भौतिक अनुसंधान प्रयोगशाला Physical Research Laboratory

Neutrino physics : Current Status and future trends

Advances in Astroparticle Physics and Cosmology
AAPCOS 2023

Srubabati Goswami

, 26 January, **2023**

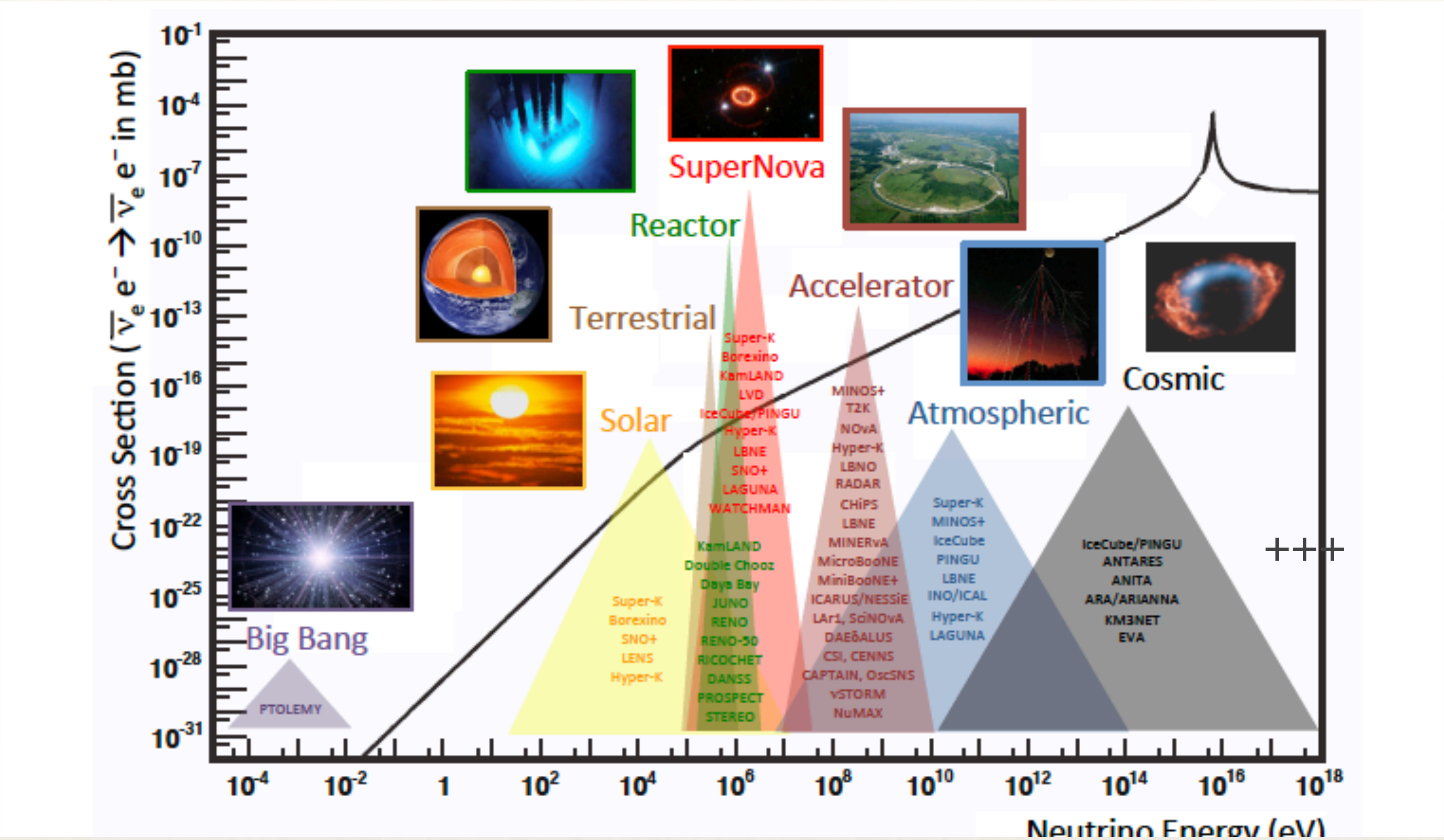
Neutrino Physics : What we know

- Neutral leptons with three flavours
- Flavour eigenstates not the same as mass eigenstates
- Leads to neutrino oscillations — have been observed
- Mixing between flavour states governed by U_{PMNS}
- Mass splittings and mixing angles are measured
- The limit on sum of neutrino masses from cosmology

Neutrino Physics: what we don't know

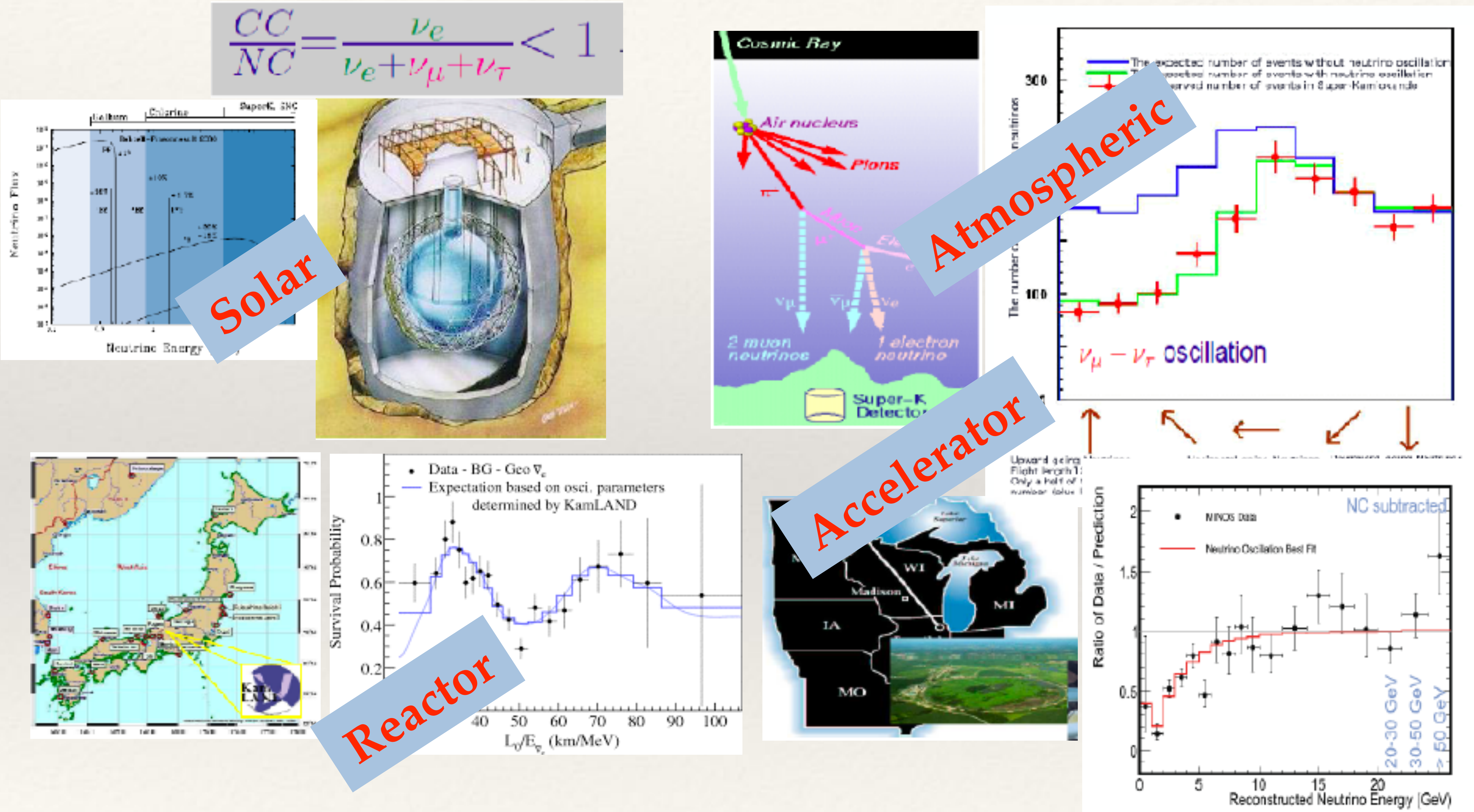
- The absolute masses of the neutrinos
- The nature of neutrinos — Dirac or Majorana
- Are there more than 3 flavours ? Sterile neutrinos ?
- More precise measurement of mixing angles, Unitarity ?
- Mass ordering and CP phases
- The origin of neutrino masses and mixing at a fundamental level —Beyond Standard Model
- Do neutrinos have non-standard interaction, decay? Is there violation of fundamental symmetries like CPT, Lorentz invariance

Neutrino Sources and experiments



https://www.slac.stanford.edu/econf/C1307292/docs/IntensityFrontier/Neutrinos-12.pdf

Neutrino Oscillation: Evidences



Three Neutrino Paradigm

- Measurement of non-zero θ_{13} in reactor experiments → three neutrino picture

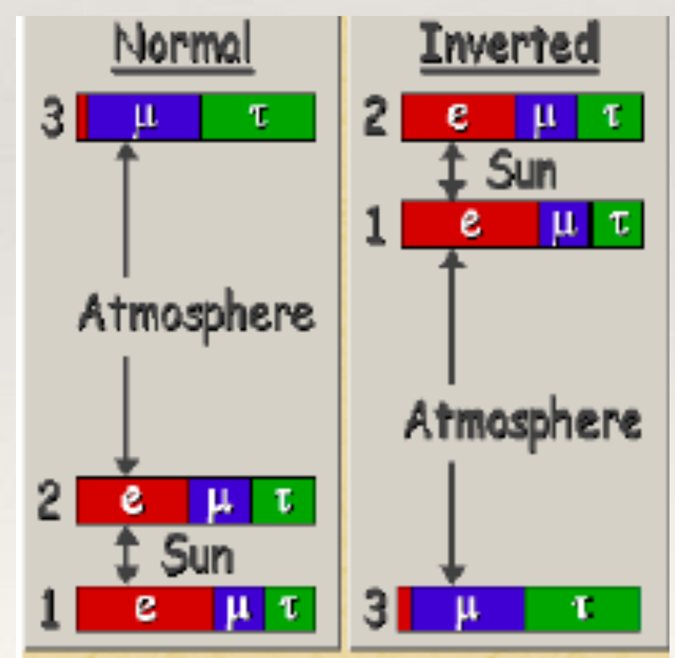
Atm +LBL | Sol+KL

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

- Δm^2_{21}, θ_{12}, θ_{13} Solar + KamLND
- Δm^2_{31}, θ_{13} Reactor
- Δm^2_{31}, θ_{23}, θ_{13}, δ_{CP} Atm + LBL

Interplay among different sectors because of θ_{13}

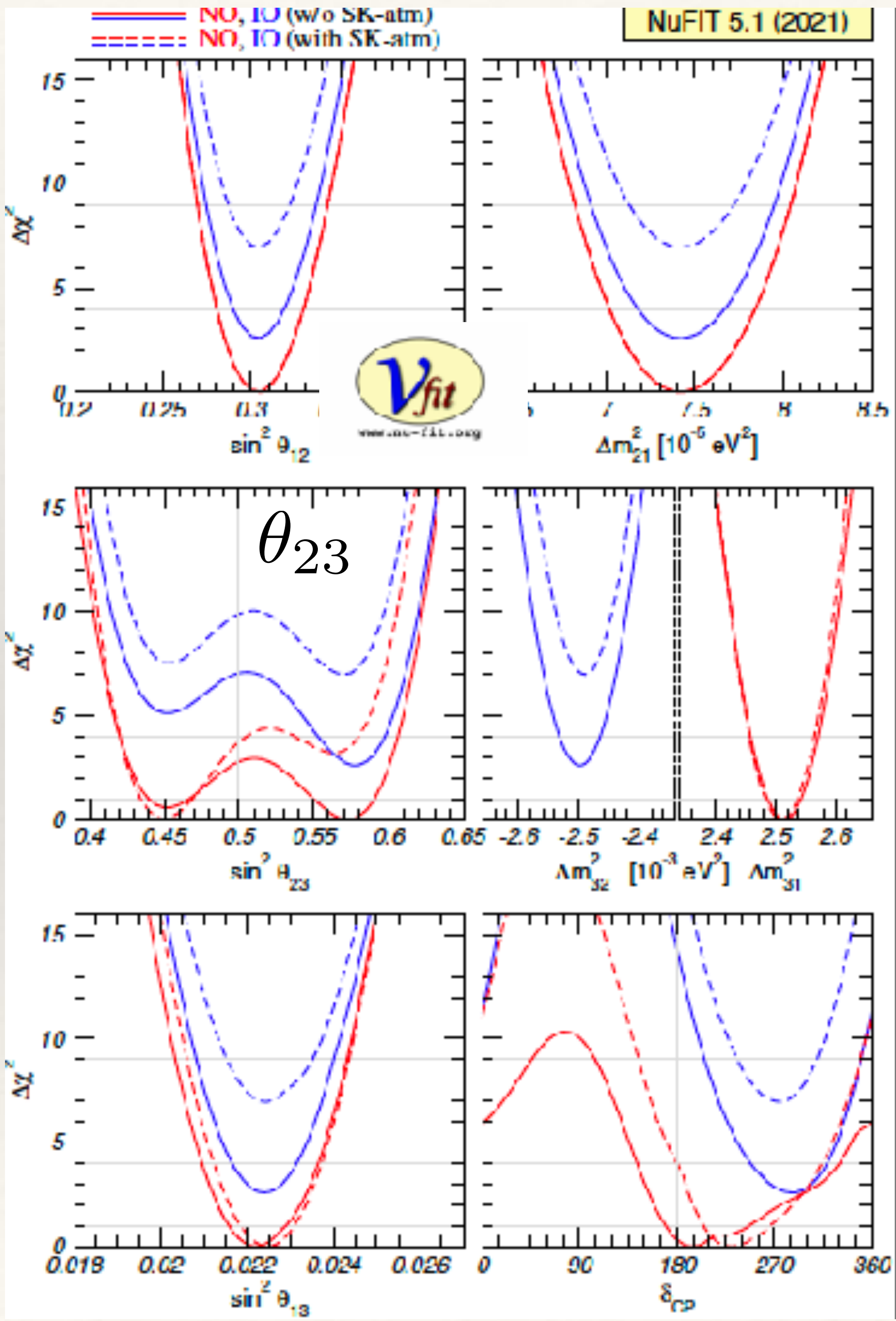


Neutrino Oscillation : from discovery to precision

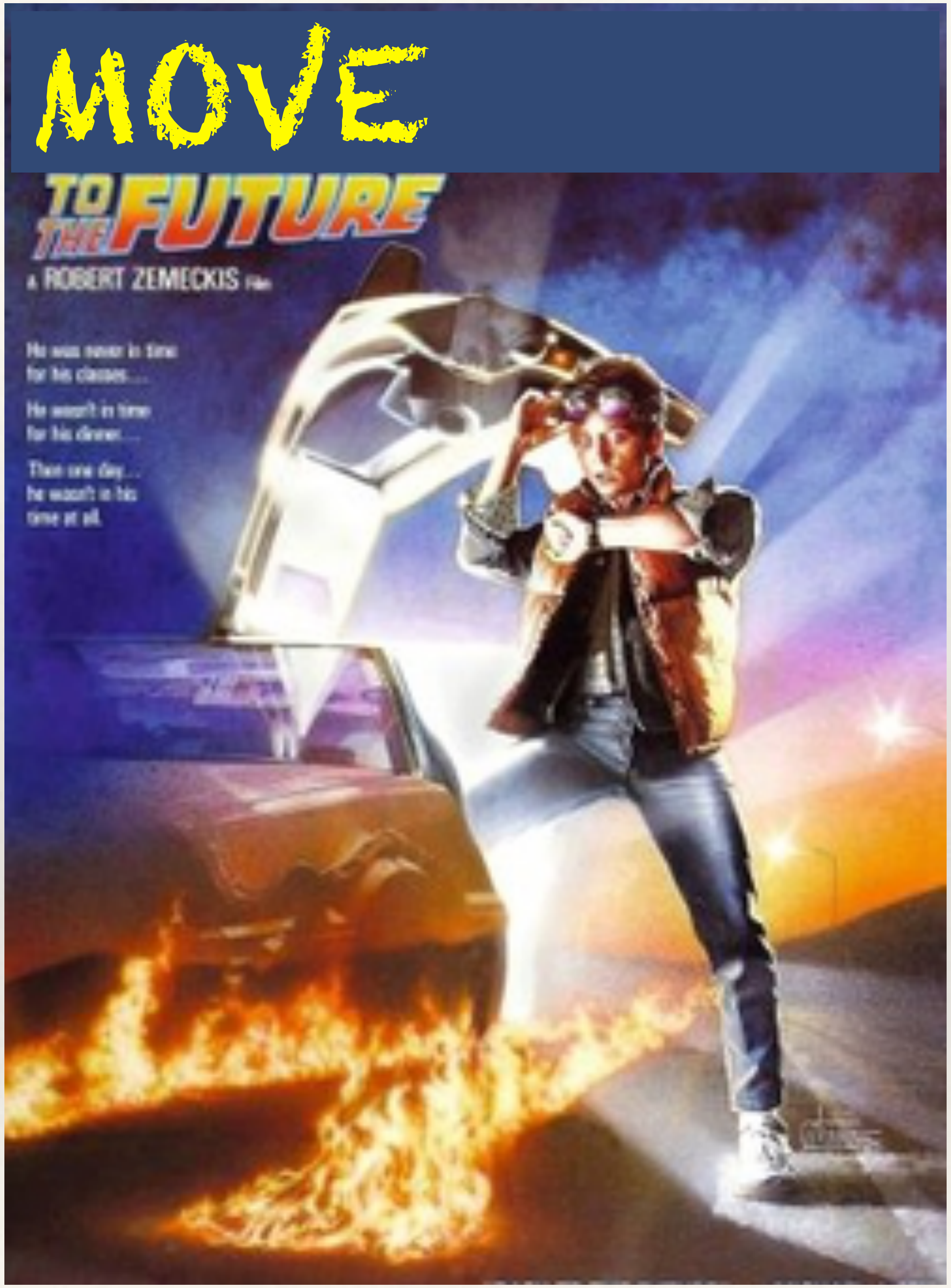
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

NuFIT 5.1 (2021)

Unknown parameters



- Best-fit θ_{23} in second octant
- Preference for NO
- $\delta_{CP} = +90^\circ$ disfavoured at more than 3σ irrespective of mass ordering
- Oscillation experiments not sensitive to Majorana phases
- Not sensitive to absolute masses


MOVE
TO THE FUTURE
ROBERT ZEMECKIS

Future Goals in Neutrino Physics

- Determination of hierarchy, octant and CP phase
- Synergy between different experiments

} Immediate Goals

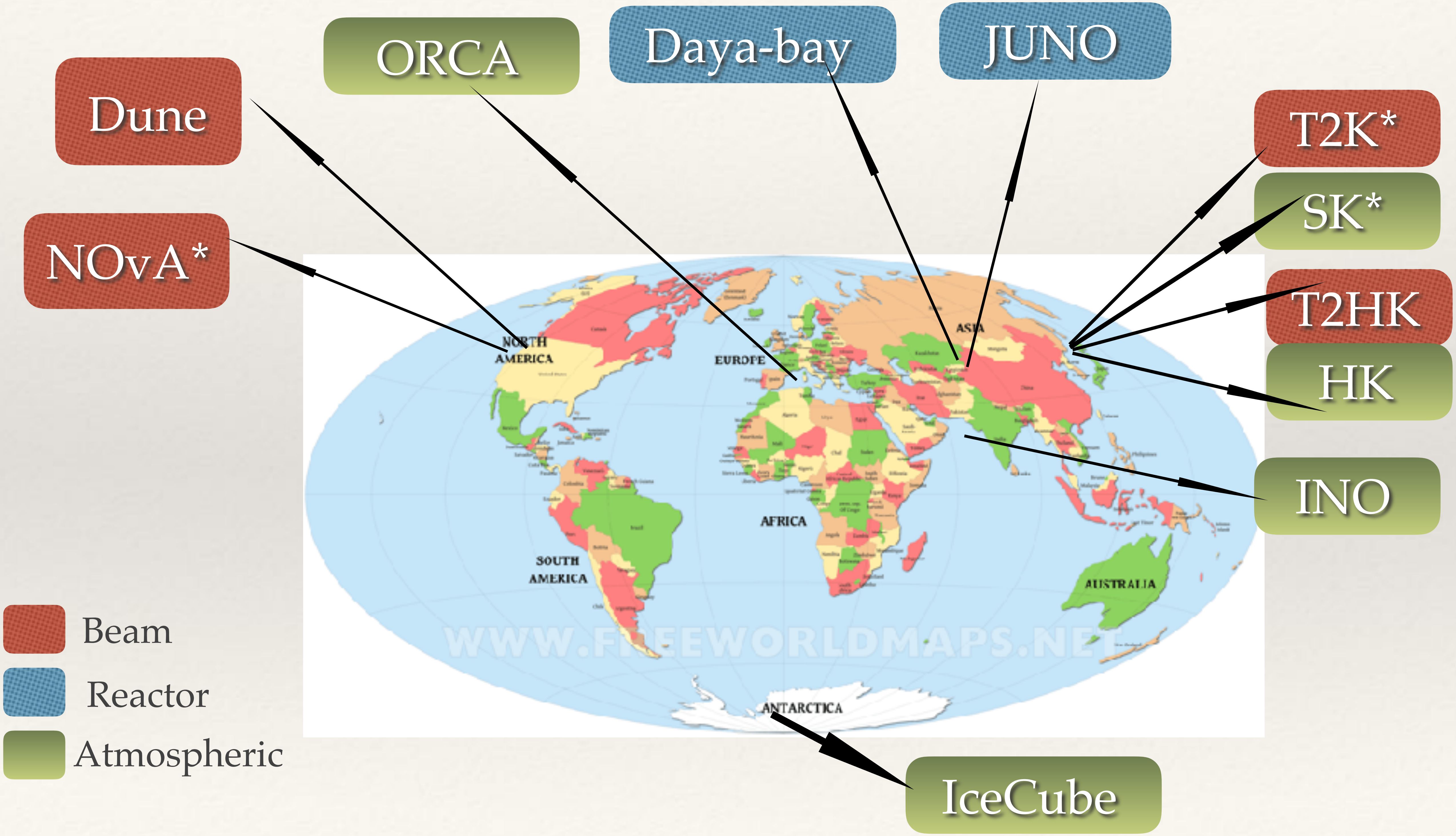
- Signatures of sterile neutrinos
- Precise Measurement of neutrino cross-sections
- Nature of neutrinos , absolute neutrino mass
- Probing new physics in oscillation experiments

} Ongoing

- Search for Dark Matter in neutrino facilities
- Probing BSM physics through new interactions
- Neutrinos and Multimessenger Astronomy

} Emerging Goals

Current and future oscillation experiments



Long baseline experiments : salient features

Expt	Baseline	E (GeV)		Details
T2K	295 km, Tokai to Kamioka	0.6		0.76 MW Super Kamiokande Water Cerenkov
NOVA	810 km, FNAL to ASH River	1.7		0.7 MW 14 kt TASD
DUNE	1300 km FNAL to South Dakota	0.5-8		1.2 MW Liquid Argon 10kt/40 kt
T2HK	295 km JPARC to Kamioka	0.6		1.3 MW , 187 kt X2 Hyper Kamiokande
T2HKK	295km, 1100 km	0.6		HK, Water Cherenkov in Korea
ESSnuSB	540 km , Lund to Gapenberg	0.3		5 MW 500 kt Water Cerenkov,

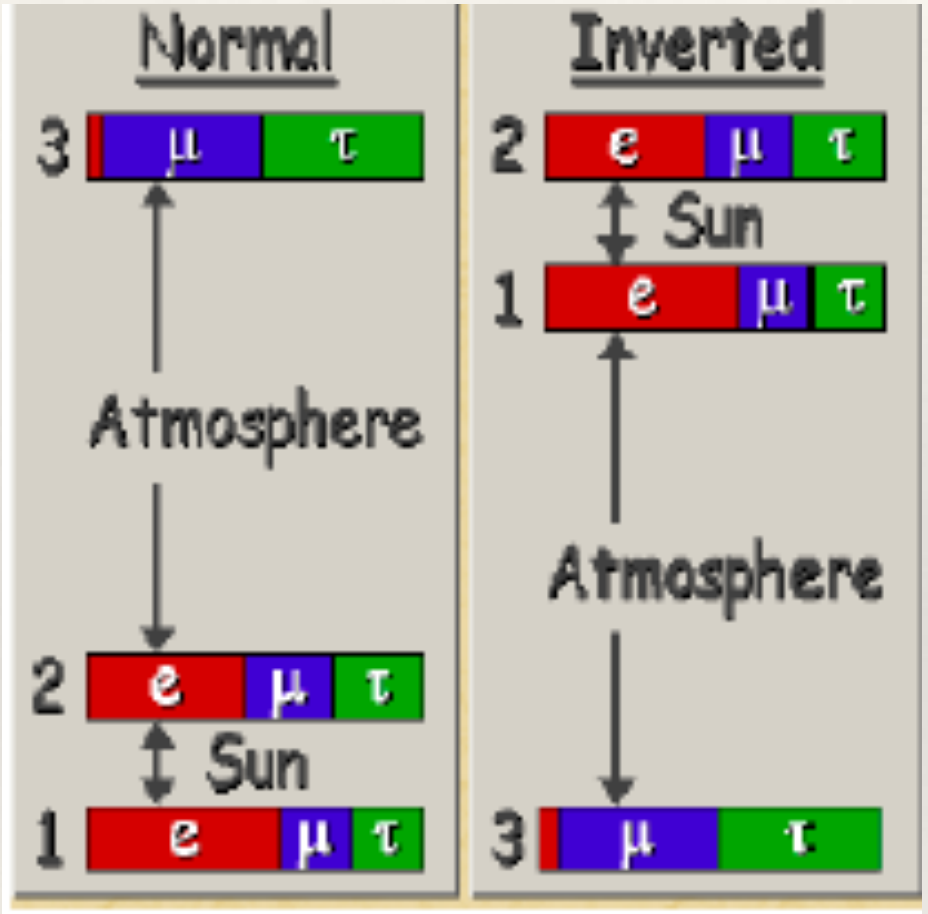
High Intensity Beams, bigger detectors

Atmospheric neutrino detectors: salient features

	Prototype	Salient features
Magnetized IRON	ICAL@INO	50 kt, muon energy and direction measurement, charge id, neutrino energy reconstruction
Water Cherenkov	Hyper Kamiokande	Megaton, no charge id, both electron and muon energy and direction
Water Cherenkov (Mediteranian)	ORCA	Multi- Megaton, tracks and showers, no charge id
ICE Cherenkov (Southpole)	PINGU IceCube	Multi megaton, tracks and showers , no charge id
Liquid Argon	DUNE	Liquid Argon, both muon and electron events Charge id for both ??

