July 24, 2017

Underground Science: Overview

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Outline

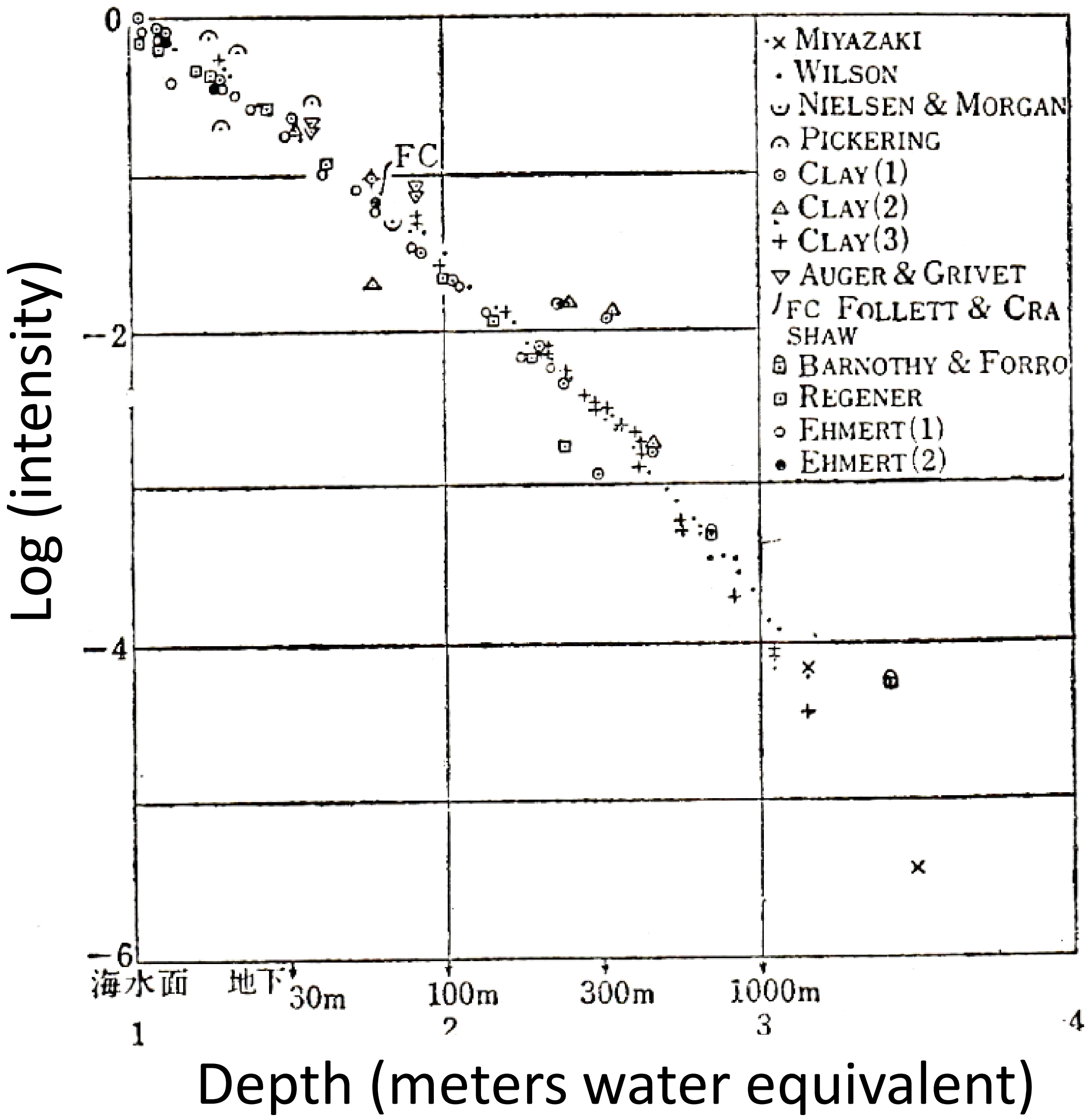
- *Introduction 1: Early days*
- *Introduction 2: 1980 ~*
- *Introduction 3: Recent 20 years*
- *Present status of Underground Science*
  1. *Nuclear Astrophysics*
  2. *Rare processes*
  3. *Gravitational waves*
  4. *Geophysics*
- *Summary*

Acknowledgements: N. Smith (SNOLAB), M. Nakahata (Kamoka), S. Ragazzi (LNGS), S. Paling (Boulby), A. Ianni (Canfranc), G. Bellini (Borexino), K. Inoue (KamLAND), A. Araya (strainmetrs)

Apology: Although I received many slides, many data are not mentioned.

Introduction 1: Early days

Early days of underground science



"Nuclear and cosmic ray experiments" (in Japanese) (Ed. M. Takentani *et al.*, 1954, Iwanami, Tokyo)

Deepest data point (@3000m.w.e.:
Y. Miyazaki, Phys. Rev. 76, 1733 (1949)

Discovery of atmospheric neutrinos (1965)


Photo by H.Sbel

In 1965, atmospheric neutrinos were observed for the first time by detectors located very deep underground.

← In South Africa

F. Reines et al., PRL 15, 429 (1965)

→ In India

C.V. Achar et al., PL 18, 196 (1965)

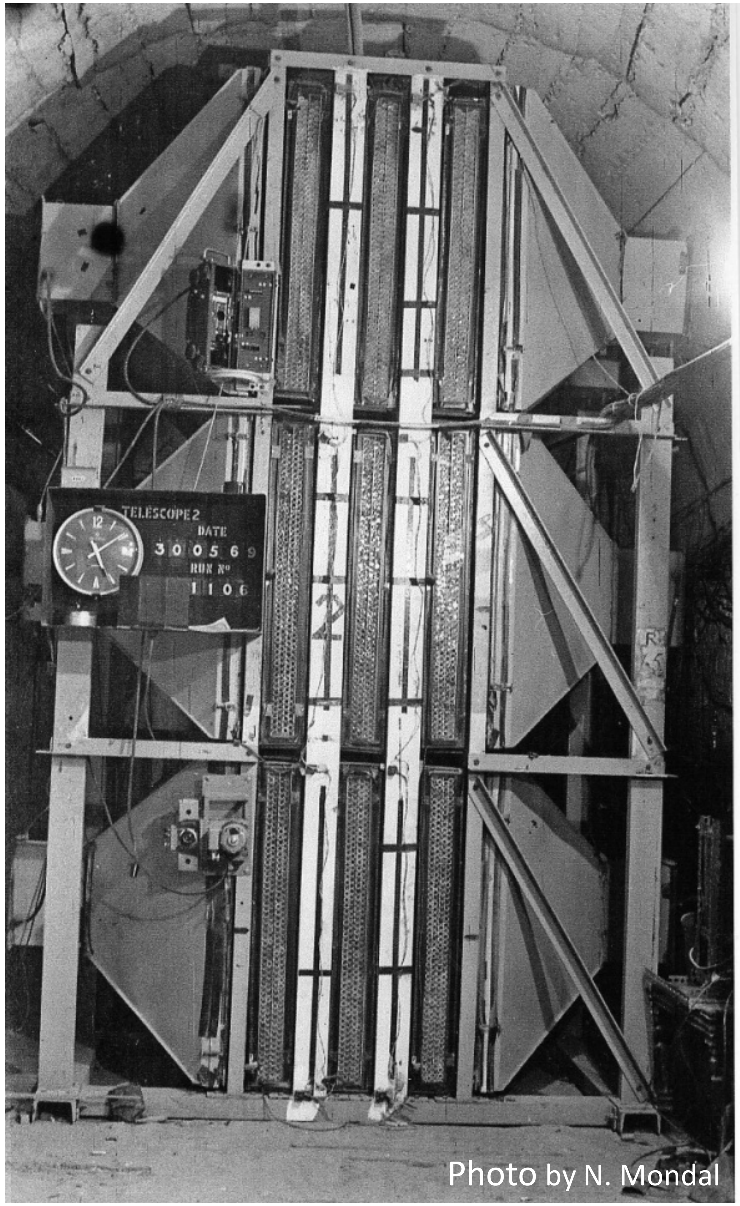
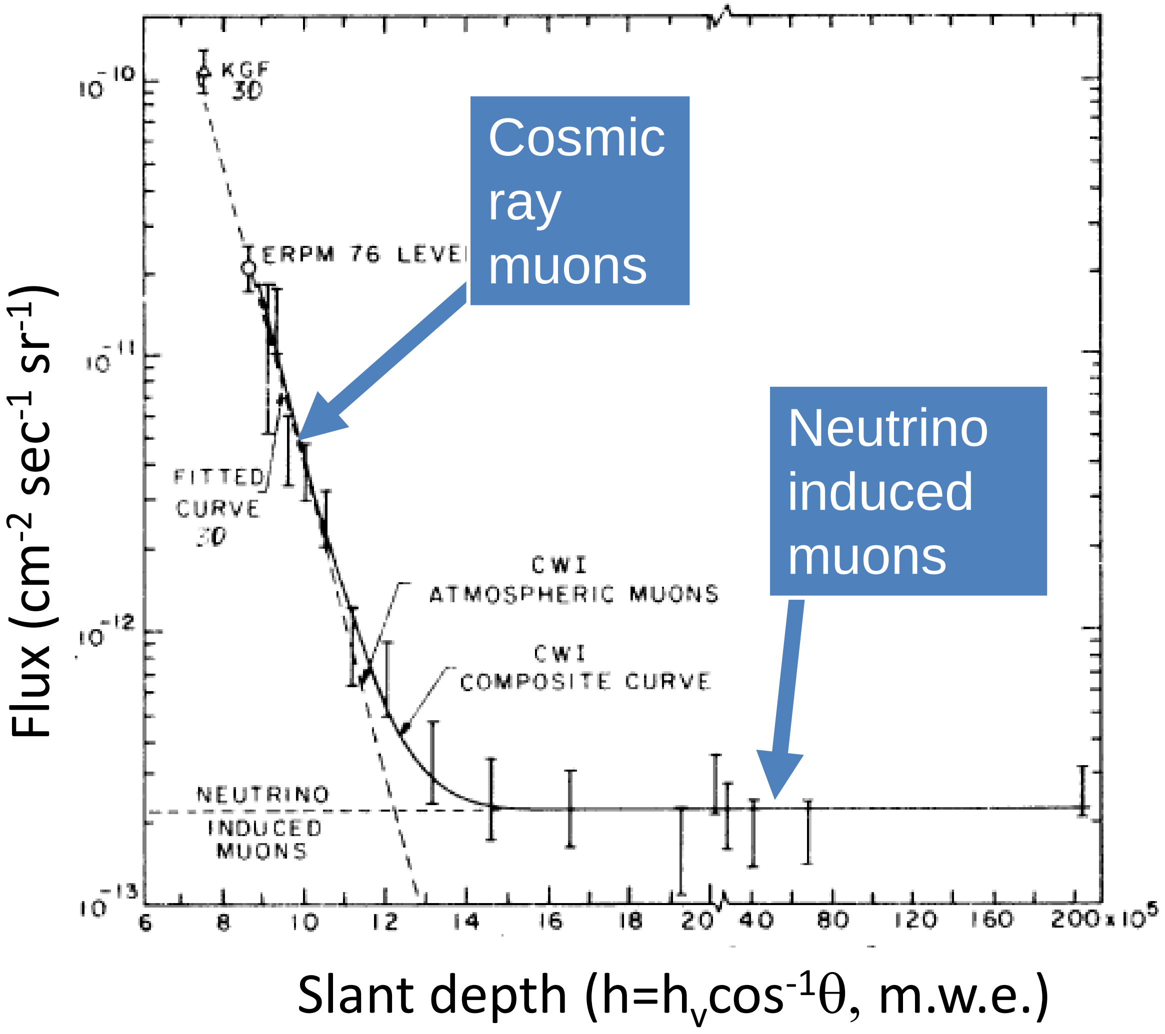


Photo by N. Mondal

Slant depth distribution
(from the South Africa experiment 1978)

M.F.Crouch et al., PRD 18 (1978) 2239

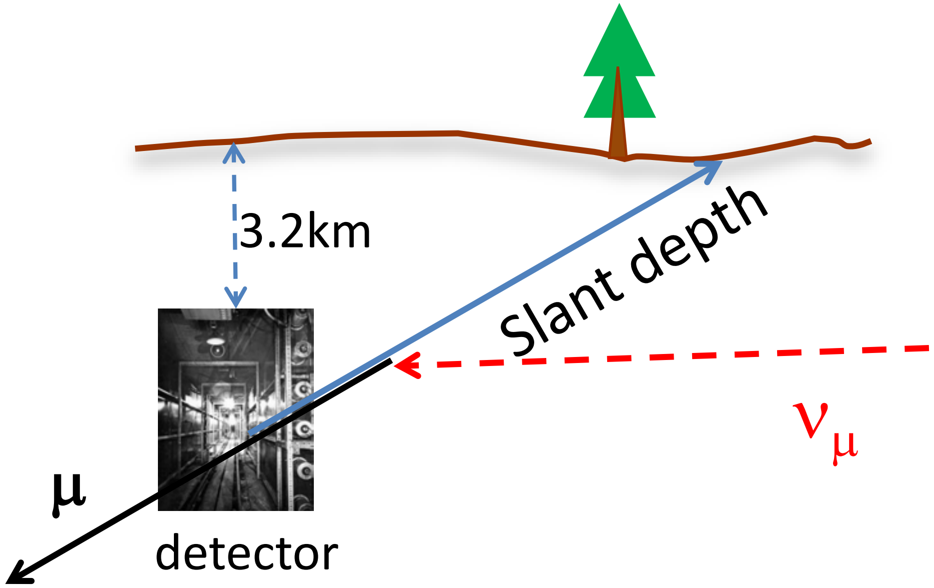


Cosmic ray muons

Neutrino induced muons

Flux (cm^{-2} sec^{-1} sr^{-1})

Slant depth ($h=h_v \cos^{-1}\theta$, m.w.e.)



3.2km

Slant depth

μ

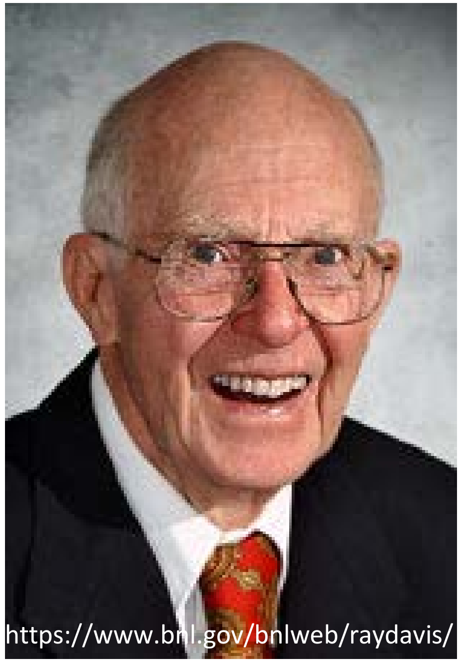
detector

ν_μ

Solar neutrinos


http://www.astronomynotes.com/starsun/s4.htm

600 ton
C_2Cl_4


https://www.bnl.gov/bnlweb/raydavis/

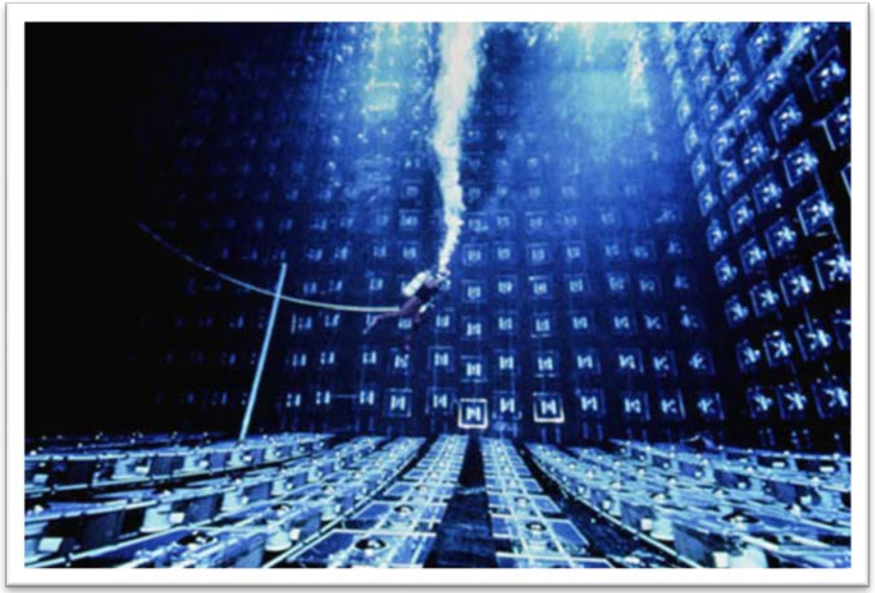
R. Davis Jr.

Pioneering Homestake solar neutrino experiment led by R. Davis began in the 1960's. The observed flux was about 1/3 of the prediction.

