Working Group 5 Summary
“Beyond PMNS”

WG Conveners
Richard Efrain Ruiz (Université catholique de Louvain, Belgium)
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Carsten Rott (Sungkyunkwan University, Korea)

THE 21ST INTERNATIONAL WORKSHOP ON NEUTRINOS FROM ACCELERATORS
August 26 - August 31, 2019
The Grand Hotel, Daegu, KOREA

Intro

- In total had 24 talks in the parallel sessions including 4 talks in the joined session with WG1
- In this summary
  - Main focus on talks and topics not already covered as part of plenary talks
  - Order does not reflect order of talks in the parallel session, but grouping of topics and synergy

Tuesday 27/08

Schedule

Tuesday (WG5 Session 1)		
14:00-14:25	Federico Scutti	Search for heavy neutrinos with the ATLAS detector
14:25-14:50	Si Hyun Jeon	Tests of neutrino mass models at CMS
14:50-15:15	Yu Seon Jeong	Prompt tau neutrinos at the LHC
15:15-15:40	Osamu Sato	Study of tau-neutrino production at the CERN SPS

Tuesday (WG5 Session 2)		
16:00-16:25	Paschal Coyle	Neutrino Oscillation measurements and BSM physics searches with Neutrino Telescopes in the Mediterranean
16:25-16:50	Tom Stuttard	Neutrino oscillations and PMNS unitarity with IceCube/ DeepCore and the IceCube Upgrade
16:50-17:15	Phillip Litchfield	Prospects for BSM physics searches and NSI at Hyper-K and T2HKK
17:15-17:40	Alan Bross	Neutral Current events and new physics at nuSTORM

Thursday 29/08

Schedule

Thursday (WG5 Session 3)		
11:00-11:30	Mathieu Perrin-Terrin	Search for exotic decays with NA62
11:30-12:00	Chunsil Yoon	Neutrino physics with the SHiP experiment at CERN
12:00-12:30	Kihyeon Cho	BSM at DUNE

Thursday (WG5 Session 4)		
14:00-14:30	Raymond Volkas	Radiative neutrino mass models and the flavour anomalies
14:30-15:00	Giovanni Gallucci	Status of the HOLMES experiment to directly measure the electron neutrino mass with a calorimetric approach.
15:00-15:30	Kang Young Lee	New physics searches with SHIP

Thursday (WG5 Session 5)		
16:00-16:30	Shao-Feng Ge	New Physics and the Leptonic CP Phase Measument
16:30-17:00	Dukjae Jang	Sterile Neutrinos in Astrophysical Environments : Big Bang Nucleosynthesis and Supernova Neutrino Process
17:00-17:30	Juan Antonio Aguilar Sánchez	Search for Dark Matter and BSM Physics with the IceCube Neutrino Observatory

Friday 30/08

Schedule

Friday (WG5 Session 6)		
14:00-14:30	Yoomin Oh	Reactor short baseline neutrino experiments including NEOS
14:30-15:00	Jaehoon Yu	Sterile neutrino searches with the ICARUS detector
15:00-15:30	Mark Ross-Lonergan	Status of the MicroBooNE Low-energy Excess Search

Friday (WG1+WG5 Session 7)		
16:00-16:25	Stephen Robert Dennis	Status of SBND
16:25-16:50	Fumihiko Suekane	Status of JSNS2 experiment
16:50-17:15	Adam Jude Aurisano	Sterile Neutrinos search via NC disapperance at NOvA
17:15-17:40	Joshua Hignight	Sterile Neutrino Searches with IceCube

Joshua Hignight 7-4

Example: Notation used in top right corner of slides (Speaker name, #Session, #Talk in session)

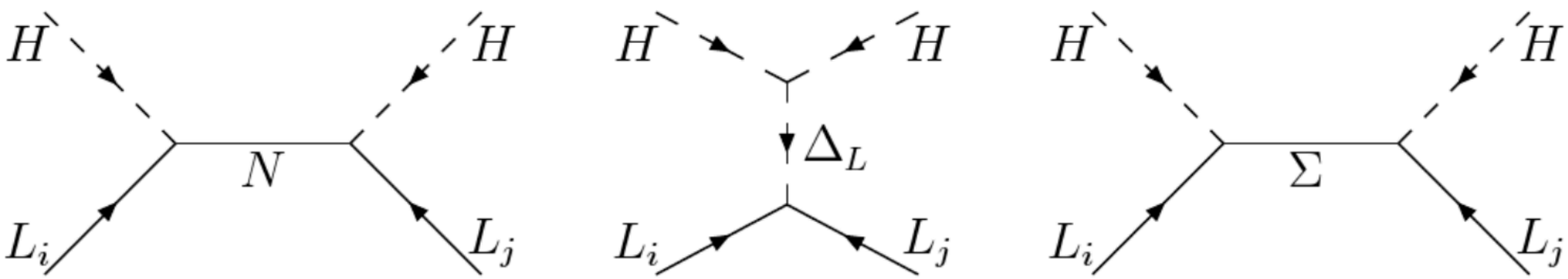
Neutrino Masses

Federico Scutti 1-1

Sihyun Jeon 1-2

Collider Searches

- Seesaw Model : natural way to generate neutrino masses
- Within the SM expand dim-5 operator at tree level : fermion singlet, scalar triplet, fermion triplet



Type-I : fermion singlet Type-II : scalar triplet Type-III : fermion triplet

Collider experiments have access to different incarnations of Type-I/II/III.

<u>Typical signatures:</u>

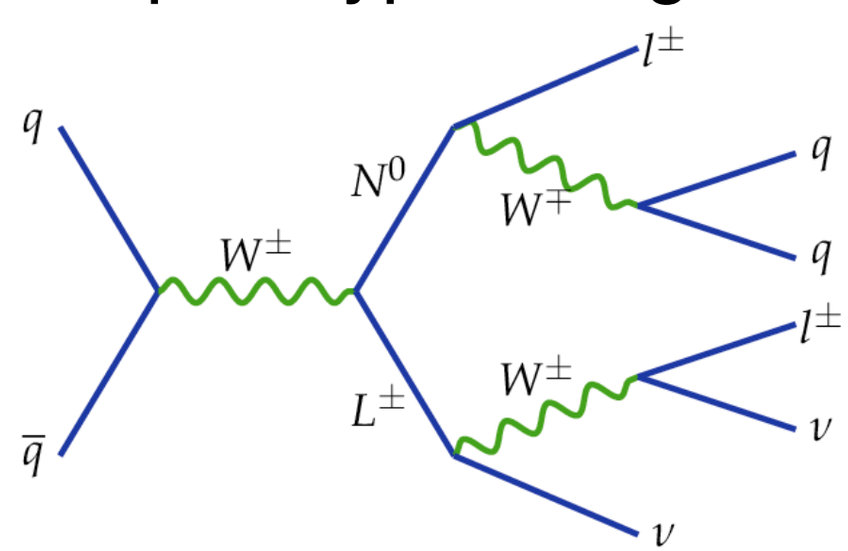
Type-I

- Signatures including muons and electrons

Type-III

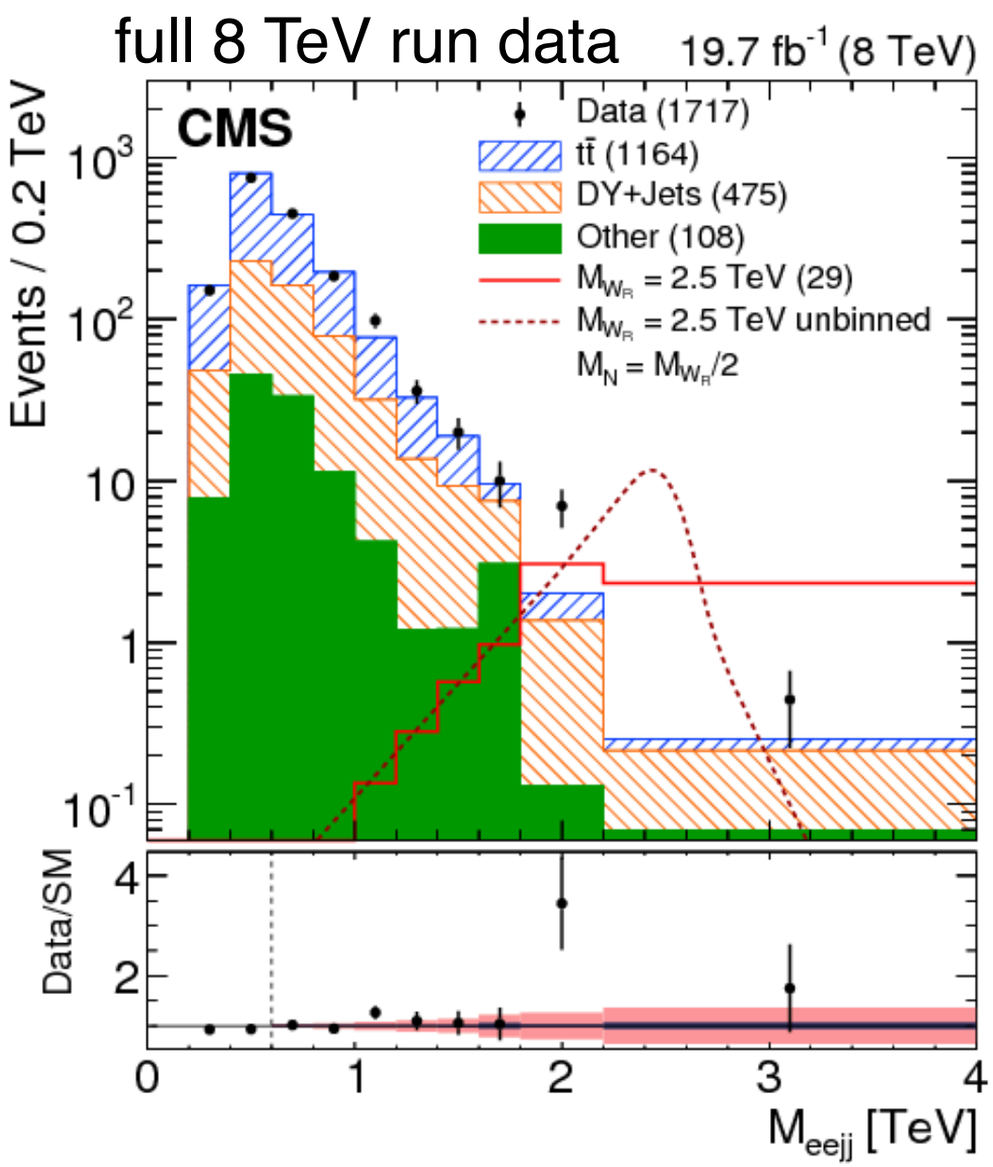
- Two leptons in final state with same or opposite charge.

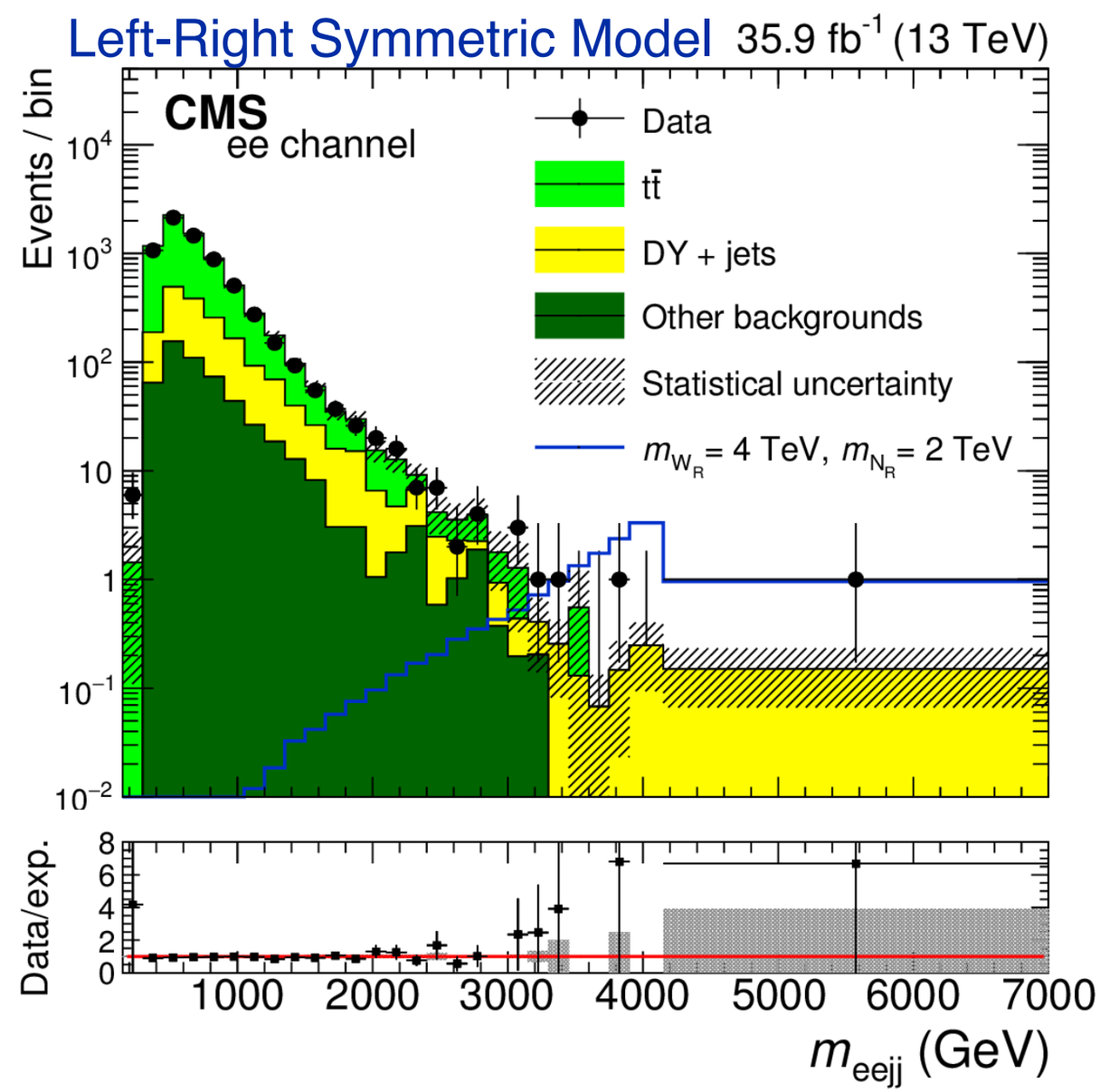
Example: Type-III signature



Sihyun Jeon 1-2

Test of Neutrino Mass Models at CMS





CMS:

2.8σ excess at m(eejj)~2 TeV

2.5σ excess also seen from Leptoquark analysis but only in e channel (eejj, evjj)

ATLAS:

SS analysis: no excess

In 13 TeV data

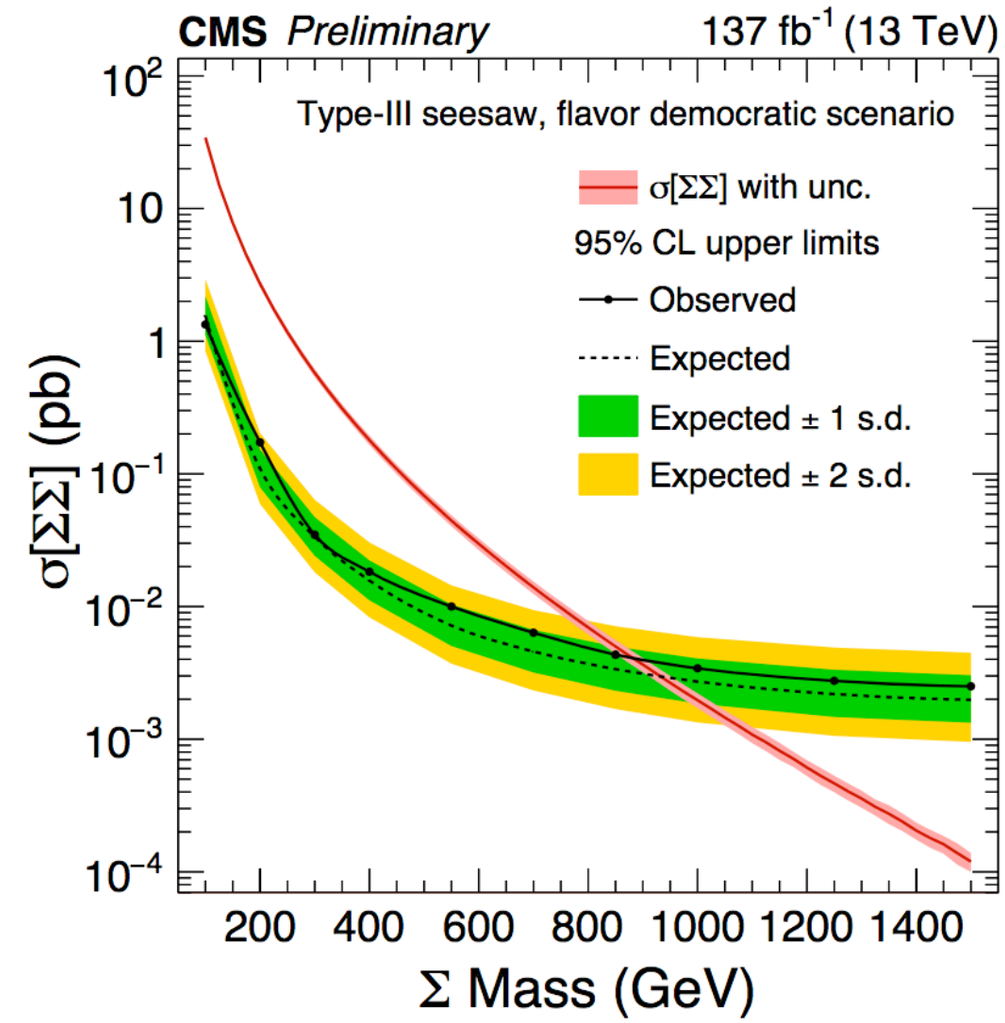
- No excess in signal region
- Exclude m_{WR} up to 4.4 TeV

Test of Neutrino Mass Models at CMS

CMS Results summary

- **Composite Model :** excluded up to m(N)=4.6 TeV for m(N)=Λ
- **Type-I Seesaw Model**
  - 2 leptons : limits on $|V_{\ell N}|^2$ set up to m(N)=1200 GeV
  - 3 leptons : limits on $|V_{\ell N}|^2$ set down to m(N)=1 GeV
- **Type-III Seesaw Model** : excluded up to 880 GeV for flavour democratic case
- **Left-Right Symmetric Model**
  - ττ : excluded up to m(N)=1.45 TeV for m(N)=m(WR)/2
  - ee/μμ : excluded up to m(N)=2.2 TeV for m(N)=m(WR)/2

More searches forthcoming using full 13 TeV run data



Used full 13 TeV run data

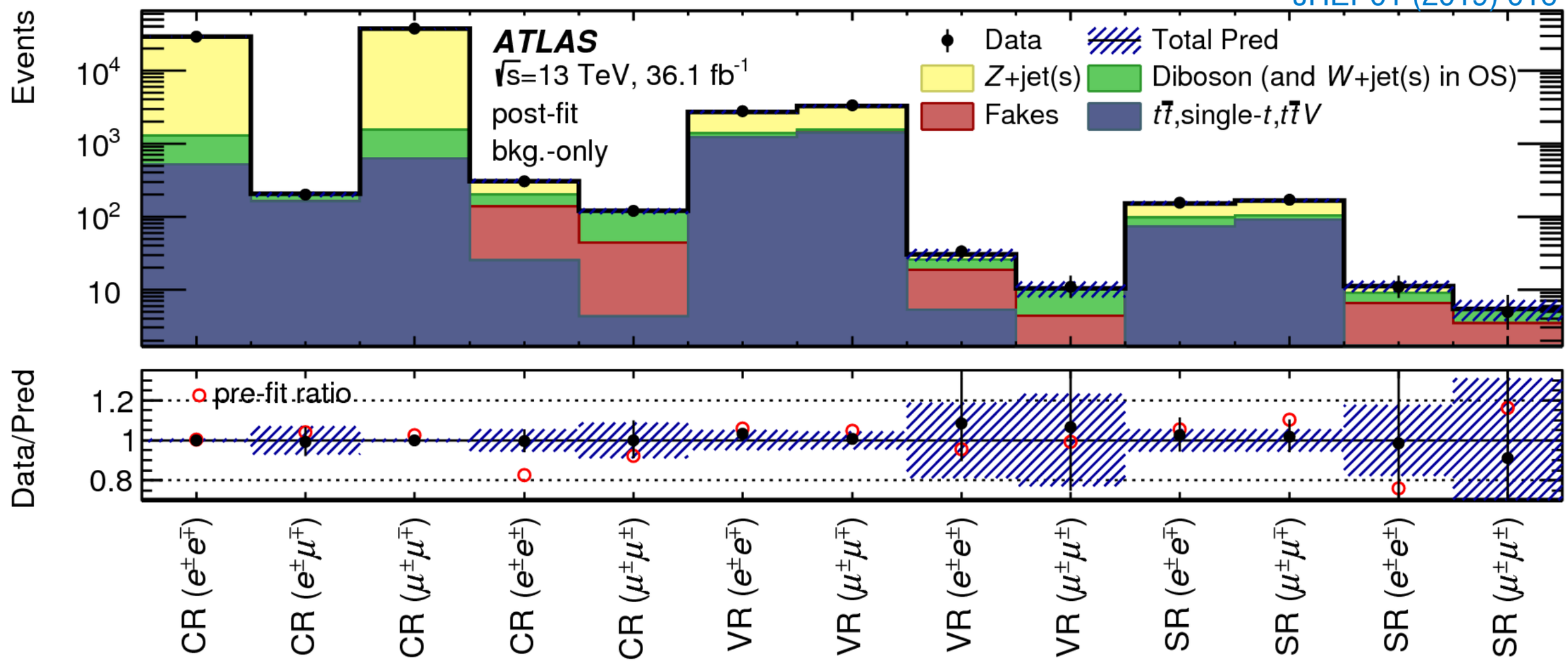
✓No excess above SM prediction

✓Excluded up to m(Σ)=880 GeV

Federico Scutti 1-1

Search for heavy neutrinos

JHEP01 (2019) 016



- ATLAS Run-II searches will be updated with the final dataset.
- Many updates in program: new channels/techniques

Analyses covered:

Minimal Type-I multi-leptonic:
- (Lint = 36.1 / 32.9 fb-1): 1905.09787.

Minimal Type-III semi-leptonic:
- (Lint = 79.8 fb-1): ATLAS-CONF-2018-020.

Left-Right symmetric Type-I semi-leptonic with resolved topology:
- (Lint = 36.1 fb-1): JHEP 01 (2019) 016.

Left-Right symmetric Type-I semi-leptonic with boosted topology:
- (Lint = 80 fb-1): 1904.12679.

Ray Volkas 4-1

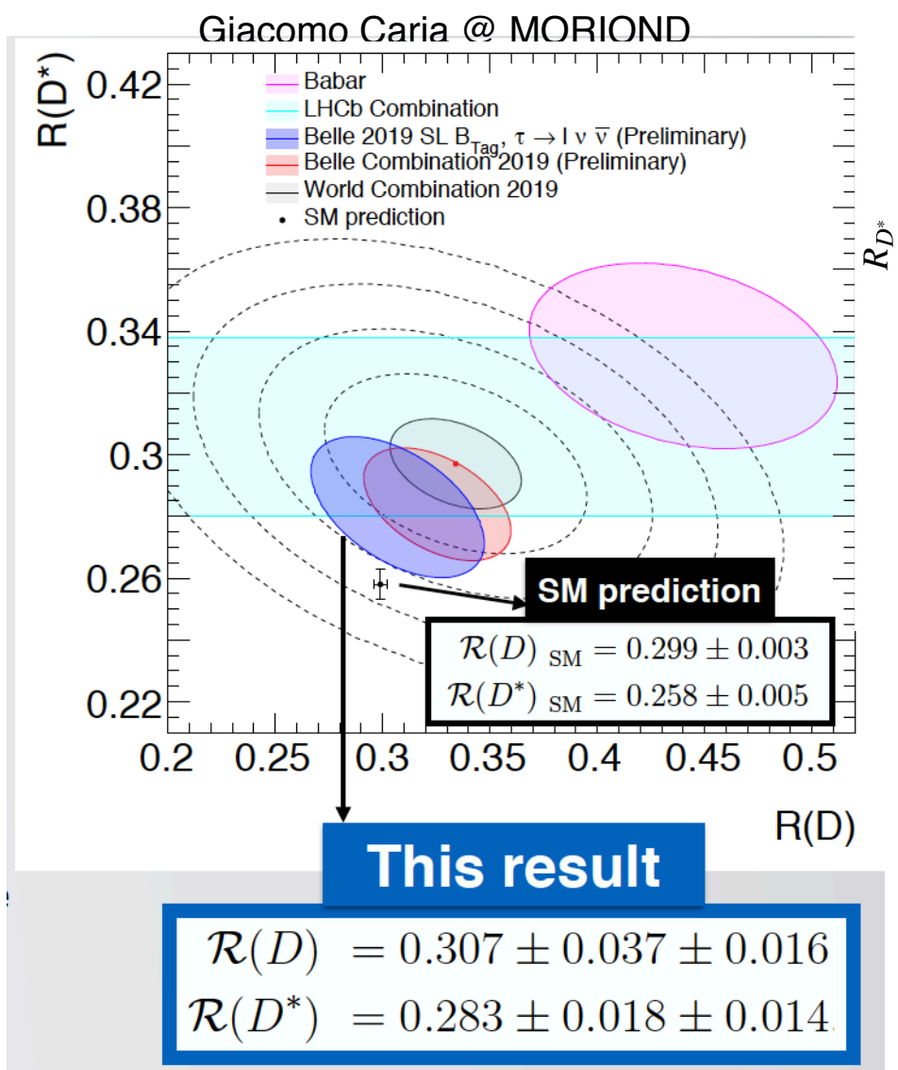
Radiative neutrino mass models and the flavour anomalies

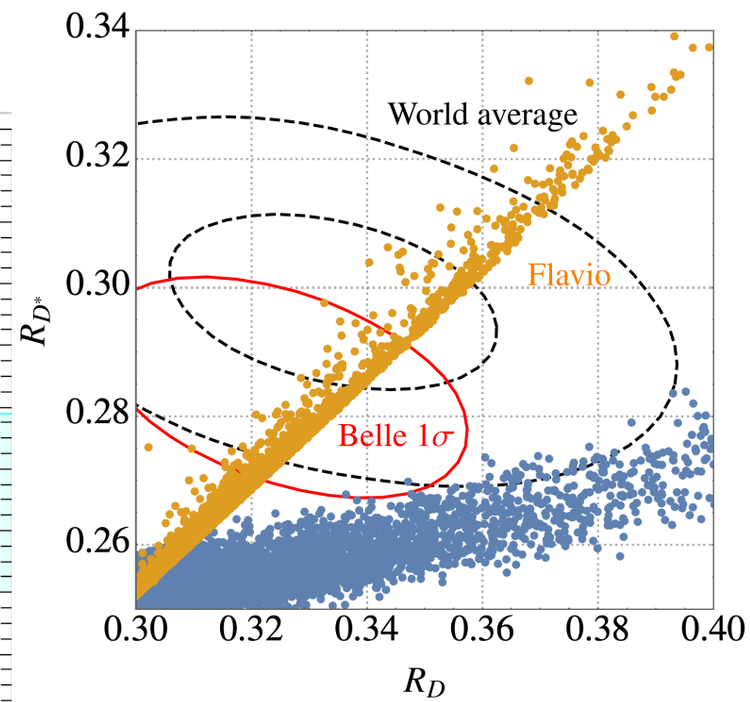
Review flavour anomalies

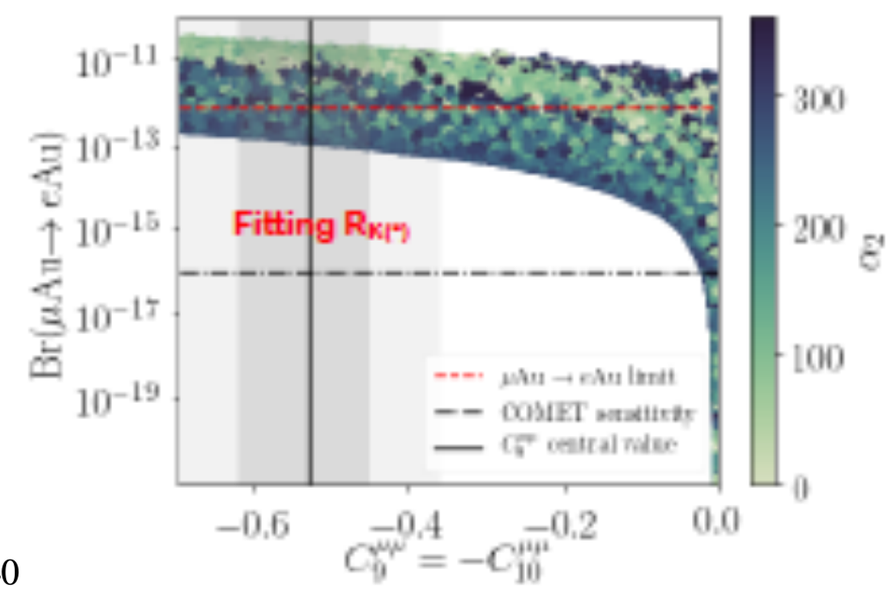
- Hints for μ vs e universality violation in b→s transitions
- Hint of non-standard angular observable in B→K*μ⁺μ⁻
- Hints for τ vs μ/e universality violation in b→c transitions

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$$

$$R_{D^{(*)}} \equiv \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$







Radiative neutrino mass models to explain neutrino masses and observed anomalies

Important future tests:

- μ→e conversion most important constraint. COMET and Mu2e experiments will probe much of the allowed parameter space!
- Belle-II

Bigaran, Gargalionis, Volkas: 1906.01870

Giovanni Gallucci 4-2

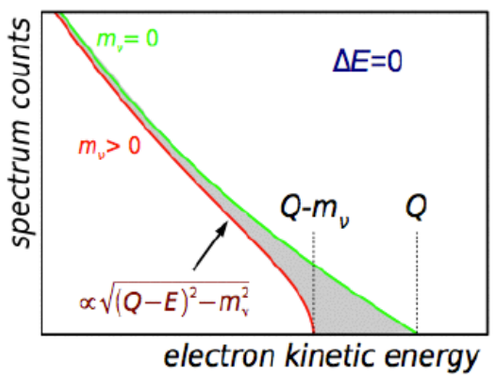
HOLMES

Direct measurement (1)

Kinematics of weak decay with ν emission:
- low Q nuclear β decays (^{3}H, ^{187}Re, ^{163}Ho...)
- model independent: only E, p conservation
- ν mass appears as a distortion in the Kurie plot

$$(A,Z) \longrightarrow (A,Z+1) + e^- + \nu_e$$

$$N(E_\beta) \propto p\beta\, E\beta\, (Q - E\beta)\sqrt{((Q - E_\beta) - m_\nu)}\, F(z,E_\beta) S(E\beta)$$



2 different approaches:
- **spectrometry**: source placed outside the detector (KATRIN approach)
- **calorimetry**: source embedded inside the detector (ECHO, MARE, HOLMES approach)

⇒ low T μ-calorimeters

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- **Direct measurement** :≲ **2eV** (Mainz & Troitsk experiments)
- **Double beta decay**: ≲ **0.5 eV** (only Majorana neutrino)
- **Cosmological** and astrophysical data : ≲ **0.2 – 1.3eV** (model dependent)

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu$

Electron capture (EC) in Holmium 163

Summary

The measurement of neutrino mass is still one of the most compelling issues in modern particle physics. Both calorimetric and spectrometric experiments are on going and could give a final answer.

HOLMES is a calorimetric experiment with ^{163}Ho that aims to reach the statistical sensitivity around 1 eV.

Three batches of ^{163}Ho are purified and ready to be moved in Genova.
The procedure to distillate holmium is tested. Some refinements are needed.
The procedure to fabricate sputter target is tested.
The installation of the implanter for isotopic separation is mainly finished
Every part has been individually tested. Integration and first tests in progress.
HOLMES detector production procedure is defined and the firsts (not implanted) detectors are being characterized.
Readout is on test and is almost ready.

