Neutrino Physics and Requirements to Accelerators

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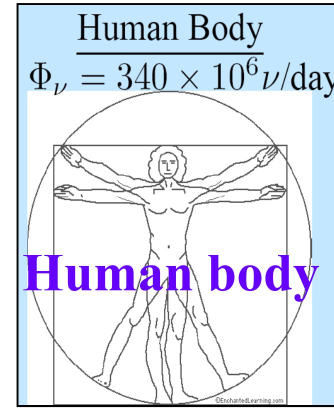
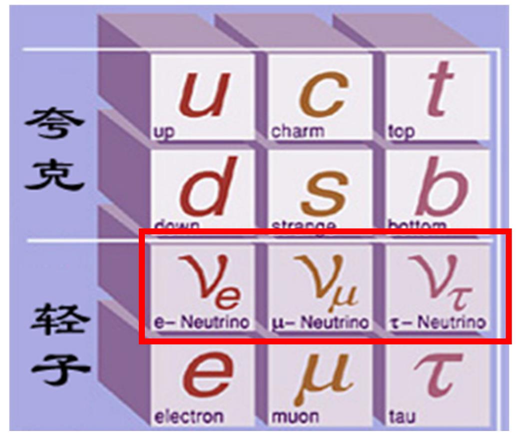
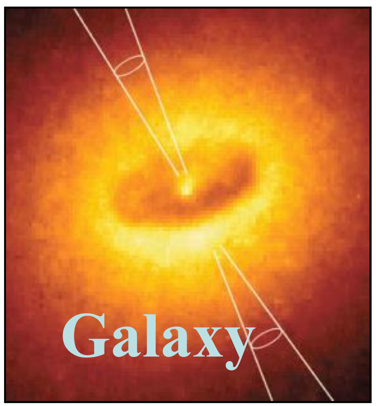
Neutrinos around us

Astrophysics

Geology



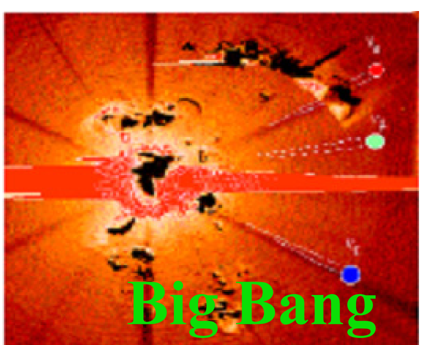


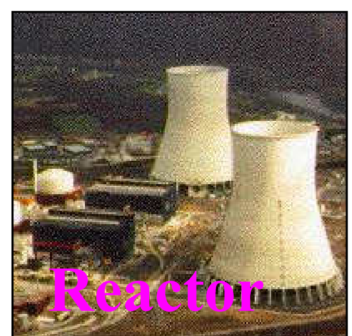


Cosmology

Nuclear physics

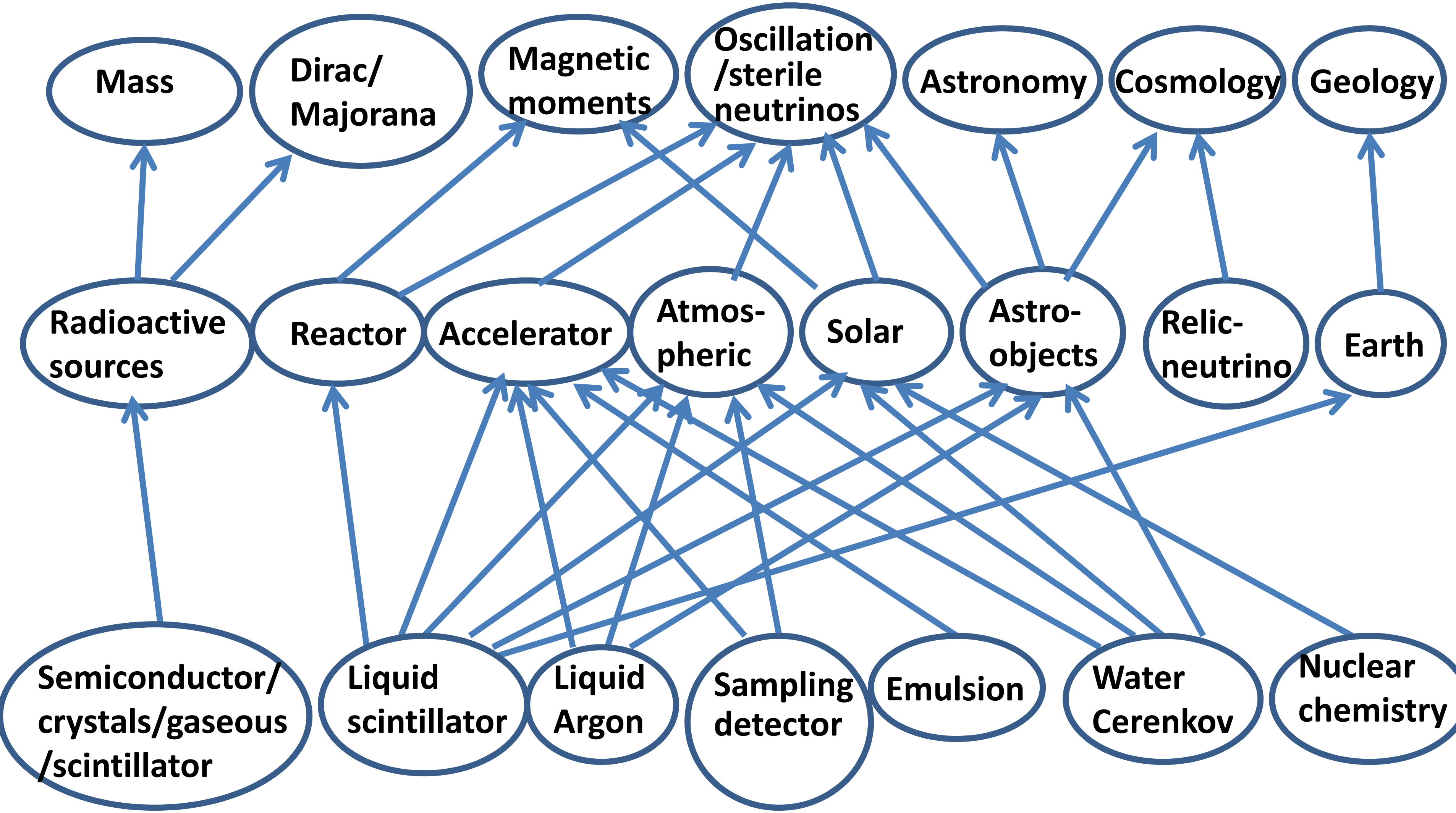
Particle physics





Neutrino industry

Neutrino physics： problems and methods



Current & Future Neutrino Experiments (selected)

- Basic properties of neutrinos
  - Magnetic moments: Texono, GEMMA, …
  - Absolute mass: Katrin, Mare, Project 8, …
- Neutrino oscillations & sterile neutrinos
  - Atmospheric neutrinos(θ_{23}): SuperK, INO, HyperK, PINGU, …
    - mass hierarchy…
  - Solar neutrinos(θ_{12}): SuperK, Borexino, LENA…
    - Solar & astrophysics
  - Reactor neutrinos(θ_{13}): Daya Bay, Double CHOOZ, Reno, DYBII…
    - mass hierarchy, sterile neutrinos,…
  - Accelerator neutrinos(θ_{23},θ_{13}): MINOS,T2K,NOVA,LBNE, HyperK, LBNO…
    - mass hierarchy, sterile neutrinos, δ, …
- Neutrino astronomy & applications
  - Supernova ➔ with solar/atmospheric/reactor neutrinos
  - Geo-neutrinos ➔ with solar/reactor neutrinos
  - High energy neutrino astronomy(Icecube, Antares, KM3,…)

Neutrino Oscillation

- **If the neutrino mass eigenstate is different from that of the weak interaction, neutrinos can oscillate: from one type to another during the flight:**

$\nu_e \rightarrow \nu_\mu \rightarrow \nu_e \rightarrow \nu_\mu \rightarrow$

Oscillation probability:

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$$

Oscillation amplitude ($\sin^2(2\theta)$)

Oscillation frequency (Δm^2)

Oscillation matrix for 3 generations:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}V_{e1} & V_{e2} & V_{e3}\\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3}\\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- **Known parameters:** θ_{23}, θ_{12}, $|\Delta M^2_{23}|$, ΔM^2_{12},
- **Recent progress:** θ_{13}
- **Unknown parameters:** **mass hierarchy(ΔM^2_{23}), CP phase δ**

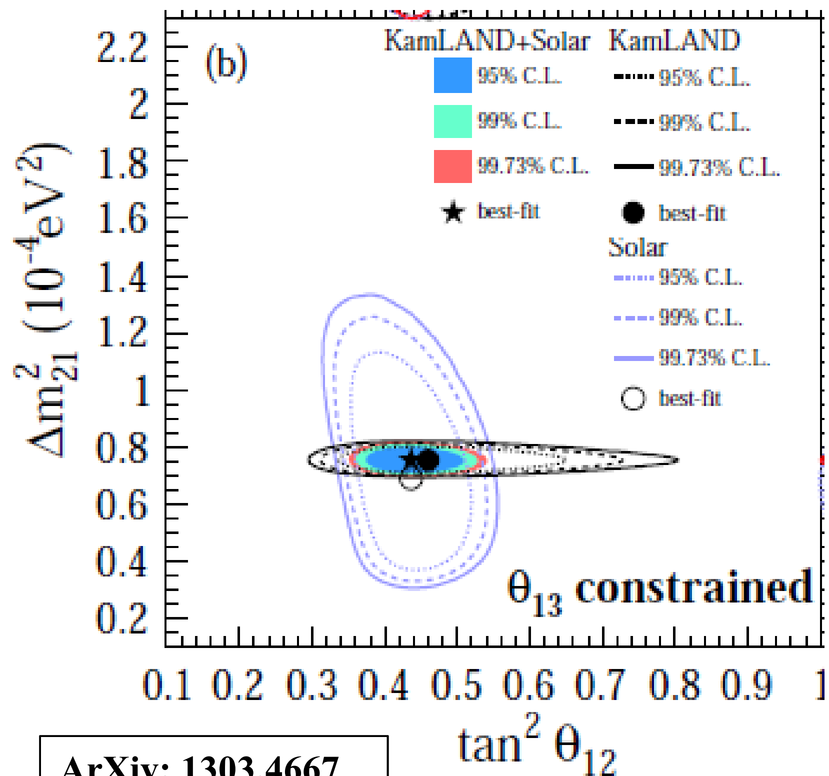
θ_{12} and ΔM^2_{12}

- **First evidence in 60's-80's by Homestake**
  - **Solar ν_e disappearance**
- **Well established by SNO using solar neutrinos in 2000:**
  - **Disappeared solar ν_e actually become $\nu_\mu+\nu_\tau$**
- **Confirmed by KamLAND using reactor neutrinos in 2001**
  - **Reactor $\bar{\nu}_e$ disappearance & θ_{12} and ΔM^2_{12} well determined**
- **Current measurements:**

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$

$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2$$

- **Issues now:**
  - **Mostly solar related**
- **Future experiments**
  - **DYBII(reactor)**



