Neutrino2022 catch-up

Julia Gehrlein

Brookhaven National Laboratory

June 7th 2022

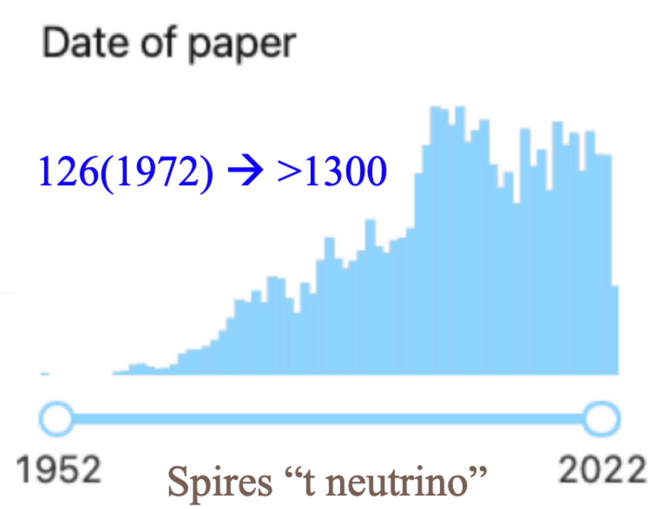
Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

Neutrino2022 catch-up

Neutrino '72, Balatonfüred, Hungary

Participants of Neutrino '72 conference. In the front row: T. D. Lee, G. L. Radicati, R. P. Feynman, B. Pontecorvo, G. Marx, V. F. Weisskopf, F. Reines, C. L. Cowan and P. Budini



Have learned a lot about neutrinos since then
→ still many open questions to explore

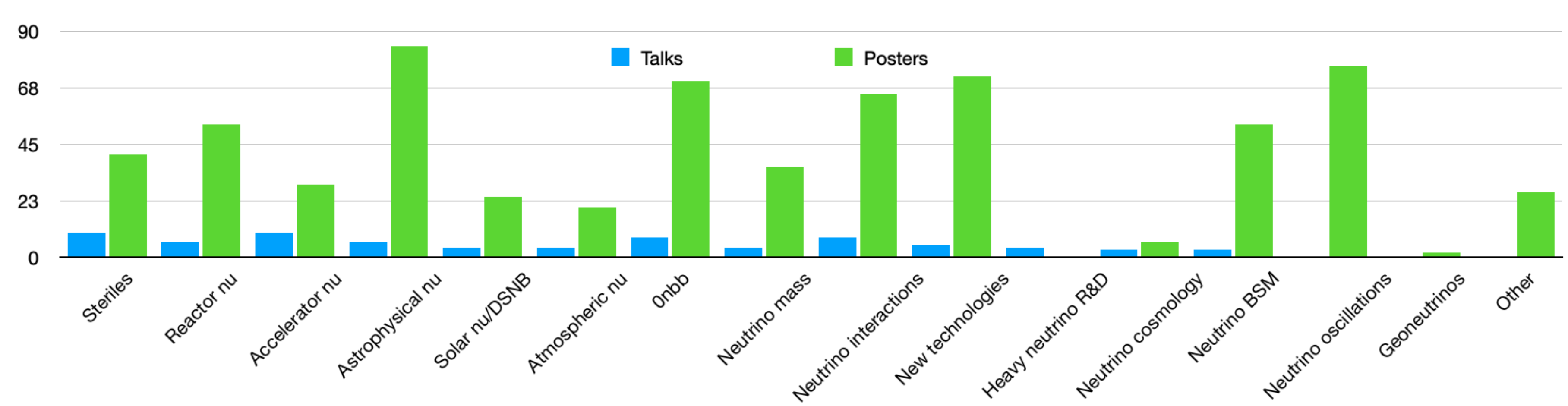
No of Participants @ INC :
139(1972) → ~ 1000

Neutrino2022 catch-up

Have learned a lot about neutrinos since then
→ still many open questions to explore

1,272 participants from 44 countries
657 posters

Sterile neutrinos
Reactor neutrinos
Accelerator neutrinos
Astrophysical neutrinos
Neutrino interactions
New neutrino technologies
Neutrinoless double beta decay
Neutrino mass
Atmospheric neutrinos
Solar/DSNB neutrinos
Heavy neutrinos, R&D
Neutrino cosmology
Neutrinos & BSM



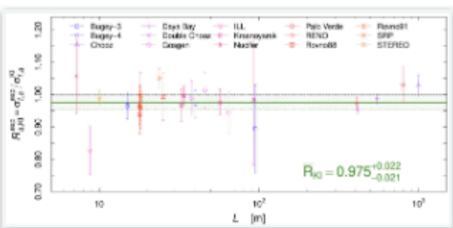
Neutrino2022: steriles

Quo Vadis, Sterile Neutrino?

The Current Status of Searches for a Fourth Neutrino

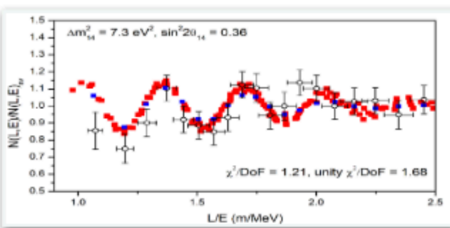
Joachim Kopp (CERN & Uni Mainz)
Neutrino 2022 | 30 May 2022

Summary



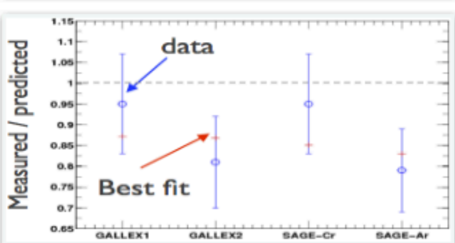
reactor flux anomaly
resolved with new input data
to flux calculation

✔



reactor spectra
is there really an anomaly?

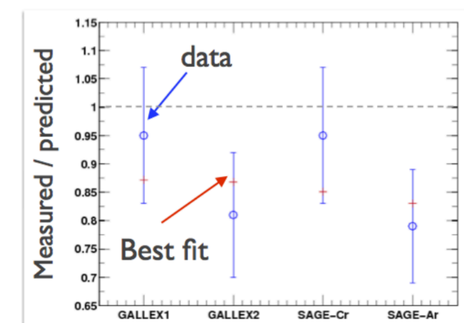
? ⇒ **Wilk's theorem often fails**

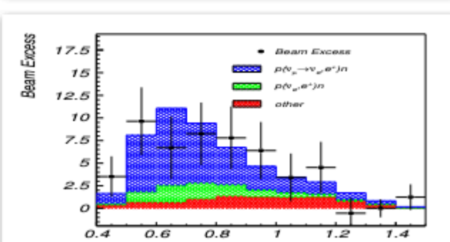


gallium anomaly
unresolved, recently reinforced

?

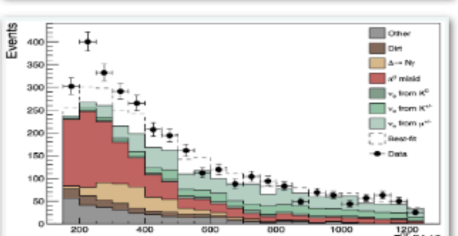
- ☑ Experiments with intense radioactive sources
- ☑ Neutrino detection via $^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$
- ☑ ~3σ deficit





LSND
unresolved

? **$\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam**



MiniBooNE
unresolved
resolvable by next-gen. SBL experiments

?

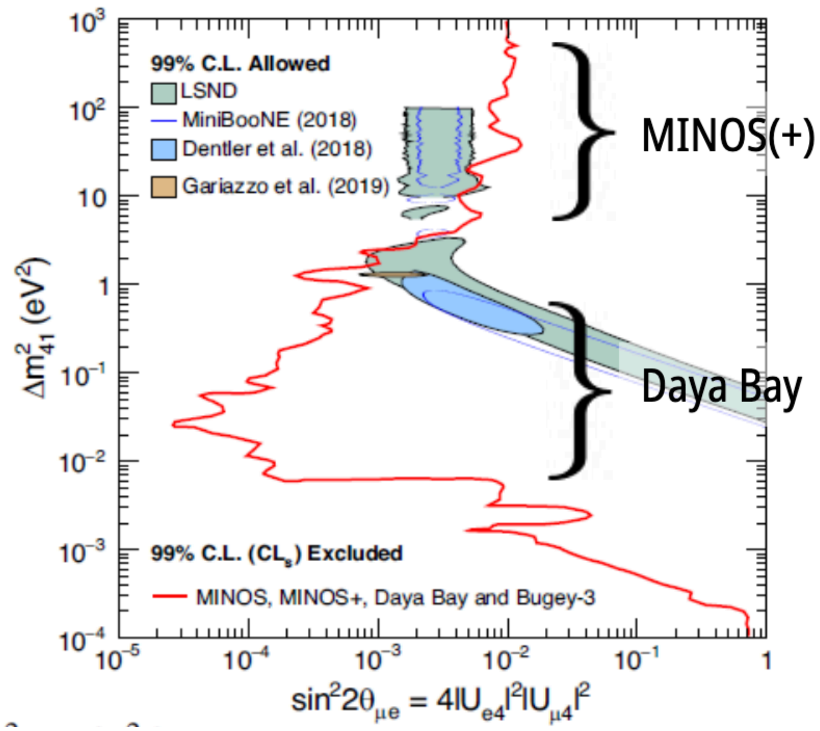
Neutrino2022: steriles

Short baseline reactor experiments

Sterile neutrinos: experimental results with reactors

Matthieu Licciardi (LPSC Grenoble, CNRS/IN2P3)

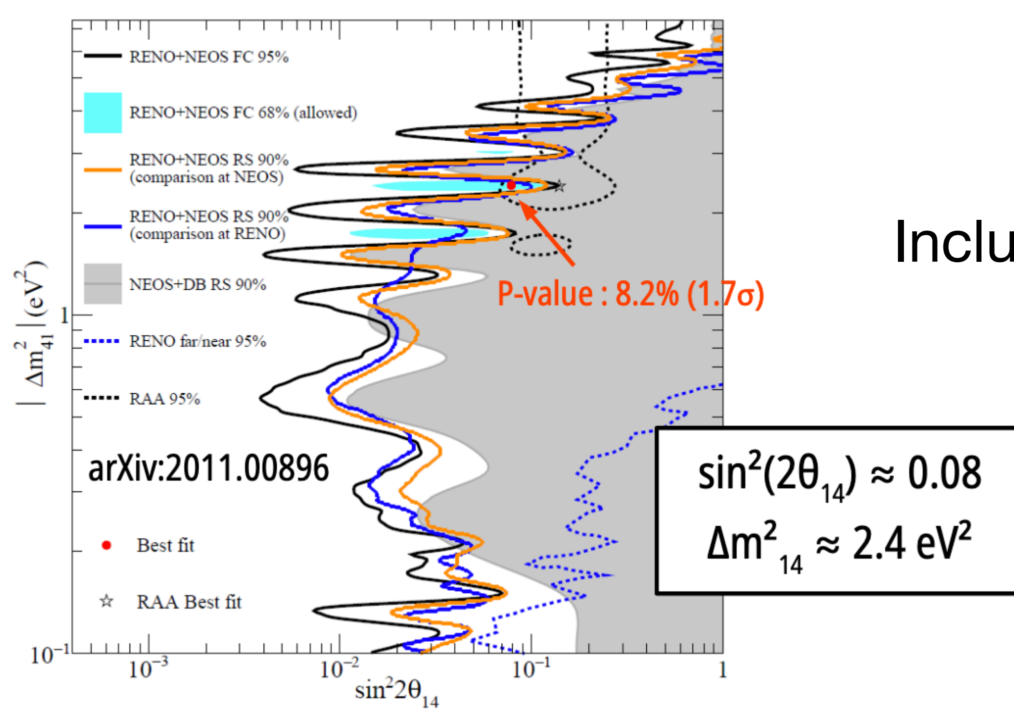
Daya Bay



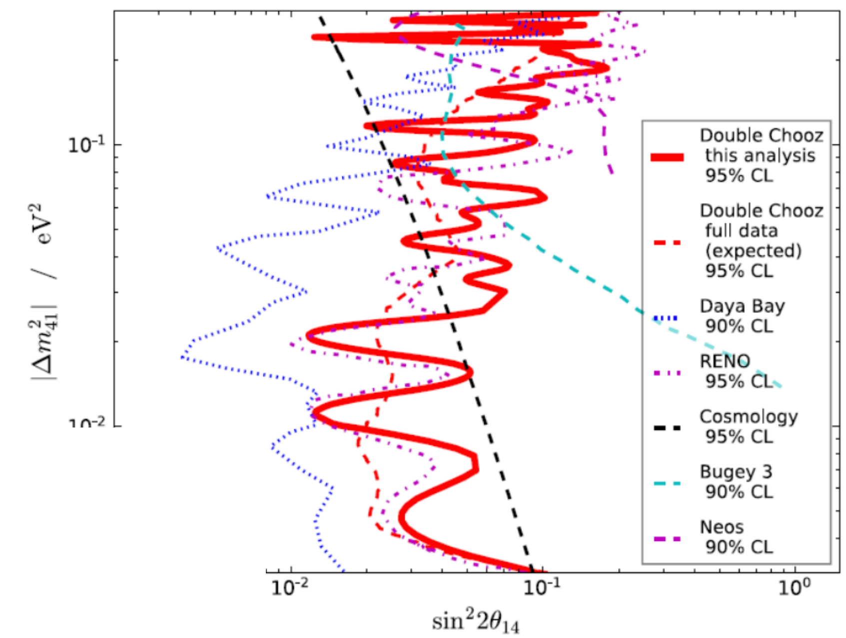
1/3 of data analyzed so far
Excludes parts of
LSND parameter space

RENO-NEOS

2200/3400 days analyzed
3 more years of data taking



Double Chooz



Inclusion of 2017 data coming

Neutrino2022: steriles

Very short baseline reactor experiments

Sterile neutrinos: experimental results with reactors

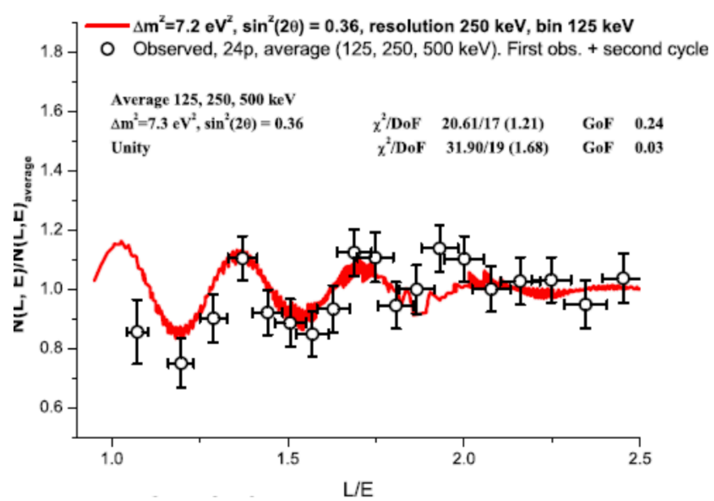
Matthieu Licciardi (LPSC Grenoble, CNRS/IN2P3)

SoLid

Currently working on
phase-I data (2 yrs of data)
Analysis will be stat. limited

Neutrino-4

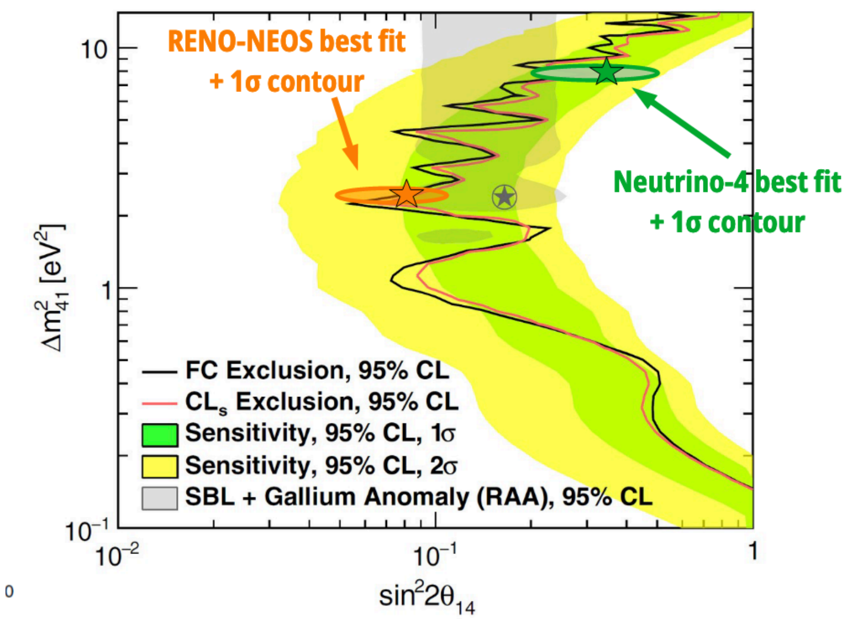
Detector upgrade in 2022,
data taking 2023-24:
3x more sensitive



$\sin^2(2\theta_{14}) \approx 0.36$
$\Delta m^2_{14} \approx 7.3\ eV^2$

***2.9σ** with Wilks thm*
***2.7σ** with F-C*

PROSPECT



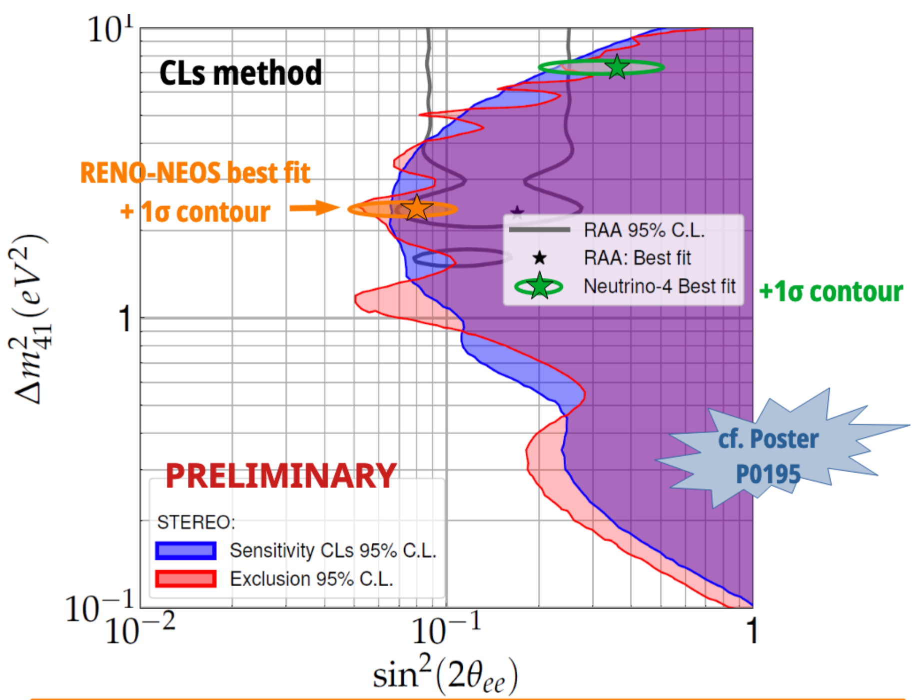
- **Rejection of the RAA+Gallium** best fit
  p-value = 1.5% (2.5σ)
- Neutrino-4 best fit + 1σ contour within sensitivity, **excluded at >95 % CL**
- RENO-NEOS best fit at the edge of exclusion contour

Neutrino2022: steriles

Very short baseline reactor experiments

STEREO

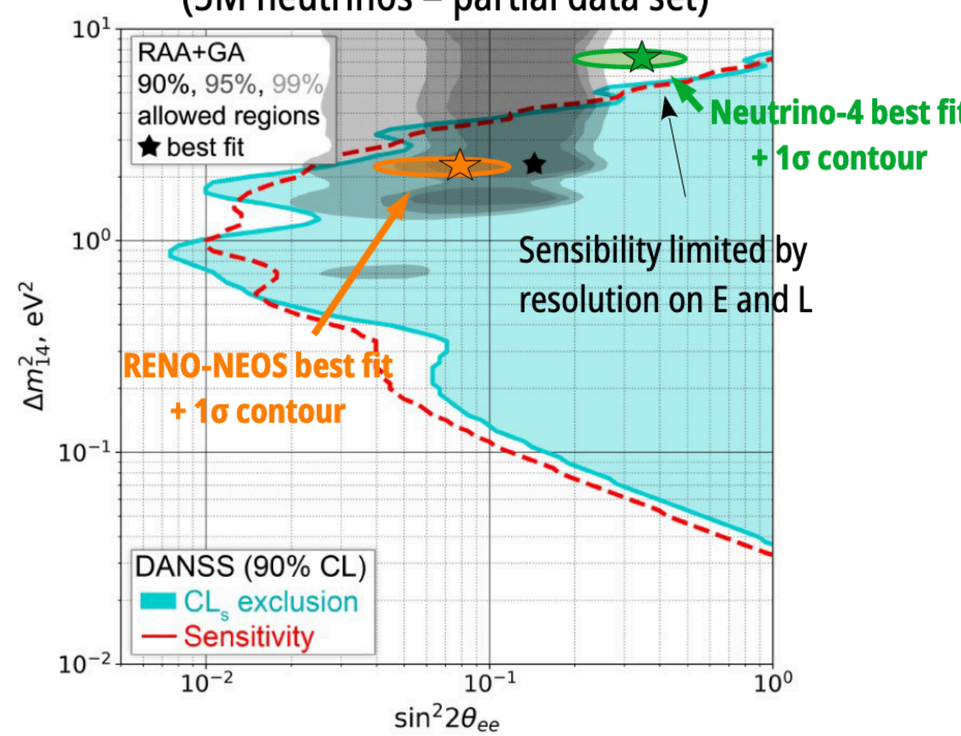
Final results with full data set



- **Strong rejection of the RAA** allowed 95% CL space
  RAA best-fit point : p-value < 10^{-4} (>4σ)
- Neutrino-4 best fit and 1σ contour within sensitivity
  Best-fit **rejected at 3.1σ** (p-value ~ 1.5 10^{-3})
- NEOS-RENO best-fit point excluded at 2.8σ

DANSS

(5M neutrinos – partial data set)



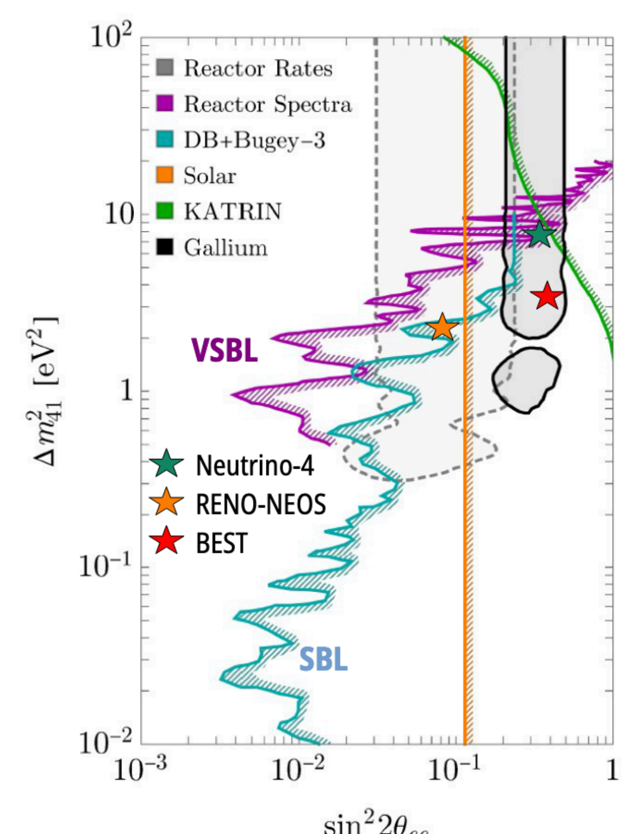
- **Rejection of the RAA + Gallium Anomaly**
  best fit point exluded at >5σ
- RENO-NEOS best fit excluded at >90%CL