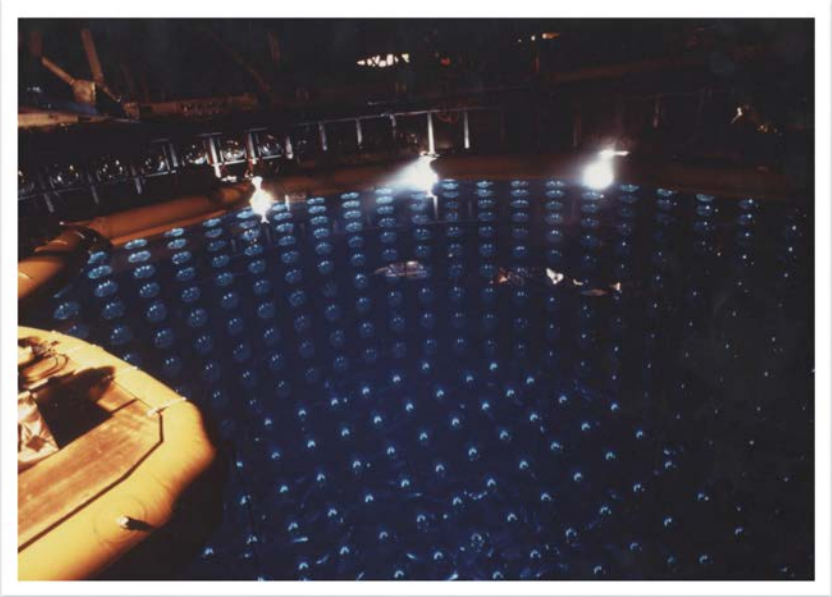
Introduction 2: 1980 ~

Proton decay experiments (1980's)

Grand Unified Theories
(in the 1970's)
➔ $\tau_p = 10^{30\pm2}$ years

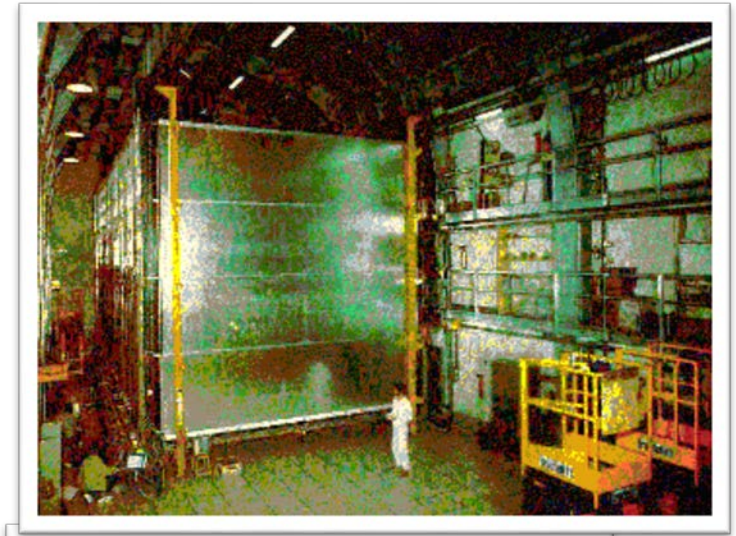


IMB
(3300ton)



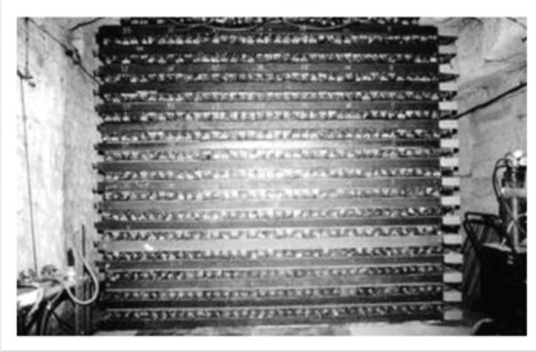
Kamiokande
(1000ton)

These experiments observed many contained atmospheric neutrino events (background for proton decay).



Frejus
(700ton)

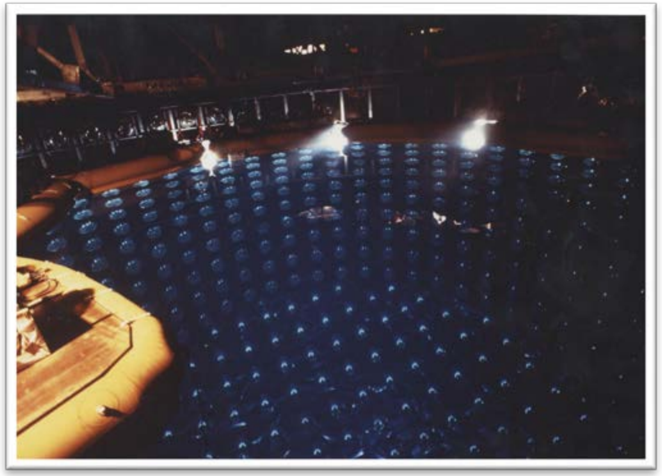
NUSEX
(130ton)

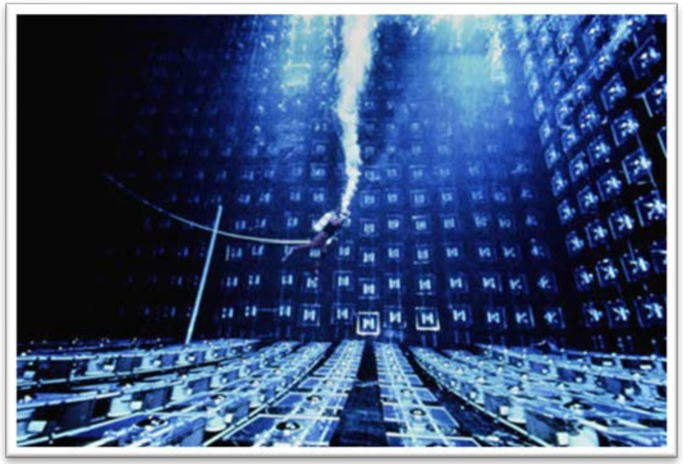


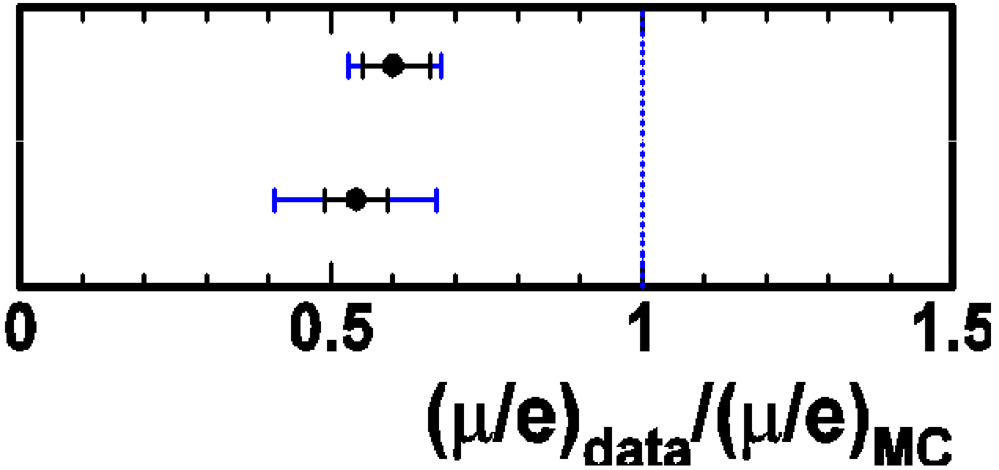
KGF
(~100ton)

Atmospheric ν_μ deficit

- ✓ Because atmospheric neutrinos are the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions.
- ✓ During these studies, a significant deficit of atmospheric ν_μ events was observed.

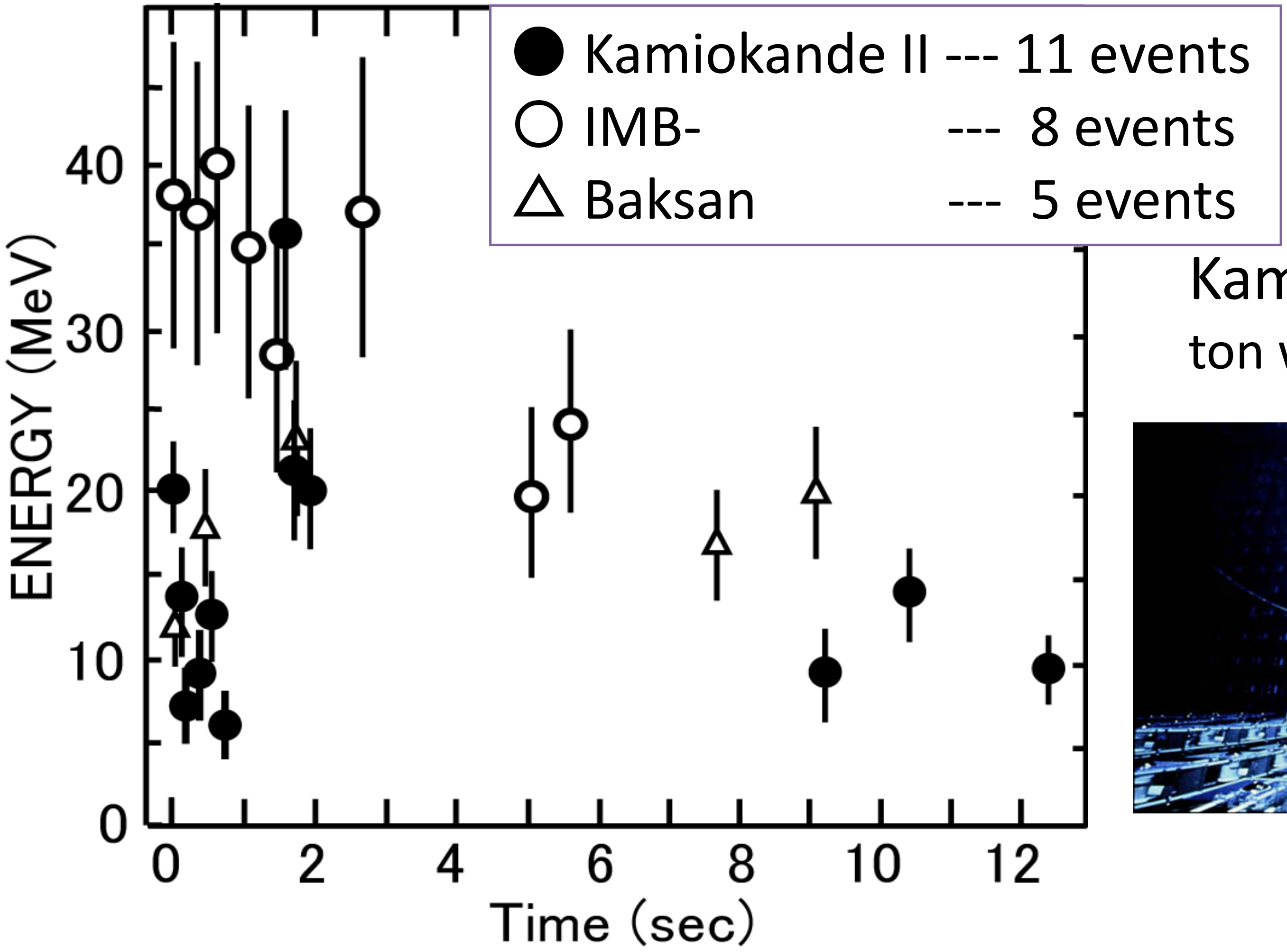






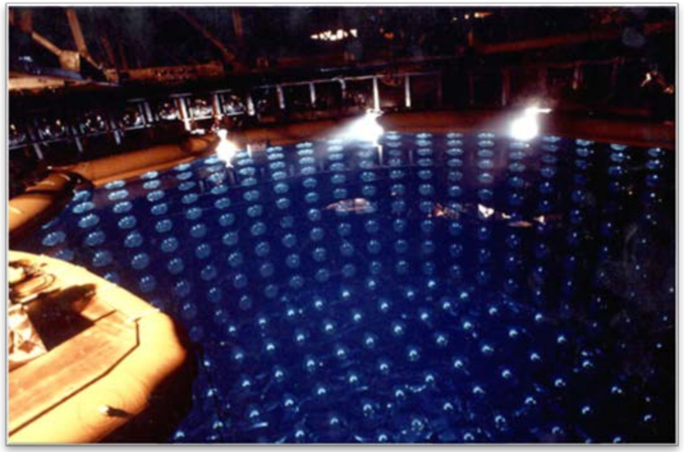
(In the 1990's, Soudan-2 also observed the ν_μ deficit.)

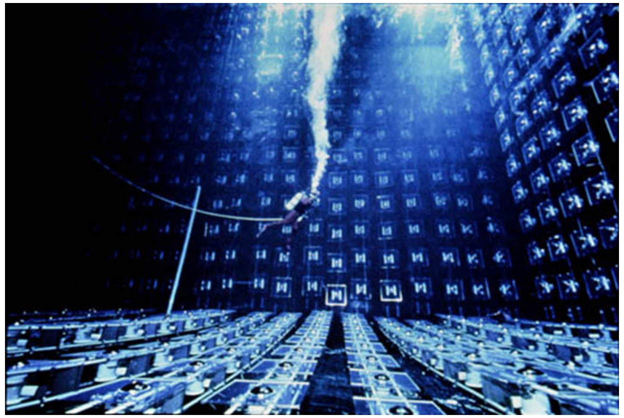
Detection of Supernova neutrinos



➔ Understood the basic mechanism of the supernova explosion!

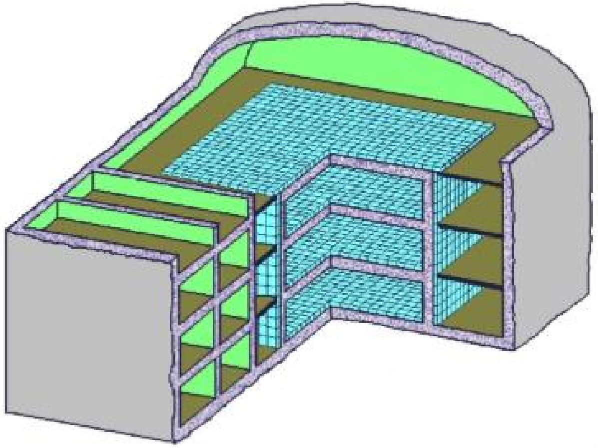
Kamiokande (3000 ton water Ch. detector)





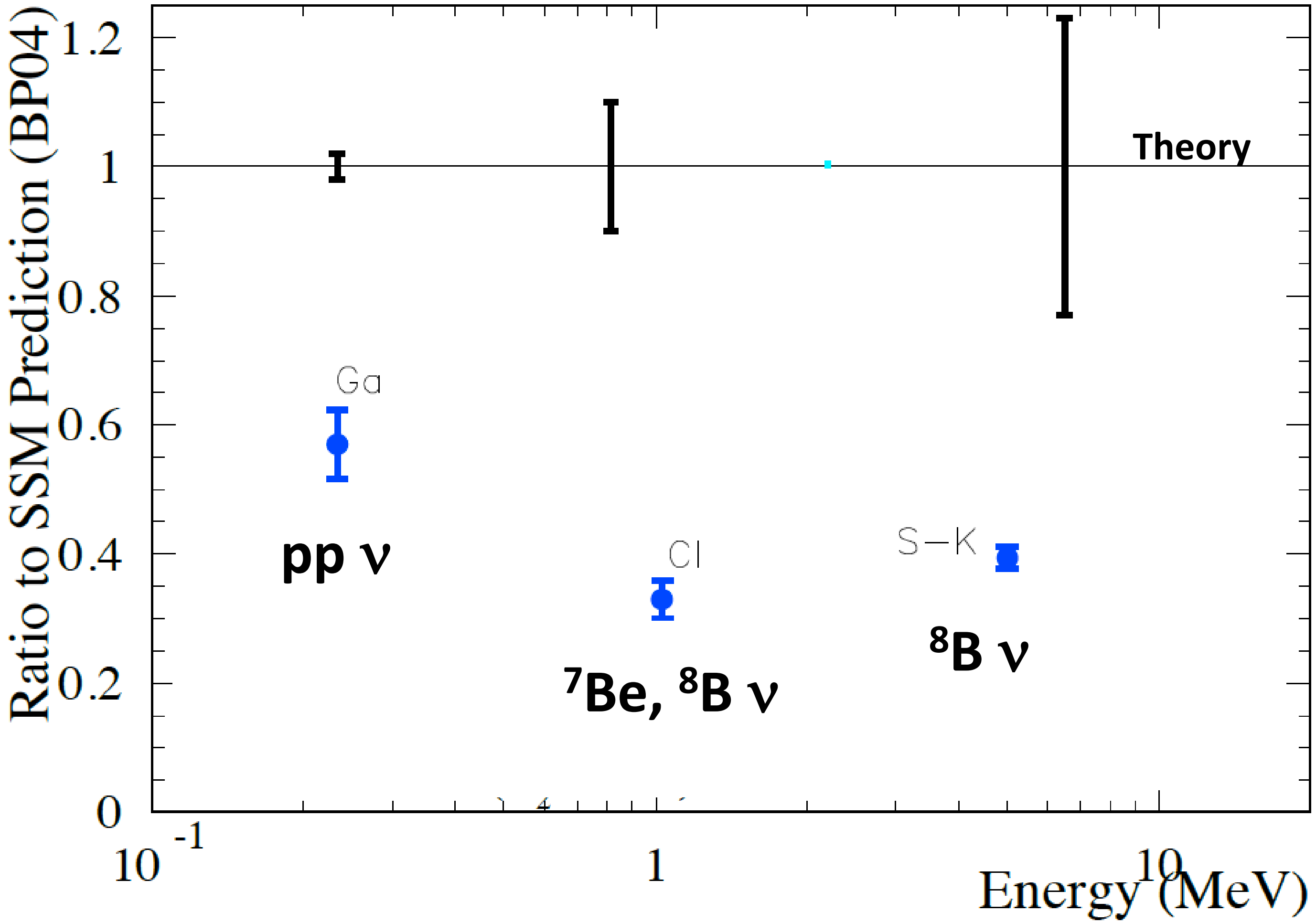
IMB-3
(8000 ton water Ch detector)

