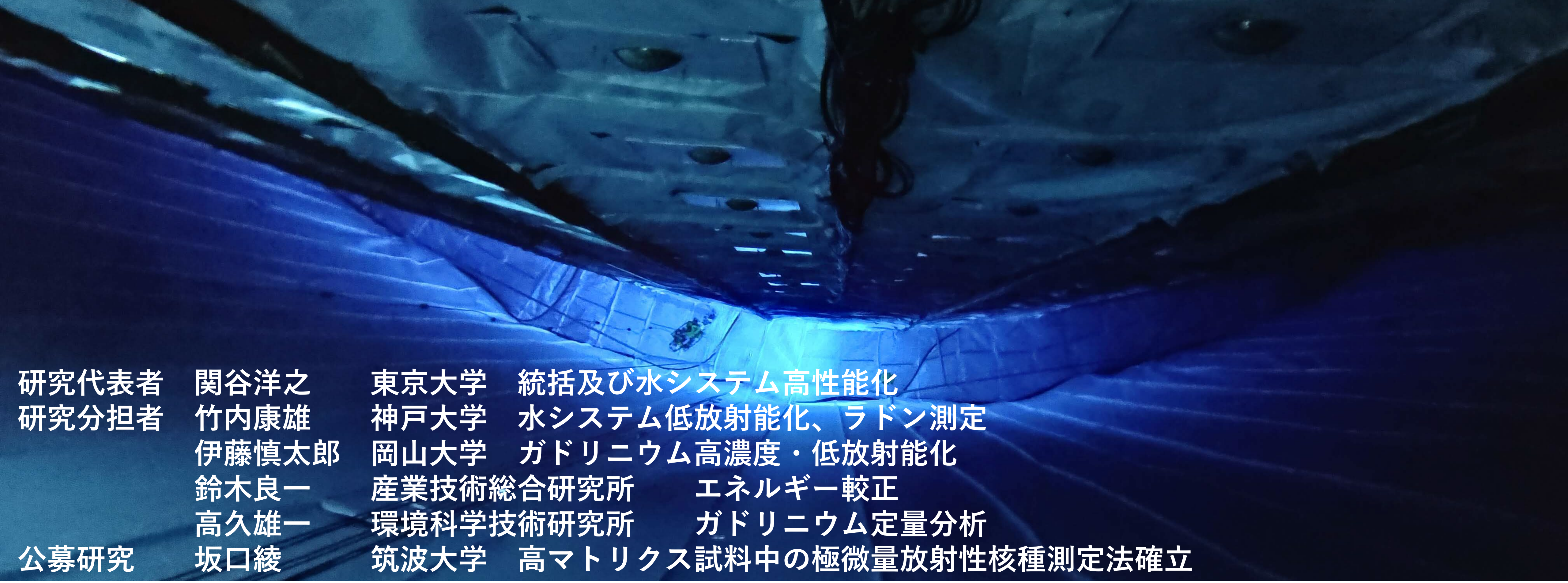

研究代表者	関谷洋之	東京大学	統括及び水システム高性能化
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	伊藤慎太郎	岡山大学	ガドリニウム高濃度・低放射能化
	鈴木良一	産業技術総合研究所	エネルギー較正
	高久雄一	環境科学技術研究所	ガドリニウム定量分析
公募研究	坂口綾	筑波大学	高マトリクス試料中の極微量放射性核種測定法確立

C01超新星背景ニュートリノの高感度観測でせまる宇宙星形成の歴史

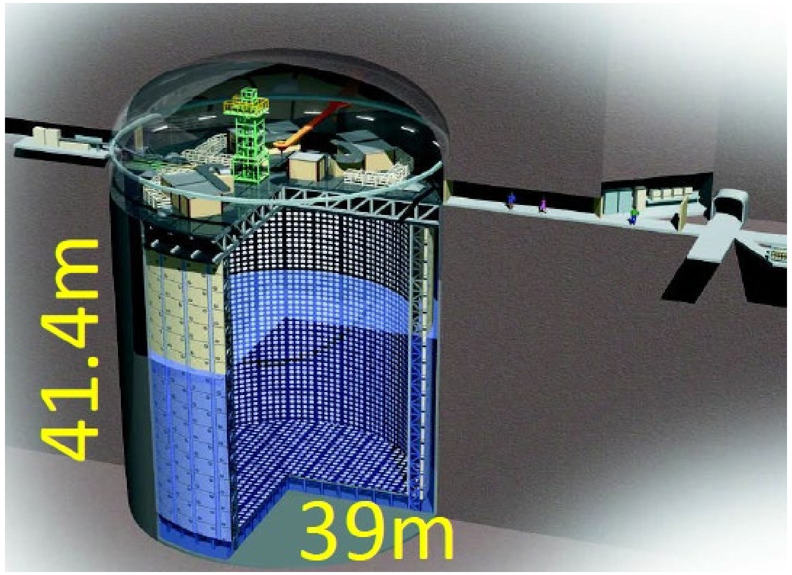
東京大学宇宙線研究所　関谷洋之

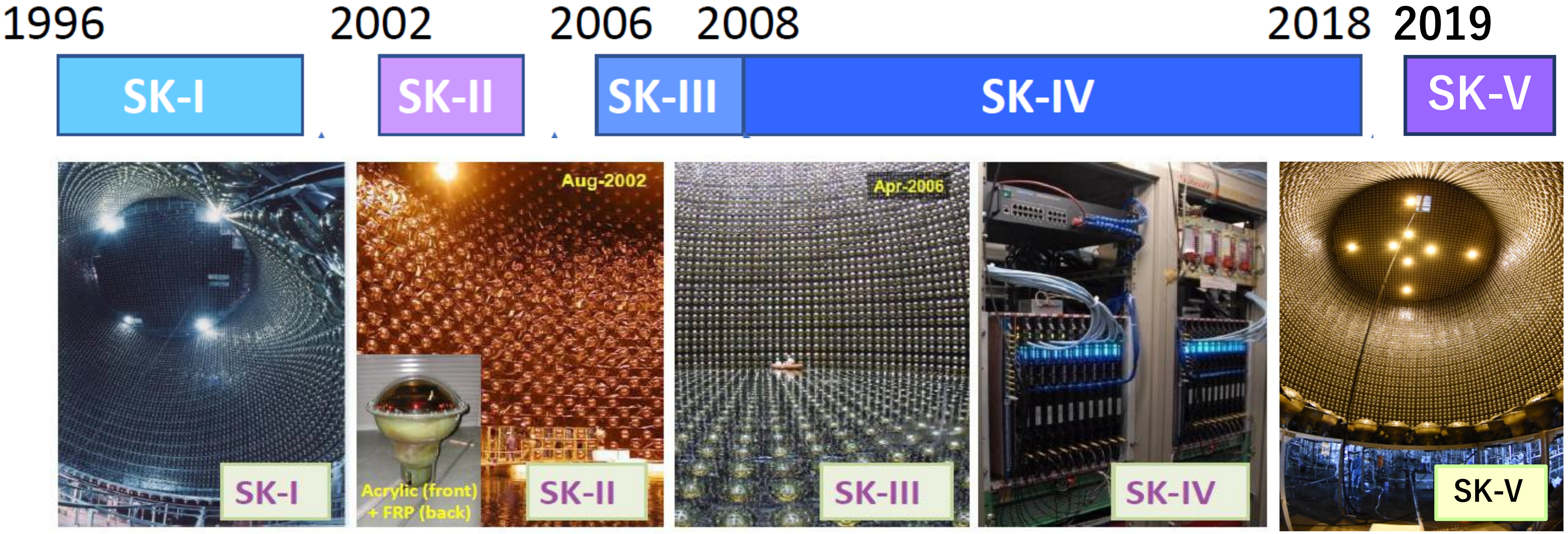
2020.6.3

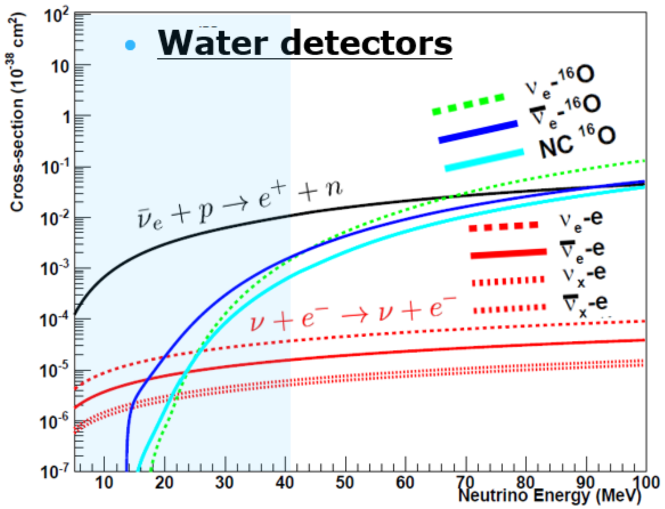
新学術「地下宇宙」領域研究会

Super-Kamiokande V

- 32kton ring imaging pure water Cherenkov detector for SNe
  - 11129 50cm PMTs for Inner detector
- 1km (2700 mwe) underground in Kamioka
- Most sensitive to SN $\bar{\nu}_e$ through inverse beta decay
- Since Jan 29, 2019, SK-V has been operated
  - After the tank refurbishment work for coming Gd-loading

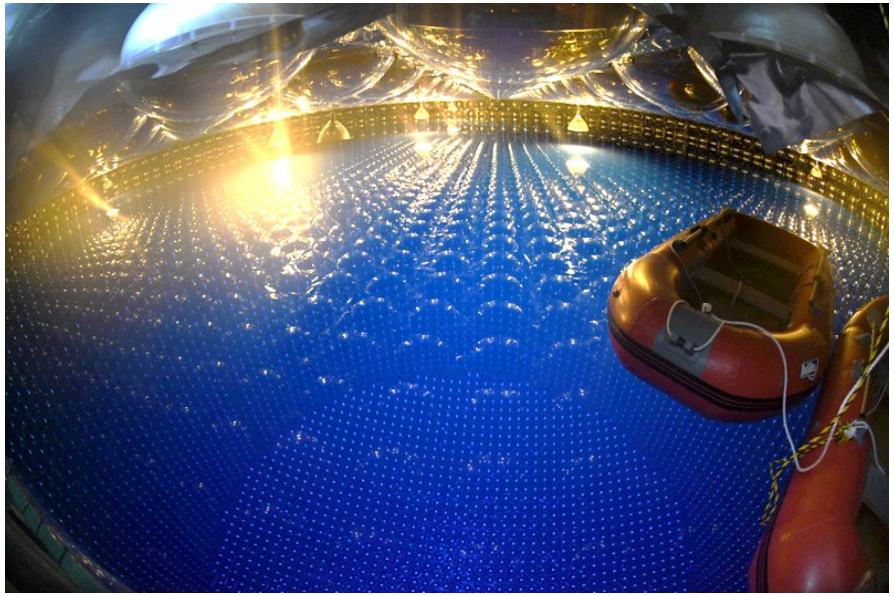






SK-V: The lowest BG phase

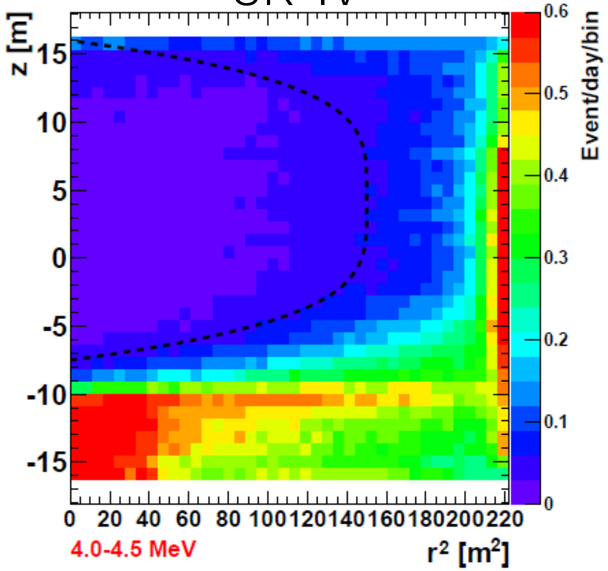
- Cleaning in 2018



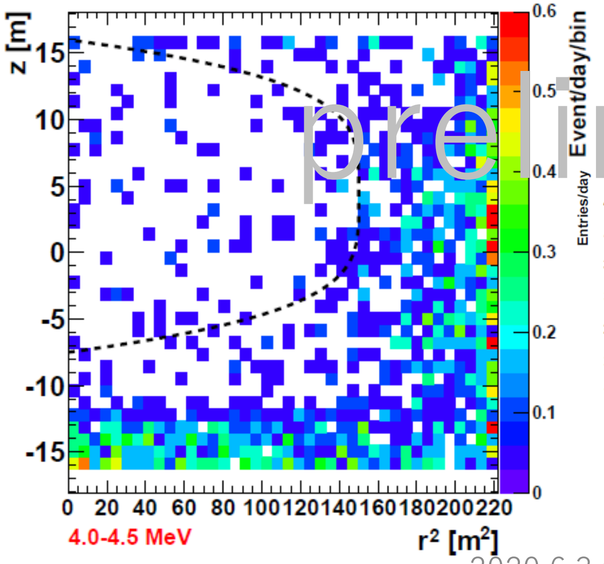
- Tuning the water flow in 2019
  - Water convection is successfully suppressed

