Grand (Experimental) Challenges in Neutrino Physics

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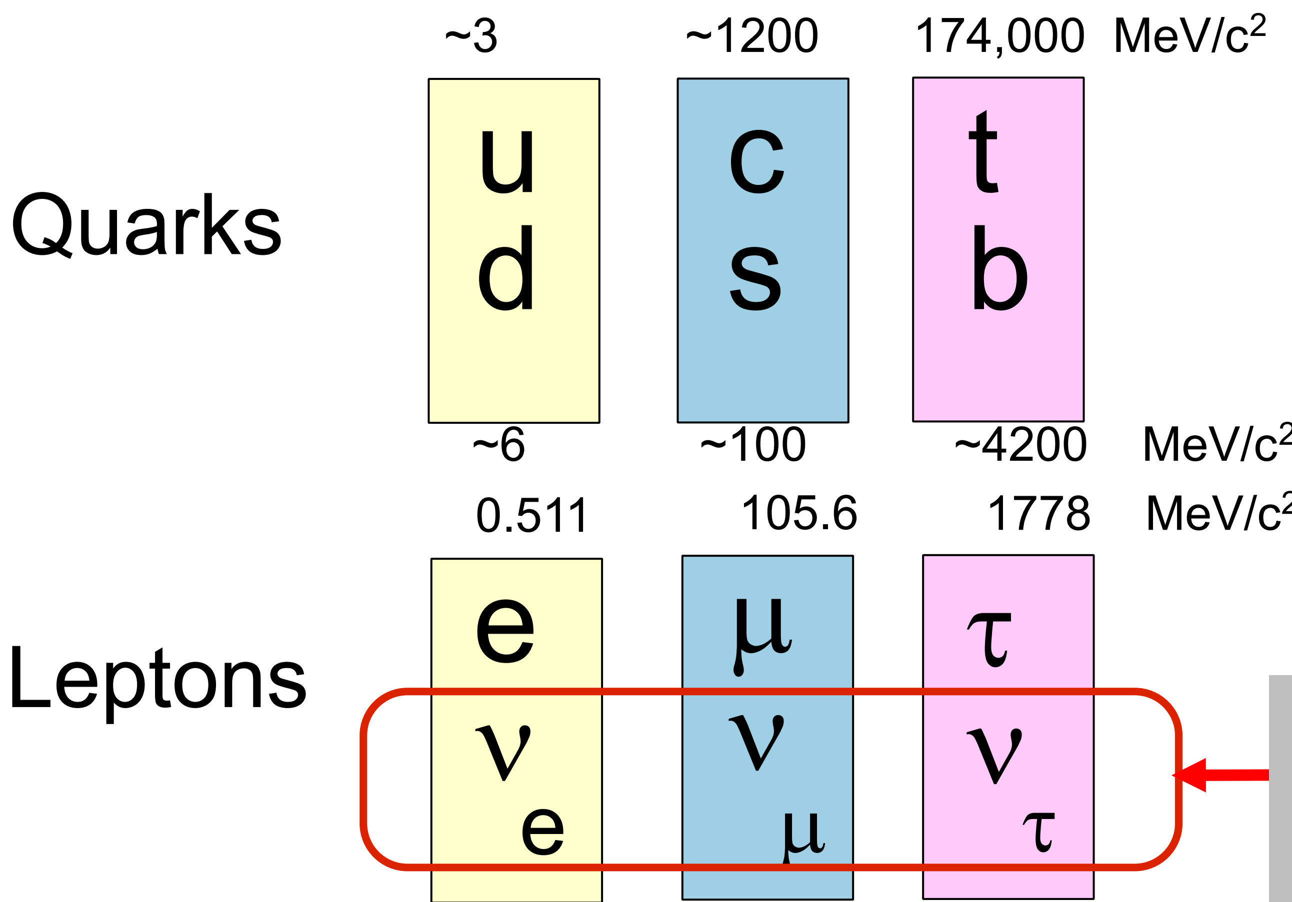
*craiyon.ai output for "grand challenges in neutrino physics"

NEUTRINOS



In the Standard Model of particle physics, neutral partners to the charged leptons

- Spin 1/2
- Zero charge
- 3 flavors (families)
- Interact *only* via ***weak interaction*** (& gravity)
- Tiny mass (< 1 eV)

Science Drivers in Neutrino Physics

Where are the grand (experimental) challenges?

Three-flavor paradigm

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

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Overarching challenge in this sector:
can we fully describe neutrino mixing?

The three-flavor paradigm

what's known,
what's left to measure?

Neutrino Oscillations
Latest 3-flavor results

Remaining unknowns in
the 3-flavor picture:
mass ordering (MO) and CP δ

The mass pattern

Absolute Mass
Status and prospects

The mass scale

Majorana vs Dirac?
Overview of NLDBD

The mass nature

Neutrino Mass and Oscillations

How can we learn about neutrino mass?

Flavor states related to mass states by a unitary mixing matrix

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{\mathrm{e}1} & \mathrm{U}^*_{\mathrm{e}2} & \mathrm{U}^*_{\mathrm{e}3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in weak interactions

unitary mixing matrix

eigenstates of free Hamiltonian

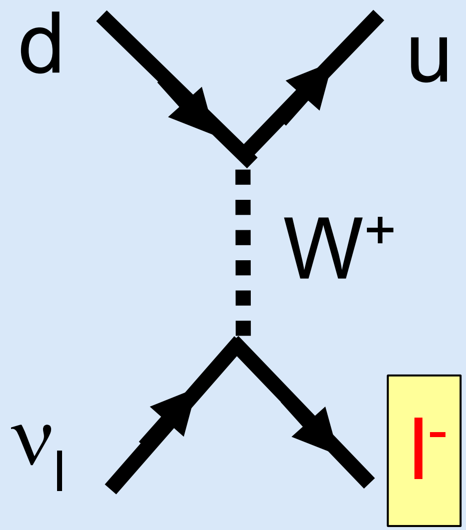
$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

If mixing matrix is not diagonal, get *flavor oscillations* as neutrinos propagate (essentially, interference between mass states)

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

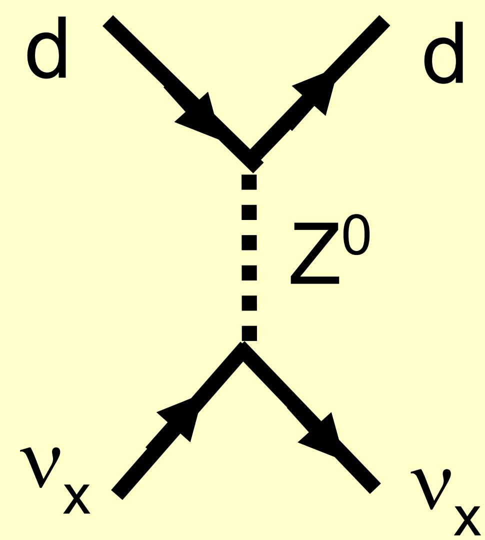


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy
to make lepton)

Neutral Current (NC)



Flavor-blind

Two-flavor case

$$|\nu_f\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_g\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

Propagate a distance L:

$$|\nu_i(t)\rangle = e^{-iE_it}|\nu_i(0)\rangle \sim e^{-im_i^2L/2p}|\nu_i(0)\rangle$$

Probability of detecting flavor g at L:

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

E in GeV
L in km
Δm^2 in eV^2

Parameters of nature to measure: θ, $\Delta m^2 = m_1^2 - m_2^2$

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

$\Delta m^2 = m_1^2 - m_2^2$

__If__ flavor oscillations are observed, *__then__* there must be at least one non-zero mass state

*Note: oscillation depends on mass *differences*, not absolute masses

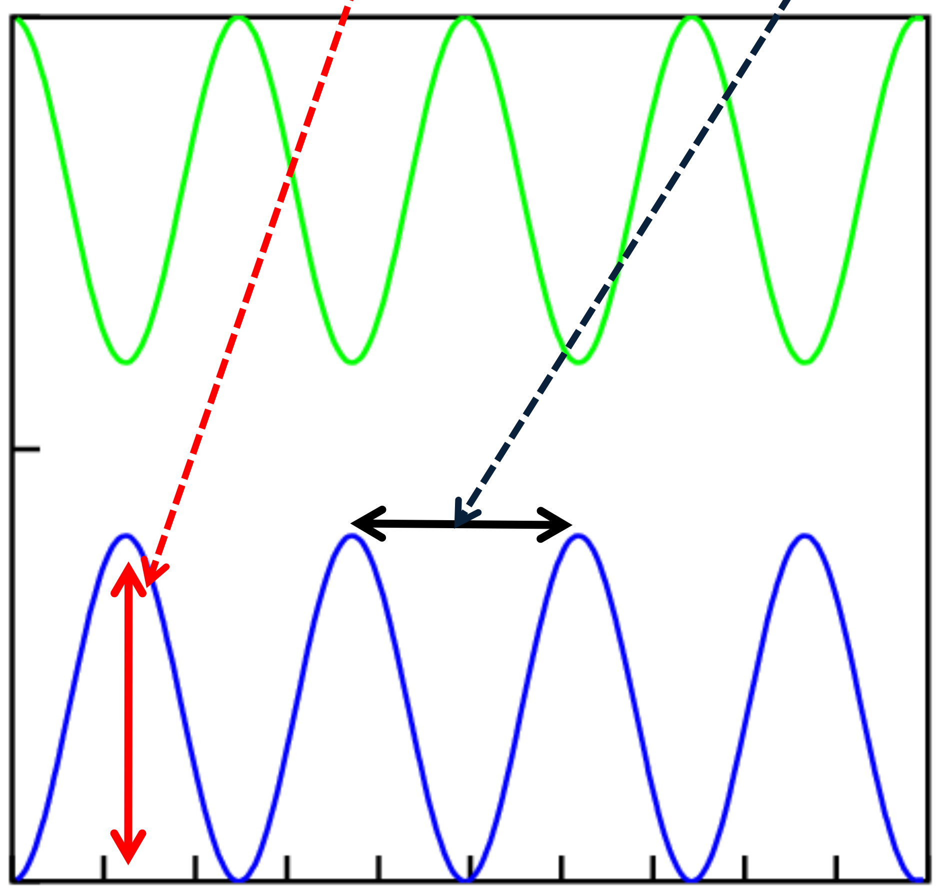
For 2 flavors:

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

amplitude

wavelength= $\pi E/(1.27\Delta m^2)$

$P(\nu_f \to \nu_f)$



$P(\nu_f \to \nu_g)$

Distance traveled

Δm^2, $\sin^2 2\theta$ are the parameters of nature;

L, E depend on the experimental setup

The Experimental Game

- Start with some neutrinos (wild or tame)
- Measure (or calculate) flavor composition and energy spectrum
- Let them propagate
- Measure flavor and energies again

Have the flavors and energies changed?
If so, does the change follow $P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$?

<u>Disappearance</u>: ν's oscillate into 'invisible' flavor

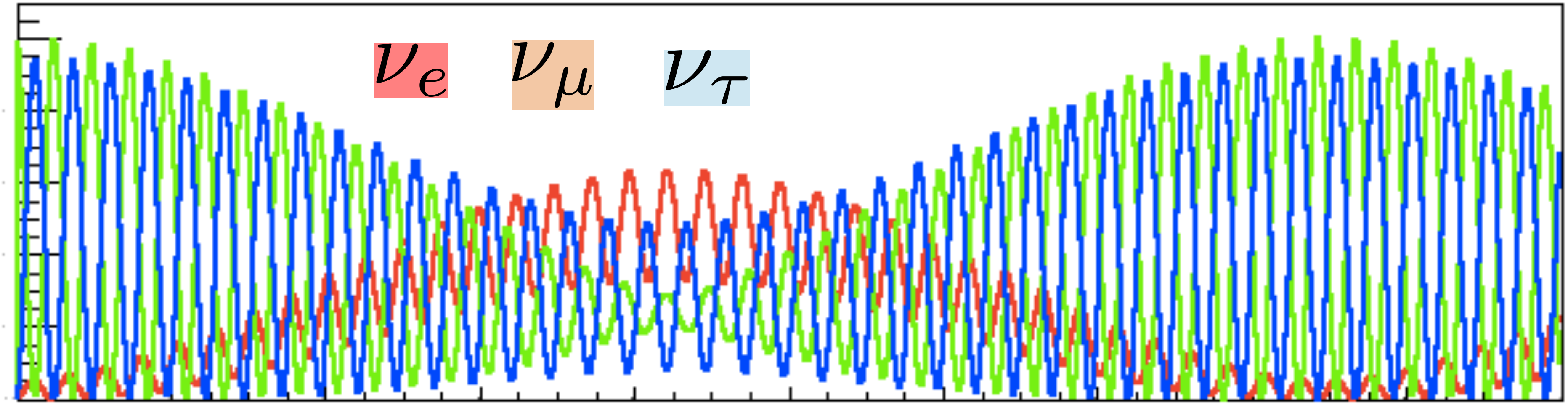
e.g. $\nu_e \rightarrow \nu_\mu$ at ~MeV energies

<u>Appearance</u>: directly see new flavor

e.g. $\nu_\mu \rightarrow \nu_\tau$ at ~GeV energies

With three flavors,
get more complicated wiggles,
of superposed short and
long wavelengths:

Prob of observing flavor



Distance traveled

Governed by three "mixing angle" parameters, θ_{12}, θ_{13}, θ_{23} and mass differences

Need to tease out the hums of three neutrinos

Oscillation probability can be computed straightforwardly:

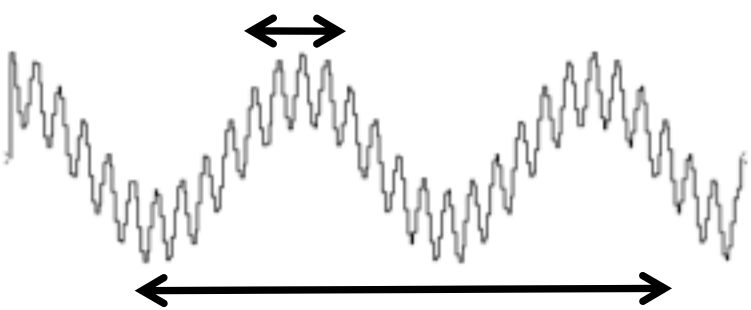
$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^*|\nu_i\rangle$$

$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ (L in km, E in GeV, m in eV)

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4\sum_{i>j} \Re(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin^2(1.27\Delta m_{ij}^2 L/E)$$

$$\pm 2\sum_{i>j} \Im(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin(2.54\Delta m_{ij}^2 L/E)$$

oscillatory behavior in L and E



$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$ ➔ two frequency scales

For appropriate L/E (and U_{ij}), oscillations "decouple", and probability can be described the two-flavor expression

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Parameters in the 3-flavor neutrino paradigm

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

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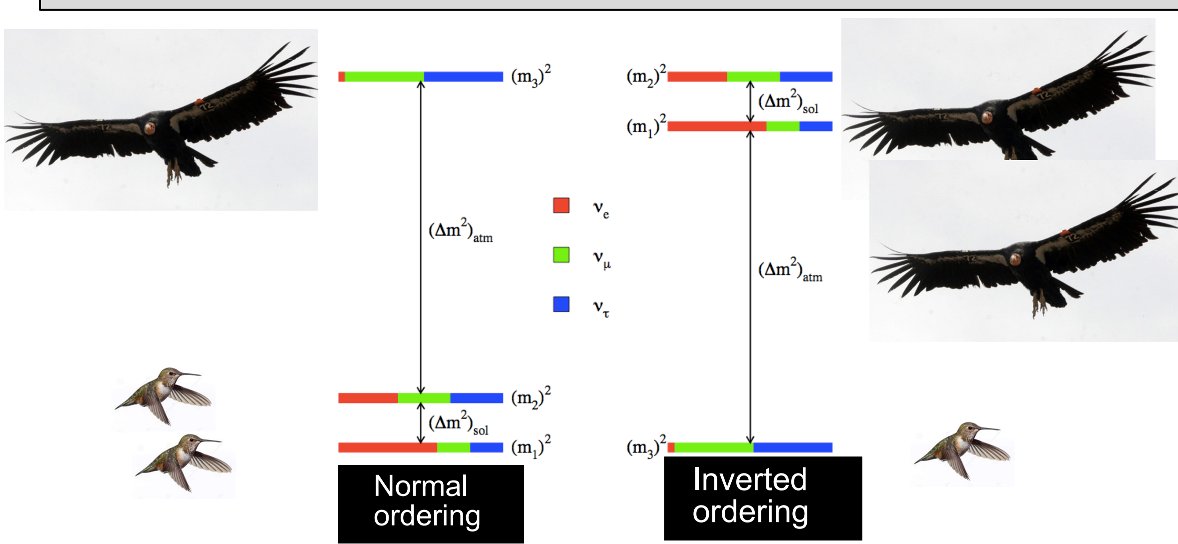
signs of the mass differences matter



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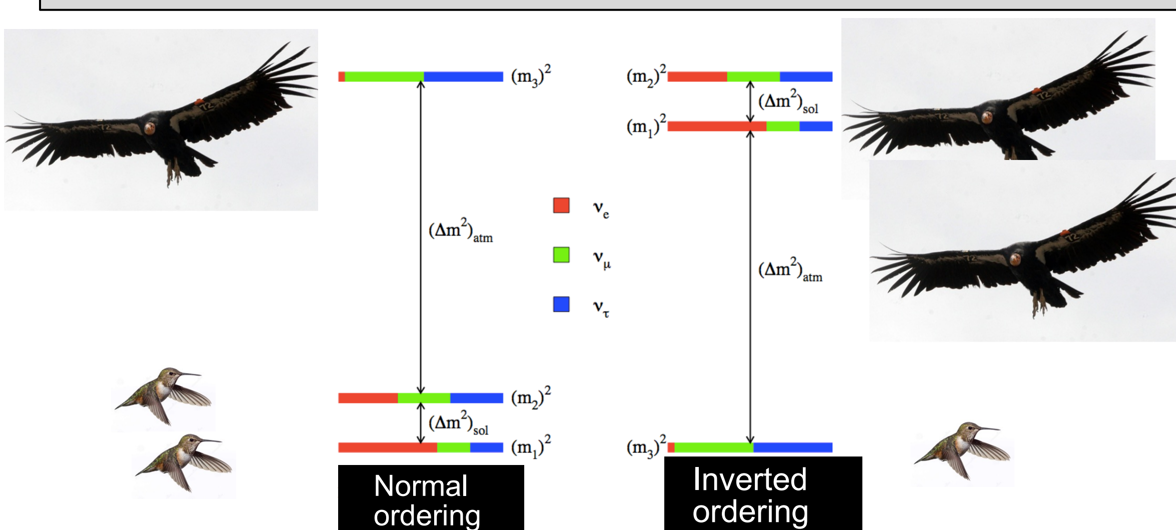

Except Majorana phases, all parameters accessible by oscillation experiments

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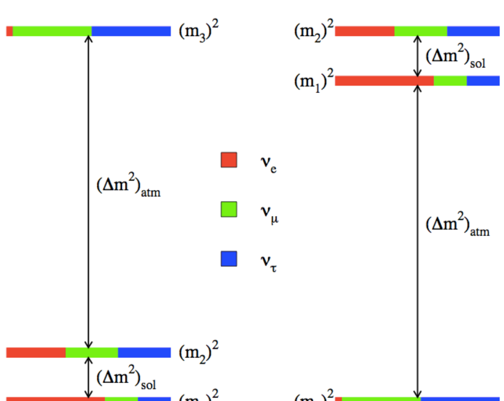
3 masses	m_1, m...
	...scale)
3 mixin...	...θ_{12}, θ_{13}
1 ...	δ
(2 ... **phases)**	α_1, α_2

Measure *all* the oscillation parameters, including CP δ

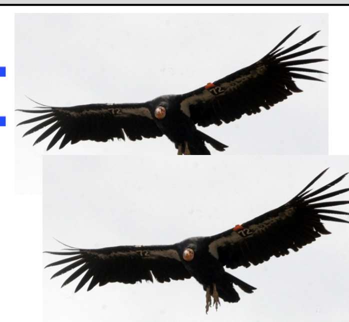
signs of the mass differences matter

Except Majorana phases, all parameters accessible by oscillation experiments

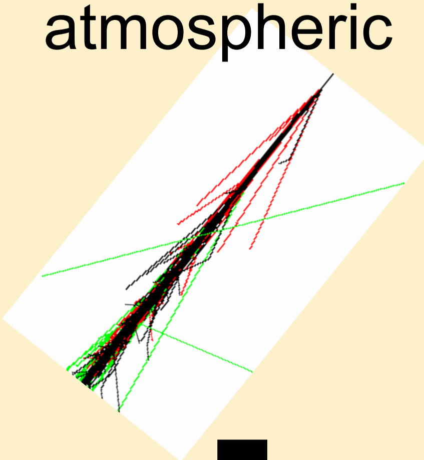


Normal ordering

Inverted ordering



atmospheric



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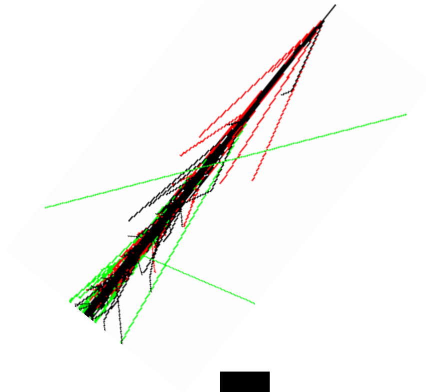
beams

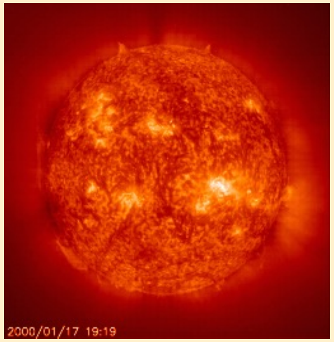
Precision measurements in the “atmospheric” sector

atmospheric



A parallel story unfolded in the "solar" or "12" sector!

solar



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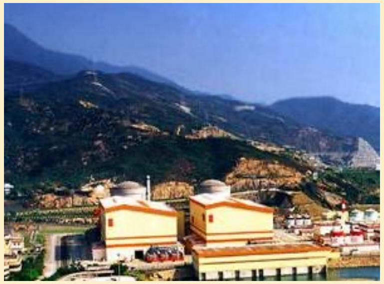
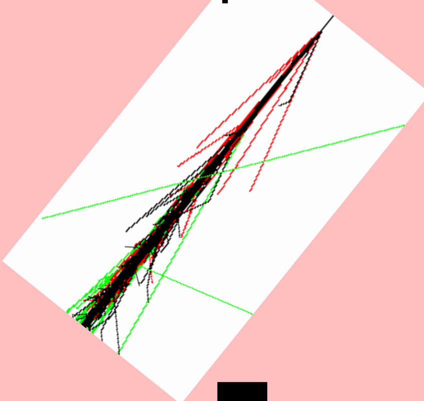
beams



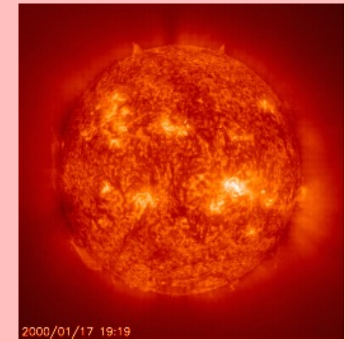
reactor

atmospheric



signal with
“wild” neutrinos...

solar



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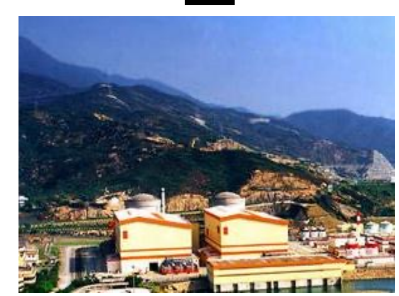
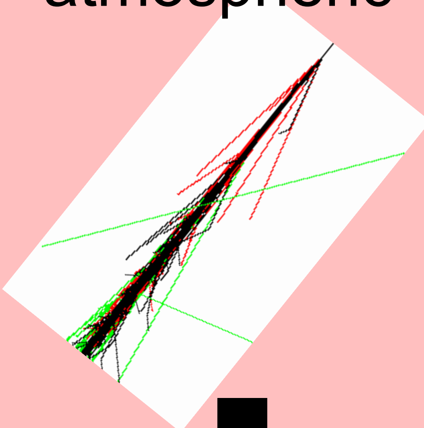
beams



reactor

atmospheric



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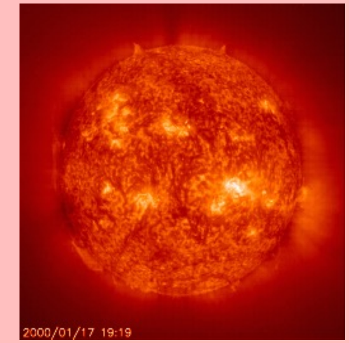

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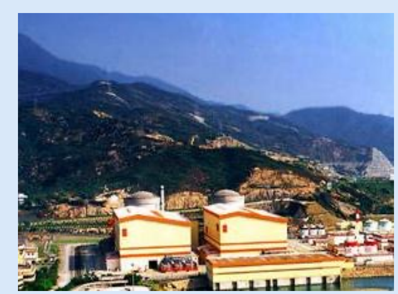
confirmed with
“tame” ones...

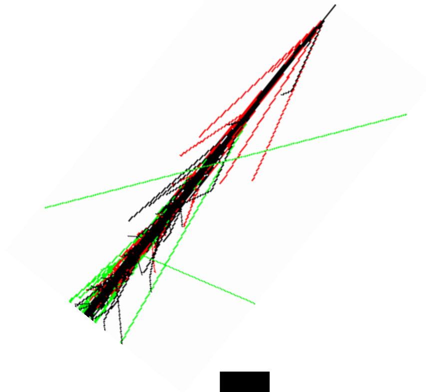
beams



reactor

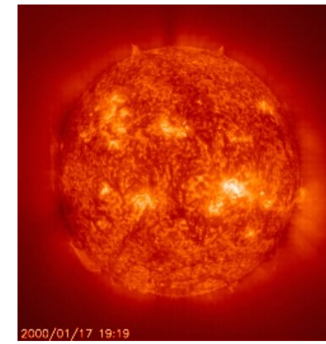
And further information from beams and burns!

atmospheric



θ_{13}, the "twist in the middle"

solar



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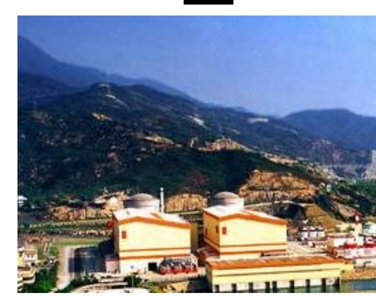
Now known to be ~9°

beams



reactor

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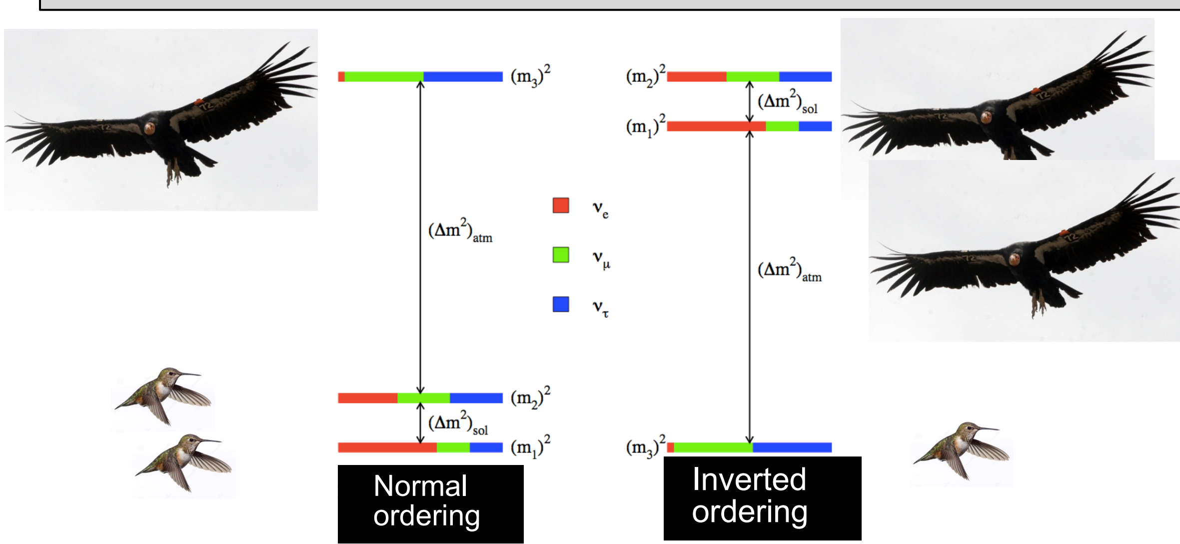


Where do we stand?

The three-flavor picture fits the data well

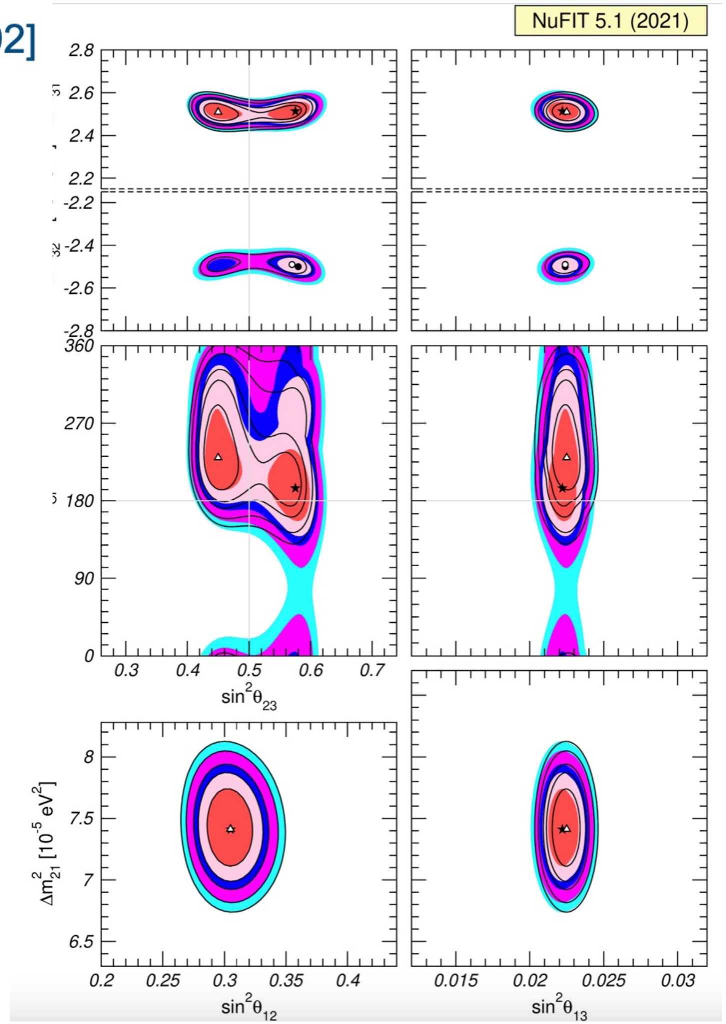
Global three-flavor fits to all data: atmospheric, solar, reactor, beams*

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

	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}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

with SK atmospheric data

$$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0 \text{ for NO and } \Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0 \text{ for IO.}$$



Esteban et al., arXiv:2007.14792, 10.1007/JHEP09(2020)178

*Does not include the very latest data

What do we *not* know about the three-flavor paradigm?

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

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	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
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Is θ_{23} non-negligibly greater or smaller than 45 deg?

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poor knowledge

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More and better info from:
beams [LBL], burns [solar, JUNO],
bangs [SNe]...

Measuring CP violation in neutrinos

B. Kayser, PDG

$$\mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

Flavor transition probability is:

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4 \sum_{i>j} \Re(U^*_{fi} U_{gi} U_{fj} U^*_{gj}) \sin^2(1.27 \Delta m^2_{ij} L/E)$$

$$\pm\, 2 \sum_{i>j} \Im(U^*_{fi} U_{gi} U_{fj} U^*_{gj}) \sin(2.54 \Delta m^2_{ij} L/E)$$

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4\sum_{i>j} \Re(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin^2(1.27\Delta m_{ij}^2 L/E)$$

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From this expression:

$$P(\nu_g \to \nu_f; U) = P(\nu_f \to \nu_g; U^*)$$

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$$P(\bar{\nu}_f \to \bar{\nu}_g) = P(\nu_g \to \nu_f)$$

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Probability for antinus same as for nus, but with U^*

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Observation of

$$P(\bar{\nu}_f \to \bar{\nu}_g) \neq P(\nu_f \to \nu_g)$$

is a signature of *intrinsic* CP violation (complex U)

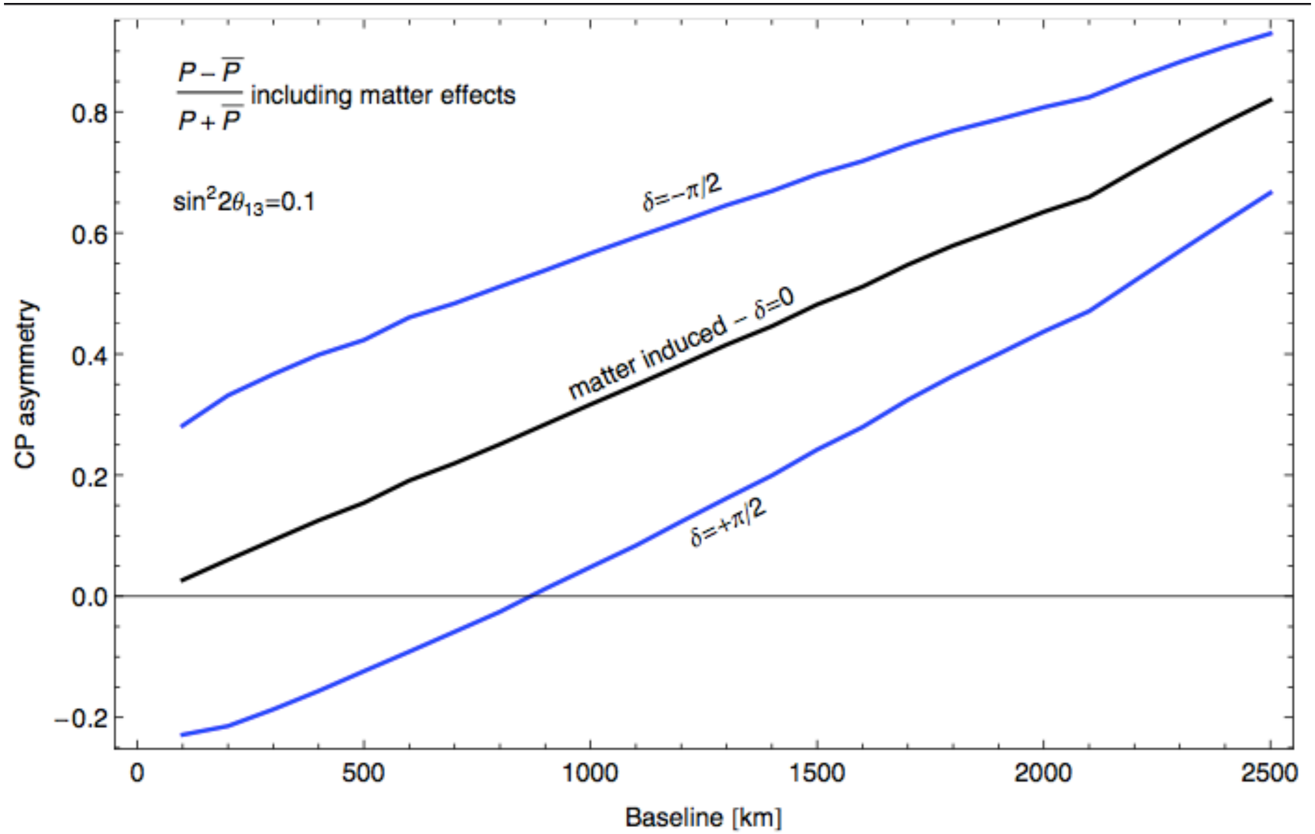
But measurement of CP violation is tangled up with matter effects (depending on MO)...

Matter potential $\nu_\mu \rightarrow \nu_e$ $V_{\rm mat} = \pm 2\sqrt{2} G_F N_e E$

+ for neutrinos, - for antineutrinos

Earth has electrons, not positrons!

Matter-induced CP asymmetry competes with intrinsic CP asymmetry



P. Huber, NuFact 2013

Long-baseline approach for going after MO and CP

Measure transition probabilities for

$\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

through matter

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right) + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

Change of sign for antineutrinos

A. Cervera et al., Nucl. Phys. B 579 (2000)

$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \quad \tilde{B}_\mp \equiv |A \mp \Delta_{13}|, \quad A = \sqrt{2} G_F N_e$$

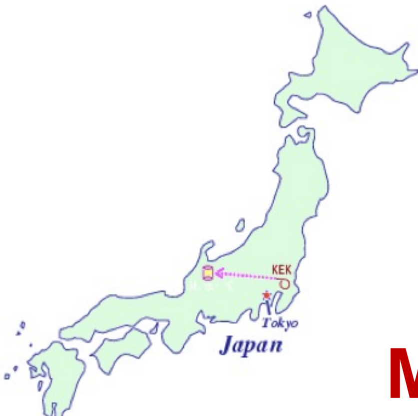
$\theta_{13}, \Delta_{12} L, \Delta_{12}/\Delta_{13}$ are small

Different probabilities as a function of L& E for neutrinos and antineutrinos, depending on:

- CP δ
- matter density (Earth has electrons, not positrons)

Where we are now with long-baseline experiments

Past — Current — Future



K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

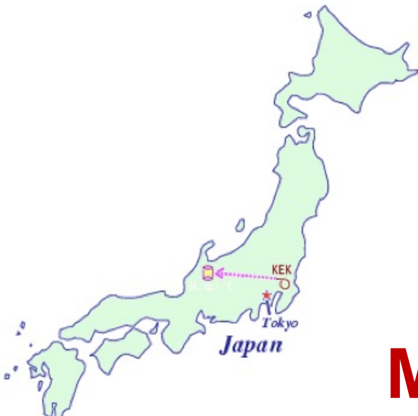
CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K
J-PARC to Kamioka
295 km, 380-750 kW

And the future...

