

Neutrino physics : future goals

HORIZONS IN ACCELERATORS,
PARTICLE/NUCLEAR PHYSICS AND
LABORATORY-BASED QUANTUM
SENSORS FOR HEP/NP



Srubabati Goswami
15 November , 2022

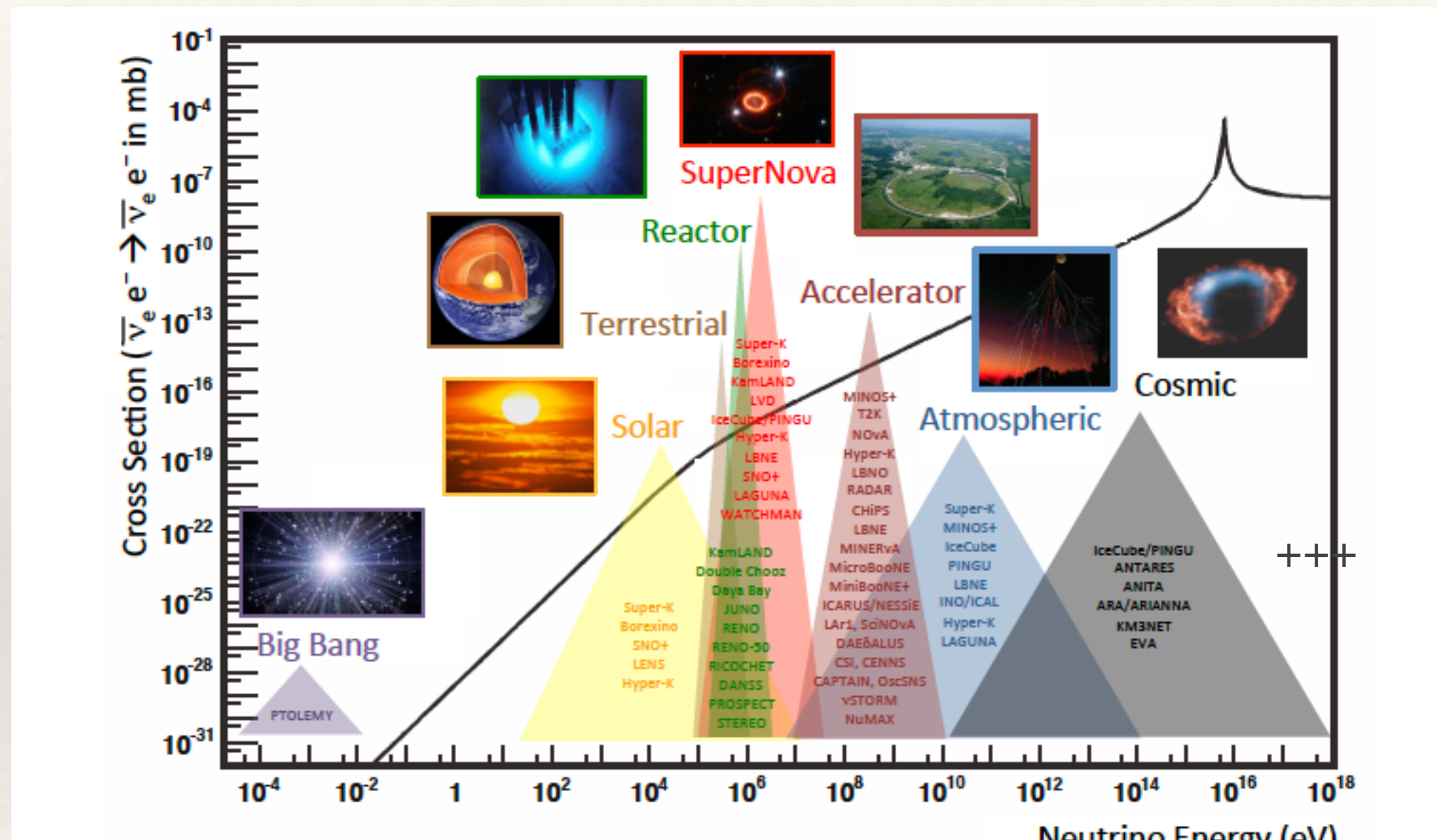
Neutrino Physics : What we know

- ❖ 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
- ❖ Does neutrinos have non-standard interaction, decay? Is there violation of fundamental symmetries like CPT, Lorentz invariance

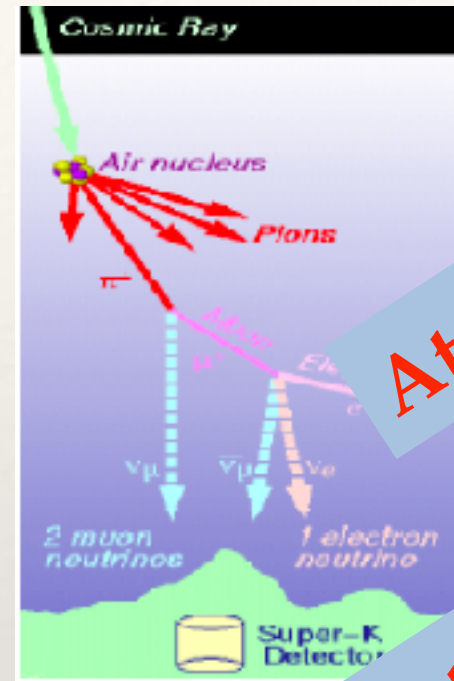
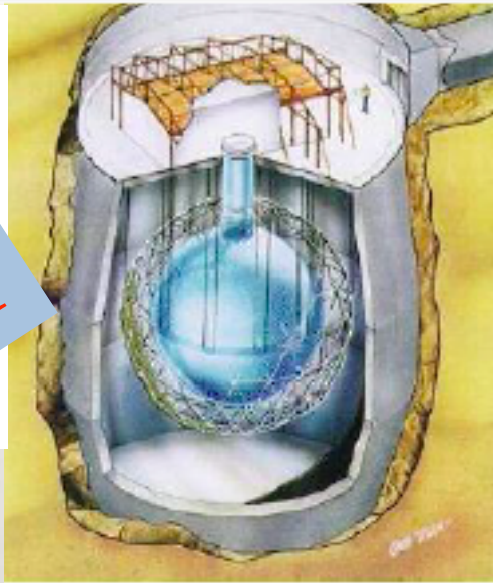
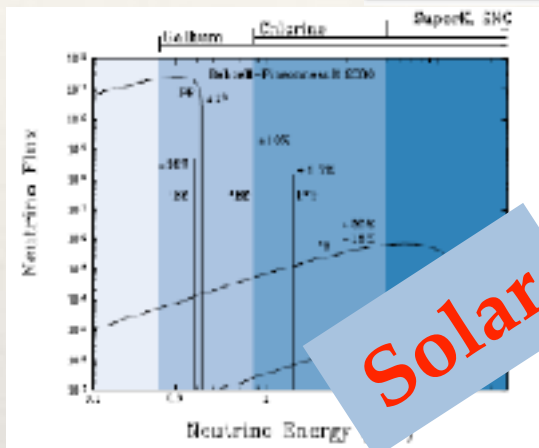
Neutrino Sources and experiments



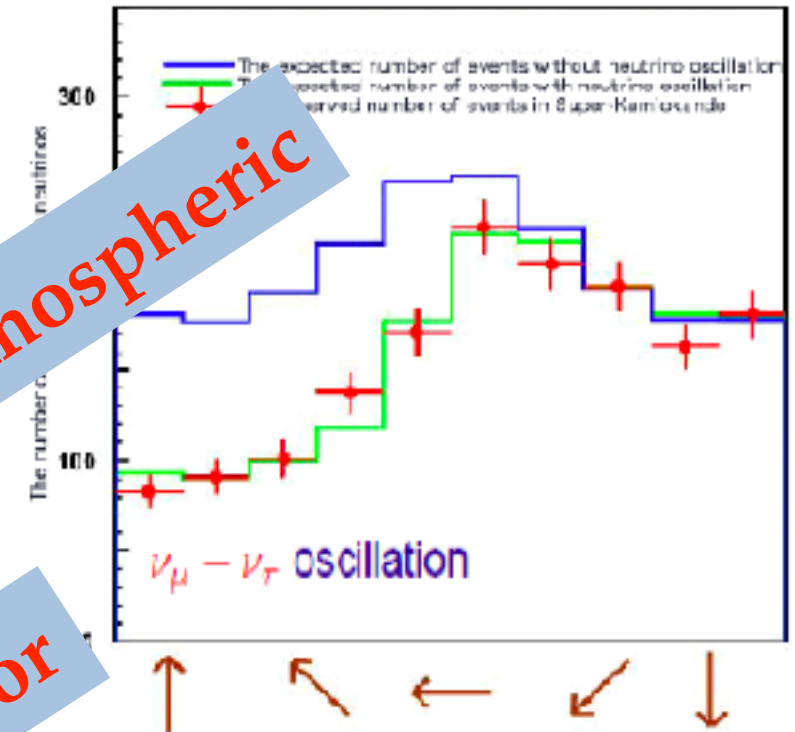
<https://www.slac.stanford.edu/econf/C1307292/docs/IntensityFrontier/Neutrinos-12.pdf>

Neutrino Oscillation: Evidences

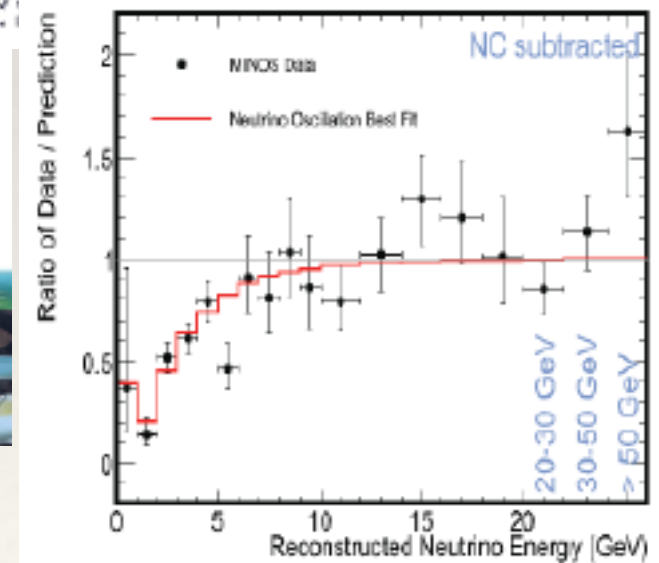
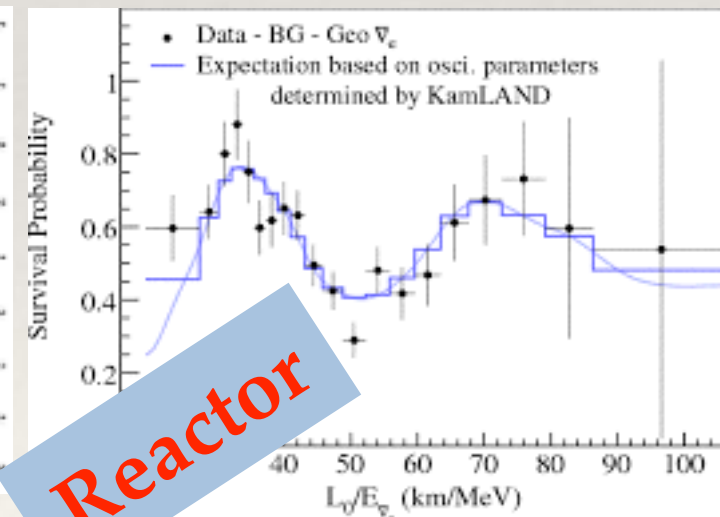
$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} < 1$$



Atmospheric



Accelerator



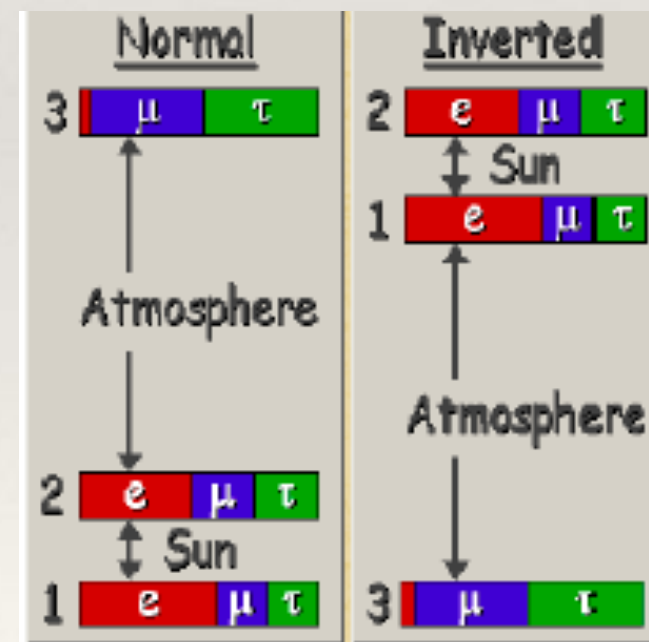
Three Neutrino Paradigm

- ❖ Measurement of non-zero θ_{13} in reactor experiments $\longrightarrow$ three neutrino picture

$$\begin{array}{c}
 \text{Atm +LBL} \qquad \qquad \qquad \text{Sol+KL} \\
 \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \\
 c_{12} = \cos \theta_{12} \text{ etc.}, \quad \delta \text{ CP-violating phase}
 \end{array}$$

- $\Delta m_{21}^2, \theta_{12}, \theta_{13}$ Solar + KamLAND
- $\Delta m_{31}^2, \theta_{13}$ Reactor
- $\Delta m_{31}^2, \theta_{23}, \theta_{13}, \delta_{CP}$ Atm + LBL

Interplay among different sectors
because of θ_{13}

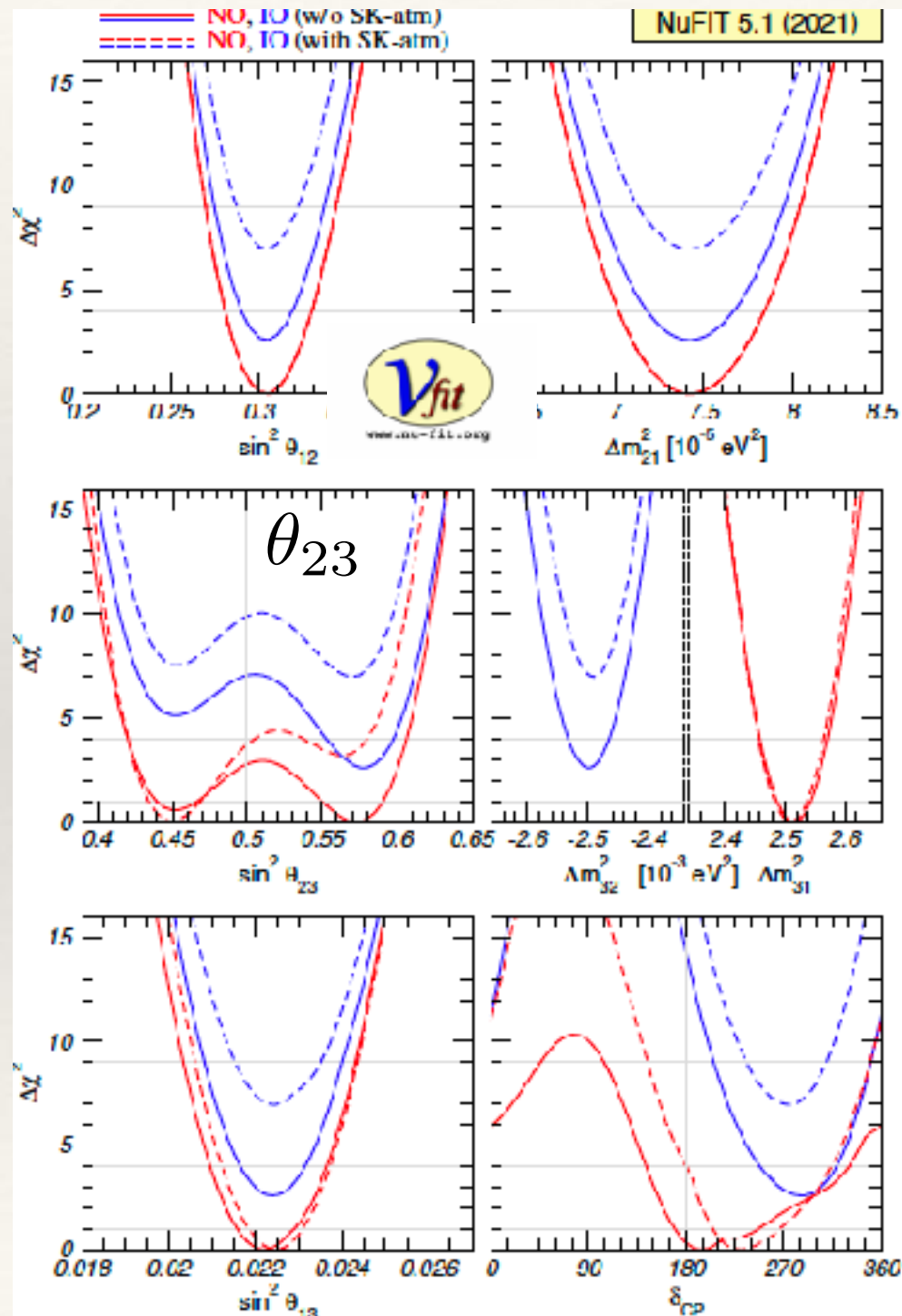


Neutrino Oscillation : from discovery to precision

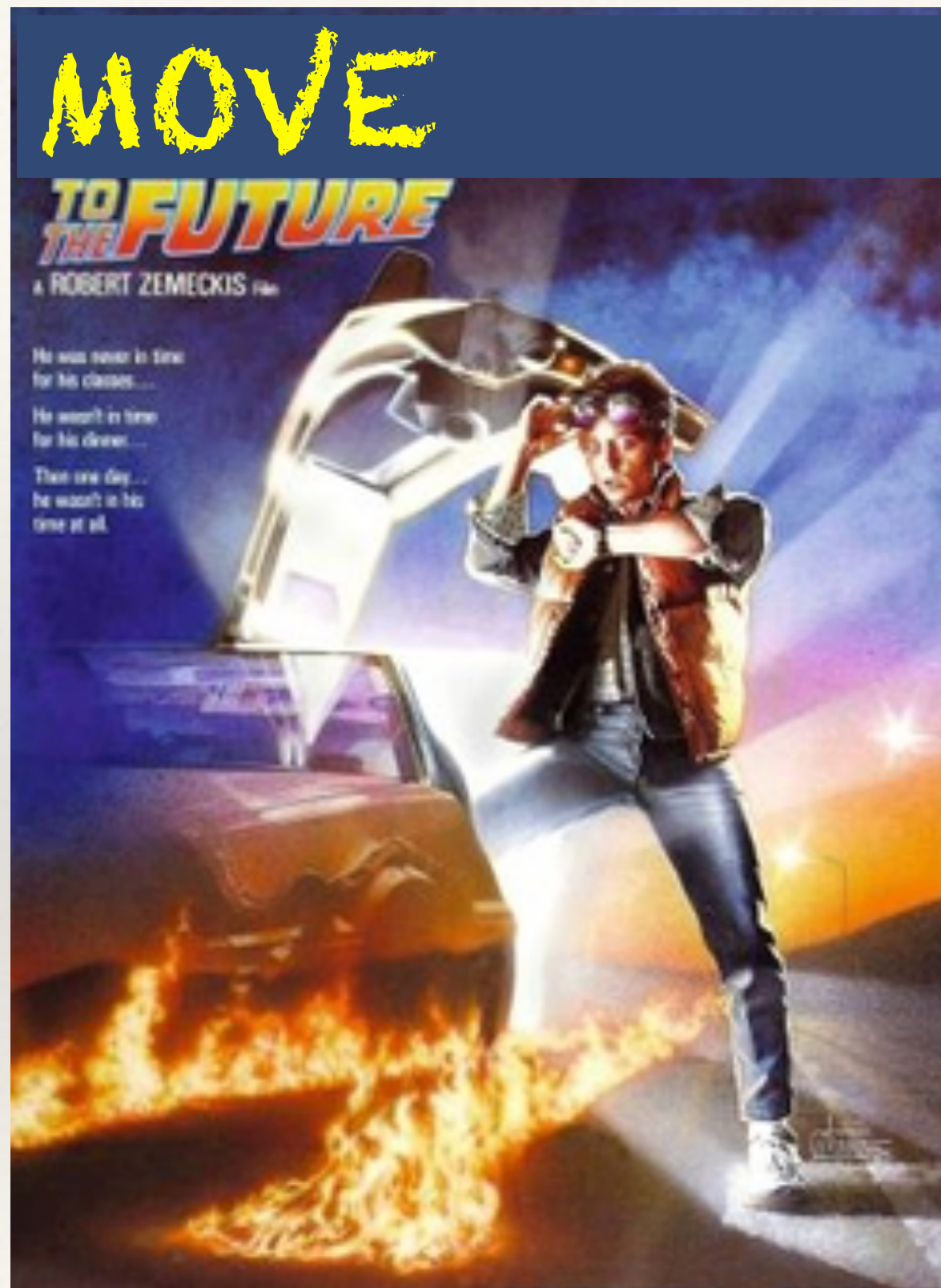
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \rightarrow 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \rightarrow 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27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

NuFIT 5.1 (2021)

Unknown parameters



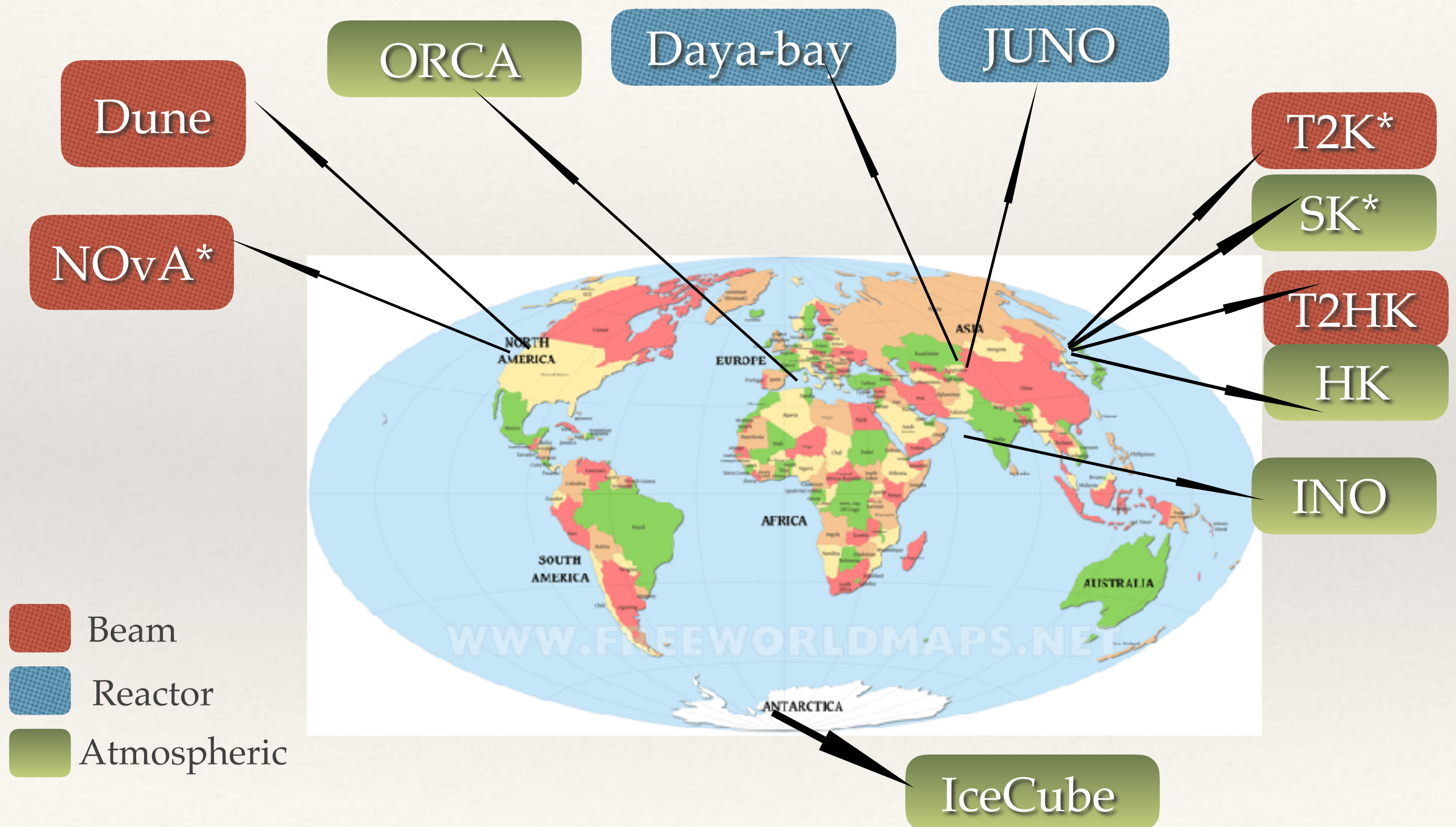
- ❖ Best-fit θ_{23} in second octant
- ❖ Preference for NO
- ❖ $\delta_{CP} = +90^\circ$ disfavoured at more than 3σ irrespective of mass ordering
- ❖ Oscillation experiments not sensitive to Majorana phases
- ❖ Not sensitive to absolute masses