Vertex distributions

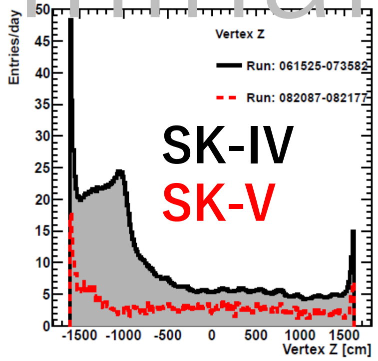
SK-IV

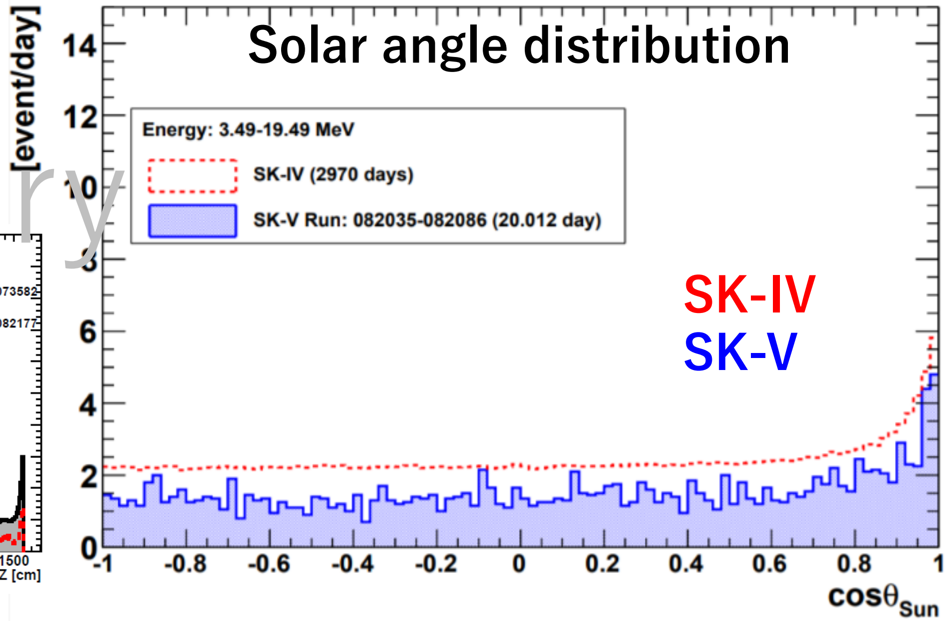


SK-V



preliminary

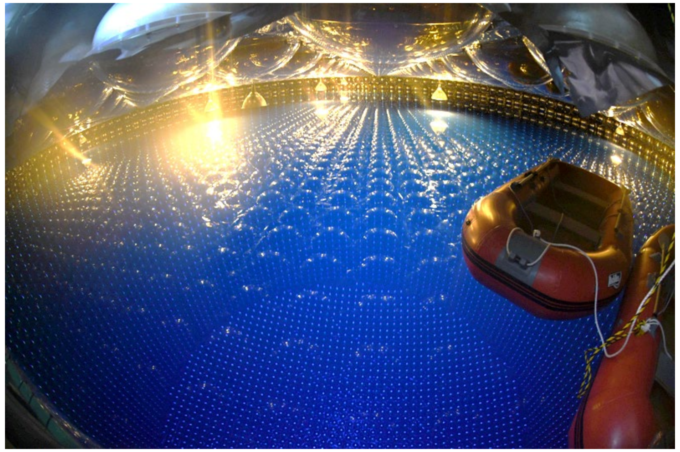




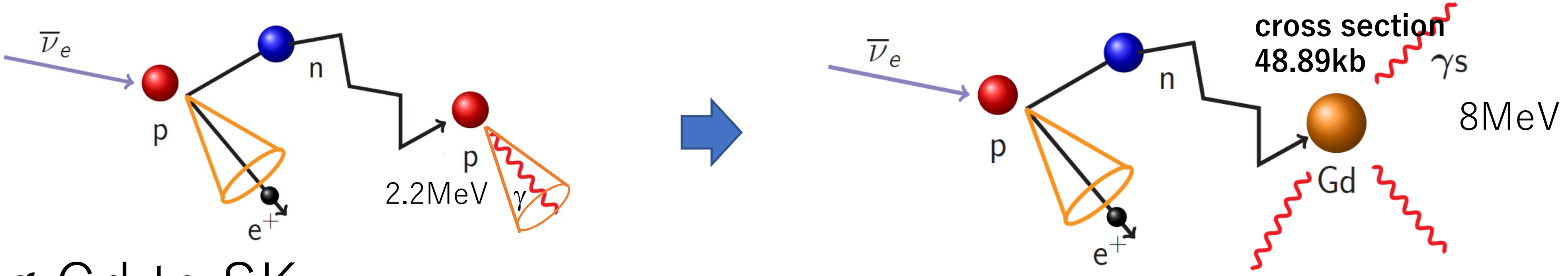
SK-Gd Project

Physic targets

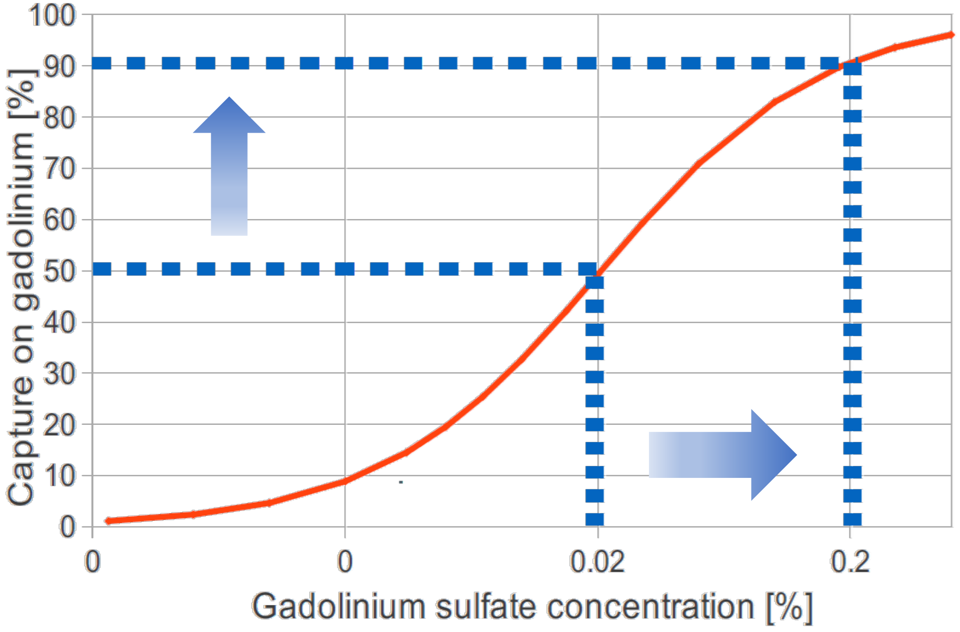
- Precursor of nearby supernova by Si-burning neutrinos
- Improve pointing accuracy for galactic supernova
- **First observation of Supernova Relic Neutrinos**
- Others
  - Reduce proton decay background
  - Neutrino/anti-neutrino discrimination
    (For T2K and atmospheric nu's analyses)
  - Reactor neutrinos



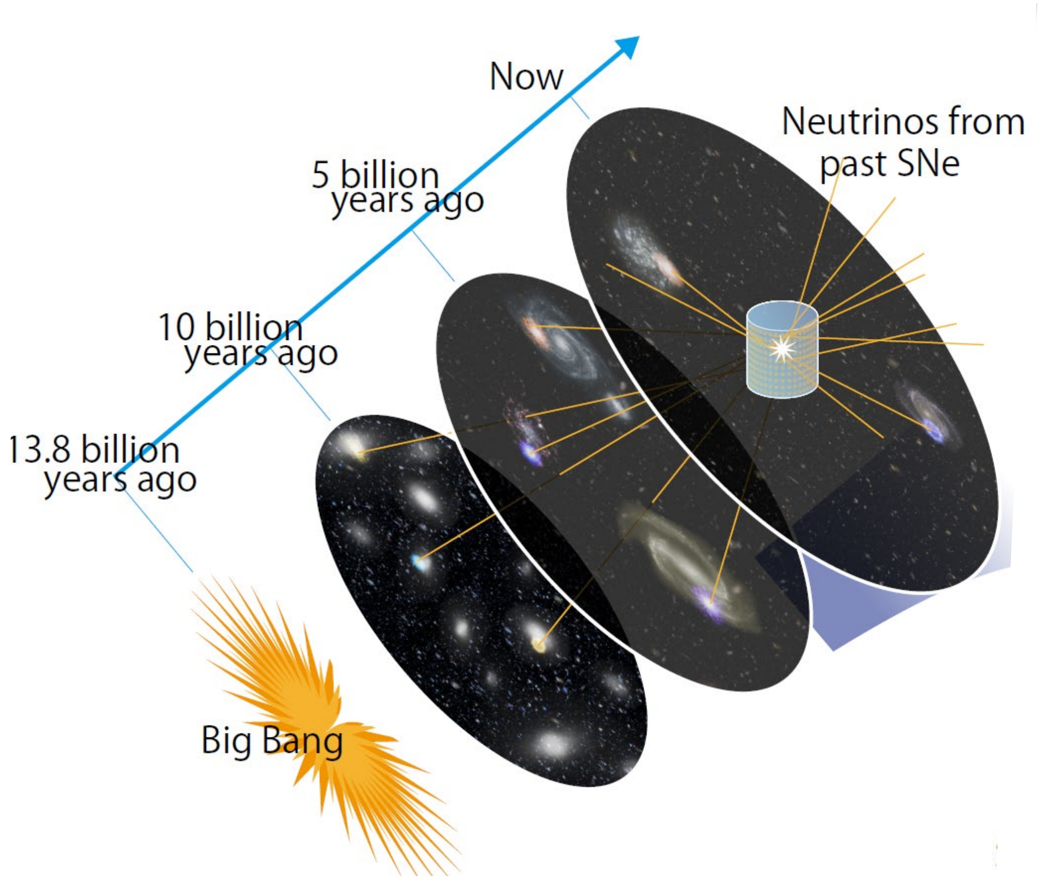
SK-Gd project



- Loading Gd to SK
  - To significantly enhance detection capability of neutrons from $\bar{\upsilon}$ interactions
  - 0.02% $Gd_2(SO_4)_3$ concentration in 2020.
    - About 50% of neutron would be captured by Gd, enhancing neutron tagging efficiency by 2-3 times.
- Planned gradual increasement of Gd
  - Final target: 90% of neutron tagging
  - Aiming at 70% with this Kakenhi



Diffused Supernova Neutrino Backgrounds
Supernova Relic Neutrino

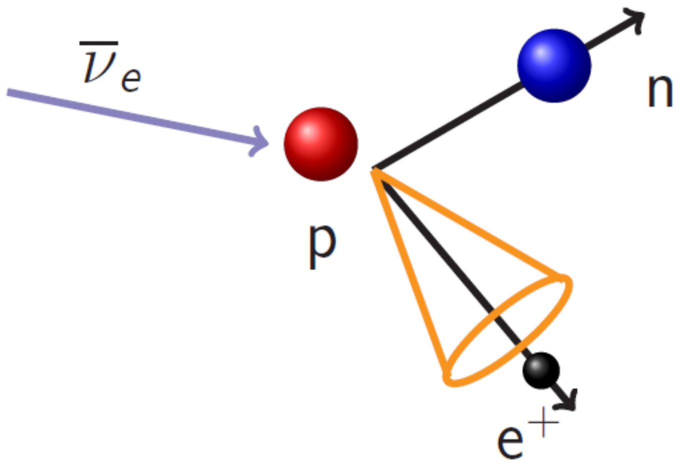


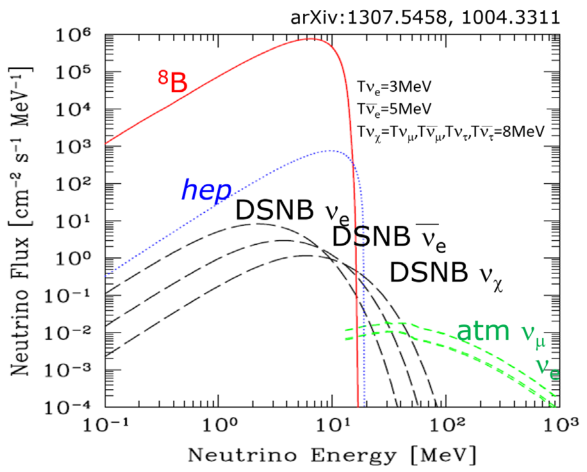
- Neutrinos produced from the past SN bursts and diffused in the current universe.
  - ~ a few SN explosions every second → $O(10^{18})$ SNe so far in this universe
  - Can study history of SN bursts with neutrinos

