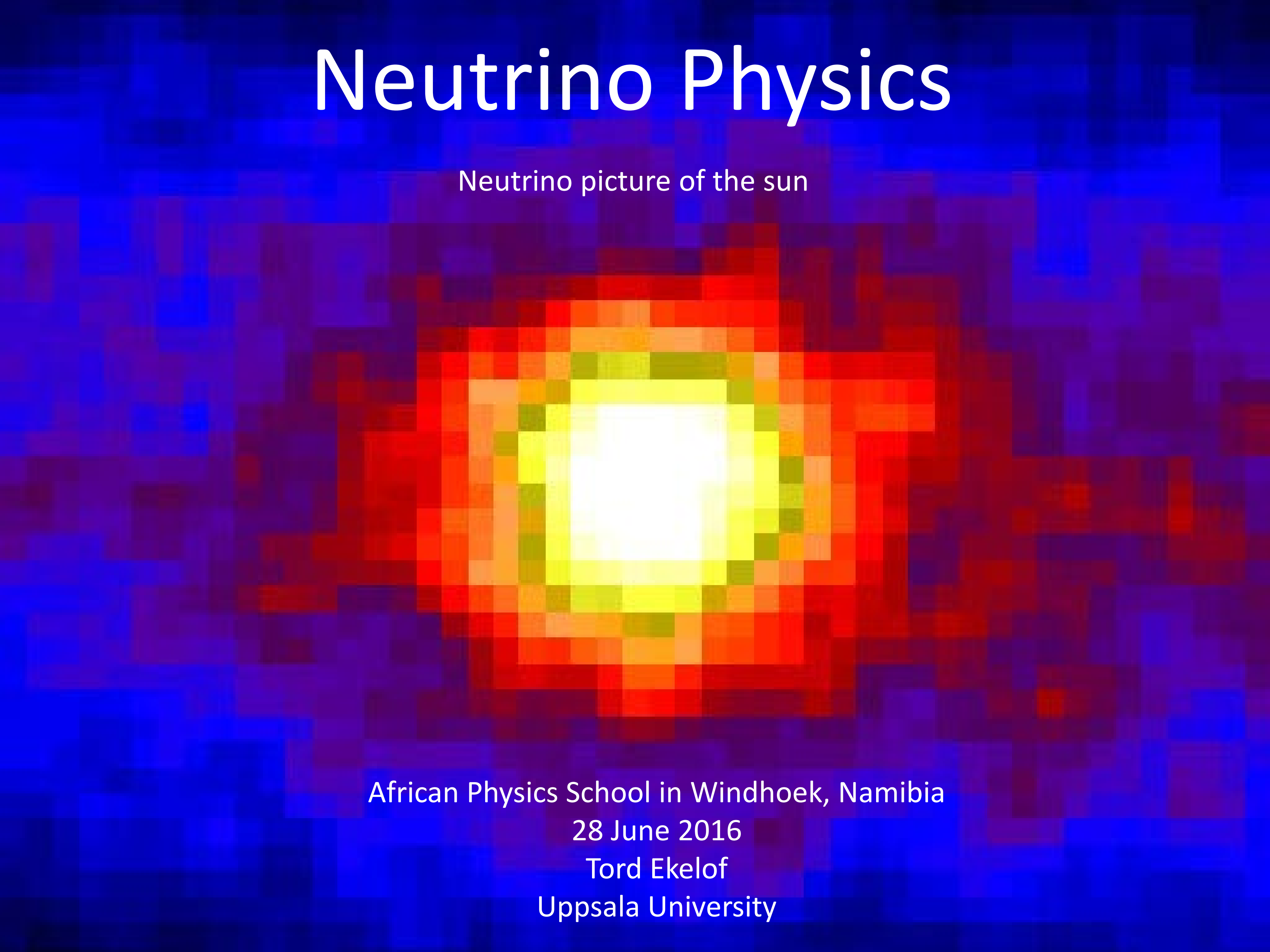
Neutrino Physics

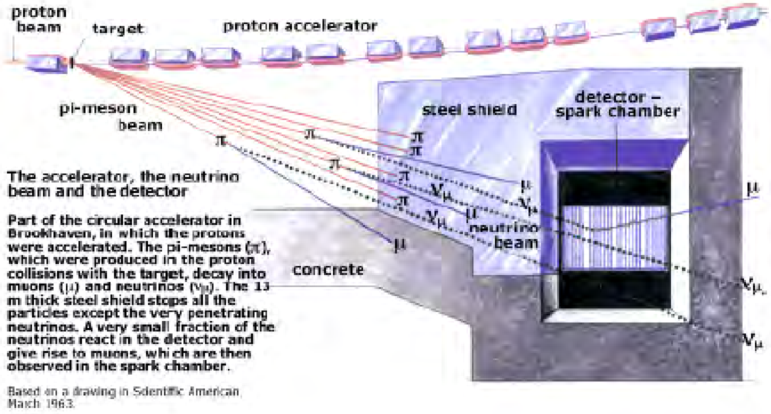


Neutrino picture of the sun

African Physics School in Windhoek, Namibia
28 June 2016
Tord Ekelof
Uppsala University

A few mile-stones

Reactor neutrinos : 1956 first neutrino detection by Reines& Cowan

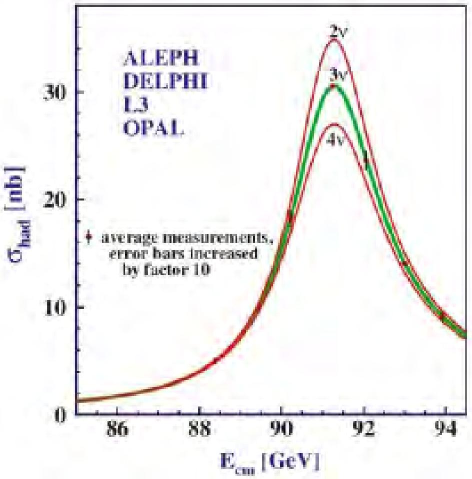


The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American March 1963.

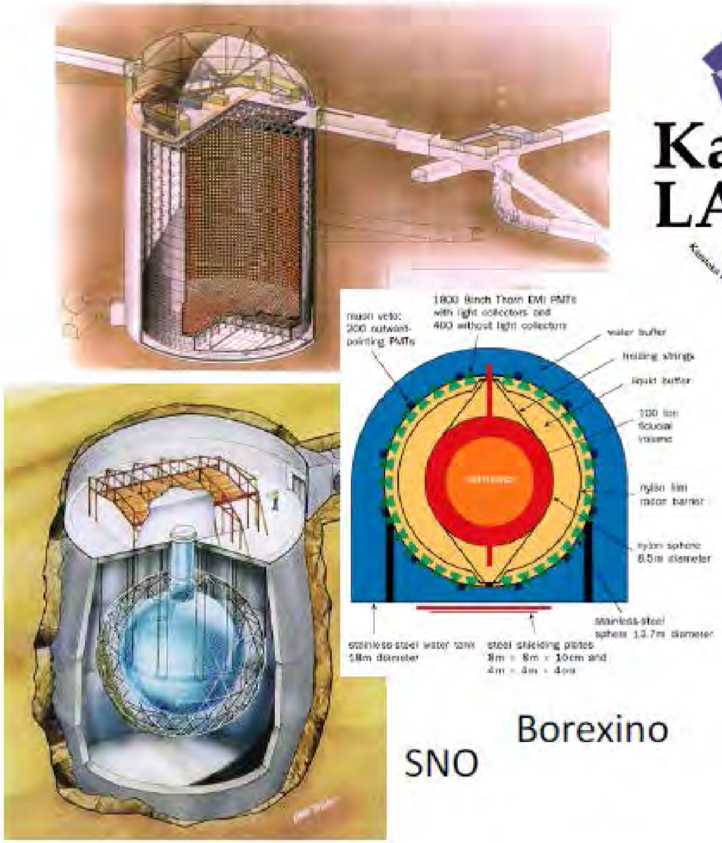
Accelerator neutrinos : 1962 established the family structure of the SM by Lederman, Schwartz, Steinberger



Collider neutrinos 90s'
LEP established 3 SM families

Almost 2 decades of revolutionary neutrino experiments have revealed a new flavour sector, which does not quite fit in the Standard Model

SuperKamiokande

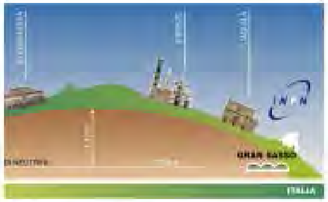


Borexino

SNO

Kam LAND

MINOS, Opera



T2K

NOvA

DOUBLE CHOOZ

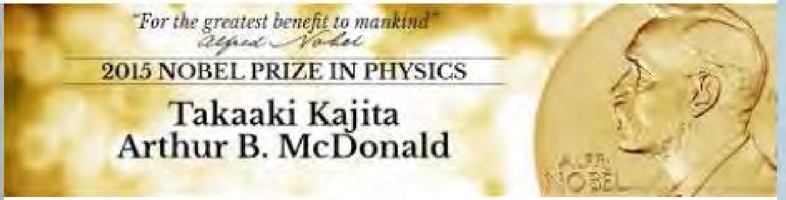
Daya Bay

θ13

RENO

…and more

"For the discovery of neutrino oscillations,
which shows that neutrinos have mass"



Neutrino oscillations constitutes the most recent experimental indication of physics beyond the Standard Model

Three neutrino mixing

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \left(1 - 2S_{13}^2\right)\right) \\ & + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\ & - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\ & + 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\ & - 8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right) \end{aligned}$$

Why so different mixing ?

CKM

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PDG

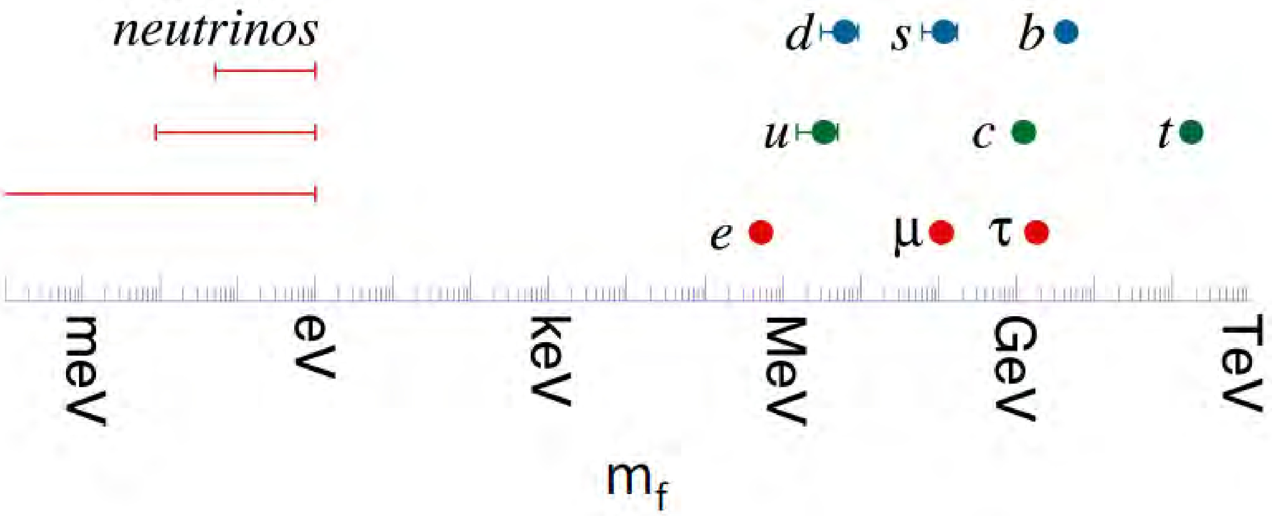
PMNS

$$|U|^{\rm LID}_{3\sigma} = \begin{pmatrix} 0.798 \to 0.843 & 0.517 \to 0.584 & 0.137 \to 0.158 \\ 0.232 \to 0.520 & 0.445 \to 0.697 & 0.617 \to 0.789 \\ 0.249 \to 0.529 & 0.462 \to 0.708 & 0.597 \to 0.773 \end{pmatrix}$$

NuFIT 2016

Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?