With 32 pixels for 1 month → m sensitivity ≈10 eV

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HOLMES Sensitivity

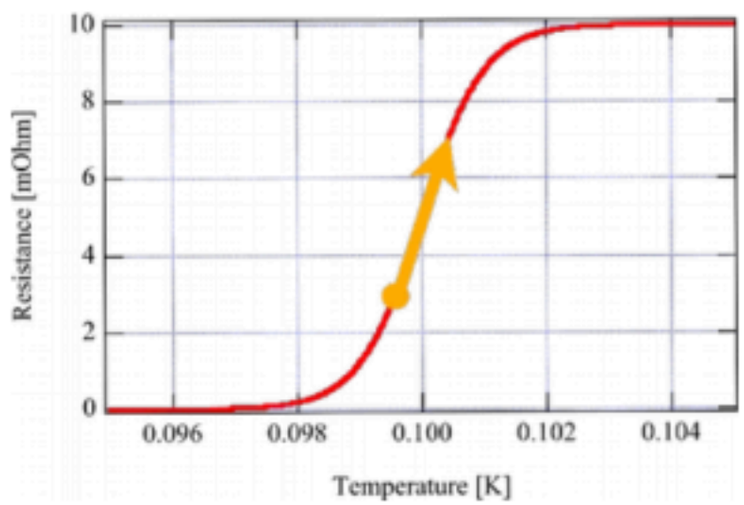
- 32pixels + 1 month ~10eV
- Expected to reach ~1eV

in comparison

- current best calorimetric measurements ~20eV
- KATRIN ~0.2eV

Advantage: HOLMES technology scalable

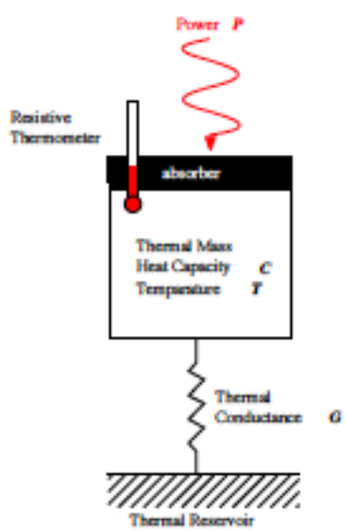
Detector design and test (1)

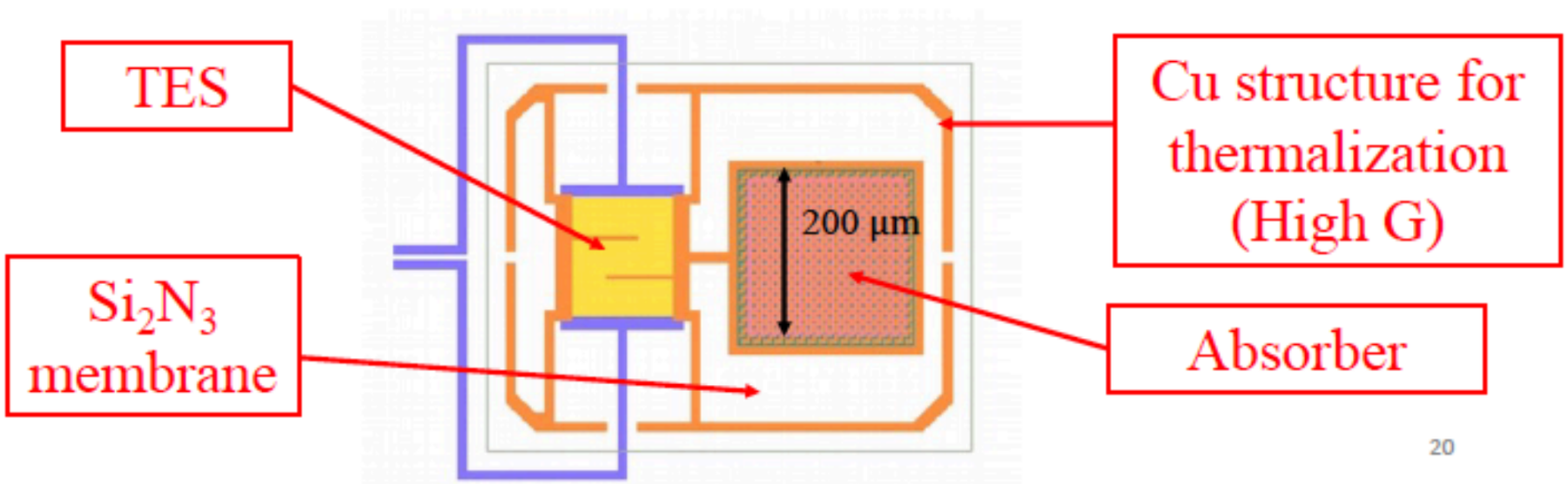


Transition Edge Sensors Superconductive Detectors (TES)

- Molybdenum/copper ($T_c \sim 100$ mK)
- Very steep R vs T dependency in transition region;
- Gold absorber with ^{163}Ho inside coupled to TES thermometer ;
- Ho sandwiched between two 1 mm thick gold layers for a total electron containment
- Fast detectors to reduce pile-up
  - tunable rise time ~ L/R
  - decay time dependent on detector characteristics C/G

TES design, production and preliminary test is done @NIST





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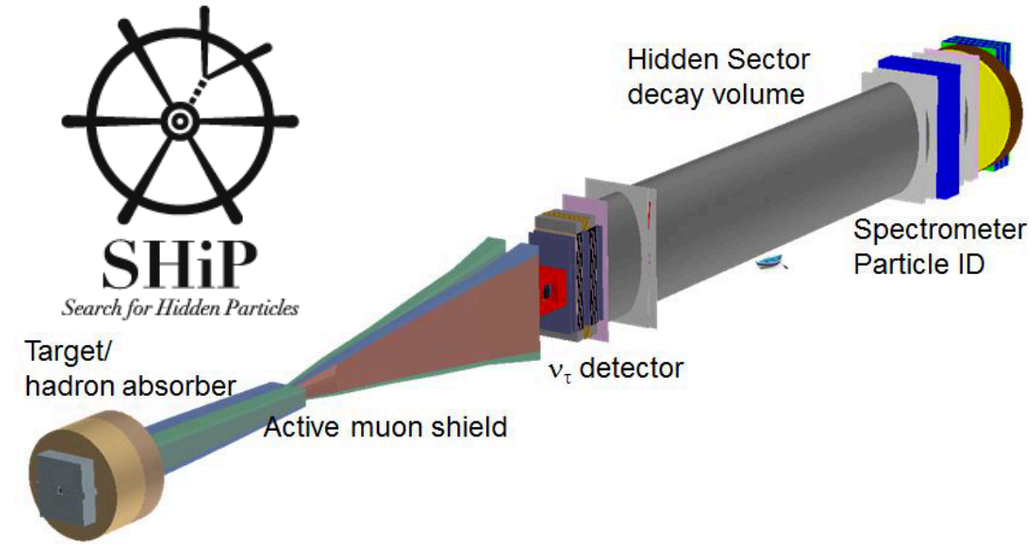
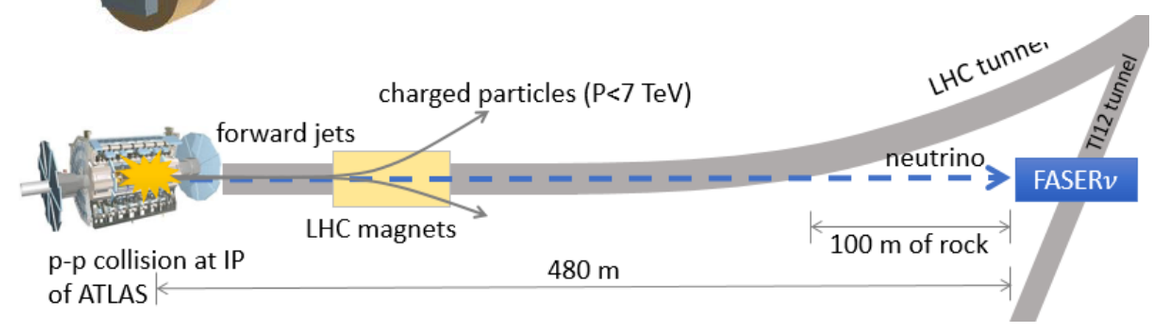
Beam Dump Experiments and Tau Neutrinos

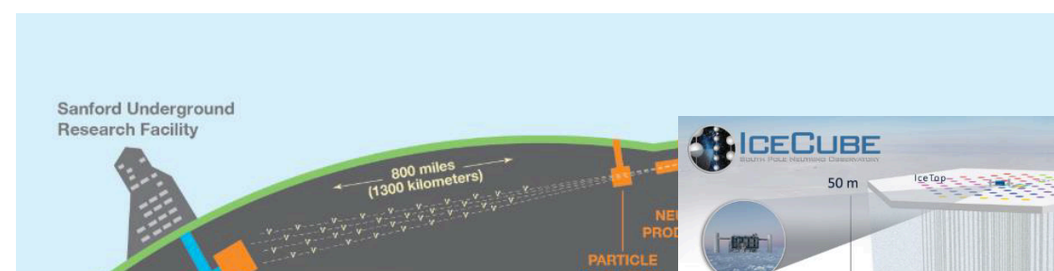
Osamu Sato 1-4

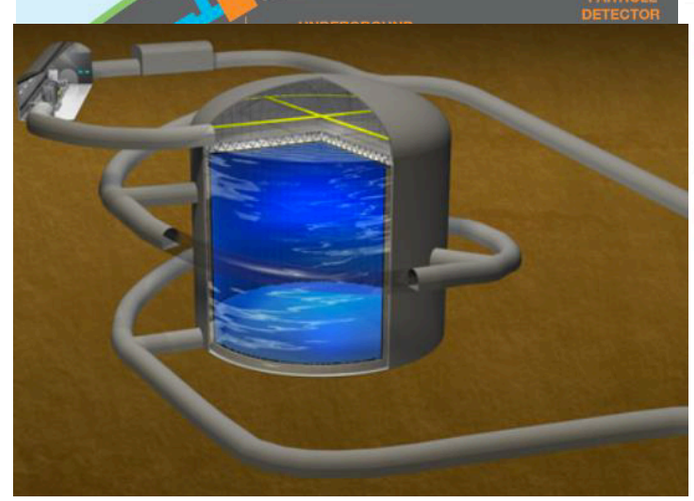
Future tau neutrino measurements

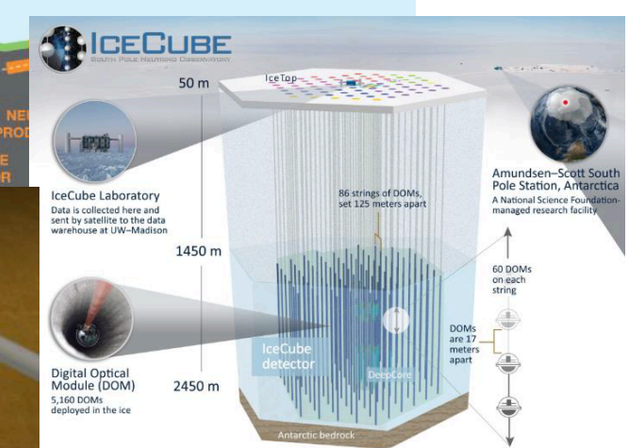
- Opportunities to measure ν_τ cross section
  - SHiP: high statistics ν_τ measurement at the SPS beam dump facility
  - reduction of ν_τ beam uncertainty with DsTau to ~10%
  - FASER: high energy ν_τ measurements at the LHC.3
- ν_τ cross section has influence to
  - Long baseline neutrino oscillation experiments
    - DUNE, Hyper-K (+KNO), T2K
    - ν_τ is background to ν_e, due to $\tau \to e$
  - Astrophysical ν_τ measurement
    - IceCube, KM3NeT, GVD, …











Sihyun Yu 1-3

Prompt

Detector Location: 480 m from ATLAS IP

Planned with **two stages**

FASER 1 (during Run 3):

R_d = 10 cm, L_d = 1.5 m,

Luminosity = 150 fb^{-1} ,

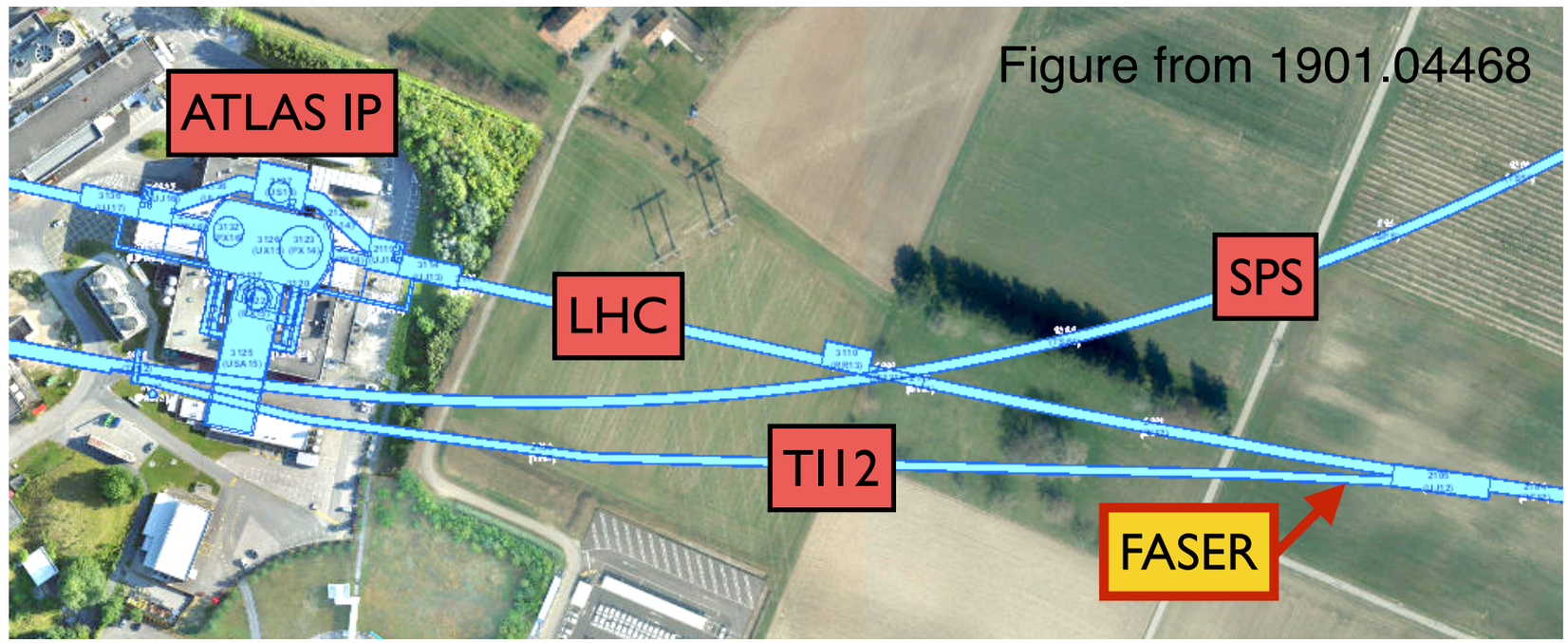
Rapidity: $\eta \gtrsim 9.2$

FASER 2 (during HL-LHC):

R_d = 1.0 m, L_d = 5.0 m,

Luminosity = 3000 fb^{-1}

Rapidity: $\eta \gtrsim 6.9$



FASER (ForwArd Search ExpeRiment)

- Neutrinos in large rapidity region will provide a good opportunity for measurement of neutrino cross section at TeV energies.
- With sizeable number of tau neutrino (ν_τ), it will be possible to test lepton universality in neutrino interaction.
- Abundant ν_τ will help investigate oscillation in/beyond the SM.
  - better understanding of ν_τ CC interaction will be able to reduce the uncertainty due to the tau (τ) decay in the oscillation experiments.
  - possible to probe oscillation between ν_τ and sterile neutrino (ν_s) using the event spectrum.

Sihyun Yu 1-3

Sterile Neutrino Searches with FASER

- Sterile neutrinos at FASER
- Abundant tau neutrinos and broad energy spectrum ($\nu_\tau \rightarrow \nu_s$) - 7000-8000 ν_τ events expected with energies ranging from 100GeV - 1TeV

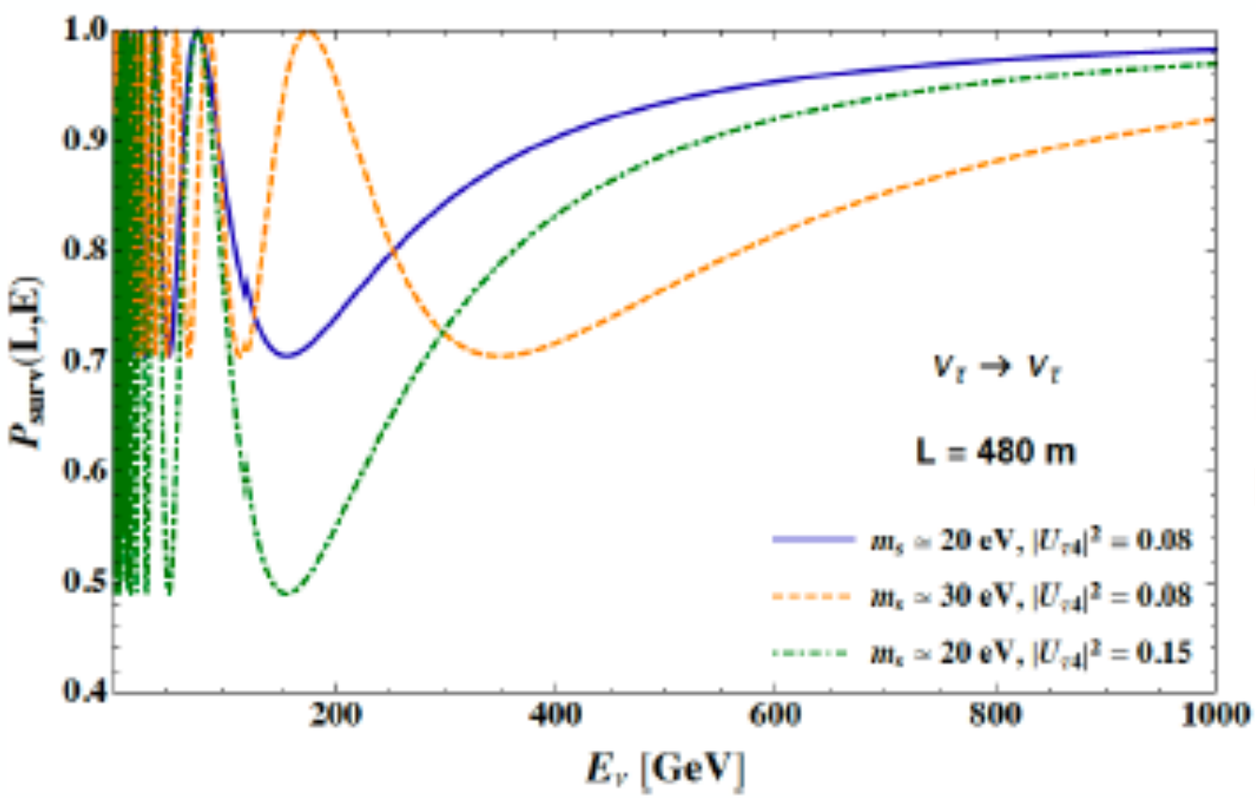
- Oscillation probability in two flavour approximation:

$$P(\nu_\alpha \rightarrow \nu_\beta) \simeq \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Condition for noticeable signal :

$$\frac{\Delta m^2 L}{4E} \sim \frac{\pi}{2}$$

- For the baseline 480 m and neutrinos with
  - E ~ 170 GeV ⇒ $\Delta m_s^2 \sim 440\ \mathrm{eV}^2$ ($m_s \sim 20$ eV)
  - E ~ 350 GeV ⇒ $\Delta m_s^2 \sim 900\ \mathrm{eV}^2$ ($m_s \sim 30$ eV)



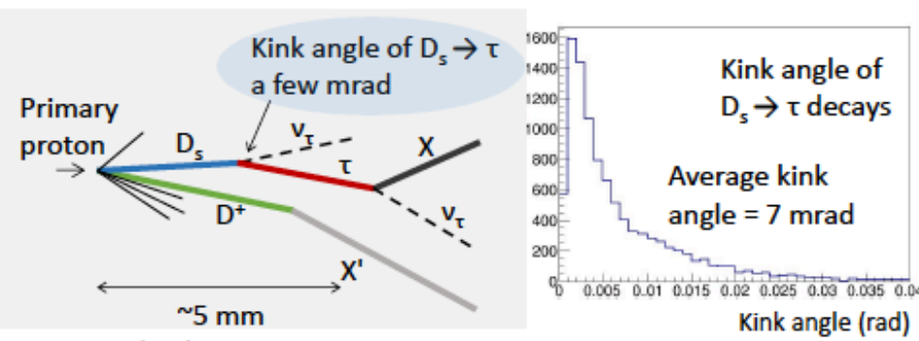
FASER can test "larger" mass sterile neutrinos ($\Delta m_s^2 > 100\mathrm{eV}^2$)

Osamu Sato1-4

DsTau

DS Tau

- **Goals:** Study of ν_τ production for future tau neutrino experiments.
  - First measurement of D_s double differential production cross section
  - To reduce uncertainty of ν_τ flux from >50% to 10%.
    - Fundamental input for future ν_τ experiment: SHiP.
  - Byproduct: charm physics, intrinsic charm component in proton.
- **Principle of the experiment**
  - Detection of "**double-kink + charm decay**" topology within some mm.
  - 4.6×10^9 protons, 2.3×10^8 proton interactions in tungsten, 10^5 charm pairs, **$1000\ D_s \to \tau \to X$ decays**.



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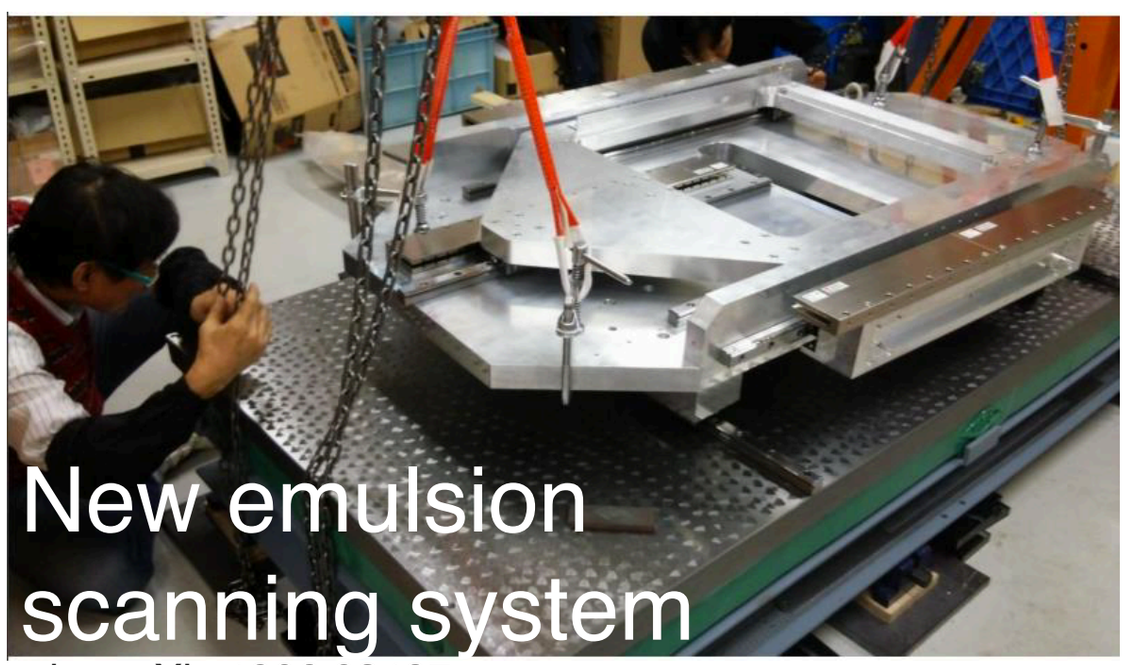


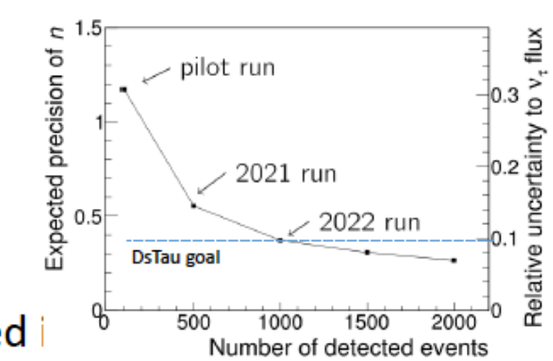
see also arXiv:1906.03487

- DsTau studies tau neutrino production in 400 GeV proton beam dump, for future tau neutrino measurements.
- Collecting 1000 Ds → τ → X double kink events from 2.3×10^8 proton tungsten interactions

June 2019 - DsTau approved by CERN Research Board as CERN NA65

Plan for physics runs in 2021, 2022 (NA65)

	# of modules	emulsion films (m^2)
Pilot run 2018	30	49
Physics run 2021	**150**	**246**
Physics run 2022	**190**	**312**



- 2 weeks each
- The exposure speed achieved i the pilot run is quick enough

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SHiP

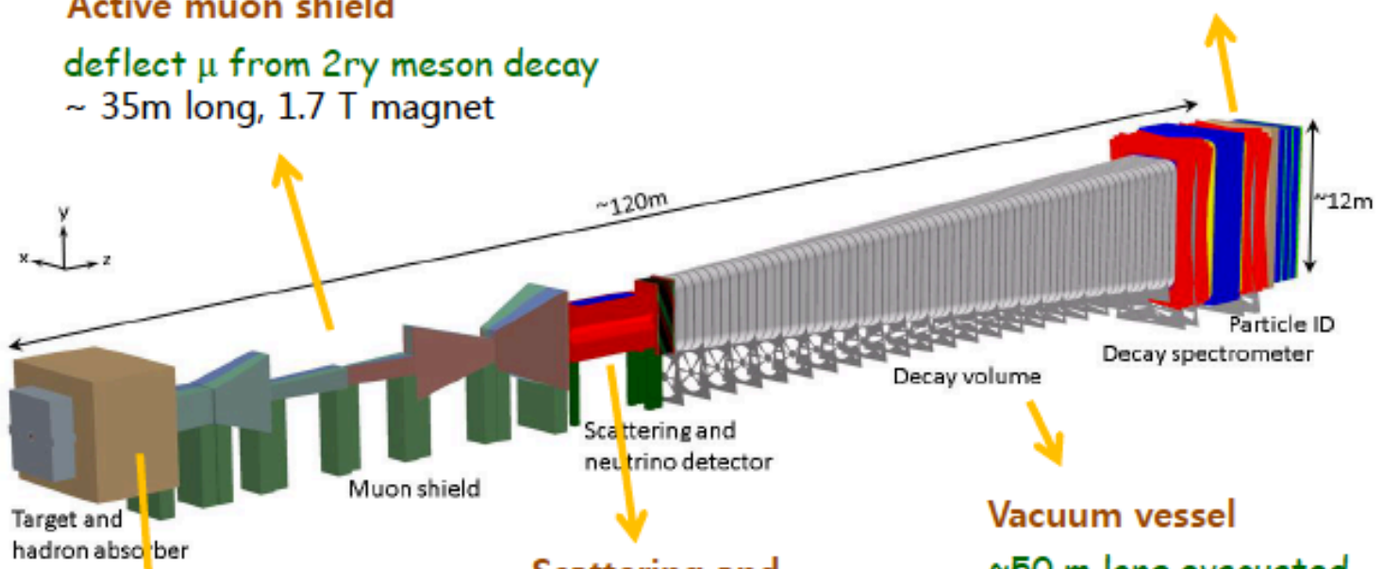
Search for Hidden Particles

SHiP

The SHiP detector

HS decay spectrometer
ECAL, Muon detector
PID, Energy & Time

Active muon shield
deflect μ from 2ry meson decay
~ 35m long, 1.7 T magnet



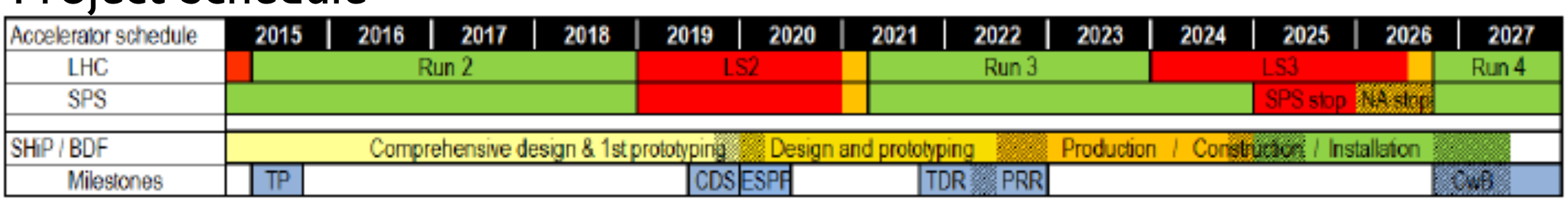
Hadron absorber
eliminate 2ry mesons
(π, K) ~ 5m Fe

Scattering and
Neutrino Detector
LDM & Tau neutrino
ECC+CES
(Nuclear emulsion)
TT, RPC

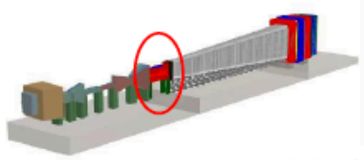
Vacuum vessel
~50 m long evacuated
decay vessel
surrounded by liquid
scintillator veto system

- Using High-intensity 400 GeV SPS proton beam
- Data expected
  - 2 x 10^{20} pot, 5 years run

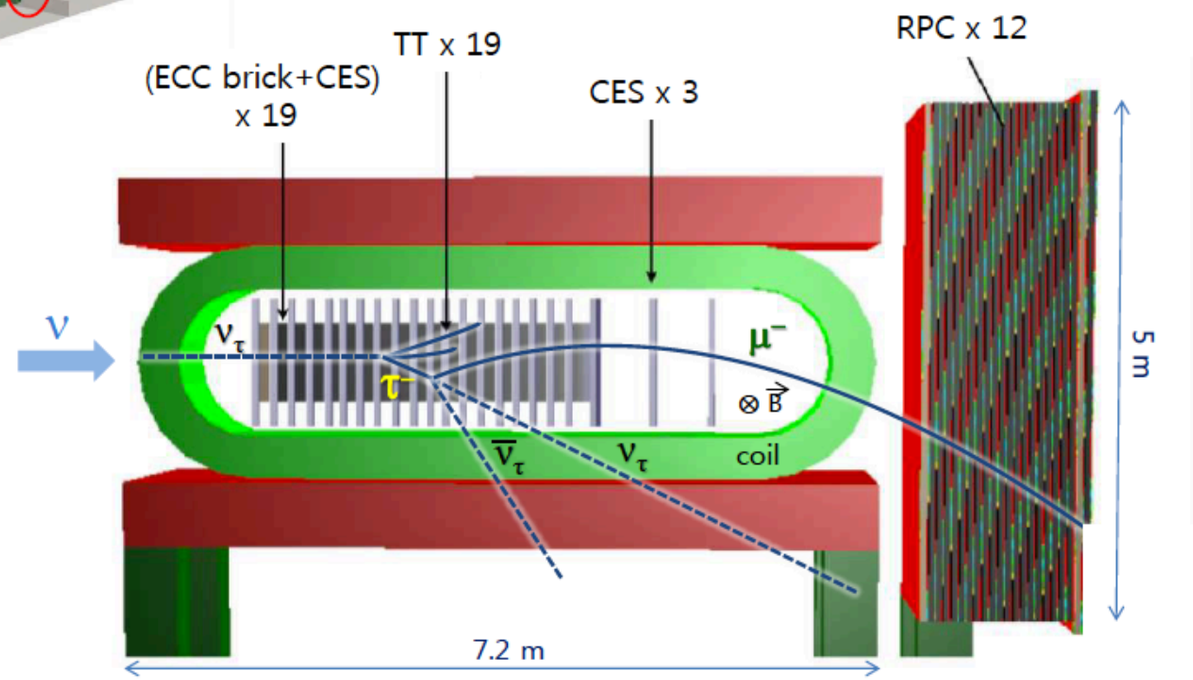
Project Schedule



SHiP



Scattering and Neutrino Detector



ECC (Emulsion Cloud Chamber) : High spatial resolution (~μm) to observe the τ decay
CES (Compact Emulsion Spectrometer) : measure muon charge & momentum
TT (Target tracker) : Electronic detector to predict ν interaction contained in ECC brick and provide the time stamp
Magnet : to measure the charge of τ products (1.25 T)
Muon filter (RPC) : Muon identification and tracking (area 2 x 5 m^2 x 12 planes)

About **10,000 Tau neutrino & Anti-tau Neutrino CC events** are expected with target mass of ~10 tons. - Expect first observation of the **Anti-tau neutrino**

Tau neutrino physics - Cross section, Magnetic moment - First evaluation of the F4 and F5 - Study of Strange quark content of nucleon

Light Dark Matter search in SND

LDM (χ) can produce via dark photon (A') decay

$pp \rightarrow \pi^0 X$

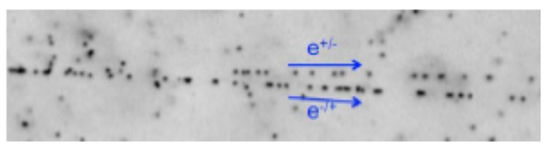
$\pi^0 \rightarrow A' \gamma$

$A' \rightarrow \chi \bar{\chi}$ χ: LDM

Scatter on e

$\chi e \rightarrow \chi e$

Electron recoil high energy



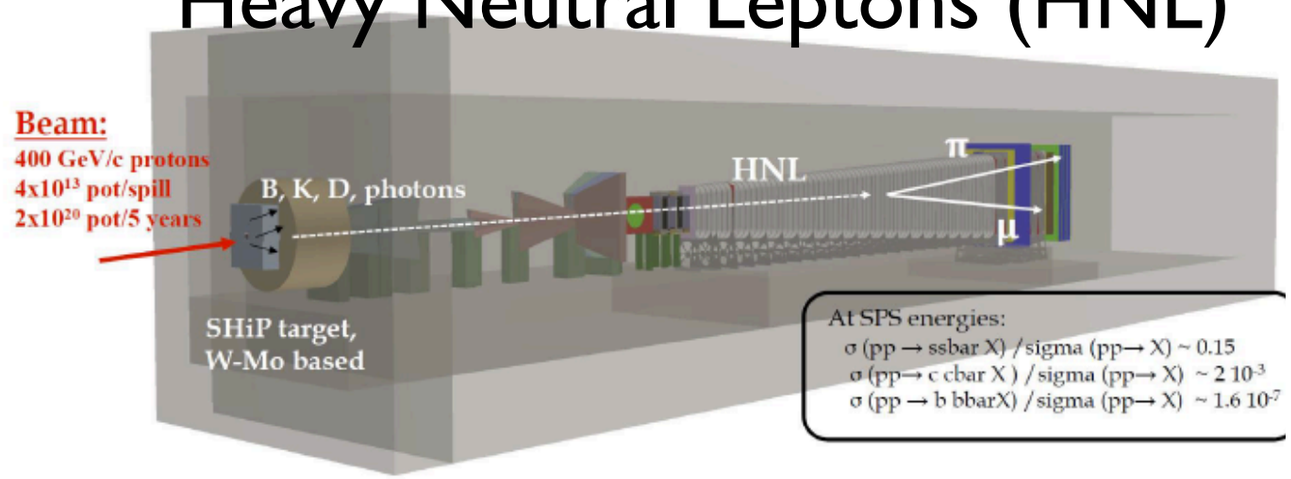
~ GeV electron sample in emulsion

Neutral Current DM-electron scattering is highly peaked in the forward direction. Cutting on very forward scattering can remove most other projected background.

Kang Young Lee 4-3

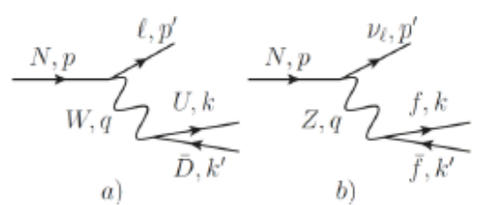
SHiP Sensitivities

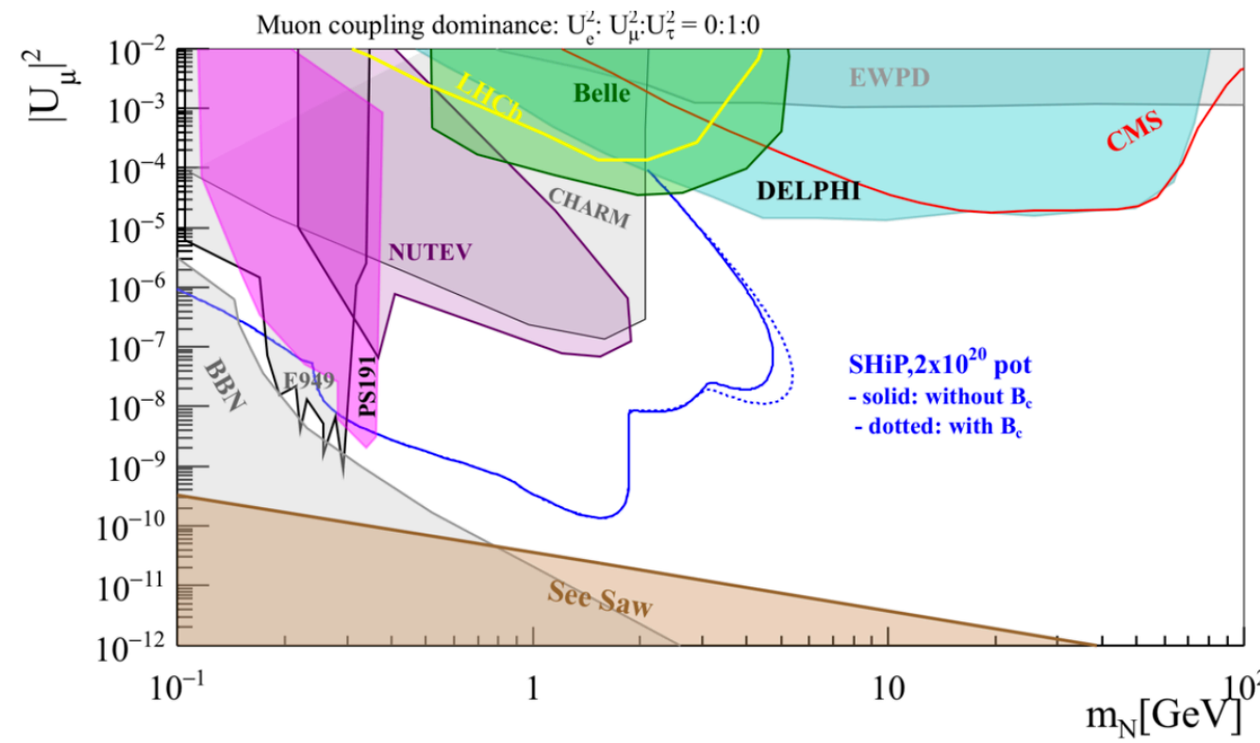
Heavy Neutral Leptons (HNL)



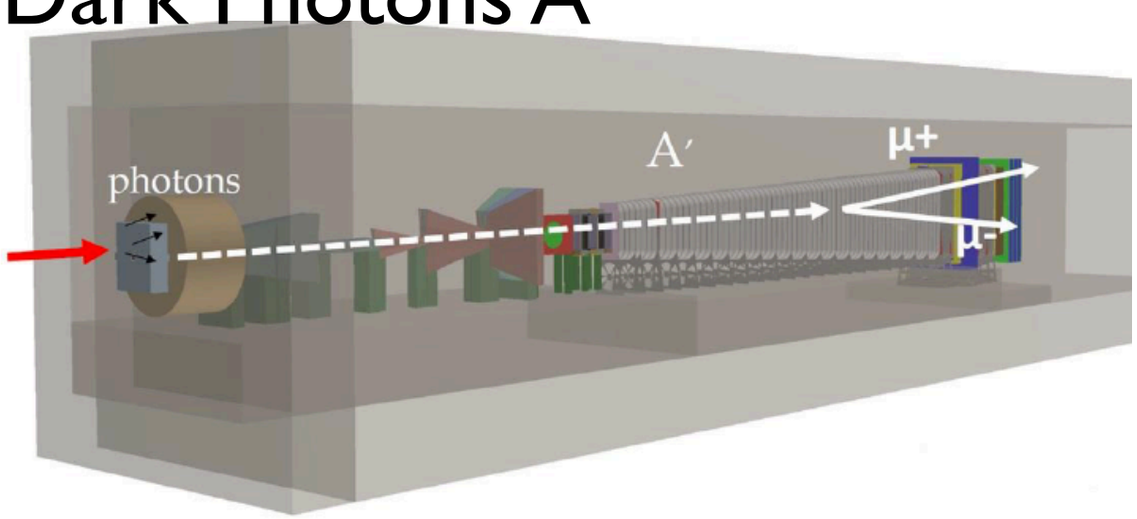
$h \to h'_P \ell N$

$h \to h'_V \ell N$

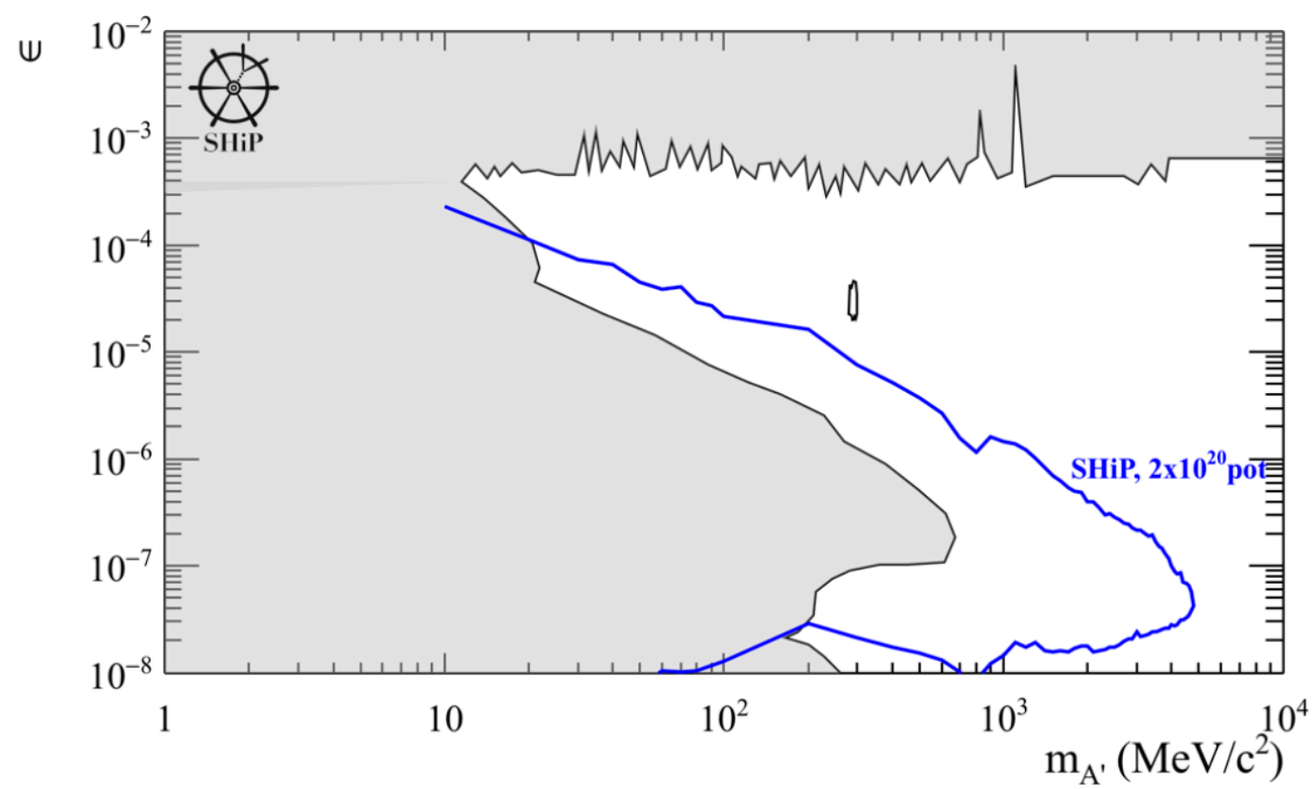




Dark Photons A'

