FROM RESEARCH TO INDUSTRY

Irfu
Institut de recherche
sur les lois fondamentales
de l'Univers

IAS TUM Institute for Advanced Study

Neutrinos from Reactor and Natural Sources

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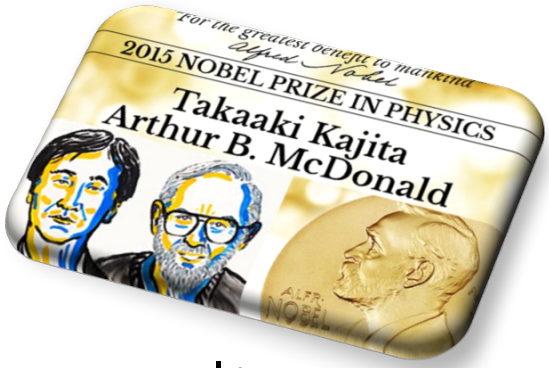
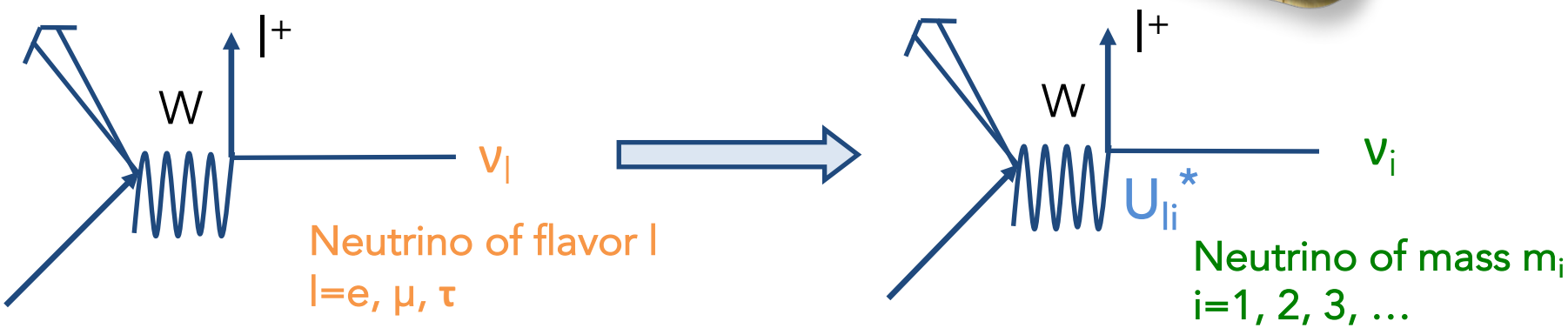
Established Neutrino Physics

- 3 flavor, spin ½, neutral, left handed, $\sigma(1\ \text{MeV}) \approx 10^{-44}\ \text{cm}^2$
- Tiny masses: $0.04\ \text{eV} < m_\nu < \approx 1\ \text{eV}$
- Mixing: two views on W-decay:





- PMNS mixing matrix U: $|\nu_i\rangle = \Sigma\, U_{\alpha i}\, |\nu_\alpha\rangle$

3 ν Oscillation Formalism

PMNS mixing matrix

Atmospheric — Cross-Mixing — Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} : "atm." angle

θ_{13}

δ dirac CP phase

θ_{12} : "solar" angle

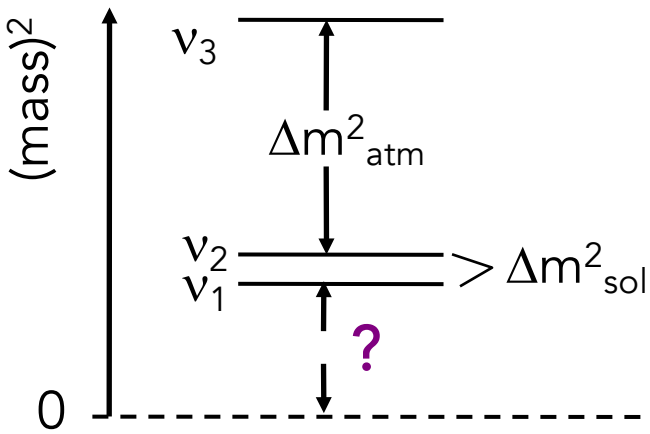
Majorana CP phases
(L violating processes)

- 3 masses m_1, m_2, m_3: $\Delta m^2_{sol} = m_2^2 - m_1^2$ & $\Delta m^2_{atm} = |m_3^2 - m_1^2|$

- Oscillation: $P(\bar{\nu}_x \rightarrow \bar{\nu}_x) = 1 - \sin^2(2\theta_i)\sin\left(1.27\frac{\Delta m_i^2\ (eV^2) L\ (m)}{E\ (MeV)}\right)$

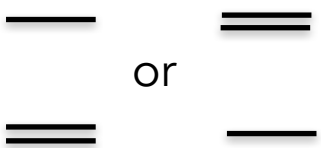
Facts & open questions

- Masses of the mass eigenstates ν_i?



} ν flavor change

} β decay, 0νββ decay, cosmology

- Spectral pattern  or ?

} ν behavior in matter, 0νββ

- Lepton Number conservation (Dirac or Majorana) ?

} 0νββ

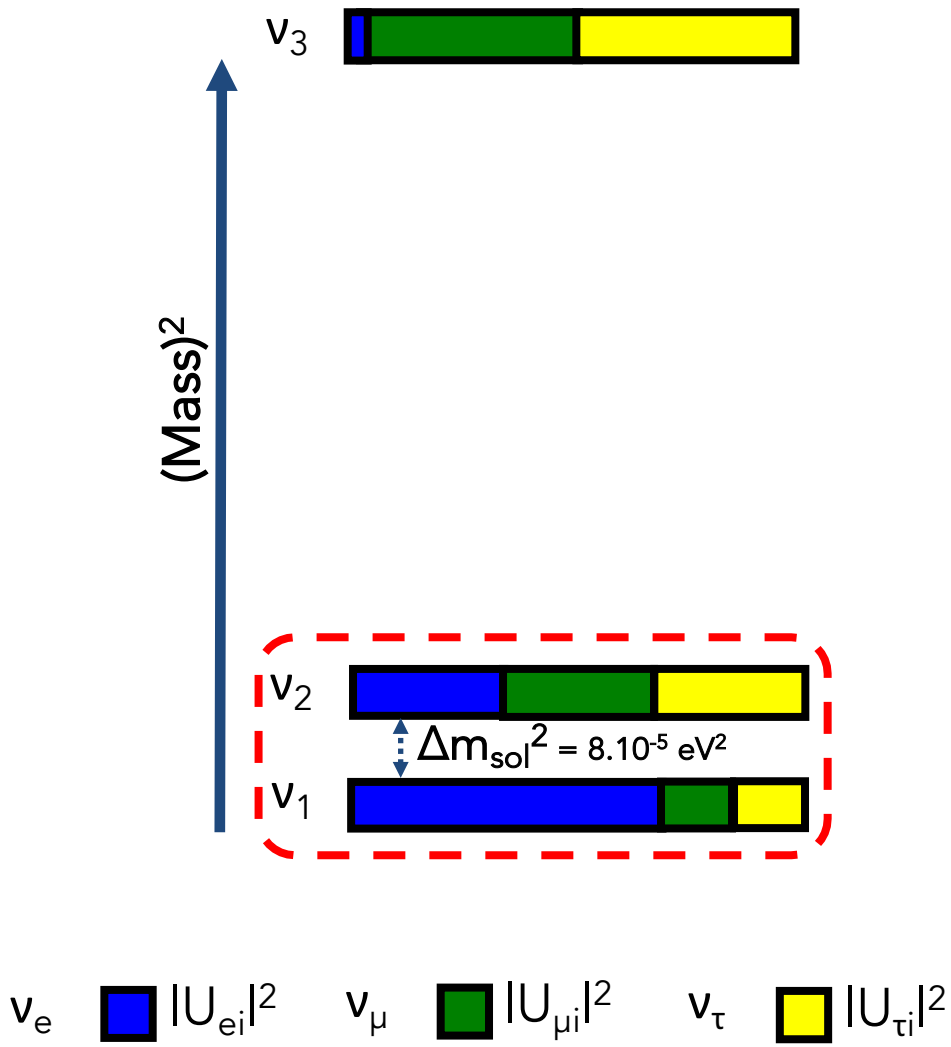
- Precise measurements of PMNS matrix?
- Is CP violated in the neutrino sector?

} ν flavor change

- Are there additional (sterile) neutrino states

} ν flavor change, cosmology

Δm^2_{21} & θ_{12}

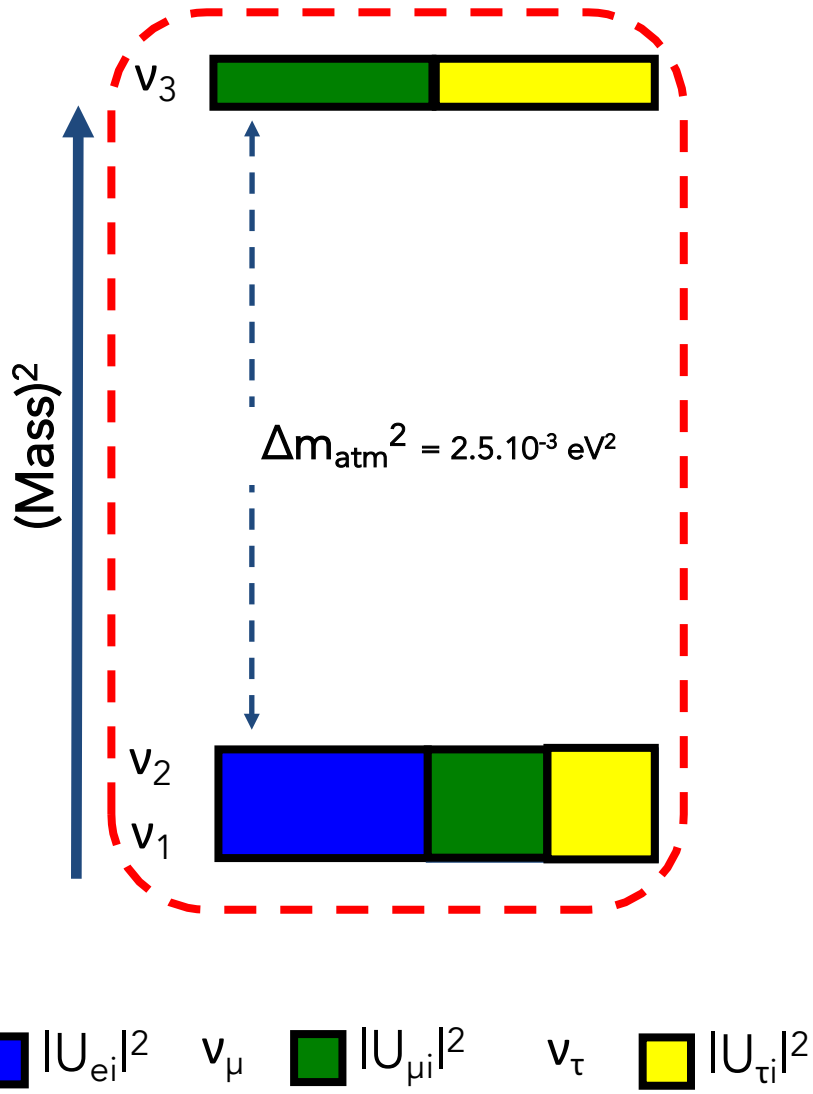


Δm^2 (eV^2) ~ L(km) / E(MeV)

Reactor
- L~100 km & E~MeV

Solar
- MSW flavor transition

Δm^2_{31} & θ_{23}



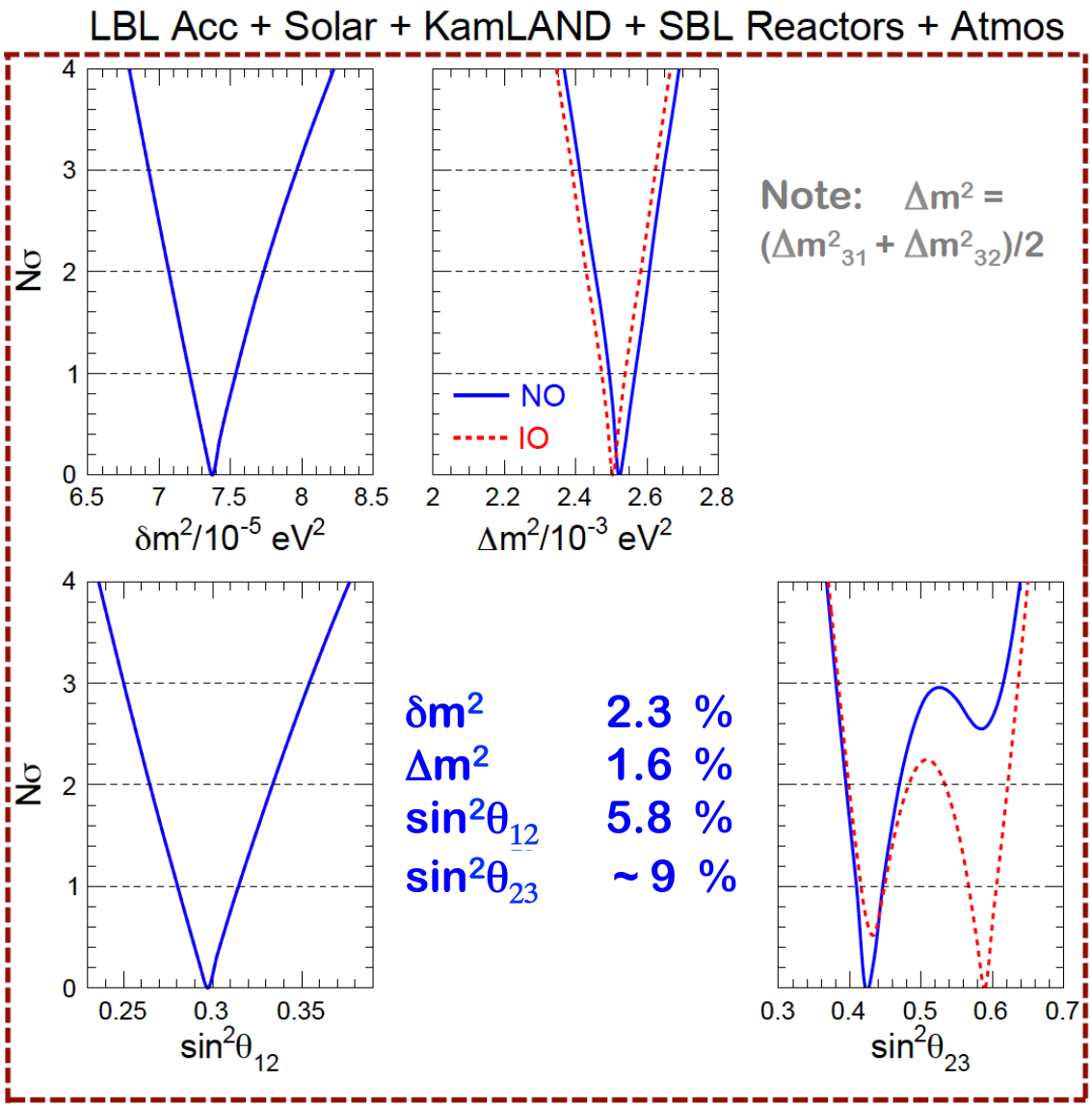
Δm^2 (eV^2) ~ L(km) / E(MeV)

Atmospheric:
- L ~ 10^4 km & E ~ 1-30 GeV

Reactors:
- L ~ 1 km & E ~ 3 MeV

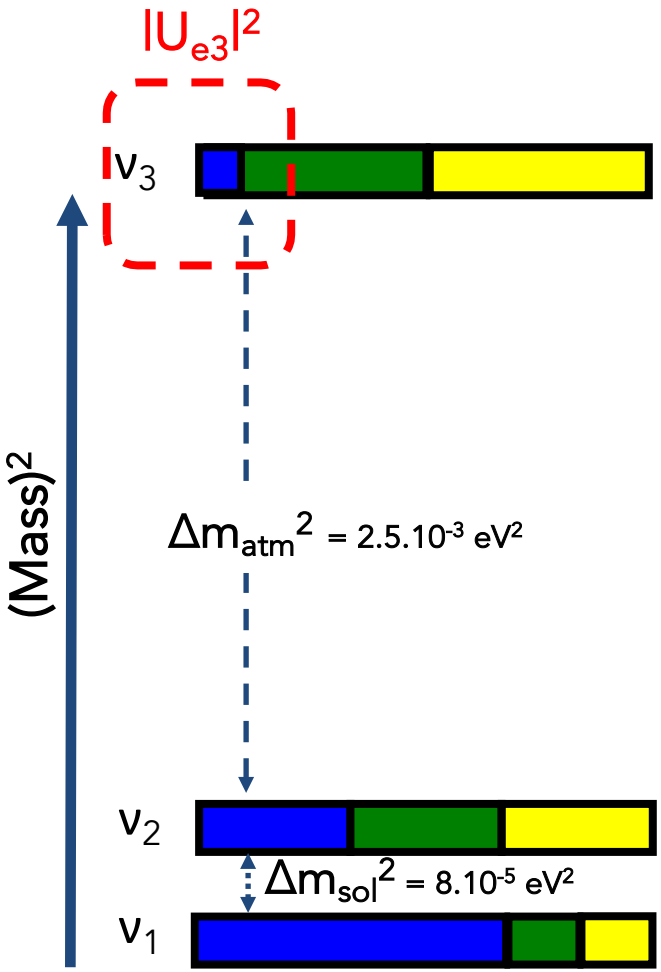
Accelerators:
- L ~ 1000 km & E ~ 3 GeV

Global analysis of ν oscill. data



@Credit: E. Lisi

θ_{13}



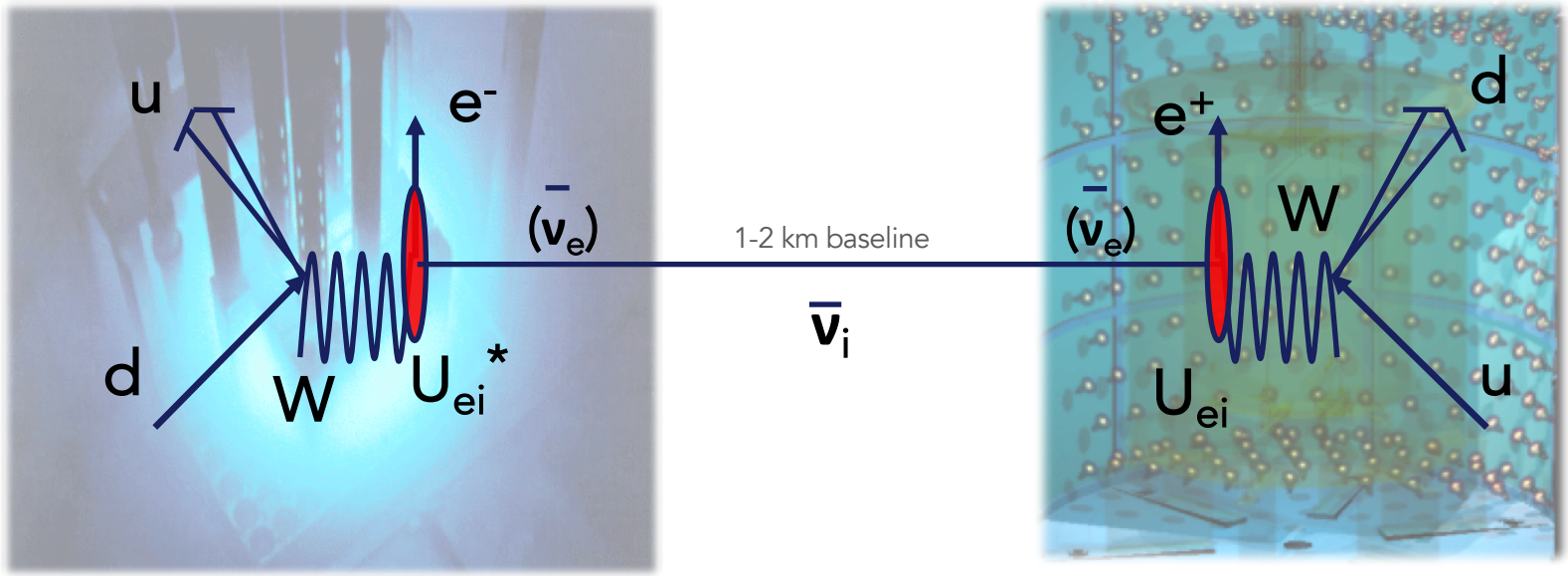
- L~1 km, E~MeV
  - reactor
  - θ_{13} only
- L~1000 km, E~GeV
  - beam
  - appearance expt. @Beam
  - θ_{13}, sign(Δm^2_{31}), δ_{CP}

ν_e $|U_{ei}|^2$ ν_μ $|U_{\mu i}|^2$ ν_τ $|U_{\tau i}|^2$

θ_{13} at Nuclear Reactors

$$^{235}U + n_{th} \rightarrow X + Y \rightarrow \beta - \text{decays}$$

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



Reactor core

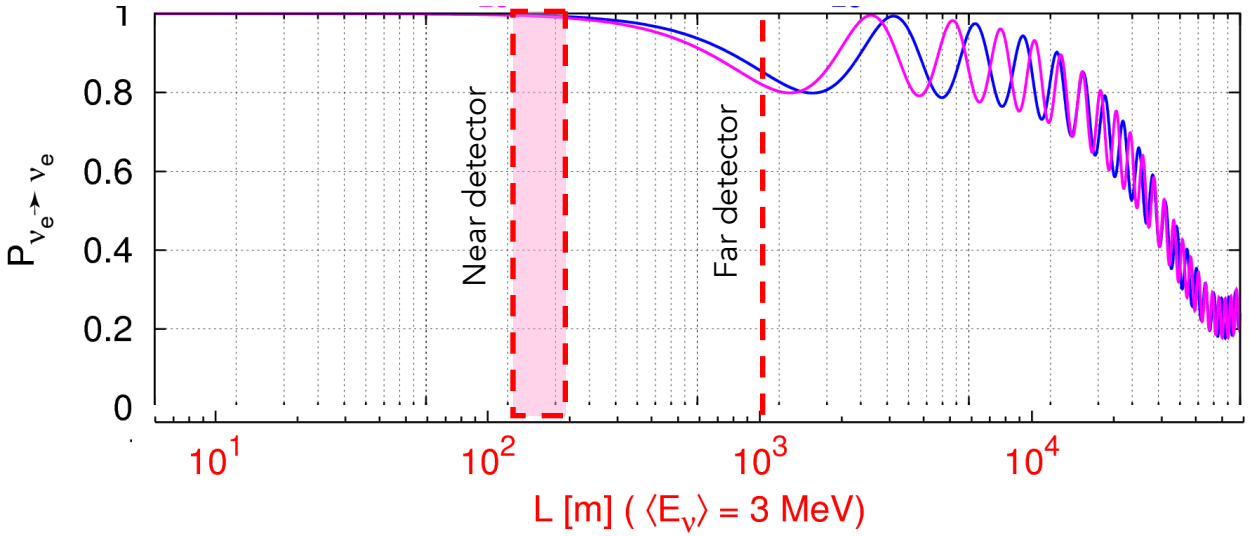
Target free protons

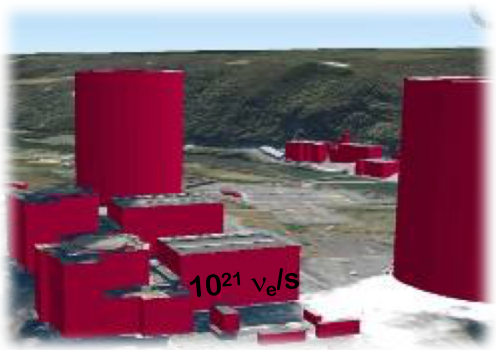
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\left[\sin\left(1.27\frac{\Delta m^2_{atm}\ (eV^2)L\ (m)}{E\ (MeV)}\right) + O\left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right)\right]$$

"clean" measurement of θ_{13}

Experimental Concept

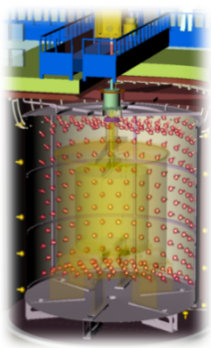
$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2 L/E)$





