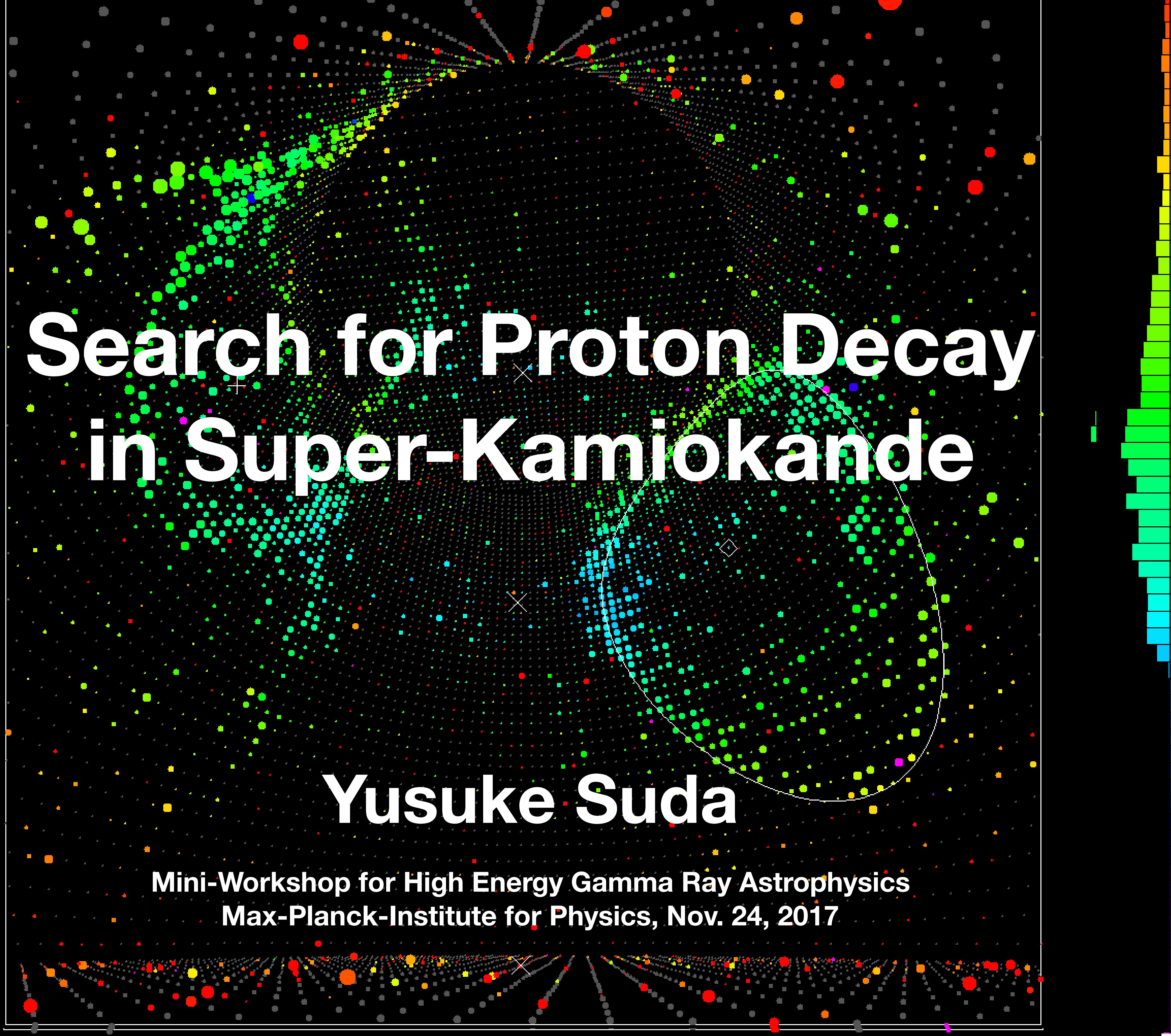


Search for Proton Decay in Super-Kamiokande

Yusuke Suda

Mini-Workshop for High Energy Gamma Ray Astrophysics
Max-Planck-Institute for Physics, Nov. 24, 2017

Who am I

- I am **Yusuke Suda** from Univ. of Tokyo, Japan
- Master of Science (Mar. 2014)
  - "*Research and Development of Large-Aperture* ***Hybrid Photo-Detectors*** *for Hyper-Kamiokande*"
- Doctor of Philosophy (Sep. 2017)
  - "*Search for* ***Proton Decay*** *Using an Improved Event Reconstruction Algorithm in Super-Kamiokande*"

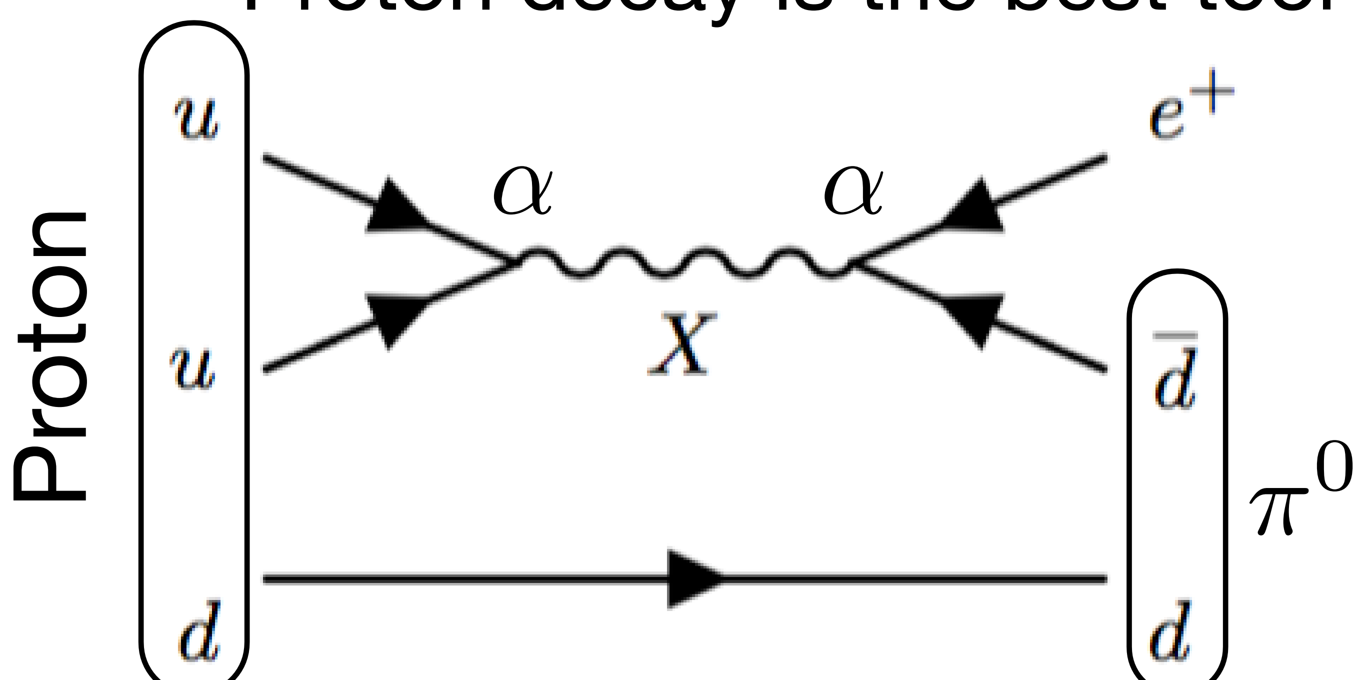
First

- Postdoc at Center for High Energy gEophysics Research (CHEER), Earthquake Research Institute (ERI), UTokyo
  - Muon radiography (***Muography***) for geoscience

What is Proton Decay

- Phenomena predicted by Grand Unified Theories (GUTs) of elementary particles
- Unification of three fundamental forces (EM, Weak, Strong)
  - Very high energy scale (≧10^{15} GeV) 

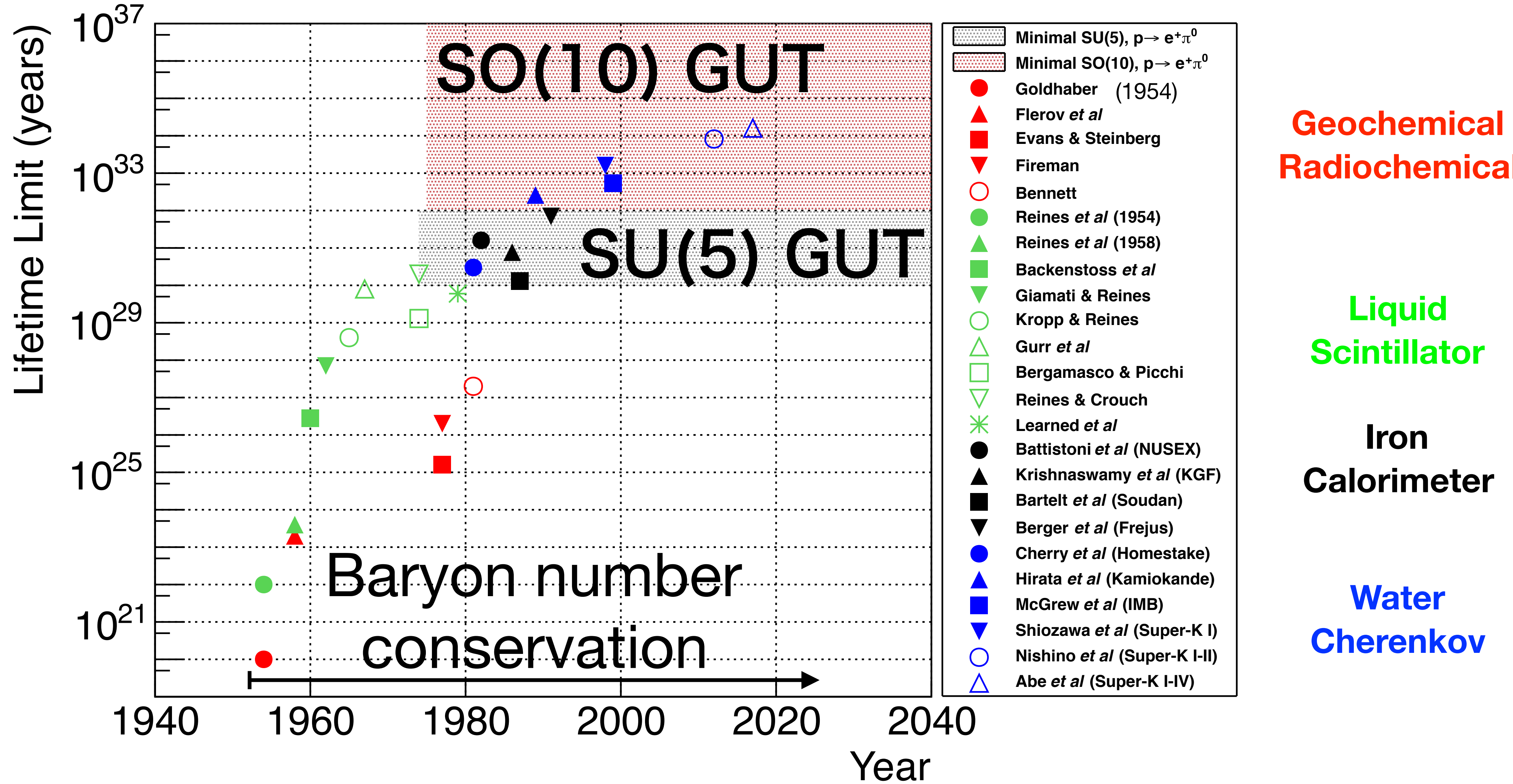
Accelerators
  - Solve electromagnetic charge quantization, etc.
  - Mixture between quarks and leptons → Proton decay
- Proton decay is the best tool to test GUTs!



