



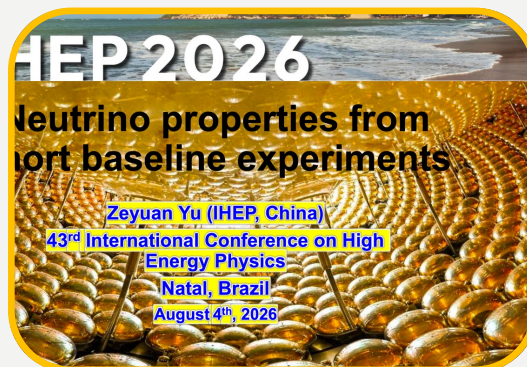
НОВОСТИ ФИЗИКИ НЕЙТРИНО

АННА ВИНОКУРОВА
РАЗЛИВ 2026

ПО МАТЕРИАЛАМ ICHEP 2026



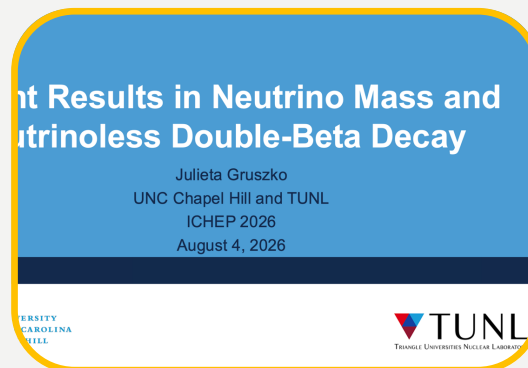
André de Gouvêa
(Northwestern University, USA)



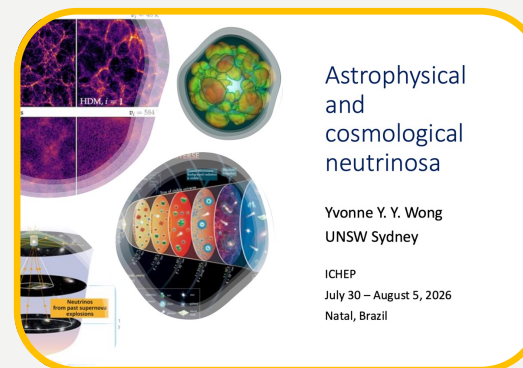
Zeyuan Yu
(IHEP, China)



Stephen Dolan
(CERN, Switzerland)



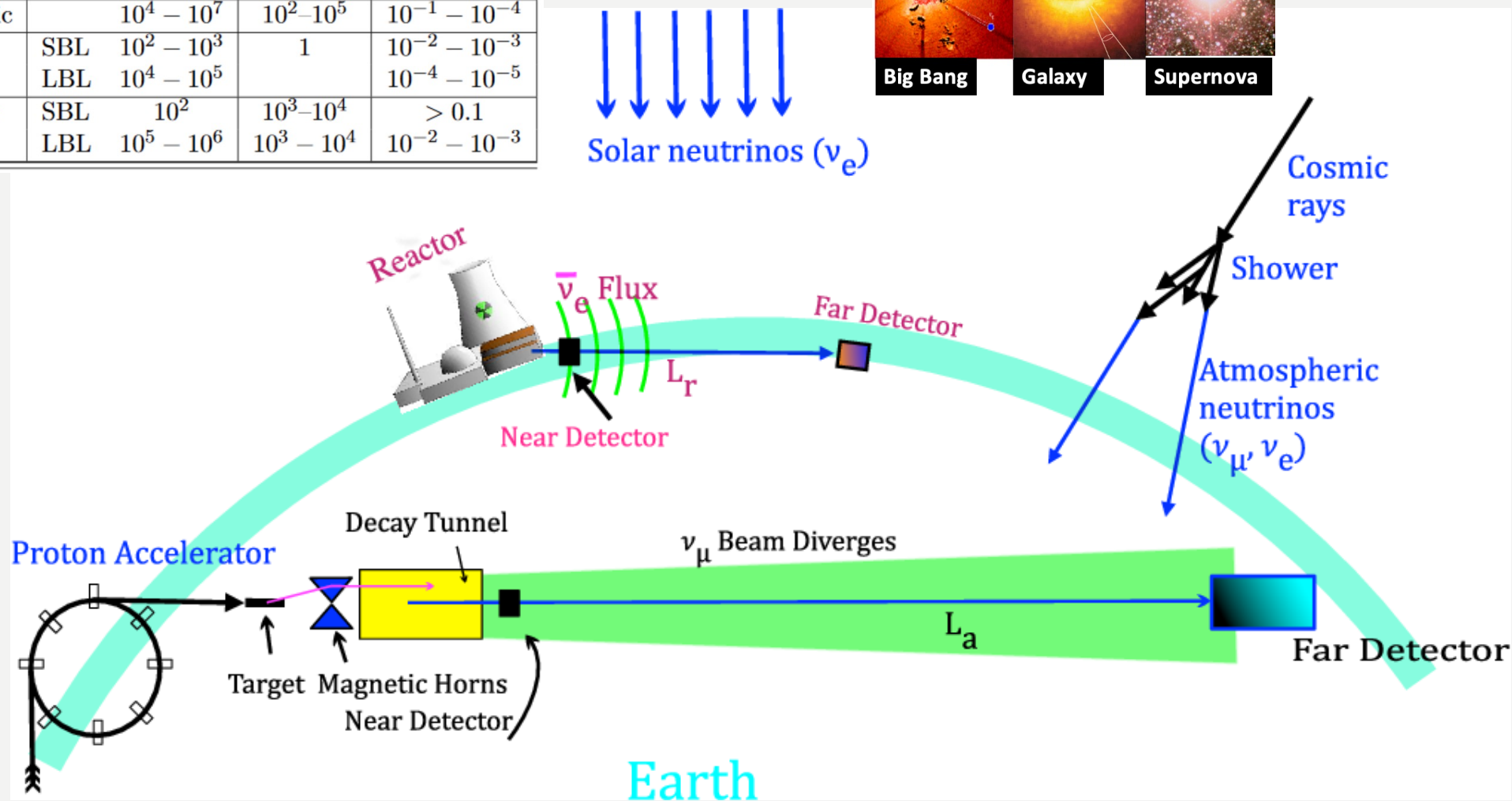
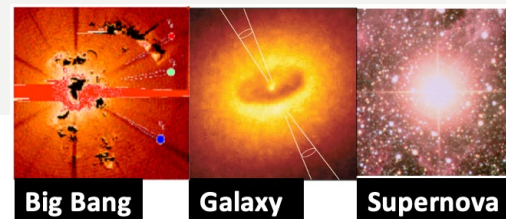
Julieta Gruszko
(University of North Carolina at
Chapel Hill and Triangle
Universities Nuclear Laboratory,
USA)



Yvonne Wong
(University of New South Wales,
Australia)

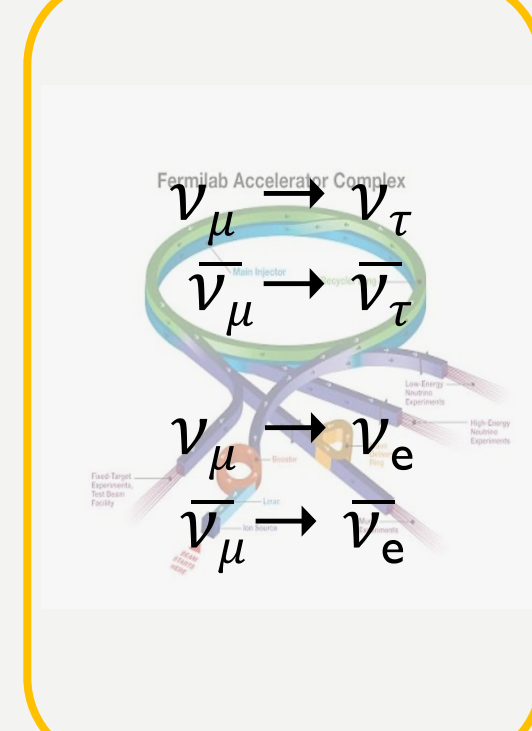
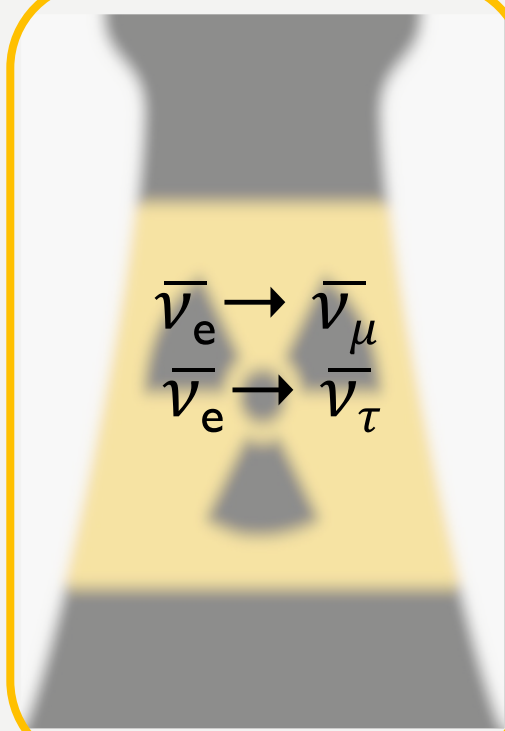
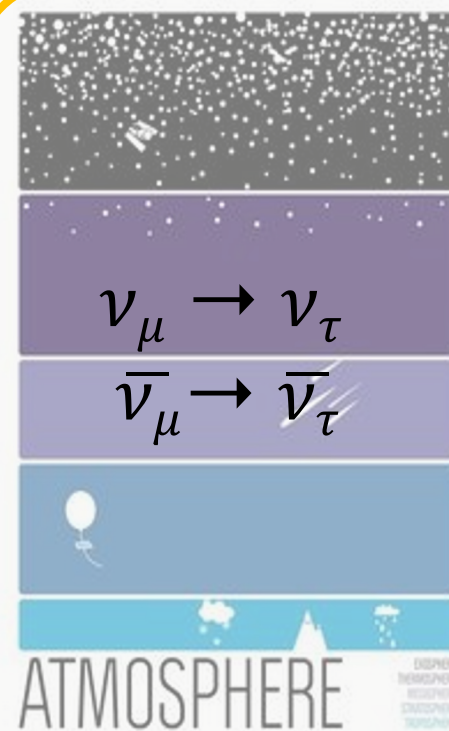
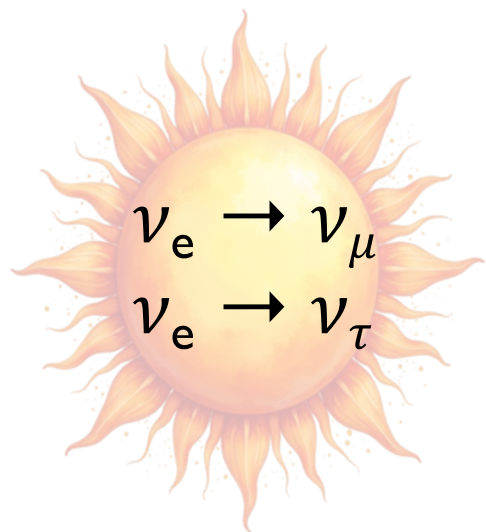
КУДА МЫ СМОТРИМ?

Experiment		L (m)	E (MeV)	$ \Delta m^2 $ (eV ²)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	$10^2 - 10^5$	$10^{-1} - 10^{-4}$
Reactor	SBL	$10^2 - 10^3$	1	$10^{-2} - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	$10^3 - 10^4$	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$



ЧТО МЫ НАБЛЮДАЕМ?

Осцилляции!



ЧТО МЫ ИЗМЕРЯЕМ?

PMNS матрица

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$P_{\alpha \rightarrow \beta} = |\langle \nu_\beta(t) | \nu_\alpha \rangle|^2 = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-im_i^2 L/2E} \right|^2$$

The **phase of the oscillation** depends on:

- The difference in neutrino mass state masses
- The distance travelled (L) over the neutrino energy (E)

The **amplitude of the oscillation** depends on:

- The PMNS neutrino mixing matrix elements

$$\Delta m_{21}^2 = (7.388 \pm 0.078) \times 10^{-5} \text{ eV}^2 \quad (1\%)$$

$$|\Delta m_{31}^2| = (2.50 \pm 0.03) \times 10^{-3} \text{ eV}^2 \quad (1\%)$$

$$\sin^2 \theta_{12}^{32} = 0.3036 \pm 0.0064 \quad (2\%)$$

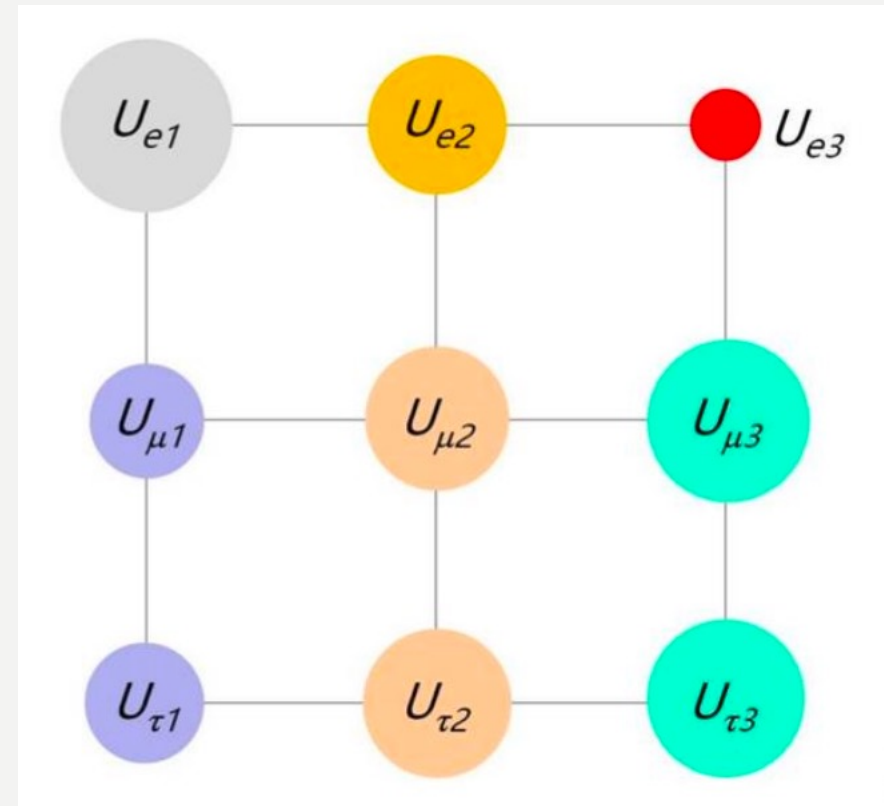
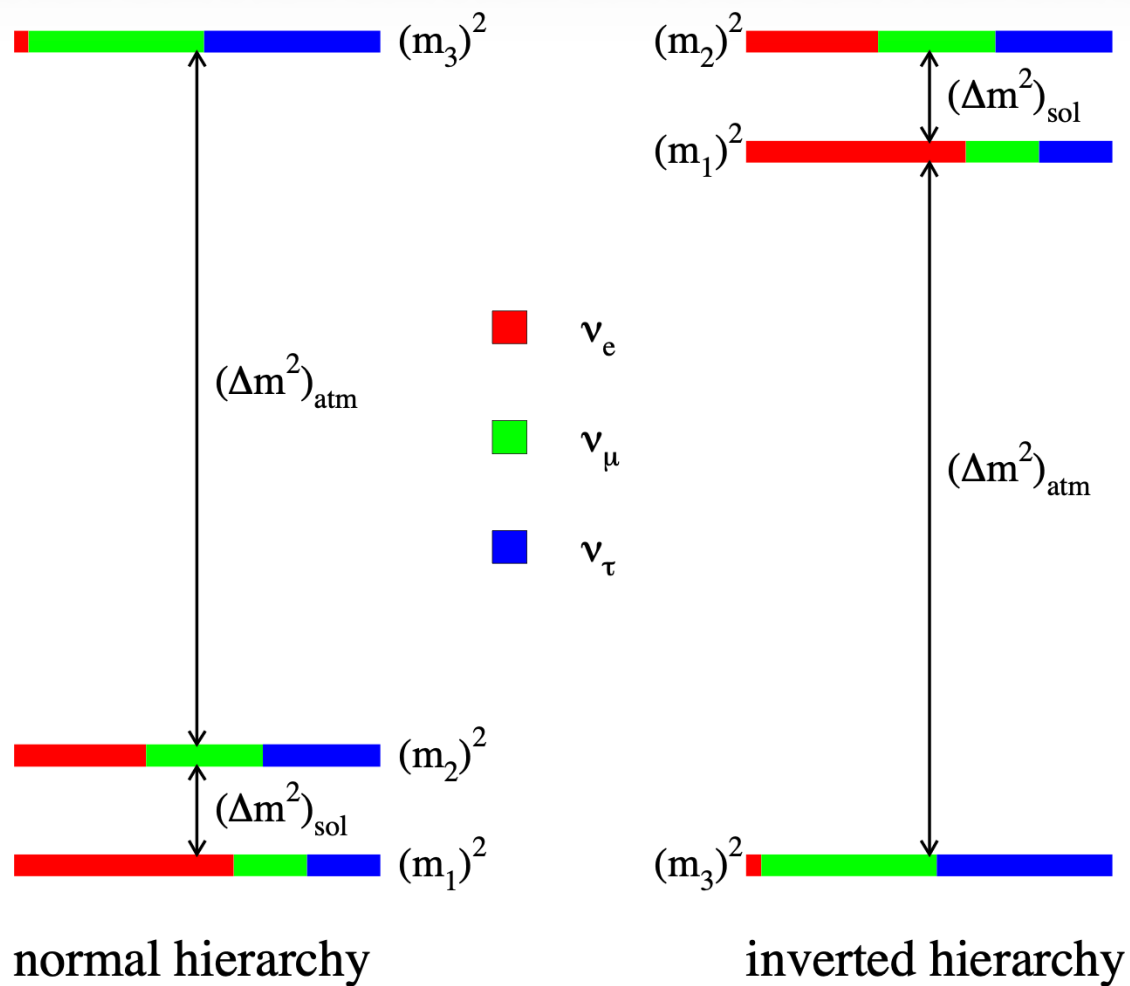
$$\sin^2 \theta_{13} = 0.02220 \pm 0.00068 \quad (3\%)$$

$$\sin^2 \theta_{23} = 0.573 \pm 0.023 \quad (5\%)$$

$$\delta_{CP} = (105 - 405)^\circ \quad (3\sigma) \quad (\text{unknown})$$

$$\text{sign}(\Delta m_{31}^2) = +, \text{ slightly favored} \quad (\text{unknown})$$

ЧТО ОТСЮДА СЛЕДУЕТ?



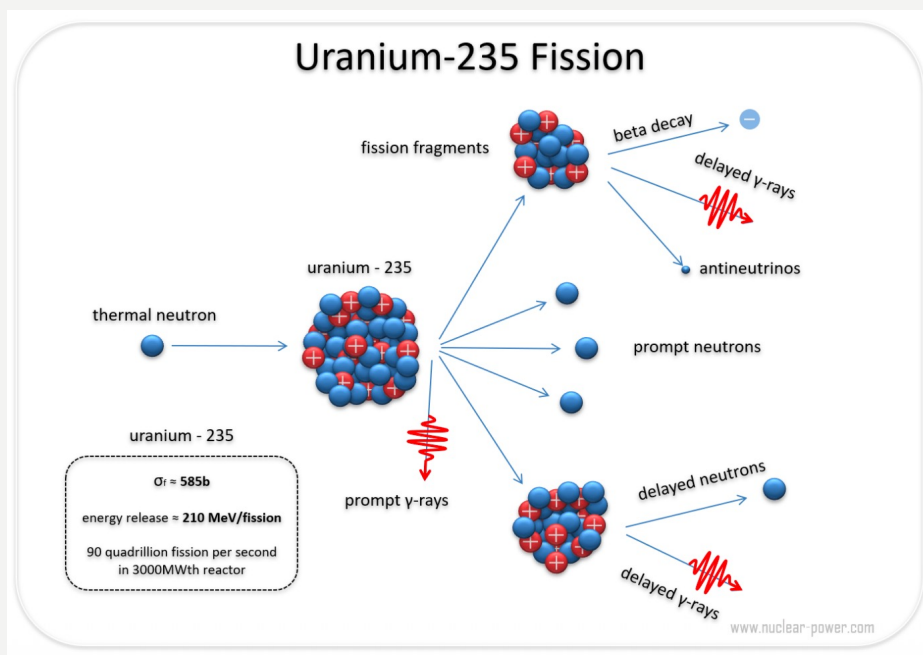
ЧТО ЕЩЕ НЕИЗВЕСТНО?

- Осциллируют ли (анти-) ν_τ ?
- Могут ли (анти-) ν_μ иметь большую длину осцилляции?
- Как по отдельности ν_e осциллирует в ν_μ и ν_τ ? Пока измерено только исчезновение ν_e .
- Насколько точна CP-инвариантность ($\nu_i \rightarrow \nu_j$ vs $\bar{\nu}_i \rightarrow \bar{\nu}_j$)?
- Насколько точна T-инвариантность ($\nu_i \rightarrow \nu_j$ vs $\nu_j \rightarrow \nu_i$)?
- Иерархия масс.
- Значения масс.
- Дирак или Майорана?
- Почему массы такие маленькие?
- Как это вписать в Стандартную Модель?



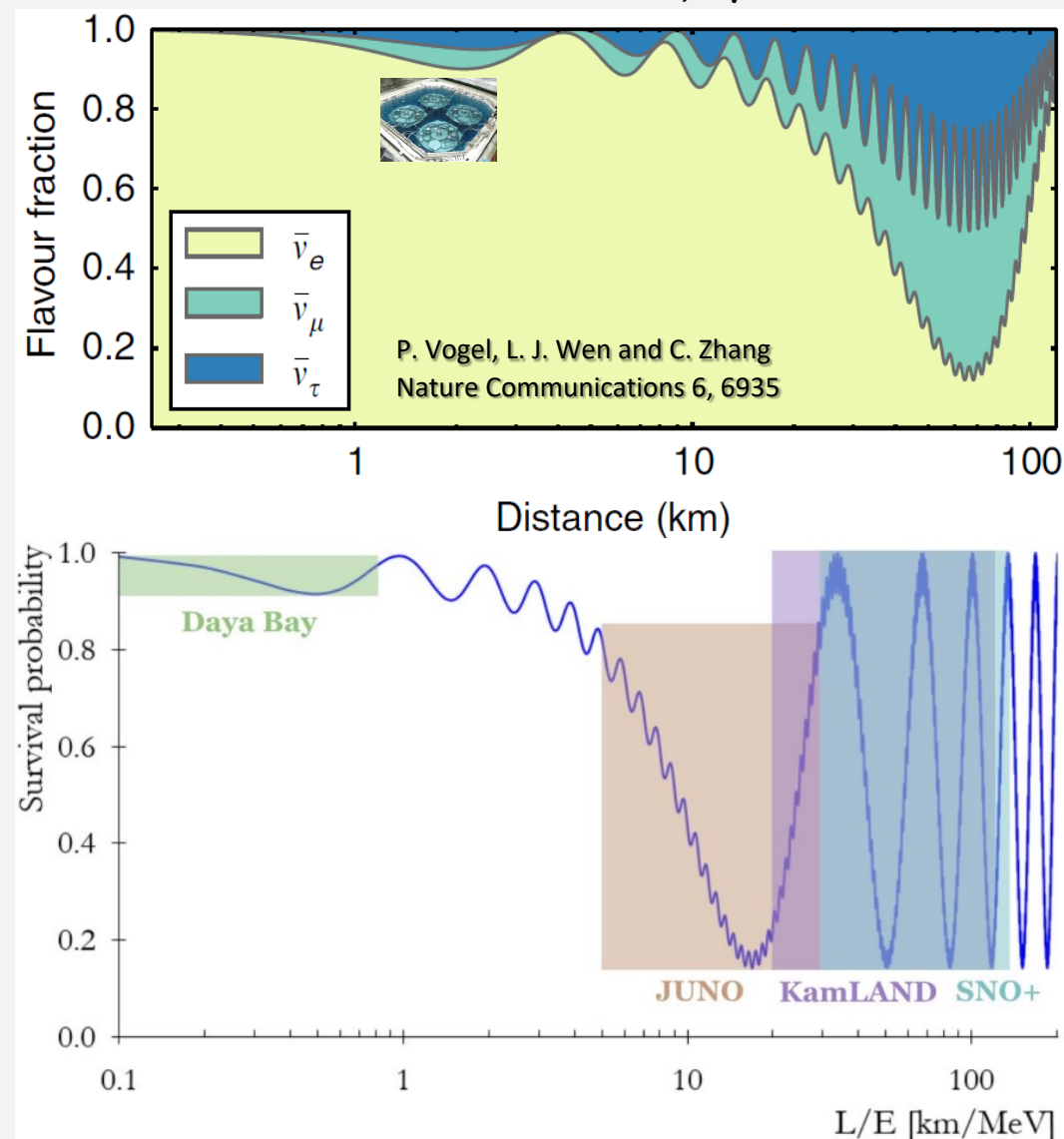
ЭКСПЕРИМЕНТЫ С «КОРОТКОЙ» БАЗОЙ (SBL)

Реакторы — самые сильные источники нейтрино на Земле (2×10^{20} штук на GW)

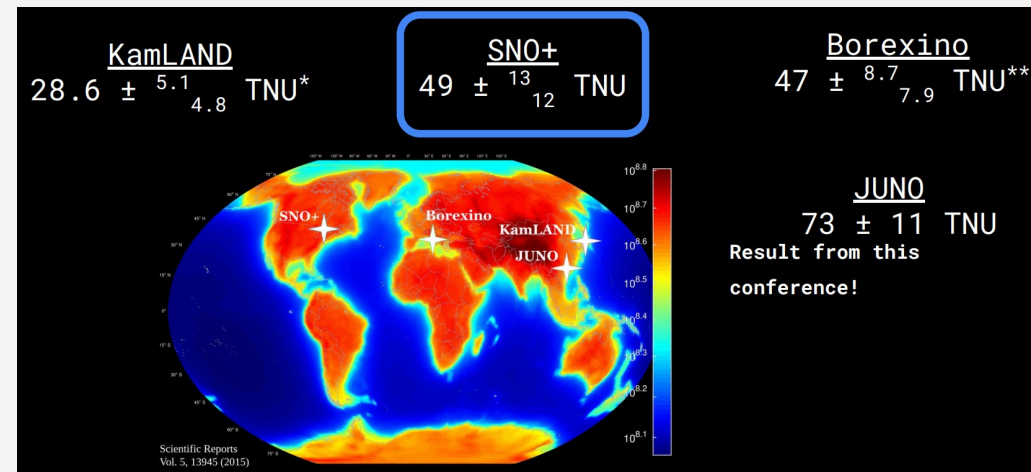
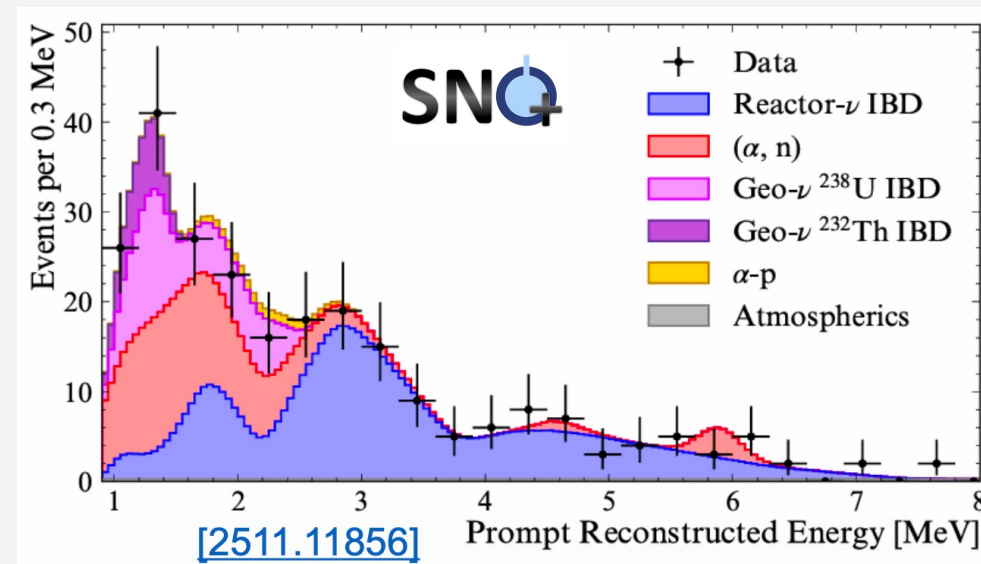
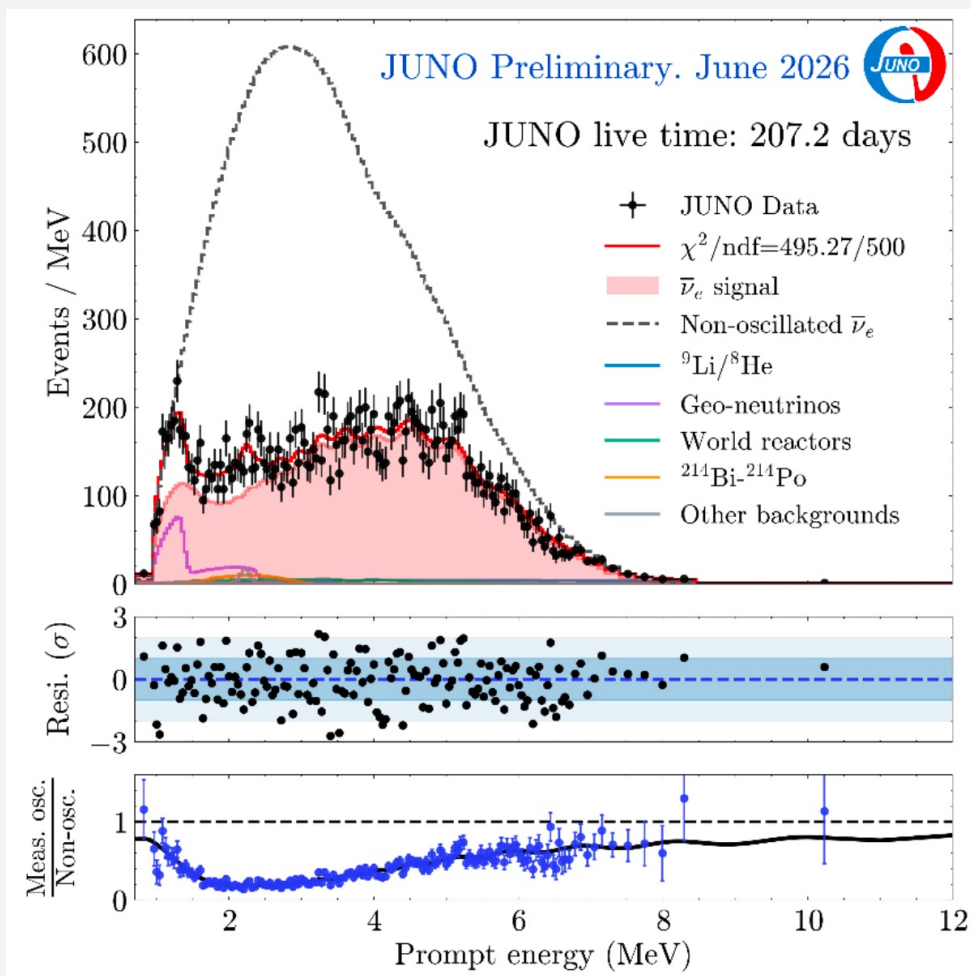


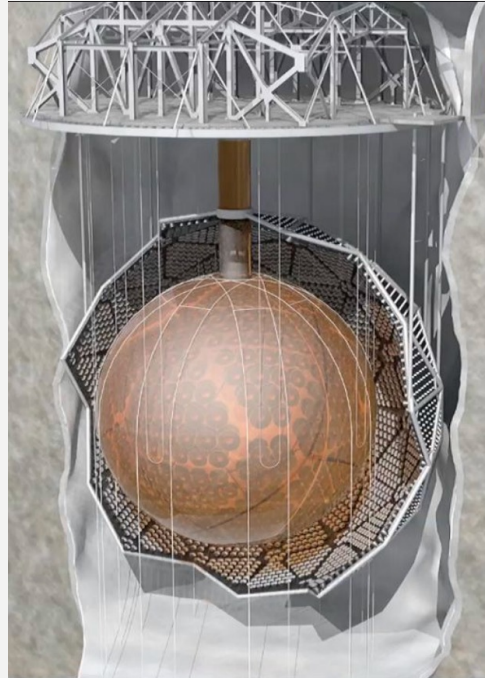
Про JUNO расскажет Андрей Соколов в следующем докладе.

