Praha, 17.12. 2014

Neutrinové oscilační experimenty

Michal Malinský

ÚČJF MFF UK

Novinky v oscilační fyzice
(od jara 2014)

- NEUTRINO 2014 v Bostonu
- NOvA
- LBNE ➜ LBNF, ELBNF + CERN Neutrino platform
- T2HK
- Daya Bay
- JUNO

Urychlovačová a atmosférická neutrina

(NOvA, ELBNF, T2HK)

NOvA

(FNAL to Ash River, MN)

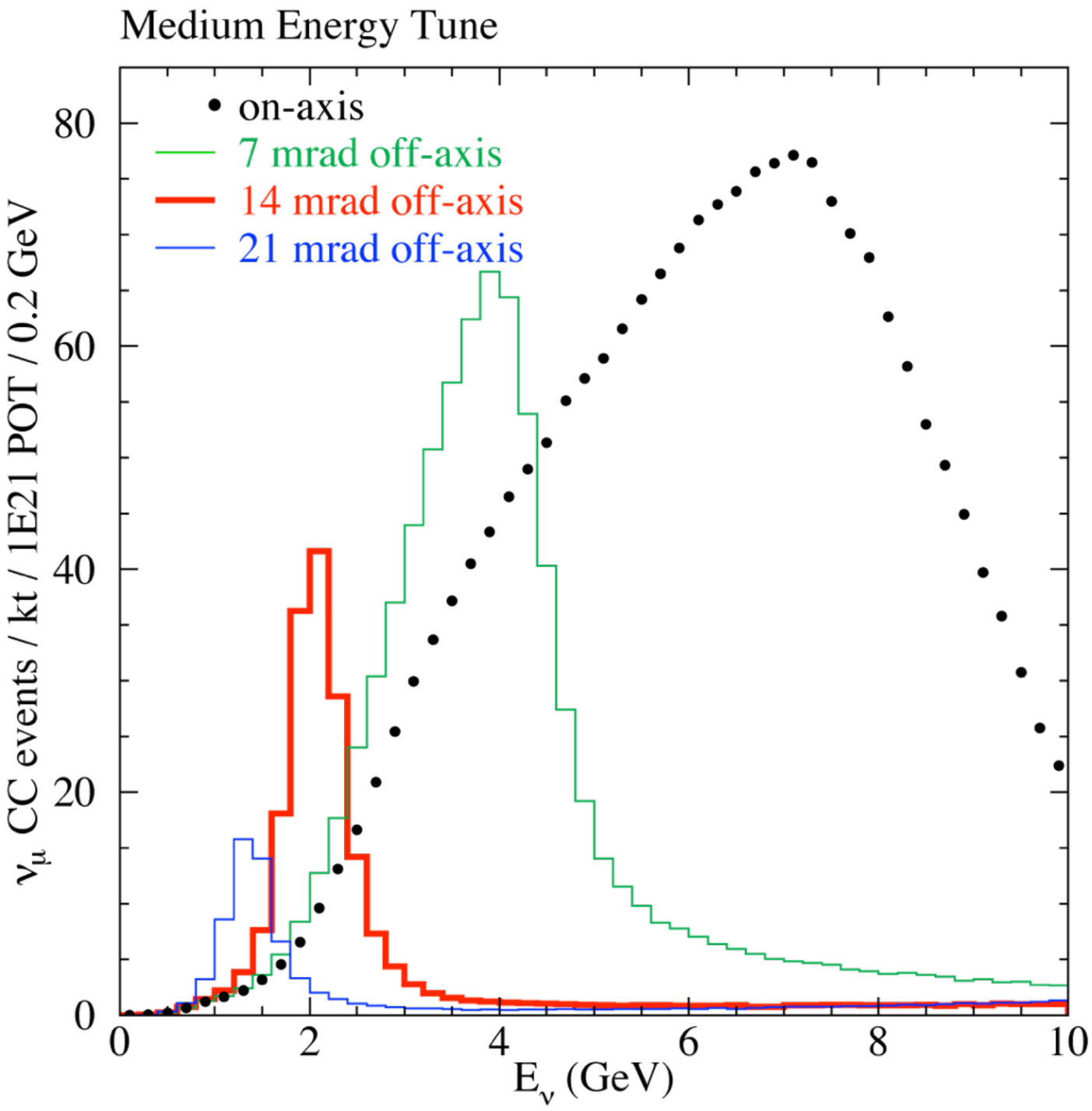

NOvA Far Detector
MINOS Far Detector
Minnesota
Ontario
Wisconsin
Milwaukee
Fermilab
Chicago


BLACKBERRY STORM
BLACKBERRY STORM
VIKINGS

NOvA

- L = 810 km (MINOS 735 km)
- Liquid scintilator tracking calorimeter
- NuMI beam (700kW ➜ 2MW) s peak energií mezi 2GeV a 7GeV

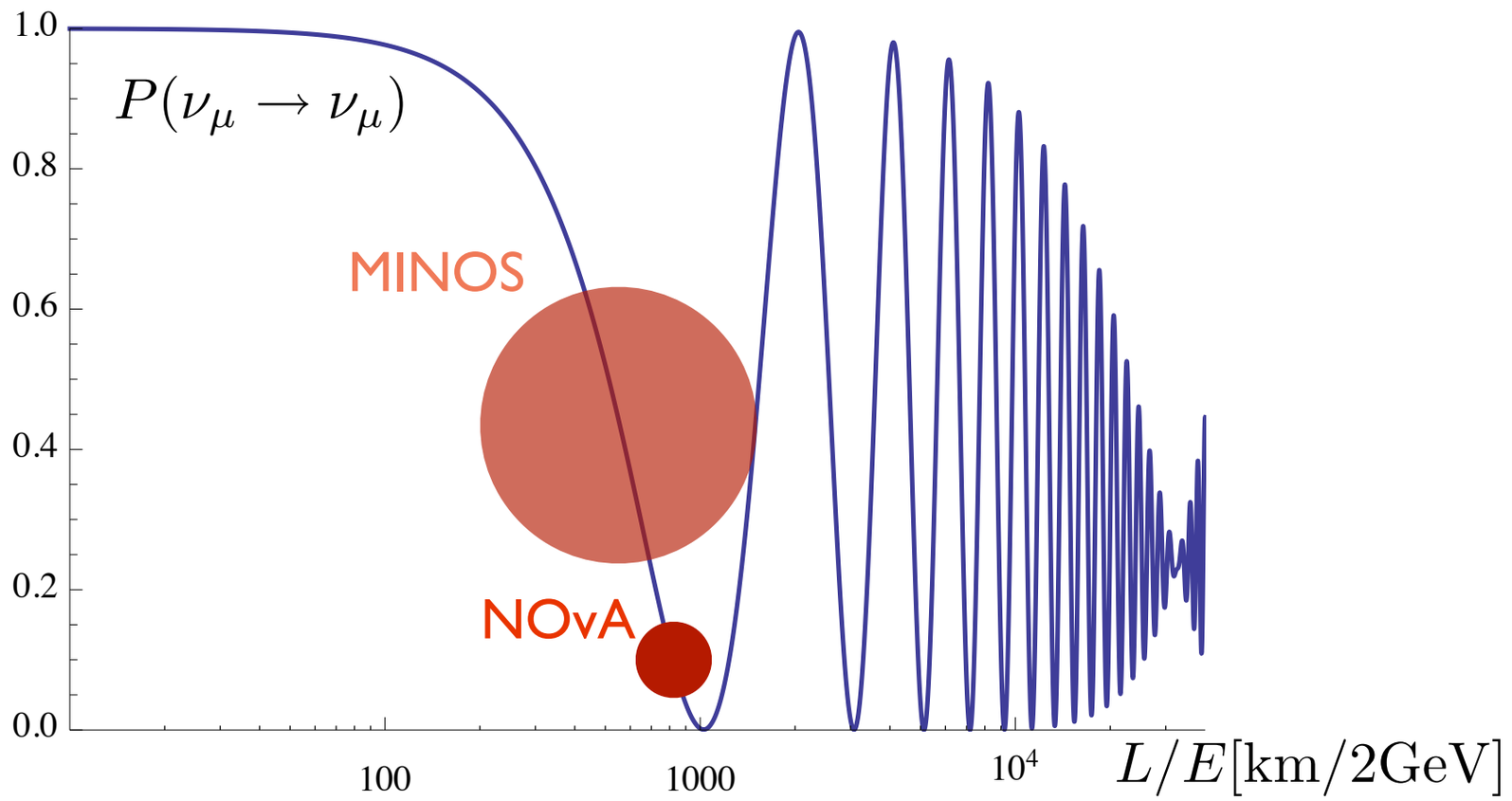
NOvA


Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
0
20
40
60
80
0
2
4
6
8
10
E_ν (GeV)

NOvA

- L = 810 km (MINOS 735 km)
- Liquid scintilator tracking calorimeter
- NuMI beam (700kW ➜ 2MW) s peak energií mezi 2GeV a 7GeV
- off-axis (monochromatické spektrum)

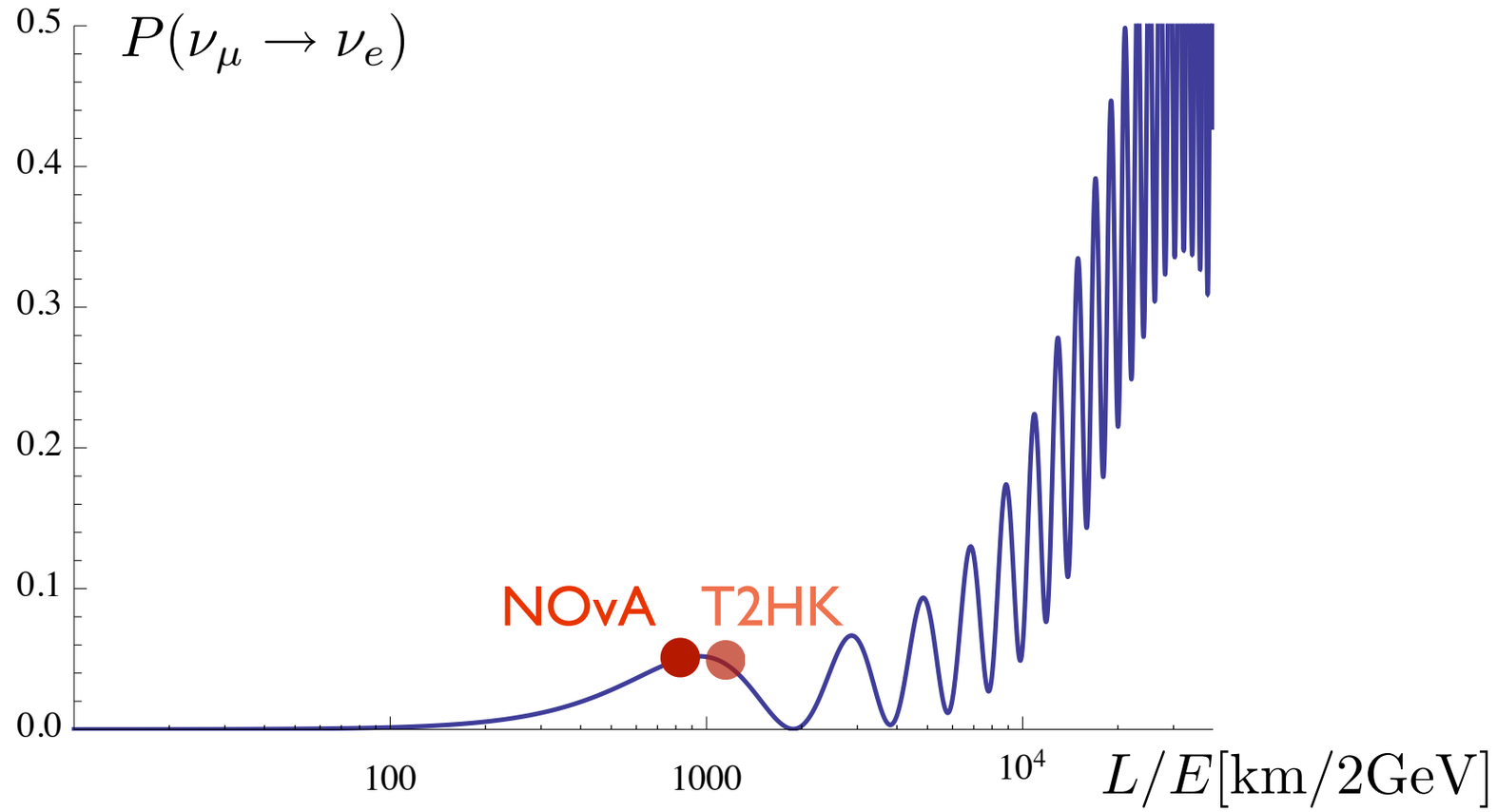
Přežití mionových neutrin @ NuMI @ 2 GeV



NOvA

- L = 810 km (MINOS 735 km)
- Liquid scintilator tracking calorimeter
- NuMI beam (700kW ➜ 2MW) s peak energií mezi 2GeV a 7GeV
- off-axis (monochromatické spektrum)
- povrchový experiment (narozdíl od MINOSu, ten je v Soudan Underground Lab 700m hluboko) - pozadí z atm. neutrin (40M:1)
- měření θ_{13} i θ_{23} úhlů (MINOS jen θ_{23}) a Δm^2_{32} včetně znamení, tj. hierarchie (v konvoluci s CP fází)
- ν_e appearance v ν_μ svazku (rozlišení e- a μ-eventů) tj. možnost měřit CP narušení - MINOS jen přežití ν_μ (je to magnetizovaný sendvič Fe+plast. scintilátor)

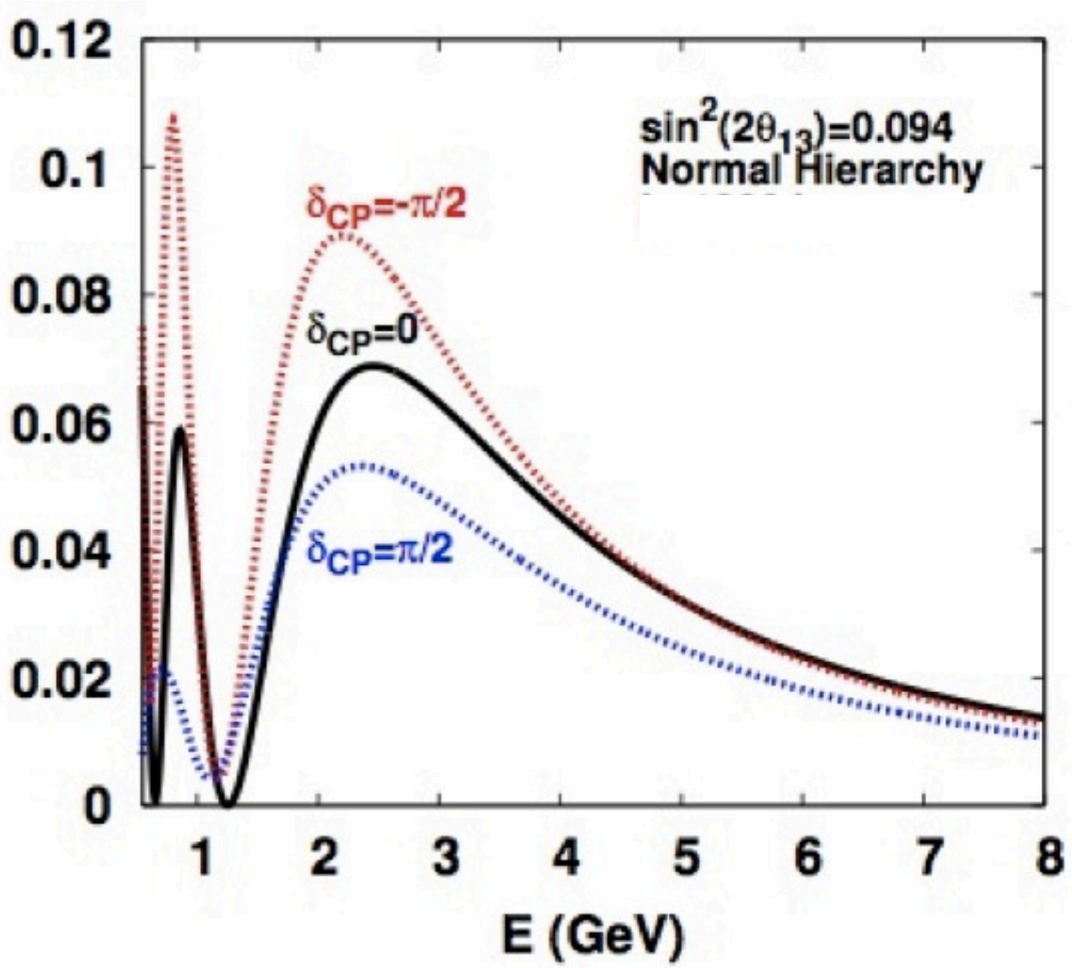
Oscilace mionových na elektronová @ NuMI @ 2 GeV (MINOS neumí)



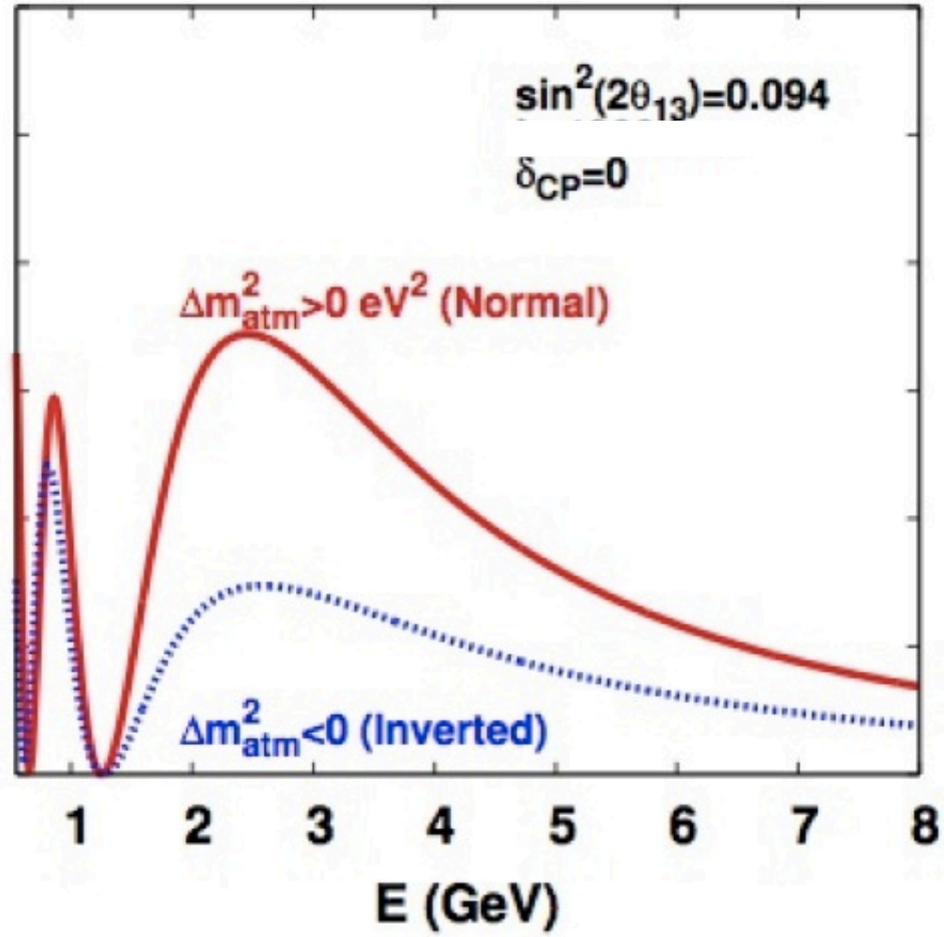
NOvA

CP efekt: $\nu_\mu \to \nu_e$, $\overline{\nu}_\mu \to \overline{\nu}_e$ velmi podobně jako na LBNE (dnes ELBNF)

CP efekt



Hierarchie



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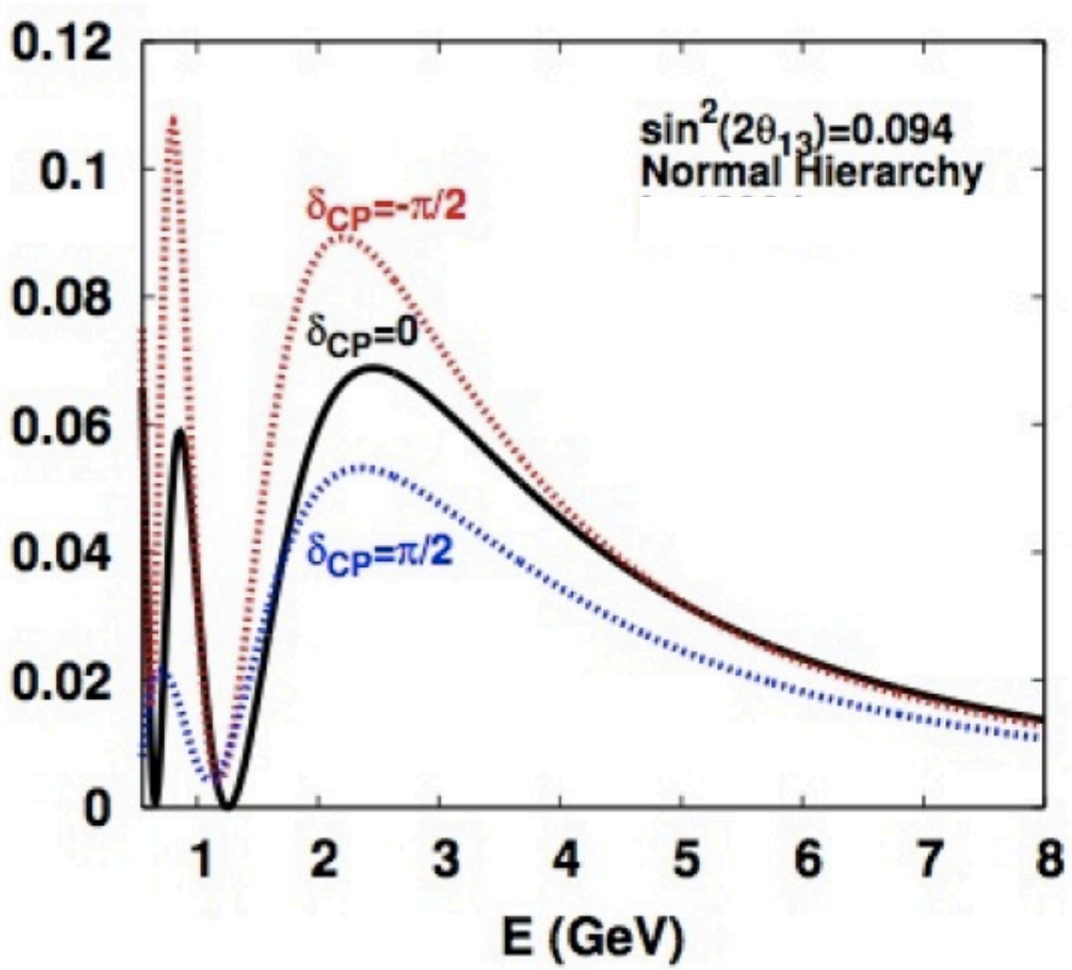
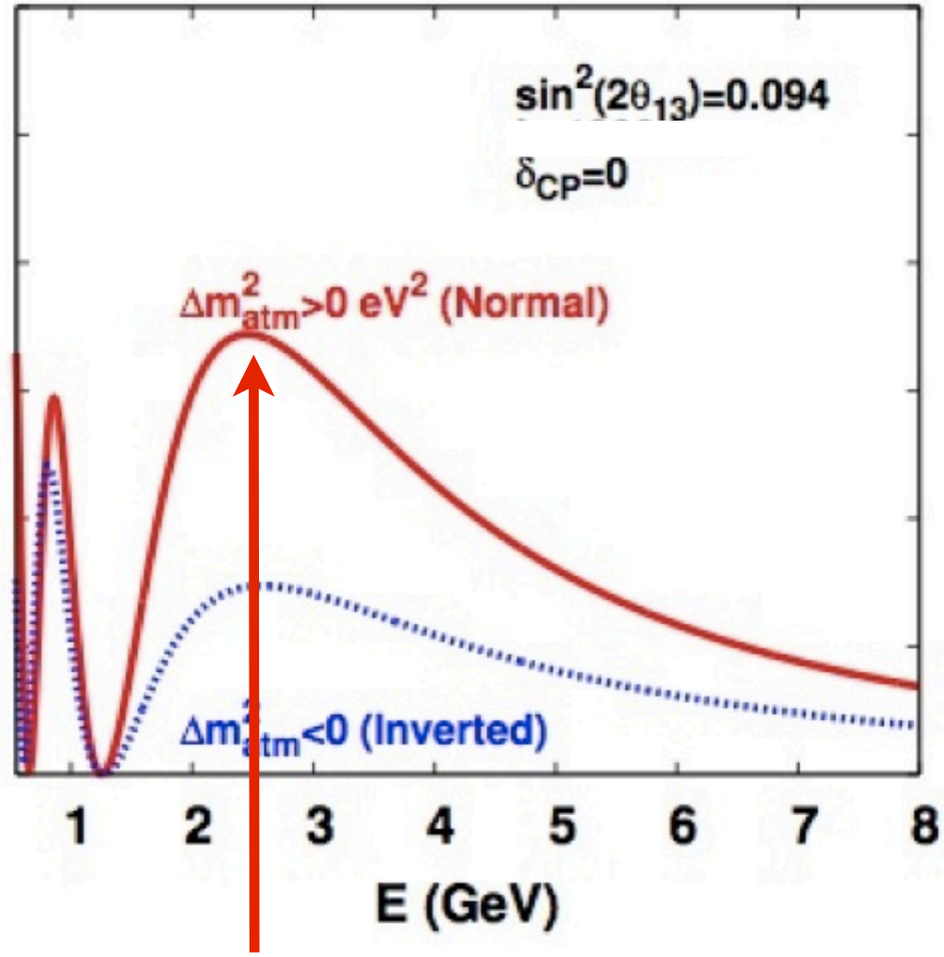
CP efekt



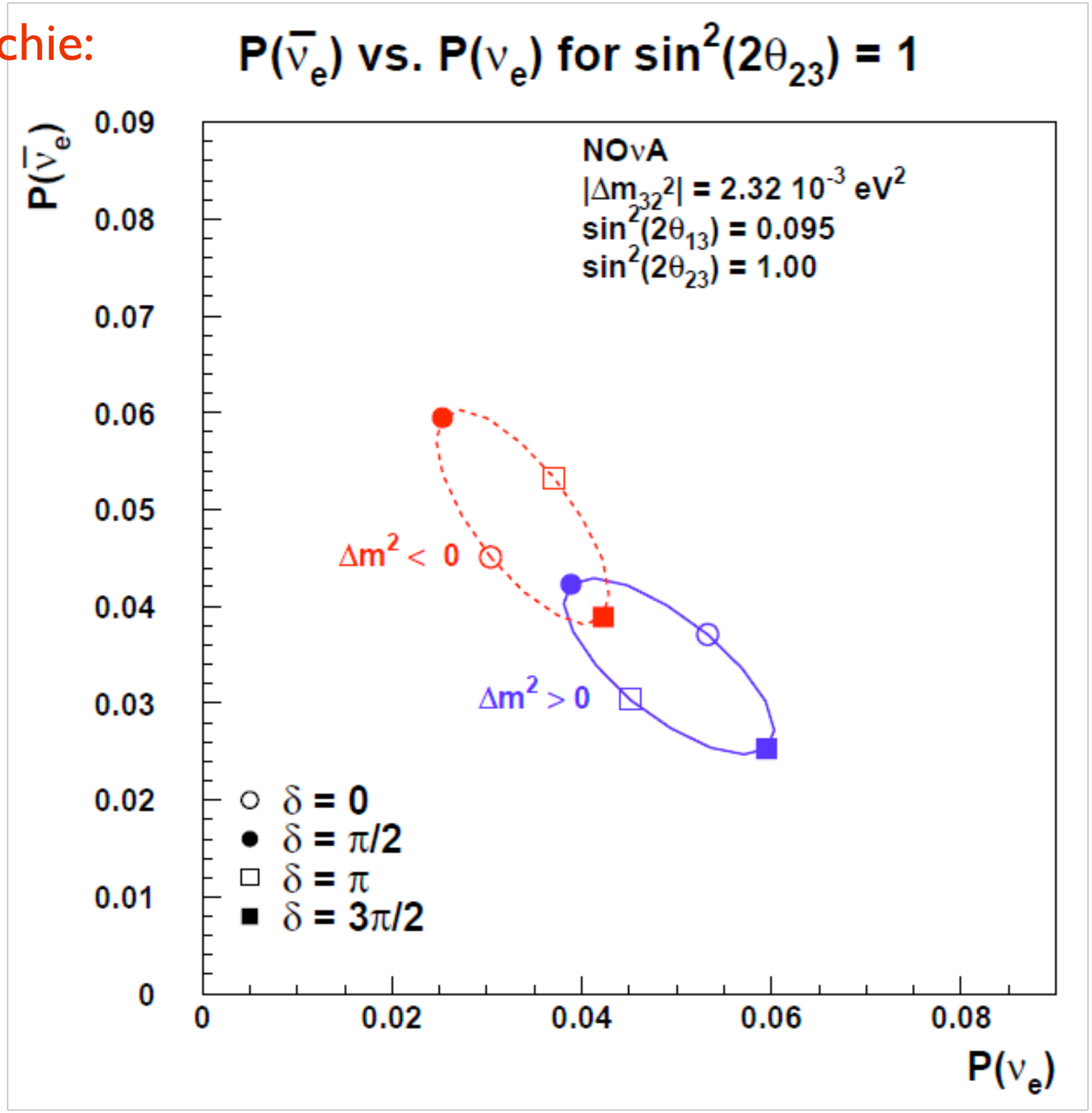
Hierarchie



velká vzdálenost - efekt hierarchie významný - degenerace

NOvA

CP fáze, hierarchie:



NOvA

Novinky za posledních 9 měsíců

- Detektory dokončeny (FarDet 29.7.2014, NearDet 12.8.2014)
- Začínají analýzy dat

NOvA

FZU

- Milos Lokajicek - vedeni projektu, computing
- Jaroslav Zalesak - NOvA run koordinator, DAQ expert, vyvoj a testy DAQ softwaru, APD expert - testovani APD (testy povrchove upravy) smeny (dohled nad provozem detektoru v kontrolni mistnosti)
- Ivo Polak - inzenyr, dlouhodobe testovani APD
- Jiri Kvasnicka - inzenyr, dlouhodobe testovani APD
- Josef Zuklin - inzenyr, dlouhodobe testovani APD
- Zdenek Kotek - technik, navrh a vyroba temneho boxu na testovani APD
- Jan Svec - IT specialista, computing
- Vaclav Zamazal - technik, dlouhodobe testovani APD
- Vlastimil Zamazal - technik, dlouhodobe testovani APD

MFF

- Karel Soustruznik - vyvoj QA (quality assurance) + DAQ softwaru (aplikace na zpristupneni QA dat, aplikace na testovani stavu hardwaru pred instalaci, DAQ downtime logger, analyza pedestal runu), stavba detektoru (plneni NearDet scintilatorem), smeny
- Petr Tas - smeny
- Tomas Nosek - student, analyza dat v ramci nue skupiny, smeny
- Zuzana Jelinkova - student, analyza dat v ramci nue skupiny, smeny
- Jiri Palacky - technik, vyroba mechanicke casti temnych boxu na testovani APD

NOvA

FJFI

- Jan Smolik - dlouhodobe testovani APD
- Filip Jediny - DCS expert (detector control systems), instalace a kalibrace DCS hardwaru, navrh noveho DCS systemu pro Blizky detektor, zodpovedny za system monitorujici prostredi vsech NOvA detektoru, smeny
- Tomas Vrba - instalace softwaru pro NOvA MC produkci, smeny
- Petr Vokac - instalace, zprovozneni a monitoring MC produkce pro NOvA
- V. Linhart - dlouhodobe testovani APD

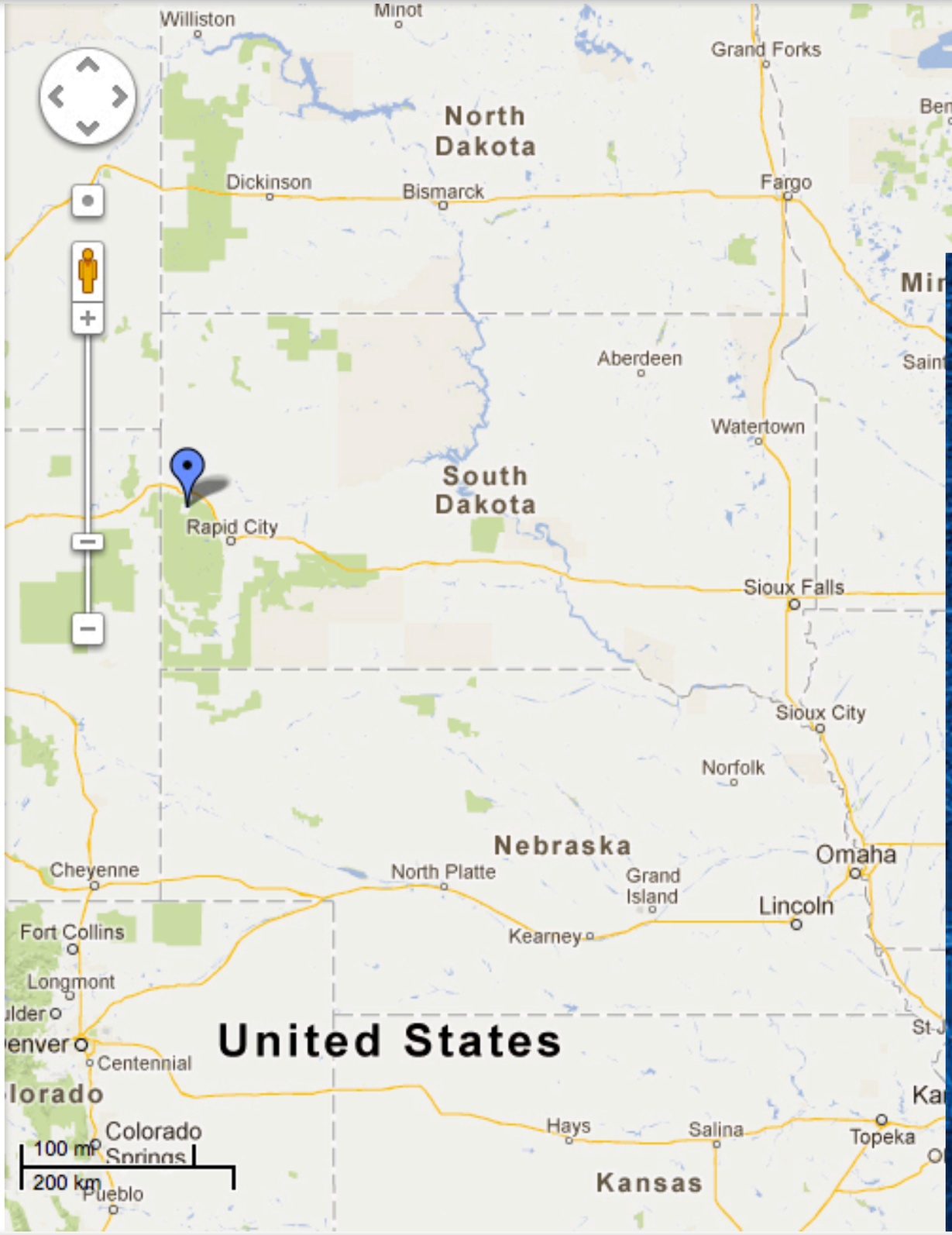
LBNE → LBNF, ELBNF + CERN ν platform

(FNAL + Sanford LAB + CERN)

LBNE


Williston
Minot
Grand Forks
Quetico Provincial Park
Bemidji
North Dakota
Dickinson
Bismarck
Fargo
Duluth
Satellite
Traffic
Minnesota
Aberdeen
Saint Cloud
Coon Rapids
Watertown
Plymouth
Minneapolis
Wausau
Traverse City
Bloomington
Eau Claire
South Dakota
Rapid City
Wisconsin
Green Bay
Appleton
Rochester
Oshkosh
Sioux Falls
Madison
Milwaukee
Grand Rapids
Kenosha
Sioux City
Waterloo
Rockford
Cedar Rapids
Norfolk
Iowa
Chicago
Naperville
Davenport
Nebraska
Omaha
Des Moines
Joliet
Cheyenne
North Platte
Grand Island
Lincoln
Fort Wayne
Kearney
Peoria
Fort Collins
Longmont
Illinois
Indiana
United States
St Joseph
Springfield
Indianapolis
Kansas City
Columbia
Hays
Salina
Topeka
Lee's Summit
Olathe
Alton
Bloomington
Columbus
Colorado Springs
100 mi
200 km
Pueblo
Kansas
St. Louis
Missouri
Louisville
Map data ©2012 Google
Report a problem

