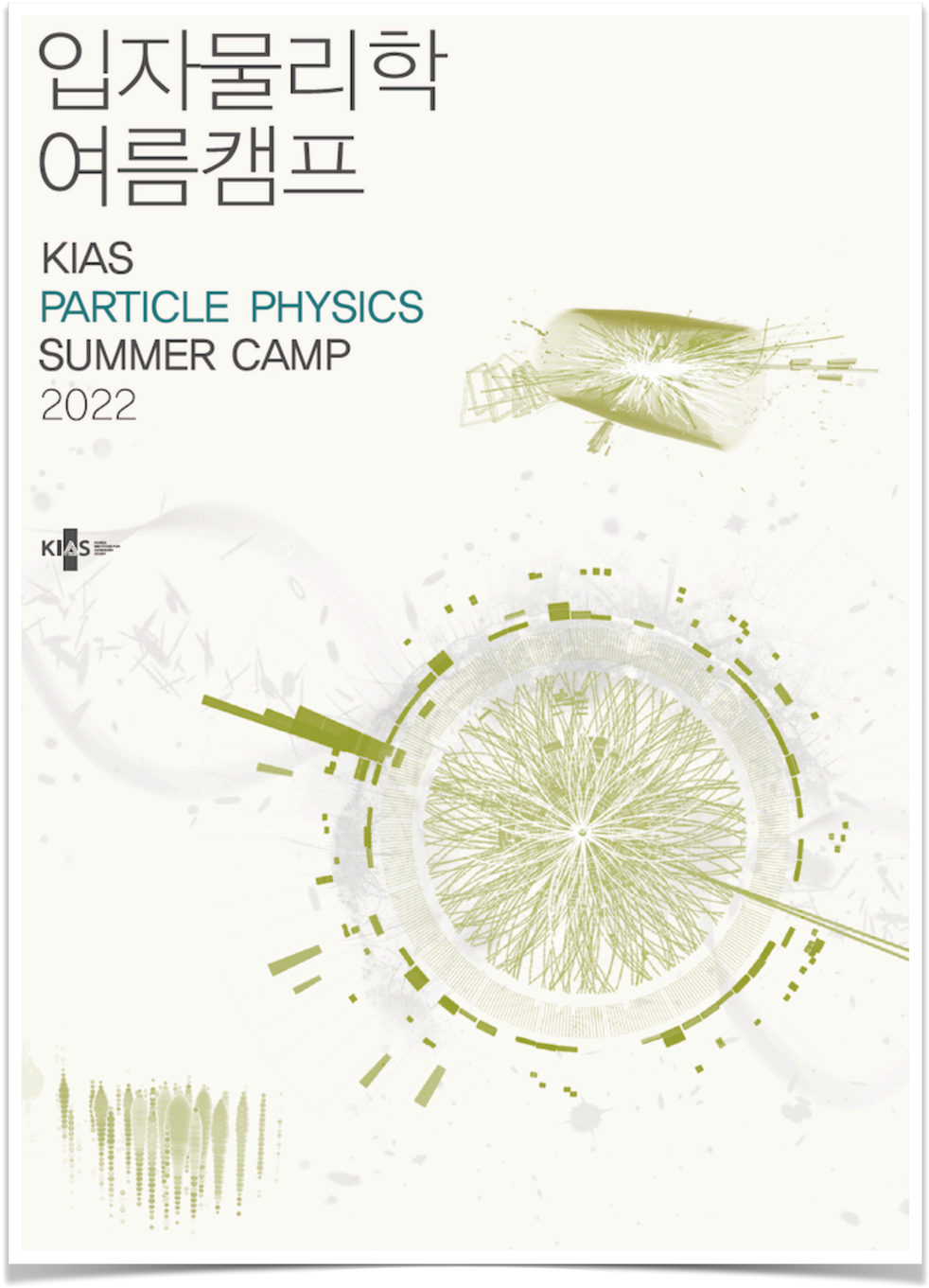
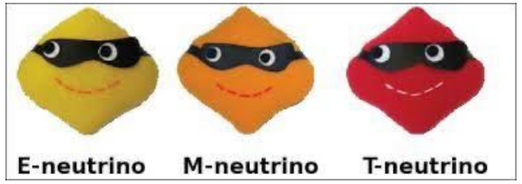






CAU 중앙대학교 CHUNG-ANG UNIVERSITY

RESL RARE EVENT SEARCH LABORATORY

중성미자 실험

KIAS Particle Physics Summer Camp 2022

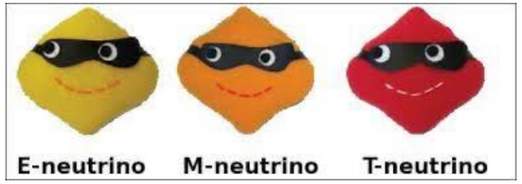
중앙대학교 물리학과 하창현

8월 23일

입자물리학
여름캠프

KIAS
PARTICLE PHYSICS
SUMMER CAMP
2022





중앙대학교
CHUNG-ANG UNIVERSITY

RESL
RARE EVENT SEARCH LABORATORY

중성미자 실험

"If you can measure something accurately enough, you have a chance of discovering something important. The history of astronomy shows that it is very likely that what you discover will not be what you were looking for."

"It helps to be lucky."
— John Bahcall


為大司成柳希奮爲司諫文勵爲司瞻寺副正黃是爲應教蔡慶先爲
修撰尹晬爲正言任兗爲兵曹佐郎姜節爲贊儀權昕爲司書黃敬中
爲說書鄭廣成爲待教○丁卯○宣州牧使崔沂辭朝 上以備忘記
諭之曰我國北連靺鞨西接山戎數百年來塞外殘虜皆不足慮者今
建州有老酋稱名者掘起拒我境不出數日觀其所爲殊非尋常之胡
西鄙其有憂乎予觀本道無關塞險阨可以守禦之處坦坦長驅真四
戰之地雖有二長江冰合則不足恃耳乃於居中設定州一鎭意亦
有在而城非據險澗而且疎生齒不繁軍民鮮少終日長道但見其平
蕪綠草孰接於天想此氣勢猝遇大賊必不免有土崩之變而人不以
爲虞曾見壬辰之前有以倭賊爲虞者乎老酋方與羅里爭衡不幸而
老酋勝更無其敵之議其後者則我爲次第受兵必無疑矣其及此時
治兵整衆以待敵至不可緩也未審本道監司有意於此否也宣州是
大將鎭守與邊城可以掎角之處爾須著遠慮撫民除弊積穀鍊兵庶
然爲關西保障萬一有變名可垂於竹帛久在近侍今當遠離賜豹皮
一令勿謝○戊辰○夜有一更客星在尾宿十度去極一百一十度形體
小於歲星色黃赤動搖五更有霧○諫院 啓曰前奉教金大德爲人

고대 천문학의 주 목적은 농사를 위한 달력을 제작. 항해를 위한 나침반 역할.

The naked-eye supernova in 1604 when Kepler saw it. Our ancestors saw it too.

7~9시 사이 손님별 전갈자리 꼬리 북극성

선조실록 : 夜(有)一更, 客星在尾宿十度, 去極一百一十度, 形體小於歲星, 色黃赤, 動搖

목성

선조 37년 9월 21일 무진

7개월간 130회 이상의 기록

태백산사고본 (국사편찬위원회)

중앙대학교 물리학과 하창현

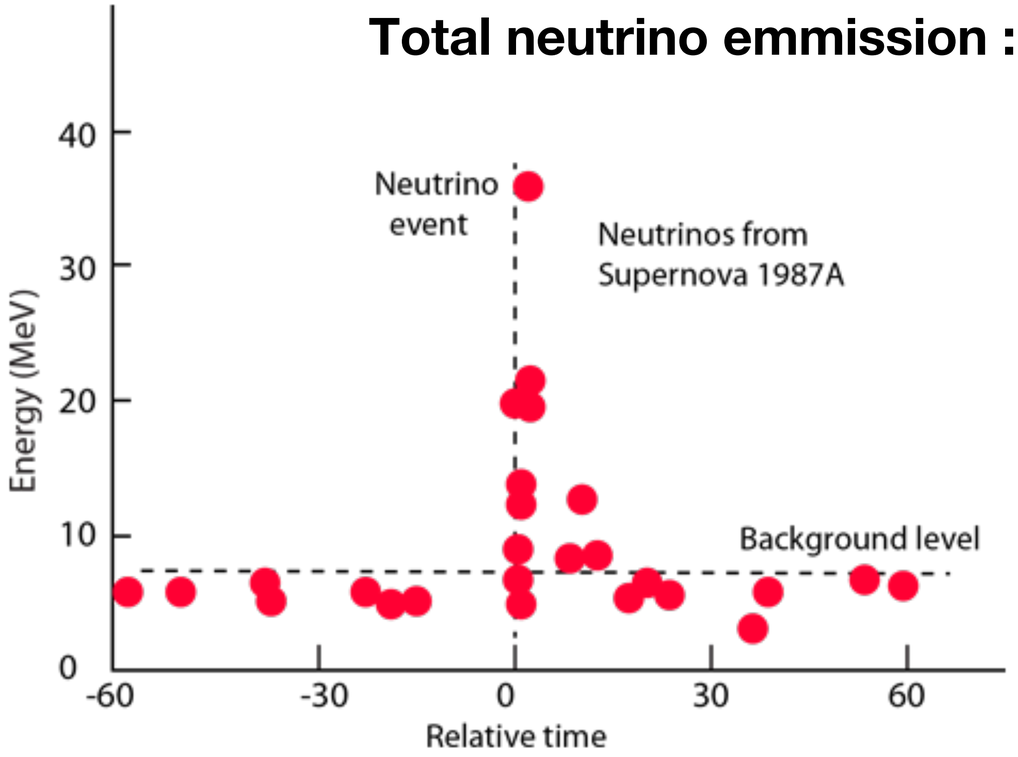
Supernova 1987A

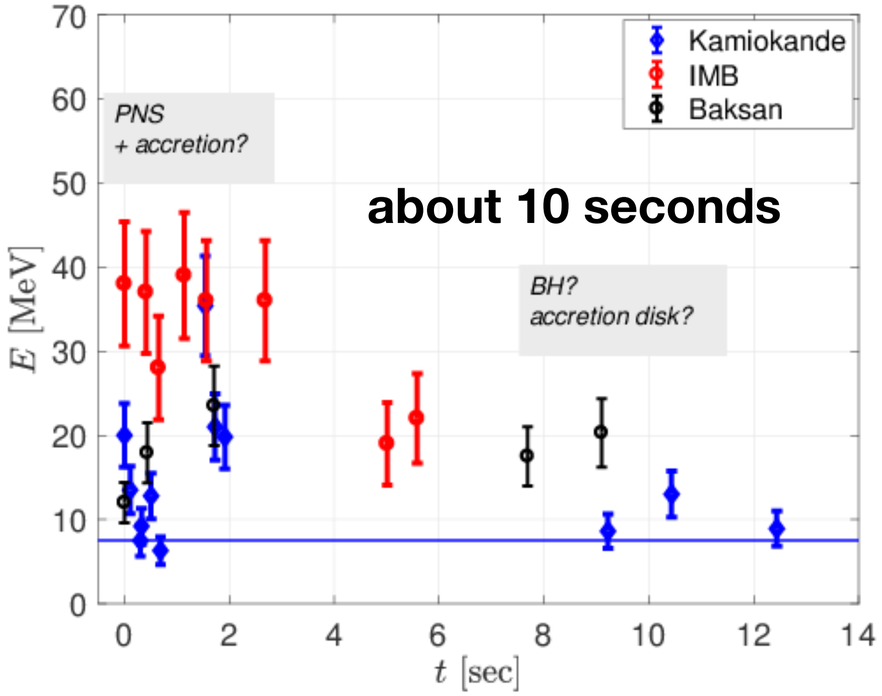
Neutrinos are emerged 3 hours before the light detection



Flux at Earth : $5\times10^{10}/cm^2$

Total neutrino emmission : 10^{55}

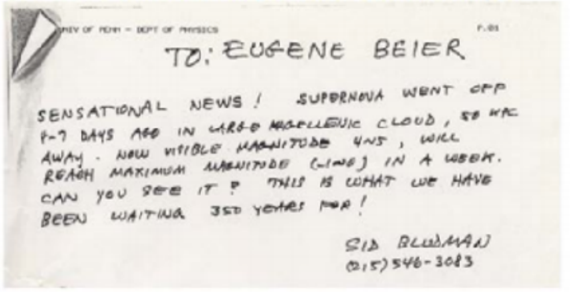




SN1987A@Kamiokande

M. Nakahata@30 years from SN1987A and the future

Feb. 25th, 1987: A fax was sent to Univ. of Tokyo


TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 6-7 DAYS AGO IN LARGE MAGELLANIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4MS, WILL REACH MAXIMUM MAGNITUDE (-1MS) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

SID BLUMAN
(215) 546-3083

Day 3

Totsuka asked Kamioka shift to send recent data tapes.





NHK

Day 4 *Feb. 27th(Fri): The data tapes arrived at Univ. of Tokyo and Nakahata analyzed the data.*

Day 5 *Feb. 28th(Sat): Hirata and Nakahata found the neutrino signals and made plots with Totsuka and Oyama.*

Day 6 *Mar. 1st(Sun): Totsuka tried to report this discovery to Koshiba but it was not possible because Koshiba was at the Hakone hot spring….*
Totsuka went to Kamioka for a work.

Day 7 *Mar. 2nd(Mon): Nakahata reported the discovery to Koshiba. Koshiba said "You must analyze all Kamiokande data and demonstrate that this is the only signal."*

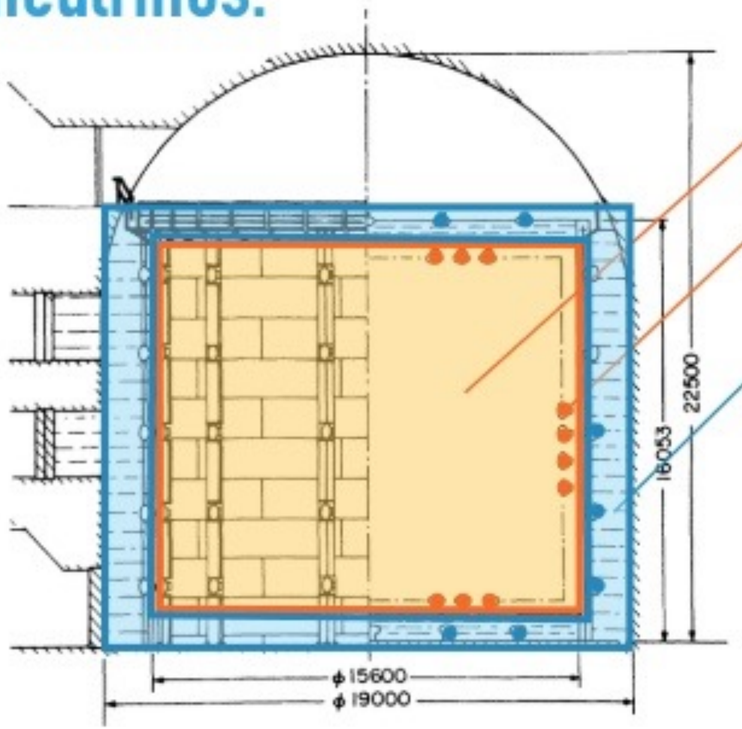
Mar. 2nd – 6th : Data analysis day after day without (enough) sleep



Day 12 *Mar. 7th(Sat): The paper was sent to Physical Review Letters by a postal mail.*

Upgraded Kamiokande II aimed to detect solar neutrinos.

FIG. 1. Schematic view of the Kamiokande II detector. The inner detector contains 3000 tons of water of which 2140 tons are fiducial volume. It is viewed by 948 20-in.-diameter PMT's mounted on a 1-m grid on the inner surface. The outer (veto) counter surrounds the inner detector and is viewed by 123 PMT's. Dimensions in the figure are in millimeters.



Schematic outline of the Kamiokande II detector

fiducial volume
2140-ton water

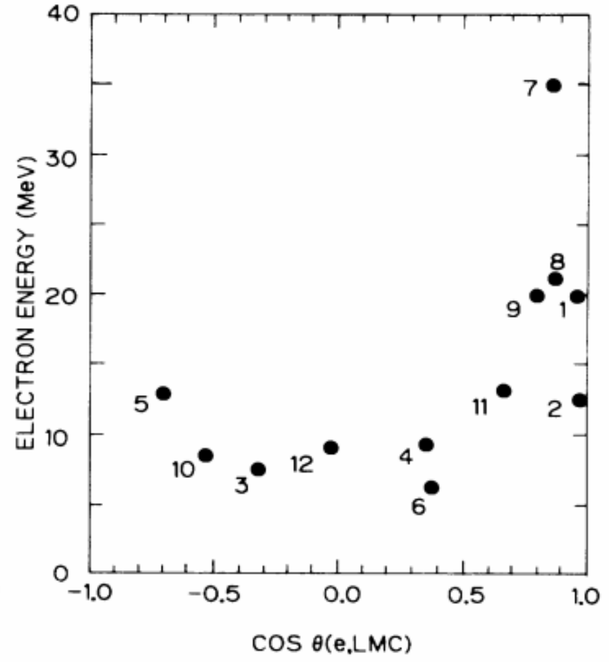
photomultiplier tube (PMT)
~20% of total surface of the fiducial volume

anticounter
- shielding against gamma rays and neutrons
- muon "veto"

- Real-time detection
- Directional sensitive
- Energy threshold of 8.8 MeV

<http://dx.doi.org/10.1103/PhysRevD.38.448>

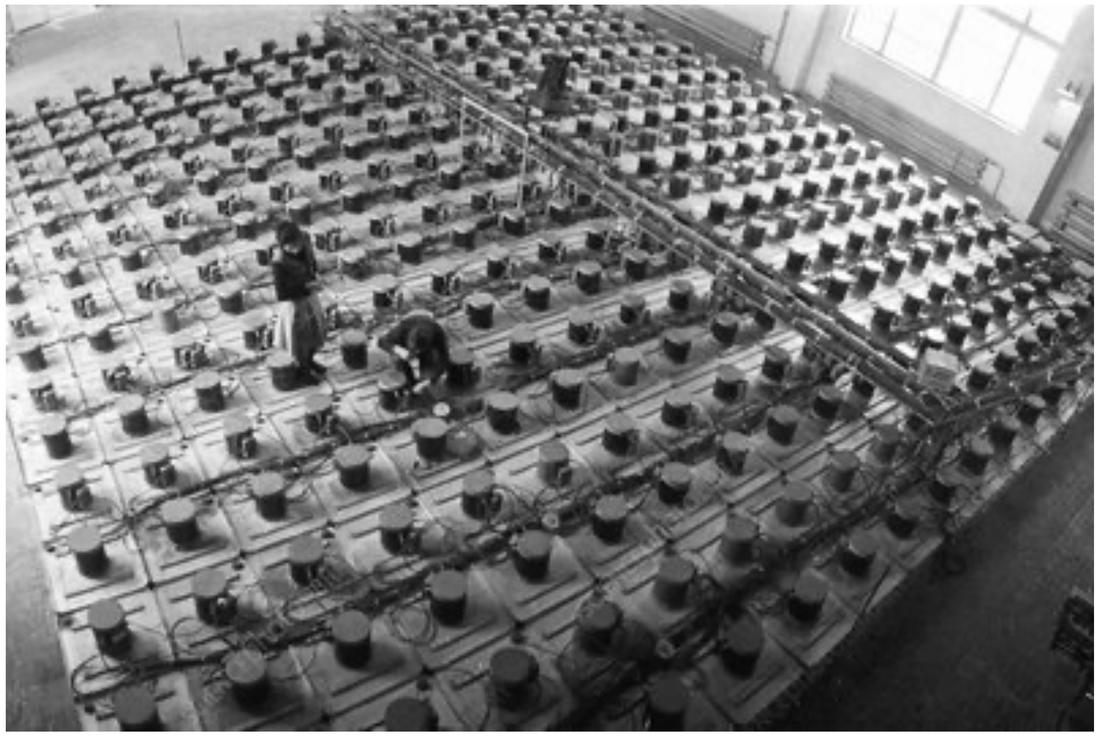
$$\nu_e + e^- \rightarrow \nu_e + e^-$$
$$\bar{\nu}_e + p^+ \rightarrow e^+ + n$$



IMB and Baksan detector

+LSD+ASD

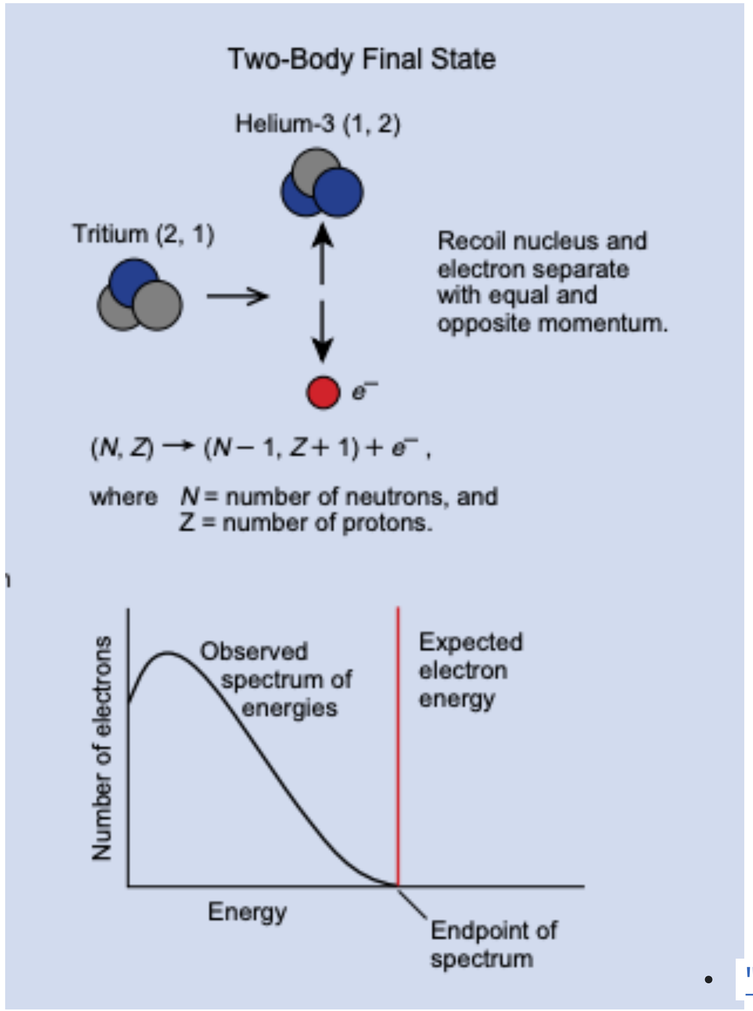




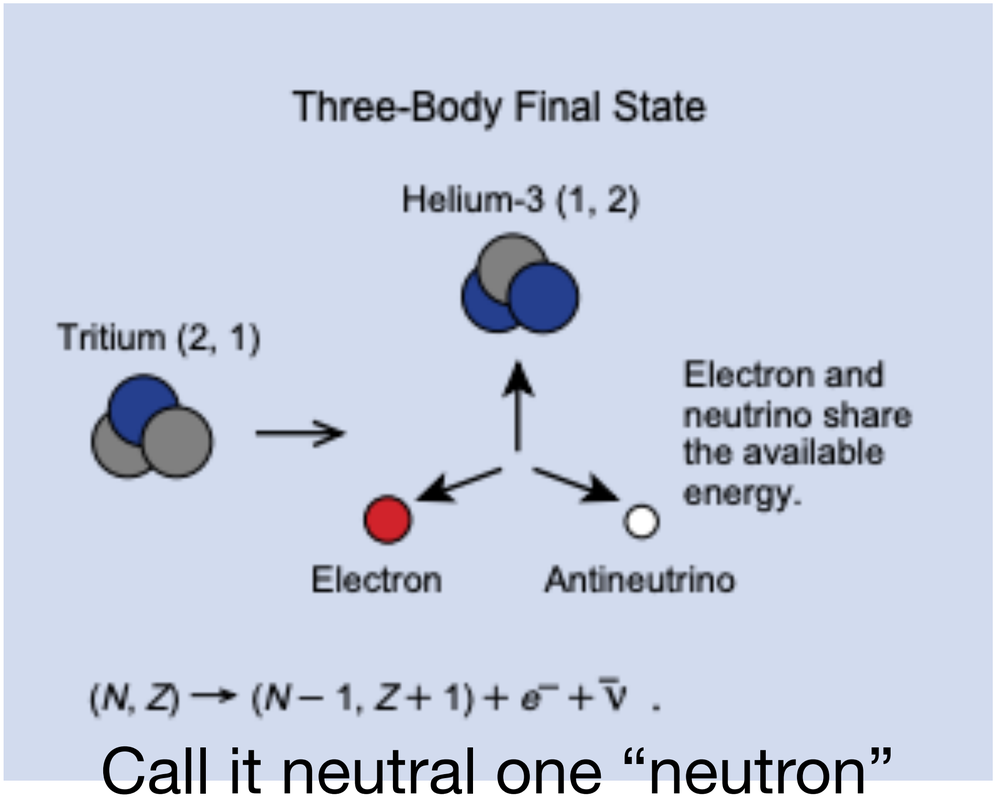
How lucky it was for these experiments! Story from Christian Spiering's "Neutrinoastronomie"

베타붕괴와 잃어버린 에너지

Energy Conservation at Risk



Pauli's solution (1930)



Call it neutral one "neutron"

- "The Reines-Cowan Experiments: Detecting the Poltergeist" (PDF). *Los Alamos Science*. **25**: 3. 1997.

절망적인 에너지 보존 법칙

W. Pauli

[This is a translation of a machine-typed copy of a letter that Wolfgang Pauli sent to a group of physicists meeting in Tübingen in December 1930. Pauli asked a colleague to take the letter to the meeting, and the bearer was to provide more information as needed.]

90년전 독일 튜빙겐

Copy/Dec. 15, 1956 PM

Open letter to the group of radioactive people at the Gauverein meeting in Tübingen.

Copy

Physics Institute of
the ETH Zürich

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen, 안녕하세요 방사능력자 여러분

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than $e \cdot (10^{-13}\text{cm})$.

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

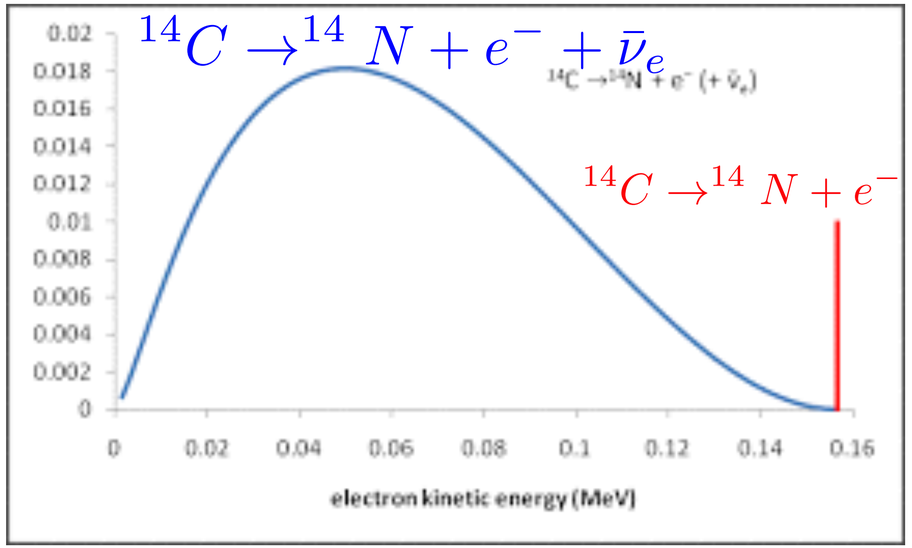
I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

[Translation: Kurt Riesselmann]

측정된 연속적인 베타 스펙트럼을 설명하고 에너지 보존 법칙을 구할 방법이 생각났습니다.

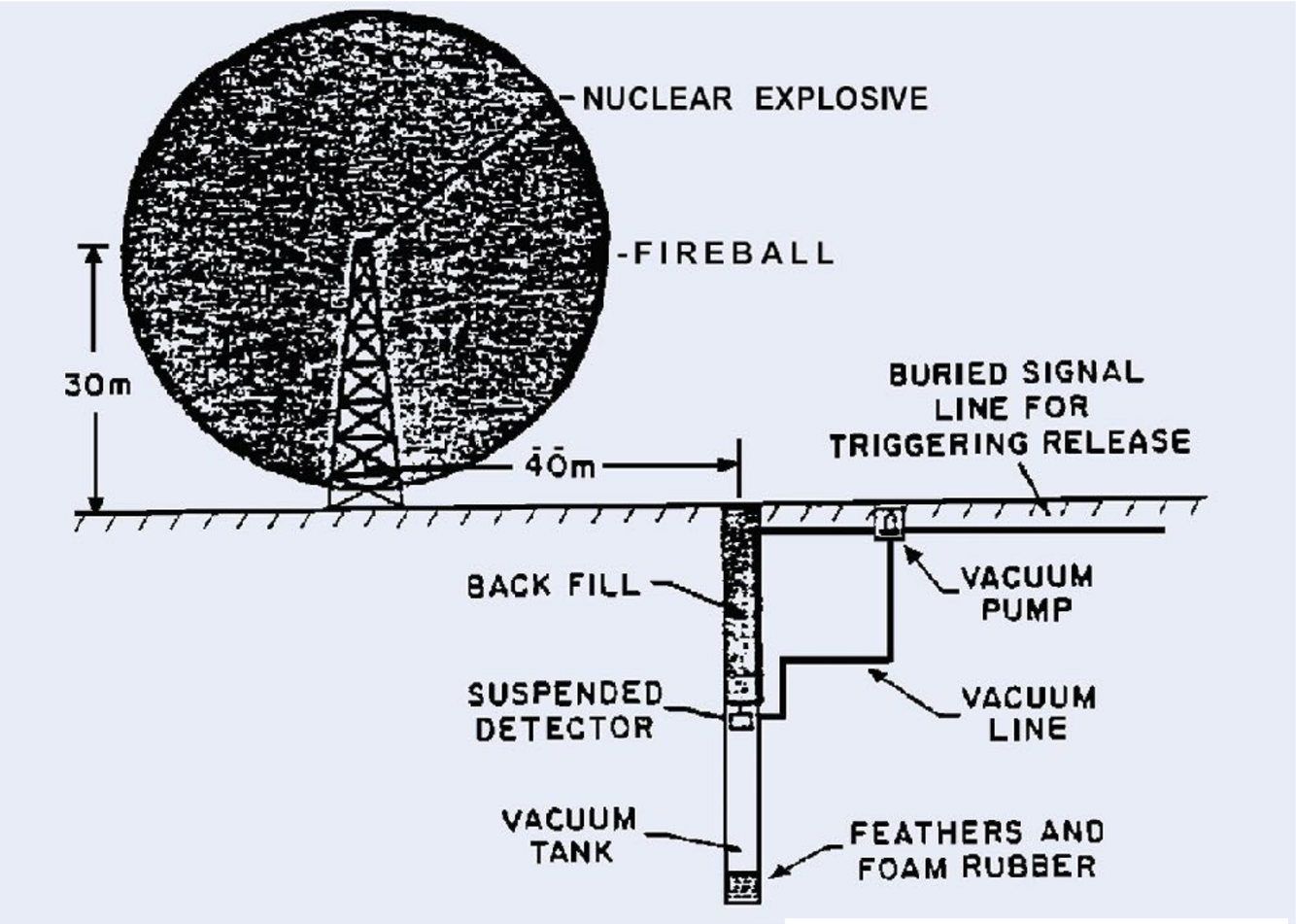
베타붕괴에 "중성자(후에 중성미자로 밝혀짐)"를 추가하면 에너지의 합을 상수로 만들수 있습니다.



취리히에 춤추러 가야해서 모임에 참석하지 못합니다.

Go Big or Go Home!

Here comes Fred Reines



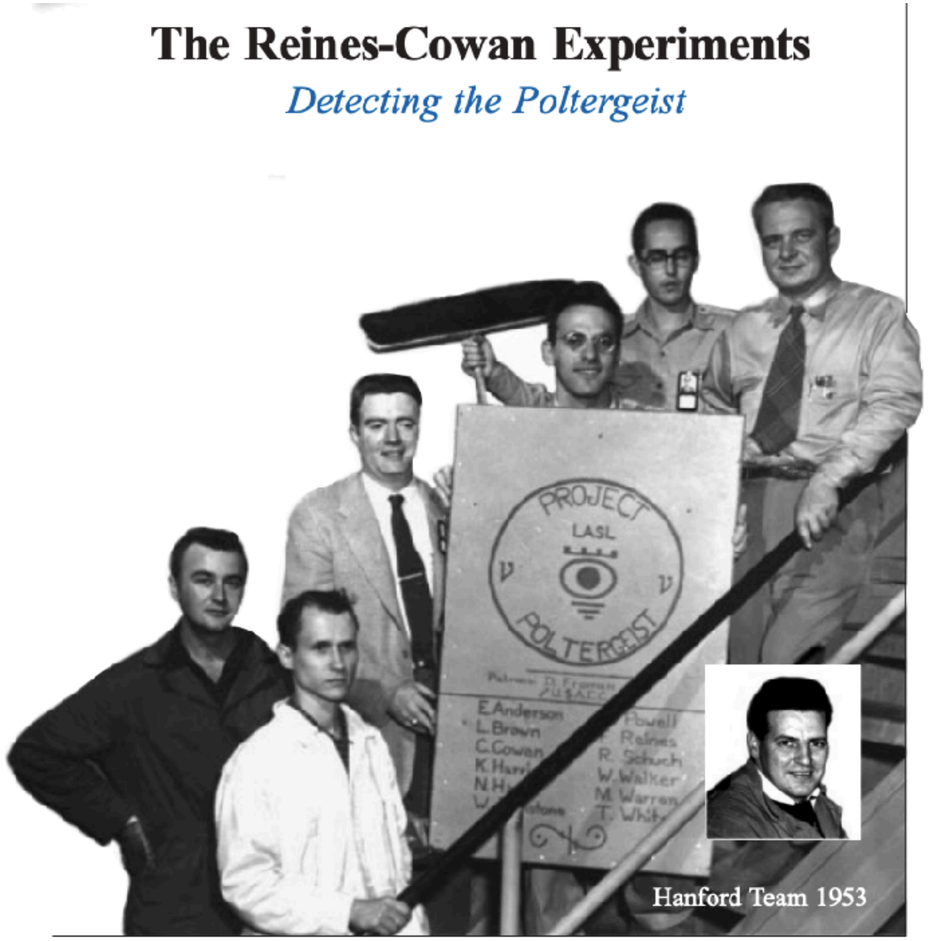
- *Los Alamos Science*. **25**: 3. 1997.



A guy from New Jersey with “CAN-DO” spirit

잃어버린 에너지를 찾아서…

Project Poltergeist



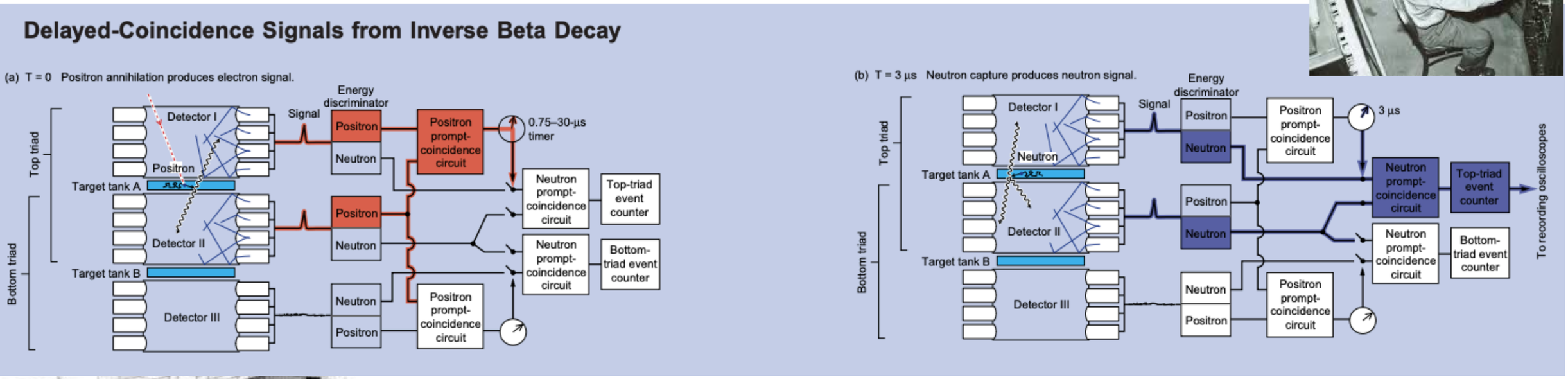


Los Alamos Science. **25**: 3. 1997.

프로젝트 폴터가이스트

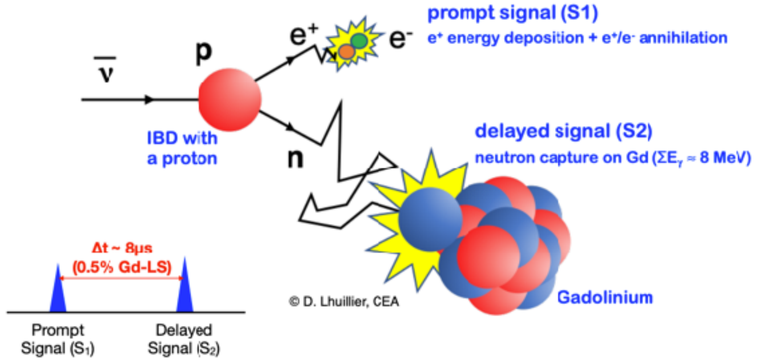
Delayed Coincidence Signal with Cadmium-loaded liquid







- *Los Alamos Science*. **25**: 3. 1997.



$$\nu_e + p \rightarrow e^+ + n$$

$$e^+ + e^- \rightarrow \gamma(0.5MeV) + \gamma(0.5MeV)$$

$$n + Gd \rightarrow Gd^*$$

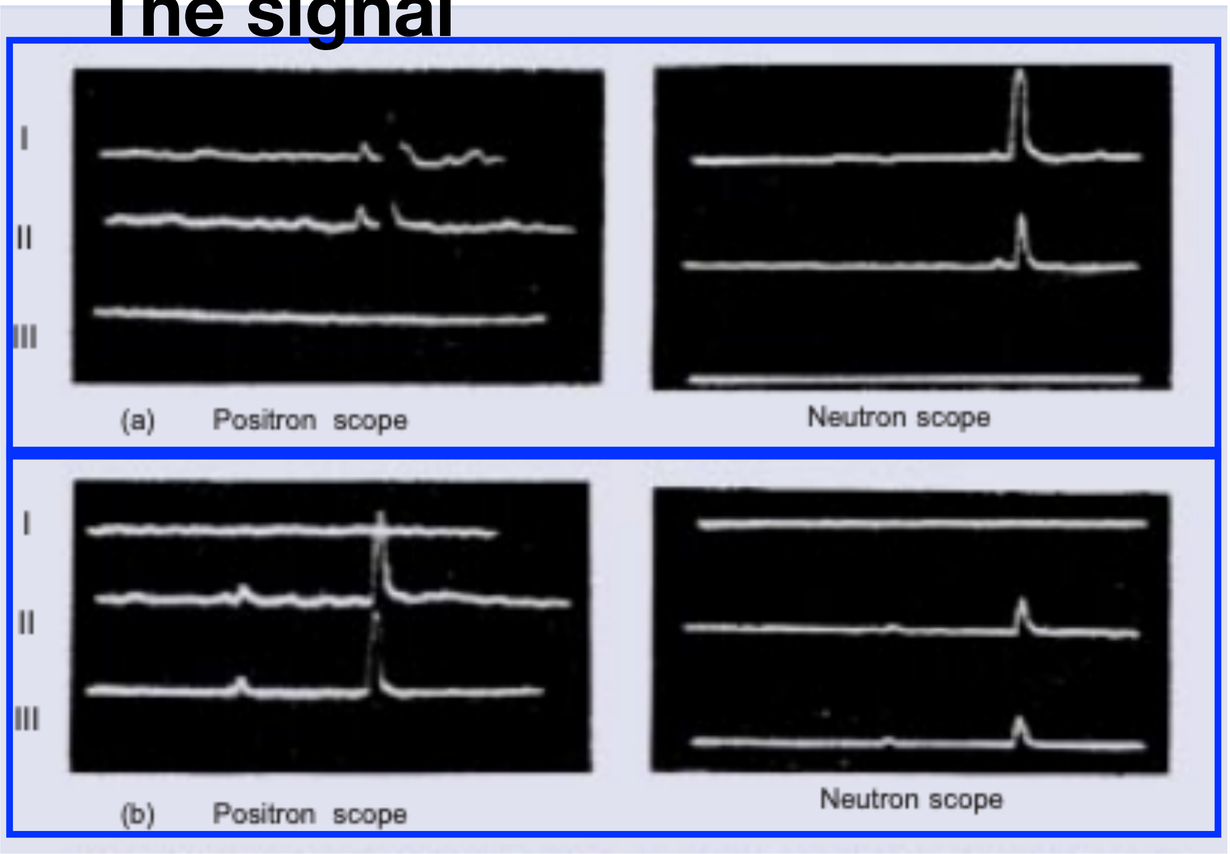
$$Gd^* \rightarrow Gd + \gamma(8\ MeV)$$

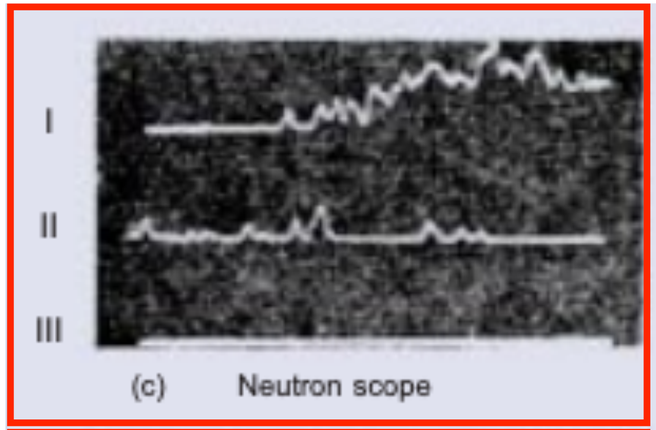
잃어버린 에너지를 찾아서…

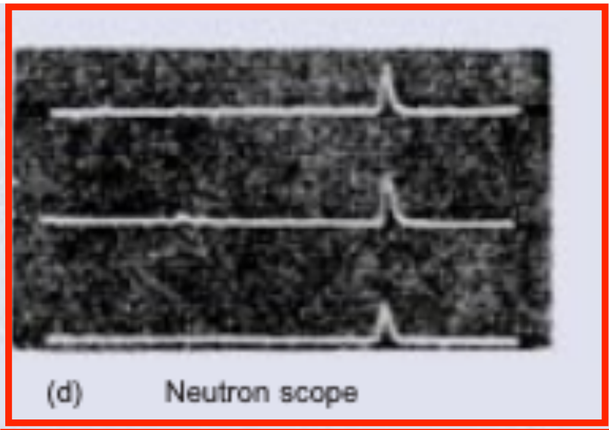
The signal

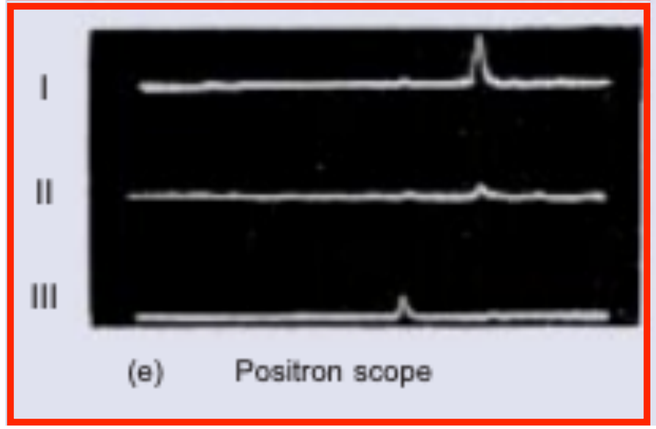
Detection of the Free Antineutrino

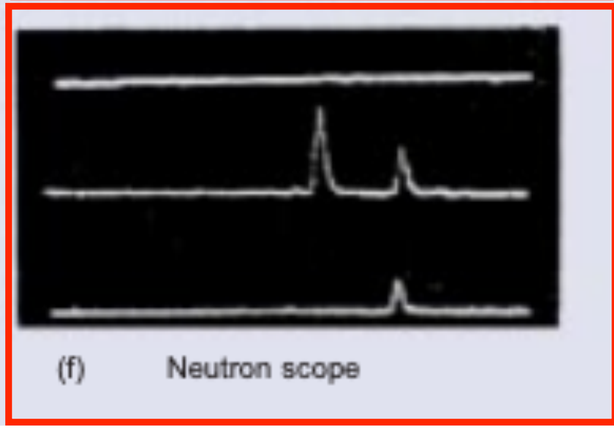
F. Reines, C. L. Cowan, Jr., F. B. Harrison, A. D. McGuire, and H. W. Kruse
Phys. Rev. **117**, 159 – Published 1 January 1960