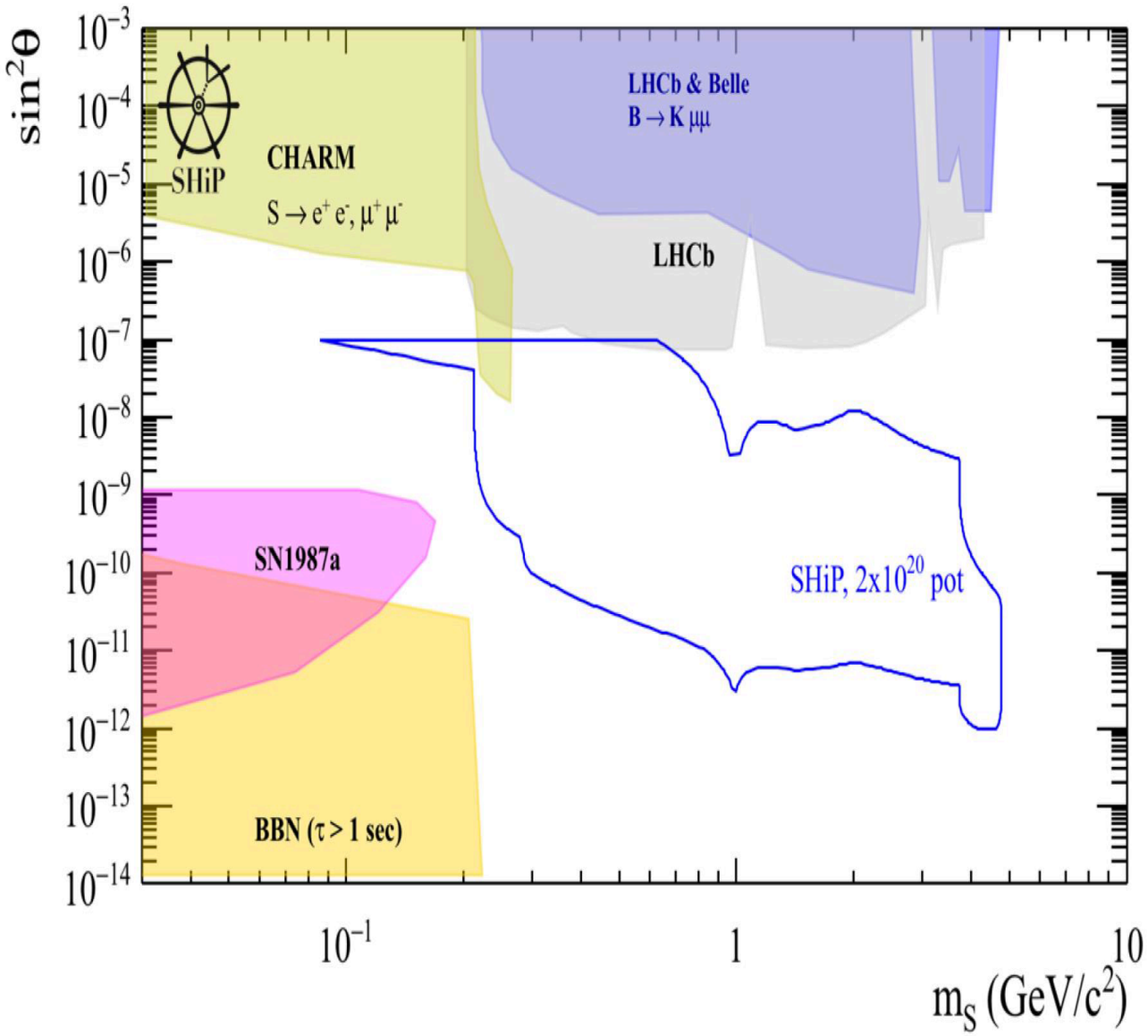


If mA′ < 2m χ, the Dark Photon decays to SM particles
If $m_{A'} > 2\, m_\chi$ the Dark Photon can decay also to DM with a couplin

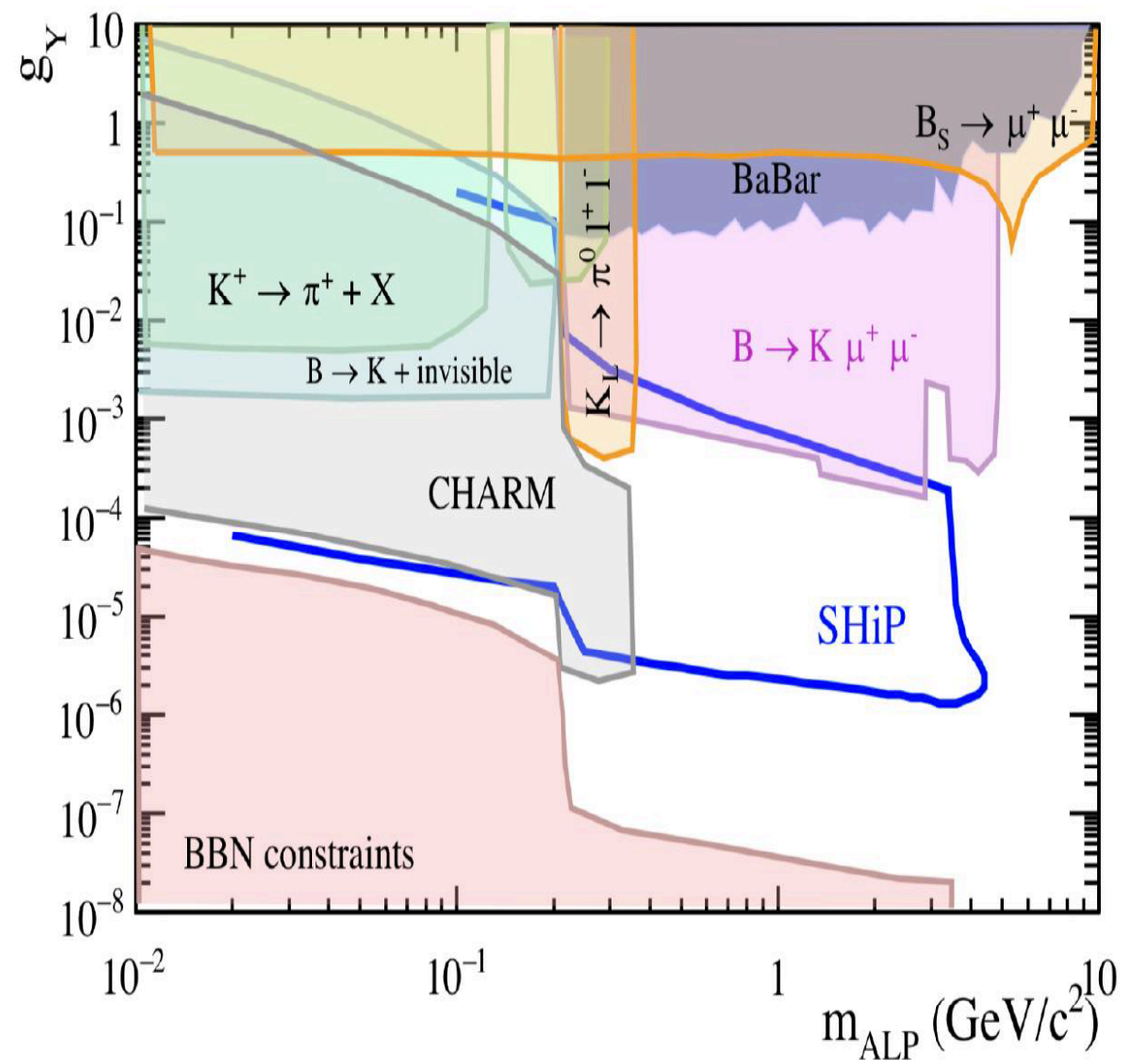


SHiP Sensitivities

Dark Scalar sensitivity



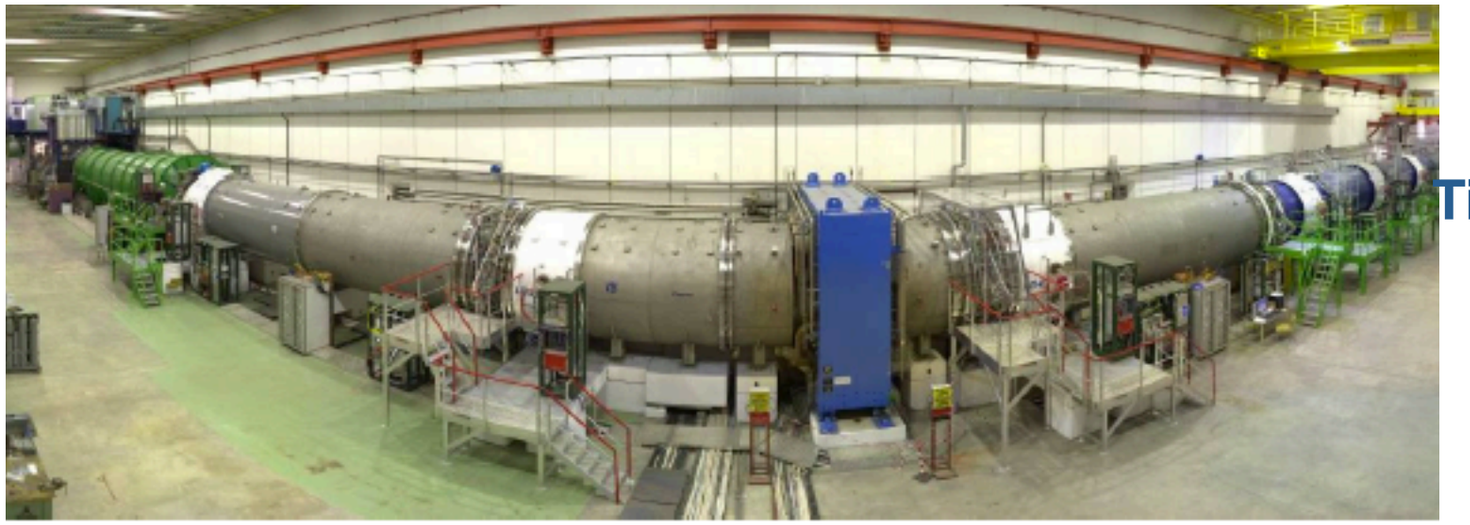
Axion Like Particles (ALP)



The NA62 Experiment

Mathieu Perrin-Terrin 3-1

The NA62 Experiment



Time Line

- **2015 -2016 Commissioning, 1% nominal intensity, no GTK**
- **2016 -2018 Physics 35% —> 65% nom. intensity**
  - **3×10^{16} POT**

Firstly Dedicated to $K^+\to\pi^+\nu\bar{\nu}$

- Precise **SM prediction**: $(8.4\pm1.0)\times10^{-11}$ [Buras JHEP11 (2015)033]
- Extraordinary sensitivity to **physics beyond SM**
- Results from **E787-E949**: $(17.3^{+11.5}_{-10.5})\times10^{-11}$ [PRD79, 092004 (2009)]
- NA62 Aim: **10% precision** measurement
- **NA62 First Results**: one candidate [Phys. Lett. B791 156-166, 2019]

Experimental Challenge

- With 10% Sig Acceptance:10^{13} K^+decays, $\mathcal{O}(10^{12})$ Bkg rejection

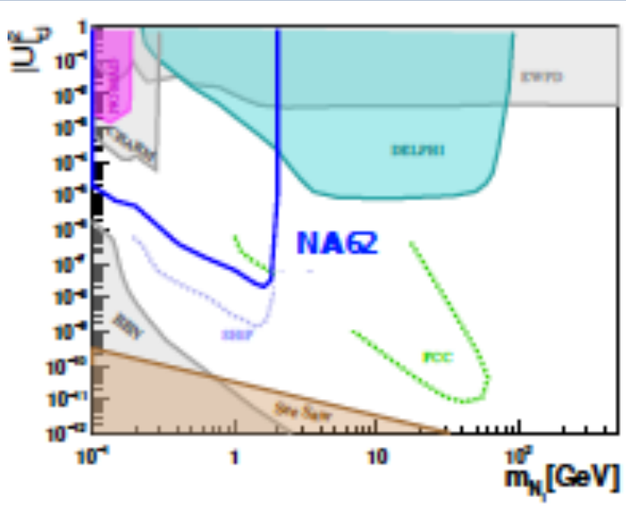
Mathieu Perrin-Terrin (CPPM, UCL) Exotics at NA62 29/08/2019

2021-2022: $K^+\to\pi^+\nu\bar{\nu}$

- Two year to complete the measurement of $\mathcal{B}(K^+\to\pi^+\nu\bar{\nu})$

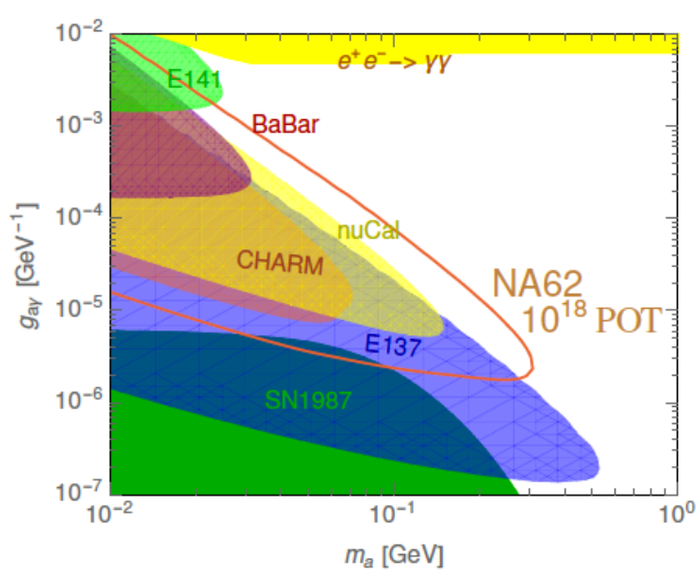
2023: Beam Dump

- One year in beam dump to accumulate $\mathcal{O}(10^{18})$ POT



$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$

Normal hierarchy of active ν masses



Science Program

- Neutrino oscillations (fully reconstructed $K^+\to\mu^+\nu$)
- Heavy Neutral Leptons
- Dark Photons
- Axion Like Particles (ALPs)

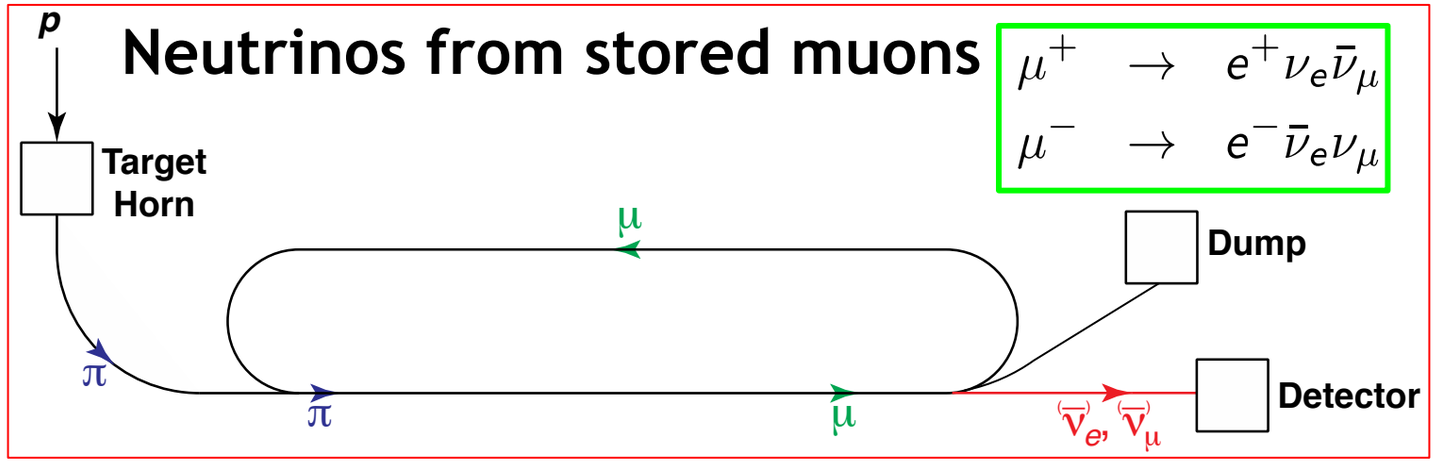
νSTORM

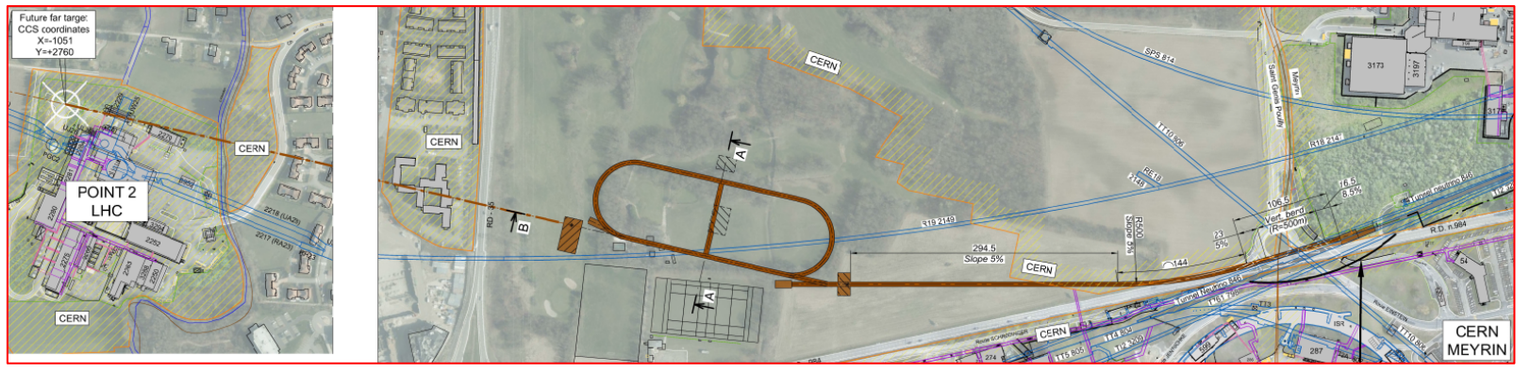
Alan Bross 2-4

NuSTORM

History ...
nuSTORM_v1: David Neuffer (1980)
nuSTORM_v2: At Fermilab (RIP 2013)
nuSTORM_v3: At CERN

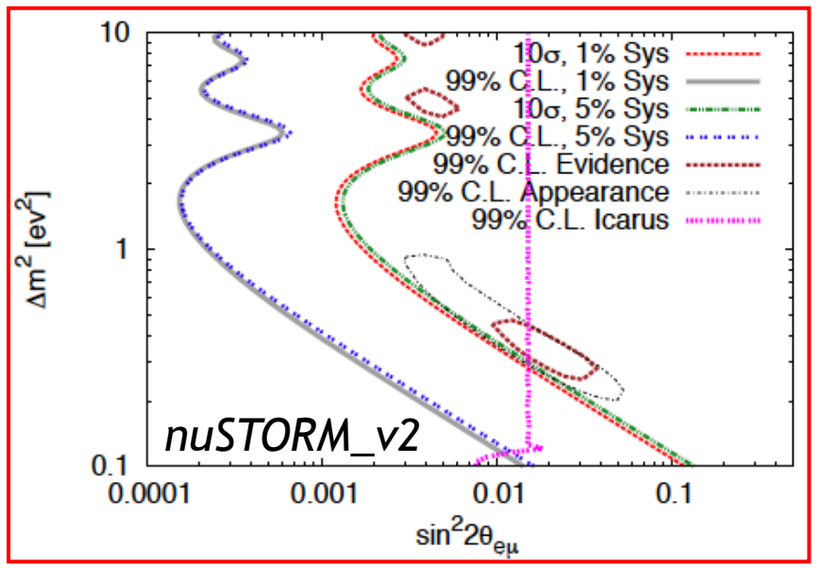
- **Scientific objectives:**
  1. %-level ($\nu_e N$) cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN





Extraction from SPS through existing tunnel

- nuSTORM_v3
  - based on existing technology
  - but reoptimization of the storage ring to cover muon energies from 1-6GeV
    - Cover both experiments (Hyper-K and DUNE)
  - Mayor cost - muon storage ring (decay ring)



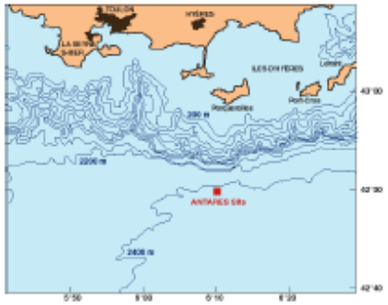
Neutrino Telescopes

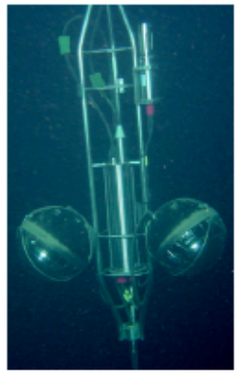
Paschal Coyle 2-1

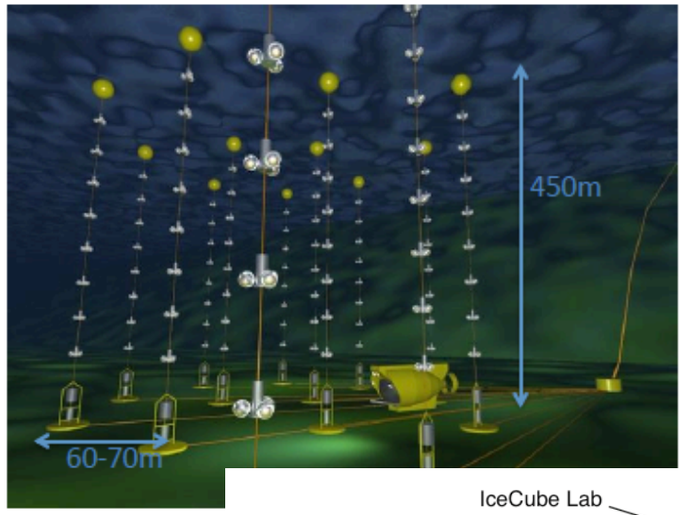
Neutrino Telescope Map

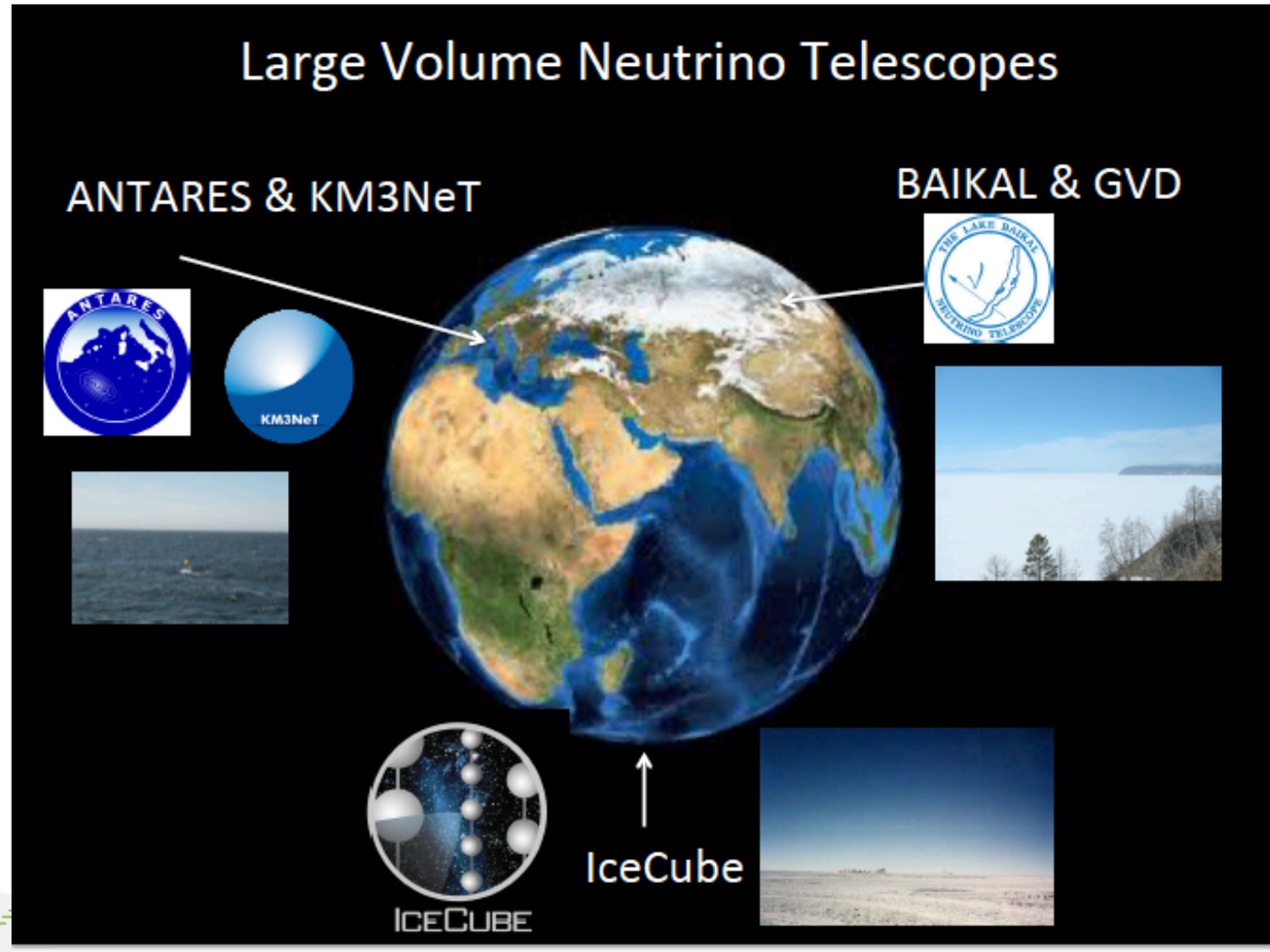
ANTARES

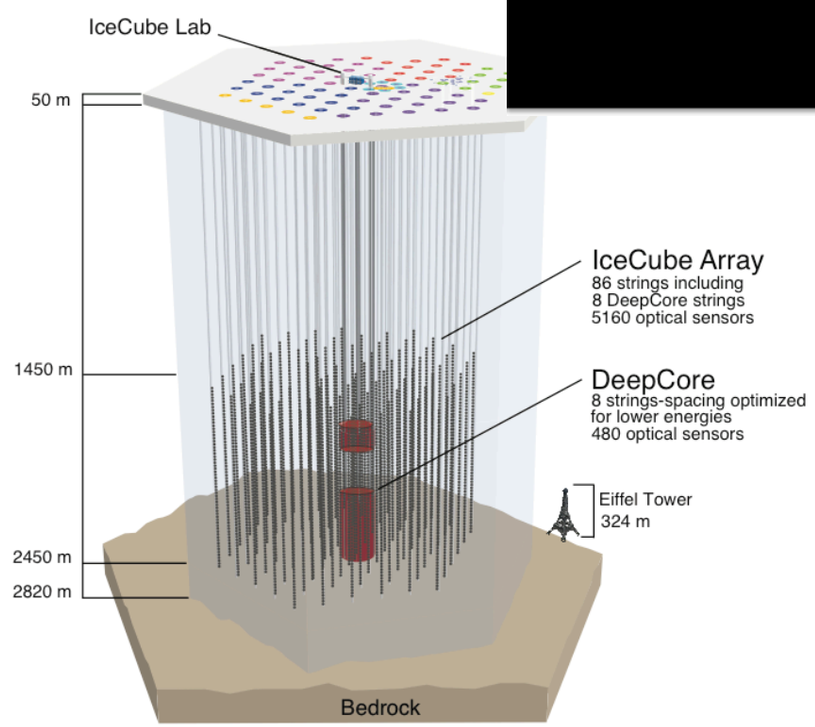
- 42km offshore Toulon, depth 2475m
- Main Electro-Optic Cable/Junction Box 2001-2002
- Completed 2008
- 12 lines, ~70m spacing
- 25 storeys per line, 15m spacing
- 3x10-inch PMTs per storey
- Decommissioning 2017





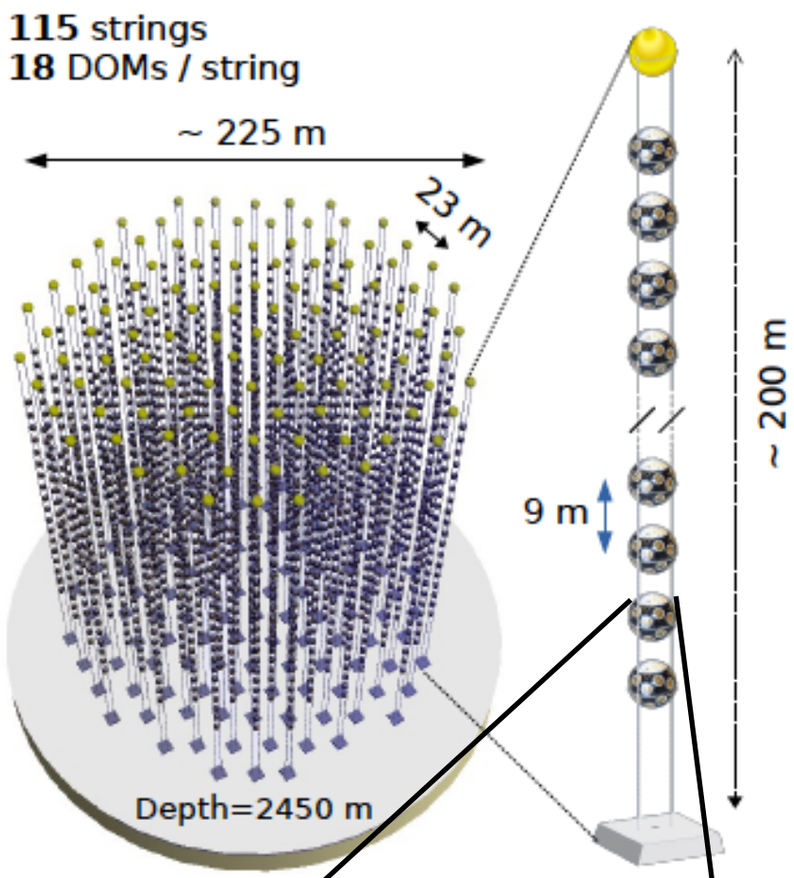


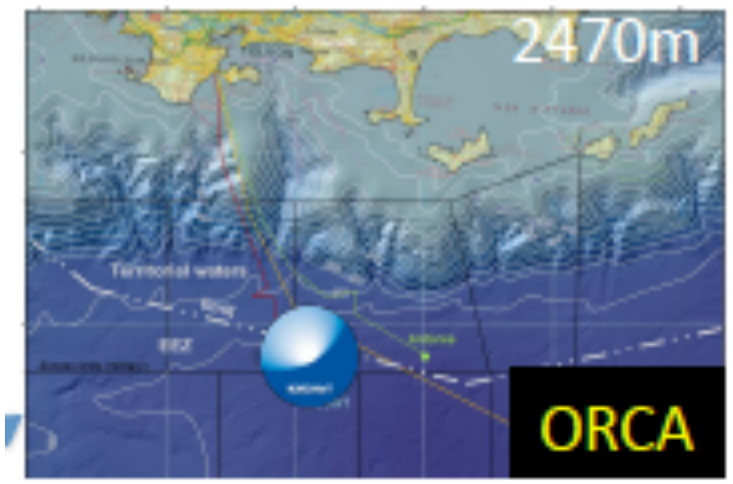




Paschal Coyle 2-1

ORCA/ARCA



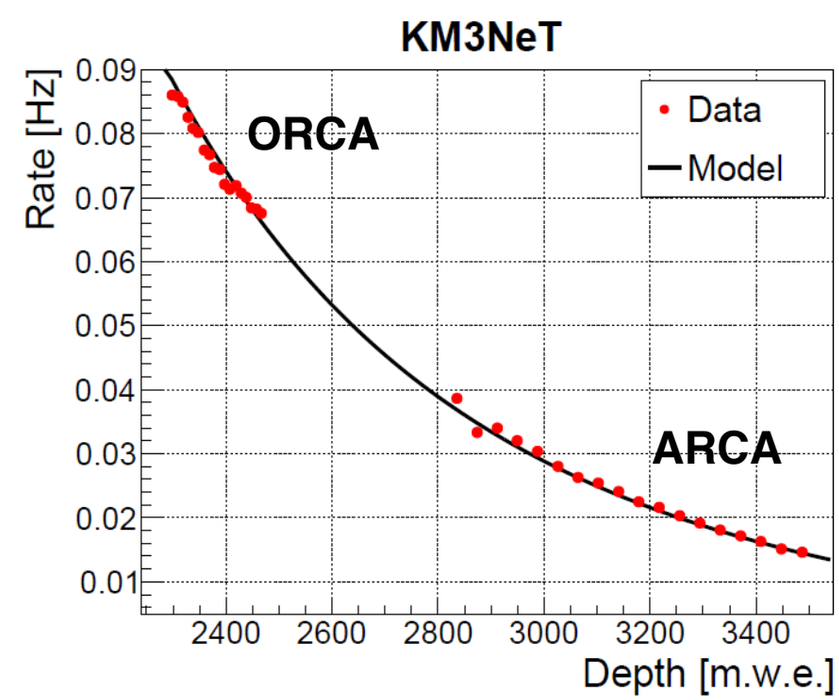


Oscillation **R**esearch with **C**osmics In the **A**byss

Astroparticle **R**esearch with **C**osmics In the **A**byss

Construction on going

	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Instrumented mass	8 Mton	500*2 Mton