$$\tau \sim \frac{M_X^4}{\alpha^2 m_p^5}$$

Predicted Proton lifetime:
10^{32} - 10^{39} years

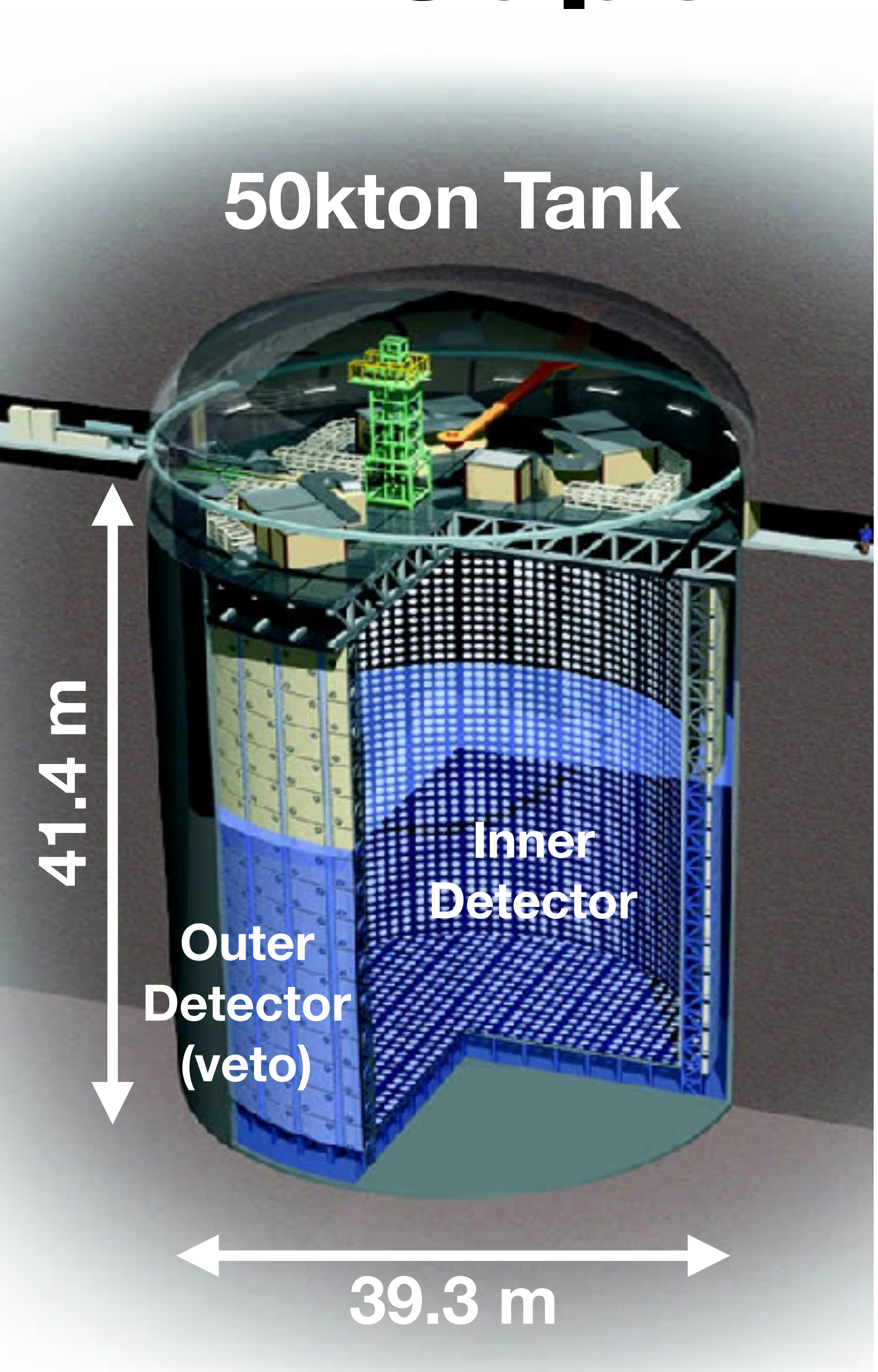
Proton Decay So Far



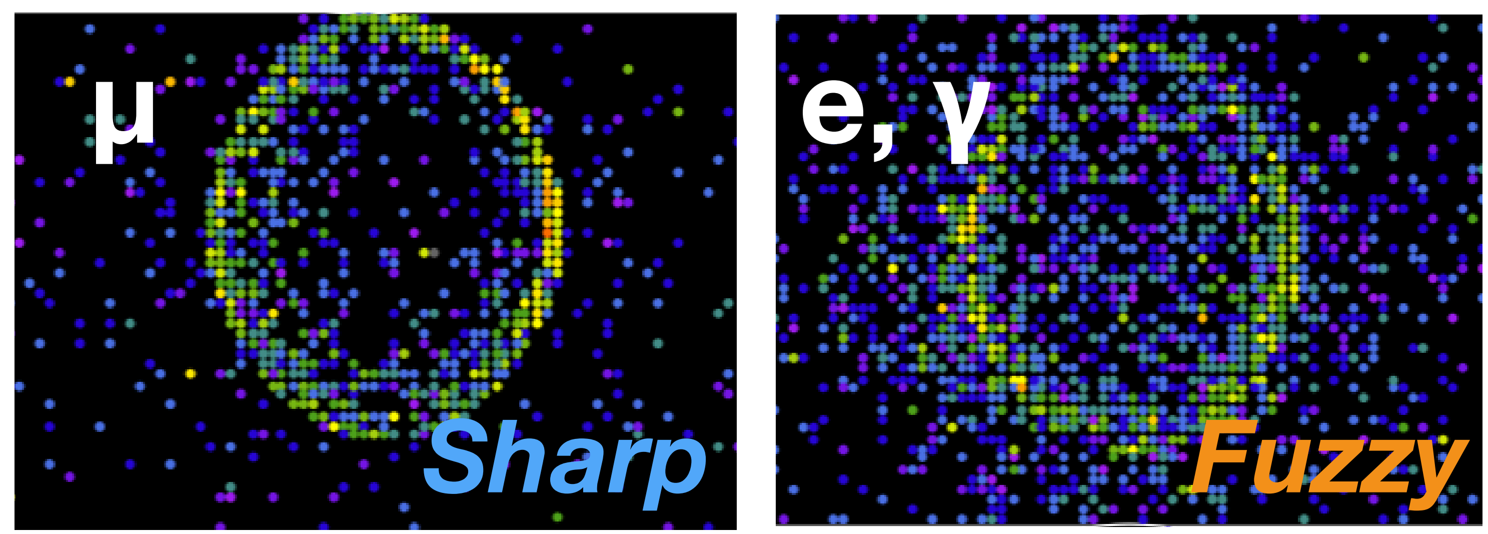
- Long history of over 60 years. No significant candidate
- Super-Kamiokande (SK) is the top and still in predictions
- Proton decay may happen at any time
- Let’s search proton decay in SK!

Super-KamiokaNDE

ucleon ecay xperiment

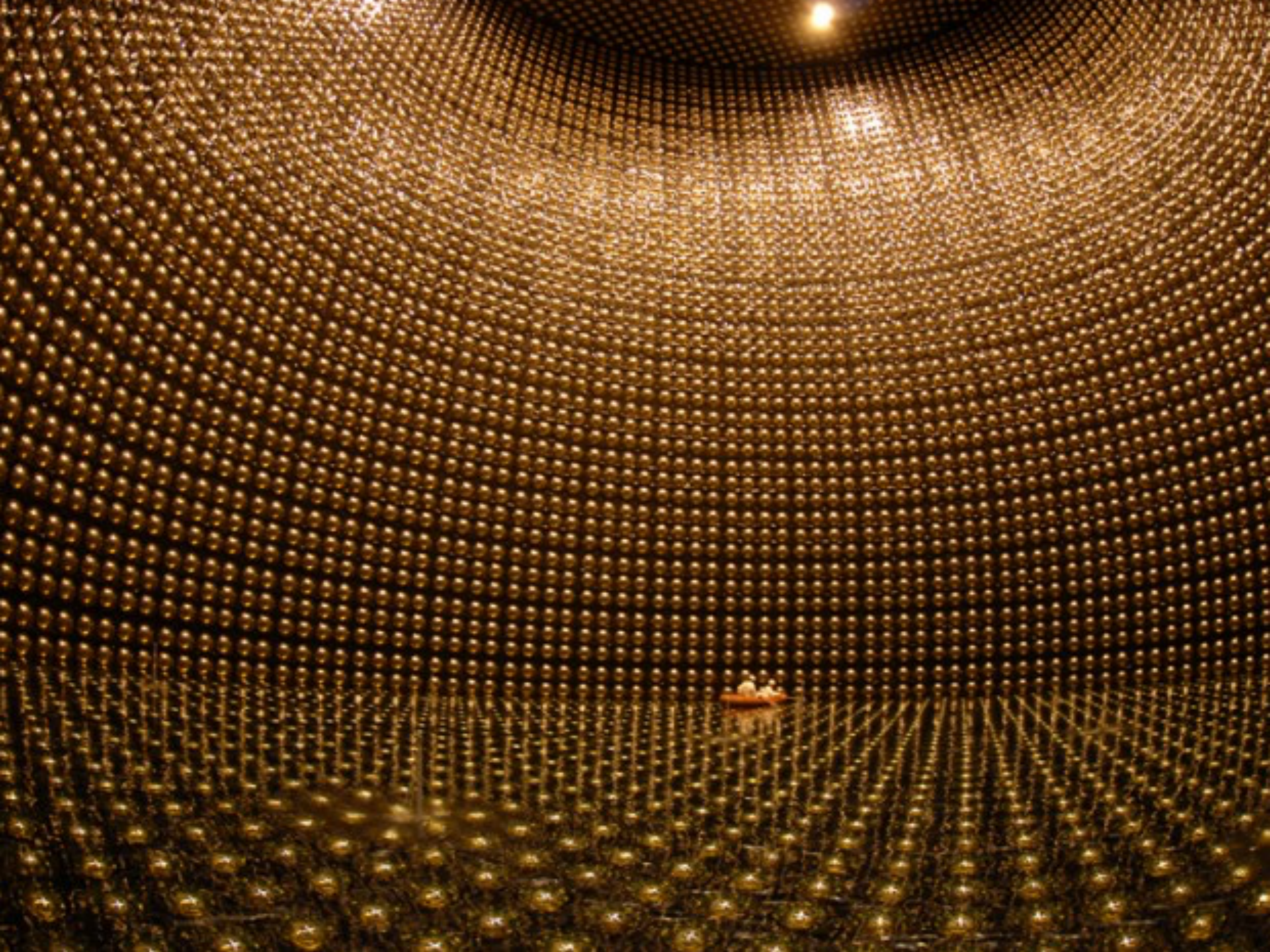


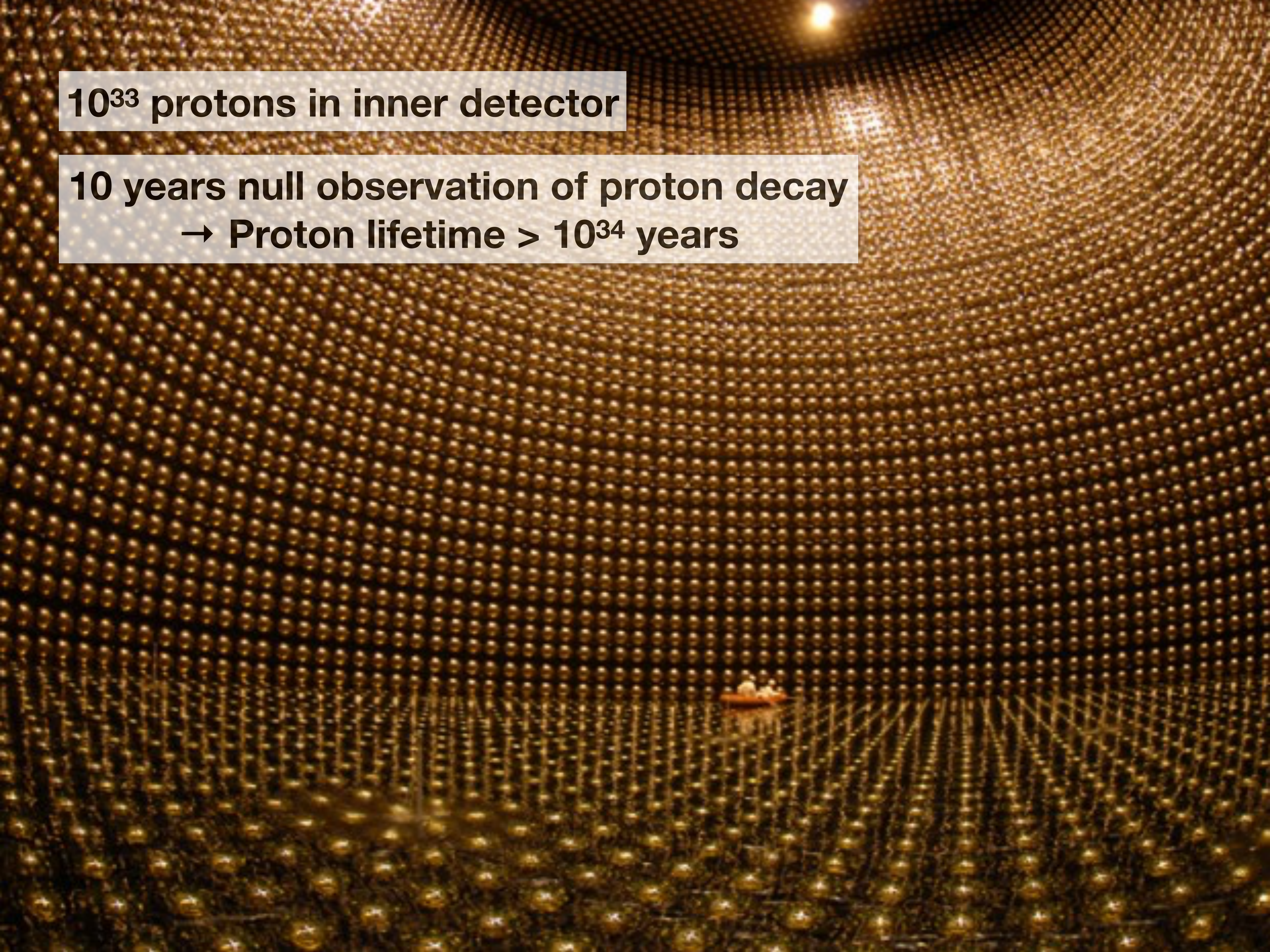
- 50kton water Cherenkov detector
  - 1000m underground, Kamioka, JPN
- Record Č light (Q・T) by 20-inch PMTs
- PID by Č ring pattern