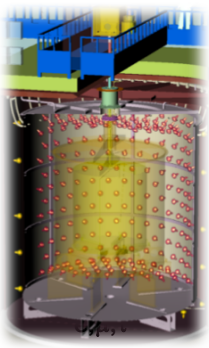
Nuclear Power Station

$\bar{\nu}_e$



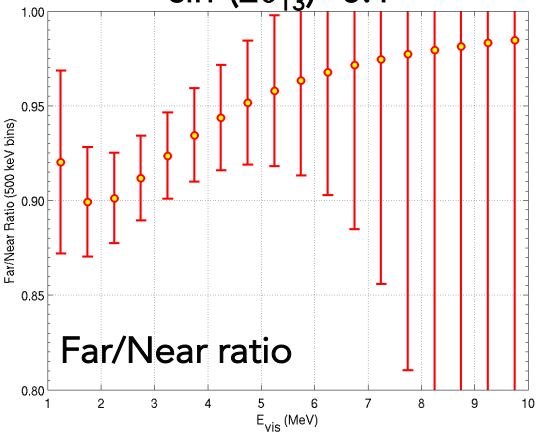
Near detector(s)
<< 1 km

$\bar{\nu}_{e,\mu,\tau}$

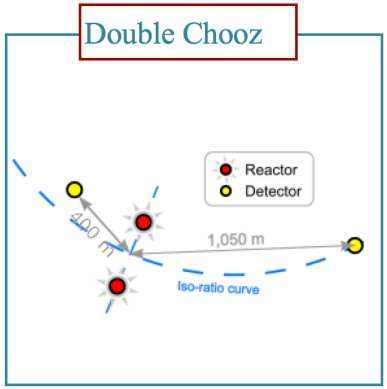


Far detector(s)
1-2 km

$\sin^2(2\theta_{13})=0.1$

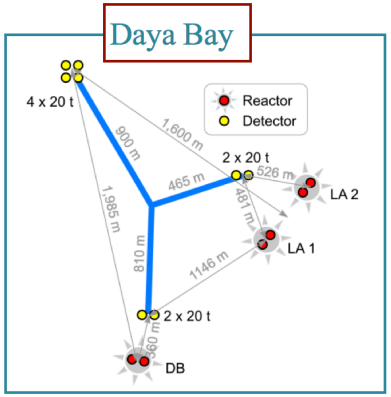


Double Chooz / Daya Bay / RENO



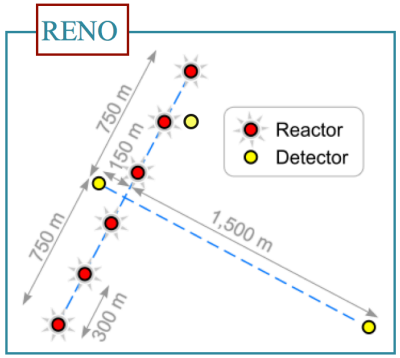
Cons: baseline – 16 tons target

Pros: 2 cores, reactor off-off time, low accidental backgrounds



Cons: 6 cores – no PMTs on lids

Pros: 160 tons target, optimal baseline, low correlated backgrounds

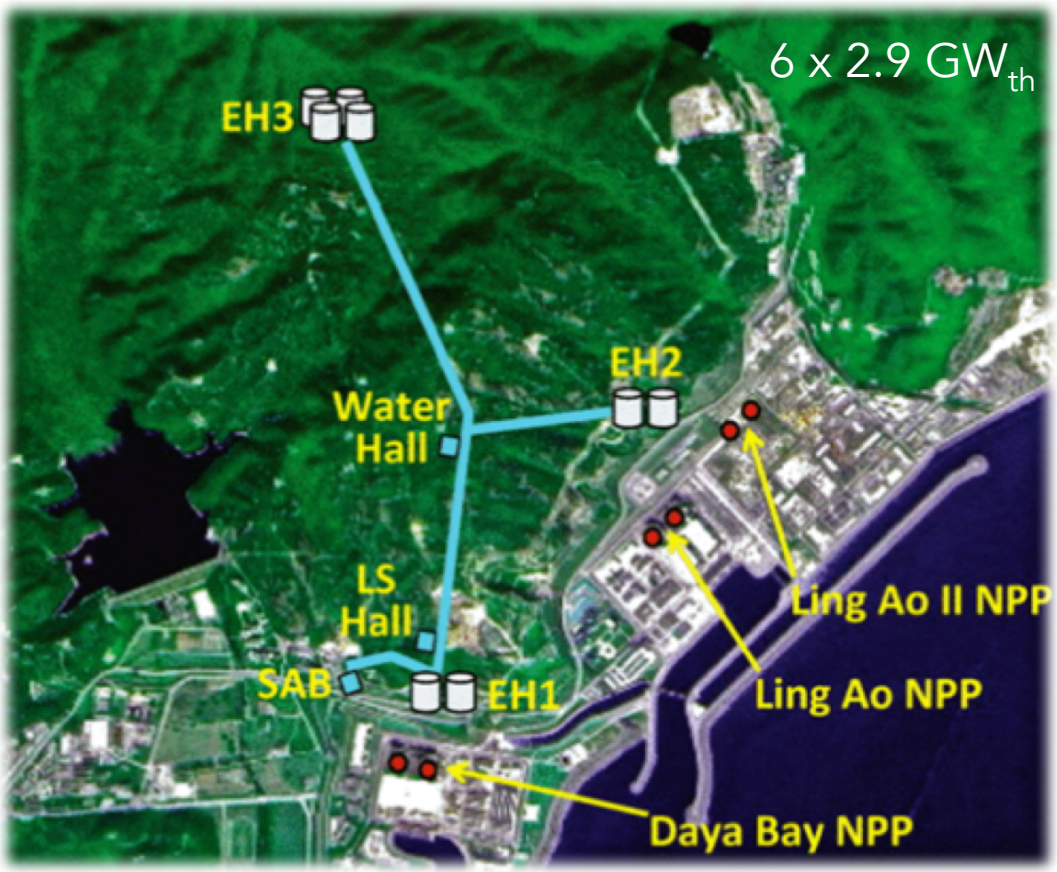


Cons: 6 cores - asymmetric configuration, accidental bkg, calibration

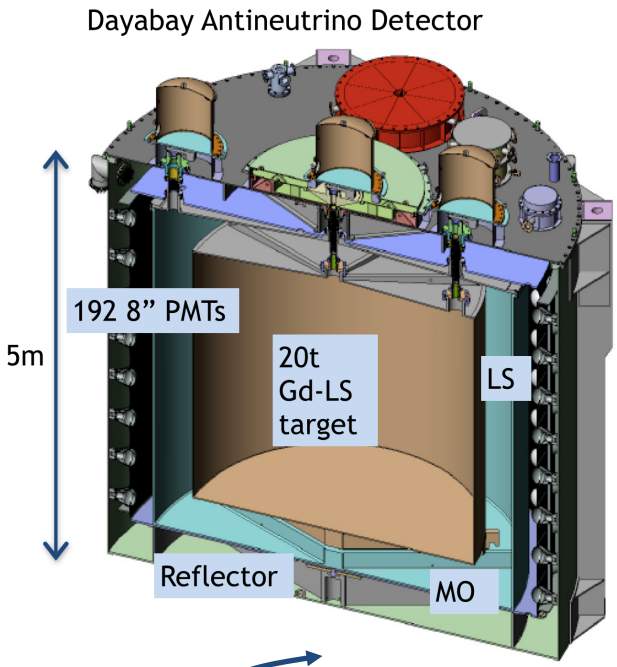
Pros: 32 tons, pragmatic

Daya Bay – China

Largest, deepest, and most precise θ_{13} experiment



1230 days of operation



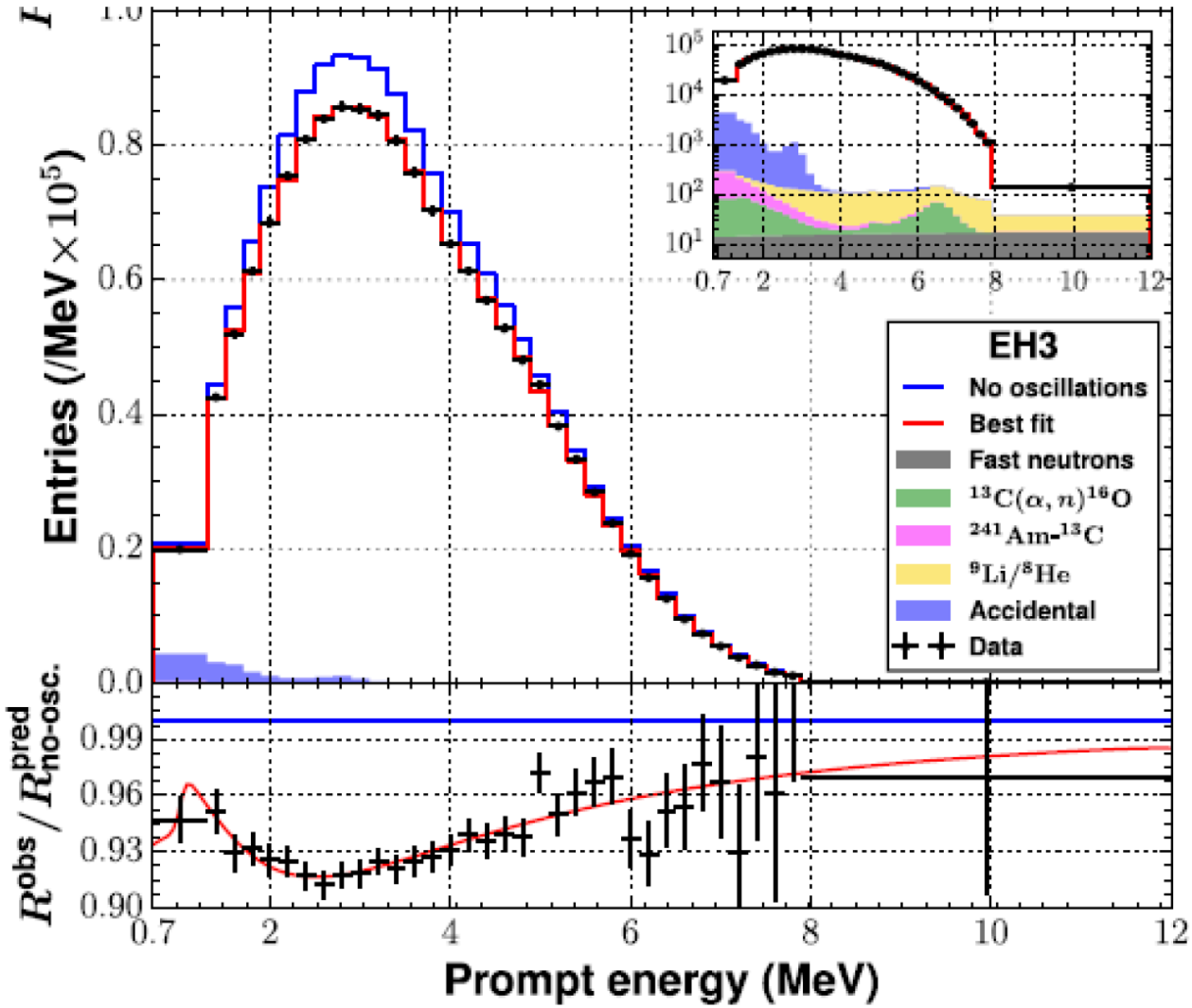
20 ton target

X 8

Daya Bay

$\sin^2(2\theta_{13}) = 0.0841 \pm 0.0033$ (stat + sys)

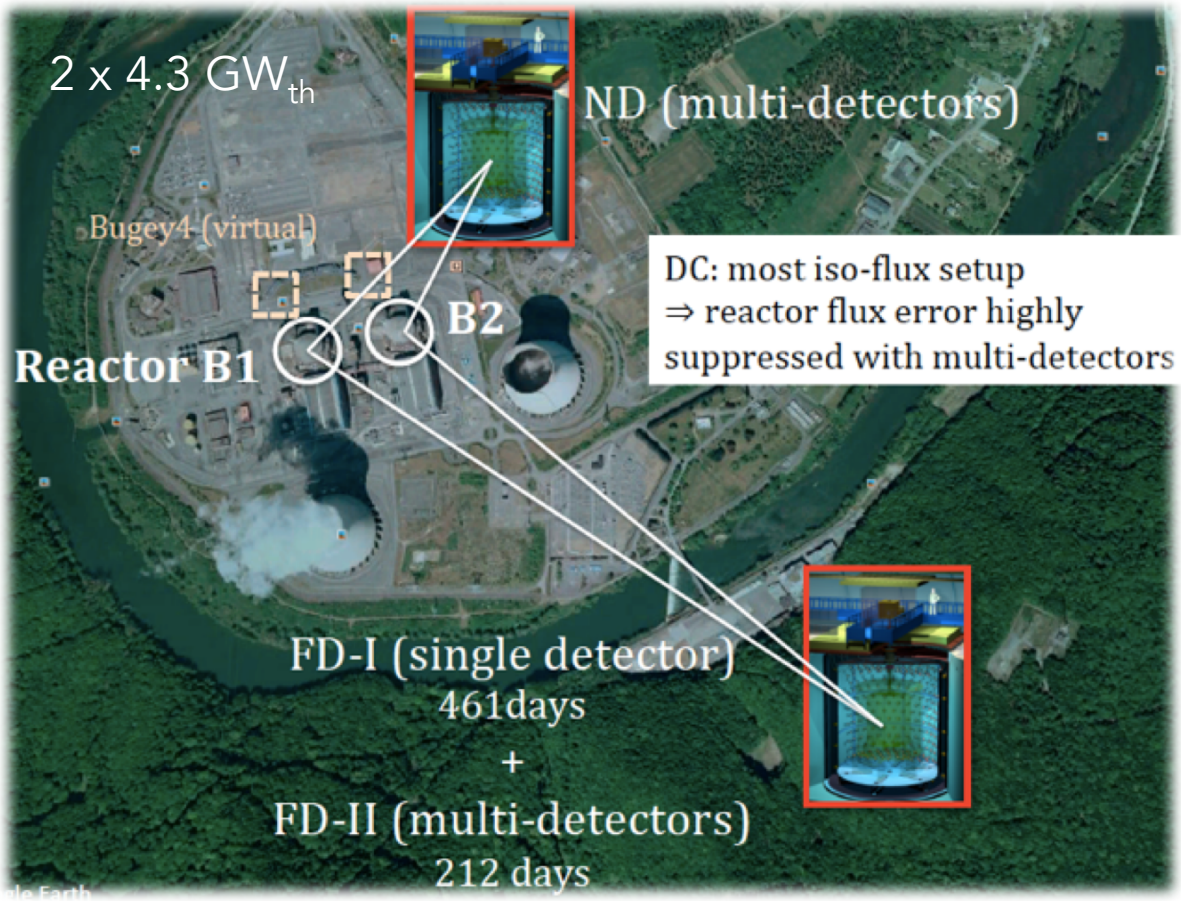
$|\Delta m_{ee}^2| = 2.50 \pm 0.06$ (stat.) $\pm$ 0.06 (syst.)

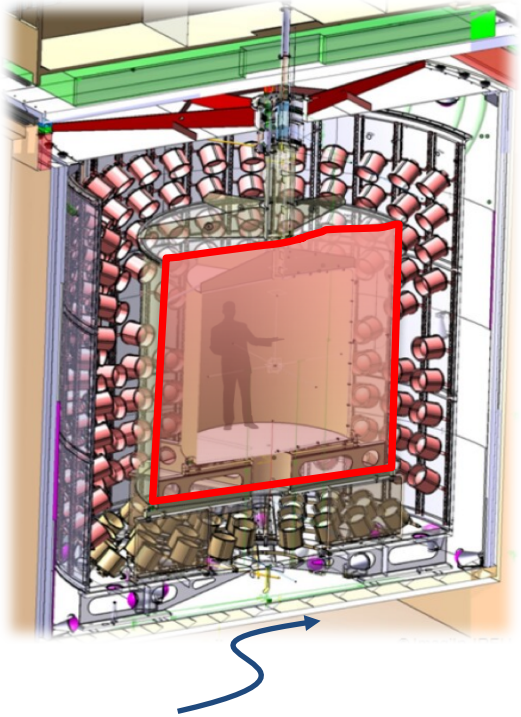


PRD 95, 072006 (2017)

Double Chooz – France

Results with two detectors and new selection (Gd + H)



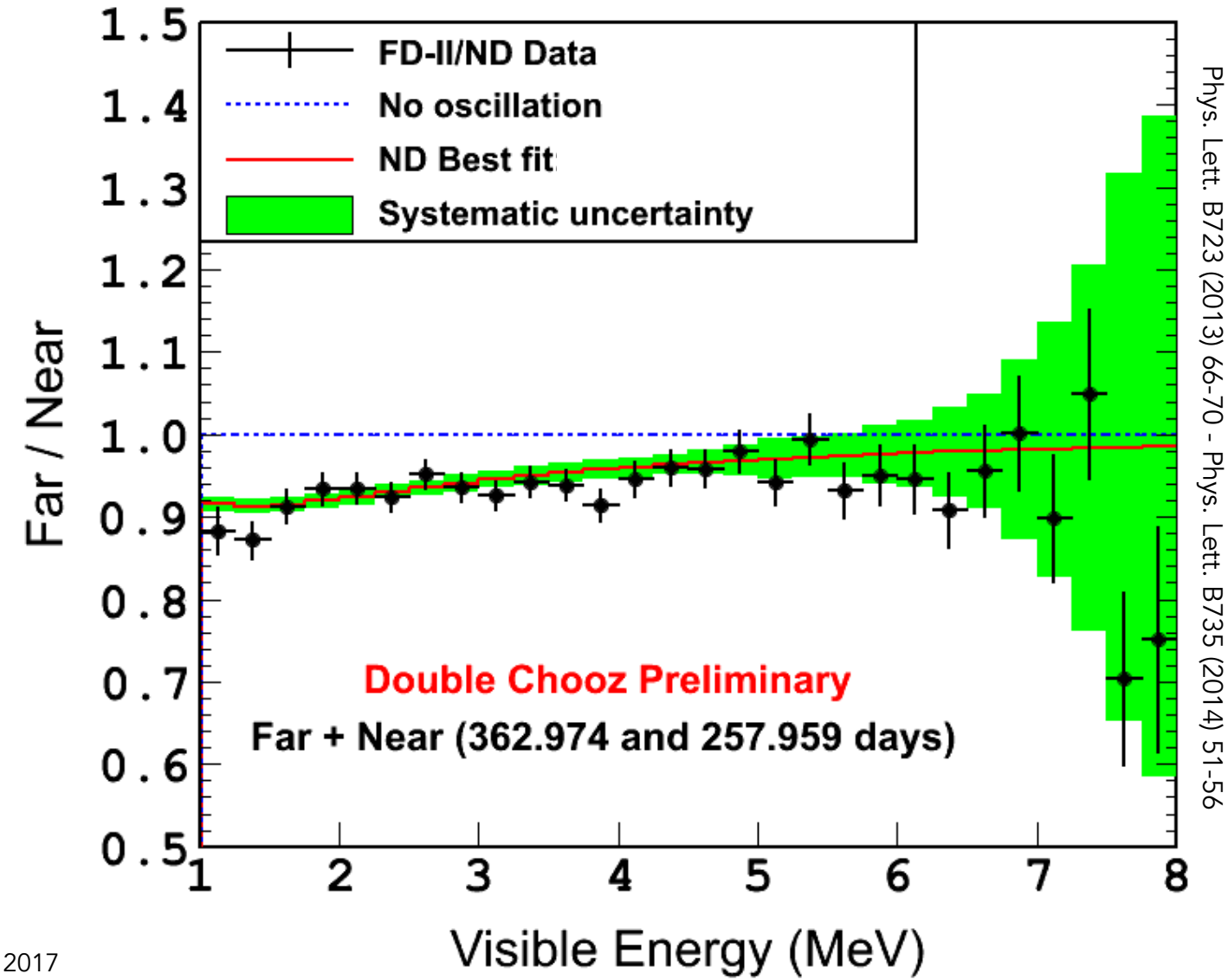


Enlarged Target
8 t (Gd) → 30 t (Gd+H)

X 2

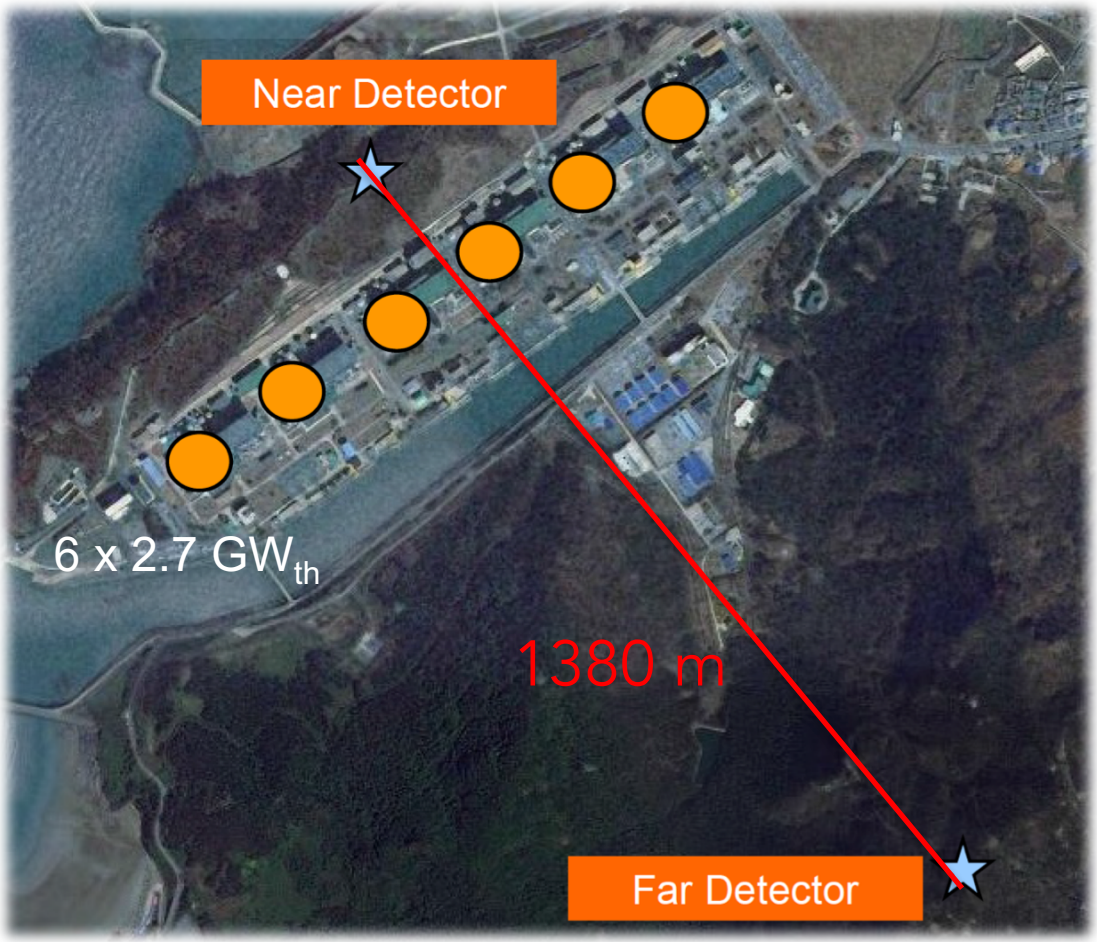
Double Chooz

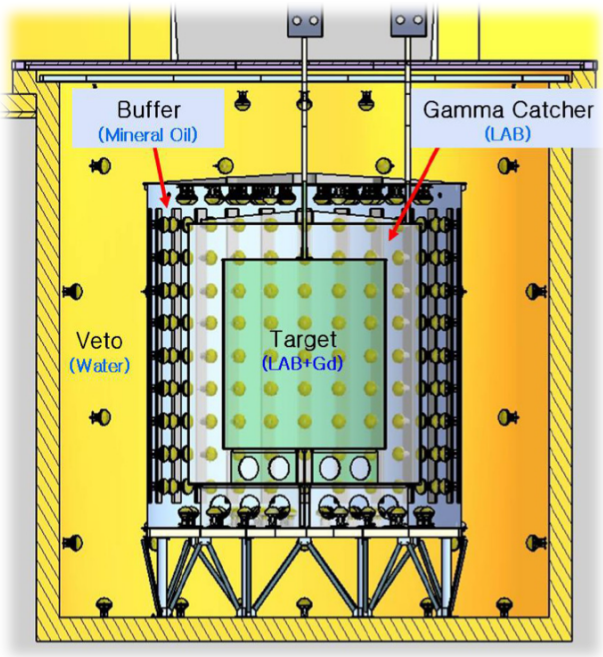
$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$ (stat + sys)



Phys. Lett. B723 (2013) 66-70 - Phys. Lett. B735 (2014) 51-56

RENO – Korea



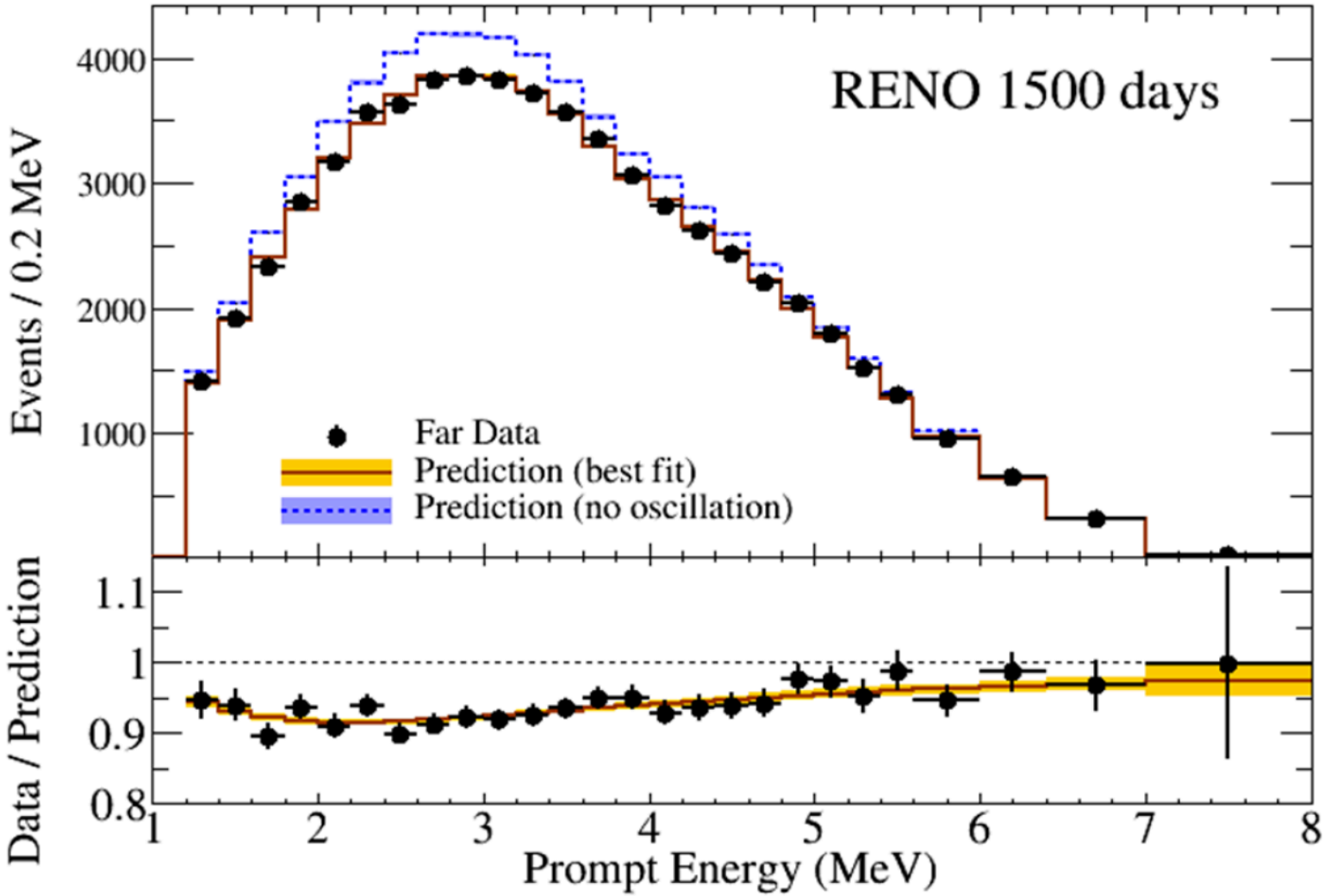


16 ton target

X 2

RENO

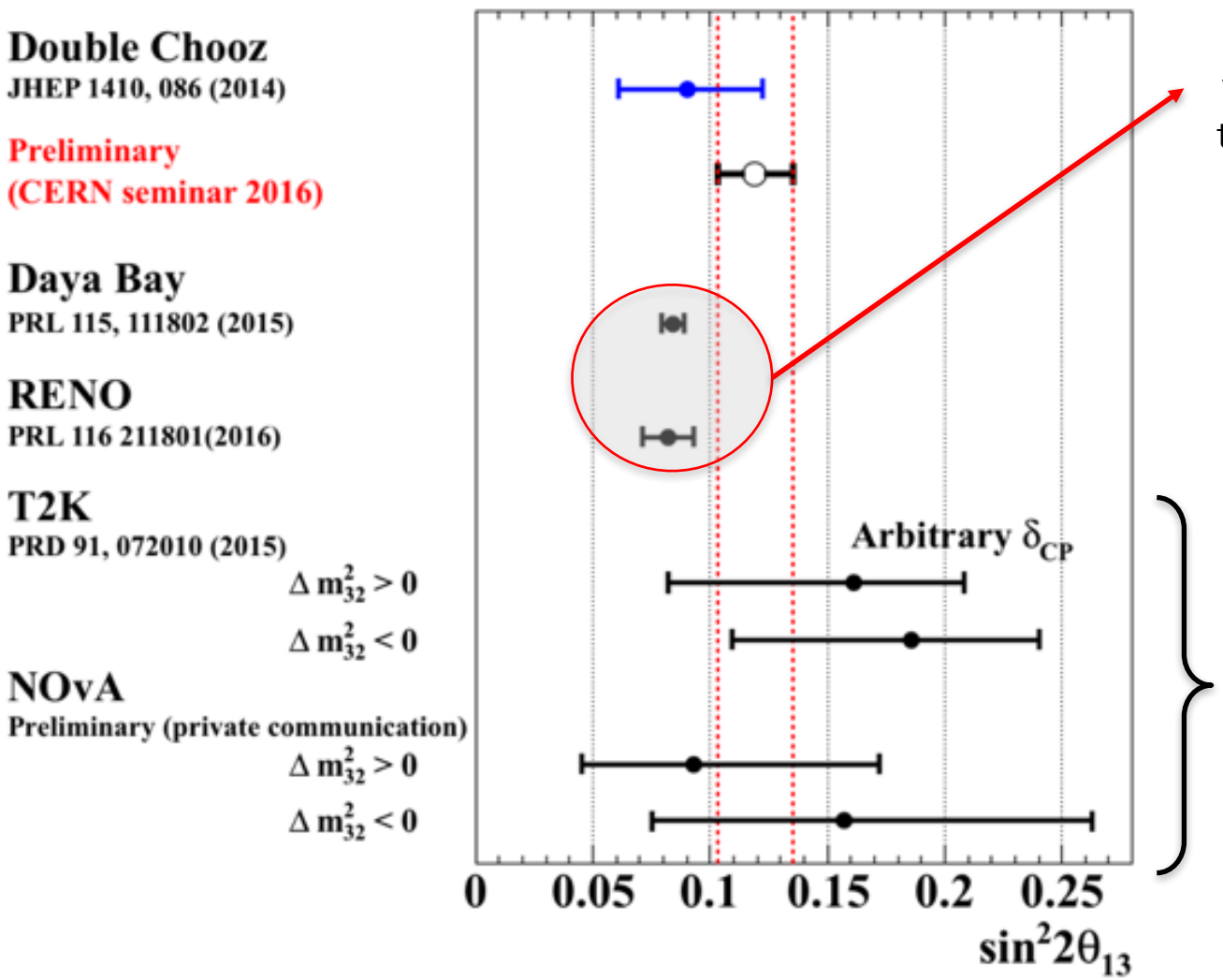
$\sin^2(2\theta_{13}) = 0.086 \pm 0.008$ (stat + sys)