LBNE


Williston
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North Dakota
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Fargo
Aberdeen
Watertown
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Rapid City
Sioux Falls
Sioux City
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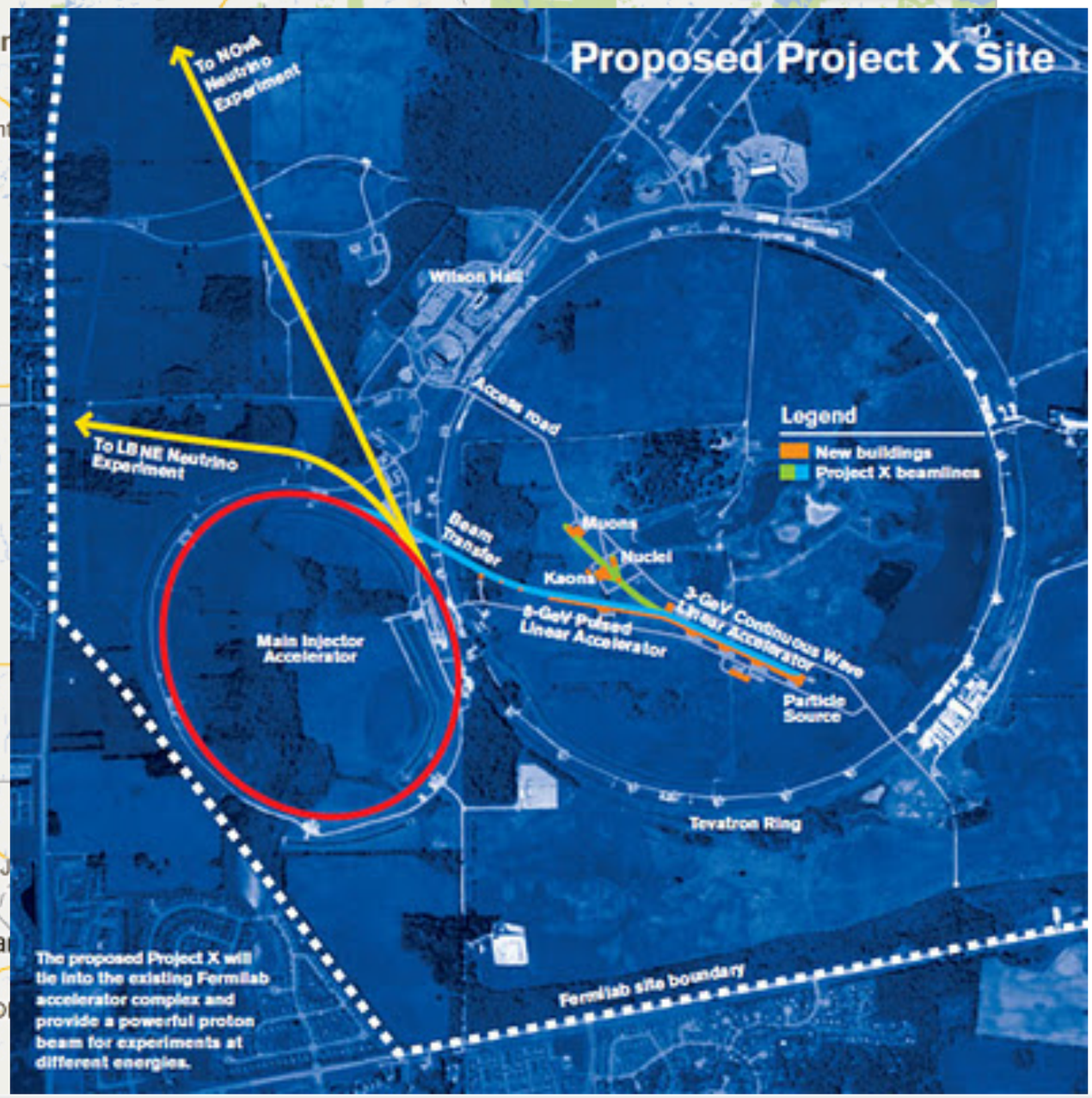
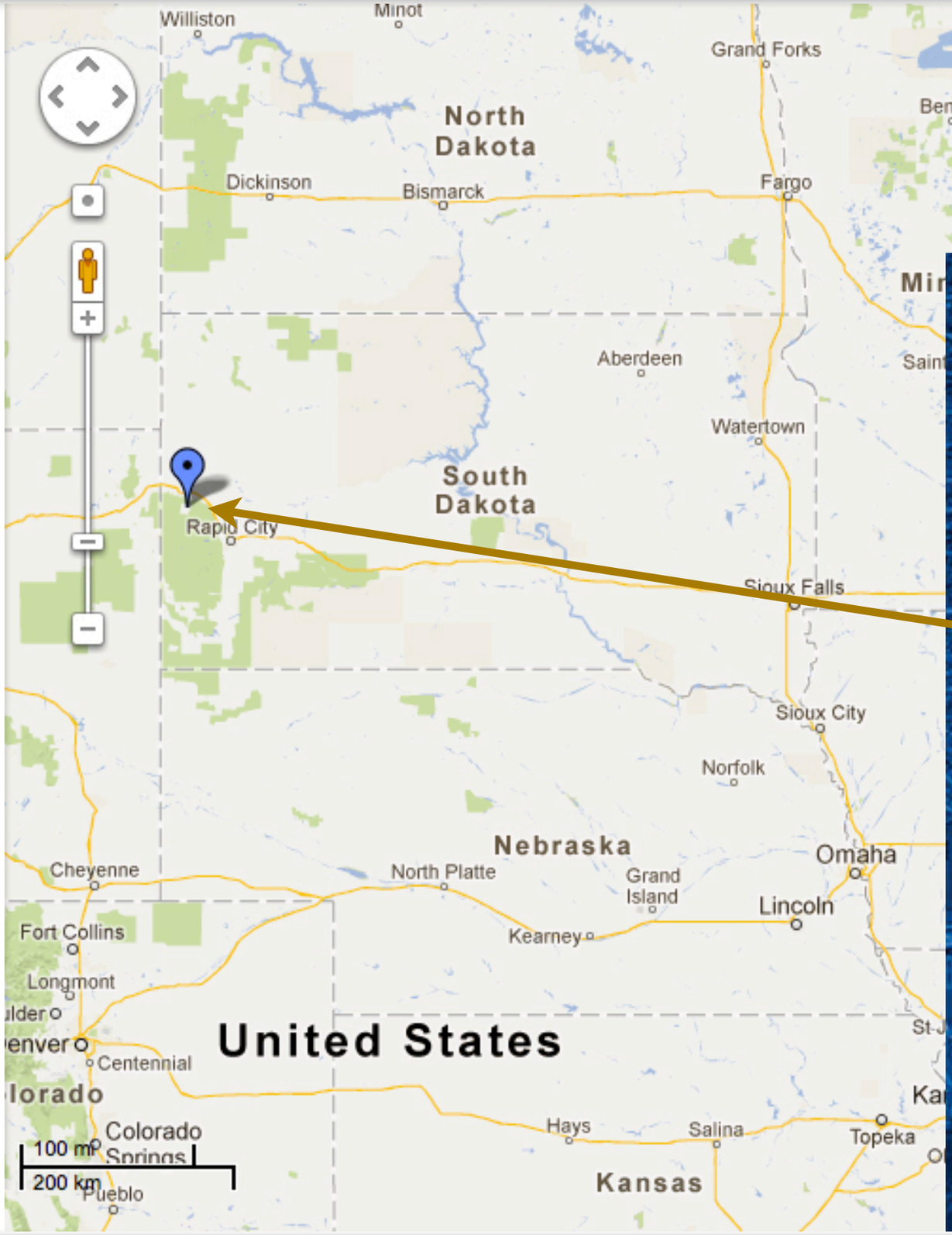
Omaha
Lincoln
Grand Island
North Platte
Cheyenne
Kearney
Fort Collins
Longmont
Denver
Centennial
Colorado
Colorado Springs
Pueblo
Hays
Salina
Topeka
Kansas
United States
100 mi
200 km


Quetico Provincial Park
Bemidji
Duluth
Satellite
Traffic


Proposed Project X Site
To NOvA Neutrino Experiment
Wilson Hall
Access road
To LBNE Neutrino Experiment
Legend
New buildings
Project X beamlines
Beam Transfer
Muons
Nuclei
Kaons
8-GeV Pulsed Linear Accelerator
3-GeV Continuous Wave Linear Accelerator
Particle Source
Main Injector Accelerator
Tevatron Ring
The proposed Project X will tie into the existing Fermilab accelerator complex and provide a powerful proton beam for experiments at different energies.
Fermilab site boundary

LBNE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Cheyenne
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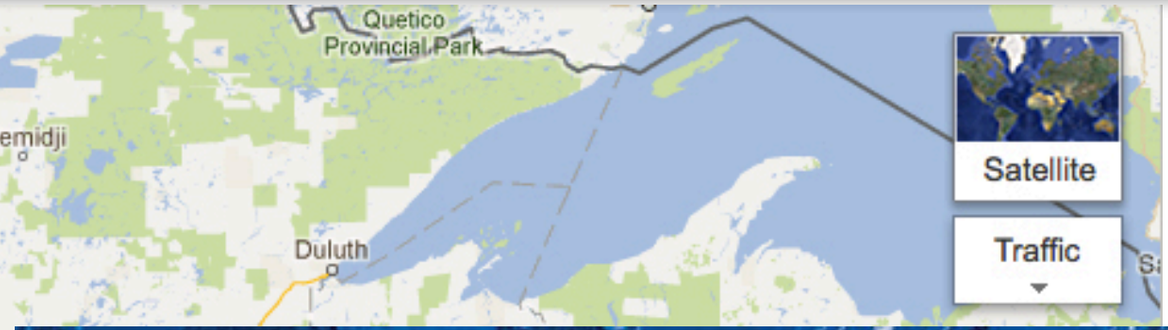
Centennial
Colorado Springs
Pueblo
Hays
Salina
Topeka
Kansas
United States
100 mi
200 km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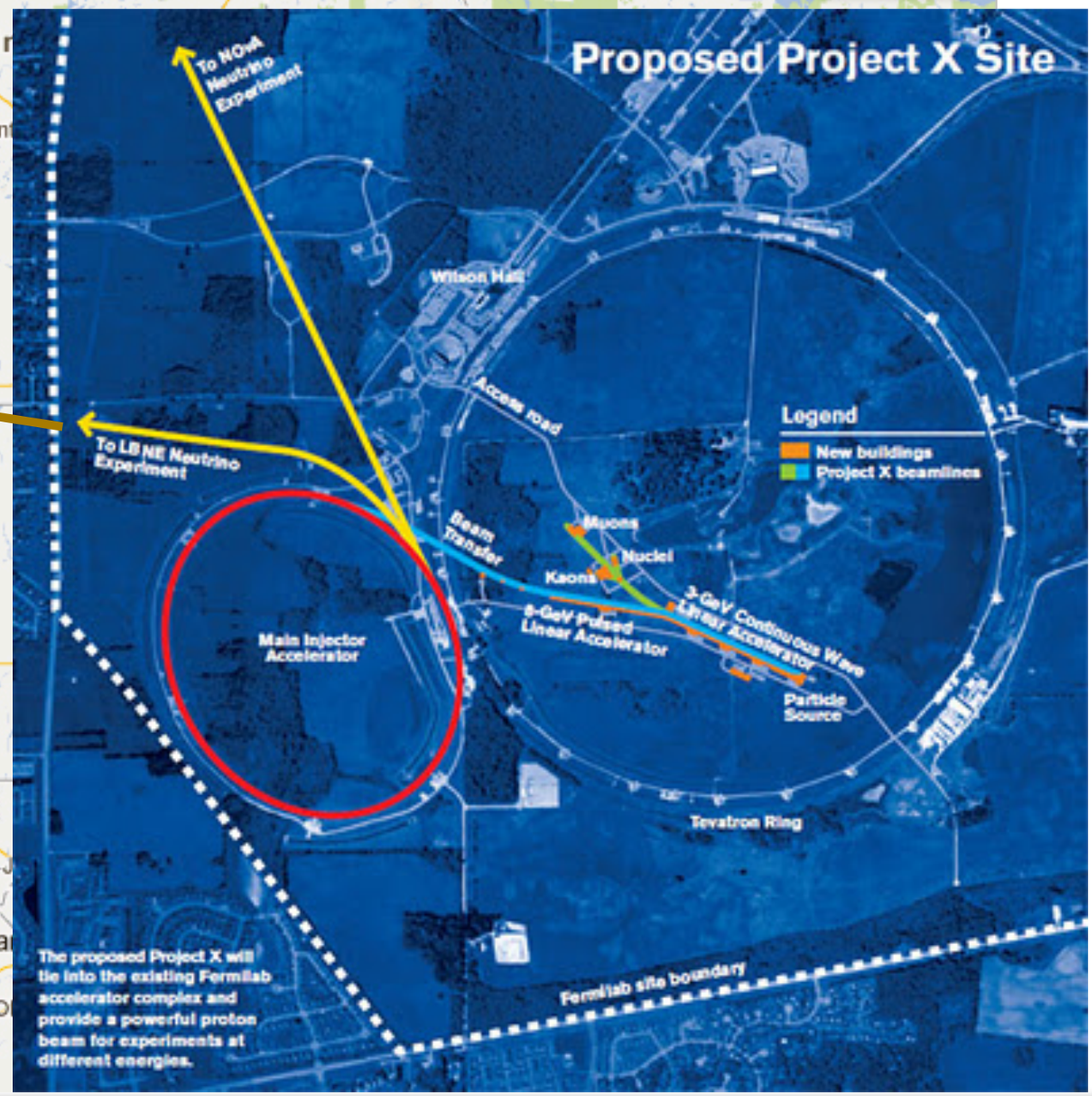
Traffic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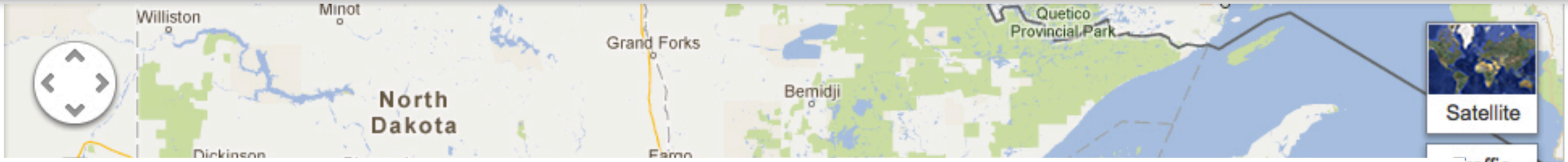
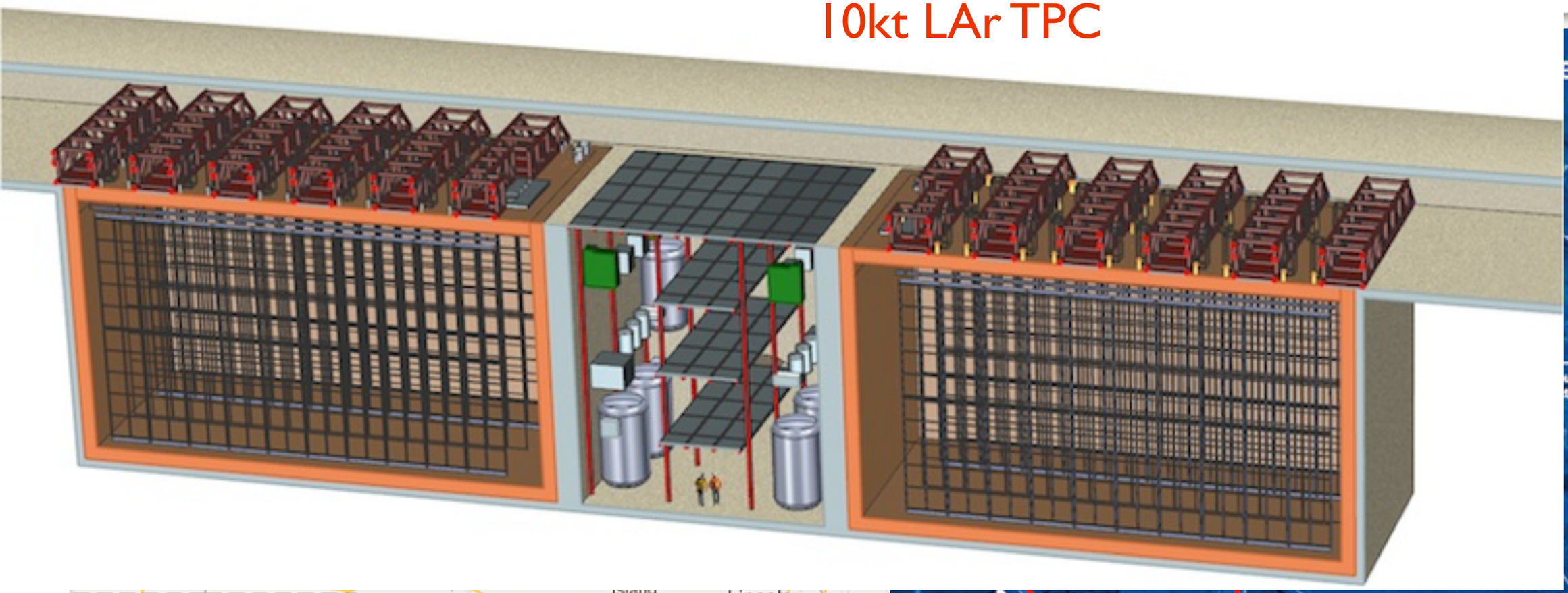
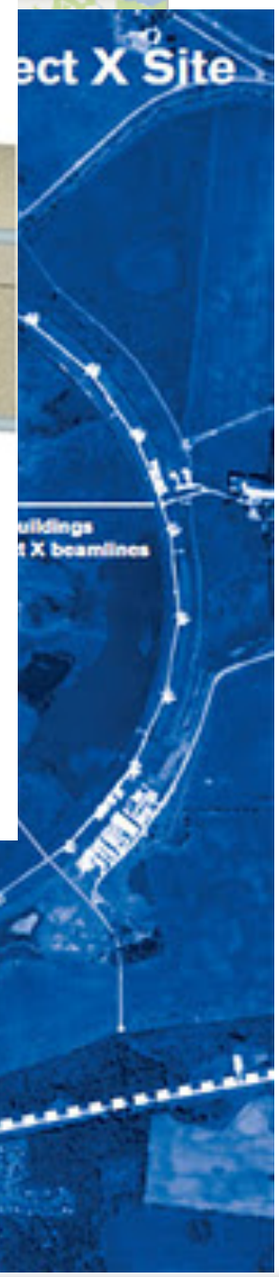
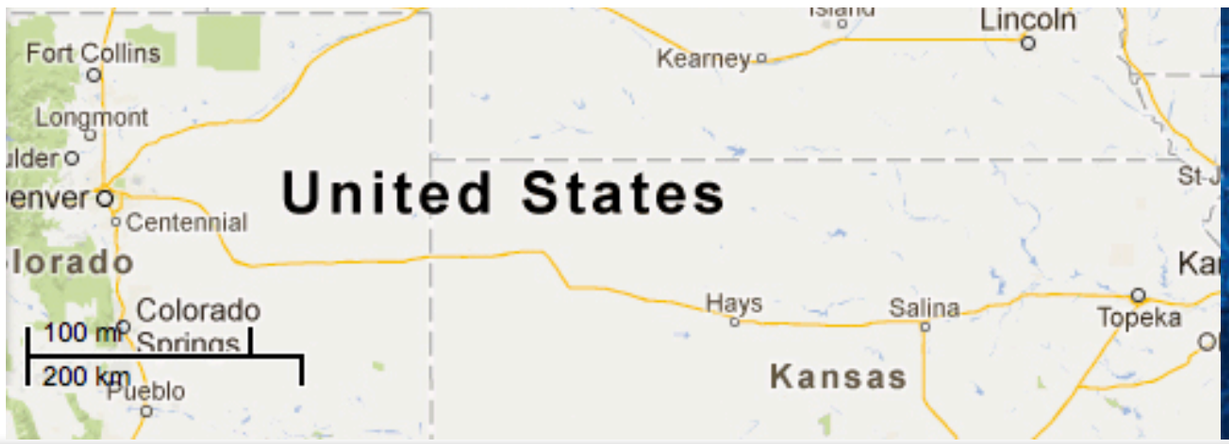


10kt LAr TPC







LBNE (+ Project X)

Situace na jaře 2014

- LBNE "stabilně podfinancováno"
- Prostředky (cca 870 M$ od DOE) sdíleny mezi svazkem a detektorem (3:1)
- Silně redukovaný program (nemožnost jít brzy pod zem, malý detektor)
- Urgentní - konkurence Hyper-K

2014: TDR

2023: start **LBNE10** @ 700 kW

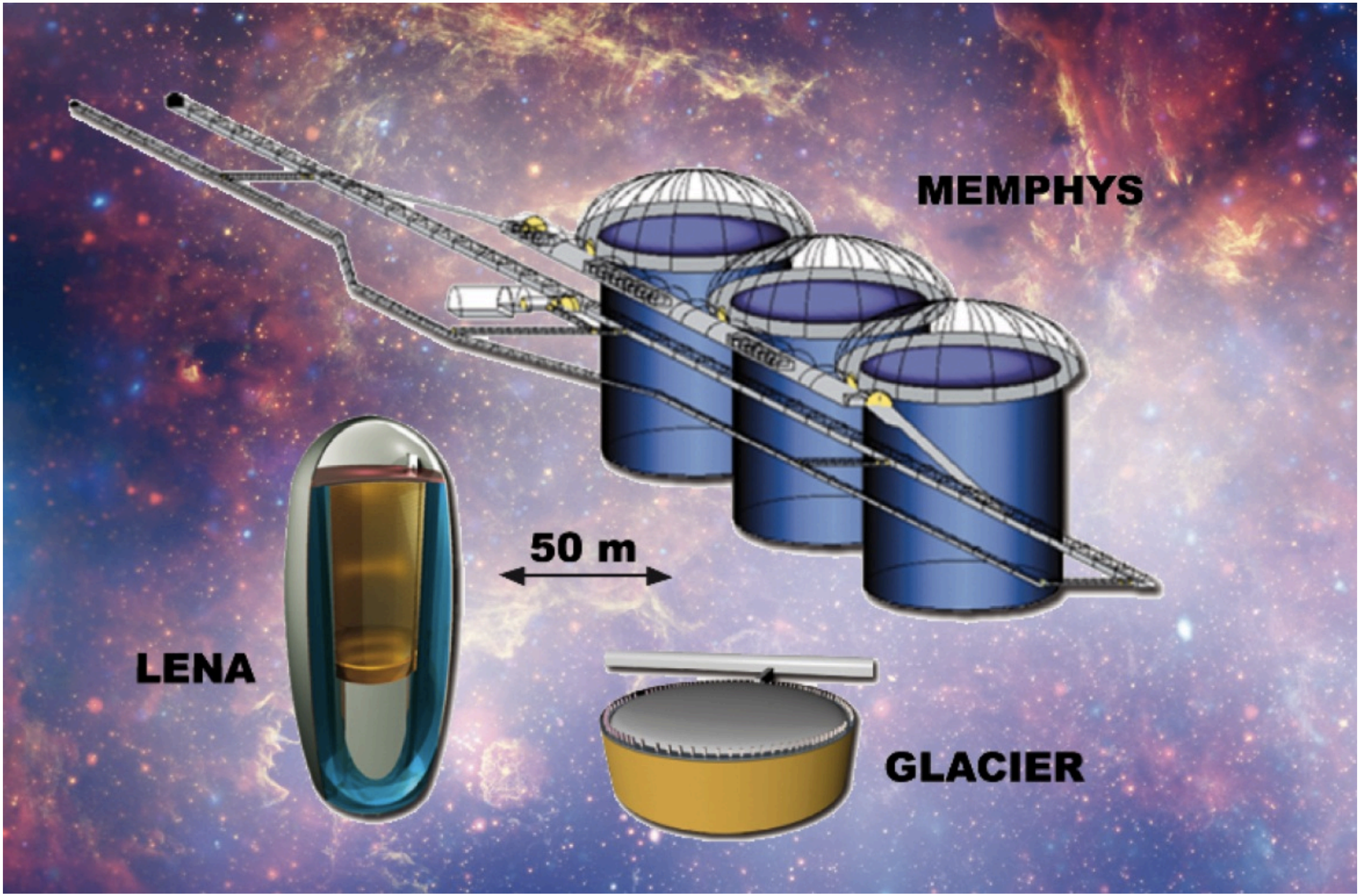
2026: 1.2 MW (project X phase 1), 20kt na povrchu

2028: 34kt na povrchu

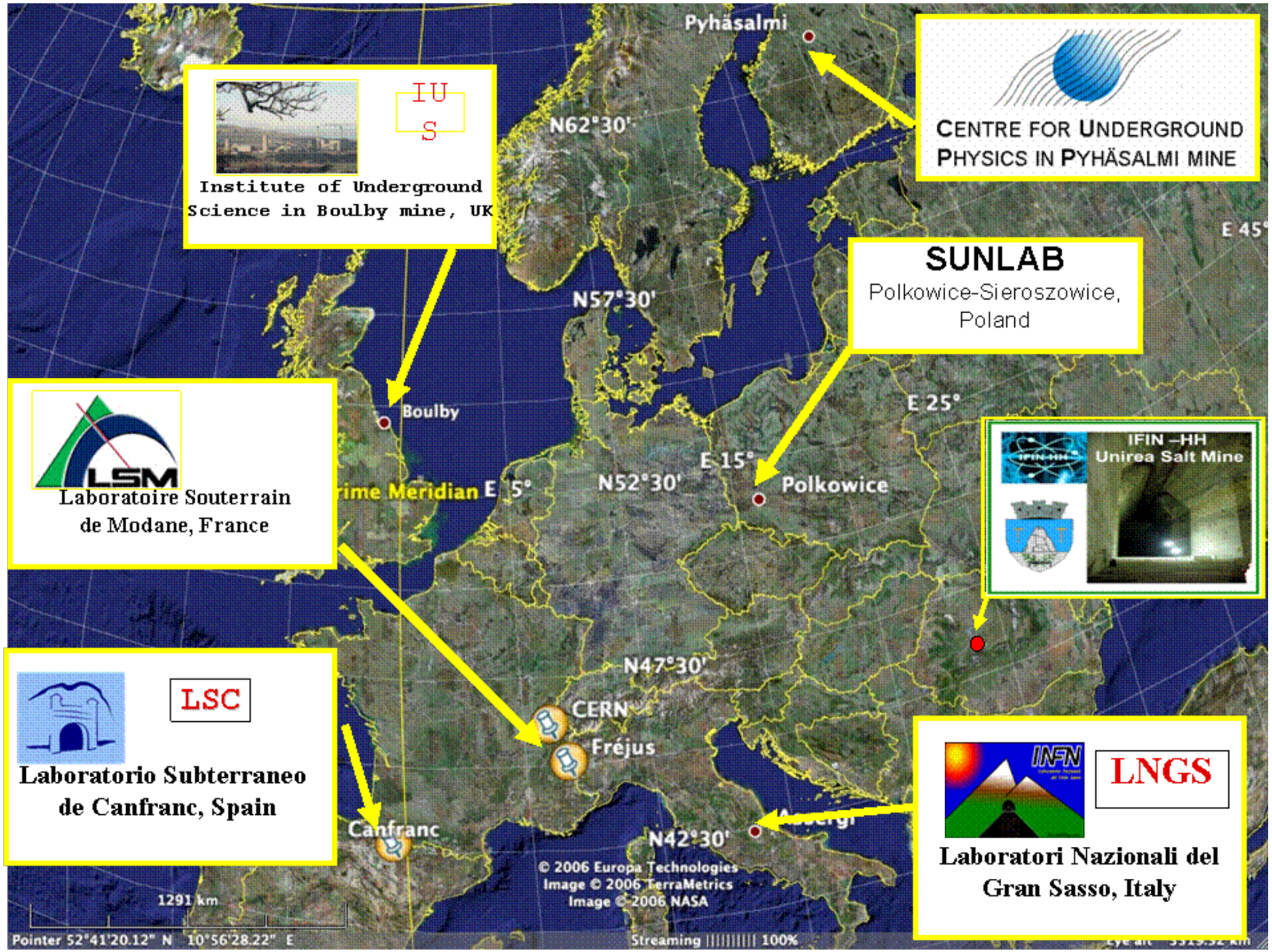
2032: 2.4 MW, nabírání dat do cca 2038

HEPAP P5 návrh na internacionalizaci projektu ➜ LBNF

LBNO + CERN



LBNO + CERN


Pyhäsalmi
CENTRE FOR UNDERGROUND PHYSICS IN PYHÄSALMI MINE
IU S
Institute of Underground Science in Boulby mine, UK
SUNLAB
Polkowice-Sieroszowice, Poland
N62°30'
N57°30'
E 45°
E 25°
E 15°
N52°30'
Boulby
Polkowice
IFIN –HH
Unirea Salt Mine
LSM
Laboratoire Souterrain de Modane, France
N47°30'
CERN
Fréjus
LSC
Laboratorio Subterraneo de Canfranc, Spain
Canfranc
N42°30'
INFN
LNGS
Laboratori Nazionali del Gran Sasso, Italy
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Image © 2006 NASA
1291 km
Pointer 52°41'20.12" N 10°56'28.22" E
Streaming 100%

LBNO + CERN

LBNO + CERN

Situace na jaře 2014

- Problémy s lokací (v Pyhäsalmi to nechtějí)
- Technologie nezafixována (LENA - LSci, GLACIER - LArTPC , MEMPHYS -WC)
- Možné potíže s výstavbou neutrinového svazku "za chodu" SPS/LHC

CERN neutrino platform (as a part of Medium Term Plan)

✓ CERN offers a platform for Neutrino detectors R&D. This platform is now part of the CERN MTP. We will support this platform in an active way and will help WA104, WA105 and others proposals in this initial phase

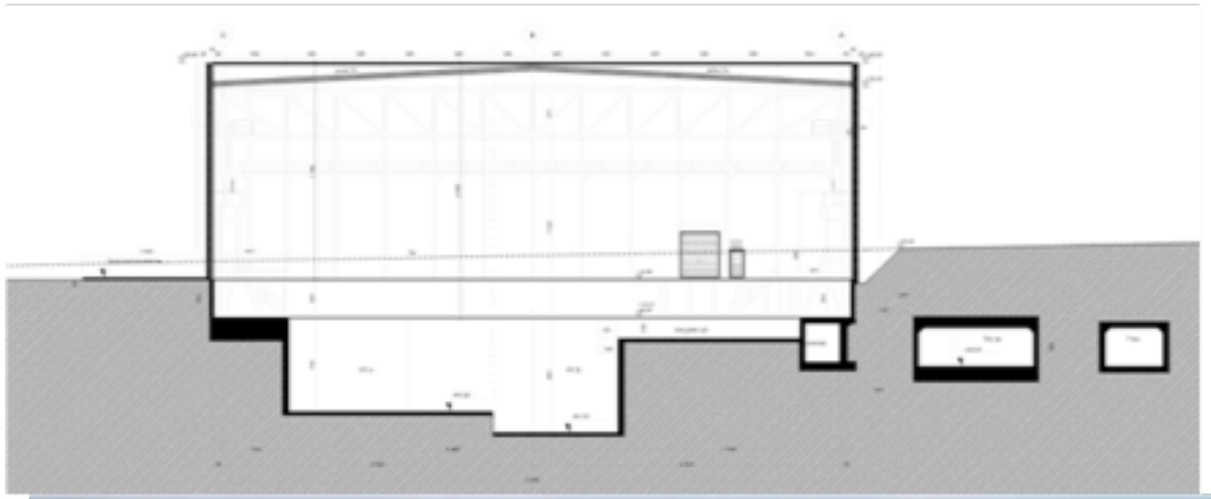
✓ CERN will construct a large neutrino test area (EHN1 extension) with charged beams capabilities, available in 2016

✓ CERN will assist the EU neutrino community in their long term common plans. For the moment CERN is not committing to any neutrino beam at CERN, in view of an agreed road map between all partners

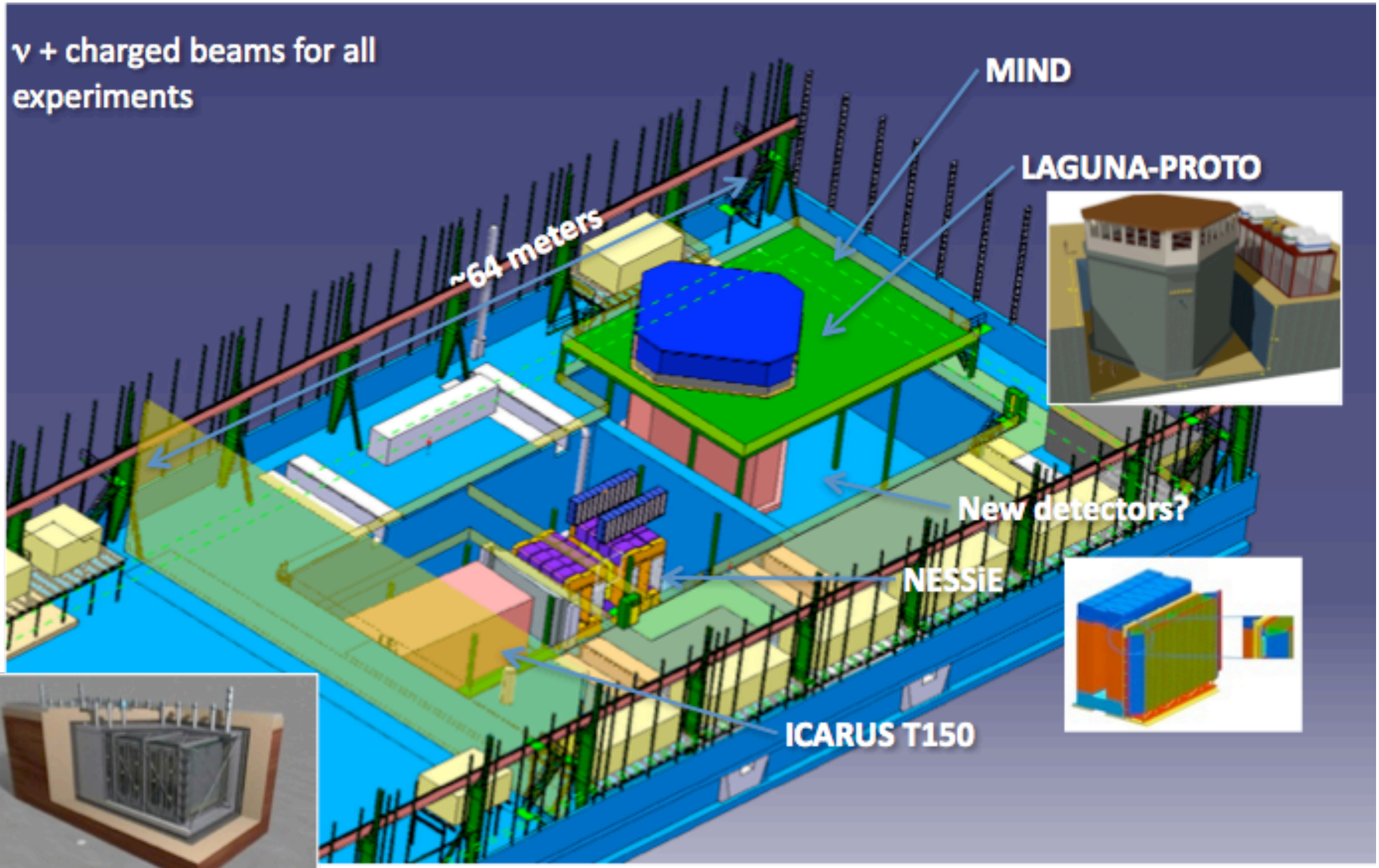
- A. Rubbia & ICARUS na cestě do FNAL (sterilní neutrina)

CERN neutrino platform - EHN1

Nord Area EHN1 extension



CERN neutrino platform - EHN1



LBNF, ELBNF + CERN ν platform

LBNF : Neutrinový svazek + infrastruktura - FNAL + mez. partneři

CERN Neutrino platform : testovací infrastruktura pro ELBNF LAr TPC

ELBNF : mezinárodní spolupráce po vzoru experimentů na LHC

- Vzniká mezinárodní struktura a řídící orgány

- Předseda dočasného sboru instuticí Sergio Bertolucci

Časový plán (předběžný):

právě teď: LOI - postupně finalizován

https://indico.fnal.gov/internalPage.py?pageId=0&confId=9090

2015: TDR
2021: 100t demonstrátor
2024: Kompletní detektor

November 5, 2014

Experimental program at the Long-Baseline Neutrino Facility (ELBNF)

Letter of Intent to Form an International Collaboration

Executive Summary

This Letter of Intent (LOI) brings together a global neutrino community to pursue an accelerator-based long-baseline neutrino experiment, as well as neutrino astrophysics and nucleon decay, with an approximately 40-kton (active mass) modular liquid argon TPC (LAr-TPC) detector located deep underground. Several independent worldwide efforts, developed through many years of detailed studies, have now converged around the opportunity provided by the megawatt neutrino beam facility planned at Fermilab and by the new significant expansion with improved access foreseen at the Sanford Underground Research Facility in South Dakota. The new international team has the necessary expertise, technical knowledge, and critical mass to design and implement this exciting discovery experiment in a relatively short timeframe. The goal is the deployment of the first 10-kton detector on the timescale of 2021. The PIP-II accelerator upgrade at Fermilab will provide 1.2 MW of power by 2024 to drive a new neutrino beam line at Fermilab. With the availability of space for expansion and improved access at the Sanford laboratory, this international collaboration will develop the necessary framework to design, build and operate a world-class deep-underground neutrino observatory. Fermilab will act as the host laboratory. This plan is aligned with the European Strategy Report and the US HEPAP P5 report.