Illustration of oscillation, $E_\nu = 4\text{MeV}$

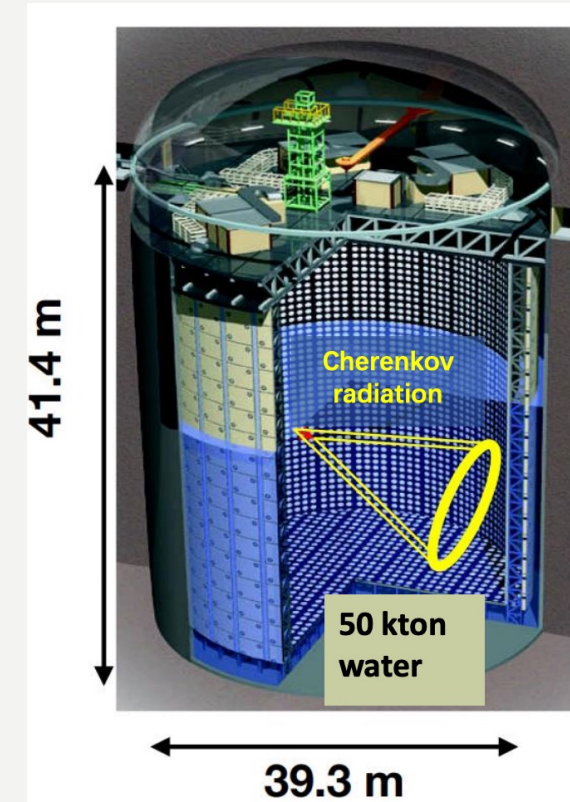


СПЕКТРЫ НЕЙТРИНО ОТ РЕАКТОРОВ И НЕ ТОЛЬКО

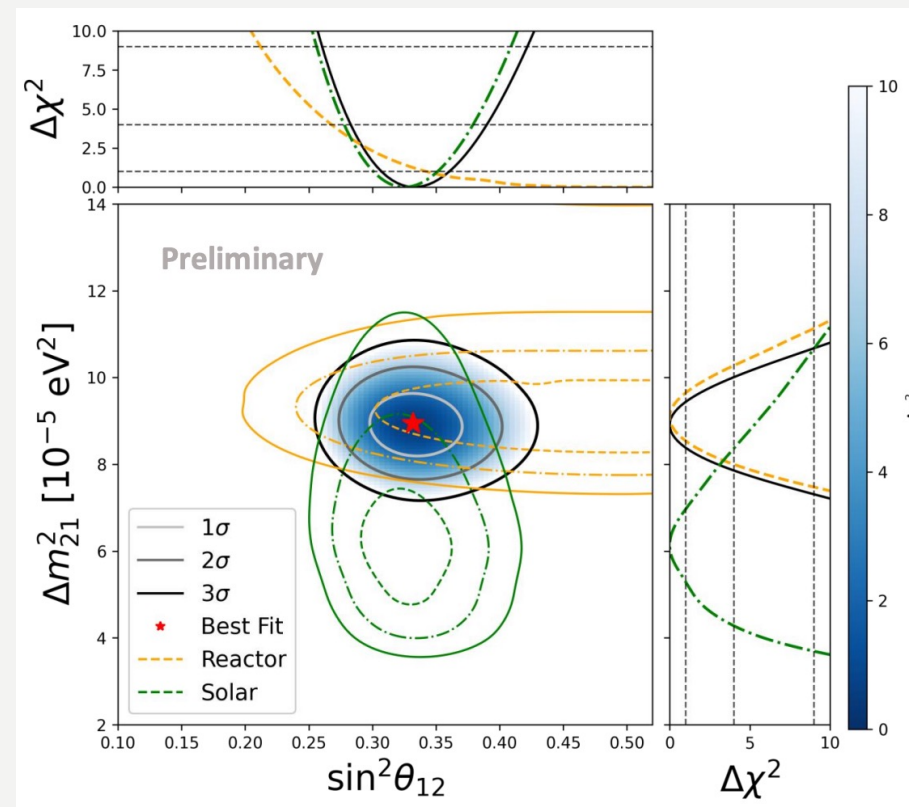
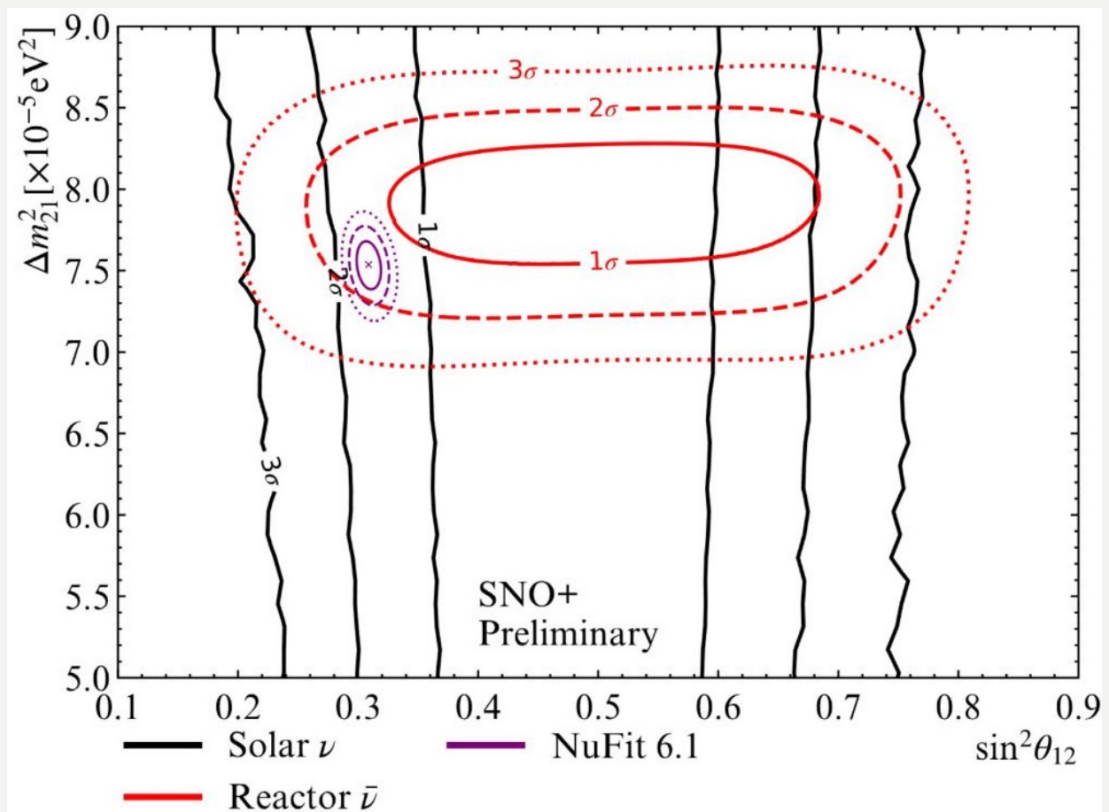




- Central acrylic vessel (AV) holds ~1 kt water (or ~780 t scintillator)
- 6 m radius AV viewed by ~9400 PMTs
- 7 kt buffer water in cavity (shielding)
- Hold-down rope net
- Upgraded calibration systems, electronics, DAQ, underground scintillator plants

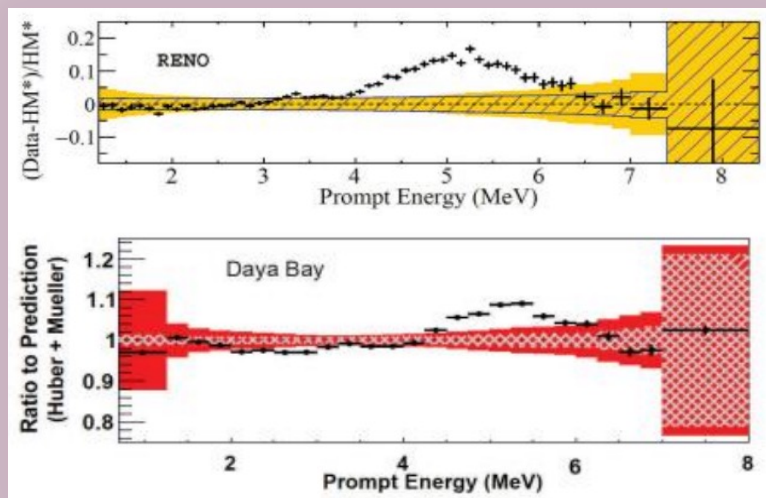


- Located at Kamioka Japan.
- **50 kton** of ultra pure water tank.
 - **20-inch PMTs, 11,129** for ID (since SK-III).
 - **22.5 kton** for analysis fiducial volume.
- Water **Cherenkov light** technique.



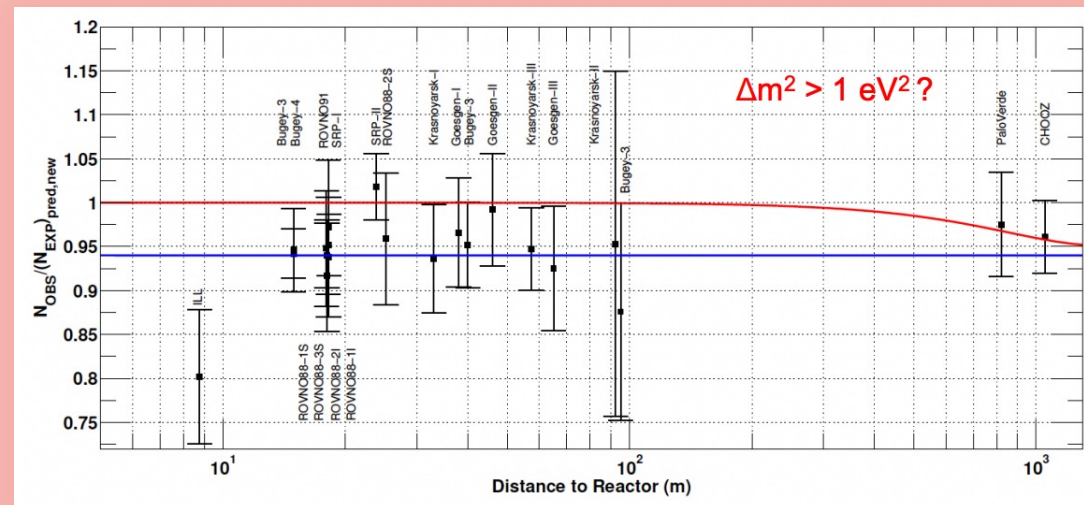
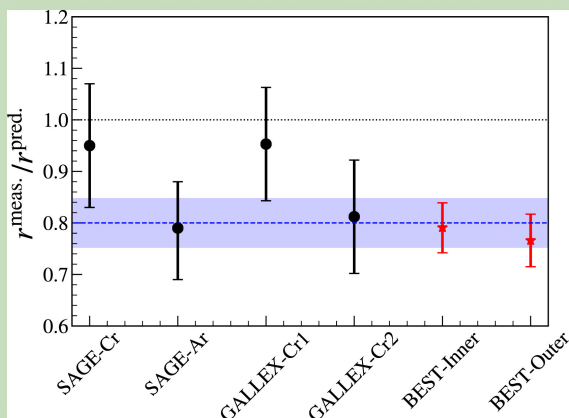
АНОМАЛИИ В SBL ЭКСПЕРИМЕНТАХ

Бамп на 5 МэВ (с 2014 видят > 10 экспериментов)



Реакторная антинейтринная аномалия (с 2011)

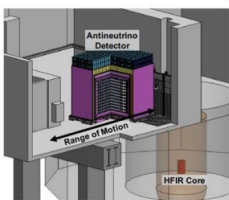
Галлиевая аномалия



ЭКСПЕРИМЕНТЫ С ЭКСТРА КОРОТКОЙ БАЗОЙ

PROSPECT · HFIR (HEU)

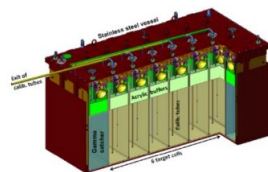
85 MW
7–12 m
segmented ${}^6\text{Li-LS}$



Phys. Rev. Lett. 134, 151802 (2025)

STEREO · ILL (HEU)

58 MW
9–11 m
6-cell Gd-LS



Nature 613, 257 (2023)

DANSS · Kalinin (LEU)

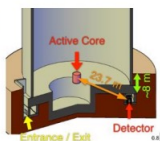
3 GW
10.7–12.9 m
movable plastic scint.



PoS ICHEP2022, 616 (2022)

NEOS / NEOS-II · Hanbit (LEU)

2.8 GW
24 m
Gd-LS
RENO+NEOS fit



Phys. Rev. D 105, L111101 (2022)

Neutrino-4 · SM-3 (HEU)

90 MW
6–12 m
movable Gd-LS



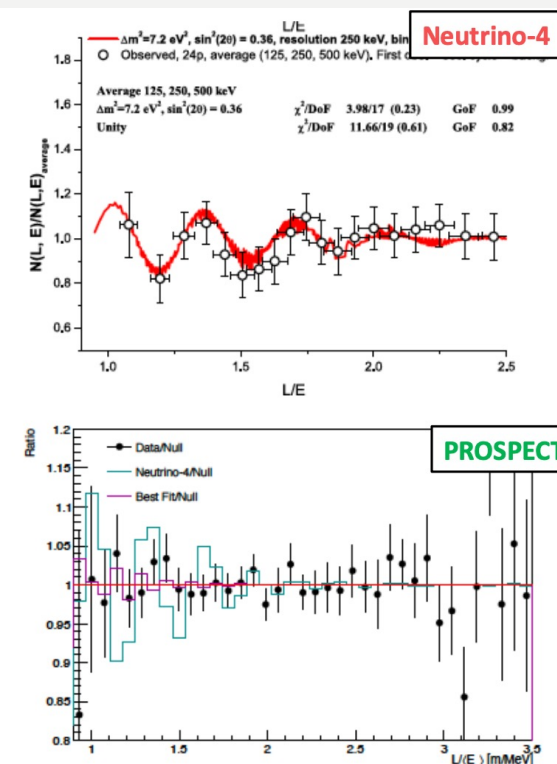
Phys. Rev. D 104, 032003 (2021)

SoLid · BR2 (HEU)

50–80 MW
6–9 m
 ${}^6\text{LiF:ZnS}$ + PVT cubes

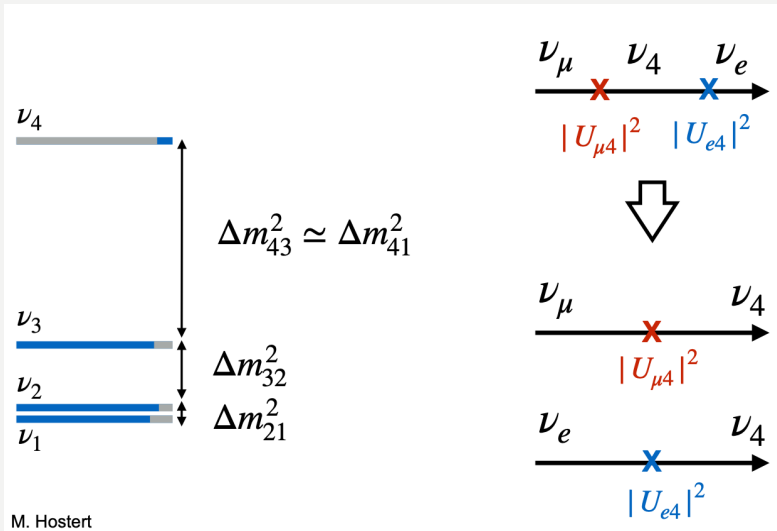


Phys. Rev. D 111, 072005 (2025)



- Измеряют относительные искажения L/E спектра на различных базах.
- В качестве референса используют экспериментальный спектр, а не теоретическую модель.
- В этом году начали работу JUNO-TAO, SBND.

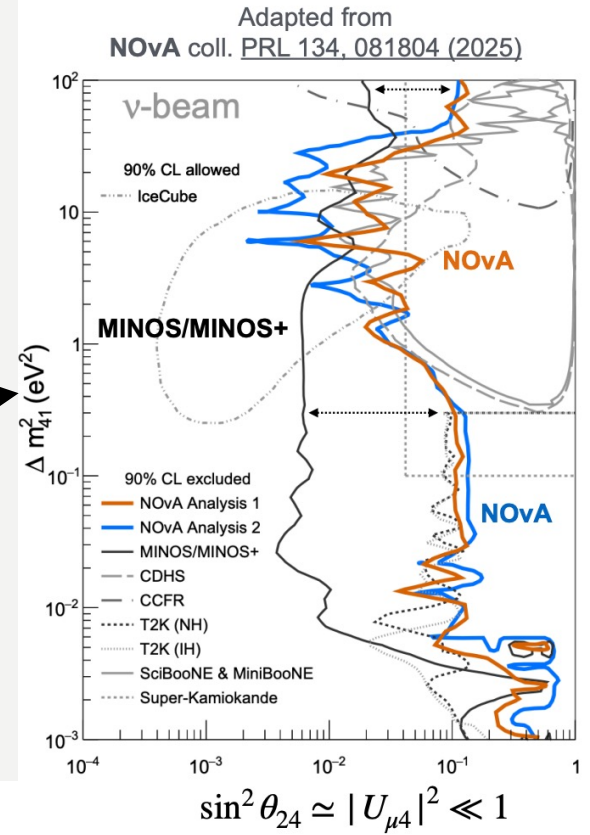
СТЕРИЛЬНОЕ НЕЙТРИНО



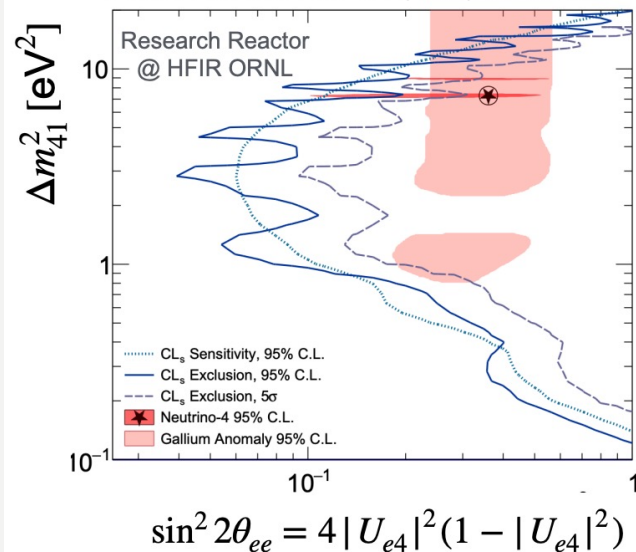
M. Hostert

исчезновение ν_μ

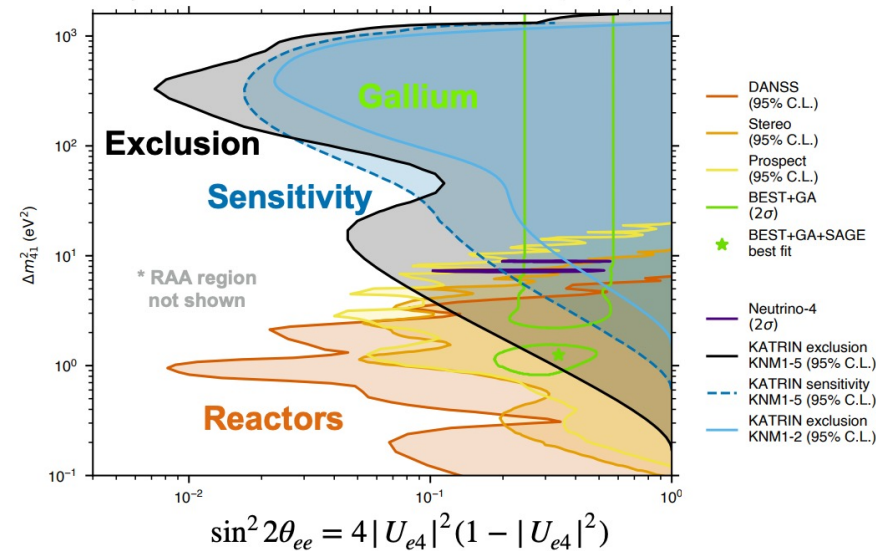
исчезновение ν_e



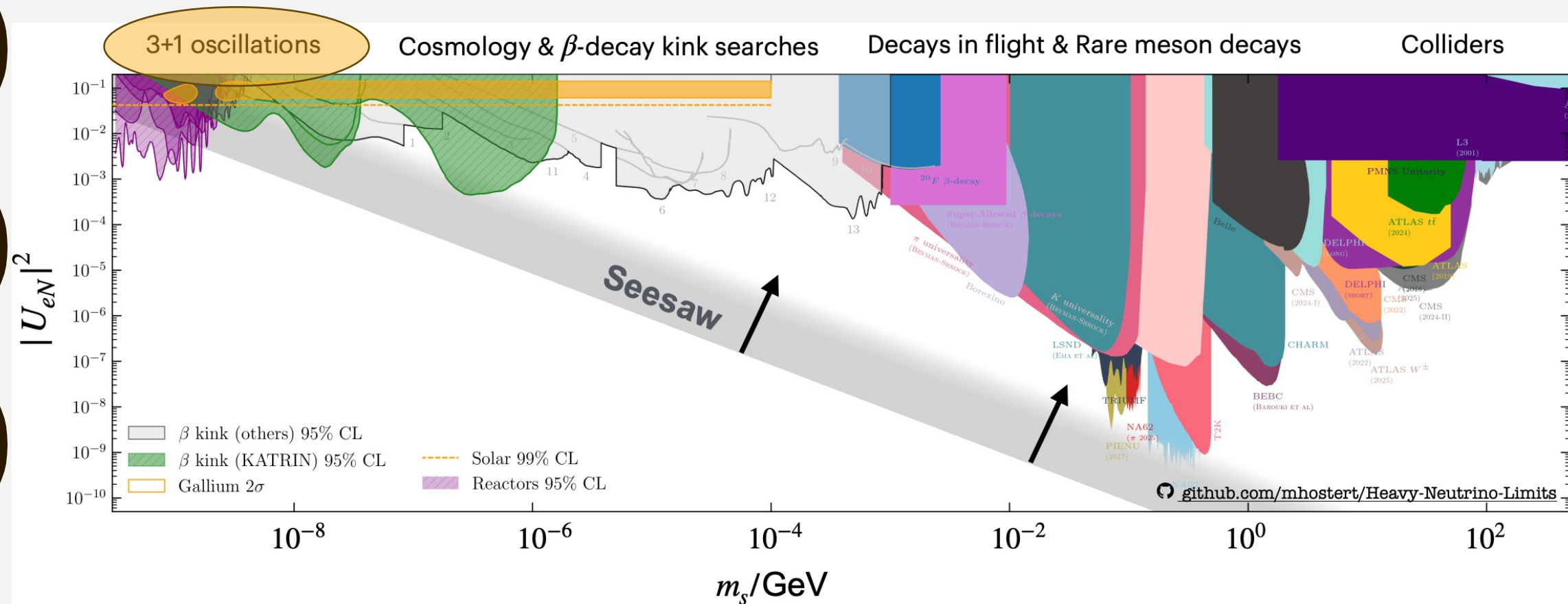
PROSPECT coll. [PRL 134 \(2025\) 15, 151802](#)



Adapted from KATRIN coll. [Nature 648 \(2025\) 8092, 70-75](#)



СТЕРИЛЬНОЕ НЕЙТРИНО



... ИЛИ ПРОБЛЕМЫ С МОДЕЛЬЮ?

Анализ спектров при разном реакторном топливе.



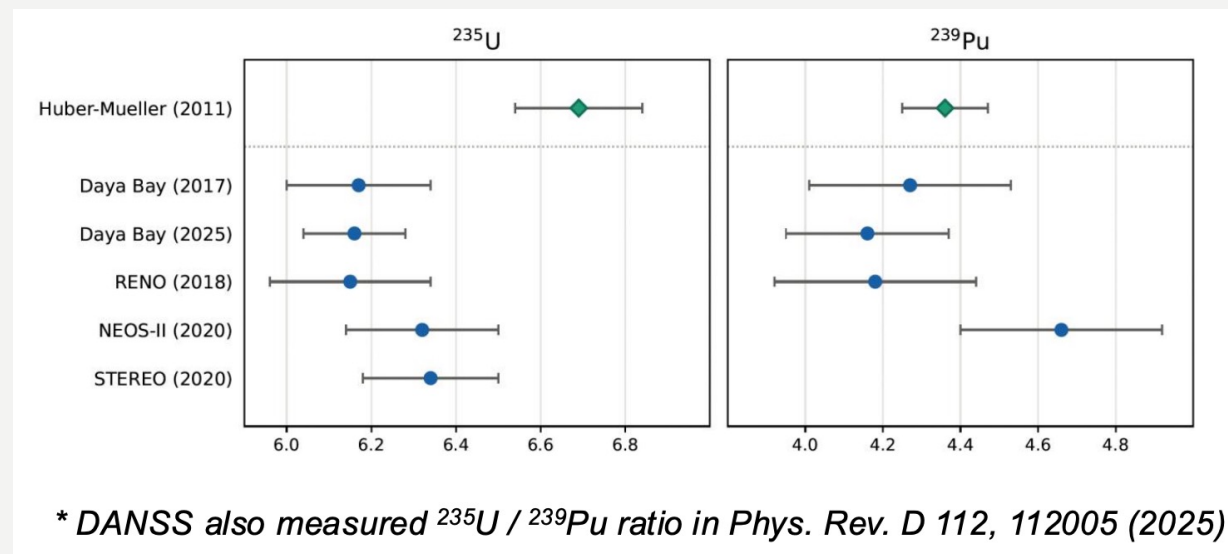
Разделение вкладов ^{235}U и ^{239}Pu .



Зависимость расхождения м/у теорией и экспериментом от изотопа.

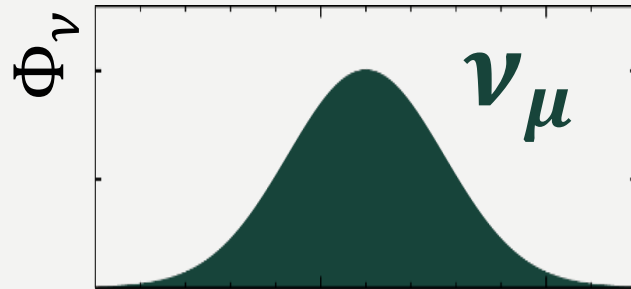
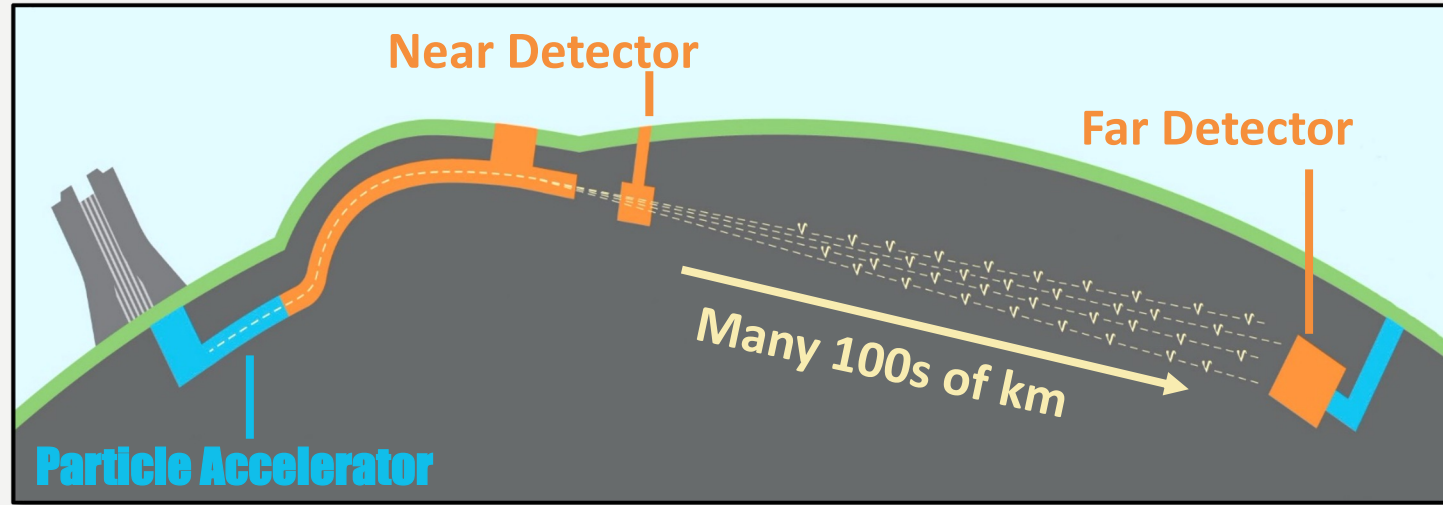


Причина не в наличии стерильного нейтрино, а в неточности модели!



