Neutron Physics in Neutrino Astronomy

10:30 - 11:00, **Coffee**
11:00 - 11:40, *Neutrons in Super- and Hyper-Kamiokande*, Matthew Malek (Sheffield)
11:40 - 12:20, *Neutrons in DUNE*, Simon Peeters (Sussex)
12:20 - 13:00, *ISIS neutron beam facility*, Goran Skoro (RAL)
13:00 - 14:00, **Lunch**
14:00 - 14:25, *Cosmogenic Neutrons - SNO and SNO+*, Jeanne Wilson (King's)
14:25 - 14:50, *Neutrino interactions with nuclei and star matter*, Carlo Barbieri (Surrey)
14:50 - 15:05, *Pulse Shape Discriminating Plastic Scintillators for Neutron Detection*, Matt Taggart (Surrey)
15:05 - 15:20, *SK-Gd calibration*, Ka Ming Tsui (Liverpool)
15:20 - 15:35, *Low-Energy Astrophysics in Super- and Hyper-Kamiokande*, Jost Migenda (Sheffield)
15:35 - 15:50, *Neutrons in IceCube*, Teppei Katori (King's)
15:50 - 16:00, break, move to room S7.07
16:00 - 17:00, **Coffee & Discussion (room S7.06)**
17:00 - 18:00, Drink & Social network (room S7.06)

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Neutrons in T2K

Teppei Katori
King’s College London
Nov. 8, 2019

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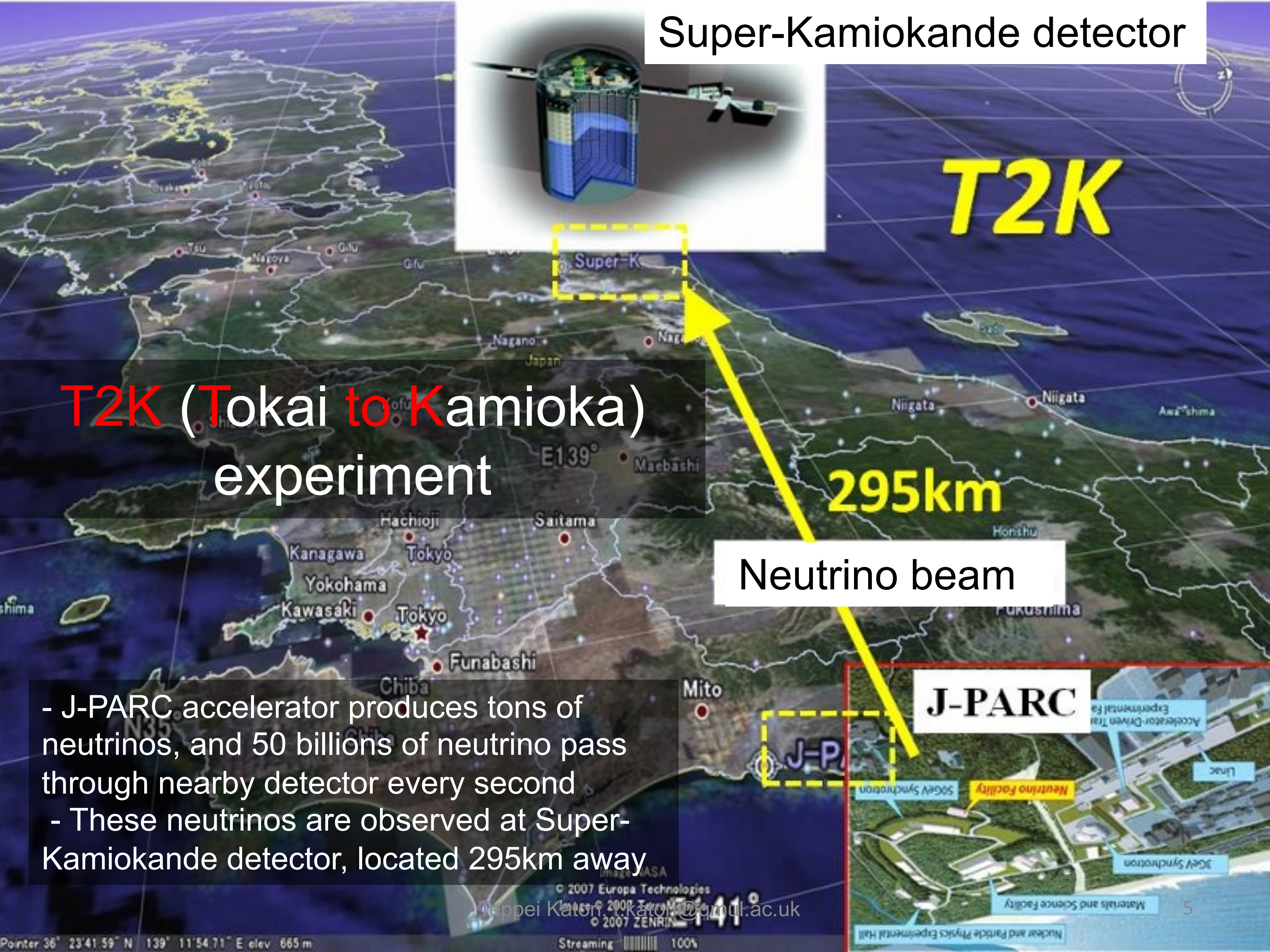
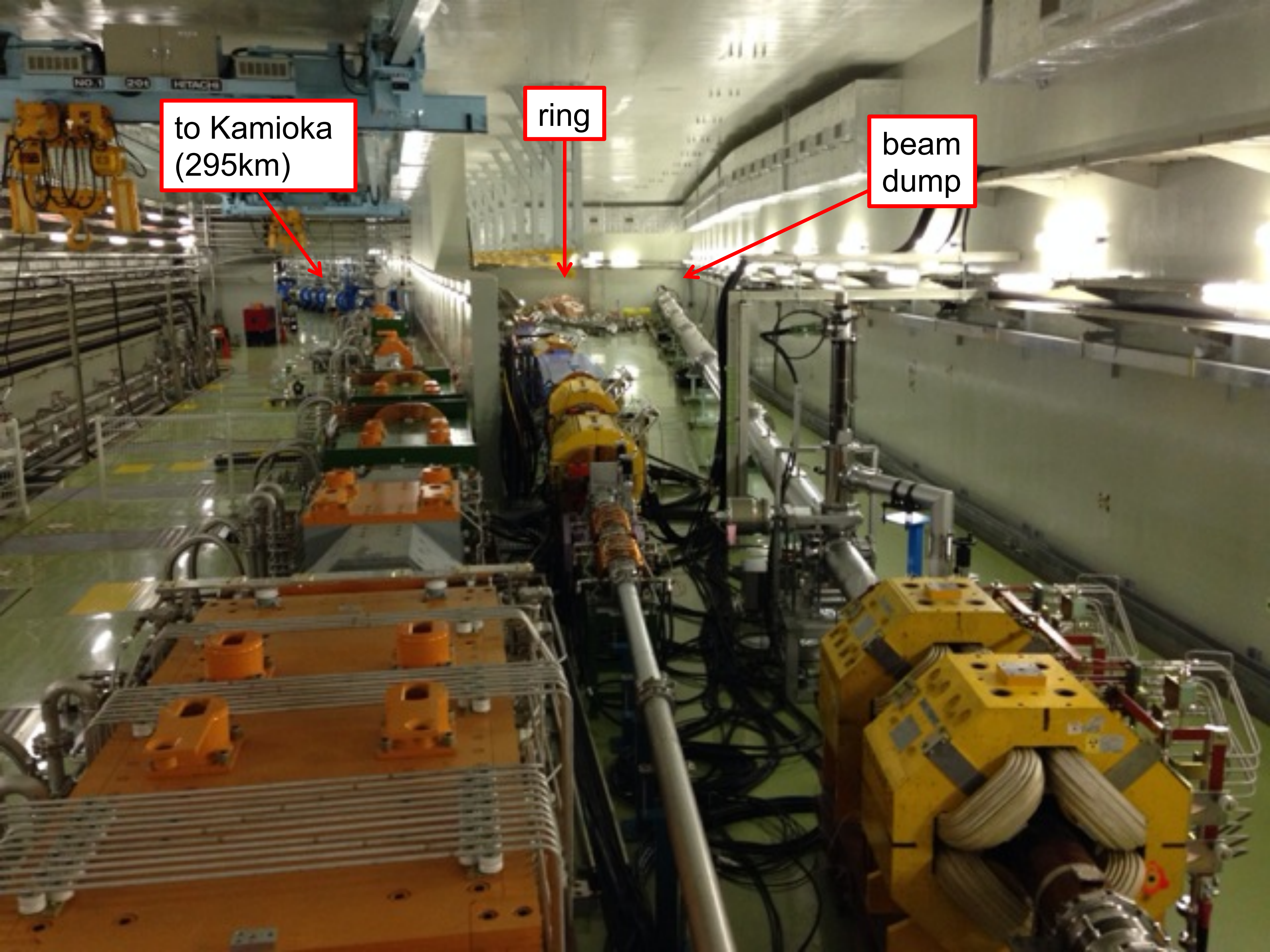
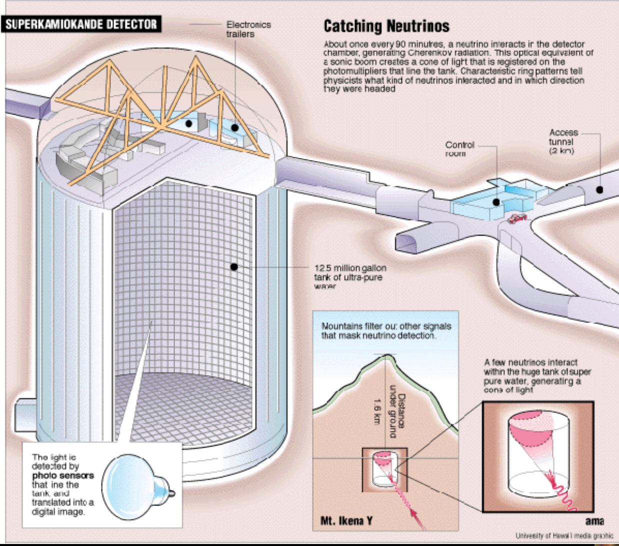
T2K (Tokai to Kamioka) experiment