Future Goals in Neutrino Physics

- ❖ Determination of hierarchy, octant and CP phase
 - ❖ Synergy between different experiments
 - ❖ Signatures of sterile neutrinos
 - ❖ Precise Measurement of neutrino cross-sections
 - ❖ Nature of neutrinos , absolute neutrino mass
 - ❖ Probing new physics in oscillation experiments
 - ❖ Search for Dark Matter in neutrino facilities
 - ❖ Probing BSM physics through new interactions
 - ❖ Neutrinos and Multimessenger Astronomy
- } Immediate Goals
- } Ongoing
- } 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,

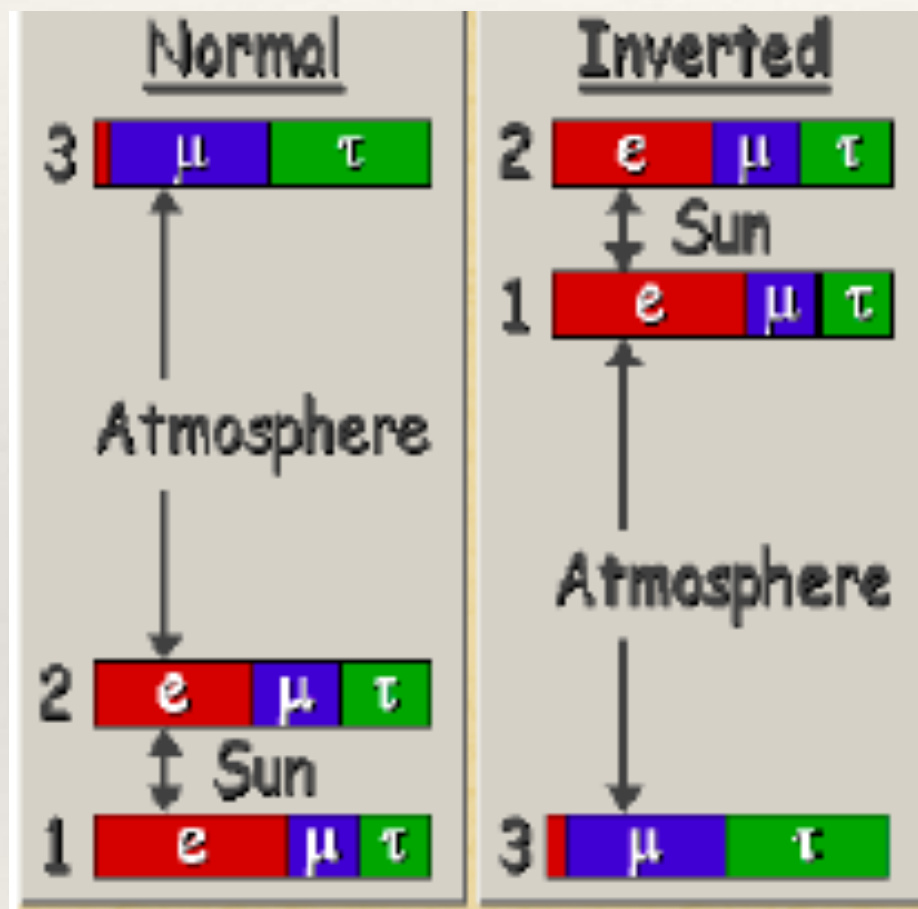
High Intensity Beams, bigger detectors

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 (Mediterranean)	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

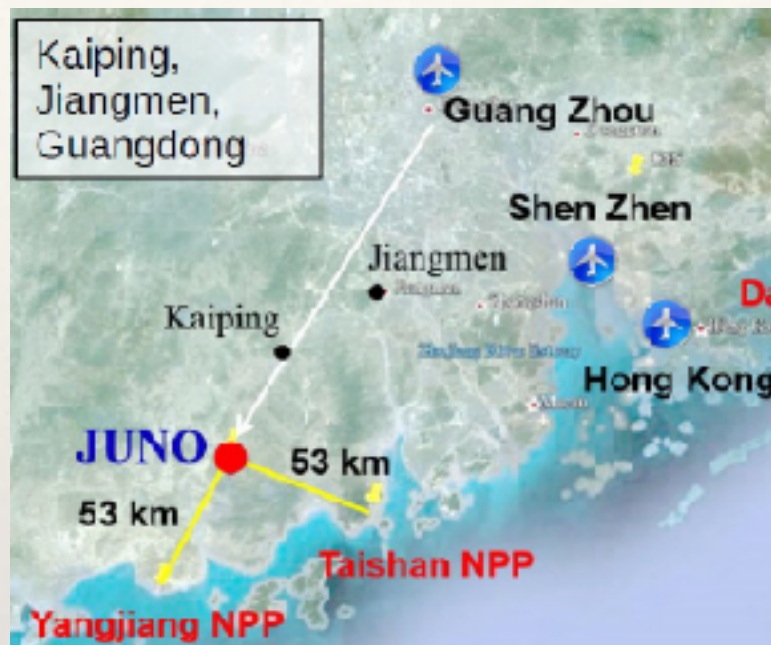


Matter effect in large baselines : long baseline beam and atmospheric neutrino experiments

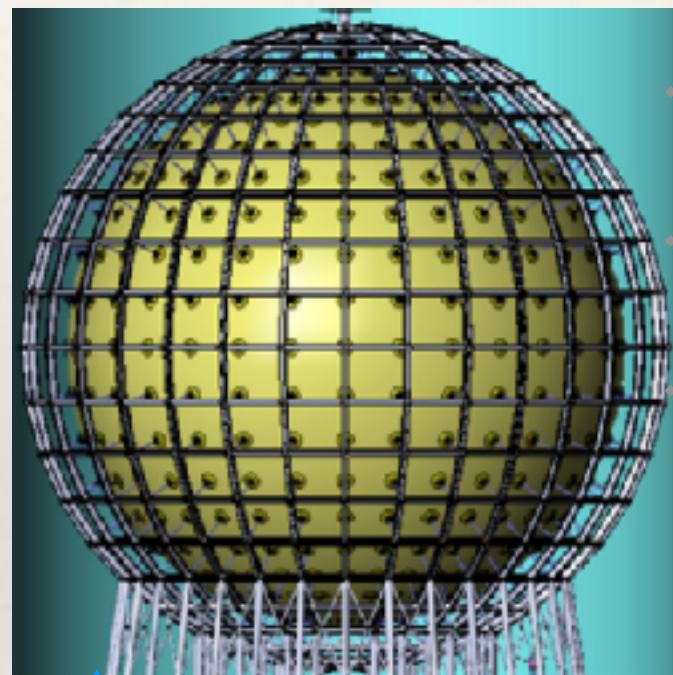
Interference effect in vacuum oscillations : reactor neutrino experiments

Absolute neutrino mass measurements
Neutrino less double beta decay, Cosmology

JUNO: Jianmen Underground Neutrino Observatory

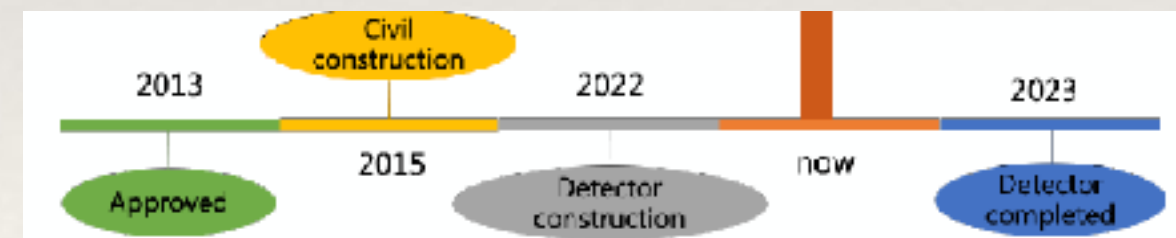
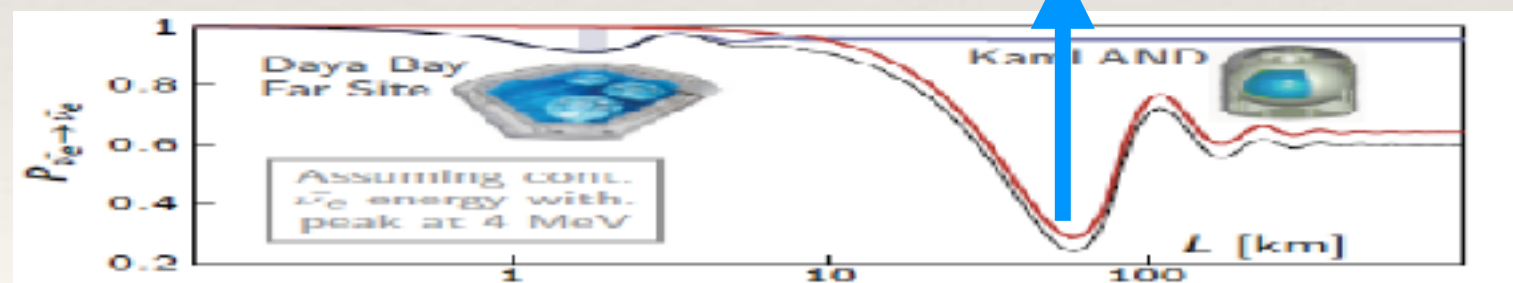


- ❖ Detector at 53 km from the the two reactors



- ❖ Reactor Antineutrino Experiment
- ❖ 20 kt Liquid Scintillator detector

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



Expected to complete detector construction in 2023

JUNO: Hierarchy and Precision

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

Precision of θ_{12}

Bandyopadhyay, Choubey, S.G. 2003

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

Hierarchy sensitivity

Distortions in the energy spectrum

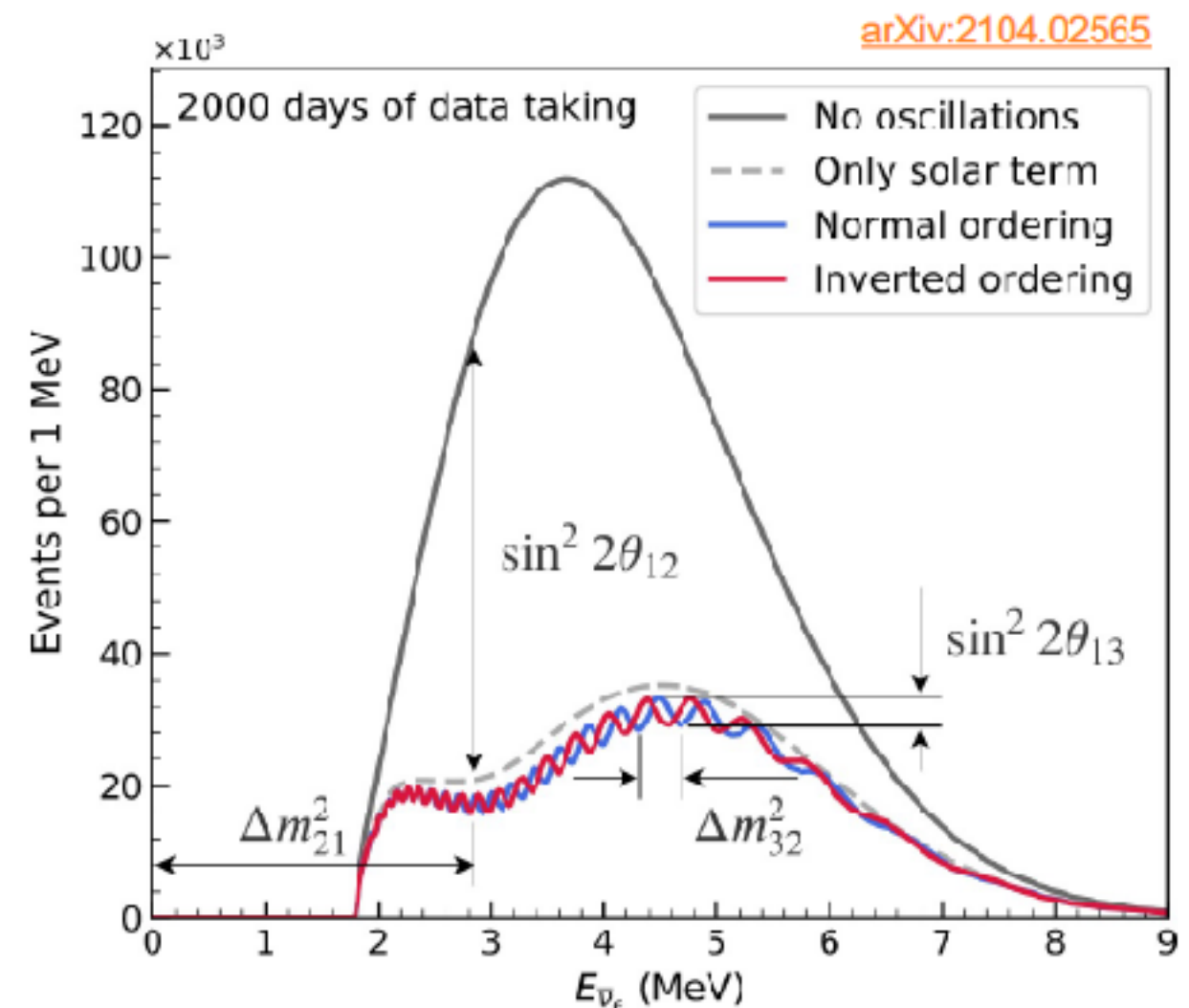
Better than 3% energy resolution needed

3σ hierarchy sensitivity in 6 years

Precision of oscillation parameters

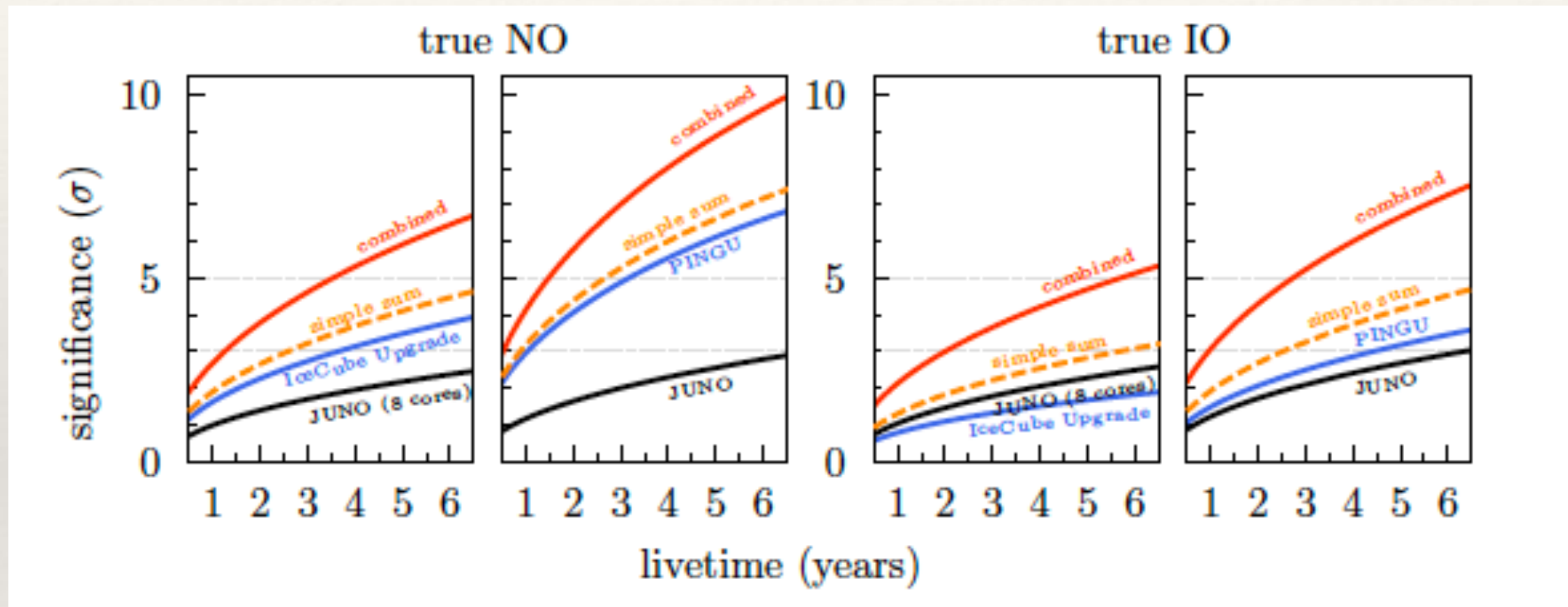
	Δm_{31}^2	Δm_{21}^2	$\sin^2 \theta_{12}$	$\sin^2 \theta_{13}$
JUNO 6 years	$\sim 0.2\%$	$\sim 0.3\%$	$\sim 0.5\%$	$\sim 12\%$
PDG2020	1.4%	2.4%	4.2%	3.2%

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

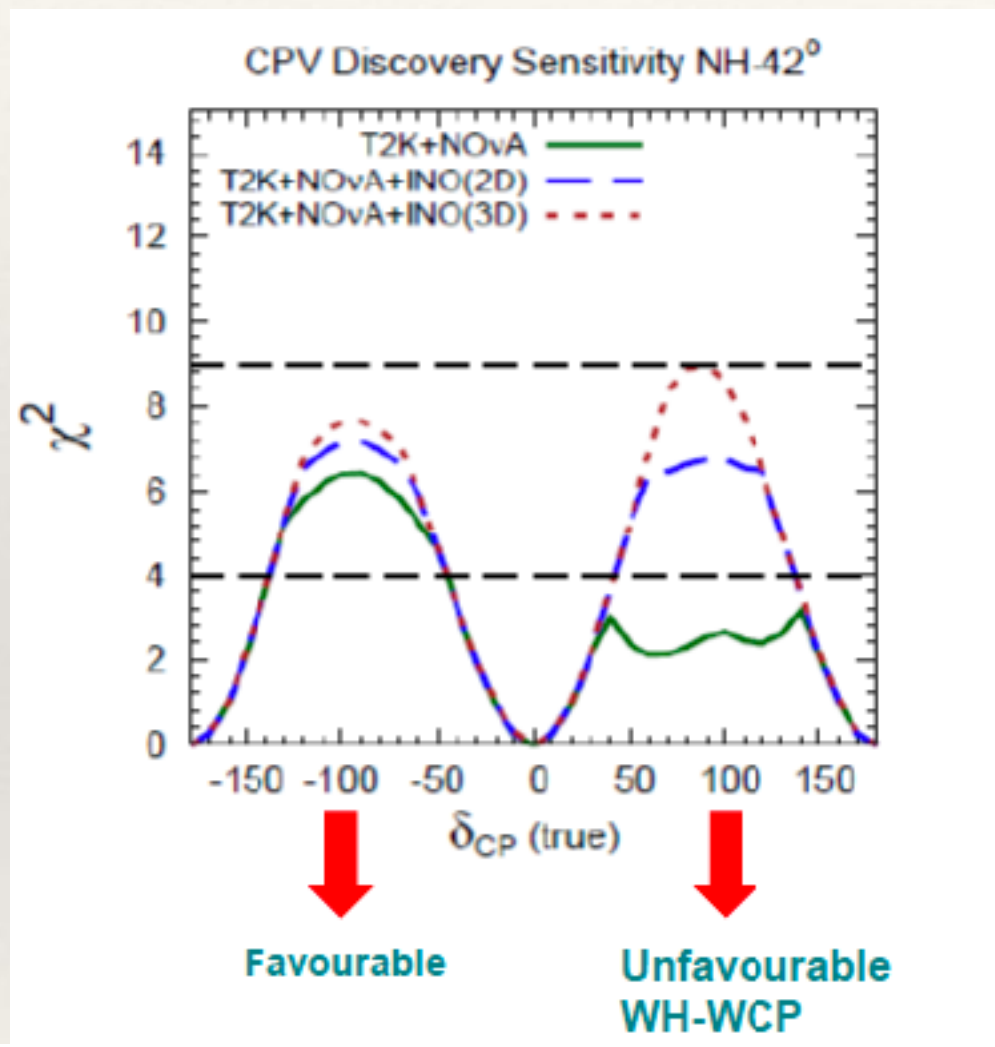
JUNO: interference effect in vacuum oscillation

} **Synergy**

hep-ex 1911.06745

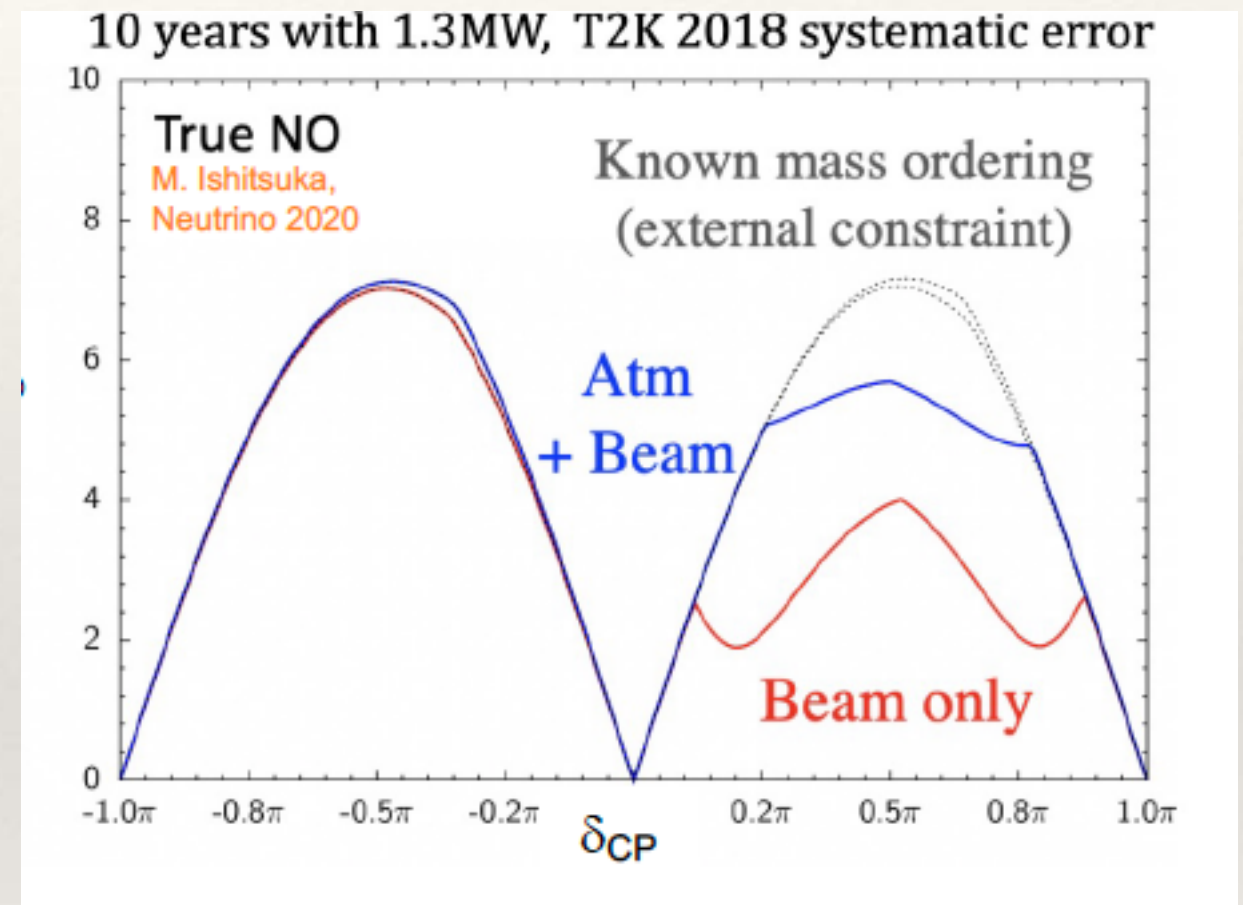
Synergy between beam + atm for δ_{CP}

T2K+NOVA+INO (500 kt-yr)



