Neutrino Physics

Outline

1. Neutrino oscillations
2. Dirac or Majorana?
3. CP violation with leptons
4. 4th neutrino search (sterile neutrino search)
5. Dark matter search with neutrinos
6. Quantum gravity search with neutrinos
7. Conclusion

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Teppei Katori
IoP, UK, July 4, 2019

1. **Neutrino oscillations**

2. Dirac or Majorana?

3. CP violation with leptons

4. 4th neutrino search (sterile neutrino search)

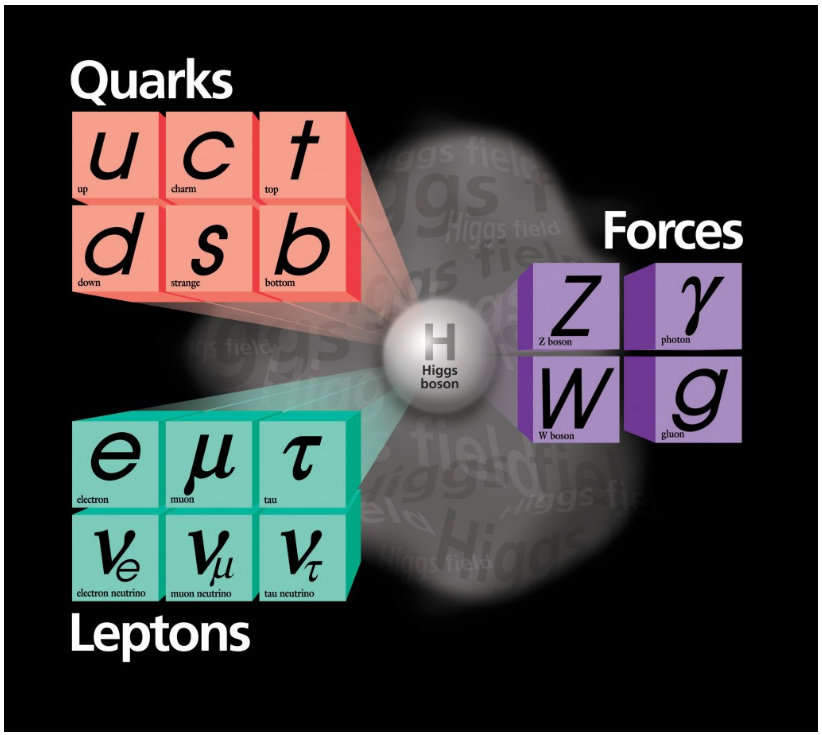
5. Dark matter search with neutrinos

6. Quantum gravity search neutrinos

7. Conclusion

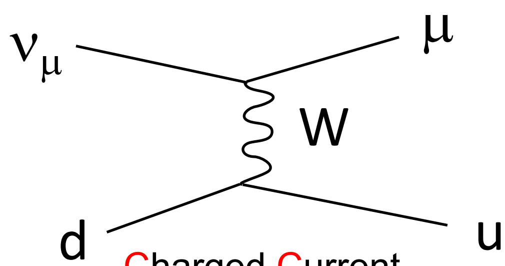
1. Neutrinos in Standard Model (SM)

SM describes 6 massive quarks, 3 massive charged leptons, 3 massless neutrinos, and 3 forces, and Higgs boson.

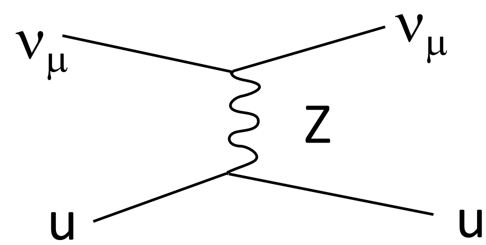


Neutrinos are special because,

1. they only interact with weak nuclear force.



Charged Current (CC) interaction
"W-boson exchange"



Neutral Current (NC) interaction
"Z-boson exchange"

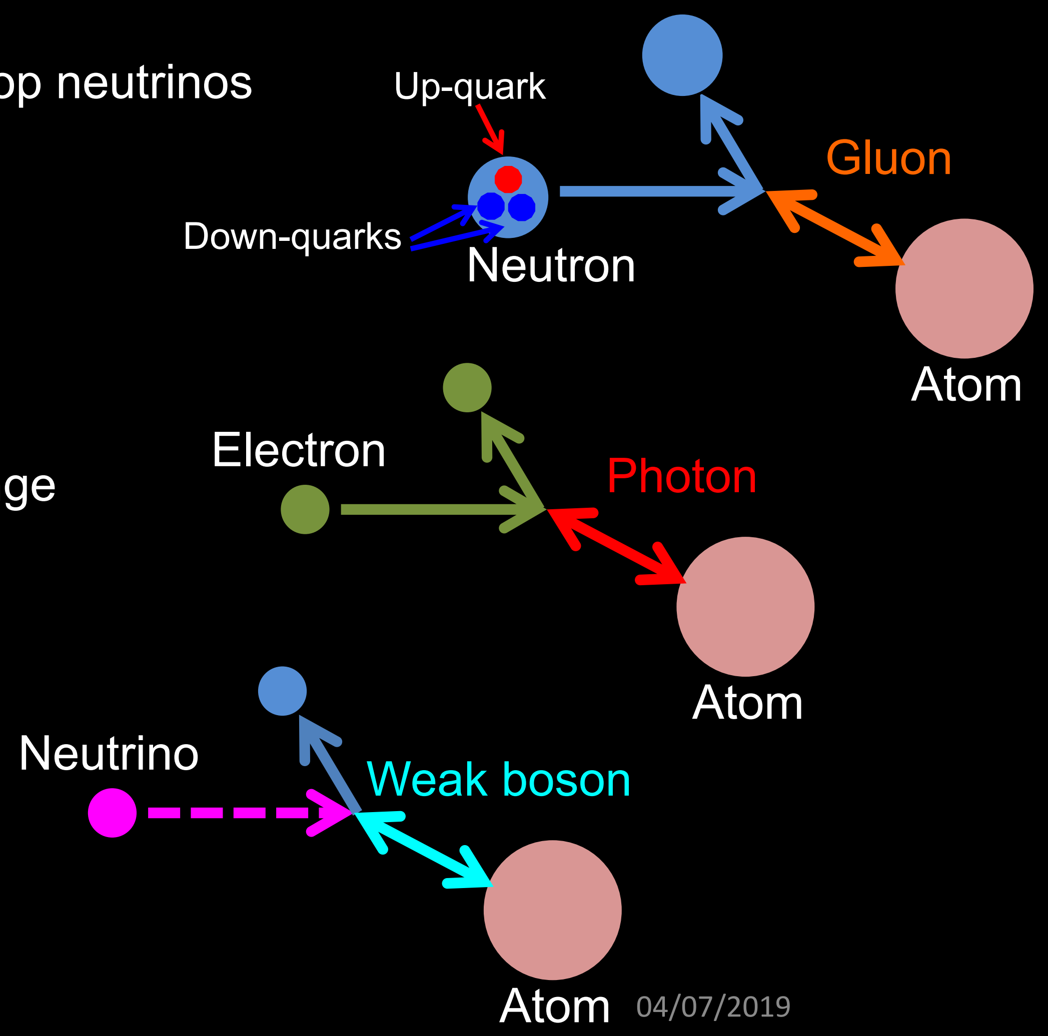
Neutrinos, Ghost particles

3 types of neutrinos
- Extremely difficult to stop neutrinos

- Quarks exchange
  - Gluons, or
  - Photons, or
  - Weak bosons

- Charged leptons exchange
  - Photons, or
  - Weak bosons

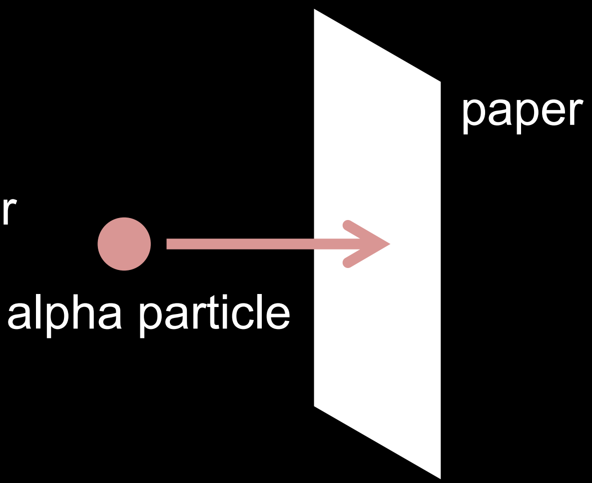
- Neutrinos exchange
  - Weak bosons



Neutrinos, Ghost particles

3 types of neutrinos
- Extremely difficult to stop neutrinos

Example: how to stop particles?
- Alpha particle (nuclei of Helium) → sheet of paper
- Beta particle (electron) → sheet of copper
- Gamma particle (photon) → chunk of lead



Neutrinos, Ghost particles

3 types of neutrinos
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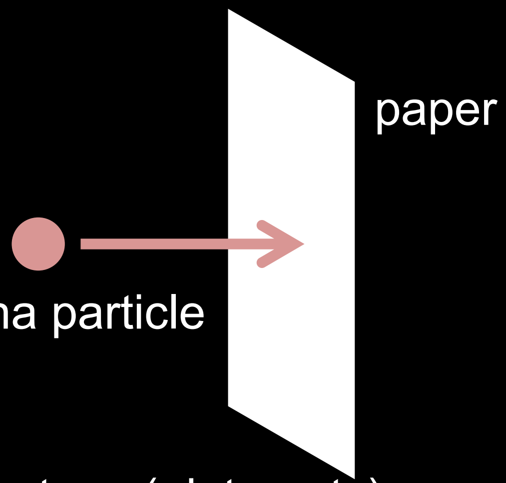
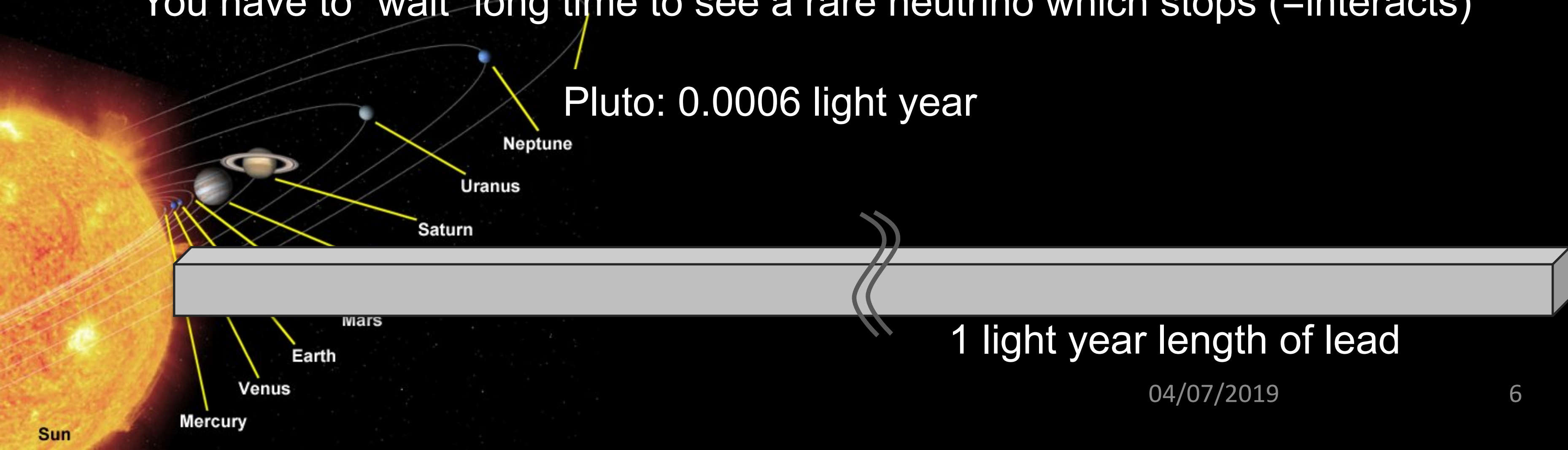
Example: how to stop particles?
- Alpha particle (nuclei of Helium) → sheet of paper
- Beta particle (electron) → sheet of copper
- Gamma particle (photon) → chunk of lead
- Neutrino → 1 light year thickness of lead



You have to “wait” long time to see a rare neutrino which stops (=interacts)



Neutrinos, Ghost particles

3 types of neutrinos

- Extremely difficult to stop neutrinos

Neutrinos are everywhere, but they penetrate without leaving any traces.

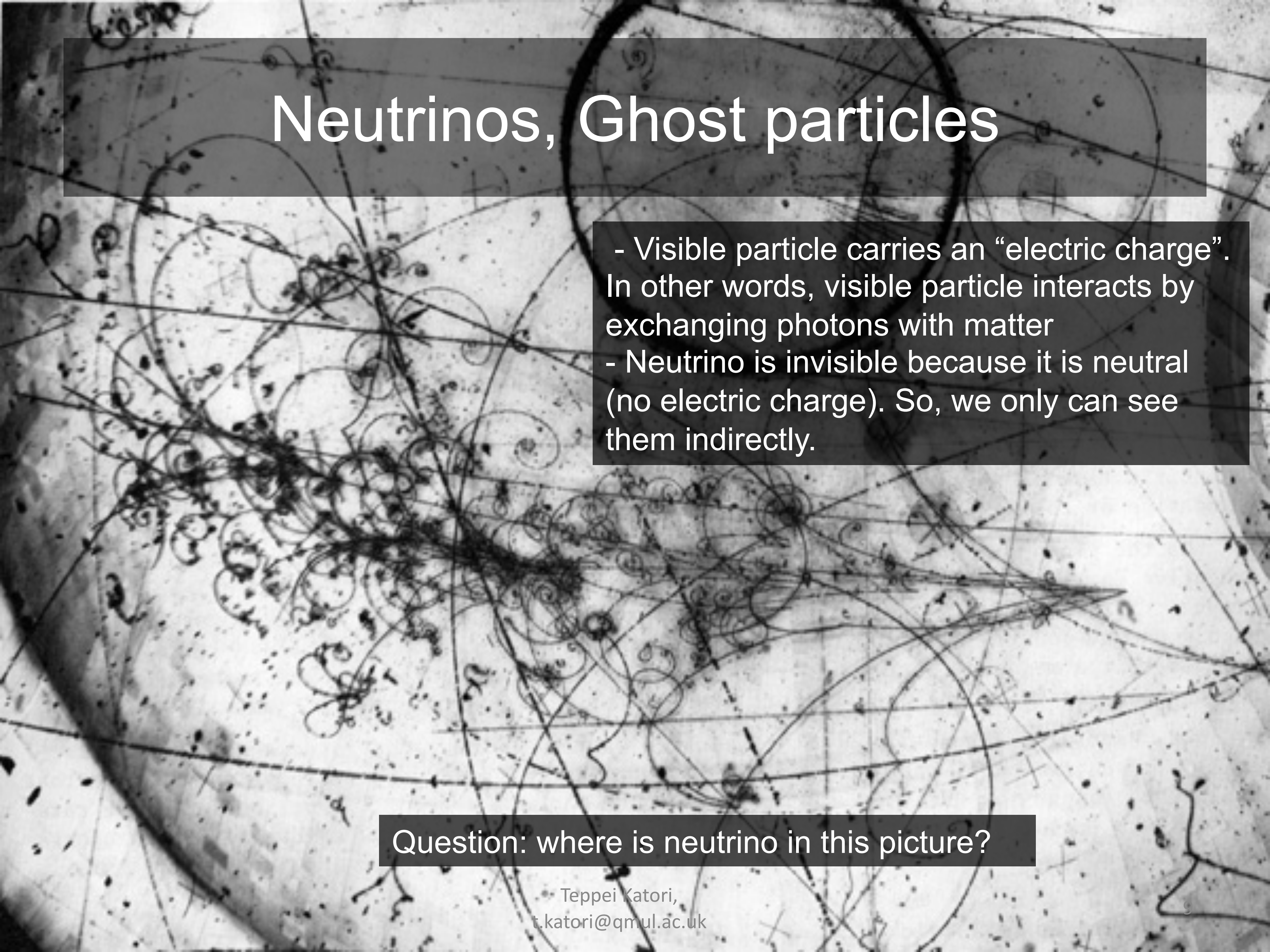
Solar neutrinos

- 60 billion electron neutrinos from the Sun pass through every 1cm^2 of the Earth every second. However you have only a 25% chance for a neutrino to hit your body in your lifetime.

Neutrinos, Ghost particles

Bubble Chamber detector
- Particles with an electric charge leave "tracks" in the detector by forming little bubbles, and we can take photos of them.

Neutrinos, Ghost particles



- Visible particle carries an “electric charge”. In other words, visible particle interacts by exchanging photons with matter
- Neutrino is invisible because it is neutral (no electric charge). So, we only can see them indirectly.

Question: where is neutrino in this picture?

Neutrinos, Ghost particles

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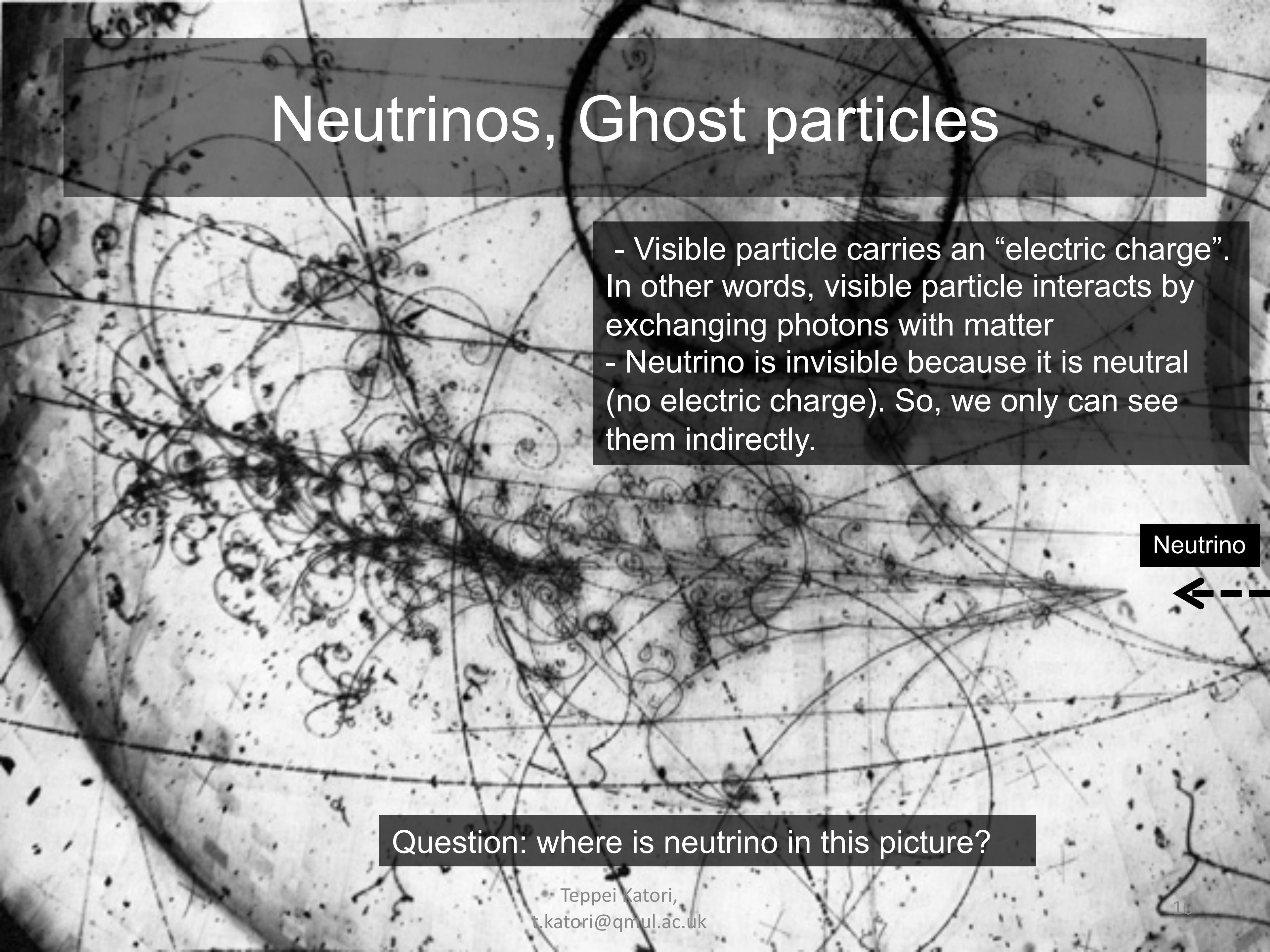

Question: where is neutrino in this picture?