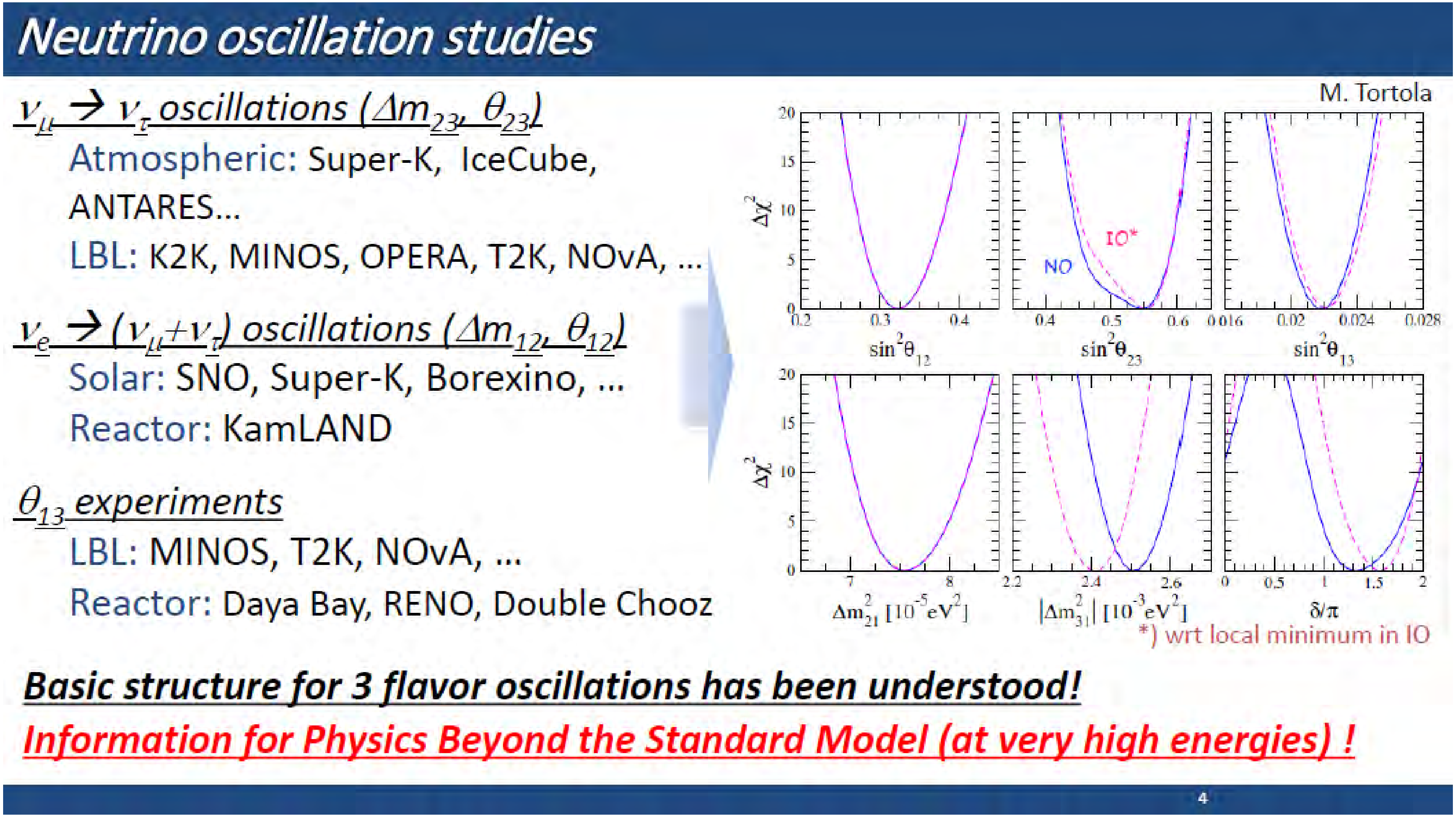


Why is there only matter and no antimatter in Universe?

The Sakharov conditions (necessary but not sufficient)
to explain the Baryon Asymmetry of the Universe (BAU):
1. At least one B-number violating process.
2. C- and CP-violation
3. Interactions outside of thermal equilibrium

Grand Unified Theories can fulfill the Sakharov conditions. However, in each m^3 of the Universe there are on average ca 10^9 photons, one proton and *no* antiproton. The CP violation measured in the quark sector is far too small (by a factor 10^9) to explain this 10^9 photon to baryon ratio.

Now, neutrino CP-violation, so far not observed, may very well be large enough to permit an explanation of BAU through the *leptogenesis* mechanism which relates the matter-antimatter asymmetry of the universe to neutrino properties: decays of heavy Majorana neutrinos generate a lepton asymmetry which is partly converted to a baryon asymmetry via sphaleron processes.



Neutrino oscillation studies

$\nu_\mu \rightarrow \nu_\tau$ oscillations (Δm_{23}, θ_{23})

Atmospheric: Super-K, IceCube, ANTARES…

LBL: K2K, MINOS, OPERA, T2K, NOvA, …

$\nu_e \rightarrow (\nu_\mu + \nu_\tau)$ oscillations (Δm_{12}, θ_{12})

Solar: SNO, Super-K, Borexino, …

Reactor: KamLAND

θ_{13} experiments

LBL: MINOS, T2K, NOvA, …

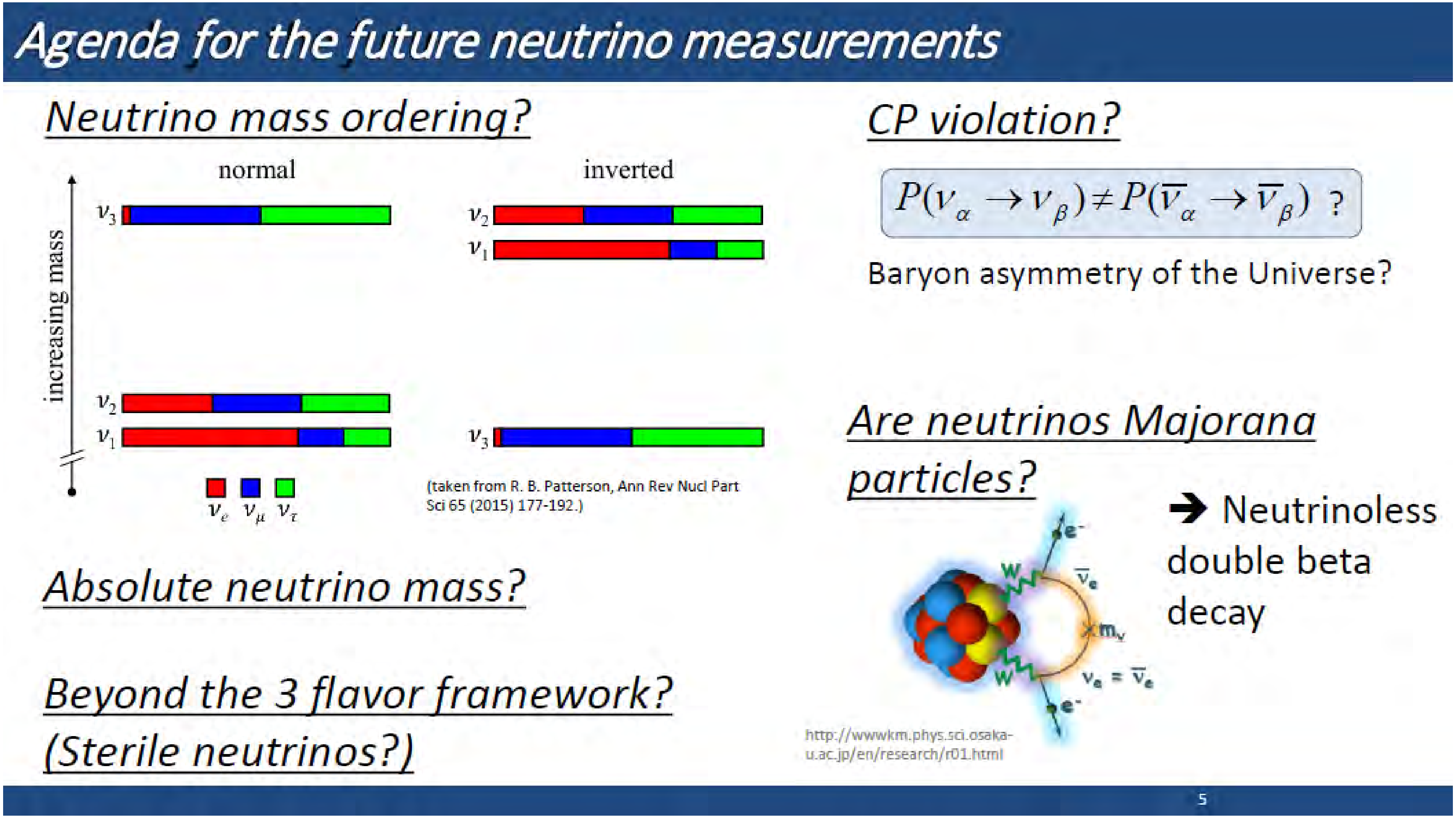
Reactor: Daya Bay, RENO, Double Chooz

M. Tortola

*) wrt local minimum in IO

Basic structure for 3 flavor oscillations has been understood!

Information for Physics Beyond the Standard Model (at very high energies) !



Agenda for the future neutrino measurements

Neutrino mass ordering?

(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

Absolute neutrino mass?

Beyond the 3 flavor framework? (Sterile neutrinos?)

CP violation?

$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \ ?$$

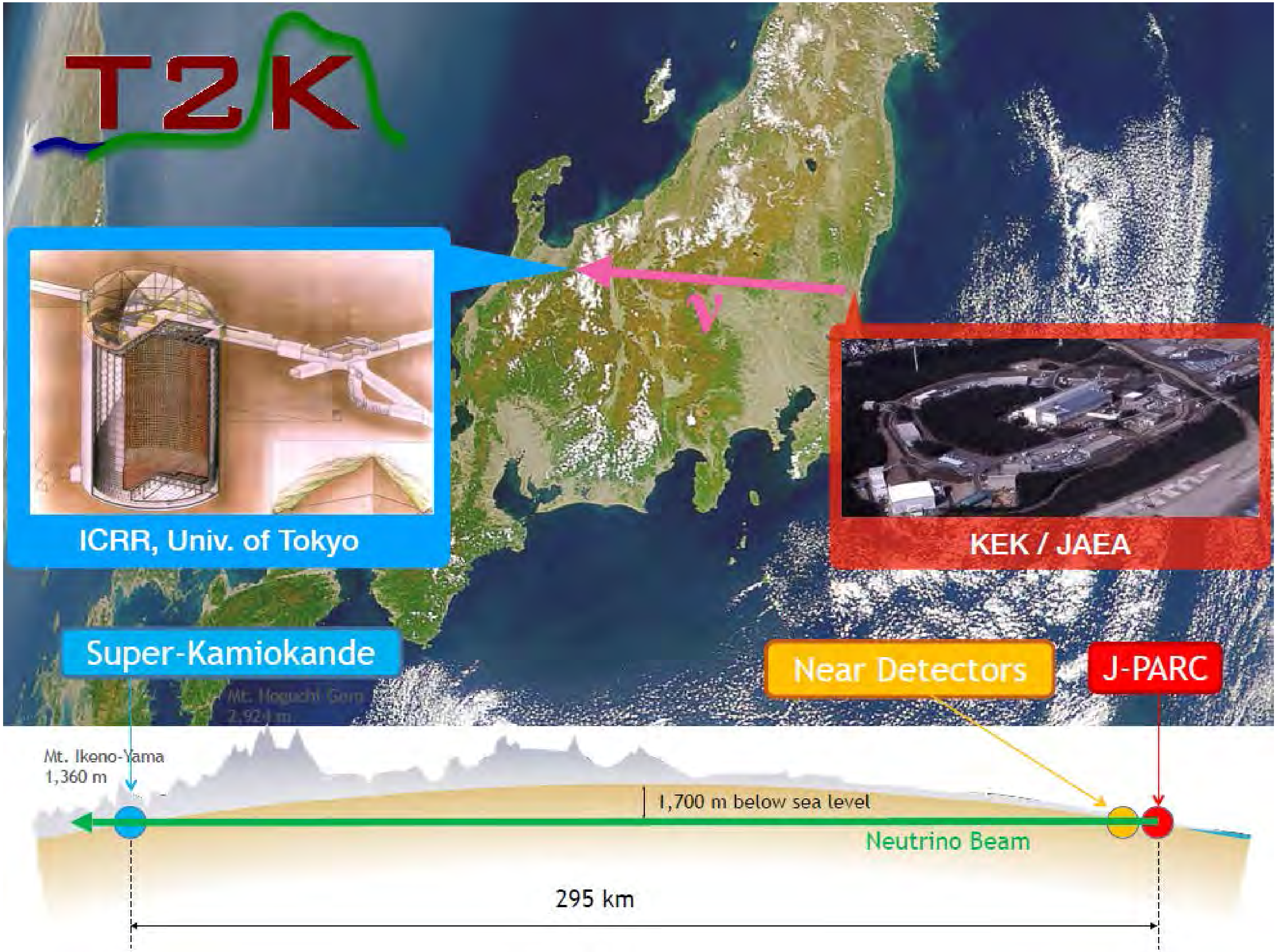
Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?