Past → Current → Future



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NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K (II)
J-PARC to Kamioka
295 km, 380-750 kW ➔>1 MW

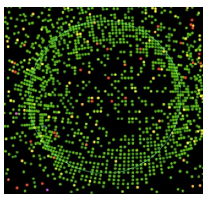
LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2+ MW)

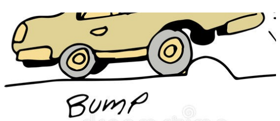
Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)

T2K appearance and disappearance samples

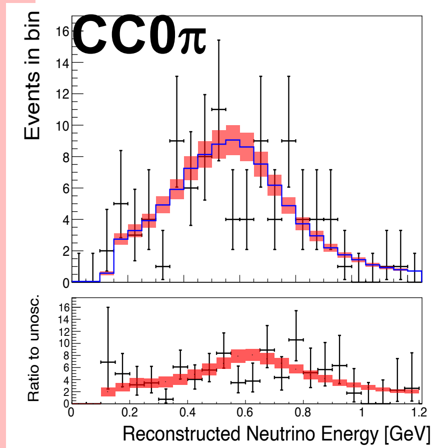
Neutrino mode / Antineutrino mode

Electron neutrino appearance

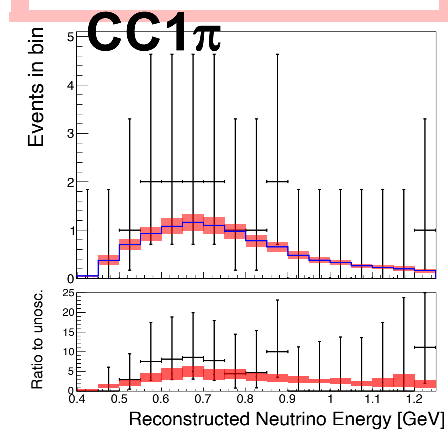




Neutrino mode

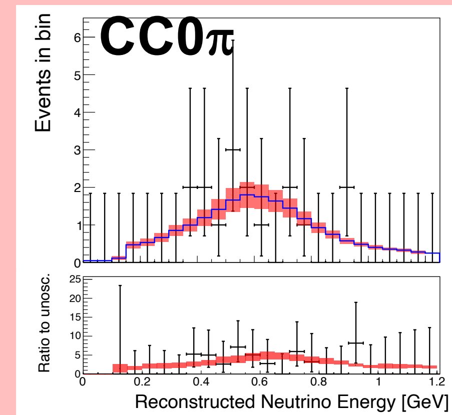


94 events



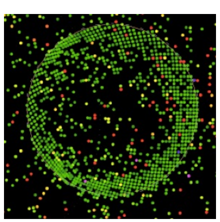
14 events

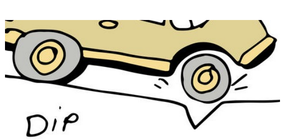
Antineutrino mode



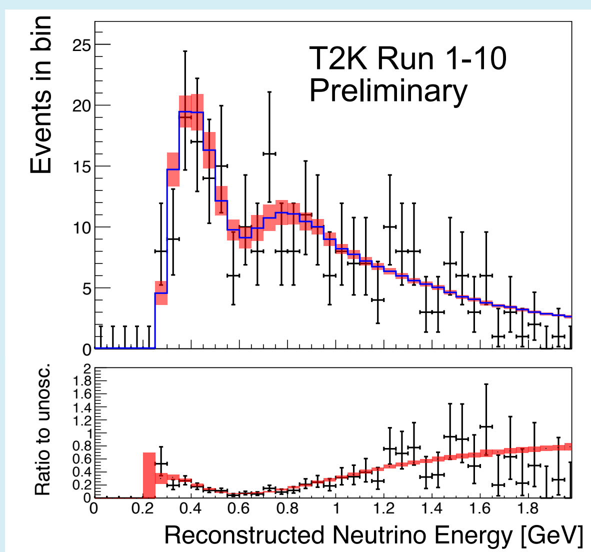
16 events

Muon neutrino disappearance



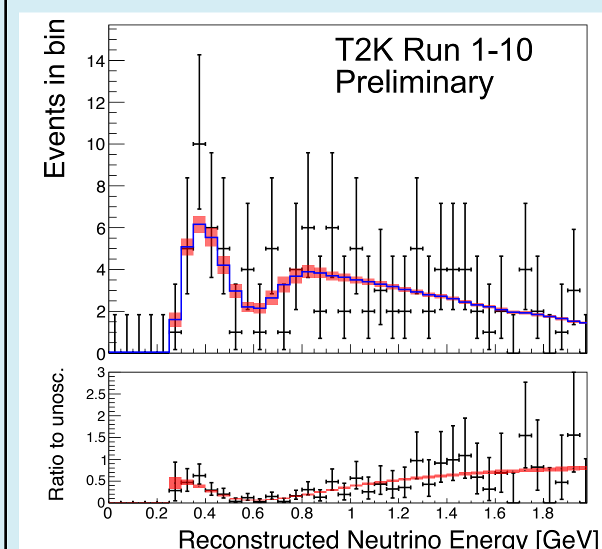


Neutrino mode



318 events

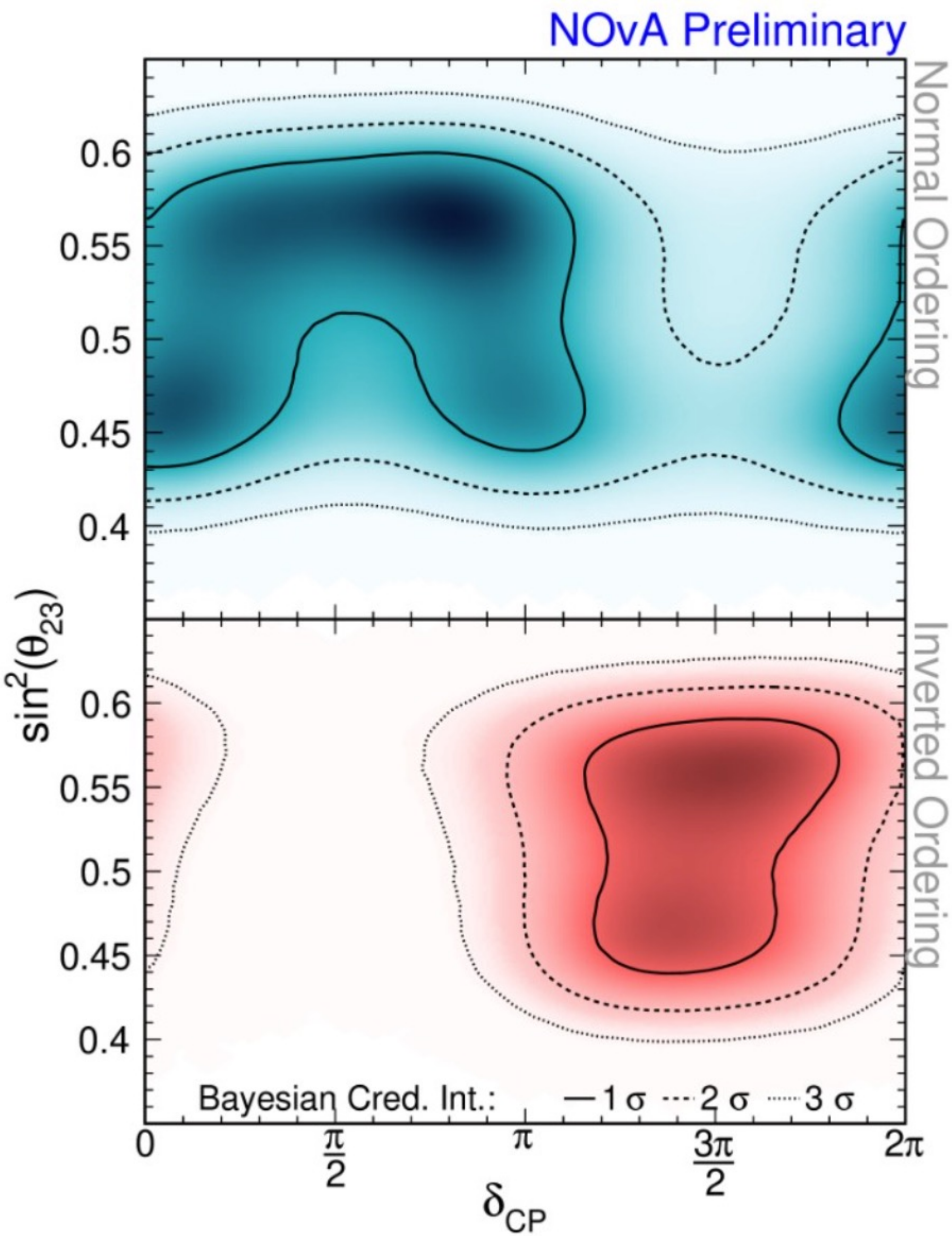
Antineutrino mode

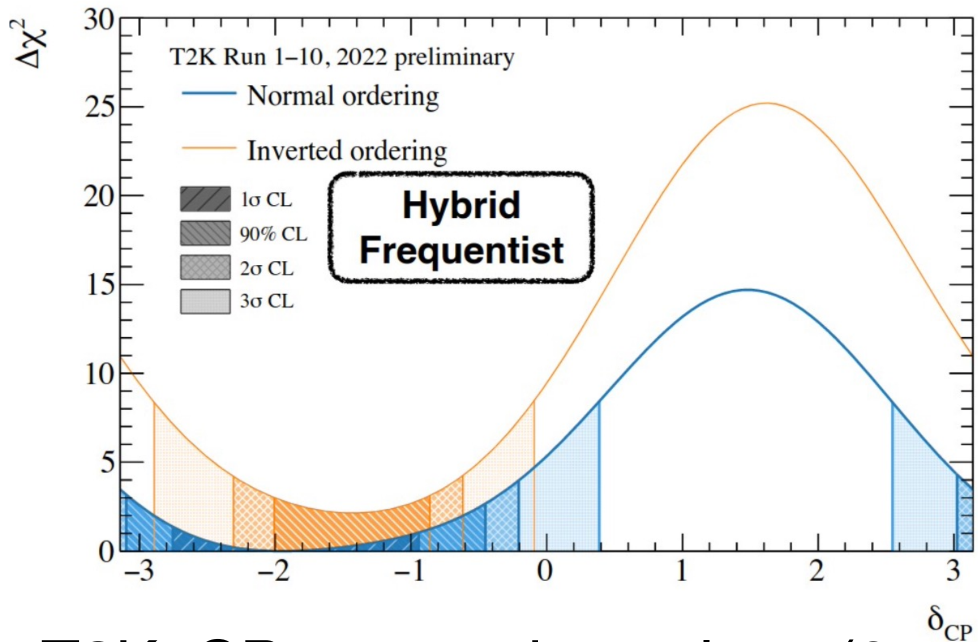


137 events

(Example: 2020 analysis)

T2K and NOvA 3-flavor parameter results





- T2K: CP-conserving values (0, $\pm\pi$) excluded at 90% but not quite at 2σ
- NOvA & T2K in *very weak* tension

...overall, *very weak* preference for normal ordering and δ=-π/2... but not "evidence" yet...

Joint T2K-NOvA analysis in the works

Projections for where we'll be this decade

Current experiments with ~5 yr projections (so, *c*. 2027)

Precision on θ_{12}, θ_{13}, Δm^2_{21}

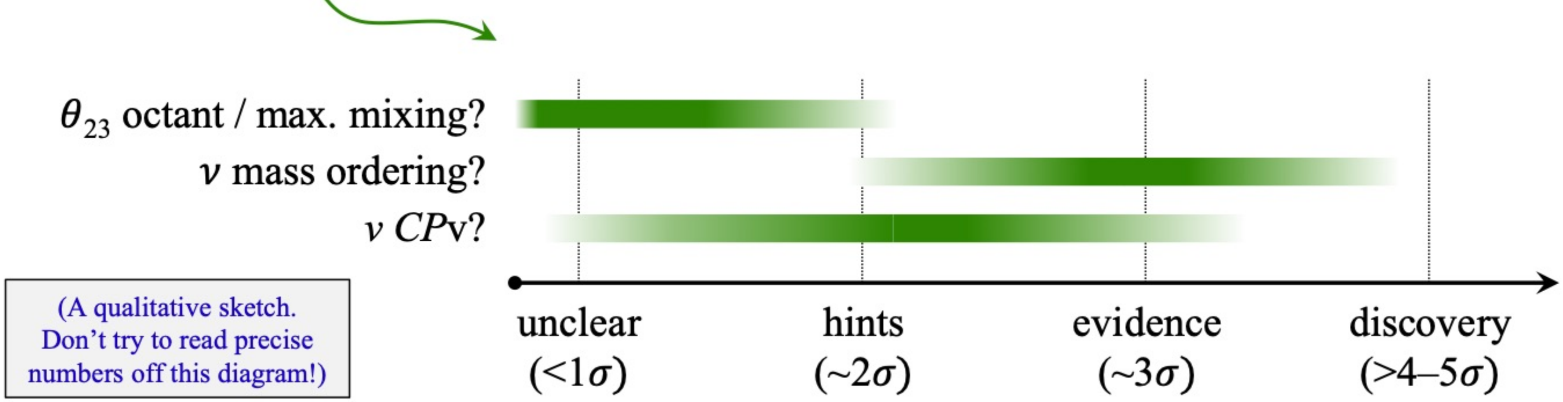
→ Minimal changes until next-gen experiments *(e.g., JUNO)*

Precision on θ_{23}, $|\Delta m^2_{32}|$

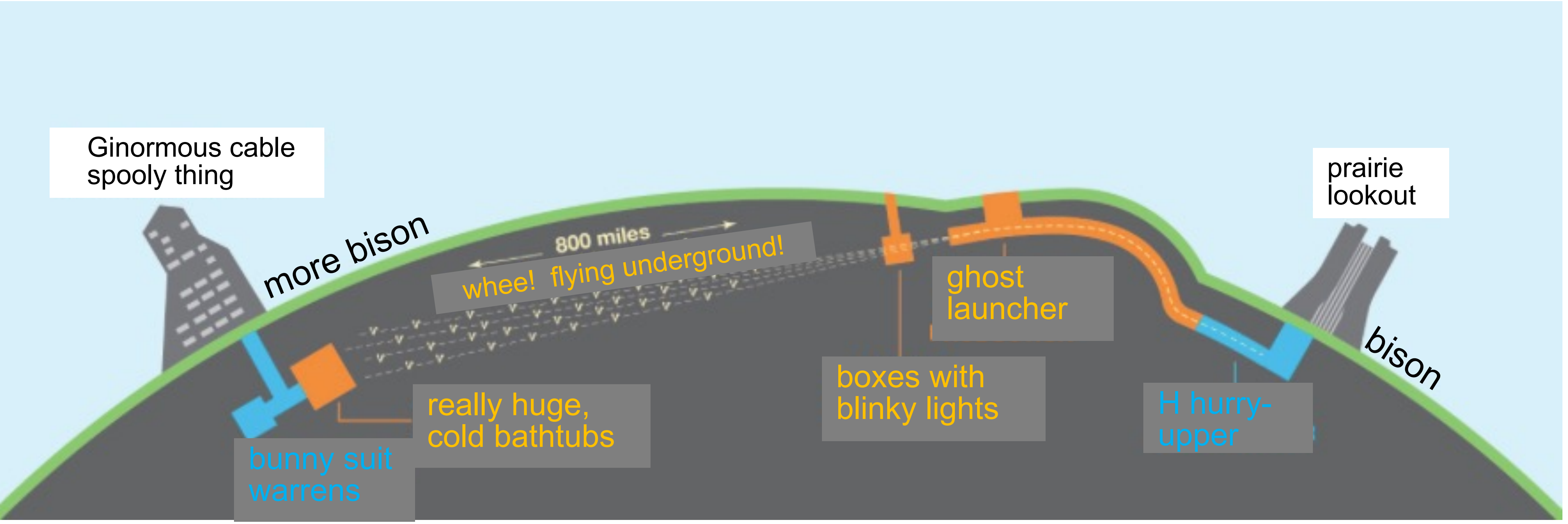
→ Some gains to come in current generation. Large gains in next-gen.

3-flavor "structural" questions

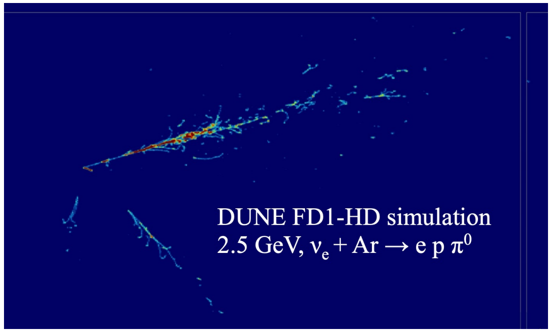
→ Reach heavily depends on (*still unknown!*) actual answers



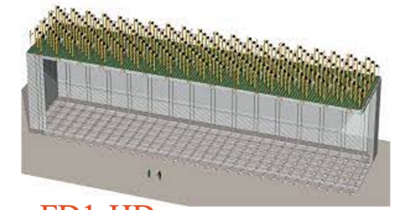
Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility



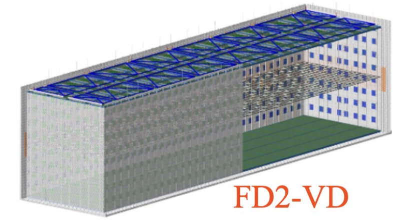
- Phase I: near + far site infrastructure, upgradeable 1.2 MW beam, 2x18 kt LArTPC, movable ND + μ catcher, on-axis ND
- Phase II: two more FD modules, >2 MW beam, ND upgrades [new ideas!]
- Broad physics program



The DUNE far detector:
4 x 17 kton of LAr,
horizontal &vertical drift designs



FD1-HD



FD2-VD

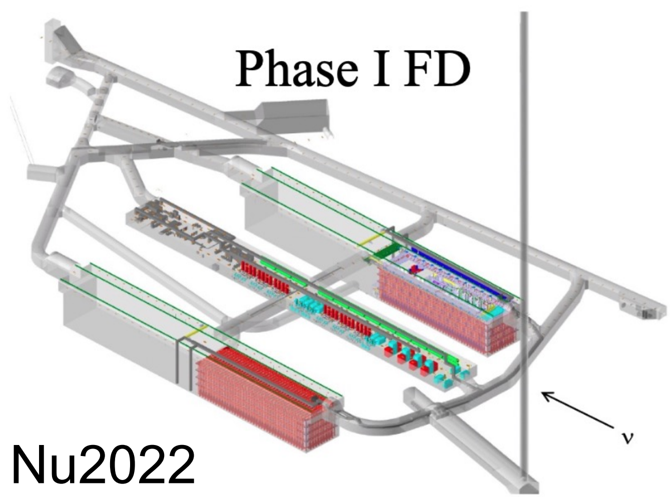
by end of this decade

Phase I

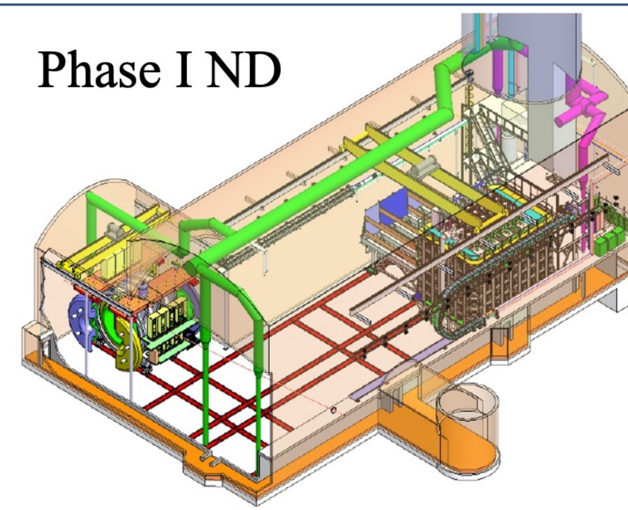
- Ramp to 1.2 MW beam intensity
- Two 17kt (10kt fid.) LAr TPC FD modules. One HD on VD.
- Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND
- Moveable to enable PRISM

Phase II Upgrades

- Proton beam increase to 2.4 MW
- Four 17kt LAr TPC FD modules
- TMS Upgraded to ND-Gar to provide enhanced ND interaction physics capabilities.



Phase I FD



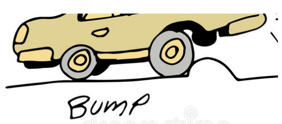
Phase I ND

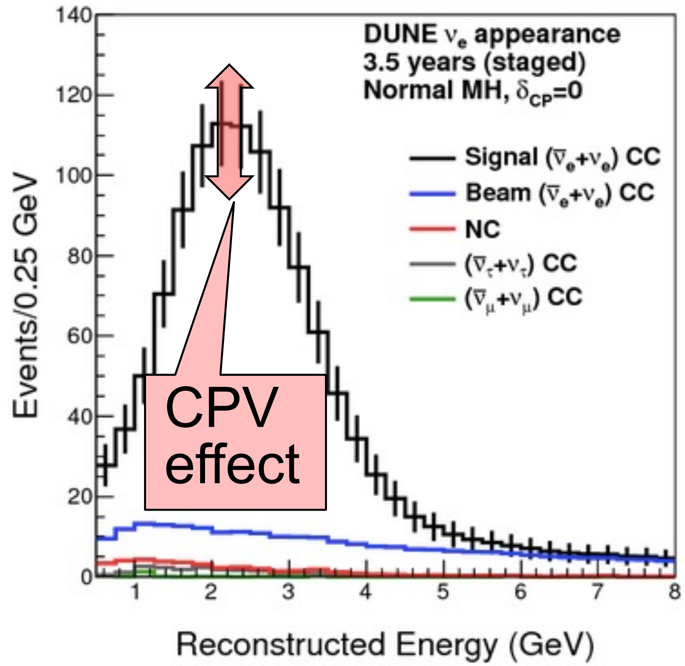
M. Muether, Nu2022

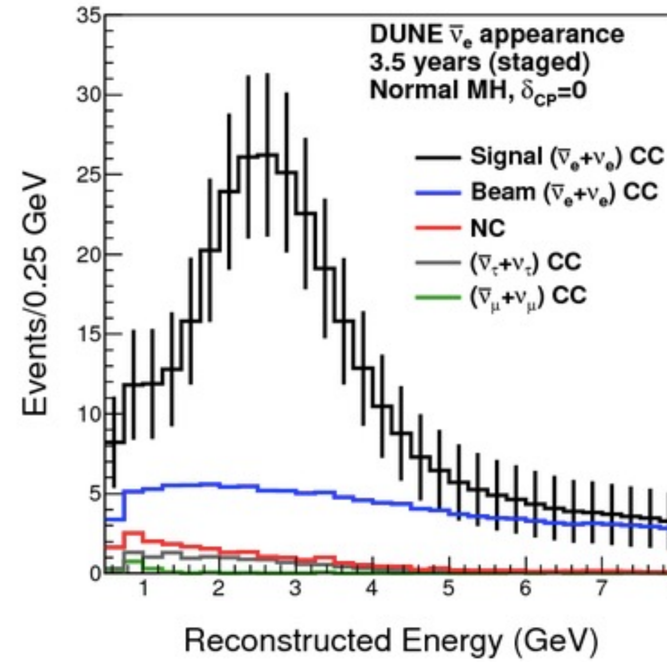
Strategy of appearance & disappearance for MO & CPV

Neutrinos | **Anti neutrinos**

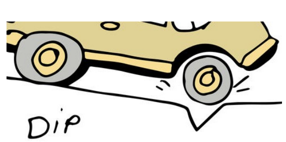
Electron flavor

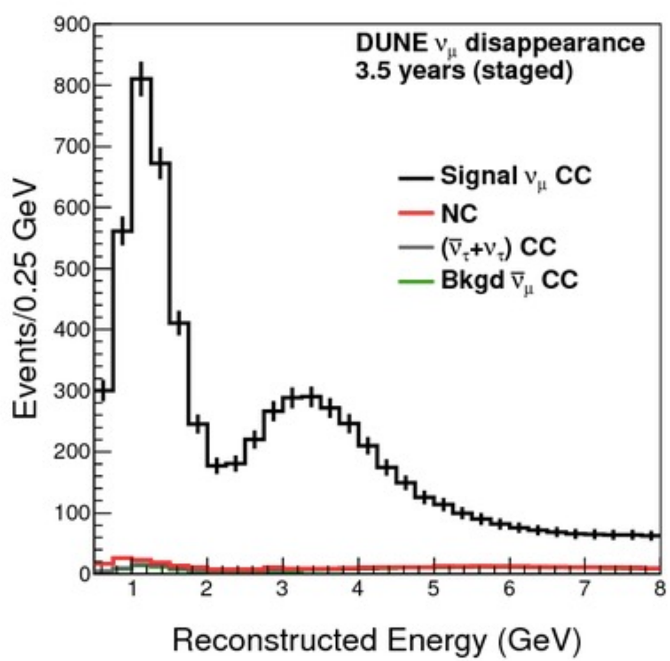


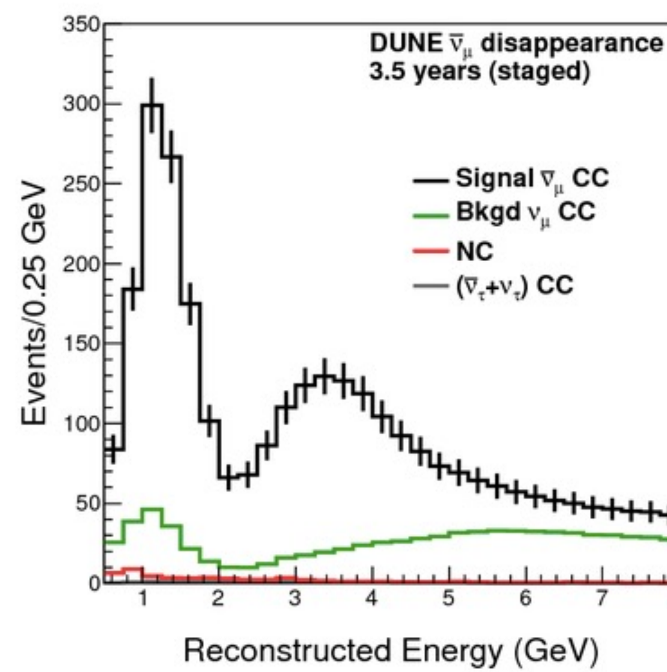




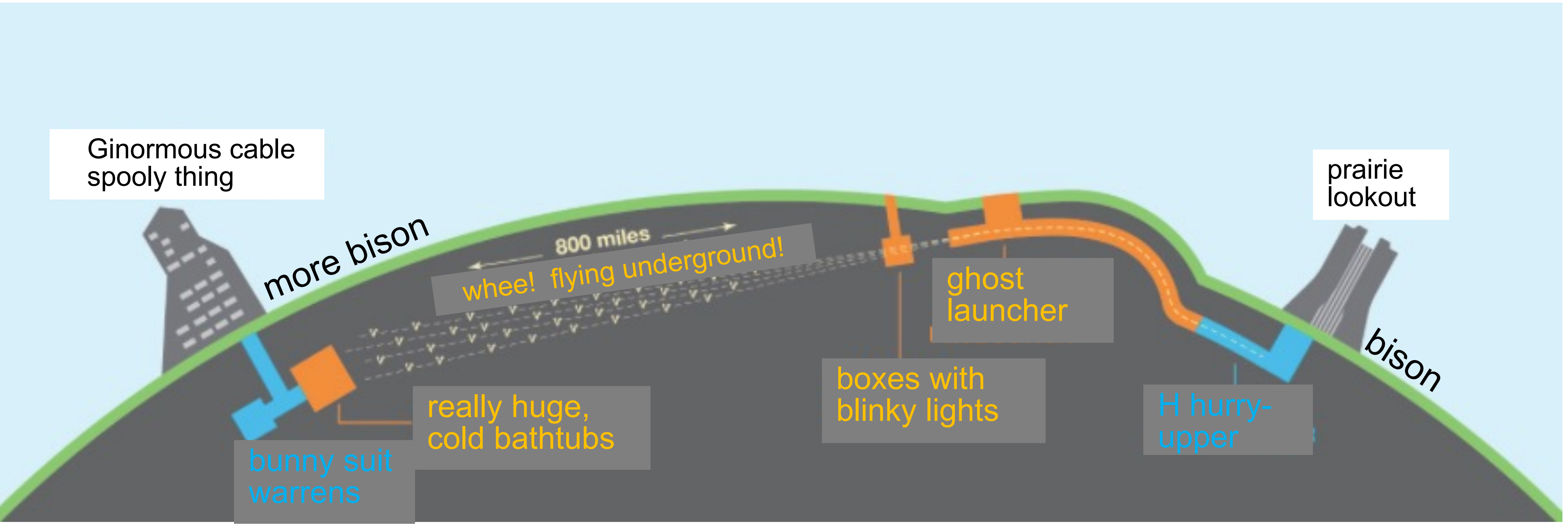
Muon flavor



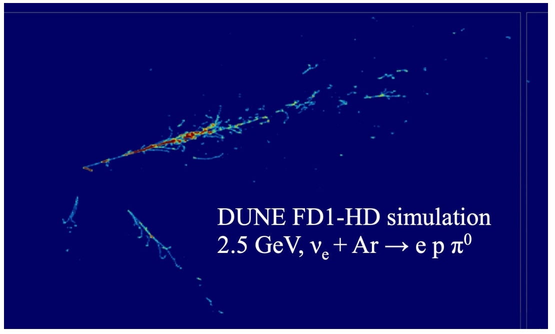




Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility

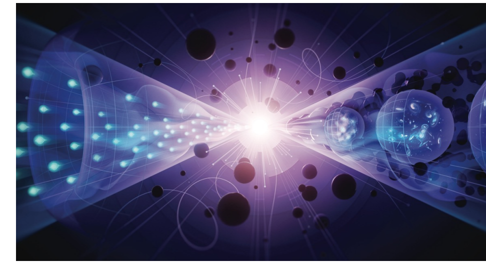


- <u>Phase I</u>: near + far site infrastructure, upgradeable 1.2 MW beam, 2x18 kt LArTPC, movable ND + m catcher, on-axis ND
- <u>Phase II</u>: two more FD modules, >2 MW beam, ND upgrades [new ideas!]
- Broad physics program



→ new P5-recommended configuration

P5 Recommendations for DUNE



Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

We reaffirm the previous P5 recommendations on major initiatives:

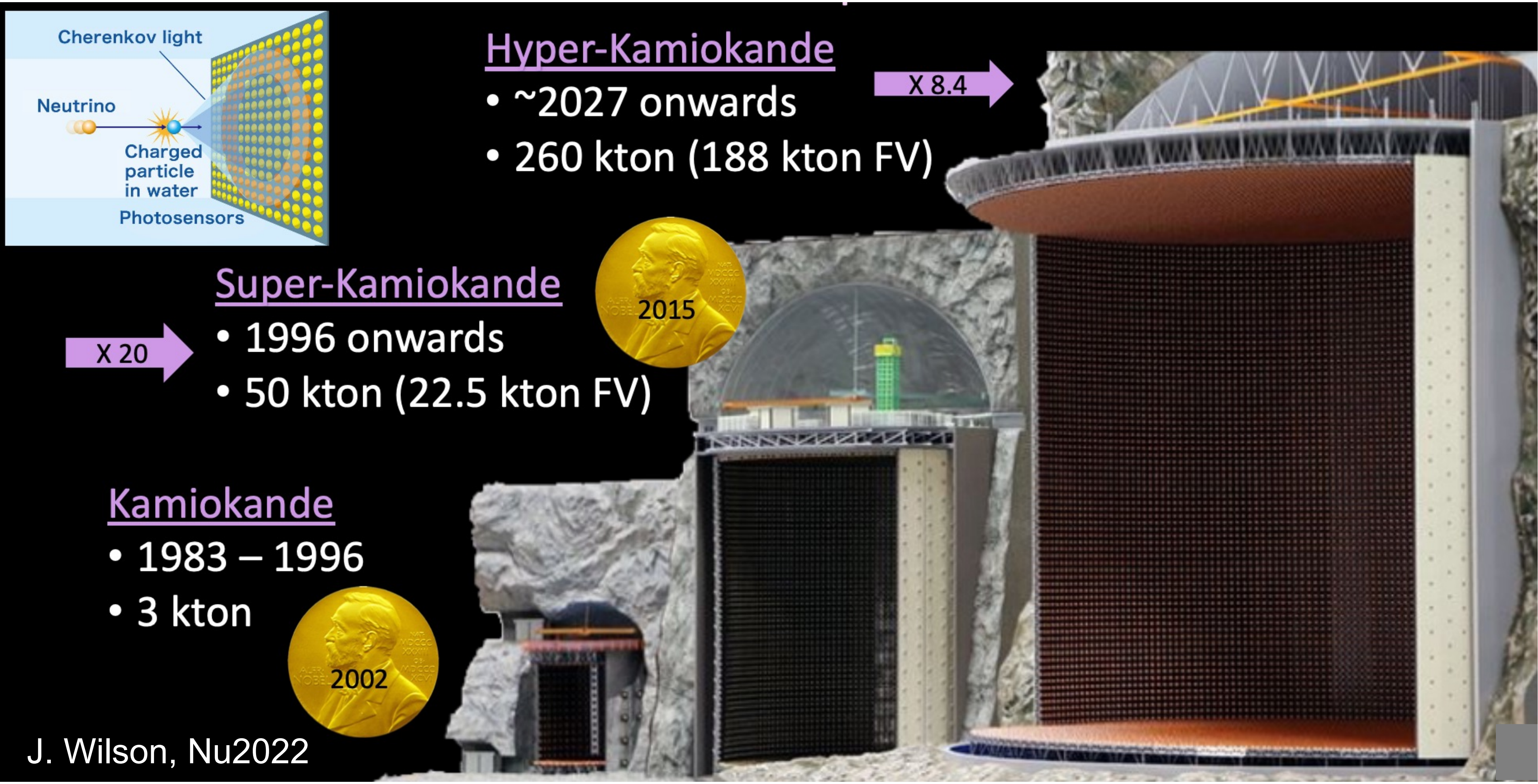
b. The first phase of DUNE and PIP-II to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science (*elucidate the mysteries of neutrinos*, section 3.1).

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

b. Re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

- Similar reach w/ 3 modules + enhanced beam
- In favorable scenario, new ideas for 4th module

Hyper-Kamiokande



- Beam from J-PARC 295 km away, upgrade to 1.3 MW
- Many non-accelerator physics topics

We can also think of oscillation physics experiments as *pushing on* the three-flavor paradigm...

There are already some slightly uncomfortable data that **don't fit that paradigm**...

Science Drivers in Neutrino Physics

Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

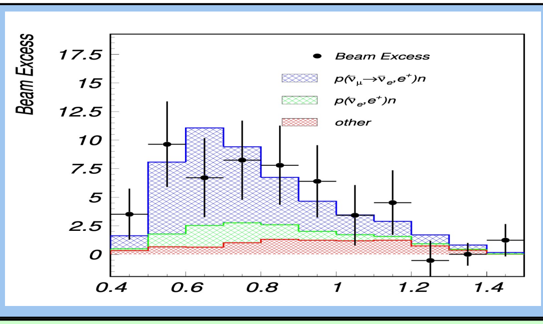
Understanding **astrophysics** and **cosmology**

There are some anomalies in the oscillation sector... can we resolve them?

Outstanding ‘anomalies’

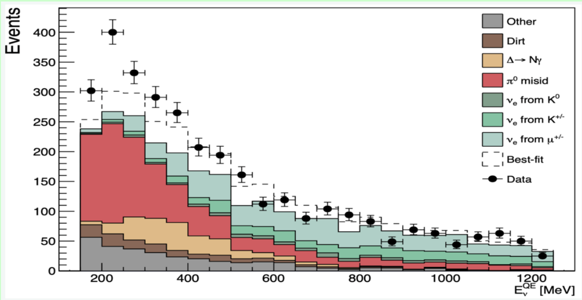
LSND @ LANL (~30 MeV, 30 m)

Excess of $\overline{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



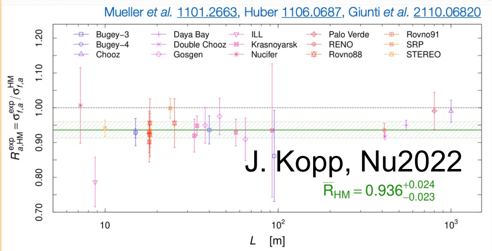
MiniBooNE @ FNAL (ν,$\overline{\nu}$ ~1 GeV, 0.5 km)

- unexplained >3 σ excess for E < 475 MeV in neutrinos
  "low-energy excess" inconsistent w/ LSND oscillation
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antinus



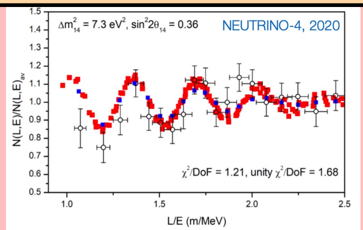
"Reactor flux anomaly"

deficit of reactor antinue absolute flux
wrt calculation



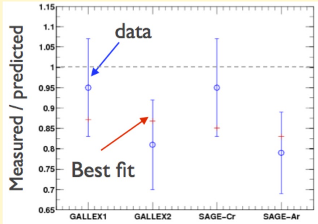
"Reactor spectral anomaly"

a wiggle, but in only one expt...



"Gallium anomaly"

~3σ deficit of nue flux from 51-Cr source in Ga

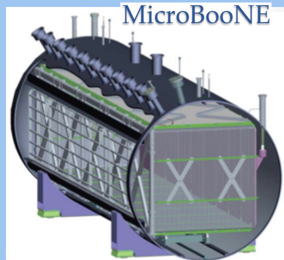


We can also think of oscillation physics experiments as *pushing on* the three-flavor paradigm...

There are already some slightly uncomfortable data that **don't fit that paradigm**...

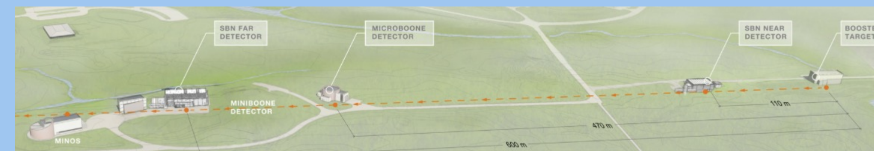
Anomalies are frequently blamed on additional neutrino states (which must be "**sterile**", i.e., no SM weak interactions, given that we know only three active light neutrinos from the Z^0 width)...

Many experiments going after (light) sterile neutrinos...

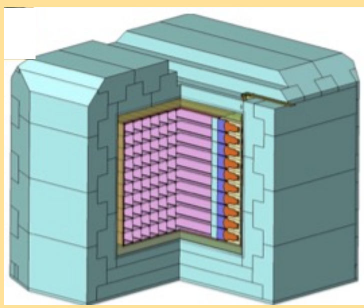


Experiments with beams

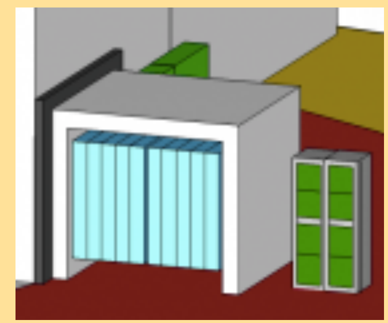
(meson decay in flight and at rest)



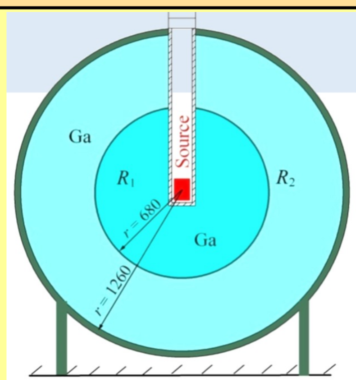
FNAL SBN, JSNS^2, ...



Experiments at reactors

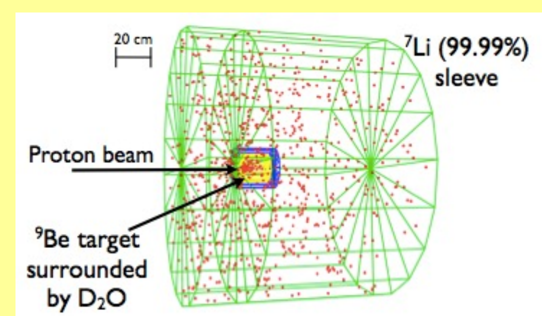


PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....



Experiments with radioactive sources

IsoDAR, BEST...

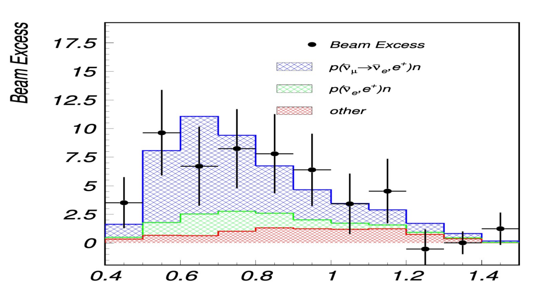


and many more, including experiments with other "day jobs"

Status of attempts to resolve anomalies...