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

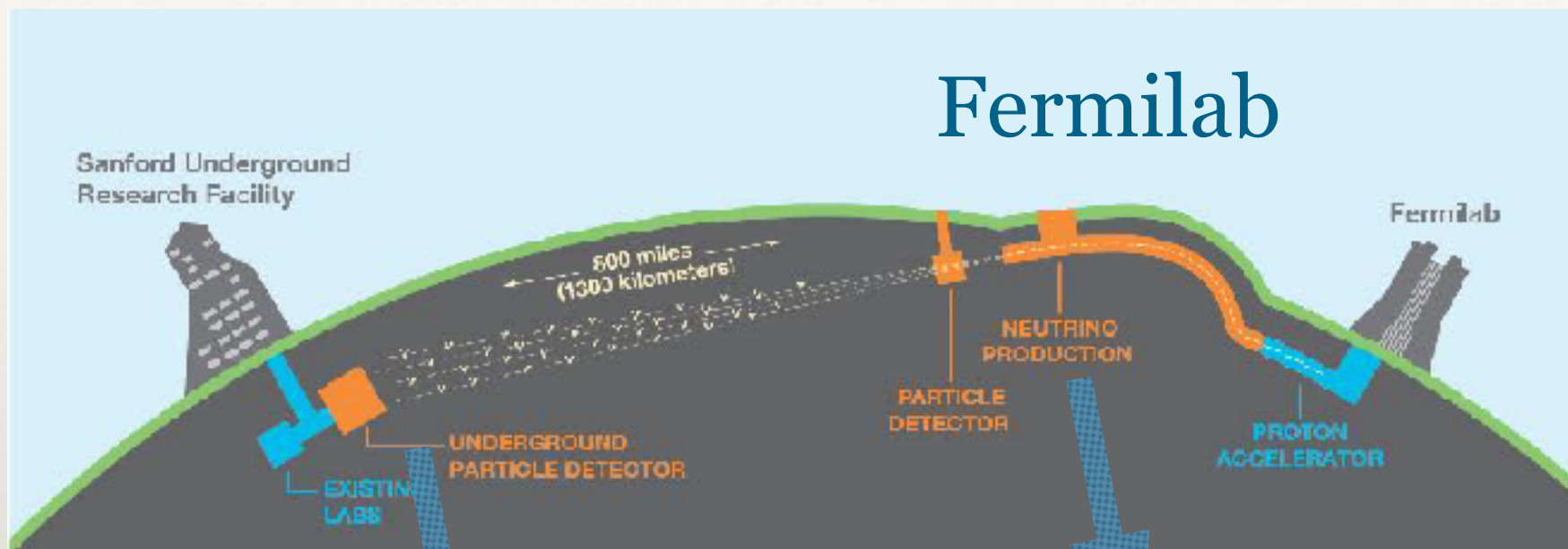
HyperK



HyperK design report arXiv: 1805.04613

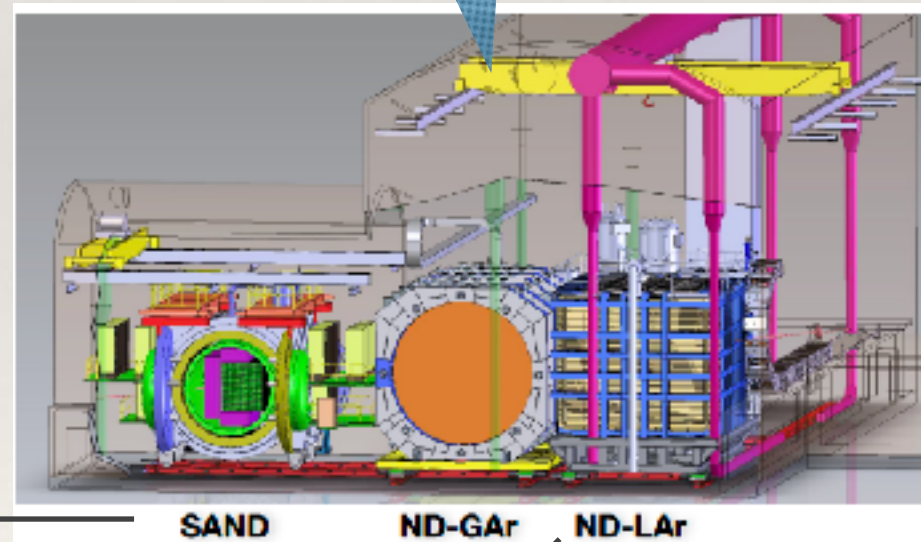
Atmospheric data can resolve hierarchy -CP degeneracy and enhances CP sensitivity

DUNE



Far Detector
Liquid Argon Time
Projection Chamber

On-axis ←



DUNE PRISM: off-axis, movable

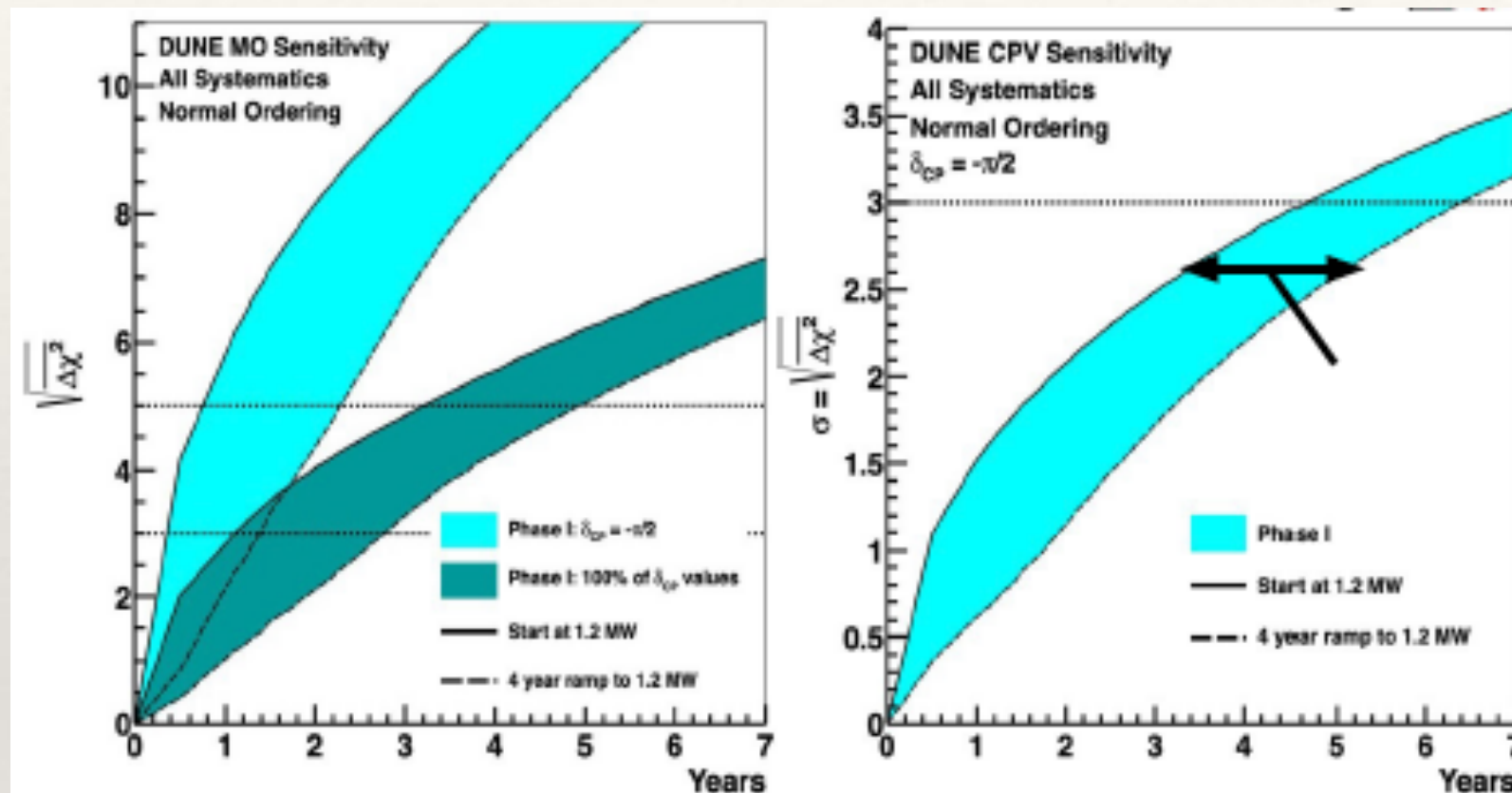
LBNE/DUNE-US Project + DUNE Int'l Project

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

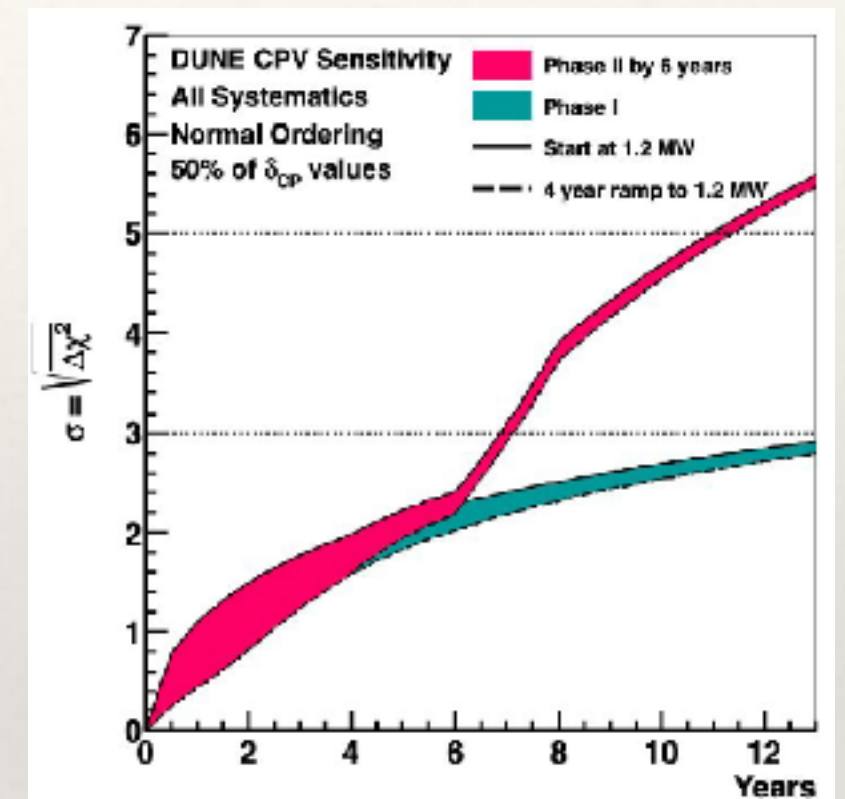
Phase II: increased far detector mass and beam power and improvement in near detector

DUNE Physics Goals

Phase 1



Phase 2



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

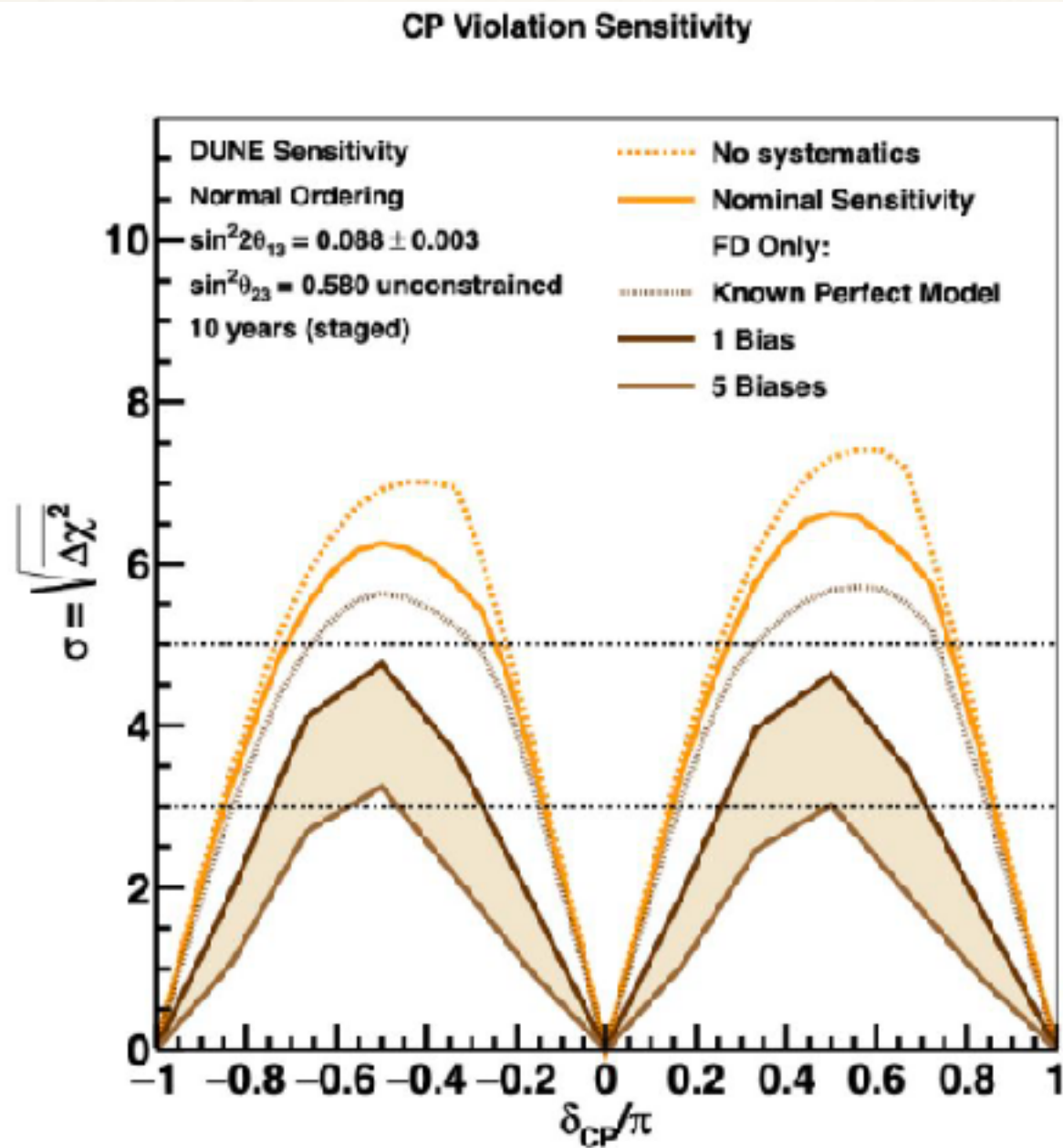
3σ CPV sensitivity in 5 years for maximum CPV

Sensitivity to supernova neutrino burst, BSM physics

Sensitivity for
50 % δ_{CP} values

Improved sensitivity to BSM physics at
ND with the beam upgrade

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 ₂ O, 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 ₂ O	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 ₂ O, Fe, Pb	Tracking+Calorimetry
	ANNIE	$\nu_\mu, \bar{\nu}_\mu$	0.6	CH, H ₂ O	Cherenkov
	NINJA	$\nu_\mu, \nu_\mu, \nu_e, \nu_e$	1	CH, H ₂ O, 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 ₂ O, Ar, TBD	Tracking Calorimetry (TBD)

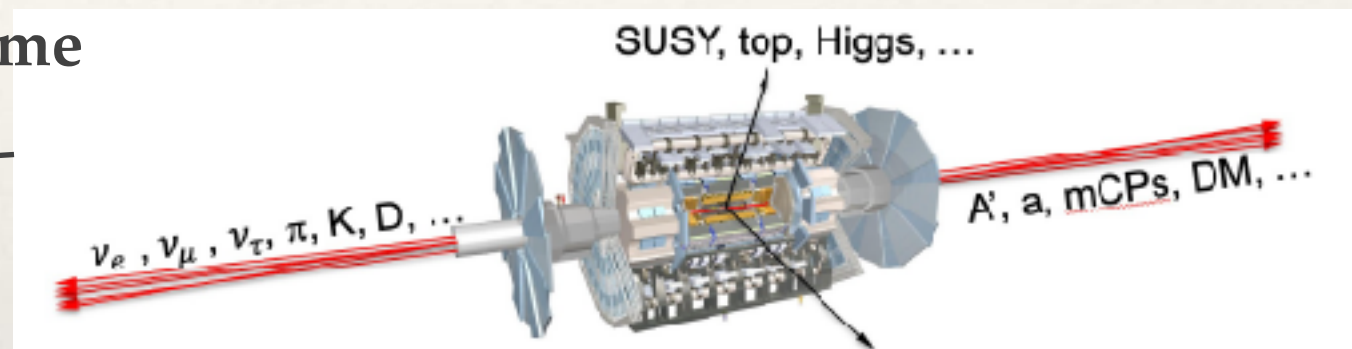
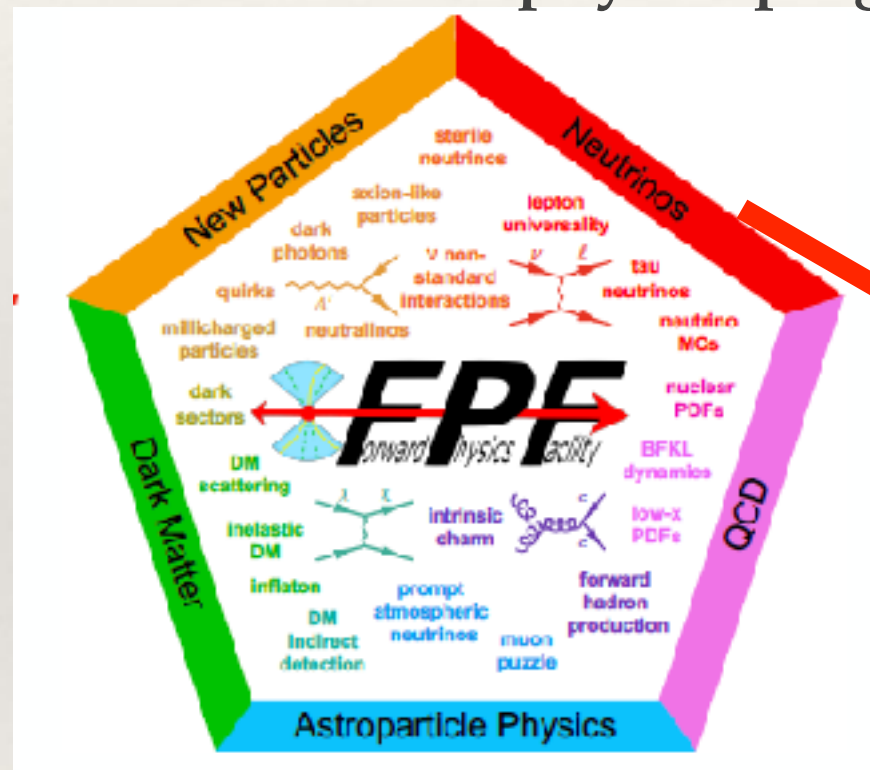
Experimental measurement of neutrino-nuclear cross-sections and refinement of theoretical calculations including many body effects, nuclear form factors from LQCD, and strategies for the Event Generators — crucial for precision neutrino measurements

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

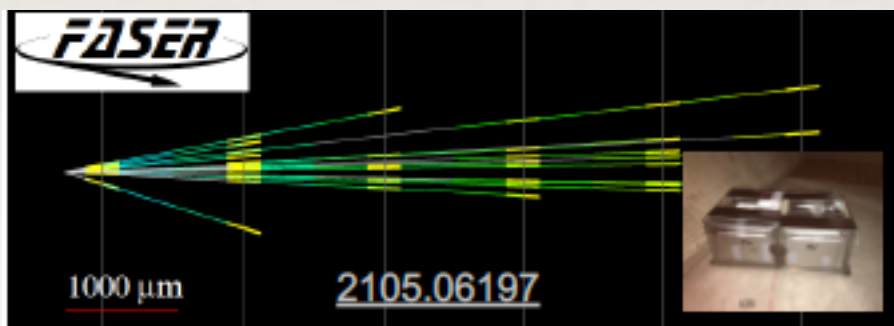


Laboratory measurements of neutrinos
at the TeV scale for the first time

Detection of thousands of tau neutrino
interactions for the first time

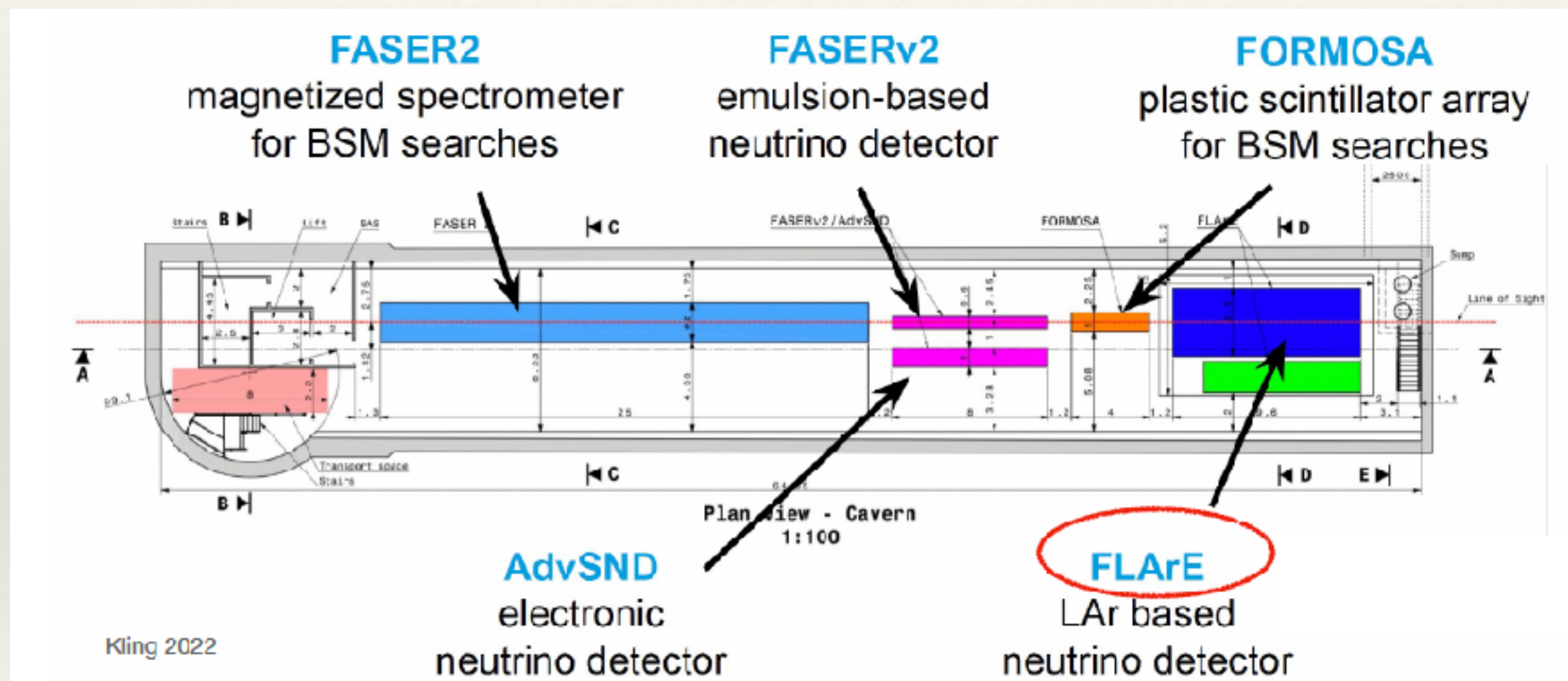
Faser detector in the far forward region
running for 4 weeks have detected 6 neutrino
events