ArXiv: 1303.4667

θ_{23} and ΔM^2_{23}

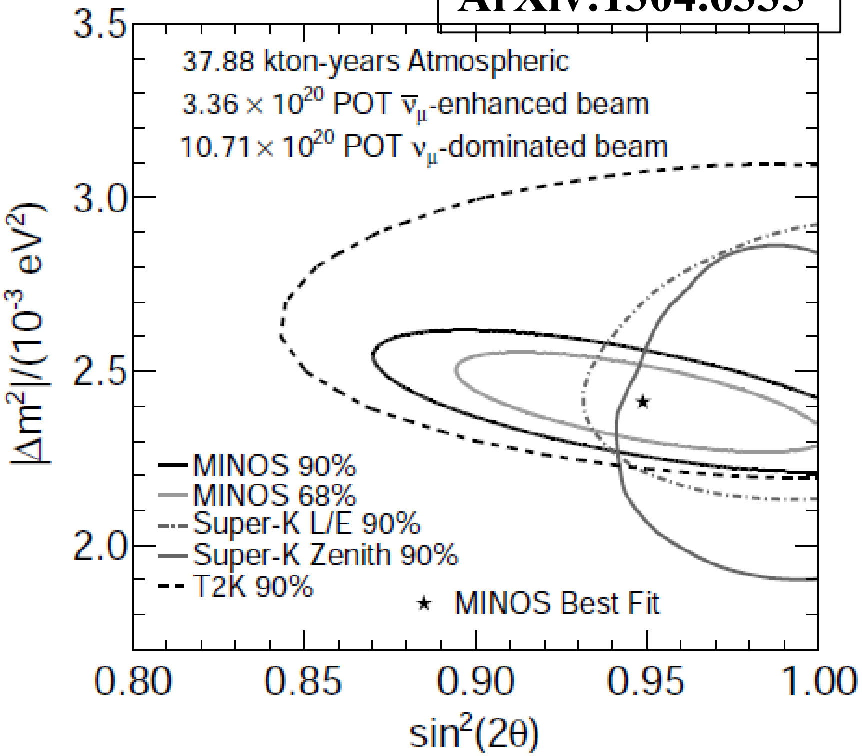
- First evidence in 80's by Kamiokande and IMB
  - ⇨ Atmospheric neutrinos ν_μ disappearance
- Well established by SuperKamiokande in 1998
  - ⇨ Atmospheric neutrinos ν_e disappearance(as a function of L/E)
- Confirmed by accelerator experiments
  - ⇨ Beam ν_μ disappearance(K2K, T2K, MINOS…)
  - ⇨ ν_τ appeared in ν_μ beam (OPERA)
- Current measurements:

$$|\Delta m^2| = (2.41^{+0.09}_{-0.10}) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.950^{+0.035}_{-0.036}$$

- Issues now:
  - ⇨ Sign of ΔM^2_{23}
  - ⇨ Is θ_{23} maximal ?
- Future experiments
  - ⇨ NOVA, INO, HyperK…

ArXiv:1304.6335

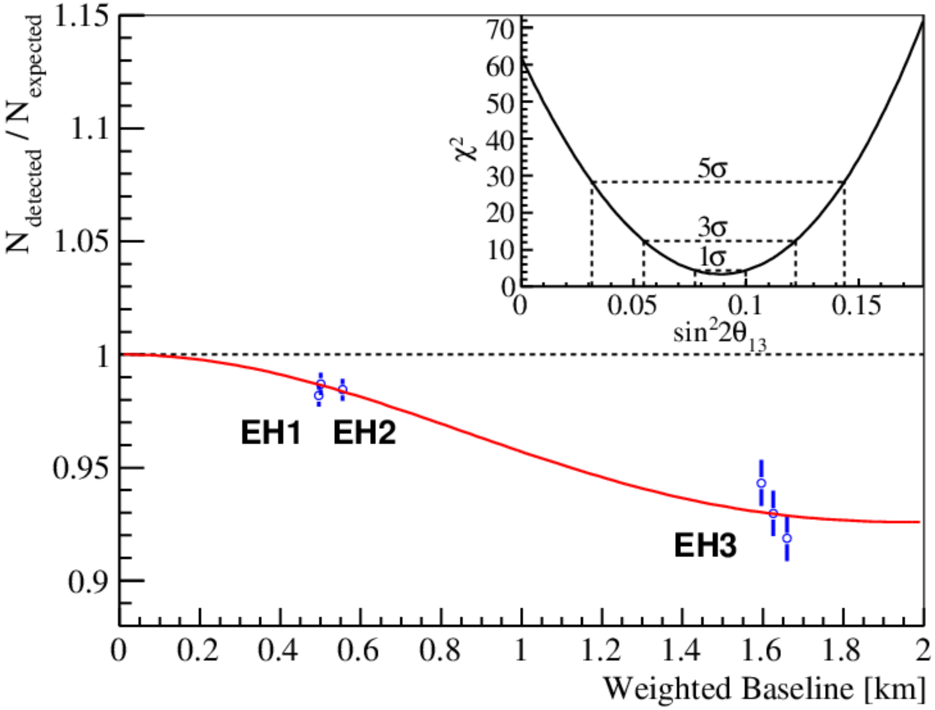


θ_{13} and ΔM^2_{13}

- First evidence of non-zero θ_{13} in 2011 by T2K, MINOS and Double Chooz
- Well established non-zero θ_{13} by Daya Bay using reactor neutrinos in 2012
- Confirmed afterwards by RENO, Double Chooz and T2K
- Precision:
  - 13% → 4% in 5 years
- Future experiments
  - None

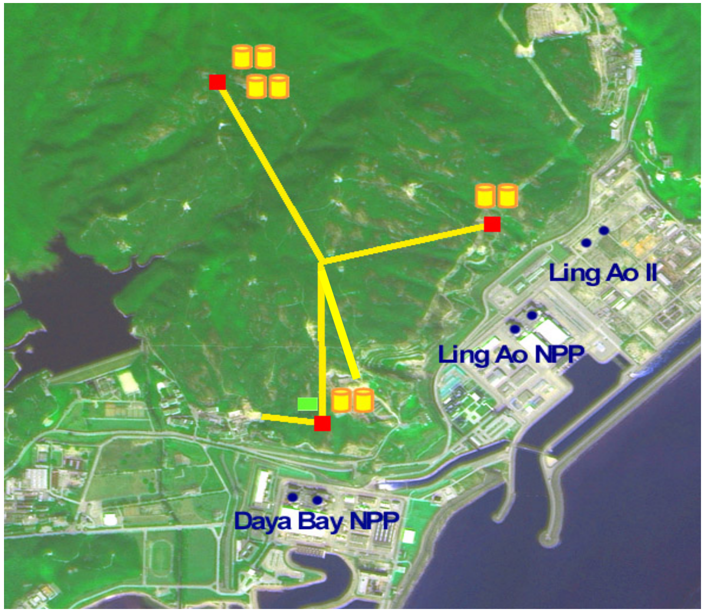
ΔM^2_{13} not independent:

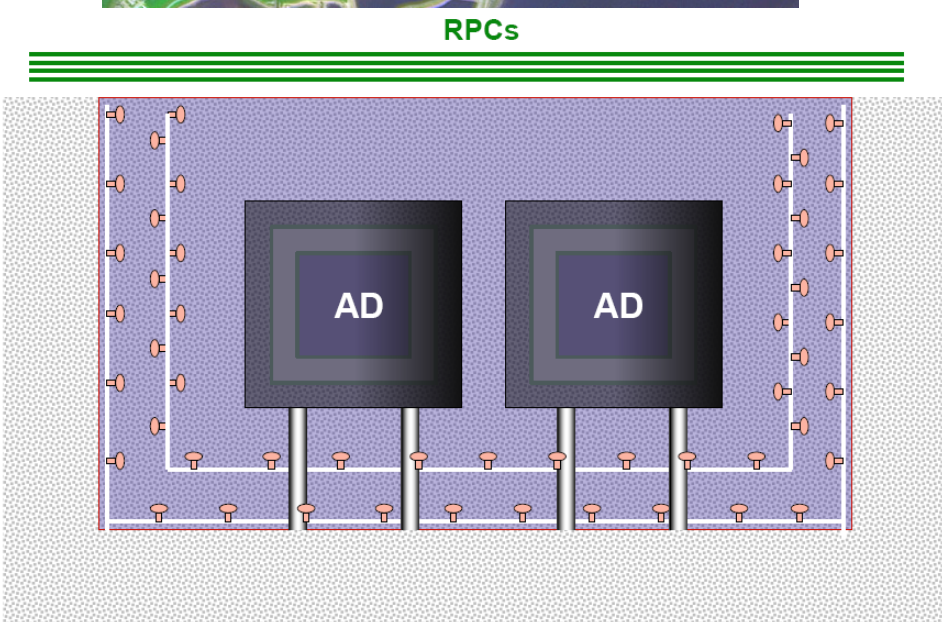
$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

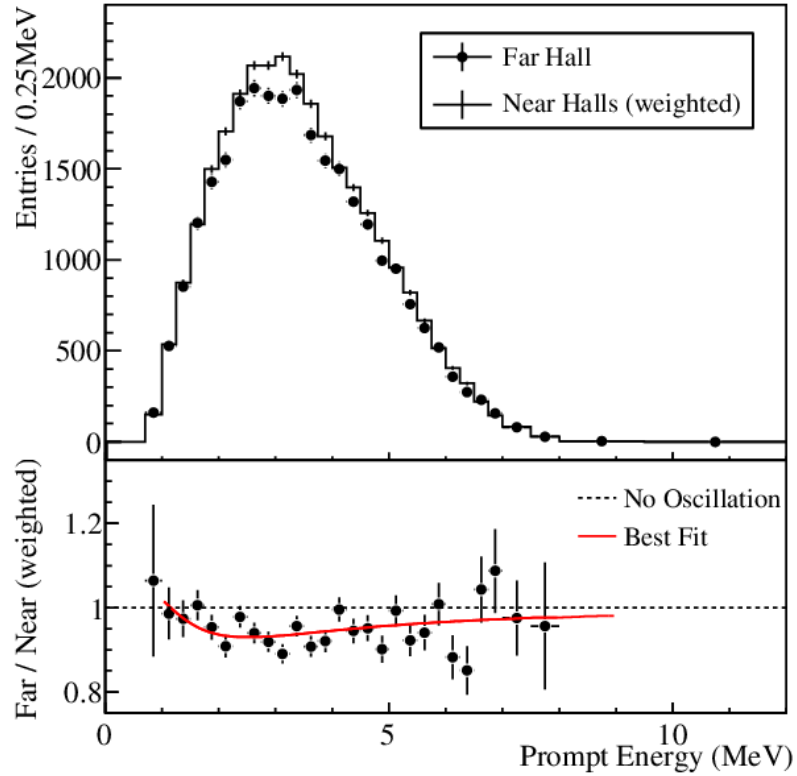


F.P. An et al., Chin. Phys.C 37(2013) 011001

Daya Bay: θ_{13} is determined







$Sin^2 2\theta_{13}=0.089\pm0.010\pm0.005$

7.7 σ for non-zero θ_{13}

F.P. An et al., Phys. Rev. Lett. 108, (2012) 171803; Chin. Phys.C 37(2013) 011001

