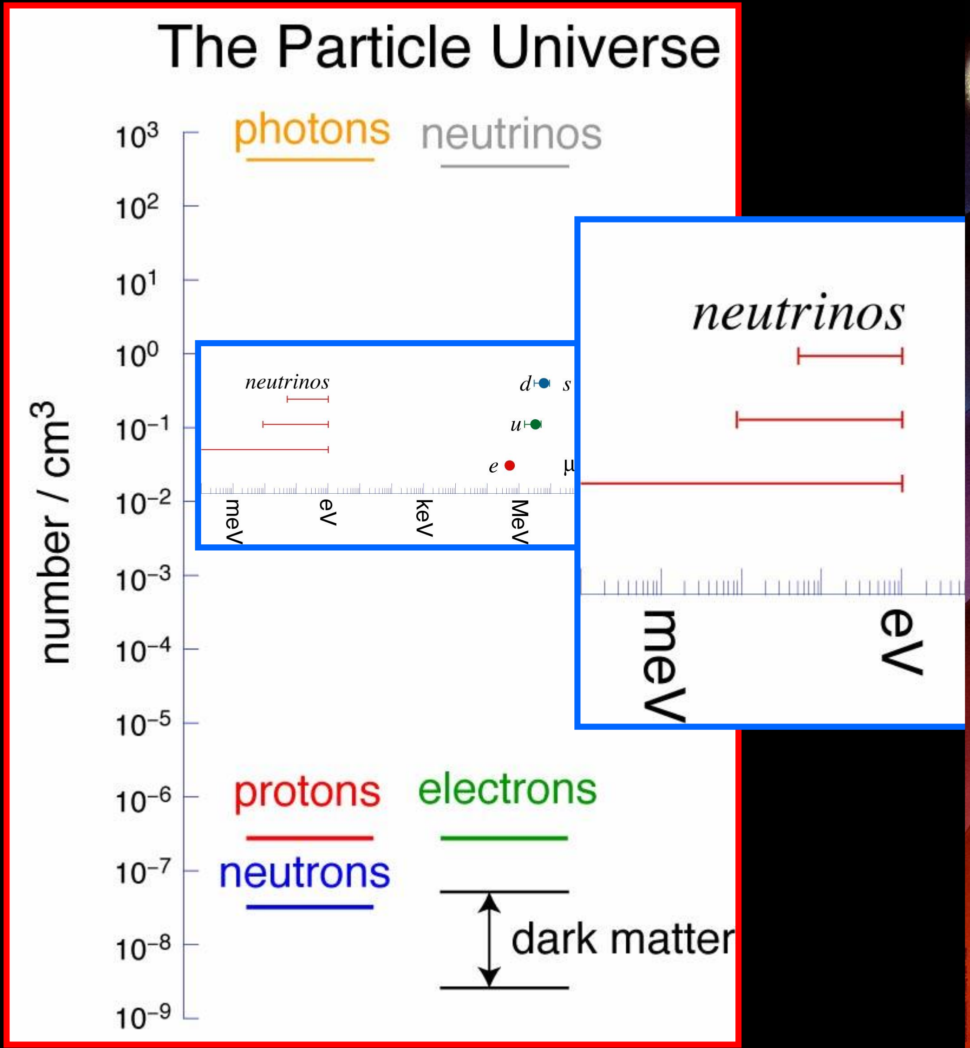
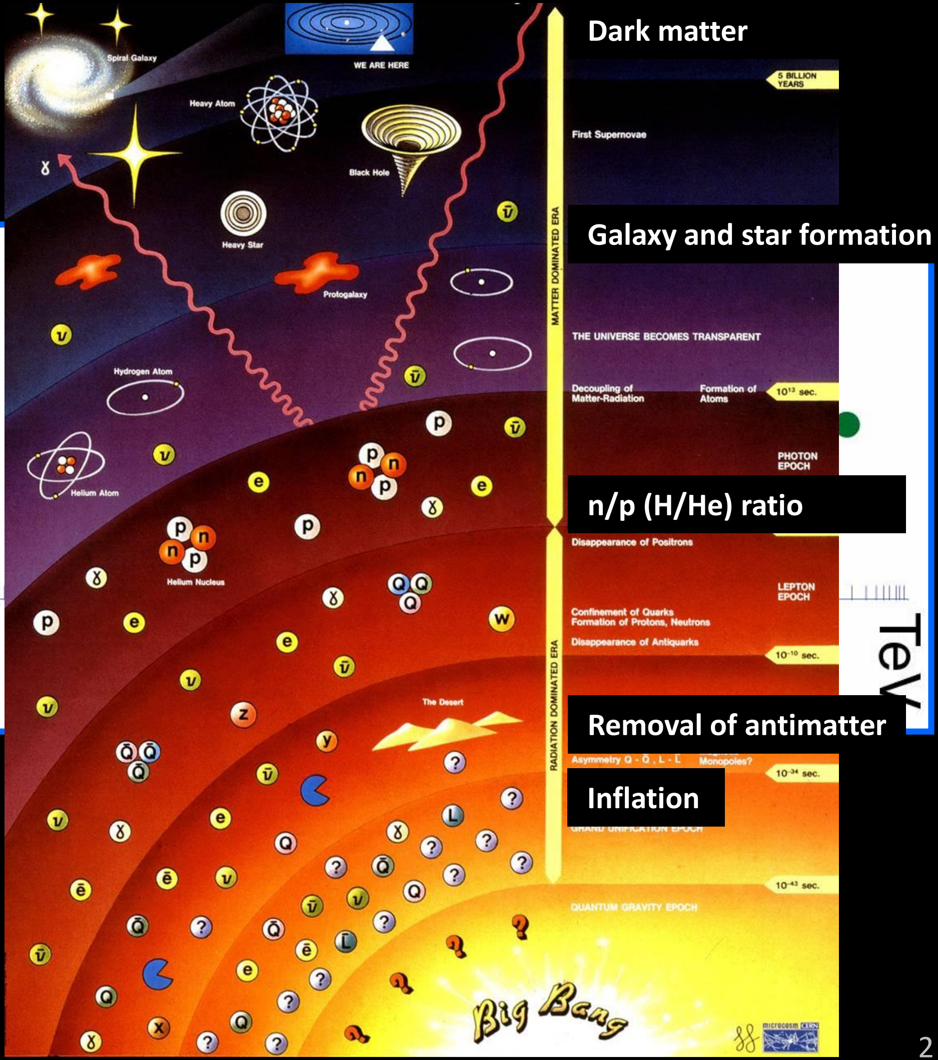
Opportunities in neutrino physics

K. Long, 18 December, 2017





Dark matter

Galaxy and star formation

n/p (H/He) ratio

Removal of antimatter

Inflation

Flavour

ν_e

ν_μ

ν_τ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathcal{U}_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

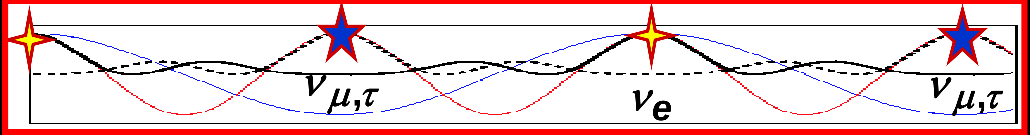
ν_1

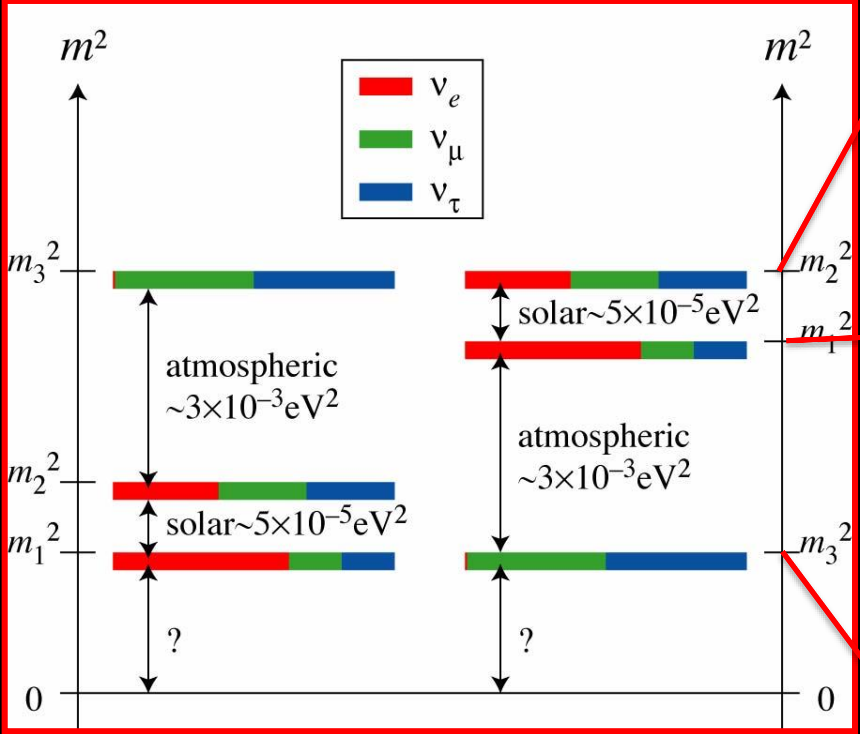
ν_2

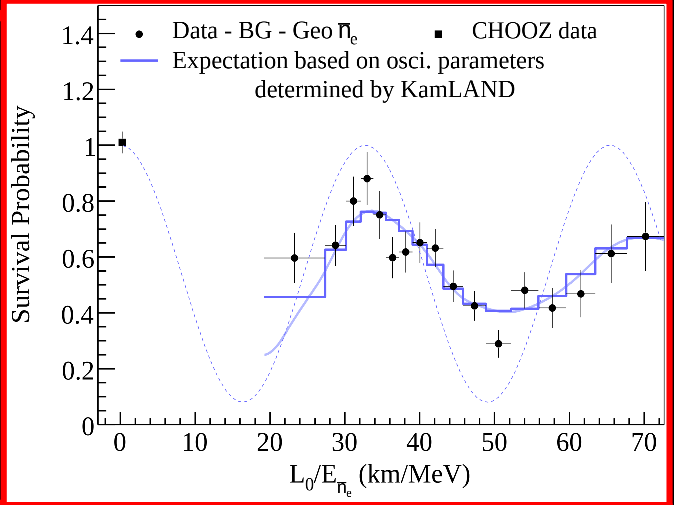
ν_3

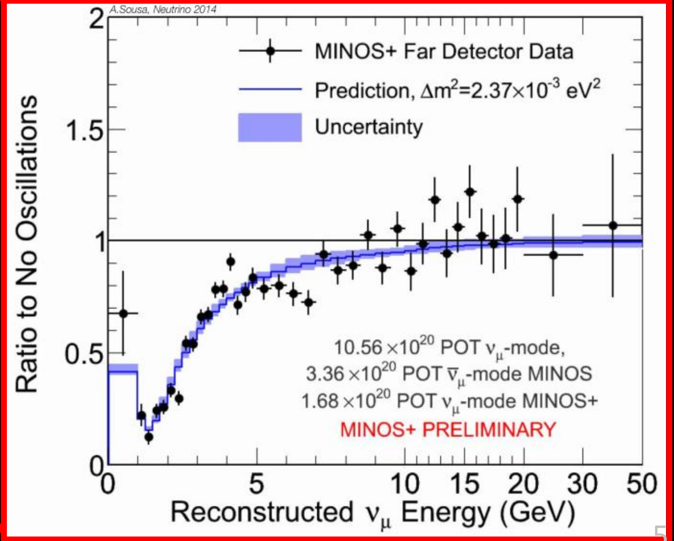
$$\mathcal{U}_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
$$\times \mathrm{diag}\left(1, e^{i\phi_1}, e^{i\phi_2}\right)$$

http://kamland.lbl.gov/FiguresPlots/; http://www-numi.fnal.gov/PublicInfo/forscientists.html









$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} \omega_{\alpha\beta}(\theta_{ij}, \delta, \cdots) e^{-i\frac{(m_i^2 - m_j^2)}{2}\frac{L}{E}}$$

Insensitive to mass scale

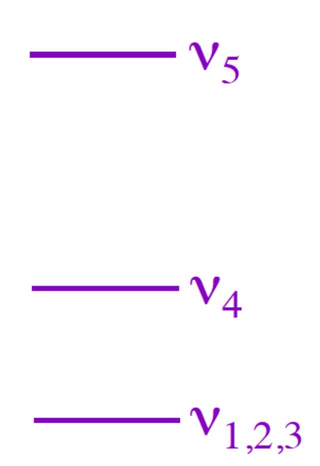
PRD 88 (2013) 073008

Anomalies; light-sterile neutrinos?