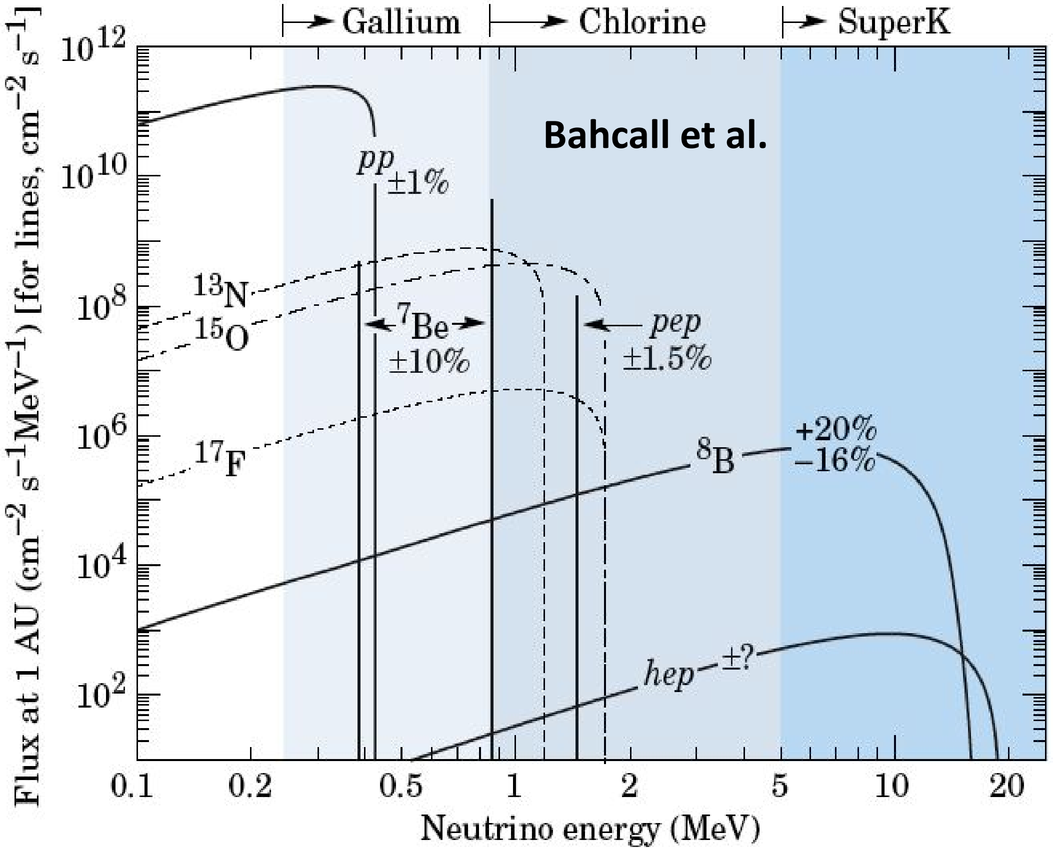
Baksan
(330 ton segmented Liq. scintillator detector)



Results from solar neutrino experiments (before ~2000)

Following the initial observation by the Homestake experiment, several experiments observed solar neutrinos.

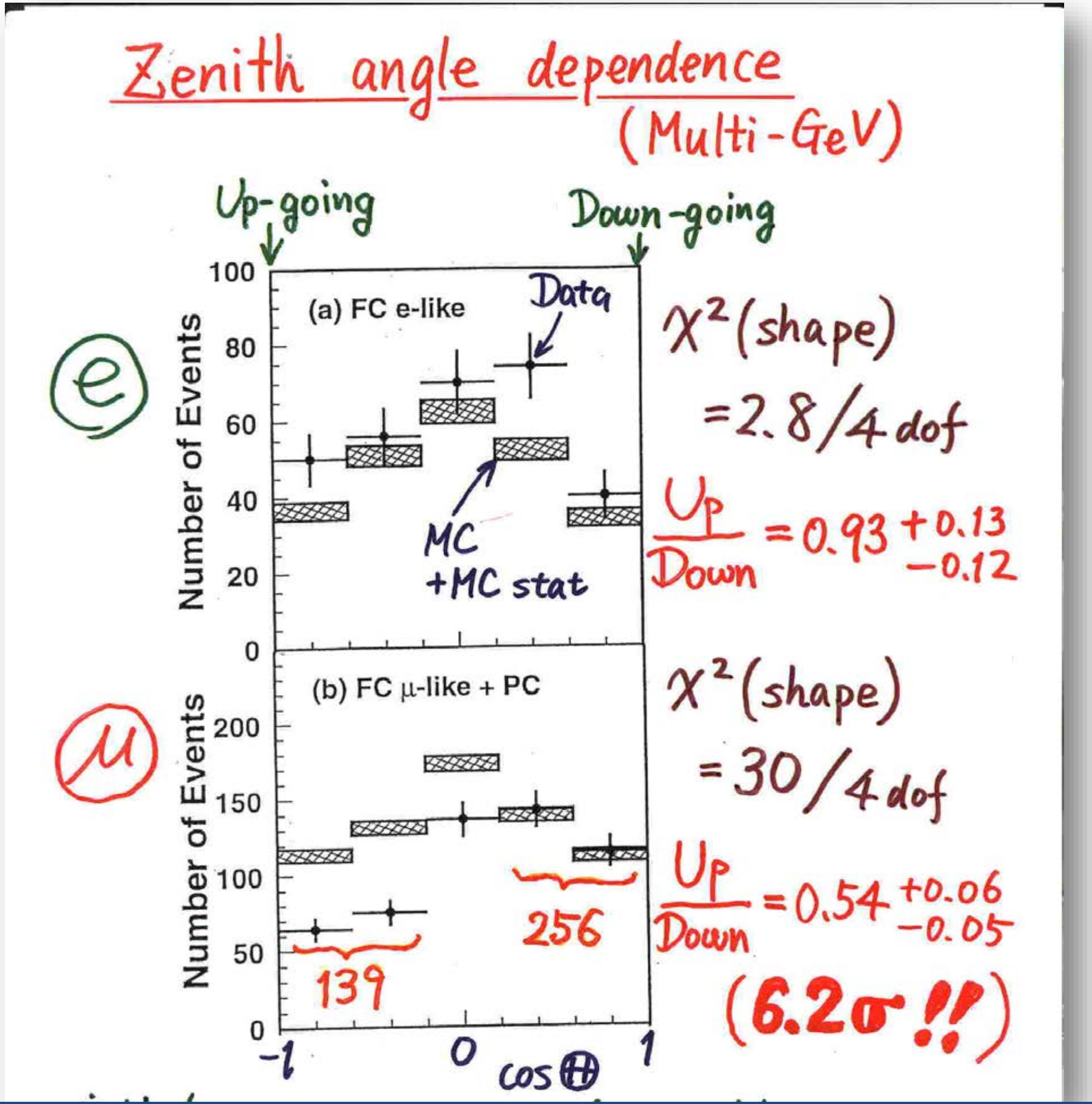




Solar neutrino experiments in the 80’s and 90’s confirmed the deficit of solar neutrinos.

Introduction 3: Recent 20 years

Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)



Zenith angle dependence

(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

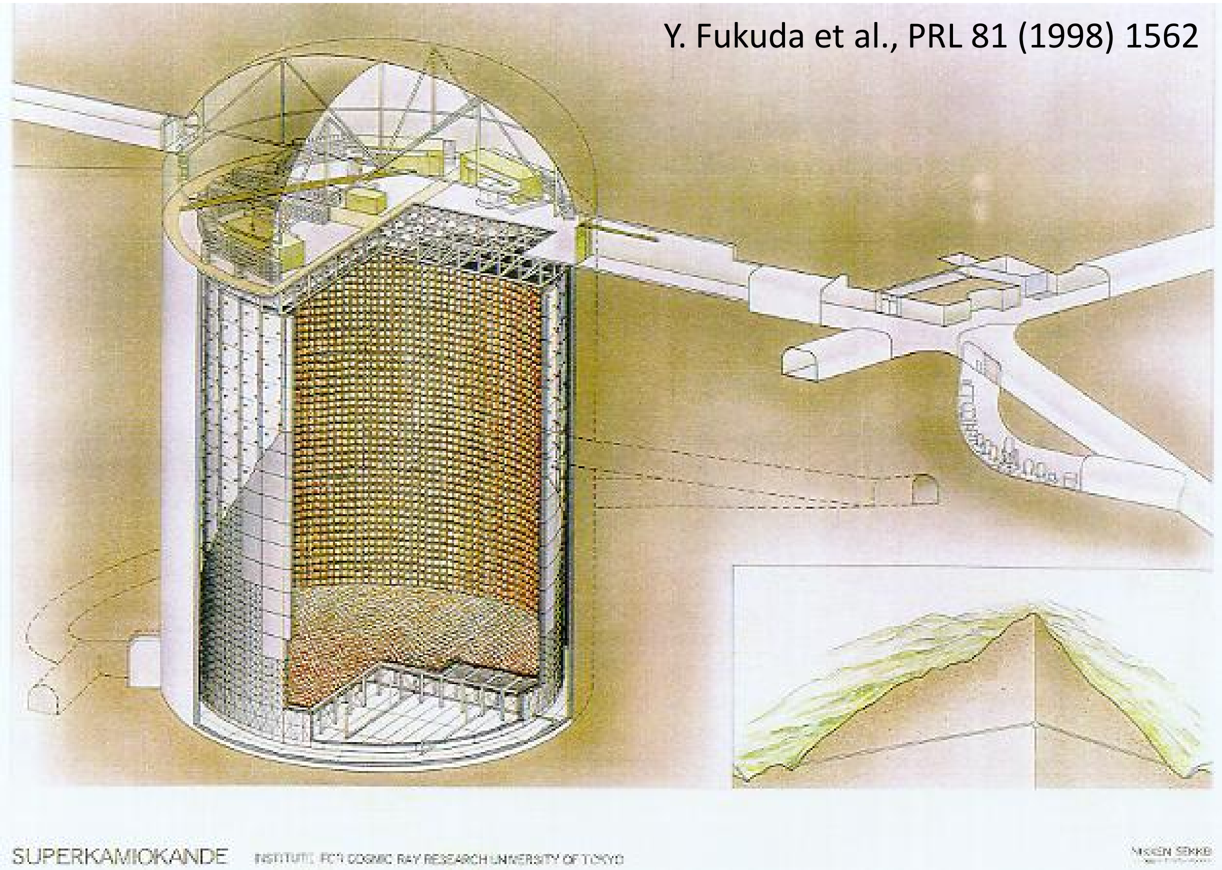
$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

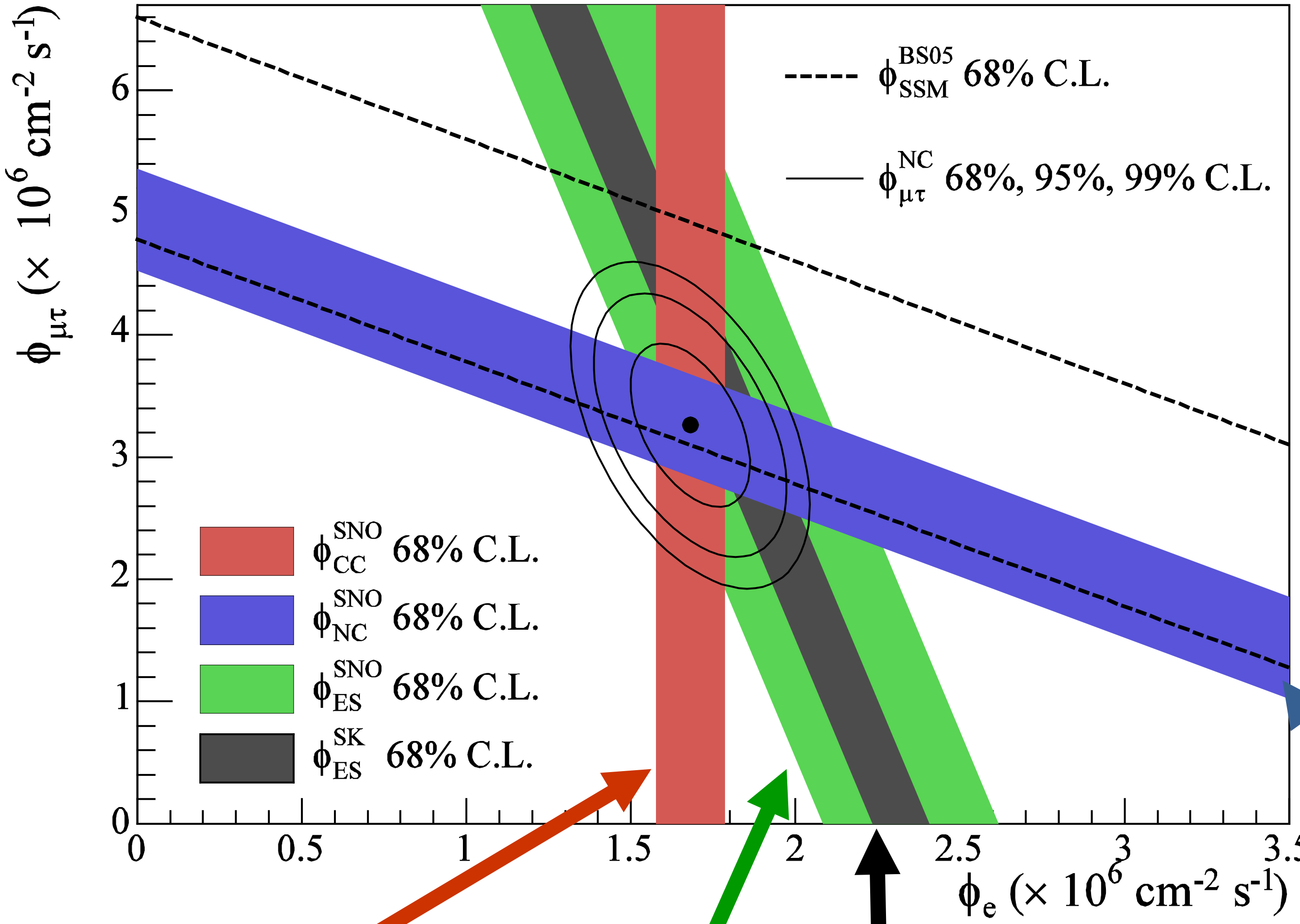
(6.2σ !!)

Y. Fukuda et al., PRL 81 (1998) 1562



Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Evidence for solar neutrino oscillations



SSM
68%CL

SNO NC
68%CL

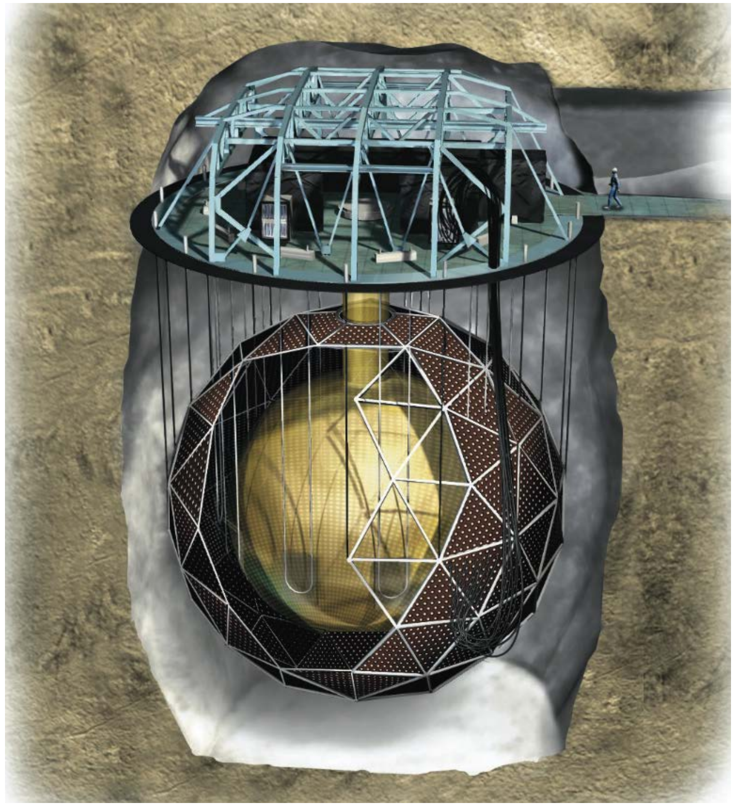
SNO CC
68%CL

SNO ES
68%CL

SK ES
68%CL

(A plot based on the salt-phase data)

SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)



Three (or four) different measurements ➔ *evidence for (ν_μ+ν_τ) flux*

Neutrino oscillation studies

$\nu_\mu \rightarrow \nu_\tau$ oscillations ($\Delta m_{23}, \theta_{23}$)

Atmospheric: Super-K, Soudan-2, MACRO IceCube/Deepcore, …

LBL: K2K, MINOS, OPERA, T2K, NOvA, …

$\nu_e \rightarrow (\nu_\mu + \nu_\tau)$ oscillations ($\Delta m_{12}, \theta_{12}$)