- Неполная информация о процессах термоядерного синтеза в реакторе (~ 800 продуктов).
- Неточное описание спектров бета распадов (~10000 бранчингов).
- Грубая оценка неопределенности (как экспериментальной, так и теоретической).

ЭКСПЕРИМЕНТЫ С ДЛИННОЙ БАЗОЙ (LBL)



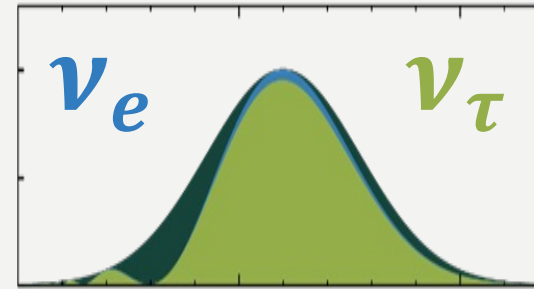
At the near detector E_ν

$$N_\mu(E_\nu) \propto \sigma(E_\nu) \Phi_\nu(E_\nu) \epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

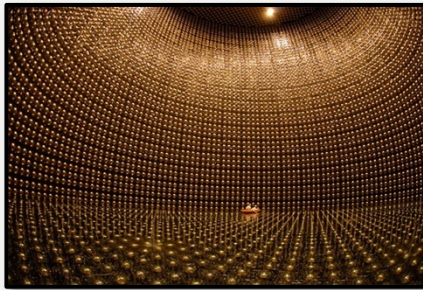
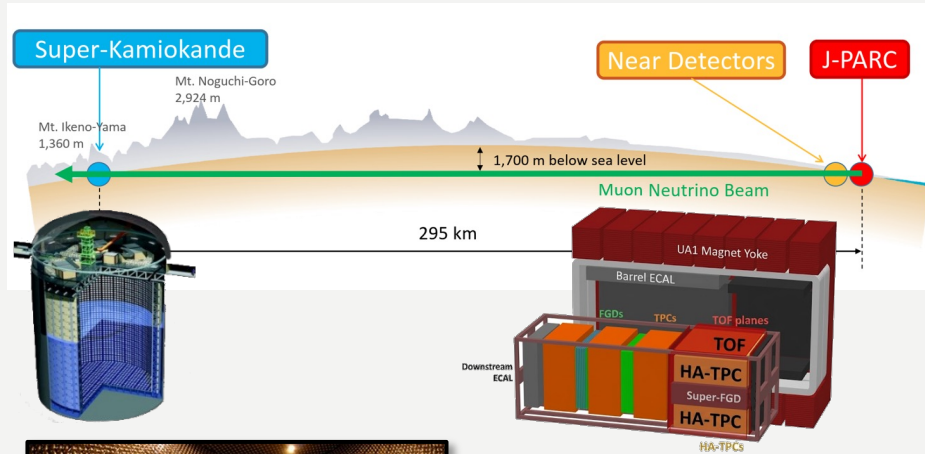


At the far detector E_ν

$$N_\mu(E_\nu) \propto P(\nu_\mu \rightarrow \nu_\mu) \sigma(E_\nu) \Phi_\nu(E_\nu) \epsilon(E_\nu)$$

$$N_e(E_\nu) \propto P(\nu_\mu \rightarrow \nu_e) \sigma(E_\nu) \Phi_\nu(E_\nu) \epsilon(E_\nu)$$

Oscillation probability



Baseline: 295 km

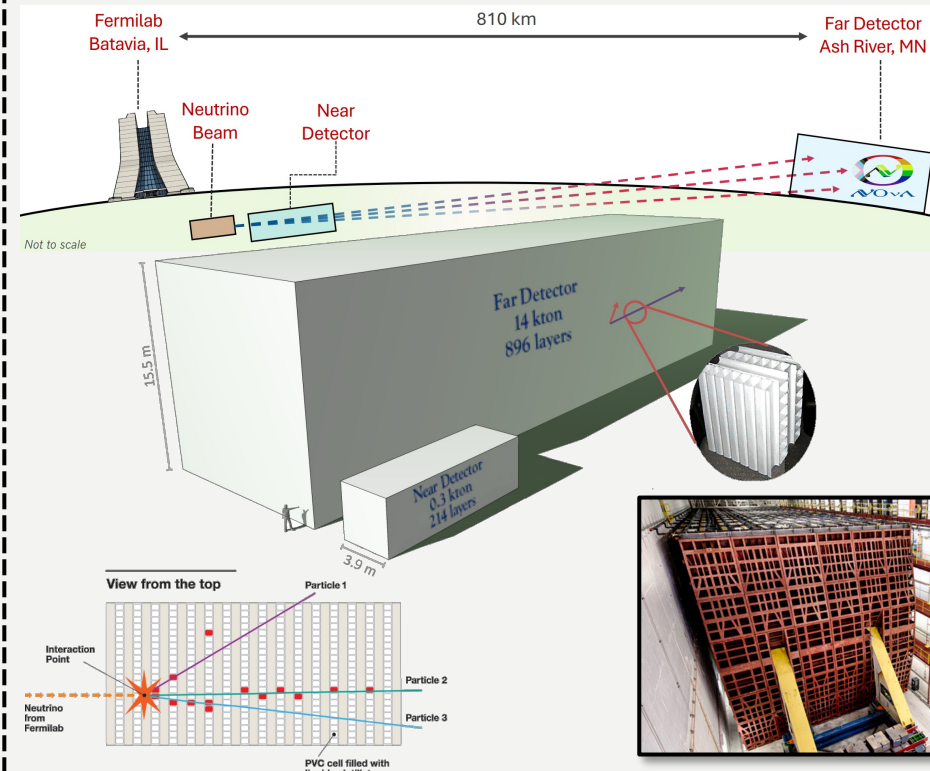
Beam: Narrow band, $\sim 0.4\text{-}0.8$ GeV

Far detector: Water Cherenkov

Far detector mass (FV): ~ 23 kt

Observed $N_{\nu_e + \bar{\nu}_e}$: ~ 150

Observed $N_{\nu_\mu + \bar{\nu}_\mu}$: ~ 450



Baseline: 810 km

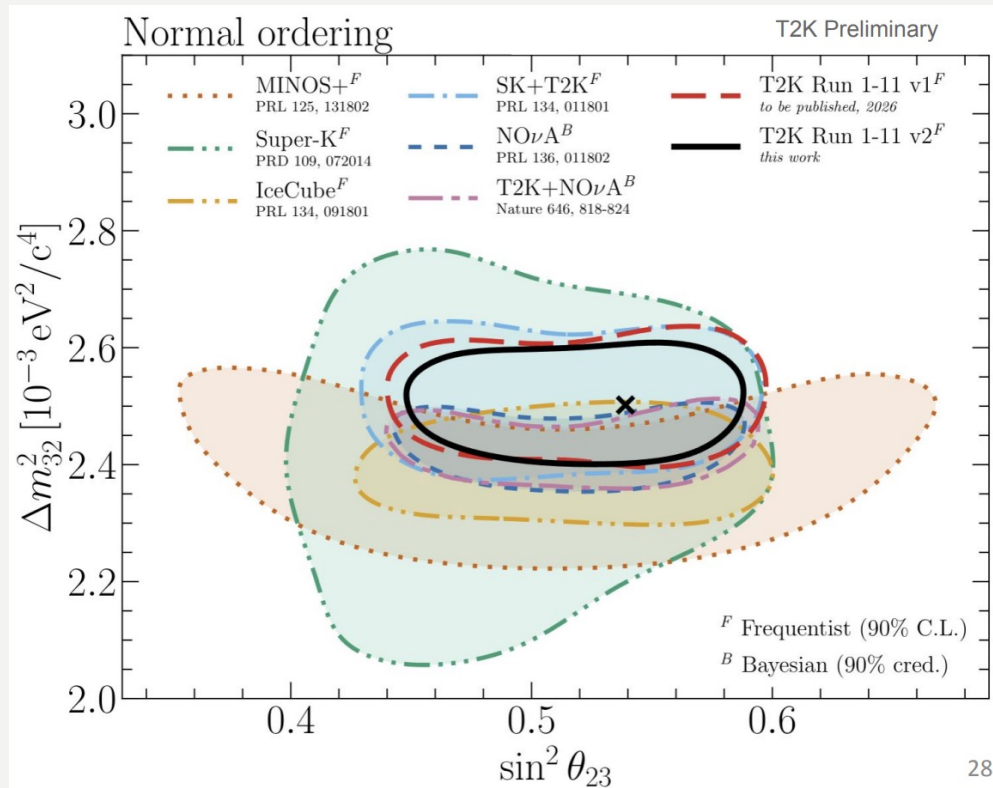
Beam: Wider band, $\sim 1.3\text{-}2.5$ GeV

Far detector: Liquid Scintillator

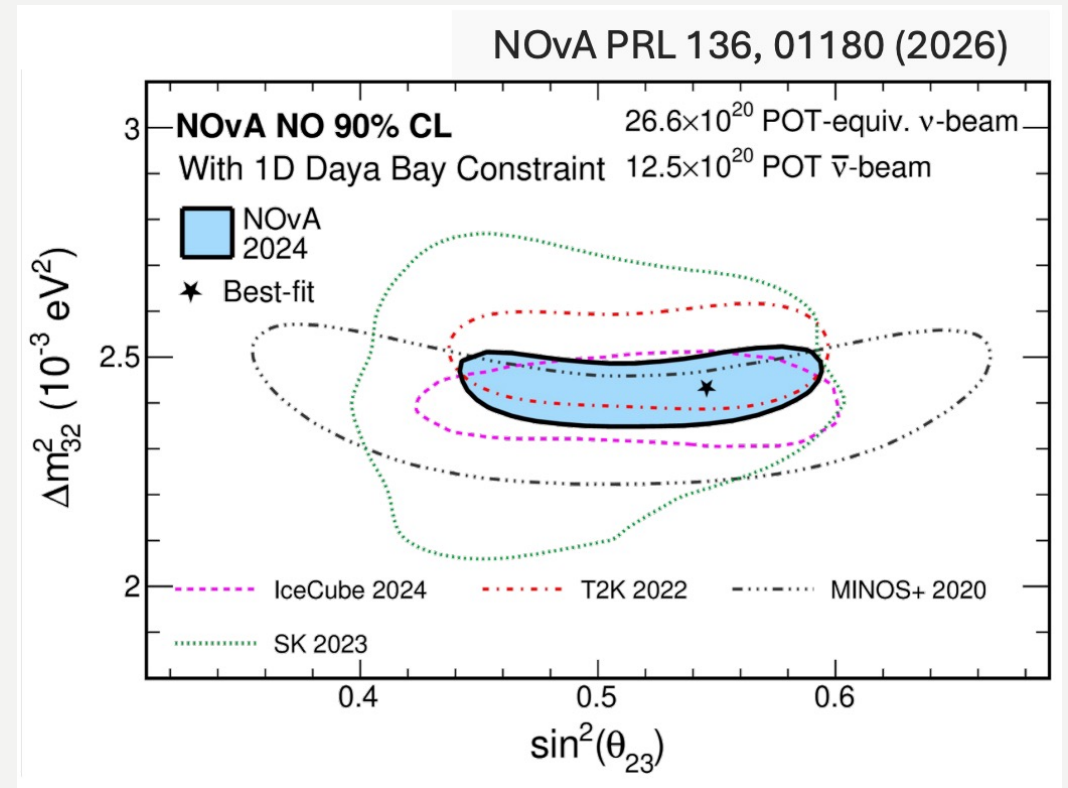
Far detector mass (FV): ~ 10 kt

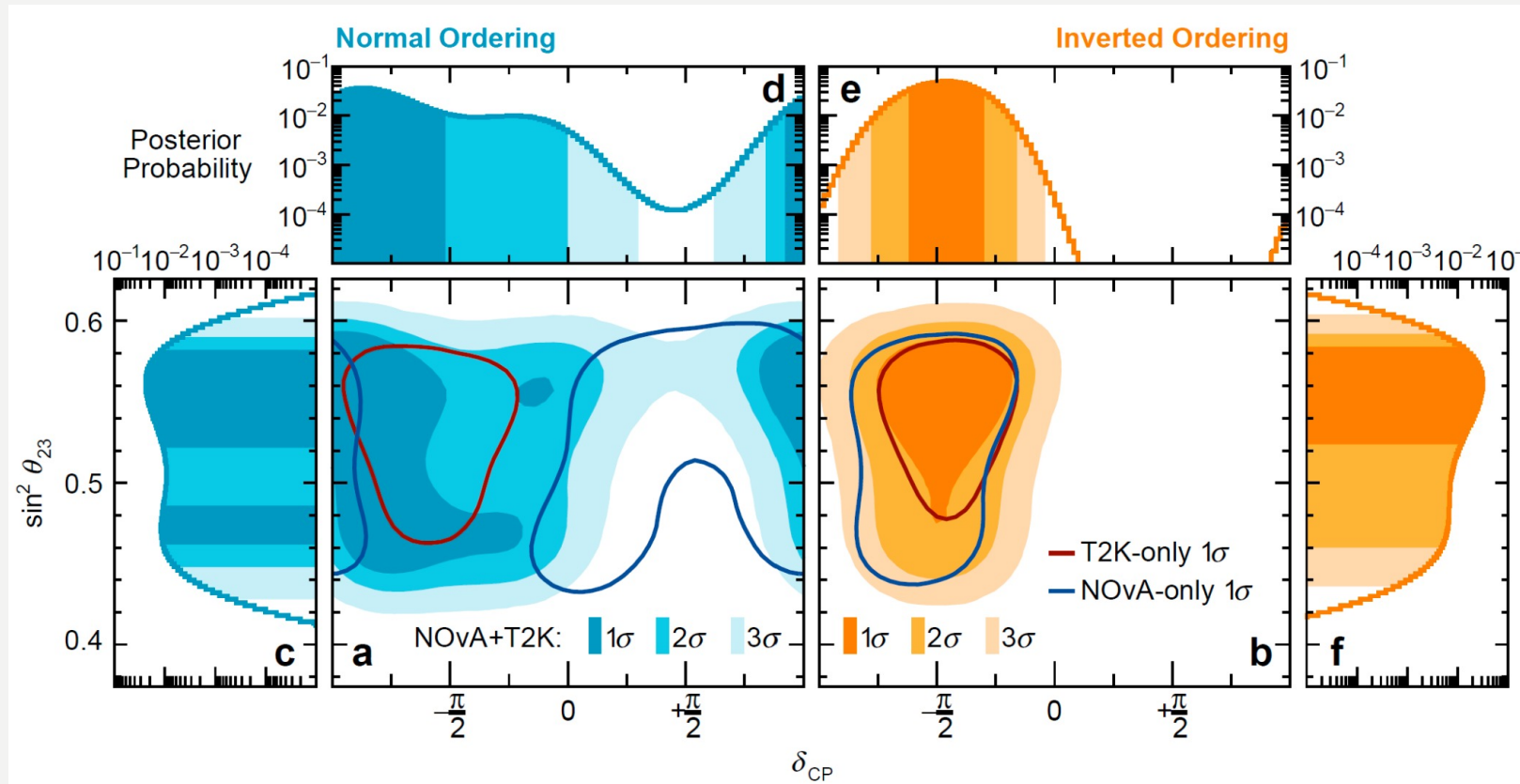
Observed $N_{\nu_e + \bar{\nu}_e}$: ~ 200

Observed $N_{\nu_\mu + \bar{\nu}_\mu}$: ~ 490



28





По отдельности и Nova, и T2K слегка предпочитают нормальную иерархию и верхний октант θ_{23} , но разные области для δ_{CP}
Совместные фиты слегка предпочитают обратную иерархию.

БУДУЩЕЕ LBL



Baseline: 295 km

Beam: Narrow band, $\sim 0.4\text{-}0.8$ GeV

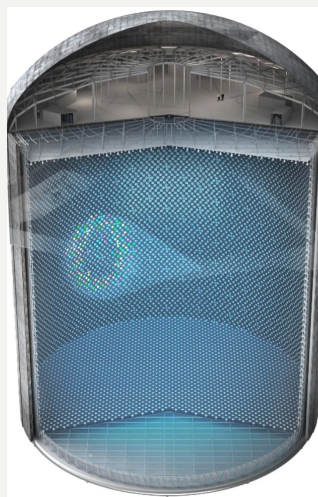
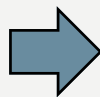
Far detector: Water Cherenkov

Far detector mass (FV): ~ 190 kt

Projected $N_{\nu_e + \bar{\nu}_e}$: ~ 4500

Projected $N_{\nu_\mu + \bar{\nu}_\mu}$: ~ 21000

First beam: ~ 2028



Baseline: 1300 km

Beam: Broad band, $\sim 0.8\text{-}3.5$ GeV

Far detector: Liquid Argon TPC

Far detector mass (FV): $\sim 4 \times 10$ kt

Projected $N_{\nu_e + \bar{\nu}_e}$: ~ 4100

Projected $N_{\nu_\mu + \bar{\nu}_\mu}$: ~ 23000

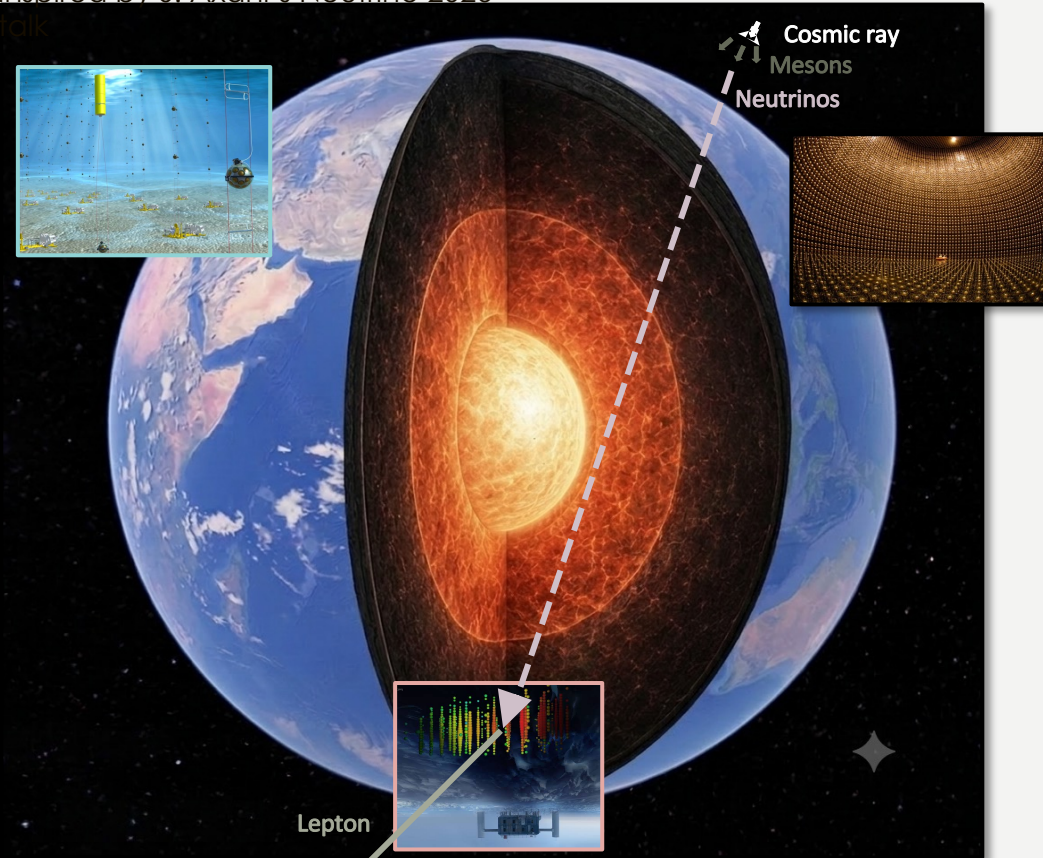
First beam: ~ 2031

Projected statistics in far-detector samples

Experiment	T2K	NOvA	Hyper-K	DUNE
$N_{\nu_\mu}^{\text{FD}} (\nu\text{-mode})$	318	384	≈ 8800	≈ 15000
$N_{\bar{\nu}_\mu}^{\text{FD}} (\bar{\nu}\text{-mode})$	137	106	≈ 12000	≈ 8100
$N_{\nu_e}^{\text{FD}} (\nu\text{-mode})$	108	181	≈ 2800	≈ 3300
$N_{\bar{\nu}_e}^{\text{FD}} (\bar{\nu}\text{-mode})$	16	32	≈ 1500	≈ 900

«АТМОСФЕРНЫЕ» ЭКСПЕРИМЕНТЫ С ЭКСТРА ДЛИННОЙ БАЗОЙ

Inspired by S. Axani's Neutrino 2026

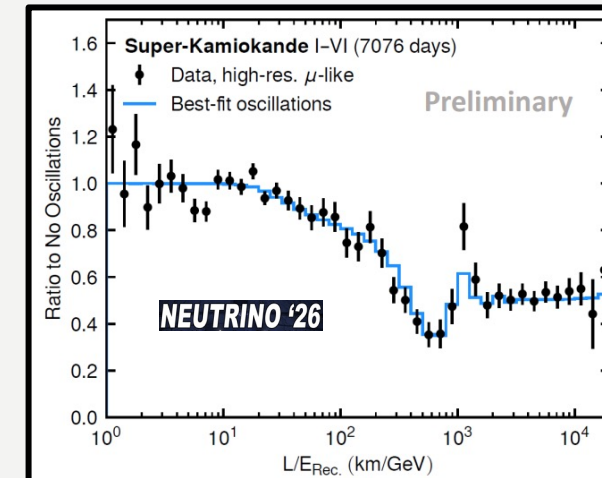
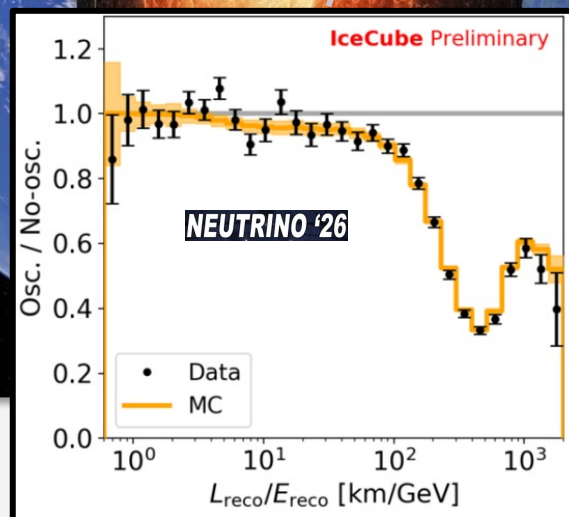
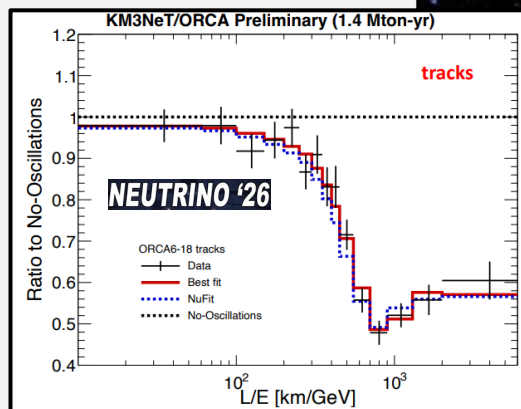
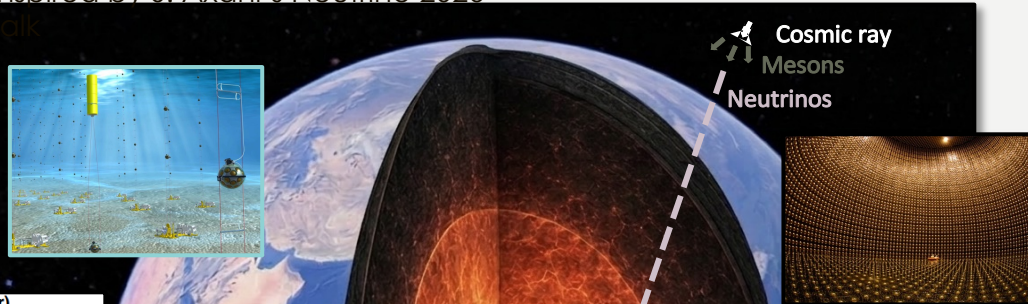


ICECUBE
NEUTRINO OBSERVATORY



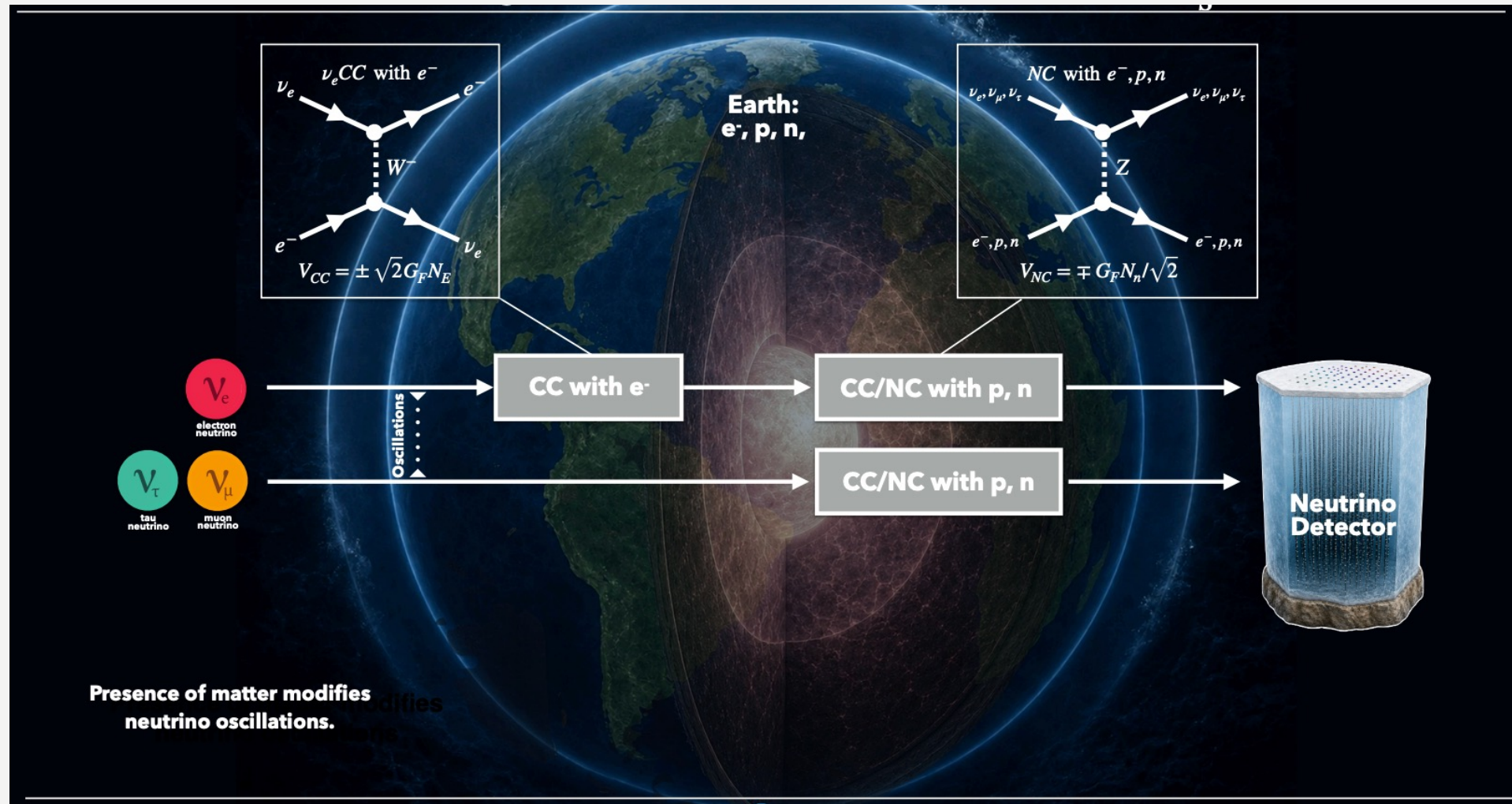
«АТМОСФЕРНЫЕ» ЭКСПЕРИМЕНТЫ С ЭКСТРА ДЛИННОЙ БАЗОЙ

Inspired by S. Axani's Neutrino 2026



ICECUBE
NEUTRINO OBSERVATORY

ОСОБЕННОСТИ ВЗАИМОДЕЙСТВИЯ С МАТЕРИЕЙ



ICESUBE СКАНИРУЕТ ЗЕМЛЮ

Neutrino tomography: mapping the Earth's interior

High energy ($> \text{TeV}$) neutrino attenuation can be used to map the Earth's interior density profile

Goal: Observe macroscopic object using the weak force: the "weak mass."



GRAVITY

Measures total mass, not how it is distributed.