	SK1	SK2	SK3	SK4
Period	1996-2001	2002-2005	2006-2008	2008-
Live time	1489.2	798.6	518.1	2650.4 (~Sep. 2016)
Photocoverage (# of PMTs)	40% (11,146)	19% (5,182)	40% (11,129)	40% (11,129)

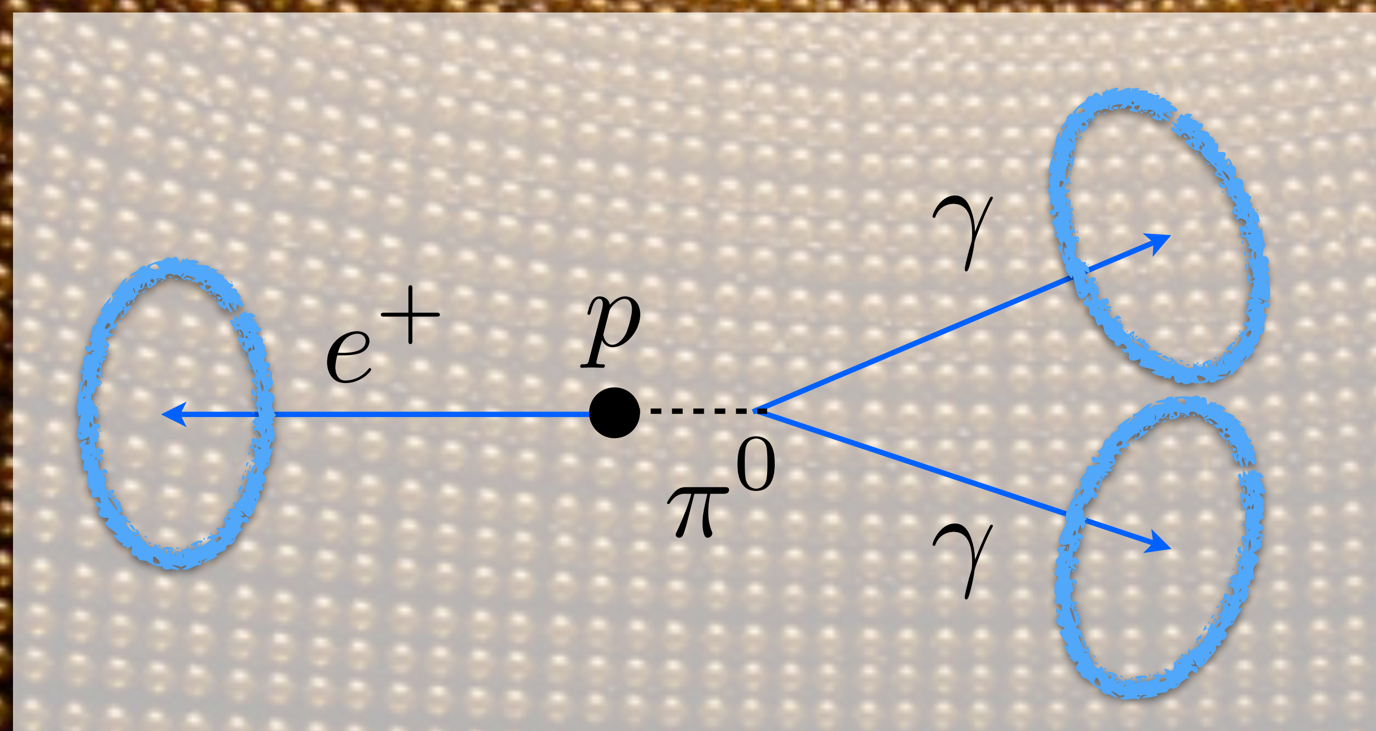
Half of the all data




10^{33} protons in inner detector
10 years null observation of proton decay
→ Proton lifetime > 10^{34} years

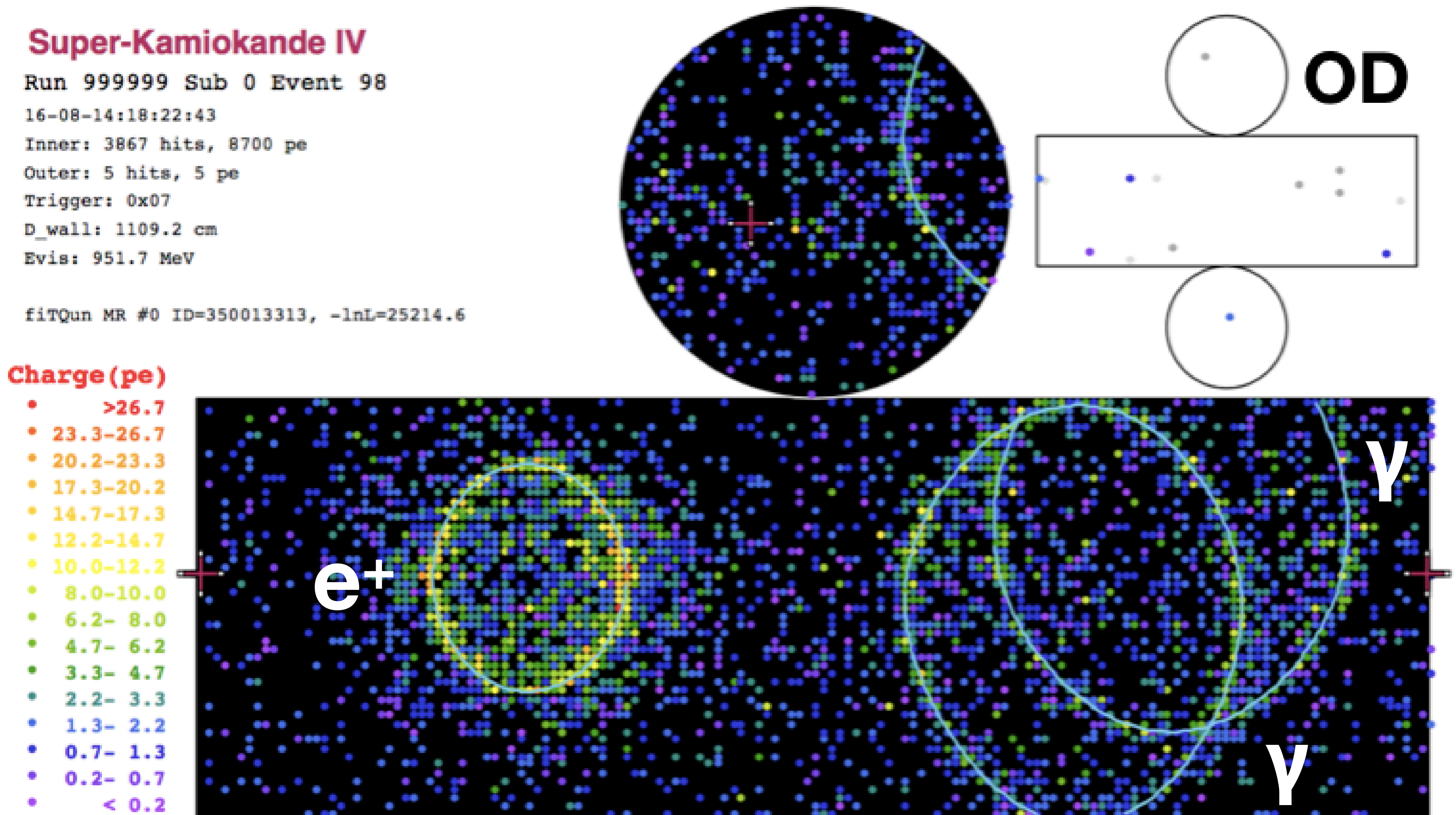
My target decay mode: $p \rightarrow e^{+}\pi^{0}$

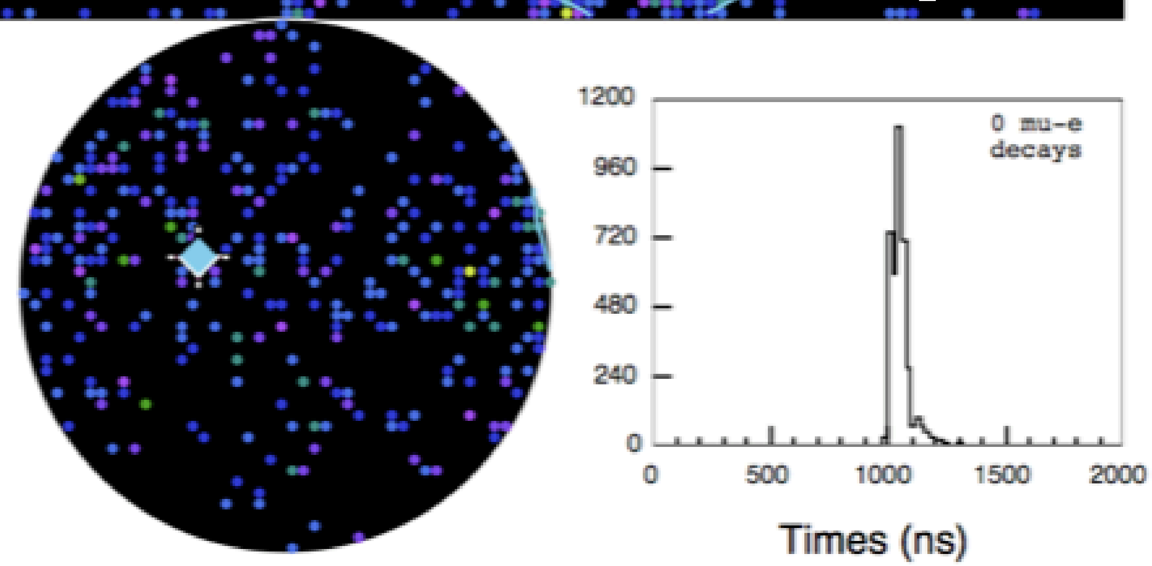
- Most dominant in non-SUSY GUTs
- Most sensitive for SK



Decay time of π^{0}: 8×10^{-17} s
Gamma conversion length: ~40cm

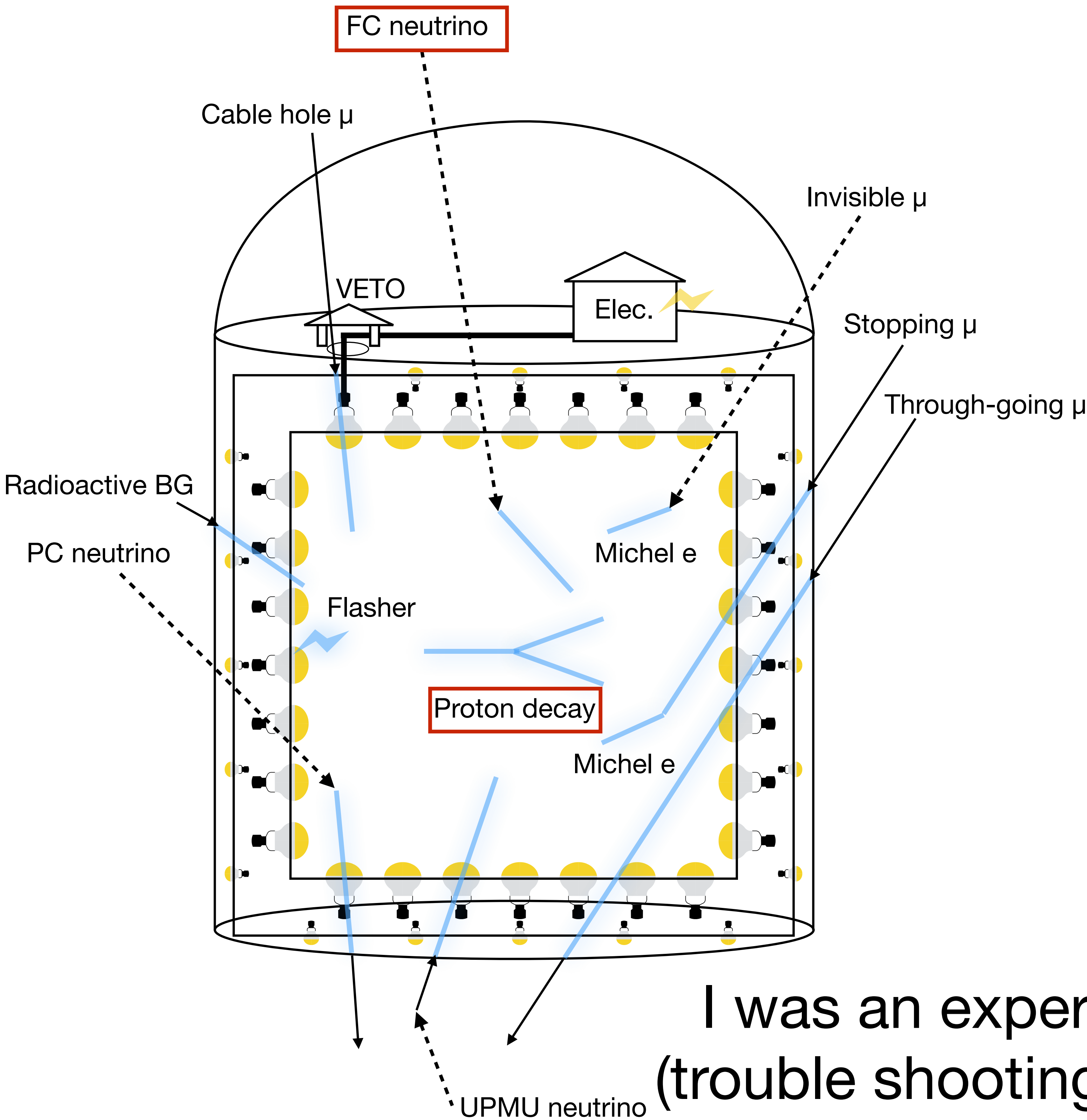
Proton Decay Simulation





Back-to-back topology
→ Easily distinguish from atmospheric neutrinos

Data Flow



10^6 events/day

↓ Fully contained reduction (no OD activity, no flasher PMT etc.)