Sterile neutrinos: experimental results with reactors

Matthieu Licciardi (LPSC Grenoble, CNRS/IN2P3)

- Upgrade with improved energy resolution Sensitivity to Neutrino-4 bf point

Current situation



Large region of parameter space probed

Positive observation of steriles (Neutrino-4, RENO-NEOS, BEST) in **strong tension** with other experiments

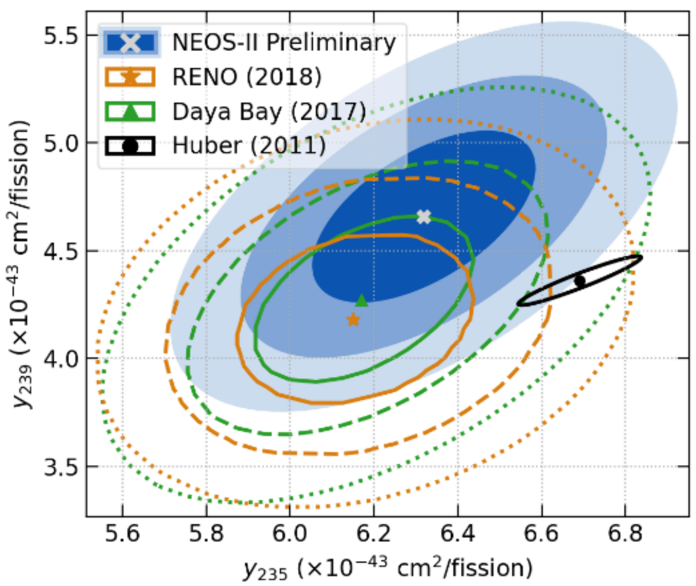
Neutrino2022: steriles

NEOS-II

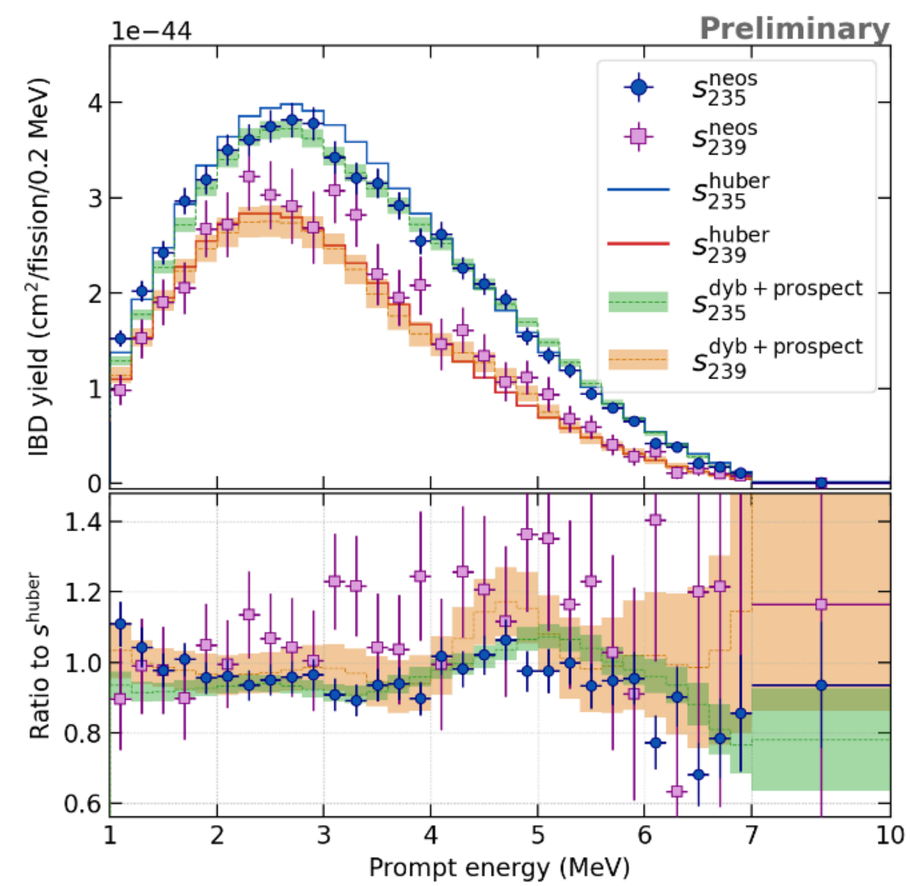
Data taking complete

NEOS-II New Results

- IBD Yields for ^{235}U & ^{239}Pu

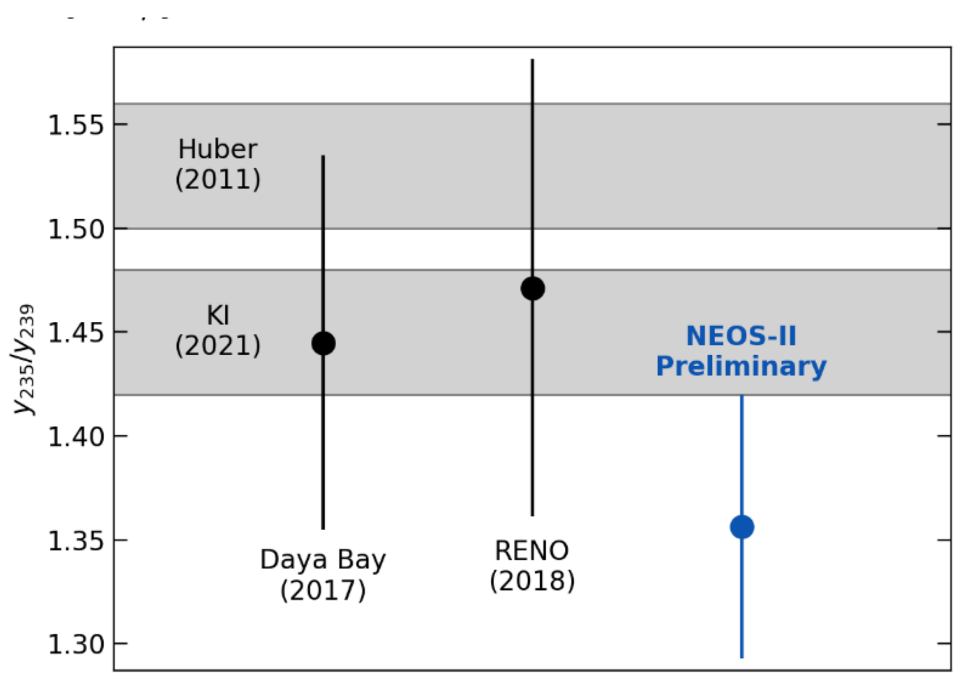


Jinyu Kim



Deficit of ^{235}U

5 MeV bump hints for ^{235}U and ^{239}Pu



Sterile neutrino analysis ongoing

Neutrino2022: steriles

JSNS^2

JSNS^2 new results

Jungsic Park (Kyungpook National University)
On behalf of the JSNS^2 / JSNS^2-II collaboration

Same source, target, detection principle as LSND
(JSNS^2-II (granted!) will fully probe LSND region)
Start of blind analysis of data

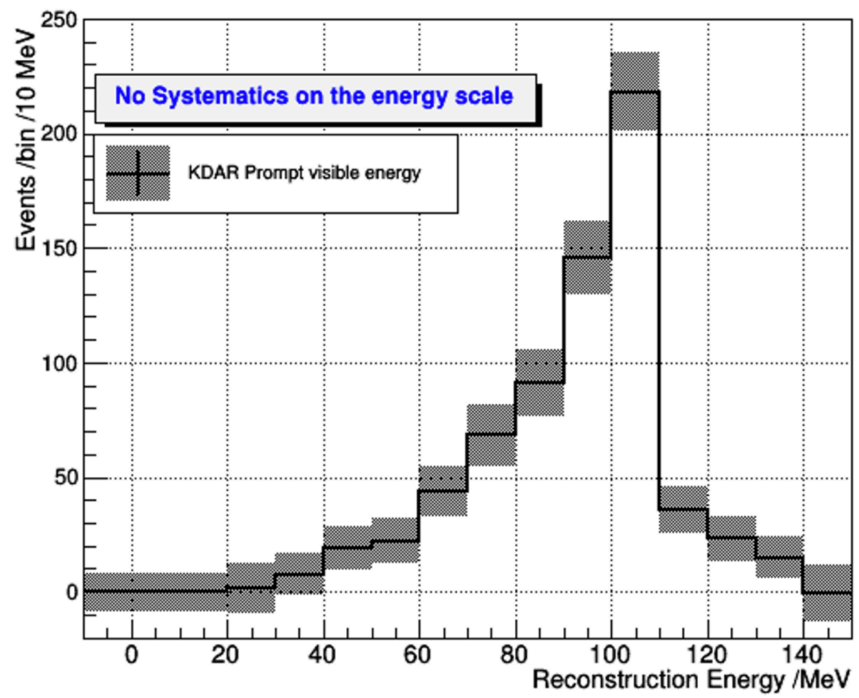
First clear KDAR signal

(Toward first precise KDAR measurement)

- **KDAR peak is clearly seen**
- **High purity (95%)** KDAR signal
  - Background: 5.2 %

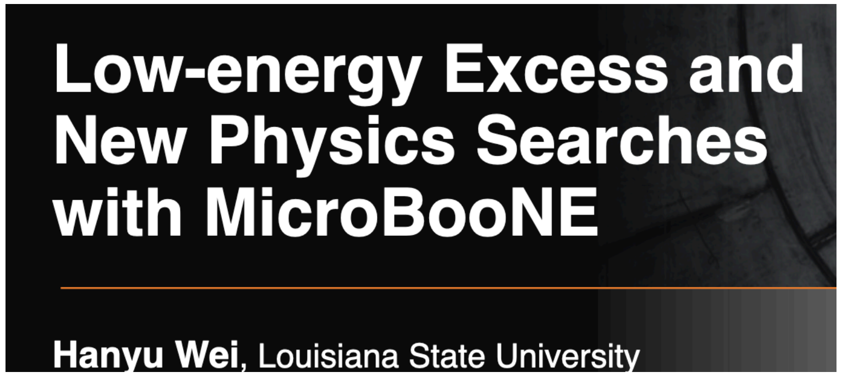
- Note that **the systematics on the energy scale are not included yet.**

BKG ID	Correlated/ Accidental	BKG (# of events)	
1	Correlated	36.6 ± 34.8	5.0 ± 5.1%
2	Accidental	1.5 ± 0.1	0.2 ± 0.01%
KDAR Signal : 730 events		38.1 ± 38.4	5.2 ± 5.3%



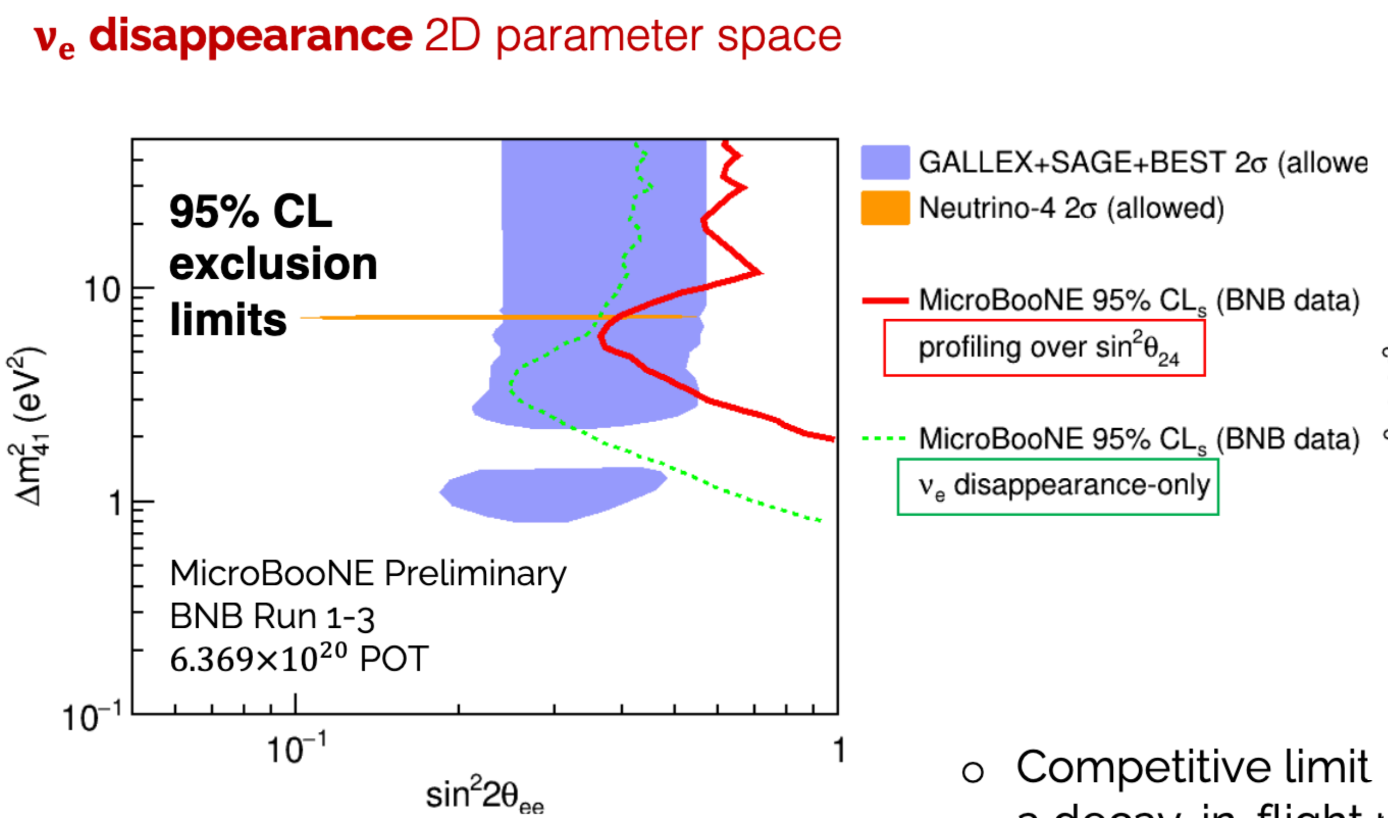
Neutrino2022: steriles

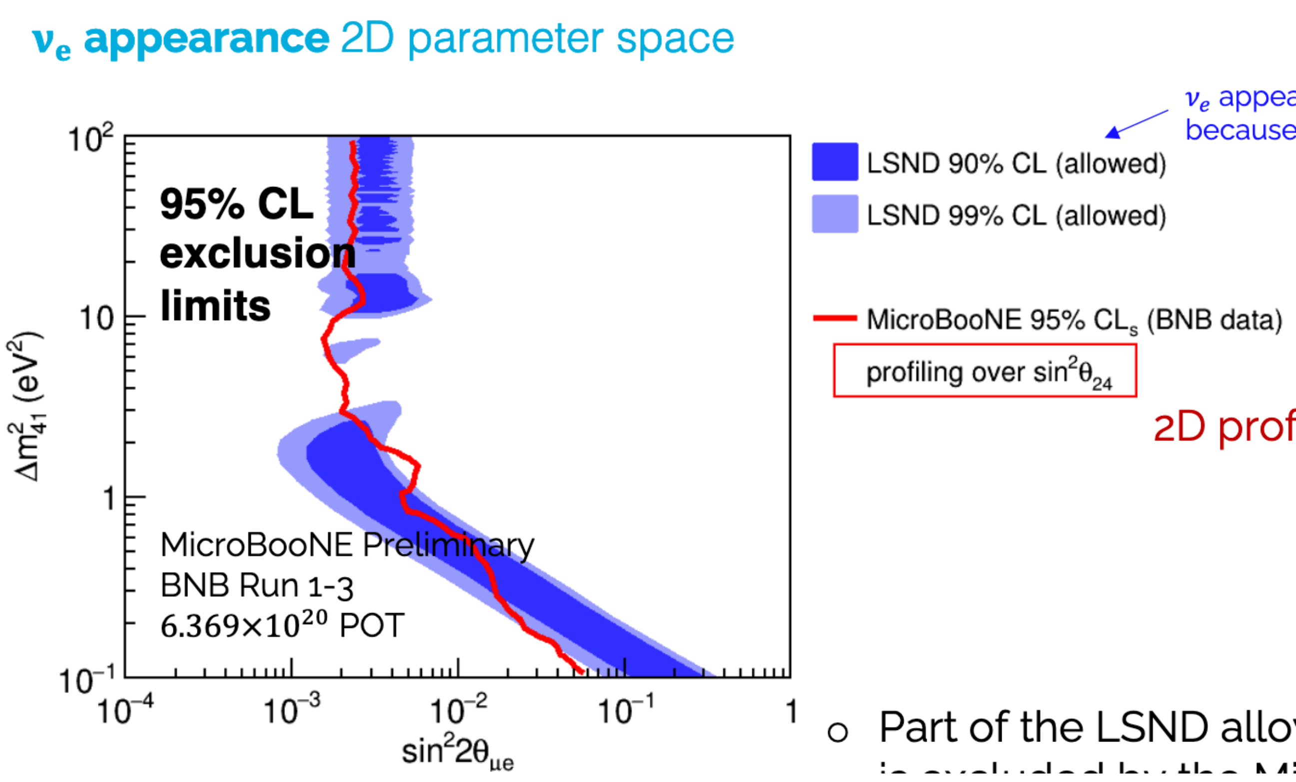
MicroBooNE



Consider ν_e disappearance,

ν_e appearance for 3+1 model





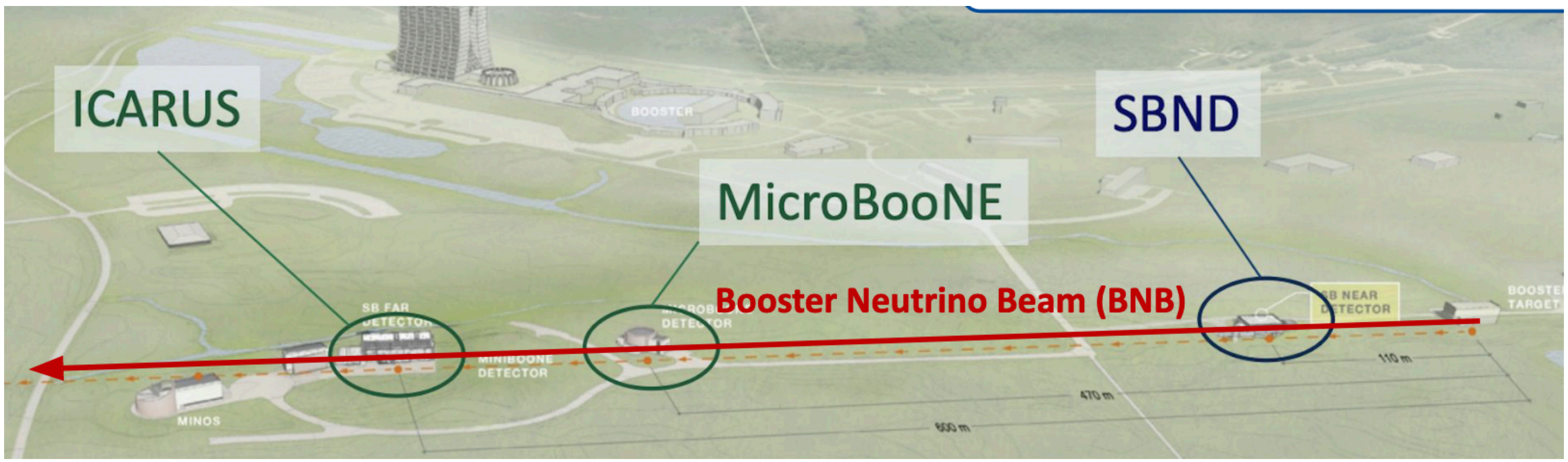
BNB Run 1-3 + NuMI Run 1 will be sensitve to Ga region and LSND region

Neutrino2022: steriles

ICARUS+SBND

ICARUS + SBND
Short Baseline Neutrino Program

Anne Schukraft



ICARUS commissioning is completing and ICARUS is preparing to *start its Physics Run*
SBND *Installation progressing very well* - expected to start operating the detector next year

Neutrino2022: steriles

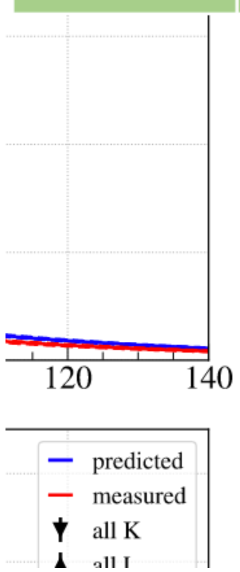
BEST

Neutrino production in source $^{51}\mathrm{Cr} + \mathrm{e}^- \rightarrow {}^{51}\mathrm{V} + \nu_\mathrm{e}$

Detection $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$

The BEST Experiment

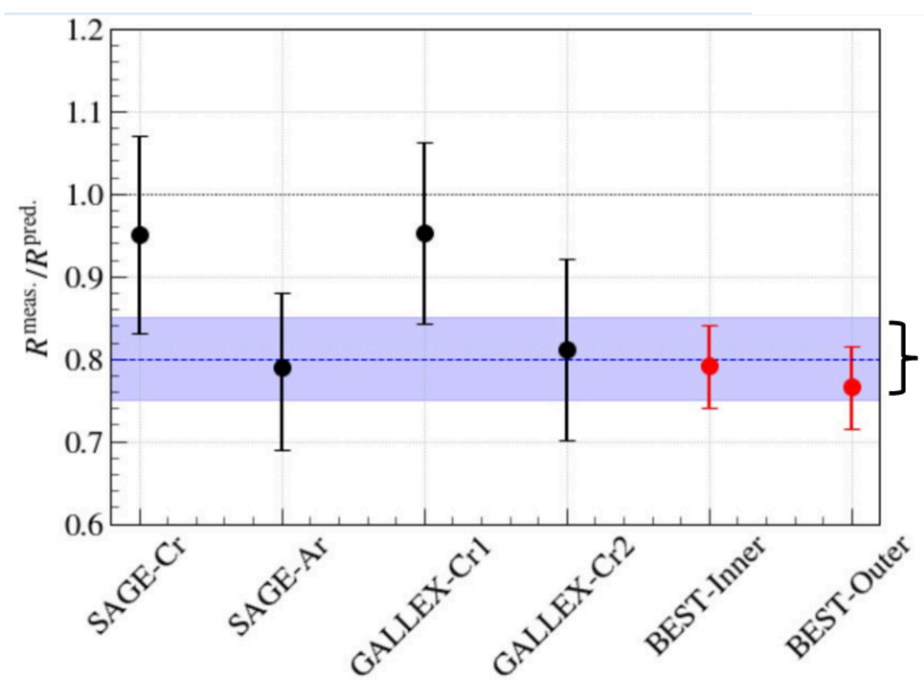
	IN	OUT
Pred.	$69.41^{+2.5}_{-2.0}$	$72.59^{+2.6}_{-2.1}$
Meas.	54.9 ± 2.9	55.6 ± 3.1
Ratio	0.79 ± 0.05	0.77 ± 0.05