➔ Neutrinoless double beta decay

http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

Current long baseline experiments

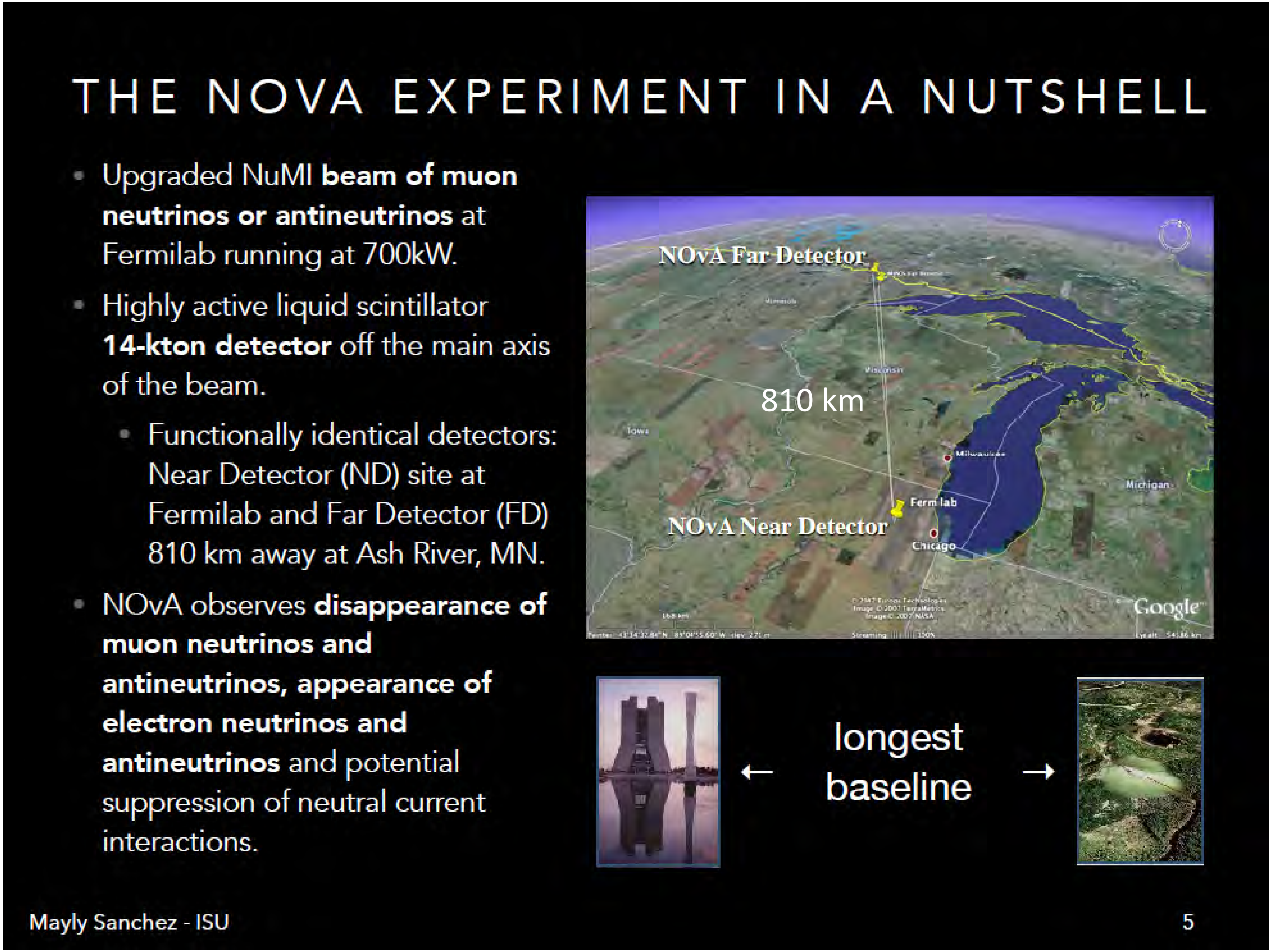

T2K
ICRR, Univ. of Tokyo
ν
KEK / JAEA
Super-Kamiokande
Mt. Noguchi Goro
2,924 m
Near Detectors
J-PARC
Mt. Ikeno-Yama
1,360 m
1,700 m below sea level
Neutrino Beam
295 km

The T2K SuperK-Kamiokande Detector

38 m diameter, 42 m hight

22.5 kton fiducial water volume

11 000 photmultplier tubes



THE NOVA EXPERIMENT IN A NUTSHELL

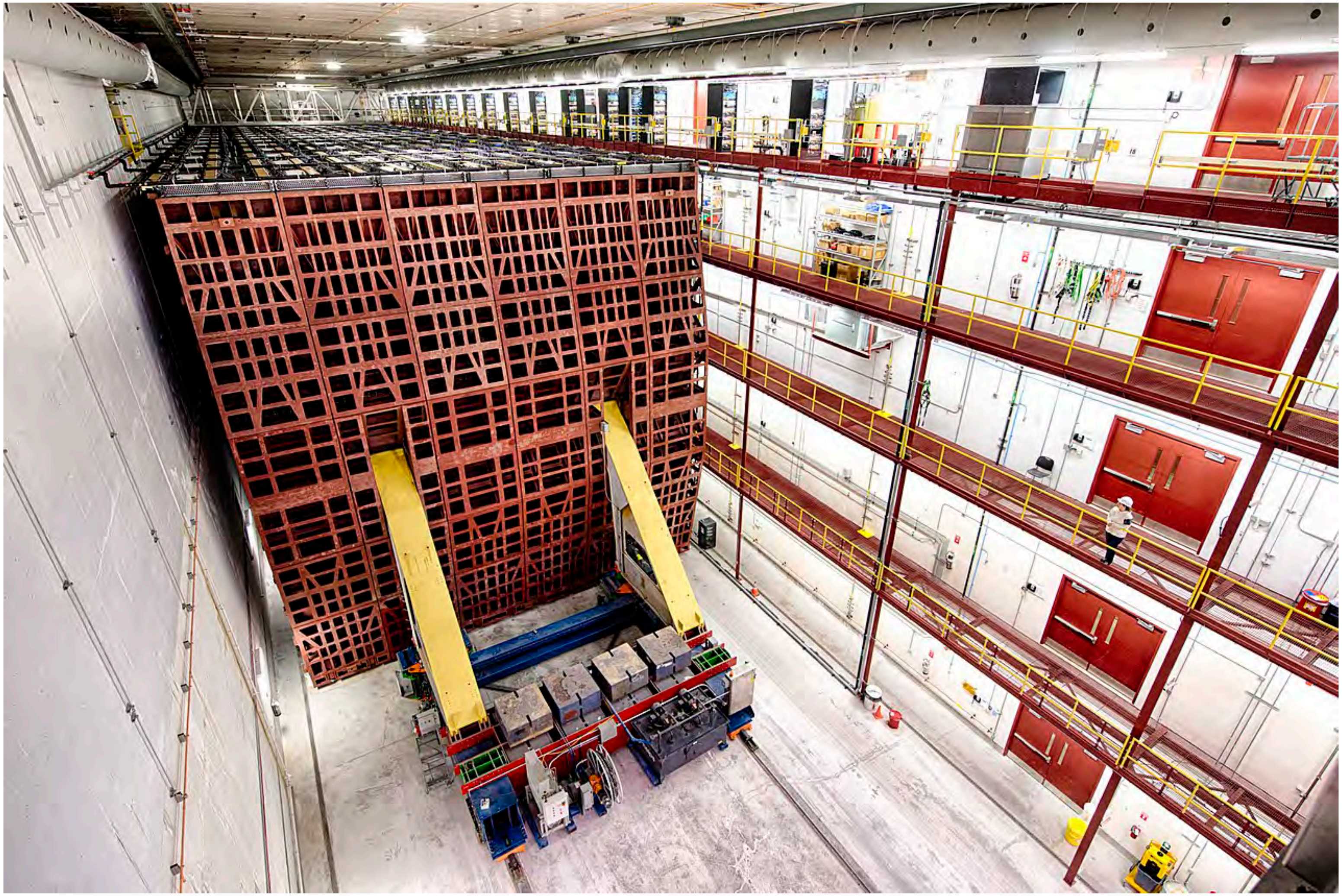
- Upgraded NuMI **beam of muon neutrinos or antineutrinos** at Fermilab running at 700kW.
- Highly active liquid scintillator **14-kton detector** off the main axis of the beam.
  - Functionally identical detectors: Near Detector (ND) site at Fermilab and Far Detector (FD) 810 km away at Ash River, MN.
- NOvA observes **disappearance of muon neutrinos and antineutrinos, appearance of electron neutrinos and antineutrinos** and potential suppression of neutral current interactions.

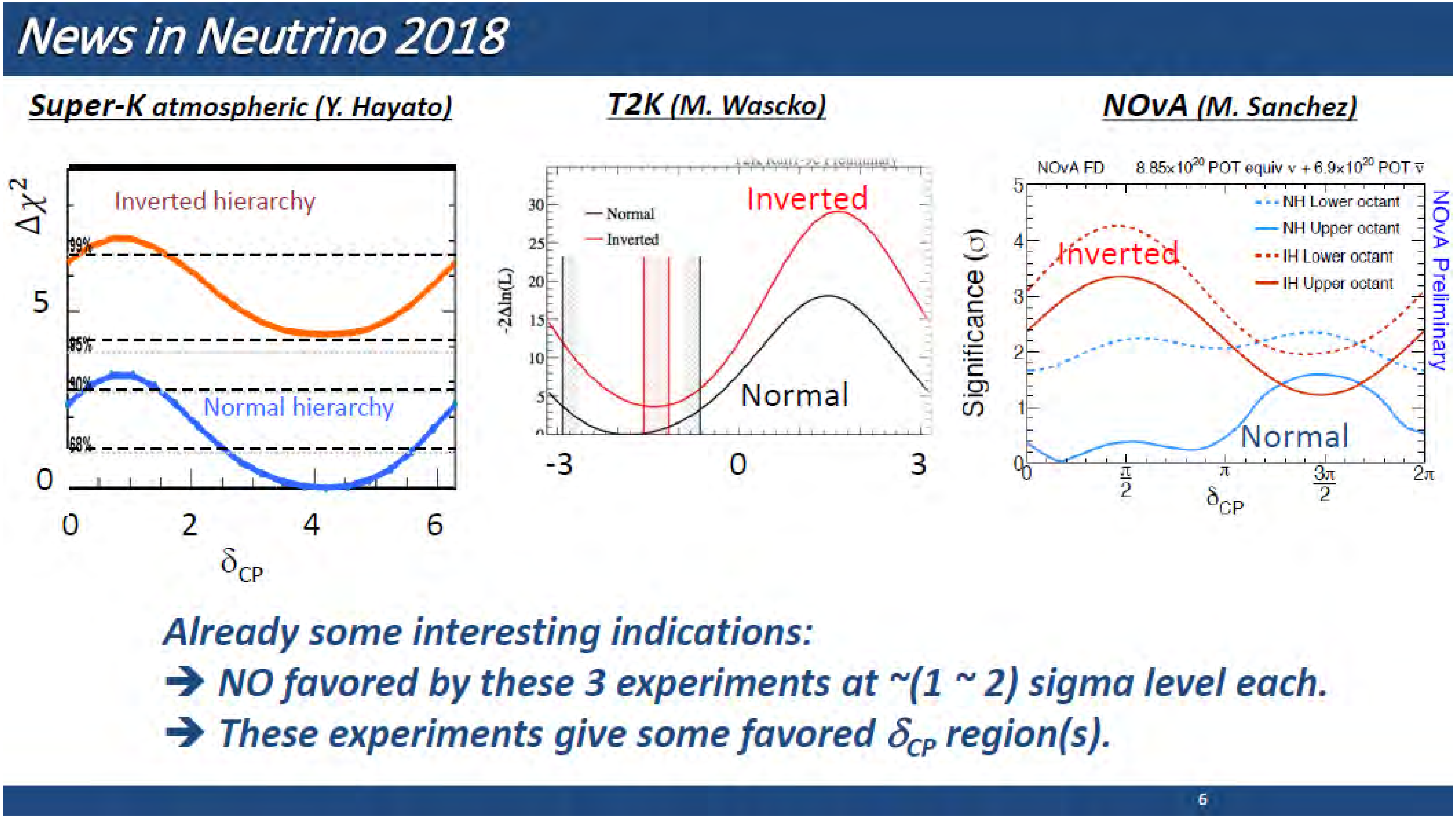
← longest baseline →

Mayly Sanchez - ISU

5

The NOvA Detector





News in Neutrino 2018

Super-K atmospheric (Y. Hayato)

T2K (M. Wascko)

