

# Neutrino Physics

## Outline

1. Neutrino oscillations
2. Dirac or Majorana?
3. CP violation with leptons
4. 4<sup>th</sup> 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

04/07/2019



# **1. Neutrino oscillations**

## **2. Dirac or Majorana?**

## **3. CP violation with leptons**

## **4. 4<sup>th</sup> neutrino search (sterile neutrino search)**

## **5. Dark matter search with neutrinos**

## **6. Quantum gravity search neutrinos**

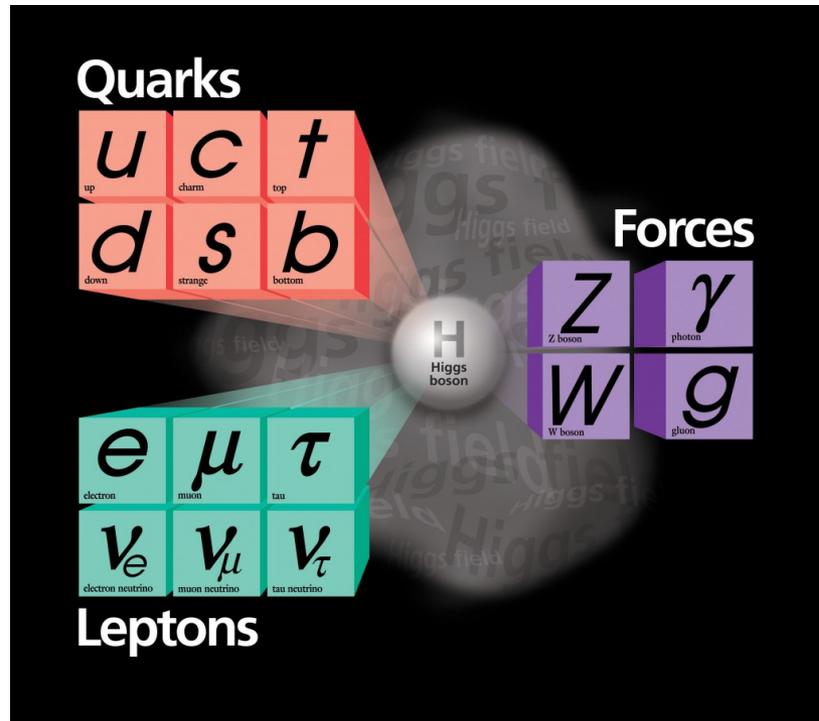
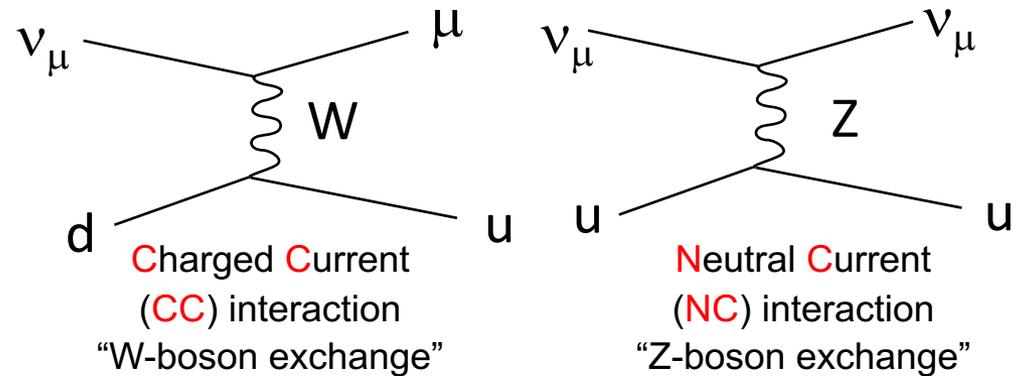
## **7. Conclusion**

# 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,

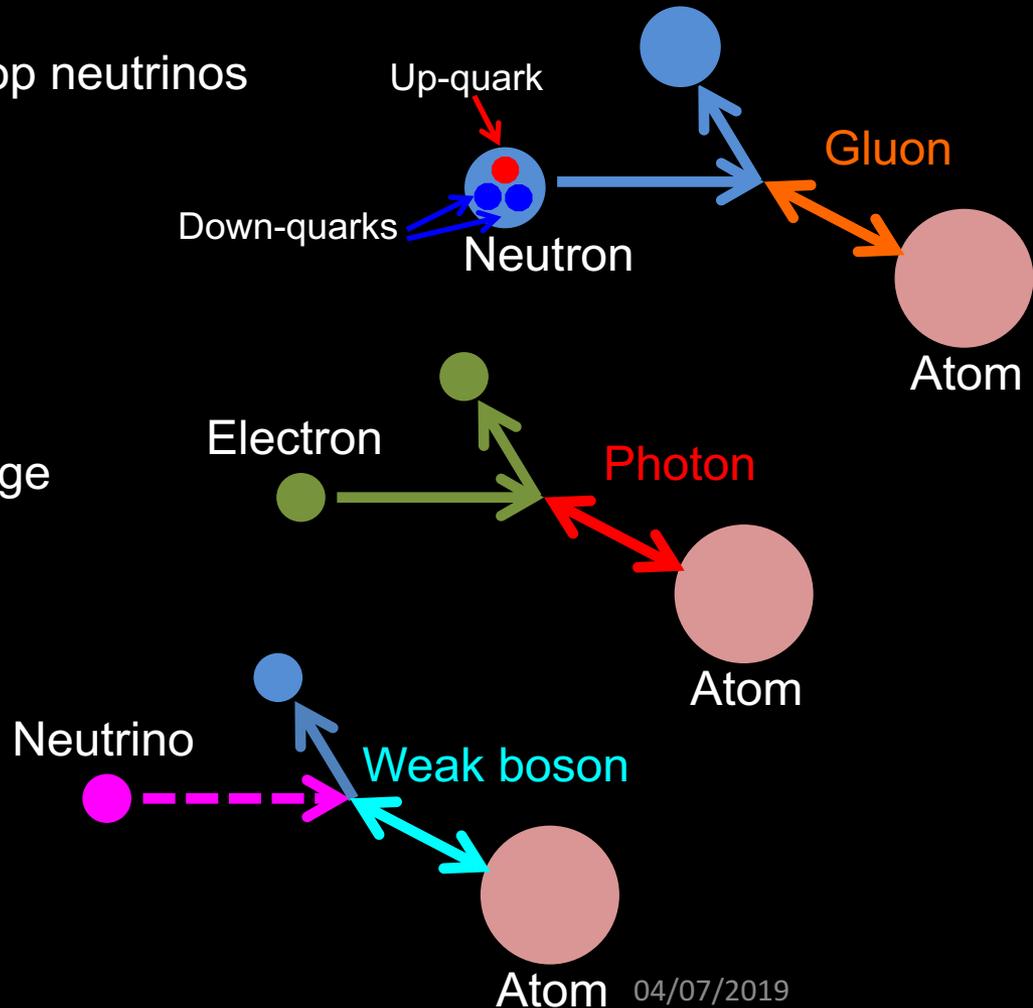
1. they only interact with weak nuclear force.



# 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



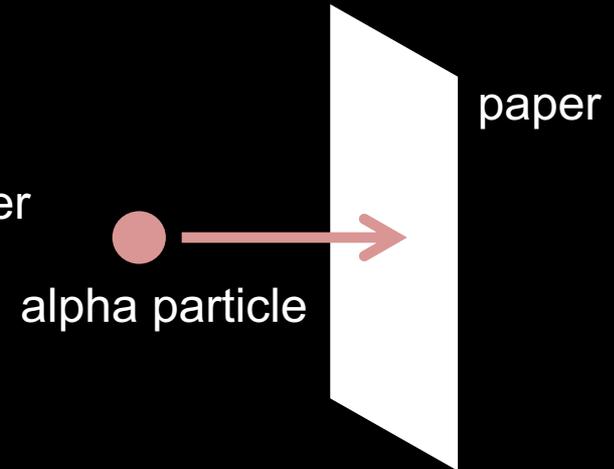
# Neutrinos, Ghost particles

3 types of neutrinos

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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



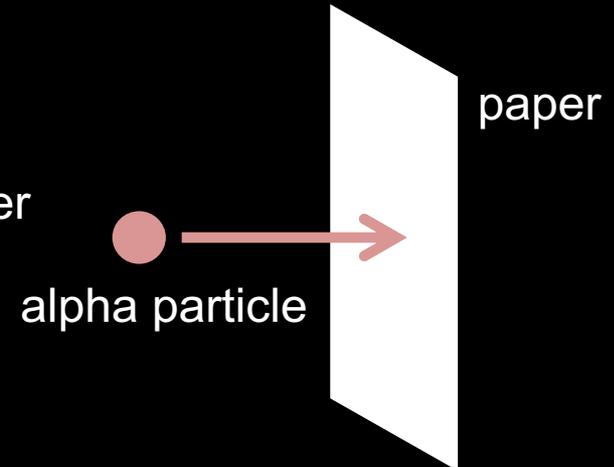
# Neutrinos, Ghost particles

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Example: how to stop particles?

- Alpha particle (nuclei of Helium) → sheet of paper
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- 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

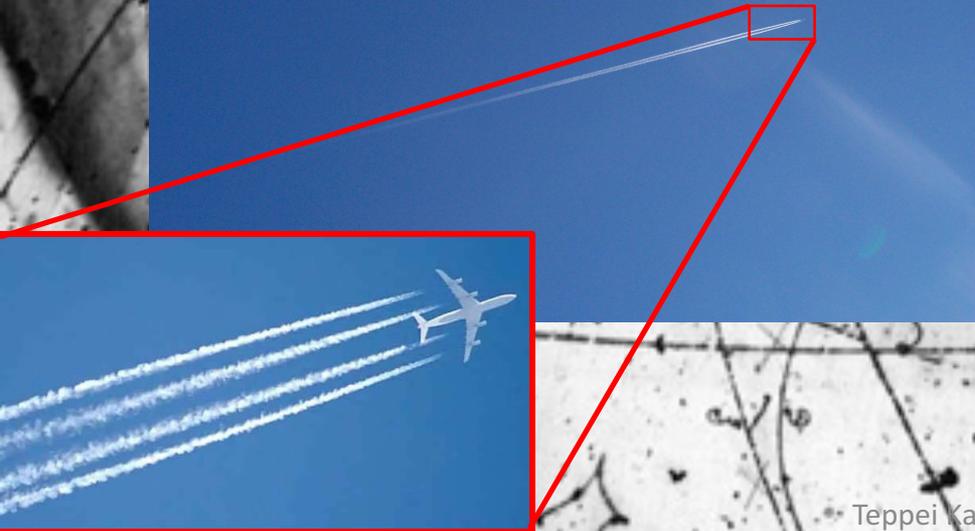
- 60 billion electron neutrinos from the Sun pass through every  $1\text{cm}^2$  of the Earth every second. However you have only a 25% chance for a neutrino to hit your body in your lifetime.

# 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.

e.g.) Contrail



# Neutrinos, Ghost particles

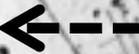
- Visible particle carries an “electric charge”. In other words, visible particle interacts by exchanging photons with matter
- Neutrino is invisible because it is neutral (no electric charge). So, we only can see them indirectly.

Question: where is neutrino in this picture?

# Neutrinos, Ghost particles

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Neutrino



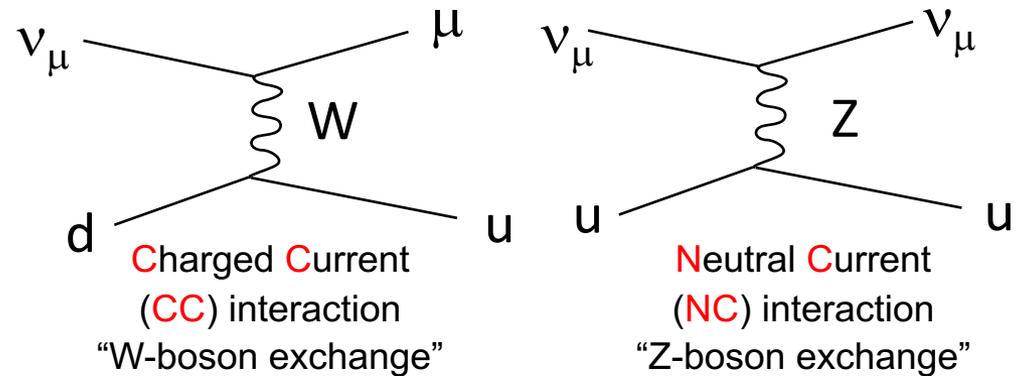
Question: where is neutrino in this picture?

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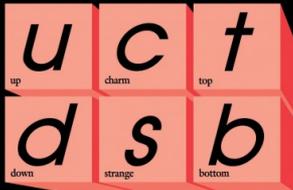
Neutrinos are special because,

1. they only interact with weak nuclear force.

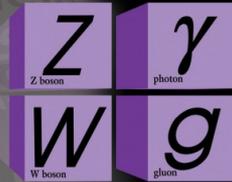


2. Weak interaction eigenstate is not Hamiltonian eigenstate (propagation eigenstate). Thus propagation of neutrinos changes their species, called **neutrino oscillation**.

## Quarks



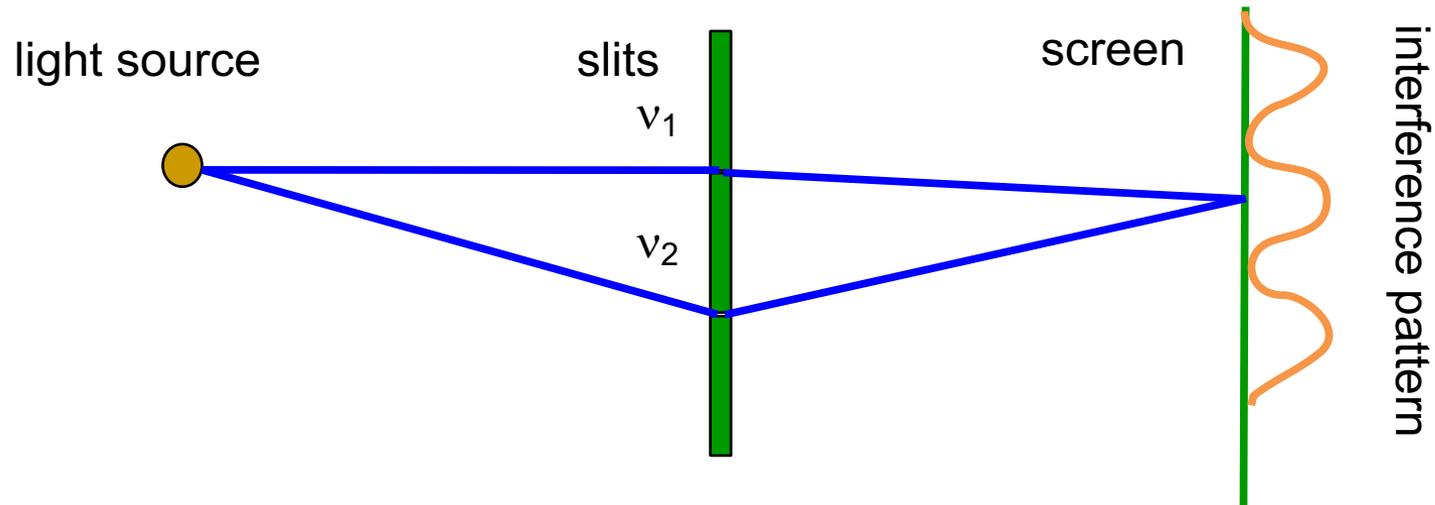
## Forces



## Leptons

# 1. Neutrino oscillations

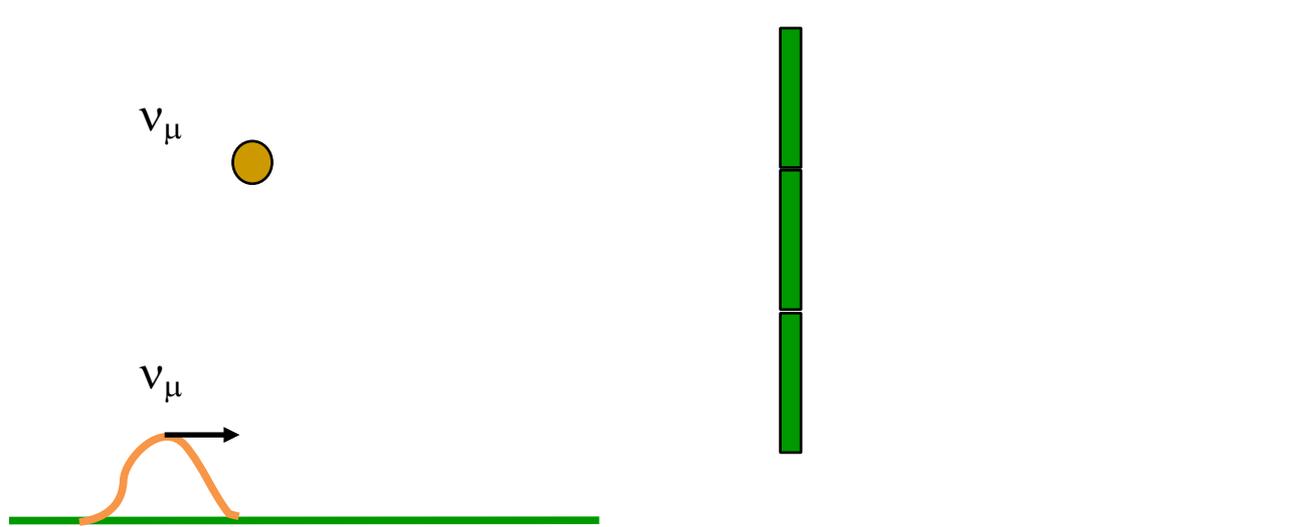
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path  $v_1$  and path  $v_2$  have different length, they have different phase rotations and it causes interference.

# 1. Neutrino oscillations

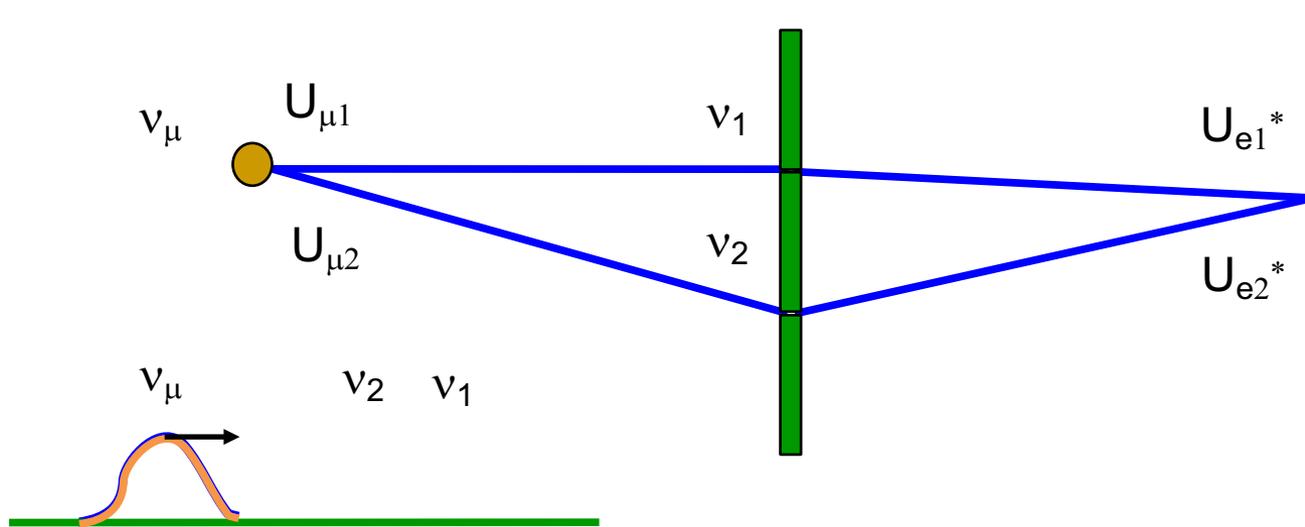
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If 2 neutrino Hamiltonian eigenstates,  $\nu_1$  and  $\nu_2$ , have different phase rotation, they cause quantum interference.