4.2σ and 4.8σ less than the unity

Note: $\frac{0.77 \pm 0.05}{0.79 \pm 0.05} = 0.97 \pm 0.07$

Steve Elliott

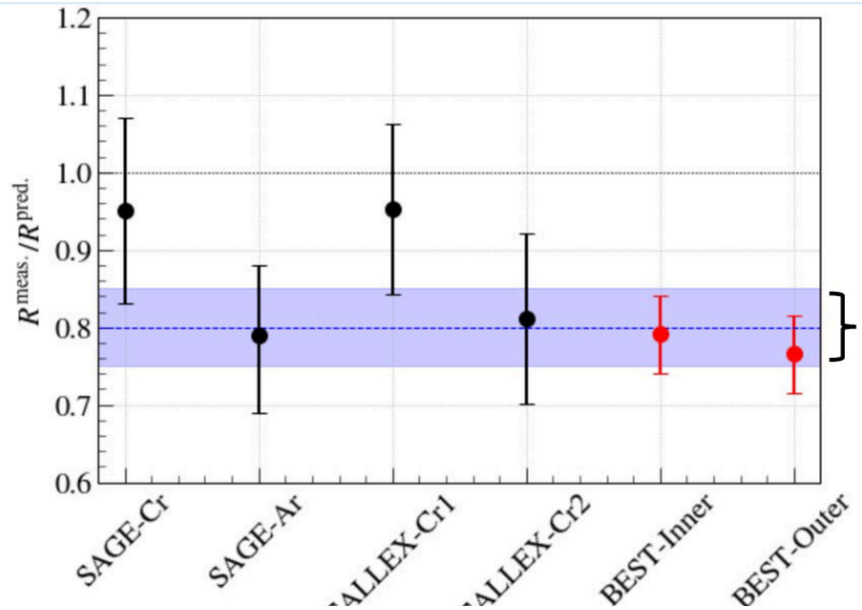


Combined result:
$\mathrm{R_0} = 0.80 \pm 0.05$

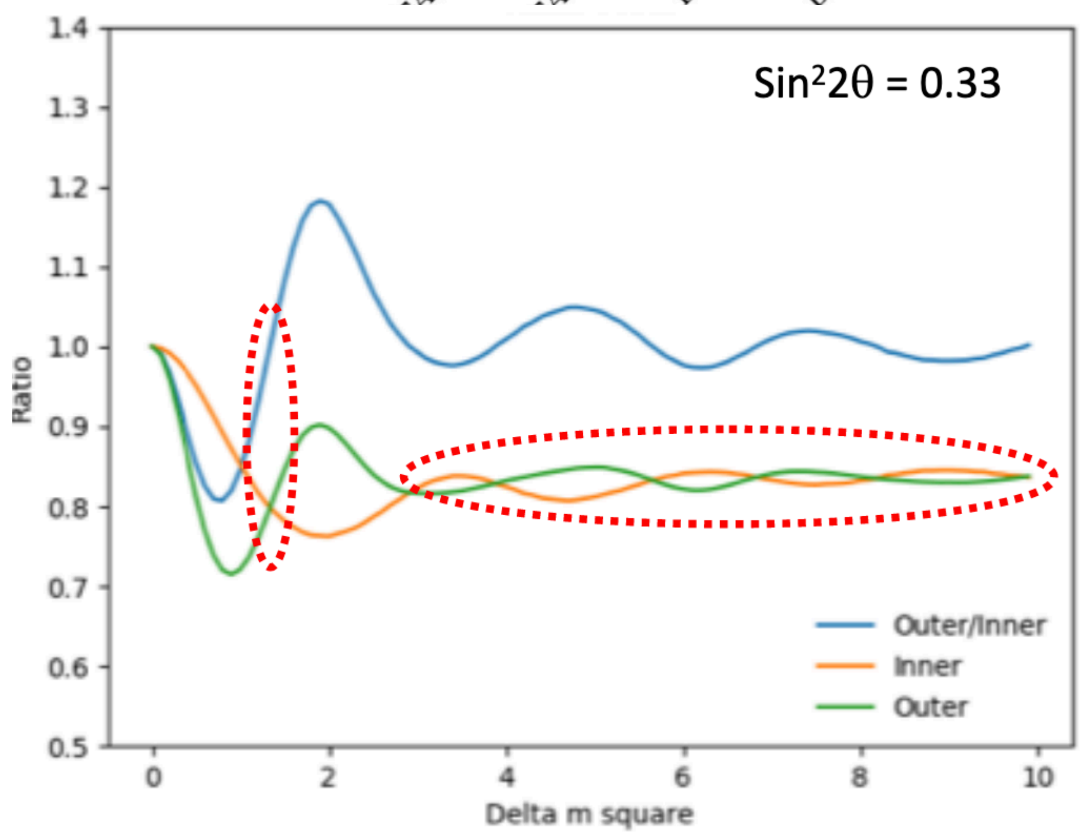
Similar deficit observed
in both zones
→ no oscillation-like dependence on distance!

Neutrino2022: steriles

BEST

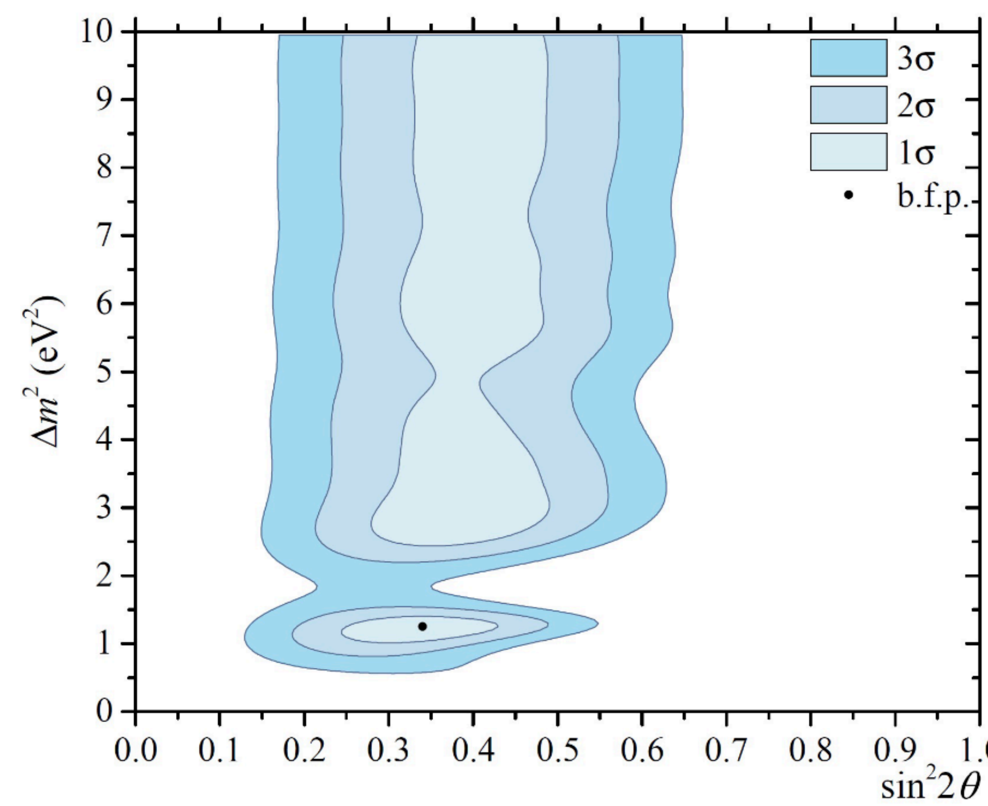


Combined result:
$R_0 = 0.80 \pm 0.05$



The BEST Experiment

Steve Elliott

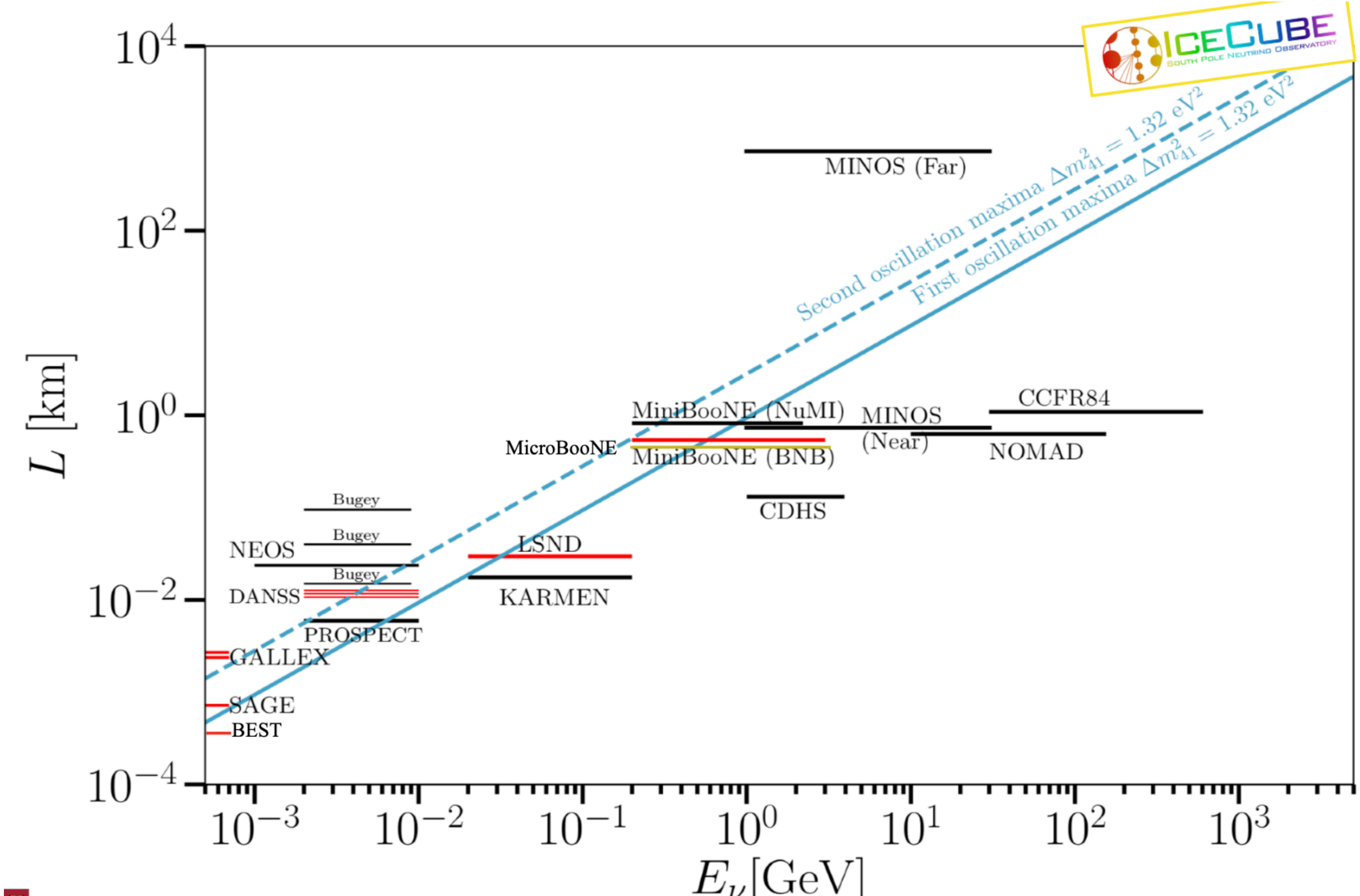


Neutrino2022: steriles

Steriles + friends

Beyond Vanilla Sterile Neutrinos and other Scenarios

Carlos Argüelles



Tension between appearance and disappearance data sets

→ go beyond vanilla 3+1 scenarios

Neutrino2022: steriles

Steriles + friends

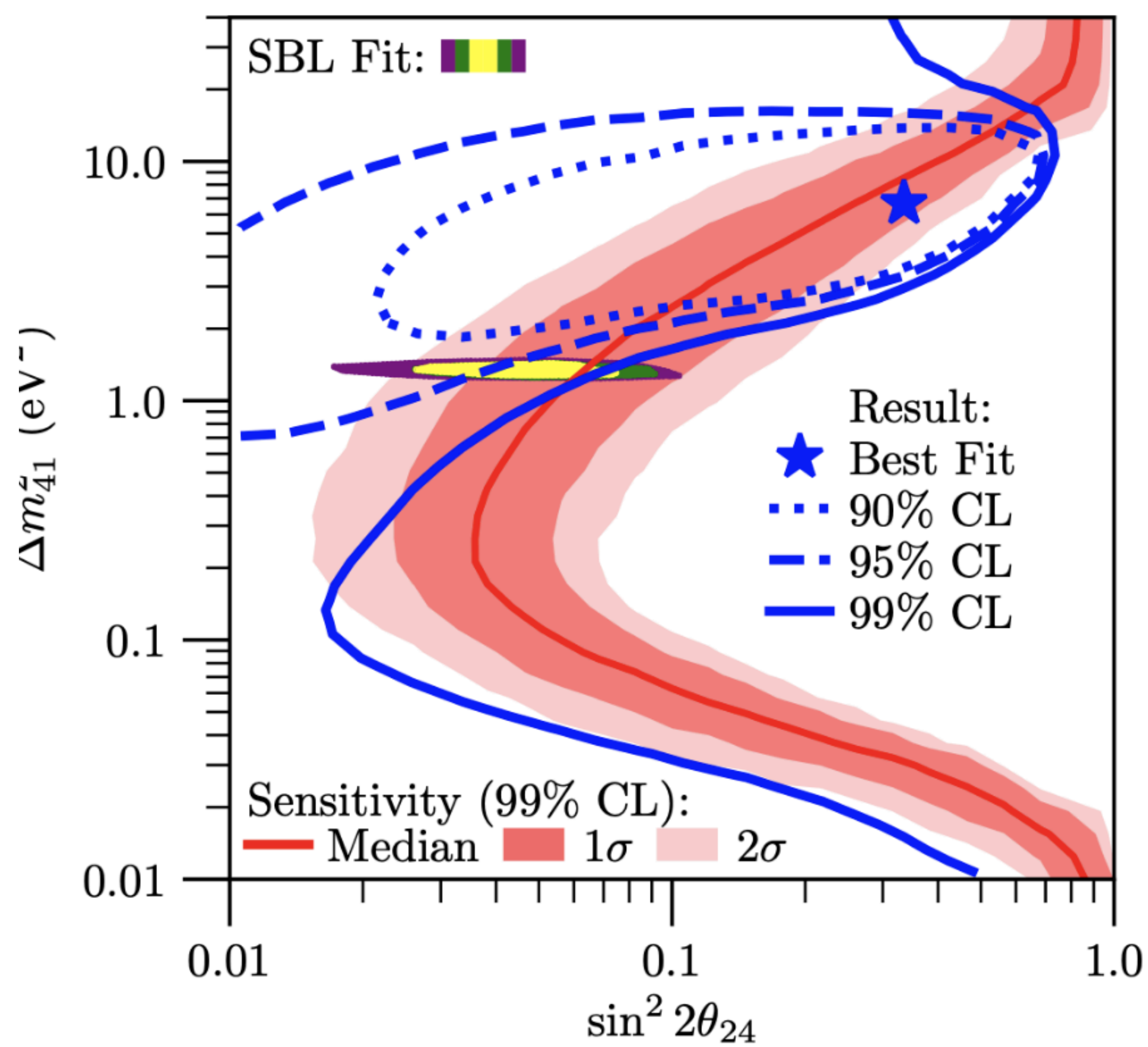
Beyond Vanilla Sterile Neutrinos and other Scenarios

Carlos Argüelles

Sterile neutrino+NSI: future studies at MINOS+, IceCube?
Sterile neutrino+decay: IceCube

$\Delta m^2_{41} = 6.7^{+3.9}_{-2.5}\text{eV}^2 \quad \sin^2 2\theta_{24} = 0.33^{+0.20}_{-0.17} \quad g^2 = 2.5\pi \pm 1.5\pi$

(slice for best-fit decay constant)

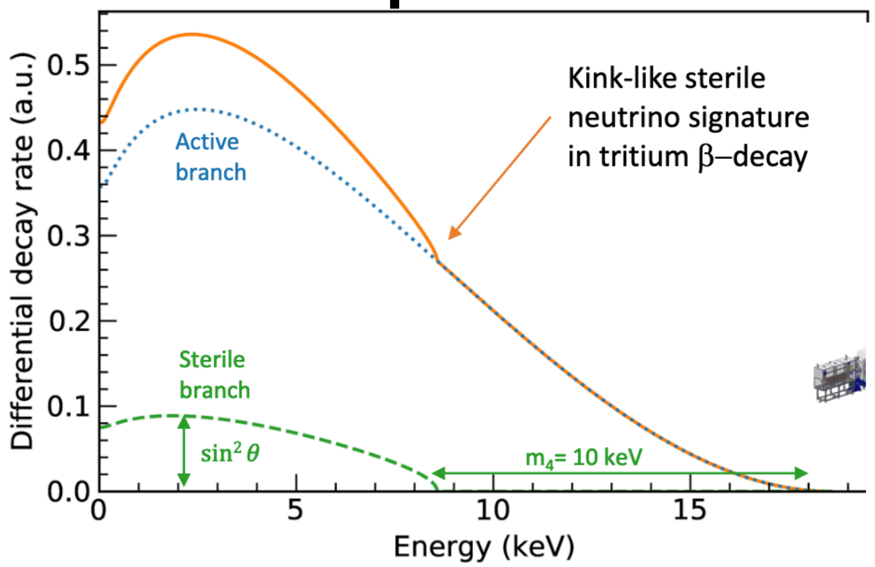


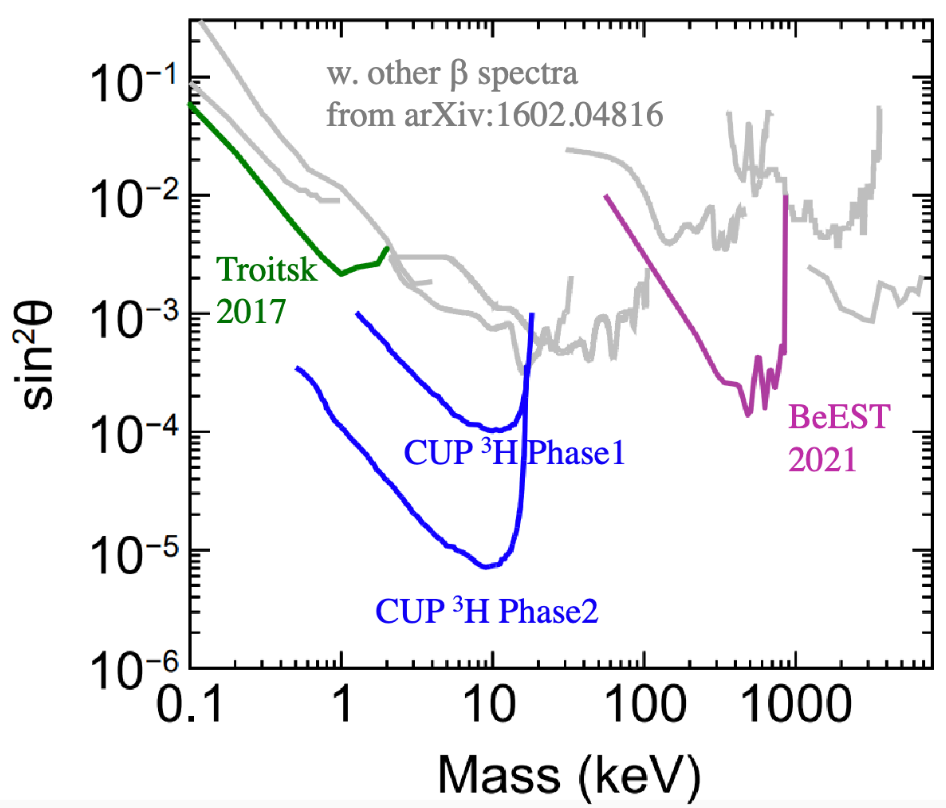
Other ideas to address SBL anomalies should be studied