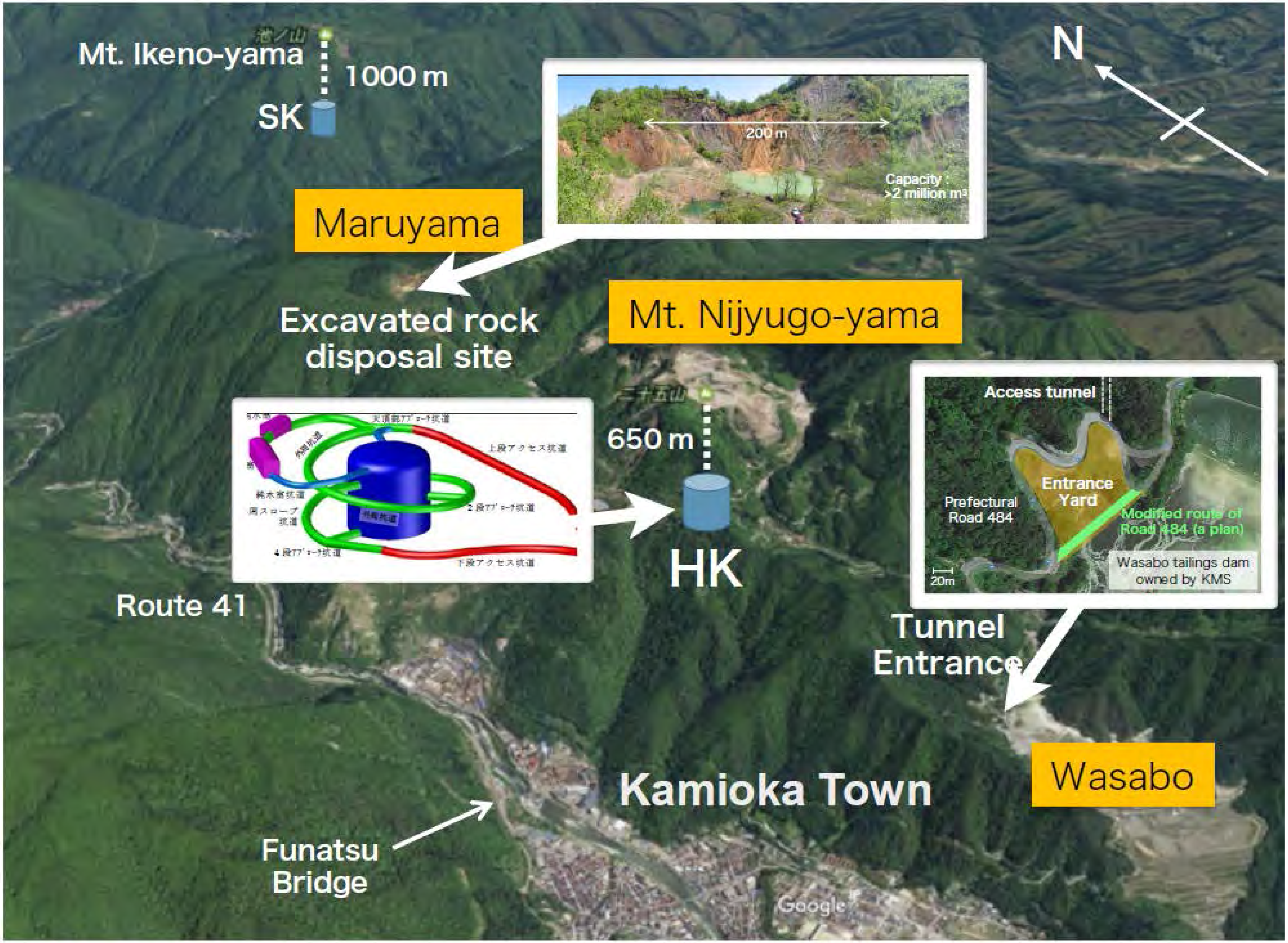
NOvA (M. Sanchez)

Already some interesting indications:

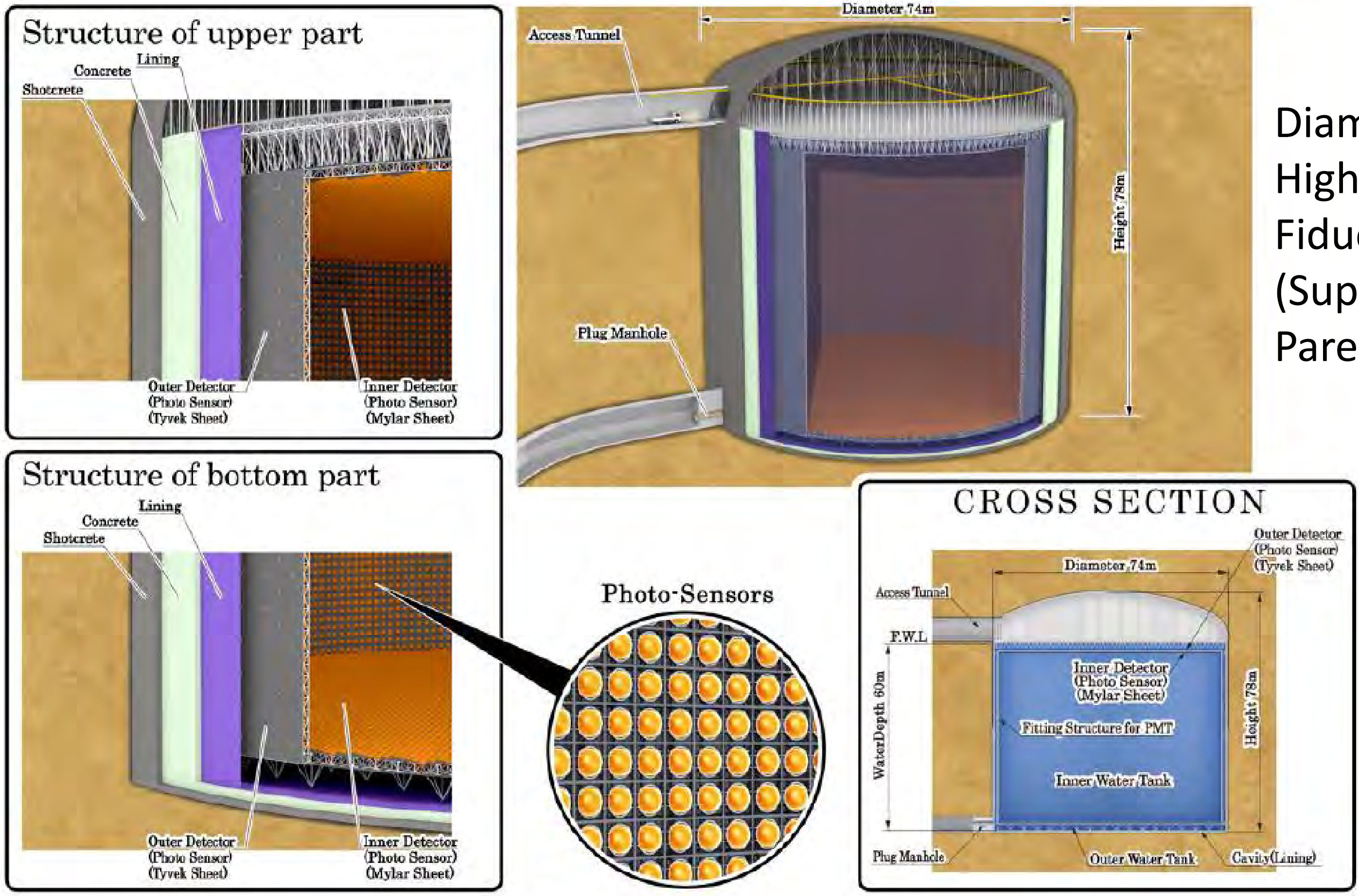
- ➔ *NO favored by these 3 experiments at ~(1 ~ 2) sigma level each.*
- ➔ *These experiments give some favored δ_{CP} region(s).*

Proposed future long baseline experiments

1. Hyper-Kamiokande



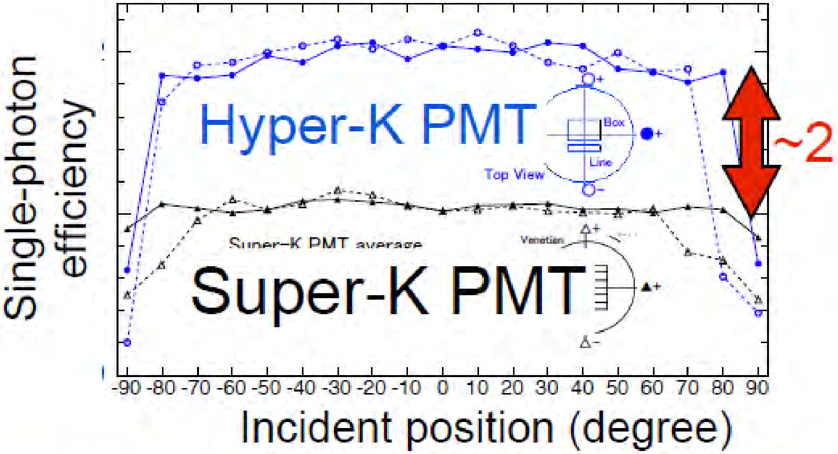
The Hyper-Kamiokande Detector



Diameter 74 (39) m
Hight 60 (42) m
Fiducial mass 187(22.5) ton
(Super-K figures in
Parenthesis)

Hyper-Kamiokande Photo-sensor R&D

- sensitivity: 2 x SK
- Time resolution: 1/2 x SK
- Pressure: 2 x SK



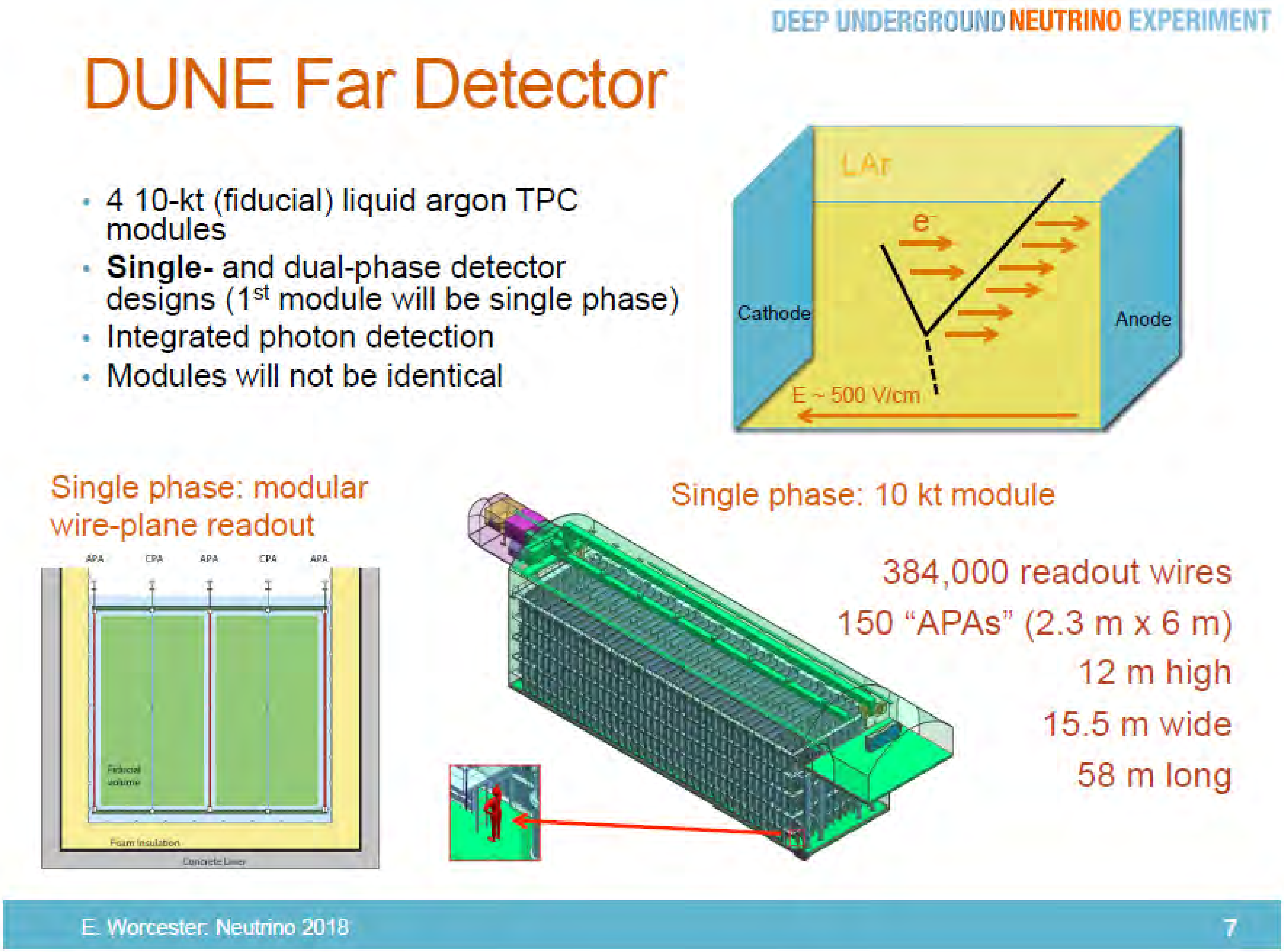
- ~140 new PMTs will be installed in Super-K this summer
  - Performance check w/ Cherenkov light, for years
- Continuous effort for improvements
  - Noise reduction, Cover design, Light concentrator under study

DEEP UNDERGROUND NEUTRINO EXPERIMENT

2. DUNE Experiment

Observe ν_e appearance and ν_μ disappearance at long baseline in wideband beam to measure MH, CPV, and neutrino mixing parameters in a single experiment. Deep underground location reduces cosmogenic background and enables sensitivity to low-energy physics.