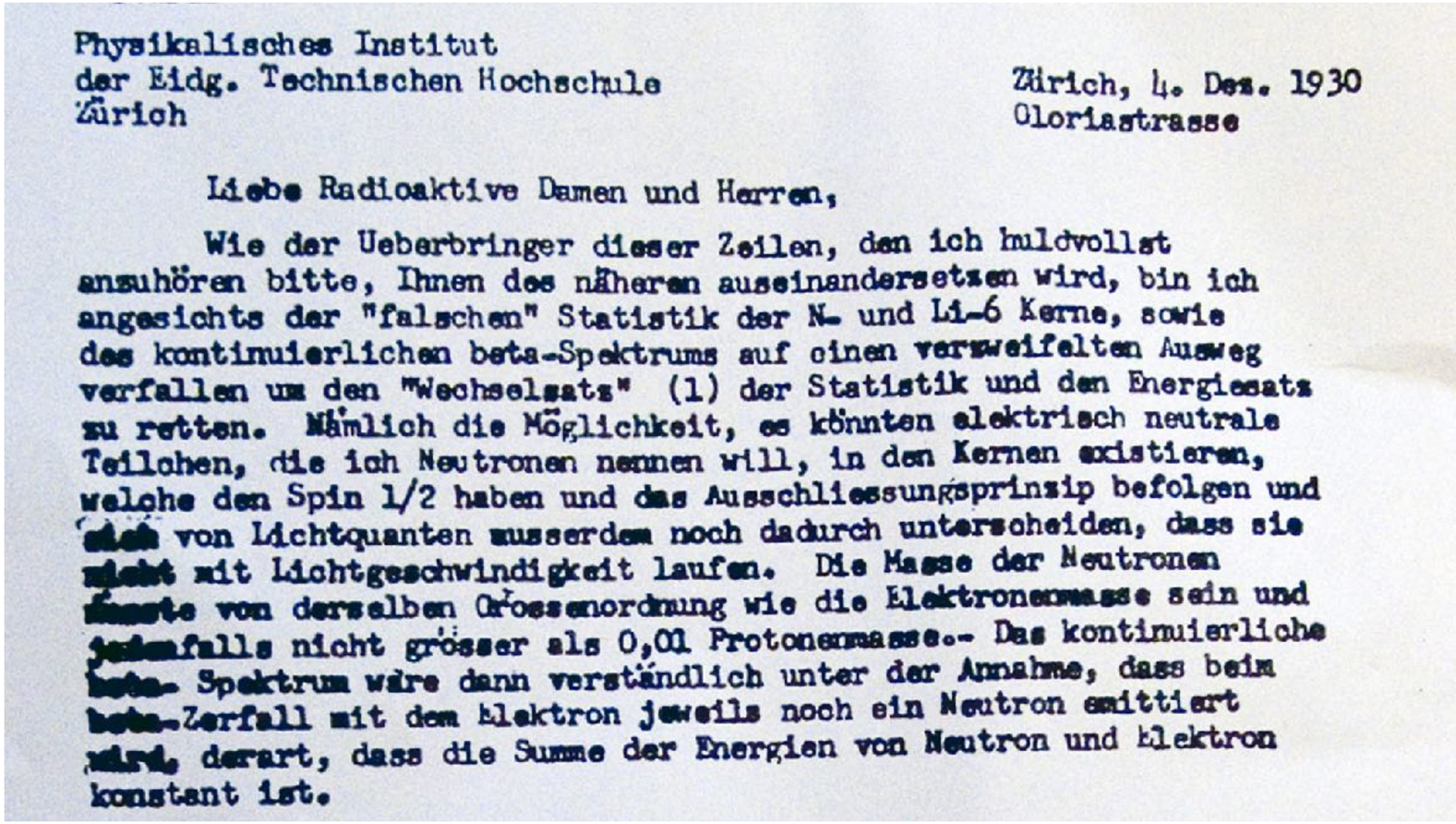




1956/6/14 To Pauli, “We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross sections agrees well …”

중성미자 역사
기발한 아이디어와 기다림

- 1930, 절망적인 치료법



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

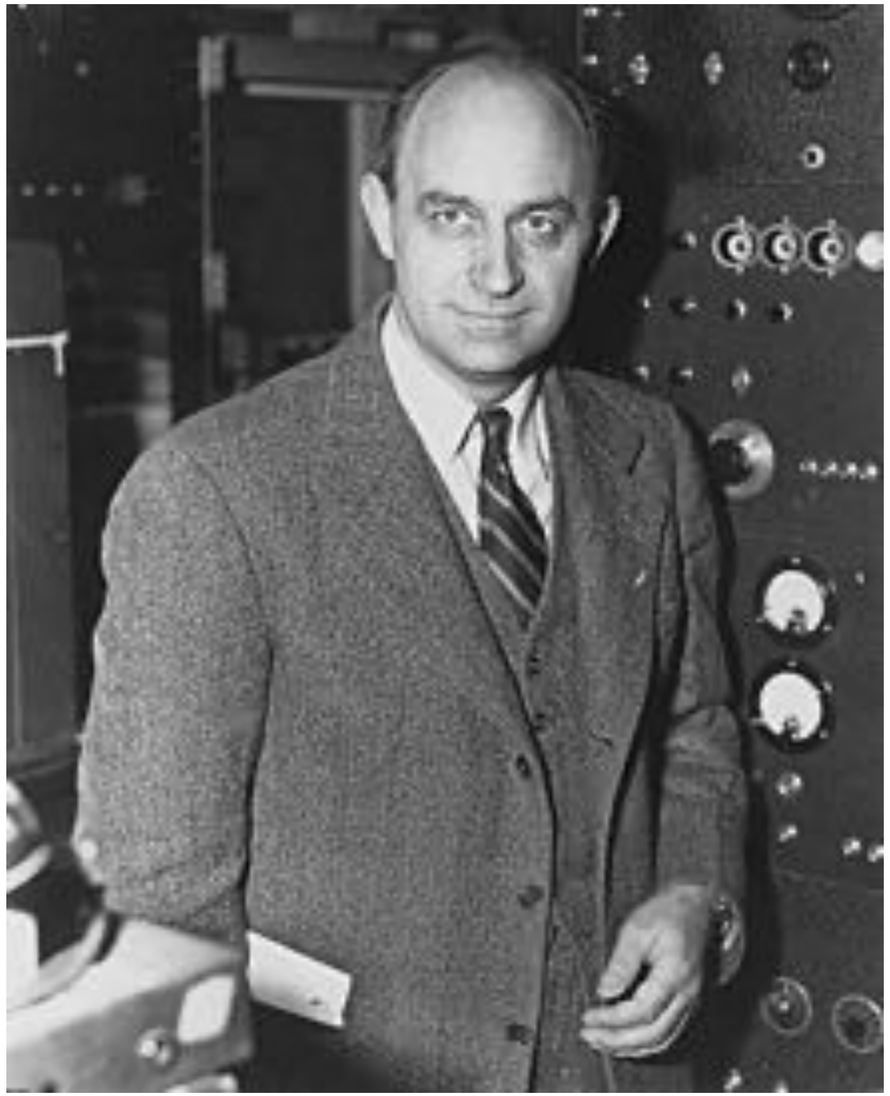
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

중성미자 역사

기발한 아이디어와 기다림

- 1930, 절망적인 치료법
- 1934, 중성미자 (엔리코 페르미)

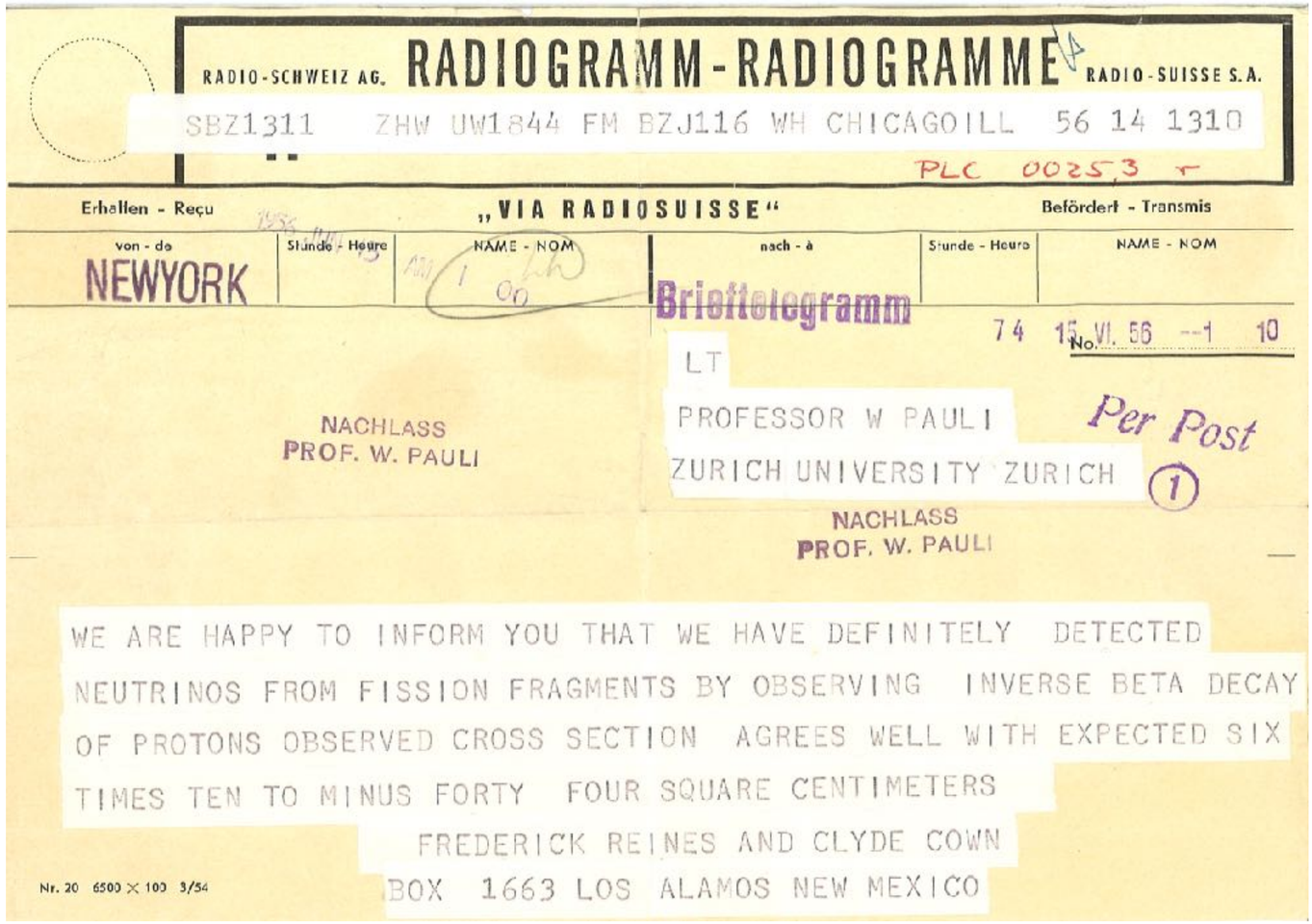


중성미자 역사
기발한 아이디어와 기다림

- 1930, 절망적인 치료법
- 1934, 중성미자 (엔리코 페르미)
- 1956, 첫 발견 (라이너스-코웬 실험)



1995 년 노벨상



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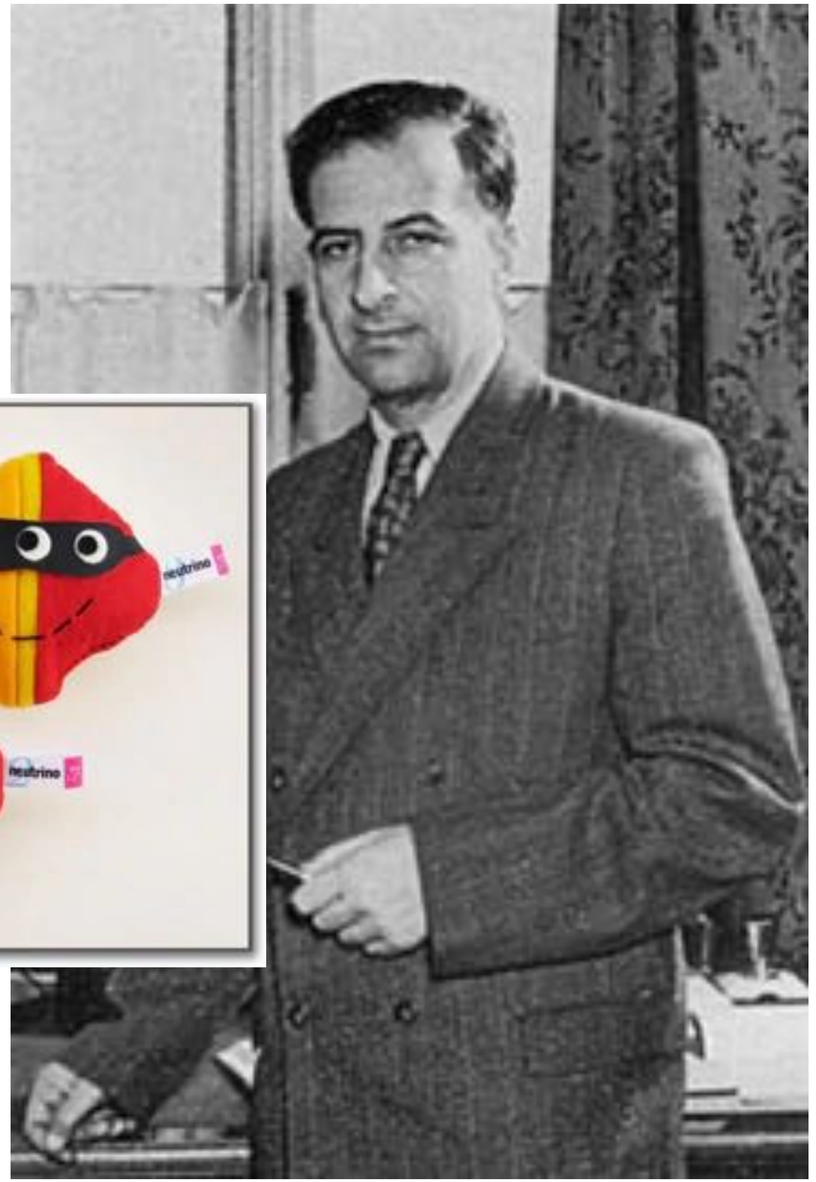
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Nr. 20 6500 × 100 3/54

중성미자 역사
기발한 아이디어와 기다림

- 1930, 절망적인 치료법
- 1934, 중성미자 (엔리코 페르미)
- 1956, 첫 발견 (라이너스-코완 실험)
- 1957, 중성미자 진동 이론 (폰테코보)

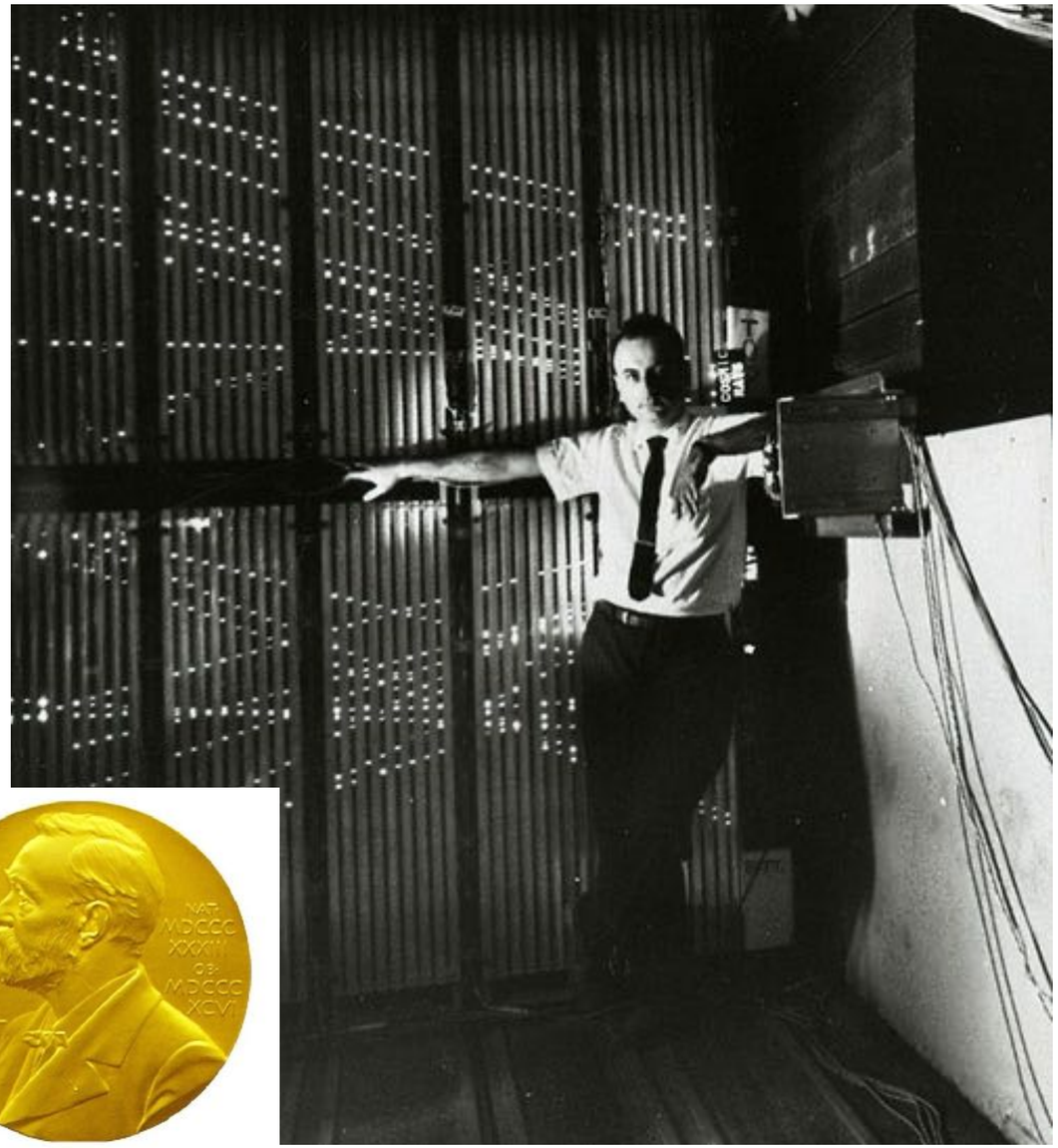




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- 1957, 중성미자 진동 이론 (폰테코보)
- 1962, 가속기 뮤온 중성미자 (러더만, 슈워츠, 스타인버거)



1988 년 노벨상

중성미자 역사

기발한 아이디어와 기다림

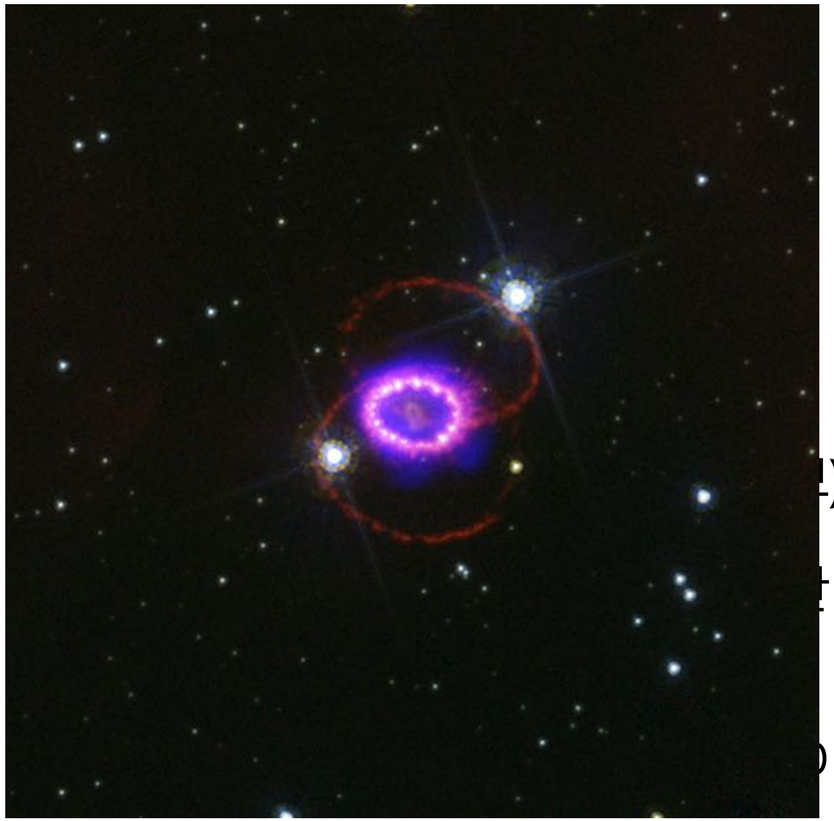
- 1930, 절망적인
- 1934, 중성미자 (
- 1956, 첫 발견 (
- 1957, 중성미자
- 1962, 가속기 뮤
  츠, 스타인버거)
- 1968, 태양 중성미자 검출 (레이 데이비스)



2002 년 노벨상

중성미자 역사

기발한 아이디어와 기다림

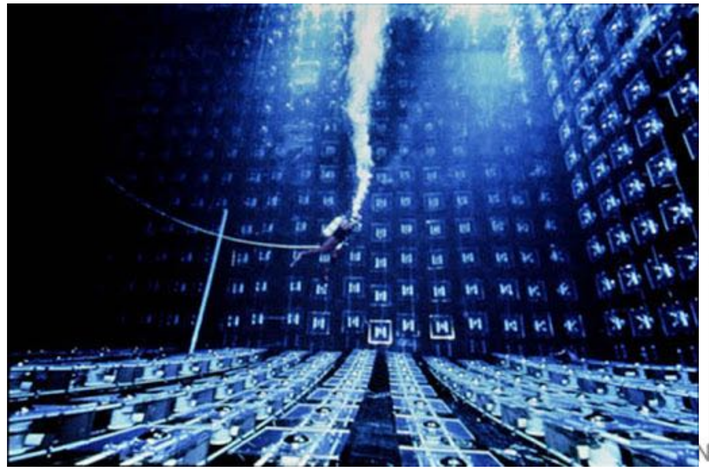


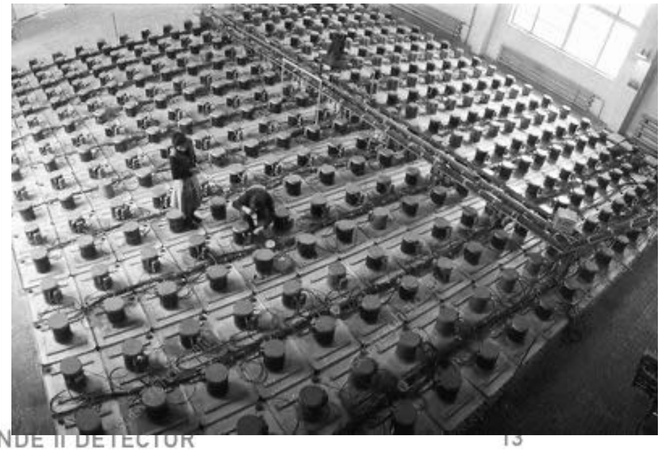
)

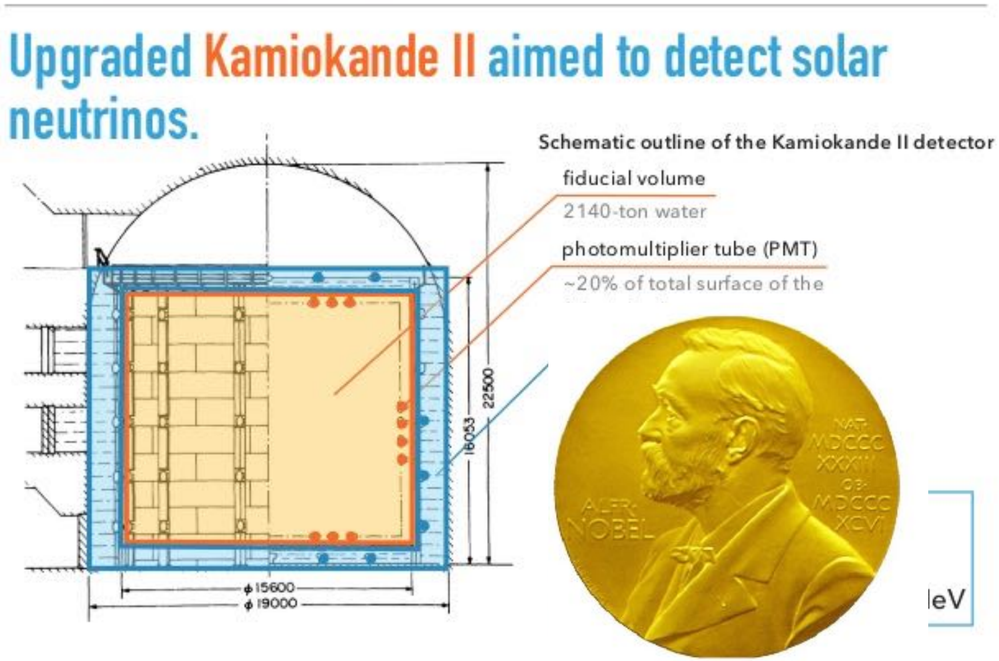
, 슈워츠, 스타인

이비스)

- 1987, 초신성 중성미자 검출 (카미오칸데, IMB, 박산)



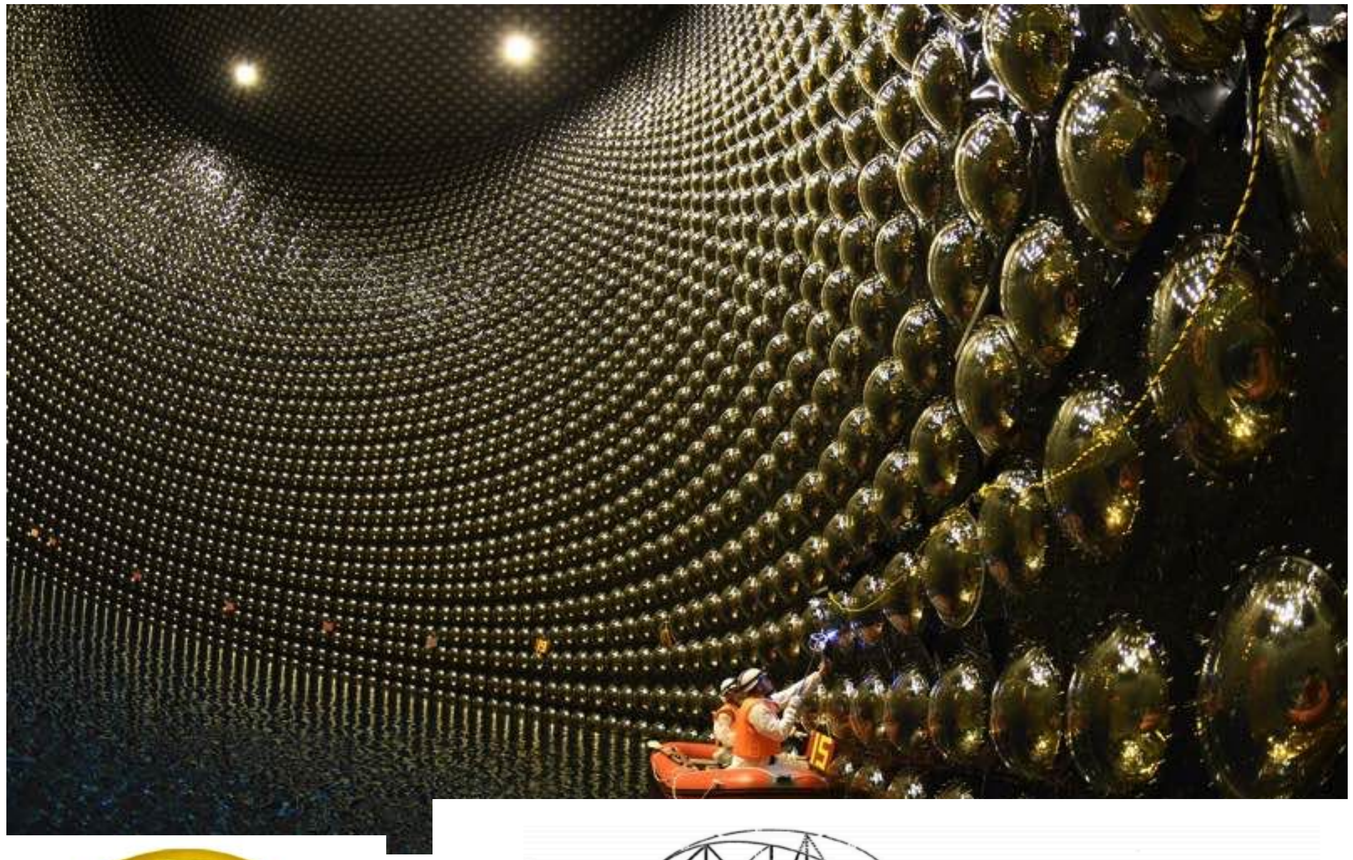




2002 년 노벨상

중성미자 역사

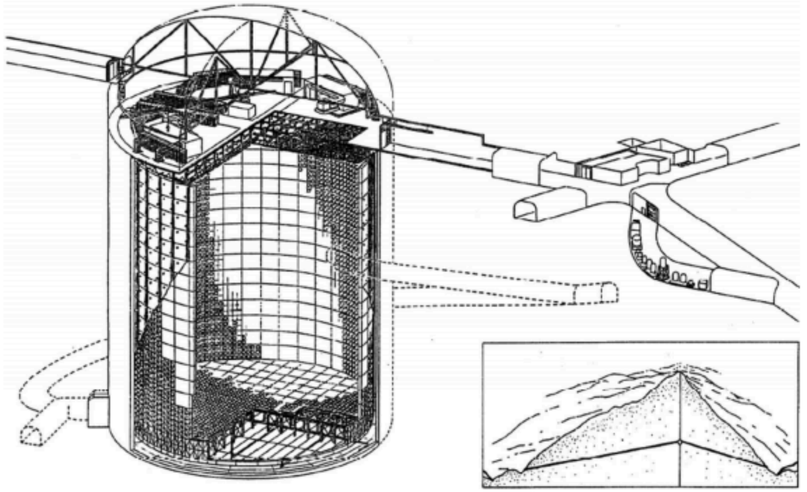
기발한 아이디어와 기다림



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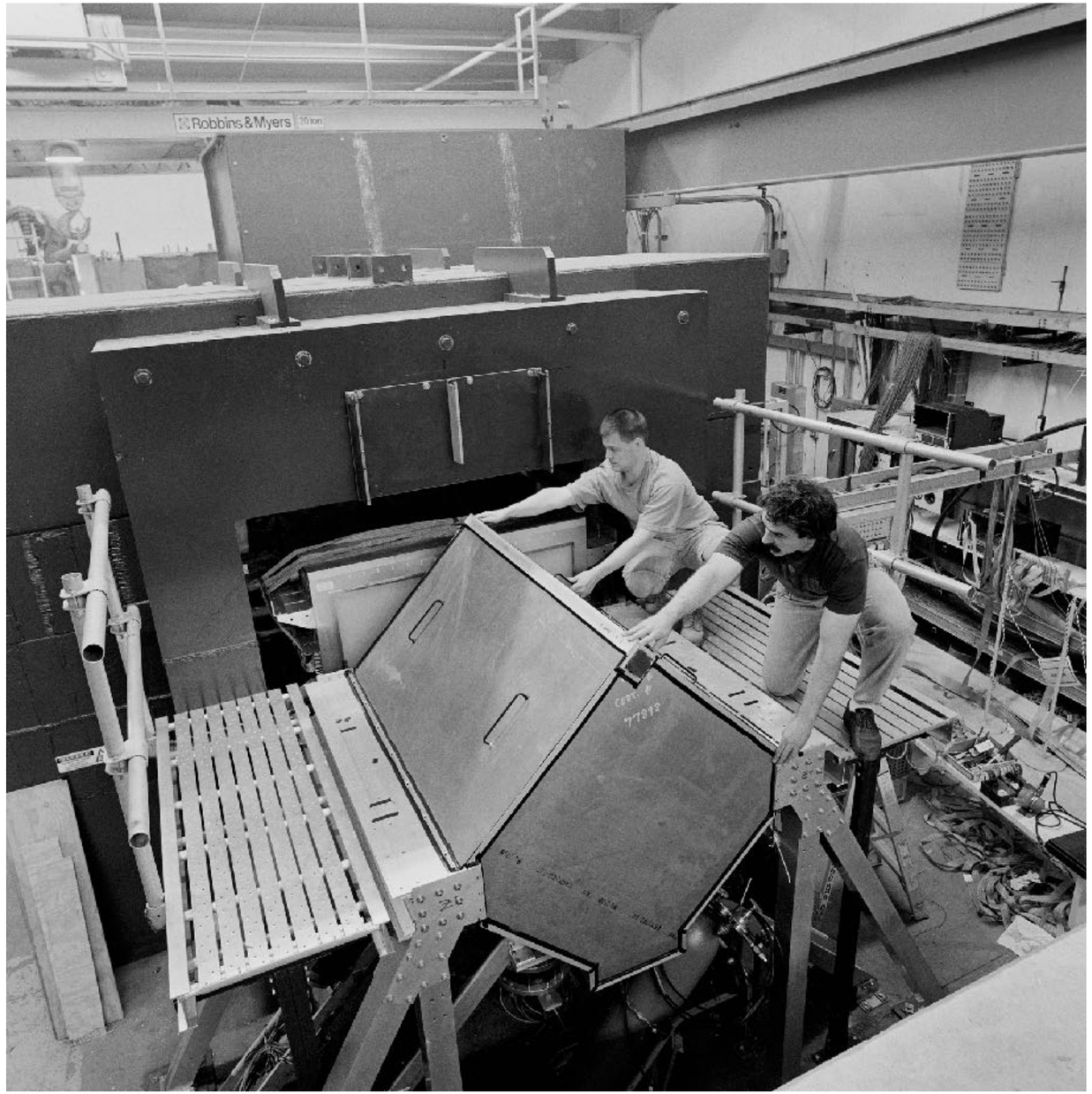


2015 년 노벨상



중성미자 역사
기발한 아이디어와 기다림

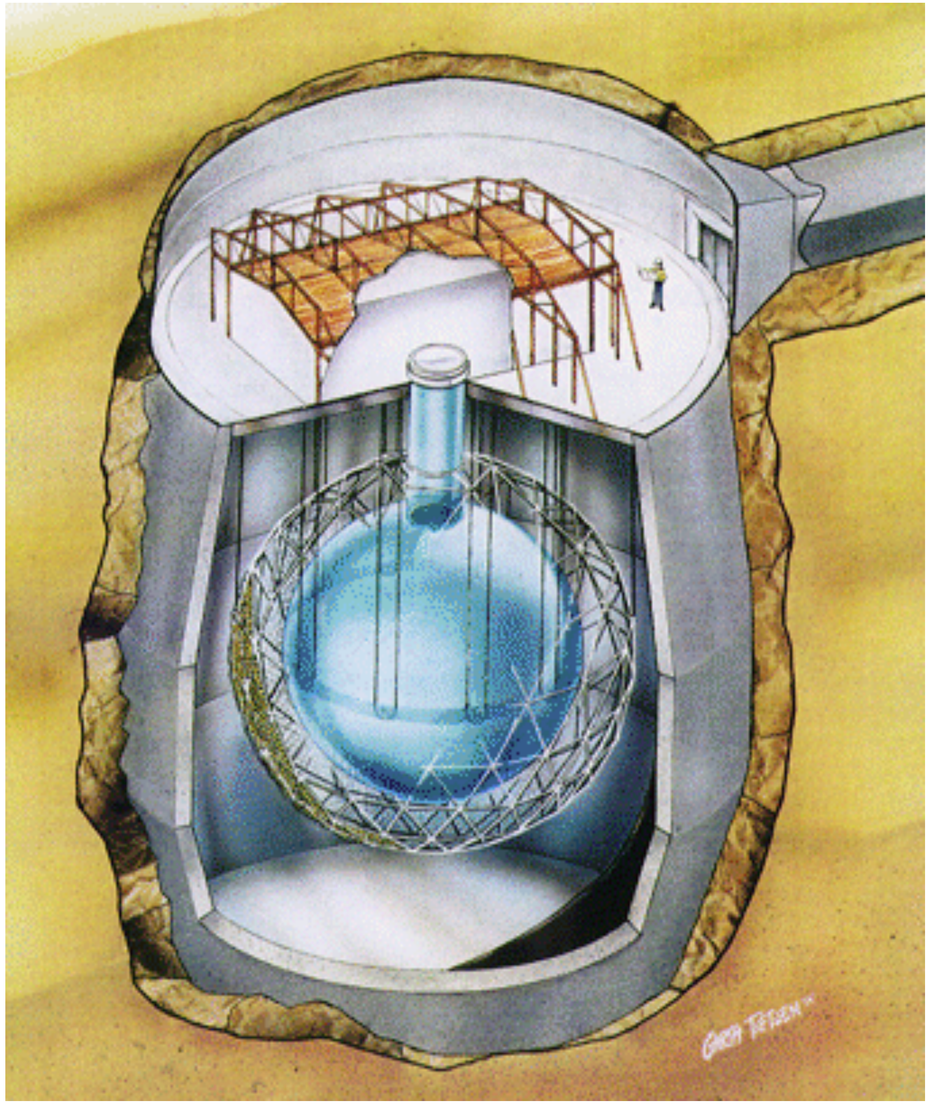
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중성미자 역사
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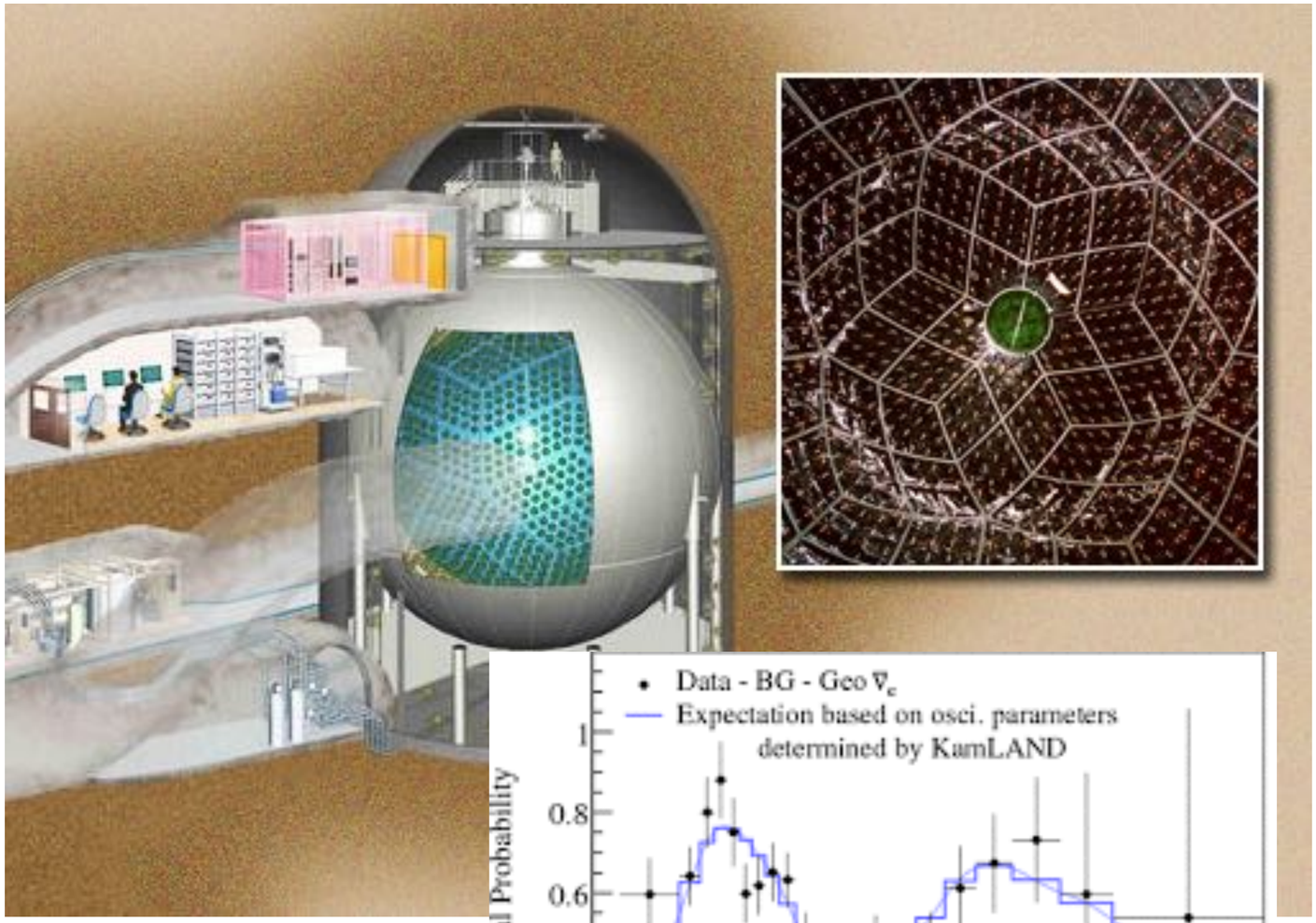


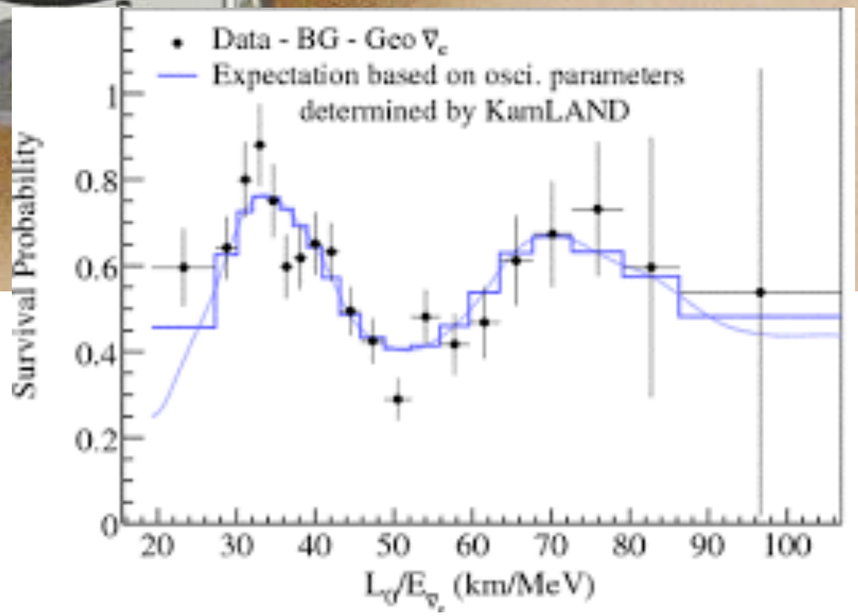


2015 년 노벨상

중성미자 역사
기발한 아이디어와 기다림

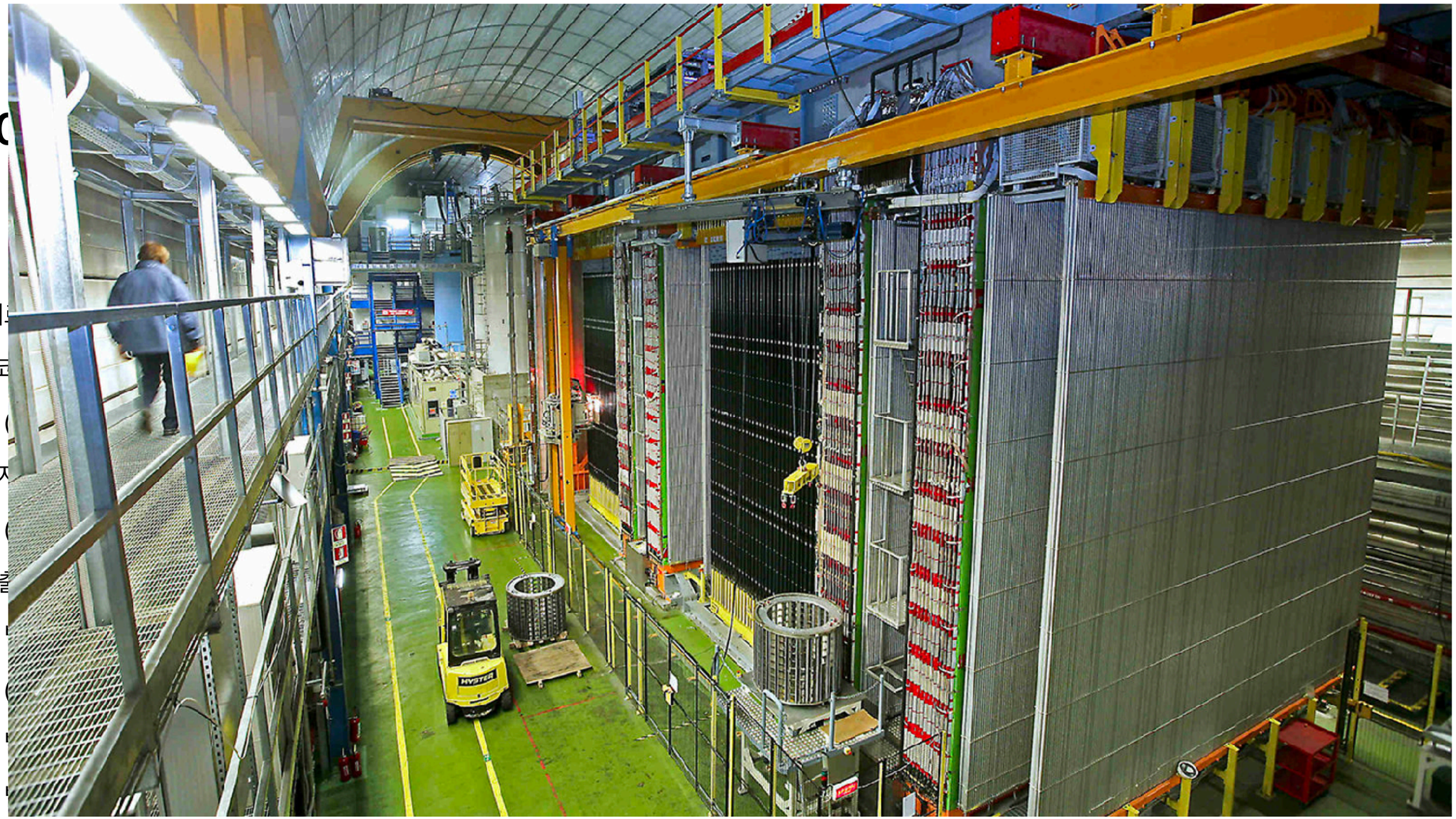
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- 2002, 태양 중성미자 진동 발견 (스노우)
- 2005, 지구 중성미자 발견, 핵발전소 중성미자 진동 발견 (캠랜드)





중성미자
기발한 아이디어

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- 2002, 태양 중성미자 진동 발
- 2005, 지구 중성미자 진동 발
- 2010, 뮤온—>타우 중성미자 진동 (오페라)