Nucl. Phys. B908 (2016) 94-115

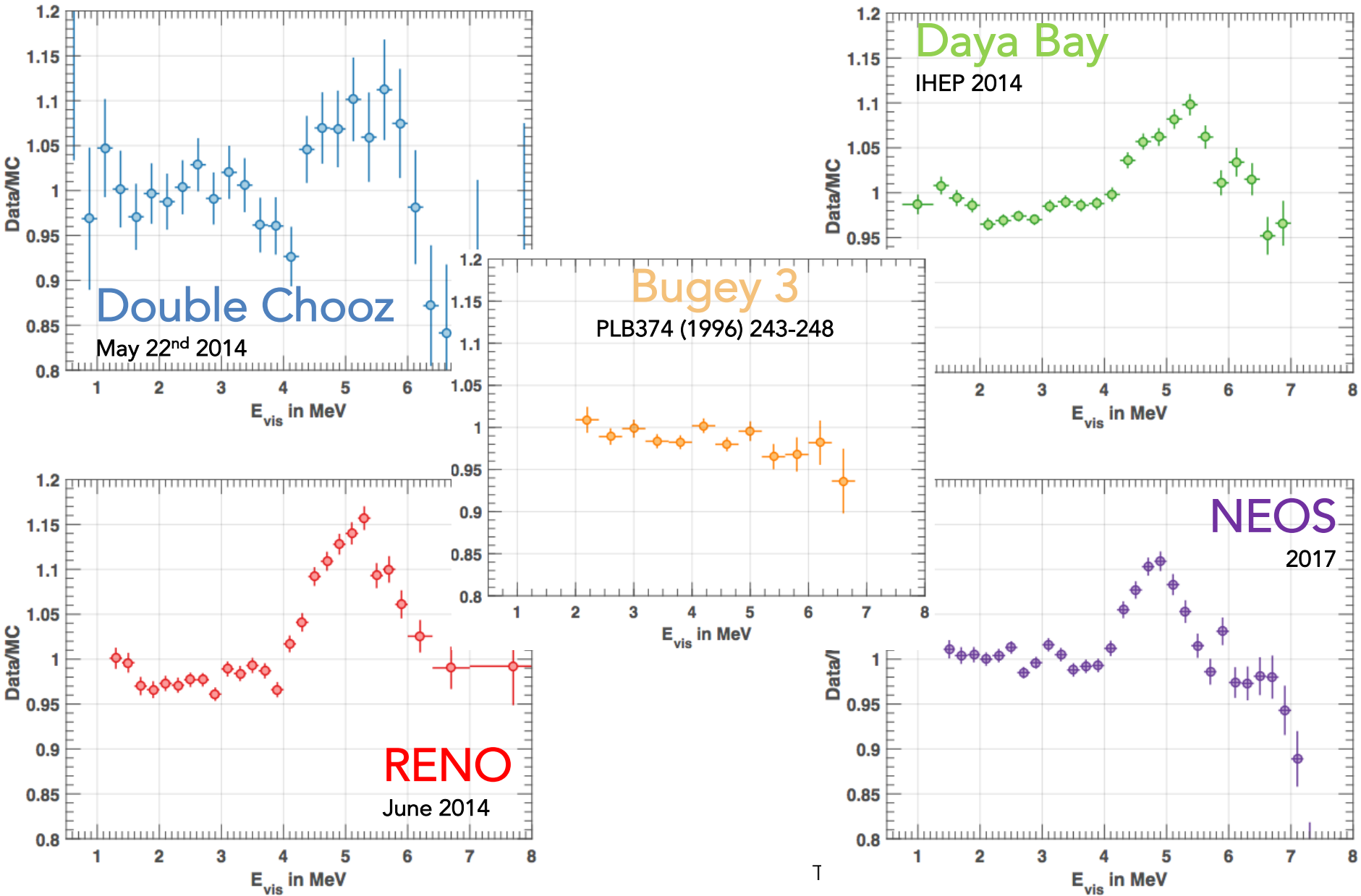
θ_{13} know within 4%

θ_{13} is a key parameter for future CP-violation and mass hierarchy experiments



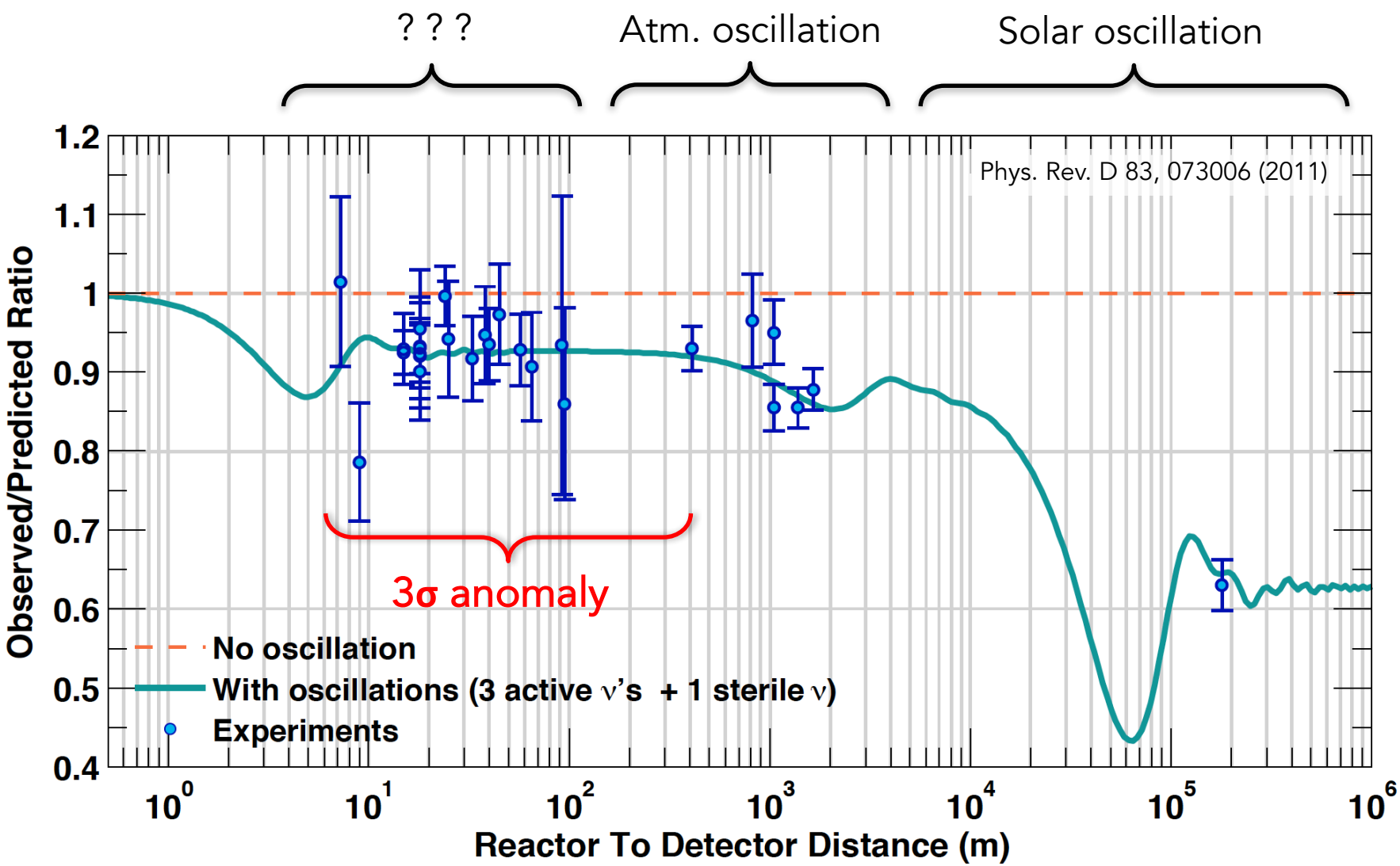
Double Chooz θ_{13} value slightly higher than Daya Bay (2.2σ)

Reactor Spectra: Data/MC



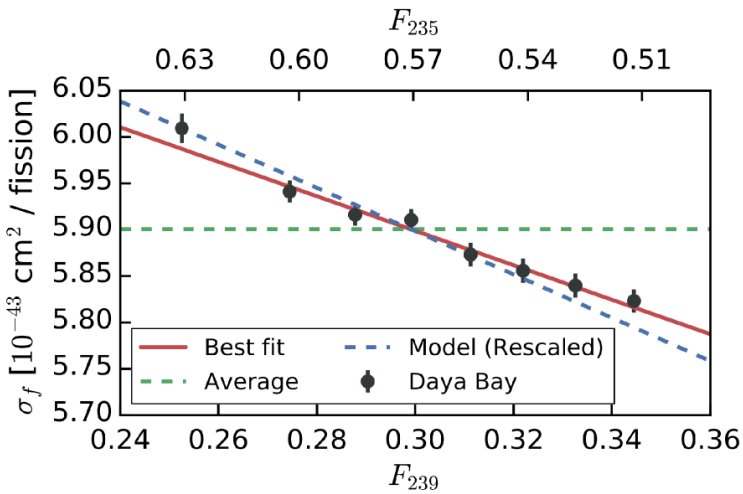
T

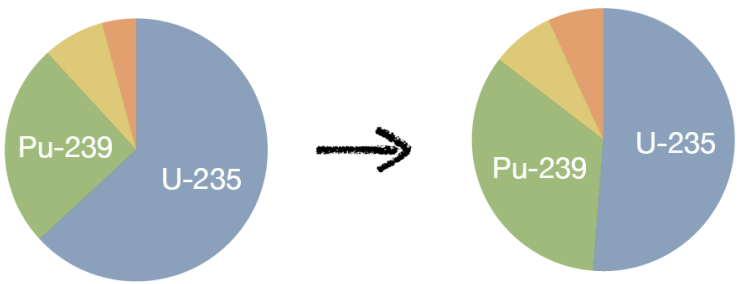
The Reactor Anomaly (RAA)



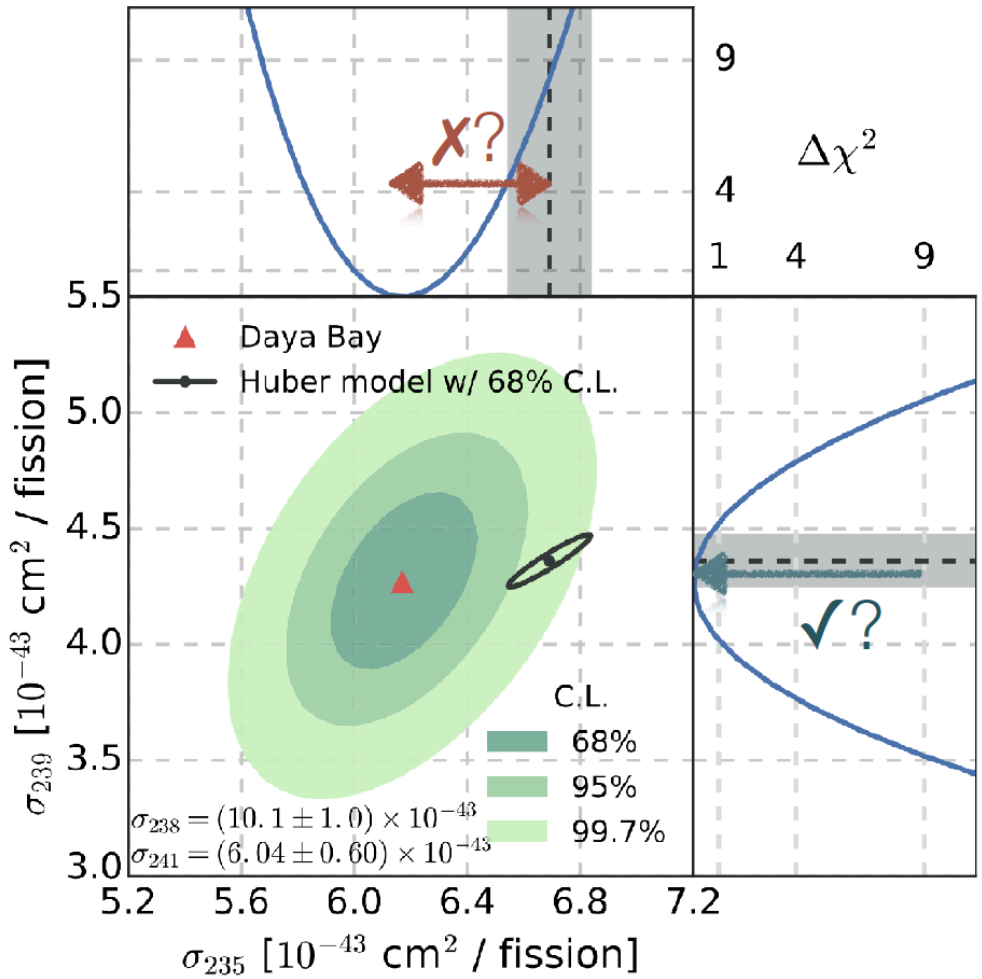
Reactor Neutrino Spectra (Daya Bay)

Mismatch concerning ^{235}U ν-flux in reactor models?





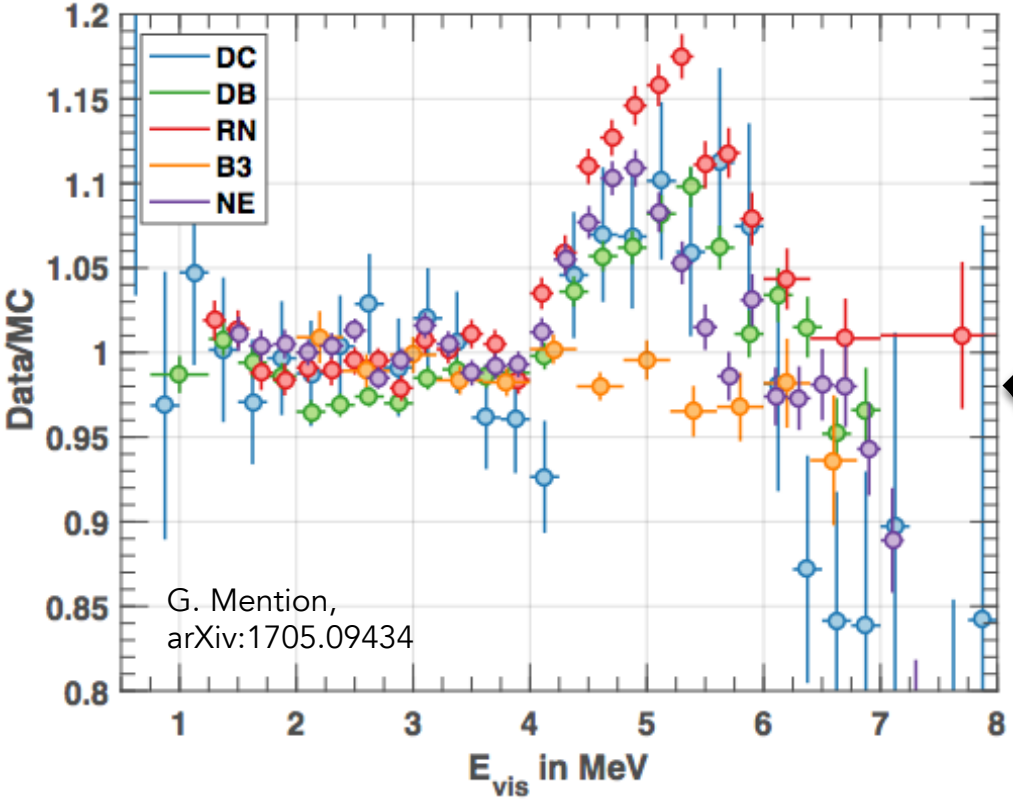
~2.2 10^6 neutrino candidates



PRL 118, 251801 (2017)

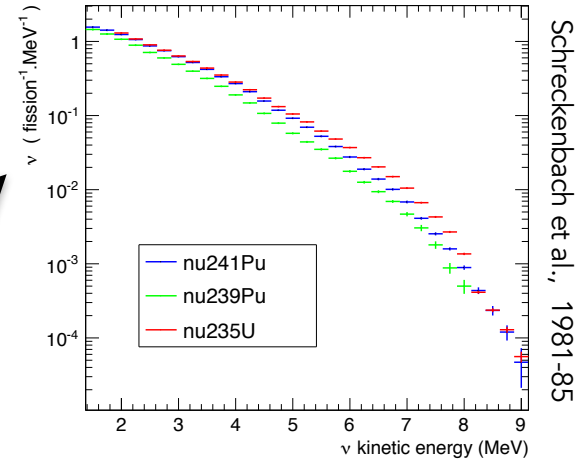
A two fold origin?

Spectral shapes are not compatible at 6.4σ



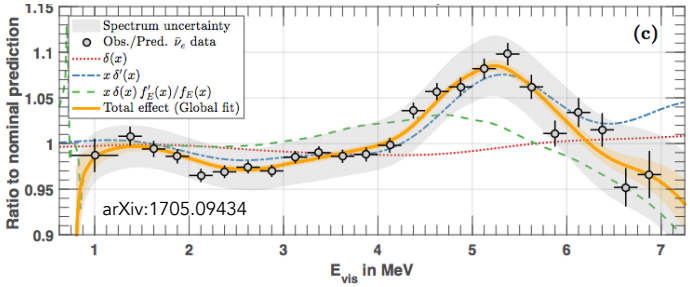
Reactor ν-spectra

Bias? Underestimated systematics?

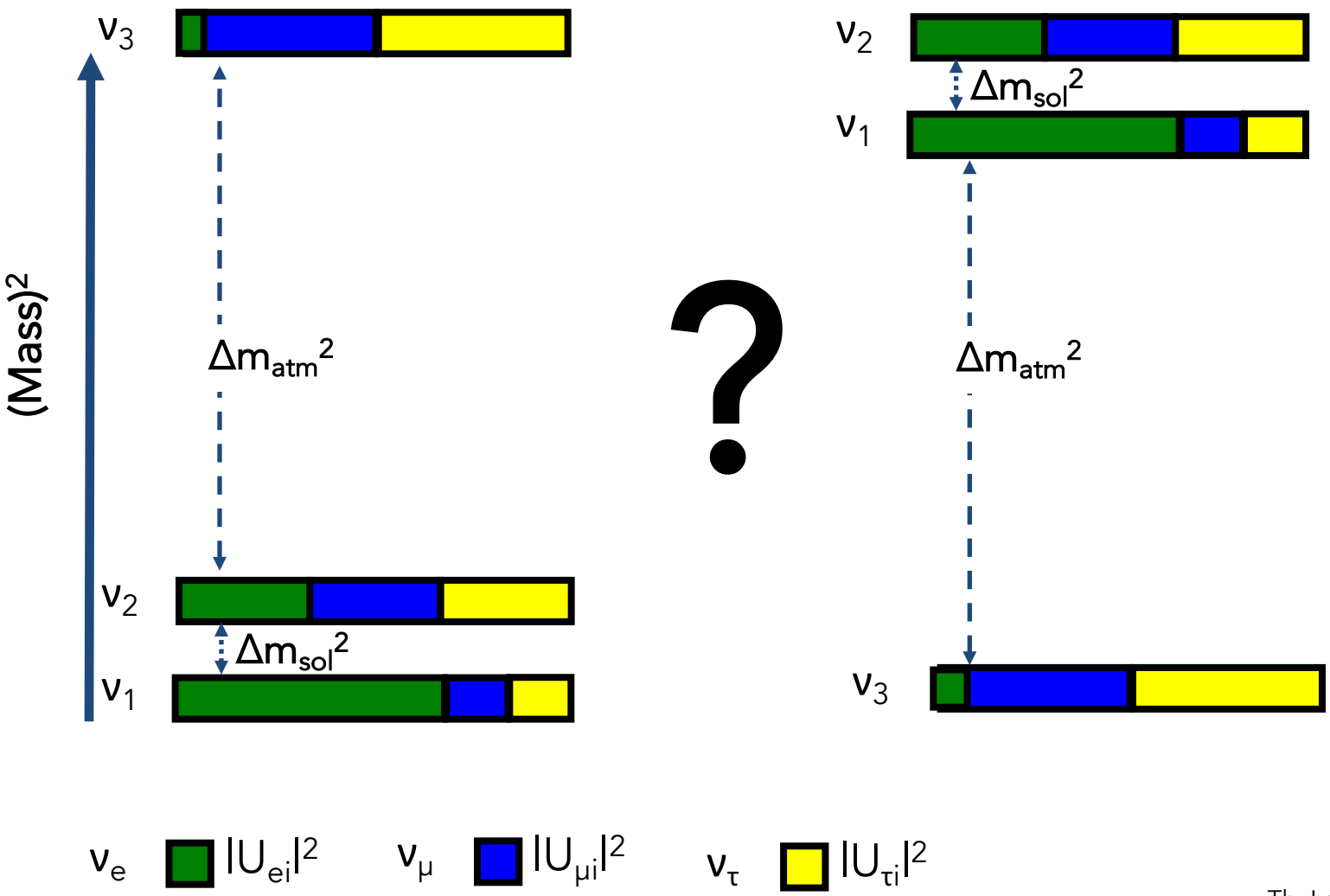


Detector calibration

1% E-scale non-linarity?



