Super-Kamiokande

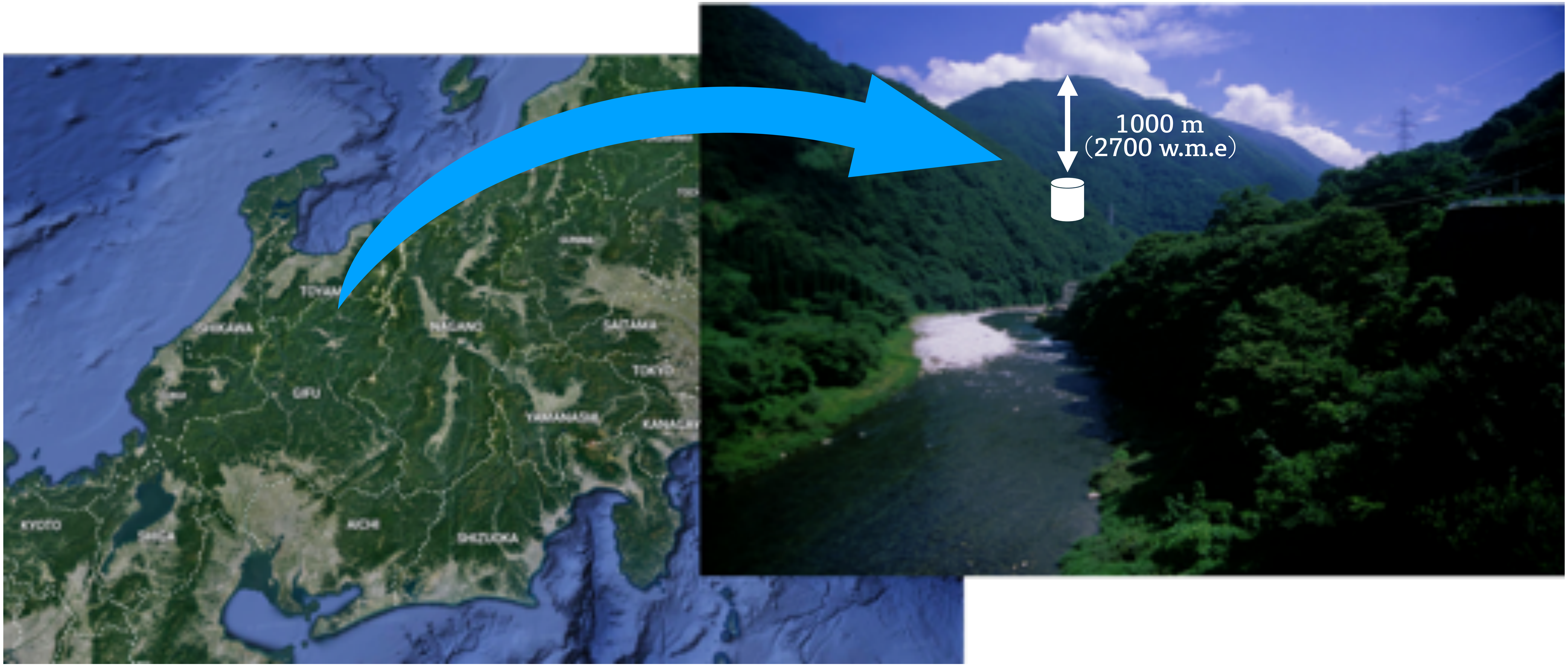
Masayuki Harada

On behalf of Super-Kamiokande Collaboration (mharada@km.icrr.u-tokyo.ac.jp)

ICRR young researchers' workshop @ICRR, Kashiwa
17-18th July 2024

Super-Kamiokande

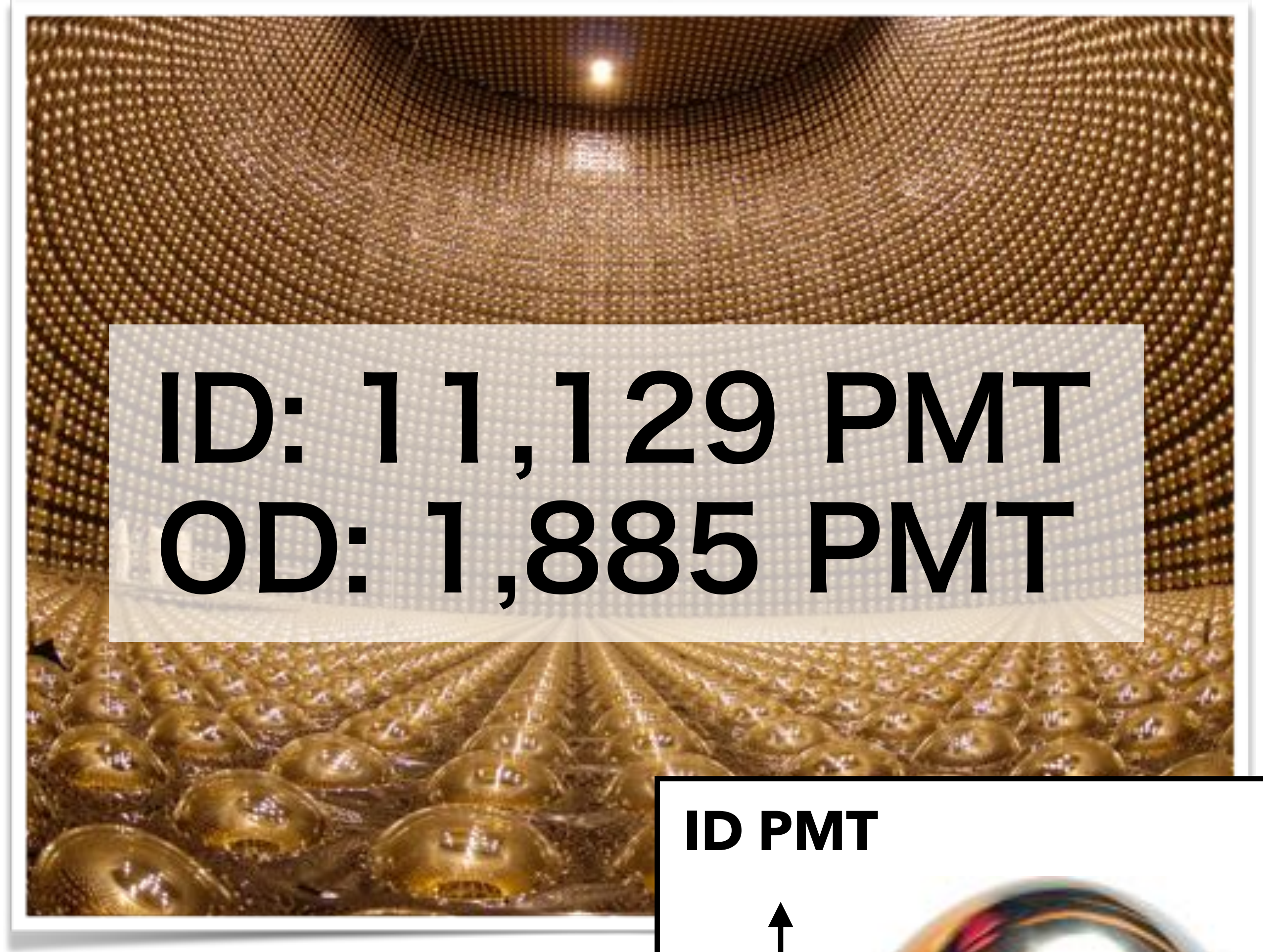
Location

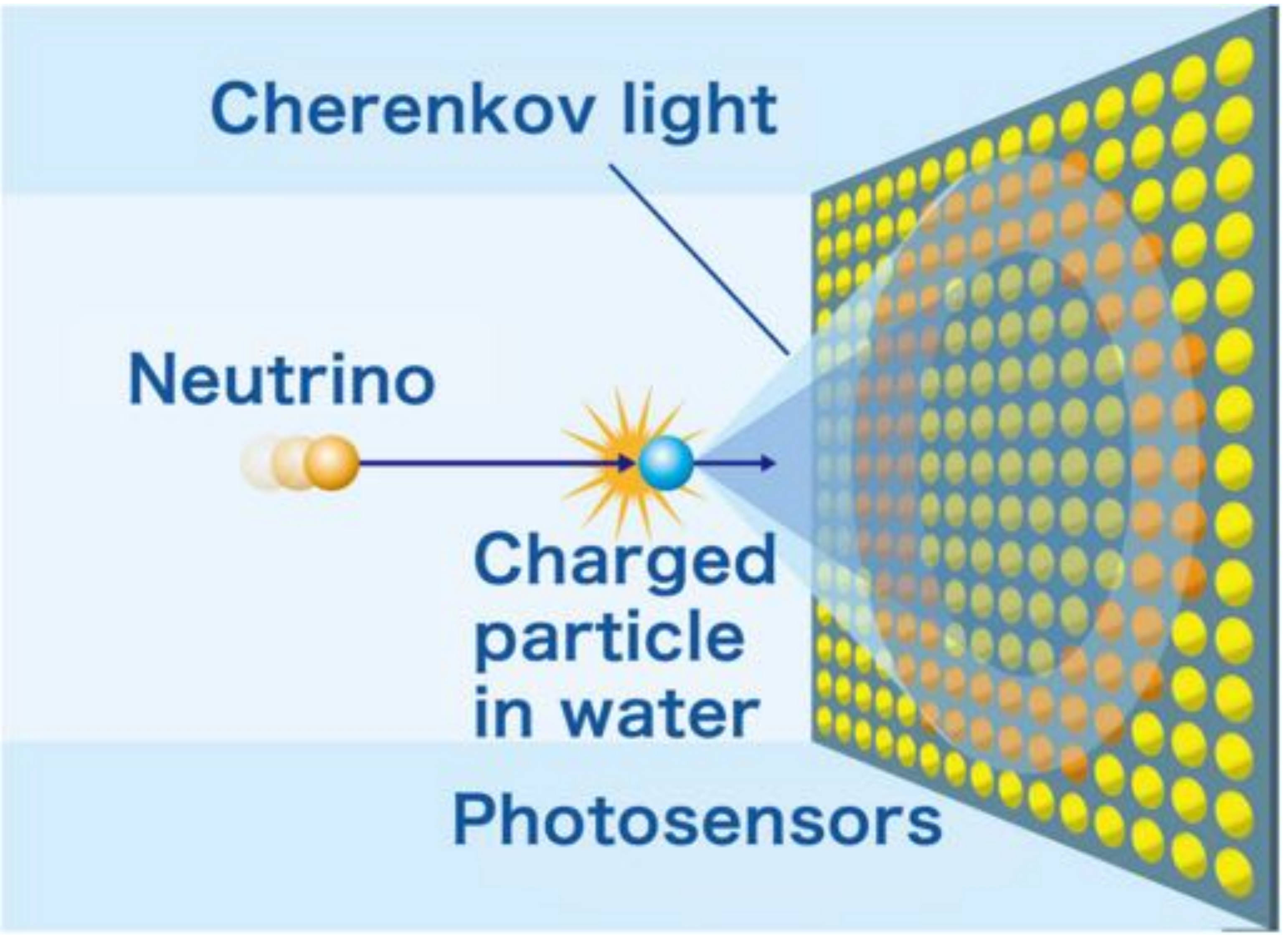


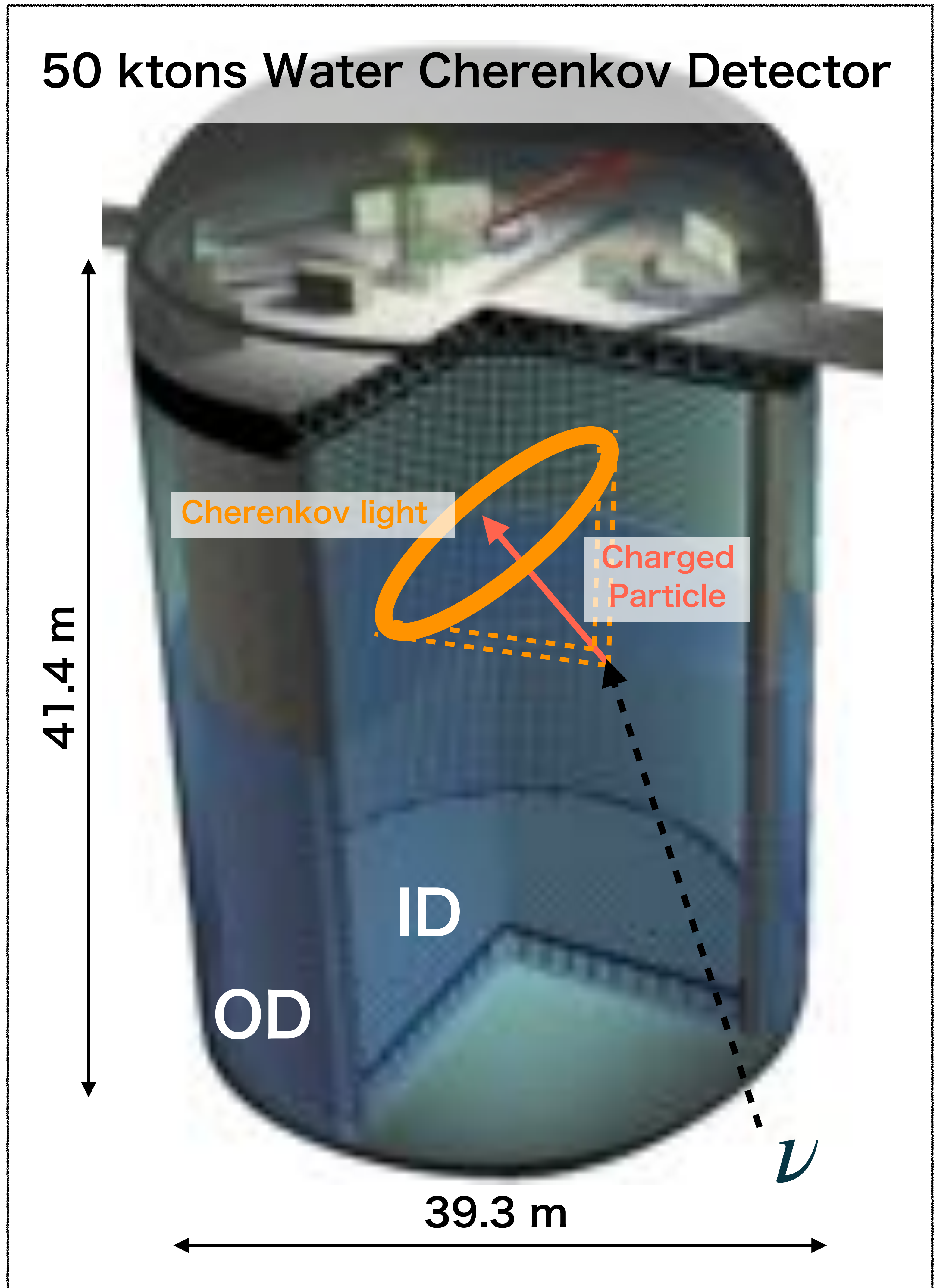
Super-Kamiokande

Detector

- Detector: Super-Kamiokande (SK)
  - 50 ktons water-based Cherenkov detector
    - From 2020, Gd is loaded
  - 50 cm PMT for ID → Event reconstruction
  - 20 cm PMT for OD → Cosmic muon veto







http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/introduction.html

Super-Kamiokande

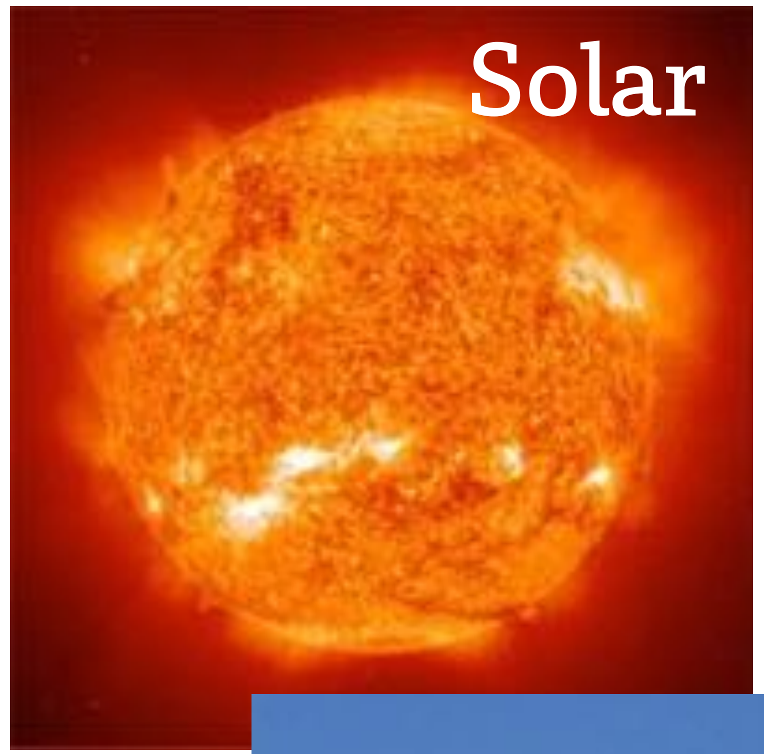
Collaboration

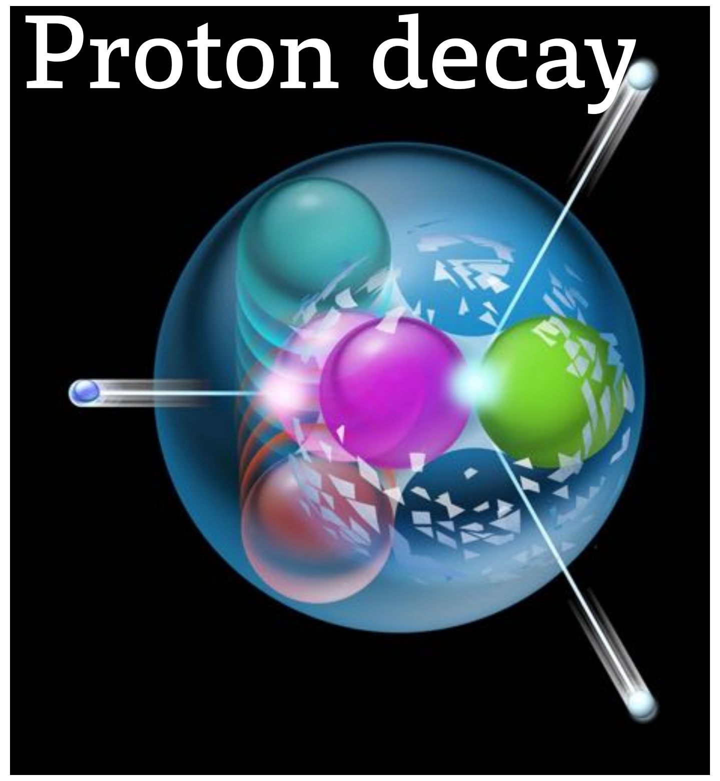
~230 collaborators from 55 institutes in 11 countries

