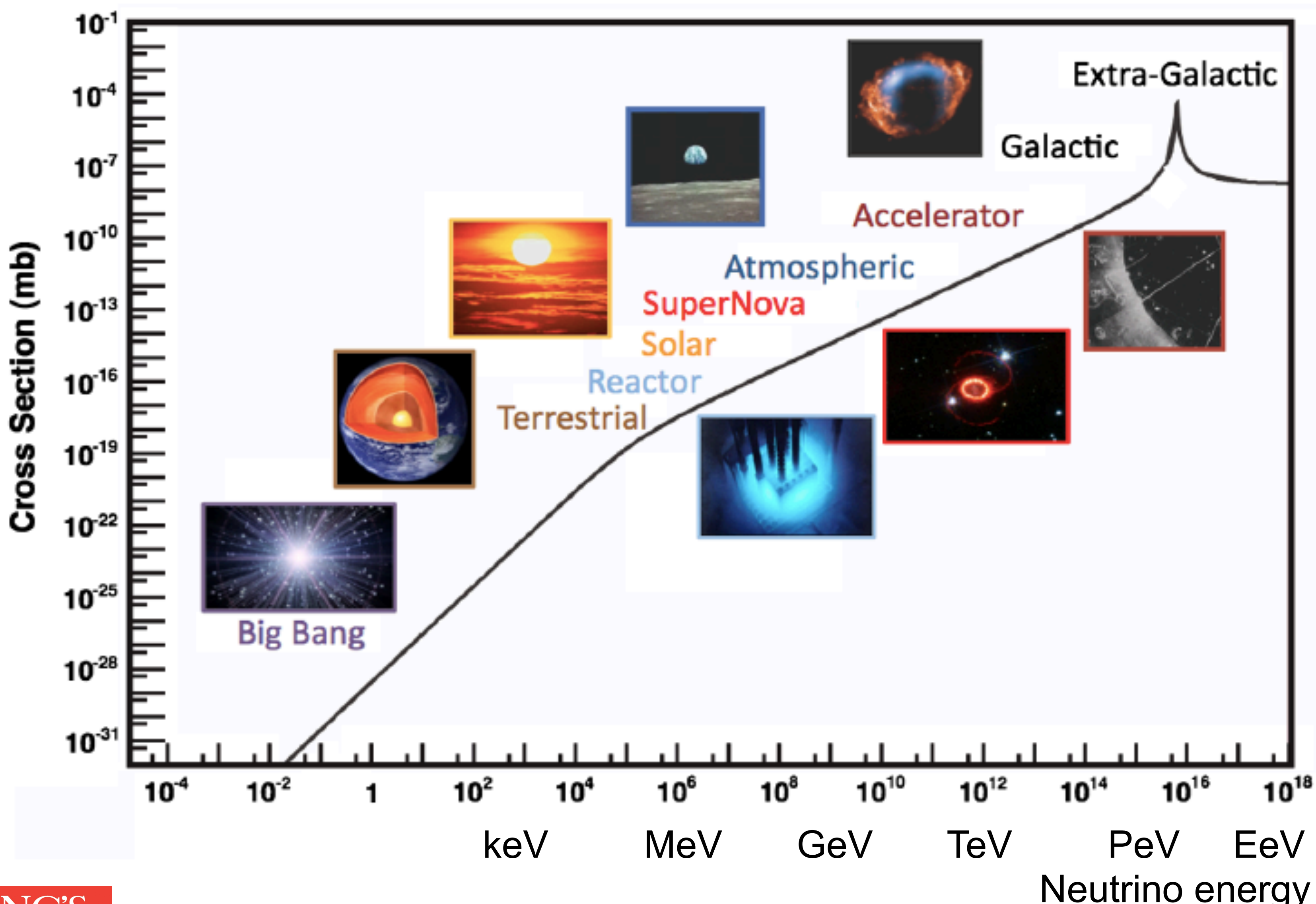
Neutrino Astronomy and Beyond

Teppei Katori (@teppeikatori)
King's College London
February 23, 2021

MicroBooNE PMT test stand
(photo by Reidar Hahn, Fermilab)

Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

Astrophysical neutrinos from eV to EeV (10^{18} eV)



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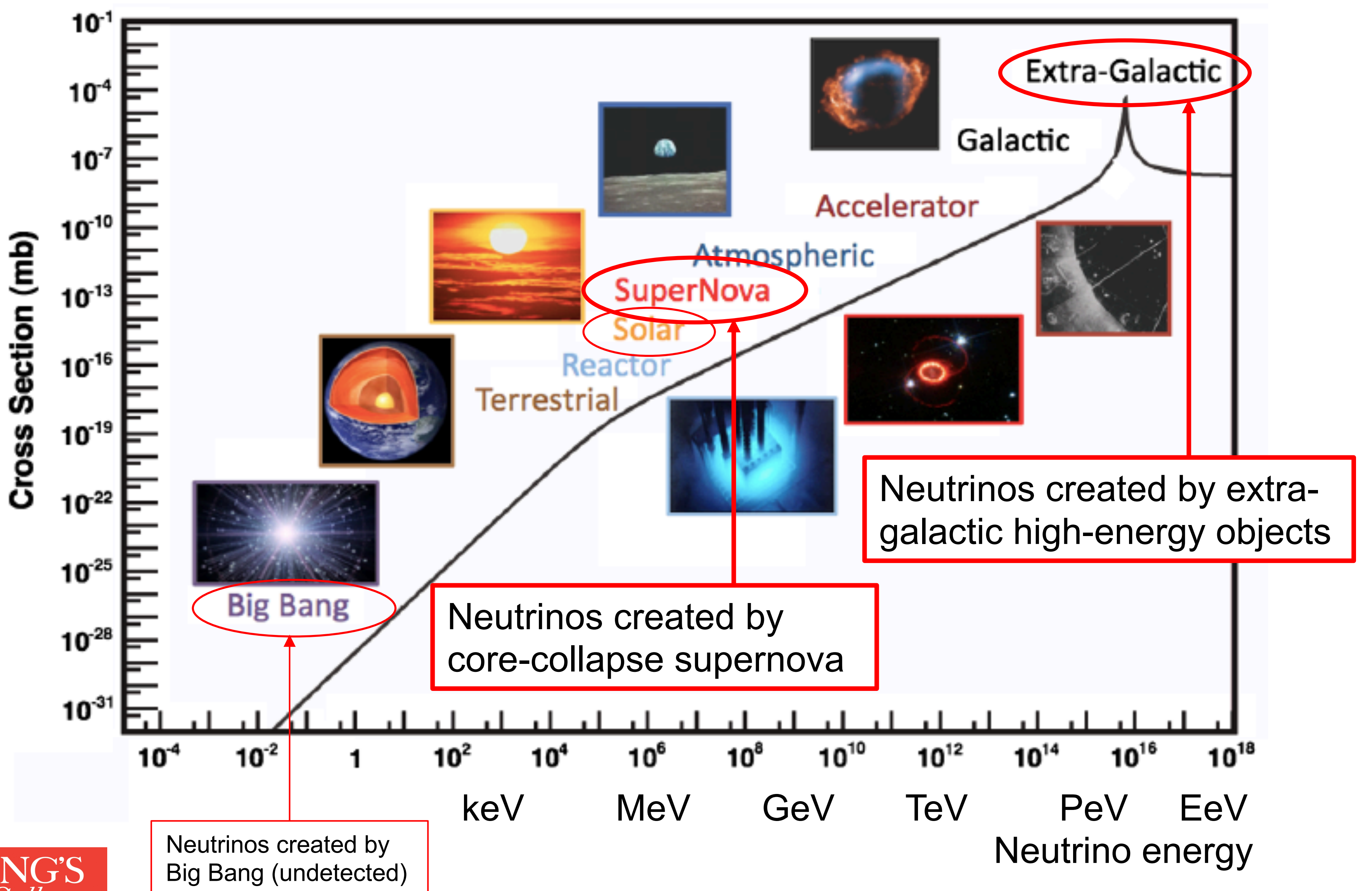
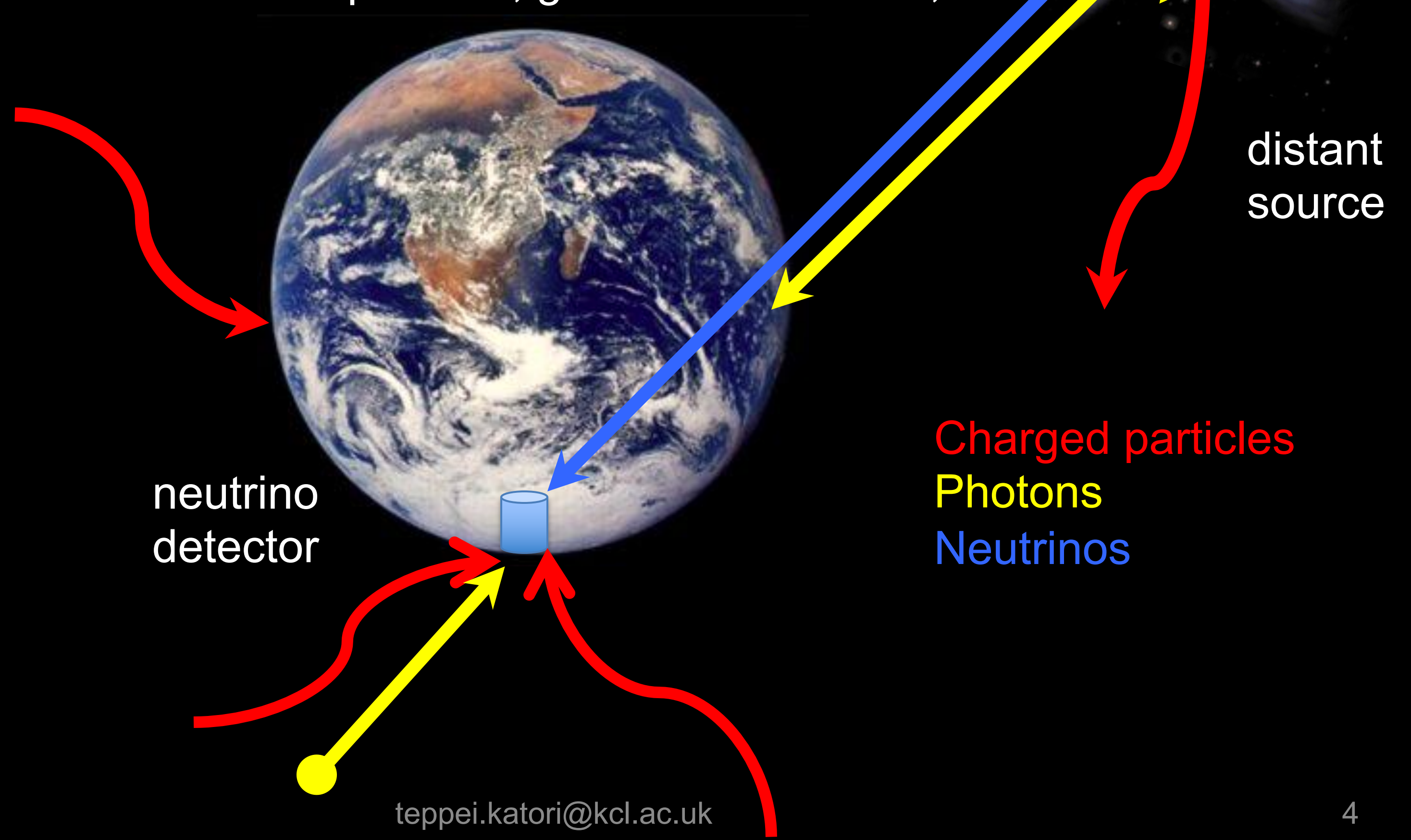


Neutrino Astronomy

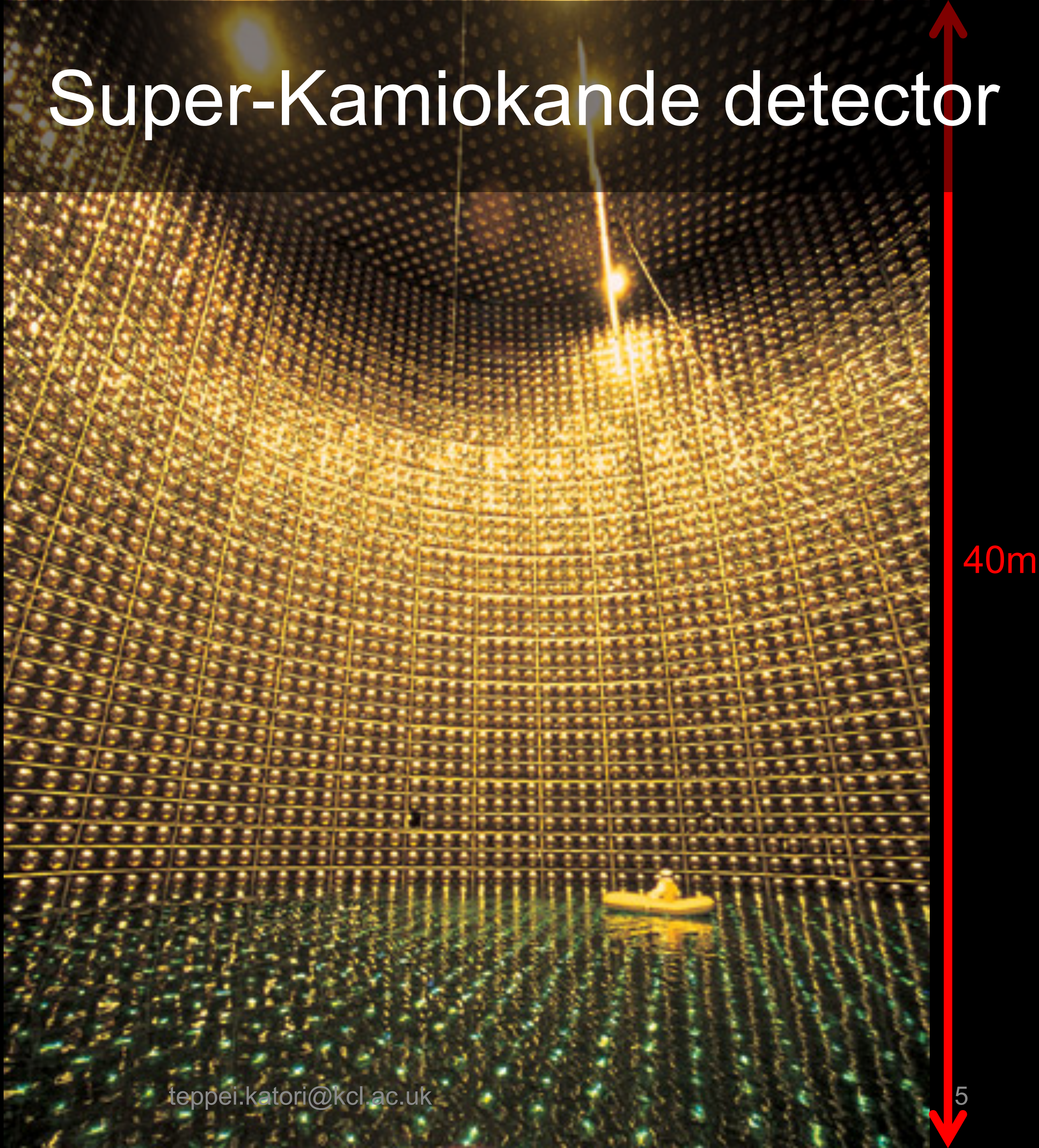
Direct messengers from the furthest celestial objects
- Neutrinos are neutral and interact only with weak force