LSND @ LANL (~30 MeV, 30 m)

Unresolved... JSNS^2 will test



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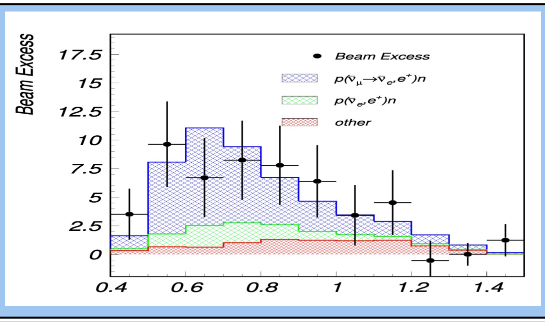
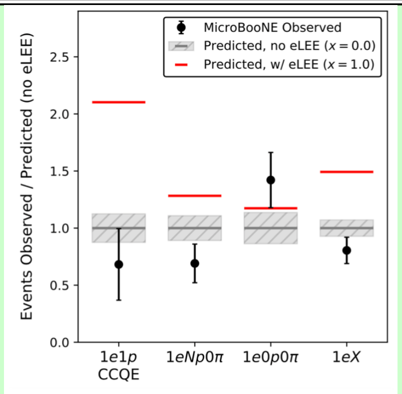


MiniBooNE @ FNAL ($\nu,\bar{\nu}$ ~1 GeV, 0.5 km)

Unresolved.... Results from MicroBooNE rule out specific electron/gamma final state explanations for LEE so far
....**more data from FNAL SBN program soon**



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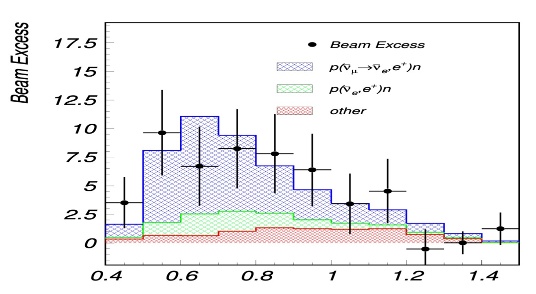

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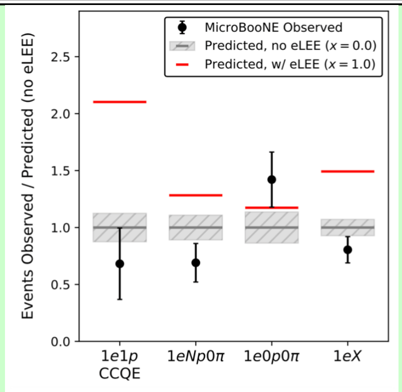
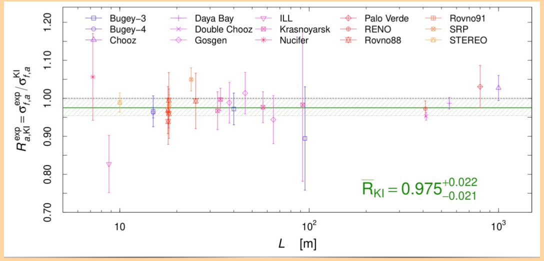


"Reactor flux anomaly"

Resolved (probably?) with new input β-decay spectra from 235-U fission



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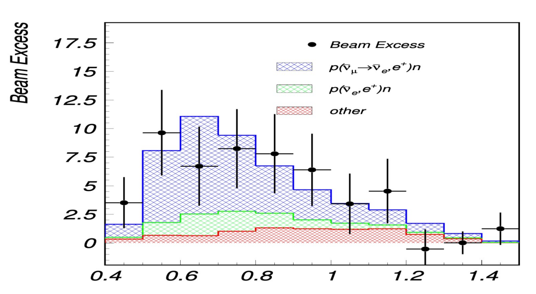

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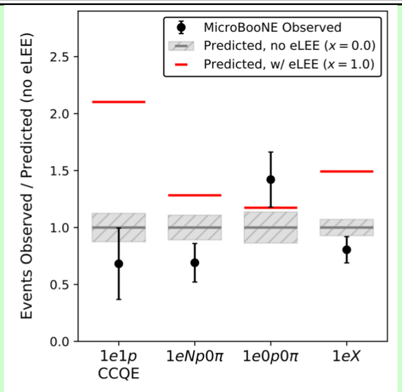

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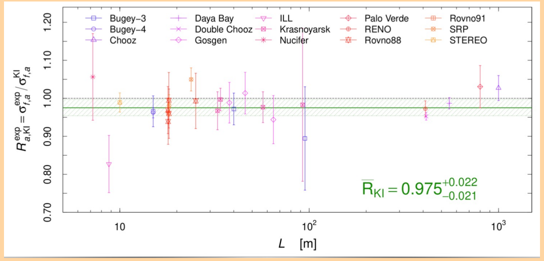
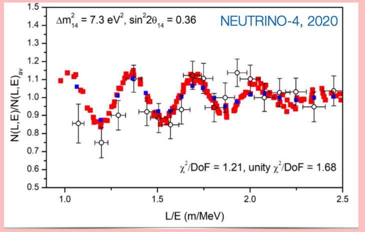
J. Kopp, Nu2022



"Reactor spectral anomaly"

~Unresolved... new data disfavor.. more data coming...

PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....



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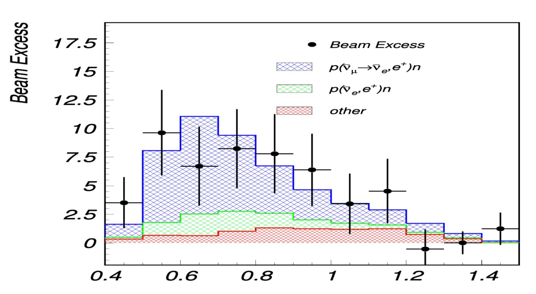

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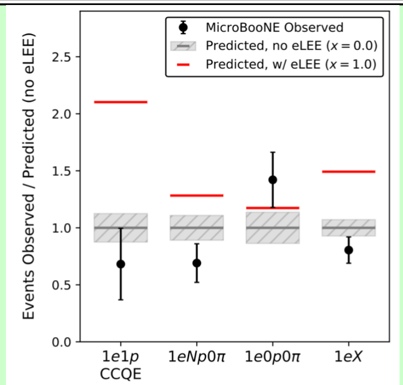

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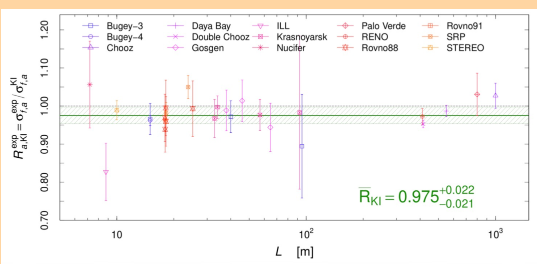

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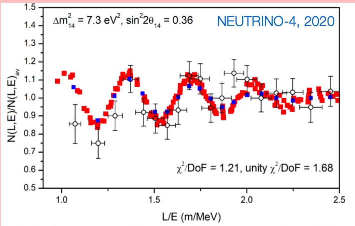
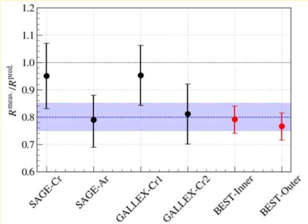


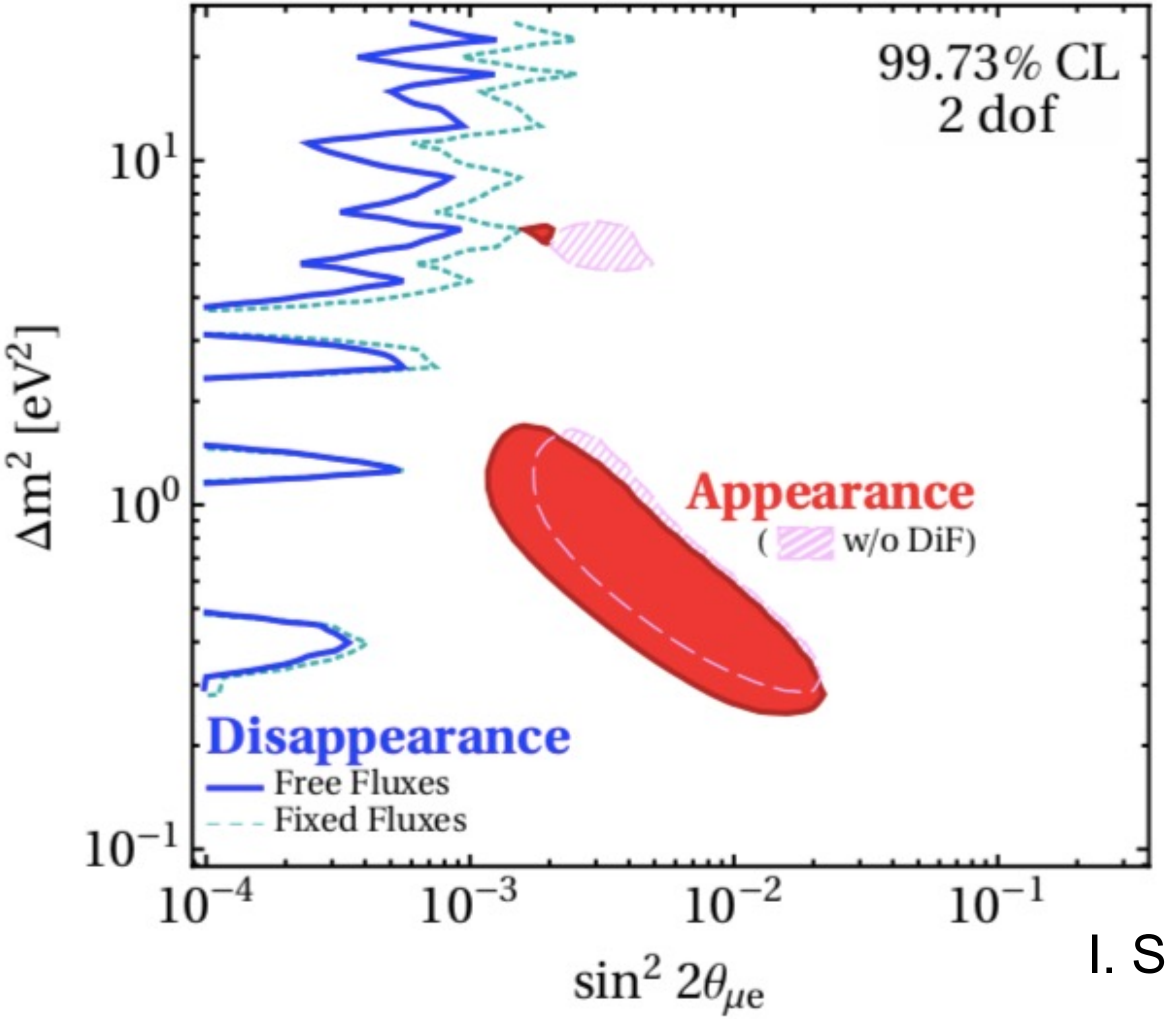
"Gallium anomaly"

Unresolved... new BEST results (5σ) confirm it

...no baseline dependence



Sterile oscillation fits to "all" the data are uncomfortable...



I. Soler

Appearance and disappearance data
are in fairly serious tension

M. Dentler et al. https://doi.org/10.1007/JHEP08(2018)010

[does not include PROSPECT, STEREO + other new data]

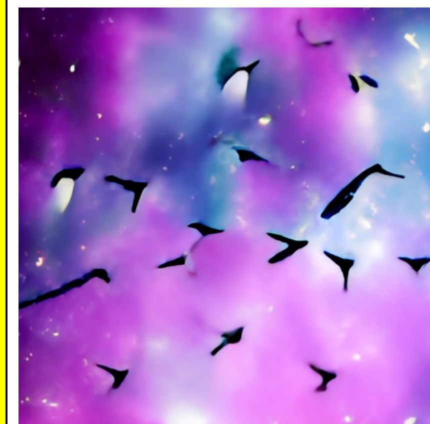
Science Drivers in Neutrino Physics

And we can search broadly for new physics

Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics



Understanding **astrophysics** and **cosmology**

Can we find new physics?

Beyond the Standard Model in the Neutrino Frontier

This includes *both* BSM in the neutrino sector, *and* BSM search opportunities in neutrino detectors

See Snowmass colloquia by J. Kopp, Z. Tabrizi, M. Toups (+NF03 report)

dim-4: the Neutrino Portal

- ☑ one of the main portals to the dark sector
- ☑ superior sensitivity at future experiments (near & far detectors!)

dim-5: Neutrino Magnetic Moments

- ☑ starting probe TeV–scale new physics
- ☑ strong synergies between different searches

dim-6: Neutrinos in SMEFT

- ☑ model-independent formalism for high-scale new physics
- ☑ easy comparison between experiments

J. Kopp, Snowmass colloquium

- sterile neutrinos over wide range of masses
- neutrino decay
- PMNS non-unitarity
- anomalous ν magnetic moments
- non-standard ν interactions
- new physics in double beta decay

Very wide array of experimental approaches

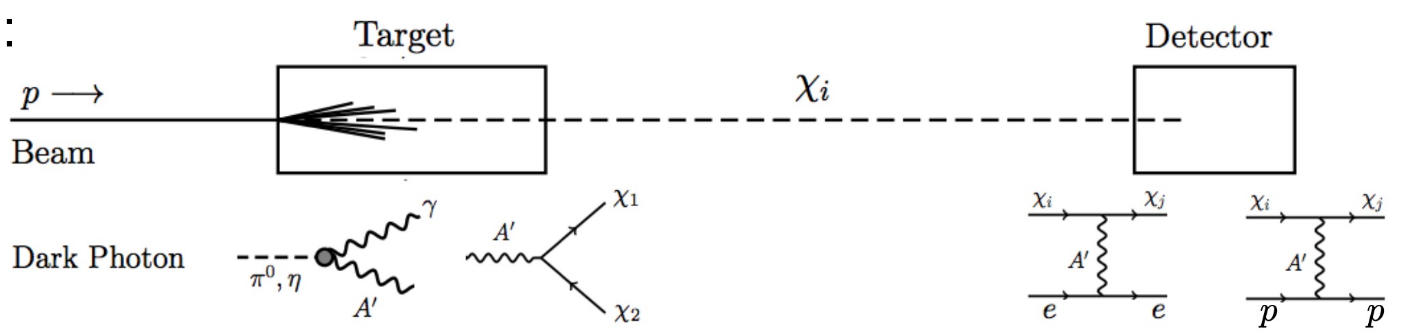
Note that in addition to BSM in the neutrino sector, there are **non-neutrino-sector BSM search opportunities in neutrino detectors**

- Baryon number violation in large detectors
- Dark sector particle searches

  beams, natural sources, cosmogenic

  - Axion-like particles
  - Light DM
  - Light Z'

For example:



Matt Toups

- DUNE near detectors
- spallation neutron sources
- beam dumps
- LHC Forward Physics Facility
- neutrino factories
- ....

Pause... Day 2

Science Drivers in Neutrino Physics

Where are the grand (experimental) challenges?

Three-flavor paradigm

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

Neutrino oscillations are not the only Grand Challenge in the 3-flavor paradigm...

Neutrino Oscillations

Latest 3-flavor results

Remaining unknowns in the 3-flavor picture: **MO and CP δ**

Beyond 3-flavor?

Absolute Mass

Status and prospects

Majorana v… D?

Overvie… NLDBD

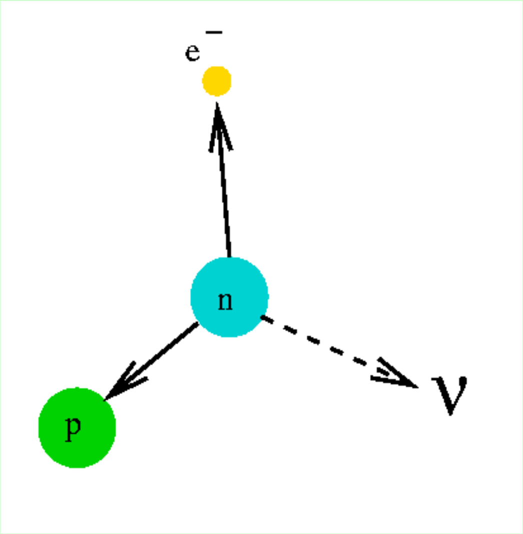
The mass pa… n

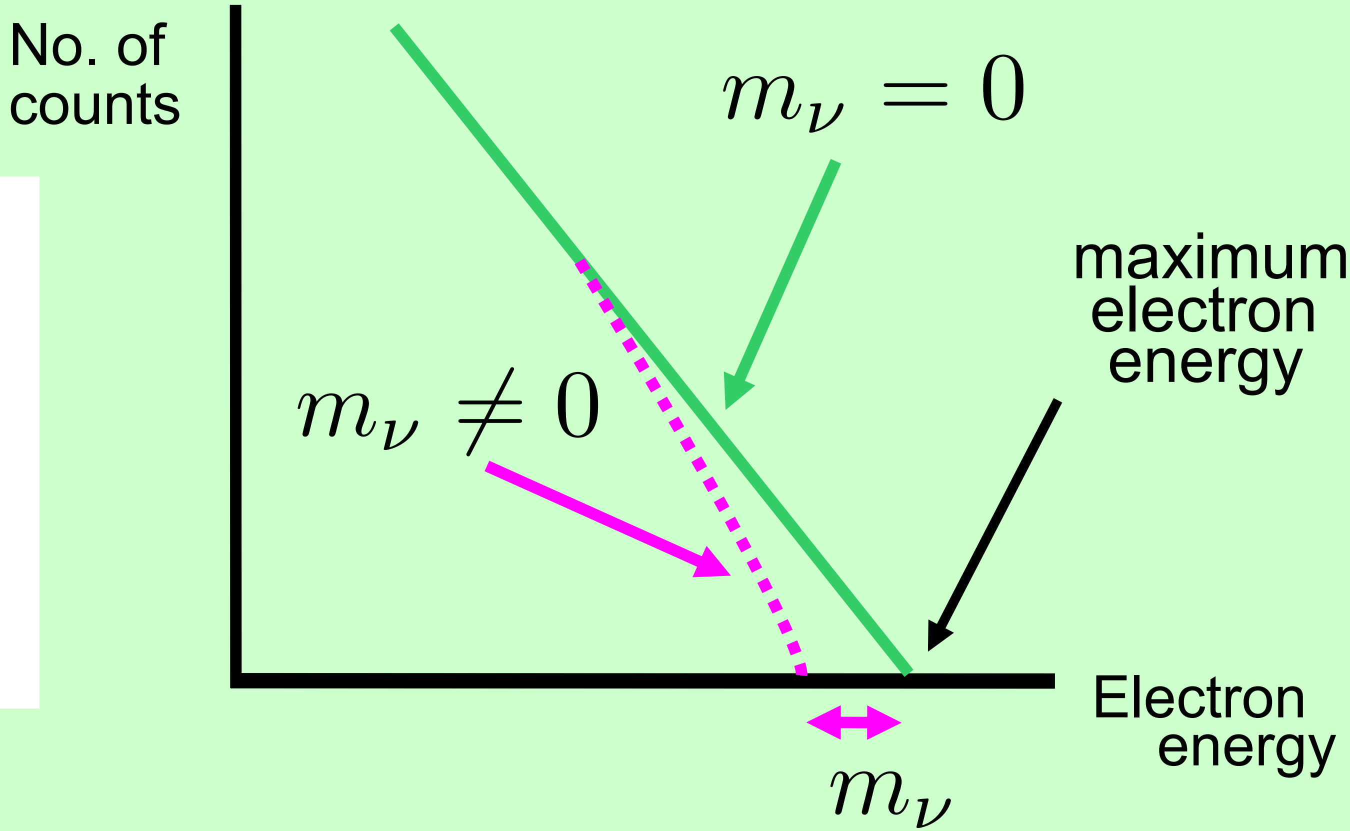
The mass scale

The mass nature

Determine the absolute mass scale

Kinematic experiments for absolute neutrino mass





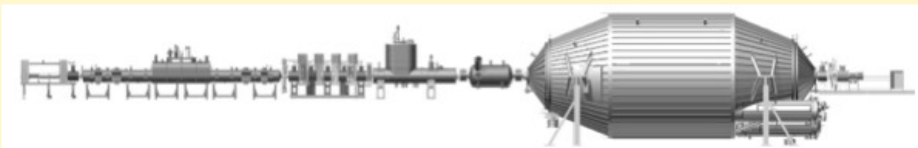
Look for distortion of β-decay spectrum near endpoint

Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

$^3\mathrm{H} \rightarrow ^3\mathrm{He} + e^- + \bar{\nu}_e$

18.6 keV endpoint

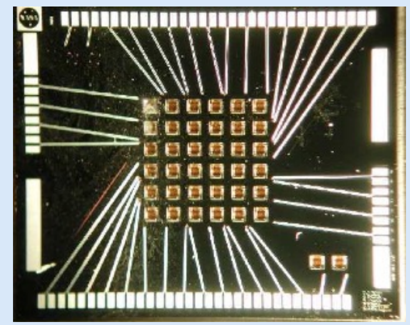


Sensitivity to ~0.2 eV

First results, taking more data

Thermal calorimetry

e.g., **MANU, MIBETA, MARE**



$^{187}\mathrm{Re} \rightarrow ^{187}\mathrm{Os} + e^- + \bar{\nu}_e$

2.5 keV endpoint

Hard to scale up...

No longer pursued

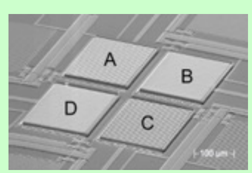
Holmium

e.g., **ECHo, HOLMES**

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

metallic magnetic calorimeters

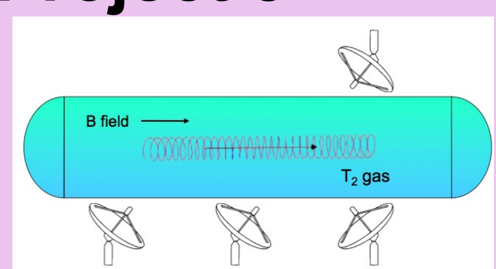


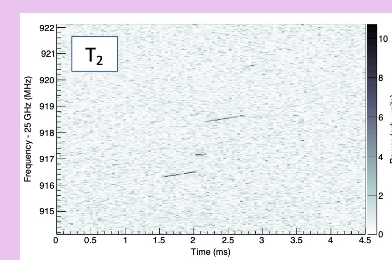
Electron capture decay,
ν mass affects deexcitation spectrum
R&D in progress

R&D

Cyclotron radiation tritium spectrometer: Project 8

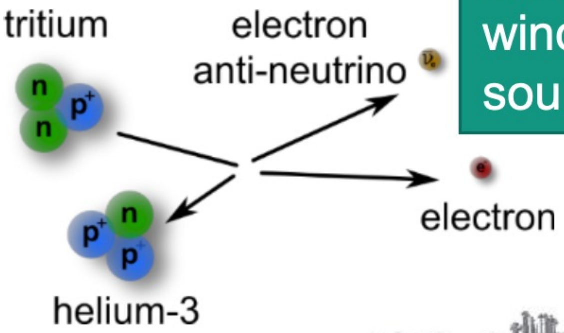
R&D, first m_β limit



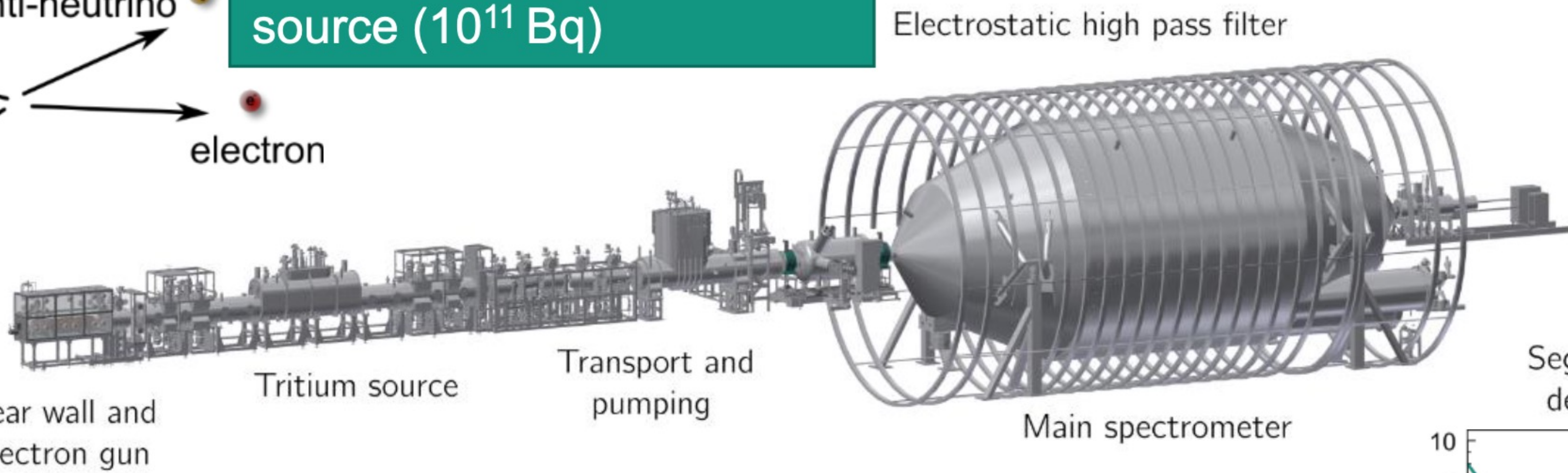


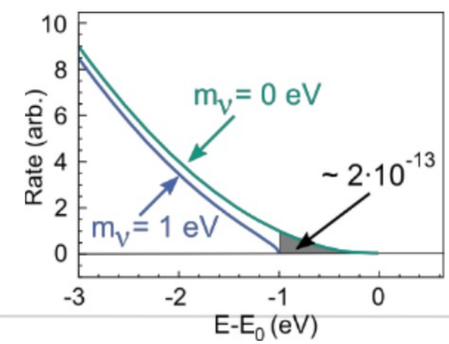
Long-term potential for
- atomic tritium w/low uncertainties
- aiming for 40 meV in long term

KATRIN results

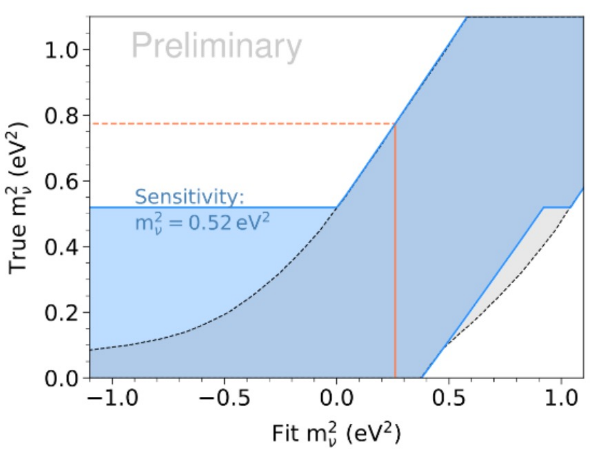


ultra-stable high-luminosity windowless gaseous tritium source (10^{11} Bq)





high-resolution MAC-E filter with < 1 eV energy resolution



Experimental sensitivity $m_\nu < 0.7$ eV (90% CL)

- Lokhov-Tkachov (90 % CL)
- Feldman-Cousins (90 % CL)
- Fit result: $m_\nu^2 = 0.26\ eV^2$
- m_ν^2 limit = 0.8 eV^2 (90 % CL)
  m_ν limit = 0.9 eV (90 % CL)

New limit from 2nd campaign
$m_\nu < 0.9$ eV (90% CL)

First campaign $m_\nu < 1.1$ eV (90% CL)

Combined:
< 0.8 eV (90% CL)

Expect sensitivity to **0.3 eV** by 2025

Magnus Schlösser – MORIOND2021

KATRIN Collab. Nat. Phys. **18,** 160–166 (2022)

Neutrino Oscillations

Latest 3-flavor results

Remaining unknowns in the 3-flavor picture: **MO and CP δ**

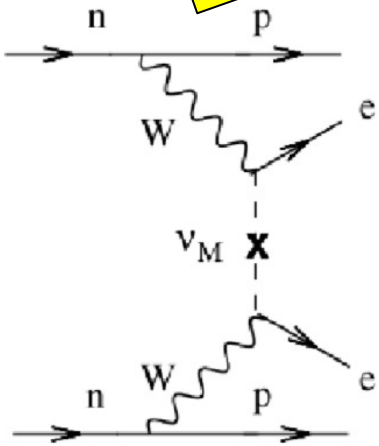
Beyond 3-flavor?

Absolute Mass

Status and pros[...]

Majorana[...]

Overview [...] NLDBD



The mass pattern

The mass scale

The mass nature

Determine whether the neutrino is its own antiparticle

Are neutrinos Majorana or Dirac?

$\nu = \bar{\nu}$

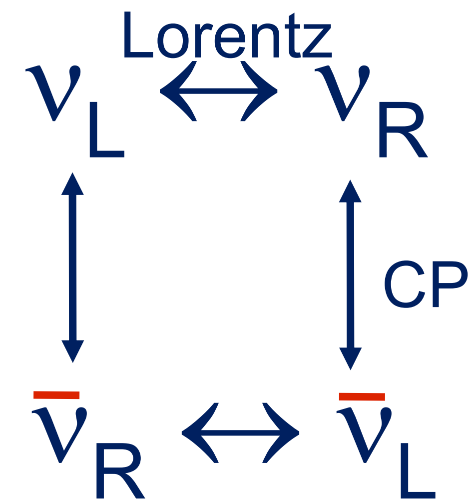
2 states

Lorentz, CP

$\nu_L \leftrightarrow \nu_R$

$\nu \neq \bar{\nu}$

4 states



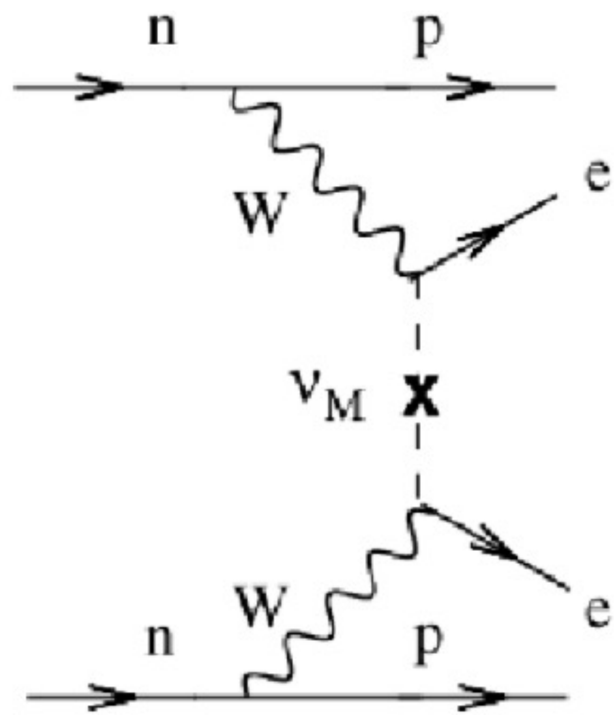
Essential for ν mass understanding....

$$\mathcal{L}_m \sim m_D\,[\,\bar{\psi}_L\psi_R + \ldots\,] + [m_L\bar{\psi}_L^c\,\psi_L + m_R\bar{\psi}_R^c\,\psi_R + h.c.]$$

e.g., "see-saw" mechanism $\Rightarrow$ Majorana ν

... may be helpful for leptogenesis...

Neutrinoless Double Beta Decay

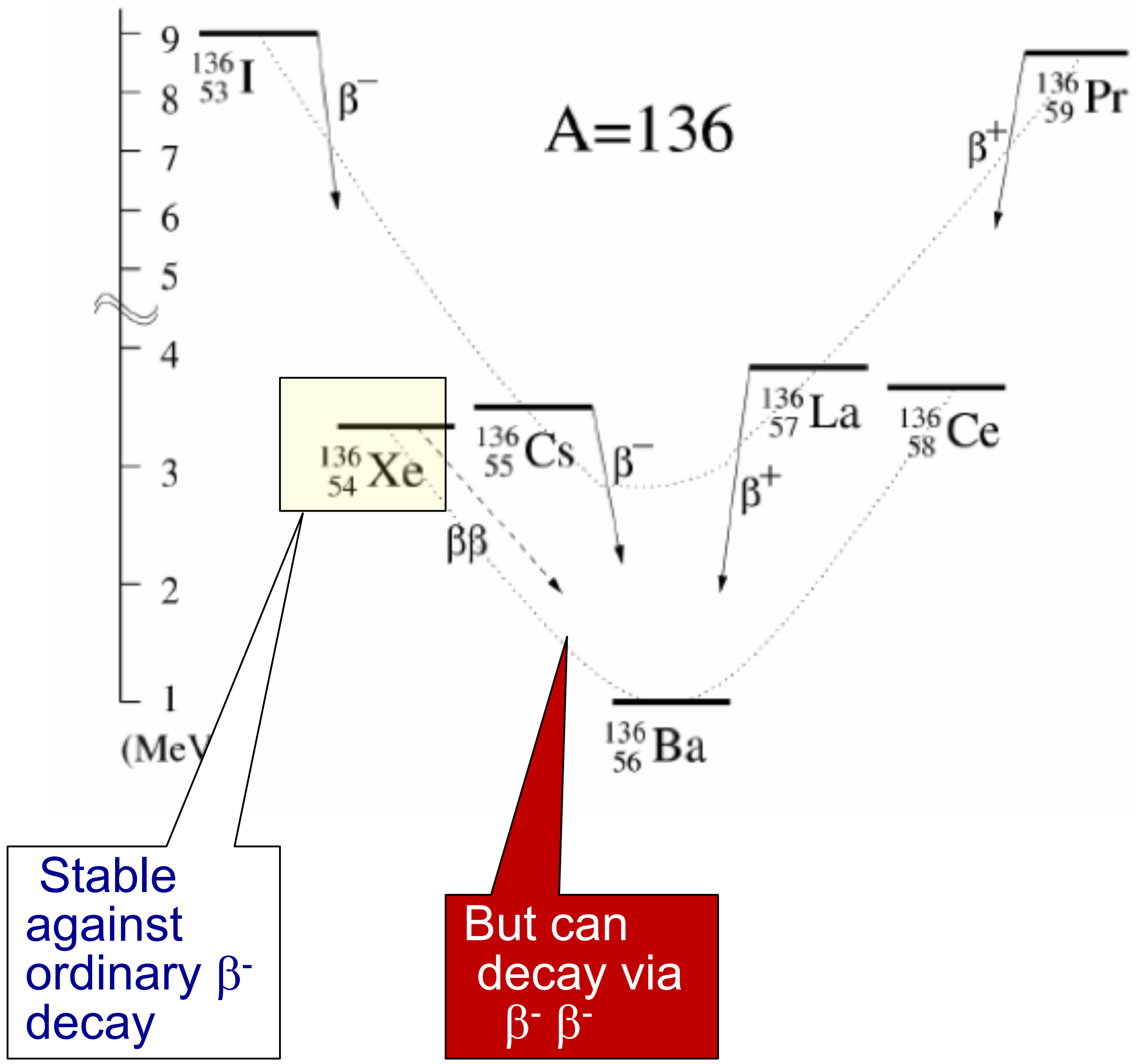


- observation would indicate:
  - **neutrinos are Majorana**
  - antimatterless matter is created

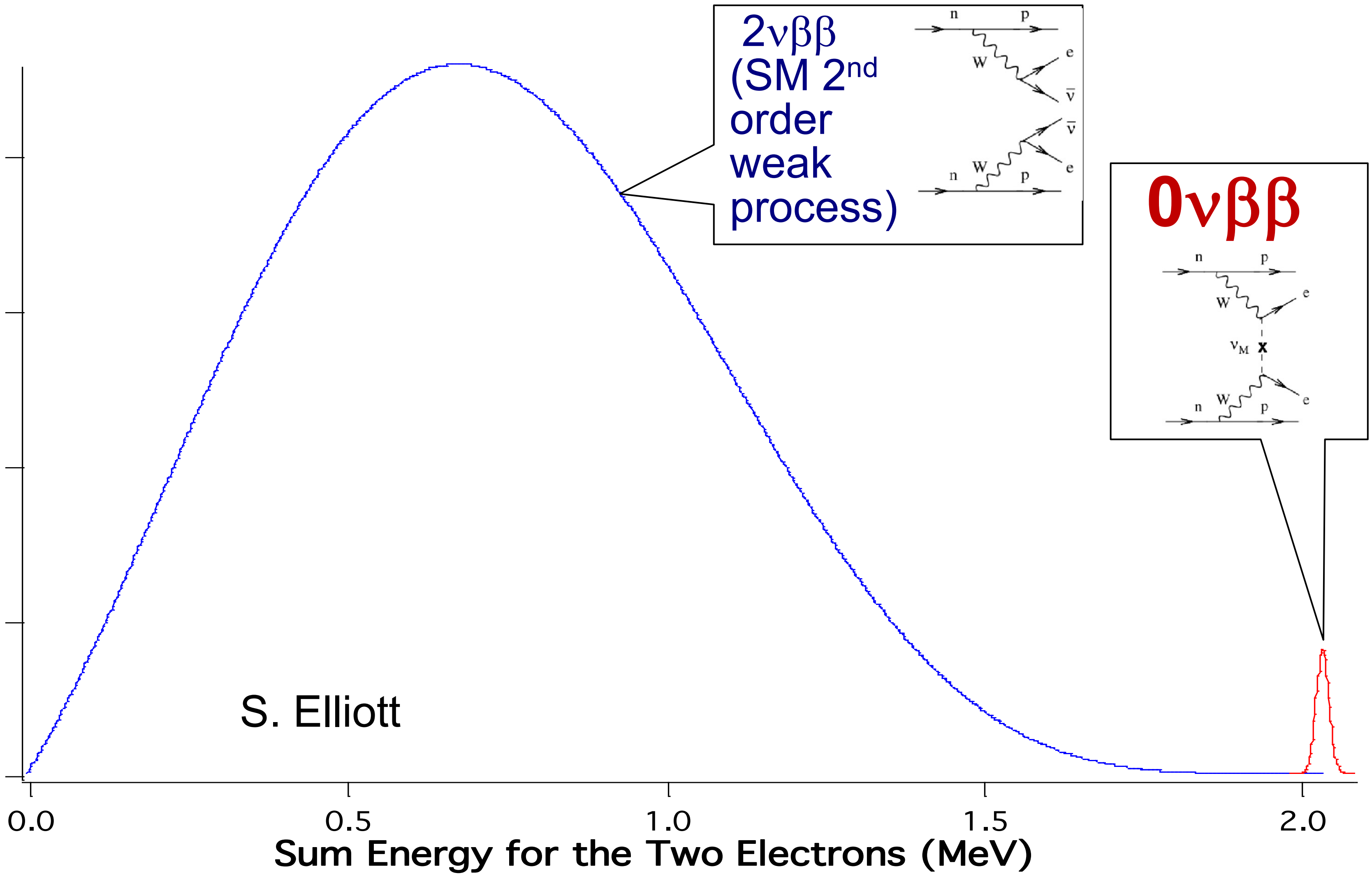
- light neutrino mediator is the nominal 3-flavor explanation
  - but can have other mediators in BSM scenarios

Experimental searches are based on nuclides for which NLDBD is energetically possible, *and* which cannot α, 1β decay

For example:



Experimental strategy: look for
peak in the two-electron spectrum
corresponding to neutrinoless final state



The list of **special NLDBD isotopes** currently being pursued

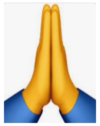
Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]	f_{enr} [c] [%]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91

want large Q value!

want high natural abundance!

or at least, ability to enrich...

Agostini, Benato, Detwiler, Menéndez & Vissani, RMP 2022, arXiv:2202.01787



Observed half-life:

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}\, g_A^4\, (M_{0\nu})^2\, \frac{m_{\beta\beta}^2}{m_e^2}$$

phase space

coupling

nuclear matrix element

effective mass

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

Effective mass depends on the mixing matrix parameters

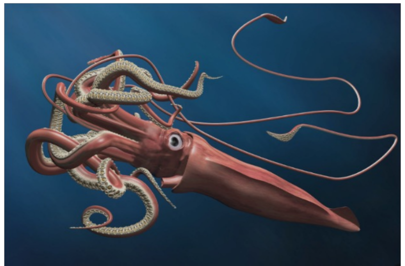
Observed half-life:

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}\, g_A^4\, (M_{0\nu})^2\, \frac{m_{\beta\beta}^2}{m_e^2}\ ^*$$

phase space · coupling · nuclear matrix element · effective mass

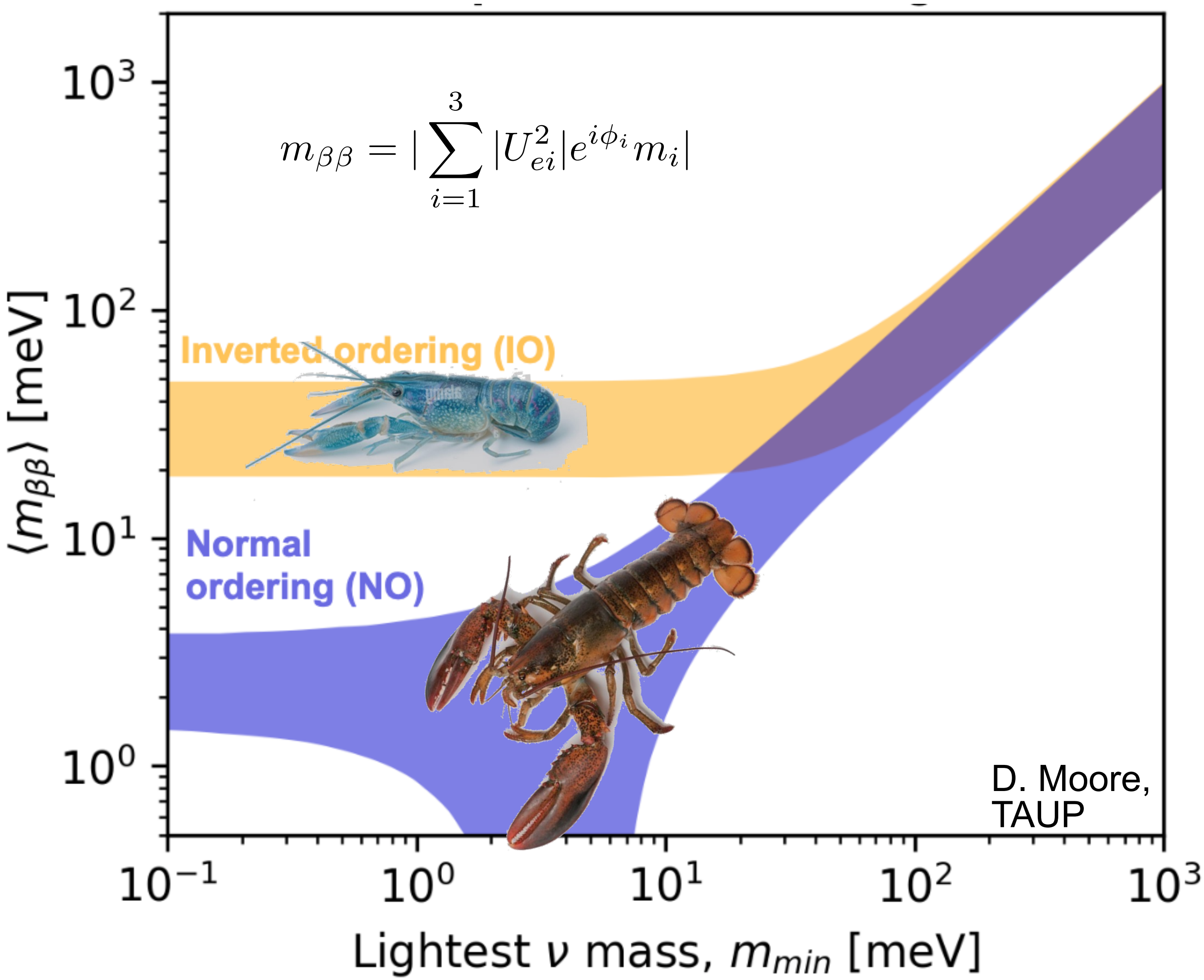
$$m_{\beta\beta} = \left|\sum_{i=1}^{3} |U_{ei}^2| e^{i\phi_i} m_i\right|$$

*Caveat: BSM physics can be hiding!