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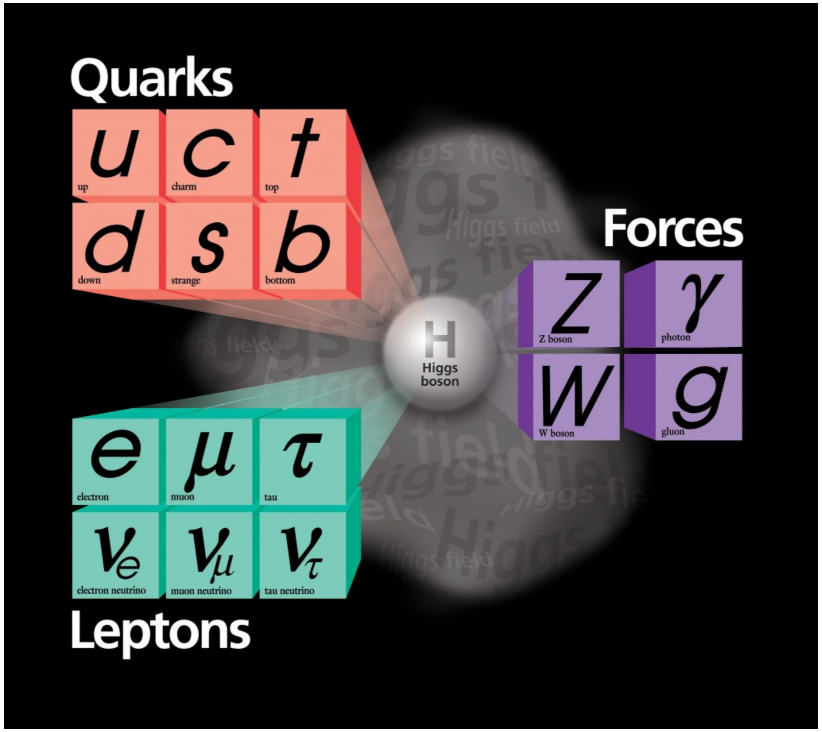

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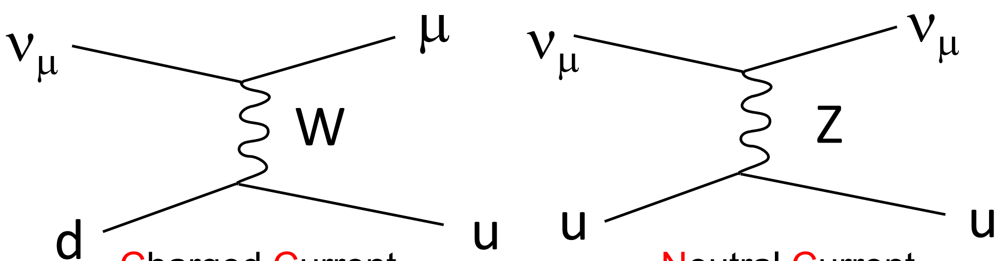


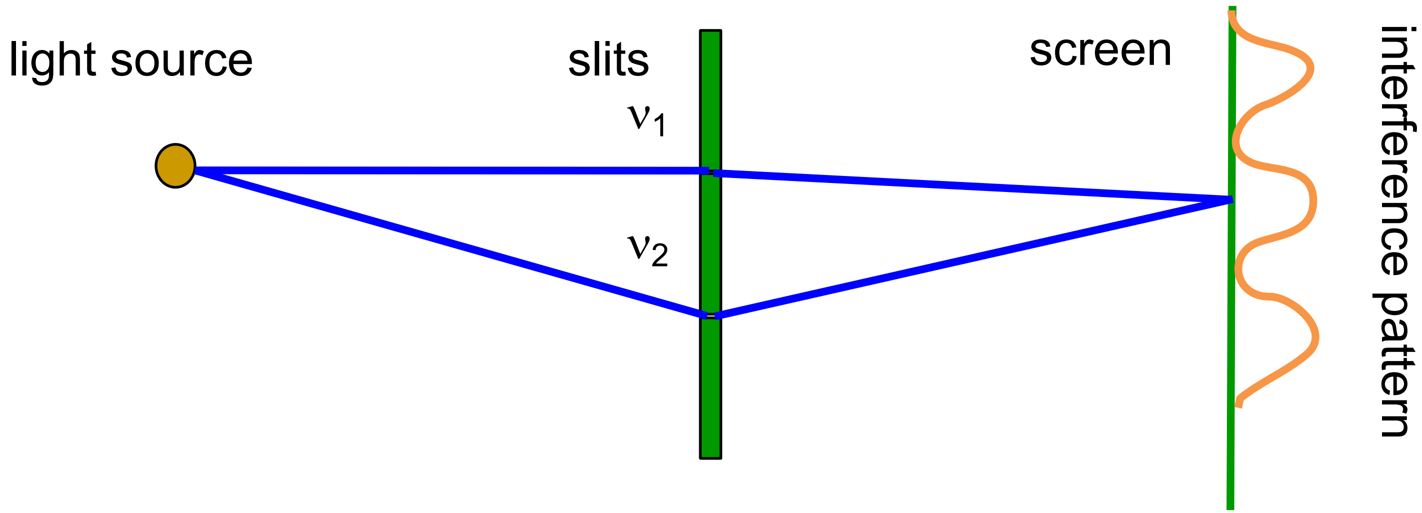
Charged Current (CC) interaction "W-boson exchange"

Neutral Current (NC) interaction "Z-boson exchange"

2. Weak interaction eigenstate is not Hamiltonian eigenstate (propagation eigenstate). Thus propagation of neutrinos changes their species, called neutrino oscillation.

1. Neutrino oscillations

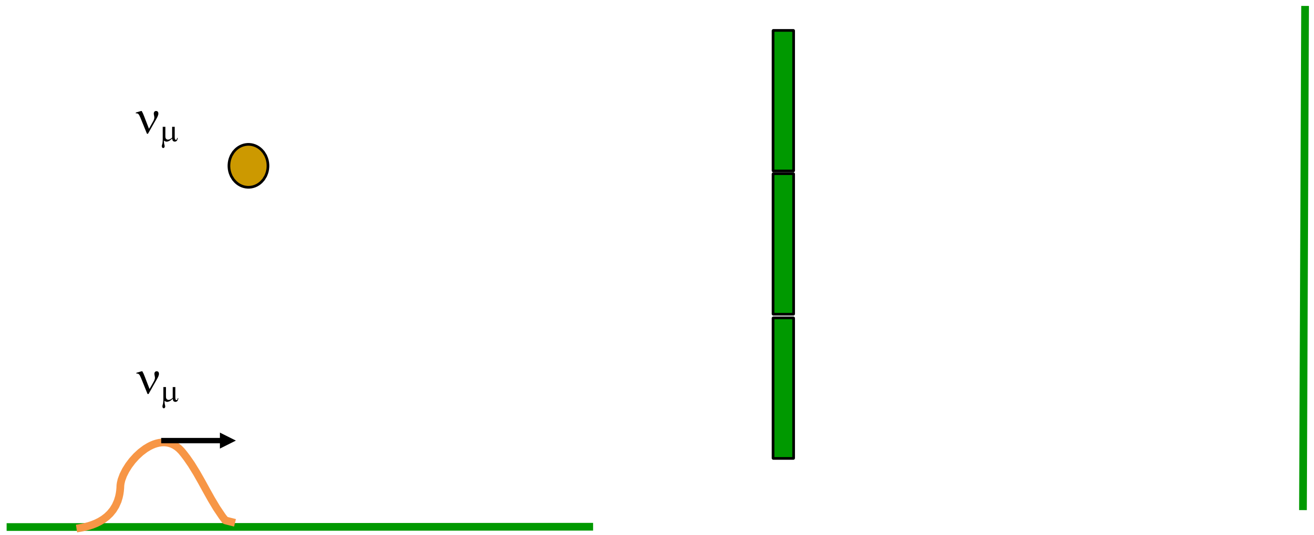
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

1. Neutrino oscillations

Neutrino oscillation is an interference experiment (cf. double slit experiment)



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

1. Neutrino oscillations

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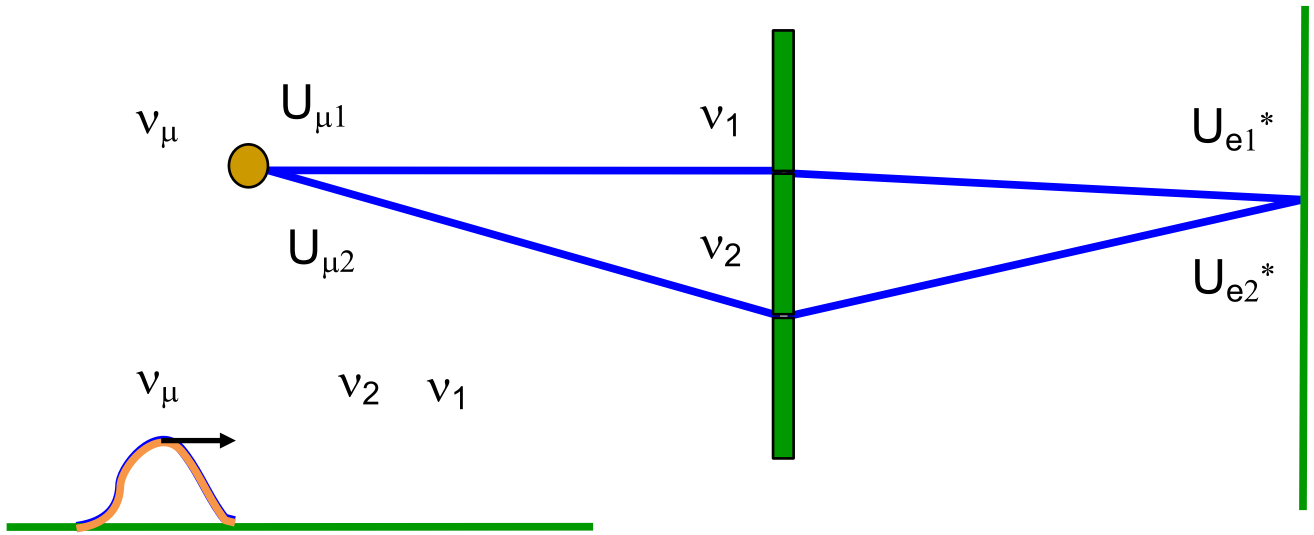

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

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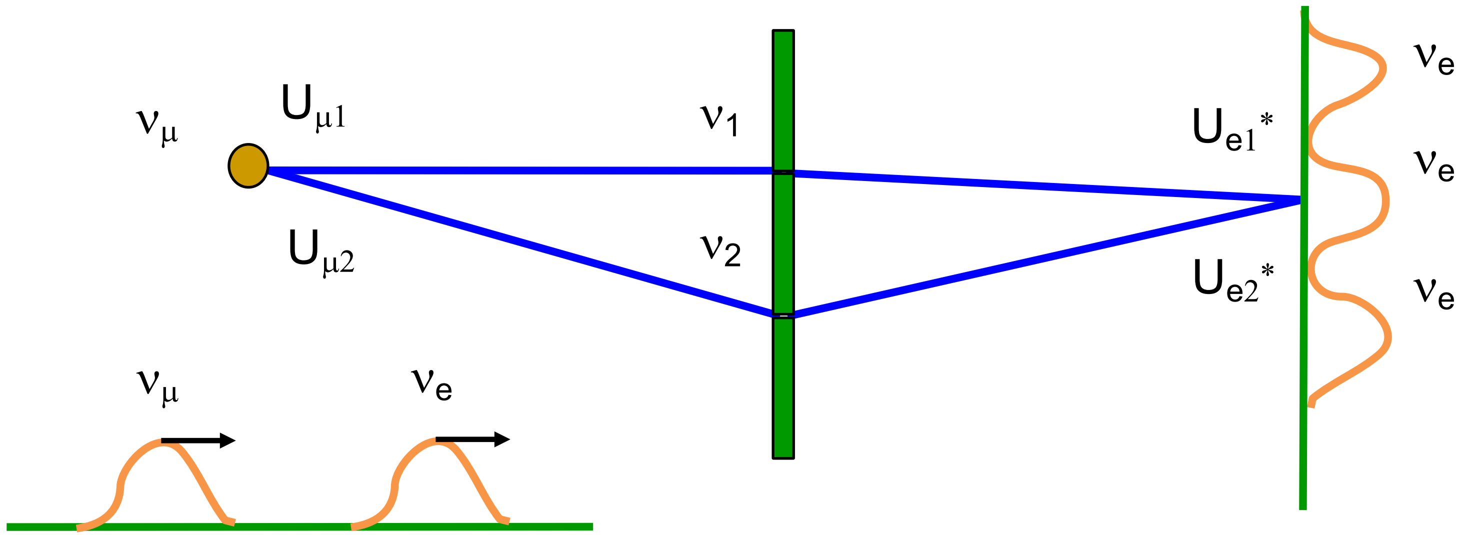
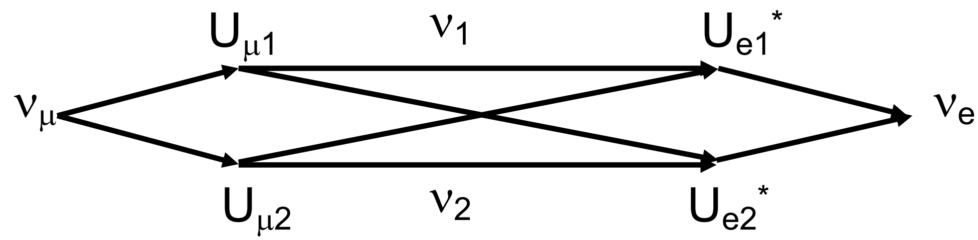


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

The detection may be different flavor (neutrino oscillations).

1. Neutrino oscillations



2 neutrino mixing

The neutrino weak interaction eigenstate (flavor eigenstate) is described by neutrino Hamiltonian eigenstates, ν_1 and ν_2, and their mixing matrix elements.

$$|\nu_\mu\rangle = U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle$$

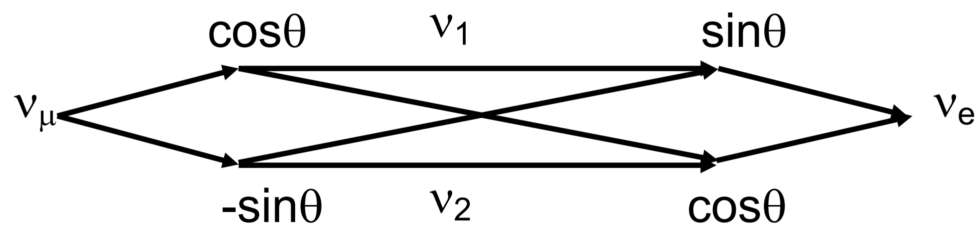
The time evolution of flavor eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of ν_1 and ν_2 .

$$|\nu_\mu(t)\rangle = U_{\mu 1}e^{-i\lambda_1 t}|\nu_1\rangle + U_{\mu 2}e^{-i\lambda_2 t}|\nu_2\rangle$$

Then the transition probability from weak eigenstate ν_μ to ν_e is,

$$P_{\mu\to e}(t) = \left|\langle\nu_e|\nu_\mu(t)\rangle\right|^2 = -4U_{e1}^*U_{e2}^*U_{\mu 1}U_{\mu 2}sin^2\left(\frac{\lambda_1-\lambda_2}{2}t\right)$$

1. Neutrino oscillations



In the vacuum, 2 neutrino effective Hamiltonian has a mass term,

$$H_{eff} \sim \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix}$$

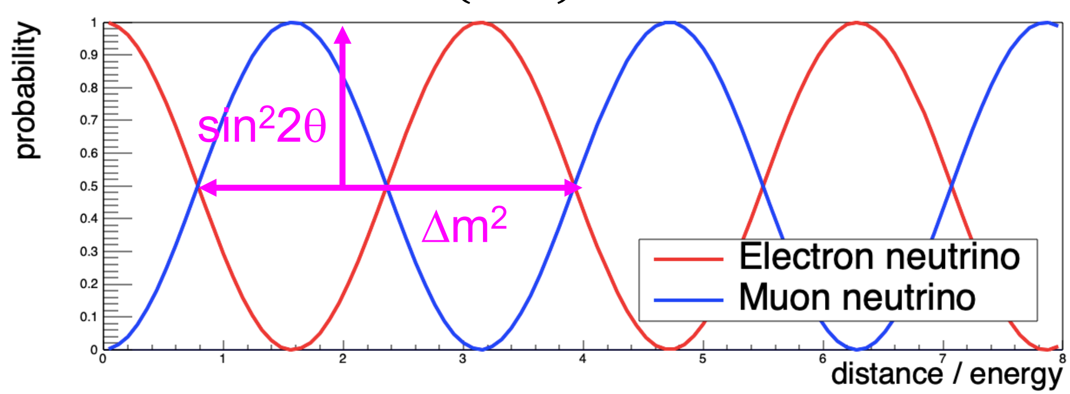
Therefore, 2 massive neutrino oscillation model is ($\Delta m^2 = |m_1^2 - m_2^2|$, t~L)

$$P_{\mu\to e}(L/E) = sin^2 2\theta sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

After adjusting the unit, 2 neutrino oscillation formula

$$P_{\mu\to e}(L/E) = sin^2 2\theta sin\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

Amplitude = mixing angle
Period = neutrino mass



BREAKTHROUGH PRIZE

2016 Fundamental Physics Breakthrough Prize

Discovery of neutrino oscillations and neutrino masses

2016 Fundamental Physics Breakthrough Prize
- Koichiro Nishikawa (K2K and T2K)
- Atsuto Suzuki (KamLAND)
- Kam-Biu Luk (Daya Bay)
- Yifang Wang (Daya Bay)
- Art McDonald (SNO)
- Yoichiro Suzuki (Super-Kamiokande)
- Takaaki Kajita (Super-Kamiokande)

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

BREAKTHROUGH
PRIZE
2016 Fundamental Physics
Breakthrough Prize
The Nobel Prize in Physics
1988
Leon M. Lederman
Prize share: 1/3
Melvin Schwartz
Prize share: 1/3
Jack Steinberger
Prize share: 1/3
Discovery of
muon neutrino
The Nobel Prize in Physics
1995
Discovery of
neutrino
© University of California Regents
Frederick Reines
Prize share: 1/2
The Nobel Prize in Physics
2002
Raymond Davis Jr.
Prize share: 1/4
Masatoshi Koshib
Prize share: 1/4
Solar neutrino
problem, supernova
neutrino detection
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T2K)
Discovery o
and neutrin
Yifang Wang and the
Daya Bay Collaboration
Kam-Biu Luk and the
Daya Bay Collaboration
Yoichiro Suzuki and the
Super K Collaboration
Atsuto Suzuki and the
KamLAND Collaboration
Koichiro Nishikawa and
the K2K and T2K
Collaboration
…and all 1440
collaborators
The Nobel Prize in Physi
Takaaki Kajita, Arthur B.
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The Nobel
2015
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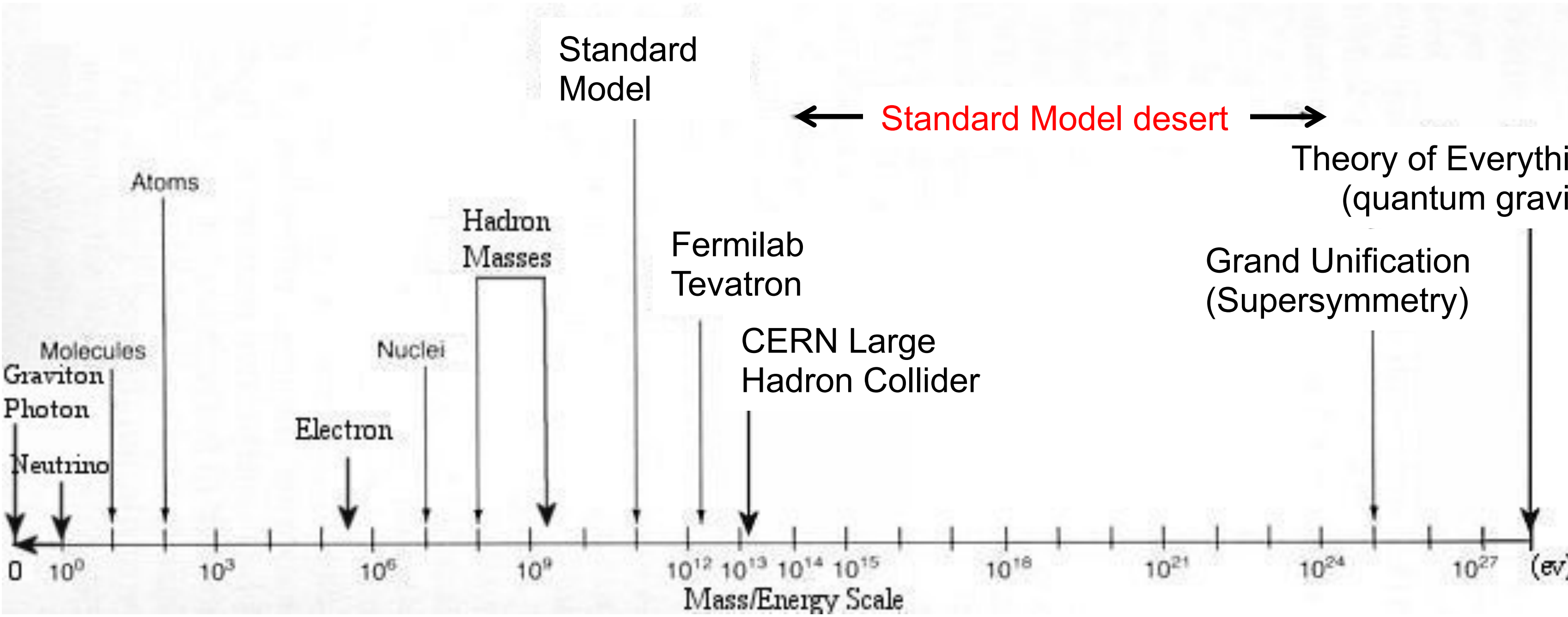
The Nobel P
Kajita and A
oscillations,
Neutrino physics is the
home of discovery physics!