Tom Stuttard 2-2

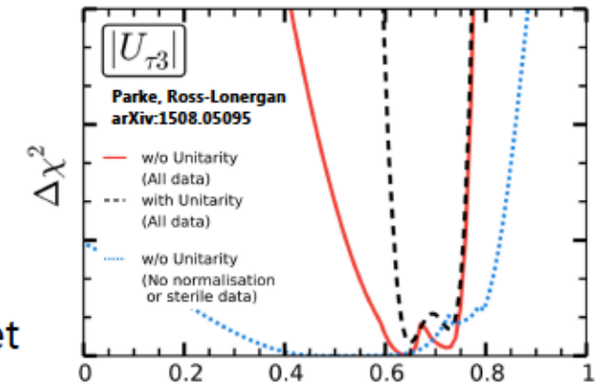
IceCube - PMNS Unitarity

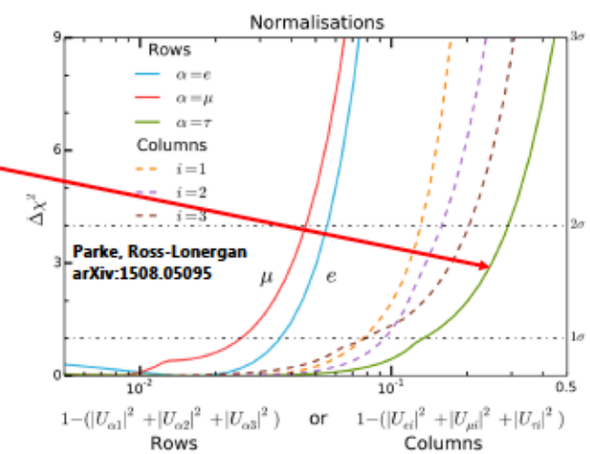
UNIVERSITY OF COPENHAGEN Tom Stuttard 5

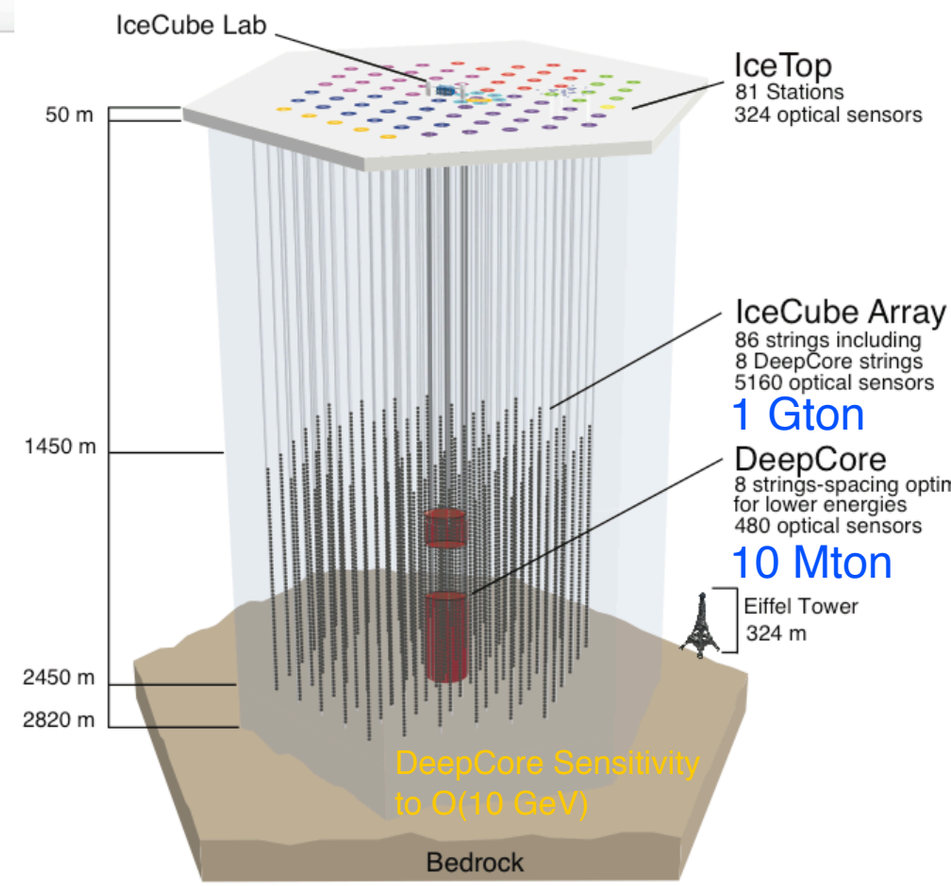
PMNS unitarity

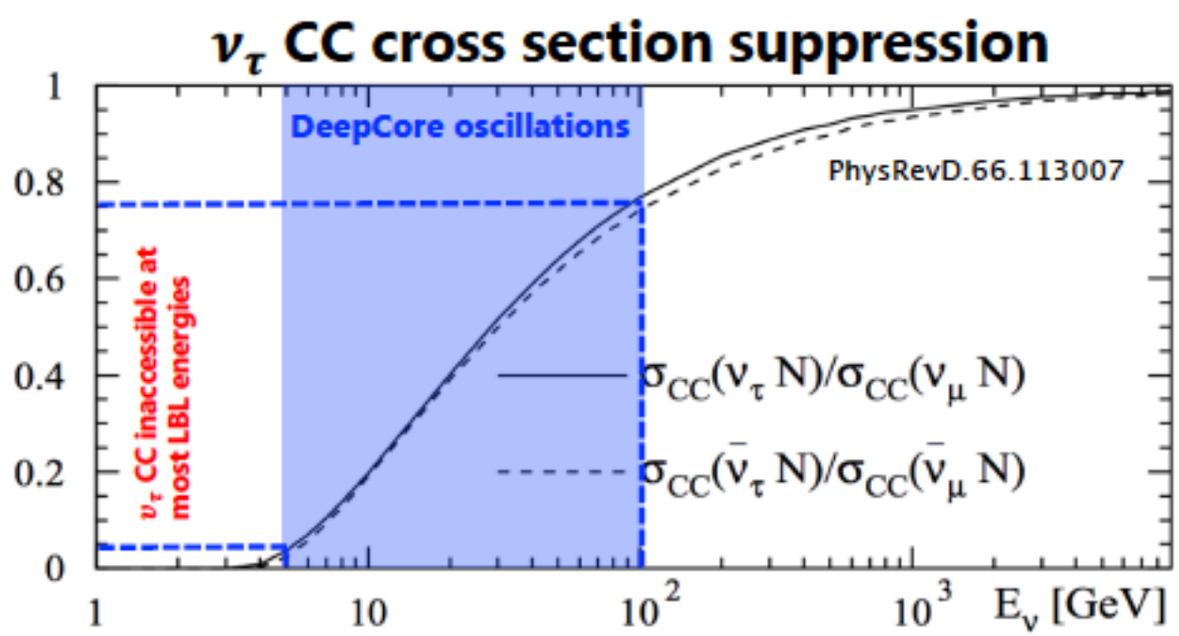
- **PMNS** mixing matrix is **unitary** in standard oscillation picture
  - e.g. mixing between the 3 known neutrino flavours
- Additional (sterile?) states → 3x3 matrix is subset of full unitary matrix
- Test unitarity by measuring 3x3 matrix elements
  - **ν_τ elements least well measured**

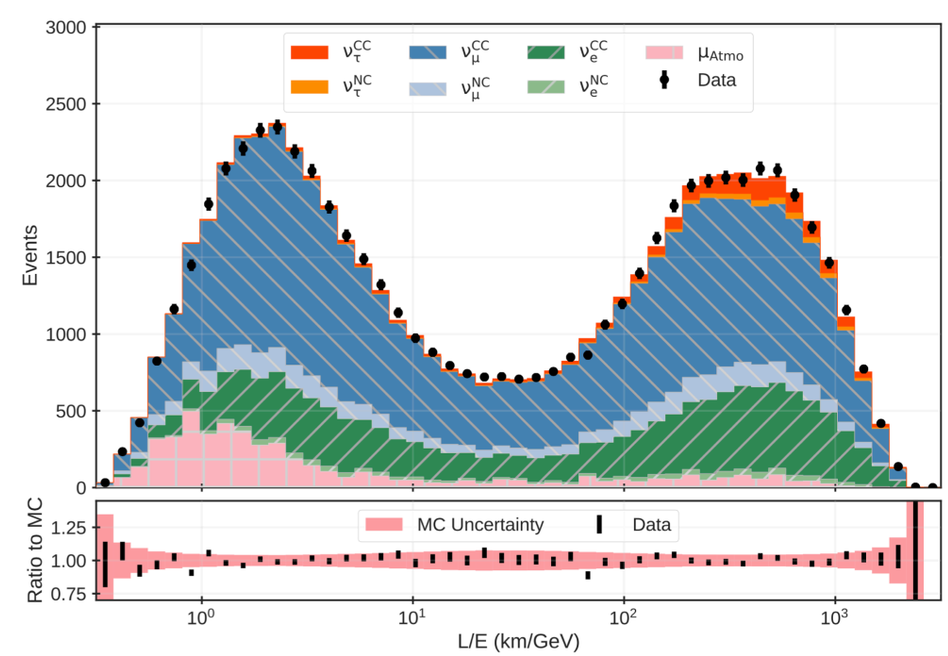
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ \boxed{U_{\tau 1} \quad U_{\tau 2} \quad U_{\tau 3}} & & & \\ \vdots & & \ddots & \end{pmatrix}}^{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$





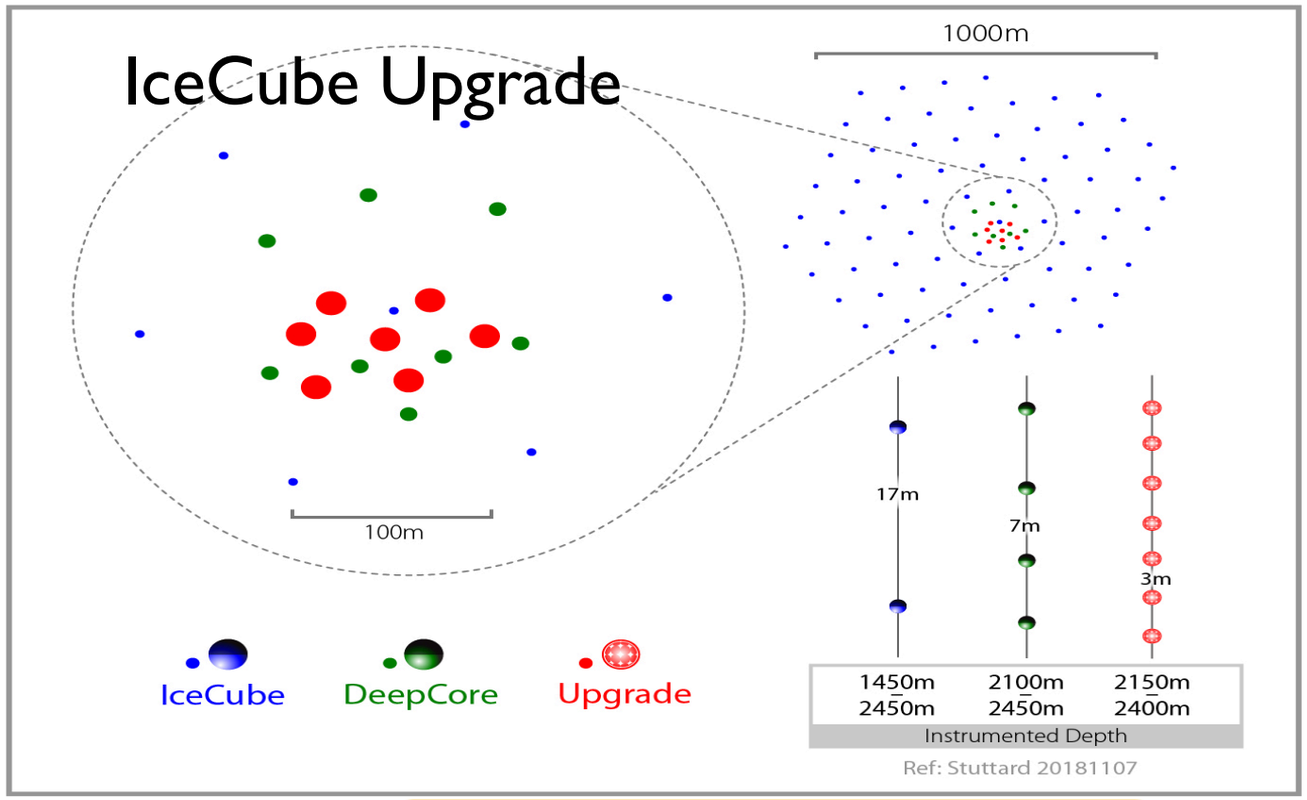






Tom Stuttard 2-2

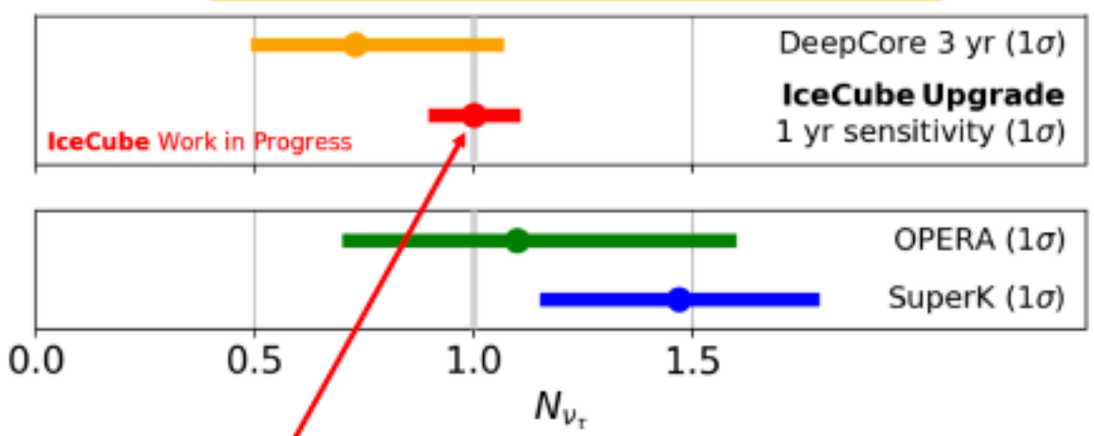
IceCube Upgrade



The IceCube Upgrade

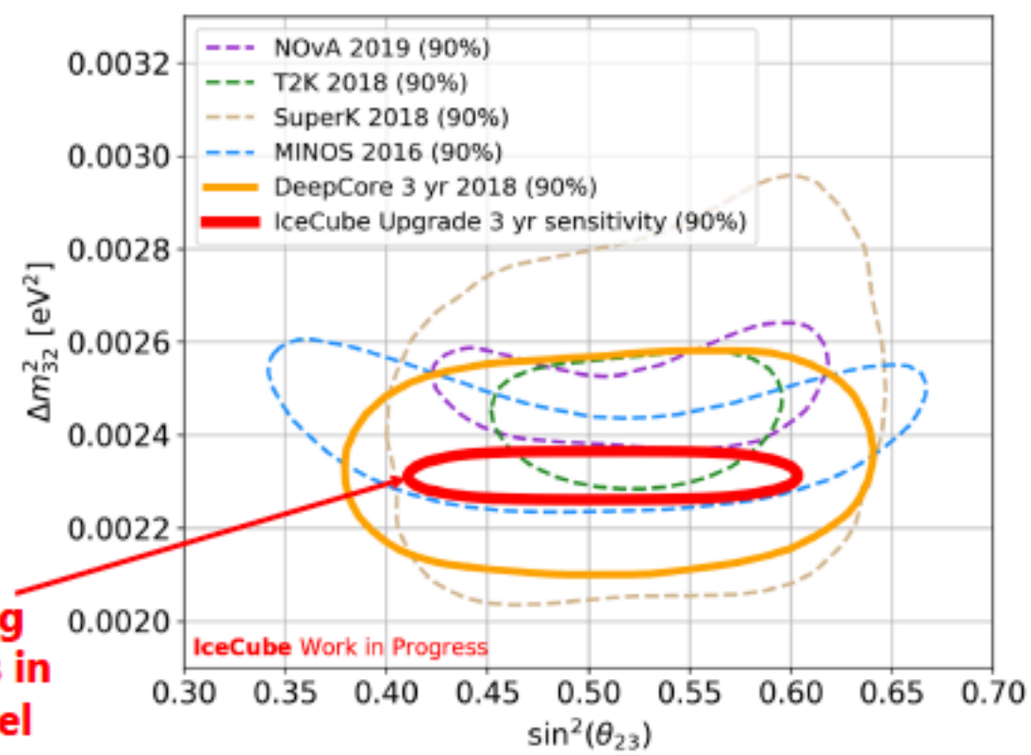
- NSF has funded a $30M extension to IceCube
  - Deployment in 2022/2023
- 700 multi-PMT sensors
- Improved ice calibration

ν_τ appearance sensitivity (1 yr)



10% precision after 1 year
(6% after 3 years)

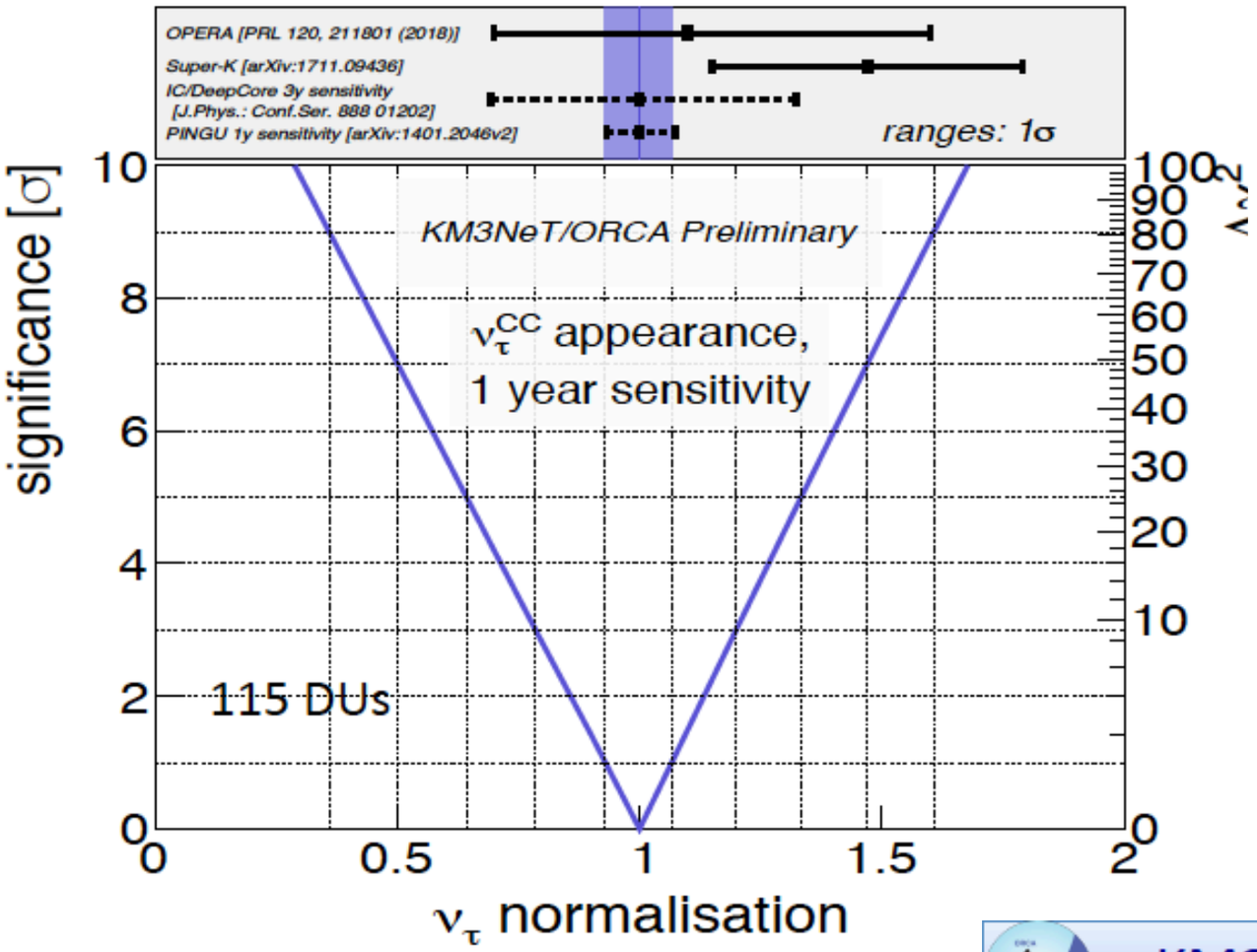
ν_μ disappearance sensitivity (3 yr)

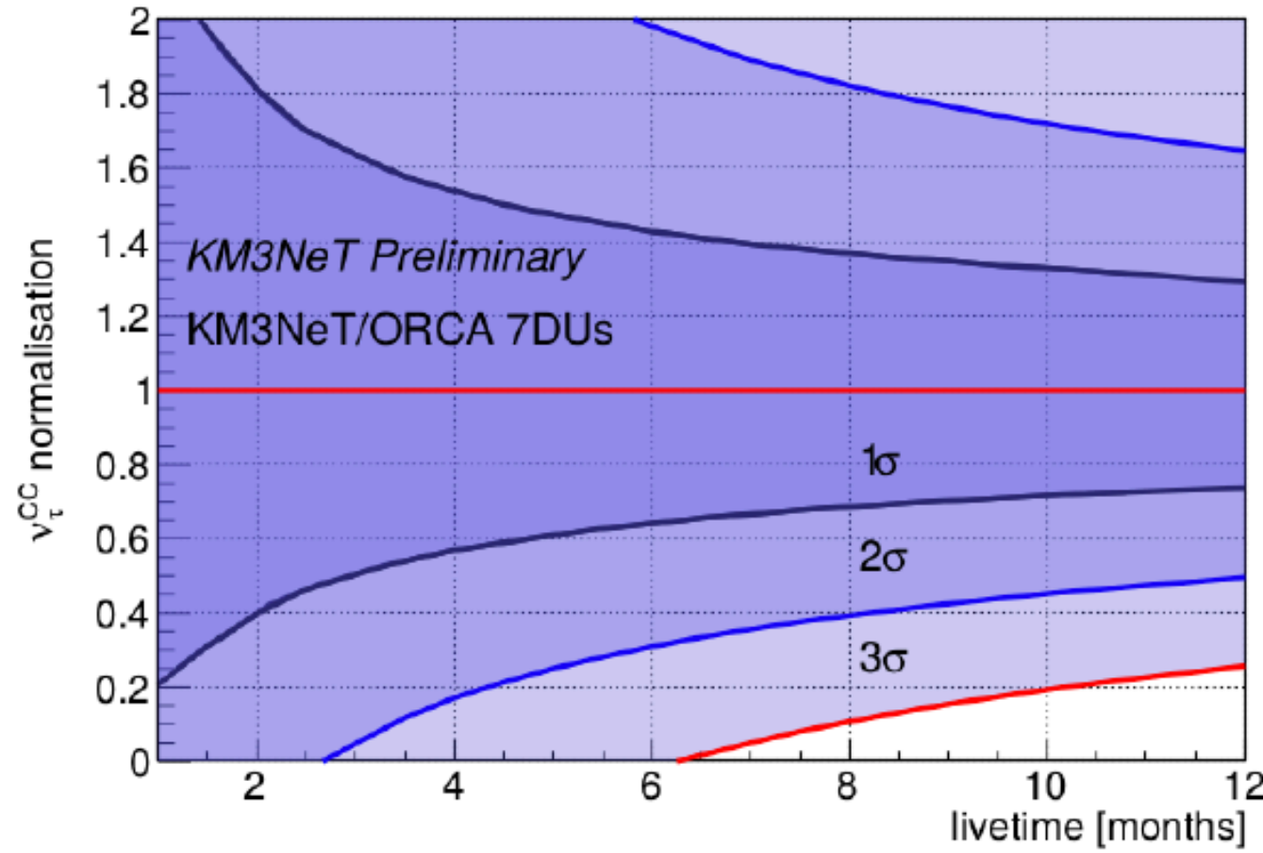


Competitive with long baseline experiments in disappearance channel

Paschal Coyle 2-1

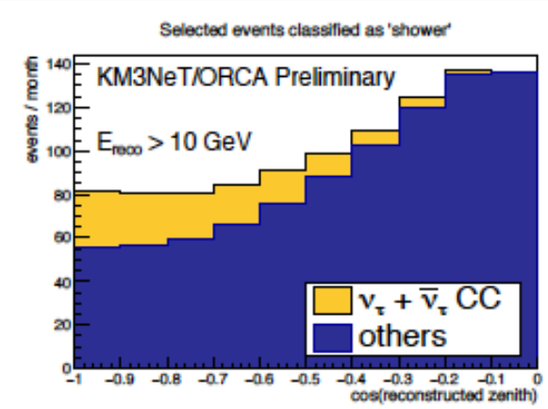
ORCA





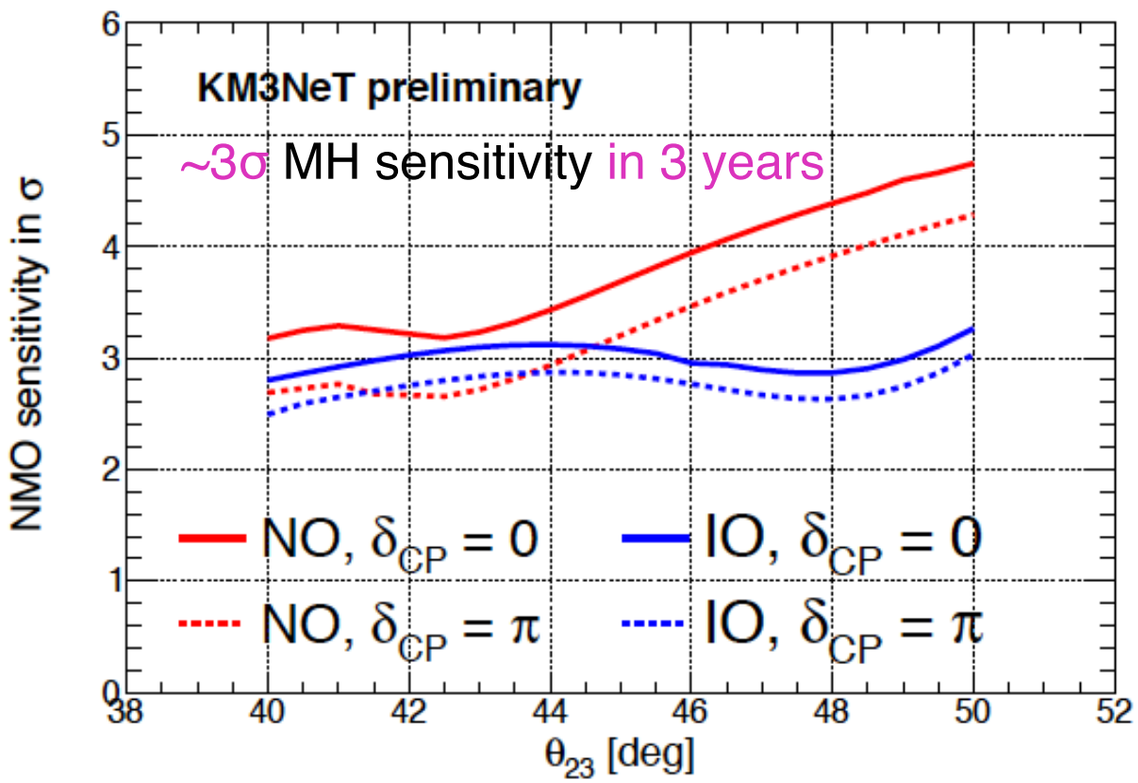
KM3NeT/ORCA: Tau neutrino appearance

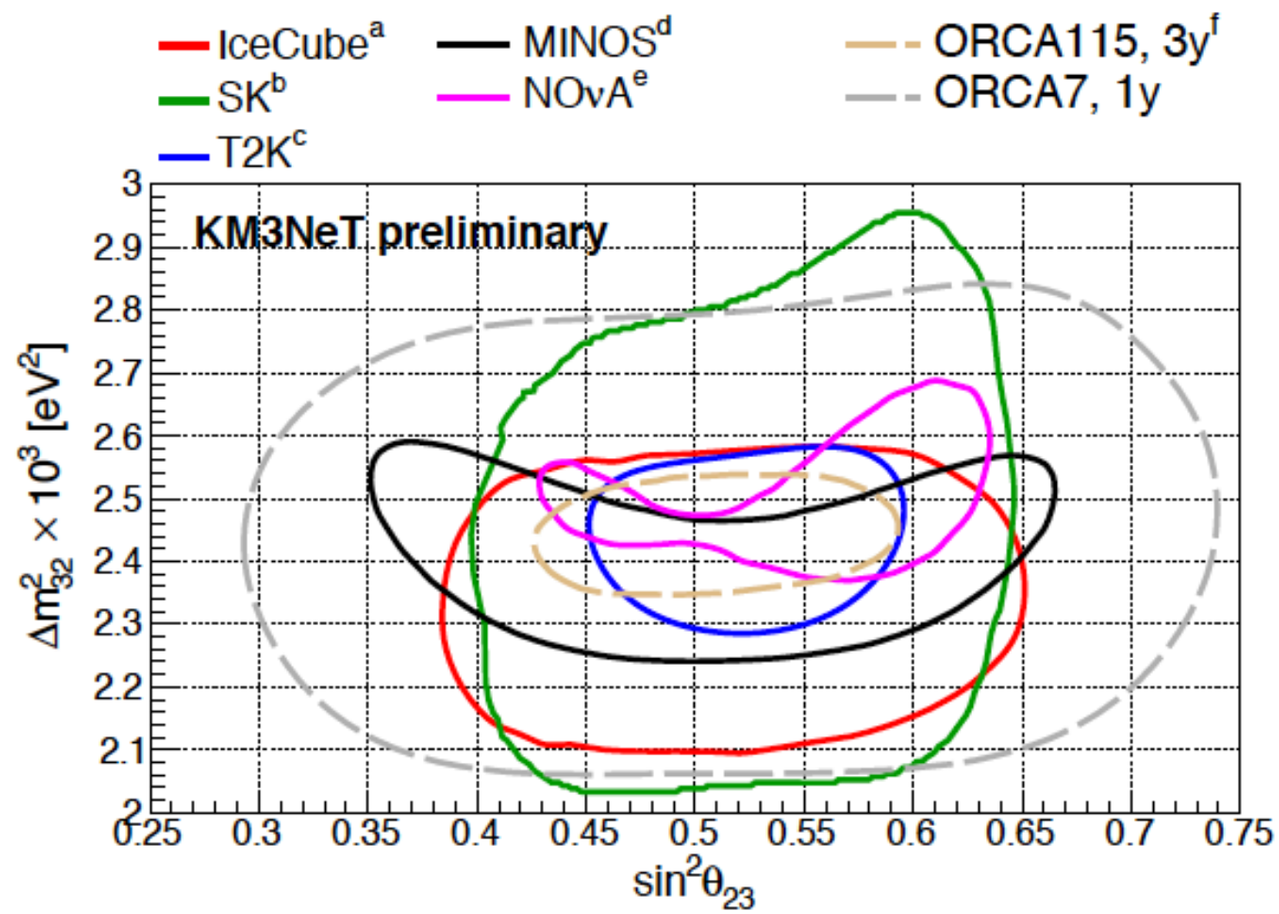
- ν_τ appearance tests PMNS unitarity and BSM theories
- 30% deviations allowed by world data
- ≈3k ν_τ CC events/year with full ORCA
- Rate constrained within ≈5 (25)% for 115 (7) DUs in 1 year



Paschal Coyle 2-1

ORCA Outlook





Further science goals of ORCA (115 lines):

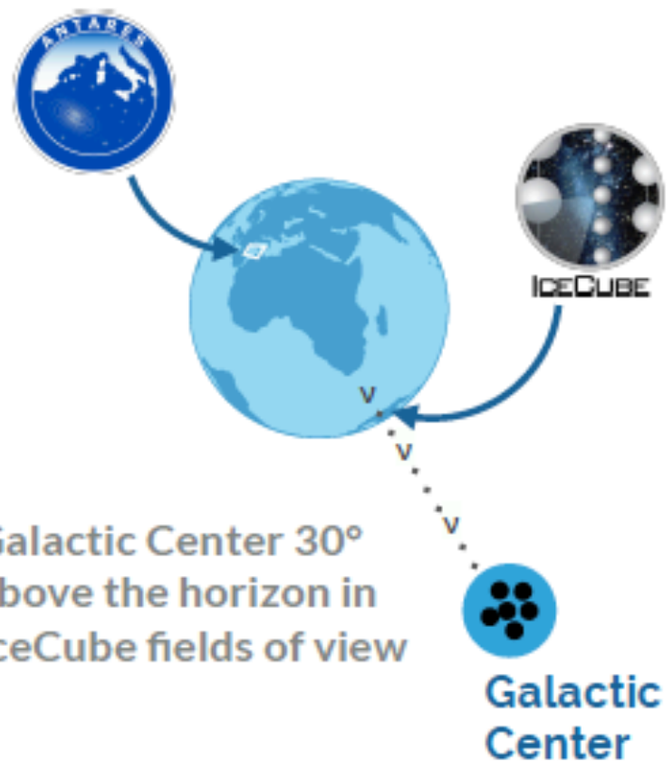
- Precision measurements of Atmospheric Neutrino Oscillation Parameters
- Determination of the neutrino mass ordering

Juan A. Aguilar 5-3

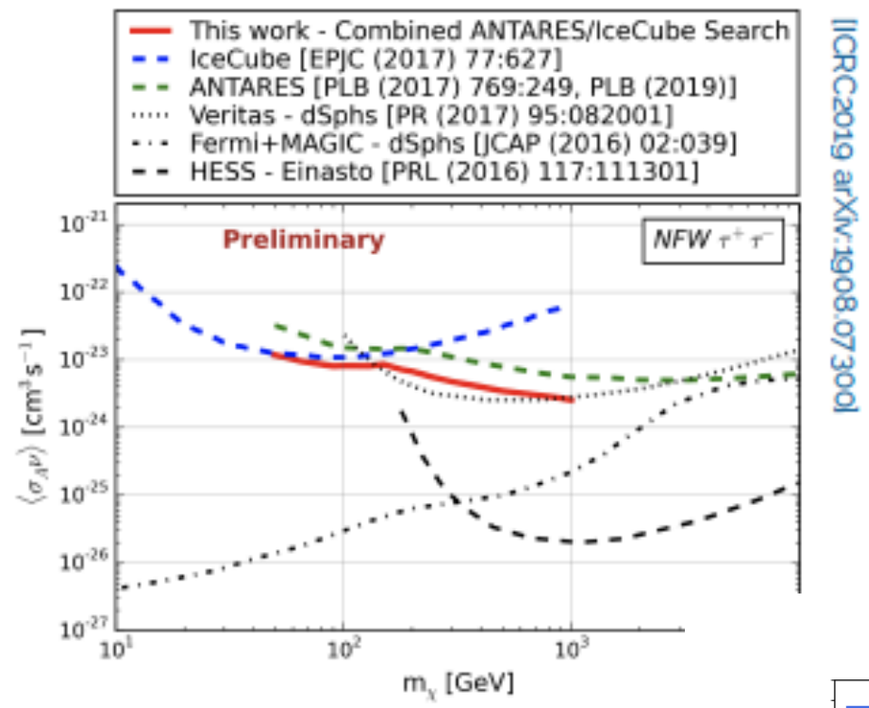
Dark Matter Searches

Galactic Center ANTARES & IceCube

9



- ANTARES uses Earth as a shield/higher masses
- IceCube uses a self-veto technique/lower masses



ICRC2019 arXiv:1908.07300

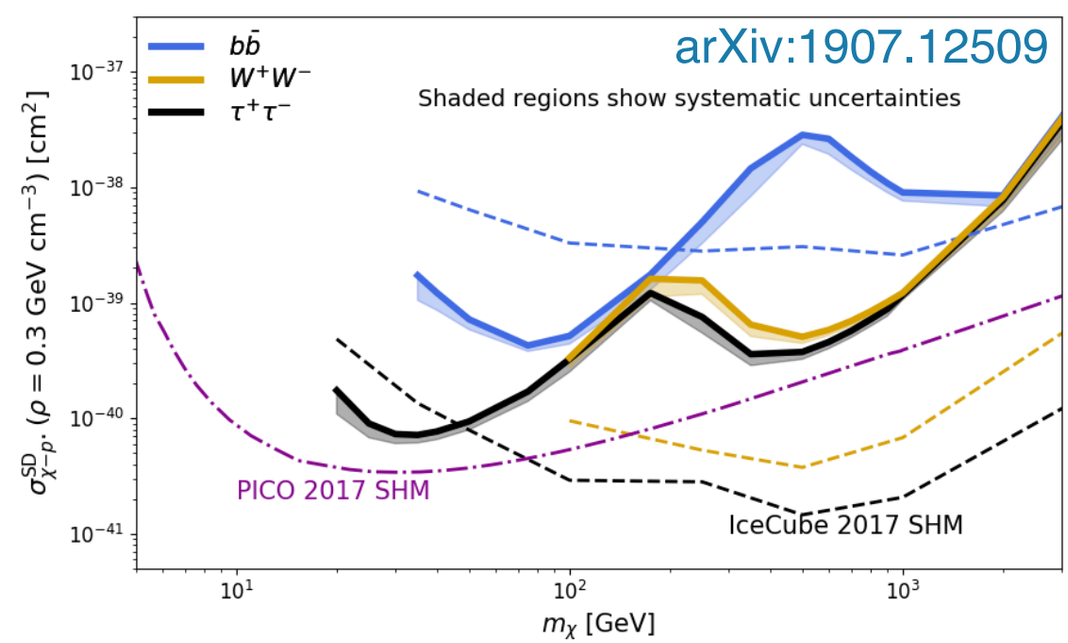
NuFACT 2019 - 29/08/2019

Velocity Independent PICO and IceCube

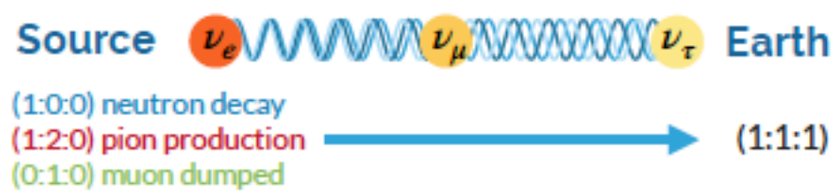
Deviations from the SHM will affect spin-dependent limits.

Construction of independent limits assuming as the superposition of streams with fixed velocity.