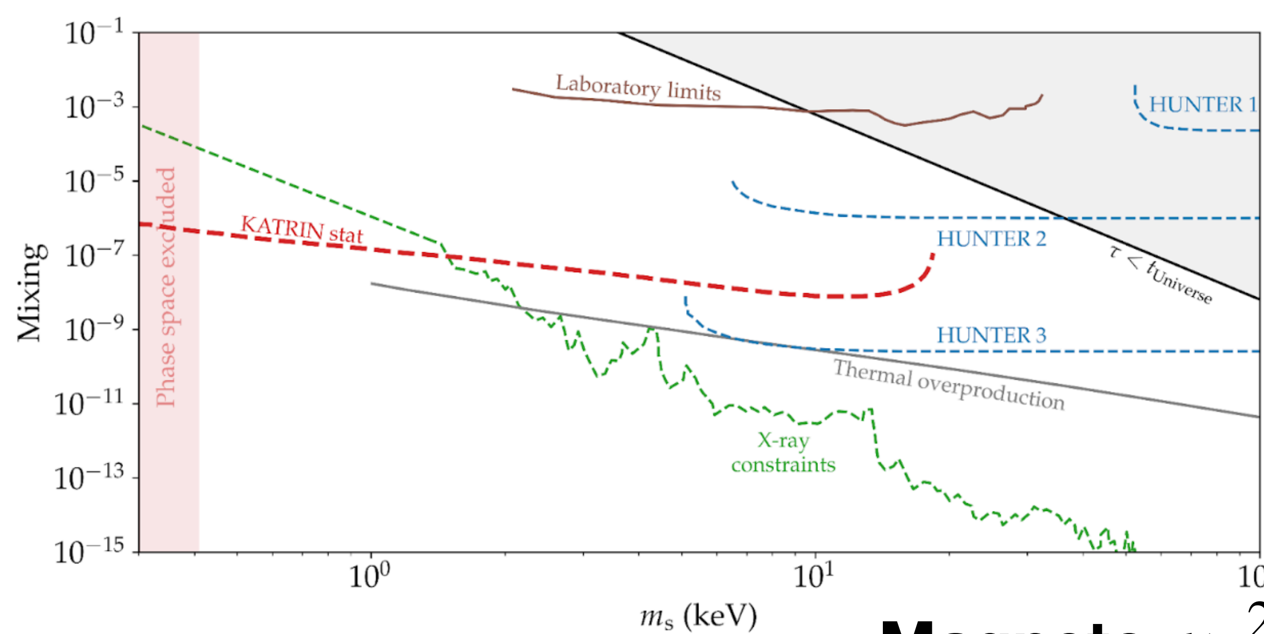
Neutrino2022: steriles

keV steriles

Tritium endpoint measurements

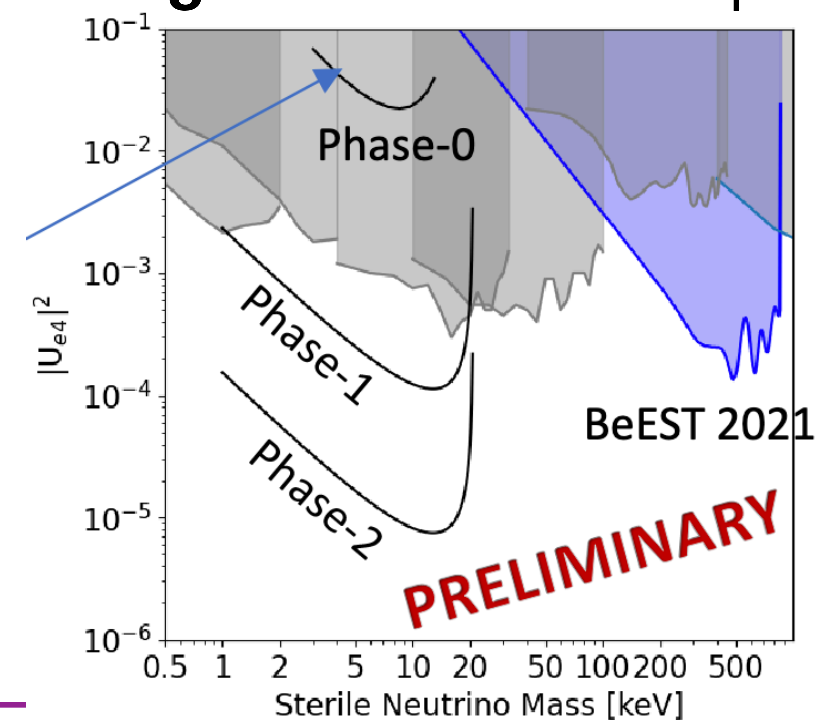






KATRIN/TRISTAN
Project 8
CUP

Magneto-ν: ^{283}Pu endpoint



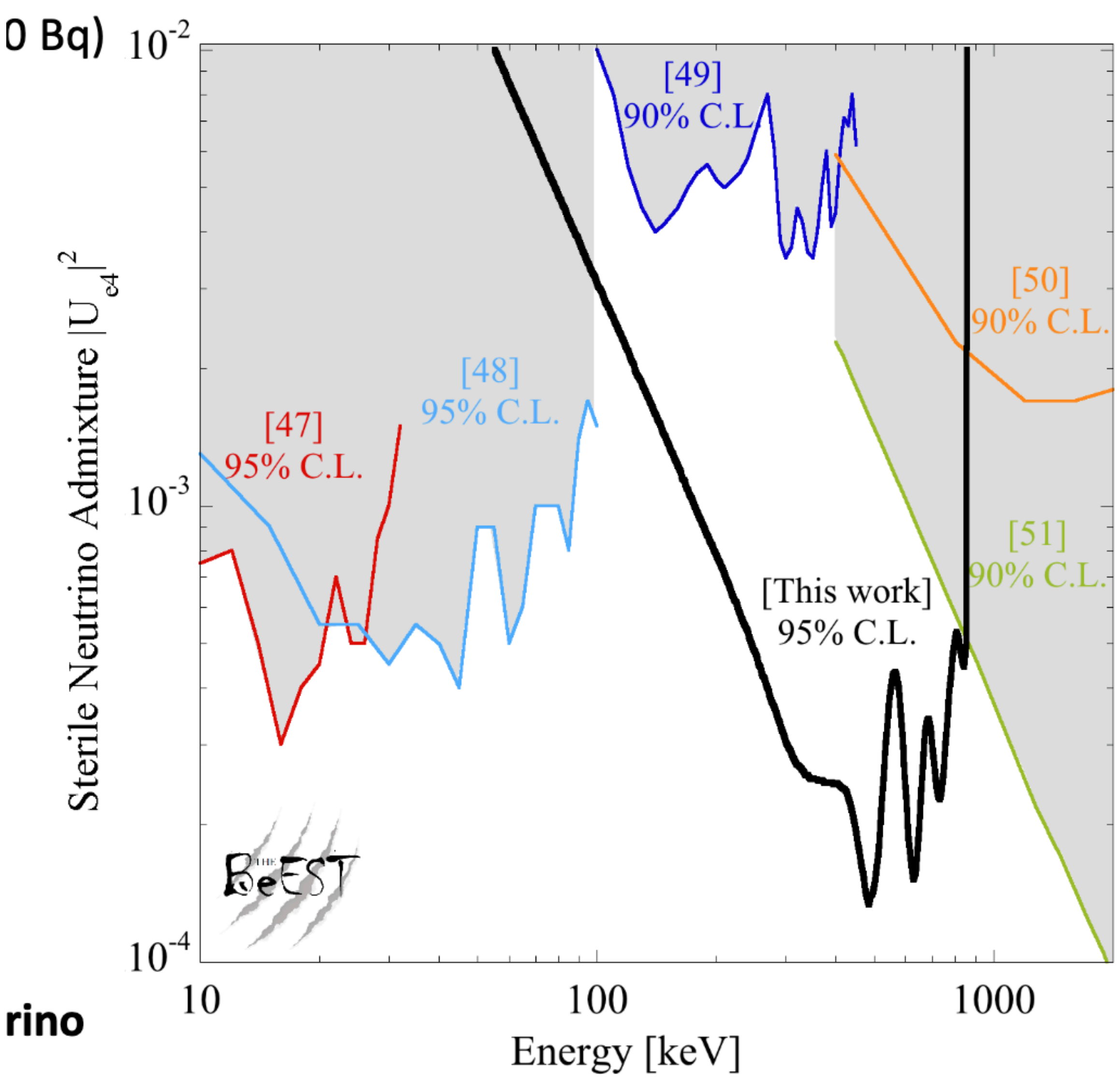
Neutrino2022: steriles

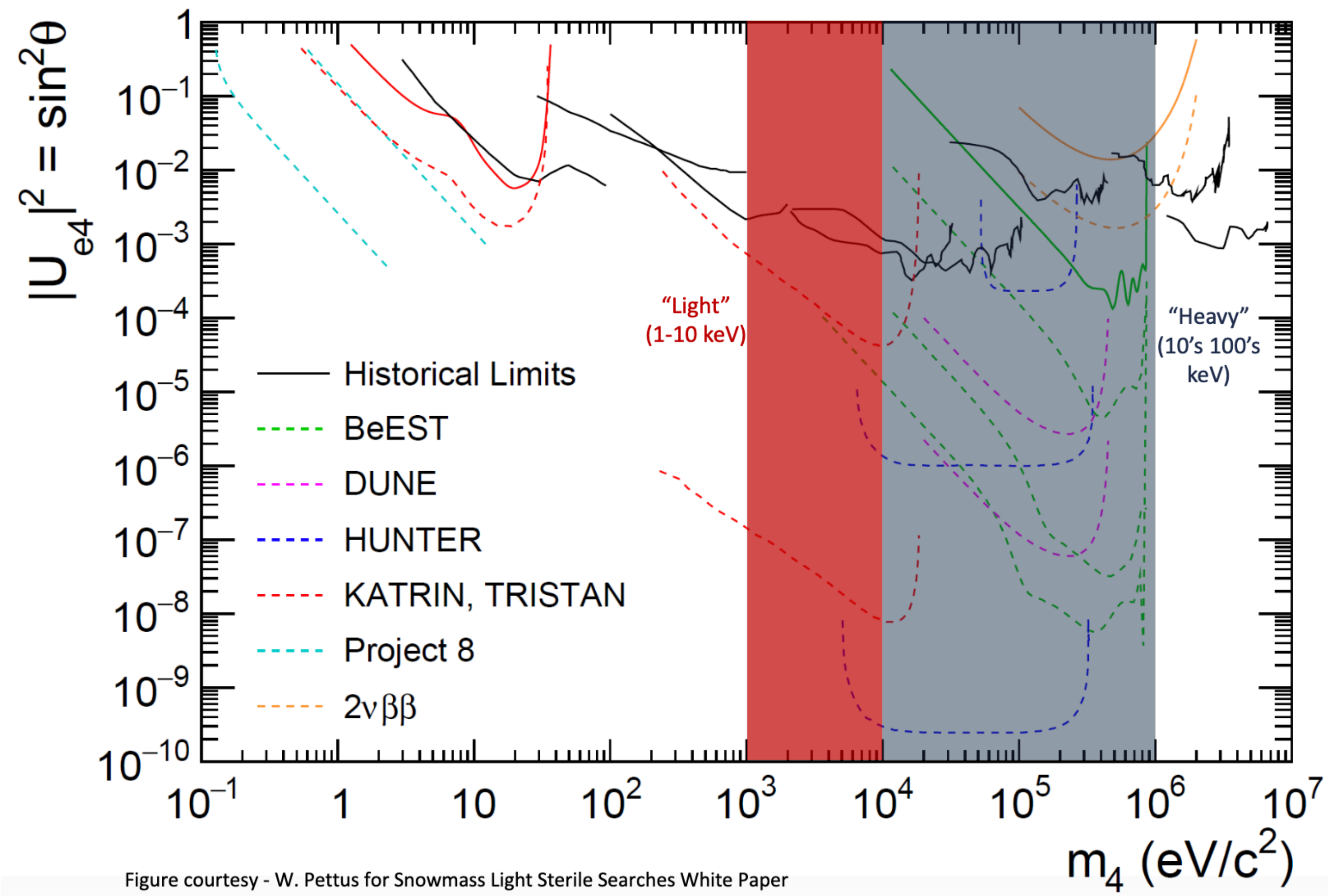
keV steriles

BeEST experiment: EC of ^{7}Be

New Results from Laboratory keV Neutrino Searches

Kyle Leach

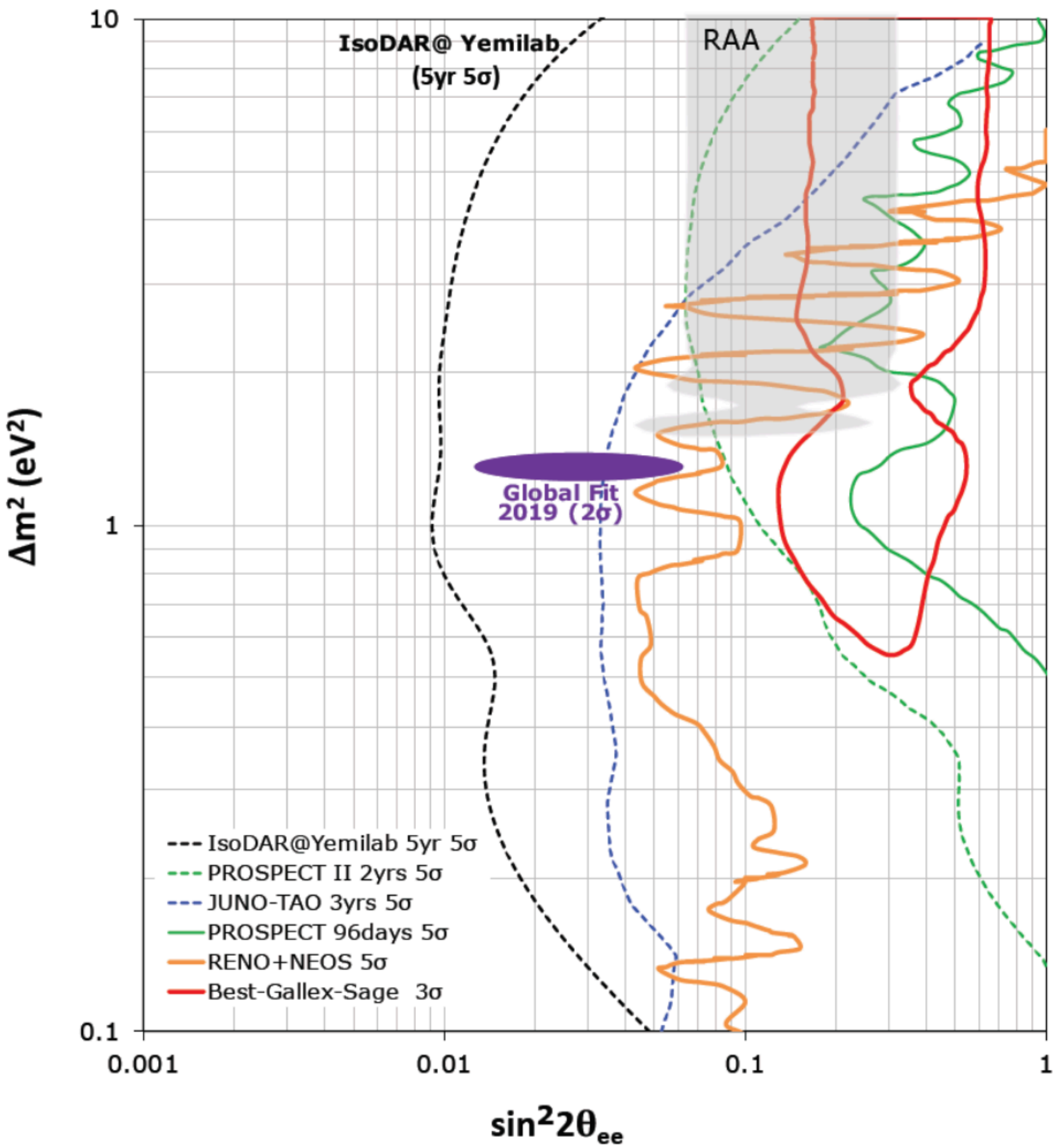




HUNTER: EC of ^{131}Cs, comissioning in CY 2022

Neutrino2022: steriles

New eV sterile searches



Prospects for new eV-scale sterile neutrino searches

JUNO-TAO, PROSPECT-II, and IsoDAR

Josh Spitz (U. Michigan) and Daniel Winklehner (MIT), 5/31/2022

JUNO-TAO: ND for JUNO, very good energy resolutions

PROSPECT-II: resolved technical issues of PROSPECT, at HFIR in Oak Ridge

IsoDAR@Yemilab: 2.3 kT LS close to IsoDar neutrino source, Pre-approved!

Neutrino2022: Neutrinoless double beta decay

Overview of current experimental and theoretical status of $0\nu\beta\beta$
Fedor Šimkovic

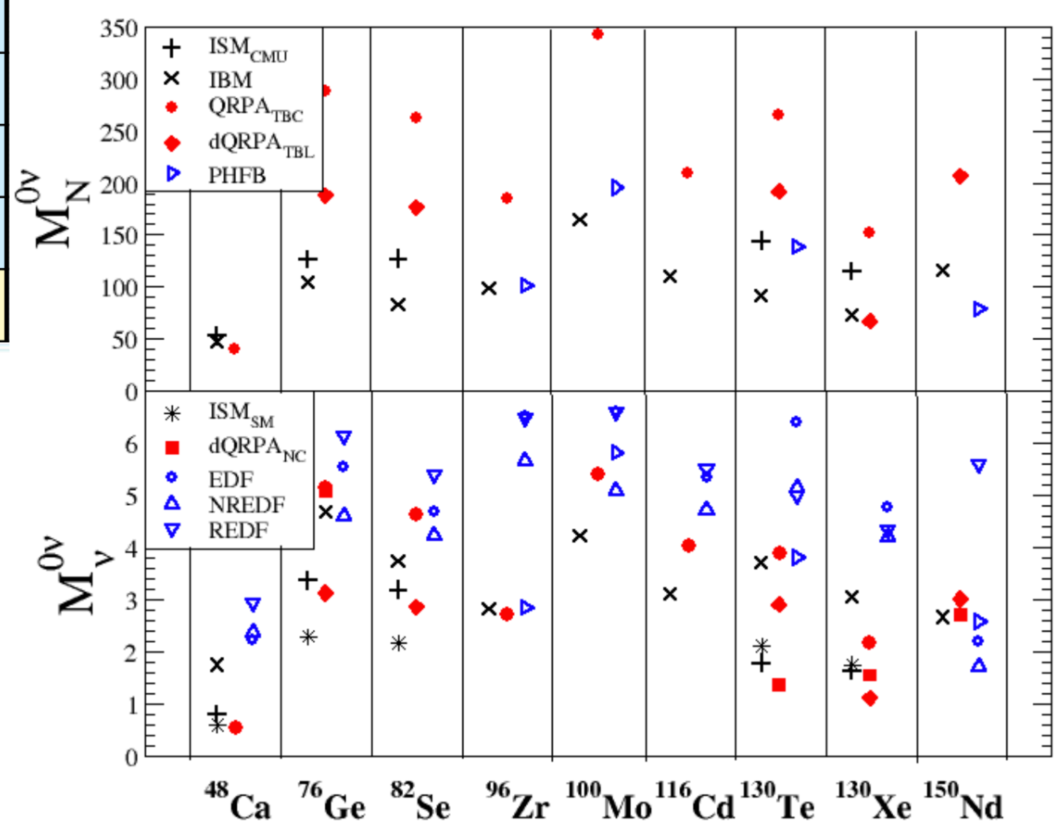
So far no observation of neutrinoless double beta decay!
Many experiments are gearing up for the future

Current constraints:

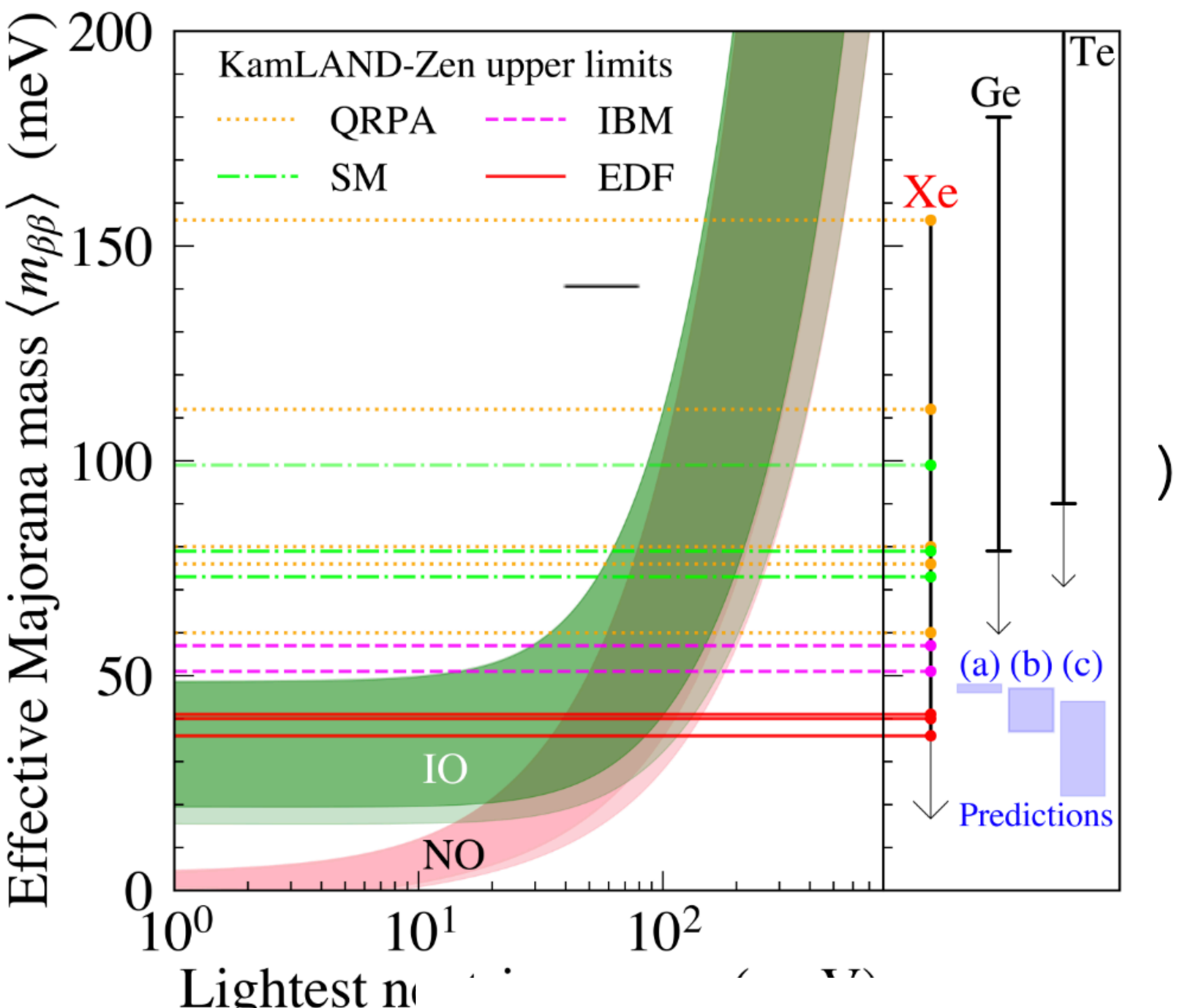
Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

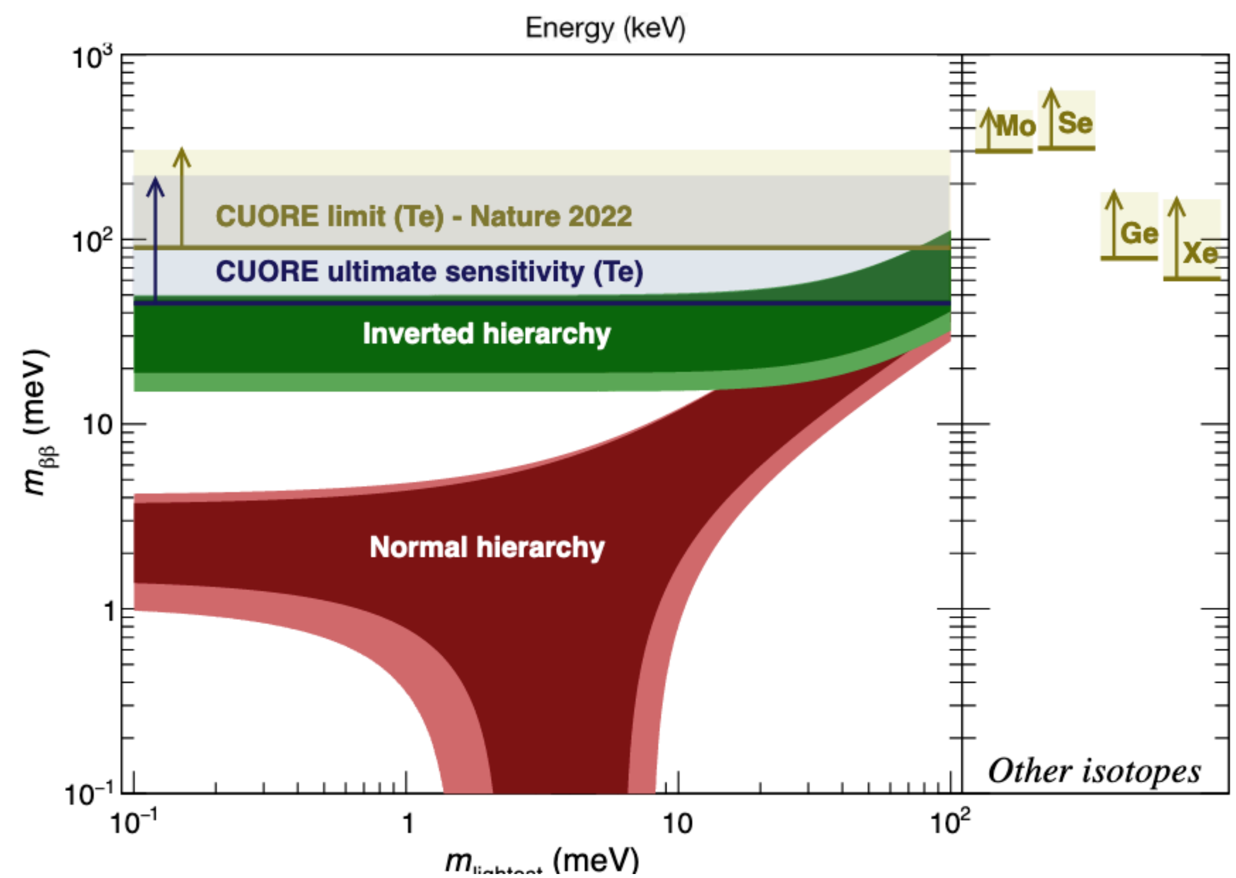
Future prospects	isotope	$m_{\beta\beta}$ [meV] 90% excl. sensitivity	$m_{\beta\beta}$ [meV] 3 σ discovery potential
Legend	^{76}Se	8.2	11.1
CUPID	^{100}Mo	11.1	12.0
nEXO	^{136}Xe	12.9	15.0