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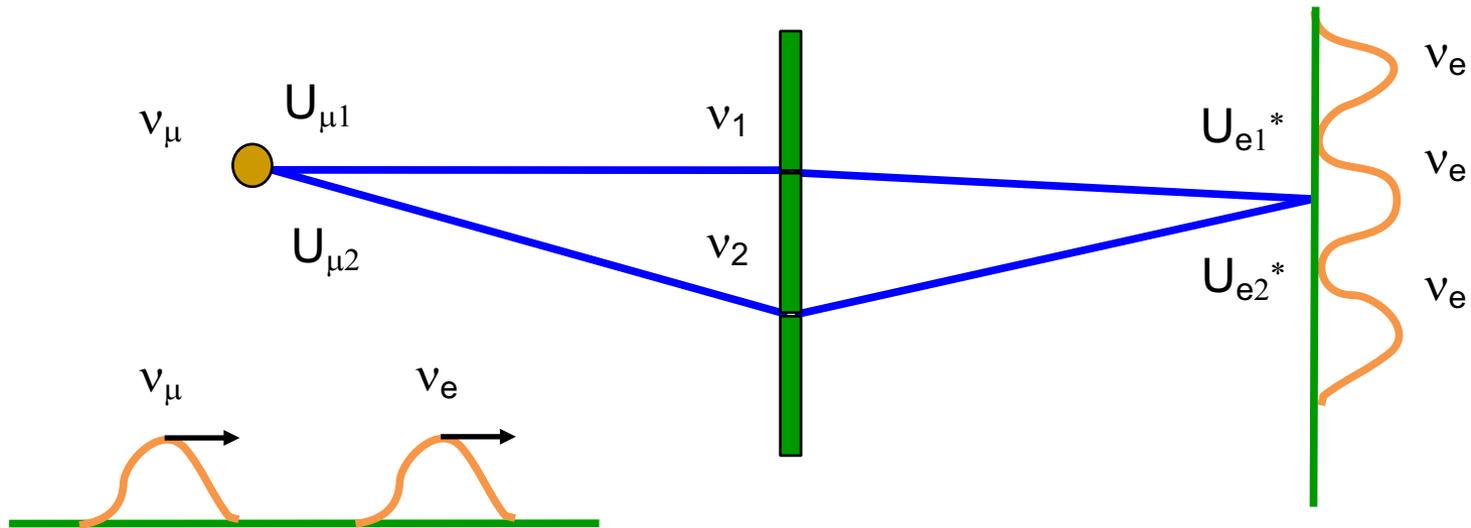


If 2 neutrino Hamiltonian eigenstates,  $\nu_1$  and  $\nu_2$ , have different phase rotation, they cause quantum interference.

If  $\nu_1$  and  $\nu_2$ , have different mass, they have different velocity, so thus different phase rotation.

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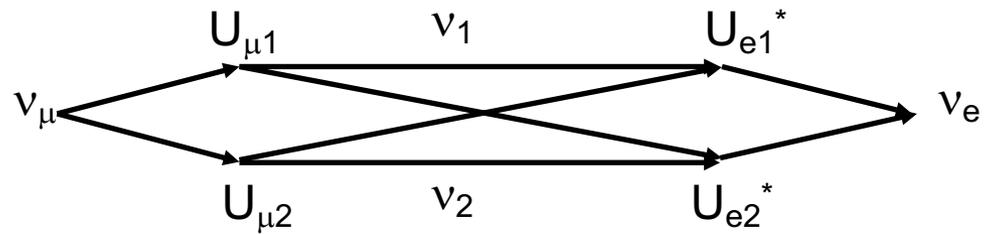


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The detection may be different flavor (neutrino oscillations).

# 1. Neutrino oscillations



## 2 neutrino mixing

The neutrino weak interaction eigenstate (flavor eigenstate) is described by neutrino Hamiltonian eigenstates,  $\nu_1$  and  $\nu_2$ , and their mixing matrix elements.

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

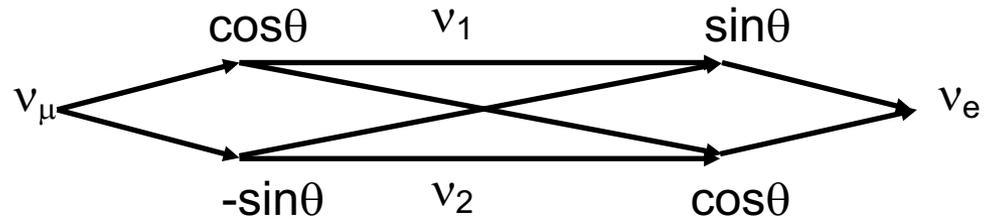
The time evolution of flavor eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of  $\nu_1$  and  $\nu_2$ .

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

Then the transition probability from weak eigenstate  $\nu_\mu$  to  $\nu_e$  is,

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

# 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 ( $\Delta m^2 = |m_1^2 - m_2^2|$ ,  $t \sim L$ )

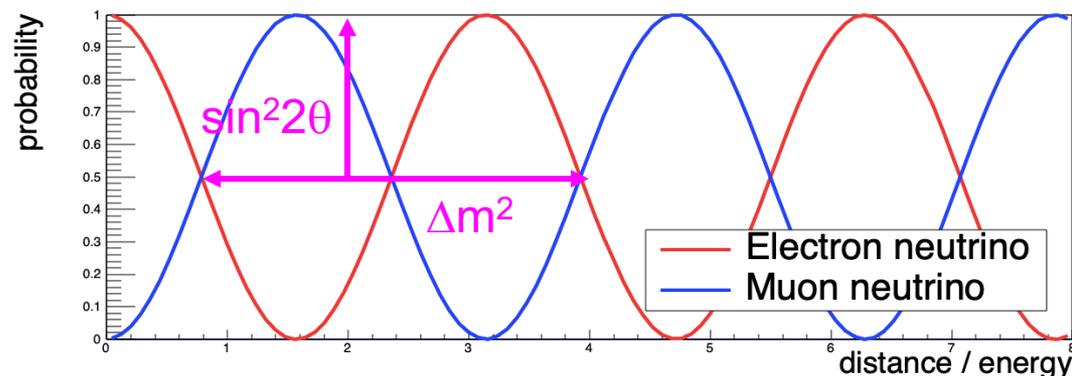
$$P_{\mu \rightarrow e}(L/E) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

After adjusting the unit, **2 neutrino oscillation formula**

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

Amplitude = mixing angle

Period = neutrino mass



# BREAKTHROUGH PRIZE

2016 Fundamental Physics Breakthrough Prize



Discovery of neutrino oscillations and neutrino masses

 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"

- 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)

# BREAKTHROUGH PRIZE

2016 Fundamental Physics Breakthrough Prize

## The Nobel Prize in Physics 1988



Discovery of muon neutrino



## The Nobel Prize in Physics 1995



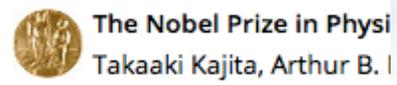
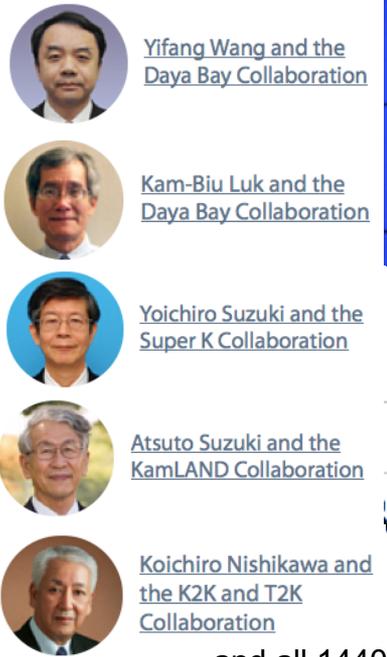
Discovery of neutrino

## The Nobel Prize in Physics 2002



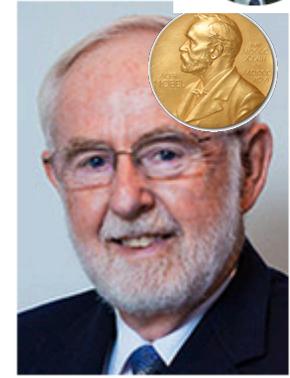
Solar neutrino problem, supernova neutrino detection

Discovery of neutrino oscillations



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## The Nobel Prize 2015



...and all 1440 collaborators

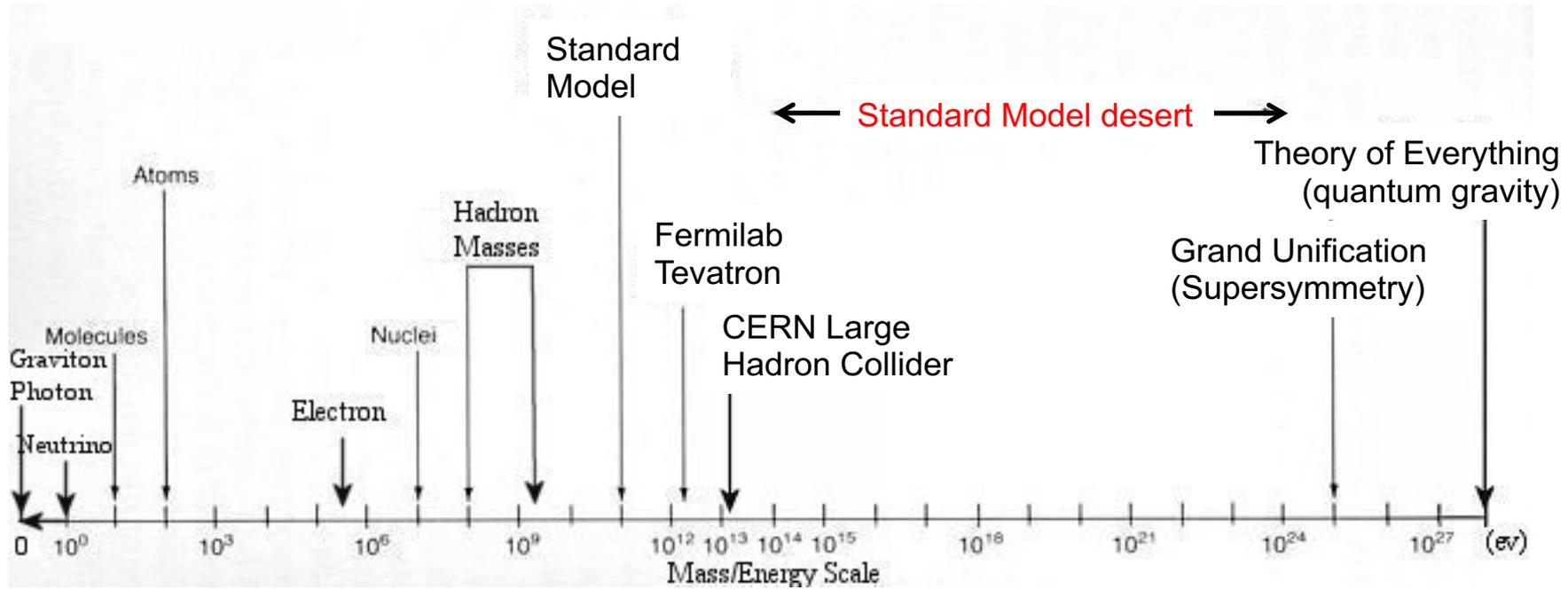
The Nobel Prize  
Kajita and McDonald  
for neutrino oscillations,

Neutrino physics is the home of discovery physics!

# 1. Neutrino masses

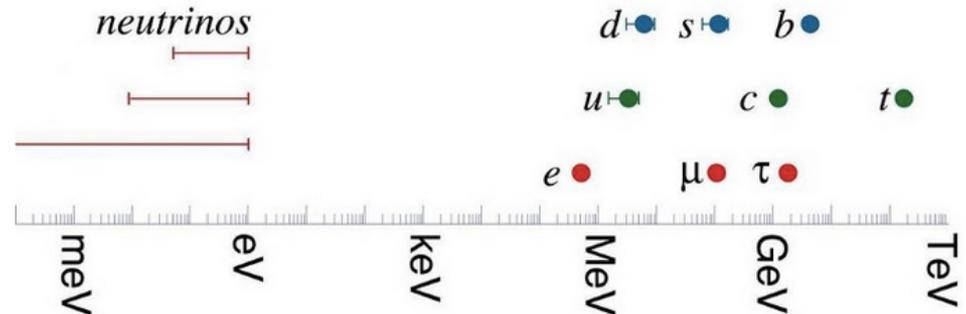
Neutrino masses are not predicted by the Standard Model

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



## Seesaw mechanism

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



# 1. Neutrino physics, 2019

## Neutrino Standard Model ( $\nu$ SM)

- SM + 3 active massive neutrino is established

## Unknown parameters of $\nu$ SM

- precise value of  $\theta_{23}$  ( $\theta_{12}$  and  $\theta_{13}$  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

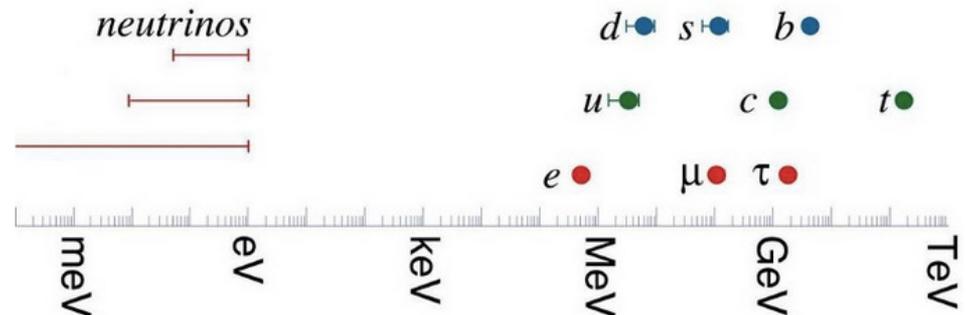
## Beyond $\nu$ SM (BSM)

- 4<sup>th</sup> 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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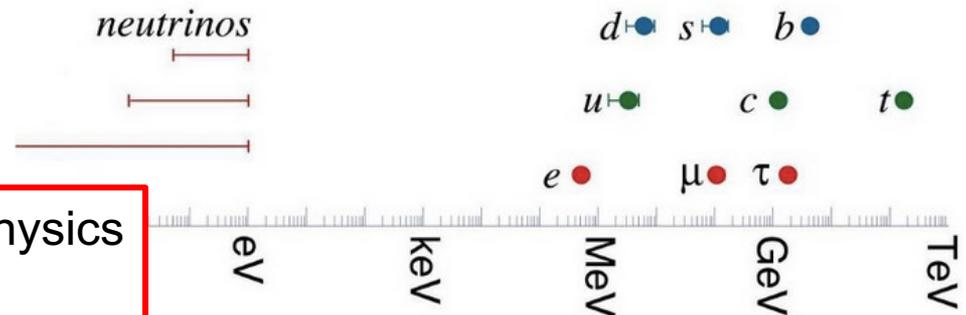
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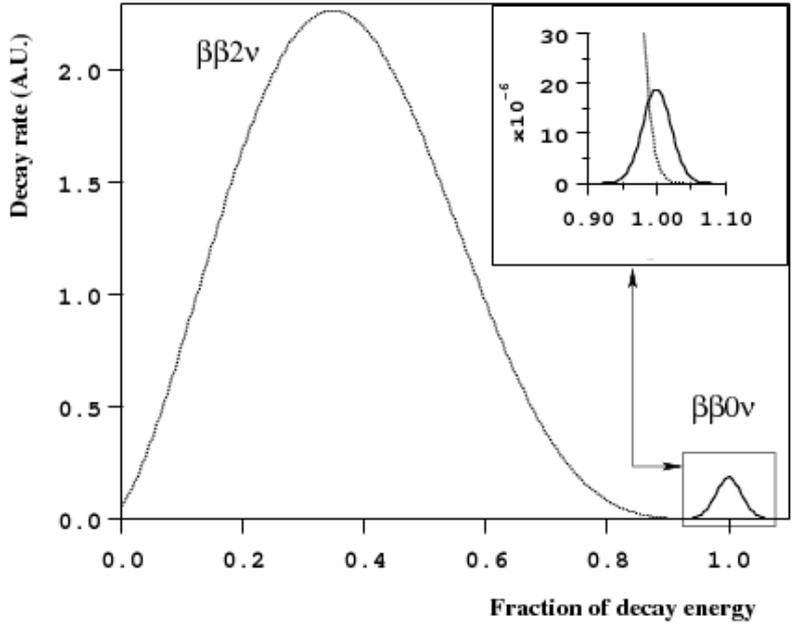
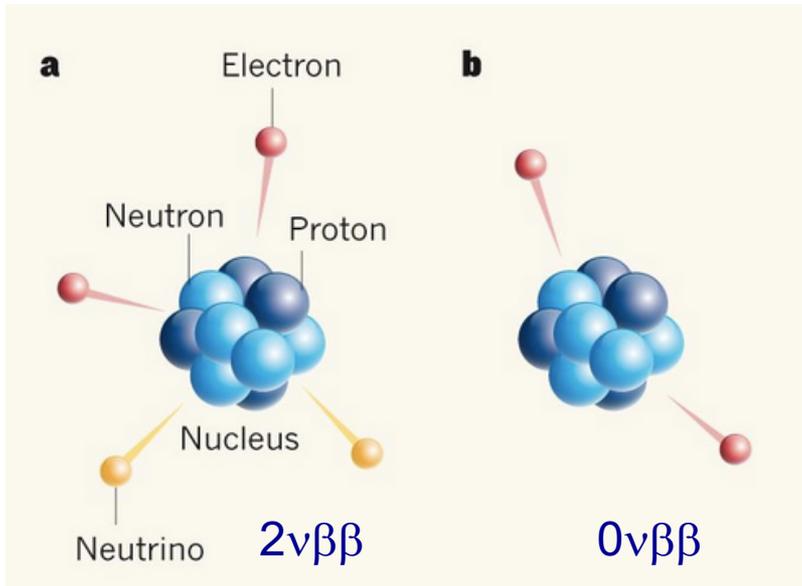
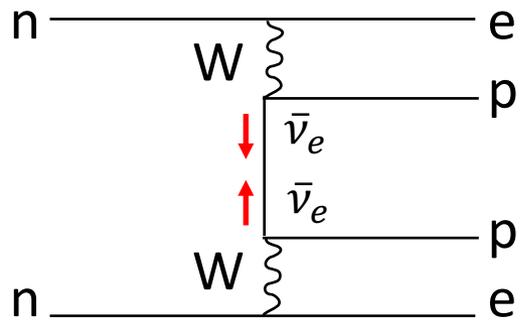
This talk is the status of new physics search within neutrino physics