중성미자 역사

기발한 아이디어와 기다림



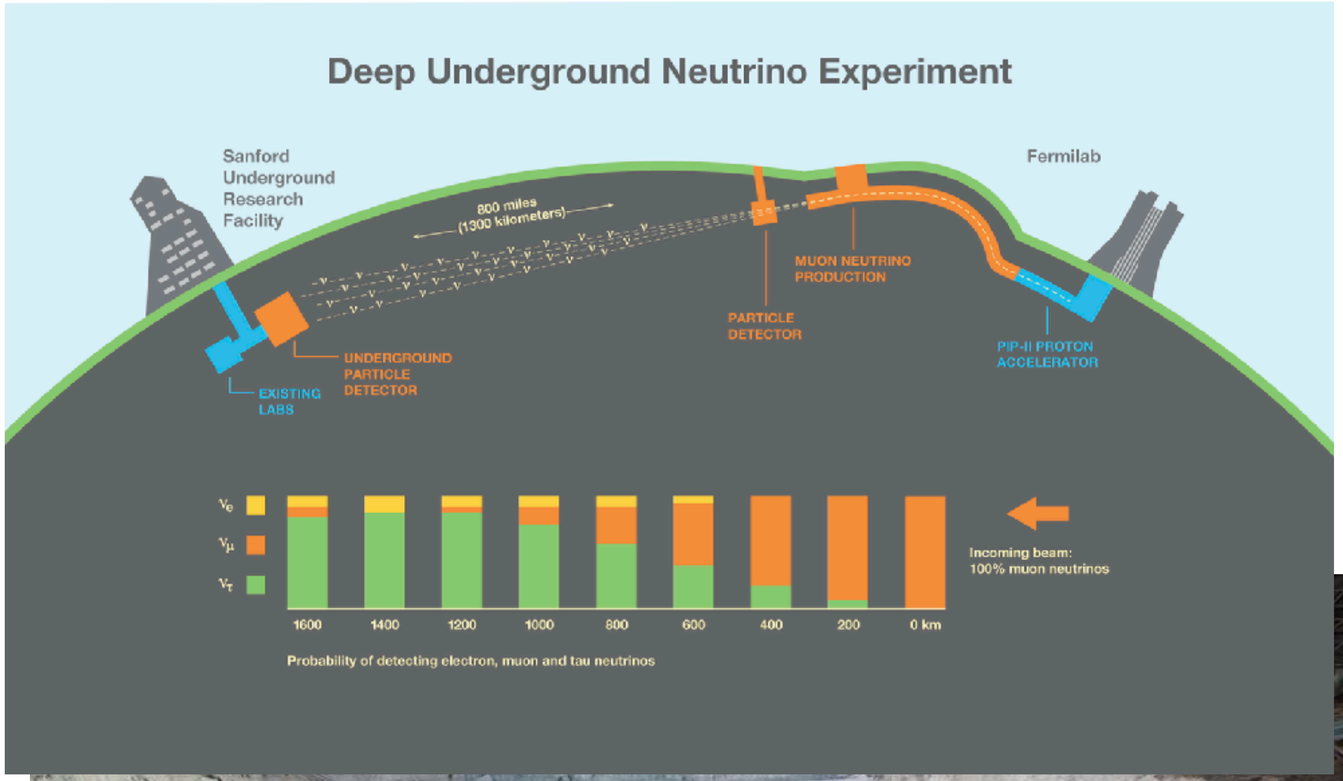
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- 2010, 뮤온—>타우 중성미자 진동 (오페라)
- 2012, 초 고에너지 중성미자 발경 (아이스 큐브)



중앙대학교 물리학과 하창현

중성미자 역사
기발한 아이디어와 기다림

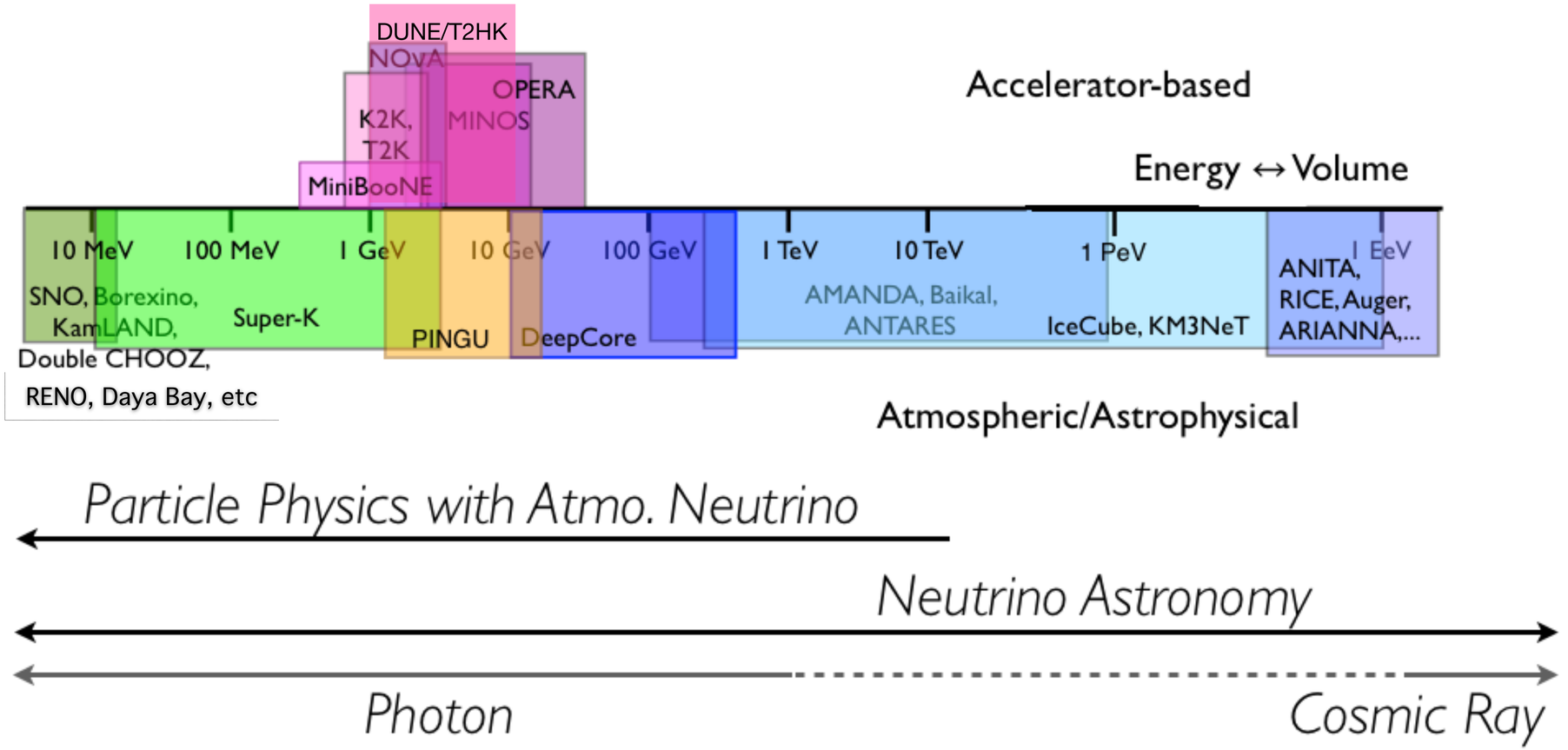
- 1930, 절망적인 치료법
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- 2005, 지구 중성미자 진동 발견 (캠랜드)
- 2010, 뮤온ㅡ>타우 중성미자 진동 (오페라)
- 2012, 초 고에너지 중성미자 발경 (아이스 큐브)
- 2017, DUNE 가속기 중성미자 실험 시작



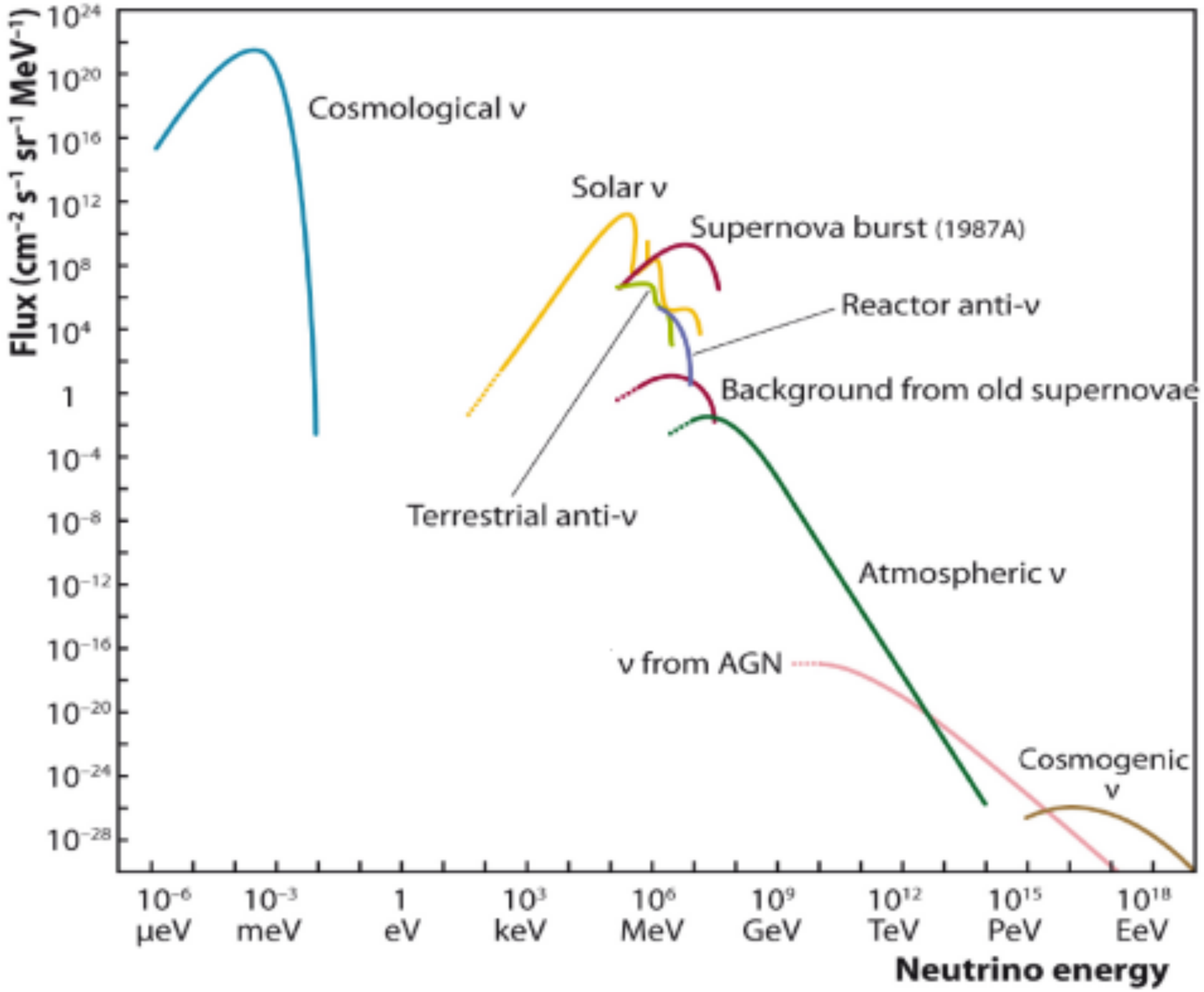


Source of Neutrinos

from the Sun & from reactors & from accelerators & from cosmic ray interactions in the atmosphere & from astrophysical sources

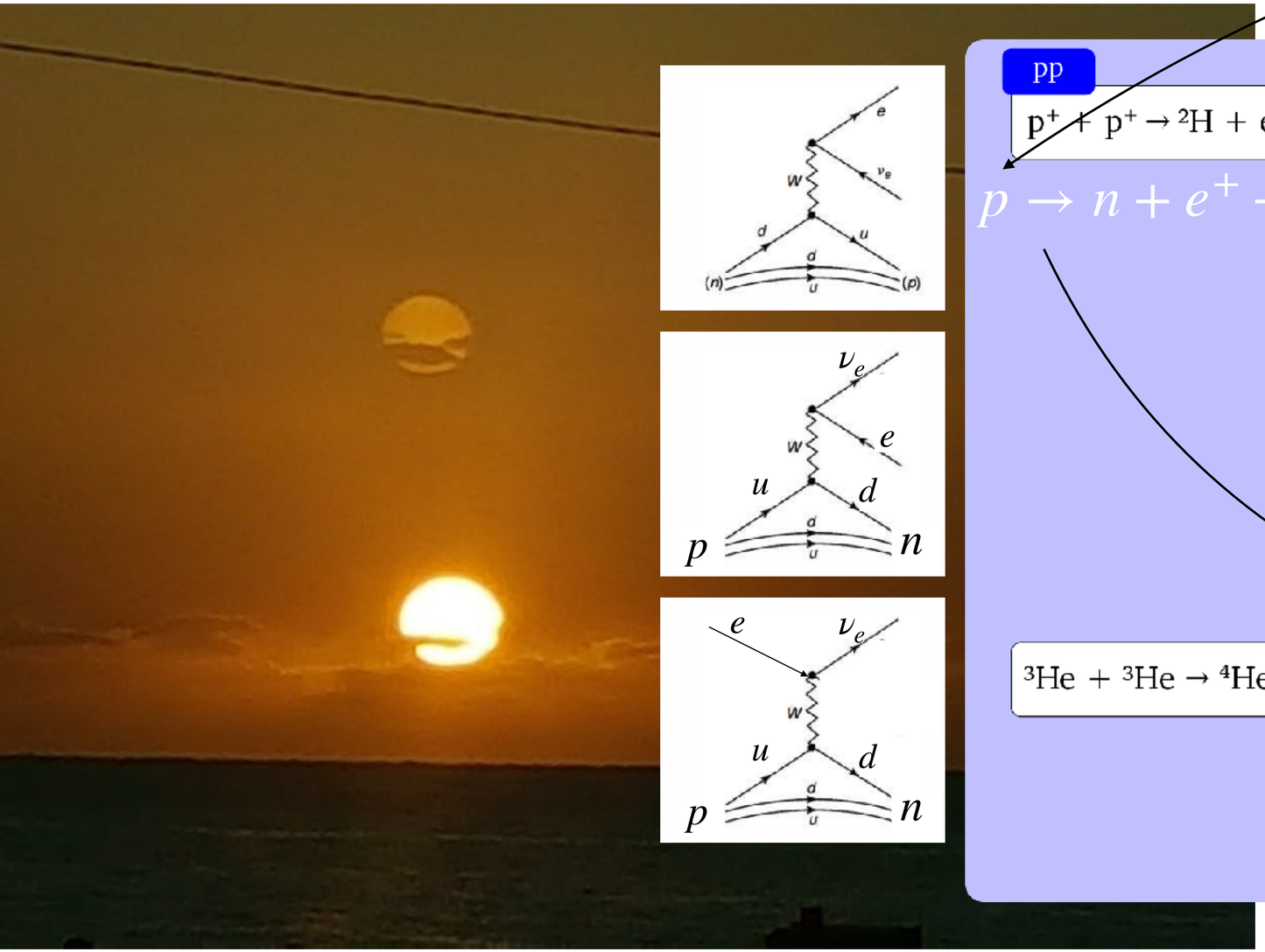


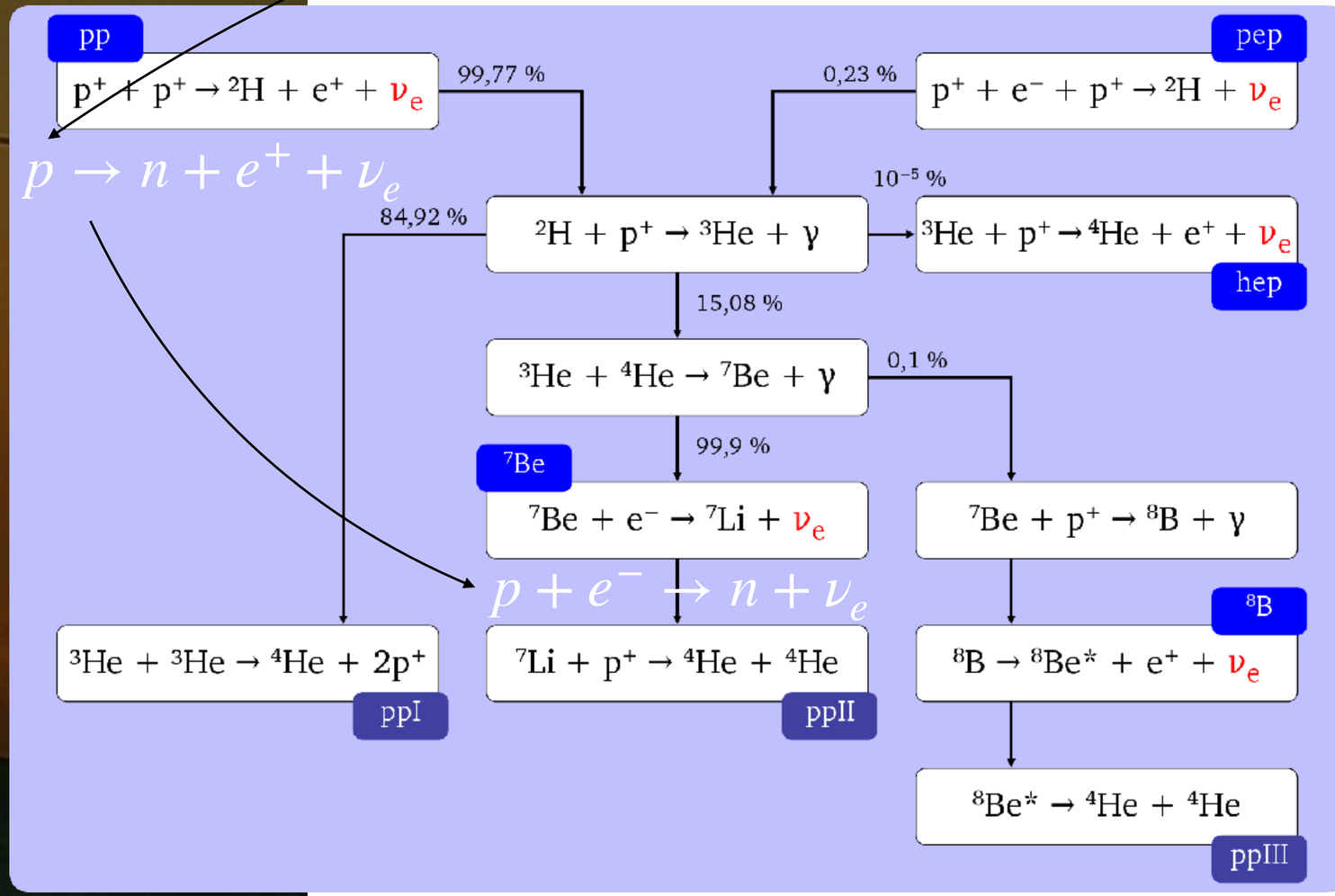
Flux of neutrinos from various sources

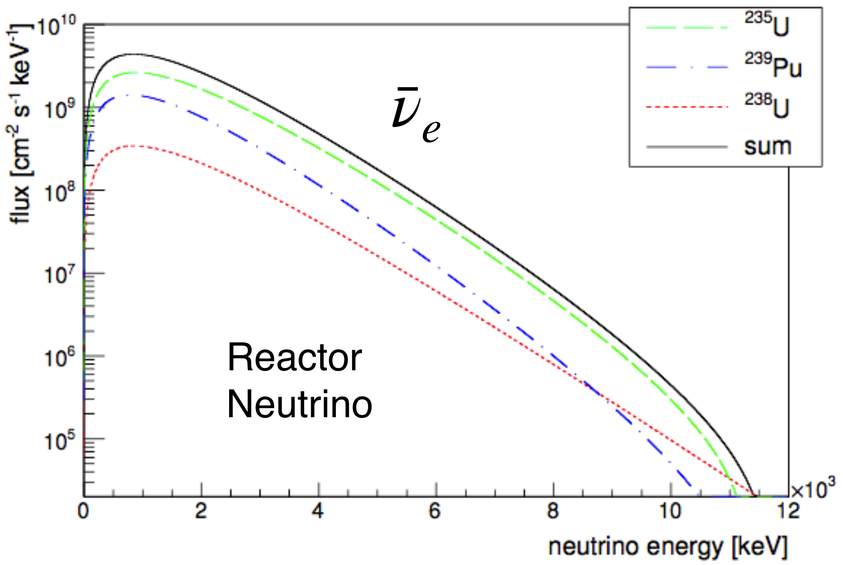


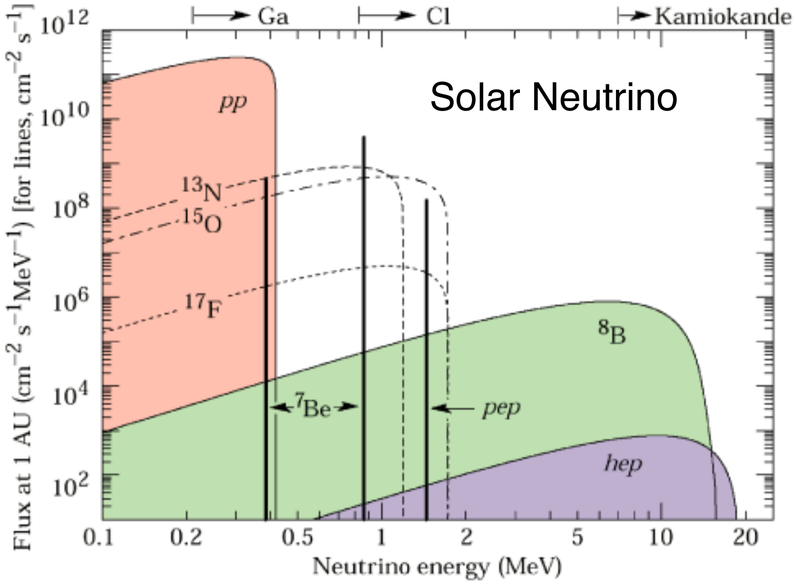
How does the Sun burn? (Beta decay Weak Interaction via W exchange)

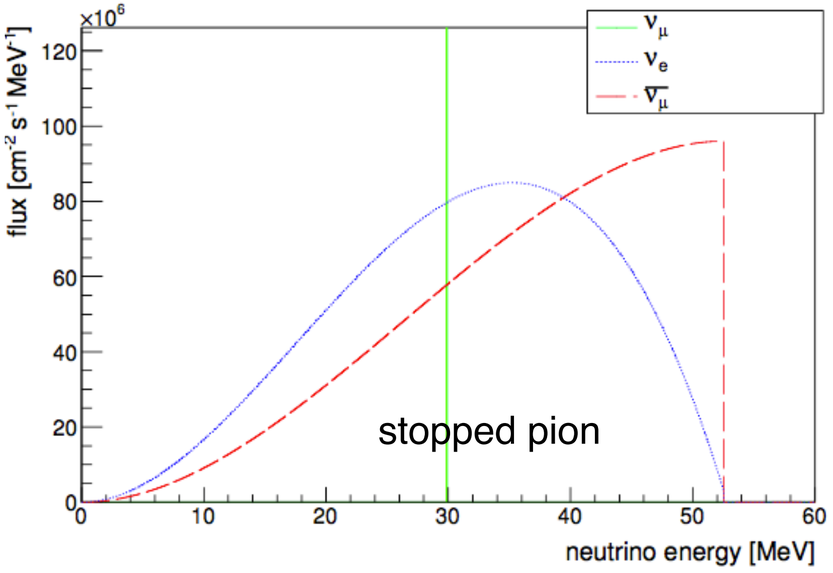
$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$d \rightarrow u + e^- + \bar{\nu}_e$$

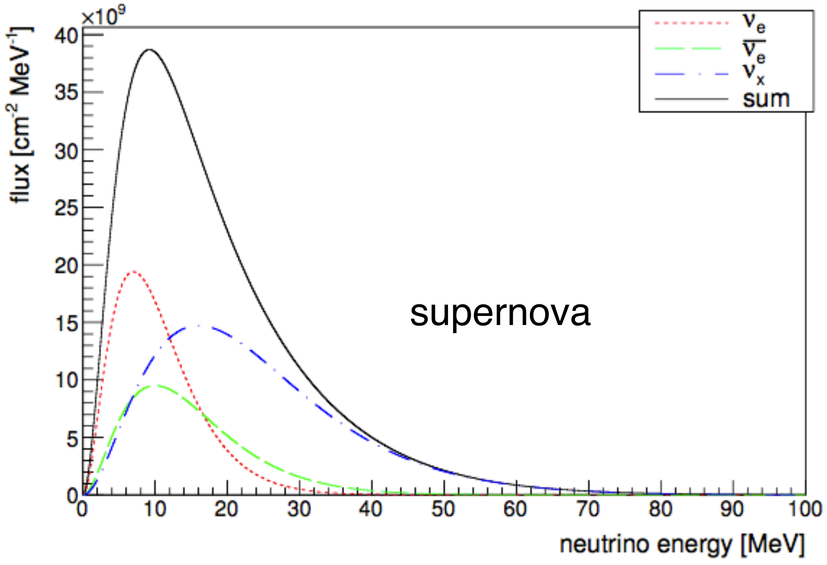


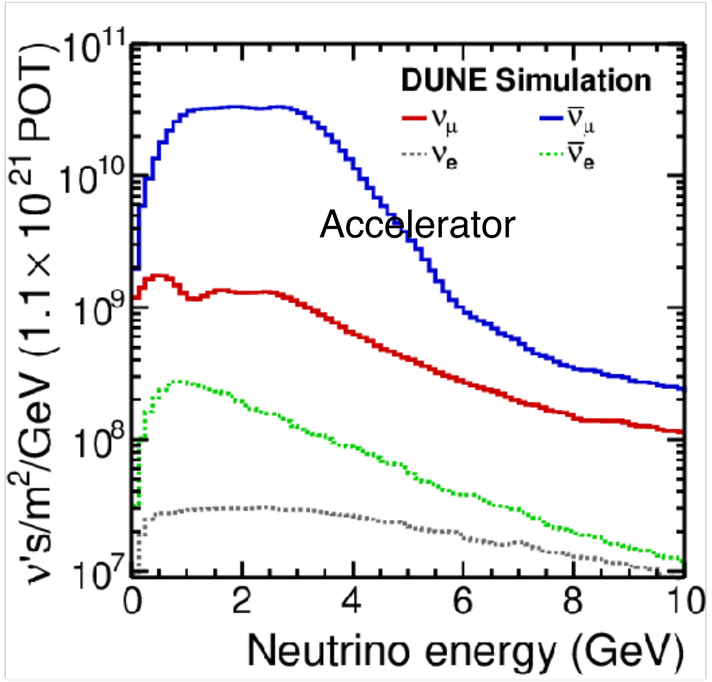


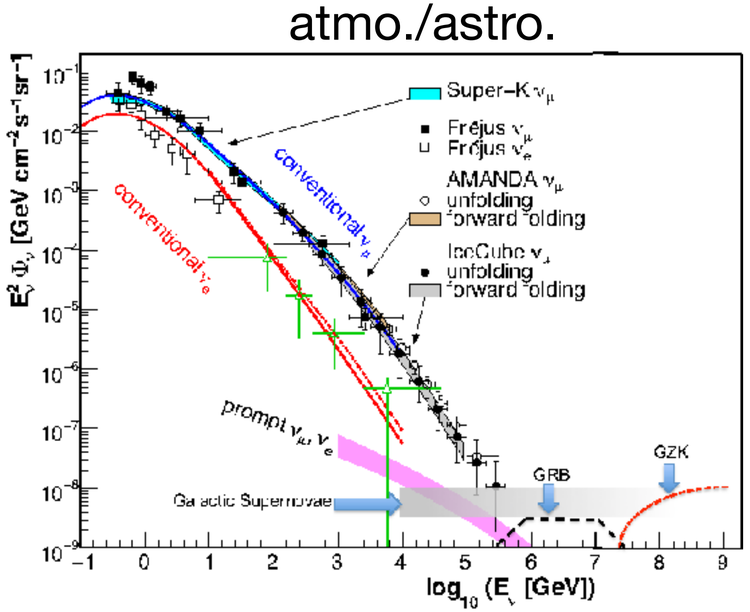

$\bar{\nu}_e$
Reactor
Neutrino
^{235}U
^{239}Pu
^{238}U
sum
flux [cm^{-2} s^{-1} keV^{-1}]
neutrino energy [keV]
×10^3


Solar Neutrino
Ga
Cl
Kamiokande
pp
^{13}N
^{15}O
^{17}F
^{8}B
^{7}Be
pep
hep
Flux at 1 AU (cm^{-2} s^{-1}MeV^{-1}) [for lines, cm^{-2} s^{-1}]
Neutrino energy (MeV)


stopped pion
ν_μ
ν_e
$\bar{\nu}_\mu$
flux [cm^{-2} s^{-1} MeV^{-1}]
×10^6
neutrino energy [MeV]


supernova
ν_e
$\bar{\nu}_e$
ν_x
sum
flux [cm^{-2} MeV^{-1}]
×10^9
neutrino energy [MeV]


Accelerator
DUNE Simulation
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
ν's/m^2/GeV (1.1 × 10^{21} POT)
Neutrino energy (GeV)

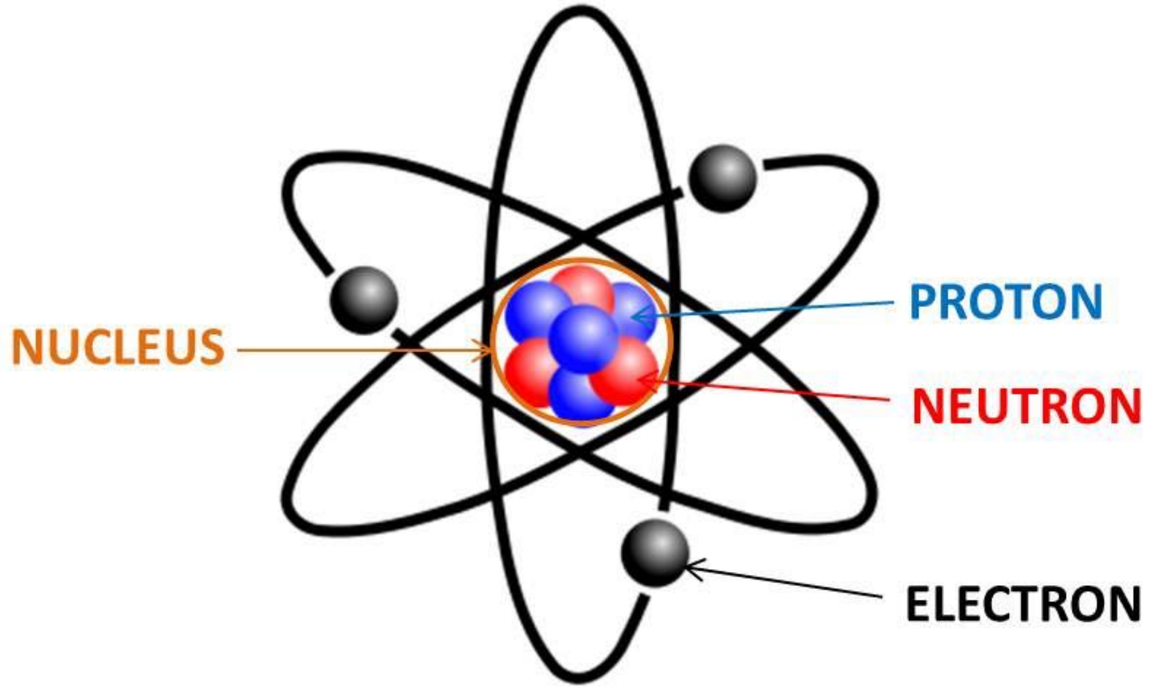

atmo./astro.
Super-K ν_μ
Frejus ν_μ
Frejus ν_e
AMANDA ν_μ
unfolding
forward folding
IceCube ν_μ
unfolding
forward folding
conventional ν_μ
conventional ν_e
prompt ν_μ, ν_e
Galactic Supernovae
GRB
GZK
E$_\nu^2$ Φ$_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
log$_{10}$ (E$_\nu$ [GeV])

Neutrino Interactions
(Depends on what the neutrino “sees”)

Incident Neutrino

ν_e •

ATOM

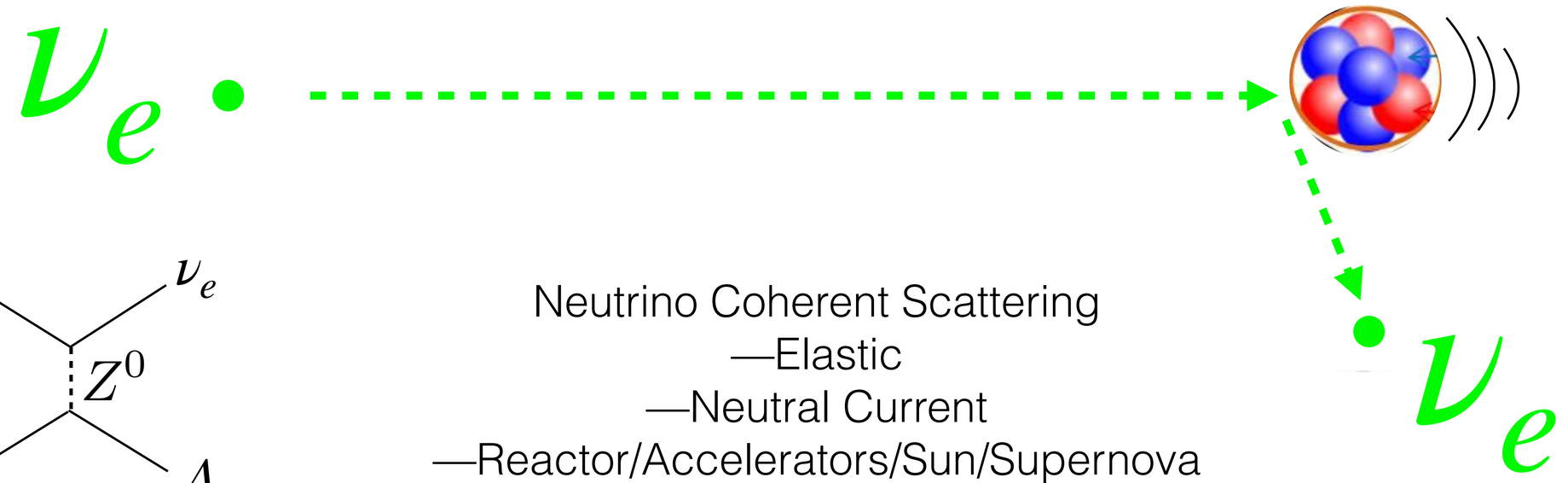


Neutrino Interactions
(Depends on what the neutrino “sees”)

Neutrino-Nucleus Neutral-Current Coherent Elastic Scattering

Incident Neutrino ($E_\nu < \sim 100\ MeV$)

Nucleus



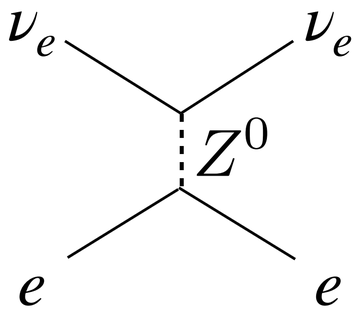
Neutrino Coherent Scattering
—Elastic
—Neutral Current
—Reactor/Accelerators/Sun/Supernova

Neutrino Interactions
(Depends on what the neutrino “sees”)

Sometimes neutrino sees electrons.

However, less often than the previous case.

In other words, smaller cross section



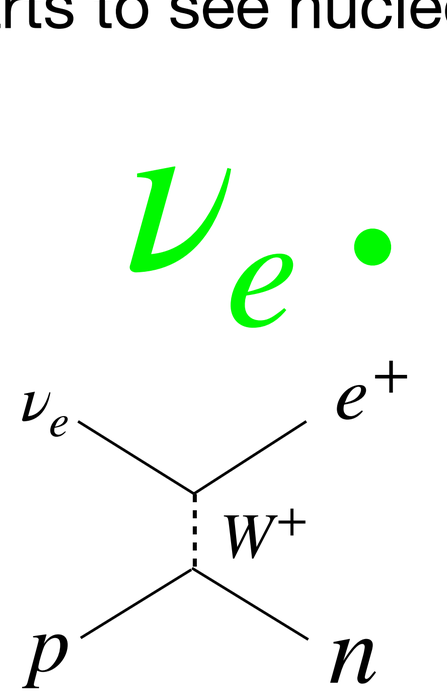
Neutrino-Electron Elastic Scattering

Neutrino Interactions
(Depends on what the neutrino “sees”)

Neutrino Quasi-Elastic Scattering

Incident Neutrino ($E_\nu \sim 1000\ MeV$)

Starts to see nucleons (protons and neutrons)





Neutrino Quasi-Elastic Scattering
—Kind of Elastic
—Element Changes from $^7Be^+$ —> ^6Li or ^7Li

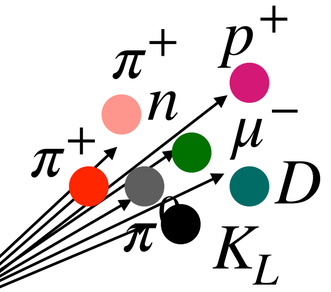
Neutrino Interactions
(Depends on what the neutrino "sees")

Neutrino Deep In-Elastic Scattering

Incident Neutrino ($E_\nu >> \sim 1000\ MeV$)

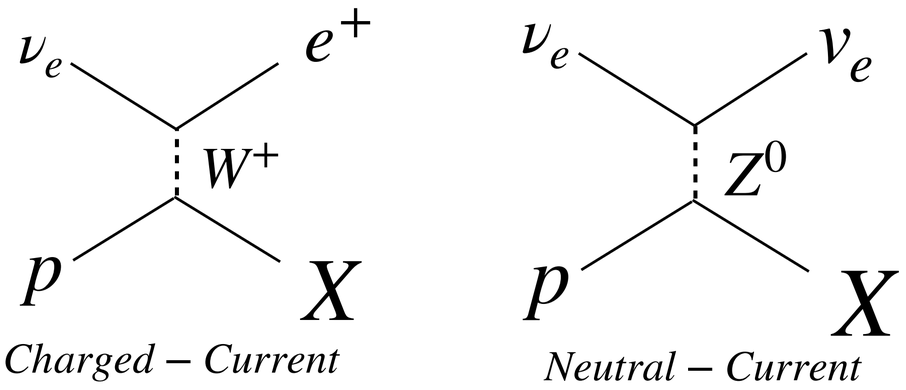
Starts to see partons (quark-gluon plasma)

Hadron Jet: X



QGP

ν_e



Neutrino Deep Inelastic Scattering
Neutrino breaks the proton apart or
"sees" the Quark-Gluon soup.

e

Neutrino Oscillations with Atm. Neutrinos
(Simple two flavor case)

Flavor transition probability

atm. mixing angle ~π/4

baseline

$$P(\nu_\alpha \to \nu_\beta) = |<\nu_\beta(0)|\nu_\alpha(t)>|^2 = \sin^2 2\theta \sin^2(1.267 \cdot \Delta m^2 L/E)$$

atm. mass-squared difference~ 2.4e-3 eV^2

energy of neutrino

Example

$$\mathrm{P}(\nu_\alpha \to \nu_\beta) + \mathrm{P}(\nu_\alpha \to \nu_\alpha) = 1$$

Assign : $(\alpha, \beta) = (\mu, \tau)$

L=10,000 km(Earth Diameter), E = 30 GeV

$P(\nu_\mu \to \nu_\mu) \sim$ **0.3**

$P(\nu_\mu \to \nu_\tau) \sim$ **0.7**

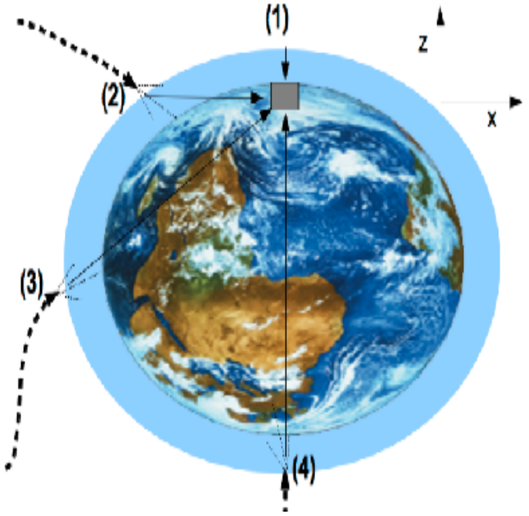
Experimentally

ν_μ type or $\nu_e(\nu_\tau)$ type

What Energy?

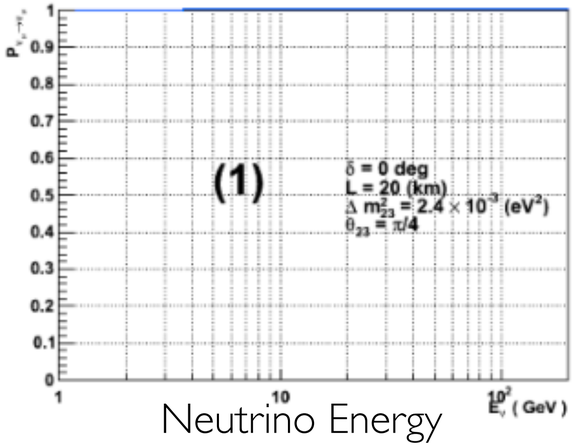
What direction?(baseline?)