Effective mass depends on the mixing matrix parameters

The Lobster Plot



***If* neutrinos are Majorana*, experimental results must fall in the shaded regions**

Extent of the regions determined by uncertainties on mixing matrix elements and Majorana phases

*and standard 3-flavor picture, light-neutrino exchange mechanism

Neutrino mixing parameters

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^* |\nu_i\rangle$$

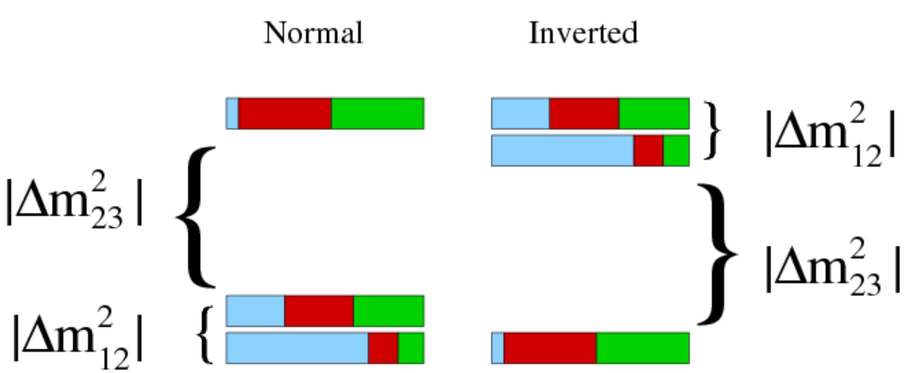
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$

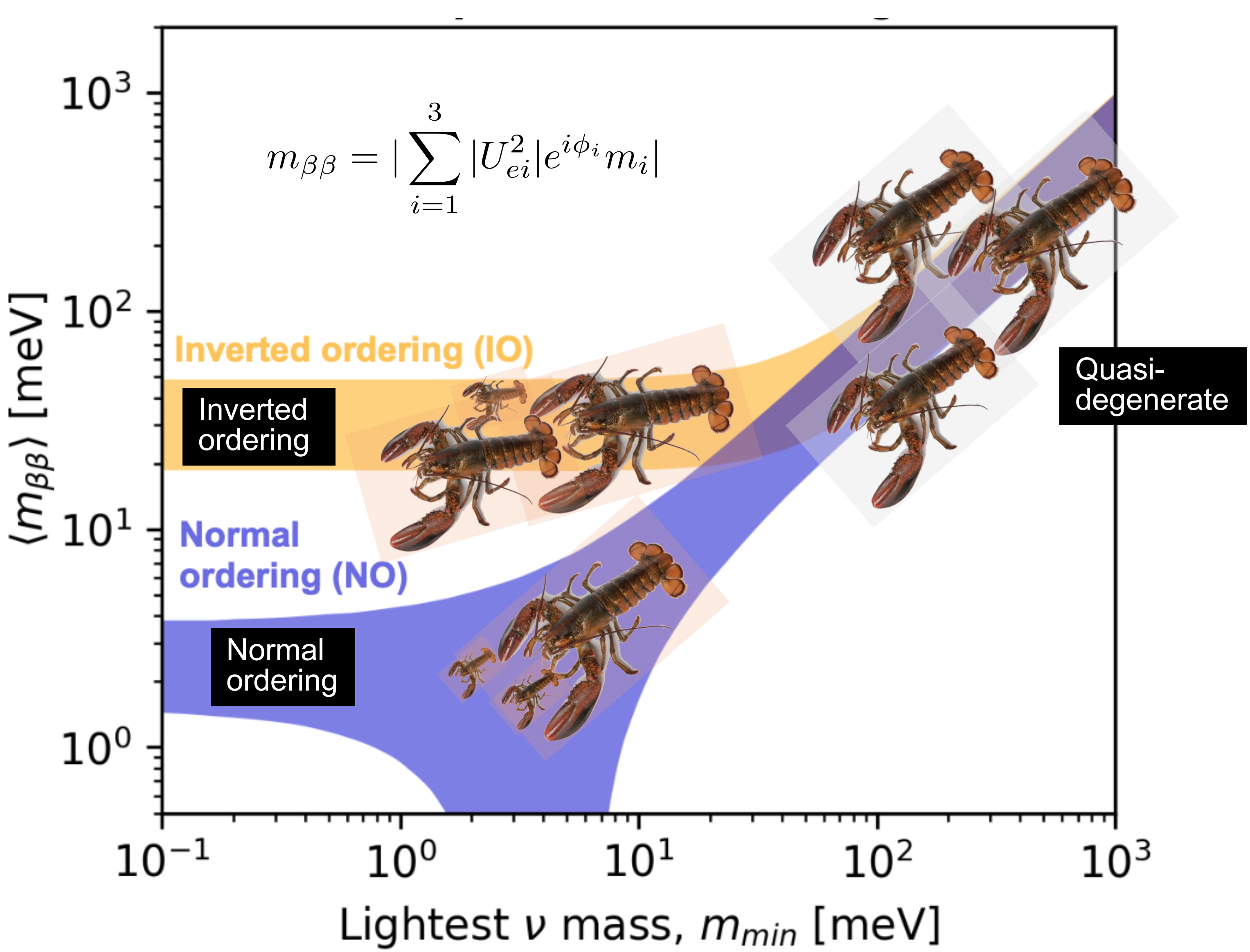
3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

Majorana phases do not affect oscillations



Observables in oscillation experiments

Assuming 3 flavors, light-neutrino exchange mechanism for NLDBD:



Clearly the **mass ordering matters** a lot for interpretation of NLDBD results

Remaining oscillation unknowns in the 3-flavor paradigm

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

with SK atmospheric data	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}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO.

Is θ_{23} non-negligibly greater or smaller than 45 deg?

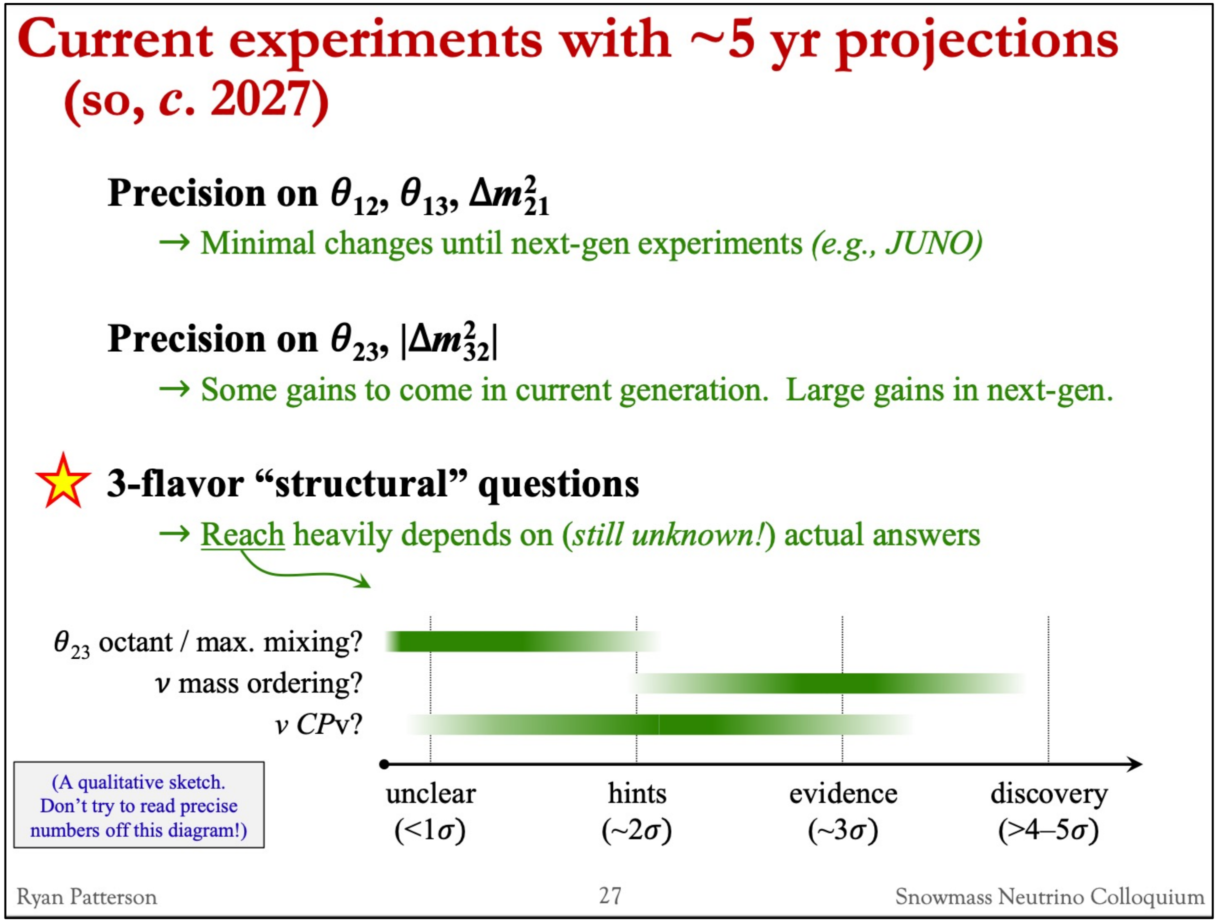
poor knowledge

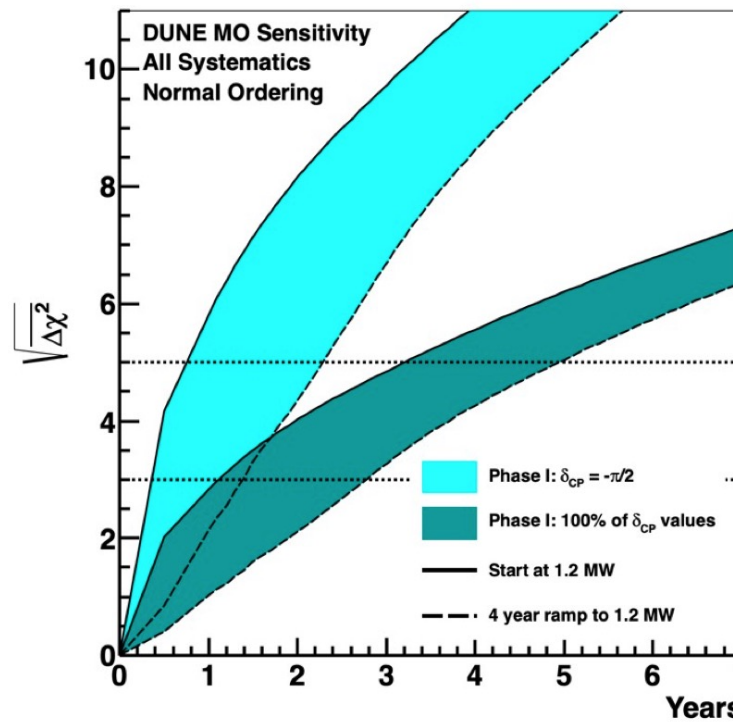
sign of Δm^2 unknown (ordering of masses)

More and better info to come from:
beams [LBL], burns [solar, JUNO],
bangs [SNe]... **what will we know about mass ordering?**

(... it's smelling like normal, but inverted is not ruled out...)

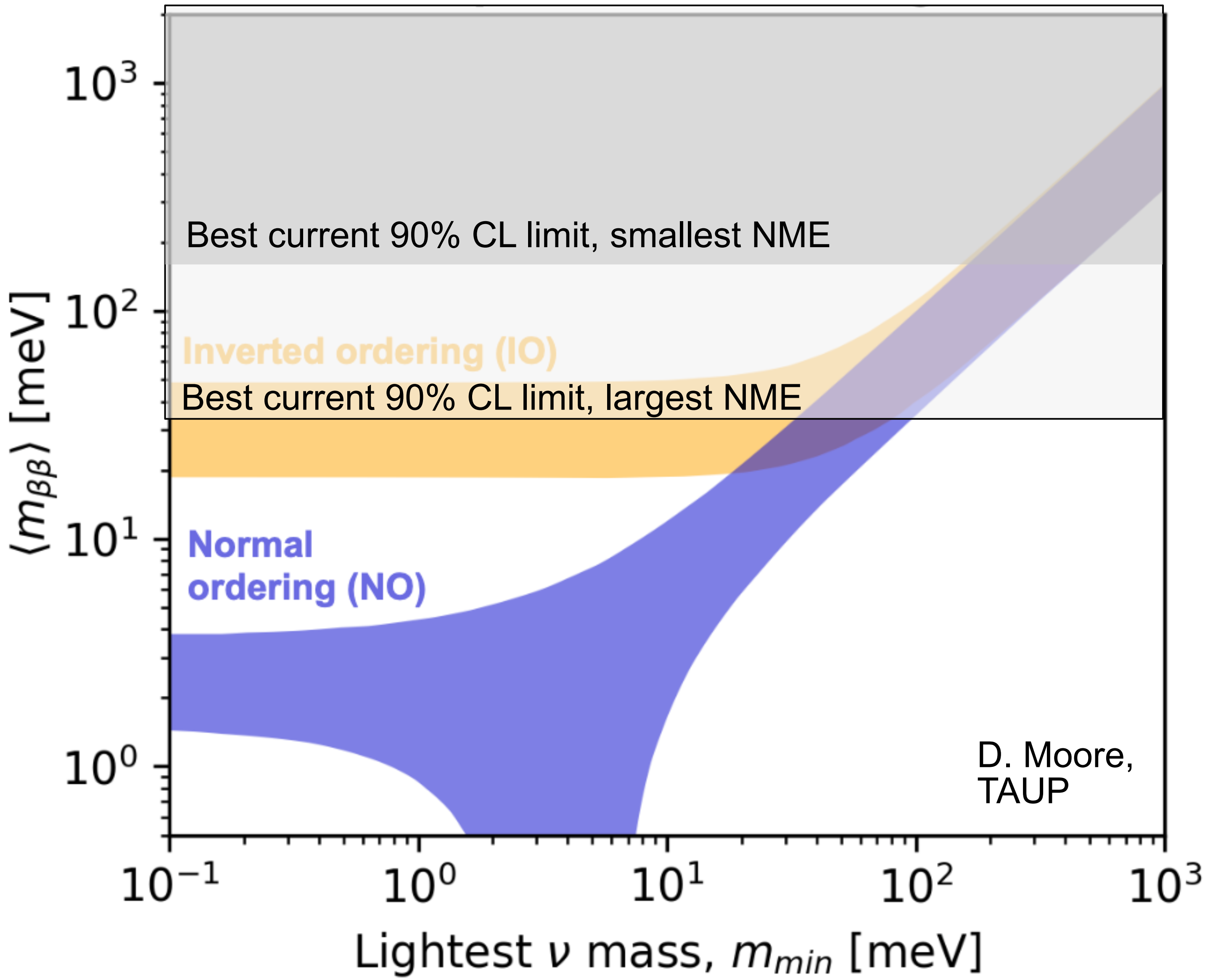
Projections from Snowmass





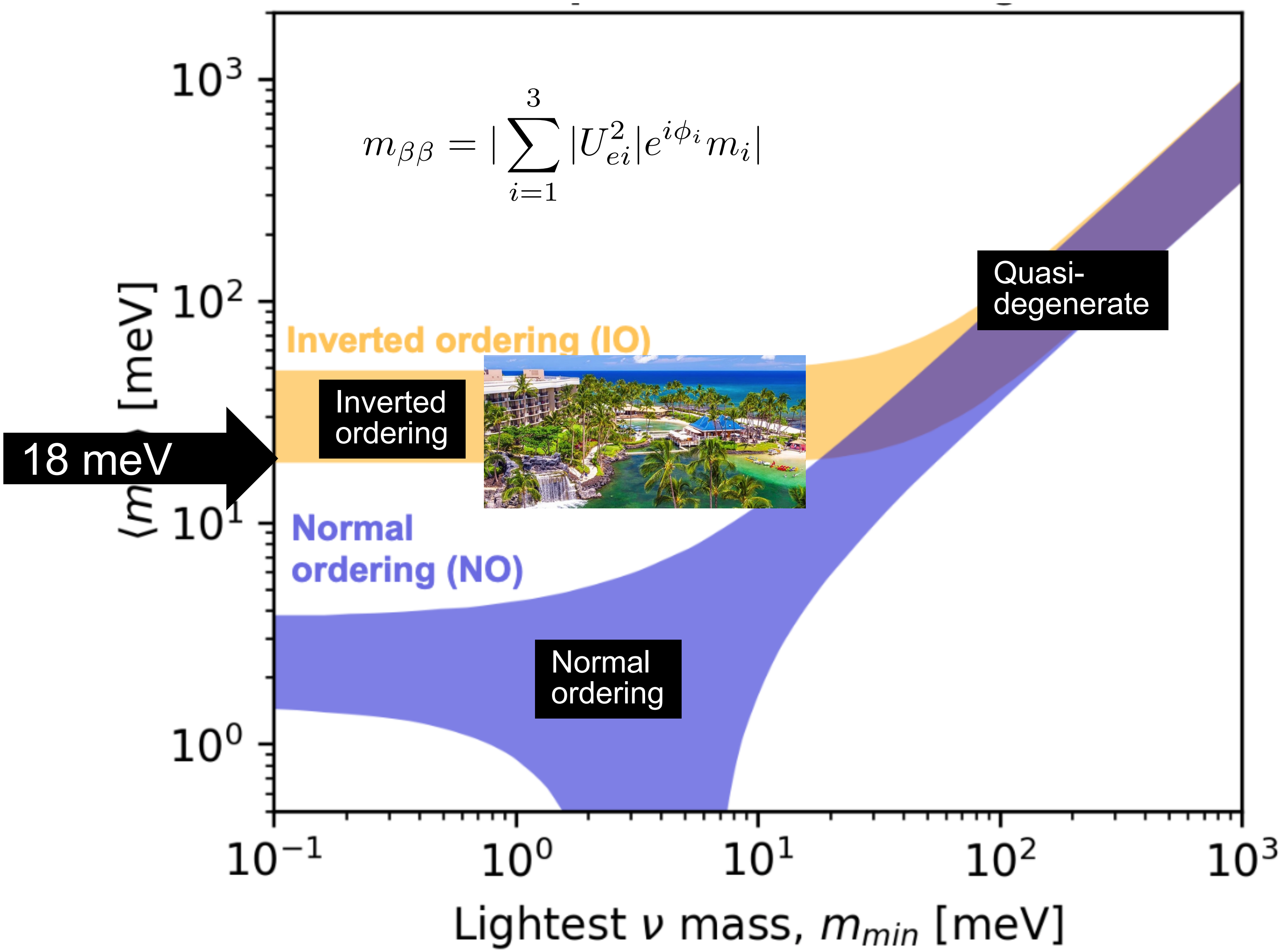
- Next ~5 years: maybe ~3σ from T2K + NOvA + JUNO
- DUNE/Hyper-K are next-generation long-baseline experiments
- DUNE will nail the mass ordering very rapidly

Where we are experimentally for NLDBD



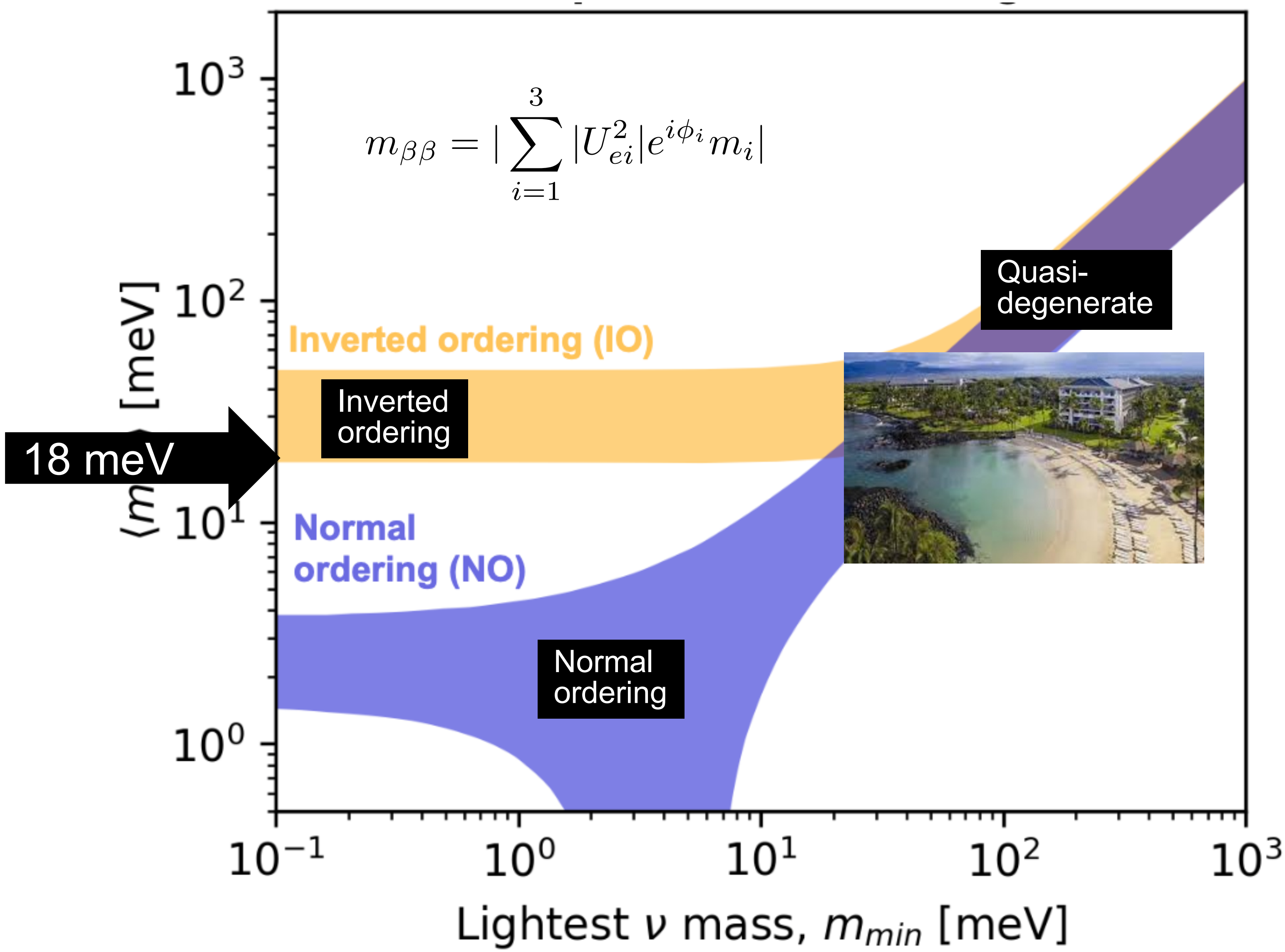
Starting to clip the IO region

Next experimental goal: cover the IO region



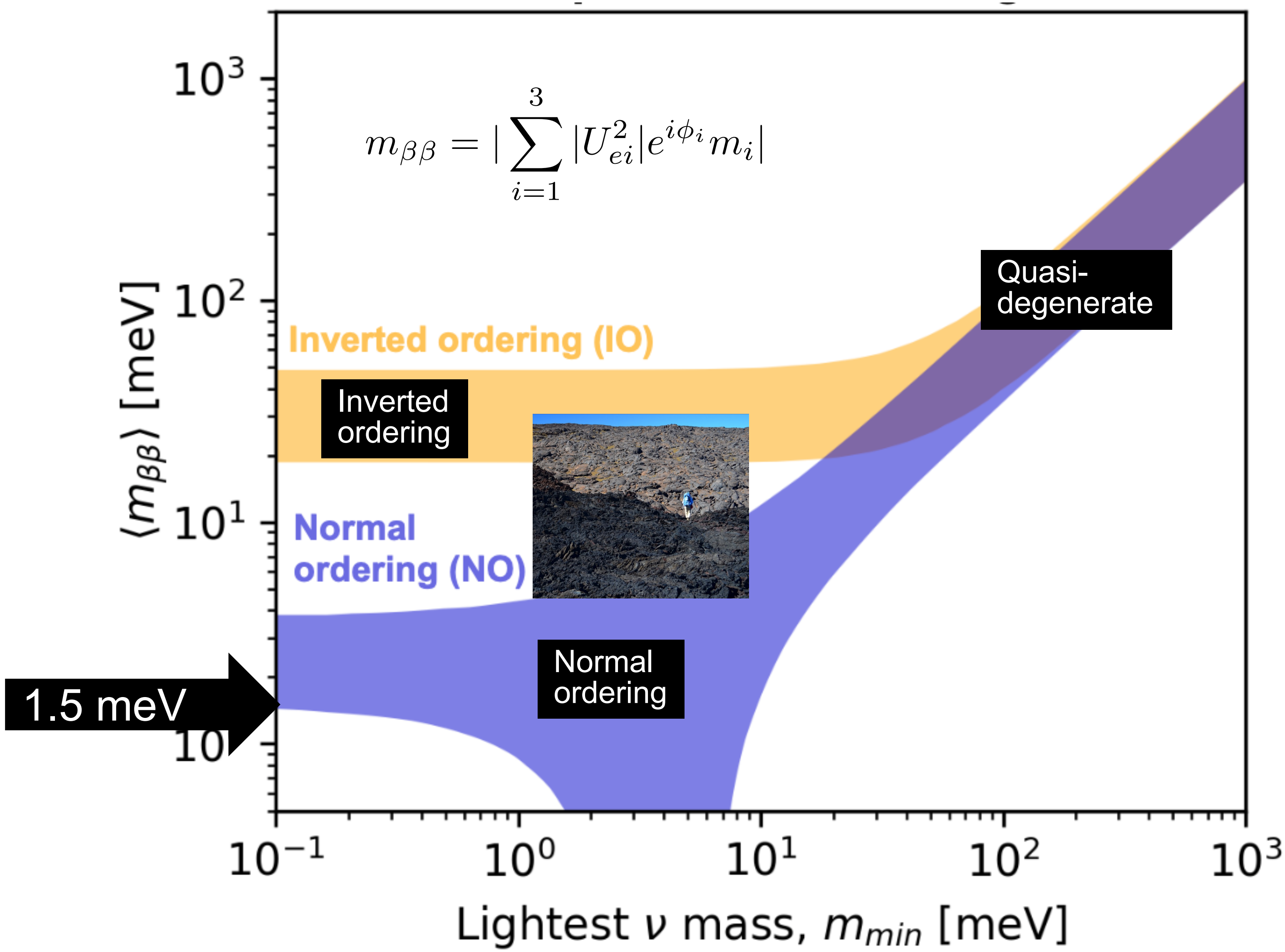
If ordering is inverted (or QD) we will be in a good place!
Either: discover NLDBD! OR (neutrinos are Dirac OR BSM)

What if the mass ordering is normal?



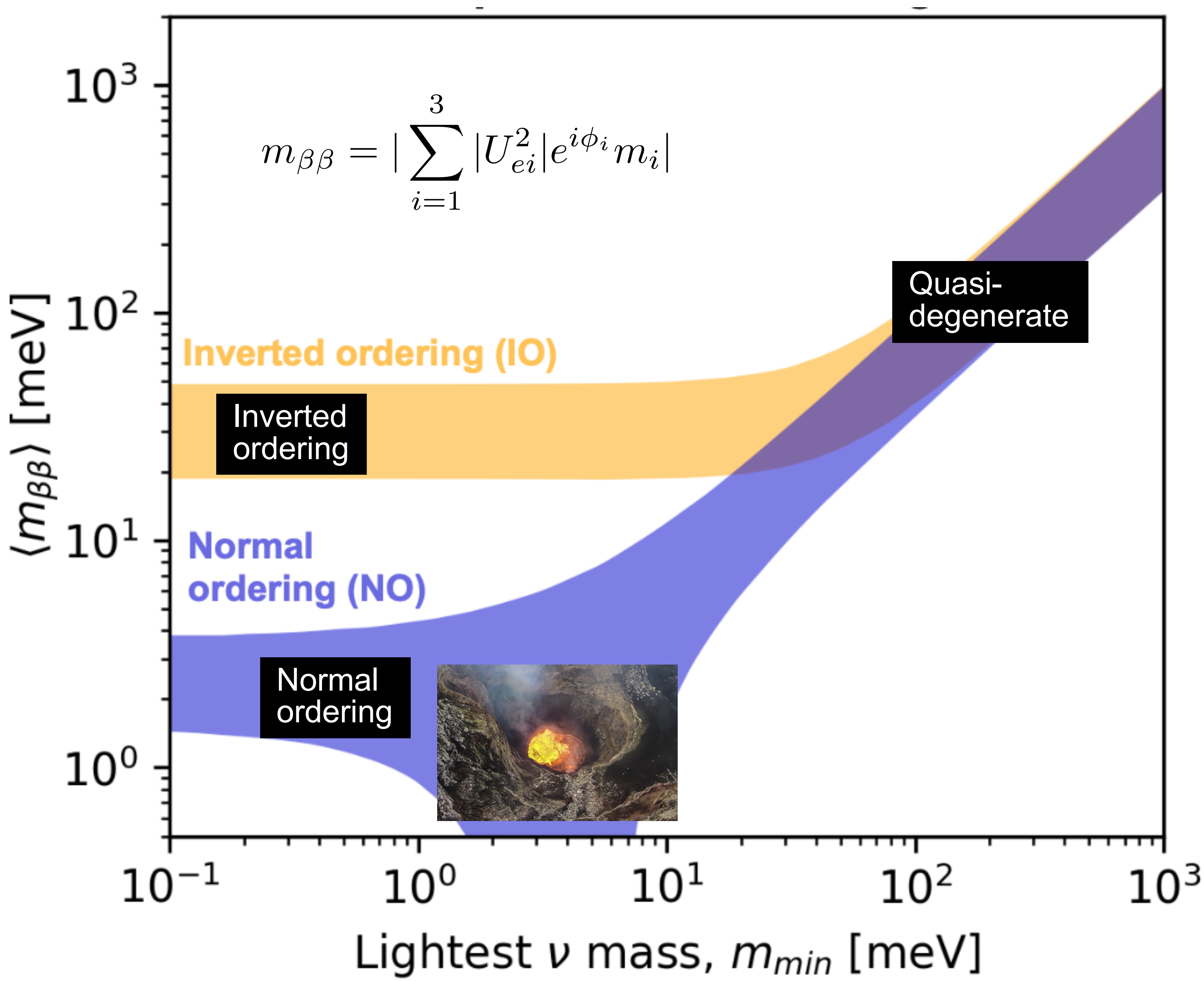
We could also have a high mass scale and discover NLDBD in the next generation ...

What if the mass ordering is normal?



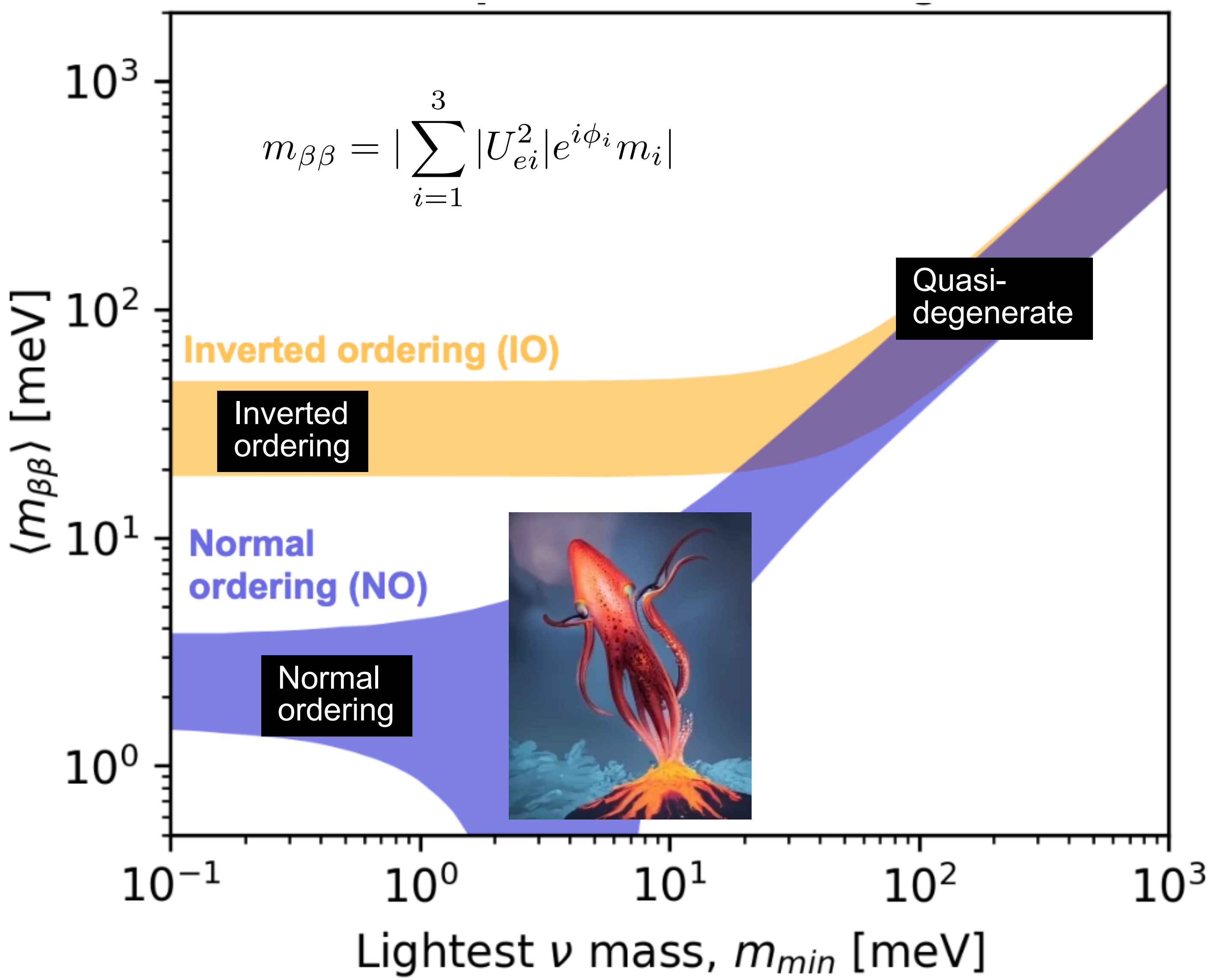
Otherwise, need to go lower...next goal for $m_{\beta\beta}$ is 1.5 meV, normal-ordering floor for m_1=0

What if the mass ordering is normal?



But... Nature could have cooked up diabolical parameters
and we could end up staring into the funnel of doom...

What if the mass ordering is normal?

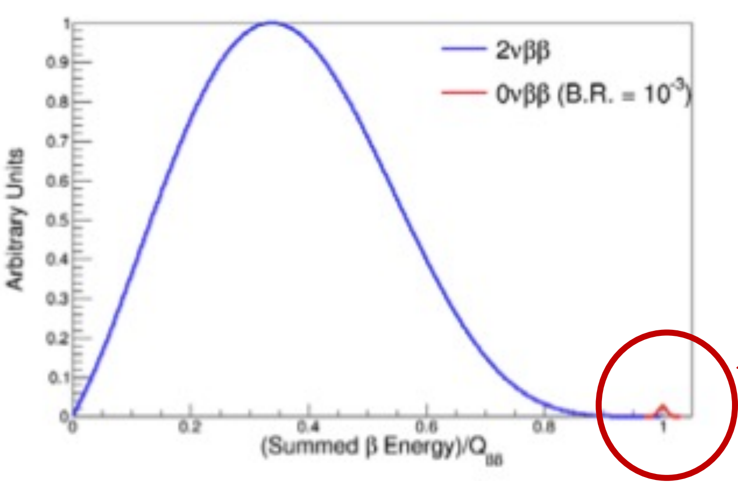


Although it's still possible BSM could surprise us!