November 18, 2014

Experimental program at the Long-Baseline Neutrino Facility (ELBNF)

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EOI: LAr TPC test @ CERN

Expression of Interest for a Full-Scale Detector Engineering Test and Test Beam Calibration of a Single-Phase LAr TPC

M.A.Leigui de Oliveira, C.A. Moura, L.Paulucci
Universidade Federal do ABC

Z. Djurcic, G. Drake, M. Goodman, S. Magill
Argonne National Laboratory

D. Adams, M.Bishai, H. Chen, G. De Geronimo, M.V. Diwan, J.Fried, S. Kettell, F. Lanni, S.Li, M. Potekhin, V.Radeka, J. Stewart, X. Qian, B. Viren, B.Yu
Brookhaven National Laboratory

J. Griskevich, M. Smy, H. Sobel
University of California, Irvine

A. Renshaw, H. Wang
University of California, Los Angeles

A.Blake, J.Marshall, M. Thomson
University of Cambridge

E. Kemp
Universidade de Campinas

J. Bremer, F. Noto, D. Mladenov, M. Nessi, U. Kose
CERN

N. Buchanan, D. Warner, R.J. Wilson
Colorado State University

CERN-SPSC-2014-027 / SPSC-EOI-011
08/10/2014

EOI: LAr TPC test @ CERN

Universidade Federal do ABC
Argonne National Laboratory
Brookhaven National Laboratory
University of California, Irvine
University of California, Los Angeles
University of Cambridge
Universidade de Campinas
CERN
Colorado State University
University of Delhi
Duke University
ETH Zurich, Institute for Particle Physics
Fermi National Accelerator Laboratory
GSSI - INFN, L'Aquila
University of Hawaii
Indiana University
INFN, LNGS, Assergi
INFN Sezione di Milano
INFN Sezione di Padova
University of Lancaster
INFN, Sezione di Pavia
INFN, Sezione di Milano Bicocca
INFN, Sezione di Catania
Lawrence Berkeley National Laboratory
University of Lancaster
University of Liverpool
Los Alamos National Laboratory
Louisiana State University
University of Manchester
University of Minnesota
University of Oxford
University of Pennsylvania
University of Pittsburgh
Princeton University
University of Sheffield
SLAC National Accelerator Laboratory
South Dakota School of Mines and Technology
Southern Methodist University
STFC/RAL
University of Sussex
University of Texas, Arlington
University of Warwick
University of Wisconsin

T2HK

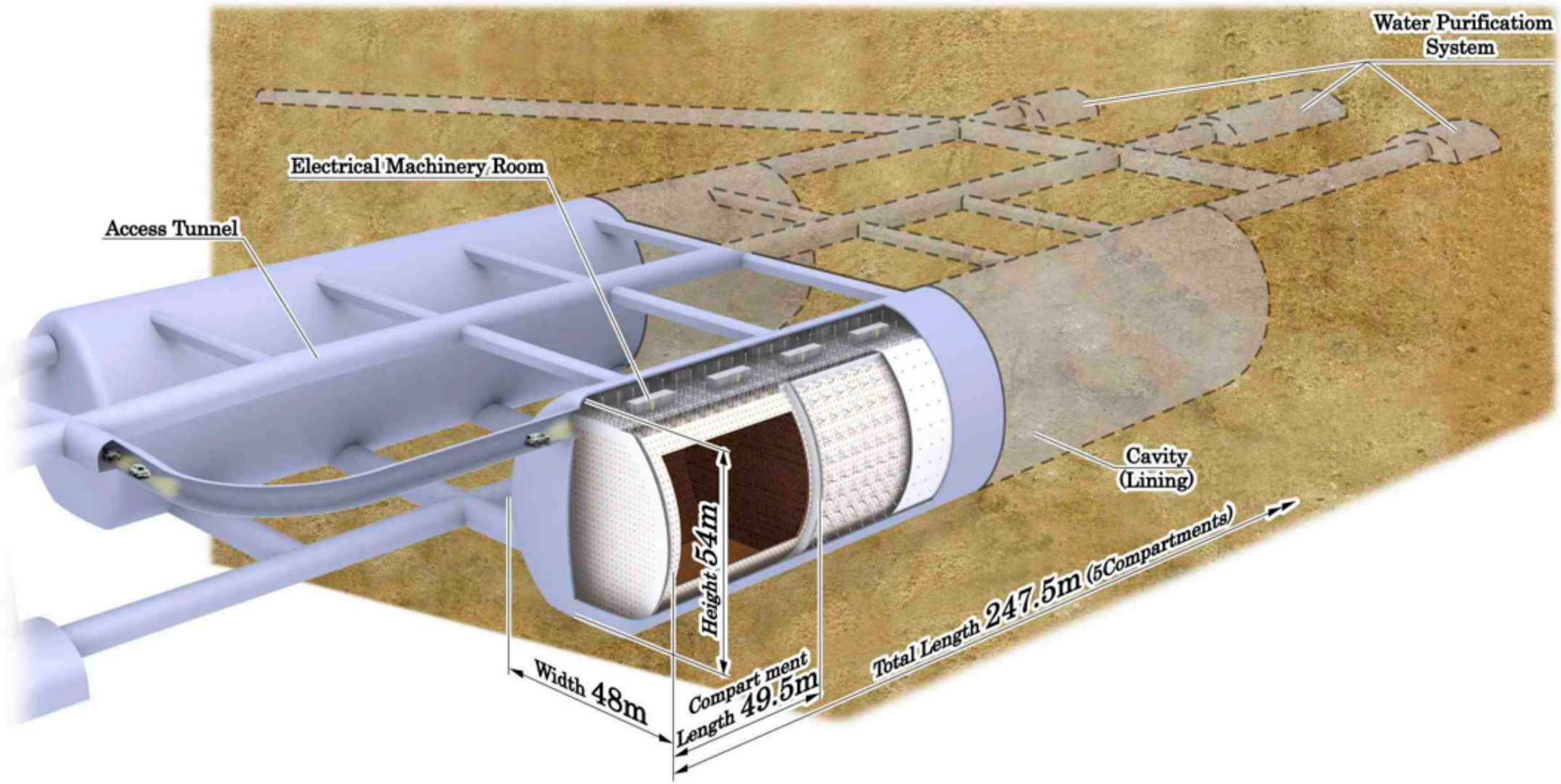
(Kamioka, Japonsko)

ハ イ パーカミオカンデ

T2HK


Yamagata
山形県
Sendai
仙台
Yamagata
山形
Niigata
新潟
Fukushima
福島
Niigata
新潟県
Fukushima
福島県
Toyama
Ishikawa
石川県
Kanazawa
金沢
Super-Kamiokande
detector
Nagano
長野
Utsunomiya
宇都宮
Maebashi
前橋
Mito
水戸
30GeV, 0.75MW
J-PARC accelerator
T2K Neutrino Beam
Ibaraki
茨城県
Fukui
福井
Nagano
長野県
Saitama
埼玉県
Fukui
福井県
Gifu
岐阜県
Kofu
Tokyo
東京
Chiba
千葉
Narita Airport
(Intnl Flights)
Tokyo Haneda Airport
(domestic flights)
Gifu
岐阜
Tokyo
東京都
Yamanashi
山梨県
Chiba
千葉県
Kyoto
京都府
Shiga
滋賀県
Kanagawa
神奈川県
Yokohama
横浜
Kyoto
京都
Nagoya
名古屋
Aichi
愛知県
Shizuoka
静岡
Shizuoka
静岡県
Kobe
神戸
Osaka
大阪
Nara
奈良
Tsu
津

T2HK

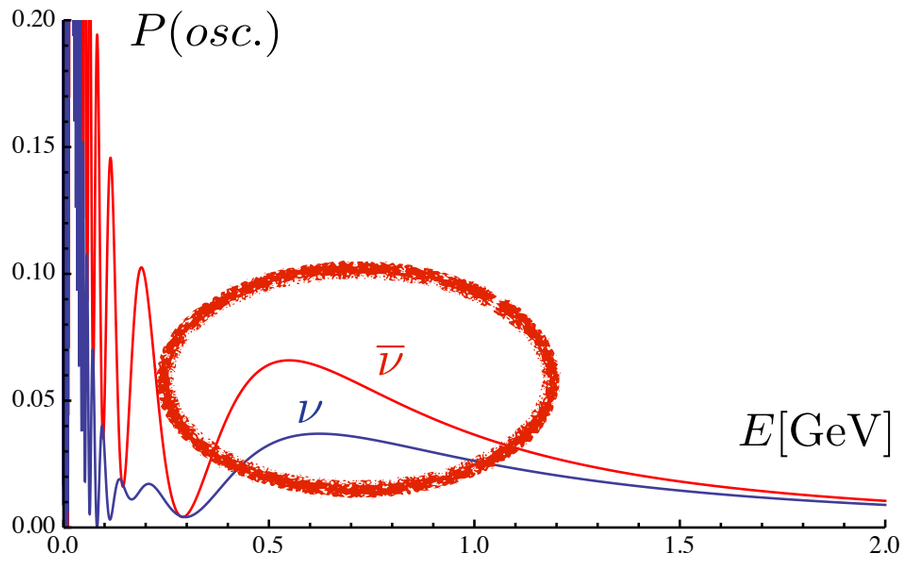


Parametry: 1Mt WC (550 kt FV) @ T2K beam (2.5 stupně off-axis)

T2HK

CP efekt: $\nu_\mu \rightarrow \nu_e\ ,\ \overline{\nu}_\mu \rightarrow \overline{\nu}_e$

3-sigma pokrytí : až 74% param. prostoru



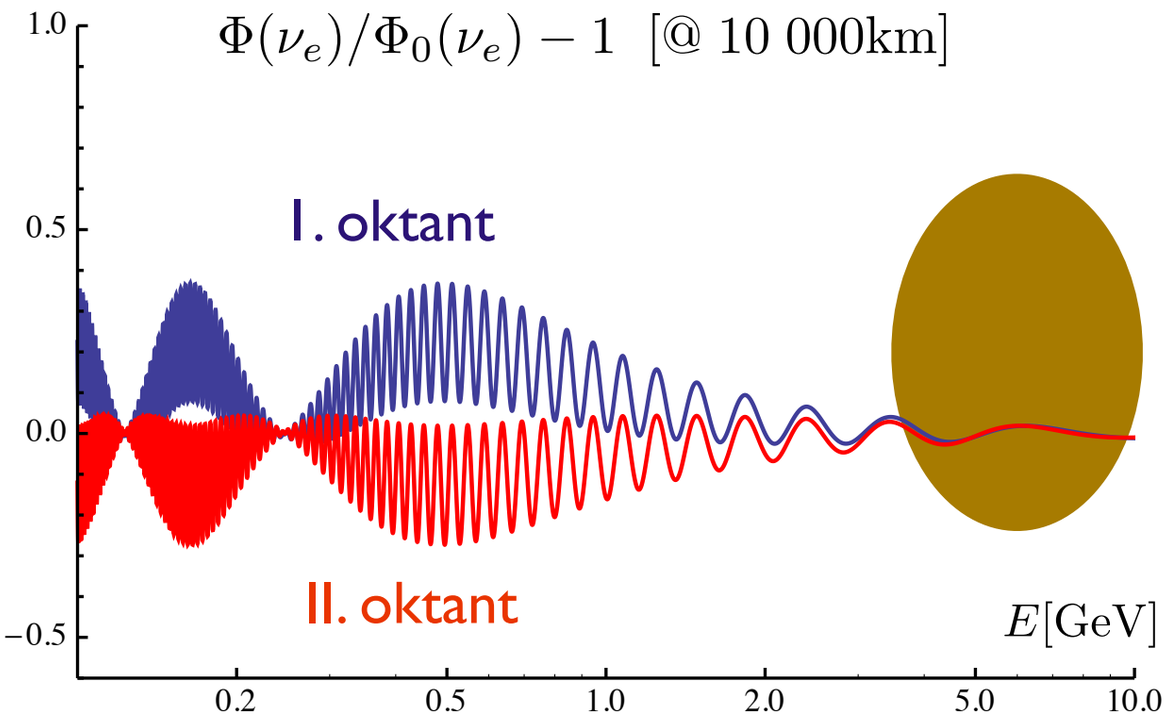
Atmosferická neutrina

Oktant θ_{23} (> 90% C.L.)

Hierarchie (> 3σ C.L.)

NH: MSW efekt pro **neutrina**

IH: MSW efekt pro **antineutrina**



T2HK

Novinky za posledních 9 měsíců

- v červnu proběhl v CERN 2. evropský otevřený mítink
- HK zařazen mezi 27 prioritních projektů jap. vědecké rady

Japanese master plan for large scale research projects

提　言

第 22 期学術の大型研究計画に関する
マスタープラン
（マスタープラン 2014）

平成２６年（２０１４年）２月２８日

日　本　学　術　会　議

科学者委員会

学術の大型研究計画検討分科会

分野	計画番号	学術領域番号	計画名称	計画の概要	学術的な意義
物理学	85	23-2	大型先端検出器による核子崩壊・ニュートリノ振動実験 Nucleon decay and neutrino oscillation experiment with a large advanced detector	スーパーカミオカンデに代わる100万トン級水チェレンコフ検出器ハイパーカミオカンデを建設し、J-PARC加速器ニュートリノビームと組み合わせる事により、世界最先端の核子崩壊・ニュートリノ研究を行う。	ニュートリノにおけるCP対(粒子・反粒子対称性)の破探索し、ニュートリノに満ち宙の進化論に対する理解をる。さらに核子崩壊探索とせ、素粒子物理学の標準理超える物理の確立を目指す
	86	23-2	高エネルギー重イオン衝突実験によるクォーク・グルーオン・プラズマ相の解明 Exploring quark-gluon-plasma with new phase of high-energy heavy-ion experiments	高エネルギー重イオン衝突実験(RHIC-PHENIX/LHC-ALICE 実験)を国際協力の下で推進し、宇宙開びゃく直後の姿である新しい物質相QGP(クォーク・グルーオン・プラズマ)の物性科学を展開する。	ハドロン物質の相構造やQ性の理解を通じて、普遍的質相構造の理解が得られイラル対称性の自発的破クォークの閉じ込め機構、度場の物理、非線形動力学相関物性現象の解明に繋が
	87	23-2	光子ビームによるクォーク核物理研究 Quark nuclear physics with photon beams	光子ビームによるクォーク核物理研究を推進し、量子色力学真空とハドロン内クォーク相関を究明する。東北大学電子光理学研究拠点と大阪大学サブアトミック科学研究拠点との拠点間連携研究計画である。	物質の質量の99.9%はハドロ担っており、その98%はQCDけるカイラル対称性の自発れによって創成されると考えており、学術的観点からは複雑な階層の研究は避けれない。
				カムランドを高性能化・汎用化	ニュートリノのマヨラナ性検

T2HK

Novinky za posledních 9 měsíců

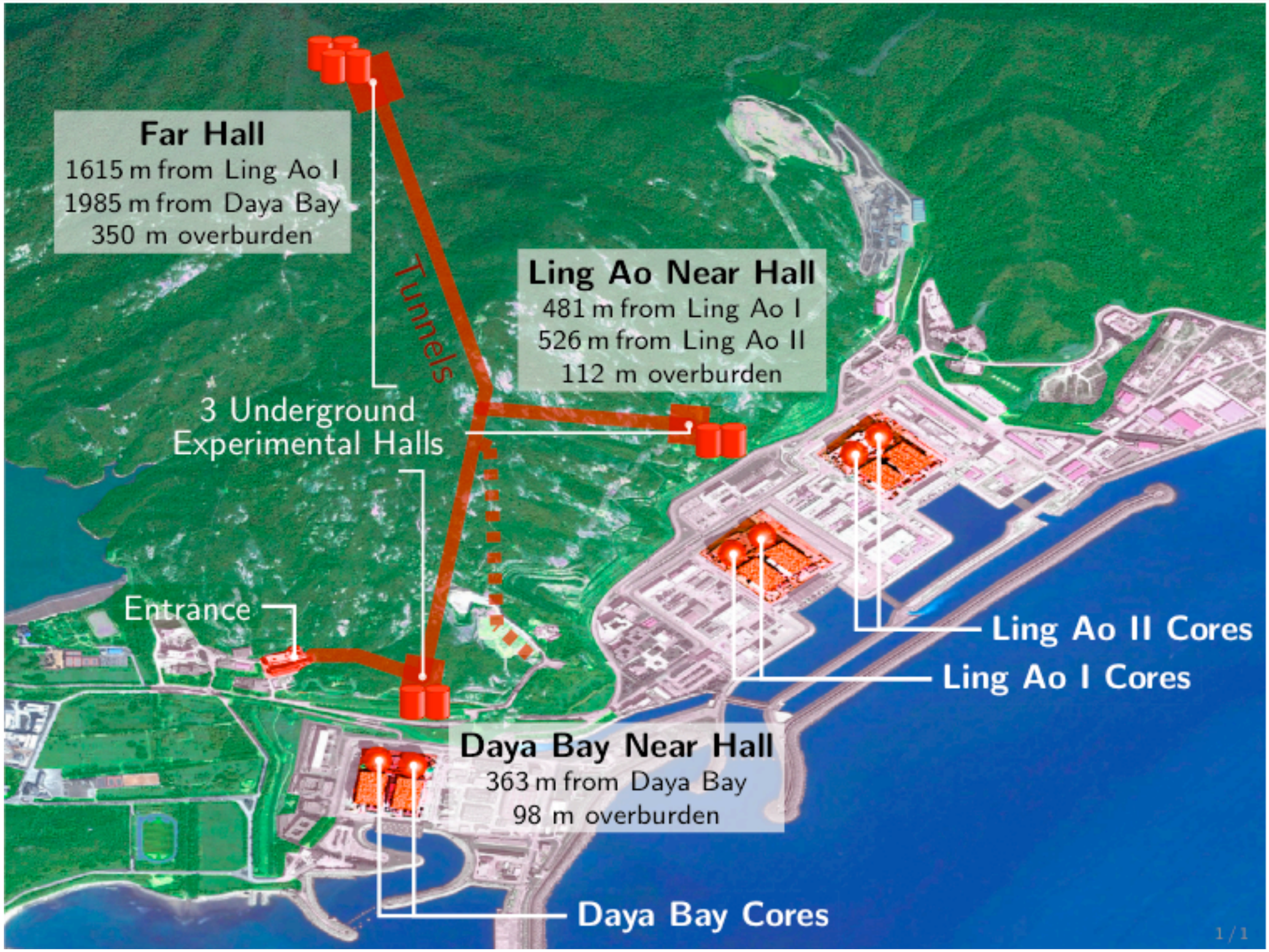
- v červnu proběhl v CERN 2. evropský otevřený mítink
- HK zařazen mezi 27 prioritních projektů jap. vědecké rady
- změna plánů, zpoždění cca 2 roky, start 2025
- financování R&D (jak Hyper-K tak T2K/J-PARC upgrade)
- R&D pro Hyper-K se soustředí na test-detektor a fotonásobiče

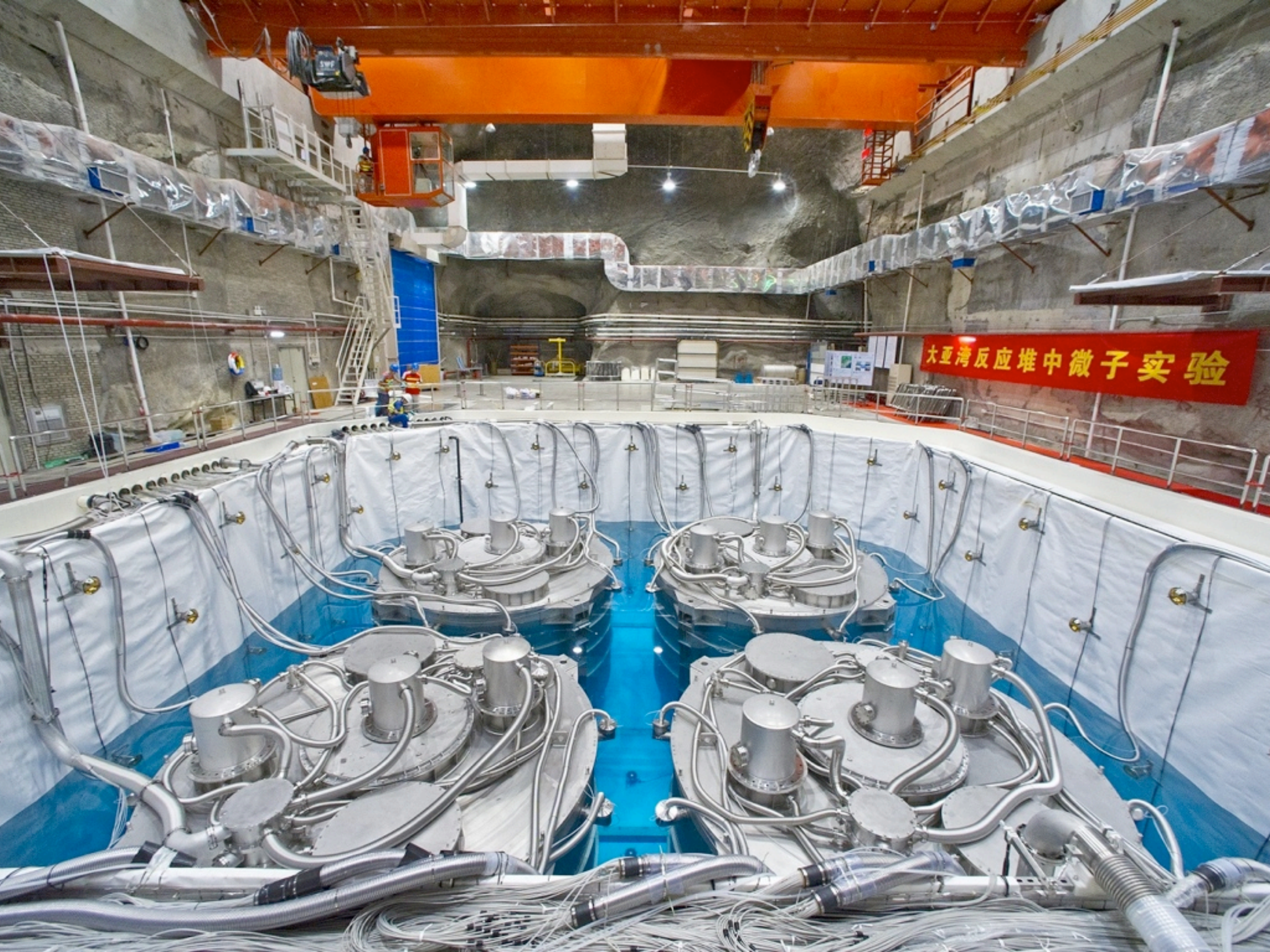
Reaktorová neutrina

(DayaBay, JUNO)

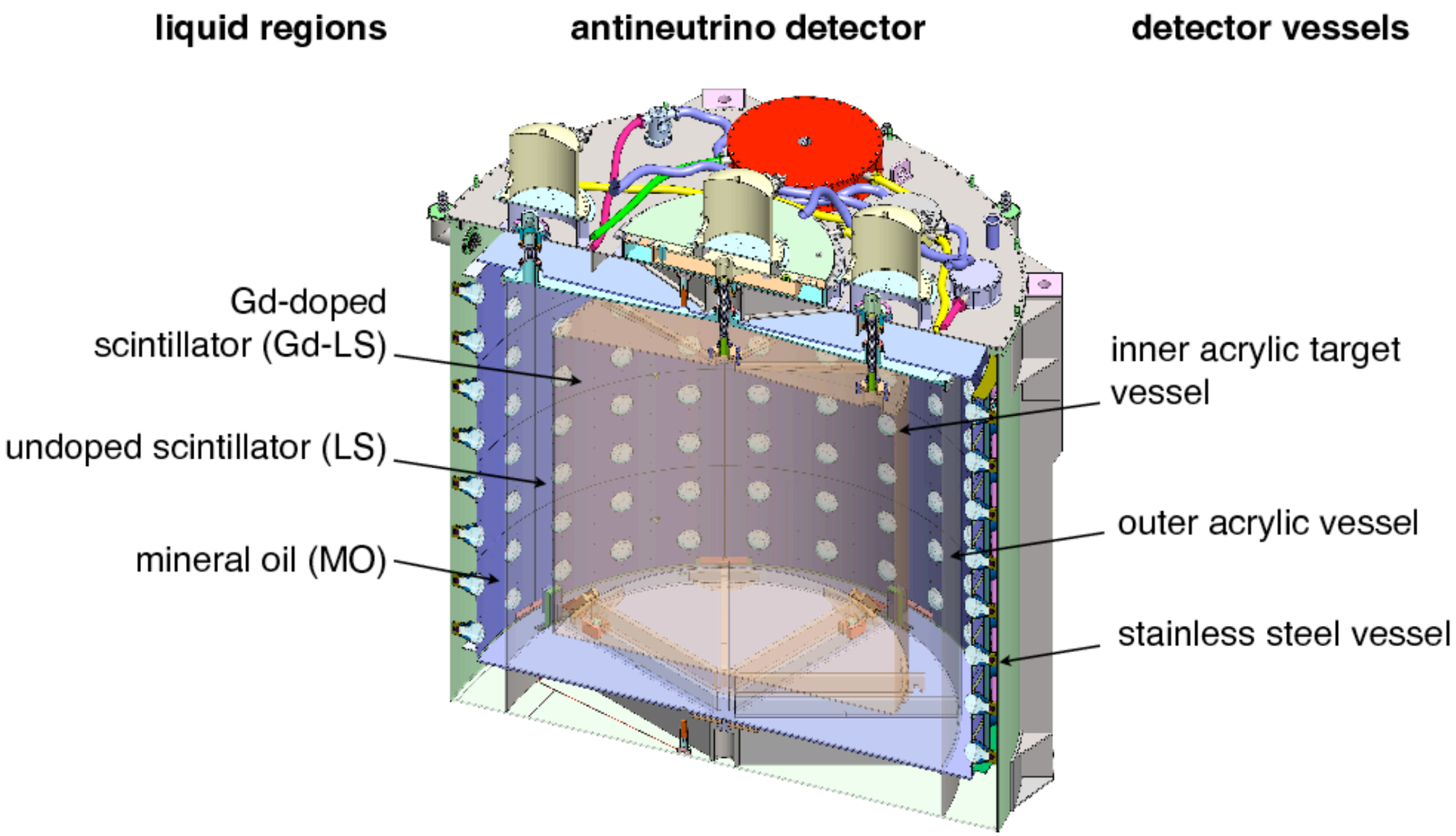
Daya Bay

Daya Bay


Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden
Tunnels
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden
Daya Bay Cores
1 / 1


大亚湾反应堆中微子实验

Daya Bay



$$\overline{\nu}\ p^+ \rightarrow n\, e^+$$

Daya Bay

Preliminary

Novinky za posledních 9 měsíců

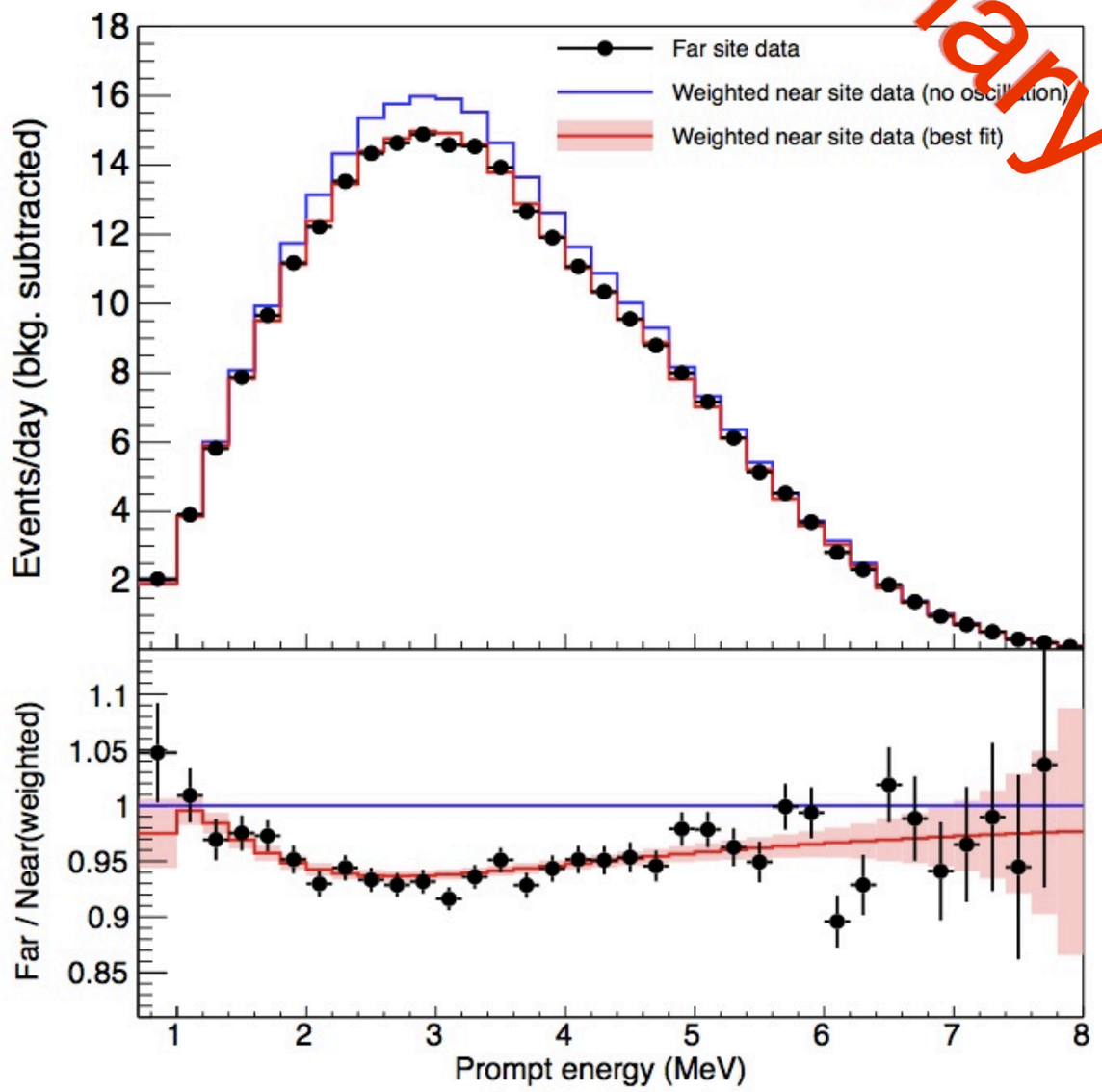
- Zpřesnění měření θ_{13} úhlu a Δm^2_{31}

  >1 milion eventů ➜ velká statistika

přesnost v θ_{13} lepší než 6%

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\text{eV}^2$$



Nabírání dat do 2017, pak se uvidí

Obrázek: C. Zhang @ NEUTRINO 2014

Daya Bay

Novinky za posledních 9 měsíců

- Měření θ_{13} ze eventů tagovaných záchytem neutronu na H (vs. Gd)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$|+H \rightarrow D + \gamma \quad 2.2\ \text{MeV} \quad 200\ \mu s$$
$$|+Gd \rightarrow Gd^* \rightarrow Gd + \gamma's \quad 8\text{MeV} \quad 30\ \mu s$$