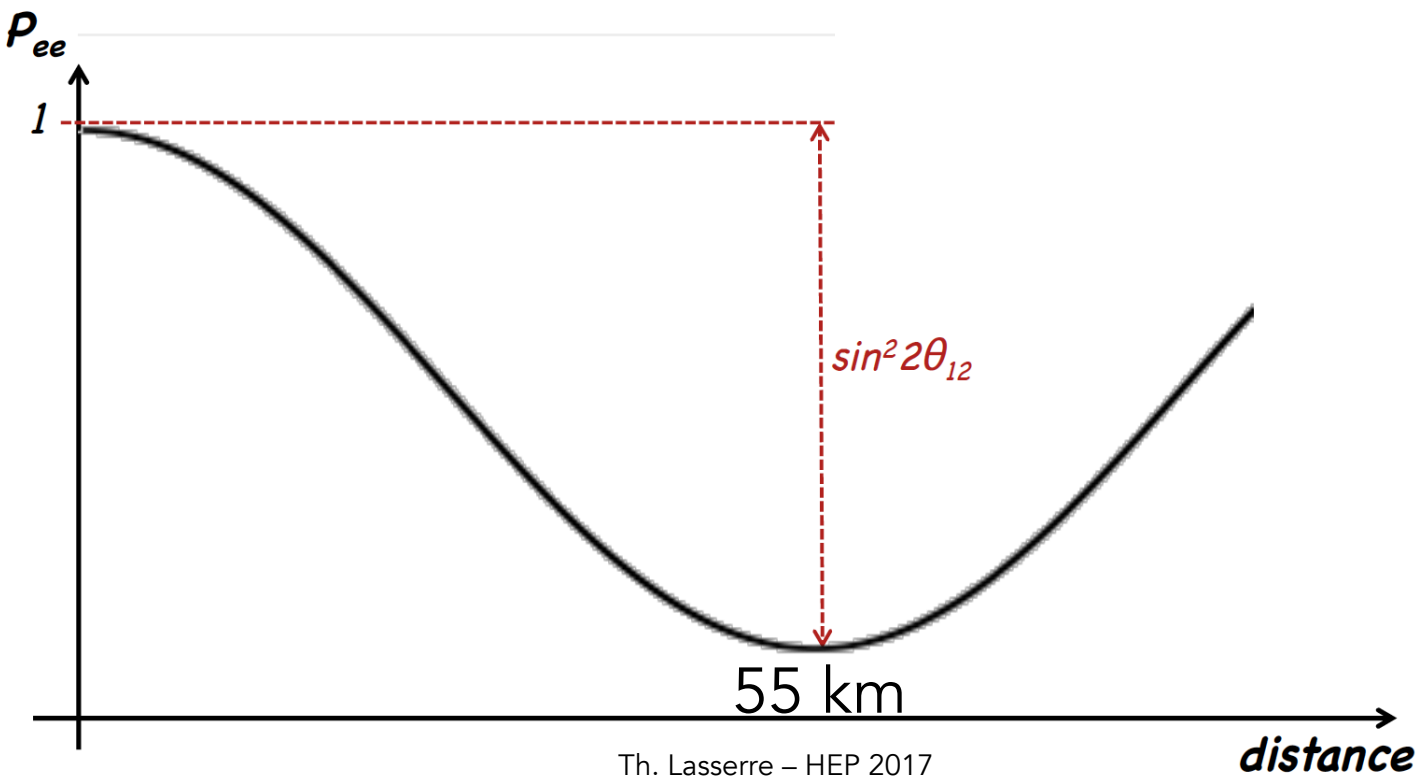
$\mathrm{sign}(\Delta m^2_{31})$



sign(Δm^2_{31}) with reactor neutrinos

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \frac{1}{2}(1 - |U_{e3}|^2)^2 \sin^2 2\Theta_{12} \left(1 - \cos \frac{\Delta m^2_{21} L}{2E}\right)$$

Solar



sign(Δm^2_{31}) with reactor neutrinos

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - 2|U_{e3}|^2(1-|U_{e3}|^2)\left(1-\cos\frac{\Delta m^2_{31}L}{2E}\right)$$

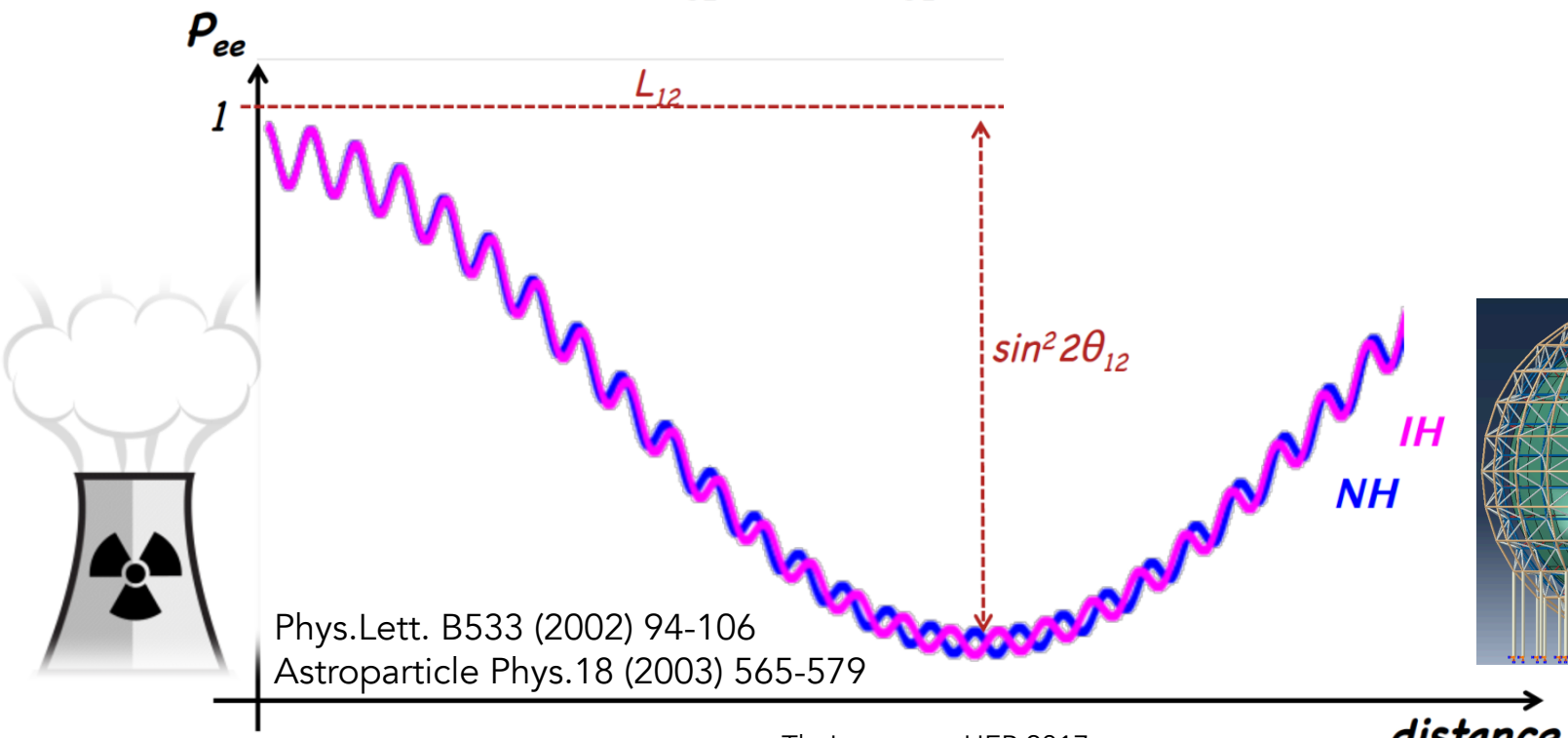
Atmospheric

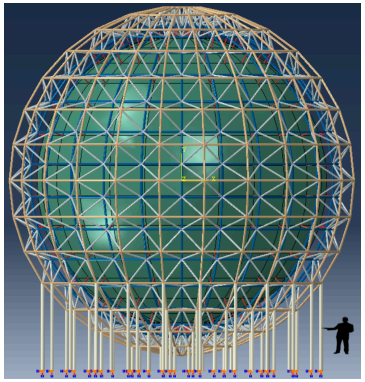
$$-\frac{1}{2}(1-|U_{e3}|^2)^2\sin^2 2\Theta_{12}\left(1-\cos\frac{\Delta m^2_{21}L}{2E}\right)$$

Solar

Interference

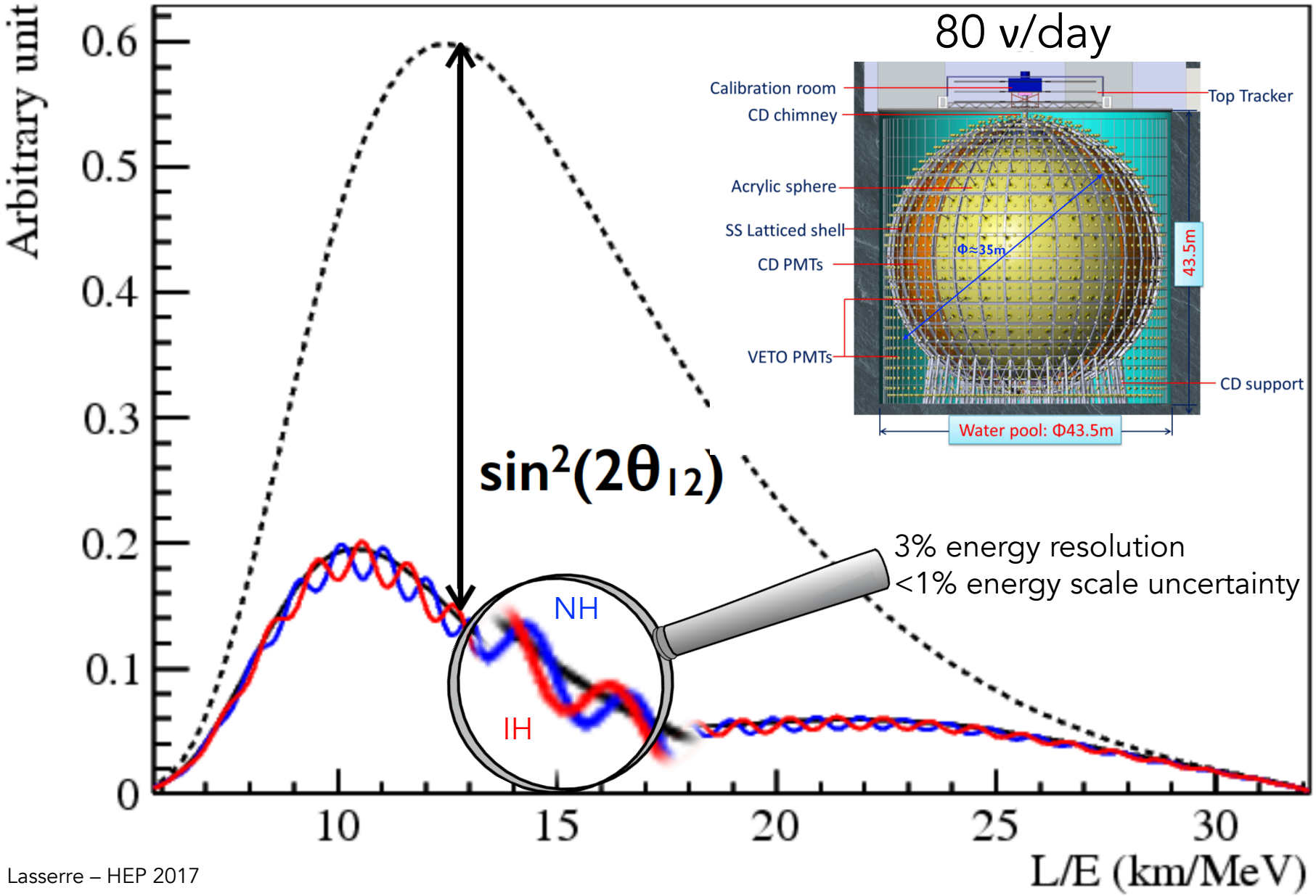
$$+2|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\Theta_{12}\left(\cos\left(\frac{\Delta m^2_{31}L}{2E}-\frac{\Delta m^2_{21}L}{2E}\right)-\cos\frac{\Delta m^2_{31}L}{2E}\right)$$





Phys.Lett. B533 (2002) 94-106
Astroparticle Phys.18 (2003) 565-579

20 kt JUNO Experiment (China, 2020)



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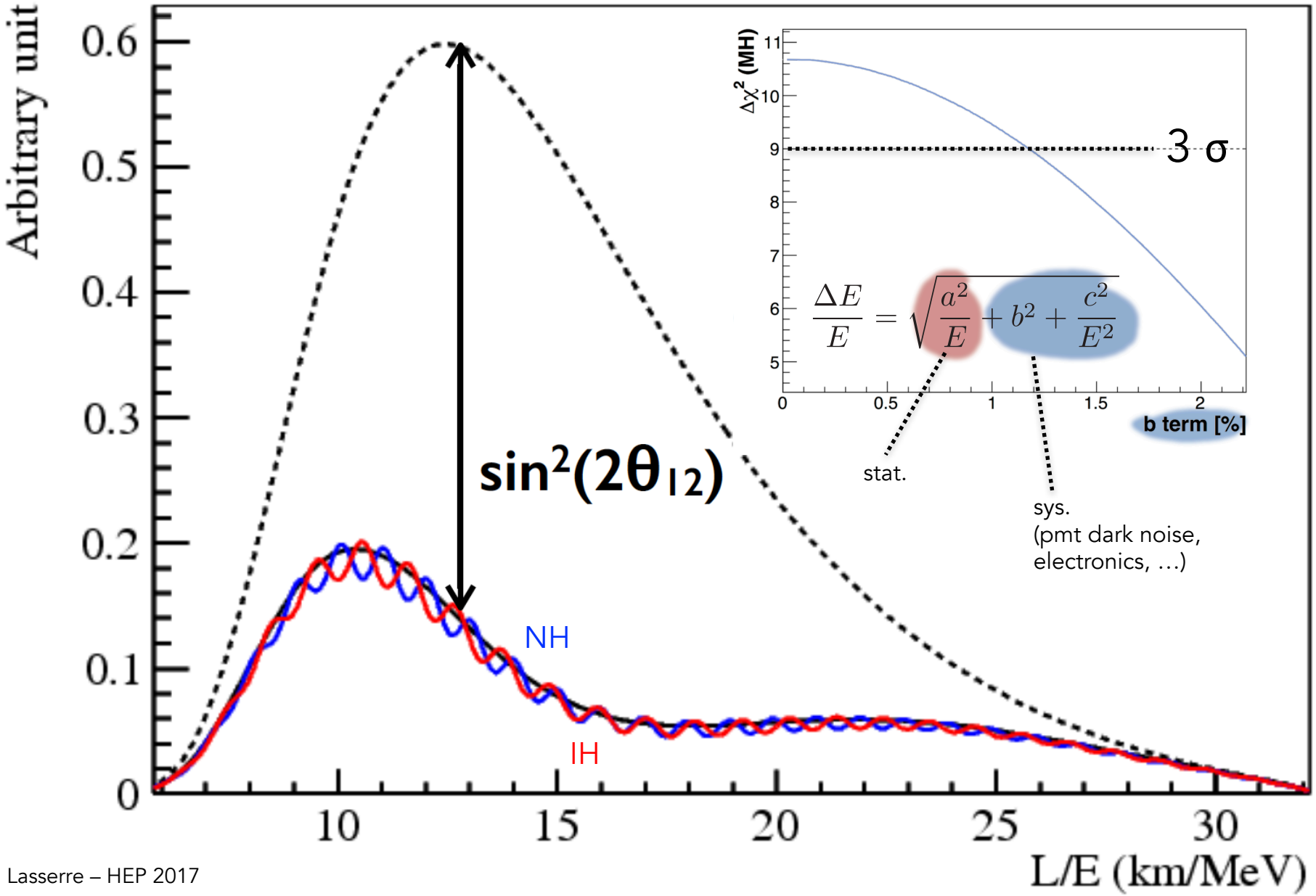
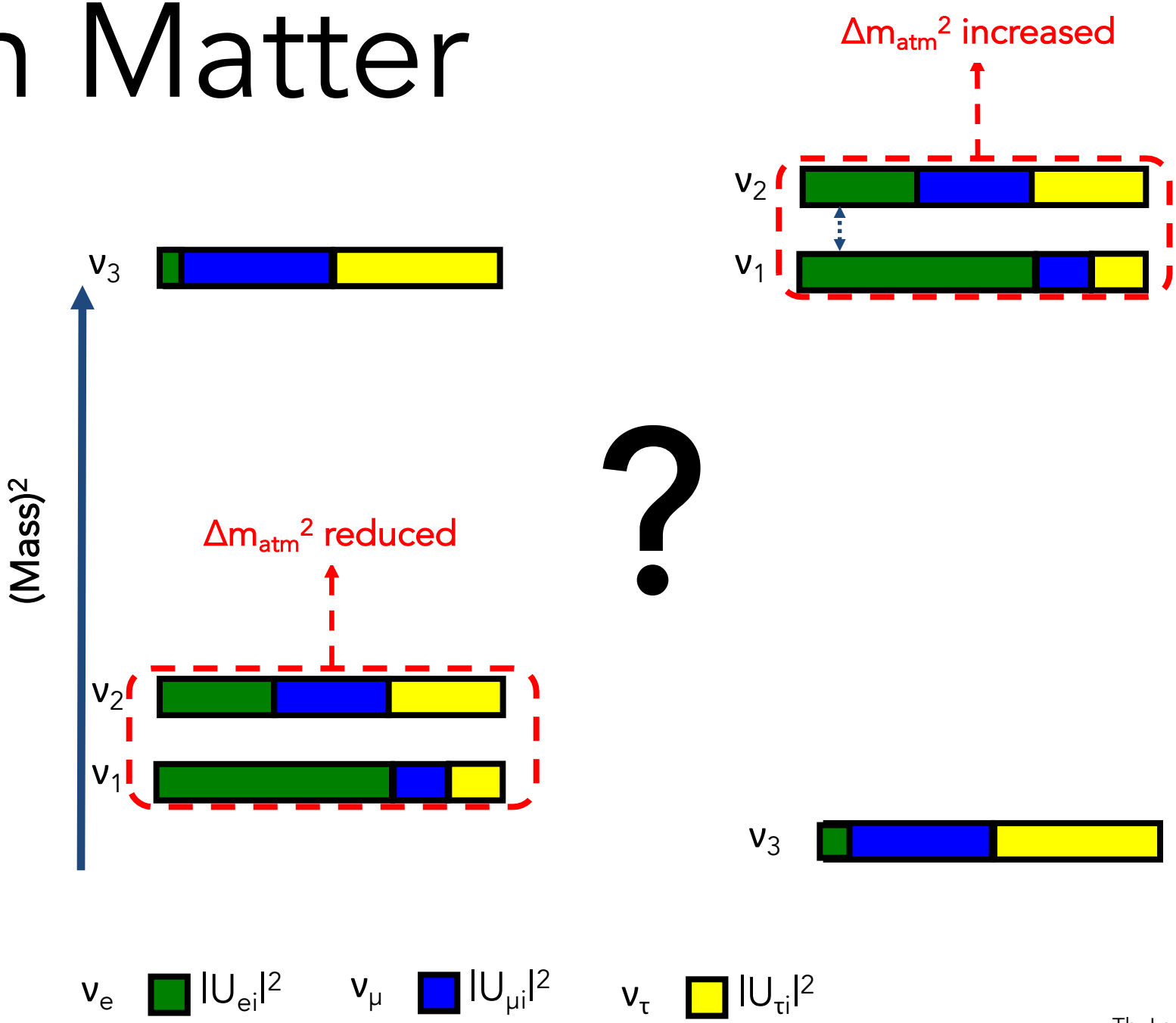
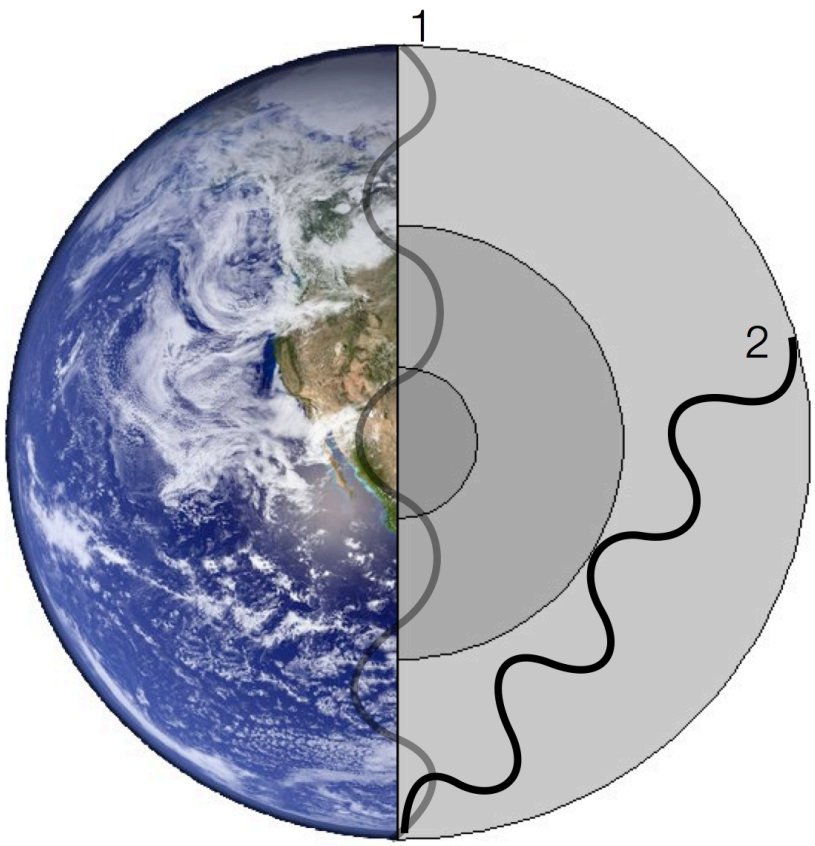


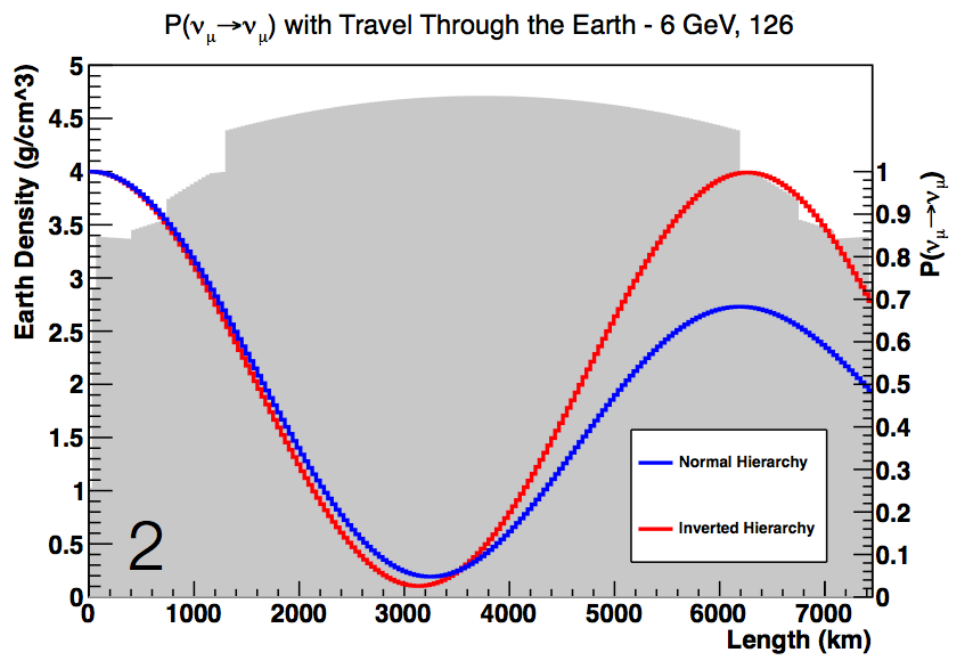
In Matter


Δm_{atm}^2 increased
ν_2
ν_1
ν_3
(Mass)^2
?
Δm_{atm}^2 reduced
ν_2
ν_1
ν_3
ν_e $|U_{ei}|^2$
ν_μ $|U_{\mu i}|^2$
ν_τ $|U_{\tau i}|^2$

Oscillation in Earth Matter



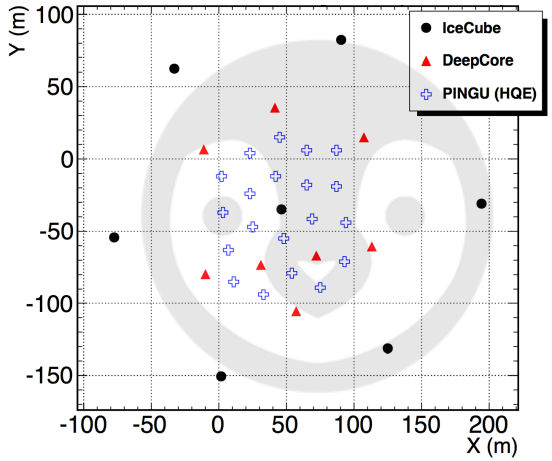
IH/NH has up to a 20% difference in oscillation probability for specific energies and zenith angles