Talk by Jonathan Feng, SNOWMASS meeting



FPF@HL-LHC

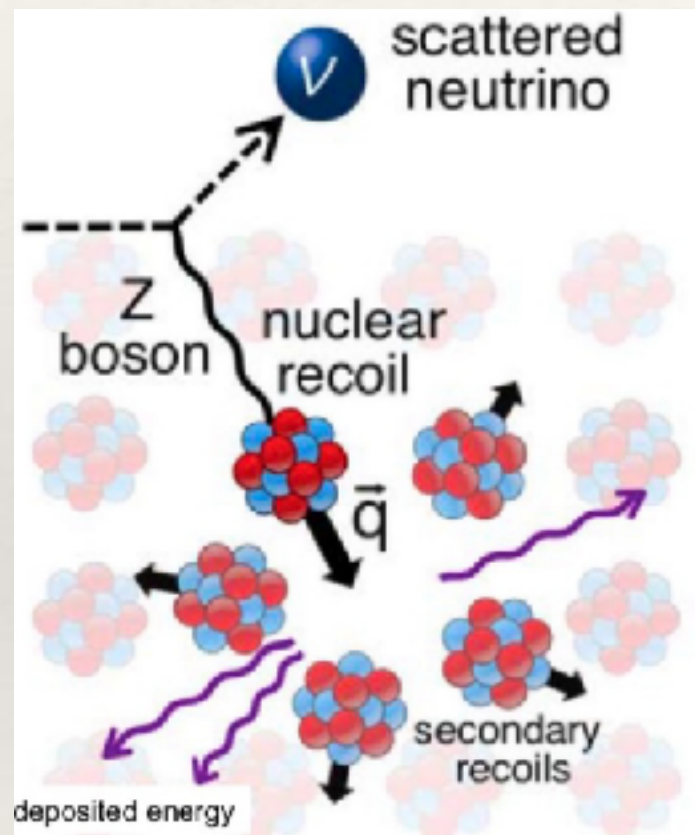
5 detectors are being developed



Conceptual design report : mid 2023

Coherent Elastic Neutrino-Nucleus Scattering

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

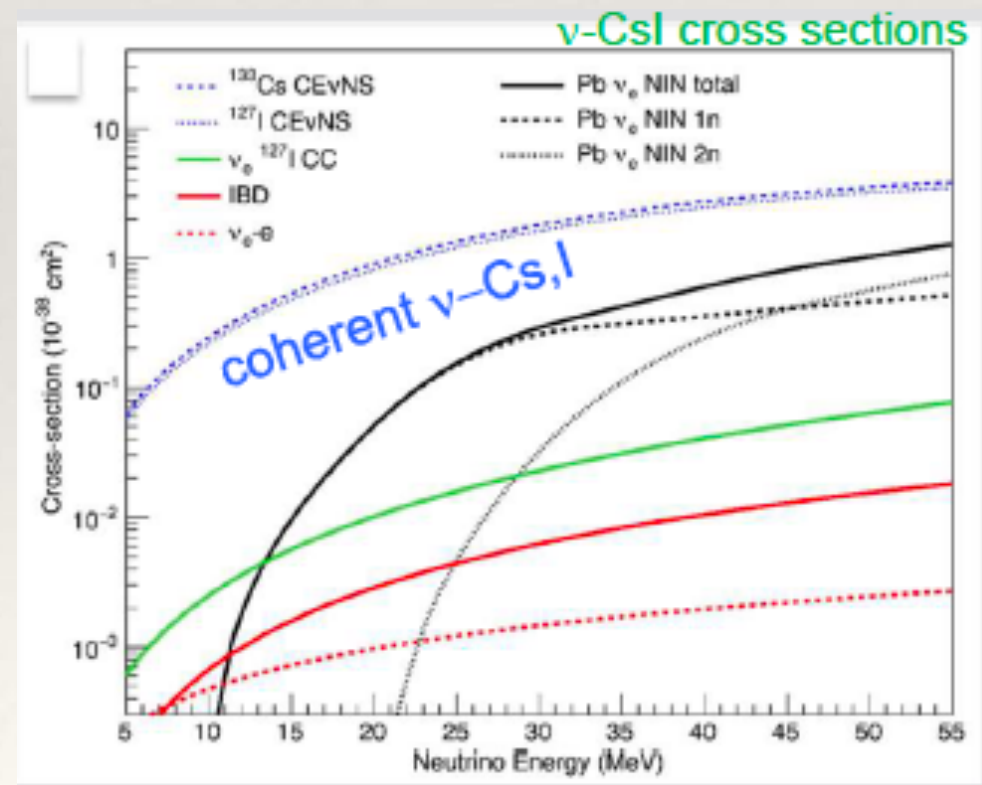


Detection : the tiny energy deposited by nuclear recoil in the target material

Challenging : recoil energy
50 KeV for 10 MeV neutrinos



COHERENT collab, Science 3 Aug, 2017



First result in 2017

6.7 σ discovery of CEvNS

Consistent with SM at 1 σ

Physics Reach

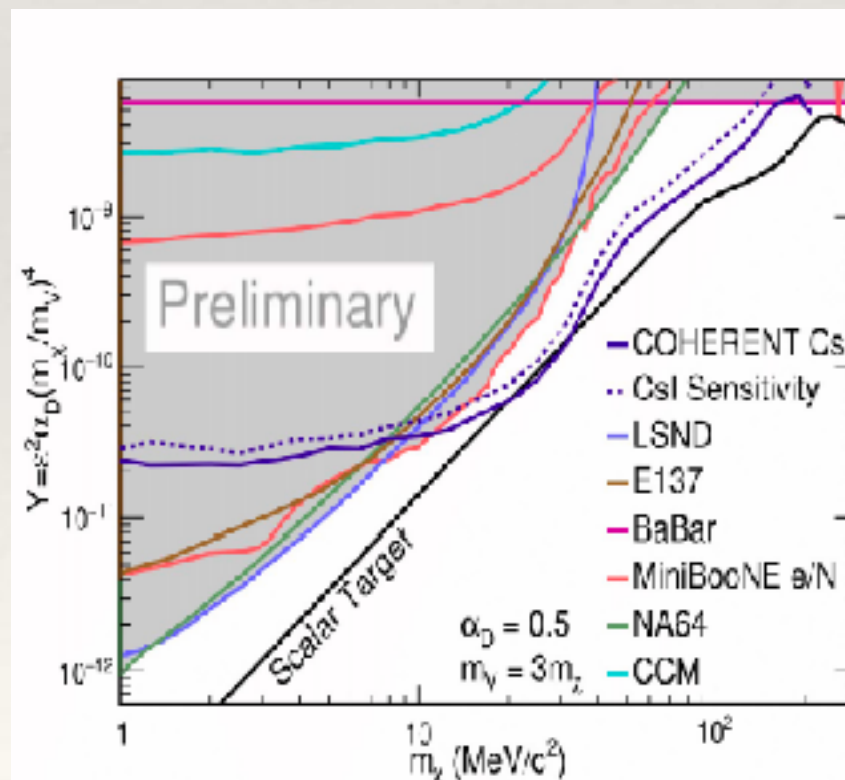
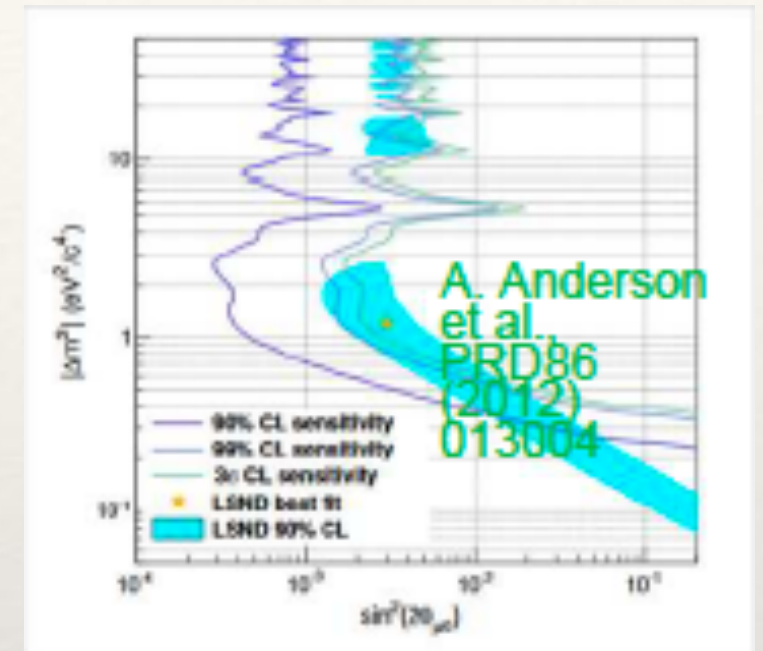
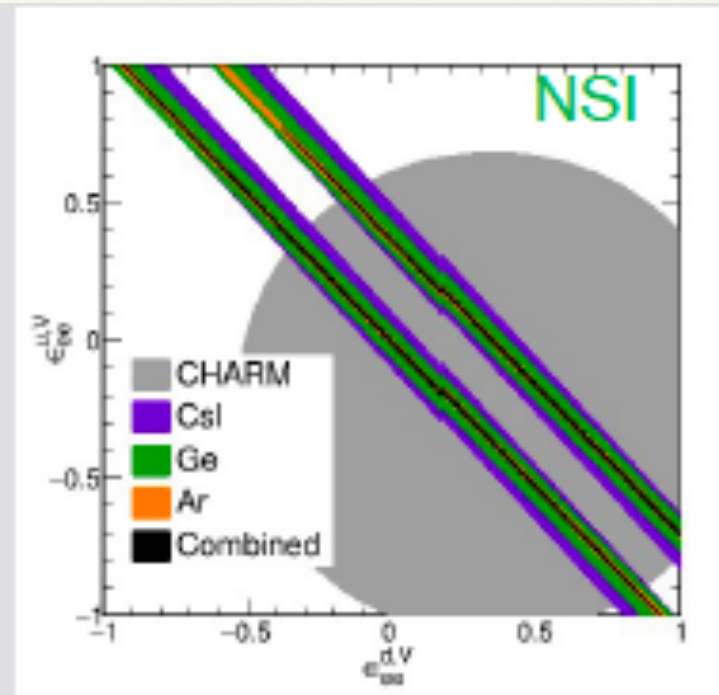
Nuclear Physics and
nuclear form factors

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 CE ν NS 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	1 st result, 2017: 10.1126/science.aao0990 updated results in press, detector removed
Liquid Ar	Scintillation	24.4/610	20	2017/2024	1 st result, 2019: 10.1103/PhysRevLett.126.012002, currently running
Ge	Ionization	18	0.5	2022	commissioning
NaI[Tl]	Scintillation	2500	13	2022	commissioning: 2022

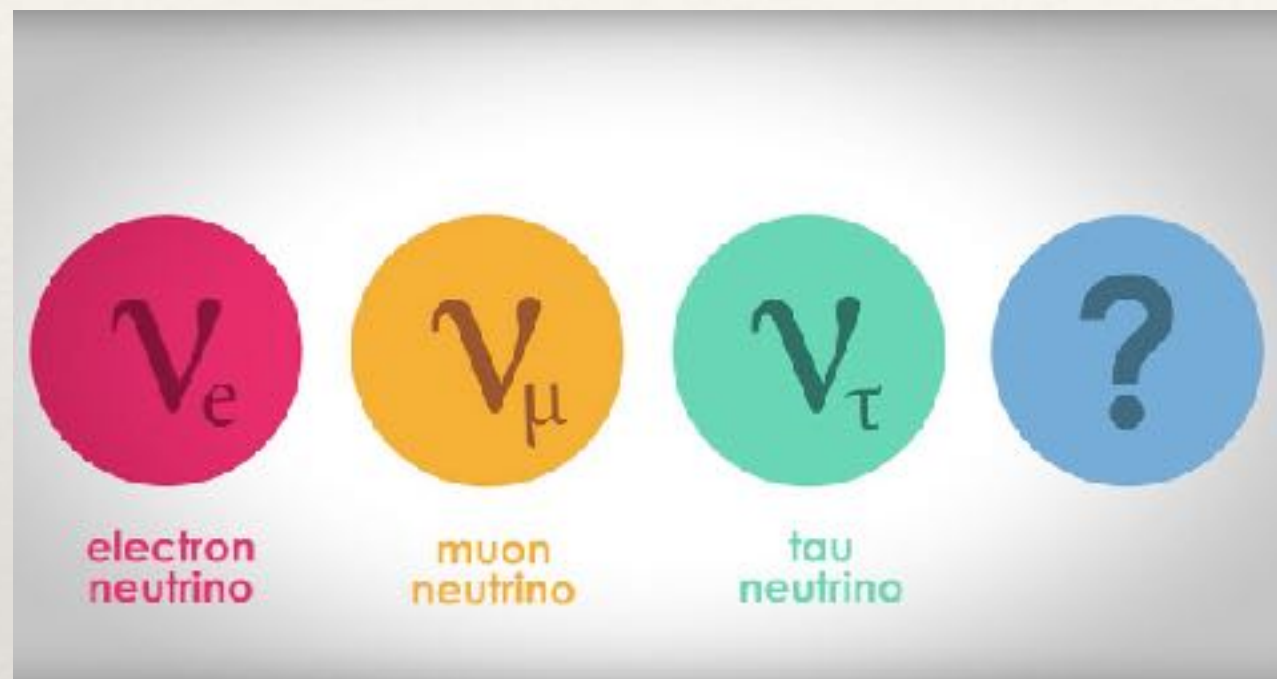
R. Tayloe, NDM2022

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

$L \simeq 30 \text{ m}$

MiniBOONE

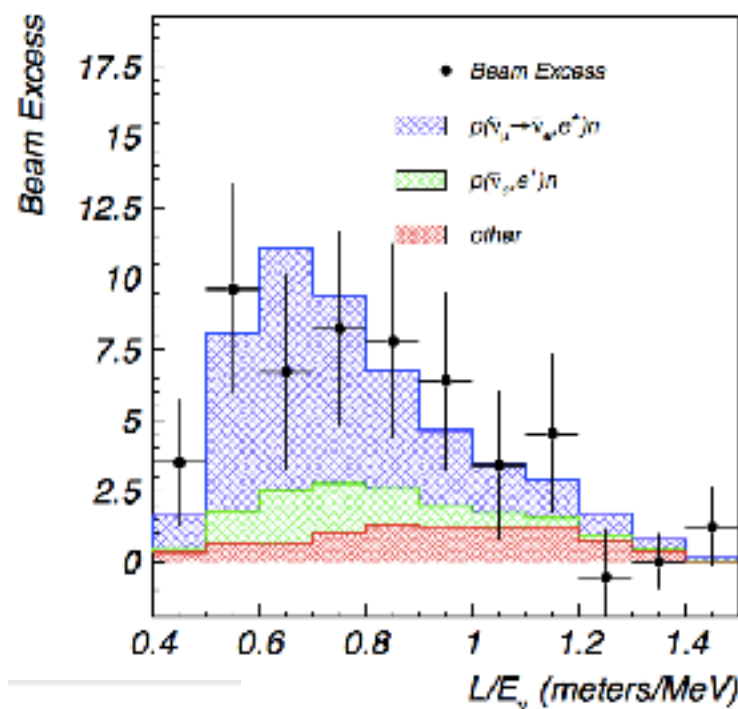
$L \simeq 541 \text{ m}$

LSND+MiniBOONE

$20 \text{ MeV} \leq E \leq 200 \text{ MeV}$

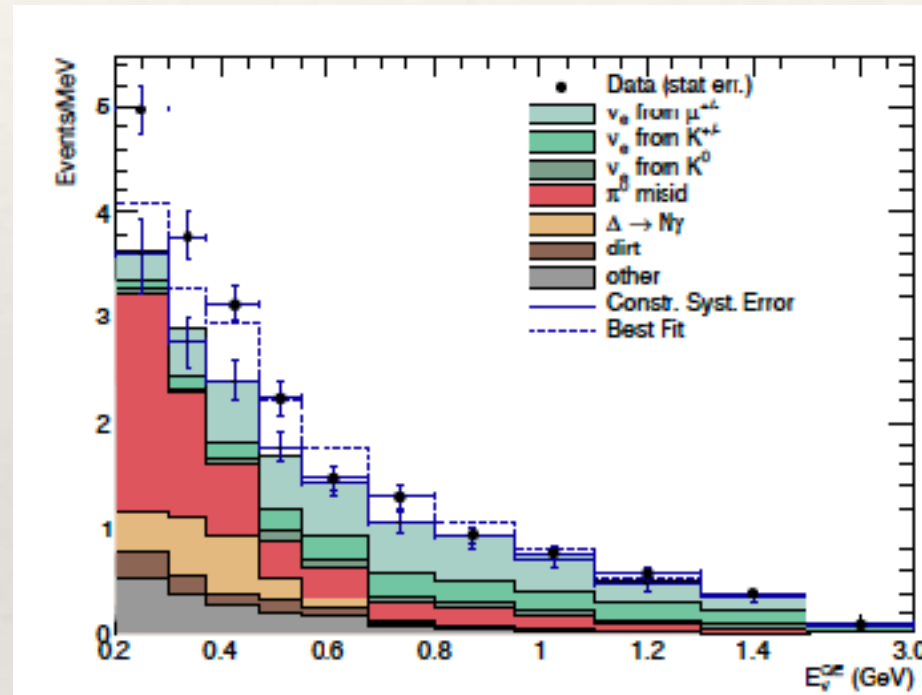
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

Same L/E

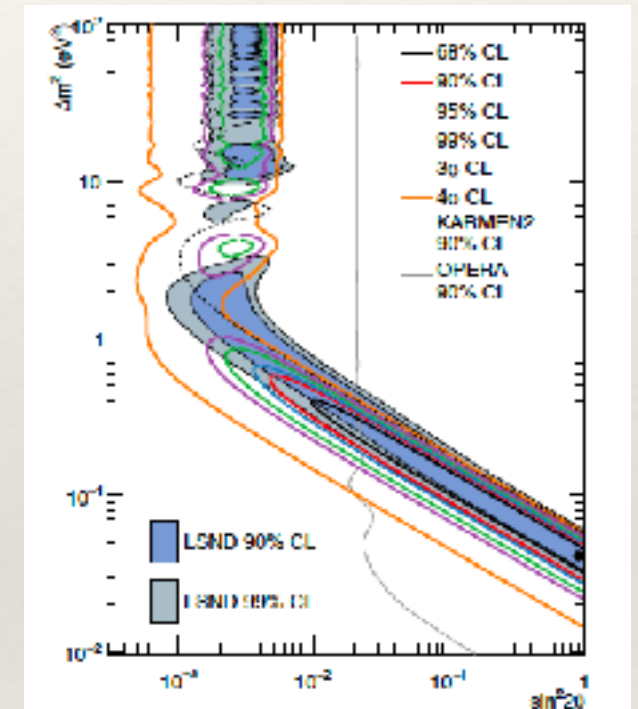


$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

LSND PRL 1995,
PRD 2001



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



3.8σ excess

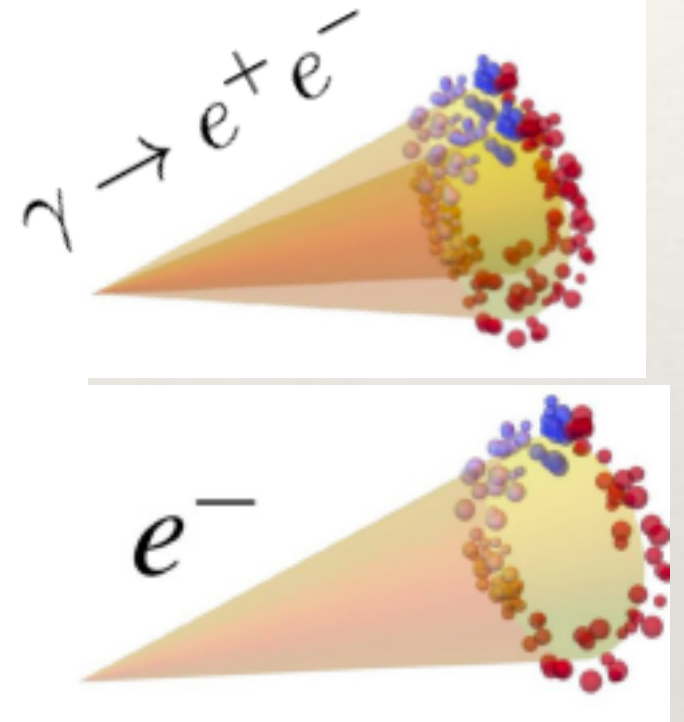
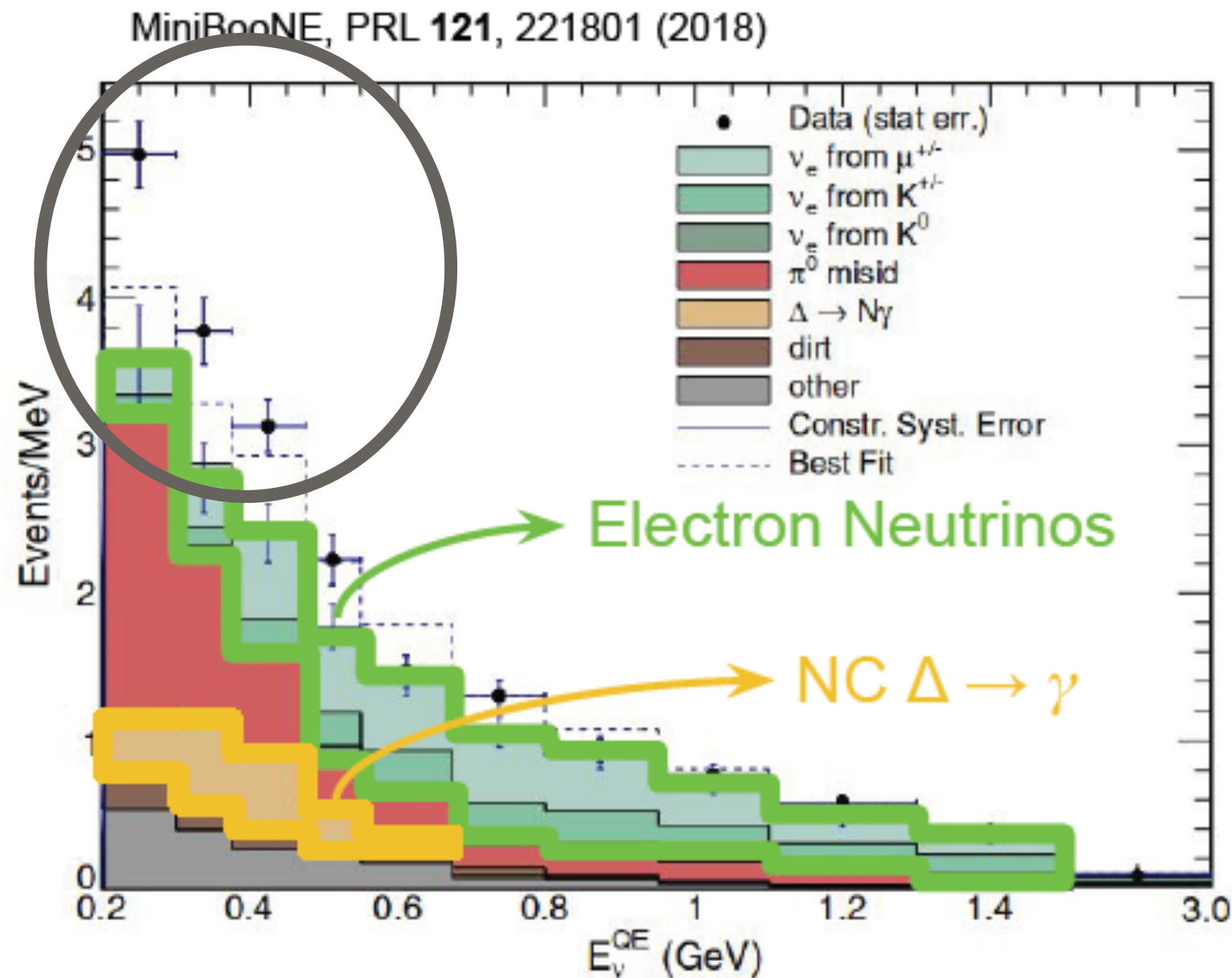
$\Delta m^2 \gtrsim 0.2 \text{ eV}^2$

