Neutrinos and the RPF

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Patrick Huber, Kate Scholberg, Elizabeth Worcester

Snowmass 2021

Rare and Precision Measurements Frontier Spring meeting, May 16-19,2022

Better than this talk...

4 neutrino frontier colloquia with 3 talks each

- Neutrinos in the three flavor paradigm:

  A. de Gouvea, R. Patterson, C. Wilkinson
- Beyond the Standard Model:

  J. Kopp, G. Karagiorgi, Z. Tabrizi
- Neutrinos & nuclear physics:

  K. Mahn, J. Gruszko, S. Mertens
- Neutrinos in astrophysics & cosmology:

  M. Toups, S. Horiuchi, Y. Wong

I used much of their material and visuals

Slides and recordings available from the NF Snowmass Wiki.

The main neutrino themes

- What are the neutrino masses?
- What is the origin of neutrino masses?
- Are neutrinos their own antiparticles?
- How are the masses ordered?
- Do neutrinos and antineutrinos oscillate differently?
- Discovering new particles and interactions
- Neutrinos as messengers

What are the neutrino masses?

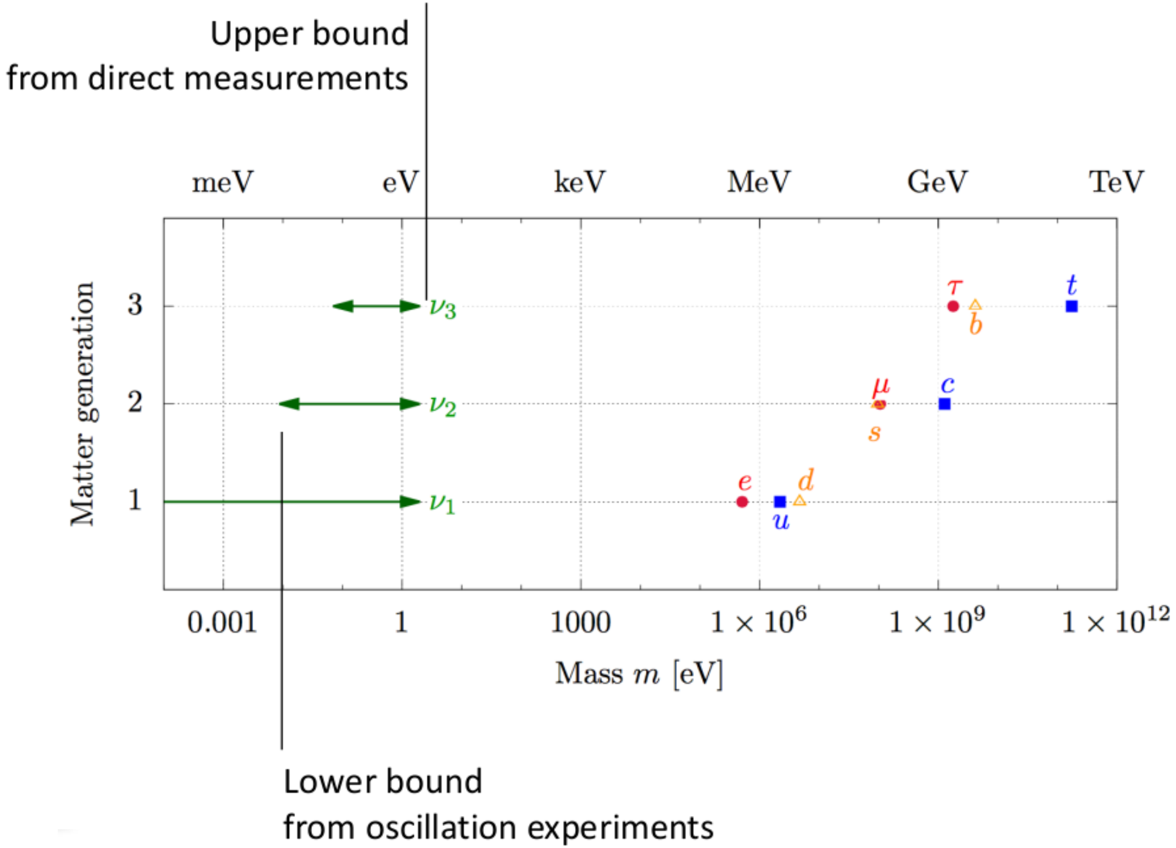


Figure from SNOWMASS neutrino colloquium by S. Mertens

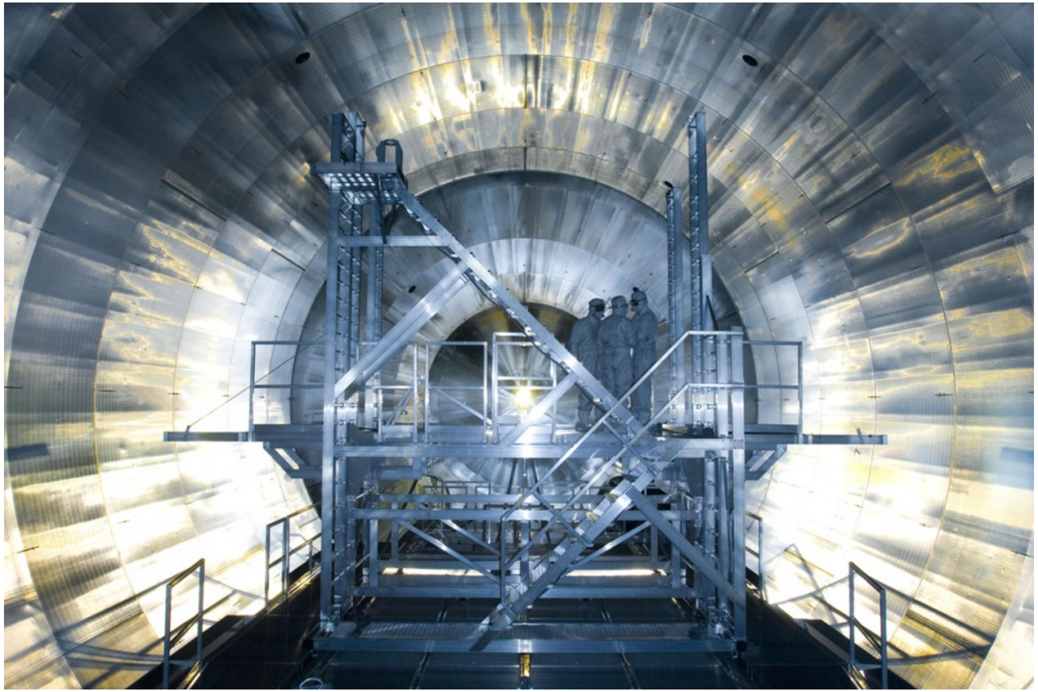
The different possibilities allowed by data have direct implications on

direct mass searches,

neutrinoless double beta decay searches

and theory.

Direct neutrino mass measurements



Katrin current limit is 0.8eV with a future sensitivity of 0.2eV

There are ideas beyond KATRIN:
Project 8, ECHO, Holmes

May reach all of inverted hierarchy mass region.