E. Worcester: Neutrino 2018 4



DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE Far Detector

- 4 10-kt (fiducial) liquid argon TPC modules
- **Single-** and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical

Single phase: modular wire-plane readout

Single phase: 10 kt module

384,000 readout wires
150 “APAs” (2.3 m x 6 m)
12 m high
15.5 m wide
58 m long

E. Worcester: Neutrino 2018 7

DEEP UNDERGROUND NEUTRINO EXPERIMENT

EHN1 at CERN

Dual phase cryostat

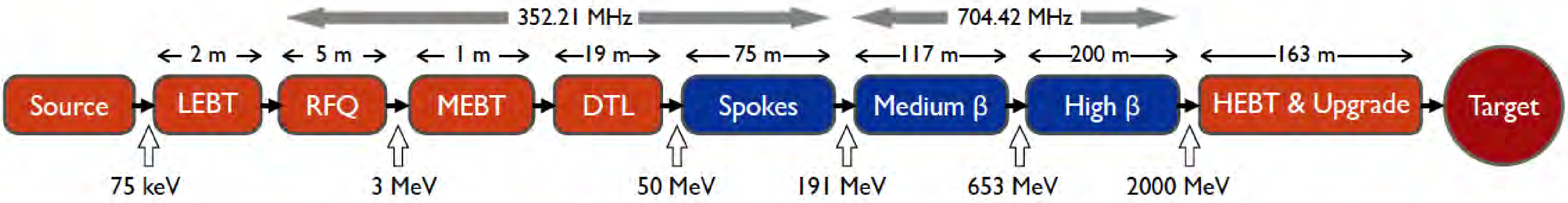
Single phase clean room and cold box

Single phase cryostat

E. Worcester Neutrino 2018 30

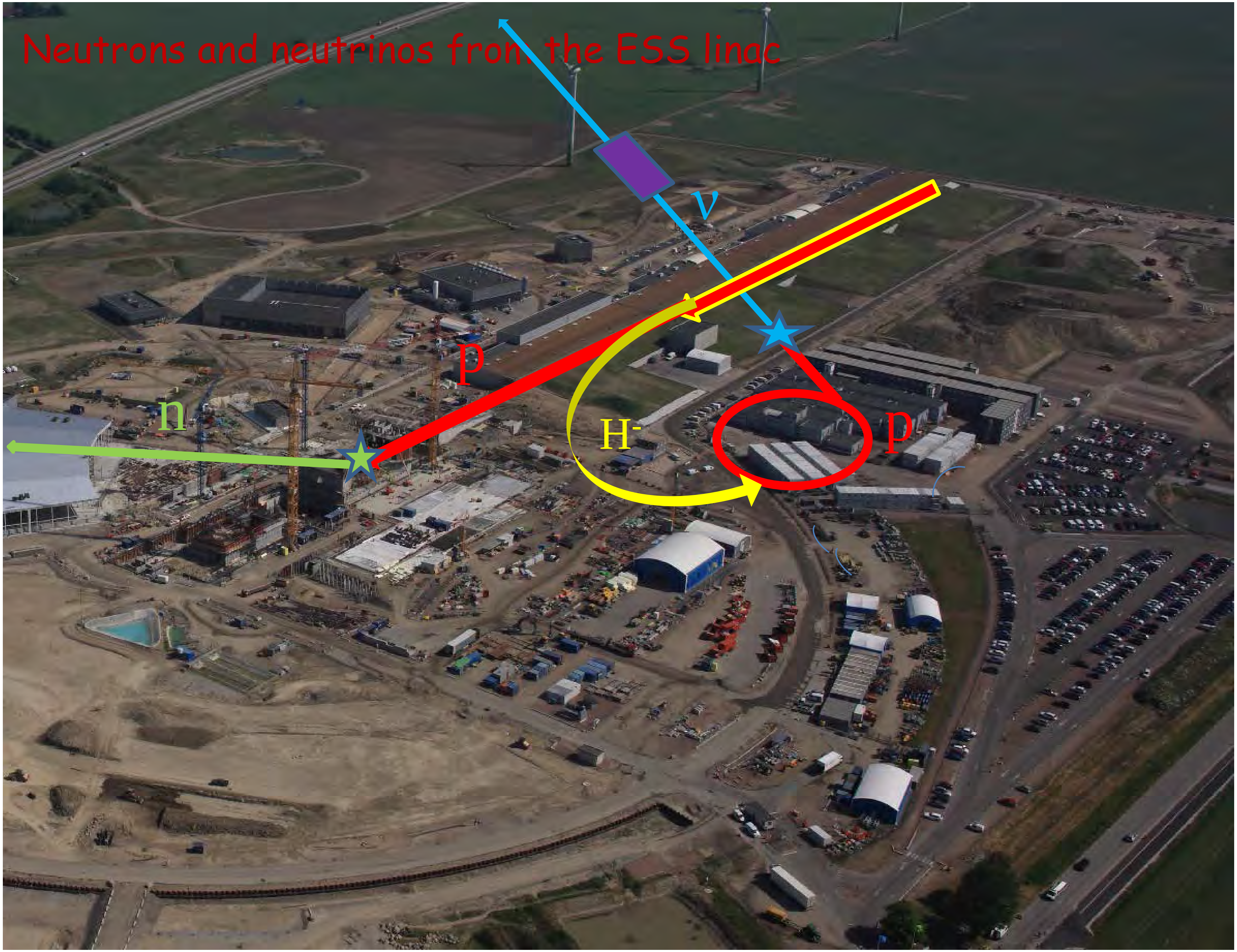
3. ESSnuSB

based on the use of the world-uniquely high power ESS linac



- The ESS will be a copious source of spallation neutrons.
- **5 MW average beam power**
- 125 MW peak power
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons)
- Duty cycle 4%
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

Neutrons and neutrinos from the ESS linac

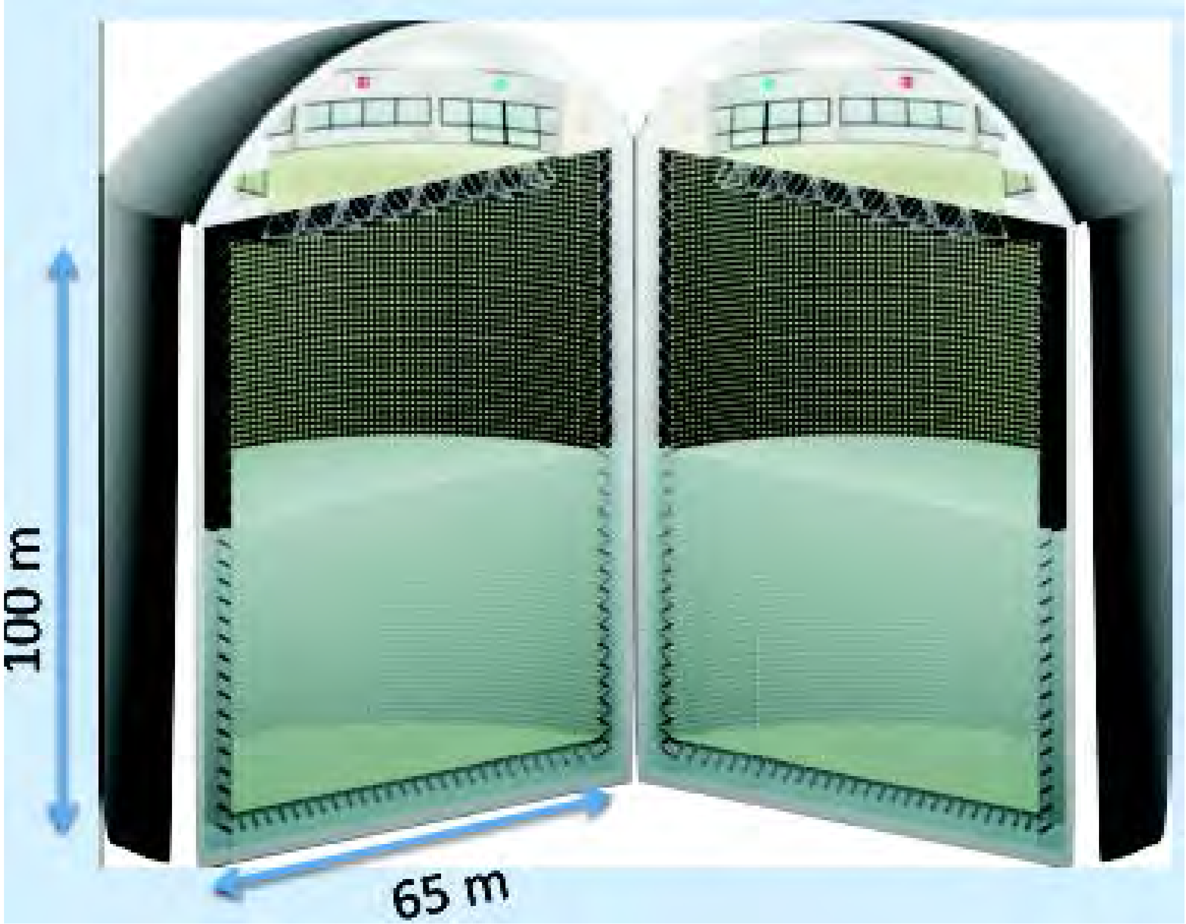


The EUROnu MEMPHYS MegatonWater Cherenkov Detector

MEMPHYS like Cherenkov detector(MEgaton Mass PHYSics studied by LAGUNA)

- 500 kt fiducial volume with two units
- Readout: ~240k 8” PMTs
- 30% optical coverage

(arXiv: hep-ex/0607026)



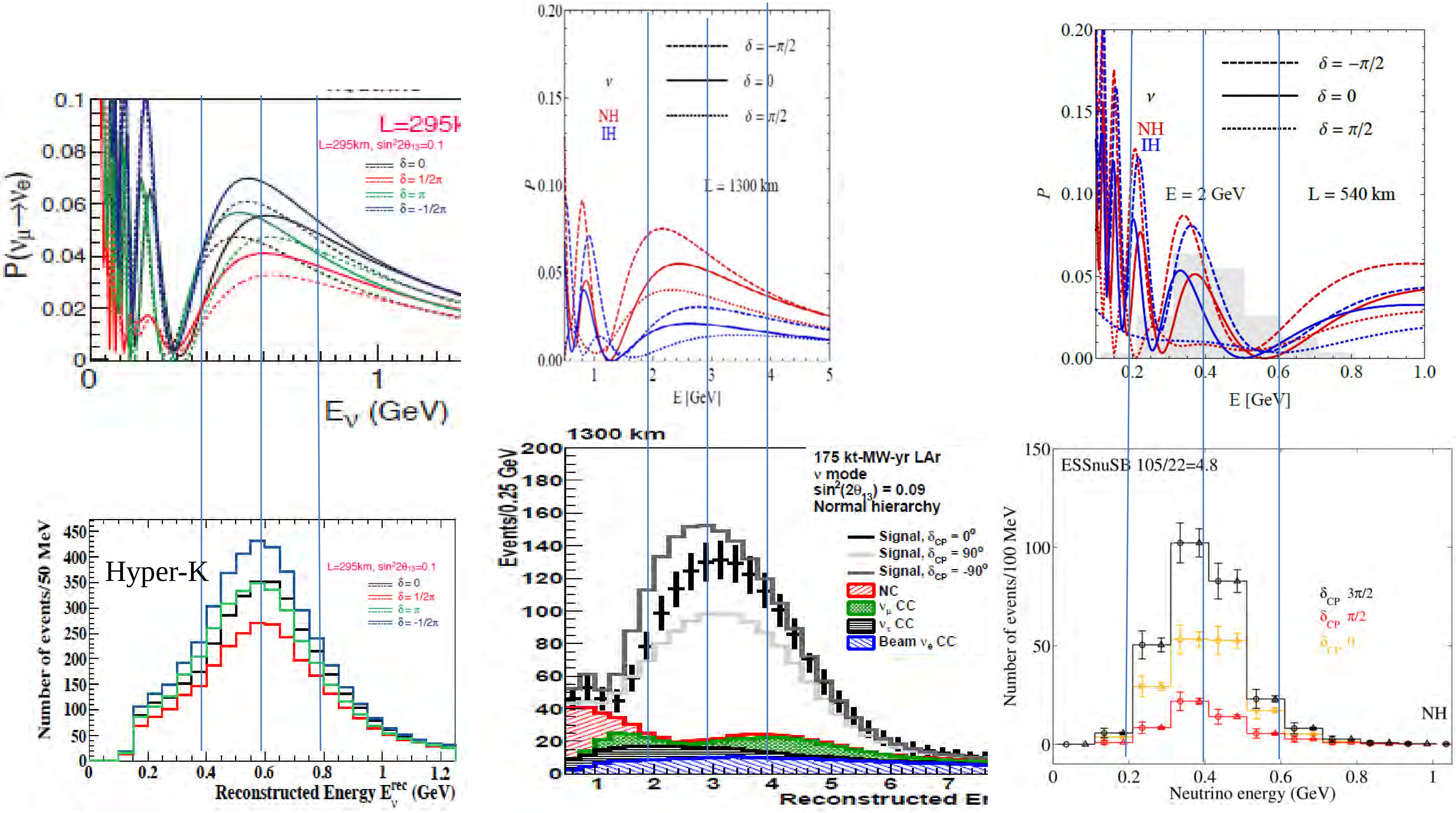
The high power of the ESS linac makes it possible to generate a neutrino beam intense enough to place the far detector at the *second oscillation maximum* where the CP signal is 3 times higher than at the first. With the ESSnuSB neutrino energy this implies a distance of ca 500 km. The 1000 m deep Garpenberg mine is located 540 km from ESS.