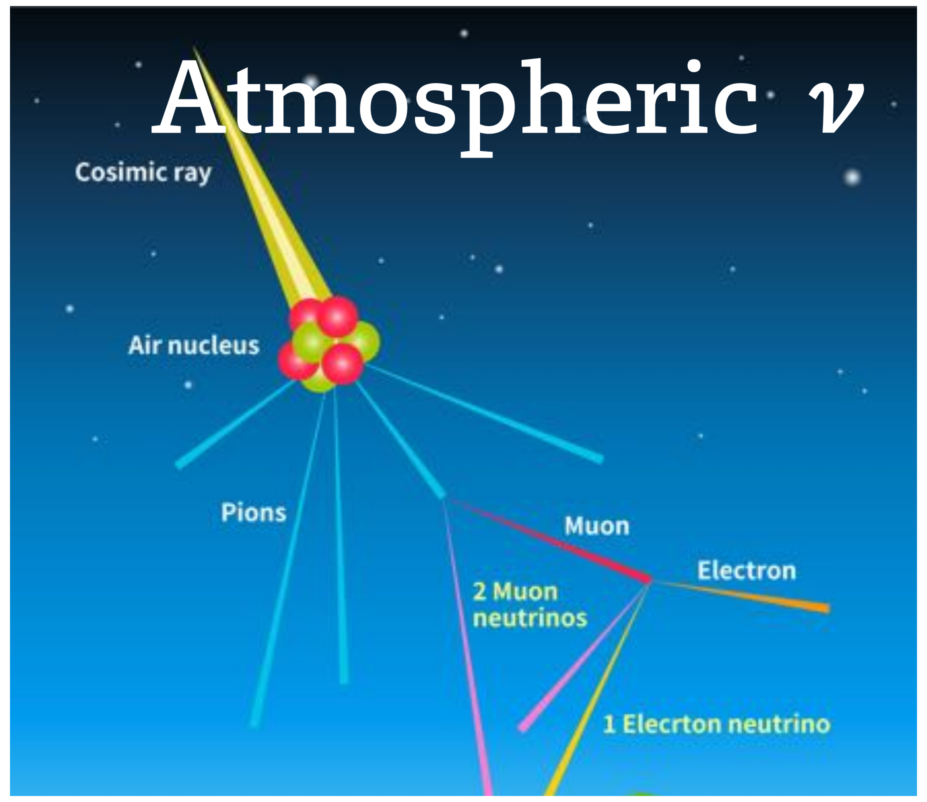
Super-Kamiokande

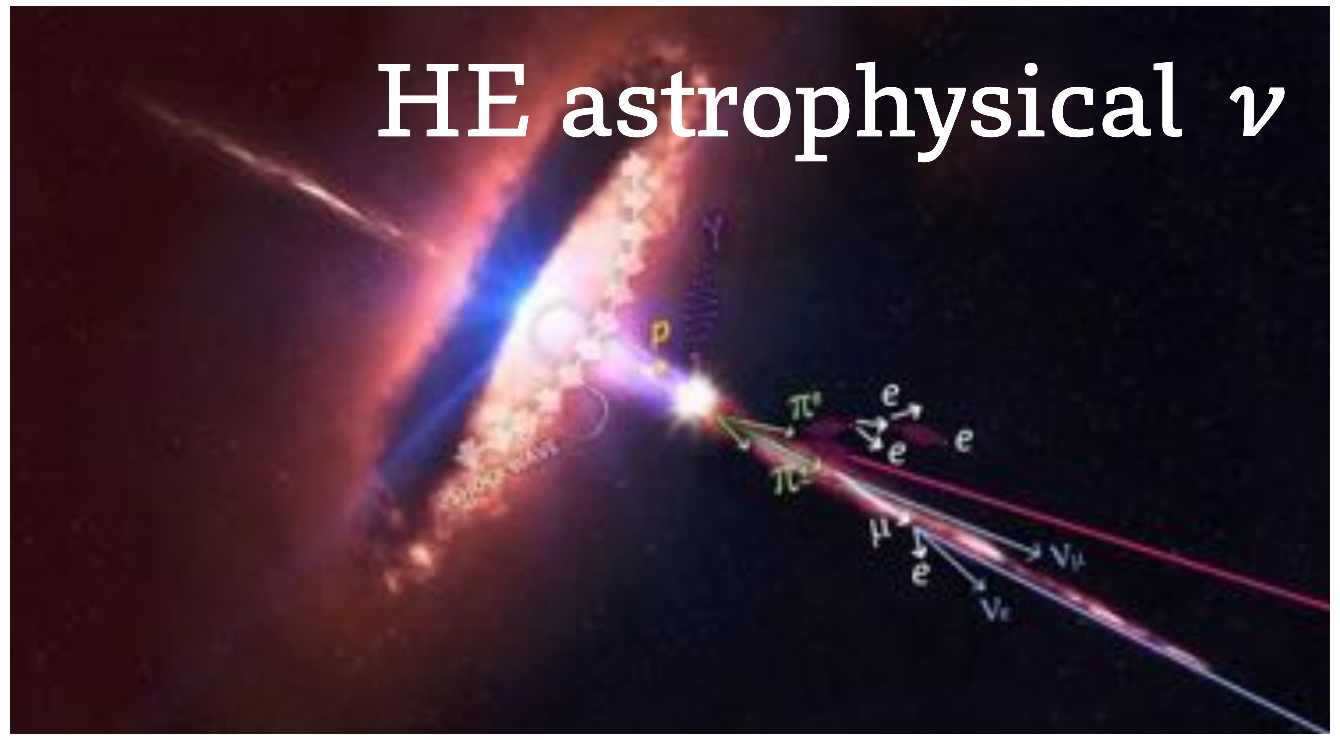
Physics target

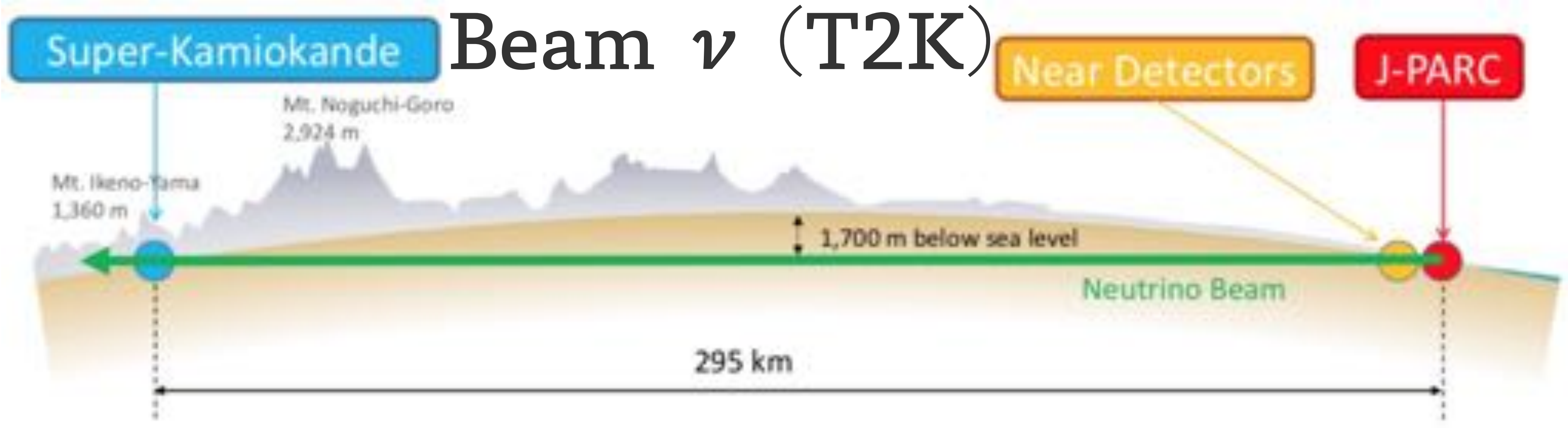
Multi-purpose detector: O(1)MeV — O(1) TeV







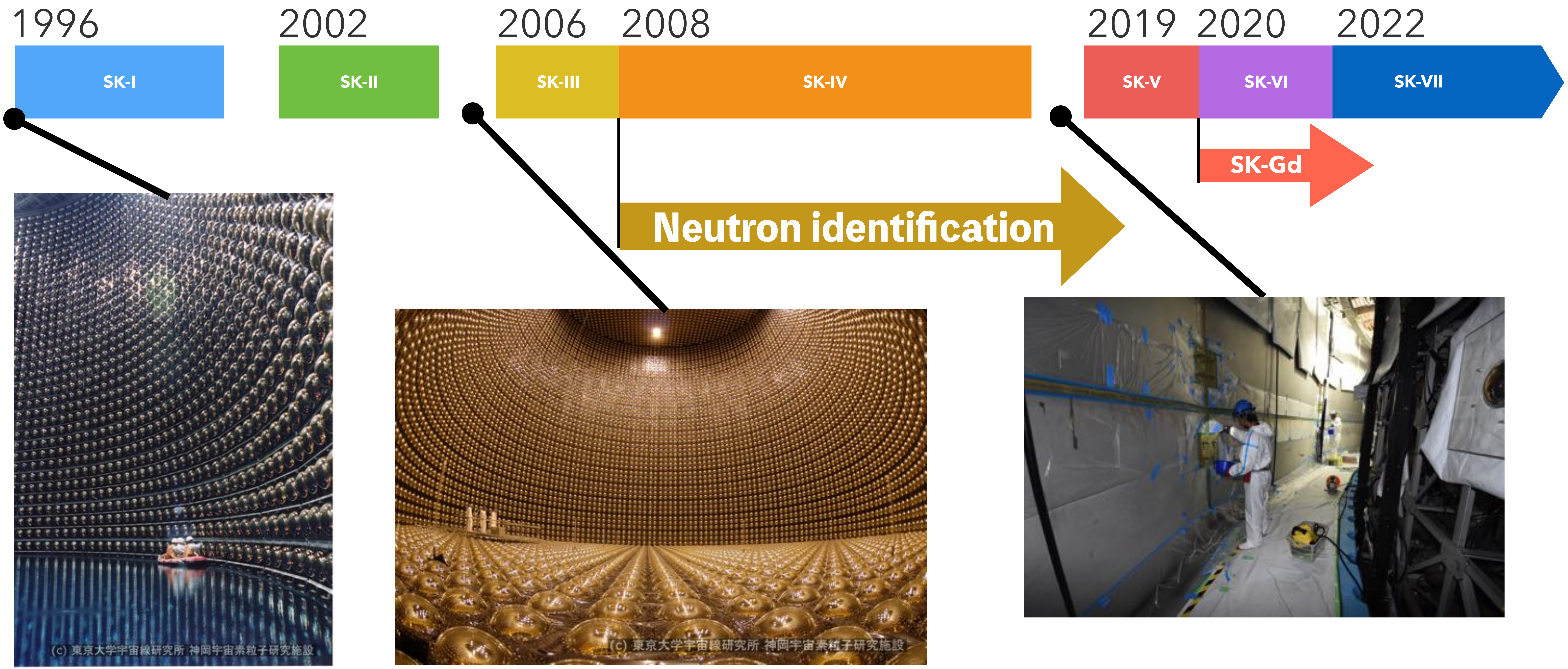




And other...

Super-Kamiokande

Experimental phase



Super-Kamiokande

Next stage “SK-Gd”

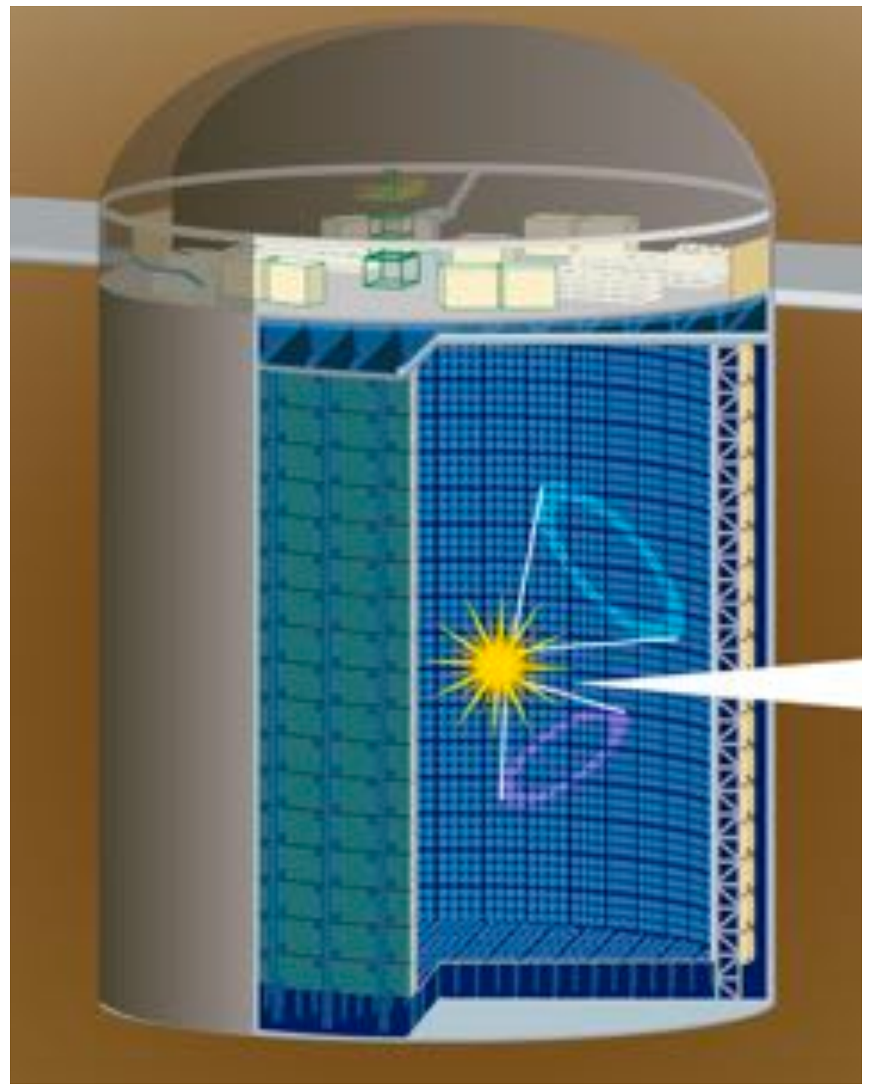
1996 | 2002 | 2006 | 2008 | 2019 | 2020 | 2022