Gell-Mann,P.Ramond,R.Slansky, "Supergravity",315 (1979) ISBN044485438X
Yanagida, Prog.Theo.Phys, 64(1980)1103

1. Neutrino masses

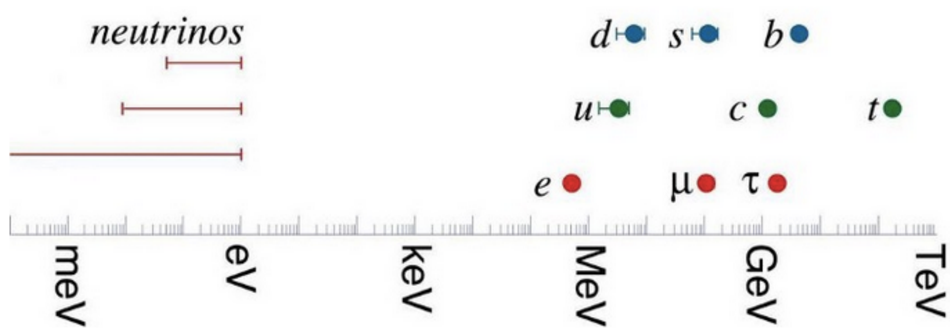
Neutrino masses are not predicted by the Standard Model

Seasaw mechanism relate extremely small neutrino masses with Grand Unification Theory (GUT)



Seasaw mechanism

$$M(\text{neutrino}) \sim \frac{(\text{Standard Model})^2}{(\text{Grand unification})}$$



1. Neutrino physics, 2019

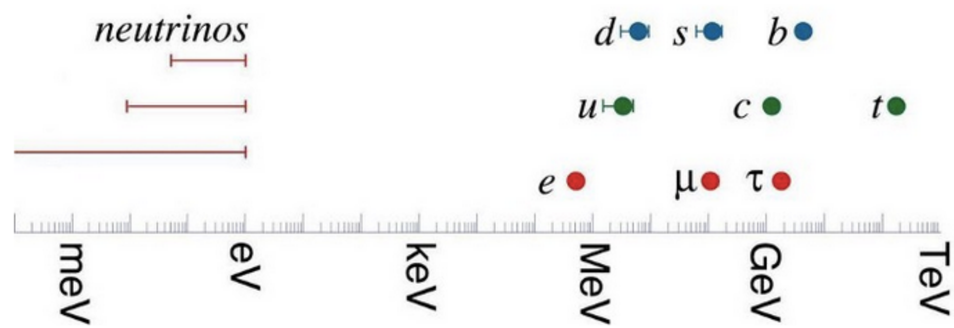
Neutrino Standard Model (νSM)
- SM + 3 active massive neutrino is established

Unknown parameters of νSM
- precise value of θ_{23} (θ_{12} and θ_{13} are precisely known)
- order of mass (normal order $m_1<m_2<m_3$ or inverted order $m_3<m_1<m_2$)
- Dirac or Majorana
- Dirac CP phase
- Majorana CP phase
- absolute neutrino mass

Beyond νSM (BSM)
- 4th neutrino search (sterile neutrino search)
- Dark matter search with neutrinos
- Space-time tests with neutrinos

etc

Undetected neutrinos
- Big bang neutrino background
- Diffuse supernova neutrino background
- Solar CNO cycle neutrinos
- Solar atmospheric neutrinos
- GZK neutrinos



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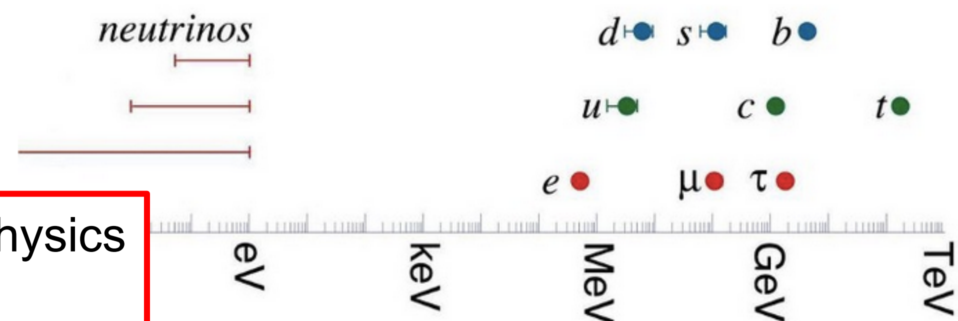


This talk is the status of new physics search within neutrino physics

1. Neutrino oscillations

2. Dirac or Majorana?

3. CP violation with leptons

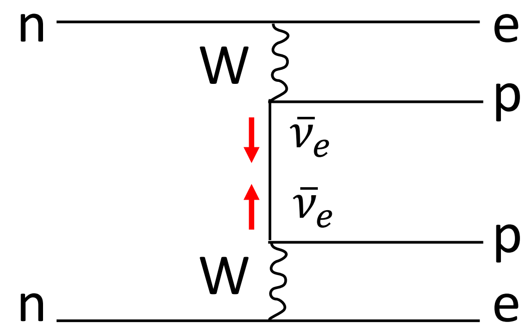
4. 4th neutrino search (sterile neutrino search)

5. Dark matter search with neutrinos

6. Quantum gravity search neutrinos

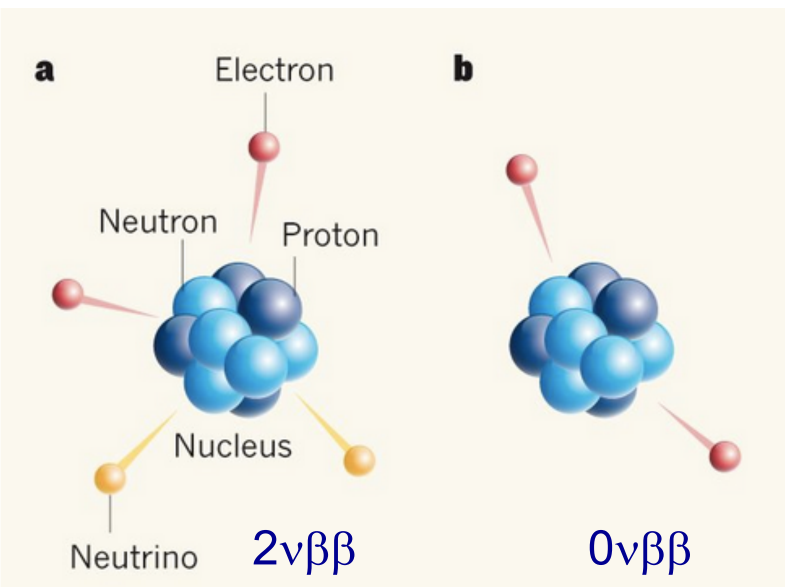
7. Conclusion

2. Neutrinoless double beta decay (0νββ)

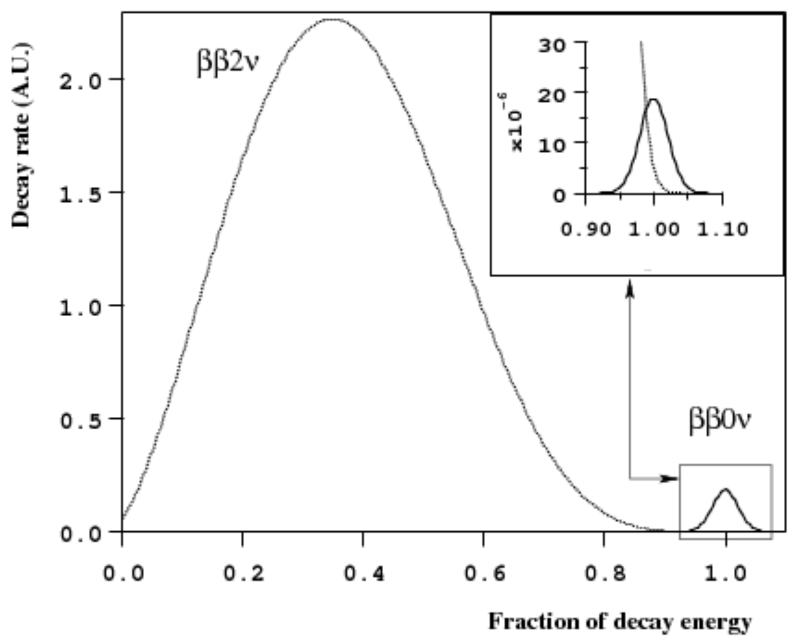


Majorana particle

- antiparticles = particles
- only neutrinos in SM can be Majorana particles
- so far, neutrinoless double beta decay (0νββ), 2X → 2e + 2X', is the only plausible test to look for Majorana nature of neutrinos
- double beta decay (2νββ) is the second order nuclear process, possible only for few elements (^{82}Se, ^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe, etc)
- 0νββ is the lepton number violation process (BSM process)
- Expected half-life, τ(0νββ) > 10^{27} yrs (>>10^{10} yrs ~ life of universe)



Gratta, Nature538(2016)48

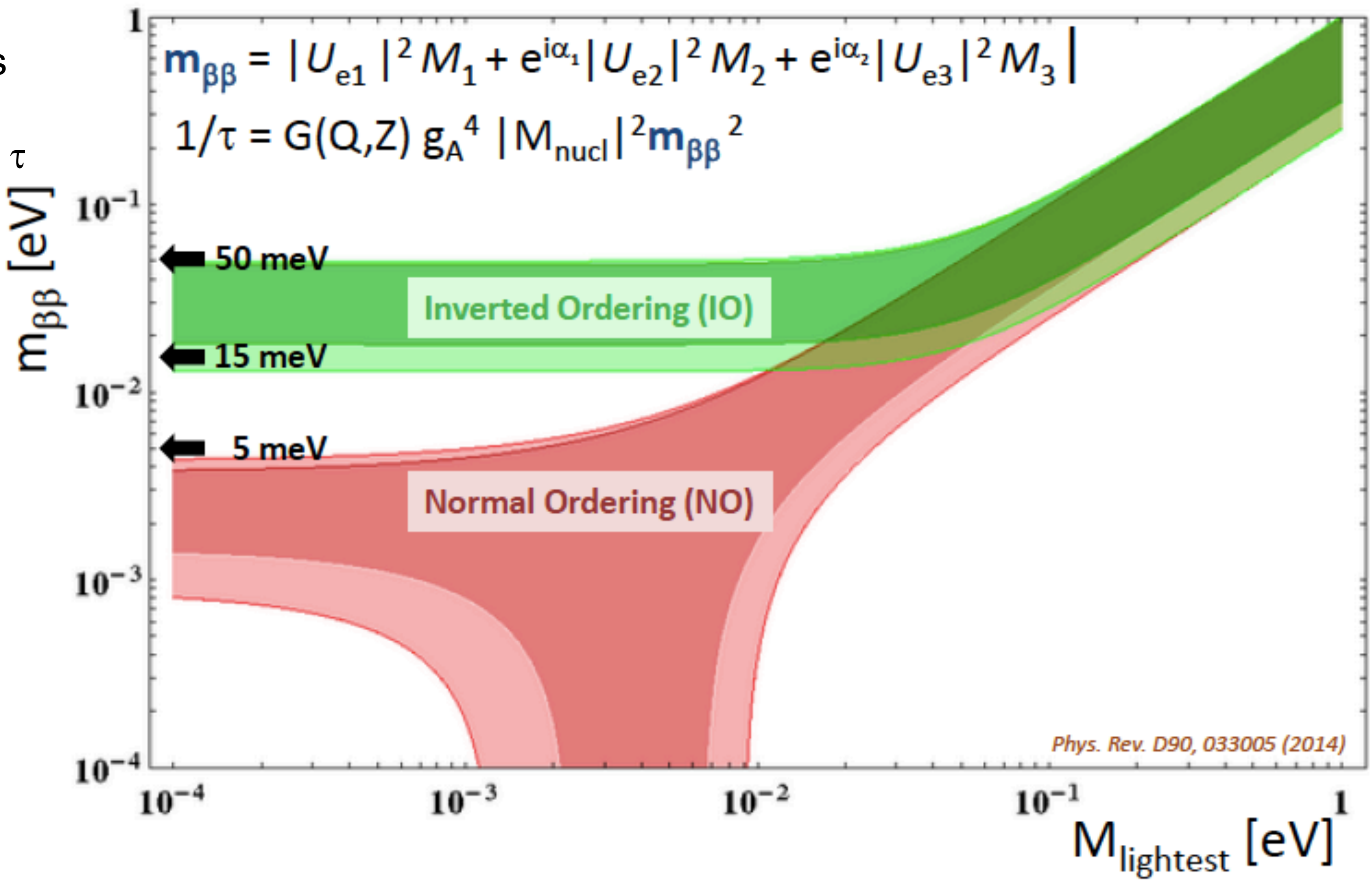


2. Neutrinoless double beta decay (0νββ)

Majorana particle

- 0νββ interpretation depends on neutrino mass ordering
- no 0νββ doesn't mean neutrino is Dirac (0νββ observation mean neutrino is Majorana)
- Current experimental limits~ 40 meV, next generation experiments ~ 10 meV

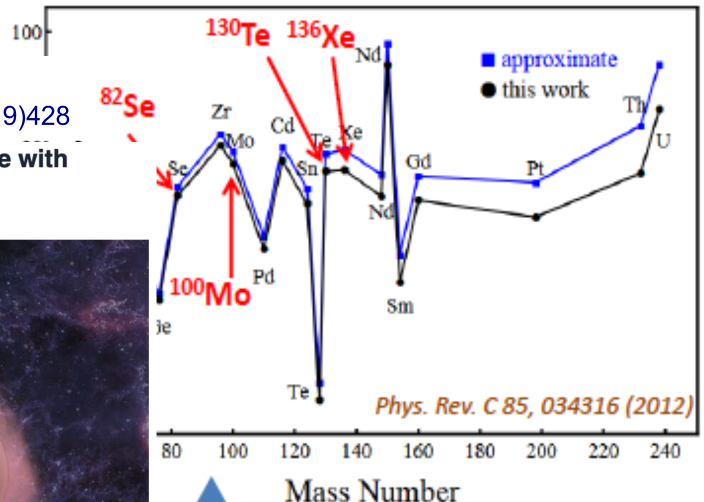
mββ (effective Majorana mass) is extracted from measured half-life τ



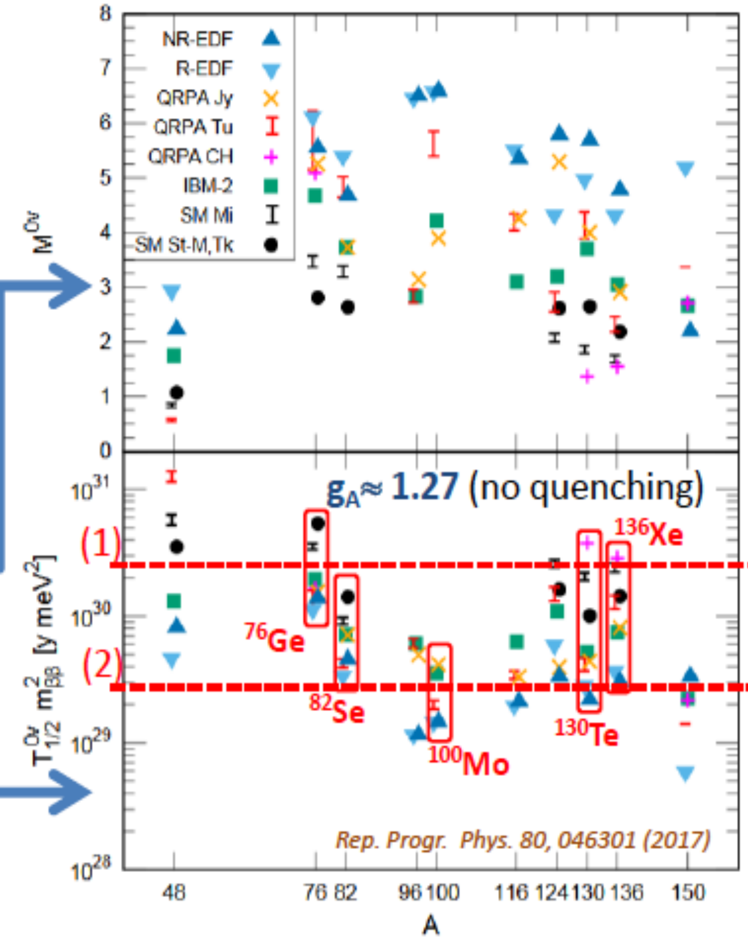
2. Neutrinoless double beta decay and nuclear physics

Nuclear physics gives large systematics to extract $m_{\beta\beta}$ from τ (half-life)
- Nuclear matric element calculation
- Nuclear quenching of g_A

Phase space: exactly calculable



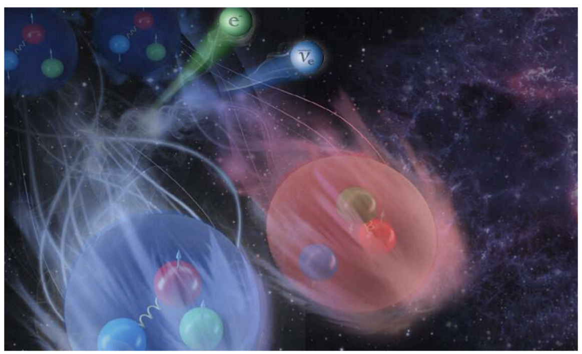
Nuclear matrix elements: several models



Or maybe no quenching?
Gysbers et al., Nature Phys. 15(2019)428

Physicists solve a beta-decay puzzle with advanced nuclear models

by Oak Ridge National Laboratory



$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2\, m_{\beta\beta}^{\,2}$$

Nuclear physics is complicated

1. Neutrino oscillations

2. Dirac or Majorana?

3. **CP violation with leptons**

4. 4th neutrino search (sterile neutrino search)

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3. CP violation with leptons

CP violation (charge-parity symmetry violation)

- Amount of different behavior between particles and antiparticles
- Necessary ingredient to explain matter-antimatter asymmetry of universe (1 of "Sakharov's 3 conditions")

CP violation with quarks

- Jarlskog invariant, J_{quark} ~10^{-5} (very small)
- CP violation of lepton, J_{lepton} ~ 10^{-2} → Leptonic CP violation may be responsible for matter-antimatter asymmetry of universe?

Neutrino oscillations

- Neutrino oscillations depends on CP violation (Dirac CP phase)
- Effect is small, need high statistics
- Need large scale long-baseline neutrino oscillation experiments

