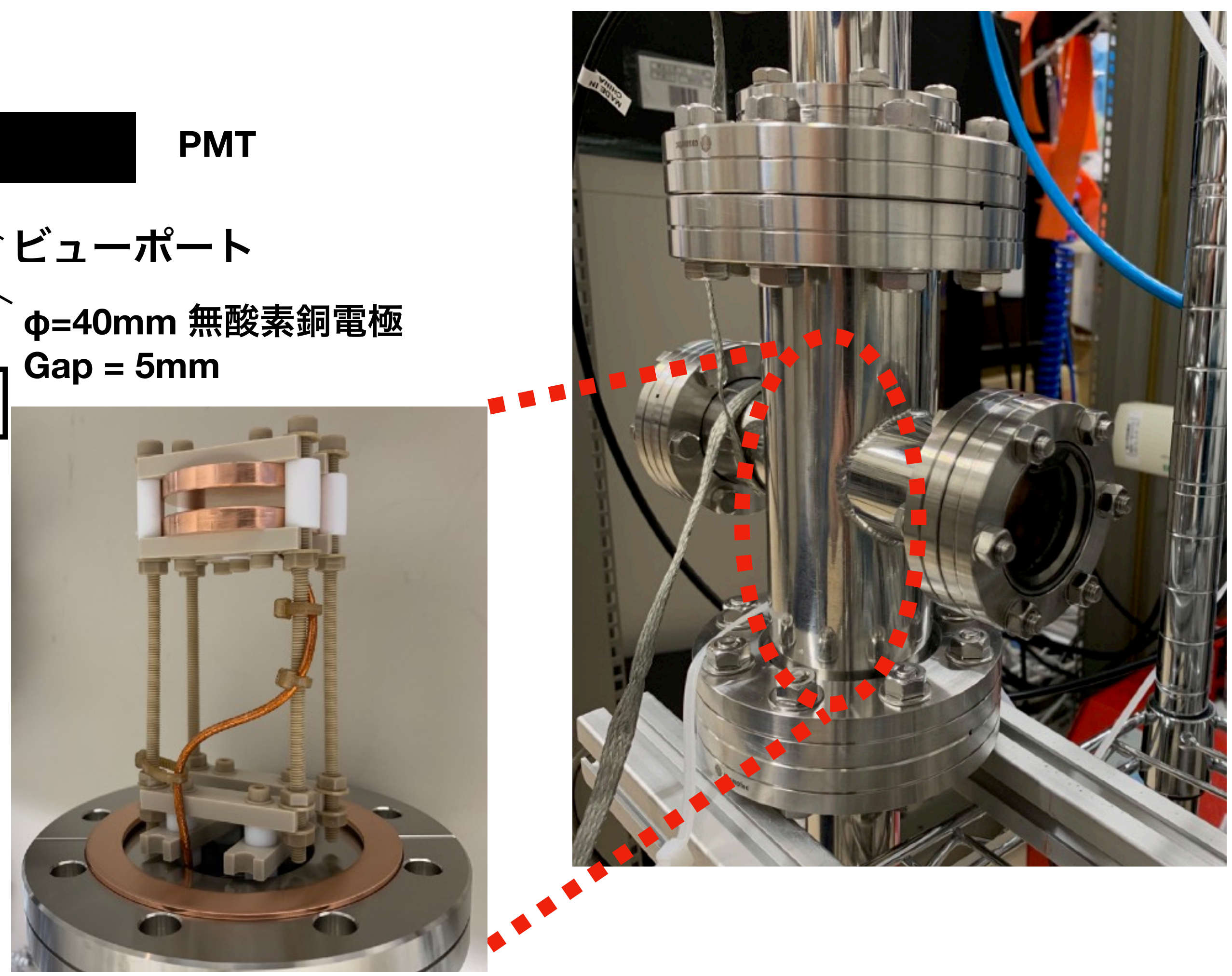
Atmospheric NCQE

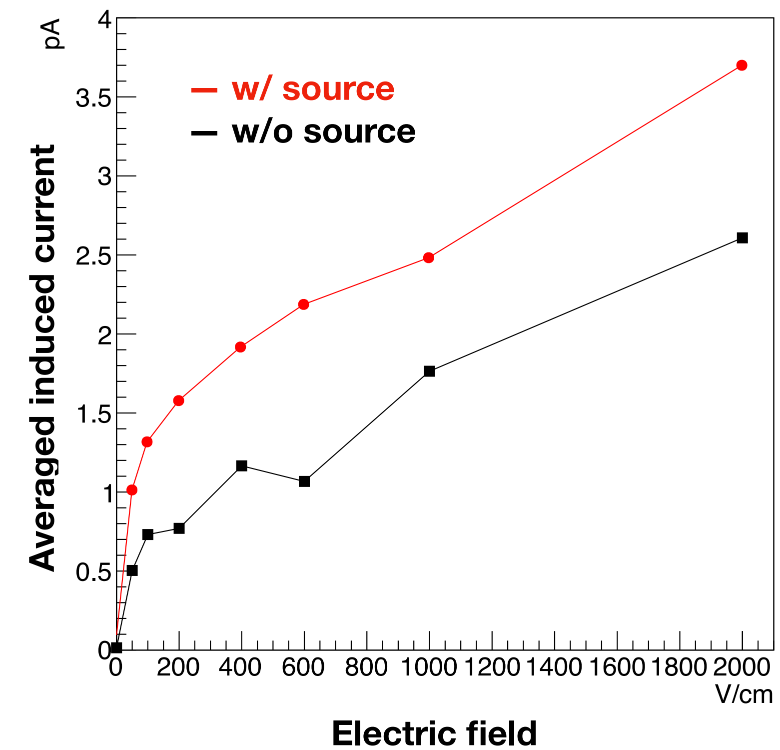


Ideal detectors for DSNB detection if realized at >10 kton scale

Test chamber at Kamioka



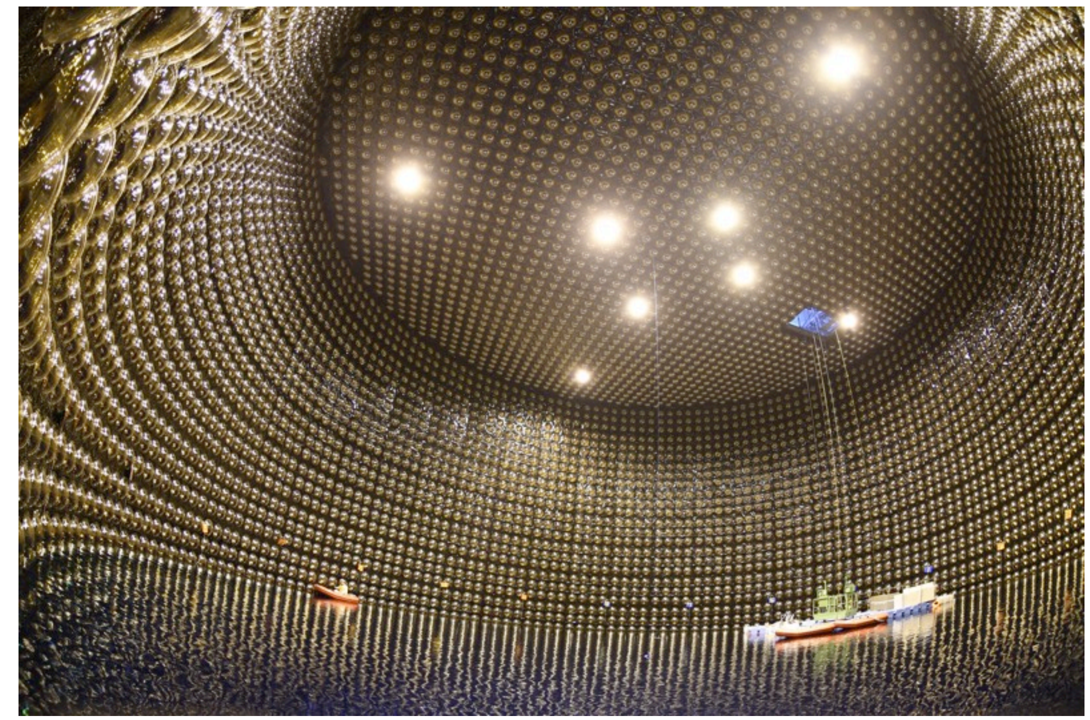




https://indico2.riken.jp/event/3144/contributions/13712/attachments/8963/11495/1-2_nakajima.pdf for more details

Summary

- SK-Gd: Gadolinium-loaded Super-K with significantly improved neutron detection efficiency
- Initial loading to 0.01% Gd concentration in spring 2020
- Many preparation works ongoing
  - More details in the next talk by Ito-san
- Further reduction and constraining of backgrounds are also important for DSNB observation
- Get ready for the first observation of DSNB at SK-Gd!



Comming soon