The sensitivity of the neutrino energy distribution to δ_{CP}

Hyper-K first maximum

LBNE/DUNE first maximum

ESSnuSB second maximum



Relative difference in counts at maximum between δ_{CP} = 3π/2 and π/2 :

430/275 = 1.6

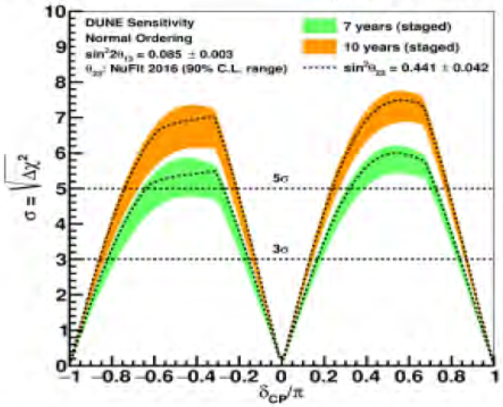
150/100 = 1.5

105/22 = 4.8

Performance of the three future experiments for CP discovery

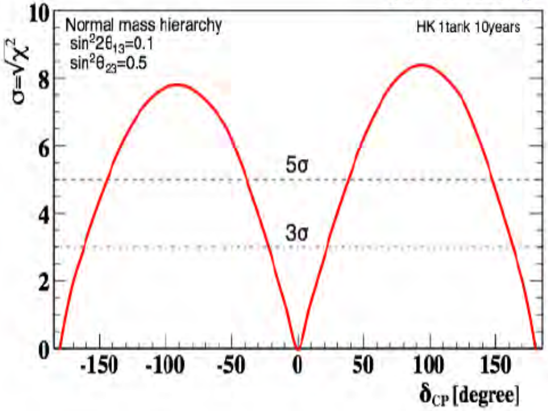
DUNE

(E. Worcester)

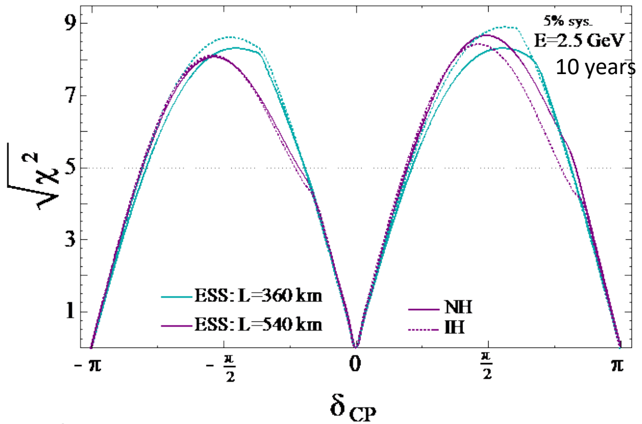


Hyper-K

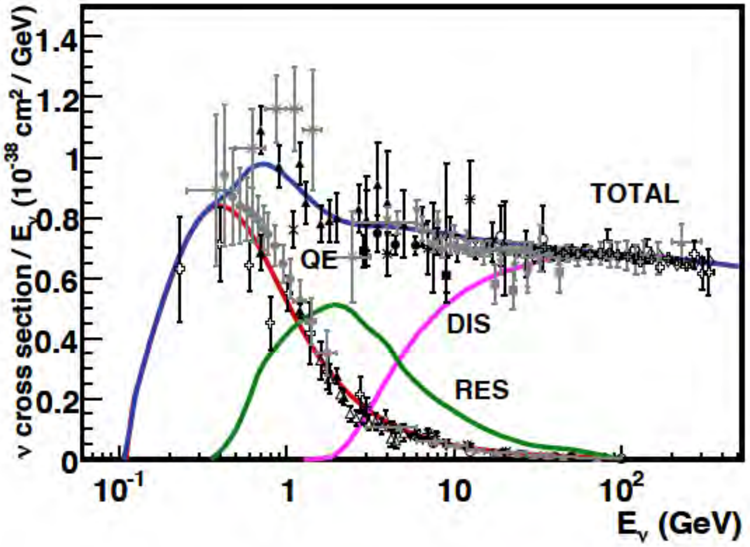
(M. Shiozawa)

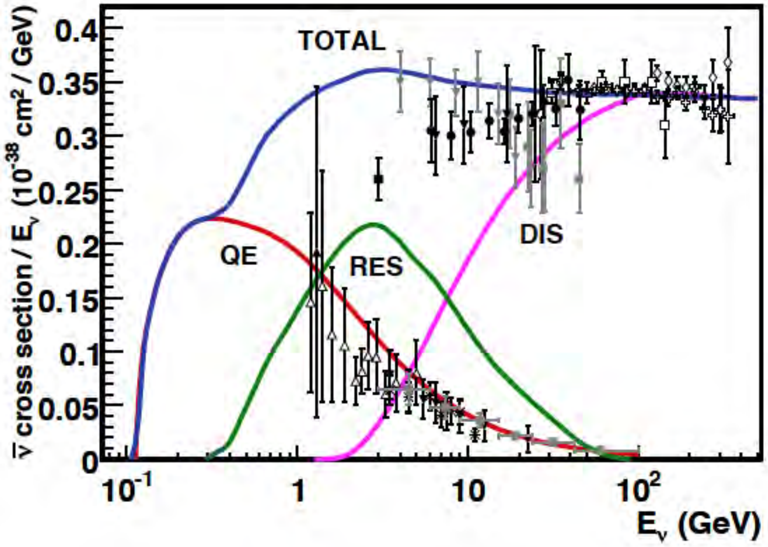


ESSnuSB



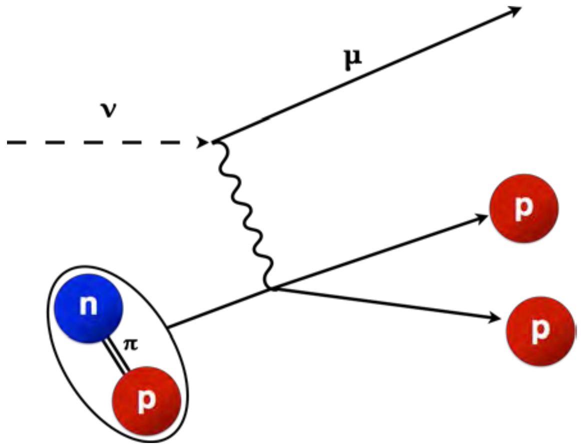
The performance appears to be on the same level for the three experiments.
The performance depends on what the specific backgrounds are and what level of systematic errors that are assumed in the simulations.

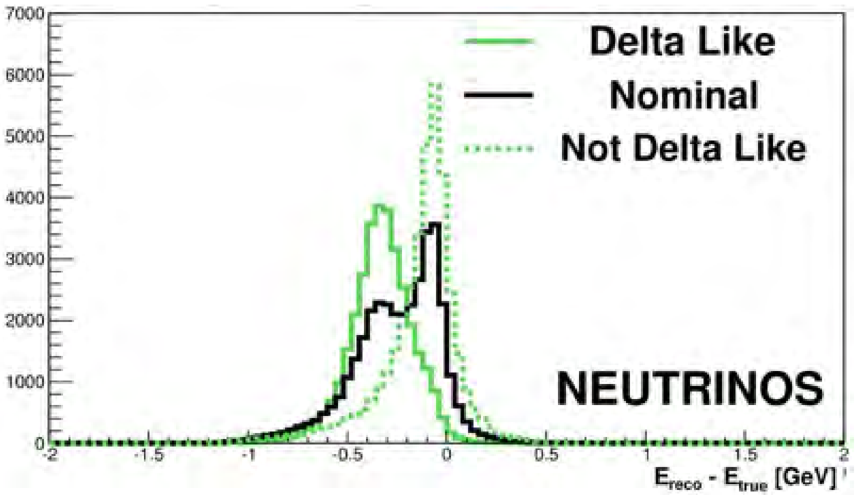




Systematic error sources

1. ν_e in the beam from K and μ decays
2. Events with π^o and γ production
3. ν_μ misidentified as ν_e
4. ν-nucleus cross-section uncertainty for QE, RES and DIS scattering
5. E_ν reconstruction error due to multi-nucleon effects



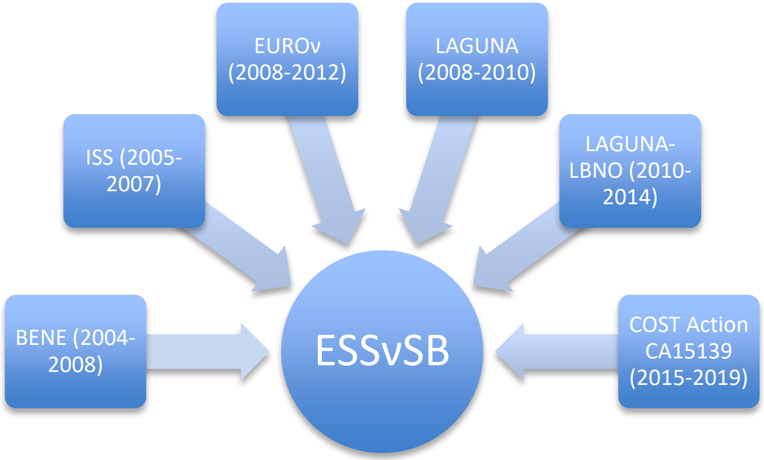


Super-K has achieved a **systematic error level of 5-6%** after ca 10 years of operation using a by now very sophisticated Near Detector.

I would like to use this occasion to make a personal invitation to African physicists to join the Europe based ESSnuSB project

EU Design Study for ESSnuSB approved by EU in December 2017 for 2018-2021

- **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
- **Duration: 4 years**
- **Total cost: 4.7 M€**
- **Requested budget: 3 M€**
- 15 participating institutes from
  11 European countries including CERN and ESS
- 6 Work Packages


EUROν (2008-2012)

LAGUNA (2008-2010)

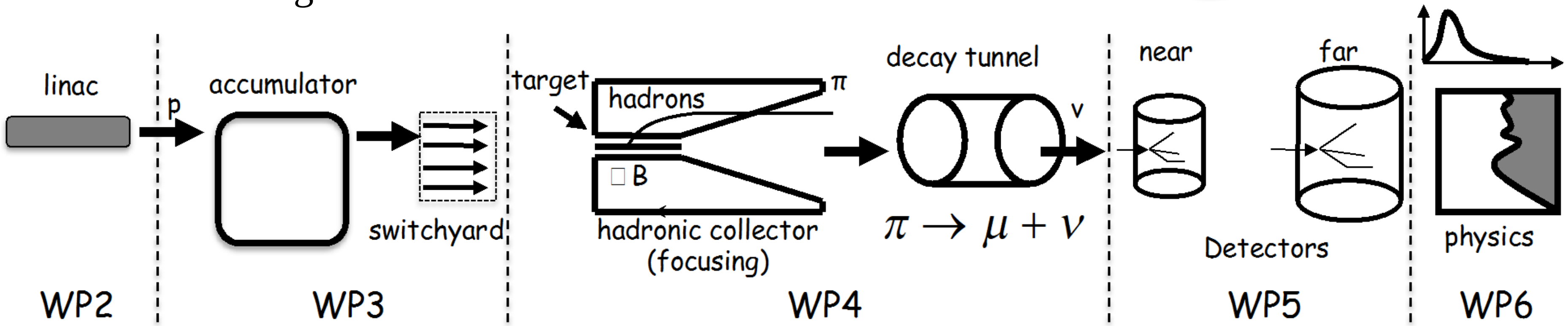
ISS (2005-2007)

LAGUNA-LBNO (2010-2014)