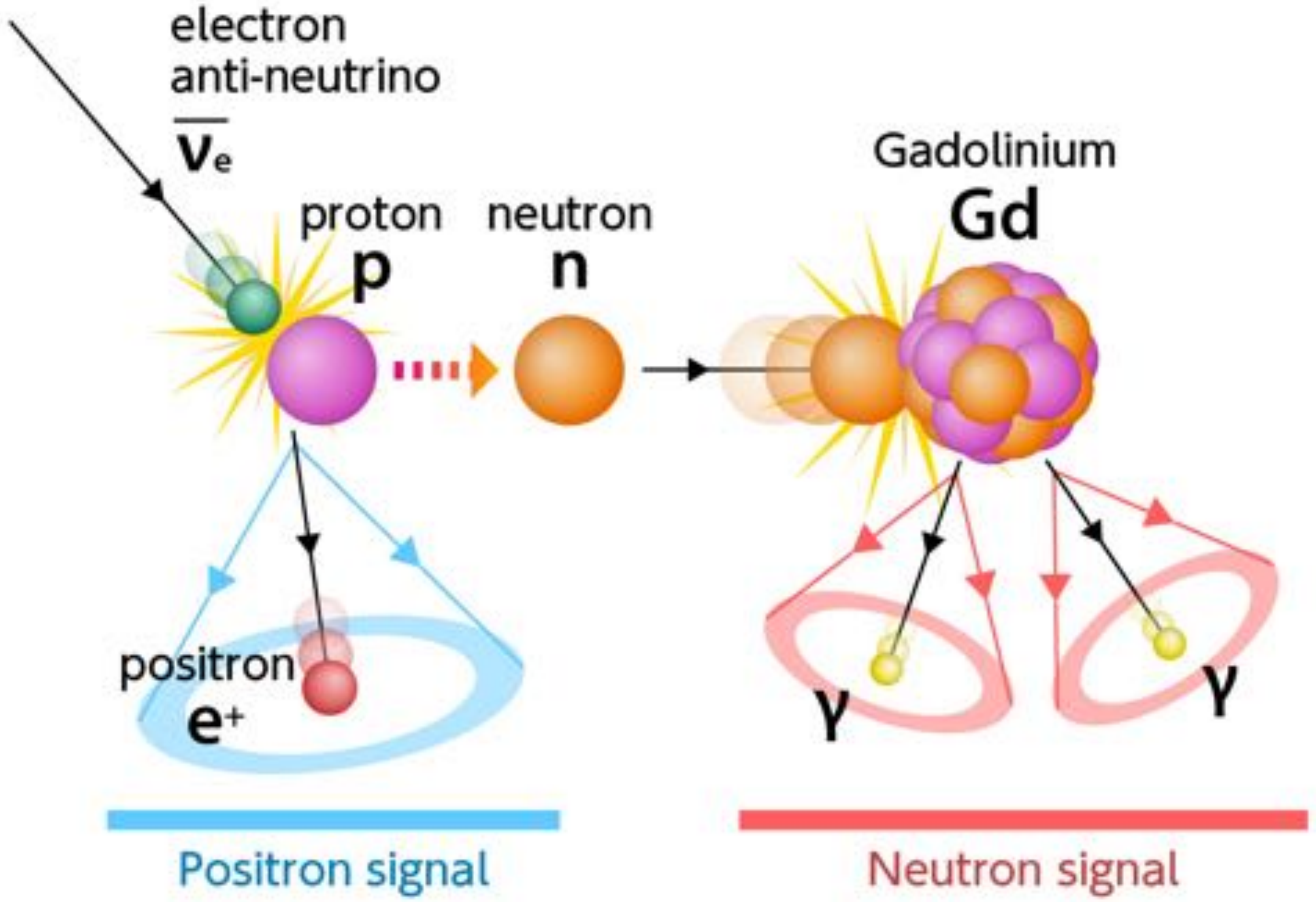
SK-I | SK-II | SK-III | SK-IV | SK-V | SK-VI | SK-VII

SK-Gd

Loading Gd

SK tank





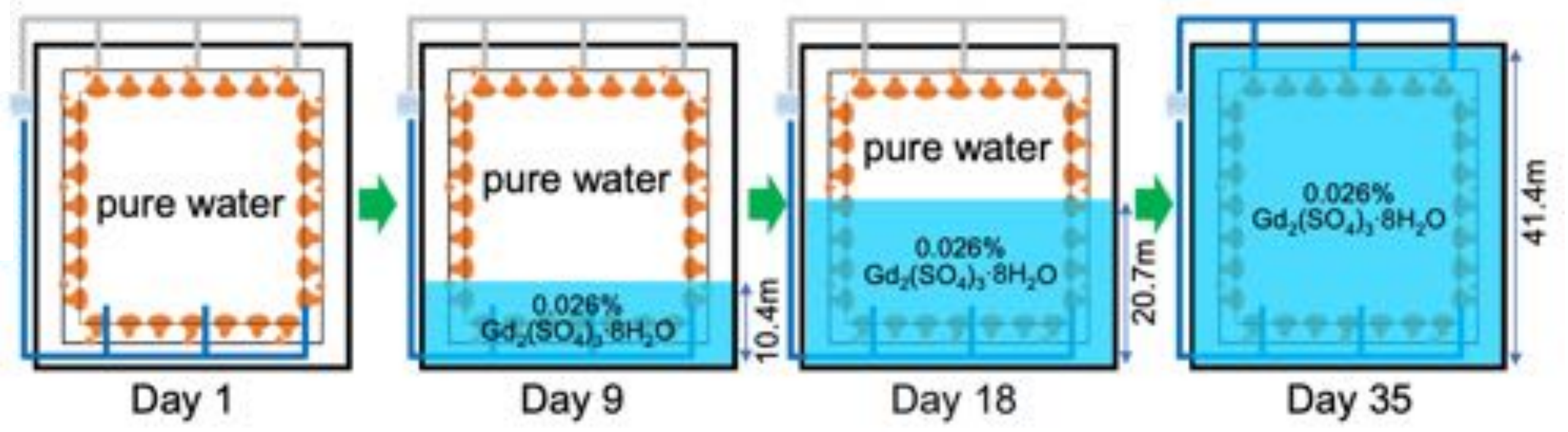
~ 13 tons Gd sulfate (SK-VI)

+ ~ 26 tons Gd sulfate (SK-VII)

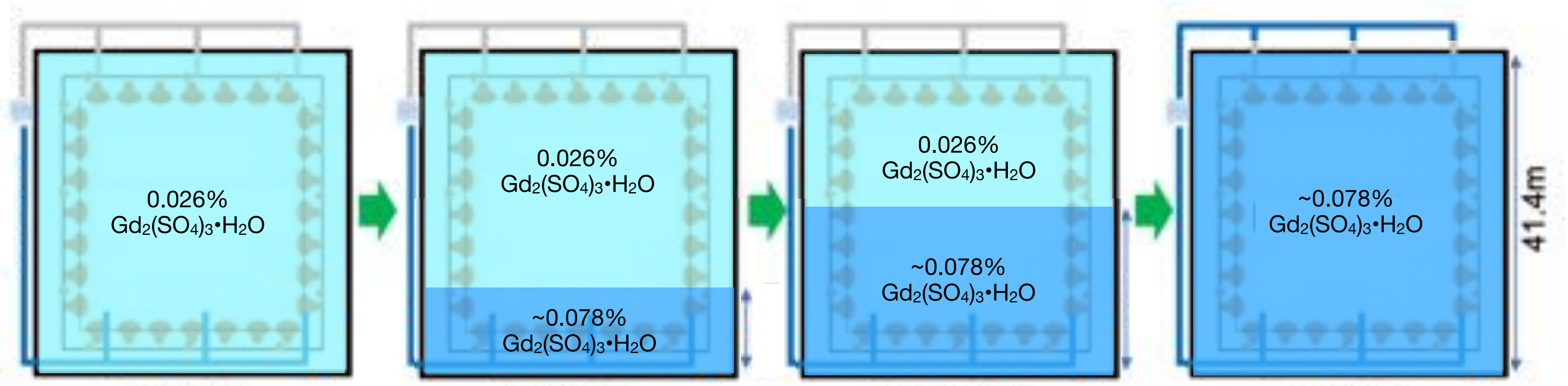
SK-Gd

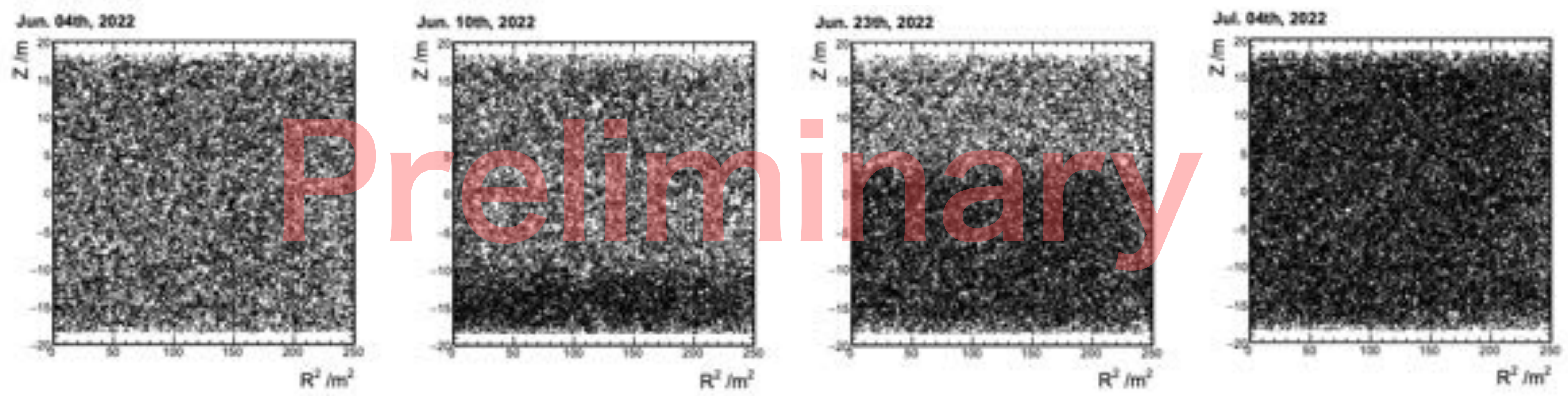
Enhanced neutron detection

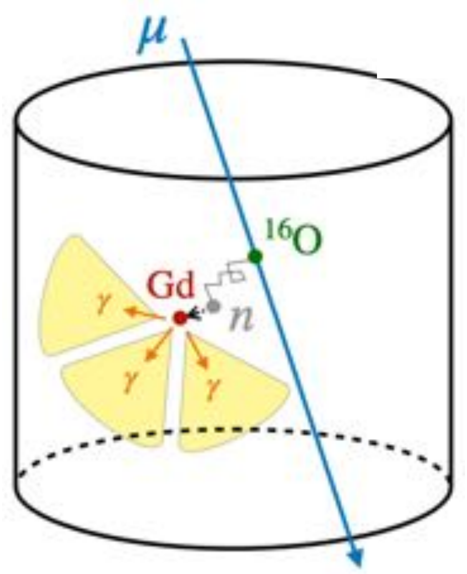
- Two times of loading Gd
  - 2020: First time to ~0.01% Gd conc.



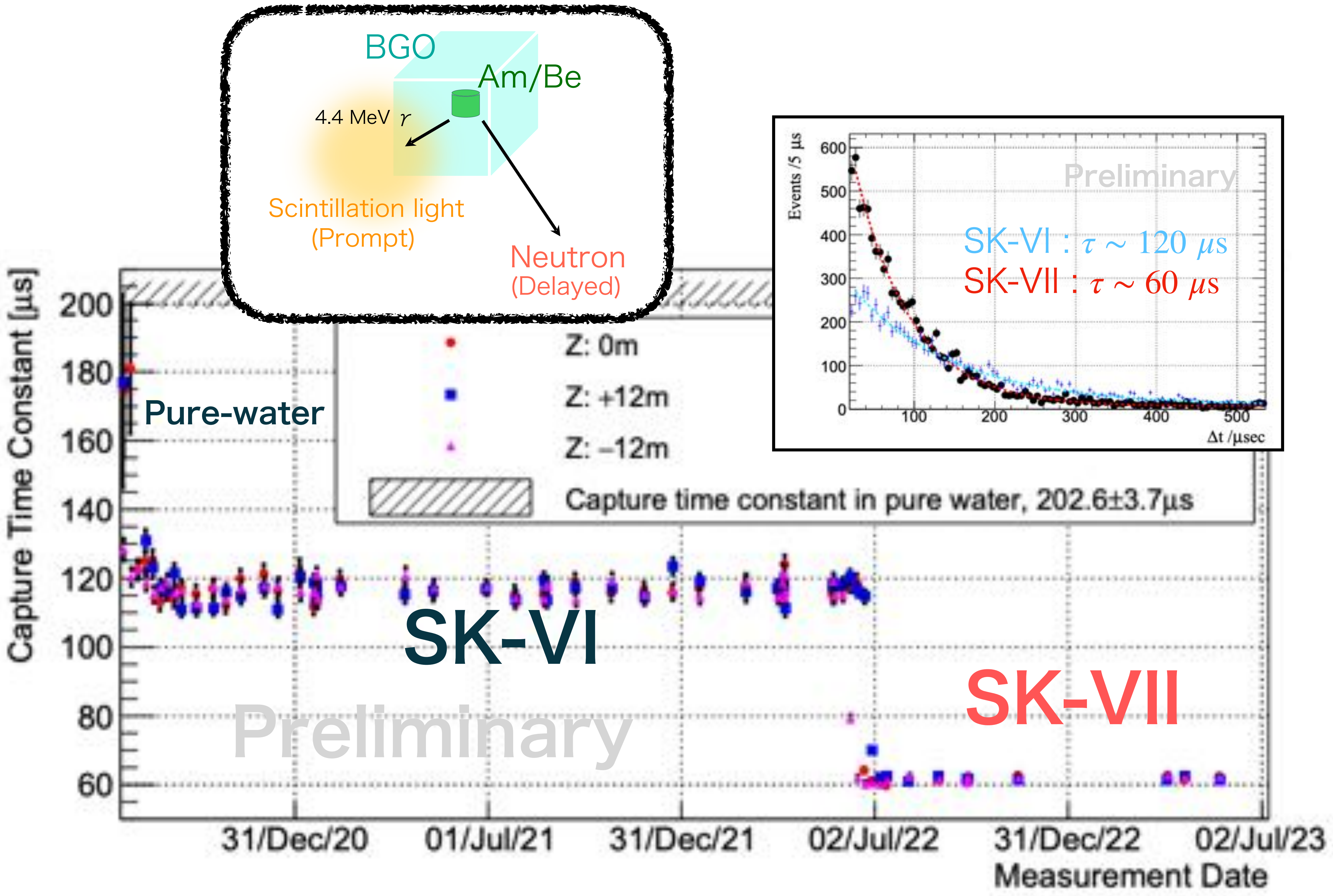
  - 2022: Second time to ~0.03% Gd con







➡ monitor by neutron from cosmic-muon

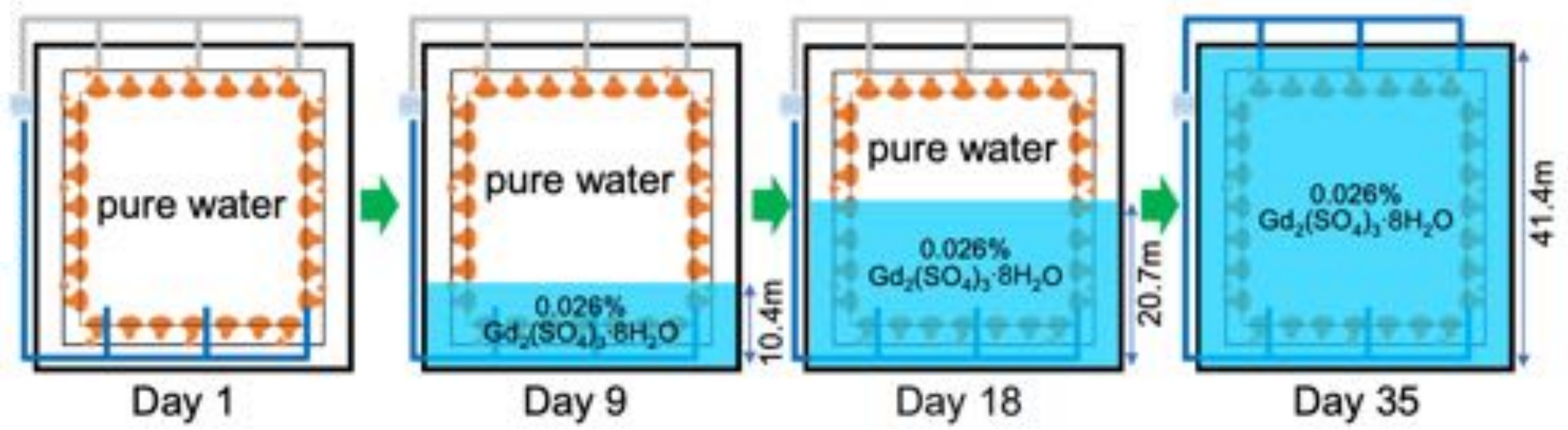


➡ confirmed Gd effect by event rate and time constant measurement

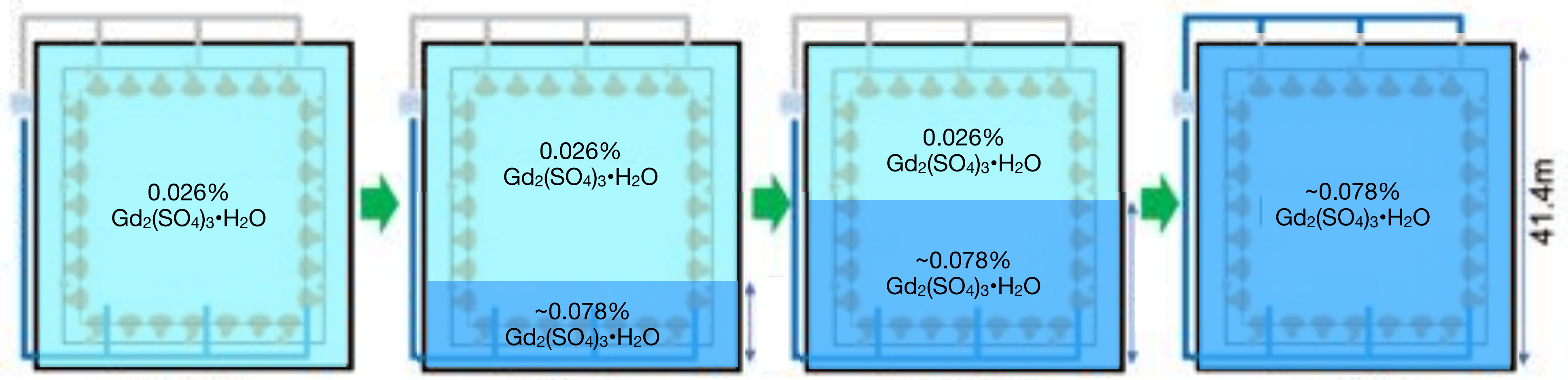
SK-Gd

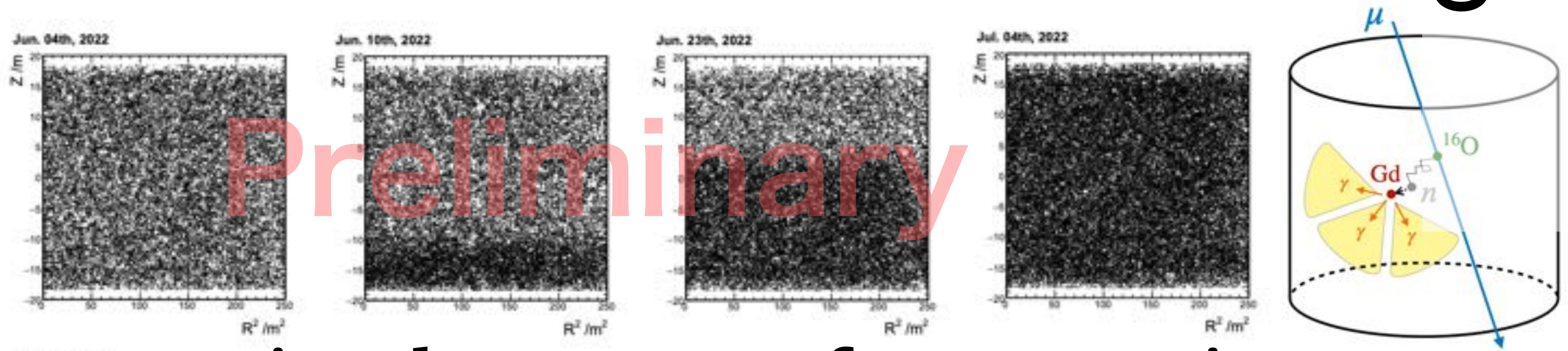
Enhanced neutron detection

- Two times of loading Gd
  - 2020: First time to ~0.01% Gd conc.