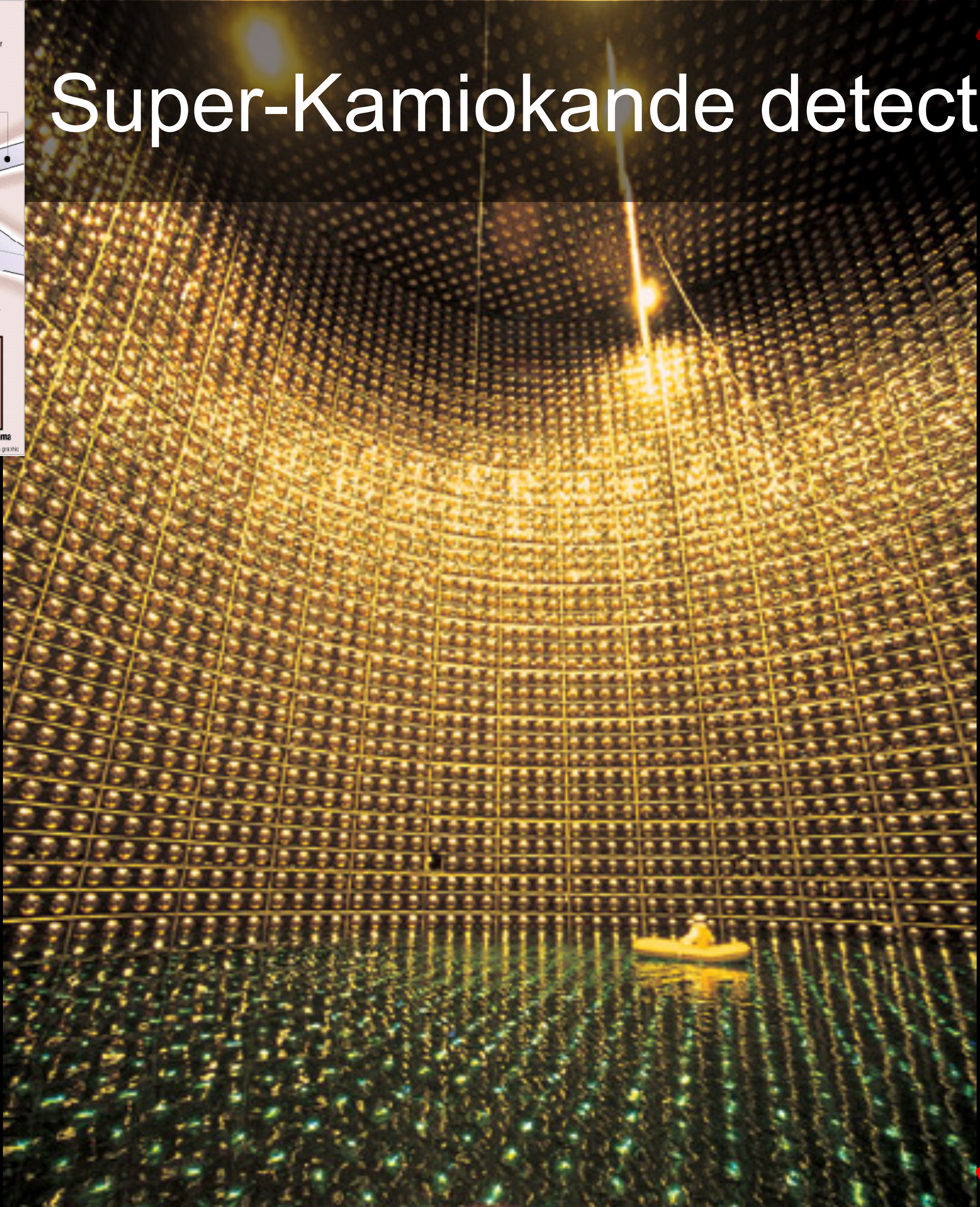
- J-PARC accelerator produces tons of neutrinos, and 50 billions of neutrino pass through nearby detector every second
- These neutrinos are observed at Super-Kamiokande detector, located 295km away




to Kamioka
(295km)
ring
beam
dump

Super-Kamiokande detector





40m

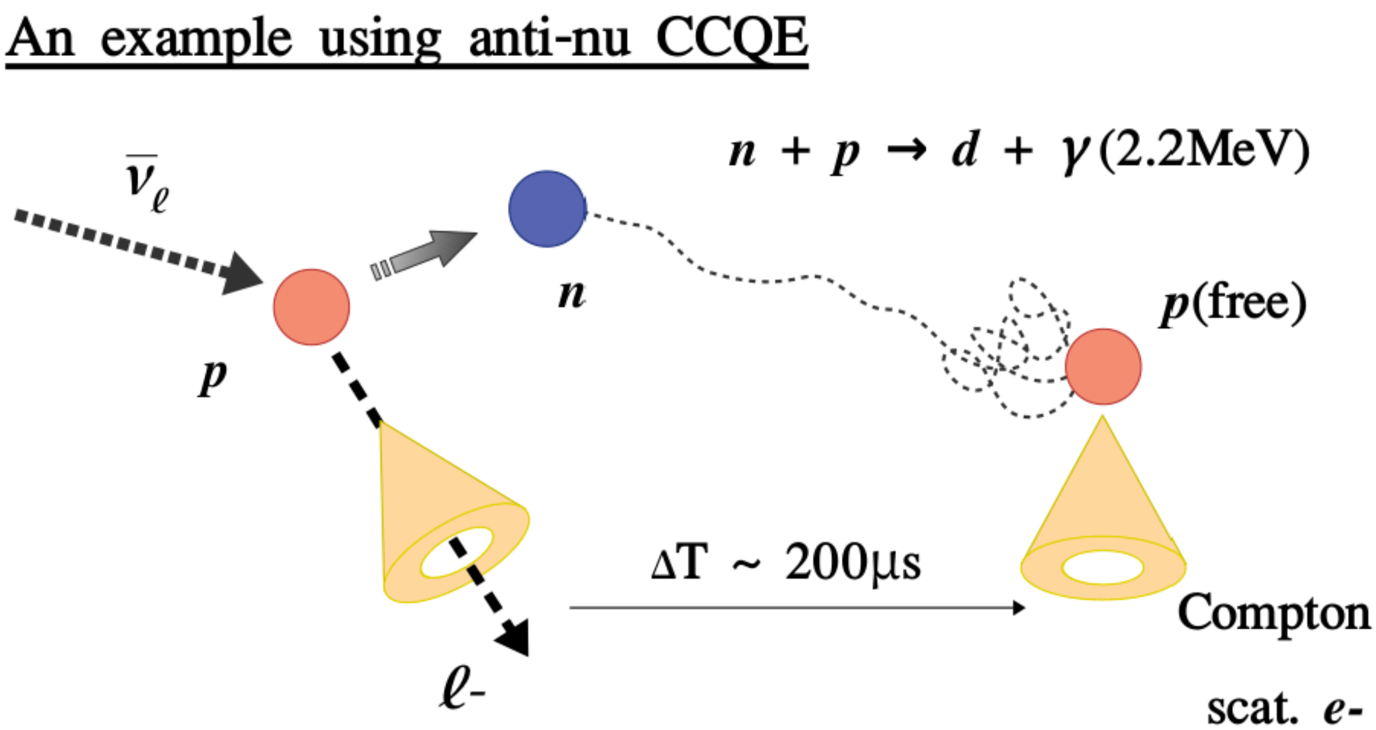
- 40m height, 40m wide, 50k ton of pure water