Back-of-the-envelope experimental sensitivity

$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE



want lots of signal
and no background
in Region of Interest

Go after the numerator:

$$T_{1/2} > \frac{\ln 2 \; \boxed{\varepsilon \cdot N_{source} \cdot T}}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE

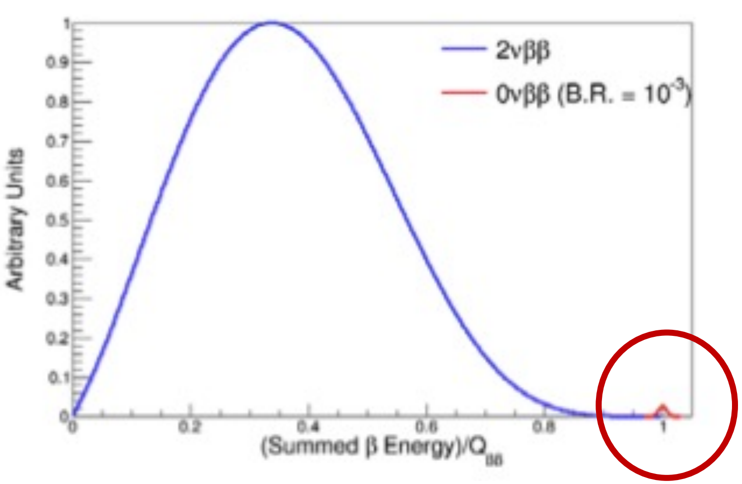
Want lots of candidate isotope!
At lifetime of $10^{26\text{-}27}$ yr ($m_{\beta\beta}$~ 50 meV in IO region)
need ~ 10^4 moles (~ 1 tonne) for 1 count/yr

➔ want high natural abundance, or effective isotope separation

Go after the denominator:

$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE



- Want small ΔE to avoid the 2νββ "friendly fire" and exclude other background
- Generally want high Q value to keep away from background
- Beat down all other background ... ultra-cleanliness, underground location needed

Neutrinoless Double Beta Decay Experiments

many, many isotopes and technologies

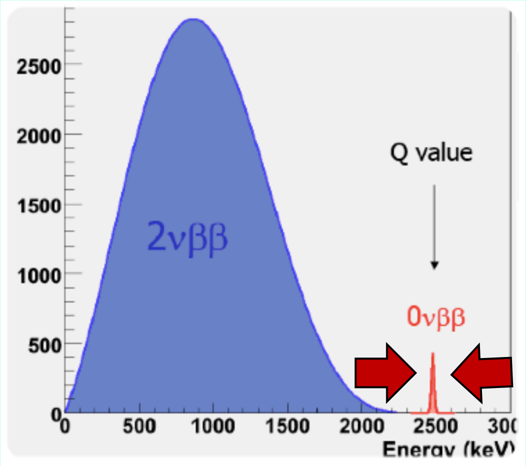
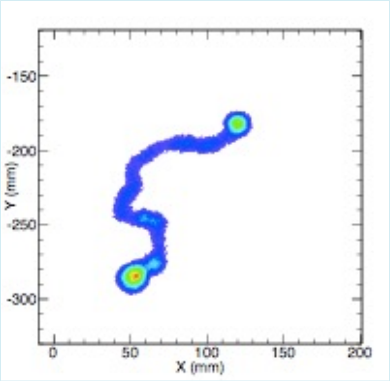
Recent and future experiments

Experiment	Isotope	Status	Lab	m_{iso} [mol]	ε_{act} [%]	$\varepsilon_{\text{cont}}$ [%]	ε_{mva} [%]	σ [keV]	ROI [σ]	ε_{ROI} [%]	$\mathcal{E}$ $\left[\frac{\text{mol}\cdot\text{yr}}{yr}\right]$	$\mathcal{B}$ $\left[\frac{\text{events}}{\text{mol}\cdot\text{yr}}\right]$	λ_b $\left[\frac{\text{events}}{\text{yr}}\right]$	$T_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
High-purity Ge detectors (Sec. VI.B)															
GERDA-II	^{76}Ge	completed	LNGS	$4.5 \cdot 10^2$	88	91	79	1.4	-2,2	95	273	$4.2 \cdot 10^{-4}$	$1.1 \cdot 10^{-1}$	$1.2 \cdot 10^{26}$	93-222
MJD	^{76}Ge	completed	SURF	$3.1 \cdot 10^2$	91	91	86	1.1	-2,2	95	212	$3.3 \cdot 10^{-3}$	$7.1 \cdot 10^{-1}$	$4.7 \cdot 10^{25}$	149-355
LEGEND-200	^{76}Ge	construction	LNGS	$2.4 \cdot 10^3$	91	91	90	1.1	-2,2	95	1 684	$1.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-1}$	$1.5 \cdot 10^{27}$	27-63
LEGEND-1000	^{76}Ge	proposed		$1.2 \cdot 10^4$	92	92	90	1.1	-2,2	95	8 736	$4.9 \cdot 10^{-6}$	$4.3 \cdot 10^{-2}$	$1.3 \cdot 10^{28}$	9-21
Xenon time projection chambers (Sec. VI.C)															
EXO-200	^{136}Xe	completed	WIPP	$1.2 \cdot 10^3$	46	100	84	31	-2,2	95	438	$4.7 \cdot 10^{-2}$	$2.1 \cdot 10^{+1}$	$2.4 \cdot 10^{25}$	111-477
nEXO	^{136}Xe	proposed	SNOLAB	$3.4 \cdot 10^4$	64	100	66	20	-2,2	95	13 700	$4.0 \cdot 10^{-5}$	$5.5 \cdot 10^{-1}$	$7.4 \cdot 10^{27}$	6-27
NEXT-100	^{136}Xe	construction	LSC	$6.4 \cdot 10^2$	88	76	49	10	-1.0,1.8	80	167	$5.9 \cdot 10^{-3}$	$9.9 \cdot 10^{-1}$	$7.0 \cdot 10^{25}$	66-281
NEXT-HD	^{136}Xe	proposed		$7.4 \cdot 10^3$	95	89	44	7.7	-0.5,1.7	65	1 809	$4.0 \cdot 10^{-5}$	$7.2 \cdot 10^{-2}$	$2.2 \cdot 10^{27}$	12-50
PandaX-III-200	^{136}Xe	construction	CJPL	$1.3 \cdot 10^3$	77	74	65	31	-1.2,1.2	76	374	$3.0 \cdot 10^{-3}$	$1.1 \cdot 10^{+0}$	$1.5 \cdot 10^{26}$	45-194
LZ-nat	^{136}Xe	construction	SURF	$4.7 \cdot 10^3$	14	100	80	25	-1.4,1.4	84	440	$1.7 \cdot 10^{-2}$	$7.5 \cdot 10^{+0}$	$7.2 \cdot 10^{25}$	64-277
LZ-enr	^{136}Xe	proposed	SURF	$4.6 \cdot 10^4$	14	100	80	25	-1.4,1.4	84	4302	$1.7 \cdot 10^{-3}$	$7.3 \cdot 10^{+0}$	$7.1 \cdot 10^{26}$	20-87
Darwin	^{136}Xe	proposed		$2.7 \cdot 10^4$	13	100	90	20	-1.2,1.2	76	2 312	$3.5 \cdot 10^{-4}$	$8.0 \cdot 10^{-1}$	$1.1 \cdot 10^{27}$	17-72
Large liquid scintillators (Sec. VI.D)															
KLZ-400	^{136}Xe	completed	Kamioka	$2.5 \cdot 10^3$	44	100	97	114	0,1.4	42	450	$9.8 \cdot 10^{-3}$	$4.4 \cdot 10^{+0}$	$3.3 \cdot 10^{25}$	95-408
KLZ-800	^{136}Xe	taking data	Kamioka	$5.0 \cdot 10^3$	55	100	100	105	0,1.4	42	1 143	$5.5 \cdot 10^{-3}$	$6.2 \cdot 10^{+0}$	$2.0 \cdot 10^{26}$	38-164
KL2Z	^{136}Xe	proposed	Kamioka	$6.7 \cdot 10^3$	80	100	97	60	0,1.4	42	2 176	$3.0 \cdot 10^{-4}$	$6.5 \cdot 10^{-1}$	$1.1 \cdot 10^{27}$	17-71
SNO+I	^{130}Te	construction	SNOLAB	$1.0 \cdot 10^4$	20	100	97	80	-0.5,1.5	62	1 232	$7.8 \cdot 10^{-3}$	$9.7 \cdot 10^{+0}$	$1.8 \cdot 10^{26}$	31-144
SNO+II	^{130}Te	proposed	SNOLAB	$5.1 \cdot 10^4$	27	100	97	57	-0.5,1.5	62	8 521	$5.7 \cdot 10^{-3}$	$4.8 \cdot 10^{+1}$	$5.7 \cdot 10^{26}$	17-81
Cryogenic calorimeters (Sec. VI.E)															
CUORE	^{130}Te	taking data	LNGS	$1.6 \cdot 10^3$	100	88	92	3.2	-1.4,1.4	84	1 088	$9.1 \cdot 10^{-2}$	$9.9 \cdot 10^{+1}$	$5.1 \cdot 10^{25}$	58-270
CUPID-0	^{82}Se	completed	LNGS	$6.2 \cdot 10^1$	100	81	86	8.5	-2,2	95	41	$2.8 \cdot 10^{-2}$	$1.2 \cdot 10^{+0}$	$4.4 \cdot 10^{24}$	283-551
CUPID-Mo	^{100}Mo	completed	LSM	$2.3 \cdot 10^1$	100	76	91	3.2	-2,2	95	15	$1.7 \cdot 10^{-2}$	$2.5 \cdot 10^{-1}$	$1.7 \cdot 10^{24}$	293-858
CROSS	^{100}Mo	construction	LSC	$4.8 \cdot 10^1$	100	75	90	2.1	-2,2	95	31	$2.5 \cdot 10^{-4}$	$7.6 \cdot 10^{-3}$	$4.9 \cdot 10^{25}$	54-160
CUPID	^{100}Mo	proposed	LNGS	$2.5 \cdot 10^3$	100	79	90	2.1	-2,2	95	1 717	$2.3 \cdot 10^{-4}$	$4.0 \cdot 10^{-1}$	$1.1 \cdot 10^{27}$	12-34
AMoRE-II	^{100}Mo	proposed	Yemilab	$1.1 \cdot 10^3$	100	82	91	2.1	-2,2	95	760	$2.2 \cdot 10^{-4}$	$1.7 \cdot 10^{-1}$	$6.7 \cdot 10^{26}$	15-43
Tracking calorimeters (Sec. VI.F)															
NEMO-3	^{100}Mo	completed	LSM	$6.9 \cdot 10^1$	100	100	11	148	-1.6,1.1	42	3	$9.4 \cdot 10^{-1}$	$3.0 \cdot 10^{+0}$	$5.6 \cdot 10^{23}$	505-1485
SuperNEMO-D	^{82}Se	construction	LSM	$8.5 \cdot 10^1$	100	100	28	83	-4.2,2.4	64	15	$3.3 \cdot 10^{-2}$	$5.0 \cdot 10^{-1}$	$8.6 \cdot 10^{24}$	201-391
SuperNEMO	^{82}Se	proposed	LSM	$1.2 \cdot 10^3$	100	100	28	72	-4.1,2.8	54	185	$5.3 \cdot 10^{-3}$	$9.8 \cdot 10^{-1}$	$7.8 \cdot 10^{25}$	67-131

ABDMV, RMP 2022, arXiv:2202.01787

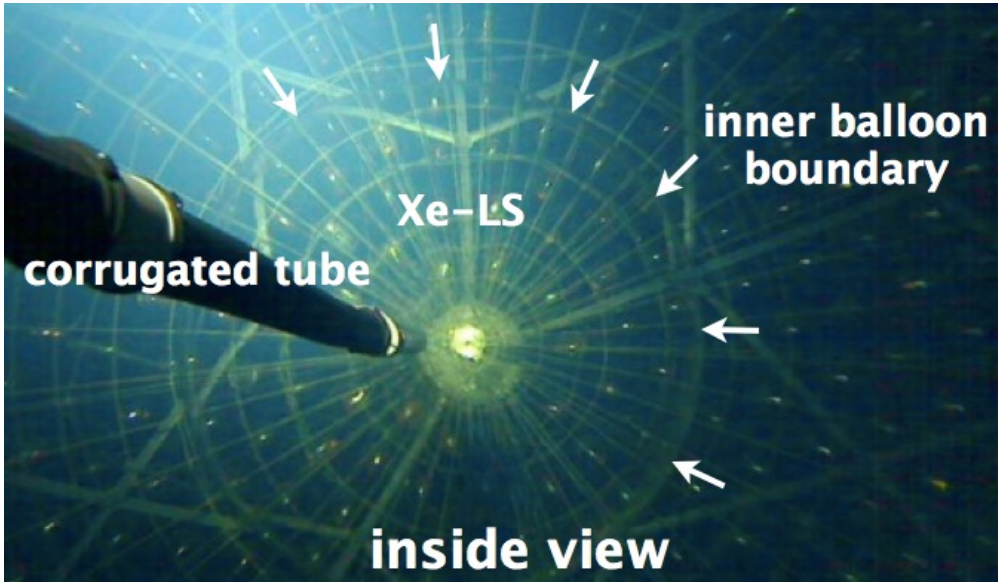
General NLDBD experiment strategies

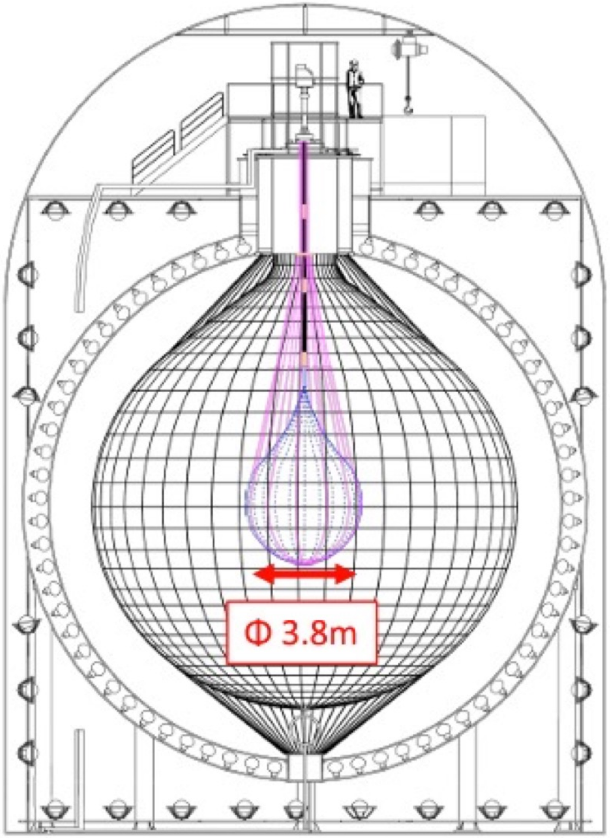
$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		
focus on the numerator with a huge amount of material (possibly sacrificing resolution)	focus on the denominator by squeezing down ΔE (various technologies)	try to make the background zero by tracking or other technique

...and many (most) experiments try to do more than one of these...

Brute Force Strategy Example: **KamLAND-Zen**

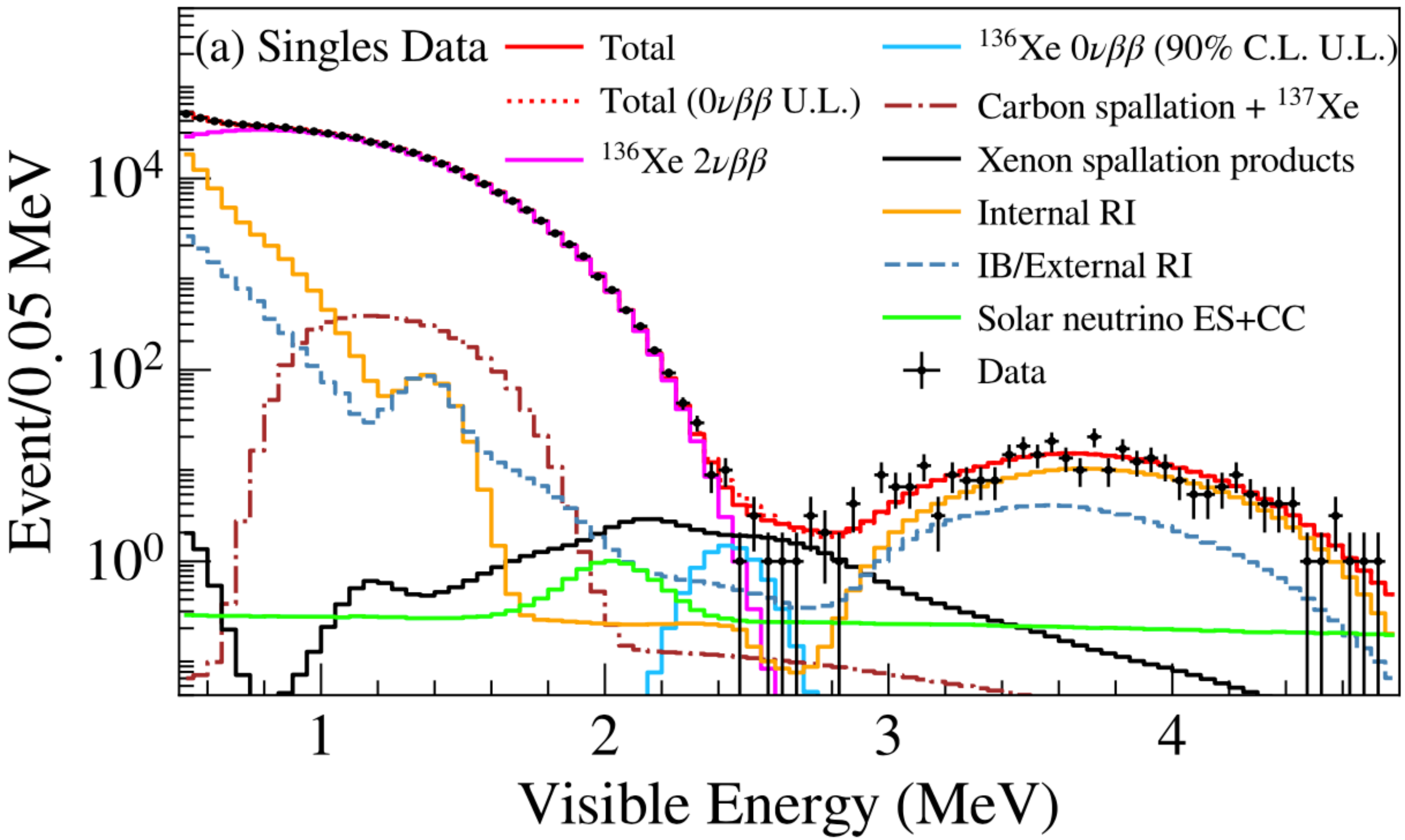




- "KamLAND-Zen 800": mini-balloon w/ 745 kg of ^{enr}Xe-loaded scintillator inside pure scintillator
- Kamioka mine in Japan

KamLAND-Zen Results

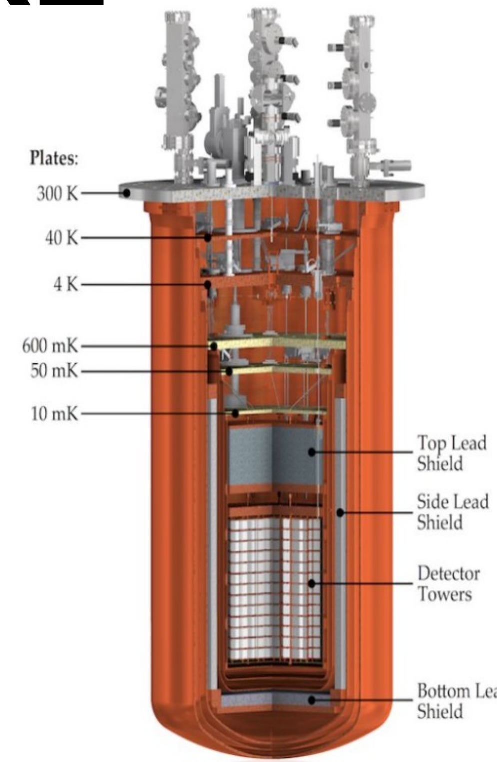
PRL **130**, 051801 (2023)



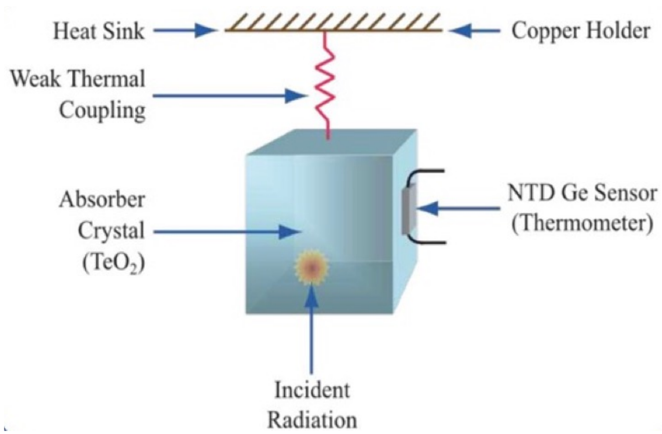
Most sensitive search to date: $m_{\beta\beta}$ < 36-156 meV

Next plans: improve energy resolution, 1 ton mass

A Peak-Squeezer: **CUORE**



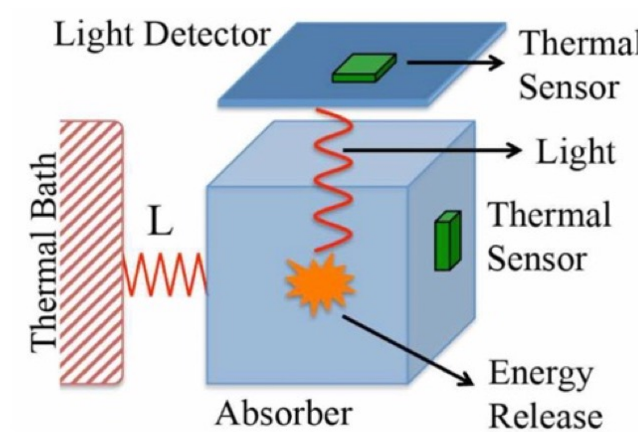
Cryogenic bolometer w/ $^{nat}TeO_2$ @ LNGS



- source = detector
- calorimetric approach w/ high intrinsic energy resolution

Next generation:
CUPID $Li_2{}^{enr}MoO_4$

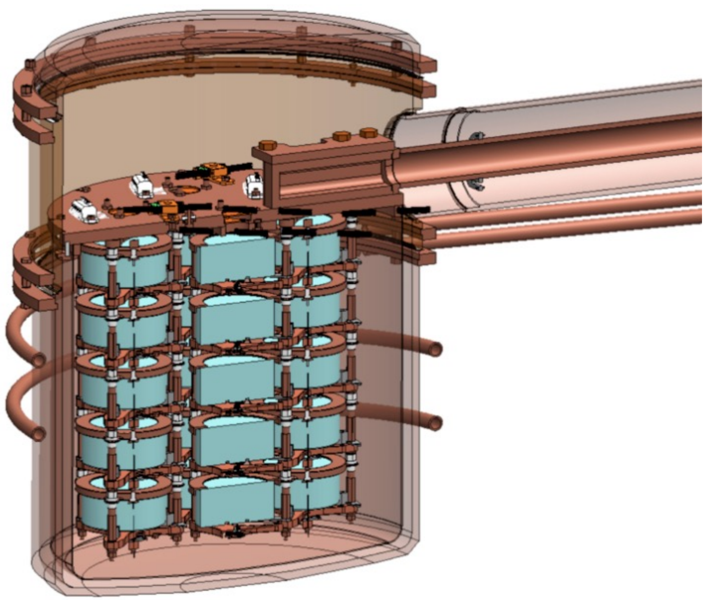
scintillating bolometer w/ particle id



More Peak-Squeezers: **Germanium**

Germanium diode detectors
enriched in ^{76}Ge; very good energy resolution

MAJORANA DEMONSTRATOR

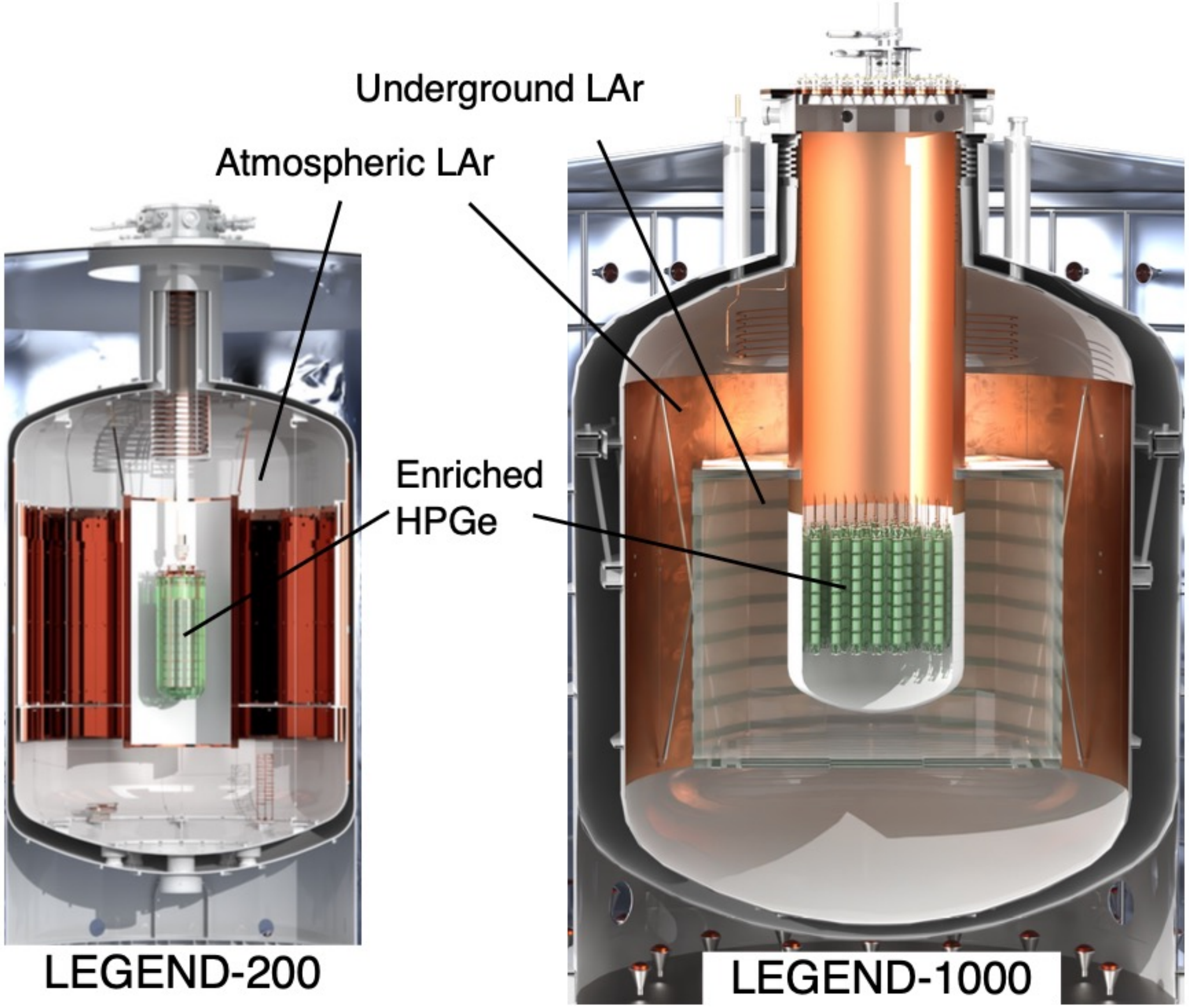


- Sanford Lab in South Dakota
- segmented detector strategy

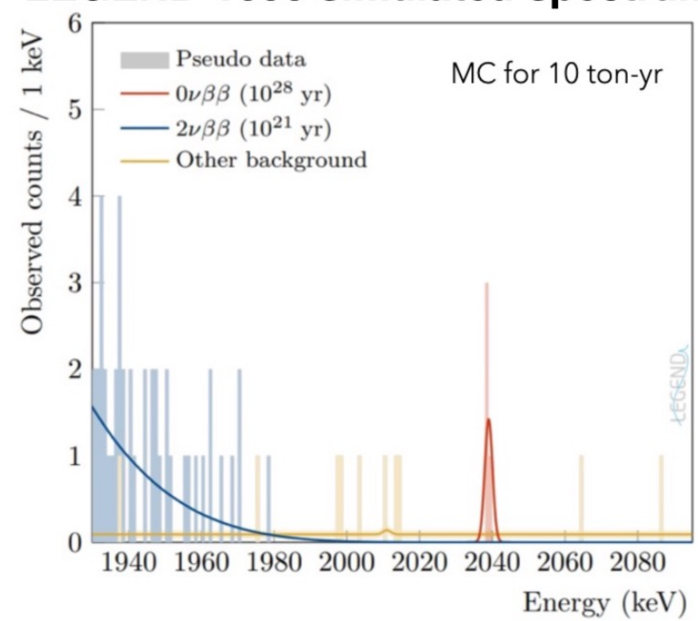
GERDA

- Gran Sasso, Italy
- detectors submerged in LAr

LEGEND tonne-scale program



LEGEND-1000 simulated spectrum:



S. Elliott, S. Schönert

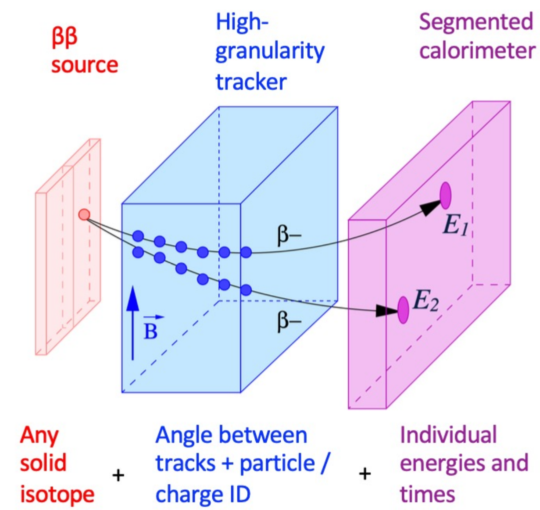
LEGEND-200 @ LNGS
- Physics data-taking March 2023 (140 kg)
- Complete 200 kg array in early 2024

LEGEND-1000
- Site TBD (LNGS or SNOLAB)
- Conceptual design in progress

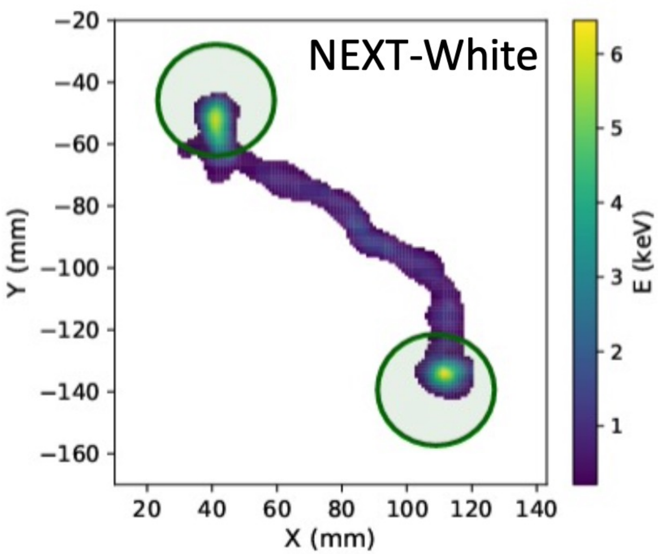
Final-State Judges

Pick out NLDBD signal from the background by precision final-state tracking

Segmented trackers (e.g., SuperNEMO)



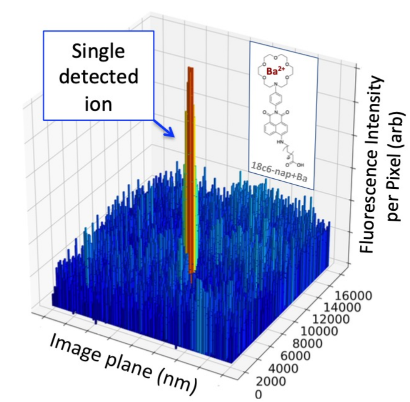
Gas Xe TPCs (e.g., NEXT)



Possibly, pick out DBD signal by final-state-nucleus ID

B. Jones

Barium tagging
in xenon liquid or gas

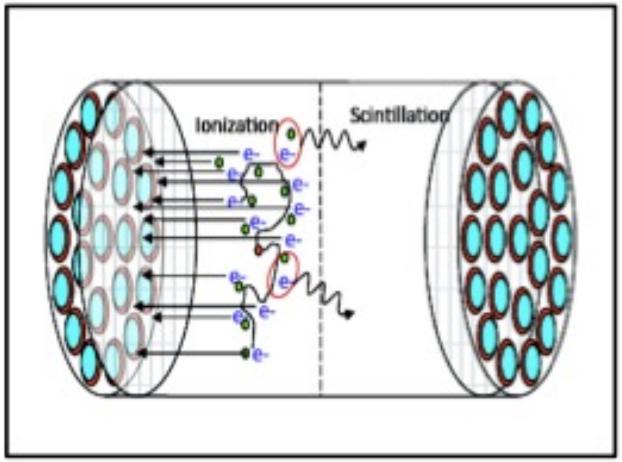


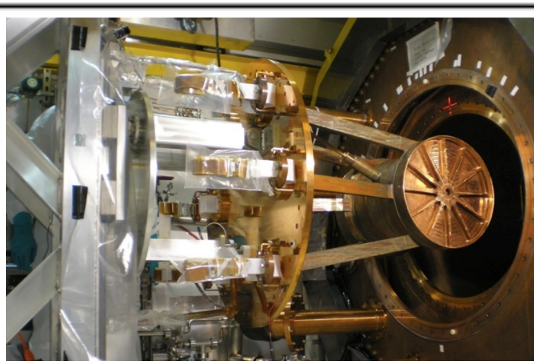
^{136}Xe$\rightarrow$^{136}Ba + 2e

Hybrid peak squeezer/brute-forcer/[final-state judging]

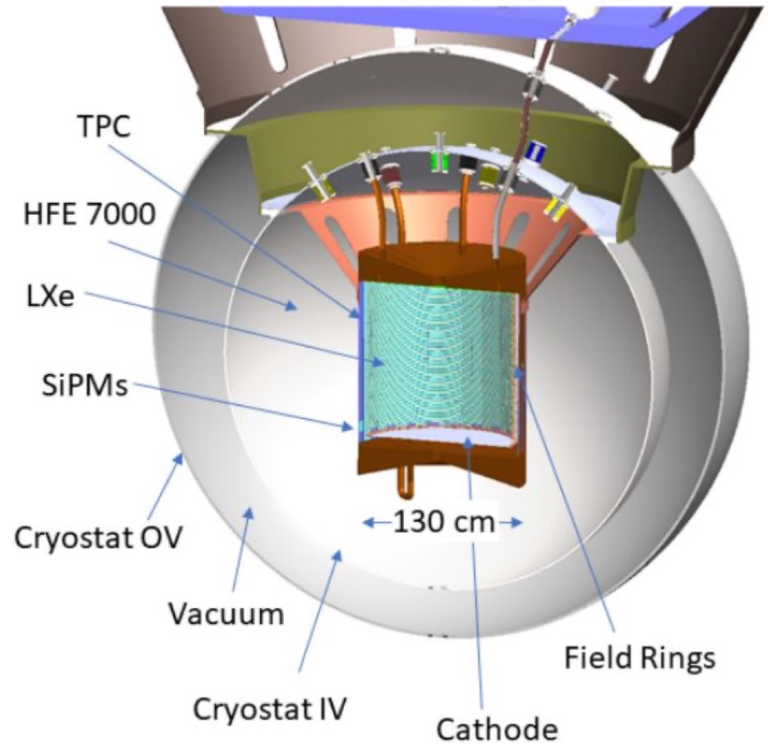
LXe TPCs

EXO-200





nEXO

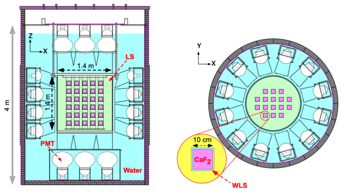


- no tracking, but single (0ν) -vs-multisite (bg) selection
- scintillation & ionization
- 80.6% enriched ^{136}Xe

- excellent background rejection by fiducialization

[+...long-term ideas for barium tagging]

And more creative ideas out there!

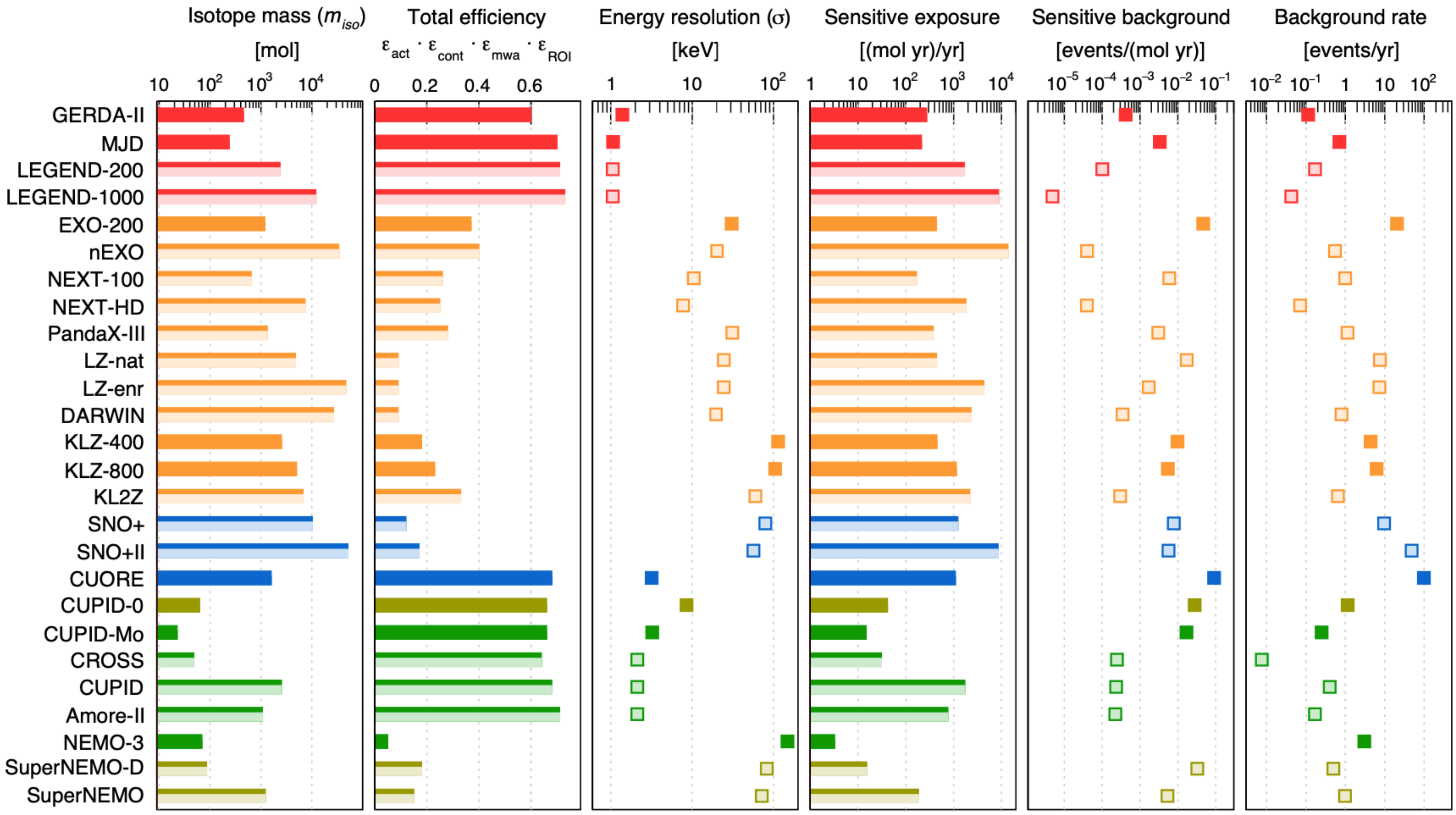


Project	Isosope(s)	Detector technology, main features, and references
CANDLES†	^{48}Ca	Array of scintillator crystals suspended in a volume of liquid scintillator. Possible operation as cryogenic calorimeters. Ajimura *et al.* (2021) and Yoshida *et al.* (2009)
COBRA†	^{70}Zn, ^{114,116}Cd, ^{128,130}Te	CdZnTe semiconductor detector array. Room temperature; multi-isotope; high granularity. Arling *et al.* (2021); Ebert *et al.* (2016a,b); and Zuber (2001)
Selena	^{82}Se	Amorphous $^{\mathrm{enr}}$Se high resolution, high-granularity CMOS detector array. 3D track reconstruction ($O(10\mu$m) resolution); room temperature; minimal shielding. Chavarria *et al.* (2017)
NνDEx	^{82}Se	High-pressure gaseous ^{82}SeF$_6$ ion-imaging TPC. $\lesssim 1\%$ energy resolution; precise signal topology; possible multi-isotope. Mei *et al.* (2020) and Nygren *et al.* (2018)
R2D2	^{136}Xe	Spherical TPC. Single readout channel; inexpensive infrastructure. Bouet *et al.* (2021)
AXEL	^{136}Xe	High-pressure TPC operated in proportional scintillation mode. High energy resolution; possible positive ion detection. Obara *et al.* (2020)
JUNO	—	Isotope loaded liquid scintillator. 20 ktons of scintillator; multi-isotope; multi-purpose. Abusleme *et al.* (2021) and Zhao *et al.* (2017)
NuDot	—	Liquid scintillator with quantum dots or perovskites as wavelength shifter for Cherenkov light. Discriminate directional backgrounds; multi-isotope. Gooding *et al.* (2018); Graham *et al.* (2019); Winslow and Simpson (2012); Aberle *et al.* (2013)
ZICOS	^{96}Zr	Zr-loaded liquid scintillator. Topology and particle discrimination via Cherenkov light readout. Fukuda (2016) and Fukuda *et al.* (2020)
THEIA	—	Water-based loaded liquid scintillator with Cherenkov light readout. Topology and particle discrimination; multi-isotope; multi-purpose; 25 ktons of water. Askins *et al.* (2020)
LiquidO	—	Opaque isotope-loaded liquid scintillator with wavelength shifting fibers for event topology. Room temperature; multi-isotope; multi-purpose. Buck *et al.* (2019) and Cabrera *et al.* (2019)