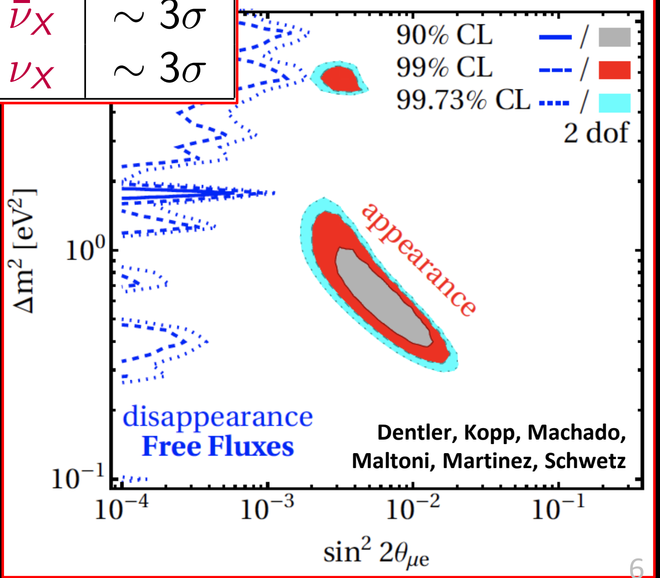
- Wide variety of data described by the 'SνM'
- Anomalous behaviour in a variety of channels:

Data inconsistent with SνM					
Appearance			Disappearance		
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\sim 4\sigma$	Reactor	$\bar{\nu}_e \to \bar{\nu}_X$	$\sim 3\sigma$
MiniBooNE	$\nu_\mu \to \nu_e$	$\lesssim 3\sigma$	Gallium	$\nu_e \to \nu_X$	$\sim 3\sigma$

Steriles



- Global analysis gives:
  - Consistent description of:
    - Appearance alone;
    - Disappearance alone
  - But:
    - Tension between appearance and disappearance



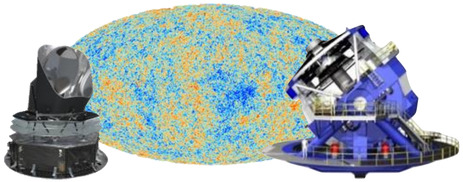
Neutrinos indicate SM is incomplete

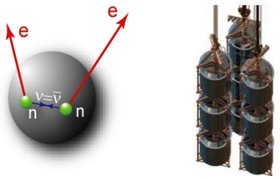
- Neutrino oscillations imply:
  - Neutrinos have mass; mass states mix to make flavour states
- Neutrino mass → new degrees of freedom:
  - Right-handed neutrinos or Majorana neutrinos
  - New interactions?
- Mixing among three neutrinos:
  - CP-invariance violation in lepton sector
  - Origin of matter-dominated Universe?
- Possible cosmological impact:
  - Inflation;
  - Galaxy and star formation;
  - Dark matter

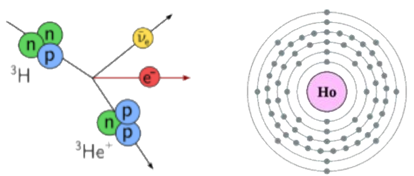
Opportunities in neutrino physics

MASS SCALE AND MAJORANA NATURE

Absolute Neutrino Mass scale







	Cosmology	Search for 0νββ	weak decays (β + EC)
Observable	! " = $ %& &	%)((= |$ *)+&%& & |)	%)(= $ |* +&|) %)& &
Present upper limit	0.17 – 0.72 eV	0.15 – 0.33 eV	2 eV
Potential	15 – 50 meV	15 – 50 meV	40 meV
Model dependence	Multi-parameter cosmological model	• Majorana ν: LNV • BSM contributions other than m(ν)? • nucl. matrix elements	Direct, only kinematics; no cancellations in incoherent sum

P.A.R. Ade et al., A&A **594** (2016) A13

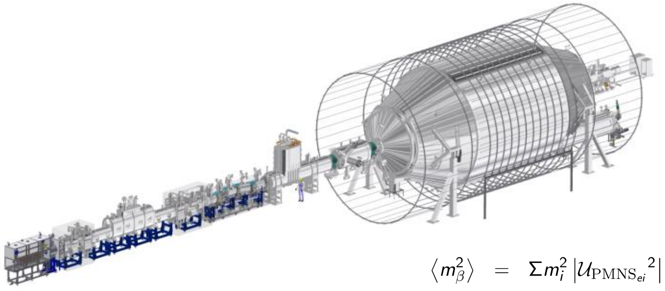
M. Agostini et al., Nature **544** (2017) 47-52

C. Kraus et al., EPJ-C **40** (2005) 447-468
V.N. Aseev et al., PRD **84** (2011) 112003
A.A. Esfahani et al., JP-G **44** (2017) 05400

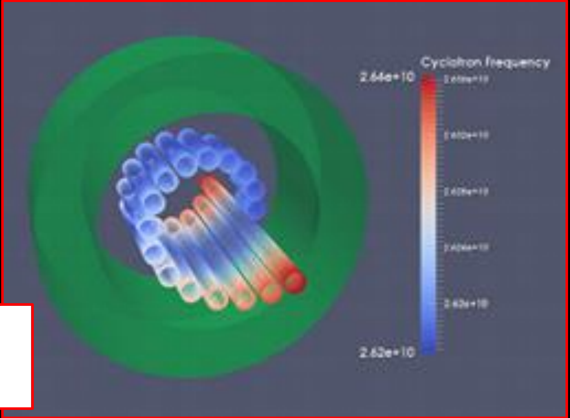
Mass scale

- **End-point measurements:**
  - Katrin (Karlsruhe Tritium Neutrino experiment):
    - "First light": Oct16
    - ^{83m}Kr measurement now
    - First tritium 2018
    - Goal $m_b < 0.2$ eV
  - Project 8:
    - Cyclotron radiation emission spectroscopy
    - In proof of principle phase
    - Goal $m_b < 0.04$ eV

http://www.katrin.kit.edu



$$\langle m_\beta^2 \rangle = \Sigma m_i^2 \left|\mathcal{U}_{\mathrm{PMNS}_{ei}}{}^2\right|$$

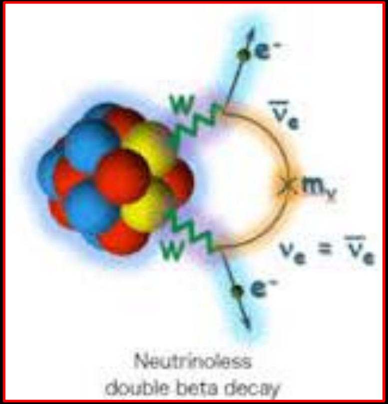


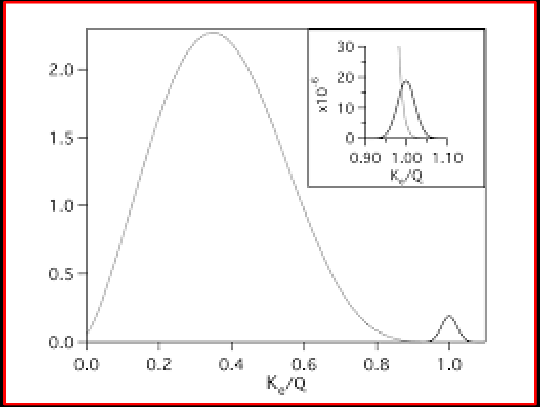
http://www.project8.org
arXiv:1703.02037

$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2},$$

Mass scale and Majorana nature

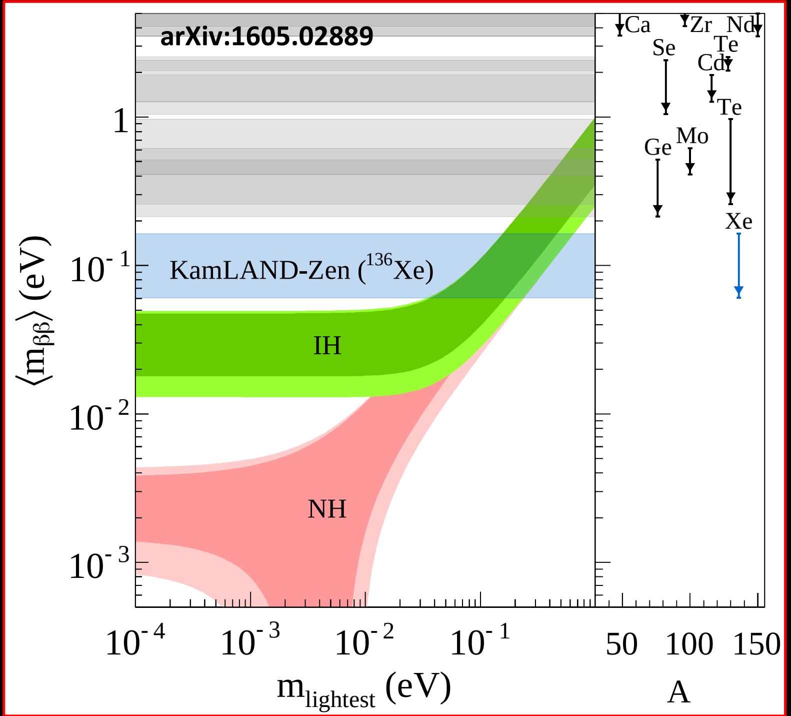
- Majorana neutrino "is its own antiparticle":
  - Removes one constraint on neutrino-mixing matrix:



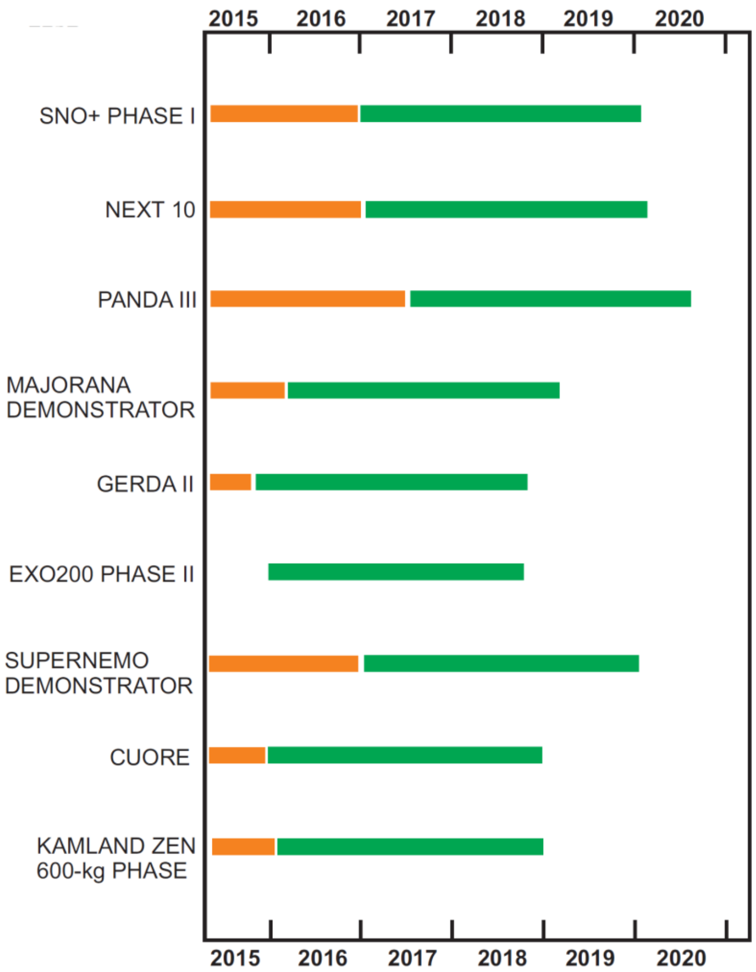


$$\mathcal{U}_{\mathrm{Majorana}} = \mathcal{U}_{\mathrm{PMNS}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_1} & 0 \\ 0 & 0 & e^{i\phi_2} \end{pmatrix}$$

$$\langle m_{\beta\beta} \rangle = \left| \Sigma m_i \left| \mathcal{U}_{\mathrm{PMNS}_{ei}}{}^2 \right| \epsilon_i \right|$$



Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved (10^{26} yr)	Location
CUORE	^{130}Te	206	>0.028	Gran Sasso
MAJORANA	^{76}Ge	24.8		SURF
GERDA	^{76}Ge	31	>0.21	Gran Sasso
EXO-200	^{136}Xe	79	>0.11	WIPP
NEXT	^{136}Xe	10→100		Canfranc
SuperNEMO	^{82}Se+	7	>0.001	Frejus
KamLAND-Zen	^{136}Xe	434	>0.19	Kamioka
SNO+	^{130}Te	160		SNOLAB
PANDAX-III	^{136}Xe	200		Jinping



Opportunities in neutrino physics

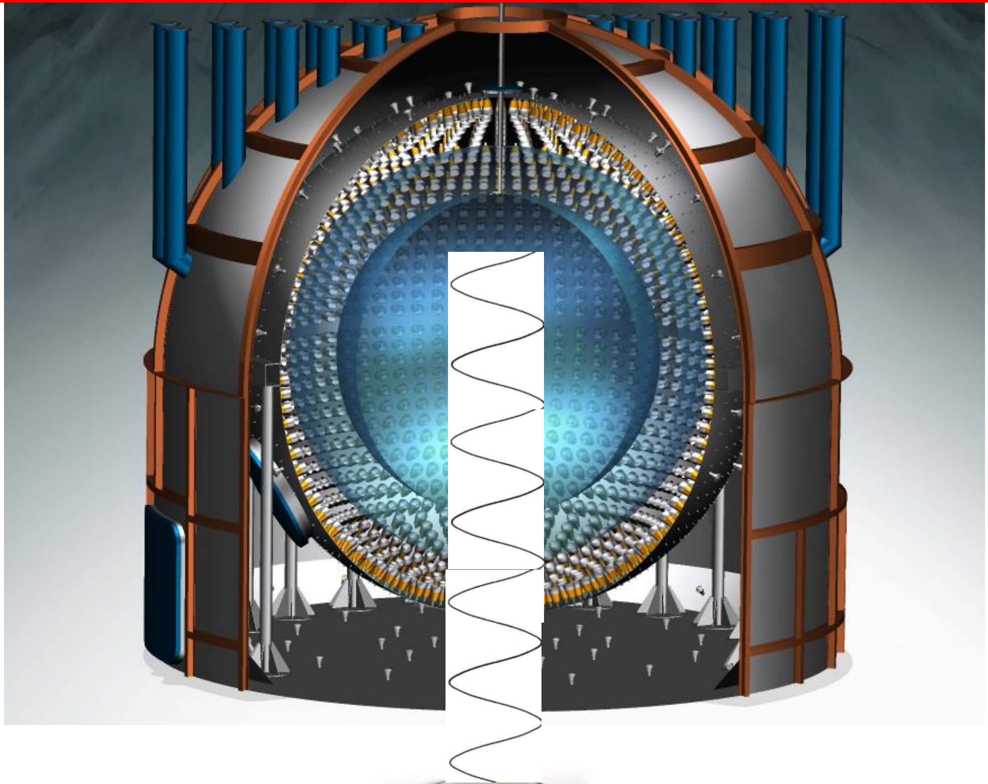
LIGHT STERILE NEUTRINOS

B. Fleming
ICFA Seminar

Light sterile neutrinos from source

SOX experiment
at Gran Sasso lab

Look for pattern of oscillations inside the Borexino Detector

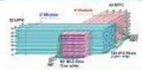
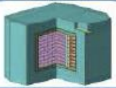
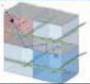


Anti electron neutrino source below the detector

Under Construction
Running 2018/2019

Sterile-neutrino searches at reactors

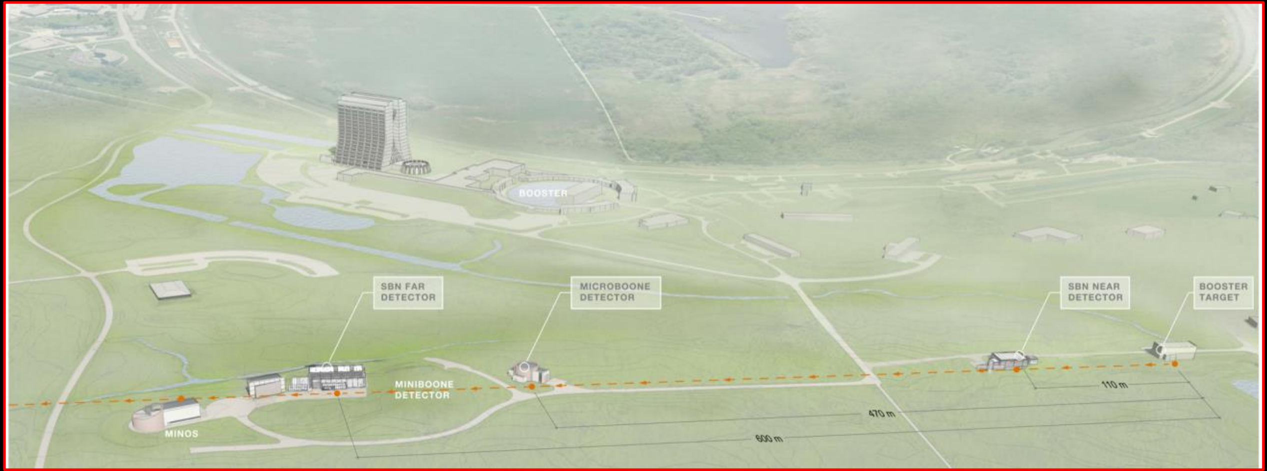
- **Re-evaluation of flux:**
  - "… not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos …" Giunti et al, arXiv:1704.02276

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

N. Bowden AAP 2016

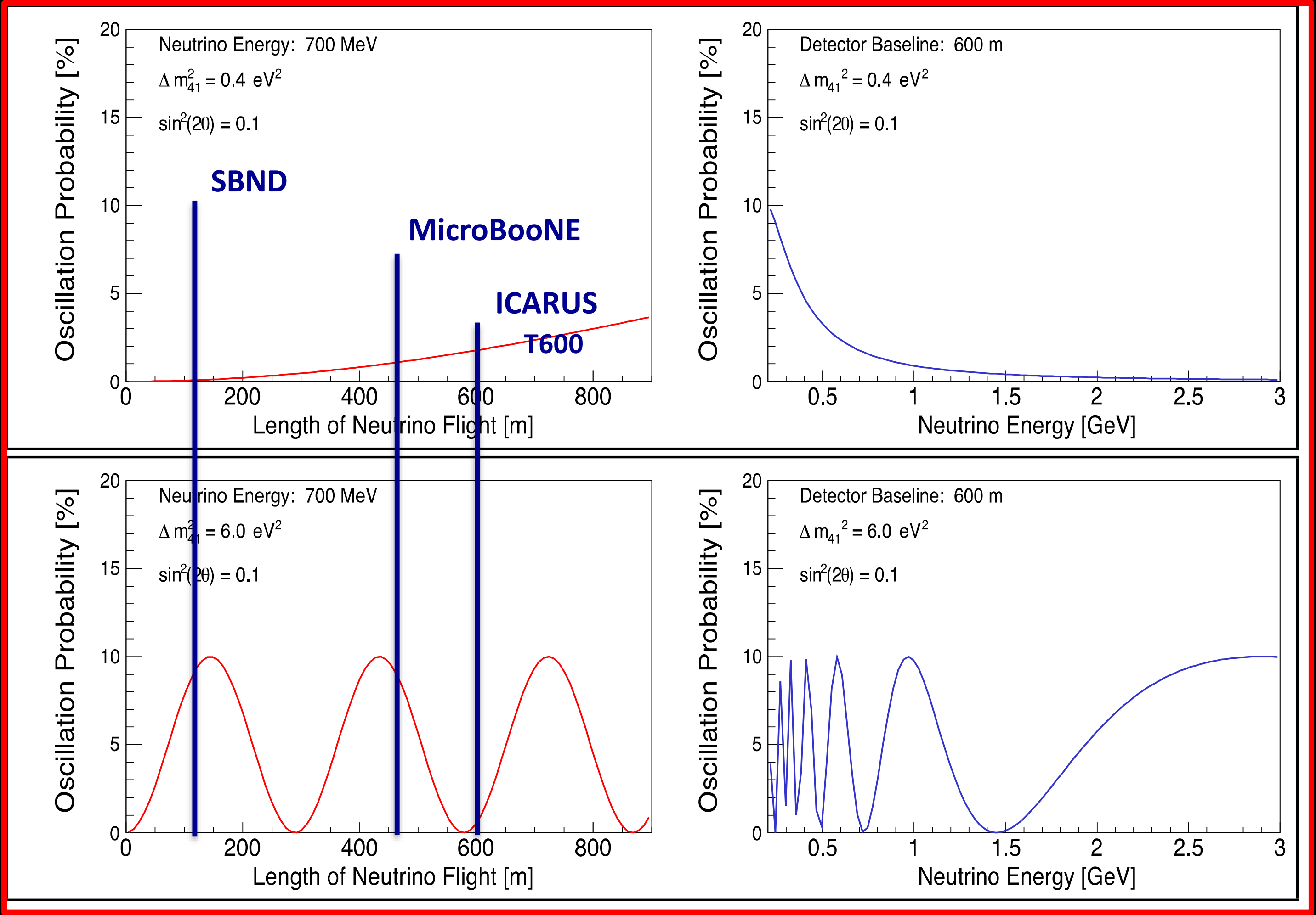
Short Baseline Neutrino programme

arXiv:1503.01520



- **Definitive search for $\Delta m^2 \sim 1\text{eV}^2$ sterile neutrinos:**
  - **Exploit *L*, *E* and *L*/*E* modulation; detectors at three baselines**
    - **Appearance, $\nu_\mu \rightarrow \nu_e$, *and*, disappearance, $\nu_\mu \rightarrow \nu_X$**
  - **Exploit 3 LAr detectors; minimise inter-detector systematics**
- **Robustly address backgrounds and uncertainties:**
  - **ν_e contamination in FNAL Booster Neutrino Beam**
  - **Photons produced by NC νN and cosmic rays**
  - **External ν interactions in earth or experimental hall**

arXiv:1503.01520

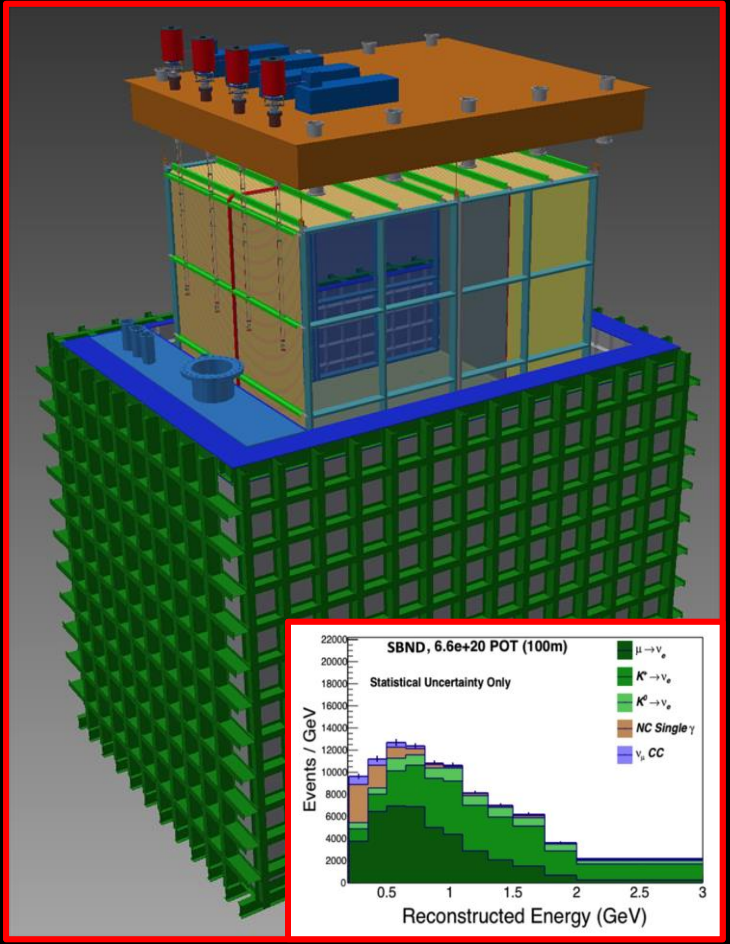


arXiv:1503.01520

Short Baseline Near Detector

- **275 T LAr TPC @ $L = 110$m**
  - Characterise beam before oscillation
  - Address many dominant systematic uncertainties