Path length — 10- 10000 km, matter effects important

Mass hierarchy

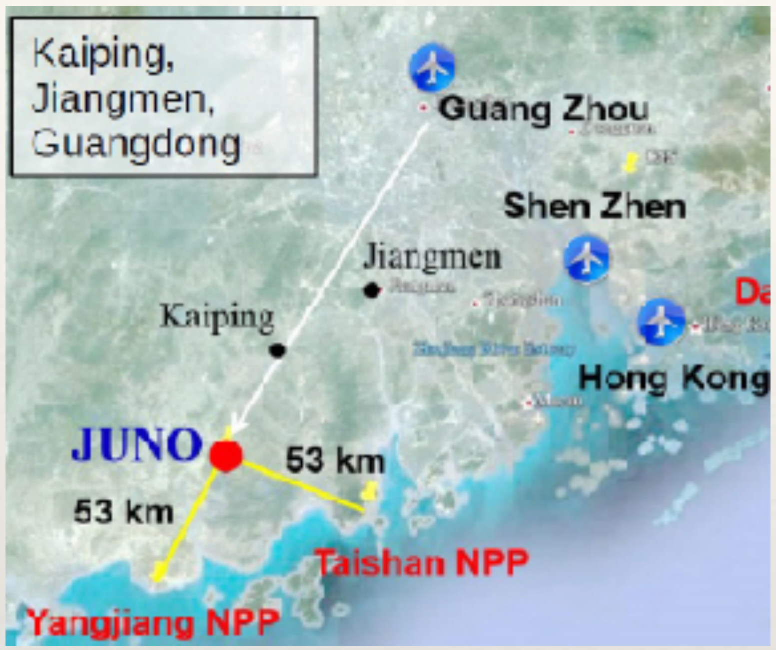


Matter effect in large baselines : long baseline beam and atmospheric neutrino experiments

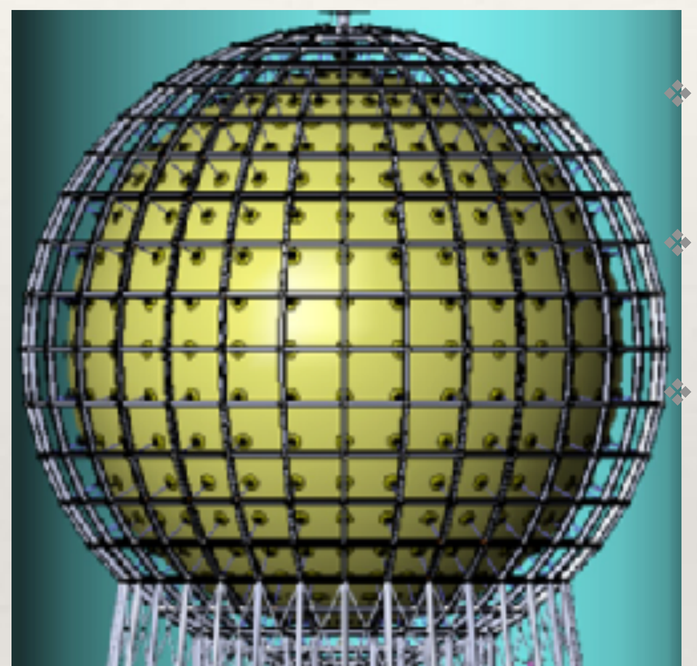
Interference effect in vacuum oscillations : reactor neutrino experiments

Absolute neutrino mass measurements
Neutrino less double beta decay, Cosmology

JUNO: Jianmen Underground Neutrino Observatory

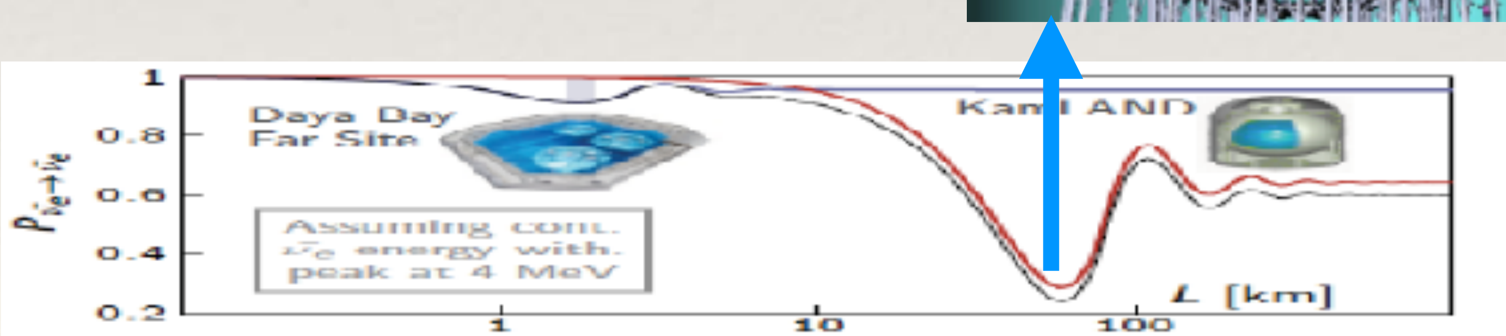


- Reactor Antineutrino Experiment
- 20 kt Liquid Scintillator detector



- Determination of mass Hierarchy
- Precision of osc. parameters
- Solar, supernova, atmospheric and geo-neutrinos

- Detector at 53 km from the two reactors



Expected to complete detector construction in 2023

JUNO: Hierarchy and Precision

$$P_R(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \left\{ \begin{array}{l} \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ +\sin^2 2\theta_{13}\sin^2\theta_{12}\left(\cos 2\Delta_{31}\sin^2\Delta_{21} - \frac{1}{2}\sin 2\Delta_{31}\sin 2\Delta_{21}\right) \end{array} \right\}$$

Precision of θ_{12}

Bandyopadhay,Choubey, S.G. 2003

Petcov, Piai, 2001, Choubey,Petcov,Piai, 2003

Hierarchy sensitivity

Distortions in the energy spectrum

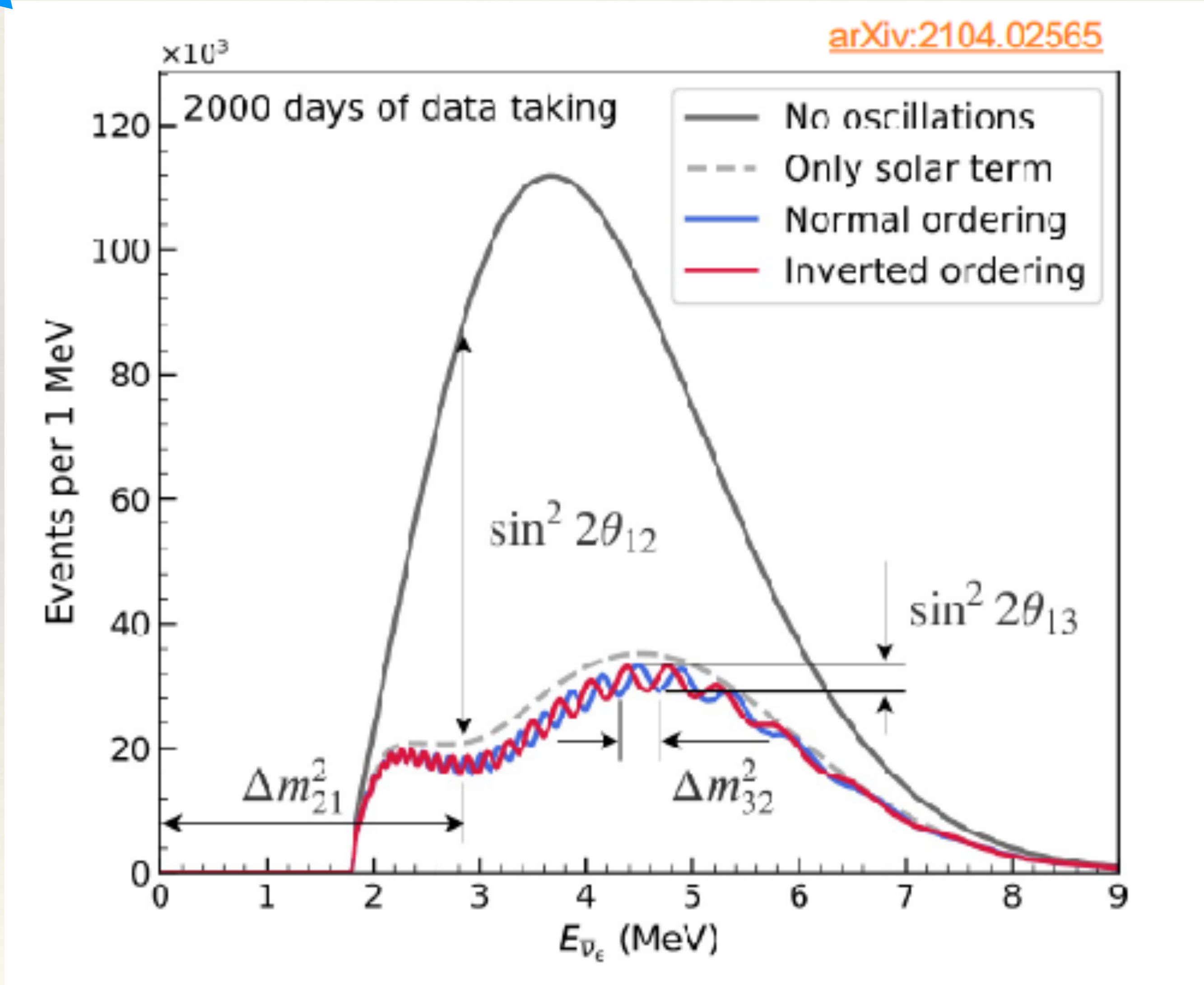
Better than 3% energy resolution needed

3σ hierarchy sensitivity in 6 years

Precision of oscillation parameters

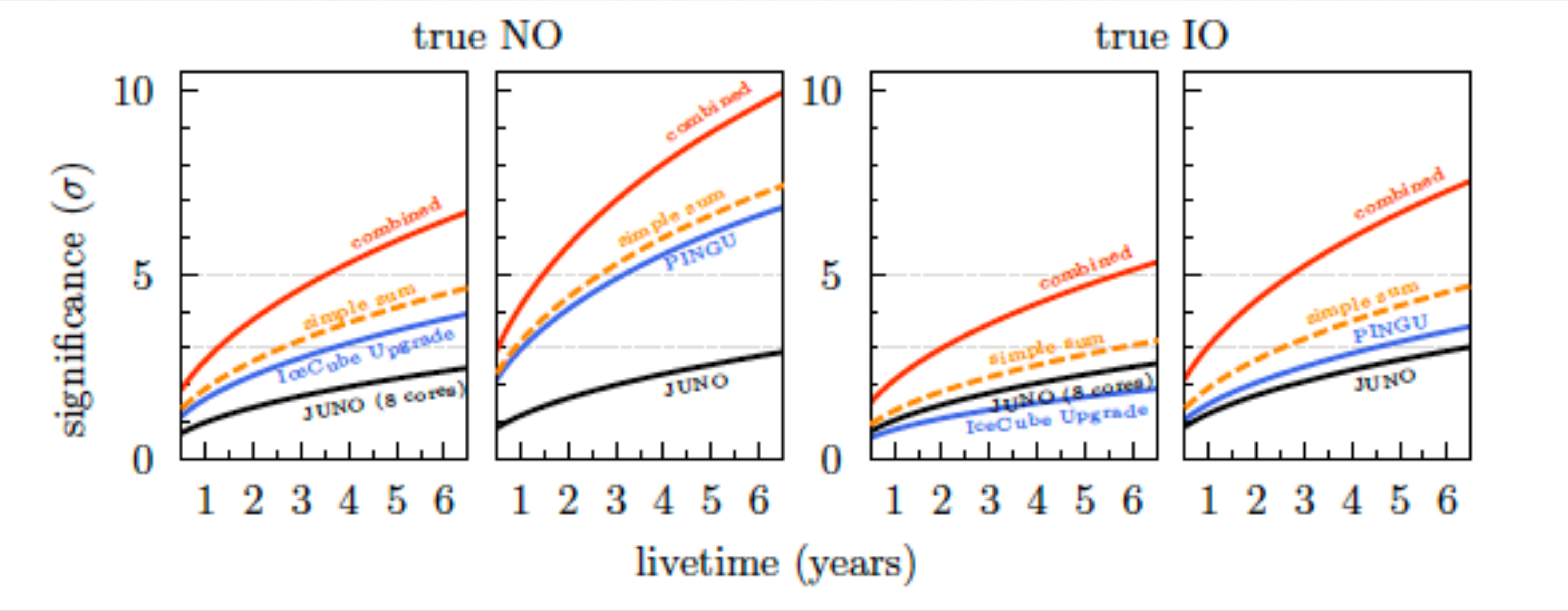
	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

Table: A. Paoloni, 2021



Hierarchy: Juno+IceCube upgrade

8 core JUNO + IceCube upgrade/PINGU / (better efficiency for lower energy neutrinos)



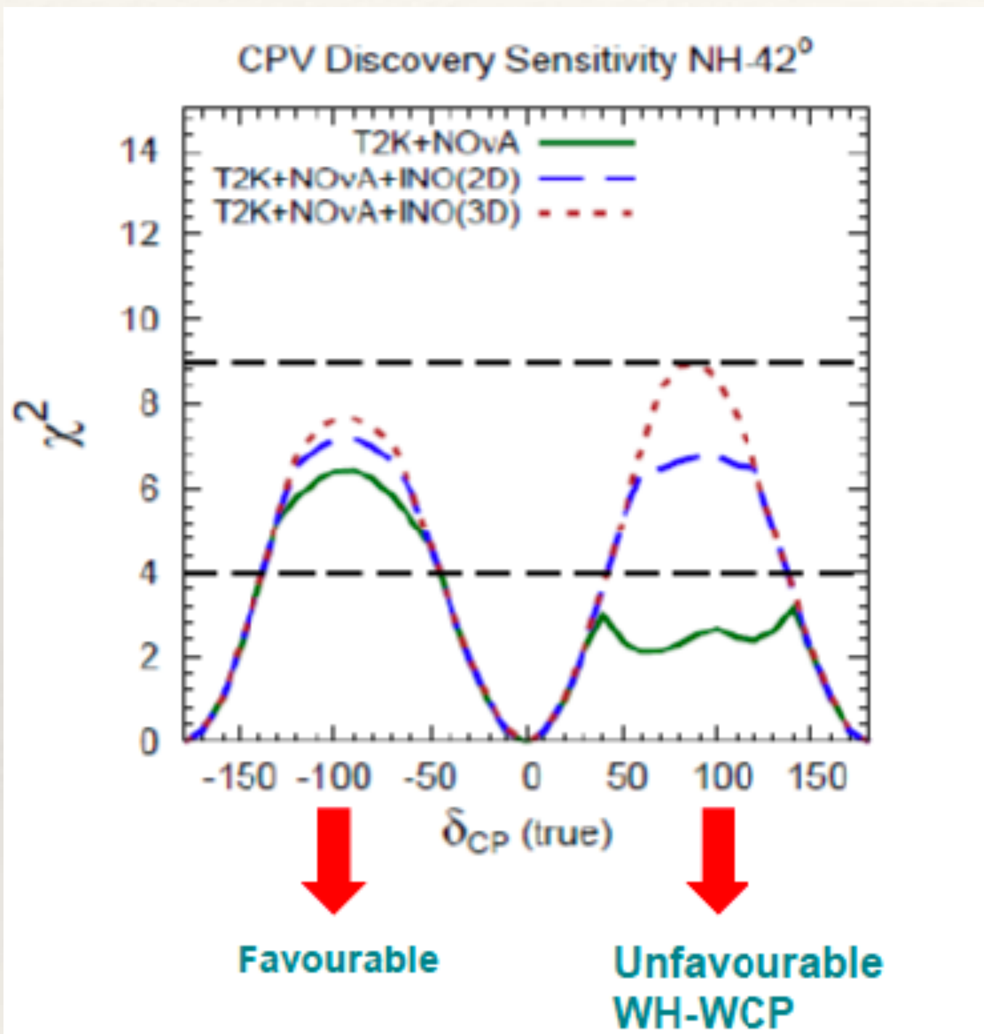
5σ sensitivity in 4(6) years NO (IO)

IceCube : **earth matter effect** of atmospheric neutrinos
JUNO: interference effect in vacuum oscillation
} **Synergy**

hep-ex 1911.06745

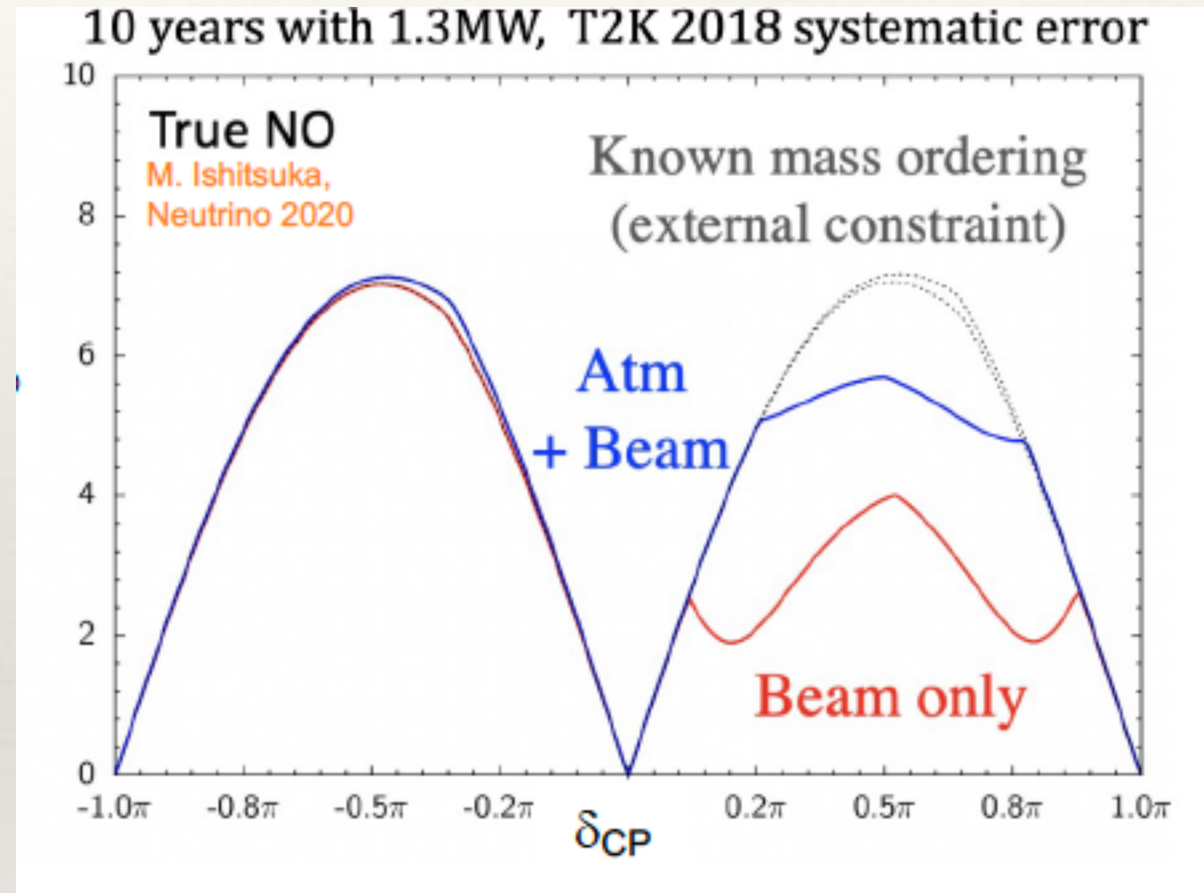
Synergy between beam +atm for δ_{CP}

T2K+NOVA+INO (500 kt-yr)