Neutrino masses from cosmology

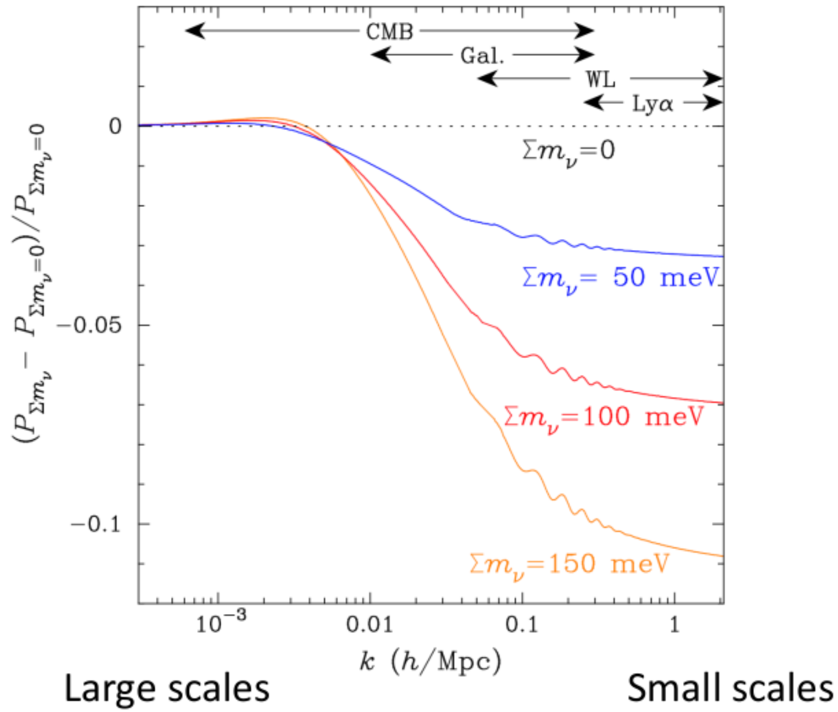


Figure from SNOWMASS neutrino colloquium by S. Mertens

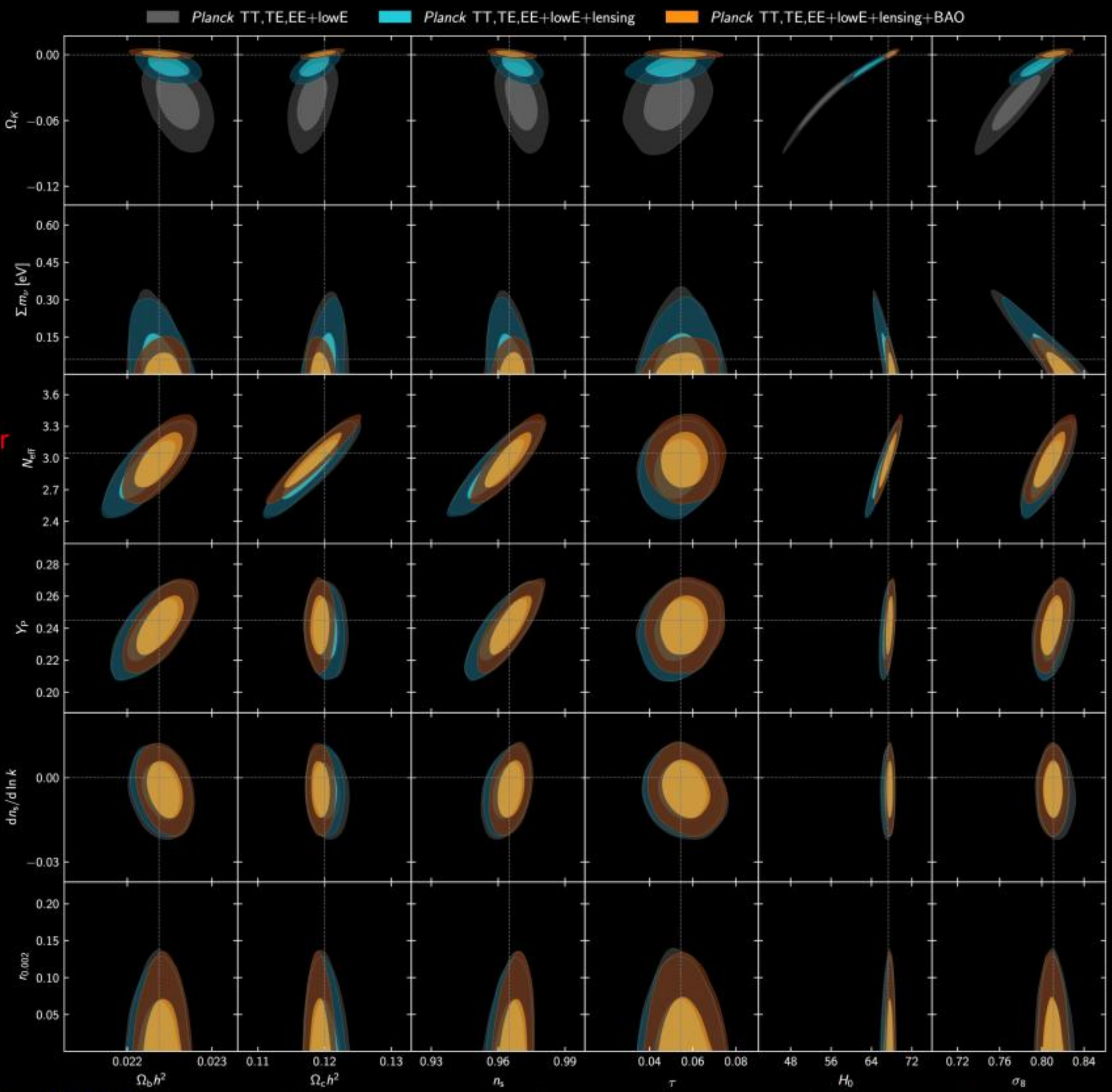
neutrino mass ↑

energy density in neutrinos ↑

small scale structure ↓

Current limits are order 0.2-0.5eV and will reach << 0.1eV soon

Relies on a long chain of inference, the more we can constrain neutrino properties in the lab, the better it is for cosmology!



Neutrino mass

Effective number of neutrinos

Aghanim et al. [Planck] 2021

Dark matter density

Spectral index

Hubble parameter

Fluctuation amplitude

A direct neutrino mass measurement or even a confirmation of the inverted mass ordering (minimum $\sum m_\nu = 0.11$ eV) by oscillation experiments would help to shrink these ellipses.

Establishing the existence (or not) of light sterile neutrino states through oscillation experiments would shrink the uncertainty in $N_{\rm eff}$ from the neutrino sector.

More accurate estimates of parameters inaccessible in the lab.

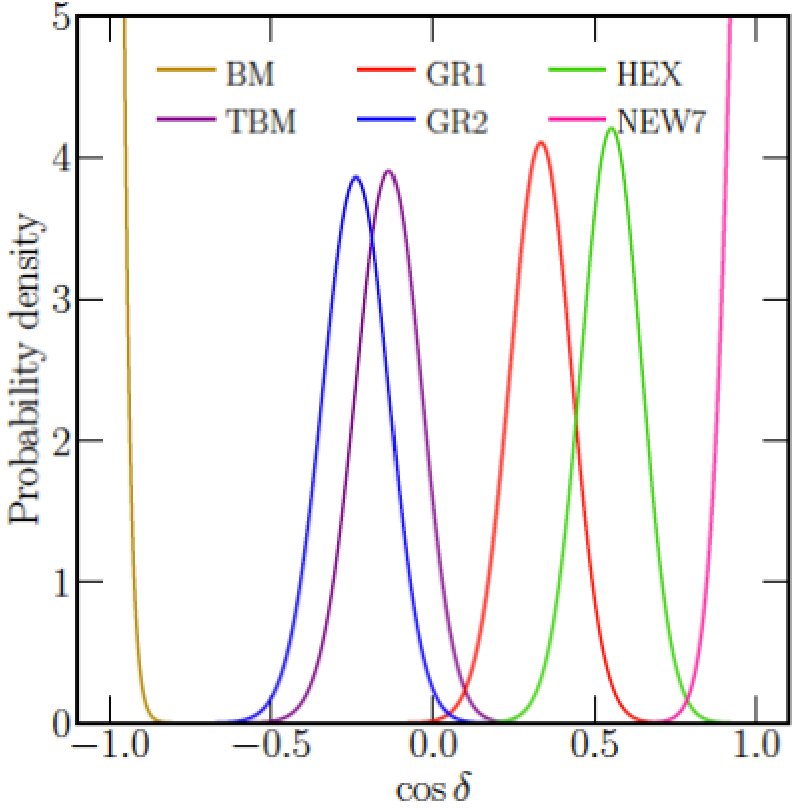
Slide from SNOWMASS neutrino colloquium by Y. Wong

Origin of neutrino masses?

- Same as all SM fermions: from interactions with the SM Higgs but with a very small coupling
- Coupling to a different Higgs
- Generated at a very different energy scale

Each of these options raises many new questions in turn.

Flavor models



Everett et al. 2019

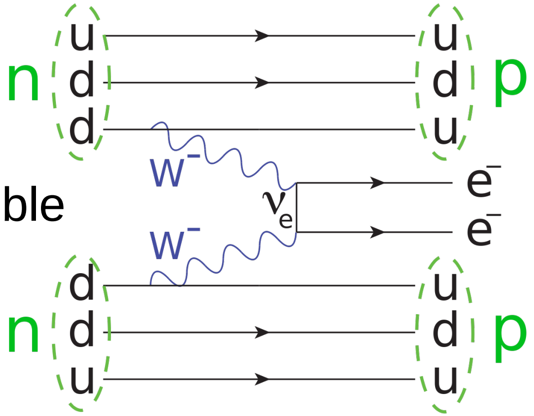
$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Symmetries are not exact, but still lead to correlations between mixing parameters.

Figures from SNOWMASS neutrino colloquium by A. de Gouvea

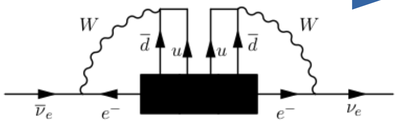
Are neutrinos their own antiparticles?

Majorana neutrino mass term → Neutrinoless double beta decay



Neutrinoless double beta decay → Majorana neutrino mass term

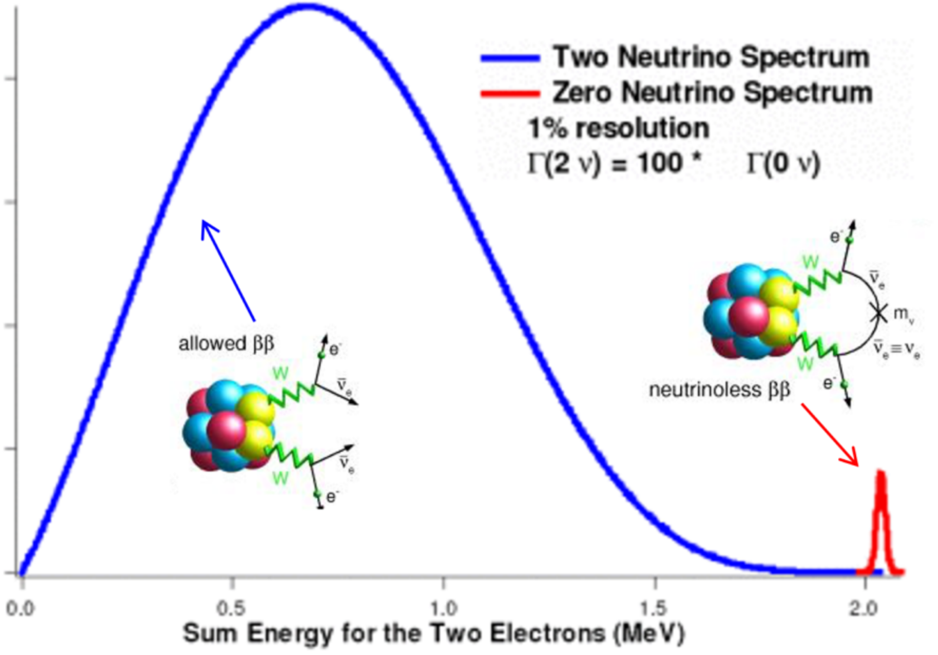
Schechter Valle theorem



… but quantitatively the Majorana mass can be tiny compared to the actual neutrino mass → effectively the neutrino behaves like a Dirac particle

Duerr, Lindner, Merle 2016

0nuBB



$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

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

Even in a vanilla Majorana mass scenario:

Nuclear matrix elements!
Neutrino oscillation parameters
CP phases (!)

2nuBB is already a rare process
τ~1E21 years

Figures from SNOWMASS neutrino
colloquium by J. Gruszko

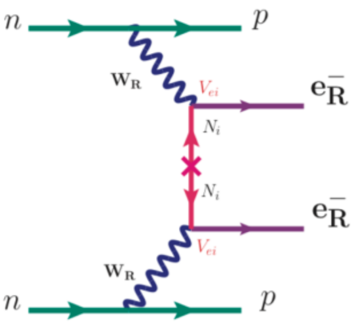
0nuBB and new physics

Many ways to generate lepton number violation and essentially all of them can lead to 0nuBB

EFT methods allow to understand the phenomenology in more model independent way.

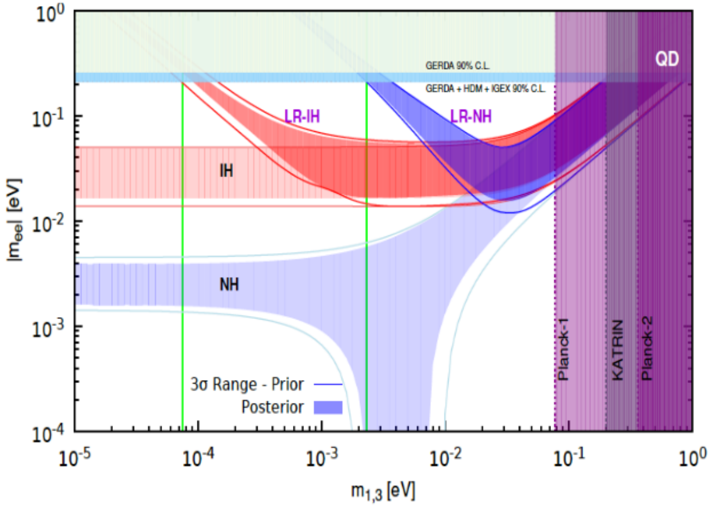
Measuring angular correlations could help.