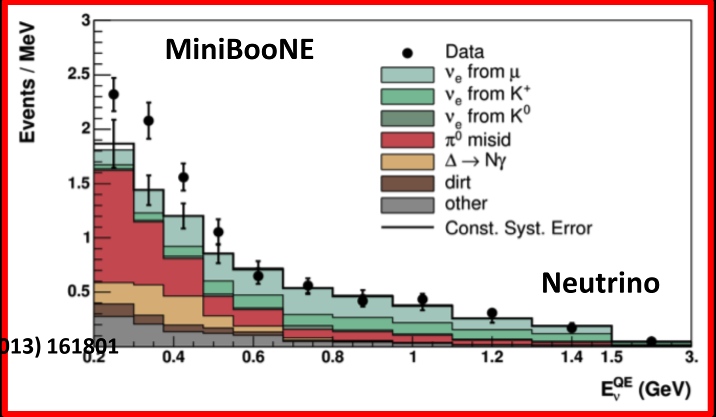
- **Neutrino scattering**
  - Total νN sample: ~7×10^6
    - From 6.6×10^{20} pot (~3 years)
  - Inclusive ν_e samples:
    - Charged current: ~37×10^3
    - Neutral current: ~14×10^3
  - High-statistics studies:
    - Cross sections
    - Final states

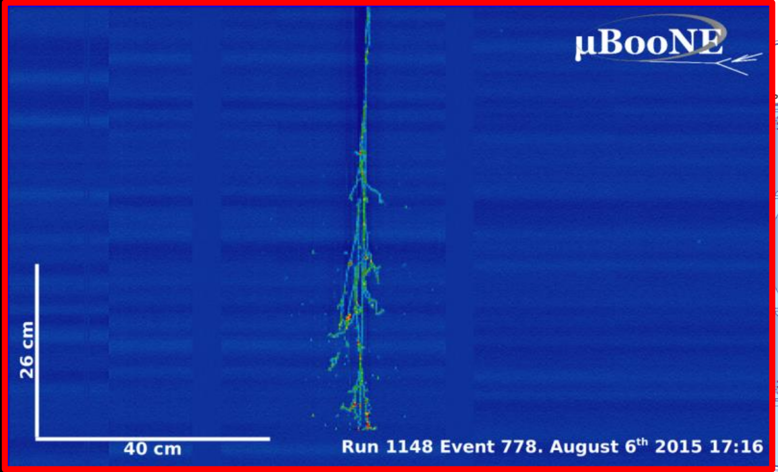


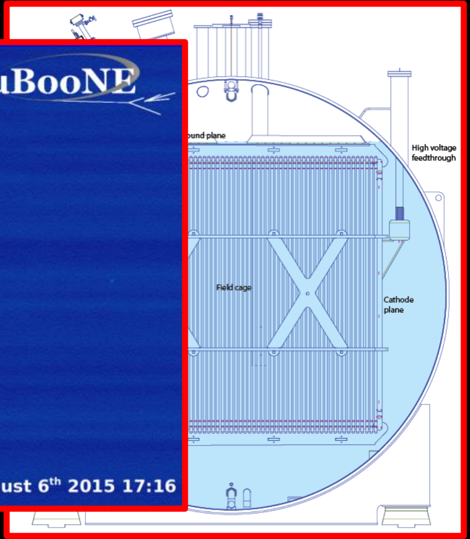
FERMILAB-PROPOSAL-0974

MicroBooNE

- 170 T LAr TPC @ $L = 470$
- Solo capabilities:
  - Investigate MiniBooNE low-energy ν_e excess;
  - Measure neutrino cross sections (BNB & NuMI)
  - LAr detector R&D
- Neutrino scattering
  - Total νN sample: $\sim 2.5 \times 10^5$
    - From 6.6×10^{20} pot (~3 years)
  - Inclusive ν_e samples:
    - Charged current: $\sim 1.5 \times 10^3$
    - Neutral current: $\sim 0.5 \times 10^3$
  - Further studies of:
    - Cross sections/final states



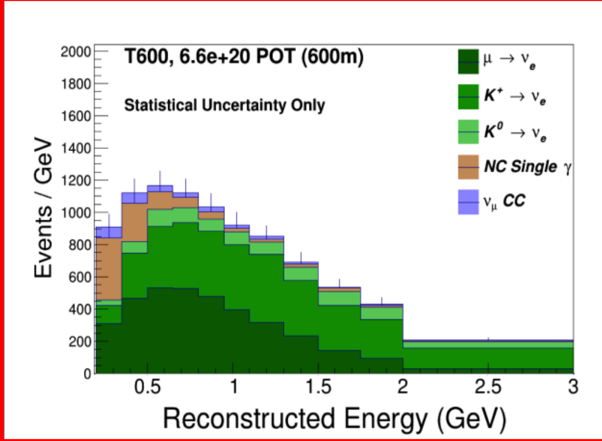




arXiv:1503.01520

ICARUS T600

- 760 T LAr TPC @ 600 m
  - Large mass gives good ν_e rate
- Exposed to:
  - Booster Neutrino Beam; and
  - Off-axis to NuMI beam
- Refurbishment; WA104:
  - Part of CERN Neutrino Platform programme
  - Both T300 modules transported from Gran Sasso to CERN
  - Refurbished and transported to FNAL
- Data taking 2018/19

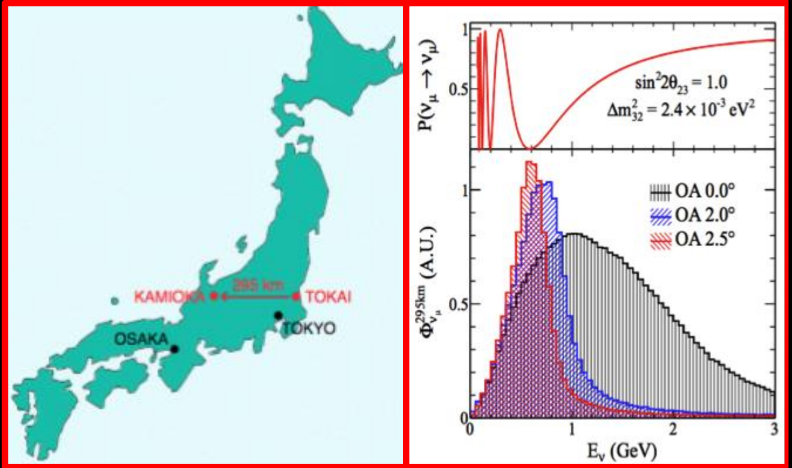


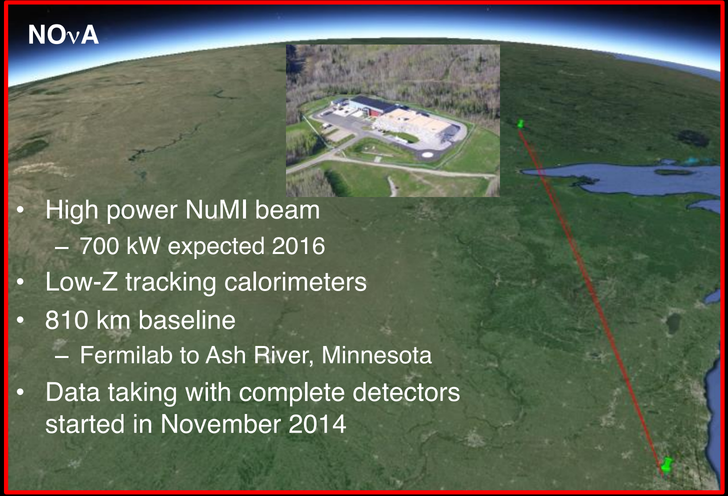
Opportunities in neutrino physics

NEUTRINO OSCILLATIONS

Long-baseline neutrino oscillation programme

- **Present/recent experiments:**
  - Europe: OPERA, ICARUS [complete]
  - Japan: T2K
  - US: MINOS, MINOS+ [in data analysis phase]
    NOvA
- **Near future:**
  - Japan: T2K-II, T2HK/T2HKK
  - US: DUNE

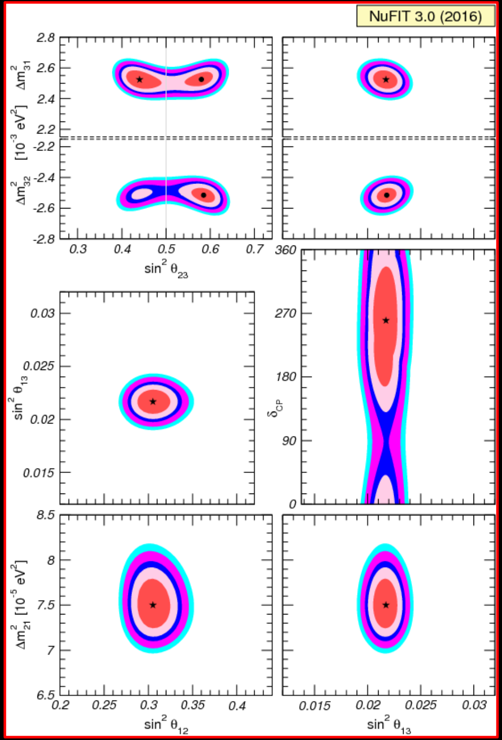


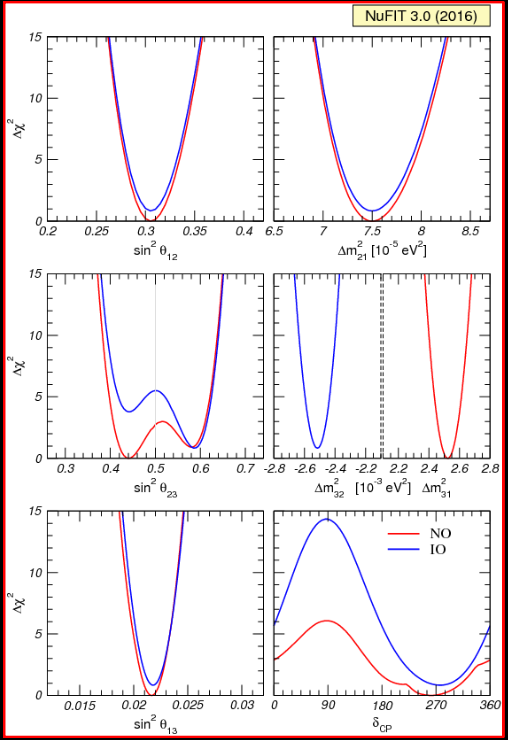


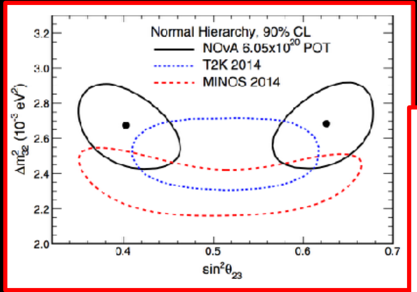
$$\mathcal{U}_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