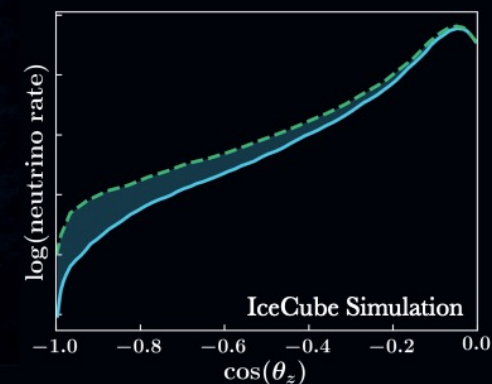
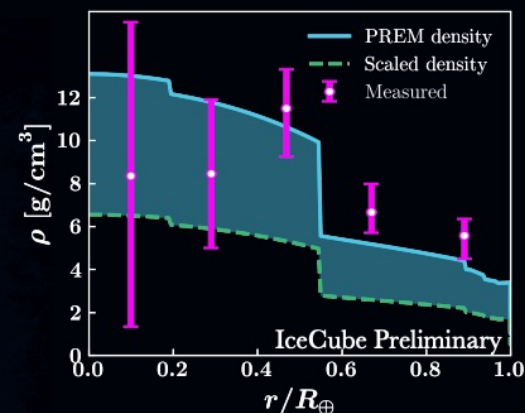
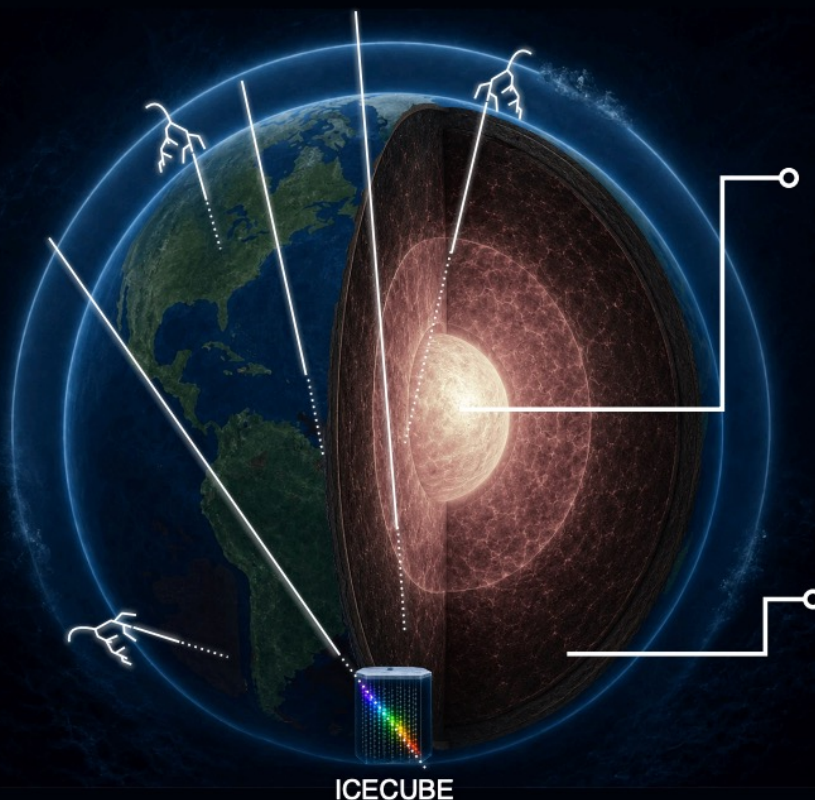
SEISMIC WAVES

Sensitive to elastic properties, not density alone.



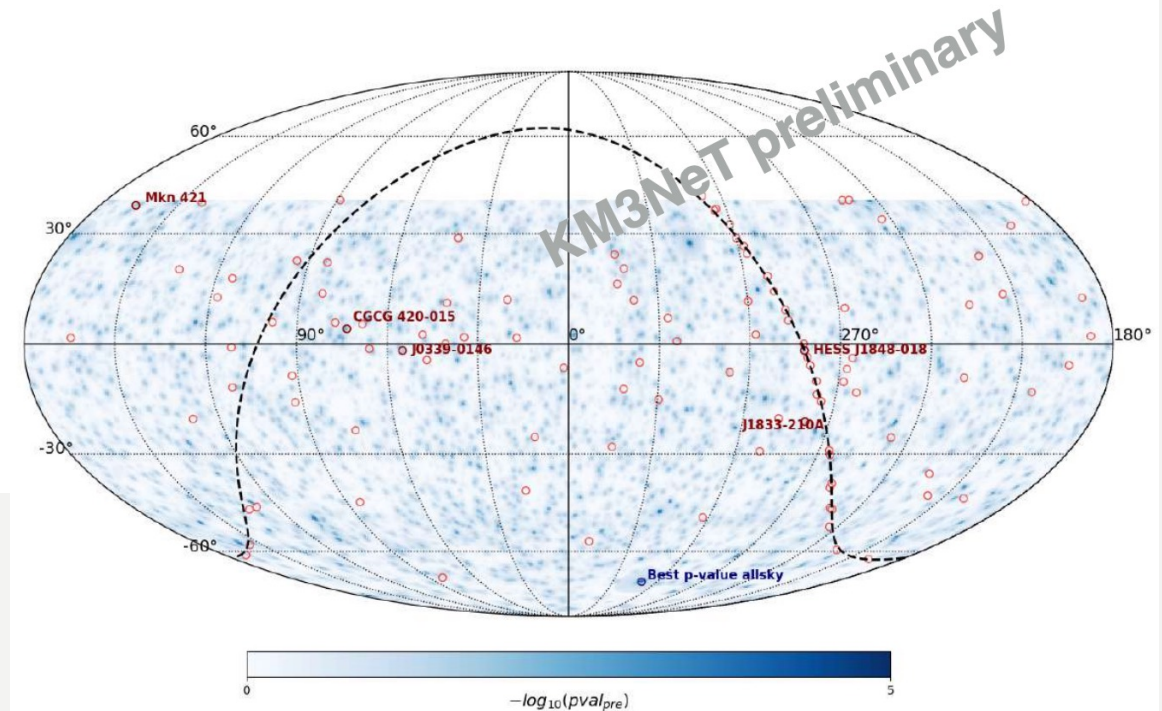
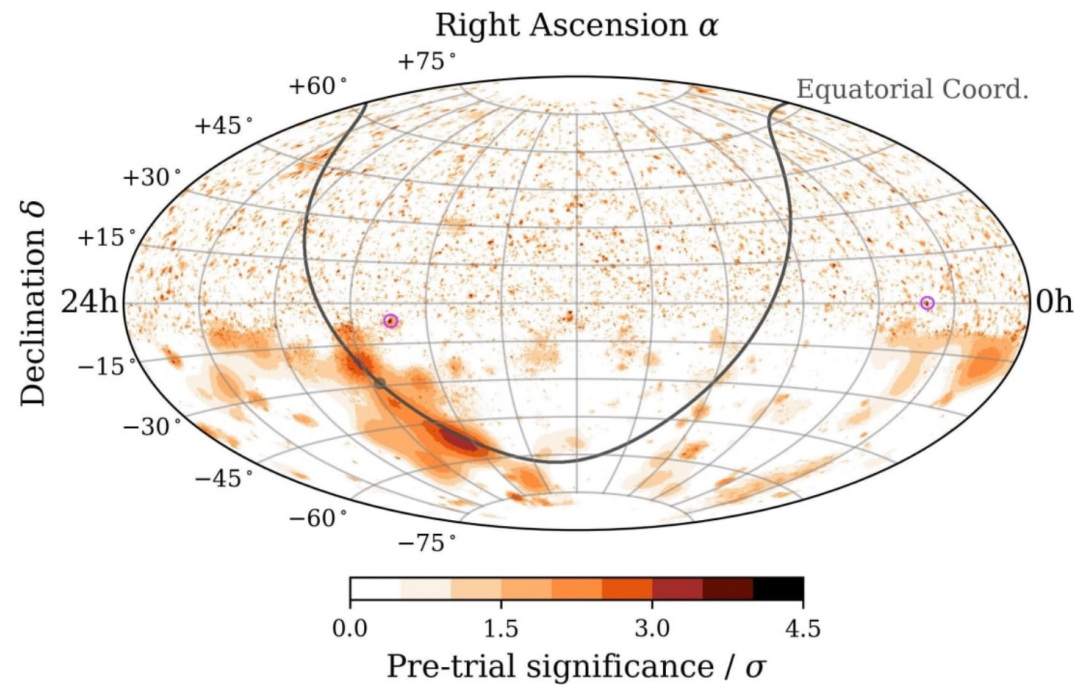
GEOMAGNETISM

Probes core dynamics, not static structure.



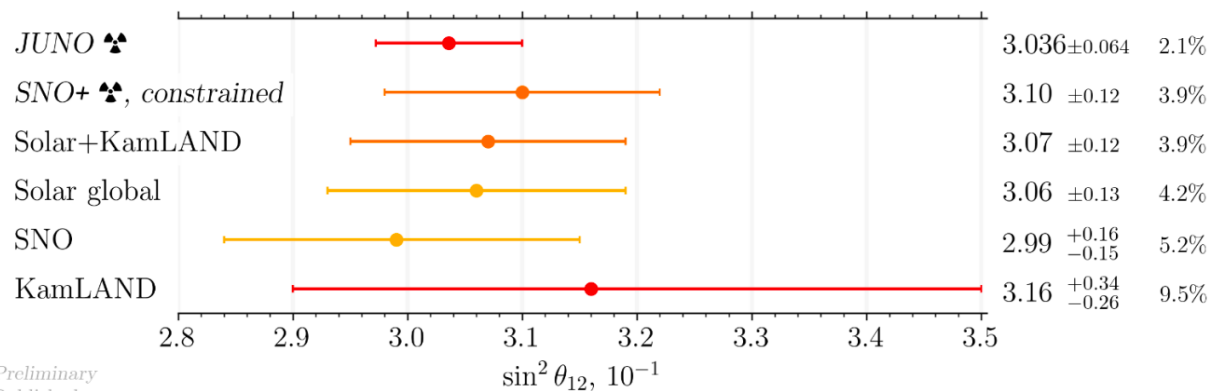
From the resulting density posteriors, we derive the Earth's mass and polar moment of inertia, found to be consistent with PREM and gravitational determination. Paper under collaboration review.

ICESUBE & KM3NET ИЩУТ ТОЧЕЧНЫЕ ИСТОЧНИКИ НЕЙТРИНО

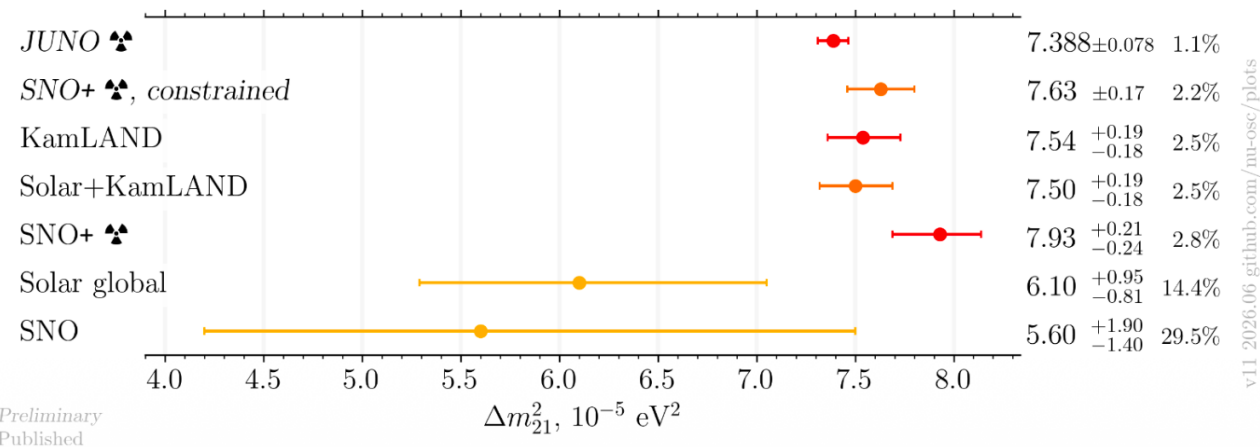


ЧТО В ИТОГЕ?

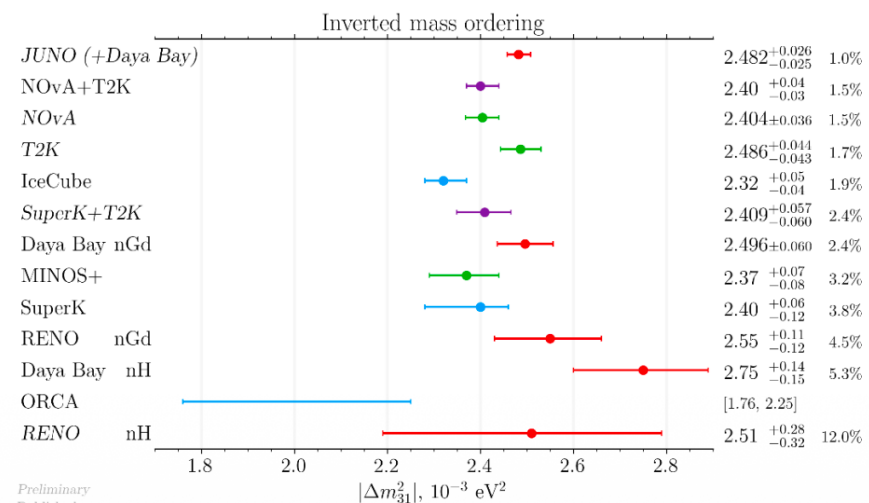
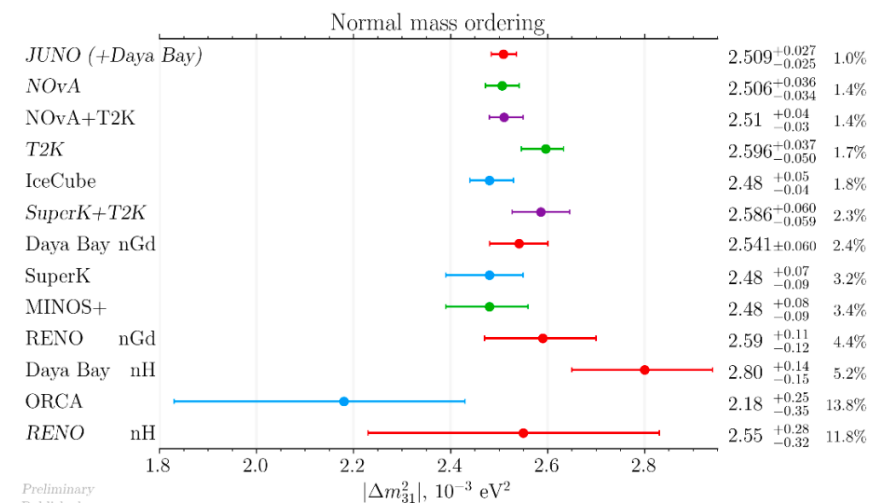
$\sin^2 2\theta_{12}$



Δm^2_{21}

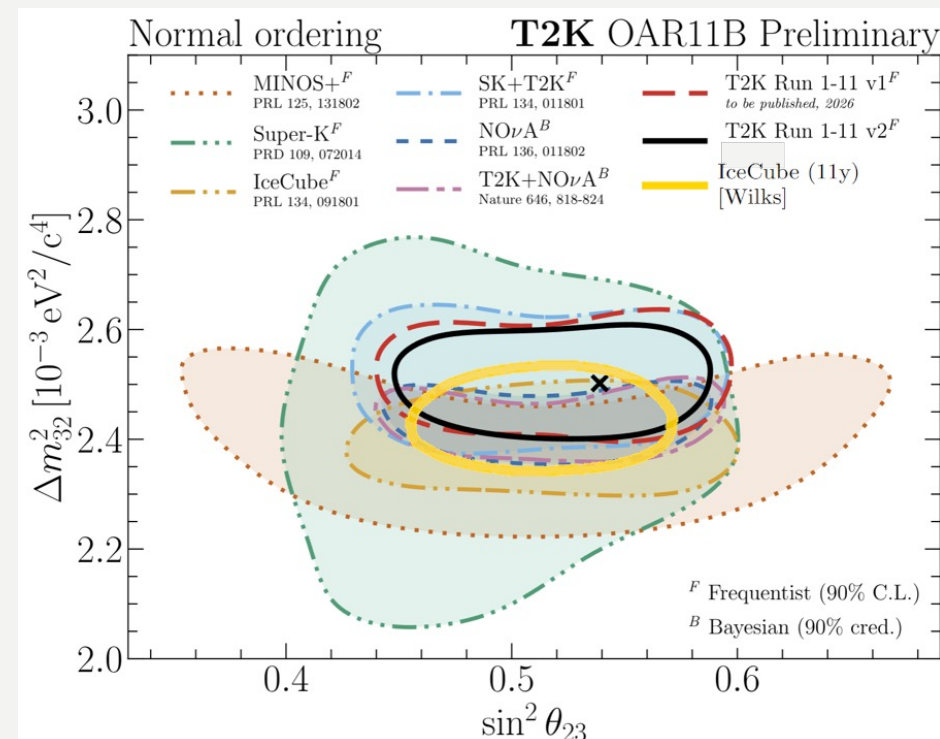
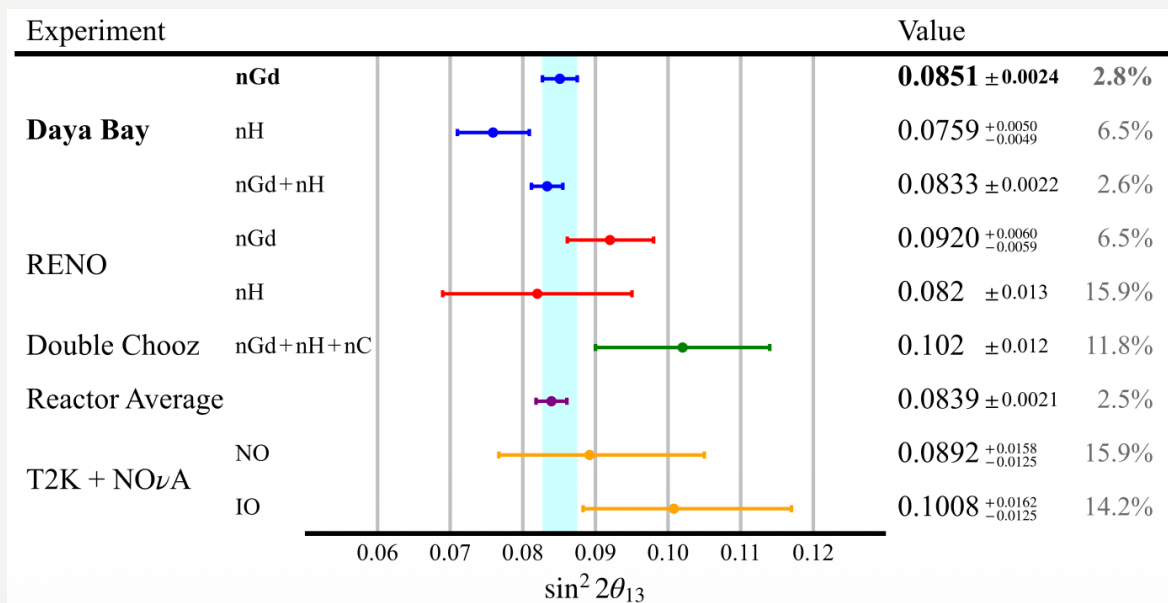


Δm^2_{31}

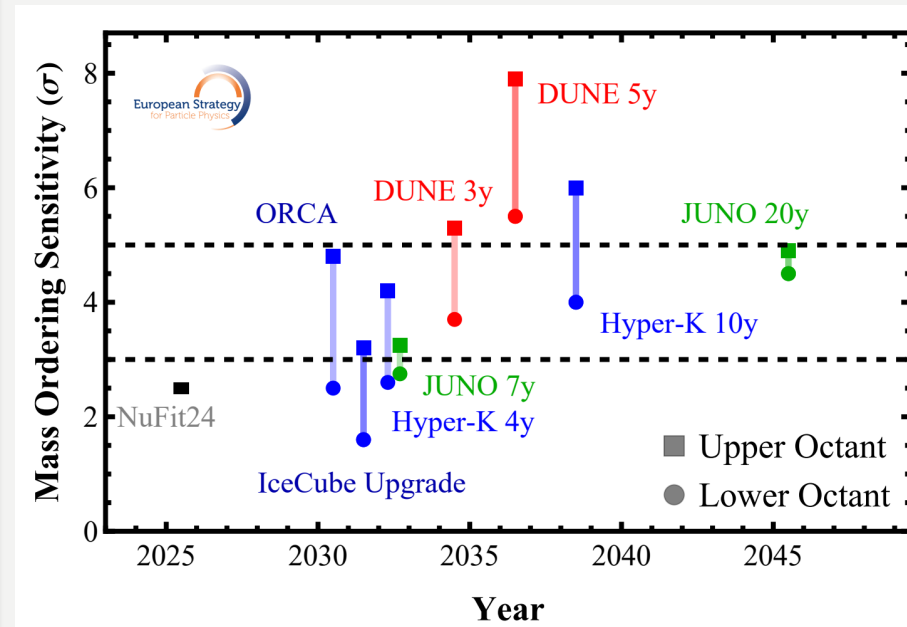
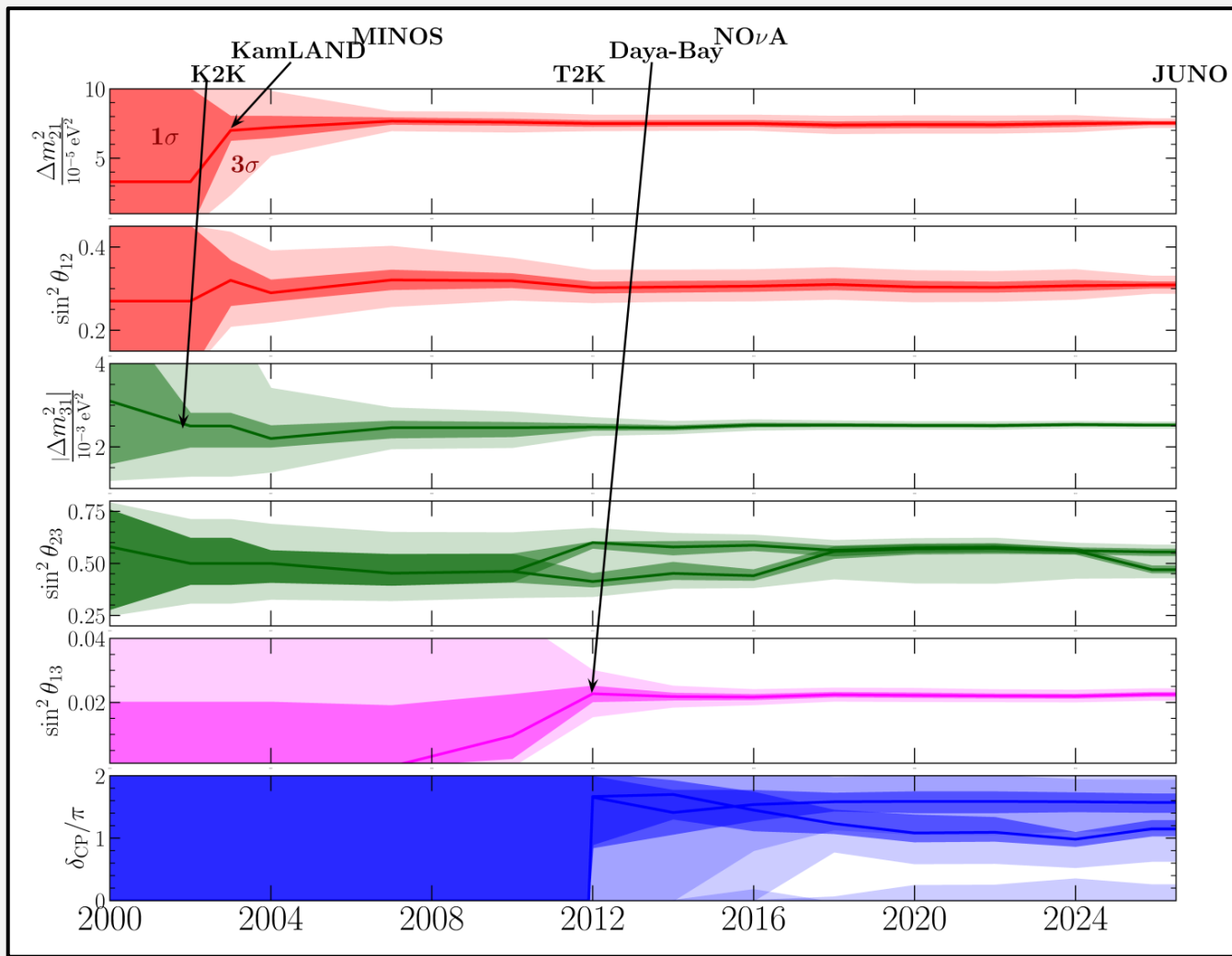


ЧТО В ИТОГЕ?

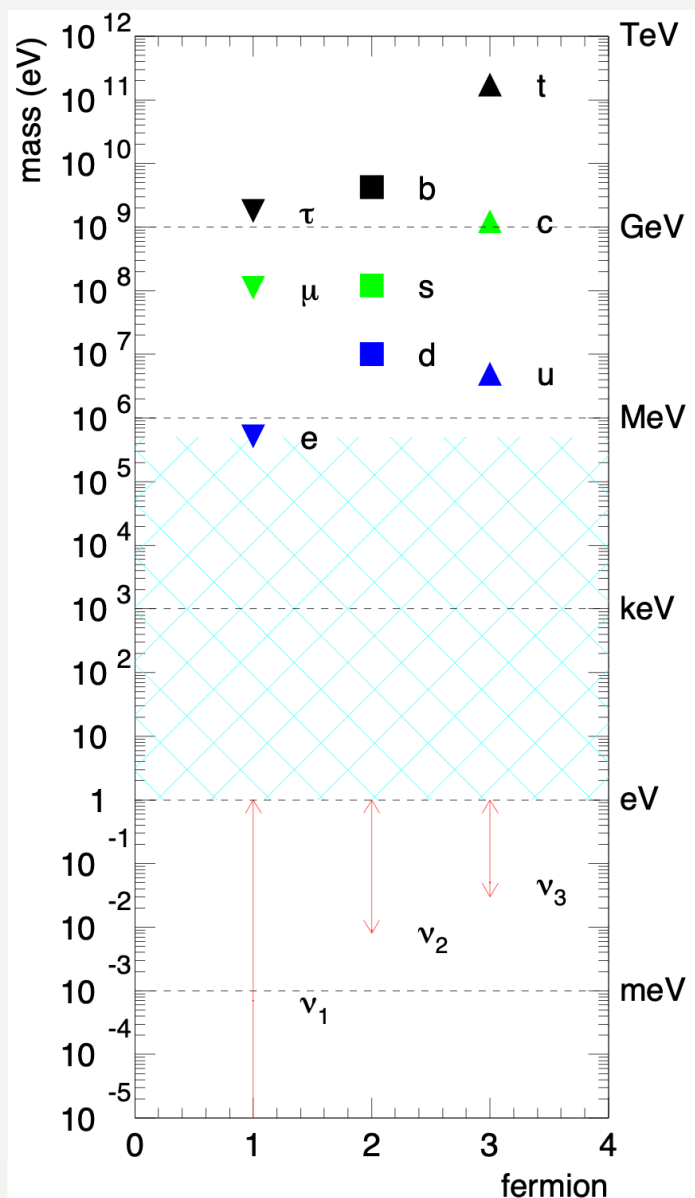
- Δm_{21}^2 , Δm_{31}^2 , Δm_{32}^2 , $\sin^2 \theta_{12}$ и $\sin^2 \theta_{23}$ измерены с процентной точностью
- CP-сохранение исключено на уровне $\sim 95\%$
- Нормальная иерархия предпочтительнее инвертированной на уровне
 - 80 – 90 % из T2K/NOvA/SuperK ($\nu_\mu \rightarrow \nu_e$)
 - > 90 % из JUNO ($\nu_e \rightarrow \nu_e$) + LBL ($\nu_e \rightarrow \nu_\mu$)



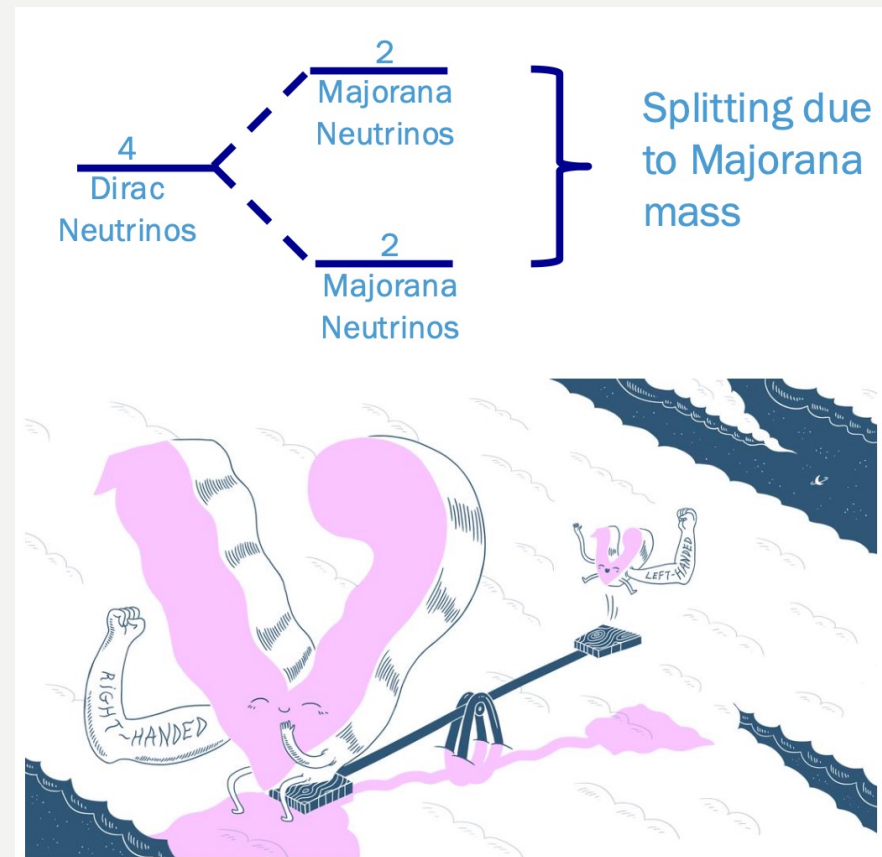
ЧТО НАС ЖДЕТ?



МАССА ЕСТЬ, НО КАКАЯ?