Extraction of nuclear matrix elements difficult



Neutrinoless double beta decay





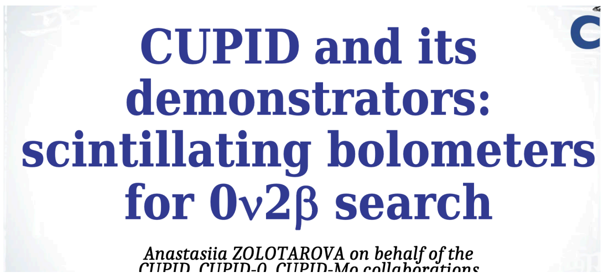
Future: CUPID

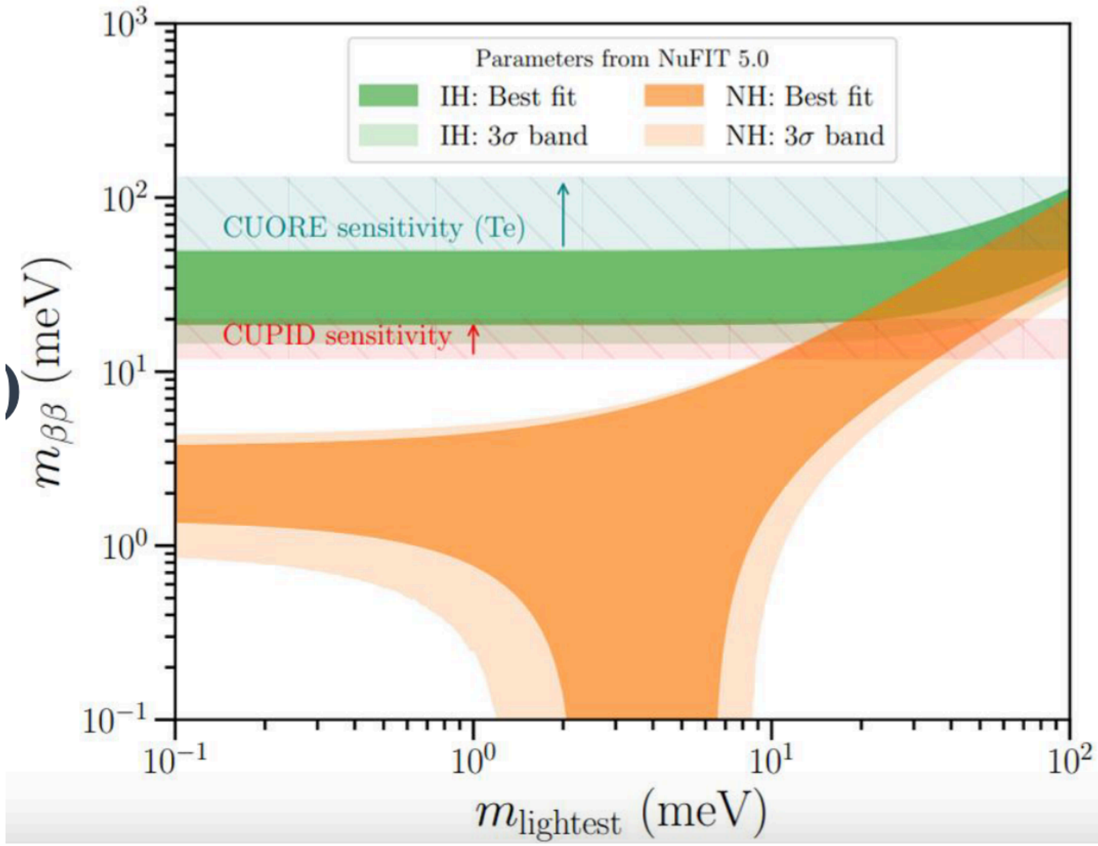
KamLand-Zen2: σ(2.6MeV) = 4% → ~2%

Target ⟨$m_{\beta\beta}$⟩ ~20 meV in 5 yrs

Results for 2β decay as well

Neutrino2022: Neutrinoless double beta decay

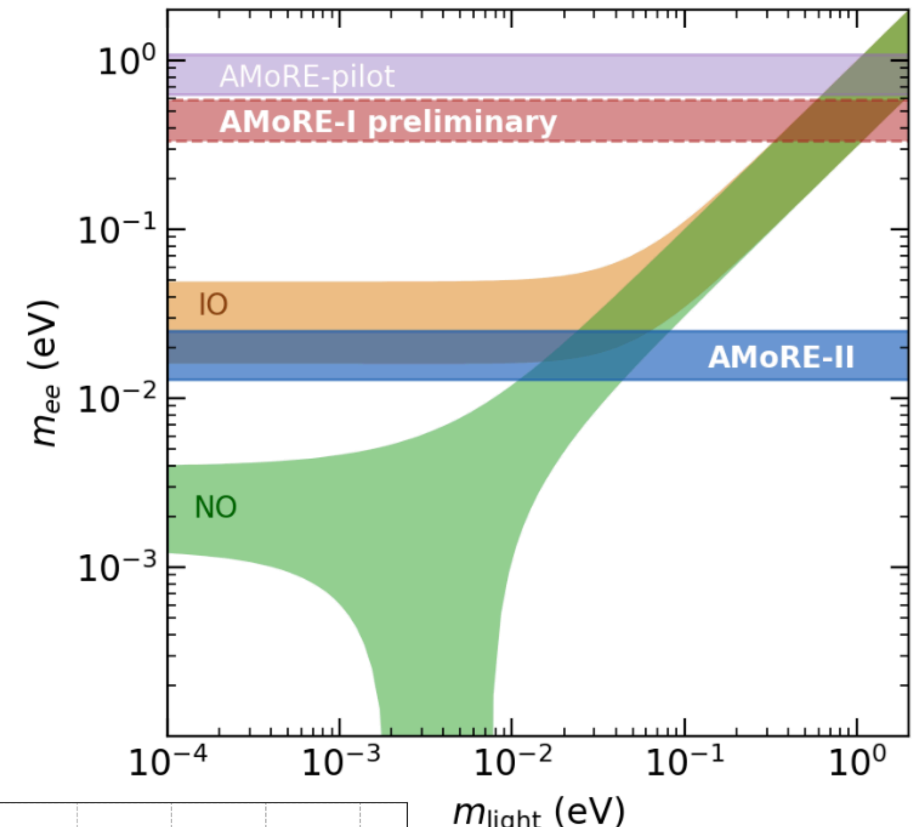


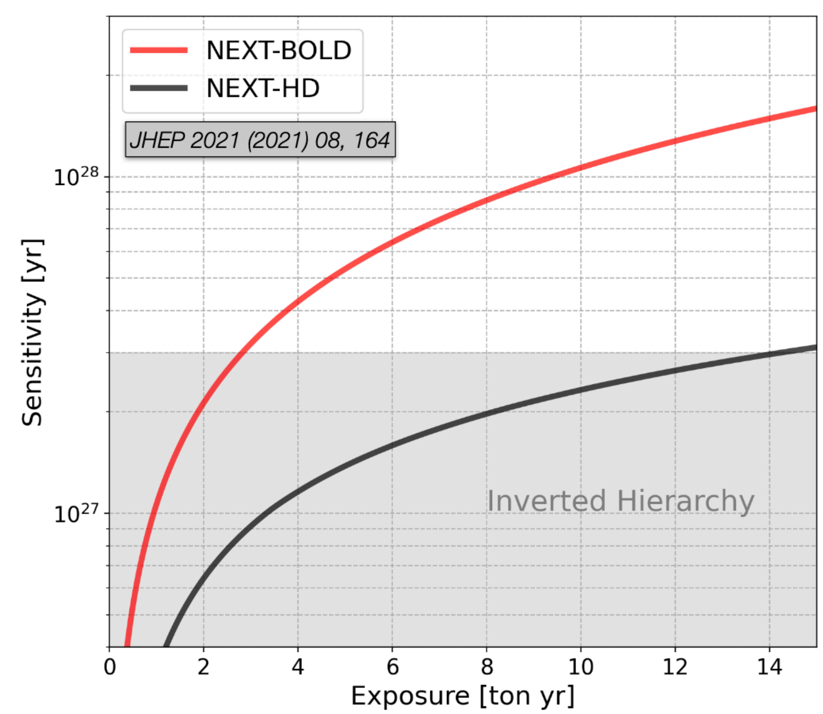


Gaseous detectors for neutrinoless double beta decay searches: NEXT and PandaX-III

NEXT: Barrium tagging

AMoRE



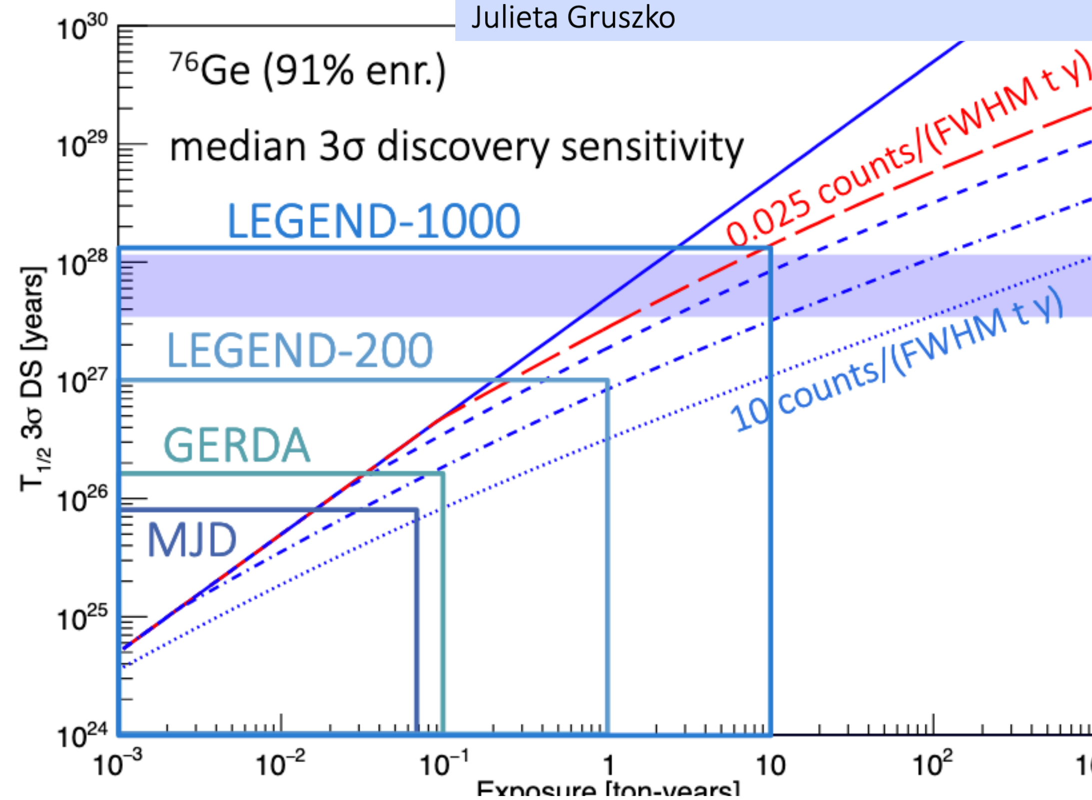


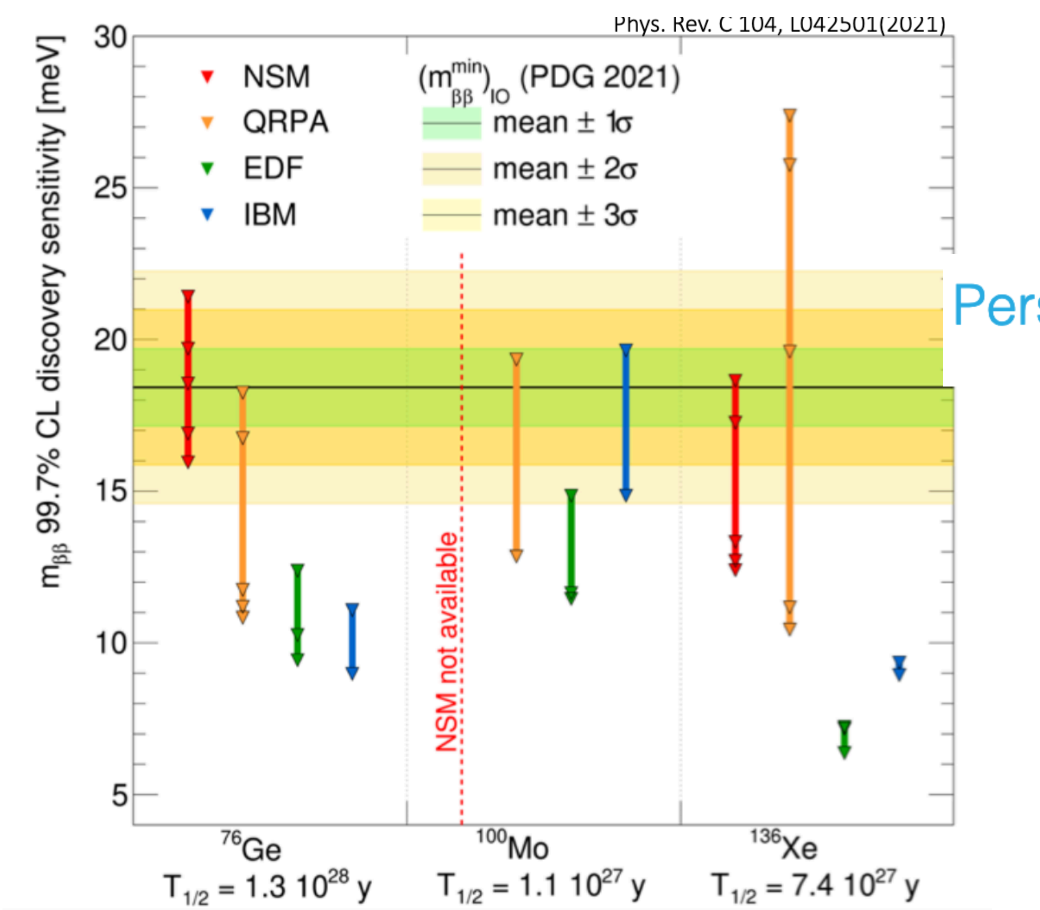
Neutrino2022: Neutrinoless double beta decay

GERDA+MAJORANA=LEGEND

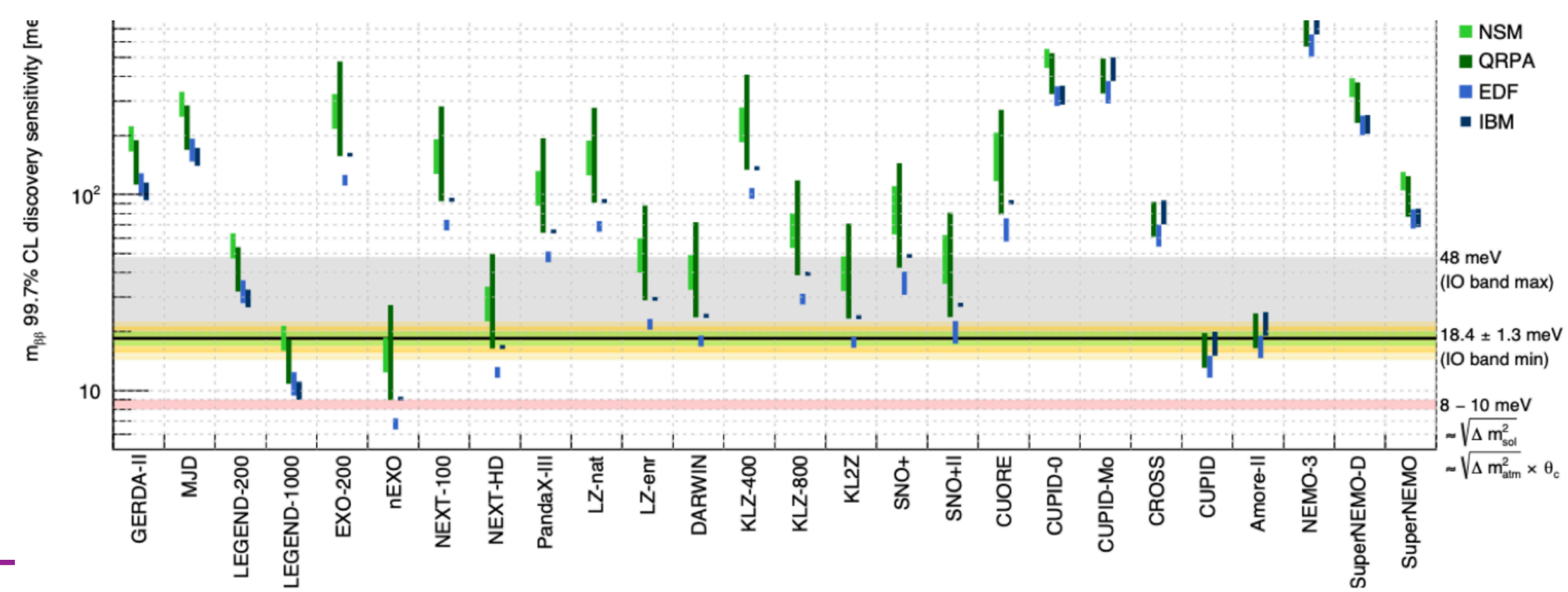
LEGEND-200 is in commissioning, with data-taking beginning later this year
LEGEND-1000 pre-conceptual design available, with R&D and conceptual design development ongoing

Neutrinoless Double-Beta Decay Searches in Germanium
Julieta Gruszko





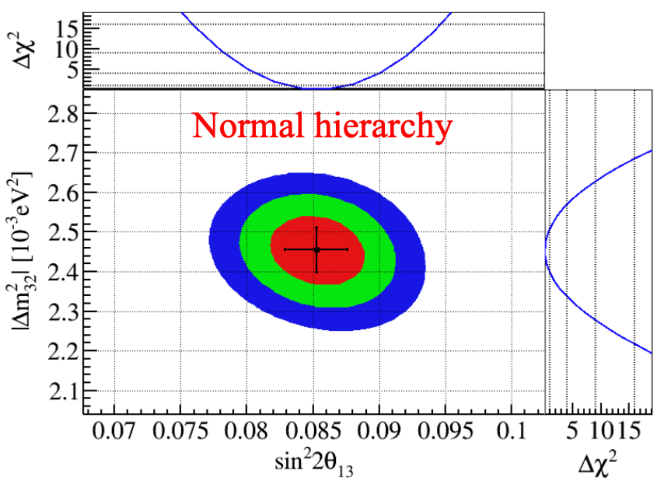
Perspectives of future neutrinoless double beta decay experiments

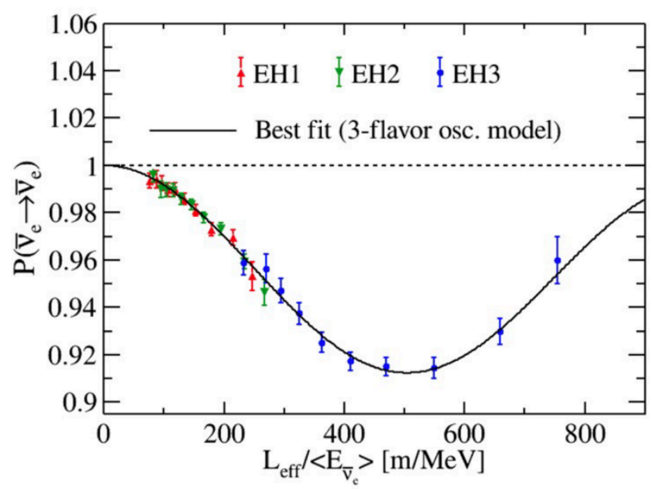


Neutrino2022: Reactor neutrinos

Improved $\sin^2 2\theta_{13}$ and Δm^2_{32}

20





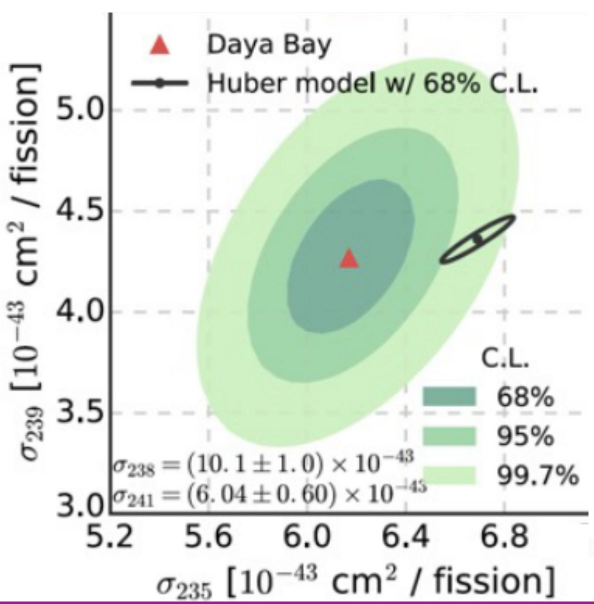
Best-fit results: χ^2/ndf = 559/518

$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

(2.3% precision)