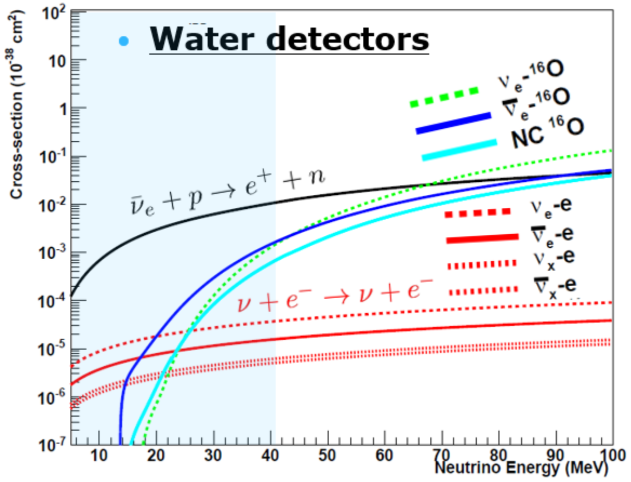
$$\frac{dF_\nu}{dE_\nu} = c \int_0^{z_{\max}} R_{\rm SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} (1+z) \frac{dt}{dz} dz$$

DSNB signal in SK

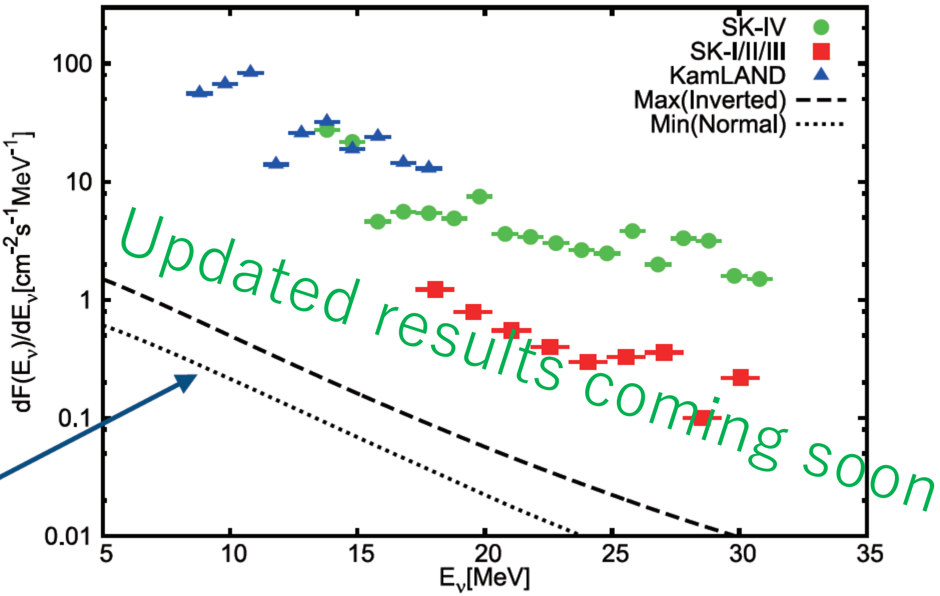
- Inverse beta decay channel







Astrophys. J. **804**, 75 (2015)



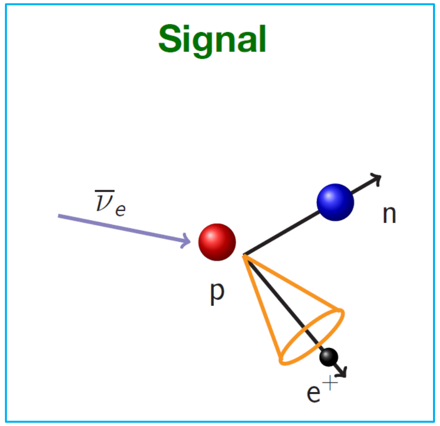
- Super-K holds the current best limits for the DSNB flux
- Sensitivity limited by backgrounds

  However, only one order magnitude above theoretical predictions.
- Should be within Super-K's reach, once we were able to reduce background!

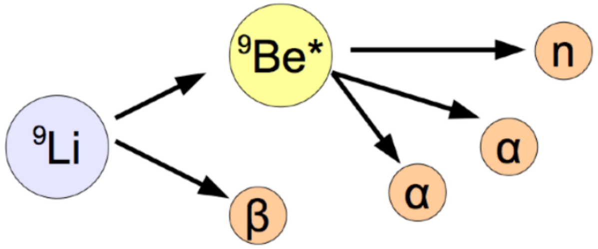
Theoretical predictions

➡ Neutron tagging!

Major backgrounds
after n-tagged

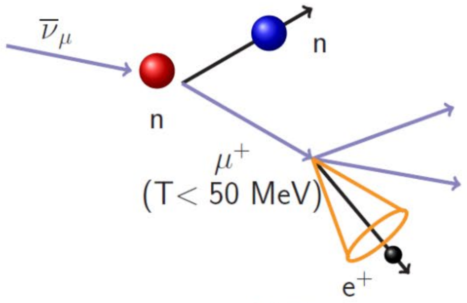


⁹Li (from cosmic muon spallation)

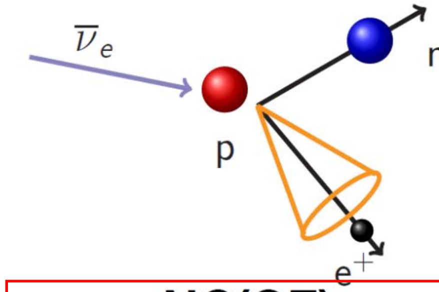


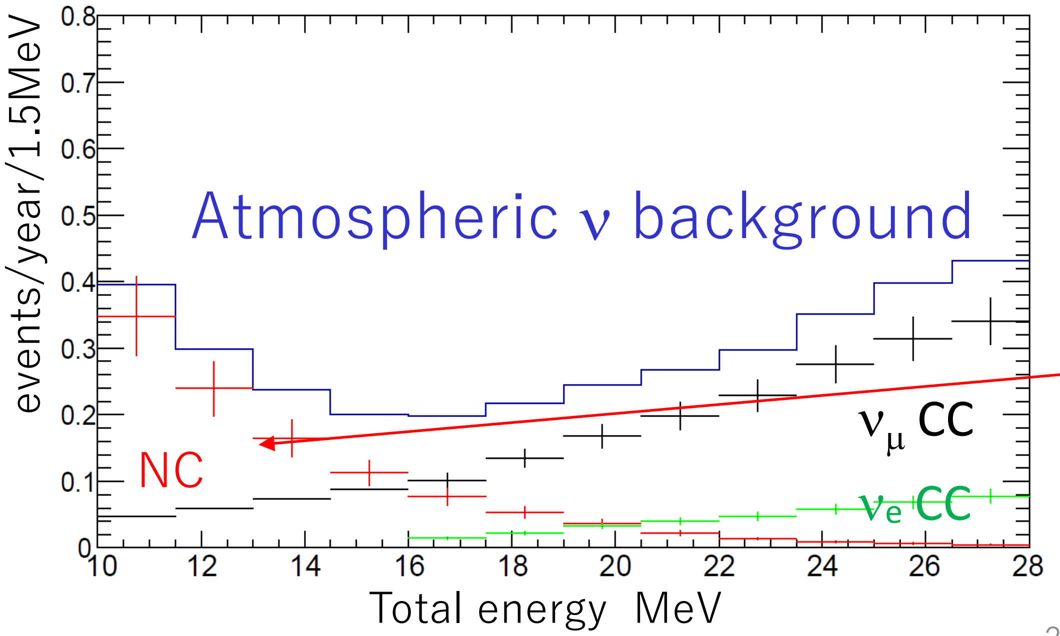
Atmospheric neutrinos

ν_μ CC

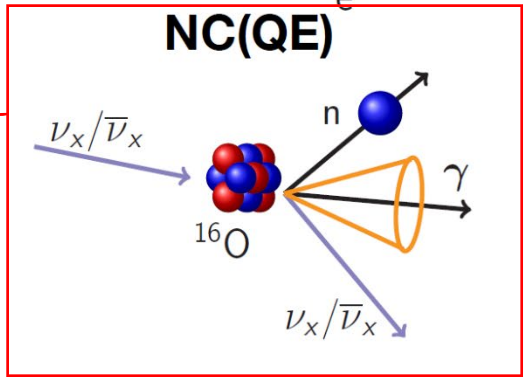


ν_e CC





Among these, atmospheric ν's NC events are the most problematic BG

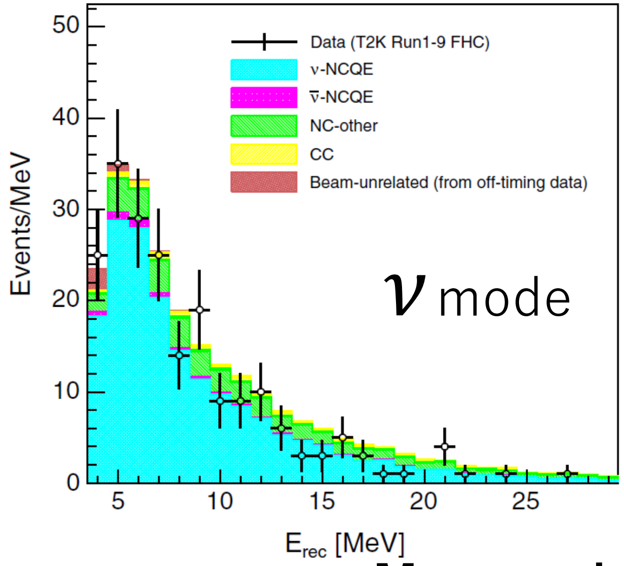


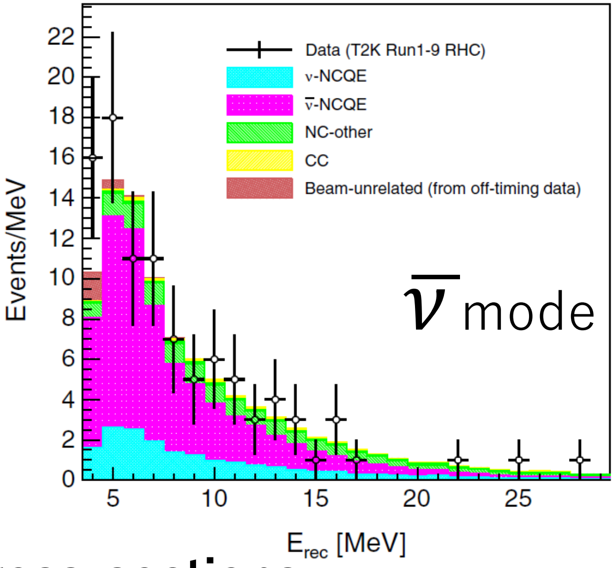
Neutrino calibration source: T2K

T2K Run 1-9 Phys. Rev. D 100, 112009 (2019)

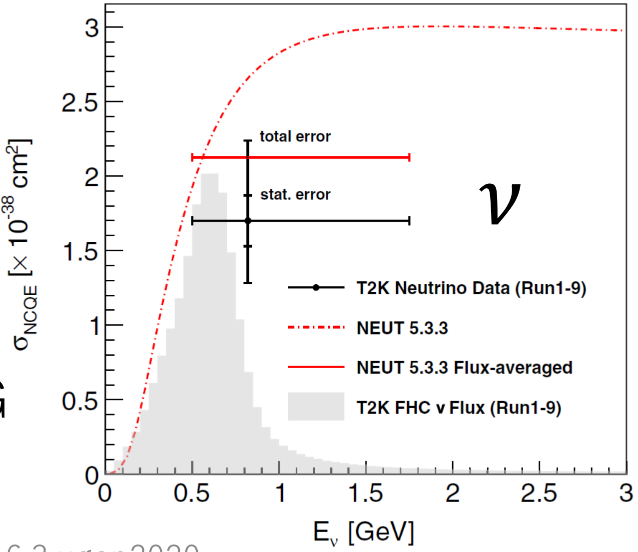
- Large part of beam energy spectrum overlaps with atmospheric neutrinos