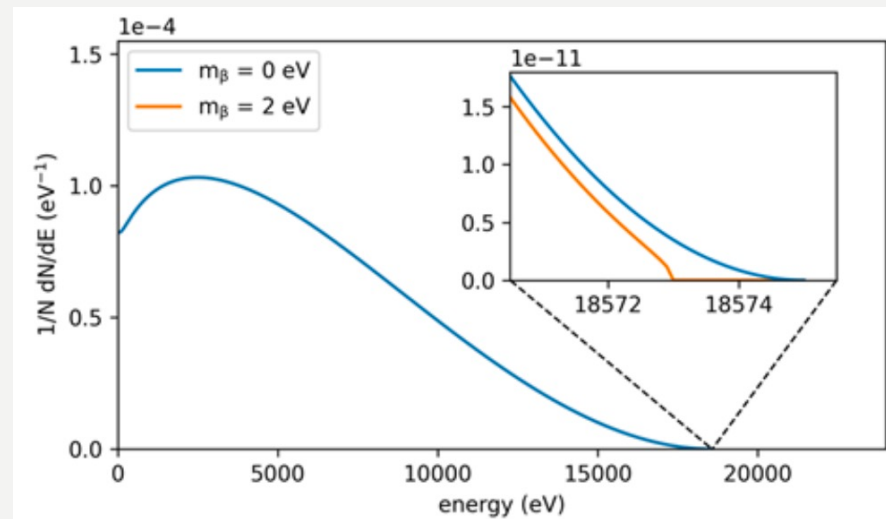
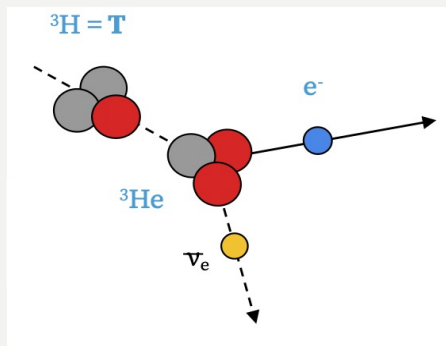
- Дираковская масса
 - два новых невзаимодействующих поля ν_R и $\bar{\nu}_L$
- Майорановская масса
 - новые поля не нужны ($\nu_L = \bar{\nu}_L$ и $\nu_R = \bar{\nu}_R$)
 - может быть сгенерирована Новой физикой на масштабе великого объединения
- Оба варианта



МЕТОД КРАЯ СПЕКТРА

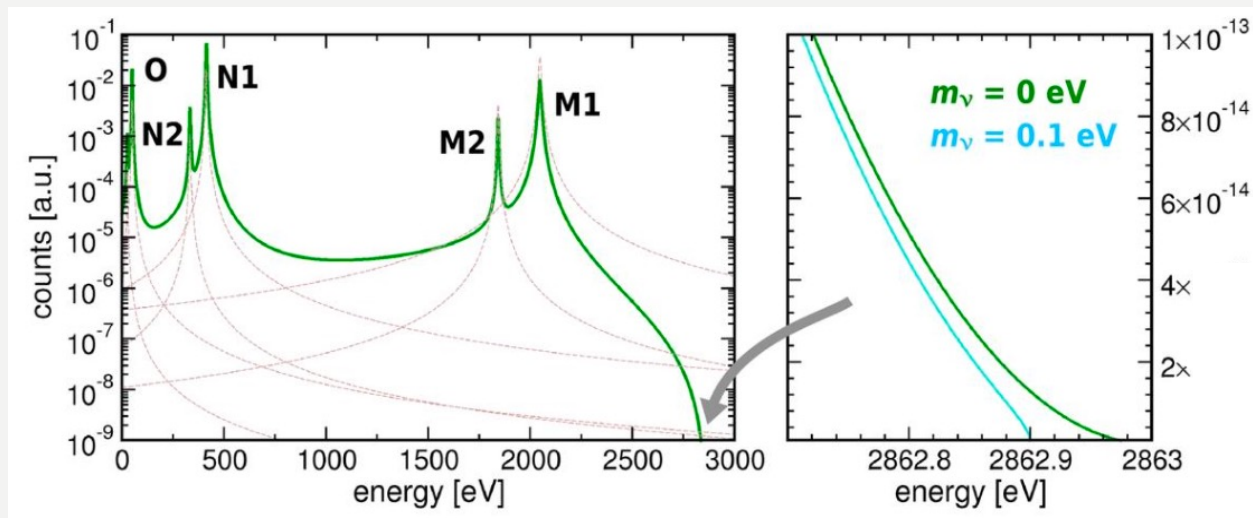
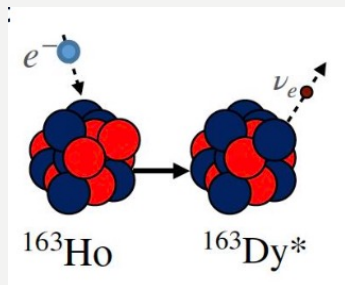
- Бета распад

- измерение энергии электрона
- распад трития хорошо изучен



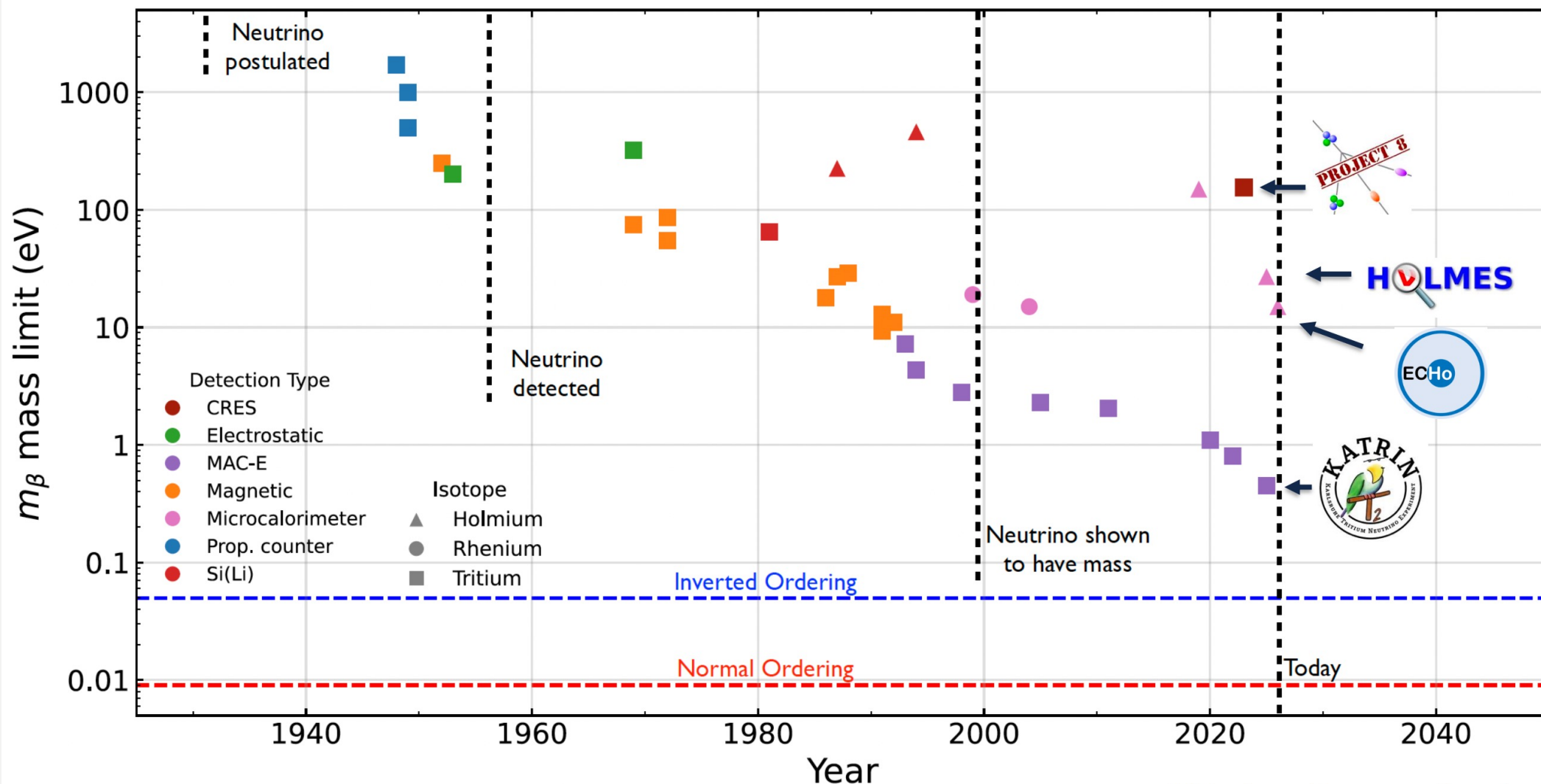
- Электронный захват

- измерение снятия возбуждения дочернего ядра
- большая доля событий на краю спектра, но нужно очень точное моделирование

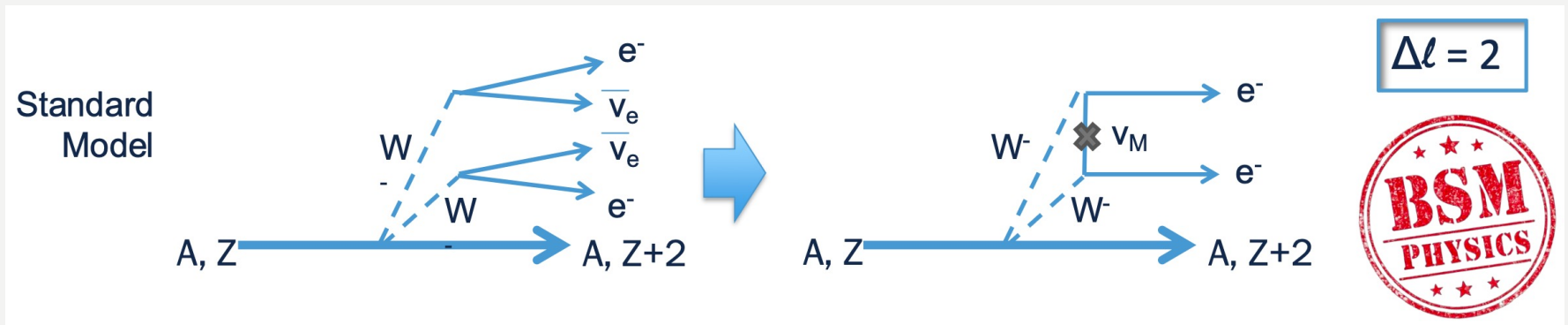


ВСЕ НИЖЕ, И НИЖЕ, И НИЖЕ...

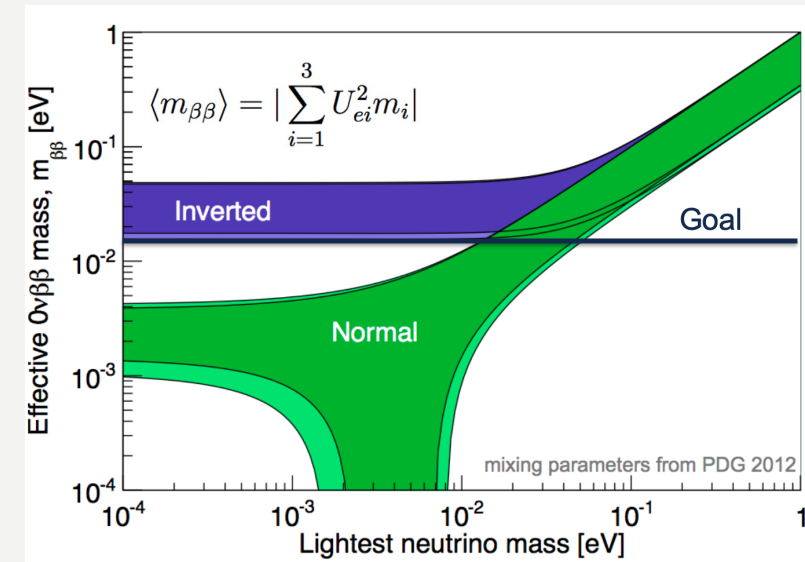
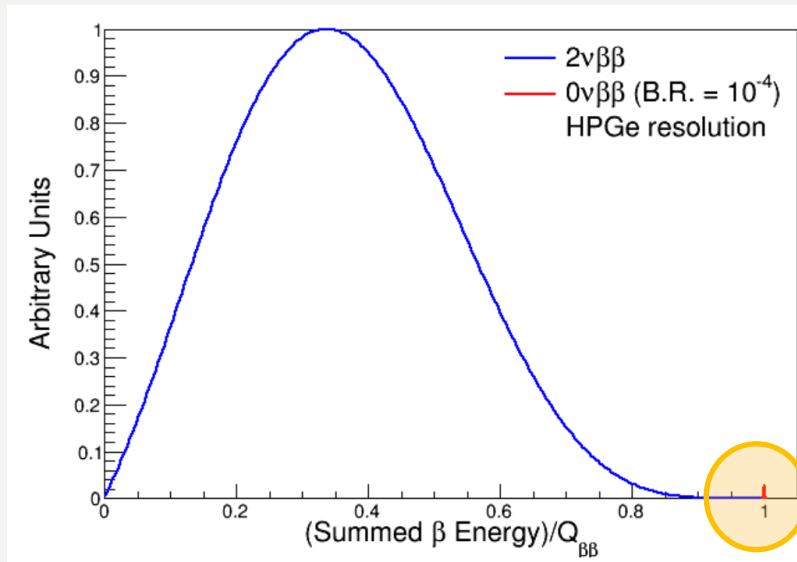
Evolution of Direct Neutrino Mass Limits



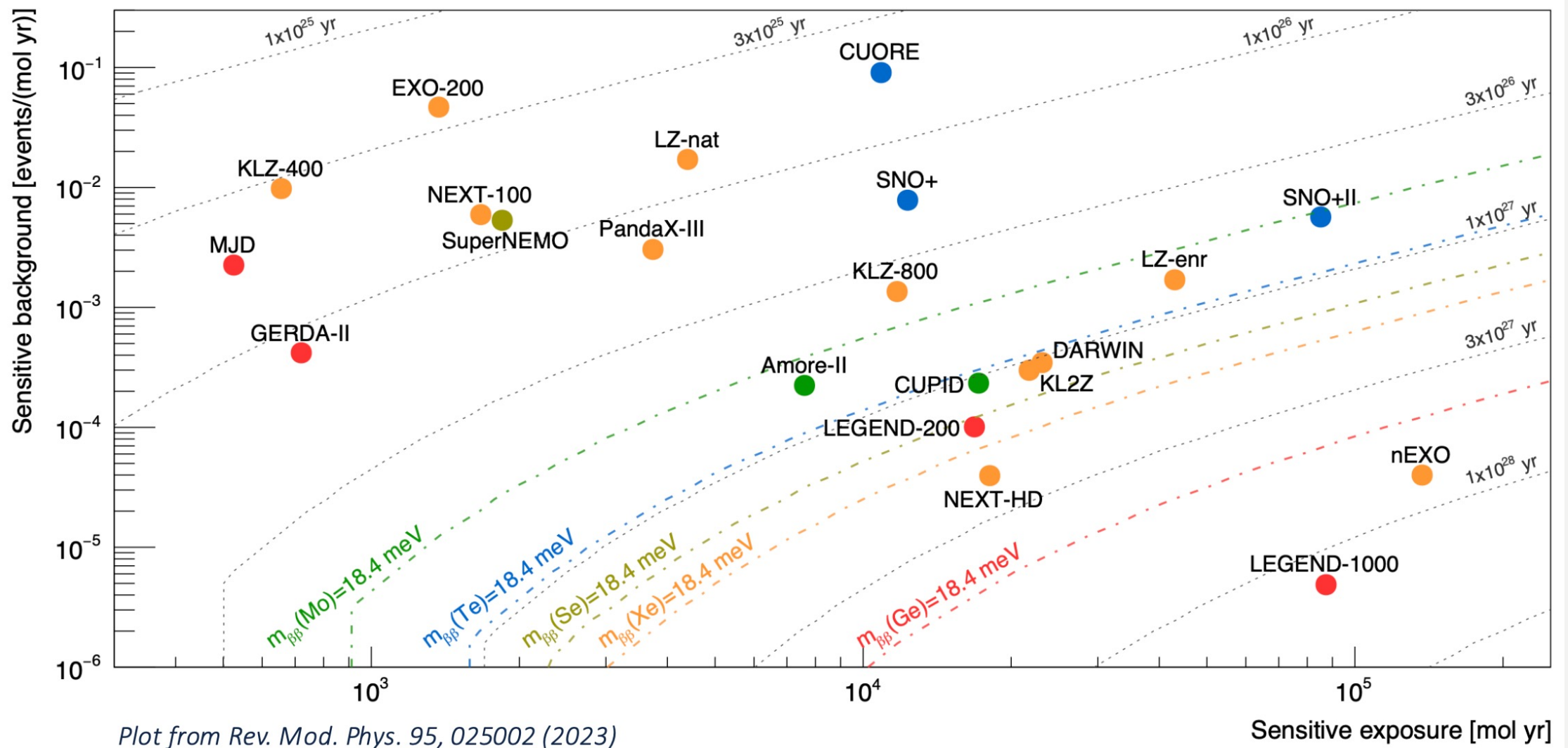
$0\nu\beta\beta$



- Для некоторых чётно-чётных ядер одинарный β -распад запрещен, вместо него доминирует двойной β -распад.
- Слабый процесс второго порядка с $T_{1/2} = 10^{19} - 10^{21}$ лет.
- Если у нейтрино Майорановская масса, то возможен безнейтринный двойной β -распад с нарушением лептонного числа ($\Delta l = 2$).



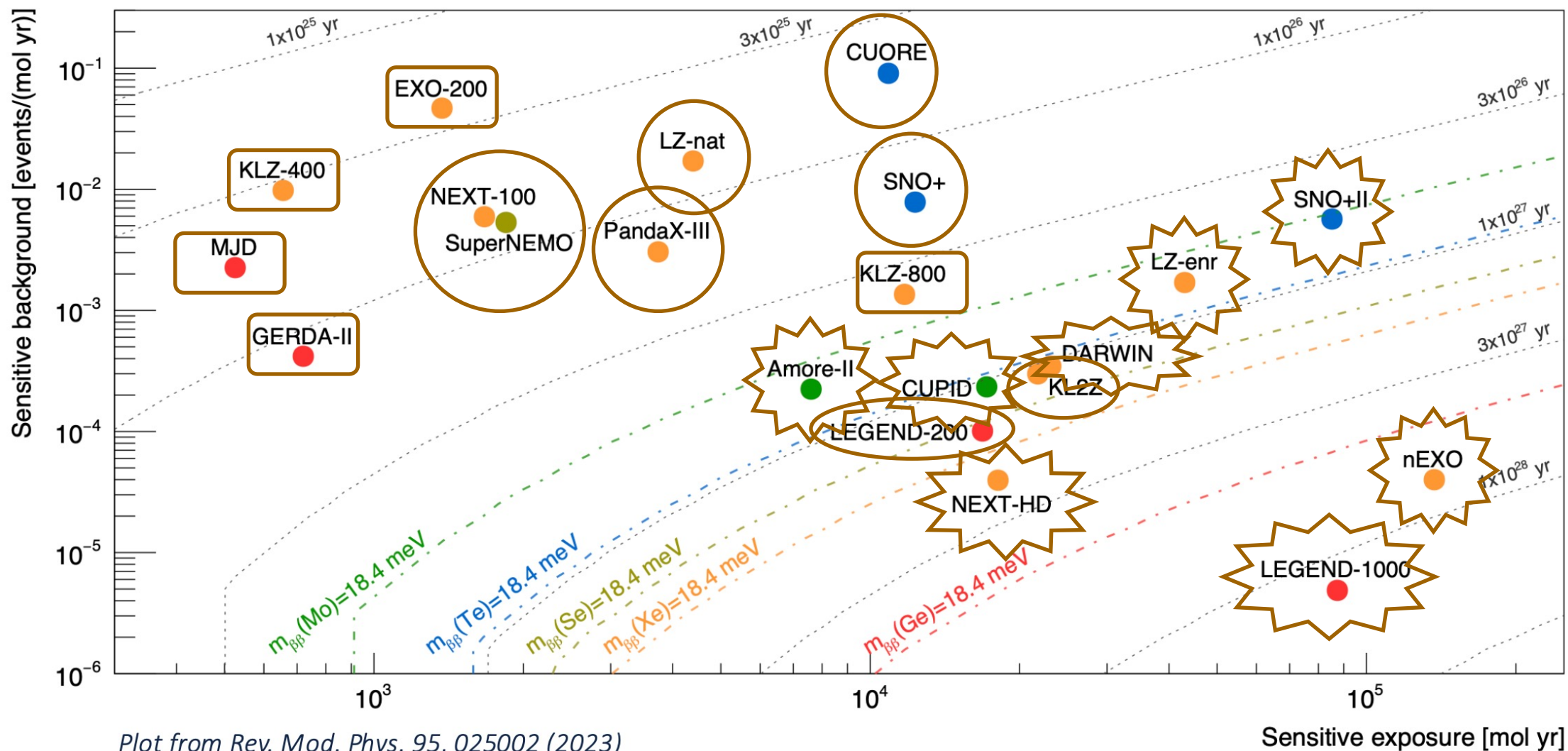
ЭКСПЕРИМЕНТАЛЬНЫЙ ЛАНДШАФТ



Завершенные

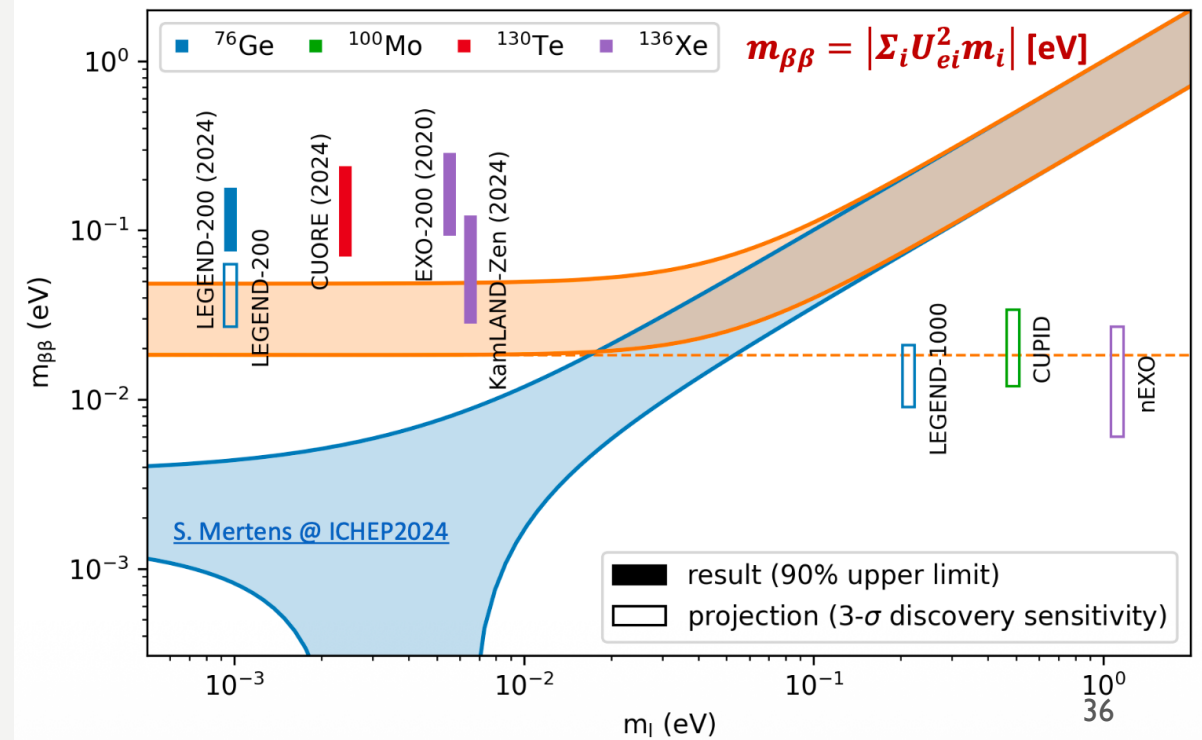
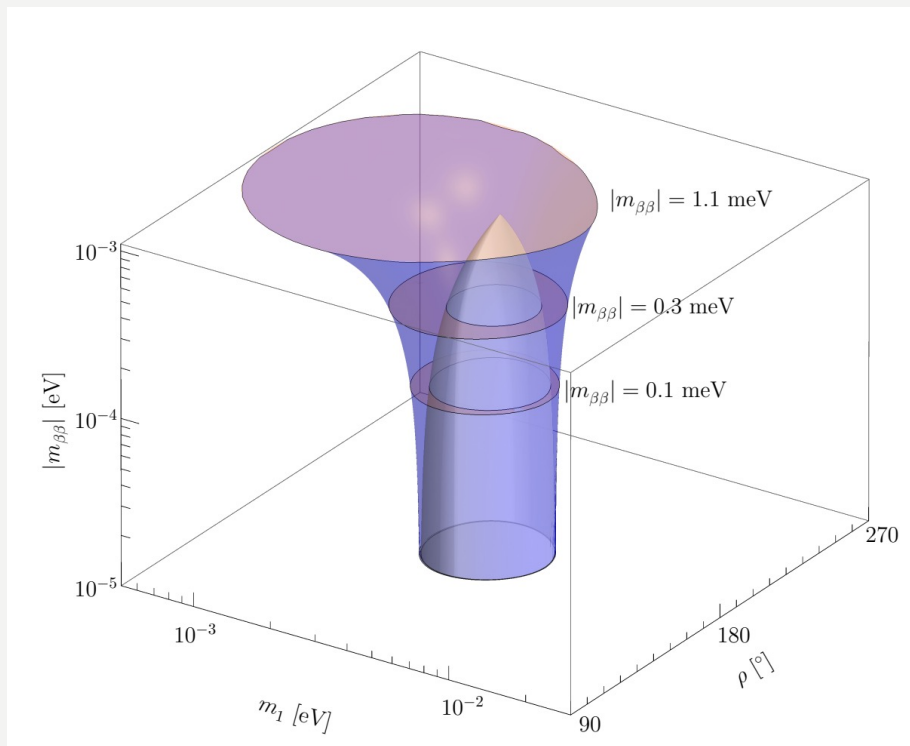
Работающие
и строящиеся

Предложенные

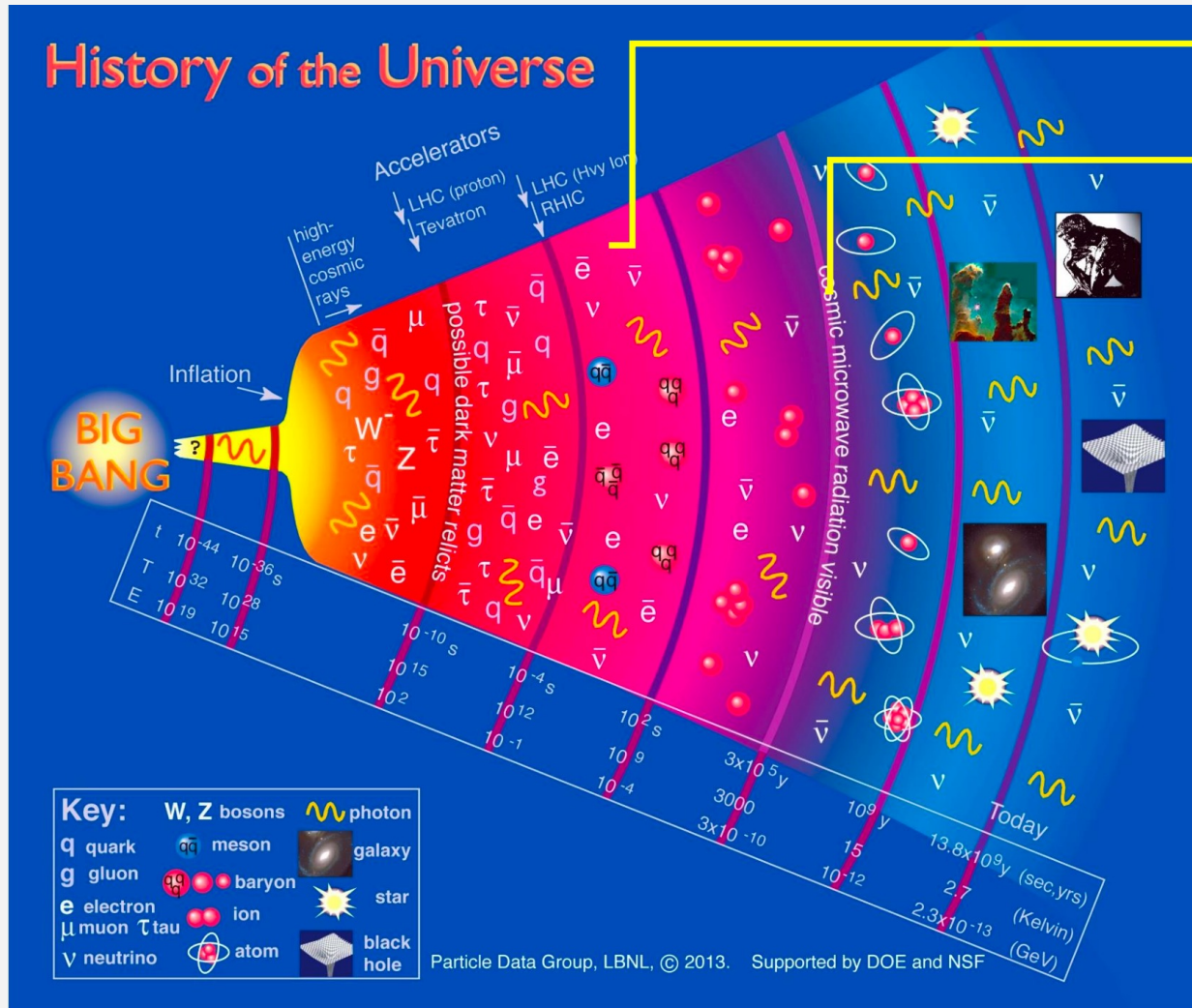


О ВАЖНОСТИ $0\nu\beta\beta$

- Найдем:
 - Майорановские нейтрино;
 - нарушение лептонного числа.
- Не найдем выше **1 meV**:
 - масса легчайшего нейтрино m_1 (0.7 — 8) meV;
 - Майорановская CP фаза (130° — 230°).



КОСМИЧЕСКИЙ НЕЙТРИННЫЙ ФОН [C ν B]



C ν B: вылетание нейтрино при $t = 1$ с

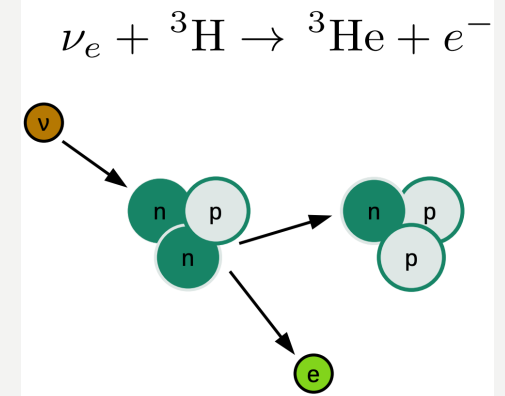
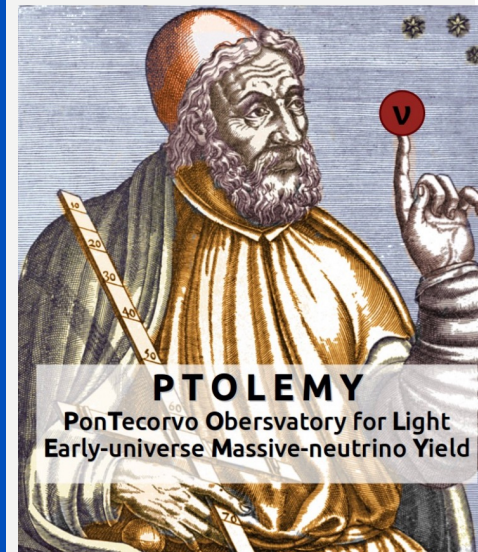
CMB: вылетание фотонов при $t = 10^5$ лет

Temperature today

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945 \text{ K}$$

Mean momentum today

$$\langle p_\nu \rangle \simeq 3.151 T_\nu \\ \simeq 5.281 \times 10^{-4} \text{ eV}$$



КОСМИЧЕСКИЙ МИКРОВОЛНОВЫЙ ФОН (СМВ)

Плотность энергии в ранней Вселенной позволяет оценить эффективное число нейтрино N_{eff} .
В поздней/современной Вселенной она зависит от суммы масс нейтрино.