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

# 2. Neutrinoless double beta decay ( $0\nu\beta\beta$ )

## Majorana particle

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



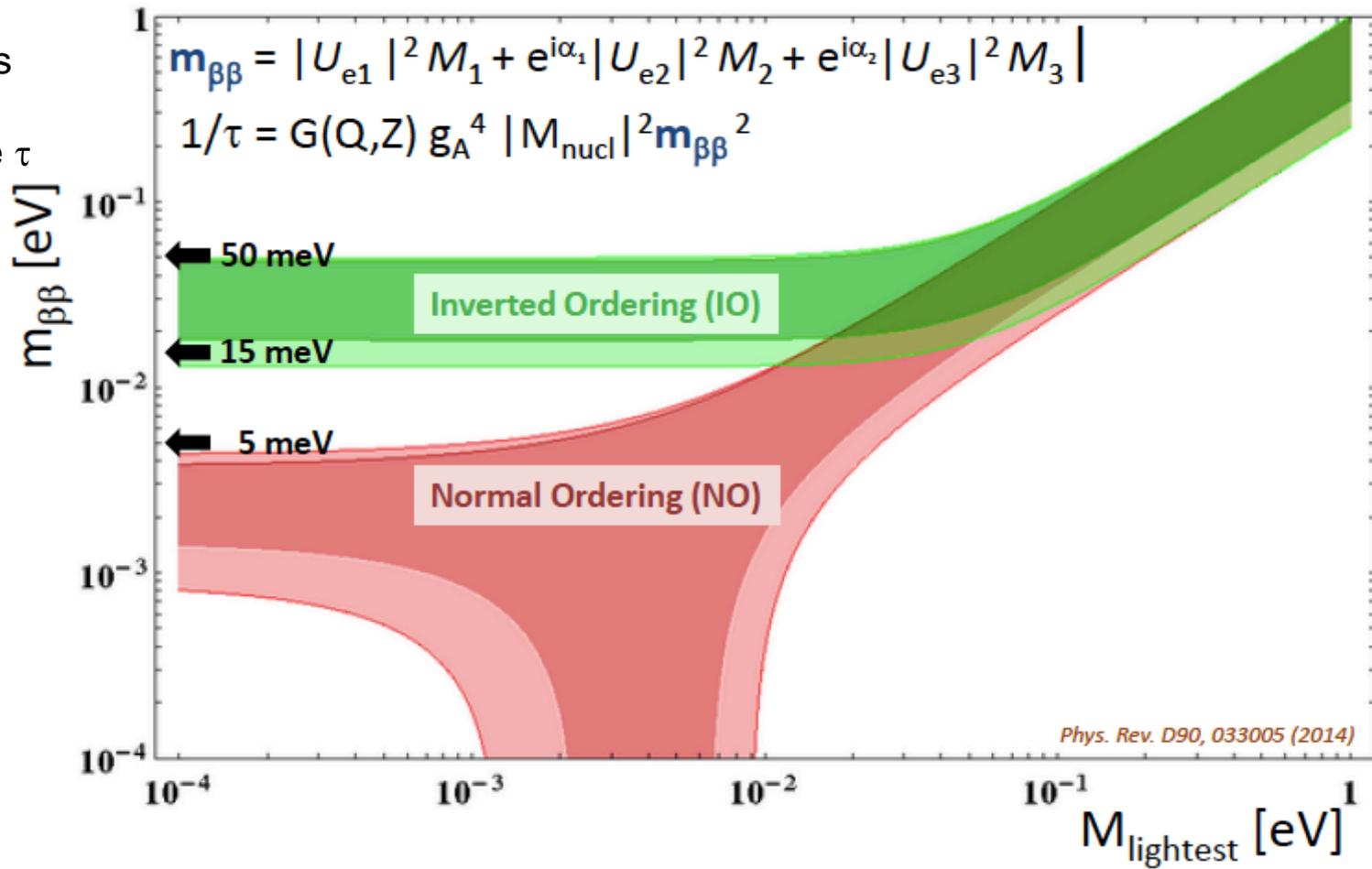
Gratta, Nature538(2016)48

## 2. Neutrinoless double beta decay ( $0\nu\beta\beta$ )

### Majorana particle

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

$m_{\beta\beta}$  (effective Majorana mass) is extracted from measured half-life  $\tau$

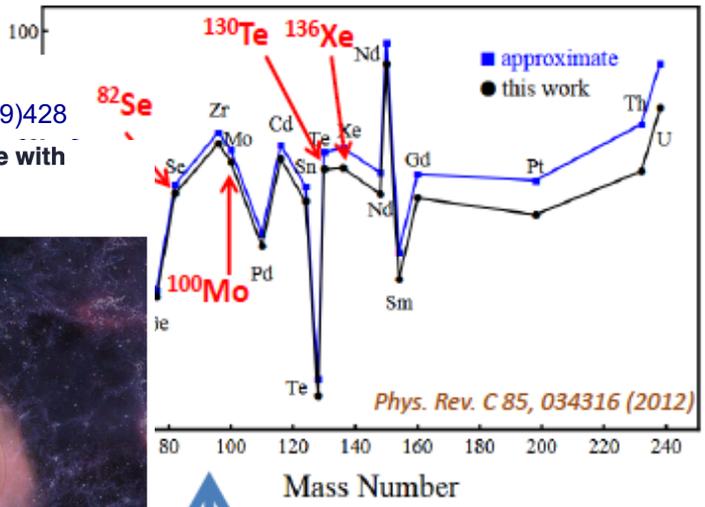


# 2. Neutrinoless double beta decay and nuclear physics

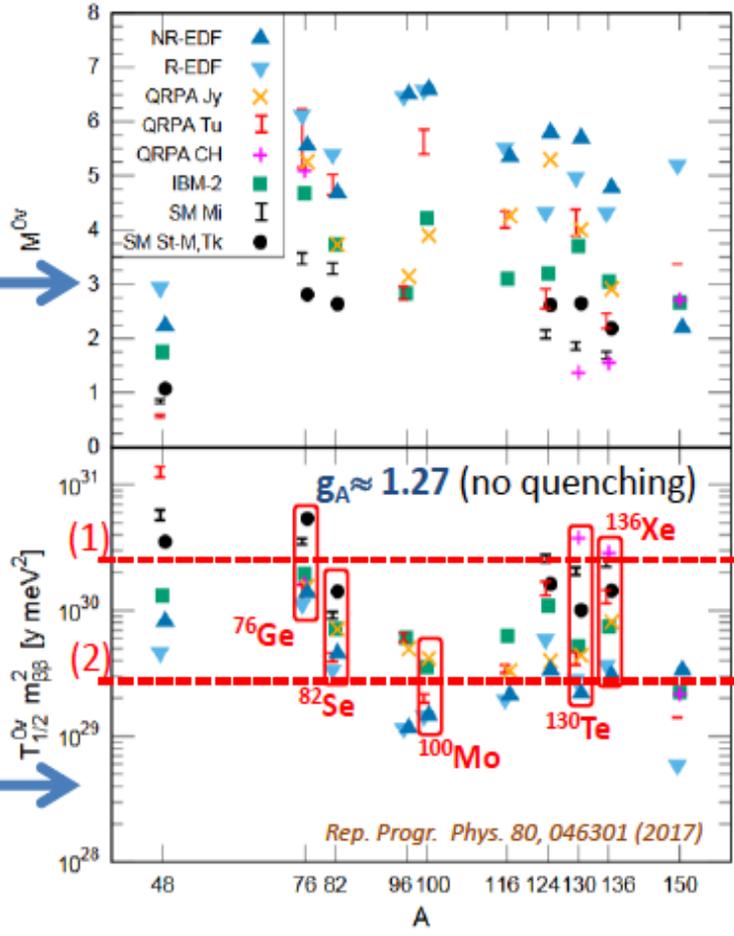
Nuclear physics gives large systematics to extract  $m_{\beta\beta}$  from  $\tau$  (half-life)

- Nuclear matrix element calculation
- Nuclear quenching of  $g_A$

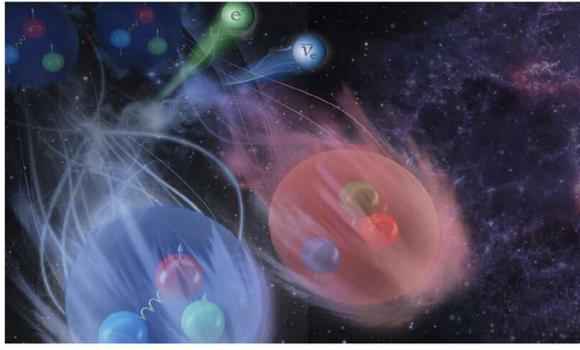
Phase space: exactly calculable



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



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

Nuclear physics is complicated

1. Neutrino oscillations
2. Dirac or Majorana?
- 3. CP violation with leptons**
4. 4<sup>th</sup> neutrino search (sterile neutrino search)
5. Dark matter search with neutrinos
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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,  $J_{\text{quark}} \sim 10^{-5}$  (very small)
- CP violation of lepton,  $J_{\text{lepton}} \sim 10^{-2} \rightarrow$  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**

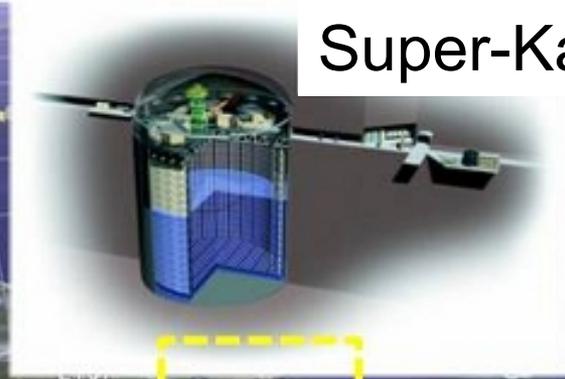
$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) &= | U_{\mu 1}^* e^{-im_1^2 L/2E} U_{e1} + U_{\mu 2}^* e^{-im_2^2 L/2E} U_{e2} + U_{\mu 3}^* e^{-im_3^2 L/2E} U_{e3} |^2 \\
 &= | 2U_{\mu 3}^* U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U_{\mu 2}^* U_{e2} \sin \Delta_{21} |^2 \\
 &\approx | \sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}} |^2
 \end{aligned}$$

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

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

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

# Super-Kamiokande detector



# T2K

## T2K (Tokai to Kamioka) experiment

### 295km

### Neutrino beam

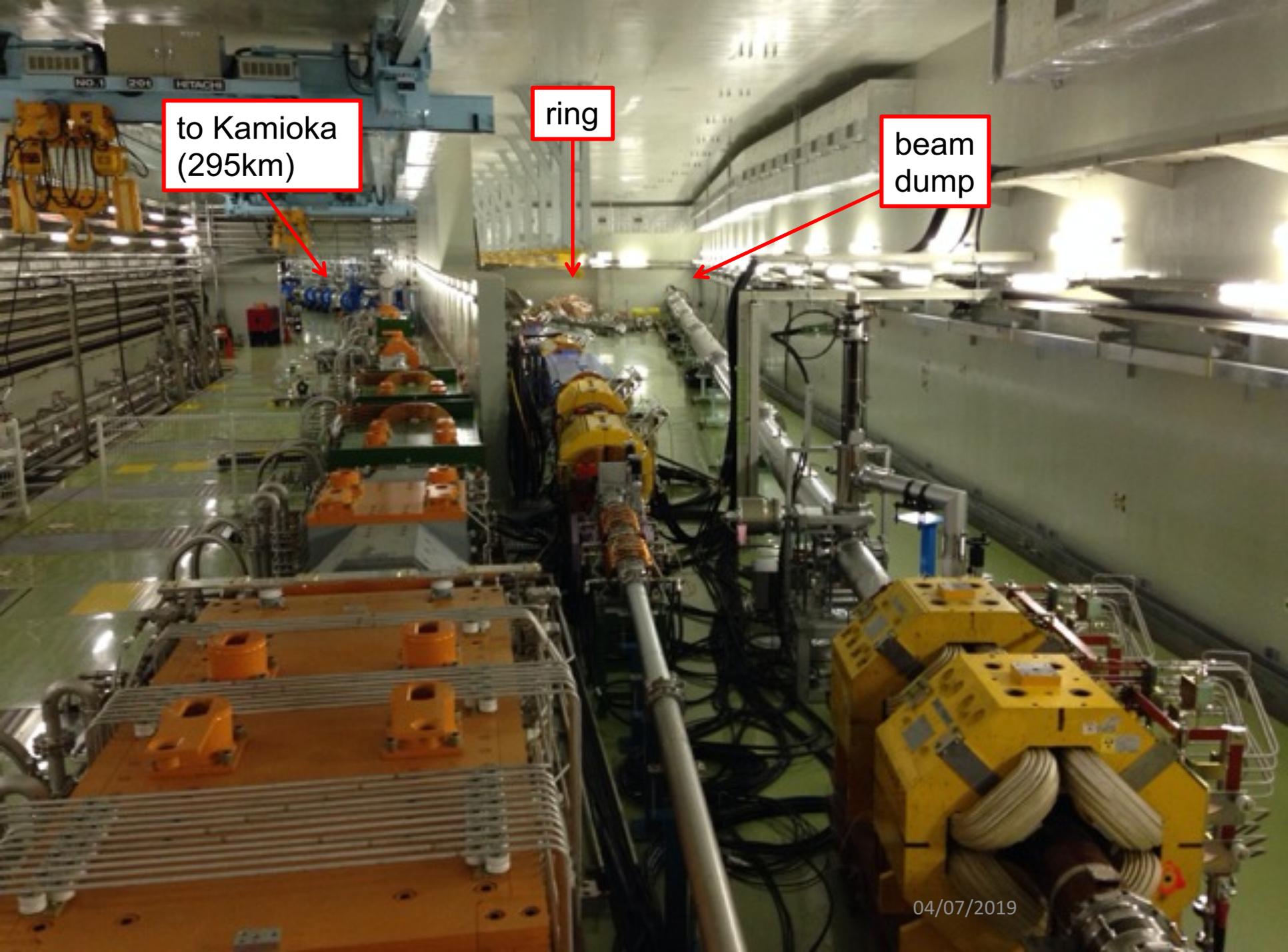
- 50 billion neutrinos from J-PARC pass through nearby detector every second
- These neutrinos are observed at Super-Kamiokande detector, located 295km away



Image NASA  
© 2007 Europa Technologies  
Image © 2007 TerraMetrics  
© 2007 ZENRIN

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29



to Kamioka  
(295km)

ring

beam  
dump



Nobel Prize in Physics 2015  
Kajita, Arthur B. McDonald

f G+ + 1.6K

## The Nobel Prize in Physics 2015

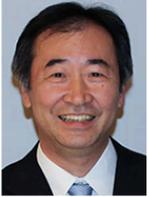


Photo © Takaaki Kajita

**Takaaki Kajita**

Prize share: 1/2



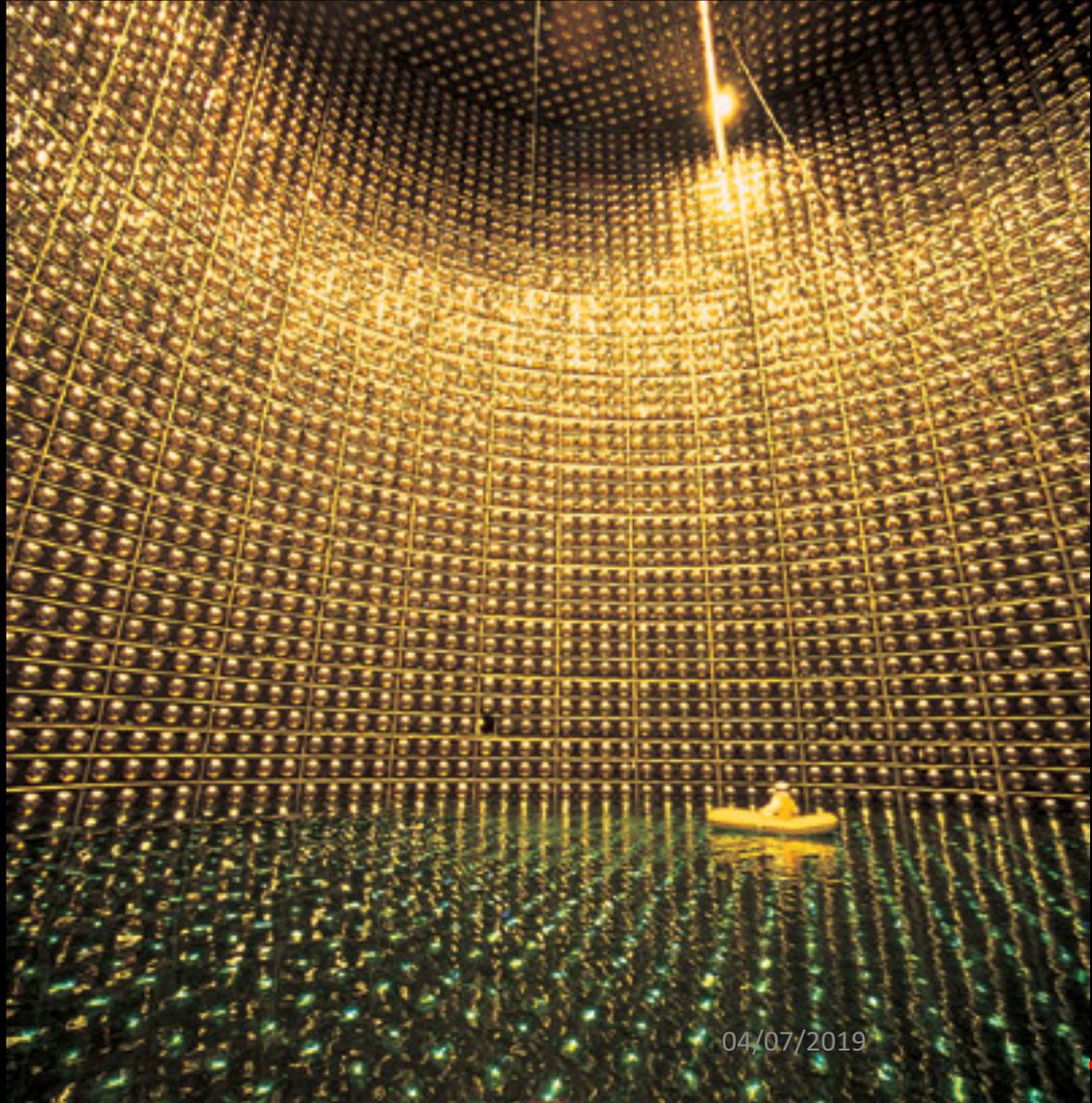
Photo: K. McFarlane,  
Queen's University  
/SNOLAB