Ghosh, Ghoshal, Goswami, Raut, 2013
Gupta, Chakraborty, Goswami, 2018

HyperK

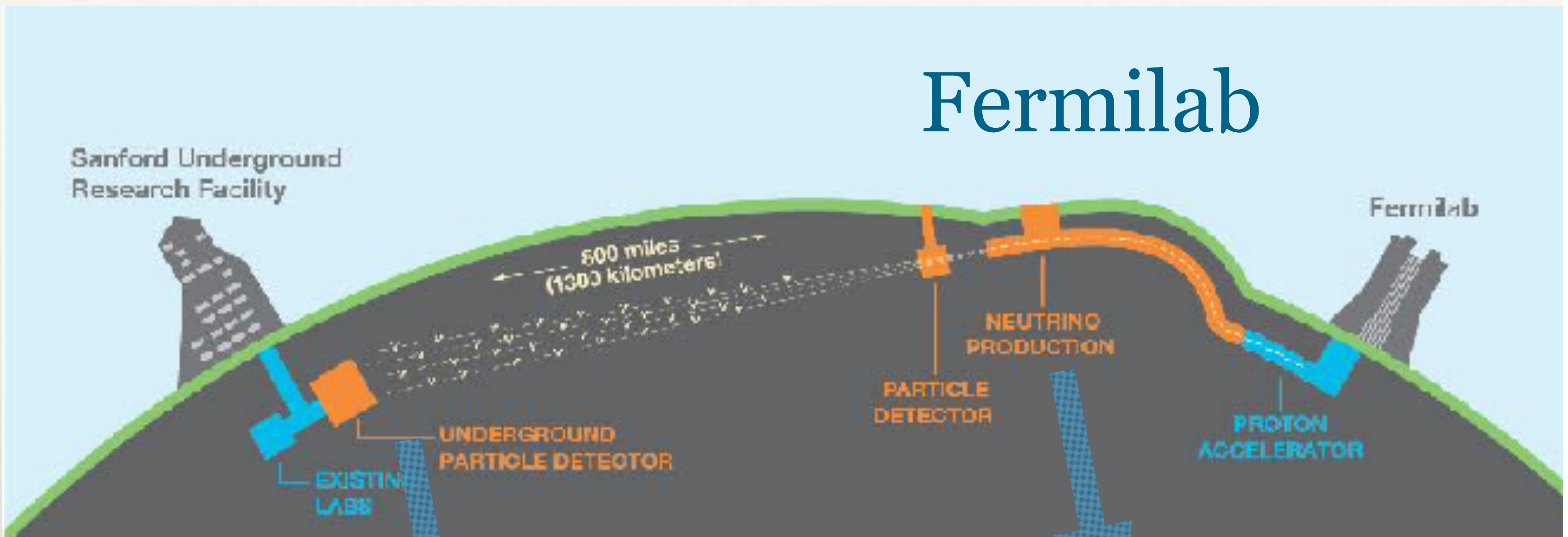


HyperK design report arXiv: 1805.04613

Atmospheric data can resolve hierarchy -CP degeneracy and enhances CP sensitivity

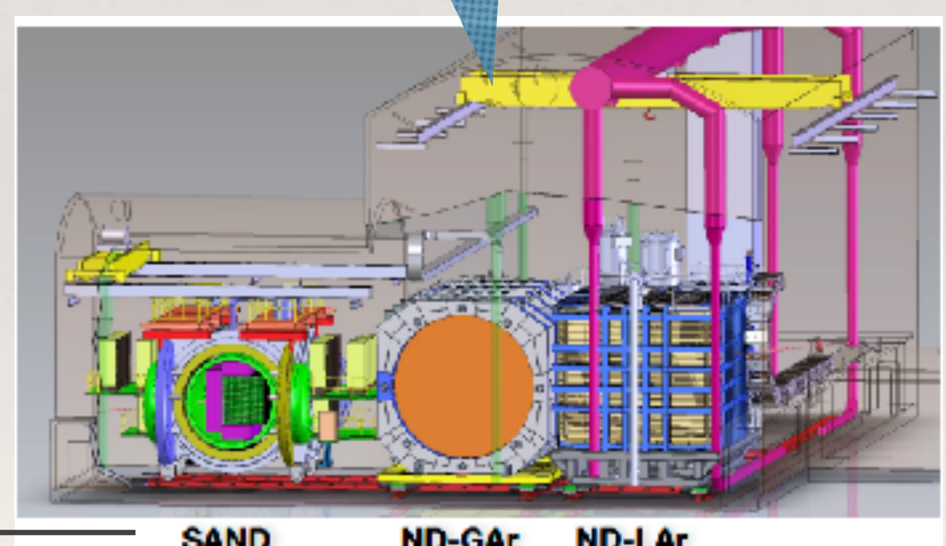
DUNE

Fermilab



LBNF/DUNE-US Project + DUNE Int'l Project		
Capability Description	Phase I	Phase II
Beamline		
1.2MW (includes 2.4MW infrastructure)	X	
2.4MW		X[1]
Far Detectors		
FD1 – 17 kton	X	
FD2 – 17 kton	X	
FD3		X[2]
FD4		X[2]
Near Detectors		
ND LAr	X	
TMS	X	
SAND	X	
MCND (ND GAr)		X

Far Detector
Liquid Argon Time
Projection Chamber



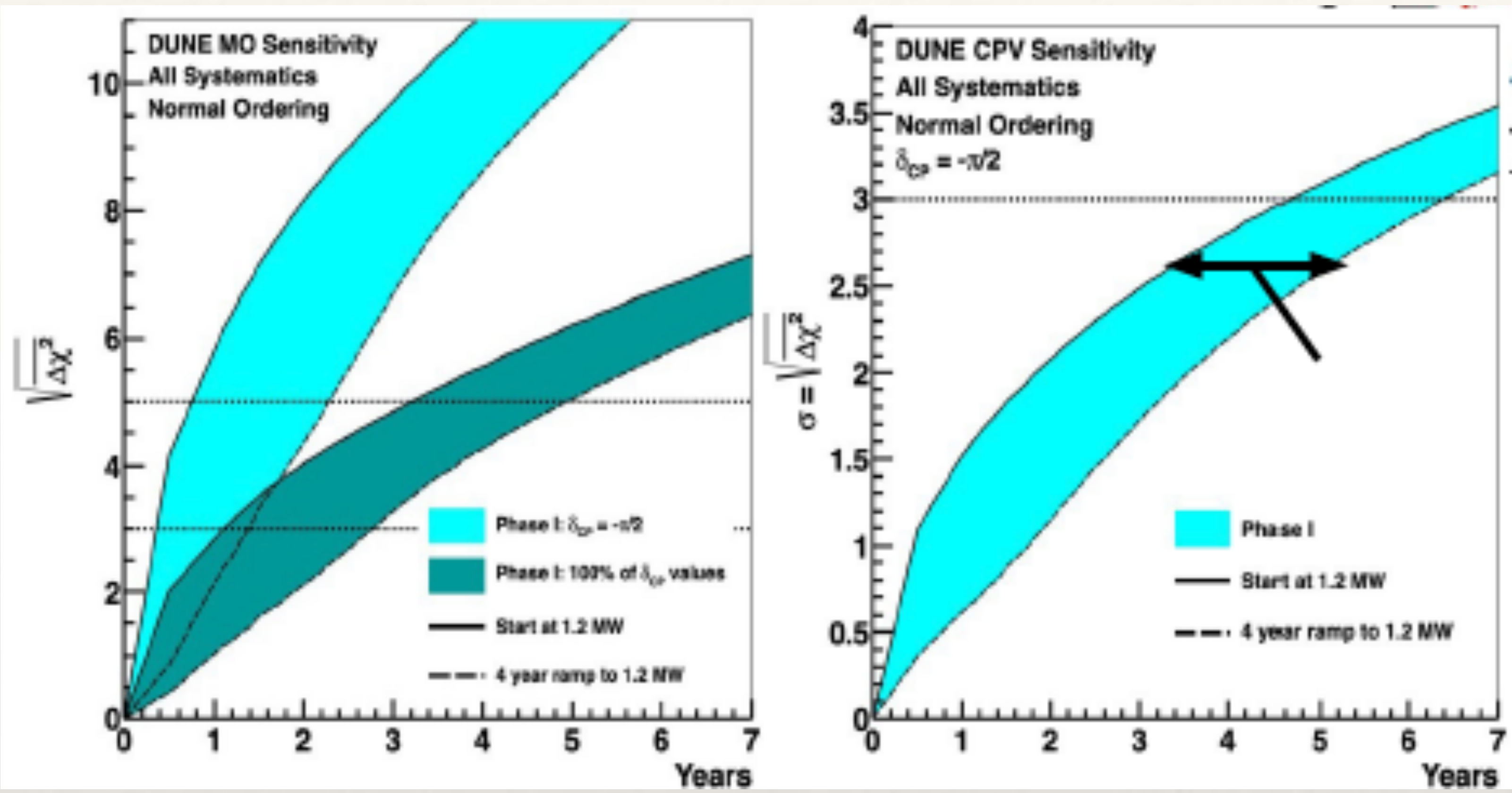
On-axis

DUNE PRISM: off-axis, movable

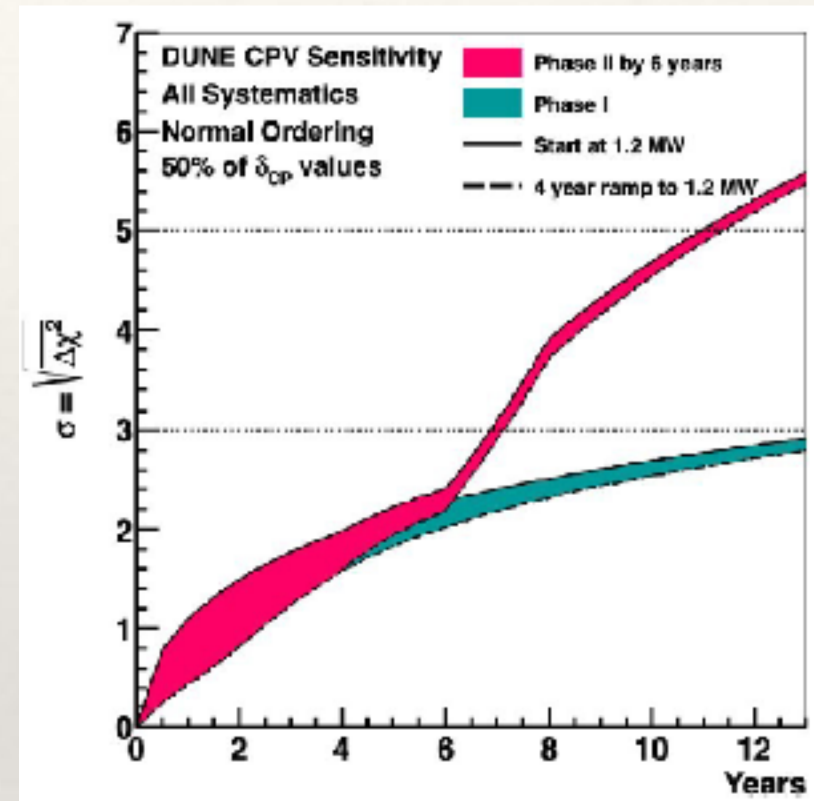
Phase II : increased far detector mass and beam power and improvement in near detector

DUNE Physics Goals

Phase 1



Phase 2



5σ **hierarchy sensitivity in 5 years for 100%** δ_{CP}

3σ **CPV sensitivity in 5 years for maximum CPV**

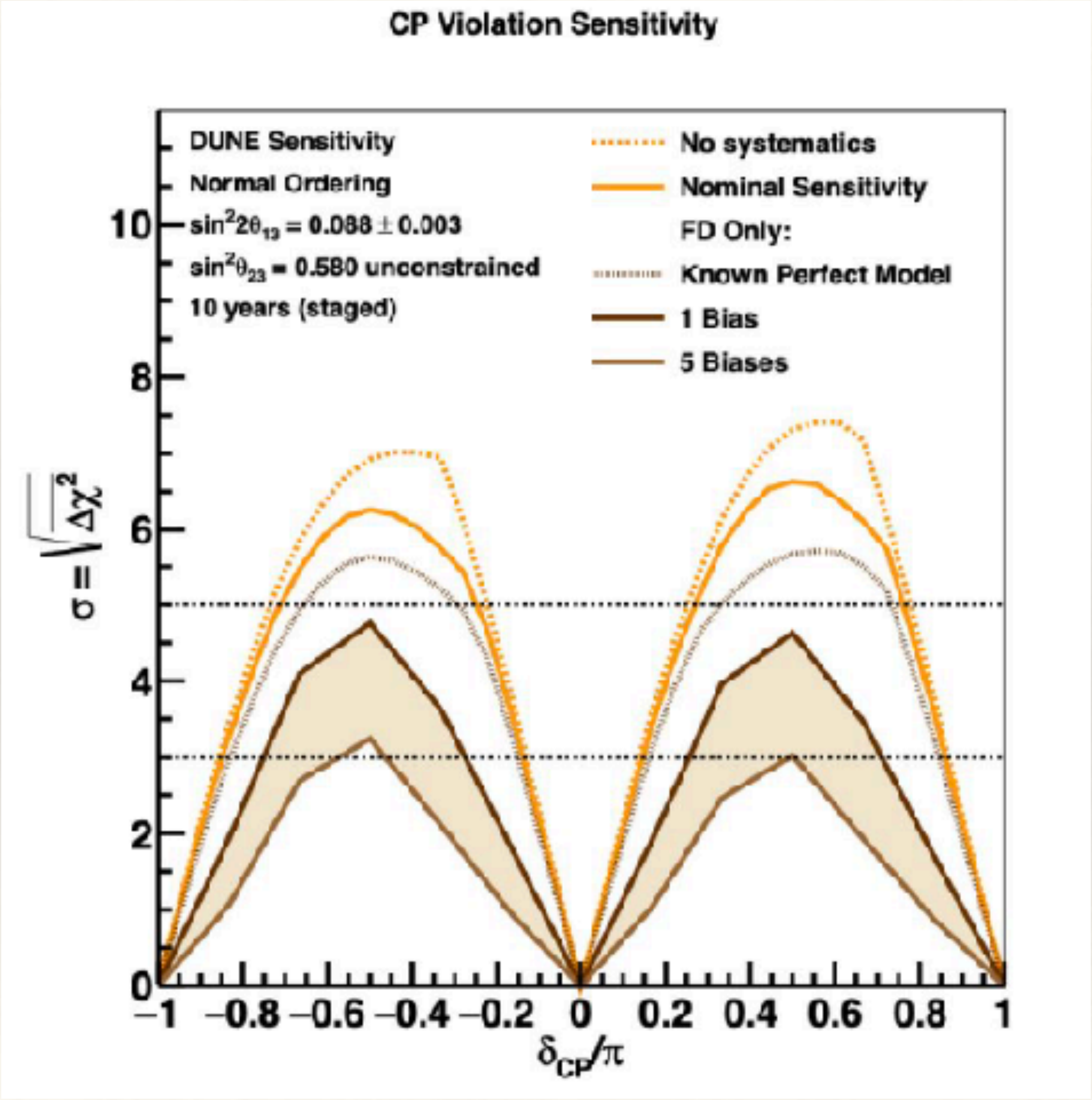
Sensitivity to supernova neutrino burst, BSM physics

Sensitivity for 50 % δ_{CP} **values**

Improved sensitivity to BSM physics at ND with the beam upgrade

S. Brice

Impact of Systematic Uncertainty



- CP violation is manifest in differences between neutrino and antineutrino probabilities —- at the level of few percents
- Needs large data samples
- Systematic uncertainties play important role for precision measurements
- Near detectors help in reducing these
- Measurement of neutrino-nucleus scattering cross-sections

Neutrino interaction cross-sections

	Experiment	Flavor	ν_μ Flux Peak (GeV)	Target	Detection
ND beam	T2K	$\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$	0.6,0.8,1	CH, H_2O, Fe	Tracking
	NOvA	$\nu_\mu,\bar{\nu}_\mu,\nu_e, \bar{\nu}_e$	2	CH_2	Tracking+Calorimetry
	DUNE	$\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$	PRISM: 0.5-3	H,C,Ar	Tracking+Calorimetry
	HK IWCD	$\nu_\mu,\nu_\mu,\nu_e,\nu_e$	PRISM: 0.4-1	H_2O	Cherenkov
SBN@Fermilab	MicroBooNE	ν_μ,ν_e	0.3,0.8	Ar	Tracking+Calorimetry
	SBND	ν_μ,ν_e	0.8 (PRISM: 0.6-0.8)	Ar	Tracking+Calorimetry
	ICARUS	ν_μ,ν_e	0.3,0.8	Ar	Tracking+Calorimetry
Dedicated	MINERvA	$\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$	3.5,6	He, C, CH, H_2O, Fe, Pb	Tracking+Calorimetry
	ANNIE	$\nu_\mu,\bar{\nu}_\mu$	0.6	CH, H_2O	Cherenkov
	NINJA	$\nu_\mu,\nu_\mu,\nu_e,\nu_e,$	1	CH, H_2O, Fe	Emulsion
LHC	FPF	$\nu_\mu,\nu_\mu,\nu_e,\nu_e,$ $\nu_\tau,\bar{\nu}_\tau$	700 GeV	W, Ar	Emulsion, Tracking+Calorimetry
	nuSTORM	$\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$	PRISM: 0.8-3	CH,H_2O,Ar,TBD	Tracking+Calorimetry (TBD)

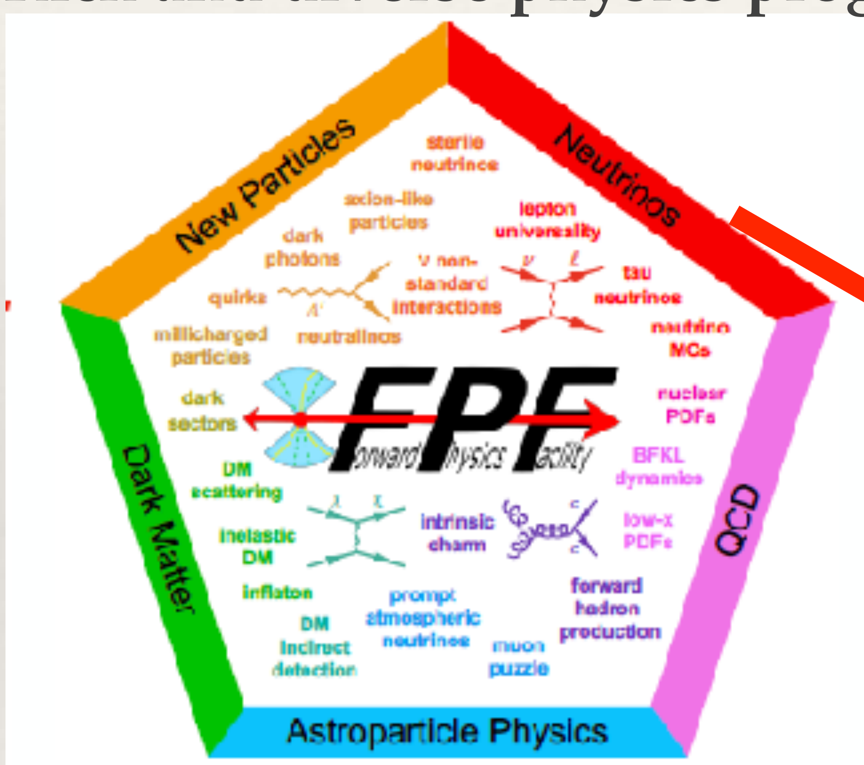
Experimental measurement of neutrino-nuclear cross-sections and refinement of theoretical calculations including many body effects, nuclear form factors from LQCD, and strategies for the Event Generators —- crucial for precision neutrino measurements

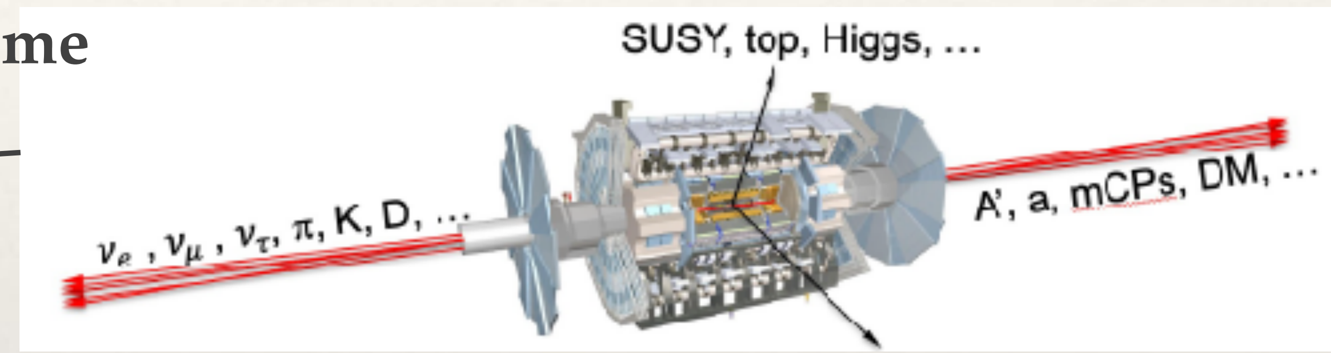
Forward Physics Facility @HL-LHC

Largest Flux of Pion, Kaon, D-Meson, neutrinos in the forward direction

There can also be dark photons, axion like particle, light dark matter etc.

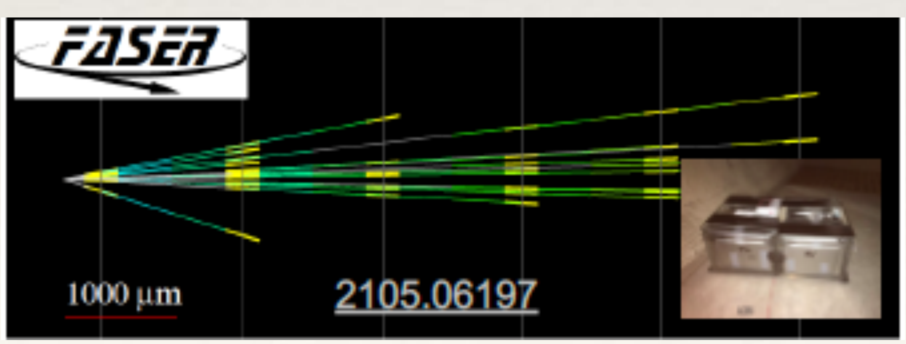
Rich and diverse physics programme





Laboratory measurements of neutrinos at the TeV scale for the first time

Detection of thousands of tau neutrino interactions for the first time

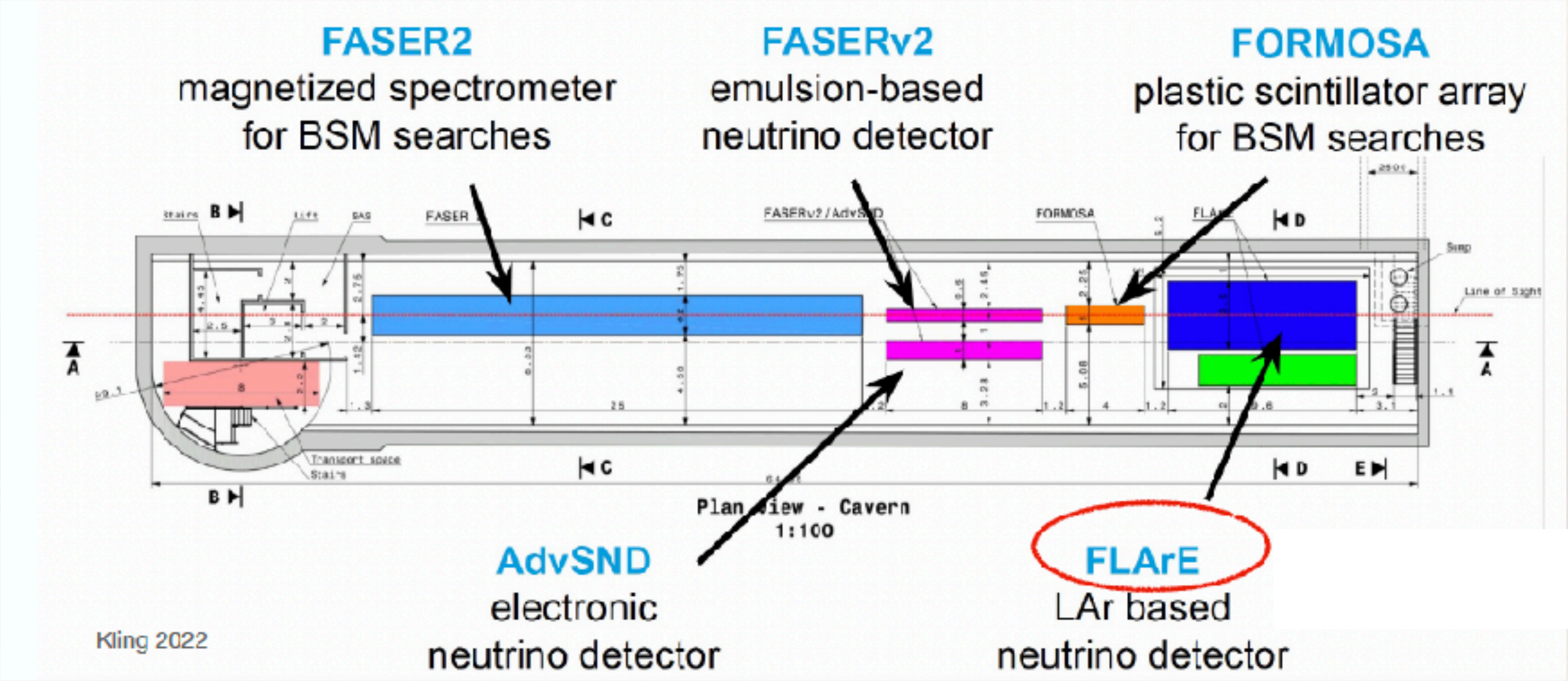


Faser detector in the far forward region running for 4 weeks have detected 6 neutrino events