  - 2022: Second time to ~0.03% Gd con





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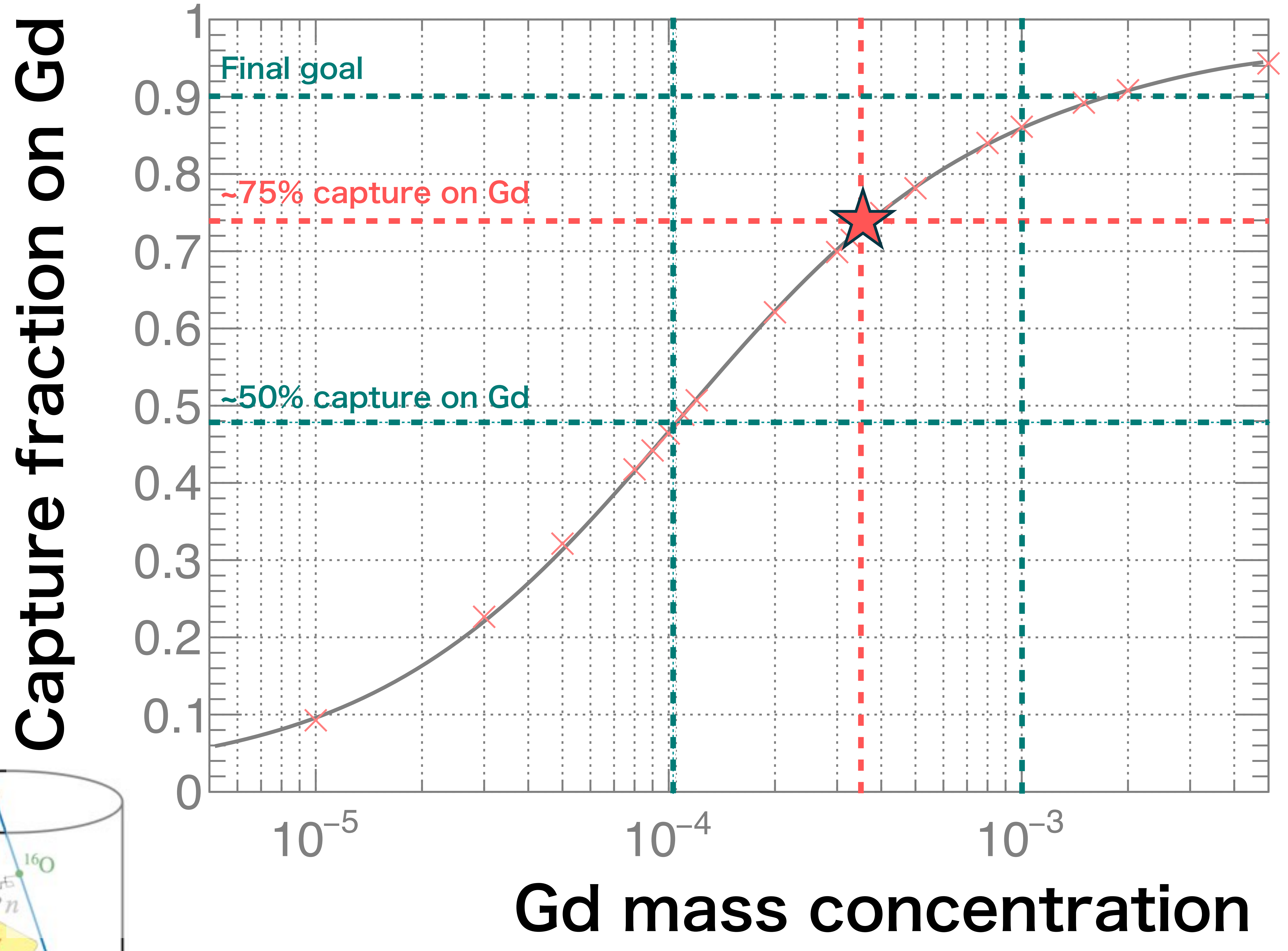


Recent physics highlight

- My selection of SK recent physics highlight using Gd
  - Diffuse Supernova Neutrino Background (DSNB)
  - Reactor neutrinos
  - Atmospheric neutrinos

DSNB: flux prediction

Major purpose of upgrading SK

$$\Phi_{DSNB}(E) \propto \int \boxed{R_{SN}(z)} \boxed{\frac{dF_{\bar{\nu}}(E,z)}{dE}} \boxed{\left|\frac{dt}{dz}\right|} dz$$

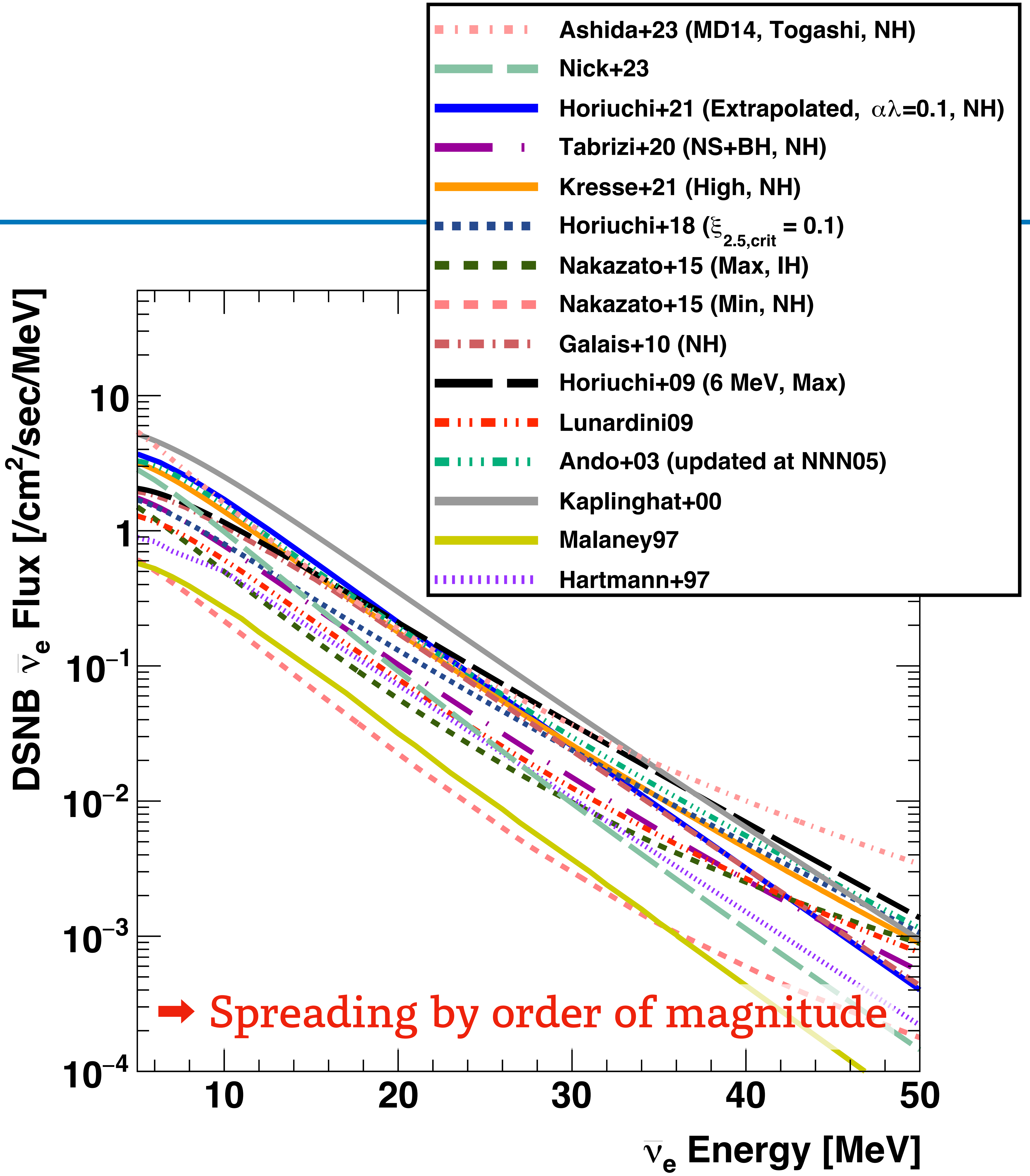
ΛCDM, cosmic expansion

SN rate

- Depends on the star formation history
  e.g.) star formation rate,
  black hole formation, ···

SN ν emission

- Typical SN ν spectrum and neutrino physics
  e.g.) SN neutrino flux, oscillation,···



Differential flux upper limits

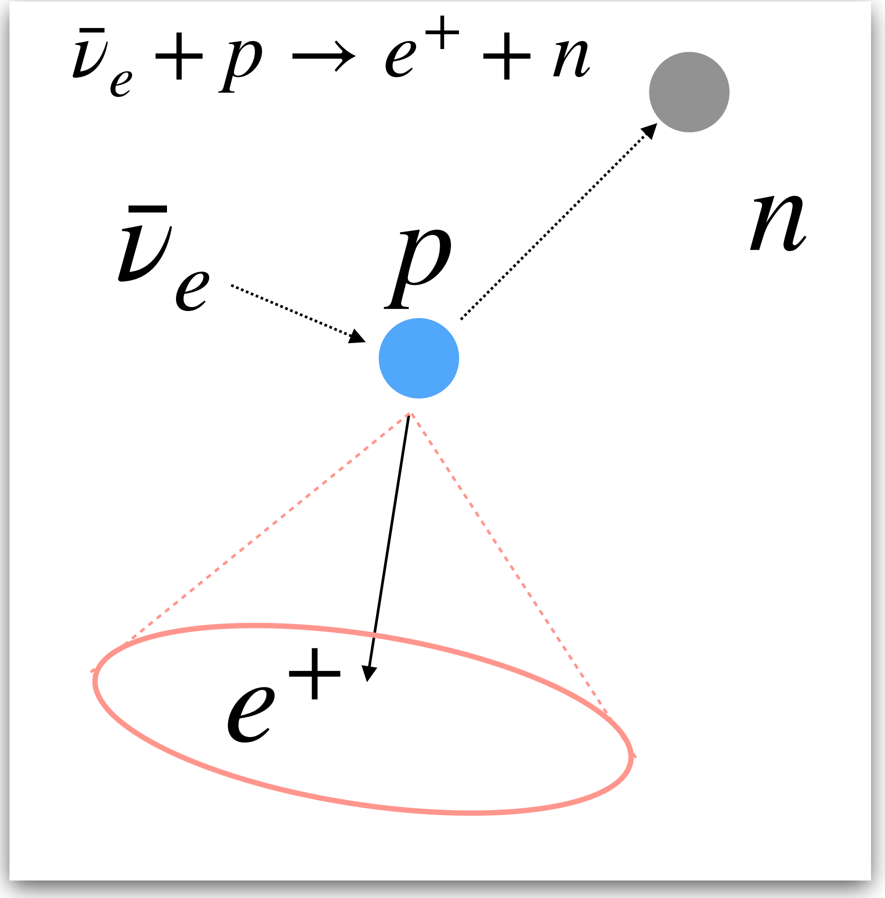
Spectral-independent analysis

Highlight:

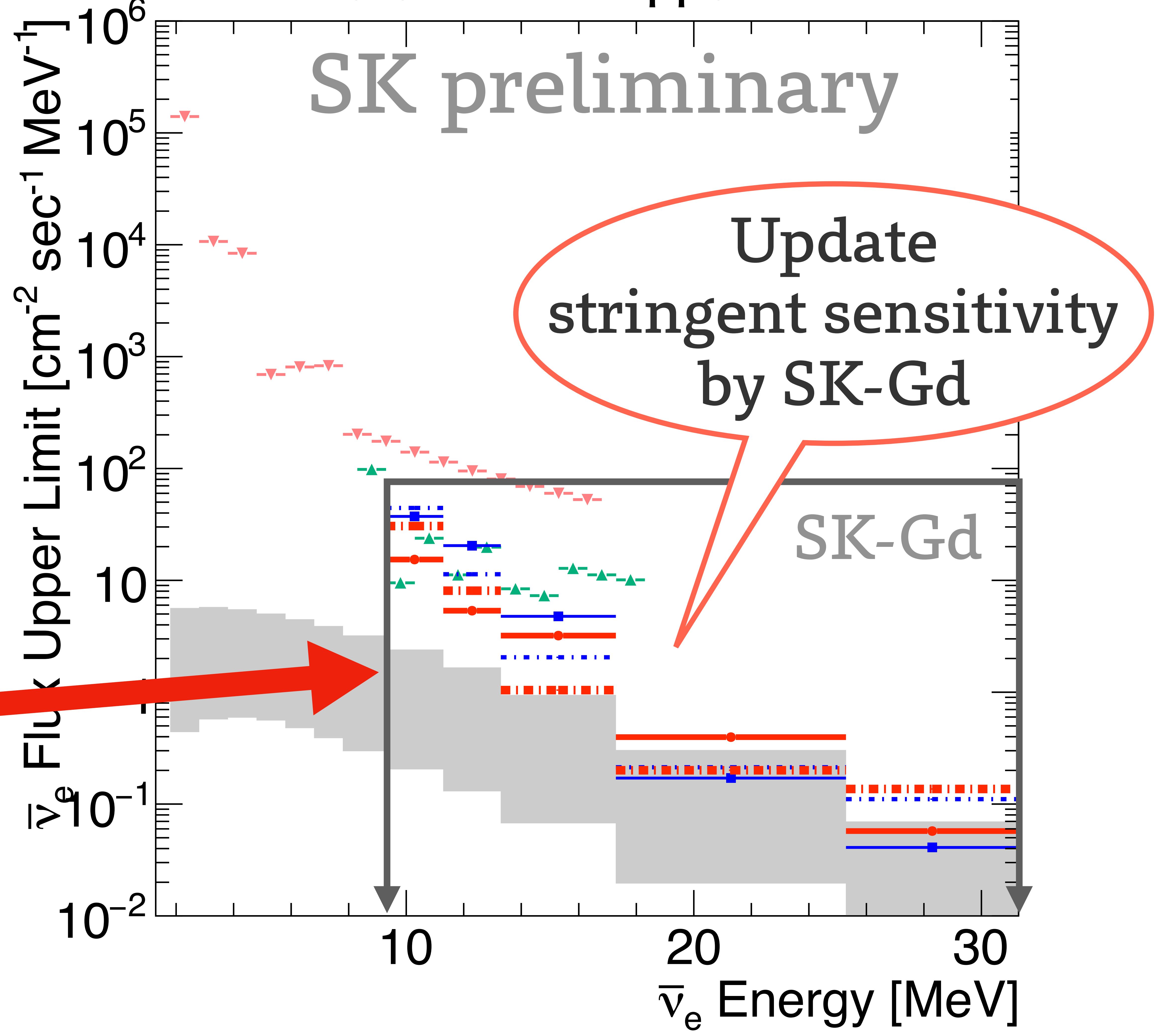
- 956 days of SK-Gd data
- Only use $N_n = 1$ events
- $9.3 < E_\nu < 31.3$ MeV