Multi-messenger astronomy
- simultaneous observation of photons, gravitational waves, and neutrinos



Super-Kamiokande detector

40m height, 40m wide, 50k ton of pure water to observe neutrinos



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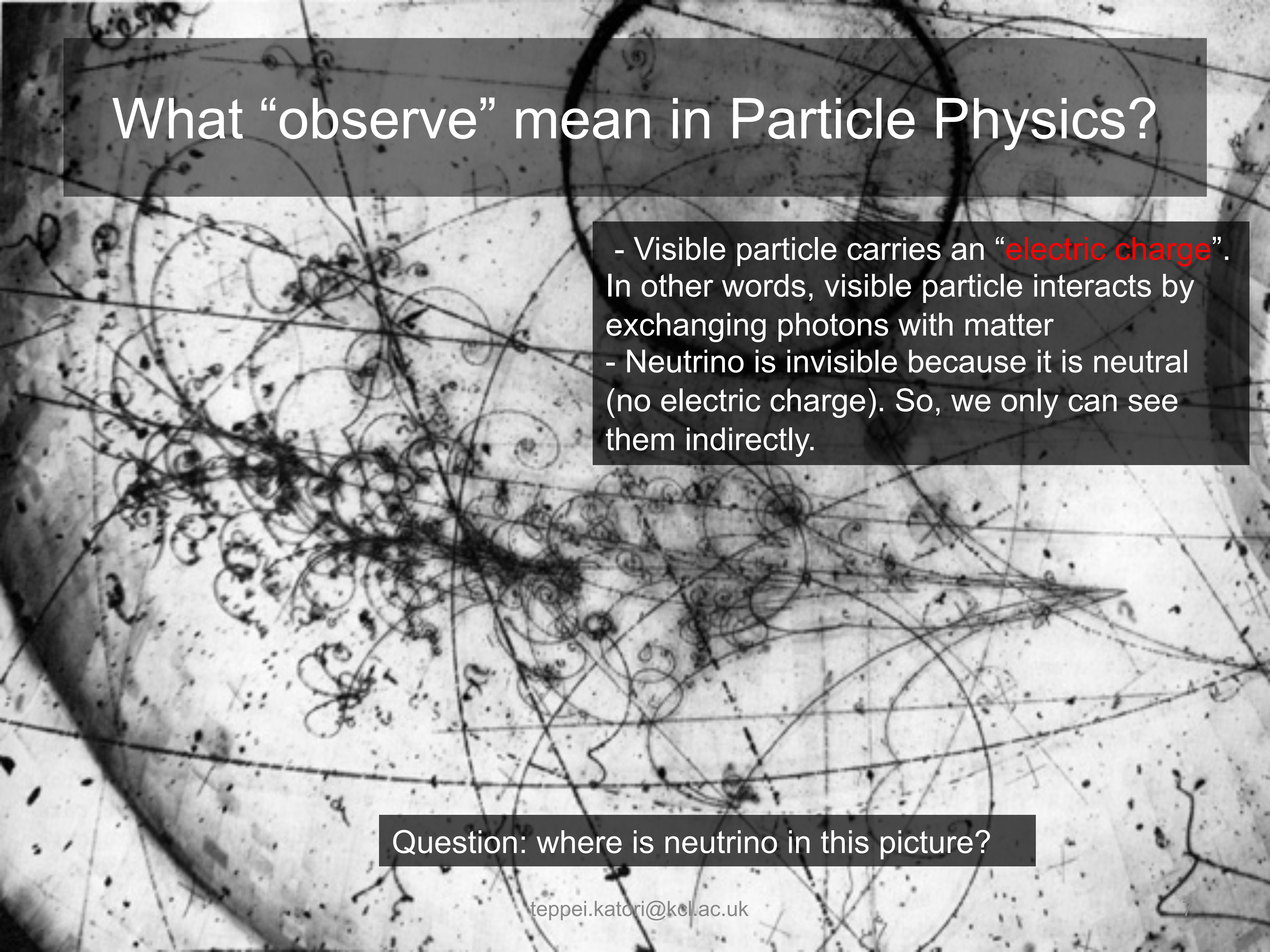
What “observe” mean in Particle Physics?

Bubble Chamber detector

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

What “observe” mean in Particle Physics?



- 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?

What "observe" mean in Particle Physics?

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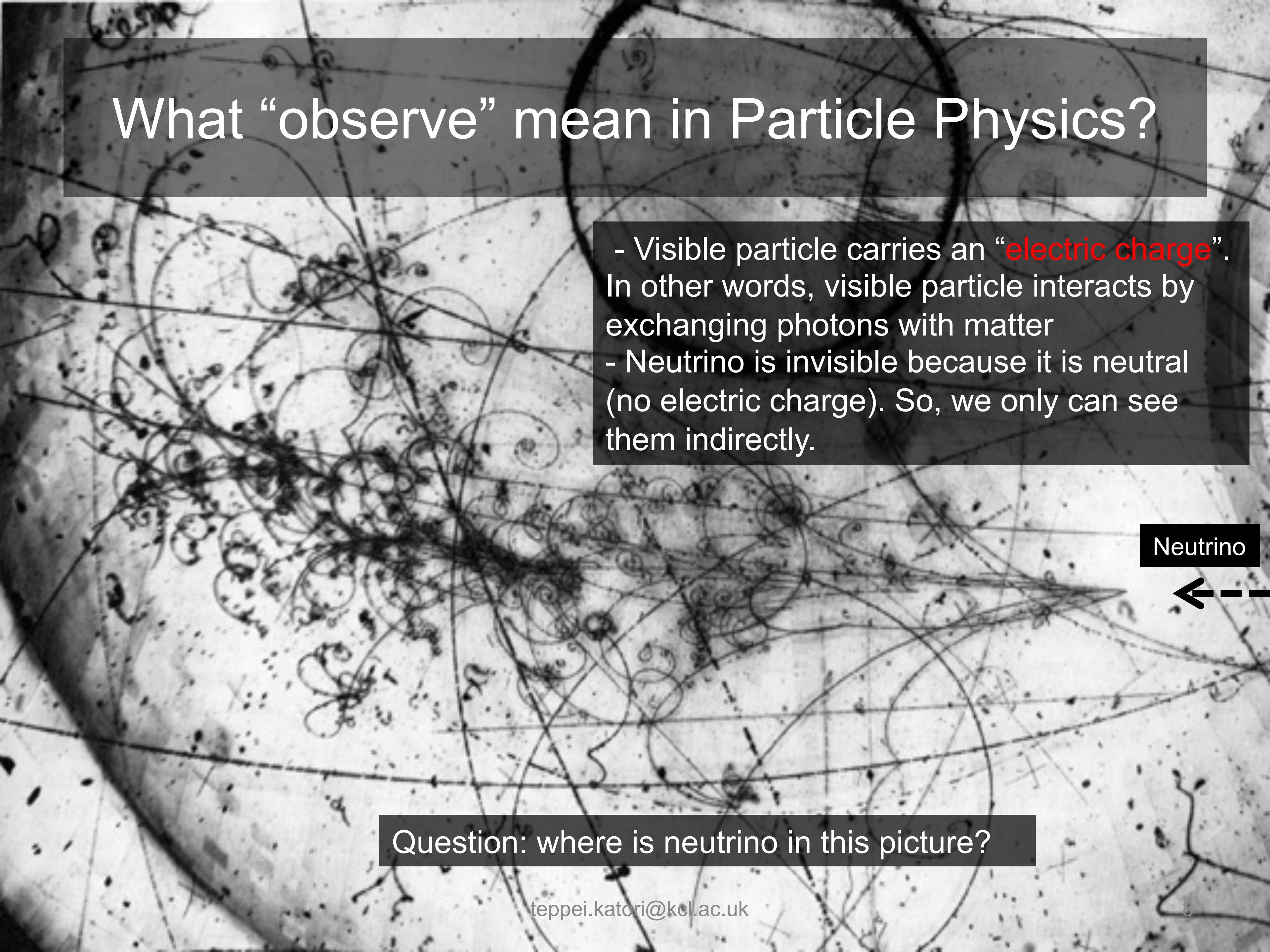
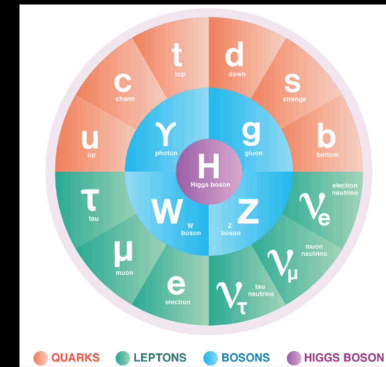
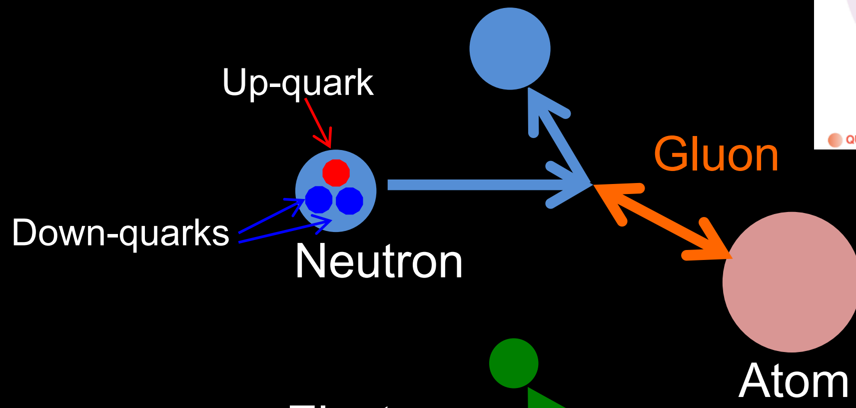


Question: where is neutrino in this picture?

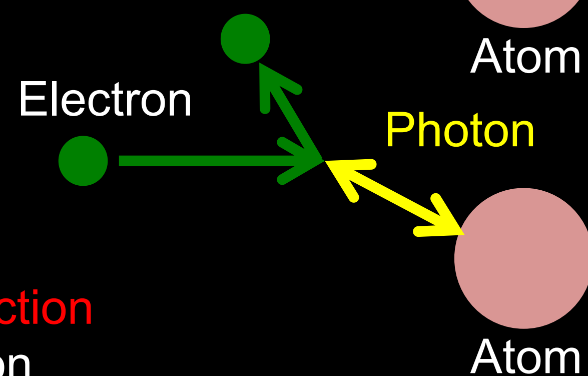
Neutrino Interactions



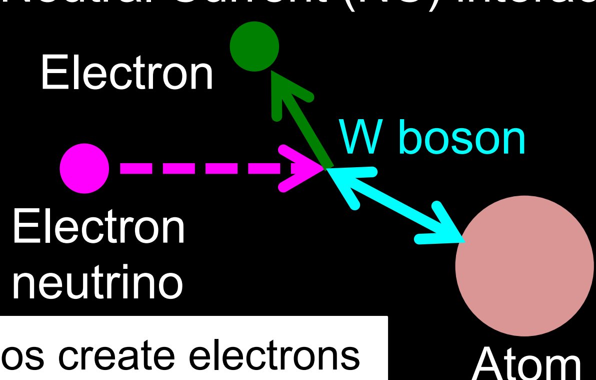
Quarks exchange
- Gluons, or
- Photons, or
  - W and Z bosons

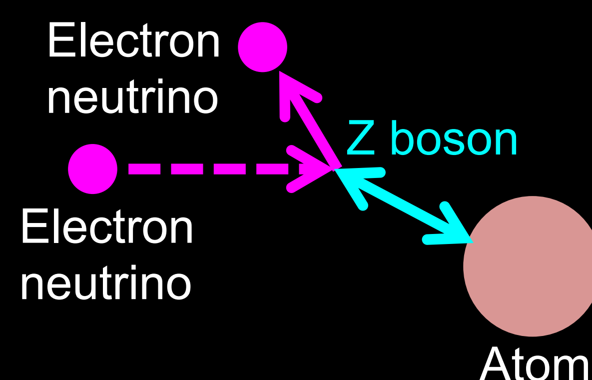


Charged leptons exchange
- Photons, or
- W and Z bosons



Neutrinos exchange
- W boson: Charged-Current (CC) interaction
- Z boson: Neutral Current (NC) interaction

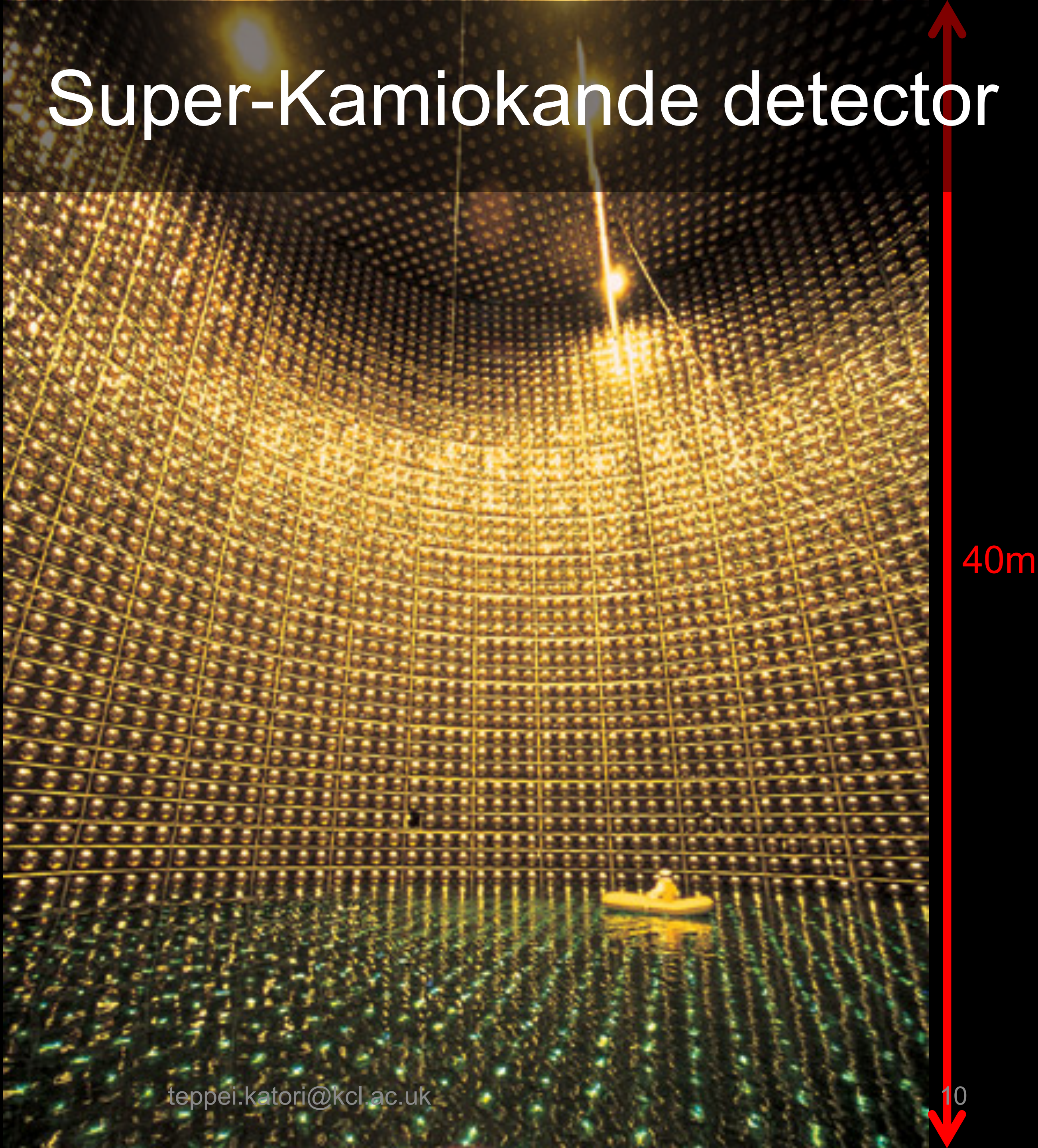




Electron neutrinos create electrons
Muon neutrinos create muons
Tau neutrinos create tauons