+ odlišná systematika

+ větší aktivní objem

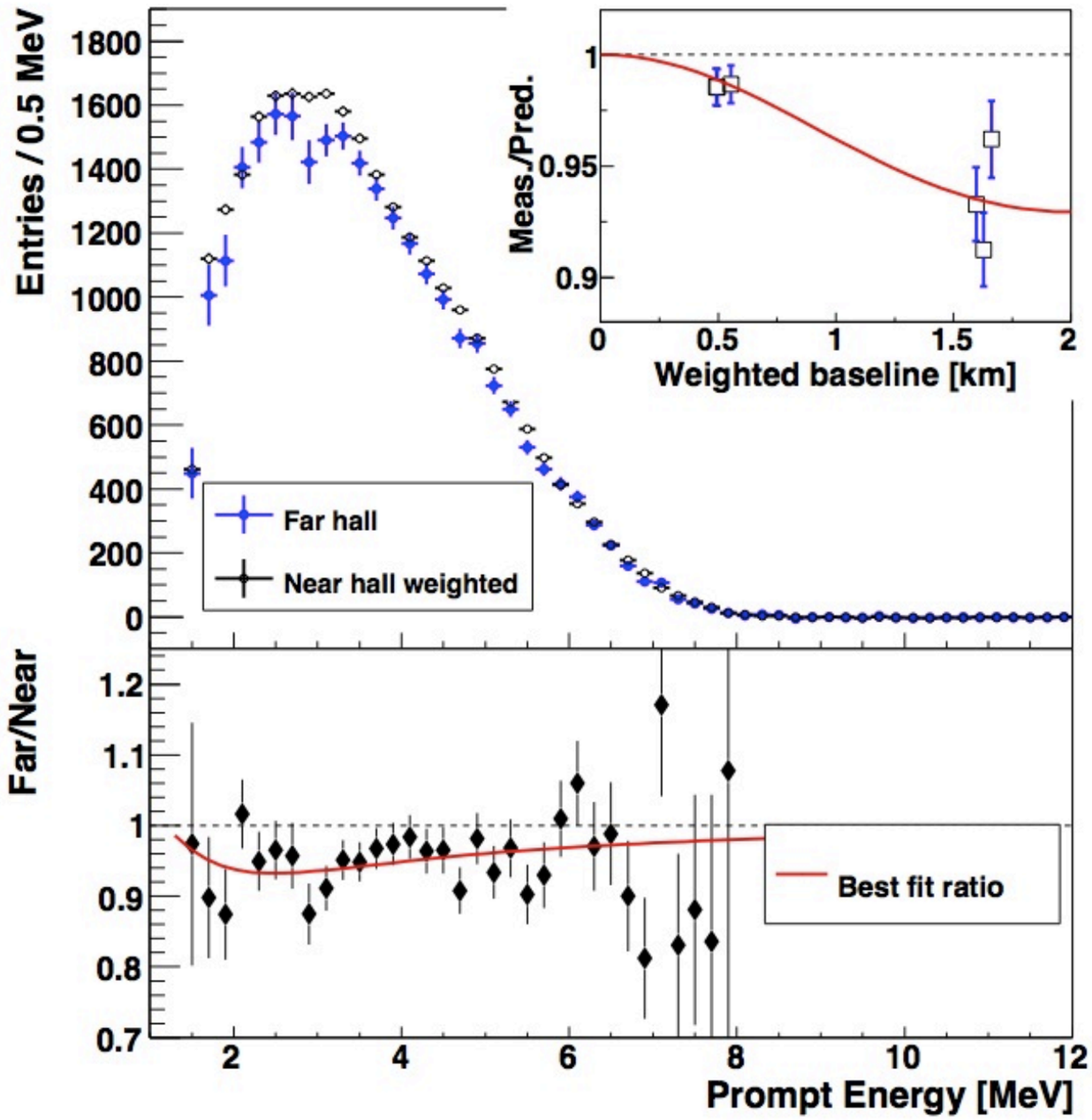
- větší background

- nižší energie a delší prodleva fotonu

$\sin^2 2\theta = 0.083 \pm 0.018$

tj. cca 20% rel. chyba

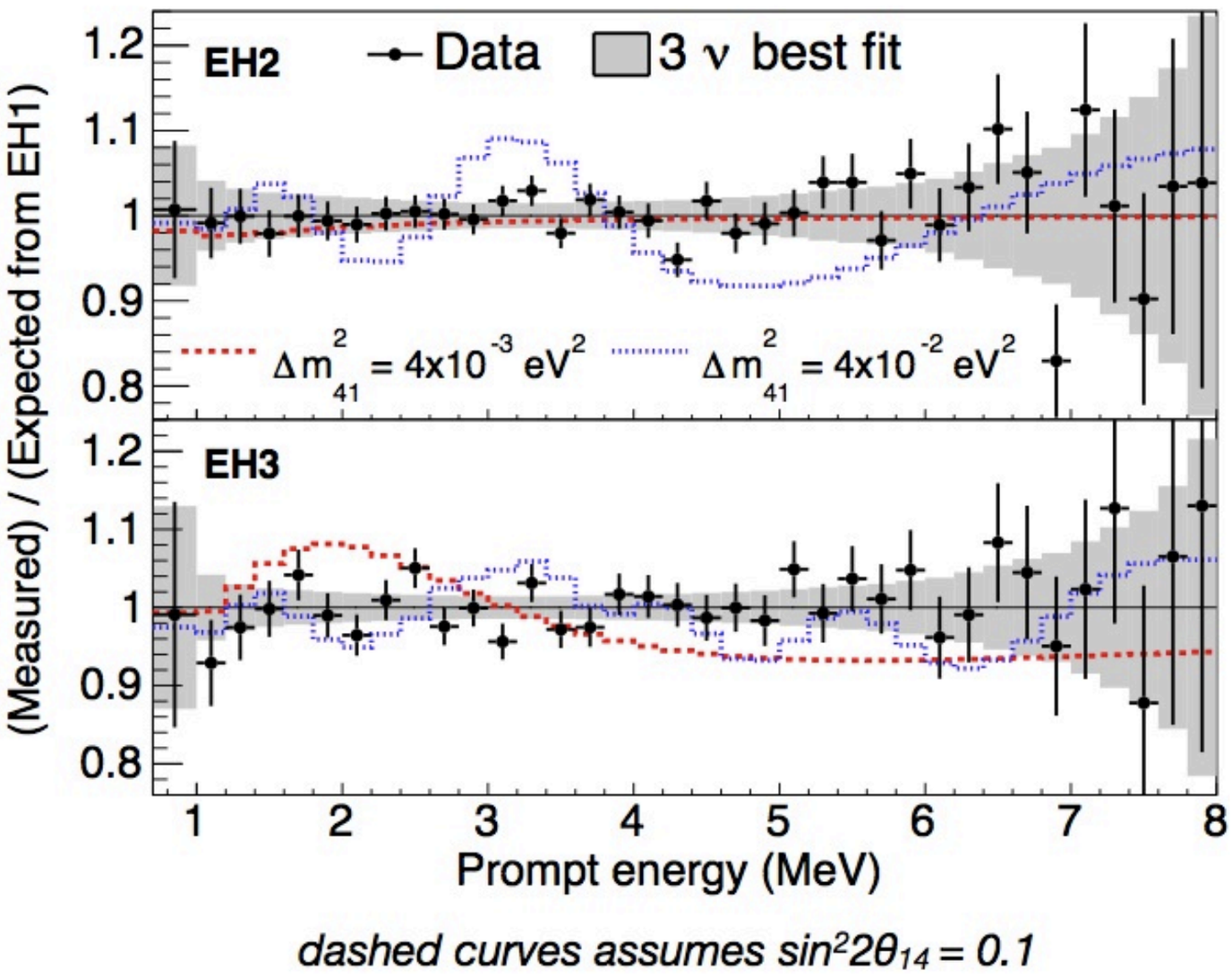
Phys.Rev. D90 (2014) 7, 071101

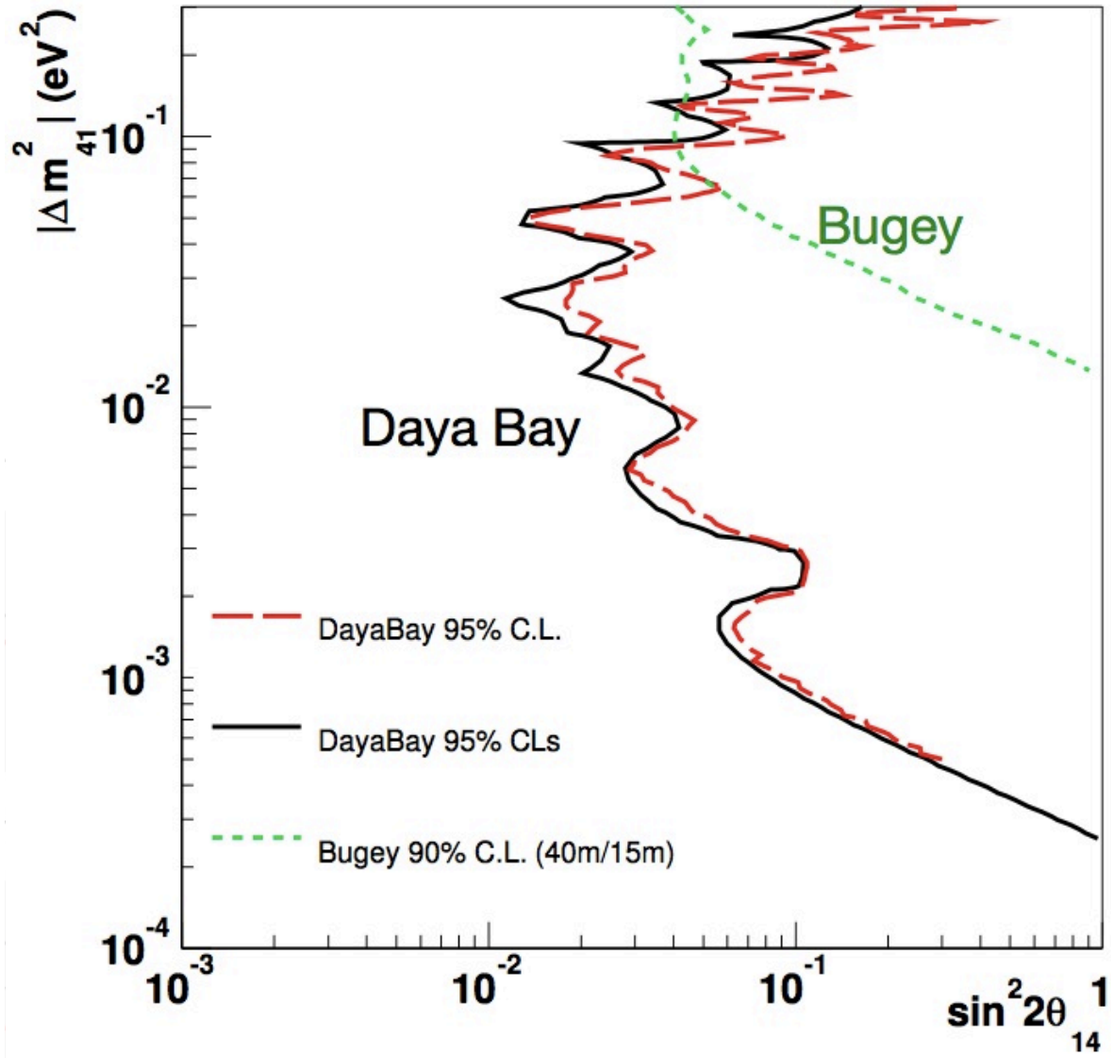


Daya Bay

Novinky za posledních 9 měsíců

- Další omezení na sterilní neutrina v oblasti $10^{-3}\ eV^2 < \Delta m^2_{41} < 0.1\ eV^2$





Obrázky: C. Zhang @ NEUTRINO 2014

Daya Bay v ČR

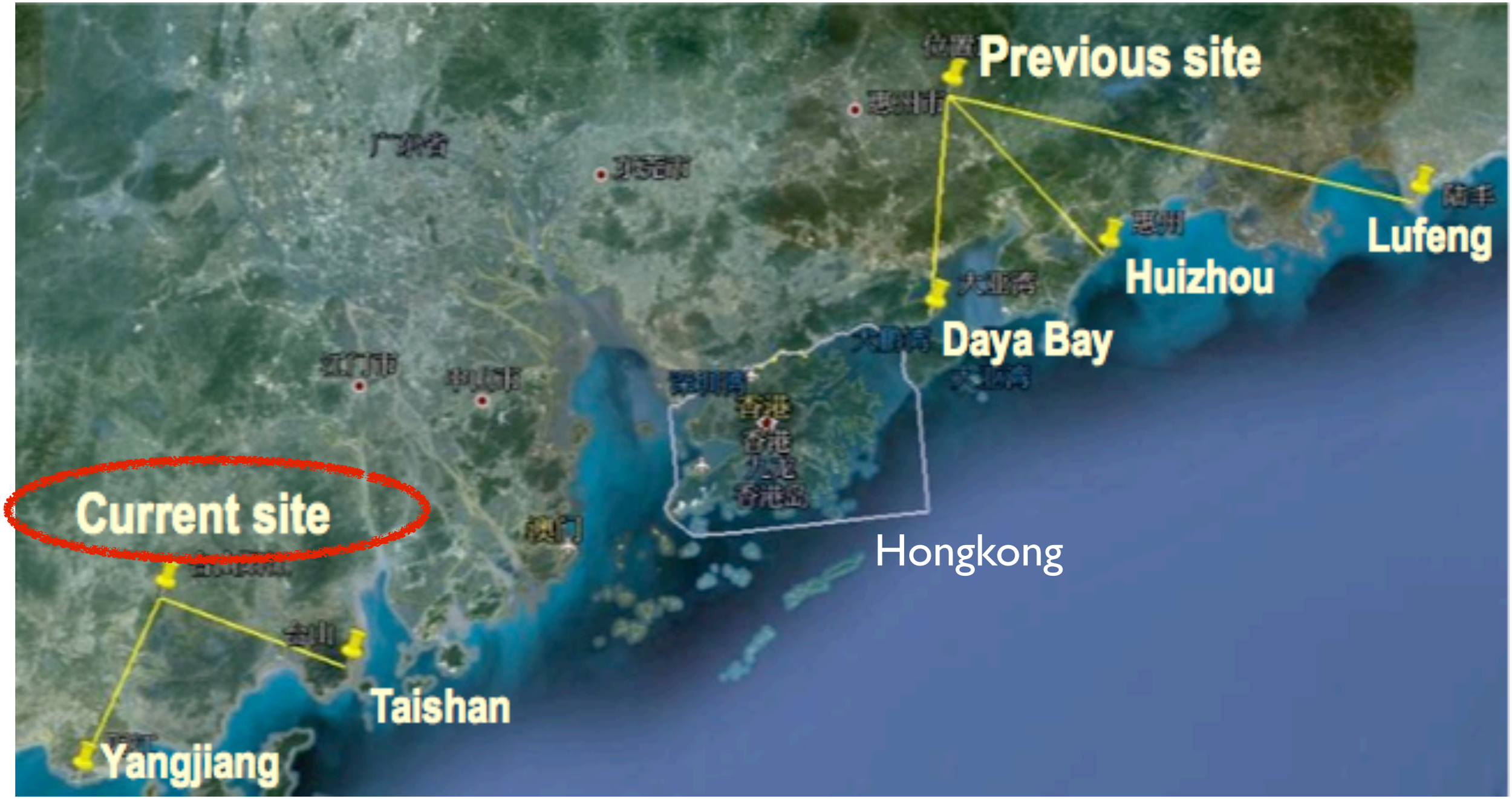
MFF

- Rupert Leitner - vedouci a clen Publication comitee
- Bedrich Roskovec - nestandardni interakce neutrin
- Viktor Pec - analyza michelovskych elektronu
- Vit Vorobel - testovani a instalace RPC

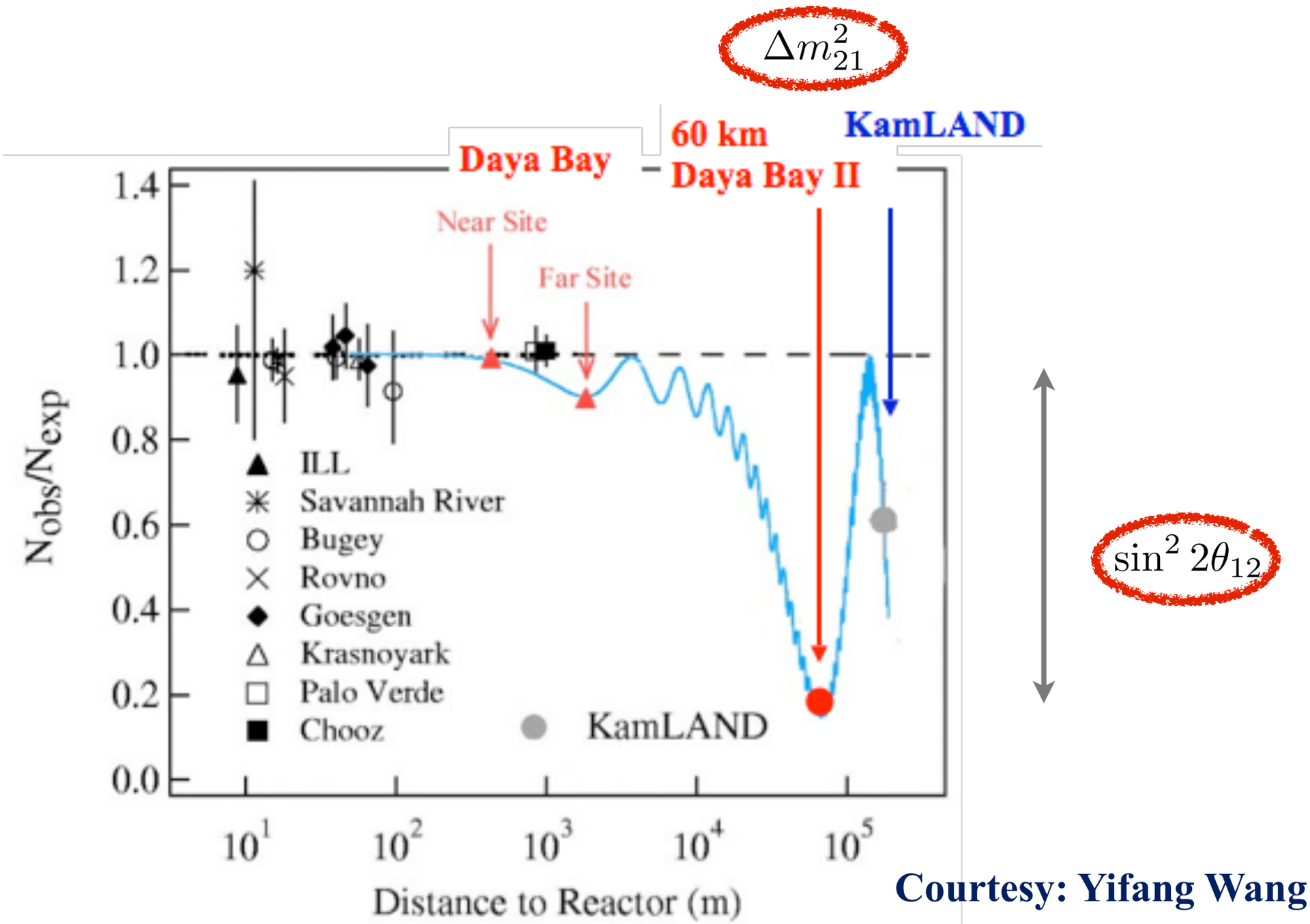
JUNO

(Jiangmen Underground Neutrino Observatory, Čína)

JUNO


Previous site
Lufeng
Huizhou
Daya Bay
Hongkong
Current site
Taishan
Yangjiang

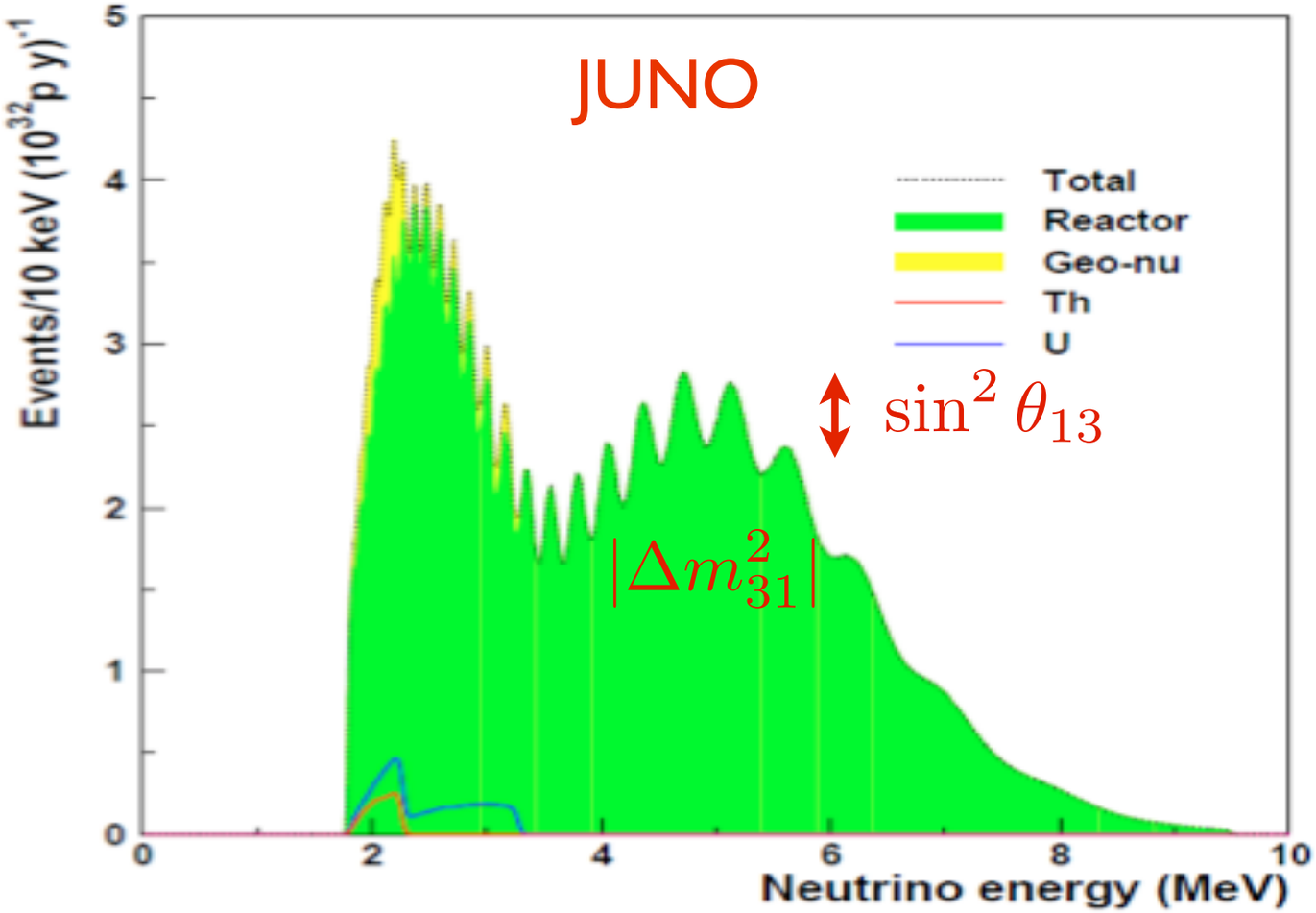
JUNO



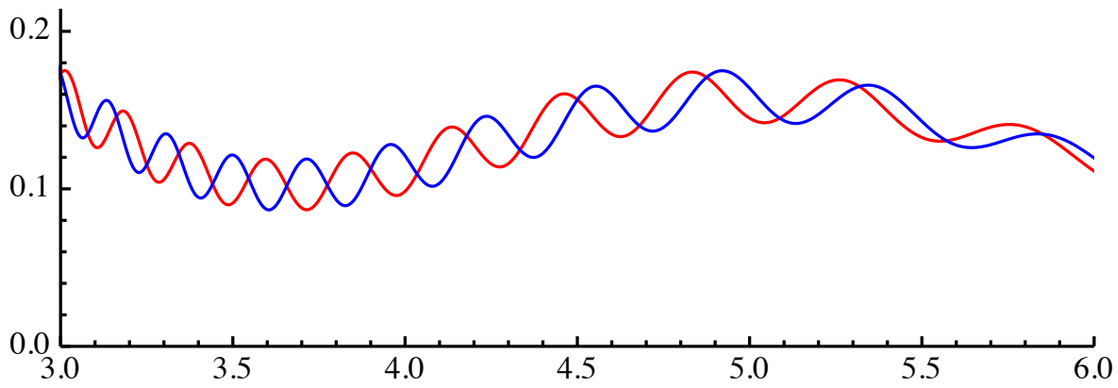
Courtesy: Yifang Wang

JUNO

Courtesy: Yifang Wang



Hierarchie:



$\Delta E_\nu \lesssim 3\%$

JUNO

Jiangmen Underground Neutrino Observatory

China to build a huge underground neutrino experiment

Mar 24, 2014 5 comments

Test site for the Jiangmen Underground Neutrino Observatory

"Work has started on a huge underground neutrino lab in China. The $330m Jiangmen Underground Neutrino Observatory (JUNO) is being built in Kaiping City, Guangdong Province, in the south of the country around 150 km west of Hong Kong. When complete in 2020, JUNO is expected to run for more than 20 years, studying the relationship between the three types of neutrino: electron, muon and tau."

Díky za pozornost !

Neutrino 2014 highlights

Novinky v oscilační fyzice
(od jara 2014)

Neutrino 2014 highlights

- První neutrinový event s E ~ 2 PeV na IceCube
-

Globální fity

Globální fity oscilačních parametrů

(jaro 2014)

Forero, Tortola, Valle
Phys.Rev. D86 (2012) 073012

Globální fity oscilačních parametrů

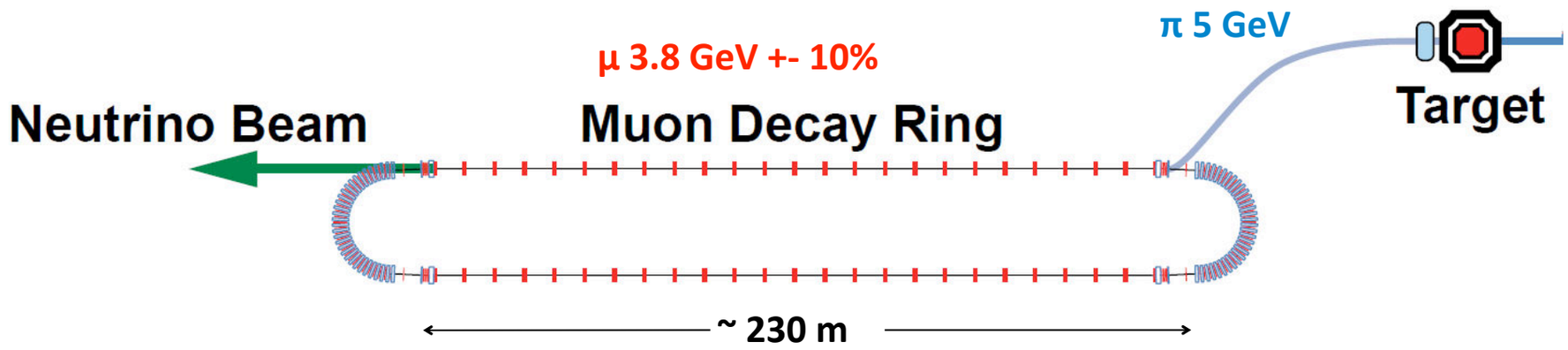
(podzim 2014)

Forero, Tortola, Valle
Phys.Rev. D90 (2014) 093006

BACKUP SLIDES

nuSTORM
(mionový akumulační prstenec)

Fermilab/CERN?



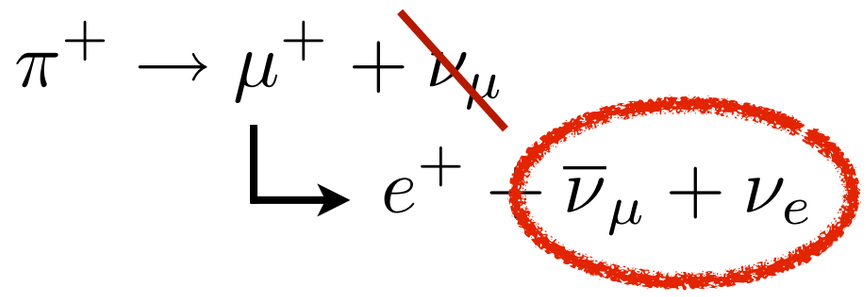
nuSTORM
(mionový akumulační prstenec)

Neutrina z rozpadů akumulovaných mionů

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

nuSTORM
(mionový akumulační prstenec)

Neutrina z rozpadů akumulovaných mionů

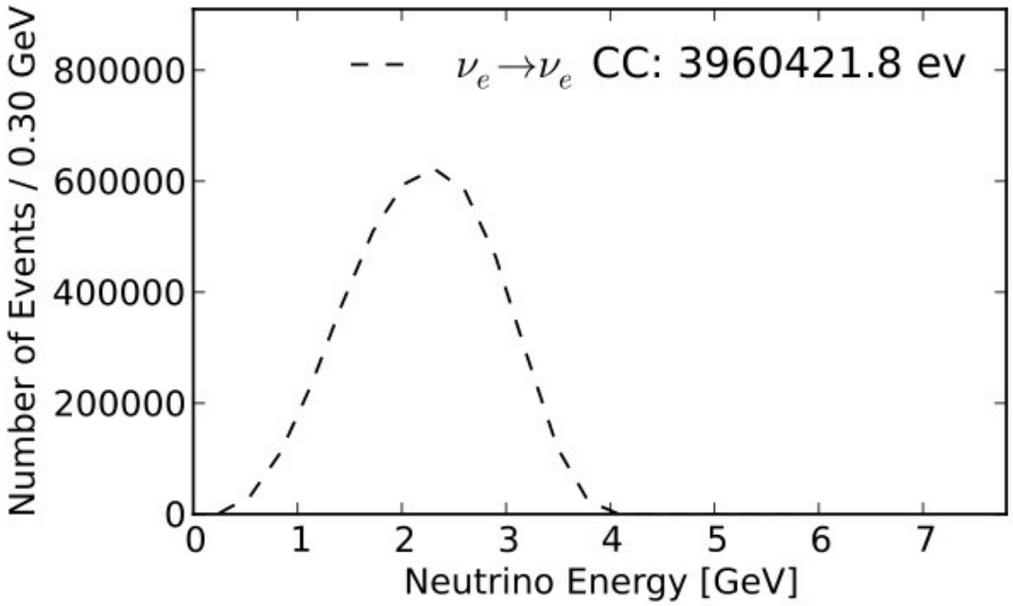


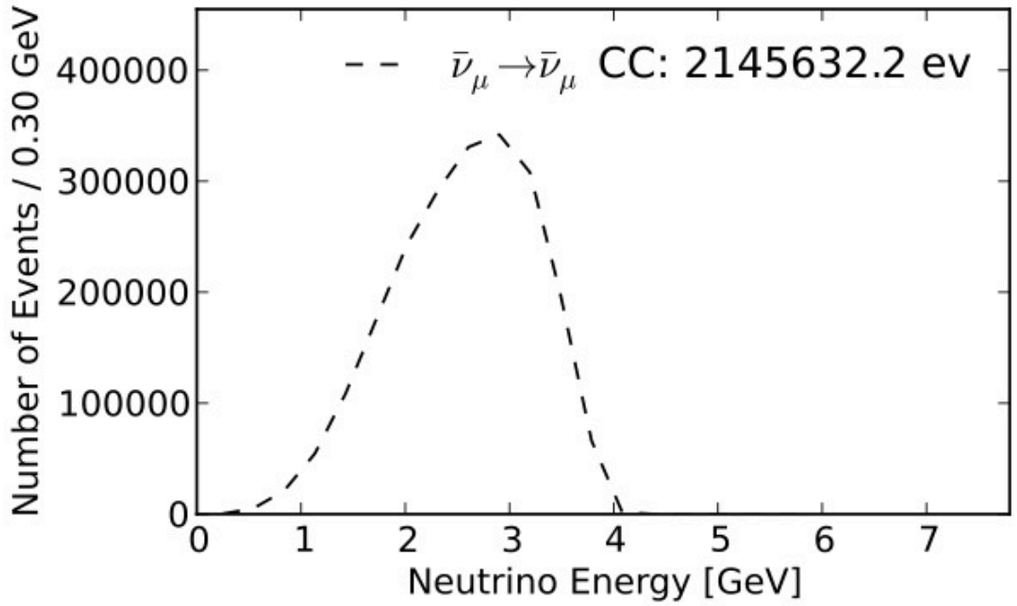
nuSTORM
(mionový akumulační prstenec)

Neutrina z rozpadů akumulovaných mionů

$$\pi^+ \rightarrow \mu^+ + \cancel{\nu_\mu}$$
$$\hookrightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

Velmi detailní znalost spektra/kompozice svazku:





100T fid. vol. near detector @ 50m & 10^{21} POT, 4GeV muons

nuSTORM
(mionový akumulační prstenec)

Detailní a definitivní test LSND anomálie (10 sigma) $\Delta m^2 \sim 1\mathrm{eV}^2$

CPT: $P(\overline{\nu}_\mu \to \overline{\nu}_e) = P(\nu_e \to \nu_\mu)$

$$L_{\pi/2} \sim 10\,\mathrm{m} \times \frac{E_\nu}{\mathrm{MeV}}$$

nuSTORM
(mionový akumulační prstenec)

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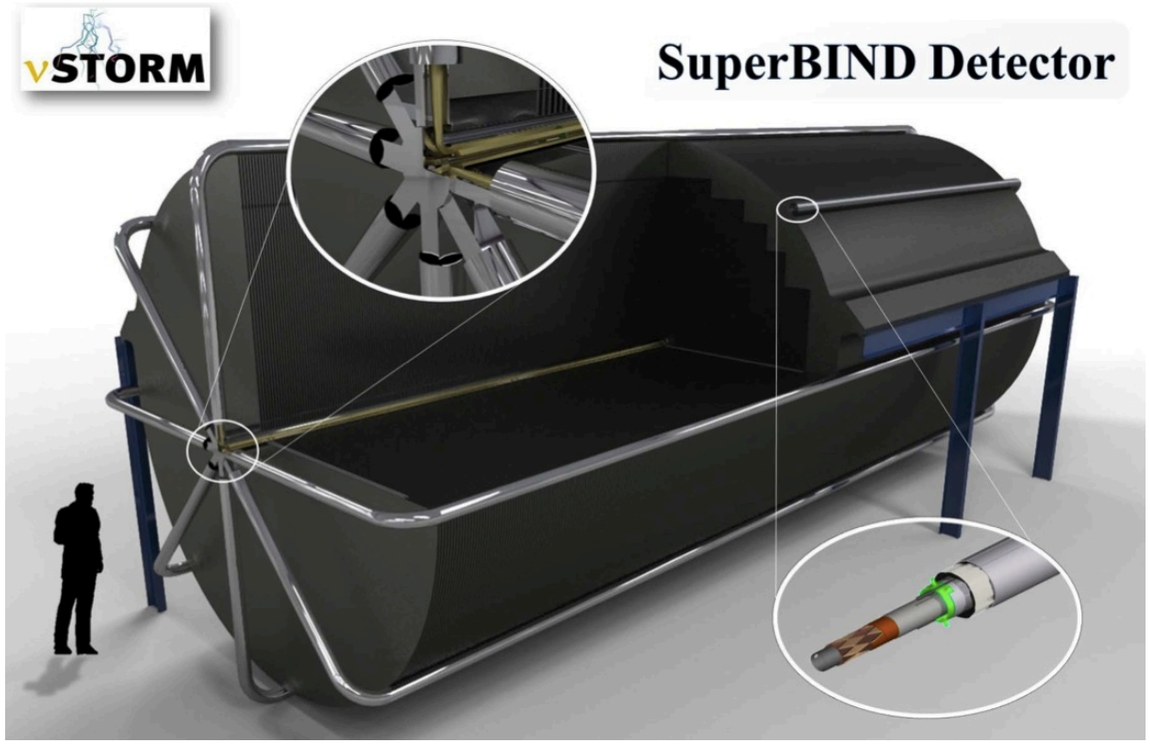
Far detector @ 2 km



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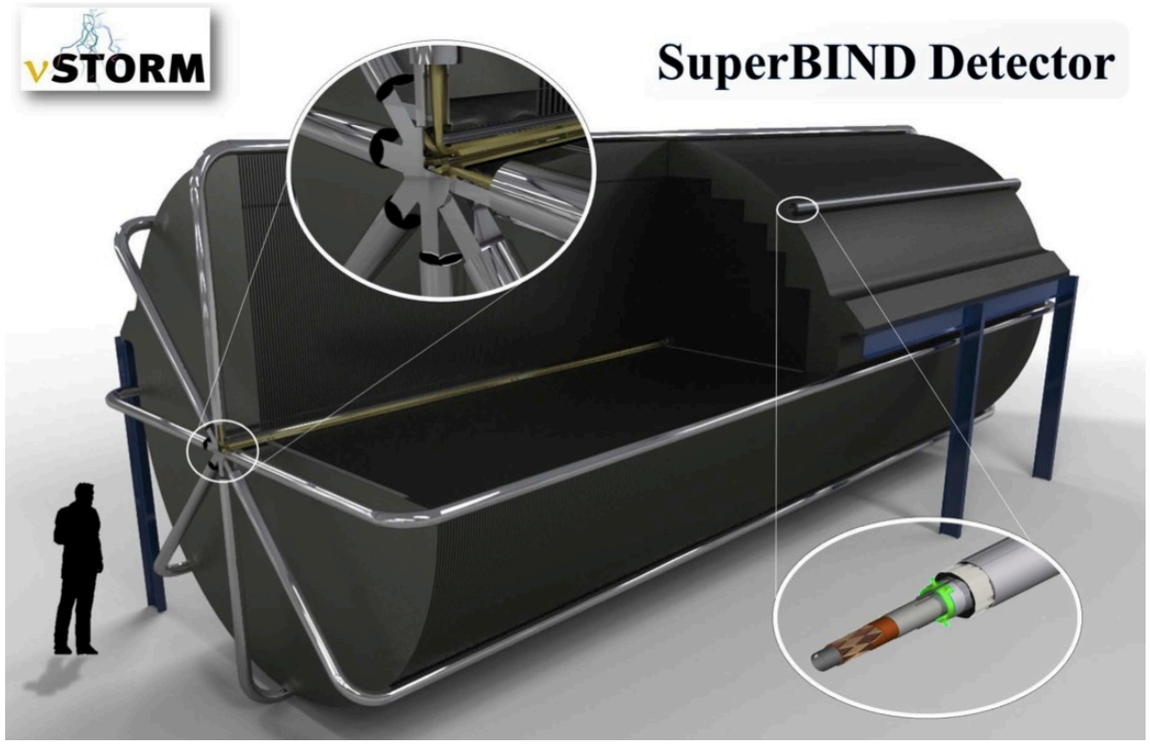

Předstupeň mionového collideru v (daleké ?) budoucnosti

Přesná měření účinných průřezů GeV neutrin (hlavně ν_e) s jádry

nuSTORM
(mionový akumulační prstenec)

LOI podepsalo cca 100 lidí

(USA, Kanada, Indie, Japonsko, Francie, Itálie, Německo, Polsko, Španělsko, Velká Británie)

Status: LOI zaslán Fermilabu v roce 2013

Odhadovaná doba realizace cca 10 let (technologie existuje)

nuSTORM
(mionový akumulační prstenec)

LOI podepsalo cca 100 lidí

(USA, Kanada, Indie, Japonsko, Francie, Itálie, Německo, Polsko, Španělsko, Velká Británie)

Status: LOI zaslán Fermilabu v roce 2013

Odhadovaná doba realizace cca 10 let (technologie existuje)

Odhad nákladů:

Sub System	Cost M$[1]
Primary Beam Line	24
Target Station	56
Transport Line	14
Decay Ring	82
Near Hall	29[2]
Far Detector	24[3]
Sub Total	**229**
Project Office	34[4]
Total	**263**

Praha, 11.3. 2014

Neutrinové oscilační experimenty - výhled

Michal Malinský

ÚČJF MFF UK

Hmotná neutrina ve SM'

$$\mathcal{L}_{\mathcal{CC}} \ni \bar{\ell}_\alpha \gamma^\mu (V_{\mathrm{PMNS}})_{\alpha i} \nu_i W_\mu^- + h.c. \qquad \mathcal{L}_{\mathcal{NC}} = \ldots$$

$$\mathcal{L}_{mass} \ni m_i \overline{\nu_{iL}} \nu_{iR} + h.c. \qquad \text{Dirac}$$

$$\mathcal{L}_{mass} \ni m_i \overline{\nu_{iL}^c} \nu_{iL} + h.c. \qquad \text{Majorana}$$

$$V_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Hmotná neutrina ve SM'

$$\mathcal{L}_{\mathcal{CC}} \ni \bar{\ell}_\alpha \gamma^\mu (V_{\mathrm{PMNS}})_{\alpha i} \nu_i W_\mu^- + h.c. \qquad \mathcal{L}_{\mathcal{NC}} = \ldots$$

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3 úhly, 3 hmotnosti (oscilace vidí jen $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$), CP fáze

Majorana: 2 CP fáze navíc (neviditelné v oscilacích)