➡ No obvious excess

Target: Inverse-beta decay



Differential flux upper limit

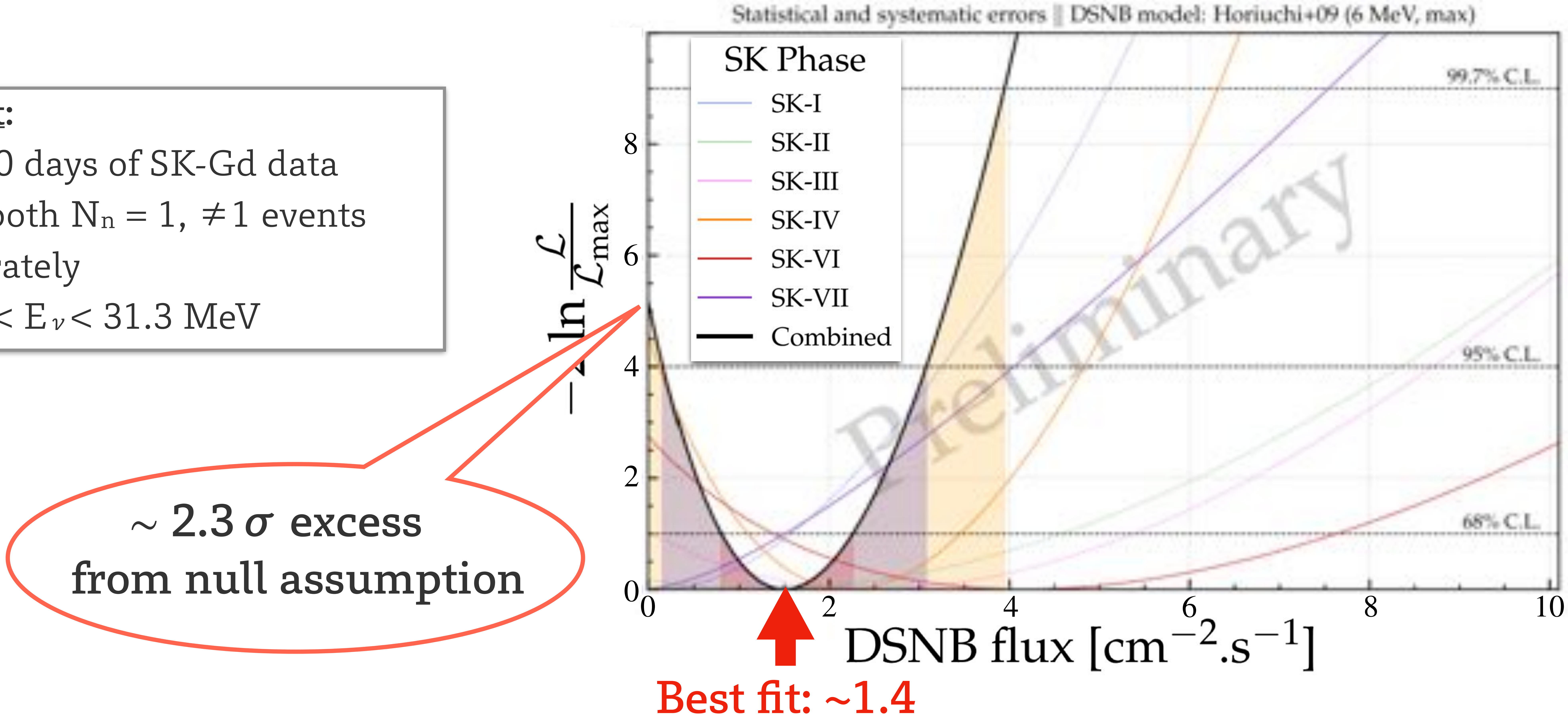


Tension from zero assumption

Spectral-fitting analysis

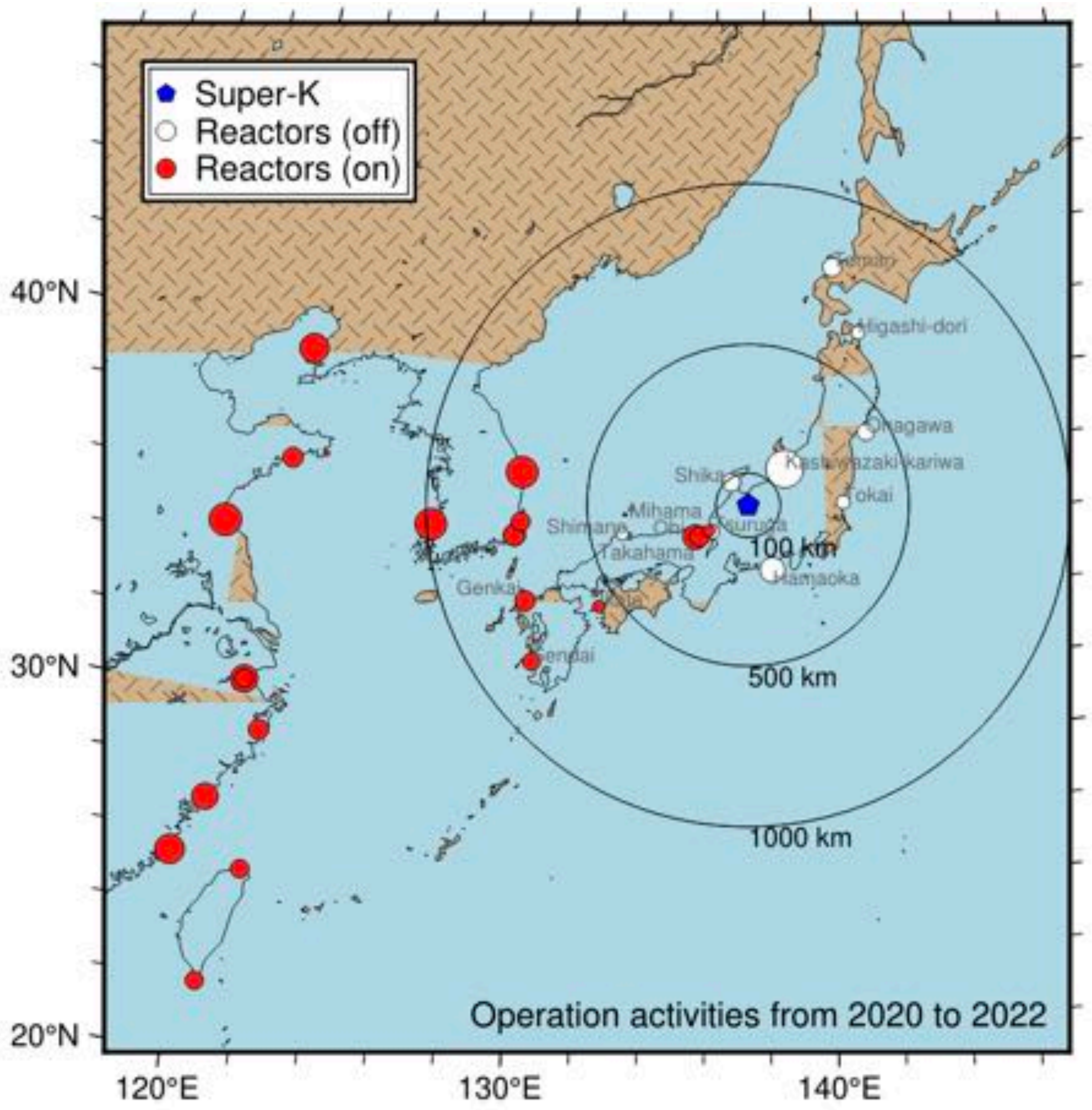
Highlight:

- ~6000 days of SK-Gd data
- Use both $N_n = 1, \neq 1$ events separately
- $17.3 < E_\nu < 31.3$ MeV



Exhibits 2.3 σ excess from null DSNB with best value within current prediction

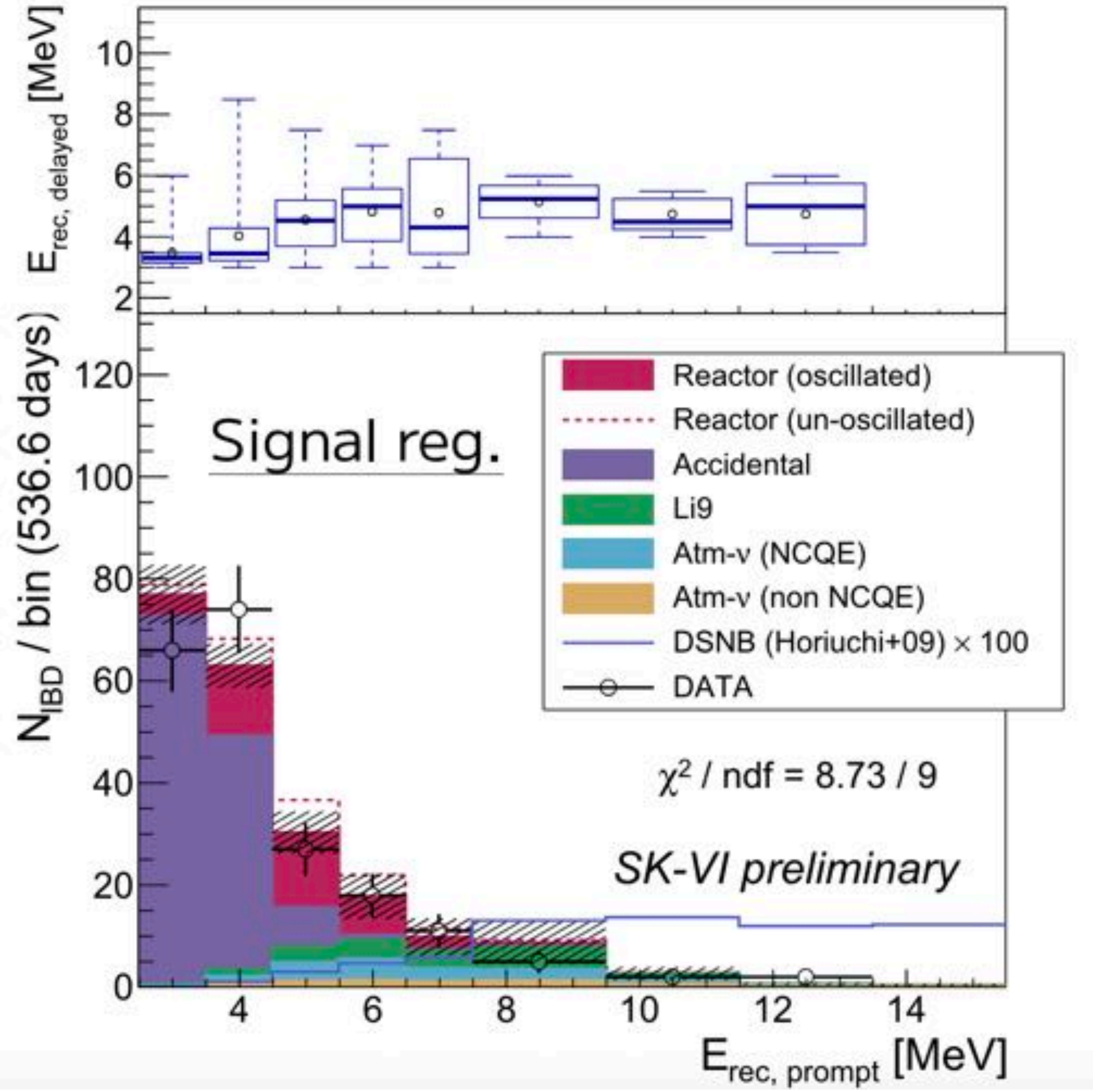
Reactor neutrinos



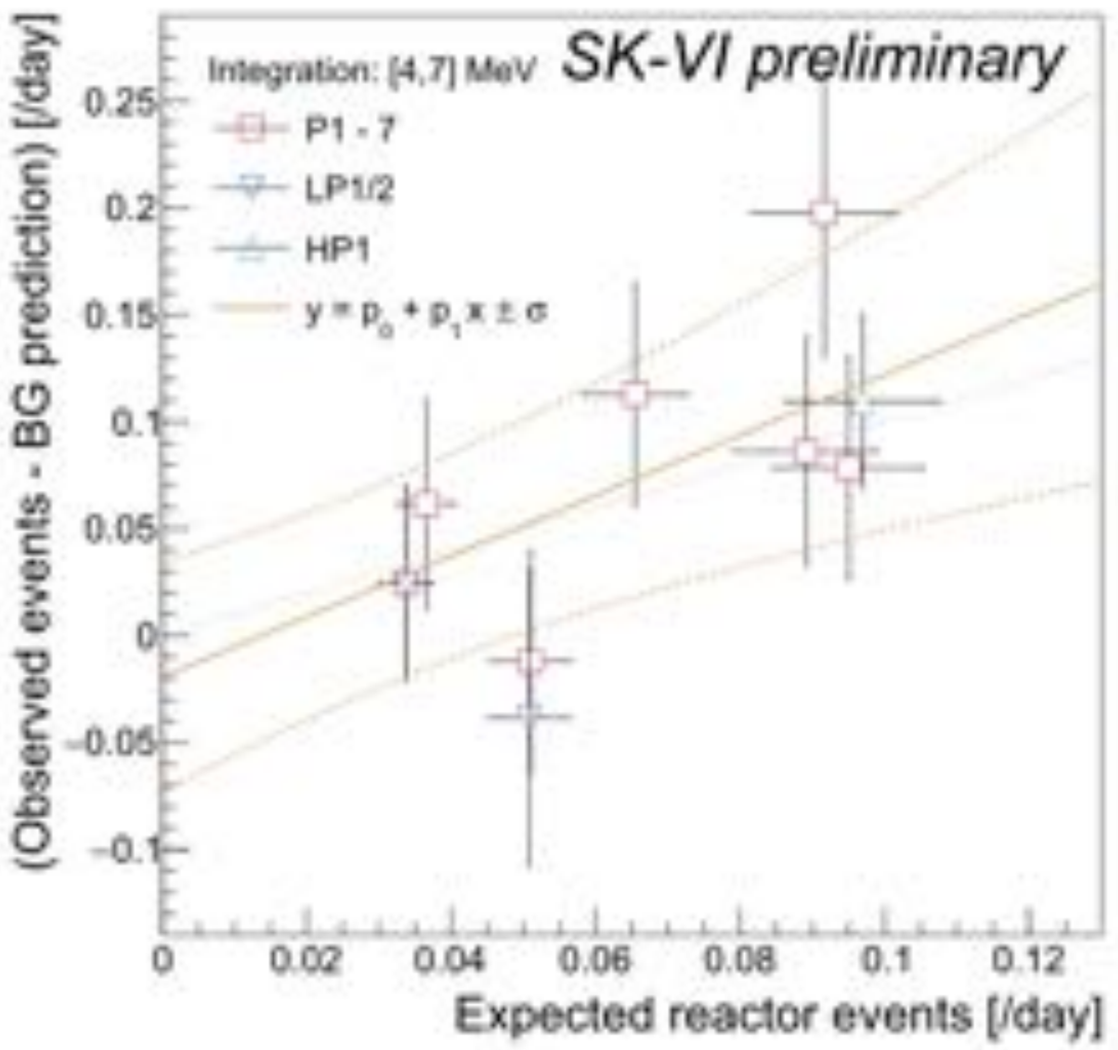
- Sensitive to θ_{13}, also used sterile neutrino search
- Nearest reactor from SK ~ 150 km: 5 event/day
  ➡ ~1/10 from before earthquake
- Very low energy (Peak at 4 MeV)
  ➡ No measurement in Water-Cerenkov detector due to large background so far (except for evidence of SNO+)