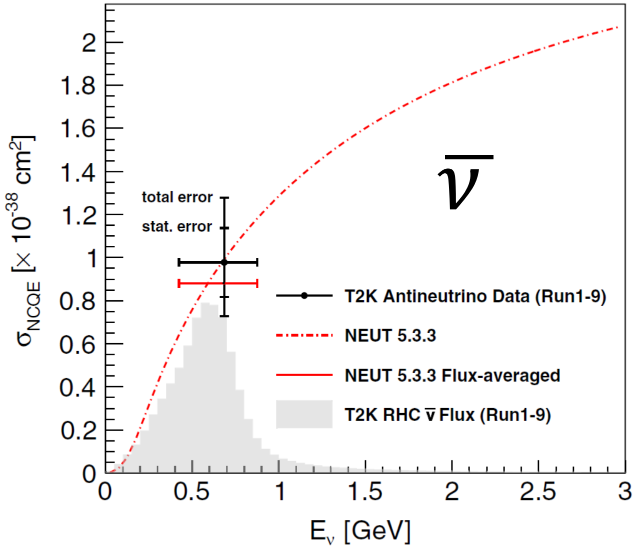
➡ Control sample of NCQE interaction





Measured cross-sections

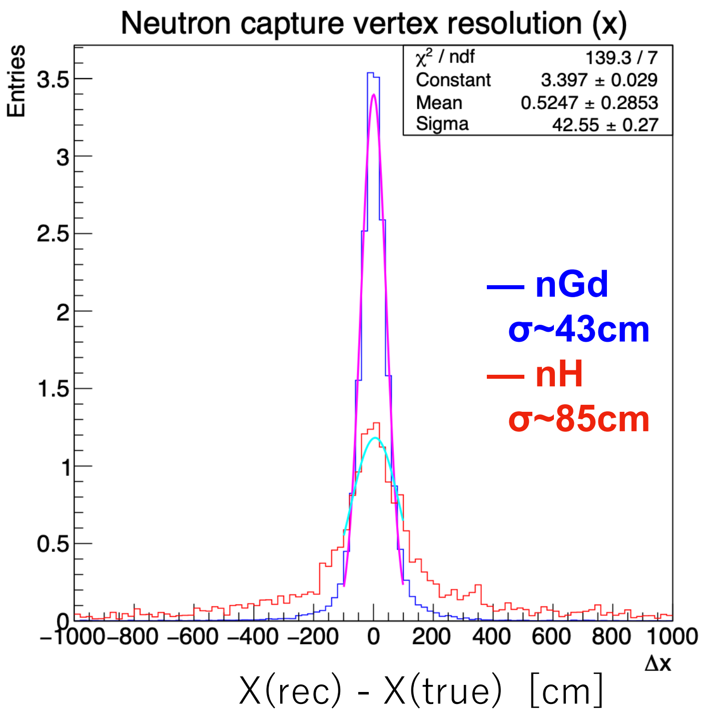


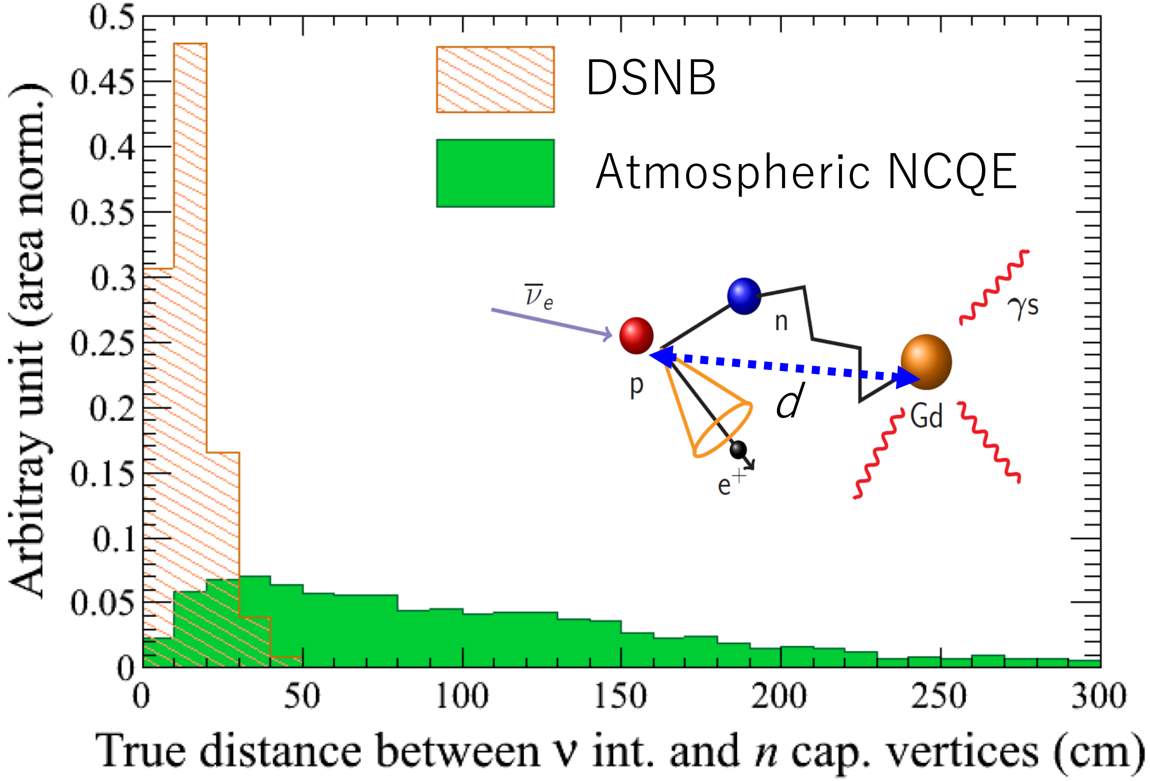


- NCQE cross sections has been measured by T2K for the first time.
  - Still large uncertainty:
    - due to small statistics
    - ~30% systematic error for NCQE BG
  - More data will come

Development of NCQE cut w/ T2K data

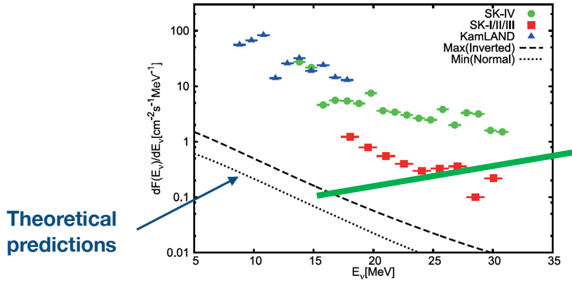
- Improved vertex resolution w/Gd will enable topology cuts.
- Further background reduction w/ event topology
  - Neutron from NQCE interaction should be more energetic