Nuclear matrix elements depend on range of the mediator



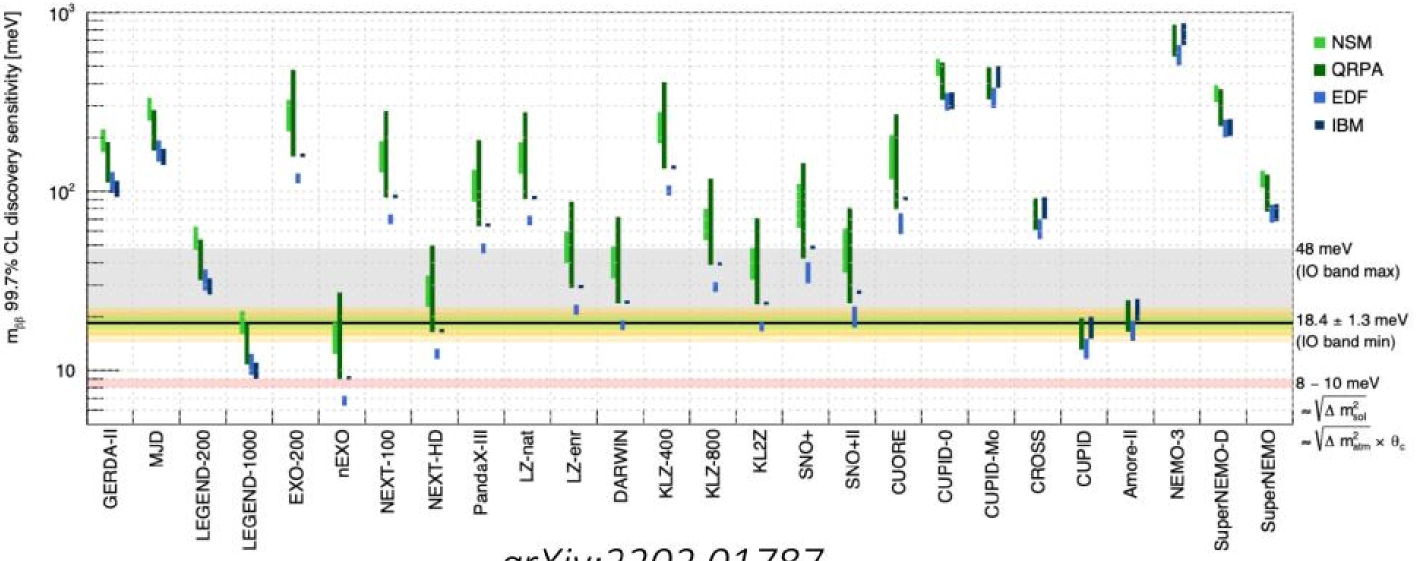
Left-Right Symmetric Model, $M_{W_R} \sim 2$ TeV, $M_N = 1$ TeV, $g_R \sim 2/3\, g_L$

JHEP 10 (2015) 077



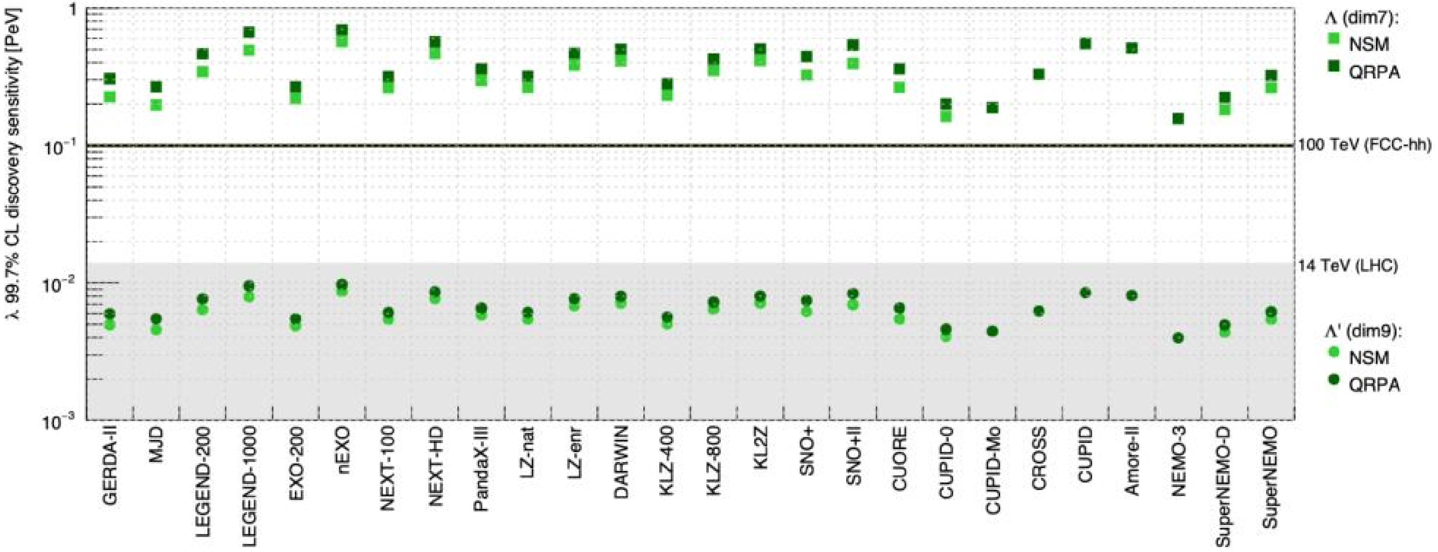
Figures from SNOWMASS neutrino colloquium by J. Gruszko

Light Majorana neutrino exchange (dim 5):



arXiv:2202.01787

0νββ via dimension 7 and 9 operators:



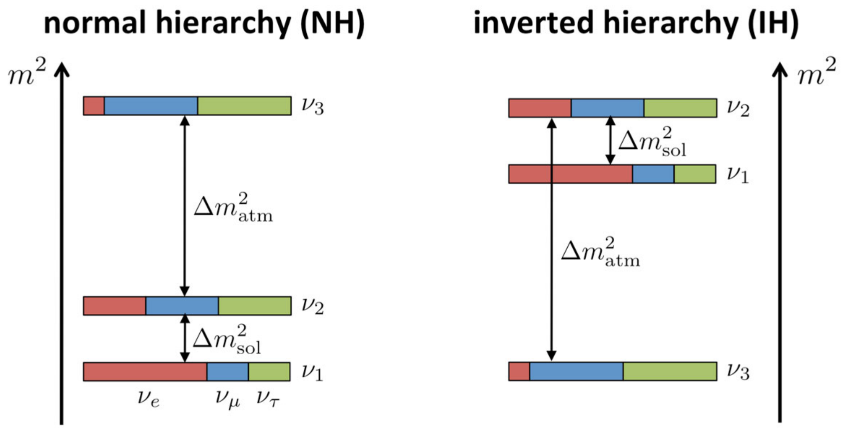
Experimental Prospects

Know how to cover inverted hierarchy region

10meV may need new ideas!

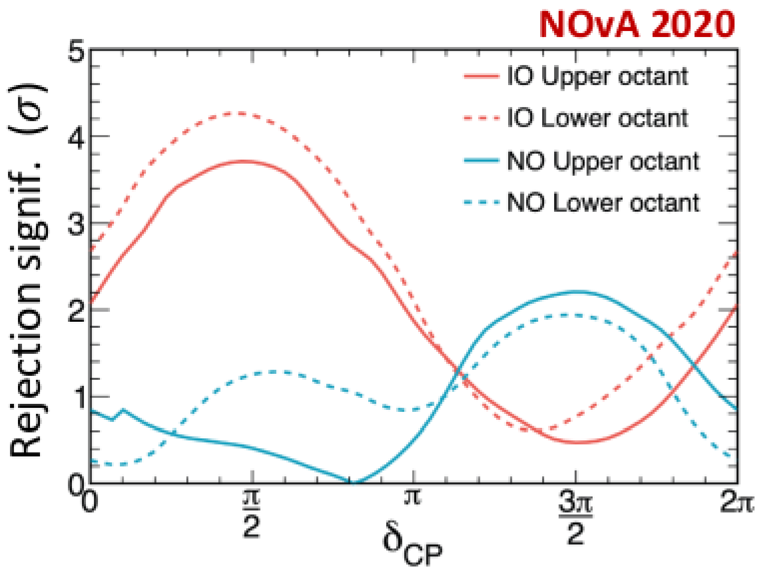
Significant potential to probe scales beyond colliders.

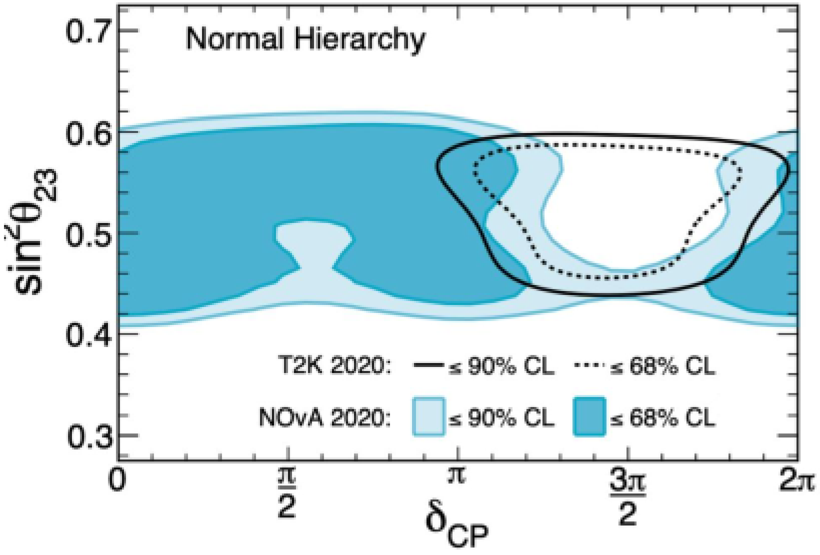
How are the masses ordered?

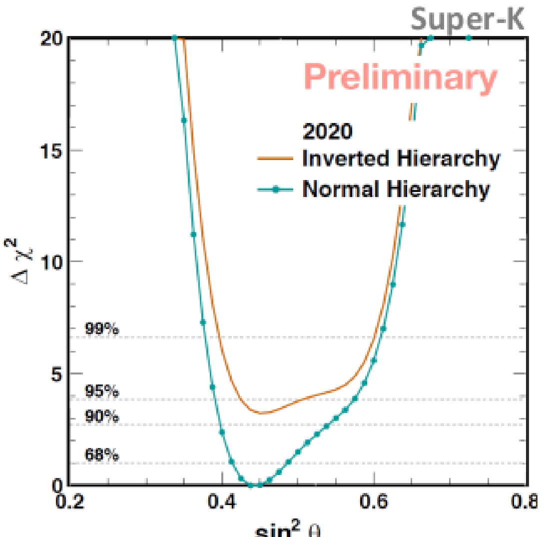


- Directly impacts mass searches
- Can distinguish between models

- Mass searches (beta decay, 0nuBB, cosmology)
- Matter effects (long-baseline oscillation, atmospheric neutrinos)
- Vacuum oscillation (reactor oscillation experiments)







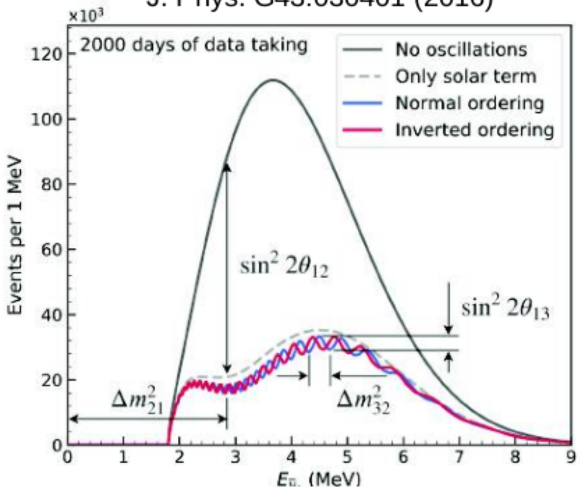
Current experiments are using matter effects to extract the mass hierarchy and thus there is a strong correlation with the value of th23 and the delta_cp

Global fits may reach 3 sigma in the next few years IF data mutually agrees.