Reactor Anomaly
Ga Anomaly

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

Low Energy Excess in MiniBooNE

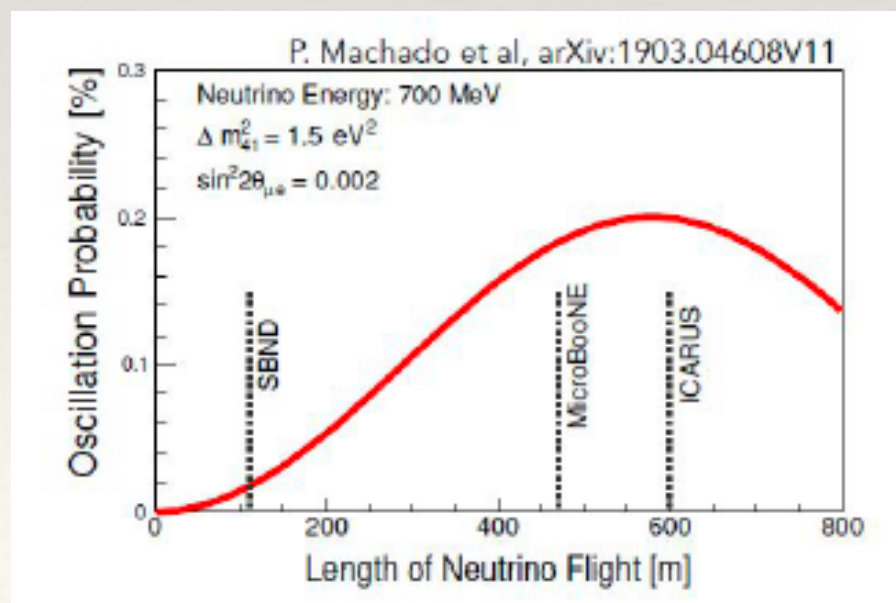
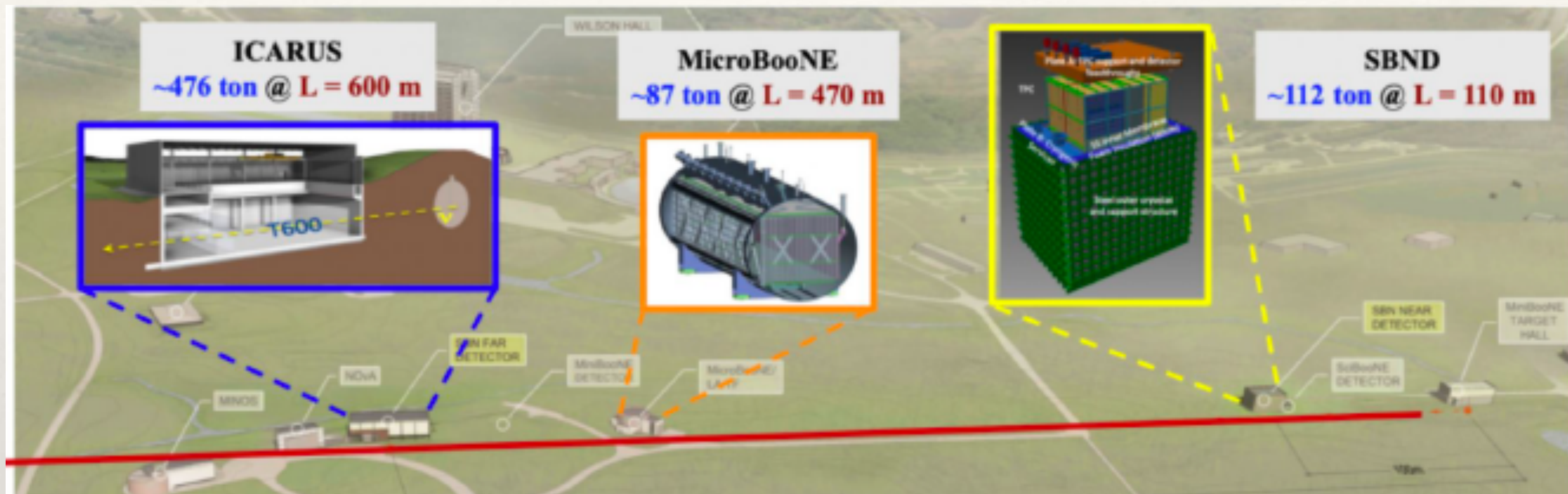
4.5σ
Excess



Cannot distinguish
between Cherenkov
cone of electrons and
single photon

SBN@FermiLab

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

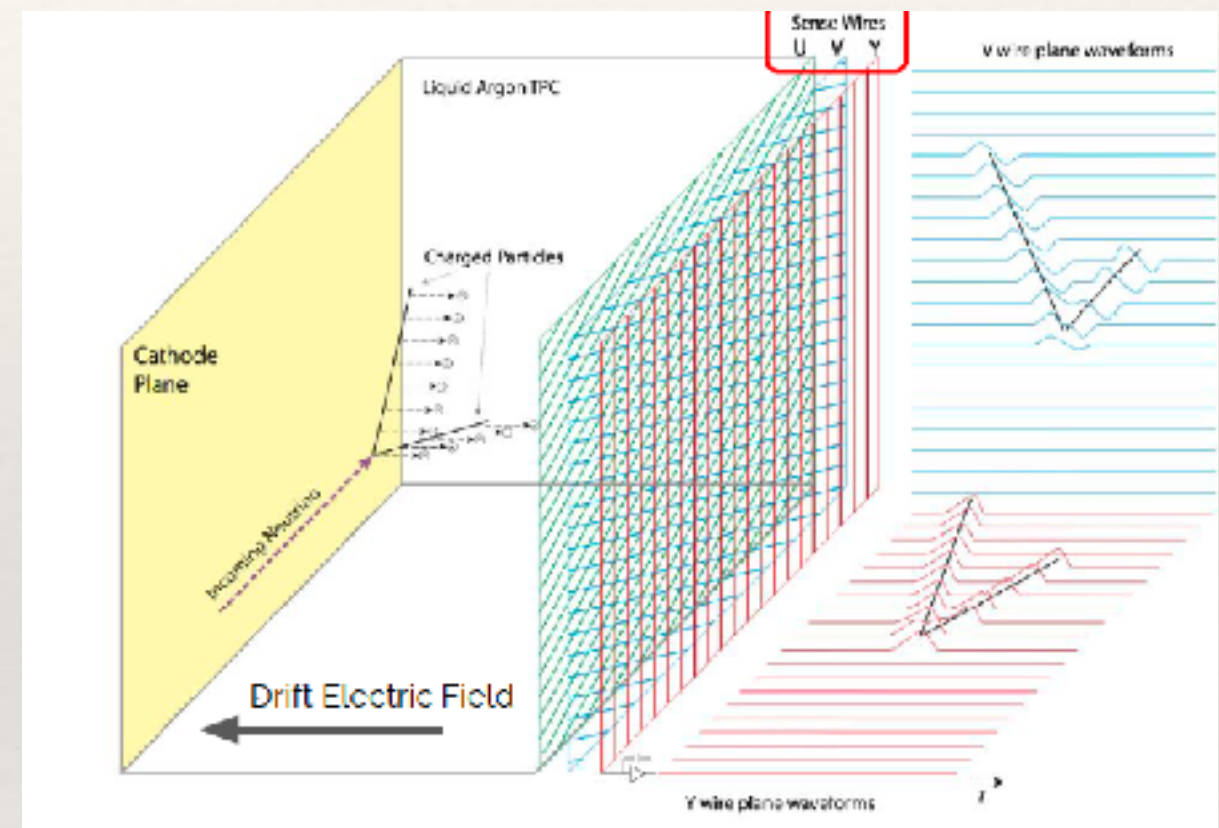


Search for sterile neutrinos
Cross-section measurement
New physics

MicroBoone

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

Same beam and similar baseline
but different detector technology



NC $\Delta \rightarrow \gamma$
SM background

Electron Neutrinos
eV steriles?

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

MicroBoone Results

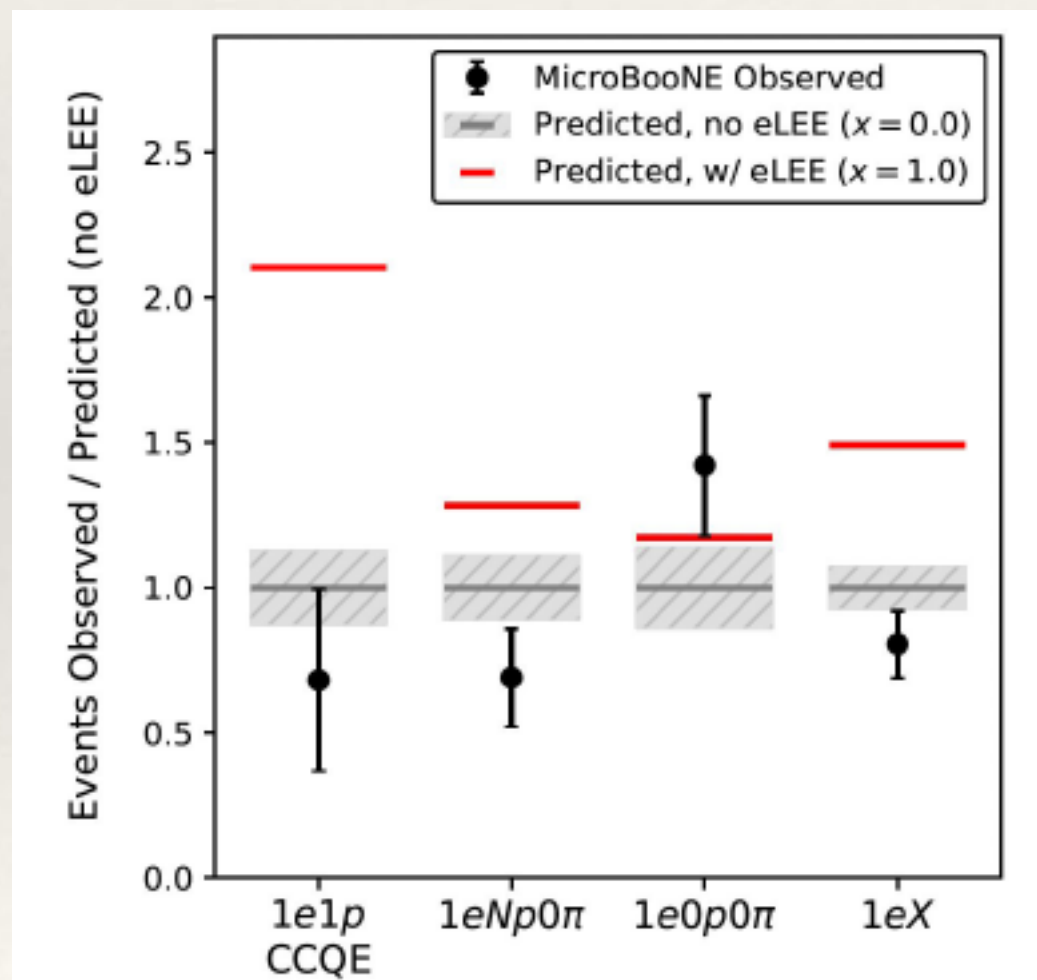
- ❖ Disfavour NC $\Delta \rightarrow \gamma$ as origin of LEE 94.8% C.L.
- ❖ No electron neutrino excess in data

New physics ?

See however

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

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



3+1 Fit	$ U_{e4} ^2$	$ U_{\mu 4} ^2$	Δm^2	$\Delta\chi^2 / \text{dof}$
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 $\Delta\chi^2/\text{dof}$ in the last column compares the 3 + 1 model to the no-oscillation model.

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

<https://arxiv.org/pdf/2110.14054.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](https://arxiv.org/abs/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. D* 99 (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](https://arxiv.org/abs/1812.08768) [hep-ph] | [PDF](#)

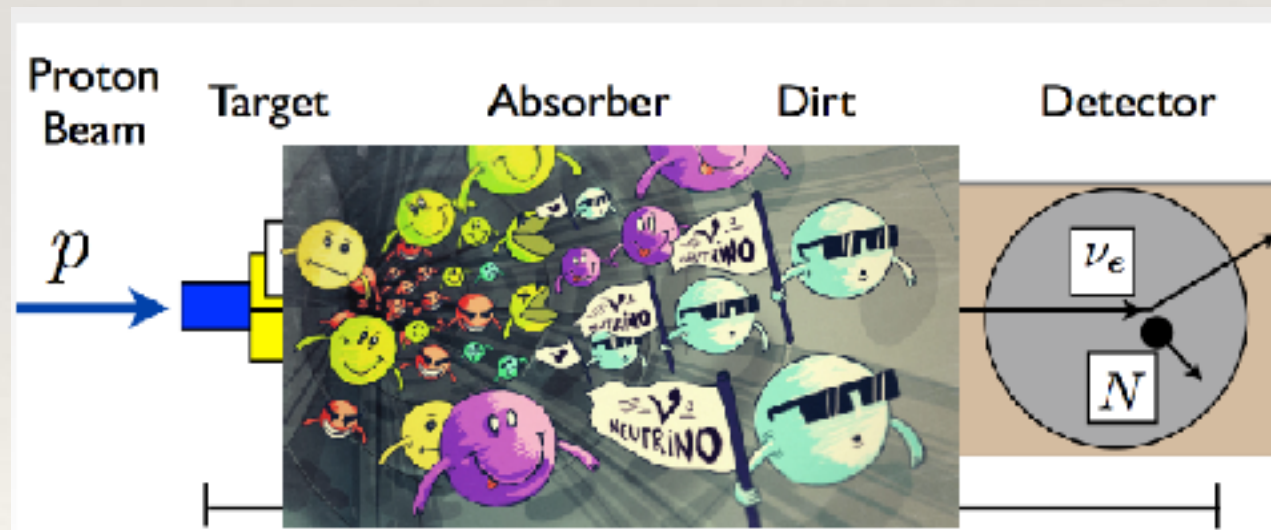
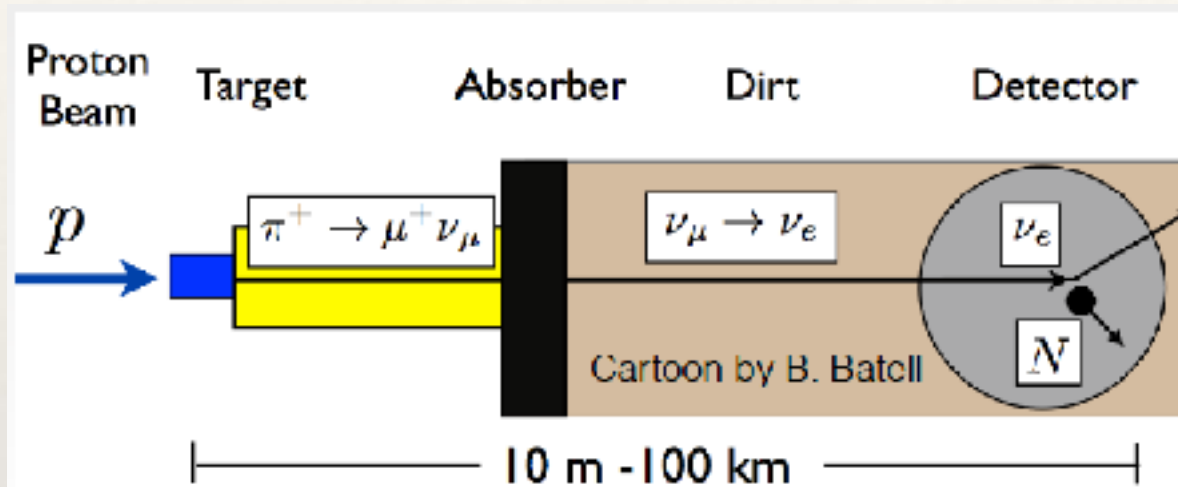
Severe Constraints on New Physics Explanations of the MiniBooNE Excess

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
FERMILAB-PUB-18-205-A-ND-PPD-2566

Many more, apologies if your paper is not listed

Slide: D. Pramanik, Whepp 2019

BSM physics @ Fixed Target Experiments



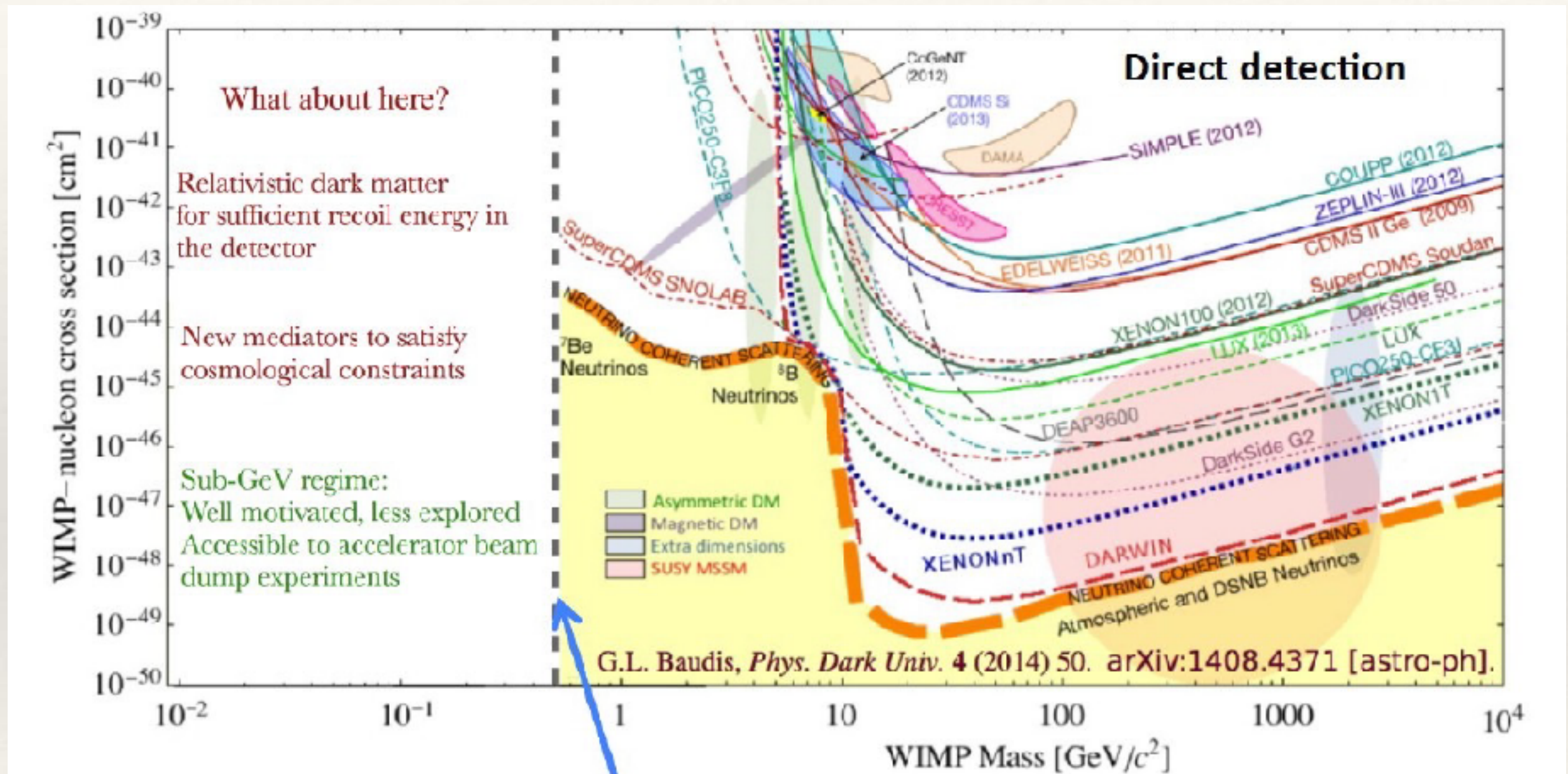
- ❖ BSM physics can be probed in fixed target experiments
- ❖ Dark Matter, Heavy Neutral Leptons, Axion like particles, extra neutral gauge bosons etc.
- ❖ NA62, MiniBooNE, NOVA, MINOS, T2K
- ❖ **DUNE, SHIP, SBN.....**

<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) <https://arxiv.org/pdf/1405.7370.pdf>
- ❖ Direct search for beam sub-GeV dark matter in neutrino experiments
[Battel, Pospelov, Ritz, arXiv: 0906.5614](https://arxiv.org/abs/0906.5614)

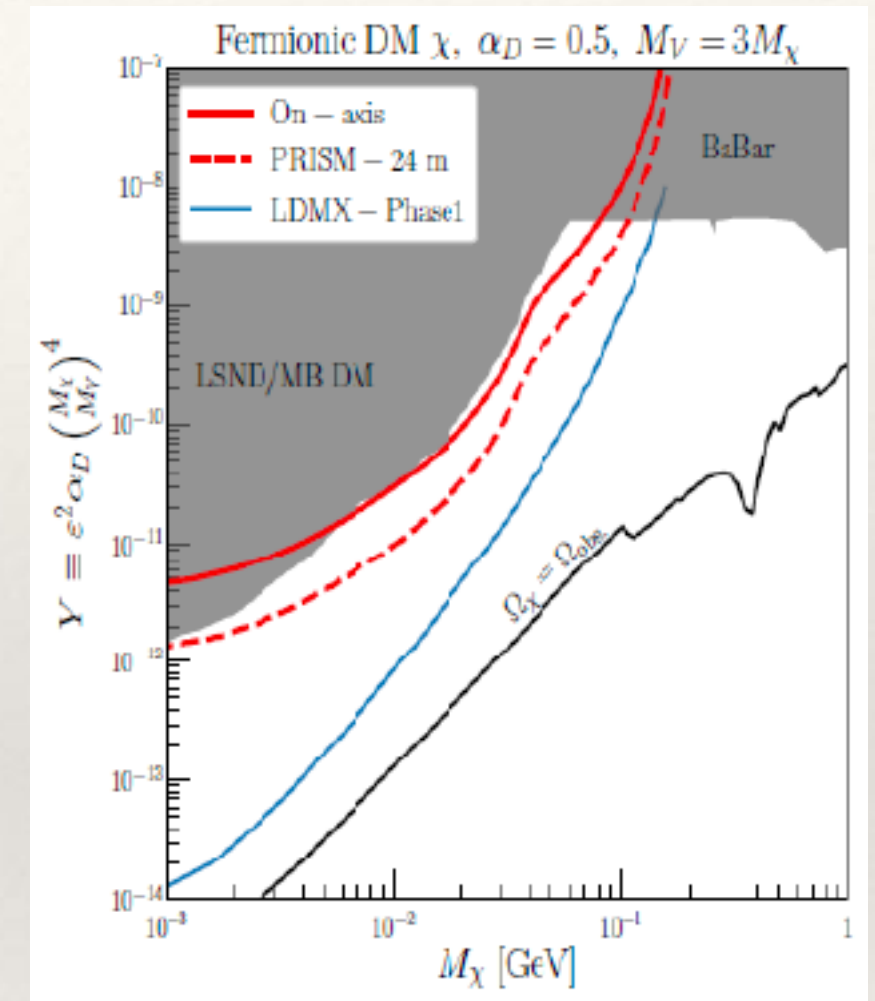
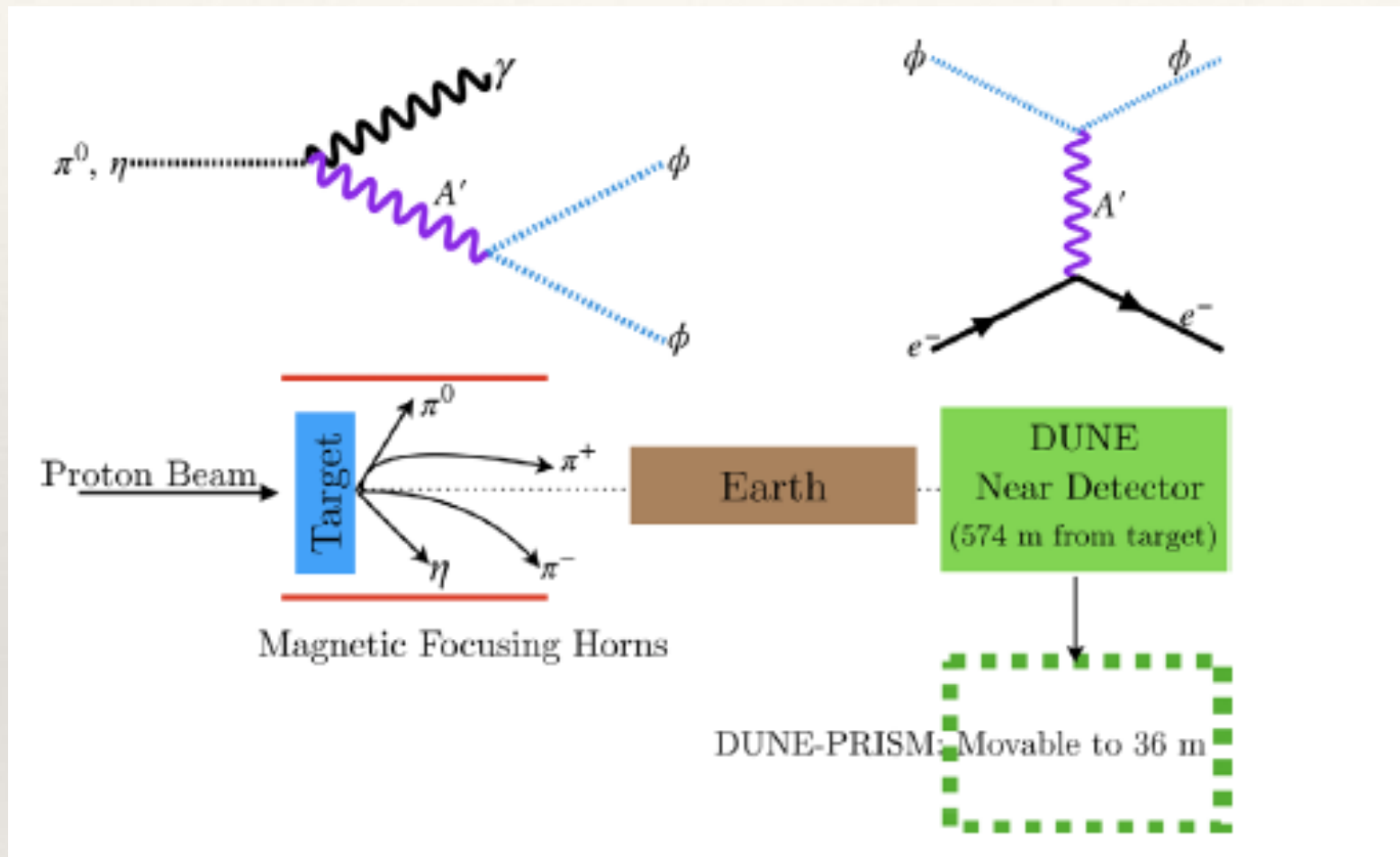
Motivation