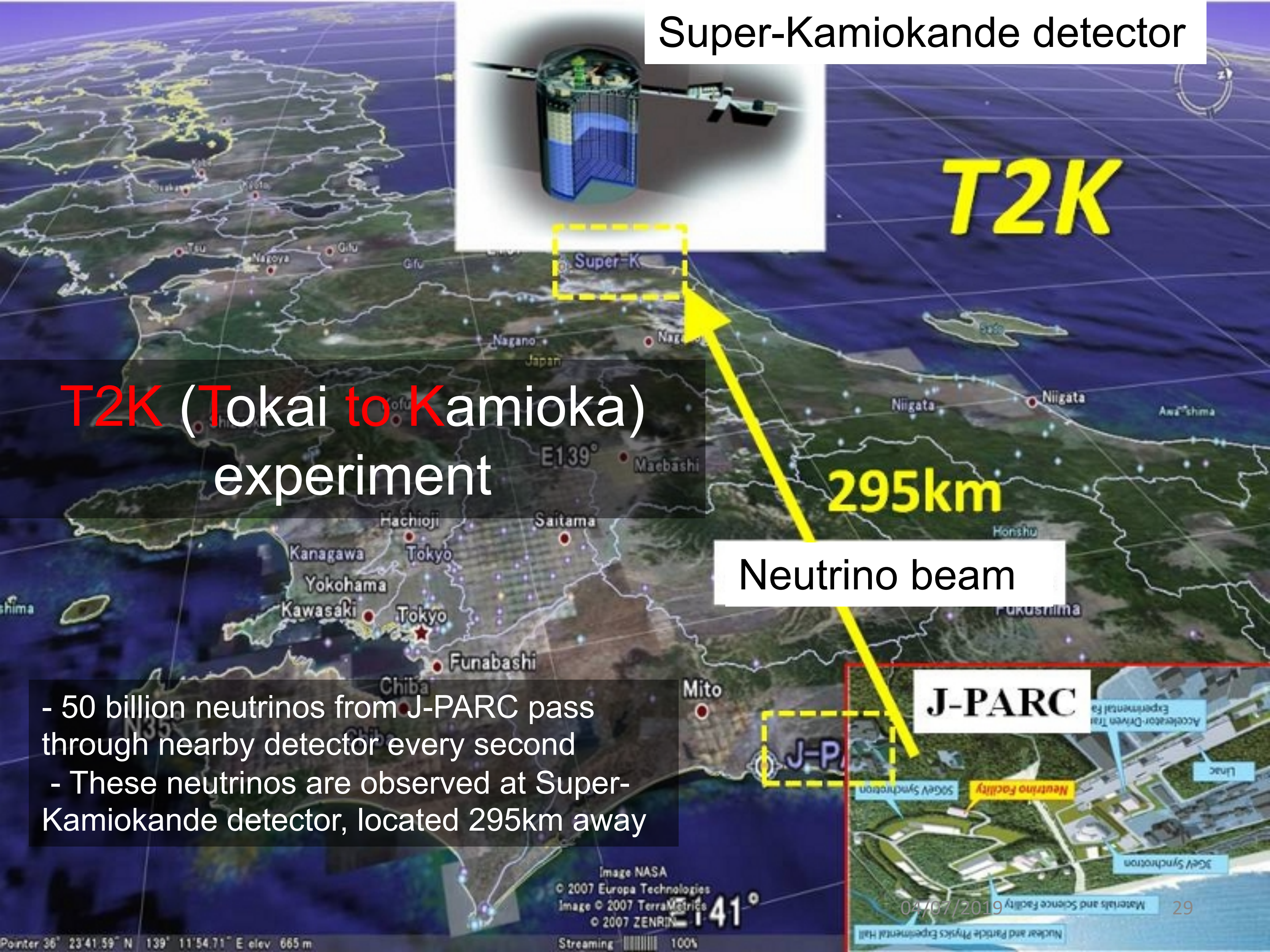
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= |\, U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} \,|^2 \\
&= |2 U^*_{\mu 3} U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2 U^*_{\mu 2} U_{e2} \sin \Delta_{21}|^2 \\
&\approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2
\end{aligned}
$$

$$\Delta_{ij} = \frac{\delta m^2_{ij} L}{4E}$$

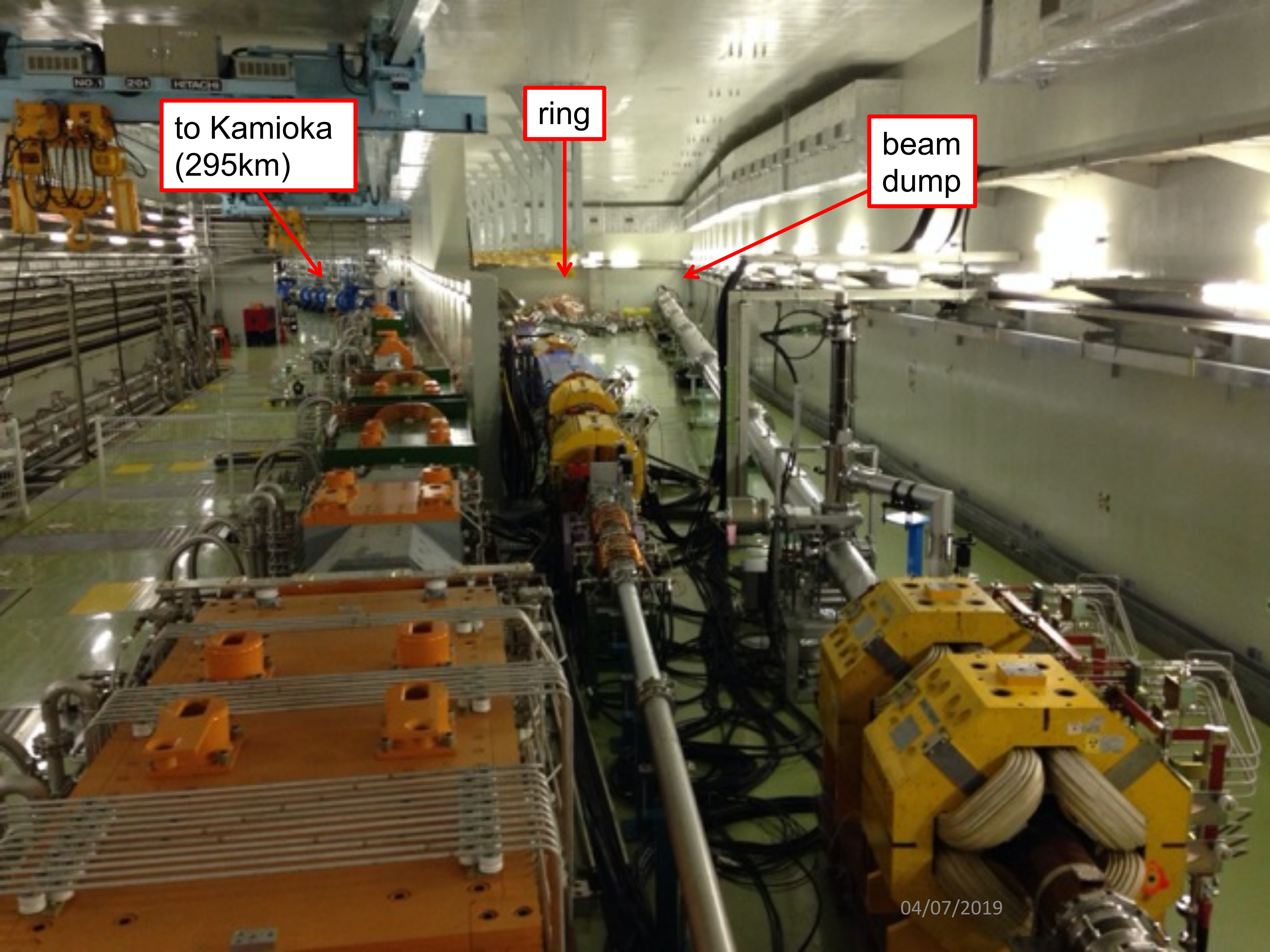
where $\sqrt{P_{atm}} = 2|U_{\mu 3}||U_{e3}| \sin \Delta_{31} = \sin\theta_{23} \sin 2\theta_{13} \sin \Delta_{31}$

and $\sqrt{P_{sol}} \approx \cos\theta_{23} \sin 2\theta_{12} \sin \Delta_{21}$.

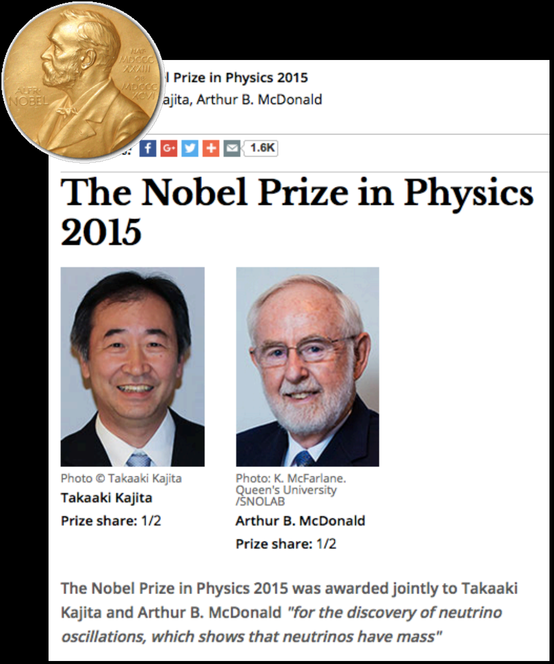
T2K (Tokai to Kamioka) experiment



- 50 billion neutrinos from J-PARC pass through nearby detector every second
- These neutrinos are observed at Super-Kamiokande detector, located 295km away


NO.1
20t
HITACHI
to Kamioka (295km)
ring
beam dump

Super-Kamiokande detector


l Prize in Physics 2015
ajita, Arthur B. McDonald
1.6K

The Nobel Prize in Physics 2015

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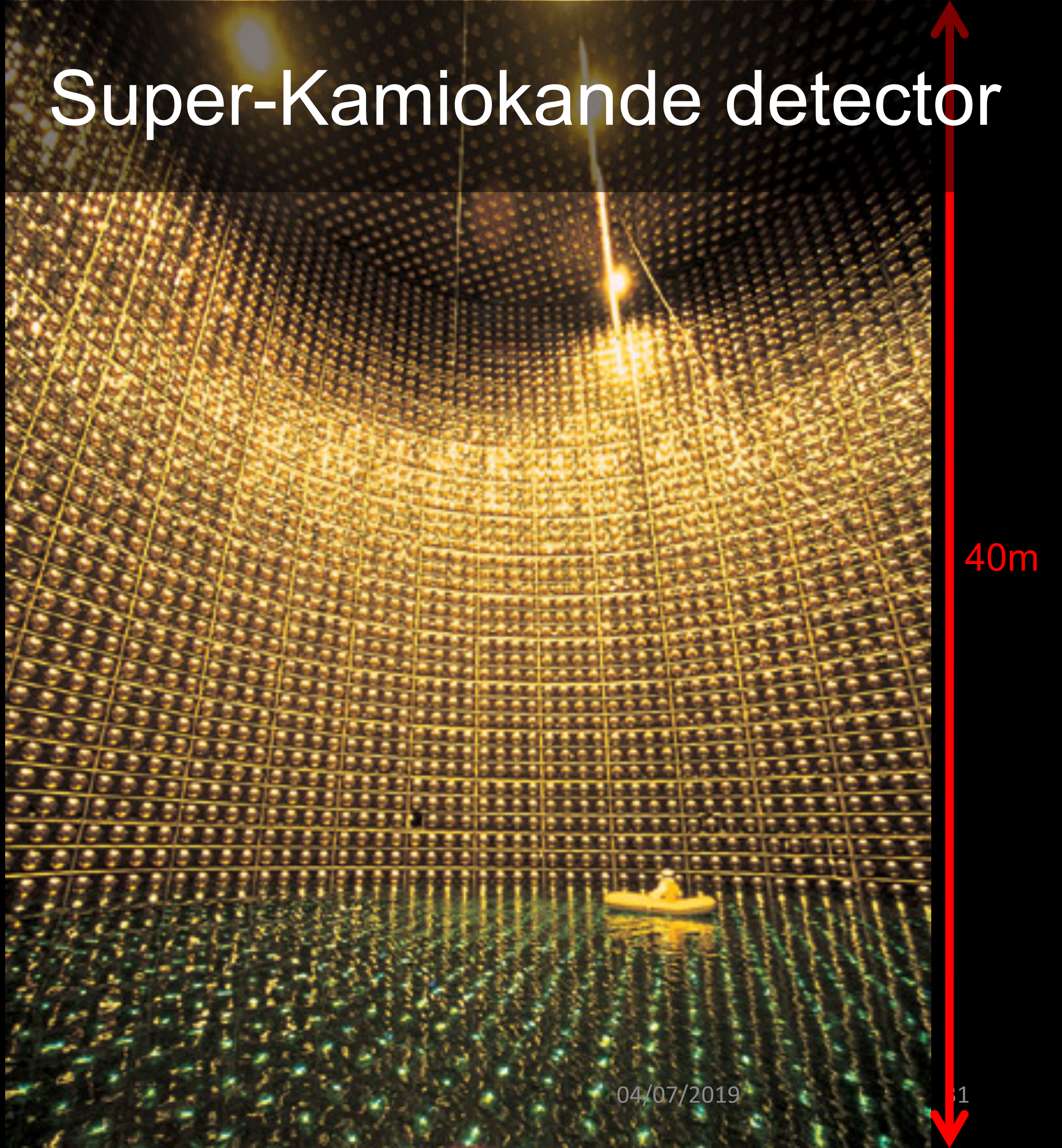
Takaaki Kajita
Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

- 40m height, 40m wide, 50k ton of pure water
- Roughly 25 million neutrino from J-PARC pass through every second (and you see <1 neutrino per day)

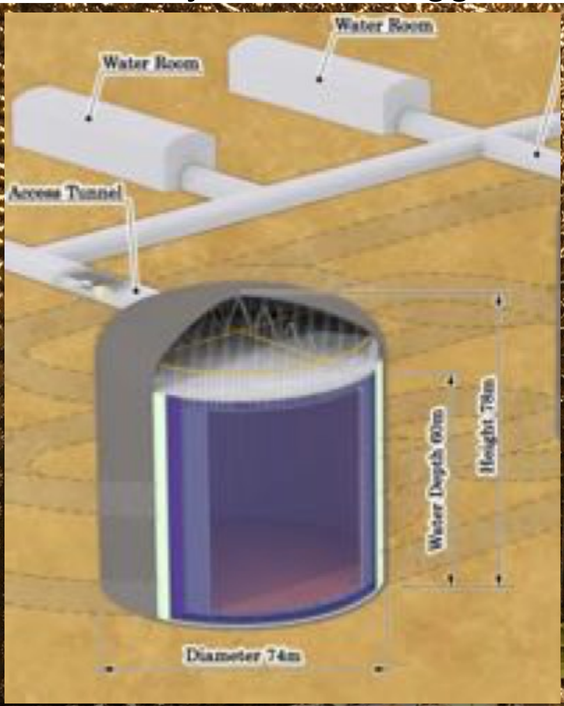


Super-Kamiokande detector refurbishment 2018

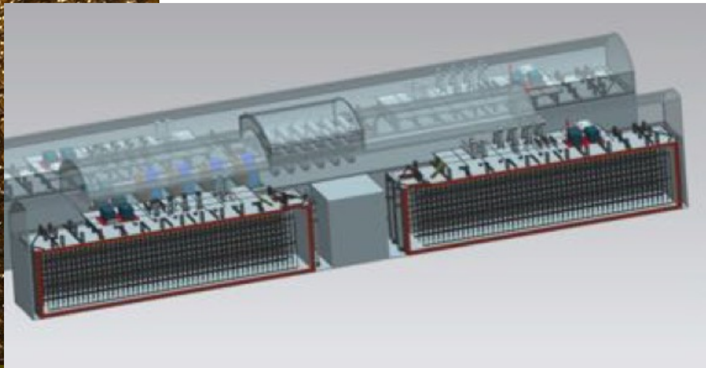
3. Hyper-Kamiokande and DUNE

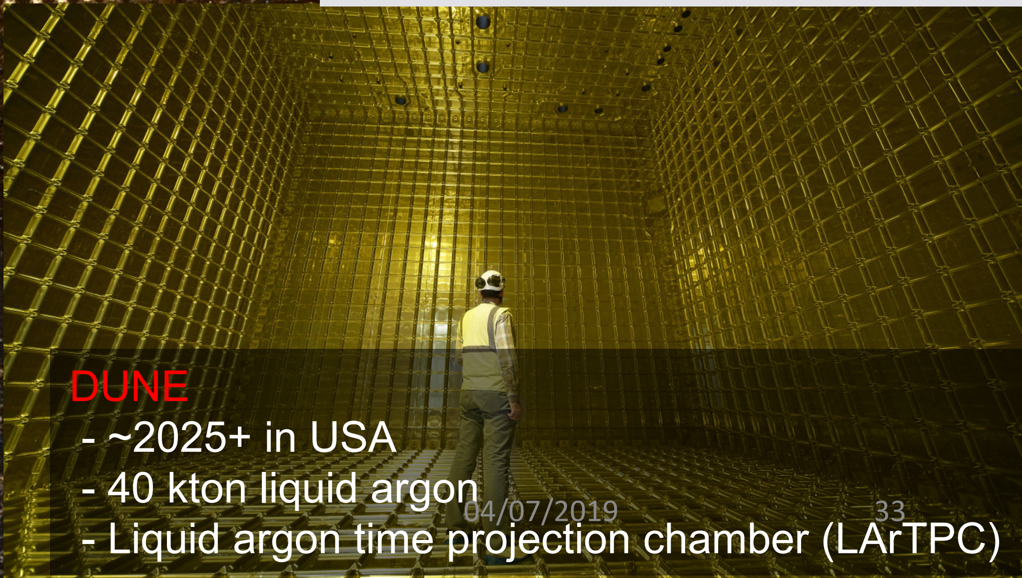
Next generation long-baseline neutrino oscillation experiments

- T2K and NOvA are leading long-baseline neutrino oscillation experiments
- As of 2019, both found an indication (2σ level signal) of leptonic CP
- Probably we need bigger experiments to find 5σ level leptonic CP violation signal



Hyper-Kamiokande
- ~2026+ in Japan
- 200 kton water
- Water Cherenkov detector

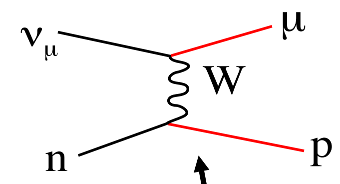




DUNE
- ~2025+ in USA
- 40 kton liquid argon
- Liquid argon time projection chamber (LArTPC)

MiniBooNE: PRD81(2010)092005
Martini et al,PRC80(2009)065501

3. Neutrino interaction physics and nuclear physics



Neutrinos are invisible, and neutrino energy is estimated from particles created by neutrino interactions. So neutrino-nucleus interactions need to be understood to measure neutrino oscillations.

me
(particle physicist)

Marco Martini
(nuclear theorist)

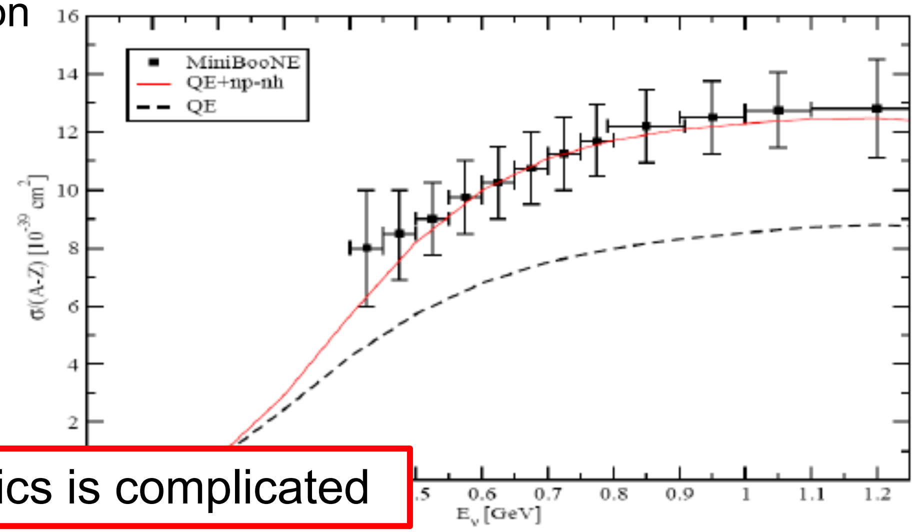
Discovery of nucleon correlation in neutrino scattering

- nuclear physics modify interaction rate and outgoing particle kinematics
- hot topic for current beam-based neutrino experiments

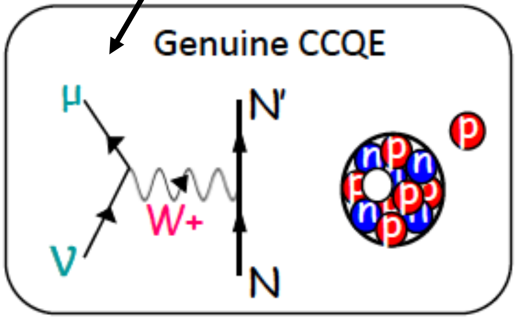
Nuclear physics will have the biggest systematic error for future long-baseline neutrino oscillation experiments…

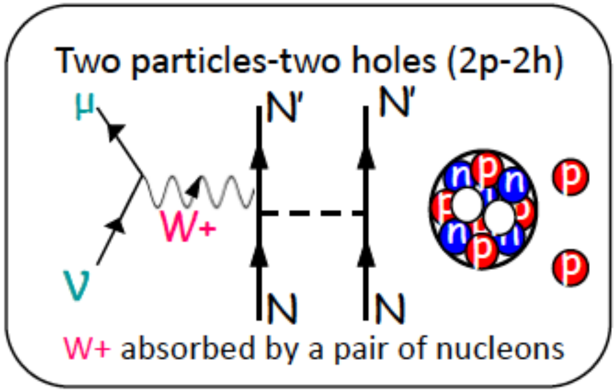
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



Nuclear physics is complicated





1. Neutrino oscillations

2. Dirac or Majorana?

3. CP violation with leptons

4. 4th neutrino search (sterile neutrino search)

5. Dark matter search with neutrinos

6. Quantum gravity search neutrinos

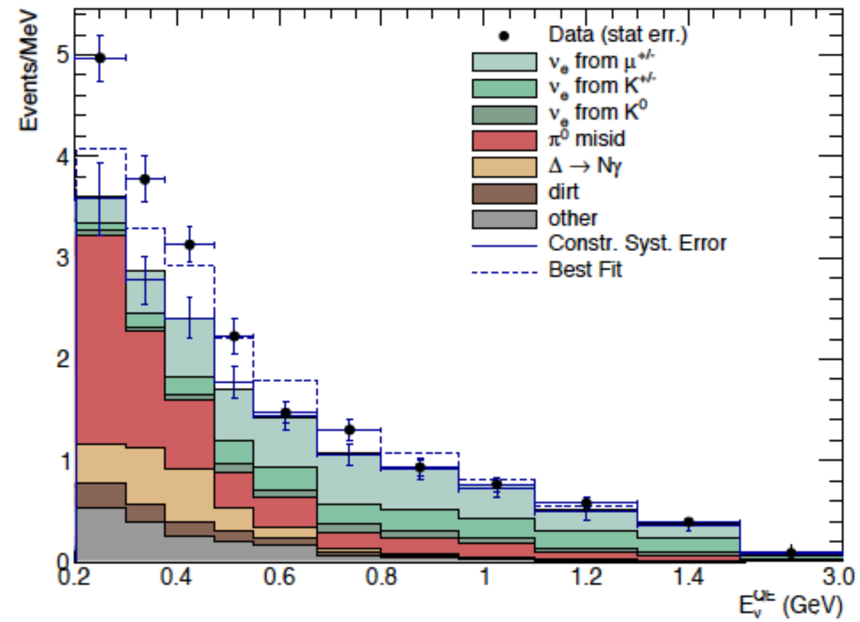
7. Conclusion

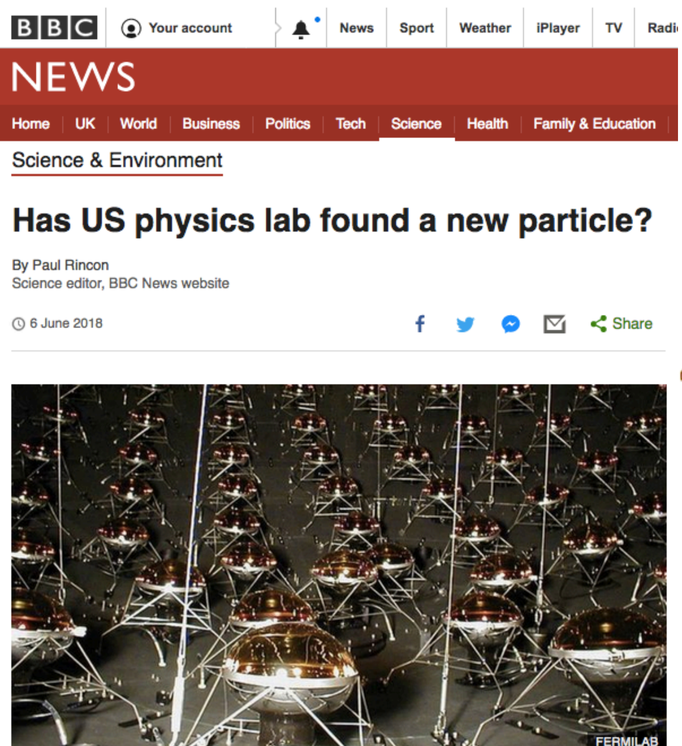
4. Sterile neutrino search

MiniBooNE

- USA based neutrino oscillation experiment persistently shows unexplained excess
- This can be interpreted $\nu_\mu \rightarrow \nu_e$ oscillation through 4th neutrino ($\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$)
- However, number of neutrinos is known to be 3 from Z-boson decay width measurement, so 4th neutrino doesn't interact with weak force