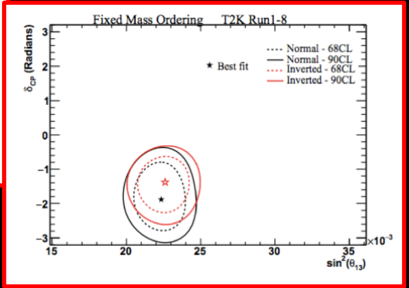
State of the art

- **Summer 2017:**
  - **NOvA:**
    - $\theta_{23} \neq 45^o$ at 2.6σ
  - **T2K:**
    - CP conservsation excluded at $\gtrsim 2\sigma$









Interesting "preference" for δ_{CP} ~ 270^o

Esteban+ 1611.01514, JHEP 1701 (2017) 087
See also: Capozzi+ 1601.07777, NPB 908 (2016) 218
Forero+ 1405.7540, PRD90 (2014) 093006

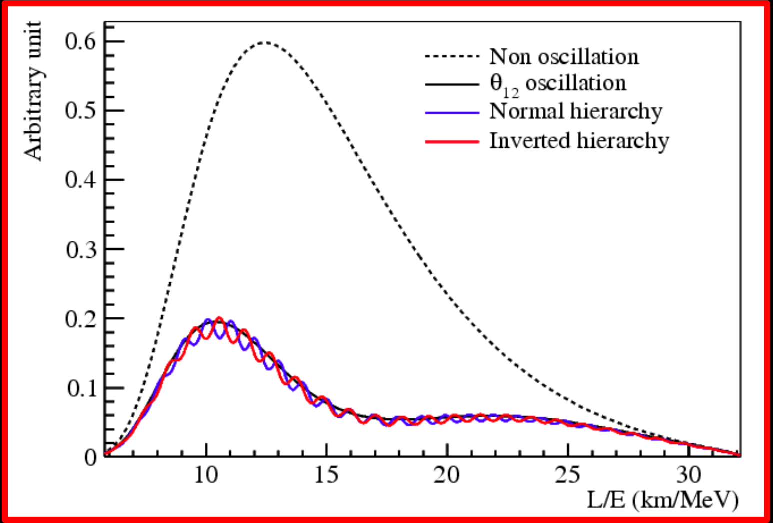
What we need to know:

- **Do neutrino oscillations violate the CP symmetry?**
- **Ordering of neutrino mass eigenstates and neutrino mass scale**
- **Empirical relationships between ν-mixing parameters ...**
  or between ν- and *q*-mixing parameters
- **Dirac or Majorana?**
- **Anomalies (aka hints for sterile neutrinos):**
  statistical fluctuations, systematic effects or indications of new physics?

Impact: particle physics, astroparticle physics, cosmology, ...

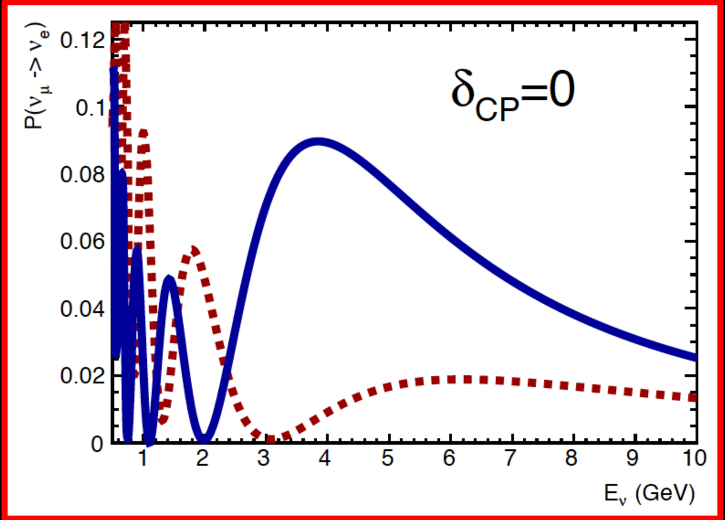
Mass hierarchy: two options

- **Exploit *L/E* spectrum:**

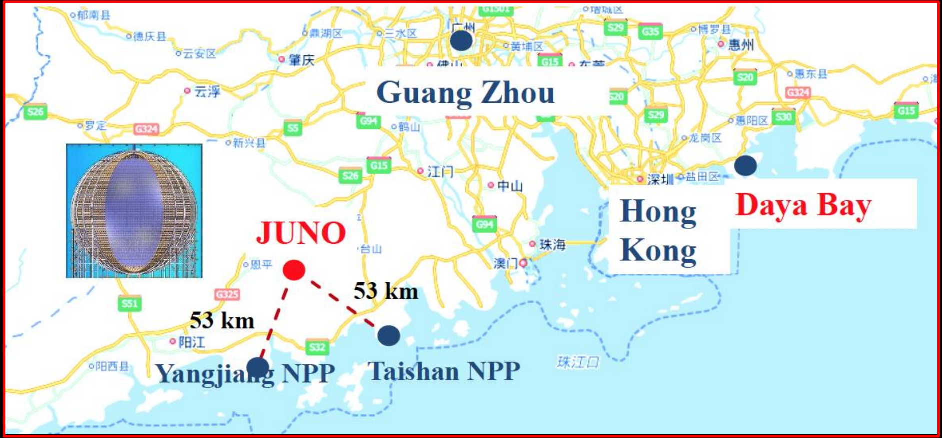


- **JUNO:**
  - Reactor-neutrino exp[t]
  - 20 kton liquid-scintillator
    - 3%/√*E* energy resolution
  - Under contruction

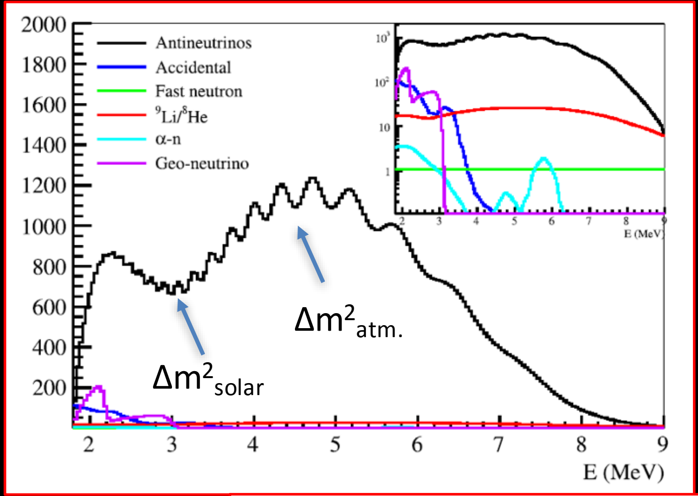
- **Exploit matter effect:**
  - Electron-neutrino may undergo charge-exchange with atomic electron
  - Modifies oscillation probability
  - Large source-detector distance



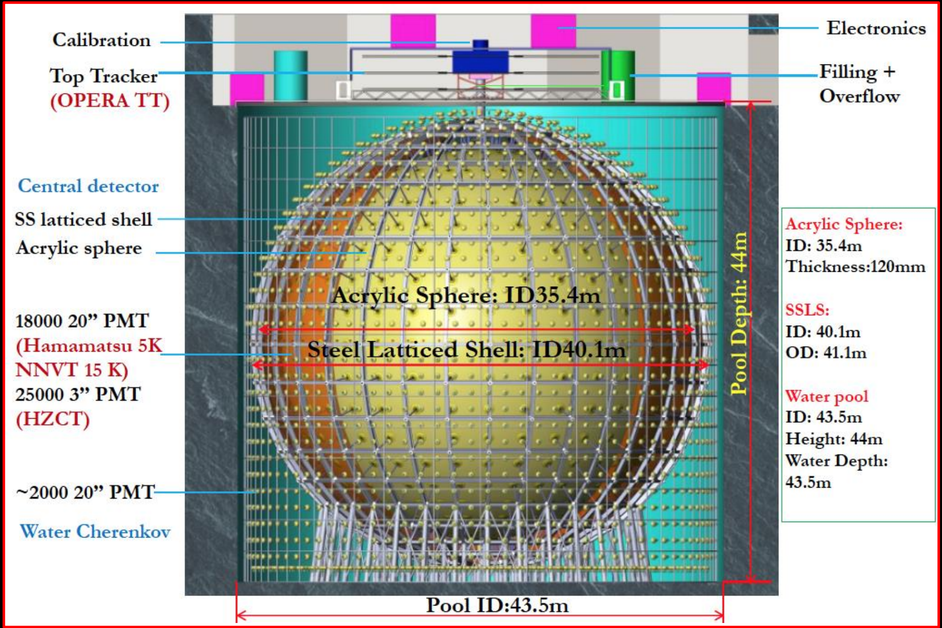
JUNO



Guang Zhou
Hong Kong
Daya Bay
JUNO
53 km
53 km
Yangjiang NPP
Taishan NPP

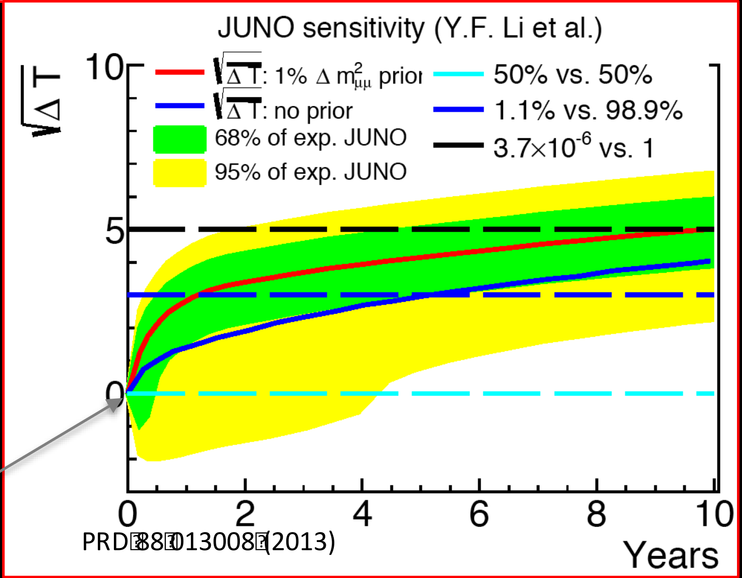


Antineutrinos
Accidental
Fast neutron
^{9}Li/^{8}He
α-n
Geo-neutrino
$\Delta m^2_{atm.}$
Δm^2_{solar}
E (MeV)



Calibration
Electronics
Top Tracker
(OPERA TT)
Filling +
Overflow
Central detector
SS latticed shell
Acrylic sphere
18000 20" PMT
(Hamamatsu 5K
NNVT 15 K)
25000 3" PMT
(HZCT)
~2000 20" PMT
Water Cherenkov
Acrylic Sphere: ID35.4m
Steel Latticed Shell: ID40.1m
Pool Depth: 44m
Pool ID:43.5m
Acrylic Sphere:
ID: 35.4m
Thickness:120mm
SSLS:
ID: 40.1m
OD: 41.1m
Water pool
ID: 43.5m
Height: 44m
Water Depth:
43.5m

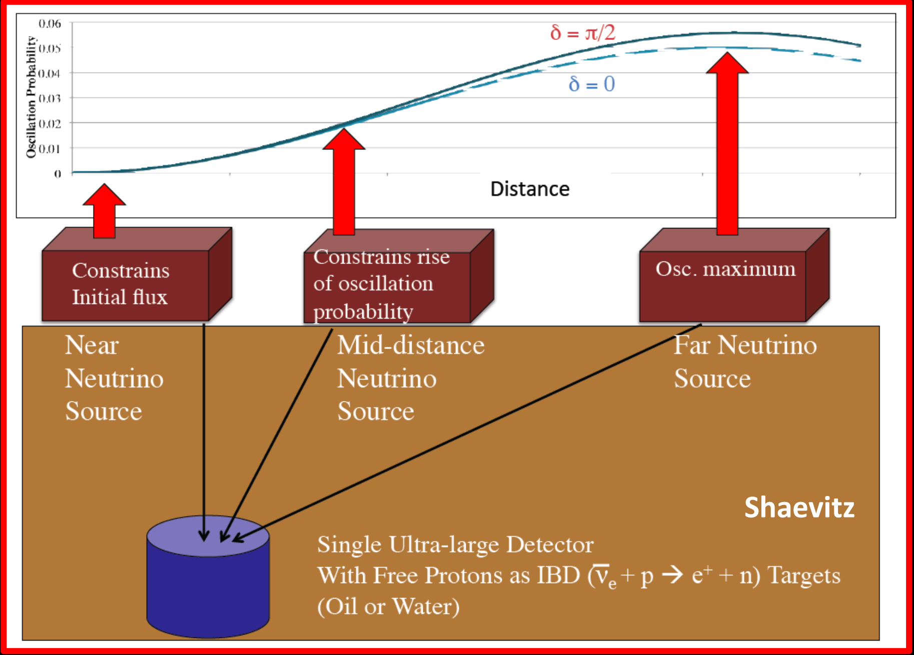
2020



JUNO sensitivity (Y.F. Li et al.)
$\sqrt{\Delta T}$: 1% $\Delta m^2_{\mu\mu}$ prior
$\sqrt{\Delta T}$: no prior
68% of exp. JUNO
95% of exp. JUNO
50% vs. 50%
1.1% vs. 98.9%
3.7×10^{-6} vs. 1
$\sqrt{\Delta T}$
Years
PRD 88 013008 (2013)