Conservative limits: only the velocity stream with the highest allowed scattering cross-section is selected



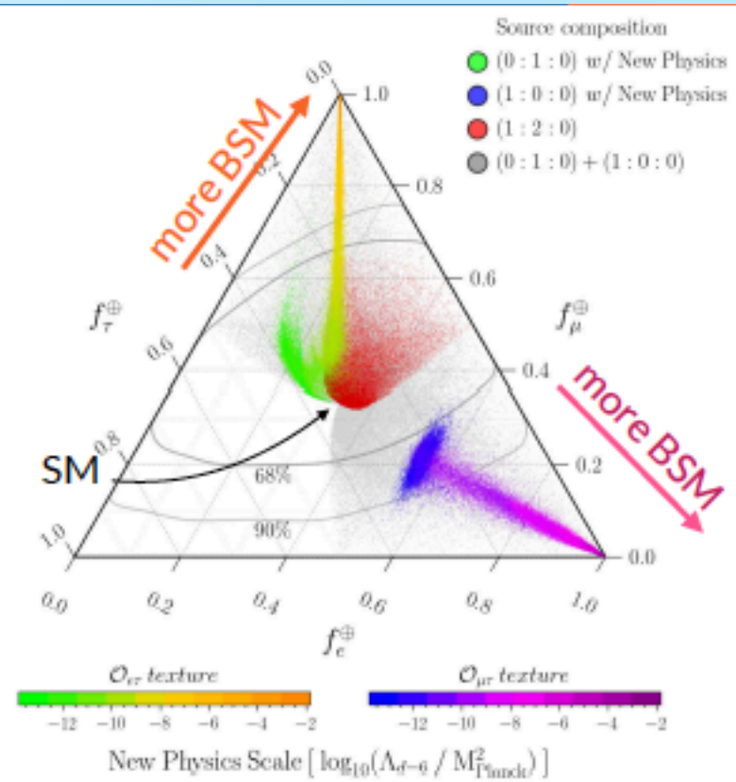
IceCube - New Physics from Astrophysical Neutrinos



- New physics can alter the 1:1:1 prediction.
- Parametrize new physics through a scale Λ_d and an operator O_d:

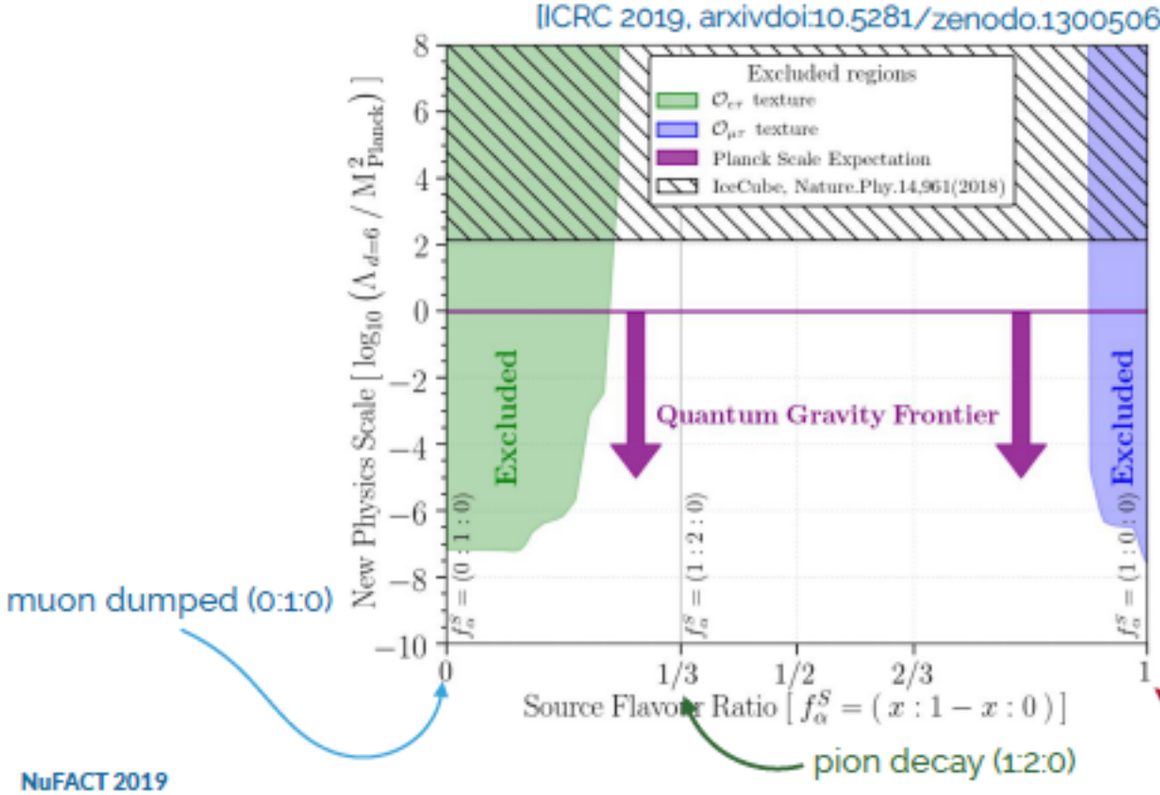
$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger$$

standard oscillations — new physics oscillations



NuFACT 2019 — Juan A. Aguilar

[ICRC 2019, arxivdoi:10.5281/zenodo.1300506]



IceCube is a multipurpose experiment with a rich program on BSM and Dark Matter searches.

Indirect detection of Dark Matter with neutrino telescopes provides complementarity to other techniques due to different backgrounds and systematics.

IceCube has world-best limits on spin-dependent scattering cross-section.

The detection of the astrophysical neutrino flux has open the opportunity

NuFACT 2019 — Juan A. Aguilar

Sterile Neutrinos in Astrophysical Environments

Dukjae Jang 5-2

Sterile Neutrinos in Astrophysical Environments

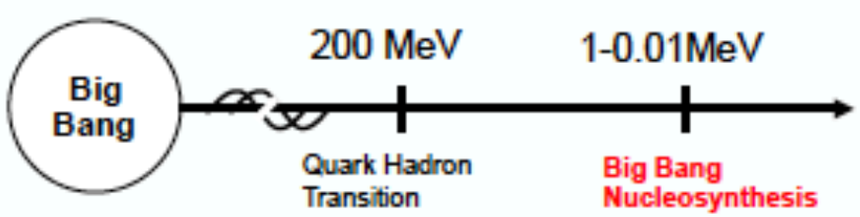
Sterile neutrinos

ν_s

Cosmic expansion rate

$$H^2 \propto \rho_{\nu_s}$$

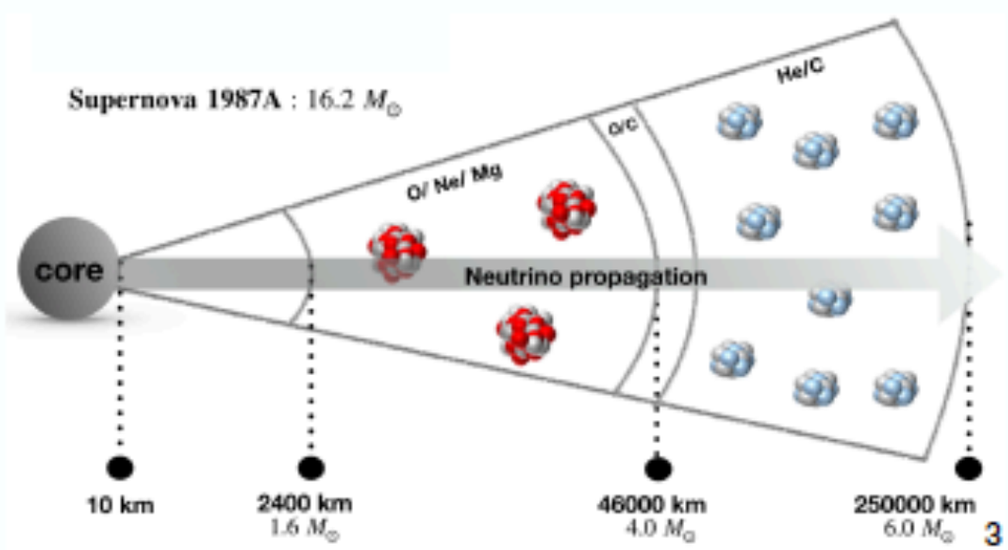
I. Big Bang Nucleosynthesis



Neutrino induced reaction rate

$$\nu_s \leftrightarrow \nu_a$$

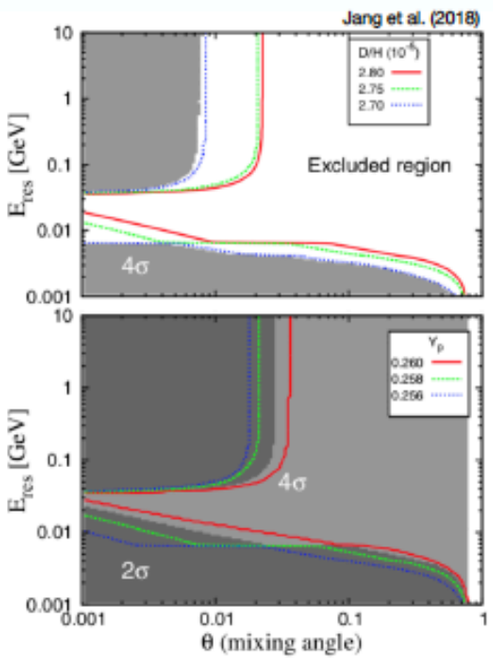
II. Supernova Neutrino process



Dukjae Jang 5-2

Sterile Neutrinos in Astrophysical Environments

BBN constraint $(m_{\nu_s} = 1\,\mathrm{eV})$



Cold Dark Matter Constraint

The energy density of the cold dark matter

$$\rho_c = (0.1261 \pm 0.0033) \times 10^{-5}\,\mathrm{GeV cm^{-3}}$$

P. A. R. Ade et al. (*Planck* Collaboration), Astron. Astrophys. **571**, A16 (2014).

For the relic sterile neutrinos, $\rho_{\nu_s} \leq \rho_c$

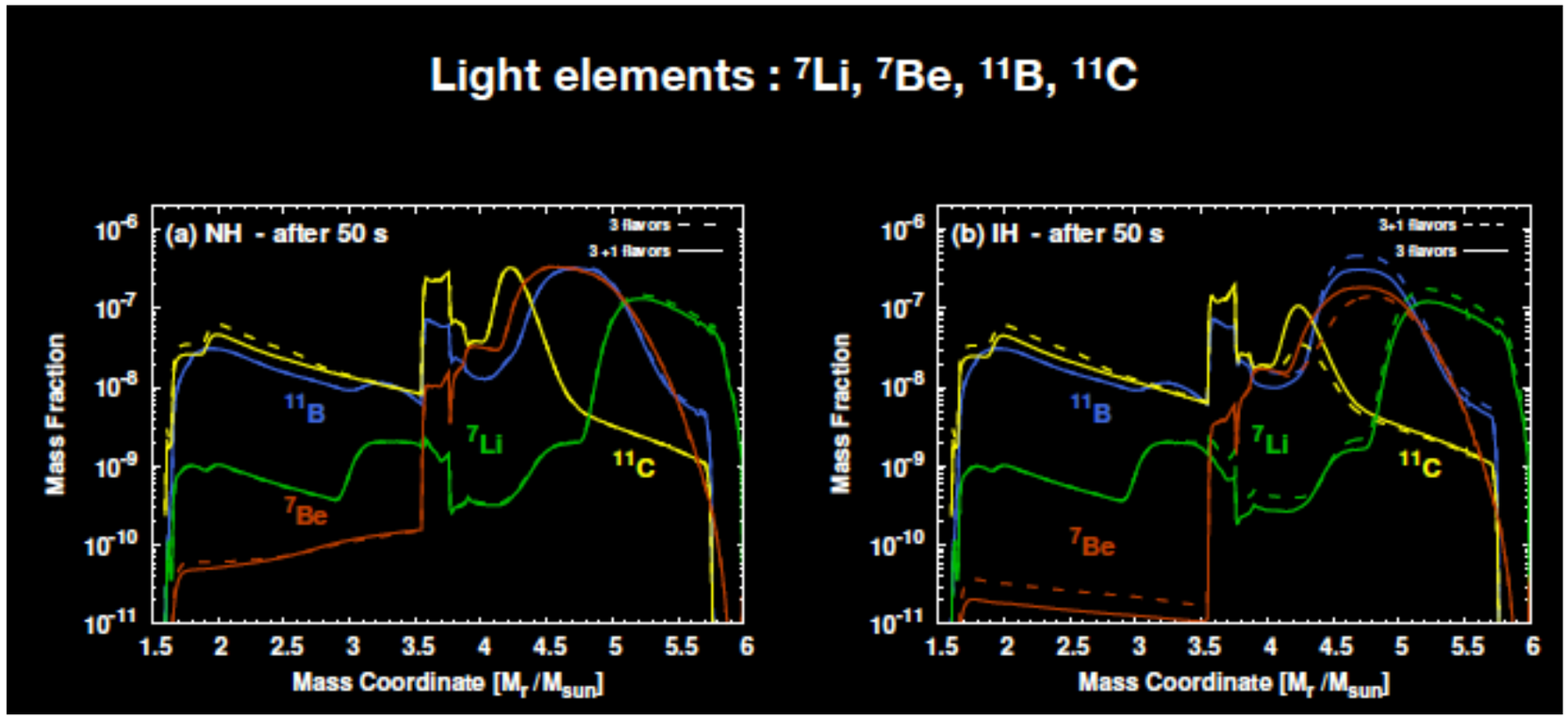
Case : $m_{\nu_s} = 1\,\mathrm{eV}$

↓

All parameter space is allowed by CMB.

D. Jang et al., Phys. Rev. D **97** 043005

The viability of 3+1 neutrino model on the supernova neutrino process

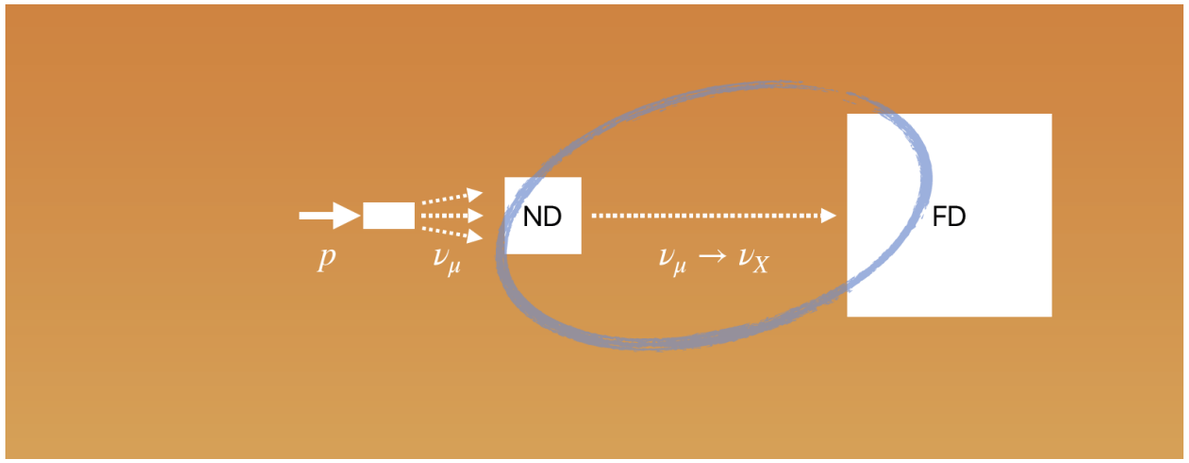


BSM with long baseline

Kihyeon Cho 3-3

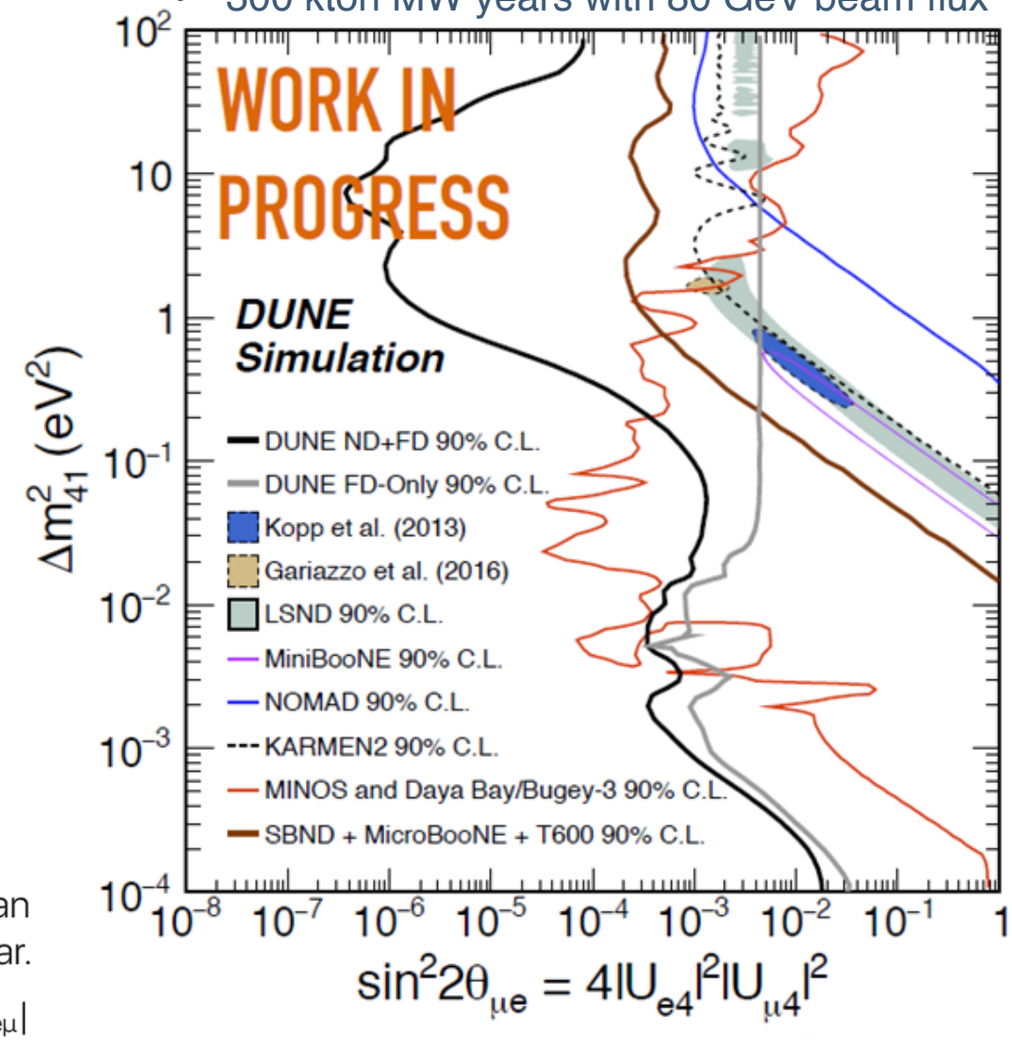
BSM DUNE

Non-standard Oscillation

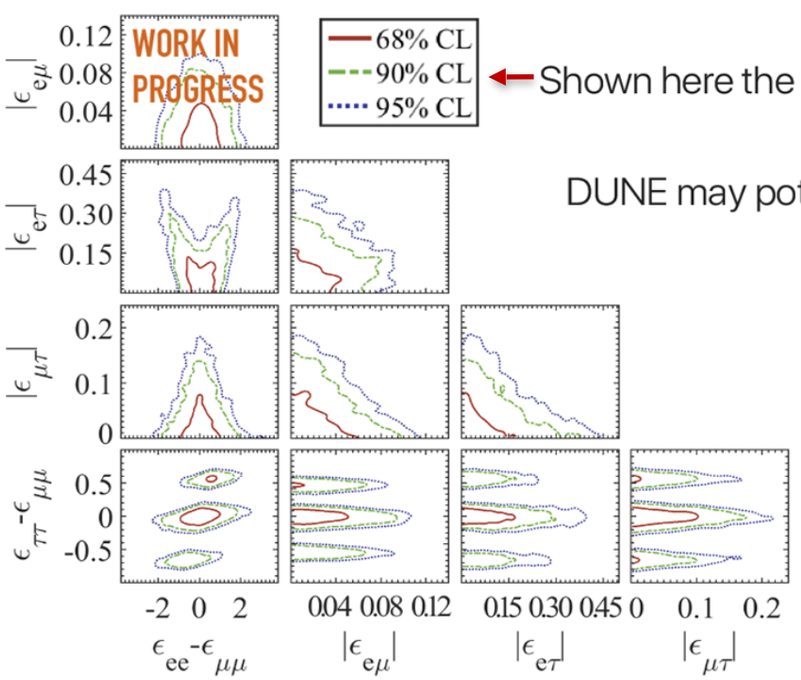


Sterile Neutrino Mixing

- 300 kton·MW·years with 80 GeV beam flux

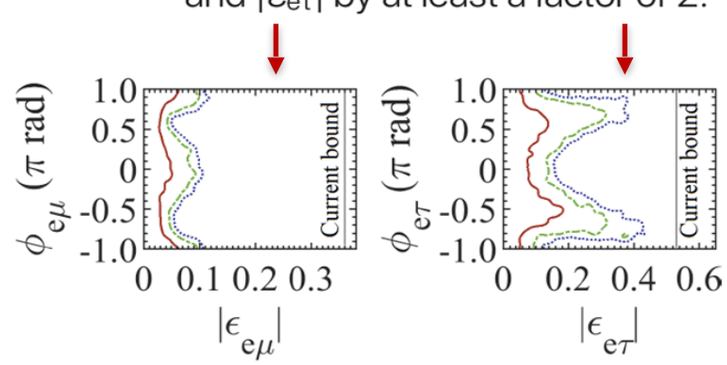


Non-Standard Interactions (NSI)



Shown here the allowed regions (68, 90 and 95% CL) for an exposure of 300 kton·MW·year.

DUNE may potentially improve present constraints on $|\varepsilon_{e\mu}|$ and $|\varepsilon_{e\tau}|$ by at least a factor of 2.

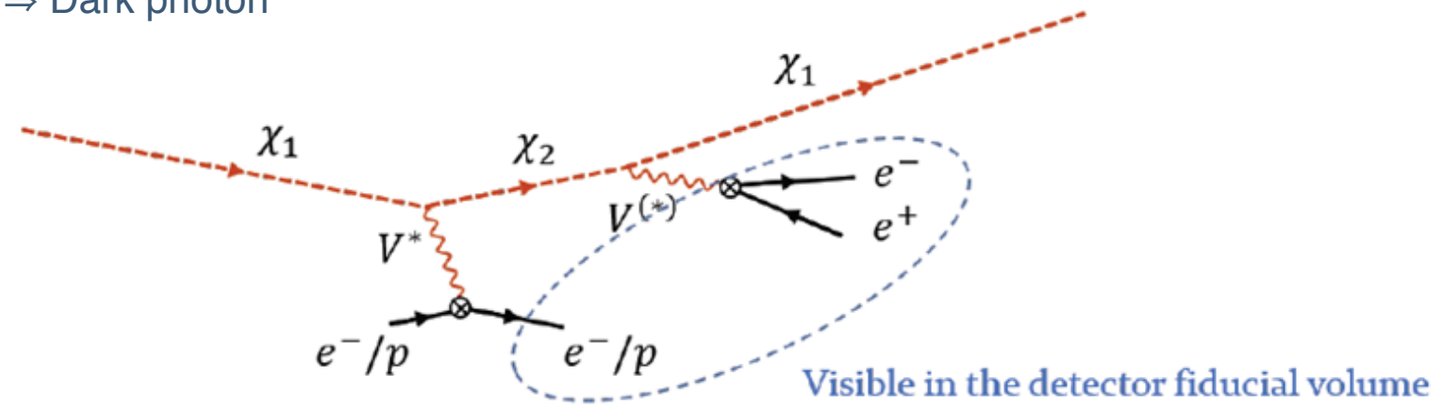


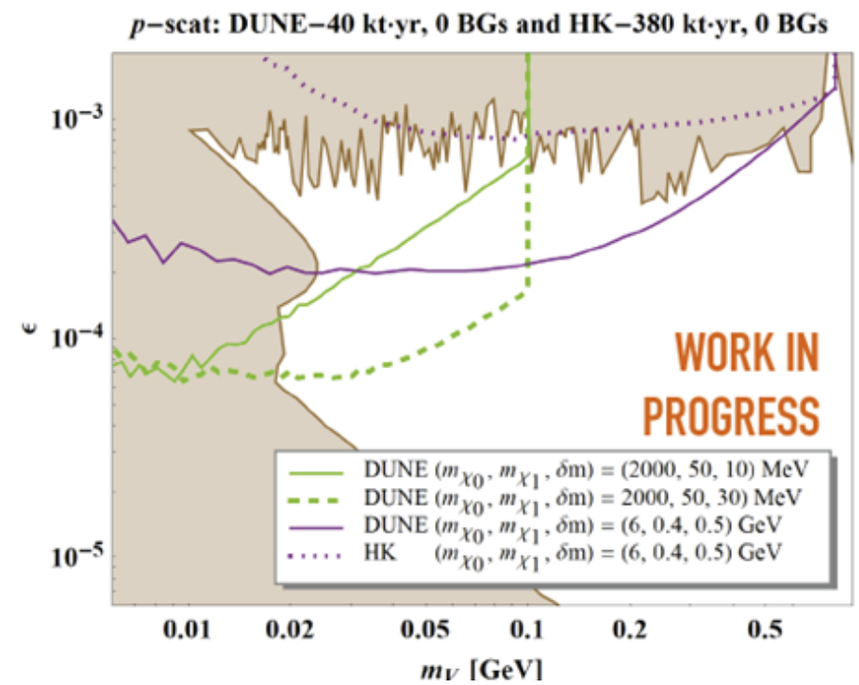
Diverse program including

- Non-Unitary Mixing
- CPT Violation
- Dark Matter
- Nucleon decay
- …

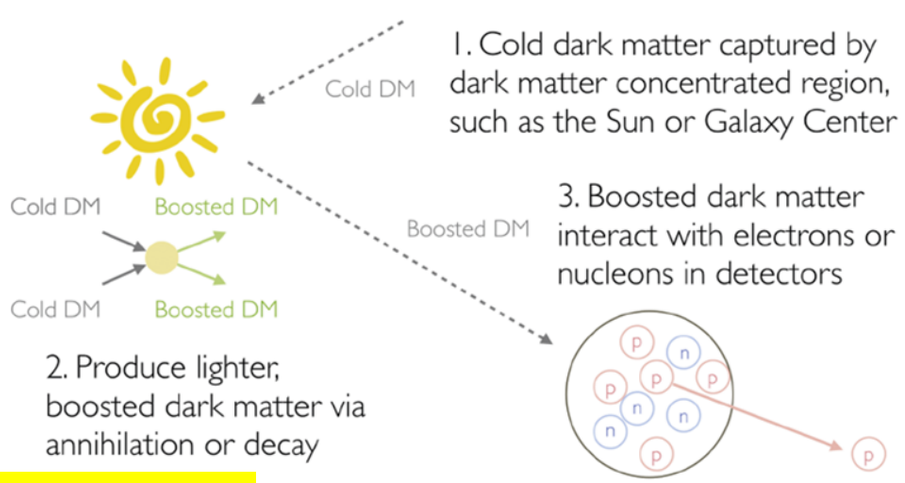
Boosted Dark Matter

- **Galactic halo** can produced dark matter which could interact inelastically in DUNE.
  ⇒ Dark photon

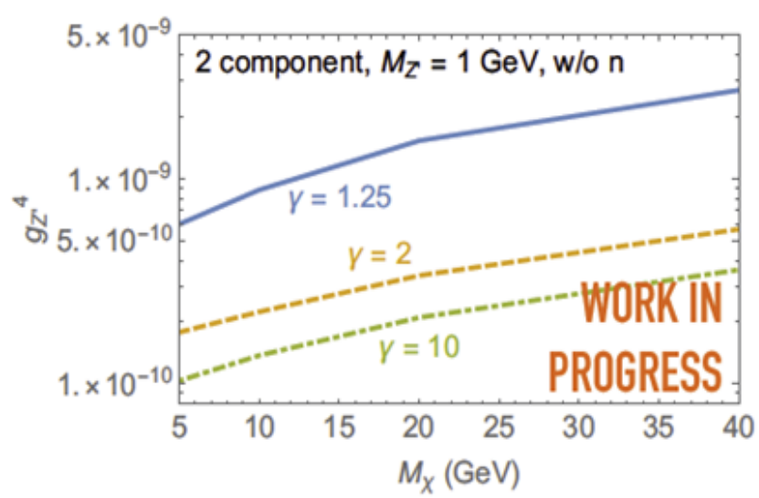




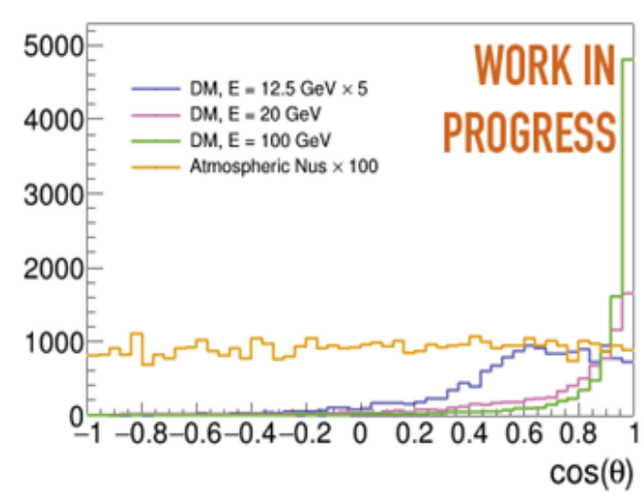
- Dark matter from the **center of the Sun** could interact elastically with the DUNE.
  ⇒ Lepto-phobic Z'



JCAP02(2015)005

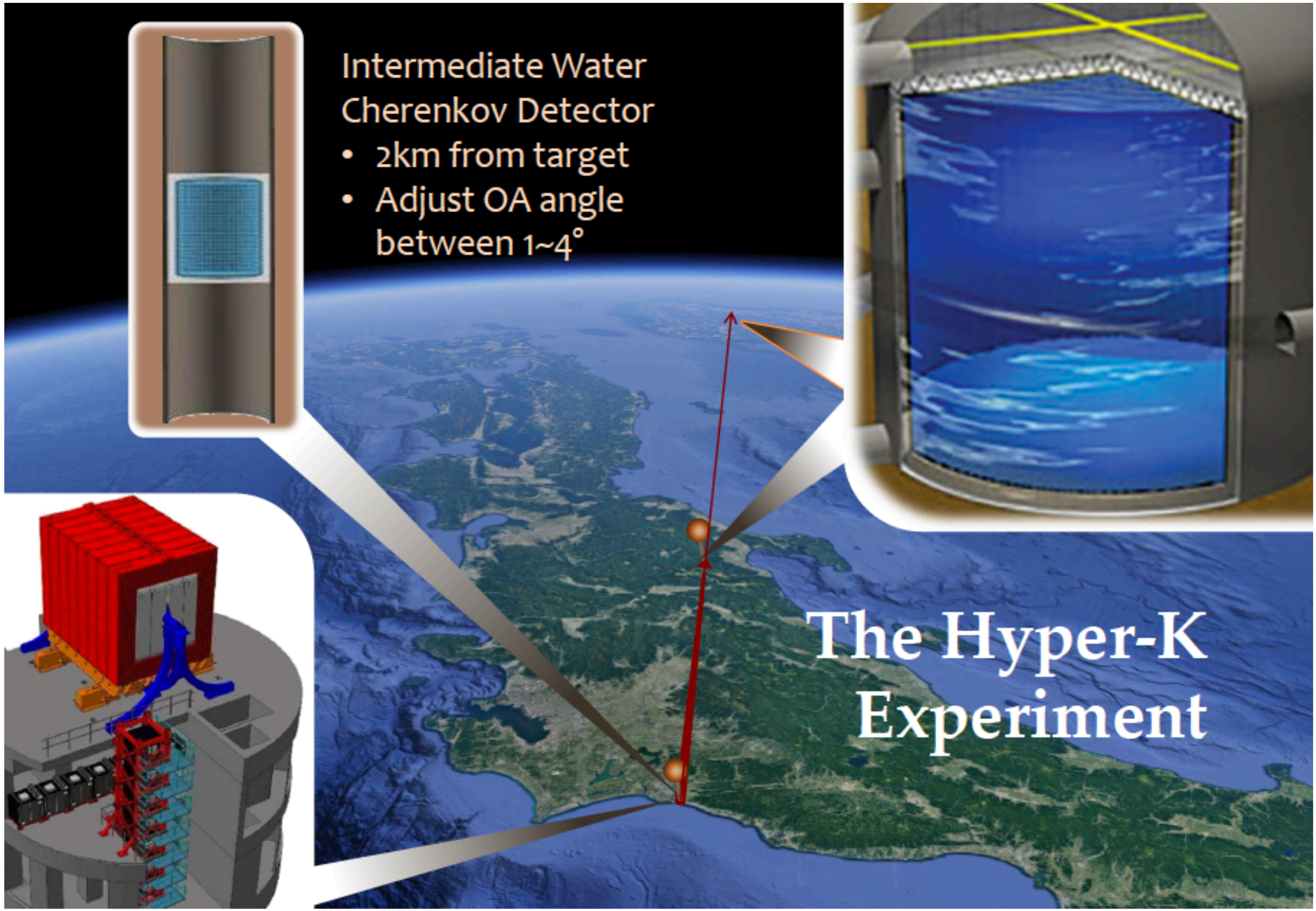


Expected 5σ discovery reach with 1year DUNE lifetime



Angle between Sun and particles produced

Phill Litchfield 2-3



Hyper-Kamiokande

Sterile analyses with Hyper-K

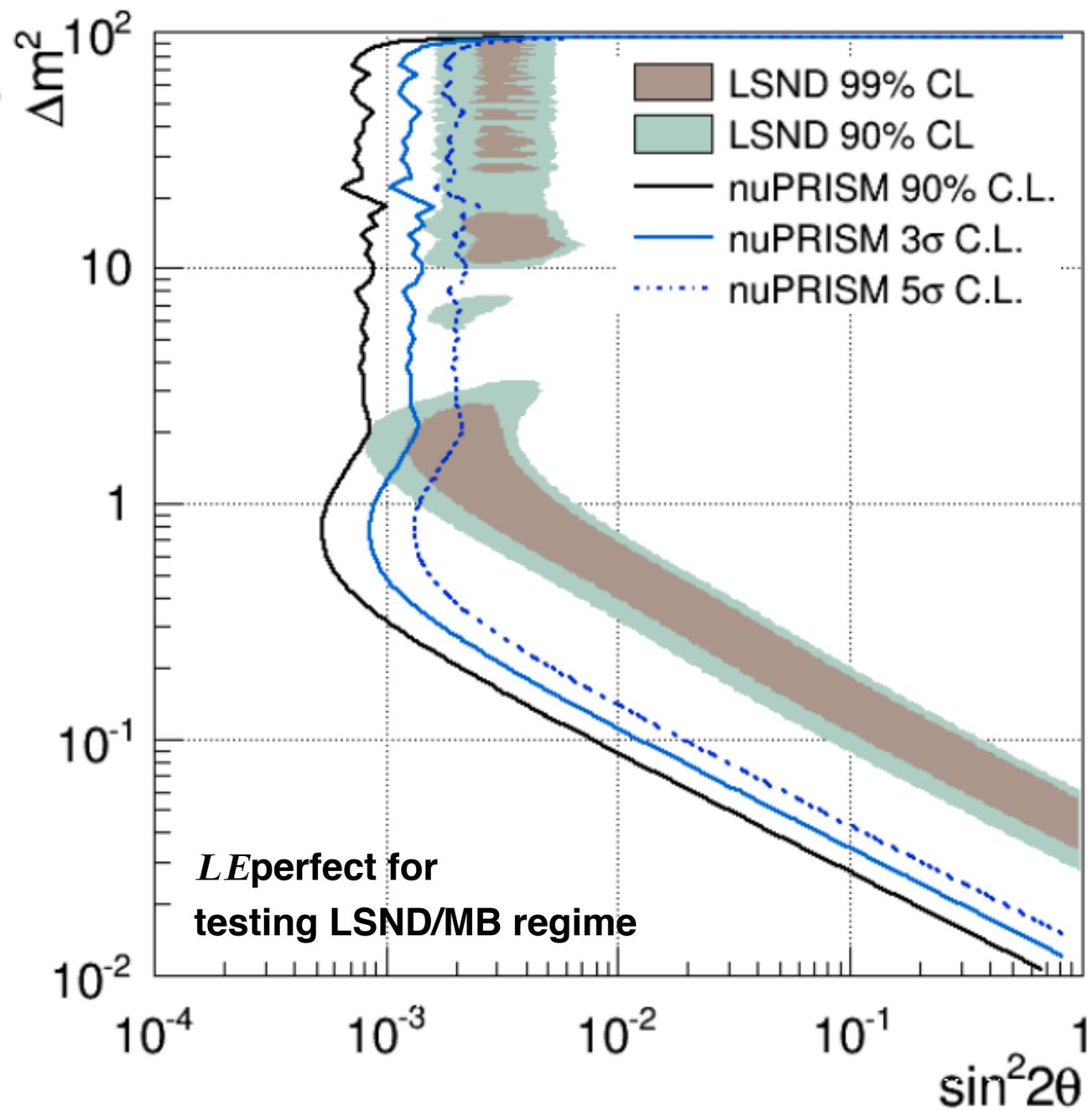
Can simply extend/improve on T2K analyses, with more statistics and improved systematic controls.

- Possibly do $P(\nu_\mu \to \nu_\mu)$ as well
- Also update SK search for ν_s with atmospheric neutrinos
  - Uses active-sterile matter effect in the core.