→ sterile neutrino





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Science & Environment

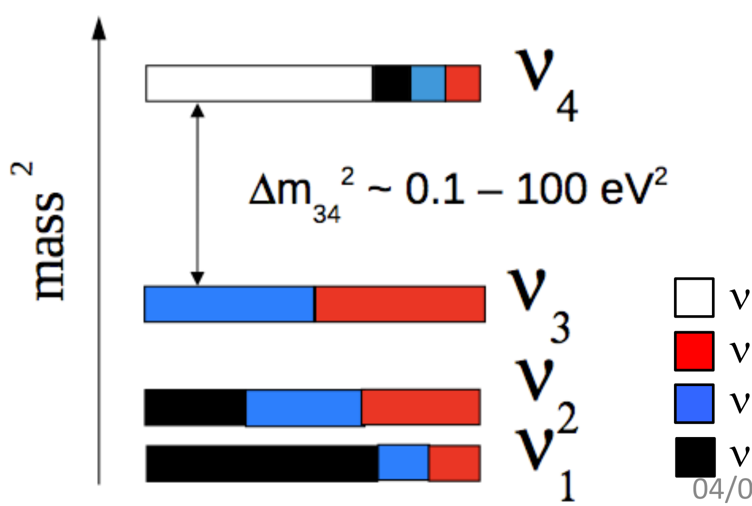
Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

6 June 2018

Share

FERMILAB



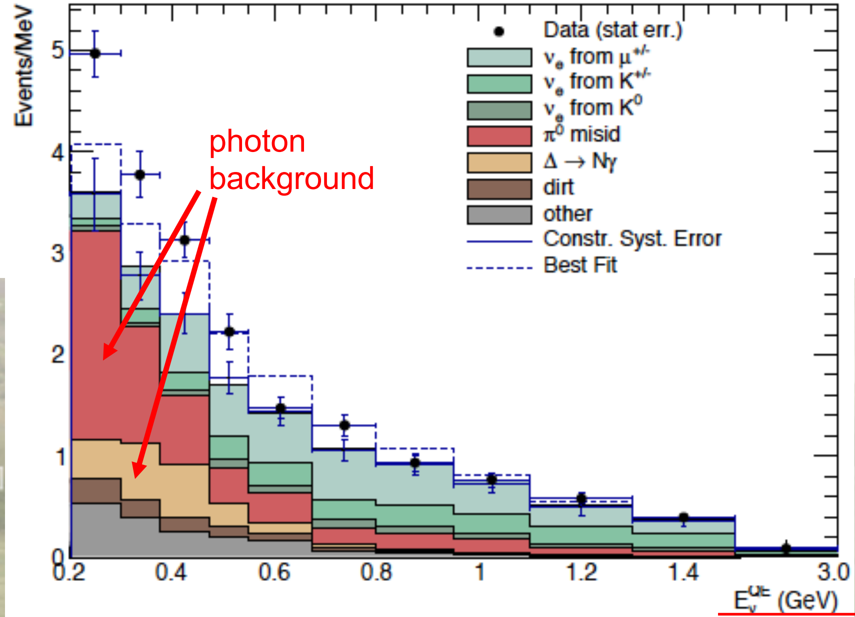
large neutrino mass
↓
short-baseline neutrino oscillation experiment
(most of large mass sterile neutrino search experiments)

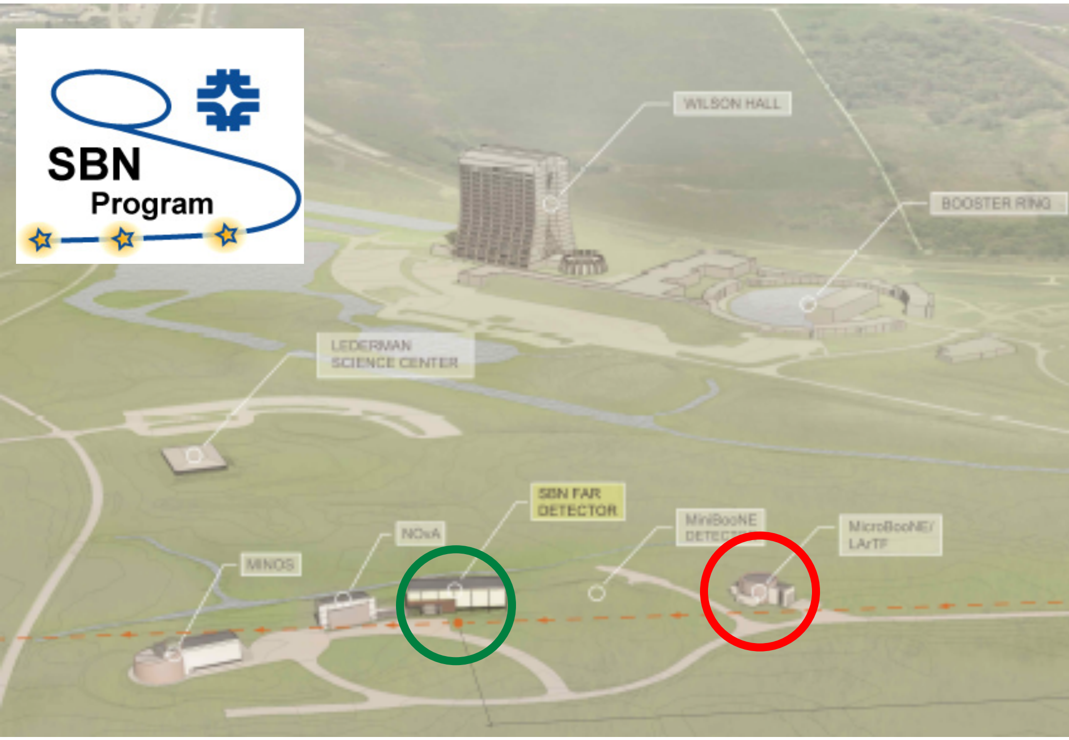
MiniBooNE, PRL121(2018)221801
Fermilab SBN program, arXiv:1503.01520

4. Fermilab short baseline neutrino (SBN) program

SBND+MicroBooNE+IACRUS

- 3 liquid argon time projection chamber detectors
- 3-D track reconstruction
- high photon background rejection
- MicroBooNE will release the first result in 2019





ICARUS
- 600 m
- 476 ton

MicroBooNE
- 470 m
- 85 ton

SBND
- 110 m
- 112 ton

← neutrino beam

MiniBooNE, PRL121(2018)221801
Fermilab SBN program, arXiv:1503.01520

4. Fermilab short baseline neutrino (SBN) program

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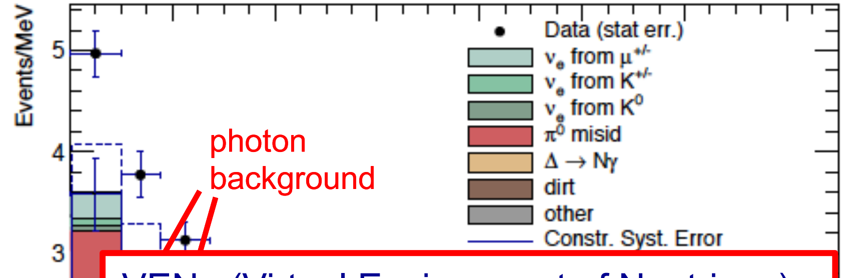
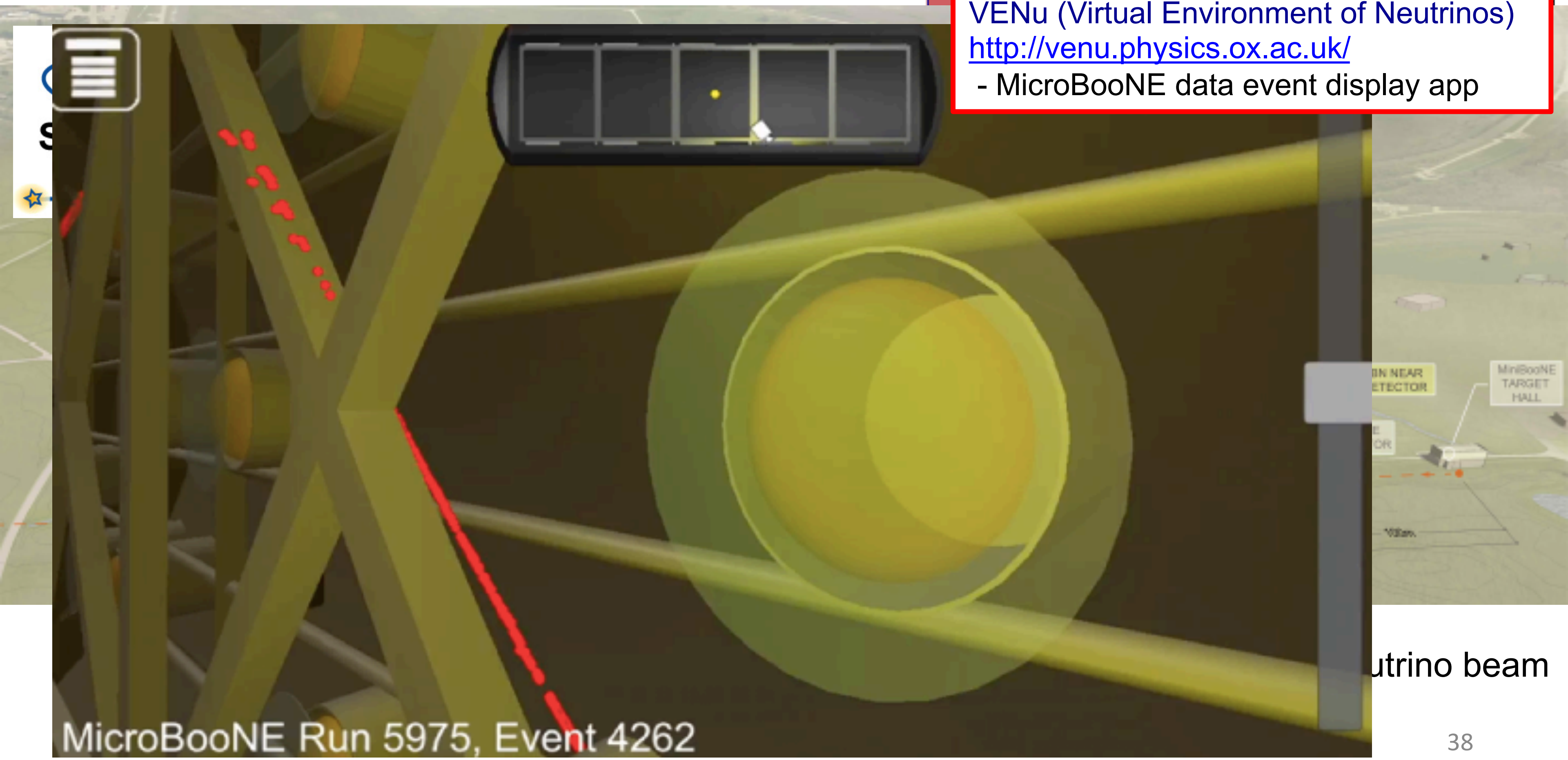


VENu (Virtual Environment of Neutrinos)
http://venu.physics.ox.ac.uk/
- MicroBooNE data event display app



utrino beam

1. Neutrino oscillations

2. Dirac or Majorana?

3. CP violation with leptons

4. 4th neutrino search (sterile neutrino search)

5. Dark matter search with neutrinos

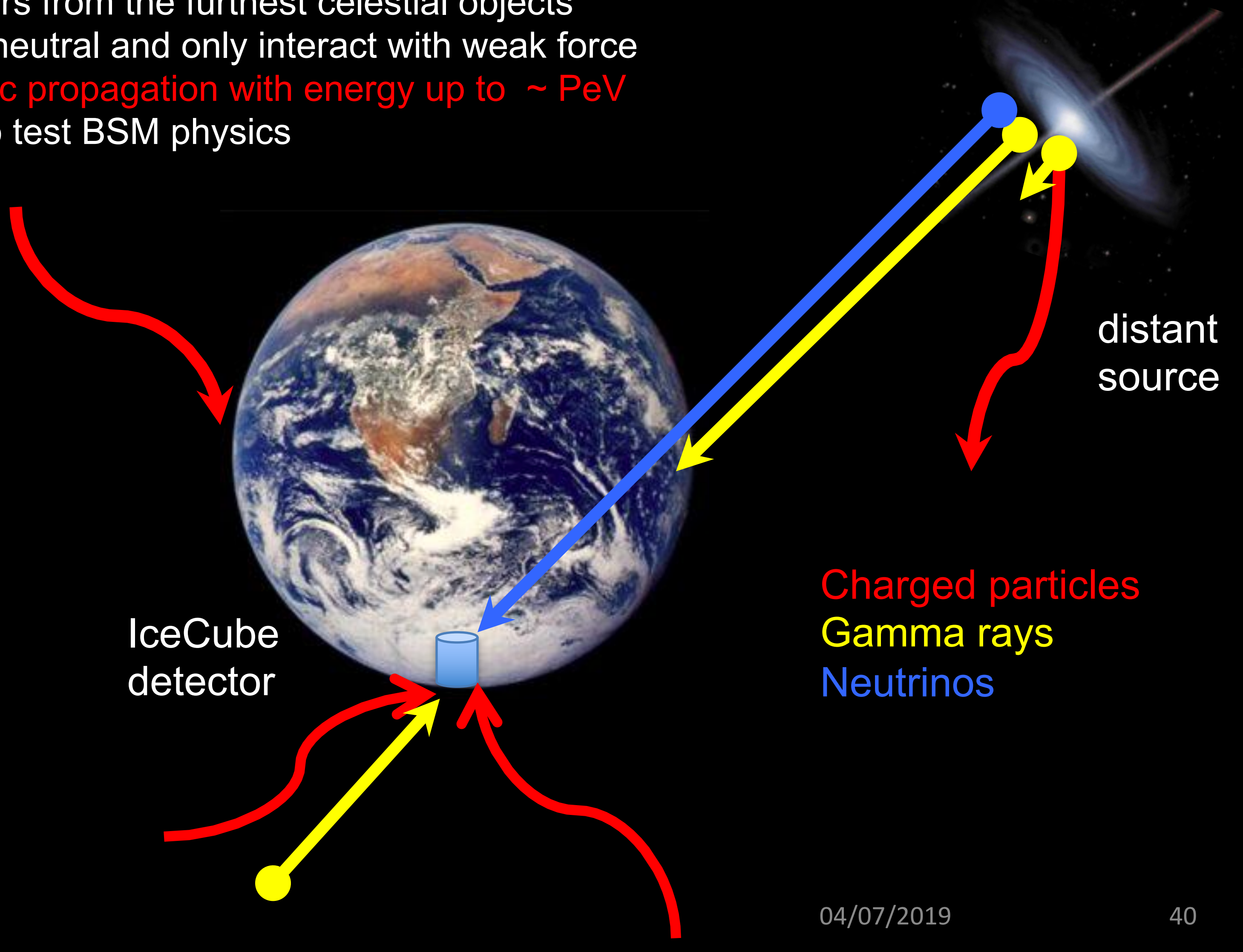
6. Quantum gravity search neutrinos

7. Conclusion

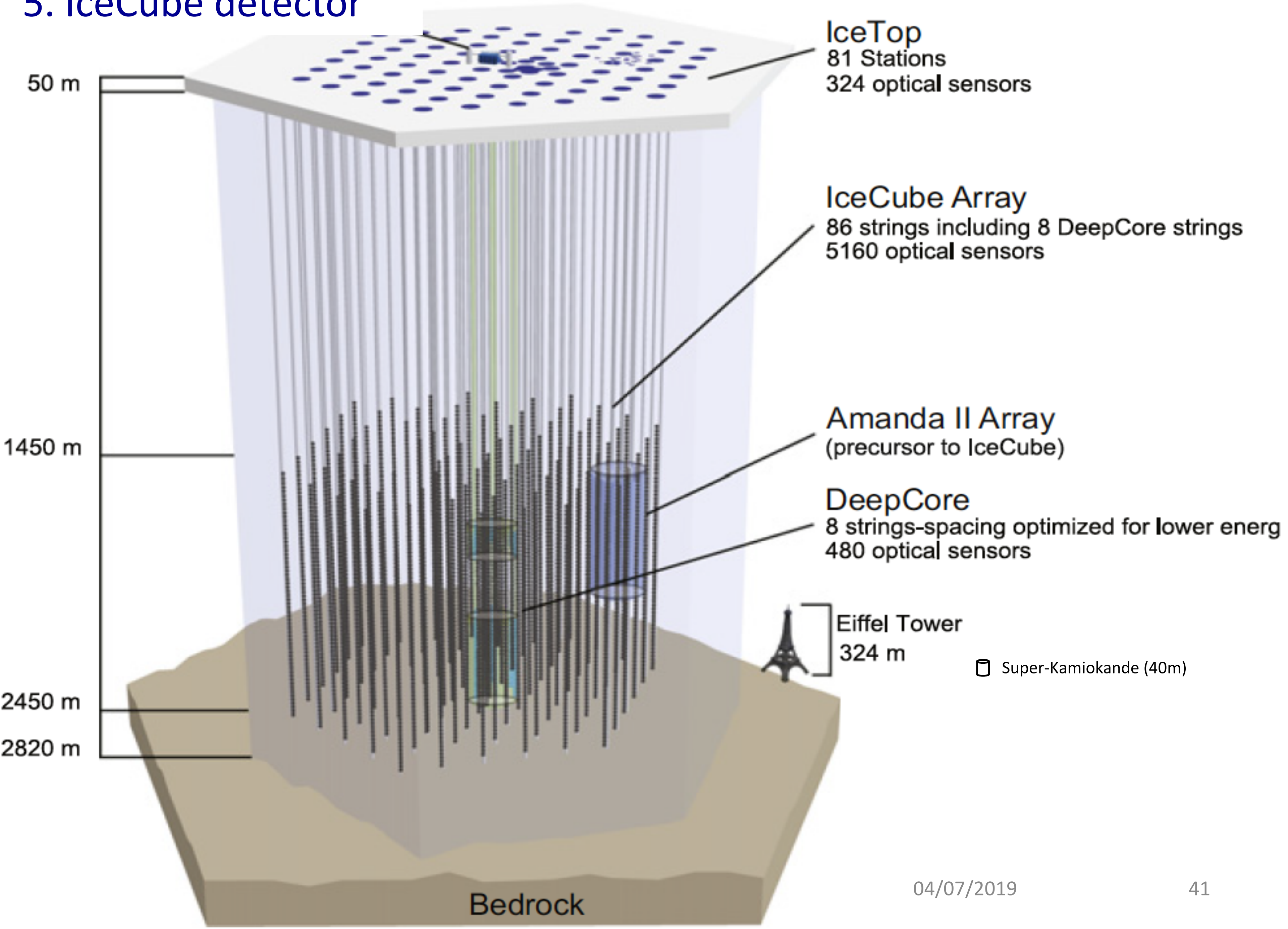
5. High-Energy Neutrino Astronomy

Direct messengers from the furthest celestial objects
- Neutrinos are neutral and only interact with weak force
- order ~100 Mpc propagation with energy up to ~ PeV