Direct Detection Threshold

Slide Courtesy : A. Chatterjee

Dark Matter in Neutrino Detectors



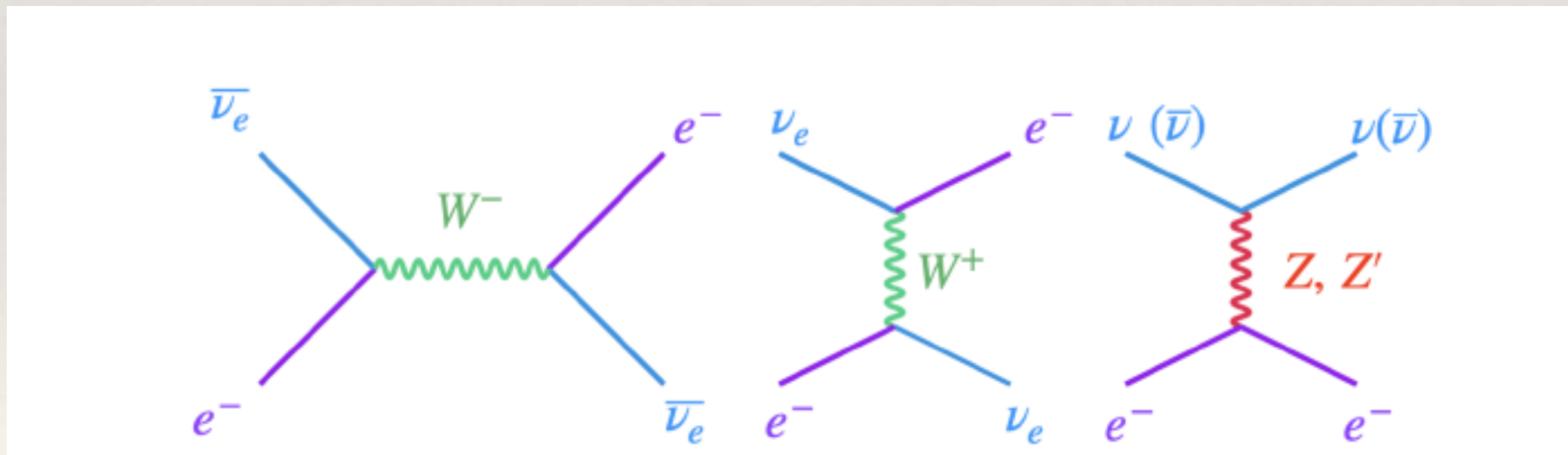
Romeri, Kelly, Machado, Phys. Rev. D 2019

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

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

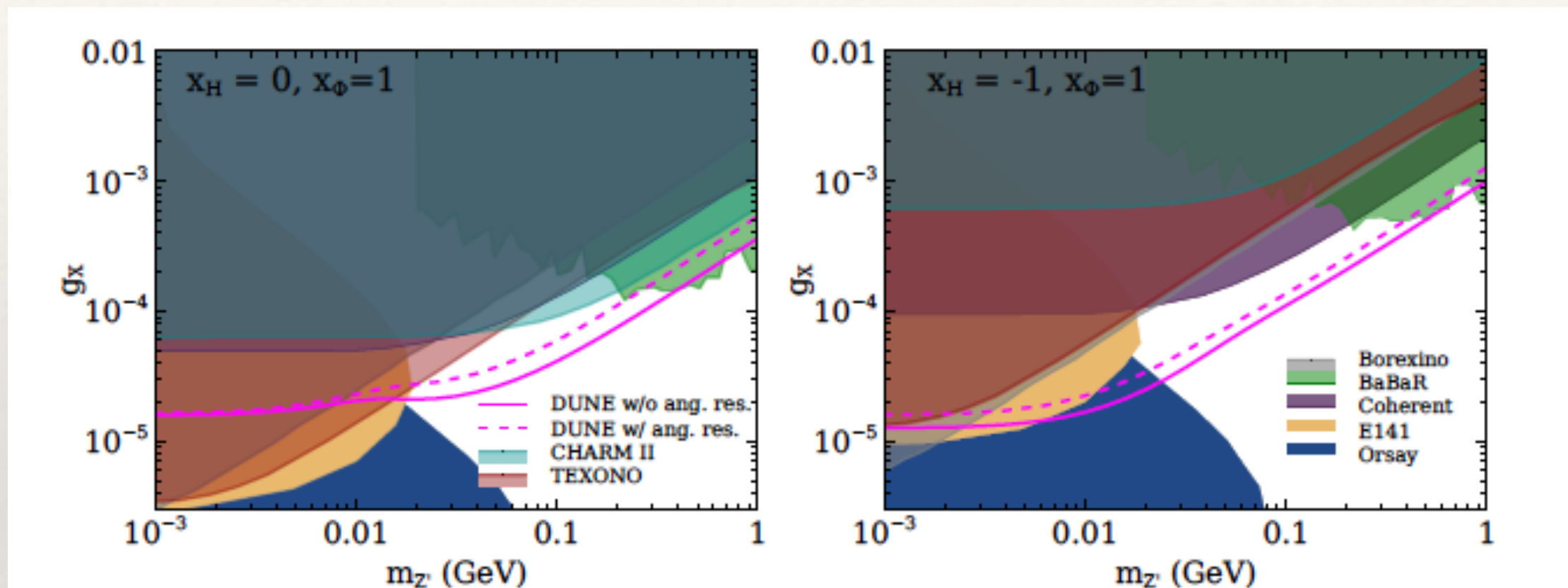
General U(1) model at DUNE

- ❖ 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

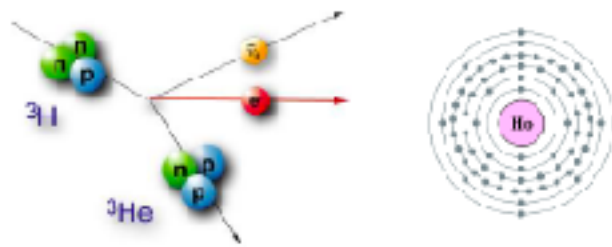
Chakraborty, Das, Goswami, Roy, JHEP 2022

Absolute neutrino mass

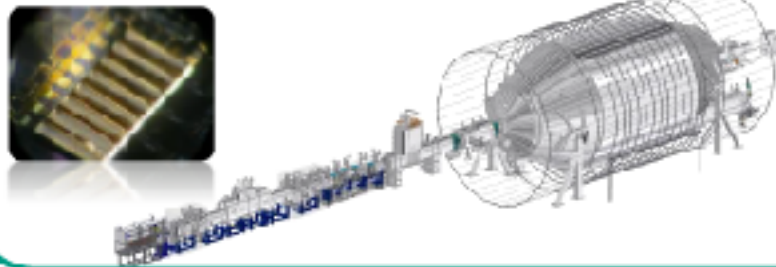
Information can come from three different sectors

kinematics of weak decays

- β -decay: ${}^3\text{H}$, EC: ${}^{163}\text{Ho}$
- **model-independent**

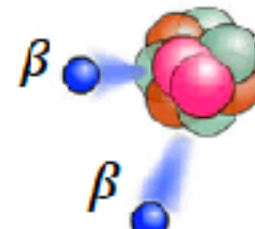


$$m(\nu_e) = \sqrt{\sum_{i=1}^3 |U_{ei}|^2 \cdot m_i^2}$$

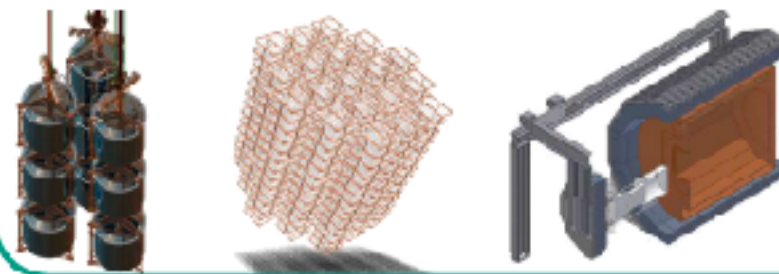


search for $0\nu\beta\beta$ -decay

- $\beta\beta$ -decay: ${}^{76}\text{Ge}$, ${}^{136}\text{Xe}$, ...
- **model-dependent** (α_i)

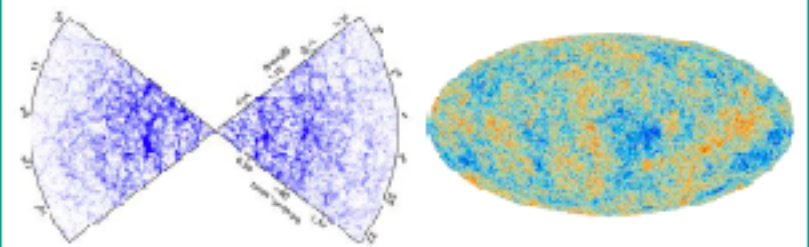


$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^3 U_{ei}^2 \cdot m_i \right|$$

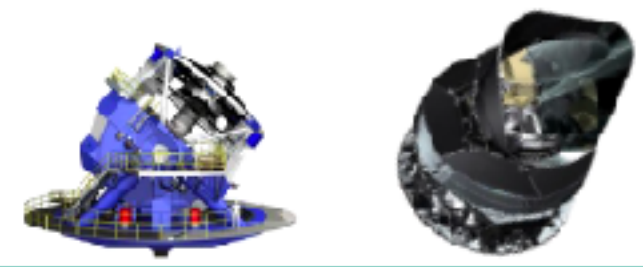


large-scale structures

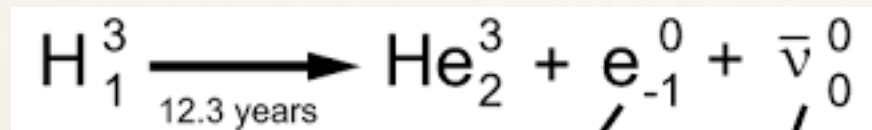
- CMB, galaxy surveys, ...
- **model-dependent** (H_0)



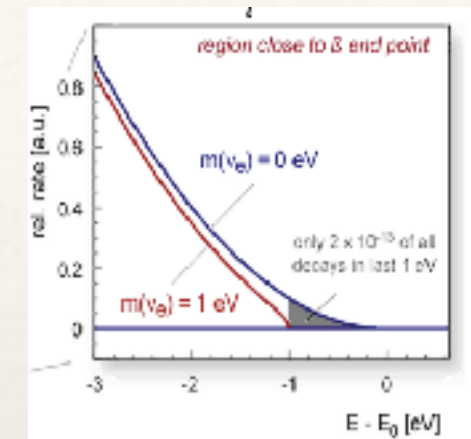
$$m_{tot} = \sum_{i=1}^3 m_i$$



Katrin: present and future limits



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

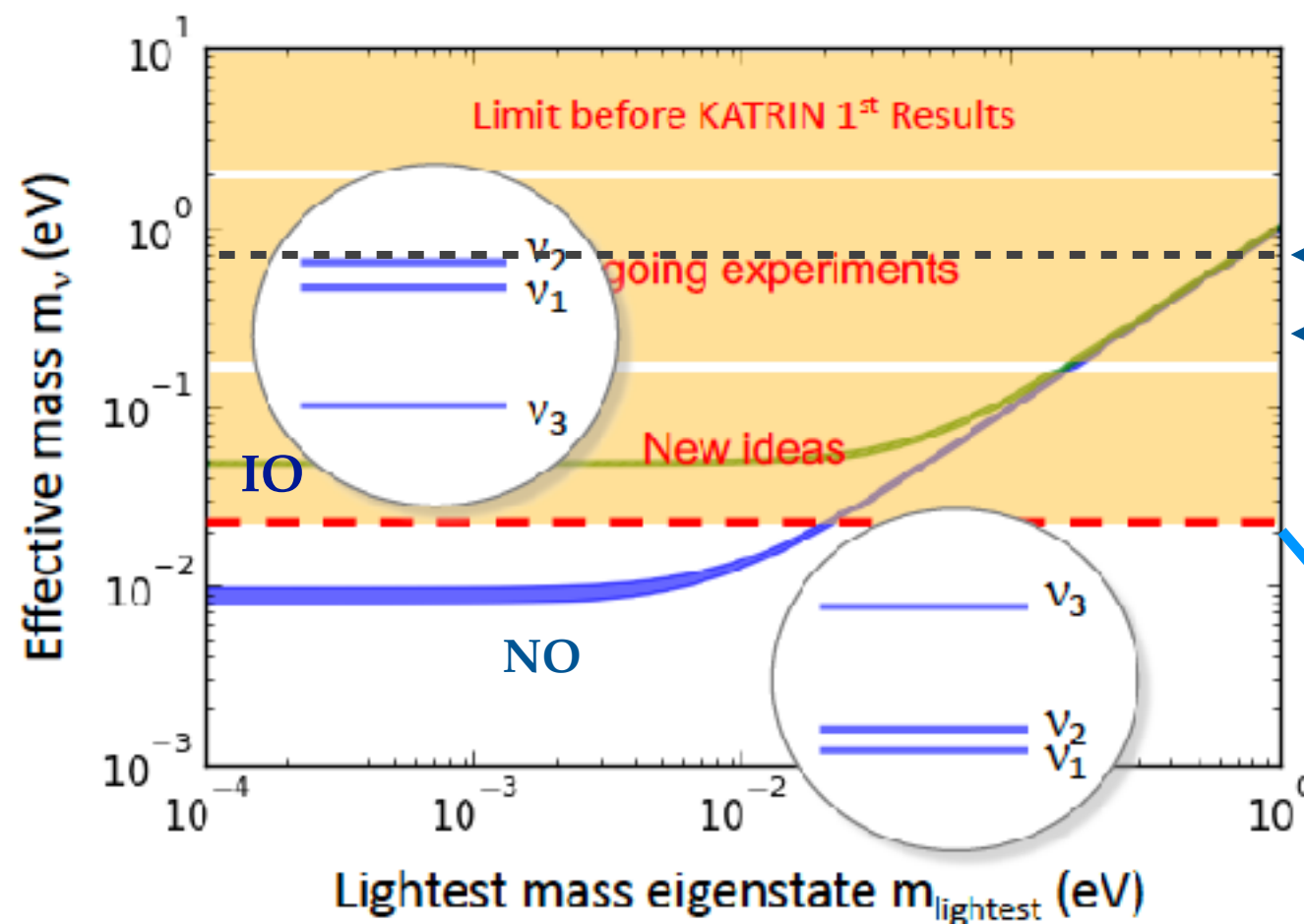


Fig: S. Mertnes, 2022

Beyond Katrin

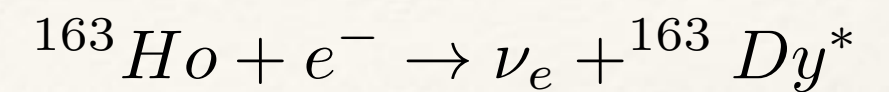
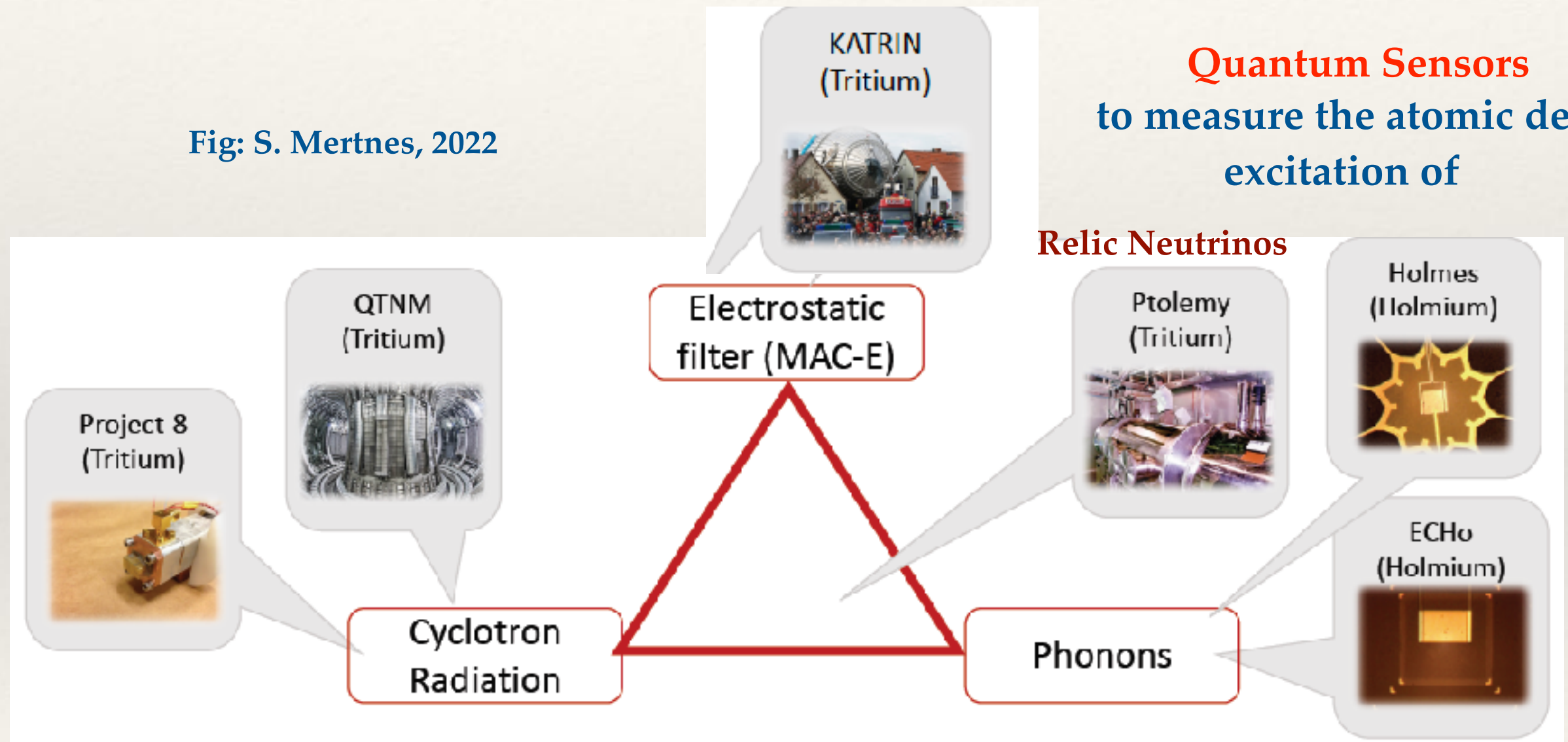


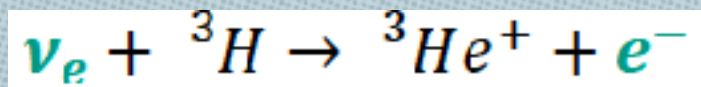
Fig: S. Mertnes, 2022



Expect to reach neutrino mass sensitivity around 1 eV and less

Katrin : other physics goals

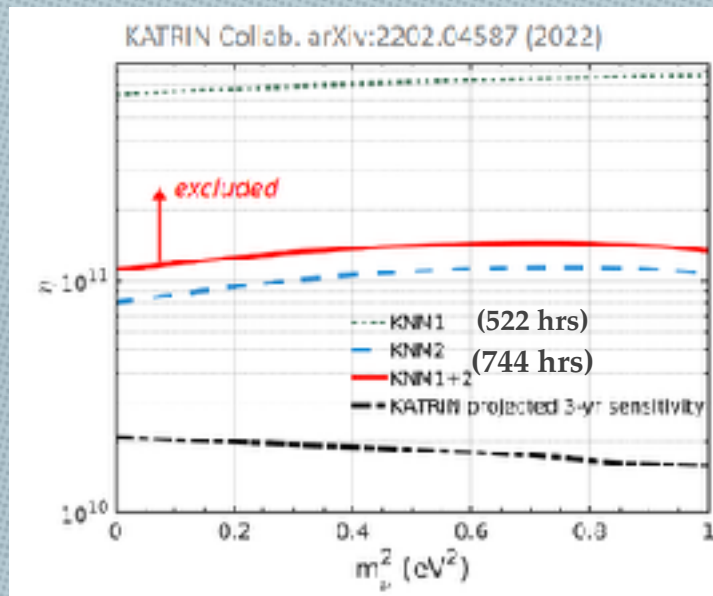
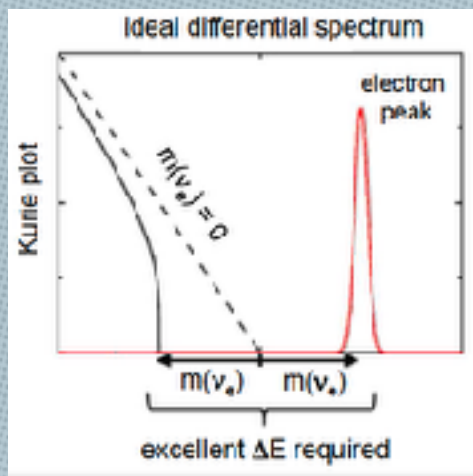
Search for relic neutrinos