Neutron-tagging in T2K oscillation analysis

Neutron information can be use to tag anti-neutrino

- Background rejection of neutrino mode beam
- Signal selection for anti-neutrino mode beam
- Statistical separation of pion production, DIS, etc

Many possibilities IF we reliably predict number of neutrinos from given interaction channels



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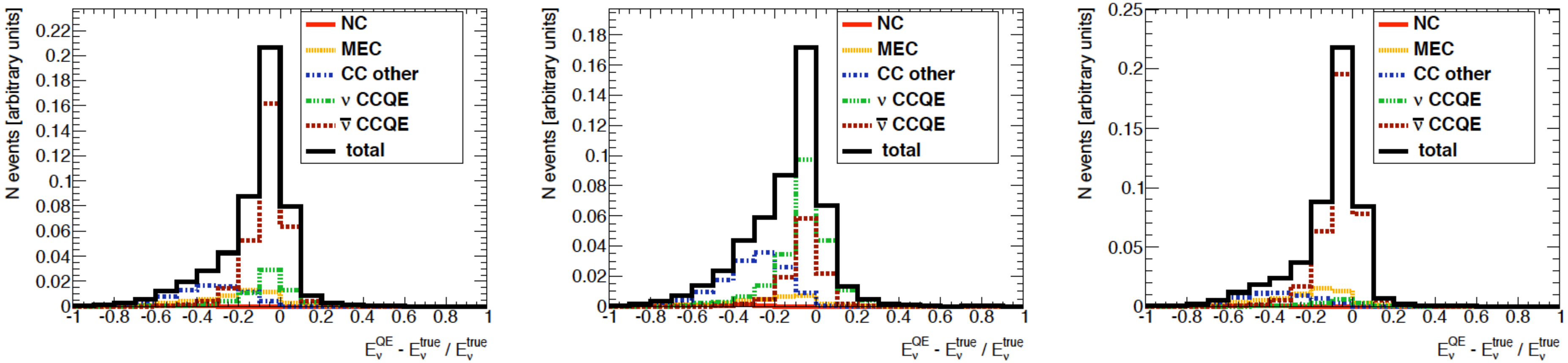
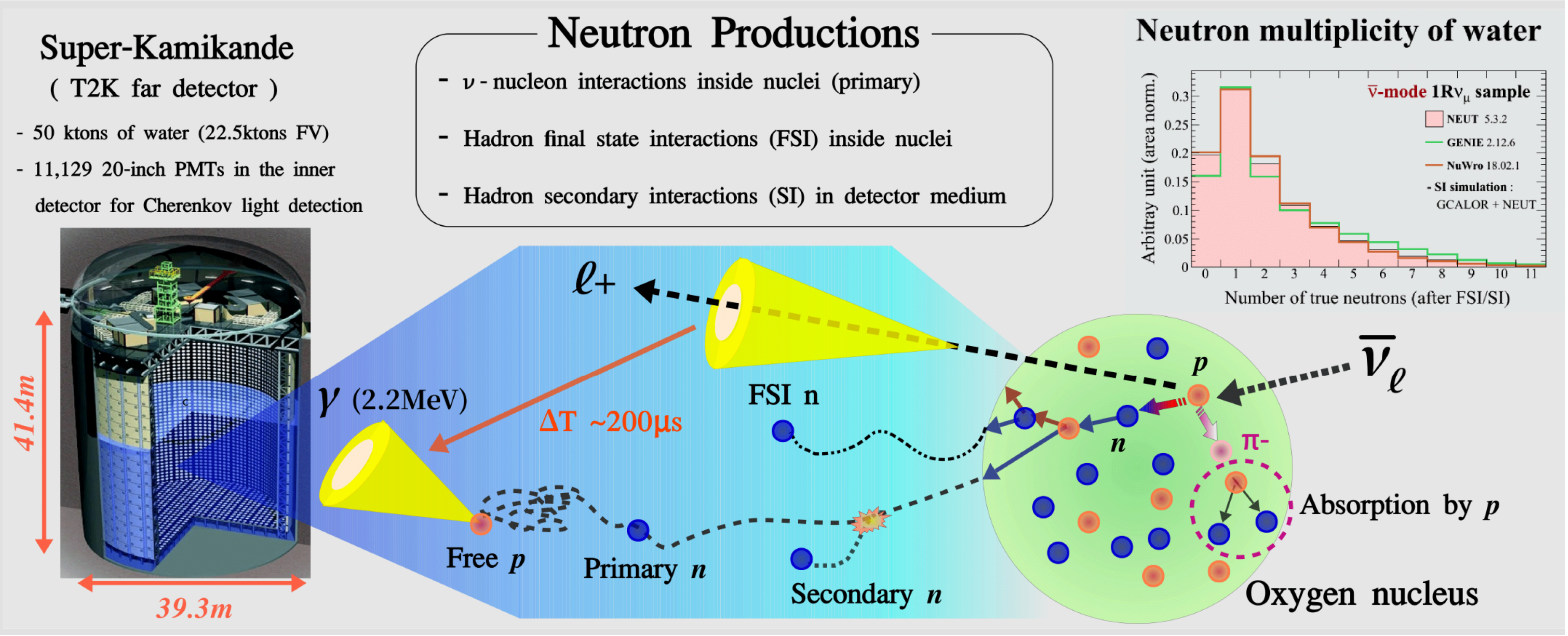
Anti-neutrino mode run (gadolinium-doped near detector)



#n=0 #n=1 #n>1

Neutron-tagging in T2K oscillation analysis

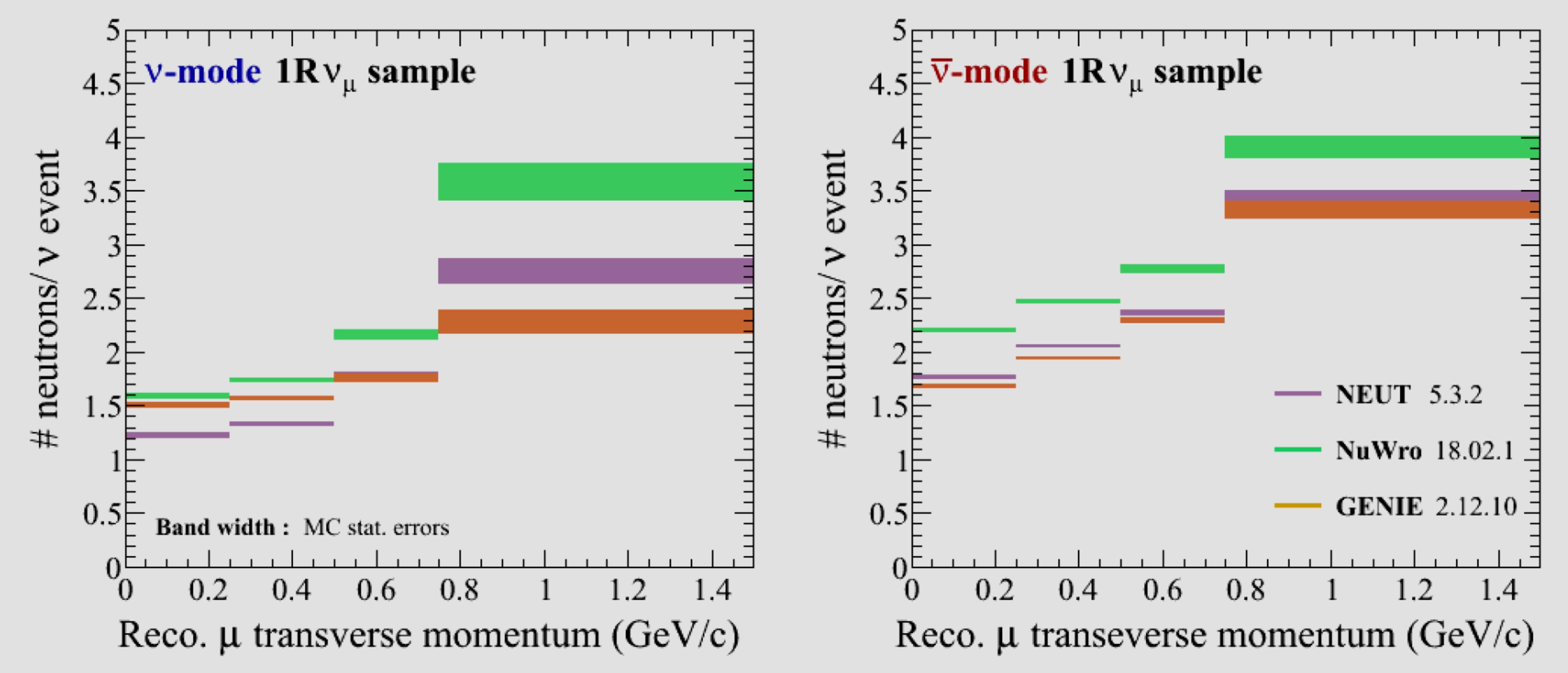
Neutron tagging in T2K
- 2.2 MeV γ ~ 10 PMT hits
- Tagging efficiency ~ 20%
- On average ~1m travel distance



Neutron-tagging in T2K oscillation analysis

Neutron multiplicity

- Generators predict very different neutron multiplicity.