**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*"

# Super-Kamiokande detector



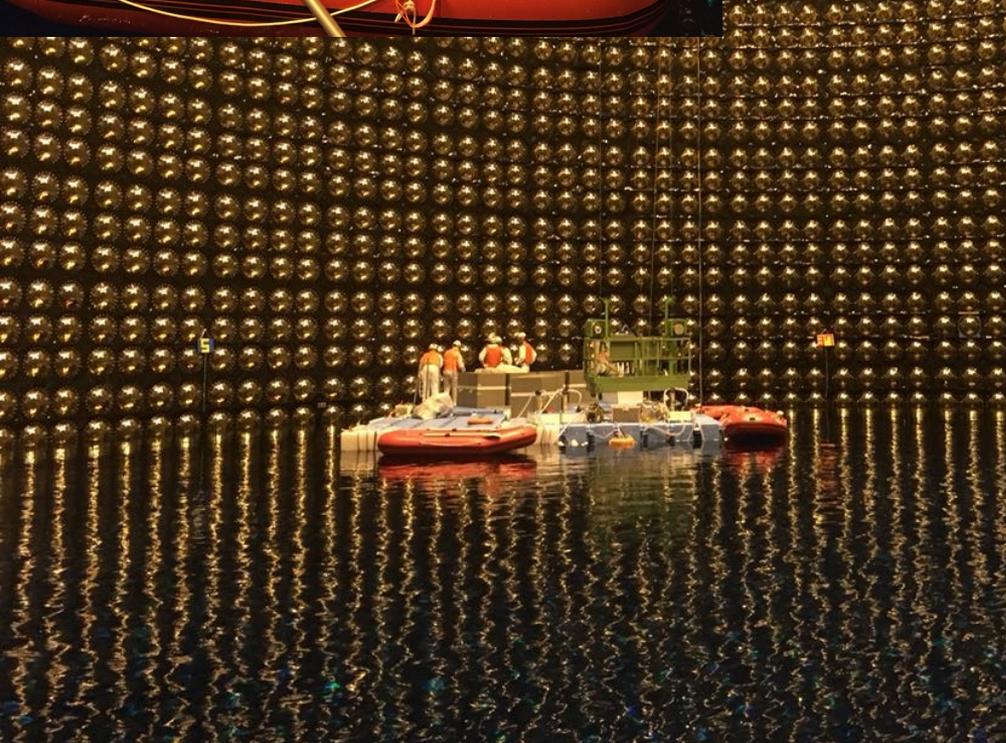
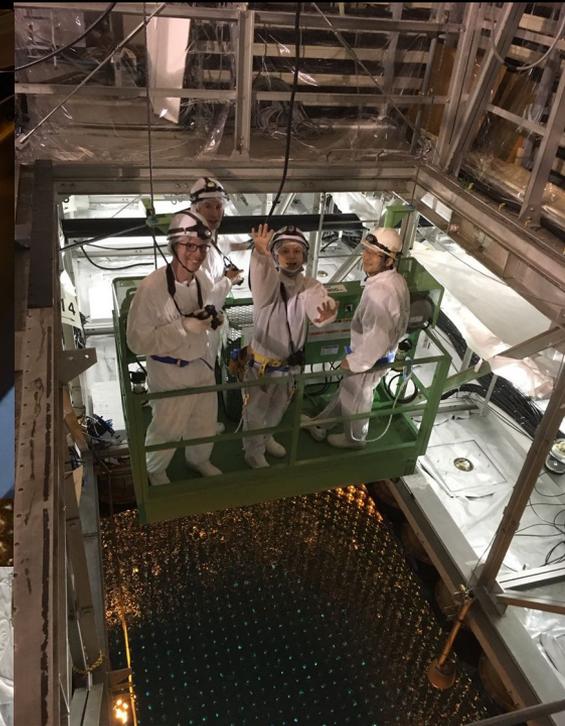
40m

- 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)

04/07/2019

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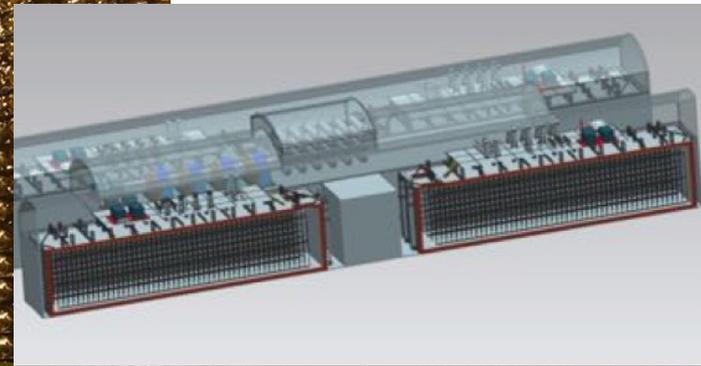
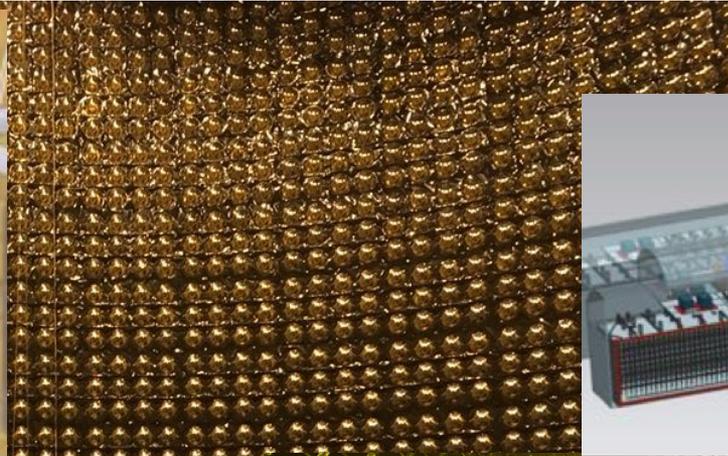
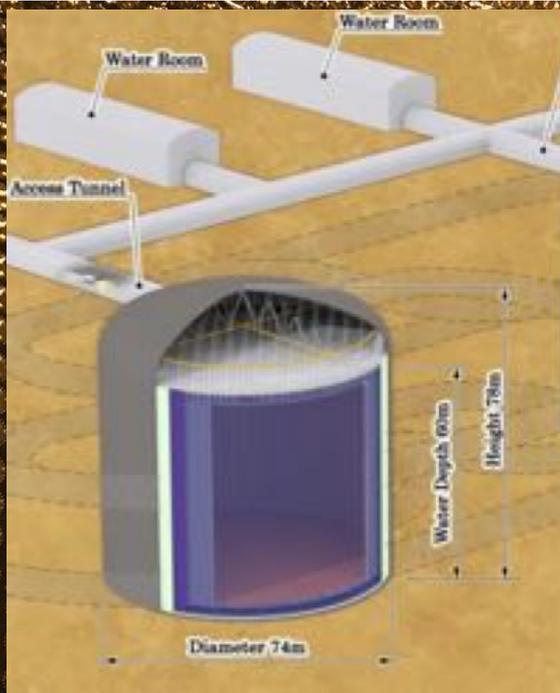
# Super-Kamiokande detector refurbishment 2018



### 3. Hyper-Kamiokande and DUNE

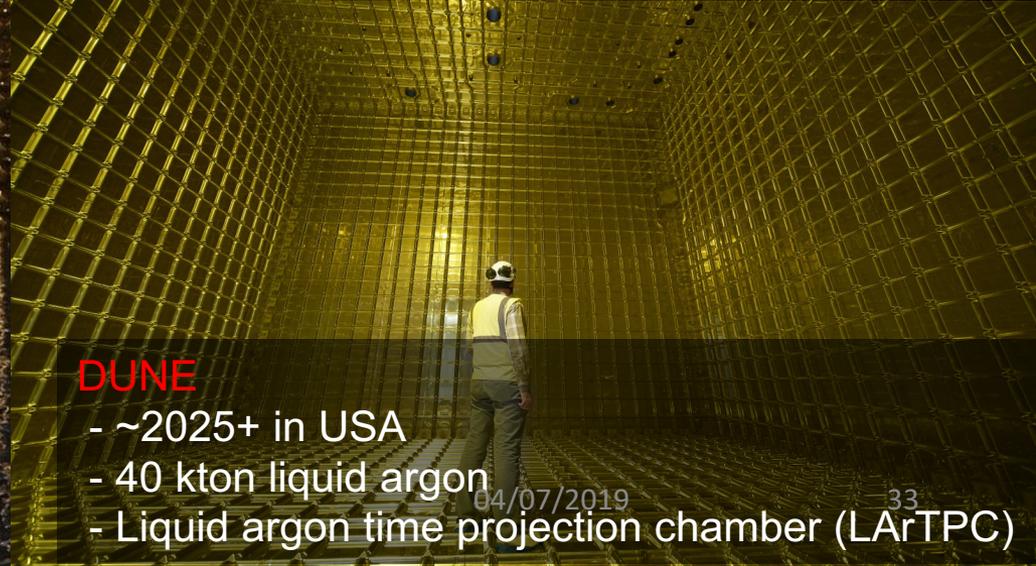
Next generation long-baseline neutrino oscillation experiments

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



#### Hyper-Kamiokande

- ~2026+ in Japan
- 200 kton water
- Water Cherenkov detect



#### DUNE

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

04/07/2019

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# 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.

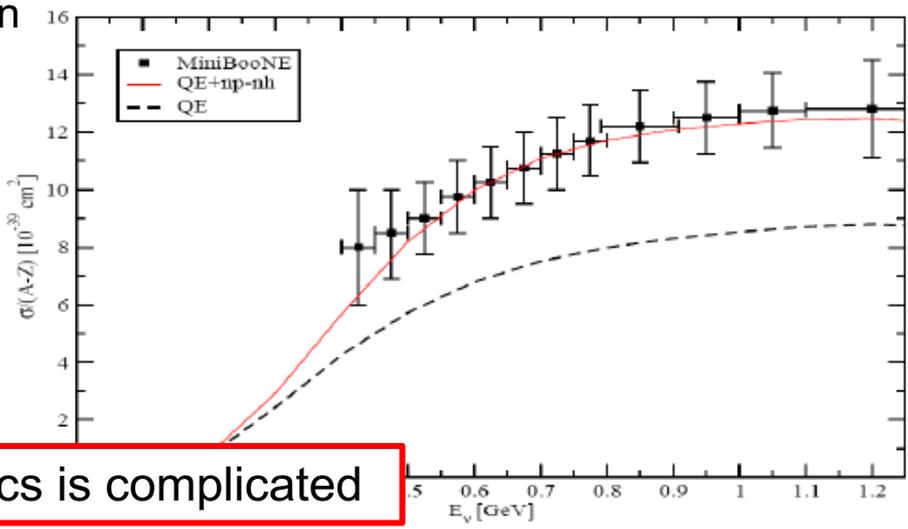
## Discovery of nucleon correlation in neutrino scattering

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

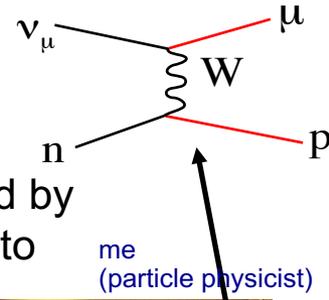
Nuclear physics will have the biggest systematic error for future long-baseline neutrino oscillation experiments...

An explanation of this puzzle

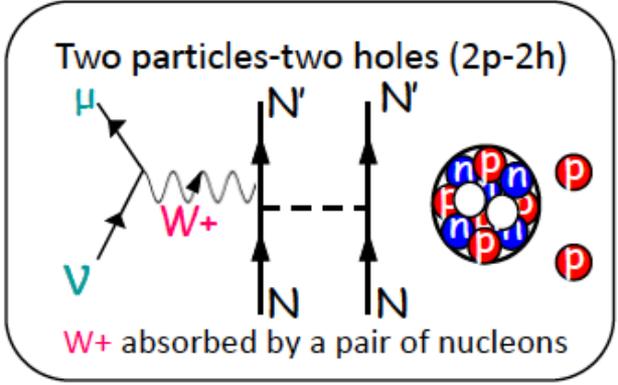
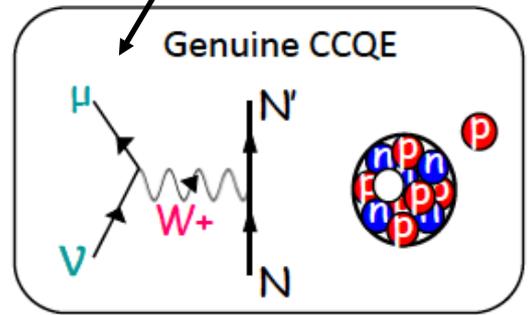
Inclusion of the multinucleon emission channel (np-nh)



Nuclear physics is complicated



Marco Martini (nuclear theorist)

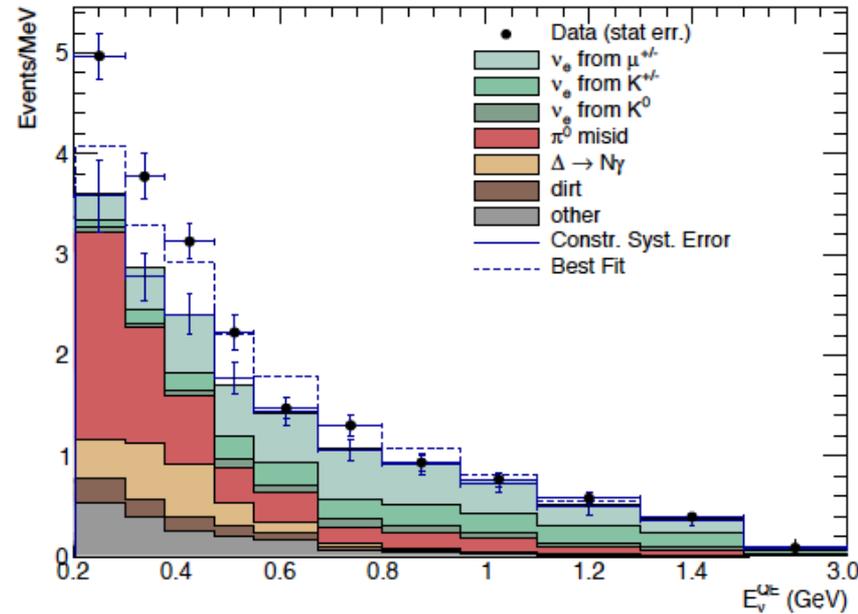


1. Neutrino oscillations
2. Dirac or Majorana?
3. CP violation with leptons
- 4. 4<sup>th</sup> neutrino search (sterile neutrino search)**
5. Dark matter search with neutrinos
6. Quantum gravity search neutrinos
7. Conclusion

# 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 4<sup>th</sup> 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 4<sup>th</sup> neutrino doesn't interact with weak force
- **sterile neutrino**

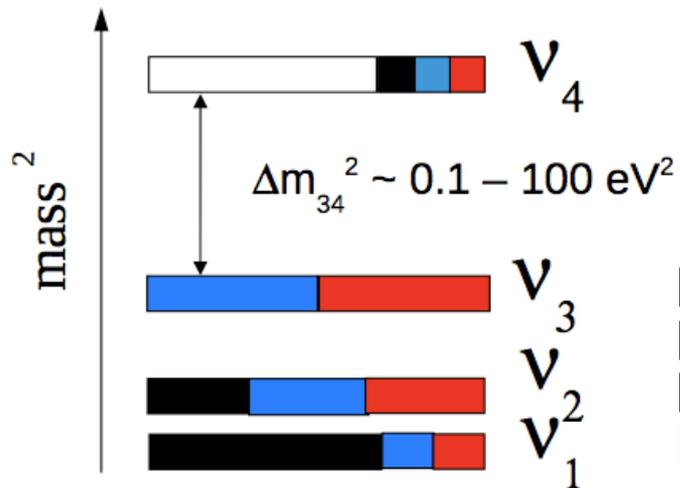
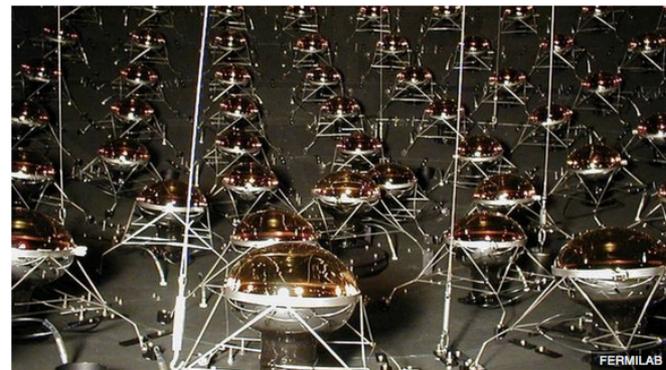


Science & Environment

## Has US physics lab found a new particle?

By Paul Rincon  
Science editor, BBC News website

© 6 June 2018



large neutrino mass



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

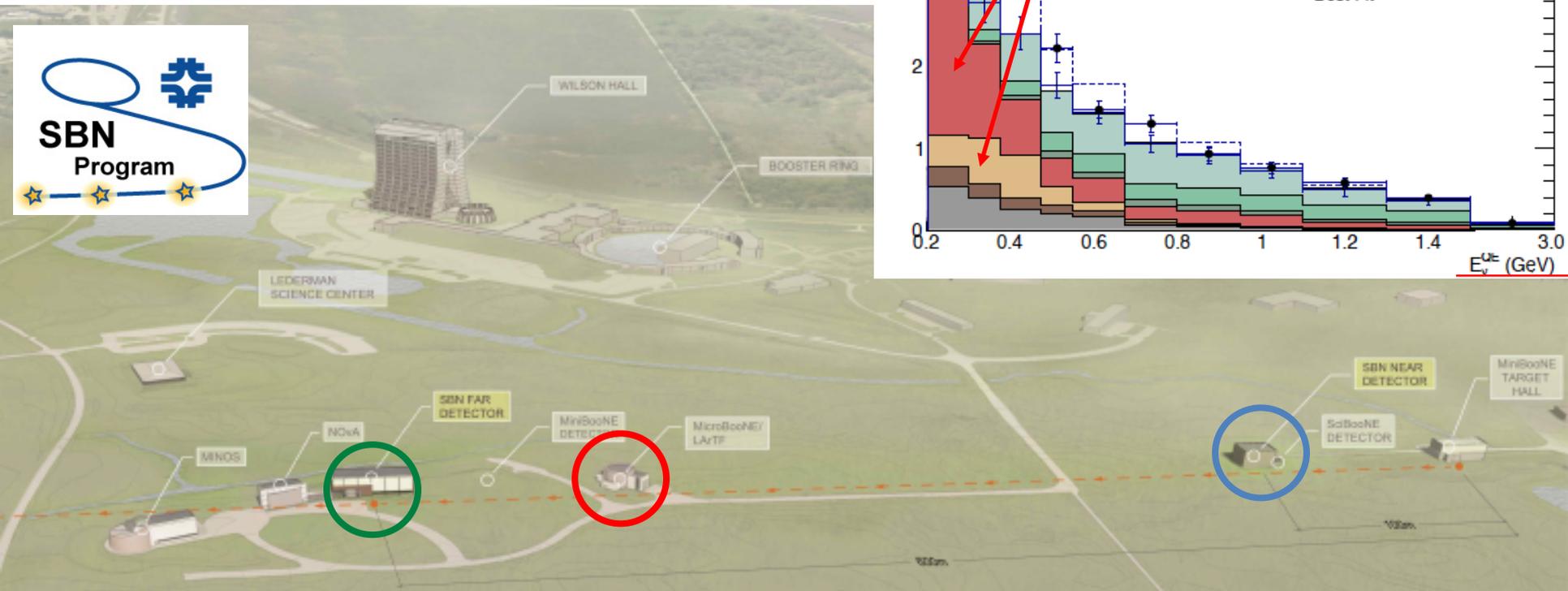
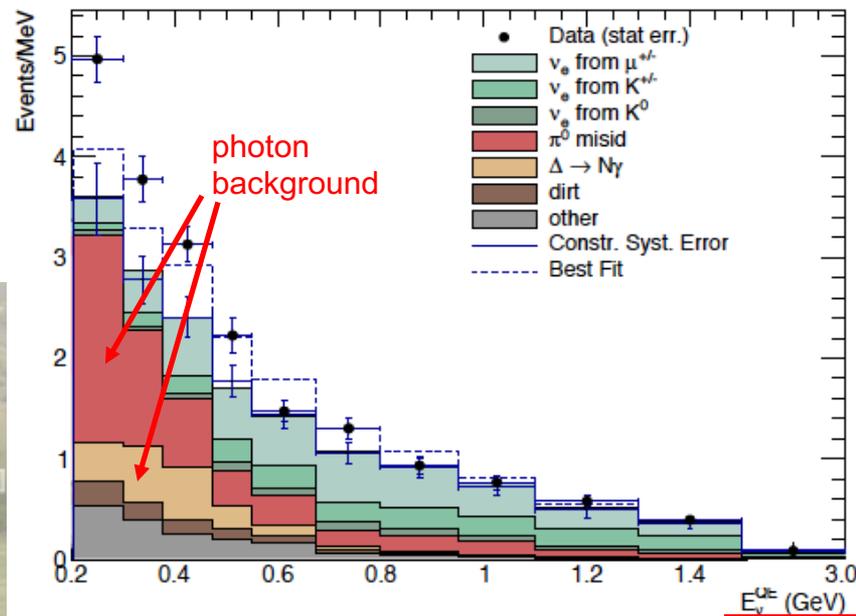
- $\nu_s$
- $\nu_\tau$
- $\nu_\mu$
- $\nu_e$