Solar: SNO, Super-K, Borexino, …

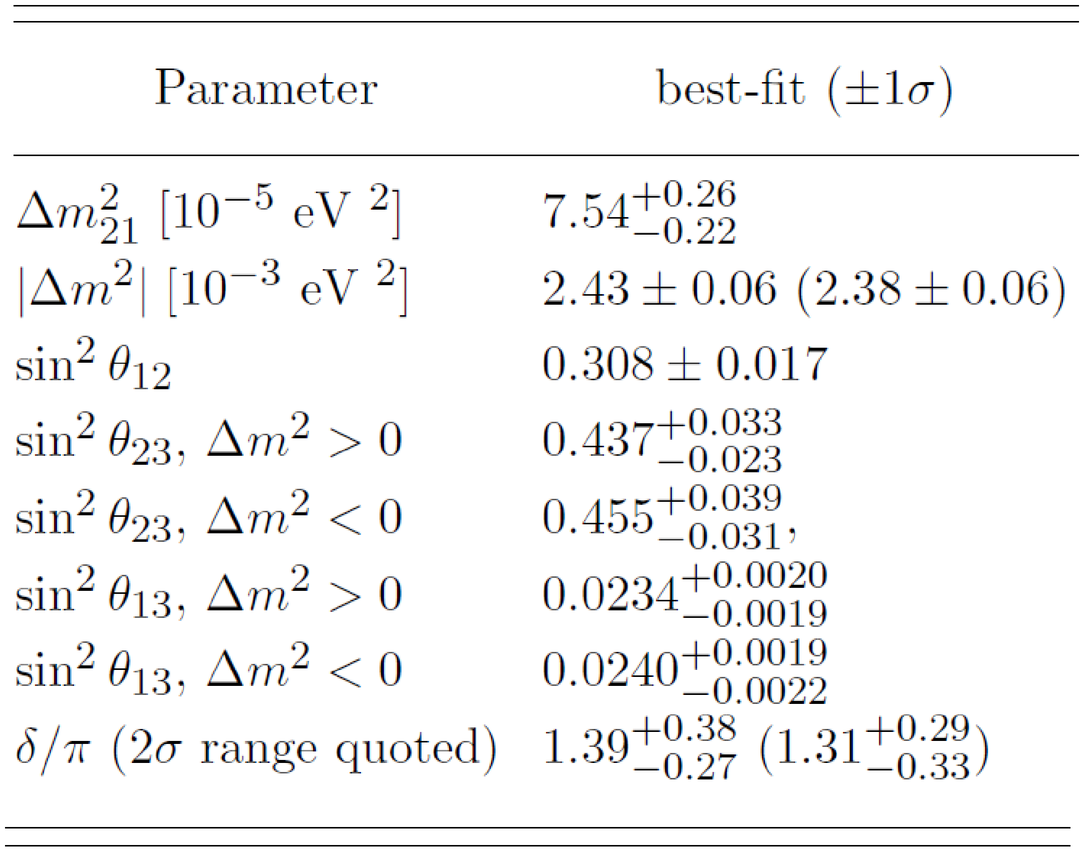
Reactor: KamLAND

θ_{13} experiments

LBL: MINOS, T2K, NOvA, …

Reactor: Daya Bay, Reno, Double Chooz

Status (before Neutrino 2016)



Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$
$\|\Delta m^2\|$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$

K. Nakamura and S.T. Petcov, “14. Neutrino mass, mixing and oscillations”

Basic structure for 3 flavor oscillations has been understood!

Summary of introductions

“Underground” has been proven to be very useful for scientific researches that measure rare processes.

Present status of Underground Science

Topics covered in underground labs

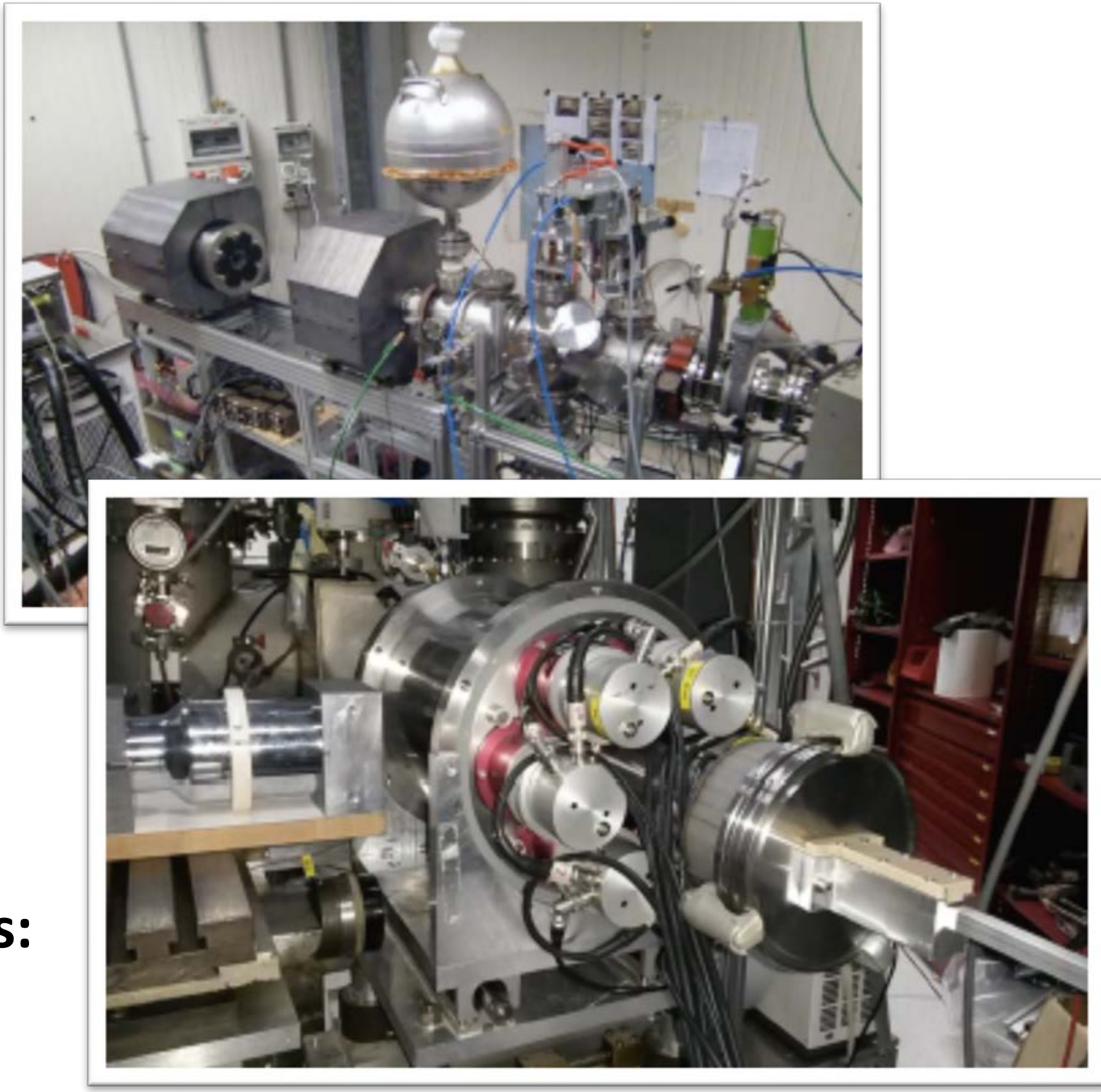
topics	Covered by the other plenary talks	Covered in this talk
Neutrino physics	✓	
Double β decay	✓	
Dark matter	✓	
Nuclear astrophysics		✓
Rare processes		✓
geophysics		✓
Gravitational waves	✓ (partially underground)	✓
General relativity		
Underground biology		
…		

Present status of Underground Science
1) nuclear astrophysics

Nuclear astrophysics

Information by S. Ragazzi

- ✓ Understanding nuclear fusion reactions is very important for understanding nucleosynthesis, energy production in stars, solar neutrino flux, ….
- ✓ Some processes have very low rate. → underground in order to minimize the background.
- ✓ The LUNA experiment @LNGS has been producing very important results in this field over the last 25 years.



E = 50 – 400kV

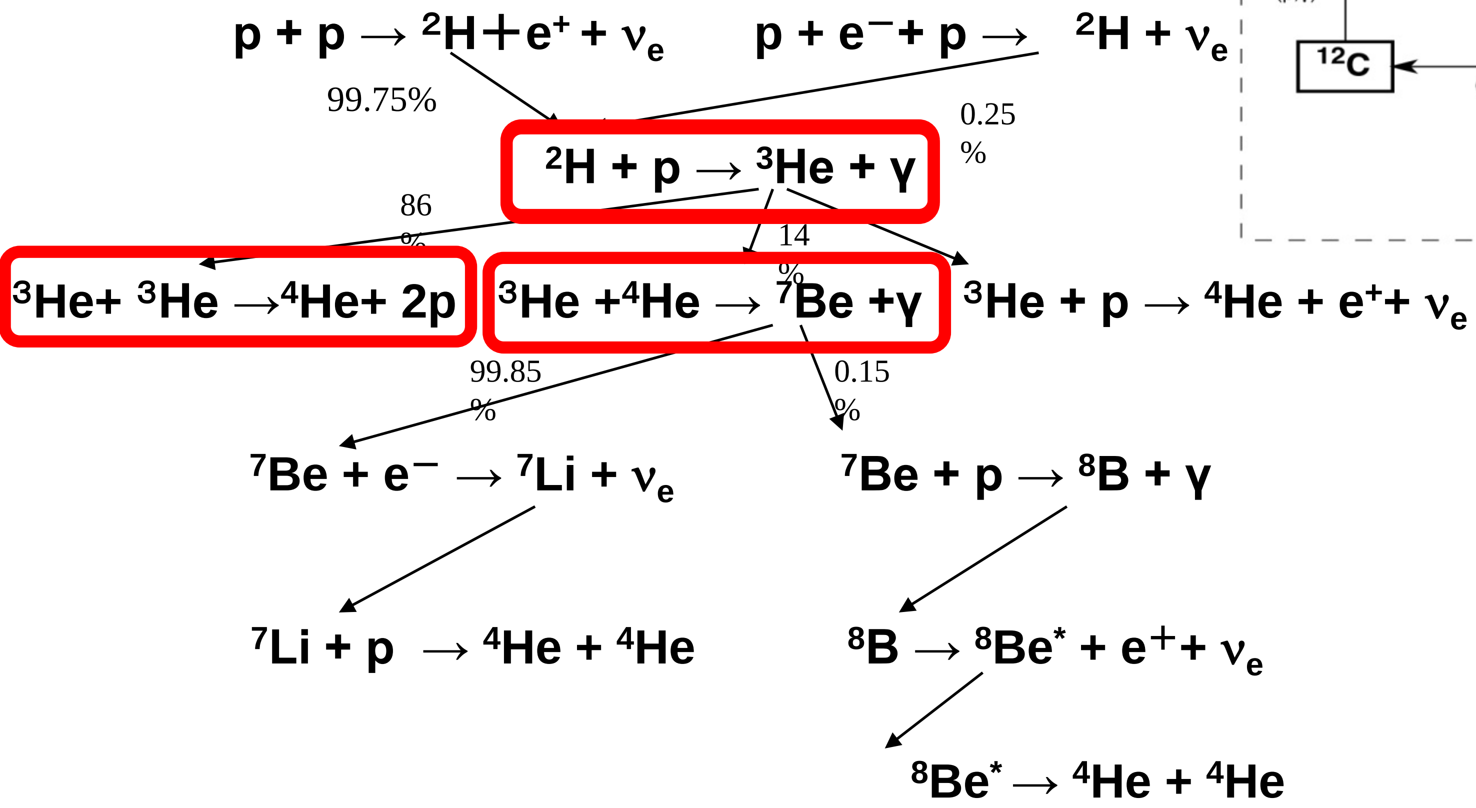
Allowed beams:

H^+, ^4He, (^3He)

Key reactions measured at LUNA (50kV – 400kV)

☐ Measured by LUNA

pp chain



$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ 99.75%

$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$ 0.25 %

$^{2}H + p \rightarrow {}^{3}He + \gamma$

86 %

14 %

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

$^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

99.85 %

0.15 %

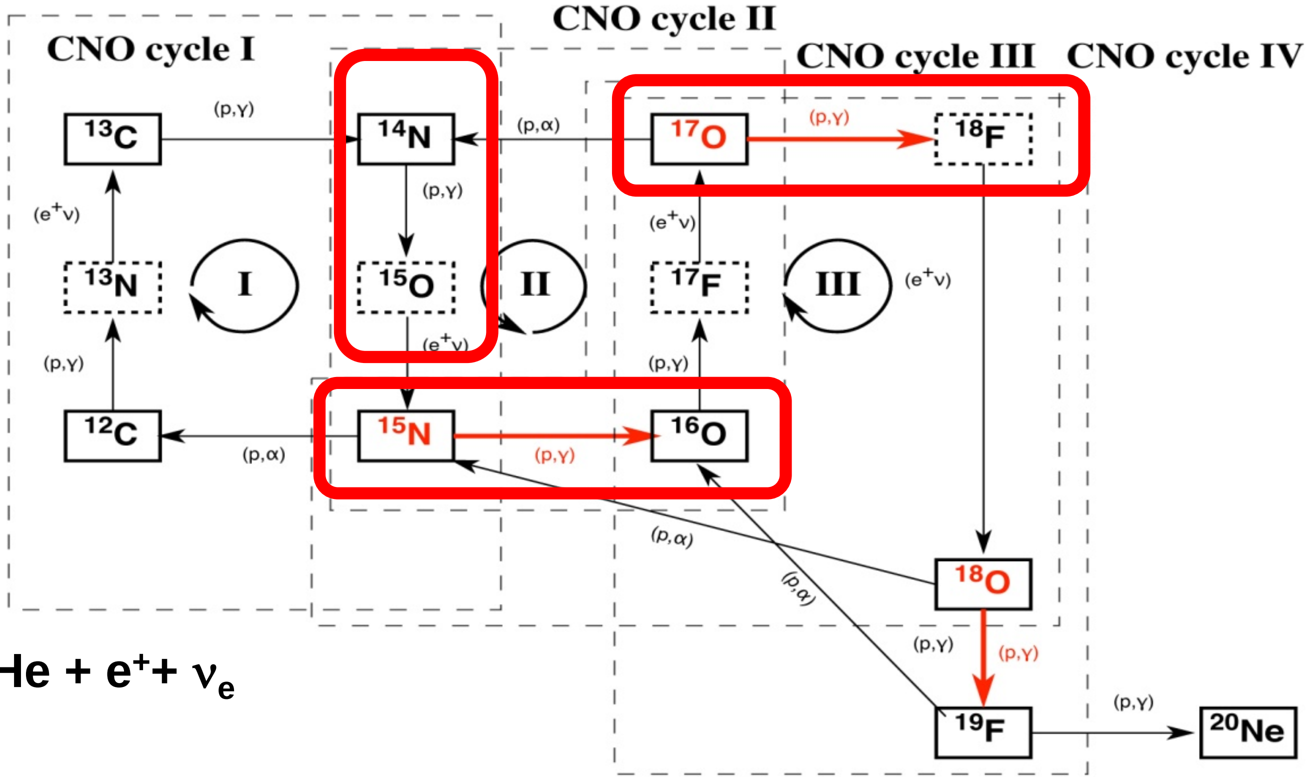
$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

$^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

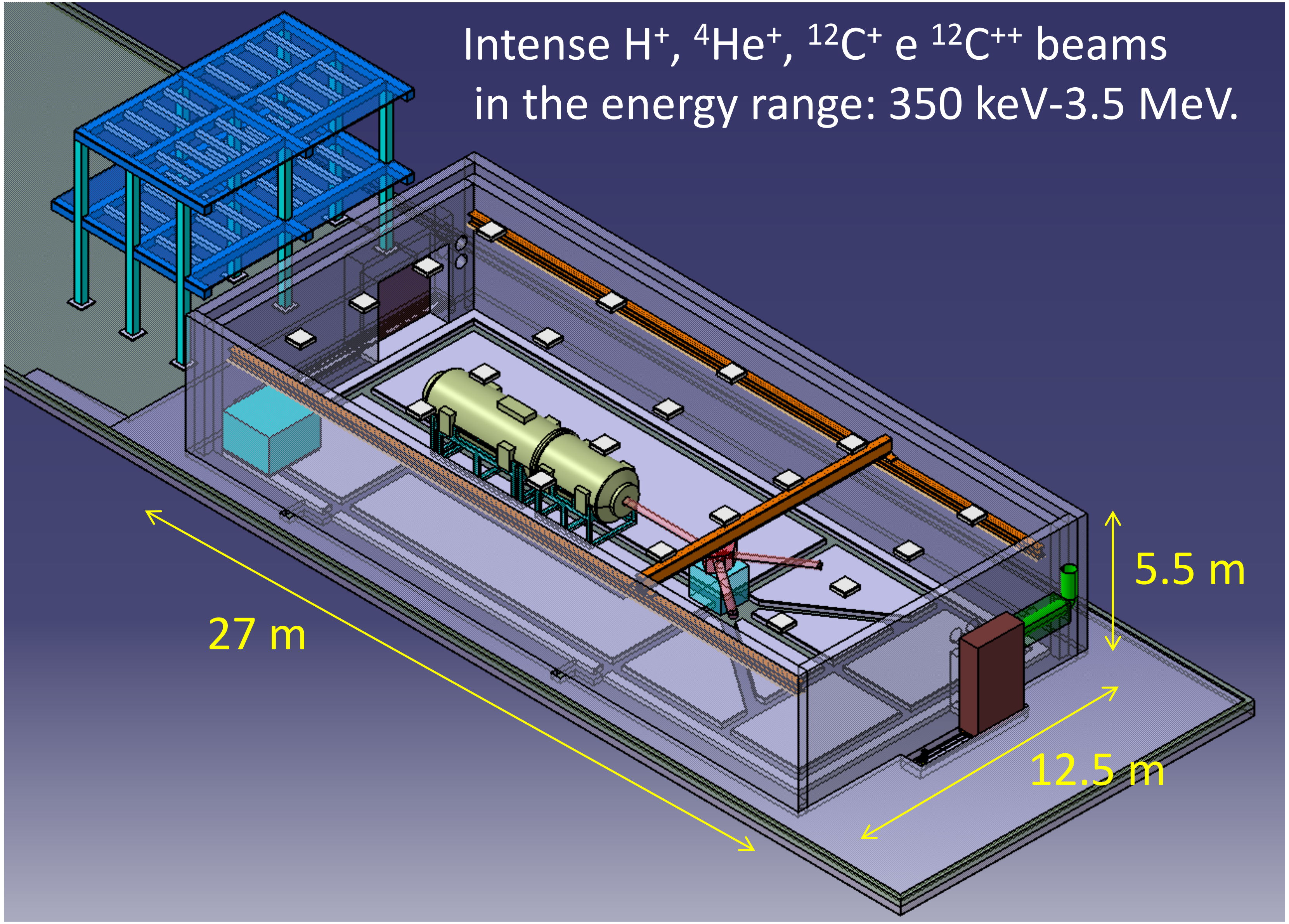
$^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

$^{8}Be^{*} \rightarrow {}^{4}He + {}^{4}He$



CNO cycle

New LUNA-MV facility


Intense H$^+$, ^{4}He$^+$, ^{12}C$^+$ e ^{12}C^{++} beams in the energy range: 350 keV-3.5 MeV.