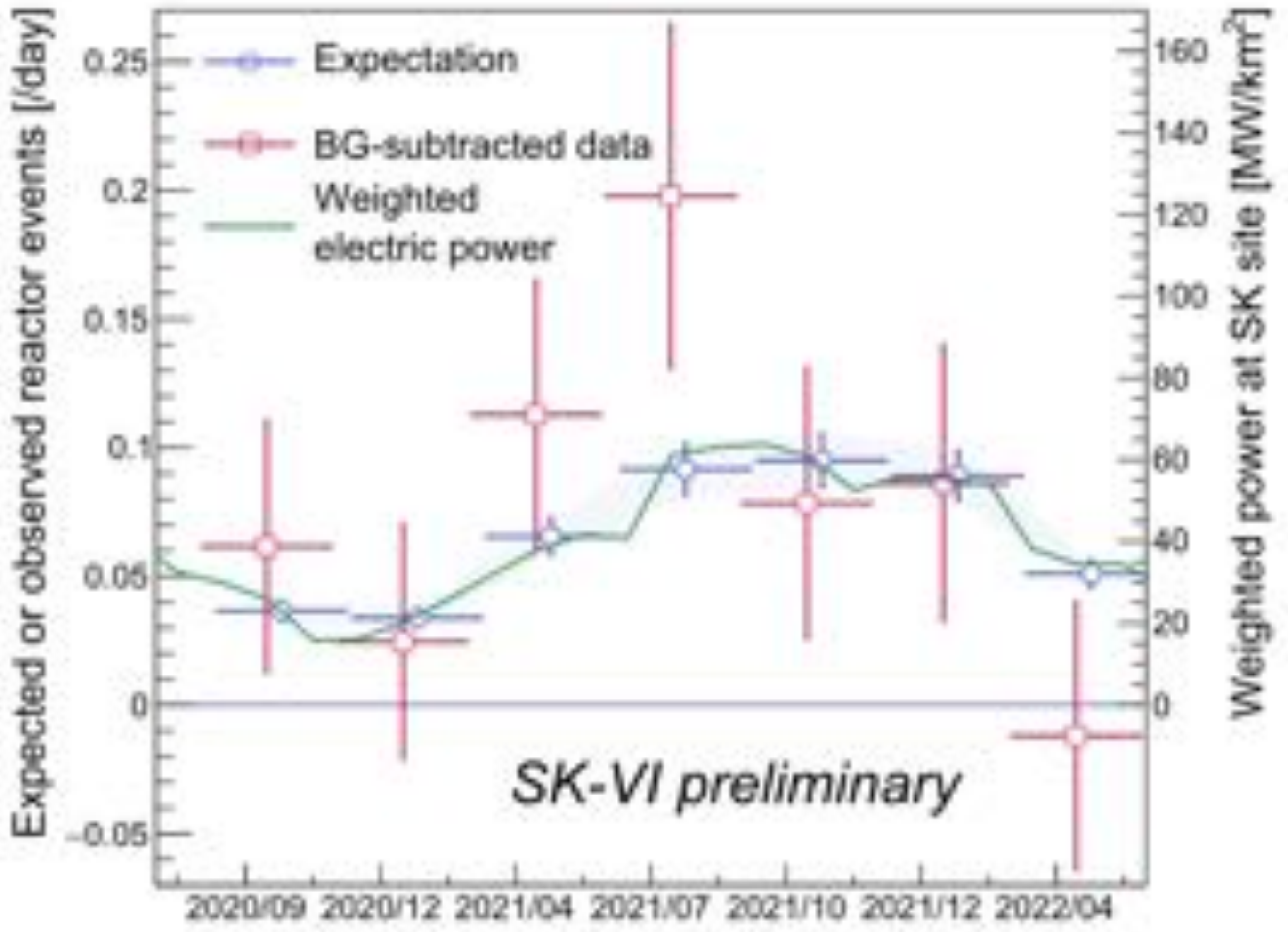
Reactor neutrinos

First positive observation of reactor neutrinos in SK



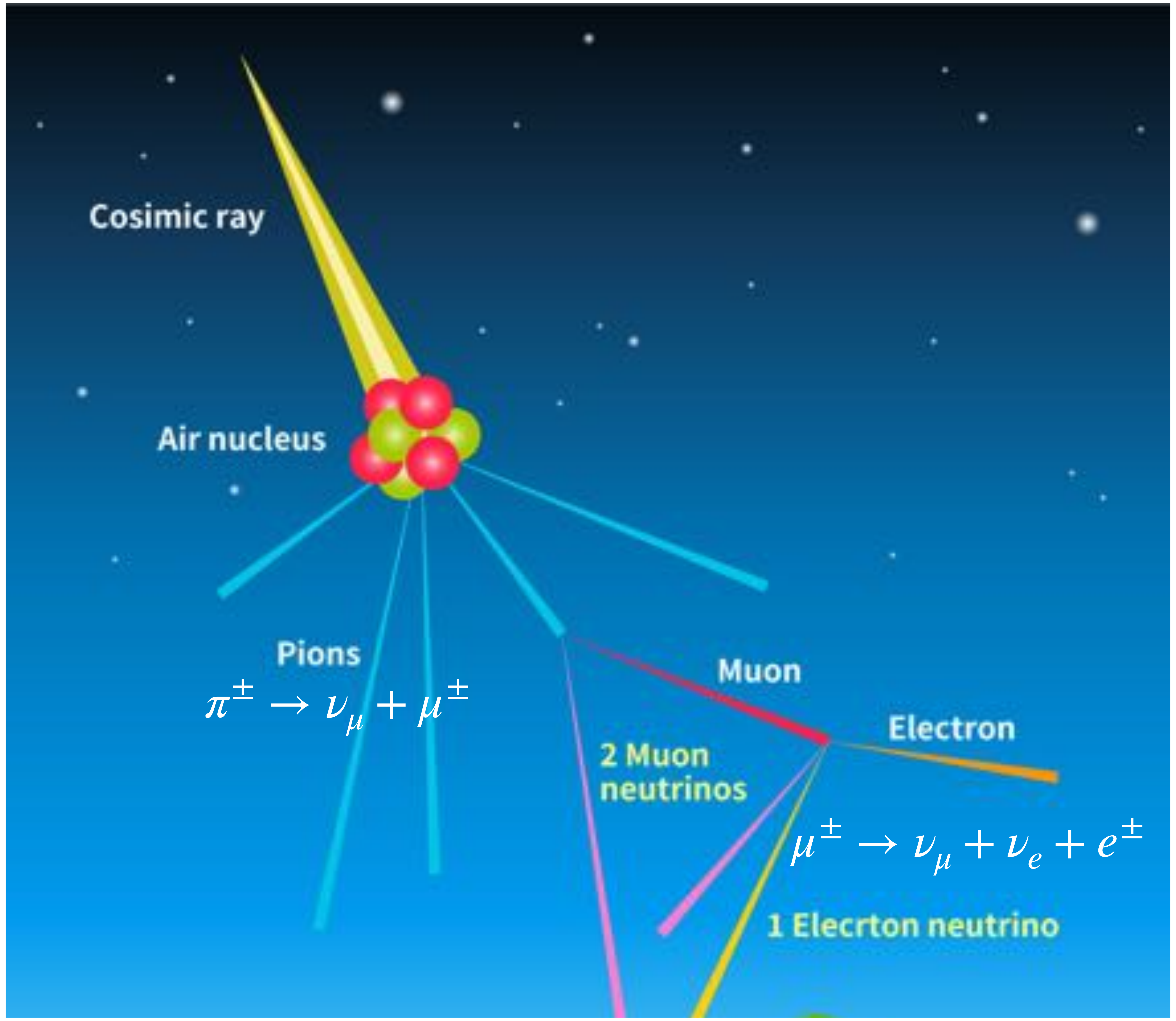
- Target interaction: IBD (same as DSNB)
  ➡lowered IBD energy threshold to ~ 3 MeV
  thanks to enhanced neutron signal
  ➡ Enough low to observe reactor neutrinos



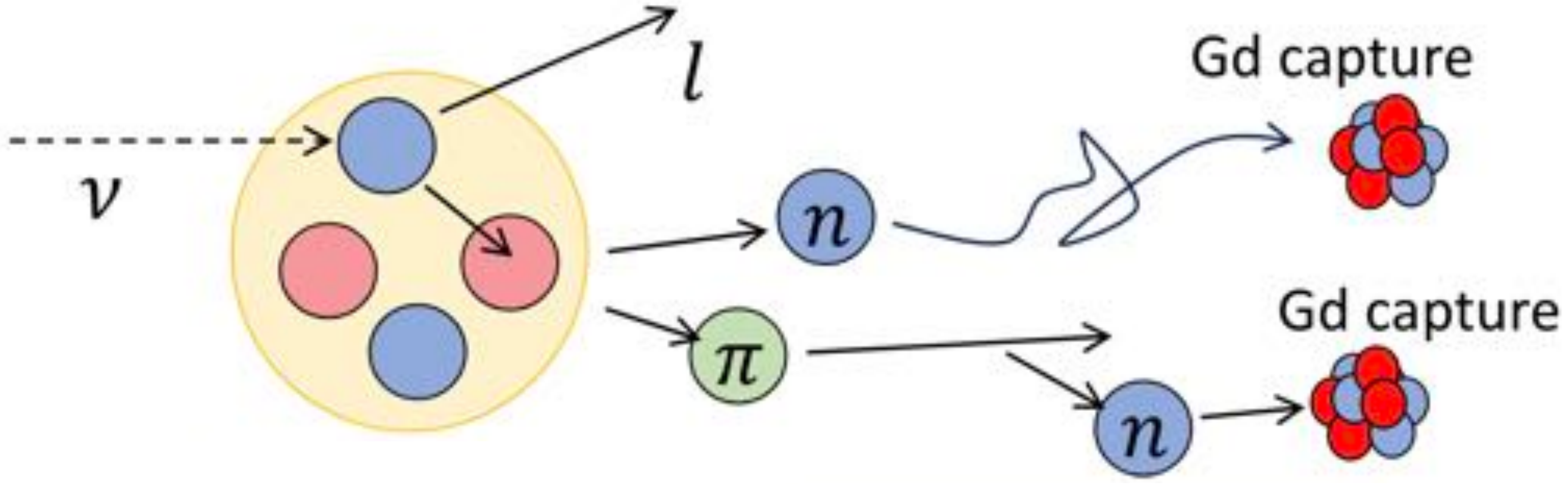


First observation reactor neutrinos by SK, correlated reactor activity though small stat.

Atmospheric neutrinos



- Sensitive to MO, Δm_{32}, δ_{CP}, and θ_{23}
- Energy: ~100 MeV to TeV
  ➡ Enough cause hadronic interaction



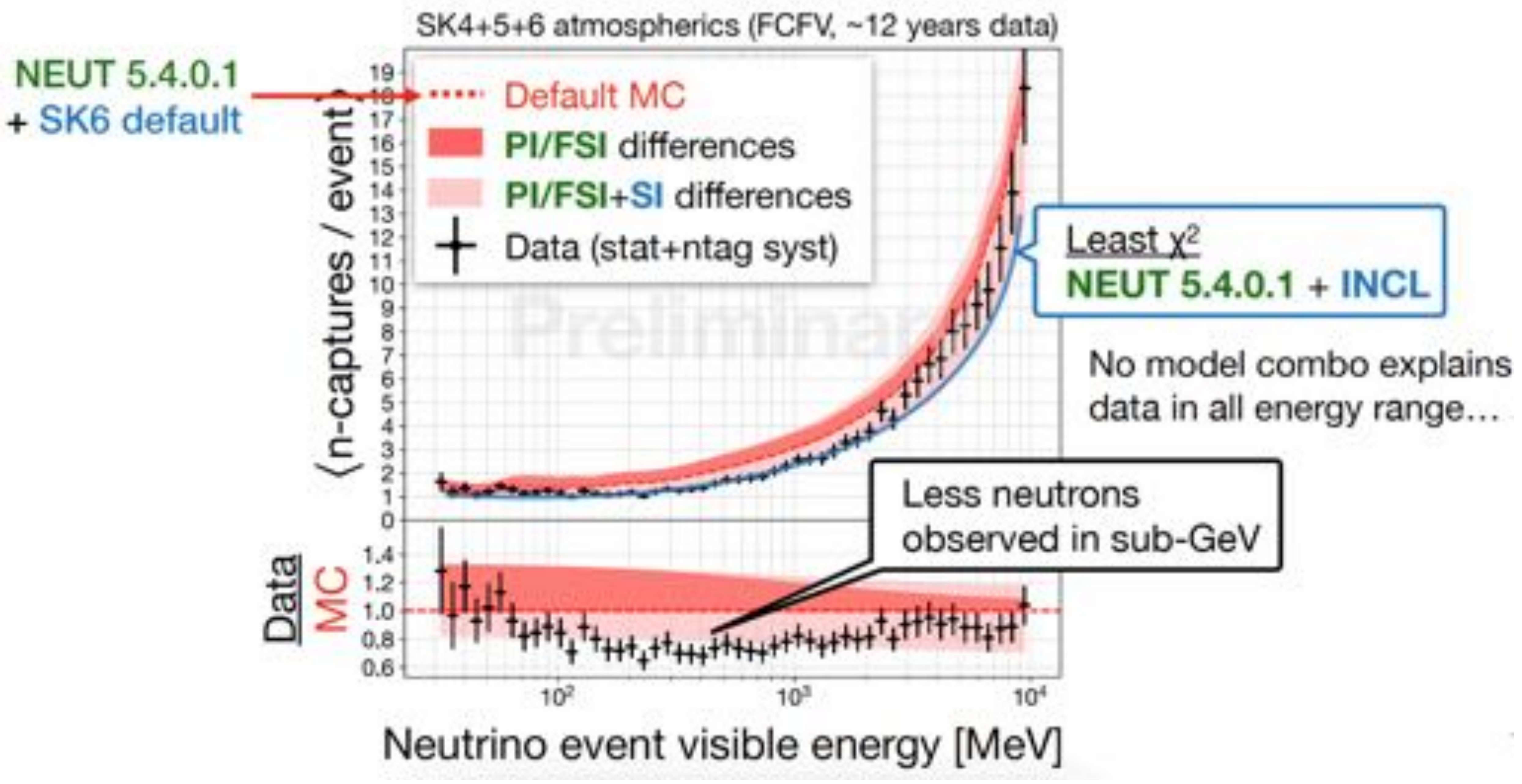
Neutrino interaction × Secondary interaction

- Neutron signal is good for validate hadronic interaction and flavor difference

Atmospheric neutrinos

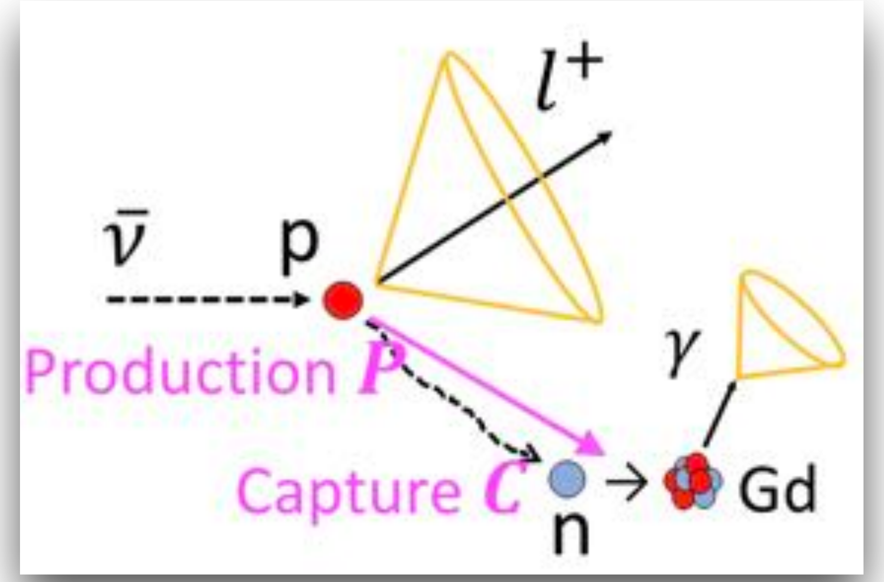
Interaction validation and event reconstruction by neutron

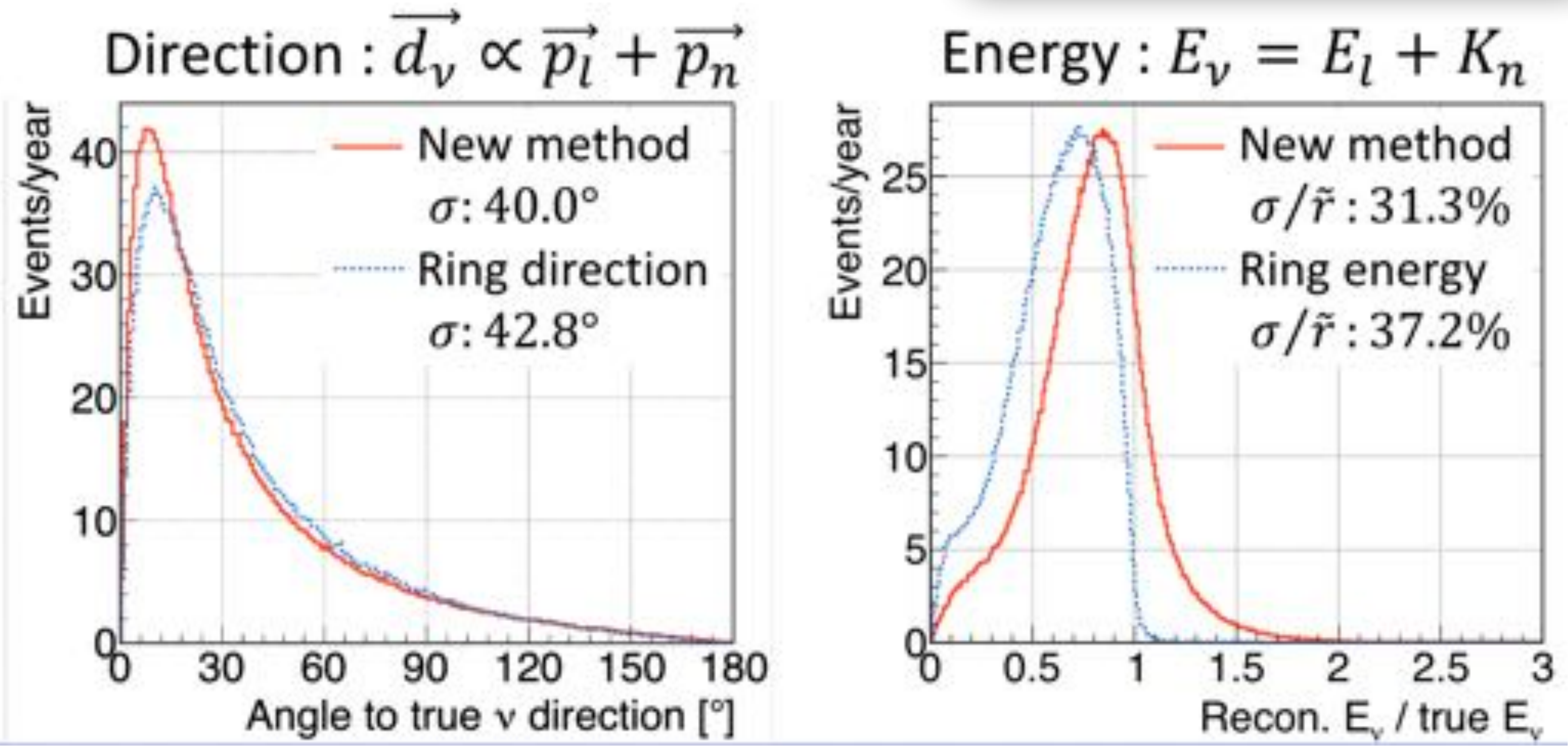
- Interaction validation using neutron
  - Compare neutron multiplicity