Oscilační parametry

JHEP12 (2012) 123

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.37 \to 36.01$
$\sin^2\theta_{23}$	$0.446^{+0.008}_{-0.008} \oplus 0.593^{+0.027}_{-0.043}$	$0.366 \to 0.663$
$\theta_{23}/^\circ$	$41.9^{+0.5}_{-0.4} \oplus 50.3^{+1.6}_{-2.5}$	$37.2 \to 54.5$
$\sin^2\theta_{13}$	$0.0231^{+0.0019}_{-0.0019}$	$0.0173 \to 0.0288$
$\theta_{13}/^\circ$	$8.73^{+0.35}_{-0.36}$	$7.56 \to 9.77$
$\delta_{\mathrm{CP}}/^\circ$	266^{+55}_{-63}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.014}_{-0.014}$	$+2.247 \to +2.623$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.411^{+0.062}_{-0.062}$	$-2.602 \to -2.226$

Oscilační parametry

JHEP12 (2012) 123

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Daya Bay

Oscilační parametry

JHEP12 (2012) 123

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.37 \to 36.01$
$\sin^2\theta_{23}$	$0.446^{+0.008}_{-0.008} \oplus 0.593^{+0.027}_{-0.043}$	$0.366 \to 0.663$
$\theta_{23}/^\circ$	$41.9^{+0.5}_{-0.4} \oplus 50.3^{+1.6}_{-2.5}$	$37.2 \to 54.5$
$\sin^2\theta_{13}$	$0.0231^{+0.0019}_{-0.0019}$	$0.0173 \to 0.0288$
$\theta_{13}/^\circ$	$8.73^{+0.35}_{-0.36}$	$7.56 \to 9.77$
$\delta_{CP}/^\circ$	266^{+55}_{-63}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.014}_{-0.014}$	$+2.247 \to +2.623$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.411^{+0.062}_{-0.062}$	$-2.602 \to -2.226$

Daya Bay

CP narušení
(Dirakovská fáze)

Oscilační parametry

JHEP12 (2012) 123

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$
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Daya Bay

CP narušení
(Dirakovská fáze)

Hierarchie

Oscilační parametry

JHEP12 (2012) 123

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Oktant $\square_{23}$

Daya Bay

CP narušení
(Dirakovská fáze)

Hierarchie

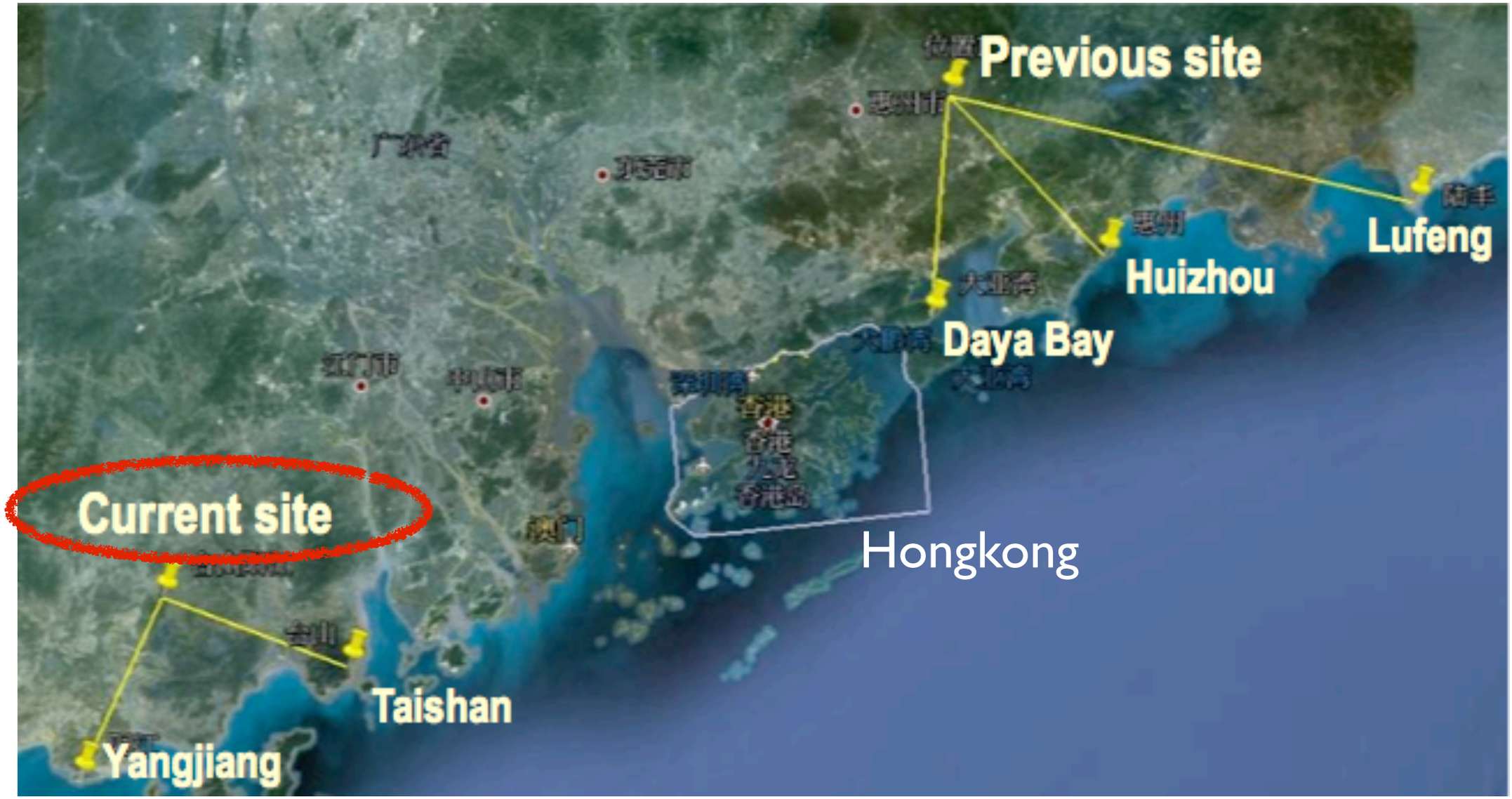
Reaktorová neutrina

JUNO

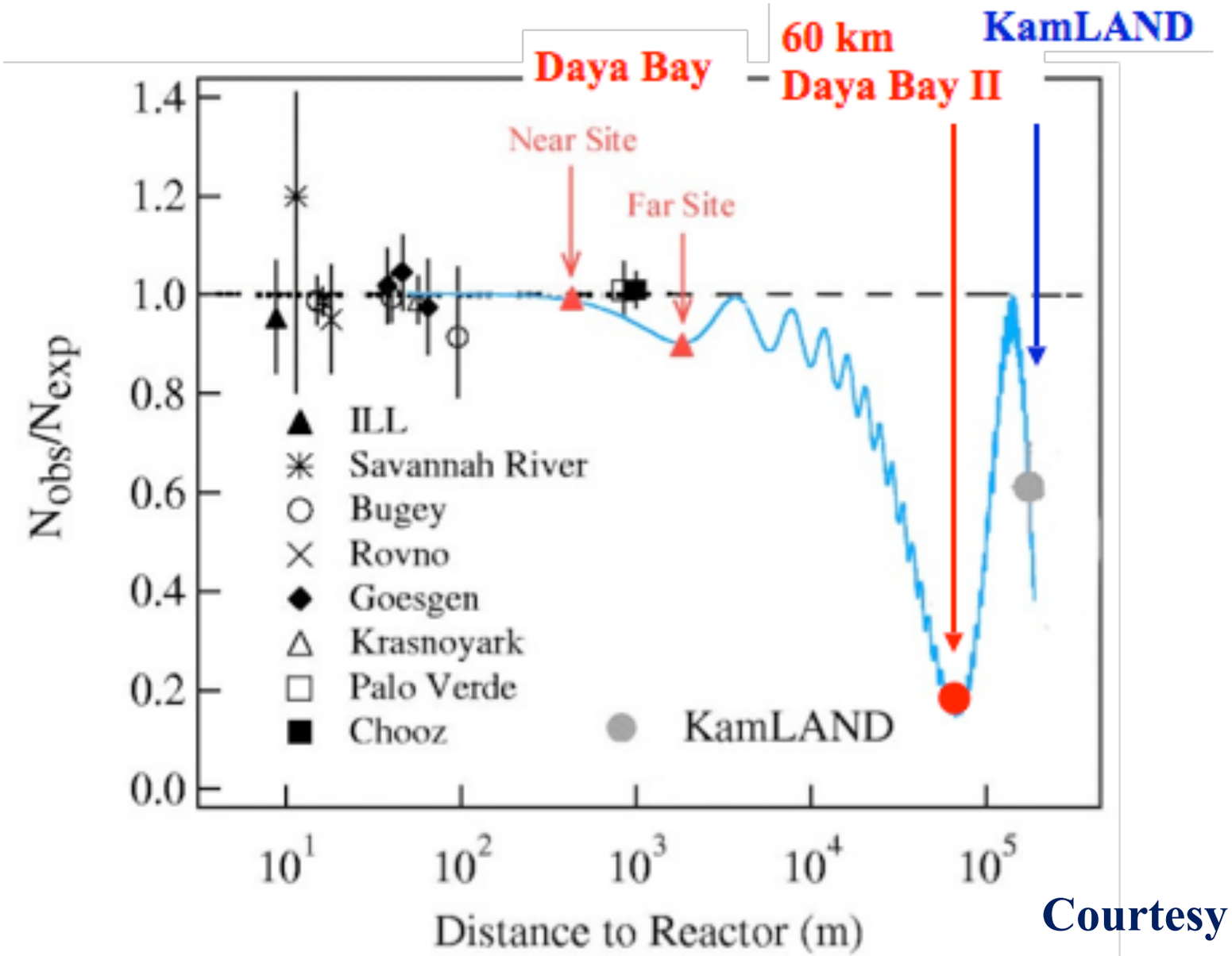
(Jiangmen Underground Neutrino Observatory, Čína)

JUNO
(reaktorová neutrina)

Jiangmen Underground Neutrino Observatory (Daya Bay II)

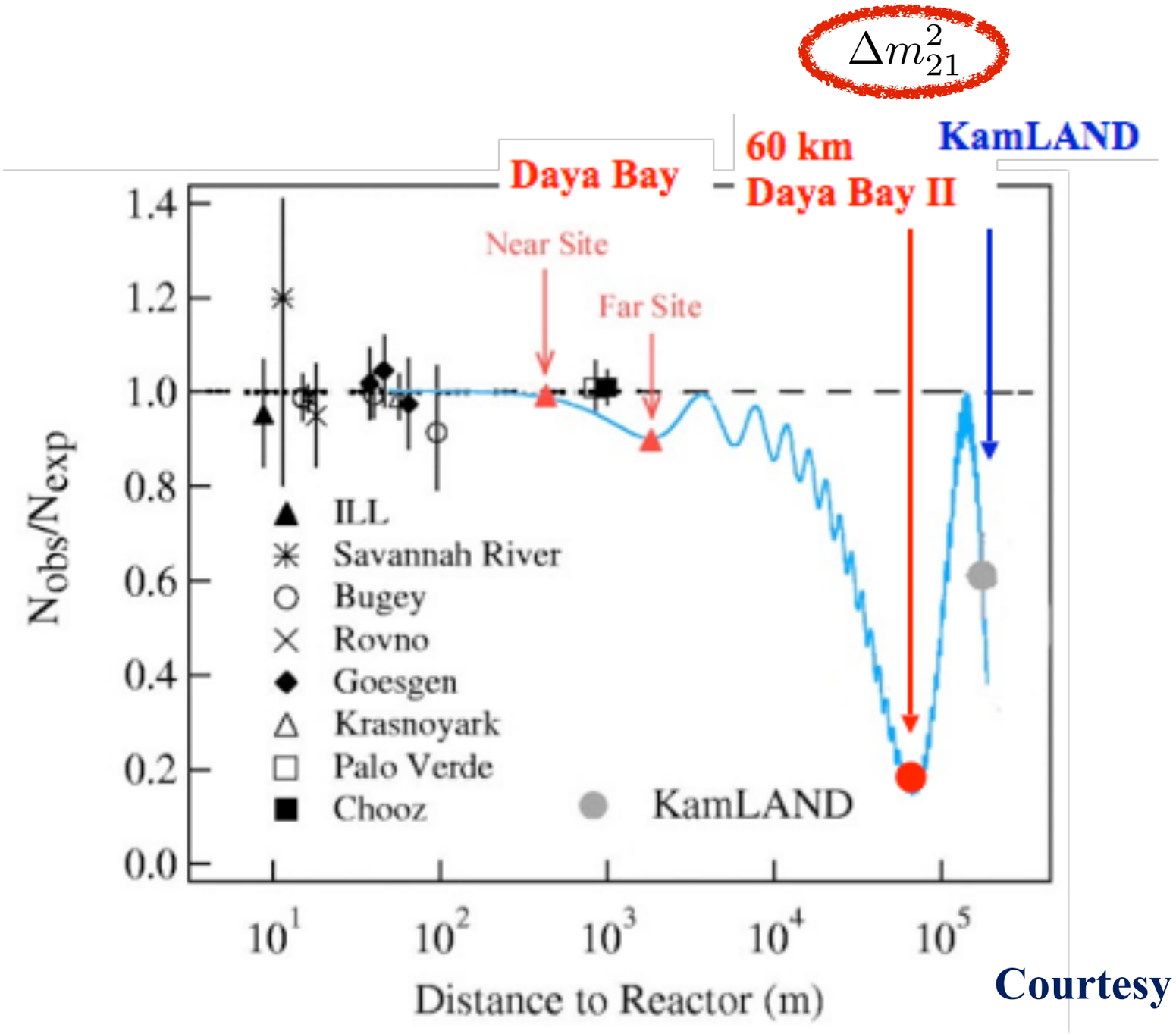


JUNO
(reaktorová neutrina)



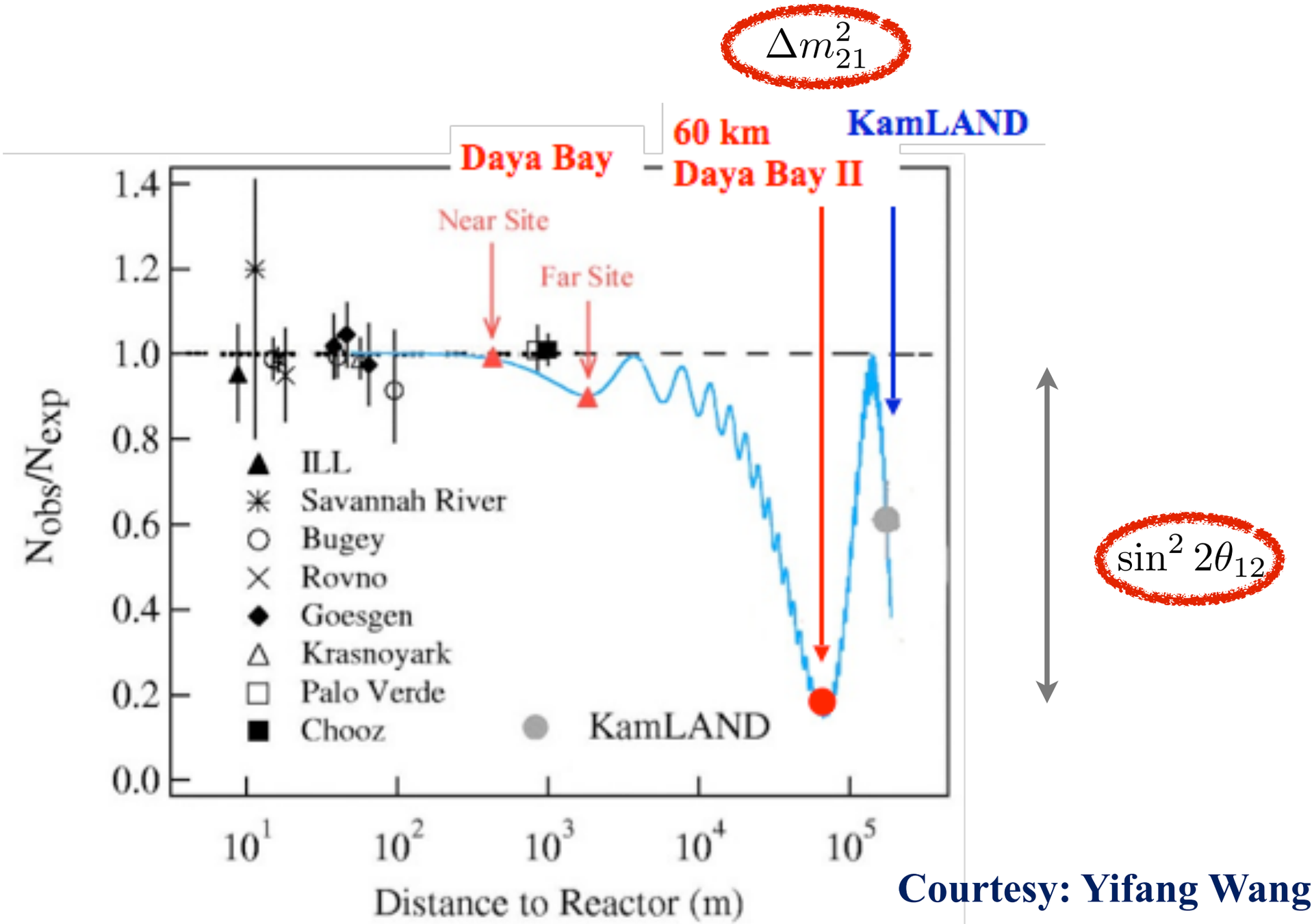
Courtesy: Yifang Wang

JUNO
(reaktorová neutrina)



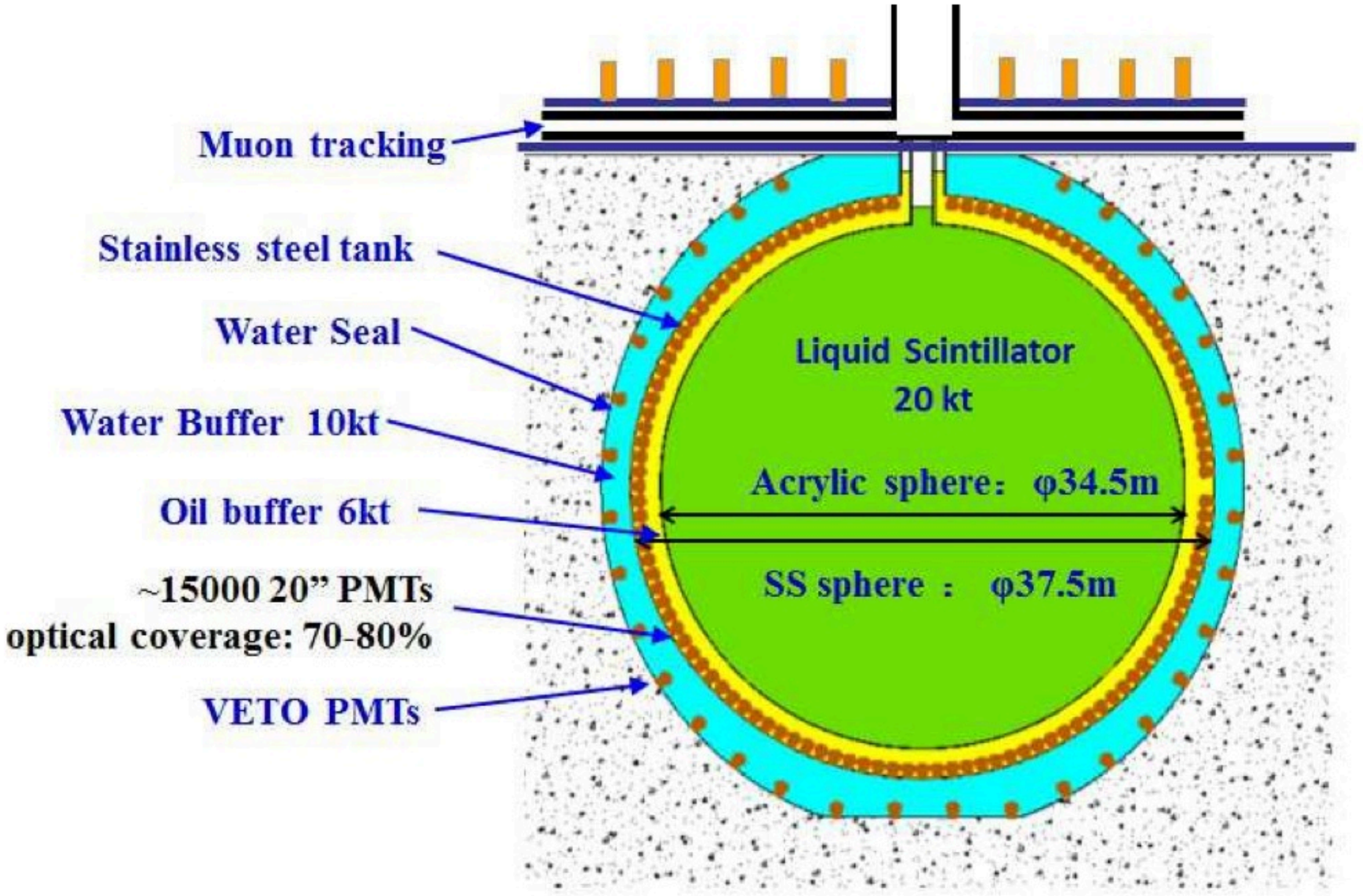
Courtesy: Yifang Wang

JUNO
(reaktorová neutrina)

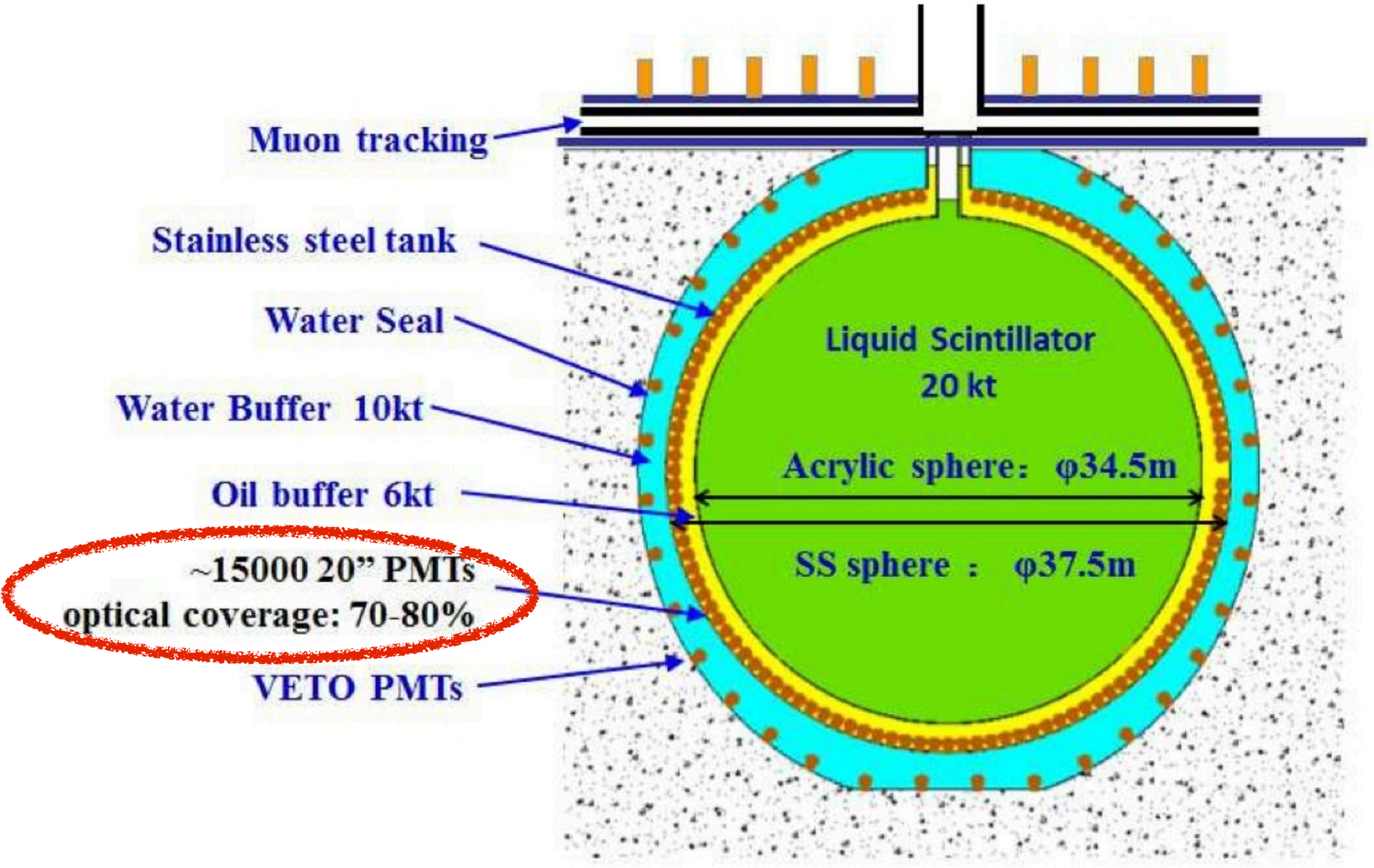


Courtesy: Yifang Wang

JUNO
(reaktorová neutrina)



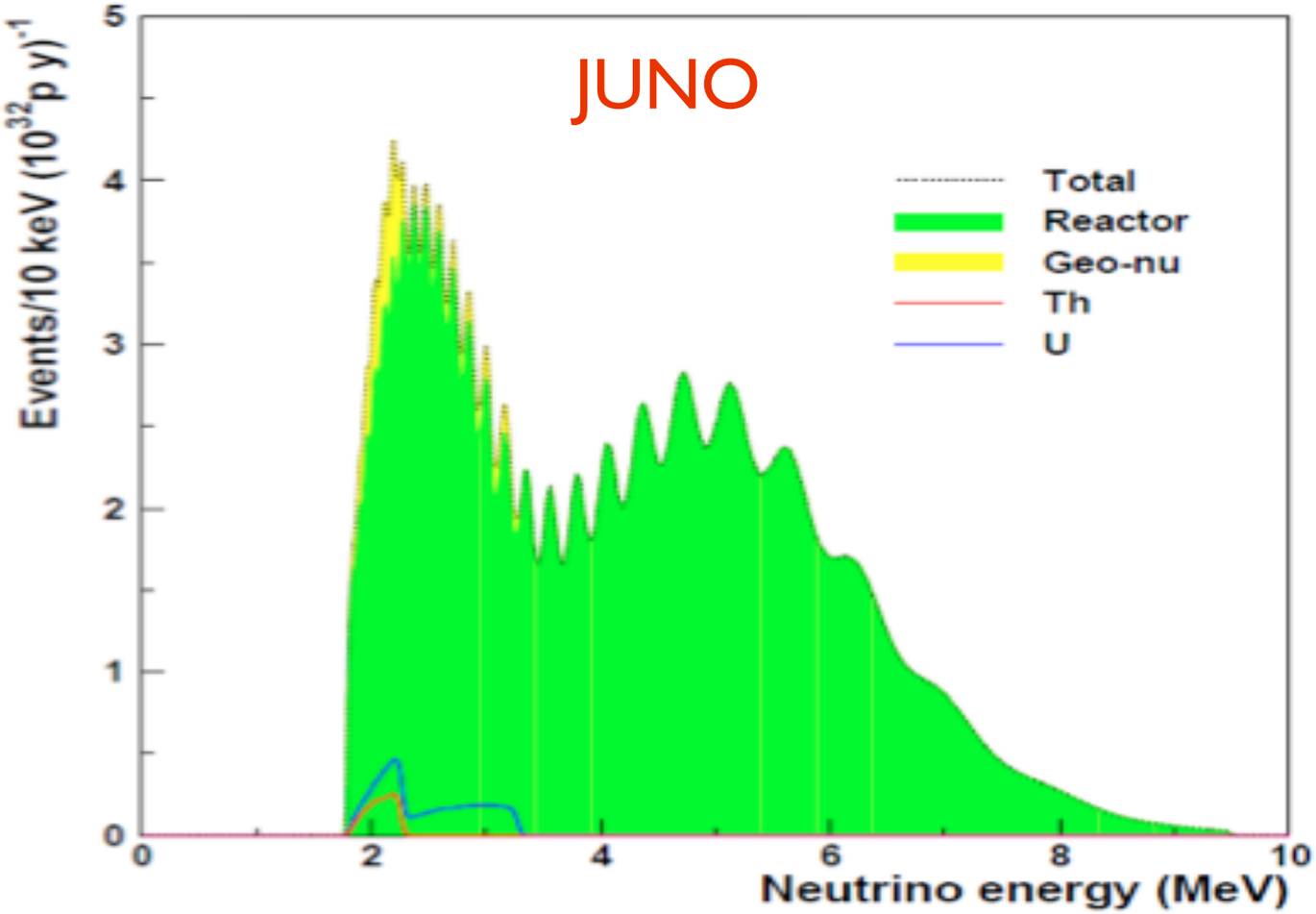
JUNO
(reaktorová neutrina)



$$\Delta E_\nu \lesssim 3\%$$

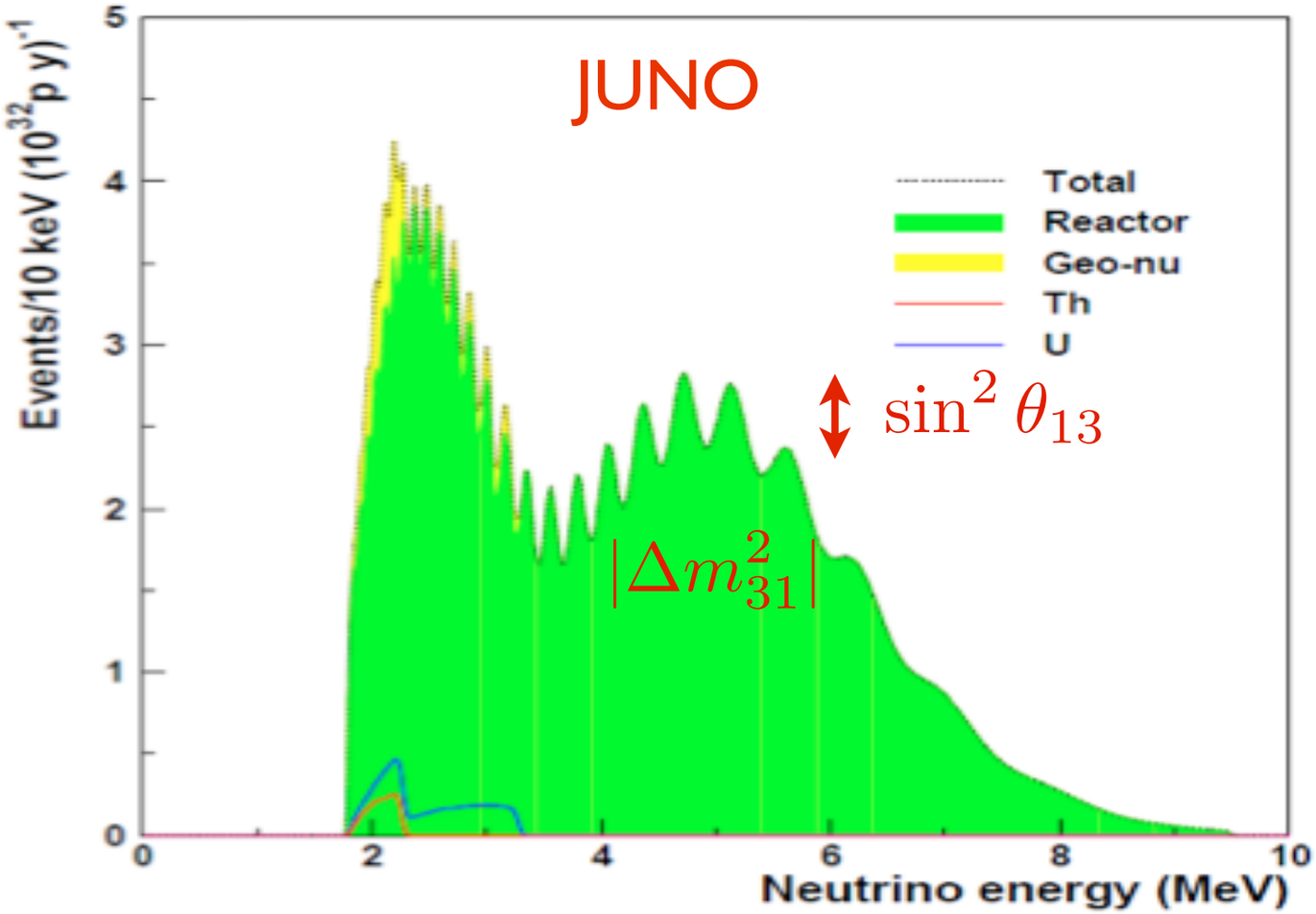
JUNO
(reaktorová neutrina)

Courtesy: Yifang Wang



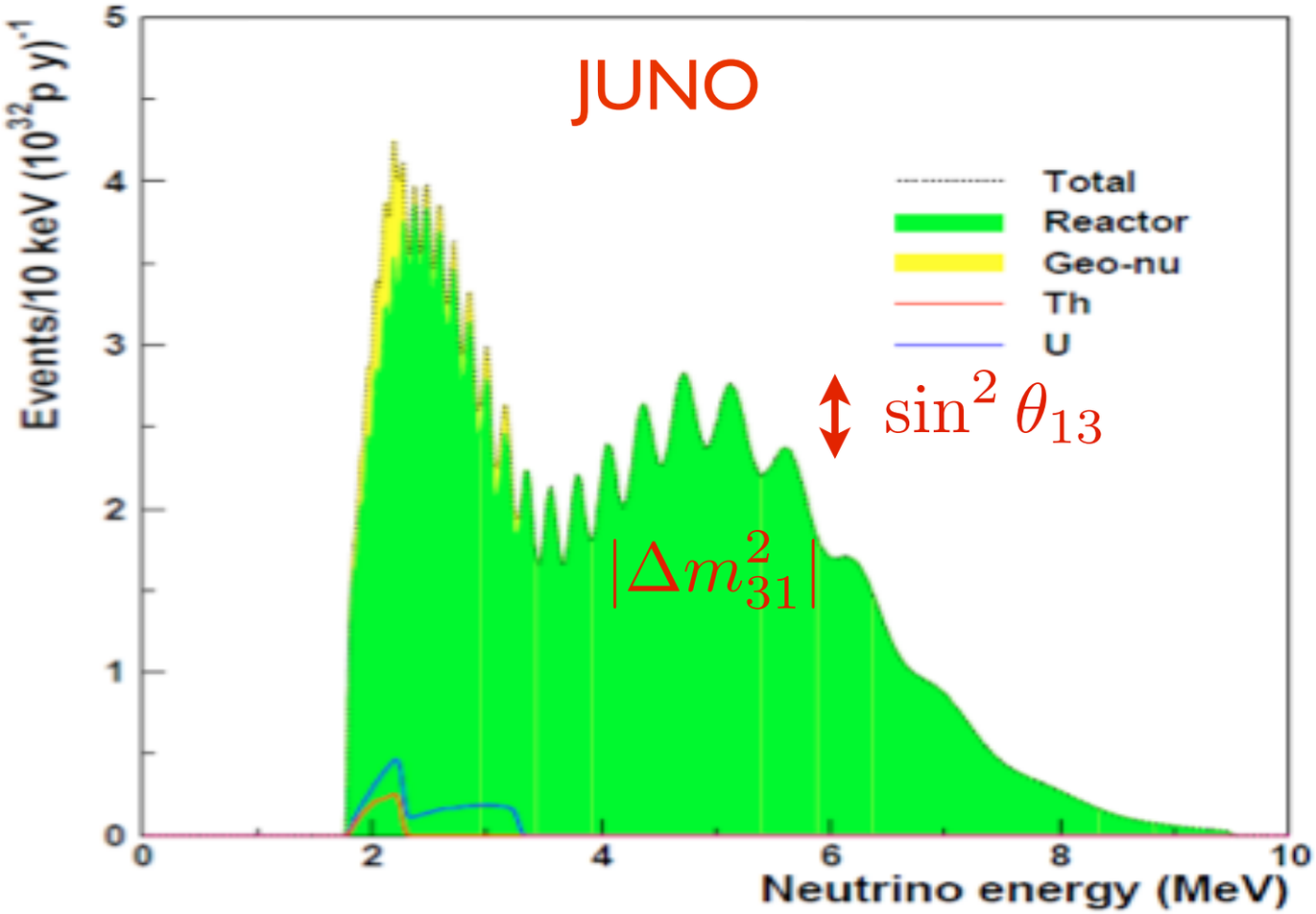
JUNO
(reaktorová neutrina)

Courtesy: Yifang Wang

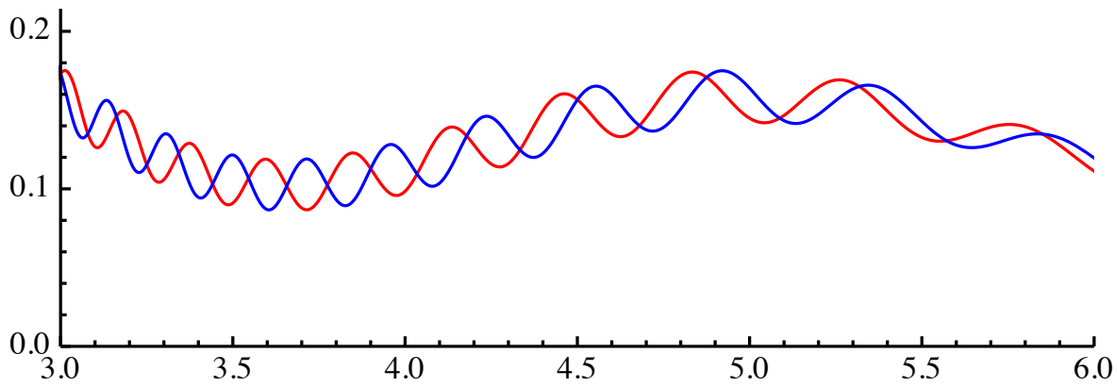


JUNO
(reaktorová neutrina)

Courtesy: Yifang Wang



Hierarchie:



JUNO
(reaktorová neutrina)

	Current	Daya Bay II
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%

2014: final CDR, civil construction, PMT prototyping?