8 events/day

↓ Mostly atmospheric neutrino events (BG for proton decay)

Reconstruction

↓ Vertex, #rings, PID, momentum etc.

Proton decay search

Cut-based analysis

I was an expert of fully contained reduction (trouble shooting, preparation for data set etc.)

Reconstruction Algorithm

- Conventional: **APfit**
  - Determine reconstruction params. step-by-step (vertex → #rings → PID → momentum)
  - Use charge&time information of "hit" PMT only
    - Momentum determination by using observed charge inside Č-cone w/ a half angle of 70° → Bias
  - Developed 20 years ago and written by Fortran (hard to maintain)
- New: **fiTQun**
  - Determine all params simultaneously by a maximum likelihood method
  - Use not only hit PMT information but also "unhit" PMT information
  - Initial development by the T2K experiment, written by C++

fiTQun

$$L(\boldsymbol{x}) = \prod_{j}^{\text{unhit}} \underbrace{P_j(\text{unhit}|\boldsymbol{x})}_{\text{Unhit PDF}} \prod_{i}^{\text{hit}} \underbrace{\{1 - P_i(\text{unhit}|\boldsymbol{x})\}}_{\text{Hit PDF}} \underbrace{f_q(q_i|\boldsymbol{x})}_{\text{Charge PDF}} \underbrace{f_t(t_i|\boldsymbol{x})}_{\text{Time PDF}}$$

Observed Q&T

Unhit PDF (Poisson w/ correction)

Hit PDF

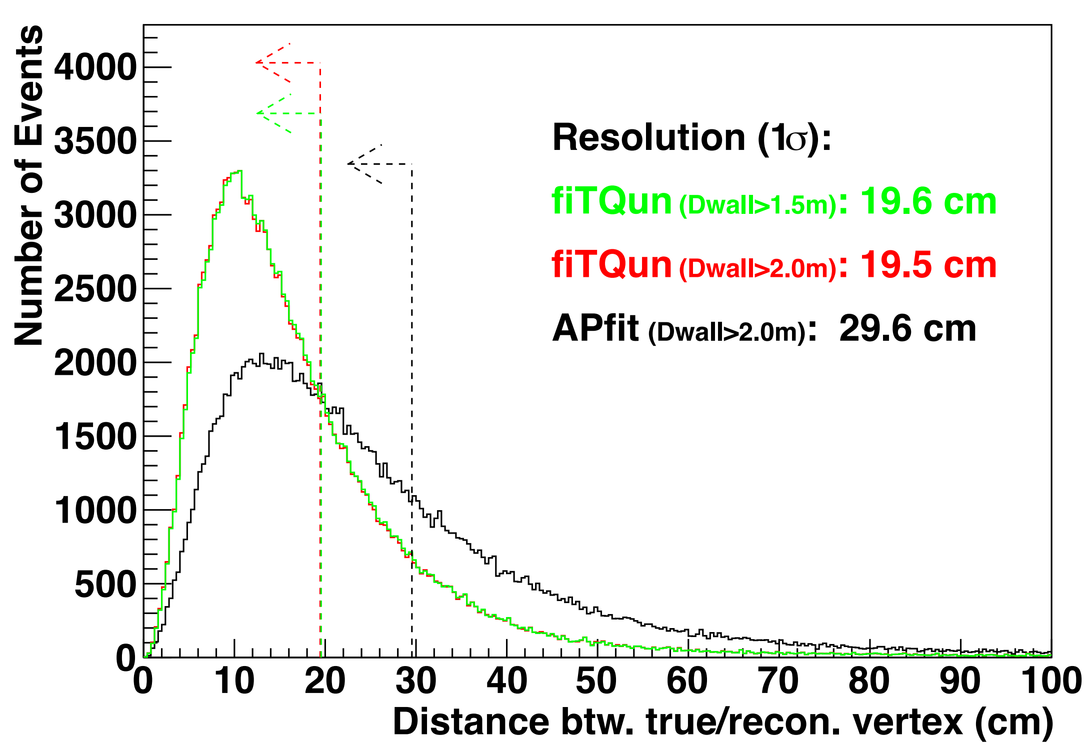
Charge PDF (Poisson)

Time PDF (Gaussian)

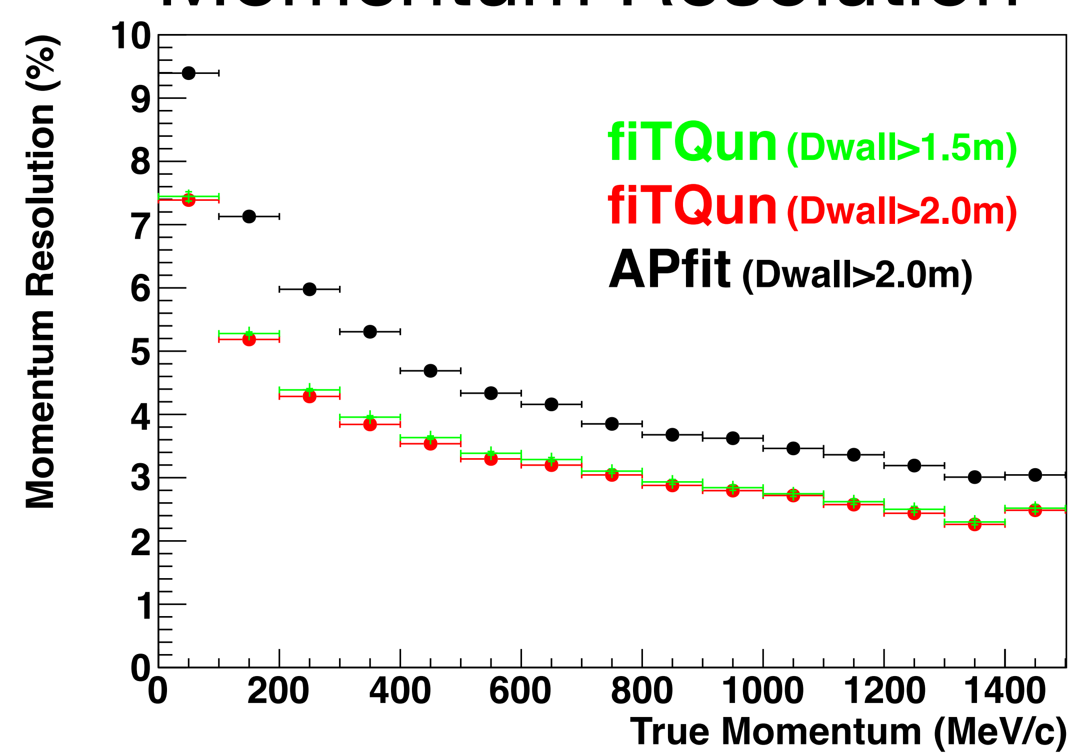
- Fit params. $\boldsymbol{x} = \{x, y, z, t, \theta, \phi, p\} \times$ (# of rings)
- Construct likelihood function for given ring(s) hypotheses
- Maximize likelihood for each event

Ex) Atm.-ν_e CCQE MC

Vertex Resolution

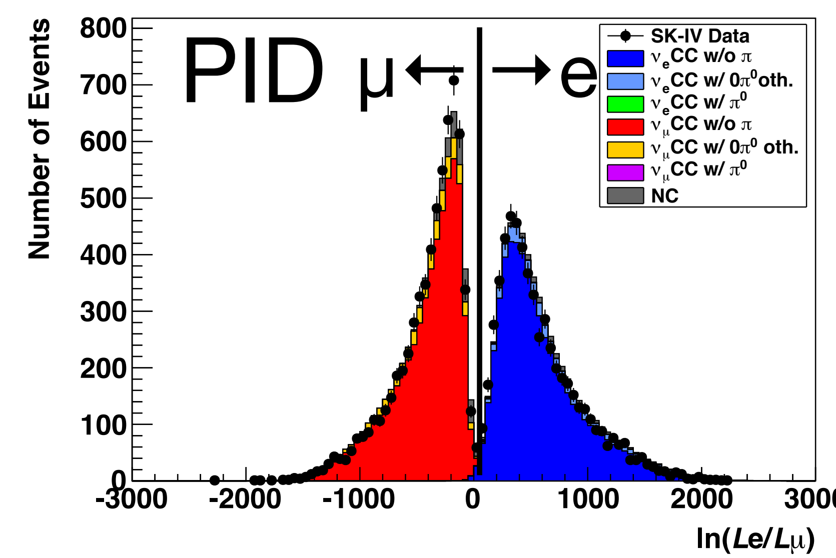


Momentum Resolution



Validation of fiTQun

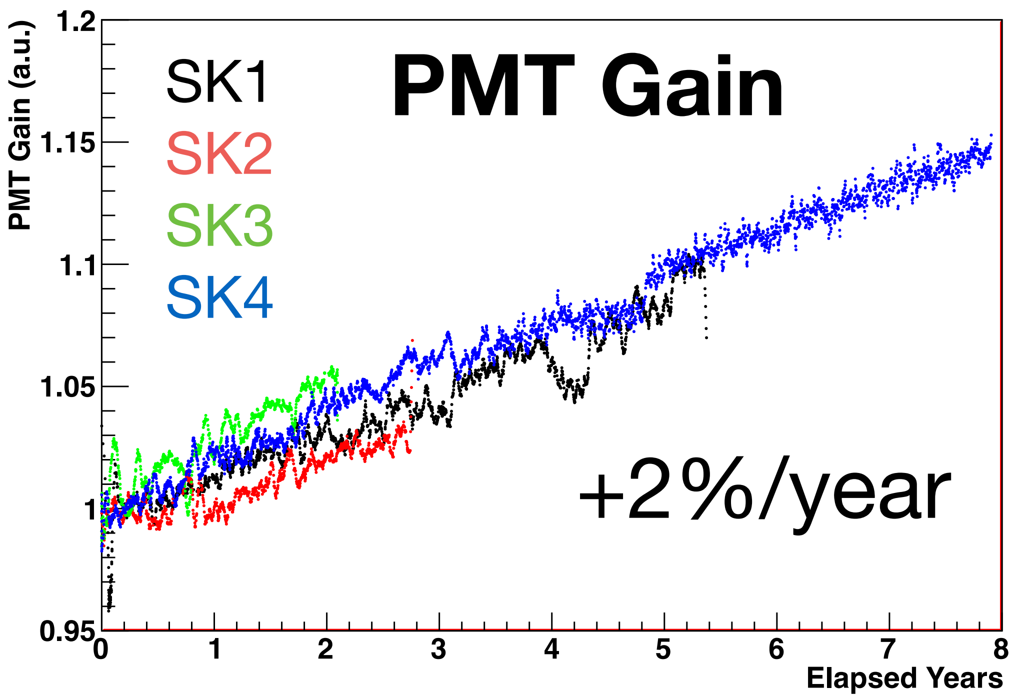
- Performance in MC was well examined, but treatment of real data was not enough to physics analysis
- I did
  - Check in data/MC likelihood distributions
  - Correction of time dependent detector params.
  - Estimation of energy scale uncertainty
    - Uncertainty 2.1%, same as APfit
  - Tuning of ring counting parameter

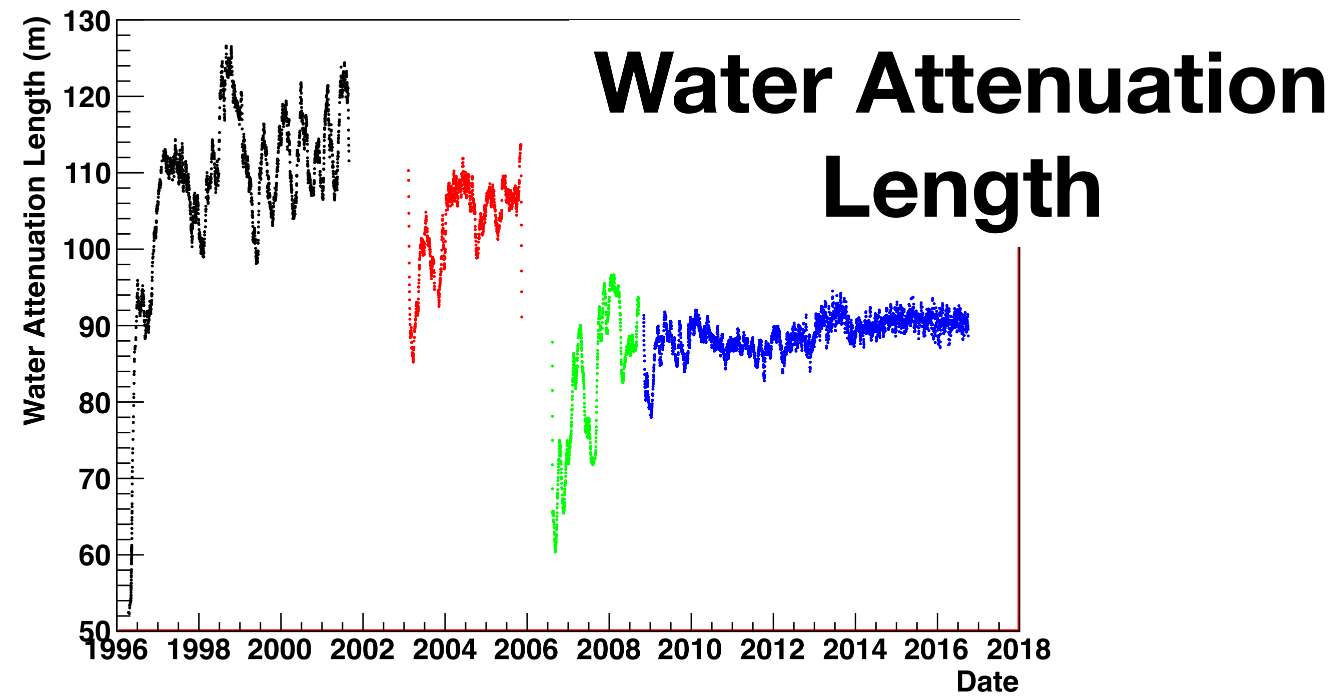


- Finally, fiTQun has been verified for SK-IV data/MC
  - Then, T2K experiment employed fiTQun for their analysis and announced a new hint for leptonic CP violation in summer 2017