10 neutrino capture/yr in 100 gm tritium

Electron peak above
end point

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



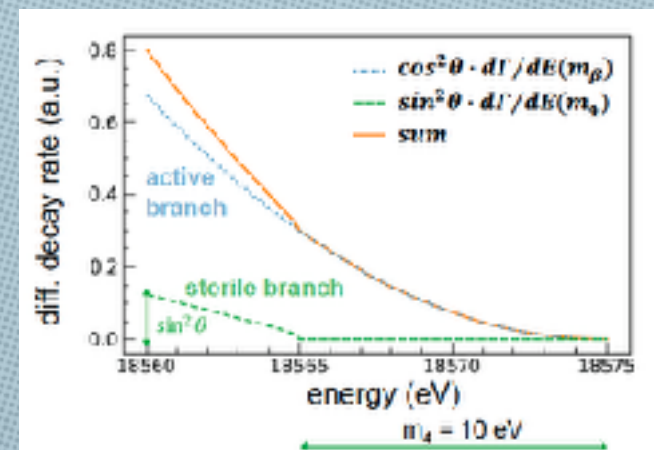
No signal observed

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

Also Lorentz Invariance Violation

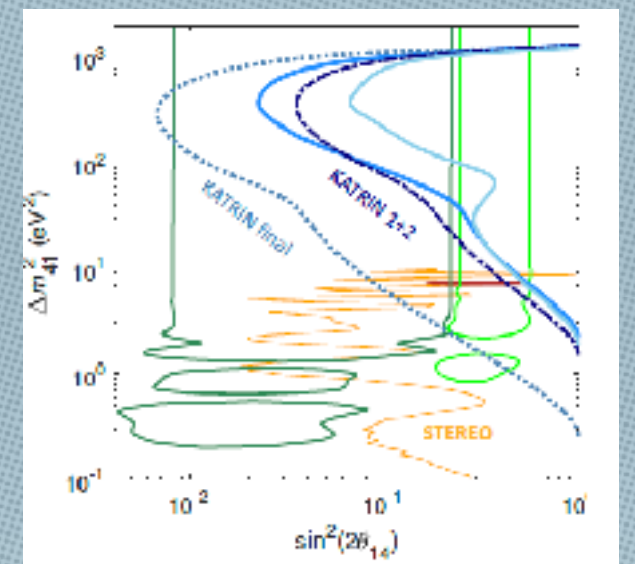
<https://arxiv.org/abs/2207.06326>

Search for sterile neutrinos



Kink in the energy
spectrum of
electrons

Complementary
probe to oscillation
experiments



Future: search for KeV sterile neutrinos

Silicon Drift Detector : TRISTAN

Neutrinoless double beta decay

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

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

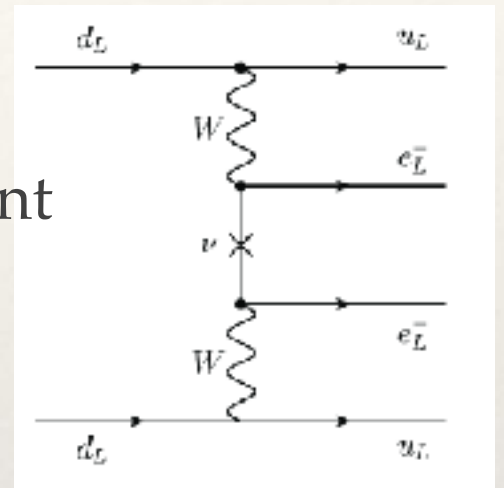
$$m_{\beta\beta} = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3 s_{13}^2 e^{2i\alpha_3}|$$

❖ Mediated by light neutrinos

$G \rightarrow$ phase space factor
 $M_\nu \rightarrow$ nuclear matrix element



Major uncertainty

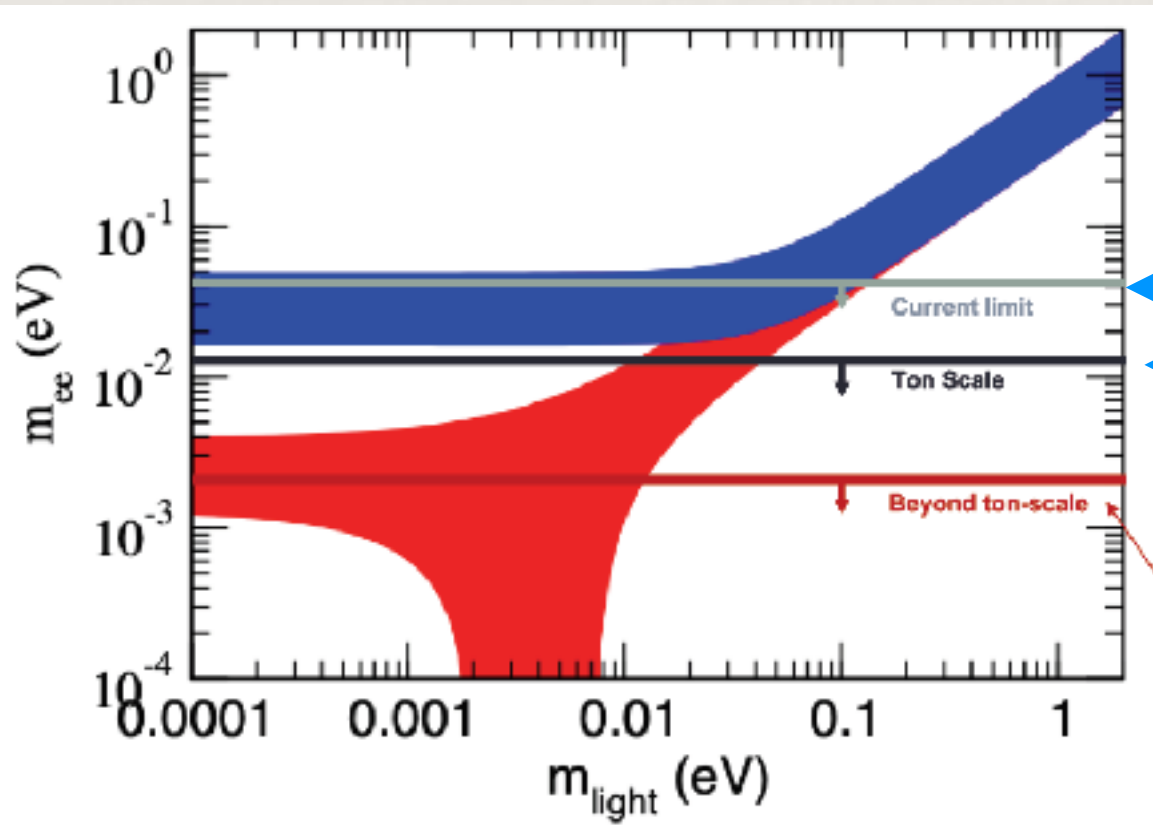


Extra diagrams in BSM
 Like sign di-lepton in
 colliders

KamLAND-ZEN + EXO

200+ GERDA + CUORE

IH can be confirmed (**nEXO, LEGEND**)

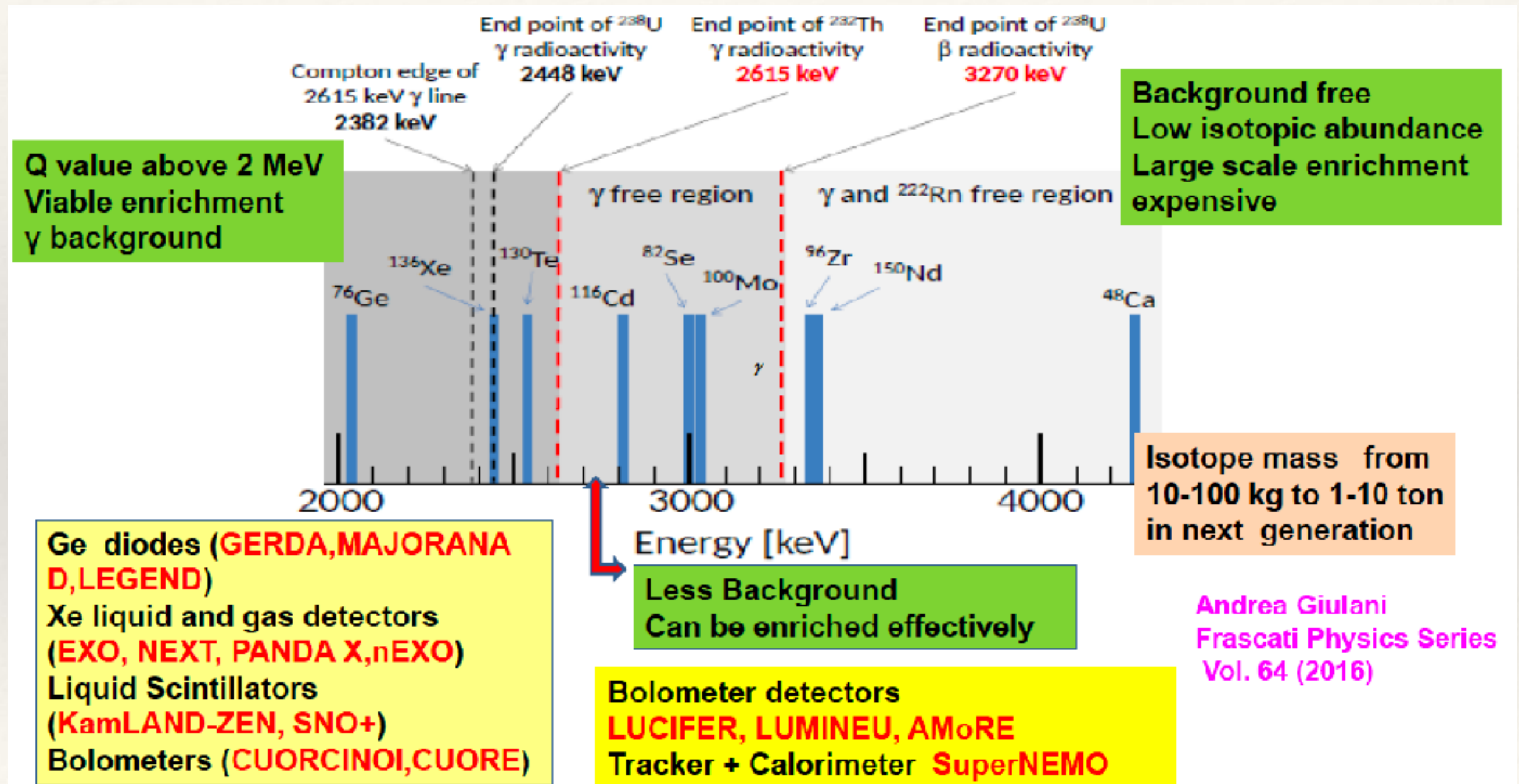


Can it be reached ?

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

Te, Mo, Ge, Xe...

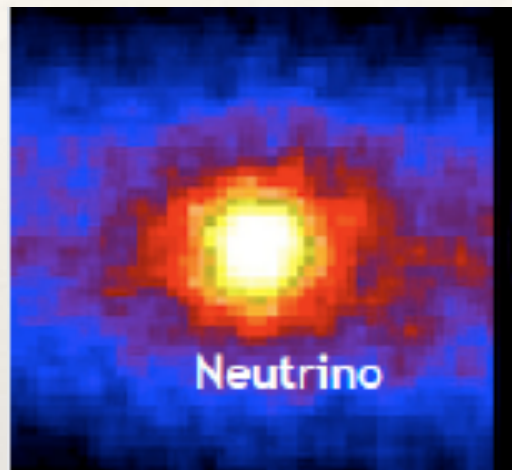
Neutrinoless double beta decay experiments



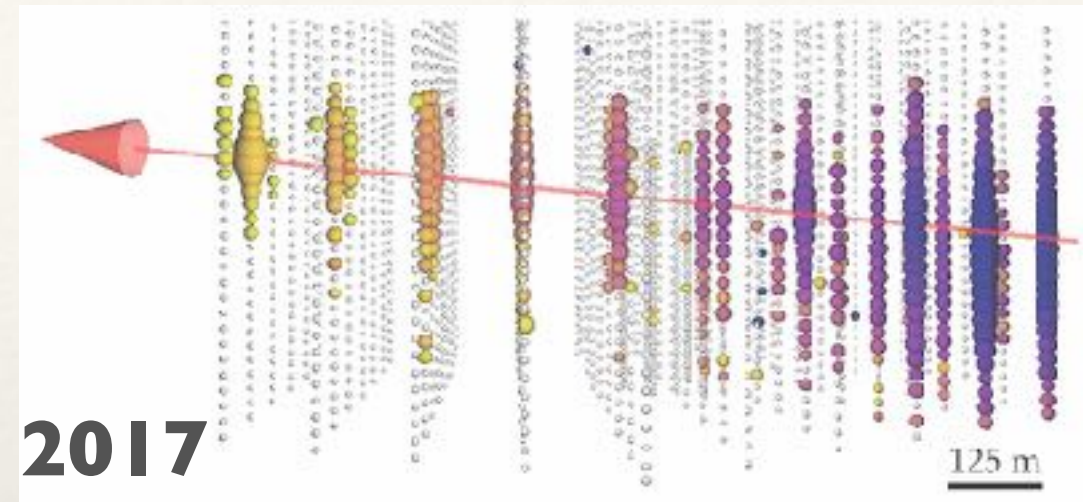
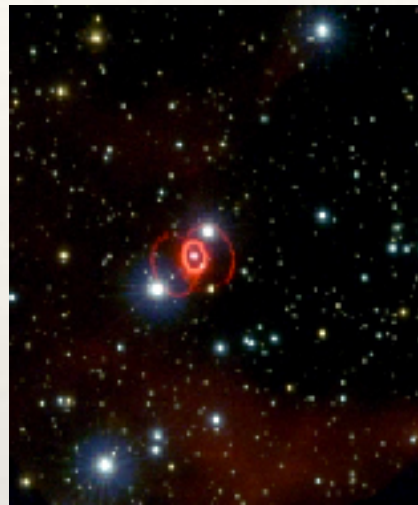
Andrea Giuliani
Frascati Physics Series
Vol. 64 (2016)

Neutrinos from Astrophysical Sources

Sun



SN1987a



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



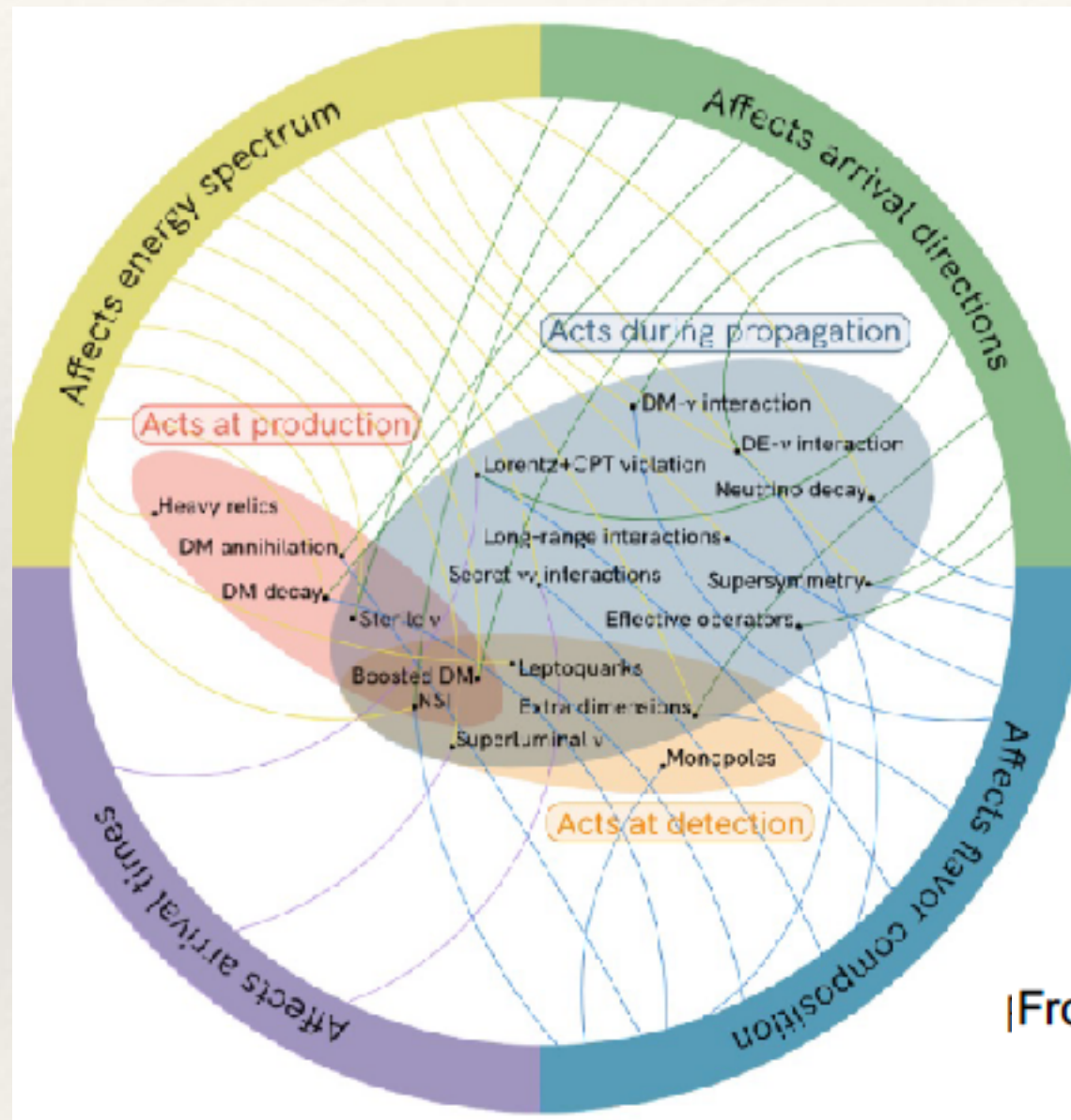
Tidal Disruption 2019
AT2019dsg



Active Galaxy
NGC 1068/Messier
2022



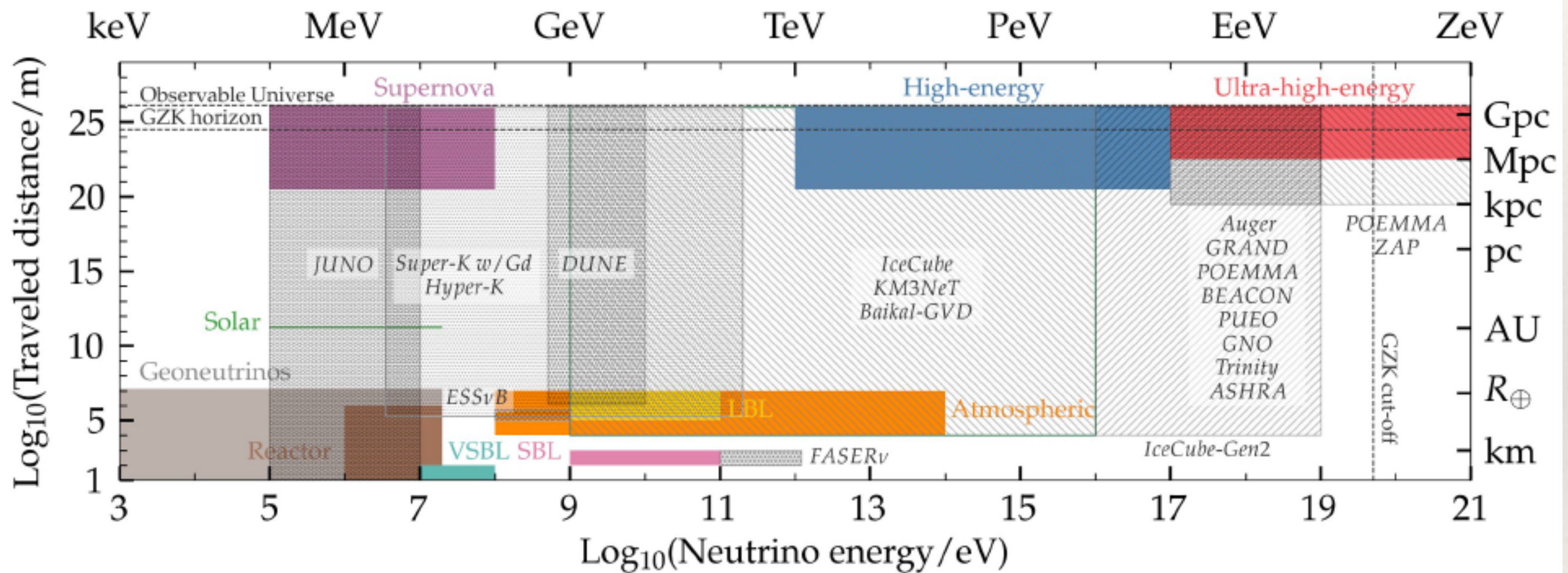
Physics using high energy neutrinos



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

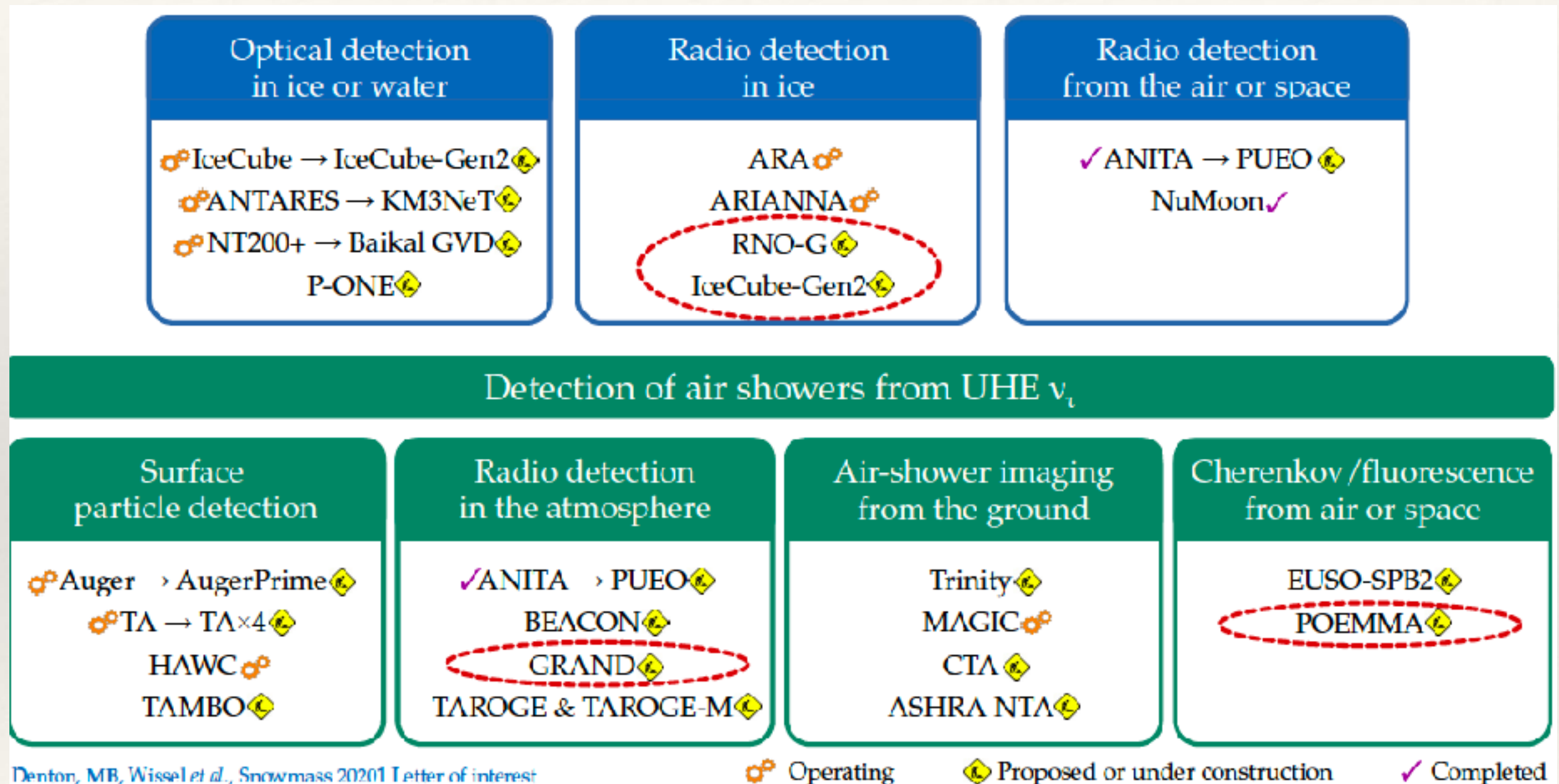
Current and planned detectors



From arXiv:2203.08096v2

Enhanced statistics, different detection technology

A snapshot of the different detectors

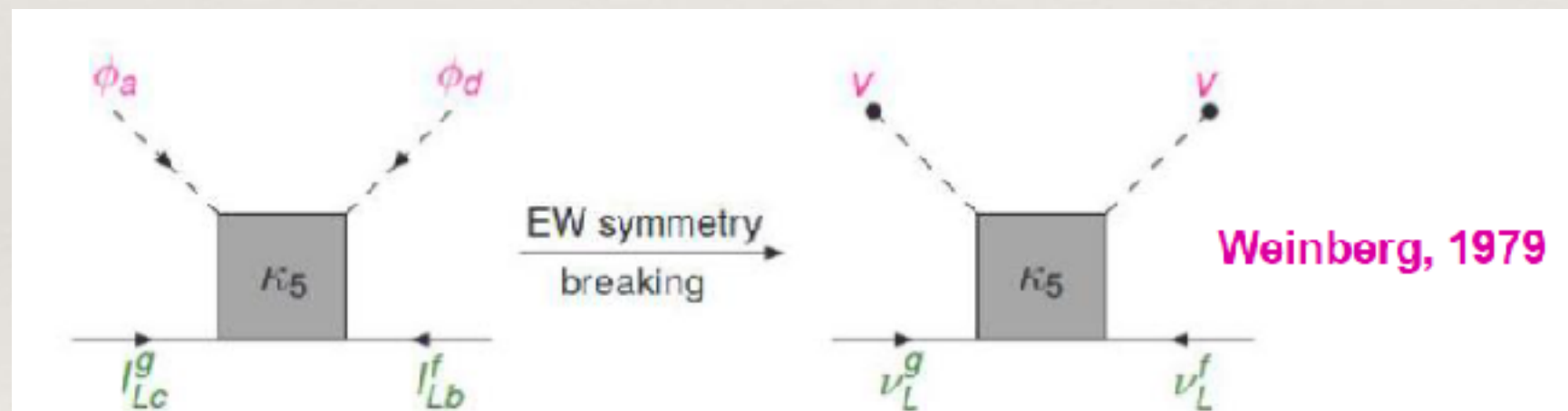


Why neutrinos masses are small ?