04/07/2019

# 4. Fermilab short baseline neutrino (SBN) program

## SBND+MicroBooNE+ICARUS

- 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

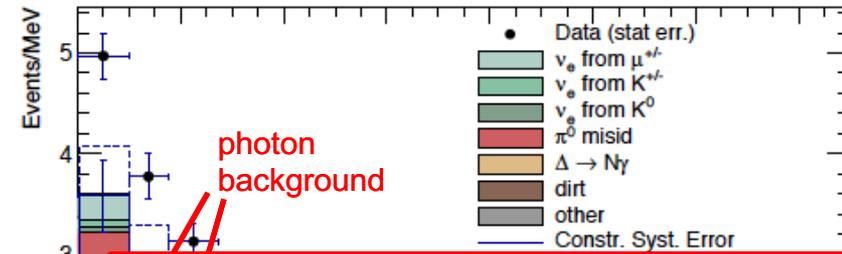
**SBND**  
 - 110 m  
 - 112 ton

← neutrino beam

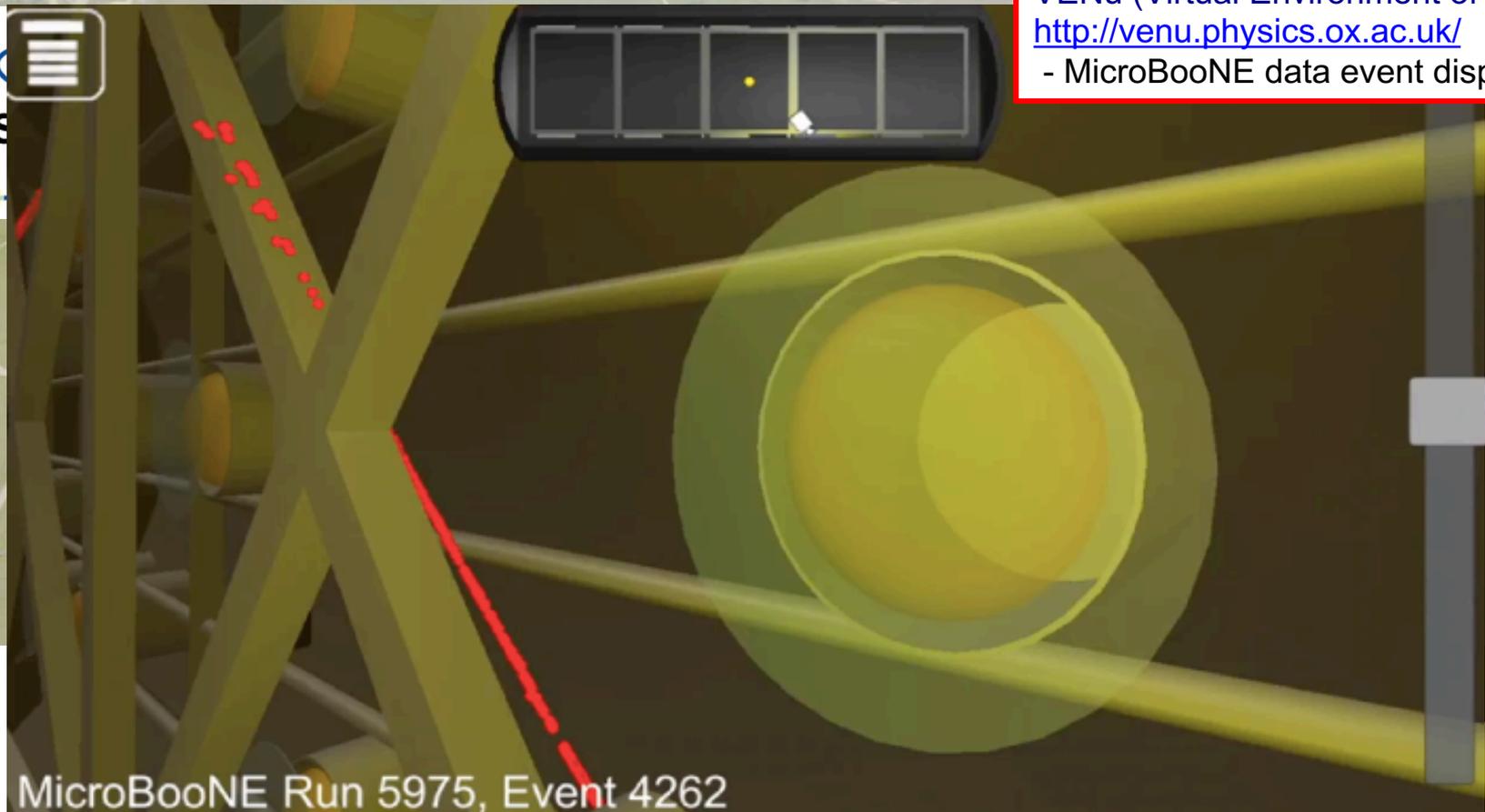
## 4. Fermilab short baseline neutrino (SBN) program

### 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



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

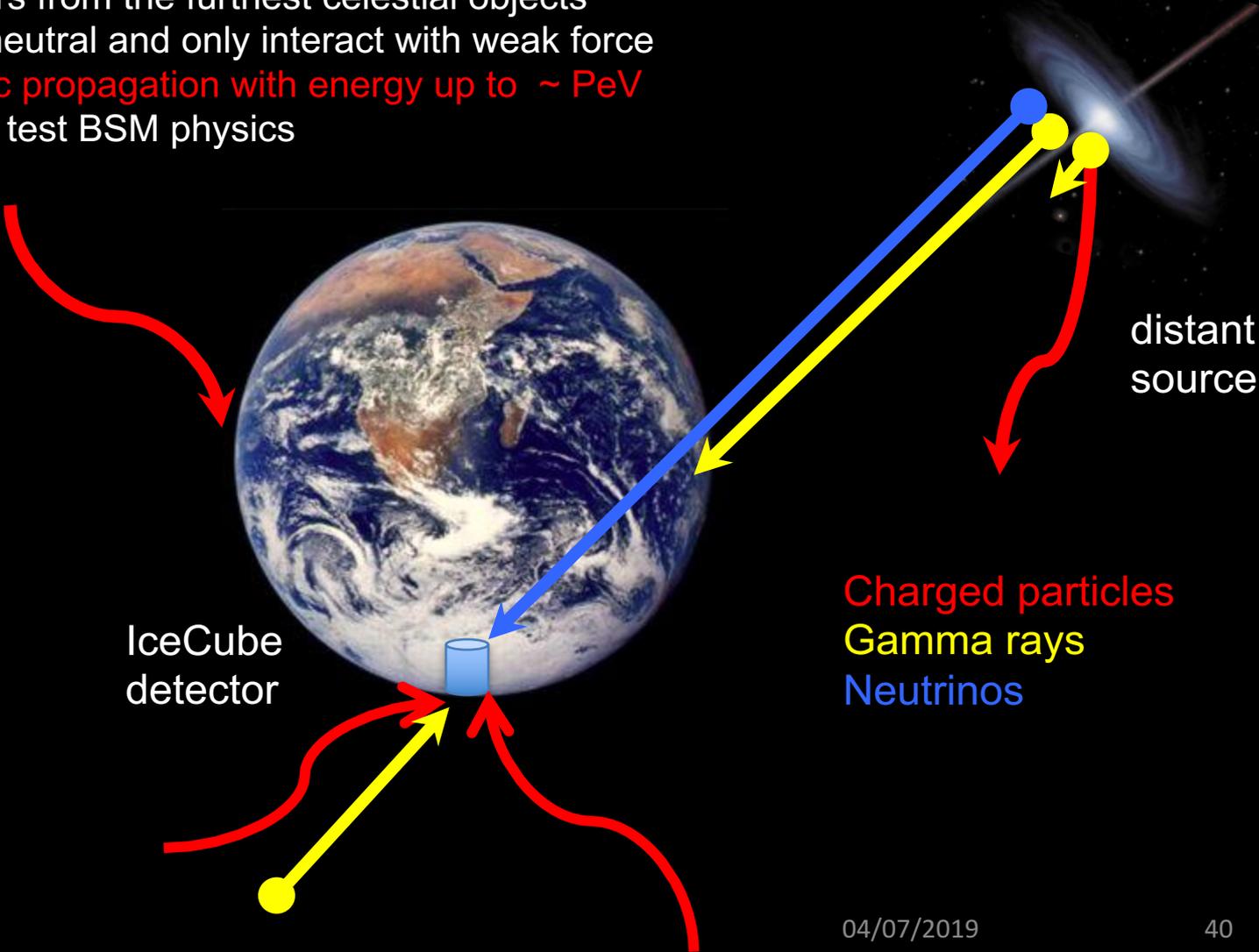


neutrino beam

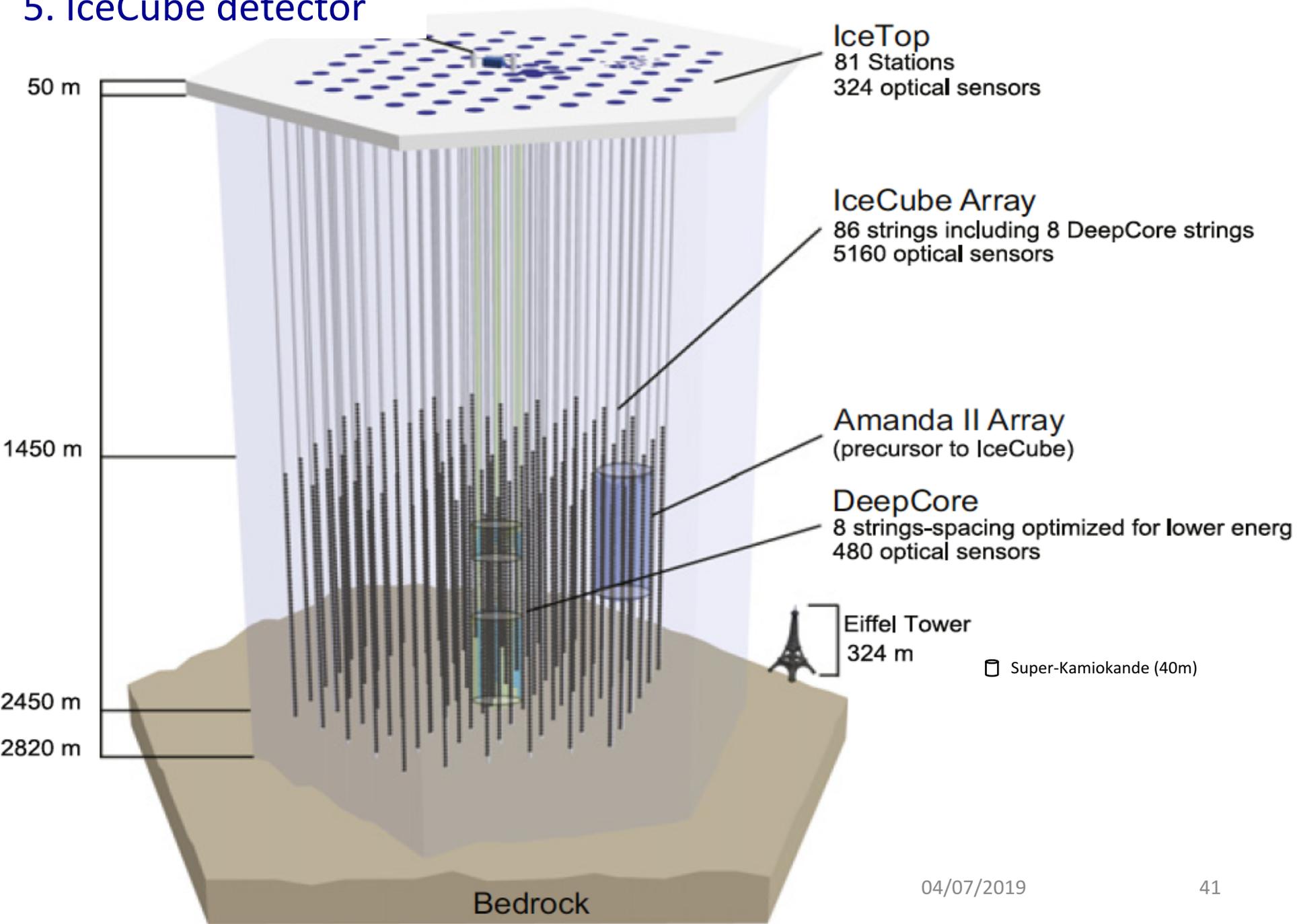
1. Neutrino oscillations
2. Dirac or Majorana?
3. CP violation with leptons
4. 4<sup>th</sup> neutrino search (sterile neutrino search)
- 5. Dark matter search with neutrinos**
6. Quantum gravity search neutrinos
7. Conclusion

# 5. High-Energy Neutrino Astronomy

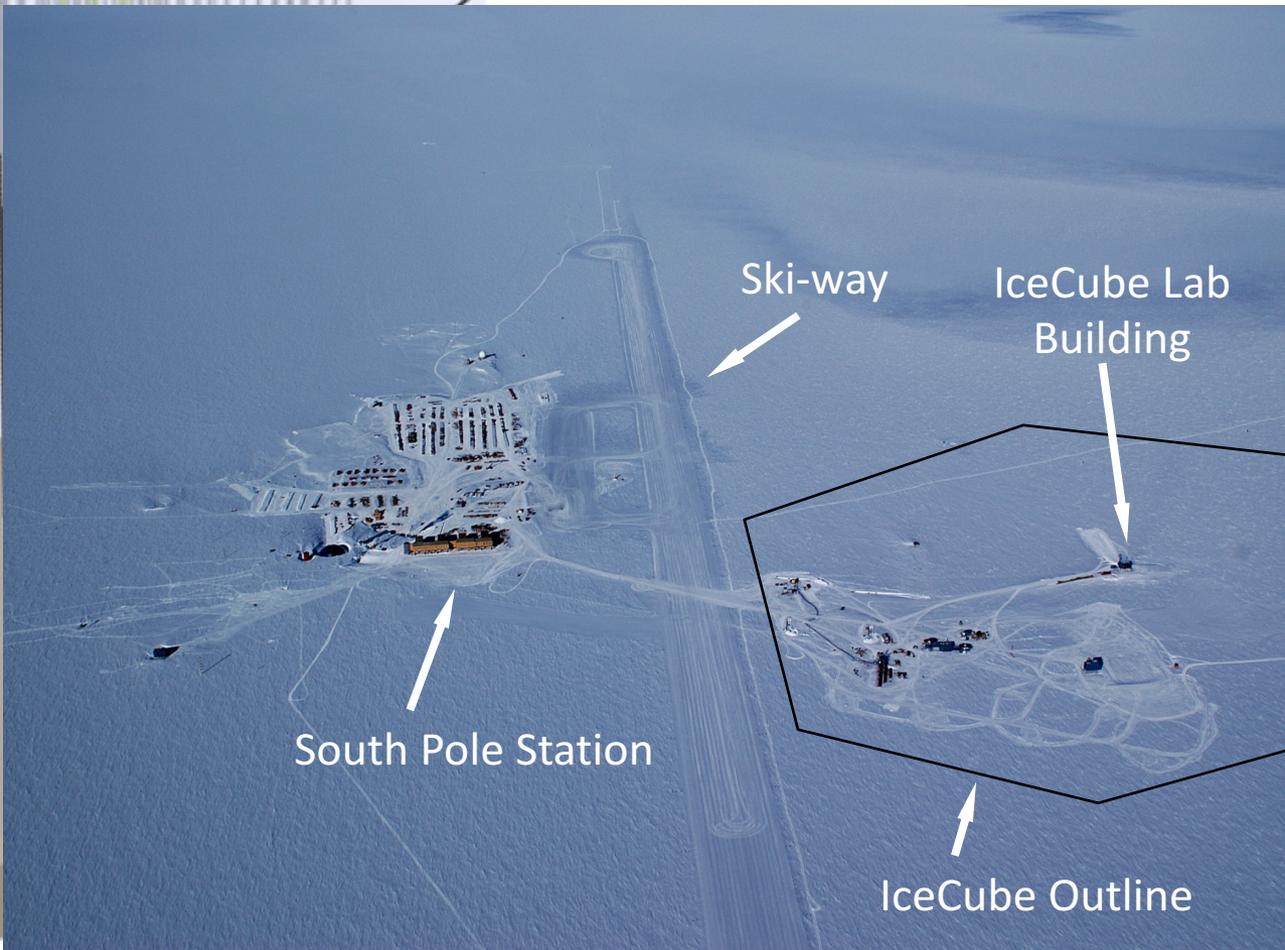
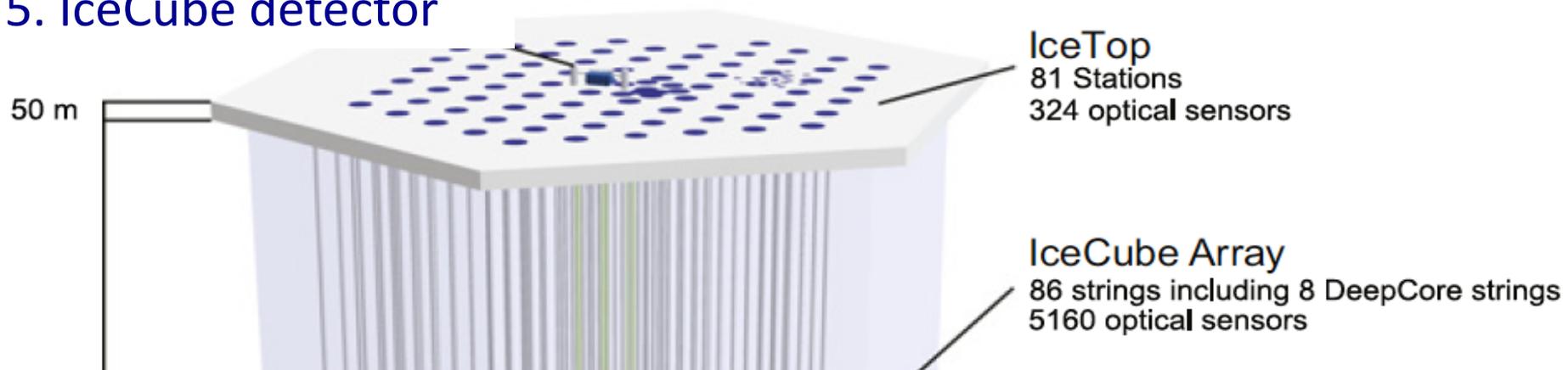
Direct messengers from the furthest celestial objects  
- Neutrinos are neutral and only interact with weak force  
- order  $\sim 100$  Mpc propagation with energy up to  $\sim$  PeV  
→ unique tool to test BSM physics