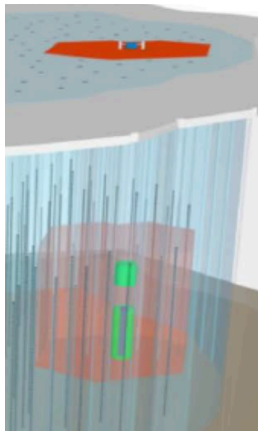


Need

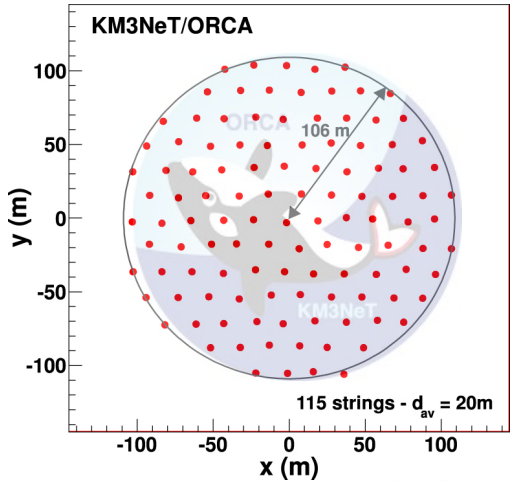
- GeV Threshold
- Megaton volume

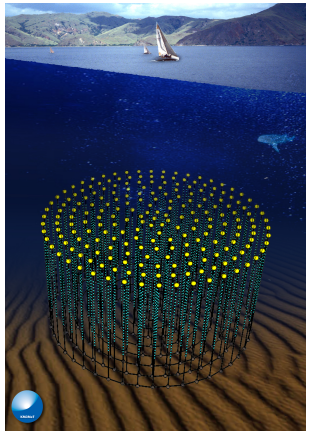
PINGU & ORCA



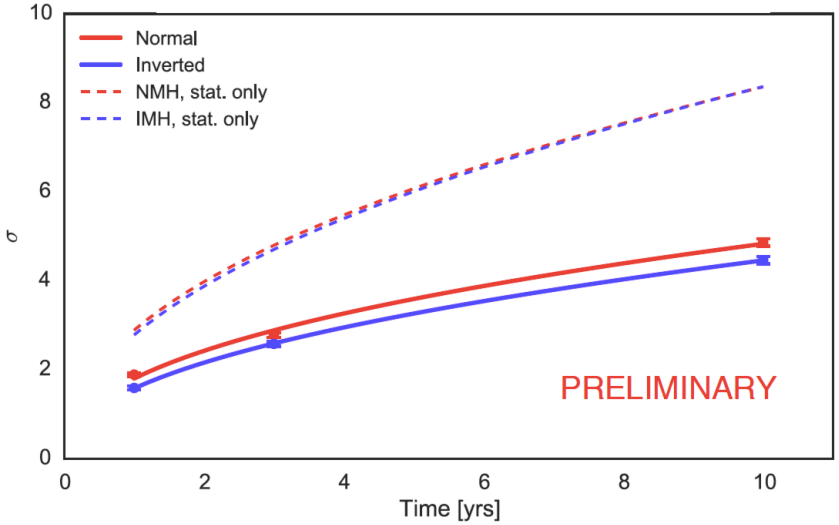


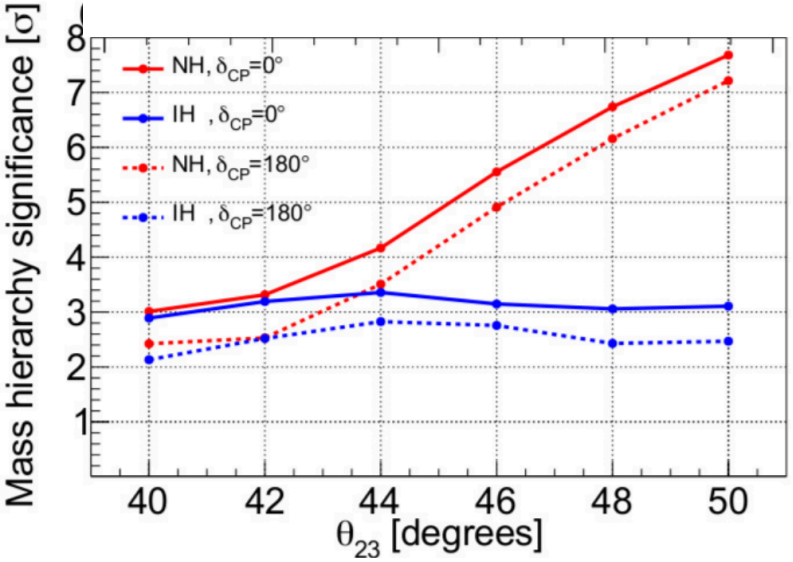
South pole



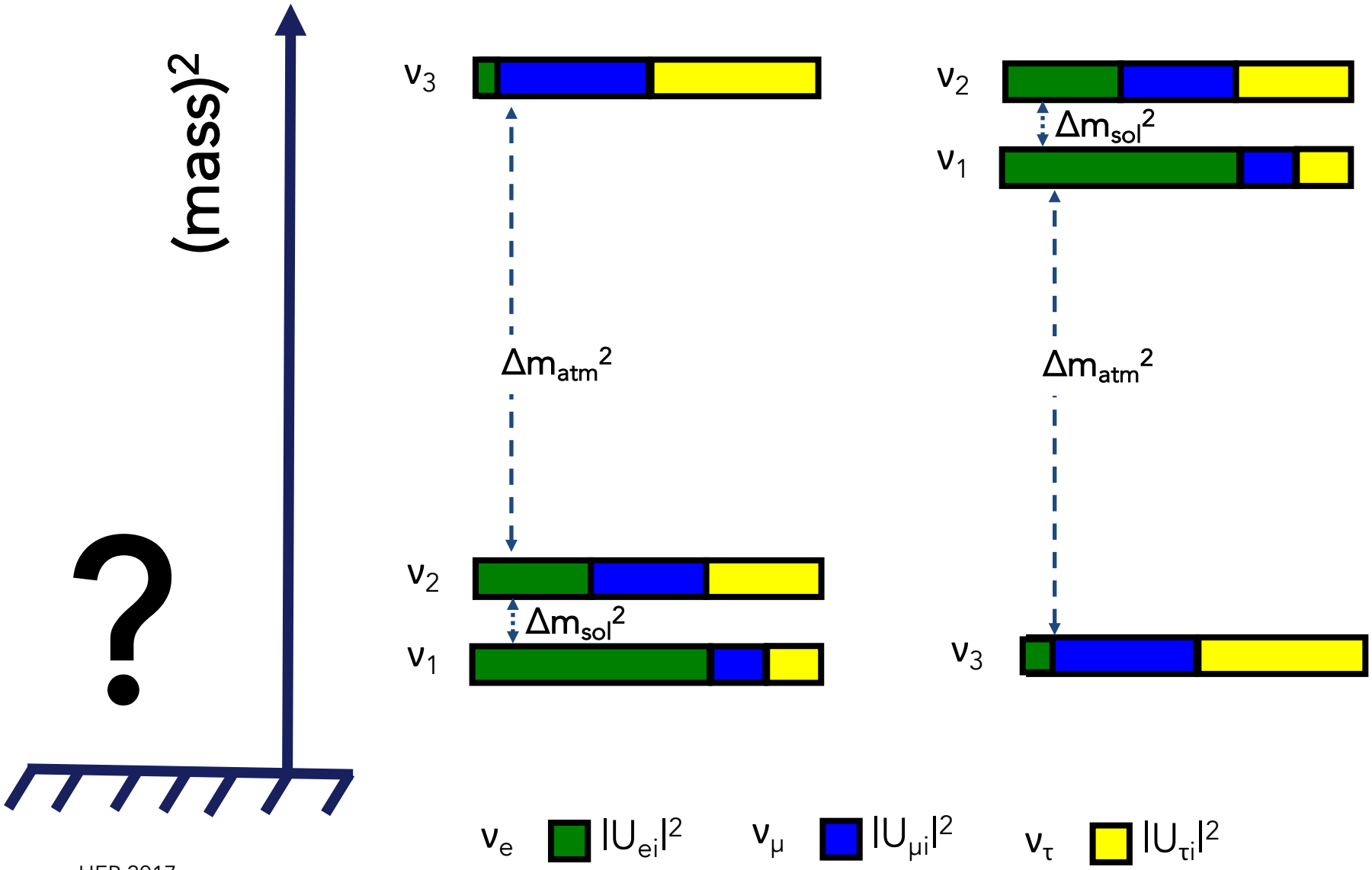


Mediteranean



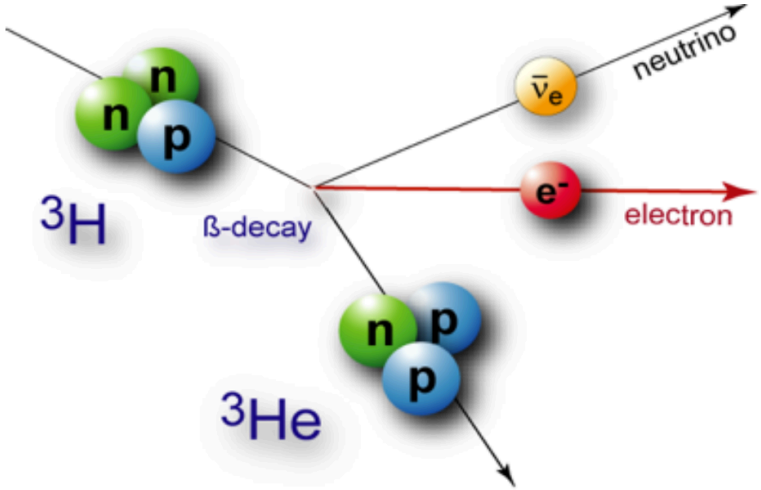


Mass scale


(mass)^2
?
ν_3
Δm_{atm}^2
ν_2
Δm_{sol}^2
ν_1
ν_2
Δm_{sol}^2
ν_1
Δm_{atm}^2
ν_3
ν_e $|U_{ei}|^2$
ν_μ $|U_{\mu i}|^2$
ν_τ $|U_{\tau i}|^2$

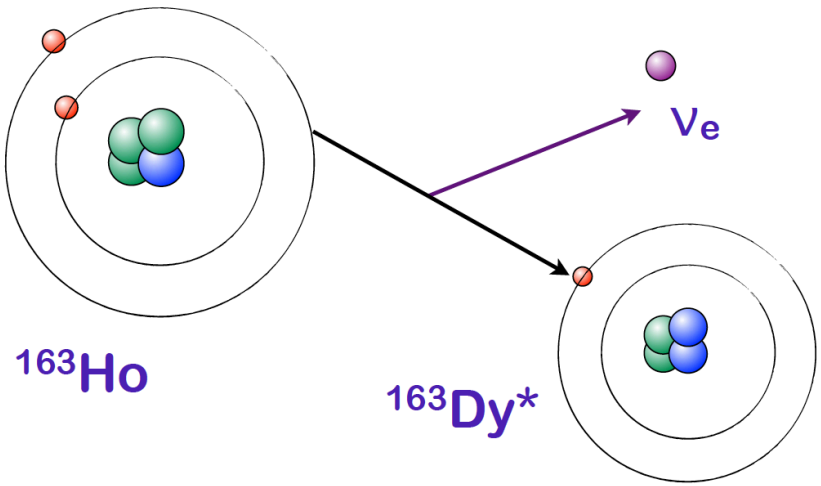
Weak β and EC decays

Tritium beta decay



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

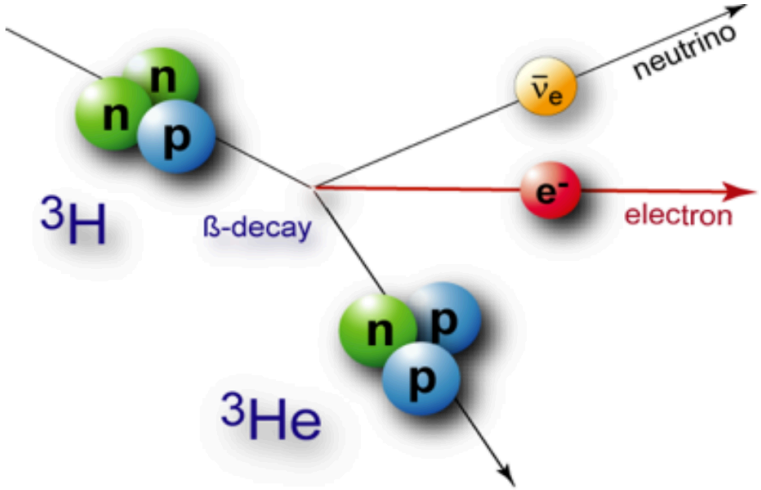
Holmium electron capture



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

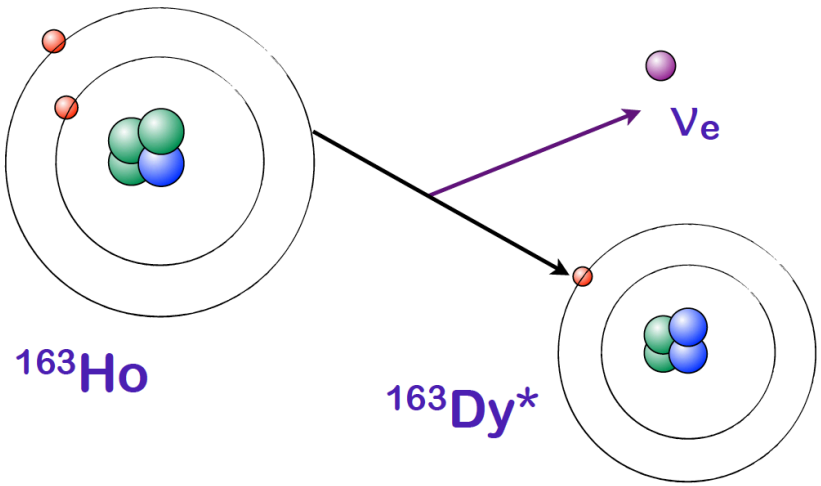
Weak decays (β and EC)

Tritium beta decay

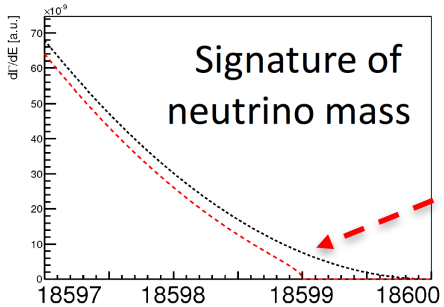


$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

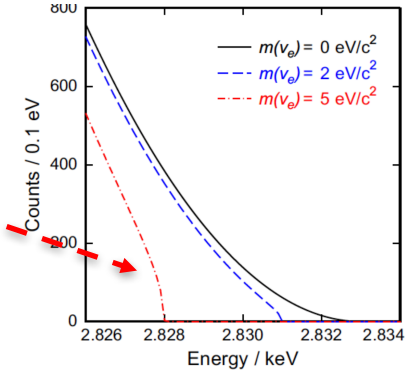
Holmium electron capture



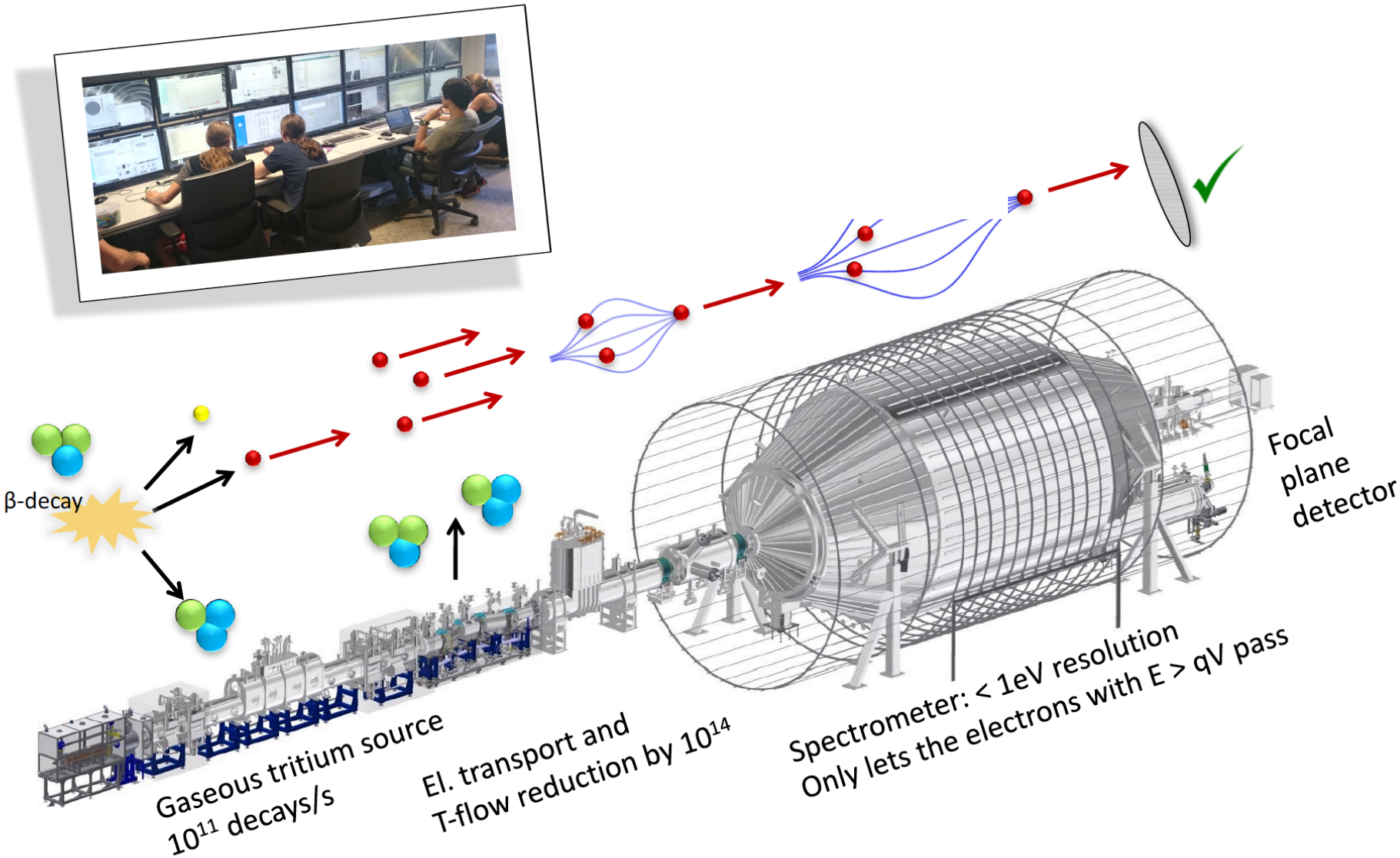
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$



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

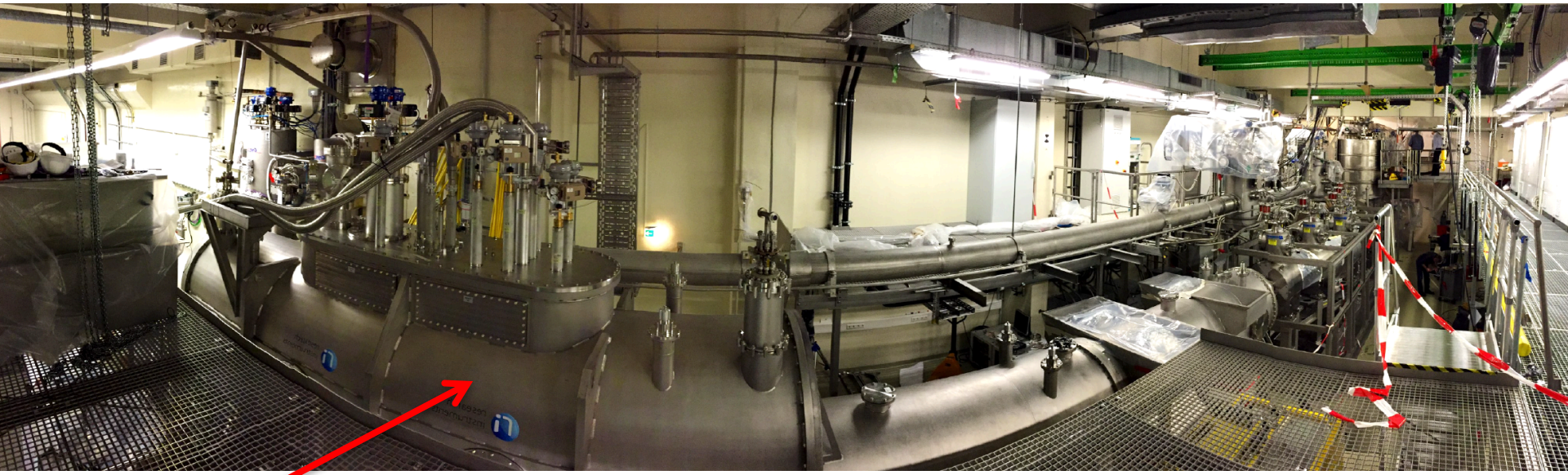


KATRIN – Tritium β-decay

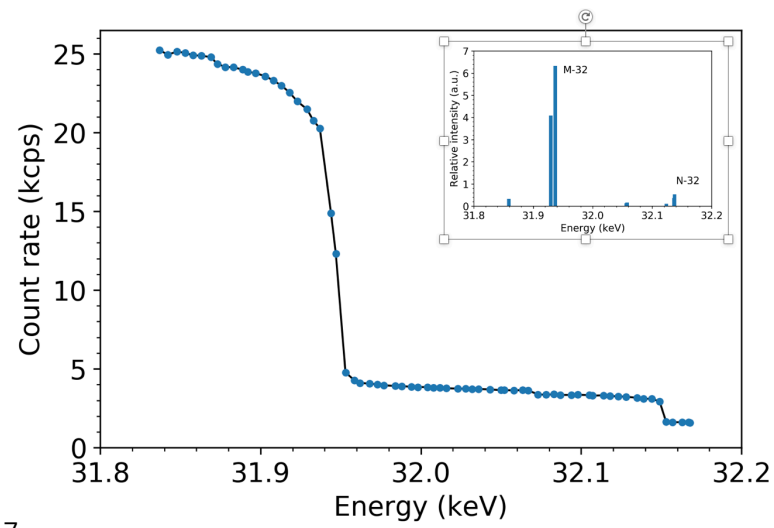


Active ν Mass with KATRIN

Setup fully installed and being commissioned. Tritium in 2018

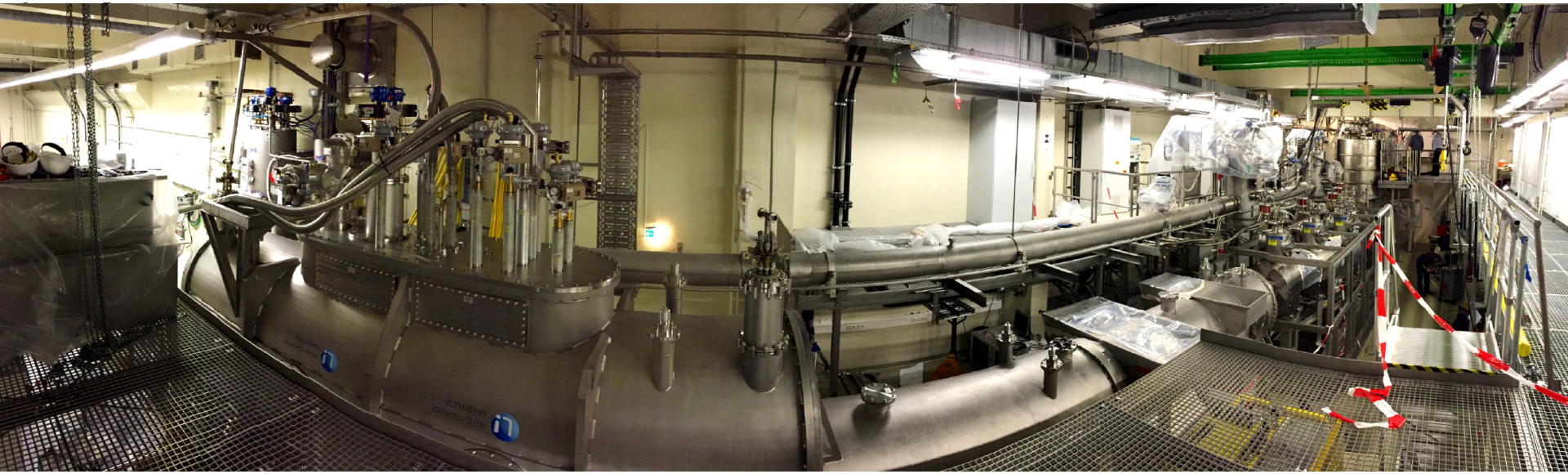


- ^{83m}Kr first lights (July 2017)
- m_ν: 200 meV sensitivity (design, 90% CL)
- Sensitivity to eV-sterile neutrinos
- Search for keV-sterile neutrinos



Active ν Mass with KATRIN

Setup fully installed and being commissioned. Tritium in 2018



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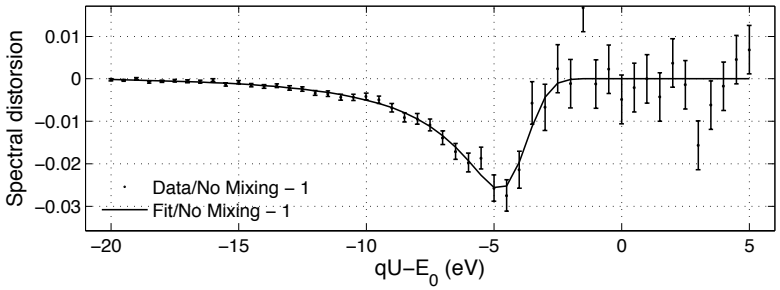
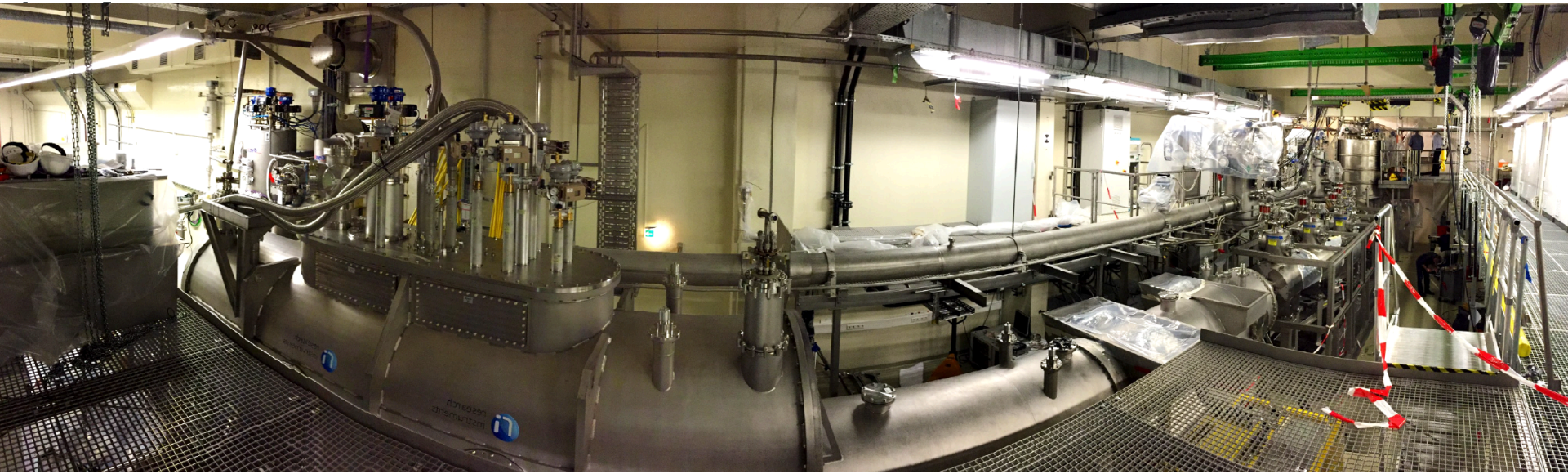