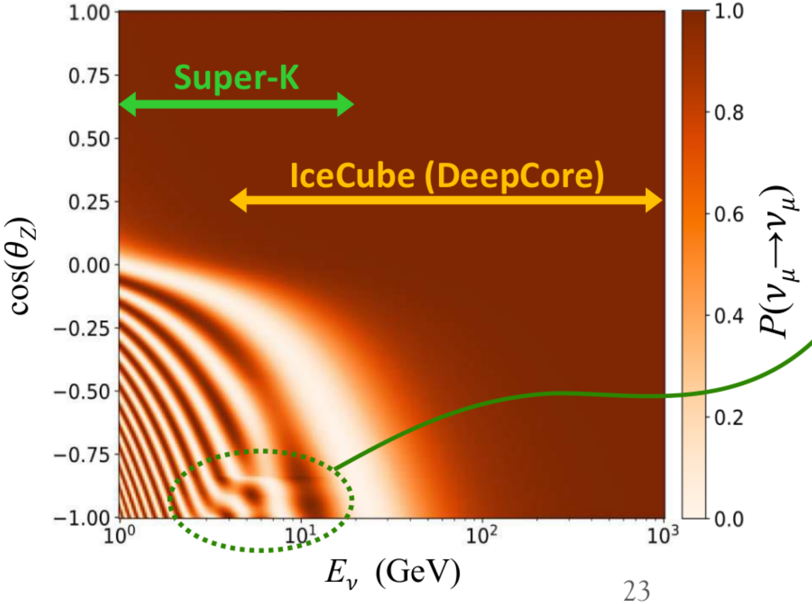
Figures from SNOWMASS neutrino colloquium by R. Patterson

Deep Core & JUNO

J. Phys. G43:030401 (2016)



JUNO uses interference between two mass scales to detect the hierarchy with a 25kt liquid scintillator detector at 55km distance from nuclear reactors

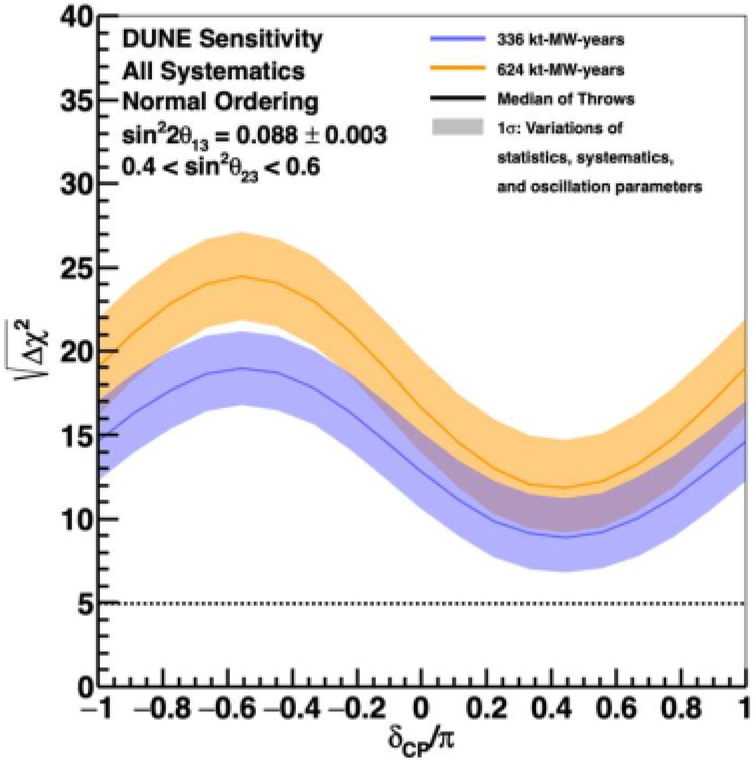


Atmospheric neutrinos in the 1-10GeV exhibit the MSW resonance, requires very large detectors

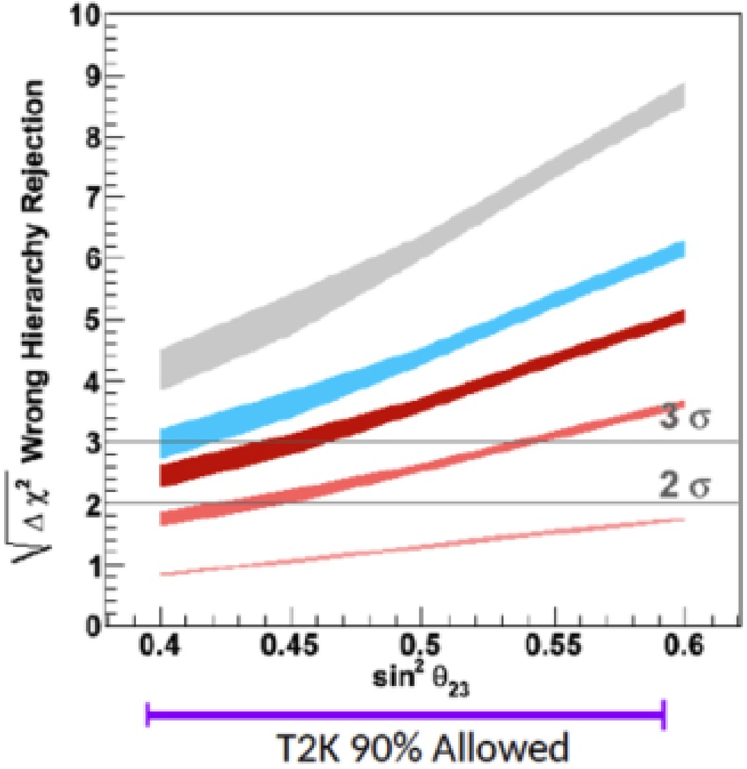
→ neutrino telescopes

Figures from SNOWMASS neutrino colloquia
by C. Wilkinson & R. Patterson

DUNE & HyperK



EPJC 80 (2020) 978



10 year

5 year

1 year

DUNE beam data – precision study of matter effects

Hyper-K atmospheric data

Figures from SNOWMASS neutrino colloquium by C. Wilkinson

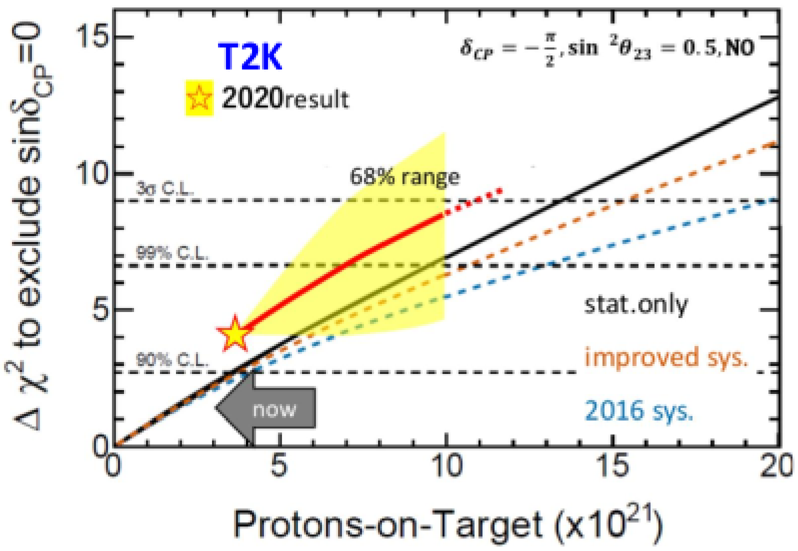
Is there CP violation in the lepton sector?

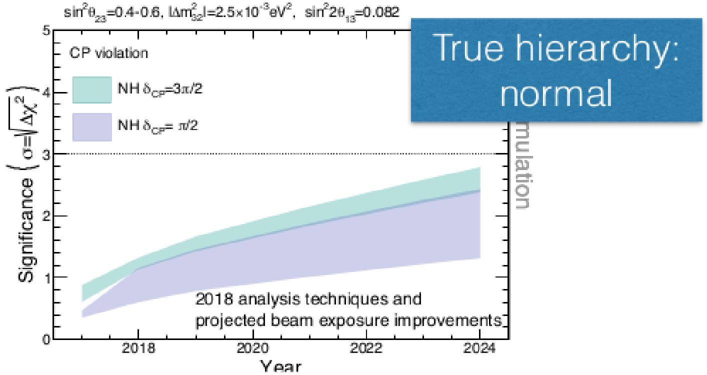
CP violation is required by the baryon asymmetry of the Universe (BAU) and there are only 3 places this can appear in the SM

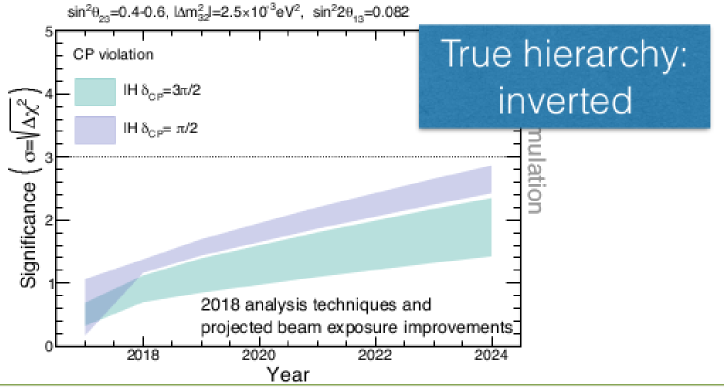
- CKM mixing phase – is large
- QCD vacuum – conserves CP to unreasonable levels
- Neutrino mixing phase and possibly 2 Majorana phases

So the neutrino mixing phase is the obvious (and currently only) target – can be studied in long-baseline appearance searches only