Super-Kamiokande detector

40m height, 40m wide, 50k ton of pure water to observe neutrinos



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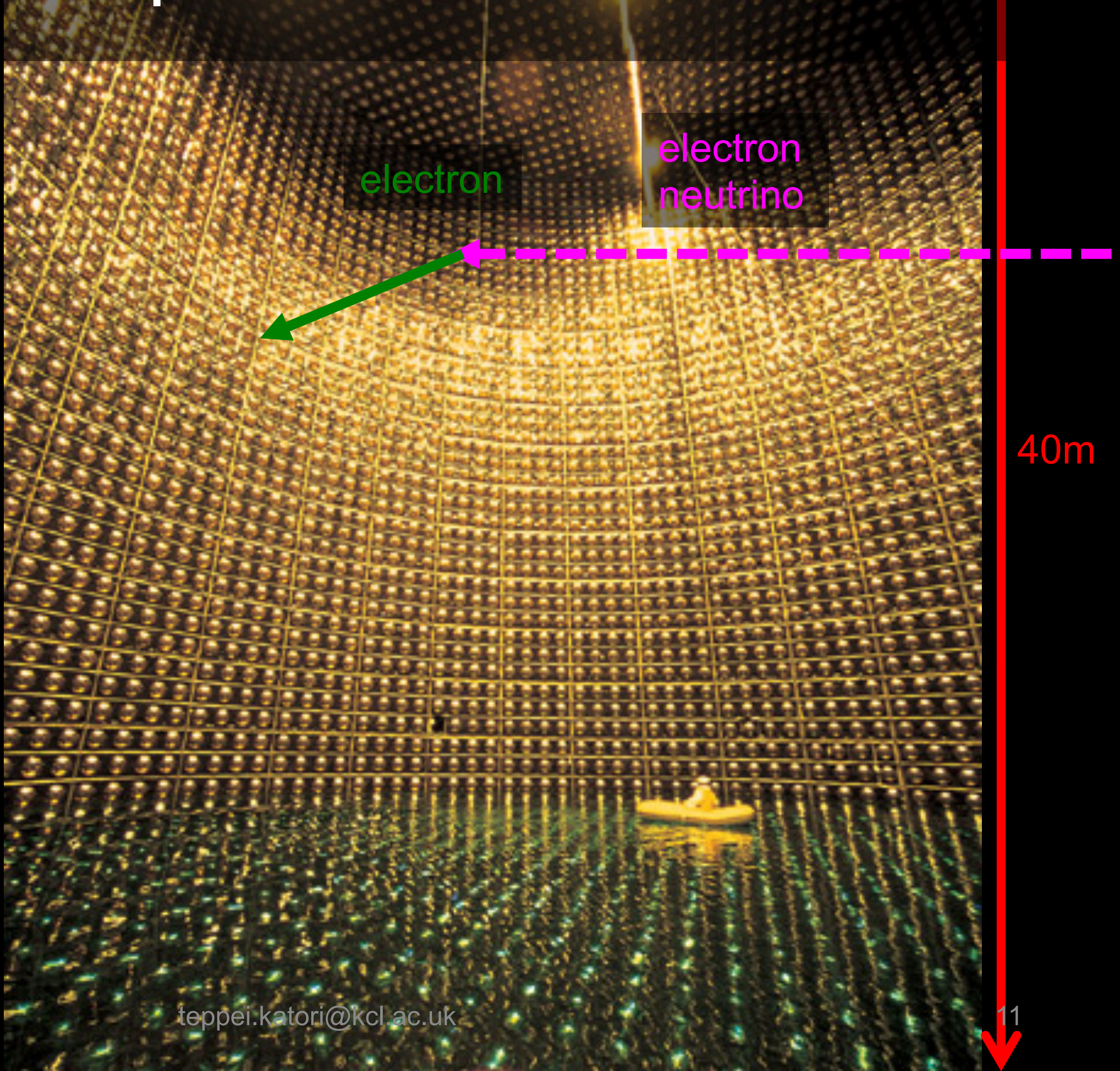
Super-Kamiokande detector

40m height, 40m wide, 50k ton of pure water to observe neutrinos

Neutrinos interact with water molecules, and produce charged leptons

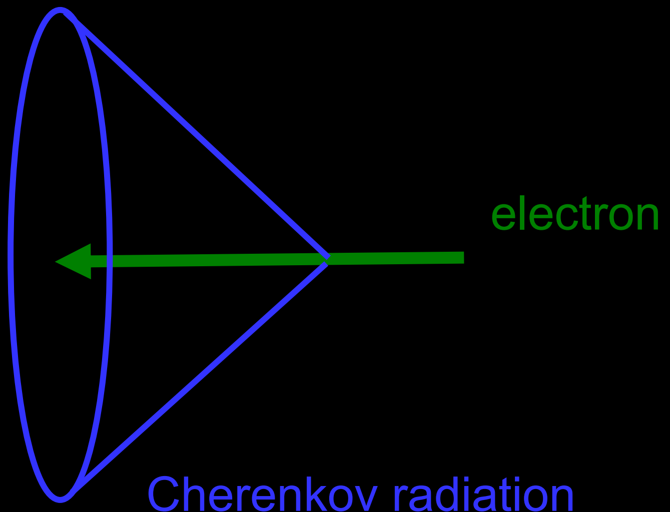


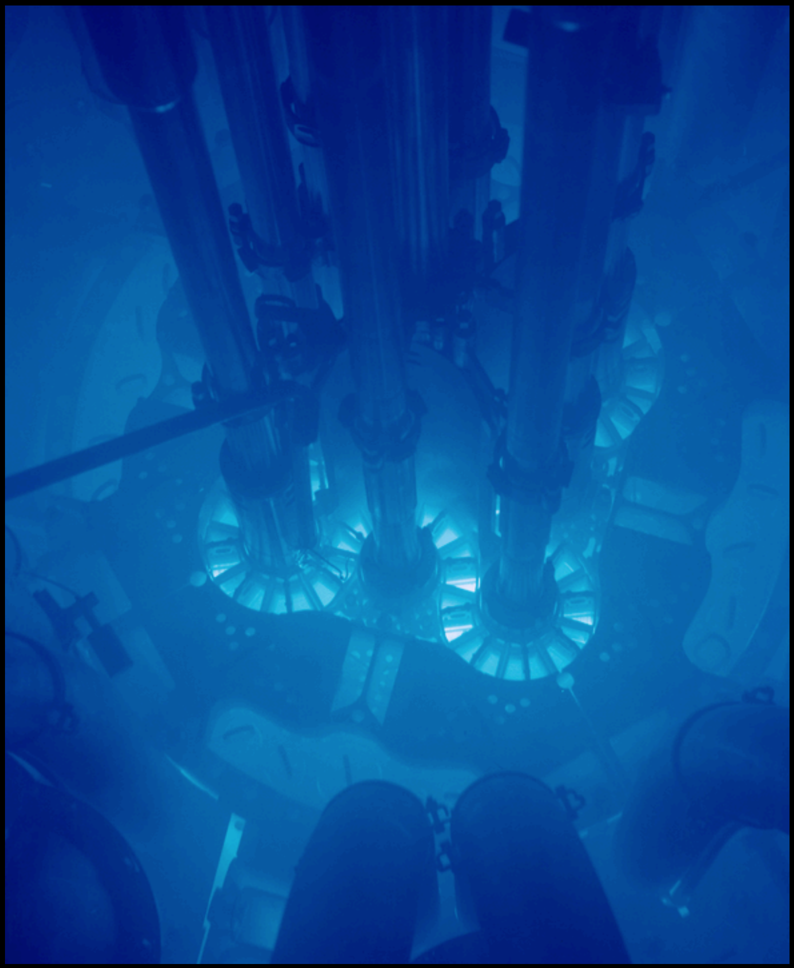
Cherenkov radiation

Speed of light is slower in media (=water), so high-energy charged particles need to emit radiations to slow down in media.

In fission nuclear reactors, blue light are Cherenkov radiations from electrons

The emission has characteristic cone shape (peak in blue spectrum in water)





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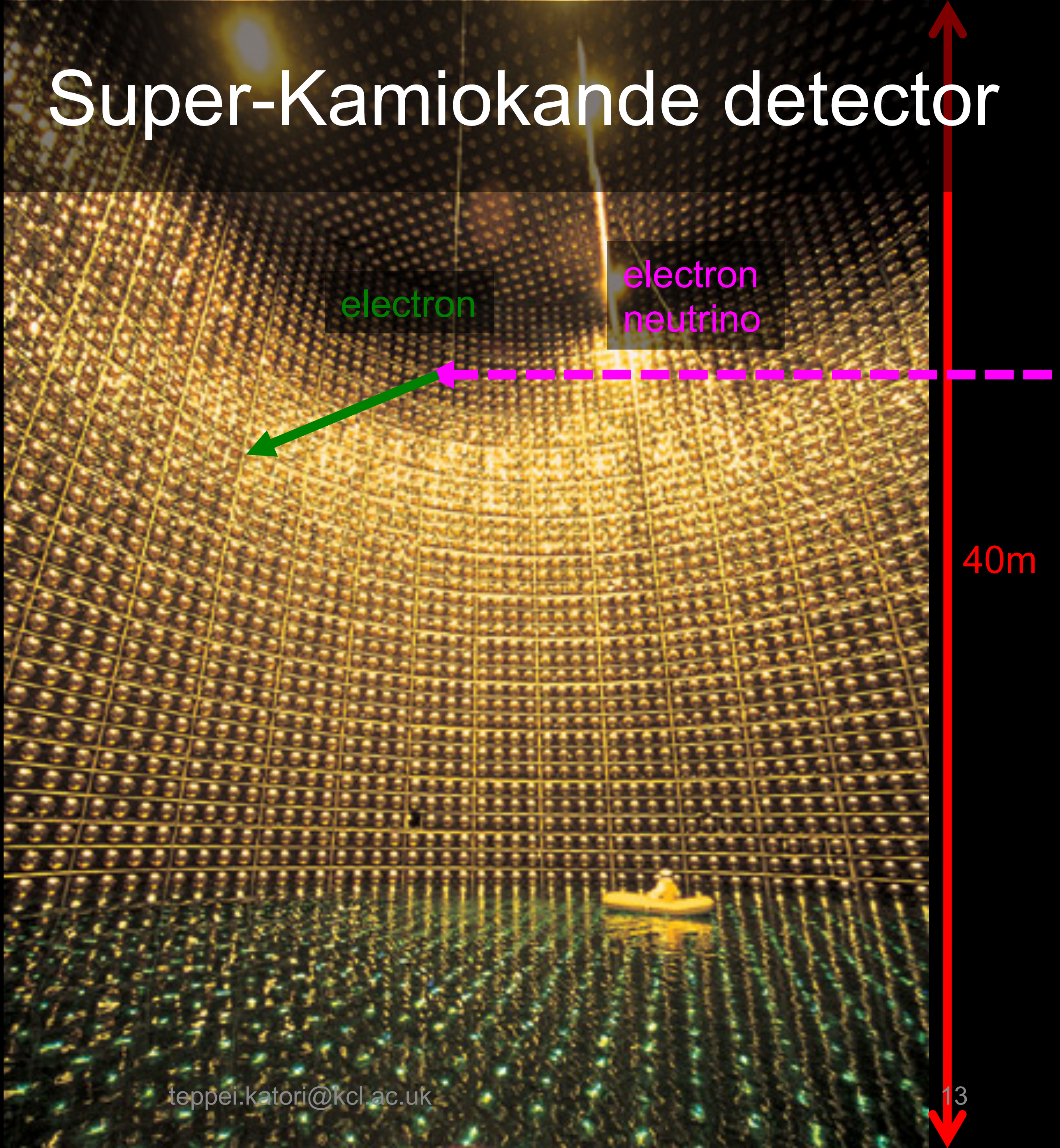

Super-Kamiokande detector

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Neutrinos interact with water molecules, and produce charged leptons

Charged leptons produce Cherenkov radiations

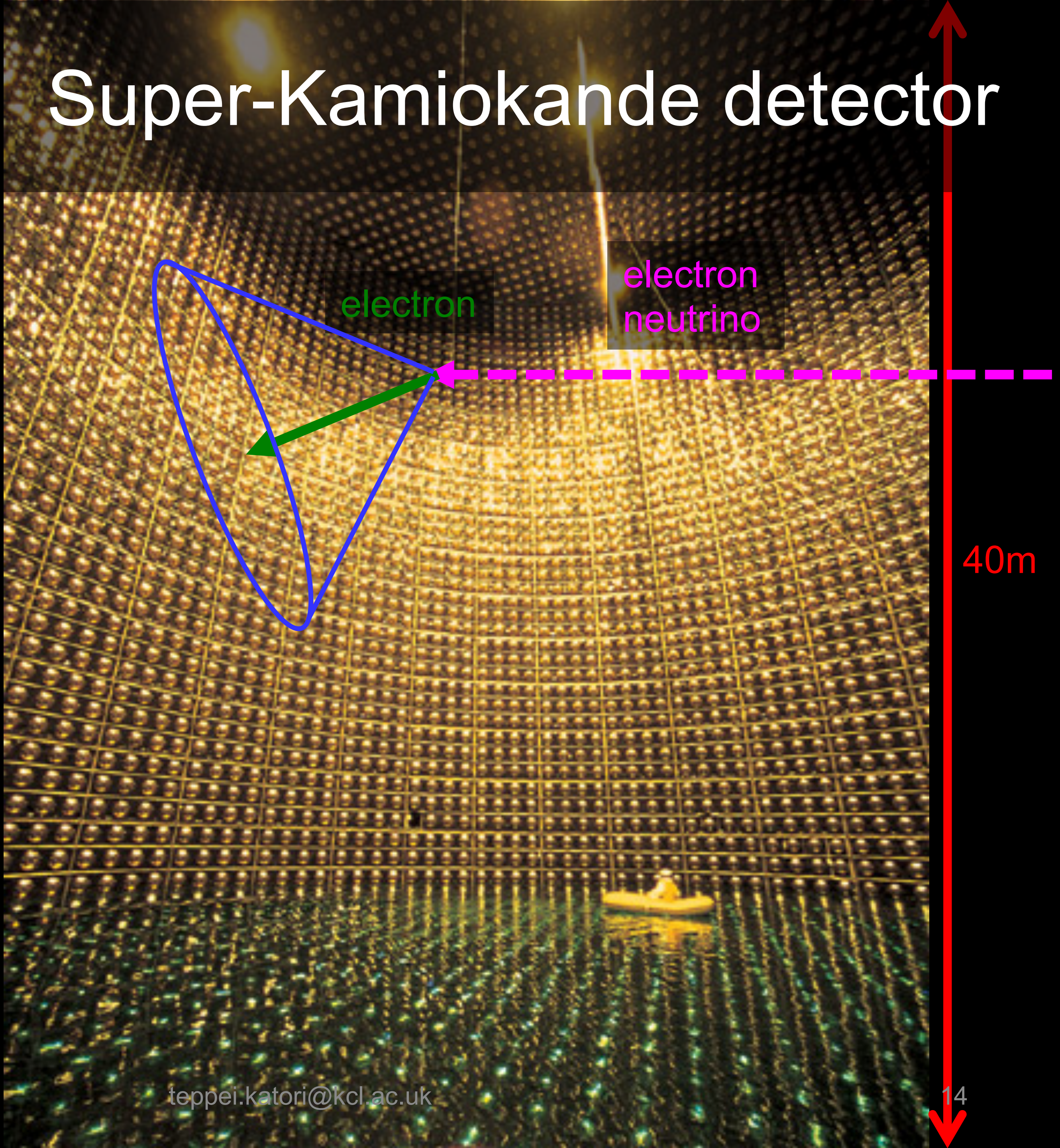


Photo-multiplier tubes (PMTs)