Talk by Jonathan Feng, SNOWMASS meeting

FPF@HL-LHC

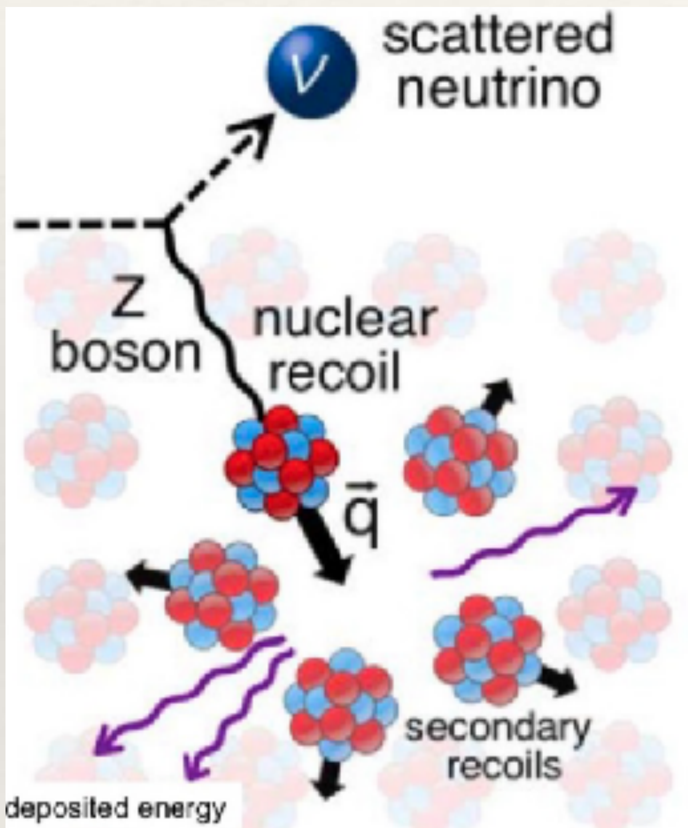
5 detectors are being developed



Conceptual design report : mid 2023

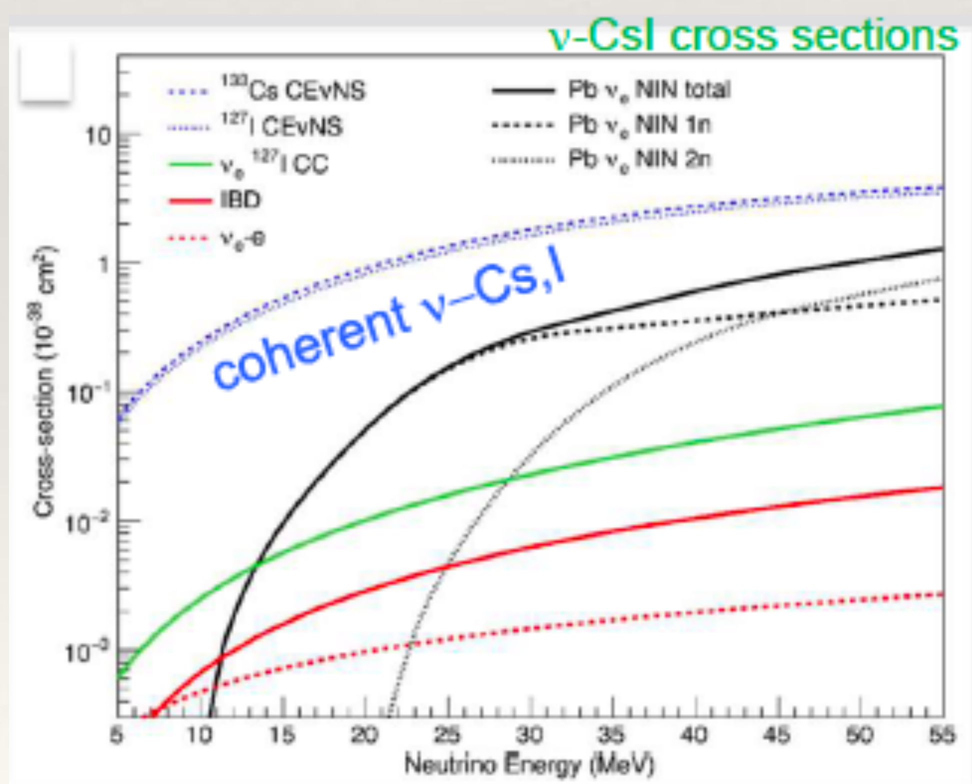
Coherent Elastic Neutrino-Nucleus Scattering

$\nu + A \rightarrow \nu + A \quad (\chi + A \rightarrow \chi + A)$



Detection : the tiny energy deposited by nuclear recoil in the target material

Challenging : recoil energy 50 KeV for 10 MeV neutrinos



COHERENT collab, Science 3 Aug, 2017

First result in 2017

6.7σ discovery of CEνN S

Consistent with SM at 1σ

R. Tayloe, NDM2022

Physics Reach

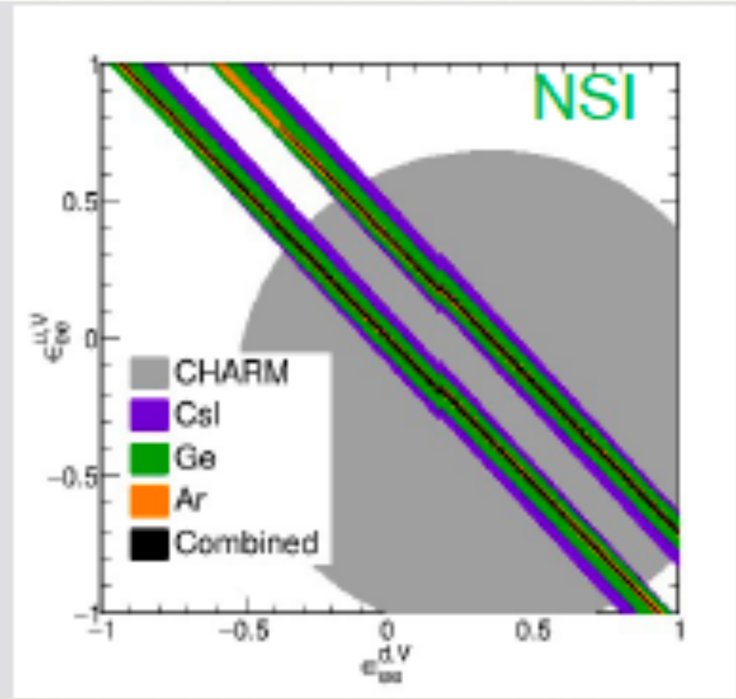
Nuclear Physics and nuclear form factors

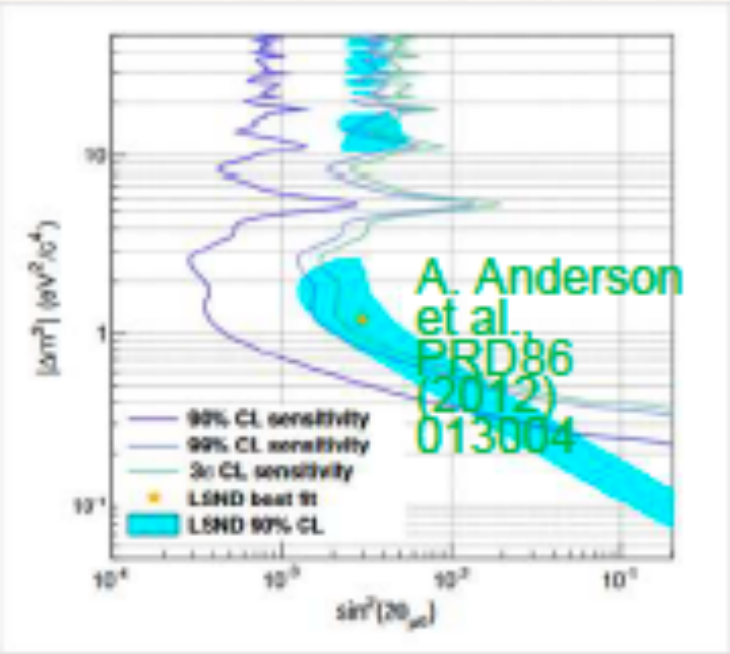
Precision SM test : weak mixing angle

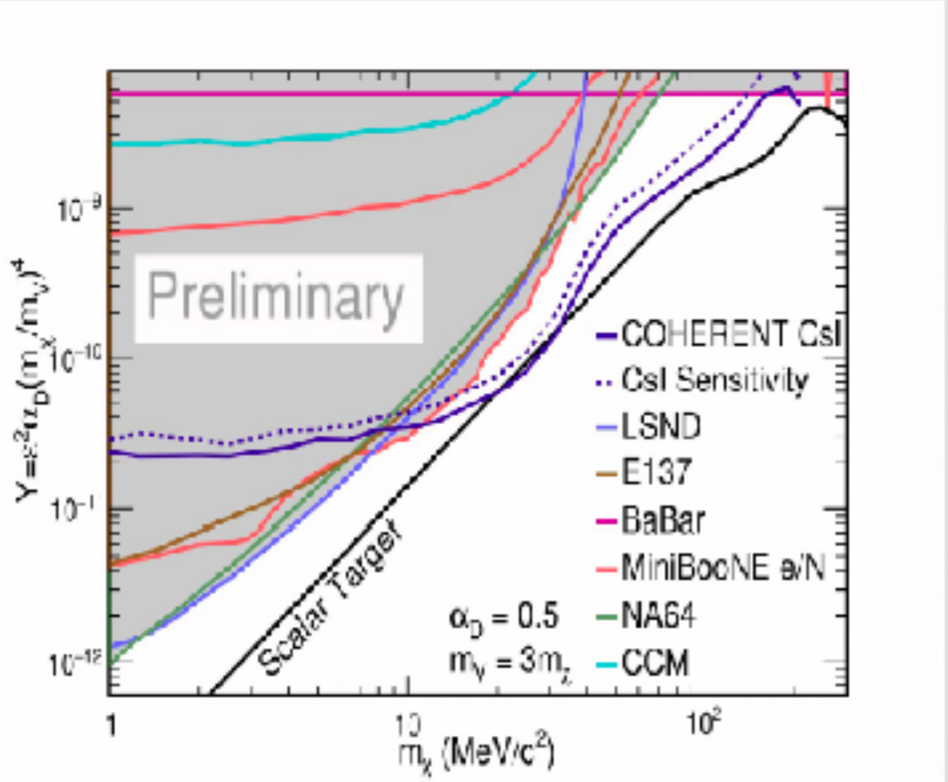
BSM physics : Non-standard interaction, neutrino magnetic moment

Supernova neutrinos : cross sections at SN nu energies

Dark Matter







Probing sub-GeV Dark matter with CsI at SNS in Oak Ridge National Laboratory

arXiv:2110.1145

COHERENT past current and future detectors

Phase 1 : Observe CEνNS process with multiple detector technologies

Phase 2 : Precision measurements with larger detectors

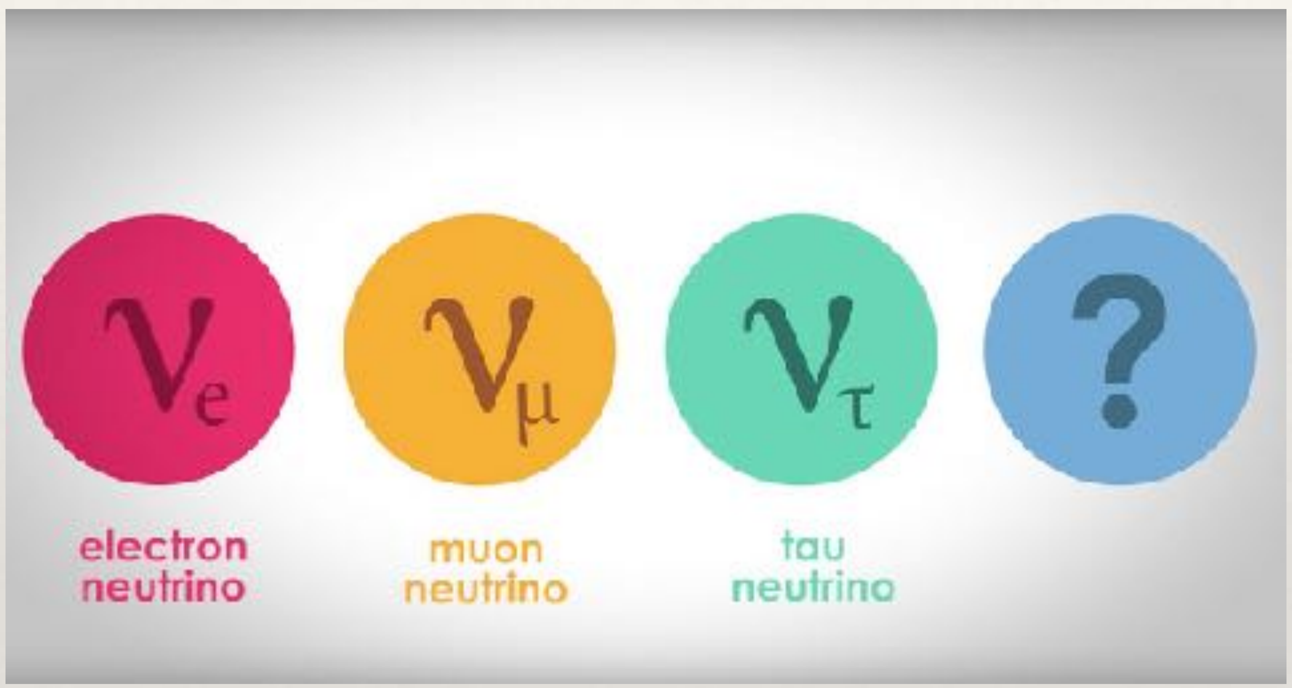
Target	Technology	Fid. Mass (kg)	Threshold (keV_{nr})	Commission dates	Pubs/status
CsI[Na]	Scintillation	14.6	6.5	2015	1st result, 2017: 10.1126/science.aao0990 updated results in press, detector removed
Liquid Ar	Scintillation	24.4/610	20	2017/2024	1st result, 2019: 10.1103/PhysRevLett.126.012002, currently running
Ge	Ionization	18	0.5	2022	commissioning
NaI[TI]	Scintillation	2500	13	2022	commissioning: 2022

R. Tayloe, NDM2022

Beyond vanilla oscillations

- Possibility of probing new physics beyond the SM in neutrino oscillation experiments
- Sterile neutrinos, non-standard interactions, non-unitarity of neutrino mixing matrices, CPT violation, long range force, unstable neutrinos ….
- Sub-leading effect
- Changes the oscillation probability
- Impact on the 3-neutrino picture — extra parameters and degeneracies
- Constraining new physics parameters
- Unique signatures of BSM physics in neutrino experiments ?

Are there more than 3 neutrinos ?

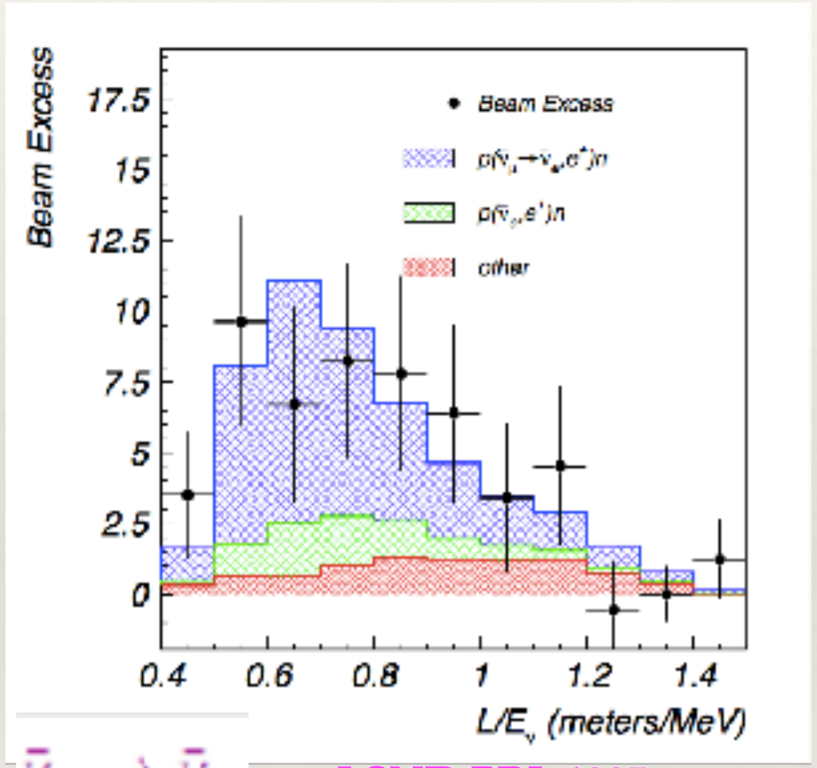


Extra sterile neutrino ?
Light or heavy ?

Evidence for sterile neutrinos

LSND $L \simeq 30\,\mathrm{m}$

$20\,\mathrm{MeV} \leq E \leq 200\,\mathrm{MeV}$



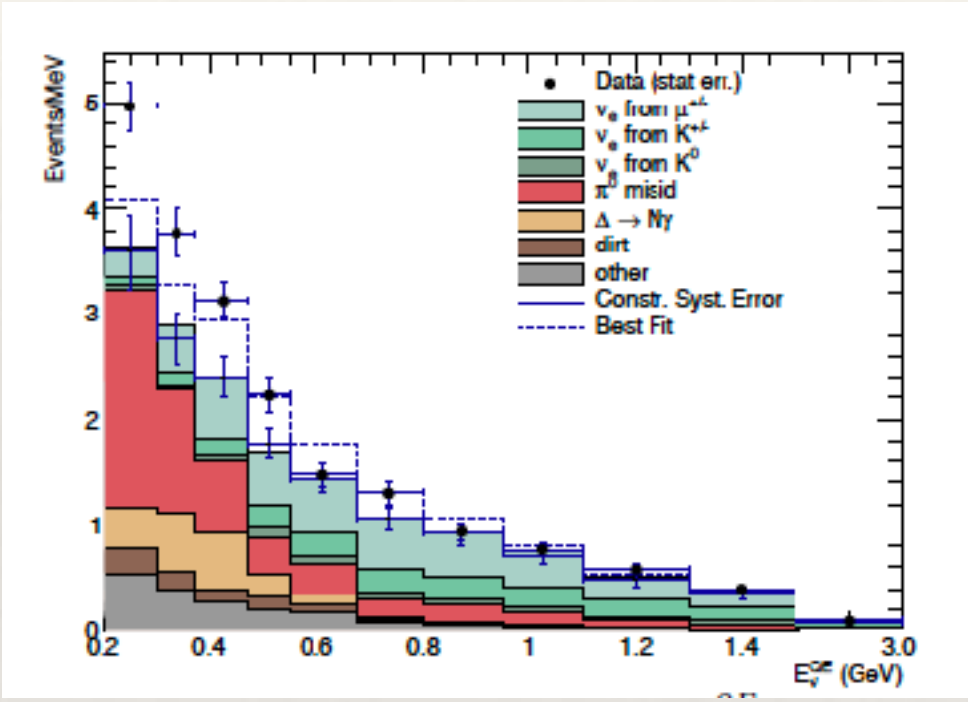
$\bar{\nu}_\mu \to \bar{\nu}_e$

LSND PRL 1995, PRD 2001

3.8σ excess $\Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2$

MiniBOONE $L \simeq 541\,\mathrm{m}$

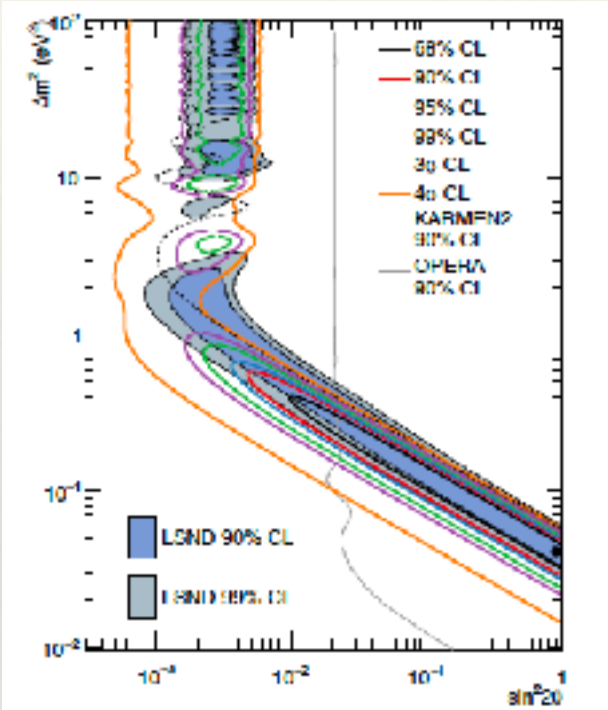
$200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$



A.A. Aguilar Arevalo, PRL 121, 221801, 2018.