More interesting is prospects from IWCD at 2km

- **Via $\nu_\mu \to \nu_e$ channel**
- Still have ND280 constraint
- Use OA variation to constrain BGs

Phill Litchfield



Phill Litchfield 2-3

NSI and CP-violation

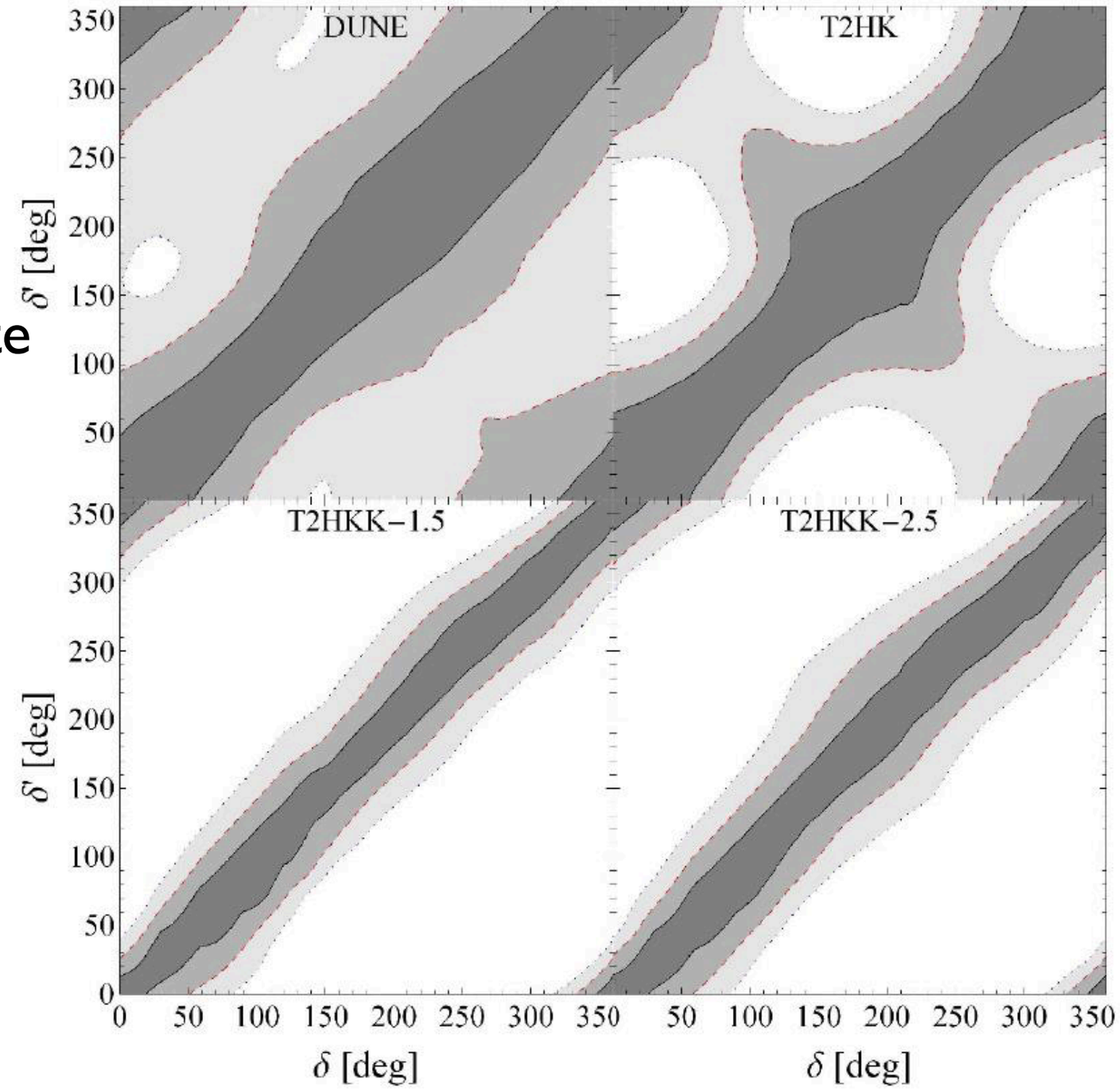
Also analysed in JHEP 01 (2017) 071:

NSI can resemble the CP-violation signal that we are looking for!

Some NSI parameter combinations are near-degenerate with normal mixing.

We couldn't discover NSI, but we would still get δ_{CP} wrong.

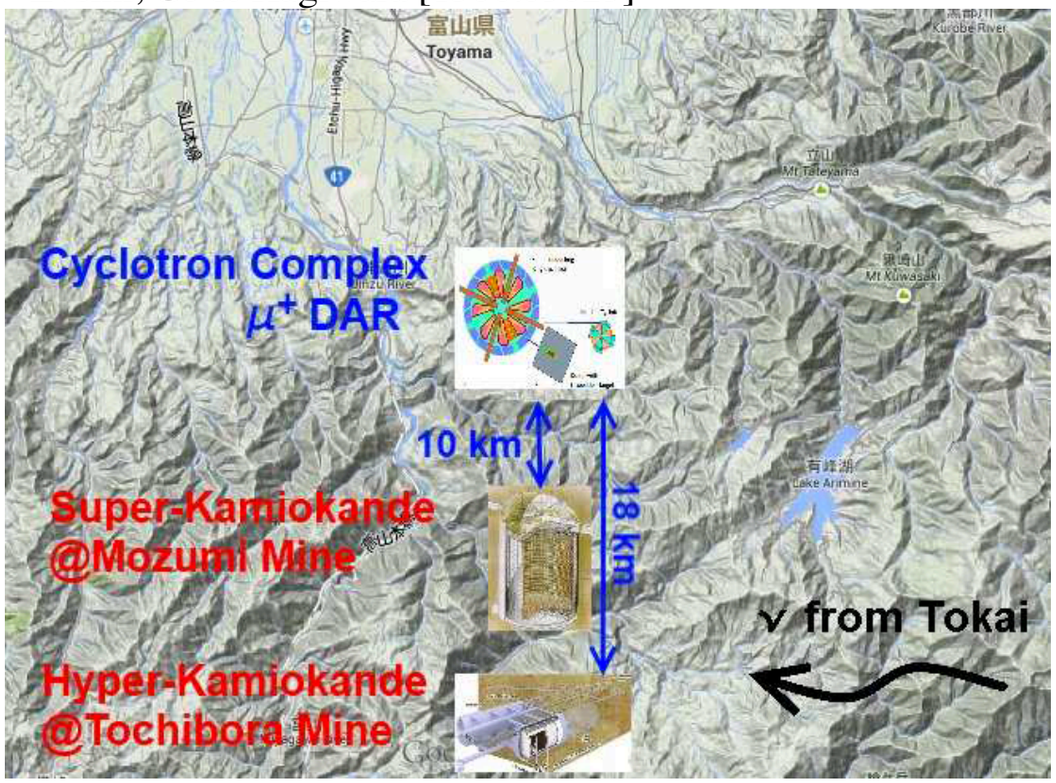
2nd detector in Korea in combination Hyper-K can resolve degeneracies



Shao-Feng Ge 5-1

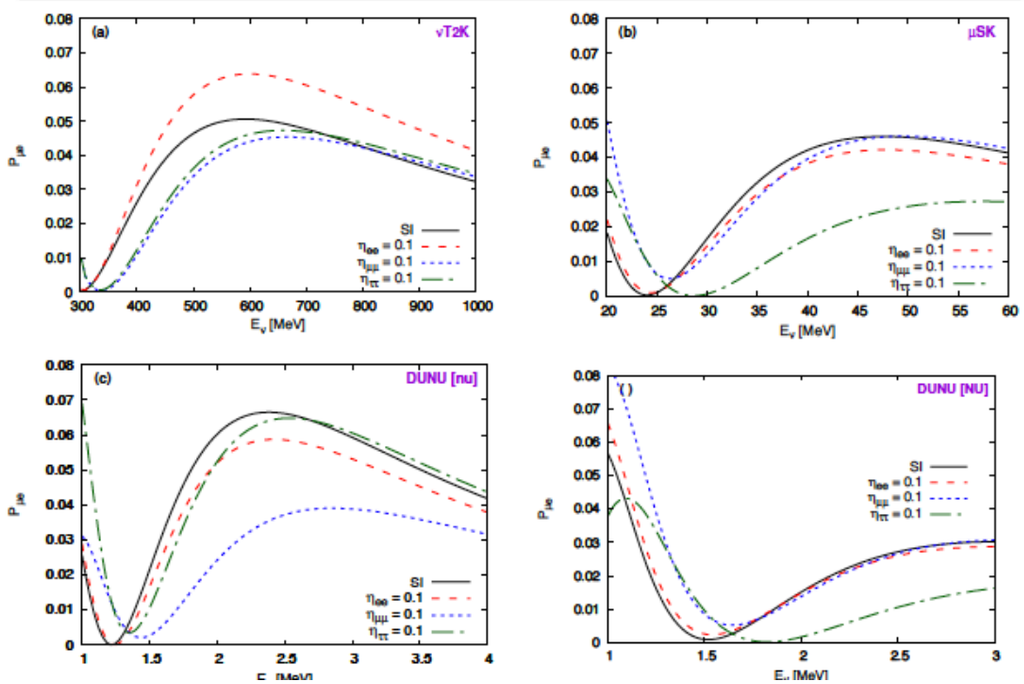
Leptonic CP Measurement & New Physics Alternatives

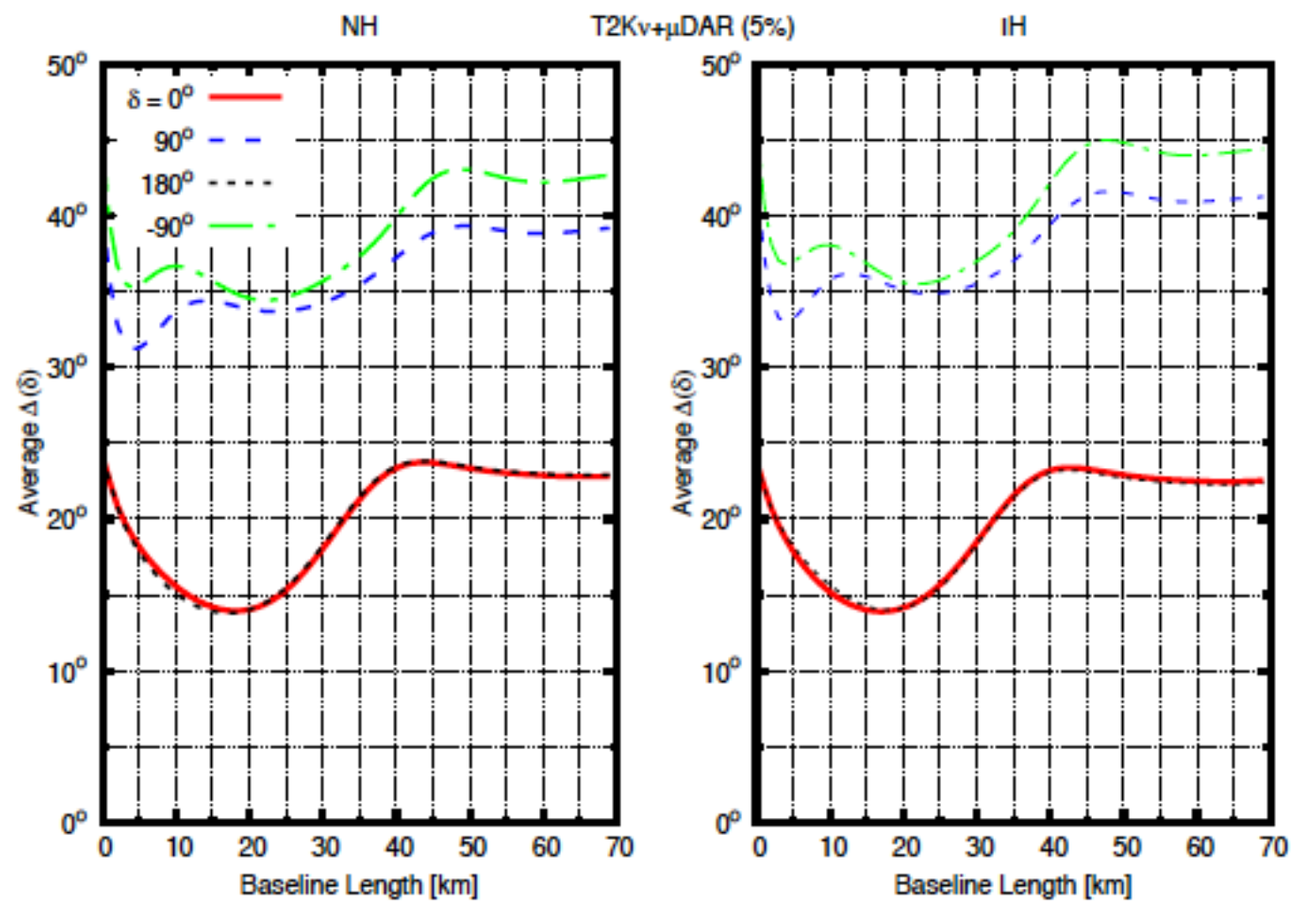
Evslin, Ge & Hagiwara [1506.05023]



Jarah Evslin, SFG, Kaoru Hagiwara, JHEP **1602** (2016) 137 [arXiv:1506.05023]
SFG, Pedro Pasquini, M. Tortola, J. W. F. Valle, PRD **95** (2017) No.3, 033005 [arXiv:160
SFG, Alexei Smirnov, JHEP **1610** (2016) 138 [arXiv:1607.08513]
SFG [arXiv:1704.08518]
SFG, Stephen Parke, Phys.Rev.Lett. **122** (2019) no.21, 211801 [arXiv:1812.08376]
SFG, Hitoshi Murayama [arXiv:1904.02518]

Scalar NSI @ Accelerator Neutrino Oscillation



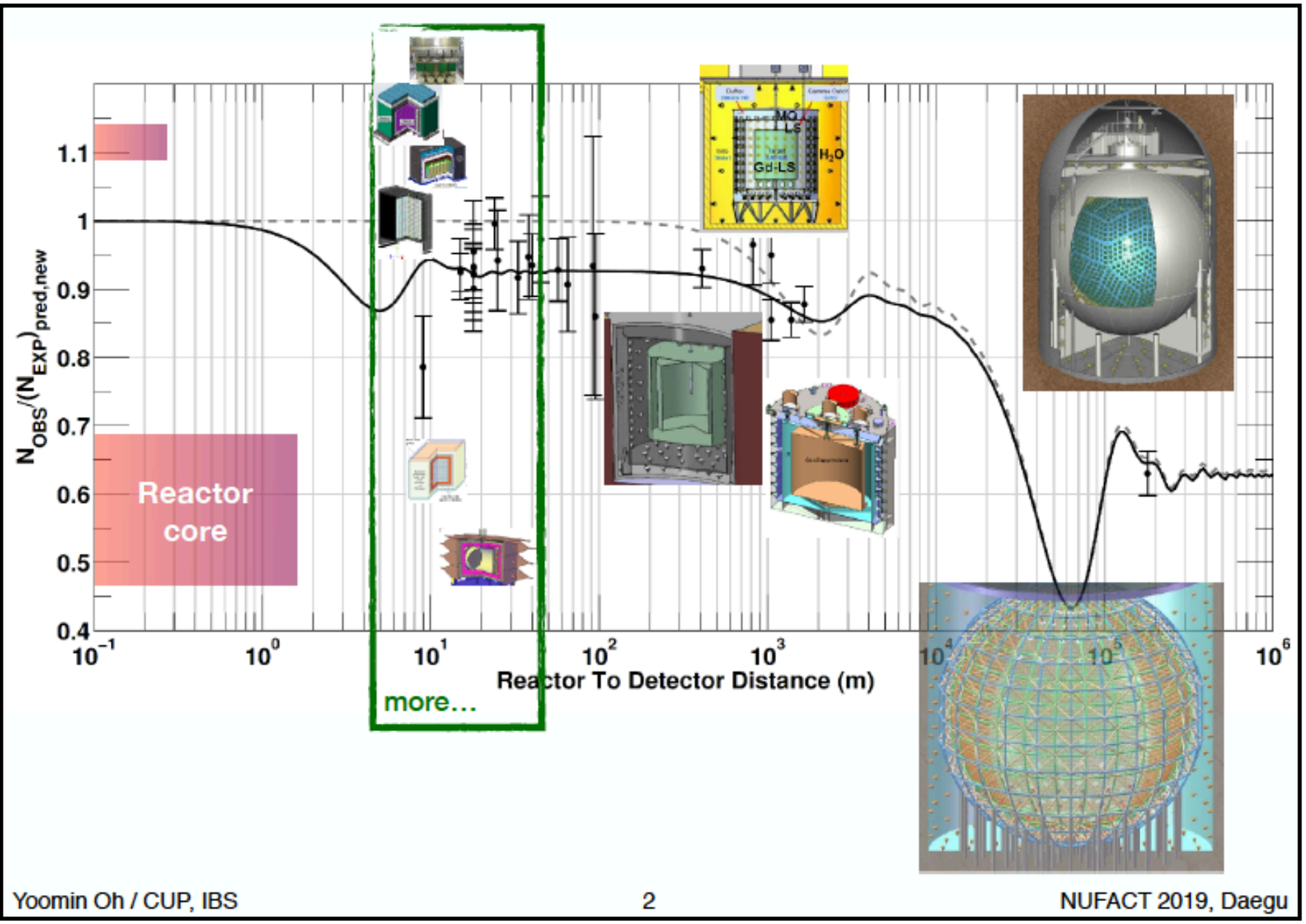


Sterile Neutrinos

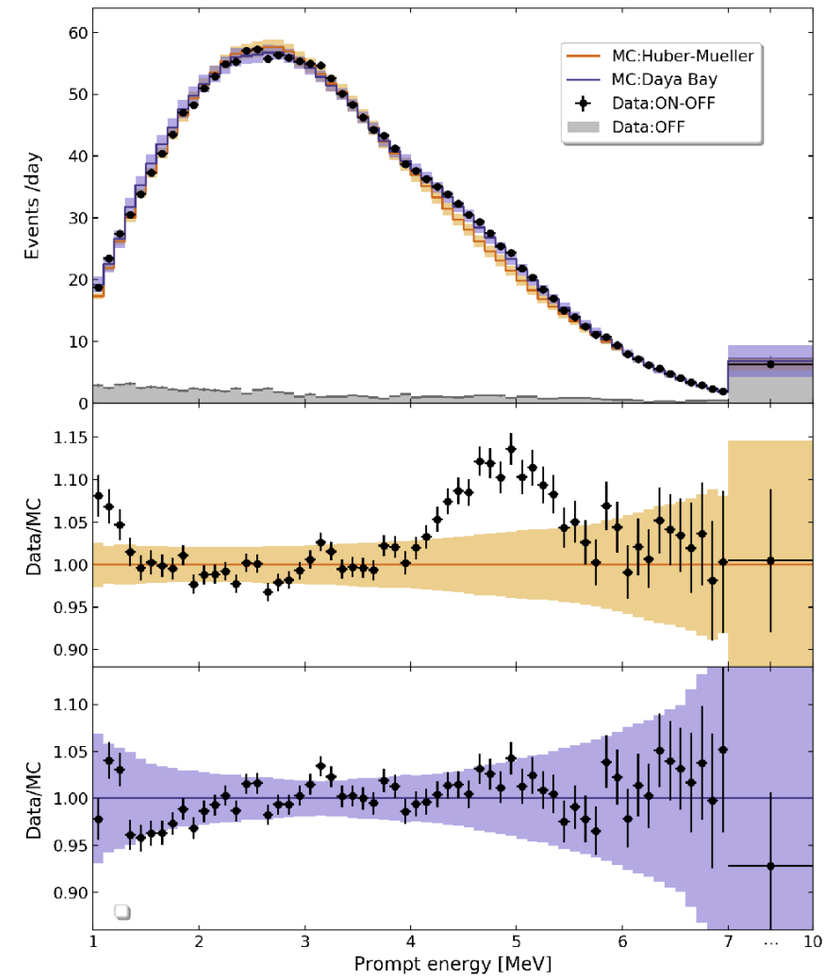
Yoomin Oh 6-1

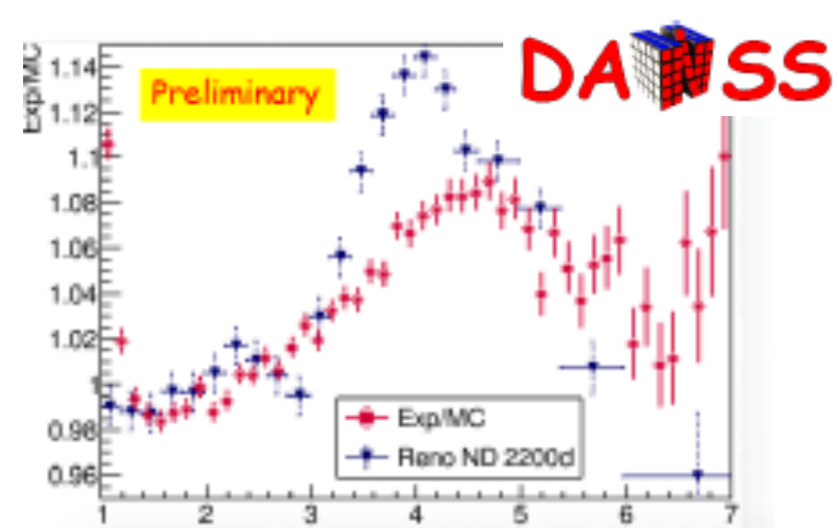
Reactor Neutrinos

Reactor Short Baseline



NEOS in 2017

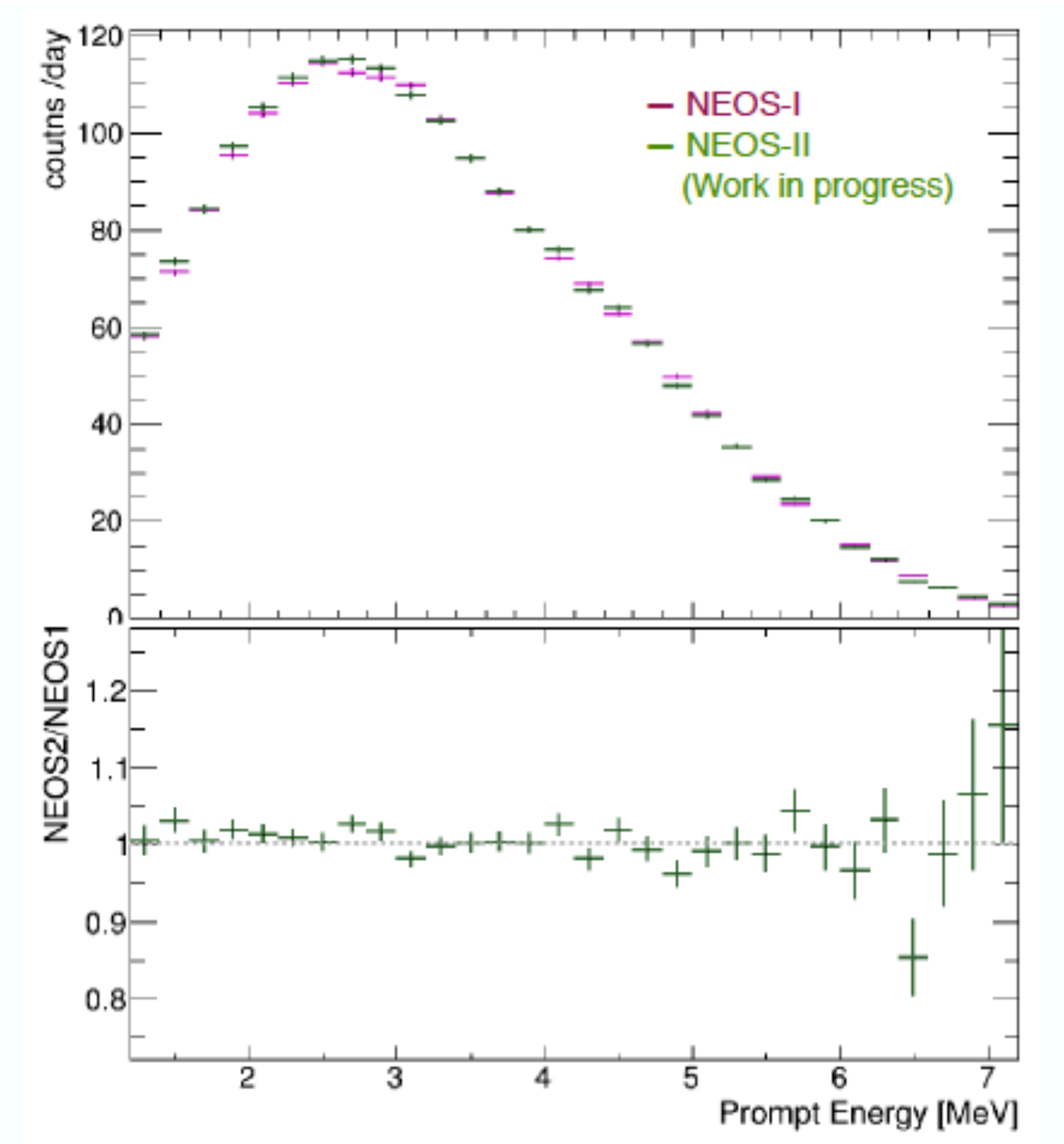




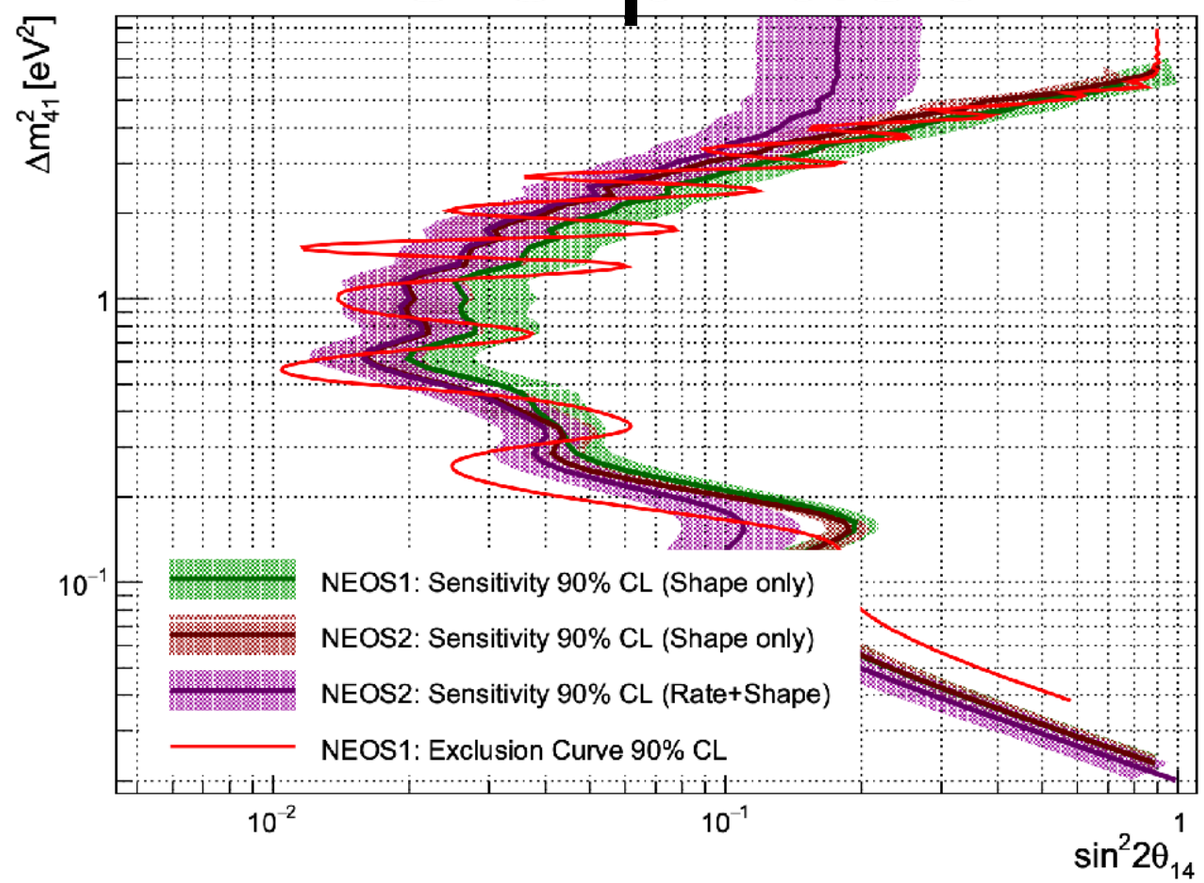
Yoomin Oh 6-1

NEOS Phase II

Phase-I and Phase-II

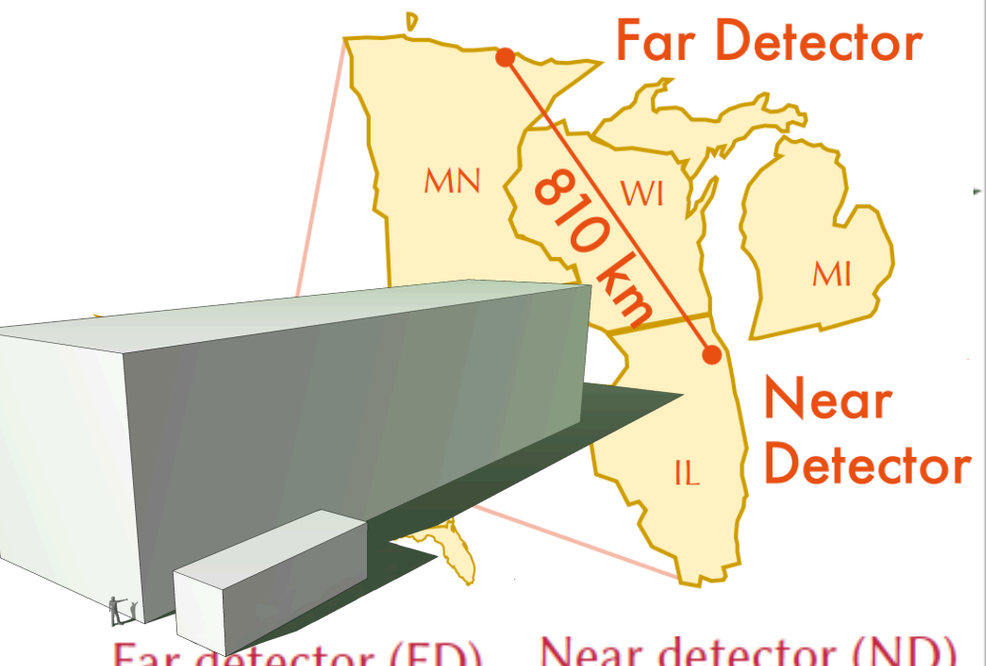


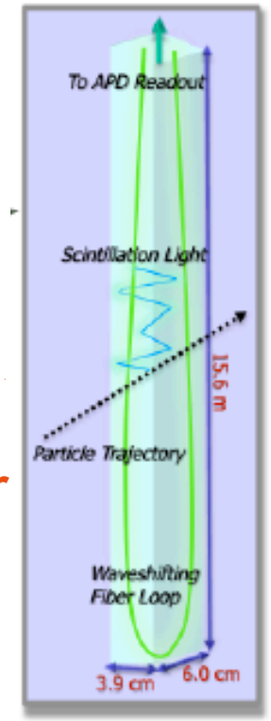
NEOS phase-II



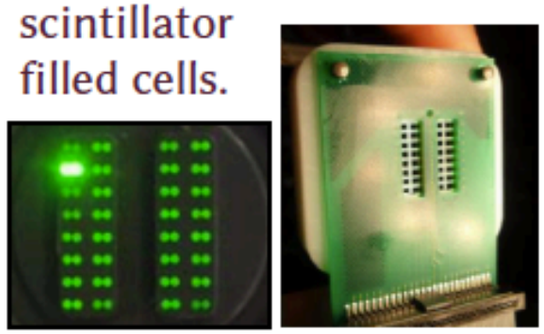
Adam Aurisano 7-3

Recent Searches for Sterile Neutrinos with NOvA





Low Z tracking calorimeter composed of alternating horizontal and vertical planes of liquid scintillator filled cells.



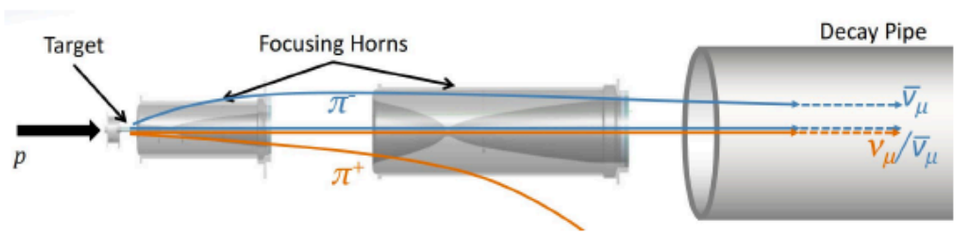
Wavelength shifting fibers carry light out of the cells to APDs.

Far detector (FD)
- 14 kton
- 15m x 15m x 60m
- 65% active mass
- ~344,000 channels

Near detector (ND)
- 0.3 kton
- 3.8m x 3.8m x 12.8m (main detector)
- Functionally equivalent to FD for systematic uncertainty reduction

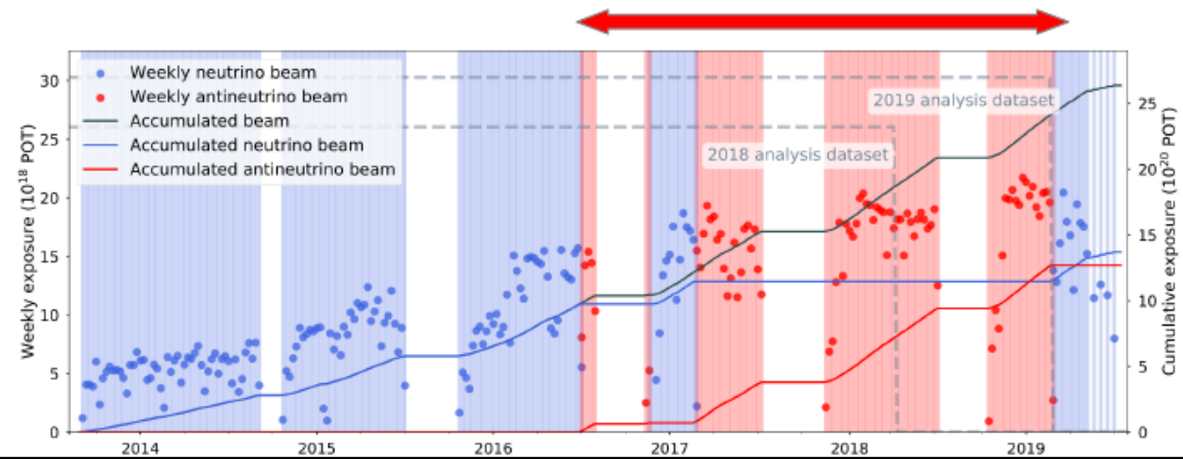
- Neutral current interaction rate is the same for 3 active neutrinos
  - NC rate is insensitive to 3 flavor oscillations
- Sterile neutrino do not interact in the detector
  - $\nu_\mu \rightarrow \nu_s$ reduce the NC rate at the FD
- One oscillation term for $\nu_\mu \rightarrow \nu_s$ oscillations at atmospheric frequency
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum

NuMI Antineutrino Beam



NuMI is the world's most powerful neutrino beam → running at 700 kW power since January 2017

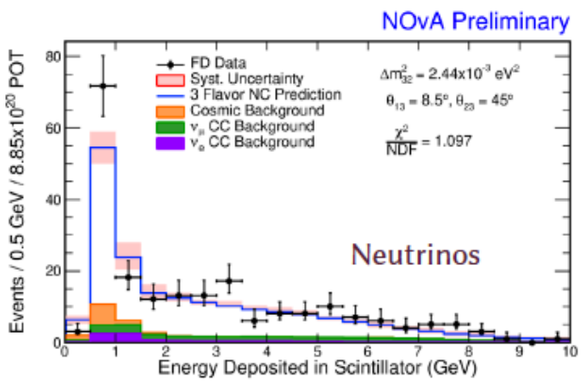
Recorded 12.5 x 10^{20} protons on target (POT) in antineutrino mode