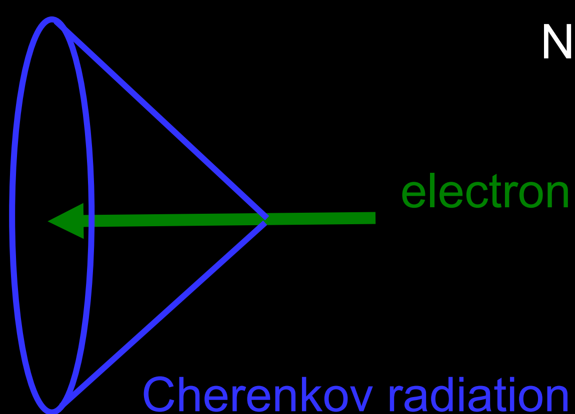
Charged particles make only several photons

Number of photons

10^{0} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} (/cm^{2})

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} (Lux)

Cherenkov radiation
from 1 charged lepton

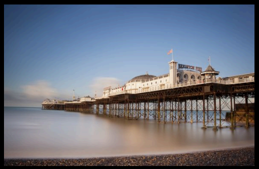


New moon

Full moon

Cloudy London

Desk lamp



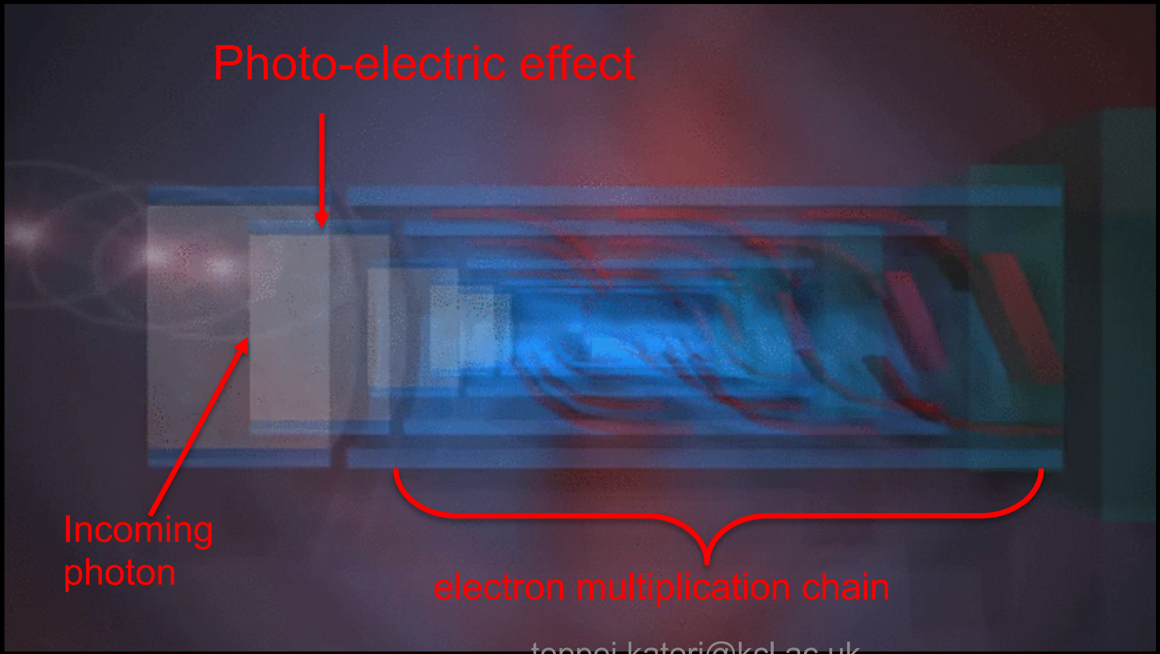
Sunny Brighton

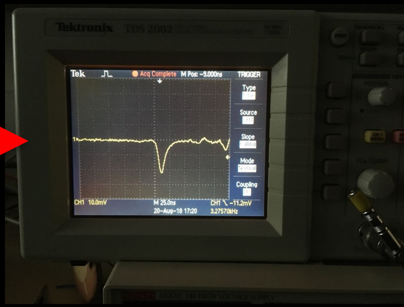
Photo-multiplier tubes (PMTs)

Charged particles make only several photons

Photo-multiplier tube converts photons to electrons by photo-electric effect

High-voltage accelerates electrons to collide on metallic place to release more electrons. This process repeats, and produce ~10^7 electrons from a photon, and strong electric pulse is produced and observed





Electric pulse (signal)

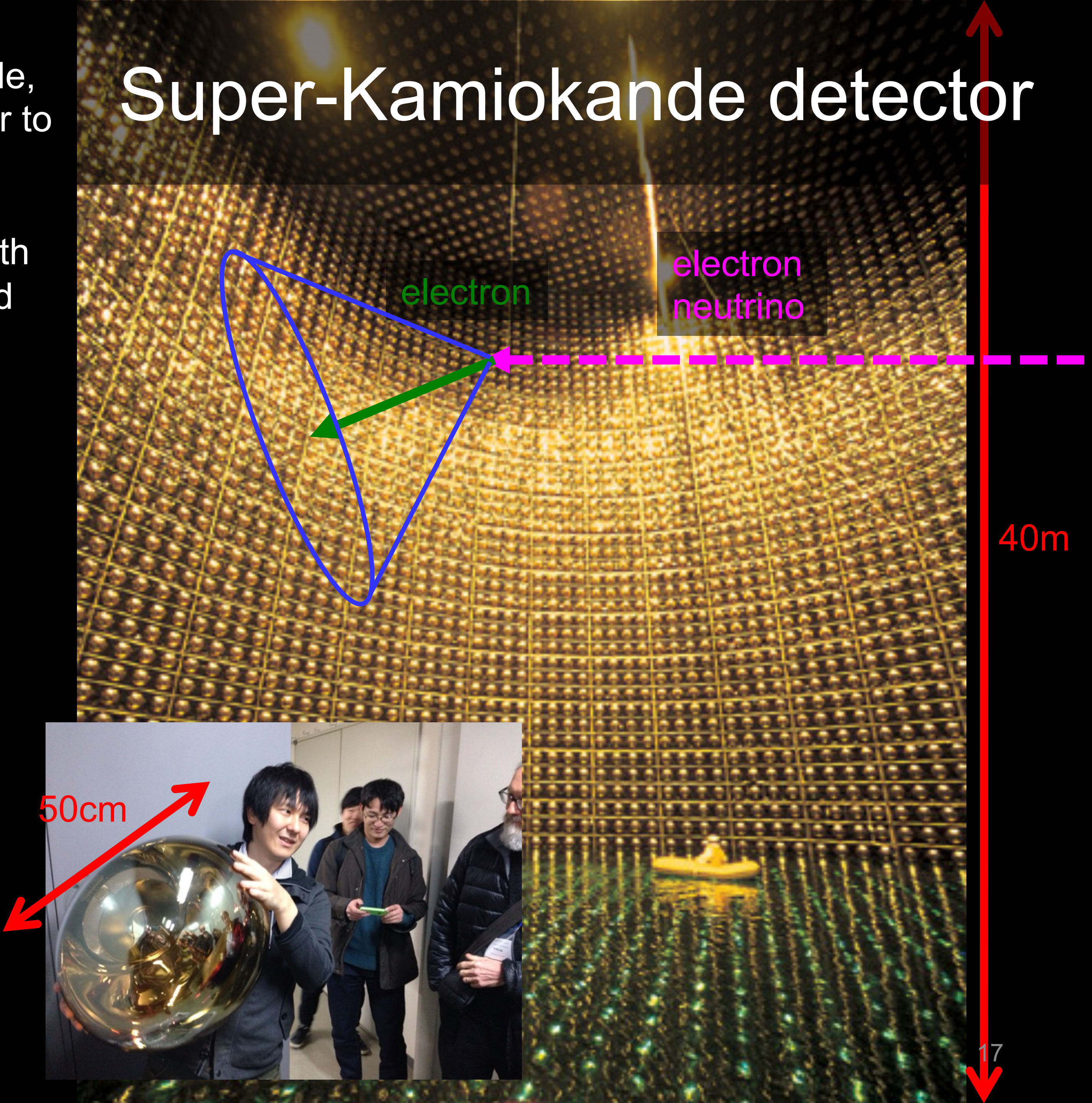
Super-Kamiokande detector

40m height, 40m wide, 50k ton of pure water to observe neutrinos

Neutrinos interact with water molecules, and produce charged leptons

Charged leptons produce Cherenkov radiations

11,000 of PMTs covered on the wall detect Cherenkov photons from Cherenkov radiation



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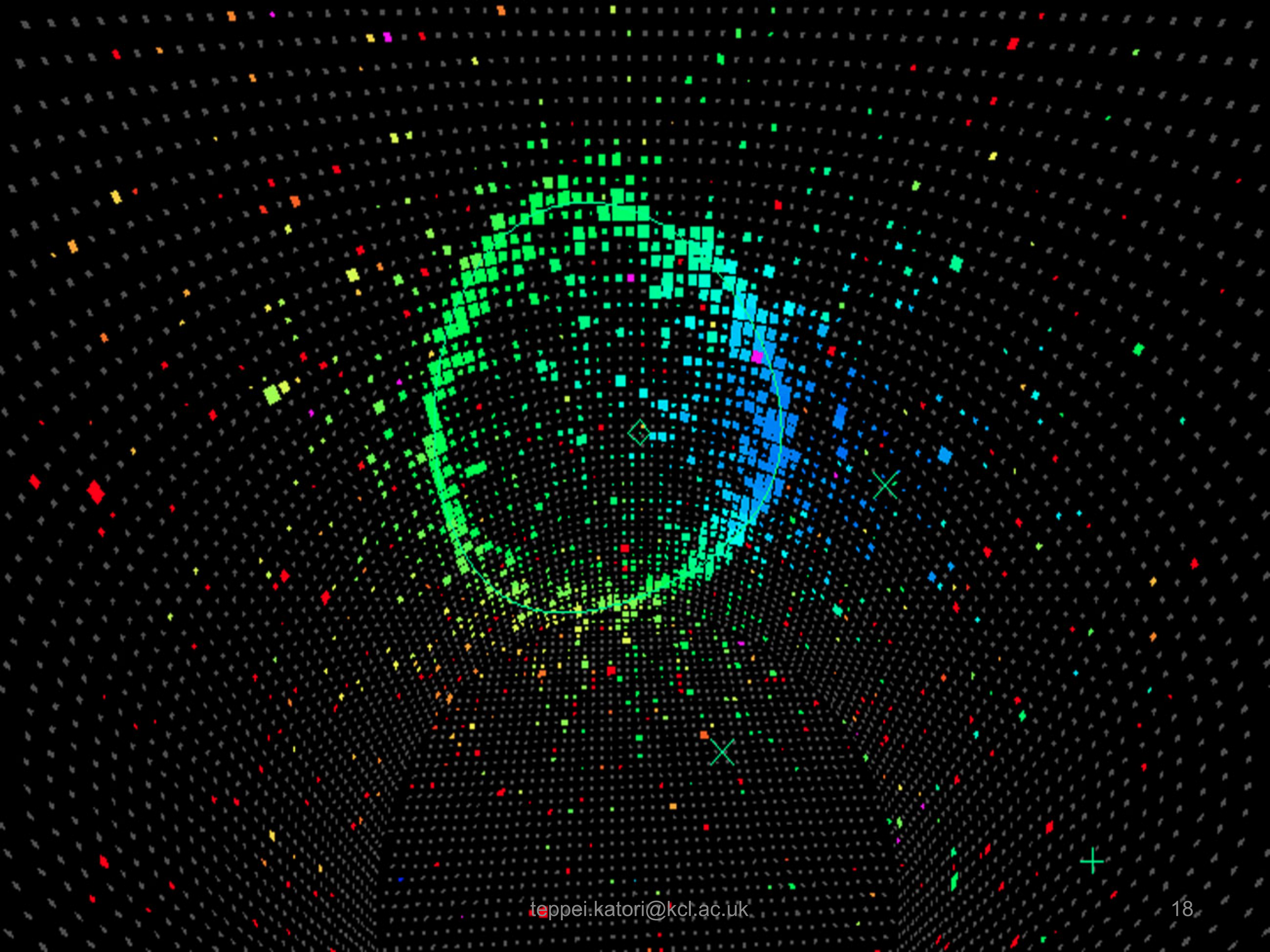


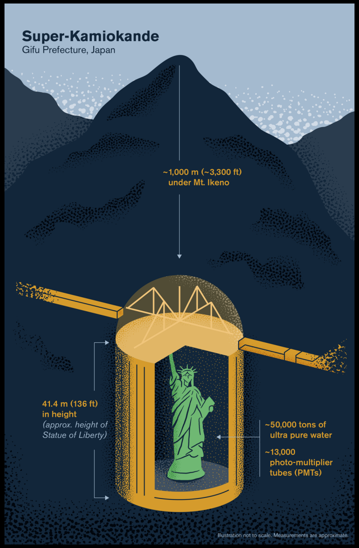
Particle Physics Experiment

Connect ladders of logics to reach the highest point

Super-Kamiokande detector

Kamioka (神岡),
Gifu prefecture (岐阜県),
Japan

Deep mountain area, and the detector is located in a former mine in the Ikenoyama mountain (池ノ山), roughly 1km from the mountain top



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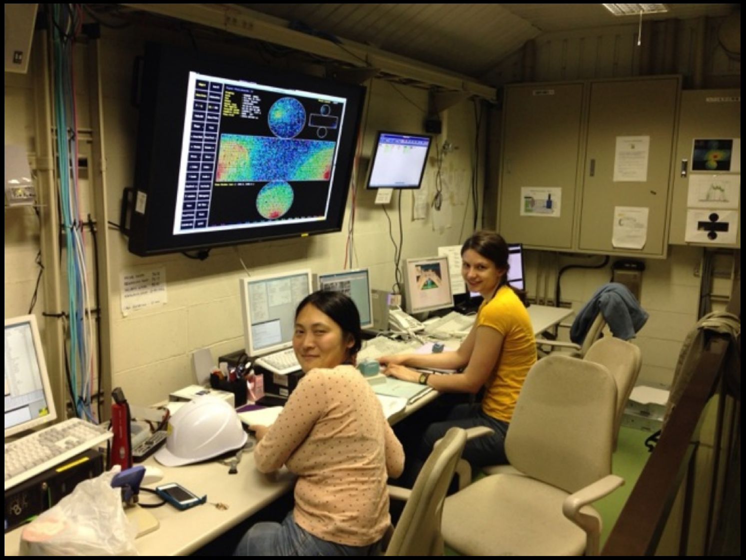
Super-Kamiokande detector



Super-Kamiokande real time monitor
http://www-sk.icrr.u-tokyo.ac.jp/realtimemonitor/

Super-Kamiokande detector refurbishment 2018

Supernova 1987A

Core-collapse supernova is very dense environment, and only neutrinos can escape efficiently (99% of energy is release by neutrinos)

To understand this mechanism, it is important to detect neutrinos from core-collapse supernova

Neutrinos from SN1987A were observed by Kamiokande (predecessor of Super-Kamiokande) and IMB detector

Super-Kamiokande is patiently waiting the next galactic core-collapse supernova and neutrinos from supernova...