Calibration of fiTQun

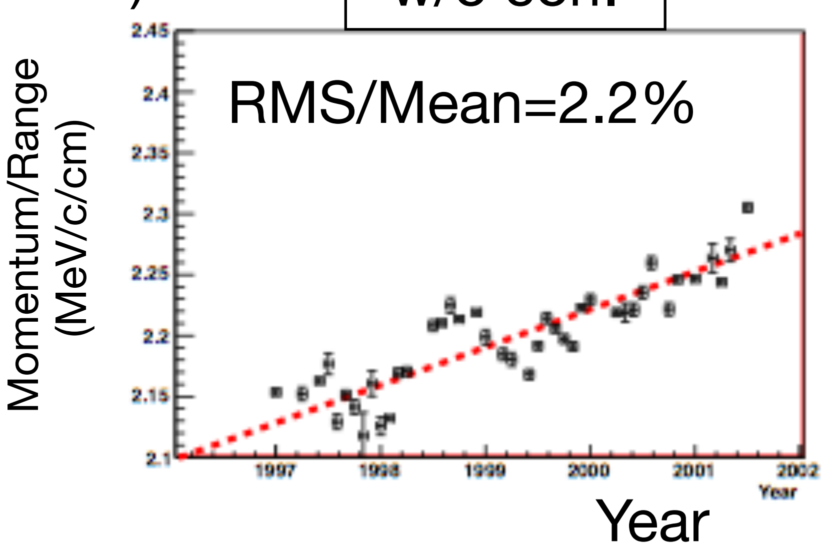
- PMT gain and water attenuation length vary with time



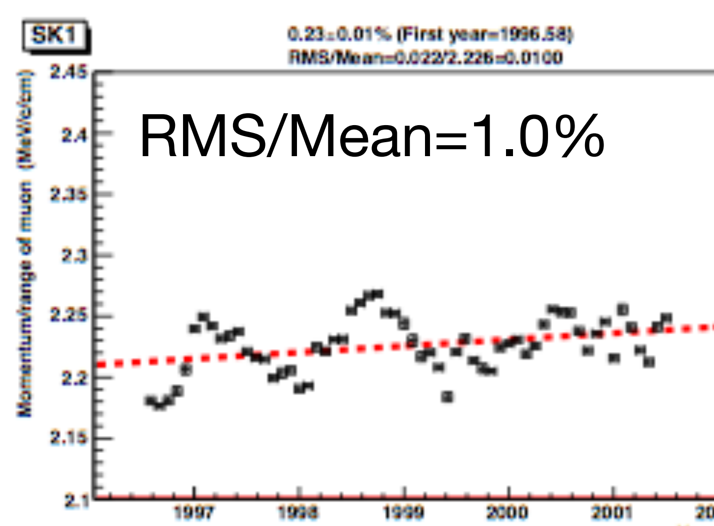


Ex) SK1

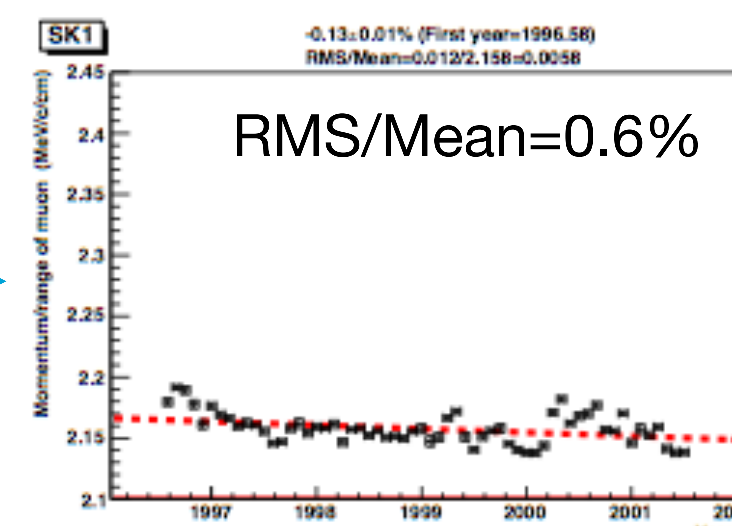
w/o corr.



PMT gain corr.



Water Atten. corr.



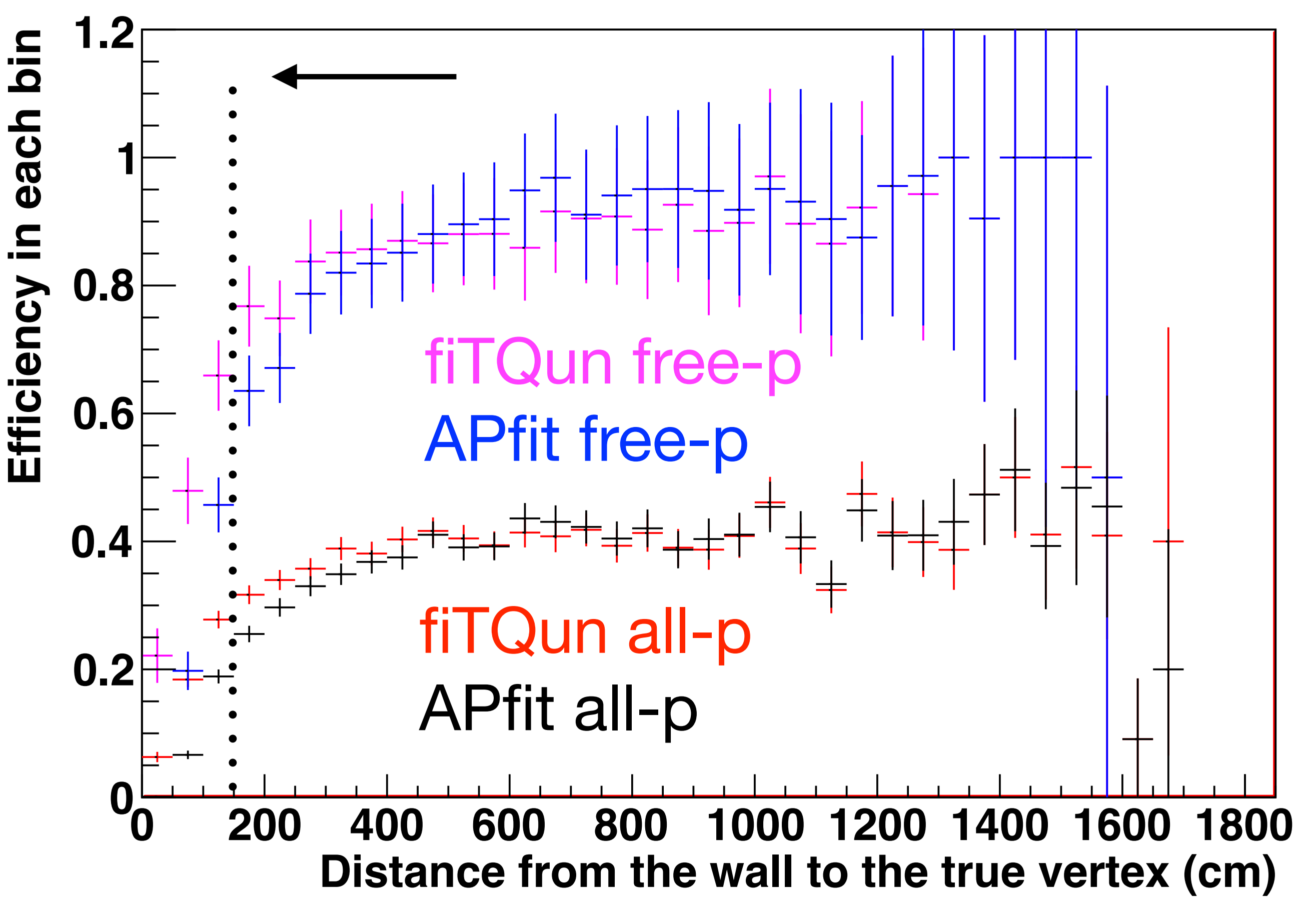
Search for Proton Decay

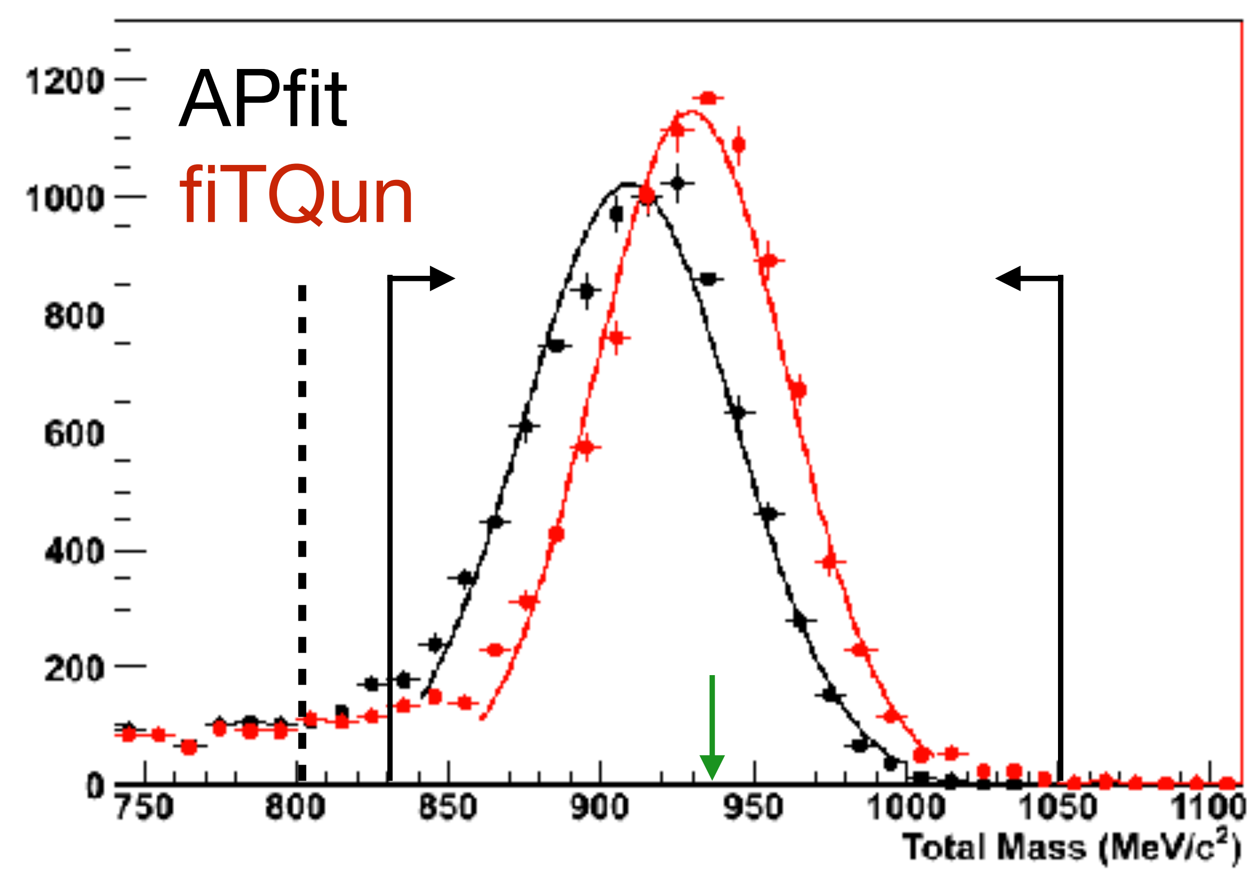
- First application of fiTQun to proton decay
- First time of changing SK proton decay analysis framework
- Target decay mode: **$p \rightarrow e^+\pi^0$**
- Hybrid search: APfit (SK1-3, null observation) + fiTQun (SK4)
- Selection criteria