# 5. IceCube detector

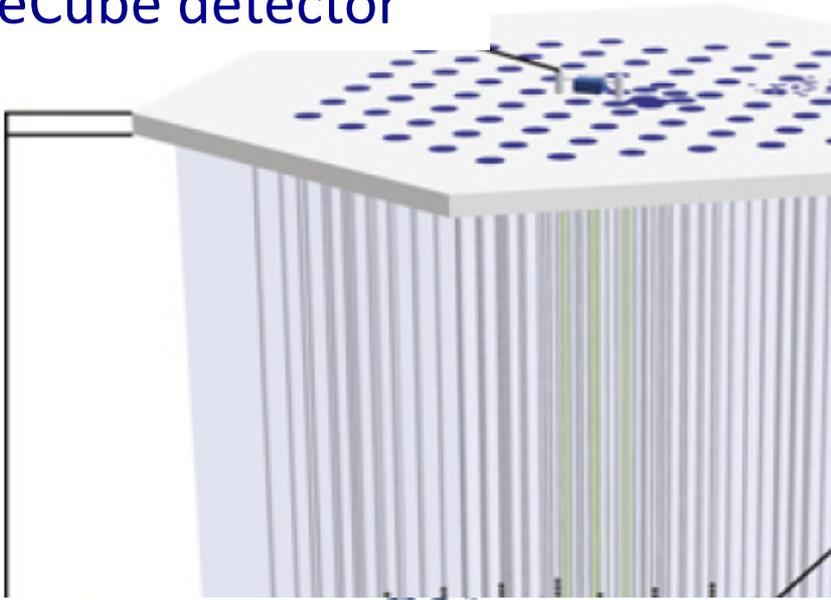


# 5. IceCube detector

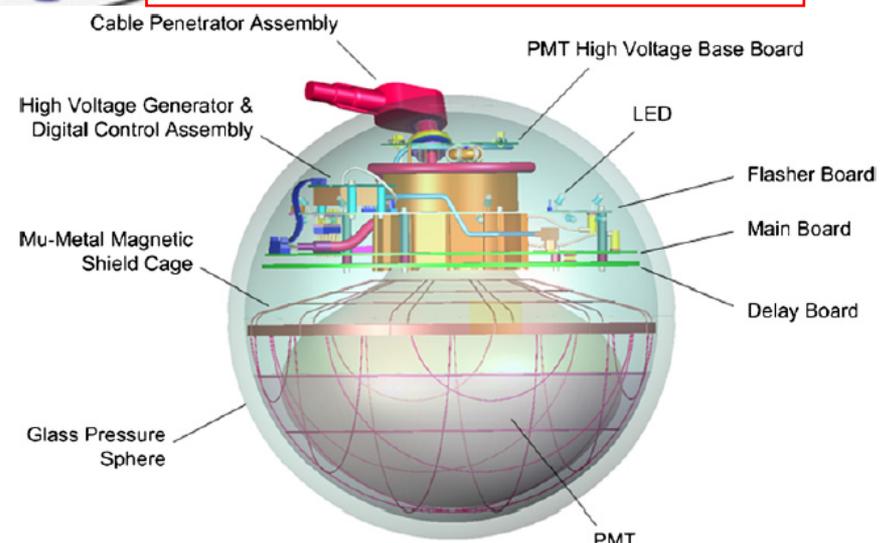


# 5. IceCube detector

50 m



digital optical module (DOM)

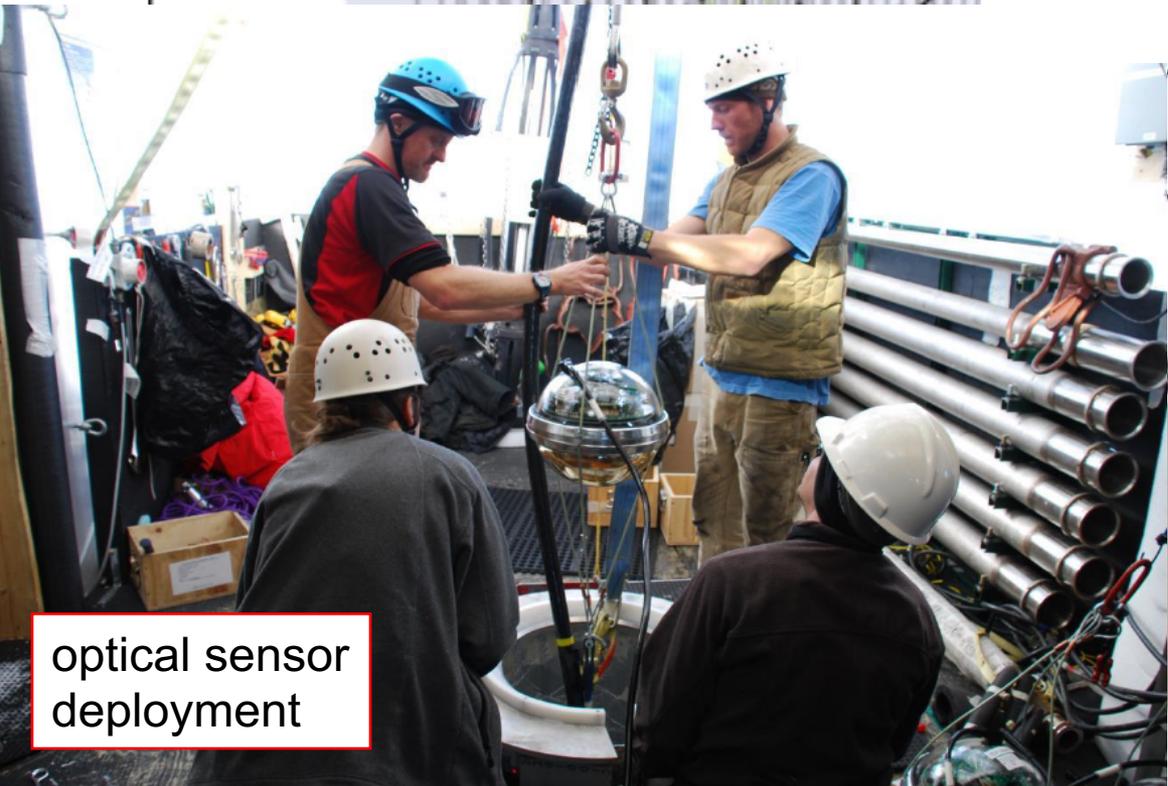


(precursor to IceCube)

DeepCore

8 strings-spacing optimized for lower energy  
480 optical sensors

Eiffel Tower  
324 m



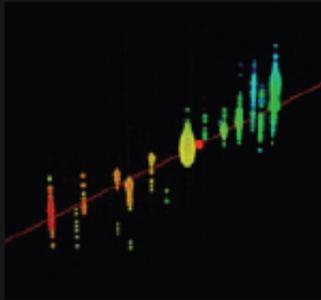
optical sensor deployment

# 5. Astrophysical High-Energy Neutrinos

Topology

- Track = muon ( $\sim \nu_\mu \text{CC}$ )
- Shower (cascade) = electron, tau, hadrons ( $\sim, \nu_e \text{CC}, \nu_\tau \text{CC}, \text{NC}$ )

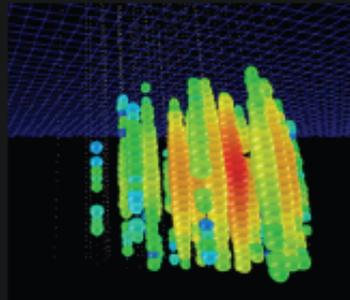
## CC Muon Neutrino



track (data)

factor of  $\approx 2$  energy resolution  
 $< 1^\circ$  angular resolution

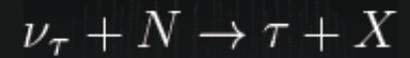
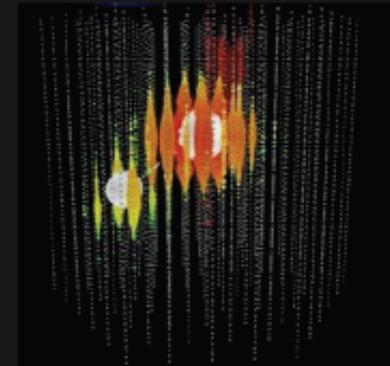
## Neutral Current / Electron Neutrino



cascade (data)

$\approx \pm 15\%$  deposited energy resolution  
 $\approx 10^\circ$  angular resolution  
 (at energies  $\gtrsim 100$  TeV)

## CC Tau Neutrino



“double-bang” and other  
 signatures (simulation)

# 5. Dark matter search with astrophysical neutrinos

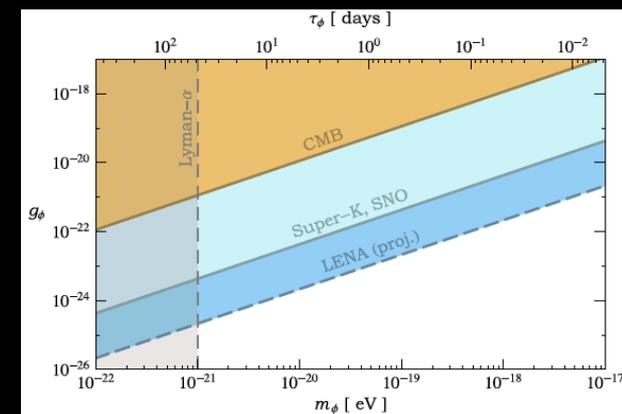
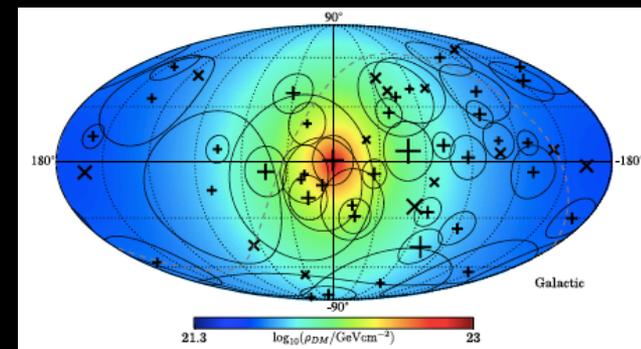
Neutrinos from Earth, Sun, Milky Way center

- 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

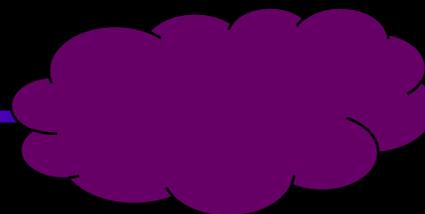
These approaches can investigate dark matter from dark matter particle mass  $\sim 10^{-22}$  eV to  $\sim 10^{13}$  eV (order 35!)



Modified neutrino signal



New physics



astrophysical neutrino



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

## 6. Quantum gravity



“Theory of Everything” is QFT+GR

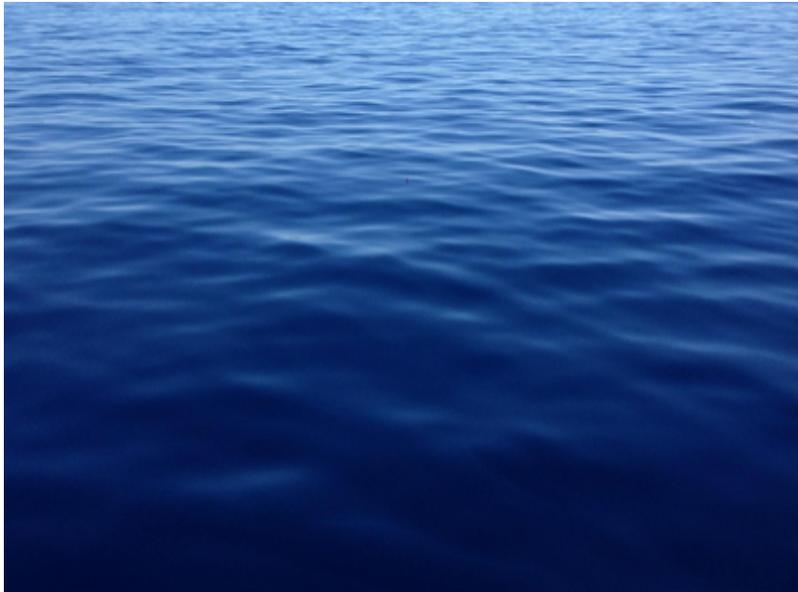
- Quantum Field Theory (QFT) → particle physics, microscopic scale
- General Relativity (GR) → gravity, large scale

A unified theory, “quantum gravity” may show new space-time structure

- $\sim 10^{19}$  GeV (Planck energy), the energy of the Big Bang and no machines can replicate
- $\sim (10^{19} \text{ GeV})^{-1}$ , expected quantum fluctuation of space-time itself ← our focus

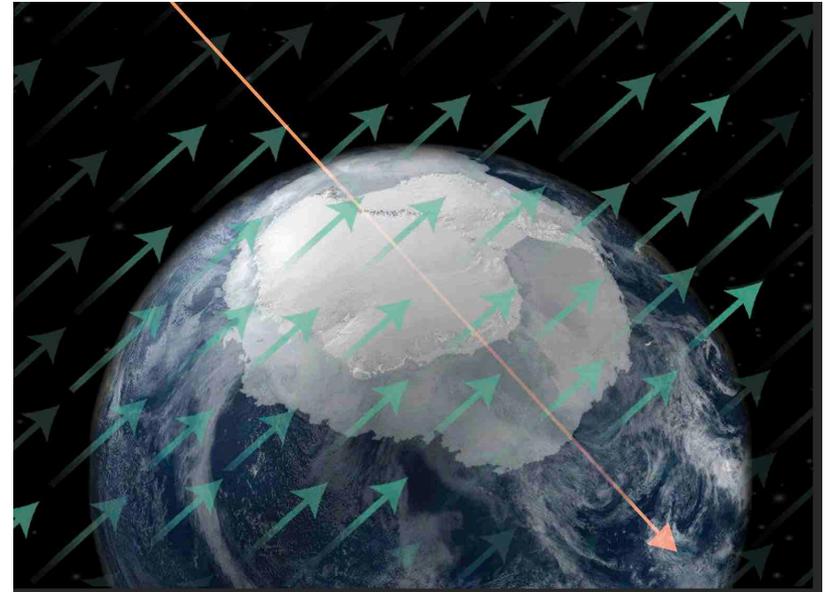
quantum foam

- quantum fluctuation of space time

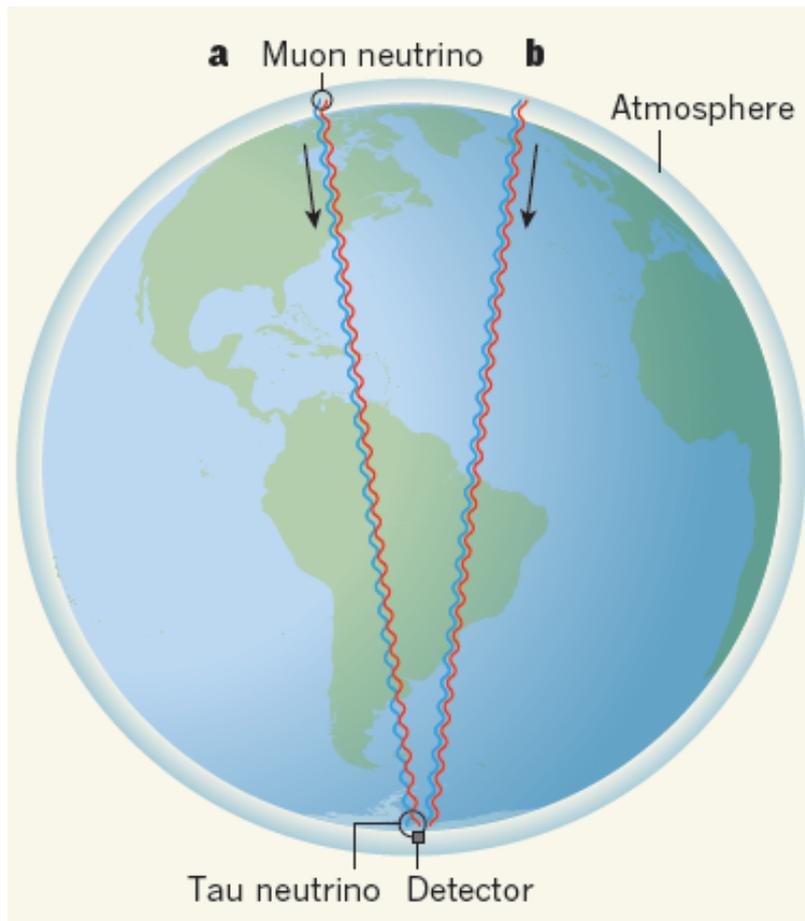


Lorentz violating field

- new field saturating the universe (aether)



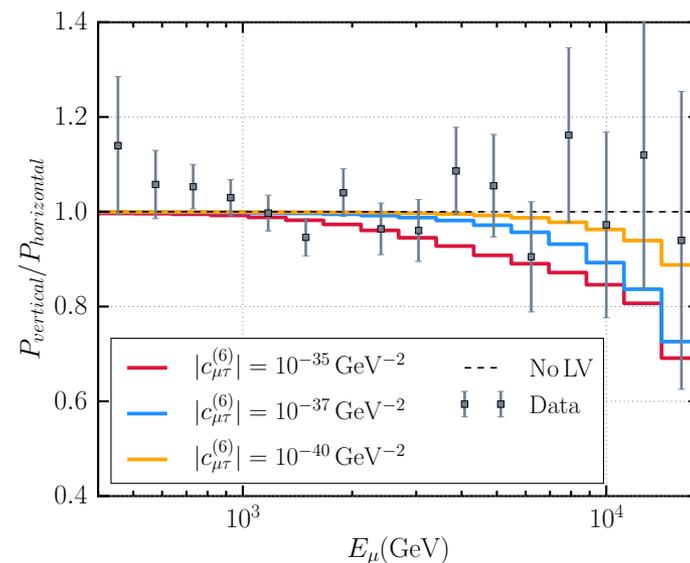
## 6. Neutrino interferometry with atmospheric neutrinos