Present status of Underground Science

2) Rare processes

Rare processes

- ✓ Observing rare processes (such as double β decay, proton decay, neutron-anti-neutron oscillations, …) is very important for fundamental physics.
- ✓ Here I discuss proton decay searches only.

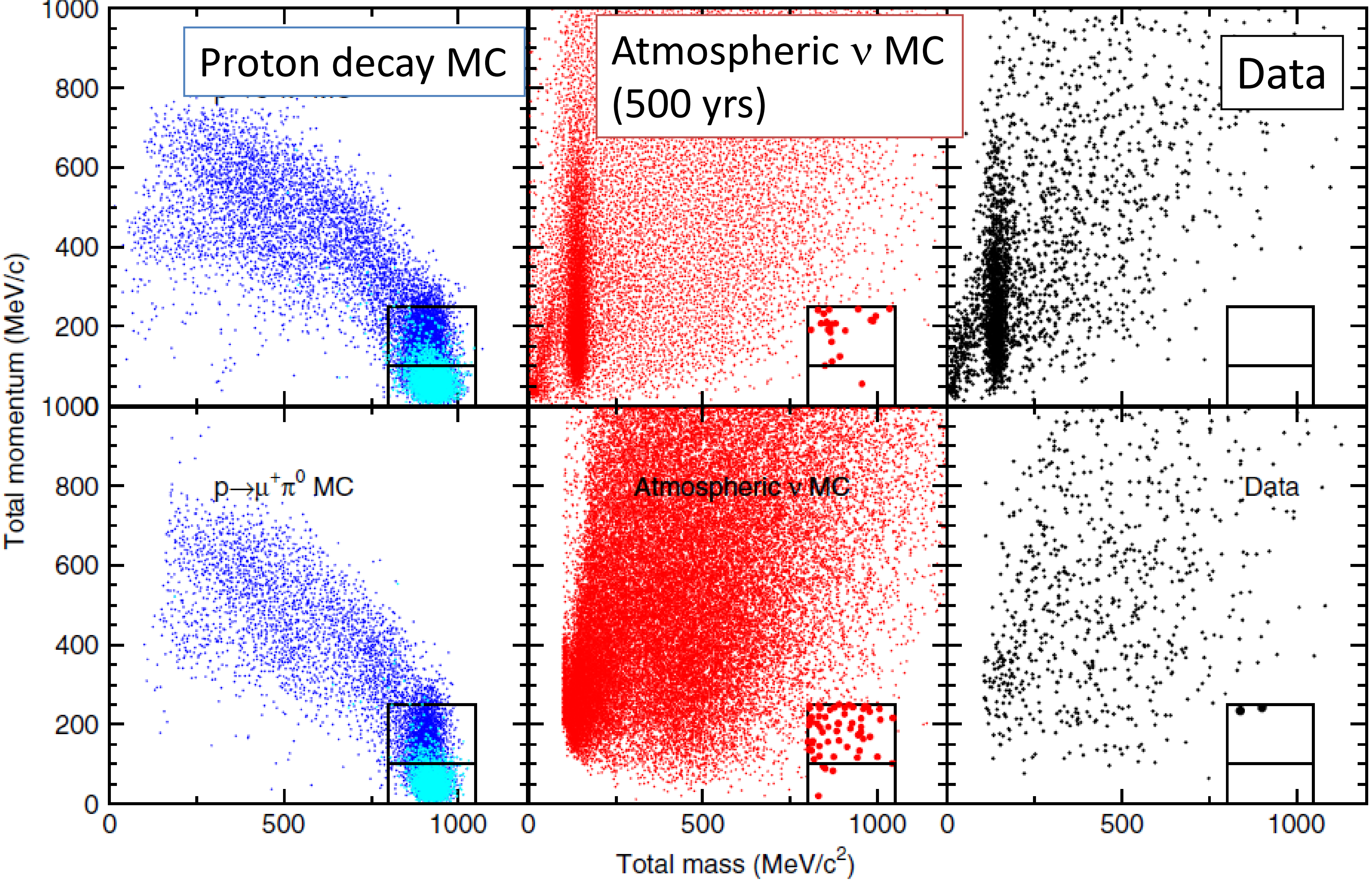
Proton decay search (1)

Super-K, PRD 95, 012004 (2017)

Super-K

P→e+π^0

P→μ+π^0



0 event

➔

> 1.6 X 10^{34} yrs

(90%CL)

2 events

(0.87 BG expected)

➔

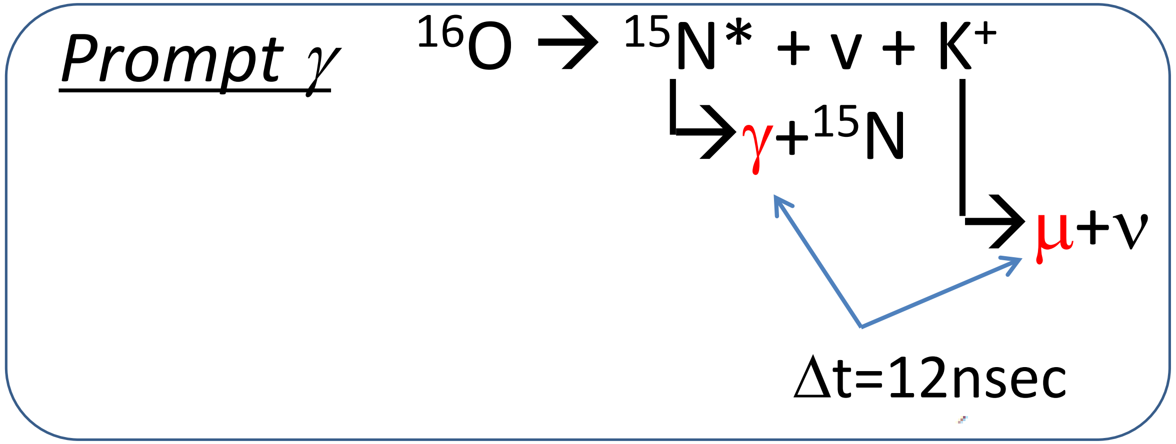
> 7.7 X 10^{33} yrs

(90%CL)

Proton decay search (2)

Super-K, PRD 90, 072005 (2014)

Super-K $P \rightarrow \nu + K^+$



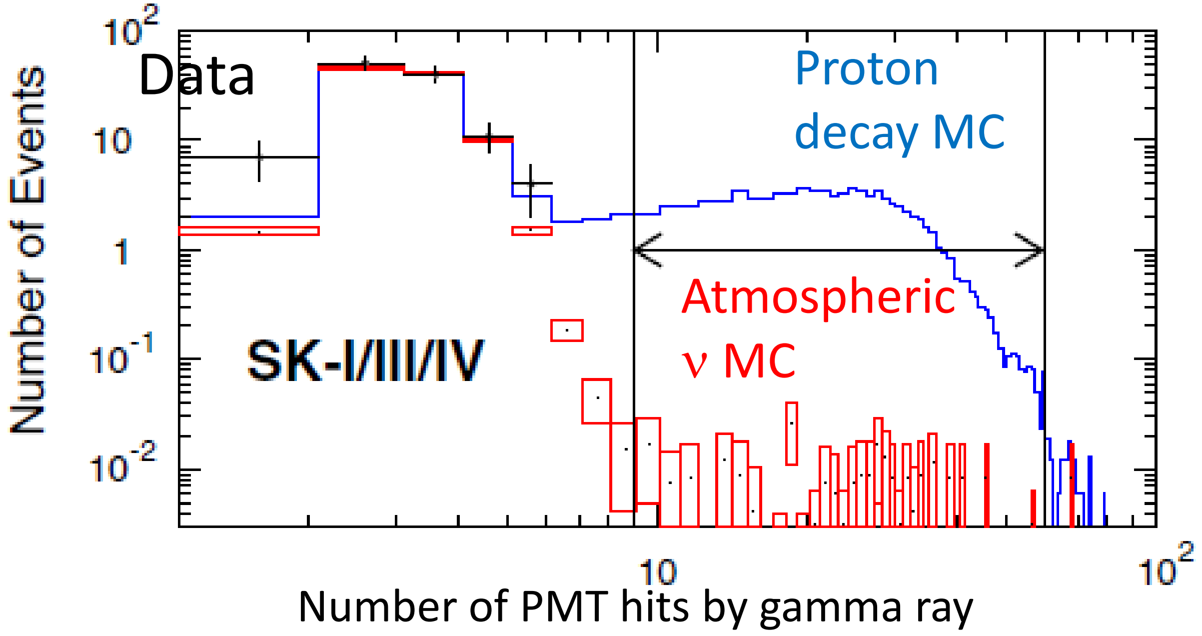
Prompt γ

$^{16}O \rightarrow {}^{15}N^* + \nu + K^+$

$\hookrightarrow \gamma + {}^{15}N$

$\hookrightarrow \mu + \nu$

Δt=12nsec



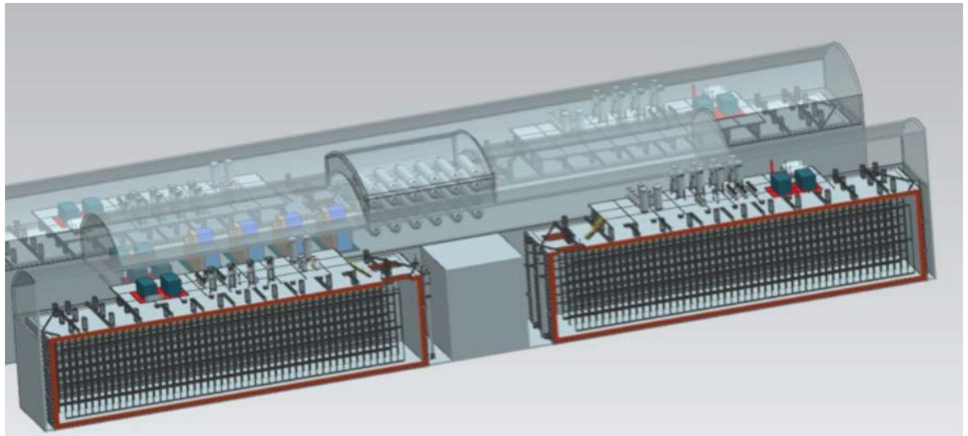
Prompt γ	Eff. (%)	6.3 (SK-II) ~ 9.1 (SK-IV)
	Total BG	0.38
	Signal	0
P_μ spectrum (K+ → $\mu + \nu$)	Eff. (%)	30.6 (SK-II) ~ 37.6 (SK-IV)
	Total BG	579.4
	Signal	566
$K^+ \rightarrow \pi^+ + \pi^0$	Eff. (%)	6.7 (SK-II) ~ 10.0 (SK-IV)
	Total BG	0.62
	Signal	0

➔ ***> 5.9 x 10^{33} yrs (90%CL)***

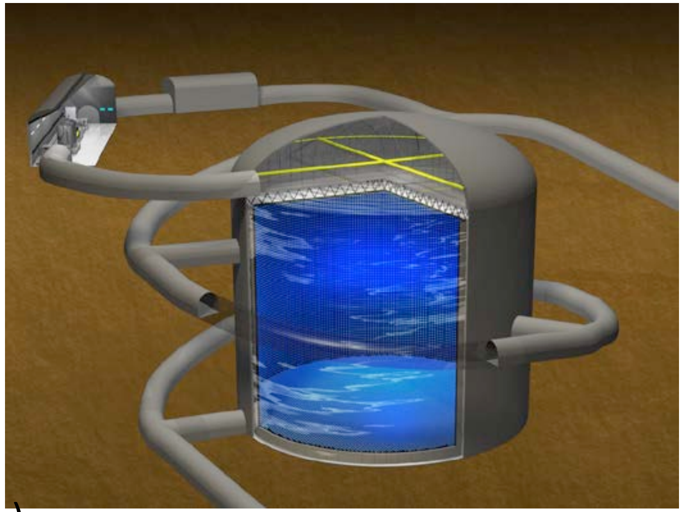
Future

W.Wang, S. Parakash PoS (ICHEP2016) 968

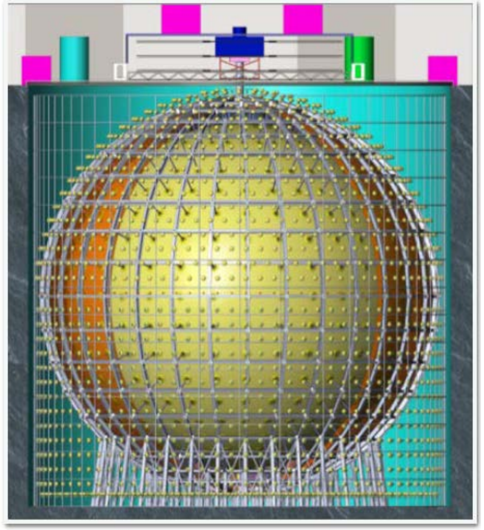
Liq. Ar (DUNE)



Water Ch. (Hyper-K)



Liq. Sci (JUNO)



Numbers for DUNE has been generated based on numbers in the literature (efficiency: 45/97%, bkg: 1/<1 event/Mton year).

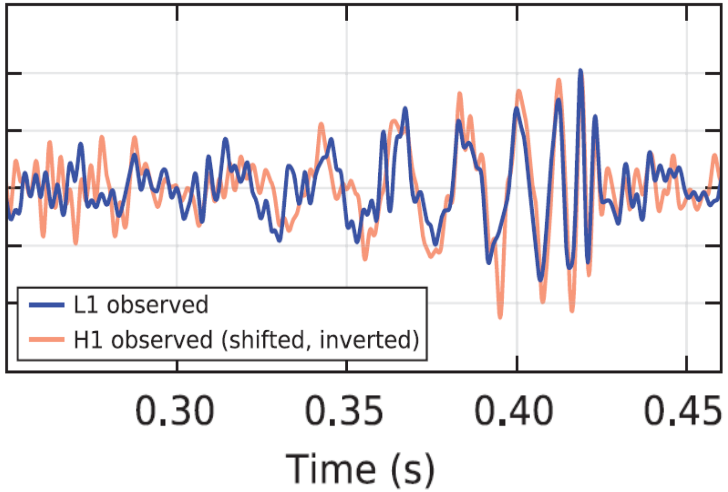
	JUNE (90%CL)	Hyper-K (90%CL)	JUNO (90%CL)
P → e π^0 (after 10 years)	~ 2.2 X 10^{34}	~ 7 X 10^{34}	
(after 20 years)	~ 4 X 10^{34}	~ 1.3 X 10^{35}	
P → ν K^+ (after 10 years)	~ 3.5 X 10^{34}	~ 3 X 10^{34}	~ 1.9 X 10^{34}
(after 20 years)	~ 7 X 10^{34}	~ 5 X 10^{34}	

Present status of Underground Science
3) gravitational waves

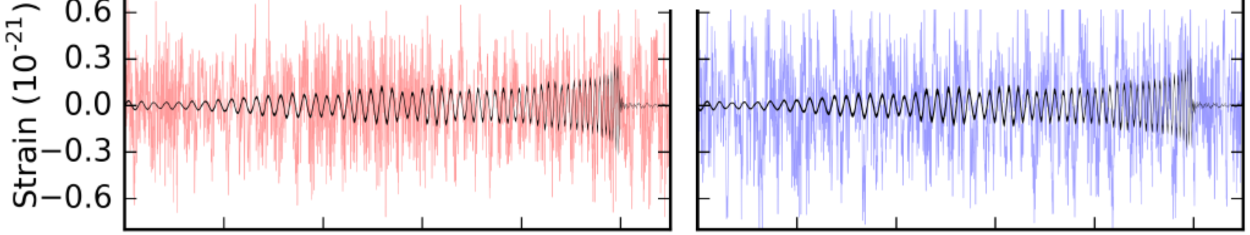
Gravitational wave (underground only)