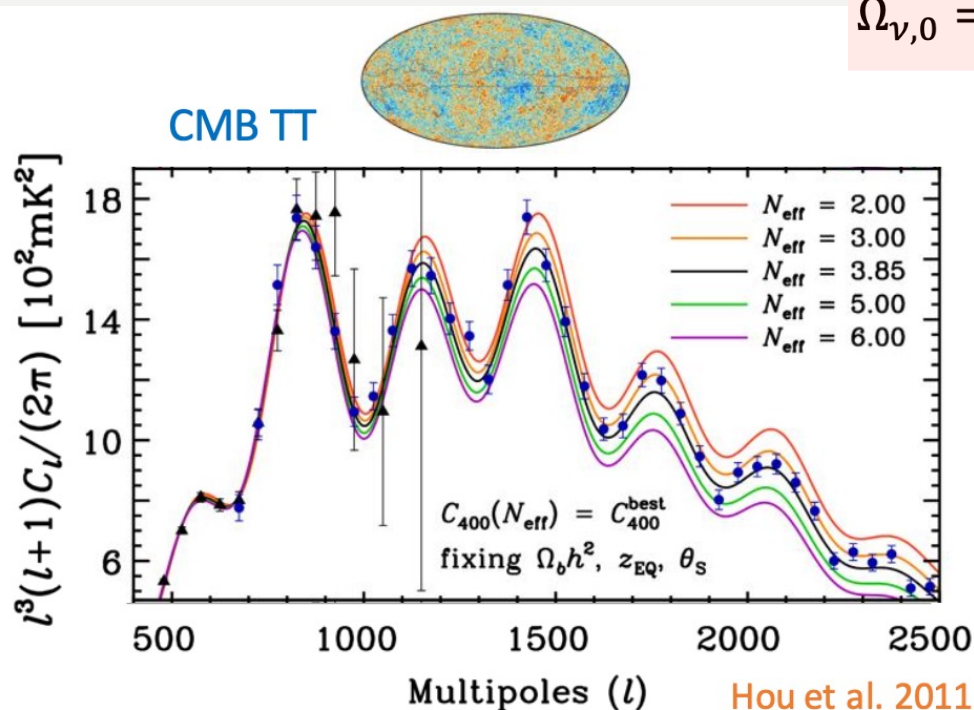
$$\rho_\nu = N_{\text{eff}} \times \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \rho_\gamma$$

SM prediction: $N_{\text{eff}}^{\text{SM}} = 3.0440 \pm 0.0002$

CMB energy density

%-level correction from QED equation of state, finite-temperature effects, flavour oscillations, transport, etc.

$$\Omega_{\nu,0} = \sum \frac{m_\nu}{93.75 h^2 \text{eV}}$$

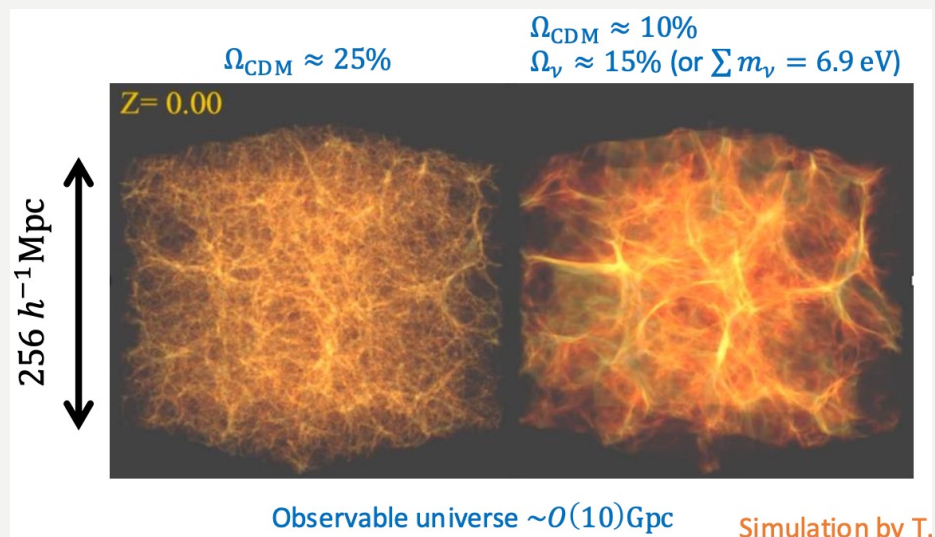


$\Lambda\text{CDM} + N_{\text{eff}}$ 7-parameter fit		
CMB only	Planck	$N_{\text{eff}} = 2.92^{+0.36}_{-0.37}$ (68% C. I.) Aghanim et al. 2020
	SPT-3G	$N_{\text{eff}} = 3.18^{+0.29}_{-0.33}$ (68% C. I.) Camphuis et al. 2025
	D1	
	ACT DR6	$N_{\text{eff}} = 2.60^{+0.22}_{-0.29}$ (68% C. I.) Calabrese et al. 2025
BBN only	Helium 4 + Deuterium	$N_{\text{eff}} = 2.94 \pm 0.092$ (68% C. I.) Yeh, Olive, Fields et al., 2026

Planck +ACT+SPT

$$\sum m_\nu < 0.19 \text{ eV (95\% C. I.)}$$

БАРИОННЫЕ АКУСТИЧЕСКИЕ ОСЦИЛЛЯЦИИ (BAO)



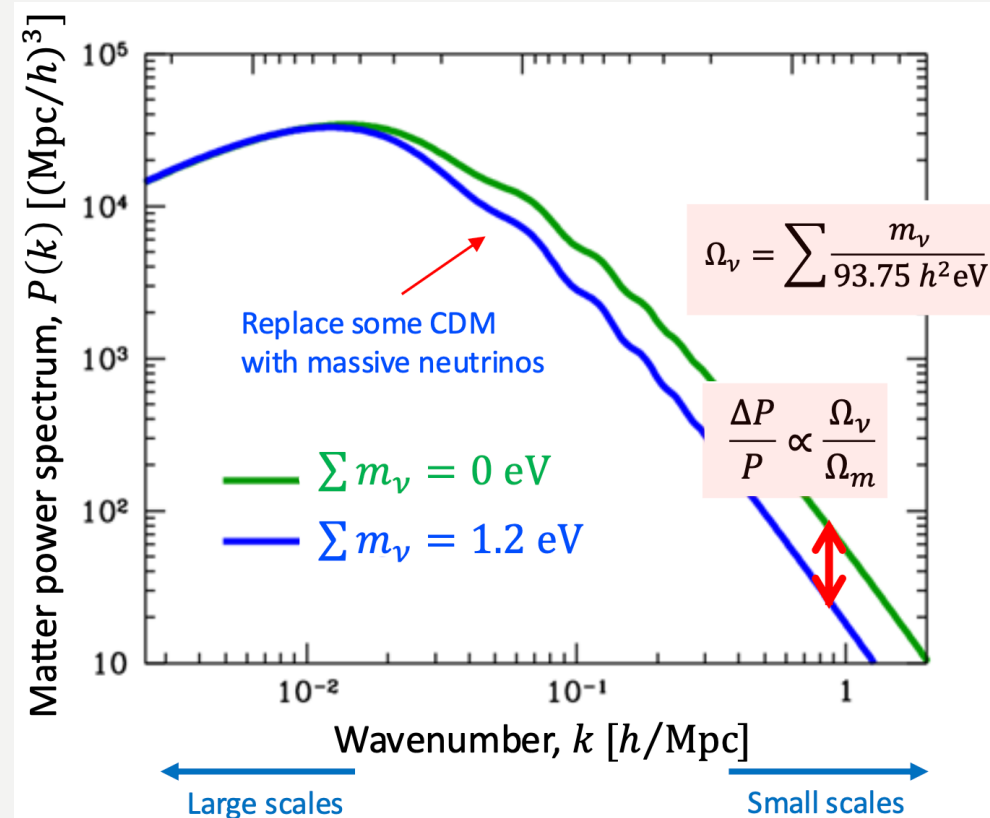
DESI (full-shape matter power spectrum+BAO)
 + BBN prior on $\Omega_b h^2$ + Planck CMB prior on n_s .

$$\sum m_{\nu} < 0.300 \text{ eV (95\%C.I.) Tight } n_s \text{ prior}$$

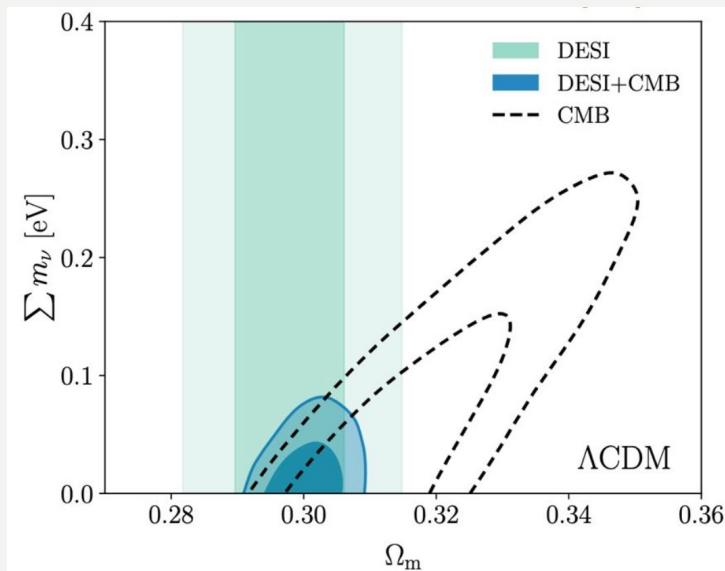
$$\sum m_{\nu} < 0.409 \text{ eV (95\%C.I.) Loose } n_s \text{ prior } [10 \times \sigma(n_s)]$$

$\Lambda\text{CDM} + \sum m_{\nu}$ 7-parameter fit

Масштаб распределения материи может быть использован для определения массы нейтрино.

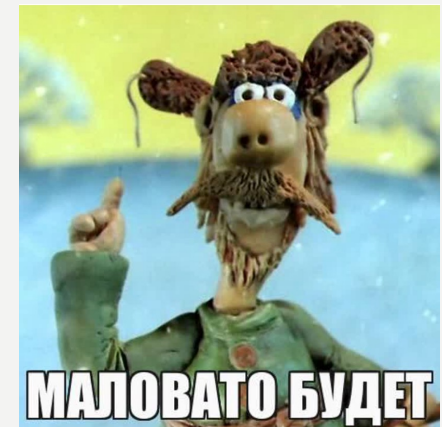


СКОЛЬКО ВЕШАТЬ В ГРАММАХ??



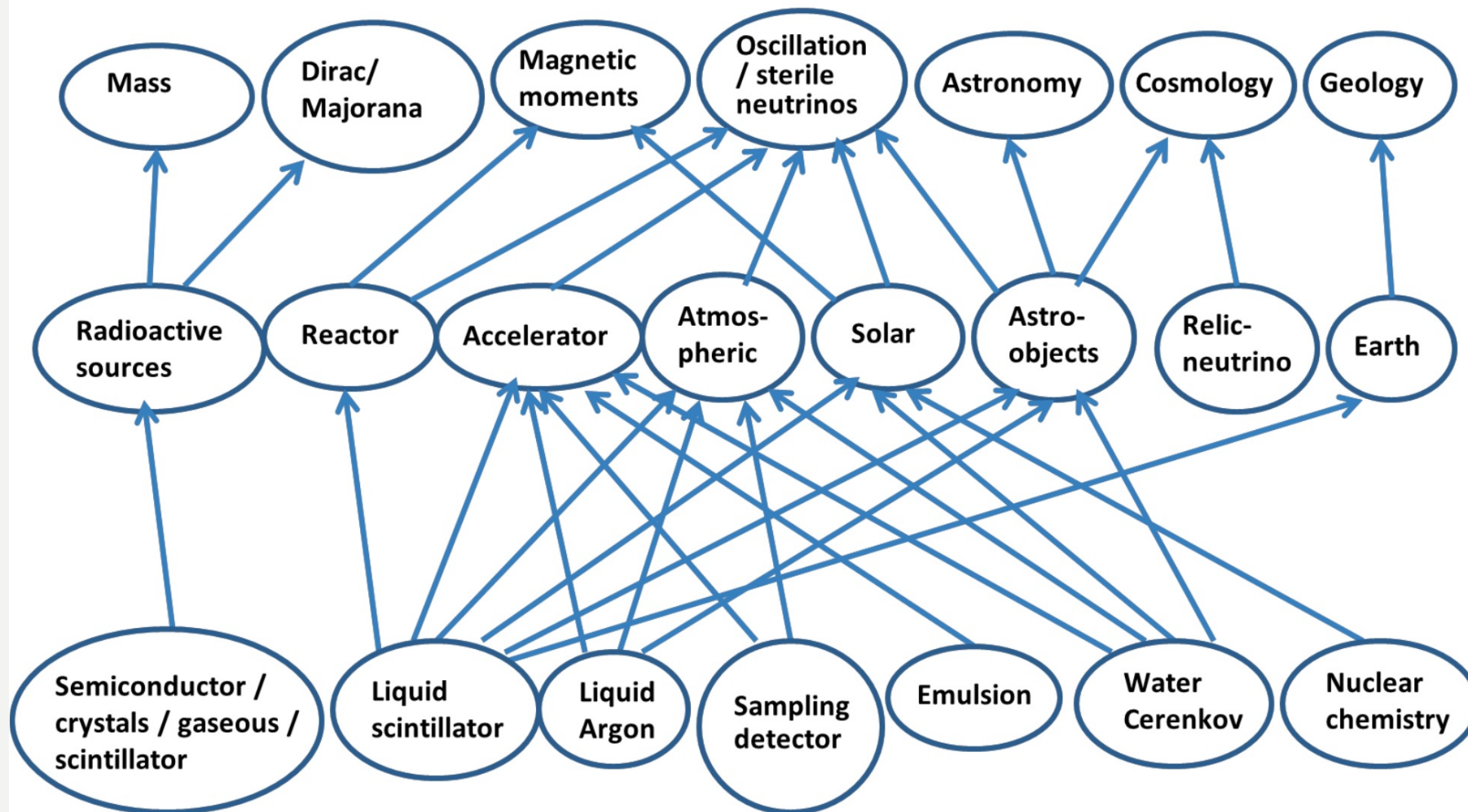
$$\sum m_\nu < 0.064 - 0.077 \text{ eV (95\%C.I.)}$$

CMB+DESI BAO; Λ CDM+ $\sum m_\nu$ 7-parameter fit, depending on the Planck likelihood used



Probes	Determine ν masses	Current	Future
^3H β decay	Effective mass in β decay $m_\beta = (\sum_i U_{ei} ^2 m_i^2)^{1/2}$	< 0.45 eV (90% C.L., KATRIN@2024)	< 40 meV (e.g., Project 8)
Cosmology	Total neutrino mass $\Sigma = m_1 + m_2 + m_3$	< 0.12 eV (95% prob., Planck@2018)	< 80 meV
$0\nu\beta\beta$ decay	Effective mass in $0\nu\beta\beta$ decay $m_{\beta\beta} = \sum_i U_{ei}^2 m_i \text{ [eV]}$	< (0.022 ~ 0.122) eV (90% C.L., KamLAND-Zen@2024)	< 10 meV (next generation)

ЗАКЛЮЧЕНИЕ





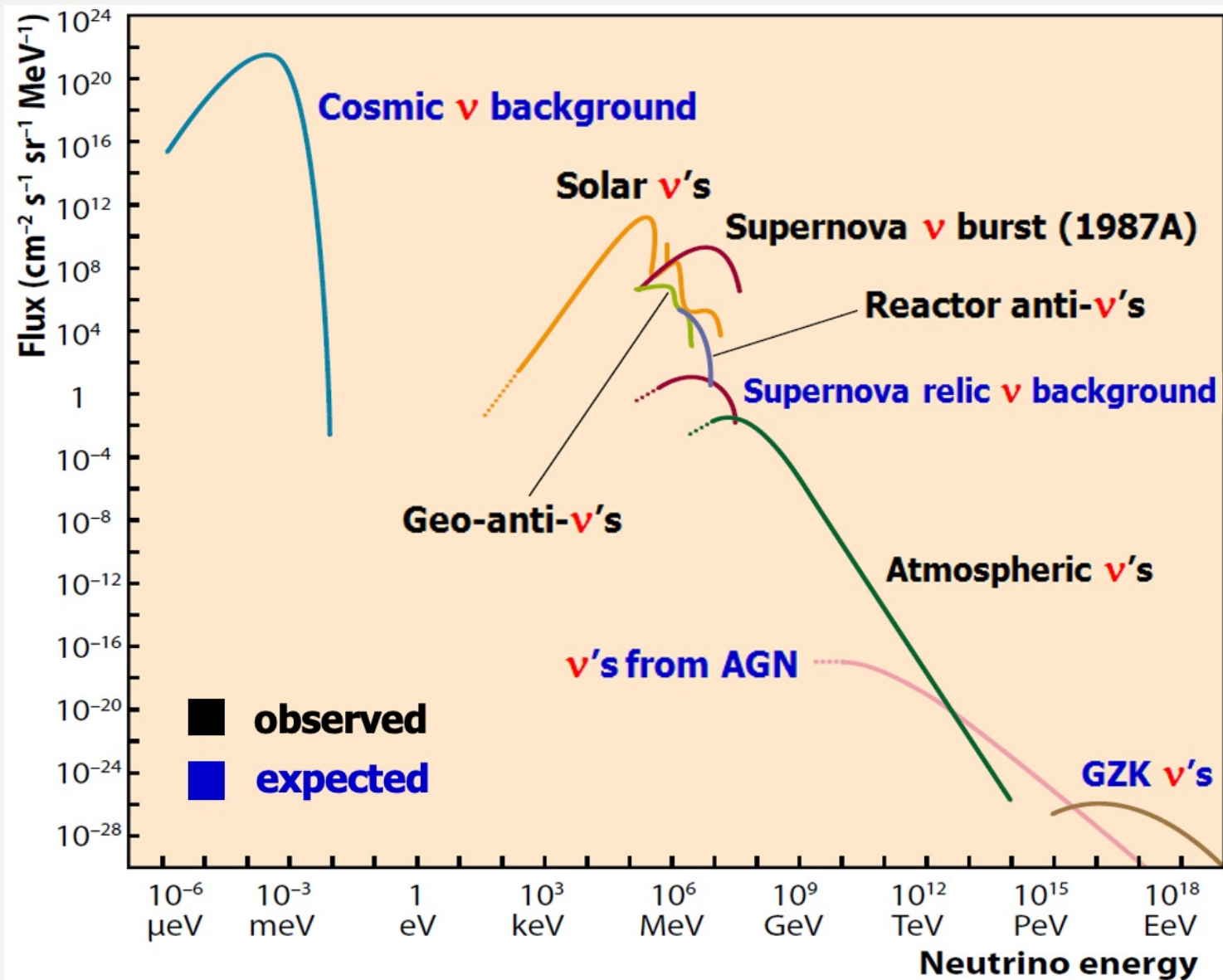
BACKUP

Test												
Abbreviation	Full name	Sensitivity ^[14]	Type	Induced reaction	Type of reaction ^[15]	Detector	Type of detector	Threshold energy	Location	Operation	Home page	
ANNE	Accelerator Neutrino Interaction Experiment								SoSeBee Hall, Illinois, United States	Future	[1] ^[17]	
ANTARES	Astronomy with a Neutrino Telescope and Alps Environmental REsearch	ATM, CR, AGN, PUL	$\nu_\mu, \nu_\tau, \nu_\tau$			Seawater	Cherenkov		Mediterranean Sea, France	2006–2022	[2] ^[18] Archived ^[19] 2011-07-19 at the Wayback Machine	
ARIANNA	Antarctic Ross Ice Shelf Antenna Neutrino Array	S, CR, AGN, γ	$\nu_\mu, \nu_\tau, \nu_\tau$						Ross Ice Shelf, Antarctica	future	[3] ^[20]	
BOUNT (INT-200+)	Baikal-GVD	S, ATM, LS, AGN, PUL	$\nu_\mu, \nu_\tau, \nu_\tau$			CC, NC	Water (H ₂ O)	Cherenkov	>10 GeV	Lake Baikal, Russia	1993–	[4] ^[21] [5] ^[22]
BOREXINO	BoRerino Experiment	LS	ν_e	$\nu_e + e^- \rightarrow \nu_e + e^+$	ES	LOS shielded by water	Scintillation	250–865 keV	Gran Sasso, Italy	May 2007–	[6] ^[23] [7] ^[24]	
BUST	Balkan Underground Scintillation Telescope						Scintillation		Balkan River valley, Russia	1977–	[8] ^[25]	
CCM	Cohesent CAPTAIN-MIA	AC				CC	Liquid Argon	Scintillation	50 keV	Los Alamos Neutron Science Center	2019–	[9] ^[26]
CHANDLER ^[27]	Carbon Hydrogen Antineutrino Detector with a Lithium Enhanced Regeneron optical lattice	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n^+ + n$		CC	WLS Plastic Scintillating Cubes and Lithium-6 loaded Zinc Sulfide Sheets	Scintillation	1.8 MeV	North Anna, Virginia, US	June 2017–	[10] ^[28]
CLEAN	Cryogenic Low Energy Astrophysics with Neutrinos	LS, SN, WIMP	ν_e	$\nu_e + e^- \rightarrow \nu_e + e^+$ $\nu_e + {}^{29}\text{Ne} \rightarrow \nu_e + {}^{29}\text{Ne}$	ES ES		Liquid Ne (10 g)	Scintillation		SNOLAB Ontario, Canada	Future	[11] ^[29] [12] ^[30]
COBRA	Cadmium zinc telluride β -neutrino double-beta Research Apparatus					BB	Cadmium zinc telluride		Gran Sasso, Italy	2007–	[13] ^[31]	
COHERENT	COHERENT	AC	$\nu_\mu, \bar{\nu}_\mu, \nu_\mu$	$\nu + \text{nucleus} \rightarrow \nu + \text{nucleus}$	ES (NC), CC	Ca[Ne], NaI(Tl), HPGe, LAU	Cohesent Elastic Neutrino Nuclear Scattering (CEANS)	few keV nuclear recoil energy	Spallation Neutron Source at Oak Ridge National Laboratory	Nov 2016–	[13] ^[32]	
CORUS / CORUS+	Cohesent Neutrino Elastic Scattering	R	$\bar{\nu}_e$	$\bar{\nu}_e + \text{nucleus} \rightarrow \bar{\nu}_e + \text{nucleus}$	ES (NC)	HPGe	Cohesent Elastic Neutrino Nuclear Scattering (CEANS)	4 detectors: 180W, 170W, 180W and 250W ^[33]	Brookhaven Nuclear Power Plant, Germany (CONUS); Lubbock Nuclear Power Plant, Switzerland (CONUS+)	2019-2022 (CONUS); 2020–Ongoing (CONUS+)	[14] ^[34]	
Days Bay	Days Bay Reactor Neutrino Experiment	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n^+ + n$	CC	Gold-doped LAB (LOS)	Scintillation	1.8 MeV	Days Bay, China	2011–2020	[15] ^[35]	
Double Chooz	Double Chooz Reactor Neutrino Experiment	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n^+ + n$	CC	Gold-doped LOS	Scintillation	1.8 MeV	Chooz, France	2011–2017	[16] ^[36]	
DUNE	Deep Underground Neutrino Experiment	AC, ATM, (S), SN	μ		NC, CC, (ES)	Liquid argon	Scintillation & Time projection chamber	around 10 MeV	Sanford Underground Research Facility	construction start 2017	[17] ^[37]	
ENUBET	Enhanced Neutrino BEams from kaon Tagging	AC	$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$	$\nu_e + n \rightarrow e^- + p$ (nL, $\times 0$) $\nu_e + n \rightarrow \mu^- + p$ (nL, $\times 0$) $\bar{\nu}_e + p \rightarrow e^+ + n$ (nL, $\times 0$) $\bar{\nu}_e + p \rightarrow \mu^+ + n$ (nL, $\times 0$)	CC (NC)				Future	[18] ^[38]		
ESSnuB ^[39]	The European Spallation Source ^[40] neutrino Super Beam	AC	$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ (Beam dump)				Water Cherenkov MEMPHYS detector	0.36 GeV	Gasperberg, Lund, Sweden	future by 2023	[19] ^[41] [19] ^[42]	
FASER	Forward Search Experiment	C	$\nu_\mu, \nu_\tau, \nu_\tau$	$\nu + N \rightarrow e^- + X$	CC + NC	Tungsten	Emulsion	>10 GeV	Large Hadron Collider	2022–	[20] ^[43]	
EXO-200	Enriched Xenon Observatory			${}^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + e^- + e^-$ ${}^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + e^- + e^-$	BB	Liquid Xenon			WIPP, New Mexico	2009–	[21] ^[44] Archived ^[45] 2013-07-12 at the Wayback Machine	
GALLIX	Gallium Experiment	LS	ν_e	$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$	CC	CaCl ₂ (90 g)	Radiochemical	233.2 keV	Gran Sasso, Italy	1991–1997	[22] ^[46]	
GERDA	The GERDA Neutrino Detector Array	BB	$\bar{\nu}_e$	${}^{76}\text{Ge} \rightarrow {}^{76}\text{As} + e^- + e^-$	BB	HPGe	Semiconductor	~20 keV	Gran Sasso, Italy	2015–2019	[23] ^[47]	
GRAND	Giant Radio Array for Neutrino Detection	AGN, CR, γ	ν_i	$\nu_i + N \rightarrow e^- + X$	CC		Electromagnetic waves caused by γ through extensive air showers in the atmosphere	Radio	10^{17} eV	China	Proposed	[24] ^[48]
HALO	Helium And Lead Observatory	SN	ν_μ, ν_τ	$\nu_e + {}^{209}\text{Po} \rightarrow e^- + {}^{209}\text{Po}$ $\nu_e + {}^{209}\text{Po} \rightarrow \nu_e + {}^{209}\text{Po}$	CC, NC	Lead (79 t) and He	High-Z	>10 MeV	Croighton Mine, Ontario	2012–	[25] ^[49]	