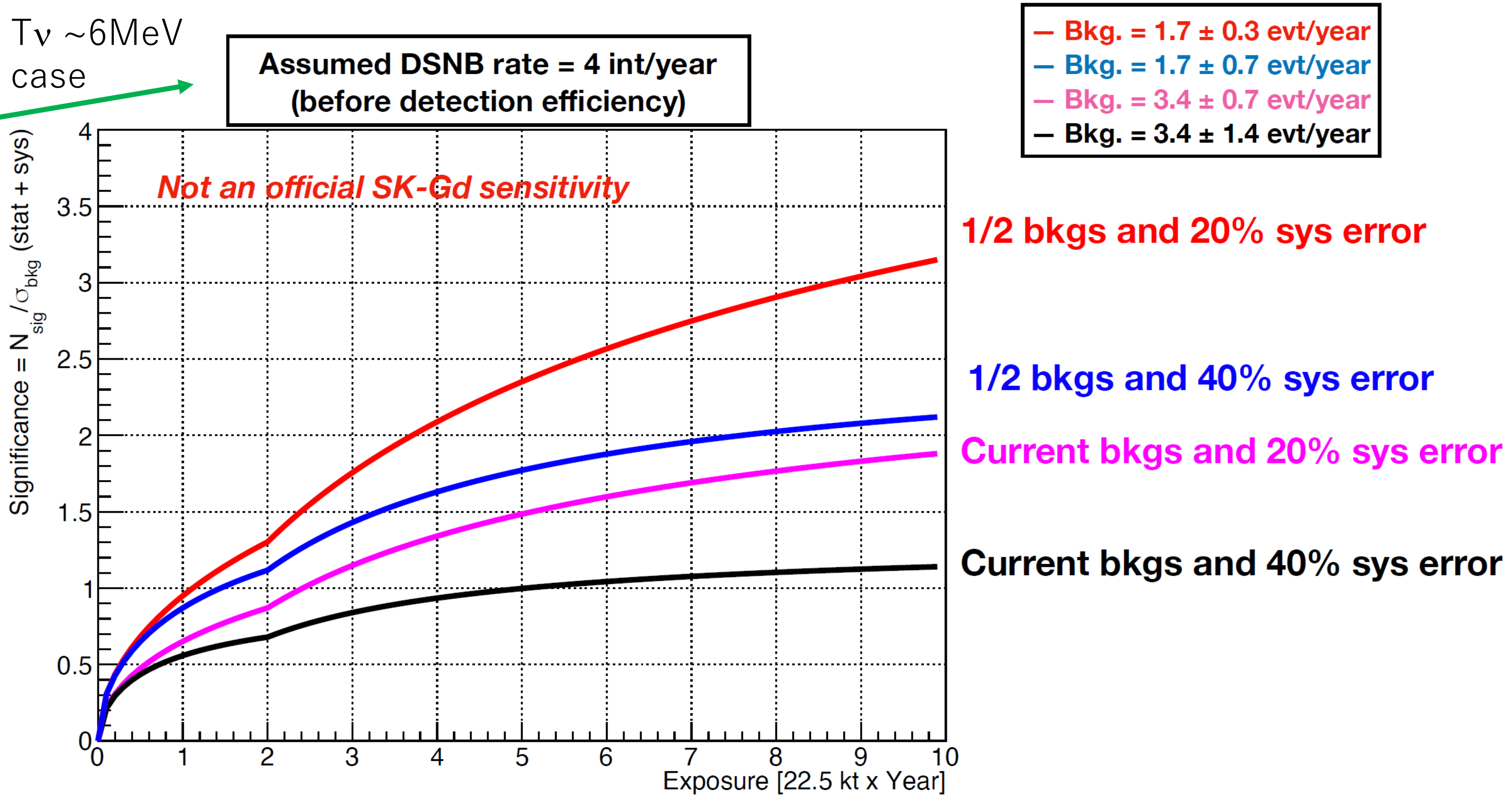


DSNB sensitivity

- Assuming neutron tagging efficiency increased to >70% in 2022

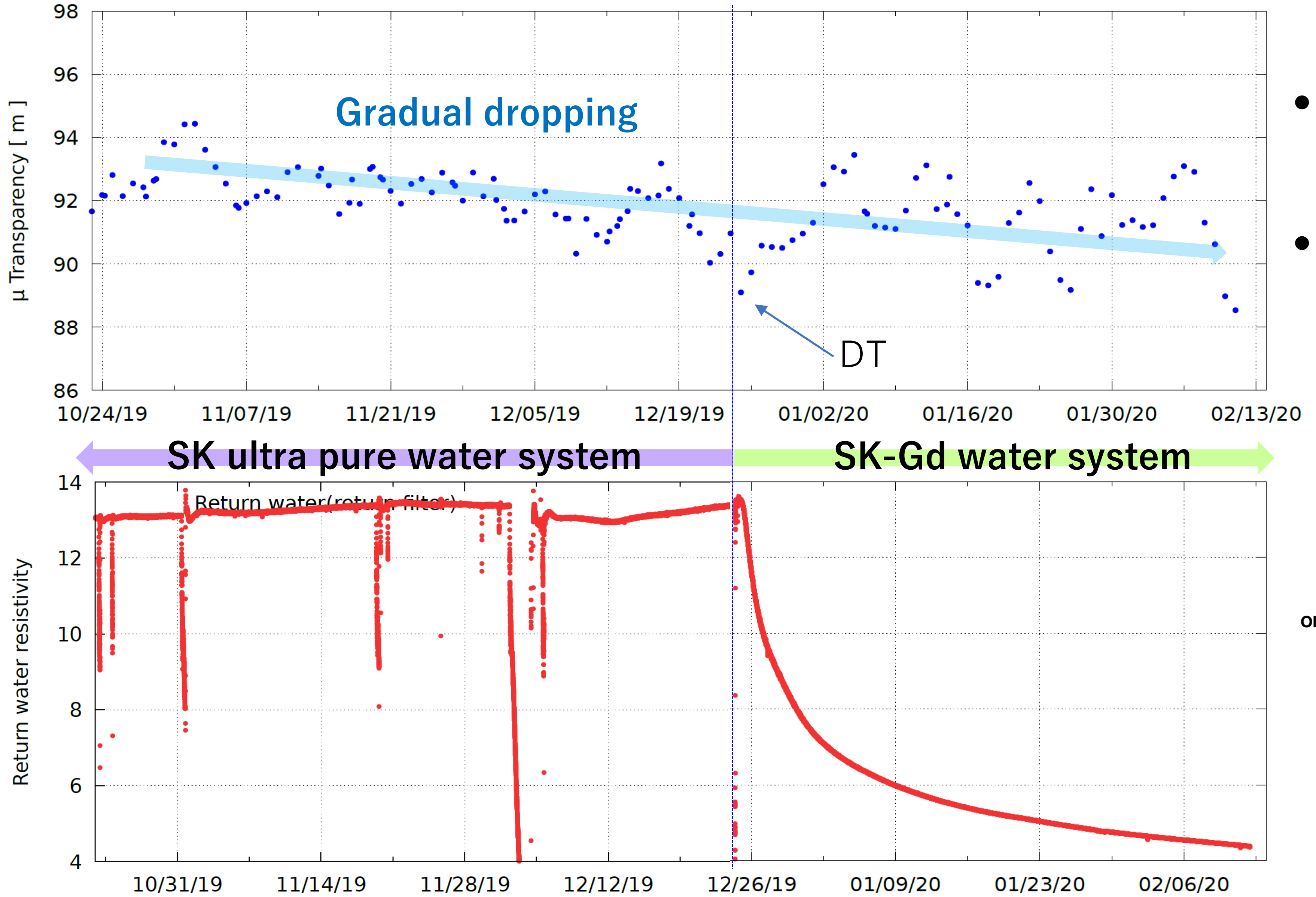


Tν ~6MeV case

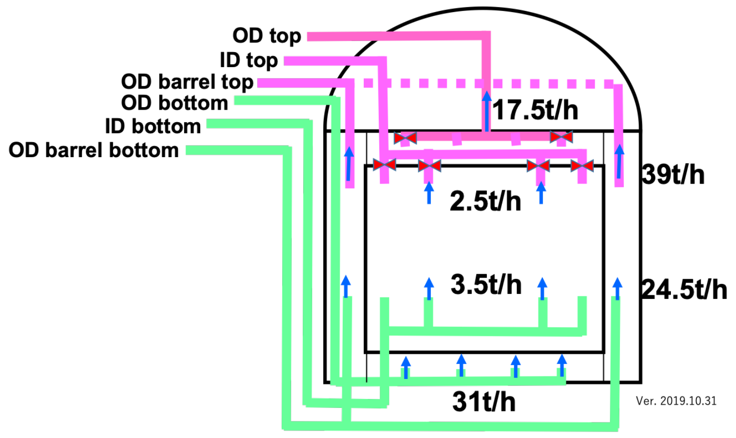


Major activities since ugap2019 meeting

Validation of SK-Gd system with non-Gd water



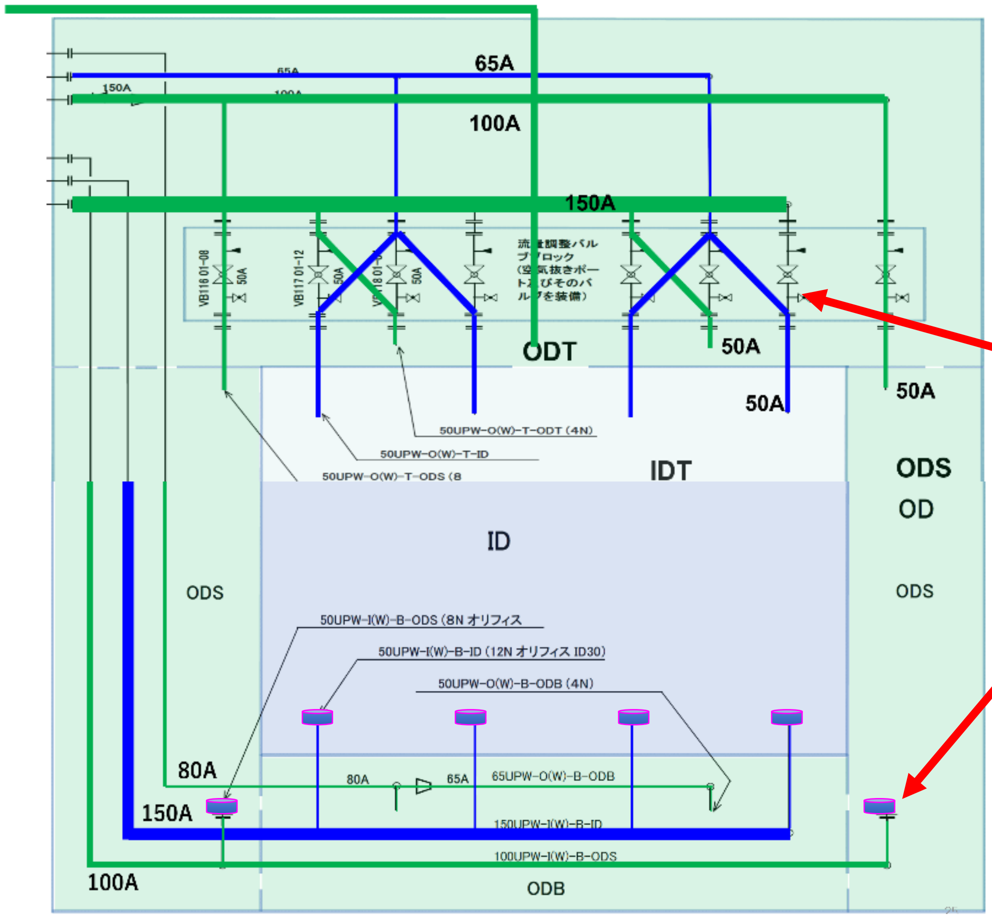
- Stagnated water is good for Rn
- No difference in transparency between SK and SK-Gd water

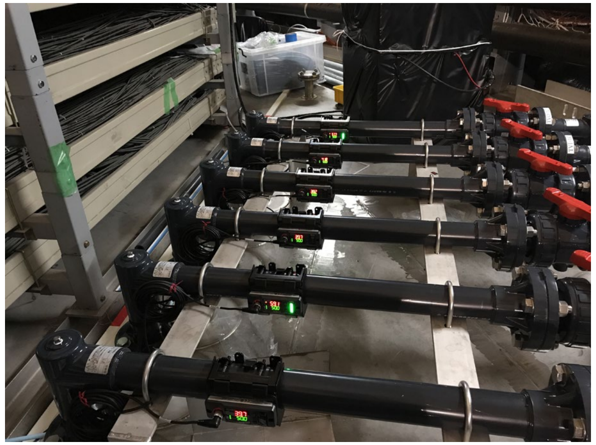


Modifications on piping in the tank

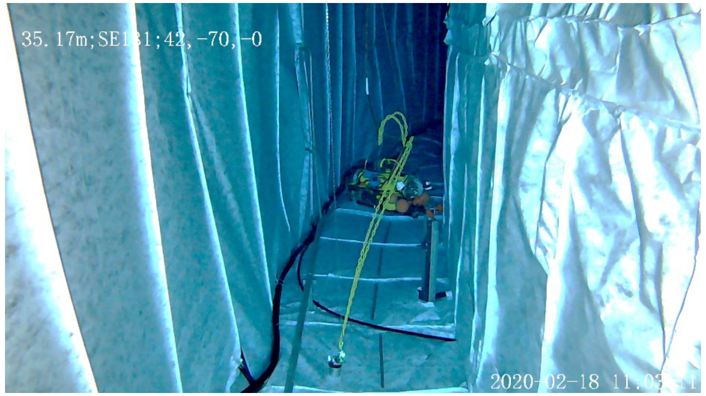
Done during Feb 12- Feb 25

For better water flow control and lower BG in 120t/h recirculation of SK-Gd

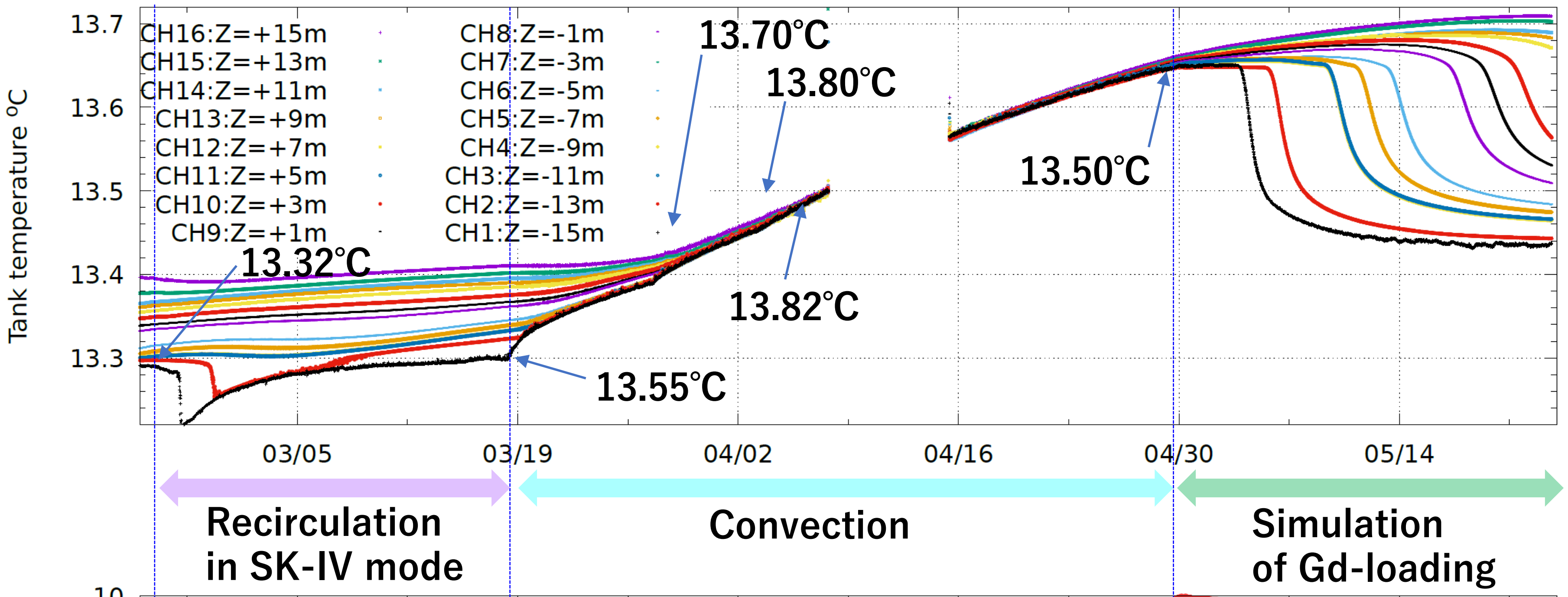


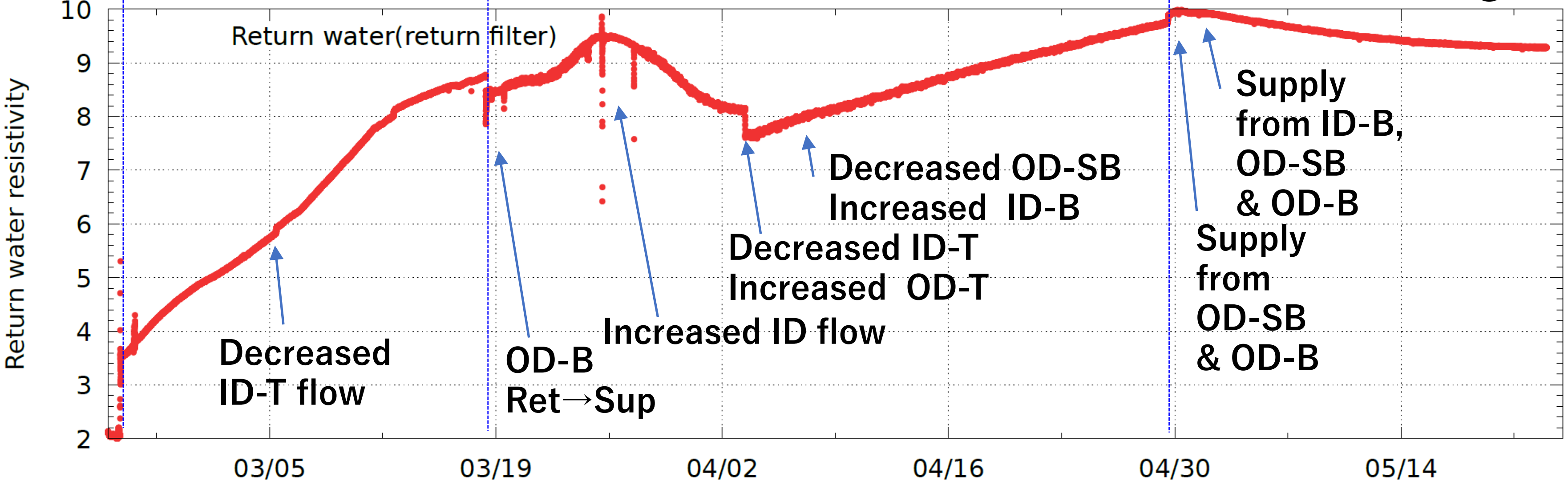


- Enhancing OD top piping
  - By swapping the main branch of ID-T(150A) and that of OD-T (65A)
- Putting diffuser caps on water outlets by RTV



The water flow control





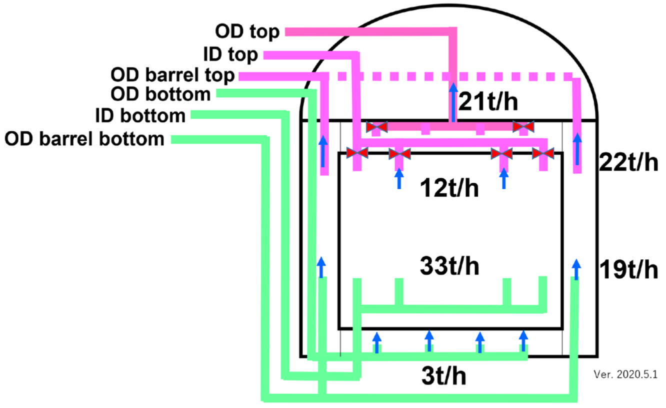
Simulation of Gd-loading

- Nice temperature gradient
- Decrease of the return water resistivity

  No mixture of supply water

→Laminar flow

Gd-loading simulation is successful! Also it shows the modifications were successful!