Feb. 23, 1987

Now

SuperK OD PMT

Originally designed for the IMB detector, USA.

After the experiment was finished, they were removed and installed in the Super-Kamiokande as outer-detector (OD) PMTs to reject cosmic ray background.

During 2018 refurbishment, several broken OD PMTs were replaced. We brought back it to London and fixed it.

IMB detector (1981)

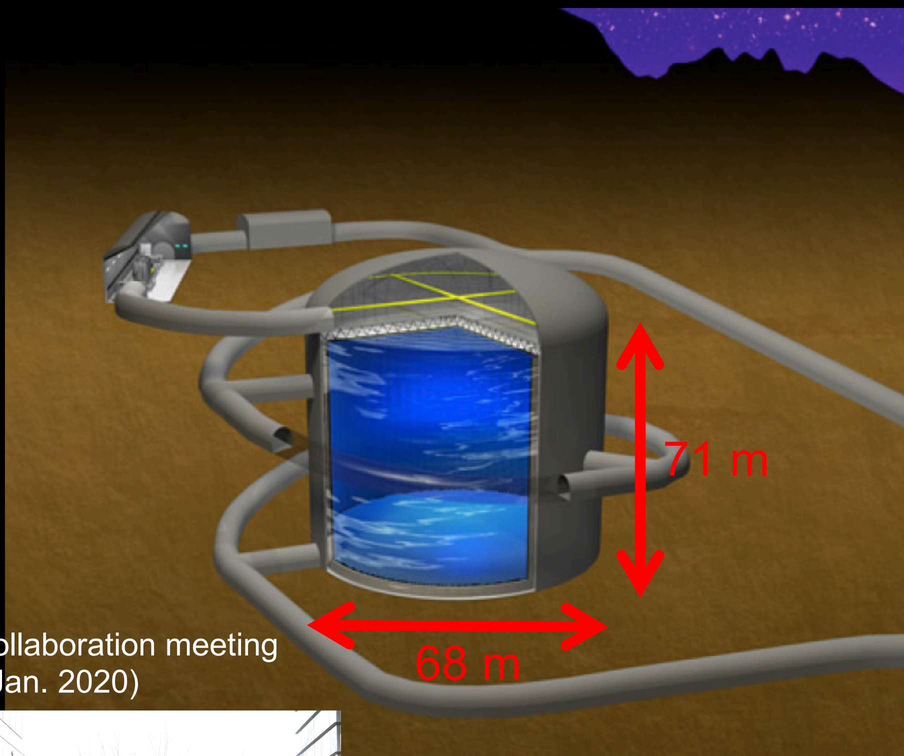
Super-Kamiokande (2018)

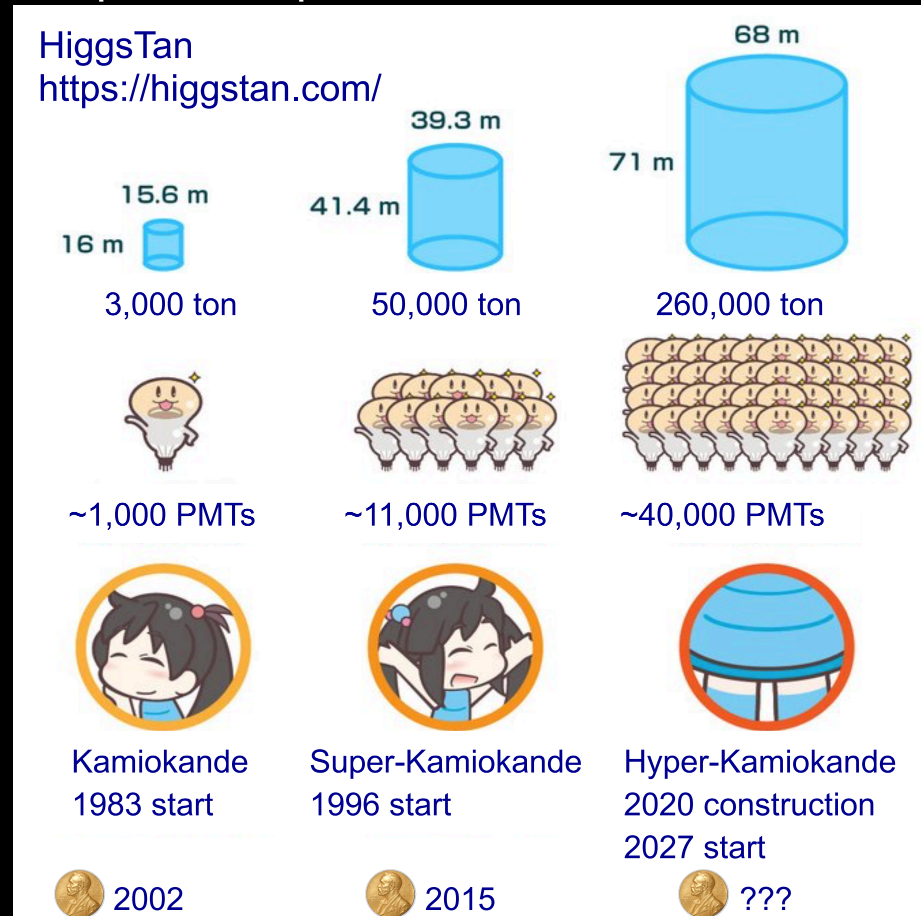
20cm

King's Lab (2021)

Hyper-Kamiokande detector

We are building a new 260 kton water tank
- More data to investigate the origin of matter and universe
- It detects neutrinos from the Sun, atmosphere, supernova, etc

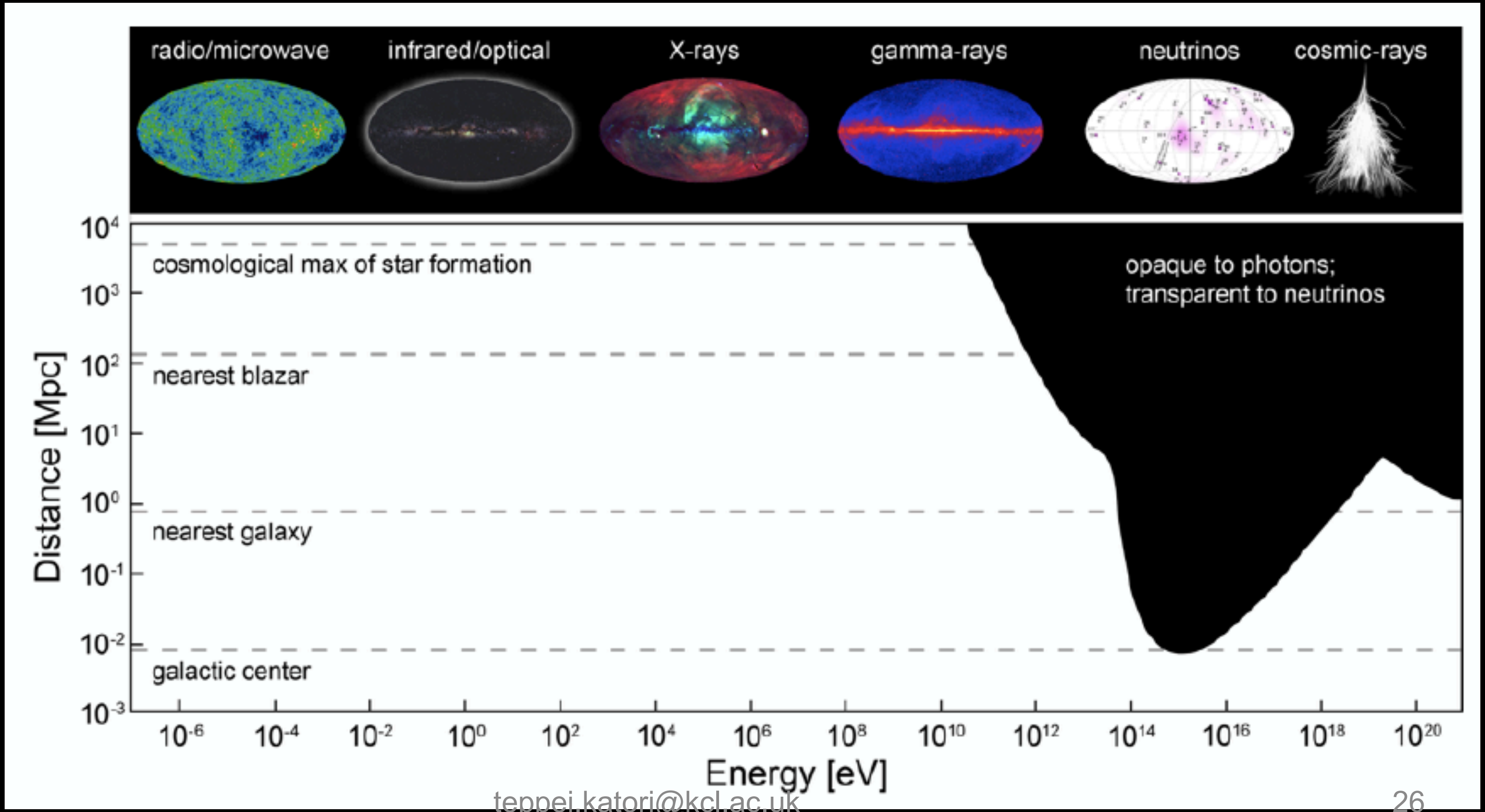




Collaboration meeting
(Jan. 2020)

Extra-galactic high-energy neutrinos

Beyond TeV range, neutrinos are only particles to escape extra-galactic high-energy objects, such as active galactic nuclei (AGNs)