HERON	Helium Roton Observation of Neutrinos	LS	ν_μ (mainly)	$\nu_e + e^- \rightarrow \nu_e + e^-$	NC		Superfluid He	Rotational excitation	1 MeV		future	[26] ¹⁷
HOMESTAKE-CHLORINE	Homestake chlorine experiment	S	ν_e	$^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$ $^{37}\text{Ar} \rightarrow ^{37}\text{Cl} + e^- + \bar{\nu}_e$	CC		C ₂ Cl ₆ (815 l)	Radiochemical	814 keV	Homestake Mine, South Dakota	1967–1998	[27] ¹⁸
HOMESTAKE-IODINE	Homestake iodine experiment	S	ν_e	$\nu + e^- \rightarrow \nu + e^-$ $\nu_e + ^{127}\text{I} \rightarrow ^{127}\text{Xe} + e^-$	ES CC		Nal in water	Radiochemical	789 keV	Homestake Mine, South Dakota	future	[28] ¹⁹
Hyper-Kamiokande	Hyper-Kamiokande	S, ATM, SN, AC	$\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$	$\nu_e + e^- \rightarrow \nu_e + e^-$ $\nu_e + n \rightarrow e^- + p$ (nL, $\times 0$) $\nu_e + n \rightarrow \mu^- + p$ (nL, $\times 0$) $\bar{\nu}_e + p \rightarrow e^+ + n$ (nL, $\times 0$) $\bar{\nu}_e + p \rightarrow \mu^+ + n$ (nL, $\times 0$)	ES, CC, (NC)		water	Cherenkov	290 MeV	Tokai and Kamioka, Japan	2027– (under construction)	[29] ²⁰
ICARUS	Imaging Cosmic And Rare Underground Signal	S, ATM, GSN	$\nu_\mu, \nu_\tau, \nu_\tau$	$\nu + e^- \rightarrow \nu + e^-$	ES		Liquid Ar	Cherenkov	5.9 MeV	Gran Sasso, Italy	2010–	[30] ²¹ Archived ²² 2012-03-07 at the Wayback Machine
IceCube	IceCube Neutrino Detector	ATM, CR, AGN, γ	$\nu_\mu, \nu_\tau, \nu_\tau$	$\nu + N \rightarrow \nu + \text{Cascade}$ $\nu + N \rightarrow \text{Charged lepton} + \text{Cascade}$	CC, NC		Water ice (1 km ³)	Cherenkov	>10 GeV	South Pole, Antarctica	2006–	[31] ²³
India-based Neutrino Observatory	Iron Calorimeter Detector @ India-based Neutrino Observatory	ATM	ν_e	$\nu_e + e^- \rightarrow \nu_e + e^-$	CC (dominant), NC		Magnetized iron (50 kton)	RFC active detector elements	<0.6 GeV	Thar, Tamil Nadu, India	2012– (lab construction); 2018– (detector operation)	[32] ²⁴
JUNO	Jiangmen Underground Neutrino Observatory	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow e^+ + n$	CC		LAB (LOS) + PFO + Be-MSB	Scintillation		Kaiping, China	2014– (construction)	[33] ²⁵
Kamiokande	Kamioka Neutrino Decay Experiment	S, ATM	ν_e	$\nu + e^- \rightarrow \nu + e^-$	ES		Water (H ₂ O)	Cherenkov	7.5 MeV	Kamioka, Japan	1986–1996	[34] ²⁶
KamLAND	Kamioka Liquid Scintillator Antineutrino Detector	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow e^+ + n$	CC		LOS	Scintillation	1.8 MeV	Kamioka, Japan	2002–	[35] ²⁷
KATRIN	Karlsruhe Tritium Neutrino experiment	MTR, ATR	$\bar{\nu}_e$	$\bar{\nu}_e + {}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$	CC		Spectrometer	Semiconductor	< 0.45 eV	Germany	2019–	[36] ²⁸
KIMeNT	KIM Neutrino Telescope	S, ATM, CR, SN, AGN, PUL	$\nu_\mu, \nu_\tau, \nu_\tau$				Sea water (>5 km ³)	Cherenkov		Mediterranean Sea	2014–	[37] ²⁹
LAGUNA	Large Apparatus studying Gravitational Unification and Neutrino Astrophysics								Future			[38] ³⁰
LEGEND	The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay	BB	$\bar{\nu}_e$	$^{76}\text{Ge} \rightarrow ^{76}\text{As} + e^- + e^-$	BB		HPGe	Semiconductor	~50 keV	Gran Sasso, Italy	2020–	[39] ³¹
LENS	Low Energy Neutrino Spectroscopy	LS	ν_e	$\nu_e + ^{115}\text{Sn} \rightarrow ^{115}\text{Sn} + \nu_e + 2\gamma$	CC		In-doped LOS	Scintillation	120 keV		proposed	[40] ³² Archived ³³ 2008-08-21 at the Wayback Machine [41] ³⁴
MoXone	The MoXone Neutrino Experiment	BB	$\bar{\nu}_e$	$^{76}\text{Ge} \rightarrow ^{76}\text{As} + e^- + e^-$	BB		HPGe	Semiconductor	~8 keV	Homestake Mine, South Dakota	2015–2021	[42] ³⁵
MicroBoNE	MicroBoNE	AC, SN	ν_μ, ν_μ		ES, NC, CC		Liquid Argon	TPC	few MeV	Ithaca, United States	2014–	[43] ³⁶
MINERvA	Main Injector Experiment for ν -A	AC	ν_e	many	CC, NC		Solid scintillator, targets of liquid helium, Carbon, Water, Iron, Lead	Scintillation	<0.5 GeV	Ithaca, United States	2009–2019	[44] ³⁷
MiniboNE	Mini Booster Neutrino Experiment	AC	ν_μ, ν_μ	$\nu_e + ^{10}\text{C} \rightarrow e^- + X$	CC		Mineral oil (1000 g)	Cherenkov	<100 keV	Ithaca, United States	2002–	[45] ³⁸
MINOS	Main Injector Neutrino Oscillation Search	AC, ATM	ν_μ, ν_μ	$\nu_e + \text{nucleus} \rightarrow \mu^- + X$	CC, NC		Solid scintillator	Scintillation	<0.5 GeV	Ithaca and Minnesota, United States	2005–2012	[46] ³⁹
MINOS+	Upgraded experiment for MINOS	AC, ATM	ν_μ, ν_μ	$\nu_e + \text{nucleus} \rightarrow \mu^- + X$	CC, NC		Solid scintillator	Scintillation	<0.5 GeV	Ithaca and Minnesota, United States	2013–	[47] ⁴⁰
MOON	Molybdenum Observatory of Neutrinos	LS, LSN	ν_e	$\nu_e + ^{100}\text{Mo} \rightarrow ^{100}\text{Tc} + e^-$	CC		^{100}Mo (1 kg) + MuF9 (gas)	Scintillation	168 keV	Washington, United States		[48] ⁴¹
MEMO-3	Neutrino Eltine Mayenne Observatory	BB	ν_e	$^{103}\text{Ru} \rightarrow ^{103}\text{Rh} + 2 e^-$ $^{103}\text{Ru} \rightarrow ^{103}\text{Rh} + 2 e^-$	BB		Tracker + calorimeter	He-Ar wire chamber, plastic scintillators	150 keV	Modane Underground Laboratory, Fréjus Road Tunnel, France	2003–2011	[49] ⁴² Archived ⁴³ 2020-05-29 at the Wayback Machine
MEMO Telescope	Neutrino Mediterranean Observatory								2007–	Mediterranean Sea, Italy		[50] ⁴⁴
Neutrino-4	Neutrino-4 Reactor Neutrino Experiment	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow e^+ + n$	CC		liquid organic scintillator loaded with Gd	Scintillation	<2 MeV	Dmitriyevsk, Russia	2014–	[51] ⁴⁵
NEVOD	Cherenkov water detector NEVOD	ATM, CR	ν_e	$\nu_e + n \rightarrow e^- + p$ $\nu_e + p \rightarrow \mu^- + n$	CC		Water (H ₂ O)	Cherenkov	<2 GeV	Moscow, Russia	1993–	[51] ⁴⁶
NEXT	Neutrino Experiment with a Xenon Time Projection Chamber	BB		$^{136}\text{Xe} \rightarrow ^{136}\text{Ba} + 2 e^-$	BB		Gaseous Xenon	Time projection chamber	<10 keV	Cabrils, Spain	2016–	[52] ⁴⁷

NOvA	NUMI OR-Axis ν_e Appearance	AC	ν_μ, ν_μ	$\nu_e + \text{nucleus} \rightarrow e^- + X$	CC		Liquid scintillator	Scintillation	<0.1 GeV	Ithaca and Minnesota, United States	2011–	[53] ⁸¹ Archived ⁸² 2007-09-05 at the Wayback Machine
NUCLEUS	NUCLEUS	R	$\bar{\nu}_e$	$\bar{\nu}_e + \text{nucleus} \rightarrow \bar{\nu}_e + \text{nucleus}$	ES (NC)		CaWO ₄ /ADOS	Photon-mediated Transition-edge sensor Bolometer	20 μeV ⁸³	Technical University of Munich, Germany (Development); Chooz Nuclear Power Plant, France	2017 (R&D); Future (Experiment)	[54] ⁸⁴
OPERA	Oscillation Project with Emulsion-tacking Apparatus	AC	ν_τ	$\nu_e + \text{nucleus} \rightarrow e^- + X$	CC		LeadEmulsion	Nuclear Emulsion	<1.0 GeV	LNGS (Italy) and CERN	2008–	[55] ⁸⁵ Deprecated: Iva archived 2014-07-13 at archive.today
Asper	Pierre Auger Observatory	CR					Cherenkov			Argentina		[56] ⁸⁶
Project 8	Project 8 experiment	ATR	$\bar{\nu}_e$	$\bar{\nu}_e + {}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$	CC		Microsieve Cavity	Radio	<0.04 eV	USA, Germany	Future	[57] ⁸⁷
RENO	Reactor Experiment for Neutrino Oscillation	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n^+ + n$	CC		Gold-doped LOS	Scintillation	1.8 MeV	South Korea	2011–	
RNO-G	Radio Neutrino Observatory Greenland	CR, AGN, γ	$\nu_\mu, \nu_\tau, \nu_\tau$		CC, NC		In-ice	Radio	>10 PeV	Summit Camp, Greenland	2021–	[58] ⁸⁸
SAGE	Soviet–American Gallium Experiment	LS	ν_e	$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$	CC		Ge (metallic)	Radiochemical	233.2 keV	Balkan River valley, Russia	1980–	[59] ⁹⁰
SubSeaNE	SubSea (Scintillator Bar) Reactor Neutrino Experiment	AC	ν_e	$\nu_e + {}^{12}\text{C} \rightarrow \mu^- + X$	CC, NC		Plastic (CH10 bar)	Scintillation	<100 keV	Ithaca, United States	2007–2008	[60] ⁹¹
SNO	Subway Neutrino Observatory	S, ATM, GSN	$\nu_\mu, \nu_\tau, \nu_\tau$	$\nu_e + {}^{10}\text{B} \rightarrow {}^{10}\text{Be} + e^-$ $\nu_e + {}^{10}\text{B} \rightarrow \nu_e + e^- + p$ $\nu_e + e^- \rightarrow \nu_e + e^-$	CC NC ES		Heavy water (1 t D ₂ O)	Cherenkov	3.5 MeV	Croighton Mine, Ontario	1999–2006	[61] ⁹²
SNO+	SNO with liquid scintillator	SLSA/T, SNLSD	ν_e	$\nu_e + e^- \rightarrow \nu_e + e^-$ $\bar{\nu}_e + p \rightarrow e^+ + n$	ES, BB		Invar alkybenzene (LAB) + PFO	Scintillation	<1 MeV	Croighton Mine, Ontario	2014–	[62] ⁹³
Solid	Short baseline Oscillation Search with Lithium-6 Detector	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n^+ + n$	CC		Plastic and aerogel scintillator	Scintillation	<2 MeV	Mel, Belgium	2015–	[63] ⁹⁴
STEREO	STEREO neutrino Reflector Oscillation experiment	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n^+ + n$	CC		Liquid organic scintillator loaded with Gd	Scintillation	<2 MeV	Grenoble, France	2013–	[64] ⁹⁵
Super-K	Super-Kamiokande	S, ATM, GSN	$\nu_\mu, \nu_\tau, \nu_\tau$	$\nu_e + e^- \rightarrow \nu_e + e^-$ $\nu_e + n \rightarrow e^- + p$ $\bar{\nu}_e + p \rightarrow e^+ + n$	ES CC CC		Water (H ₂ O)	Cherenkov	250 MeV	Kamioka, Japan	1996–	[65] ⁹⁶ Archived ⁹⁷ 2008-08-05 at the Wayback Machine [66] ⁹⁸
SuperNEMO	SuperNEMO	BB	ν_e	${}^{100}\text{Sn} \rightarrow {}^{100}\text{In} + 2 e^-$ ${}^{100}\text{Sn} \rightarrow {}^{100}\text{In} + 2 e^-$	BB		Tracker + calorimeter	He-Ar wire chamber, plastic scintillators	150 keV	Modane Underground Laboratory, Fréjus Road Tunnel, France	2017–	[67] ⁹⁹ Archived ¹⁰⁰ 2020-05-29 at the Wayback Machine
TRIDENT	TRIDENT Neutrino Telescope	S, ATM, CR, SN, AGN, PUL	$\nu_\mu, \nu_\tau, \nu_\tau$		CC, NC		Seawater (7.5 cubic km)	Cherenkov		Western Pacific Ocean	Proposed: Post 2026 Full operation: 2030	[68] ¹⁰¹
T2K	Tokai to Kamioka	AC	$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$	$\nu_e + e^- \rightarrow e^- + p$ (nL, $\times 0$) $\nu_e + n \rightarrow \mu^- + p$ (nL, $\times 0$) $\bar{\nu}_e + p \rightarrow e^+ + n$ (nL, $\times 0$) $\bar{\nu}_e + p \rightarrow \mu^+ + n$ (nL, $\times 0$)	CC (NC)		Water (H ₂ O)	Cherenkov	200 MeV	Tokai, Japan Kamioka, Japan	2011–	[69] ¹⁰²
UNO	Underground Neutrino decay and neutrino Observatory	S, ATM, GSN, RBN	$\nu_\mu, \nu_\tau, \nu_\tau$	$\nu_e + e^- \rightarrow \nu_e + e^-$	ES		Water (440 t H ₂ O)	Cherenkov		Henderson Mine, Colorado	abandoned	[70] ¹⁰³

СПЕКТР НЕЙТРИНО



The New Minimal Standard Model

- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino

* With SM fields: Use ν_L^c is right-handed

$$\mathcal{L} - \mathcal{L}_{SM} = -\frac{1}{2}M_\nu \overline{\nu_L} \nu_L^c + h.c. \Rightarrow \begin{cases} L \text{ is violated} \Rightarrow \text{Majorana } \nu = \nu^c \\ SU(2)_L \text{ is violated} \Rightarrow \text{Effective LE} \end{cases}$$

* Introduce ν_R AND impose L conservation

$$\mathcal{L} - \mathcal{L}_{SM} = -M_D \overline{\nu_L} \nu_R - \frac{1}{2}M_{\cancel{R}} \overline{\nu_R} \nu_R^c + h.c. \Rightarrow \text{Dirac } \nu \neq \nu^c:$$

- Either way $\Rightarrow$ Charged current interactions of massive leptons are not diagonal

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} (U_{\text{LEP}}^{ij} \overline{\ell^i} \gamma^\mu L \nu^j + U_{\text{CKM}}^{ij} \overline{U^i} \gamma^\mu L D^j) + h.c.$$

For $N = 3 + s$ ν 's: $U_{\text{LEP}} = 3 \times N$ $U_{\text{LEP}} U_{\text{LEP}}^\dagger = I_{3 \times 3}$ $U_{\text{LEP}}^\dagger U_{\text{LEP}} \neq I_{N \times N}$

- Either way $\Rightarrow$ Lepton flavours not conserved in ν propagation

The New Minimal Standard Model: ν flavour oscillations

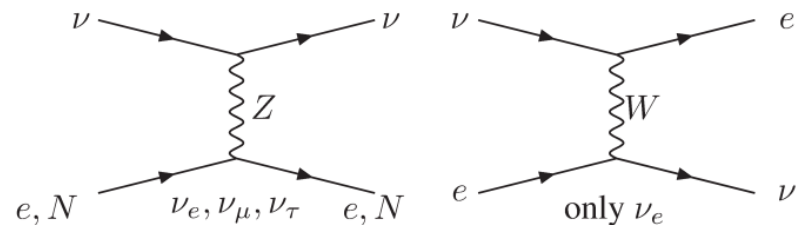
- In vacuum:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{j \neq i}^n \text{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2 \left(\frac{\Delta_{ij}}{2} \right) + 2 \sum_{j \neq i} \text{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin(\Delta_{ij})$$

$$\Delta_{ij} = (m_i^2 - m_j^2) \frac{L}{4E} \Rightarrow \text{No information on } \nu \text{ mass scale nor Majorana/Dirac}$$

- When osc between 2- ν dominates: $P_{\alpha \neq \beta} = \sin^2(2\theta) \sin^2 \left(\Delta m^2 \frac{L}{4E} \right)$
 $\Rightarrow$ No information on Mass Ordering ($\equiv \text{sign}(\Delta m^2)$) nor octant of θ nor CPV

- If ν cross matter regions (Sun, Earth...)
it interacts coherently
Different flavours have different interaction



$$\Rightarrow \text{Effective potential in } \nu_e \text{ evolution: } V_e \neq V_{\mu, \tau} \Rightarrow \Delta V^{\nu_e} = -\Delta V^{\bar{\nu}_e} = \sqrt{2} G_F N_e$$

$\Rightarrow$ Modification of mixing angle and oscillation wavelength (MSW)

$\Rightarrow$ Solar ν'_e s: 2ν -dominant dependence on θ octant

$\Rightarrow$ LBL & ATM $\nu_{\mu(e)}, \bar{\nu}_{\mu(e)}$: Dependence on $\text{sign}(\Delta m^2)$

Seesaw Mechanism

- ✿ ν_L has a right-handed partner ν_R
- ✿ In addition to the usual “Dirac mass” connecting ν_L with ν_R , there is also a large mass connecting ν_R with its conjugate $(\nu^c)_L$

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- ✿ M_R is not protected by any symmetry, and can be very large. $\Rightarrow$

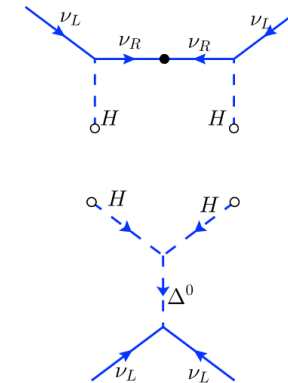
$$m_\nu^{\text{light}} = \frac{m_D^2}{M_R}$$

- ✿ For $m_D \sim 100$ GeV, $M_R \sim 10^{15}$ GeV, light neutrino mass of 10^{-2} eV is obtained. $M_R \sim 10^{15}$ GeV is close to the scale of grand unification

Varieties of Seesaw

- ✿ $\nu_L - \nu_R$ seesaw is termed “Type-I” seesaw. Here one integrates out a heavy fermion, the ν_R
- ✿ A second “Type-II” seesaw can be realized by integrating out scalars:

$$m_\nu^{\text{light}} \sim Y \left(\frac{\mu v^2}{M_\Delta^2} \right)$$



Left-Right Symmetric Models

- ✿ Gauge symmetry is extended to:

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Pati, Salam (1974); Mohapatra, Pati (1975); Mohapatra, Senjanovic (1979)

- ✿ Fermions transform in a left-right symmetric manner:

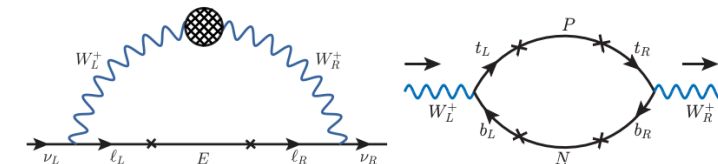
$$Q_L (3, 2, 1, 1/3) = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad Q_R (3, 1, 2, 1/3) = \begin{pmatrix} u_R \\ d_R \end{pmatrix},$$

$$\Psi_L (1, 2, 1, -1) = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \Psi_R (1, 1, 2, -1) = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}.$$

- ✿ Note the natural appearance of the right-handed neutrino
- ✿ Under Parity symmetry $Q_L \leftrightarrow Q_R$, $\Psi_L \leftrightarrow \Psi_R$, $W_L \leftrightarrow W_R$

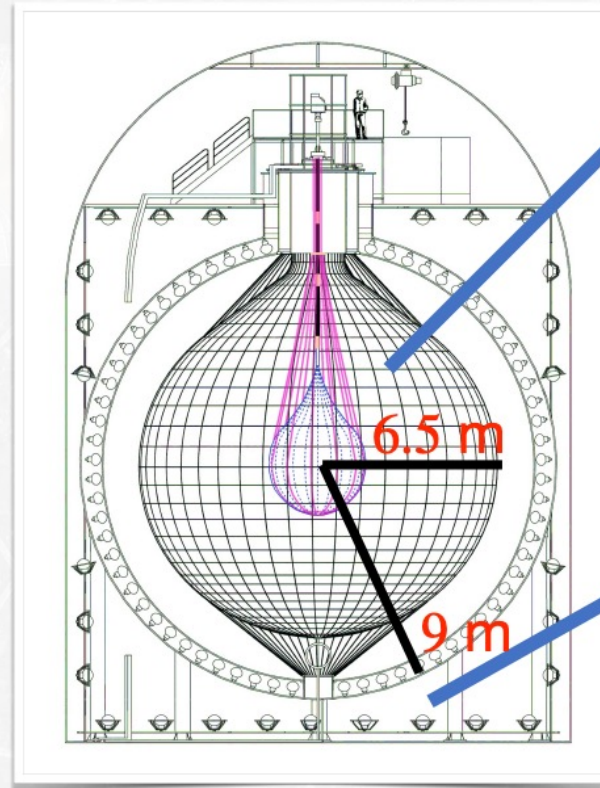
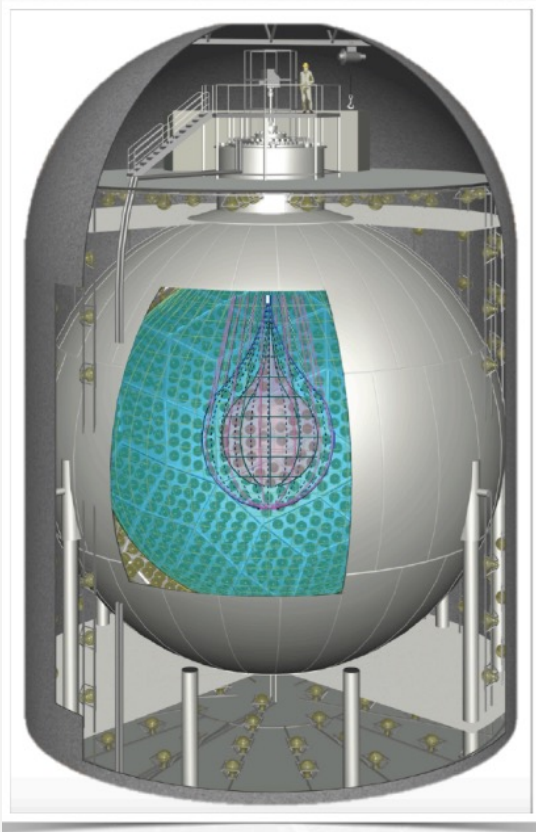
Two-loop Dirac Neutrino Masses

- Neutrino masses arise as quantum corrections
- $W_L^+ - W_R^+$ mixing is absent at tree-level in the model
- $W_L^+ - W_R^+$ mixing induced at loop level, which in turn generates small Dirac neutrino mass at two loop Babu, He (1989)



- Flavor structure of two loop diagram needs to be studied to check consistency
- Oscillation data fits well within the model regardless of Parity breaking scale Babu, He, Su, Thapa (2022)

Turning KamLAND into a $0\nu\beta\beta$ Detector



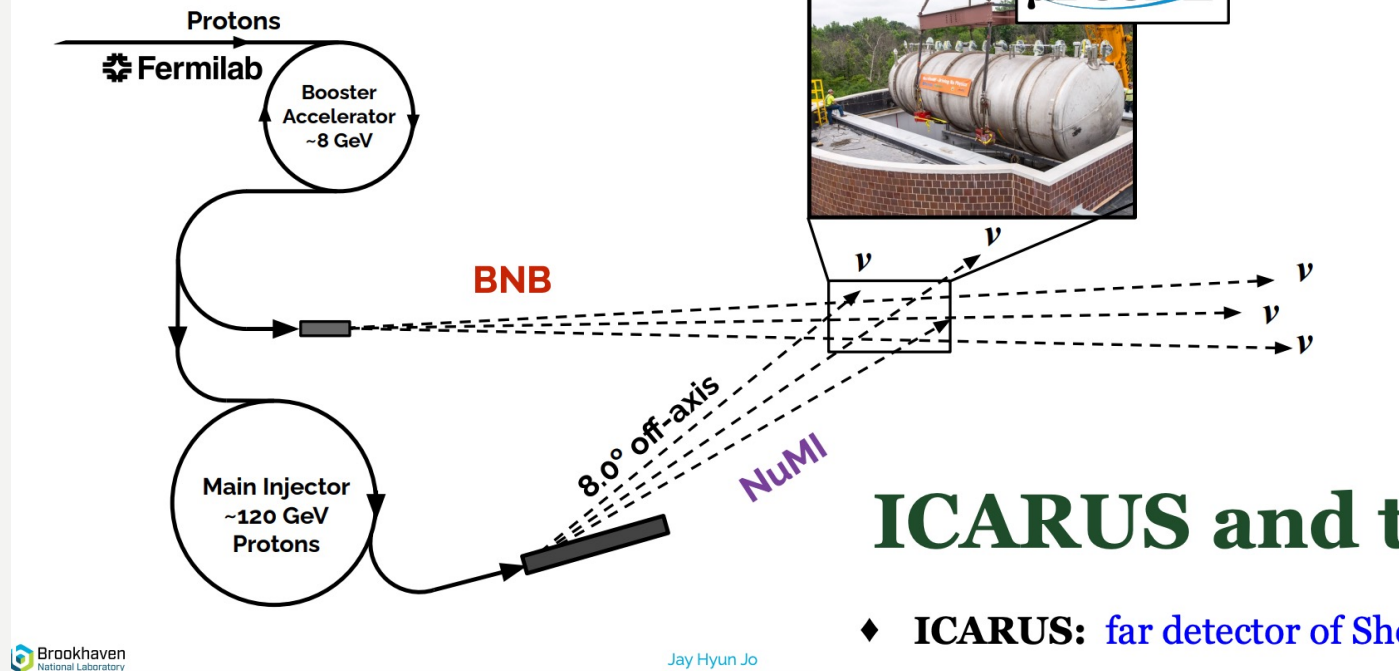
KamLAND Liquid Scintillator

1 kton liquid scintillator
made of 80 % dodecane
+ 20 % pseudocumene
+ 1.36 g/L PPO

Water Cherenkov (Veto) Detector

3.2 kton water for
muon veto

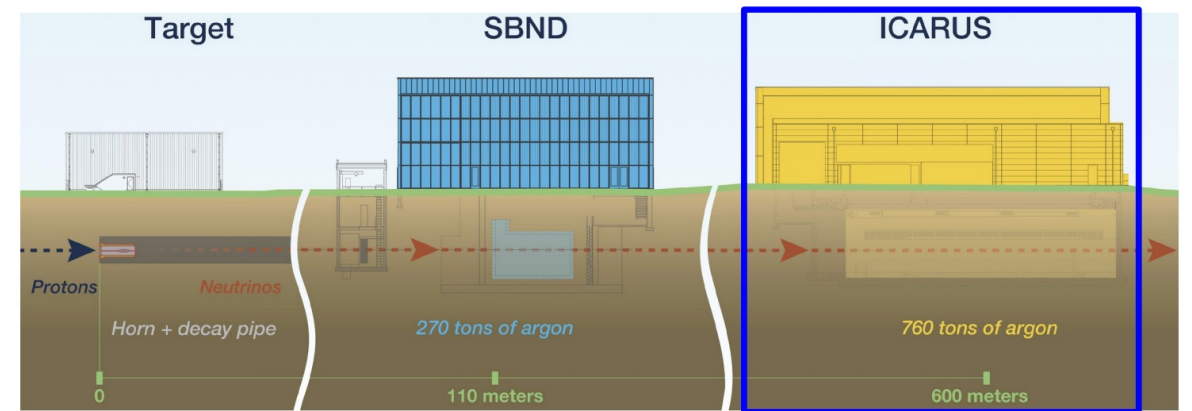
3+1 Sterile Neutrino Search: Two beam lines



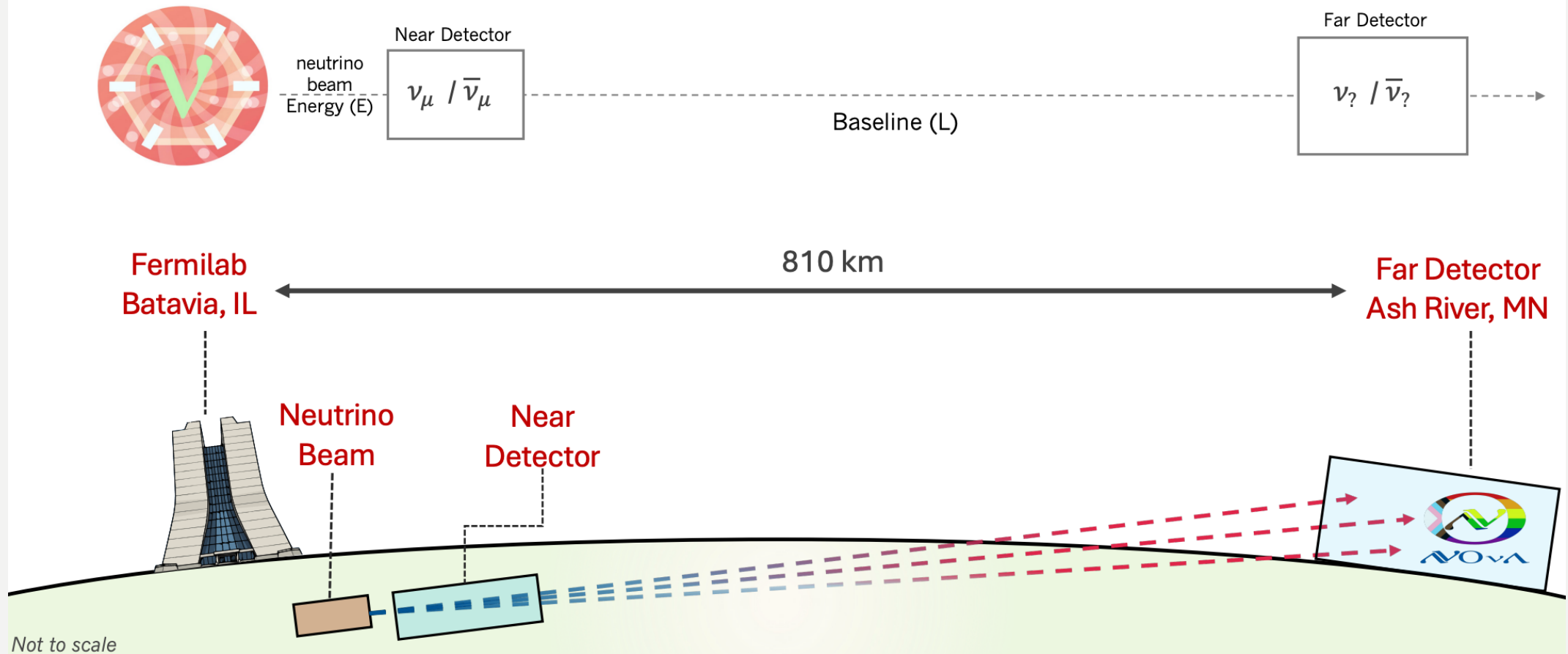
ICARUS and the SBN Program

- ◆ **ICARUS**: far detector of Short-Baseline Neutrino (SBN) Program at Fermilab
- ◆ Originally operated at LNGS (Gran Sasso, Italy); shipped to US in 2018
- ◆ Primary physics goal: **study anomalous neutrino oscillations** (e.g. sterile neutrinos) at short baselines ($L \sim 600$ m) and $L/E \sim 1$ m/MeV using the **BNB**

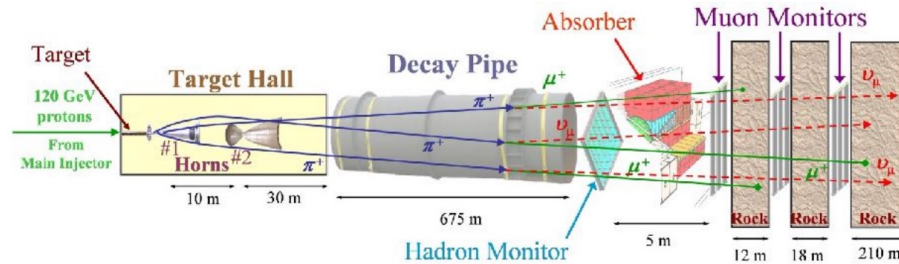
**Booster
Neutrino
Beamline
(BNB)
@
Fermilab**



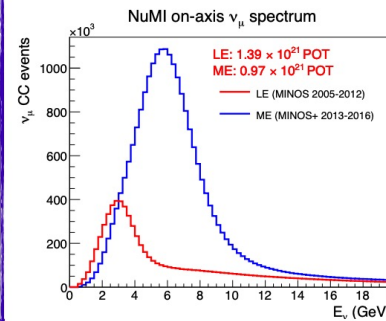
NOvA is a long-baseline neutrino oscillation experiment.