Preparation of Gd detail→『極低放射能研究会』

- Getting 14 tons of “uniform quality Gd” is difficult.
  - Getting “Uniform feedstock quality” is almost impossible! →坂口さん
- ^{238}U,^{232}Th,^{40}K are not only the targets.
  - Chemical process::broken equilibrium
  - ^{228}Ra, ^{228}Ac
  - ^{235}U, ^{231}Pa,^{227}Ac
  - ^{176}Lu
  - ^{138}La,^{134}Cs,^{137}Cs,…
- Not only RIs
  - Ce, Eu,… wavelength shifter

→Evaluation methods themselves must be developed
  - Chemical pretreatment: separation, extraction, concentration…
  - Ultra sensitive Ge and ICP-MS are indispensable.

  →高久さん、伊藤さん、市村さん、坂口さん

Our Requirement

Radioactive chain	Part of the chain	SRN (mBq/kg)	Solar ν (mBq/kg)
^{238}U	^{238}U	< 5	-
	^{226}Ra	-	< 0.5
^{232}Th	^{228}Ra	-	< 0.05
	^{228}Th	-	< 0.05
^{235}U	^{235}U	-	$<$ 30
	^{227}Ac / ^{227}Th	-	$<$ 30

TABLE VII. Physics-based requirements for radioactive impurities. Where no number is given (-), the corresponding requirement is less restrictive than that for the other physics analysis.

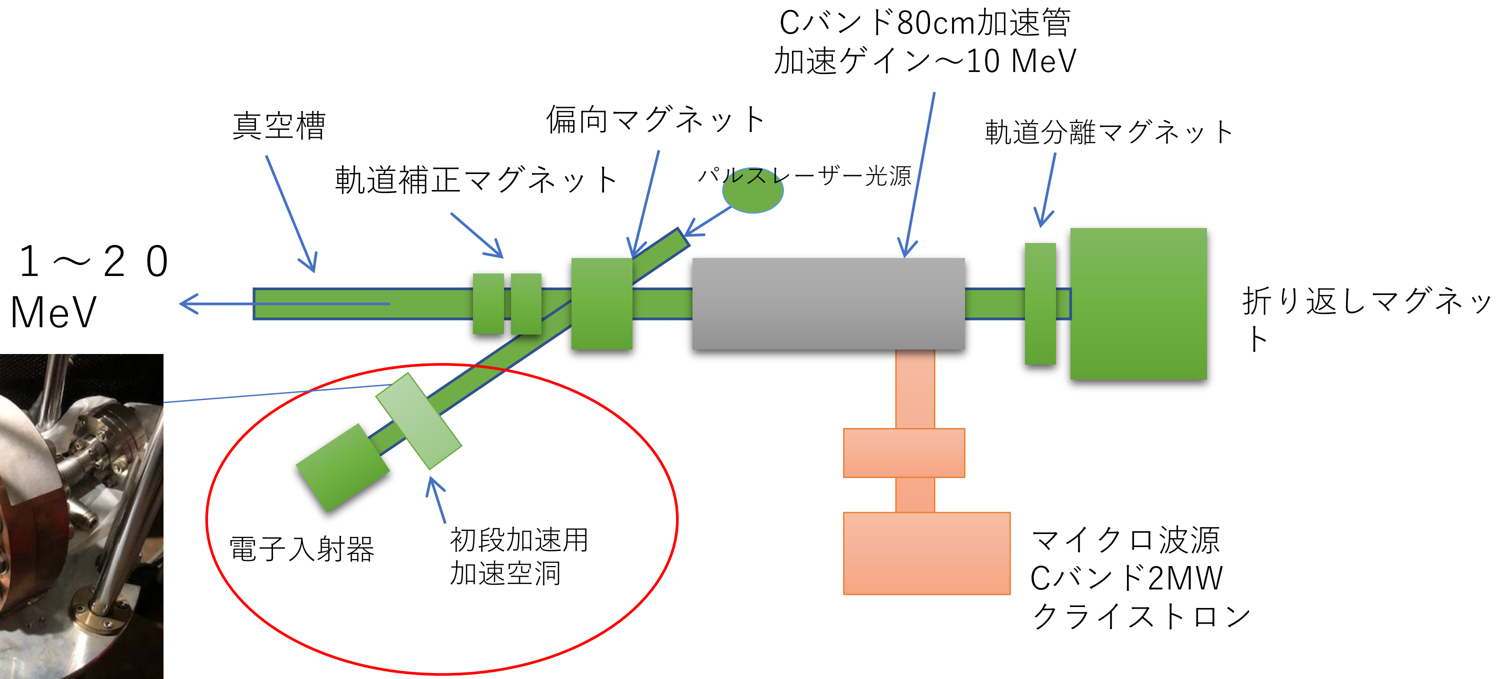
^{222}Rn: Gd水溶液中測定＋膜脱気の開発(竹内さん)

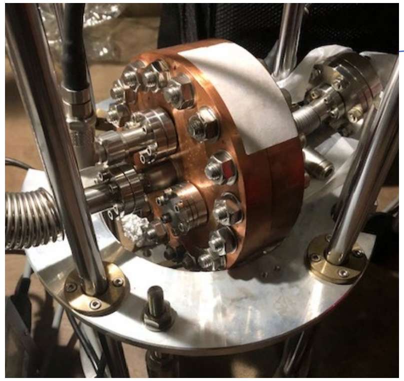
- **目的： 感度 ~0.5 mBq/m^{3}のGd水中^{222}Rn 測定に対応した、「80Lラドン検出器+中空糸膜モジュール」を開発し、SK-Gdの給水モニター、XENONnT nVeto中Rnモニターに応用する。(D01+C01)**
- **進捗： 脱気膜モジュールのキャップ部分をステンレス化し、ステンレス配管部分との間の水漏れの可能性を無くした。（従来はRTネジ）**
- **予定： 更にハウジング部分もステンレス化した脱気膜モジュールを試作し、BGレベルの確認を行う。**

従来型の脱気膜モジュール

ステンレスキャップの脱気膜モジュール

エネルギー較正:電子加速システム(鈴木さん)





電子入射器＋初段加速部の開発

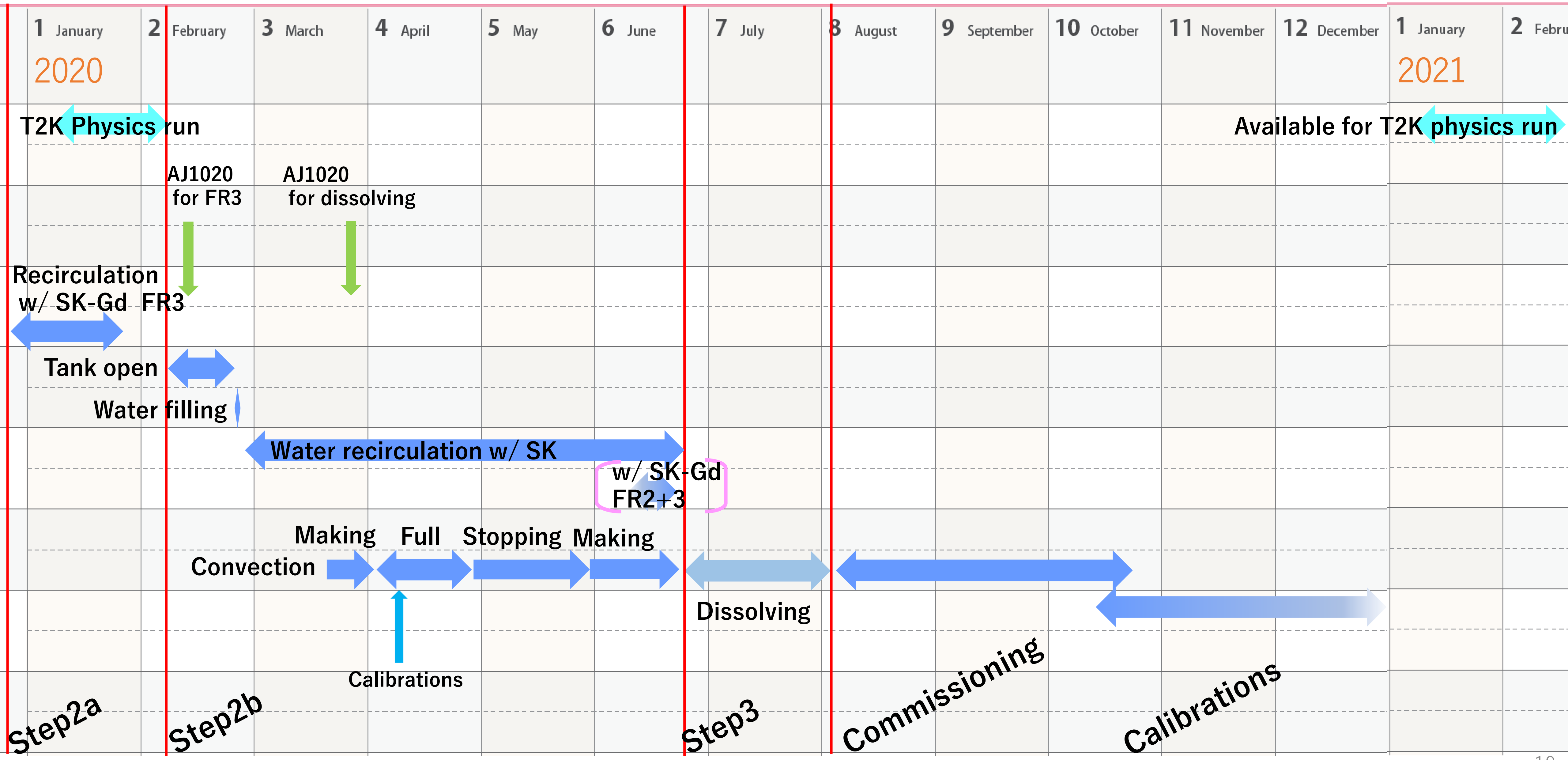
今年度加速実験の目標：　250-300 keV　主加速管では3MeV程度

電子入射器　　紫外光照射による光電効果での電子発生部を設計

今後試作し静電加速で　150～200 keVの電子を発生する

初段加速空洞　　特性評価を実施、RF加速で数十～100 keV 程度加速が見込めることを確認

T1 modified plan; Quick recovery from COVID-19



Water system & Gd are ready to go

- 14 tons of ultrapure $Gd_2(SO_4)_3\ 8H_2O$ are prepared.