Go to page 79

ABDMV, RMP 2022, arXiv:2202.01787

Summary of recent and future experiments



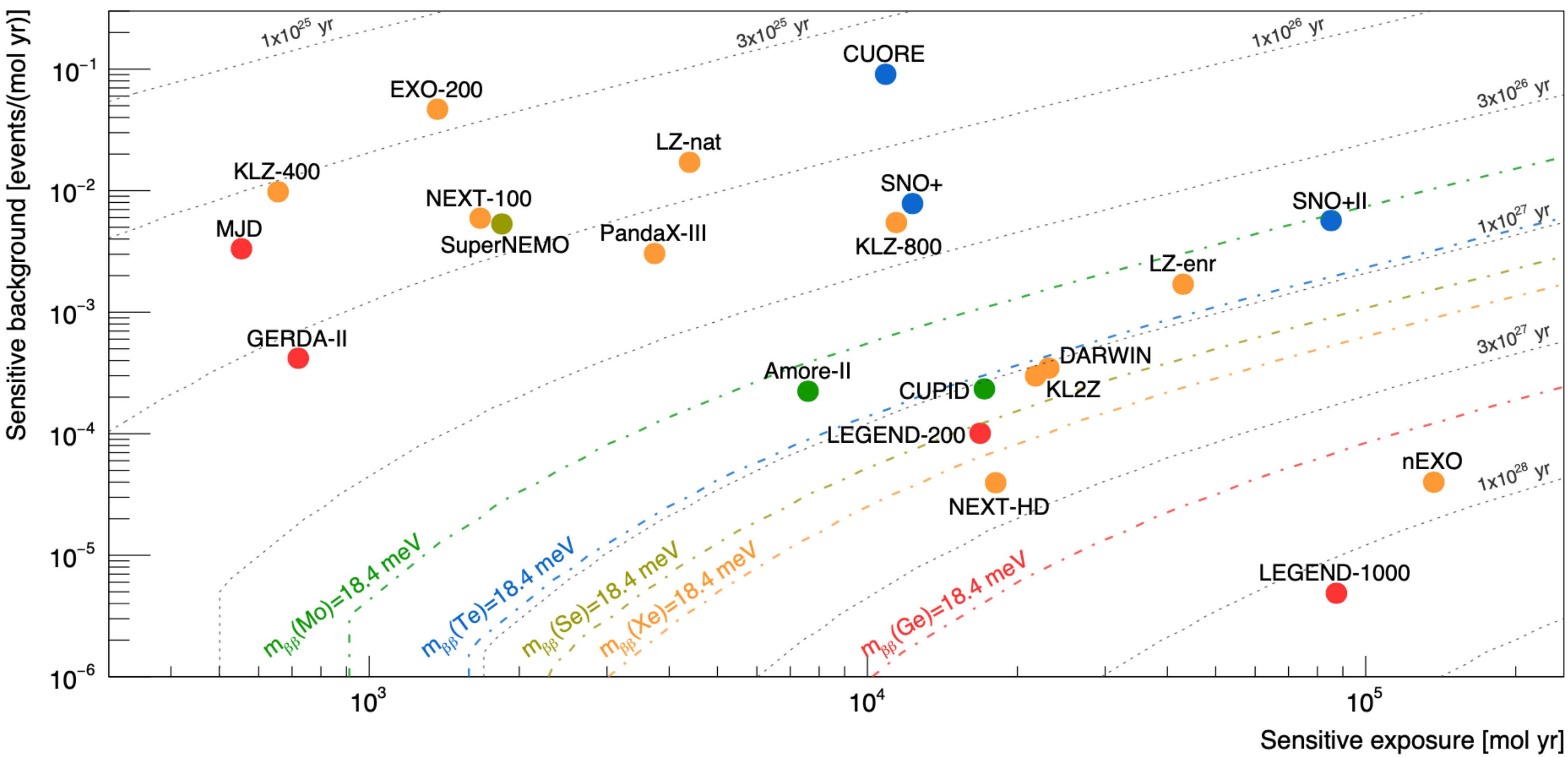
ABDMV, RMP 2022, arXiv:2202.01787

Experiment	Isotope	Half-life limit (1026 years)	mββ limit (meV)
MAJORANA	Germanium-76	0.83	113–269
GERDA	Germanium-76	1.8	79–180
EXO-200	Xenon-136	0.35	93–286
KamLAND-Zen	Xenon-136	2.3	36–156
CUORE	Tellurium-130	0.22	90–305

Up-to-date limits from LRP

Sensitive background and exposure for recent and future experiments

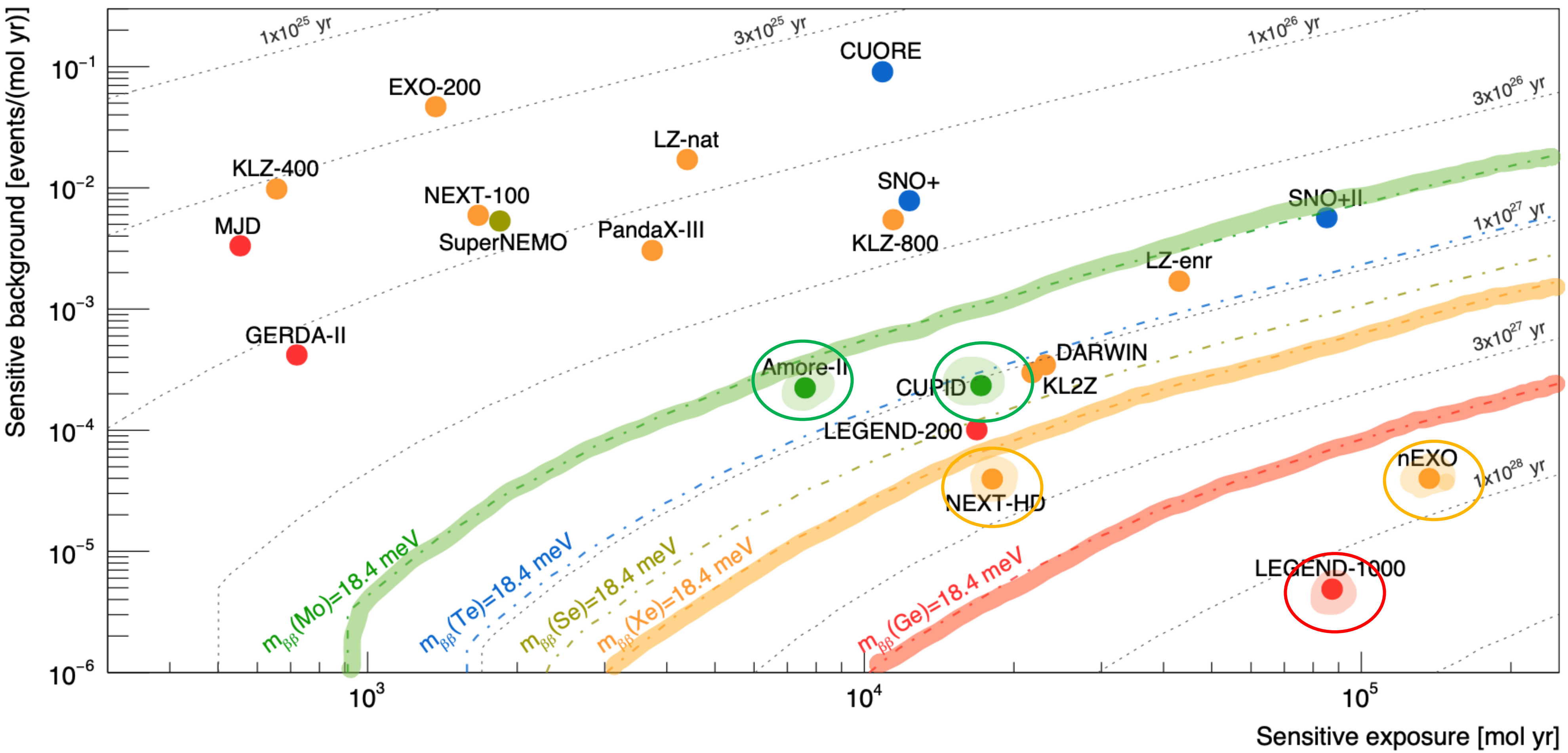
ABDMV, RMP 2022, arXiv:2202.01787



Grey dashed lines: discovery sensitivity on the NLDBD $T_{1/2}$ (isotope-independent)

Sensitive background and exposure for recent and future experiments

ABDMV, RMP 2022, arXiv:2202.01787



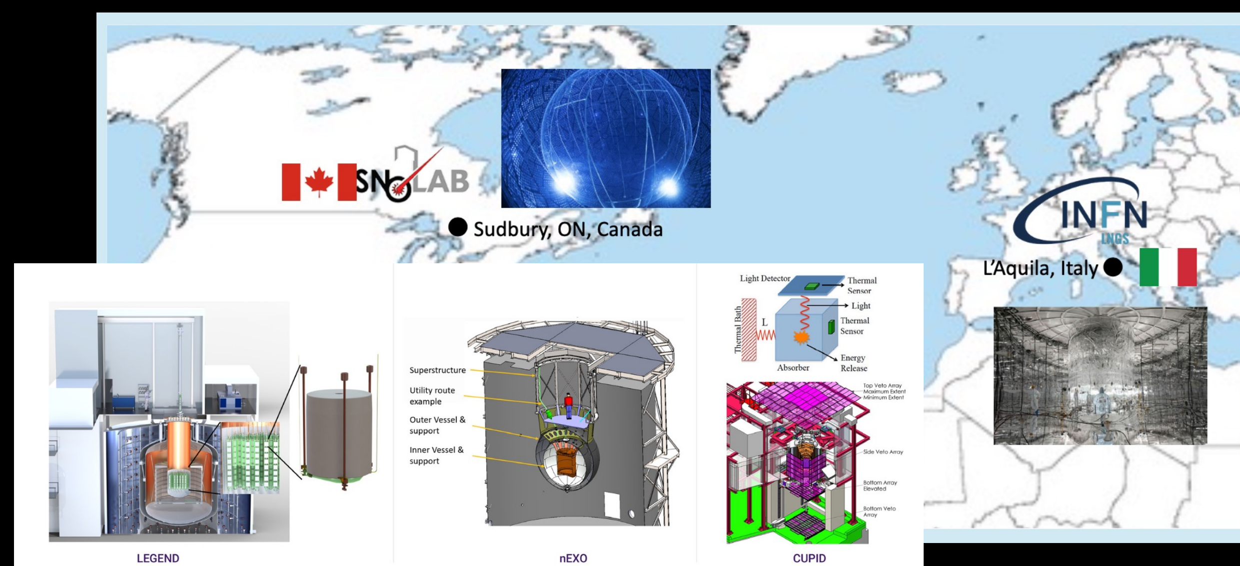
Grey dashed lines: discovery sensitivity on the NLDBD $T_{1/2}$ (isotope-independent)
Colored dashed lines: $m_{\beta\beta}$ sensitivities to **get to the bottom of the IO region** for *specific isotopes*, taking into account NME & phase space

[specific ~optimistic NME assumption] → **want to be to the lower right of *your* colored line!**

NLDBD in the US Nuclear Physics Long Range Plan

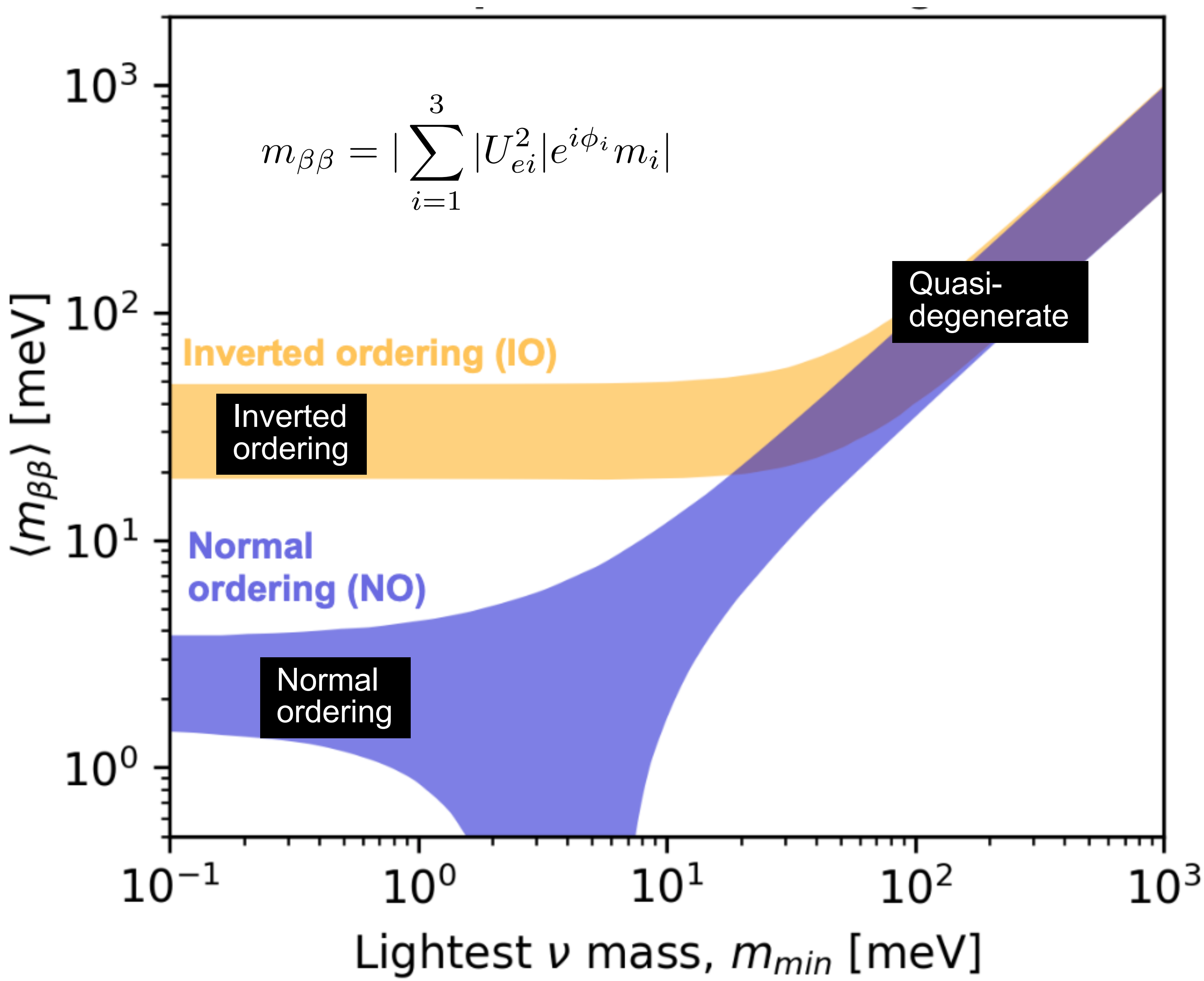
RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.



CUPID, nEXO, LEGEND @ LNGS & SNOLAB

A really grand challenge...



Can we learn about a Majorana phase?

Science Drivers in Neutrino Physics

Where are the grand (experimental) challenges?

Three-flavor paradigm

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

Summary of the 3-flavor challenges:

- fill in the oscillation parameters MO & δ
- measure the absolute mass scale
- determine if the neutrino is Majorana or Dirac
- [measure the Majorana phases...]

These challenges assume the 3 flavor paradigm holds....

Science Drivers in Neutrino Physics

Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

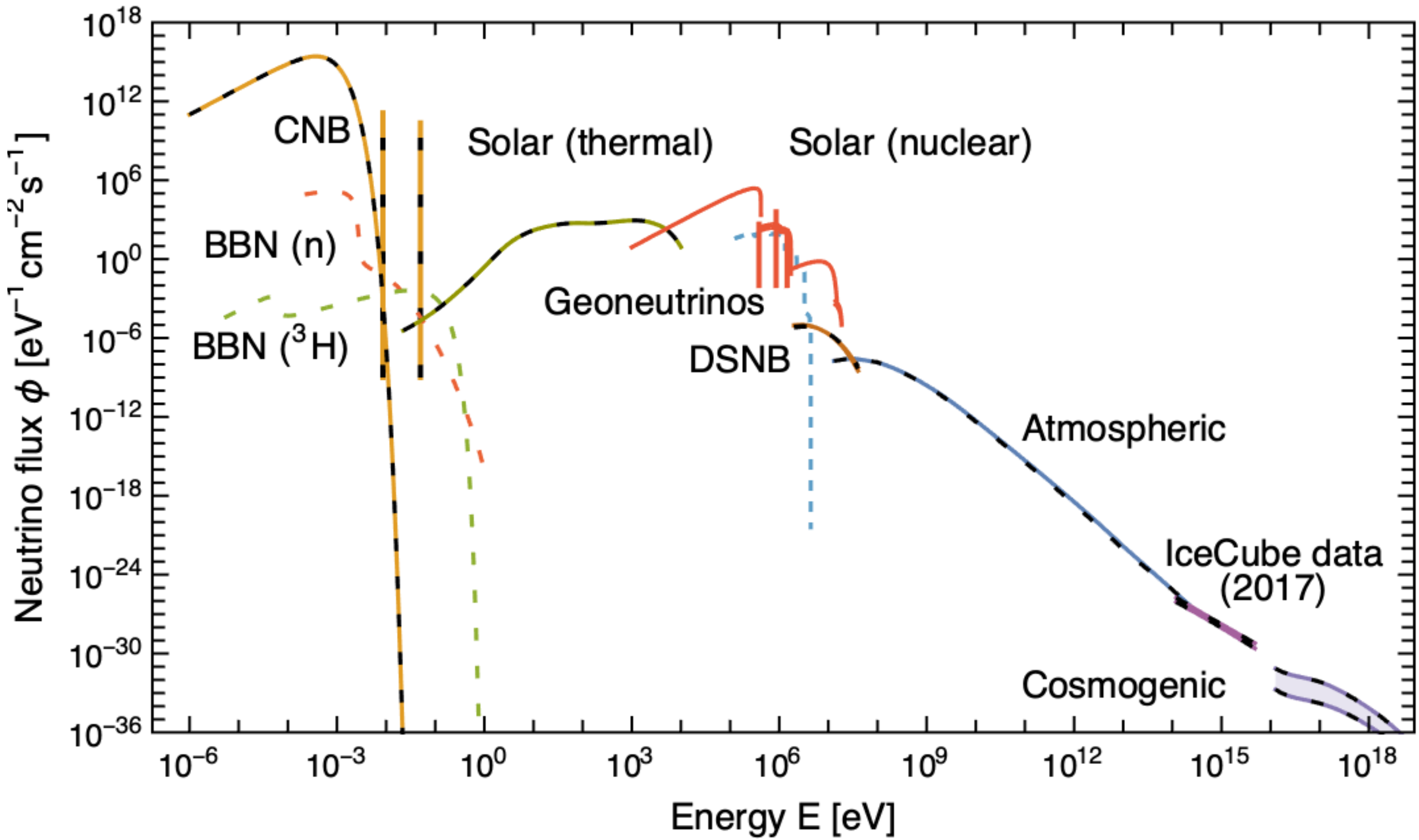
Understanding **astrophysics** and **cosmology**

Many diverse challenges!

(overlapping with others)

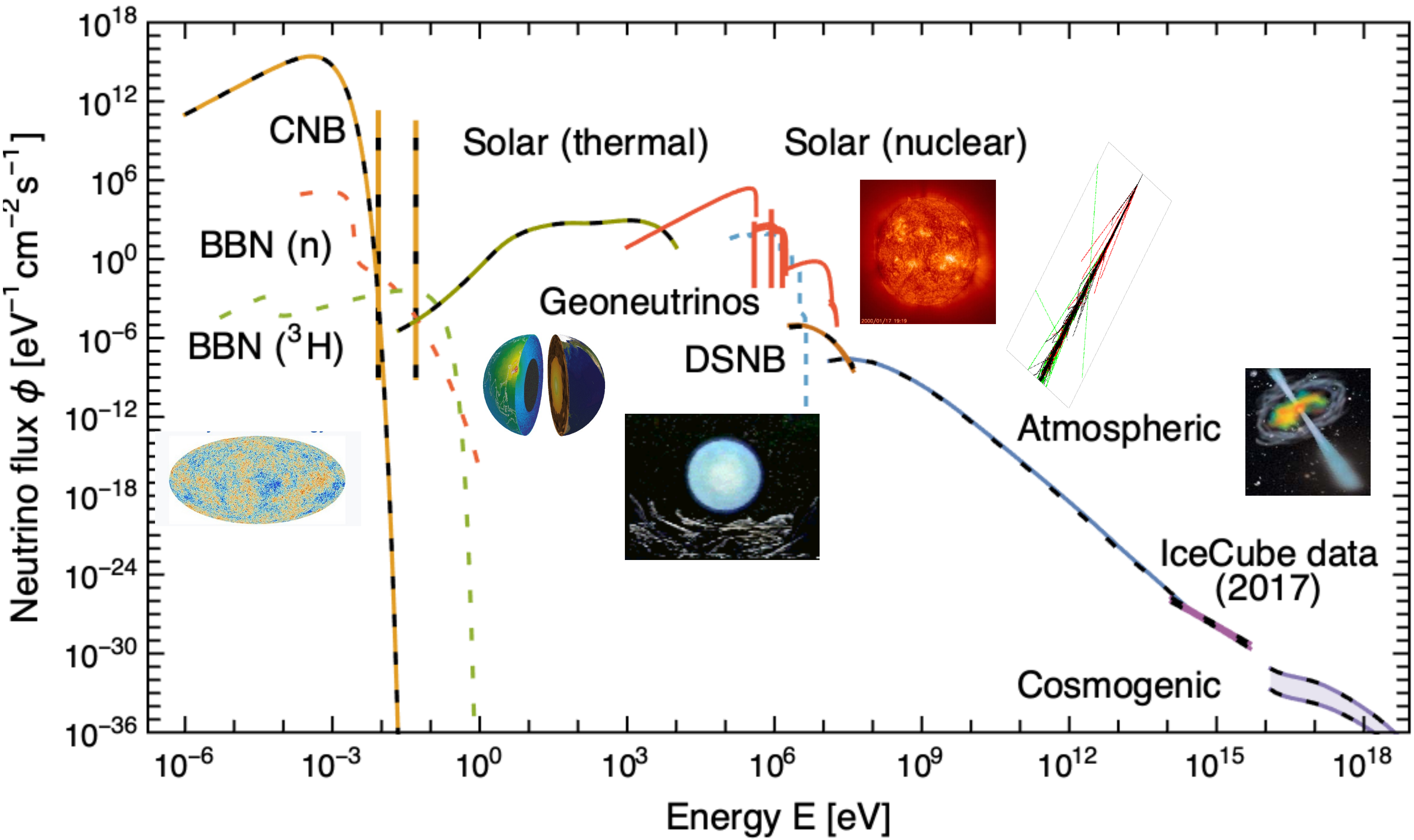
Natural neutrinos pervade the Universe....

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF



Neutrinos bring unique information about the

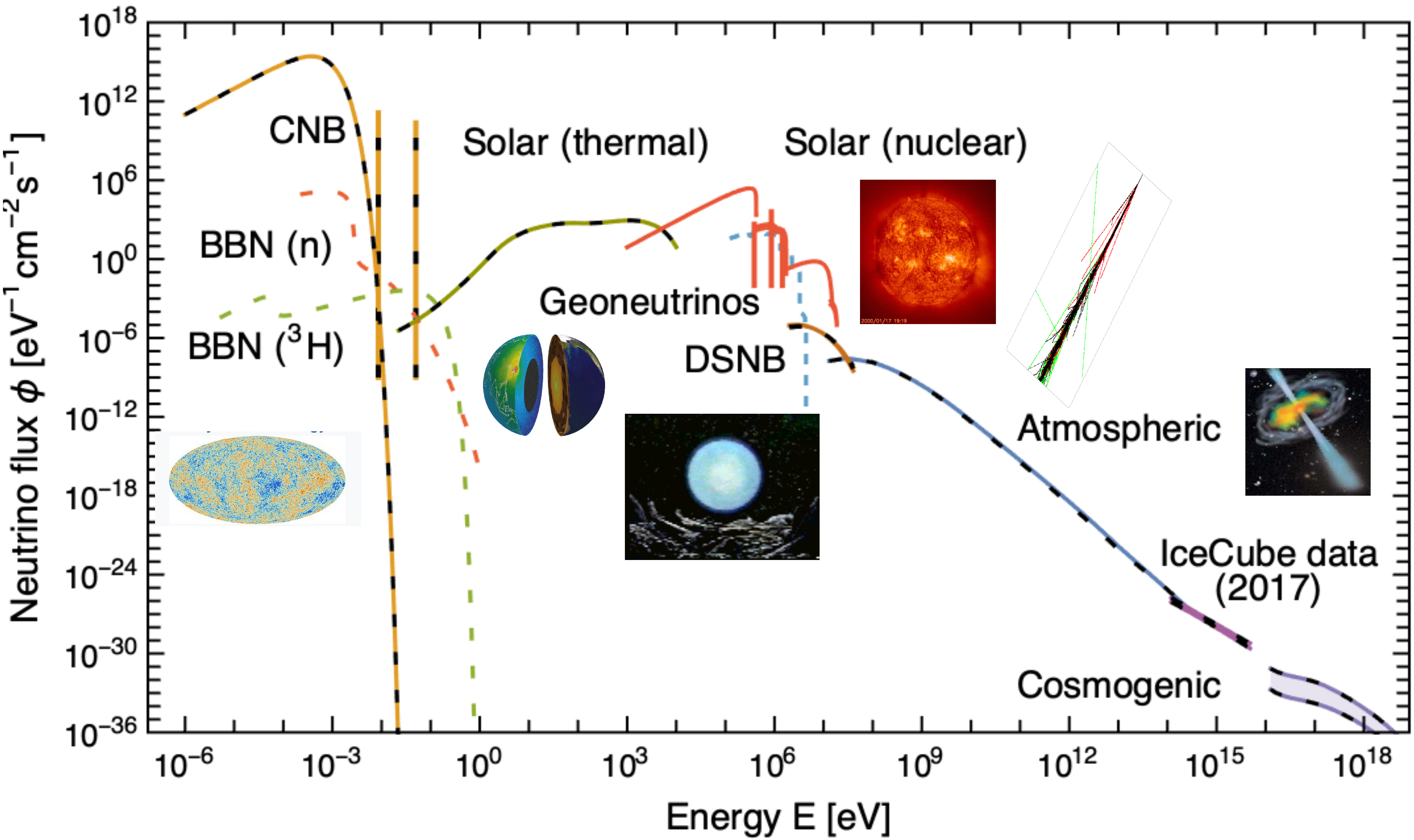
nature of natural sources



- Information from deep inside astronomical objects
- Messages ~unperturbed by matter & em fields

} thanks to the weakness of the interaction

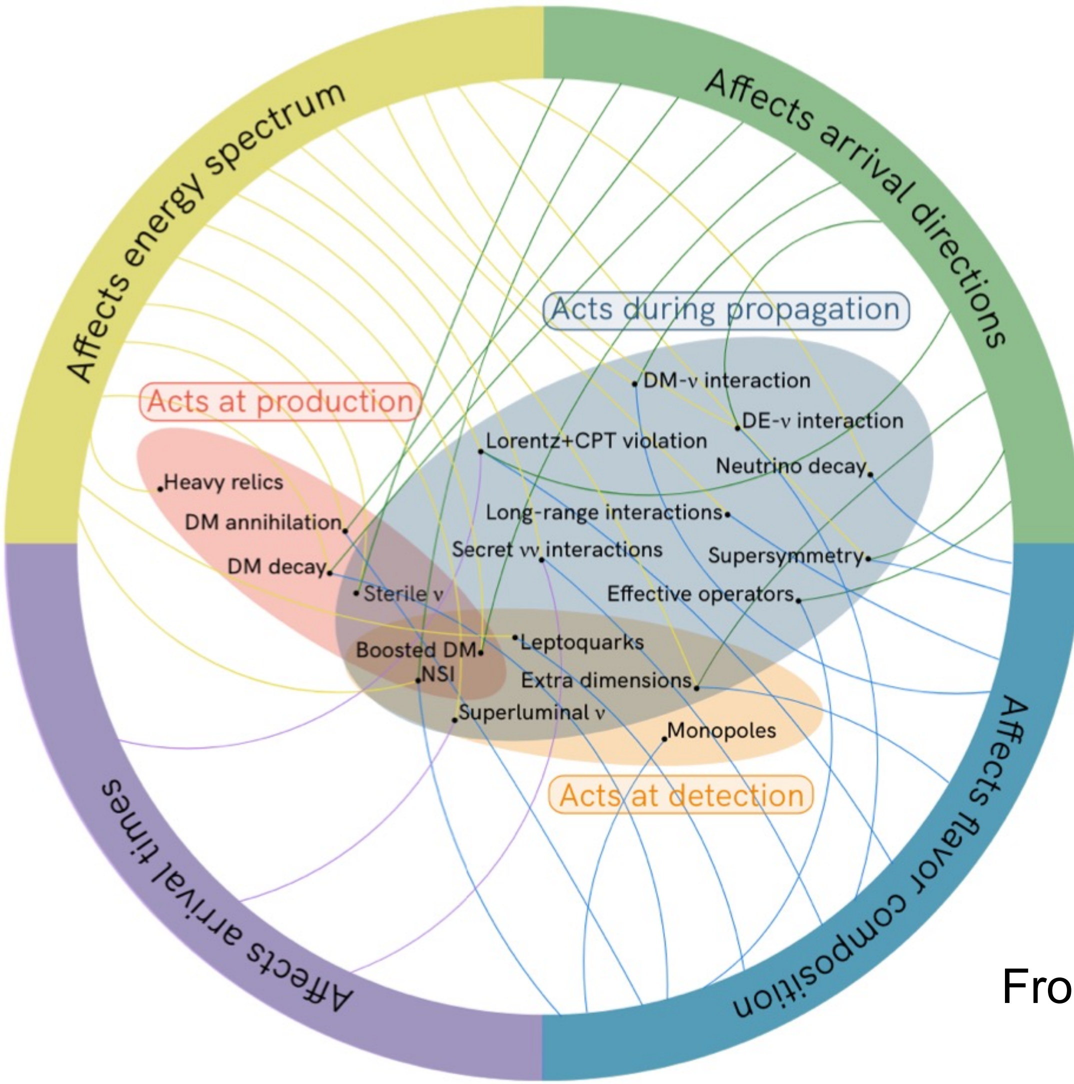
And astrophysical objects in turn give us sources for the study of **neutrino physics**...



... 3-flavor oscillations, anomalies, BSM searches...

Many opportunities to probe BSM physics

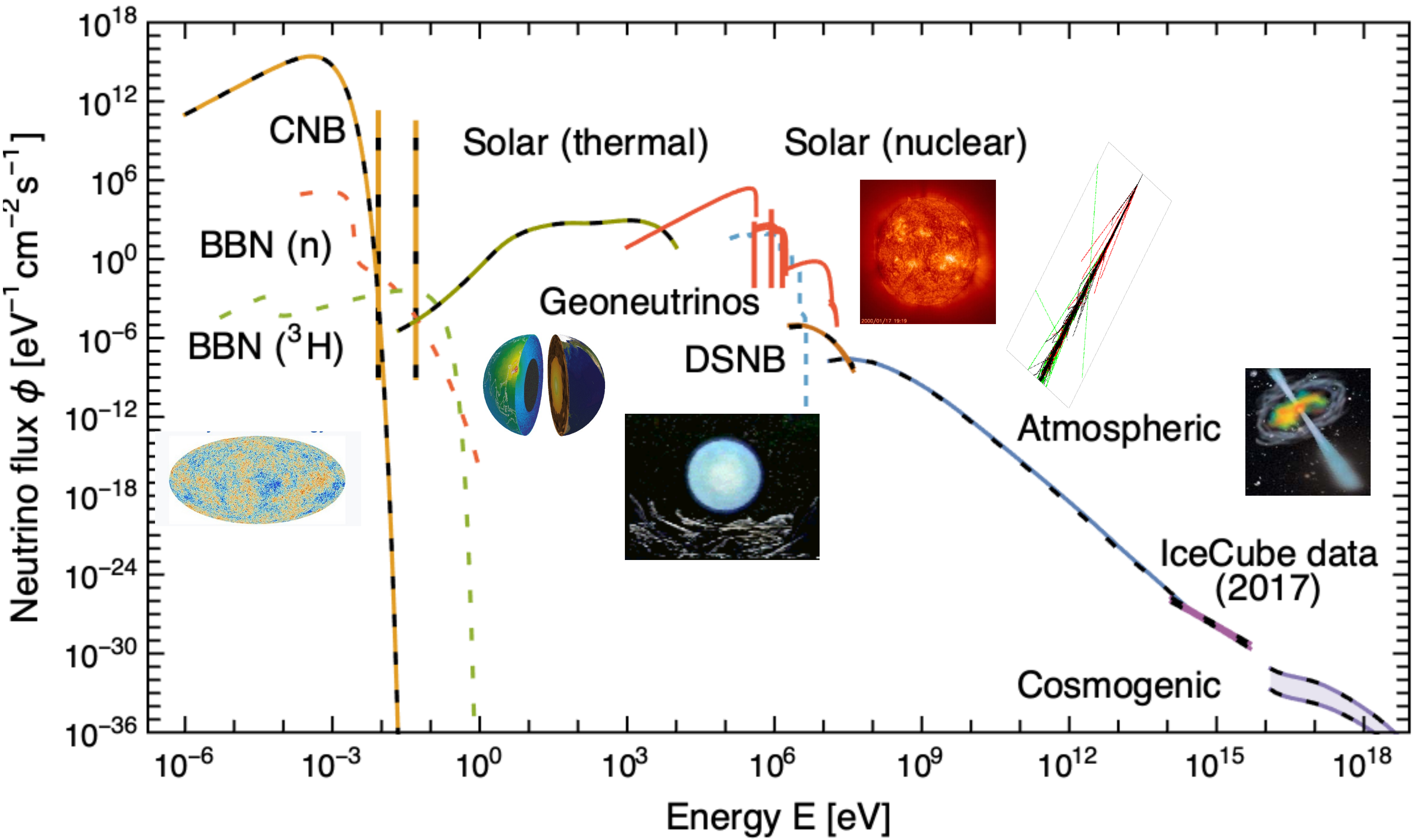
Neutrino observables*: energy, direction, time, flavor



From arXiv:2203.08096v2

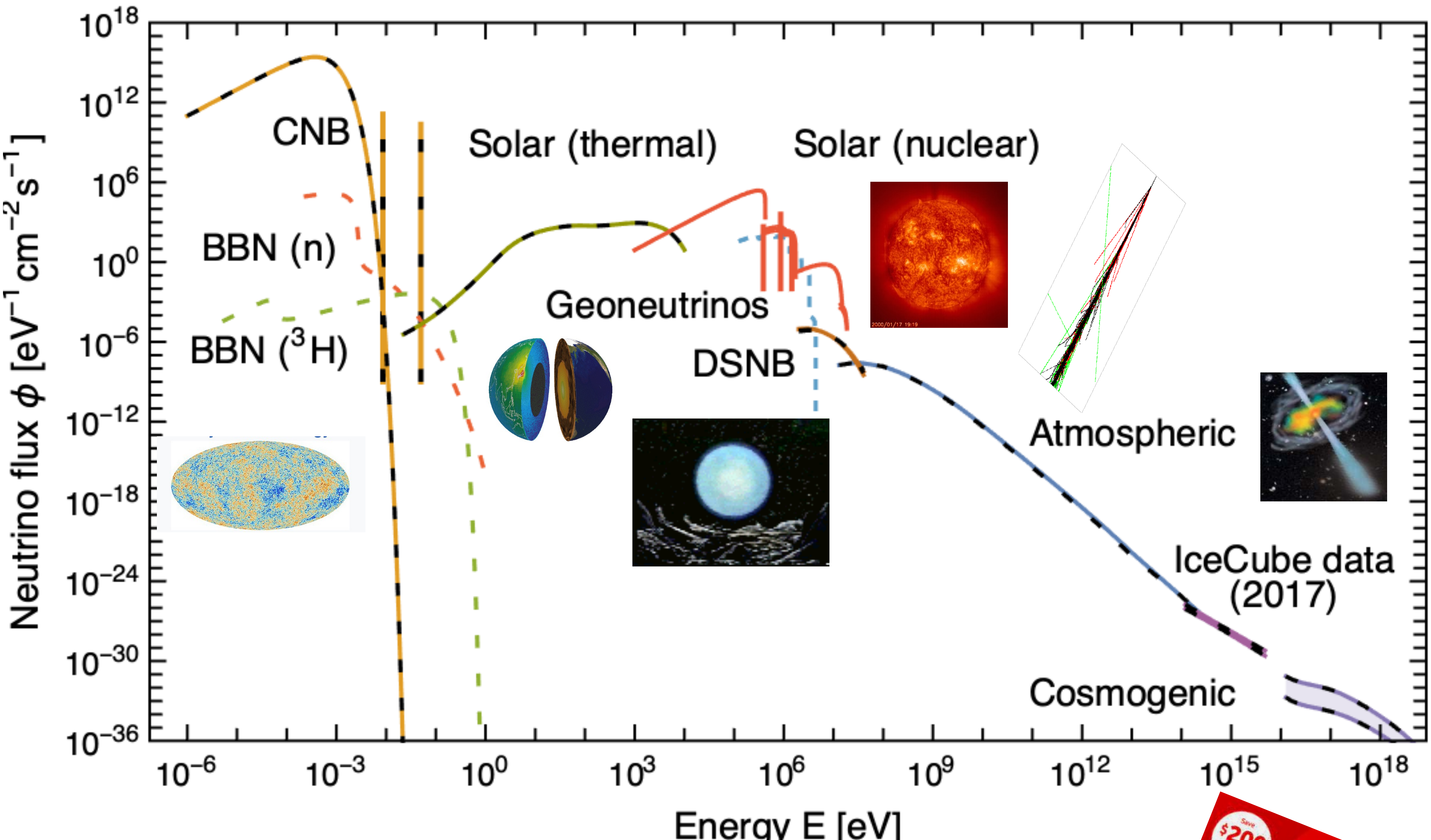
*also, non-neutrino-sector BSM signatures in neutrino detectors

And astrophysical objects in turn give us sources for the study of **neutrino physics**...



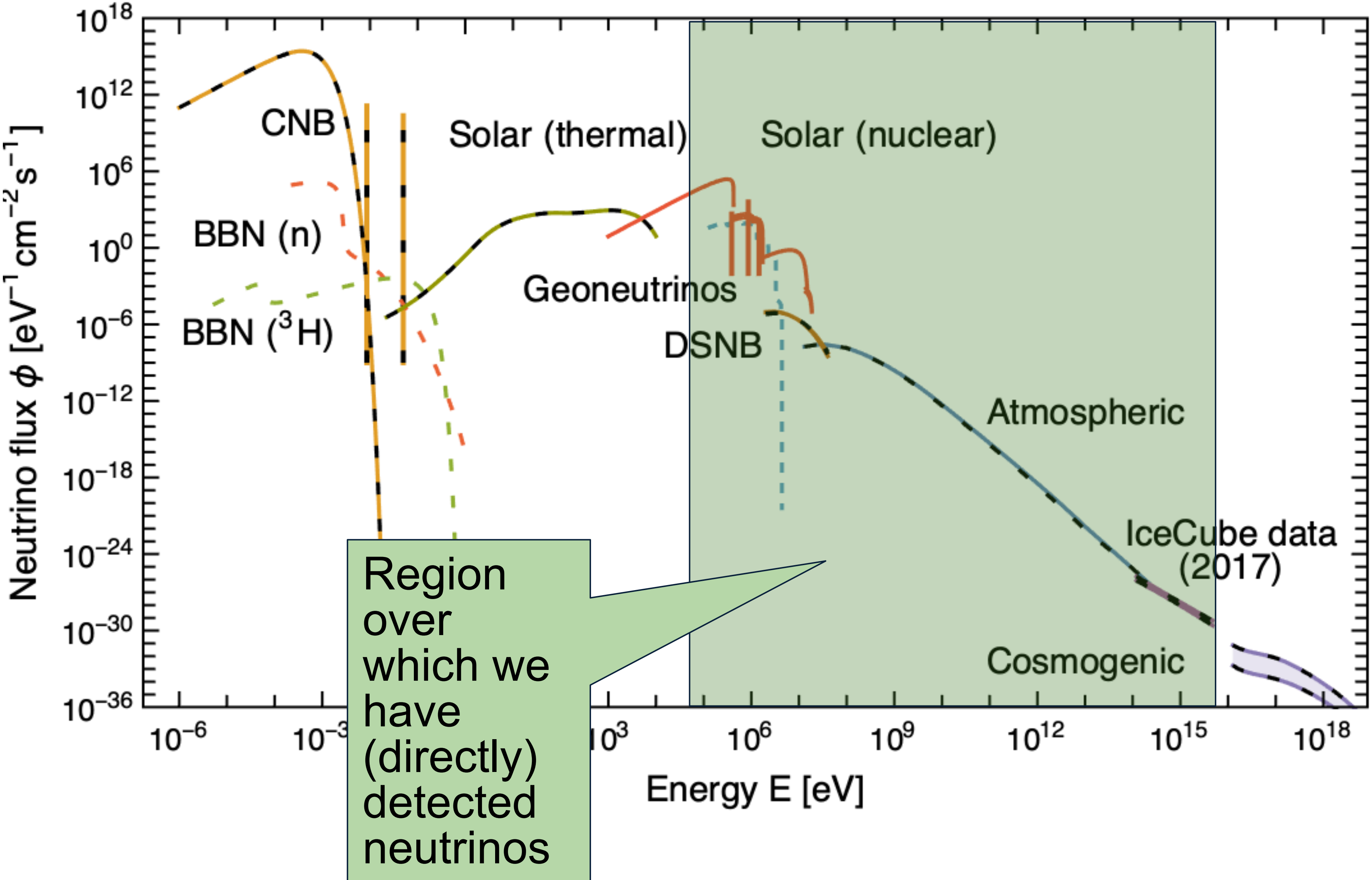
...for free! Just need to look up (and down!)

And astrophysical objects in turn give us sources for the study of **neutrino physics**...