LSND+MiniBOONE

Same L/E

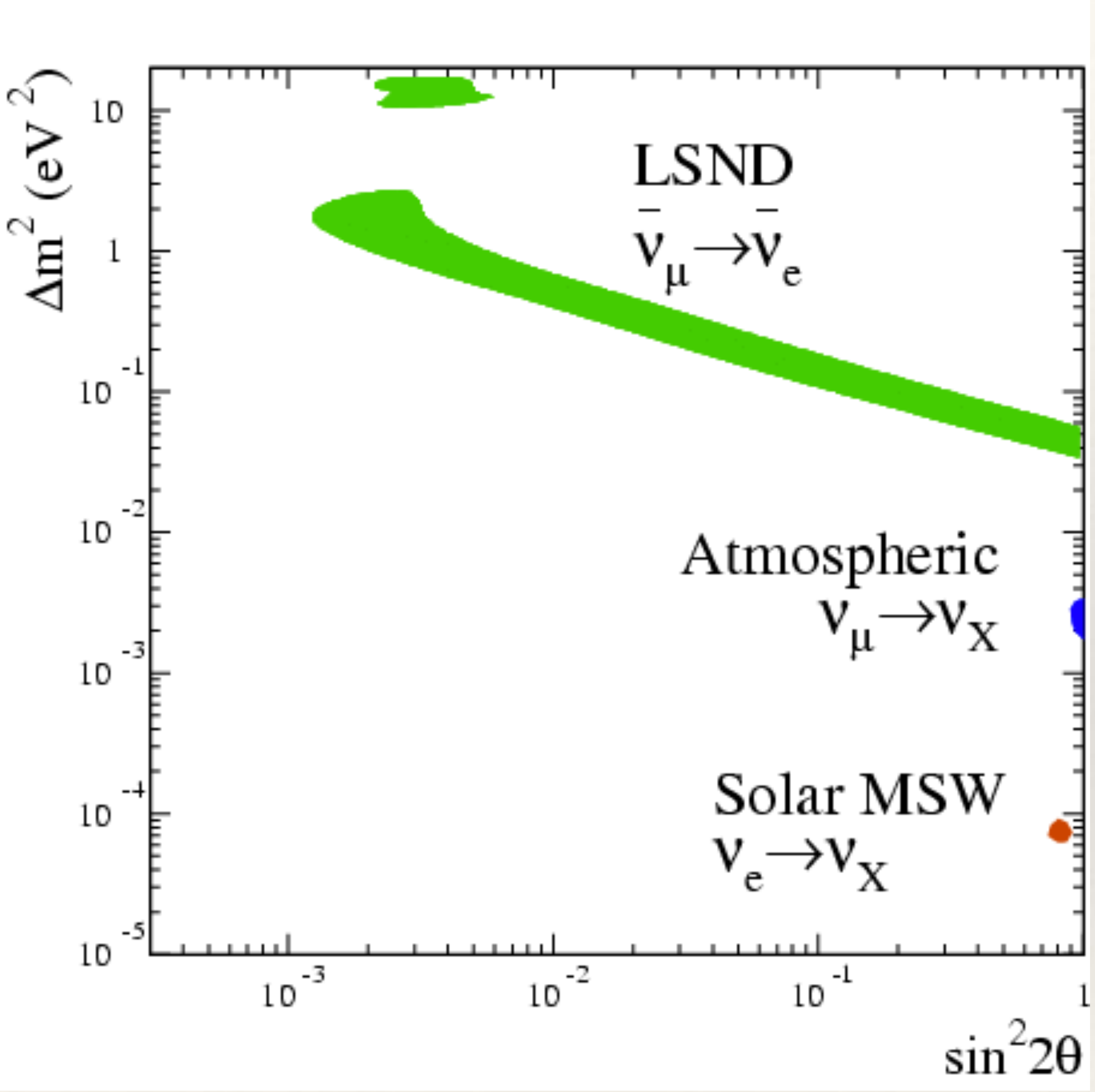


$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2\left[1.27\frac{\Delta m_{41}^2 L}{E_\nu}\left(\frac{\mathrm{eV}^2\cdot\mathrm{m}}{\mathrm{MeV}}\right)\right]$$

Reactor Anomaly

Ga Anomaly

Sterile Neutrino



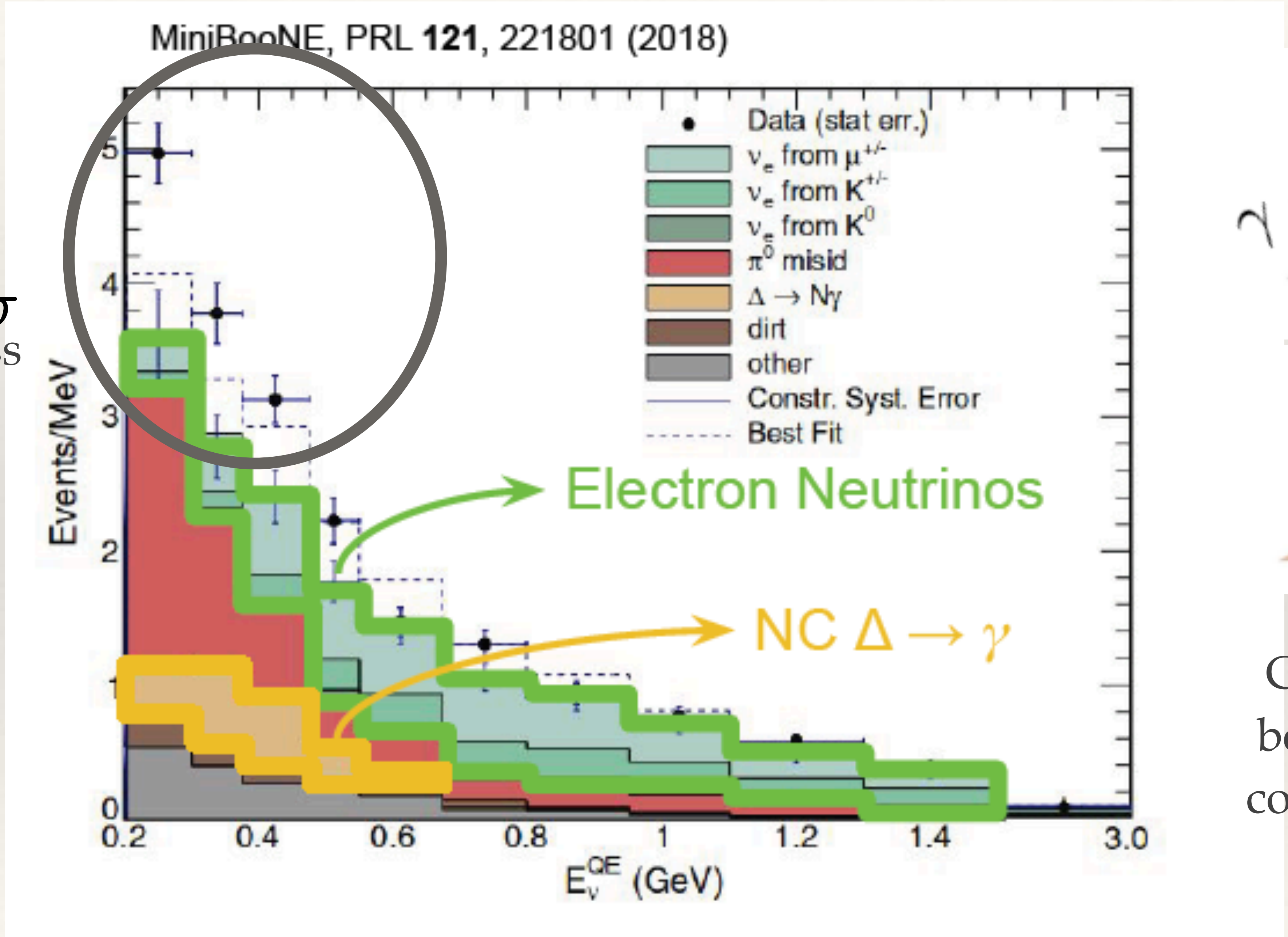
$$\Delta m^2_{solar} = 10^{-5} eV^2$$
$$\Delta m^2_{atm} = 10^{-3} eV^2$$

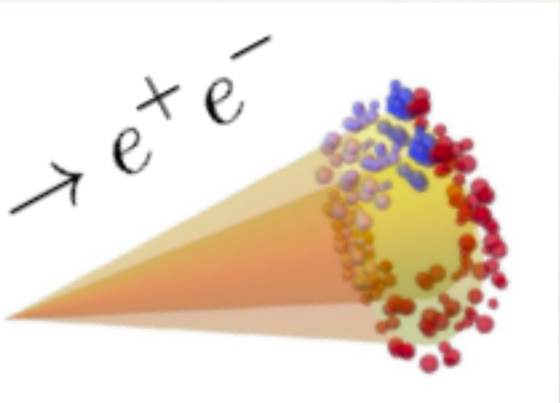
Requires at least one additional neutrino (3+1)

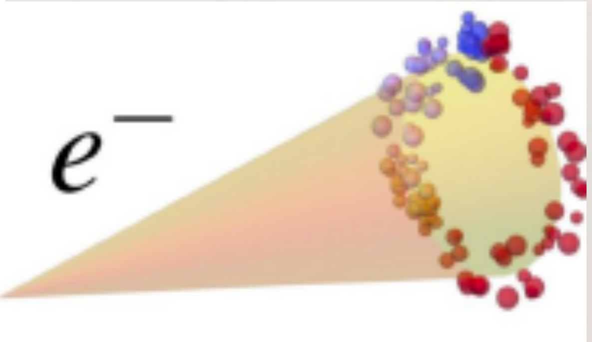
- The constraints from Z decay => the additional neutrino is sterile i.e has no Standard Model interaction
-

Low Energy Excess in MiniBoone

4.5σ
Excess



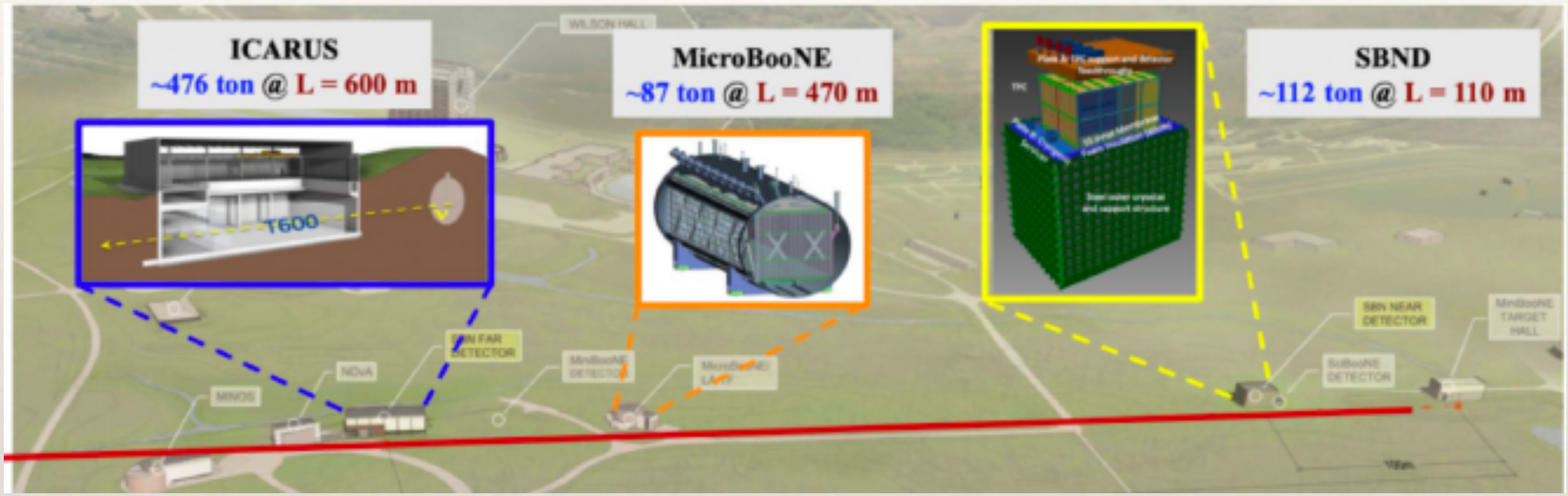


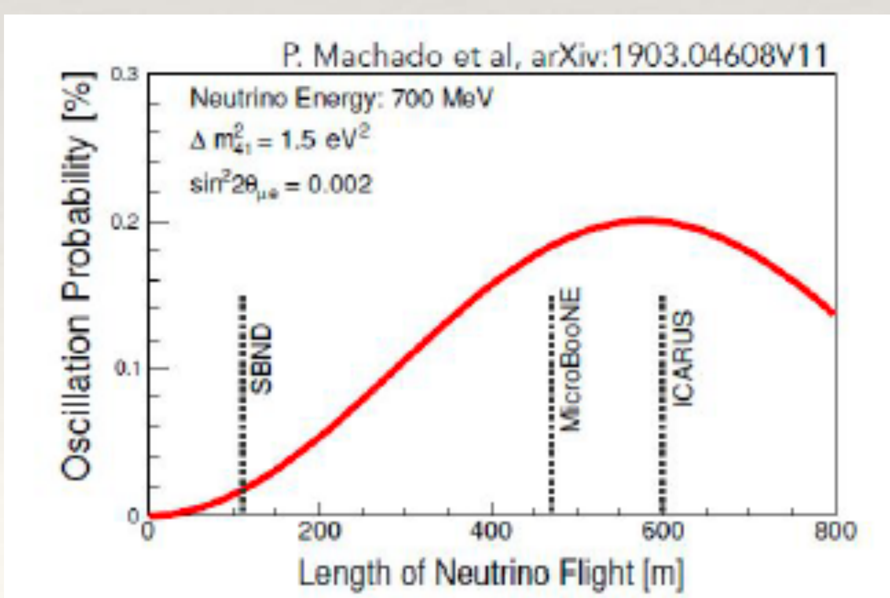


Cannot distinguish between Cherenkov cone of electrons and single photon

SBN@FermiLab

3 Liquid Argon TPCs located along the Booster Neutrino Beamline in FERMILAB





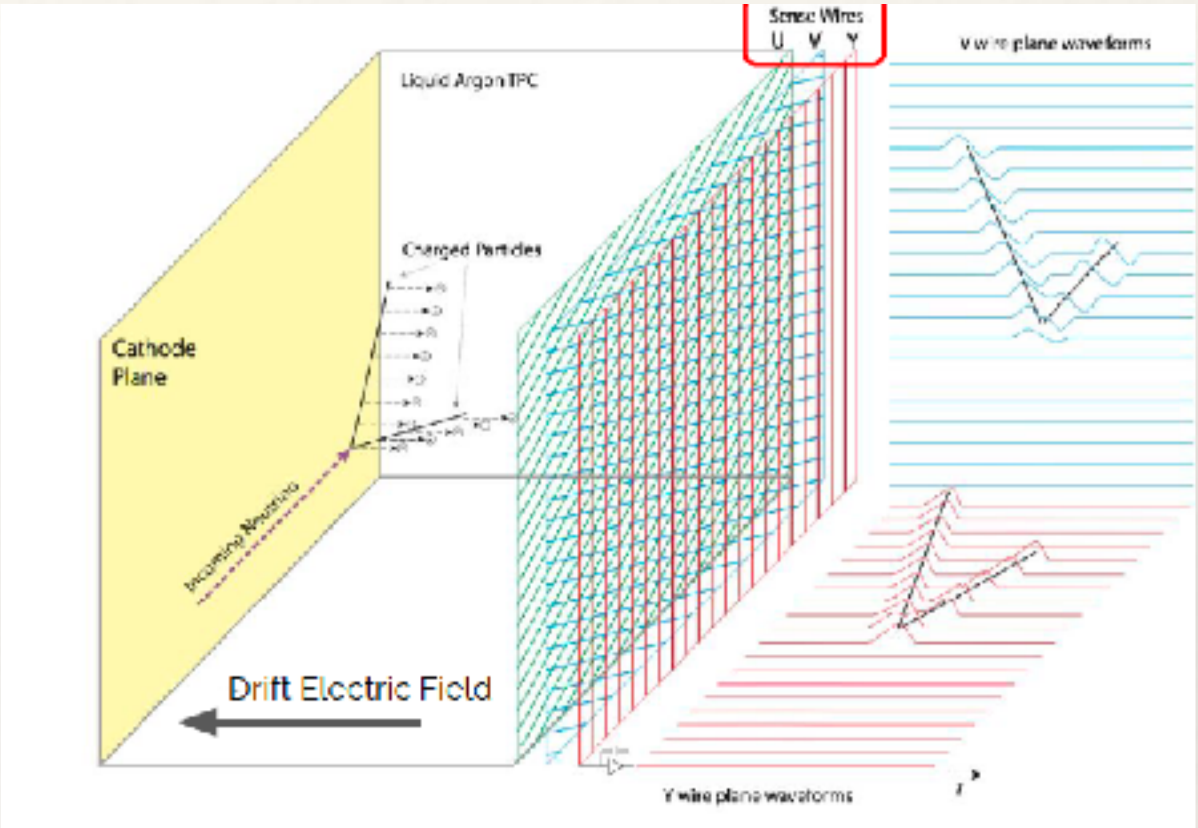
Search for sterile neutrinos
Cross-section measurement
New physics

MicroBoone

- 8 ton surface based LArTPC detector
- Taking data since 2015
- Primary goal is to identify if the MiniBoone LEE is

NC $\Delta \rightarrow \gamma$	Electron Neutrinos
SM background	eV steriles?

Same beam and similar baseline but different detector technology



- Can separate electrons and photons because of excellent resolution of LiqAr detectors

MicroBoone Results

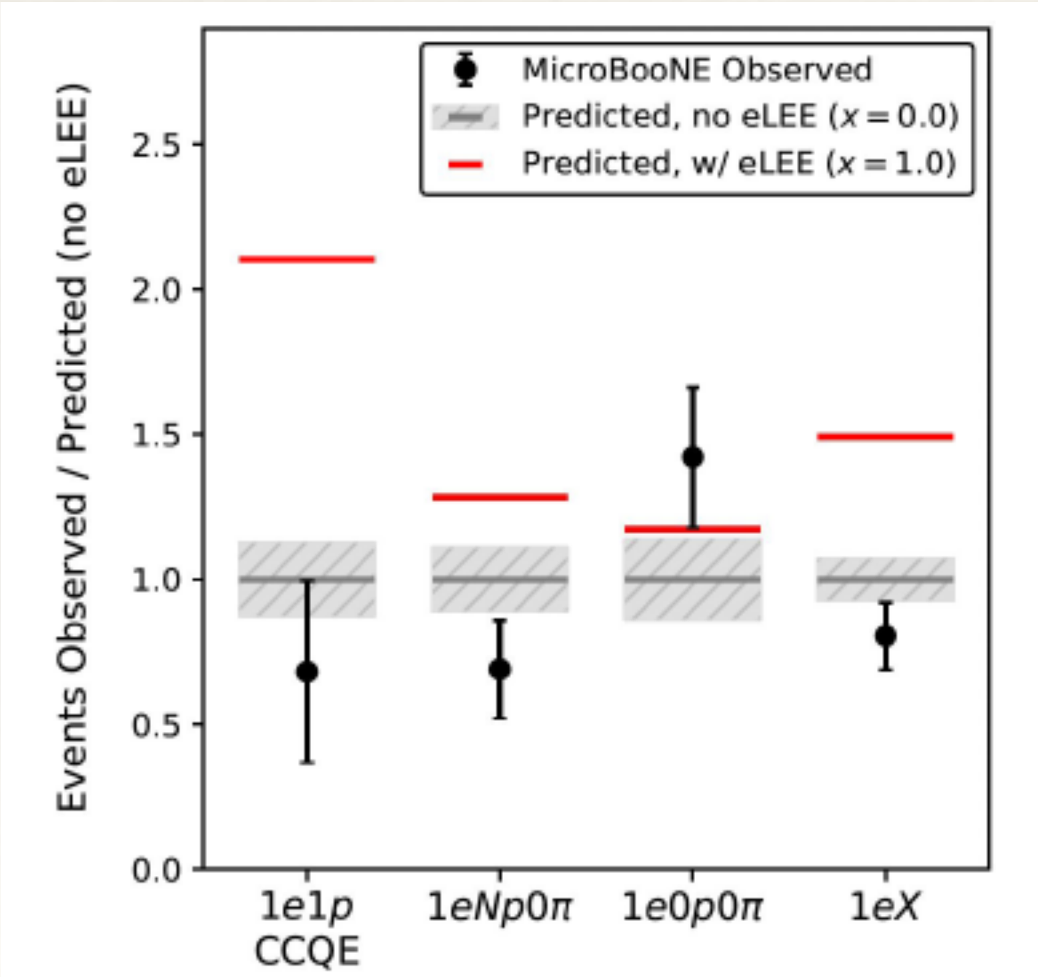
- Disfavour NC $\Delta \rightarrow \gamma$ as origin of LEE 94.8% C.L.
- No electron neutrino excess in data

New physics ?

See however

.https://arxiv.org/pdf/2111.10359.pdf

The electron neutrino excess cannot be excluded in a mode independent way



https://arxiv.org/pdf/2110.14054.pdf

3+1 Fit	$\lvert U_{e4}\rvert^2$	$\lvert U_{\mu 4}\rvert^2$	Δm^2	$\Delta\chi^2$/ dof
MiniBooNE only	0.508	0.0205	0.191	27.8 / 3
Combination	0.502	0.0158	0.209	24.7 / 3

TABLE I. Summary of results. The $\Delta\chi^2$/dof in the last column compares the $3+1$ model to the no-oscillation model.

https://arxiv.org/pdf/2201.01724.pdf

Result from all 3 detectors in SBN

Alternative explanations

Dark Neutrino Portal to Explain MiniBooNE excess
Enrico Bertuzzo (Sao Paulo U.), Sudip Jana (Oklahoma Ctr. High Energy Phys. & Oklahoma State
Published in **Phys.Rev.Lett. 121 (2018) no.24, 241801**

Explaining the MiniBooNE excess by a decaying sterile neutrino with mass in the 250 MeV range
Oliver Fischer, Álvaro Hernández-Cabezudo, Thomas Schwetz (KIT, Karlsruhe, IKP). Sep 20, 2019. 26 pp.
e-Print: arXiv:1909.09561 [hep-ph] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

U(1)' mediated decays of heavy sterile neutrinos in MiniBooNE
Peter Ballett, Silvia Pascoli (Durham U., IPPP), Mark Ross-Lonergan (Nevis Labs, Columbia U.). Aug 8, 2018. 8 pp.
Published in **Phys.Rev. D99 (2019) 071701**
IPPP/18/70

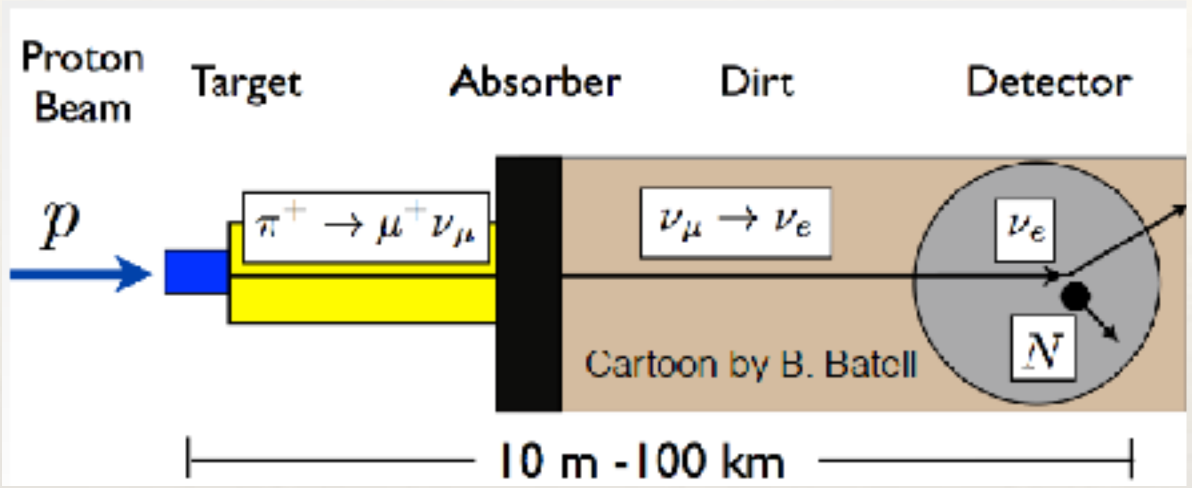
Testing New Physics Explanations of MiniBooNE Anomaly at Neutrino Scattering Experiments
Carlos A. Argüelles (MIT, Cambridge, Dept. Phys.), Matheus Hostert (Durham U., IPPP), Yu-Dai Tsai (Fermilab). Dec 20, 2018. 7 pp.
IPPP/18/113, FERMILAB-PUB-18-686-A-ND-PPD-T
e-Print: arXiv:1812.08768 [hep-ph] | PDF

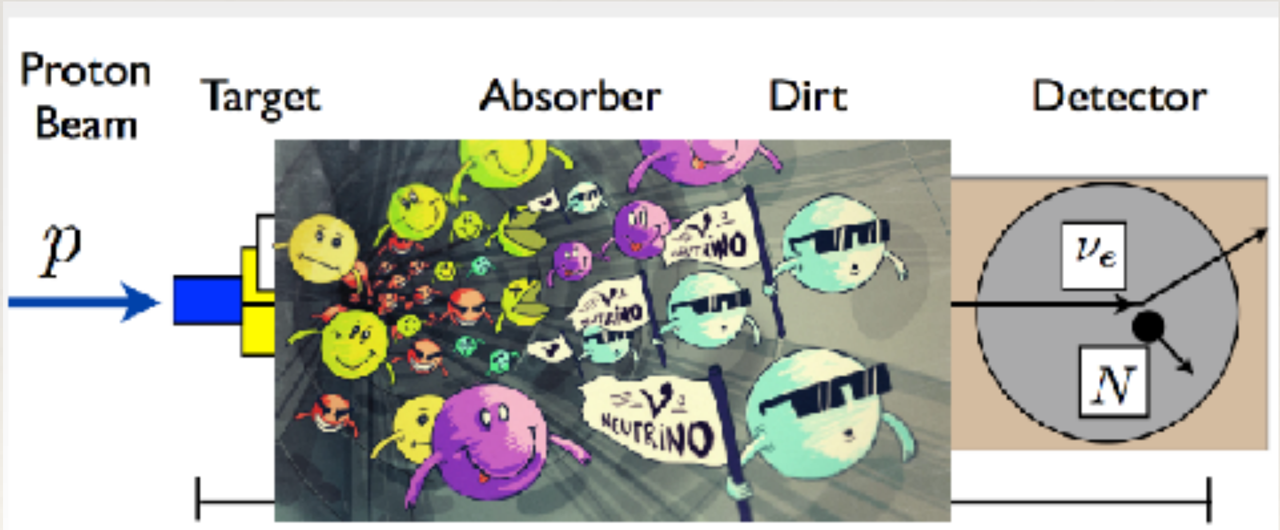
Severe Constraints on New Physics Explanations of the MiniBooNE Excess
Johnathon R. Jordan (Michigan U.), Yonatan Kahn (Princeton U. & Chicago U., KICP & Illinois U., Urbana (main))
2018. 7 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.8, 081801**

Many more, apologies if your paper is not listed

Slide: D. Pramanik, Whepp 2019

BSM physics @ Fixed Target Experiments





- BSM physics can be probed in fixed target experiments
- Dark Matter, Heavy Neutral Leptons, Axion like particles, extra neutral gauge bosons etc.
- NA62,MiniBooNE,NOVA, MINOS, T2K
- DUNE, SHIP, SBN…..