Enable to do validation neutrino and hadronic interaction by atm. Neutrino events

- Neutrino event reconstruction
  - Utilize to **reconstruct neutrino direction and energy**





Neutrino event reconstruction is improved
➡ 10% increase to the mass ordering sensitivity

Summary

- SK-Gd started from 2020, and currently operation continues with 0.03% Gd concentration
- Producing physics result using Gd-neutron signal

- Some of the highlight (my selection)
  - DSNB: 2.3 σ rejection of null DSNB hypothesis
  - Reactor neutrinos:
    - Lowering IBD search energy threshold
    - First positive observation by SK→ Achieving all oscillation source by SK
  - Atmospheric neutrinos:
    - not only oscillation but also interaction validation is enabled
    - Utilize neutron to reconstruct neutrino events

Backup

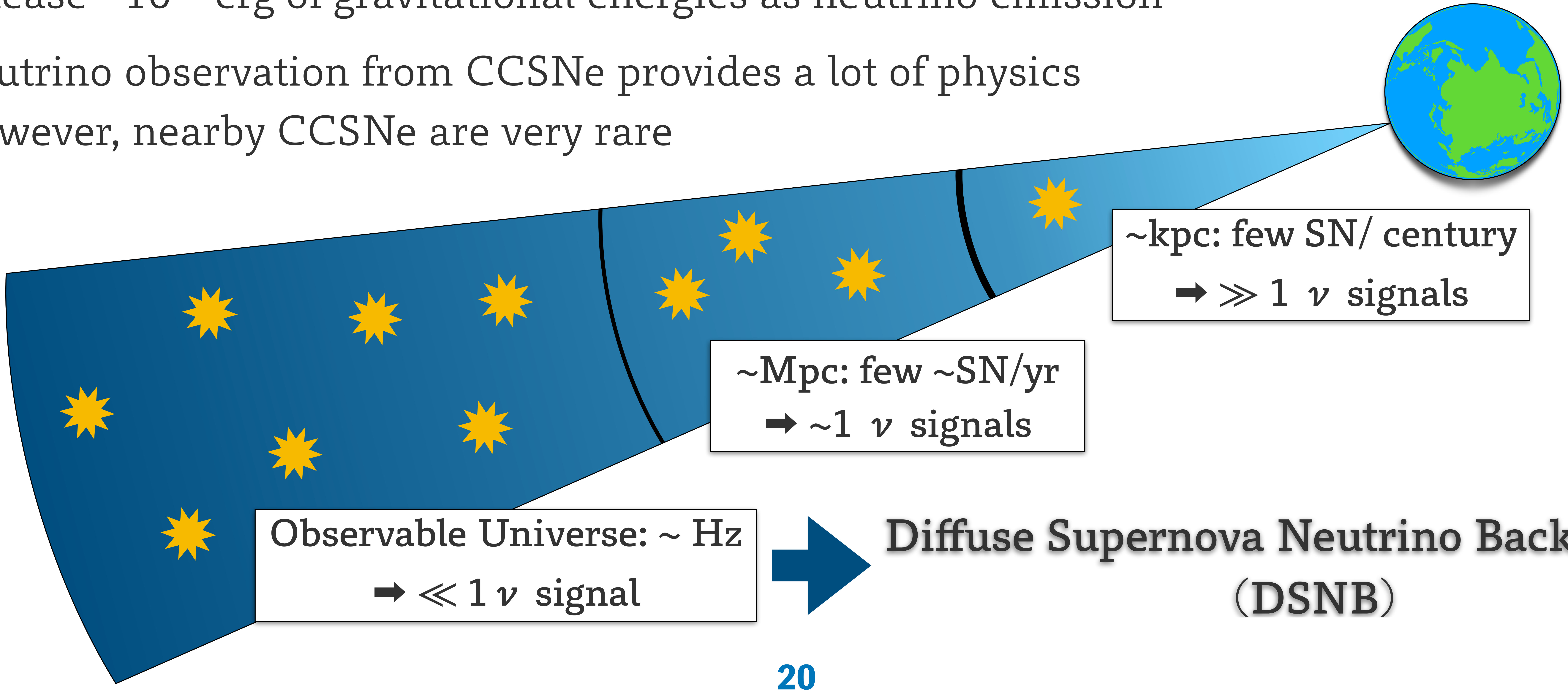
Neutrinos from Supernova

Source of Diffused Supernova Neutrino

Core-Collapse Supernova (CCSN)

- Release ~10^{53} erg of gravitational energies as neutrino emission
- Neutrino observation from CCSNe provides a lot of physics

However, nearby CCSNe are very rare



➡ Diffuse Supernova Neutrino Background (DSNB)

DSNB: Detection

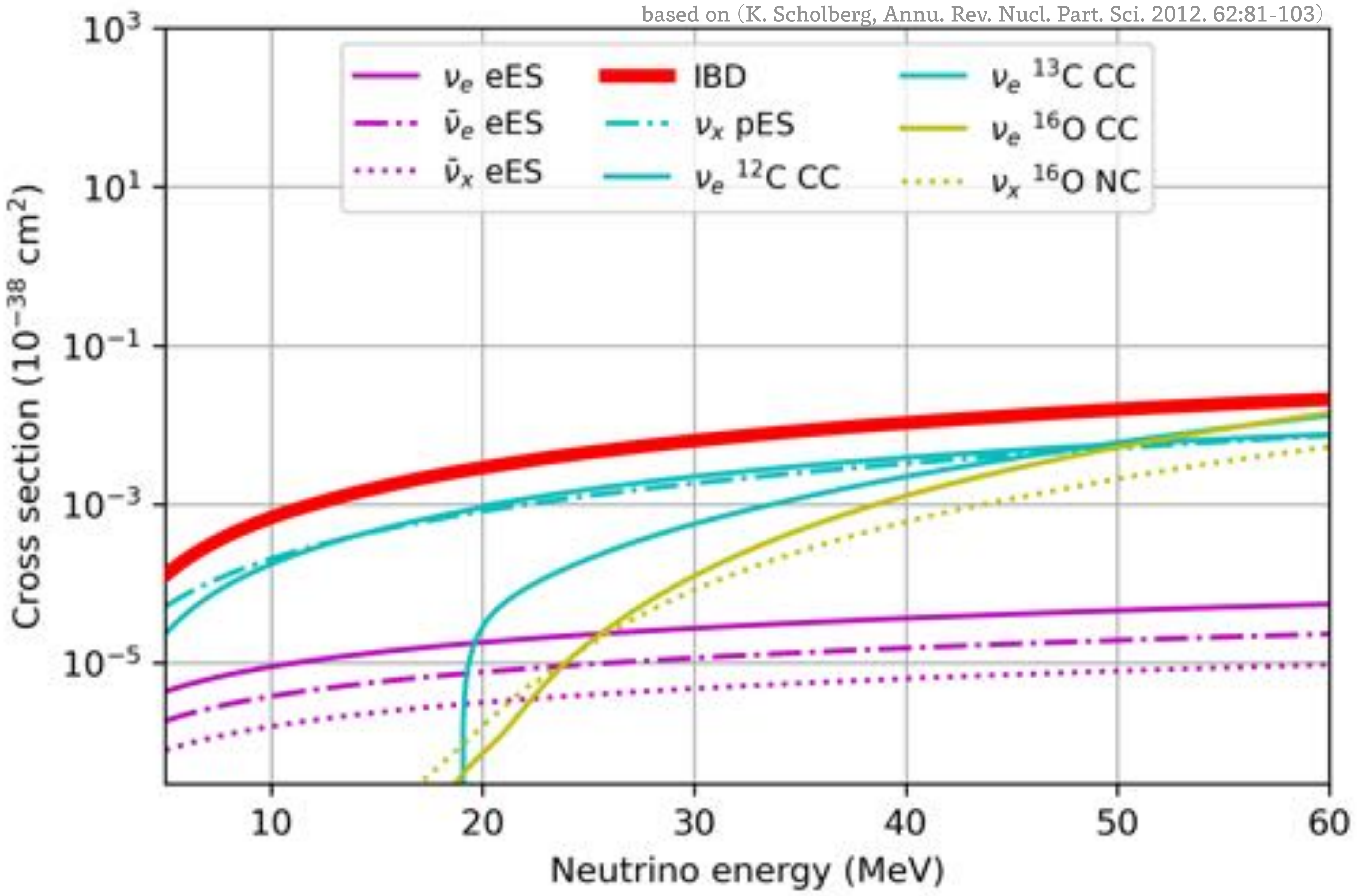
How we can detect DSNB

- Roughly equal flux for all ν flavors
- Large volume is required to search DSNB due to its low flux and cross-section

Main channels

- **Inverse beta decay:** $\bar{\nu}_e + p \to e^+ + n$
  - Main channel for DSNB detection
  - Simple topology with one e+ and n
    ➡ Coincidence detection reduces enormous background
- Charged current with nucleus: $\nu_e + N$
  - Subdominant channel for higher energy
- Neutral current with nucleus: $\nu_x + N$
  - Lower prob., but interact for all flavor

based on (K. Scholberg, Annu. Rev. Nucl. Part. Sci. 2012. 62:81-103)



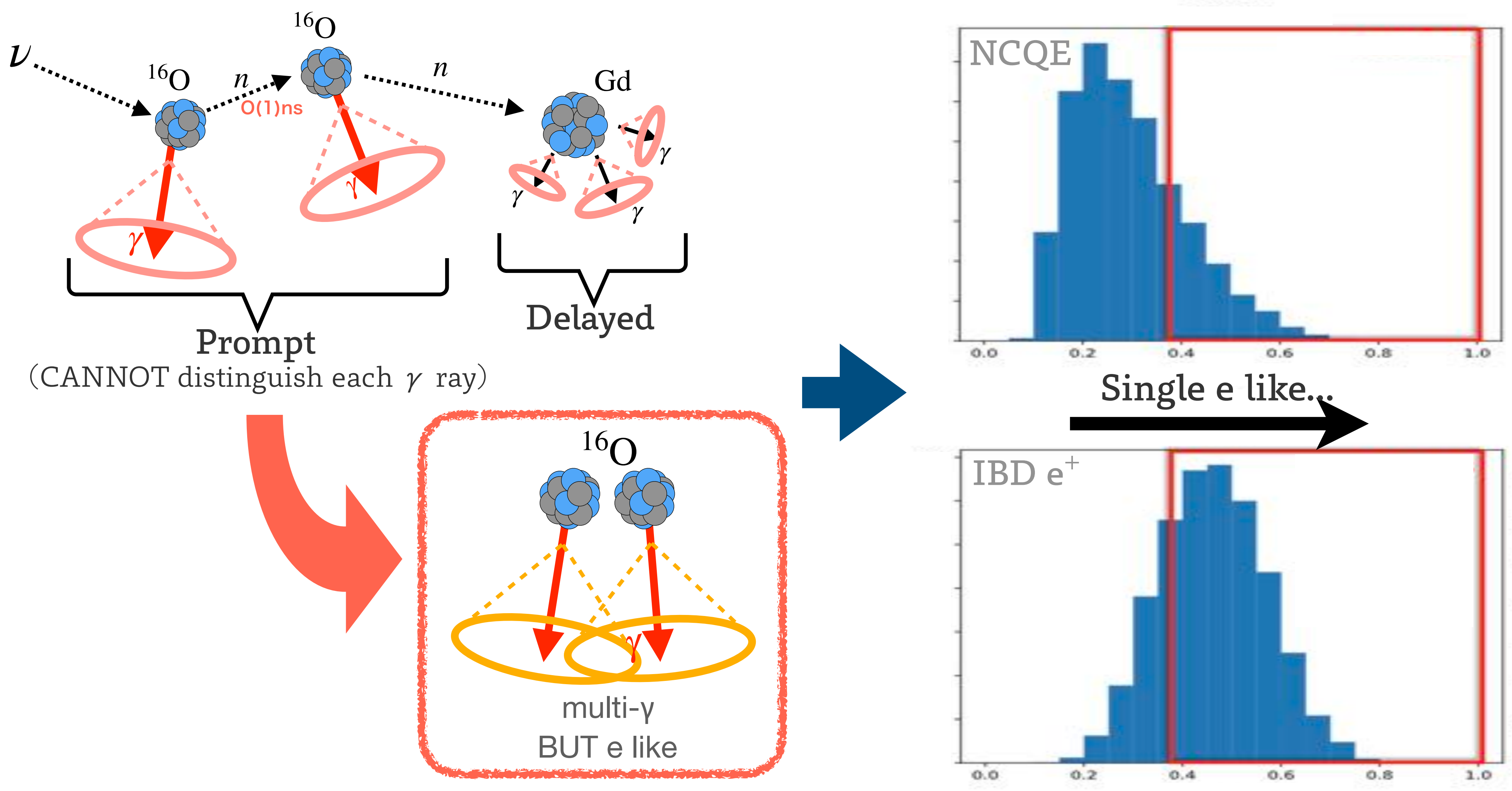
Latest analysis of SK-Gd

Analysis improvement

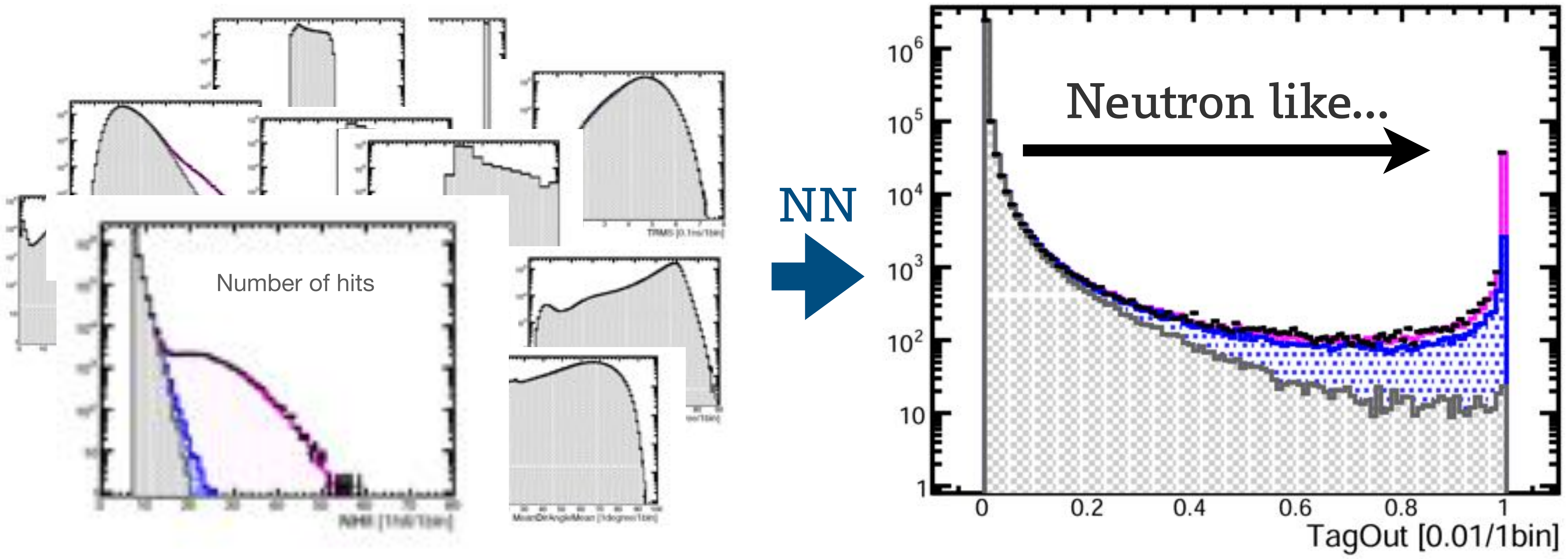
- SK-Gd continued observation and acquired additional 404 days with 0.03w% Gd (SK-VII)
  ➡ **Totally 956 days of SK-Gd data**

Analysis Improvement (Santos et al., poster 637)

- Developed new reduction for NCQE event using gamma-ray cut variable
  ➡ Further reduced ~90% of NCQE