    1. Fiducial volume
    2. Number of rings (2 or 3)
    3. PID (all shower ring, no Micheal-e)
    4. π^0 mass (for 3-ring events)
    5. No gamma-ray from neutron capture
    6. Total invariant mass and momentum cut

- By changing selection criteria for fiTQun, I did
    - Expand fiducial volume by **10%** (22.5 kton → 24.7kton)
    - Reduce # of BG events by arrpox. **30%**
        - Tighter total invariant mass cut is applied
    - While keeping similar level of signal efficiency as APfit

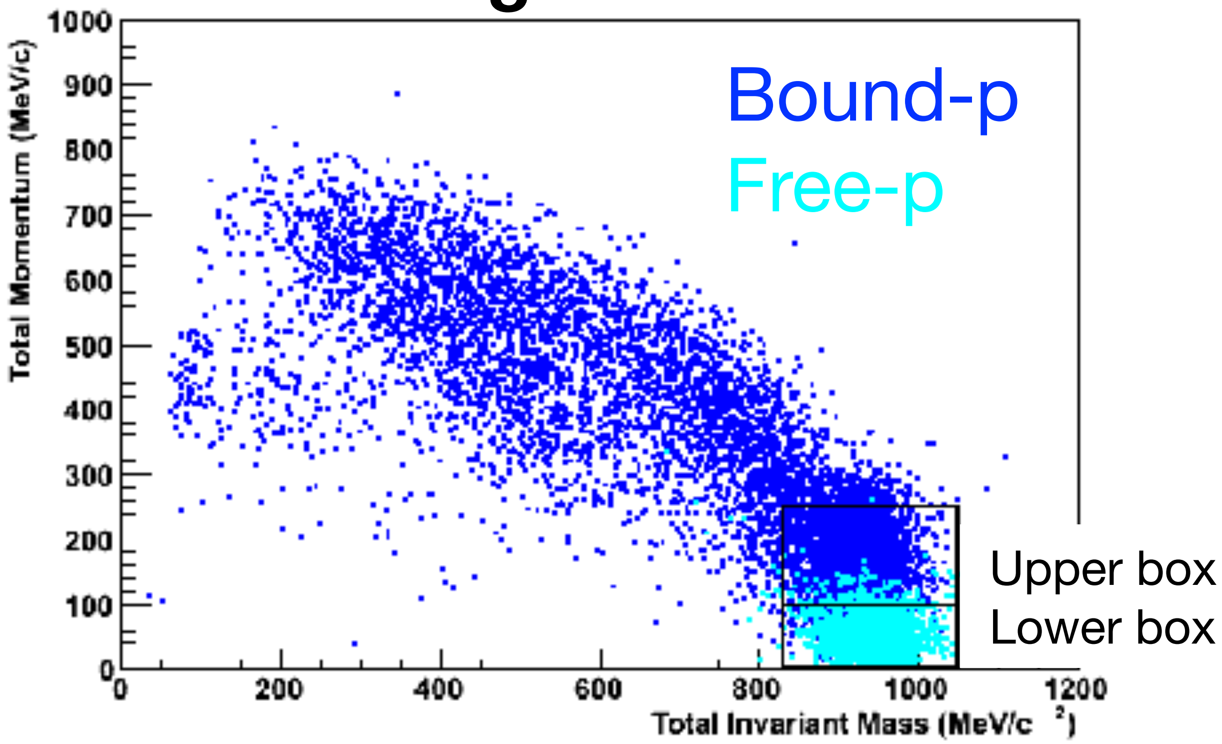
Chance of discovery!



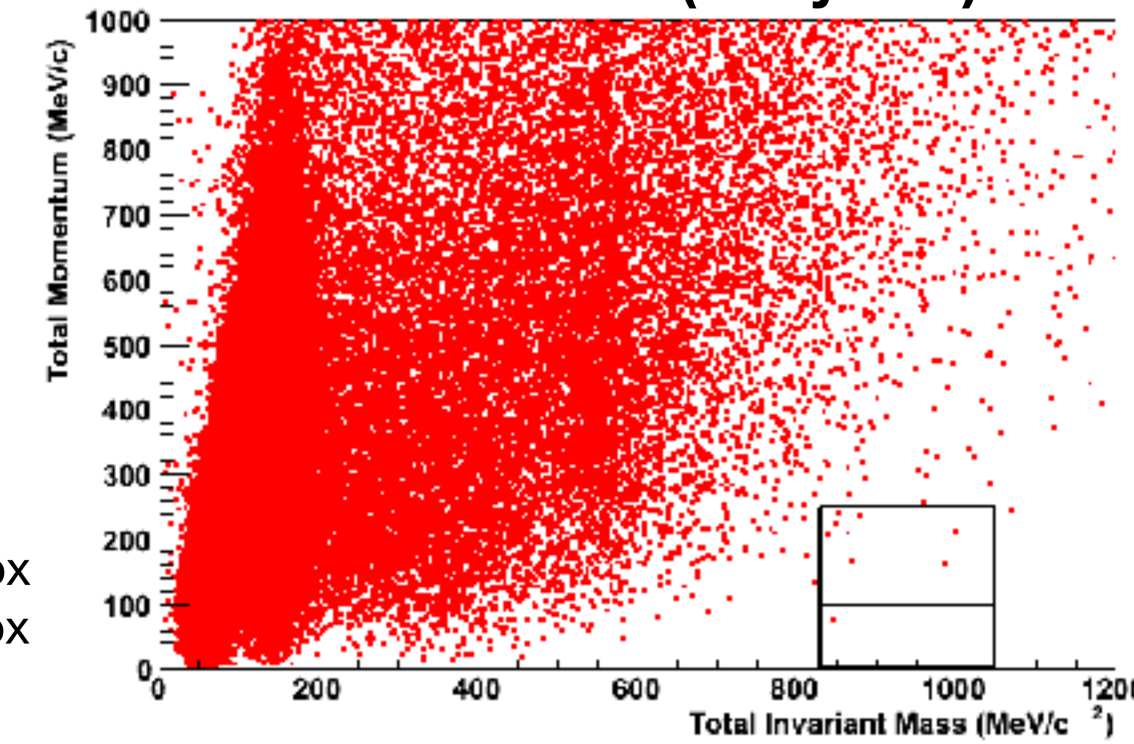


- To enhance sensitivity, signal region is divided by two
    - Lower box: less BGs & systematics error (Fermi motion)
- #total BG in SK4: ~0.14 (0.19) events for fiTQun (APfit)

Signal MC



Atm-ν MC **(500 years)**

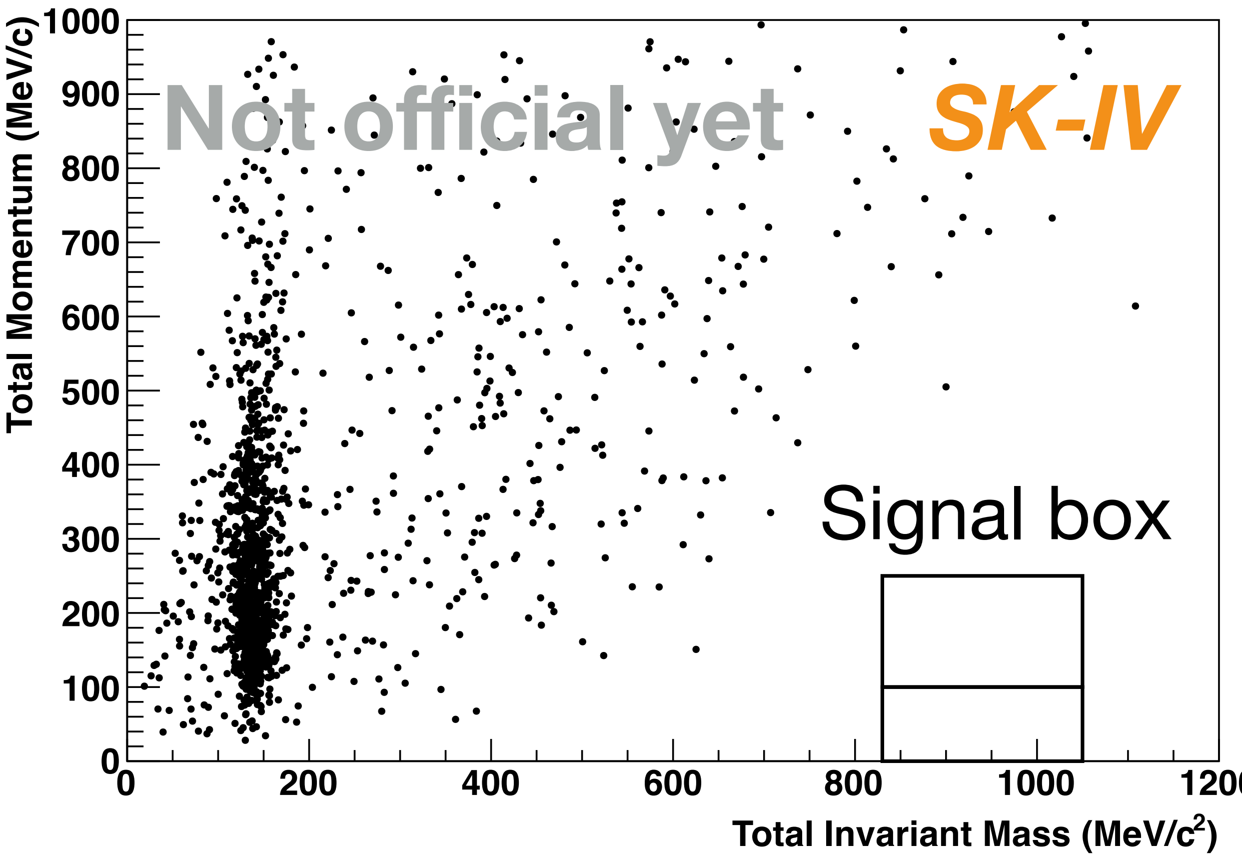


	fiTQun		APfit	
	Lower box	Upper box	Lower box	Upper box
Eff. (all) (%)	20.0±0.3	18.1±0.3	19.0±0.3	19.0±0.3
BG (/Mt/yr)	0.028±0.019	0.778±0.102	0.030±0.021	1.116±0.132

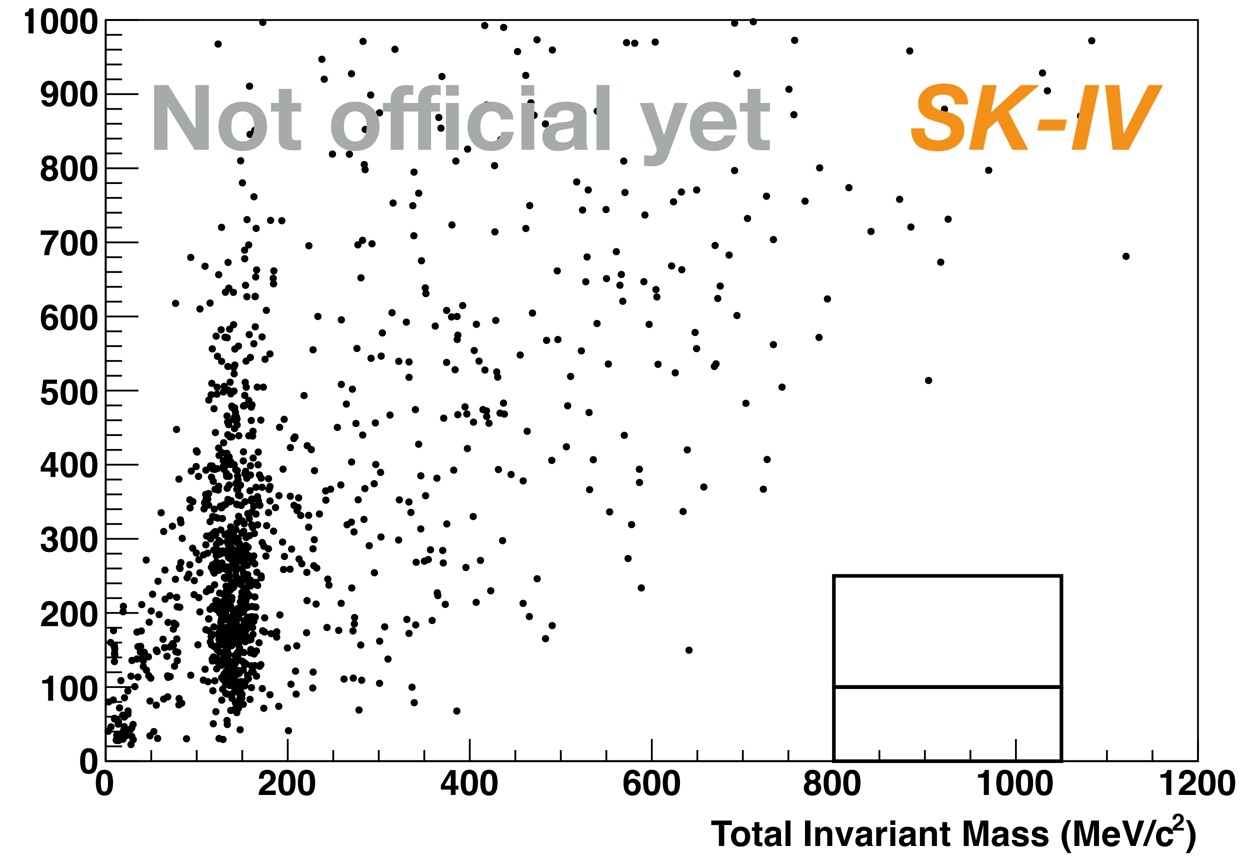
＊stat. error only

Result

fiTQun (179.5 kton*years)



APfit (163.0 kton*years)



- **No candidate** was found in SK-IV data for both fitters
- Combine with the other SK data (APfit, no candidates) and calculate lower lifetime limit by Bayes' theorem
- Lifetime limit: **$\tau/B(p \rightarrow e^{+}\pi^{0}) > 1.88\times10^{34}$ years** @ 90% C.L.
  - 5% improvement from APfit-based analysis

Summary

- Proton decay is a smoking gun for GUTs
- Developed and validated the new event reconstruction algorithm, fiTQun
- Improved search for $p \rightarrow e^{+}\pi^{0}$ with fiTQun was conducted
  - Same efficiency but fiducial volume +10%, #BGs -30%
- No candidate was found
- World leading proton lifetime limit:
  1.88×10^{34} years @ 90% C.L.
- Most stringent constraint for non-SUSY GUT

Detail information can be found in Suda's thesis
http://www-sk.icrr.u-tokyo.ac.jp/sk/publications/index-e.html#doctor

Let’s go as much as we can!