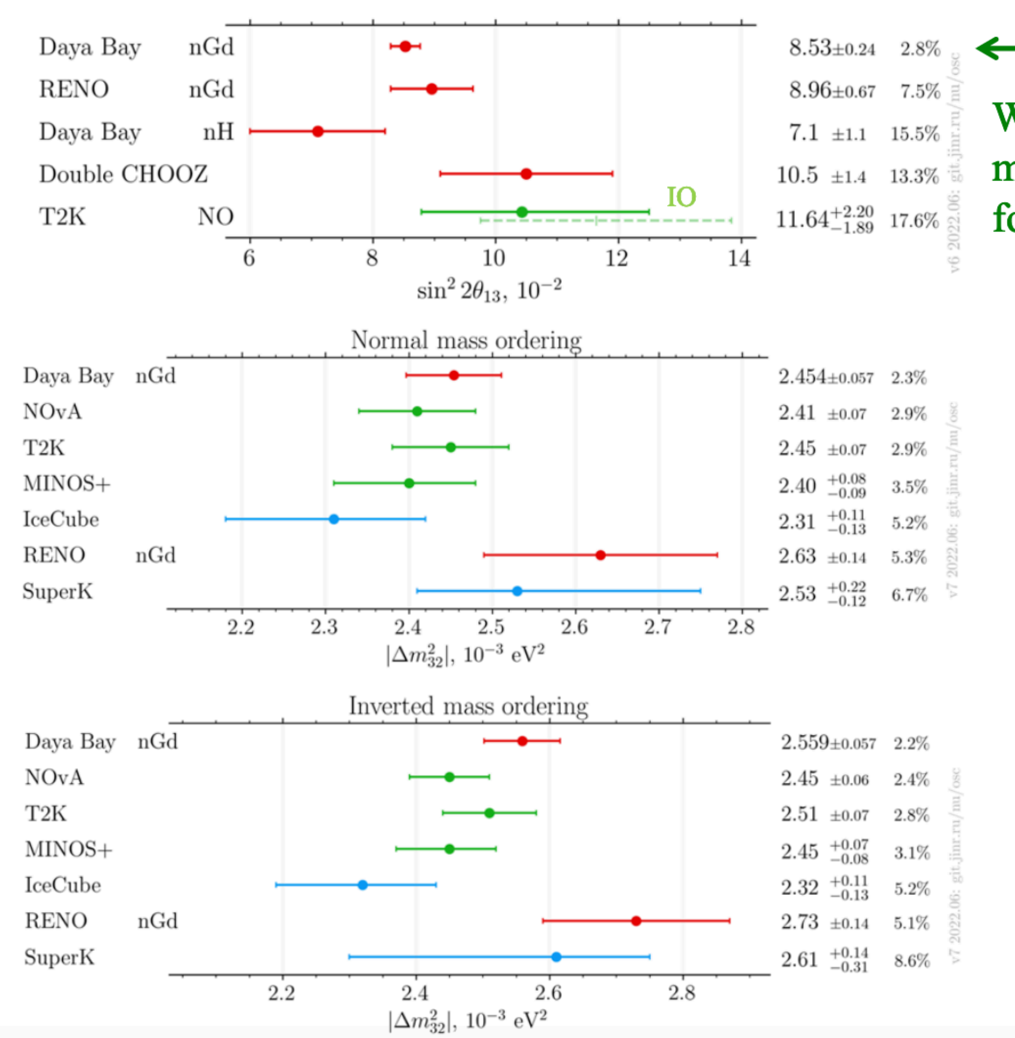
^{239}Pu fission in agreement with HM
^{235}U in tension

Present Global Landscape

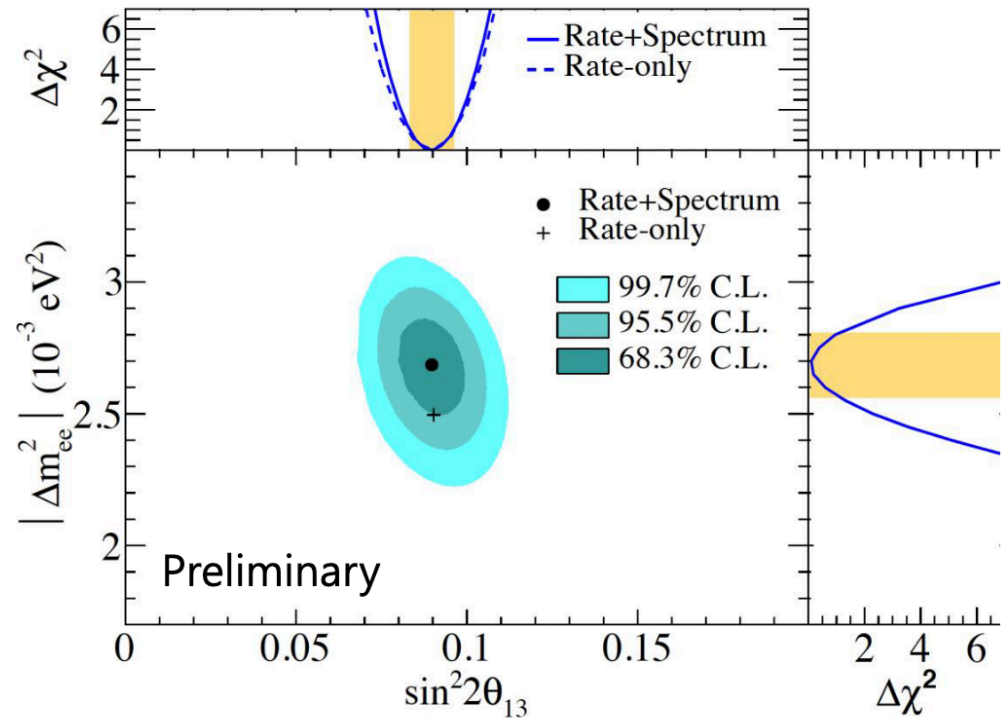
$\sin^2 2\theta_{13}$

Δm^2_{32} (NO)

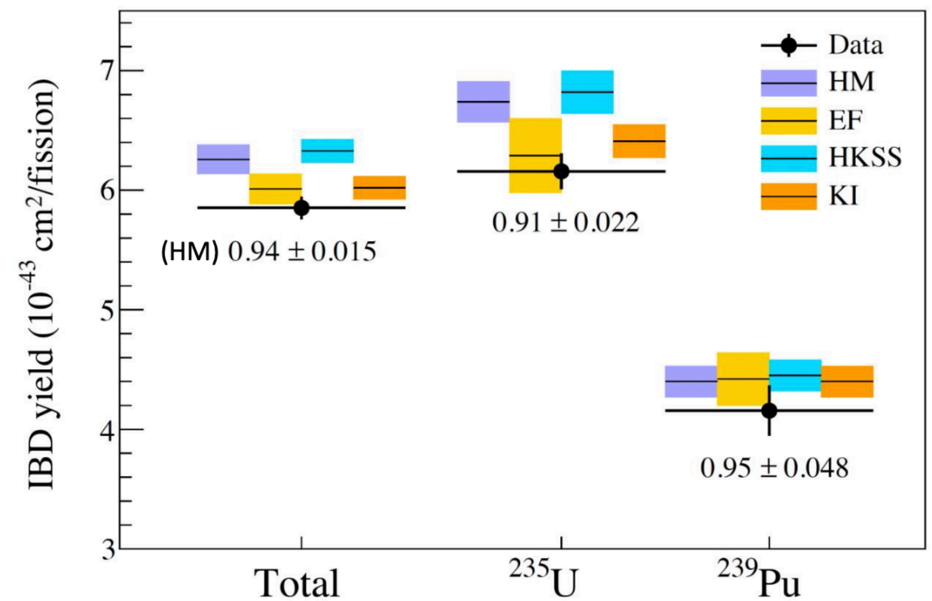
Δm^2_{32} (IO)

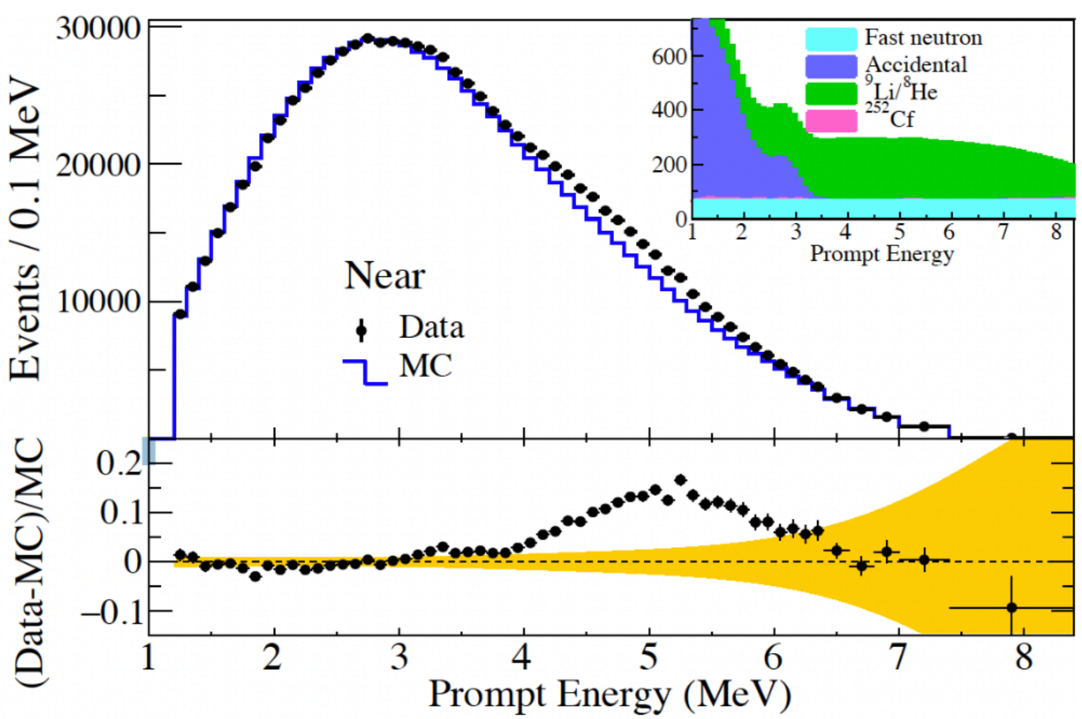


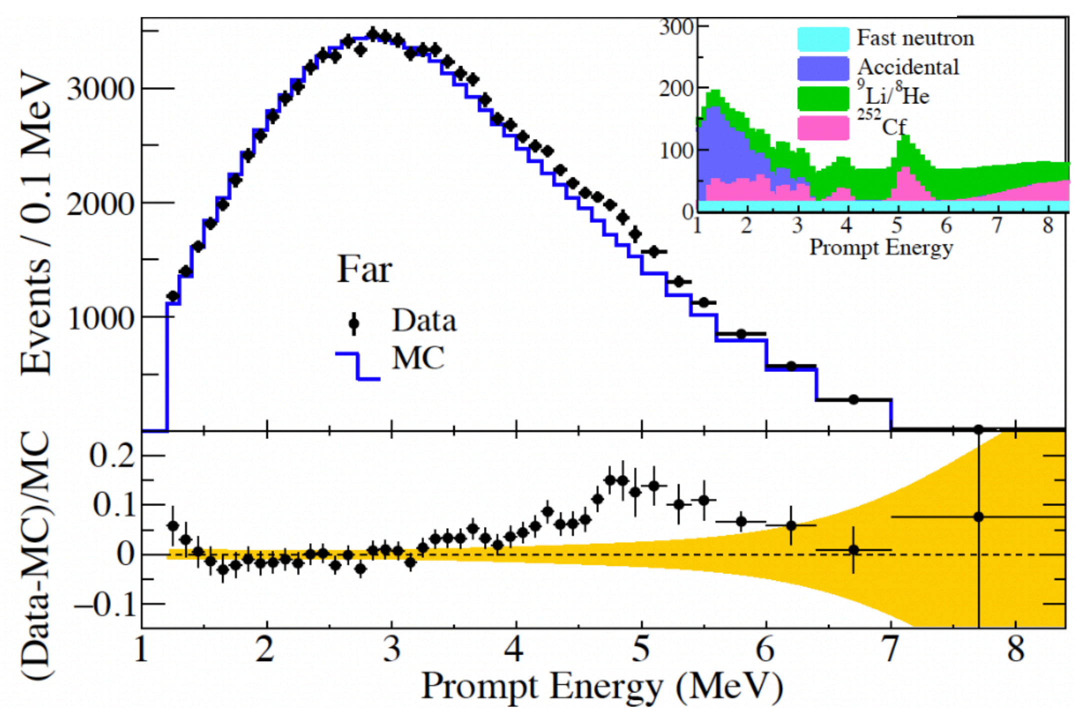
Neutrino2022: Reactor neutrinos



Results of reactor antineutrinos at RENO





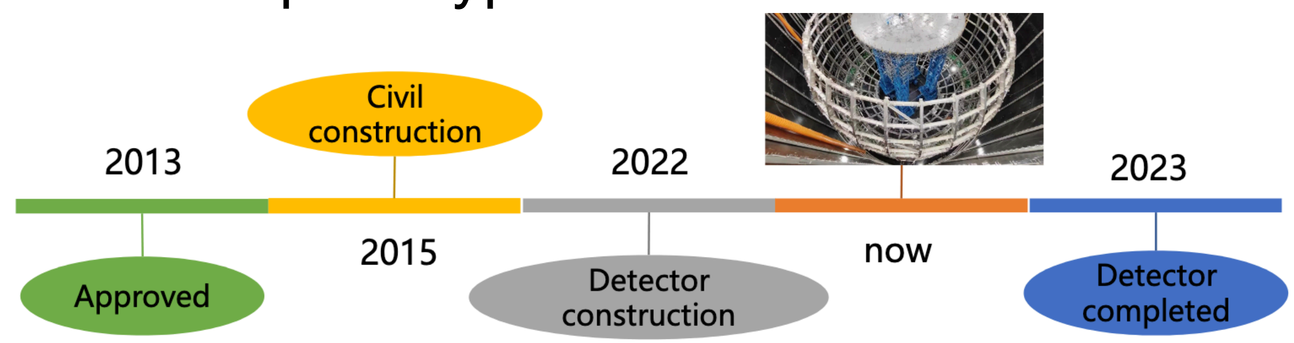


- **5 MeV excess :**
  - ^{235}**U** = **(2.5 ±0.7) %** of the observed total flux (**3.9σ**)
  - ^{239}**Pu** = **(0.9 ± 1.7) %** to the observed total flux (**0.6σ**)

Neutrino2022: Reactor neutrinos

	Design (J. Phys. G 43:030401 (2016))	Now (2022)
Thermal Power	36 GW_{th}	**26.6 GW_{th} (26%↓)**
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	**4 Hz (33%↑)**
Muon veto efficiency	83%	**93% (12%↑)**
Signal rate	60 /day	**47.1 /day (22%↓)**
Backgrounds	3.75 /day	**4.11 /day (10%↑)**
Energy resolution	3% @ 1 MeV	**2.9% @ 1 MeV (3%↑)**
Shape uncertainty	1%	**JUNO+TAO**
3σ NMO sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~ 6 yrs × 26.6 GW_{th}

Installation ongoing
TAO prototype will be build in Summer

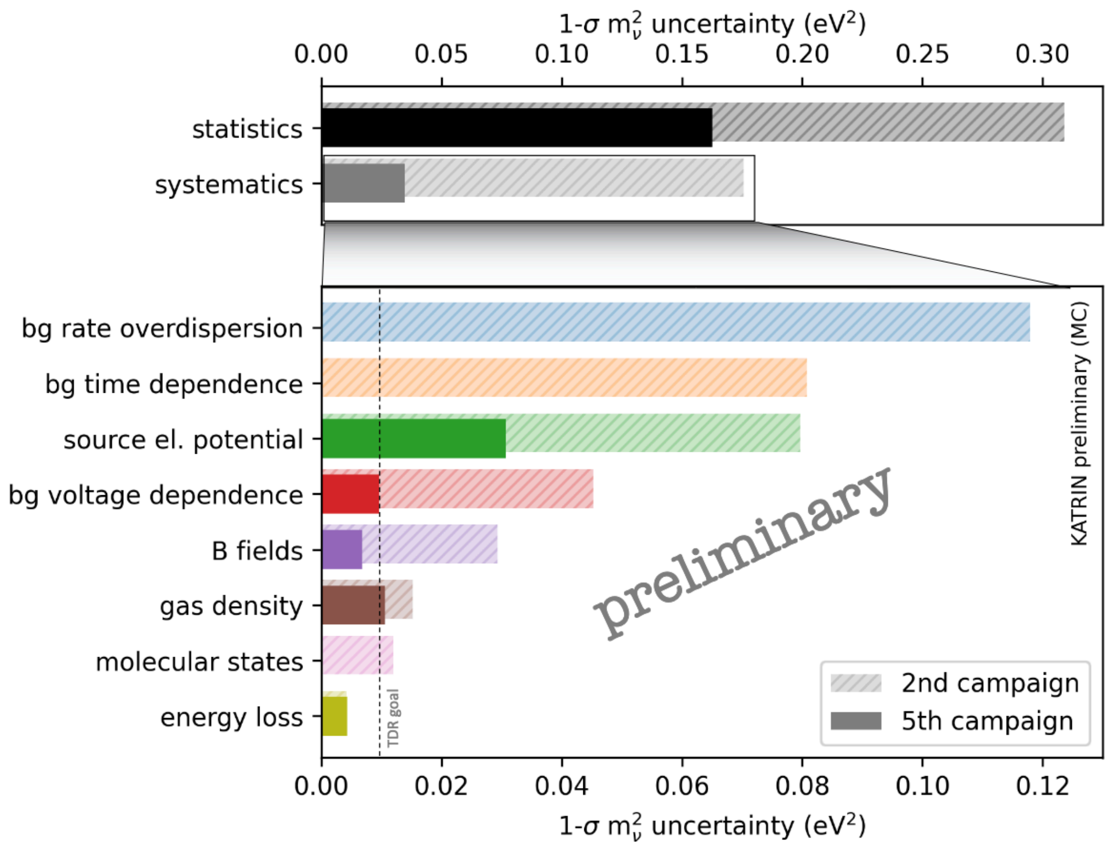


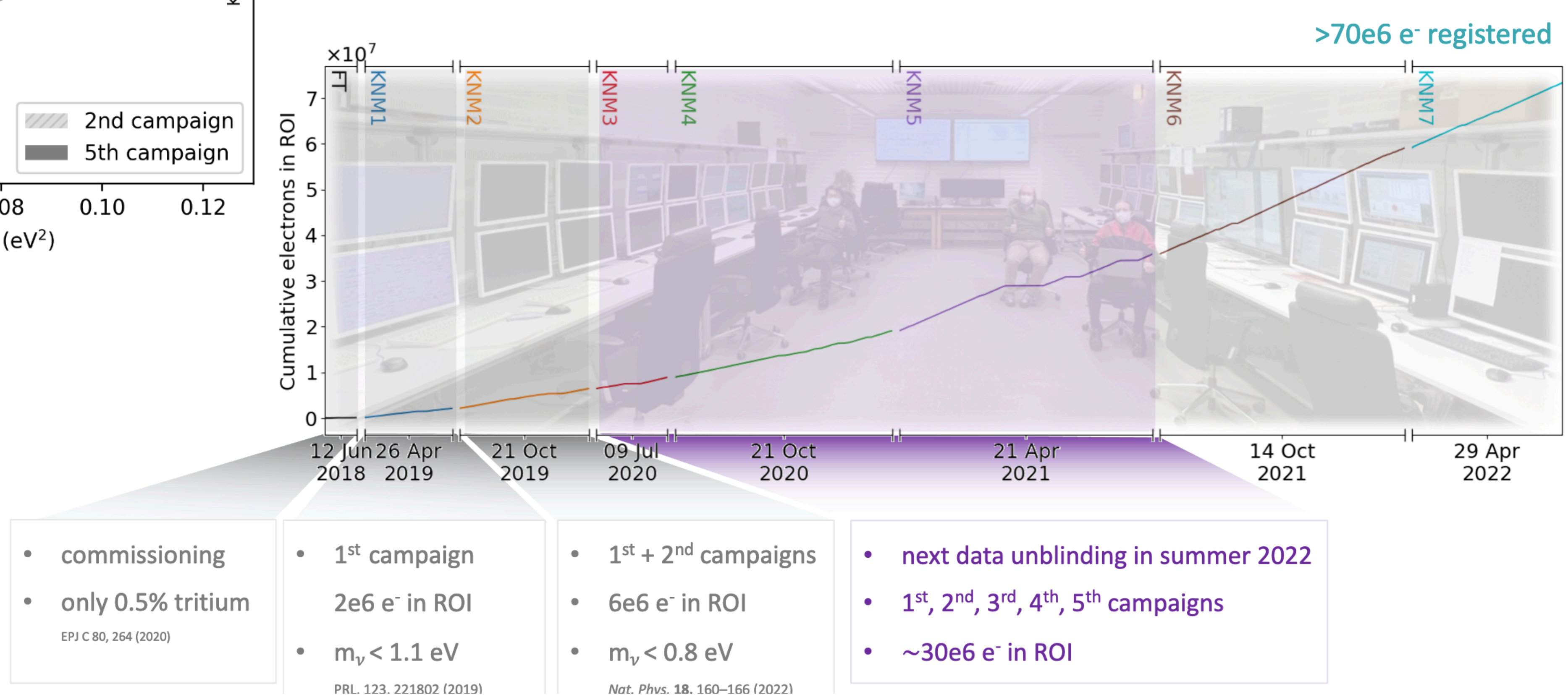
The improvement in precision of oscillation parameters over existing constraints will be about one order of magnitude

Physics	Sensitivity
Neutrino Mass Ordering	3σ ($\sim 1\sigma$) in 6 yrs by reactor (atmospheric) $\bar{\nu}_e$
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{32}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor neutrinos
DSNB	3σ in 3 yrs
Solar neutrino	Measure Be7, pep, CNO simultaneously, measure B8 flux independently
Nucleon decays ($p \to \bar{\nu} K^+$)	8.3×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs

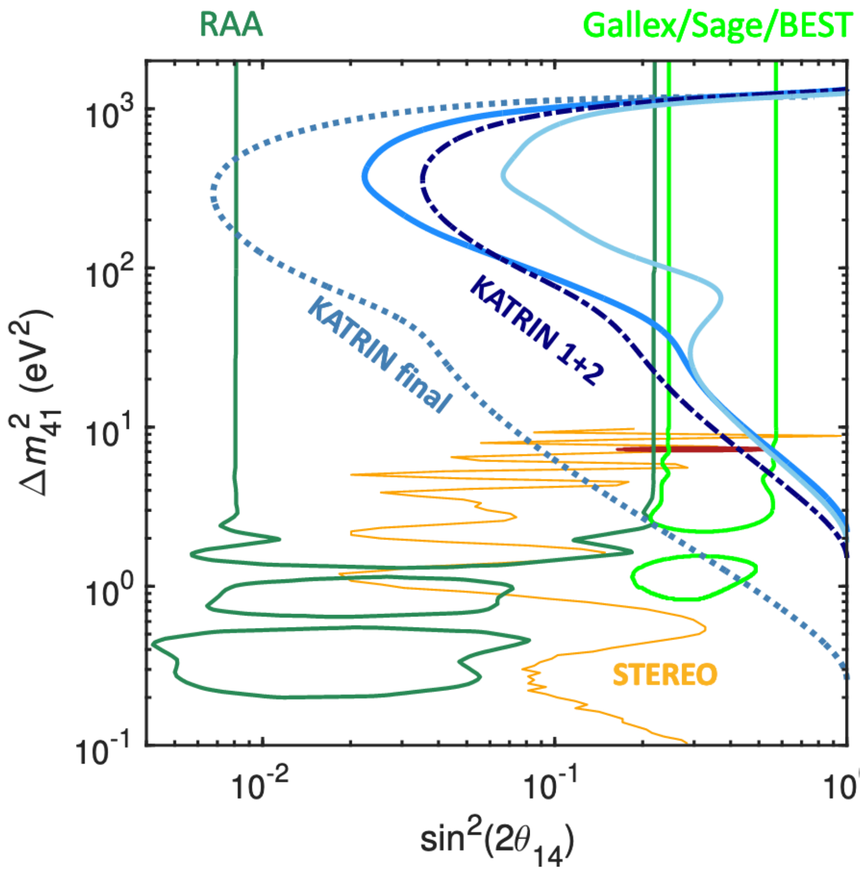
Neutrino2022: Neutrino mass

Combined result: $m_\nu < 0.8$ eV (90% CL)