2016: PMT production

2017: Detector

2018: LS production

2019: Instalation

2020: Running

Celkové náklady: 300 M$

Pro nás: přirozené pokračování DB

Neutrina z urychlovačů + atmosférická

Hyper-K

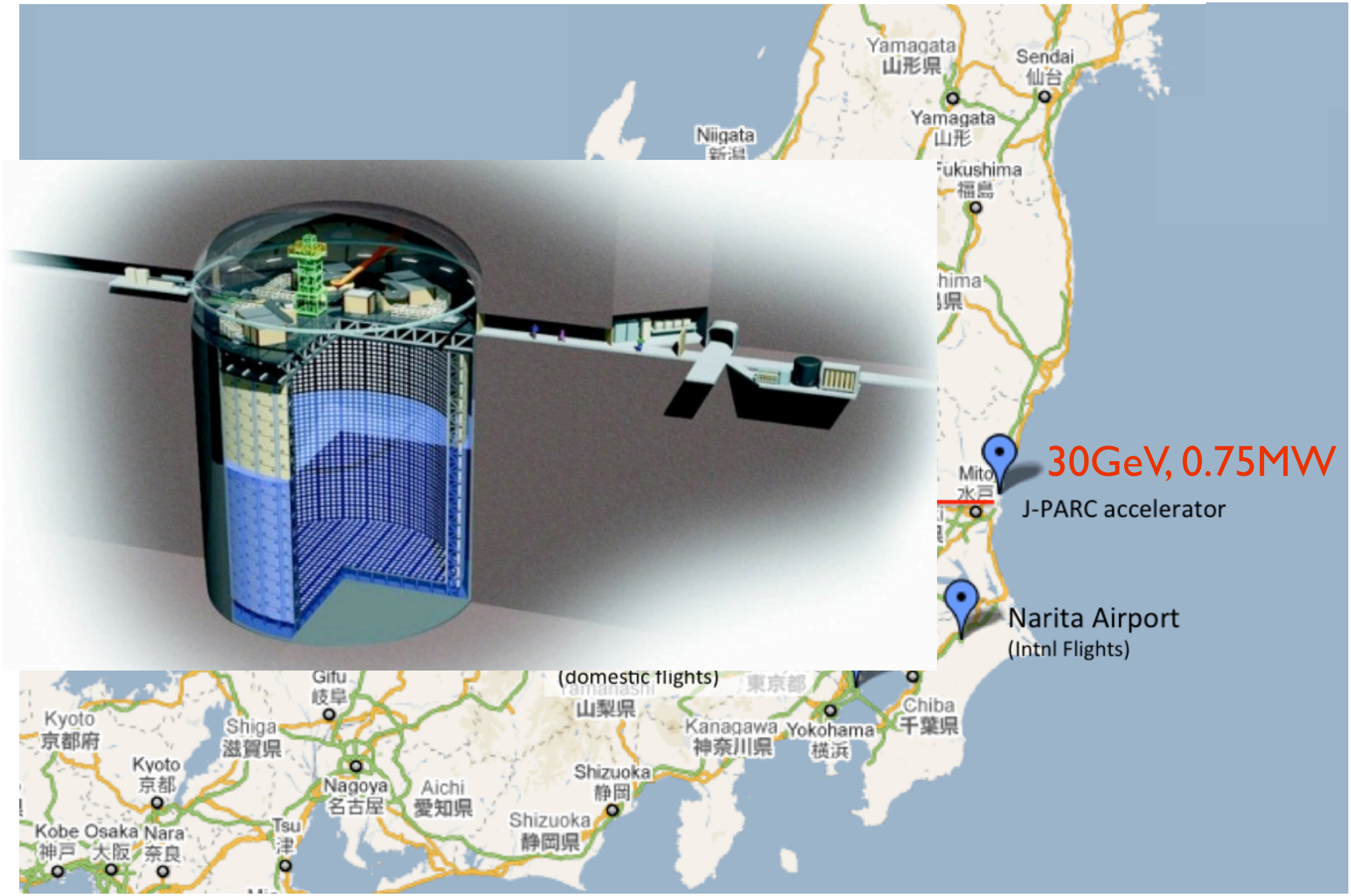
(Kamioka, Japonsko)

T2K

(urychlovačová & atmosferická neutrina)

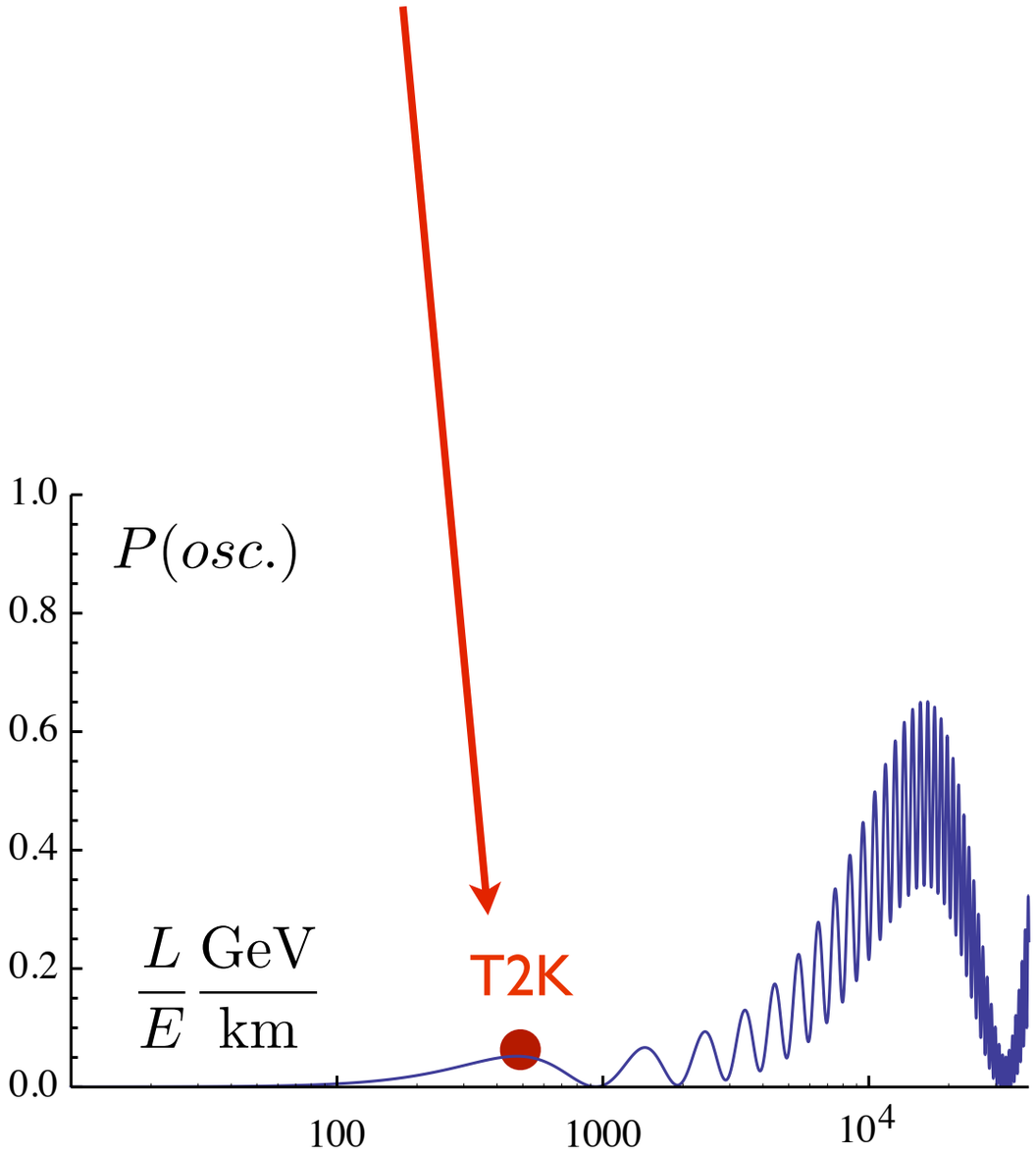
T2K

(urychlovačová & atmosferická neutrina)



T2K
(urychlovačová & atmosferická neutrina)

neutrina z urychlovače (J-PARC) $\nu_\mu \to \nu_e\,,\ \overline{\nu}_\mu \to \overline{\nu}_e$ $E_\nu^{\mathrm{peak}} \sim 0.5\,\mathrm{GeV}$



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(urychlovačová & atmosferická neutrina)

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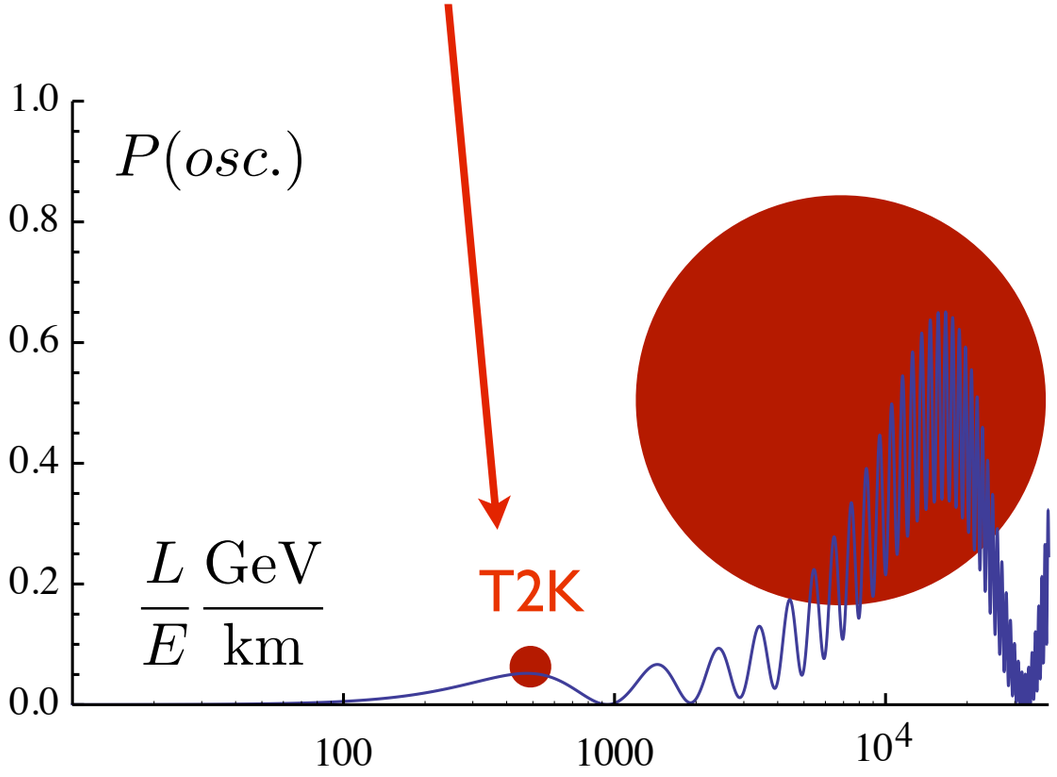
atmosferická neutrina - appearance

$\nu_\mu \to \nu_e\,,\ \overline{\nu}_\mu \to \overline{\nu}_e$

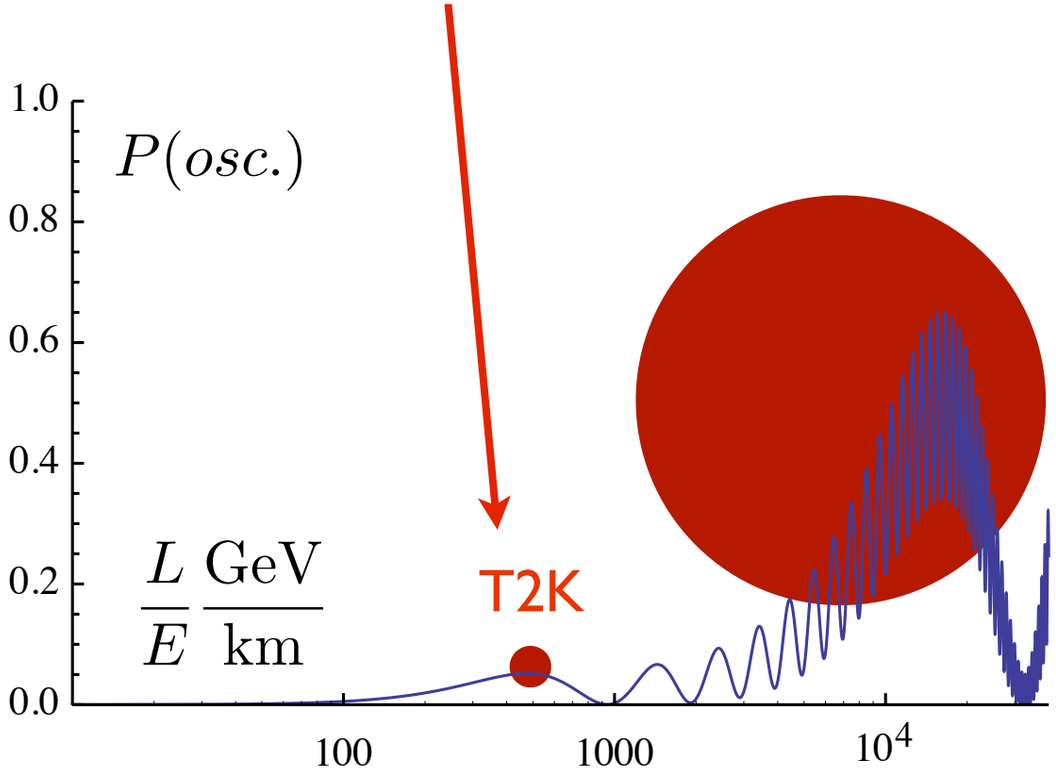


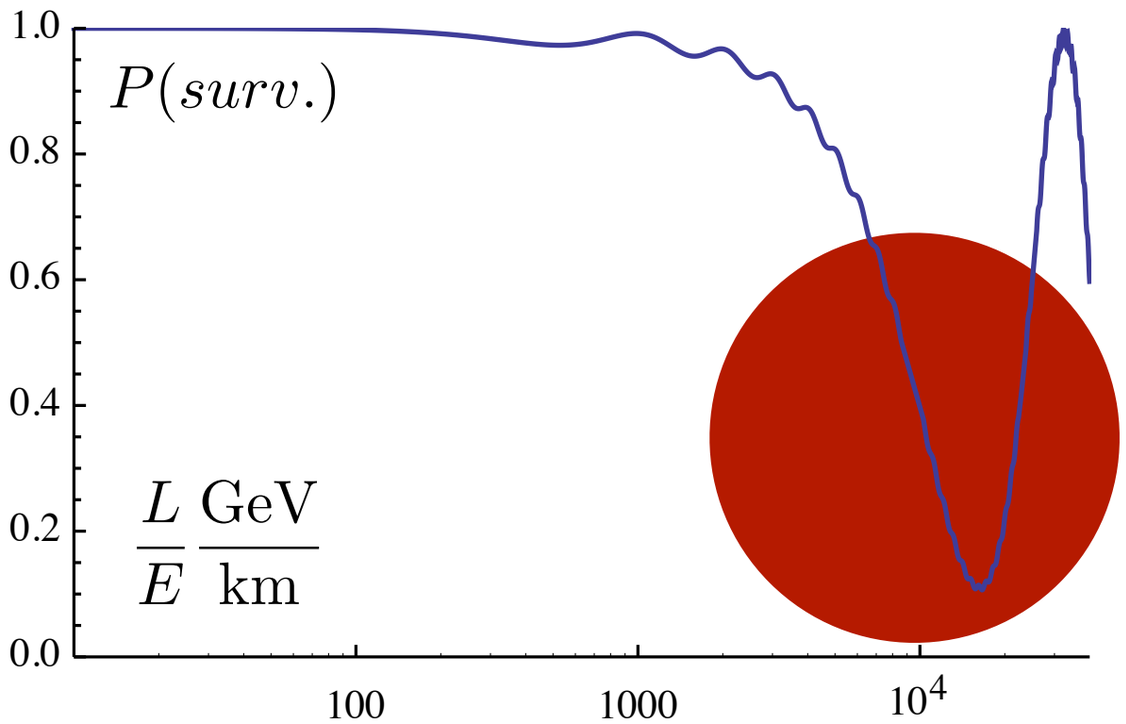
T2K
(urychlovačová & atmosferická neutrina)

neutrina z urychlovače (J-PARC) $\nu_\mu \to \nu_e\,,\ \overline{\nu}_\mu \to \overline{\nu}_e$ $E_\nu^{\mathrm{peak}} \sim 0.5\,\mathrm{GeV}$

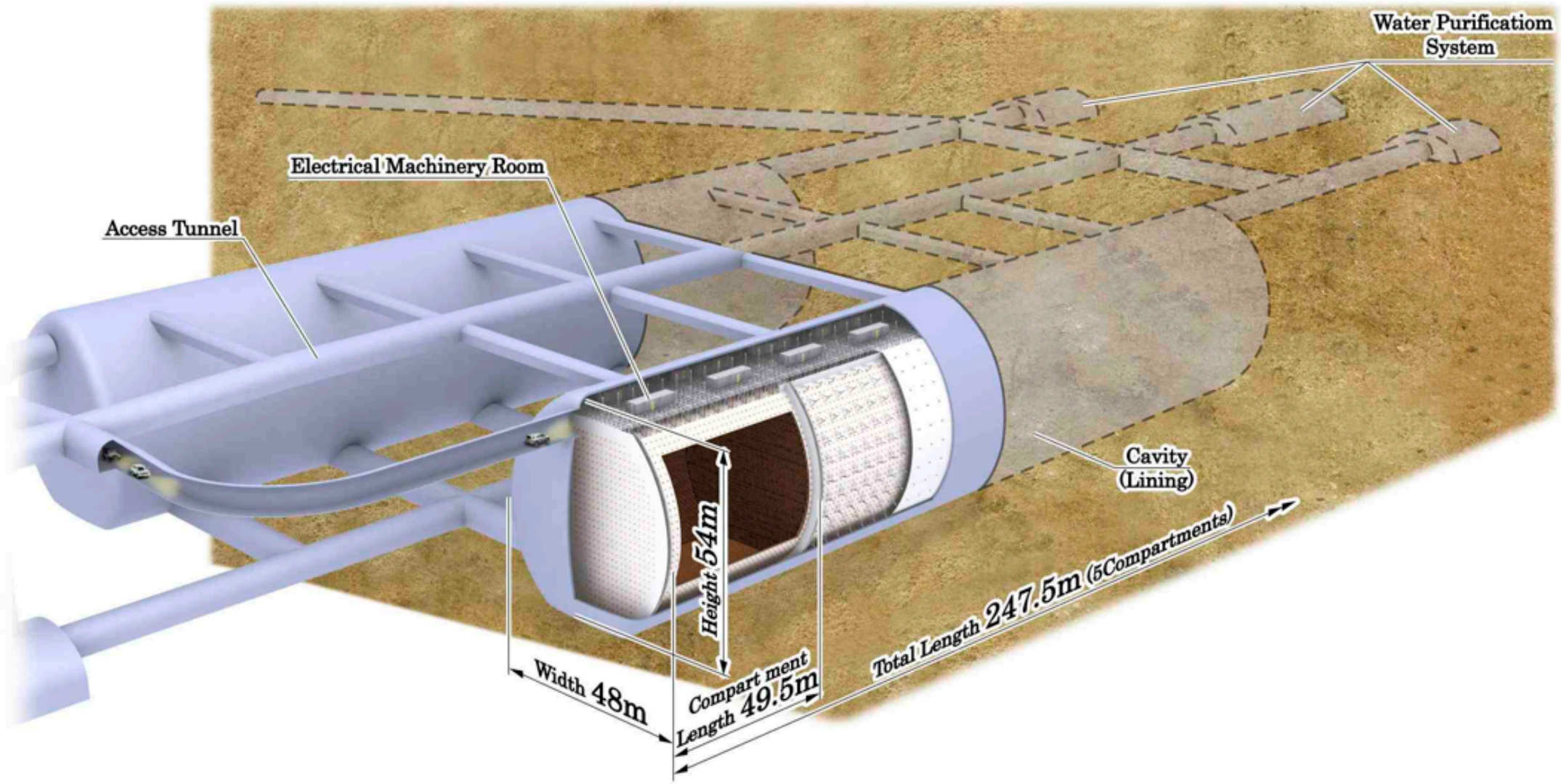
atmosferická neutrina - appearance
$\nu_\mu \to \nu_e\,,\ \overline{\nu}_\mu \to \overline{\nu}_e$

atmosferická neutrina - survival
$\nu_e \to \nu_e\,,\ \overline{\nu}_e \to \overline{\nu}_e$





Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

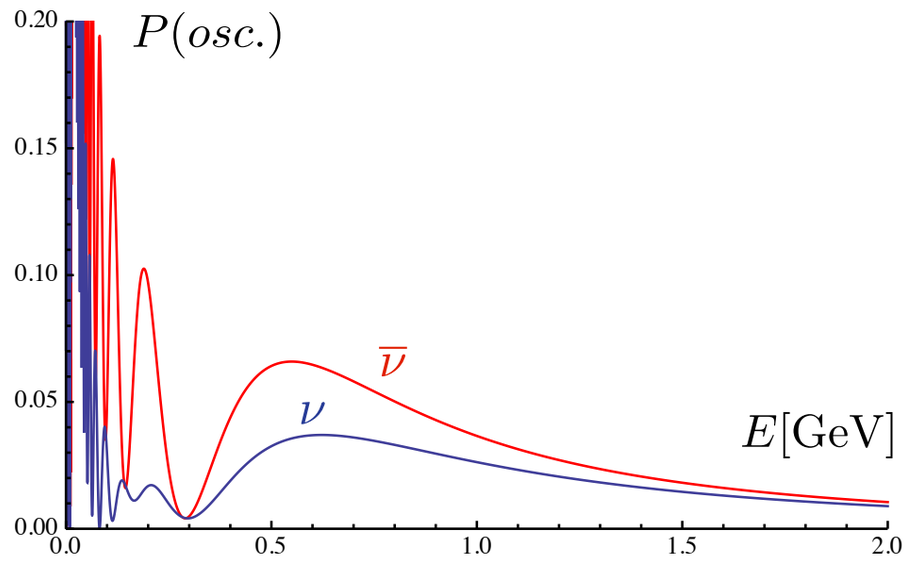


Parametry: 1Mt WC (550 kt FV) @ T2K beam (2,5 stupně off-axis)

Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

T2Hyper-K

CP efekt: $\nu_\mu \to \nu_e\ ,\ \overline{\nu}_\mu \to \overline{\nu}_e$



Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

T2Hyper-K

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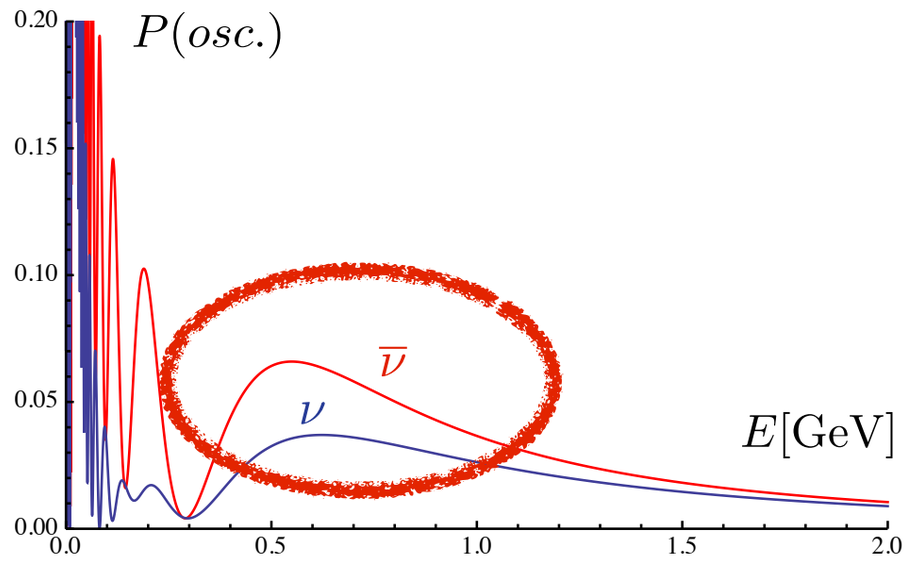

Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

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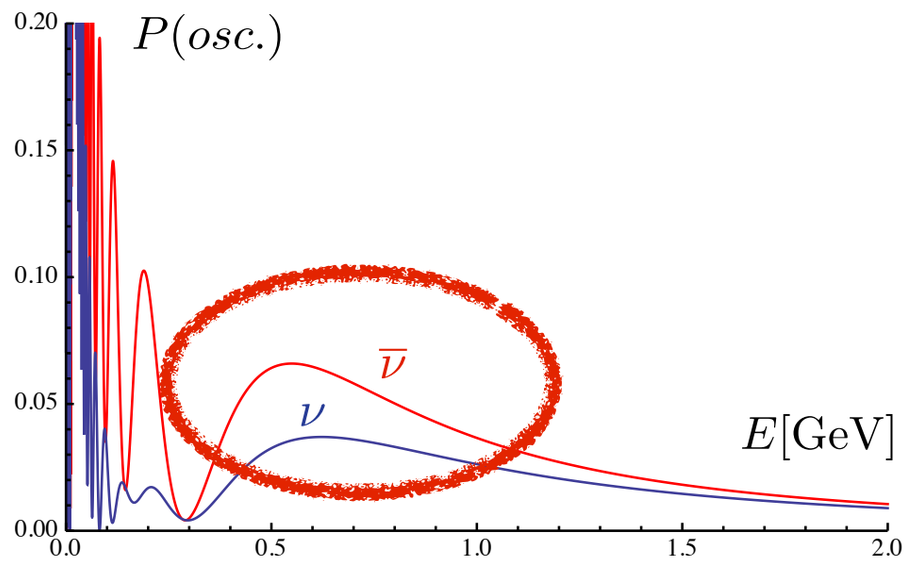
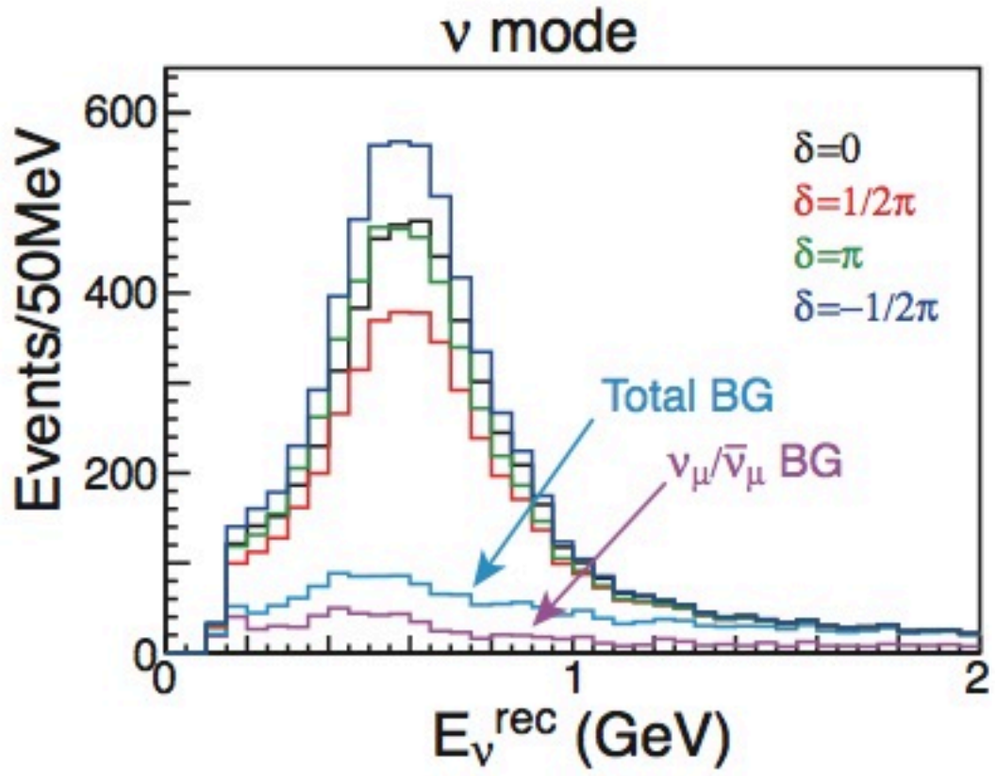
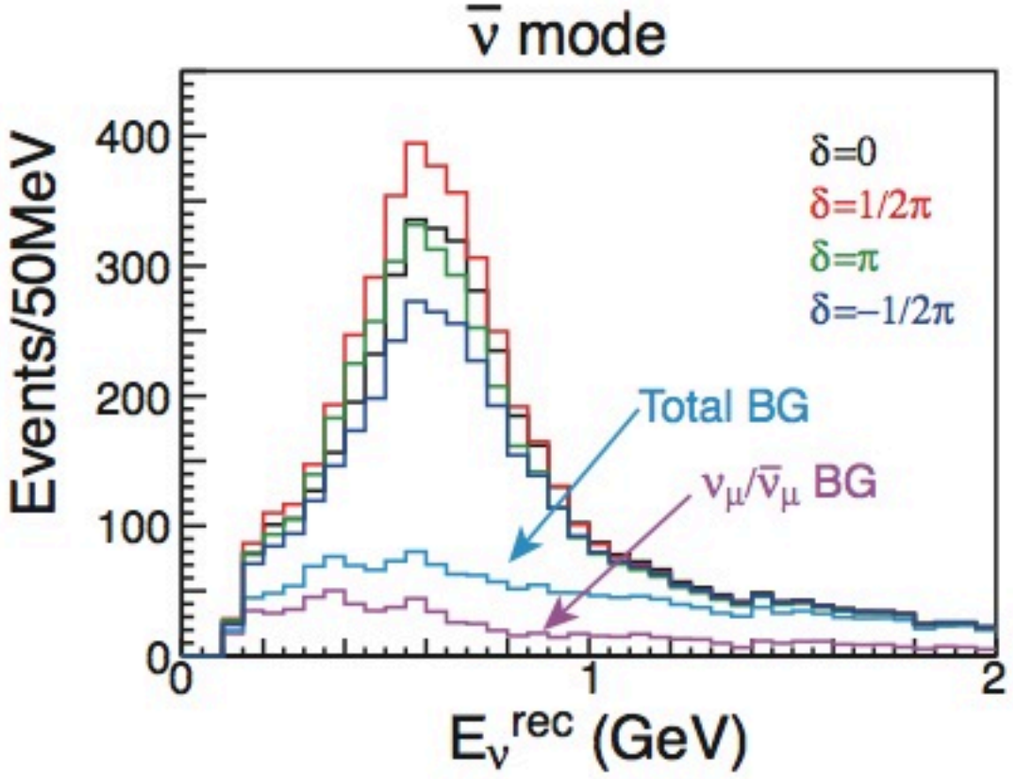


3-sigma pokrytí : až 74% param. prostoru

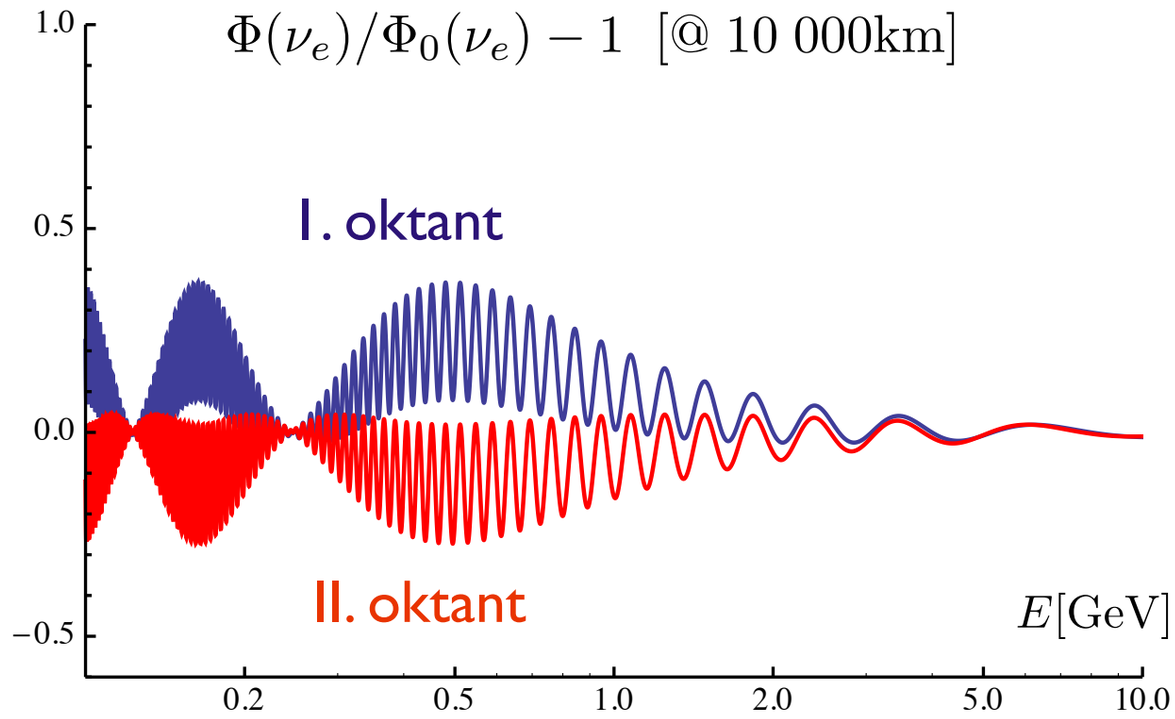




Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

Atmosferická neutrina v Hyper-K

Oktant $\square_{23}$ (> 90% C.L.)



Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

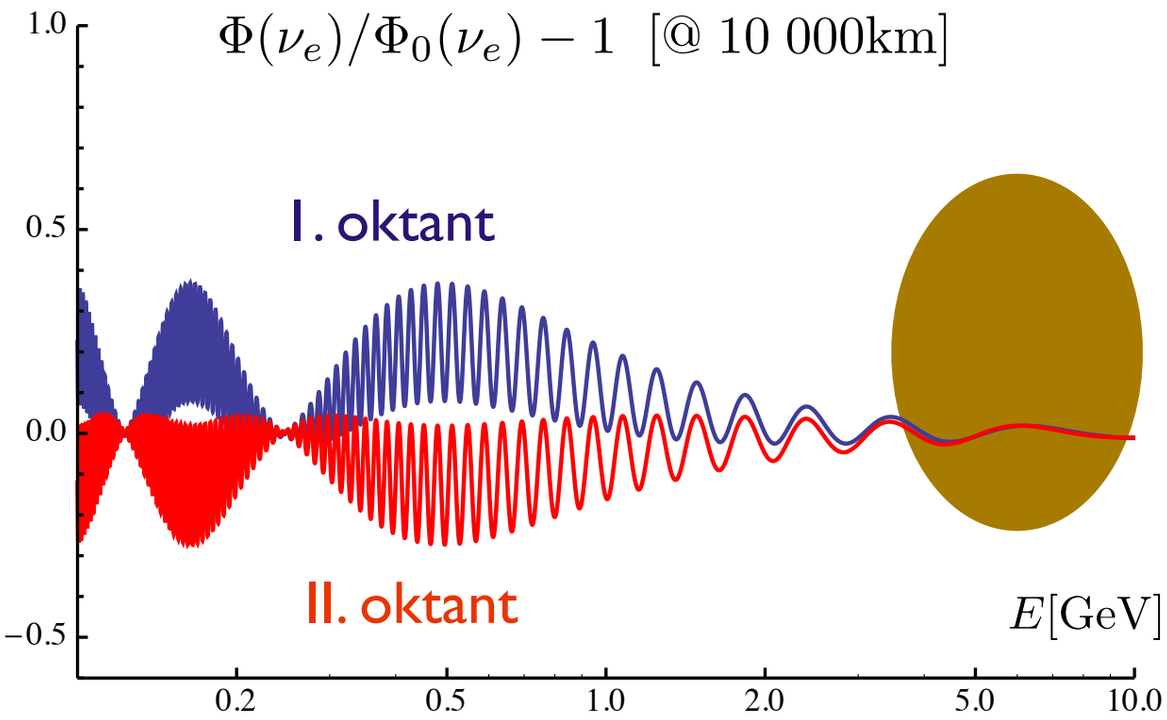
Atmosferická neutrina v Hyper-K

Oktant $\square_{23}$ (> 90% C.L.)