Near term prospects



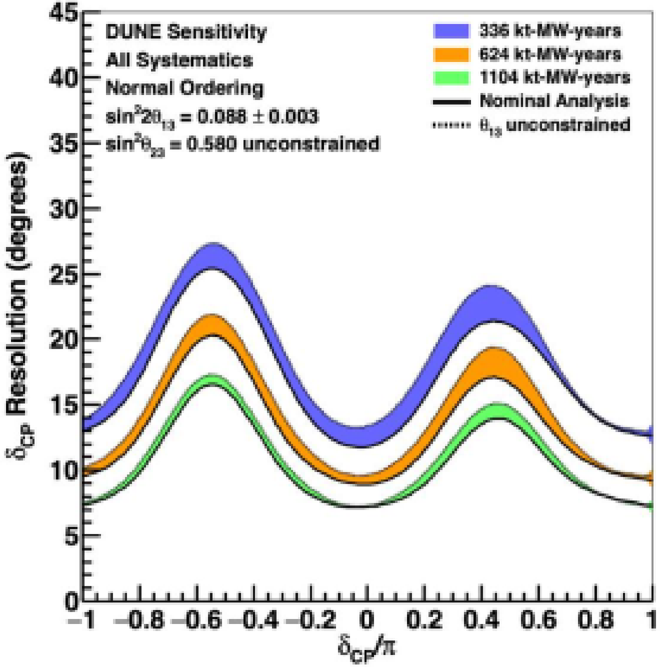




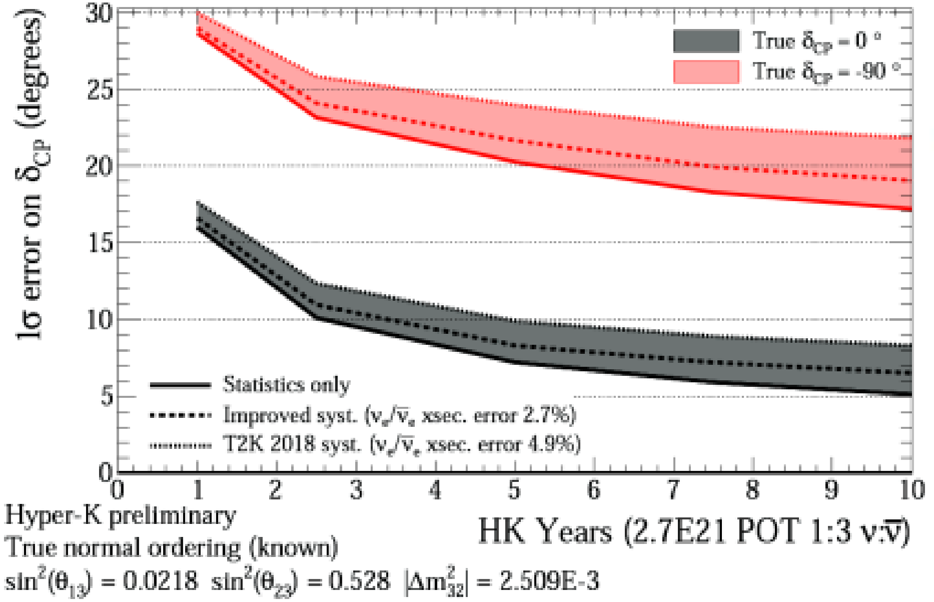
Maybe 3 sigma with the current experiments...

Figures from SNOWMASS neutrino colloquium by R. Patterson

DUNE & Hyper-K



Snowmass year = 10^7 s

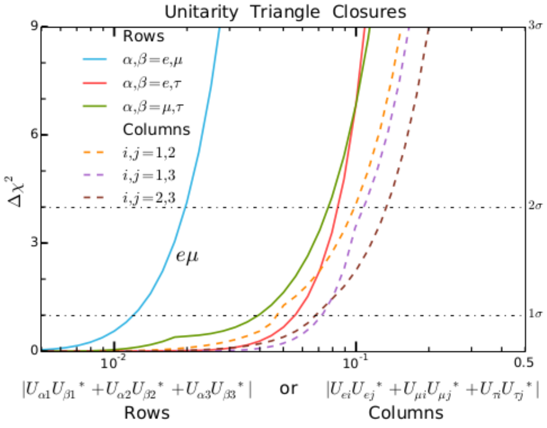


Comparable sensitivities

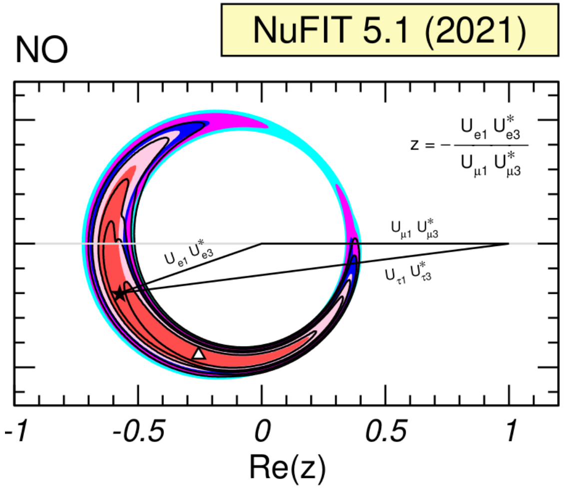
– but very complementary systematics

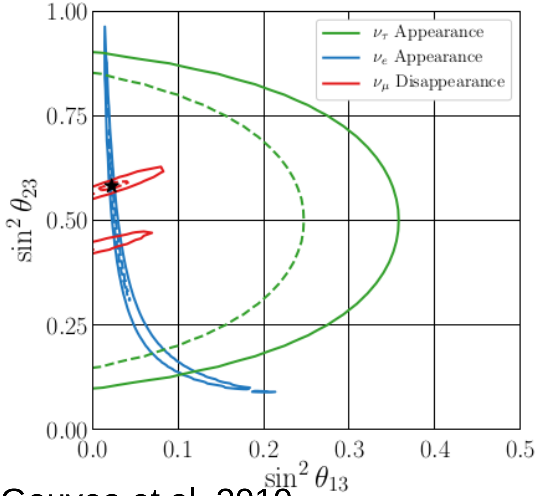
Figures from SNOWMASS neutrino colloquium by C. Wilkinson

Testing the 3 flavor framework



Parke, Ross-Lonergan 2015





De Gouvea et al. 2019

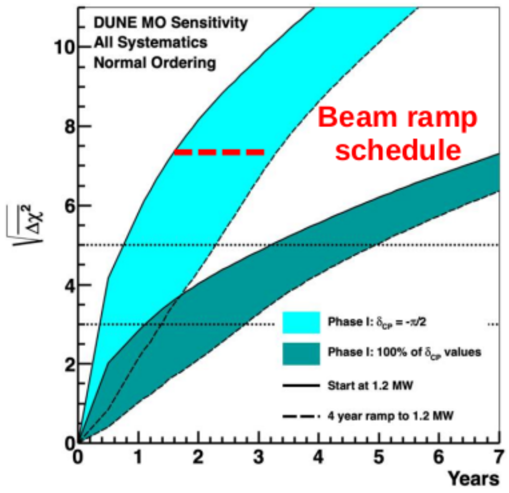
Past

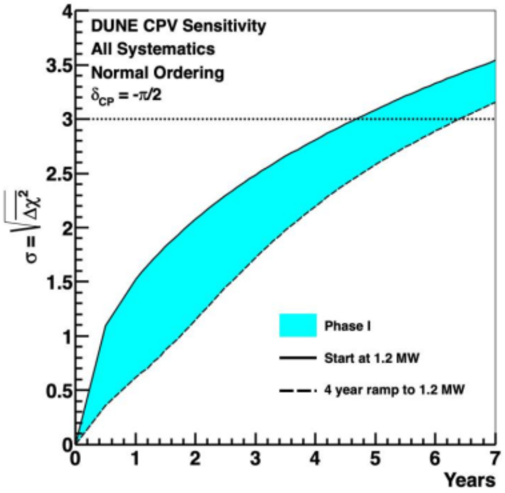
Present

Future

Requires observation of tau neutrinos in the final state – hard !

DUNE staging





Phase I:

✔ Unambiguous MO

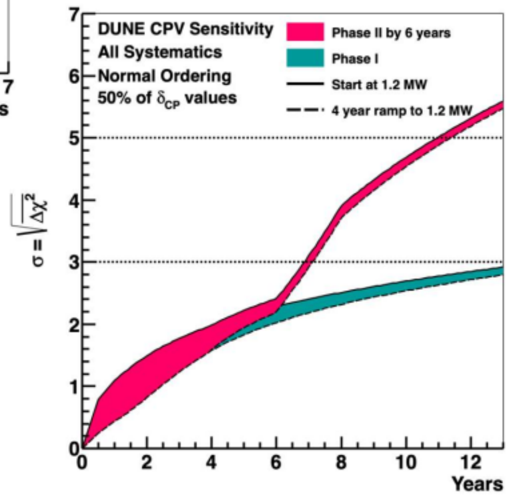
✔ 3σ CPV at maximal δ_{CP}

Phase II:

✔ P5 goal of 5σ CPV for 50% of δ_{CP}

✔ Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}

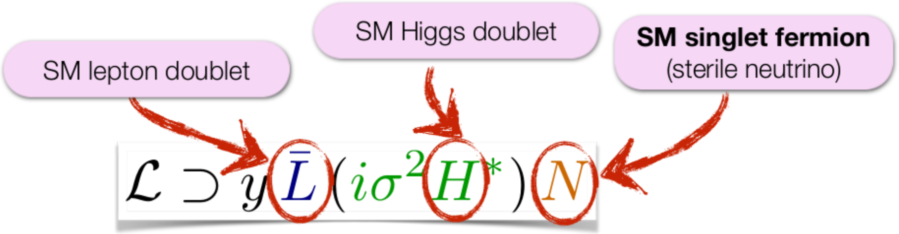
Requires 2.4 MW, 40 kt and full ND



Figures from SNOWMASS neutrino colloquium by C. Wilkinson

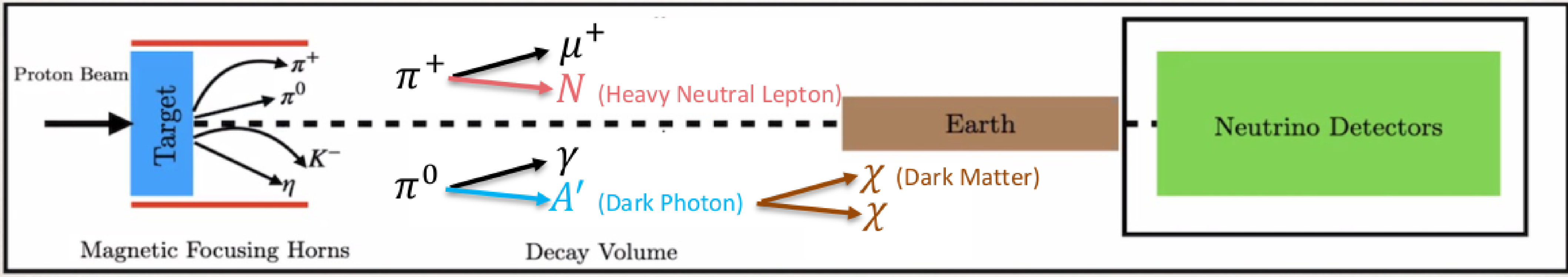
Discovering new things

- New neutrinos or new neutrino interactions



- New light states not related to neutrinos

Figures from SNOWMASS neutrino colloquia by J. Kopp and Z. Tabrizi



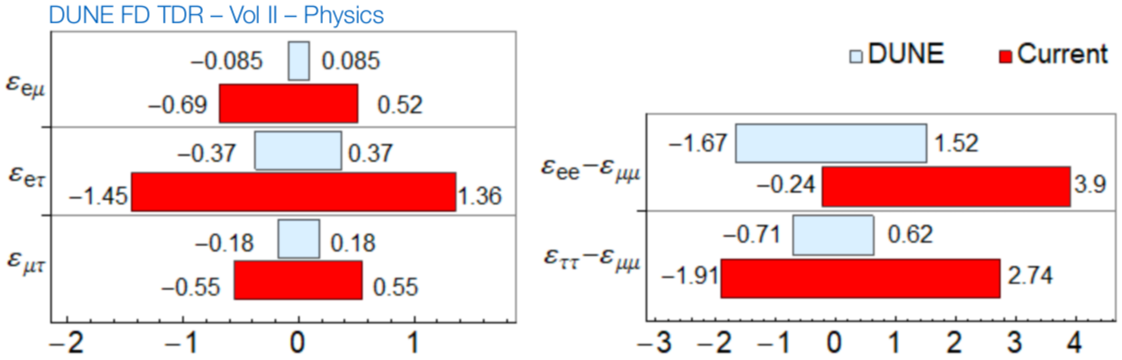
Non-Standard Interactions

$$\mathcal{L}_{\mathrm{NSI,NC}} = \sum_{f,\alpha,\beta} 2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f} \gamma^\mu P f) + \mathrm{h.c.}$$