Extra-galactic high-energy neutrinos

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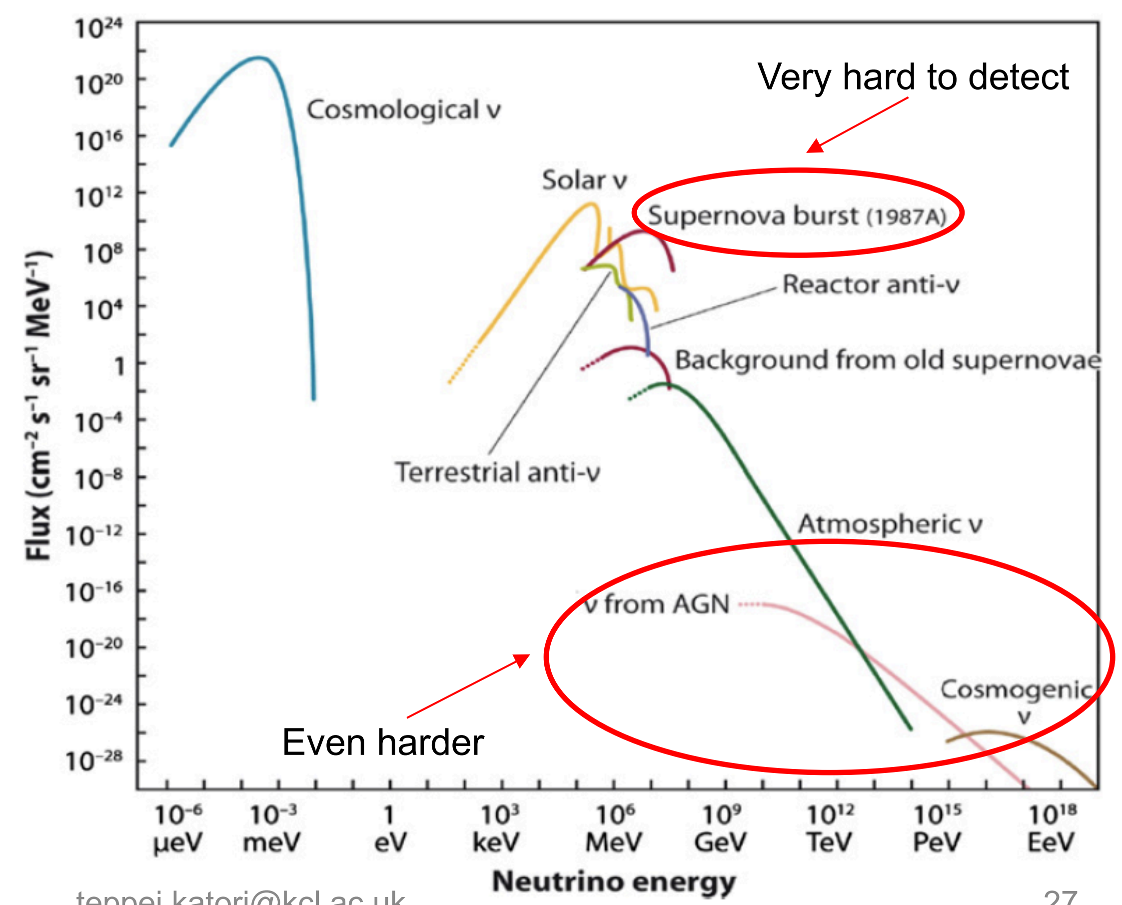
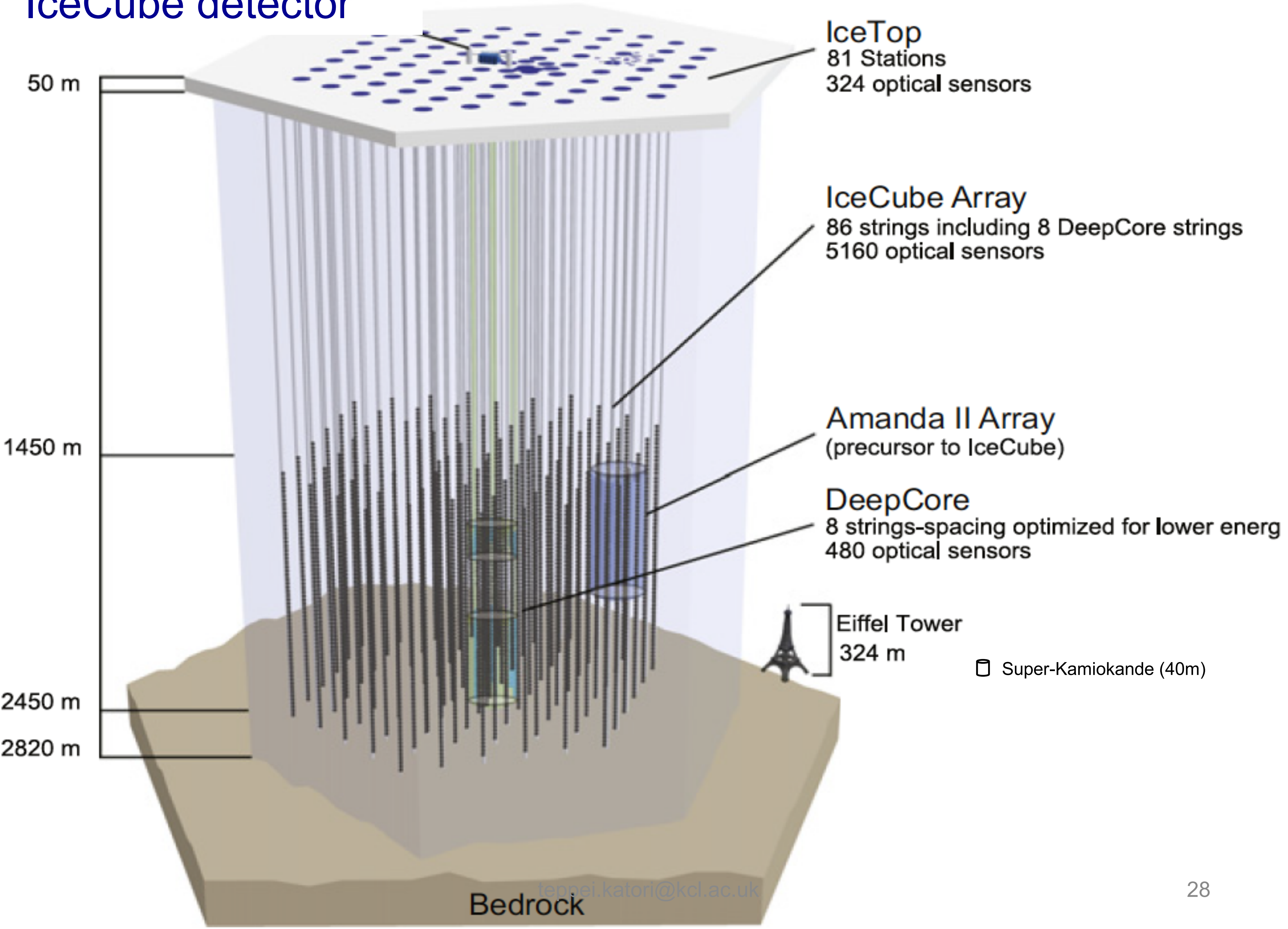
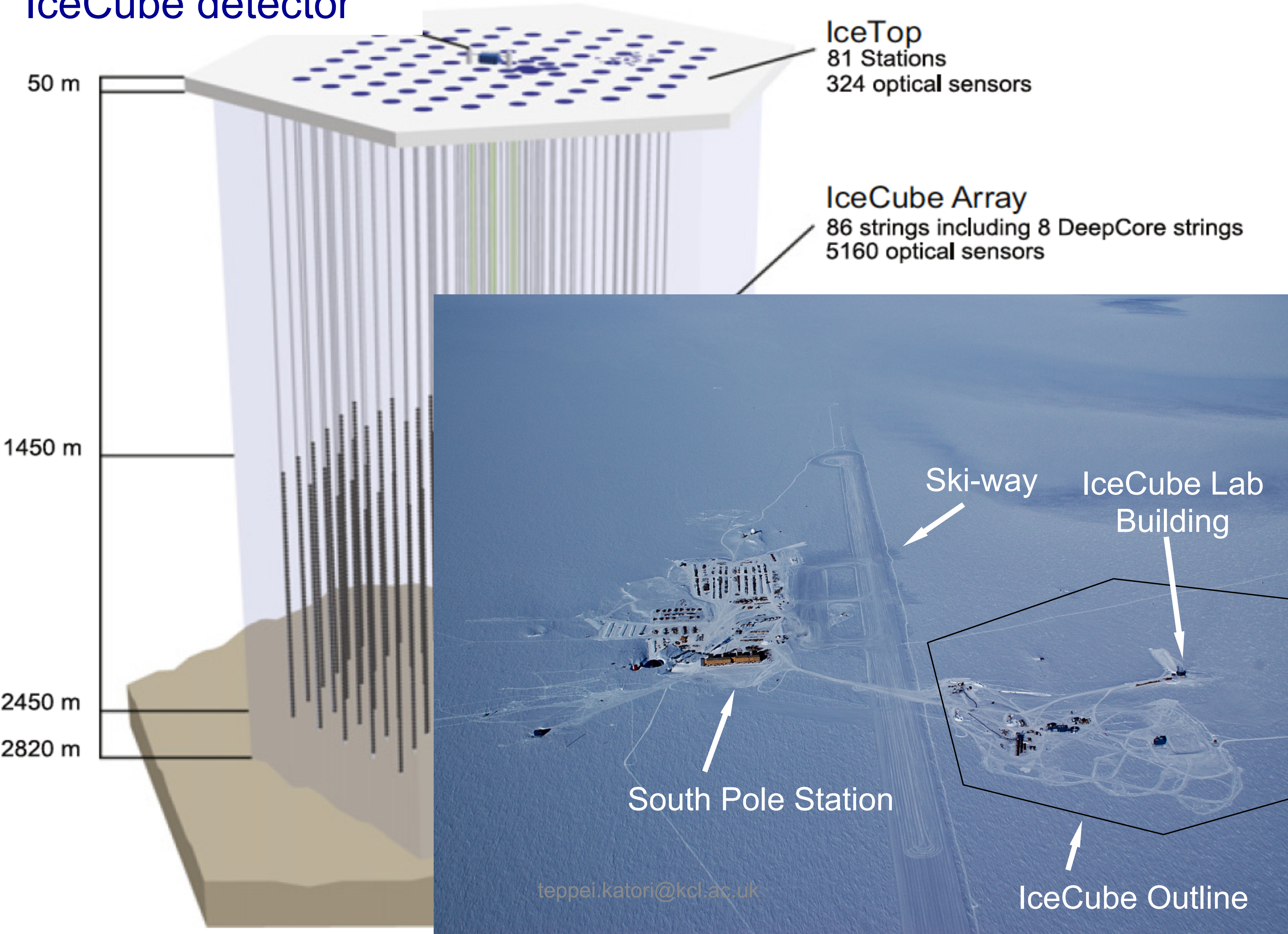
Problem: Flux of such neutrinos are so low, and you need order magnitude bigger detector to observe them