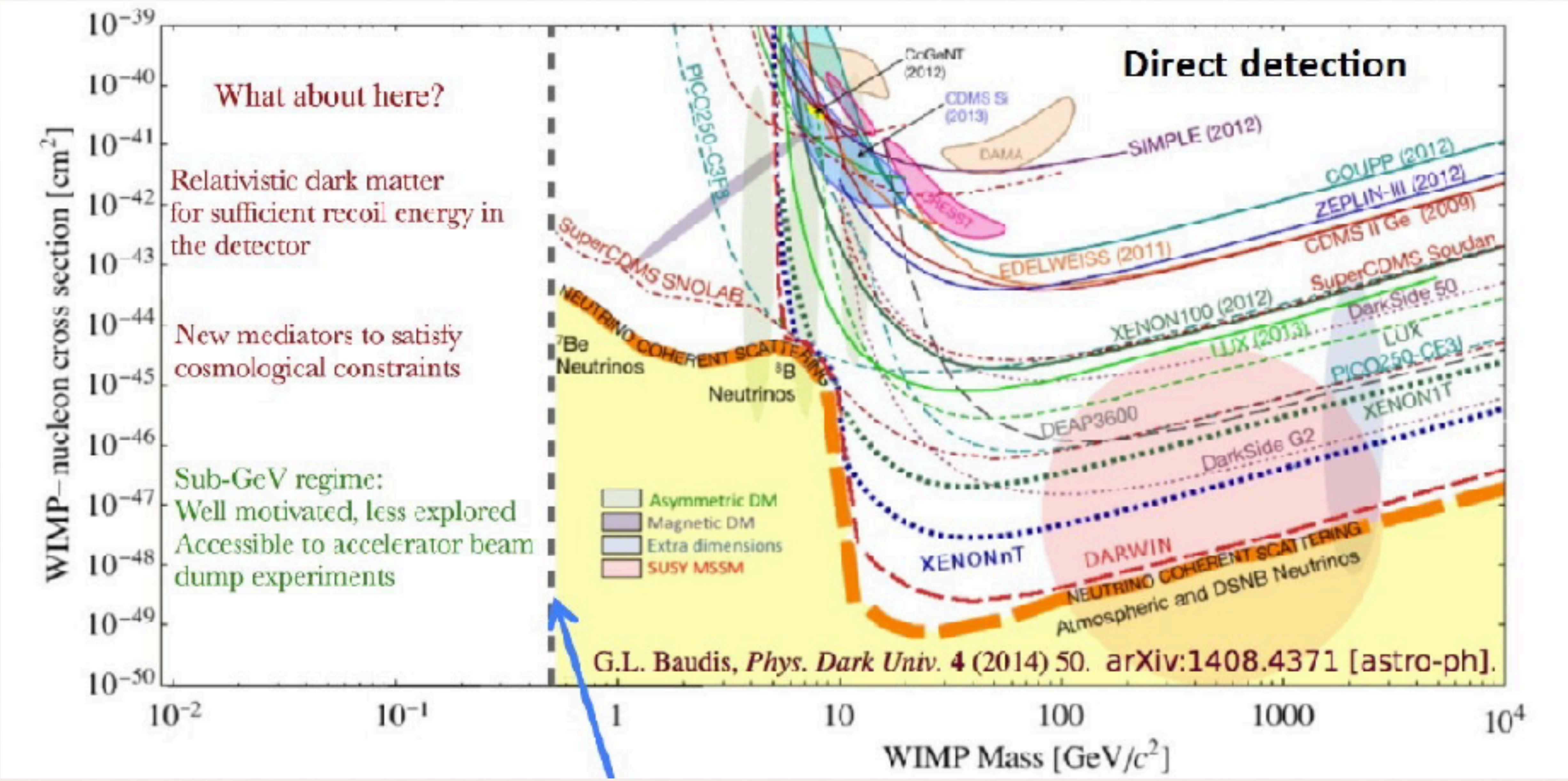
http://dx.doi.org/10.1088/1361-6633/ab9d12

Dark sector from neutrino frontier

- Indirect detection of dark matter from natural sources in neutrino detectors
- Direct search for boosted dark matter from natural sources in neutrino detectors. **Agashe, Cui, Necib, Thaler** https://arxiv.org/pdf/1405.7370.pdf
- Direct search for beam sub-GeV dark matter in neutrino experiments

Battel, Pospelov, Ritz, arXiv: 0906.5614

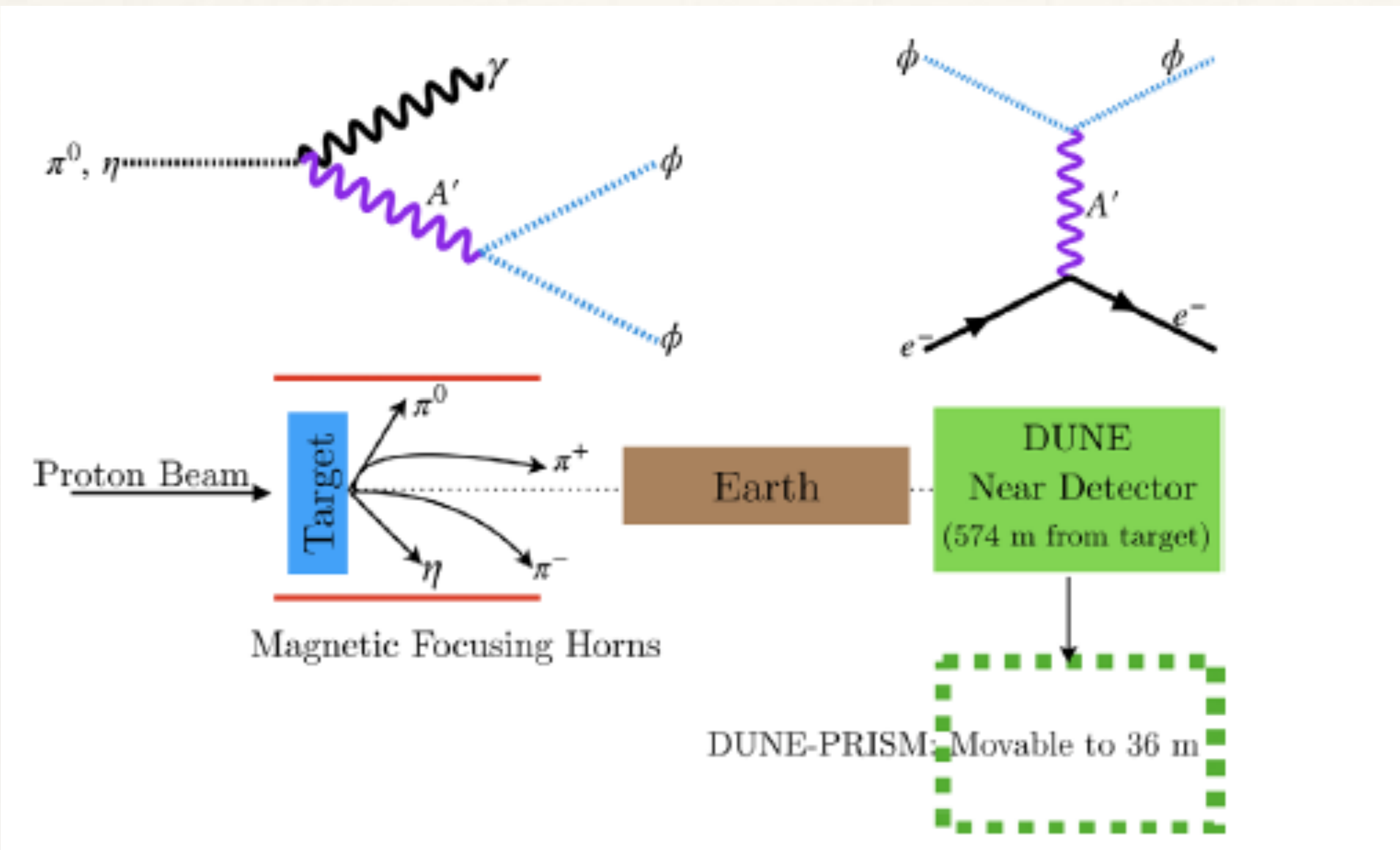
Motivation



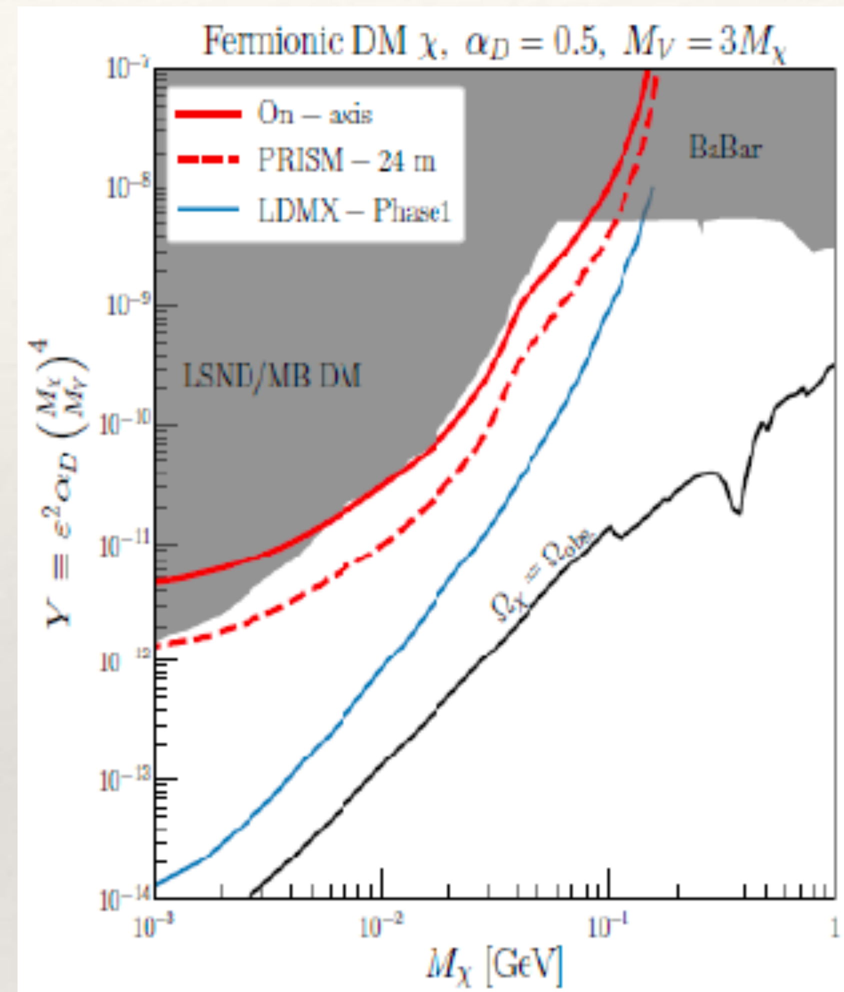
Direct Detection Threshold

Slide Courtsey : A. Chatterjee

Dark Matter in Neutrino Detectors



Romeri, Kelly, Machado, Phys. Rev. D 2019

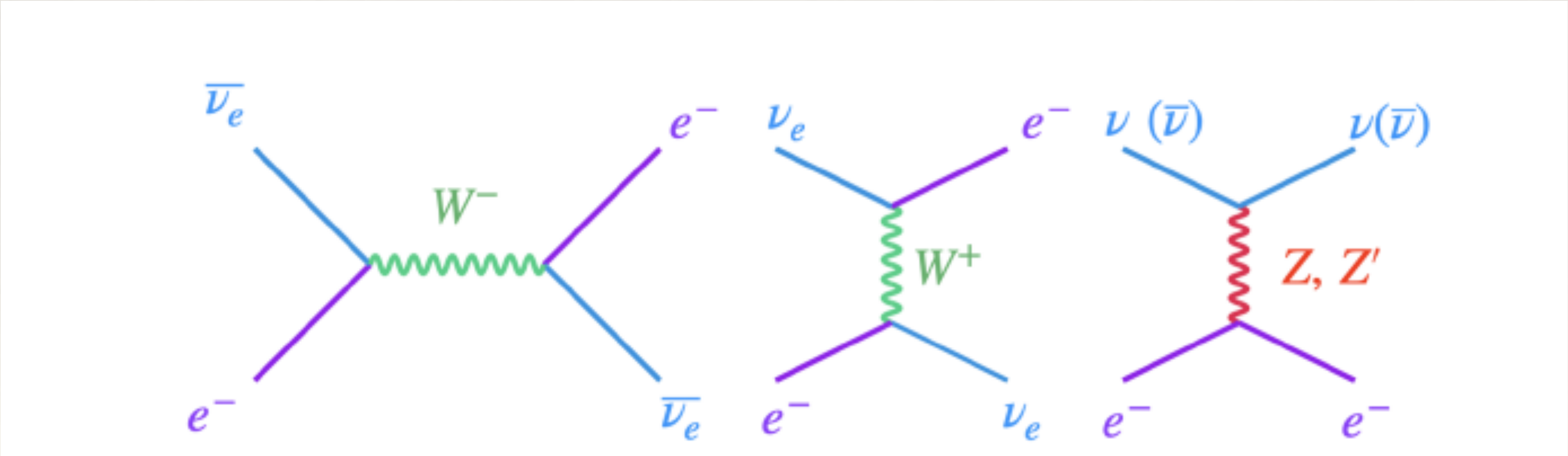


Eur. Phys. J. C (2021) 81 :322

Main background from neutrino interactions — off axis, target less DUNE

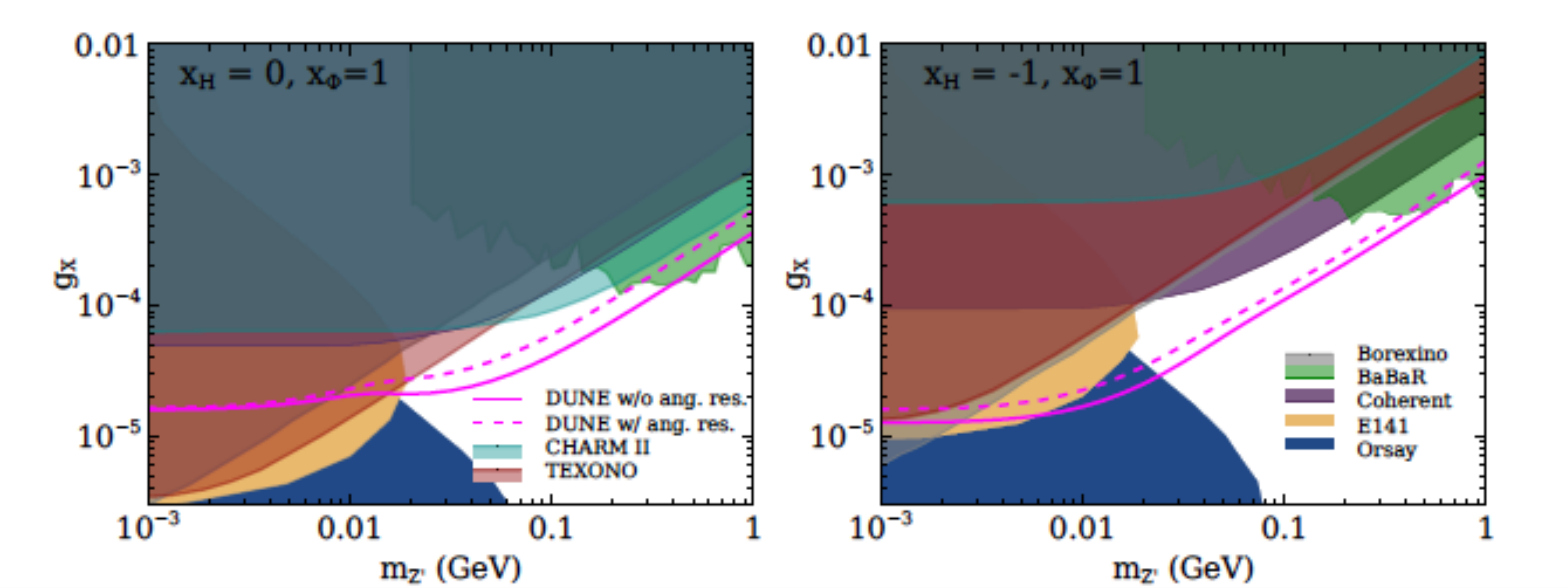
General U(1) model at DUNE

- Consider Standard Model, augmented by extra U(1)
- Contains extra Z'
- We consider neutrino-electron scattering at DUNE ND



Ballet et al. PRD, 2019, Dev et al. PRD 2021, Bishcer and Rodejohann, PRD 2019, ……

Results



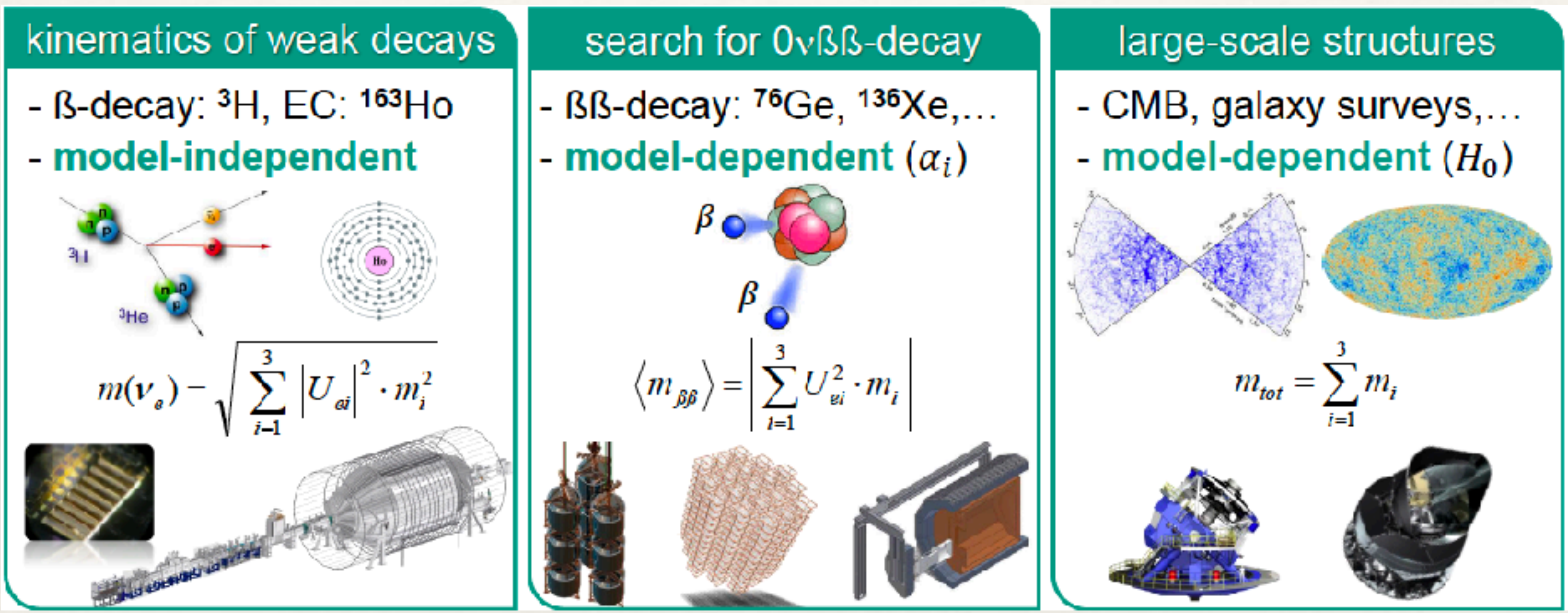
Constraints (90% C.L.) on mass and coupling plane of Z'

1.2 MW beam, 75 ton mass, 3.5 +3.5 years exposure in neutrino +antineutrino

Chakraborty, Das, Goswami, Roy, JHEP 2022

Absolute neutrino mass

Information can come from three different sectors

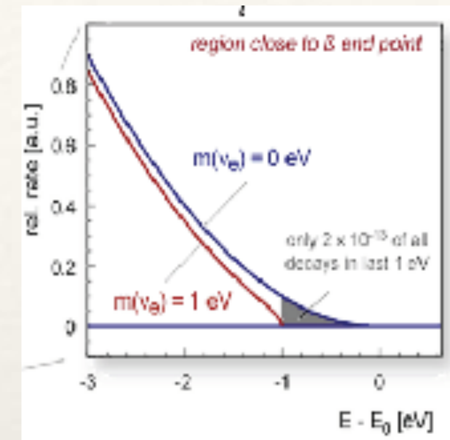


Slide : G. Drexlin, NOW 2022

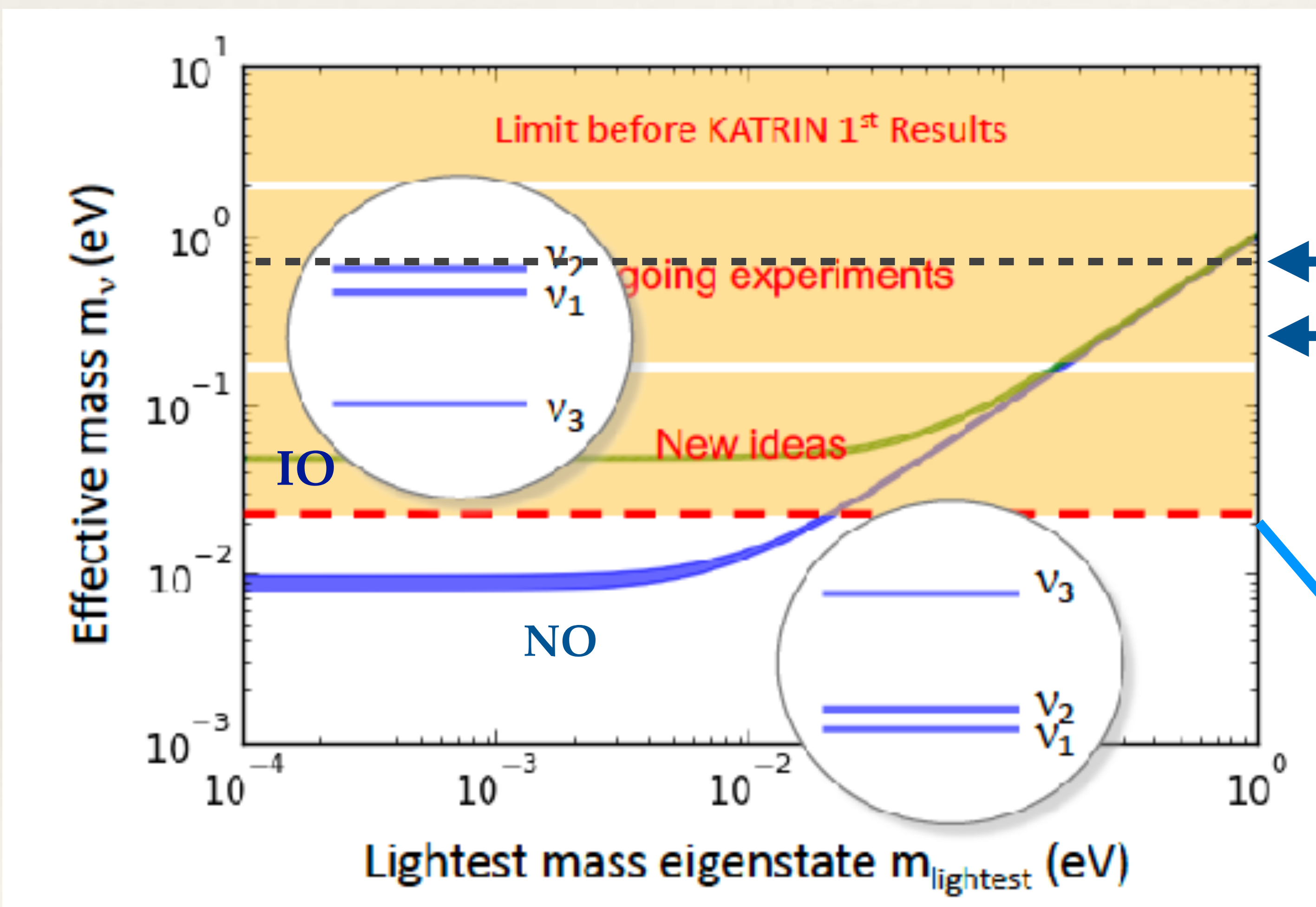
Katrin: present and future limits

$$H^3_1 \xrightarrow{12.3\ \text{years}} He^3_2 + e^0_{-1} + \bar{\nu}^0_0$$

Measures the end point spectrum



https://doi.org/10.1038/s41567-021-01463-1



Present Limit < 0.8 eV, 90% C.L.