Active ν Mass with KATRIN

Setup fully installed and being commissioned. Tritium in 2018



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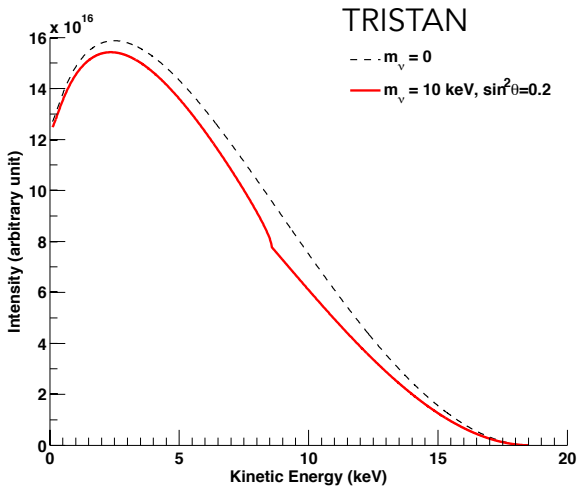
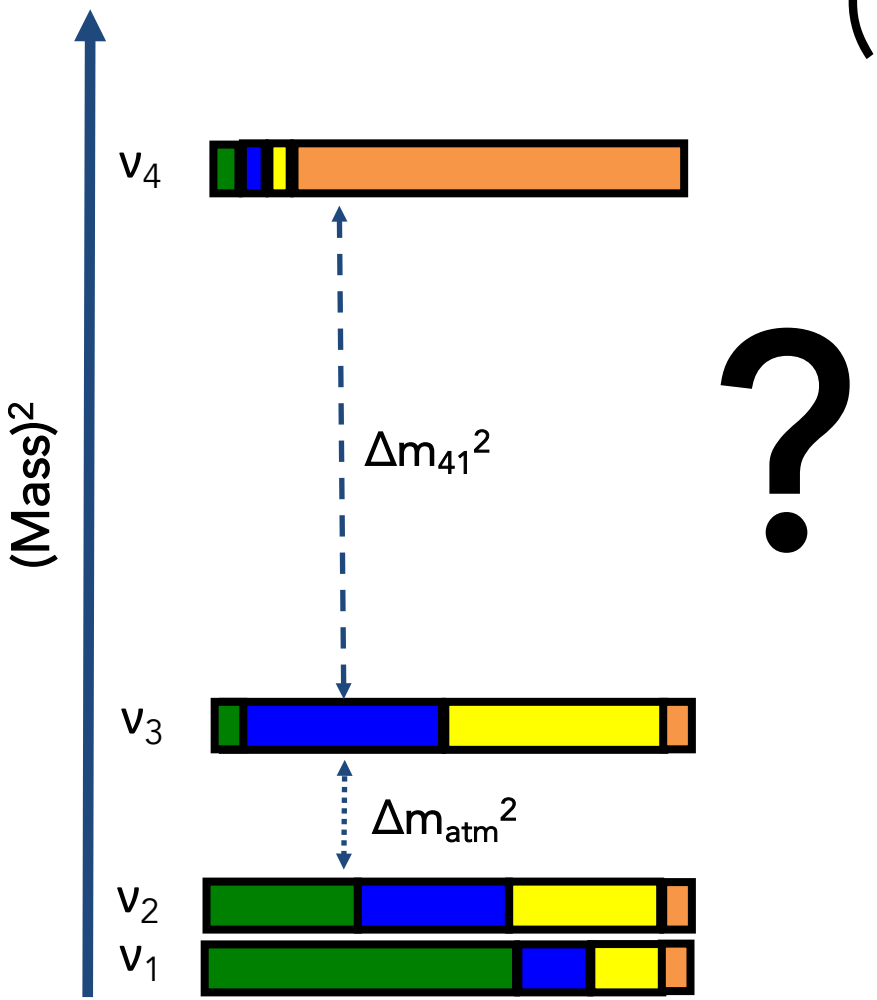
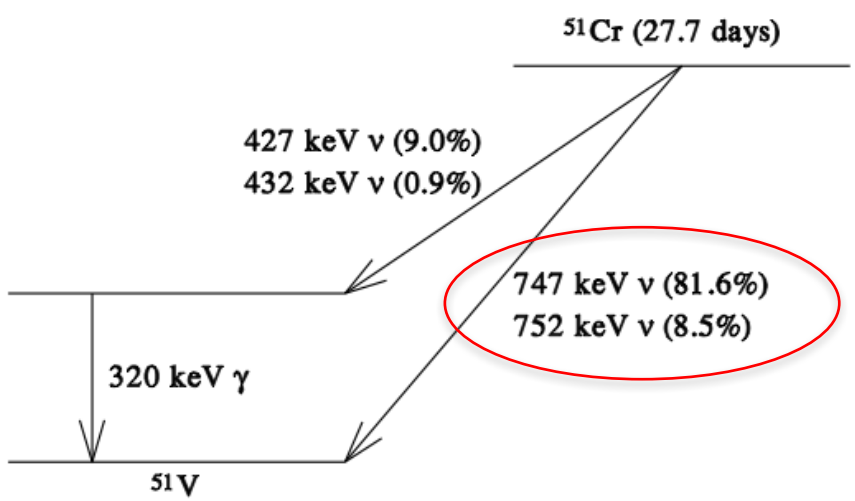


eV-scale massive neutrino (mainly sterile)

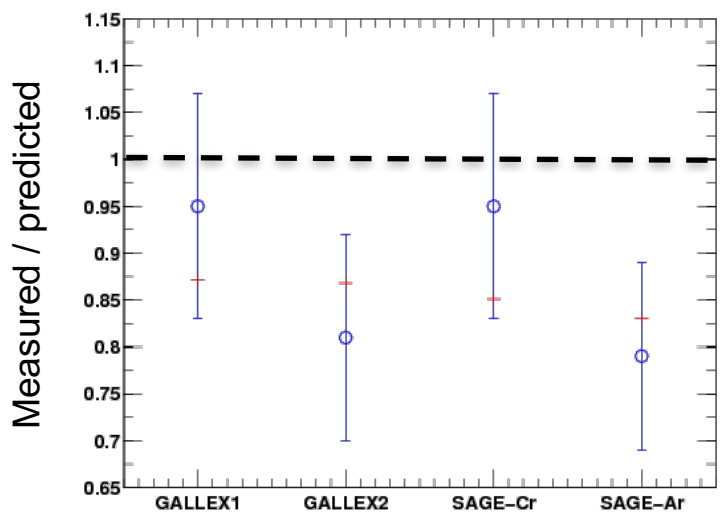


ν_e $|U_{ei}|^2$ ν_μ $|U_{\mu i}|^2$ ν_τ $|U_{\tau i}|^2$ ν_s $|U_{si}|^2$

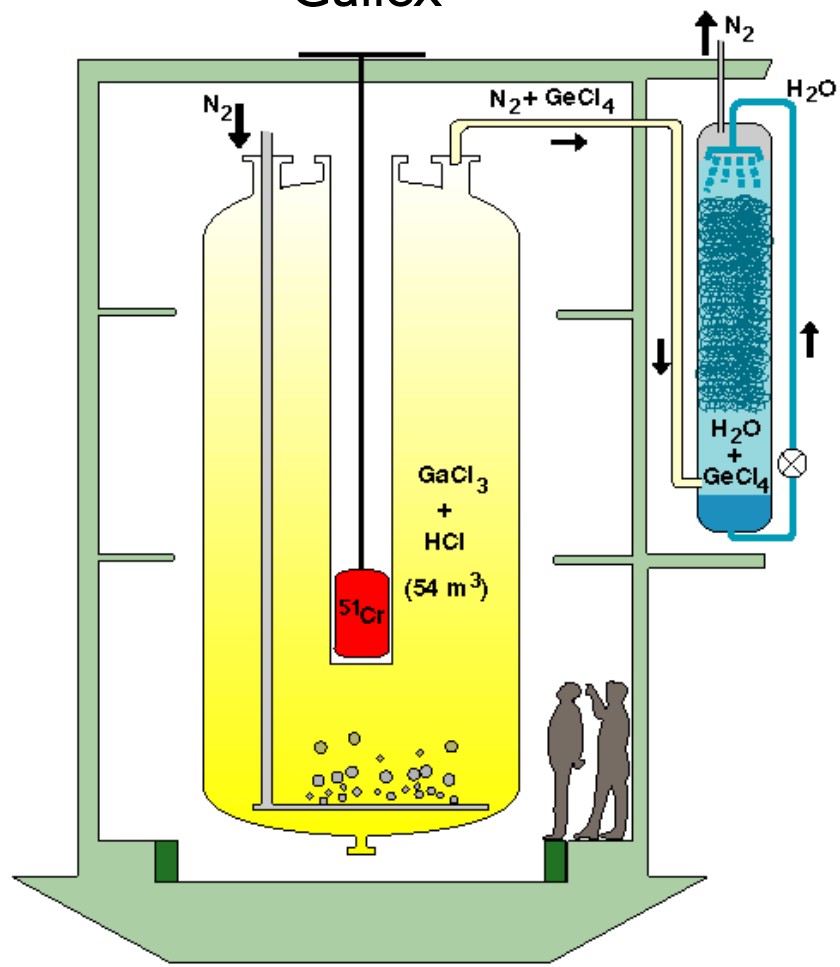
The Gallium Anomaly (GA)



3σ anomaly



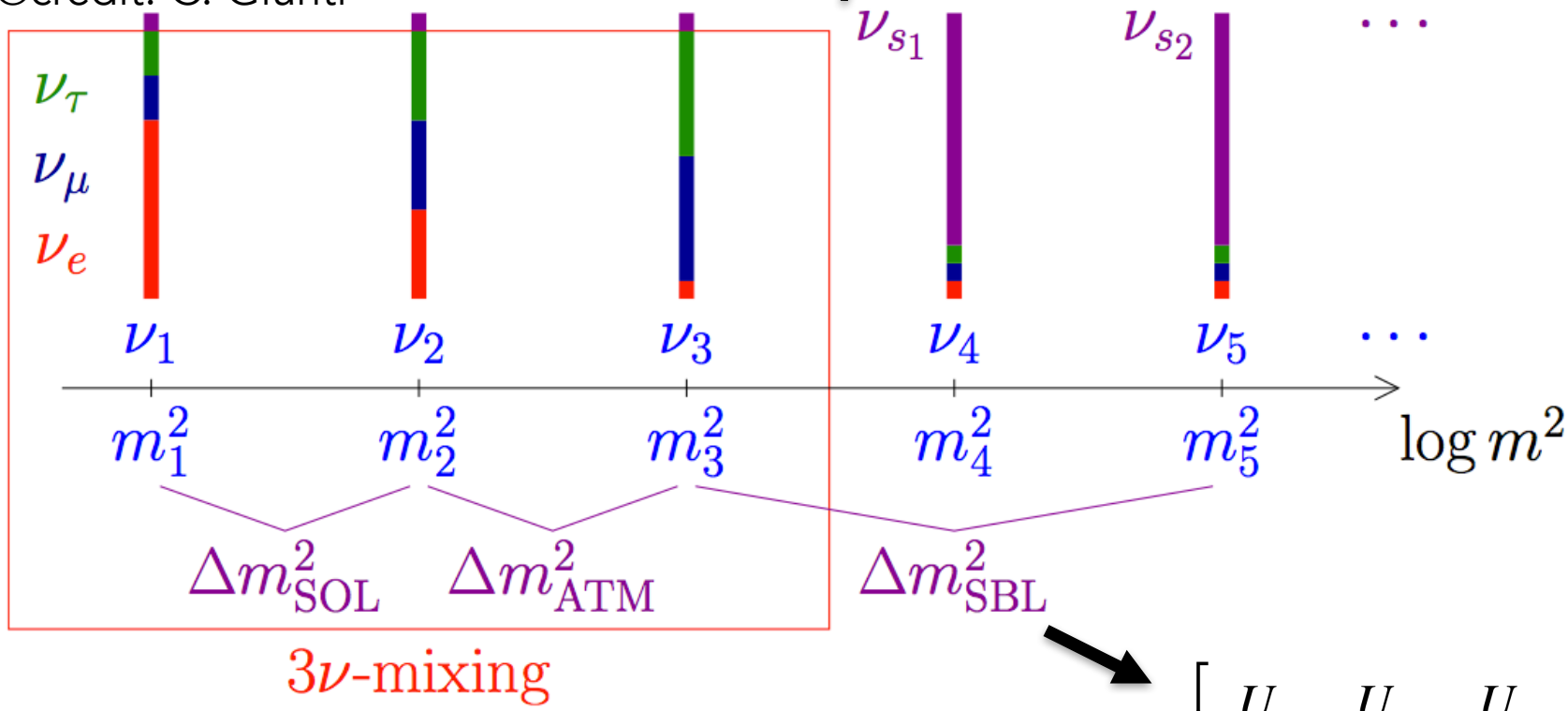
Gallex



An eV-scale Sterile Neutrino?

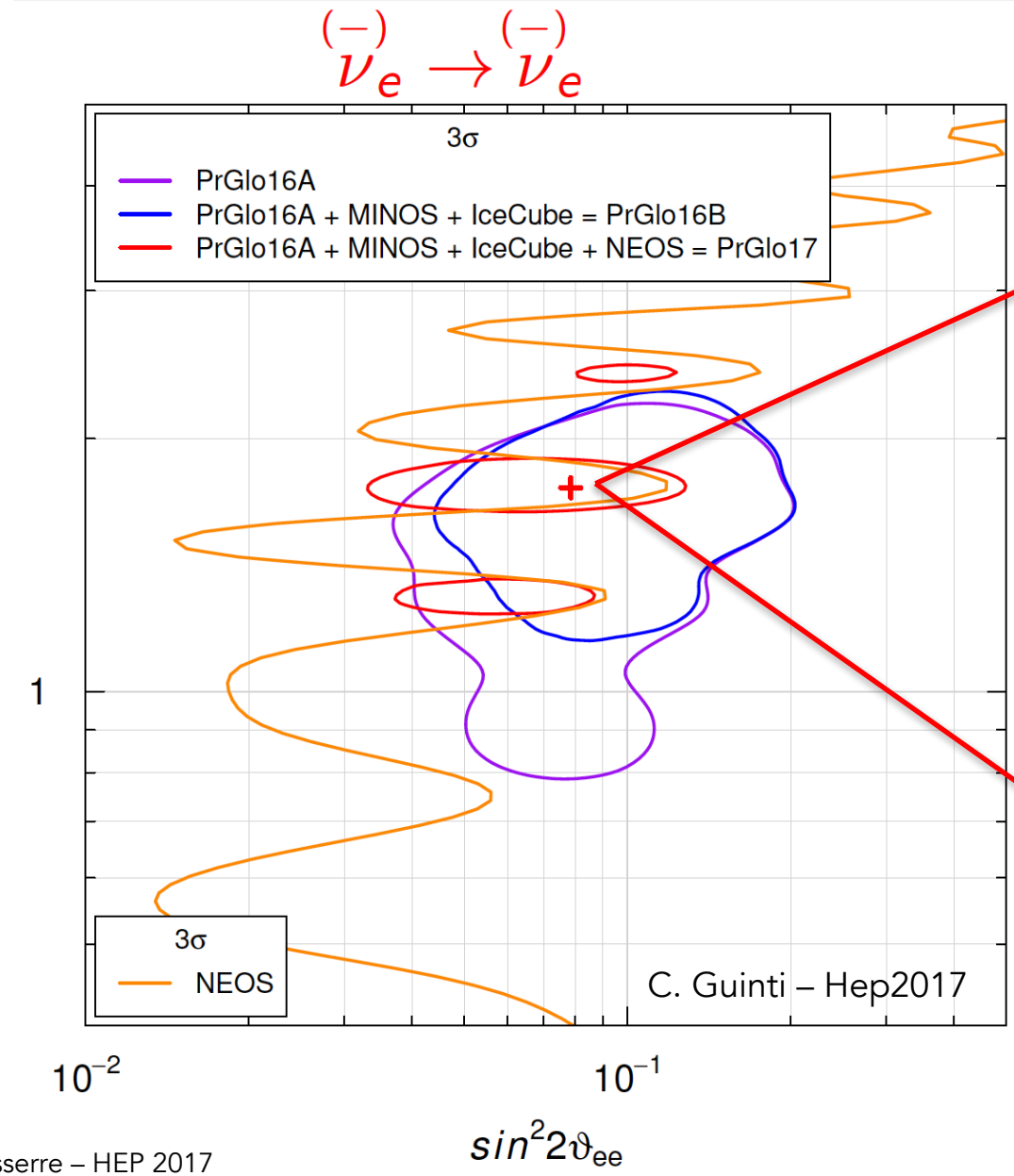
No – or extra-weak SM interaction
Mixing with active ν's

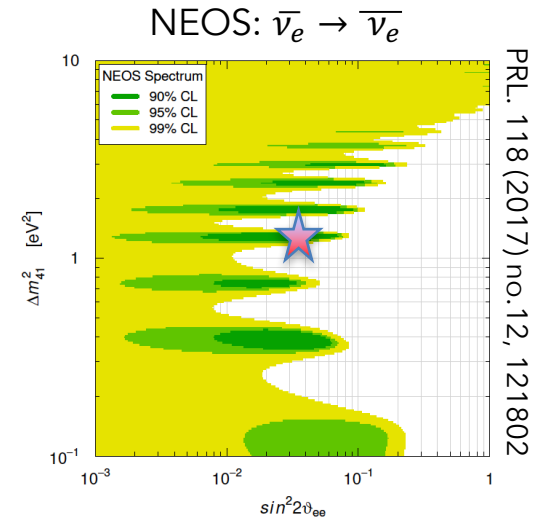
@credit: C. Giunti

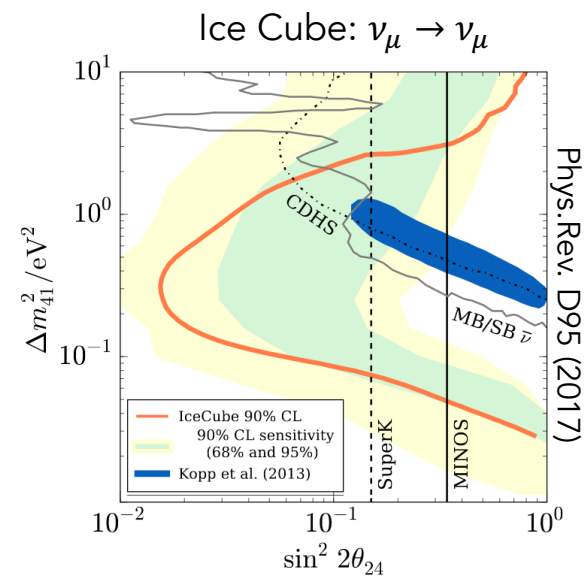


$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

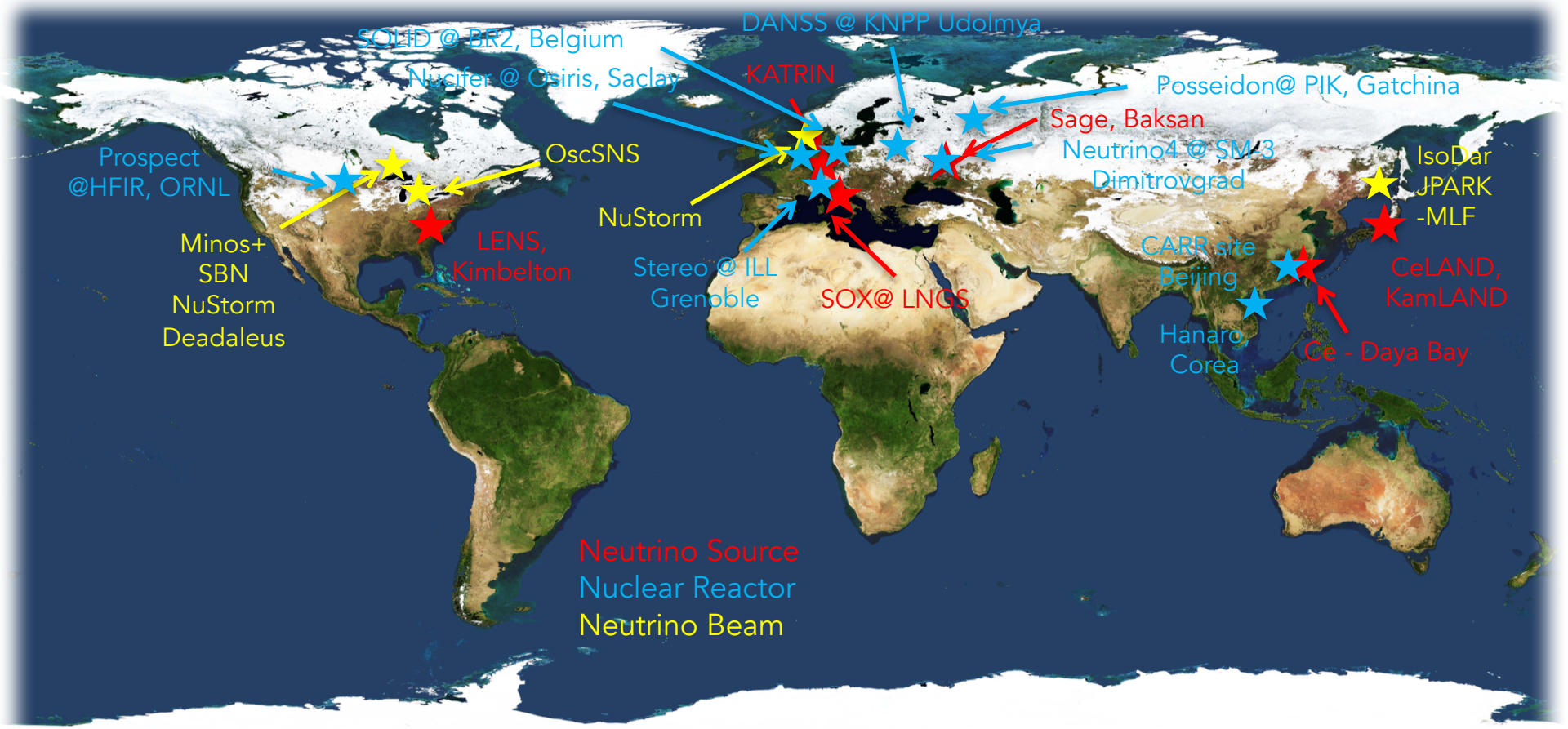
$\overset{(-)}{\nu}_e$ disappearance global fit (3+1)







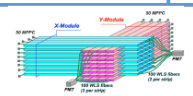
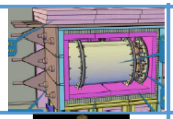
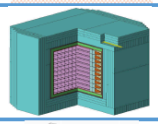
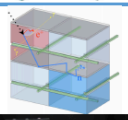
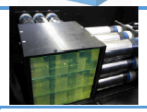
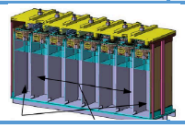
Searches for eV Sterile-ν



- This talk: ν_e disappearance only

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

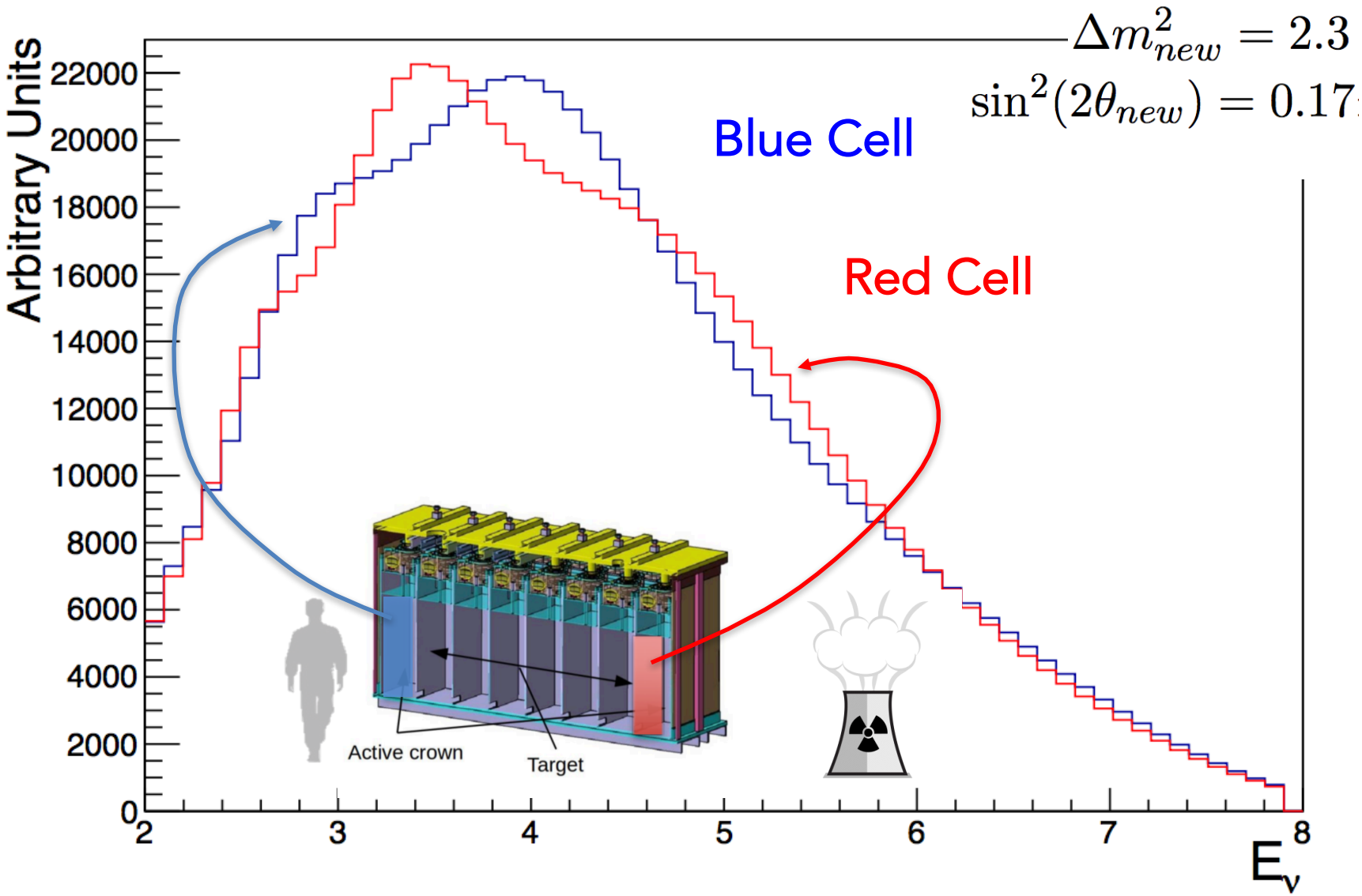
Ongoing Efforts @Nuclear Reactors

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

N. Bowden AAP 2016

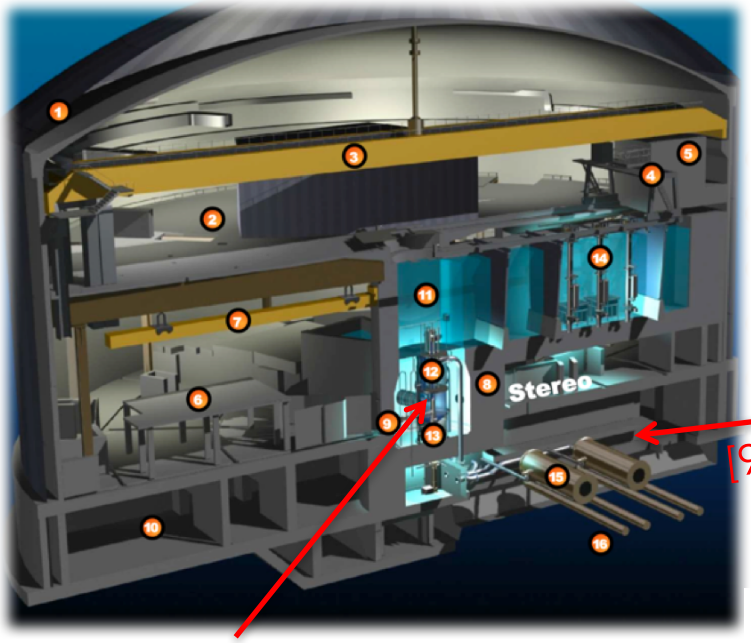
@Credit: K. Heeger

Expected Signal @Reactor



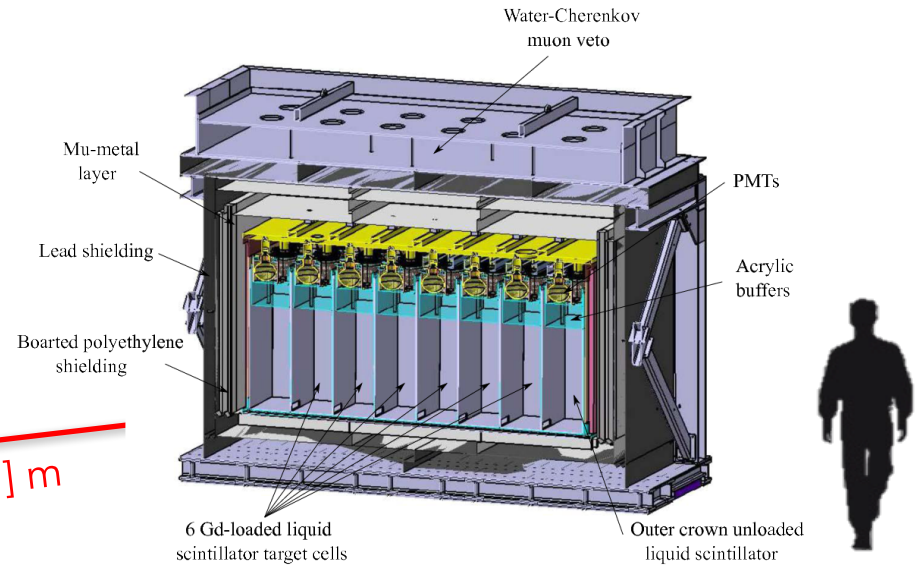
Stéréo @ ILL (*Gd-LS*)