Neutrino-induced neutron final state prediction is tough

Neutron multiplicity
 - Generators predict very different neutron multiplicity.

You need a good “XS + FSI + SI” for data-MC agreement

Neutrino cross section model (XS)
 - number of neutrons produced by neutrino interaction need to be predicted correctly. Hadron exclusive channel predictions are not easy.

Final state interaction (FSI)
 - neutron re-scattering (elastic, inelastic, absorption, charge exchange) need to be modelled correctly. This is not easy.

Secondary interaction (SI)
 - neutron propagation in water need to be modelled correctly. This can be studied by neutron beam tests.

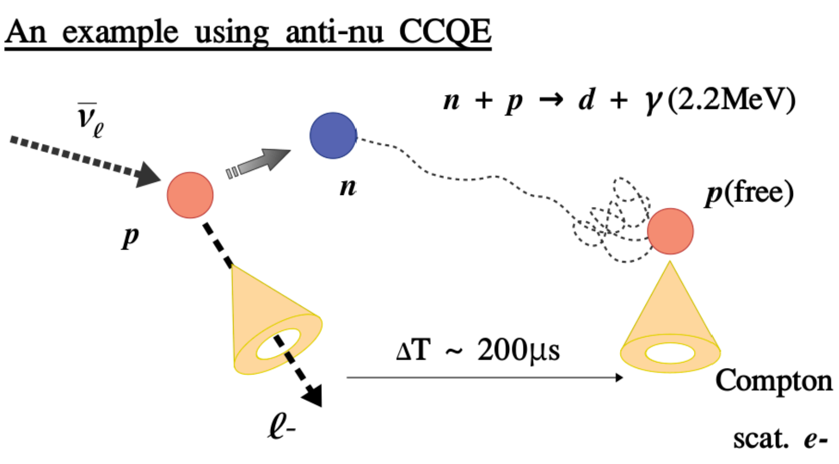
Super-Kamiokande detector refurbishment 2018

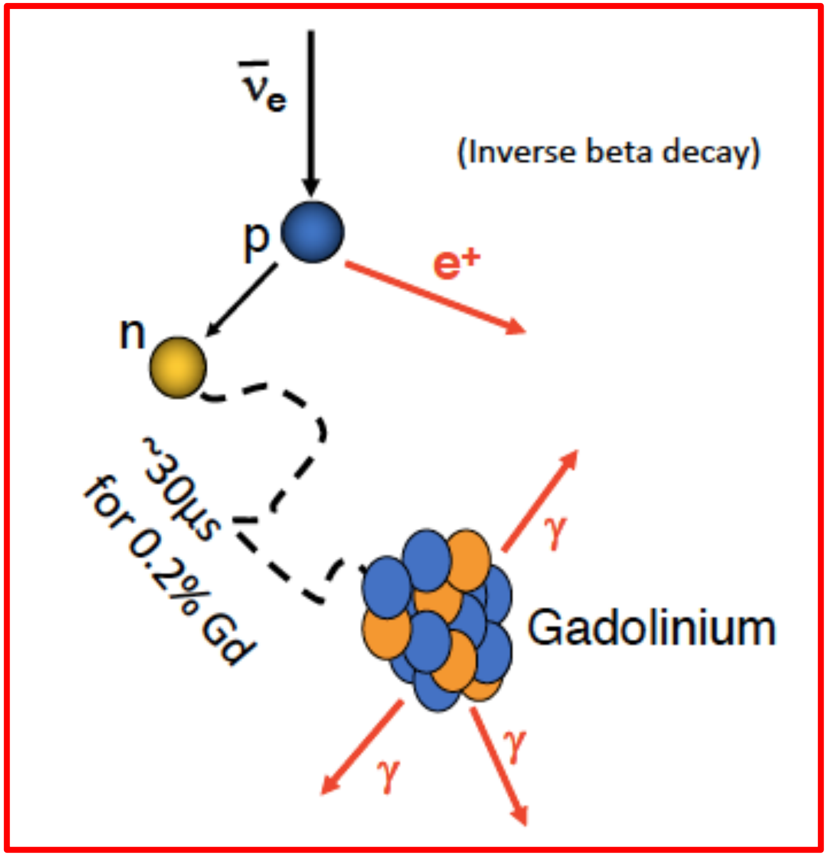
Gadolinium-doped Super-Kamiokande (SK-Gd)

See talks by Jost Migenda and Ka Ming Tsui
20% neutron tagging efficiency (hydrogen) → ~90% efficiency

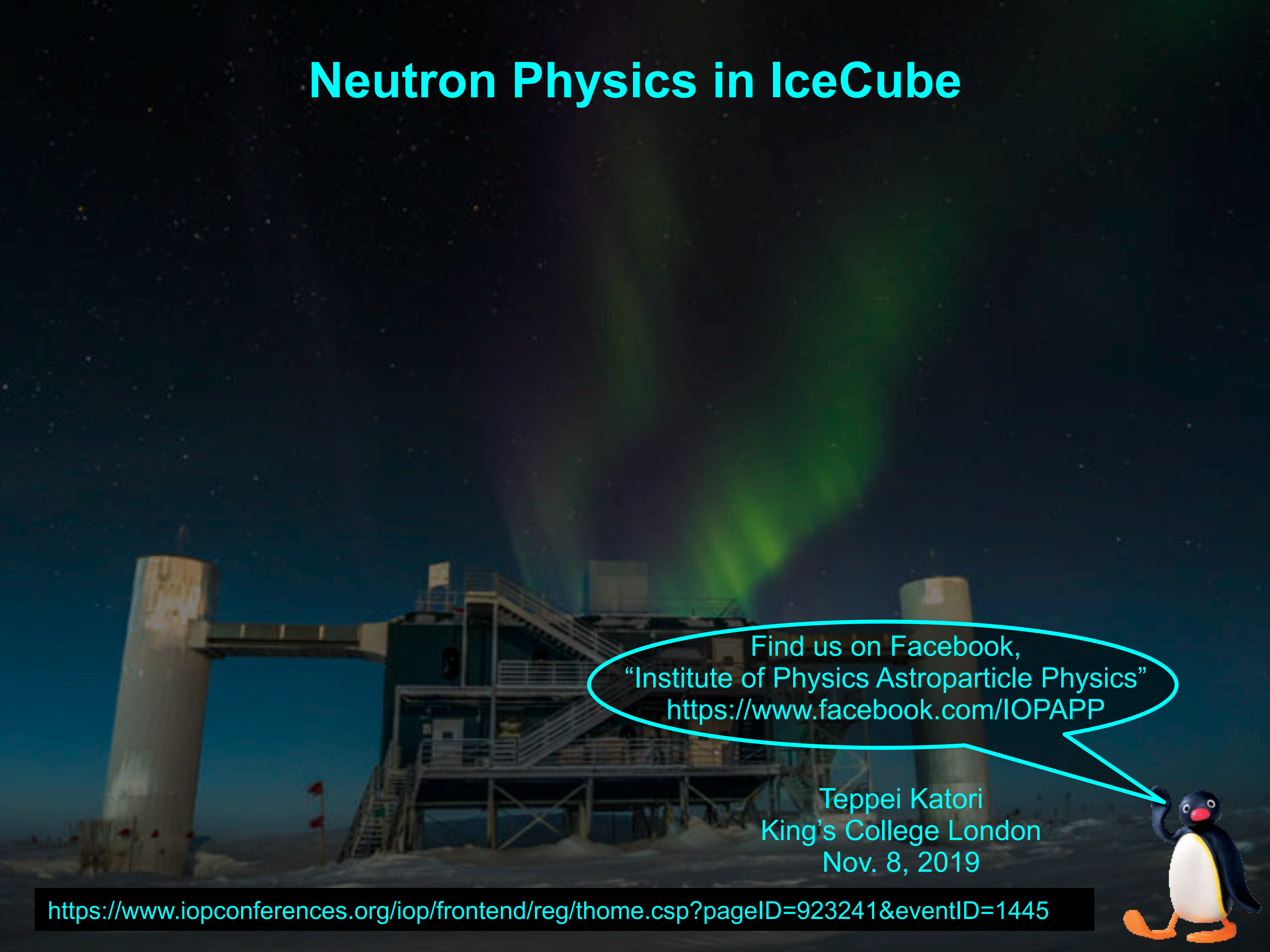
More physics with neutrons are possible in very near future
- Oscillation physics
- Astrophysics
- New physics search