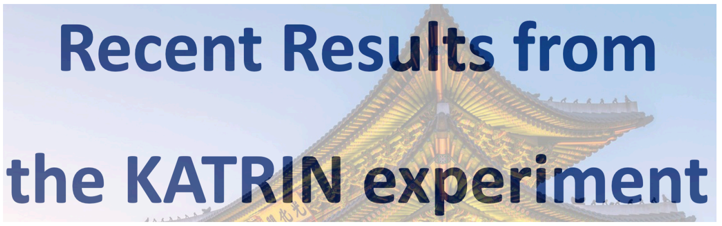




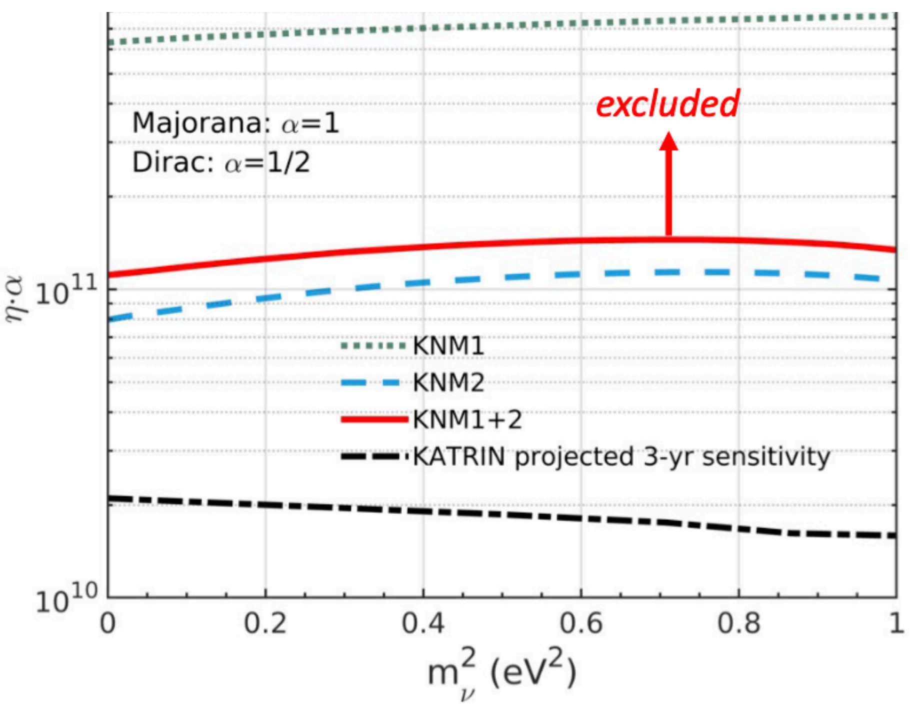
Neutrino2022: Neutrino mass

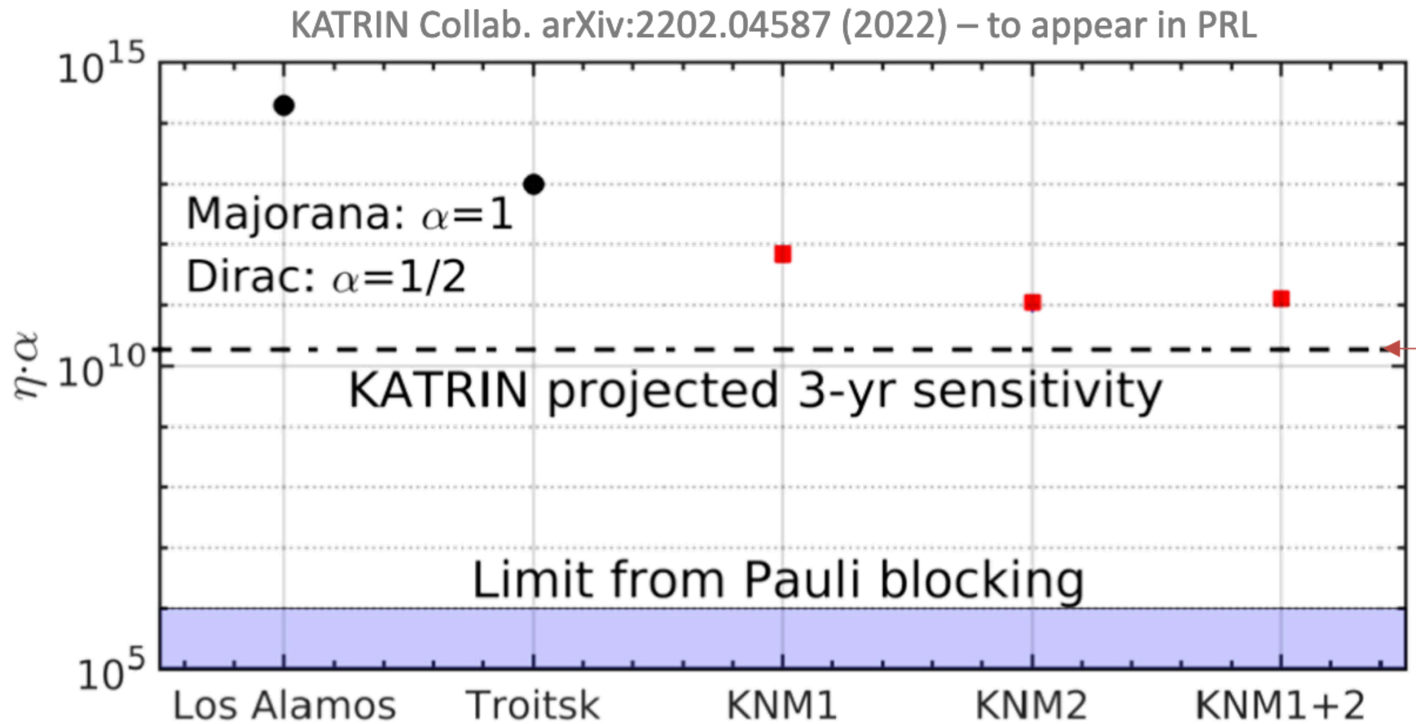


Sterile search



Cosmic neutrino background: overdensity η





KATRIN
1000 days
sensitivity:
$\eta \lesssim 1.4 \cdot 10^{10}/$c

Neutrino2022: Neutrino mass

EC in ^{163}Ho

Neutrino mass determination with ^{163}Ho – ECHo & HOLMES

ECHo at Mainz University

HOLMES at PSI Zurich

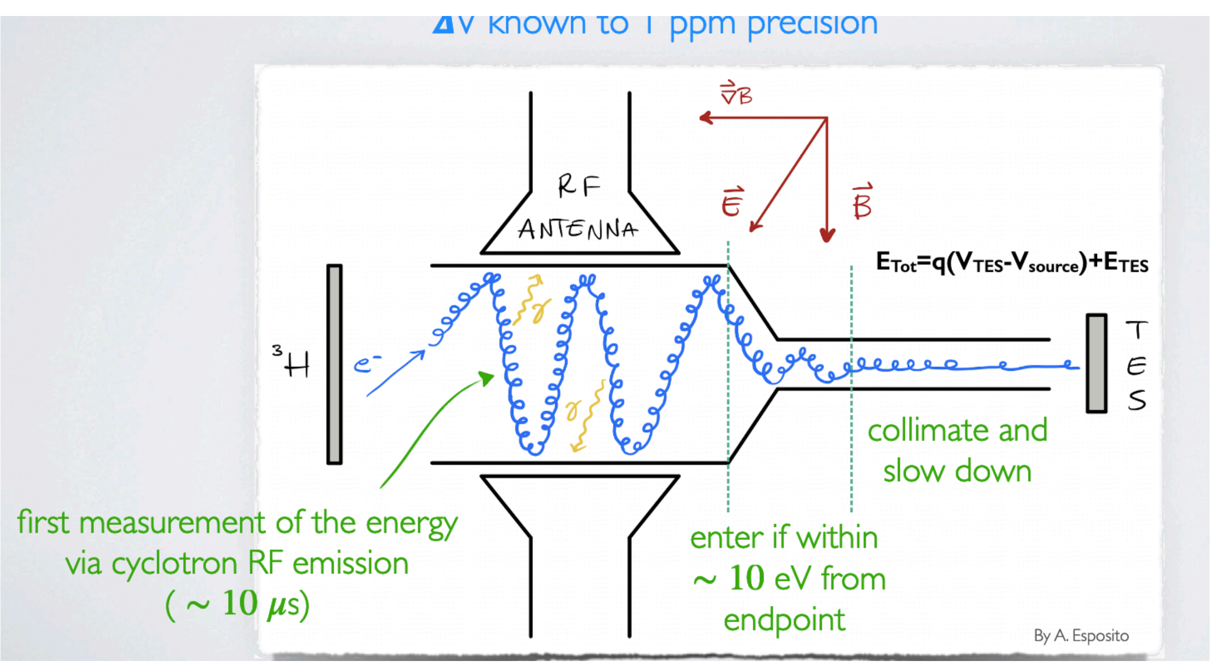
^{163}Ho available for each experiment

ECHo	$\sim 6 \times 10^{18}$ atoms (30 MBq)
HOLMES	$\sim 2 \times 10^{19}$ atoms (100 MBq)

ECHo results

- Q_{EC} = (2838 ± 14) eV
- $m(\nu_e)$ < 150 eV (95% C.L.)

Neutrino2022: Neutrino mass



The PTOLEMY NEW Results and Status

M Messina on behalf of the PTOLEMY collaboration

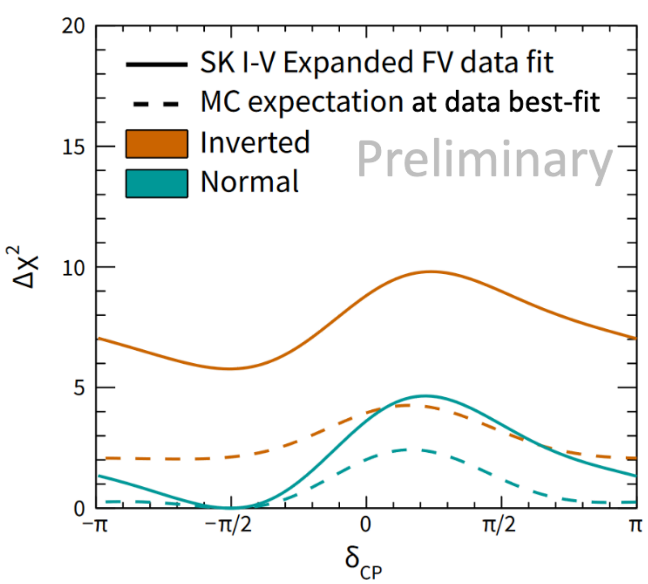
- The detector prototype will be ready at LNGS by the next year
- Prototype baseline option is: T embedded on graphene; New concept EM filter in final configuration; electron energy resolution measured in several steps (MCP/SDD). Ultimately operate TES with sub-eV energy resolution.
- Possible intermediate results from Prototype on neutrino mass measurement
- Ultimate goals of demonstrator: instrumented mass ~ hundreds of μg, energy resolution 50-100 meV, T storage solution will come from optimisation of atomic T support structure. Time scale 5 years.

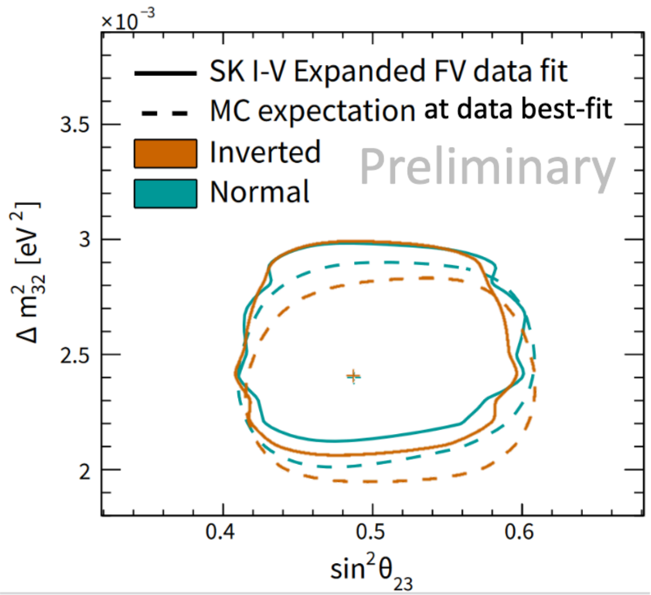
Neutrino2022: Atmospheric neutrinos

New Results with Atmospheric Neutrinos at Super-Kamiokande

Linyan Wan, Boston University

Oscillation Measurements (SK only)





SK atmospheric neutrino data favors:

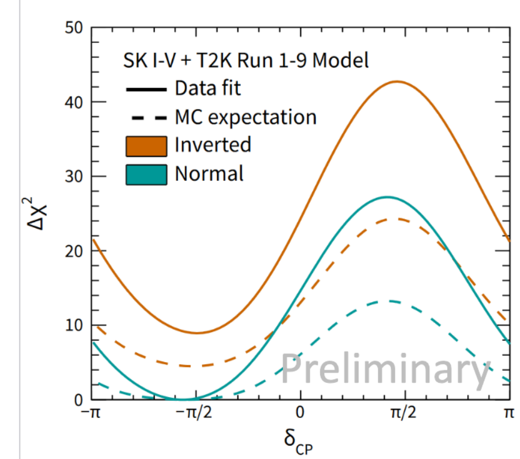
- maximal mixing
- $\delta_{CP} \approx -\frac{\pi}{2}$
- NO ($\Delta\chi^2 = 5.8$)

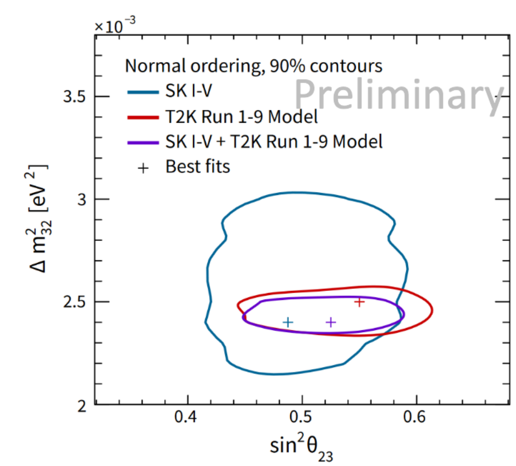
930 bins	χ^2	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23}
SK NO	1000.42	4.71	0.49	2.4×10^{-3} eV^2
SK IO	1006.19	4.71	0.49	2.4×10^{-3} eV^2

Preliminary

*Results on MO and δ_{CP} exceed sensitivity.

Oscillation Measurements (SK+T2K)





SK + external T2K constraints favor:

- maximal mixing
- $\delta_{CP} \approx -\frac{\pi}{2}$
- NO ($\Delta\chi^2 = 8.9$)

1020 bins	χ^2	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23}
SK+T2K NO	1086.33	4.54	0.53	2.4×10^{-3} eV^2
SK+T2K IO	1095.25	4.71	0.53	2.4×10^{-3} eV^2

Preliminary

*Results from both experiments exceed sensitivity.