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



## 6. Quantum gravity search with astrophysical neutrinos

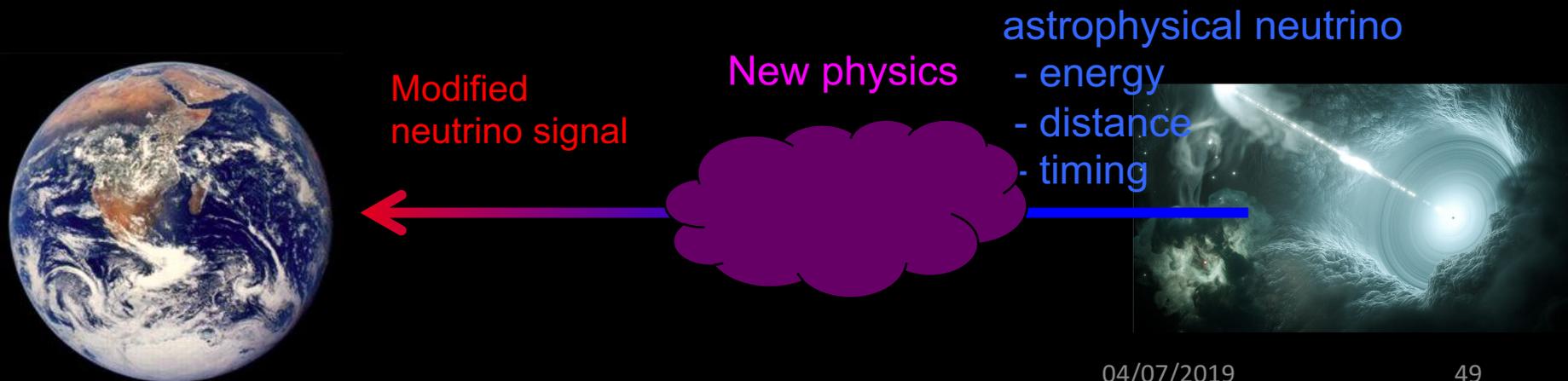
TXS0506+056

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

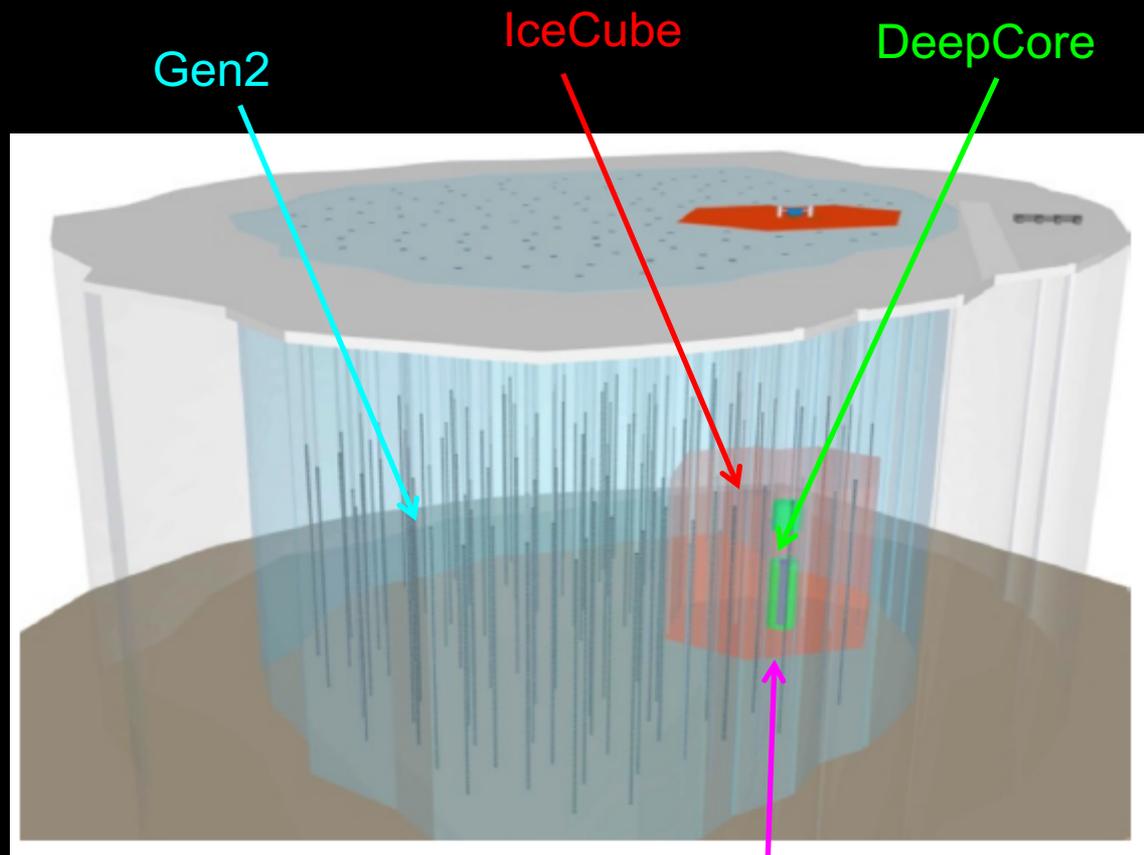
Neutrino time of flight

- 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  $10^{-16} \text{ GeV}^{-1}$

Need more statistics to study the quantum gravity



# 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



PINGU



**SHOP ICECUBE**  
OFFICIAL SHOP OF THE ICECUBE NEUTRINO OBSERVATORY

[https://charge.wisc.edu/icecube/wipac\\_store.aspx](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 ( $\nu$ SM)

- SM + 3 active massive neutrino is established

Properties of  $\nu$ SM

- small neutrino masses  $\rightarrow$  related to high energy scale physics (GUT)?
- Majorana neutrino  $\rightarrow$  lepton number violation process?
- Dirac CP phase  $\rightarrow$  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

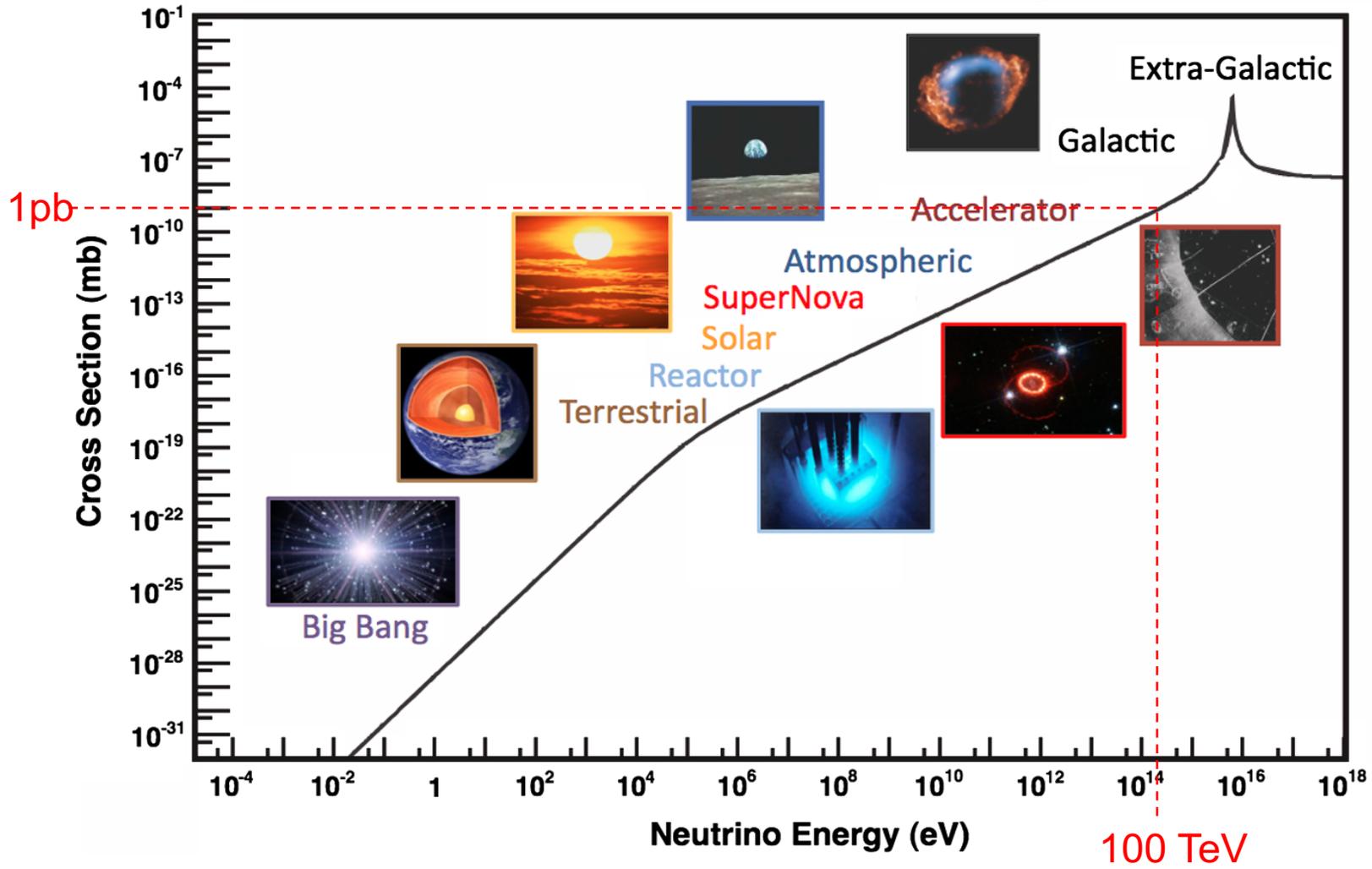
**Thank you for your attention!**

04/07/2019

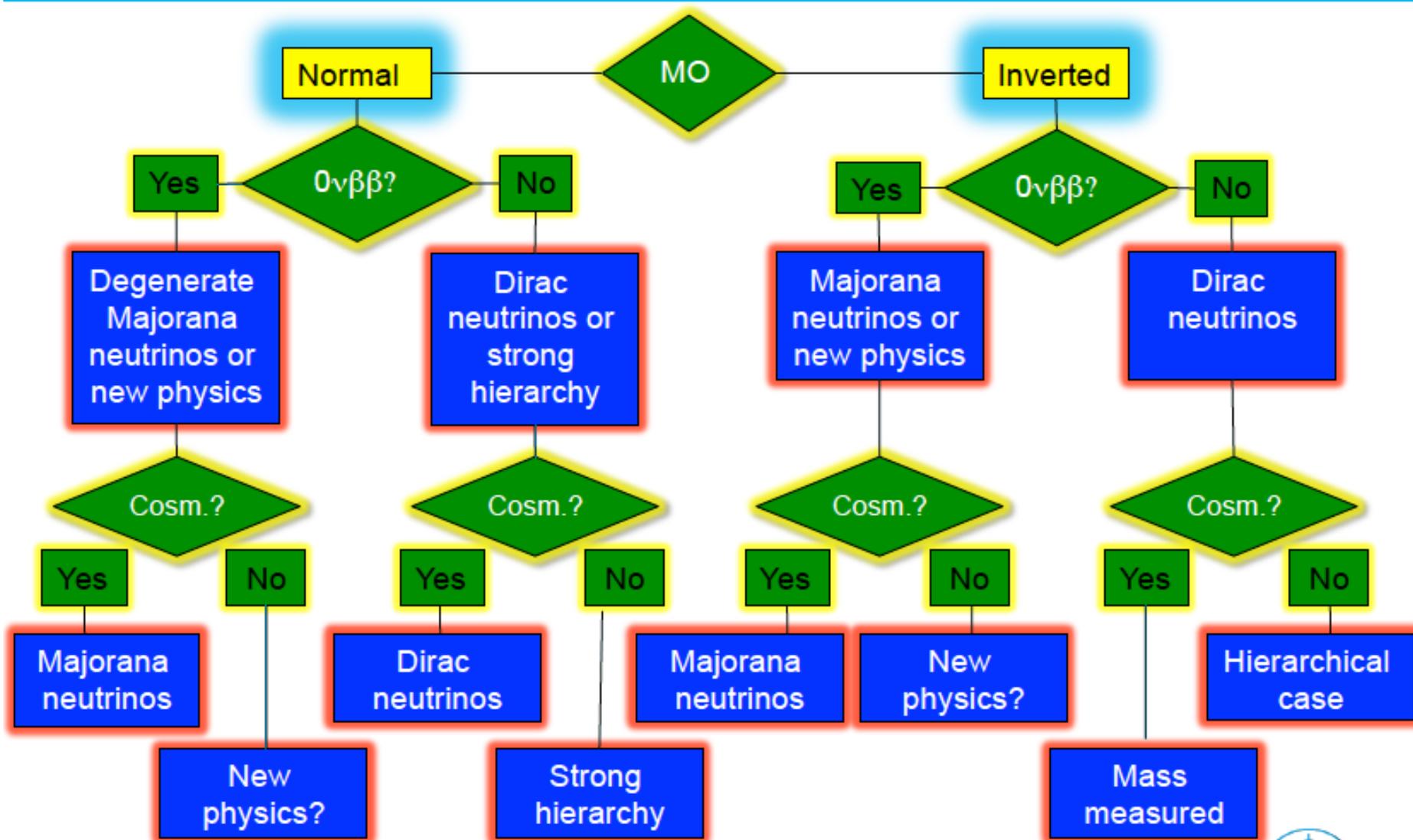


# 1. Neutrinos – from meV to EeV

electron antineutrino - electron elastic scattering cross section



# Impact of direct mass ordering (MO) measurement



## 5. Neutrino-less Double Beta Decay

### Approaches and experiments

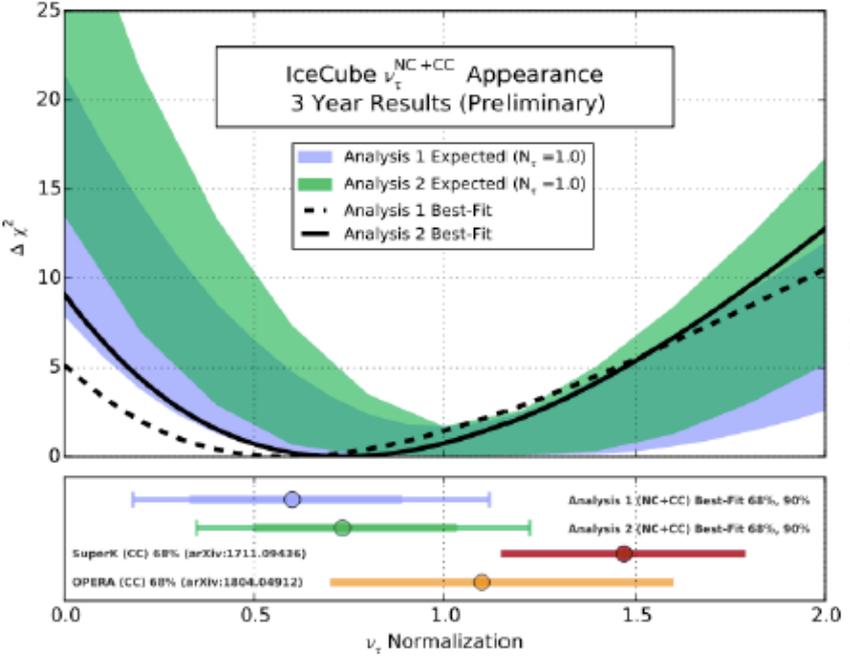
source = detector		NOW	MID-TERM	LONG-TERM
Scalability	Fluid embedded source	Xe-based TPC EXO-200 NEXT-10	NEXT-100 PandaX-III	nEXO NEXT-2.0 PandaX-III 1t
	Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High $\Delta E$ and $\epsilon$	Crystal embedded source	Germanium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

# 6. Atmospheric neutrinos

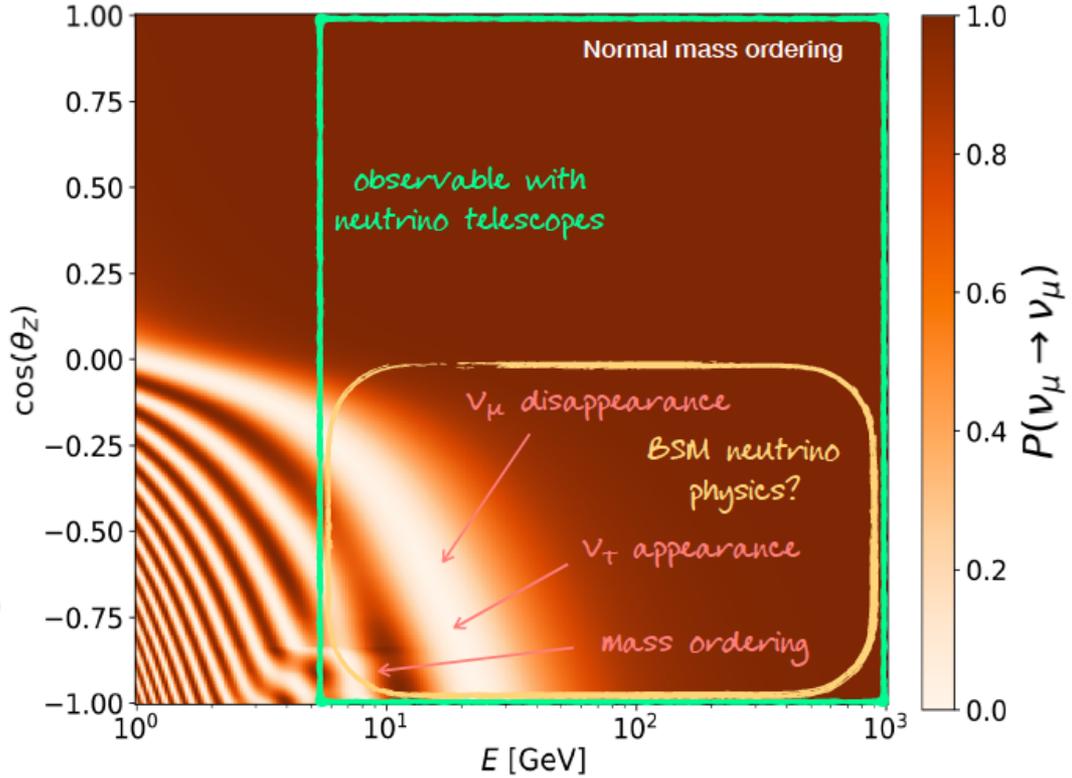
## PINGU and ORCA

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

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



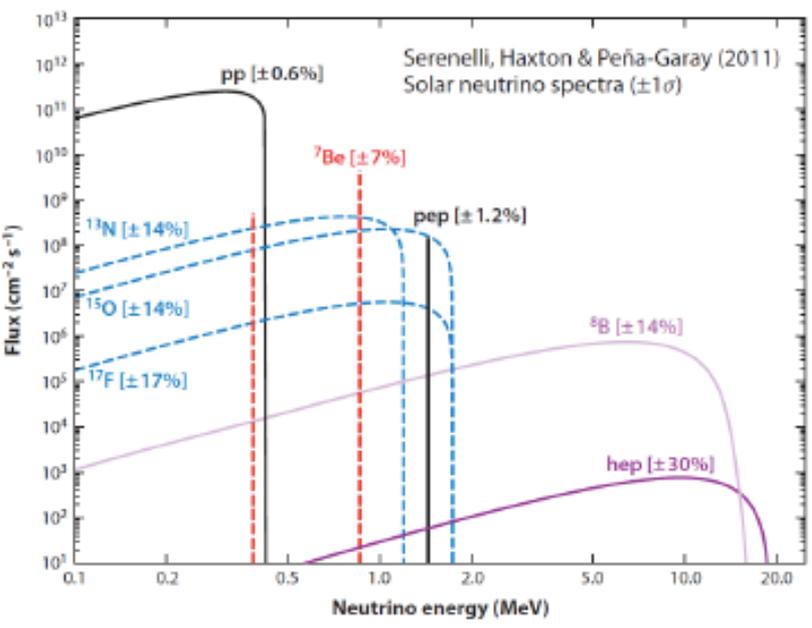
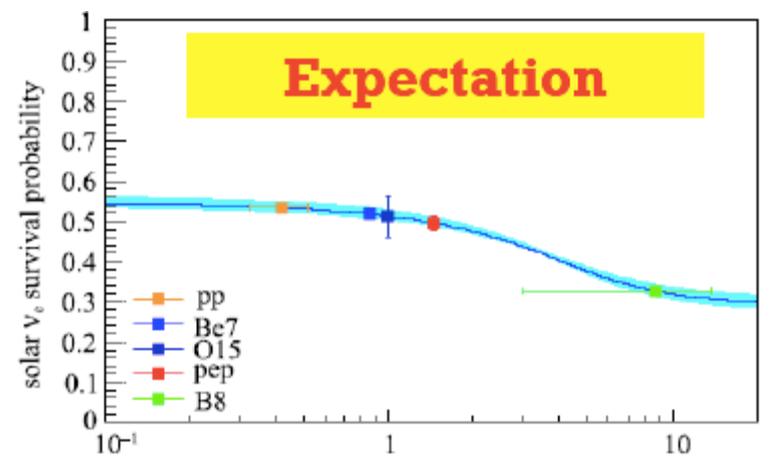
## Oscillograms