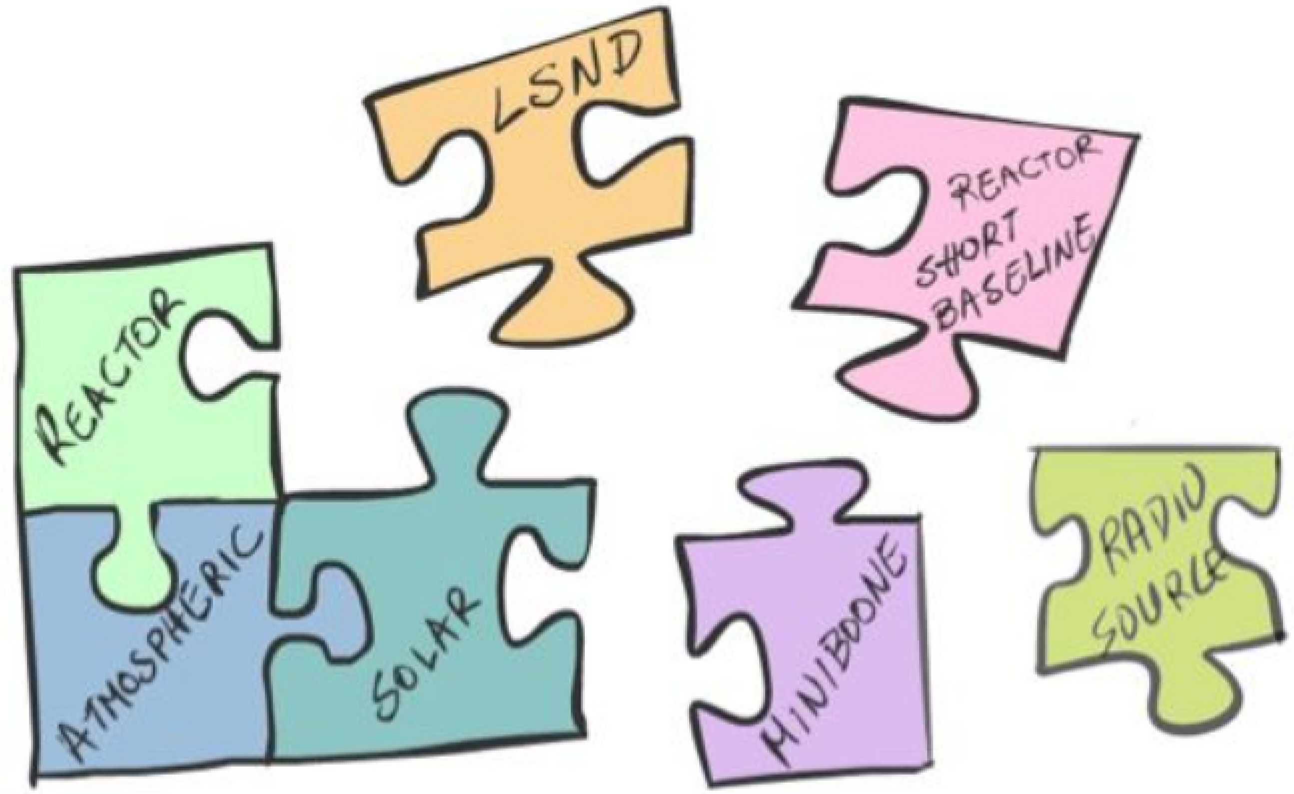
$$\mathcal{L}_{\mathrm{NSI,CC}} = \sum_{f,f',\alpha,\beta} 2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{ff',P} (\bar{\nu}_\alpha \gamma_\mu P_L \ell_\beta)(\bar{f}' \gamma^\mu P f) + \mathrm{h.c.}$$

SMEFT (>100GeV) →
WEFT (<100GeV) →
NSI as dimension 6 operators

Anomalous NC modifies matter effects – DUNE uniquely sensitive



Figures from SNOWMASS neutrino colloquia by J. Kopp



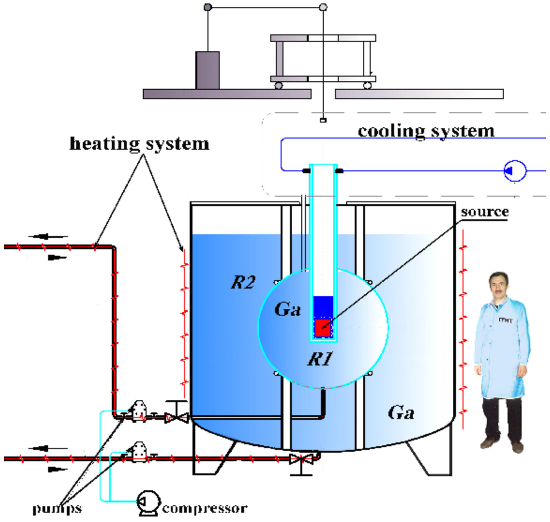
Evolving set of Anomalies

Individually could be explained by extra (sterile) neutrinos

Global fits show significant tension

Figures from SNOWMASS neutrino colloquium by G. Karagiorgi

Gallium anomaly

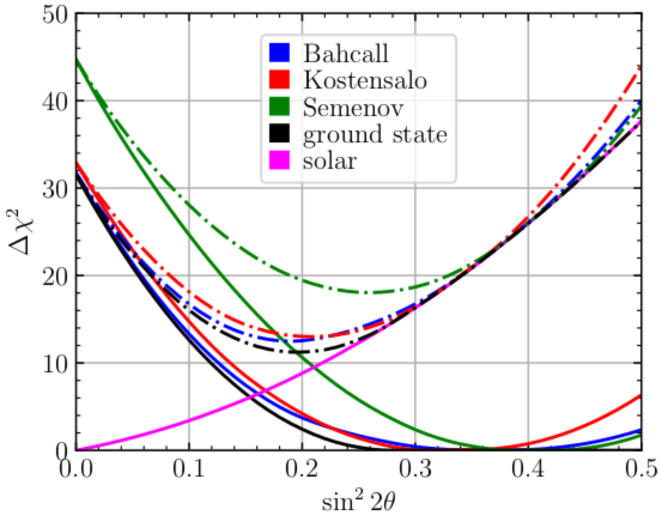


BEST collab. 2021

>5 sigma significance

Not a cross section issue

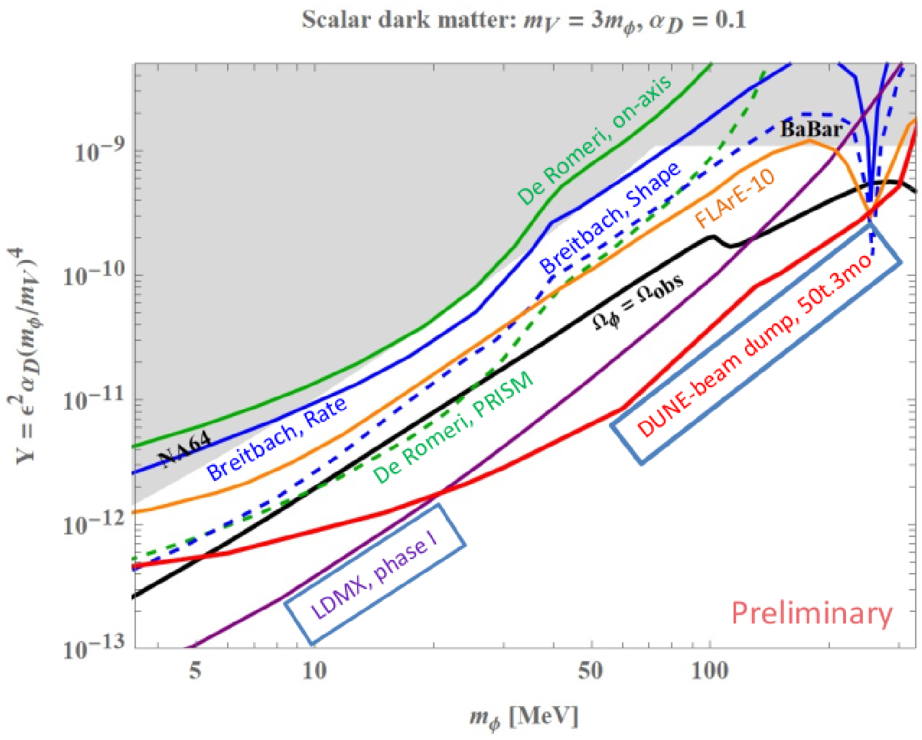
3 sigma tension with solar

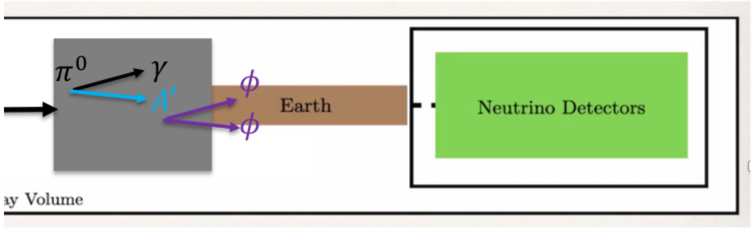


Berryman et al. 2021

GALLEX [10]	GALLEX [10]	SAGE [7]	SAGE [8]	BEST [26] (inner)	BEST [26] (outer)
0.953 ± 0.11	0.812 ± 0.10	0.95 ± 0.12	0.791 ± 0.084	0.791 ± 0.044	0.766 ± 0.045