Start Data Taking started in June 2016

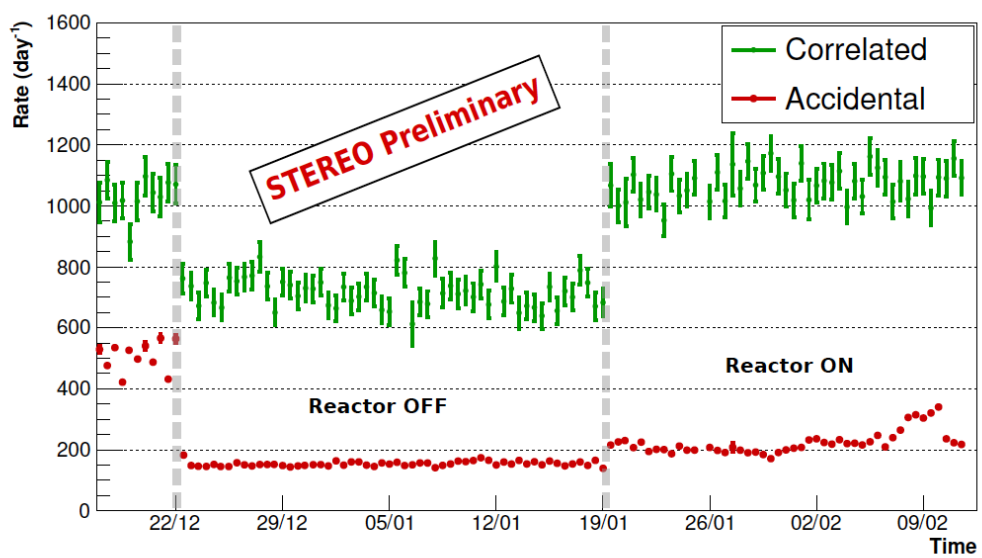


50 MW
compact core

[9-11] m



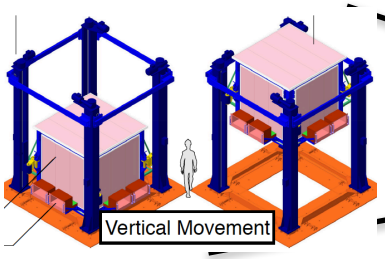
STEREO collected
>100 days of data

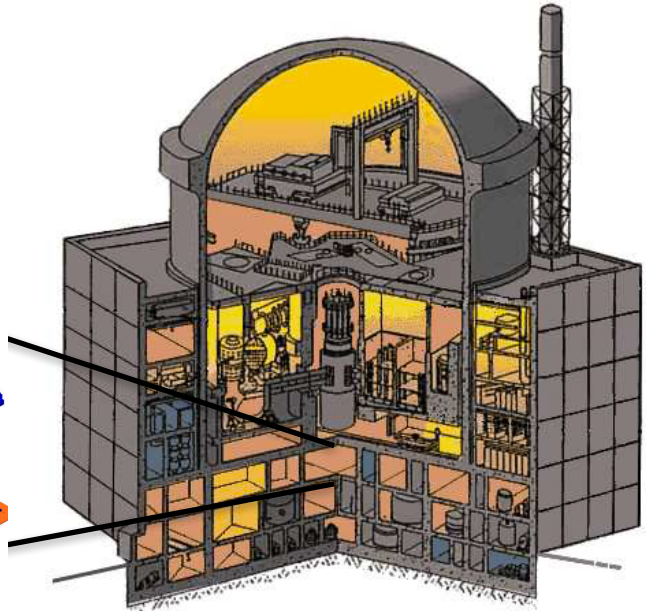


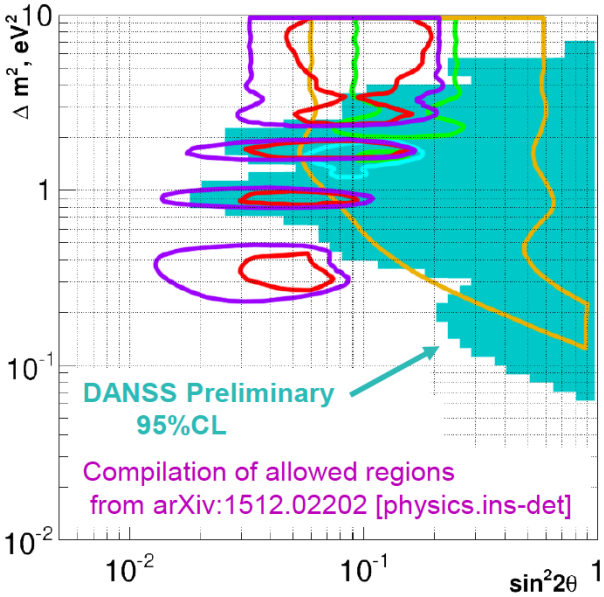
DANSS @ KNPP *(Russia)*

- 3 GW <u>extended</u> core
- Good overburden
- Vertical motion of the detector (9.7-12.2 m)
- Plastic strips with Gd-loaded interlayer, WLS fibers
- Preliminary exclusion limits

5000 evt/day

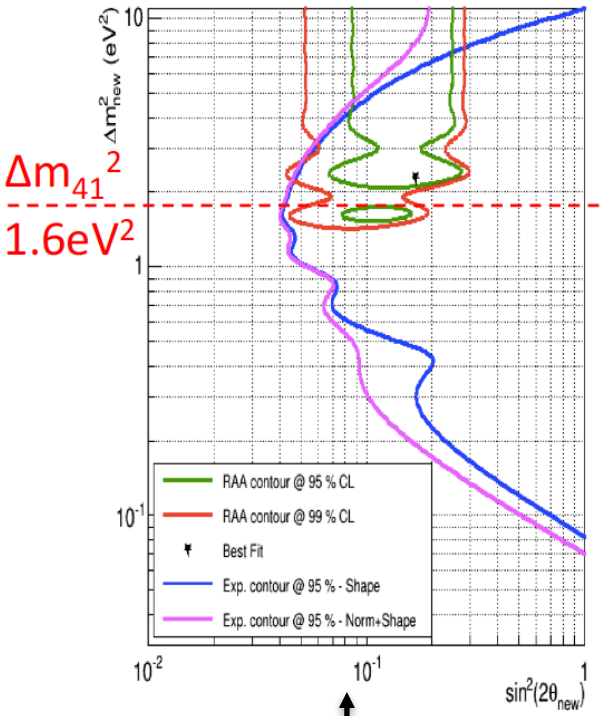






Projected Sensitivities @Reactor

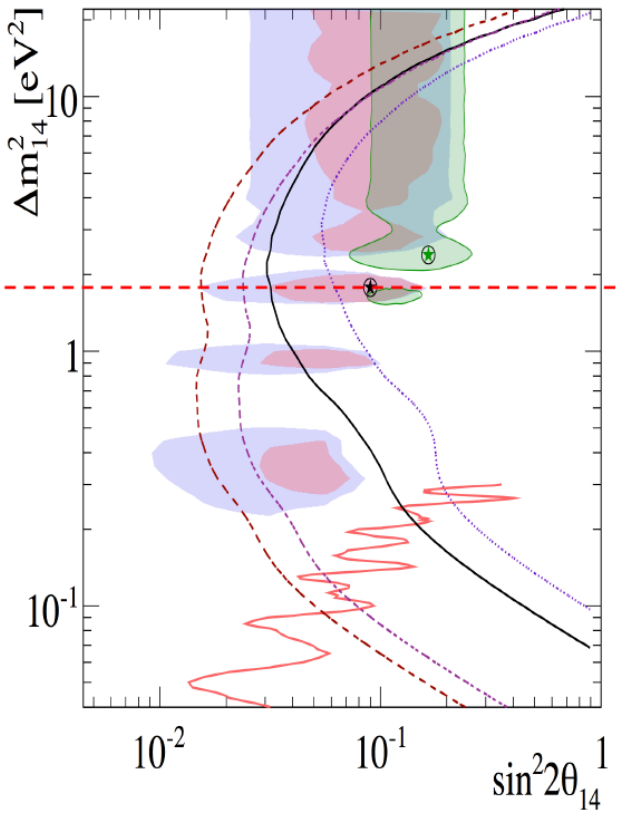
STEREO



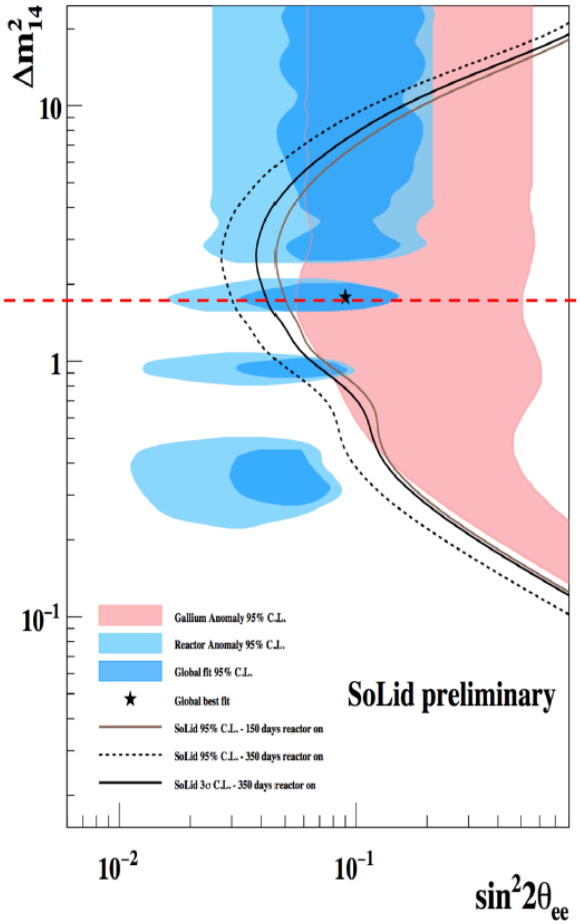
Δm_{41}^2
$1.6 eV^2$

data taking

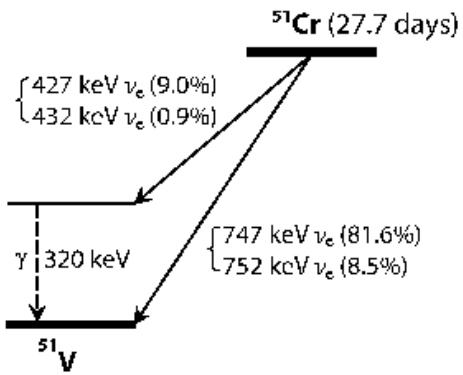
PROSPECT

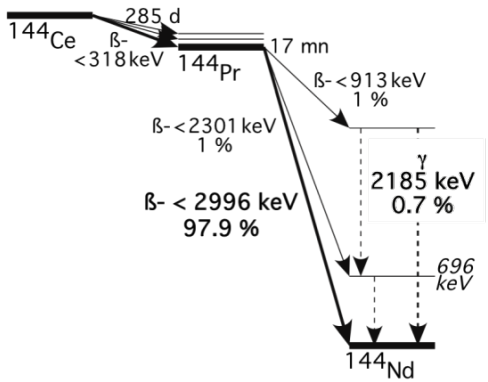


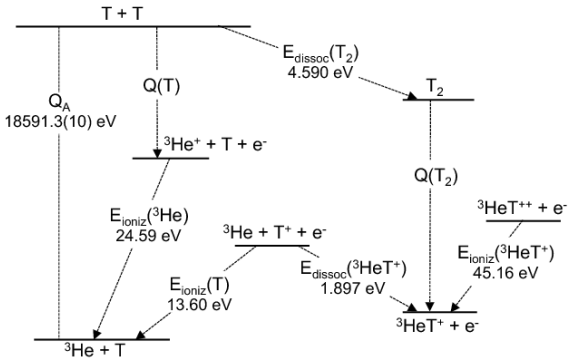
SoLid



ν-generator : CeSOX / KATRIN / BEST

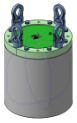


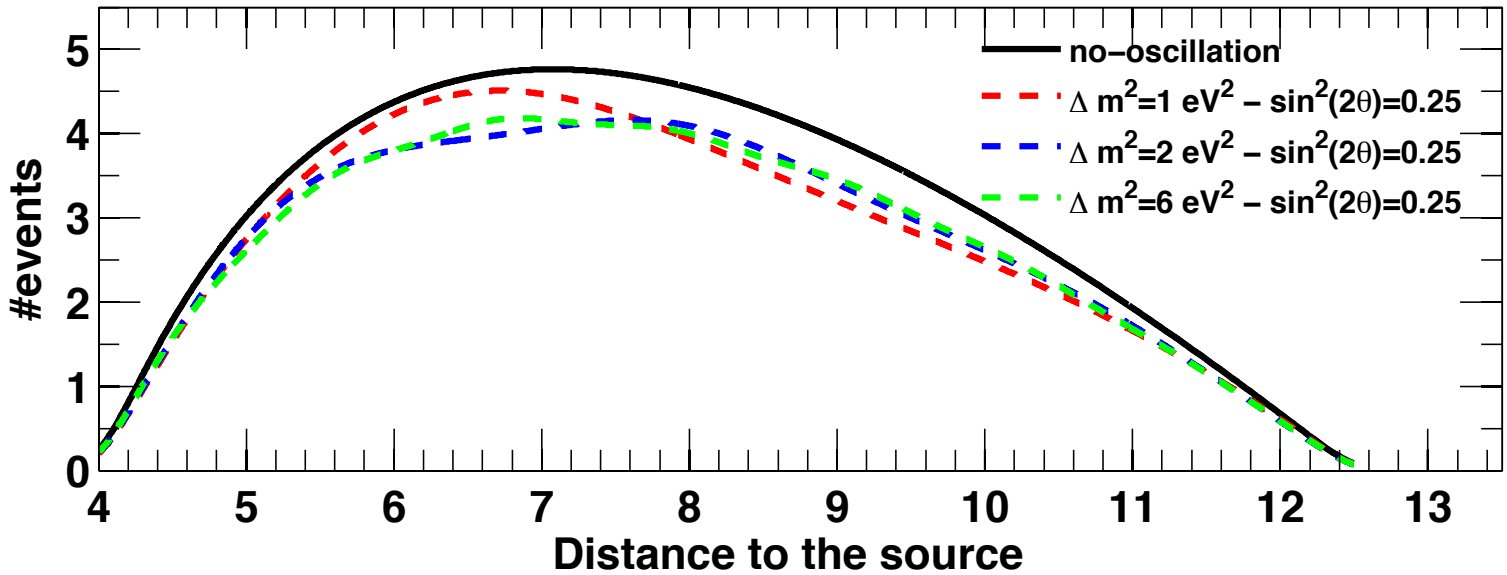


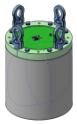


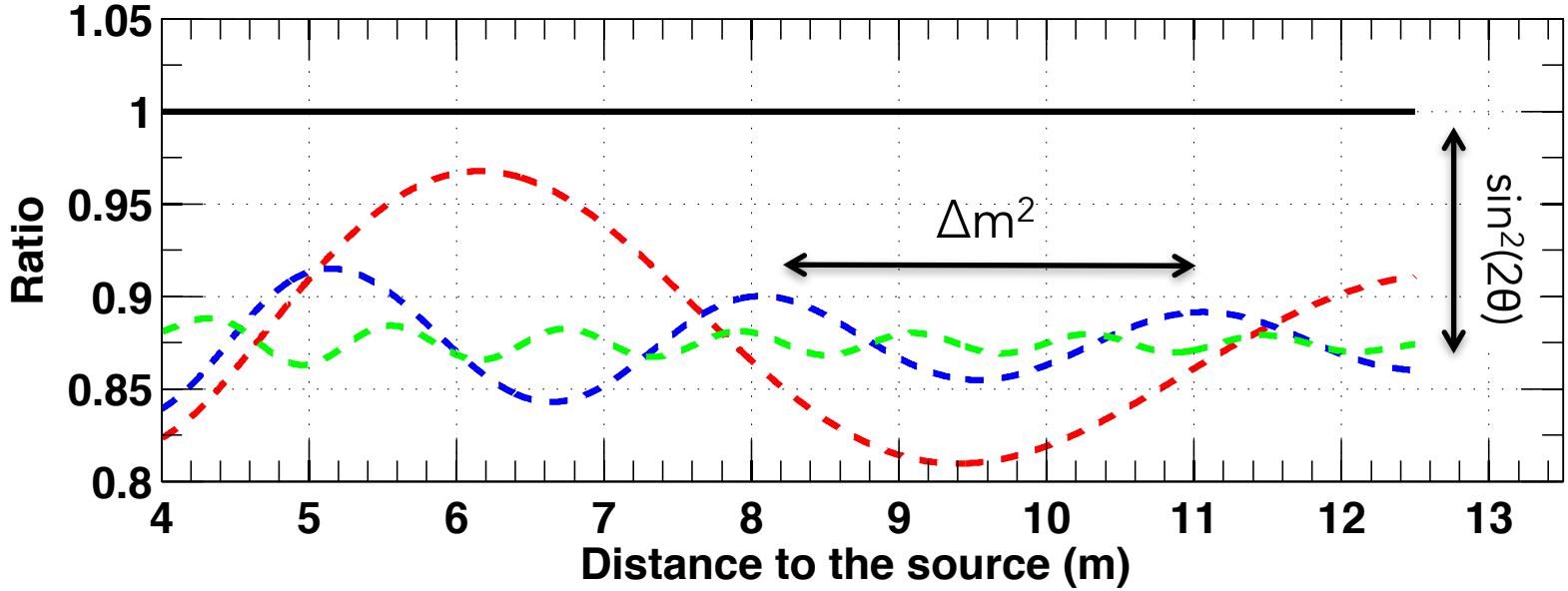
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	ν_e capture	Solar ν	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n-irradiation	>110 PBq	BEST (?)
$\bar{\nu}_e$	$\bar{\nu}_e$ p → e$^+$ n	---	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing	5 PBq	CeSOX (2018)
	^{3}H→He e$^-$ $\bar{\nu}_e$	e$^-$	^{3}H E<18 keV	n-irradiation	110 GBq	KATRIN (2018)