LIGO-Virgo

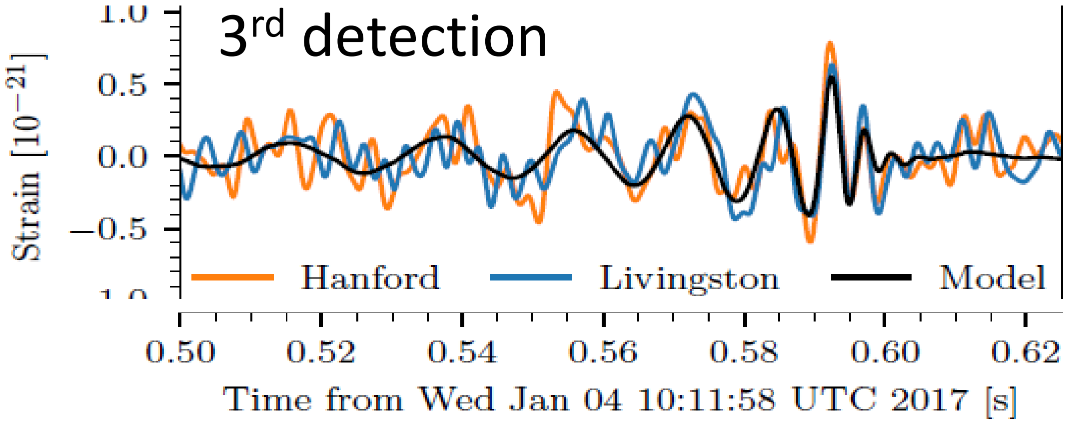
1st detection



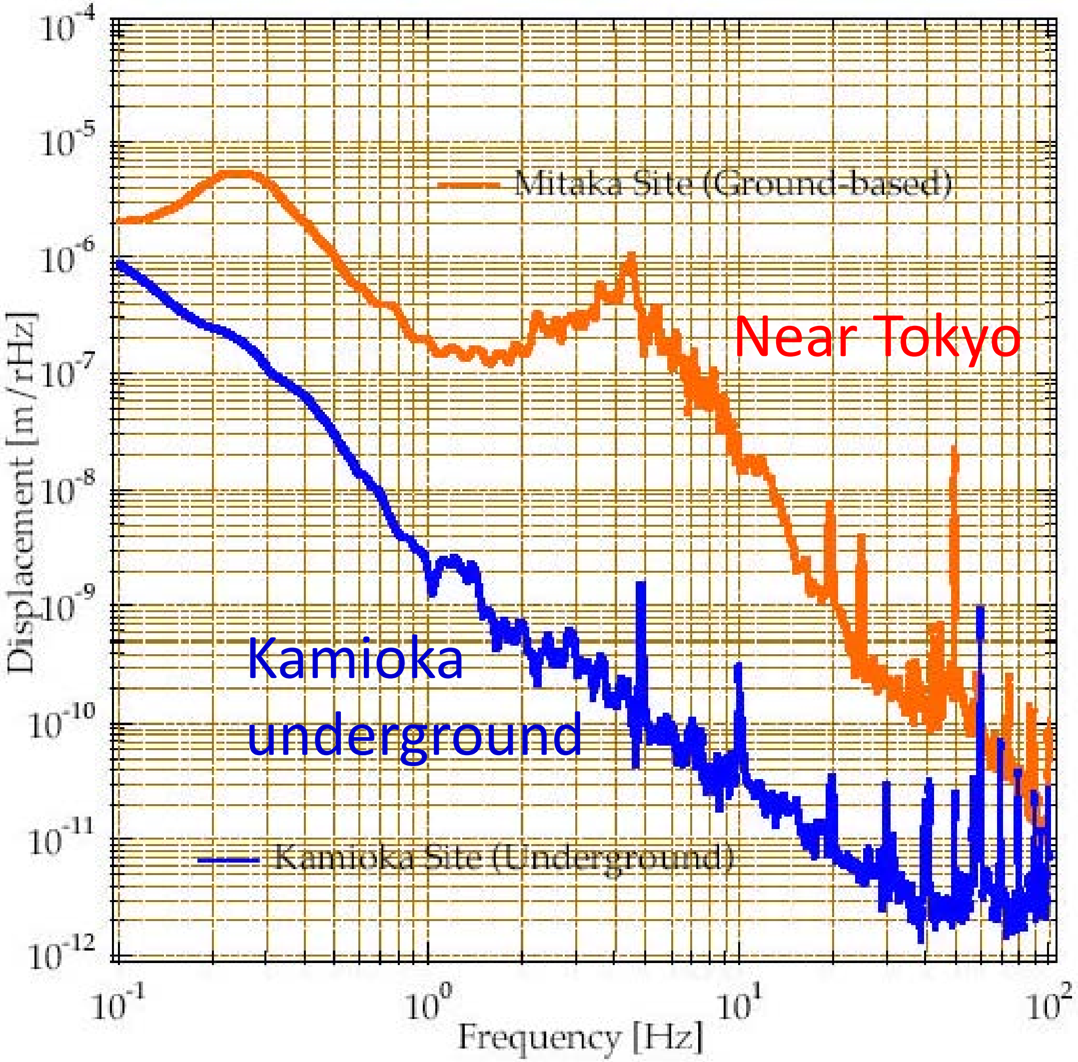
2nd detection



3rd detection

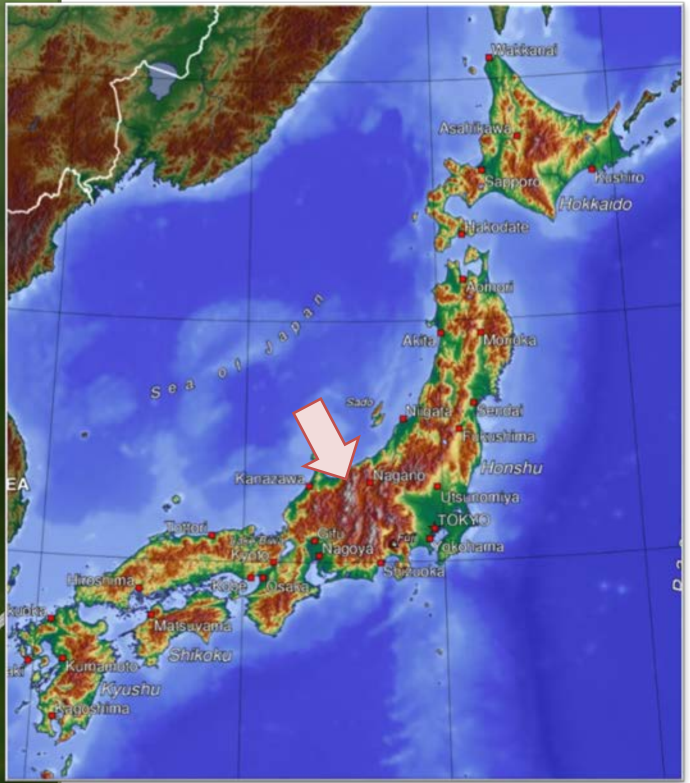


Why underground?



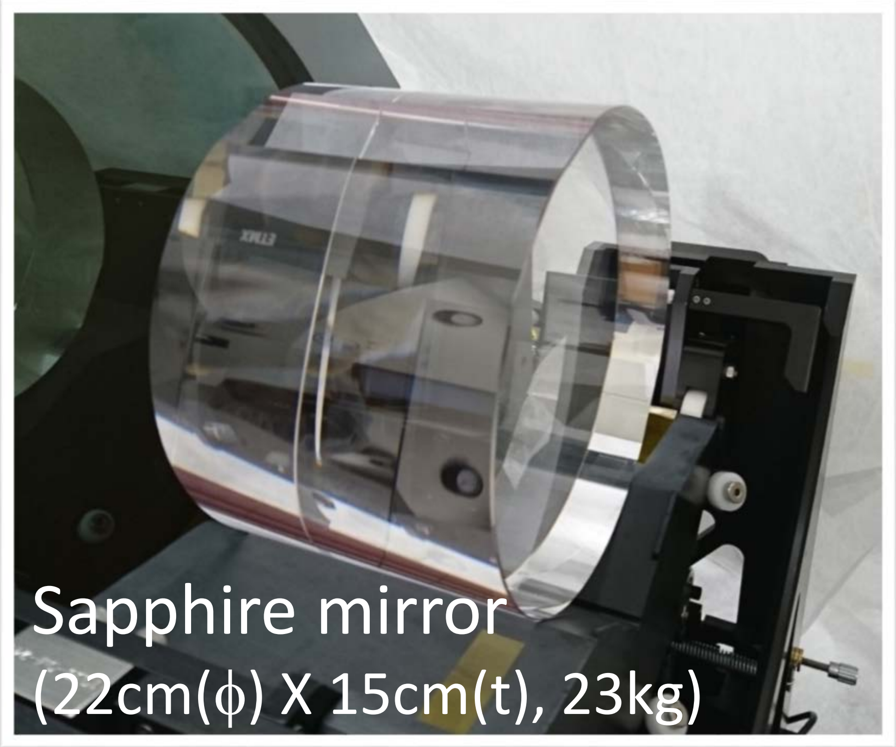
KAGRA

- ➢ 3km X 3km arm lengths
- ➢ Design sensitivity similar to LIGO and Virgo.
- ➢ Expected to begin the operation in 2019-20.



KAGRA: key features

The detector is under construction in underground Kamioka.
➔ Reduction of seismic noise (to approximately 1/100).

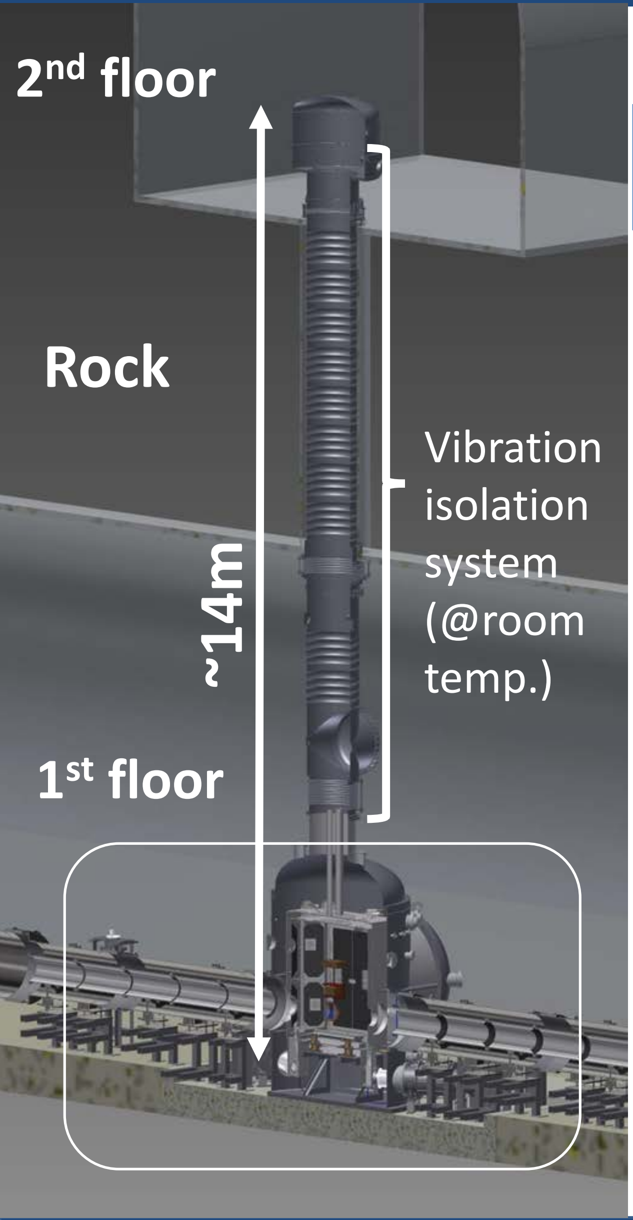


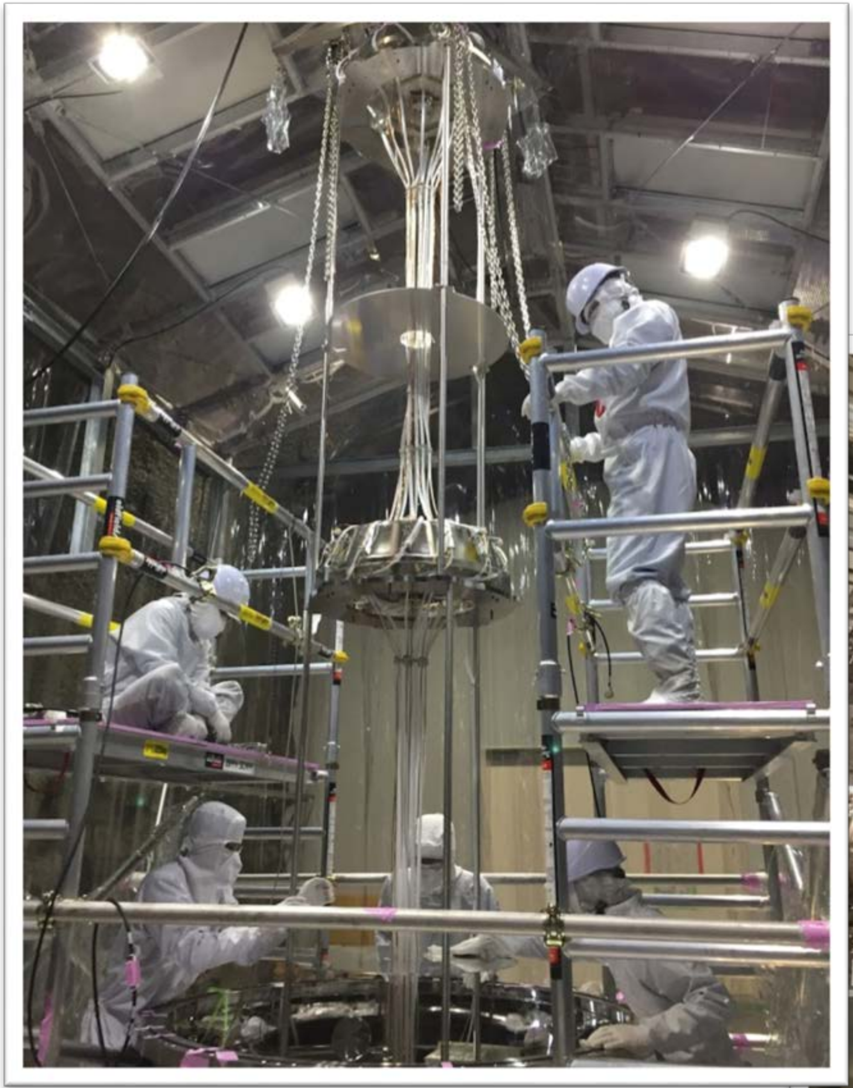
Sapphire mirror
(22cm(ϕ) X 15cm(t), 23kg)

Main mirrors (4 mirrors) will be cooled down to 20K to reduce the thermal noise.

➔ High sensitivity

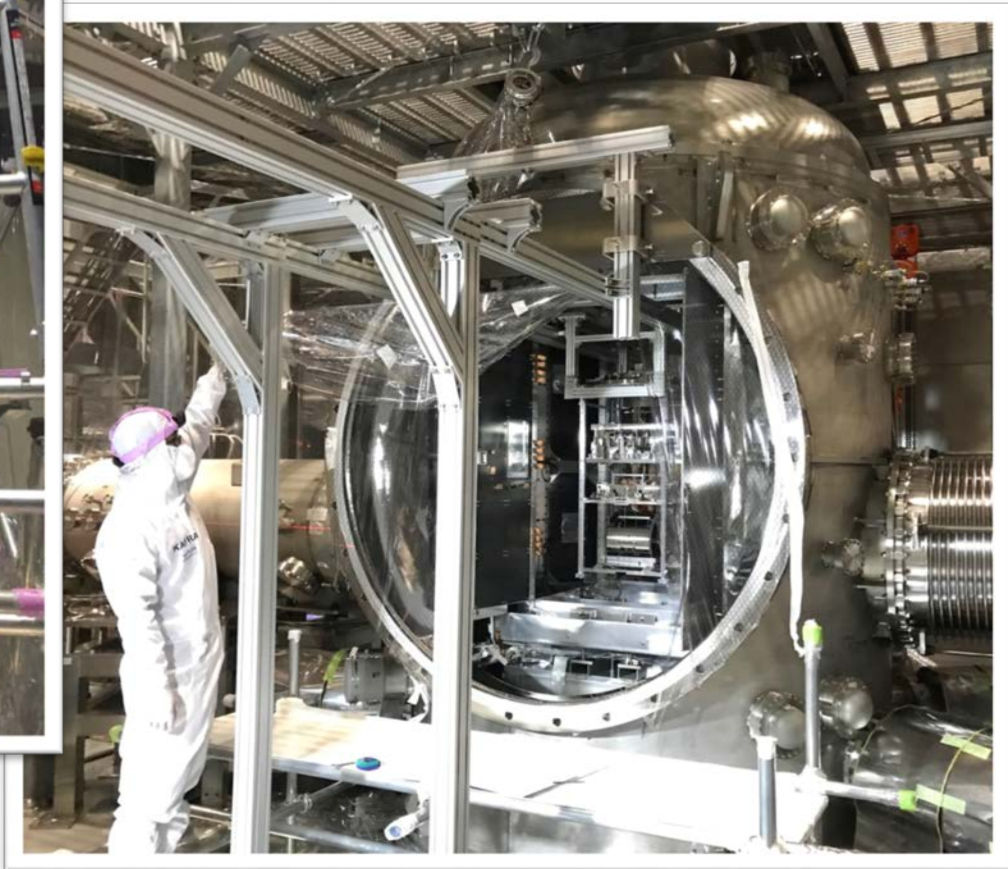
Another advantage of underground





2nd floor (May 2017)