RENO, Double Chooz & T2K confirmed the results at 3-5 σ

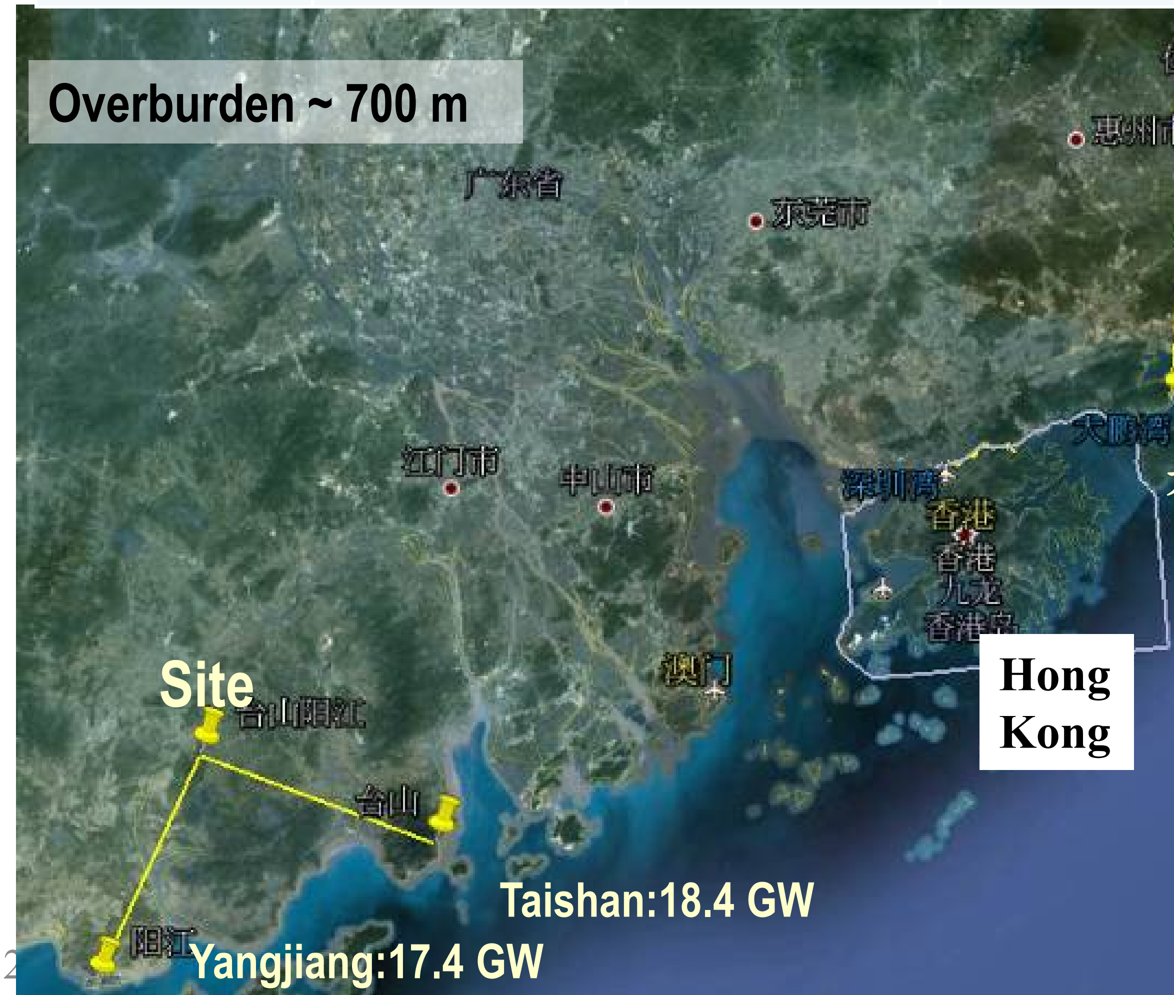
Neutrino physics in the Future

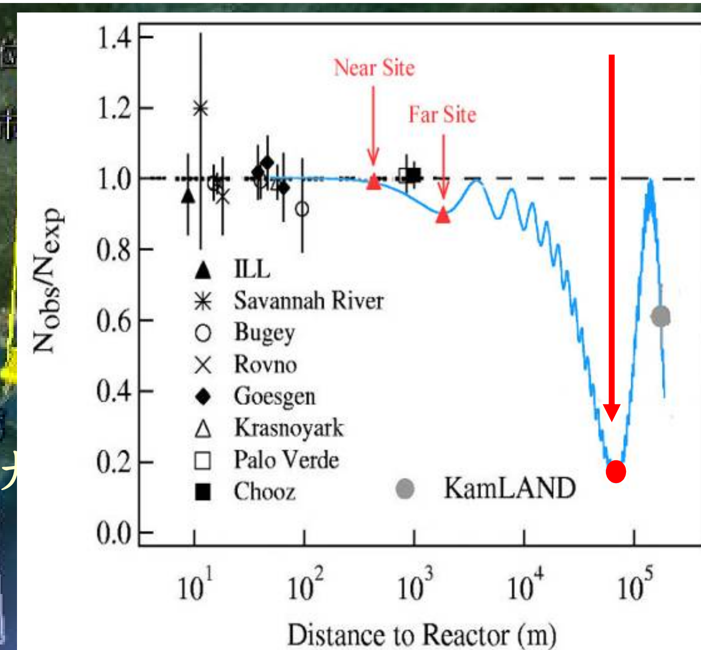
Thanks to the large θ_{13}

- **Mass hierarchy**
  - By reactor neutrinos: DBYII
  - By atmospheric neutrinos: INO, HyperK, PINGU
  - By Long baseline accelerator neutrinos: HyperK, LBNE, LBNO,…
- **CP phase**
  - By atmospheric neutrinos: HyperK
  - By Long/medium baseline accelerator neutrinos: HyperK, LBNE, LBNO,…
- **Sterile neutrinos**
  - Radioactive sources: CeLAND, SoX,…
  - By reactor neutrinos: Nucifer, Stereo, Solid …
  - By short baseline accelerator neutrinos: MicroBoone, IsoDAR, Icarus/Nessie, nuSTORM…

Mass Hierarchy by reactors: DYBII

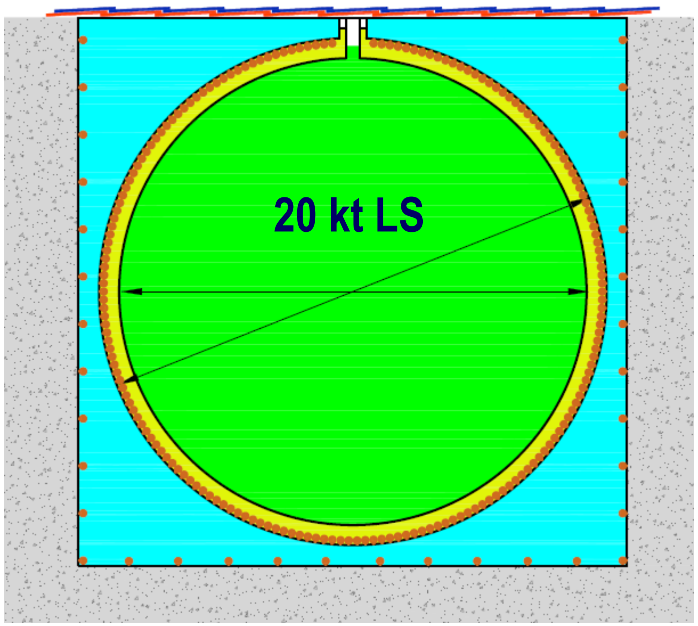
	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	running	planned	approved	Construction	construction
power/GW	17.4	17.4	17.4	17.4	18.4

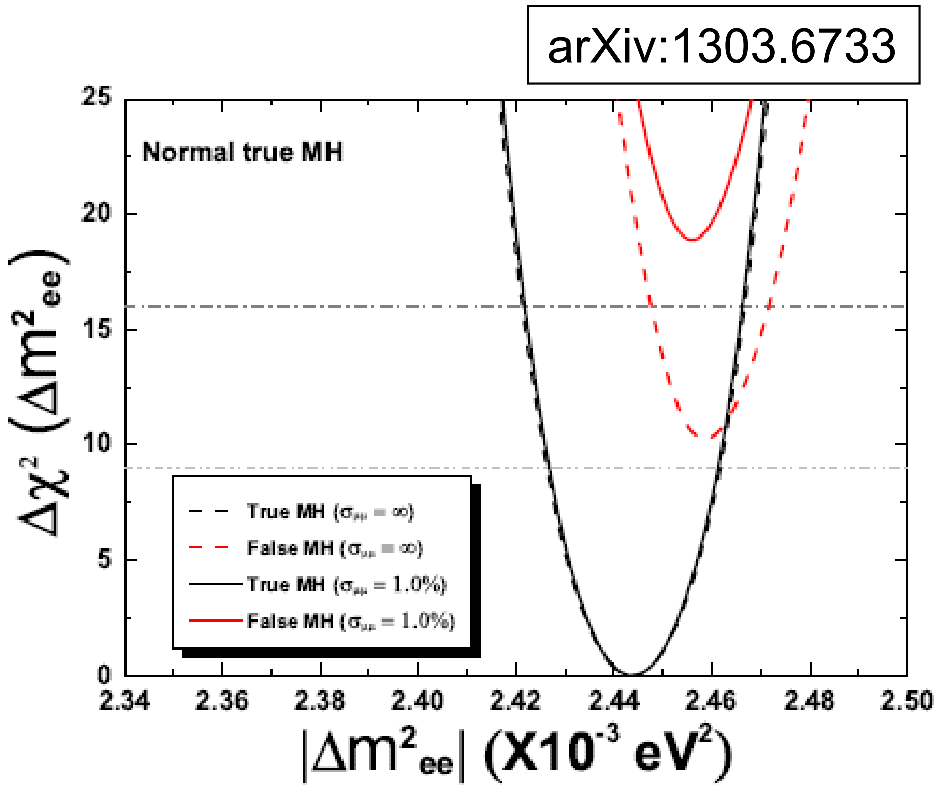




- Mass Hierarchy
- Mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos

Physics reach of DYBII



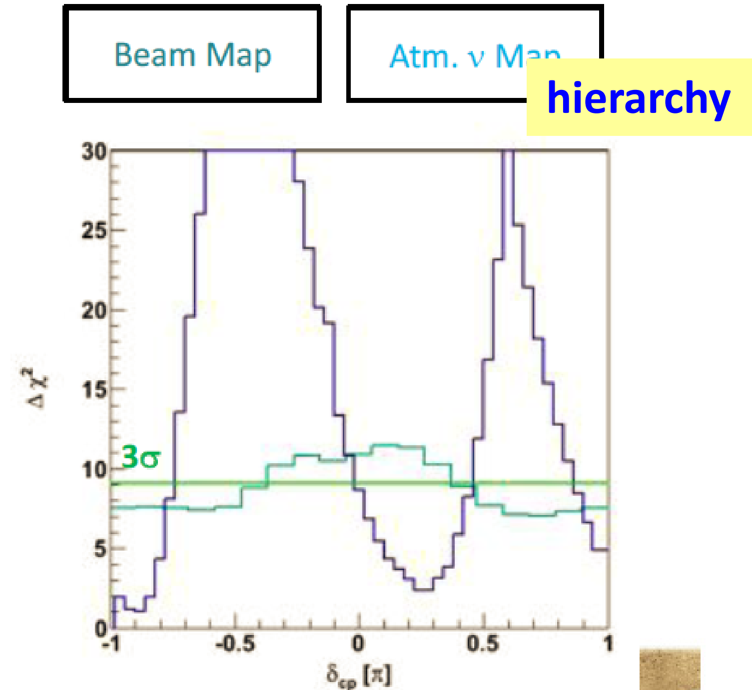


	current	Our precision
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	14%→ 4%	~ 15%

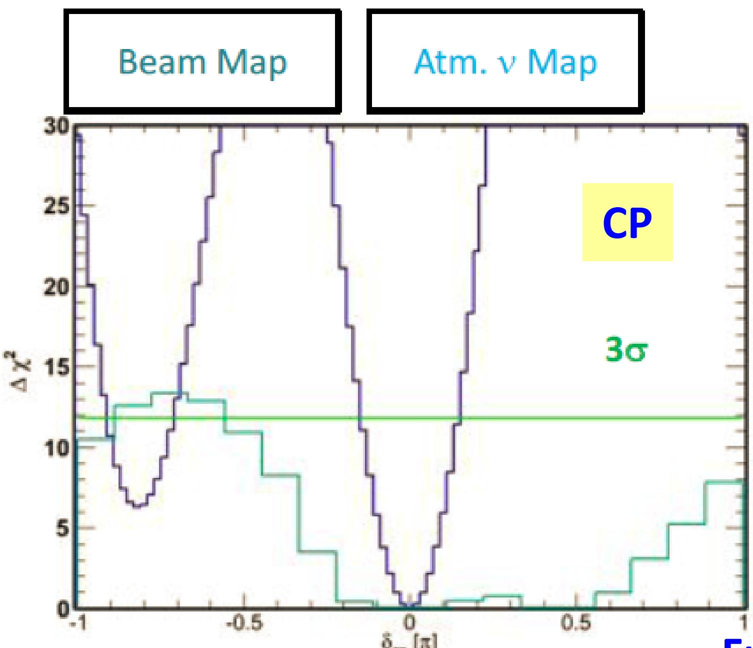
For 6 years, taking into account all uncertainties and with the help of $\Delta m^2_{\mu\mu}$ from T2K and Nova, sensitivity can reach 4σ