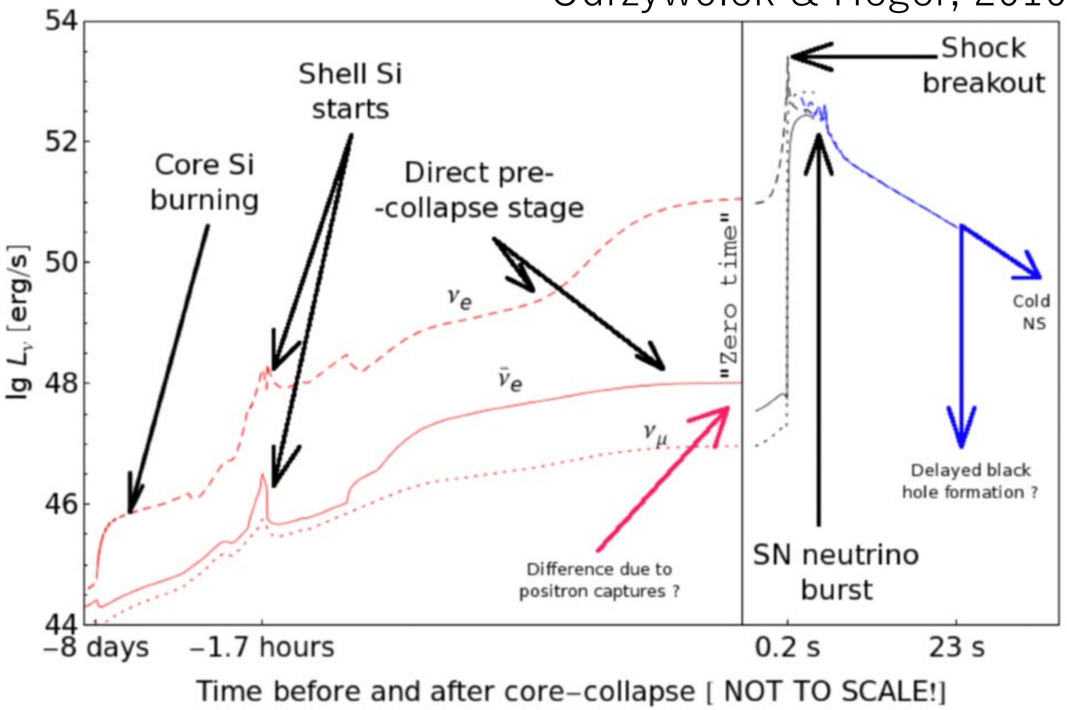
- These Gd will be dissolved in July!

Extra slides

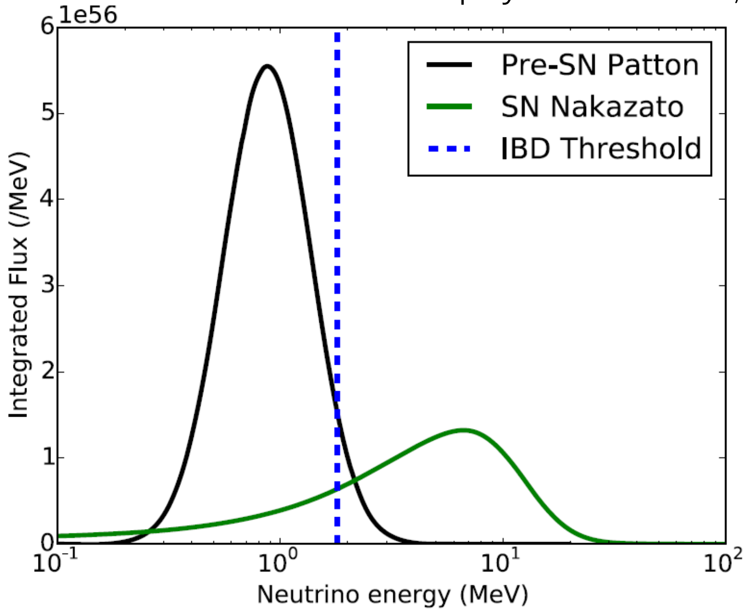
Pre-supernova signals

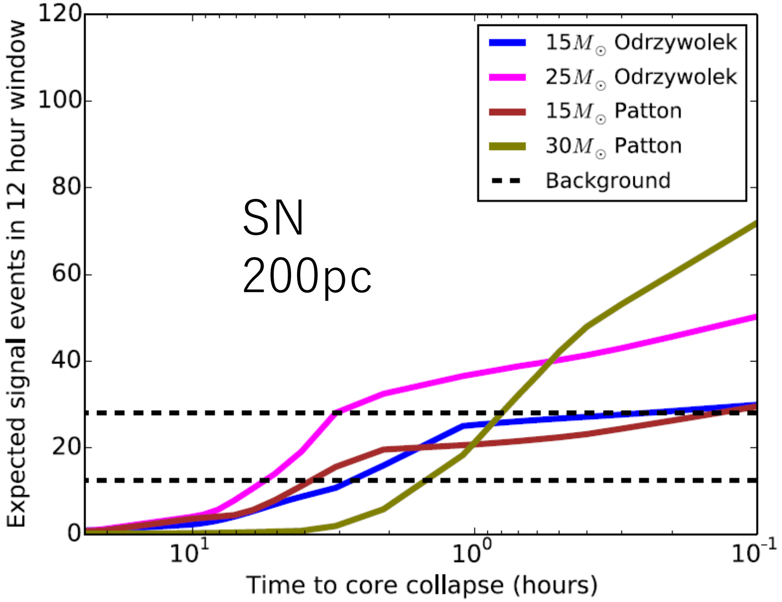
- Precursor signal from Si-burning is detectable for SK-Gd
  - Pre-SN's ν energy is lower than SN's
  - Gd loading is a requirement for SK

Odrzywolek & Heger, 2010



The Astrophysical Journal, 885:133, 2019

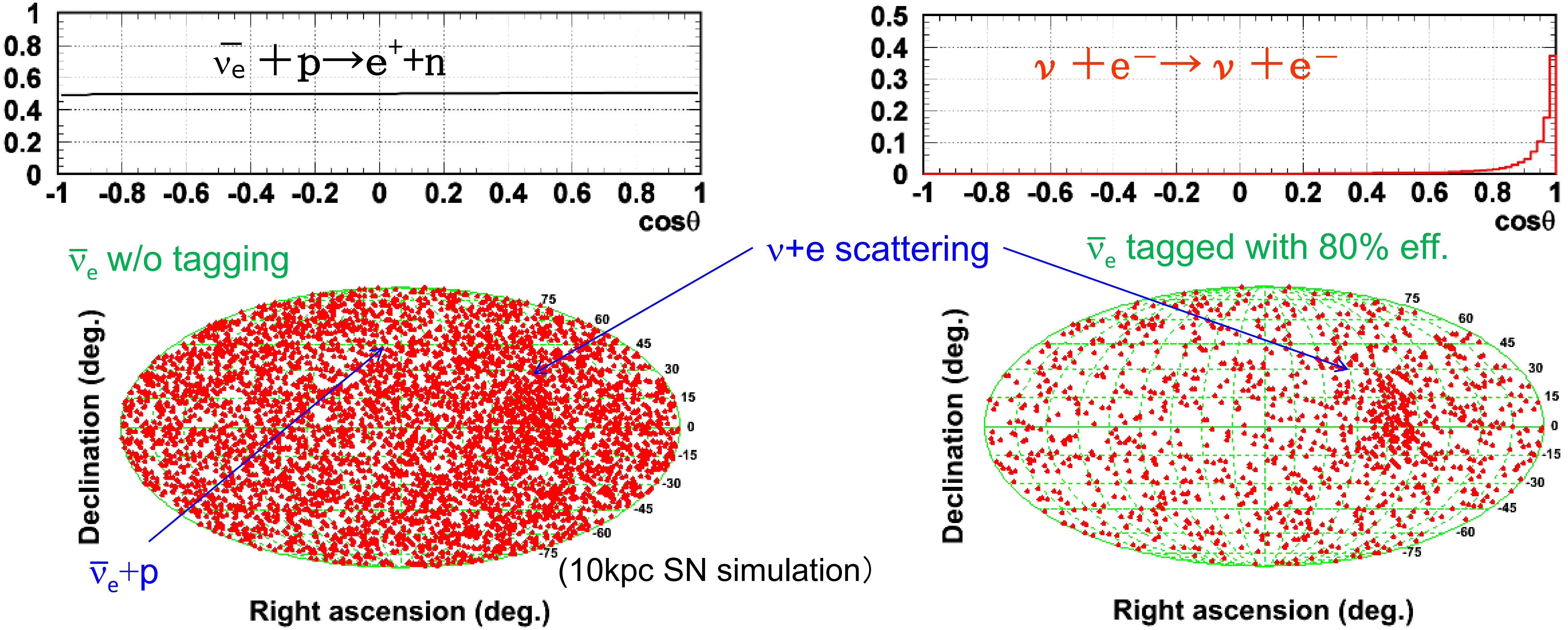




Early warning system will be prepared

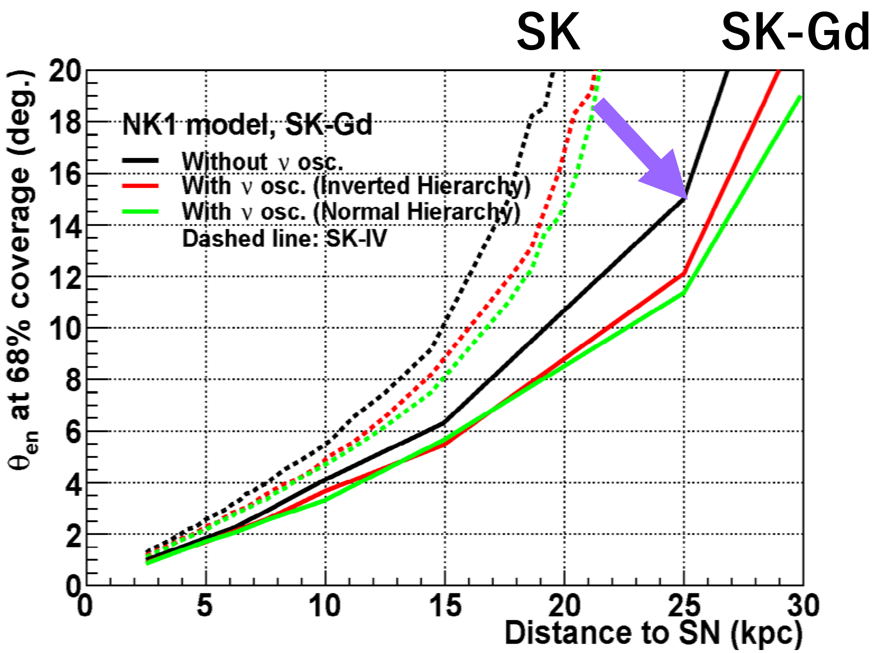
SK-Gd pointing accuracy

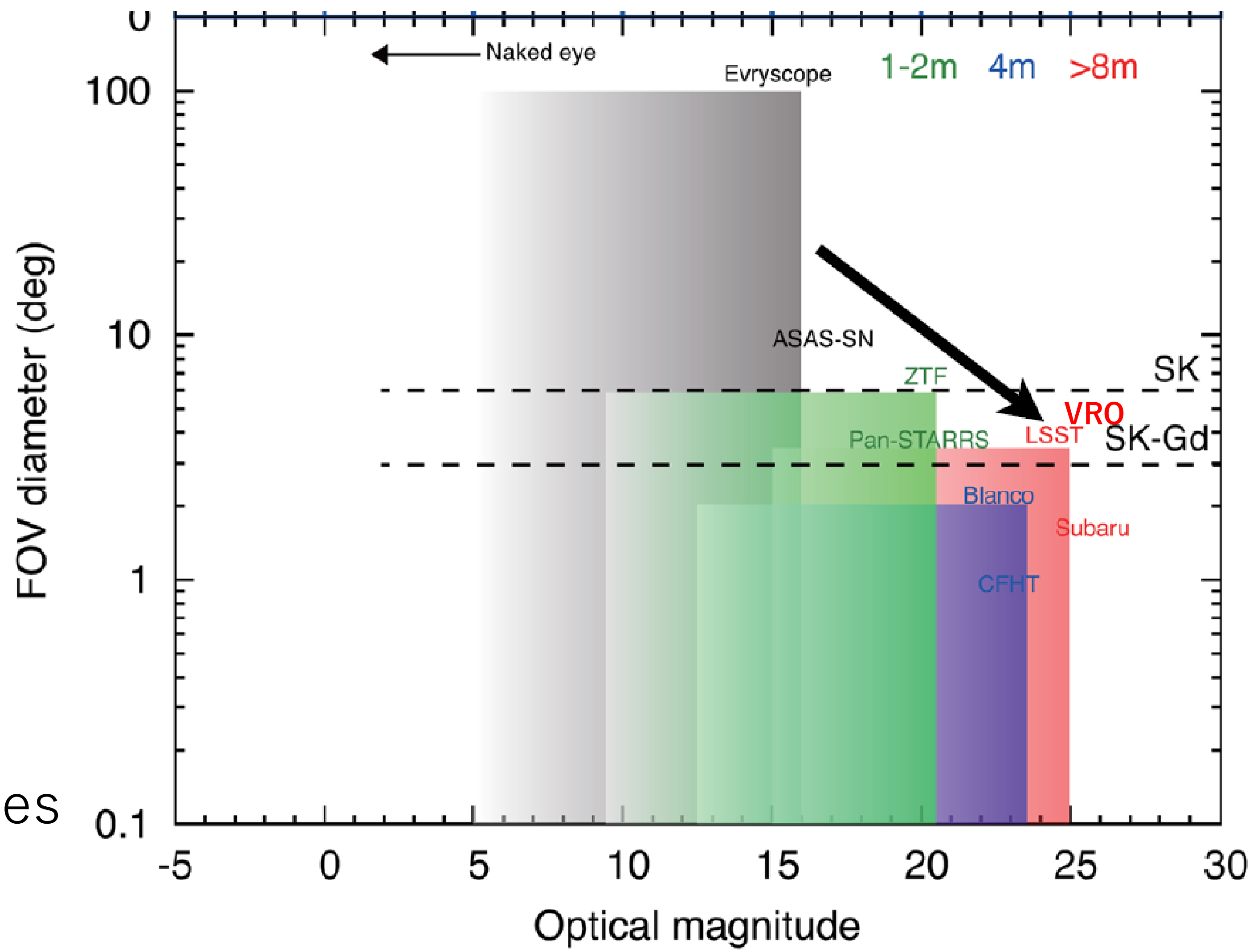
- $\bar{\nu}_e$ events can be tagged and rejected, and directional events (ν_e+e scattering events) are enhanced.