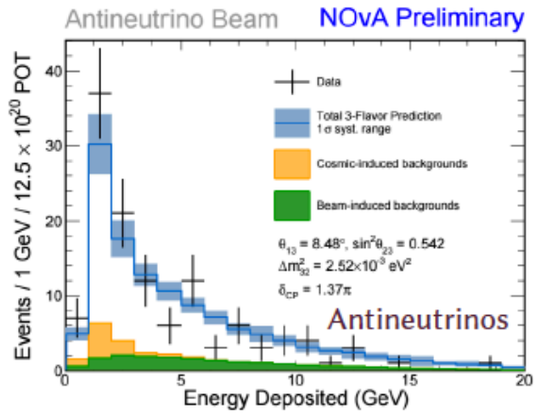


Adam Aurisano 7-3

Recent Searches for Sterile Neutrinos with NOvA

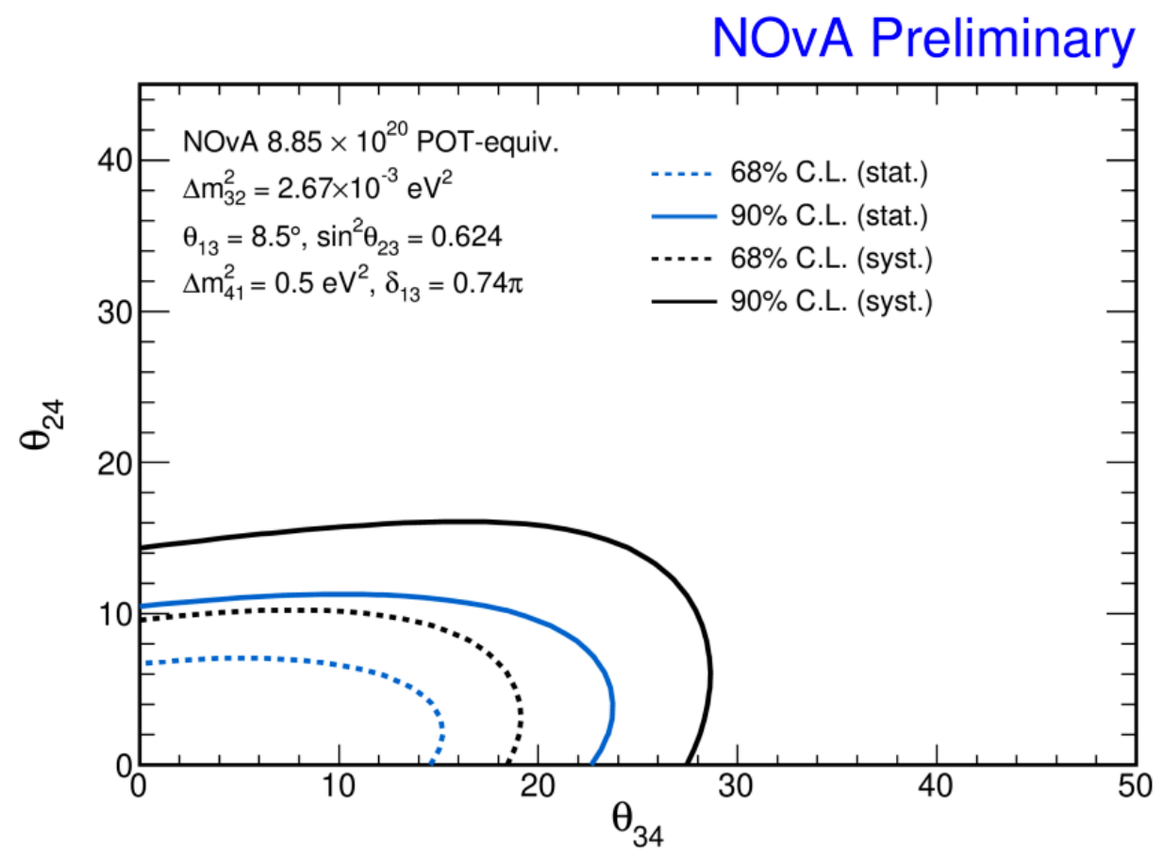
Far Detector Spectra

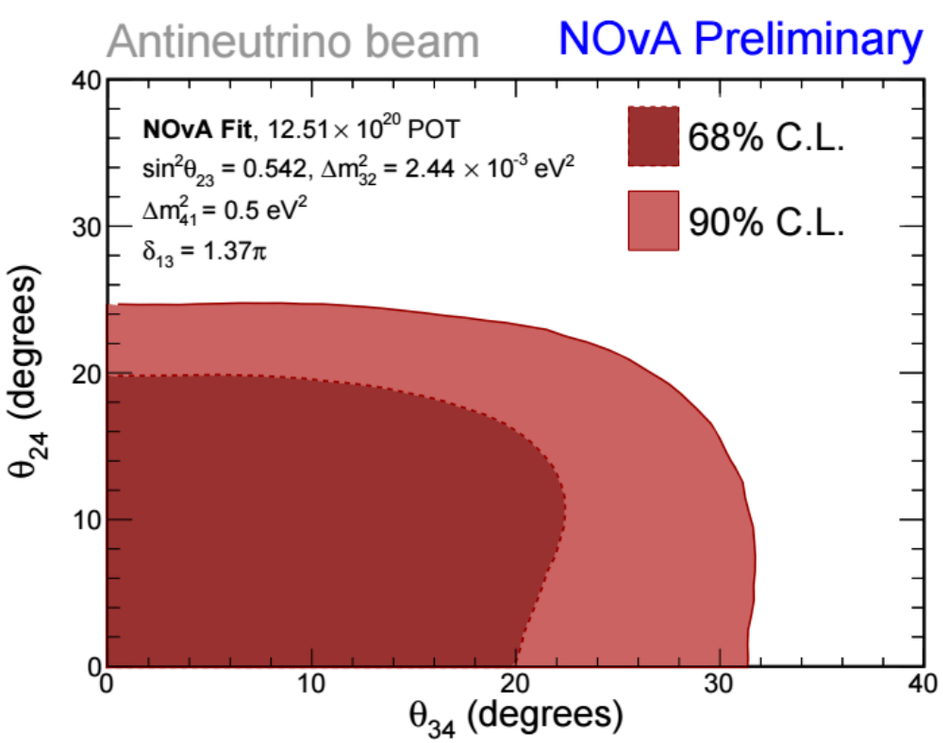




- Neutrino data:
  - Predicted **191.2 ± 13.8 (stat) ± 22.0** (syst) events
  - Observed **214** events
- Antineutrino data:
  - Predicted **122 ± 11 (stat) ± 18 (syst)** events
  - Observed **121** events

No significant suppression of neutral current





Observe **no evidence** for sterile-neutrino-driven oscillations in the neutral current channel in either neutrino or antineutrino beam modes

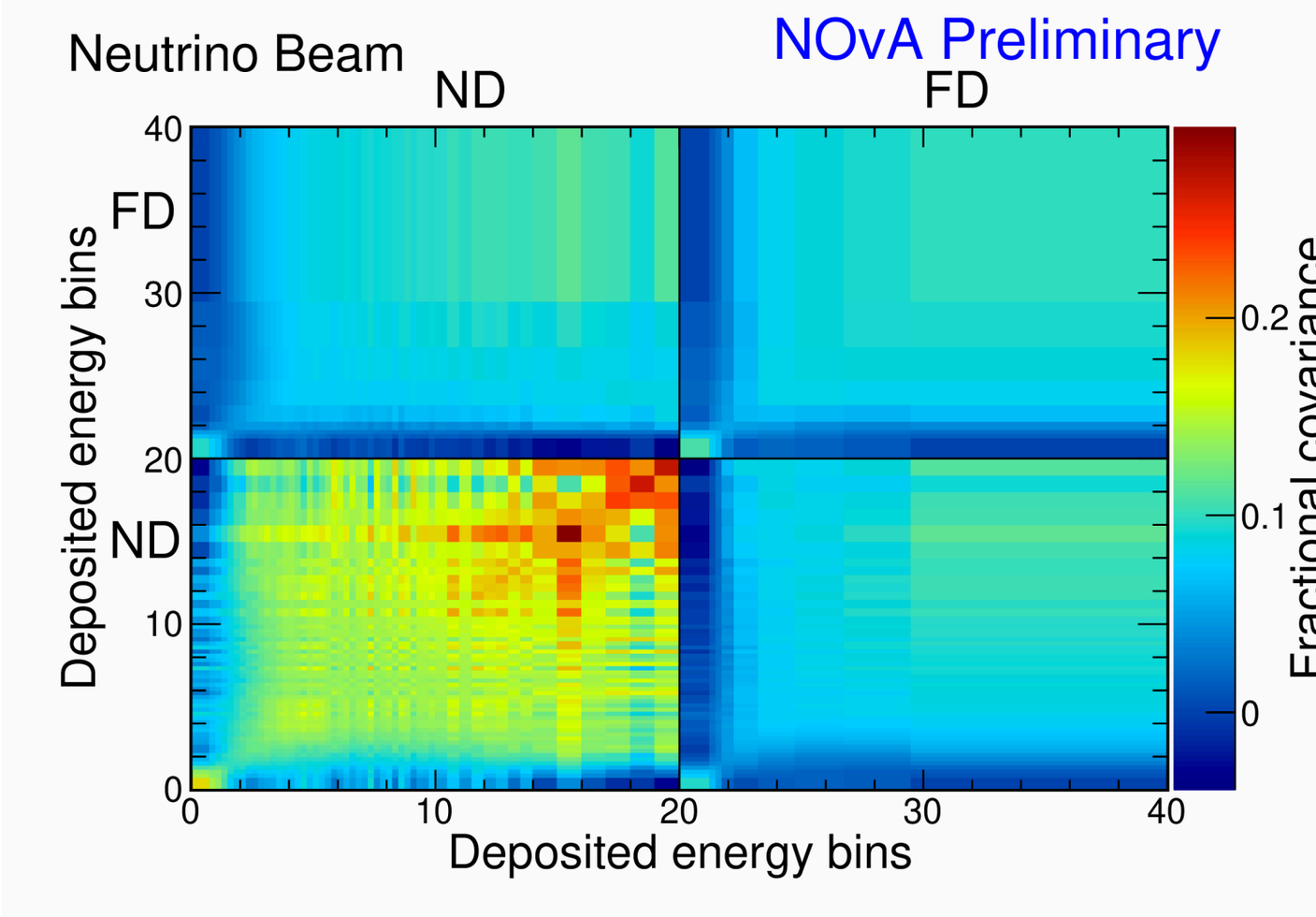
Next steps

- Analysis improvements to allow for fitting a wider range of Δm^2_{41} are in progress
- Test beam program is in progress to significantly reduce uncertainties on detector response to hadrons, currently the dominant uncertainty

Adam Aurisano 7-3

Recent Searches for Sterile Neutrinos with NOvA

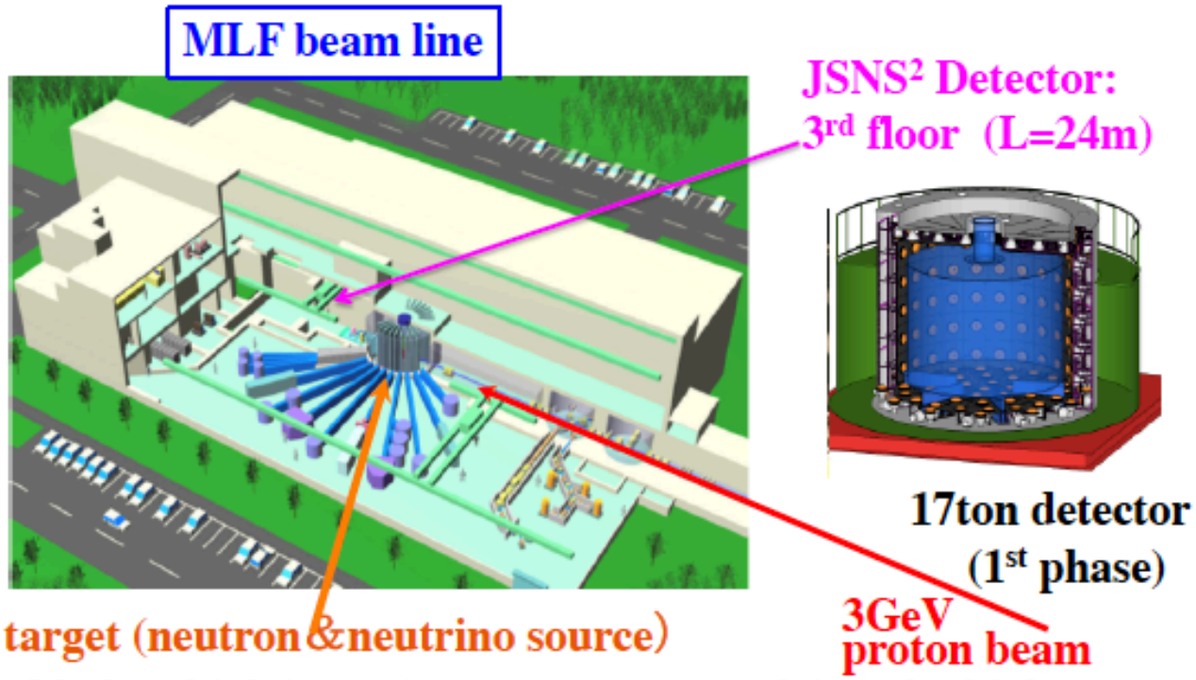
- At high Δm^2_{41}, extrapolation method breaks down due to disappearance in Near Detector.
- Perform joint fit in both detectors, treating ND and FD on equal footing
- Use covariance matrix to account for correlated systematics between two detectors, maintaining the cancellation of uncertainties
  - Technique recently used by MINOS/MINOS+ (Phys. Rev. Lett. 122, 091803 (2019)), but this will be the first use in NOvA

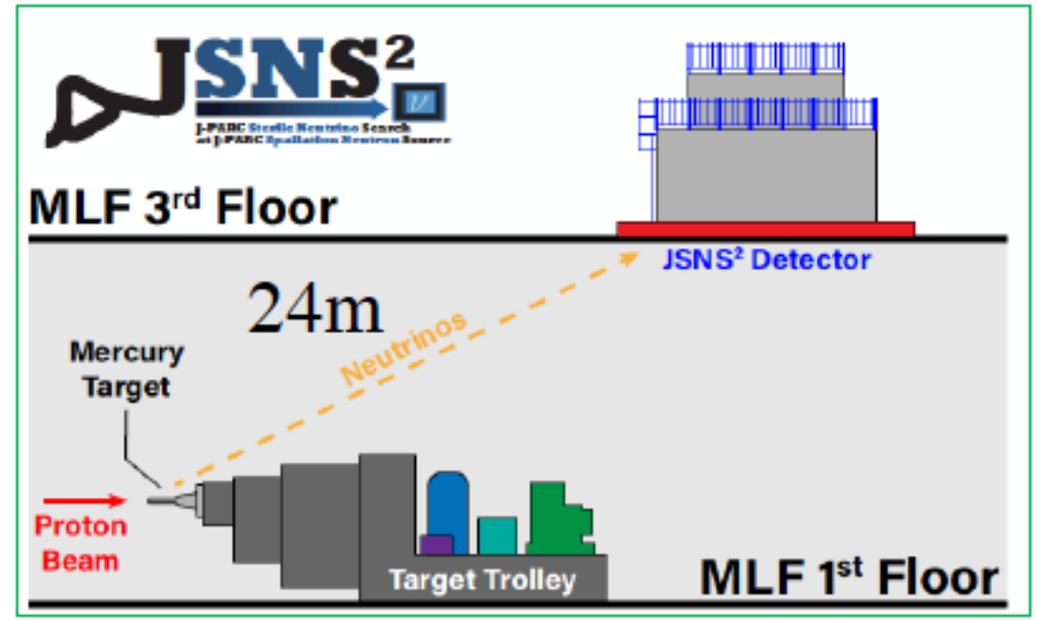


- Status:
  - Analysis improvements to allow for fitting a wider range of Δm^2_{41} are in progress
  - Test beam program is in progress to significantly reduce uncertainties on detector response to hadrons, currently the dominant uncertainty
  - Start data taking after the summer shutdown

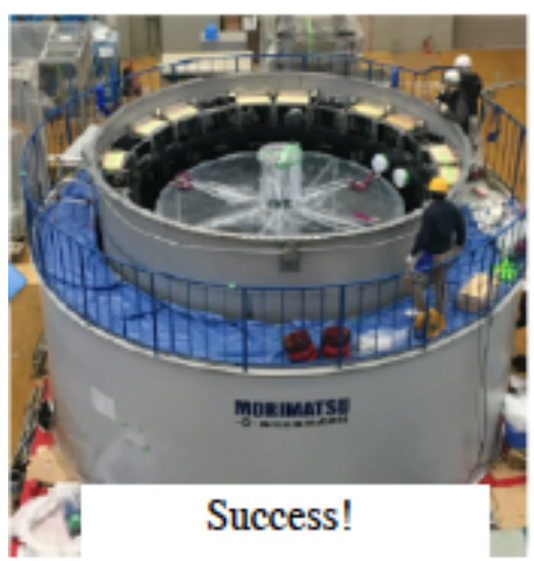
F. Suekane 7-2

JSNS²





- World-class high intensity neutron source driven by high power proton beam
  - beam energy: 3GeV
  - design beam power: 1MW



JSNS² vs LSND

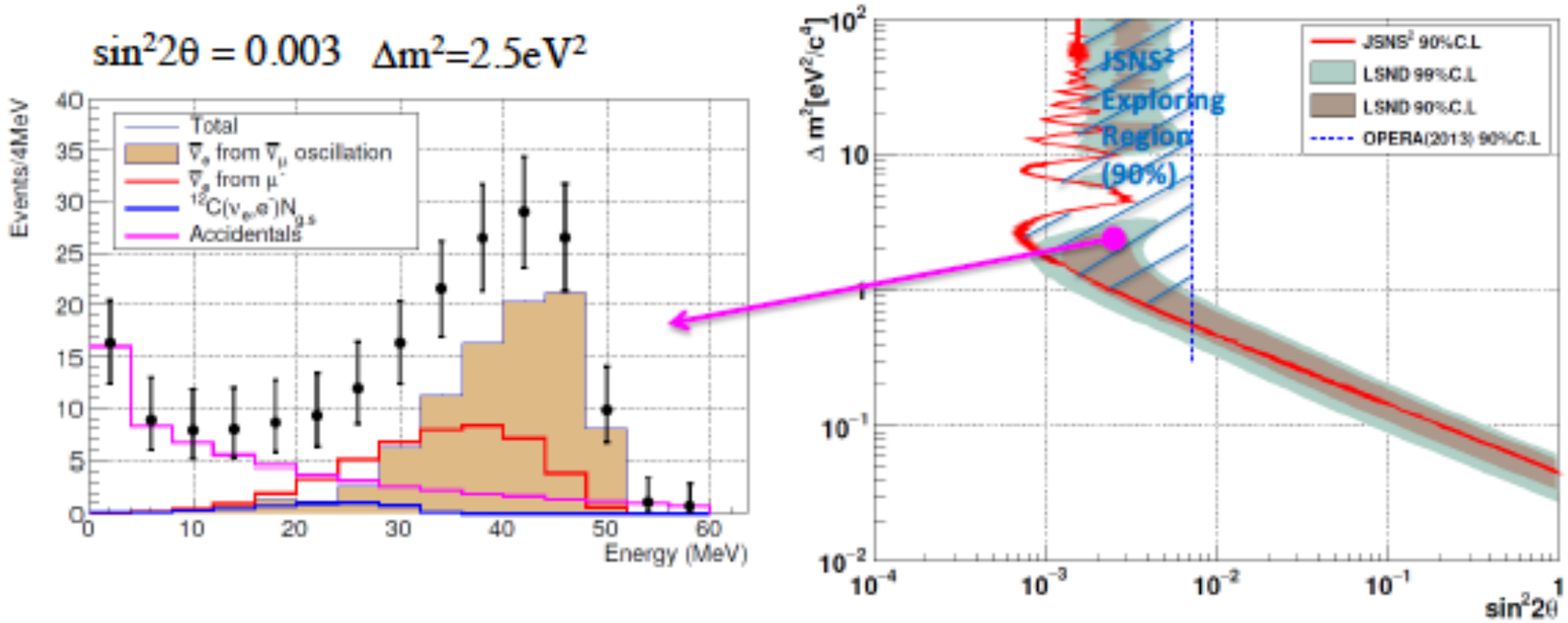
	JSNS²(1st phase)	LSND
Target Mass.	17t	167t
Baseline	24m	30m
Beam energy	3GeV	0.8GeV
Beam power	1MW	--
Beam Duty Factor	1/8,800	1/14
Stopping μ^-/μ^+	1.7×10^{-3}	6.5×10^{-4}
Delayed signal	8MeV, $\Delta t \sim 30\mu s$	2.2MeV, $\Delta t \sim 200\mu s$
Liquid Scintillator	Gd Loaded	Cherenkov + Low LO Scinti.
Cosmic fast n rejection	Pulse Shape Discri.	Cherenkov
$\bar{\nu}_e$ signal events	29/year ($\sin^2 2\theta = 0.003$)	15/year
$\Delta E/E$	3%@35MeV	7%@45MeV

JSNS2 16

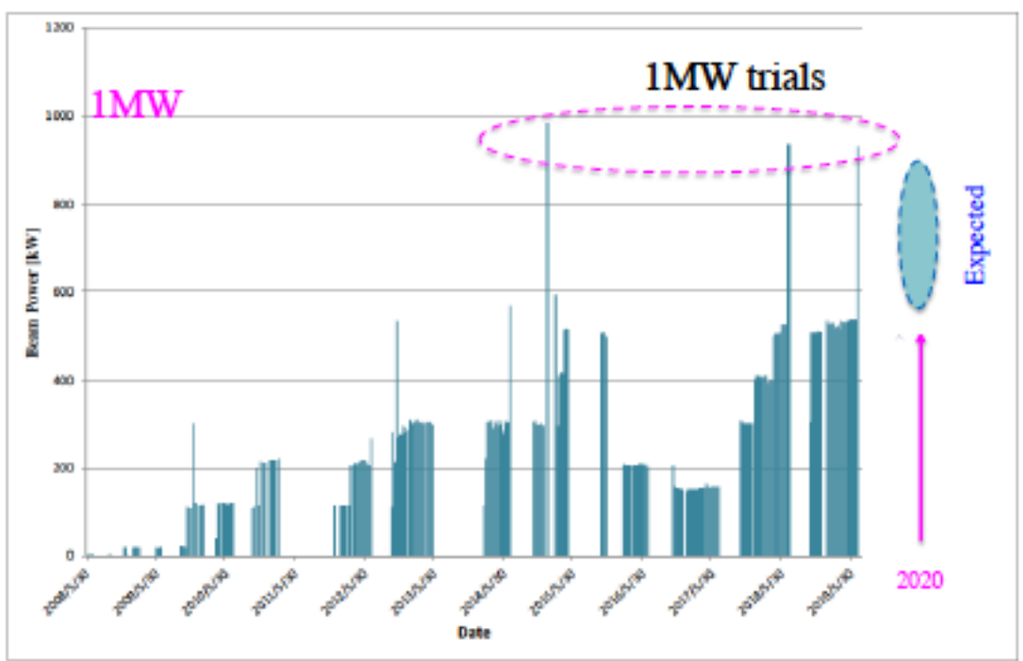
F. Suekane 7-2

JSNS²

Sensitivity after 3 years physics run

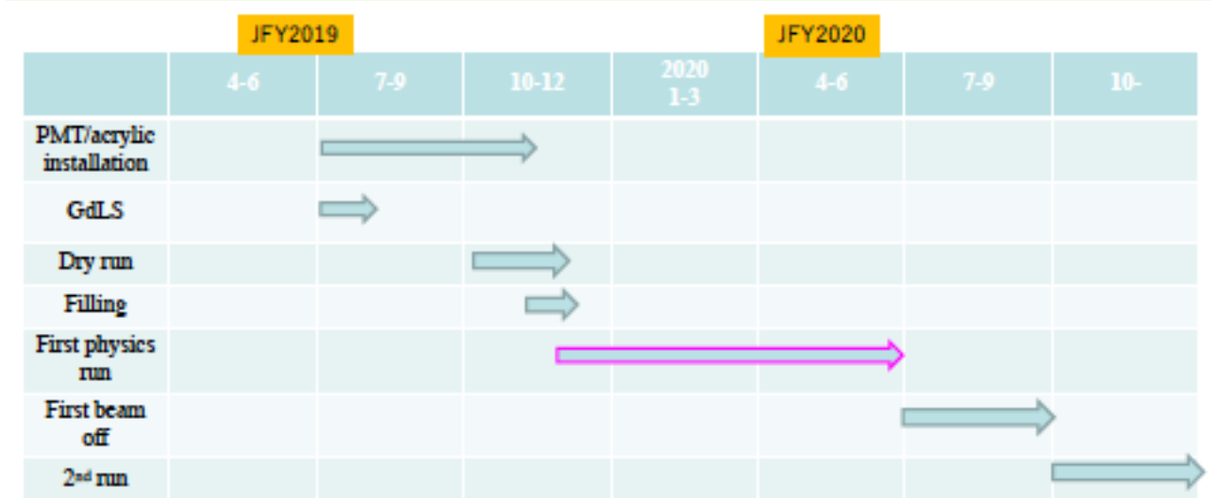


Beam power history and future projection



0.5~0.9MW operation is planned in 2020.

Overall schedule



Start data taking from early 2020!

Mark Ross-Lonergan 6-3

MicroBooNE

Enter MicroBooNE

MicroBooNE is an 89-ton surface based Liquid Argon Time Projection Chamber (LArTPC) that has been collecting data in the same Fermilab BNB since Autumn 2015.

One of its **primary goals** is to definitively identify if the origin of the observed MiniBooNE Low Energy Excess **(LEE)** is **due to electrons** or **photons**.

This can be achieved due to LArTPC's **excellent spatial resolution and calorimetry**

For further details and the wor
itself and latest publications, s

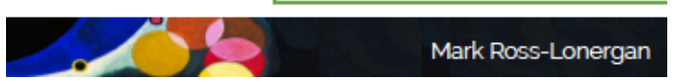
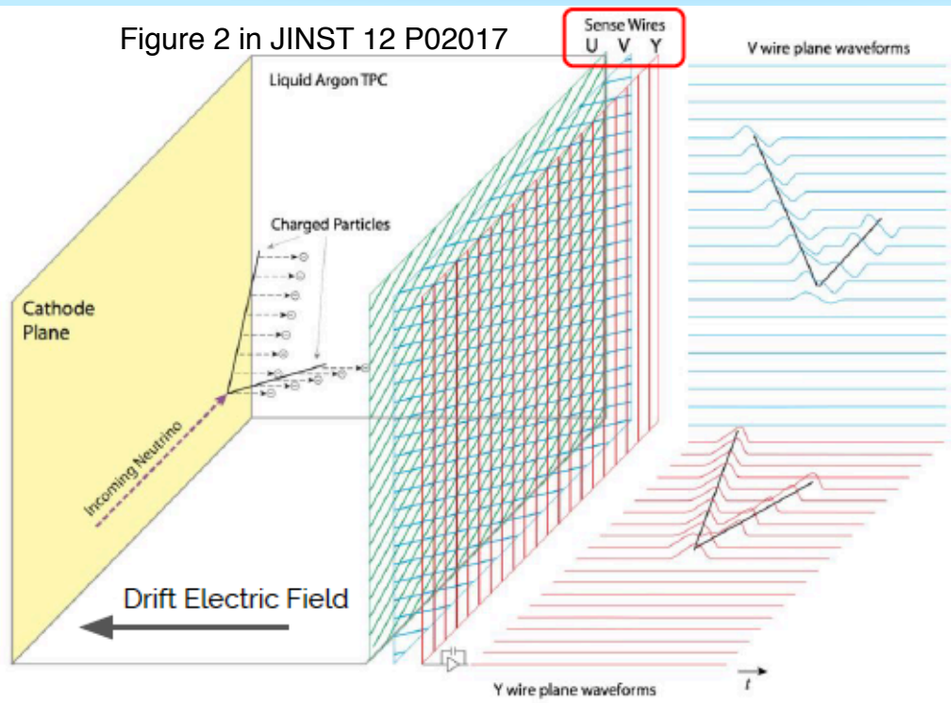
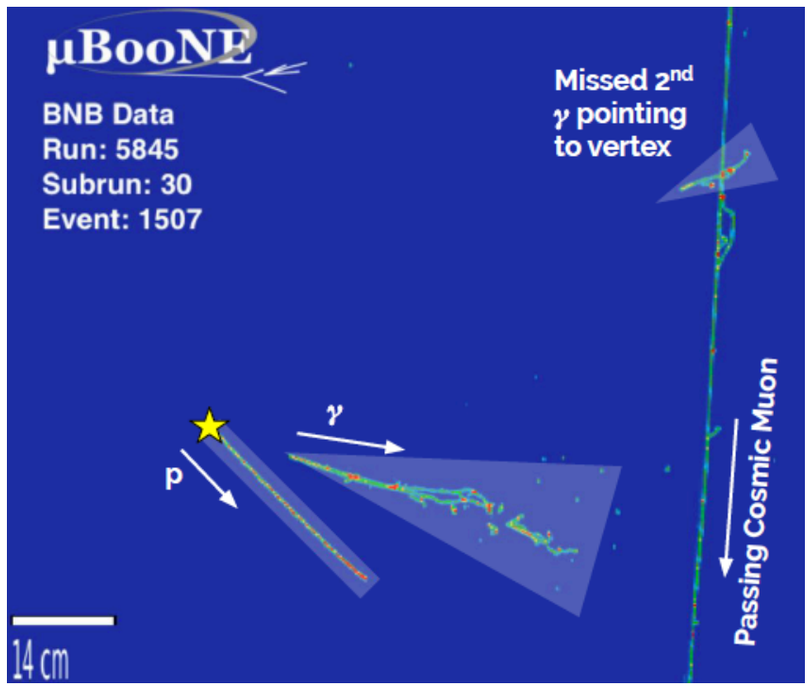


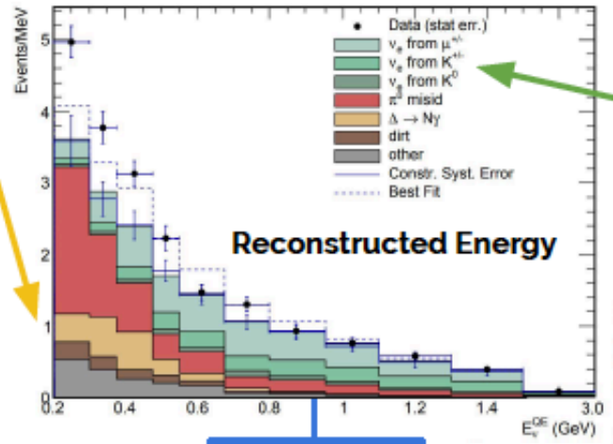
Figure 2 in JINST 12 P02017



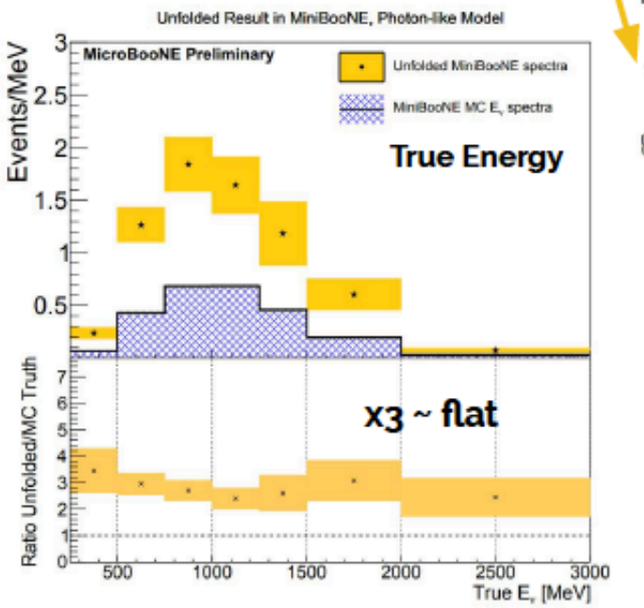


Unfolding results for an electron hypothesis

Assuming the LEE is due to an increase in the rate of **NC resonant Δ with subsequent radiative decays**

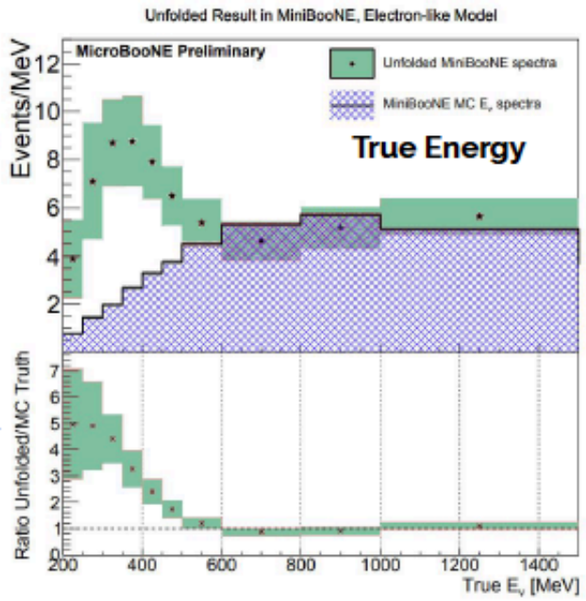


Assuming the LEE is due to an energy dependant **increase in the rate of CC ν_e** events



Unfolding

Remove
Detector Smearing, Reconstruction Effects, Analysis Selections, ..etc..



Mark Ross-Lonergan 6-3

MicroBooNE

Conclusions

MicroBooNE's LEE search involves using **multiple reconstruction frameworks** on **multiple complementary analysis topologies** for a variety of signal hypotheses

All analysis's have now moved to our latest state-of-the-art Monte Carlo simulation involving the **Genie v3** event generator **overlayed with real cosmic data recorded *in-situ* at MicroBooNE**, use of the **Cosmic Ray Tagger** (CRT) as well as latest improvements in **signal processing** and **reconstruction**

Both electron and photon specific LEE analysis are tailoring further refinements to the sideband selections to provide the **strongest constraints** to the **systematic uncertainties of any irreducible backgrounds**

Primary focus now is on fully incorpering and understanding all possible **detector systematics** of our LArTPC to ensure as robust a measurement as possible

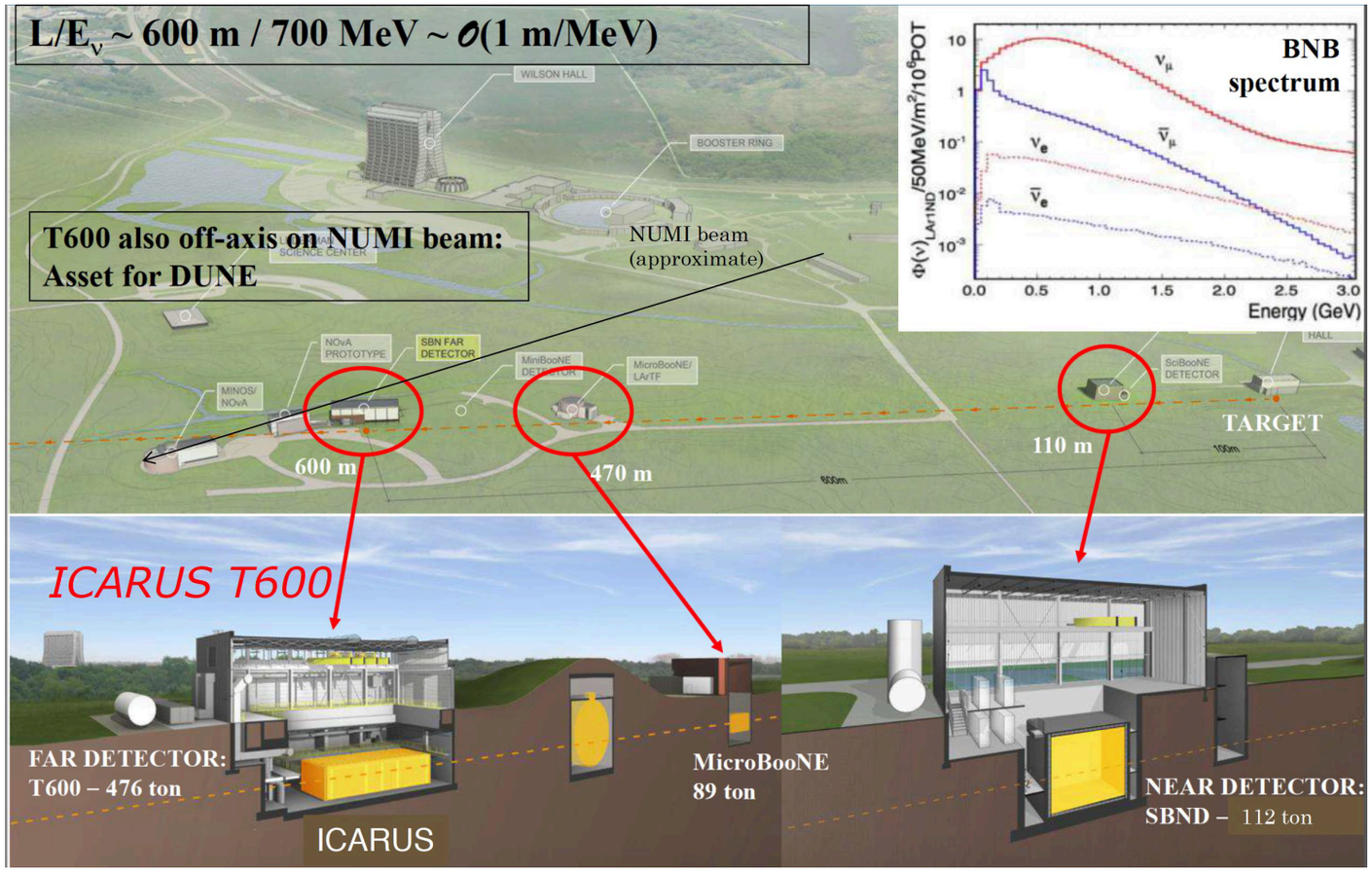
Mark Ross-Lonergan 30th August 2019 34

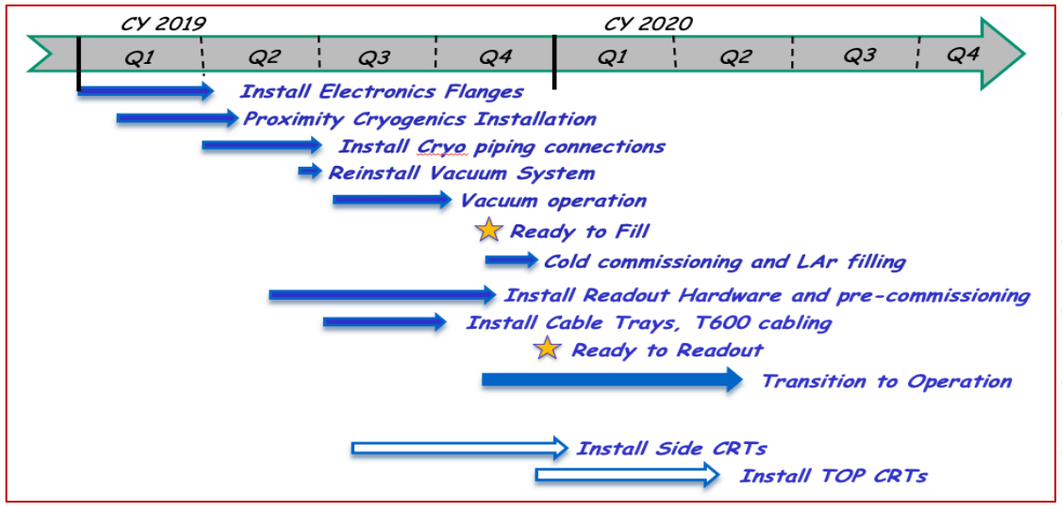
All LEE analyses at MicroBooNE are blind, with only 5e19 POT of data currently open for testing and comparison (~4% out of a total 13.2e20 POT in full data set)

Jae Yu 6-2

ICARUS T600

Light Collection System Upgrade



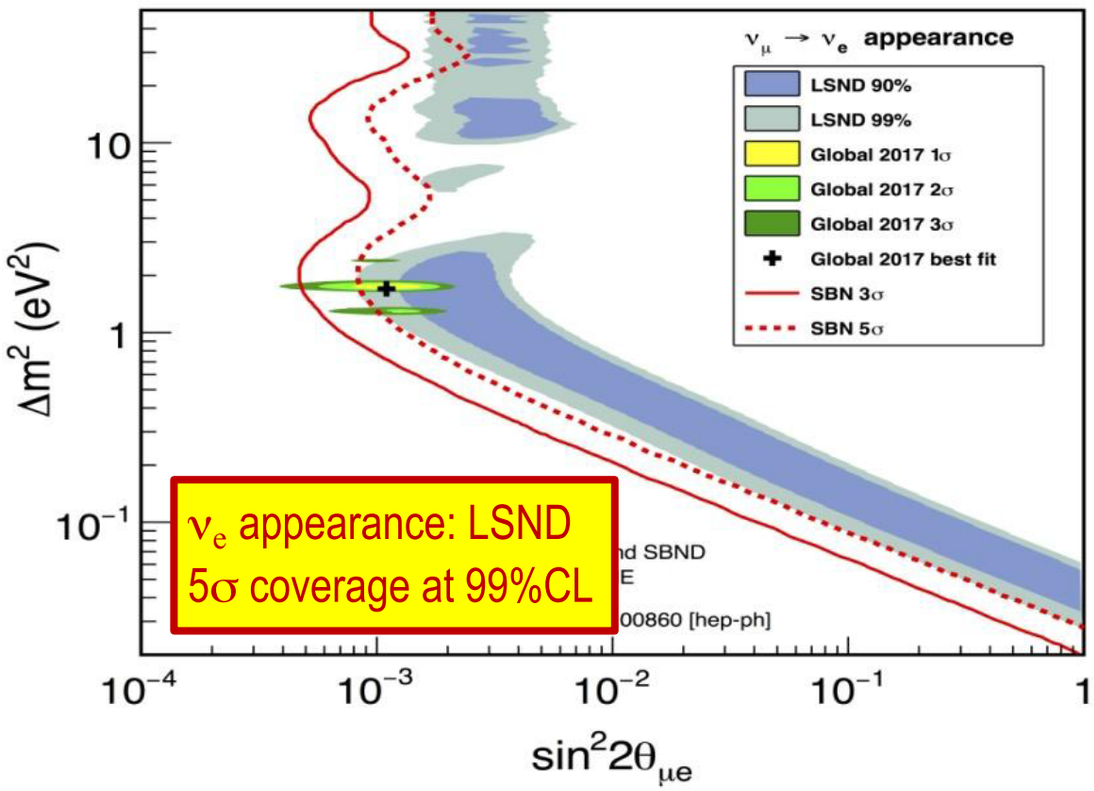


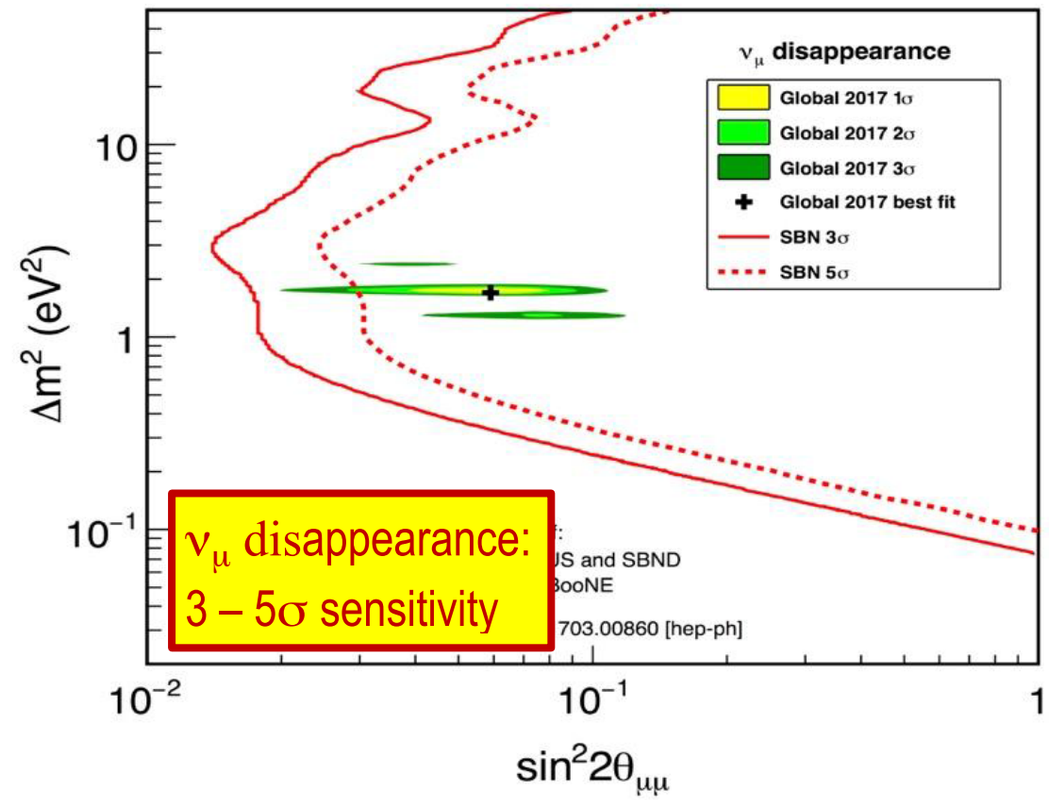
ICARUS @ FNAL Plans

- TPC/TRG electronics and PMT electronics installation to be completed and tested by summer 2019
- After cryogenics commissioning, cool down and filling
- ICARUS T600 should be full and operational in Q4 of 2019
- Commissioning of CRT, DAQ, trigger and slow controls will follow.
- Commissioning with cosmics and neutrino beam to begin by the end of this year.