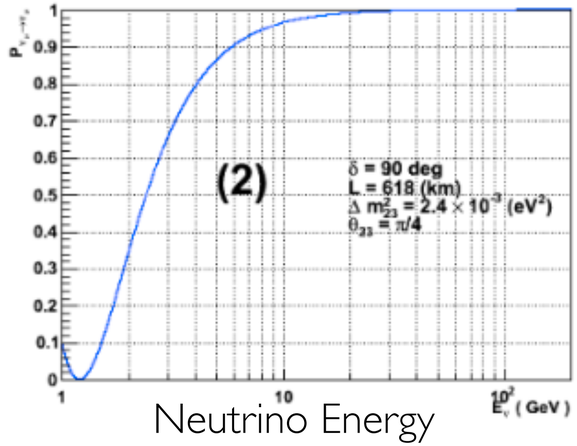
Neutrino Oscillations through the Earth (simplified two flavor case)

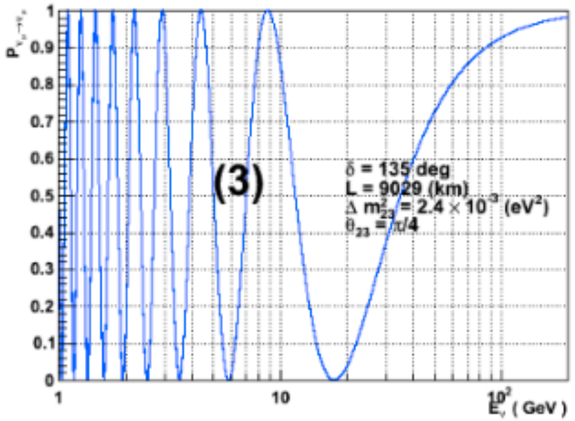


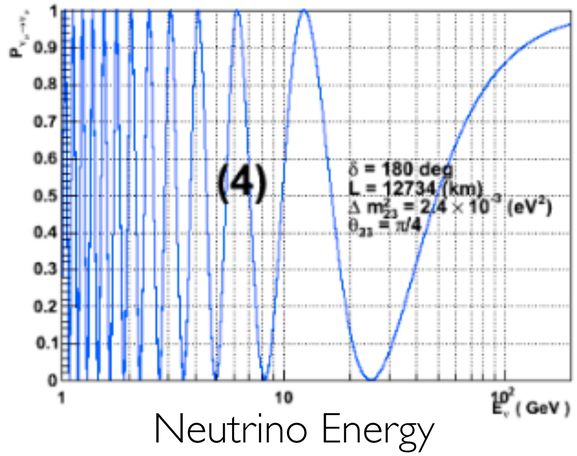
$P(\nu_\mu \to \nu_\mu)$

Muon Neutrino Survival Probability

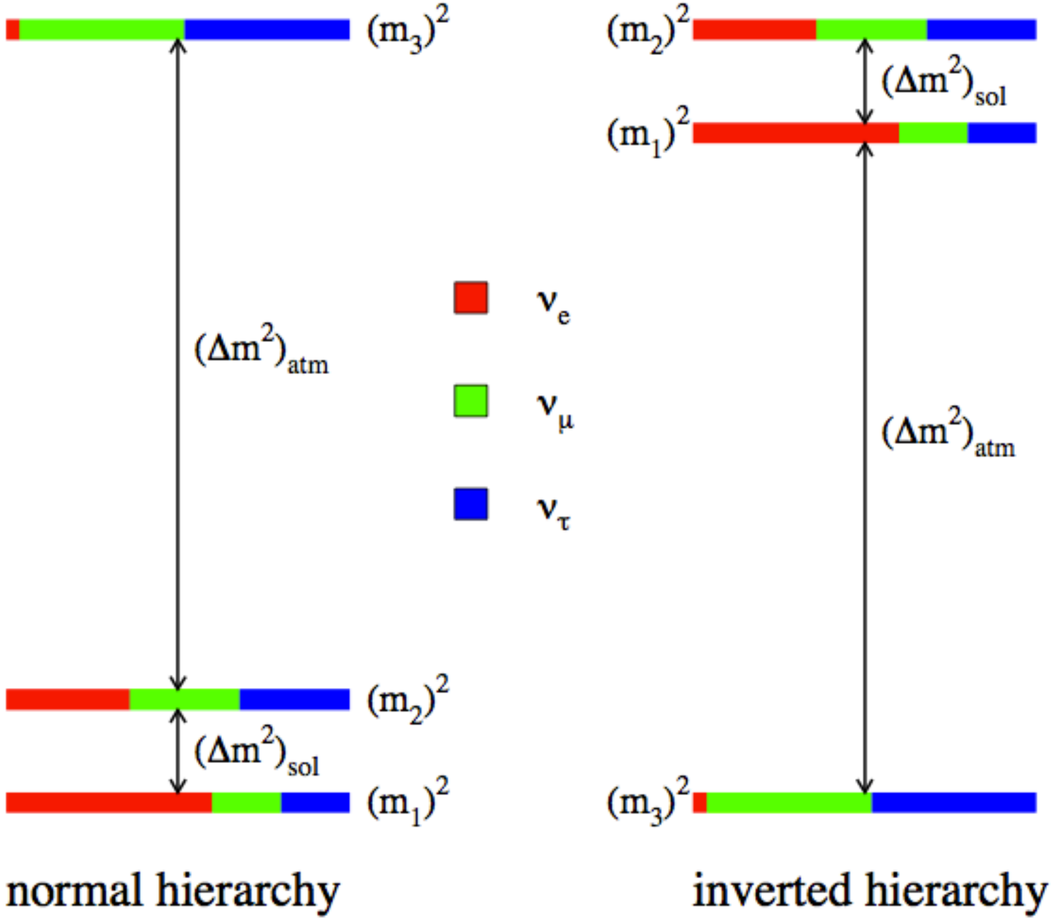








Neutrino Oscillation Properties

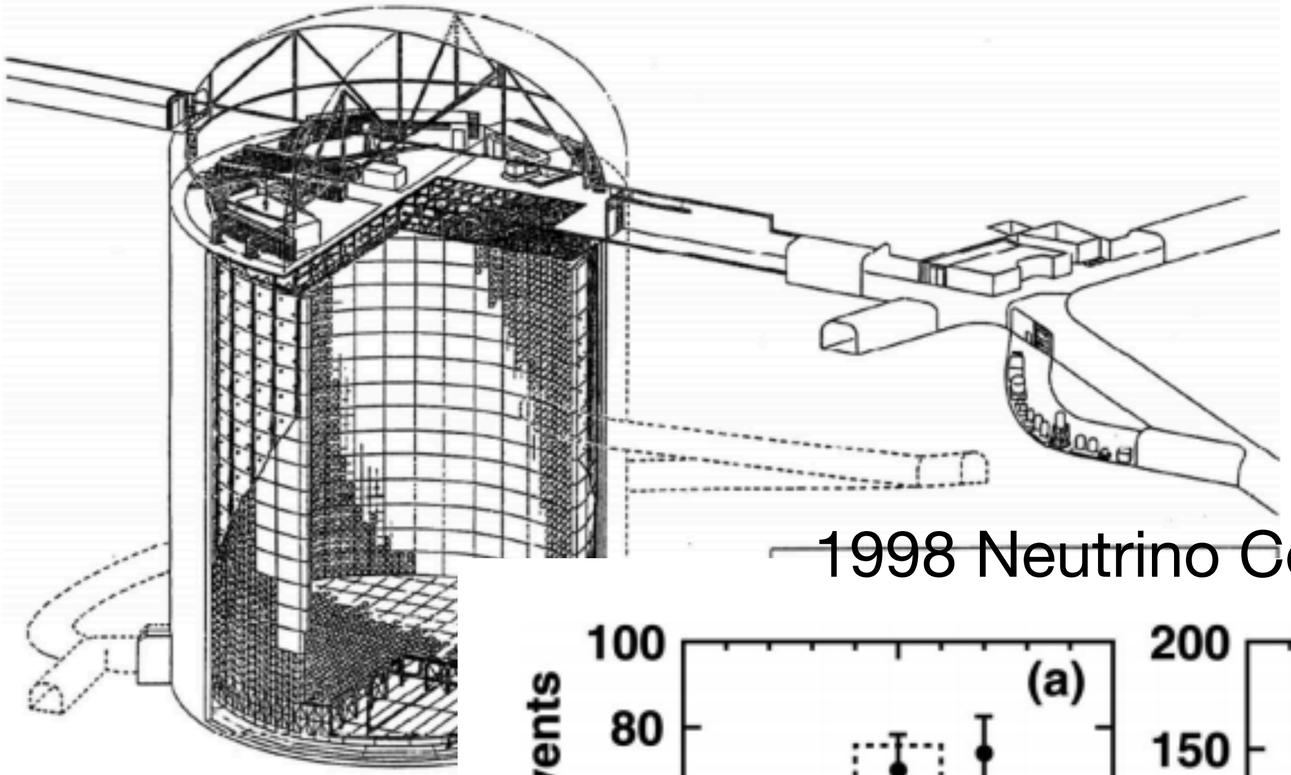


$\Delta m_{32}^2>0$ Normal Hierarchy

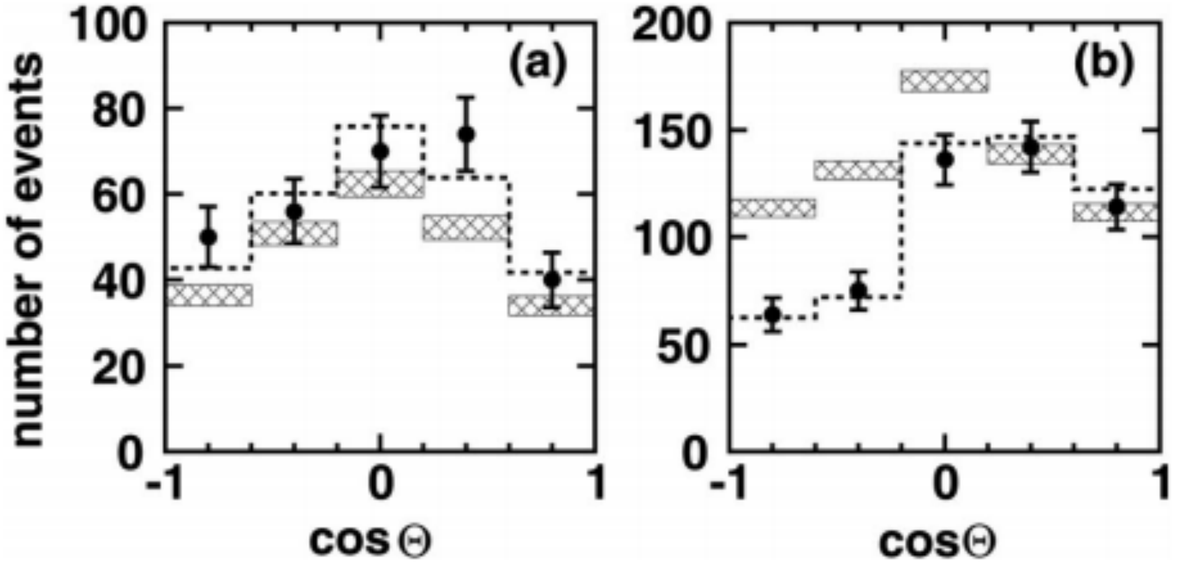
$\Delta m_{32}^2<0$ Inverted Hierarchy

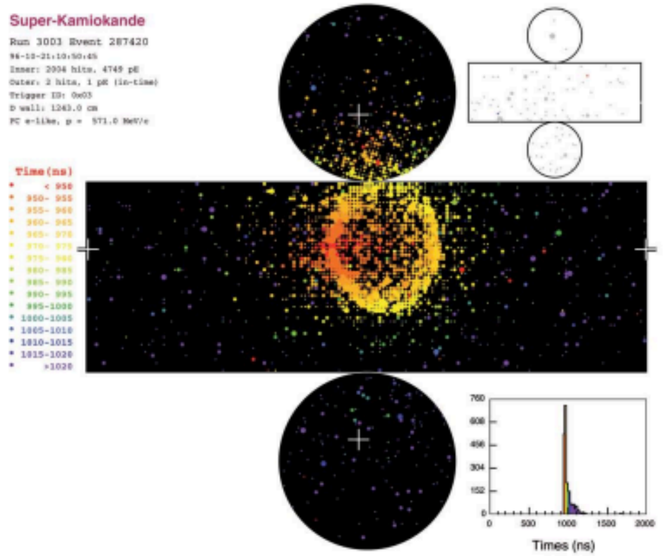
-Sign of Δm_{21}^2(solar) is known from Matter Effect in the Sun
-Sign of Δm_{32}^2(atm.) is unknown
-Help CP violation phase measurement
-Define the scope of neutrinoless double beta decay experiment
-Help determine absolute mass scale of neutrino

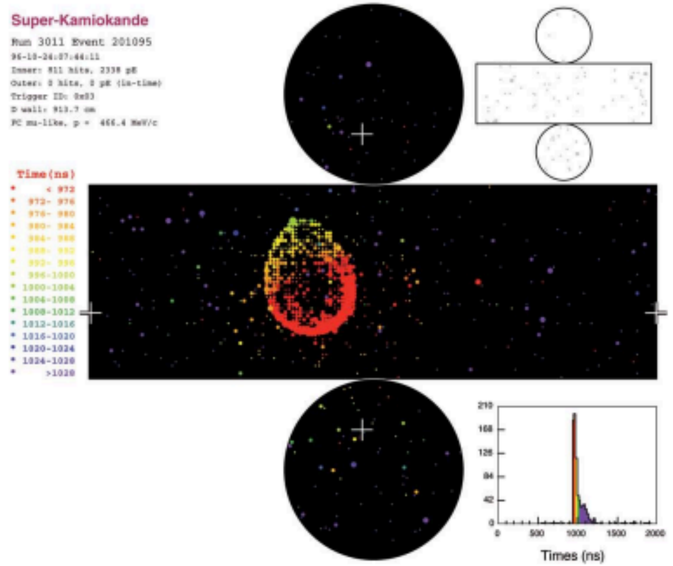
Neutrino Oscillation in Super Kamiokande



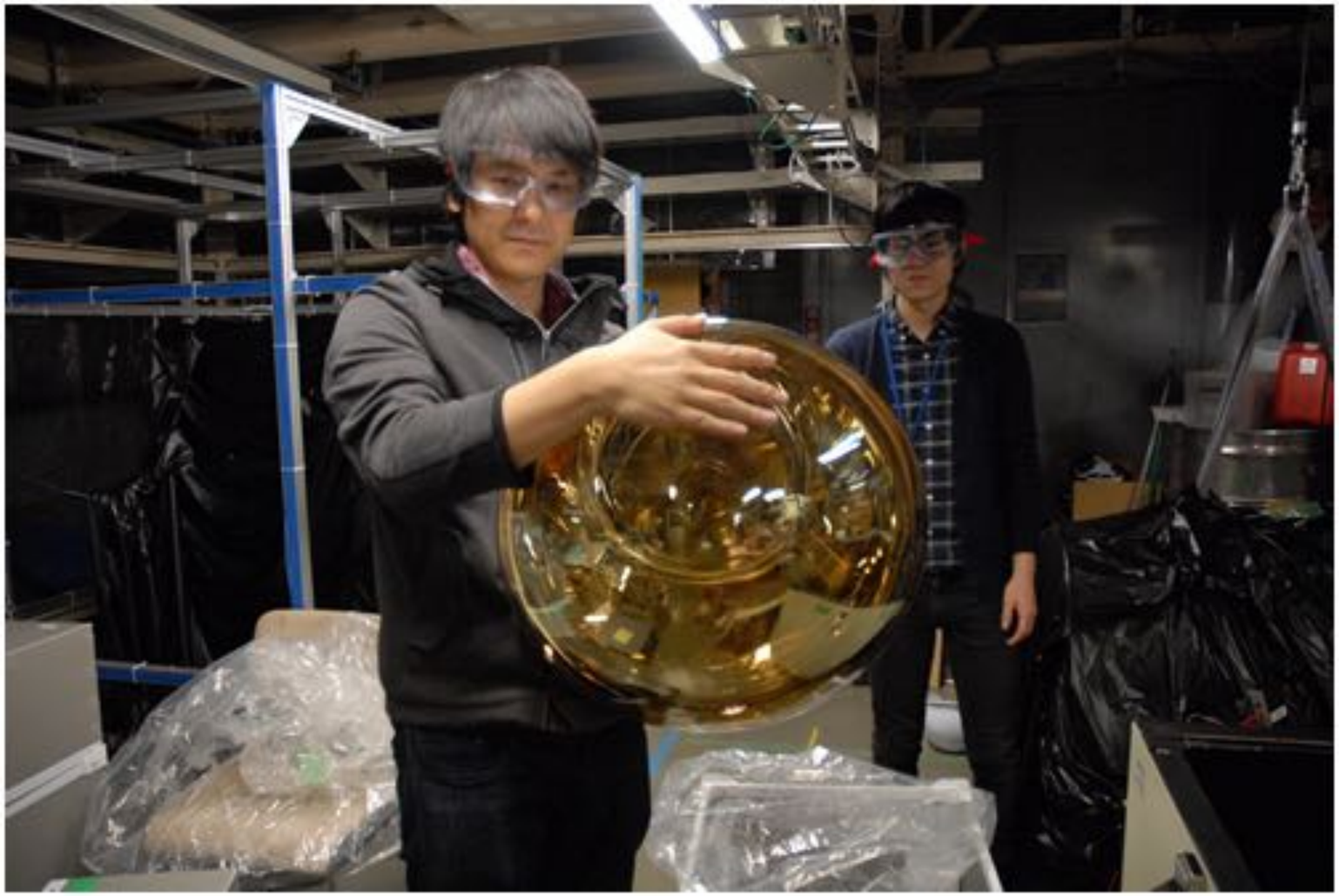
1998 Neutrino Conference



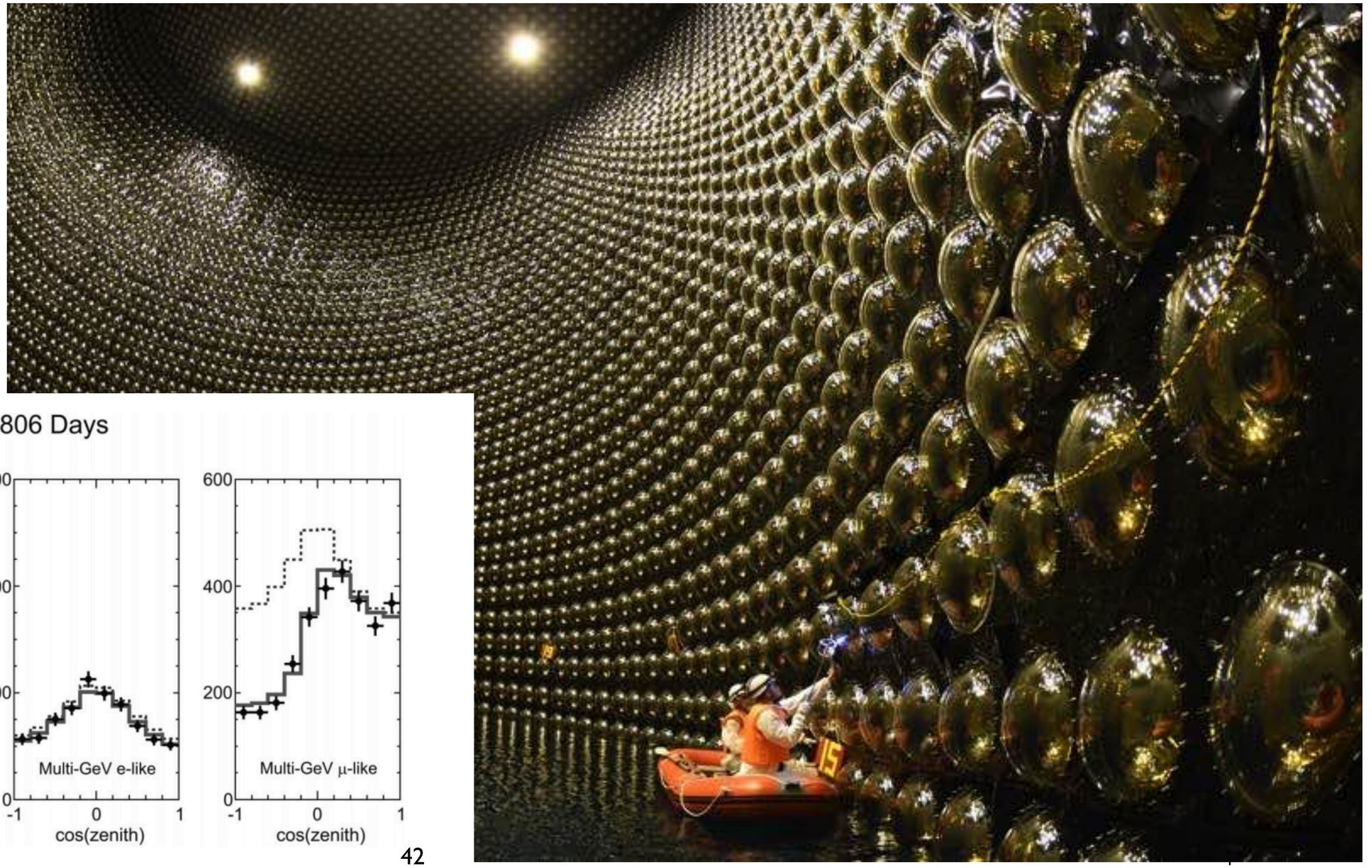


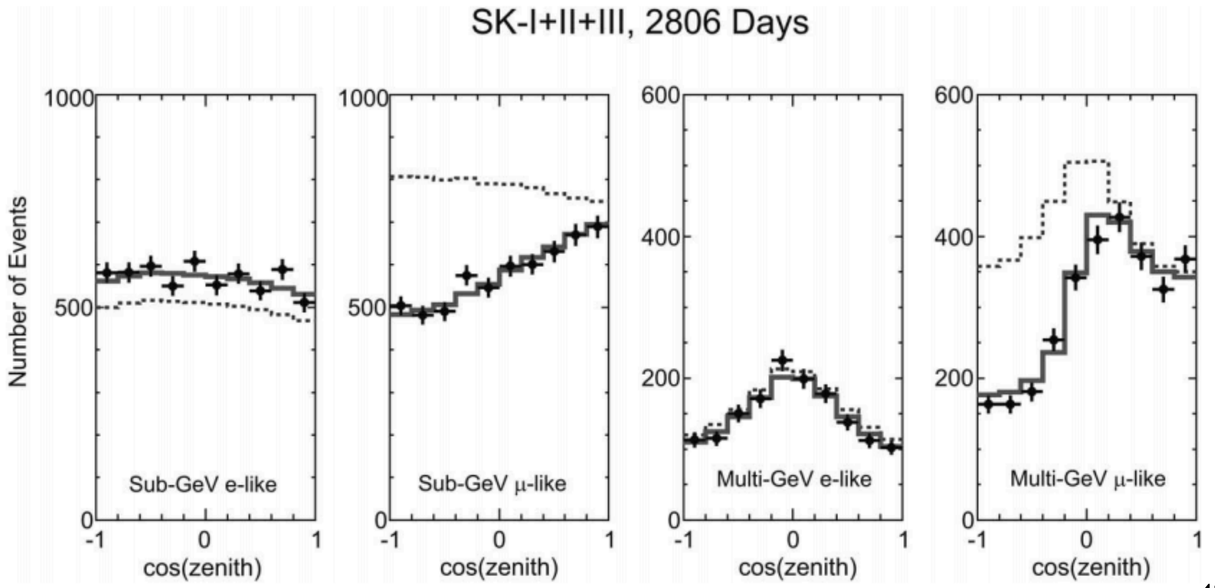


50cm Diameter Photomultiplier Tube

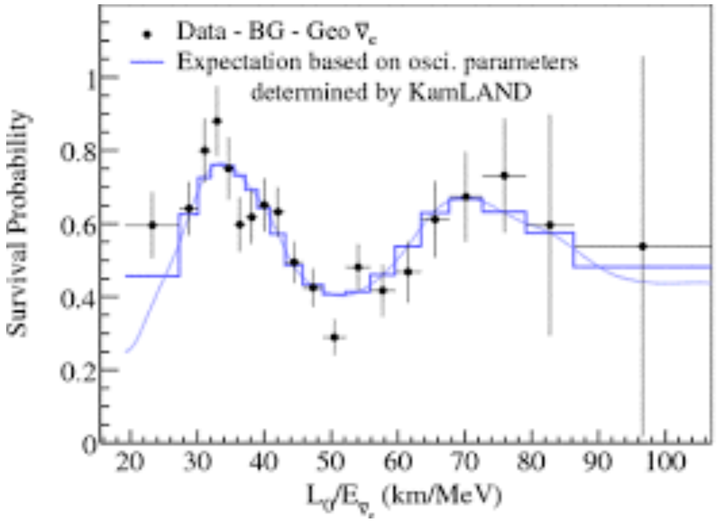


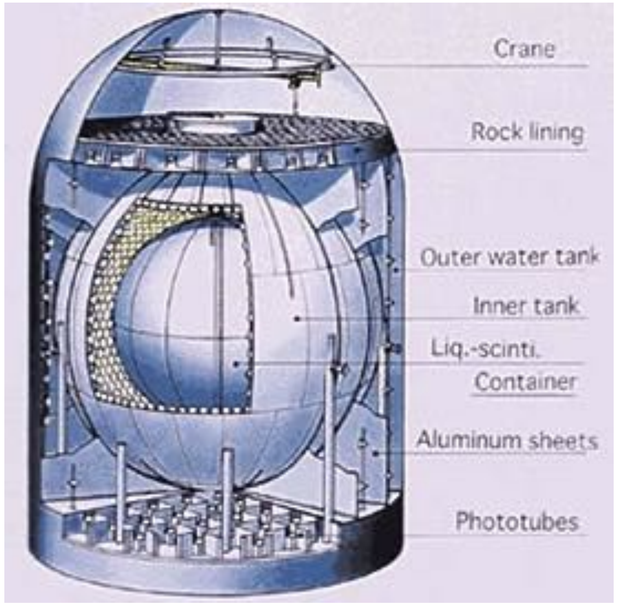
Super-Kamiokande Detector





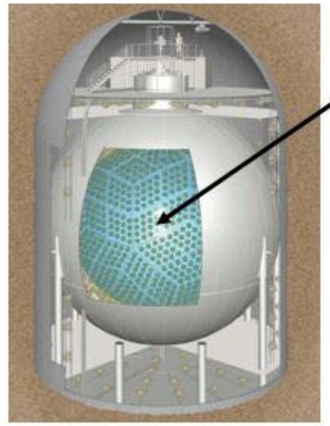
Reactor Neutrino Experiment : KamLAND

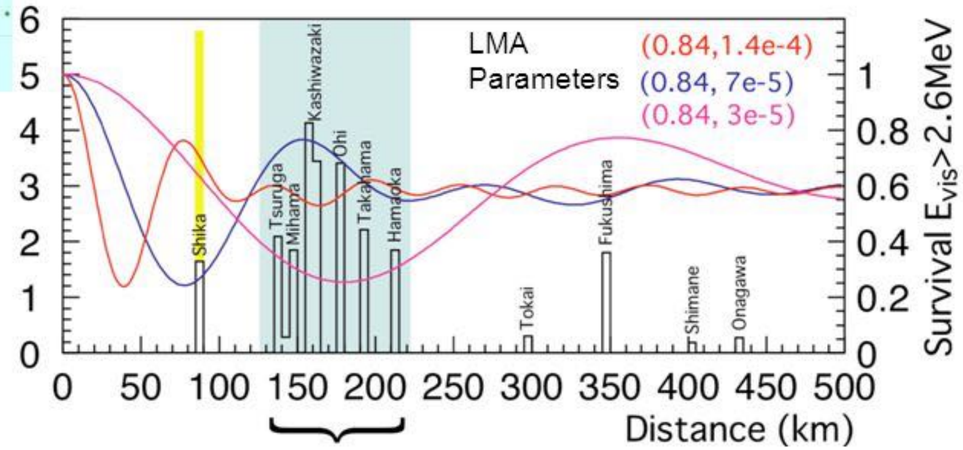




The KamLAND Experiment





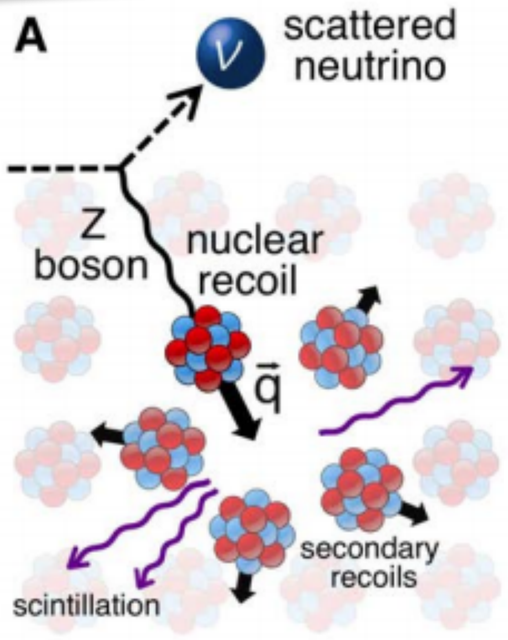


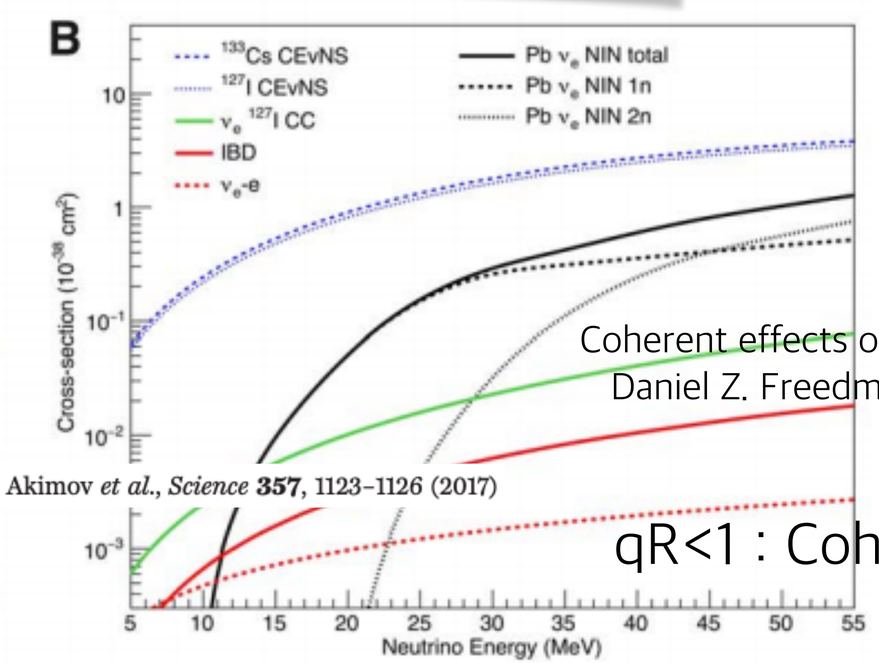
80% of total contribution comes from 130~220km distance

Coherent Neutrino Nucleon Scattering (CNNS) Motivation

- The process predicted 46 years ago and the first measurement came just a few years ago (stopped pion) by the COHERENT collaboration.
- Aim at detection of Coherent scattering in reactors.
  - Single flavor (electron anti-neutrino) & N^2 dependence

- Neutrino Magnetic Moment
- Neutrino Non-Standard Interactions
- Neutrino-electron scattering.
- Sterile neutrinos (reactor anomaly)





Akimov *et al.*, *Science* **357**, 1123–1126 (2017)

Coherent effects of a weak neutral current
Daniel Z. Freedman (PRD 9,1389) 1974)

qR<1 : Coherent requirement

$\bar{\nu}_e$

~MeV

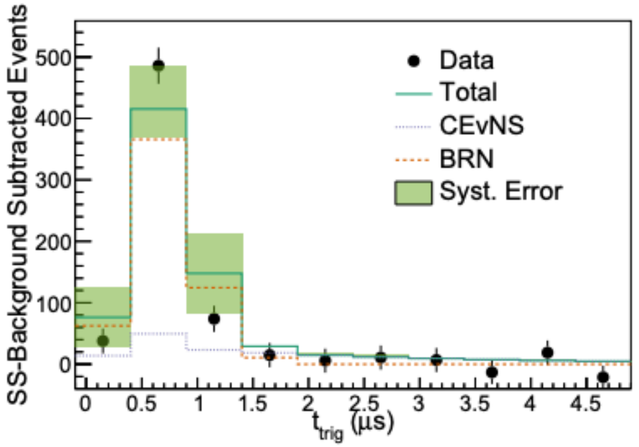


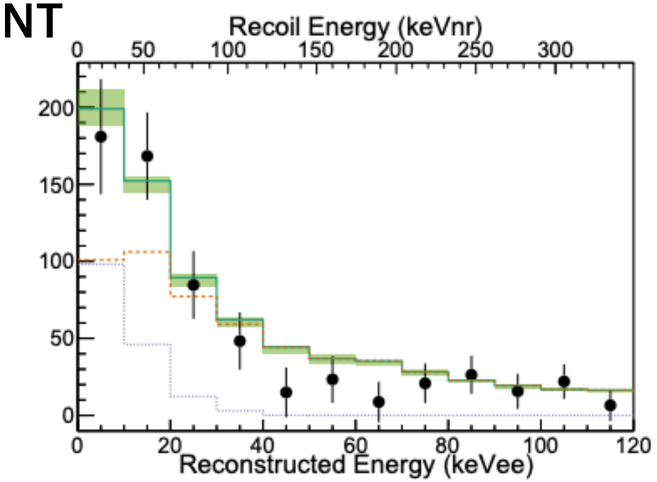
~keV

Na

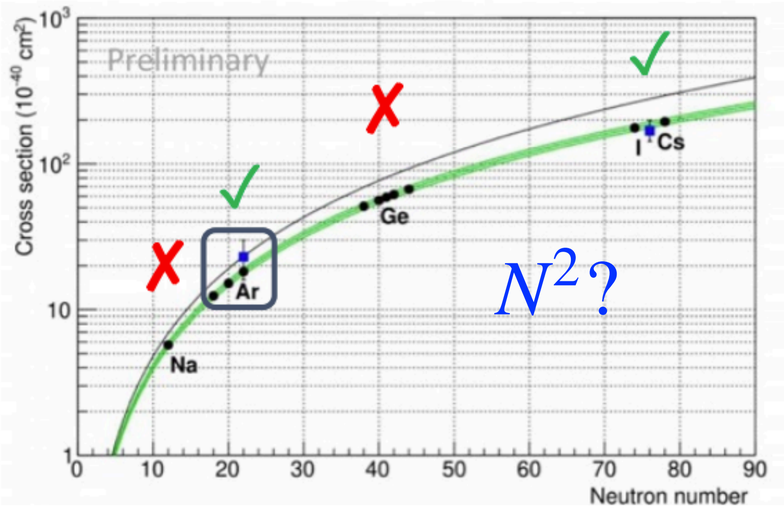
CNNS Cross section is the largest!

Observed in Ar from COHERENT

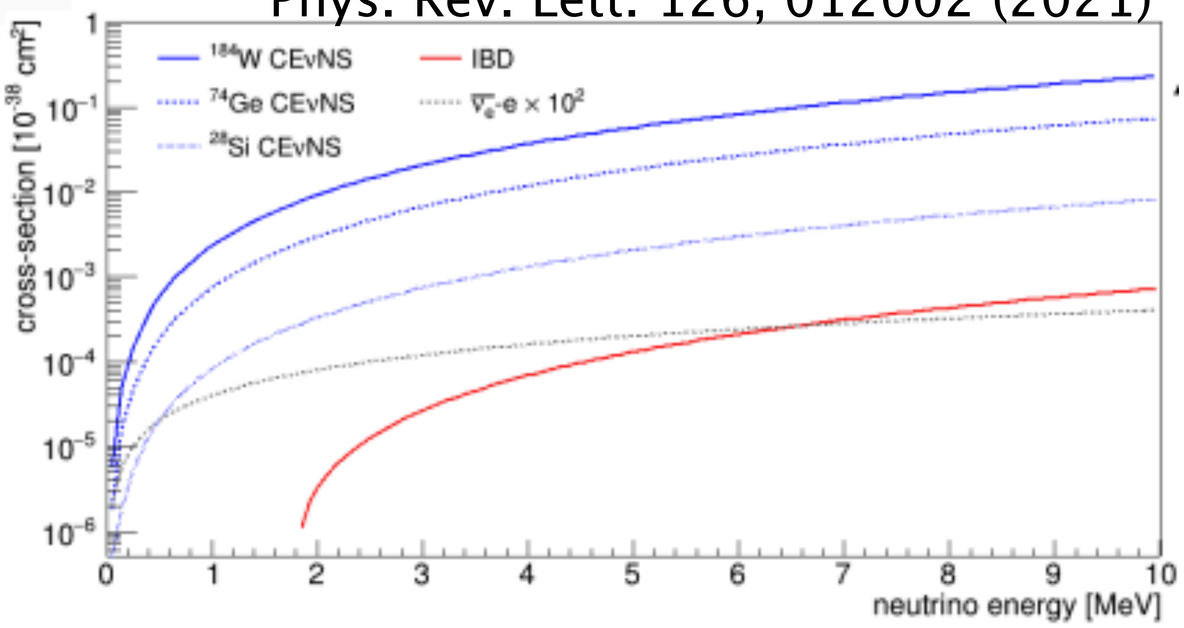


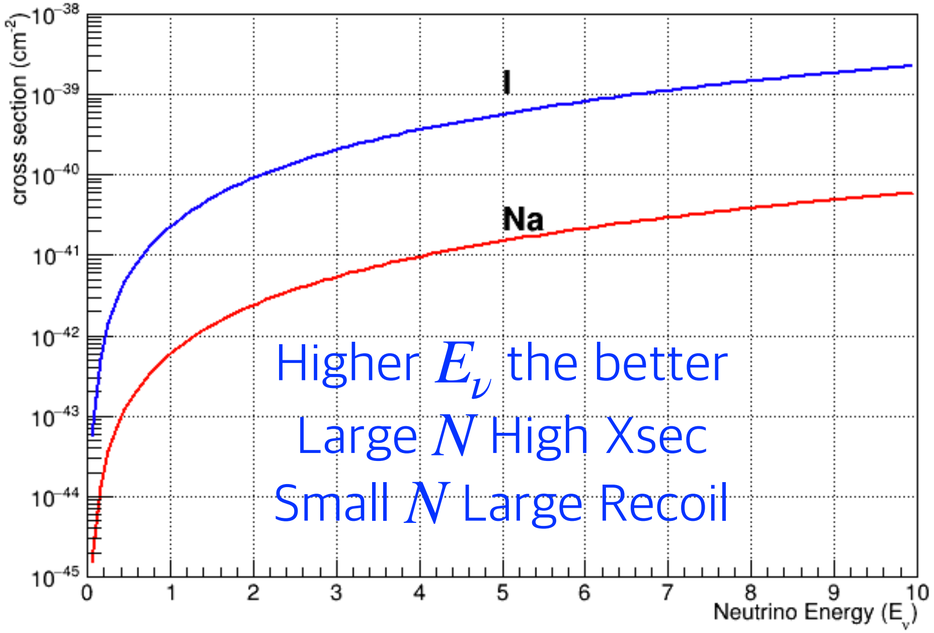


Phys. Rev. Lett. 126, 012002 (2021)



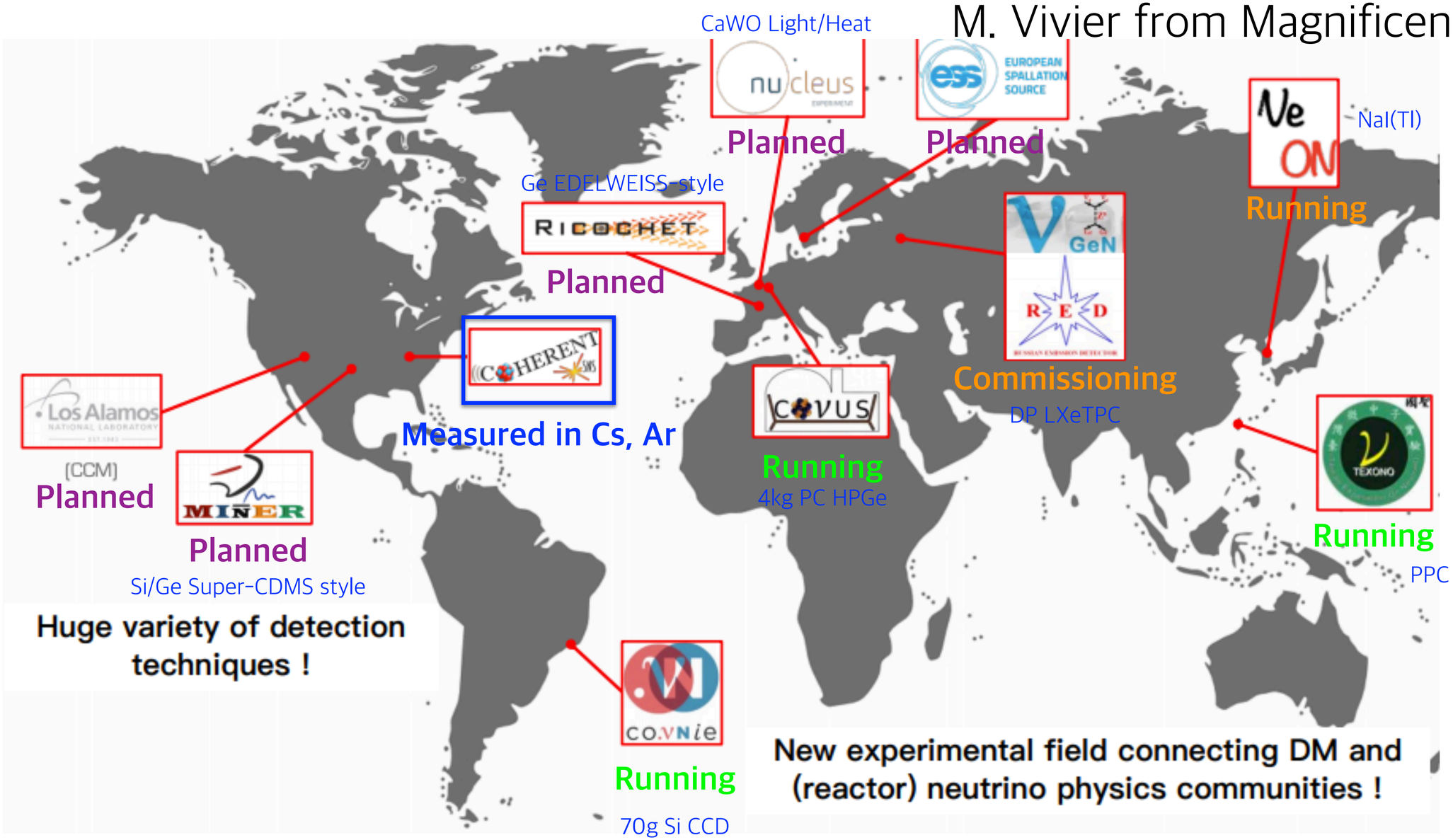
CNNS cross sections on NaI



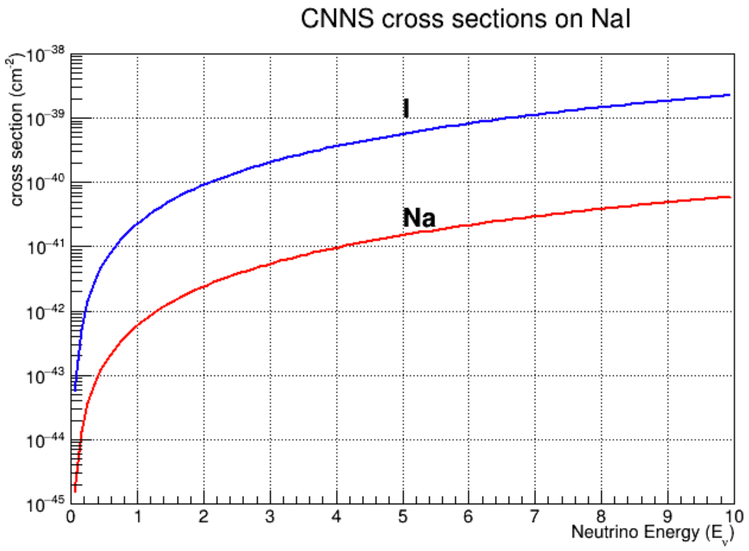


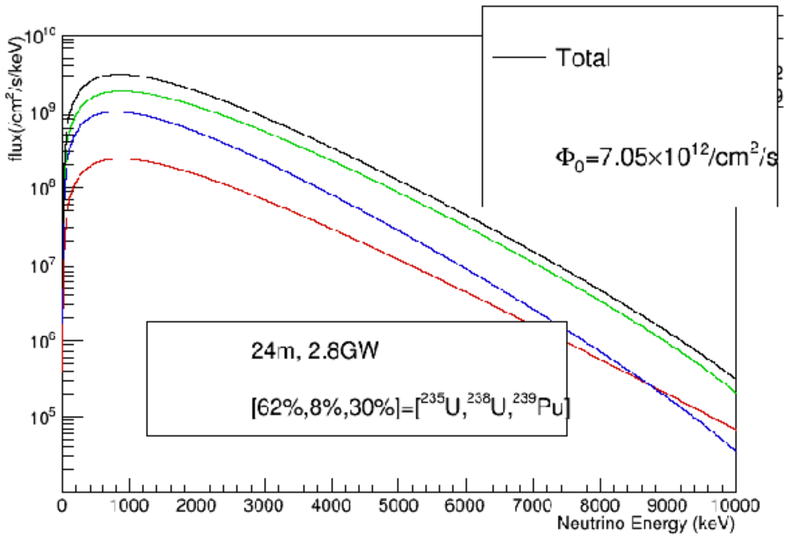
Worldwide efforts for CNNS

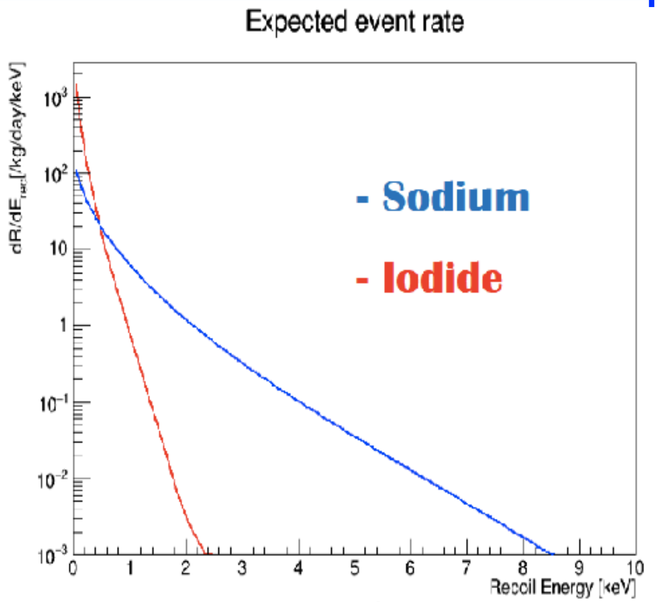
M. Vivier from Magnificent 2020



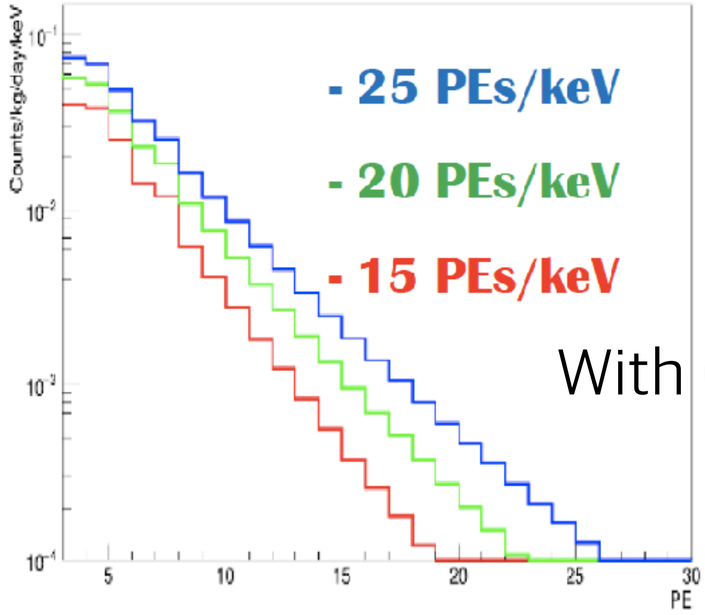
Reactor Neutrino CNNS Rate on NaI(Tl) target @ NEOS







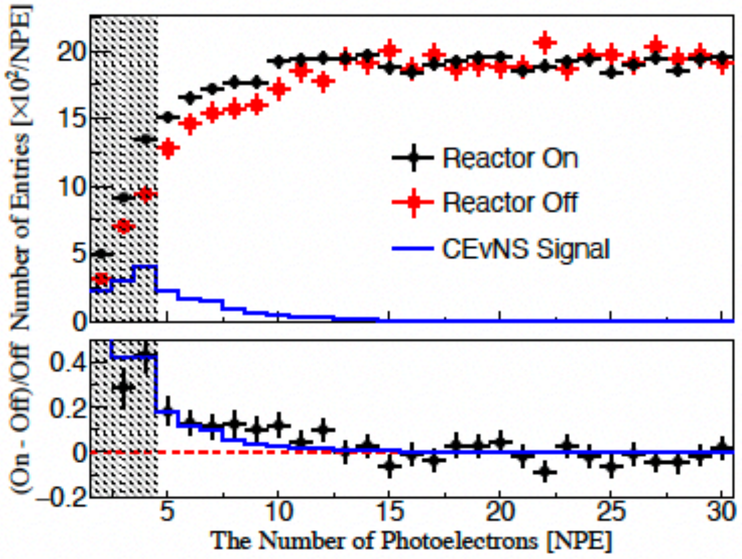
- Iodine recoil unreachable above 0.5 keV so ignore it.
- Assume the flux at 24m from the Core of the 2.8 GW reactor
- Quenching (Light output/Energy deposit) is key factor

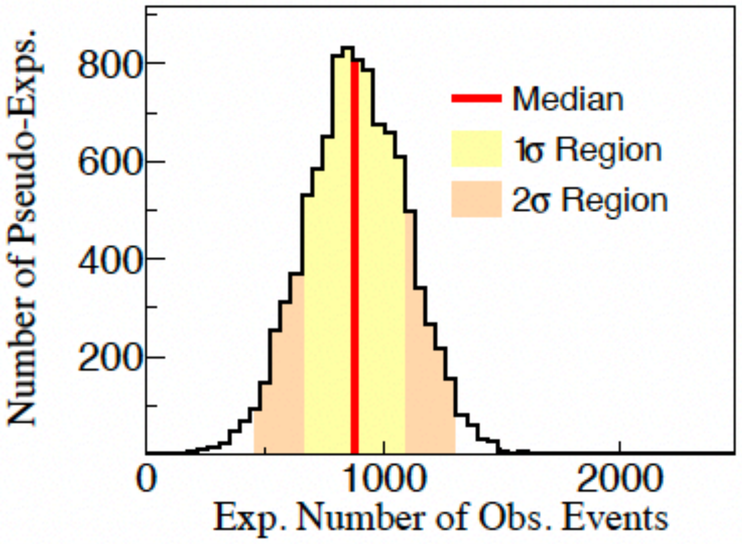


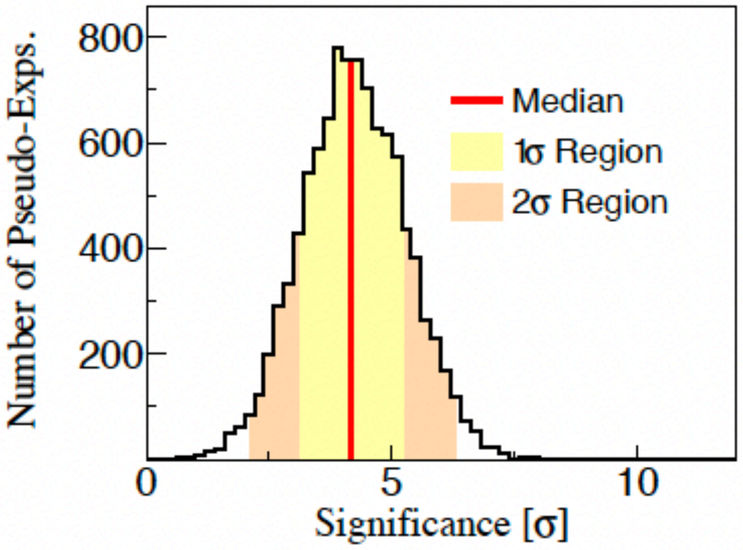
With Quenching on Na

Expected Rate and Sensitivity for NaI(Tl) crystal detectors

arXiv:2204.06318







878 ± 211

$(4.2 \pm 1.0)\sigma$

- Assumption for sensitivity study
- ✓ 22-photoelectrons/keV(PEs/keV) light yield
- ✓ 13.5-kg mass of detector
- ✓ 7-counts/kg/day/keV flat background
- ✓ 5-PEs threshold
- ✓ 365/100-days reactor-on/-off data

$$\chi^2 = \sum_i \frac{(N_{\mathrm{on},i} - \alpha_t N_{\mathrm{off},i} - \psi E_i)^2}{N_{\mathrm{on},i} + \alpha_t^2 N_{\mathrm{off},i}}$$

- 10^4 Pseudo-experiment
- χ^2- Analysis

The NEON Collaboration

15 members, 3 institutes

Active members of
the COSINE and NEOS experiments

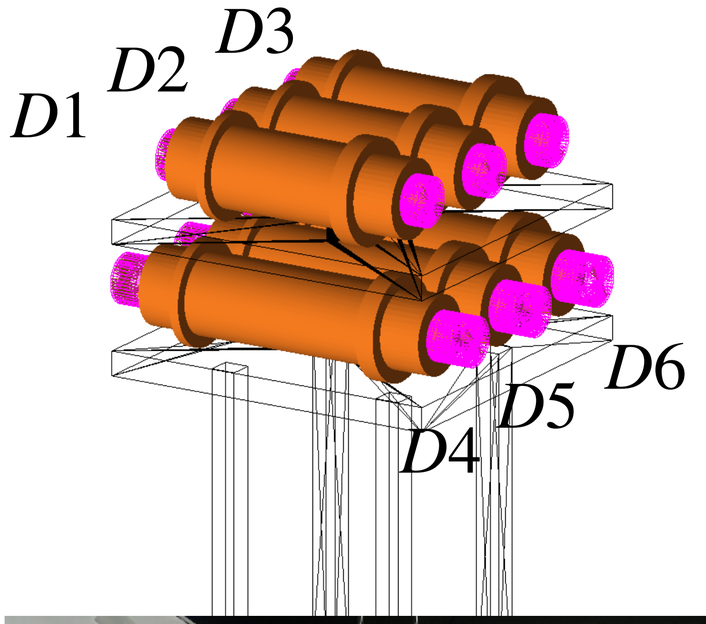


+Koh

Goal : CNNS measurements in NaI(Tl) crystals from nuclear reactor.
(Low-background dark matter Crystal experts + Reactor neutrino experiment experts)

The Key Questions & Requirements for NEON

- Assumption for sensitivity study
  - ✓ 22-photoelectrons/keV(PEs/keV) light yield
  - ✓ 13.5-kg mass of detector
  - ✓ 7-counts/kg/day/keV flat background
  - ✓ 5-PEs threshold
  - ✓ 365/100-days reactor-on/-off data



D1, D3
(1.64 kg)





D2,D4,D5,D6
(3.35 kg)

Currently upgraded to 16.64 kg mass detector

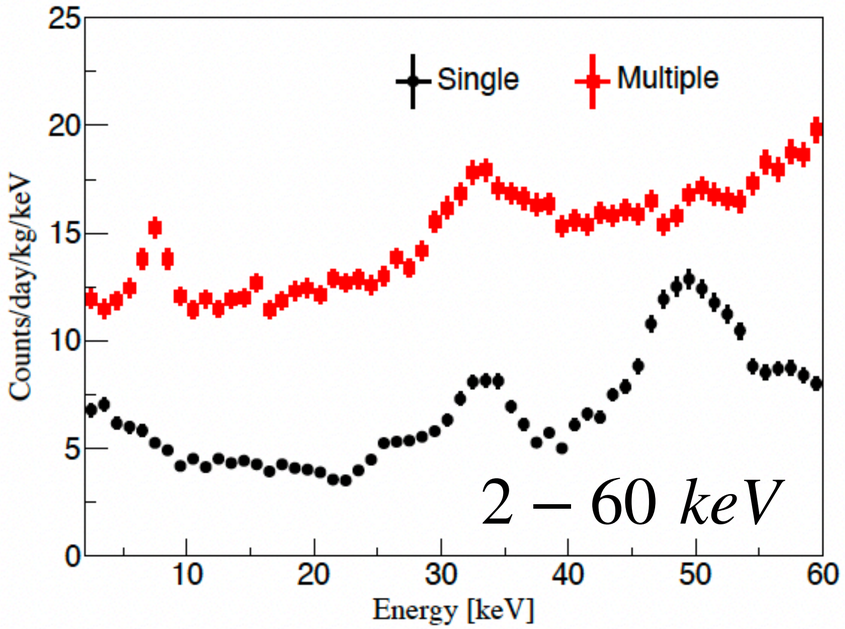


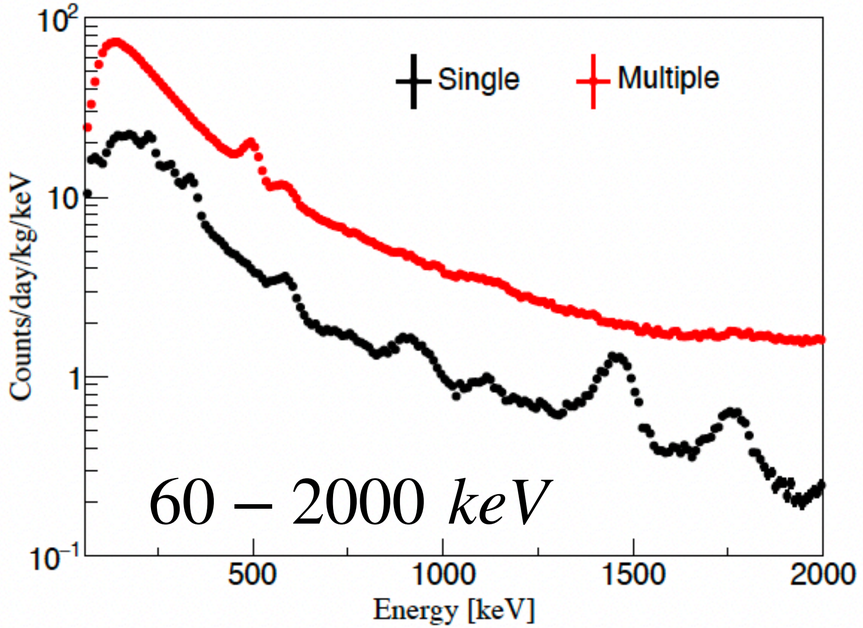
The Key Questions & Requirements for NEON

•Assumption for sensitivity study

- ✓ 22-photoelectrons/keV(PEs/keV) light yield ✓
- ✓ 13.5-kg mass of detector ✓
- ✓ 7-counts/kg/day/keV flat background ✓
- ✓ 5-PEs threshold
- ✓ 365/100-days reactor-on/-off data

- Can you reach 7 dru at the threshold region?
- Current : 6 counts/kg/day/keV at 2-6 keV
- Higher at the threshold region
- This means crystals are pure enough and LS veto is working.
- To do : Analysis needs to be further developed to characterize the lowest energy events.