IceCube detector

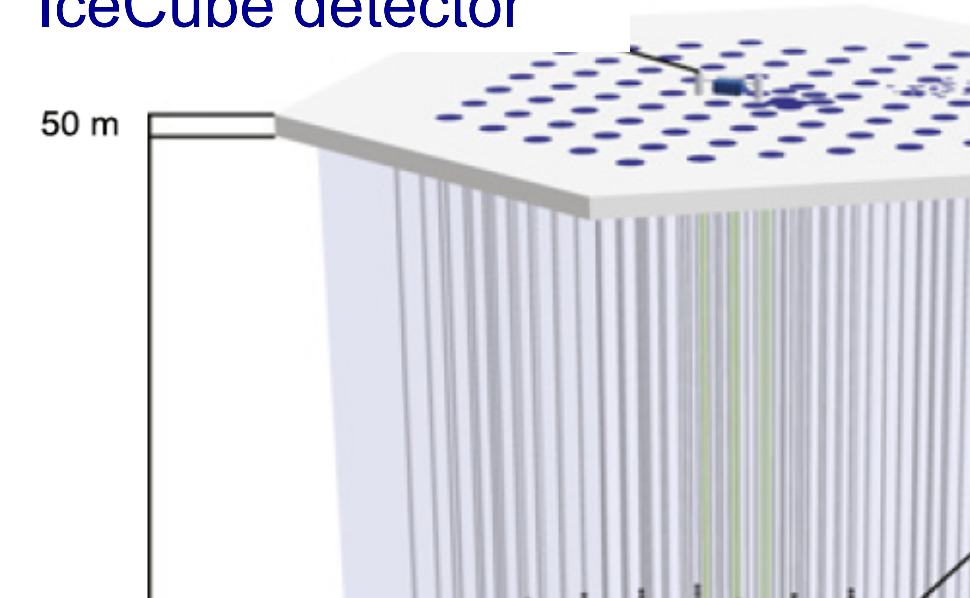


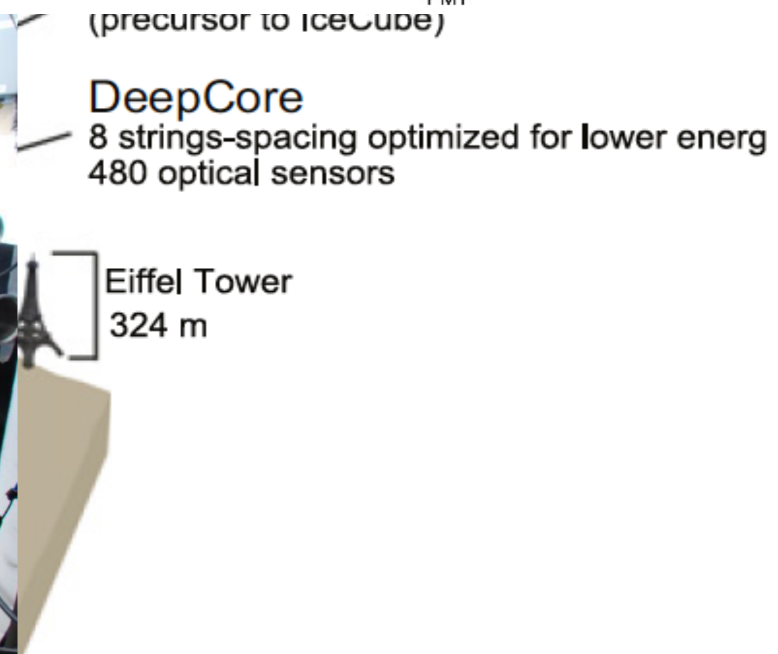
IceCube detector



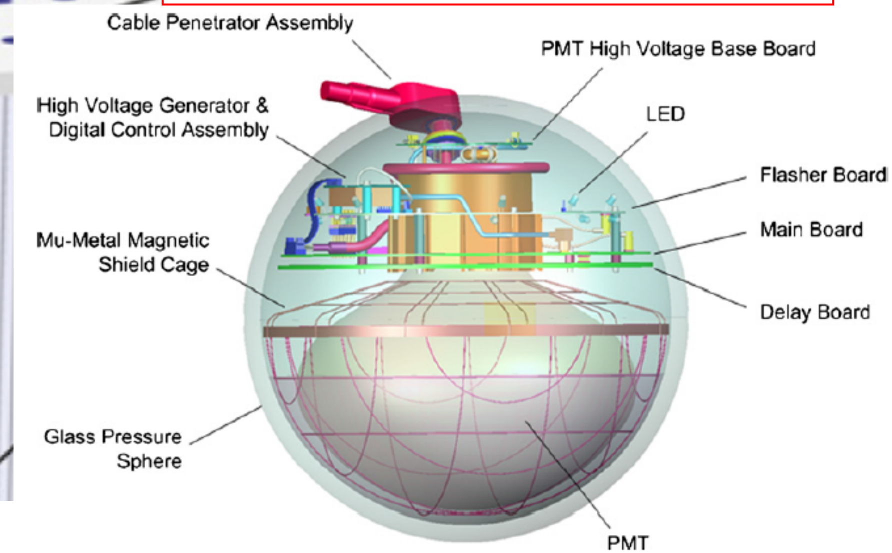
teppei.katori@kcl.ac.uk

IceCube detector

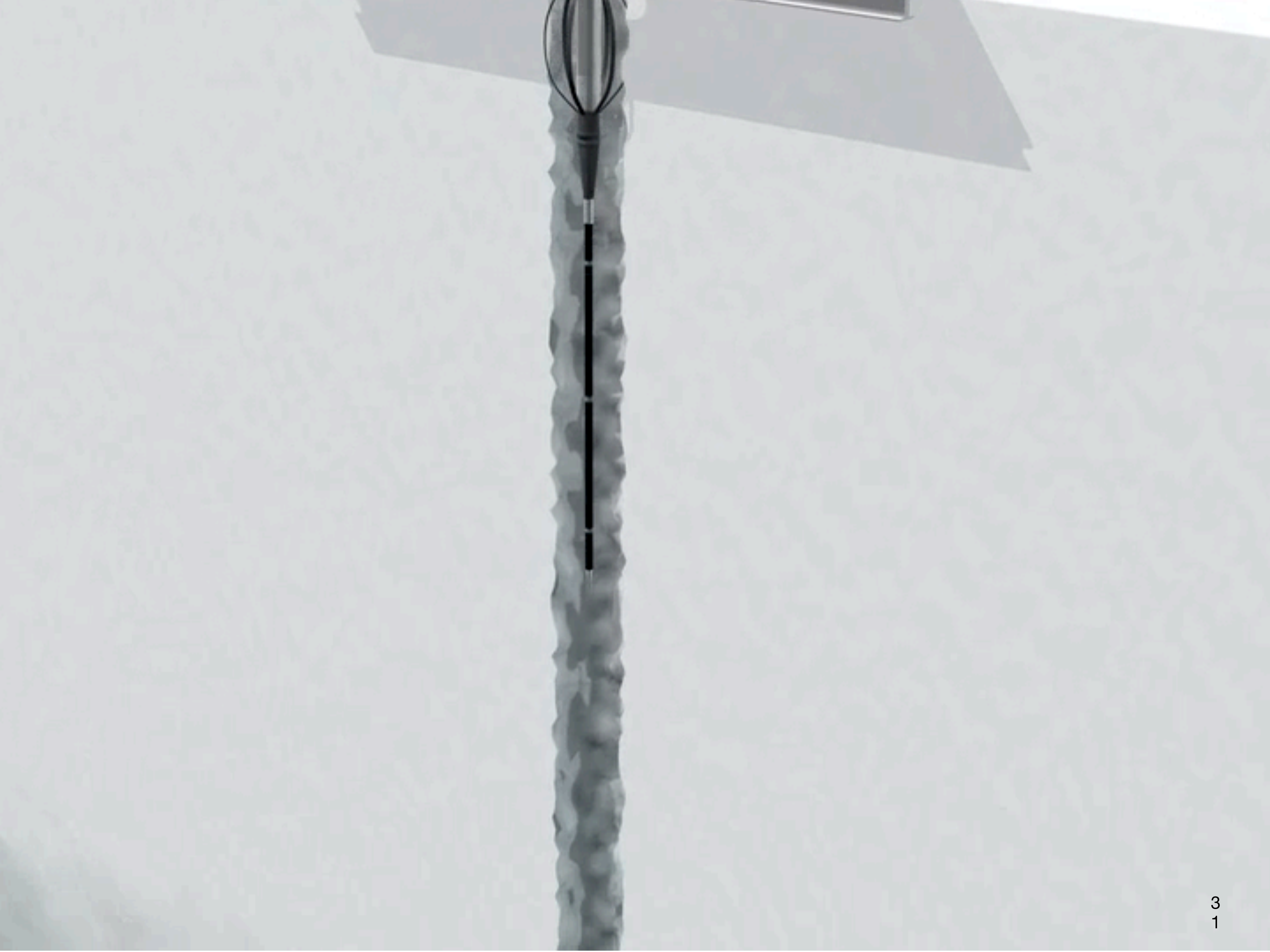


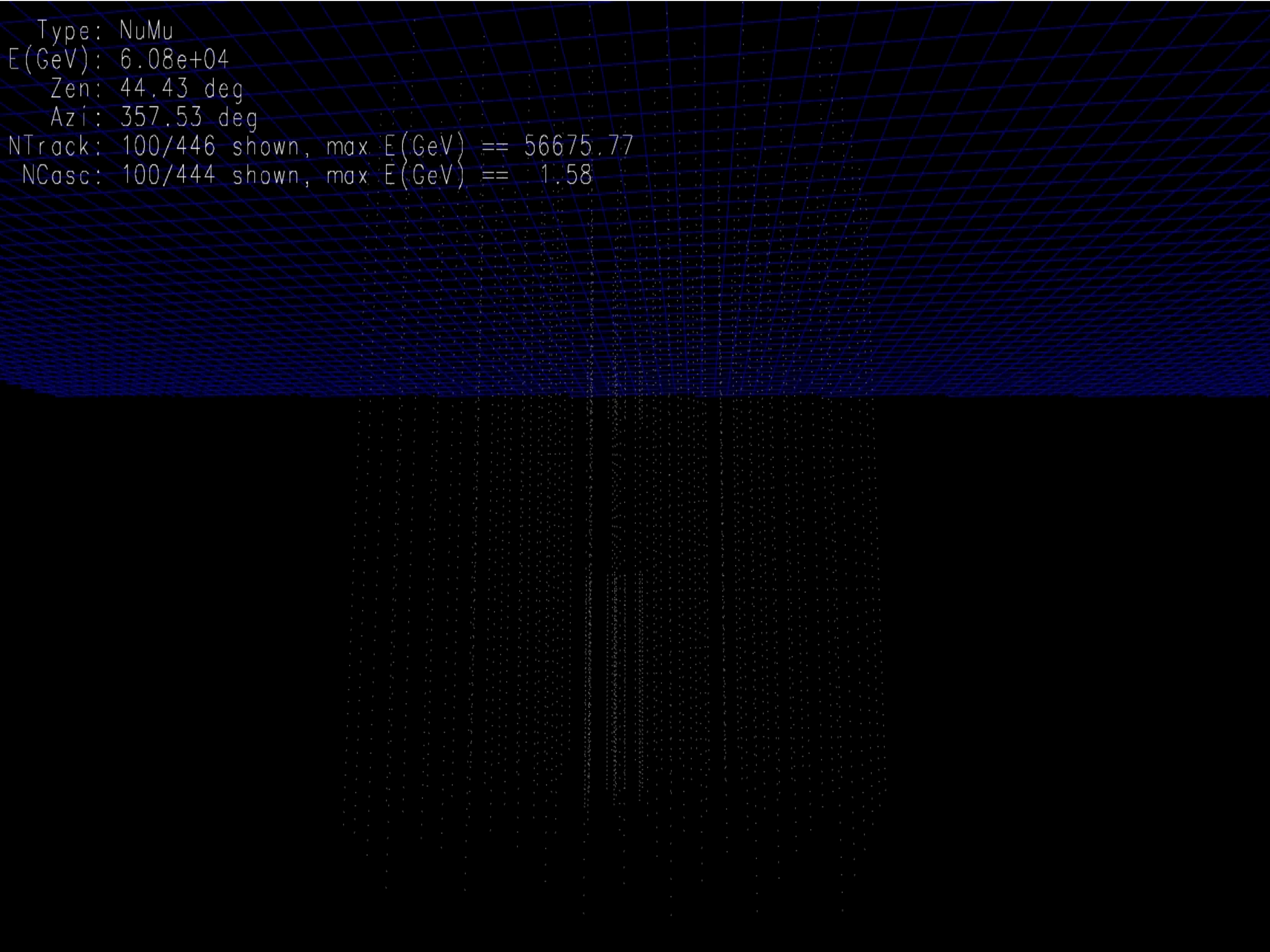


Digital Optical Module (DOM)



optical sensor deployment



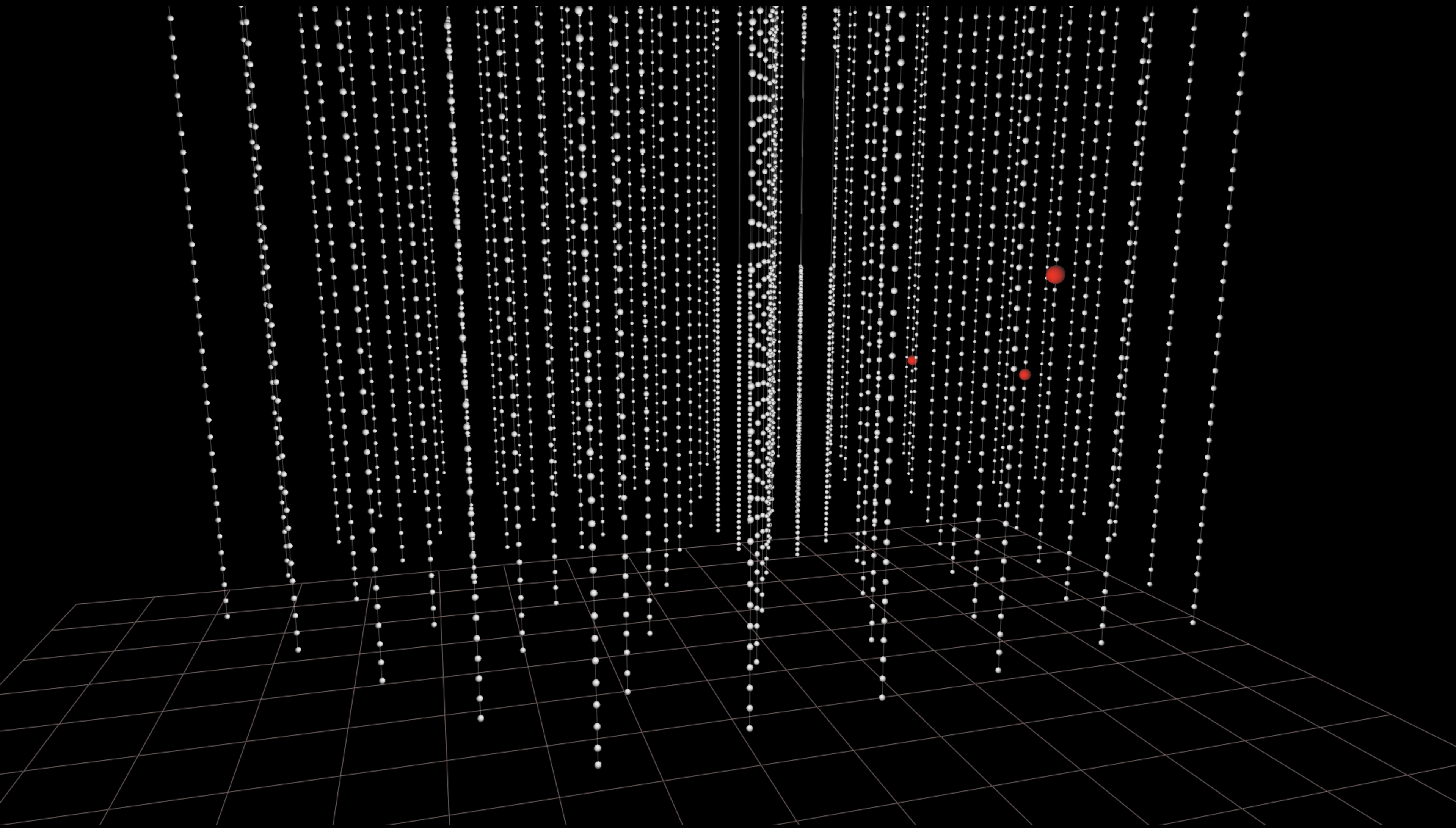

Type: NuMu
E(GeV): 6.08e+04
Zen: 44.43 deg
Azi: 357.53 deg
NTrack: 100/446 shown, max E(GeV) == 56675.77
NCasc: 100/444 shown, max E(GeV) == 1.58

Digital Optical Module (DOM)

25cm PMT in a 36cm borosilicate glass shell which sustains 70 MPa.

It has own electronics, including High-voltage generator, digitizer to process electric pulses and send digital signal, LED driver to test other DOMs.

IC170922, 290 TeV astrophysical neutrinos



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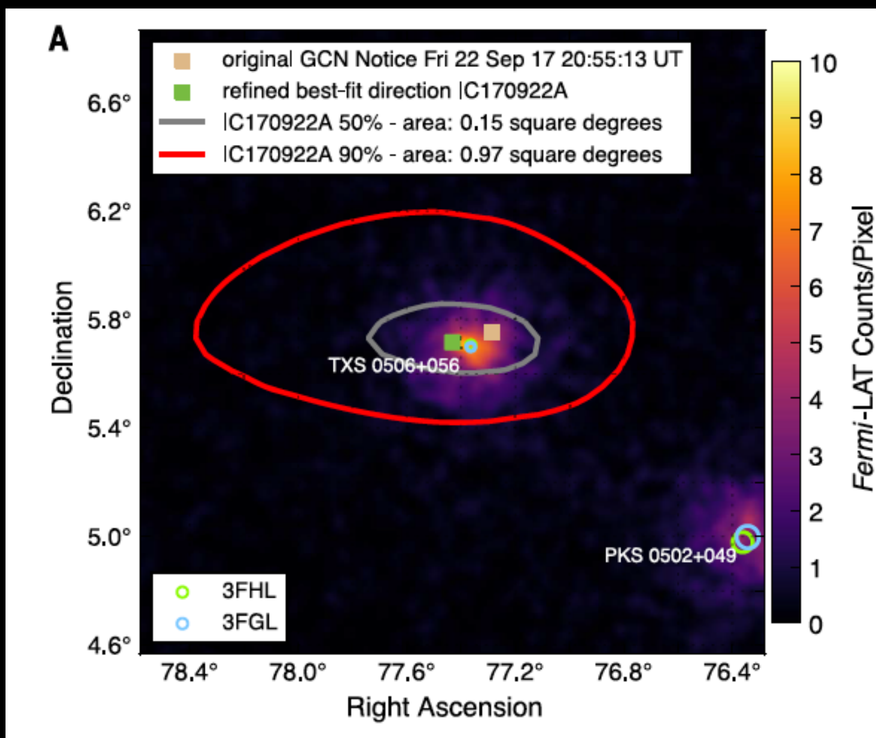
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

IC170922, 290 TeV astrophysical neutrinos

Within ~1min, public alert was distributed to observatories
- Fermi-LAT satellite found TXS0506+056 blazar was actively flaring
- MAGIC telescope found gamma ray flux from TXS0506+056

Redshift of blazar is ~0.3365 → ~4.6Glyr



The astronomer's telegram
http://www.astronomerstelegram.org/

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

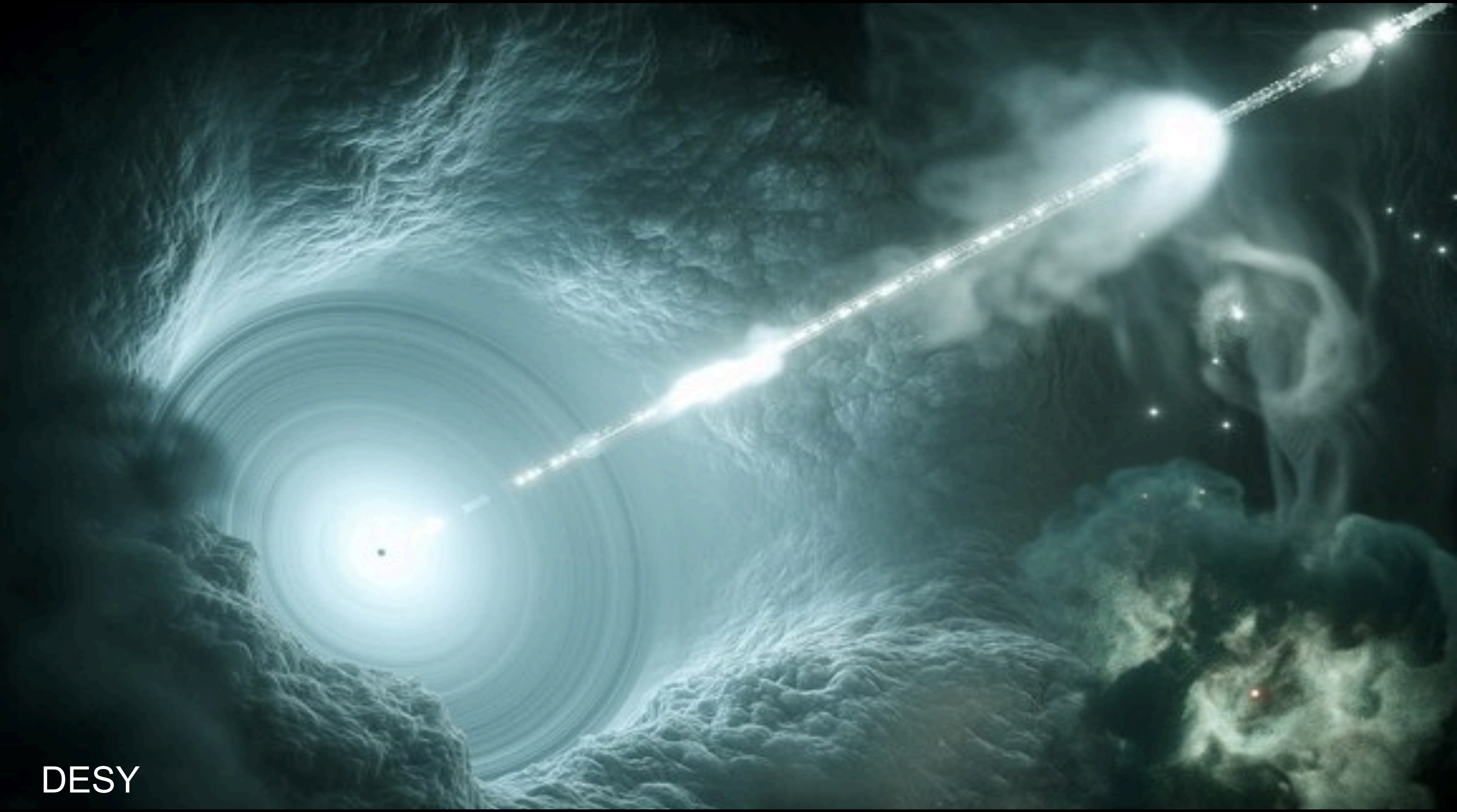
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