Precise neutron simulation (multiplicity, kinematics) is even more important in near future





Neutron Physics in IceCube



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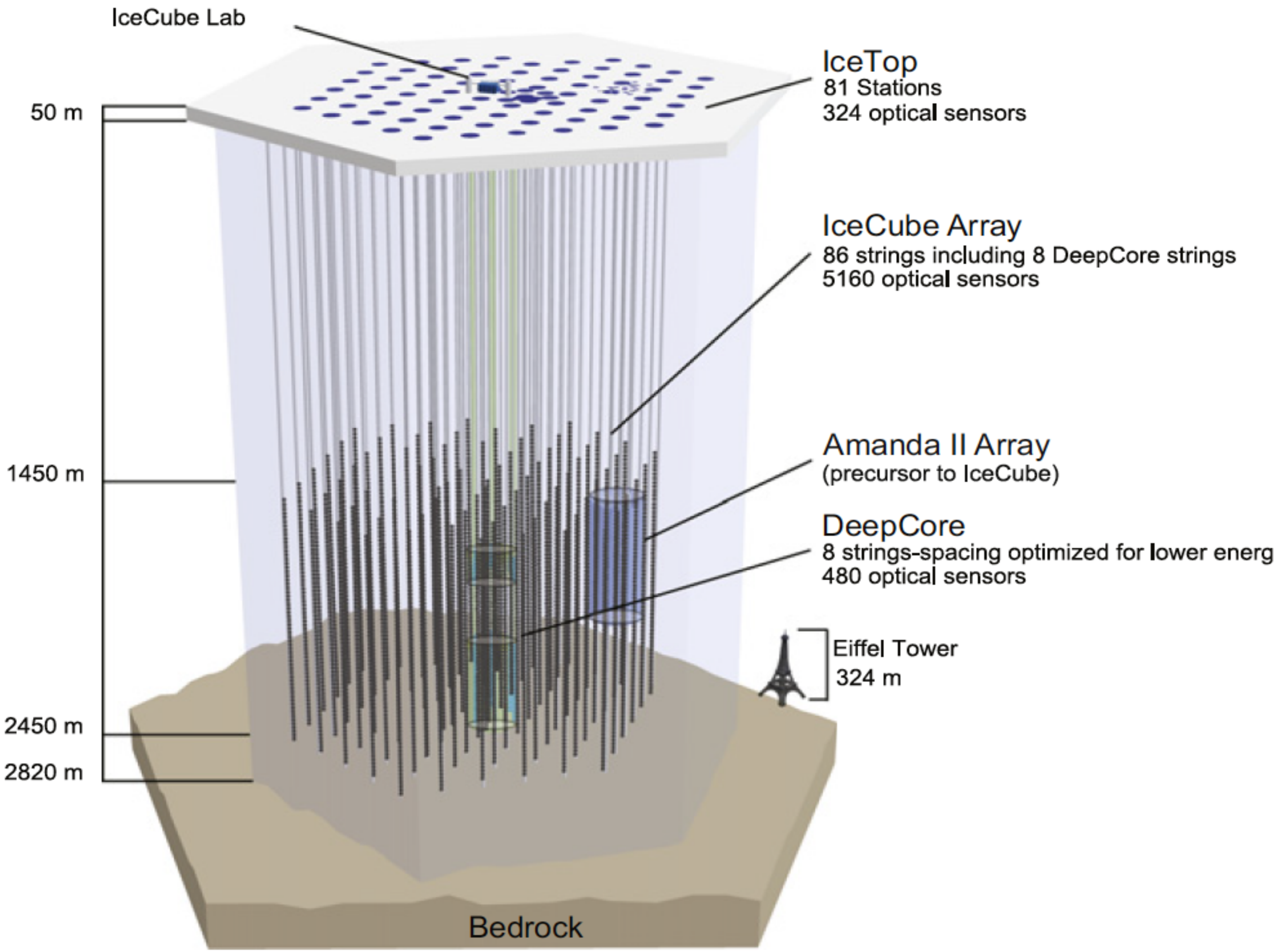
IceCube Neutrino Observatory



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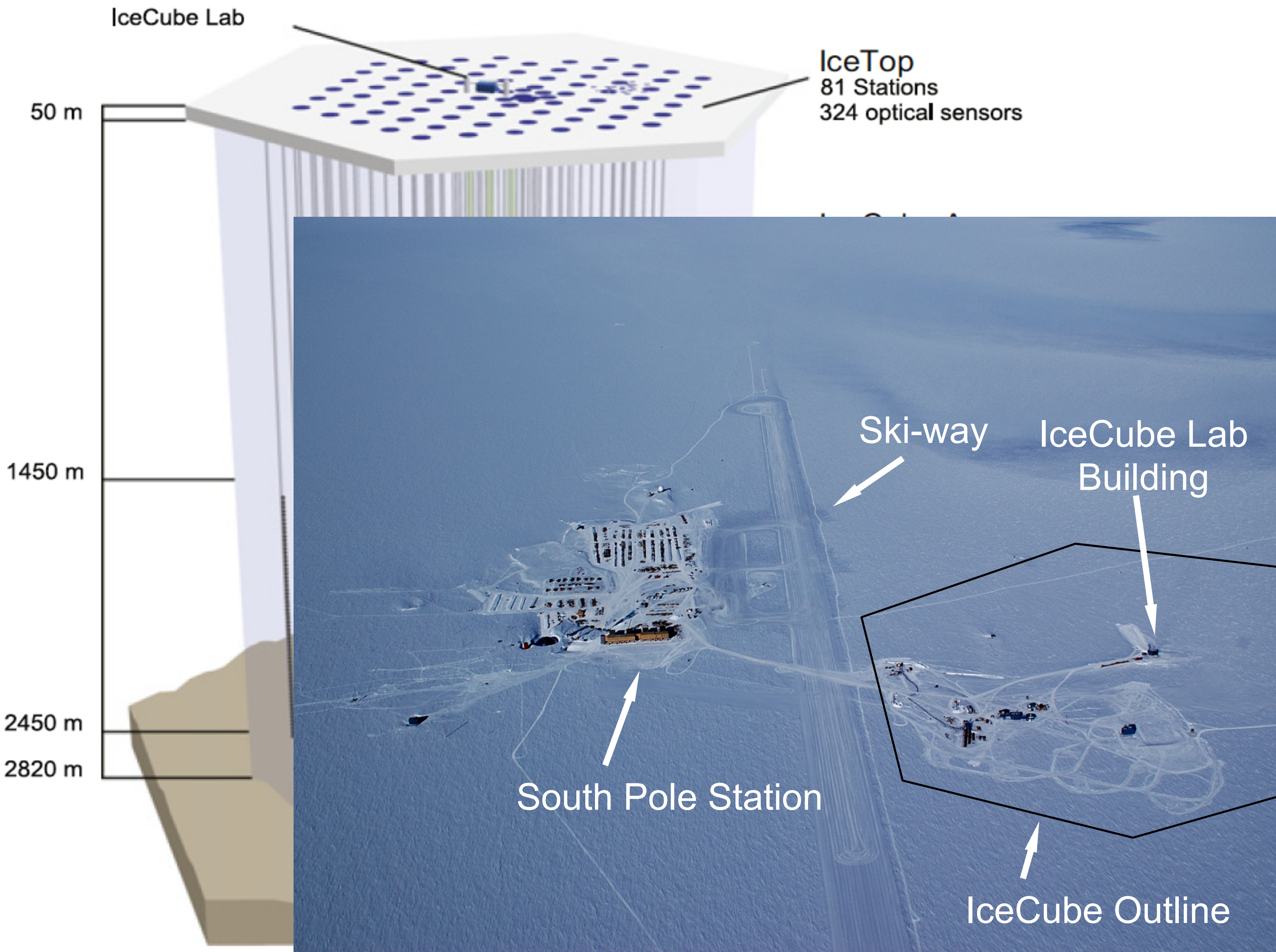
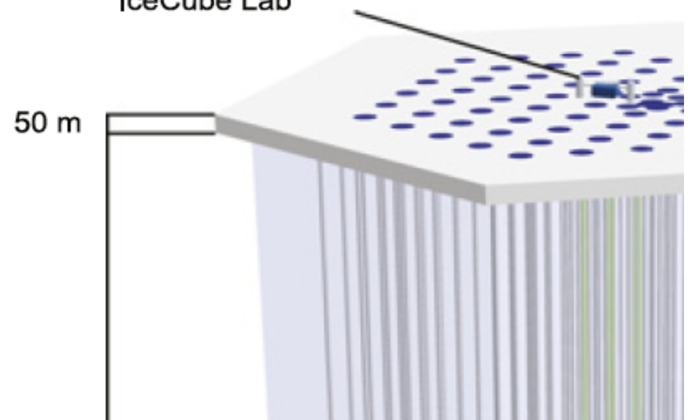
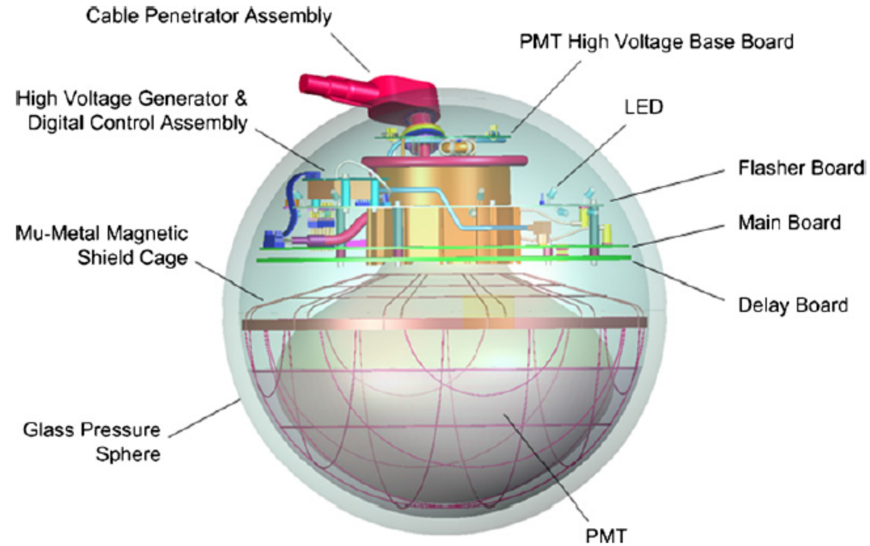
IceCube Neutrino Observatory