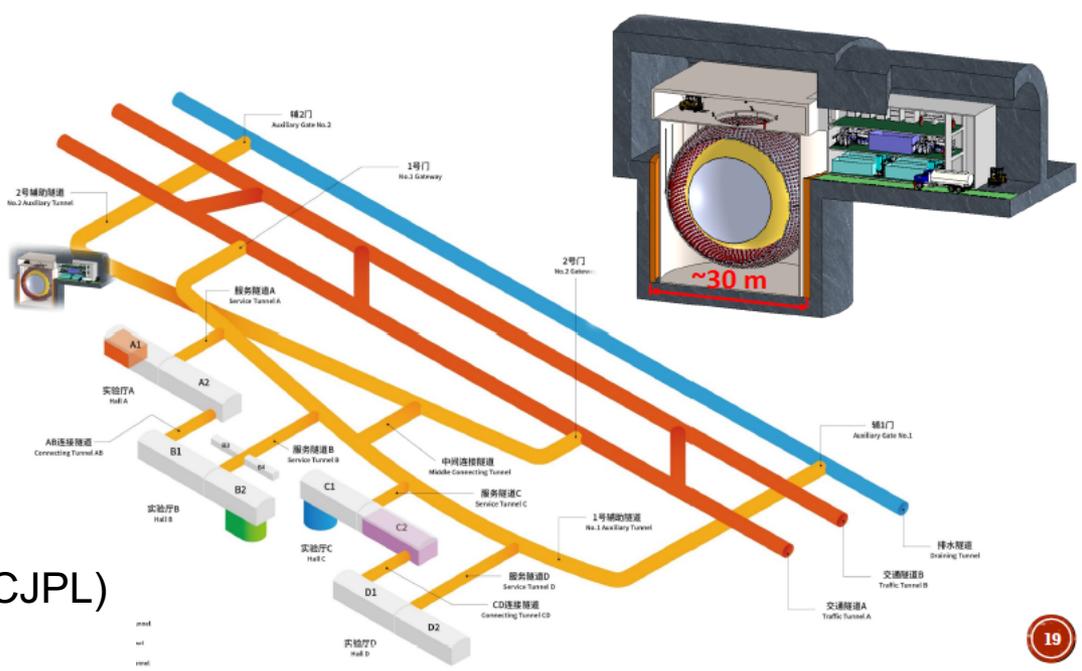
# 6. Solar neutrinos

## 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



## Jinping neutrino detector

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

## 6. Supernova neutrinos

Galactic supernova (~3 per century)

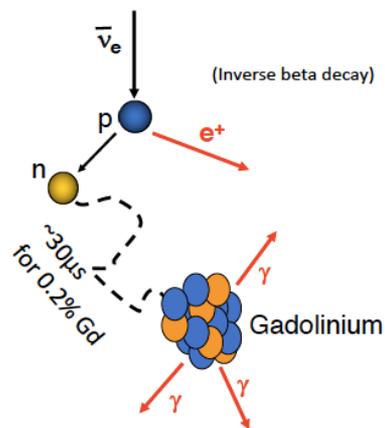
- Good luck for HyperK, DUNE, IceCube, etc

Diffused supernova background (DSNB)

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

SuperK-Gd

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



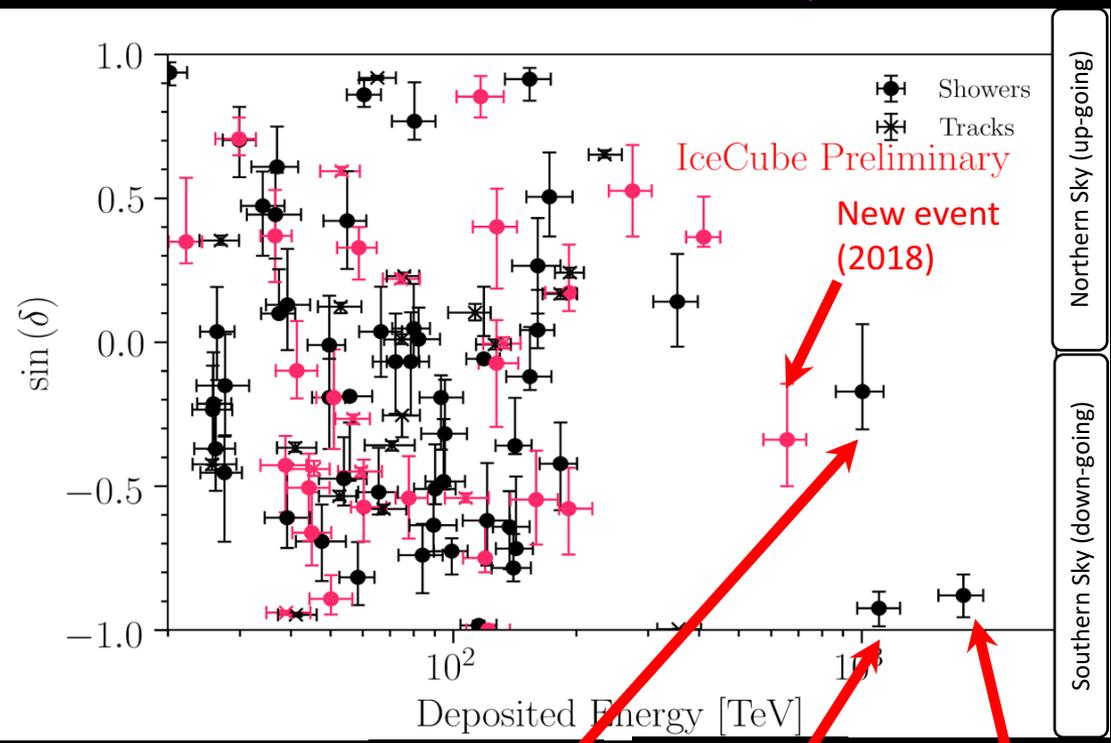
Riding the SuperK boat!  
Dream of all neutrino physicists!



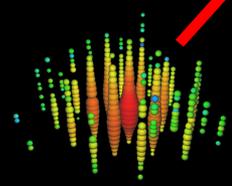
# 6. Astrophysical Very-High-Energy Neutrinos

First observation (2013)  
- 30-2000 TeV neutrinos

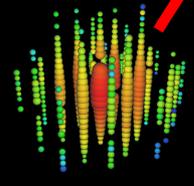
Taboada, Neutrino 2018



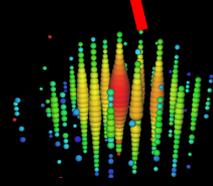
“Bert”  
1.1 PeV



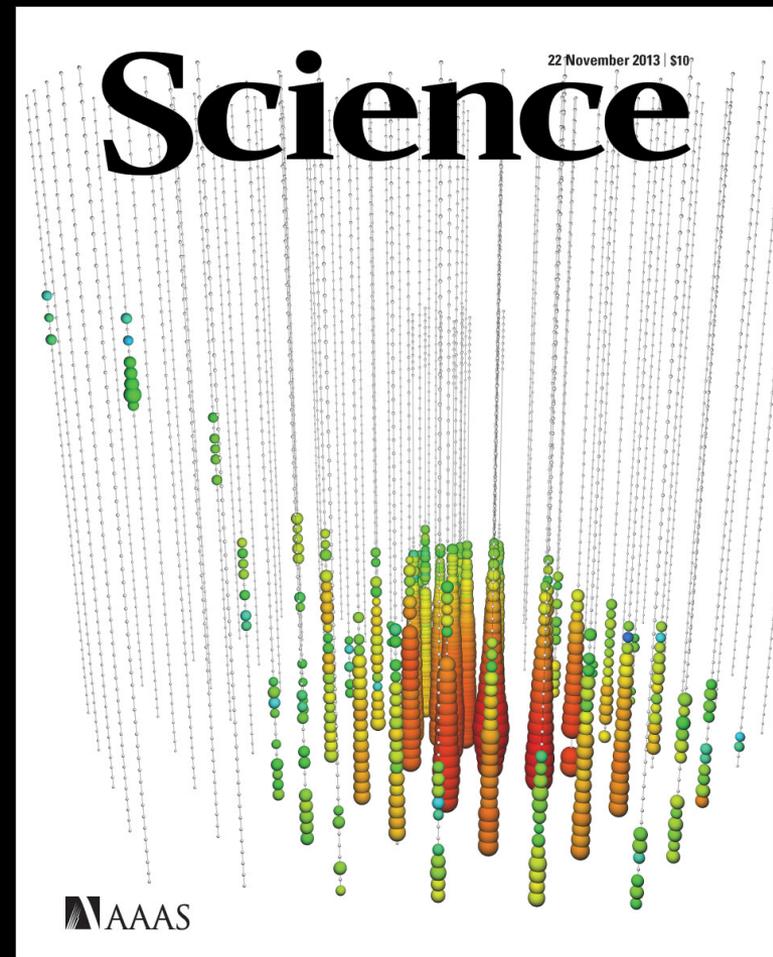
“Ernie”  
1.0 PeV



“Big Bird”  
2.0 PeV



Northern Sky (up-going)  
Southern Sky (down-going)



## 6. Cosmic Neutrino Background (CvB)

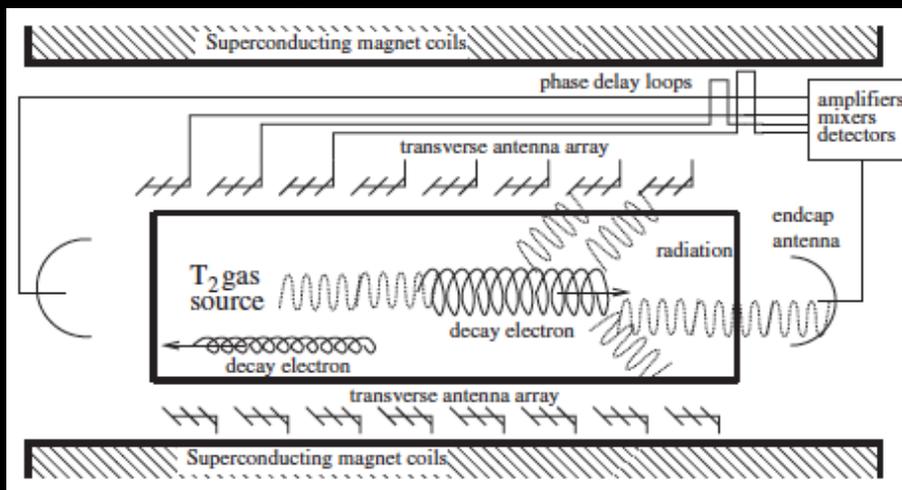
PTOLEMY and Project 8

- Motivated by KATRIN
- Tritium  $\nu_e$  capture (no threshold)
- Measure end point of tritium (18 keV) from cyclotron radiation of single electron RF
- Target:  $\sim$ meV shift of end point due to neutrino mass.

$Q - m_\nu \rightarrow$  neutrino mass effect on  $\beta$ -decay

$Q + m_\nu \rightarrow$  CvB capture

### Project 8 concept



# 4. Neutrino physics for Peace

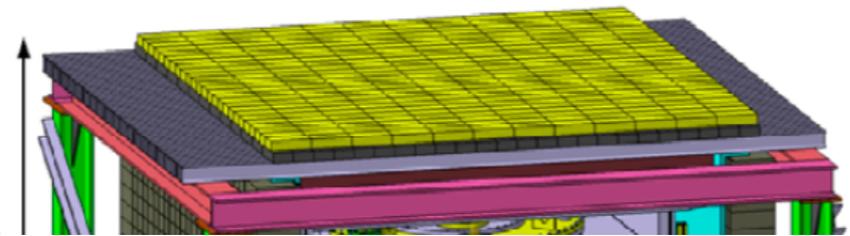
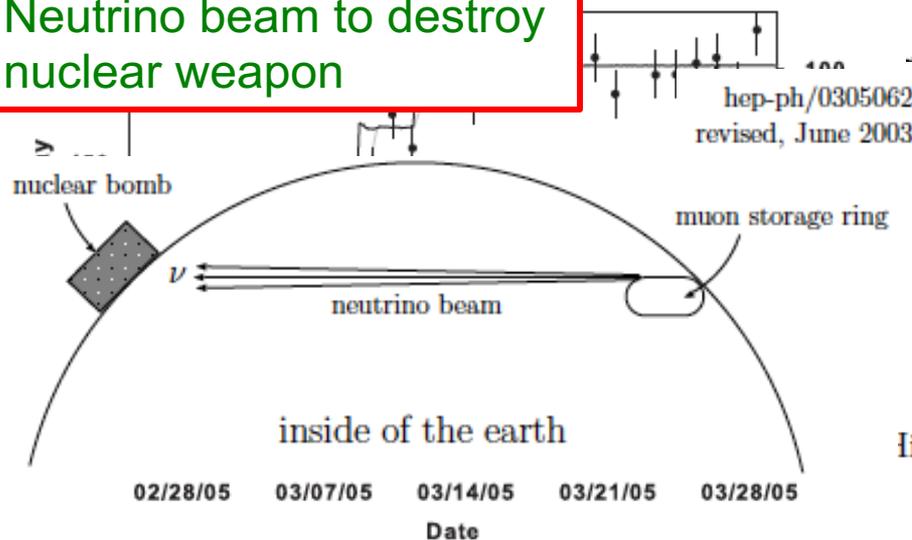
Paper Number: IAEA-CN-184/27

## 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



## Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiro —

Iirotaka Sugawara\*    Hiroyuki Hagura†    Toshiya Sanami‡

3 m

## 4. Neutrino physics to become Rich

Paper Number: IAEA-CN-184/27

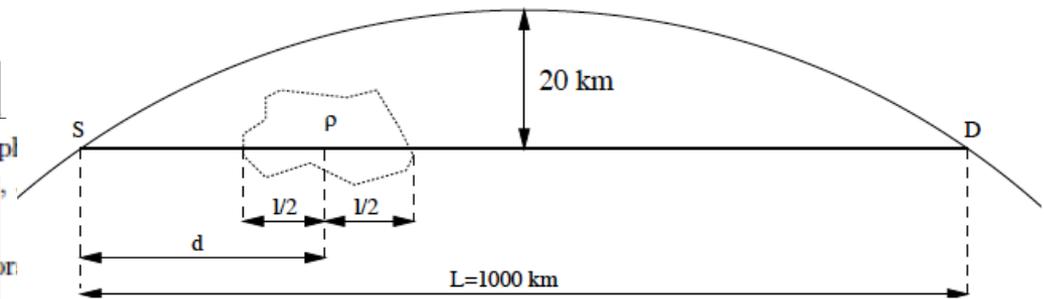
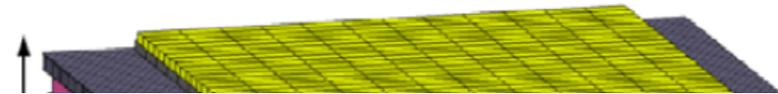
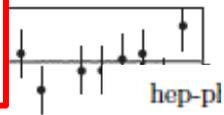
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Neutrino nuclear reactor monitoring

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(\*\*)

*Institut für Theoretische Physik, Physik-Department, Technische Universität München  
James-Franck-Straße, 85748 Garching bei München, Germany*

## 4. Neutrino Communications

Contents lists available at [ScienceDirect](#)



Physics Letters B

### Reactor Neutrino Detection

Using neutrino to communicate submarines under the deep water

Th. Lasserre, V.M. Bui, M. Cribier, Letourneau, D. Lhuillier, J. Martino C. Varignon, F. Yermia

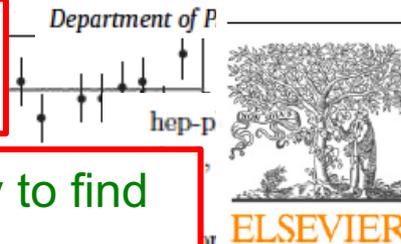
Neutrino nuclear reactor monitoring

### Submarine neutrino communication

Patrick Huber

Neutrino beam to destroy nuclear weapon

Neutrino earth tomography to find oil reservoir



Contents lists available at [ScienceDirect](#)

Physics Letters B

High power neutrino beam to communicate with Aliens(?)

## Could one find petroleum in matter?

### Galactic neutrino communication

John G. Learned<sup>a</sup>, Sandip Pakvasa<sup>a,\*</sup>, A. Zee<sup>b</sup>

T. OHLSSON(\*) and W. WINTER(<sup>a</sup> Department of Physics and Astronomy, University of Hawaii, 2505 Correa Road, Honolulu, HI 96822, USA  
<sup>b</sup> Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA)

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## 4. Neutrino Communications

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at ScienceDirect

Letters B

Communicate  
deep water

Reactor

Finally, MINERvA experiment sent Morse code signal through neutrino beam

### DEMONSTRATION OF COMMUNICATION USING NEUTRINOS

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Neutrino monitoring

Neutrino from nuclear waste

Neutrino from oil reservoir

Could occur in matter

# 4. Neutrino Communications



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## The Future Of Stock Trading: Neutrino Beams



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### Tomorrow's stocks could be traded via neutrino beam

Robert T. Gonzalez  
Filed to: FUTURISM 5/01/12 2:59pm

3,958

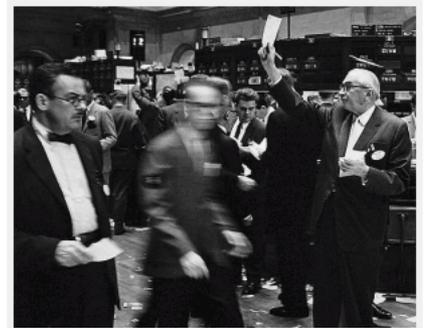
## Neutrinos to Give High-Frequency Traders the Millisecond Edge

13 comments, 5 called-out

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.

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



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



Neutrinos may not travel faster than light, but that doesn't mean they can't be put to good use.