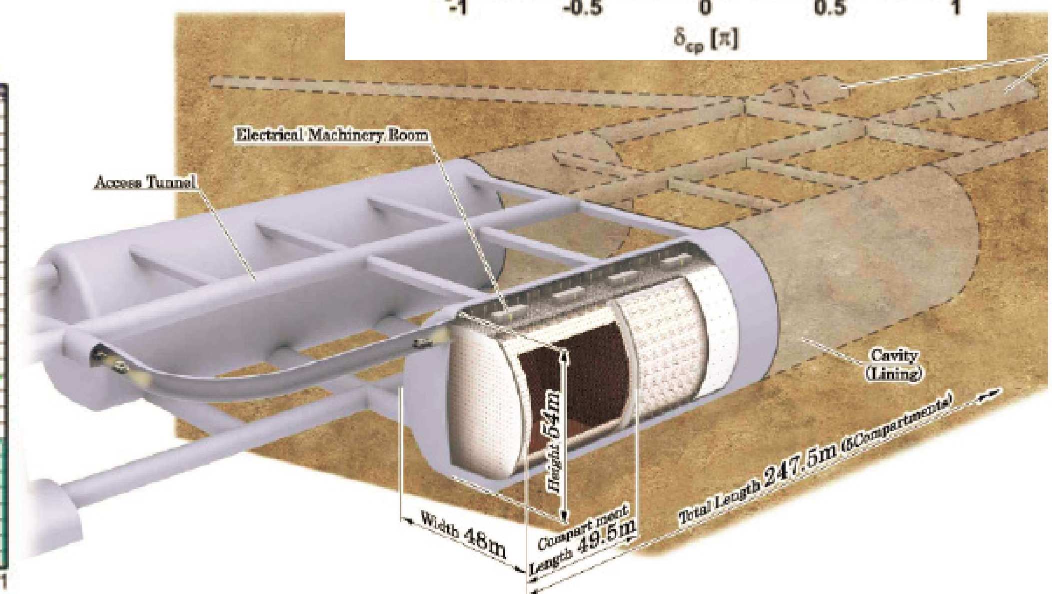
HyperK for Mass Hierarchy & CP

- Atmospheric & accelerator neutrinos
- 1 Mt water Cerenkov detector
- Beam from J-PARC (0.75 MW, 295 km)
- Physics:
  - Mass hierarchy
  - CP phase δ
  - θ_{23}



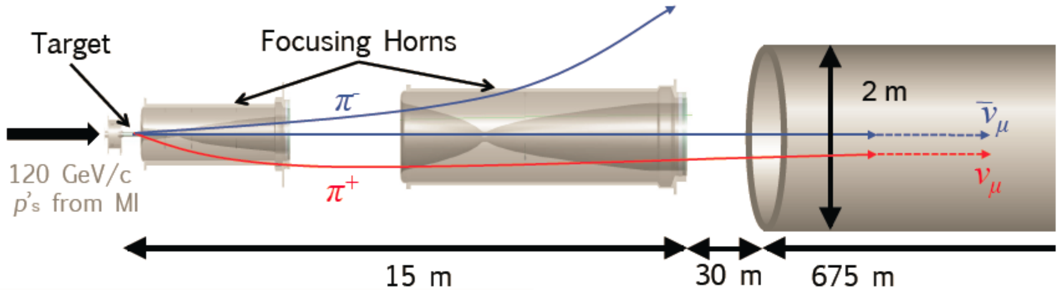
Sensitivity mostly from the beam

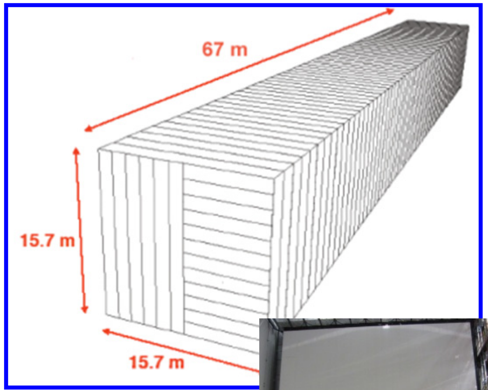




From T. NaKaya, talk at NeuTel 2013

Future Accelerator Neutrino Experiments

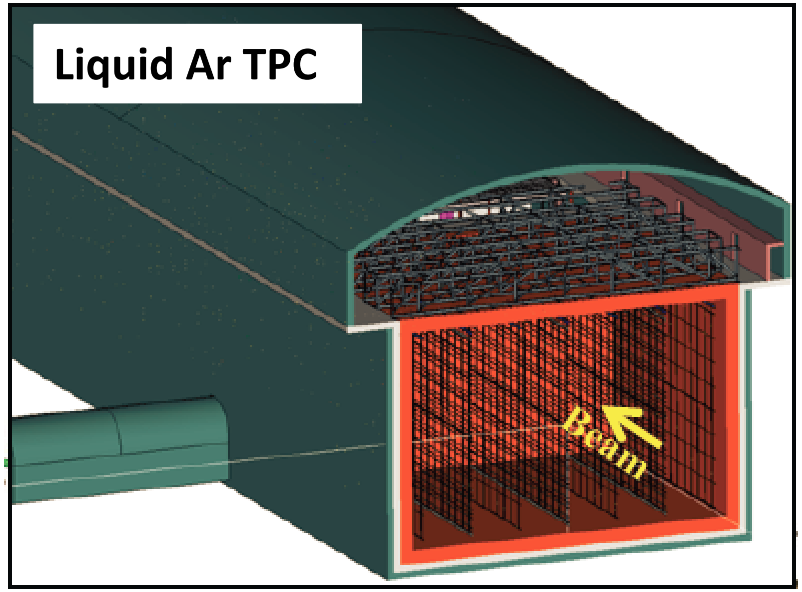


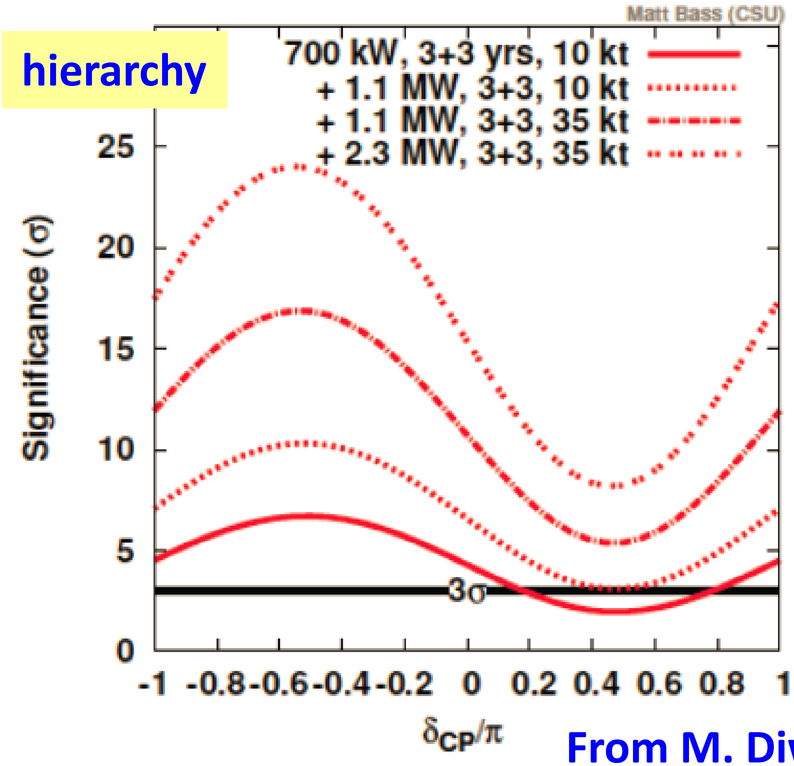


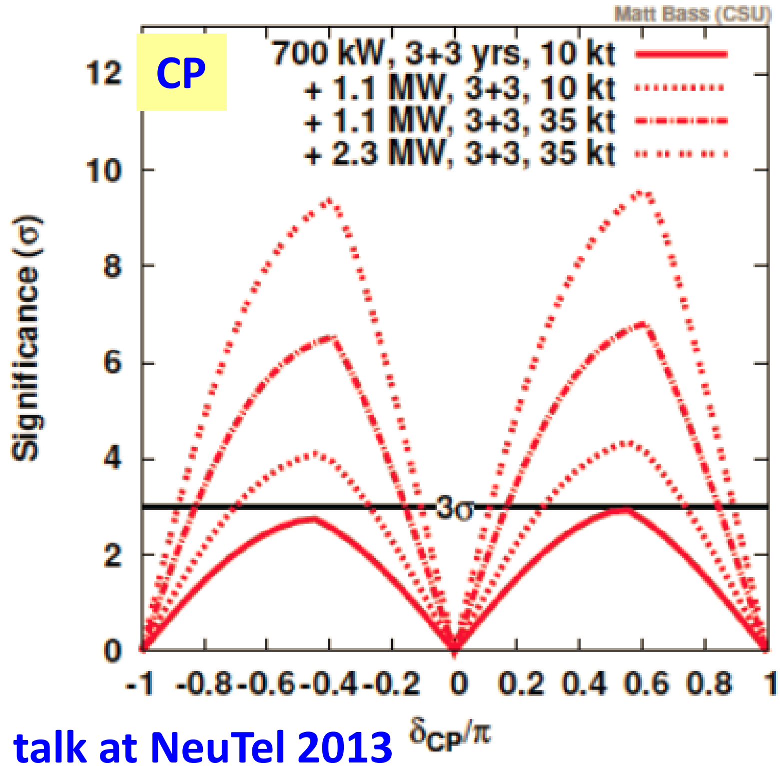
	Beam power(MW)	Baseline (km)	Detector	Start time
NOVA	0.7	810	14 kt Iron calorimeter	2015
HyperK	0.75	295	560 kt Water Cerenkov	~ 2022
LBNE	0.7 → 2.3	1300	10 kt→ 35kt Liquid Ar TPC	~ 2022 → ?
LBNO	0.75 → 2.0	2300	20 kt LAr TPC + 35 kt MIND	?

LBNE & project-X

- From Fermilab Main injector(& its upgrade) to Homestake(1300 km)
- Program in phases:
  - beam power: 0.7-2.3 MW
  - LAr TPC mass: 10 -35 kt