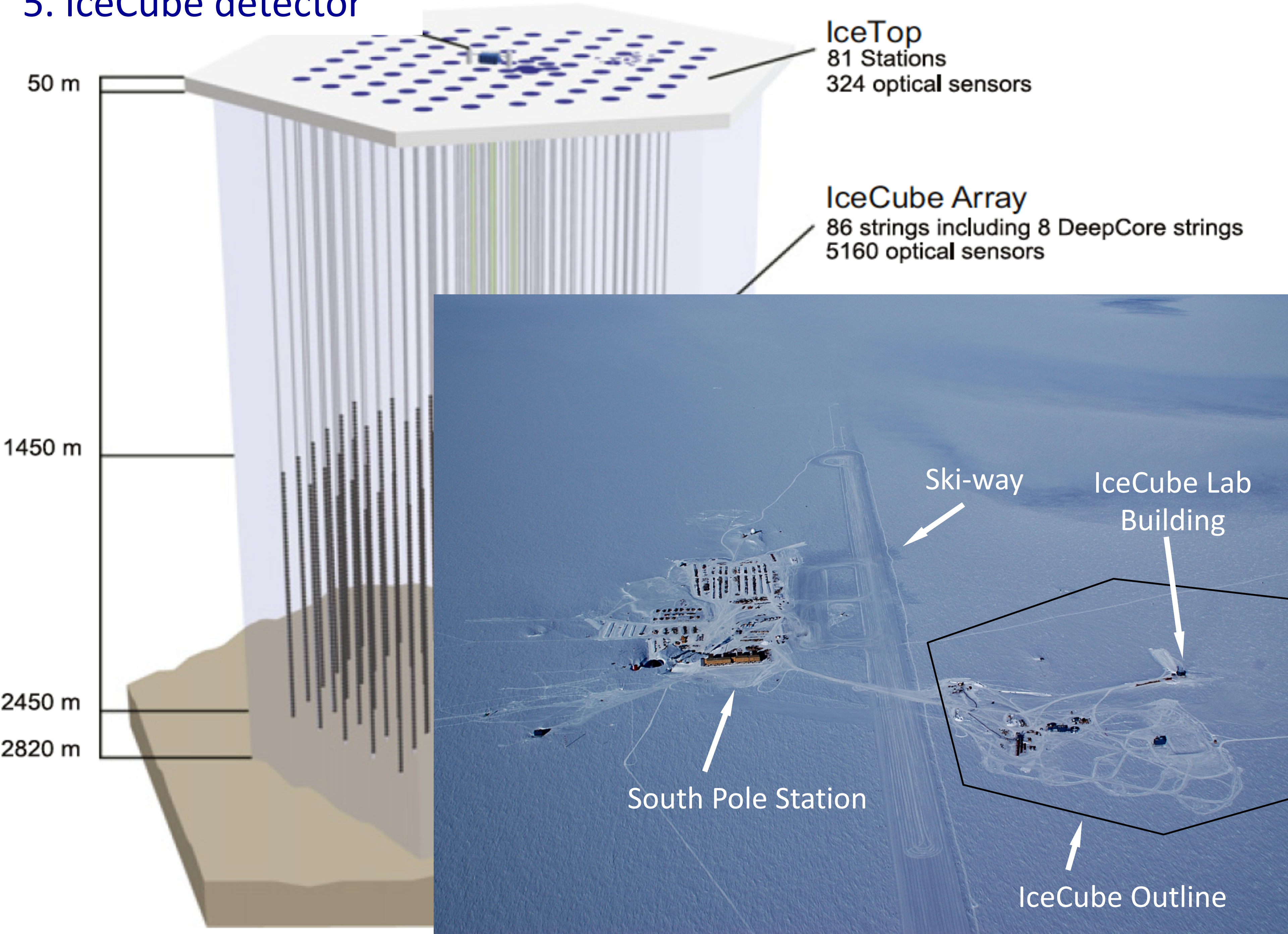
→ unique tool to test BSM physics



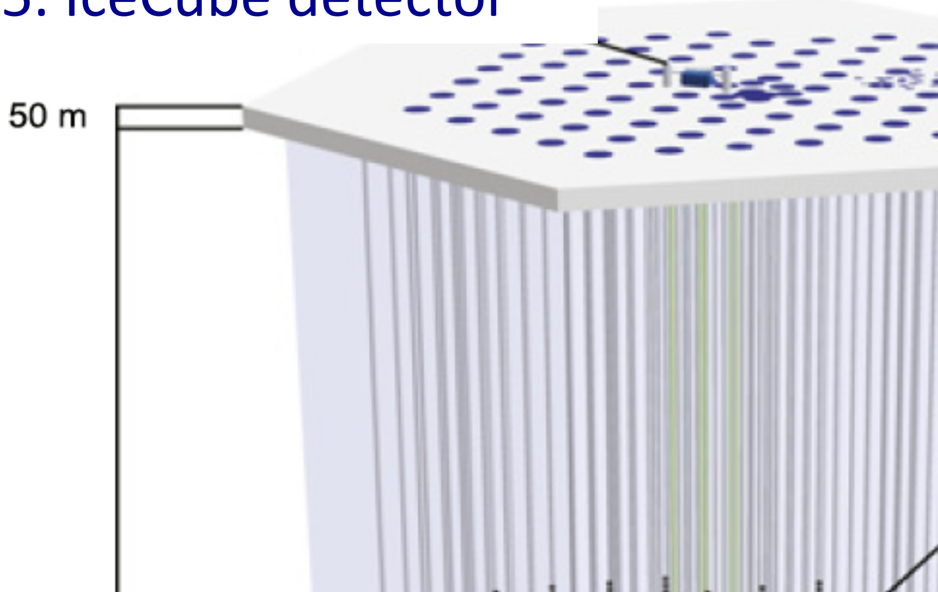
5. IceCube detector

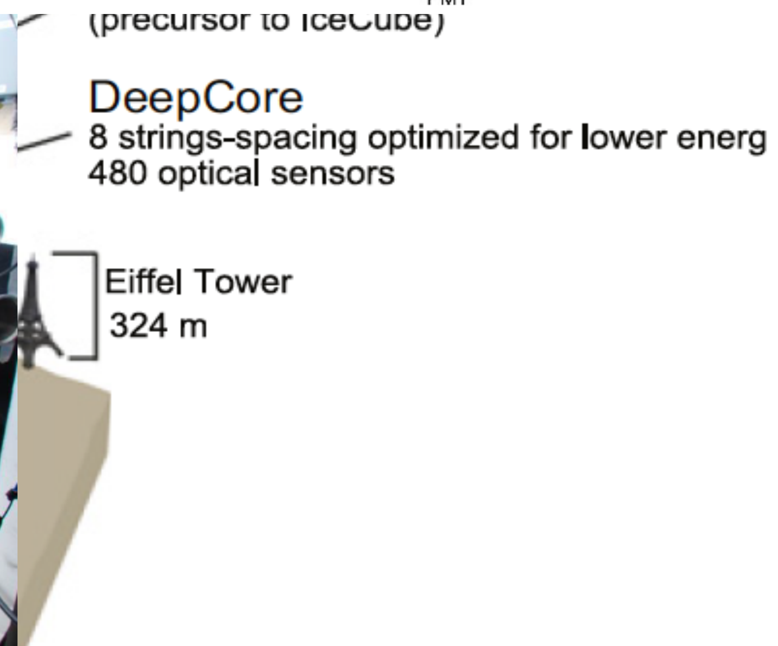


5. IceCube detector

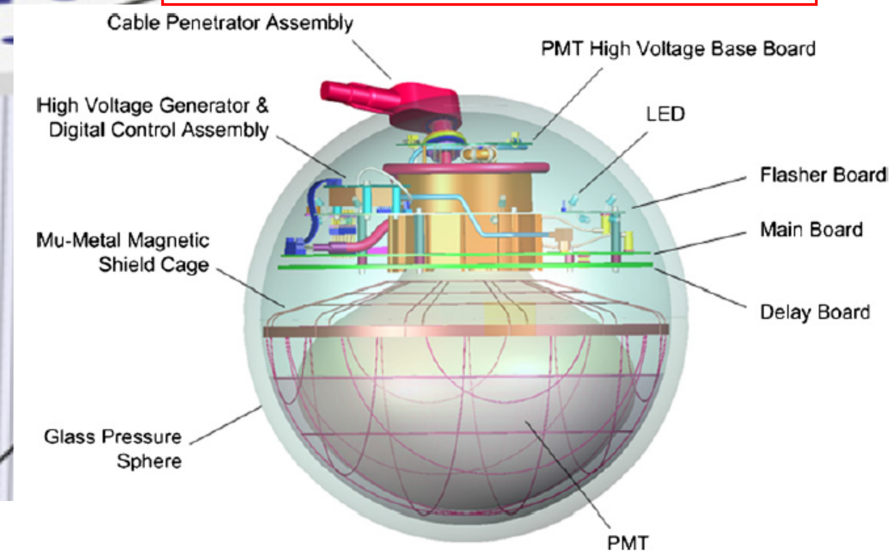


5. IceCube detector





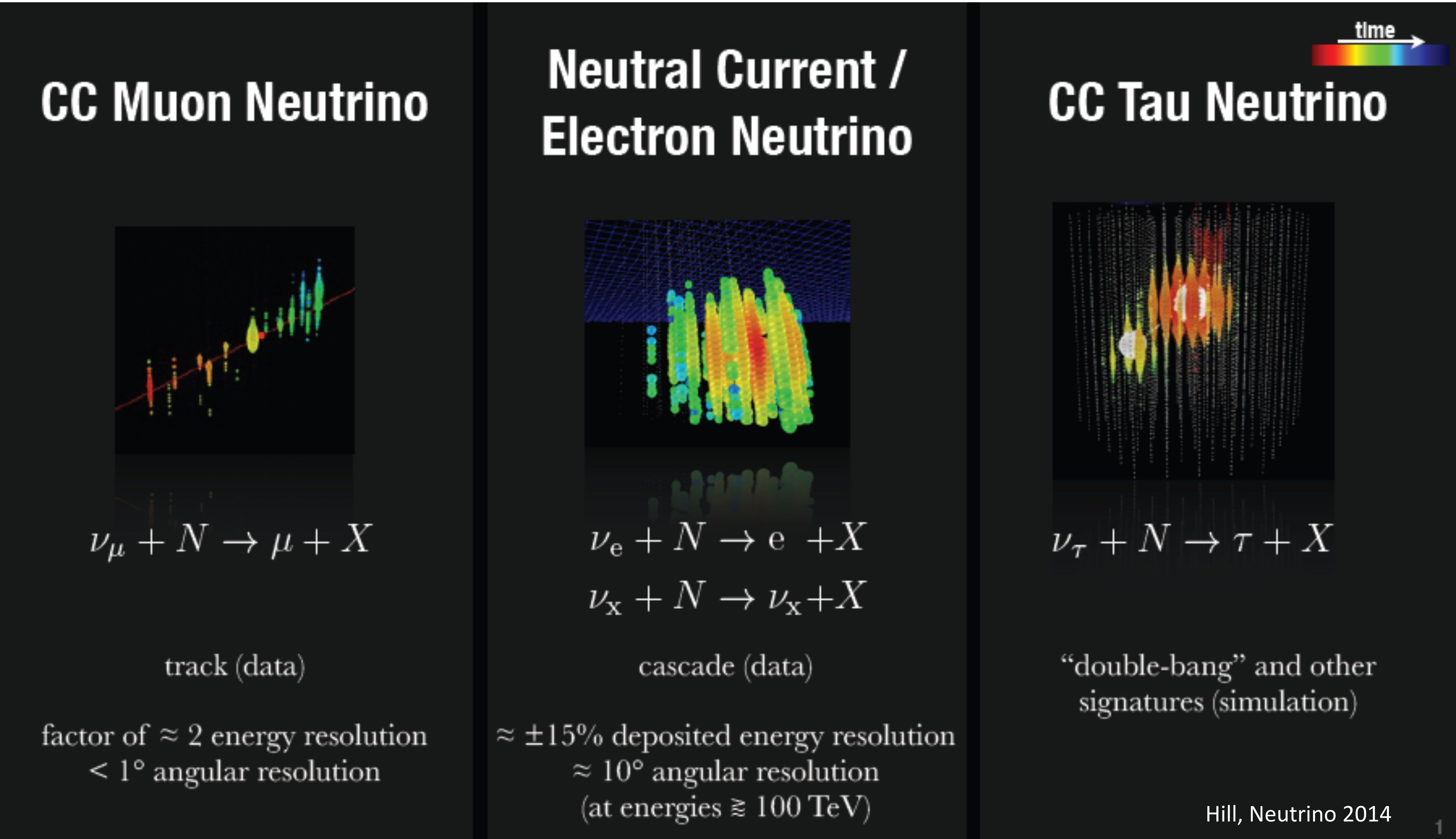
digital optical module (DOM)



optical sensor deployment

5. Astrophysical High-Energy Neutrinos

Topology
- Track = muon ($\sim\nu_\mu$CC)
- Shower (cascade) = electron, tau, hadrons ($\sim$, ν_eCC, ν_τCC, NC)



Hill, Neutrino 2014

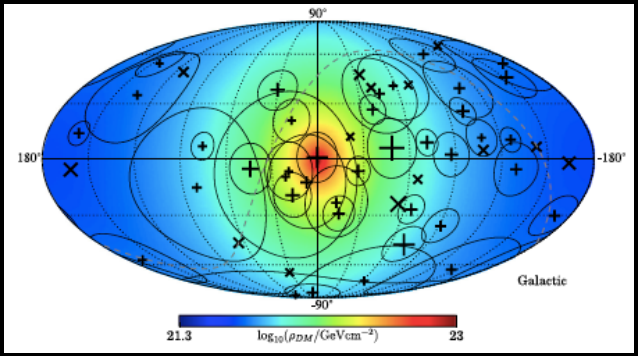
IceCube, EPJC76(2016)531, Berlin, PRL117(2016)231801
Argüelles,Kheirandish,Vincent, PRL119(2017)201801

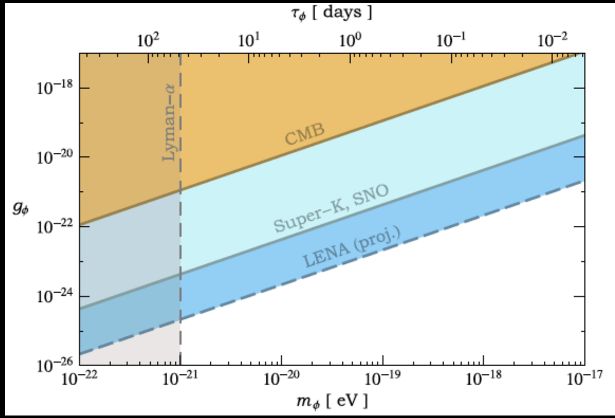
5. Dark matter search with astrophysical neutrinos

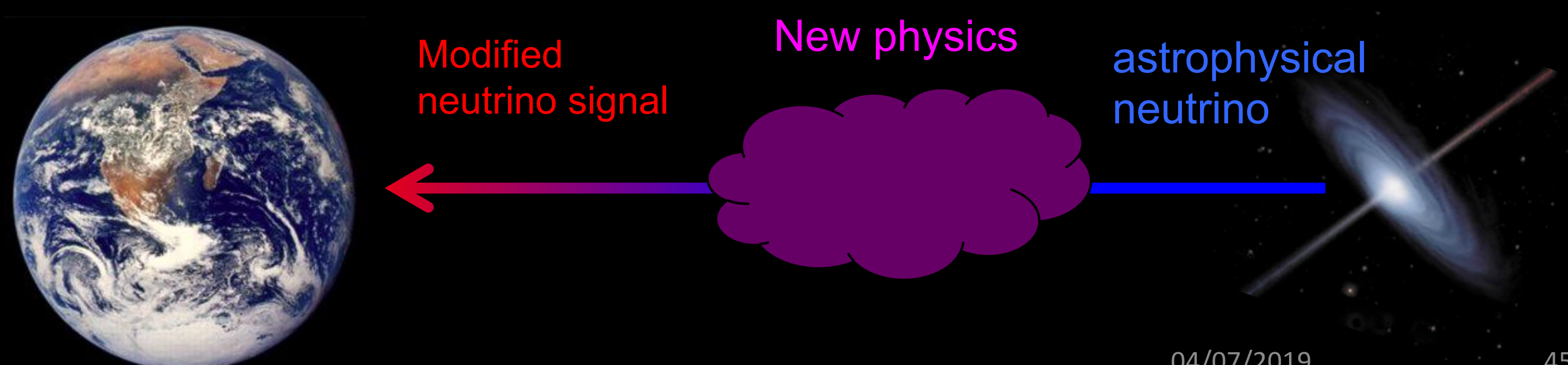
Neutrinos from Earth, Sun, Milky Way center
- Signal of dark matter annihilation to neutrino pair emission
→ no excess in Earth, Sun, Milky Way center

Astrophysical neutrino spectrum distortion, flavor anomaly
- Signal of neutrino-dark matter interaction
→ no modification of spectrum, flavors

These approaches can investigate dark matter from dark matter particle mass ~10^{-22} eV to ~10^{13} eV (order 35!)







1. Neutrino oscillations

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7. Conclusion

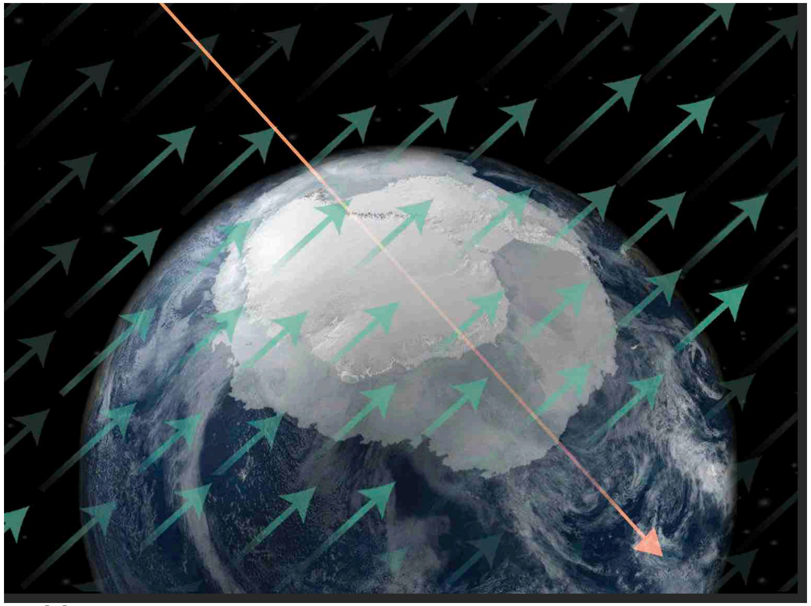
6. Quantum gravity

"Theory of Everything" is QFT+GR
- Quantum Field Thoery (QFT) → particle physics, microscopic scale
- General Relativity (GR) → gravity, large scale

A unified theory, "quantum gravity" may show new space-time structure
- ~10^{19} GeV (Planck energy), the energy of the Big Bang and no machines can replicate
- ~$(10^{19}\text{ GeV})^{-1}$, expected quantum fluctuation of space-time itself ← our focus

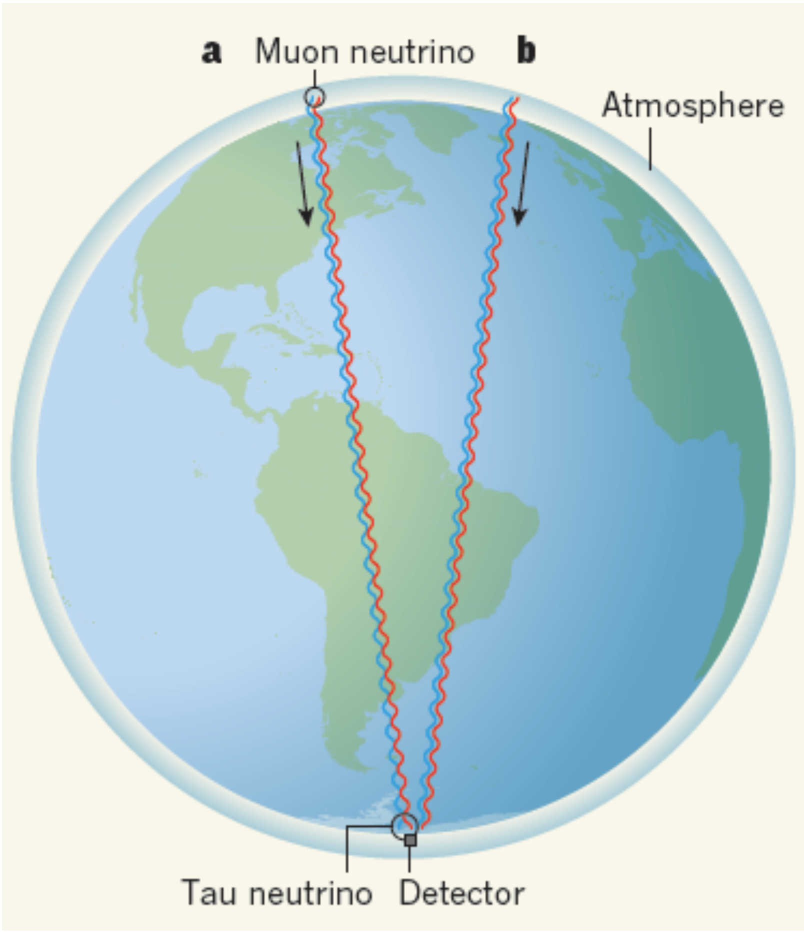
quantum foam
- quantum fluctuation of space time

Lorentz violating field
- new field saturating the universe (aether)



IceCube, Nature Physics 14 (2018) 961
Mewes, Nature 560 (2018) 316

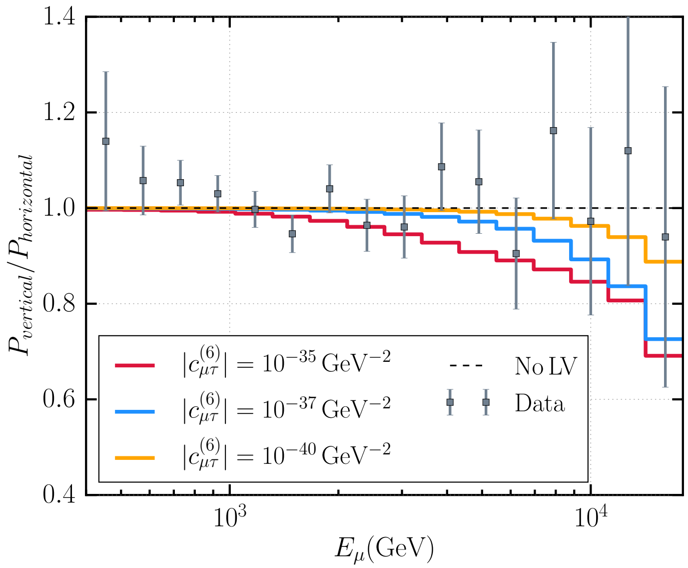
6. Neutrino interferometry with atmospheric neutrinos



Neutrinos are natural interferometer. And the biggest interferometer on the Earth is the size of Earth diameter.