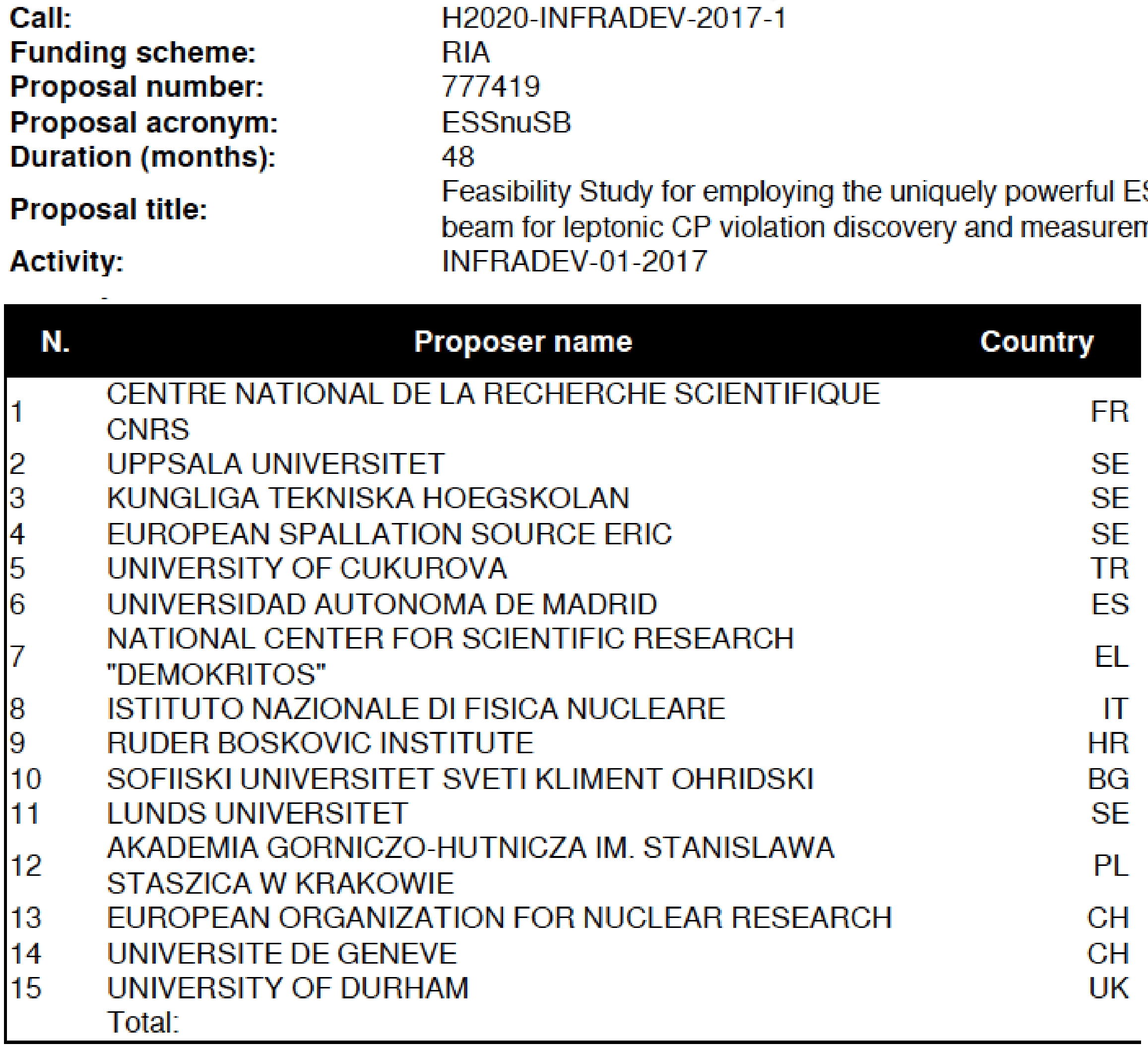
BENE (2004-2008)

ESSνSB

COST Action CA15139 (2015-2019)



Design Study ESSνSB (2018-2021)



Call:	H2020-INFRADEV-2017-1
Funding scheme:	RIA
Proposal number:	777419
Proposal acronym:	ESSnuSB
Duration (months):	48
Proposal title:	Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.
Activity:	INFRADEV-01-2017

N.	Proposer name	Country
1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UPPSALA UNIVERSITET	SE
3	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
4	EUROPEAN SPALLATION SOURCE ERIC	SE
5	UNIVERSITY OF CUKUROVA	TR
6	UNIVERSIDAD AUTONOMA DE MADRID	ES
7	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
8	ISTITUTO NAZIONALE DI FISICA NUCLEARE	IT
9	RUDER BOSKOVIC INSTITUTE	HR
10	SOFIISKI UNIVERSITET SVETI KLIMENT OHRIDSKI	BG
11	LUNDS UNIVERSITET	SE
12	AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	PL
13	EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH	CH
14	UNIVERSITE DE GENEVE	CH
15	UNIVERSITY OF DURHAM	UK
	Total:	

Very supportive letter from ESS director

ESSνSB has already started engaging postdocs.

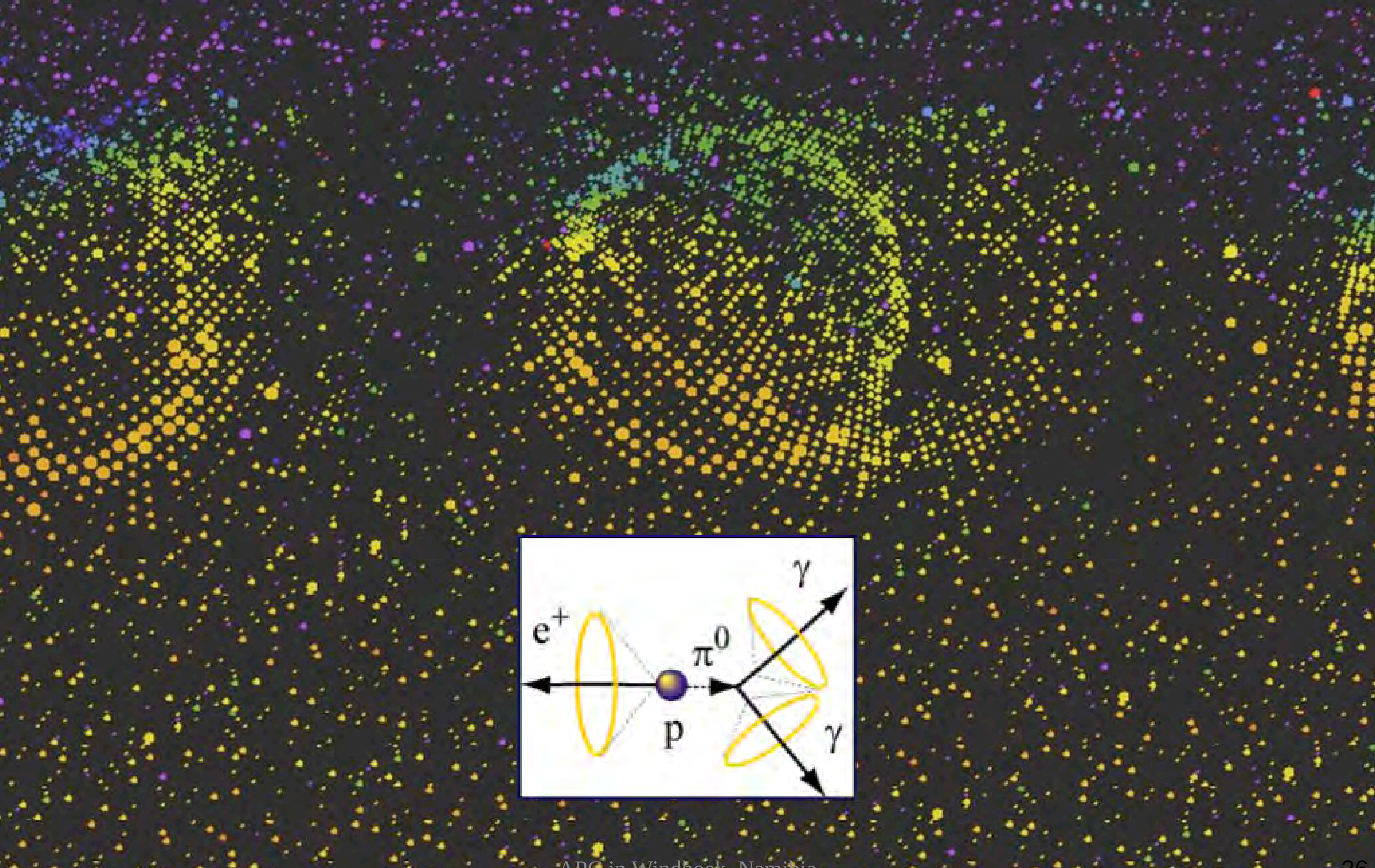
partners: IHEP, BNL, SCK•CEN, SNS, PSI, RAL

Concluding remarks

- **Neutrino oscillations constitute the most recent experimental indication of physics beyond the Standard Model**
- **Leptonic CP violation discovery and measurement appears as achievable with the new generation of proposed long baseline experiment and would shed light on one of the outstanding problems of fundamental physics: why is there matter in Universe – and not just light.**
- **The proposals for the these complementary long baseline experiments should therefore be pursued with highest priority.**
- **There are a number of other outstanding questions in neutrino physics – neutrino mass ordering, sterile neutrinos, neutrino absolute mass scale, Majorana neutrinos, heavy ”see-saw”partners of the light neutrinos, what can we learn from cosmic neutrinos – that it was regretfully not possible to review within this brief presentation.**

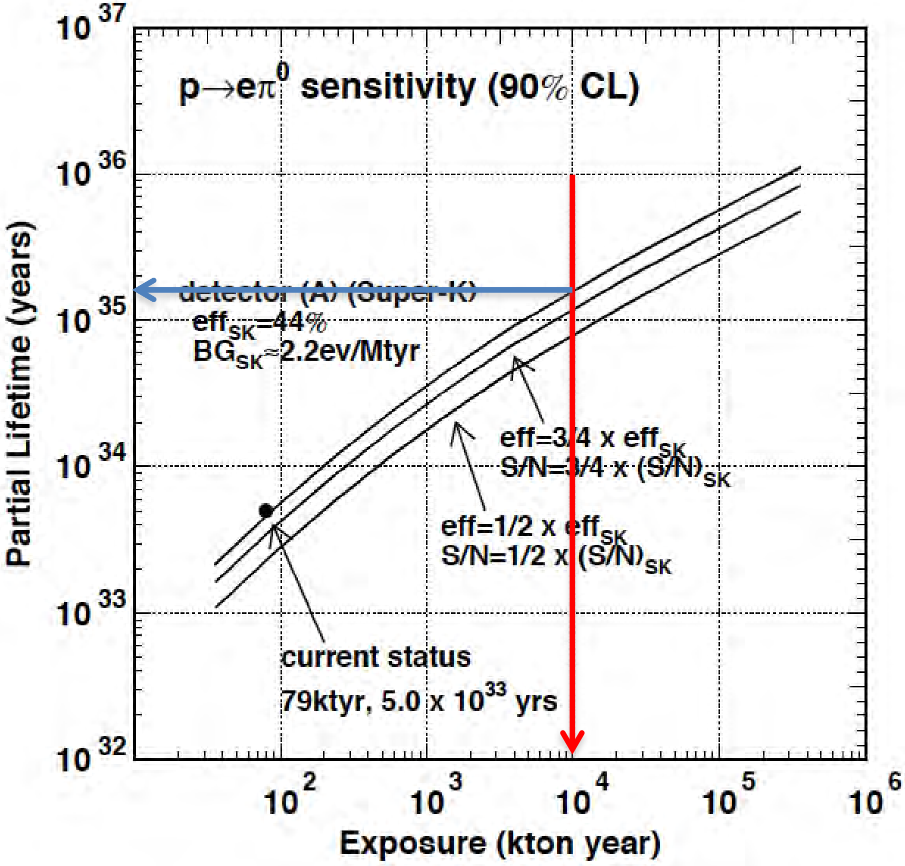
A few backup slides on other important problems that will be studied with the proposed long baseline experiments