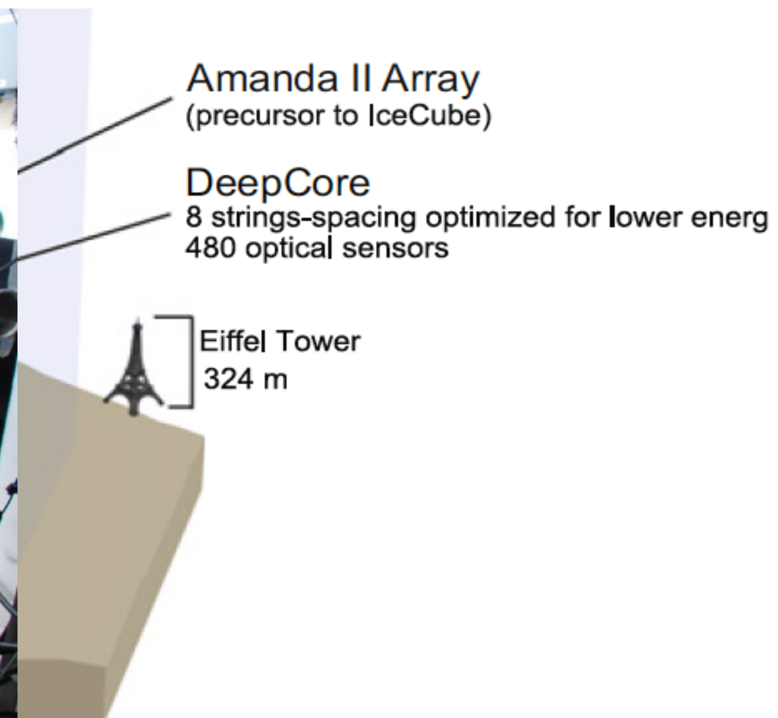
IceCube Neutrino Observatory



digital optical module (DOM)



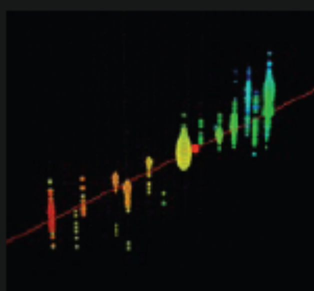
optical sensor deployment



Particle Identification (PID) in IceCube

The main event topologies are “track” and “cascade” (double bang is rare)
- Track = muon (~ν_μCC)
- Cascade (shower) = electron, tau, hadrons (~, ν_eCC, ν_τCC, NC)

CC Muon Neutrino

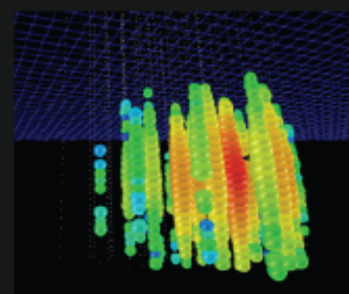


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / Electron Neutrino



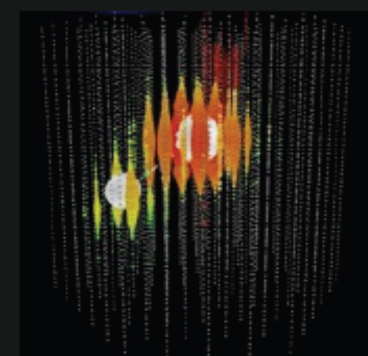
$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

CC Tau Neutrino

time



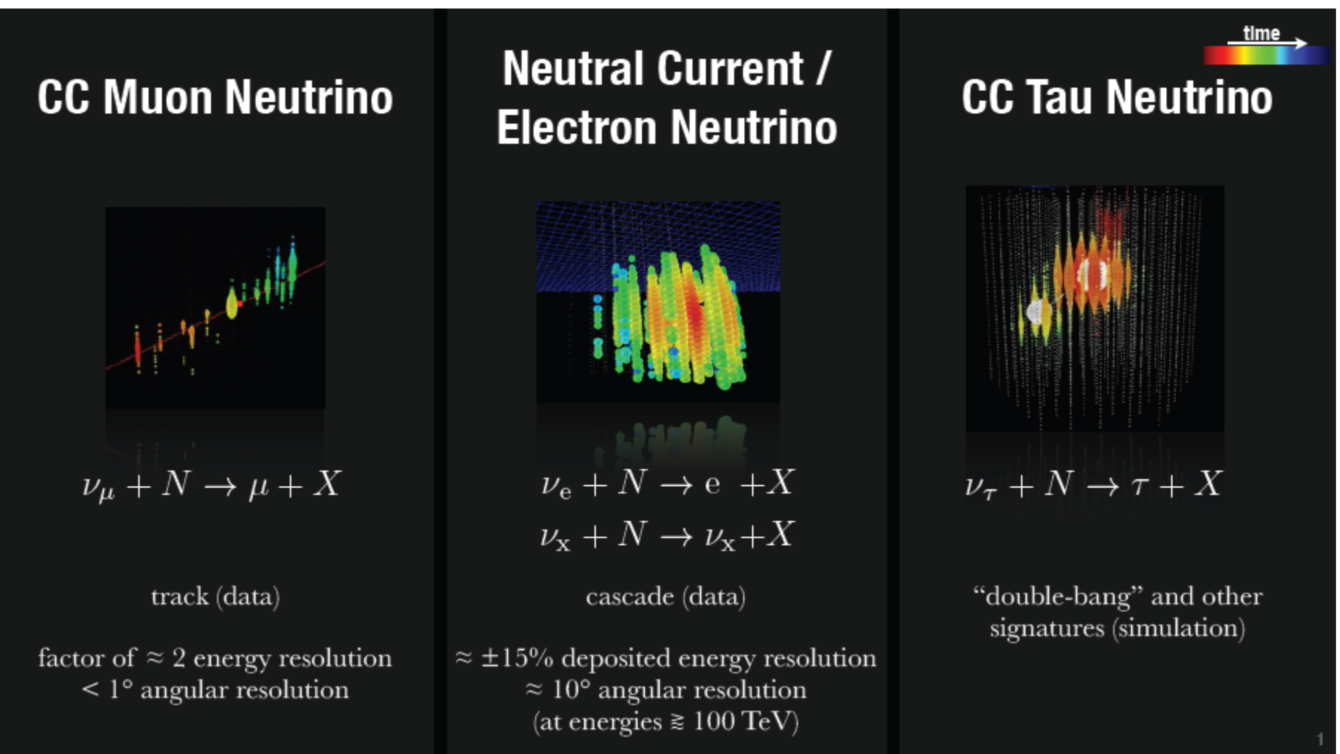
$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

Astrophysical High-Energy Neutrinos

First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown (diffuse)
- From both southern and northern sky
- Spectrum, no good fit
- Shower topology is dominant