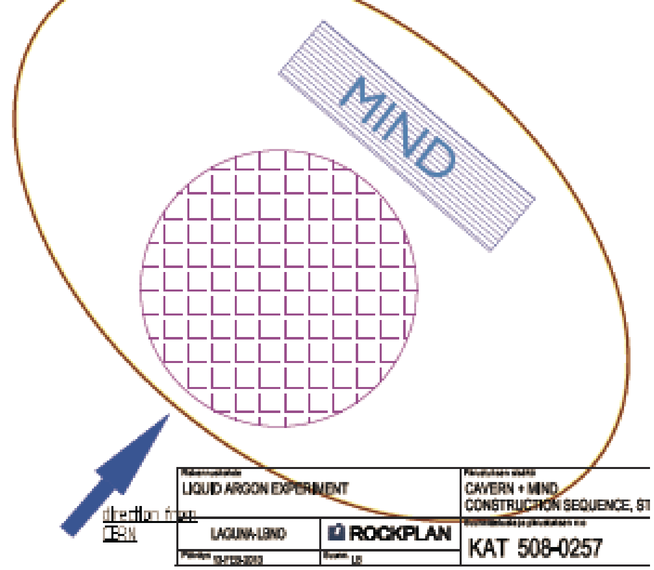


From M. Diwan, talk at NeuTel 2013

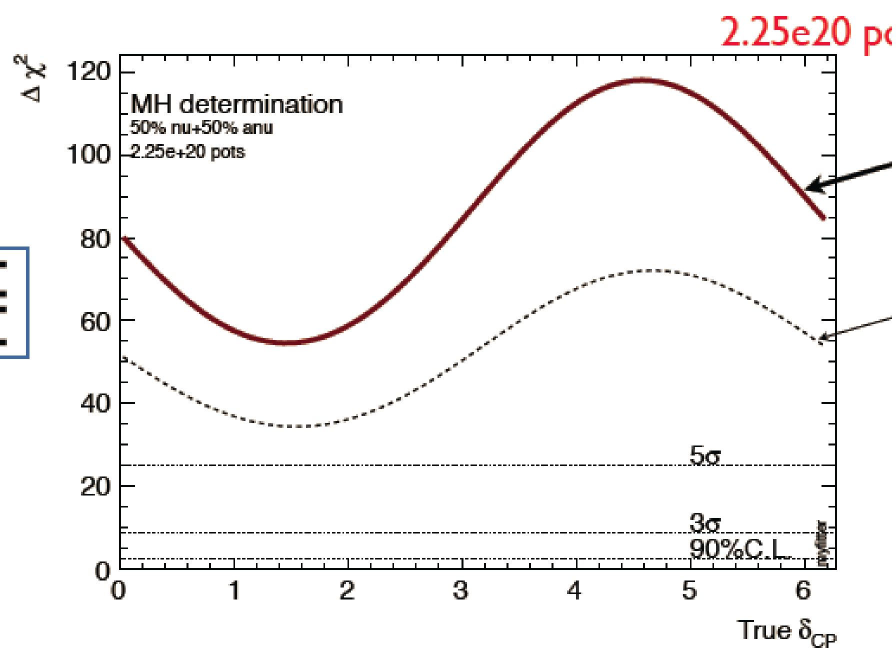
LBNO

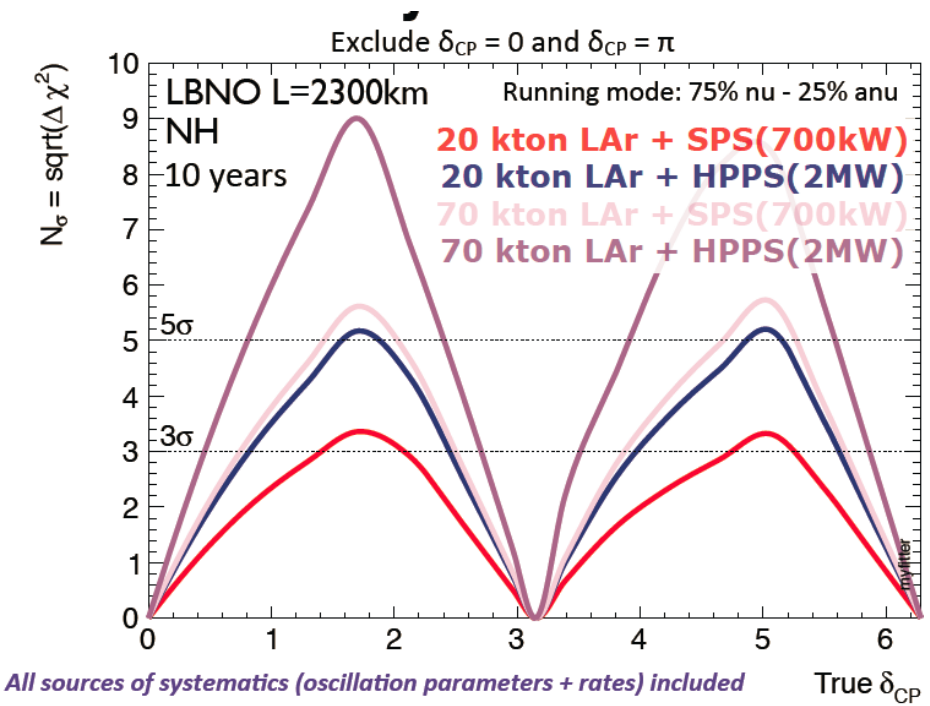
20kton LAr +
35 kton MIND

- From CERN SPS(& its upgrade) to Pyhäsalmi(Finland)
- Beam power: 0.7MW ➔ 2.0 MW
- Baseline of 2300 km: better MH sensitivity than that of LBNE
- Overburden is ~1400m, good for many other physics



MH

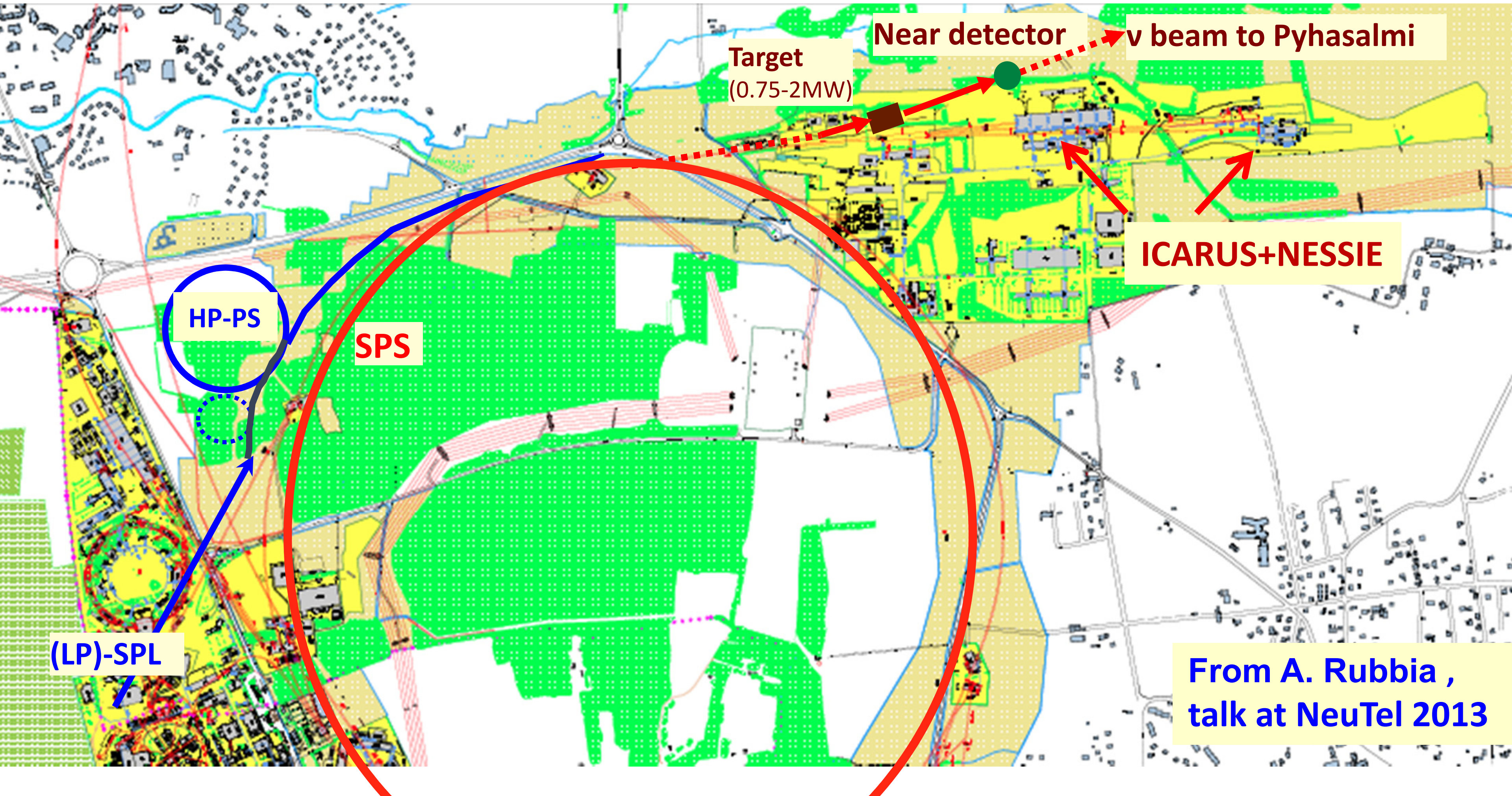




From A. Rubbia, talk at NeuTel 2013

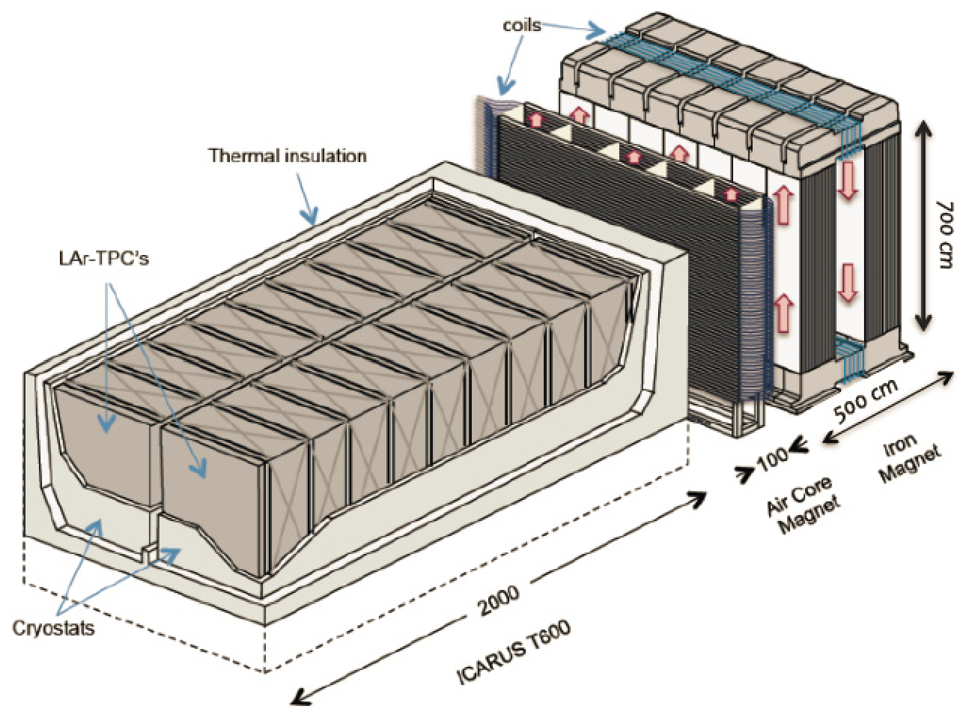
The CN2PY beam

- Phase 1 : use the proton beam extracted beam from SPS
  - 400 GeV, max 7.0 10^{13} protons every 6 sec, 750 kW beam power
- Phase 2 : use the proton beam from the new HP-PS



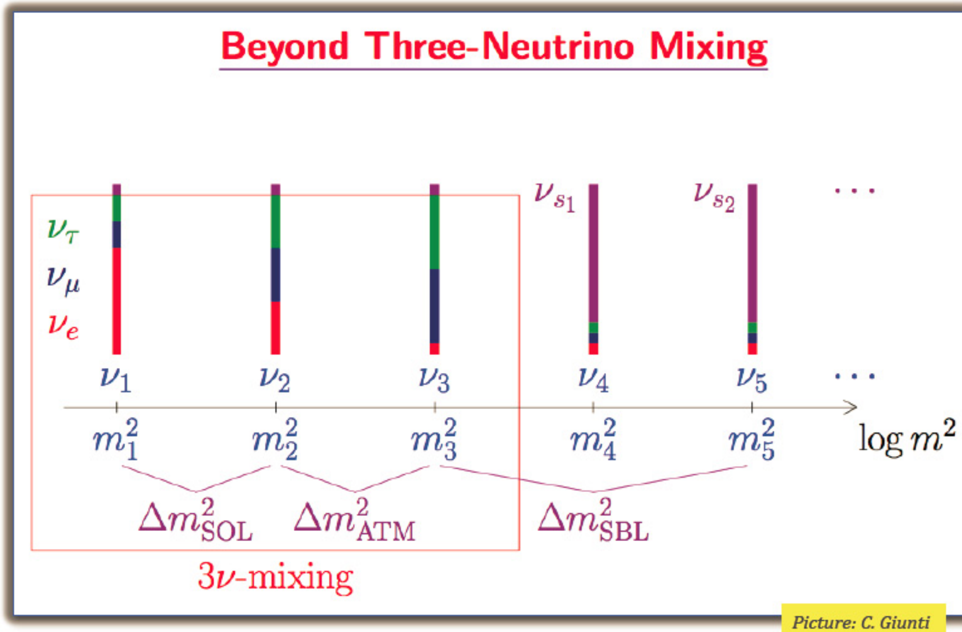
First phase: ICARUS+NESSIE

- Beam from SPS: as an initial phase of the neutrino physics program at CERN
- Two types of detector for background rejection:
  - NESSIE: magnetized Iron calorimeter
  - ICARUS: Liquid Ar TPC
- Key parameters:
  - Near site @ 300m
    - NESSIE mass=840t
    - ICARUS mass= 119t
  - Far site @ 1600
    - NESSIE mass=1515t
    - ICARUS mass= 476t
- Physics: sterile neutrinos