- ❖ 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

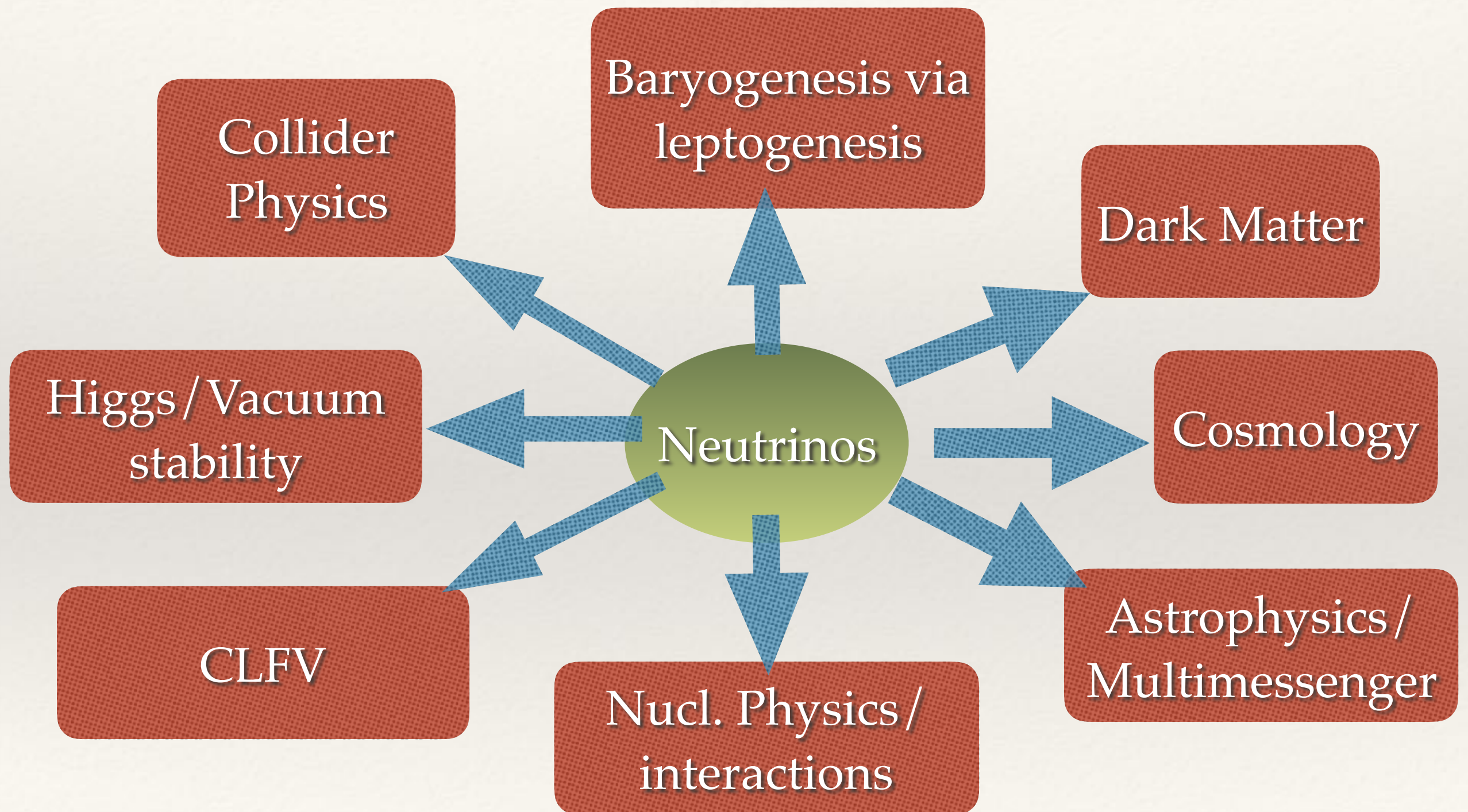
$$\mathcal{L} = \kappa_5 l_L l_L \phi \phi, \quad \kappa_5 = y_\kappa / \Lambda$$

$$m_\nu \sim \kappa_5 v^2 / \Lambda$$



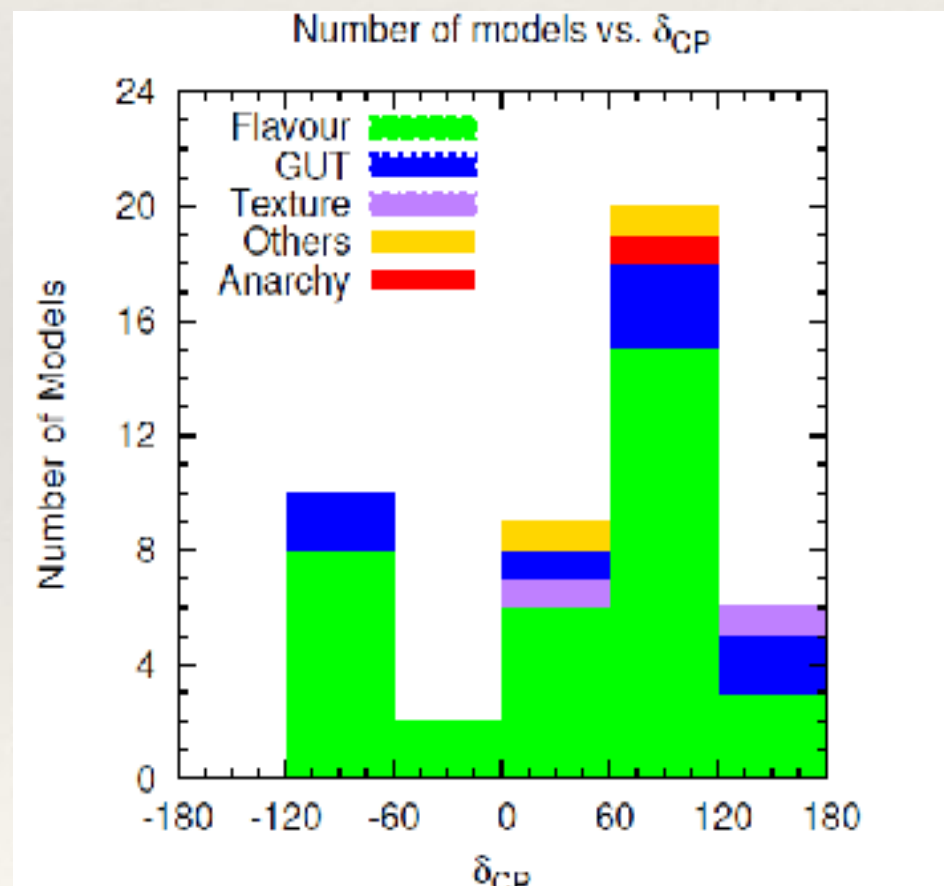
- ❖ Violation of lepton number ➡ Majorana nature of neutrinos
- ❖ Radiative mass generation, Models with higher dimensional operators

Neutrino Connections



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)

Concluding Remarks

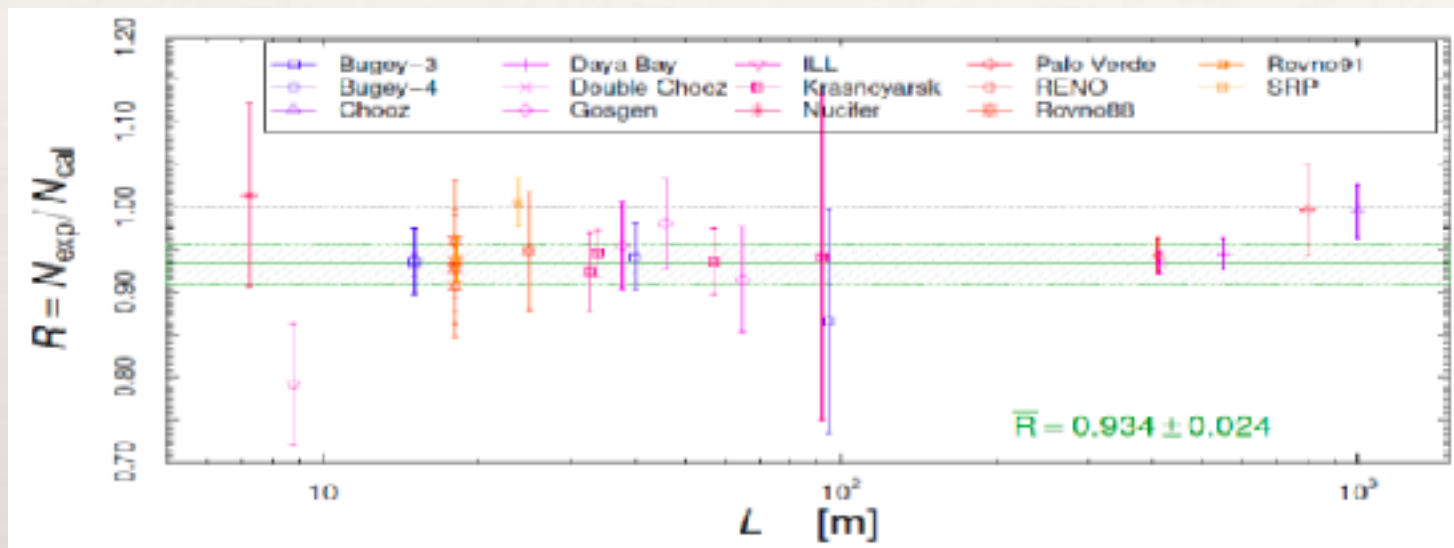
- ❖ Remarkable progress in past decade in unravelling oscillation parameters, three flavour paradigm well established
- ❖ A rich and diverse future programme — several experiments, new detection techniques, development of analysis tools connection with nuclear physics, astrophysics, cosmology, BSM physics 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



$$\Delta m_{41}^2 = 2.4 \text{ eV}^2 \quad \sin^2(2\theta_{14}) = 0.14$$

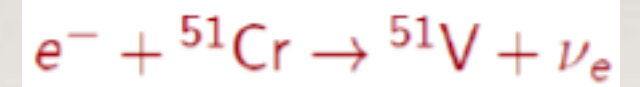
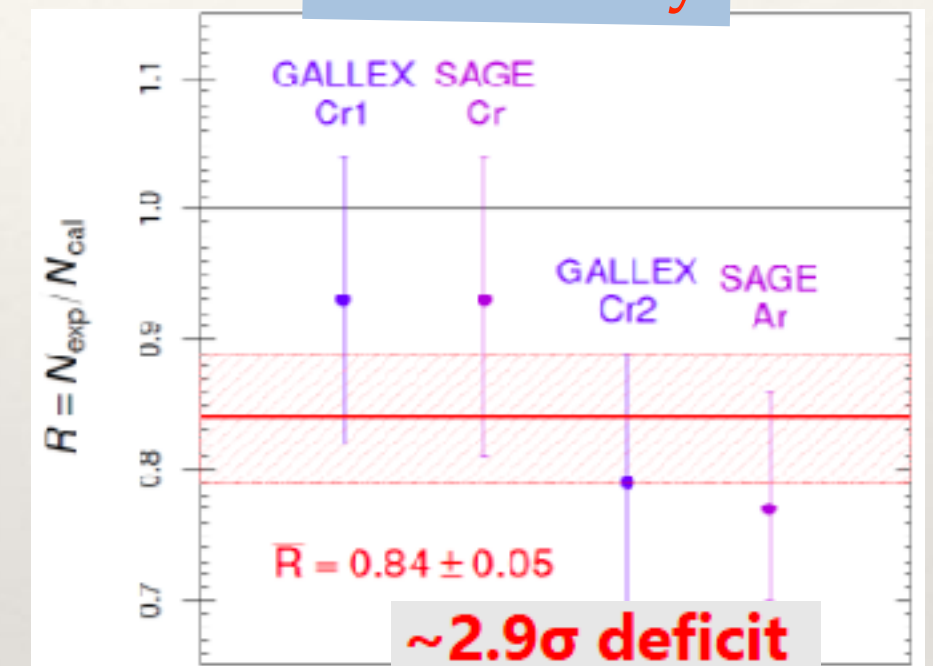
$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2 \left[1.27 \frac{\Delta m_{41}^2 L}{E_\nu} \left(\frac{\text{eV}^2 \cdot \text{m}}{\text{MeV}} \right) \right]$$

Mueller et al PRC 2011

Huber PRC 2011

Mention et al PRD 2011

Ga Anomaly



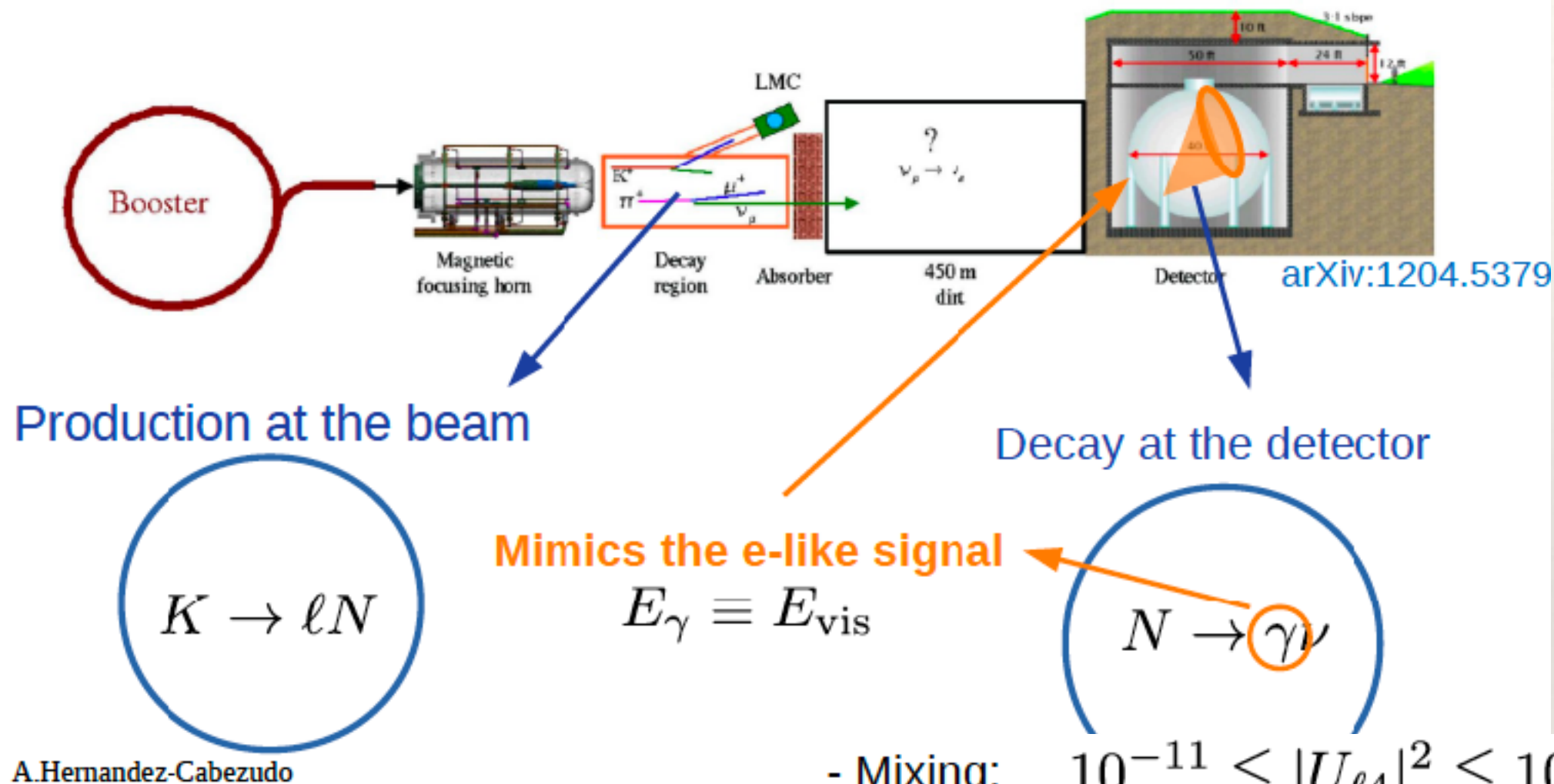
~0.8 MeV

Lavedar et al 2017

SAGE PRC 2007

GALLEX PRC 2007

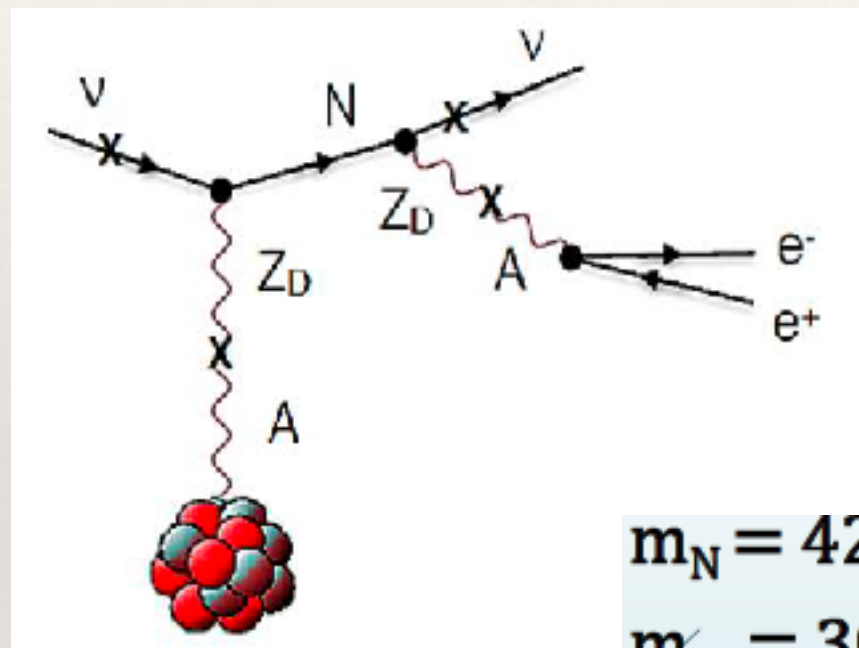
Heavy sterile neutrinos



- Mixing: $10^{-11} \lesssim |U_{\ell 4}|^2 \lesssim 10^{-7}$
- Mass: $\sim 250 \text{ MeV}$
- New physics scale: $10^4 \text{ TeV} \lesssim \Lambda \lesssim 10^7 \text{ TeV}$

Dark neutrino portal

$$\mathcal{L}_D \supset \frac{m_{Z_D}^2}{2} Z_{D\mu} Z_D^\mu + g_D Z_D^\mu J_{D\mu} + e\epsilon Z_D^\mu J_\mu^{\text{em}} + \frac{g}{c_W} \epsilon' Z_D^\mu J_\mu^Z$$



$$\alpha_D = 0.25$$

$$\alpha\epsilon^2 = 2 \times 10^{-10}$$

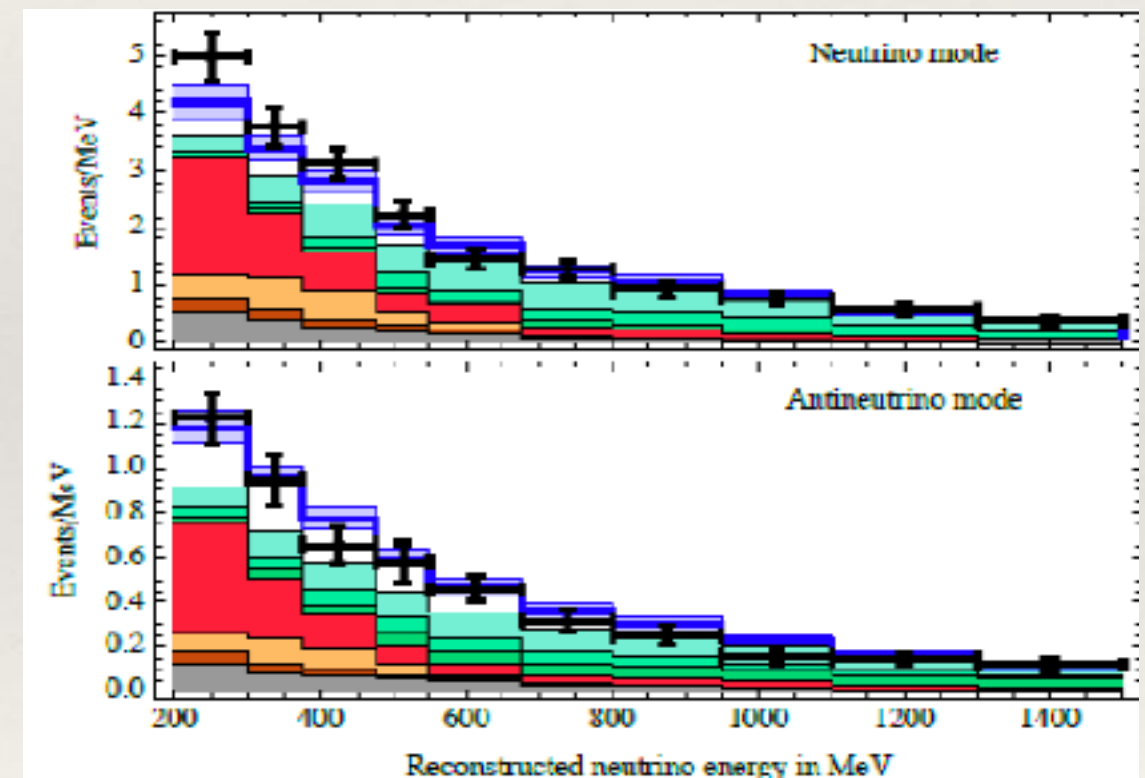
$$\chi^2/\text{dof} = 33.2/36$$

$$m_N = 420 \text{ MeV}$$

$$m_{Z_D} = 30 \text{ MeV}$$

$$|U_{\mu 4}|^2 = 9 \times 10^{-7}$$

Right handed neutrinos part of dark sector



Bartuzzo, Jana, Machado, Zukanovich-Funchal, PRL 2018