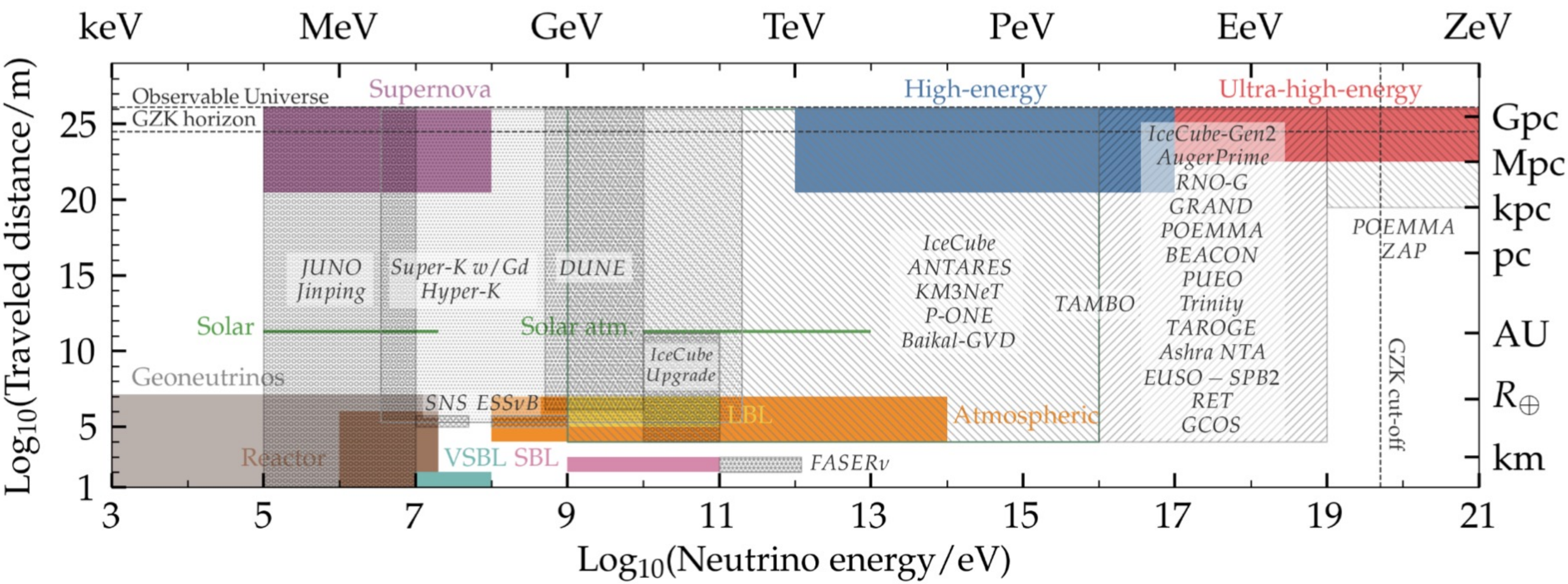


The catch: need some detectors!

There is information over ~25 orders of magnitude in energy



There is a vast array of detector technologies,
and detector instances, existing and proposed



From arXiv:2203.08096v2

Multi-Messenger Astrophysics

Many, many detectors

ν

SuperK + gadolinium
JUNO
DUNE
Hyper-Kamiokande
KM3NeT
IceCube-Gen2
ARA, RNO-G

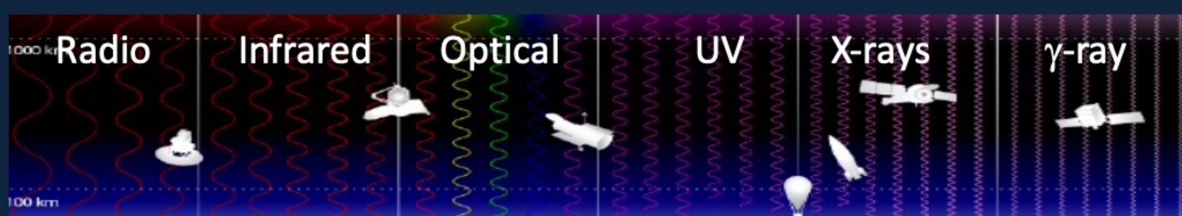
CR

LHAASO
PUEO
GRAND
TAMBO
POEMMA

GW

KAGRA
LIGO-India
LIGO Voyager
Cosmic Explorer
Einstein Telescope
LISA

γ



Radio	Infrared	Optical	X-rays	γ-ray
LAST SKA	JWST	LSST TMT ELT	Athena	CTA SWGO

Shunsaku Horiuchi,
Snowmass Neutrino Colloquium

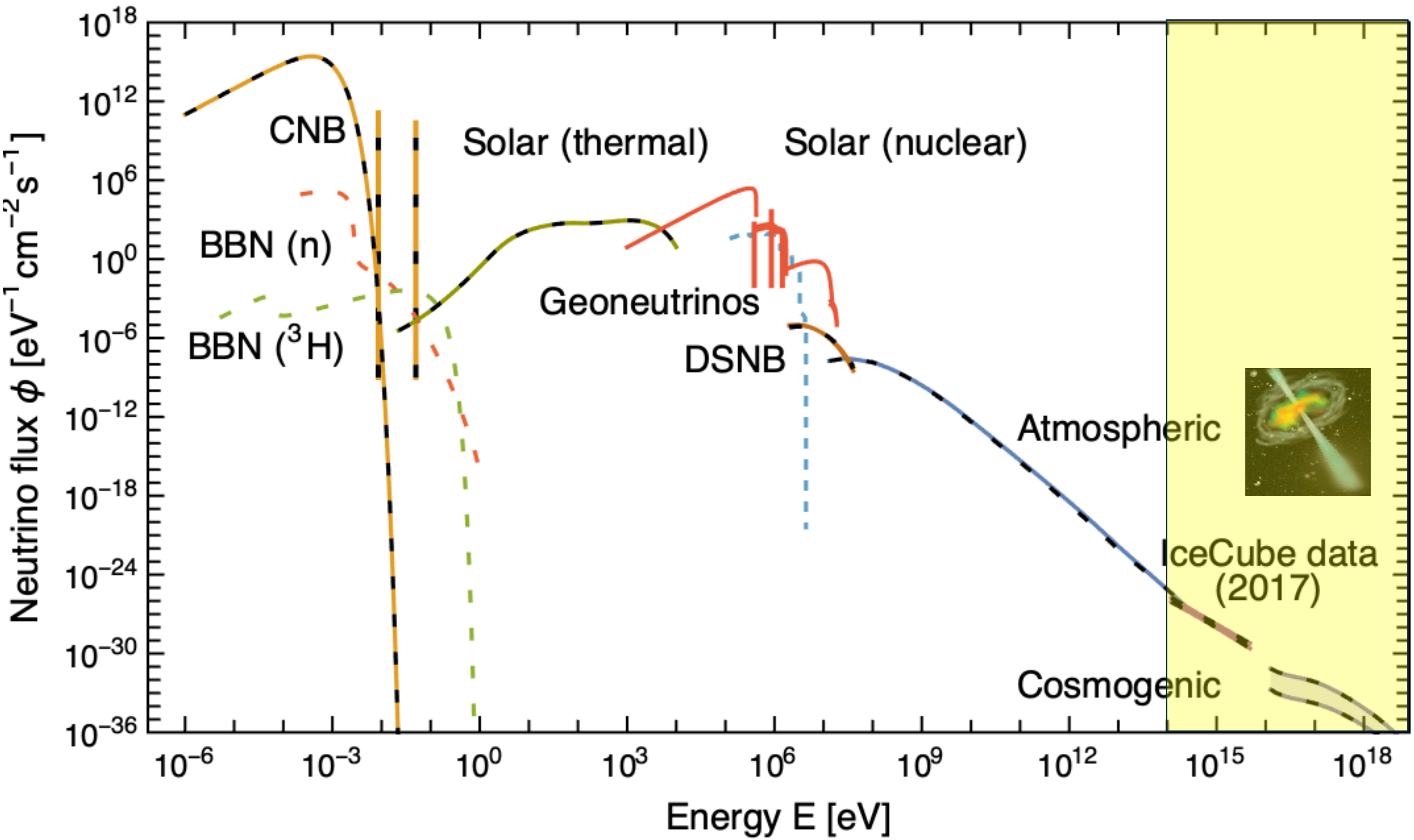
The standard disclaimer...

Multi-messenger astronomy

Neutrino astrophysics

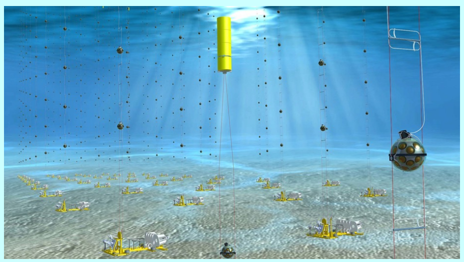
A "flight" of examples

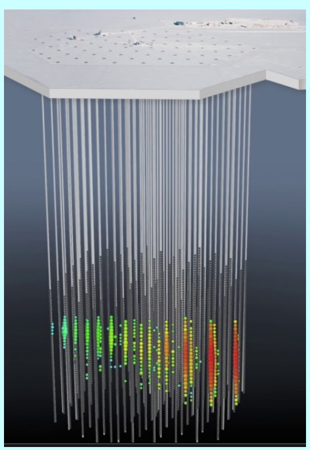
Start at the ultra-high-energy end



Detectors for ultra-high energy neutrinos (>TeV)

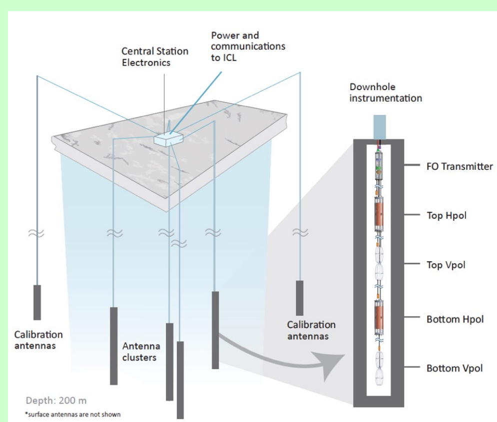
Long-string Water Cherenkov





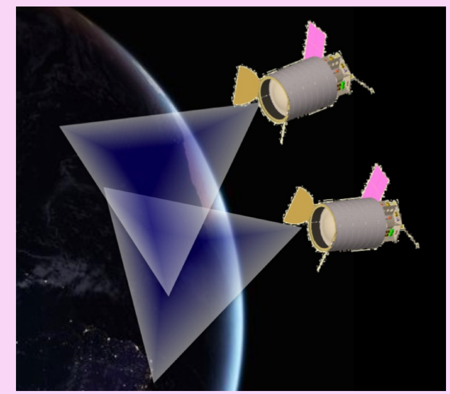
Water and ice

Antenna-based detectors



Balloon or in-ice

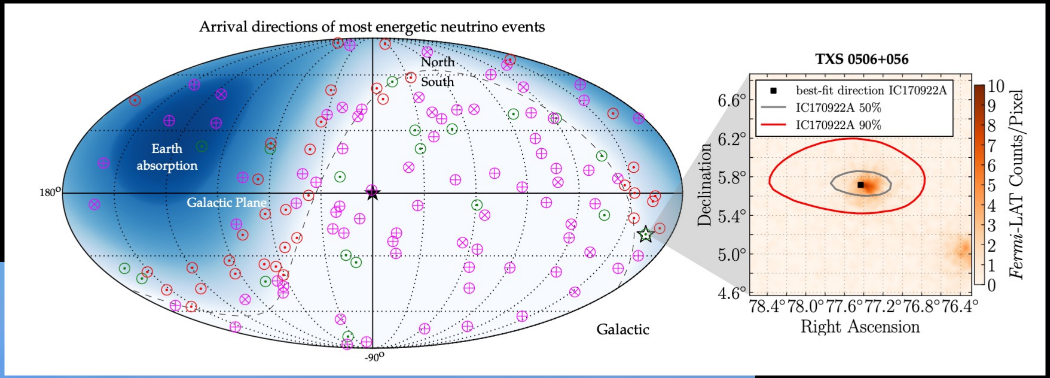
Cosmic-ray shower detectors

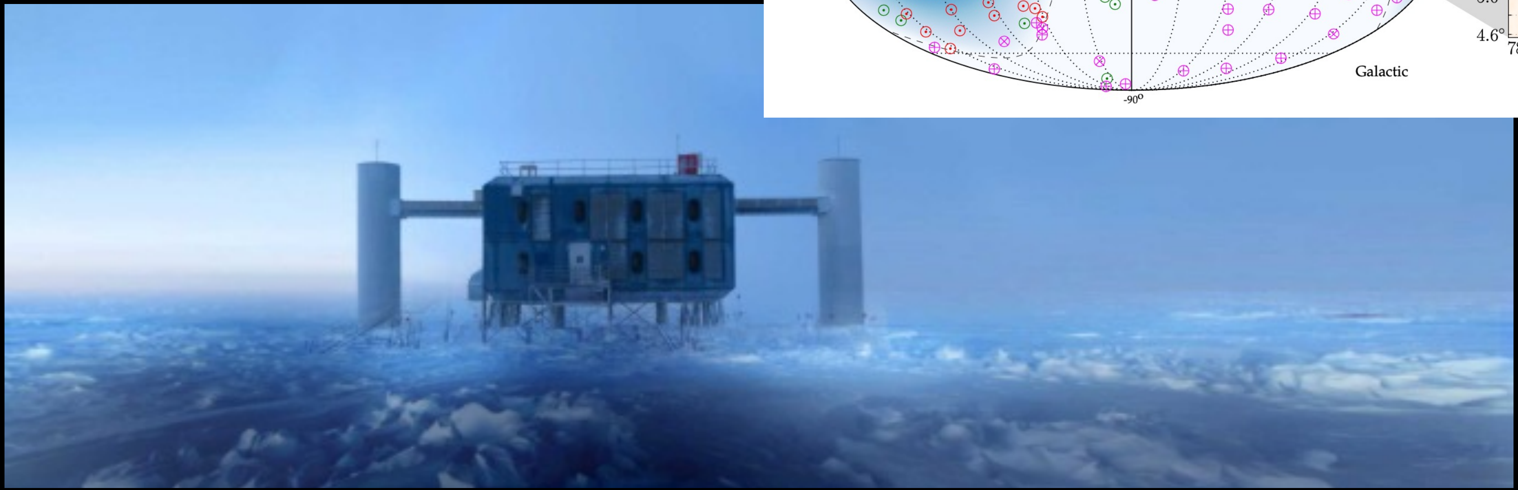


Ground-based or space-based

IceCube

hugely successful
program @South Pole

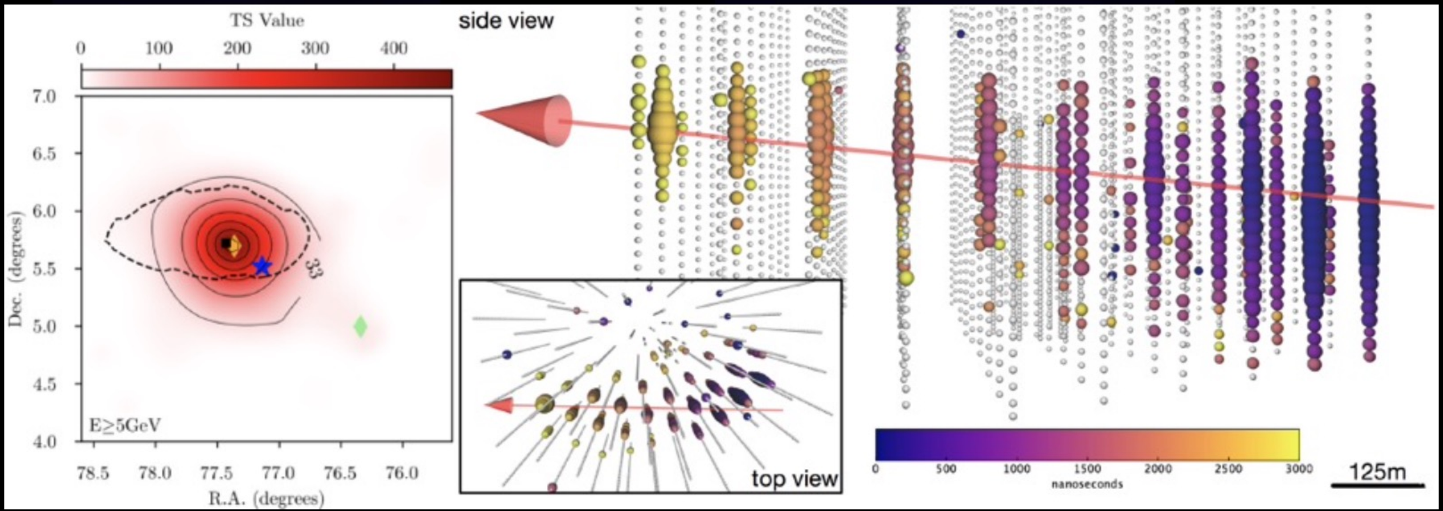




possible
"jetted
AGN"

TXS0506+056

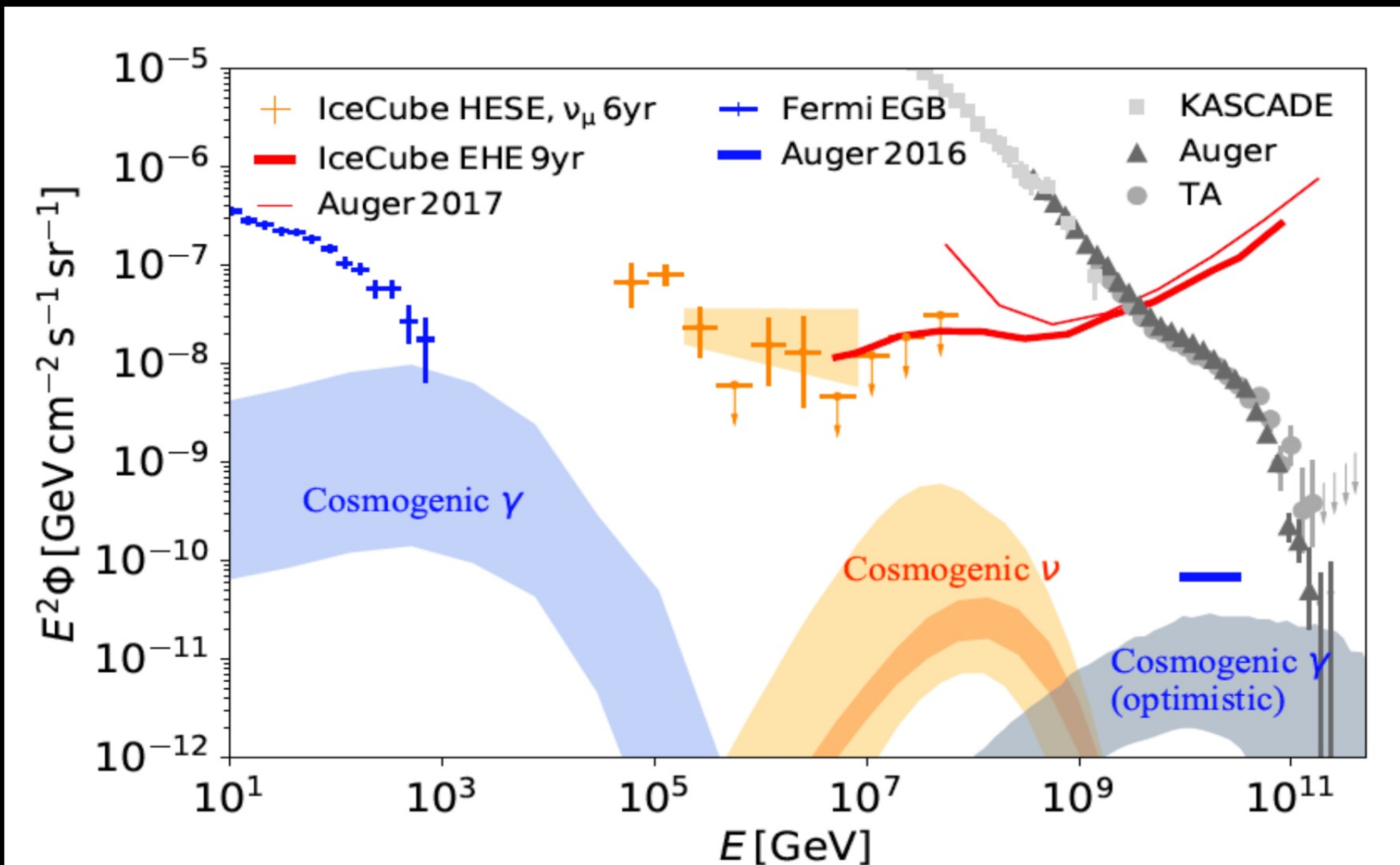
IceCube-170922

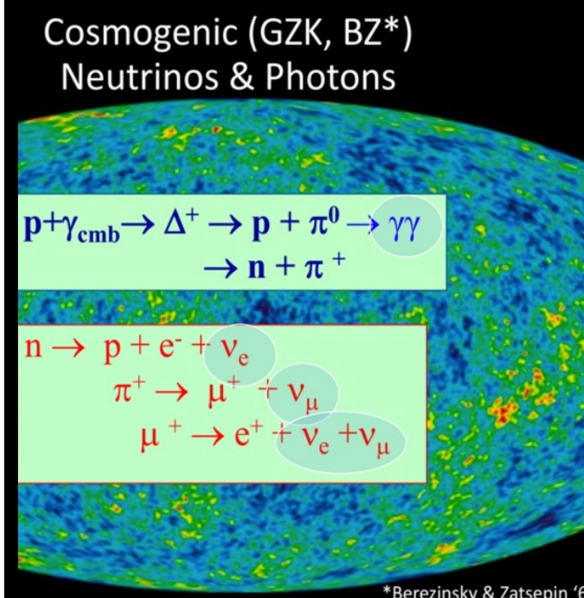


"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A", The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018

A. Olinto @ Snowmass"Blue Sky" session

Cosmogenic Neutrinos



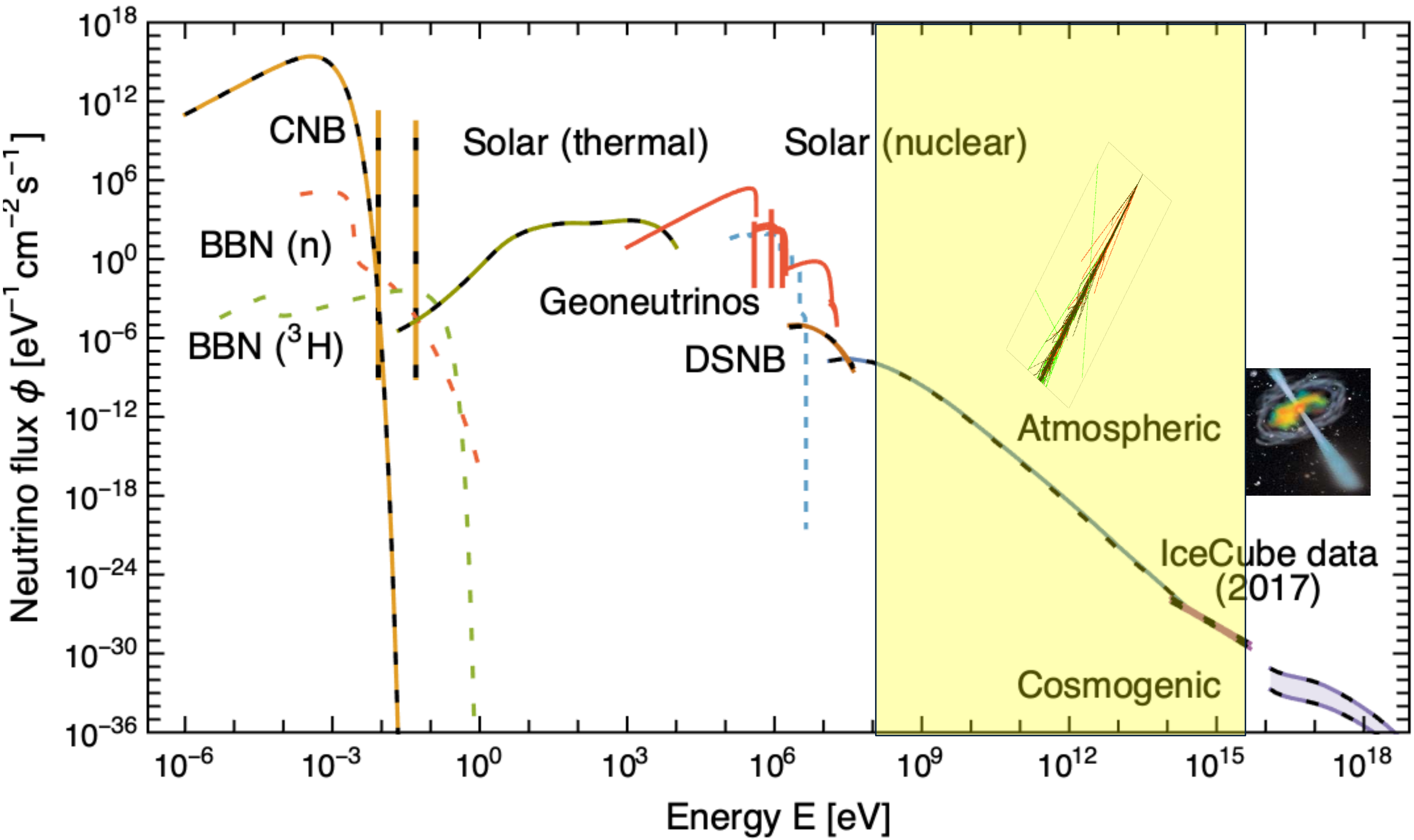


Batista et al, arXiv:1903.06714.pdf

Multiple programs going after these

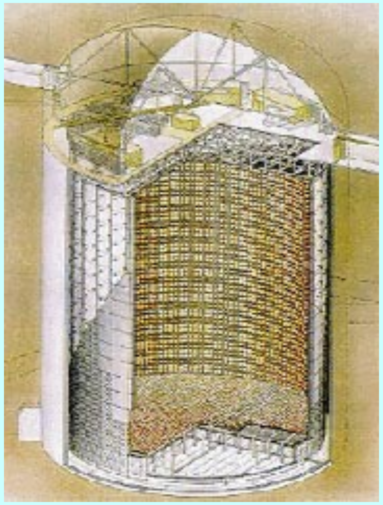
A. Olinto @ Snowmass "Blue Sky" session

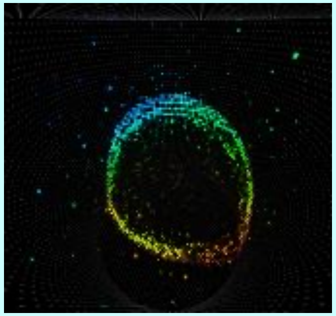
GeV-TeV scale: inhabited by atmospheric neutrinos



Large (multi-kton) detector technologies for ~GeV scale

Water Cherenkov

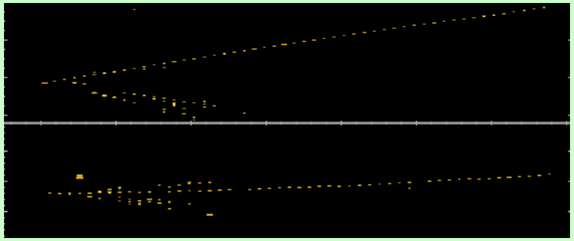




Cheap material, proven at very large scale

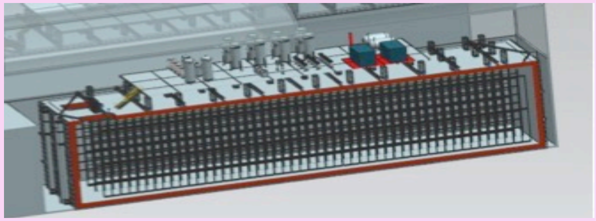
Trackers

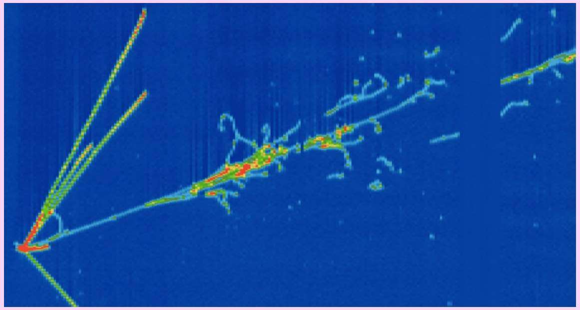
(a diverse category)



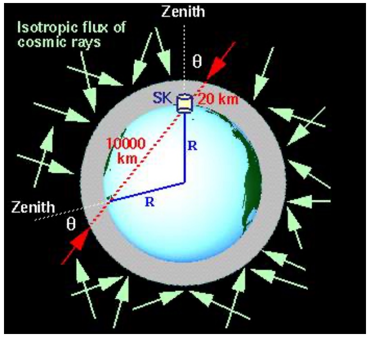
Good particle reconstruction

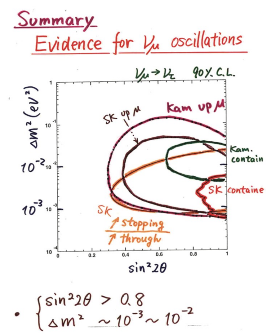
Liquid Argon Time Projection Chamber





Excellent particle reconstruction

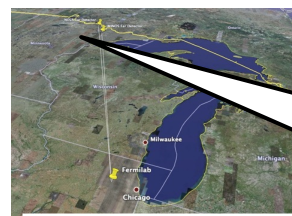




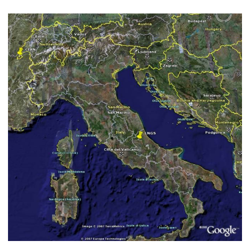
Water & tracking detectors made the original atmospheric neutrino oscillation measurements, and are now combined w/beams...

K2K
KEK to Kamioka

MINOS (+)
FNAL to Soudan

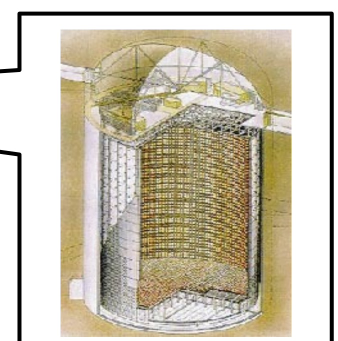


NOνA
FNAL to Ash River



CNGS
CERN to LNGS

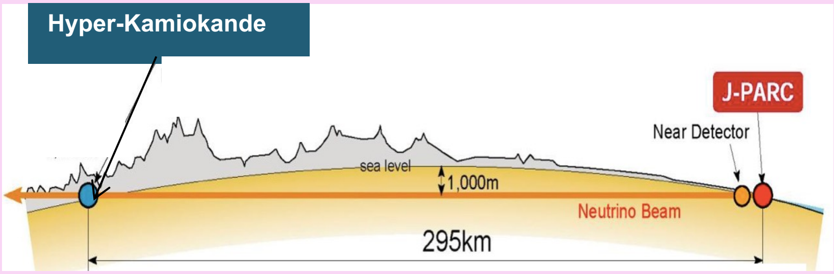
T2K
J-PARC to Kamioka



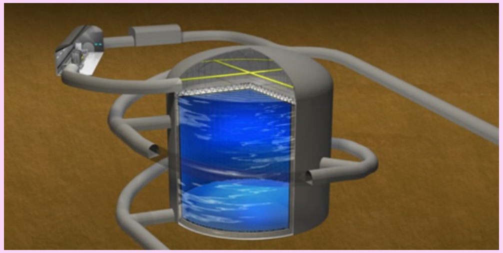
...they make good neutrino telescopes too!

Next-generation long-baseline beam experiments

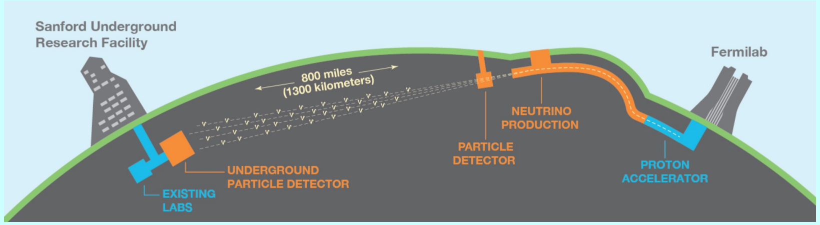
Hyper-Kamiokande



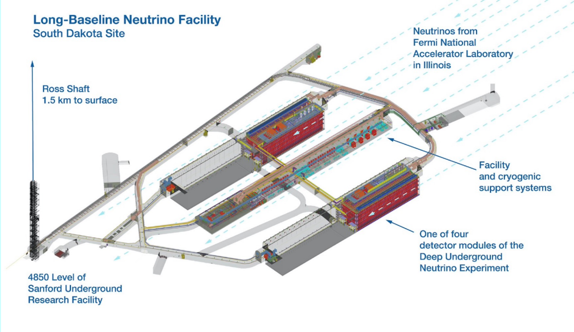
- 295-km baseline
- 260k (188k) ton mass
  water Cherenkov detector
- First data in 2027



DUNE/LBNF

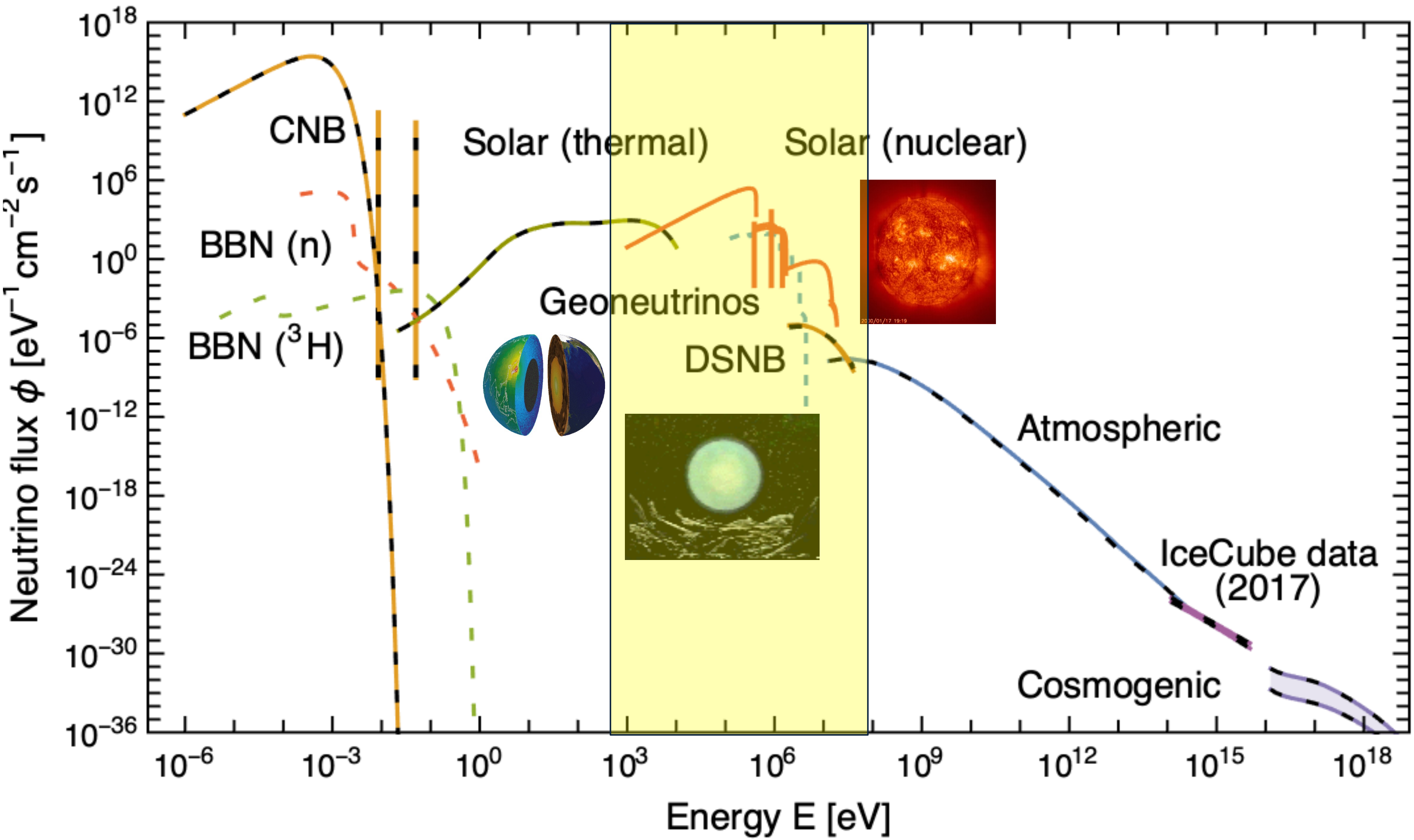


- 1300-km baseline
- 4 10-kton LArTPC modules
- 4850-ft depth
- Phase 2 "Module of Opportunity"
  for 3&4



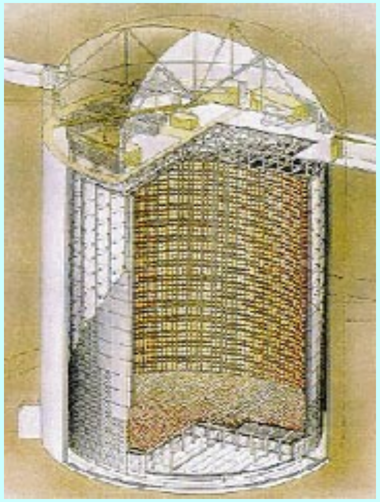
Multi-purpose detectors, broad physics programs in both cases, including astrophysical neutrinos (over a range of energies)

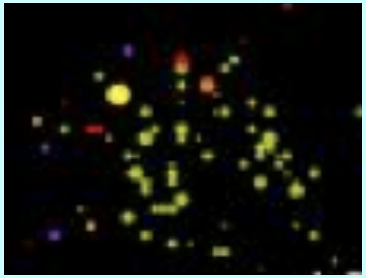
Now moving down in energy to the few-100 MeV scale



Large detector technologies for low energies

Water Cherenkov

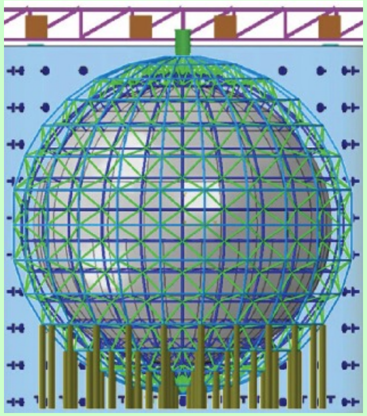


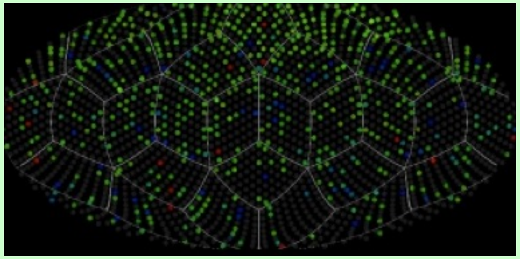


- Cheap, large
- Good directionality
- Low light yield

Liquid scintillator

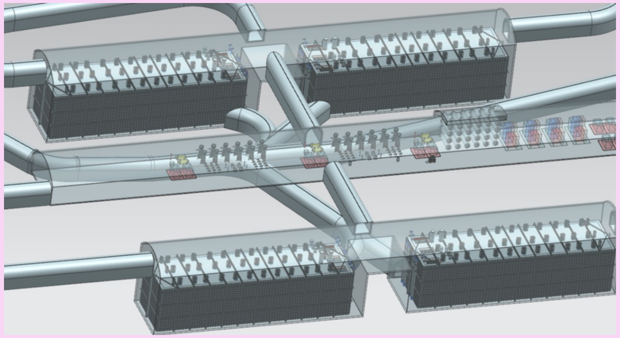
(and water-based LS, hybrid Ch/scintillation)