Dark matter in neutrino beams

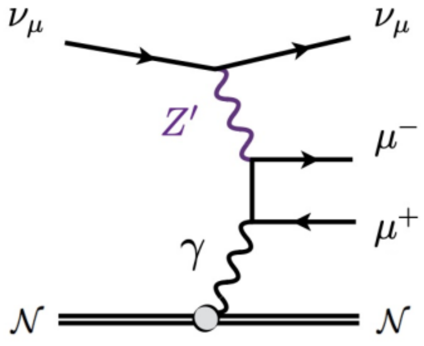


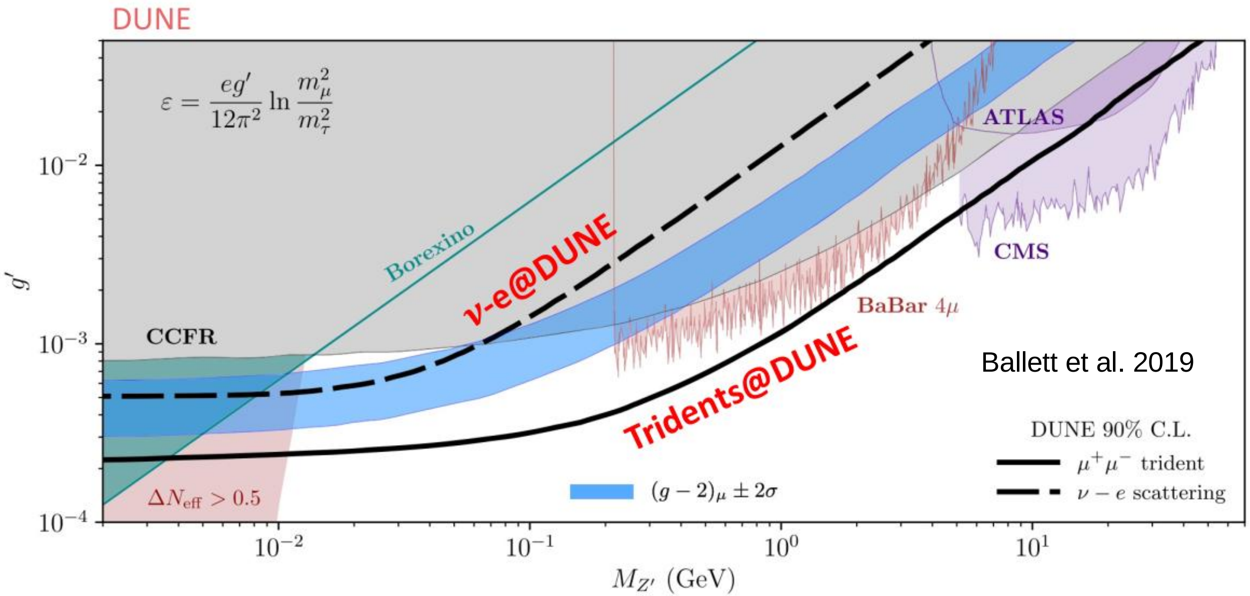


Nothing to do with neutrinos at all.

Figures from SNOWMASS neutrino colloquium by Z. Tabrizi

Light Z': L_μ-L_τ Model

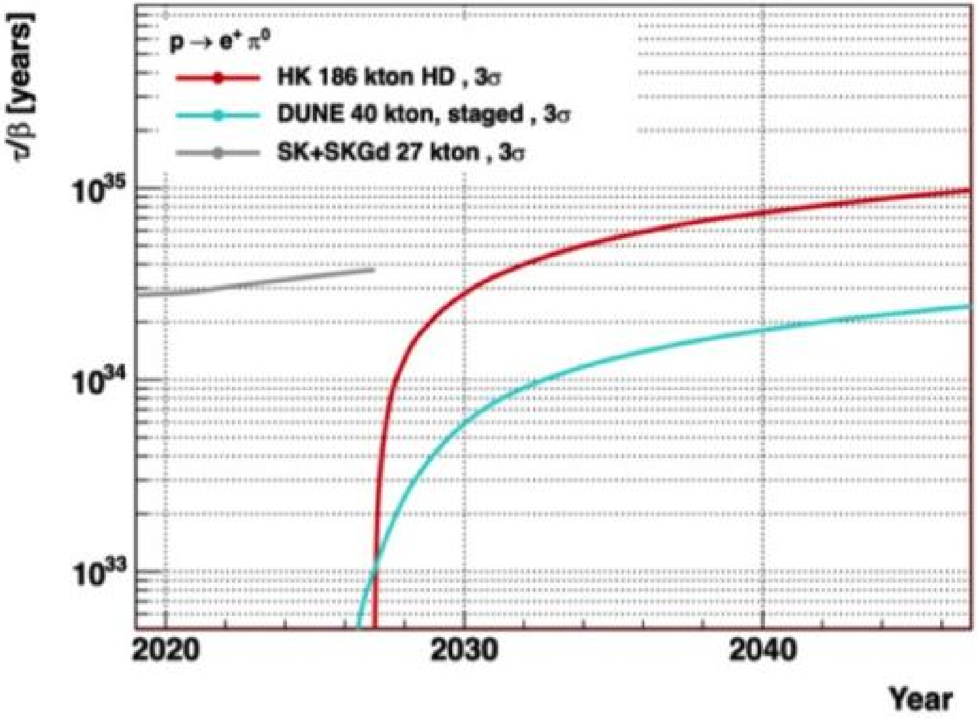


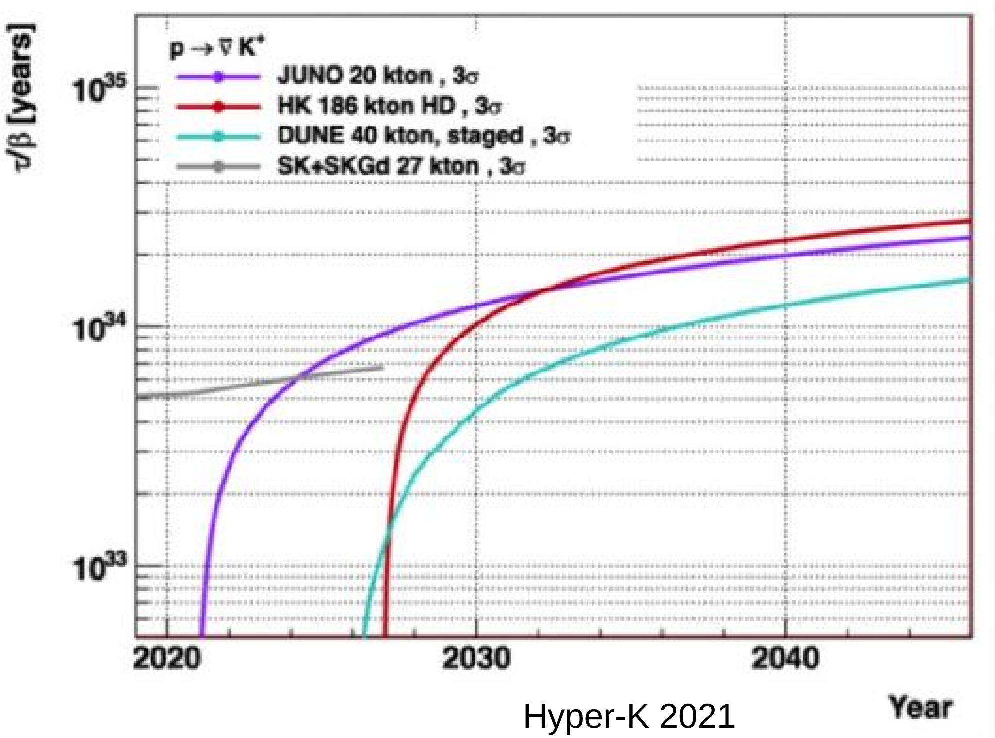


Z' couples only to muon and tau neutrinos, could explain muon g-2.

Figures from SNOWMASS neutrino colloquium by Z. Tabrizi

Proton decay

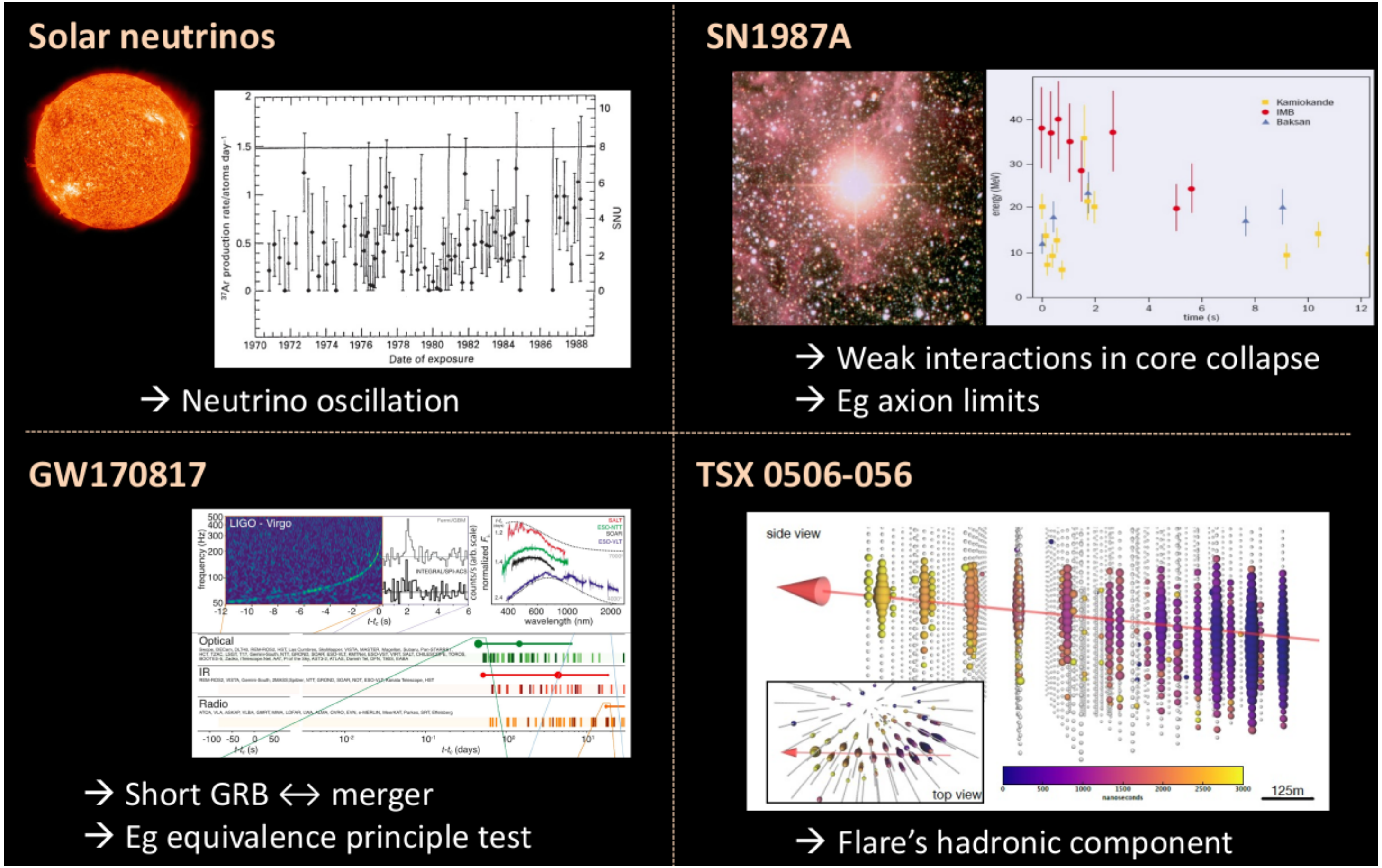




Hyper-K 2021

Large detectors → high “luminosity”