Projected reach < 0.2 eV, 90% C.L.

Can differentiate between degenerate and hierarchical spectrum

Can distinguish between NO and IO

Fig: S. Mertnes, 2022

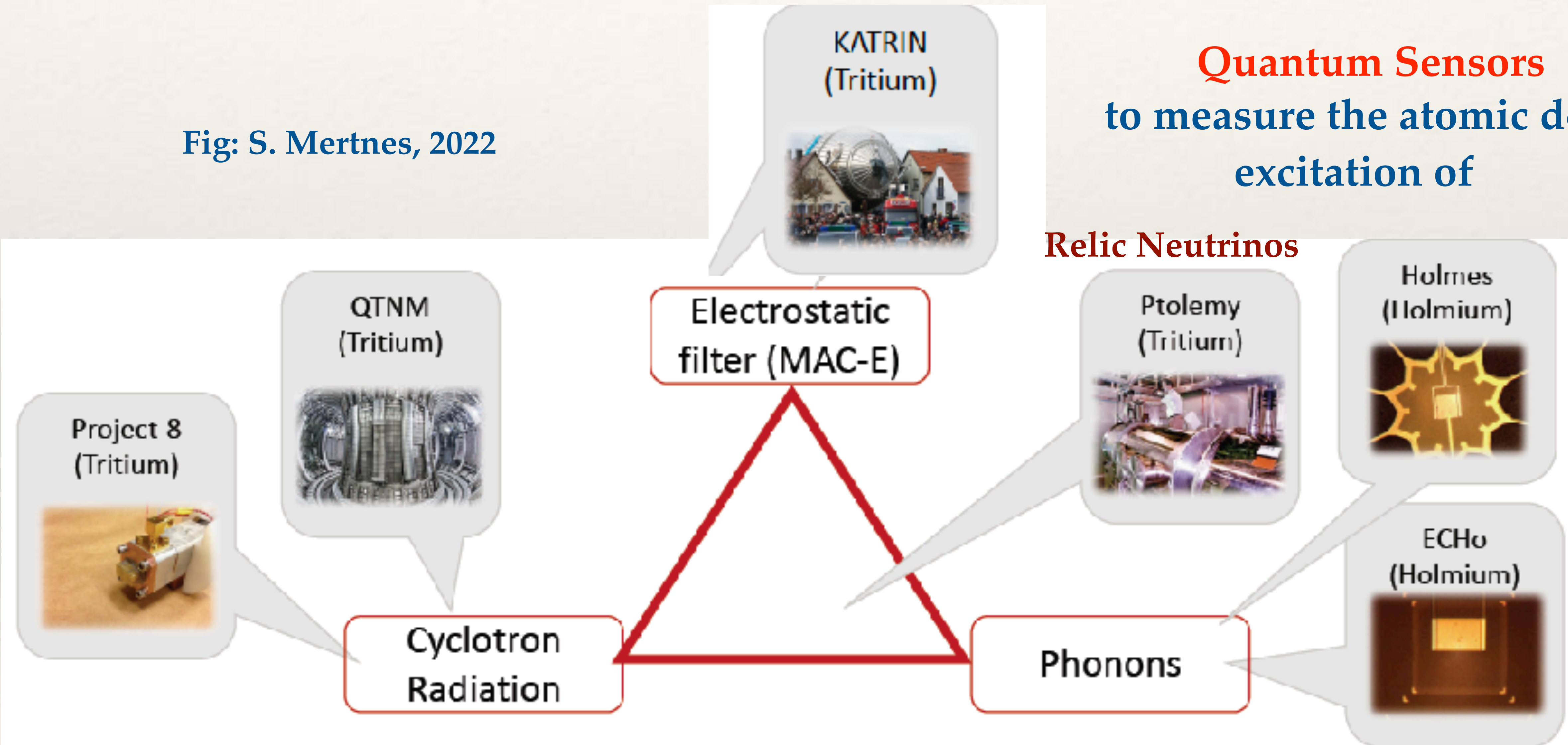
Beyond Katrin

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

Quantum Sensors to measure the atomic de-excitation of

Fig: S. Mertnes, 2022

Relic Neutrinos



Expect to reach neutrino mass sensitivity around 1 eV and less

Katrin : other physics goals

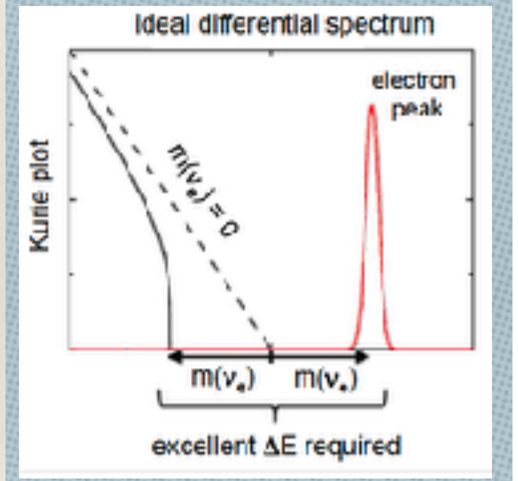
Search for relic neutrinos

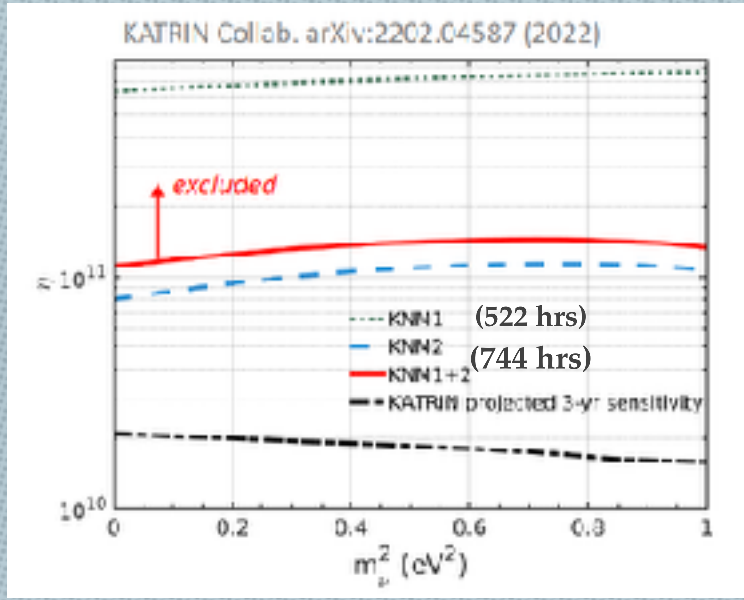
$$\nu_e + {}^3H \rightarrow {}^3He^+ + e^-$$

10 neutrino capture/yr in 100 gm tritium

Electron peak above end point

Phys. Rev. Lett. 129, 011806 (2022)

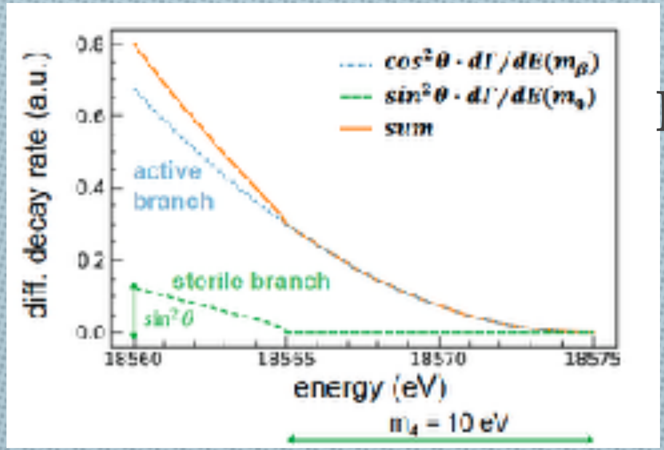




No signal observed

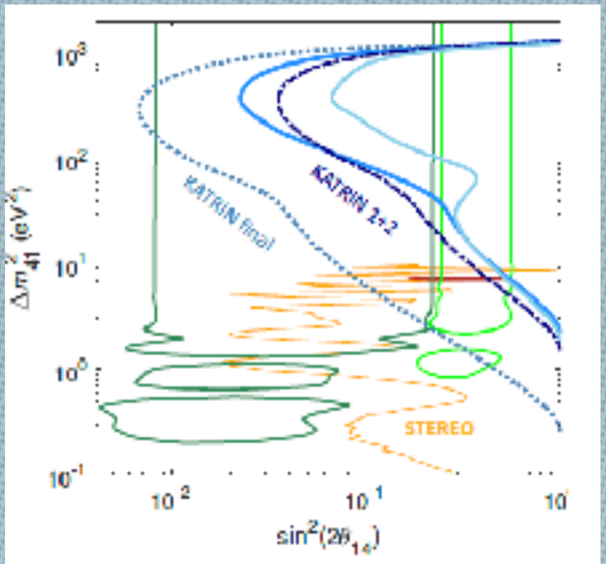
$\eta < 1.1 \cdot 10^{11}/\alpha$ at 95% CL

Search for sterile neutrinos



Kink in the energy spectrum of electrons

Complementary probe to oscillation experiments



Also Lorentz Invariance Violation

https://arxiv.org/abs/2207.06326

Future: search for KeV sterile neutrinos

Silicon Drift Detector : TRISTAN

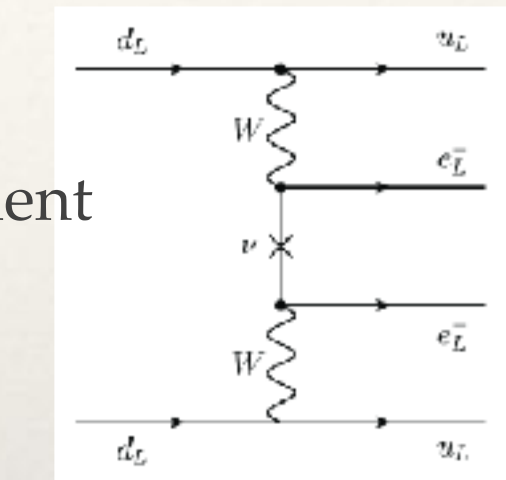
Neutrinoless double beta decay

$$(A,Z) \to (A,Z+2) + 2e^- \quad (0\nu\beta\beta)$$

$$\frac{1}{T_{1/2}^{0\nu}} = G|\mathcal{M}_\nu|^2 \left|\frac{m_{ee}^\nu}{m_e}\right|^2 ,$$

$$m_{\beta\beta} = |m_1\, c_{12}^2 c_{13}^2 + m_2\, s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3\, s_{13}^2 e^{2i\alpha_3}|$$

- Mediated by light neutrinos



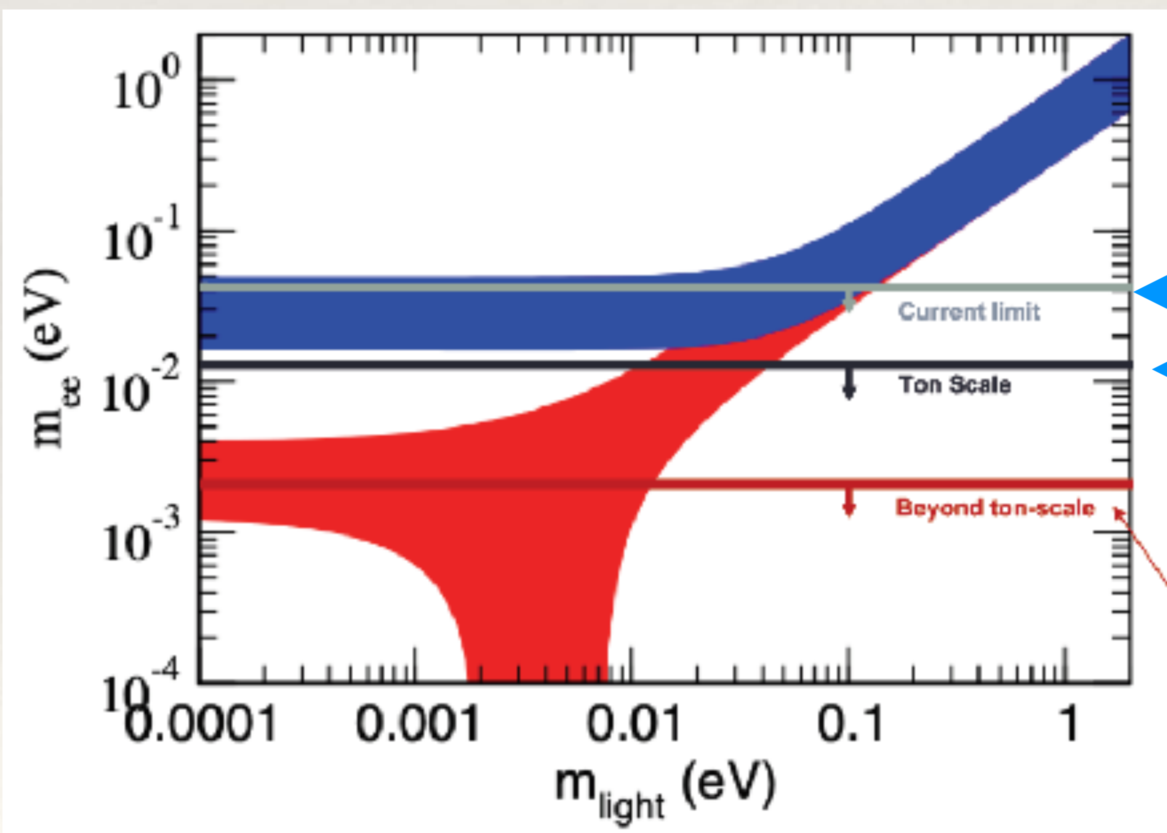
G ⟶ phase space factor

M_ν ⟶ nuclear matrix element

Major uncertainty

Extra diagrams in BSM

Like sign di-lepton in colliders



KamLAND-ZEN + EXO 200+ GERDA + CUORE

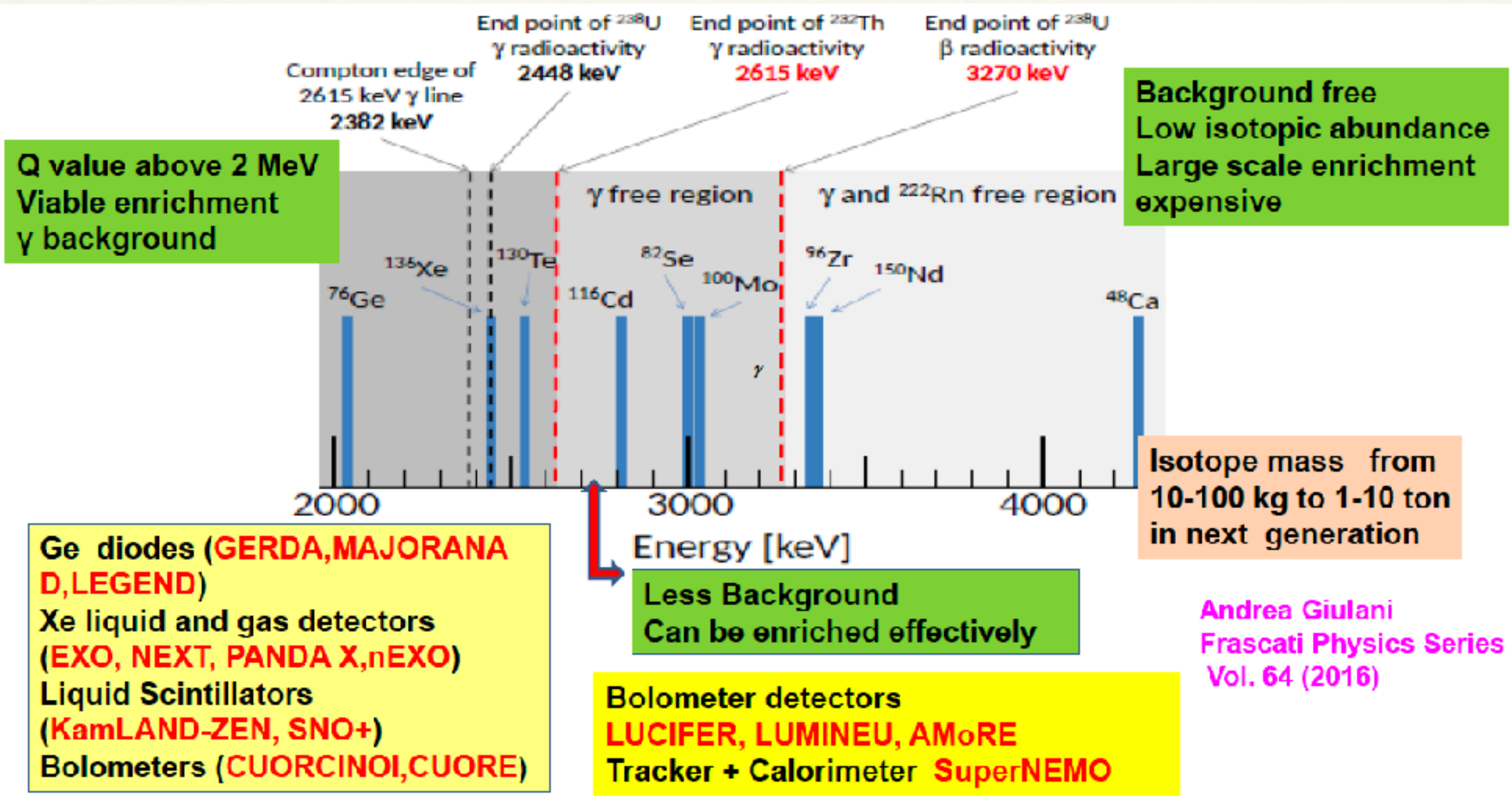
IH can be confirmed (nEXO,LEGEND)

Can it be reached ?

Enrichment R&D and major facilities needed to produce isotopes at the scale needed

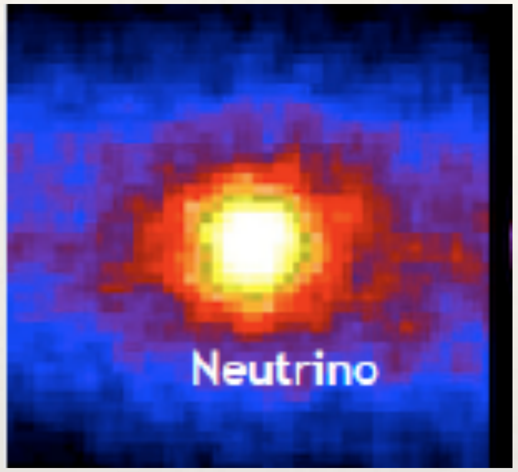
Te, Mo,Ge,Xe…

Neutrinoless double beta decay experiments

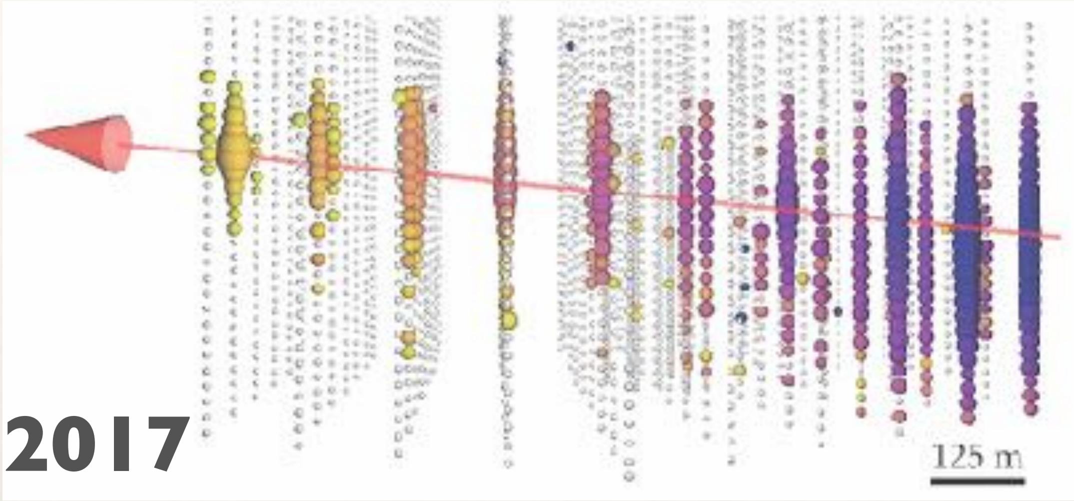


Neutrinos from Astrophysical Sources

Sun



SN1987a

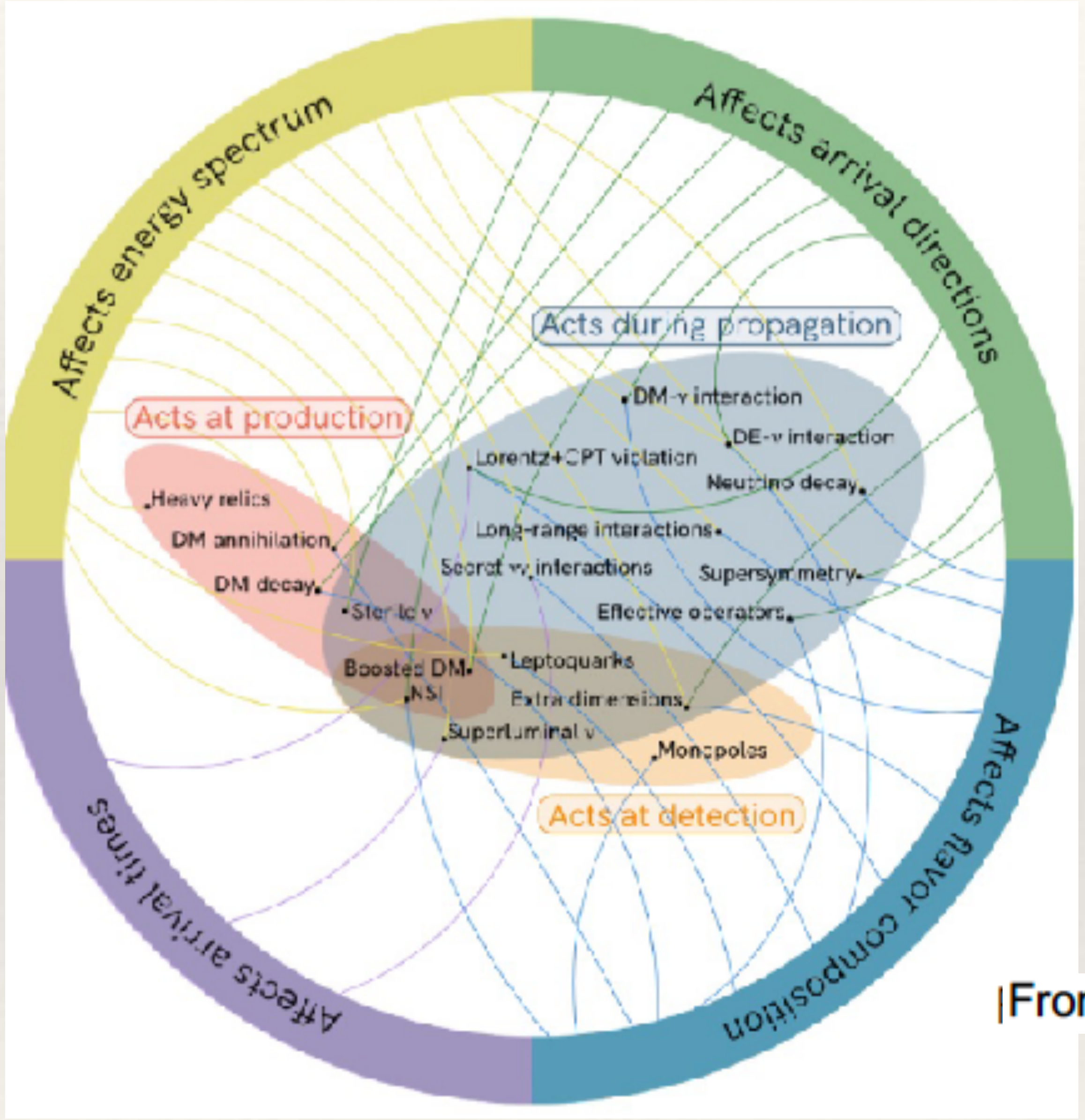


Correlation between a high-energy neutrino (IC170922) and a flaring blazar (TXS 0506+056)