Hierarchie (> 3σ C.L.)

NH: MSW efekt pro **neutrina**

IH: MSW efekt pro **antineutrina**



Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

Atmosferická neutrina v Hyper-K

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Hierarchie (> 3σ C.L.)

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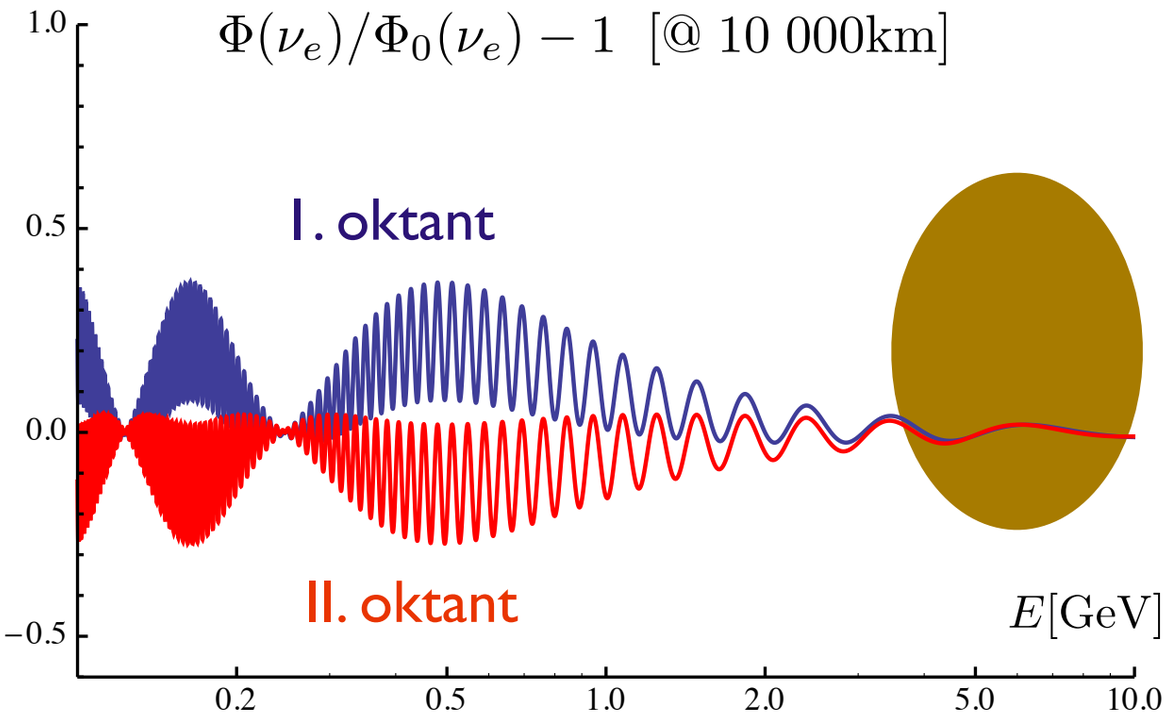

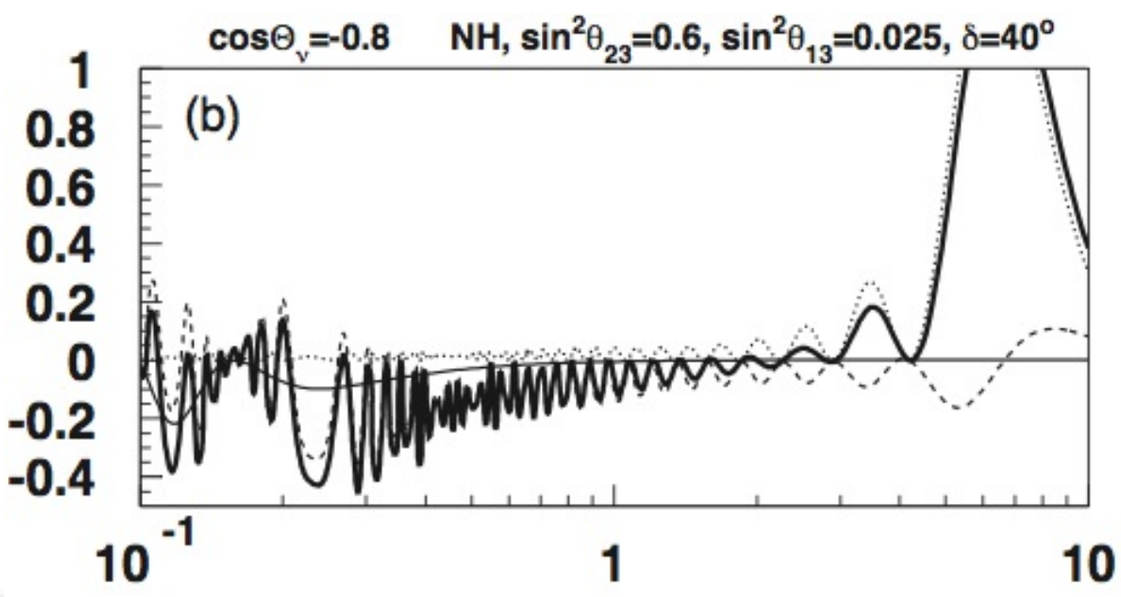

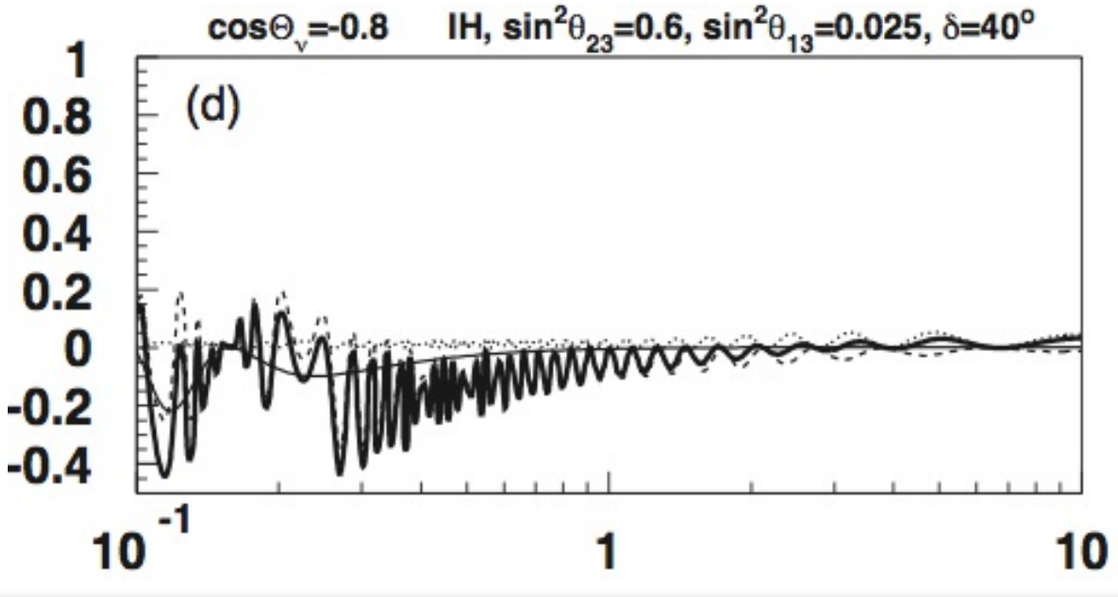

Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

Physics Target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		1.66 MW $\times$ 5 years (1 year $\equiv 10^7$ sec)
$-$ CP phase precision	$< 18°$	@ $s^2 2\theta_{13} (\equiv \sin^2 2\theta_{13}) > 0.03$ and mass hierarchy (MH) is known
$-$ CPV 3σ discovery coverage	74% (55%)	@ $s^2 2\theta_{13} = 0.1$, MH known(unknown)
	74% (63%)	@ $s^2 2\theta_{13} = 0.03$, MH known(unknown)
	66% (59%)	@ $s^2 2\theta_{13} = 0.01$, MH known(unknown)
Atmospheric neutrino study		10 years observation
$-$ MH determination	$> 3\sigma$ CL	@ $0.4 < s^2\theta_{23}$ and $0.04 < s^2 2\theta_{13}$
$-$ θ_{23} octant determination	$> 90\%$ CL	@ $s^2 2\theta_{23} < 0.99$ and $0.04 < s^2 2\theta_{13}$
Nucleon Decay Searches		10 years data
$-$ $p \to e^+ + \pi^0$	1.3×10^{35} yrs (90% CL)	
	5.7×10^{34} yrs (3σ CL)	
$-$ $p \to \bar{\nu} + K^+$	2.5×10^{34} yrs (90% CL)	
	1.0×10^{34} yrs (3σ CL)	

Hyper-K & T2HK

(urychlovačová & atmosferická neutrina)

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Hyper-K & T2HK
(urychlovačová & atmosferická neutrina)

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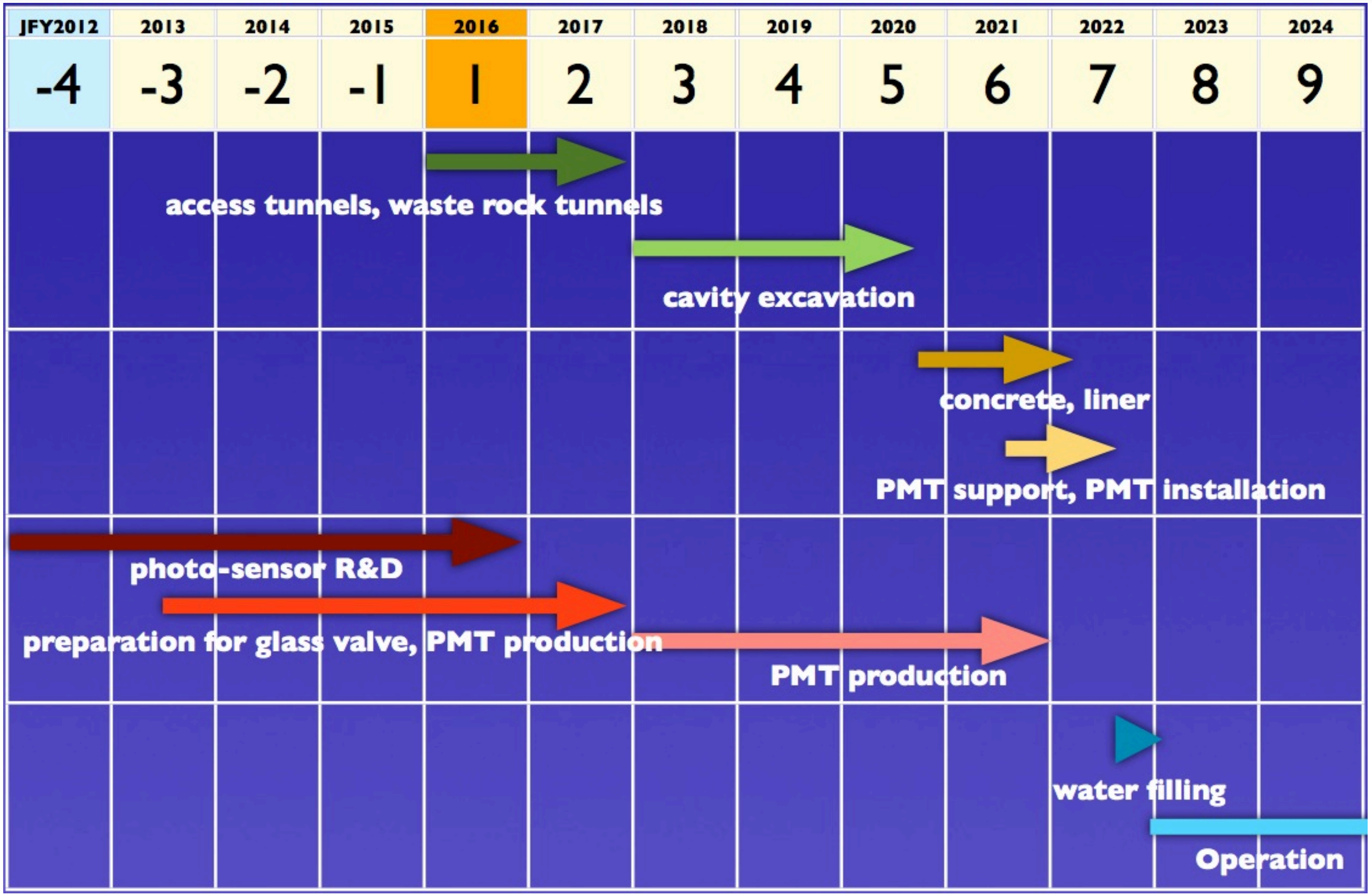
Nucleon Decay Searches		10 years data
$-$ $p \to e^+ + \pi^0$	1.3×10^{35} yrs (90% CL)	
	5.7×10^{34} yrs (3σ CL)	
$-$ $p \to \bar{\nu} + K^+$	2.5×10^{34} yrs (90% CL)	
	1.0×10^{34} yrs (3σ CL)	

ROZPAD PROTONU!

Hyper-K

(urychlovačová & atmosferická neutrina)



Hyper-K
(urychlovačová & atmosferická neutrina)

Cost Estimate

Total	800M USD*	
Cavern	300M USD	
Tank & structure	200M USD	
Photo-sensors	200M USD	
Near Detector	30M USD	@Tokai

*The cost of rock disposal and water purification system to be added in the future

Jaro 2014:

- CDR, čeká se na finální rozhodnutí o financování (2016)
- formuje se evropská část kolaborace
  (QMUL, ICL,U. Liverpool, INFN, U. Geneva, Krakow, Saclay, Lisbon, ...)

Pro nás (?) elektronika, kalibrace, blízký detektor @ J-PARC ...

Neutrina z urychlovačů + atmosférická

LBNE

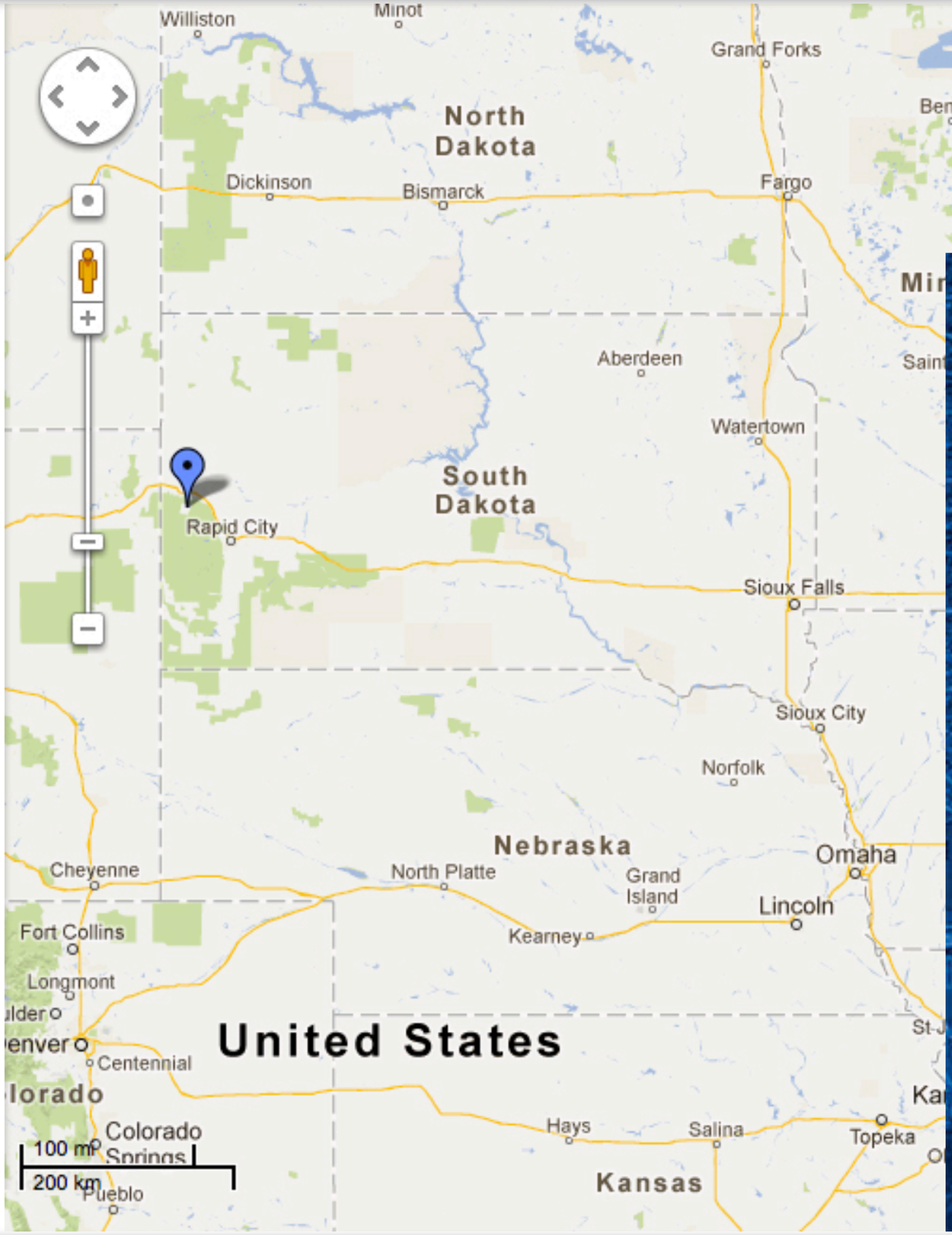
(Long Baseline Neutrino Experiment, Lead, Jižní Dakota, USA)

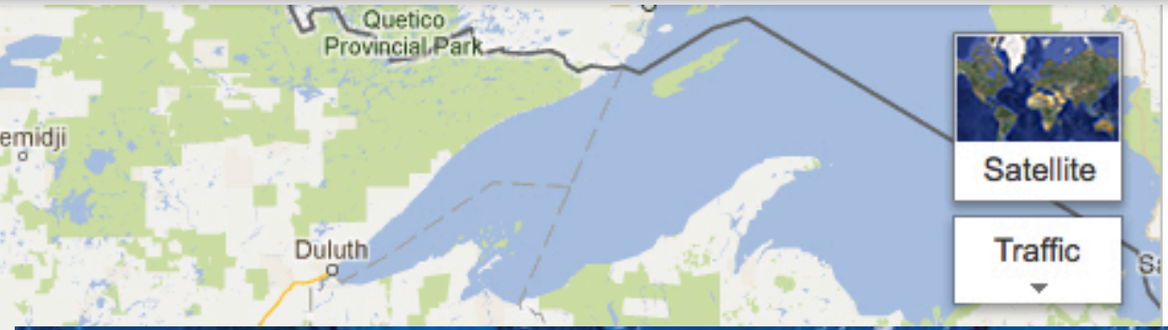
LBNE

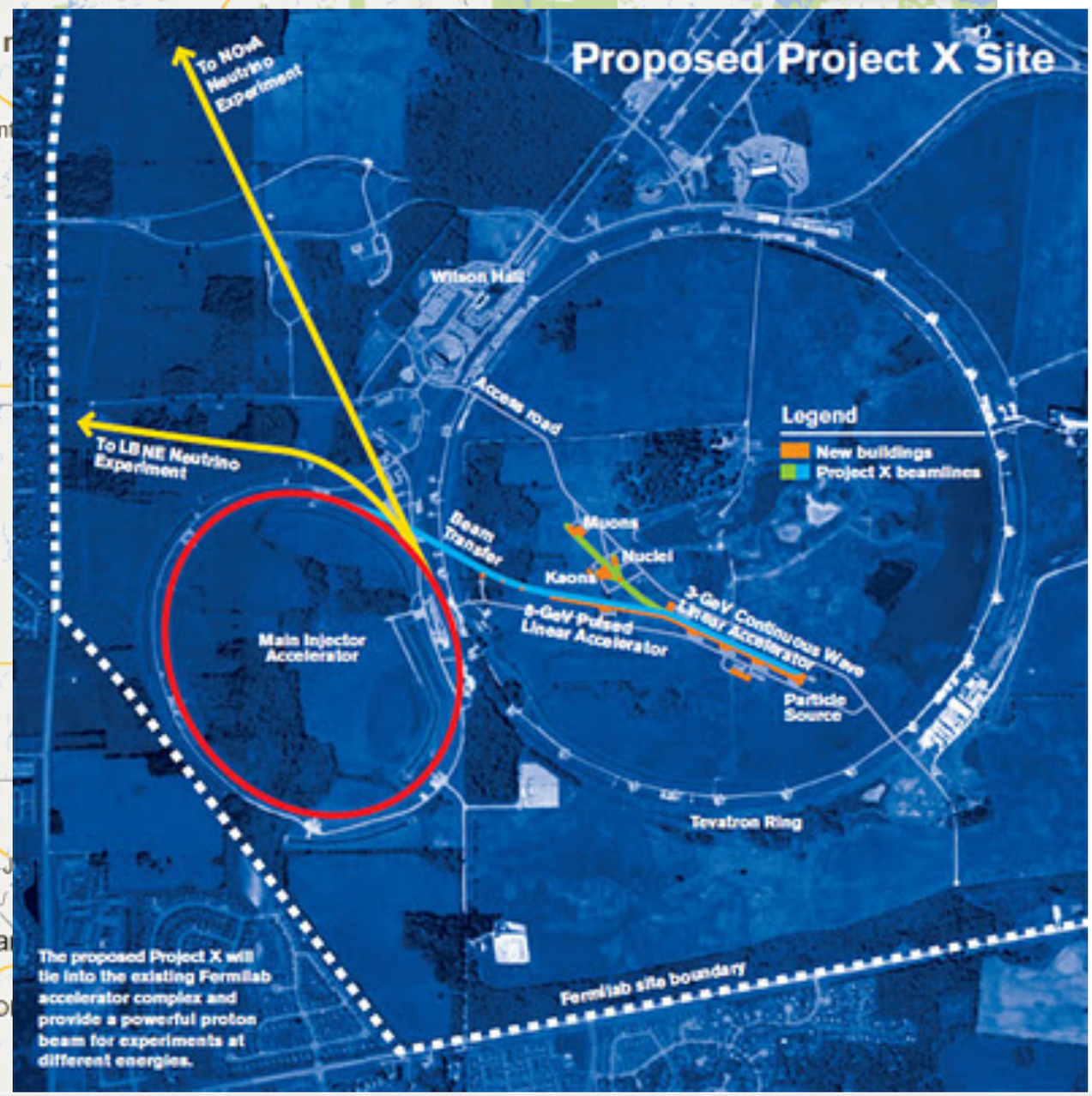
(urychlovačová & atmosferická neutrina)

LBNE

(urychlovačová & atmosferická neutrina)

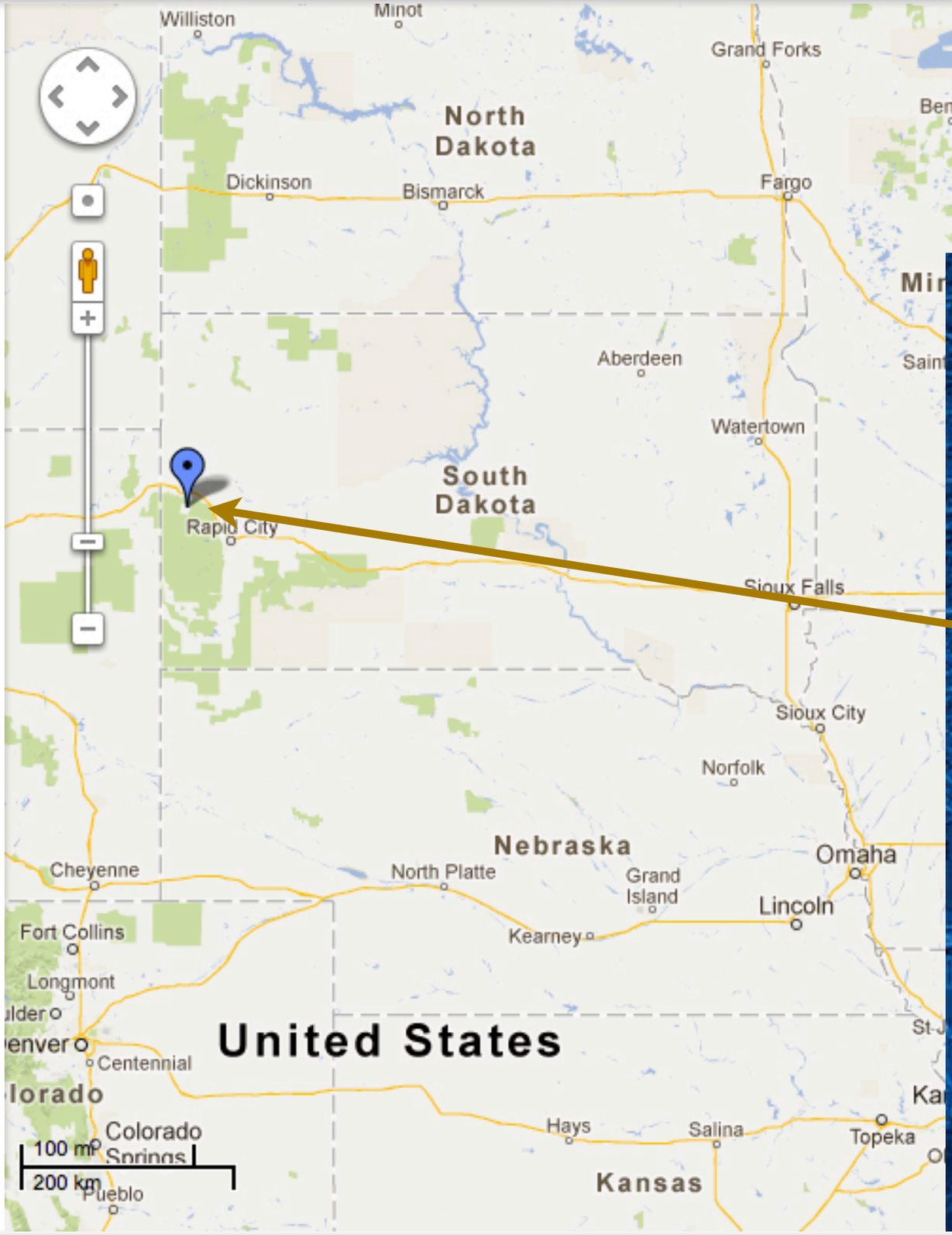


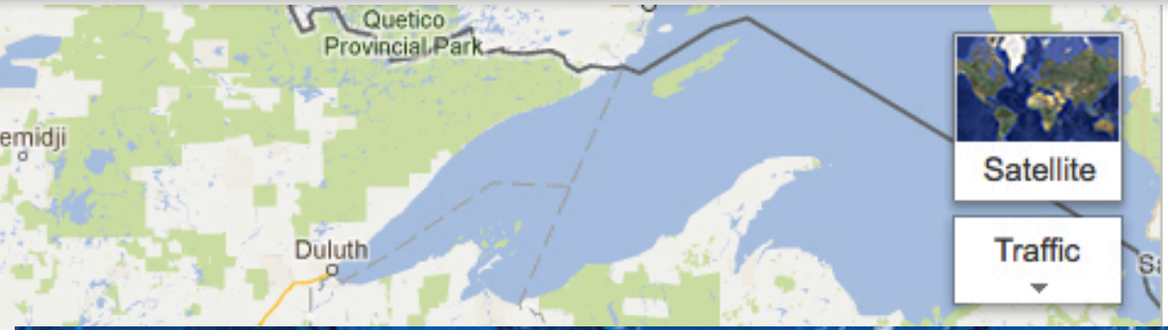


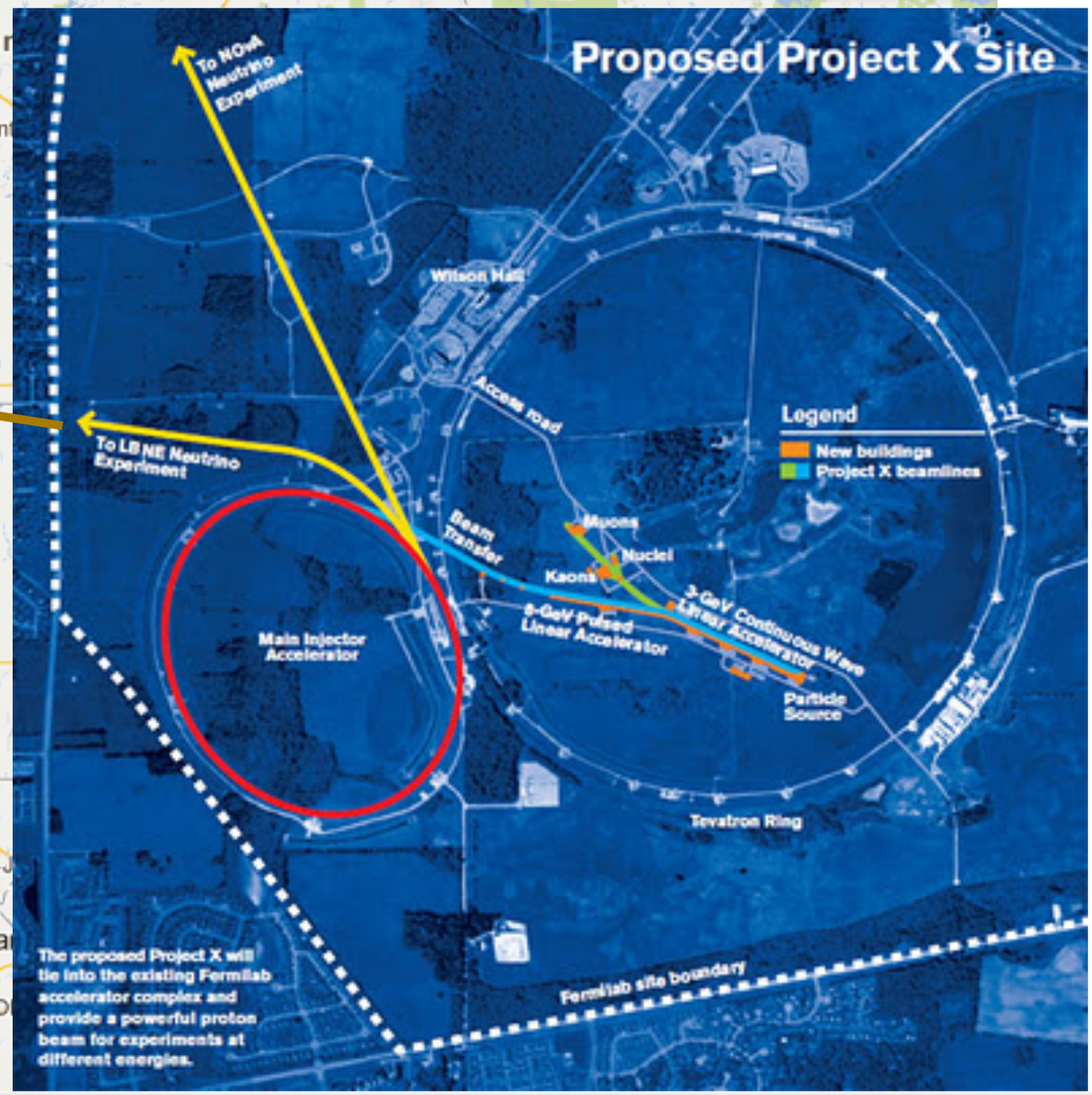


LBNE

(urychlovačová & atmosferická neutrina)







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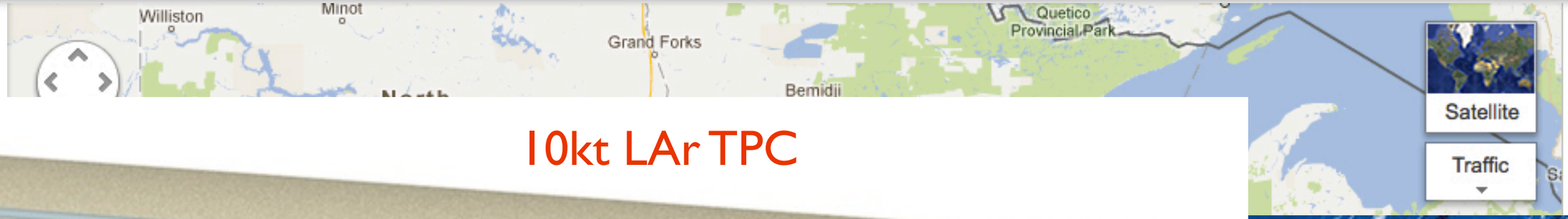
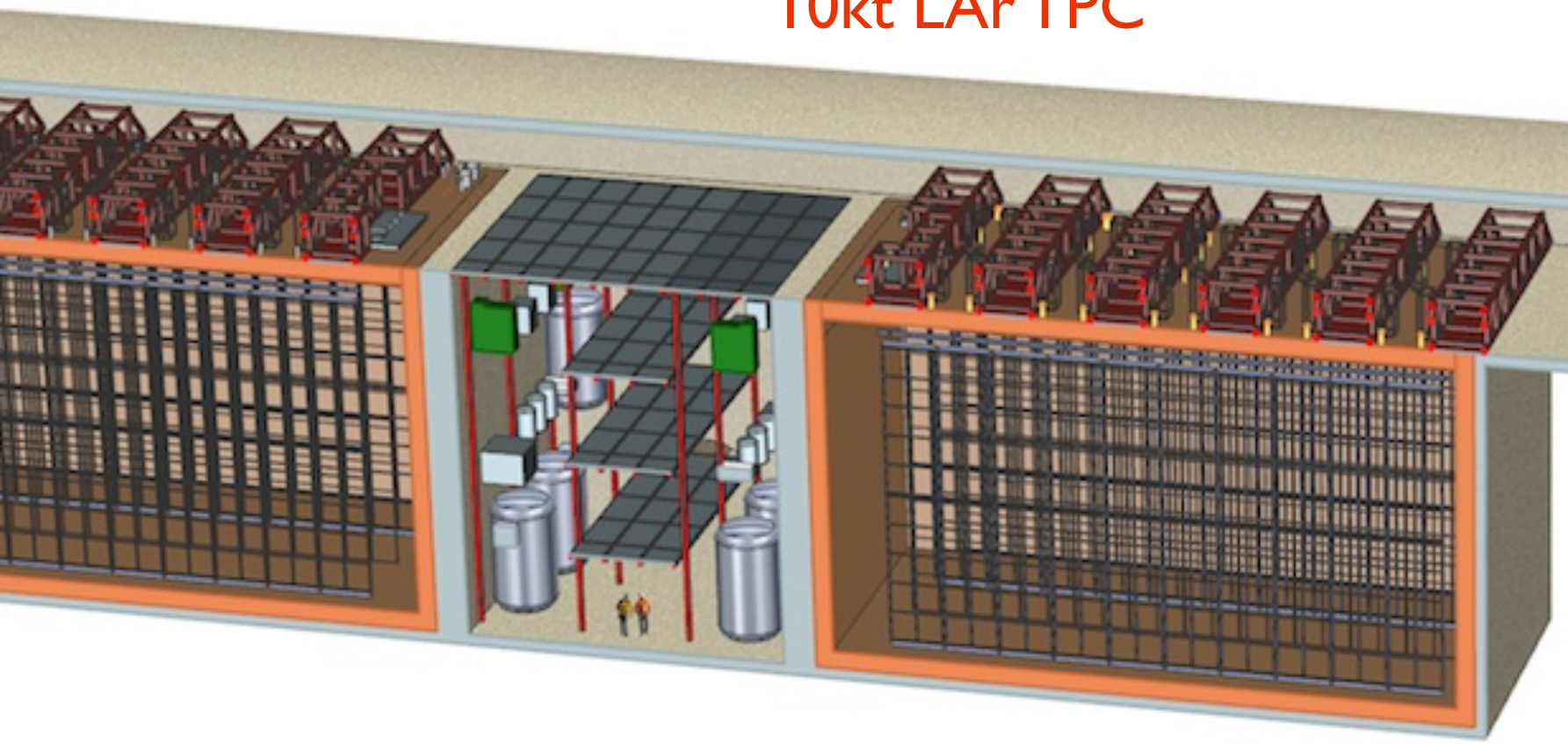
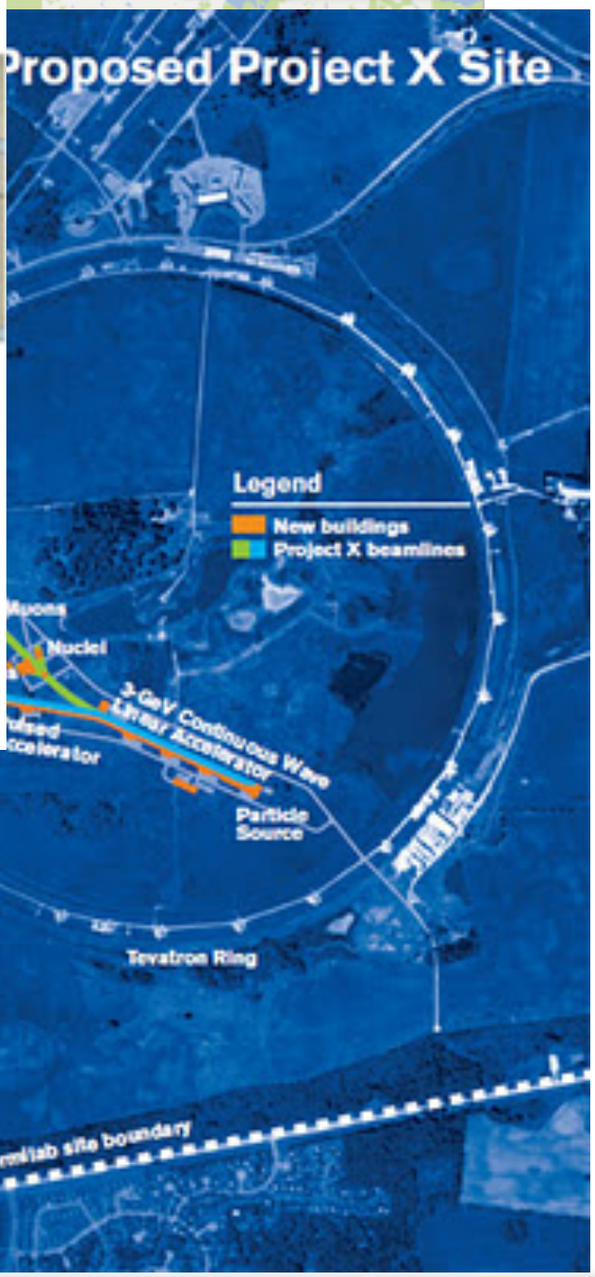