Using atmospheric neutrinos produced on other side of the Earth, we can test violation of Lorentz invariance with the highest precision.

There is no anomalous neutrino oscillation, Lorentz invariance is valid with very high-precision



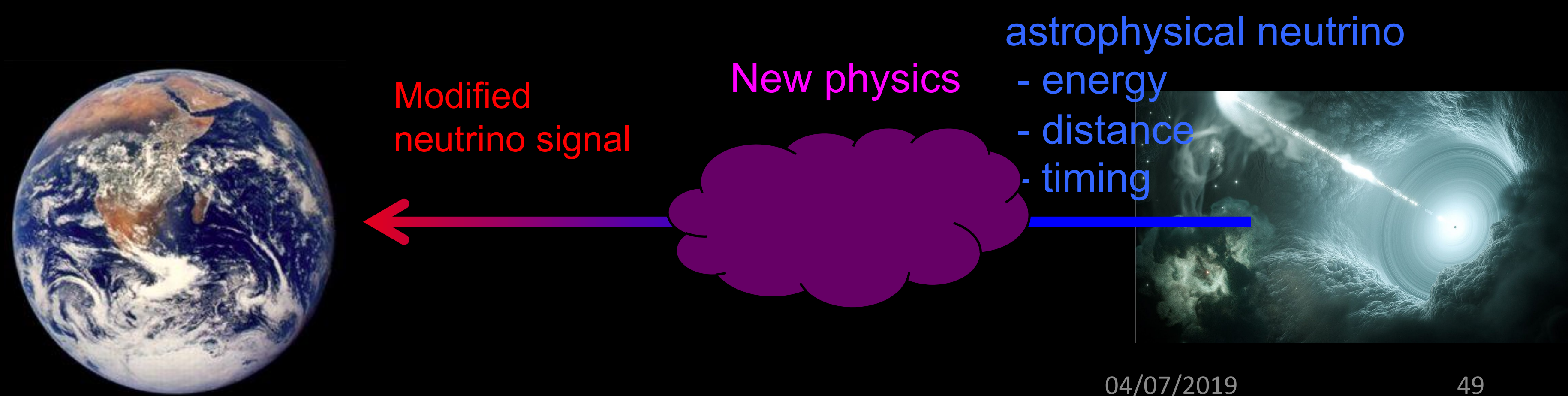
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378
Ellis et al., PLB 789 (2019) 352

6. Quantum gravity search with astrophysical neutrinos

TXS0506+056
- Blazar, a type of active galactic nuclei (AGNs)
- Coincidence signals of neutrinos and photons are detected
- 3rd celestial neutrino source (Sun, supernova 1987A)

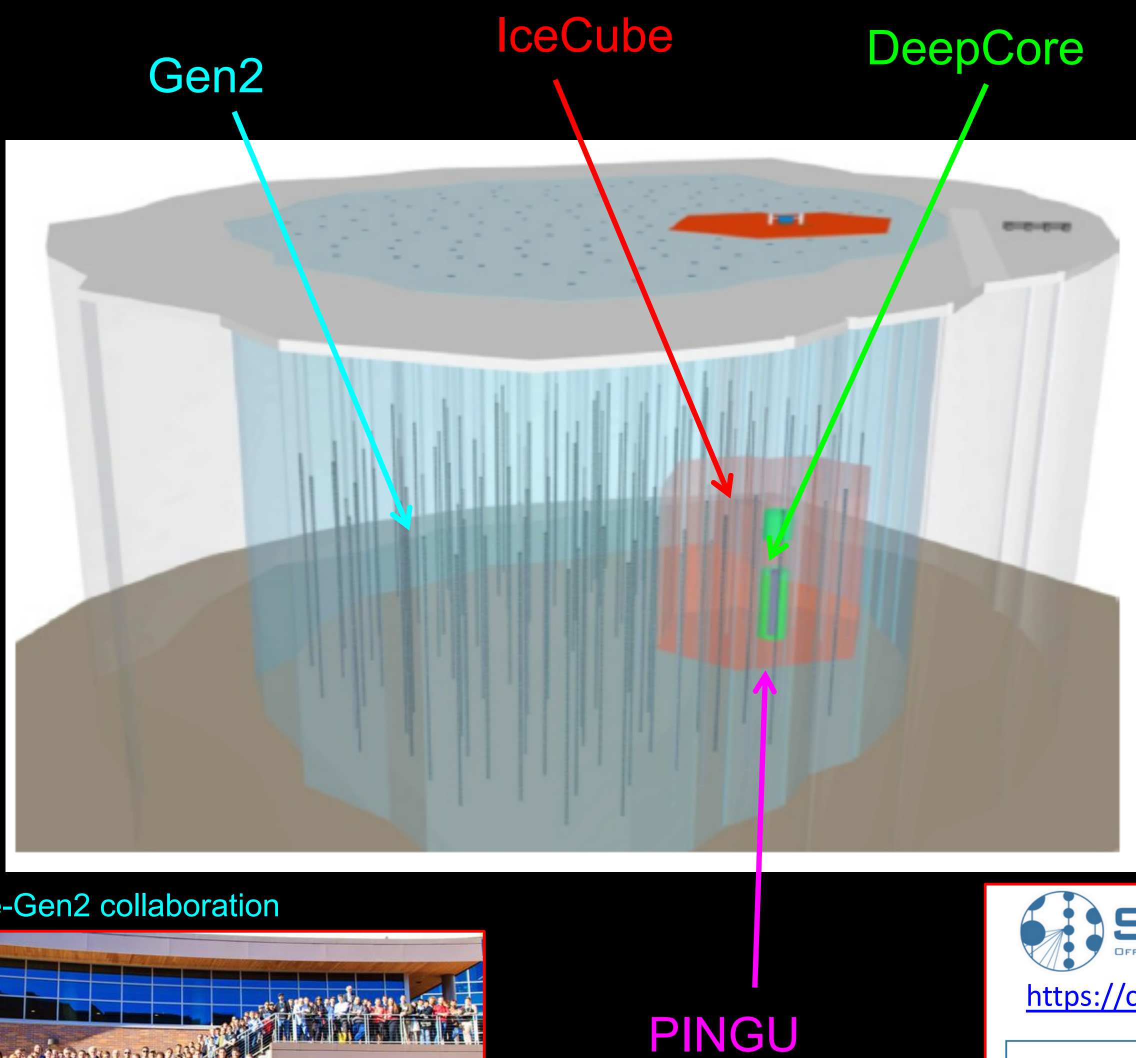
Neutrino time of flight
- Fuzzy quantum gravity space-time may slow down neutrinos
- From the distance of TXS0506+056 (1.3 Gpc), energy of astrophysical neutrinos (>200 TeV), and time delay (~10 days), scale of quantum fluctuation of space-time is limited to < 10^{-16} GeV^{-1}

Need more statistics to study the quantum gravity



IceCube-Gen2, arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

6. IceCube-Gen2



Bigger IceCube and denser DeepCore can push their physics

Gen2
Larger string separations to cover larger area

PINGU
Smaller string separation to achieve lower energy threshold for neutrino mass hierarchy measurement

IceCube-Gen2 collaboration

SHOP ICECUBE
OFFICAL SHOP OF THE ICECUBE NEUTRINO OBSERVATORY

https://charge.wisc.edu/icecube/wipac_store.aspx

IceCube IC170922 t-shirt (Crew-Neck)
$18.00
The front side features an image of "IC170922" and the IceCube logo on the back
Heathered navy, crewneck, rinspun cotton/polyester, Available in unisex sizes S-2XL. Runs small.

Support IceCube!

Conclusions

Current paradigm: Neutrino Standard Model (νSM)
- SM + 3 active massive neutrino is established

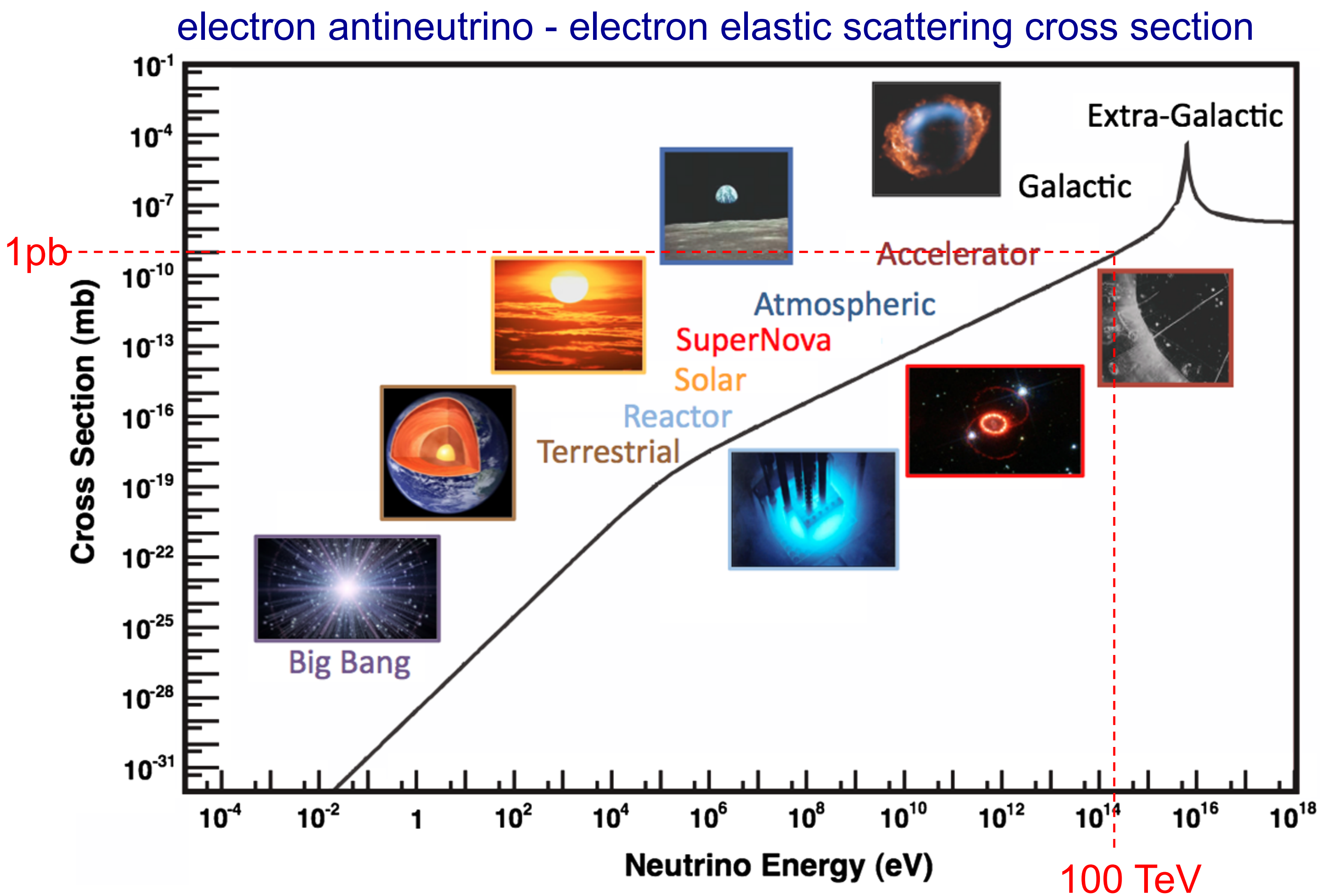
Properties of νSM
- small neutrino masses → related to high energy scale physics (GUT)?
- Majorana neutrino → lepton number violation process?
- Dirac CP phase → matter-antimatter asymmetry of universe?

BSM physics with neutrinos
- Neutrino oscillations (interferometer) can be used to look for new physics
- Long propagation & high energy is useful to look for new physics

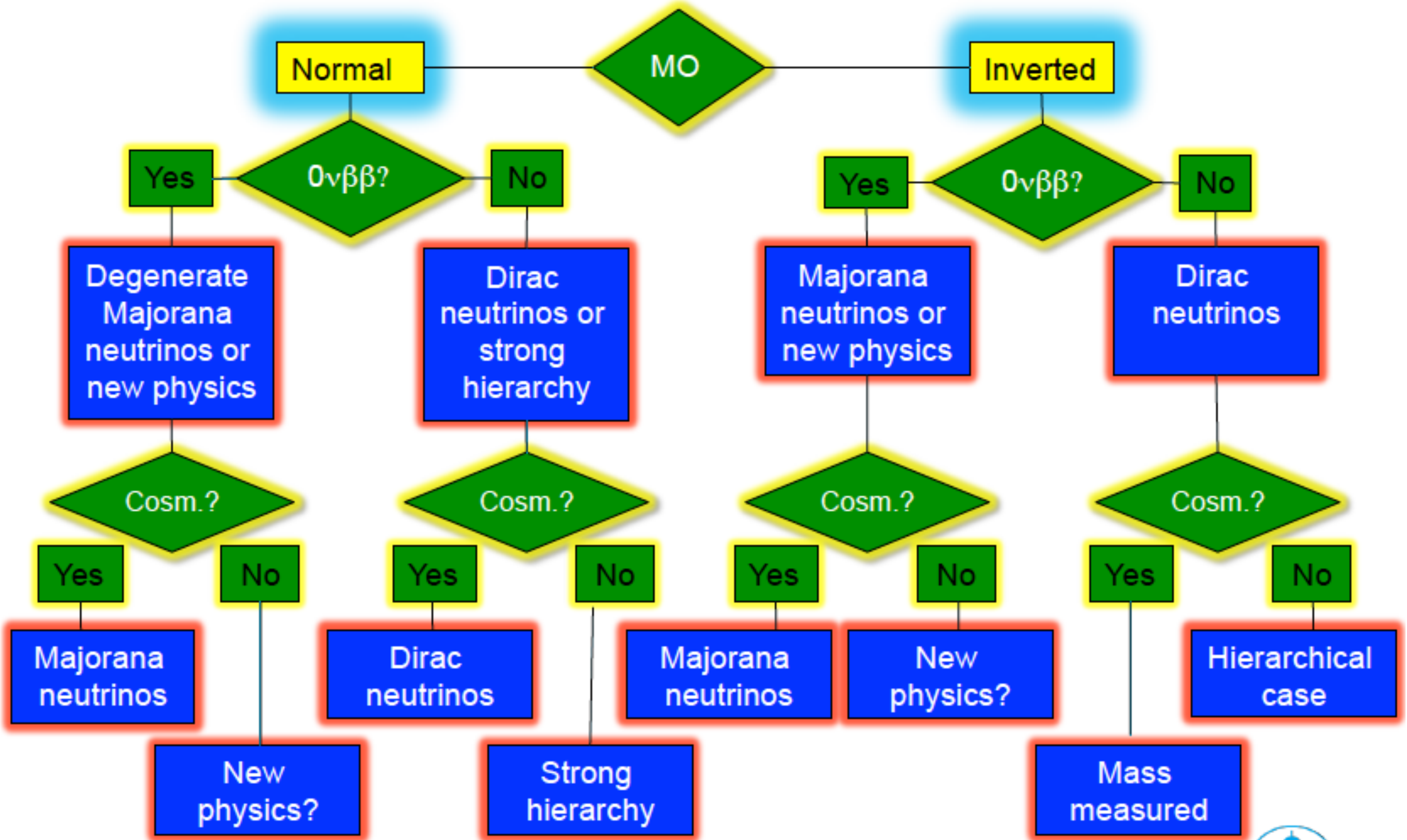
There are many ongoing experiments and future planned experiments

Thank you for your attention!

1. Neutrinos – from meV to EeV



Impact of direct mass ordering (MO) measurement



5. Neutrino-less Double Beta Decay

Approaches and experiments

source = detector

			NOW	MID-TERM	LONG-TERM
Scalability	**Fluid embedded source**	Xe-based TPC	EXO-200 NEXT-10	NEXT-100 PandaX-III	nEXO NEXT-2.0 PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High ΔE and ε	**Crystal embedded source**	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000
		Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID-Mo	AMoRE II	CUPID

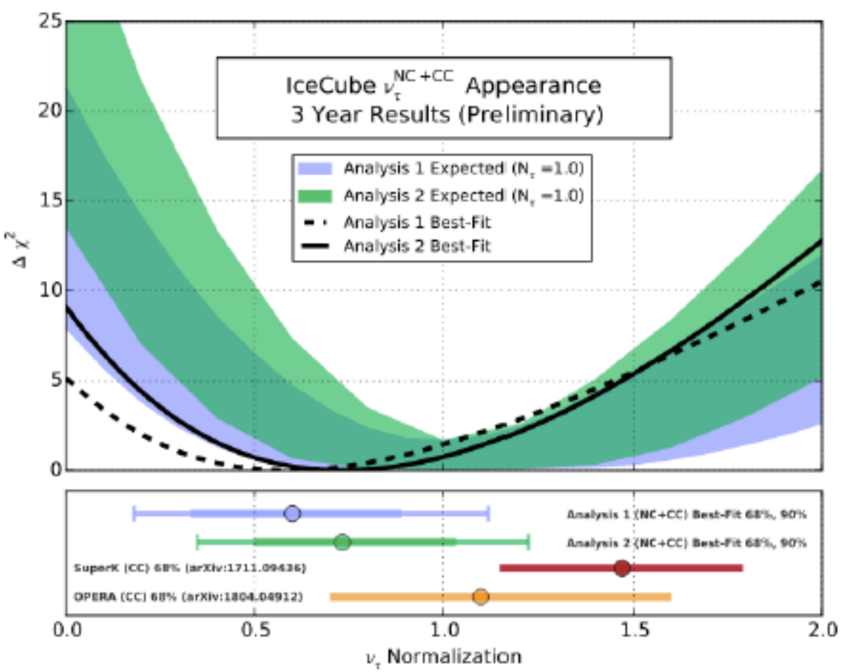
DeYoung, Neutrino 2018

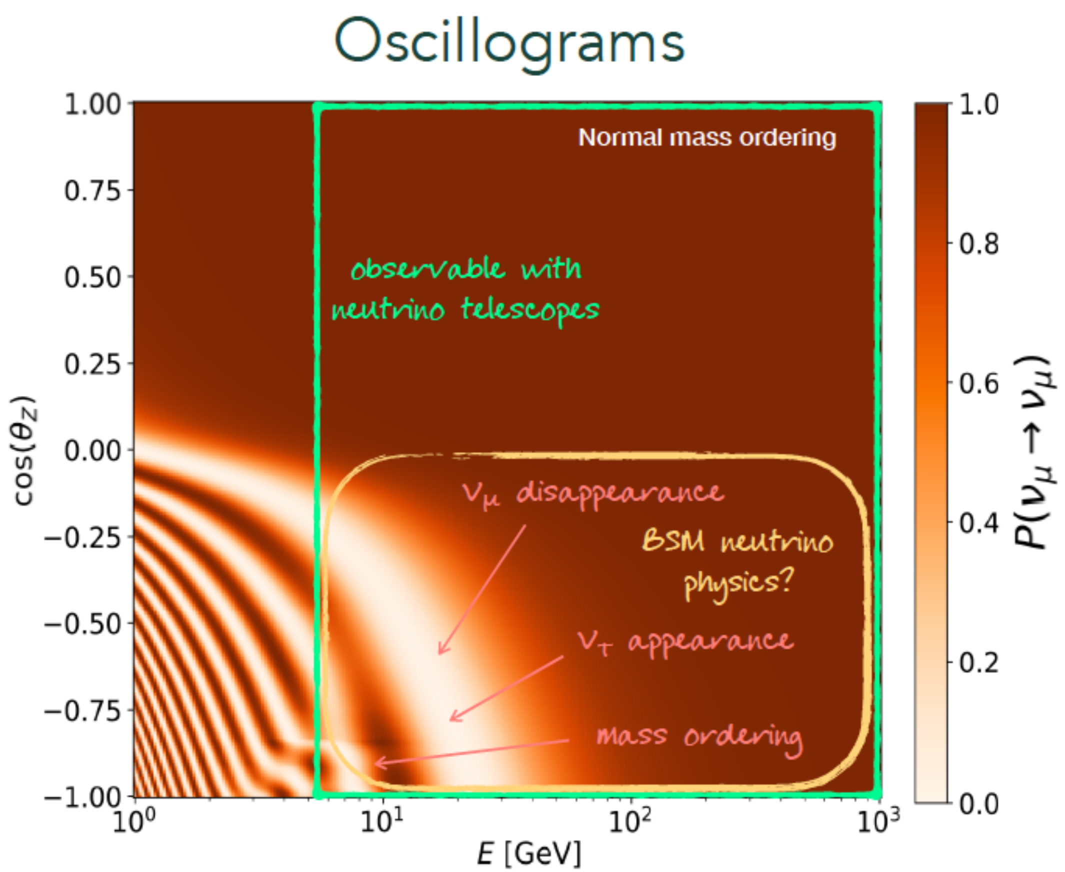
6. Atmospheric neutrinos

PINGU and ORCA

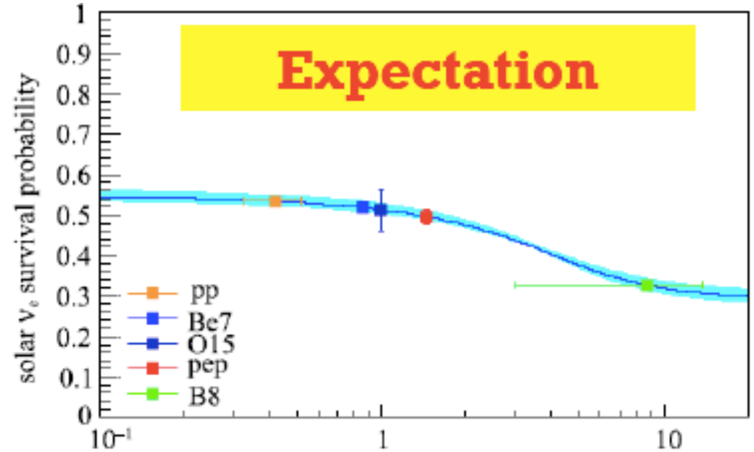
- Dense arrays of PMTs in South Pole ice or Medetrrenian sea water (=lower threshold)
- NMO by MSW effect around 4-6 GeV.
- Large ν_τ appearance data (PMNS unitary test)