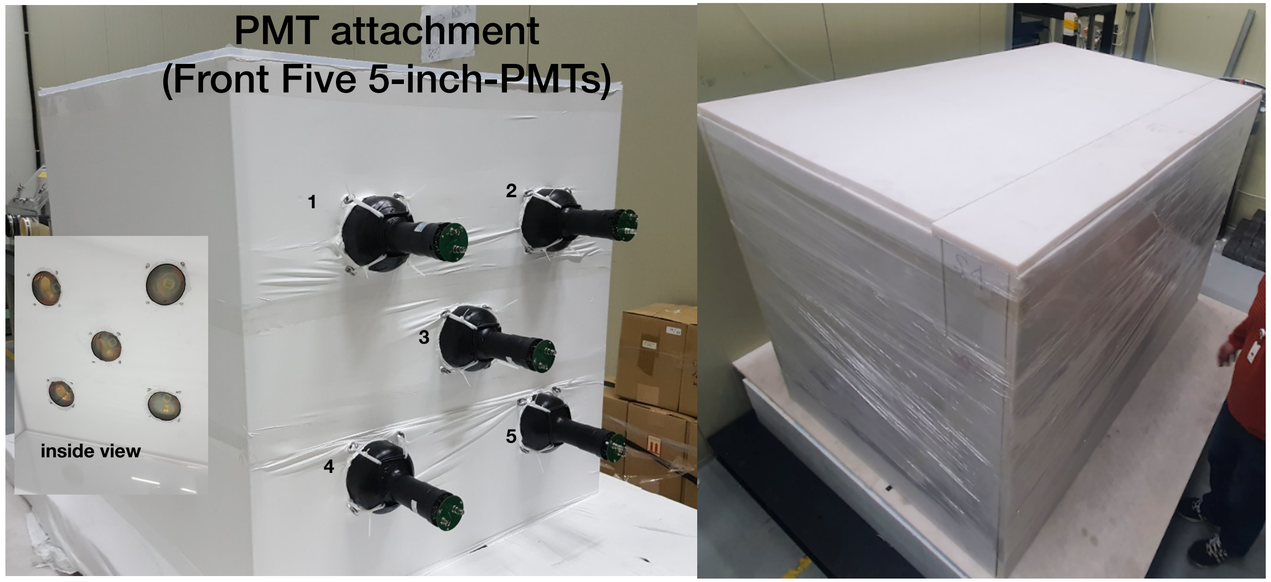


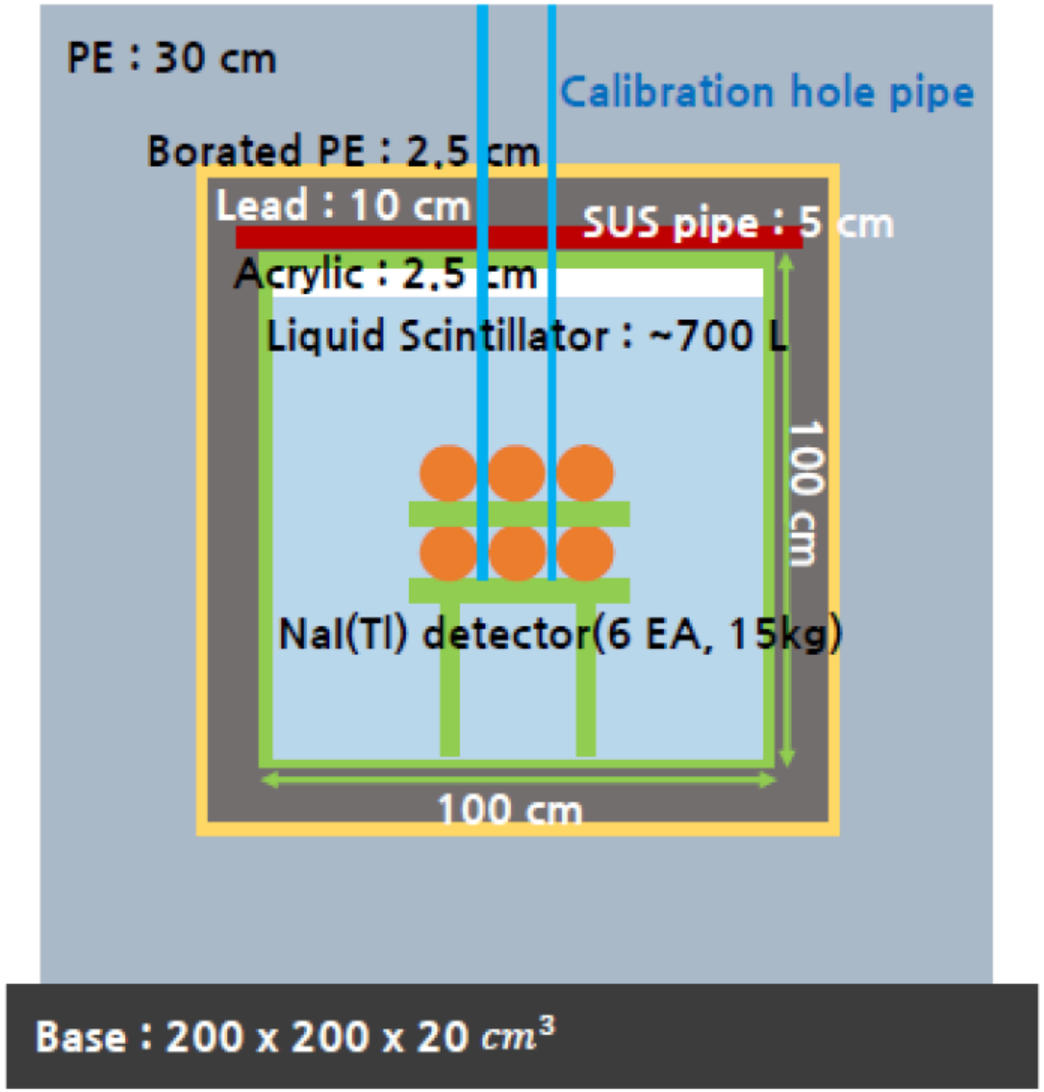


The single-hit 2-6 keV has approximately 6 counts/kg/keV/day.

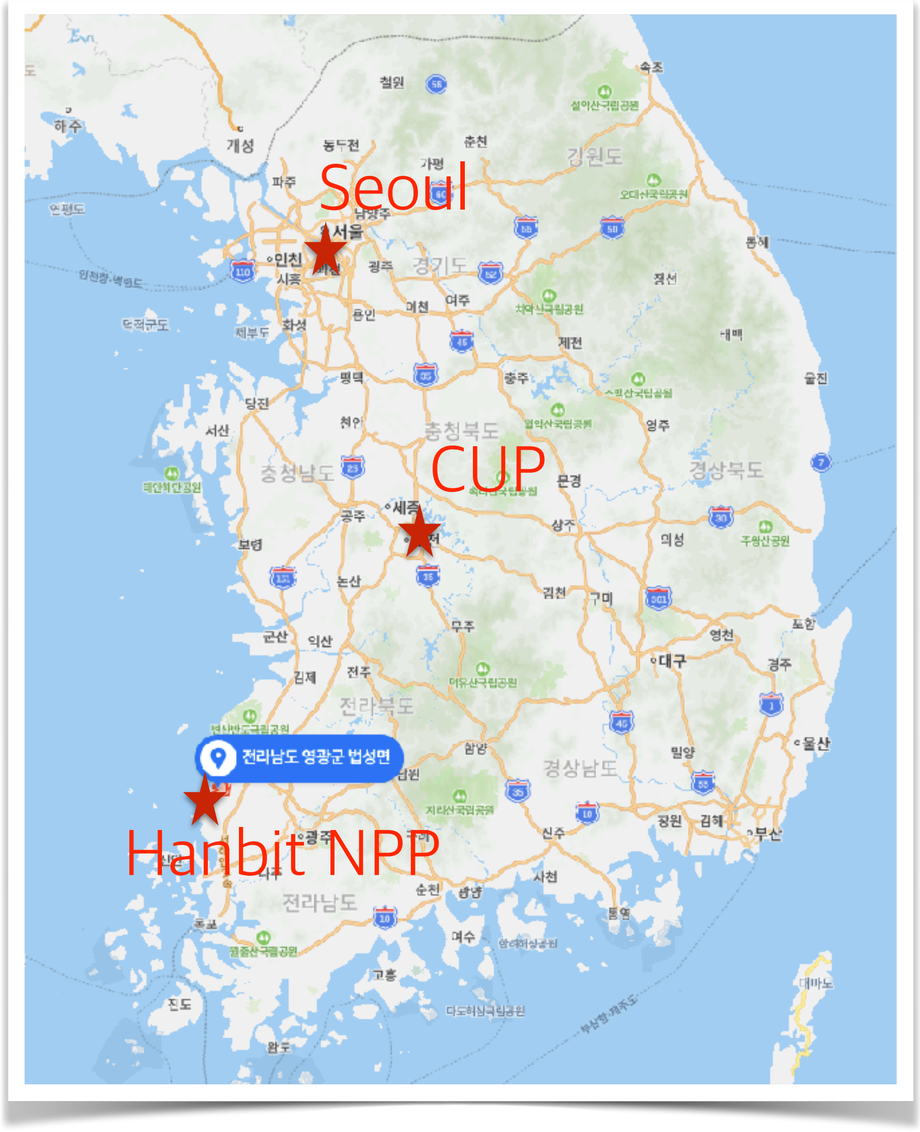
The Key Questions & Requirements for NEON

- Assumption for sensitivity study
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  - ✓ 5-PEs threshold
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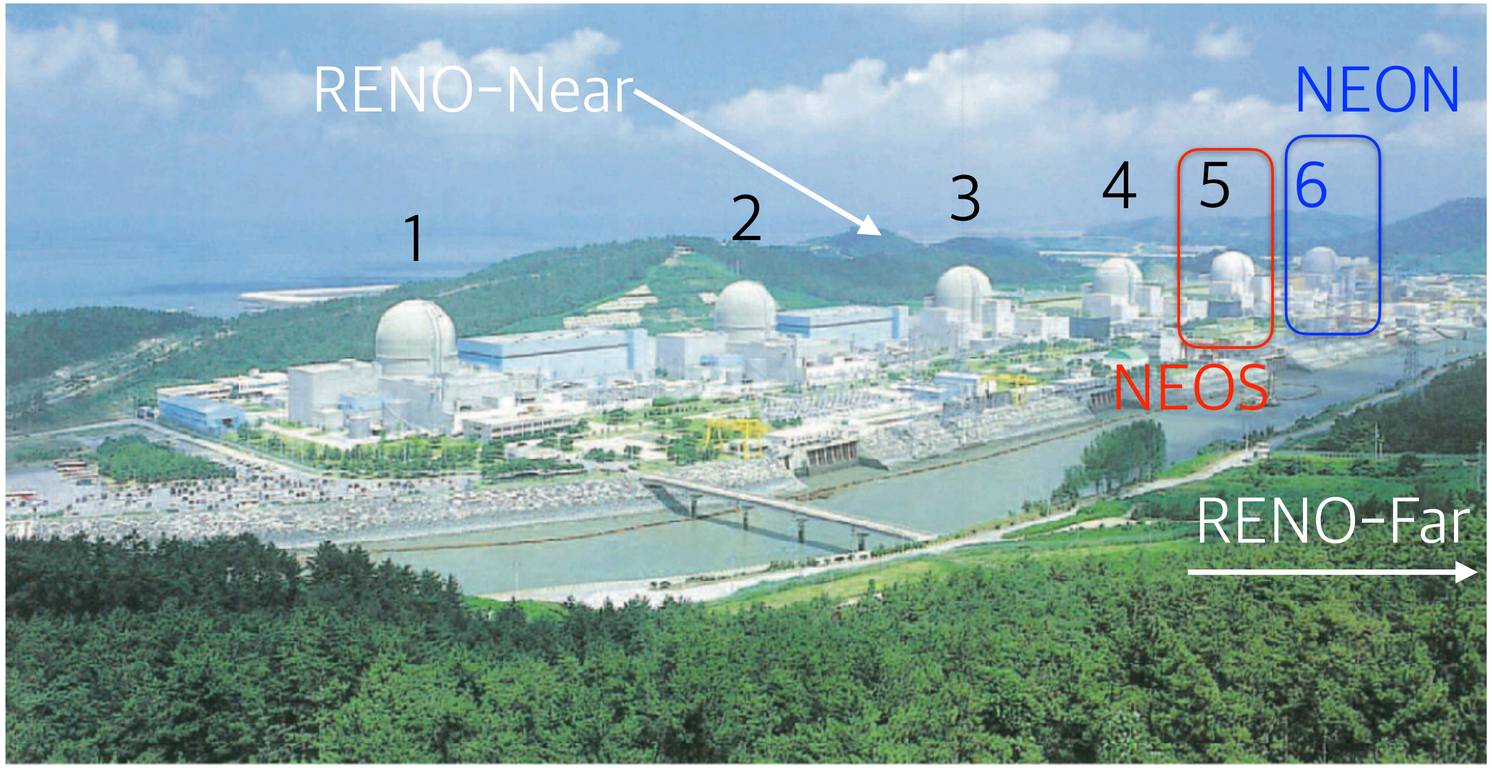




NEON Experimental Site : Hanbit Nuclear Power Plant Unit #6



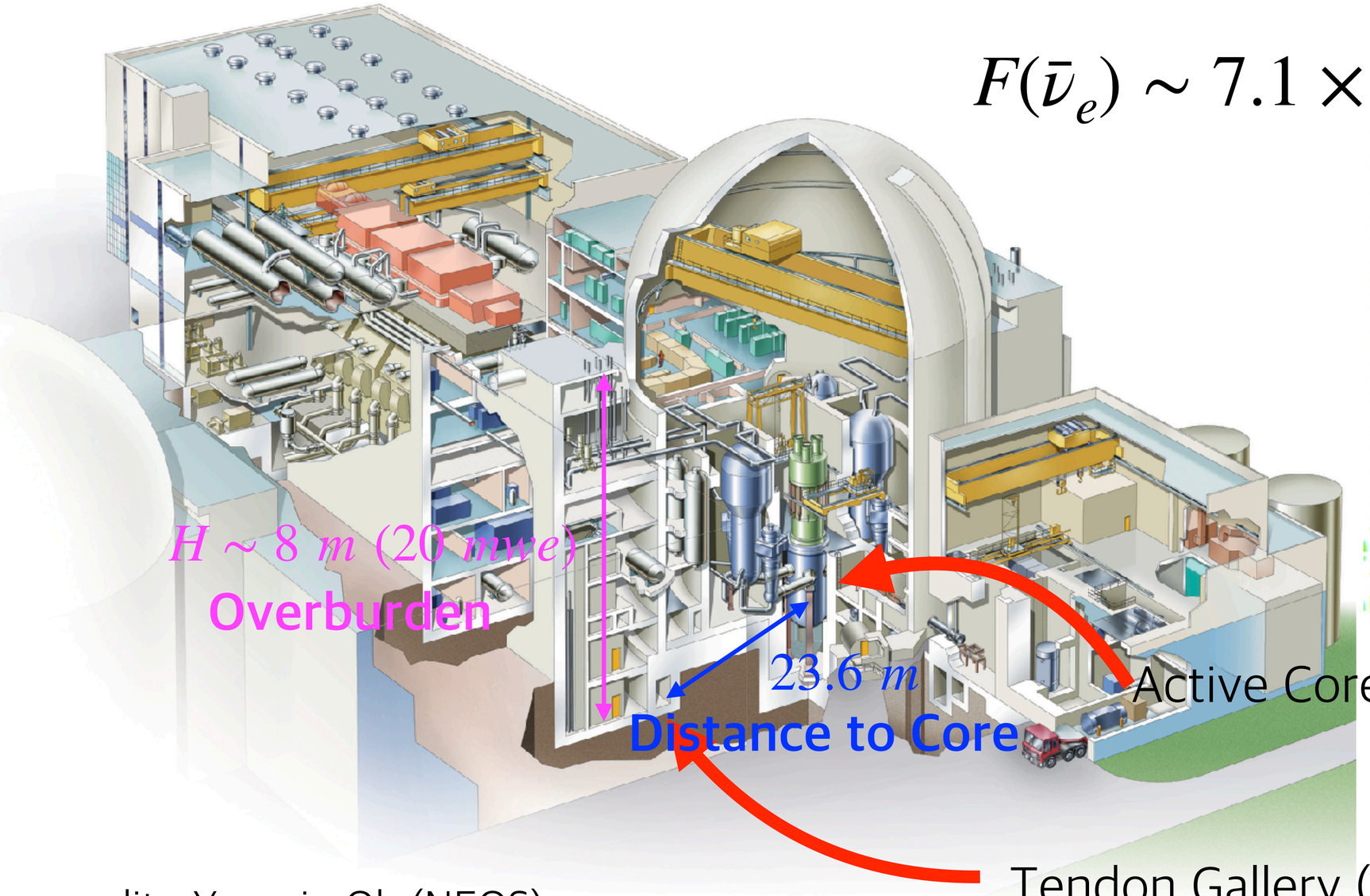
NEON at the reactor #6 in Hanbit NPP, Yeonggwang, Korea

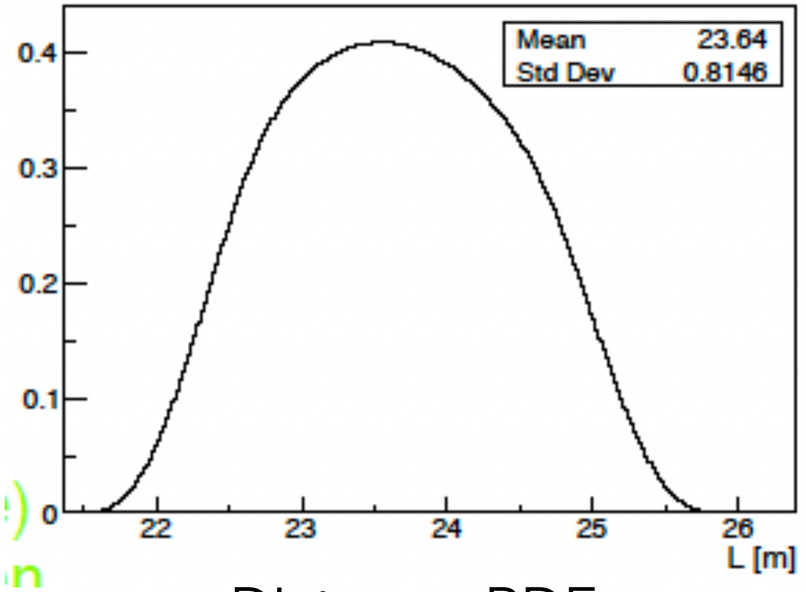


NEOS experiment and RENO experiment use the same reactor complex

Experimental Site & Detector Location

$$F(\bar{\nu}_e) \sim 7.1 \times 10^{12}\ cm^{-2}s^{-1}$$





Distance PDF

credit : Yoomin Oh (NEOS)

Construction of the NEON Experiment

November 2020

No. 6 Reactor



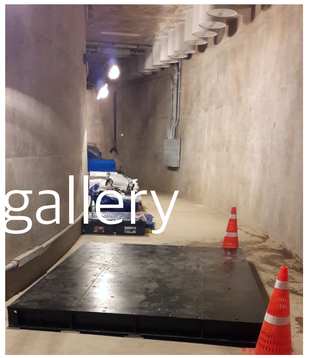
NEON prototype @IBS



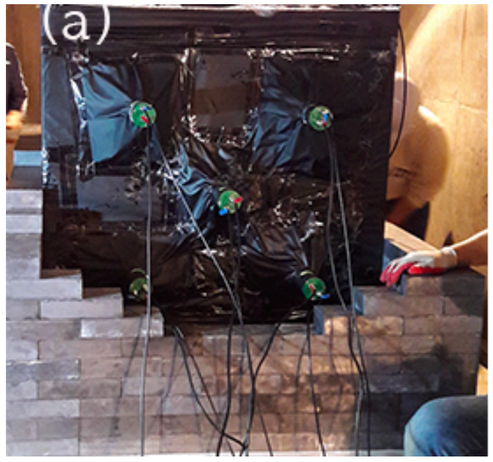
Transfer

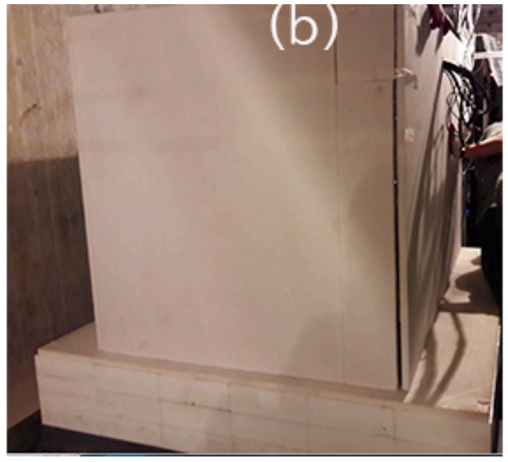




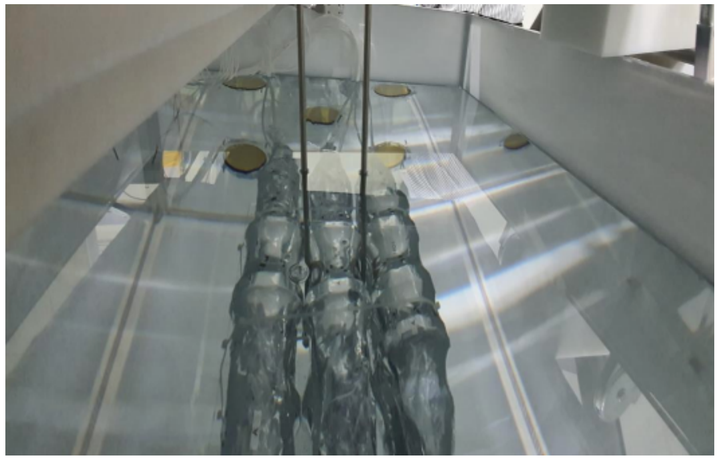


Installation and construction

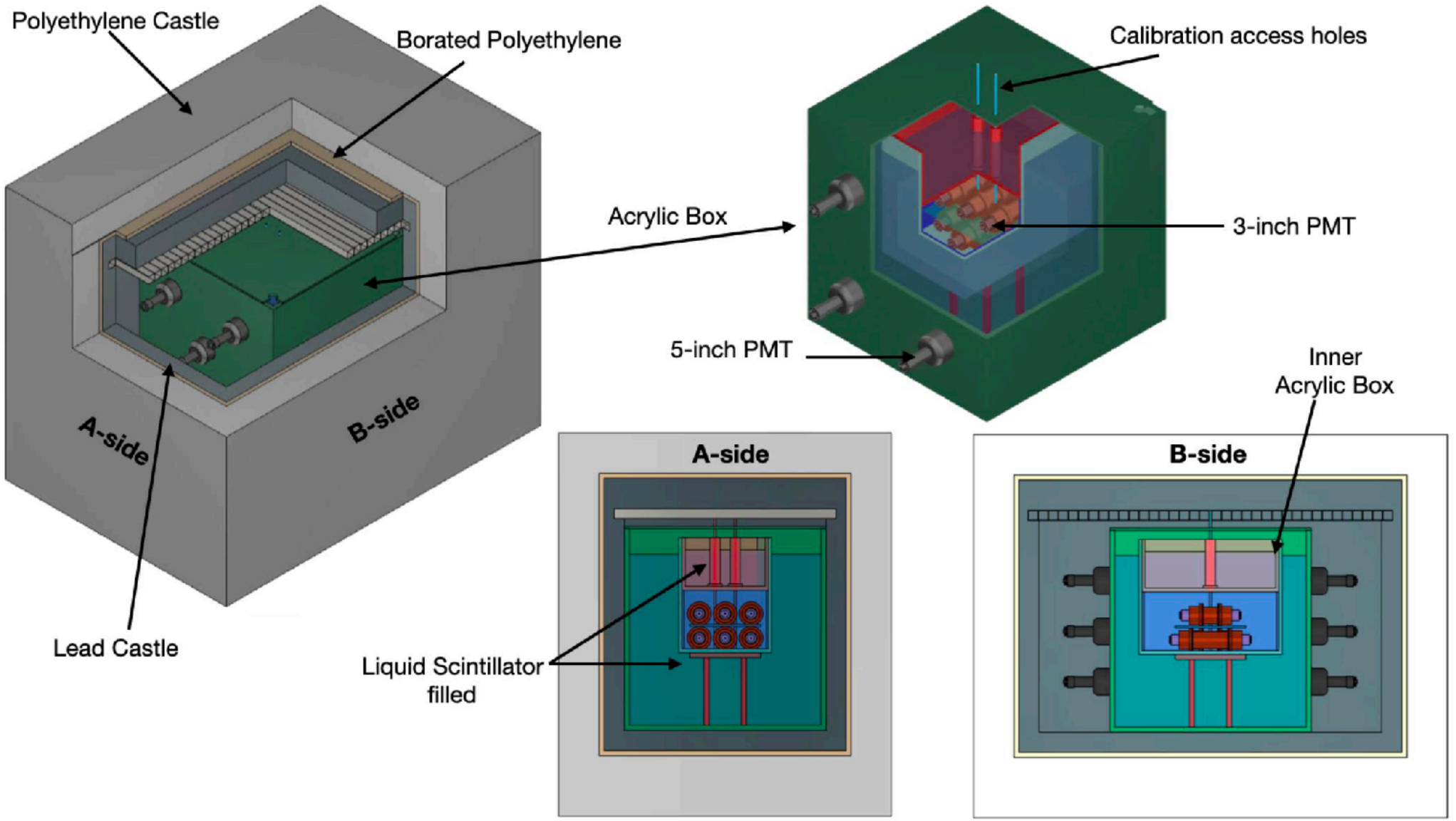








Construction of the NEON Experiment



Schedule for the NEON Experiment

- Assumption for sensitivity study
  - ✓ 22-photoelectrons/keV(PEs/keV) light yield
  - ✓ 13.5-kg mass of detector
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  - ✓ 5-PEs threshold
  - ✓ 365/100-days reactor-on/-off data

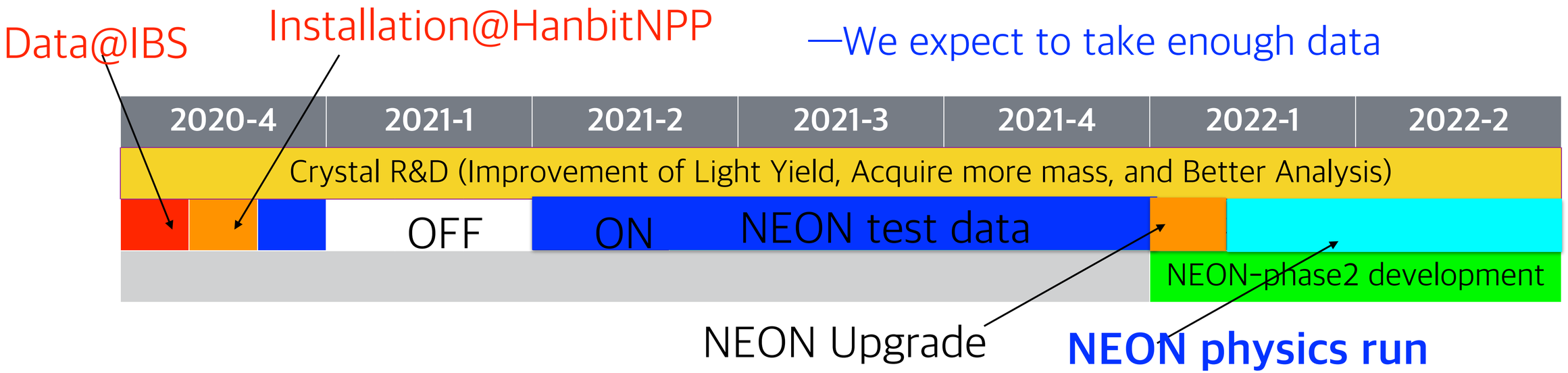
Can you actually do this?

—We have achieved high light yields and enough detector mass

—Currently the background is 6 dru between 2—6 keV

—Threshold needs to be improved further

—We expect to take enough data



Nuclear Non-proliferation

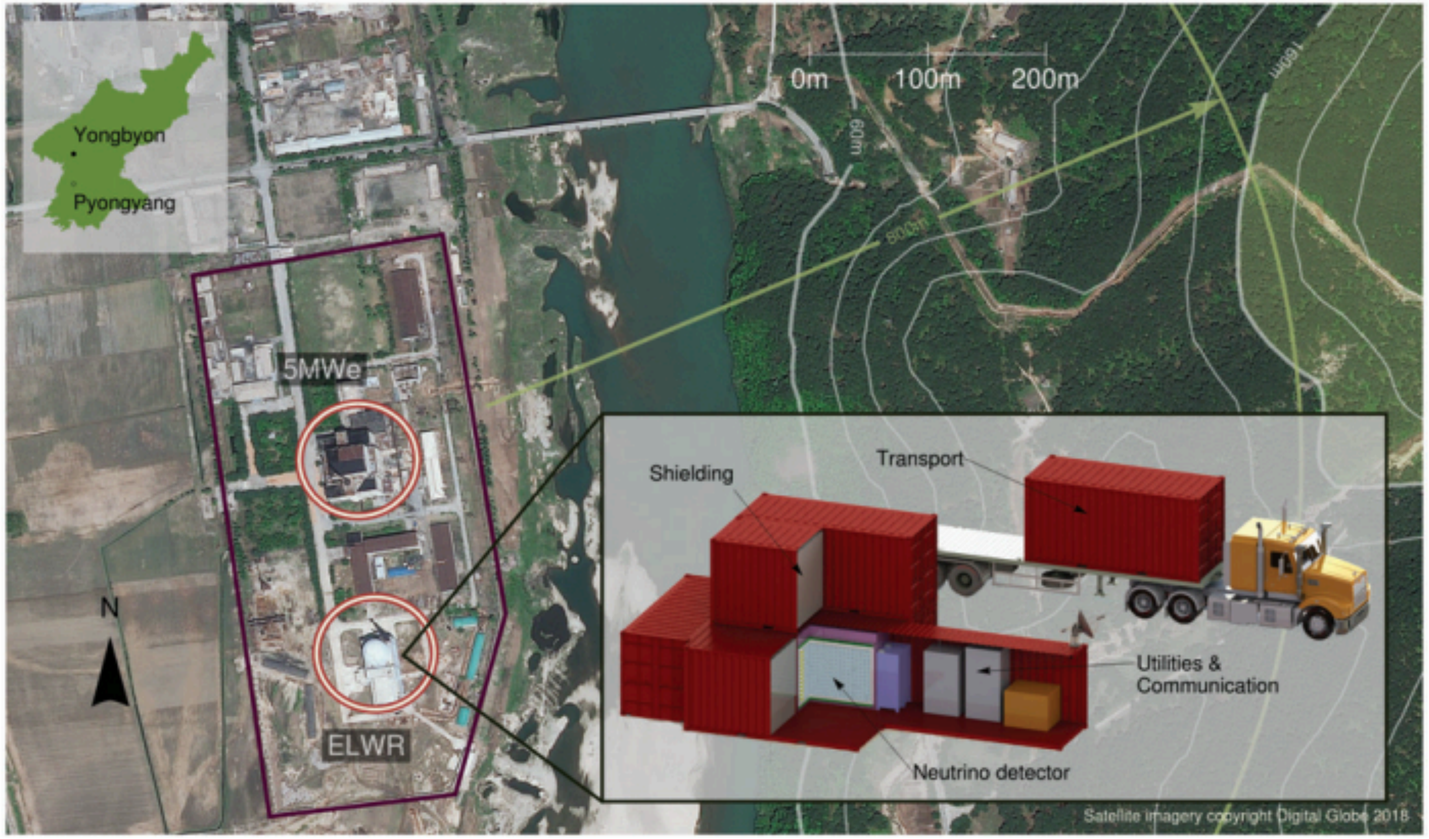
Original Articles

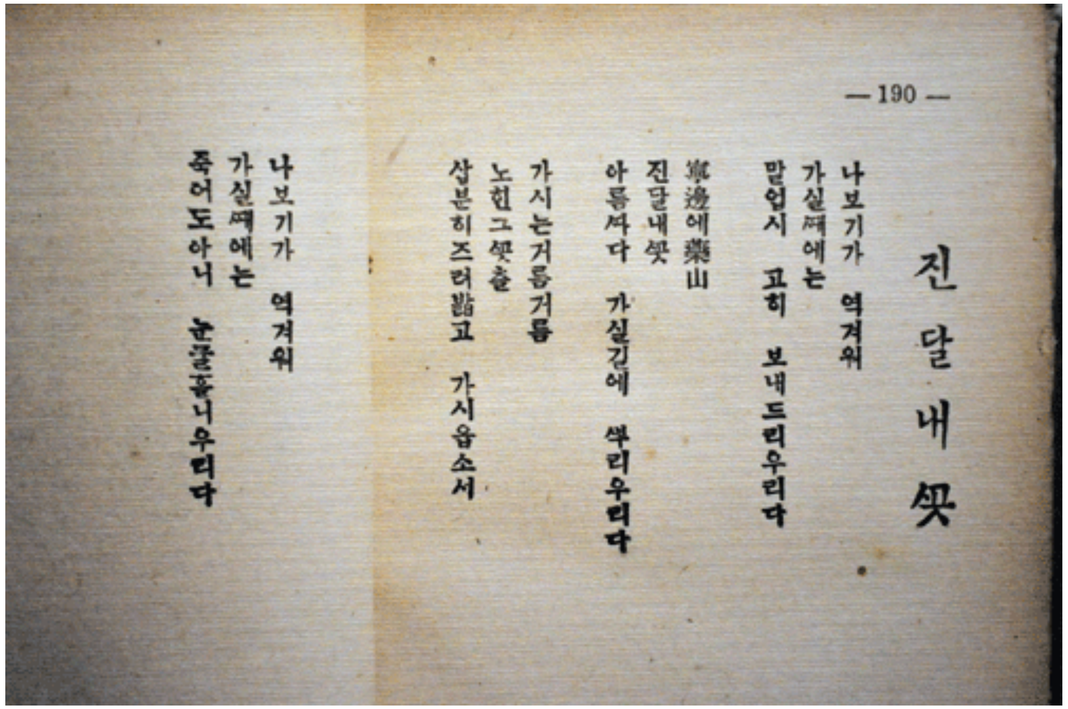
Neutrino-Based Tools for Nuclear Verification and Diplomacy in North Korea

Rachel Carr, Jonathon Coleman, Mikhail Danilov, Giorgio Gratta, Karsten Heeger, Patrick Huber, YuenKeung Hor, Takeo Kawasaki, Soo-Bong Kim, Yeongduk Kim, John Learned, Manfred Lindner, Kyohei Nakajima, James Nikkel, Seon-Hee Seo, Fumihiko Suekane, Antonin Vacheret, Wei Wang, James Wilhelmi & Liang Zhan ...show less

Pages 15-28 | Received 19 Dec 2018, Accepted 06 Mar 2019, Published online: 05 Jun 2019

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— 190 —

진 달 내 꽃

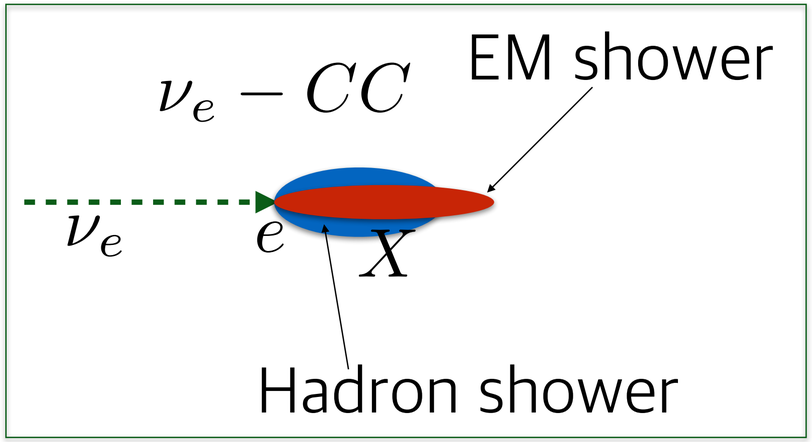
나보기가 역겨워
가실때에는
말업시 고히 보내드리우리다

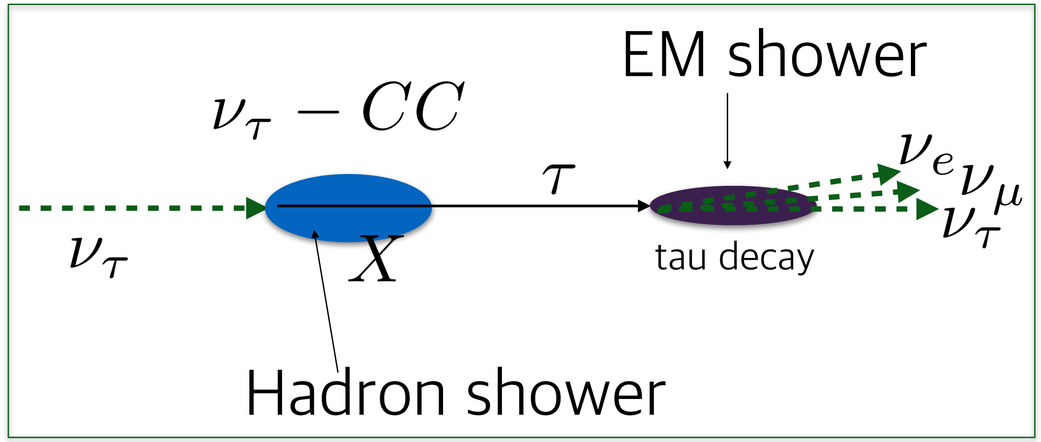
寧邊에藥山
진달내꽃
아름짜다 가실길에 색리우리다

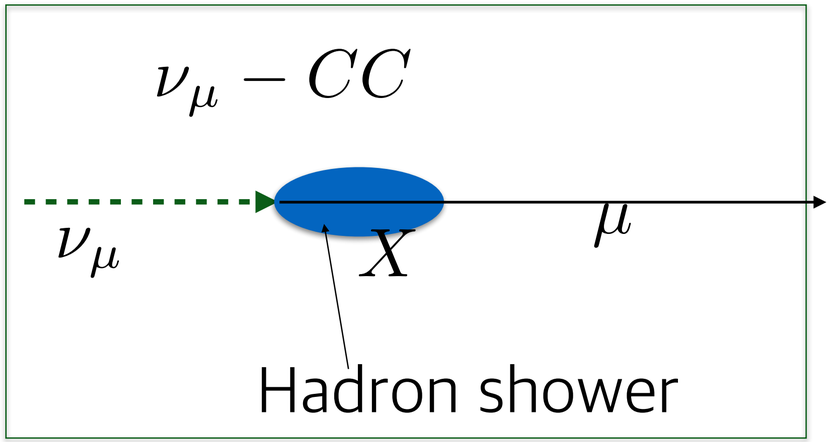
가시는거름거름
노힌그꽃츨
삽분히즈려밟고 가시옵소서

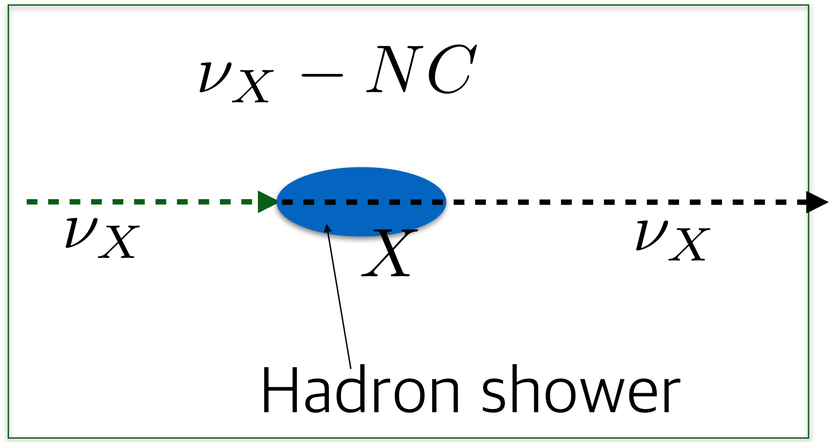
나보기가 역겨워
가실때에는
죽어도아니 눈물흘니우리다

Neutrino interactions at high energy



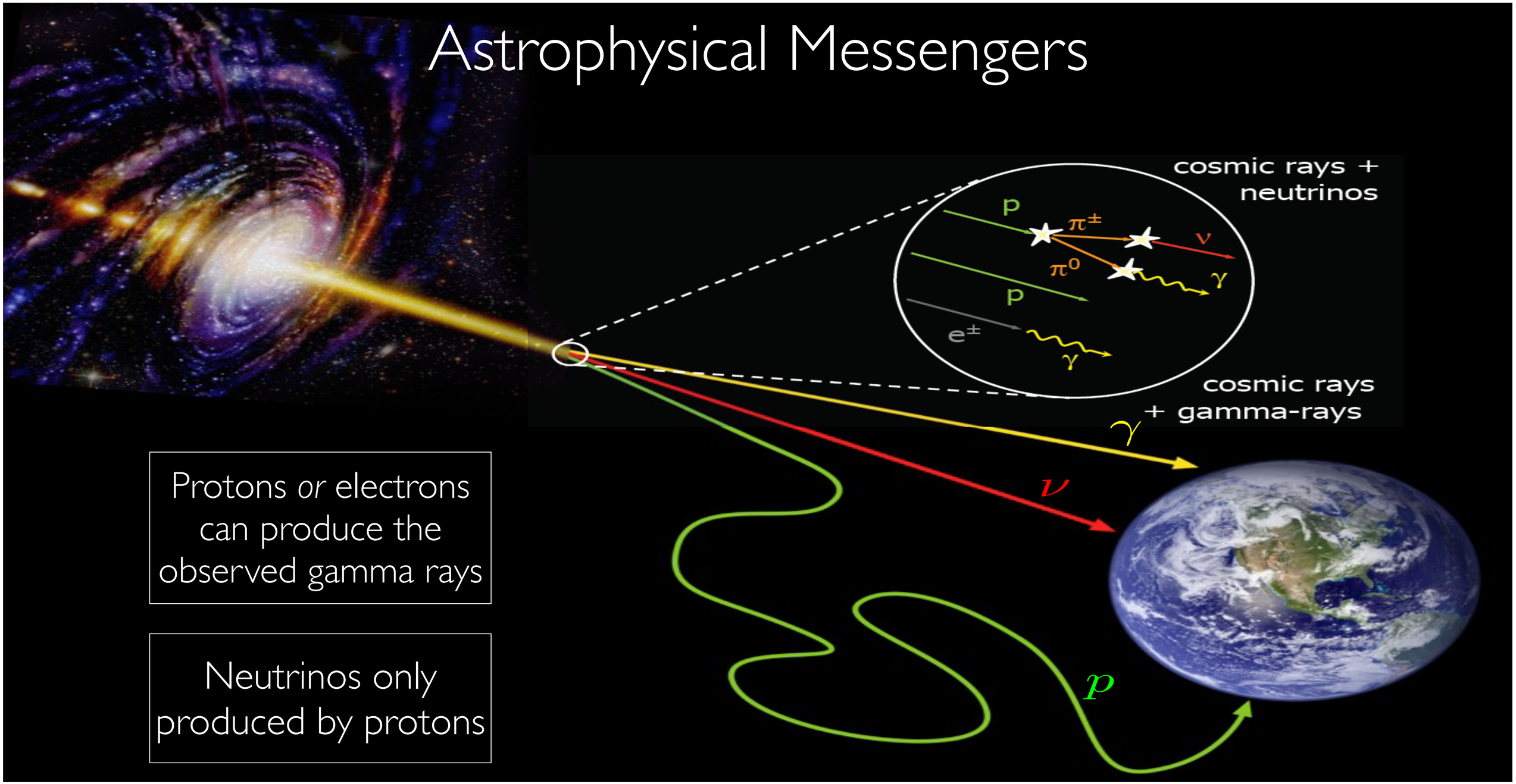






The electron from ν_e goes ~10 m while the muon from ν_μ goes forever for a few EeV ($10^{18}\ eV$) incident particle