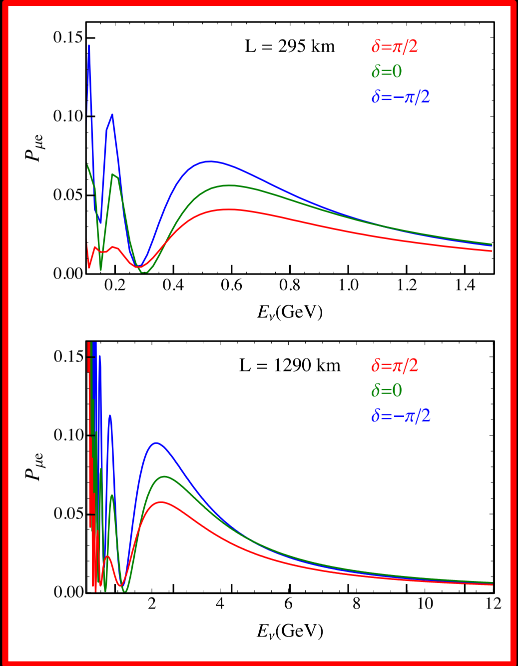
CP-invariance violation: two options

- **Exploit *L/E* spectrum:**
  - DAEδALUS



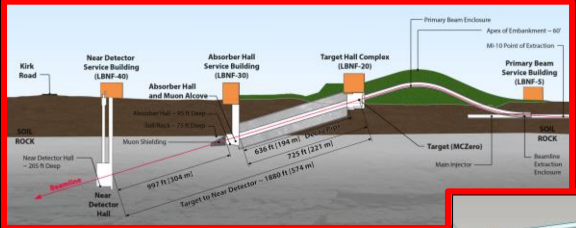
- **Measure asymmetry:**

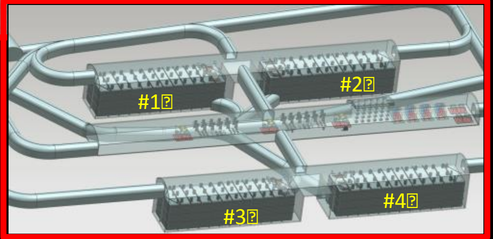
$$\frac{P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)}{P(\nu_\alpha \rightarrow \nu_\beta) + P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$



Next generation experiments

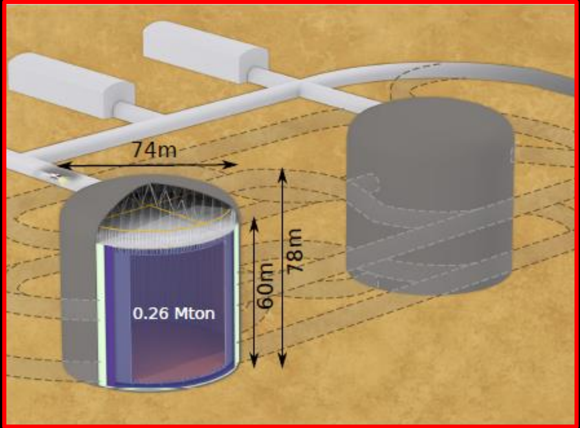
- **DUNE**
  - New beam from FNAL
    - Horn-focused, wide-band beam
    - Peak in $E_\nu \sim 3$ GeV; matched to 1300 km baseline
  - Modular, 40 kton LAr





"Bubble-chamber quality" measurement

- **Hyper-K(K)**
  - Upgrade to J-PARC beam
    - Off-axis, narrow band
  - Two 260 kton H_2O Cherenkov
    - Considering second tank in Korea (>1000 km)



The importance of the near detector

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

- Seek to extract P_{osc}
- Near detector:
  - Unoscillated estimates of flux and cross section
- Test beam exposures:
  - Map *P*(*E*|*E'*)
- But, imperfect cancellation of:
  - Cross sections as a function of *E':*
    - Near and far species are not identical
  - Flux as a function of *E'*:
    - Sampling of neutrino beam not identical near and far
  - *P*(*E*|*E'*) not necessarily the same near and far

Getting all this right requires an industry!

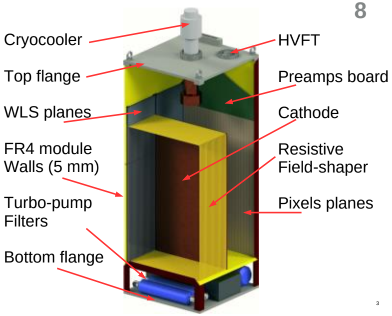
J.M. Albo
EPS-HEP 2017

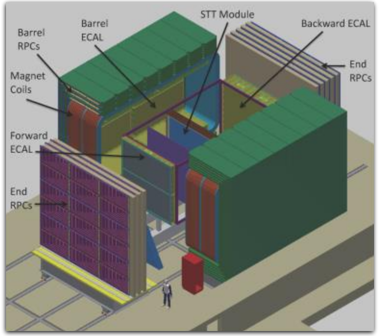
Near detector concepts

- **DUNE:**

DUNE NEAR DETECTOR

- ND has fundamental role for LBL physics, constraining systematic uncertainties through the measurement of neutrino flux and interaction cross sections.
- It will record largest sample of neutrino interactions ever collected.
- Also sensitive to new physics (e.g. heavy sterile neutrinos).
- DUNE ND currently under design. Conceptual design ready by 2018.
- It will likely feature a modular liquid argon TPC and a magnetised, high-resolution tracker.

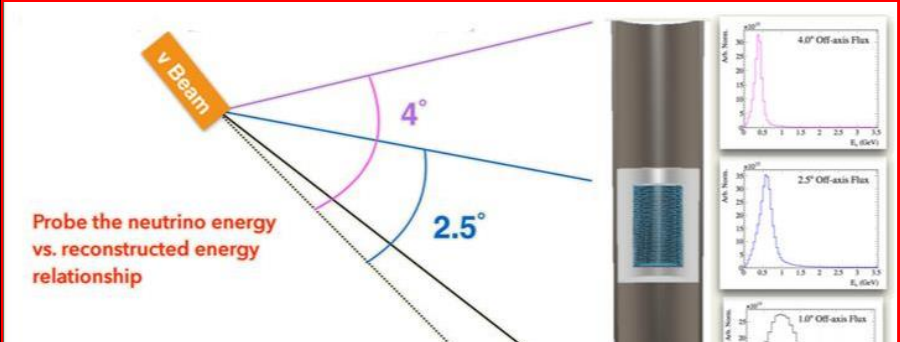




- **Hyper-K**

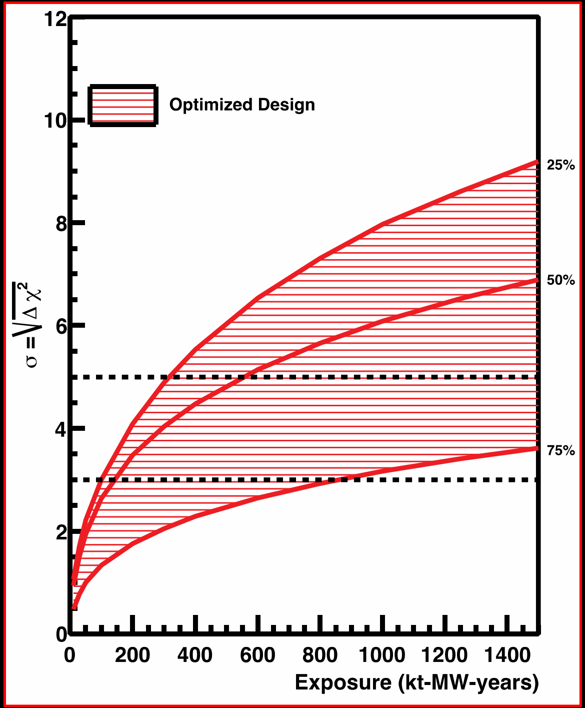
B. Richards
EPS-HEP 2017

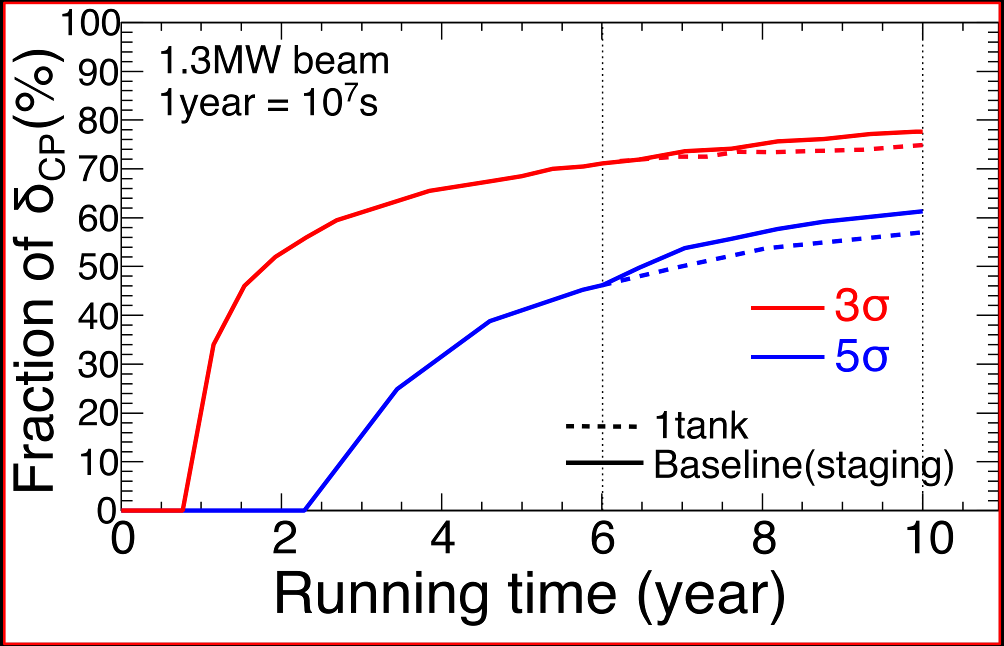
ND280 to continue For Hyper-K



1.2 km, 'intermediate' detector under consideration

Sensitivity to CPiV





- **DUNE and Hyper-K alone:**
  - **5σ sensitivity over >50% of all values of δ_{CP} after 10 yrs**
- **Combined—sensitivity enhanced**

Opportunities in neutrino physics

SUPPORTING PROGRAMME

S. Bordoni
EPS-HEP 2017

CERN Neutrino Platform

- **Goal:**
  - **"Support European efforts in neutrino experiments in the US and Japan"**