Jae Yu 6-2

SBN Sensitivity





After an extensive overhaul, ICARUS at final stage of installation as the SBN FD at FNAL

SBN data taking expected in early 2020 followed by ND in 2021.

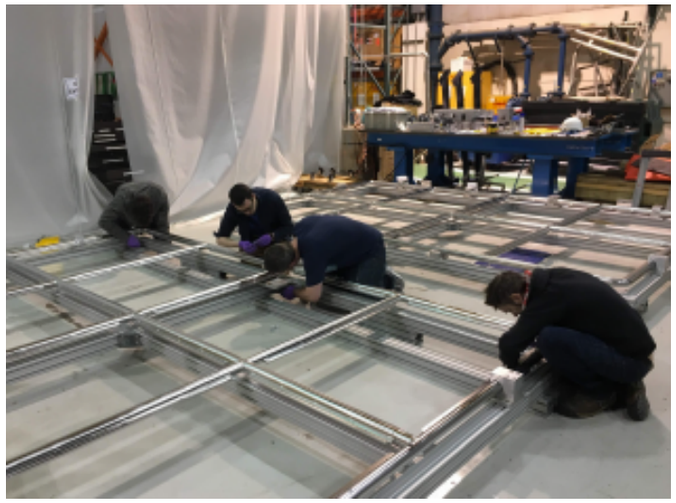
•ICARUS will see the first neutrinos early 2020!

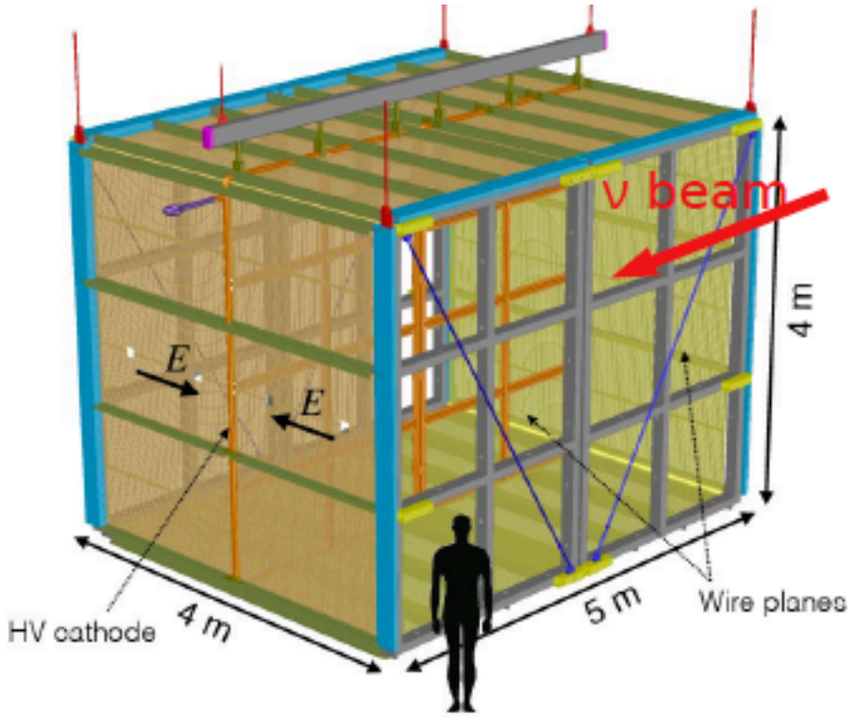
Steve Dennis 7-1

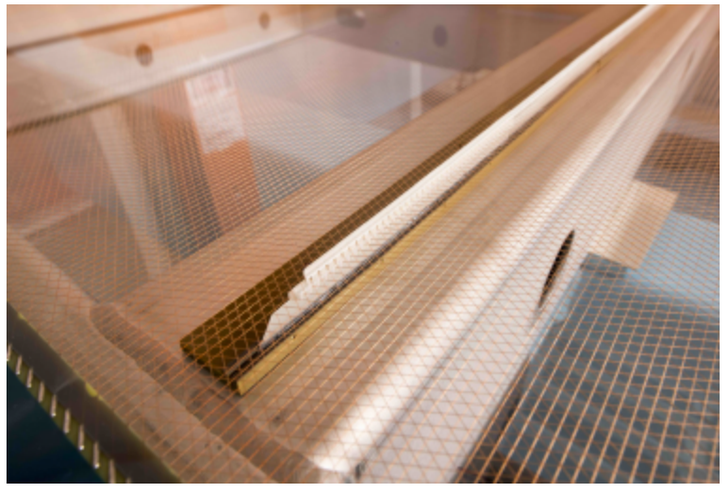
SBND

Short Baseline Near Detector

- The largest, and closest detector.
- 112t LArTPC placed at 110m from the beam pipe.
- Capable of excellent precision cross-section measurements.
  - On argon
  - Which of course can feed into DUNE.
- Under construction.
  - All TPC components have arrived at Fermilab!
  - Expect to start taking physics data in early 2021.



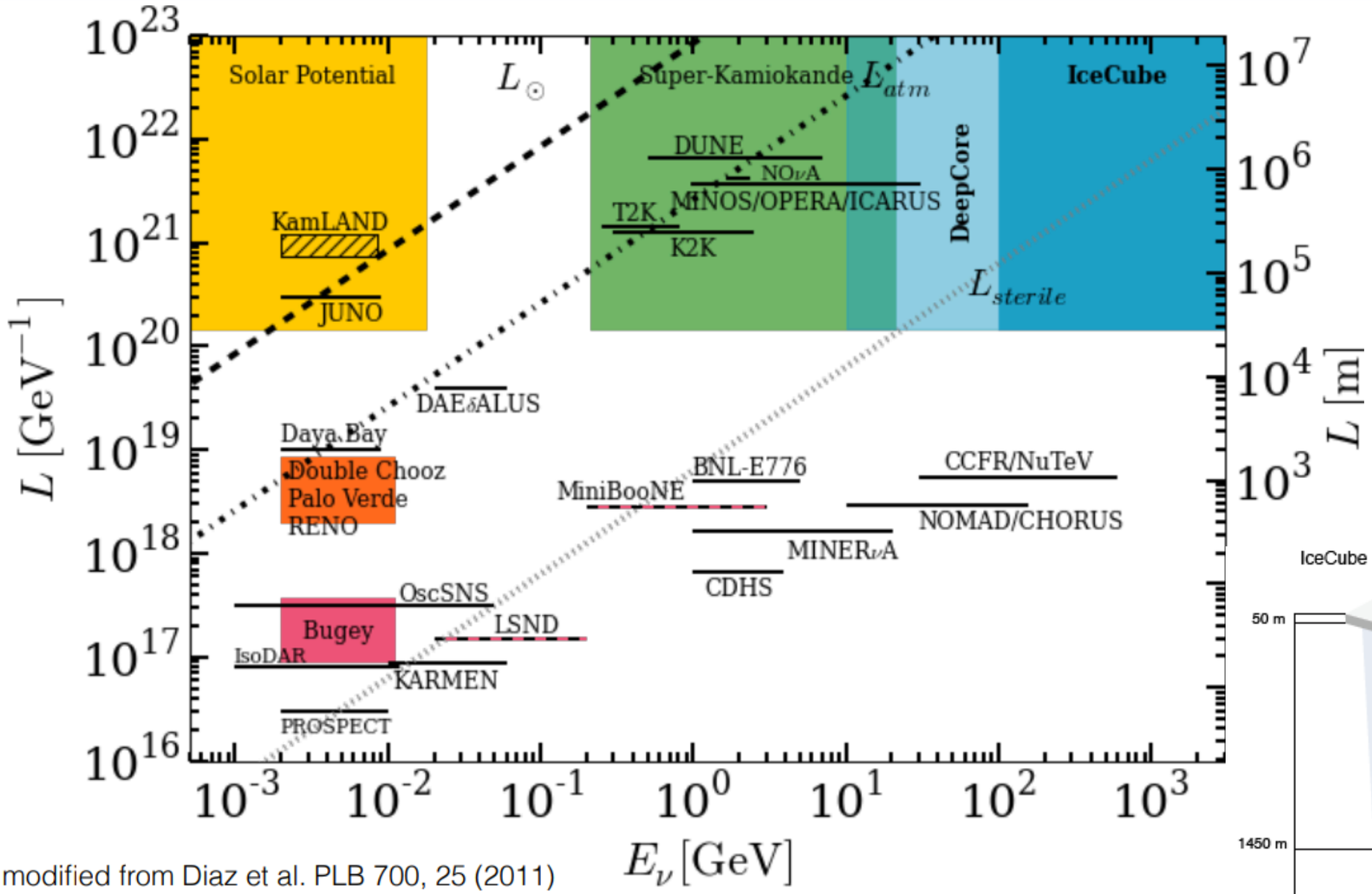




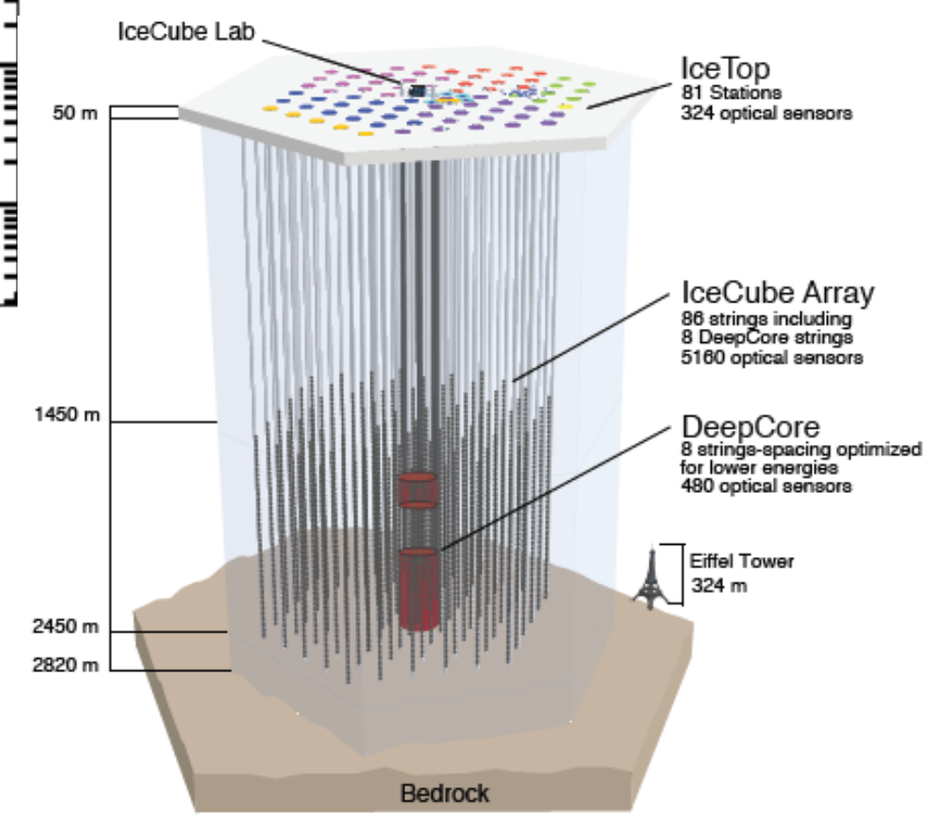
- SBND is a new Liquid Argon TPC being built for the SBN program at FNAL.
  - Powerful capability to investigate potential light steriles and other new physics.
  - Unprecedented precision cross-section measurements on Argon.
- Rapid progress being made.
  - Most components now at FNAL.
    - Cryostat to be assembled in October 2019.
    - TPC to be completed and moved to final building early 2020.
    - Commissioning and filling in 2020.
    - Collect 3 years of neutrino beam data from early 2021.
- An exciting time to be on SBND!

Joshua Hignight 7-4

Sterile Neutrinos L/E complementarity



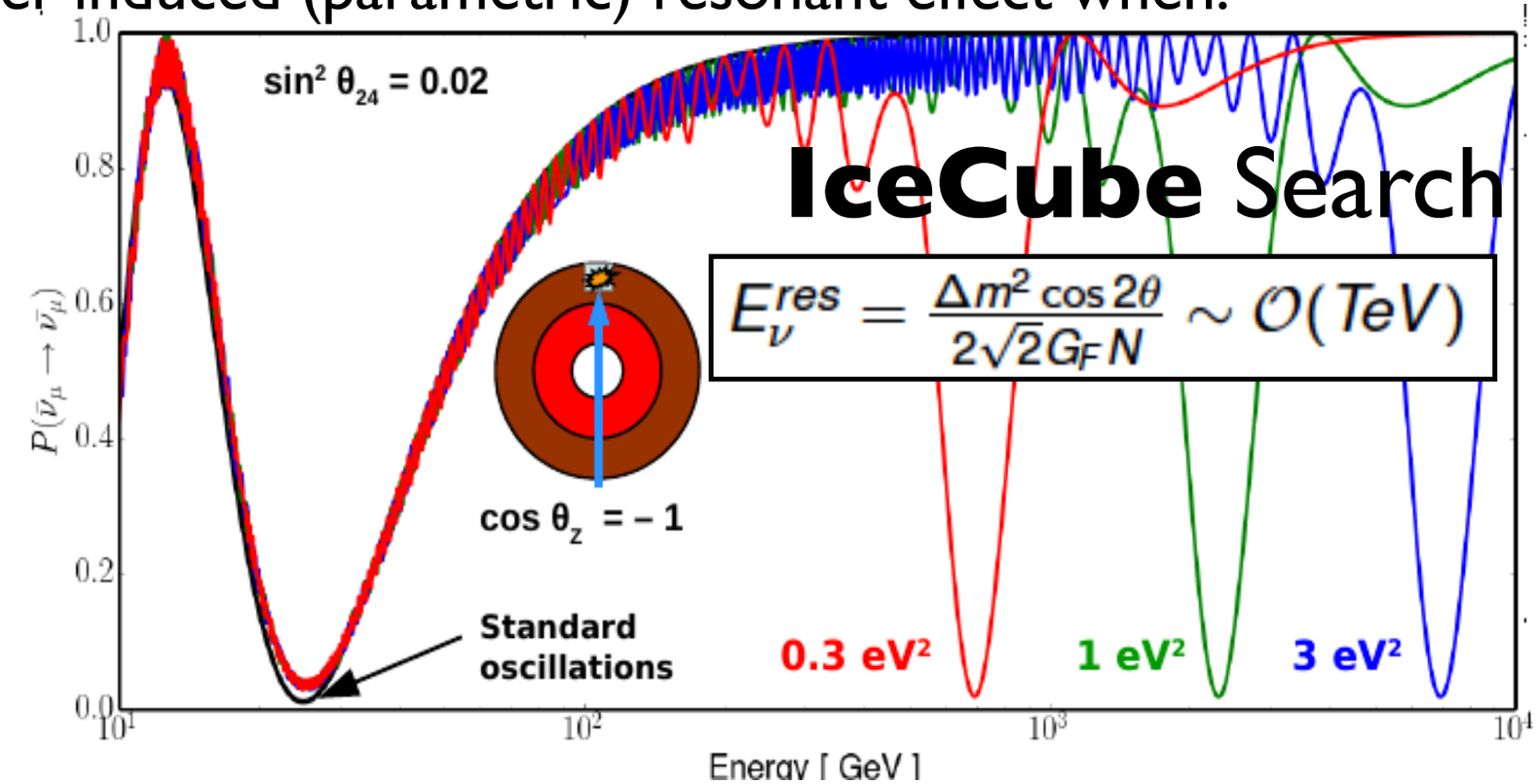
modified from Diaz et al. PLB 700, 25 (2011)

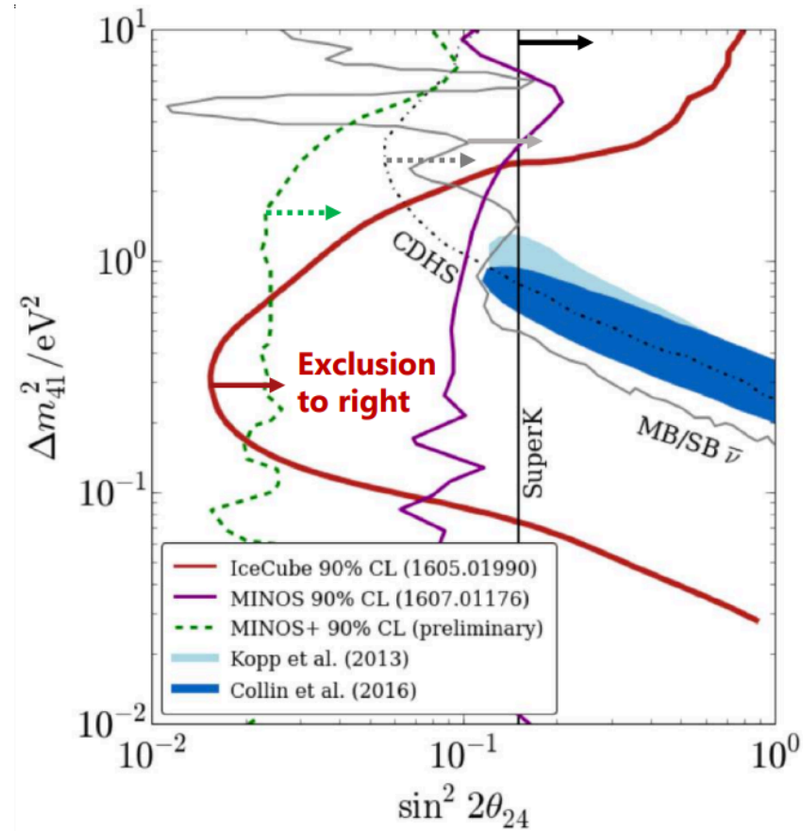


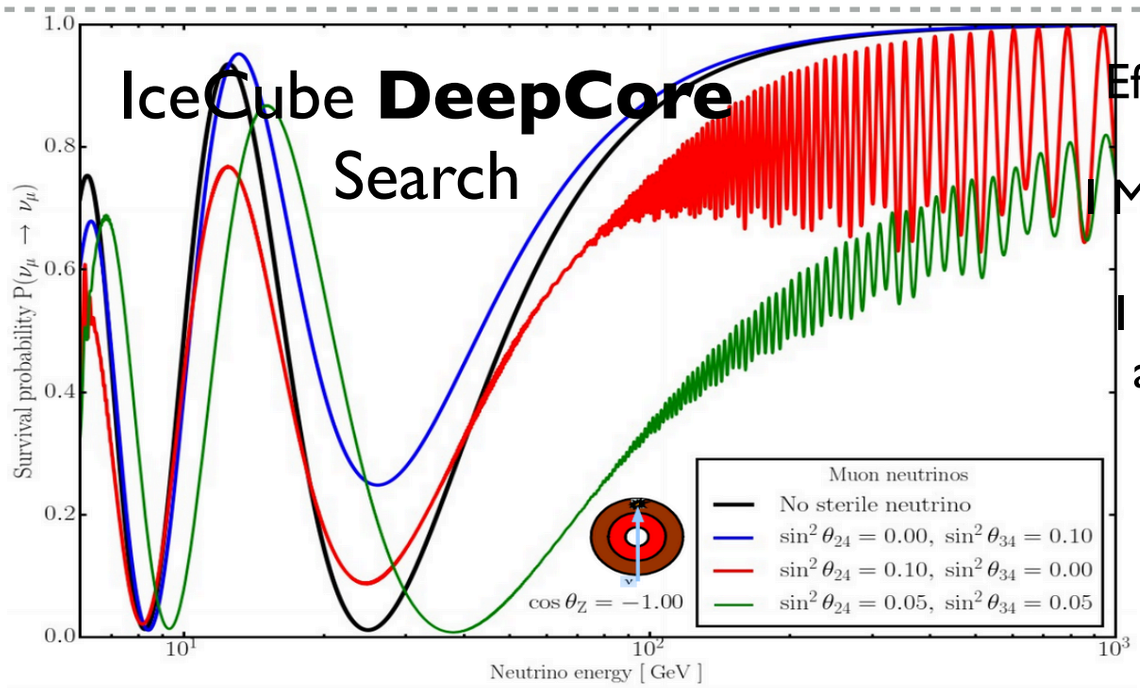
Joshua Hignight 7-4

Sterile Neutrino Search Results

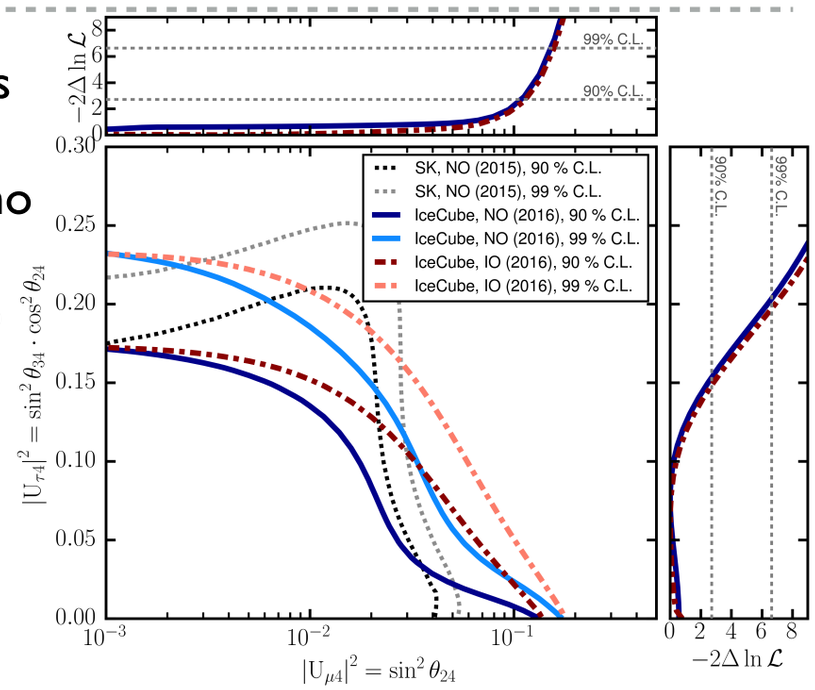
In the Earth, for sterile neutrinos of $\Delta m^2 = O(1eV^2)$ there is a matter-induced (parametric) resonant effect when:





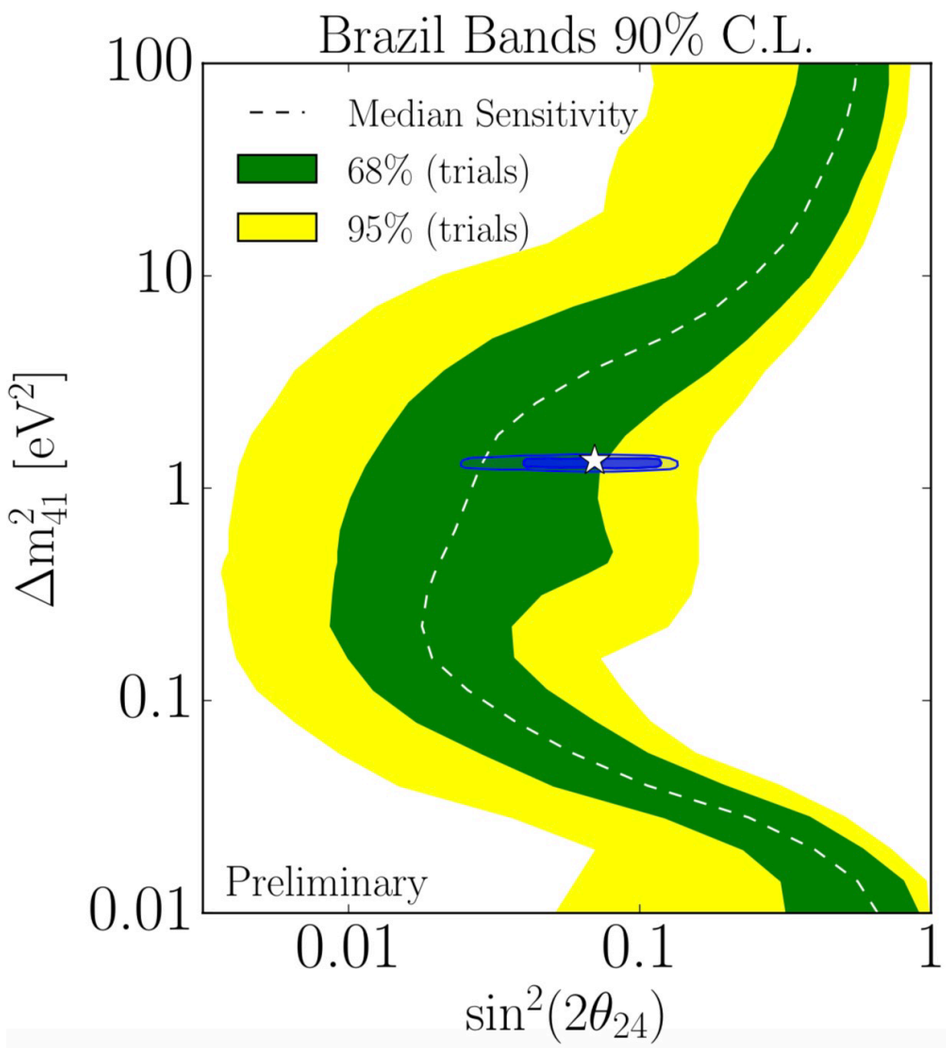


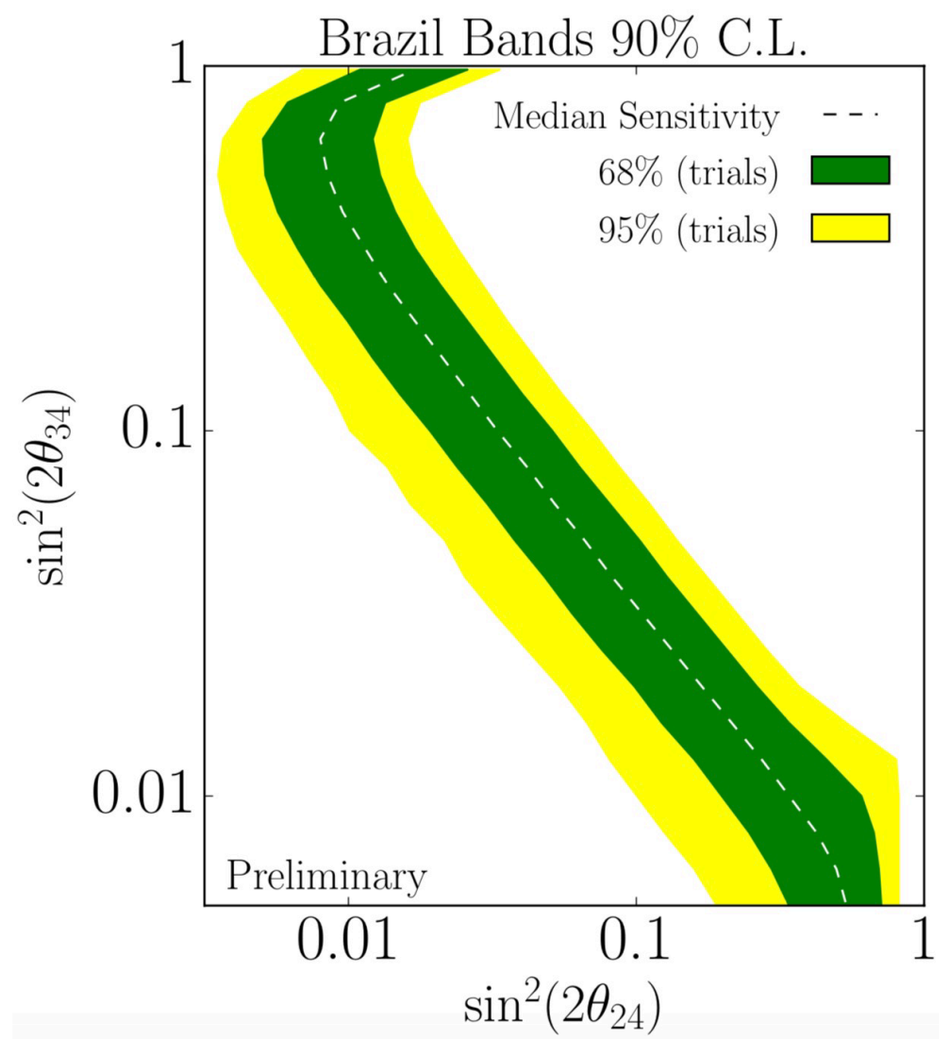
- Effects of sterile neutrinos below 100 GeV
- Modifies standard neutrino oscillations
- Effect is proportional to amount of matter along neutrino path



Joshua Hignight 7-4

Future prospects





- Next generation sterile neutrino analysis
  - Improved event selection criteria
  - Reduced systematic uncertainties
  - Data sample (1year ⇒7years)

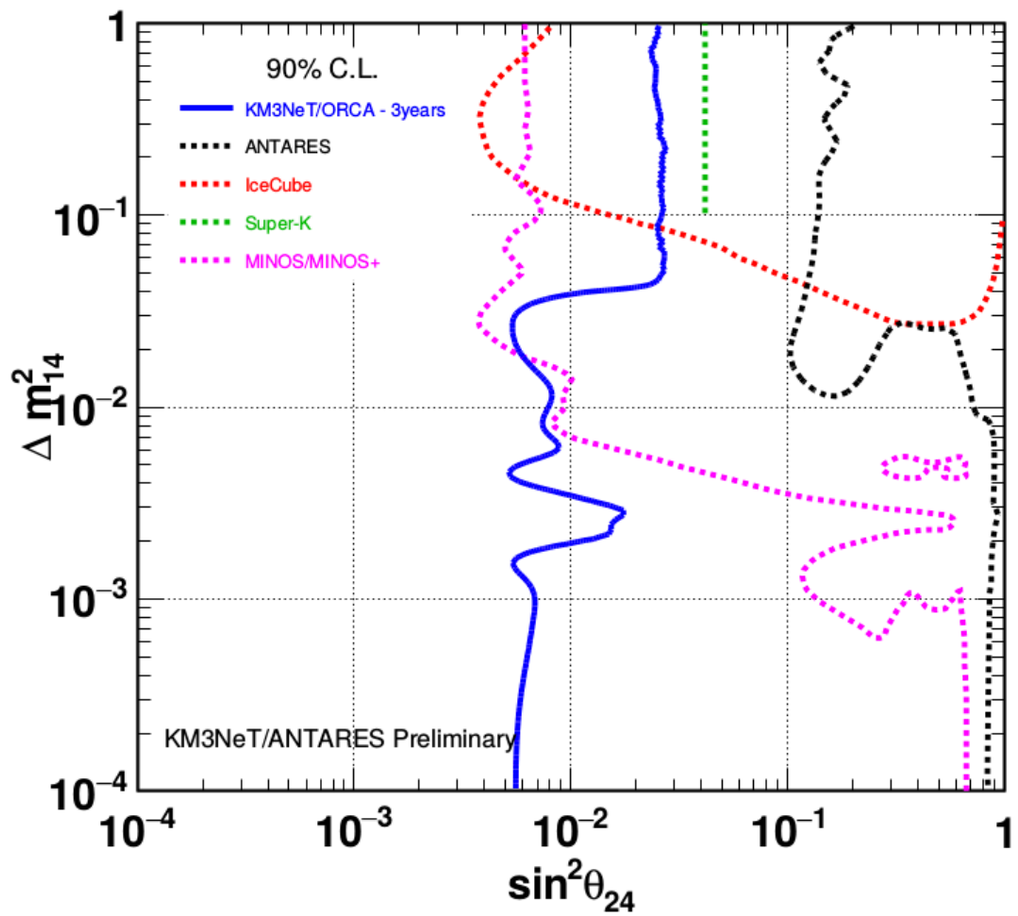
Test both θ_{24} and θ_{34}
Expected to test current global fit regions

Paschal Coyle 2-1

Sterile Neutrinos at KM3NeT

KM3NeT/ORCA Sensitivity

$\Delta m_{41}^2 < 0.1\ eV^2$



Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude

Conclusions

Summary

- Rich science program to search for BSM physics at neutrino detectors
- Essential to understand the observed anomalies and what they are telling us about nature
- Tremendous potential for future search and expand scientific programs
- Thanks to all the speakers and their contributions to the WG5 session
- Thanks for chairing sessions !
  - Ana Teixeira, Juanan Aguliar, Jose Valle, Josh Spitz, Jaehoon Yu