- High light yield → low threshold, good energy resolution
- Poor directionality

Liquid Argon Time Projection Chamber



- Ionization + scintillation
- Good directionality

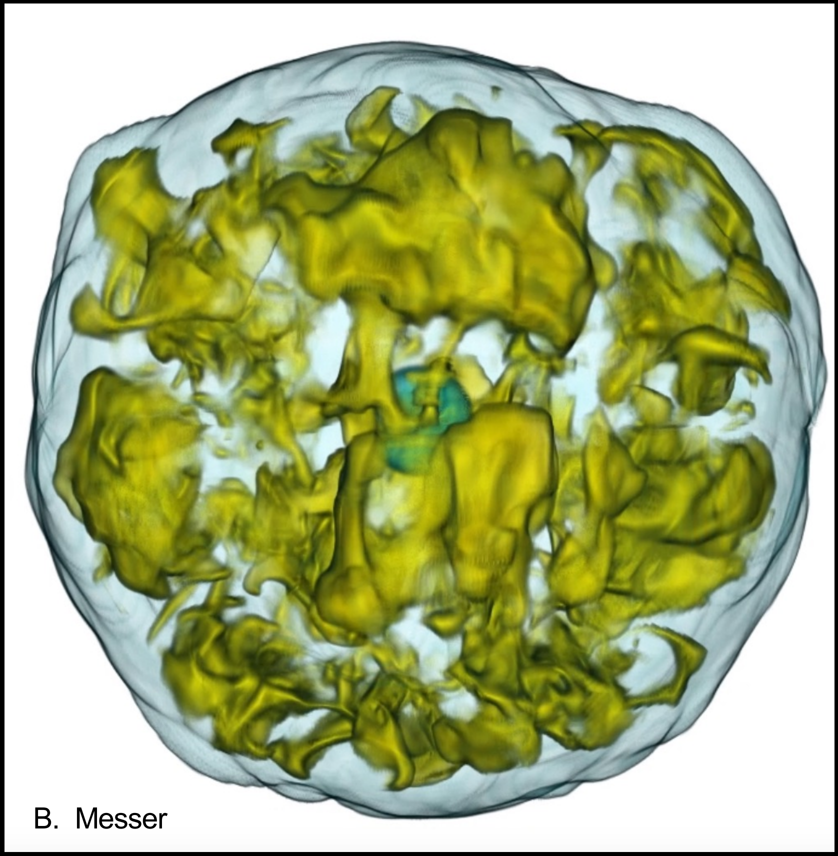
Generally limited by efficiency & background at ~MeV scale

Neutrinos from core-collapse supernovae

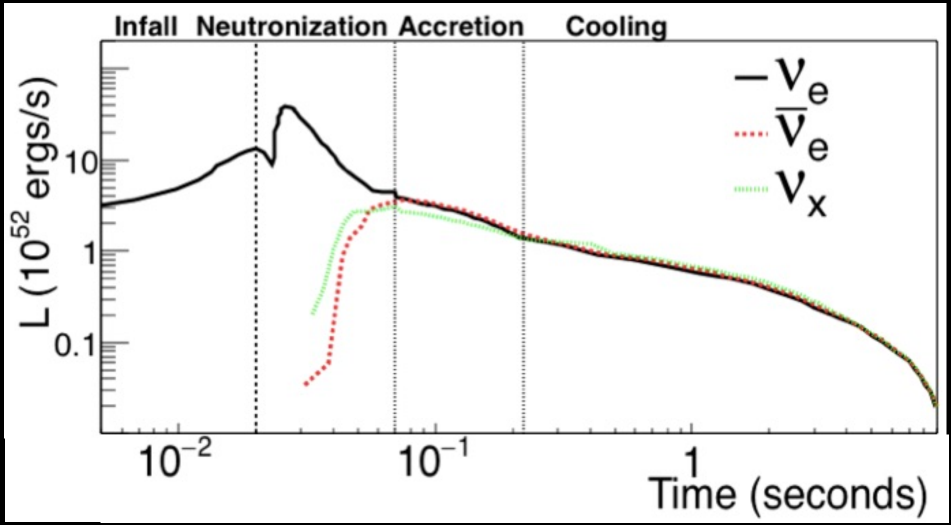
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

Mostly ν-νbar pairs from proto-nstar cooling

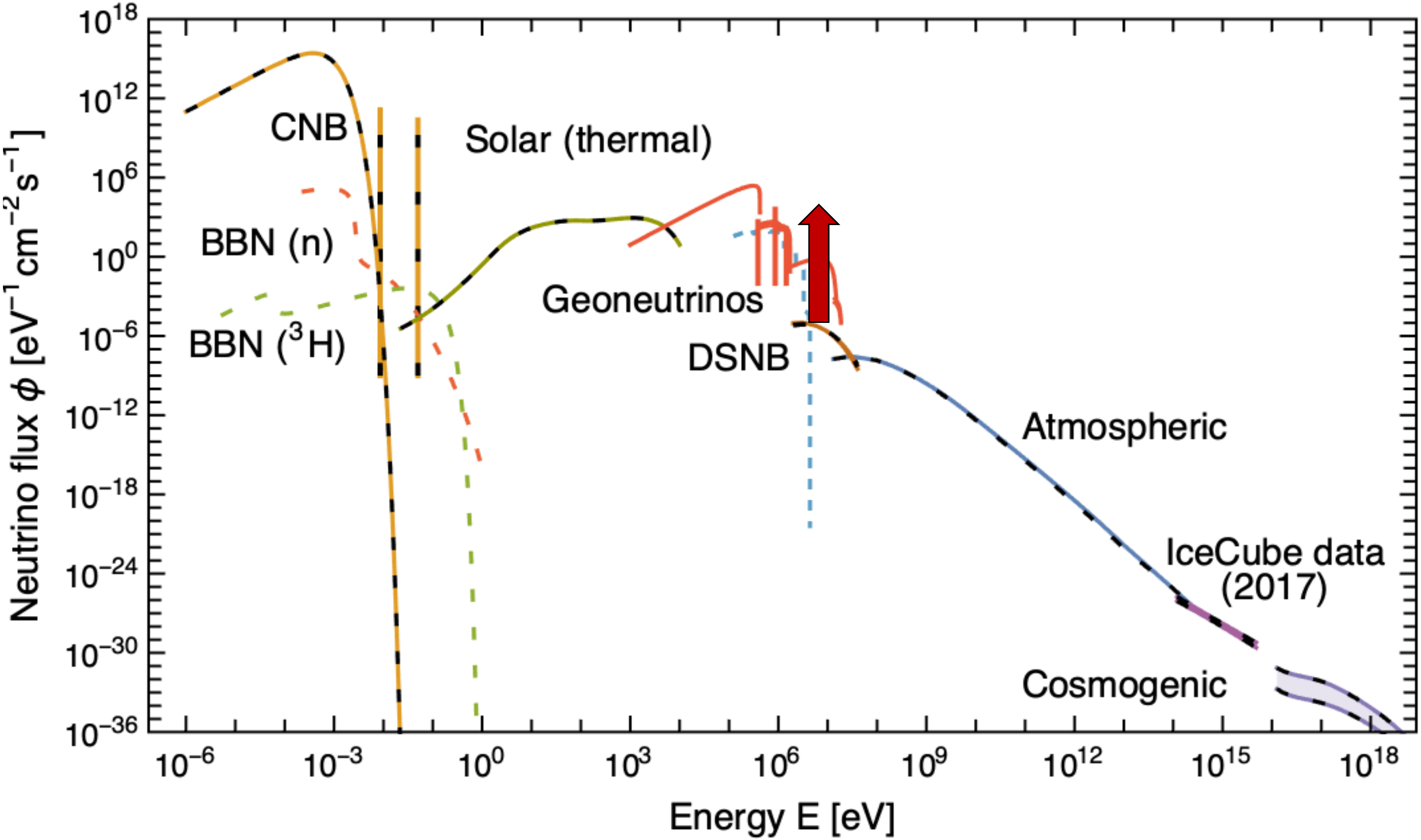


Timescale: *prompt* after core collapse, overall Δt~10's of seconds



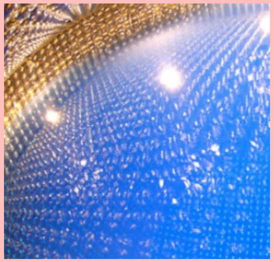
On this flux plot, for ~10 seconds,

diffuse supernova neutrino background x 10^{9} - 10^{10} !



Supernova neutrino detector types

Water



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\bar{\nu}_e$

Water, long-string

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

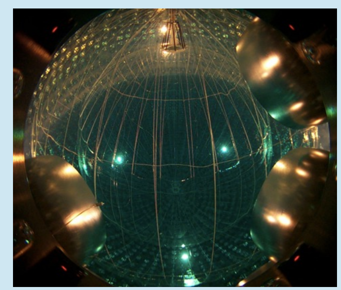
$\bar{\nu}_e$

Argon

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

ν_e

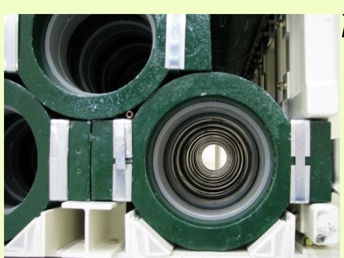
Scintillator



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\bar{\nu}_e$

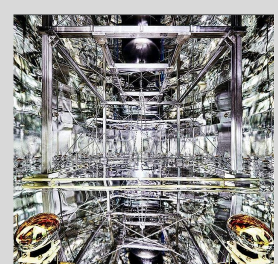
Lead



$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$$

ν_e

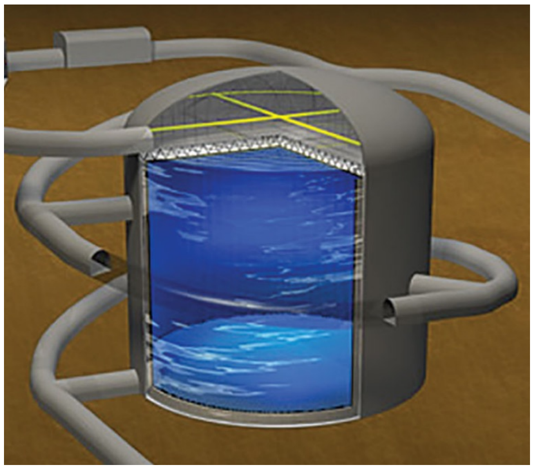
DM (Noble liquid)

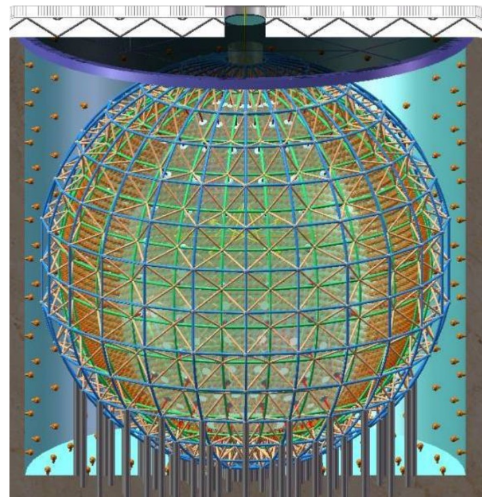


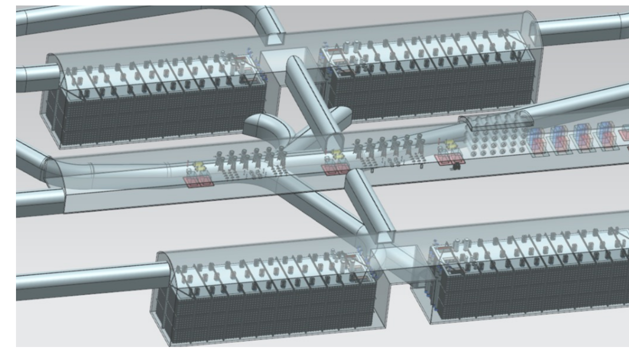
$$\nu_x + \mathrm{A} \rightarrow \nu_x + \mathrm{A}$$

ν_x

Future Large Supernova-Burst-Sensitive Neutrino Detectors







Hyper-Kamiokande
260 kton water
Japan

JUNO
20 kton scintillator (hydrocarbon)
China

DUNE
40 kton argon
USA

- Hyper-K /JUNO are primarily sensitive to **nuebar**

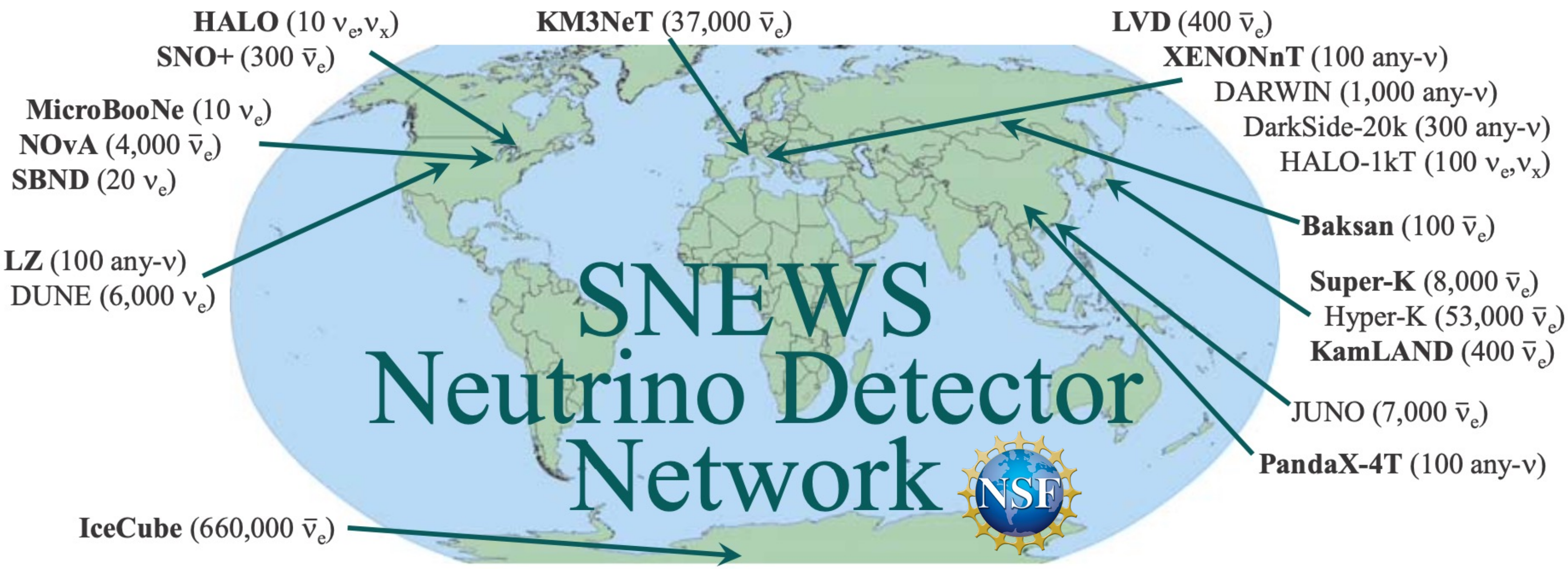
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- DUNE is primarily sensitive to **nue**

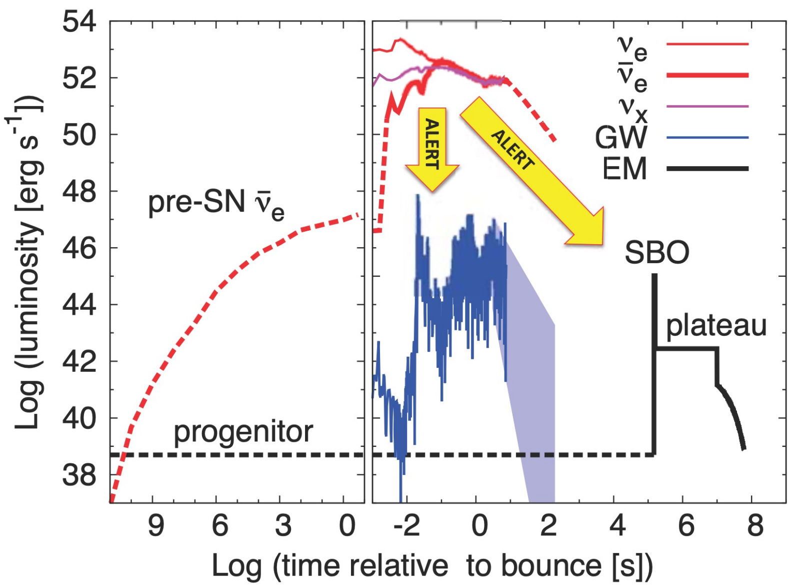
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

extreme complementarity

In general, the whole is more than the sum of the parts for multi-messenger astronomy

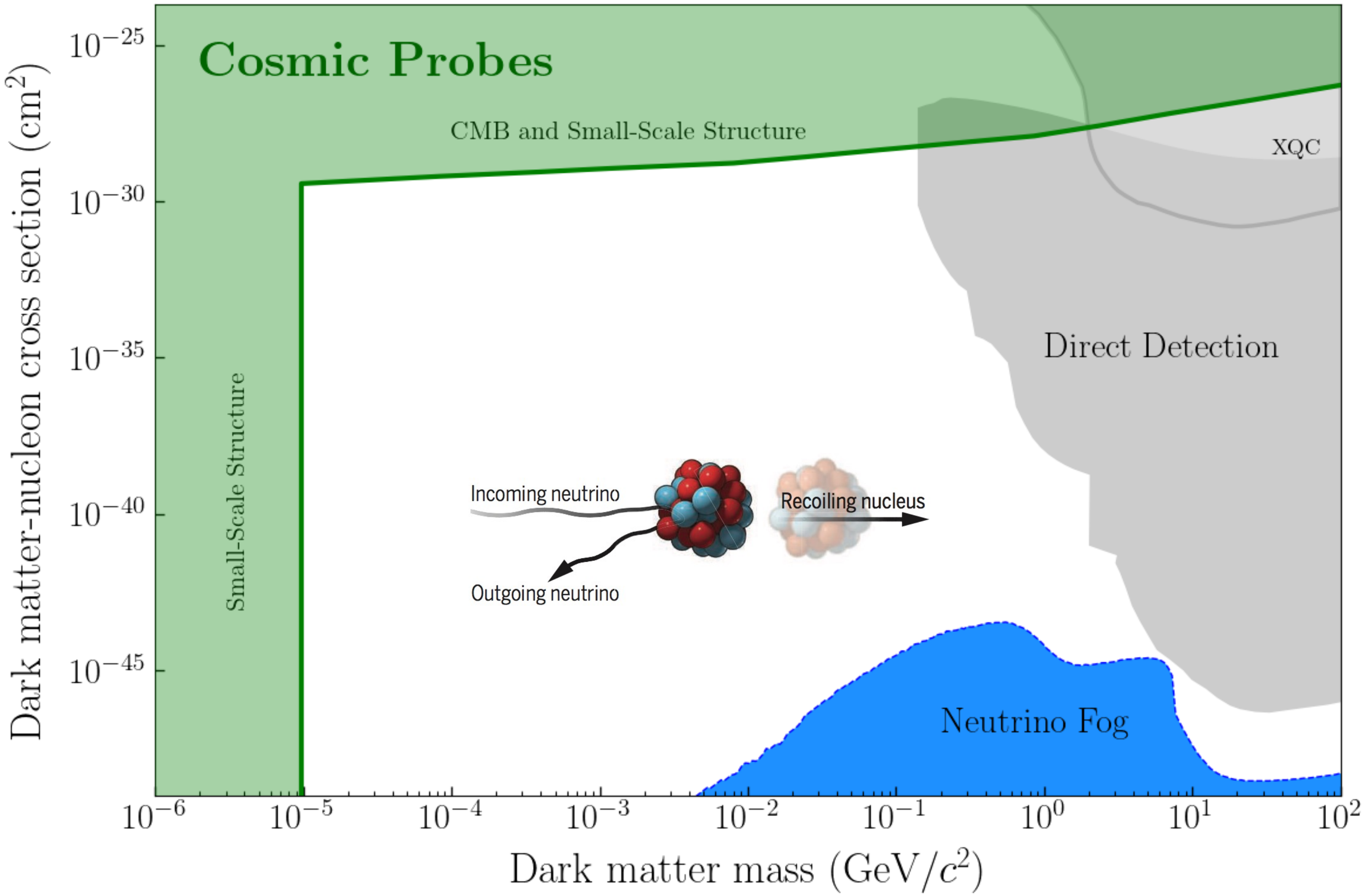


K. Nakamura et al., MNRAS 2016



Neutrinos arrive earlier than the first light from a supernova... combine signals for a high-confidence prompt alert, enabling more physics & astrophysics

Dark matter detectors as **neutrino observatories**

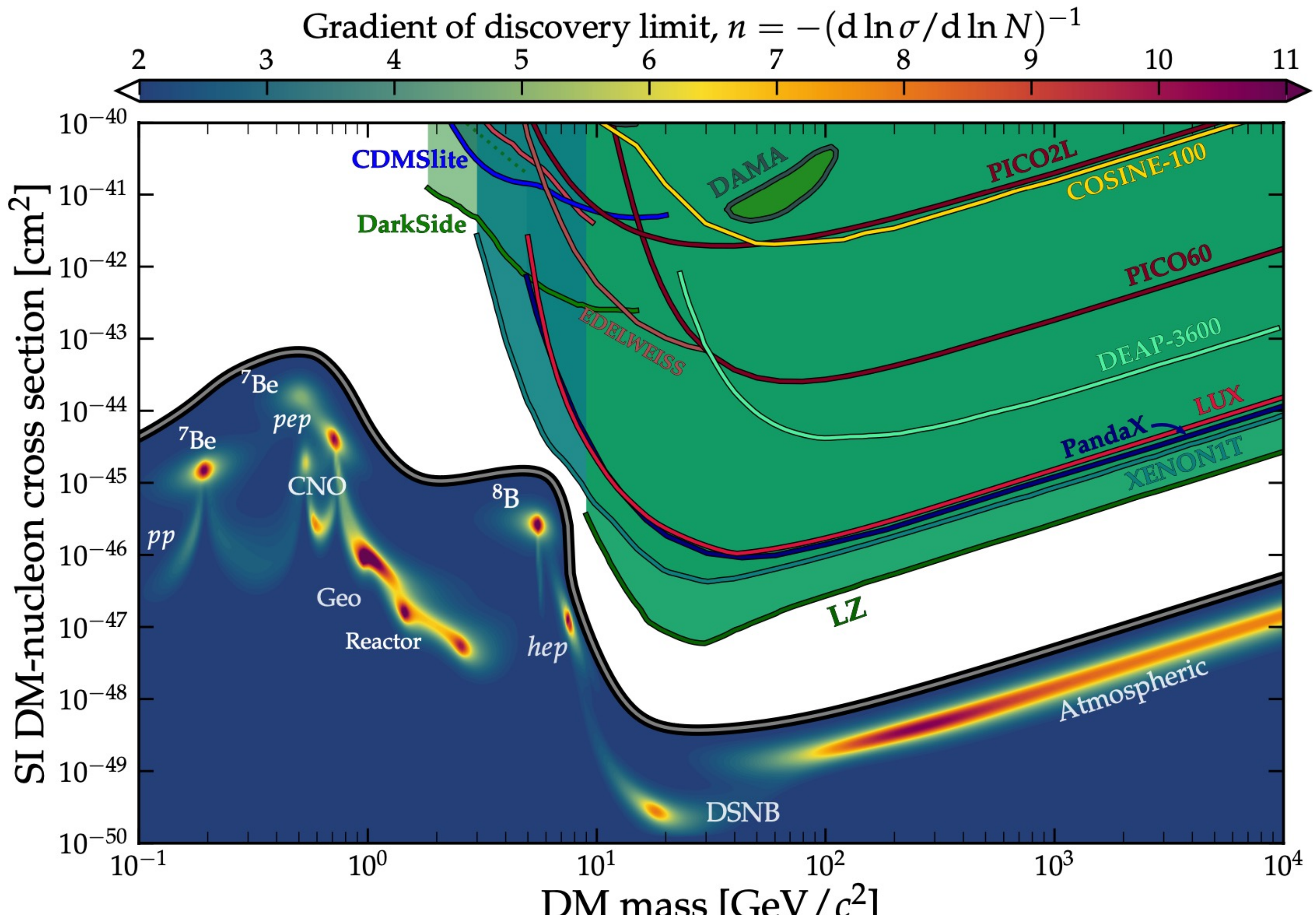


Plot from CF01

Image: J. Link *Science* Perspectives

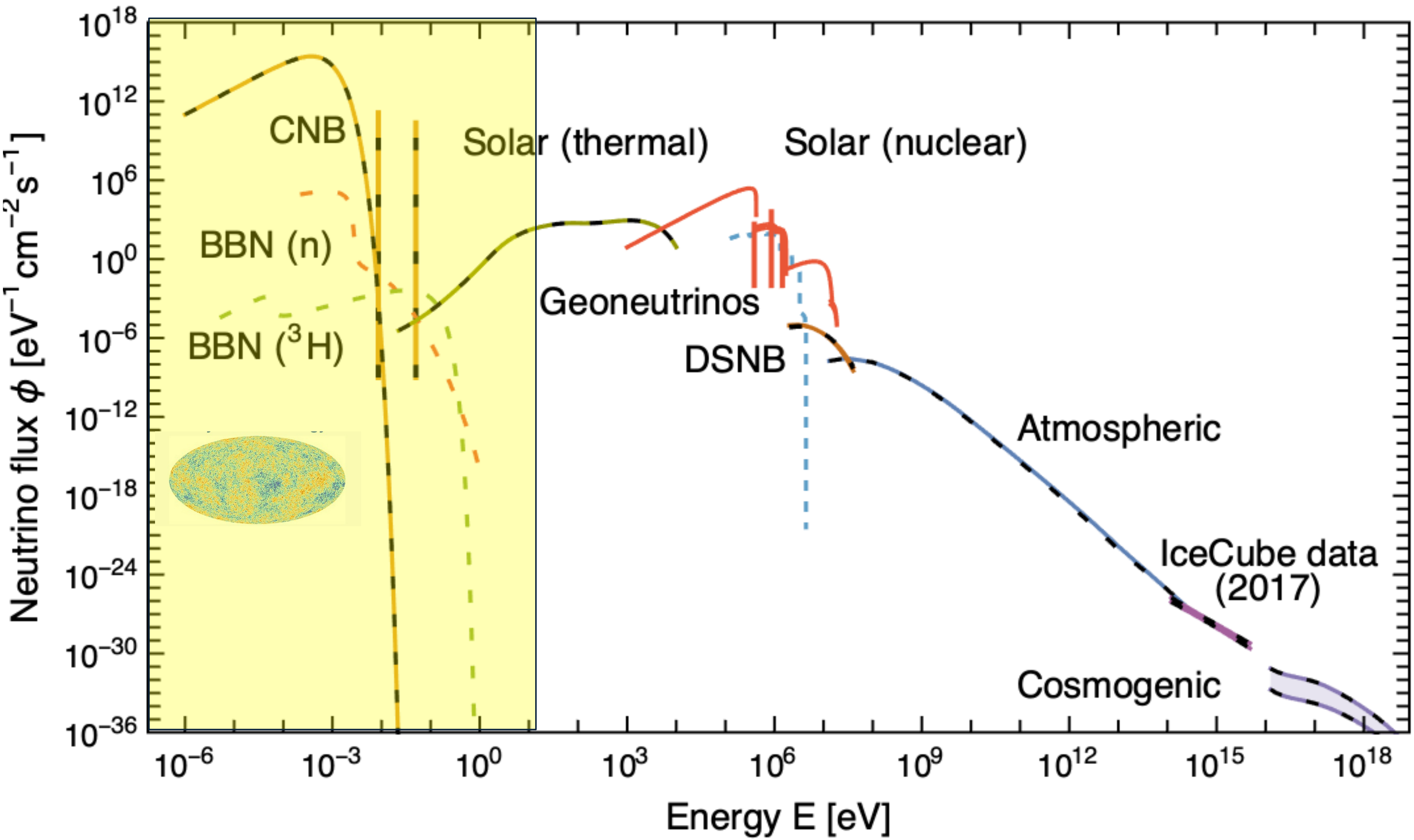
Once nuclear recoil detectors get sensitive enough, they are blinded by natural neutrinos

Interesting things may eventually emerge from the fog...



O'Hare [2109.03116]

And now, down at the lowest energy end....



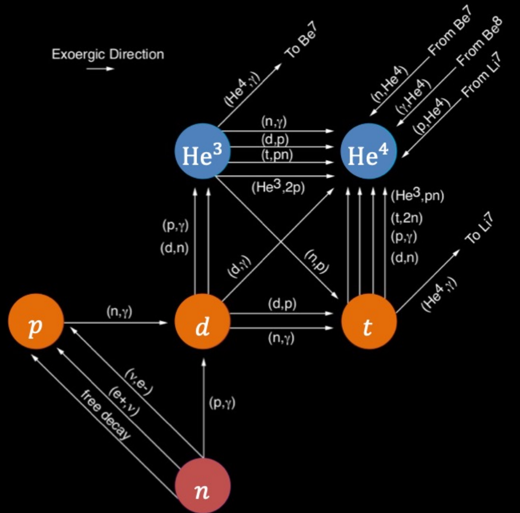
Indirect information about CNB from cosmology

Yvonne Wong, Snowmass Neutrino colloquium

Cosmological observables…

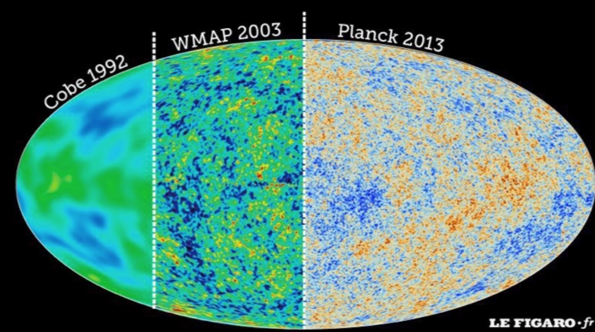
+ Supernova Ia, local H_0, etc.
(No direct neutrino effects)

Light element abundances from primordial nucleosynthesis



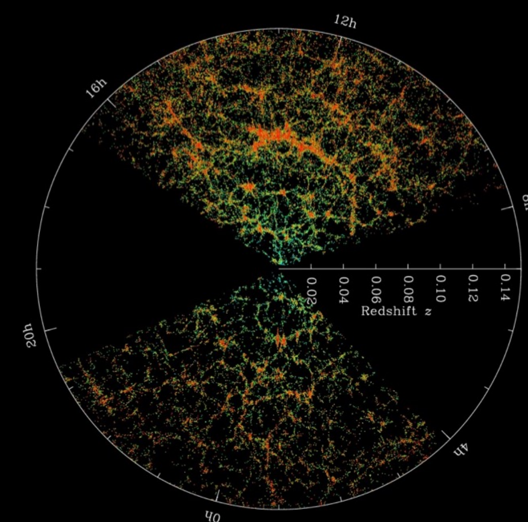
$N_{\rm eff}$ (expansion rate)

Cosmic microwave background anisotropies



$N_{\rm eff}$ (expansion rate)
Interactions (free-streaming)
Lifetime (free-streaming)

Large-scale matter distribution



$\sum m_\nu$ (perturbation growth)

Planck TTTEEE+lowE+lensing+BAO; 7-parameters

$$N_{\rm eff} = 2.99 \pm 0.34 \text{ (95\% CL)}$$

Aghanim et al. [Planck] 2021

→ Remarkably consistent with Standard Model prediction $N_{\rm eff} \approx 3$

Planck TTTEEE+lowE+lensing+BAO; 7-parameters

$$\sum m_\nu < 0.12 \text{ eV (95\% CL)}$$

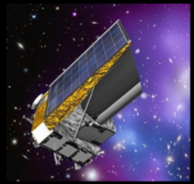
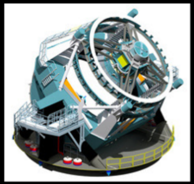
Aghanim et al. [Planck] 2021

At face value a factor of 30 tighter than current lab bound from KATRIN, $\sum m$ <2.4 eV (90% C.L.) Aker et al. [KATRIN] 2022

Indirect information about CNB from cosmology

Yvonne Wong, Snowmass Neutrino colloquium

Future cosmological probes…

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to $N_{\rm eff}$
	**ESA Euclid**	2024	$0.011 - 0.02$ eV	0.05
	**LSST**	2024	0.015 eV	0.05
	**CMB-S4**	2027	0.015 eV	$0.02 - 0.04$

Minimum $\sum m_\nu = 0.06$ eV
From neutrino oscillations
(assuming normal mass ordering)

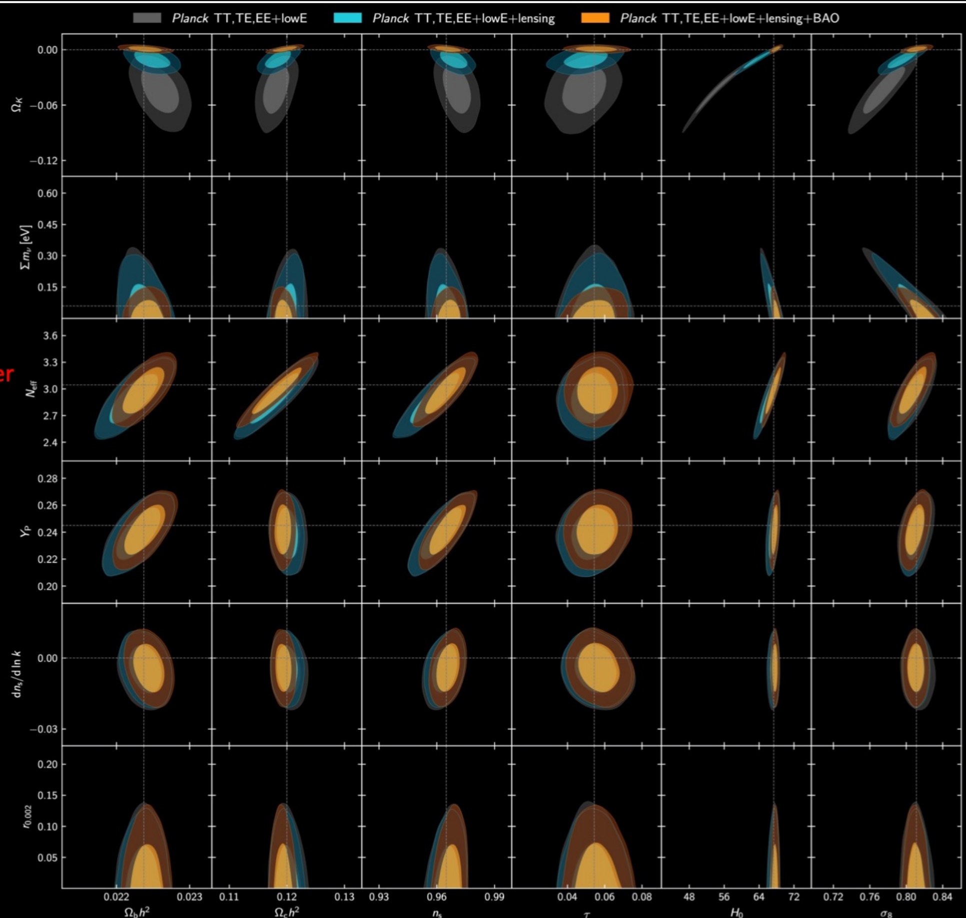
→ Detection of the absolute neutrino mass may be possible!

Neutrinos and Cosmology: indirect CNB

Yvonne Wong, Snowmass Neutrino colloquium

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.

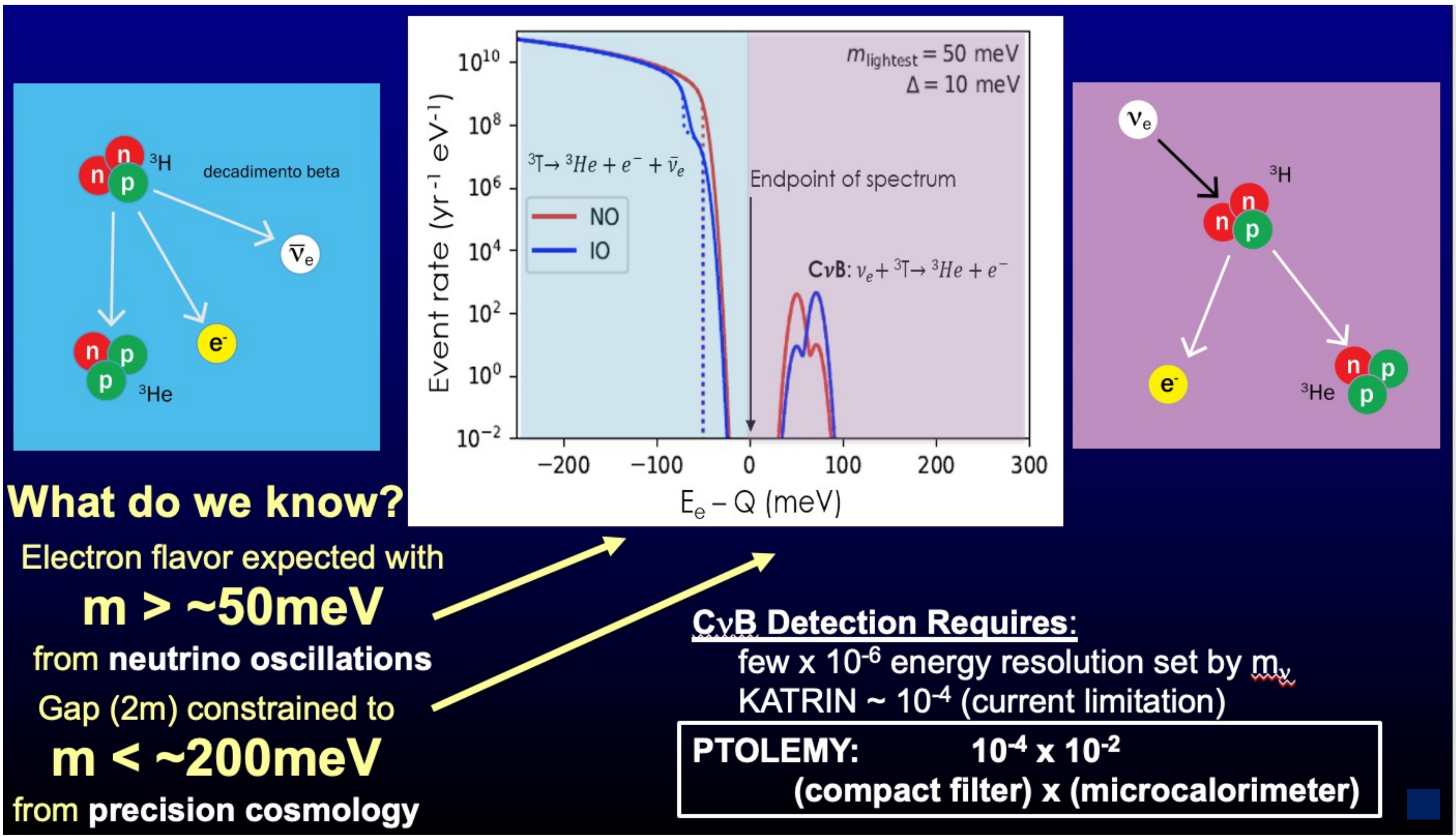
More accurate estimates of parameters inaccessible in the lab.

- Cosmological measurements tell us about ν properties
- **Lab experiments help to constrain cosmological fits**

Direct detection of Cosmic Neutrino Background

Very, very hard... lots of ideas but few promising...
Best possibility: "zero-threshold reactions"

C.Tully, Snowmass white paper workshop talk



Science Drivers in Neutrino Physics

Three-flavor paradigm: filling in the remaining pieces

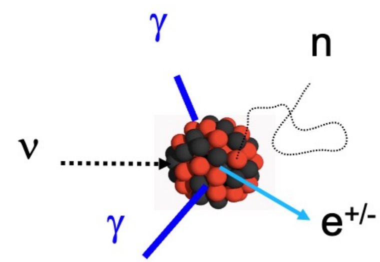
Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

The Grand Challenge: catch 'em all!

And a final note: understanding of **neutrino interactions with matter** is very important, and connects to ~everything ... especially critical for oscillation physics



BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Astrophysics: supernova bursts, solar models

Tests of neutrino mixing model

Experiment	Source	Target
COHERENT	πDAR	Na, Ar, Ge, CsI,
Coherent CAPTAIN Mills	πDAR	Ar
JSNS^2	πDAR	
ESS	πDAR	
CHILLAX	Reactor	Ar
CONNIE	Reactor	Si
CONUS	Reactor	Ge
MINER	Reactor	Ge, Si
NEON	Reactor	Na
NUCLEUS	Reactor	
NUXE	Reactor	Xe
PALEOCCENE	Paleo	
Ricochet	Reactor	Ge, Zn
RED-100	Reactor	Xe
NuGen	Reactor	
SBC	Reactor	Ar
TEXONO	Reactor	Ge
NEWSG	Reactor	H, He, C, Ne

Many experimental & theory efforts over many orders of magnitude of neutrino energy

Short baseline Neutrino Program:
MicroBooNE, SBND, ICARUS
sbn.fnal.gov/

ANNIE
annie
annie.fnal.gov/

NuSTORM

MINERvA
minerva.fnal.gov/
MINERvA

NINJA
NINJA
Recent: Phys. Rev. D 102, 072006

Kendall Mahn, Snowmass

Overall Summary

Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

We've already met some grand challenges,
.... **but more to go!**
Still exciting years ahead for neutrinos

Extras/Backups