Sterile neutrinos

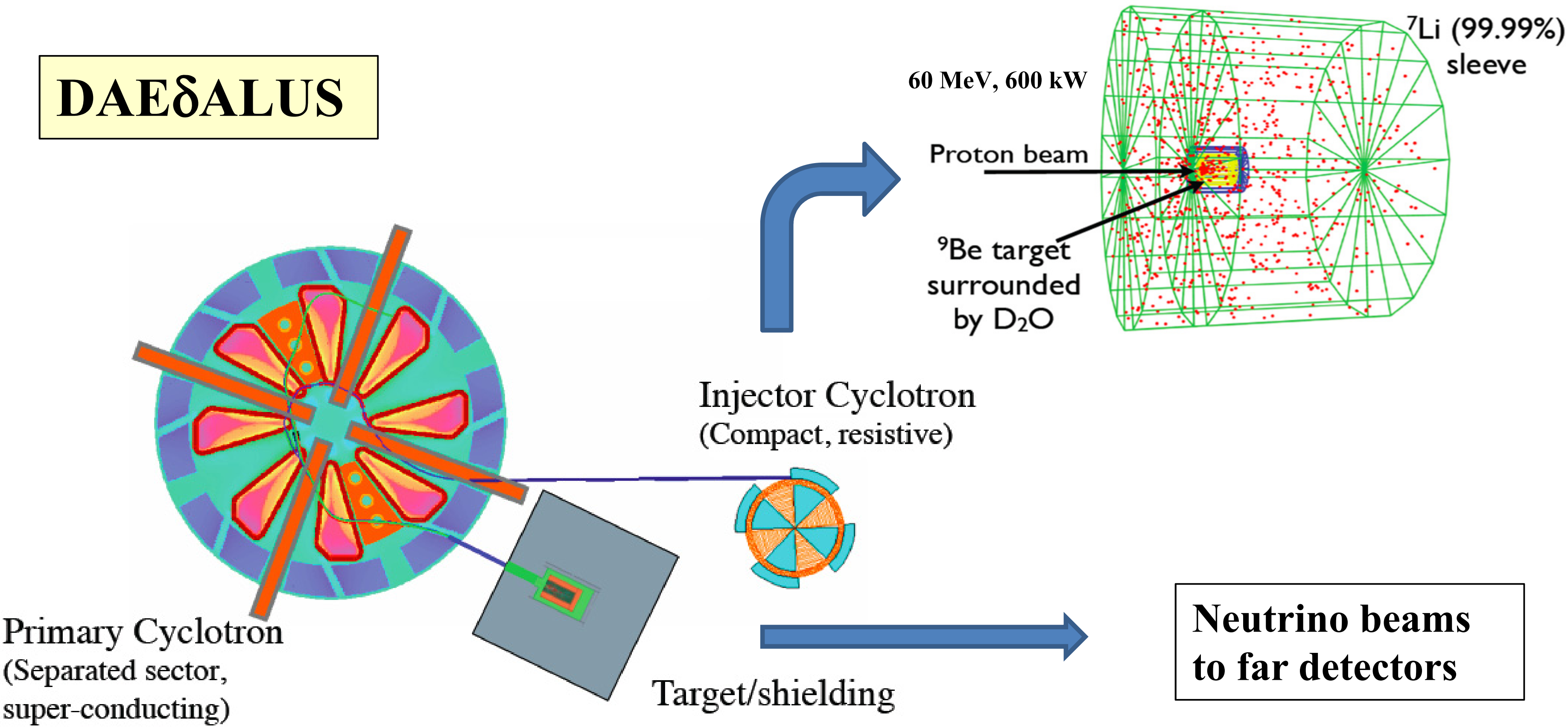
- Sterile neutrinos as the partner of active neutrinos, may exist and oscillate with their active partners.
- Theoretical motivation: various extension of SM
- Experimental "hints": LSND: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam; MiniBooNE: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam; Reactor: $\bar{\nu}_e$ deficit; Gallex: ν_e deficit
- Global fit with severe tensions
- Not favored by cosmological bounds (PLANCK) but there are ways out
- Solution: experiments
  - Radioactive sources(or):
    - CeLAND(^{144}Ce in KamLAND), SoX(^{51}Cr in Borexino),…
  - Reactors
    - Nucifer, Stereo, Solid,…
  - Accelerator beams
    - IsoDAR, MicroBoone, Icarus/Nessie, nuSTORM…



Picture: C. Giunti

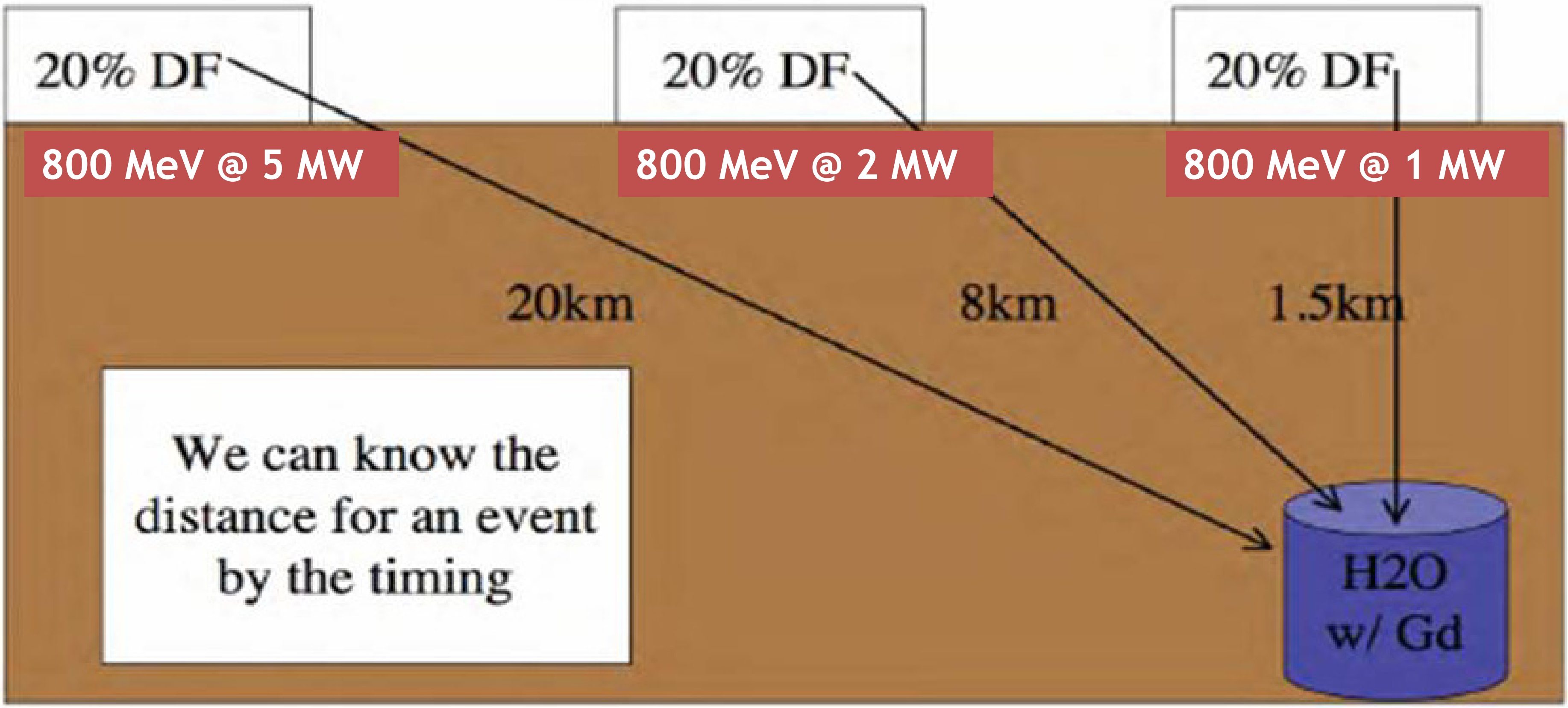
IsoDAR

- A proton beam on $^{9}Be \rightarrow n \rightarrow n + {}^{7}Li \rightarrow {}^{8}Li \rightarrow \overline{\nu_e}$
- Site may be at KamLAND or SNO
- Phased program of DAEδALUS :



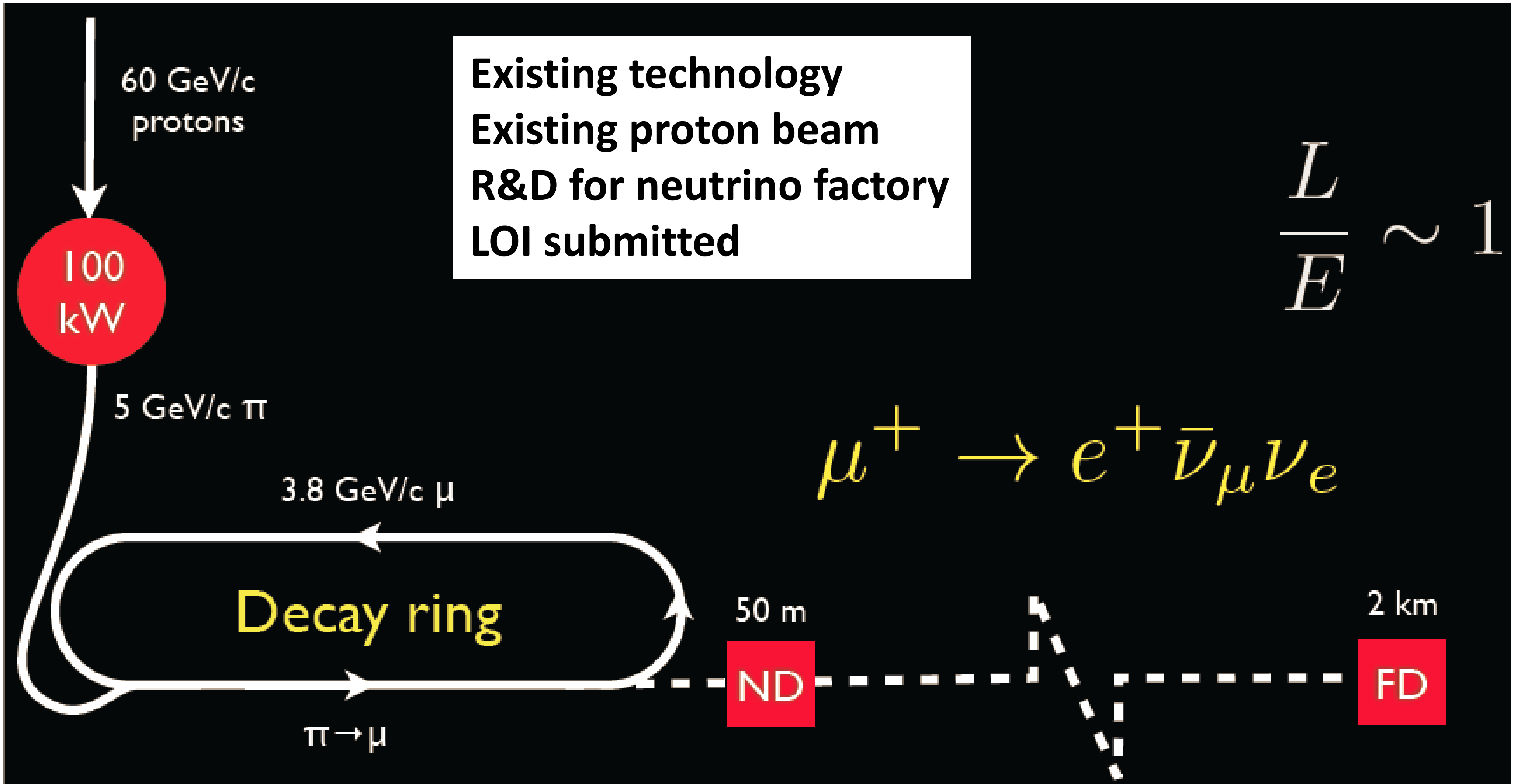
DAEδALUS

- Multiple superconducting Cyclotrons to produce muon neutrinos from π decays at rest
- Look for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation with a L/E dependence to measure the CP phase δ