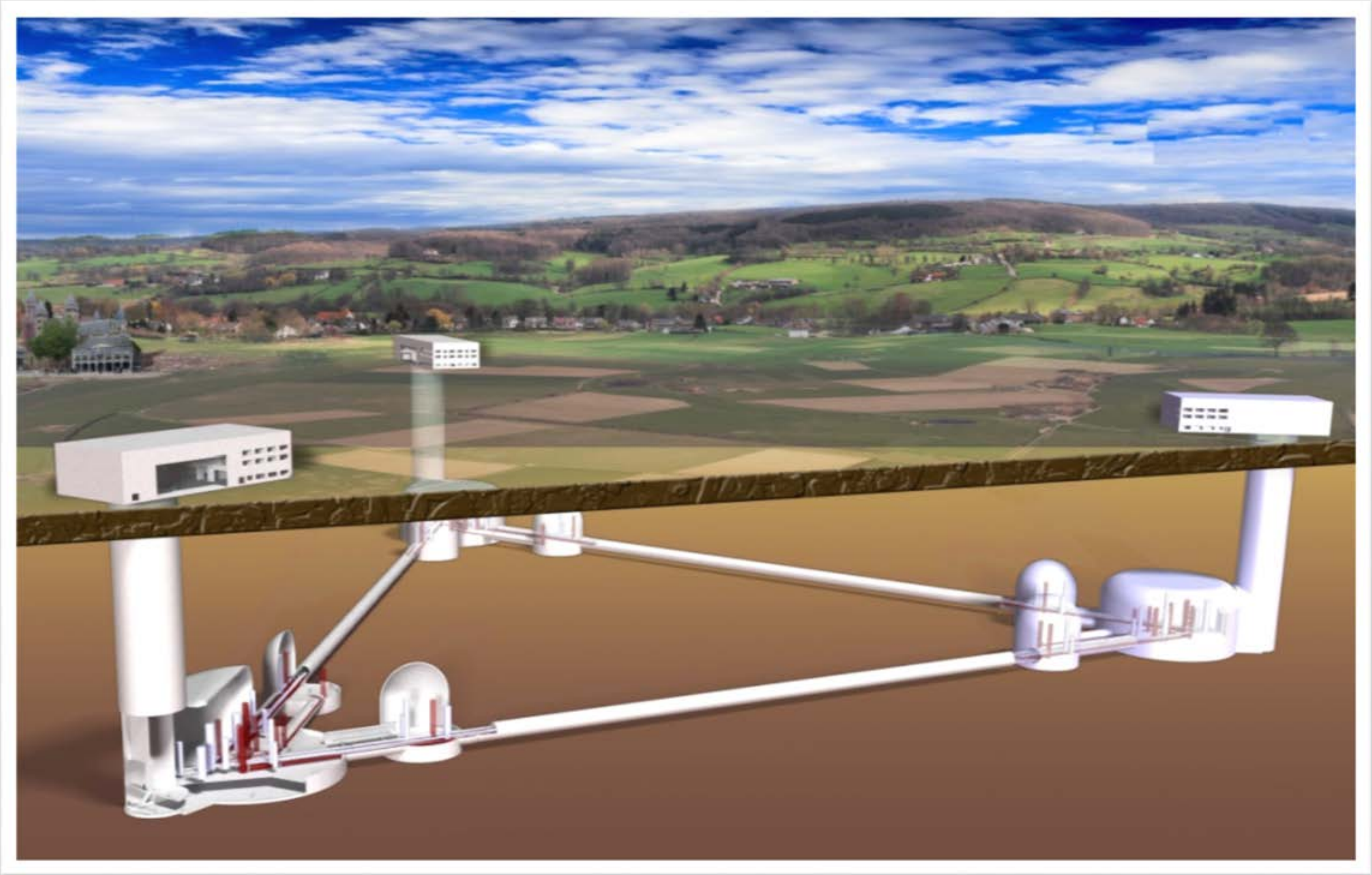
1st floor (June 2017)



Next generation

Einstein Telescope

- ✓ Another 1 order improvement in sensitivity
- ✓ A lot of science!
- ✓ R&D going on
- ✓ Start science run in the late 2020’s ?



In LIGO, the future plans are under serious discussion. The LIGO Voyager concept seems to assume the location on the surface. (Report from the Dawn-II workshop (2016))

Present status of Underground Science

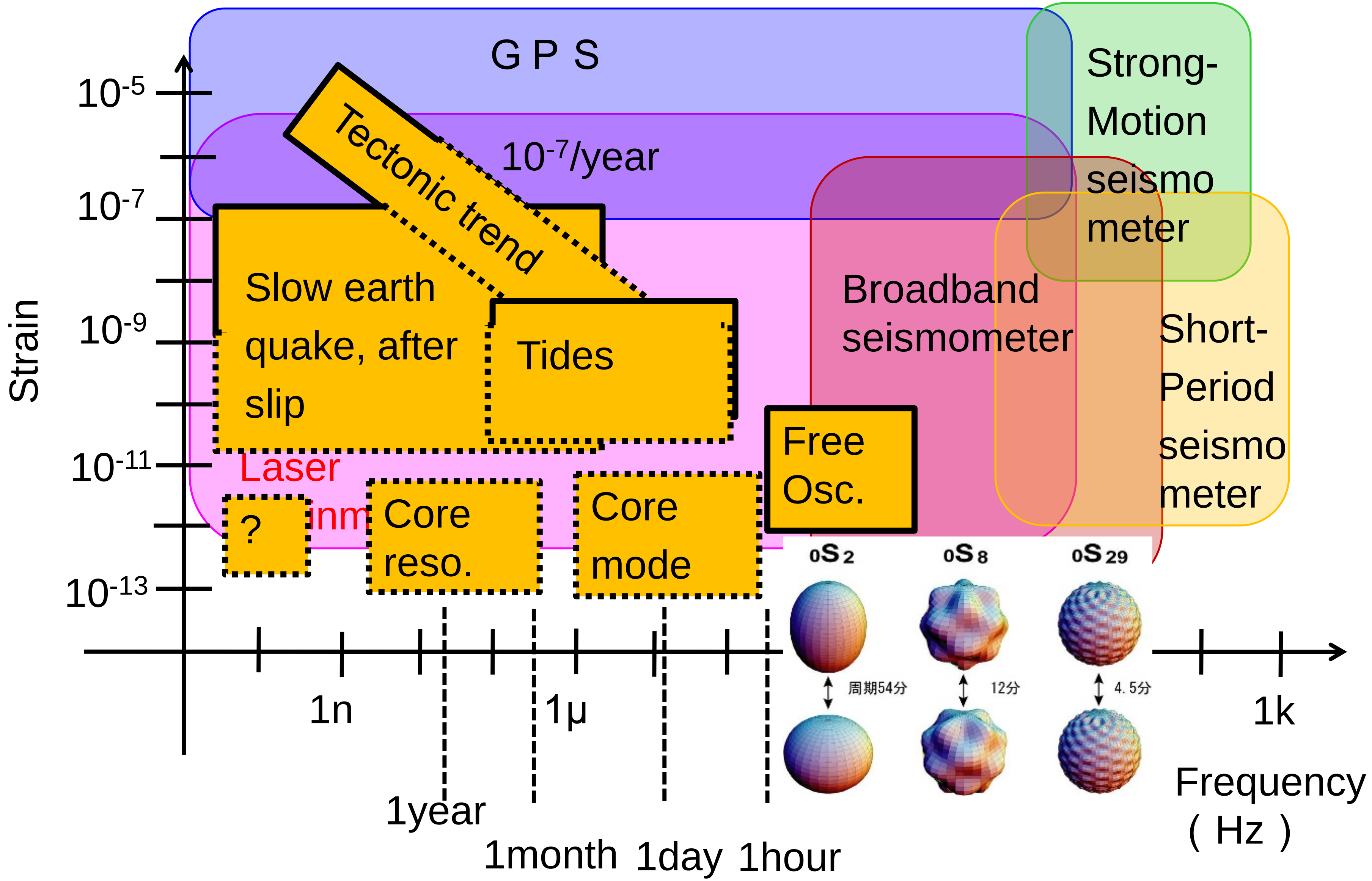
4) geophysics

Geophysics

Observable strain ranges and timescales

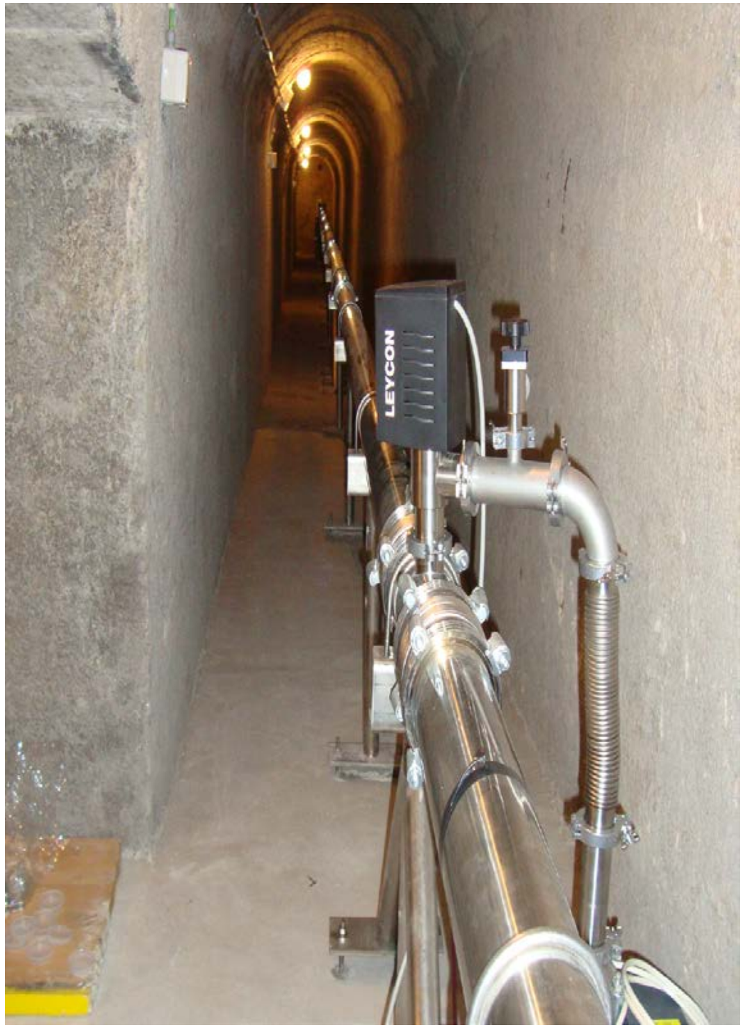
One has to minimize the disturbances on the surface (temperature change, wind, …). Also one has to measure the strain by attaching the instrument to the rock.

Underground



Laser strainmeters (partial list)

Site	Baseline	Depth	Reference
Pinon Flat Obs. (USA)	731m	Surface	Berger, 1970
Boulder (USA)	30m	-60m	Levine, 1973
Baksan (Russia)	75m	-400m	Milyukov, 2007
Gran Sasso (Italy)	90m	-1100m	Amoruso, 2009
Canfranc (Spain)	70m	-850m	Amoruso, 2016
Moxa (Germany)	26.5m	-35m	Kobe, 2016
Kamioka (Japan)	100m, 1500m	-1000m, -400m	Takemoto, 2004, Araya, 2017

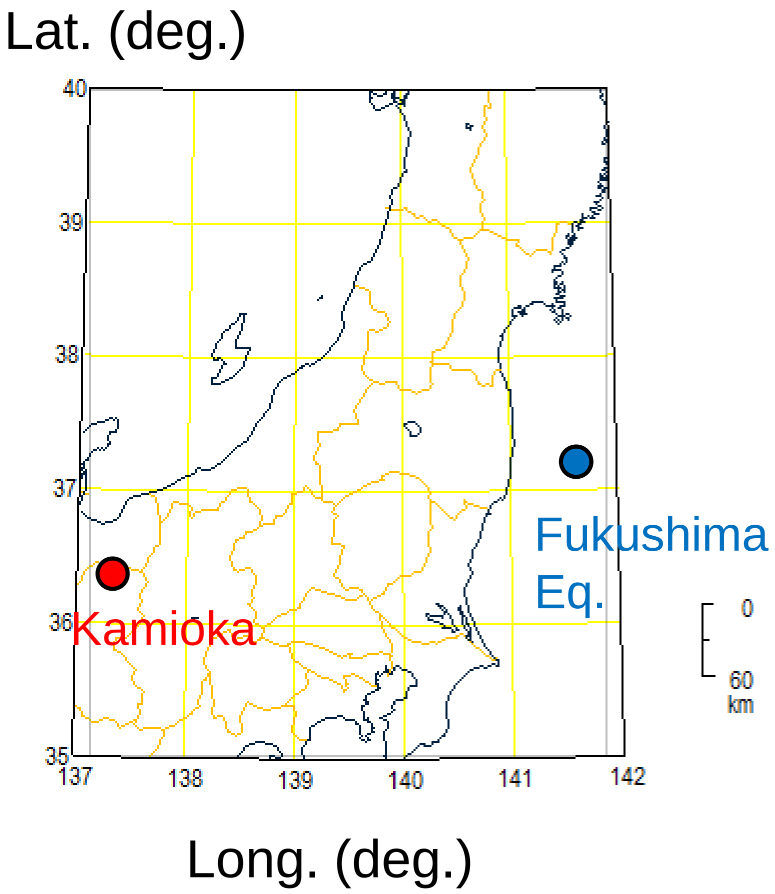


Canfranc

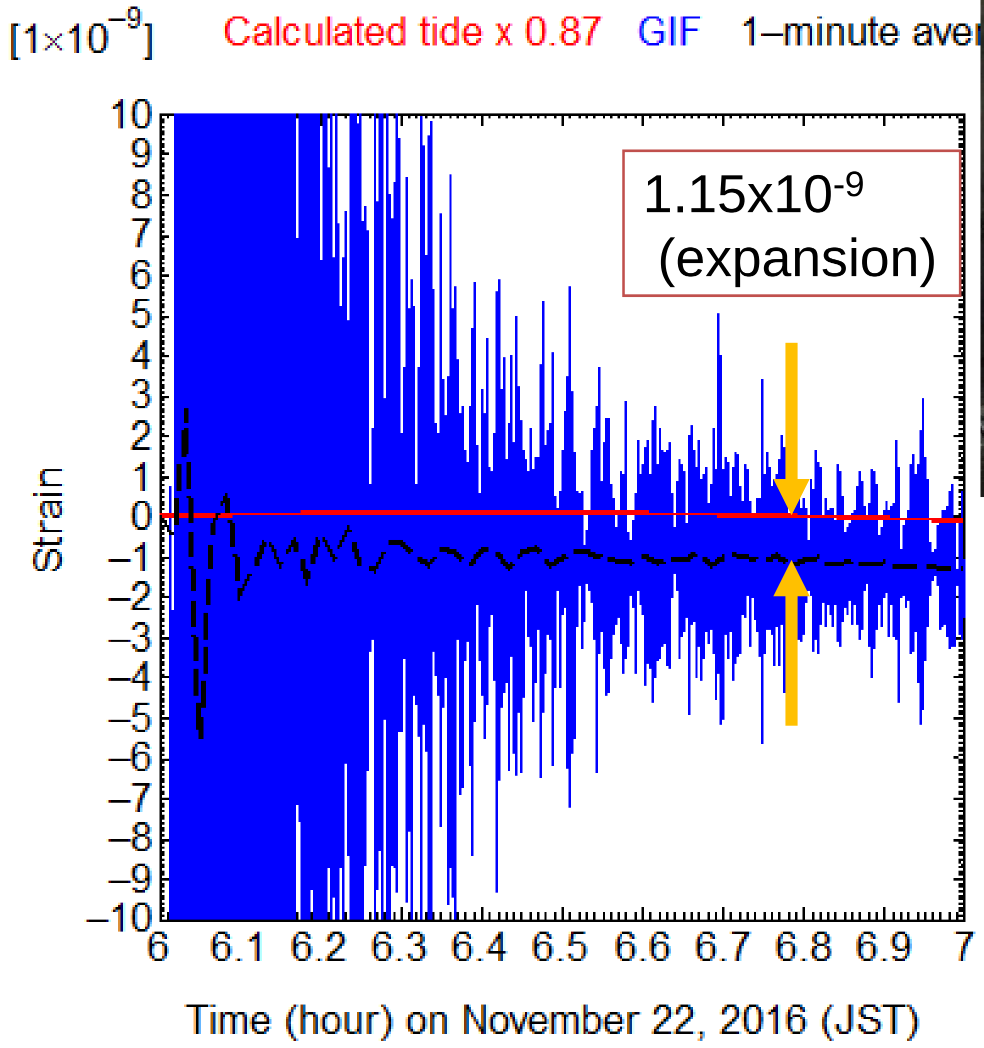
An example data from a strainmeter @Kamioka

A. Araya, private communication

1.5 km strainmeter at the KAGRA site has begun operation.