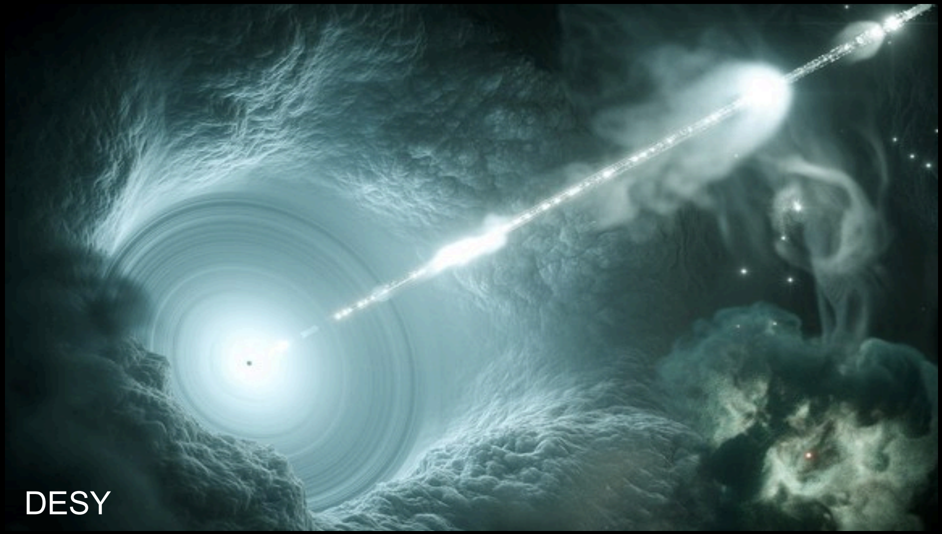
TXS0506+056 Blazar (artistic image)



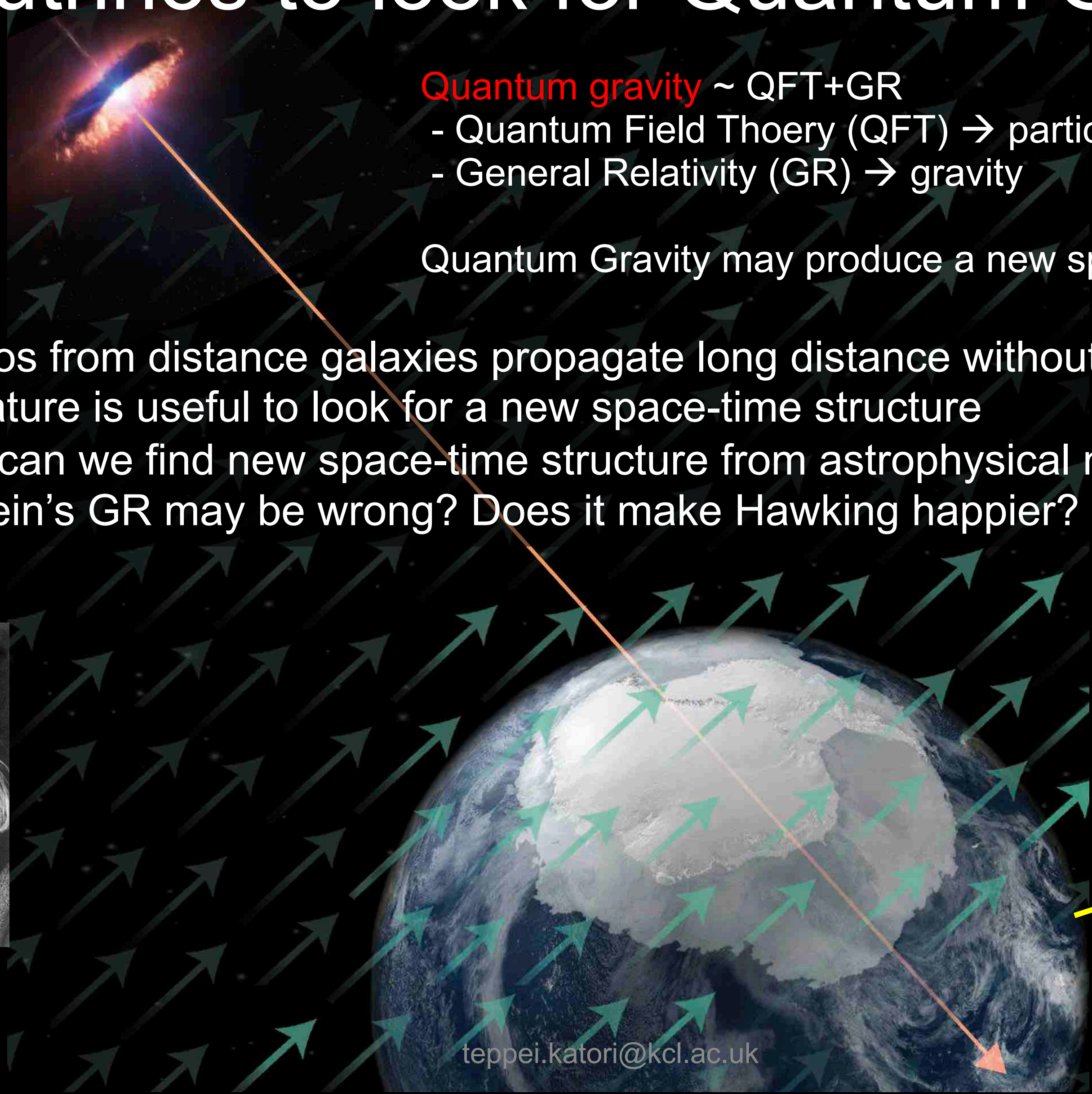
DESY

Blazar neutrinos

Blazars
- Active galactic nuclei (AGNs) are galaxies with a bright core.
- Spinning black hole with accretion disk, beyond Eddington luminosity.
- If the jet is oriented toward Earth, it is called a blazar.
- They are known to accelerate particles to the highest observed energies.



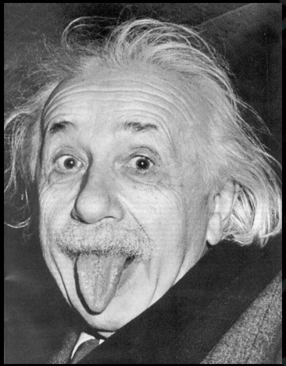
Neutrinos to look for Quantum Gravity



Quantum gravity ~ QFT+GR
- Quantum Field Thoery (QFT) → particle physics
- General Relativity (GR) → gravity

Quantum Gravity may produce a new space-time structure

Neutrinos from distance galaxies propagate long distance without interactions.
This feature is useful to look for a new space-time structure
- If so, can we find new space-time structure from astrophysical neutrino data?
- Einstein's GR may be wrong? Does it make Hawking happier?



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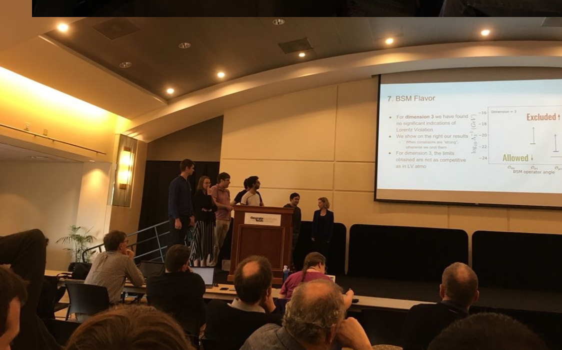
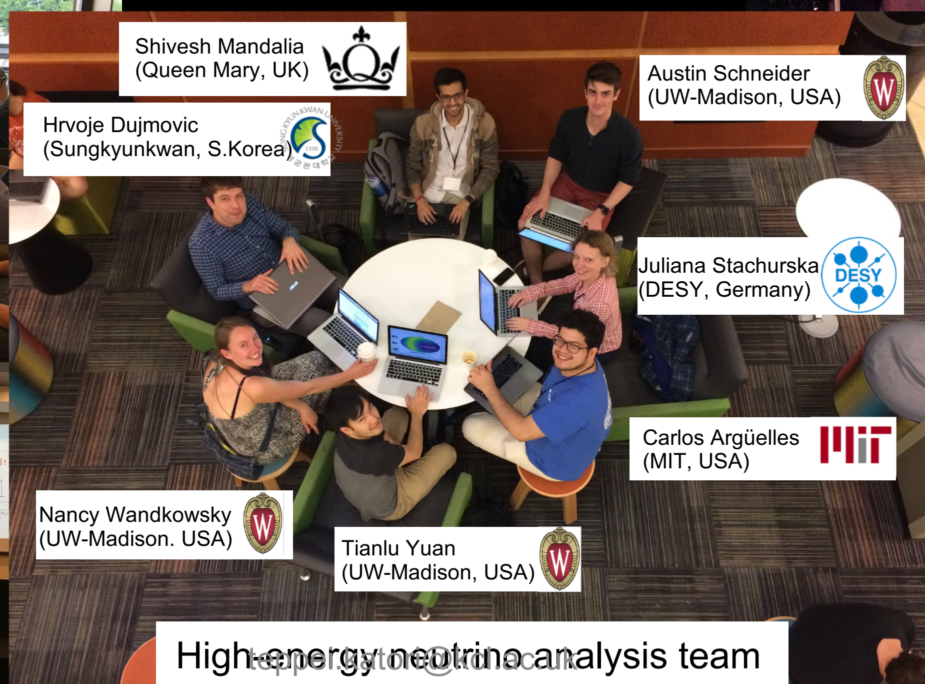
Big data science is fun!

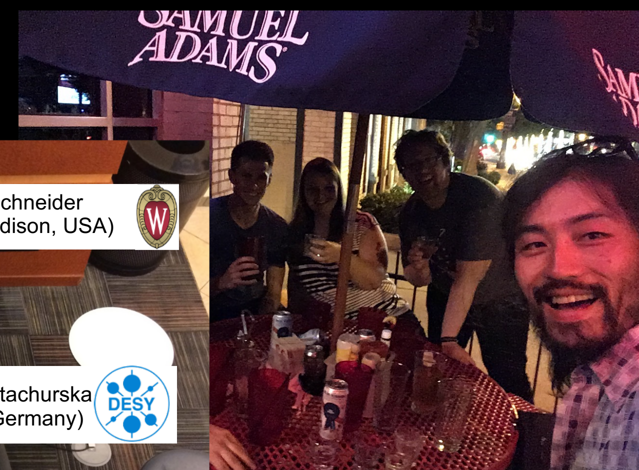
Particle physics experiments are large collaborations
- Detector: design, construction, simulation, operation, monitoring, etc…
- Data: software development, analysis tools

But more importantly, working in a collaboration, with a team, is a lot of fun!





High-energy neutrino analysis team



End

Neutrinos are ghostly elementary particles, penetrating everything

Kamiokande observed neutrinos from supernova, but Super-Kamiokande and Hyper-Kamiokande can observe more neutrinos from the next galactic supernova

IceCube observes extra-galactic neutrinos from a blazar. These are the highest energy particles which can escape from the highest energy environment in the universe.

Neutrinos can study new space-time structure predicted by Quantum Gravity

Research of neutrinos is a new field, and all excitement continues to the future!

Back up

Neutrino applications

EUROPHYSICS LETTERS

Europhys. Lett., **60** (1), pp. 34–39 (2002)

Could one find petroleum using neutrino oscillations in matter?

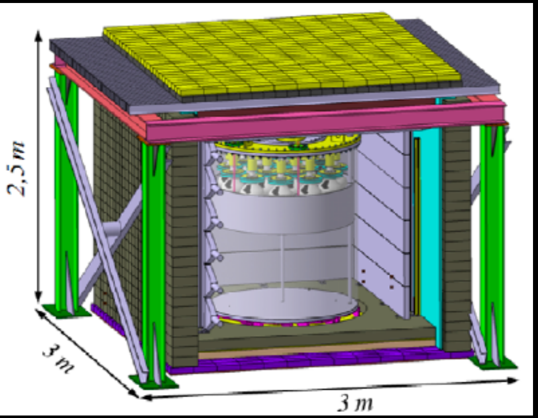
T. Ohlsson(*) and W. Winter(**)

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

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



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

World Scientific
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DEMONSTRATION OF COMMUNICATION USING NEUTRINOS

ELSEVIER
www.elsevier.com

Submarine neutrino communication

Patrick Huber

Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA

Letters B 671 (2009) 15–19

ts available at ScienceDirect

sics Letters B

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www.elsevier.com/locate/physletb

Galactic neutrino communication

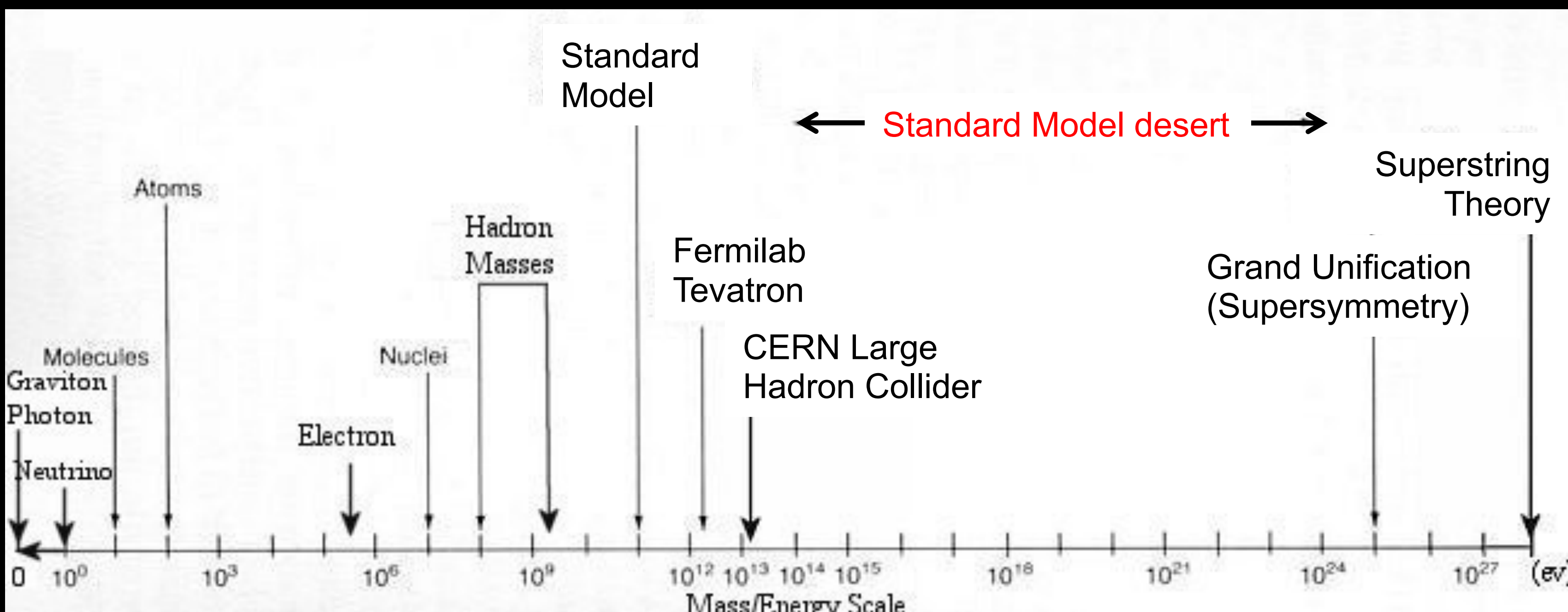
John G. Learned [a], Sandip Pakvasa [a,*], A. Zee [b]

[a] Department of Physics and Astronomy, University of Hawaii, 2505 Correa Road, Honolulu, HI 96822, USA
[b] Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA

Neutrinos, beyond the Standard Model?

- Neutrino masses are not predicted by the Standard Model
- Extremely small neutrino masses are related with Grand Unification Theory?

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



Neutrinos may be related to unification of three forces (electromagnetic force, weak nuclear force, strong nuclear force) in Standard Model?