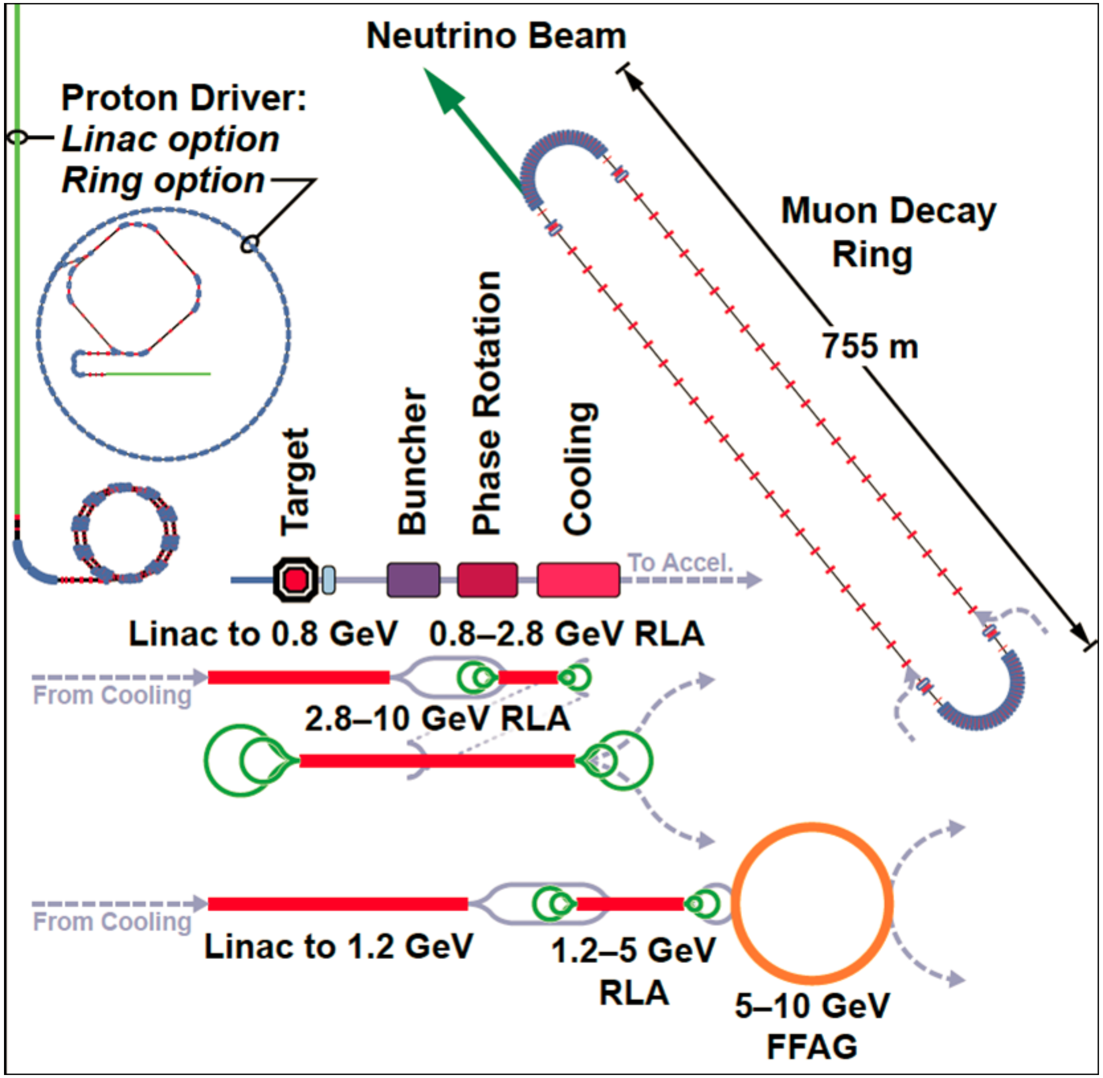
nuSTORM

- A 3.8 GeV muon storage ring + Minos-like detector to solve sterile neutrino problem, proposed at Fermilab
- A phased program for neutrino factory



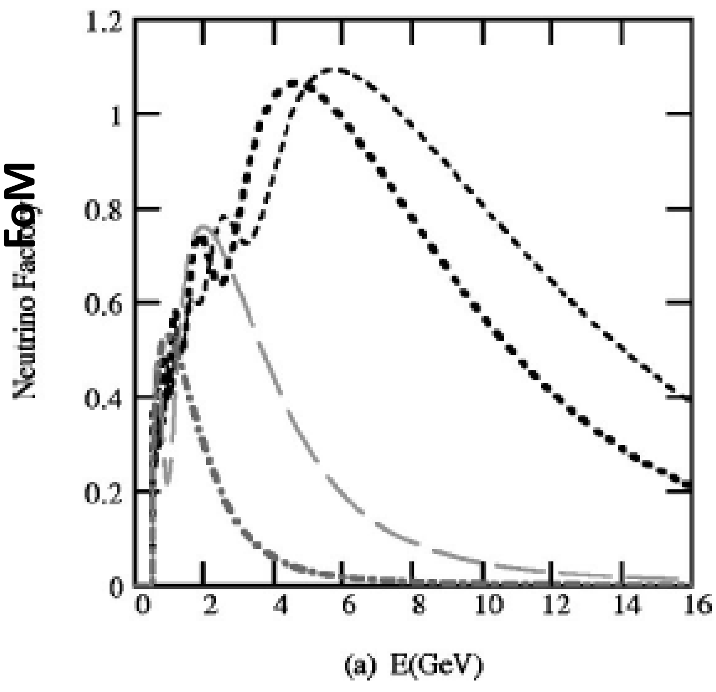
Neutrino Factory

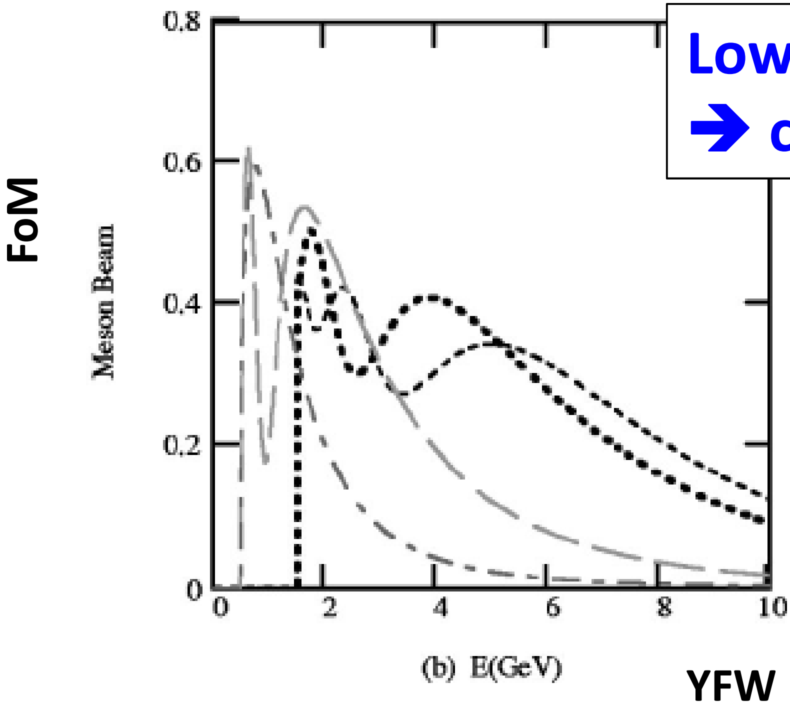
- Neutrinos from muon decays for θ_{13}, MH & CP
- Typical parameters:
  - ~10 GeV muon beam
  - ~10^{21} ν/year
  - ~4 MW power
  - ~2000 km baseline
  - 0.1 – 1.0 Mt detector
- Technology is far from mature. Global efforts:
  - Proton driver ➔ also needed by super-beams
  - Target➔ MERIT
  - Cooling ➔ MICE
  - Muon acceleration ➔ EMMA
- Also a pre-stage for muon collider



Where are we heading for ?

- Neutrino factory is a dream machine for θ_{13}, MH & CP
  - Long Baseline, high energy & high power ➔ expensive
- Previously discussed beta-beams are similar
- Since θ_{13} is known, and MH will likely be determined by DYBII/ HyperK/LBNE/LBNO, we need only a machine to determine CP
- What is the best machine if HyperK/LBNE/LBNO did not find CP ?



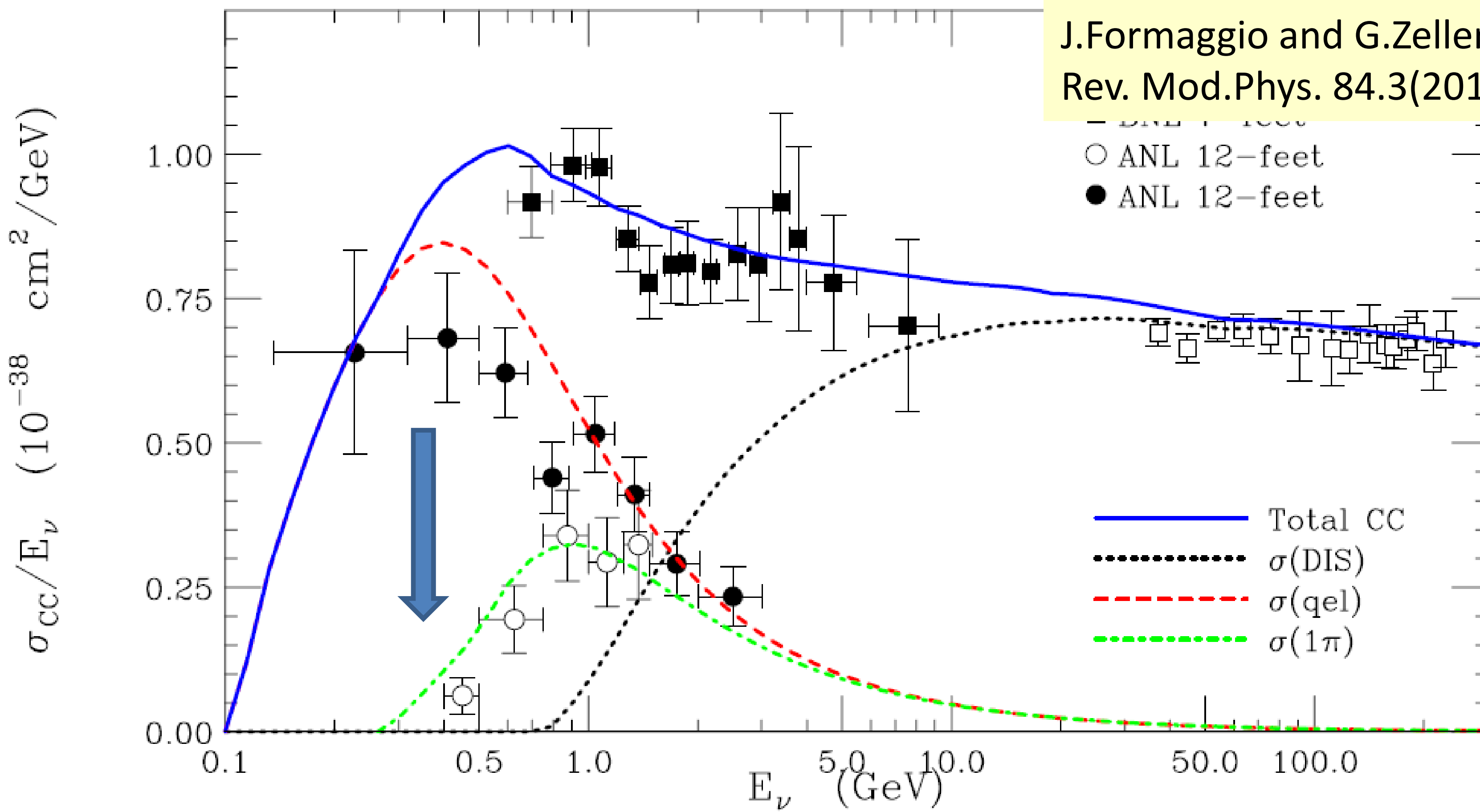


Low energy ➔ cheaper

YFW PRD 65,073006

How low is the best for CP ?