Astrophysical Messengers

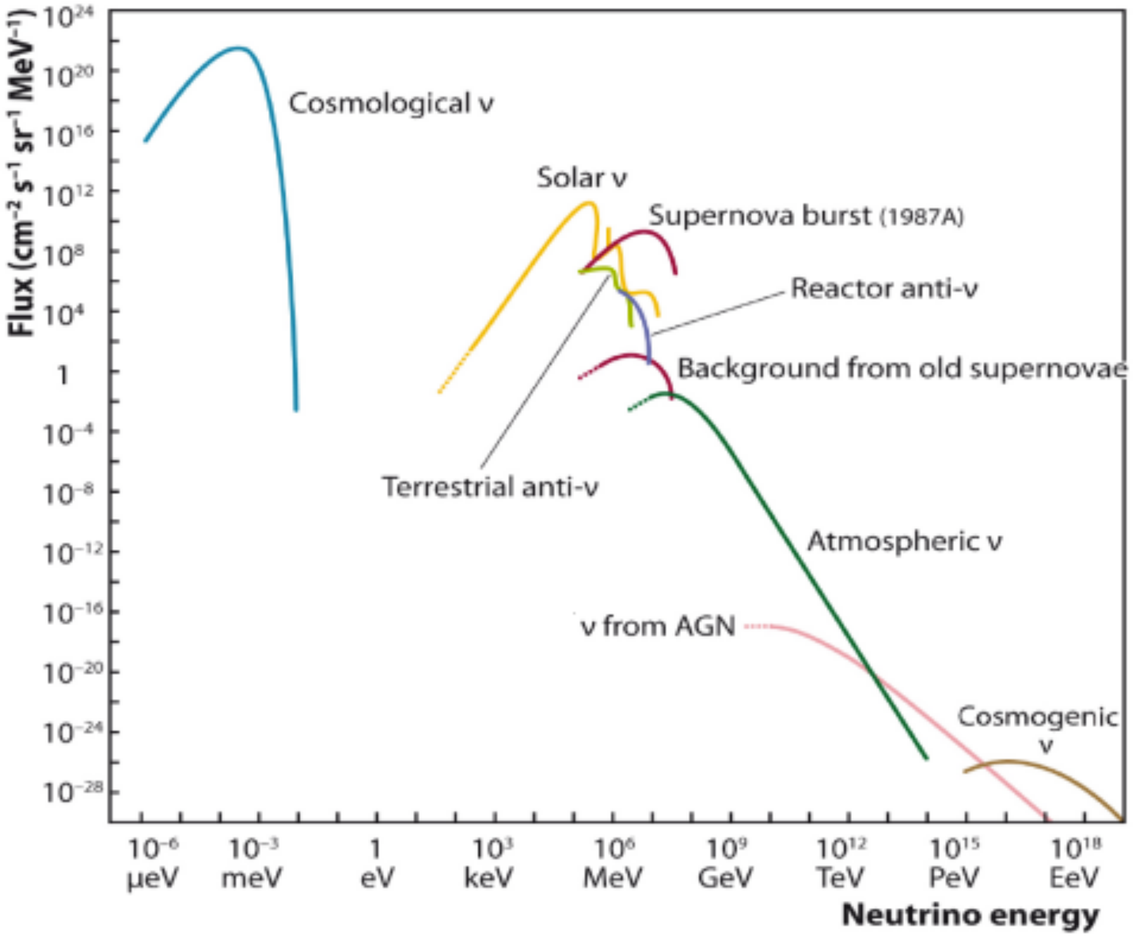


Protons *or* electrons can produce the observed gamma rays

Neutrinos only produced by protons

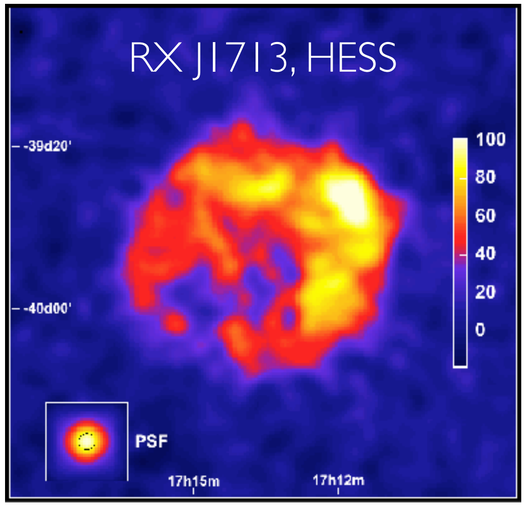
High Energy Neutrino Telescope

- Neutrinos are everywhere
  - Cosmic Rays, Atmosphere, Sun, Nuclear Reactor, Human etc.
  - e.g. Solar neutrino flux = 65,000,000,000 / sec / cm^2
- They interact rarely (weakly).
  - High energy neutrinos act as astrophysical messengers
  - Deliver original information directly but hard to catch
- Require a large, transparent body of natural medium, e.g. Water, or *Ice* to observe Cherenkov radiation
- When neutrinos interact near the detector, they produce secondary particles which are easier to detect.

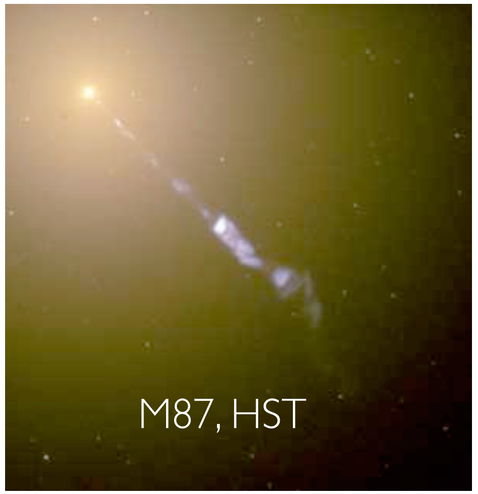


우주 중성미자는 어디서 올까?

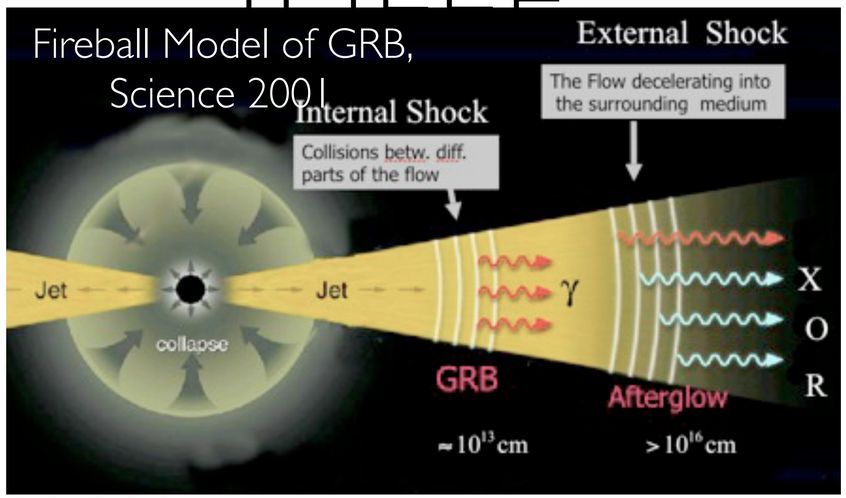
초신성 잔해



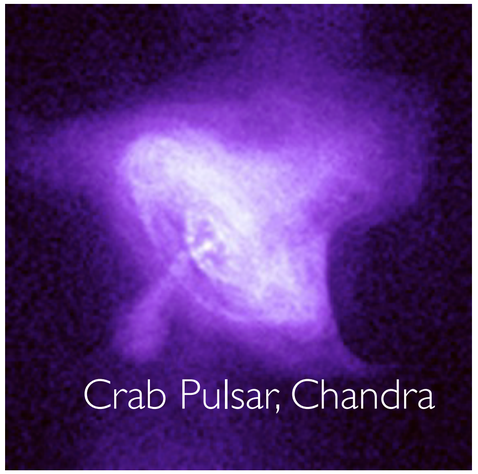
블랙홀 (Blazar)



감마선분출

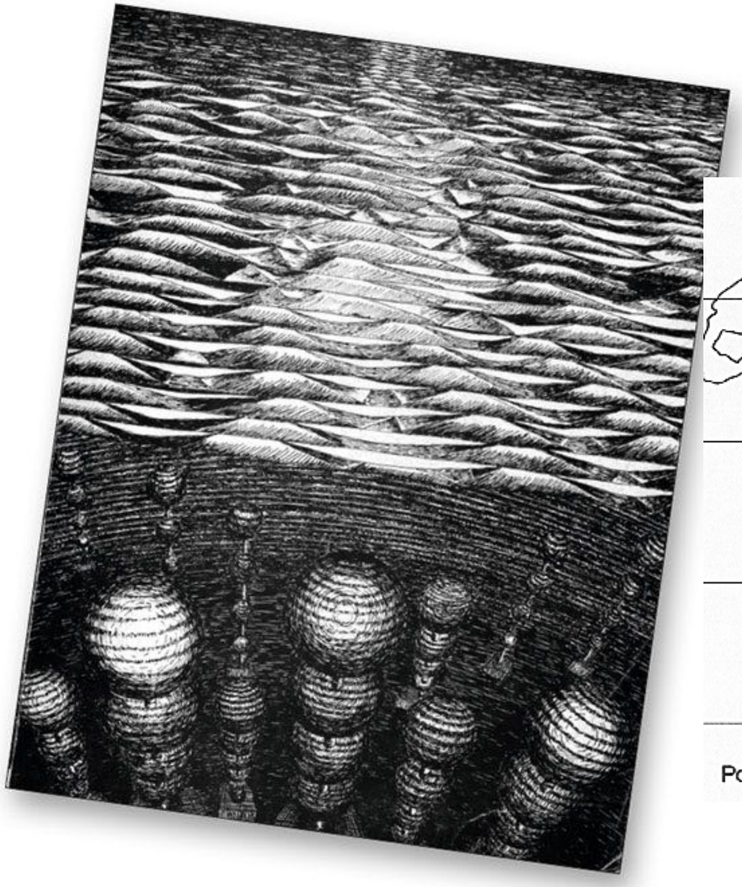


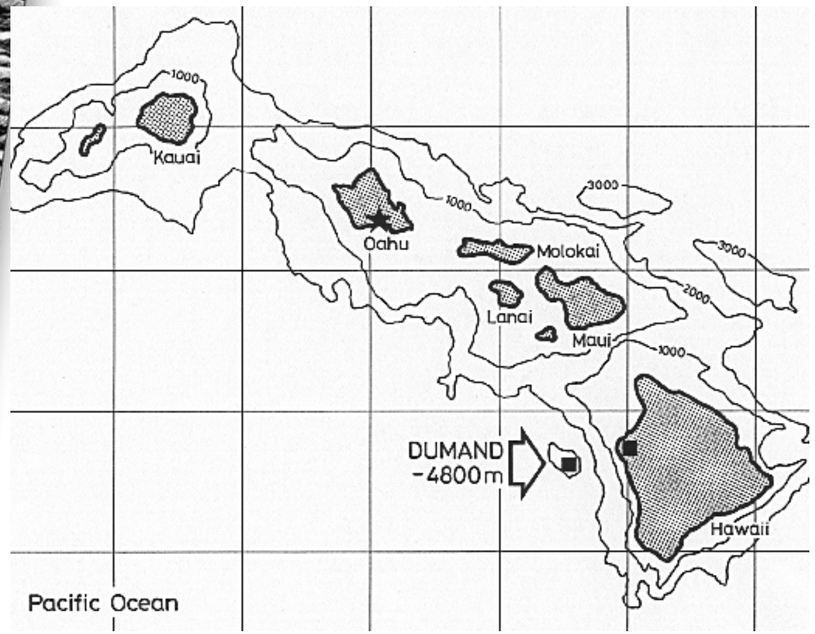
펄사



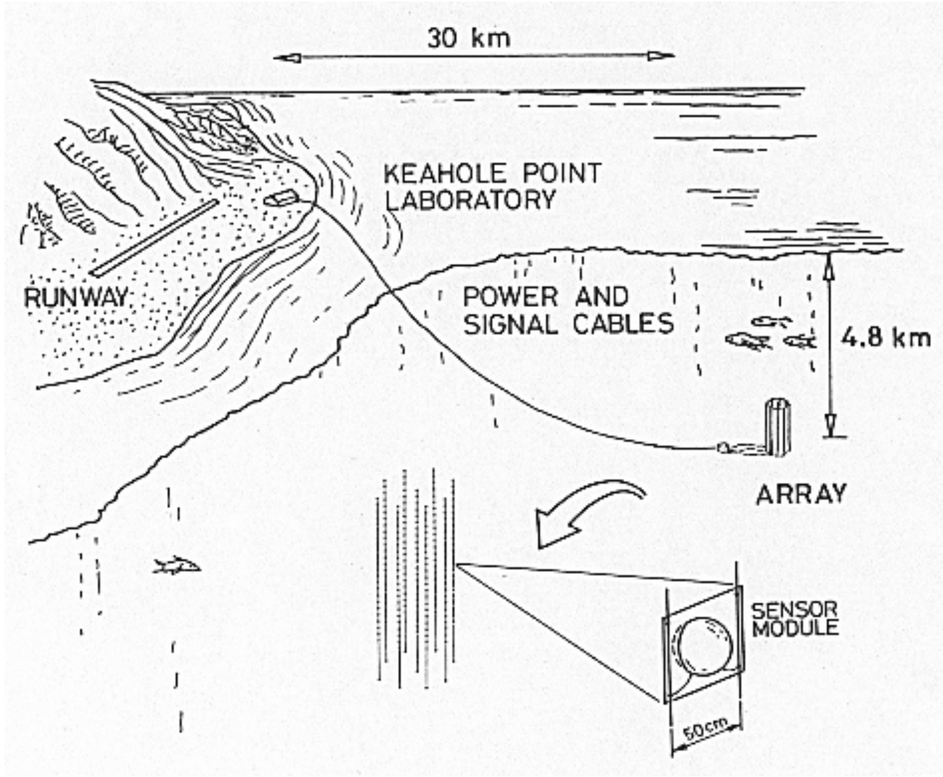
DUMAND (Deep Underwater Muon and Neutrino Detector)

1976 Meeting at Waikiki

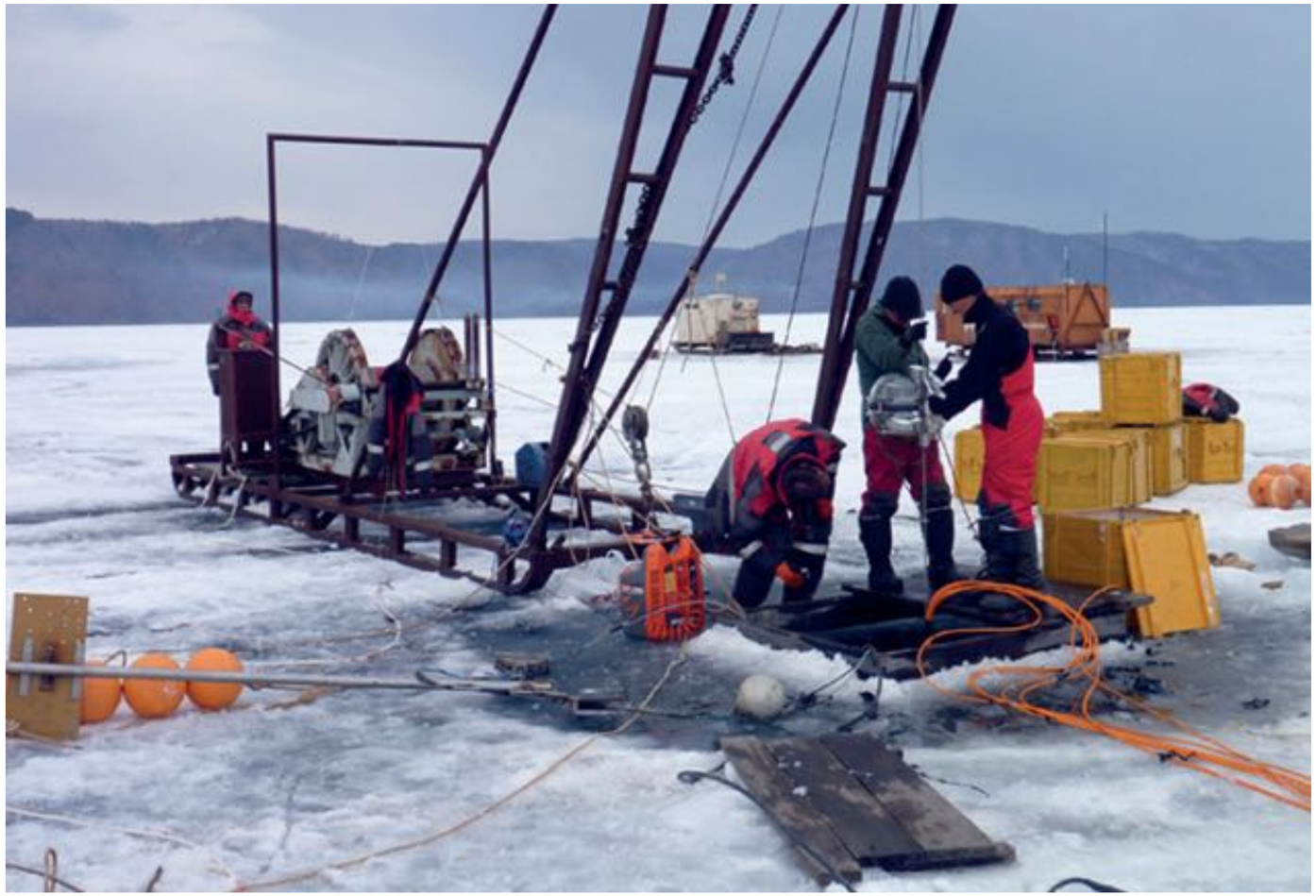




1995 Cancelled after the first deploy

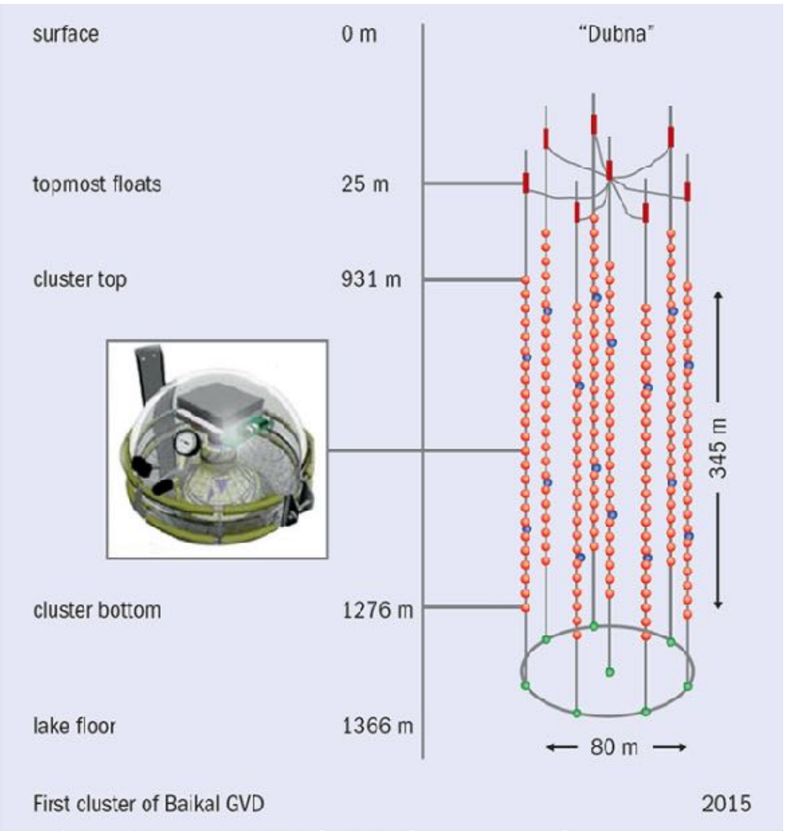


Baikal Collaboration



https://cerncourier.com/a/a-new-neutrino-telescope-for-lake-baikal/

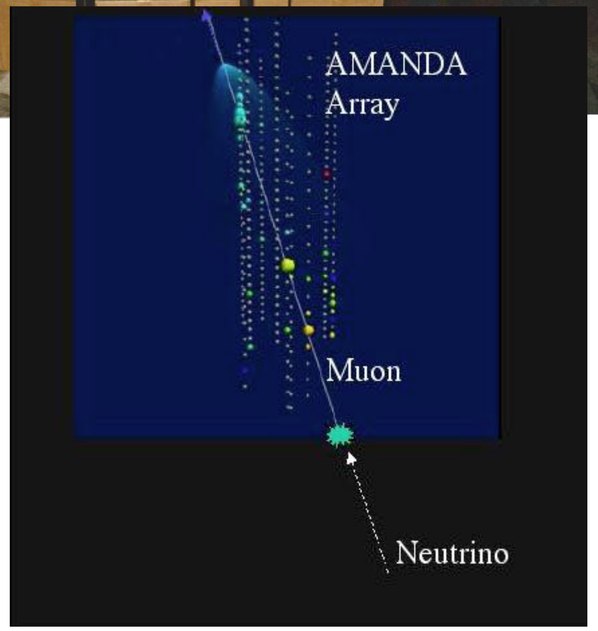


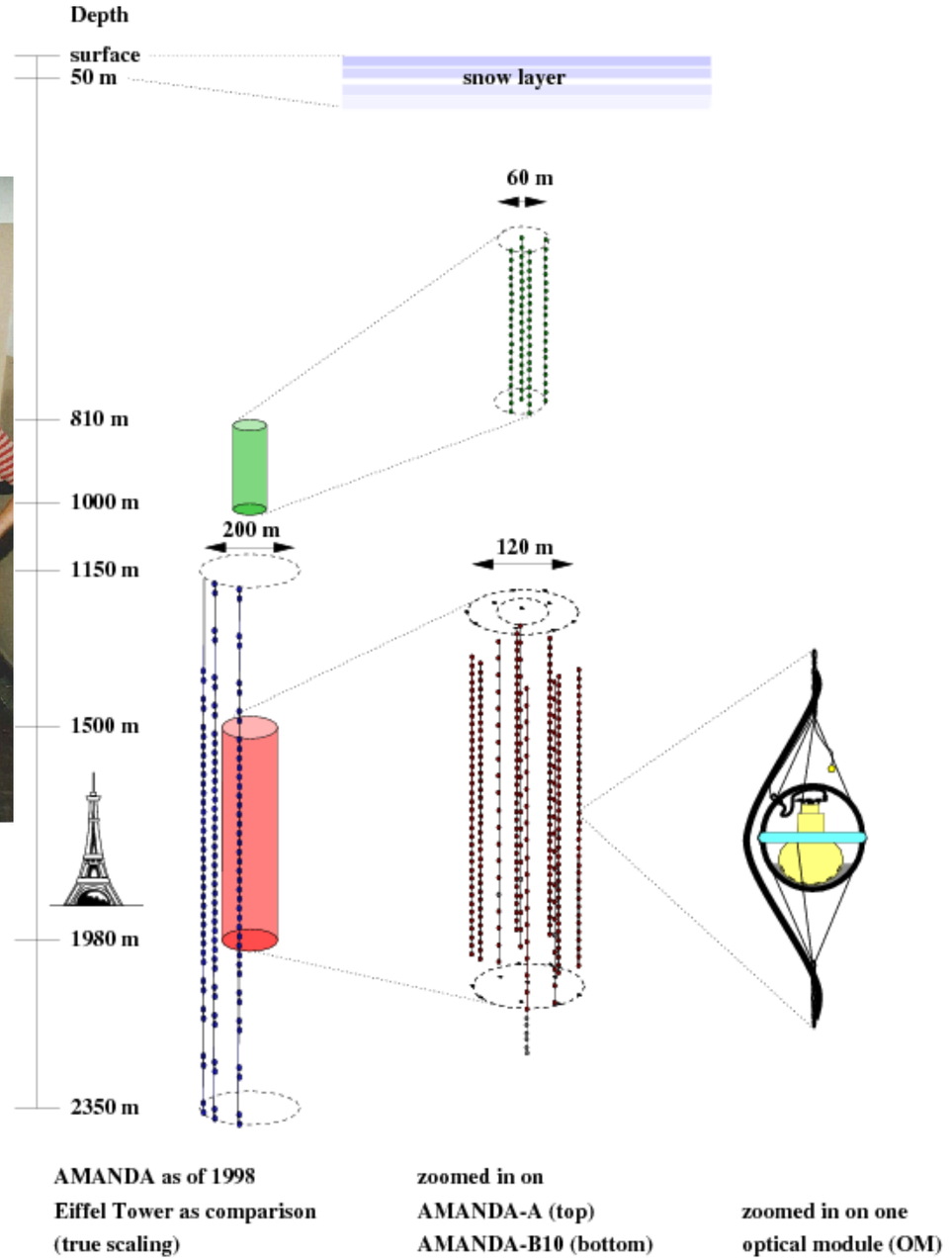


AMANDA Collaboration

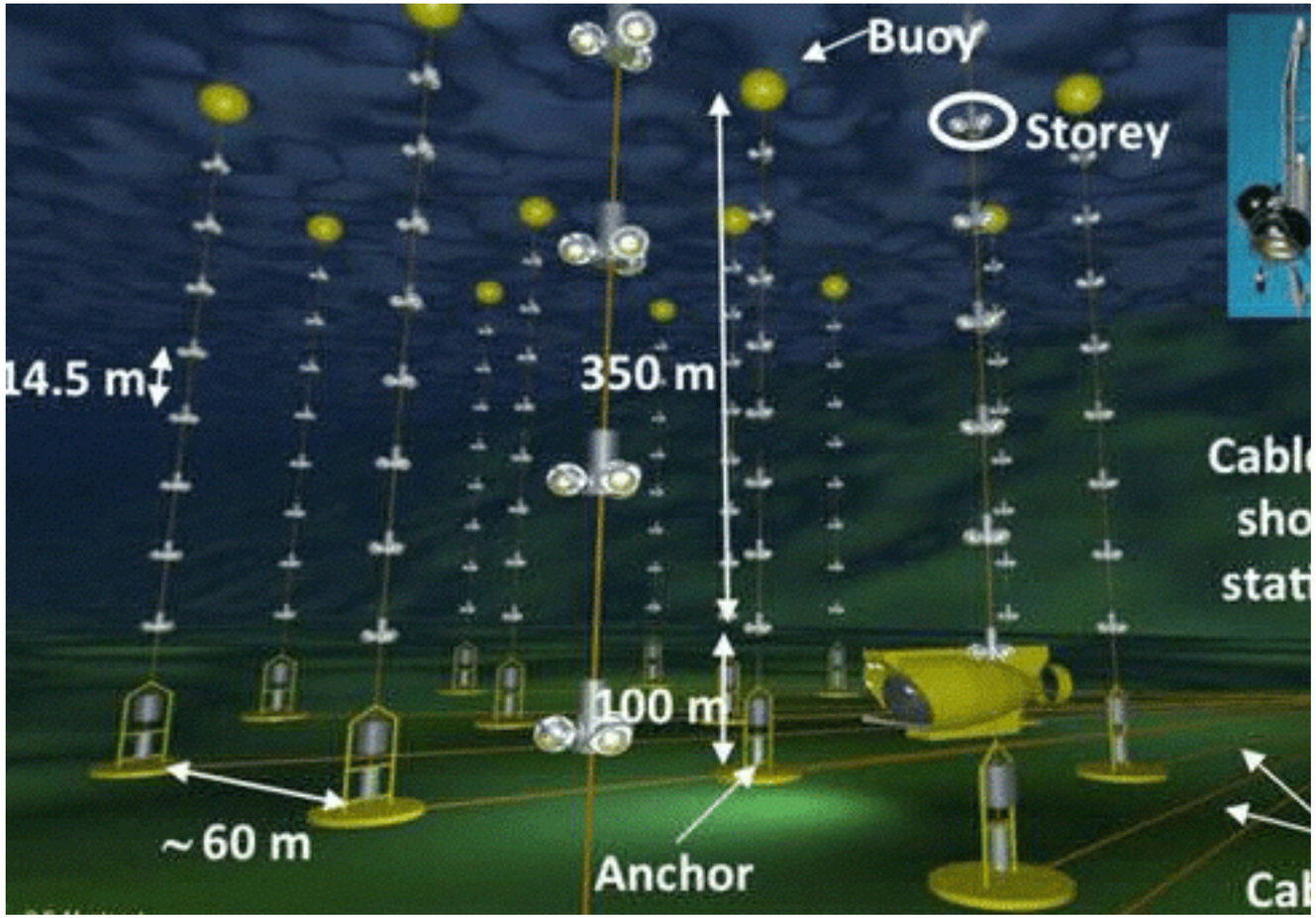


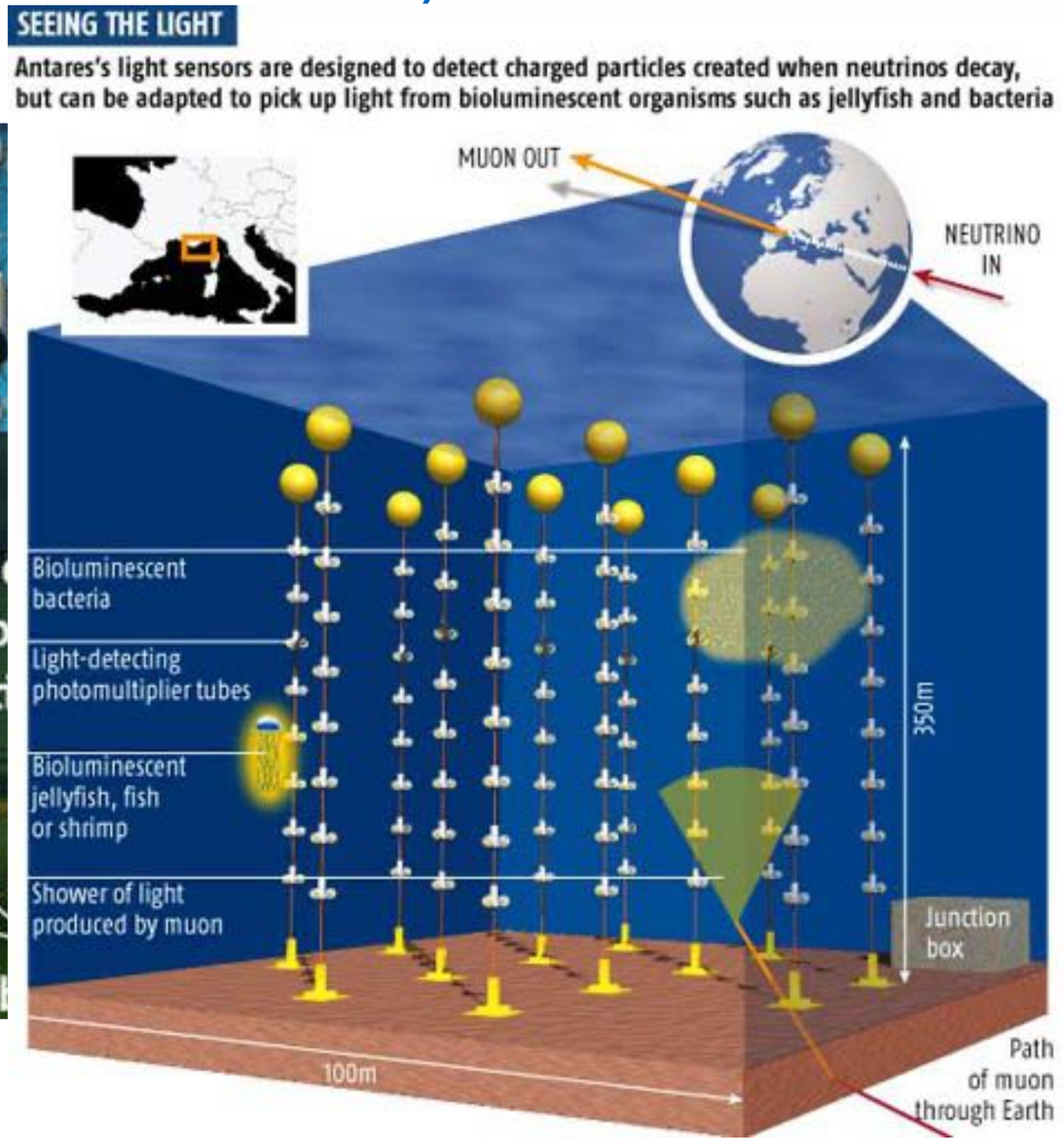




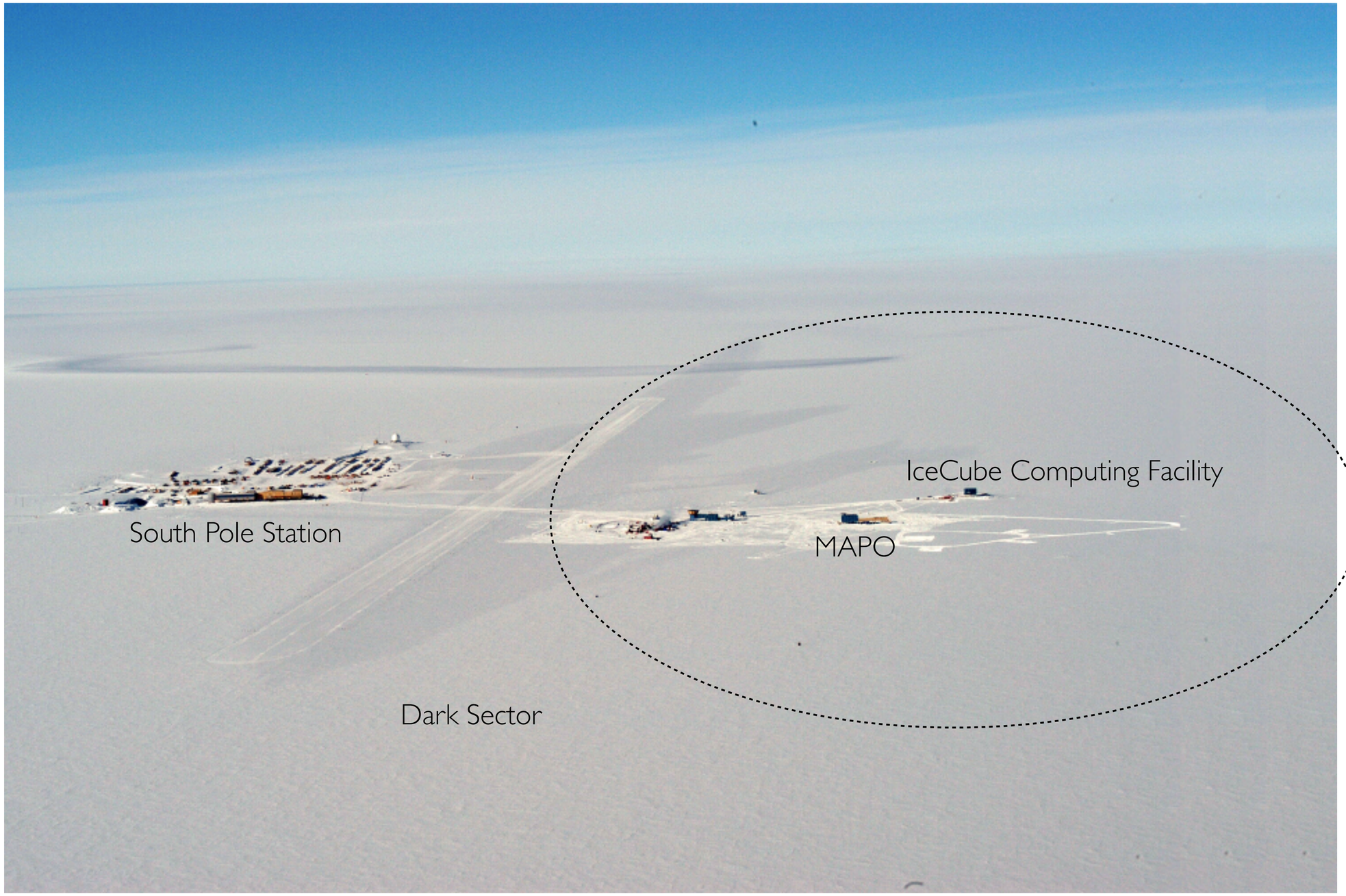


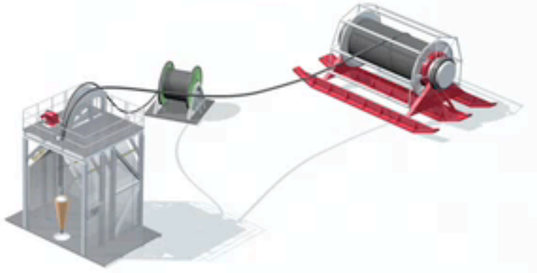
ANTARES Collaboration (KM3NeT/ORCA)



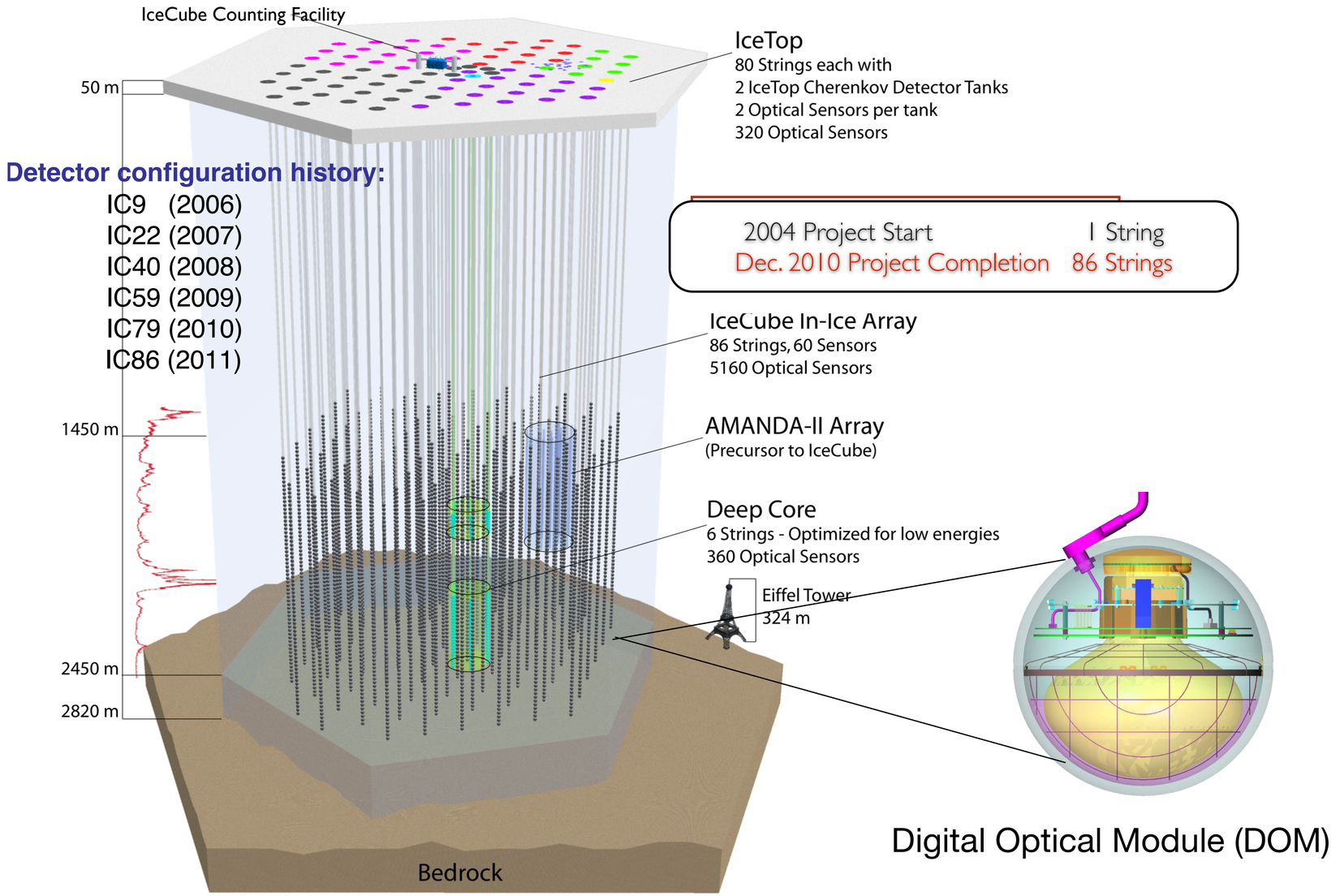



THE ICECUBE COLLABORATION
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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
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SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
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Sungkyunkwan University
+Chung-Ang University
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Stockholms universitet
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UNITED KINGDOM
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Marquette University
Massachusetts Institute of Technology
Mercer University
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The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
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ICECUBE
icecube.wisc.edu