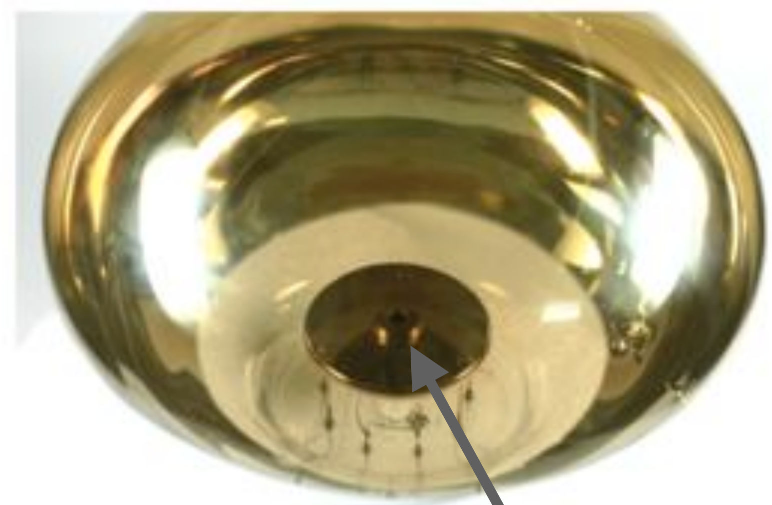
Think Bigger

- Hyper-Kamiokande project (~10 times bigger than SK)
- Search region of proton decay will reach 10^{35} years
- Many rich physics: CP violation, ν mass hierarchy, SN relic etc.
- FiTQun is compatible with HK
- Photosensor is a key to success

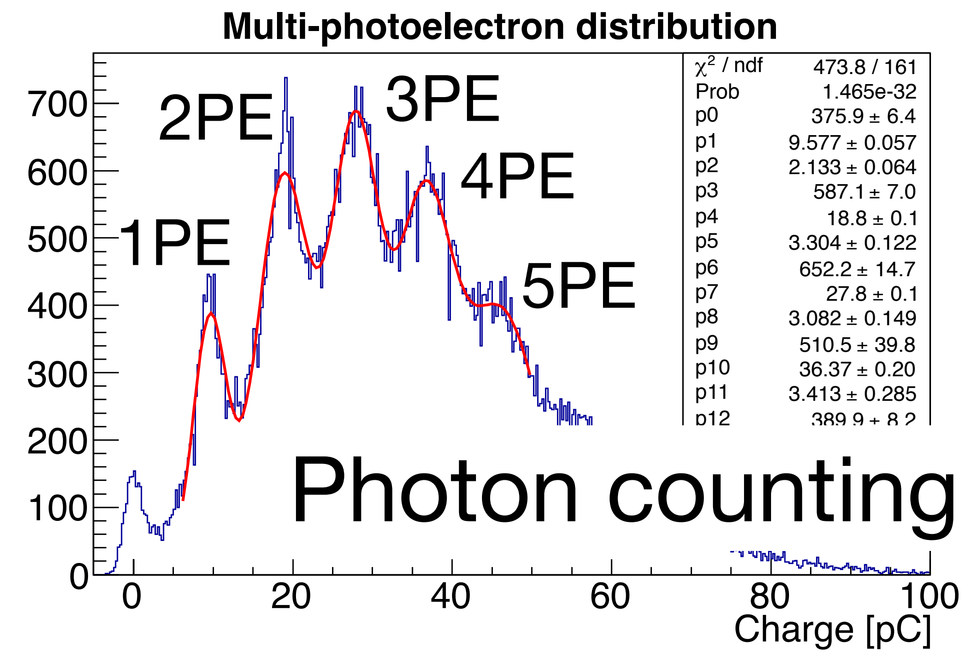
R&D of Hybrid Photo-Detector

- One of candidates. Better performance than SK PMT
- Hope to use in HK (20-inch HPD is testing in water tank)