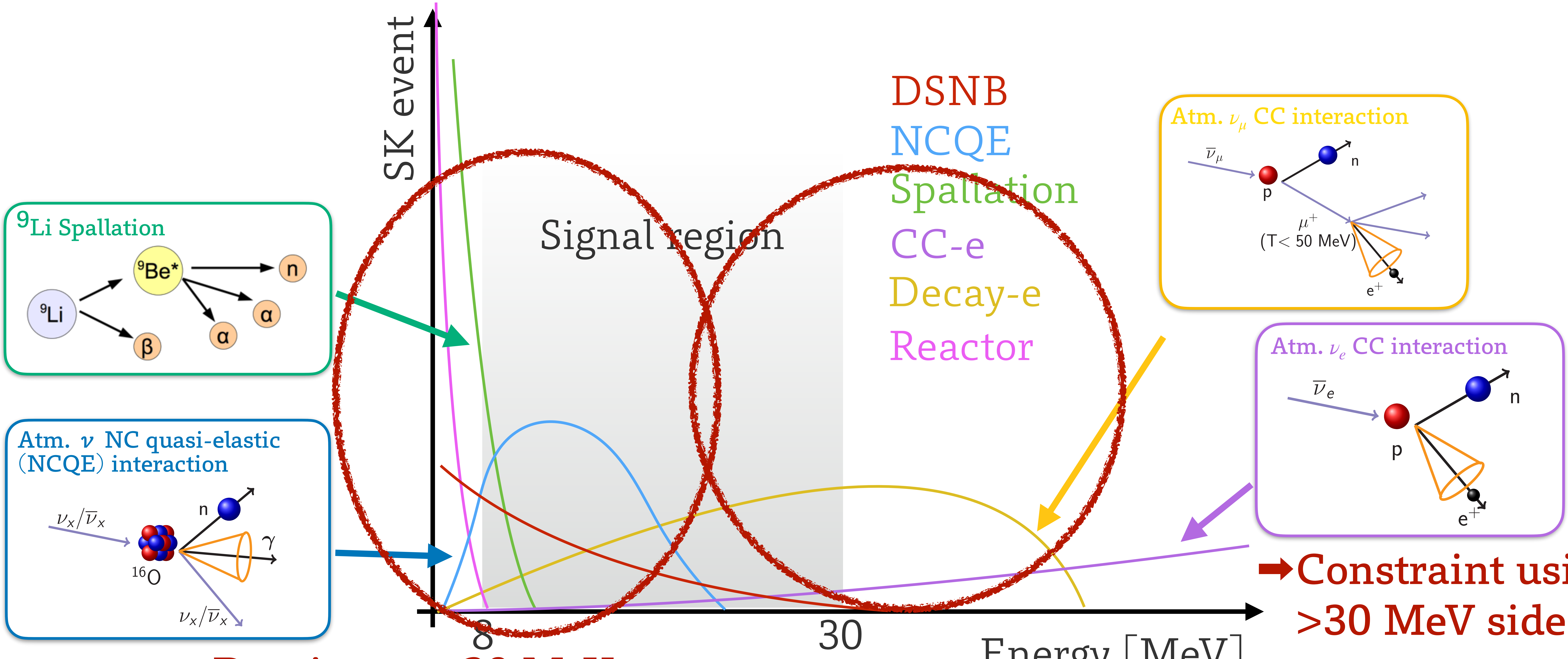


- Developed new neutron tagging methods based on multivriate analysis,
  - Search neutrons with 500 μs window
    ➡ achieving >60% efficiency in SK-VII



DSNB search in SK-Gd

Signal and background

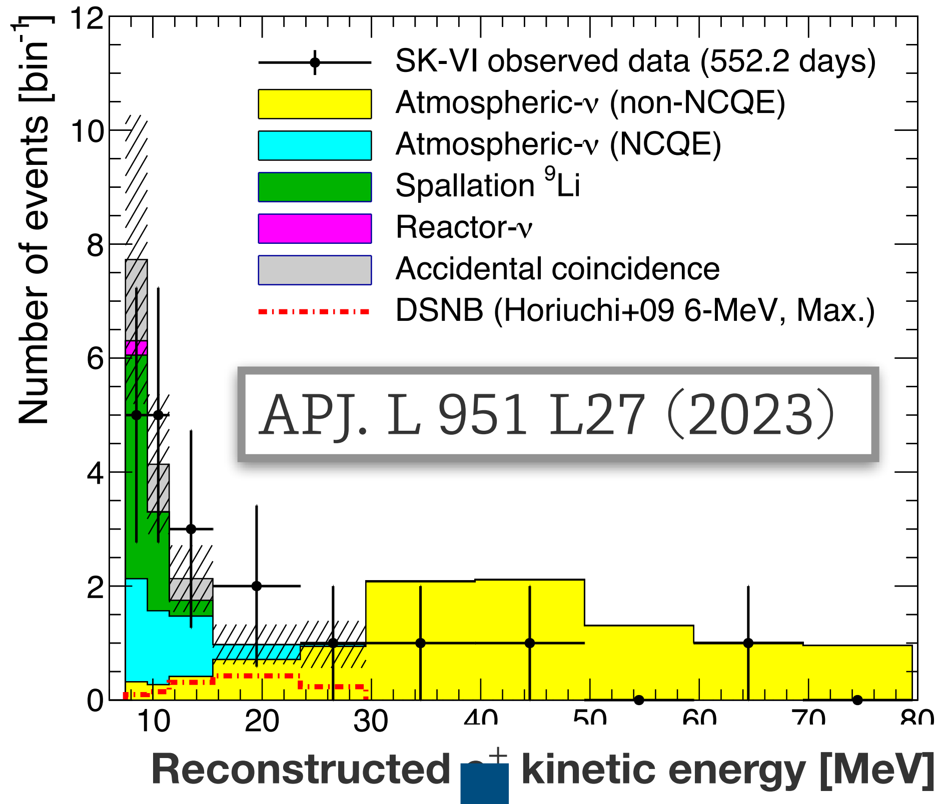


➡ Dominant < 20 MeV

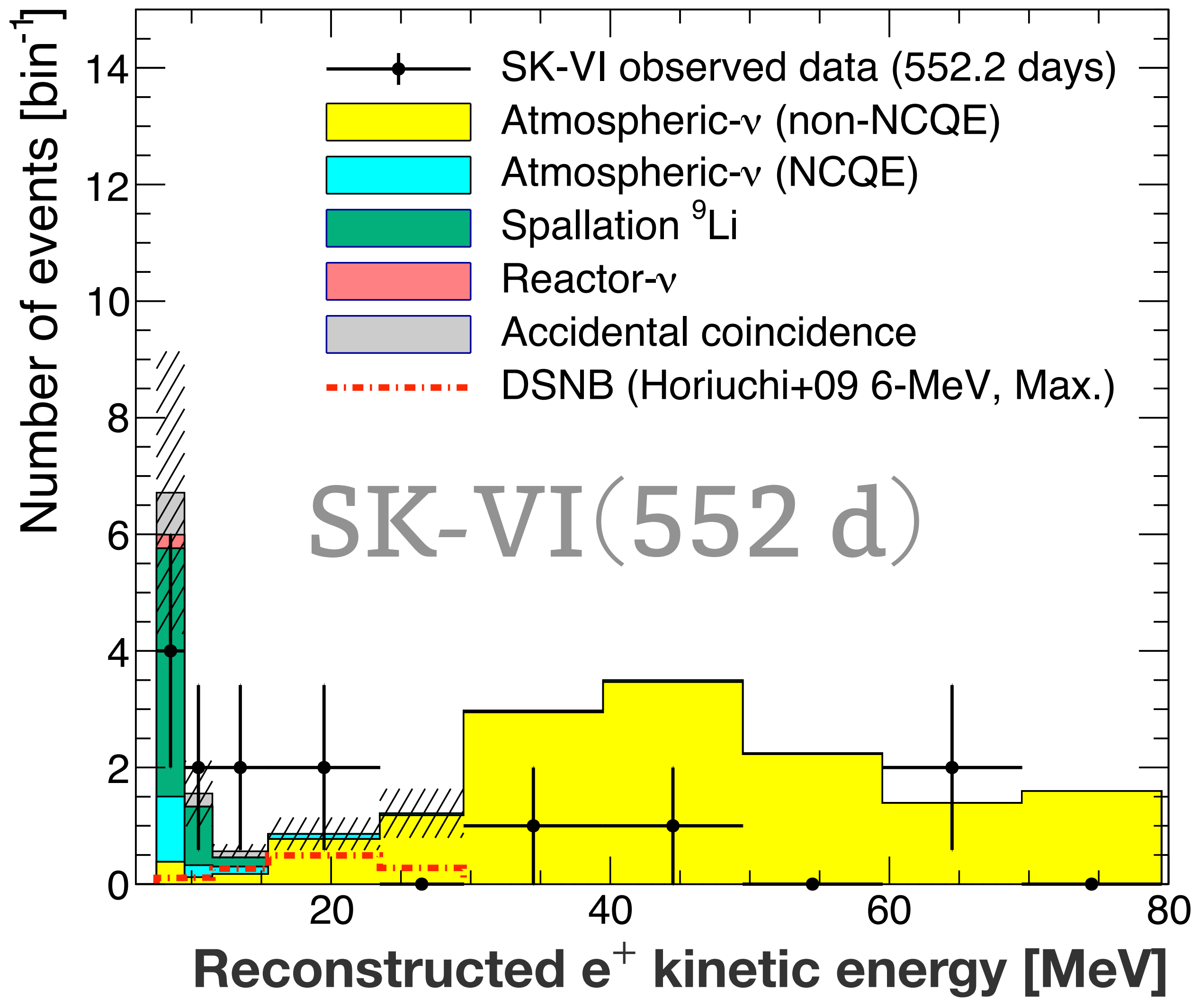
➡ Constraint using >30 MeV side-band

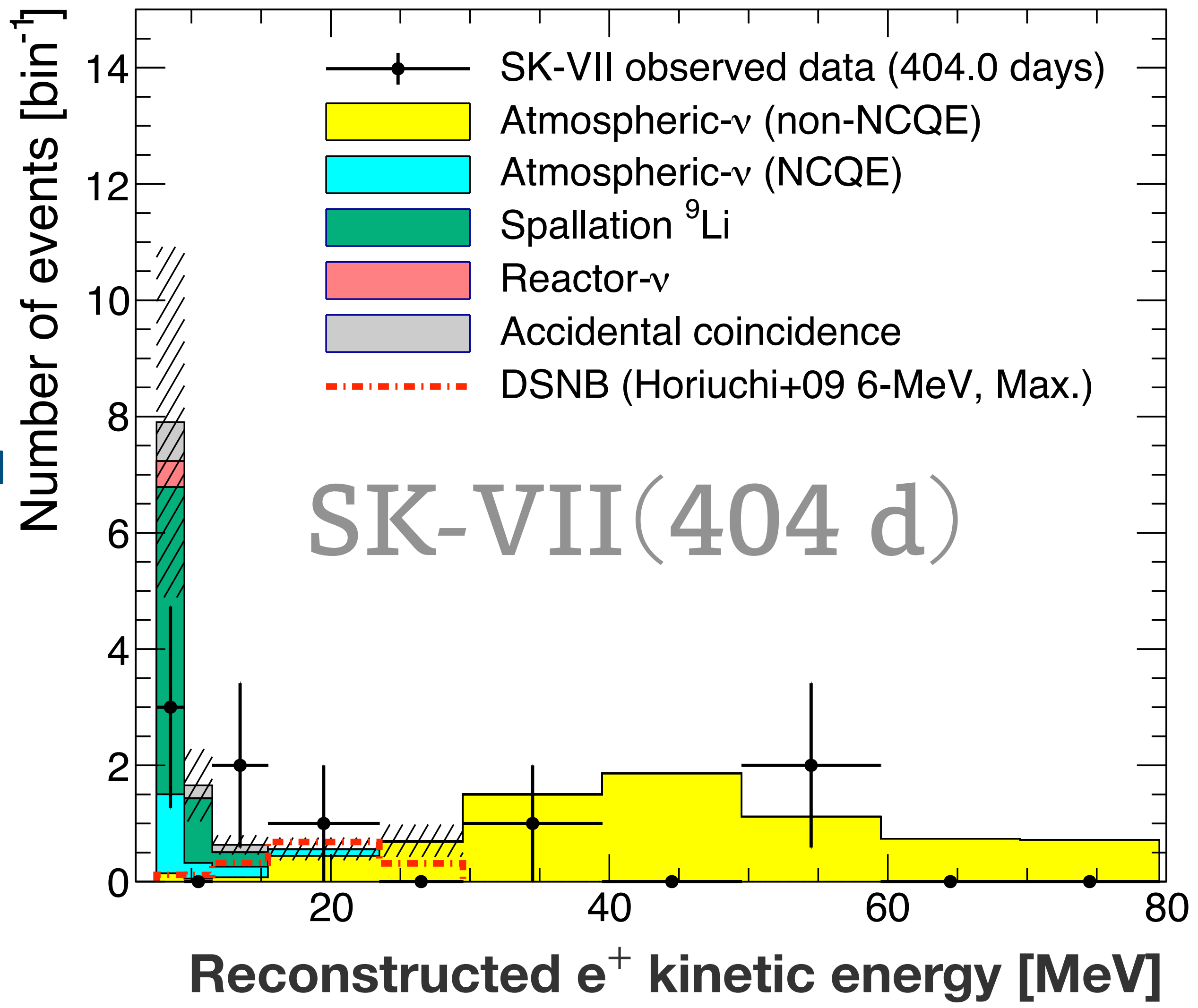
Results

SK-Gd energy spectrum



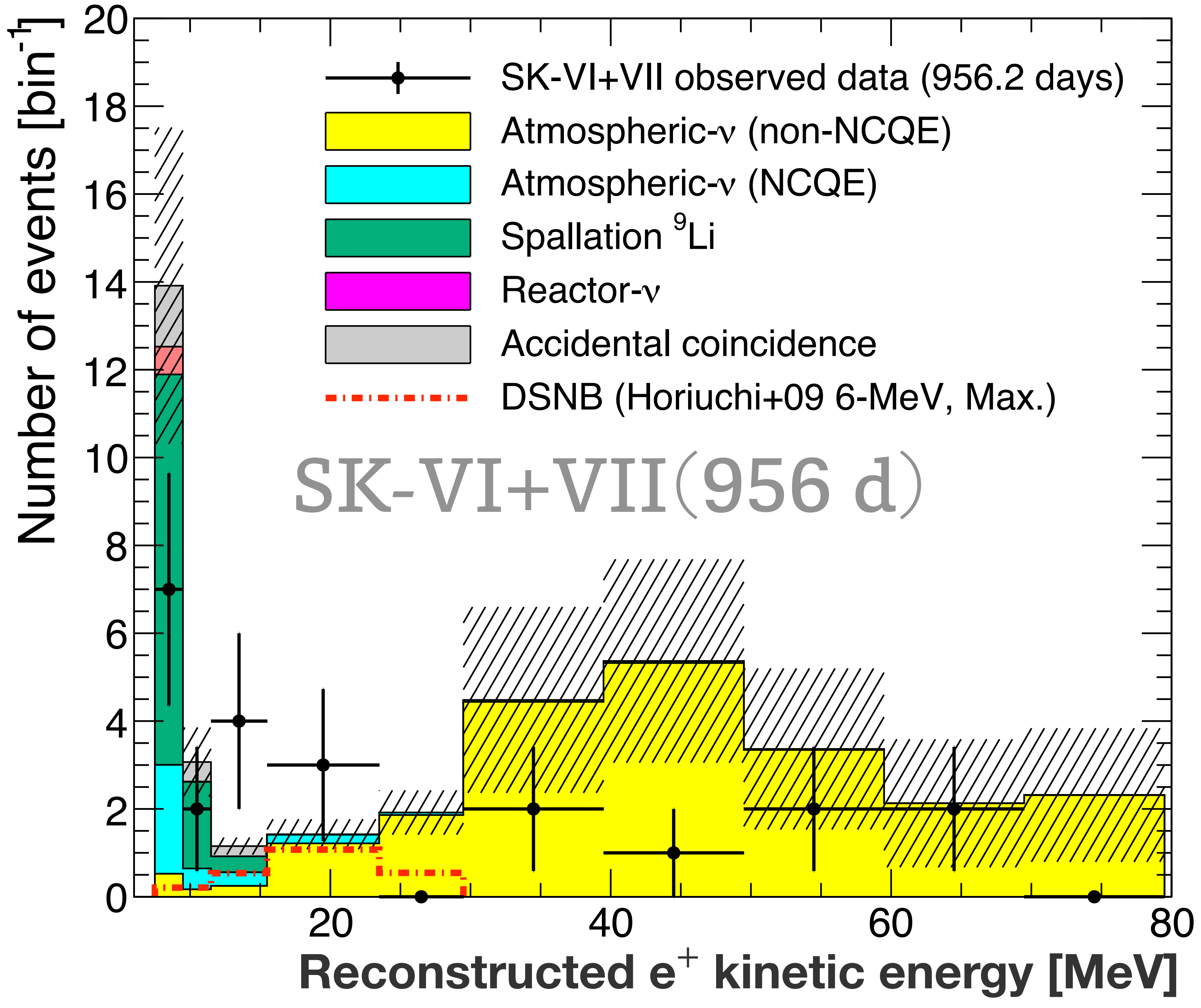
New n-tag, NCQE reduction





Highlight:

- Additional 404 days with 0.03% Gd ➡ Totally 956 days SK-Gd data
  - Select only $N_n = 1$
  - New neutron ID and background reduction
- No signal obvious excess, but indicates (min. p-value=0.04)



Preparation of Gd loading

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