Neutrinos as messengers



Neutrinos are one leg of multi-messenger astronomy

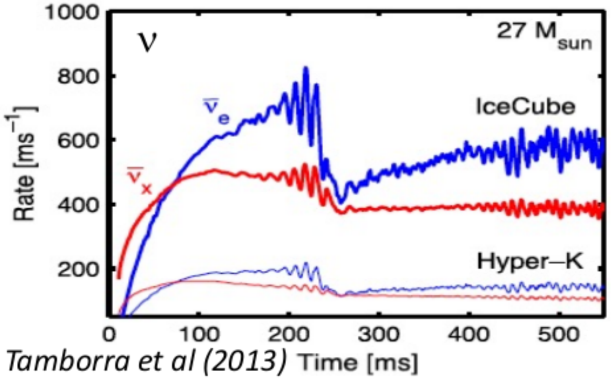
Combination with photons from radio to gamma rays
and gravitational waves

Figures from SNOWMASS neutrino colloquium by S. Horiuchi

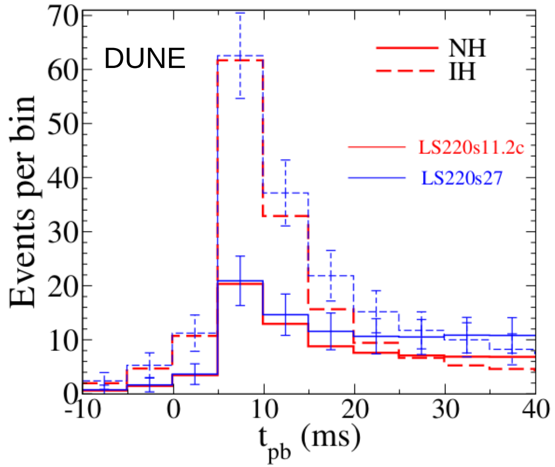
Next galactic supernova

Experiment	Type	Mass (kt)	Location	11.2 $M_\odot$	27.0 $M_\odot$	40.0 $M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18

SNEWS 2021



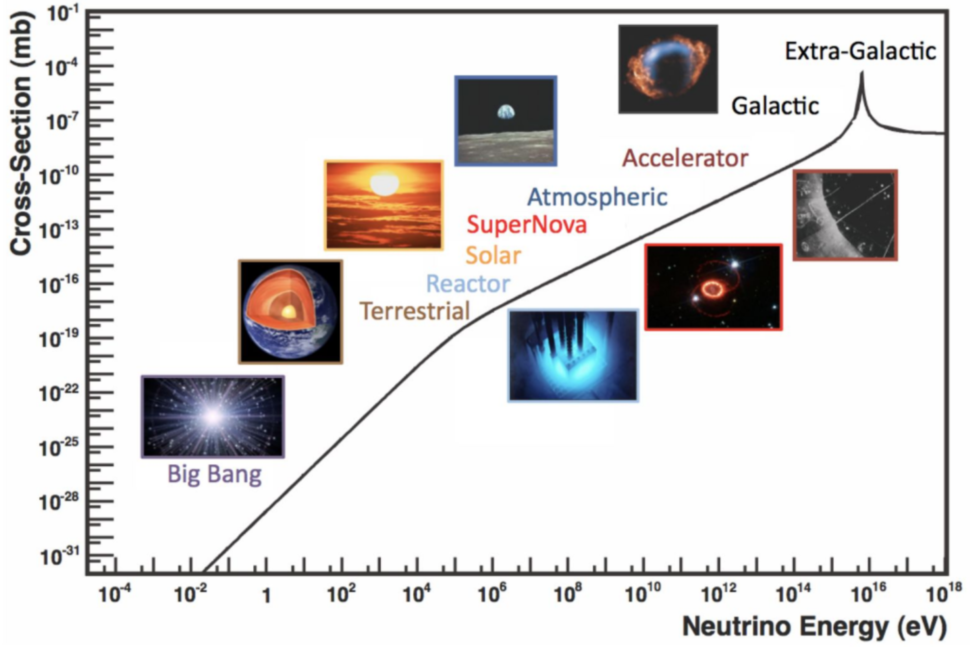
Tamborra et al (2013)



Mirizzi et al. 2016

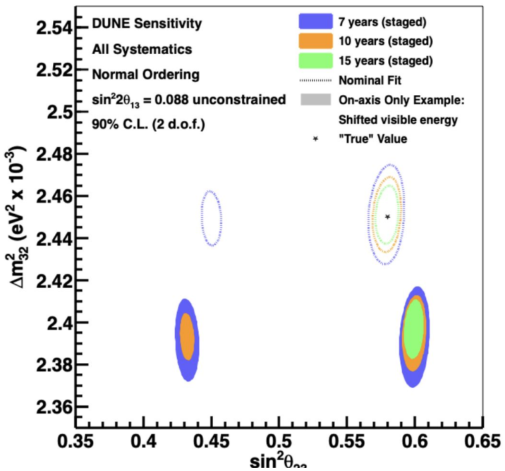
Figures from SNOWMASS neutrino colloquium by S. Horiuchi

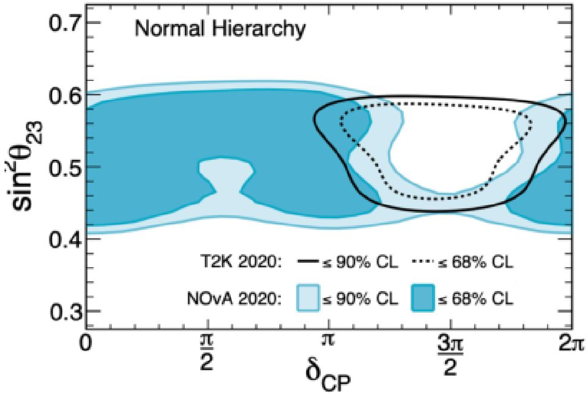
Neutrino interactions



Measuring SM processes

DUNE Physics TDR arxiv. 2002.03005





New physics or cross section mismodeling?

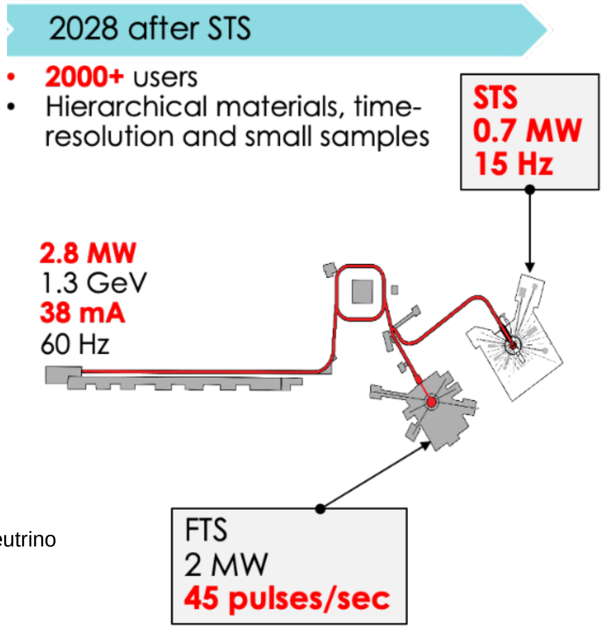
Robust program at many energy scales underway – essential to do physics

Figures from SNOWMASS neutrino colloquium by K. Mahn

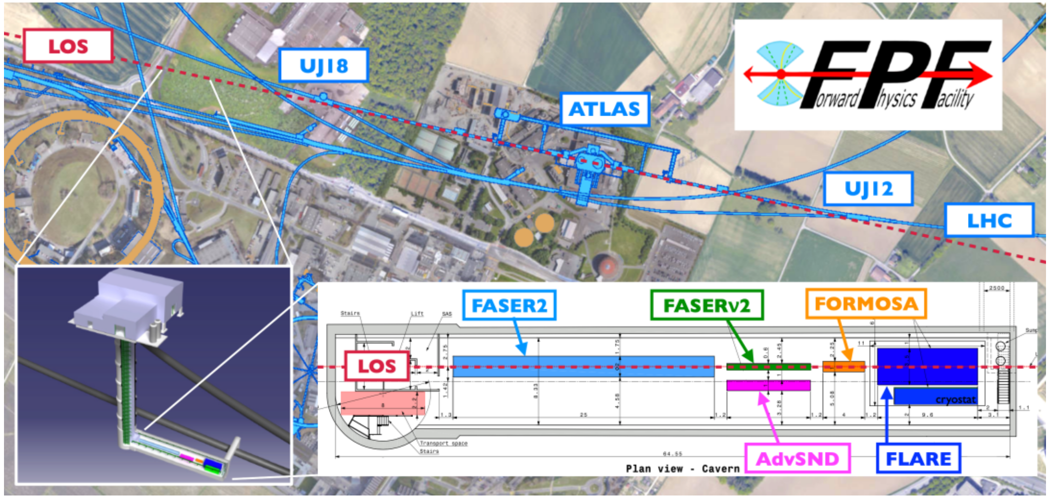
Synergies at the machine level

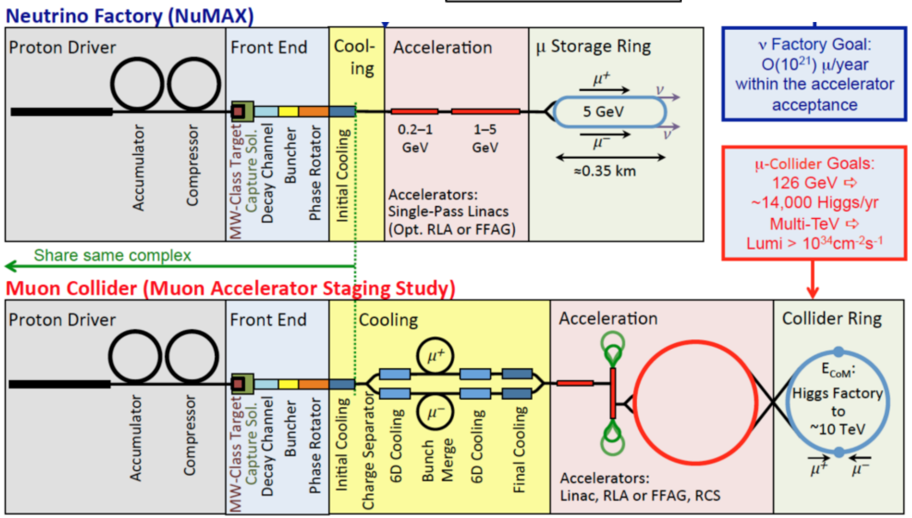
Experiment	Dark Sectors	ν Physics	CLFV	Precision tests	R&D
Lepton flavor violation: μ-to-e conversion					
Lepton flavor violation: μ decay					
PIP2-BD: ~GeV Proton beam dump					
SBN-BD: ~10 GeV Proton beam dump					
High energy proton fixed target					
Electron missing momentum					
Nucleon form factor w/ lepton scattering					
Electron beam dumps					
Muon Missing Momentum					
Muon beam dump					
Physics with muonium					
Muon collider R&D and neutrino factory					
Rare decays of light mesons					
Ultra-cold neutrons					
Proton storage ring for EDM and axions					
Tau neutrinos					
Proton irradiation facility					
Test-beam facility					

Booster replacement



Figures from SNOWMASS neutrino colloquium by M. Toups





Summary

- Neutrino physics covers a very broad range of topics and energies from meV to PeV
- Diverse set of experiments at all scales
- Strong synergies within HEP but also with the broader physics program in nuclear physics, astrophysics and cosmology
- Neutrino physics is discovery science!