Impact of SK-Gd

Nakamura, Horiuchi et al., MNRAS, 461, 3296 (2016)



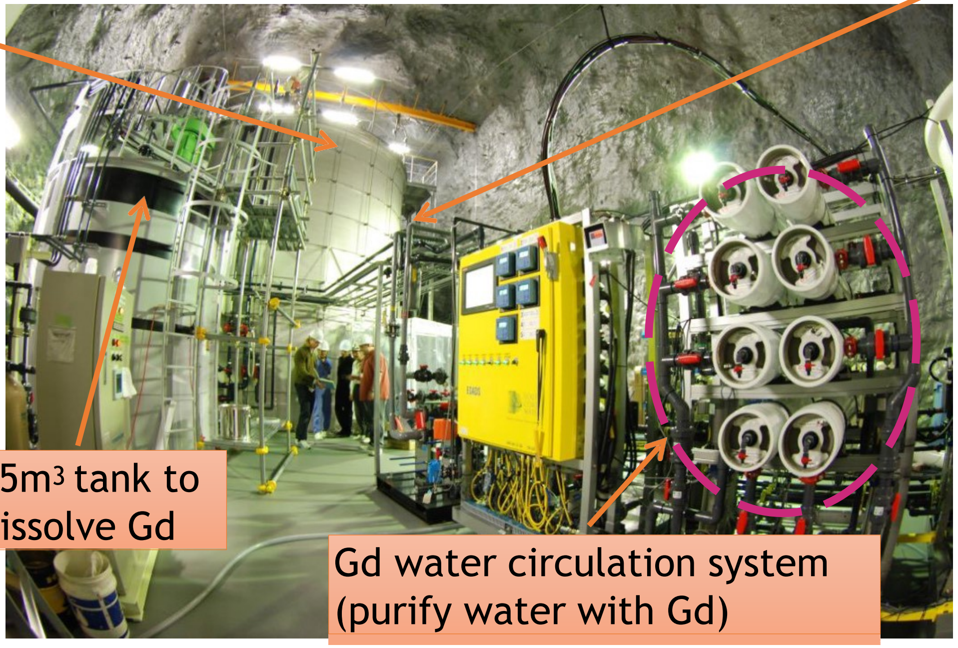


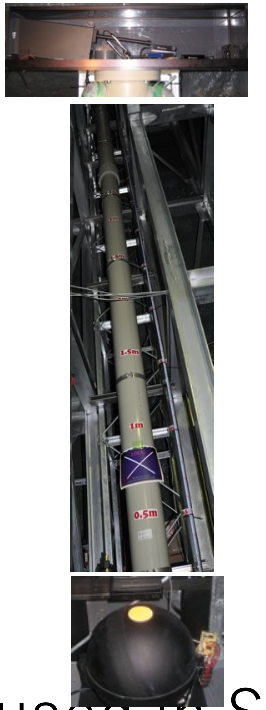
For 10kpc SN ~5° → ~3°

- Pointing in 3° accuracy will allow the follow-up with large telescopes

Tests with the EGADS (200t tank) demonstrator

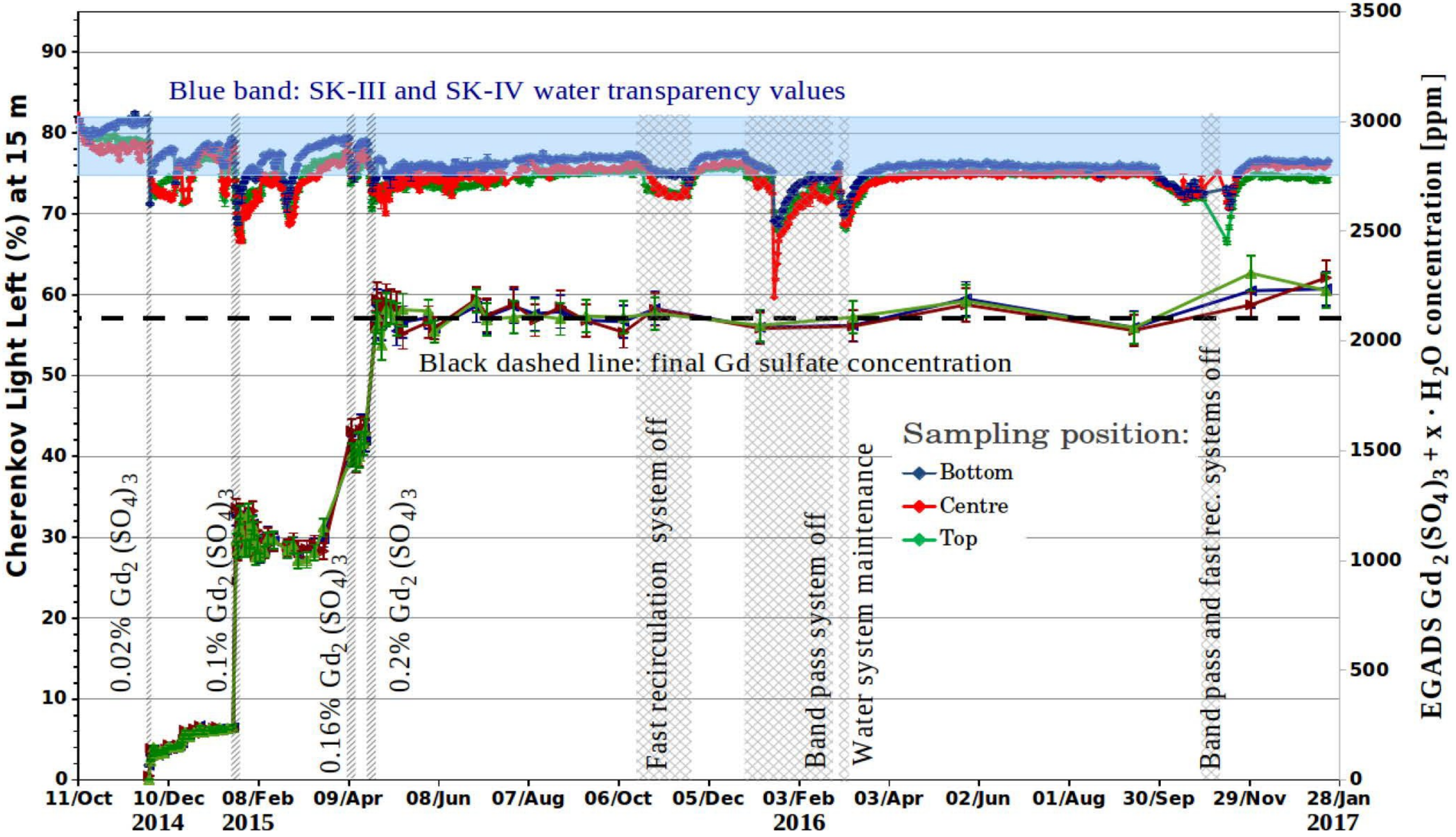
Evaluating Gadolinium’s Action on Detector Systems





- Studying Gd water quality with actual detector materials used in SK
  Also testing 13 HPDs for Hyper-K
- Have been operating with full (0.2%) Gd2(SO4)3 loading since 2015

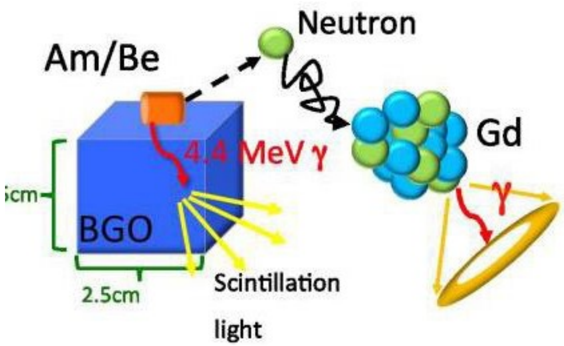
EGADS water quality



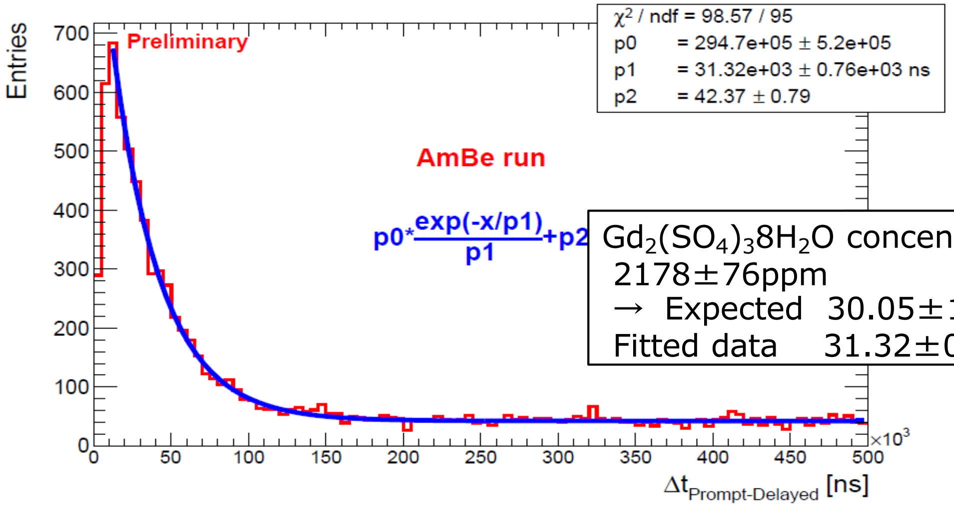
- The light left at 15 m has been stable at ~75% for 0.2% Gd2(SO4)3, corresponds to ~92% of SK-IV average.
- No loss of Gd: >99.99% of Gd remains after circulating the water system for more than 350 times

Neutron Calibrations in EGADS

- Calibration done w/ AmBe neutron source
- BGO crystal used to detect 4.4 MeV “prompt” γ signal
- Decay time constant consistent w/ expectation
- Energy distribution well reproduced by MC

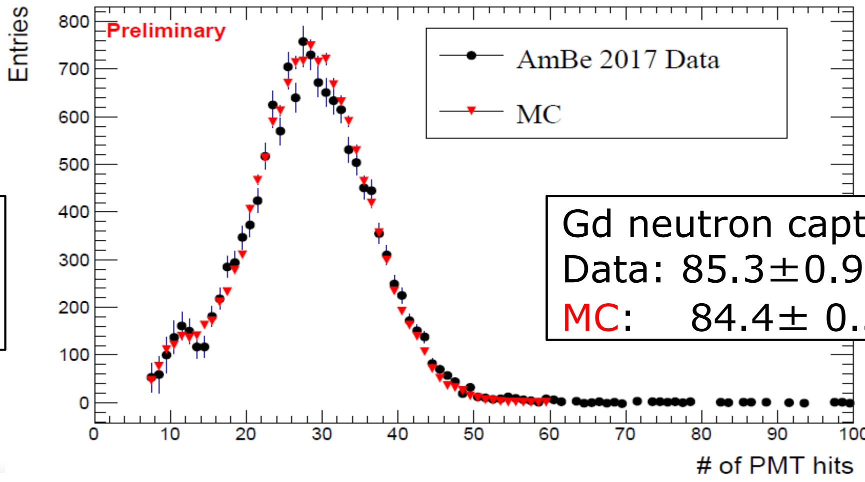


Time to delayed signal



Gd$_2$(SO$_4$)$_3$8H$_2$O concentration
2178±76ppm
→ Expected 30.05±1.14 μs
Fitted data 31.32±0.76 μs

Delayed signal spectrum



Gd neutron capture efficiency
Data: 85.3±0.9% (stat)
MC: 84.4± 0.3% (stat)

Demonstrated neutron detection with Gd in water Cherenkov detectors