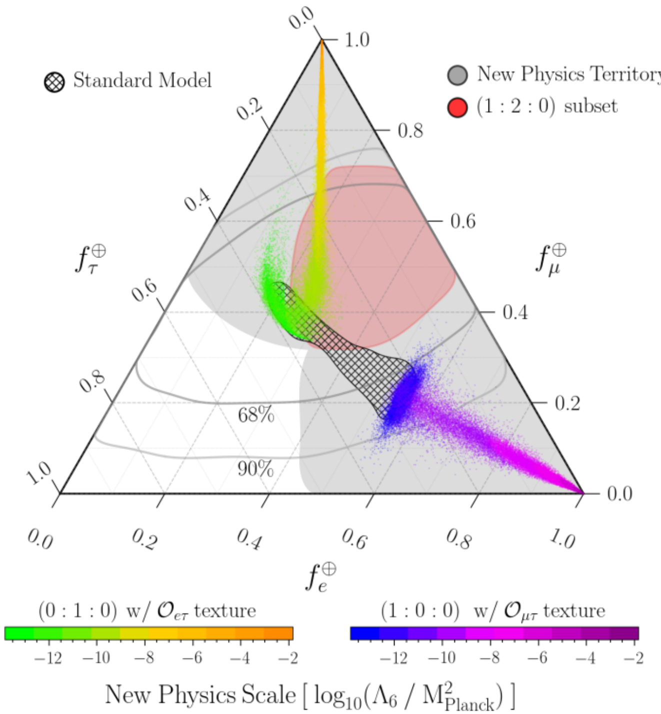


ID	Deposited energy (TeV)	Event type
1	$47.6^{+6.5}_{-5.4}$	Shower
2	117^{+15}_{-15}	Shower
3	$78.7^{+10.8}_{-8.7}$	Track
4	165^{+20}_{-15}	Shower
5	$71.4^{+9.0}_{-9.0}$	Track
6	$28.4^{+2.7}_{-2.5}$	Shower
7	$34.3^{+3.5}_{-4.3}$	Shower
8	$32.6^{+10.3}_{-11.1}$	Track
9	$63.2^{+7.1}_{-8.0}$	Shower
10	$97.2^{+10.4}_{-12.4}$	Shower
11	$88.4^{+12.5}_{-10.7}$	Shower
12	104^{+13}_{-13}	Shower
13	253^{+26}_{-22}	Track
14	1041^{+132}_{-144}	Shower
15	$57.5^{+8.3}_{-7.8}$	Shower
16	$30.6^{+3.6}_{-3.5}$	Shower
17	200^{+27}_{-27}	Shower
18	$31.5^{+4.6}_{-3.3}$	Track
19	$71.5^{+7.0}_{-7.2}$	Shower
20	1141^{+143}_{-133}	Shower
21	$30.2^{+3.5}_{-3.3}$	Shower
22	220^{+21}_{-24}	Shower
23	$82.2^{+8.6}_{-8.4}$	Track
24	$30.5^{+3.2}_{-2.6}$	Shower
25	$33.5^{+4.9}_{-5.0}$	Shower
26	210^{+29}_{-26}	Shower
27	$60.2^{+5.6}_{-5.6}$	Shower
28	$46.1^{+5.7}_{-4.4}$	Track

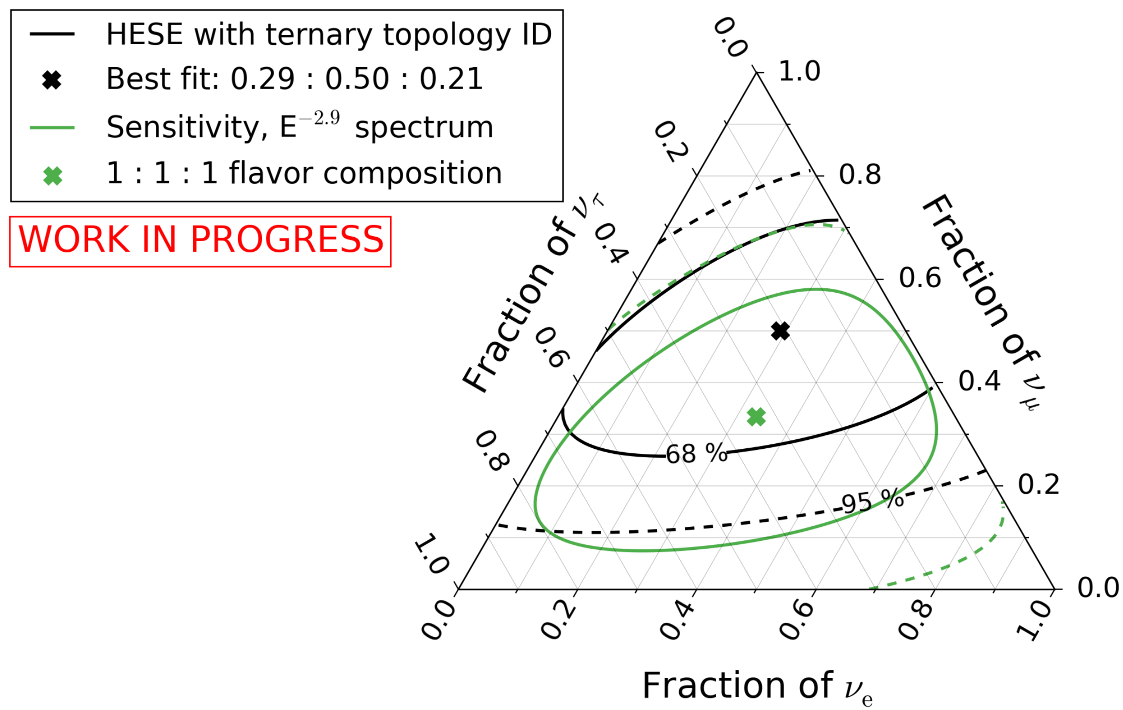
Astrophysical neutrino flavor physics

A lot of new physics opportunities from astrophysical neutrino flavor, but PID of IceCube is poor.

Problem: Separation of cascade signal is very difficult, and the likelihood between ν_eCC and ν_τCC is very shallow.



The latest IceCube HESE analysis (high-energy starting event) uses an improved tauPID, and indeed we found 2 astrophysical tau neutrino candidates (out of ~100 events).



The standard theory predict
$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$
and deviation from this could be new physics.

Neutron Echo for tau-neutrino PID

ν_eCC, ν_τCC, and NC all make cascade events.
However, their showers develop in different way.

- ν_eCC: electromagnetic shower

$$\nu_e + X \rightarrow e + hadrons$$

- NC: hadronic shower with lots of μ-decays and n-capture

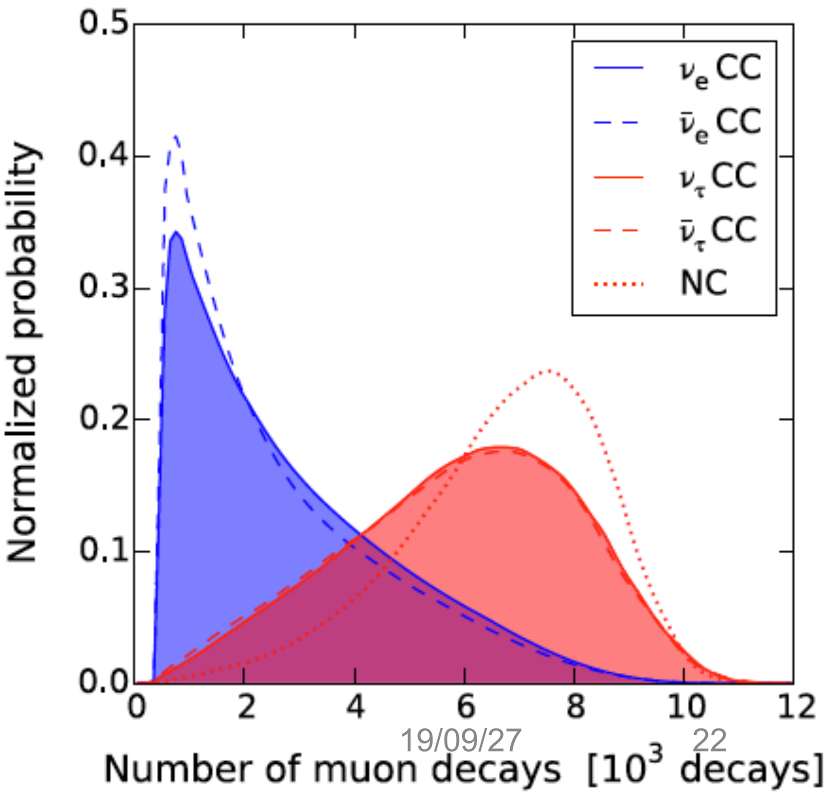
$$\nu_x + X \rightarrow \nu_x + hadrons,$$

$$\pi \rightarrow \mu + \nu, \qquad \mu \rightarrow e + \nu + \bar{\nu}\,(2.2\mu s), \qquad n + p \rightarrow d + \gamma\,(222\mu s)$$