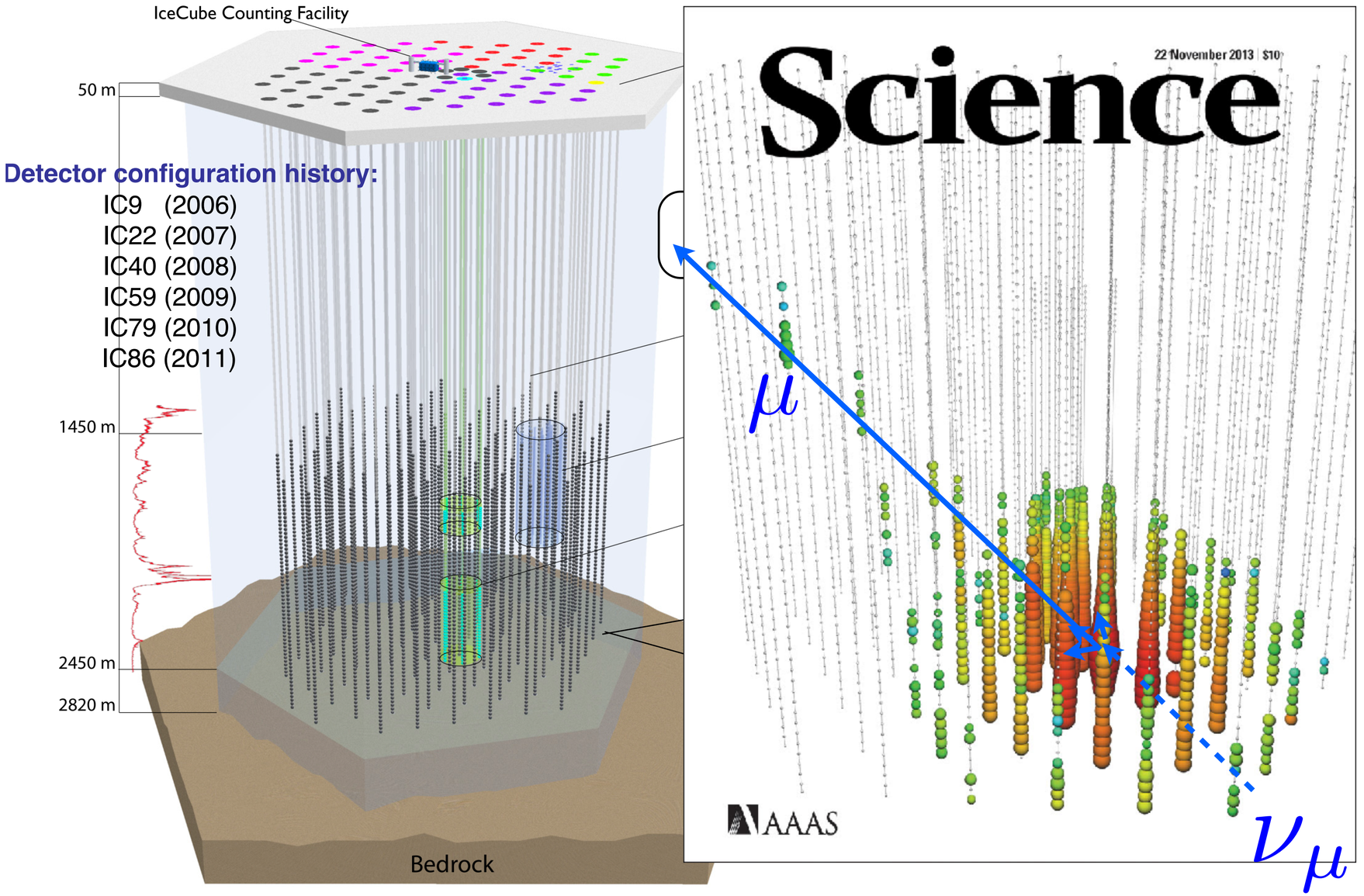

South Pole Station
IceCube Computing Facility
MAPO
Dark Sector



아이스큐브 실험

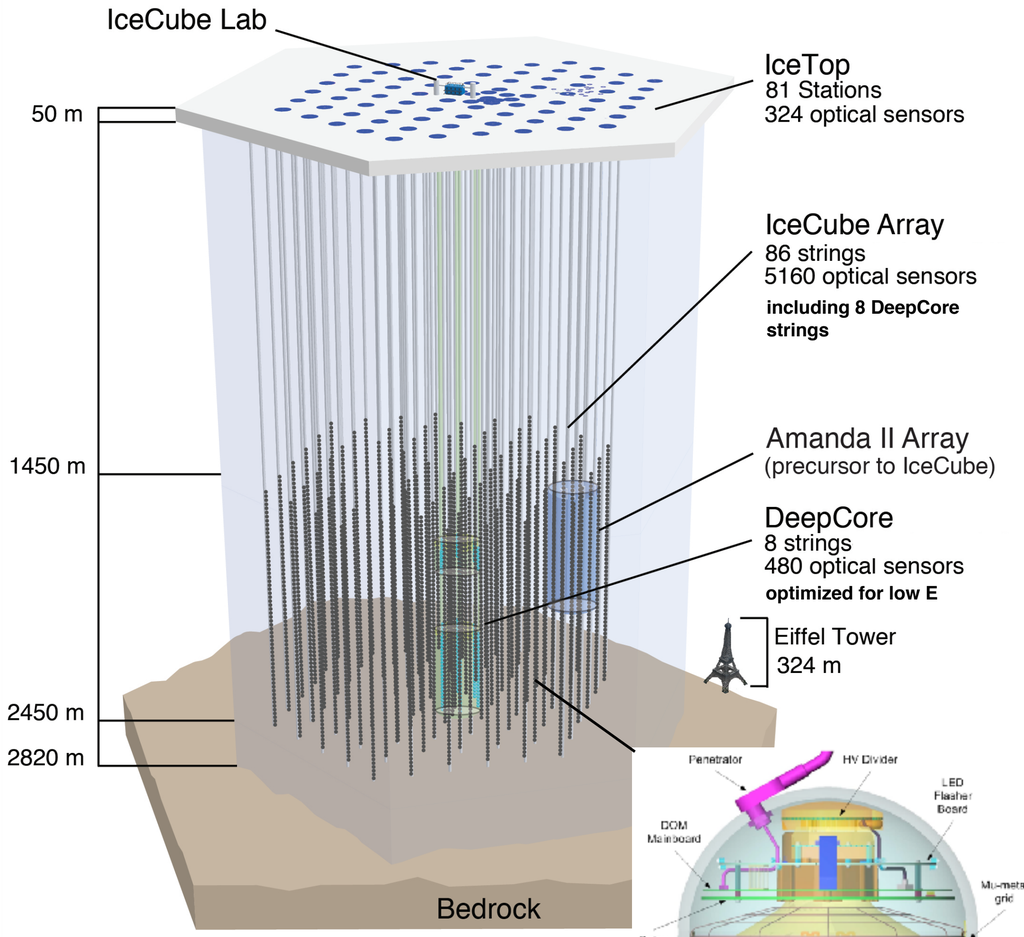

IceCube Counting Facility
50 m
IceTop
80 Strings each with
2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors
Detector configuration history:
IC9 (2006)
IC22 (2007)
IC40 (2008)
IC59 (2009)
IC79 (2010)
IC86 (2011)
2004 Project Start
1 String
Dec. 2010 Project Completion
86 Strings
IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors
1450 m
AMANDA-II Array
(Precursor to IceCube)
Deep Core
6 Strings - Optimized for low energies
360 Optical Sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock
Digital Optical Module (DOM)

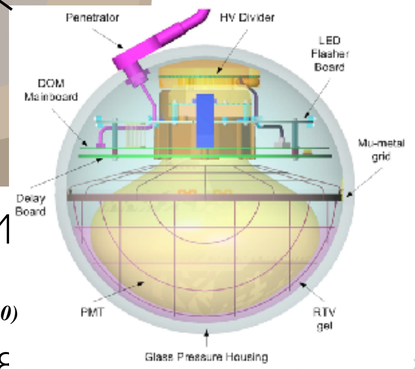
아이스큐브 실험


IceCube Counting Facility
50 m
Detector configuration history:
IC9 (2006)
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IC79 (2010)
IC86 (2011)
1450 m
2450 m
2820 m
Bedrock
Science
22 November 2013 | $10
AAAS
μ
ν_μ

IceCube : 1 km^3 Neutrino Telescope

- Detects Cherenkov photons in ice from charged particles created by high-E neutrino interactions
- 5160 Digital Optical Modules (DOMs) with a 10 inch PMT on 86 vertical strings
- IceTop air shower array
  - 162 Tanks each with 2 DOMs
- Low-E ($E_{threshold}$ ~ 10 GeV) DeepCore array
  - 8 strings include high quantum efficiency DOMs

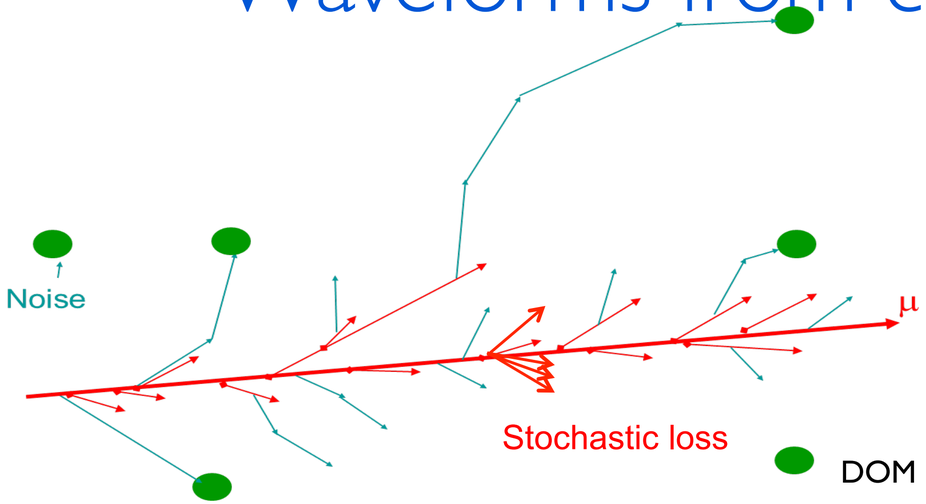




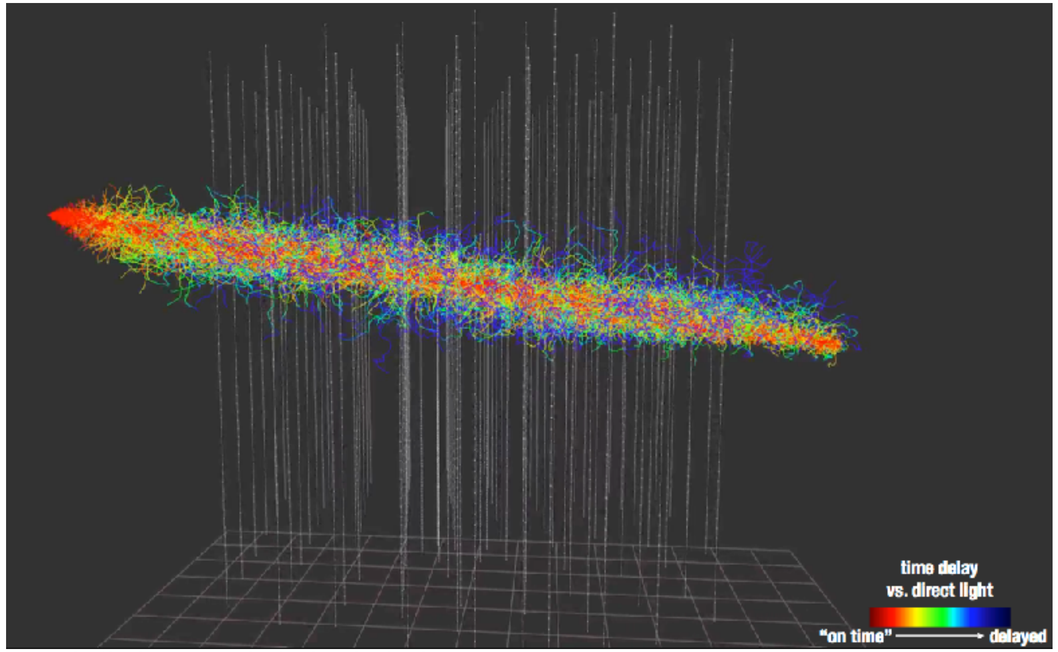
DOM

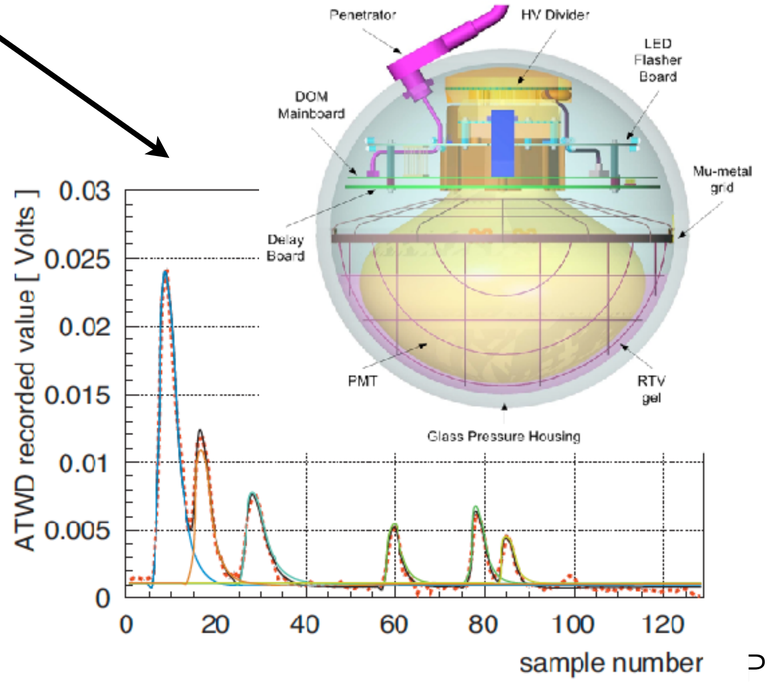
F. Halzen and S. R. Klein. Rev. Sci. Instrum. 81, 081101 (2010)

Waveforms from charged particles in ice

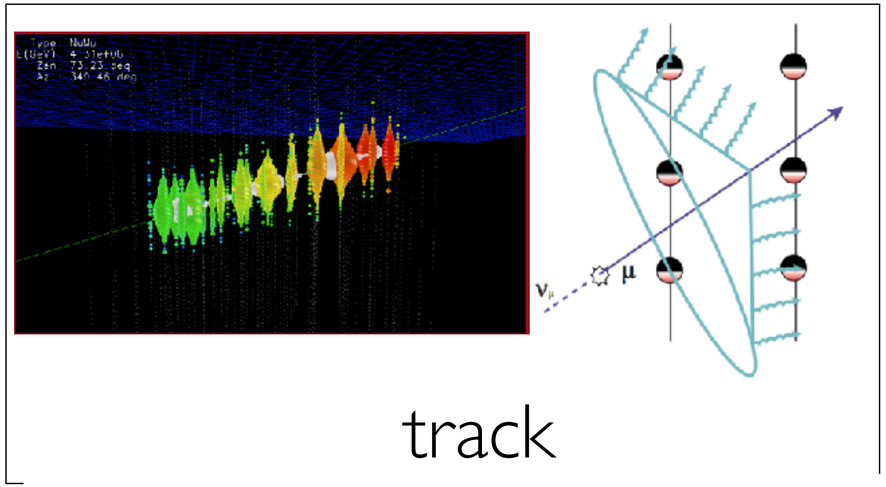


- Charged particles produce radiation from ionizations and stochastics in ice
- DOMs digitize the PMT waveforms of photoelectrons
- Arrival time and recorded charge information used to reconstruct events

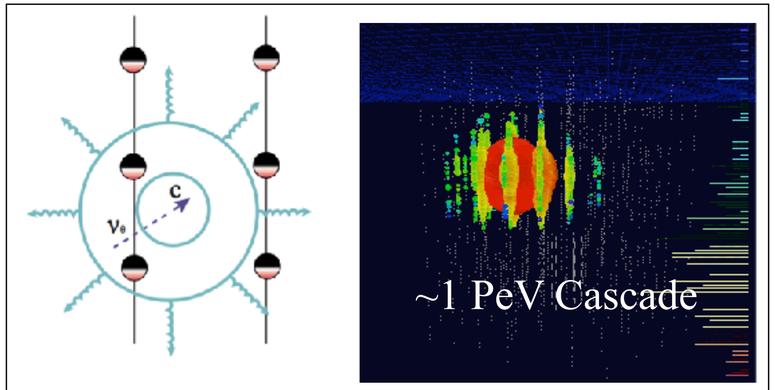




Detection Methods - Cherenkov Radiation



track



cascade

symbols	process	signature	note
ν_μ^{CC}	$\nu_\mu + N \rightarrow \mu + X$	track	cascade+track if contained
ν_e^{CC}	$\nu_e + N \rightarrow e + X$	cascade	E.M. shower + Hadronic shower
ν_τ^{CC}	$\nu_\tau + N \rightarrow \tau + X$	cascade	tau travels ~50 m at 1 PeV
ν_α^{NC}	$\nu_\alpha + N \rightarrow \nu_\alpha + X$	cascade	$\alpha = \mu, e, \tau$

N= Target Nucleon and X = Hadronic Shower

Neutrinos and Cosmic Rays

Needle in a needle stack?

What we see	Type	Direction	How many
Atmospheric Muon	Background	Downward-going	66,000,000,000 / year
Atmospheric Neutrino	Background	Upward-going	74,000 / year
Astrophysical Neutrino	Signal	Upward-going	10/year maybe?



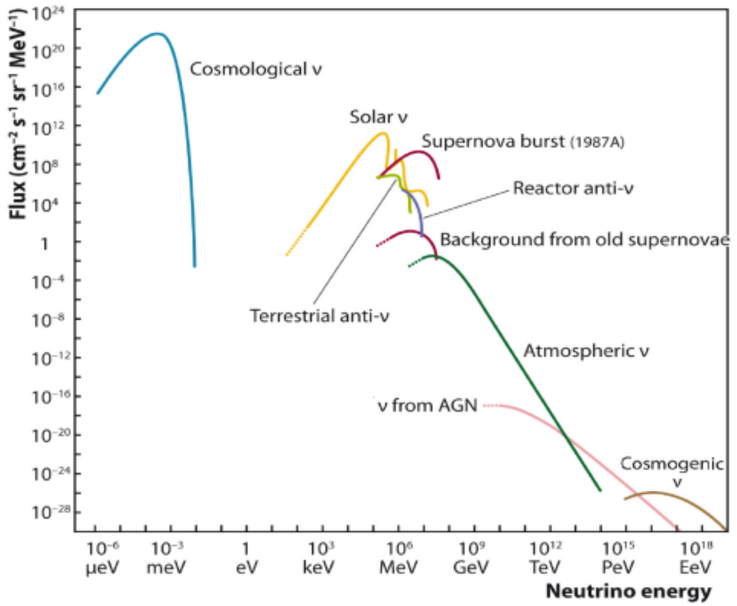
needle in a haystack



needle in a needle stack

Needle in a needle stack?

What we see	Type	Direction	How many
Atmospheric Muon	Background	Downward-going	66,000,000,000 / year
Atmospheric Neutrino	Background	Upward-going	74,000 / year
Astrophysical Neutrino	Signal	Upward-going	10/year maybe?

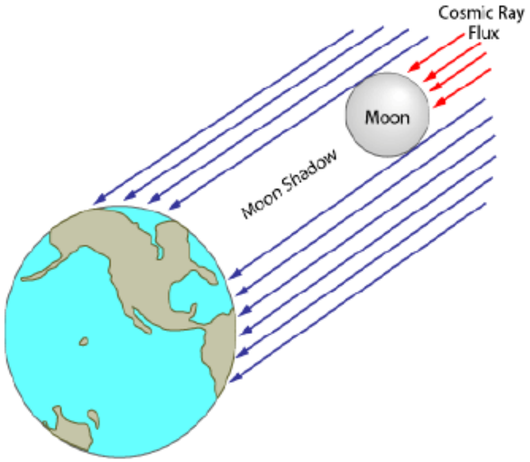




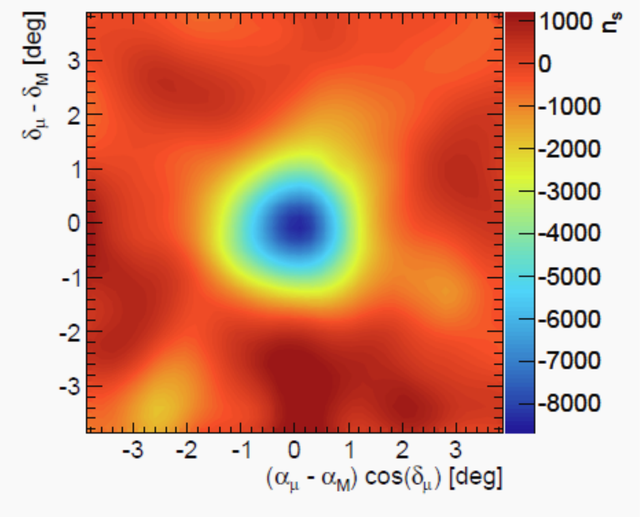
needle in a needle stack

IceCube Detector Performance

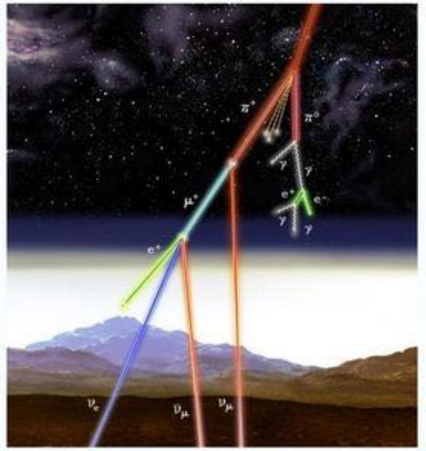
- The full detector (86 strings) has been running for more than 10 years
- IceCube built on time, on budget, and exceeds design requirements
  - 5160 Sensors are deployed, only 1.5% not taking data
  - 99% up-time
- Cosmic ray muon Moon shadow verifies ~1° pointing resolution
- Understanding optical properties in ice is an ongoing calibration effort (arXiv:1301.5361, NIM. A711 (2013) 73)
- High-E sample ~7 X 10^4 ν_μ per year (1.3 event per 10 min) at final analysis level (<E>~1TeV).
- Low-E sample (DeepCore) ~10^4 ν_μ per year at final (<E>~30 GeV)



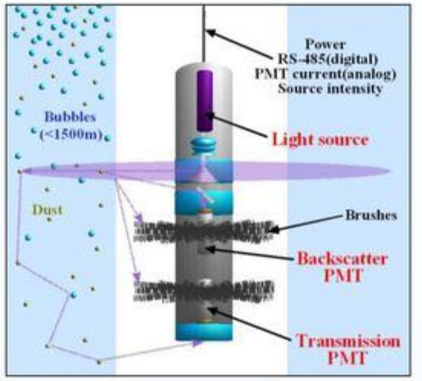
Phys. Rev. D 89, 102004 (2014) arXiv:1305.6811



IceCube Calibration Devices



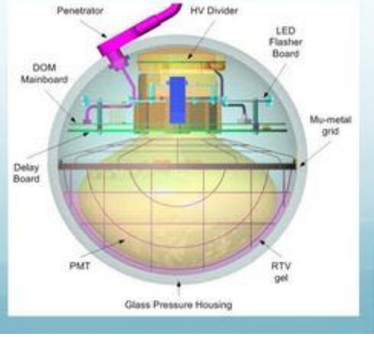
Muons from cosmic ray-induced air showers



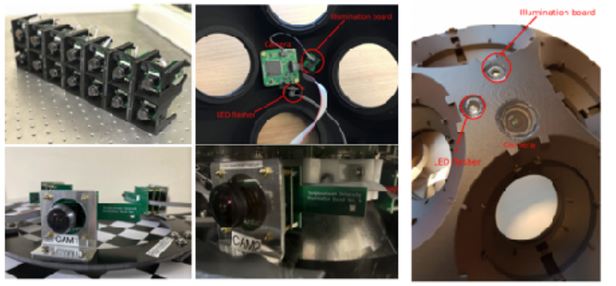
Dust logger (8 locations)



2 nitrogen laser "standard candles"

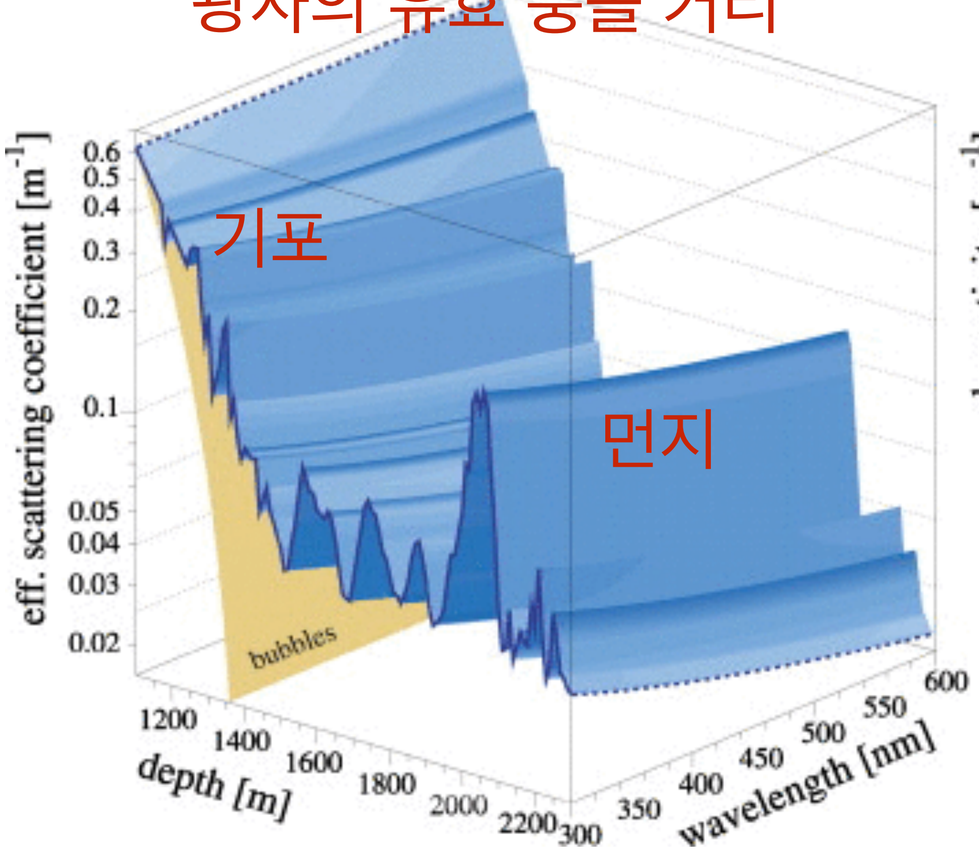


12 LED
aboard each DOM



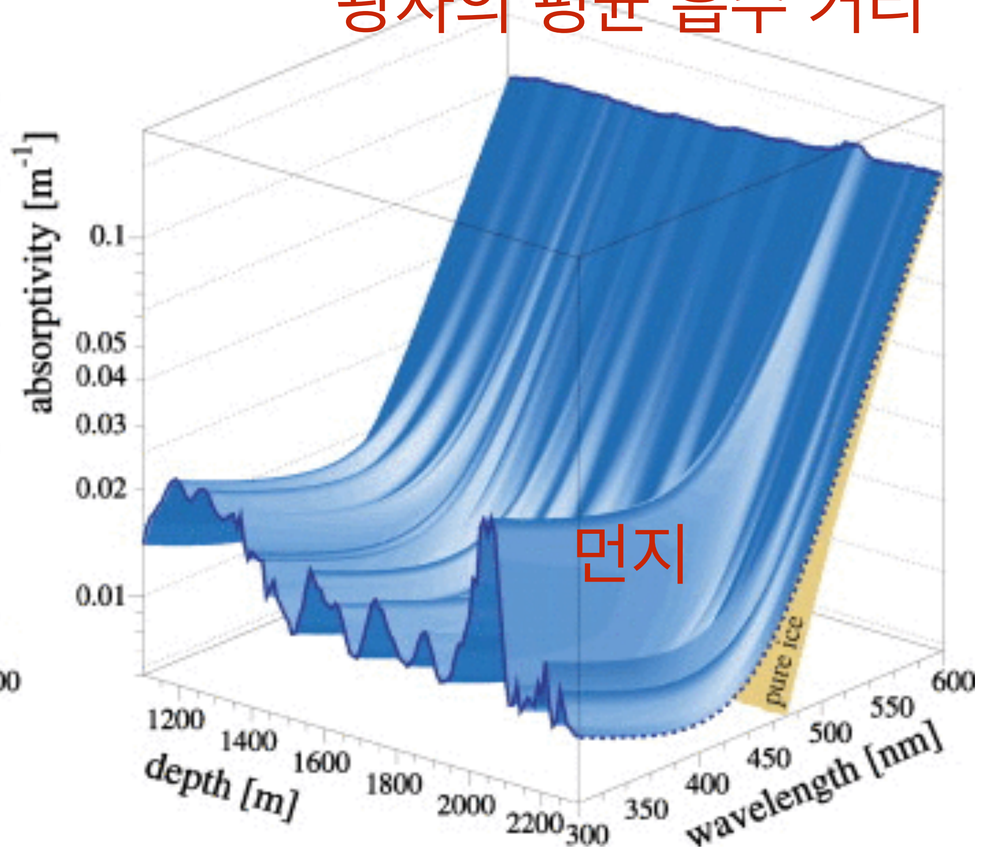
Polar Ice Optical Properties

광자의 유효 충돌 거리



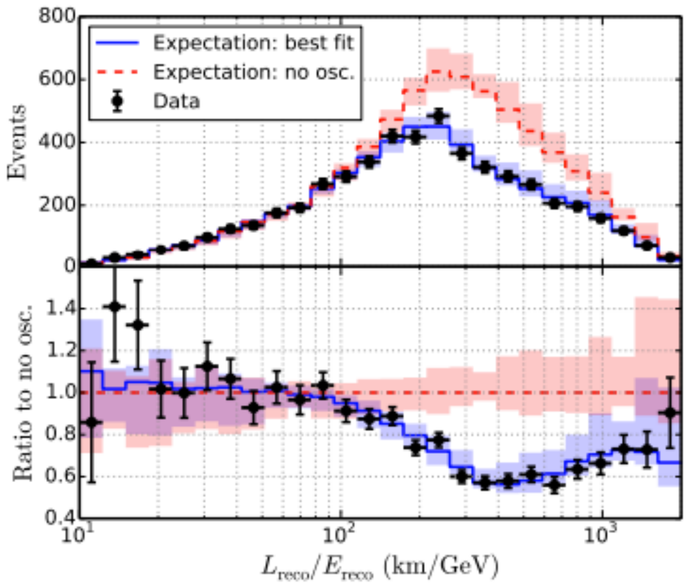
$$\lambda_{scatt} \sim 20\ m @ 400\ nm$$

광자의 평균 흡수 거리



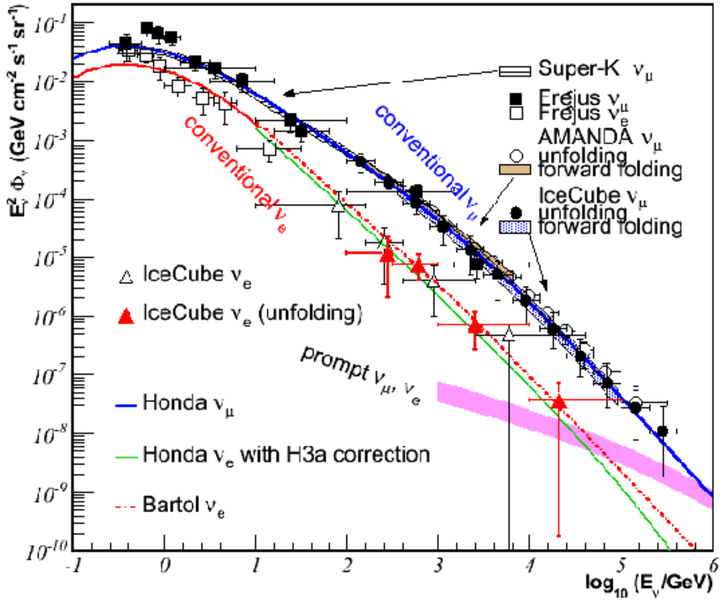
$$\lambda_{abs} \sim 110\ m @ 400\ nm$$

IceCube 검출기를 이용한 다양한 물리 프로그램



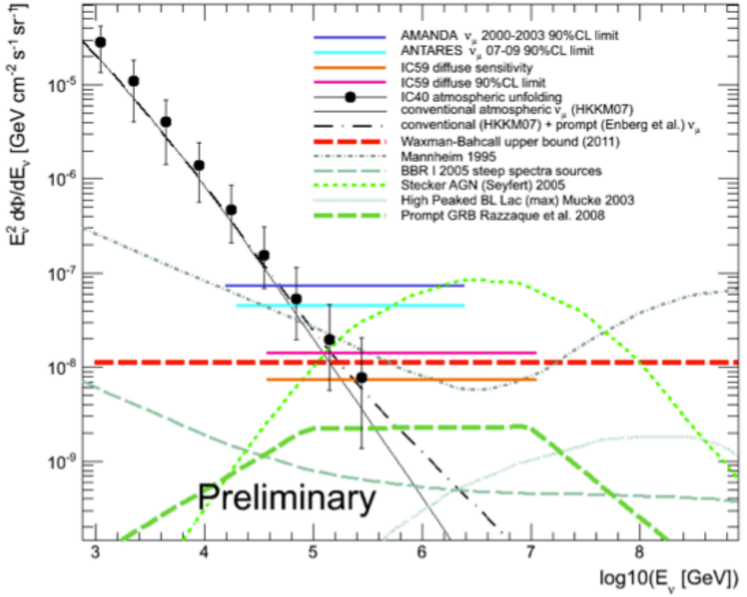
Phys. Rev. Lett. arXiv:1410.7227

중성미자 진동에 대한 측정



PHYSICAL REVIEW D **90,** 023009 (2014)

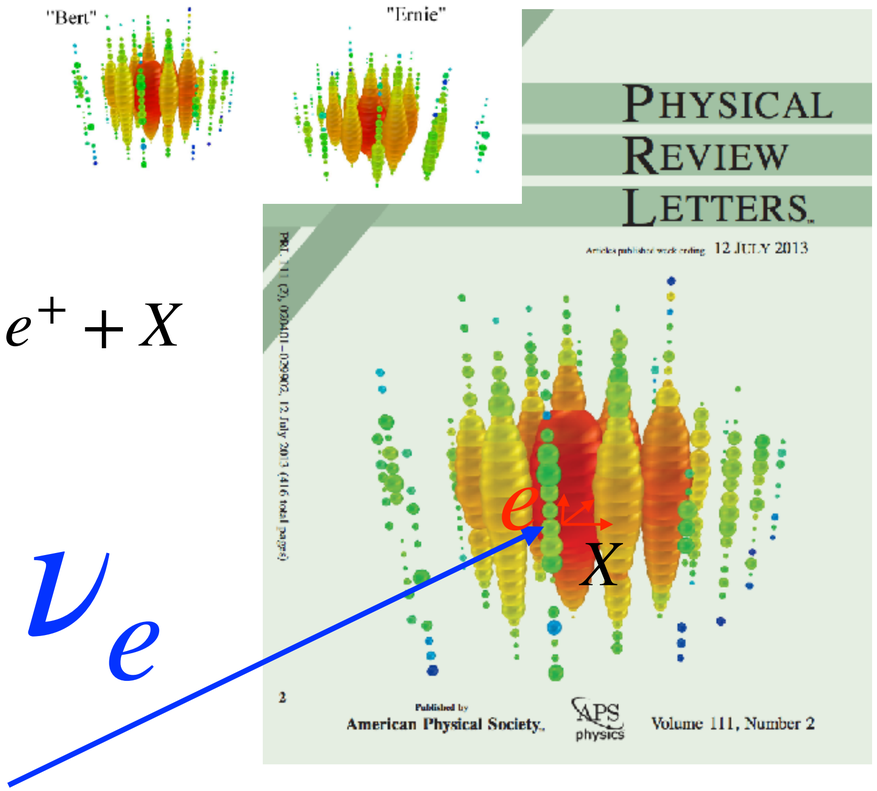
대기에서 발생하는 중성미자 스펙트럼



우주에서 오는 중성미자 탐색

Sesame Street Muppets on the covers

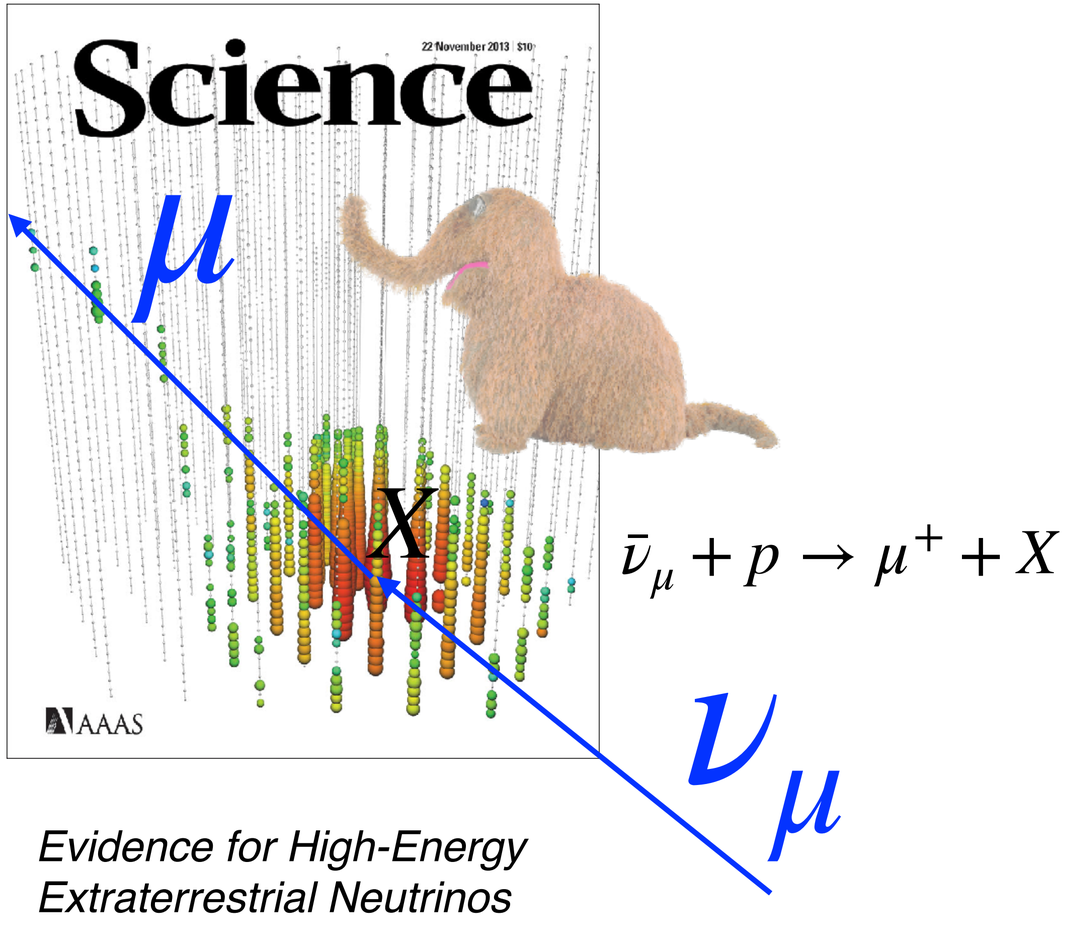




$$\bar{\nu}_e + p \rightarrow e^+ + X$$

Observation of PeV-Energy Neutrinos

Physical Review Letters 111 (2013) 021103 [arXiv:1304.5356]

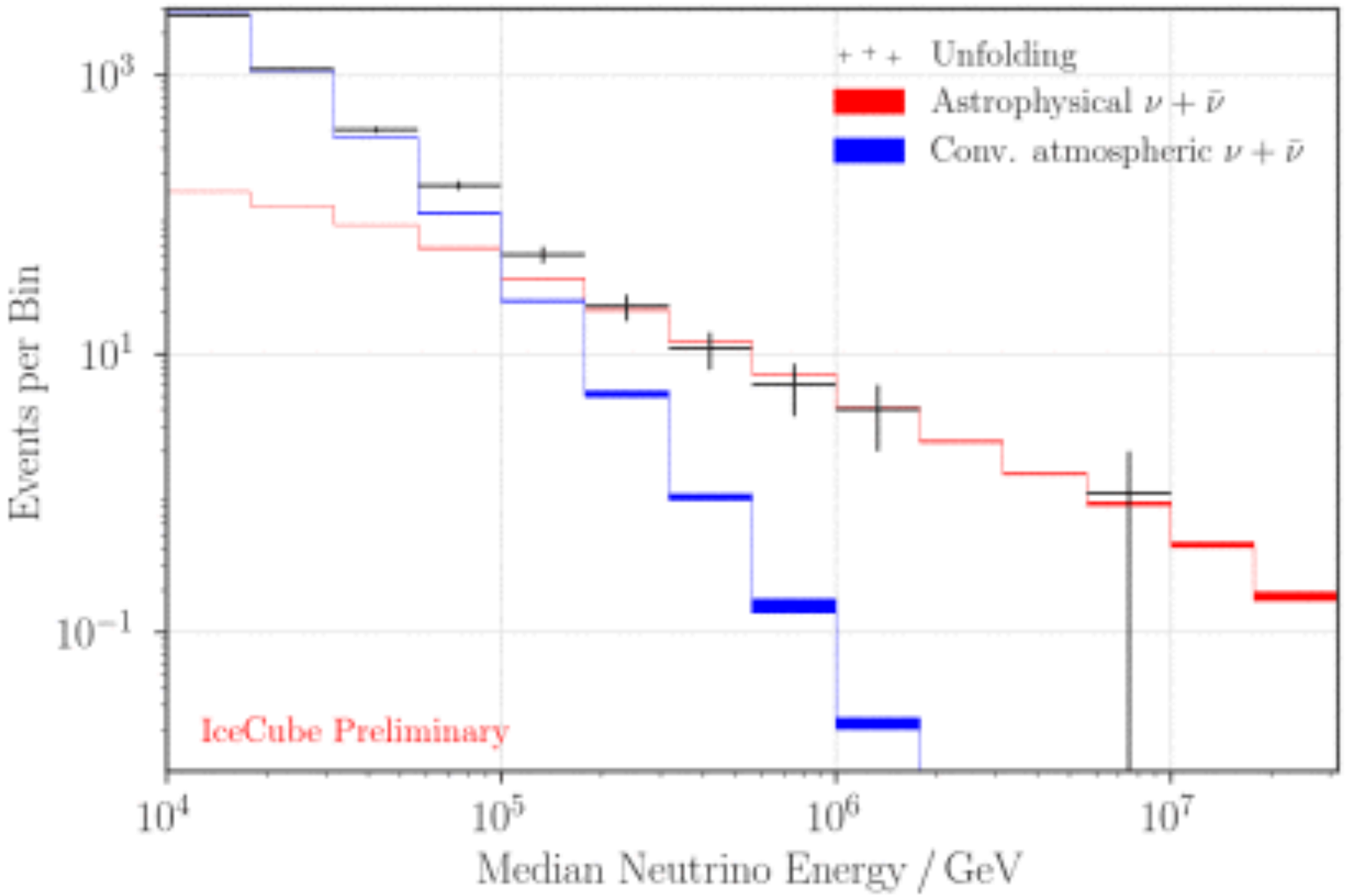


$$\bar{\nu}_\mu + p \rightarrow \mu^+ + X$$

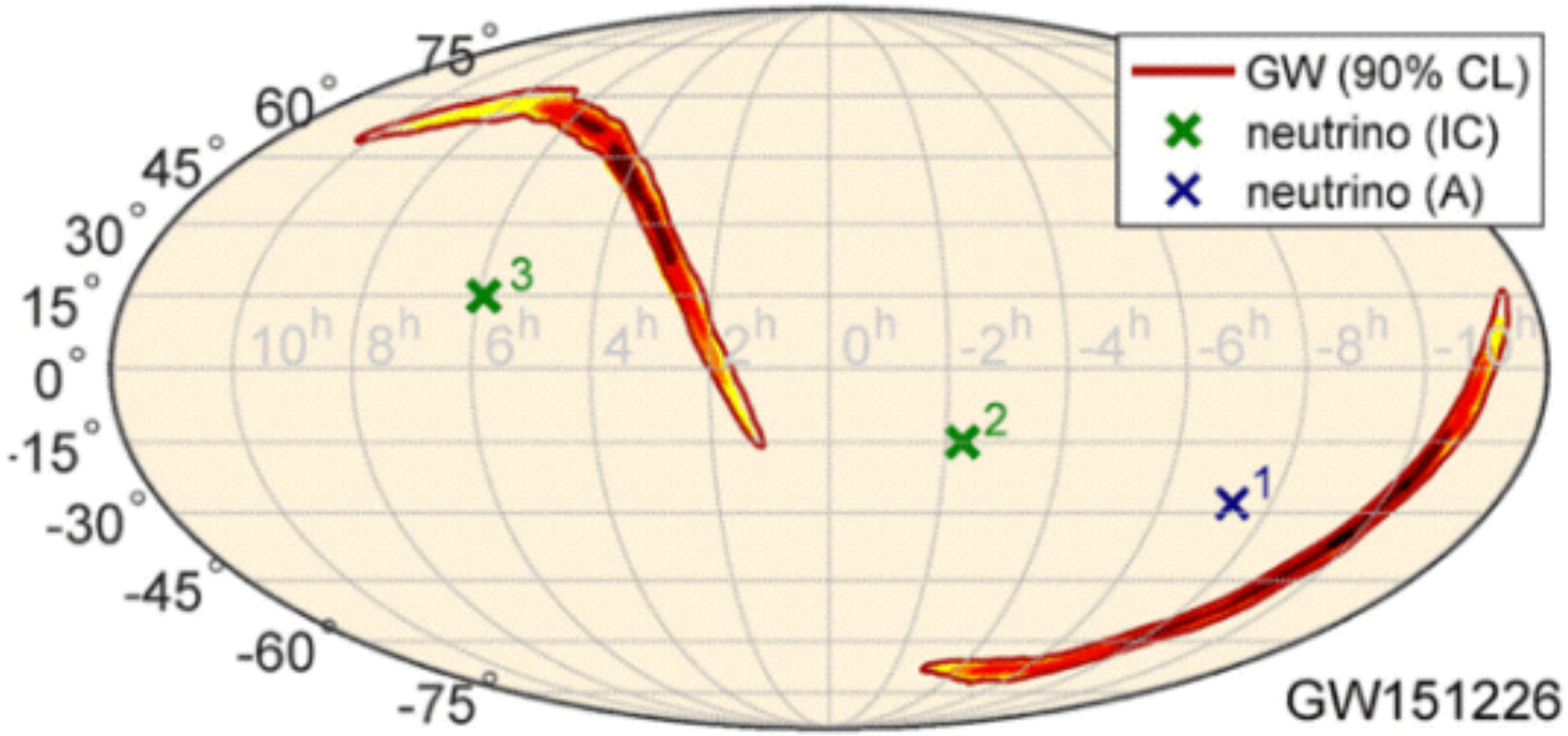
Evidence for High-Energy Extraterrestrial Neutrinos

Science 342, 1242856 (2013) [arxiv:1311.5238]