DeepCore $\nu\tau$ appearance result has a small tension with SuperK and OPERA



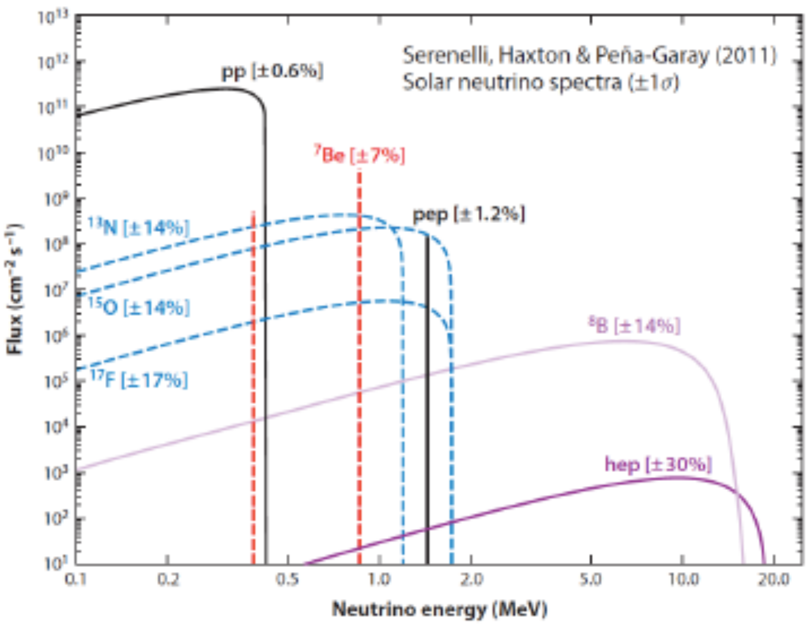


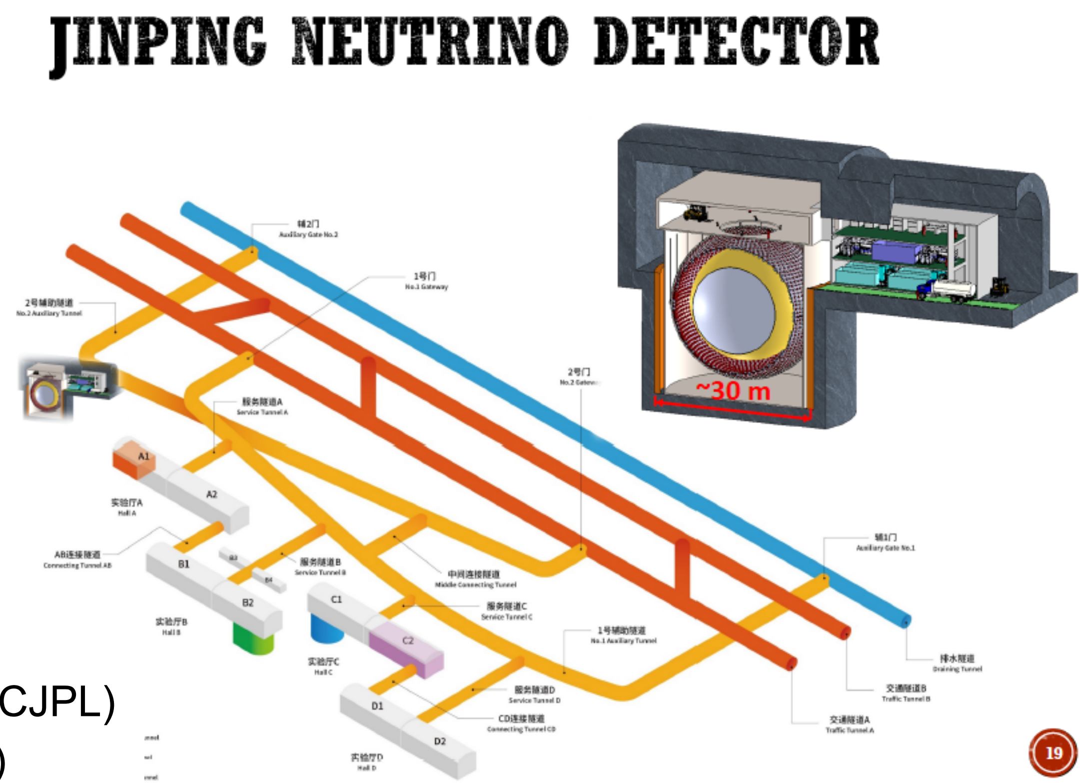
6. Solar neutrinos



Solar neutrino open questions

- Detection of hep neutrino → HyperK
- Day-night asymmetry measurement → HyperK
- MSW upturn at 3 MeV → Jinping
- Precise CNO neutrino measurement → Jinping





Jinping neutrino detector

- China Jinping underground Laboratory (CJPL)
- 2kton slow Liquid scintillator (directional)

Simpson, Sussex Supernova Nu workshop 2018

6. Supernova neutrinos

Galactic supernova (~3 per century)

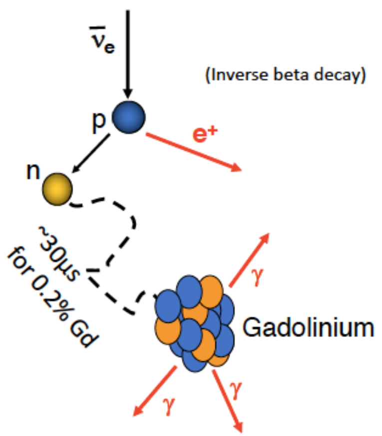
- Good luck for HyperK, DUNE, IceCube, etc

Diffused supernova background (DSNB)

- Guaranteed signal, ~few events/yr by SuperK-Gd
- lower ebergy than galactic SN (<20 MeV)

SuperK-Gd

- Gd-loaded (neutron capture)
- Massive refurbishment work during summer 2018

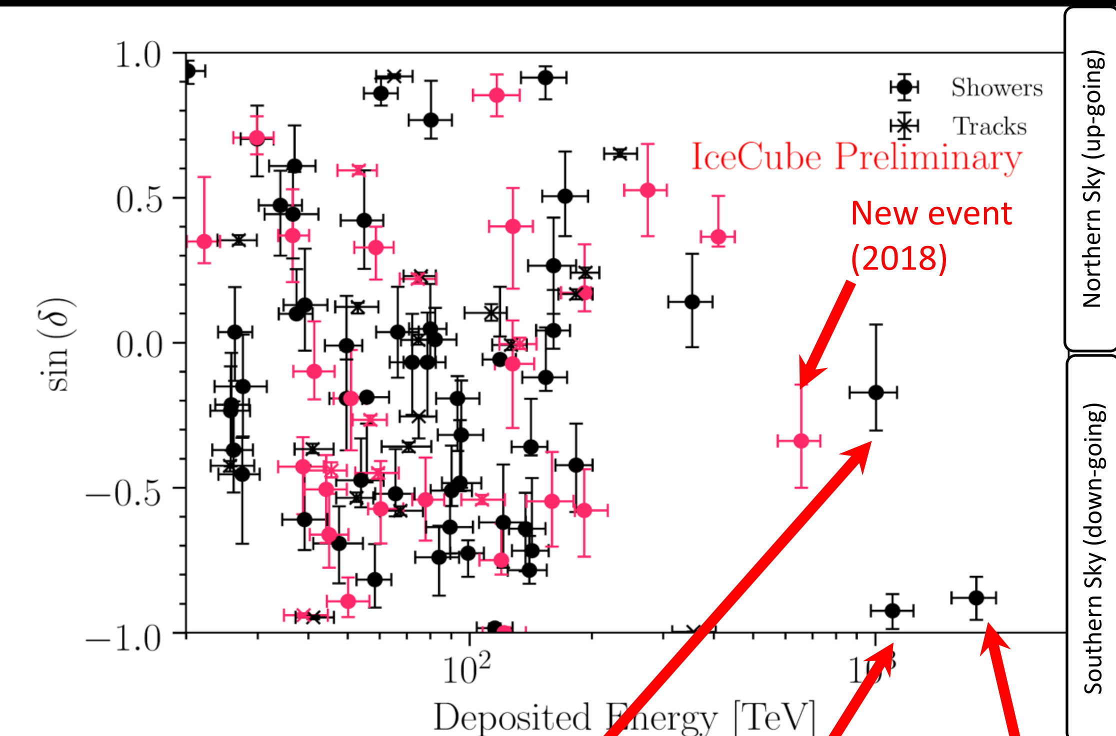


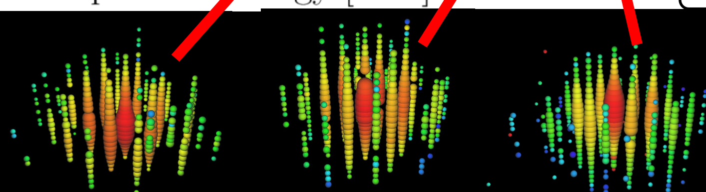
Riding the SuperK boat!
Dream of all neutrino physicists!

6. Astrophysical Very-High-Energy Neutrinos

First observation (2013)
- 30-2000 TeV neutrinos

Taboada, Neutrino 2018

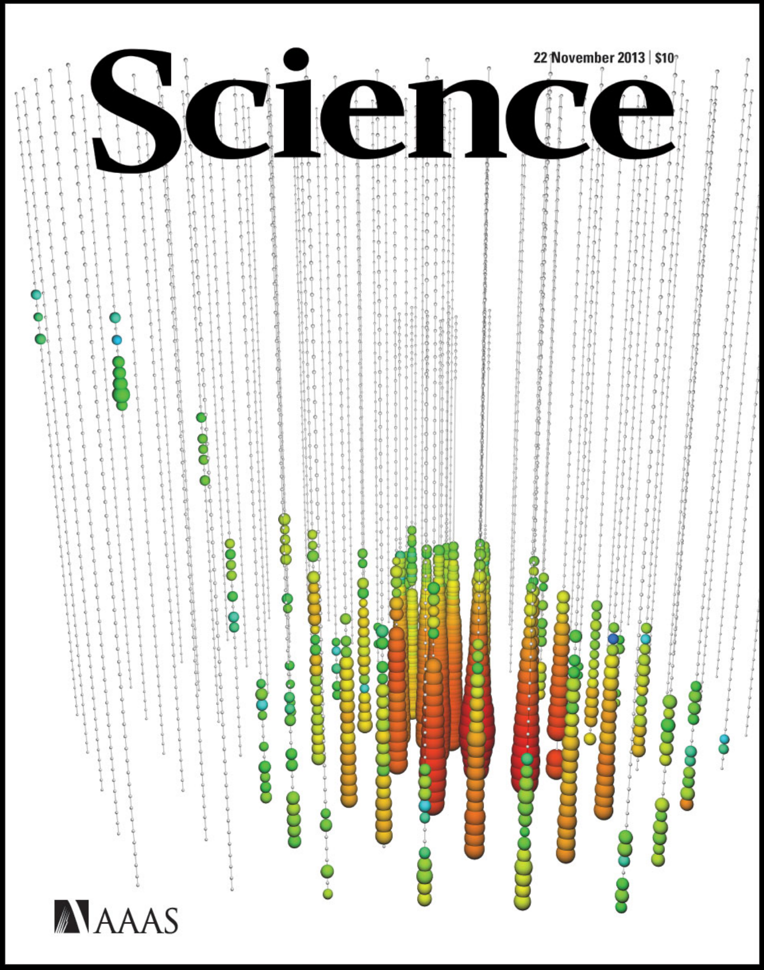




"Bert"
1.1 PeV

"Ernie"
1.0 PeV

"Big Bird"
2.0 PeV



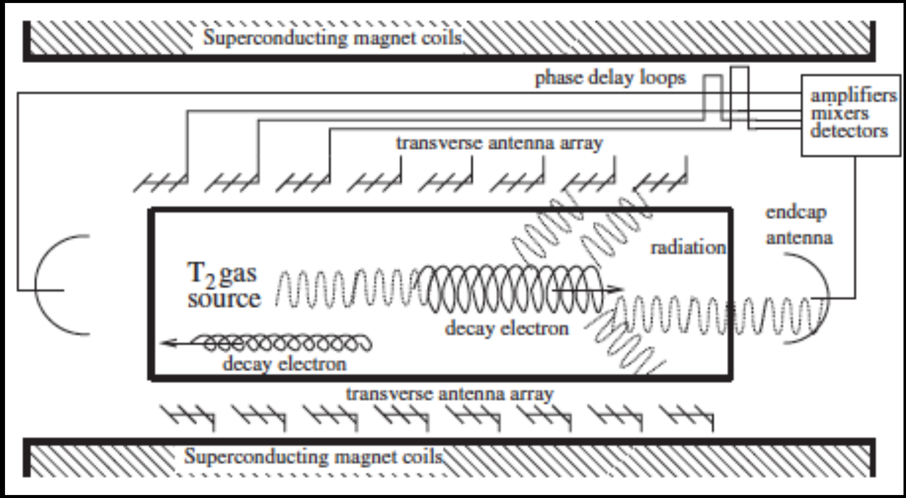
PTOLEMY, arXiv:1808.01892
Project 8, PRD80(2009)051301

6. Cosmic Neutrino Background (CνB)

PTOLEMY and Project 8
- Motivated by KATRIN
- Tritium ν_e capture (no threshold)
- Measure end point of tritium (18 keV) from cyclotron radiation of single electron RF
- Target: ~meV shift of end point due to neutrino mass.

$Q-m_\nu$ → neutrino mass effect on β-decay
$Q+m_\nu$ → CνB capture

Project 8 concept



4. Neutrino physics for Peace

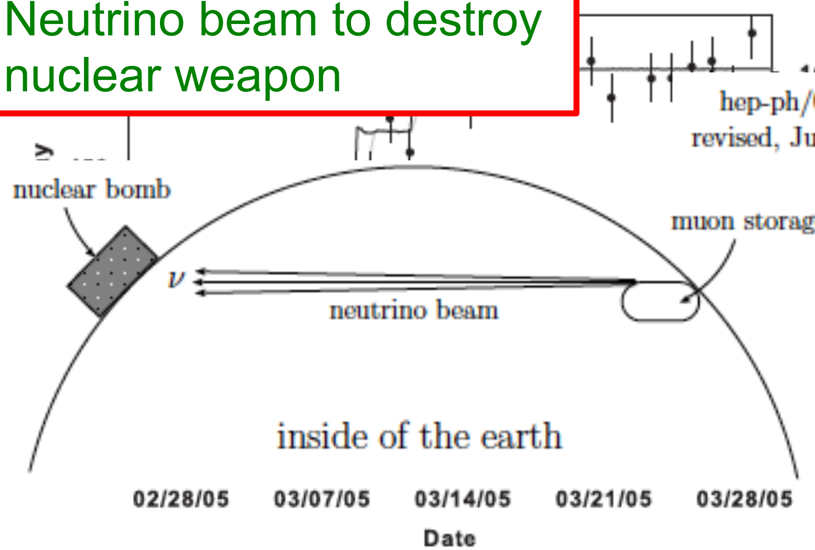
Paper Number: IAEA-CN-184/27

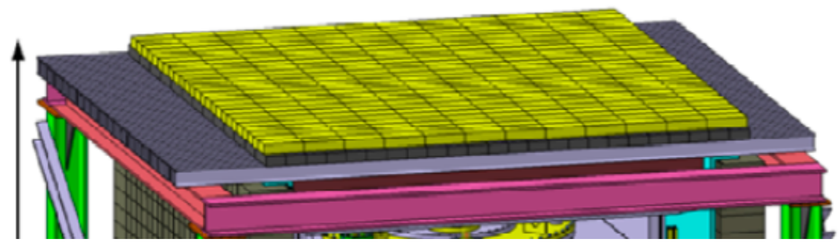
Reactor Neutrino Detection for Non Proliferation with the NUCIFER Experiment

Th. Lasserre, V.M. Bui, M. Cribier, A. Cucoanes, M. Fallot, M. Fechner, J. Gaffiot, L. Giot, R. Granelli, A. Letourneau, D. Lhuillier, J. Martino, G. Mention, D. Motta, Th.A. Mueller, A. Porta, R. Queval, J. L. Sida, C. Varignon, F. Yermia

Neutrino nuclear reactor monitoring

Neutrino beam to destroy nuclear weapon



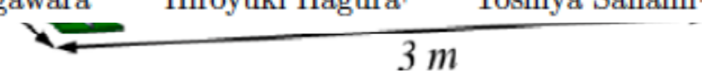


hep-ph/0305062
revised, June 2003

Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

Iirotaka Sugawara* Hiroyuki Hagura† Toshiya Sanami‡



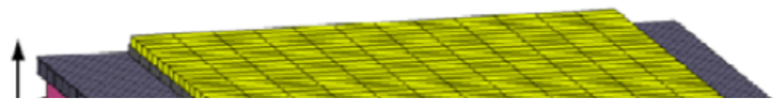
4. Neutrino physics to become Rich

Paper Number: IAEA-CN-184/27

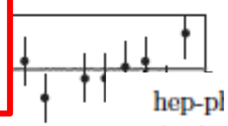
Reactor Neutrino Detection for Non Proliferation with the NUCIFER Experiment

Th. Lasserre, V.M. Bui, M. Cribier, A. Cucoanes, M. Fallot, M. Fechner, J. Gaffiot, L. Giot, R. Granelli, A. Letourneau, D. Lhuillier, J. Martino, G. Mention, D. Motta, Th.A. Mueller, A. Porta, R. Queval, J. L. Sida, C. Varignon, F. Yermia

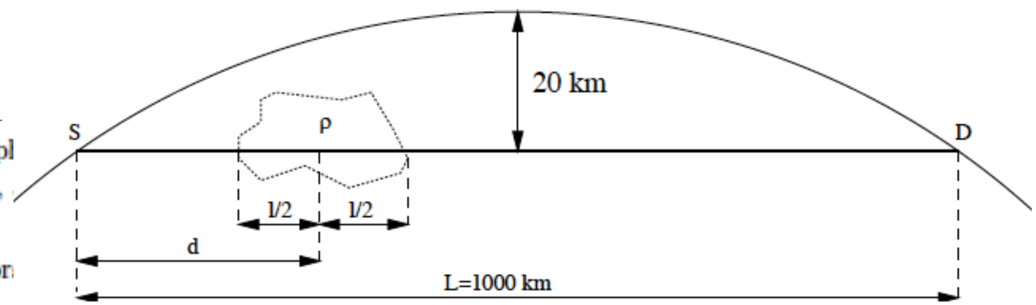
Neutrino nuclear reactor monitoring



Neutrino beam to destroy nuclear weapon



Neutrino earth tomography to find oil reservoir



Could one find petroleum using neutrino oscillations in matter?

T. Ohlsson(*) and W. Winter(**)

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Galactic neutrino communication

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Modern Physics Letters A
Vol. 27, No. 12 (2012) 1250077 (10 pages)
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DOI: 10.1142/S0217732312500770

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Finally, MINERvA experiment sent Morse code signal through neutrino beam

DEMONSTRATION OF COMMUNICATION USING NEUTRINOS

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The Future Of Stock Trading: Neutrino Beams

INVESTOPEDIA.com By James Kerin
July 7, 2012 9:36

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Robert T. Gonzalez
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Neutrinos to Give High-Frequency Traders the Millisecond Edge

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Eighty some years after Wolfgang Pauli first postulated its existence, the lowly neutrino is now on the cusp of being harnessed to facilitate automated high-frequency trading through earth itself. That is, if this weakly-interacting, electrically-neutral subatomic particle can be successfully time-encoded and pointed from one financial center to another.

The idea is that by sending neutrino-based buy-and-sell messages via a 10,000 km shortcut through earth; high-velocity traders could handily beat their competitors.

Trading floor of the New York Stock Exchange a few years before the arrival of computer-driven information technology. Credit: Wikicommons

Most neutrinos are leftover relics of thermal reactions that took place during the Big Bang, some 13.7 billion years ago. Today, however, they're artificially generated inside

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