- ν_τCC: slightly less hadrons than NC

$$\nu_\tau + X \rightarrow \tau + hadrons$$

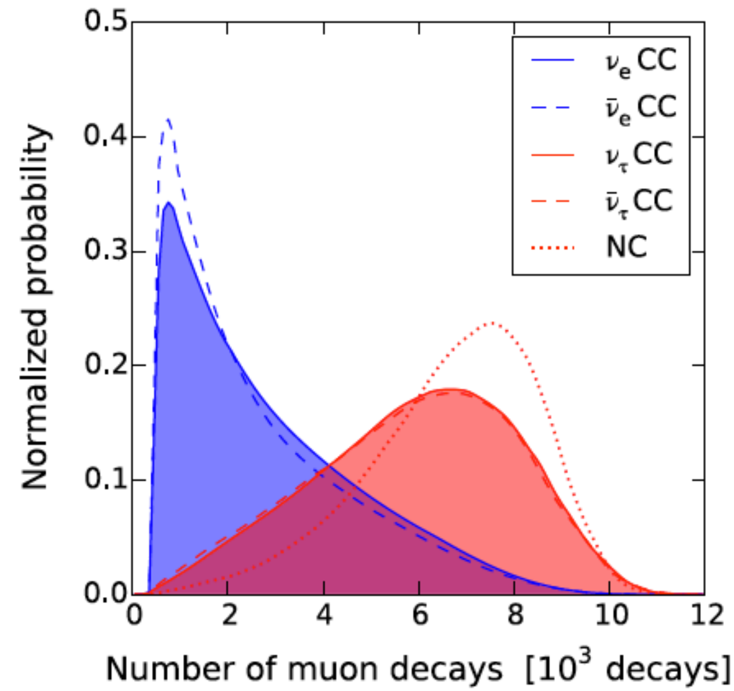
$$\tau \rightarrow hadrons, \qquad \tau \rightarrow \mu + \nu + \bar{\nu}\,(17\%)$$



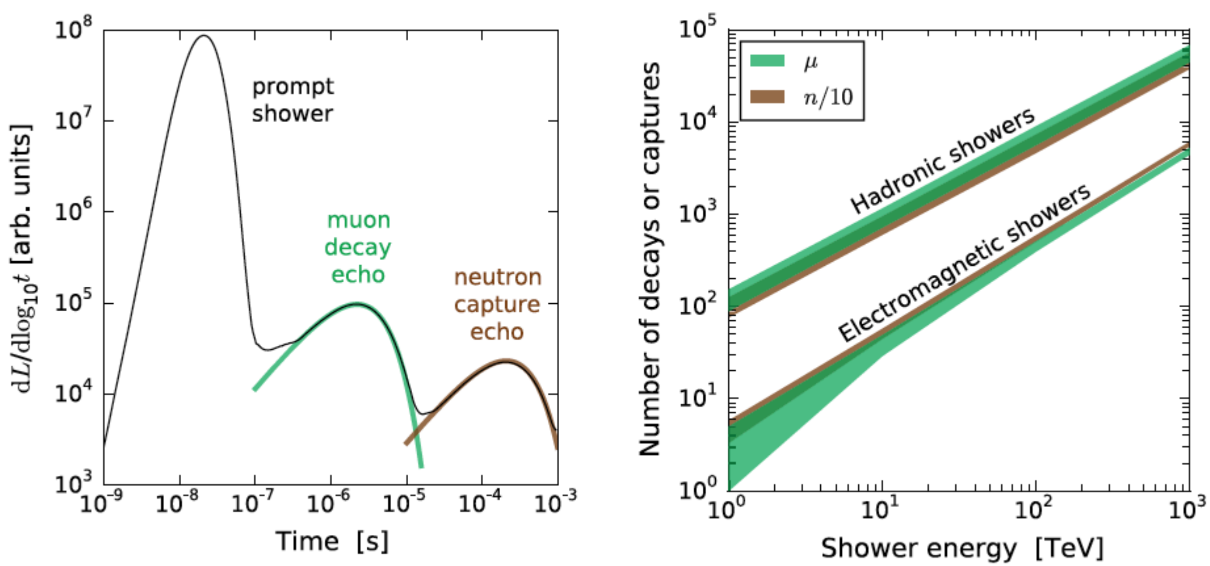
Neutron Echo for tau-neutrino PID

Li et al (FLUKA + back-of-the-envelope)

From a 100 TeV hadronic shower
- μ-decay signal is ~0.3% of total photons
- μ-decay time scale ~2.2us
- n-capture signal is ~0.06% of total photons
- n-capture time scale ~200us



PHYSICAL REVIEW LETTERS 122, 151101 (2019)



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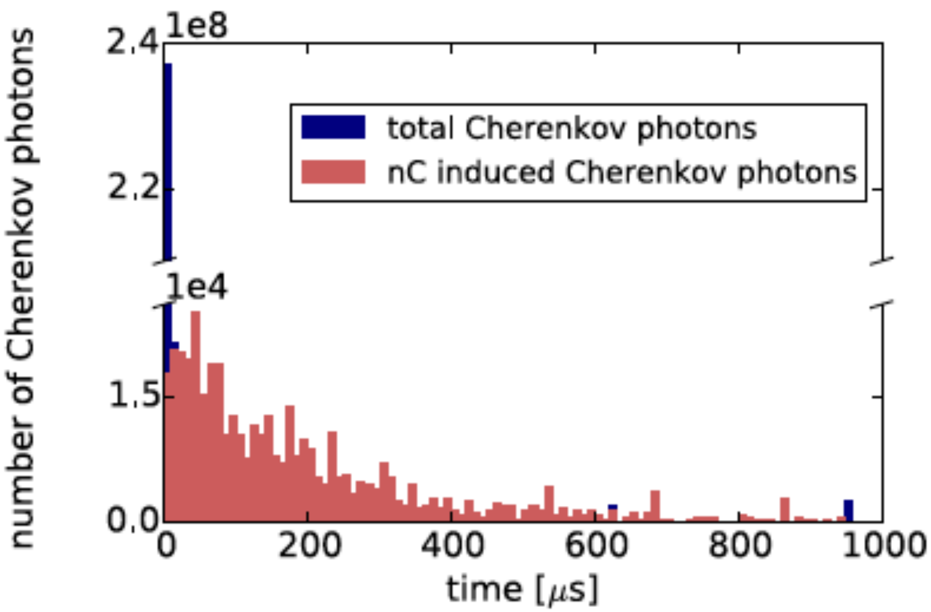
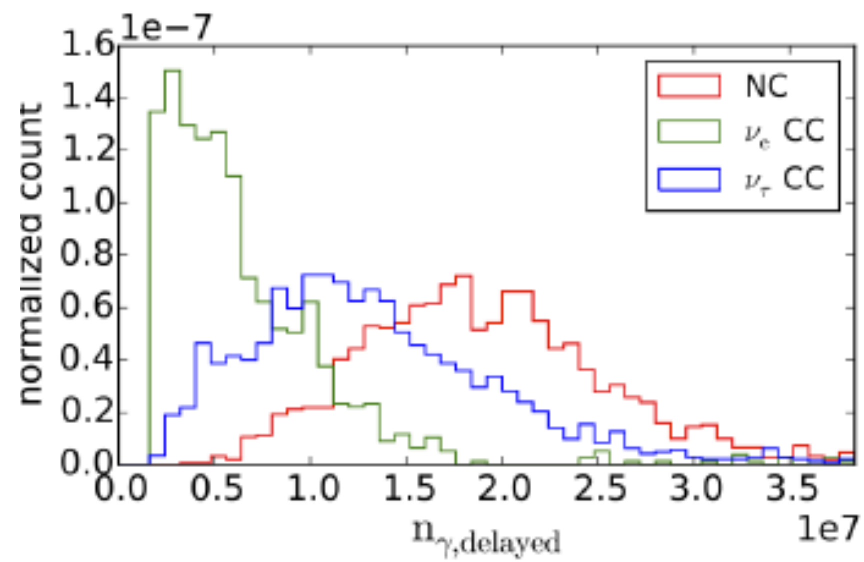
Neutron Echo for tau-neutrino PID

Steuer et al (Geant4)

- ~60% of neutrons produced in the ice will be captured
- ~98% of neutrons are captured by hydrogens
- ~222us neutron capture time in ice, with ~1m travel
- 2.2 MeV γ produces ~230 Cherenkov photons
- n-capture photons is ~0.1% of total photons (Eν>10TeV)





Li, Bustamante, Beacom, PRL122(2019)151101
Steuer, PhD thesis (Mainz, 2019)

Neutron Physics in IceCube

How many neutrons are produced by ν_eCC, ν_τCC, and NC?
- Good DIS model (CSMS)
- PYTHIA8

How many neutrons are captured in ice?
- Geant4

How much photons can be deposited to DOMs?
- Geant4

Can we trust Geant4 for these simulation?
Is there any important measurement? (neutron propagation in ice?)