Astrophysical Neutrinos

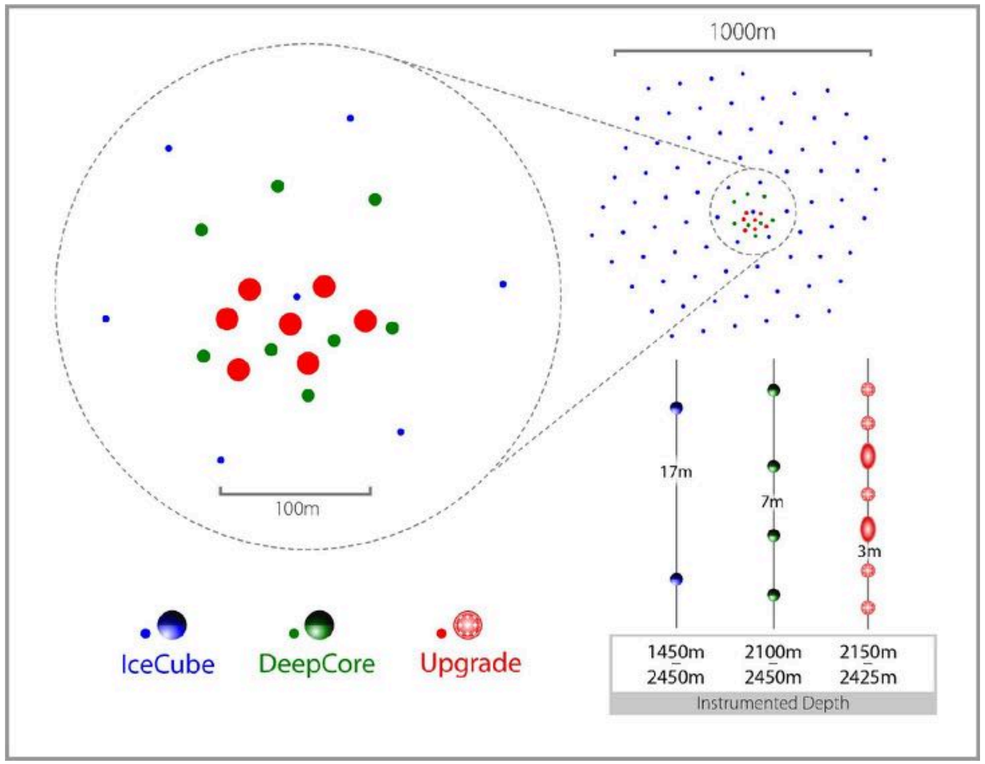


다중 신호 천체물리학

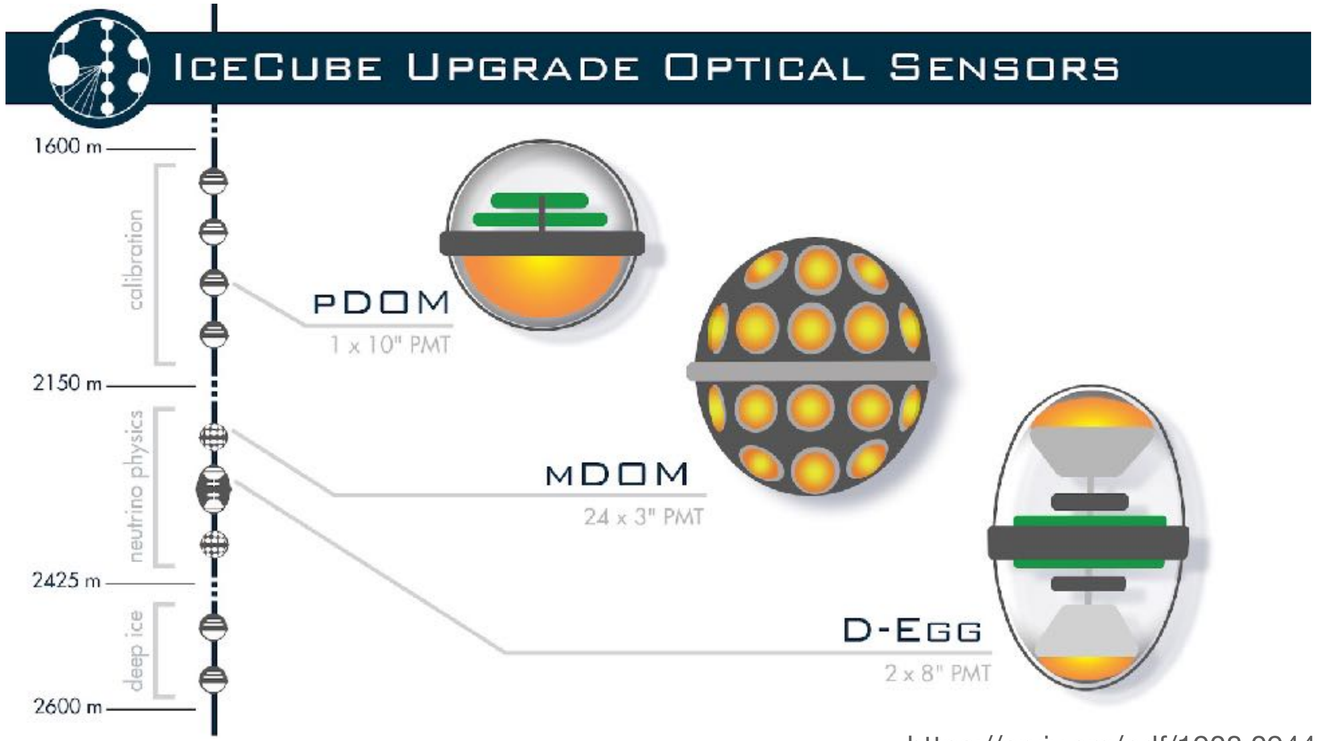

GW (90% CL)
neutrino (IC)
neutrino (A)
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
10h
8h
6h
4h
2h
0h
-2h
-4h
-6h
-8h
1
2
3
GW151226

IceCube Upgrade

- Instrument additional 7 strings
  - 60-100 DOMs in each string
- Detect neutrinos below 10 GeV
- Low risk, Quick deployment



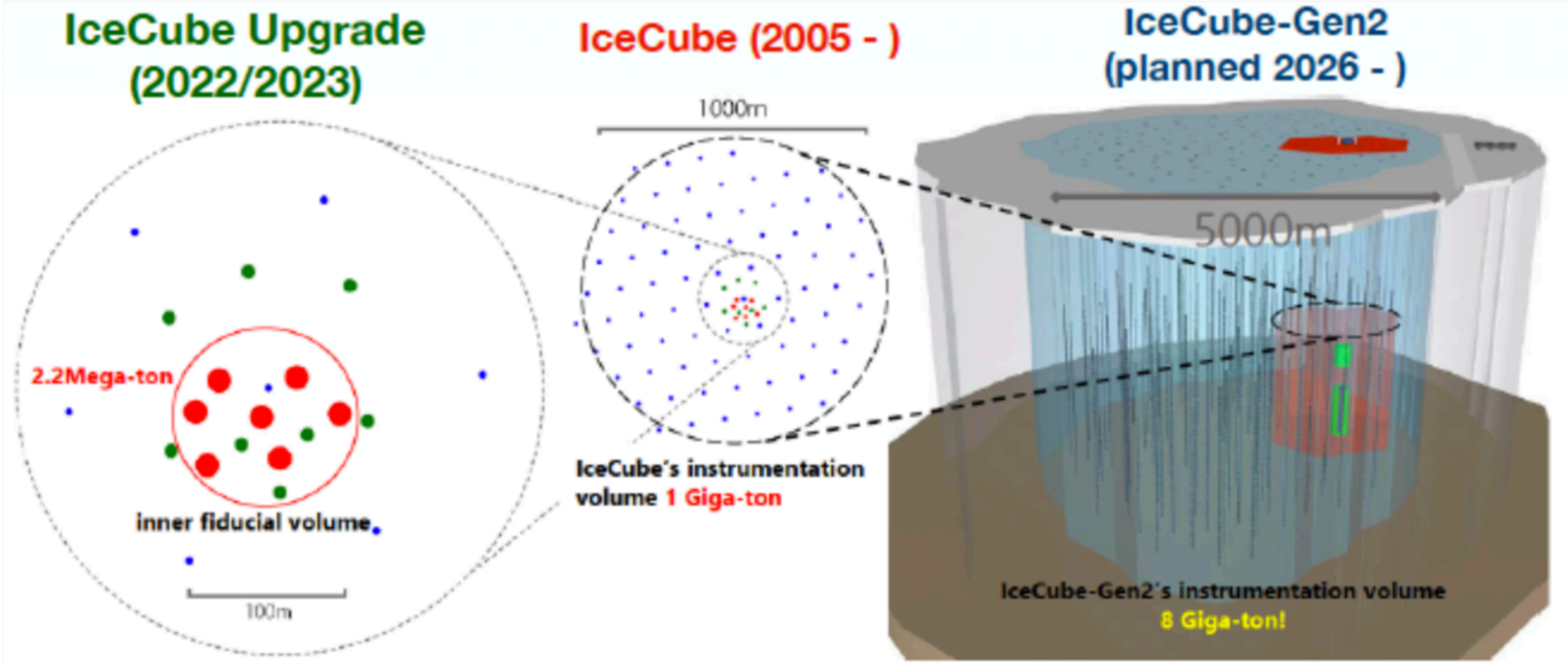
- Neutrino Oscillations study,
- Neutrino Mass Hierarchy measurement with the Upgrade.
- Neutrinos with Earth matter and density effect in varying baseline
  - Understanding the systematics is the key to the measurement
  - Additional calibration devices can be added



https://arxiv.org/pdf/1908.09441.pdf



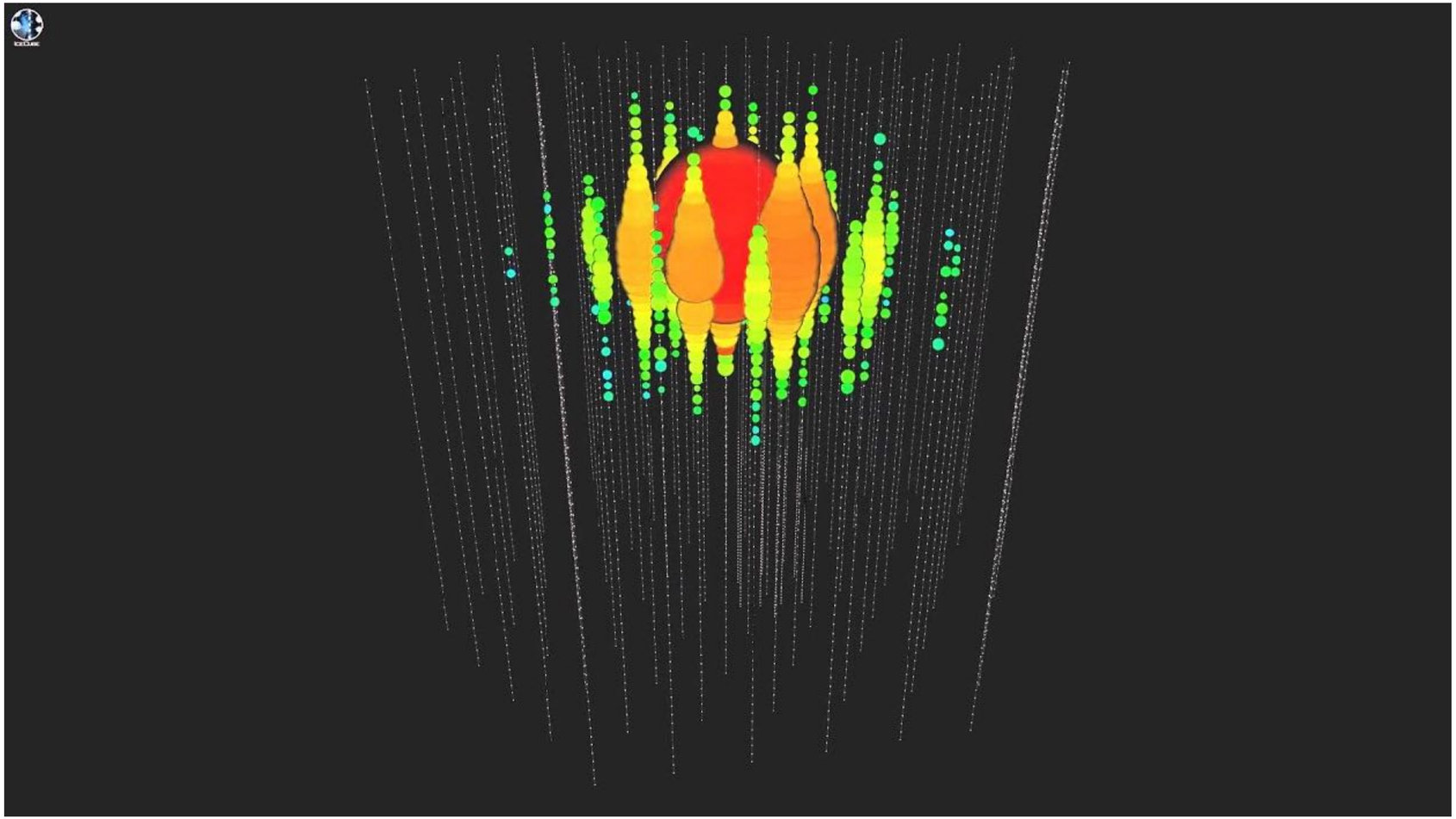
IceCube Gen2



IceCube (2005 - ...)	1 Giga-ton	• Diffuse astrophysical neutrinos • Optimized for TeV Neutrinos
IceCube Upgrade (2022/2023)	2.2 Mega-ton	• GeV neutrinos, PMNS unitarity • Calibration of the IceCube detector
IceCube-Gen2 (planned 2026 -)	~ 8 Giga-ton	• Astrophysical neutrino sources • GZK neutrinos, PeV Neutrinos

IceCube-Gen2: A Vision for the Future of Neutrino Astronomy in Antarctica (arXiv:1412.5106)

Big Bird

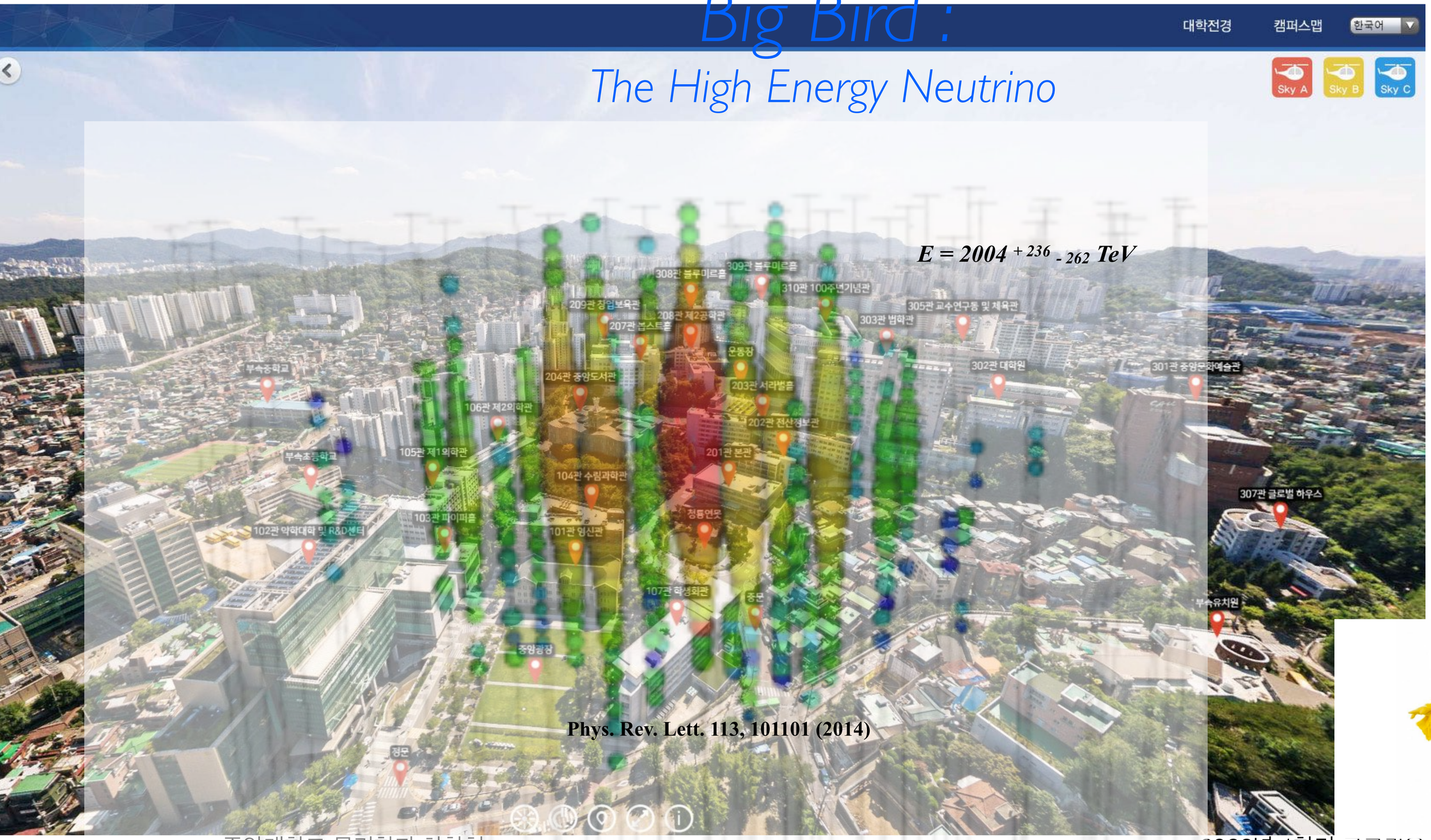




중앙대학교 물리학과 하창현

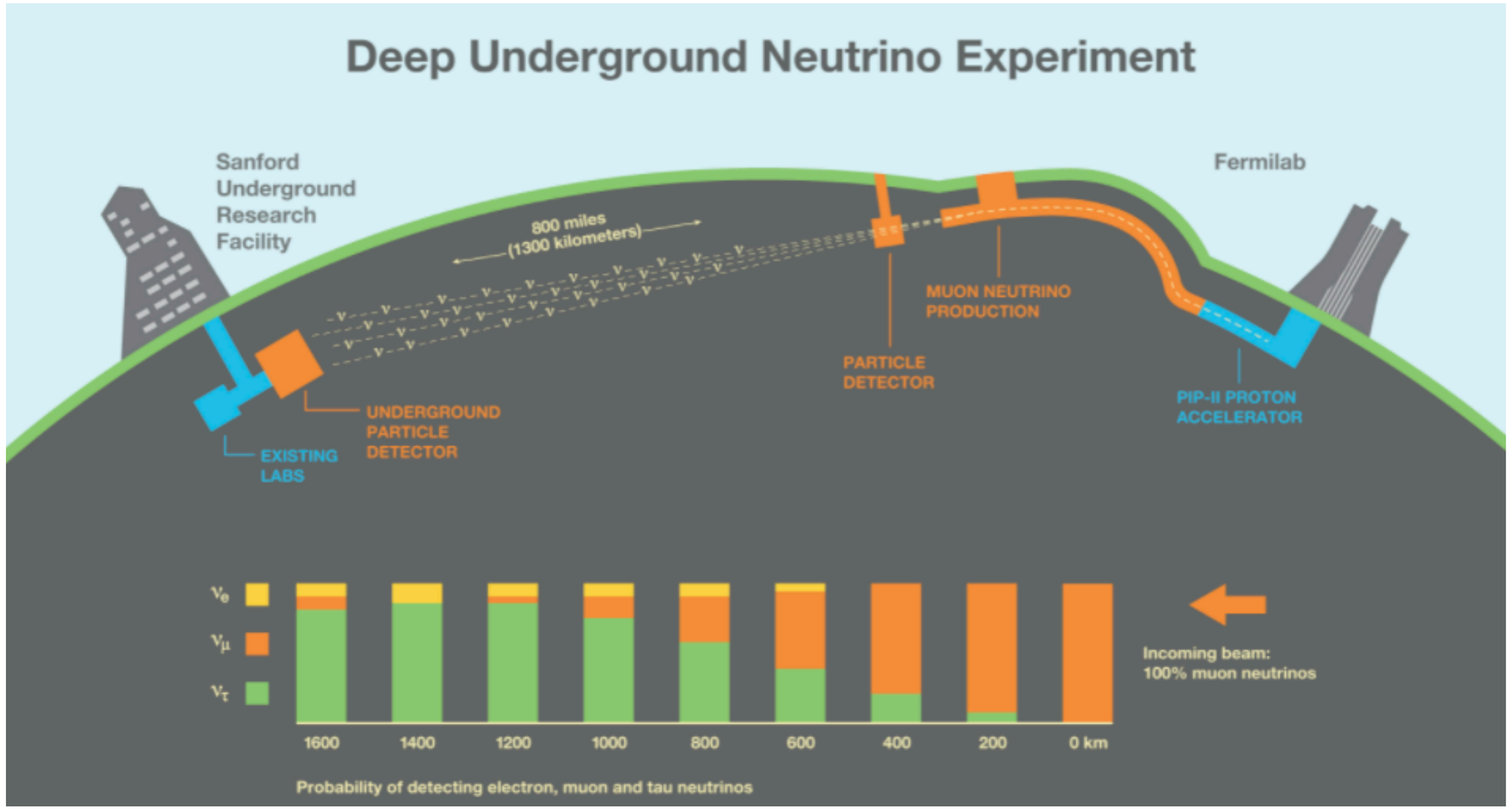
Big Bird :

The High Energy Neutrino





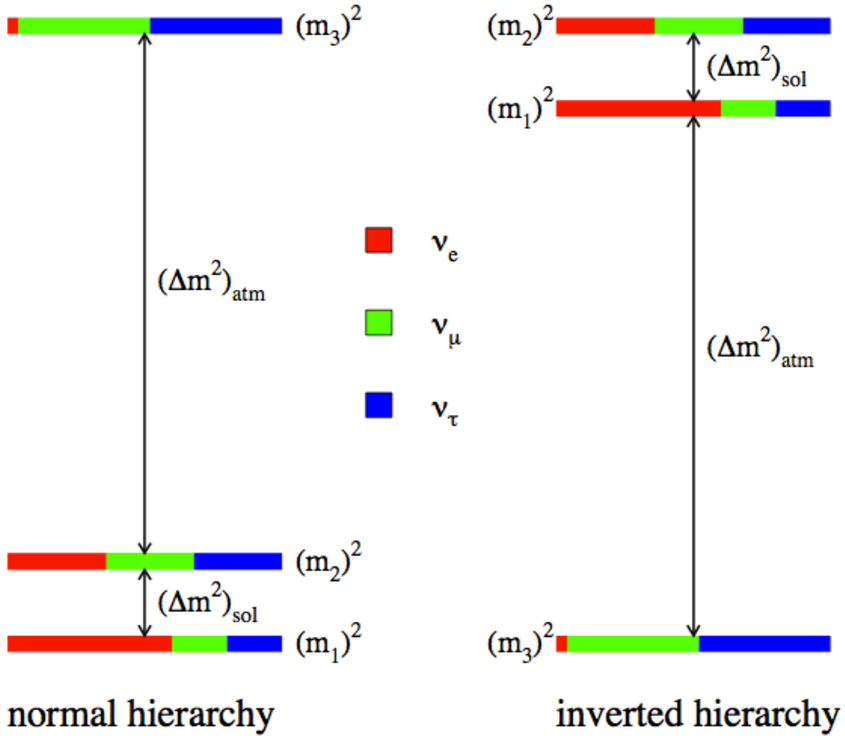
Deep Underground Neutrino Experiment (DUNE)



Key Features in DUNE

- Broad range of neutrino energy spectrum (broad band beam)
- High-energy beam makes a relatively large matter effect (mass ordering & δCP together)
- LArTPC technology improves resolutions
- Better systematics control

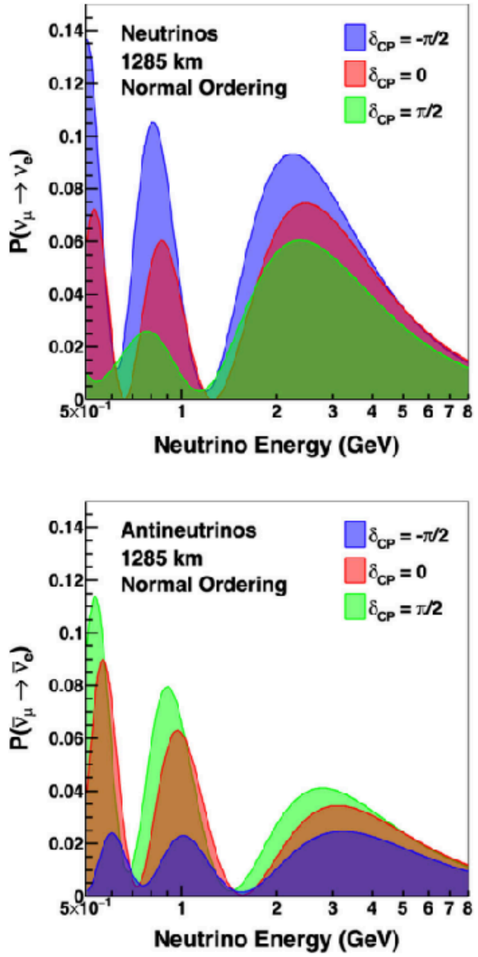
Neutrino Oscillations in DUNE



$\Delta m_{32}^2 > 0$ Normal Ordering

$\Delta m_{32}^2 < 0$ Inverted Ordering

André DeGouvea



Eur. Phys. J. C (2020) 80 :978

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12} \times \frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31} \times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} \pm \delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

where

$$a = \pm\frac{G_F N_e}{\sqrt{2}} \approx \pm\frac{1}{3500\ \text{km}}\left(\frac{\rho}{3.0\ \text{g/cm}^3}\right),$$

Matter effect term

Experimental Determination of Rate difference between $\nu_e : \bar{\nu}_e$ at the Far Site

High statistics neutrino sample provides systematics in CP measurements

Far-to-Near ratio on the neutrino counts per energy bin

$$\phi_{\nu_e}^{far}(E_\nu)$$

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * T_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * T_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

We need to know various constraining parameters to have δCP measurements.

—Detector systematics (Energy Reconstruction, Far and Near detector configurations)

—Cross-section ratio of ν_e to ν_μ

—Flux extrapolation from near to far.

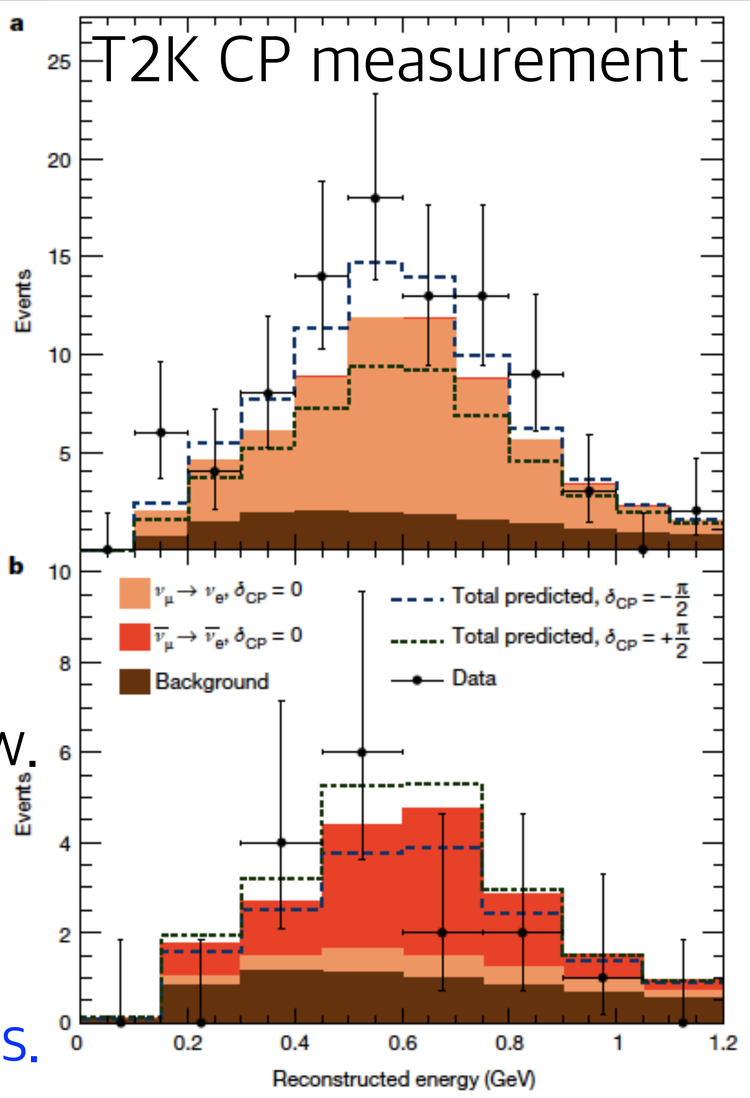
—Flux of near detector

c	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

Counts at Far detector are low.

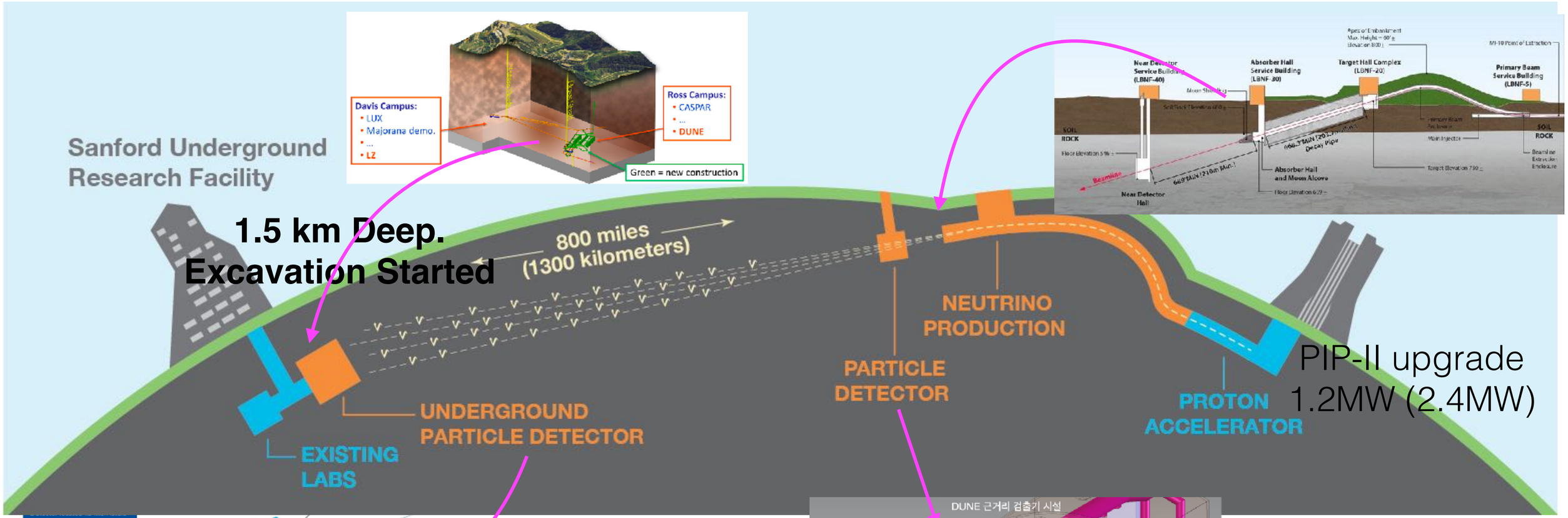
Nature volume 580, pages 339–344(2020)

T2K CP measurement

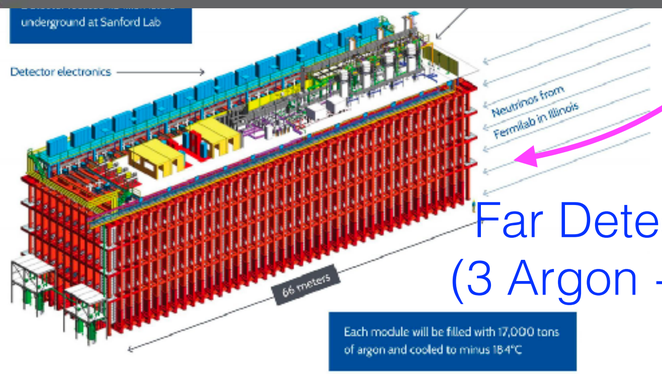


High statistics ν_μ, *and* ν_e sample can provide needed constraints.

Long Baseline Neutrino Facility overview

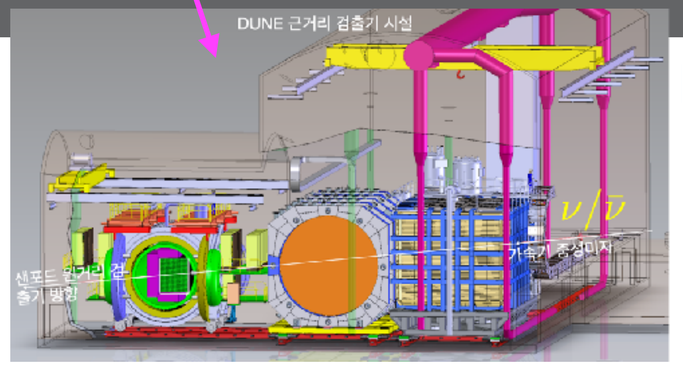


PIP-II upgrade
1.2MW (2.4MW)



FD TDR: arXiv.2002.03005

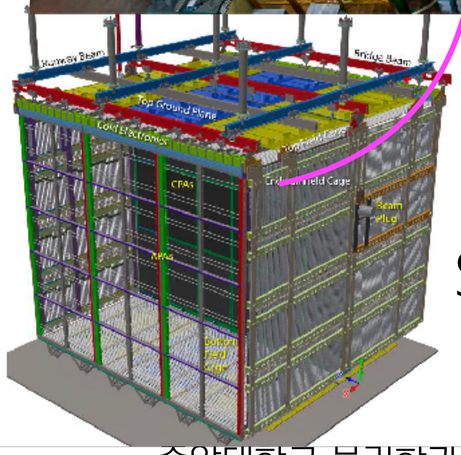
Far Detector : 17 kton x 4 modules
(3 Argon + 1 possible water module)



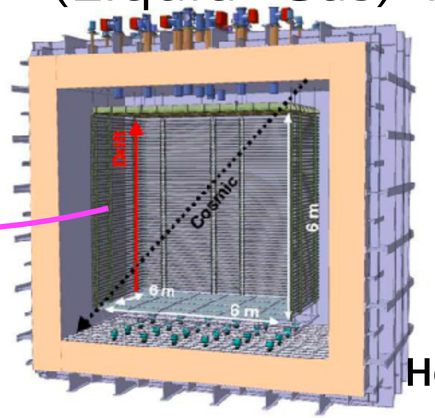
Near Detector : Beam Monitoring (SAND), Neutrino Interactions (Gas Argon TPC & Liquid Argon TPC)

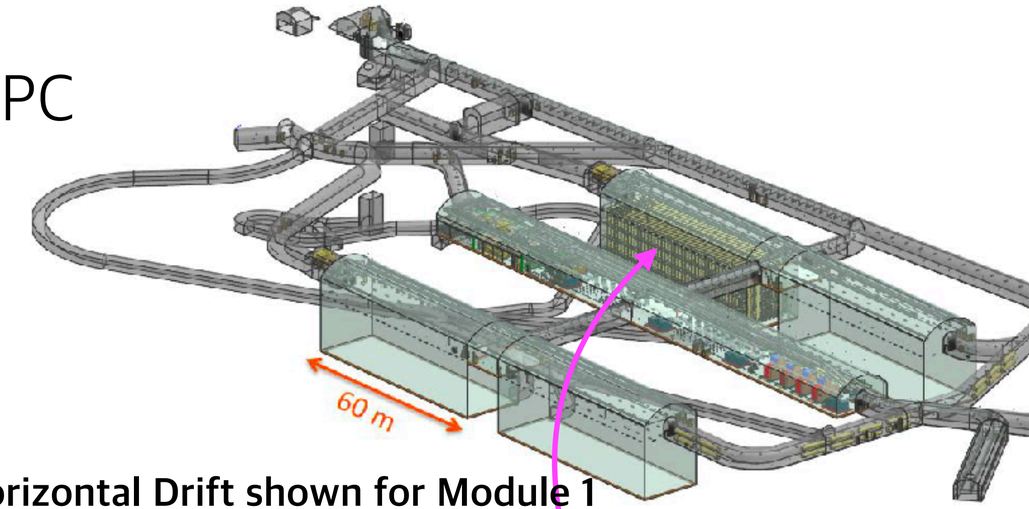
The Far Detectors : Oscillated Neutrino Detection



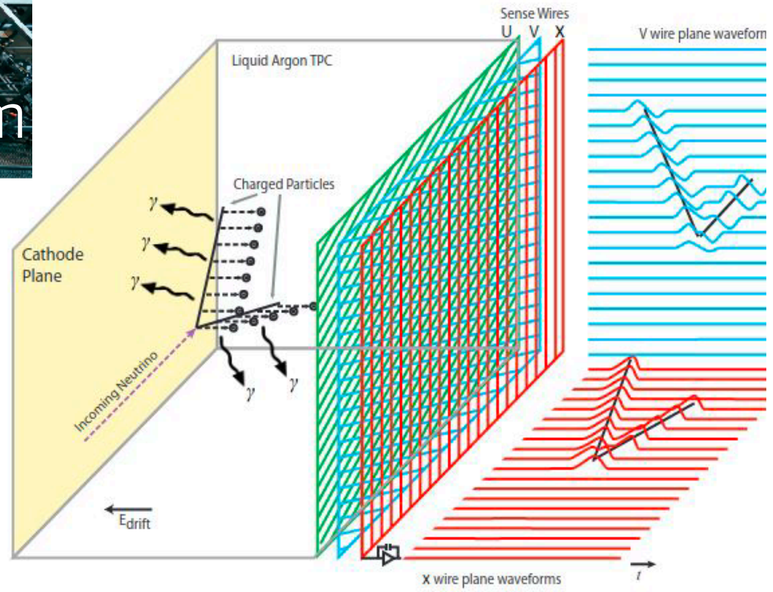


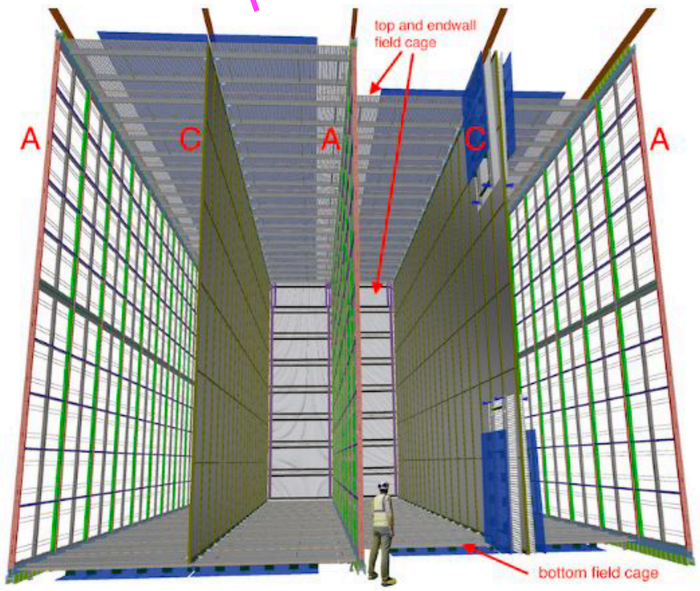
Dual Phase
(Liquid+Gas) TPC



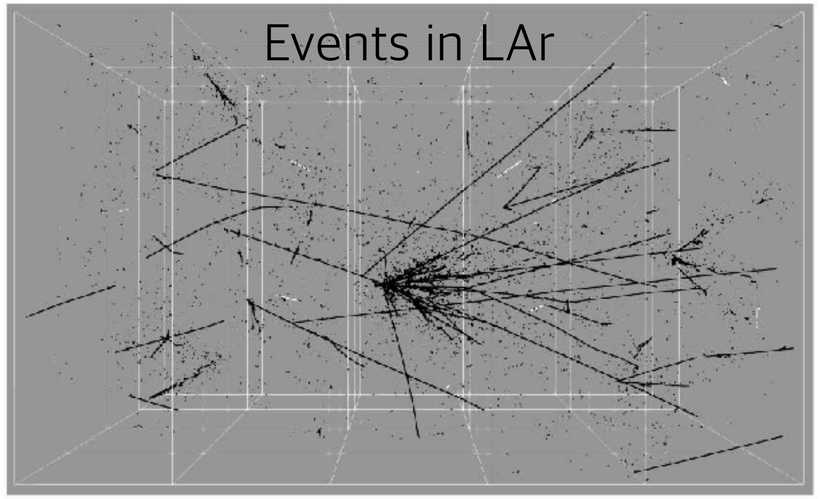


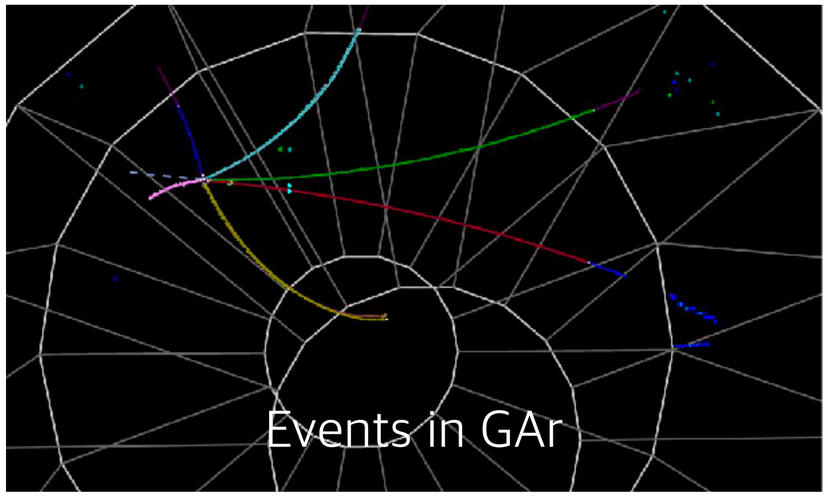
Horizontal Drift shown for Module 1
Vertical Drift is another option



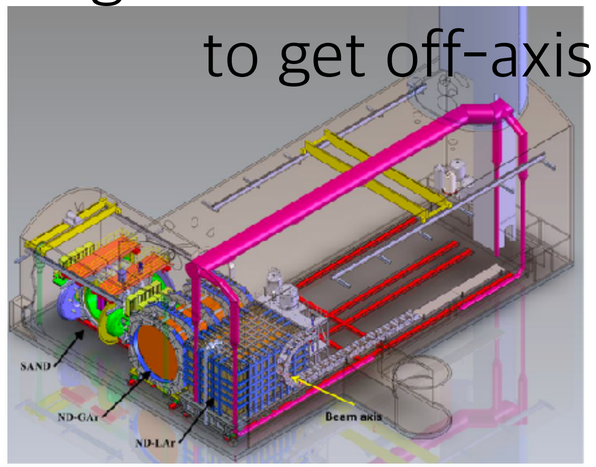


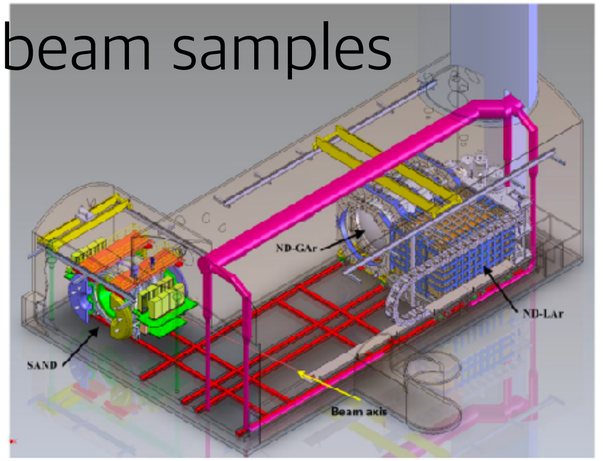
The Near Detector system :
Control Neutrino Interaction Systematics



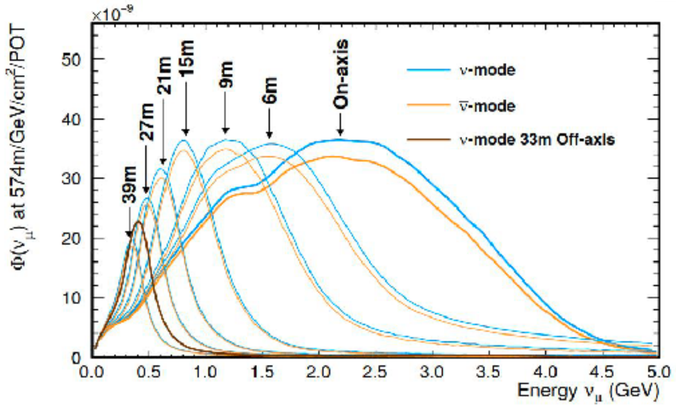


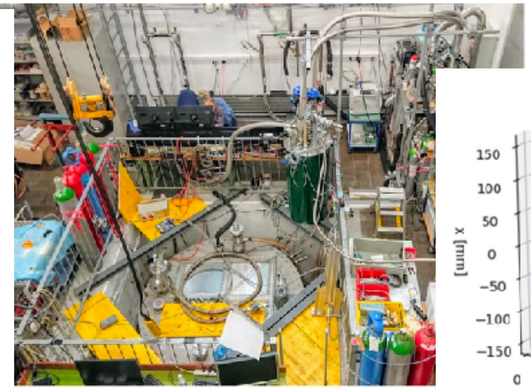
Argon Detectors are movable horizontally
to get off-axis beam samples





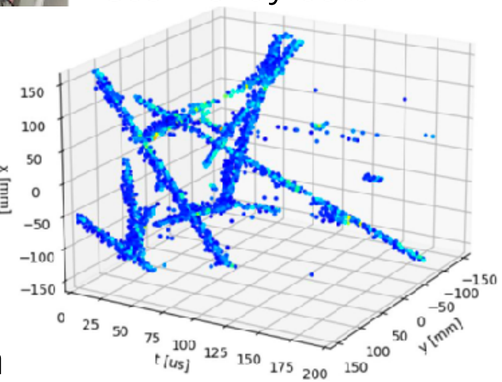
Neutrino Flux at different locations





LArTPC Prototype @ Bern

Cosmic ray data



요약

- 중성미자는 도처에 존재합니다.
- 태양에서, 대기에서, 인간이 만든 핵발전소 혹은 가속기에서 그리고 우주 먼곳에서도 지금도 무수히 많이 만들어지고 있습니다.
- 일반적으로 에너지가 큰 중성미자는 갯수가 적고 작은 에너지의 중성미자는 무수히 많습니다.
- 중성미자는 약한 상호작용을 하기때문에 아주 커다란 검출기가 필요합니다.
- 중성미자와 매질의 반응에서 만들어진 또다른 강입자와 경입자를 통해 반응을 검출합니다.
- 국내 많은 연구자들이 중성미자 연구에 몰두하고 계십니다.
- 그중 저와 관련이 있는 NEON, IceCube, AMoRE 등에 대해 소개하였습니다.
- 국내 연구진이 참여하는 중성미자 연구에 많은 관심 부탁드립니다.