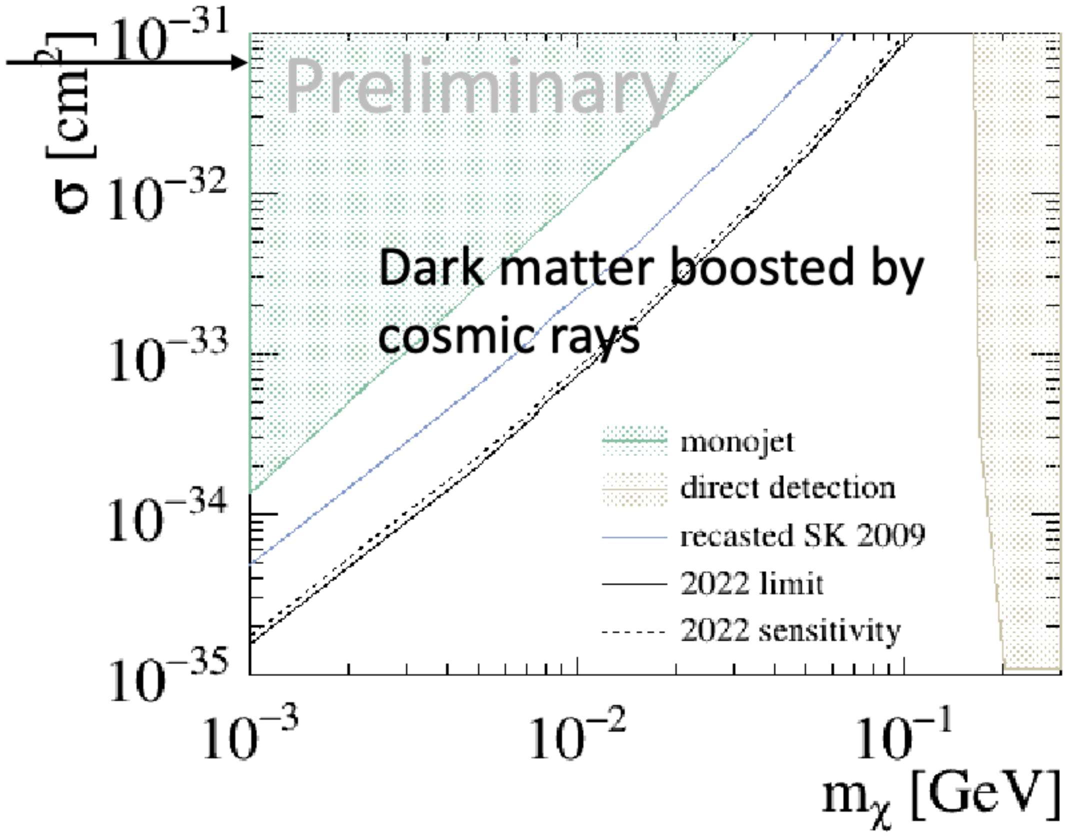
$\sin^2\theta_{13} = 0.0220 \pm 0.0007$

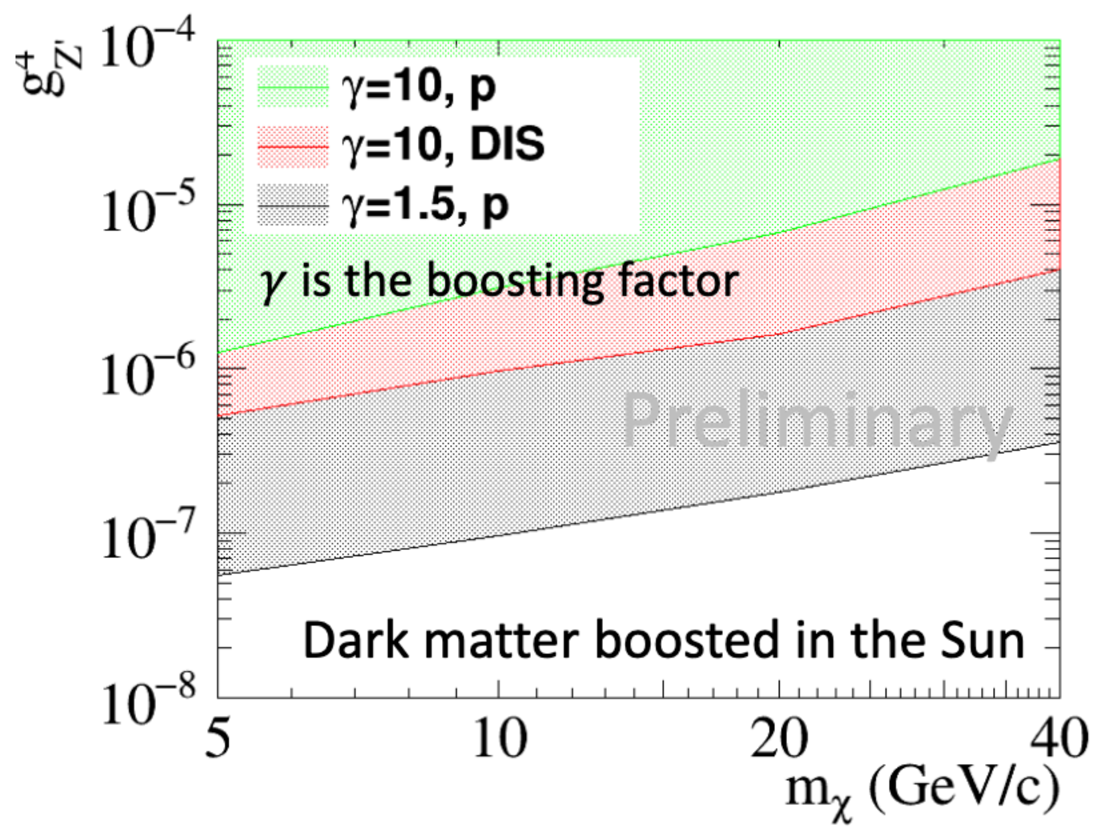
Neutrino2022: Atmospheric neutrinos

New Results with Atmospheric Neutrinos at Super-Kamiokande

Linyan Wan, Boston University

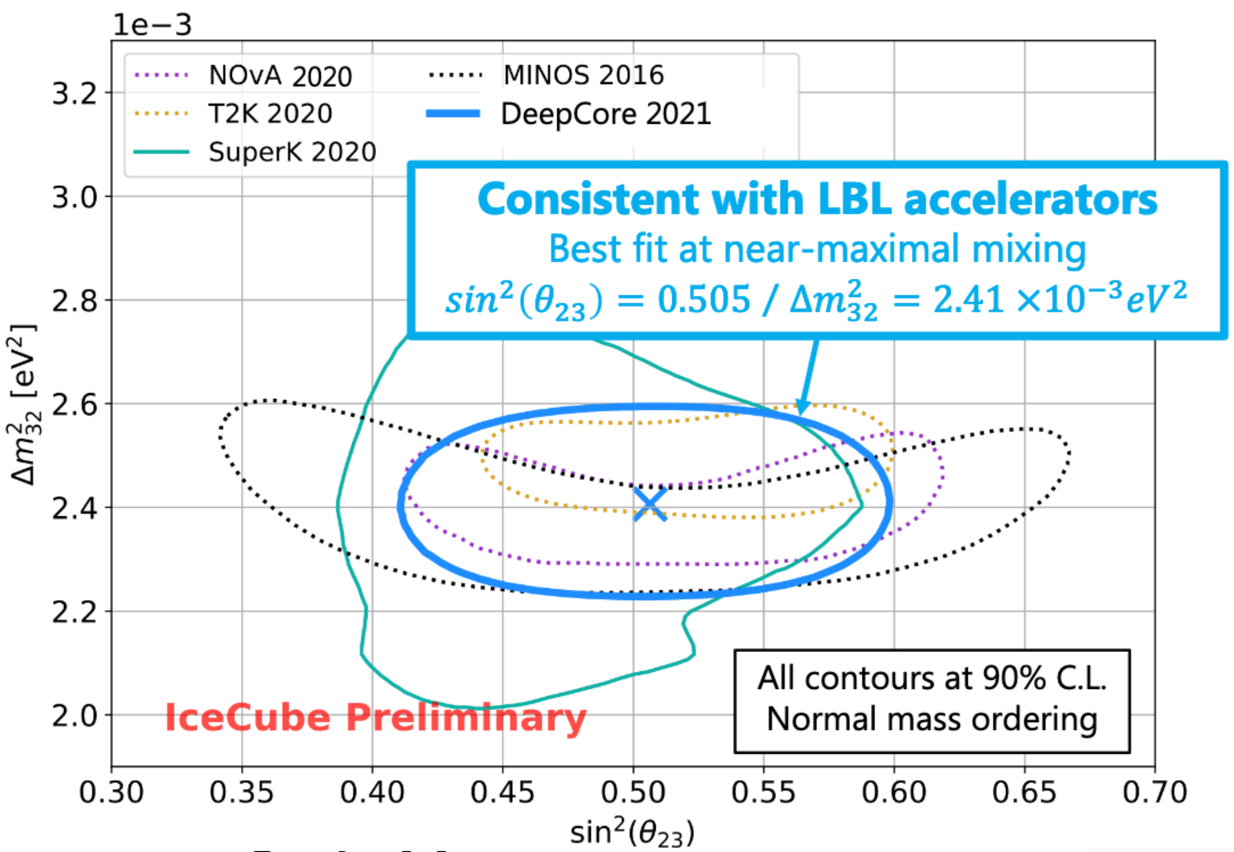
PandaX-II
Phys. Rev. Lett. 128, 171801





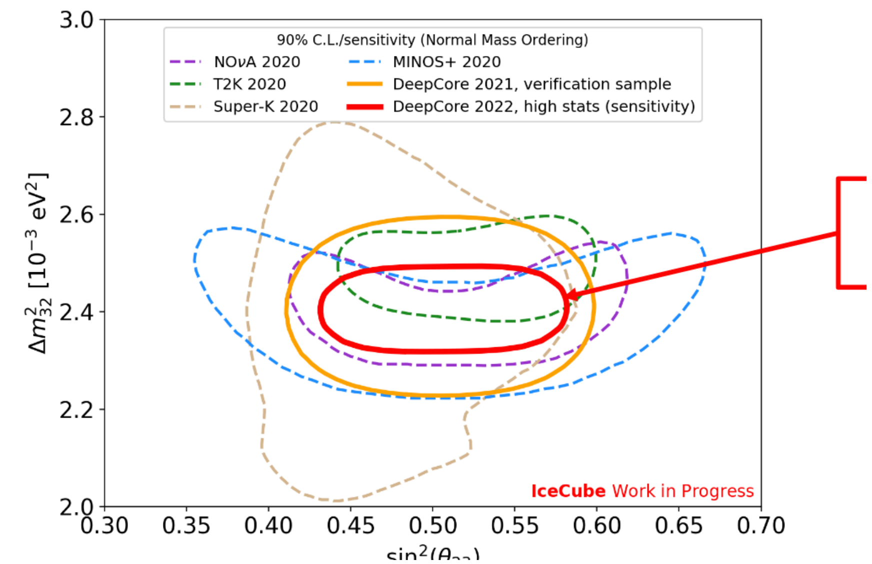
Observation of n capture on Gd

Neutrino2022: Atmospheric neutrinos

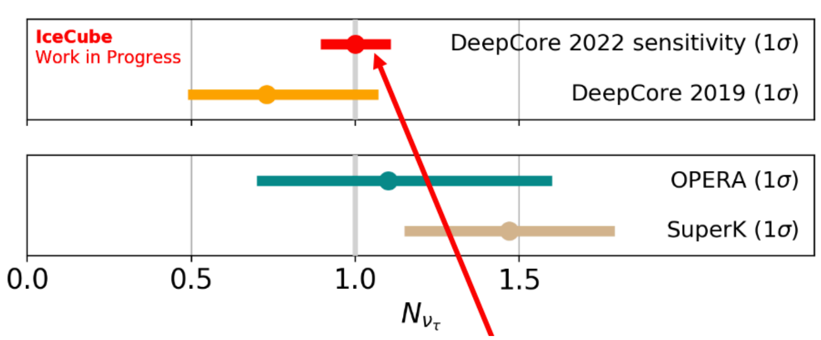


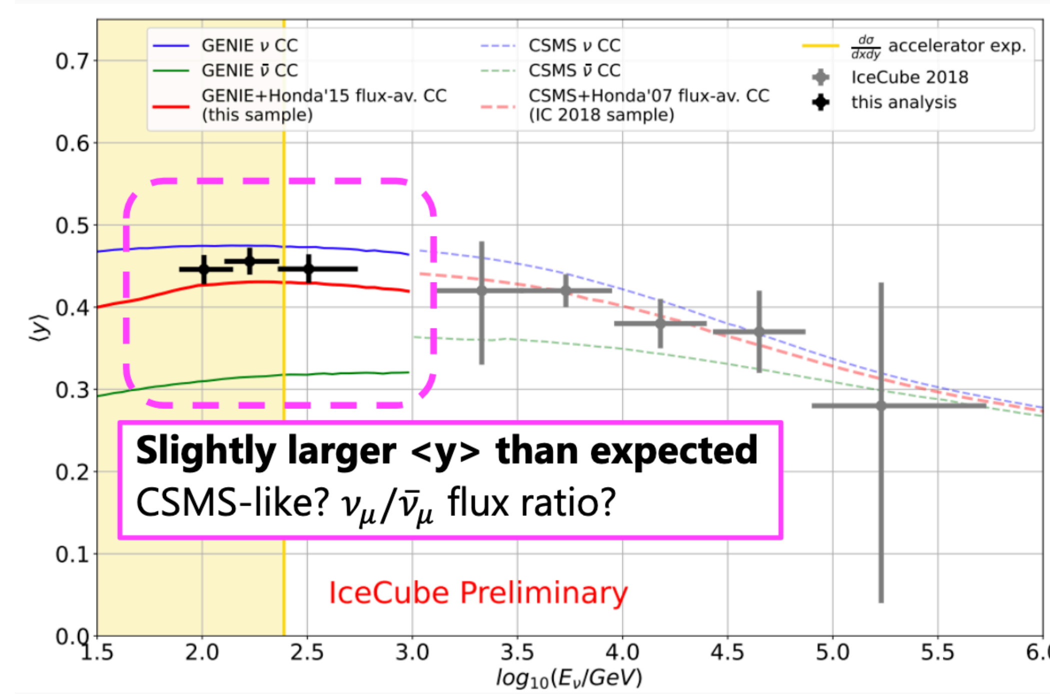
Particle physics with atmospheric neutrinos at IceCube/DeepCore
Tom Stuttard for the IceCube collaboration

Atmospheric mixing parameter sensitivity



ν_τ normalization sensitivity





Low energy inelasticity measurement

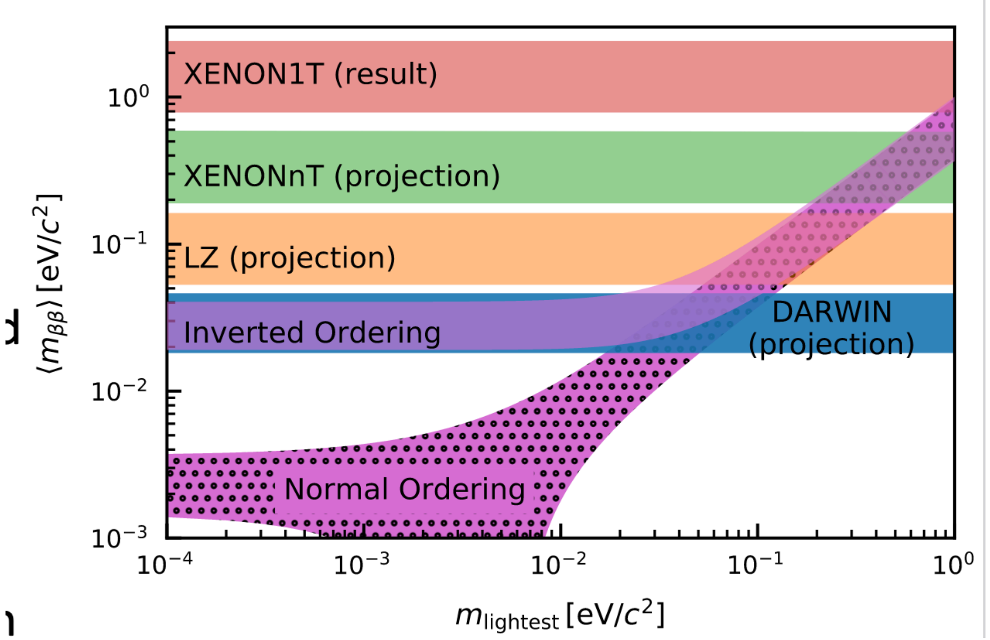
Neutrino2022: Neutrinos in cosmology

Neutrino physics with Dark Matter detectors

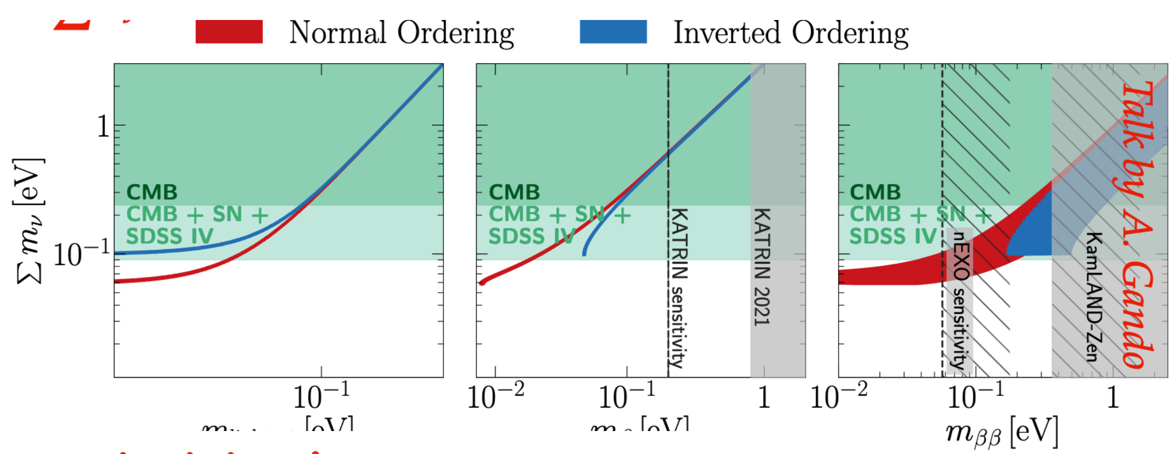
Tim Michael Heinz Wolf

Neutrino floor at DM experiments:
no detection so far

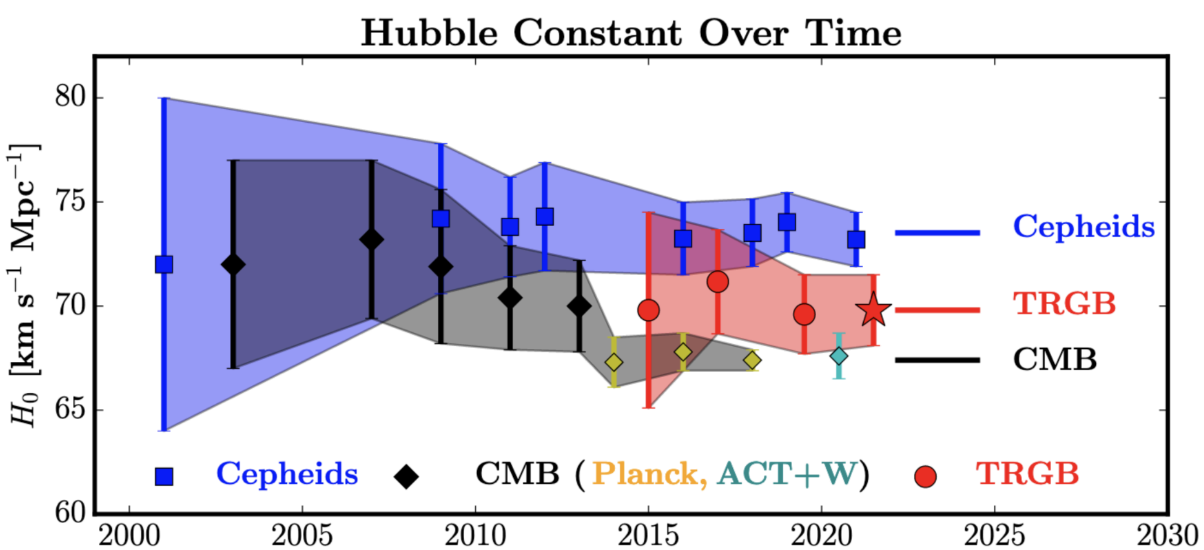
Search for
neutrinoless double beta decay
in DM experiments

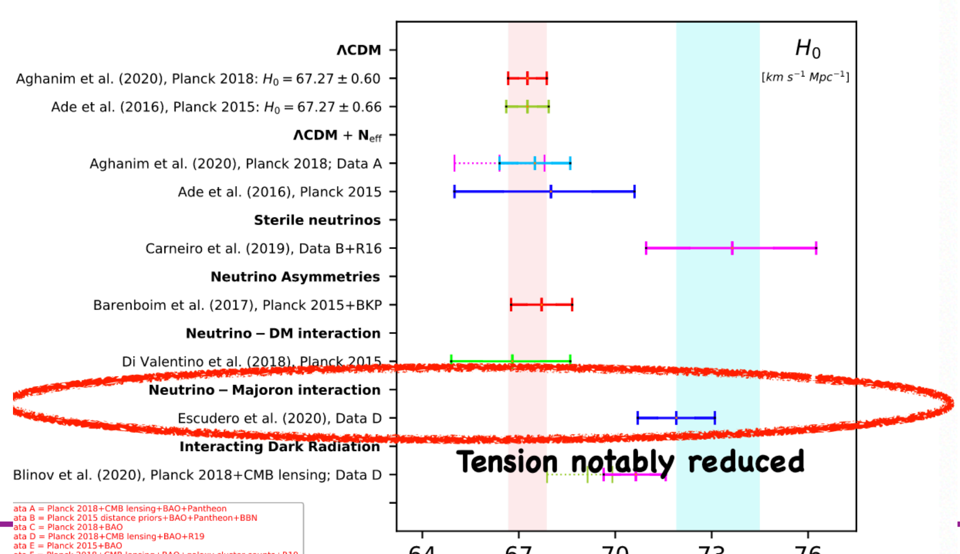


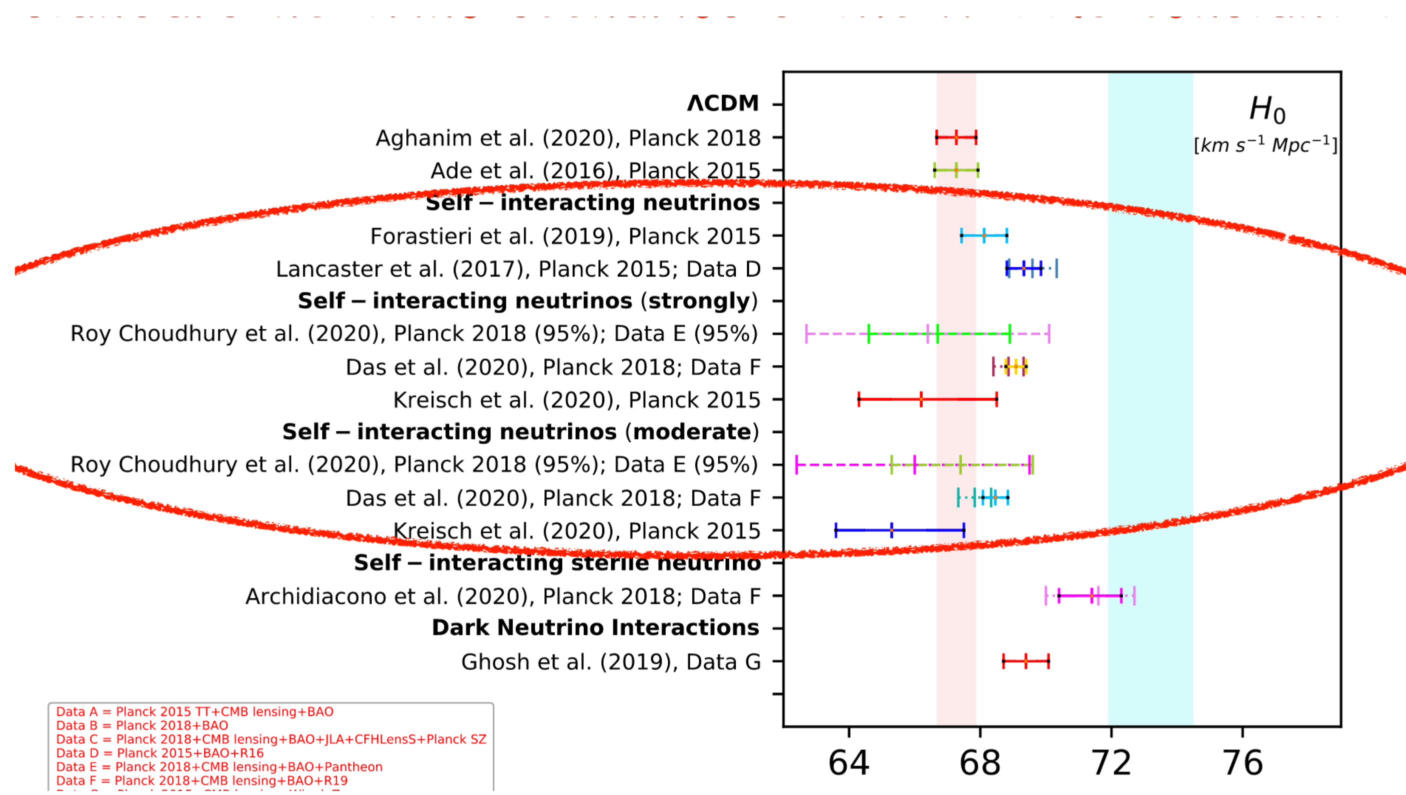
Neutrino2022: Neutrinos in cosmology



The Hubble constant tension *W. Freedman, APJ'21*



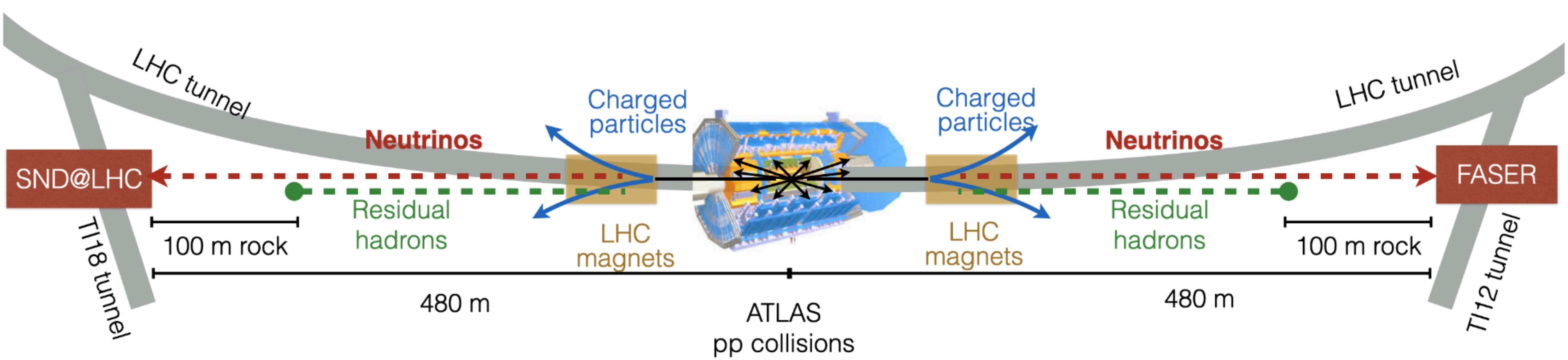




Neutrino2022: Neutrinos & BSM

NEUTRINO PHYSICS AT LHC:
CURRENT EXPERIMENTS

SND@LHC & FASERv are taking data
Future: Forward Physics Facility



Neutrino2022: Neutrinos & BSM

Proton decay

Tommy Ohlsson

- $p \to e^+ + \pi^0$ channel: **no** candidate events have been found.

$$\tau/B(p \to e^+\pi^0) > 2.4 \cdot 10^{34} \text{ years} \quad @\ 90\ \%\ \text{C.L.}$$

- $p \to \mu^+ + \pi^0$ channel: **one** candidate event remains.

$$\tau/B(p \to \mu^+\pi^0) > 1.6 \cdot 10^{34} \text{ years} \quad @\ 90\ \%\ \text{C.L.}$$

A generic estimate for proton lifetime in GUTs:

$$\tau(p \to e^+\pi^0) \simeq 7.47 \cdot 10^{35} \left(\frac{M_{\rm GUT}}{10^{16}\ \text{GeV}}\right)^4 \left(\frac{0.03}{\alpha_{\rm GUT}}\right)^2 \text{ years}$$

Upper bound on proton lifetime for any GUT with or without SUSY [see e.g. Doršner & Fileviez-Pérez (2005); Nath & Fileviez-Pérez (2007)]:

$$\tau_p \lesssim 6.0 \cdot 10^{39} \frac{1}{\alpha_{\rm GUT}^2} \left(\frac{M_X}{10^{16}\ \text{GeV}}\right)^4 \left(\frac{0.003\ \text{GeV}^3}{\alpha_{\rm ChPT}}\right)^2 \text{ years}$$

Predicted proton lifetimes

An incomplete list of models:

Model class	Lifetime [years]	Ruled out?
Minimal SU(5) [Georgi & Glashow (1974)]	$10^{30} - 10^{31}$	yes
Minimal SUSY SU(5) [Dimopoulos & Georgi; Sakai & Yanagida]	$10^{28} - 10^{34}$	yes
SUGRA SU(5) [Nath, Chamseddine & Arnowitt (1985)]	$10^{32} - 10^{34}$	yes
SUSY (MSSM/ESSM) SO(10)/G(224) [Babu, Pati & Wilczek]	$2 \cdot 10^{34}$	yes
SUSY (MSSM/ESSM, $d=5$) SO(10) [Lucas & Raby; Pati]	$10^{32} - 10^{35}$	partially
SUSY SO(10) + U(1)$_{\rm fl}$ [Shafi & Tavartkiladze (2000)]	$10^{32} - 10^{35}$	partially
SUSY ($d=5$) SU(5) – option I [Hebecker & March-Russell (2002)]	$10^{34} - 10^{35}$	partially
SUSY (MSSM, $d=6$) SU(5) or SO(10) [Pati (2003)]	$\sim 10^{34.9\pm1}$	partially
Minimal non-SUSY SU(5) [Doršner & Fileviez-Pérez (2005)]	$10^{31} - 10^{38}$	partially
Minimal non-SUSY SO(10)	???	no
SUSY (CMSSM) Flipped SU(5) [Ellis, Nanopoulos & Walker (2002)]	$10^{35} - 10^{36}$	no
GUT-like models from string theory [Klebanov & Witten (2003)]	$\sim 10^{36}$	no
Split SUSY SU(5) [Arkani-Hamed *et al.* (2005)]	$10^{35} - 10^{37}$	no
SUSY ($d=5$) SU(5) – option II [Alciati *et al.* (2005)]	$10^{36} - 10^{39}$	no

Minimal non-SUSY SO(10) hep-ph/940423

Minimal non-SUSY SO(10) $\longrightarrow \mathcal{G} \longrightarrow \mathcal{G}_{\rm SM}$, $\tau_p = \tau(p \to e^+\pi^0)$

Model A ($\mathcal{G} = G_{422D}$):	$\tau_p = 1.44 \cdot 10^{32.1\pm0.7}$ years	ruled out
Model B ($\mathcal{G} = G_{422}$):	$\tau_p = 1.44 \cdot 10^{37.4\pm0.7}$ years	allowed
Model C ($\mathcal{G} = G_{3221D}$):	$\tau_p = 1.44 \cdot 10^{34.2\pm0.7}$ years	partially
Model D ($\mathcal{G} = G_{3221}$):	$\tau_p = 1.44 \cdot 10^{37.7\pm0.7}$ years	allowed

Thanks!