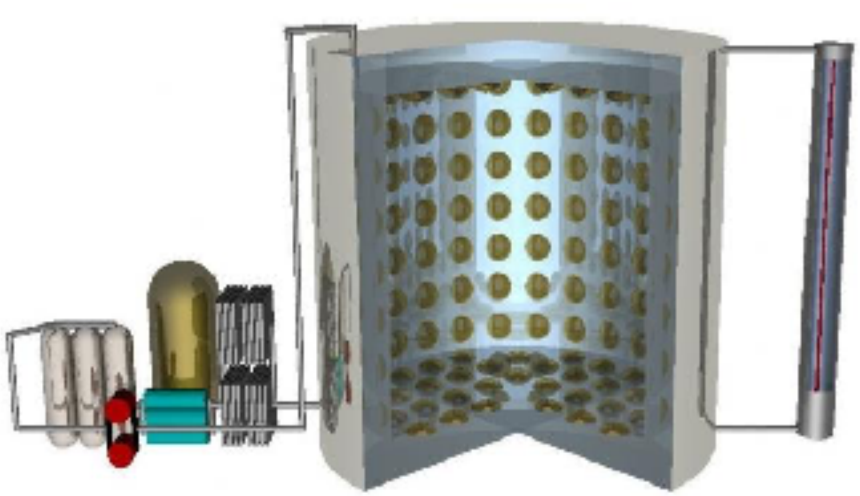
8-inch



Avalanche Diode

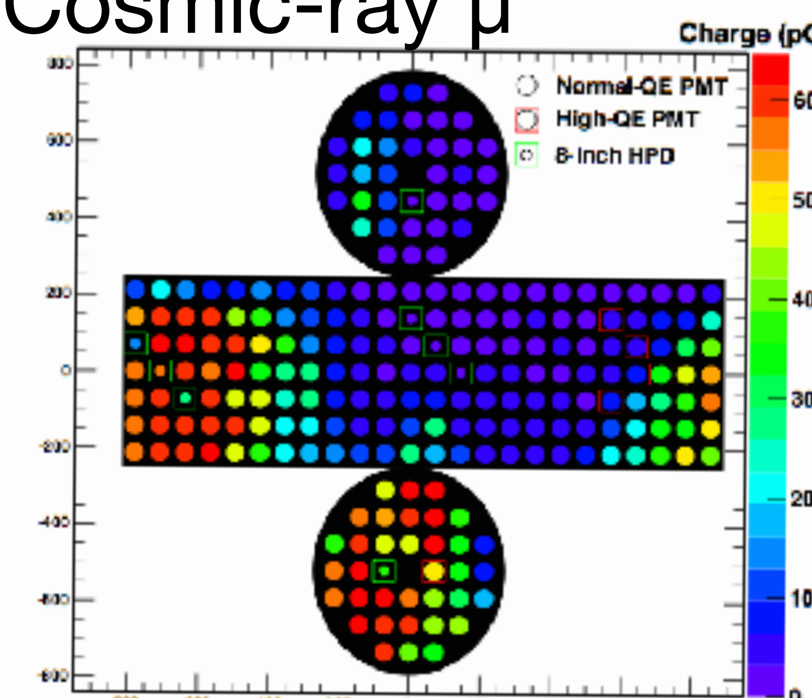


Install



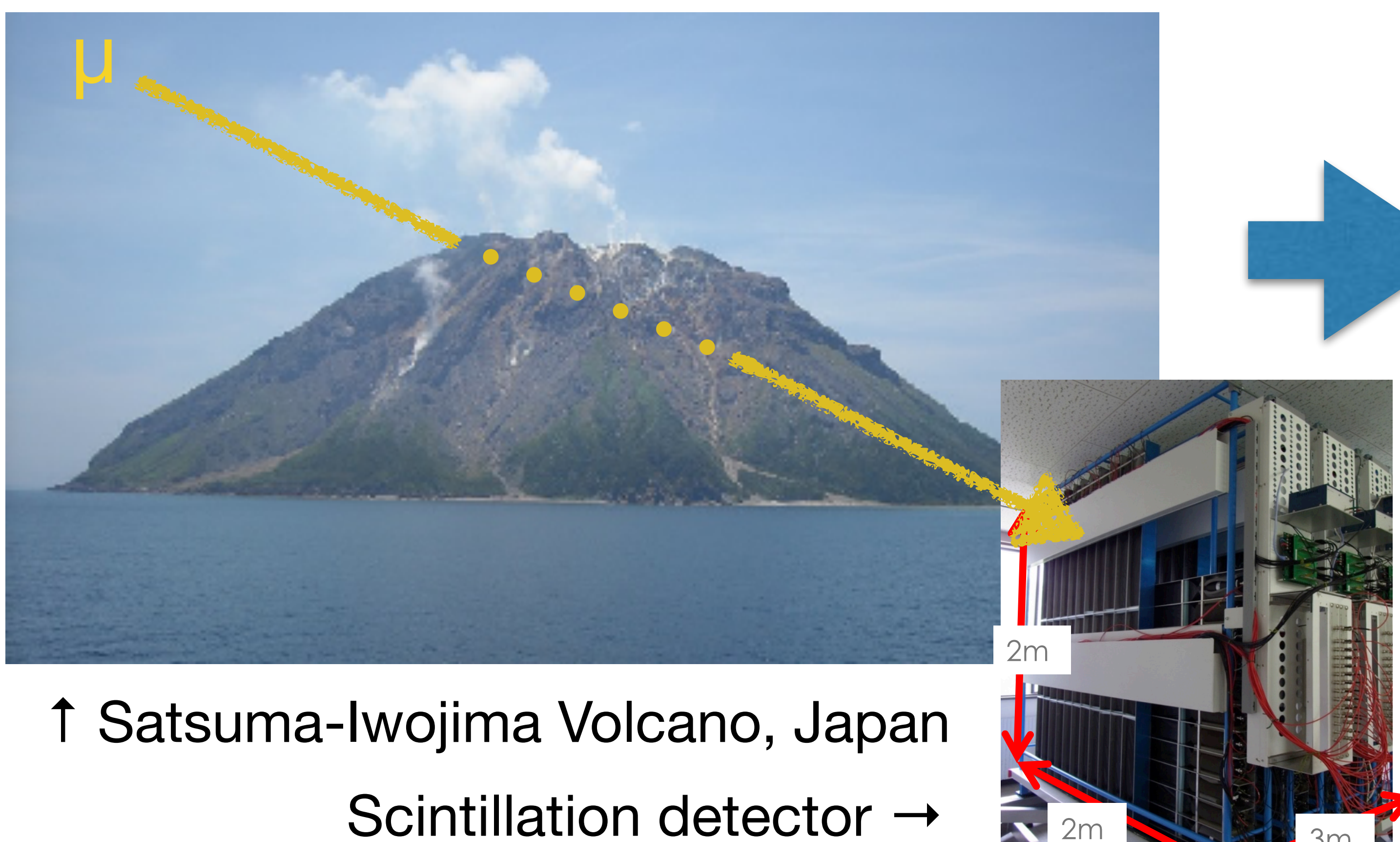
200ton tank

Cosmic-ray μ



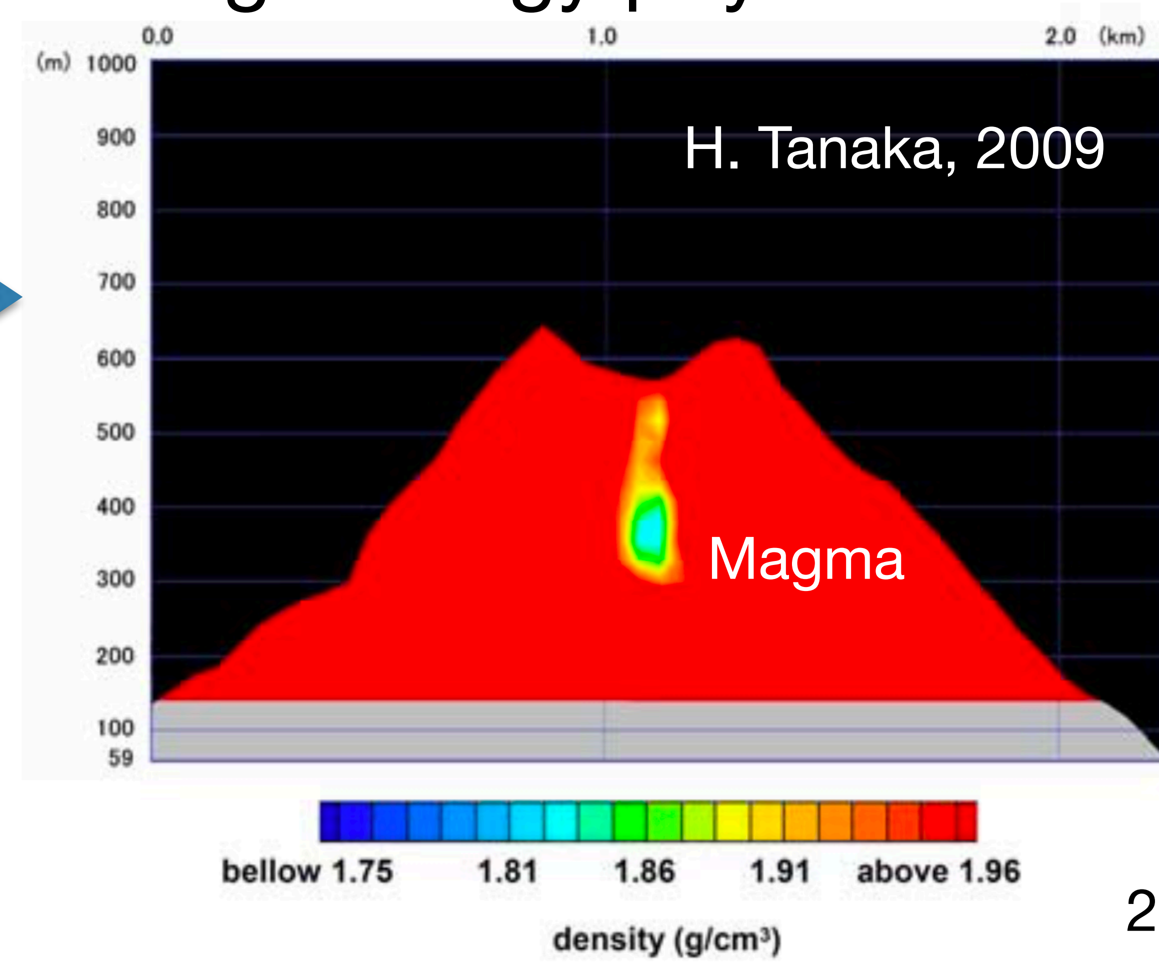
Current Research

- Muon radiography (*Muography*)
  @ Earthquake research institute, Japan
- Explore inner structure of volcanos and active fault by measuring cosmic-ray muon flux through target
- Commit to geophysics and disaster prevention
  - One of the few applications of high energy physics



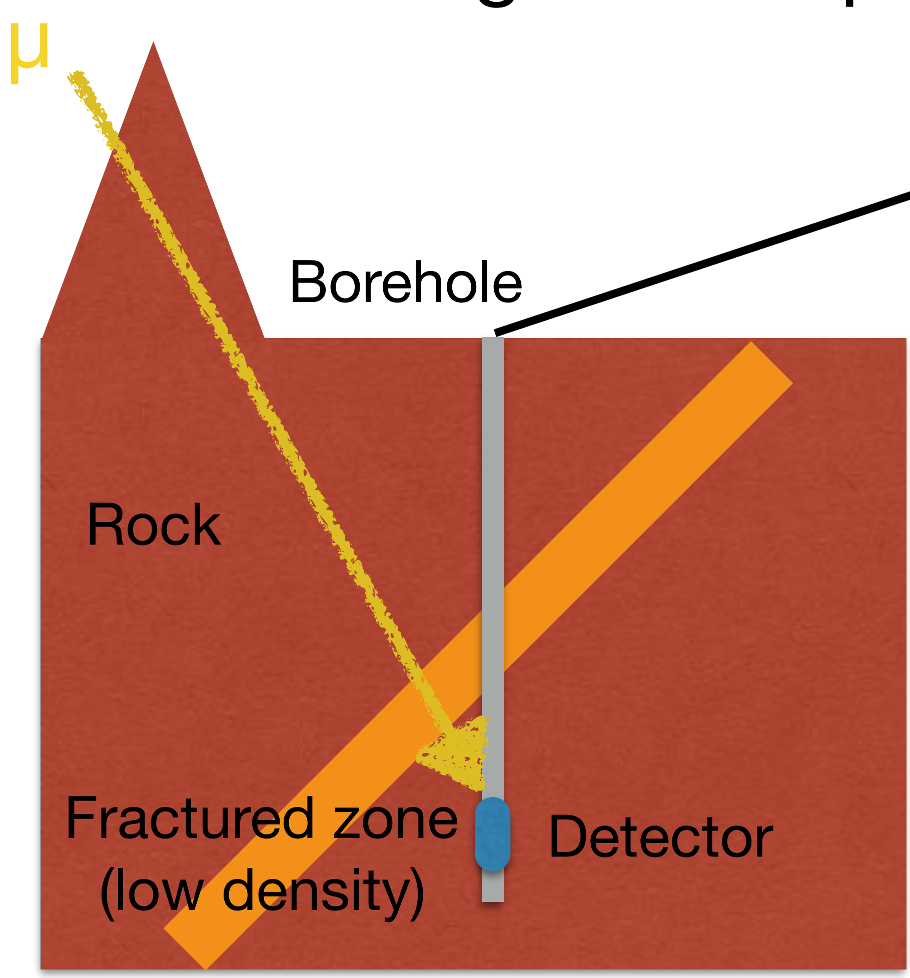
↑ Satsuma-Iwojima Volcano, Japan

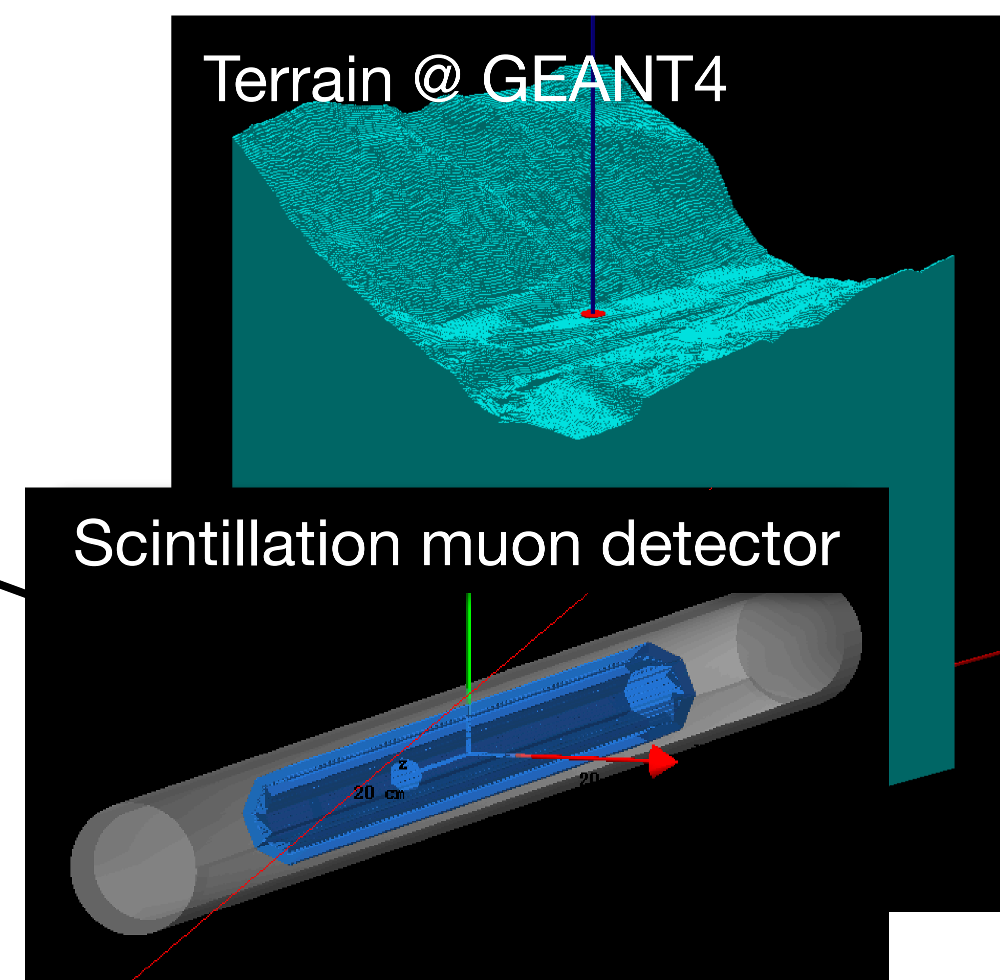
Scintillation detector →



Active Fault

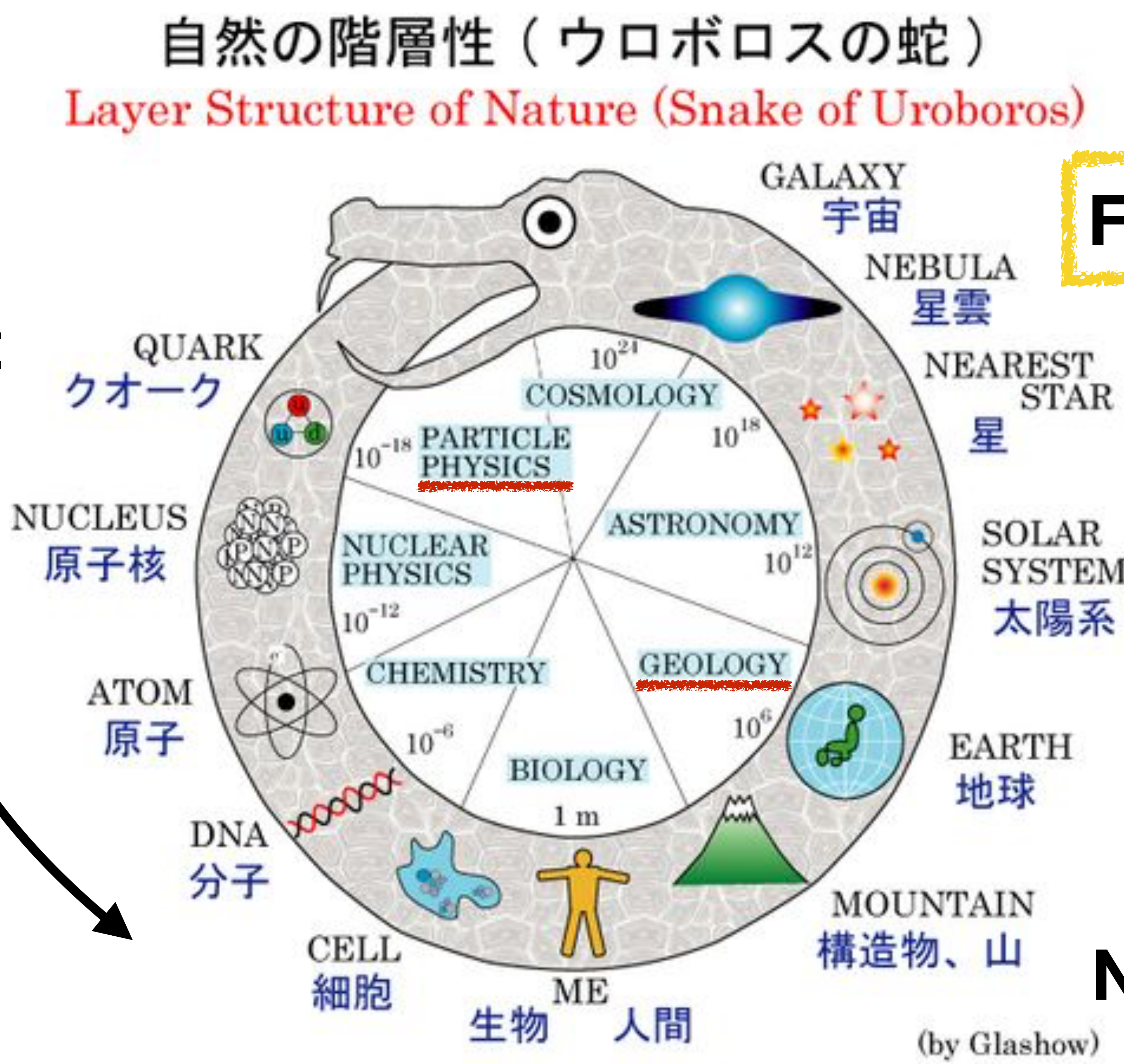
- Muography of *Atotsugawa* fault (near Super-K)
- Estimation of 3D density profile of the fault by measuring muon flux (θ, ϕ) at each depth (Data taking is ongoing)
- I will evaluate expected muon flux at detector by GEANT4
- Working hard to publish the world's first result





Transition of My Research

Past



Future?

Now

Expected Future Work

- Gamma-ray burst search @ CTA LST
  - GRB is the brightest explosion in the universe
  - Explore mechanisms of jet formation and particle acceleration especially for long GRBs with LST's high statistics data
- I would like to contribute to
  - Low energy threshold (20GeV or less) in order to detect GRBs
    - PMT calibration and analysis tool development utilizing my experience (fiTQun, HPD, etc.)
  - Pointing calibration in order to not miss GRBs
- Eager to accomplish the first measurement of a GRB by the ground based telescope