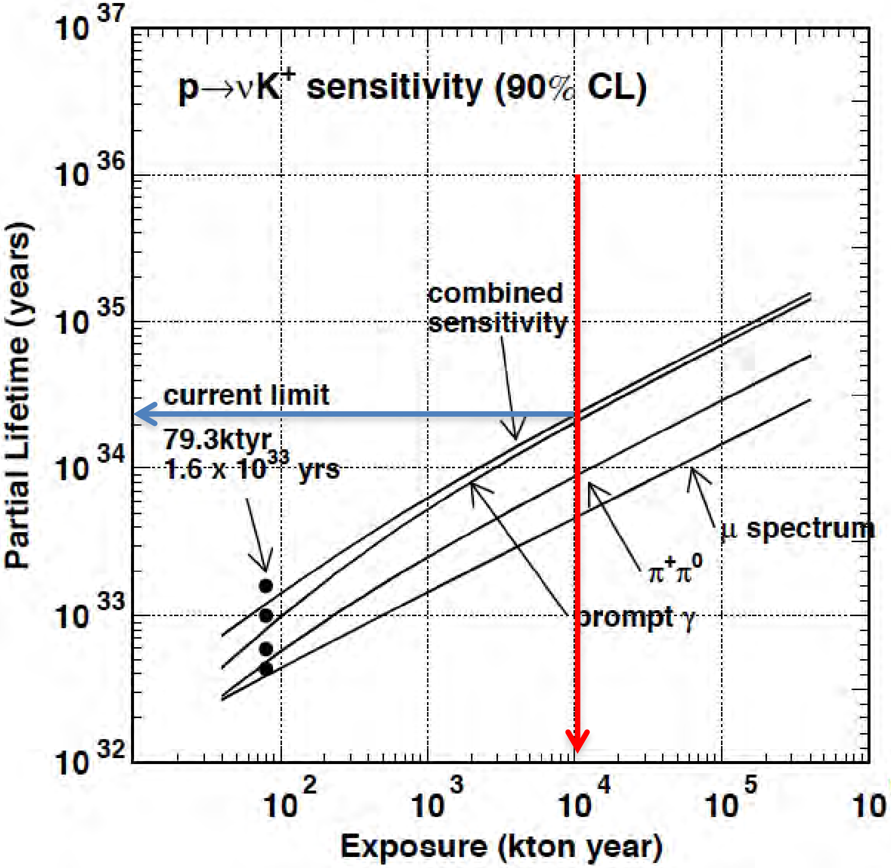
Proton Decay



ESSnuSB-MEMPHYS sensitivities

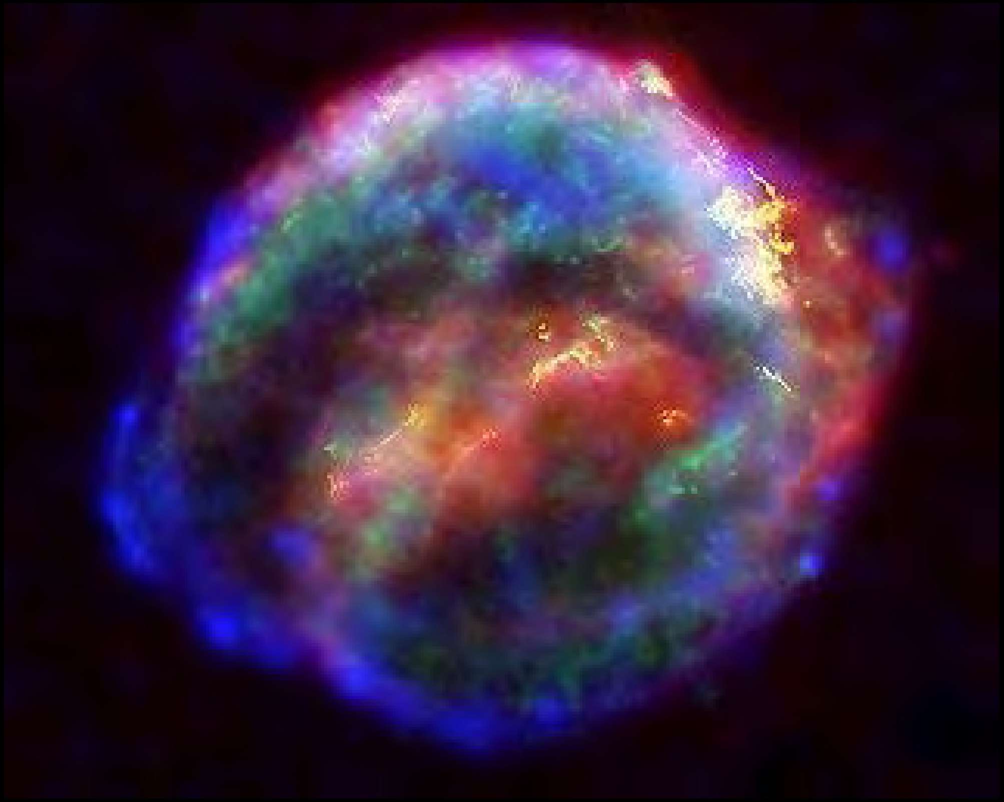
proton decay





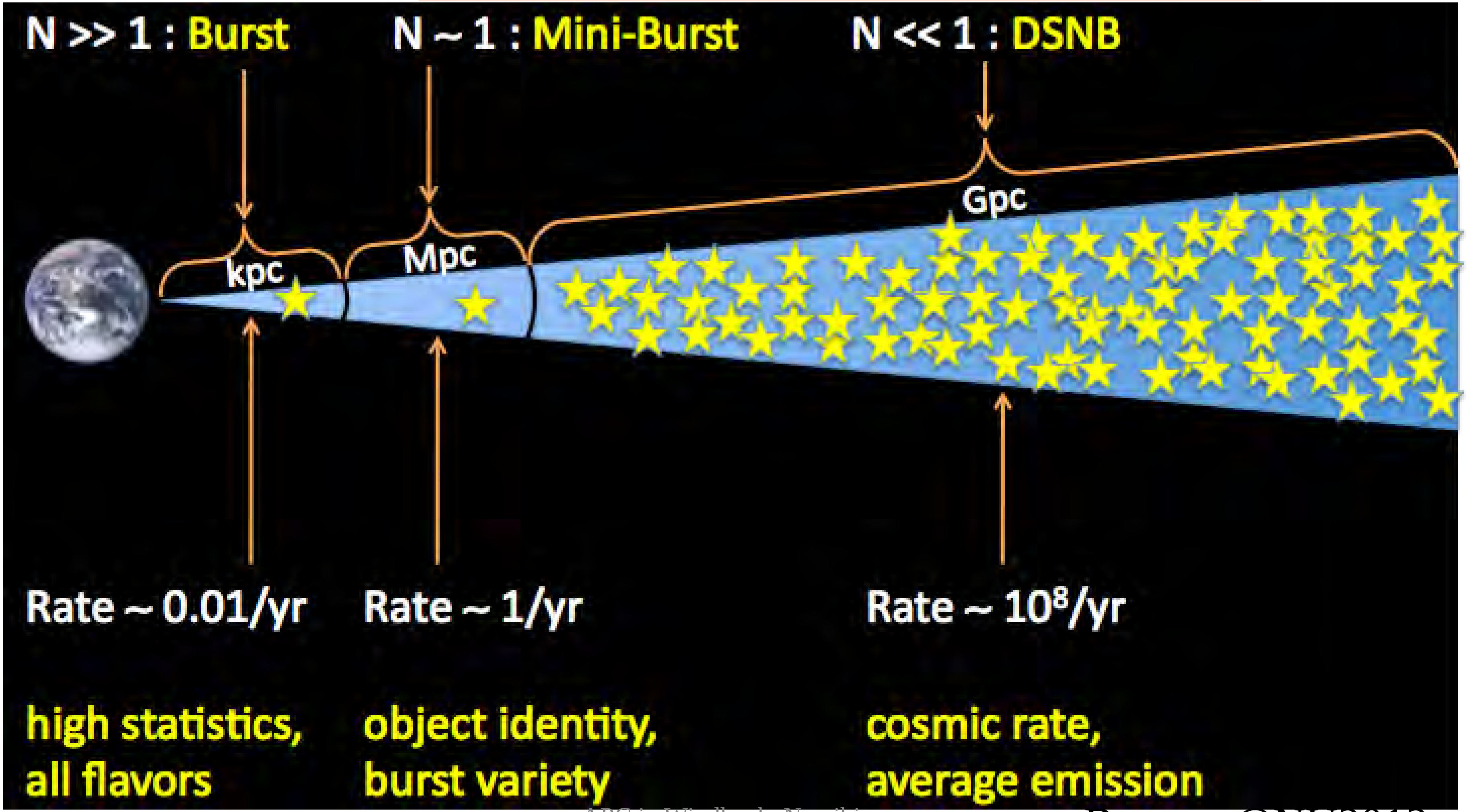
(arXiv: hep-ex/0607026)

Supernova



Distance scale and exp'd rate

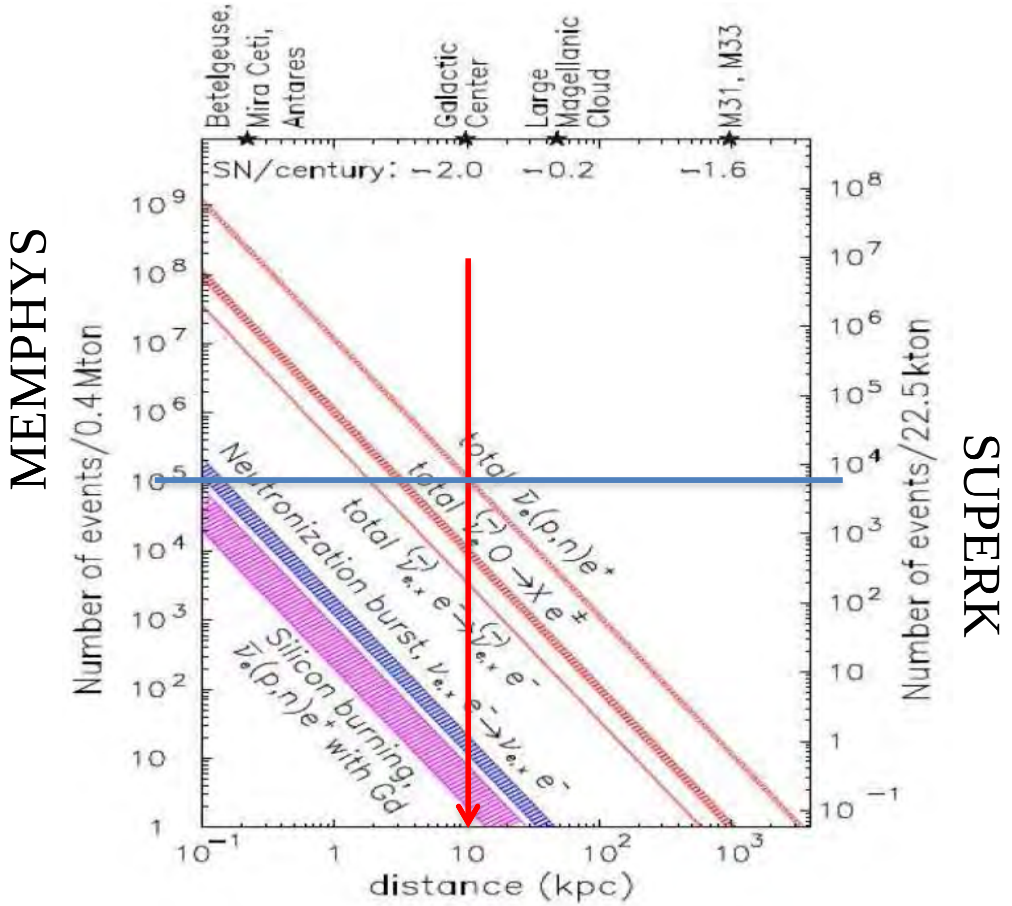
Milky way Nearby galaxies Distant galaxies

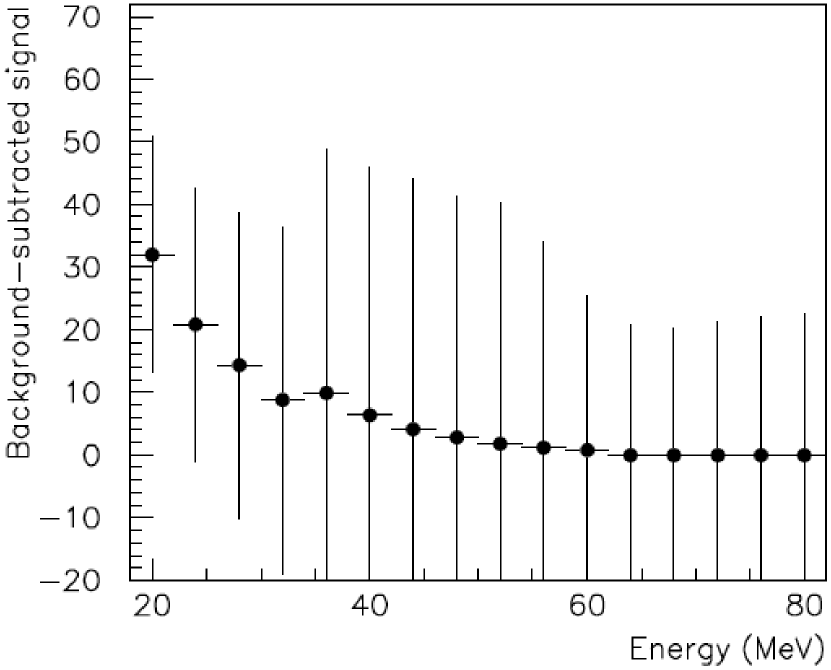


Beacom@NU2012

ESSnuSB-MEMPHYS sensitivities

Supernova explosion and relics





Diffuse Supernova Neutrinos
(10 years, 440 kt)

For 10 kpc: ~10^5 events