Occurred on 22 Nov. , 2016
6:59:49, Mw6.9 off Fukushima



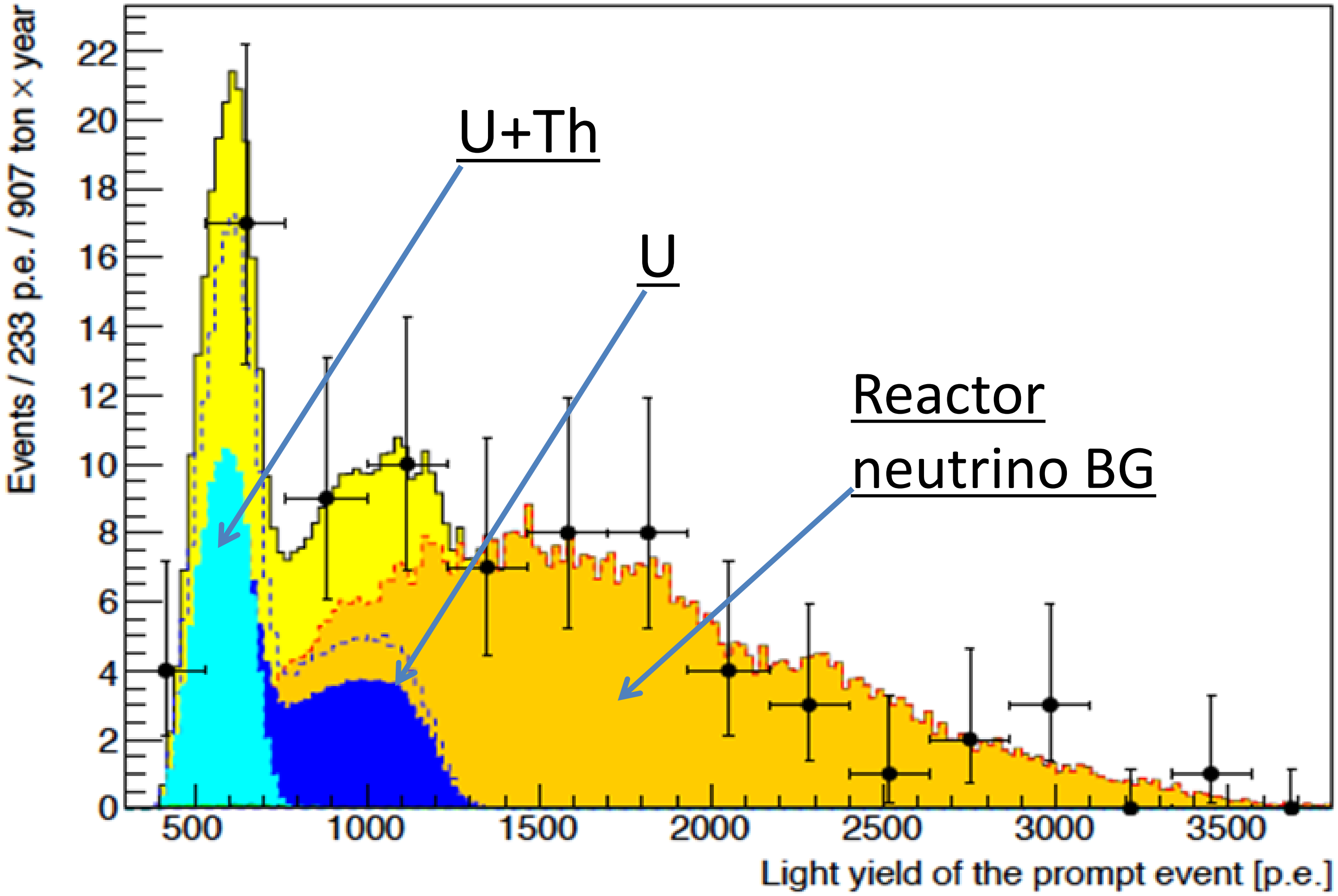
1.15×10^{-9}
(expansion)

Observed strain step agreed well with the fault model.

Geo-neutrino data from Borexino

Borexino is far from nuclear power reactors.
➔ Good for the geoneutrino detection.

Borexino, PLB 722, 295 (2013)
G. Bellini, JINR, Sep. 2016



U+Th

U

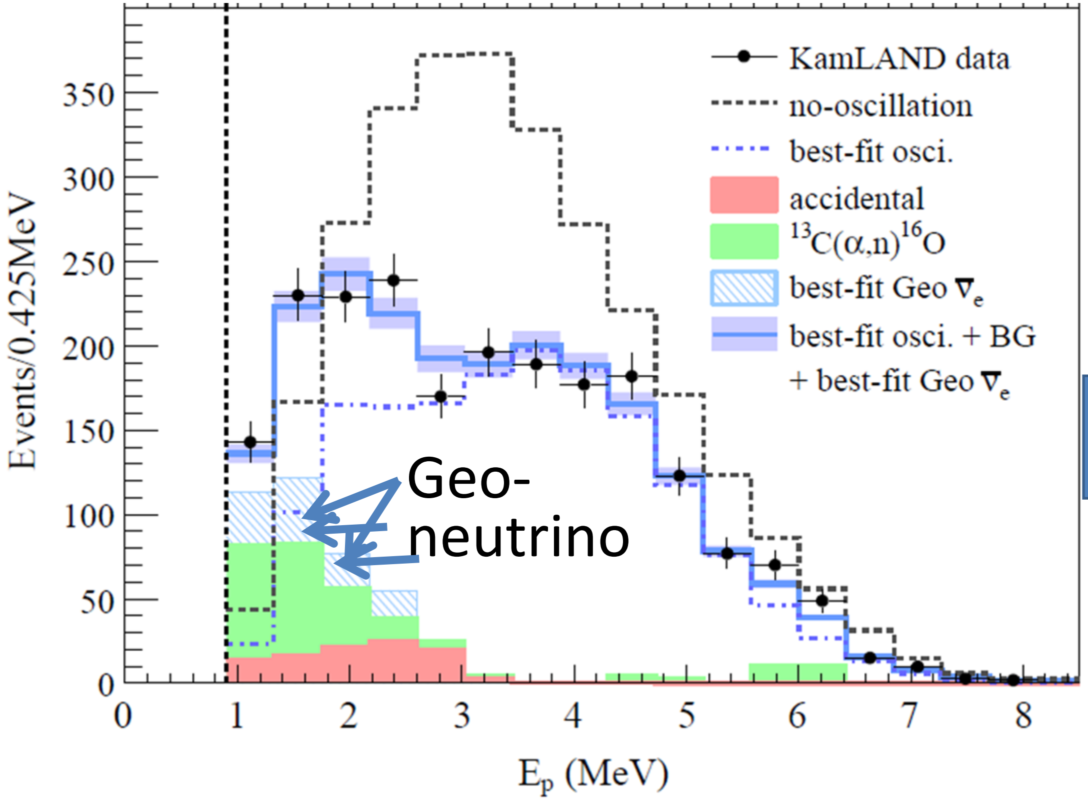
Reactor neutrino BG

$$N^{events}_{geo} = 23.7^{+6.5}_{-5.7}(stat.)^{+0.9}_{-0.6}(syst.)$$

Non-zero flux at 5.9σ level.
(Assuming a fixed Th/U ratio of 3.9)

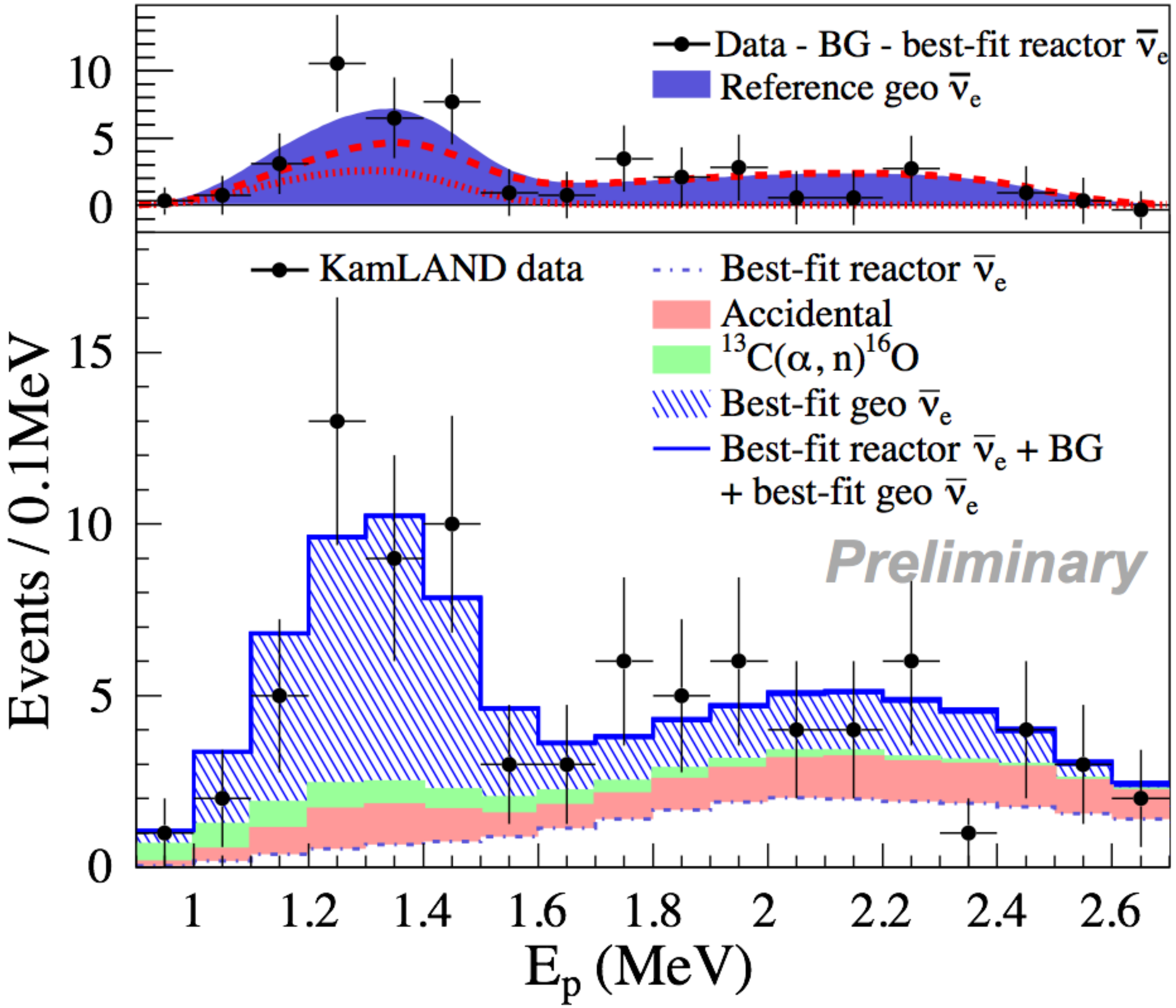
Geo-neutrino data from KamLAND

KamLAND, PRD 83, 052002 (2011)



Geo-neutrino

KamLAND (2017, Preliminary, by K.Inoue)

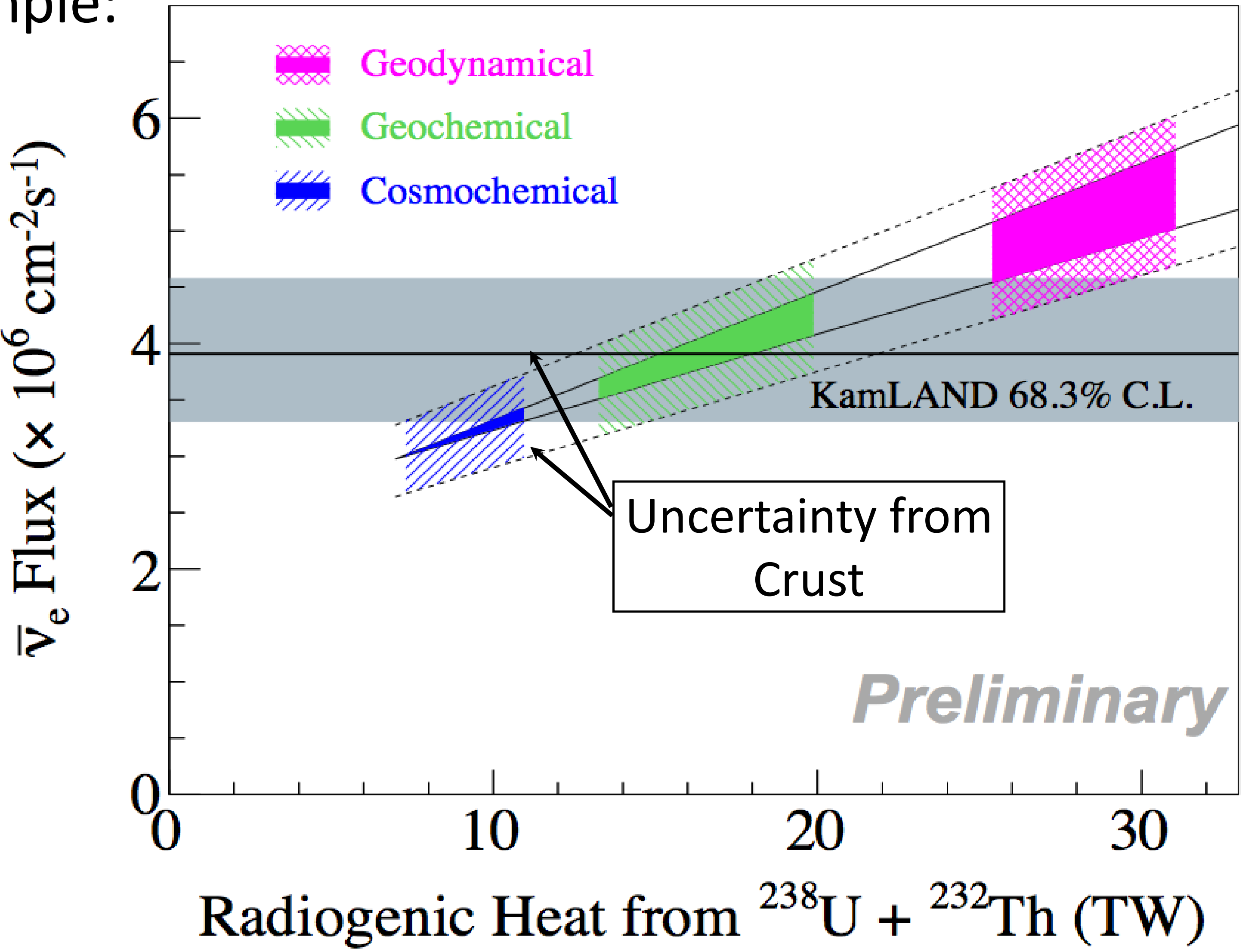


$N_{geo\text{-}\nu}=164^{+28}_{-25}$ (7.92σ)

What can we learn from geo-neutrinos?

Example:

KamLAND (2017, Preliminary, by K.Inoue)

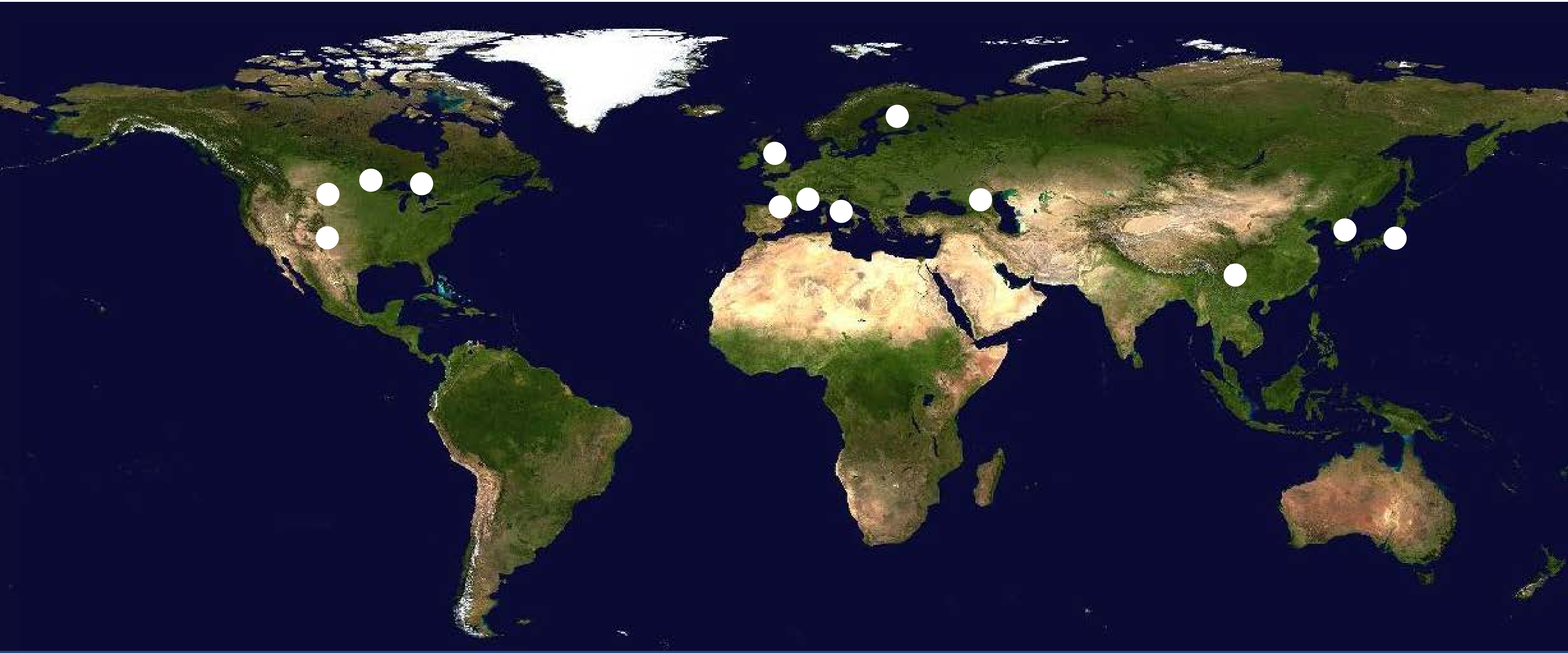


The data begin to tell the dynamics of the interior of the Earth, ….

Underground facilities (a partial list)

It has been proven that underground facilities are very important for varieties of science!

For scientific reasons, It would be very nice if there is (at least) one in the Southern hemisphere…



Summary

- ✓ The scientific topics carried in underground facilities is expanding significantly!

We have many topics to be discussed in TAUP (Topics in Astroparticle and Underground Physics)!