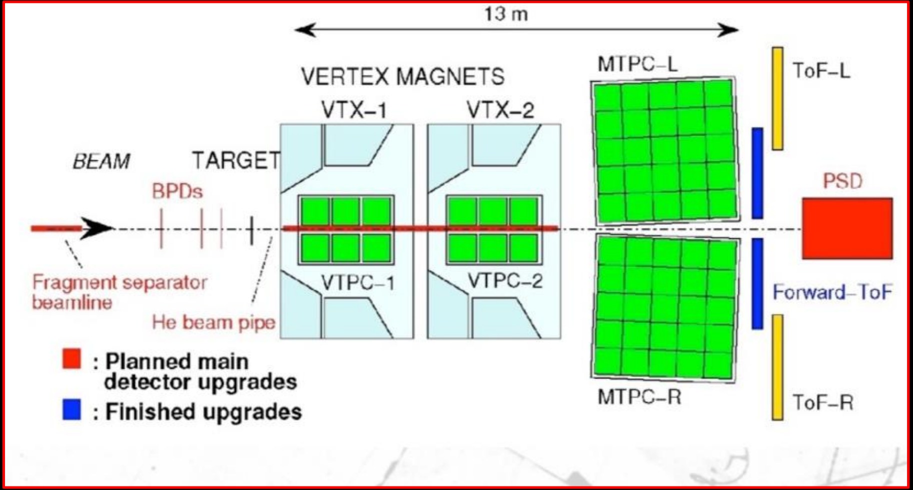
- **NP01** (WA104/ICARUS) : far detector for the US Short Baseline program
- **NP02** (protoDUNE-DP WA105): demonstrator + engineering prototype for a Double phase (LAr+GAr) TPC
- **NP04** (protoDUNE-SP): engineering prototype for a LAr TPC
- **NP05** (Baby MIND): a magnetised muon spectrometer for the WAGASCI experiment in Japan

\+

- **NP03:** generic R&D framework
- ArgonCUBE: R&D for a modular (magnetised) LAr TPC

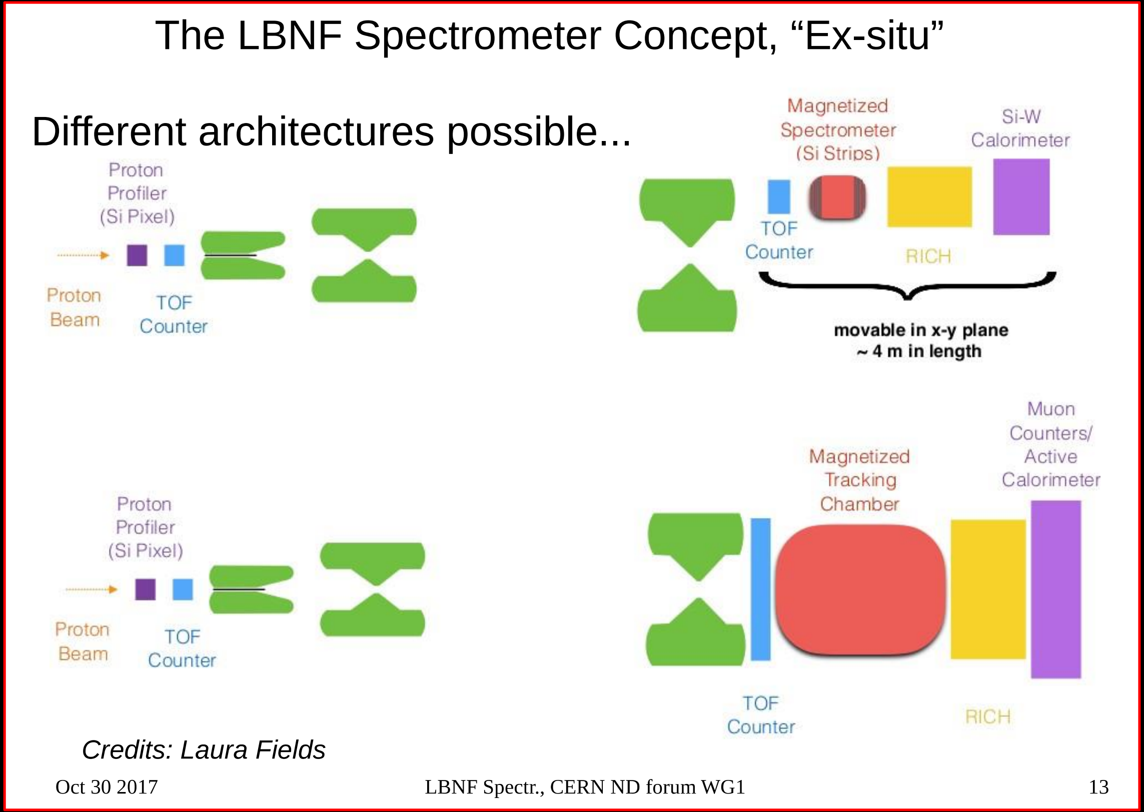
Hadroproduction to predict neutrino flux

- **NA61/SHINE:**
  - Proton and ion beams from the SPS
  - Thin target:
    - Absolute hadroproduction spectra
  - Thick target:
    - Replica of ν-production target
      - Includes effect of re-interactions of particles.

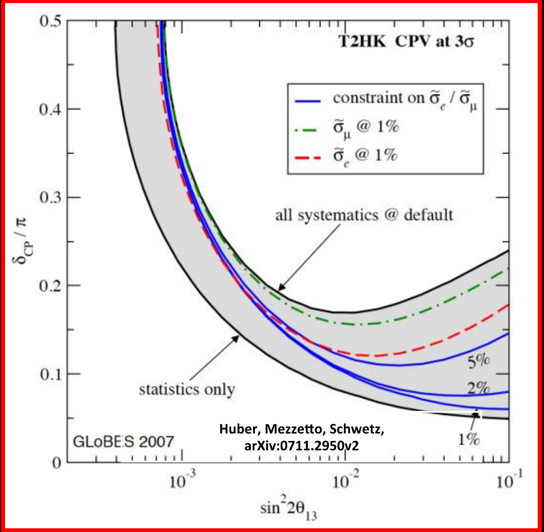


Hadron spectra “ex-situ”

- **DUNE considering instrumenting replica neutrino target and capture:**

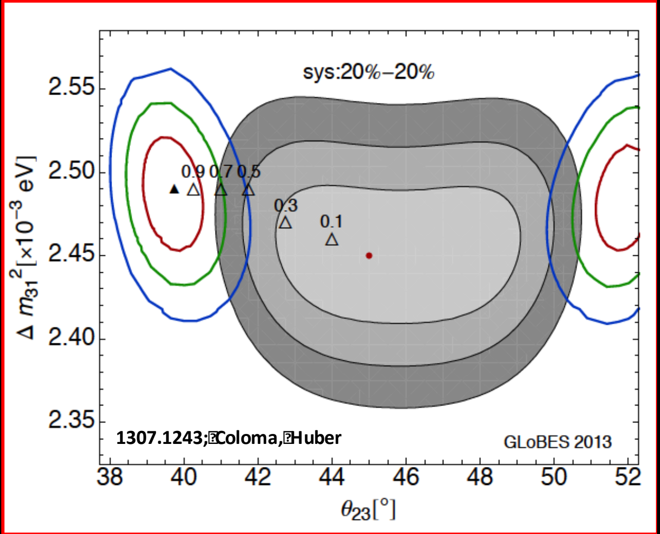


Systematic uncertainty and/or bias

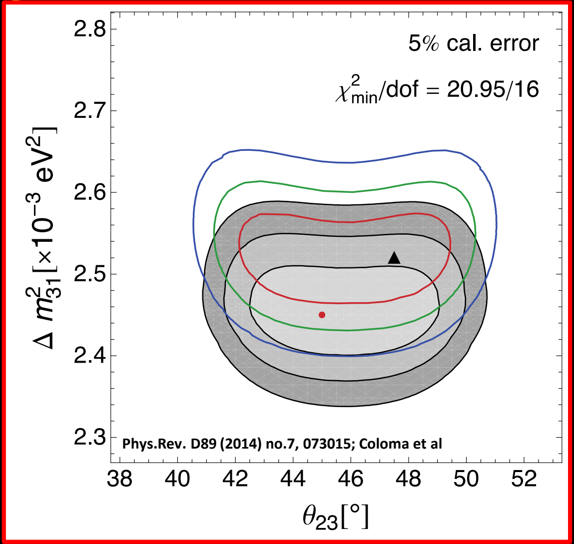


Uncertainty

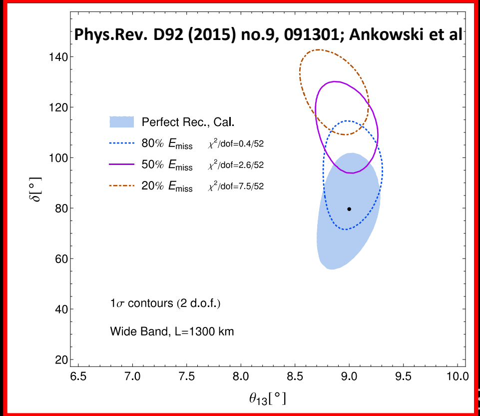
(cross section and ratio)



Event mis-classification

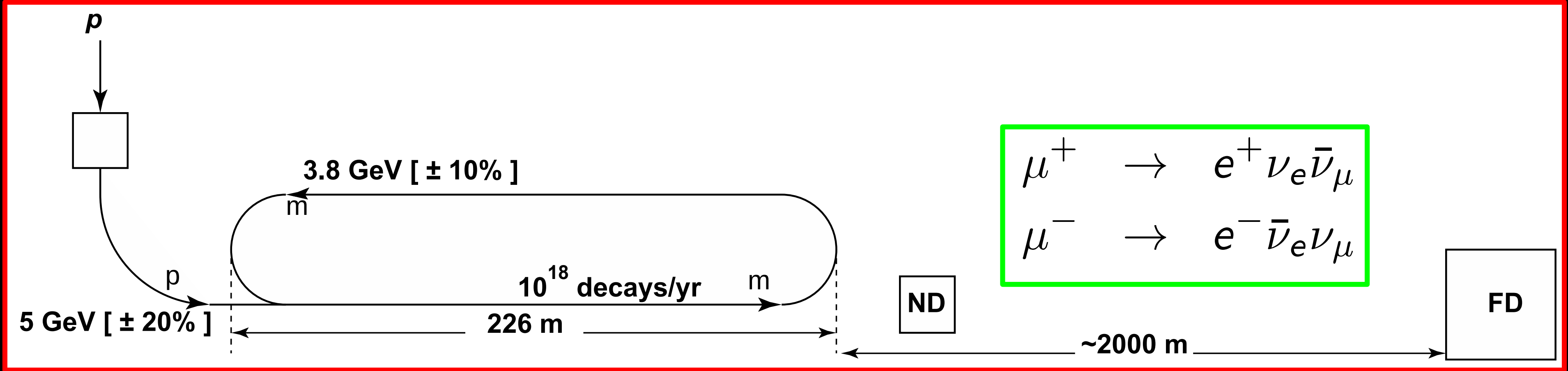


Energy scale mis-calibration



Missing energy (neutrons)

Neutrinos from stored muons

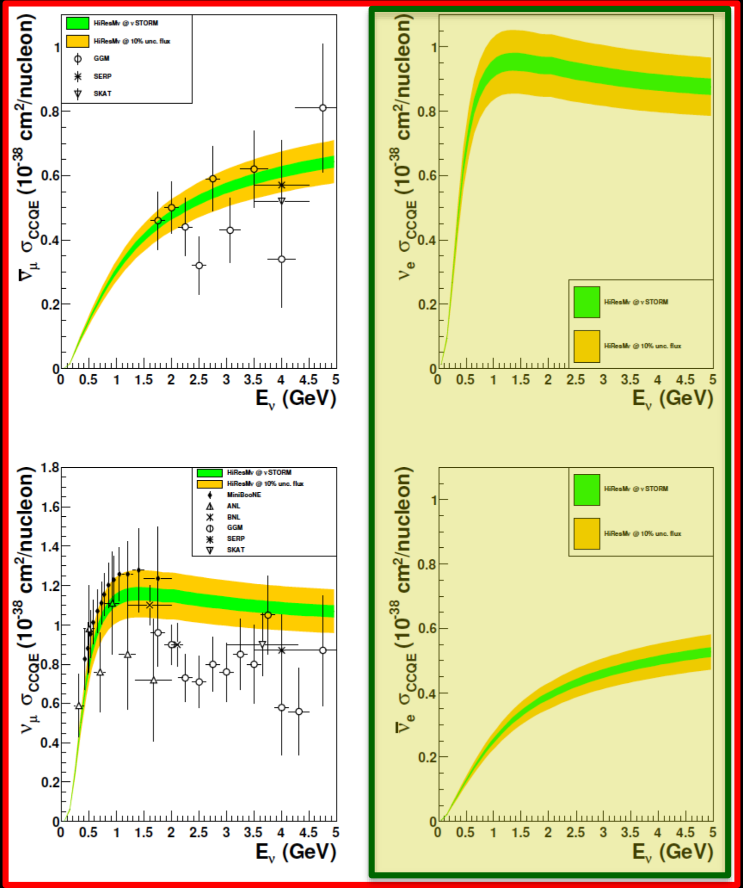


- **Scientific objectives:**
  1. %-level ($\nu_e N$) cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN

- Precise neutrino flux:
  - Normalisation: < 1%
  - Energy (and flavour) precise
- π → ↗ injection pass:
  - "Flash" of muon neutrinos

CCQE measurement at nuSTORM

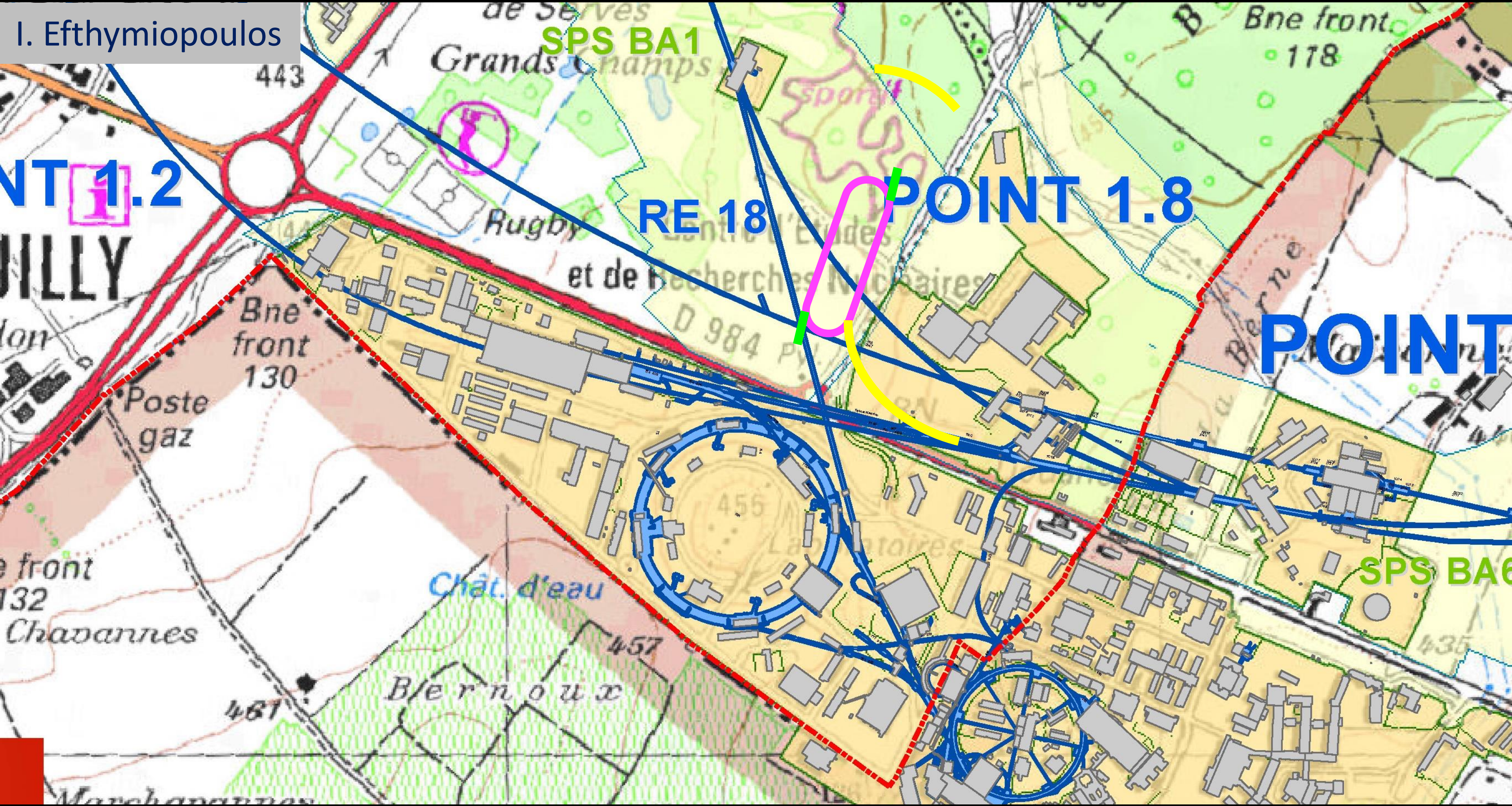
- CCQE at nuSTORM:
  - Six-fold improvement in systematic uncertainty compared with "state of the art"
  - Electron-neutrino cross section measurement unique
- Require to demonstrate:
  - ~<1% precision on flux



Individual $ν_e$ measurements from T2K and MINERvA [10.1103/PhysRevLett.113.241803, 10.1103/PhysRevLett.116.081802]

10.1103/PhysRevD.89.071301; arXiv:1305.1419

I. Efthymiopoulos



Opportunities in neutrino physics

TESTING THE PARADIGM

What we need to know:

- Do neutrino oscillations violate the CP symmetry?
- Ordering of neutrino mass eigenstates and neutrino mass scale
- Empirical relationships between n-mixing parameters ... ??
  or between n- and q-mixing parameters
- Dirac or Majorana?
- Anomalies (aka hints for sterile neutrinos):
  statistical fluctuations, systematic effects or indications of new physics?

Impact: particle physics, astroparticle physics, cosmology, ...

6

Taking stock

- CPiV:
  - T2K/NOvA, T2K-II, HK/DUNE
- Mass ordering:
  - SK, NOvA, JUNO, HKK/DUNE, ORCA, PINGU
- Empirical relationships?
  - Requires sensitivity and precision
- Dirac or Majorana:
  - KamLand-ZEN, …
- Anomalies:
  - SBND, reactor-neutrino experiments, long-baseline neutrino experiments

- **Pursuing understanding requires:**
  - **Novel, high-resolution detectors**
  - **Novel beams with known flux and energy spectrum**

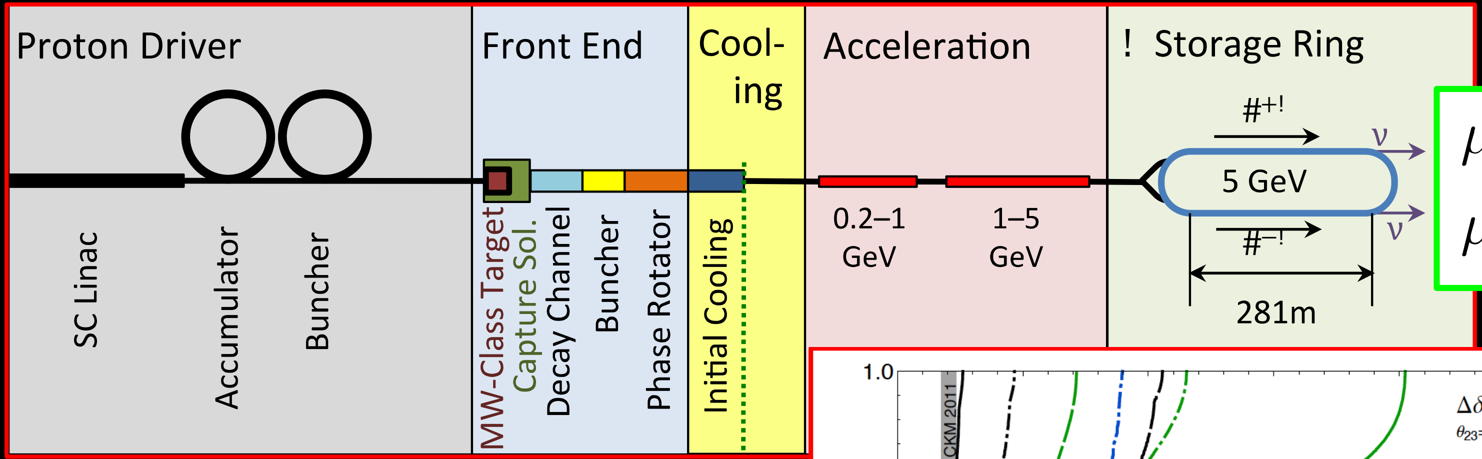
The potential of muon beams, pros and cons

- Muon beams have the potential to:
  - Revolutionise the study of the neutrino
  - Provide a route to multi-TeV lepton-antilepton annihilation

- Unique potential arises because:
  - Heavy: $200\, m_e < m_\mu < 0.1\, m_p$
    - Enormous (5×10^{-10} cf e) reduction in beam-/bremsstrahlung
    - Enhanced (5×10^{4} cf e^+e^-) s-channel coupling to Higgs
  - Decay: lifetime at rest 2.2 μs
    - ν_e, ν_μ – 50/50
    - Precisely known energy spectrum

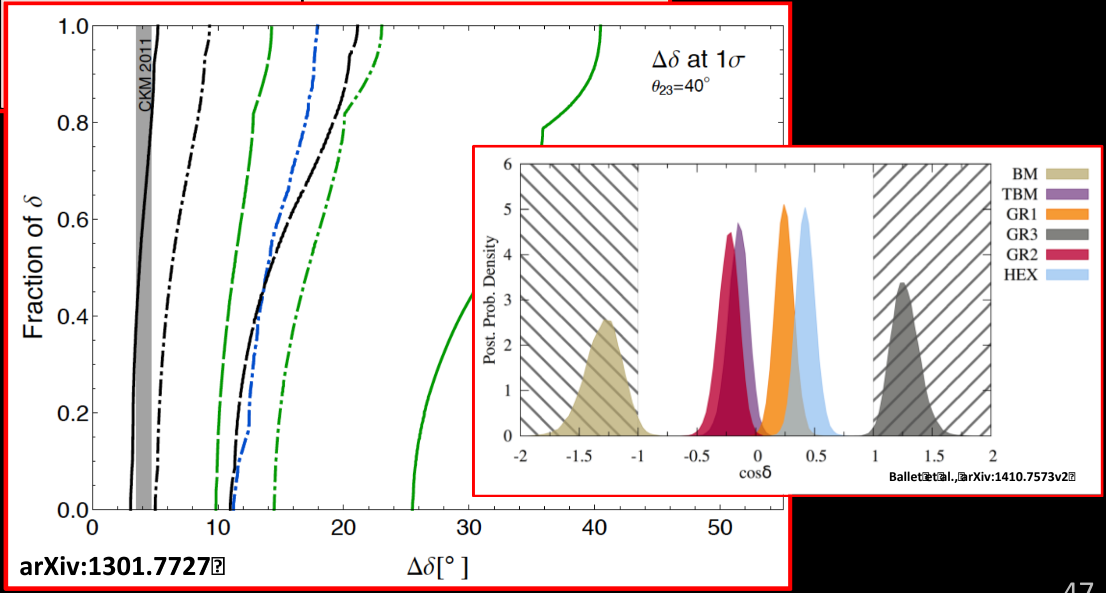
- Challenges:
  - Tertiary beam
  - Decay: lifetime at rest 2.2 μs

Neutrino Factory: sensitivity & precision



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- **Unique:**
  - **Large, high-energy ν_e ($\bar{\nu}_e$) flux**
    - ***Muon-beam cooling***
  - **Favourable rigidity:**
    - **Optimise *E* for given *L***



Opportunities in neutrino physics

CONCLUSIONS

Conclusions

- Neutrino oscillations imply that "new physics" exists:
  - The study of the neutrino is the study of physics beyond the Standard Model
  - Just starting; much to measure, still more to learn

- Opportunities in neutrino physics:
  - The flagship programmes:
    - DUNE and Hyper-K
      - Particularly the critical near detectors that are not yet defined
    - Sterile neutrino searches:
      - Accelerator based, at FNAL SBN
      - Many opportunities at reactors and sources
  - Supporting programmes:
    - Drive advances in detector and accelerator technologies; CENF
    - Measurement of hadroproduction spectra
    - Measurement of neutrino cross sections—especially ν_eN at nuSTORM at CERN

- Neutrino physics programme will remain important for a long time to come!