Tidal Disruption 2019
AT2019dsg

Acive Galaxy
NGC 1068/Messier
2022

Physics using high energy neutrinos



From arXiv:2203.08096v2

Neutrino interactions at high energies

Probing flavour conversion @high energy

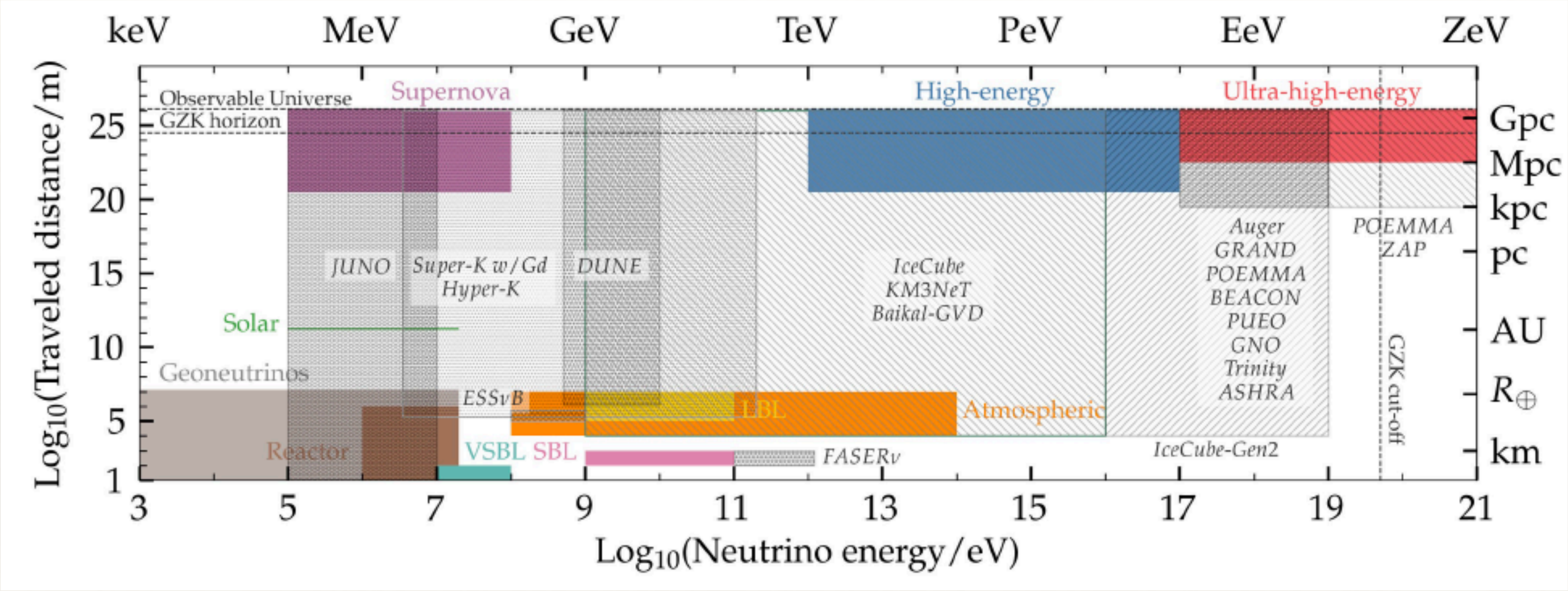
Test of neutrino properties

Probing BSM in neutrino detectors

Studying distant astrophysical sources

Current and planned detectors

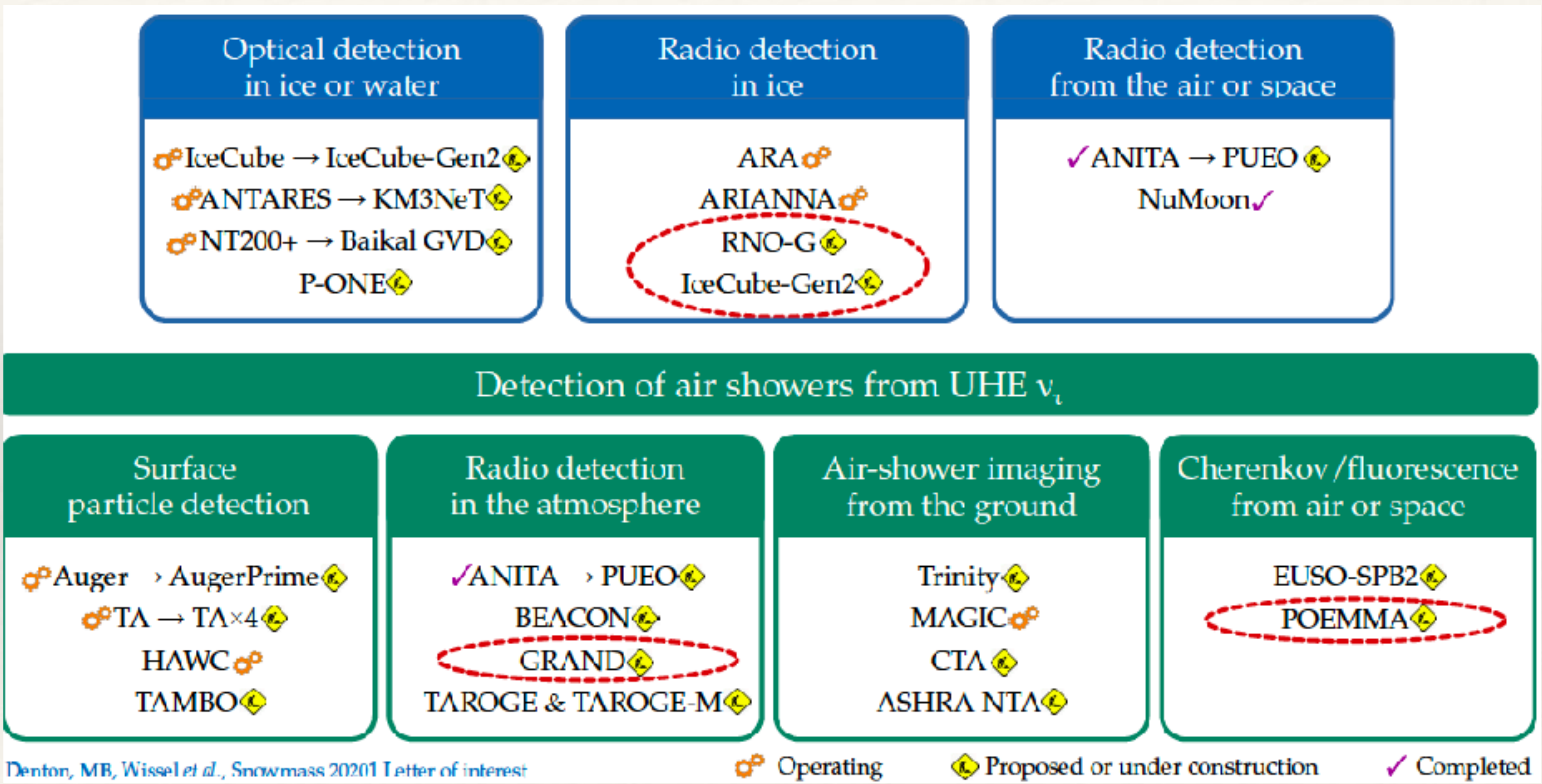
}



From arXiv:2203.08096v2

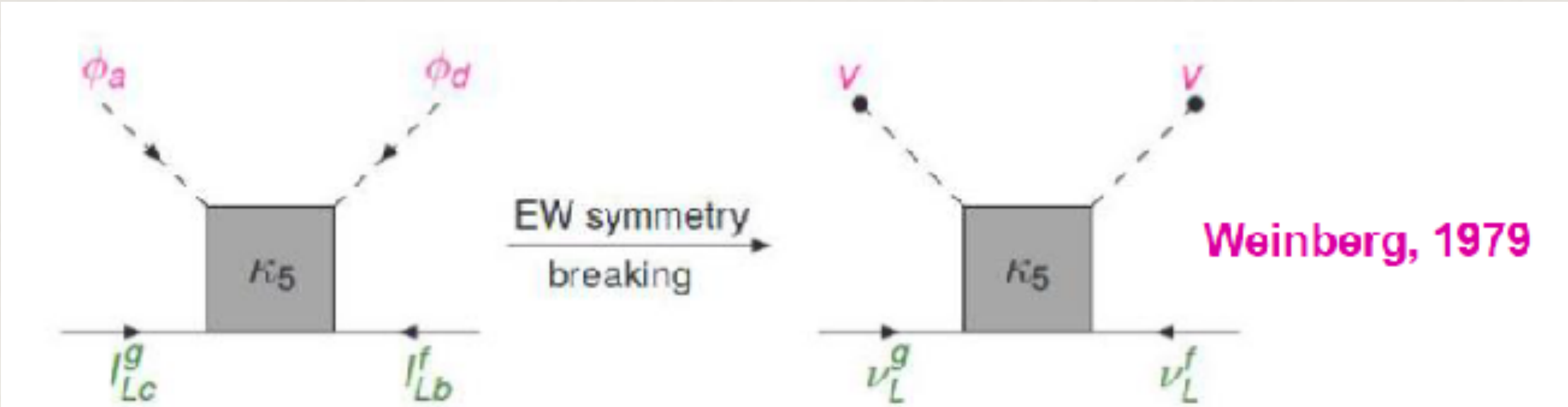
Enhanced statistics, different detection technology

A snapshot of the different detectors



Why neutrinos masses are small ?

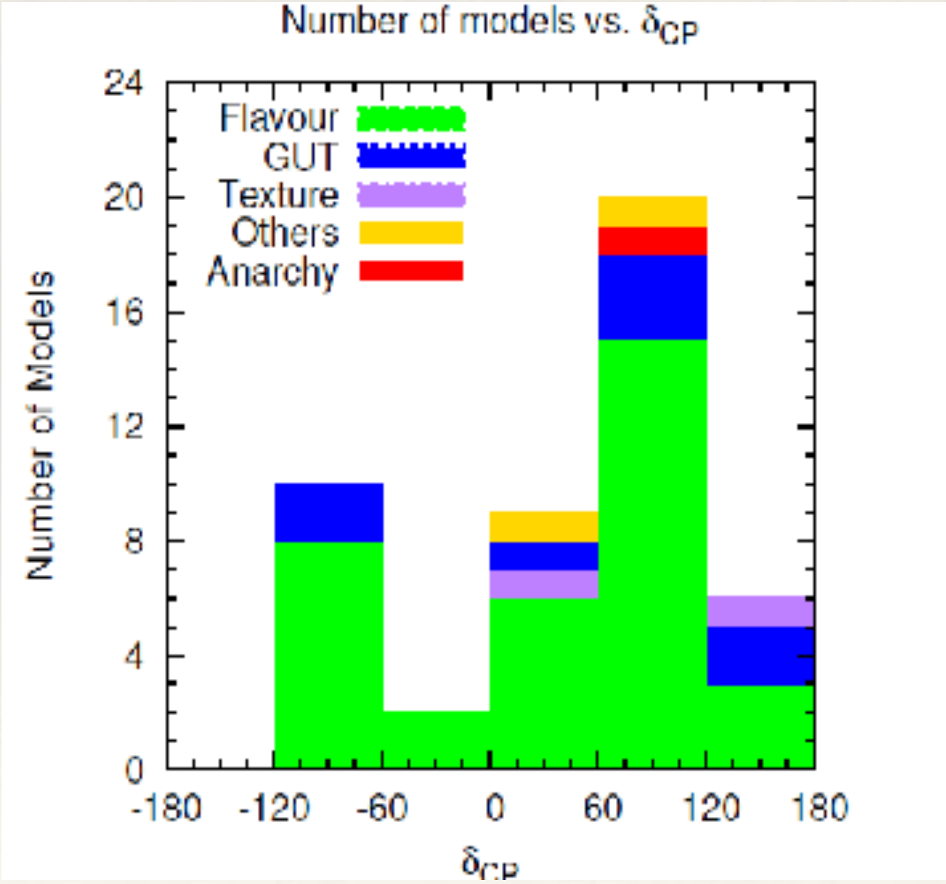
- A natural way to explain small neutrino masses is via seesaw mechanism
- Relates smallness of neutrino masses with new physics at a high scale
- Tree level exchange of some heavy particle gives rise than effective dimension 5 operator at the low scale
- $\mathcal{L} = \kappa_5 l_L l_L \phi\phi, \quad \kappa_5 = y_\kappa/\Lambda$ $\qquad m_\nu \sim \kappa_5 v^2/\Lambda$



- Violation of lepton number → Majorana nature of neutrinos
- Radiative mass generation, Models with higher dimensional operators

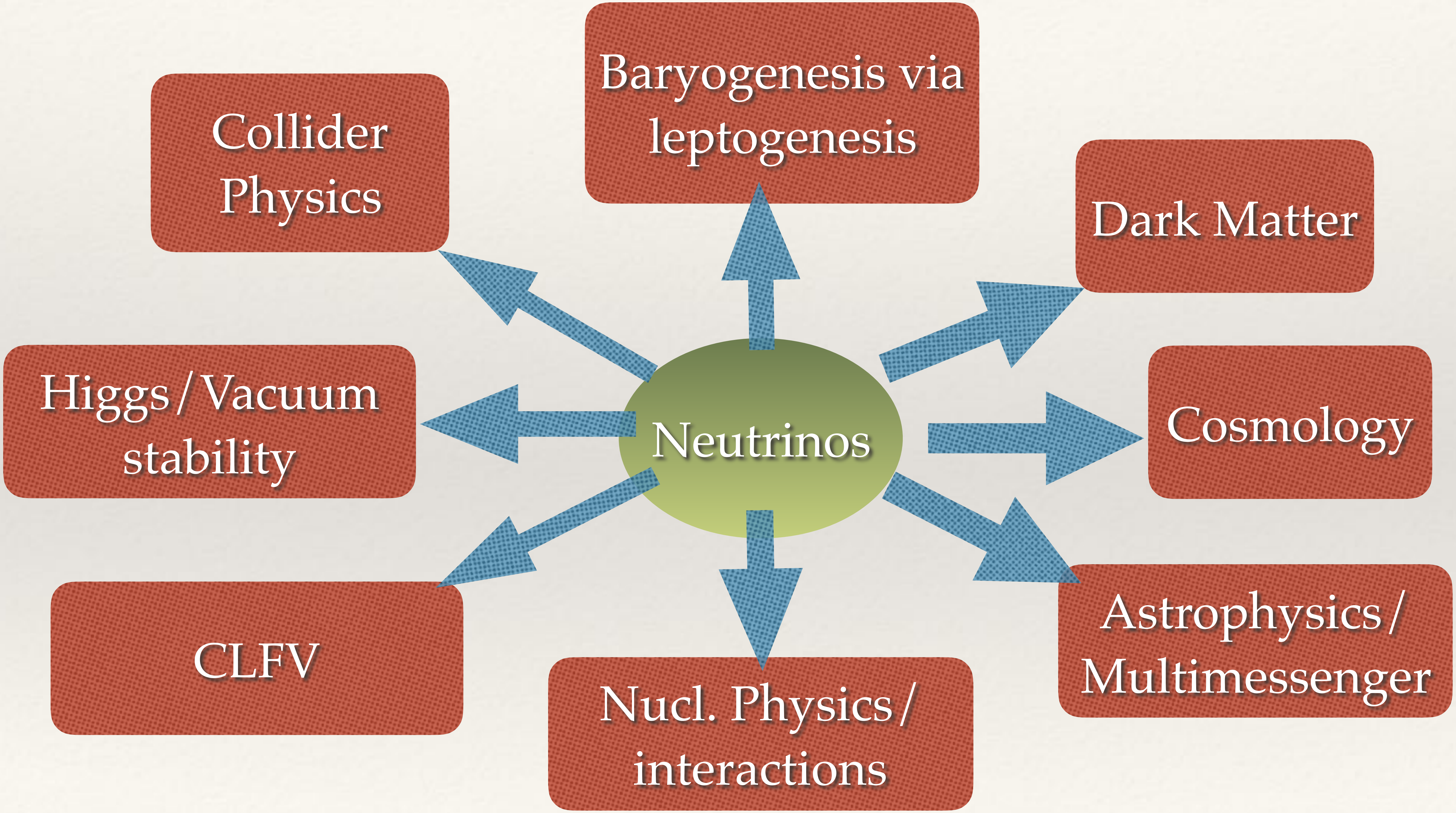
What explains the mixing pattern ?

- Why two large and one small mixing unlike quark sector where all mixing angles are small ?
- Flavour symmetry — discrete non-abelian symmetries



Goswami, Nucl. Part. Phys. Proc. 273-275, 100(2016)

Neutrino Connections



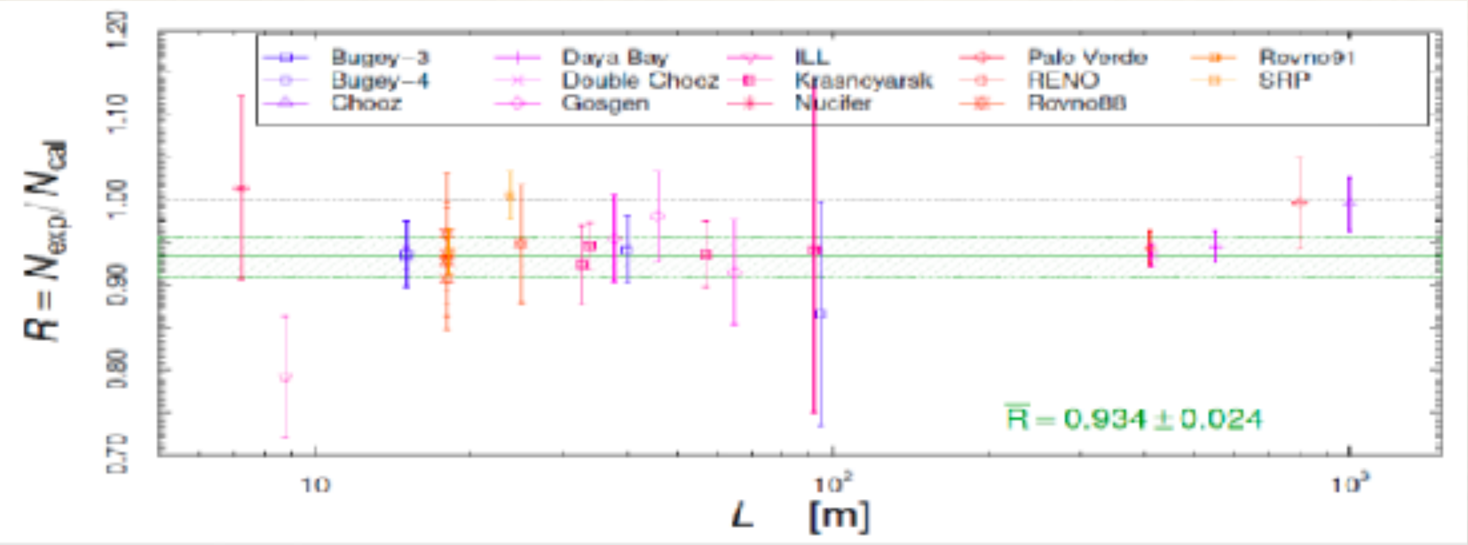
Concluding Remarks

- Remarkable progress in past decade in unravelling oscillation parameters, three flavour paradigm well established
- A rich and diverse future programme — several experiments, new detection techniques, development of analysis tools connection with nuclear physics, astrophysics, cosmology, BSM physics at neutrino detectors (both oscillation and non-oscillation) — an emerging field
- Measurement of neutrino mass — many proposed detectors with modern detection technology
- **Future goals for supernova neutrinos, neutrino cosmology, geo-neutrinos solar neutrinos (not included in this talk)**
- HE and UHE neutrinos and multi messenger astronomy holds lots of promises, surprises (?)
- Origin of neutrino masses and mixing — still under mist.

Acknowledgement : Talks by various colleagues, Snowmass reports and talks, NDM talks, NOW 2022 talks
Discussion with Dr. Animesh Chatterjee

Additional evidences

Reactor Anomaly

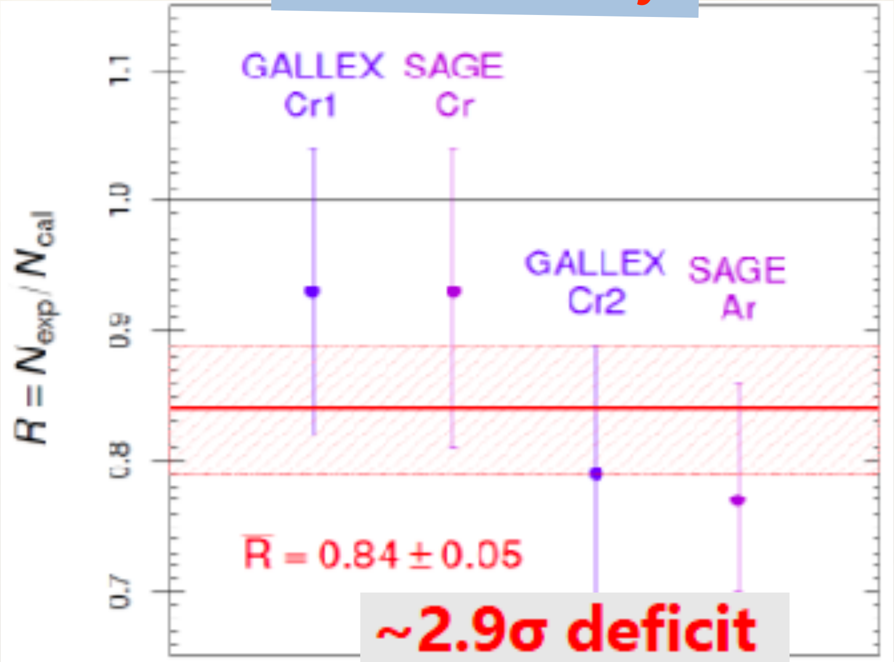


Δm^2_{41} = 2.4 eV^2 $\sin^2(2\theta_{14})$ = 0.14

$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2 \left[1.27 \frac{\Delta m^2_{41} L}{E_\nu} \left(\frac{\text{eV}^2 \cdot \text{m}}{\text{MeV}} \right) \right]$$

Mueller et al PRC 2011
Huber PRC 2011
Mention et al PRD 2011

Ga Anomaly



$$e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$$

~0.8 MeV

Lavedar et al 2017
SAGE PRC 2007

GALLEX PRC 2007