10kt LAr TPC





LBNE
(urychlovačová & atmosferická neutrina)

Rozpočet: DOE příslibil 867M$, většina na svazek, detektor cca 25%

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LBNE: 35kt pod zemí (cca 1500 m), blízký detektor

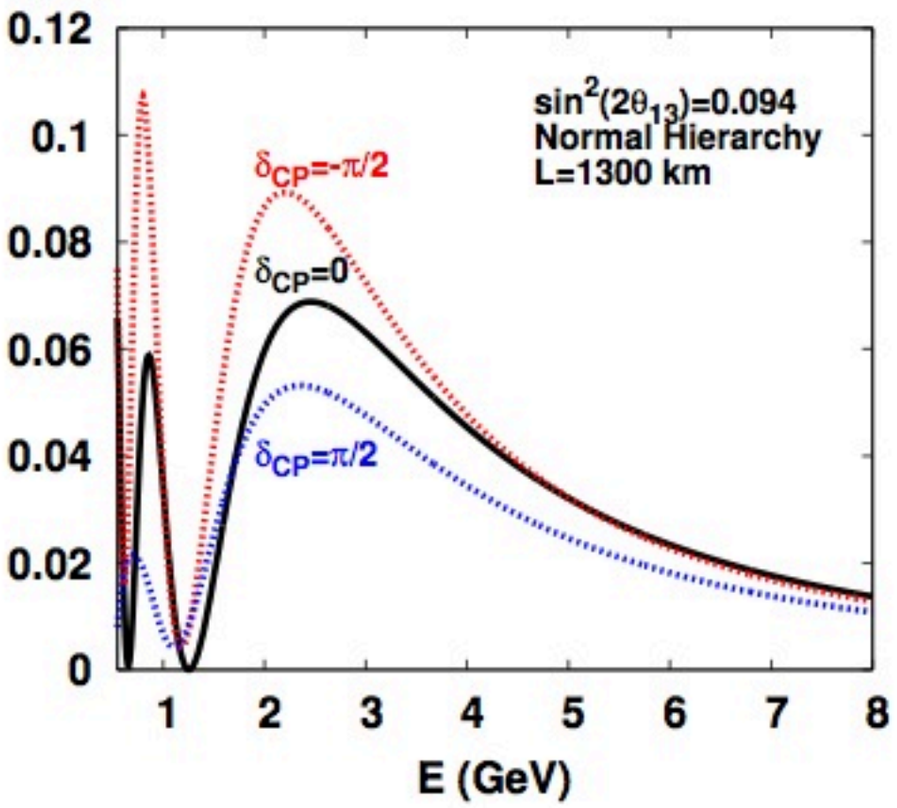
Svazek: 700 kW, v planu upgrade na 1.2 MW, eventuelně 2.3 MW (project X)

LBNE

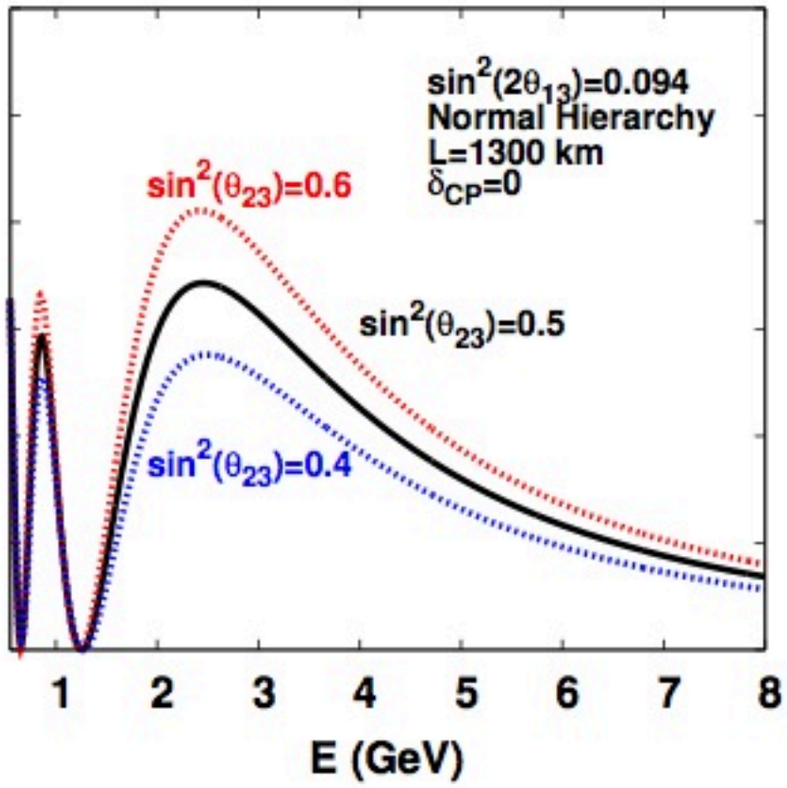
(urychlovačová & atmosferická neutrina)

$$P(\nu_\mu \to \nu_e)$$

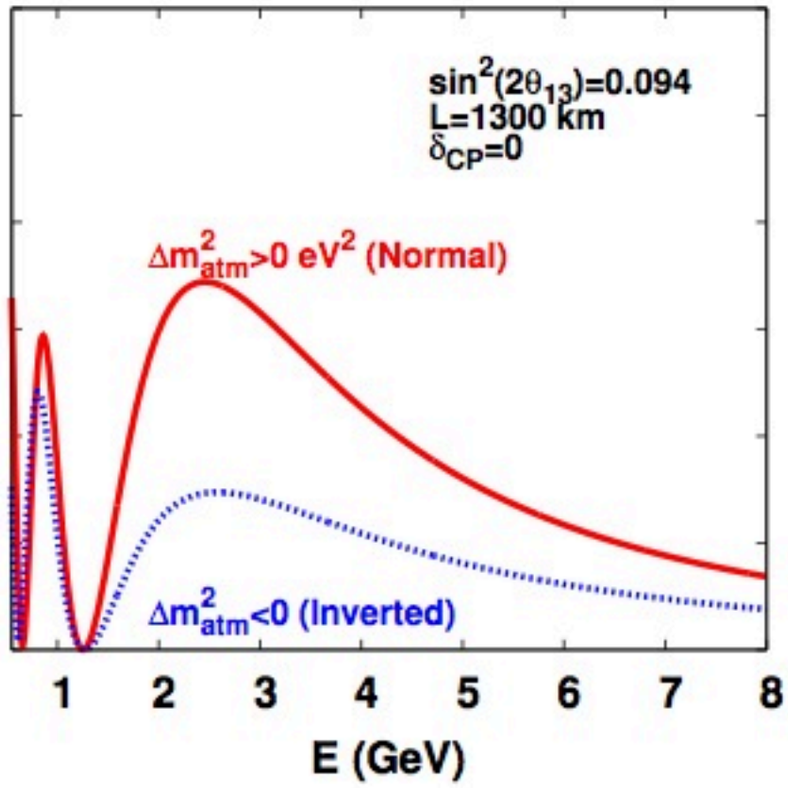
CP efekt



Oktant



Hierarchie



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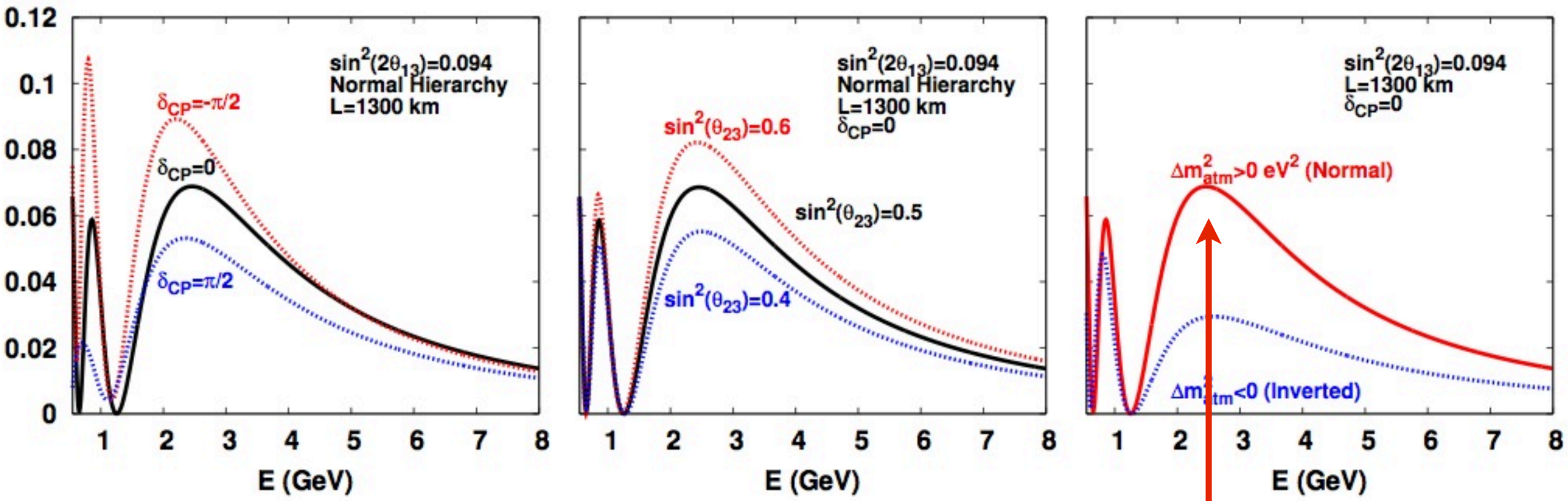
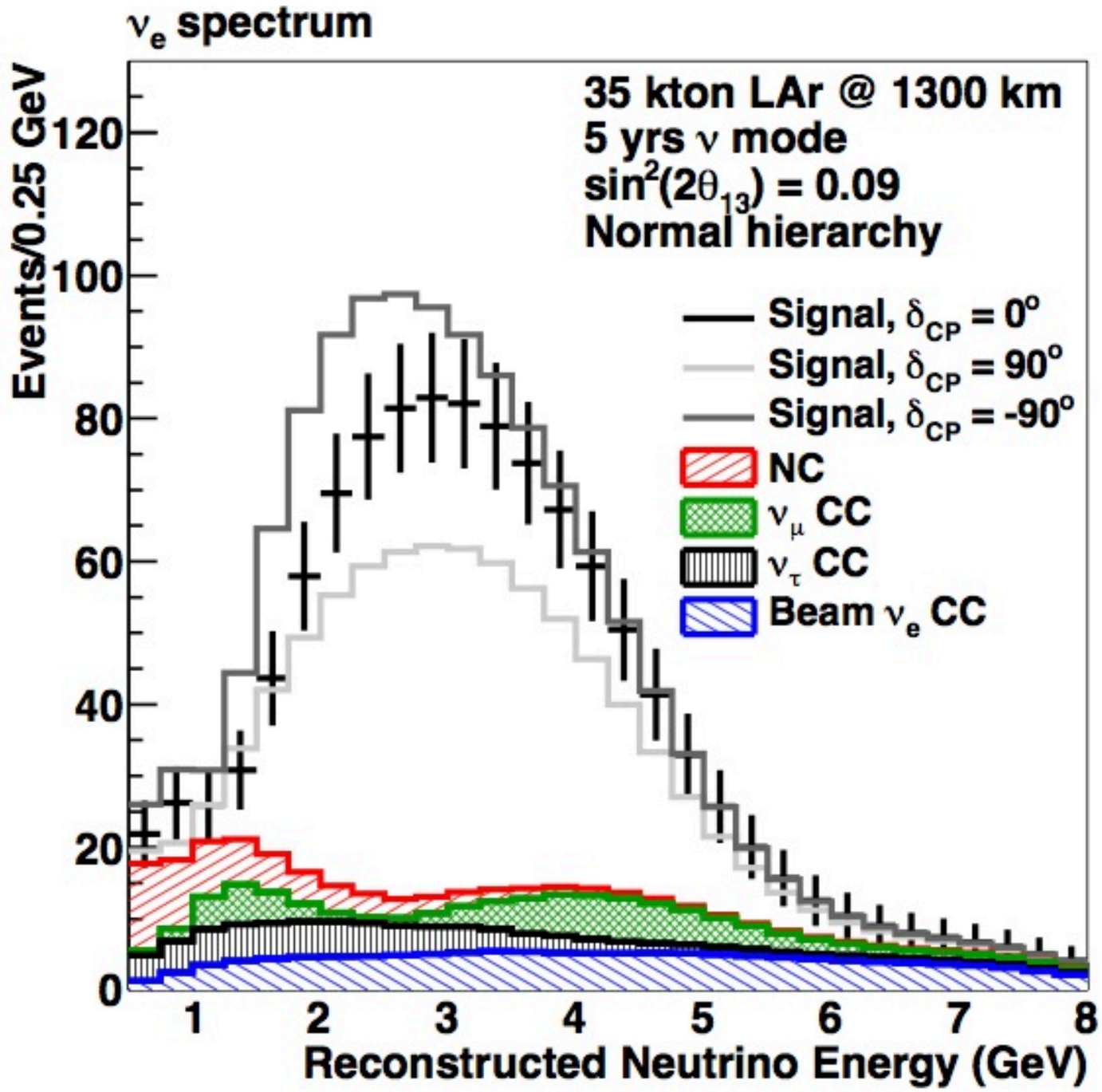


L(LBNE) = 1300 km > L(T2HK) - efekt hierarchie významný

LBNE

(urychlovačová & atmosferická neutrina)

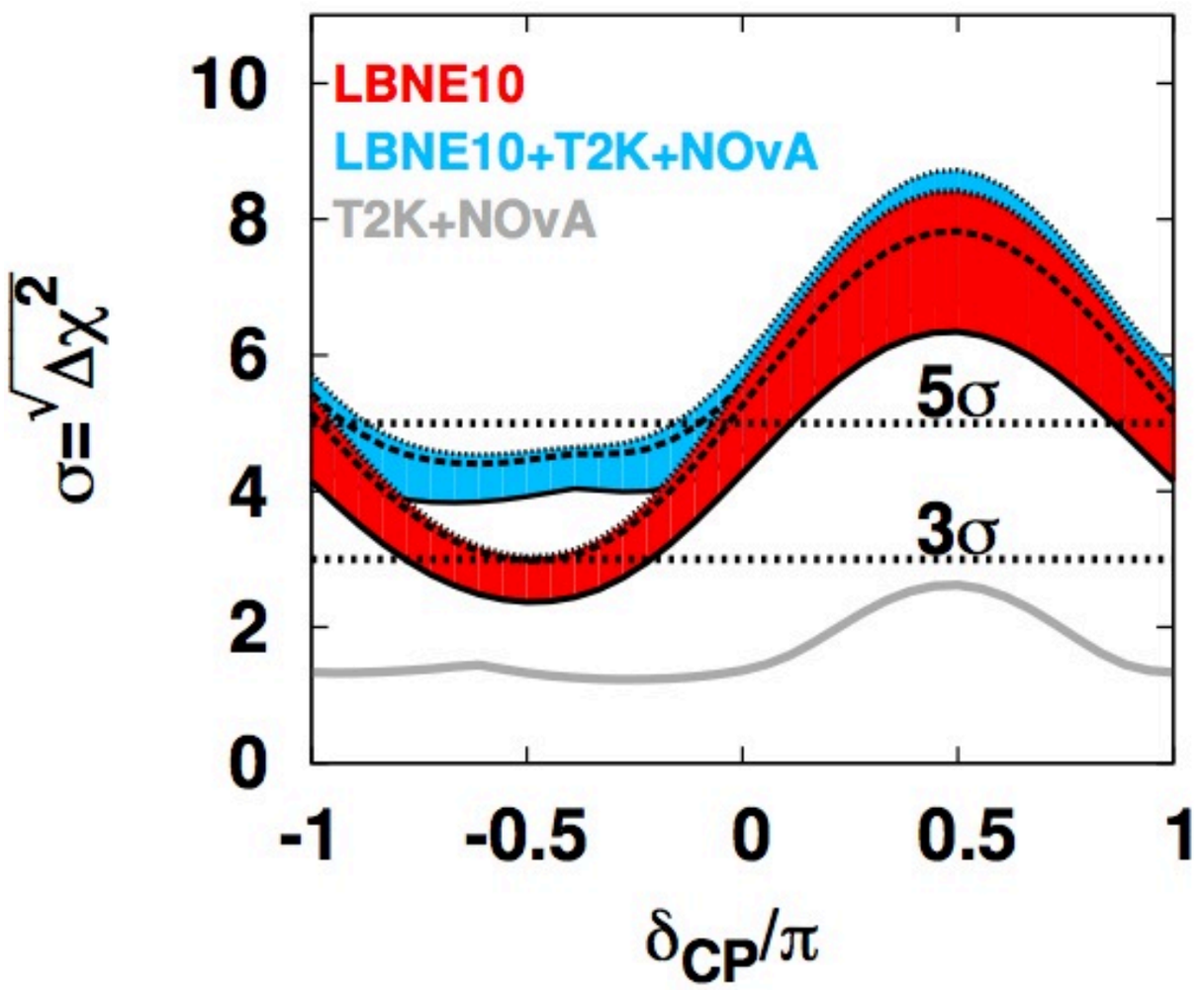


LBNE

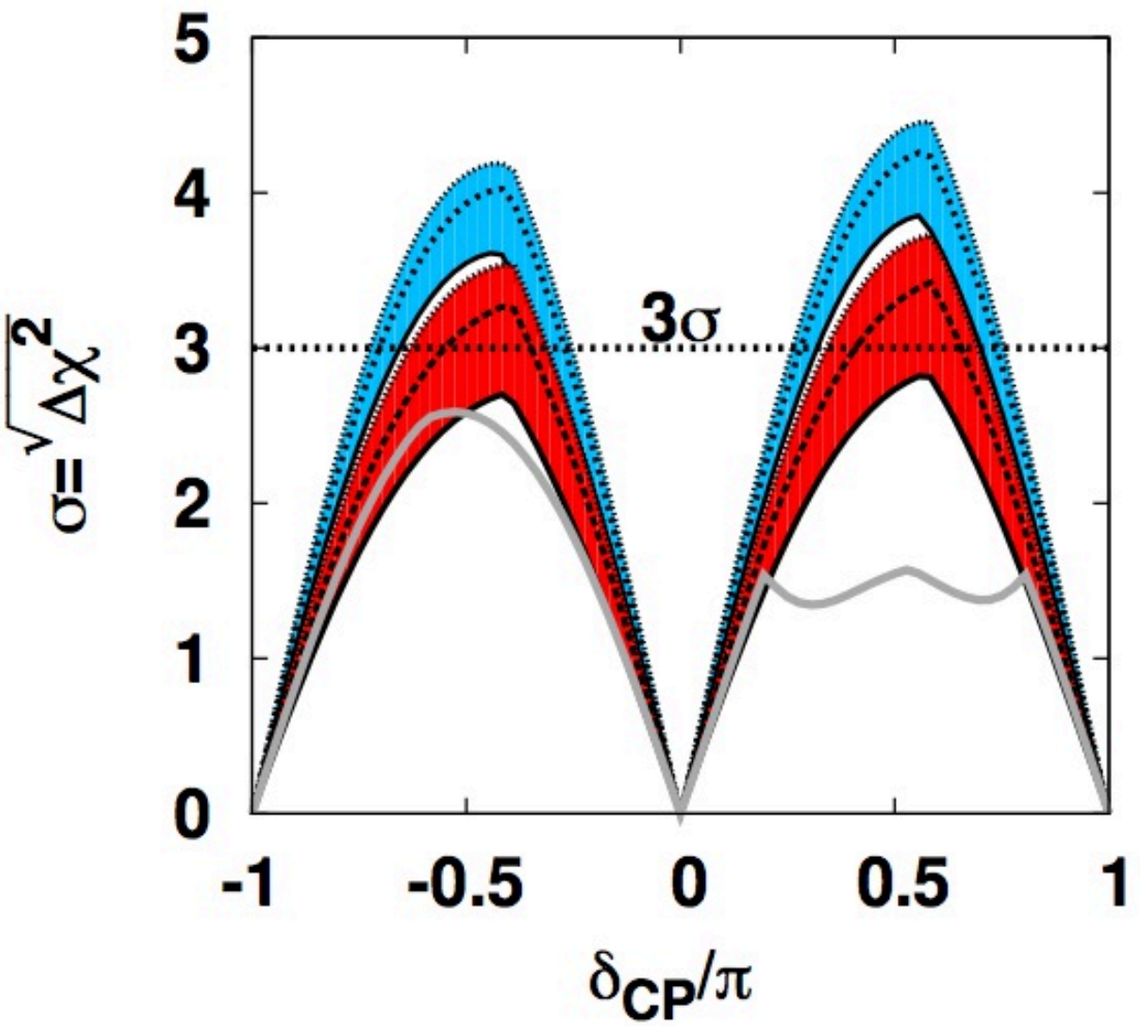
(urychlovačová & atmosferická neutrina)

Citlivosti zhruba srovnatelné s T2HK

Hierarchie



CPV



LBNE
(urychlovačová & atmosferická neutrina)

Prototyp: 35t LAr TPC vyzkoušený, čistota Ar klíčová

Status & timeline: 2014: TDR

2023: start **LBNE10** @ 700 kW

2026: 1.2 MW (project X phase 1), 20kt na povrchu

2028: 34kt na povrchu

2032: 2.4 MW, nabírání dat do cca 2038

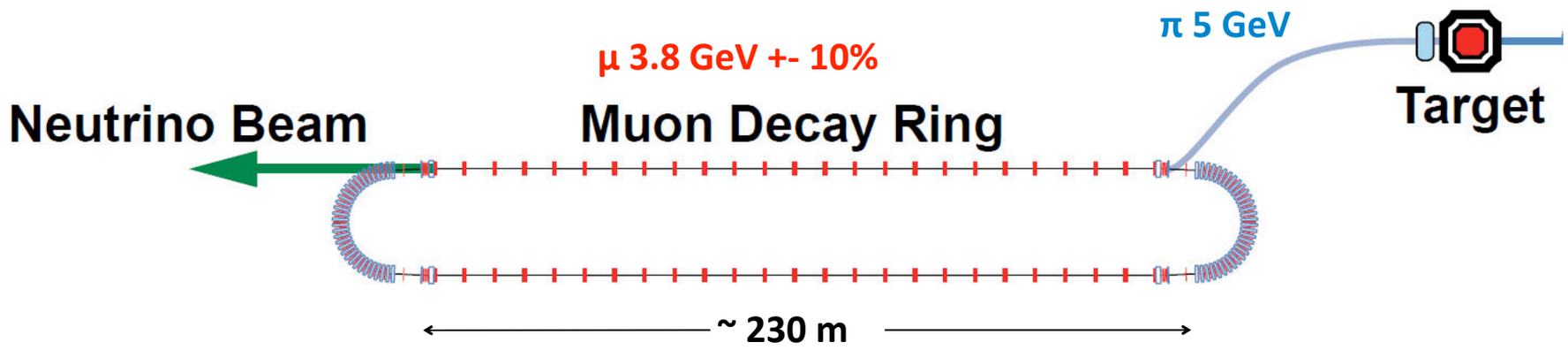
Neutrinos from STORed Muons

nuSTORM

(Fermilab ? CERN ?)

nuSTORM
(mionový akumulační prstenec)

Fermilab/CERN?



nuSTORM
(mionový akumulační prstenec)

Neutrina z rozpadů akumulovaných mionů

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

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(mionový akumulační prstenec)

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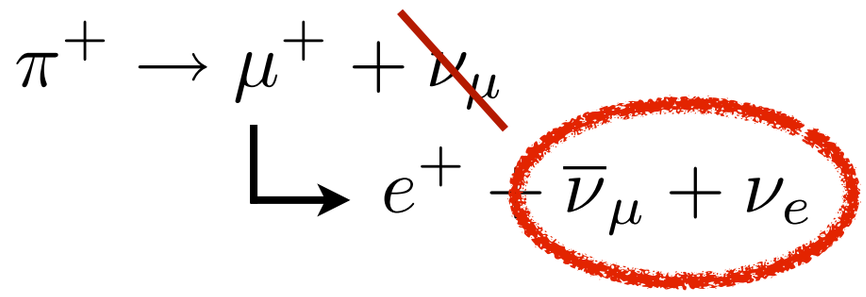

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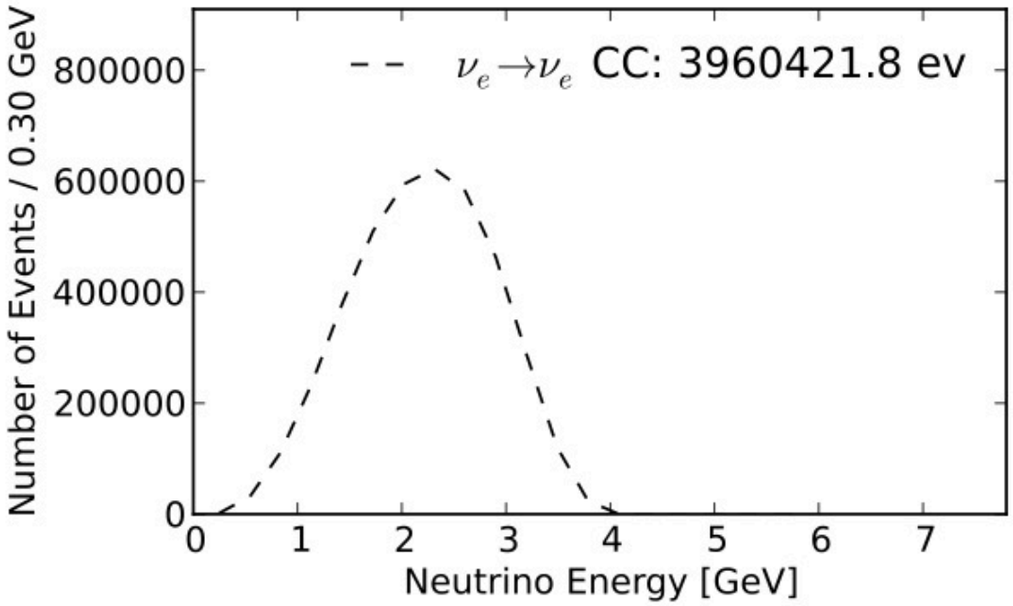
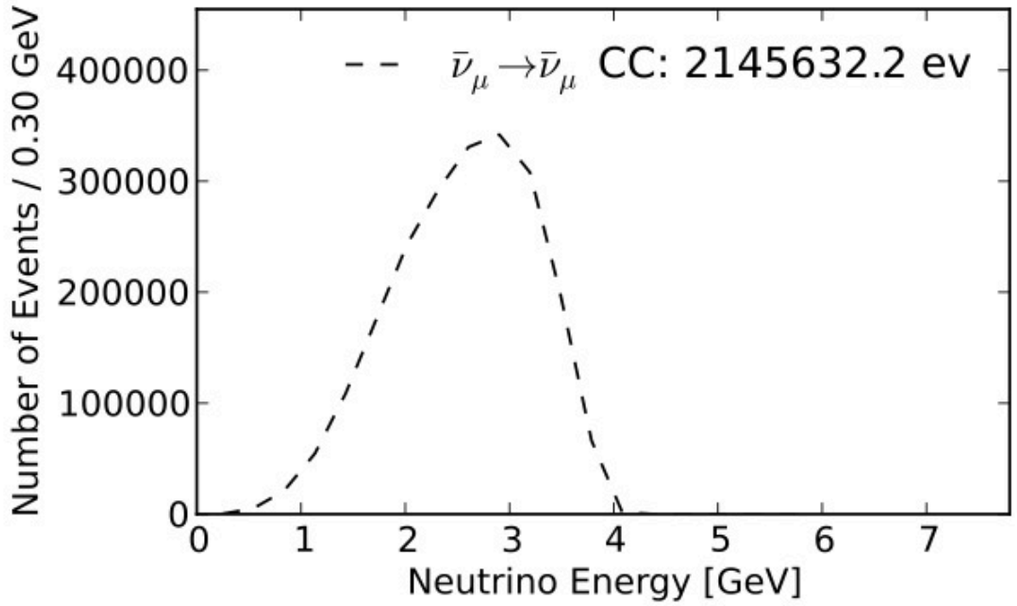
Velmi detailní znalost spektra/kompozice svazku:





100T fid. vol. near detector @ 50m & 10^{21} POT, 4GeV muons

nuSTORM
(mionový akumulační prstenec)

Detailní a definitivní test LSND anomálie (10 sigma) $\Delta m^2 \sim 1\mathrm{eV}^2$

CPT: $P(\overline{\nu}_\mu \to \overline{\nu}_e) = P(\nu_e \to \nu_\mu)$

$$L_{\pi/2} \sim 10\,\mathrm{m} \times \frac{E_\nu}{\mathrm{MeV}}$$

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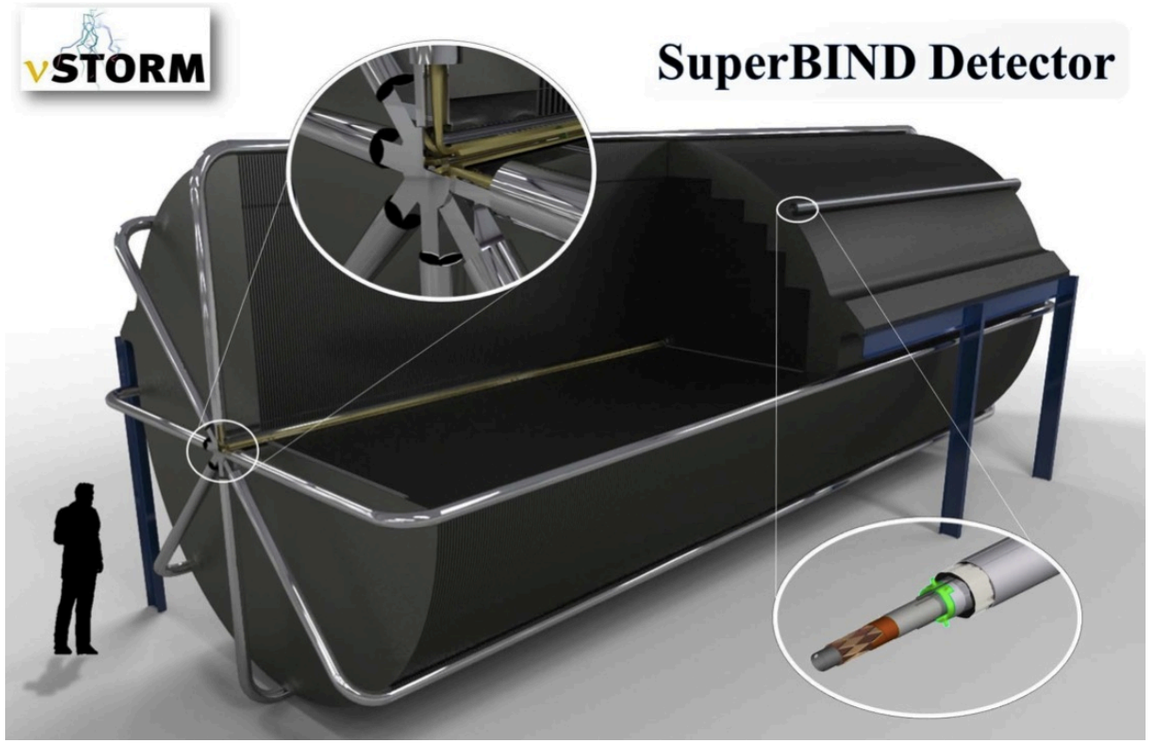
Far detector @ 2 km



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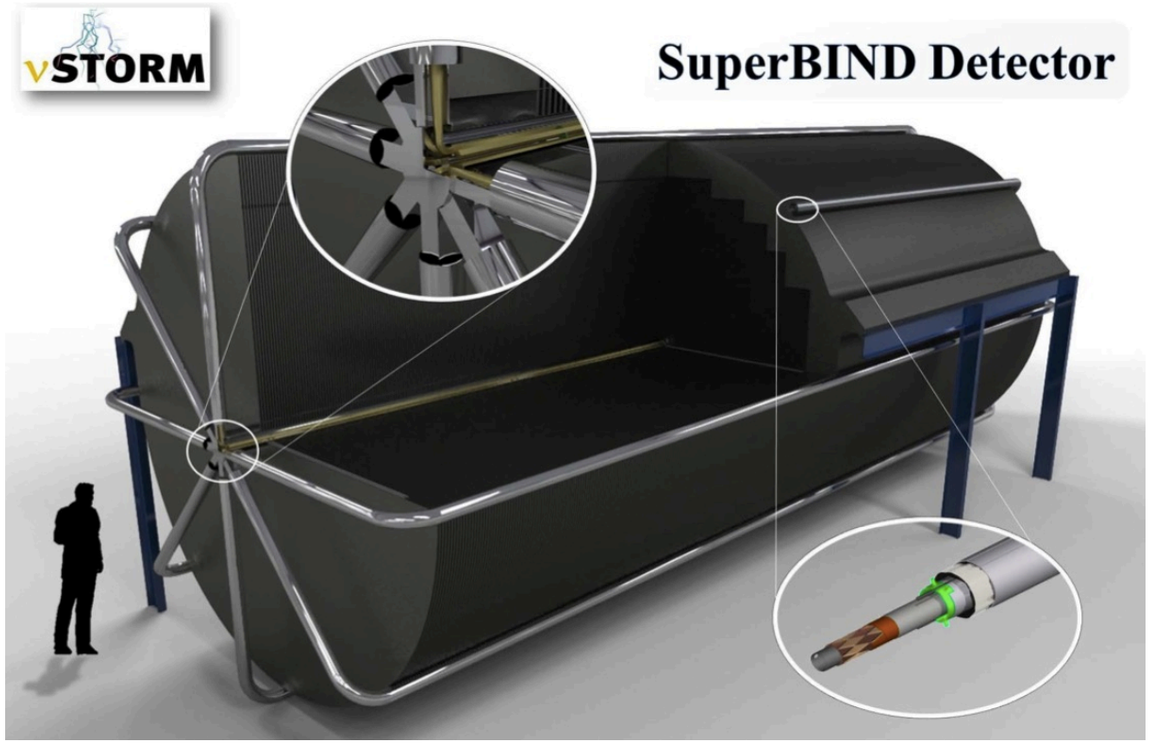

Předstupeň mionového collideru v (daleké ?) budoucnosti

Přesná měření účinných průřezů GeV neutrin (hlavně ν_e) s jádry

nuSTORM
(mionový akumulační prstenec)

LOI podepsalo cca 100 lidí

(USA, Kanada, Indie, Japonsko, Francie, Itálie, Německo, Polsko, Španělsko, Velká Británie)

Status: LOI zaslán Fermilabu v roce 2013

Odhadovaná doba realizace cca 10 let (technologie existuje)

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Odhad nákladů:

Sub System	Cost M$[1]
Primary Beam Line	24
Target Station	56
Transport Line	14
Decay Ring	82
Near Hall	29[2]
Far Detector	24[3]
Sub Total	**229**
Project Office	34[4]
Total	**263**