The NuMI Beam at FNAL



- Lowest energy possible was chosen as final LE setting (**just** low enough!)
 - Low Energy configuration, energy peak around 3 GeV (2005-2012)
 - Medium Energy configuration, energy peak at around 7 GeV (2013-2016), result of optimising off-axis flux at NOVA
- Hardware (slow) failings and component changes over time
- Forward Horn Current (FHC, ν) and Reverse Horn Current (RHC) $\bar{\nu}$ -bar



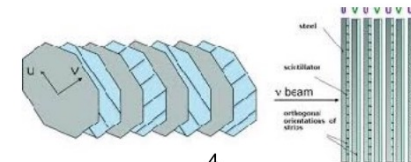
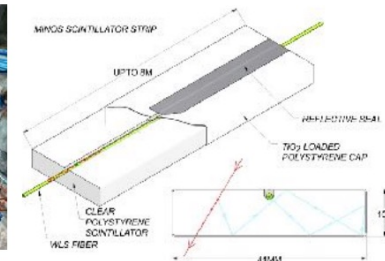
3

The MINOS Experiment

- MINOS detectors were two functionally identical, magnetised (1.4T), tracking, sampling calorimeter detectors.
- Oriented for beam ν_μ -charged current (CC) events (track orthogonal to planes), full event containment (muon and shower)



Far Detector
735 km from beam target
5.4 kton mass

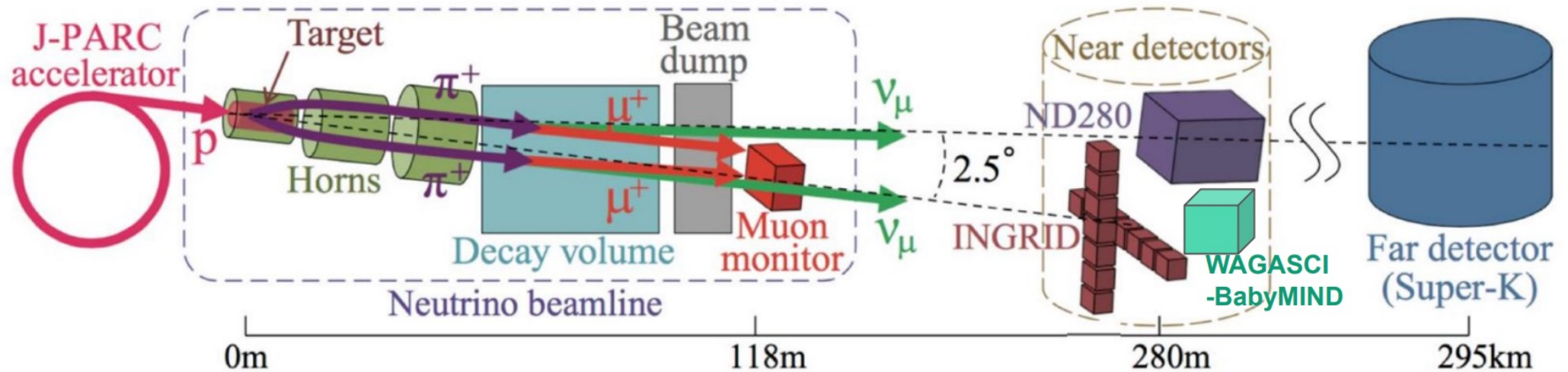


Near Detector
1 km from beam target
1 kton mass

4

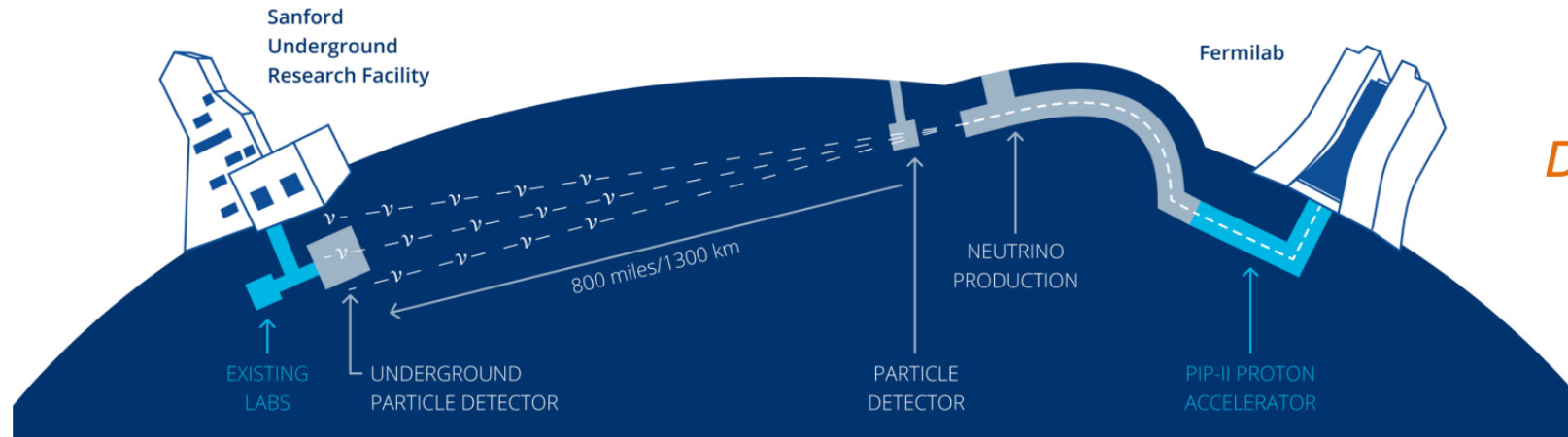
The T2K Experiment

- Accelerator-based neutrino oscillation experiment in Japan



- High intensity **neutrino beam**, predominantly ν_μ ($\bar{\nu}_\mu$)
- On/Off-axis near detectors (280 m): **INGRID**, **ND280**, **WAGASCI-BabyMIND**
- Off-axis far detector (295 km): **Super-Kamiokande**

DUNE in a Nutshell



DUNE has entered the installation phase!

LBNF: Long Baseline Neutrino Facility

The Science (DUNE)

- CPV in neutrinos
- neutrino mass ordering
- Test 3-flavor paradigm
- New Physics
- Astrophysics

The Technology (DUNE)

- Four 17 kiloton LAr detectors – largest of its kind!
- A movable near detector

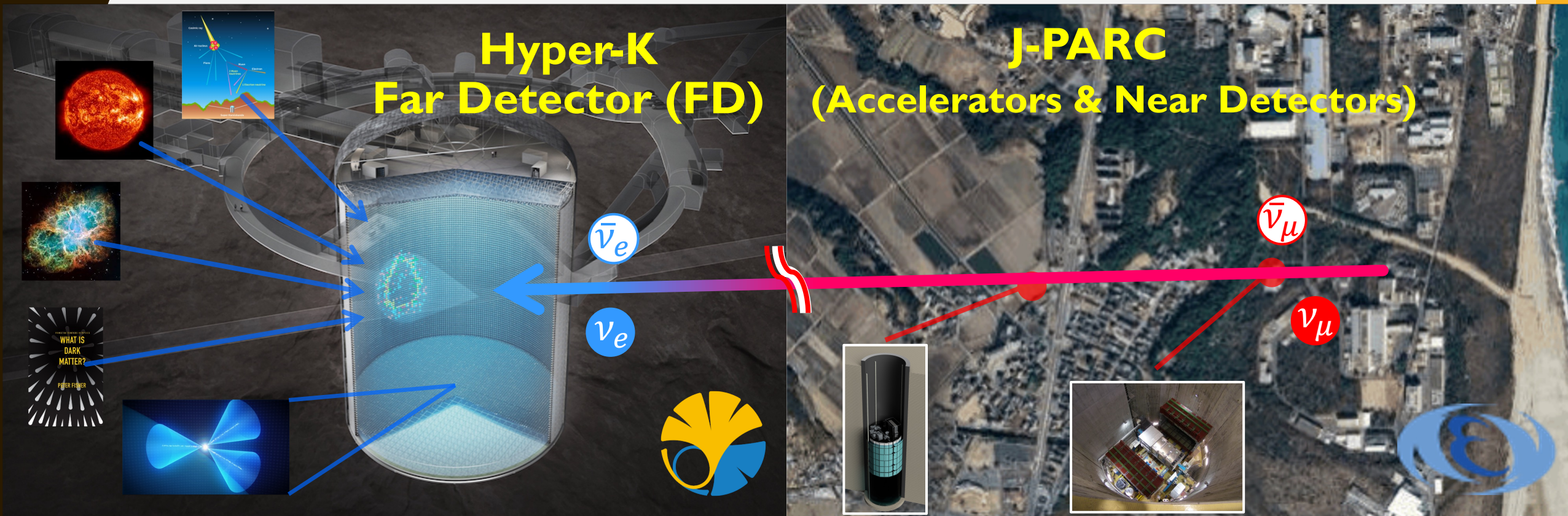
DUNE will be built in two phases

The Facility (LBNF)

- Colossal caverns at 1.5 km underground
- World's most intense neutrino beam (> 2 MW) and wide-band
- longest distance accelerator neutrinos ever traveled

THE HYPER-KAMIOKANDE PROJECT

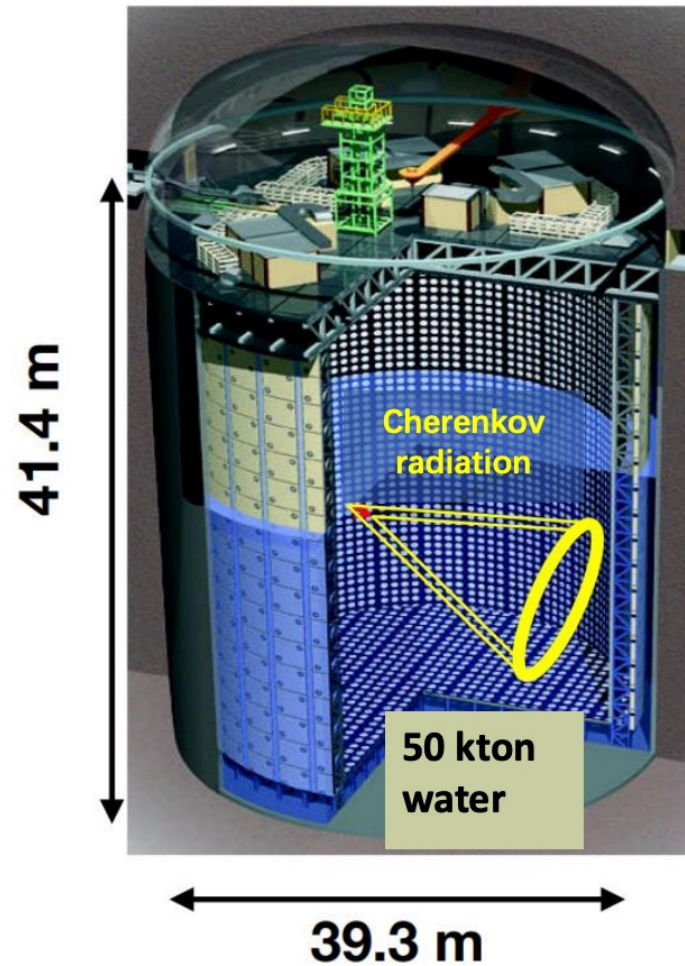
54



- Rich physics program with discovery potential
- Operation planned for 2028
- Hosted by two institutes; UTokyo & KEK



The Super-Kamiokande Detector



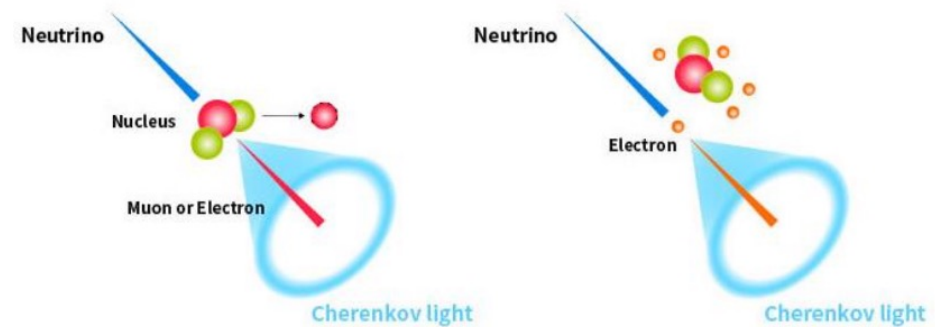
- Located at Kamioka, Gifu, Japan
- Under Mt. Ikenoyama (2,700 m.w.e)
- Inner detector watched by >11,000 20-inch PMTs
- Multi-purpose neutrino observatory

► Solar neutrinos

► Reactor neutrinos

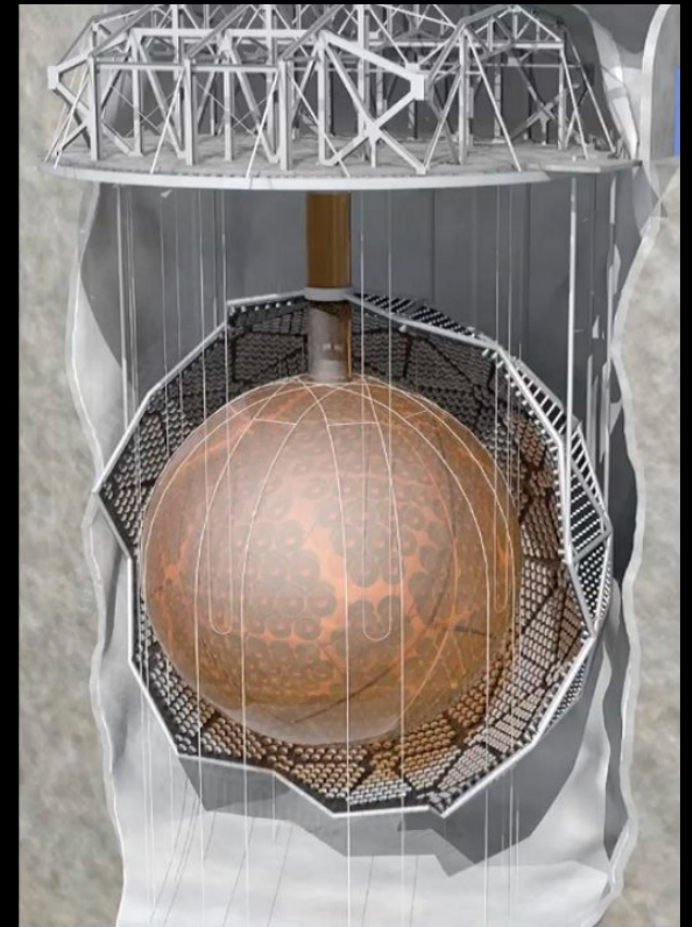
- Supernova neutrinos
- Accelerator neutrinos

► Atmospheric neutrinos



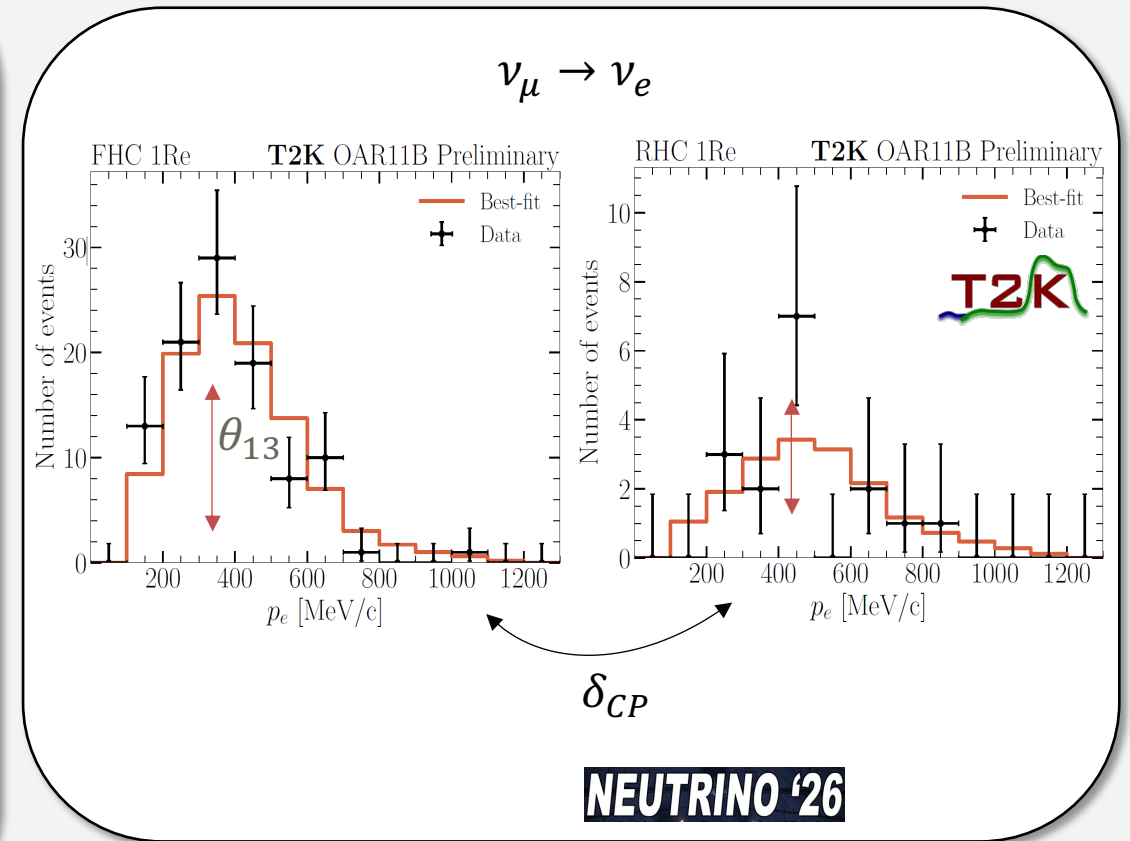
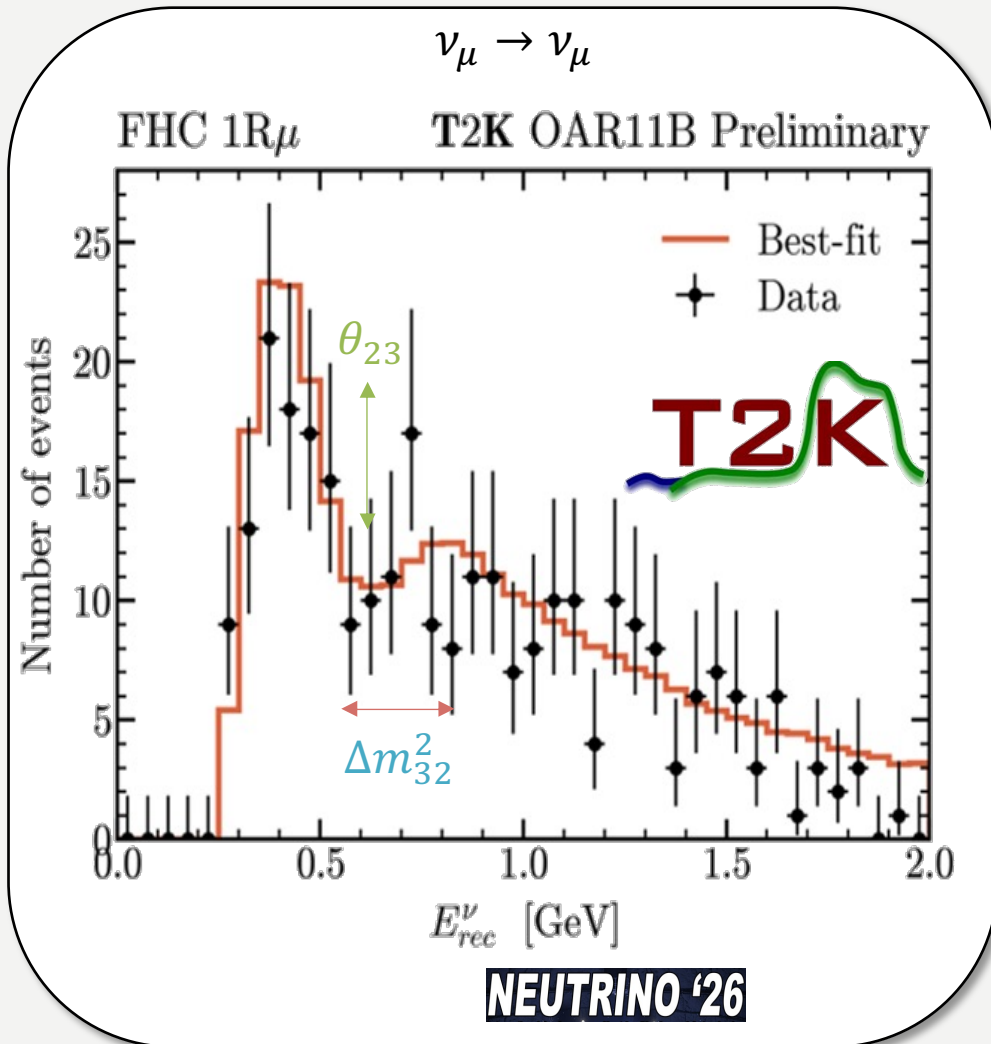
SN0+ detector

- Central acrylic vessel (AV) holds ~1 kt water (or ~780 t scintillator)
- 6 m radius AV viewed by ~9400 PMTs
- 7 kt buffer water in cavity (shielding)
- Hold-down rope net
- Upgraded calibration systems, electronics, DAQ, underground scintillator plants

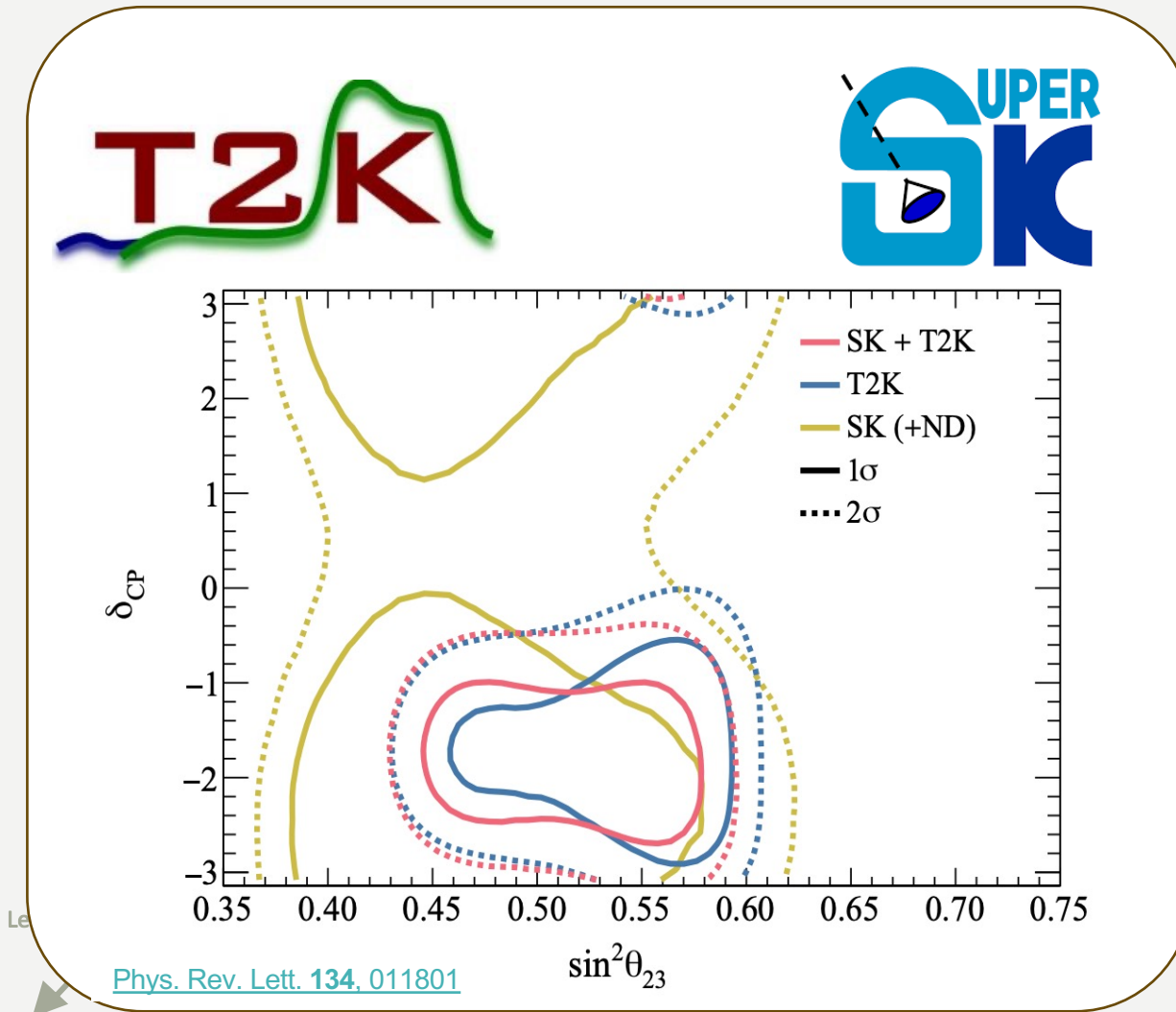


SN0+ detector paper: JINST 16 P08059 (2021)

T2K & NOVA

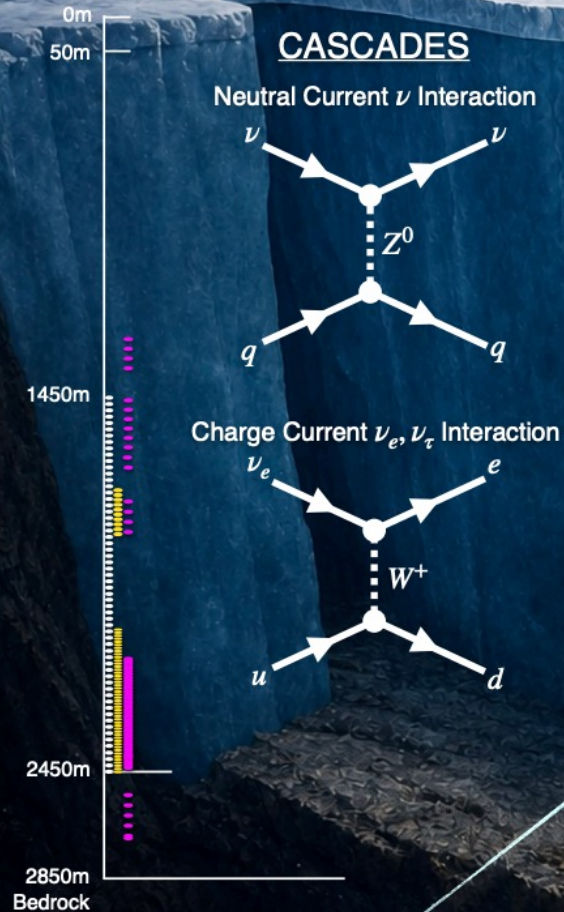


T2K + SUPERKAMIOKANDE





A CUBIC KILOMETER OF CLEAR
ANTARCTIC ICE INSTRUMENTED
TO DETECT NEUTRINOS



In-Ice Optical Modules



DIGITAL OPTICAL MODULE (DOM)

Each DOM contains:

- 10" PMT
- Readout electronics
- Calibration LEDs

5,160 DOMs total



MULTI-PMT DOM (mDOM)

Each mDOM contains:

- x24 3.15" PMT
- Readout electronics
- x10 flasher LEDs
- Three cameras

288 mDOMs total



DUAL SENSORS IN AN ELLIPSOID GLASS FOR GEN2 (D-Egg)

Each D-Egg contains:

- Two 8" HQE PMT
- Readout electronics
- x12 UV LEDs
- Three cameras

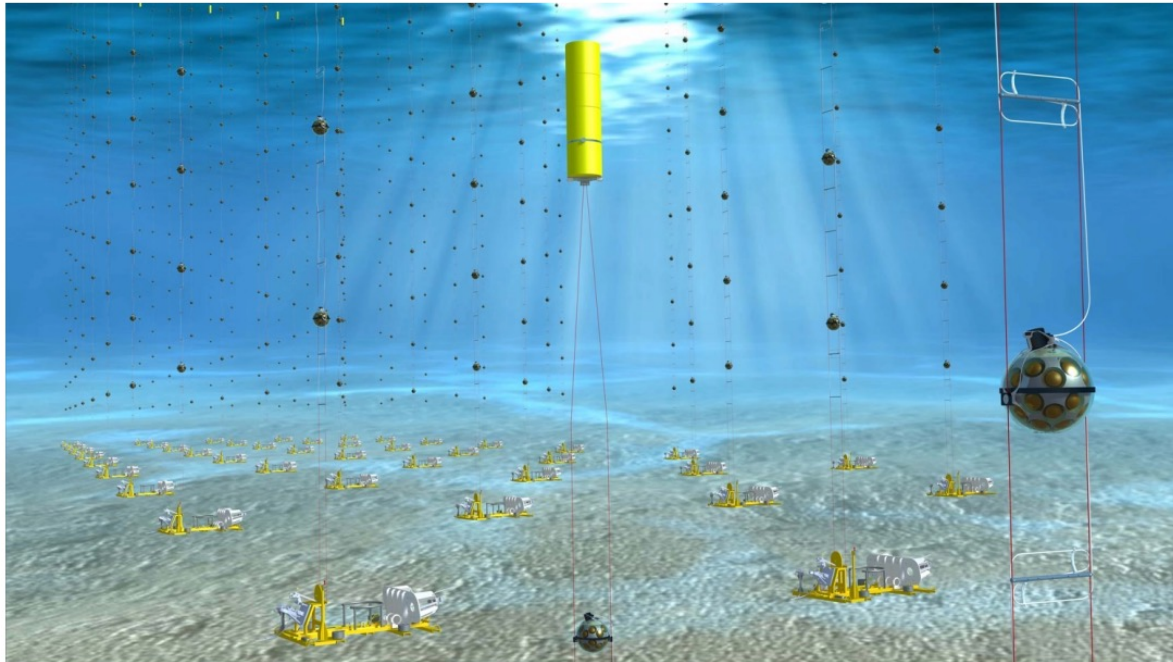
200 D-Eggs total

+ additional special devices

KM3NeT: research infrastructure in the Mediterranean Sea

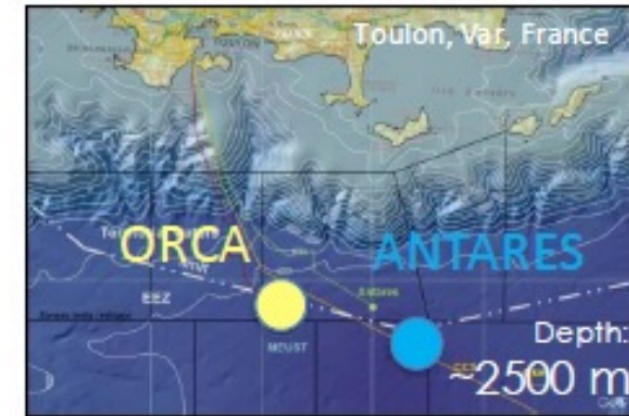
Two neutrino telescopes + portal for earth/sea sciences and marine biology

km³ Neutrino Telescope



3D array of light sensors in glass spheres at large depth.
Lines connected to sea-floor network, real-time data to shore station.

Uses Cherenkov light: single photon sensitivity, precise timing.



6/26/2026

Atmospheric neutrinos in KM3NeT

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