- **Below in-elastic threshold: ~ 300 MeV ➔ baseline = 150 km**
- **Such a threshold is similar for CC/NC & ν/νbar**
- **Although we loose statistics due to the lower cross section, but we have less systematics by being π^0 free**

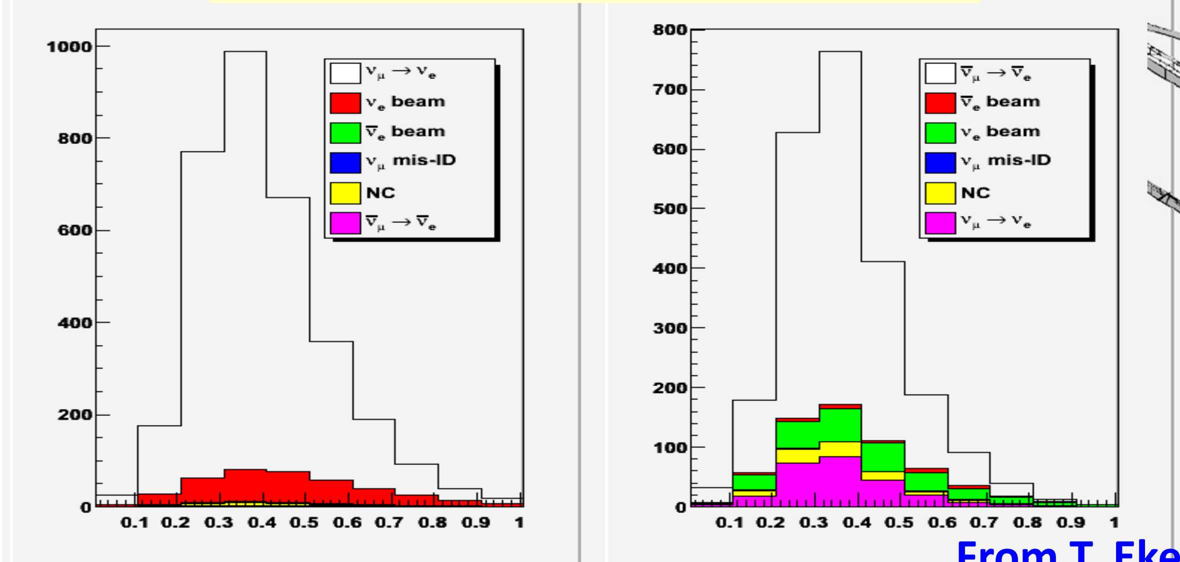


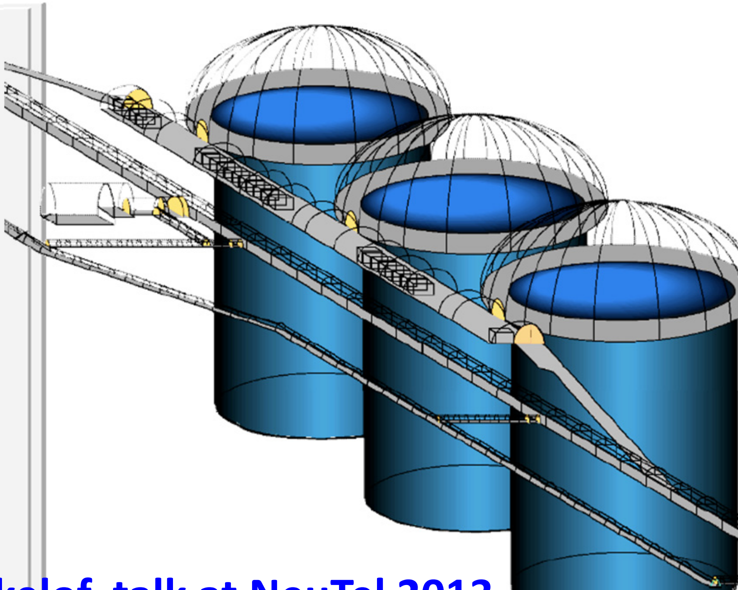
J.Formaggio and G.Zeller,
Rev. Mod.Phys. 84.3(2012)1307

Europe efforts: Super-beams(pi)

- **CERN HP-SPL**
  - 4.5 GeV proton driver, 4 MW power
  - Baseline: 130 km to Frejus
- **European Neutron Spallation Source at Lund (ESS)**
  - 2.5 GeV, 5 MW Superconduction Linac
  - Baseline: 260 km up; 540 km Garpenberg Mine ?
- **Possible detector:** 440 kt fiducial mass **MEMPHYS**
- **Neutrinos from π decays suffer from backgrounds**

ESS E_{ν} spectrum: peaked at 300 MeV

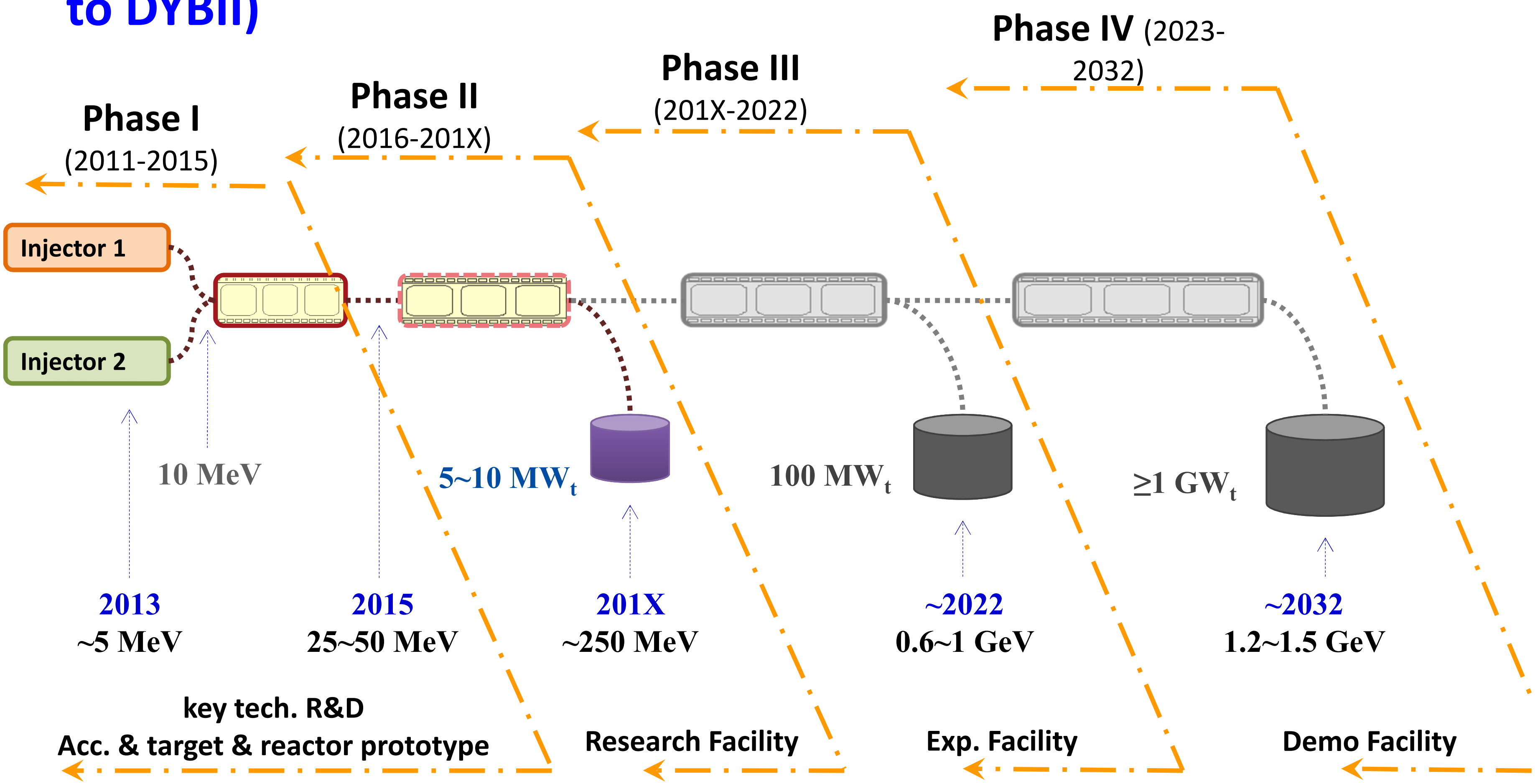




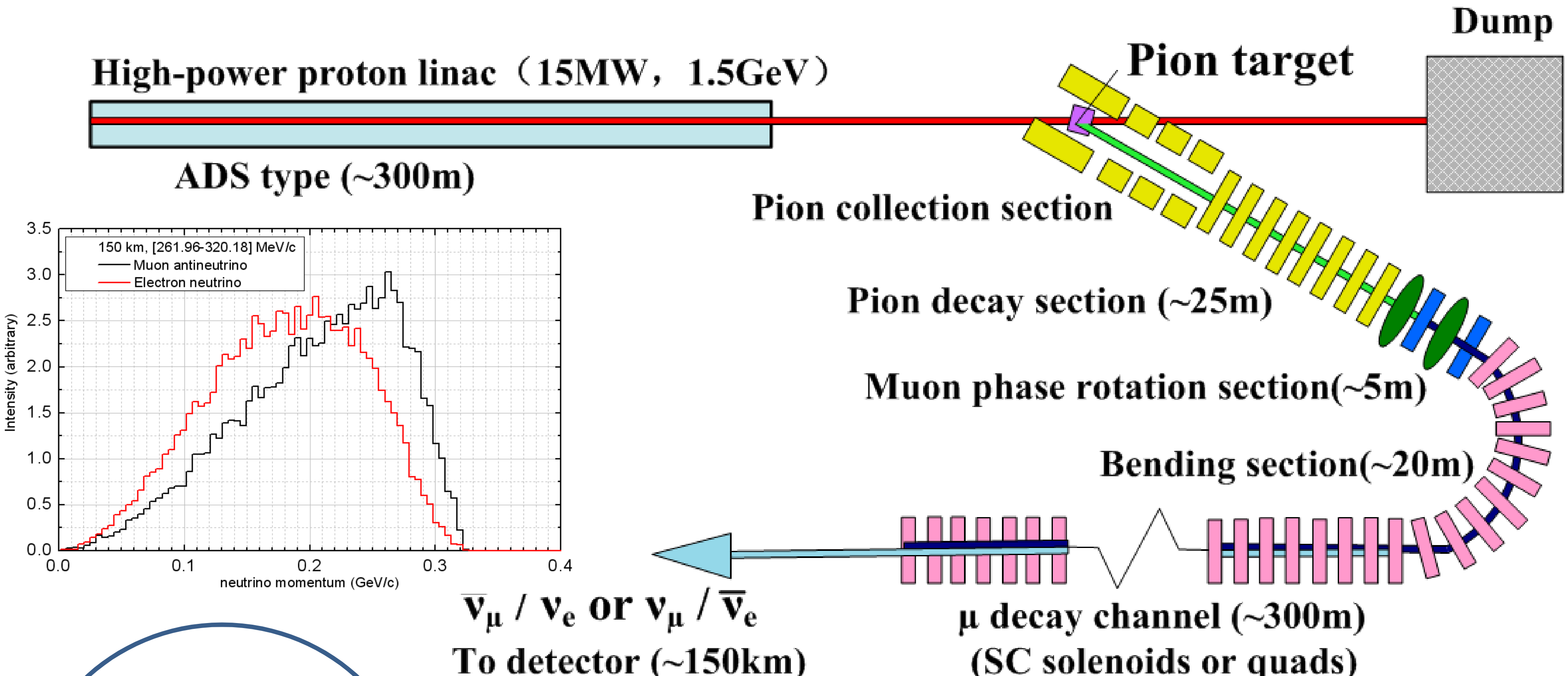
From T. Ekelof, talk at NeuTel 2013

Efforts in IHEP: DYBIII

- A proton LINAC for ADS is now under development in China
- If R&D is successful, a CW Linac based ~15 MW proton driver can be used for neutrino beams
- Shoot towards the Daya Bay II detector ? (150 km from CSNS site to DYBII)



Neutrinos from the muon decay



Detector:

- Flavor sensitive
- Charge sensitive
- NC/CC sensitive

Neutrinos after the target/collection/decay: ~ 10^{21} ν/year

Issues (common to many proposals)

- **Proton accelerators**
  - High power CW machine, easier ?
  - Challenges in RFQ and low-β superconducting cavities
  - Extremely low beam loss
- **Target**
  - Thermal load & radiation damage
- **Superconducting solenoids**
  - Some experience in low power case, but…
  - High heat load from radiation (kW level)
  - Radiation damage
- **Muon beam transport and decay channel**
  - Very large acceptance (>15000 mm-mrad)
  - Bunch rotation by superconducting cavities (100 MV)
- **Detector**
  - Flavor sensitive; Charge sensitive; NC/CC sensitive → MIND or water w/ Gd ?

Summary

- Neutrinos are important in our universe
- Significant progress in the past
- Great prospects in the future
- (Accelerator + target + magnet) play a vital role: but a lot of technical challenges in front of us
- We need your help and let's work together to discover the neutrino CP phase δ

Thanks
谢谢