Measurements @ν-generator

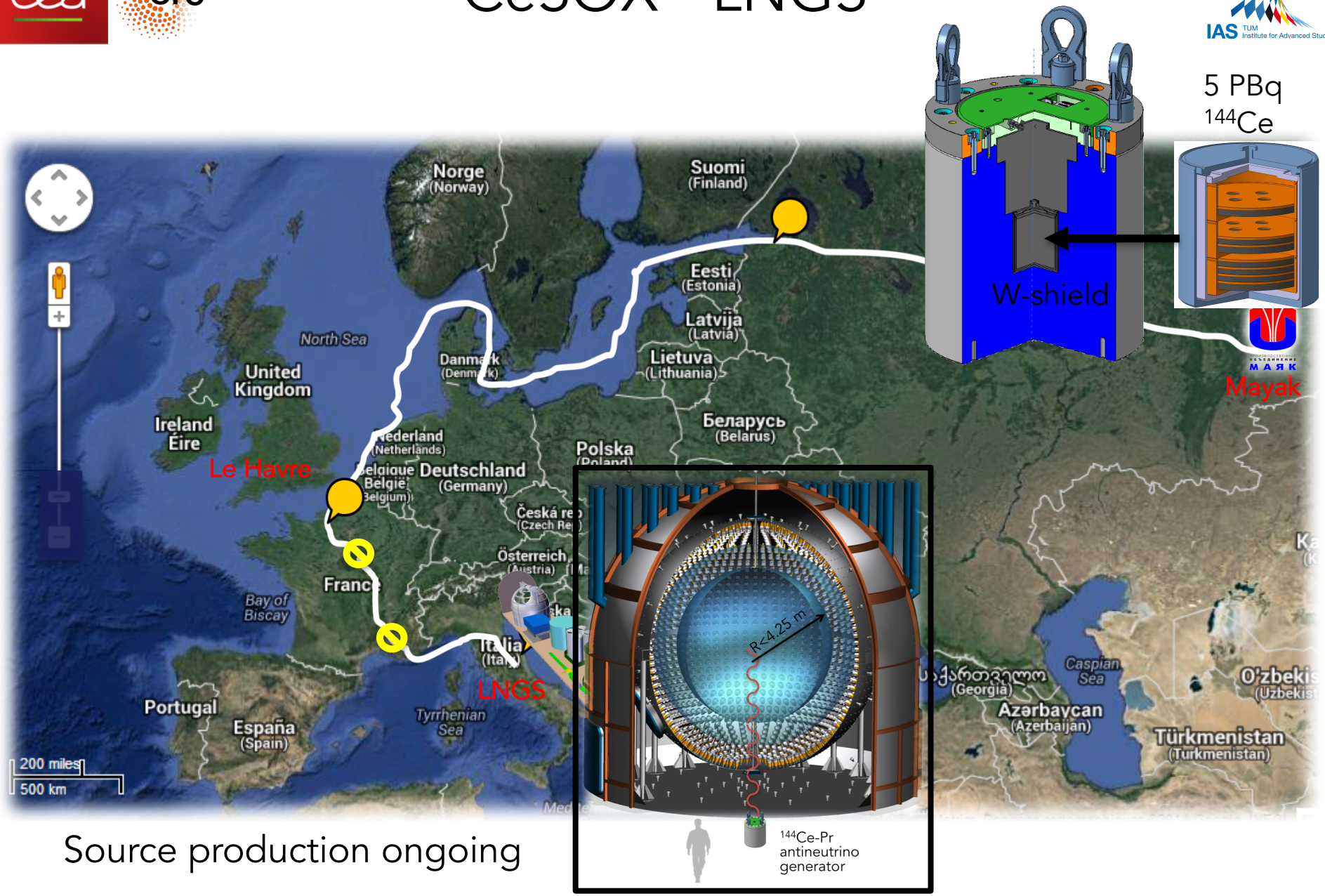






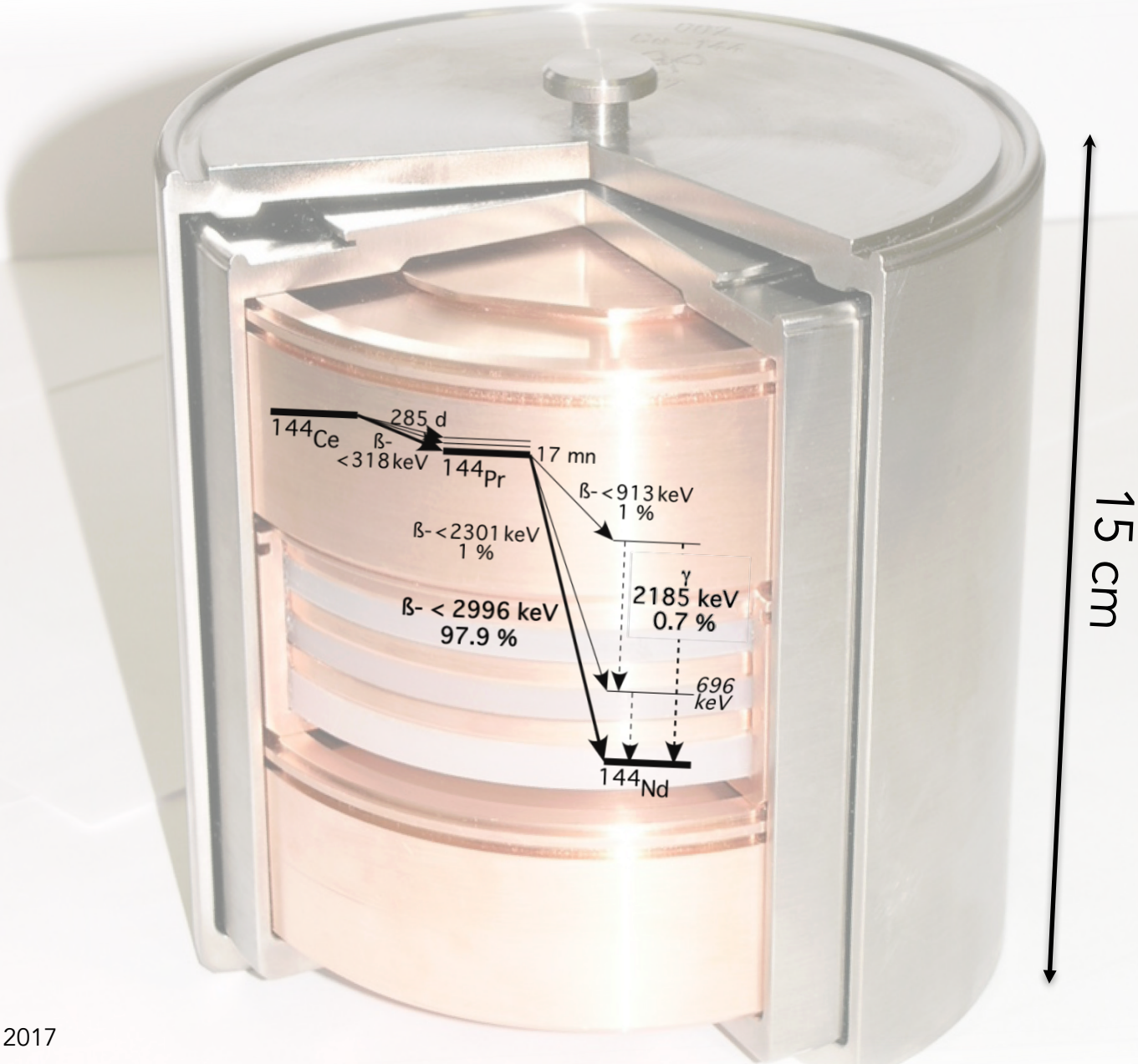


CeSOX - LNGS

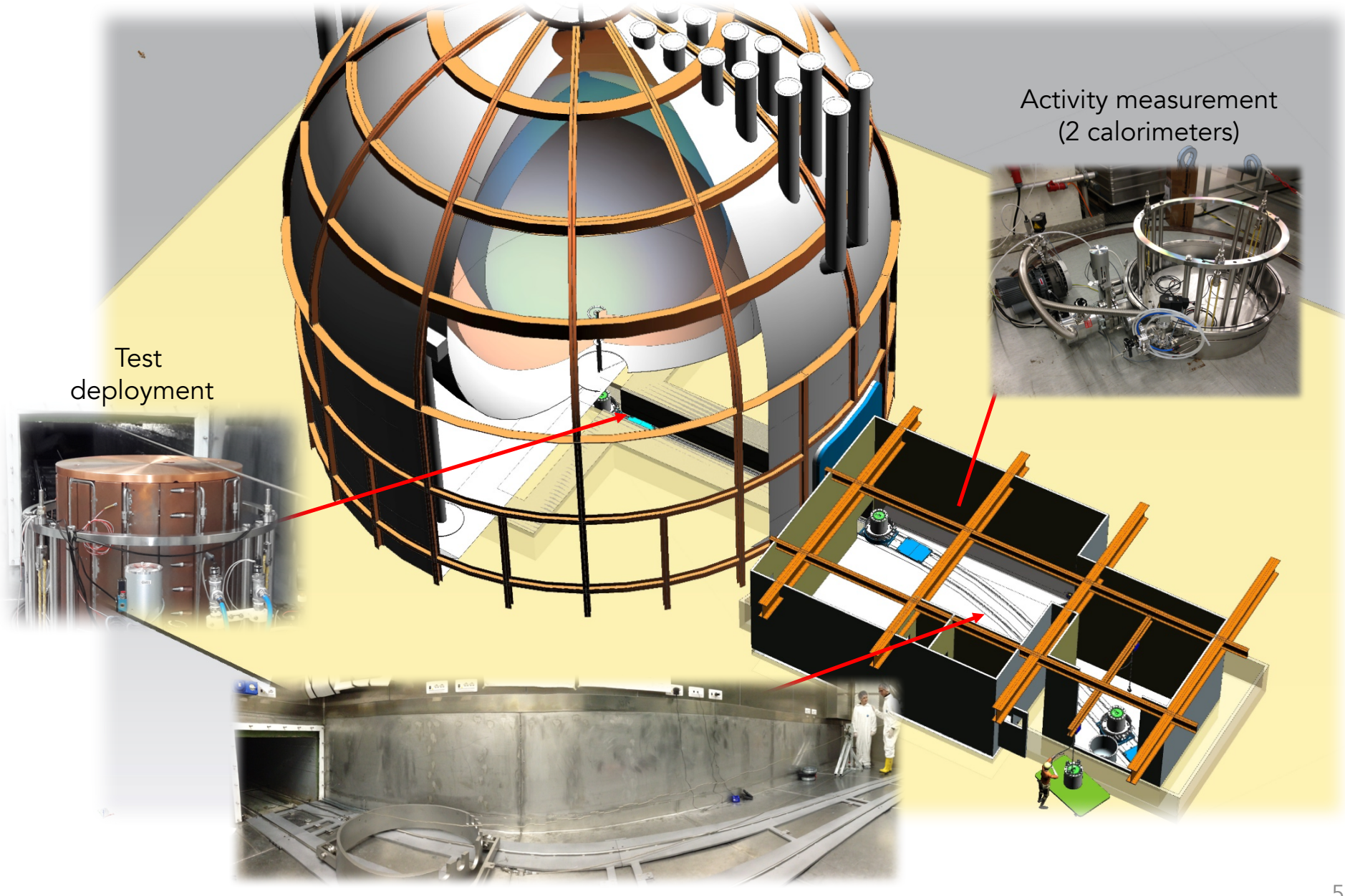


Source production ongoing

^{144}Ce-^{144}Pr Antineutrino Generator

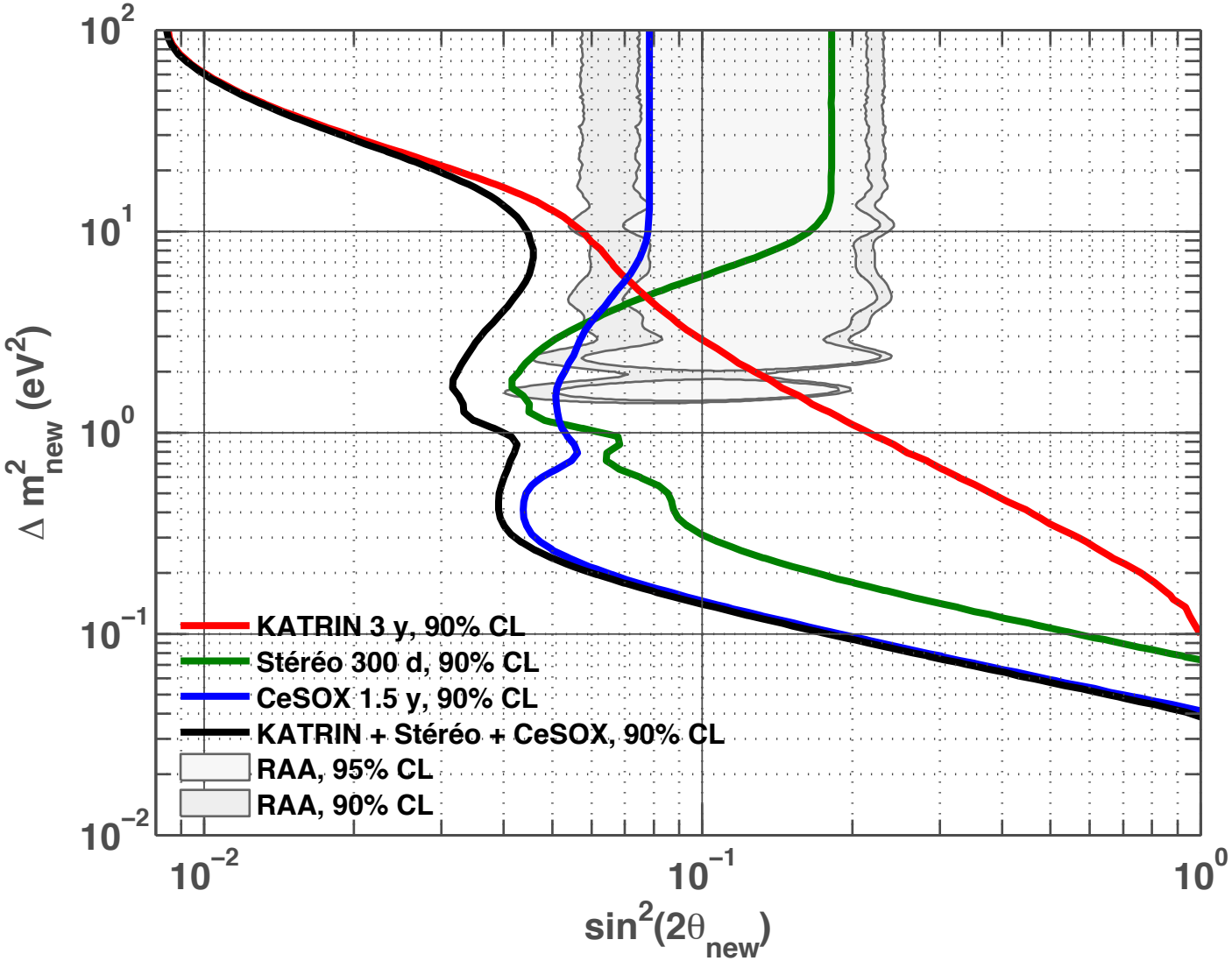


Data Taking by Jan-April 2018



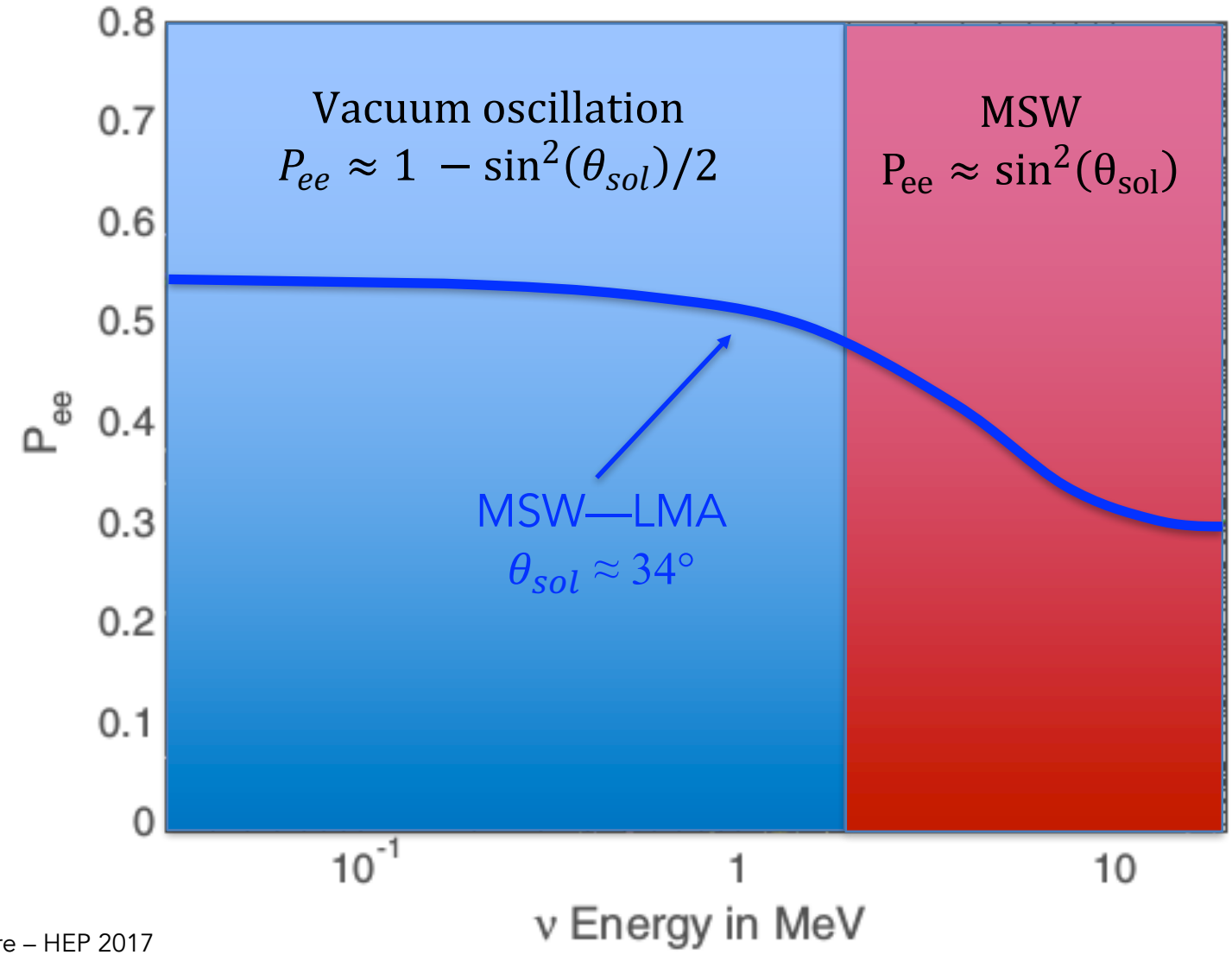
Example: KATRIN + Stéréo + CeSOX

The RAA+GAA parameter space is probed at 98% C.L.



Solar ν: Survival Probability

Test of the Mikheyev-Smirnov-Wolfenstein Large Mixing Angle model



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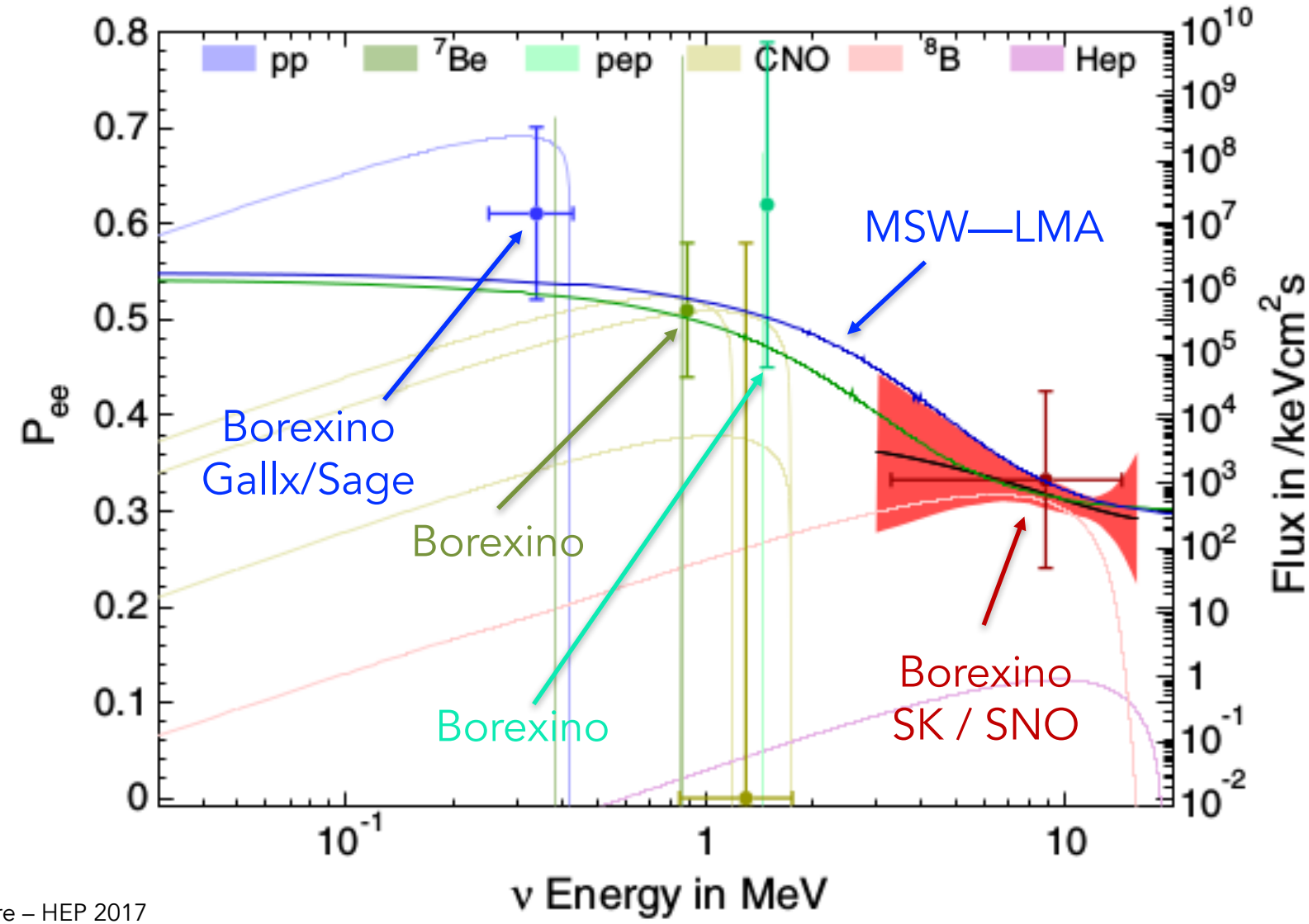
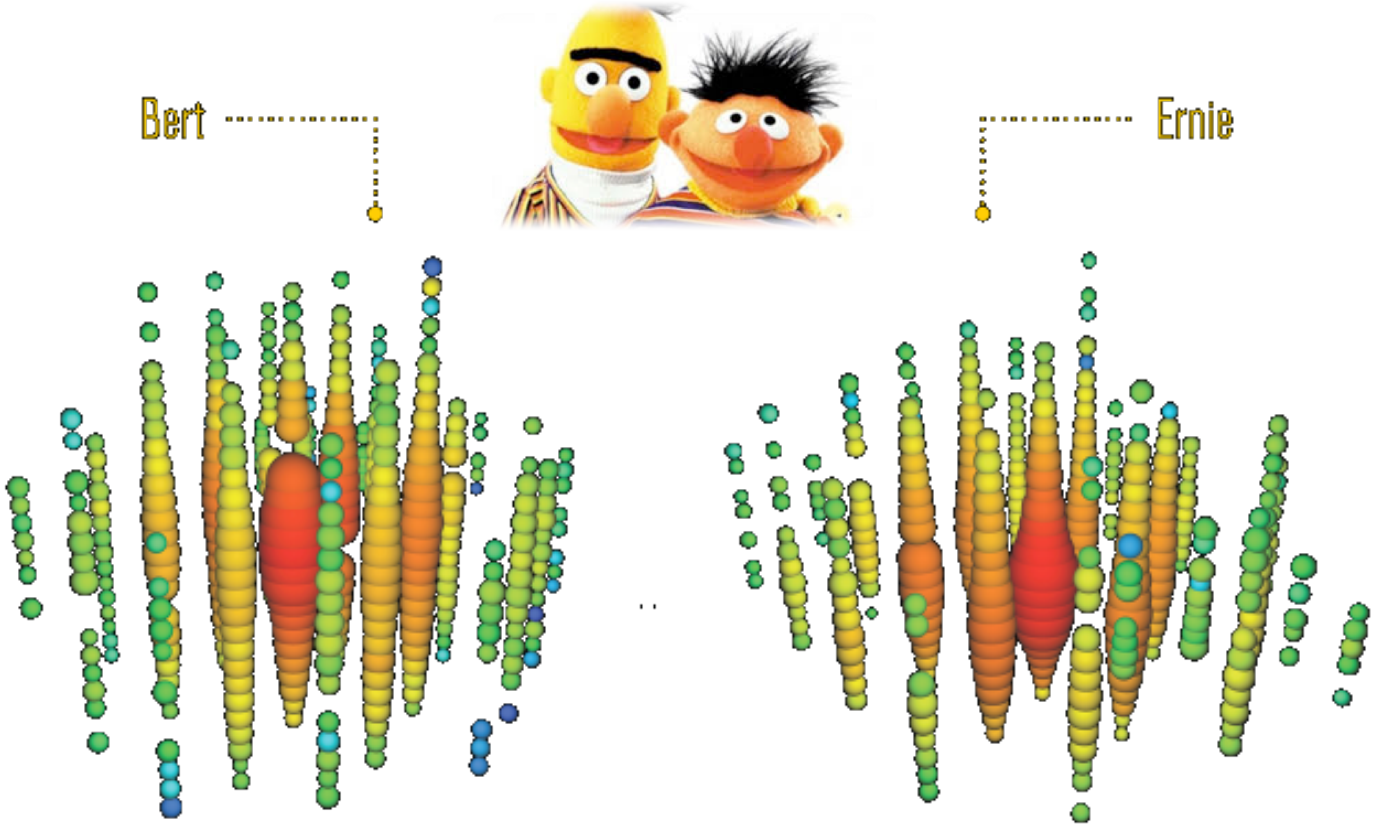
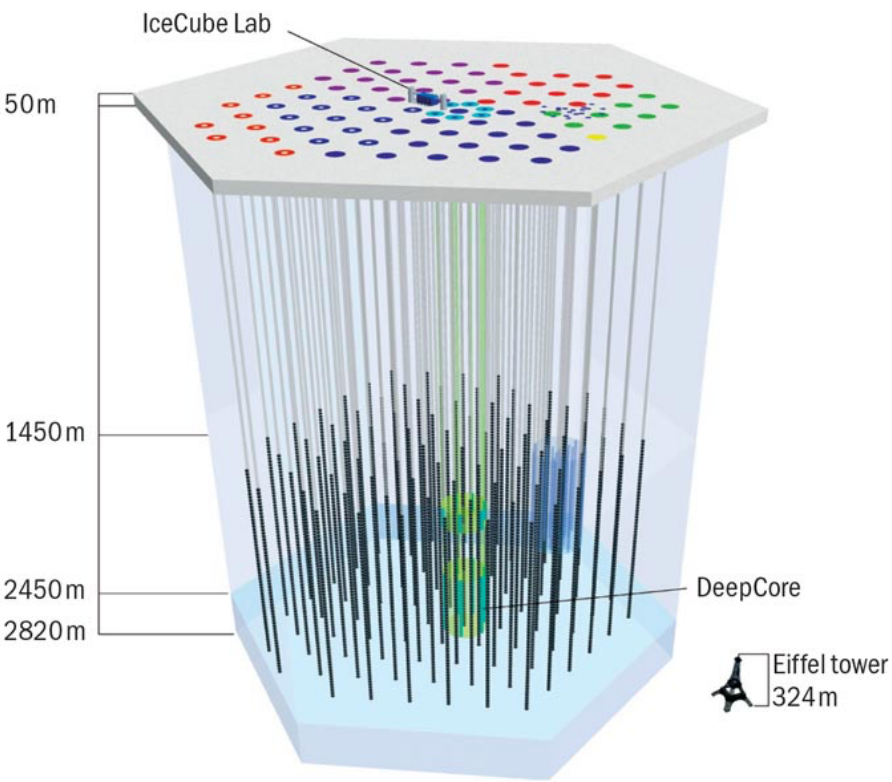
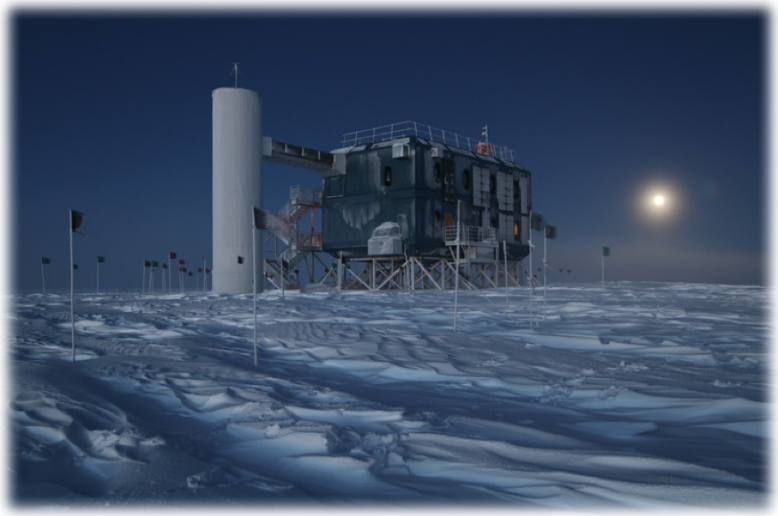



Bert
Ernie

IceCube Neutrino Telescope

Existing: 1 km^3 antarctic ice instrumented with 5160 PMTs
+ 20 short distant strings to reduce threshold (deep core)

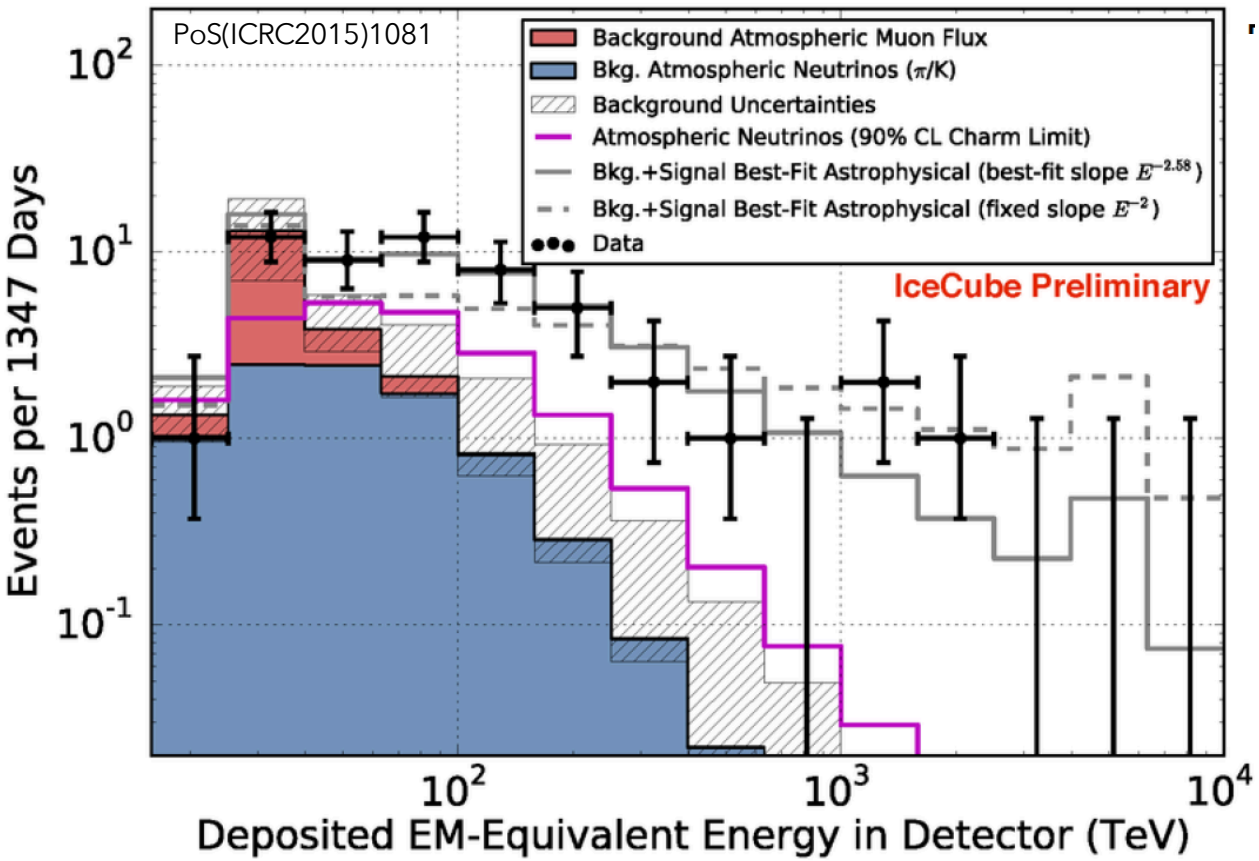




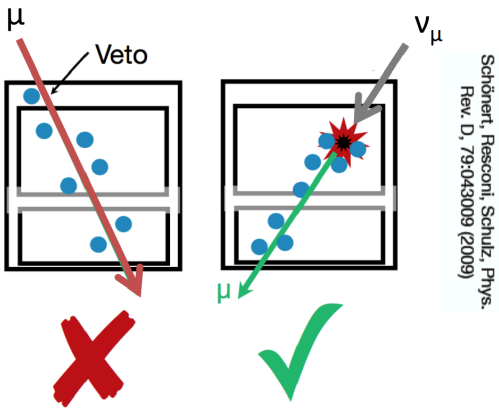
Next: expanding the effective area for high energy events

IceCube – High Energy Events

Discovery of a new
Astrophysical Neutrino Flux



μ-veto



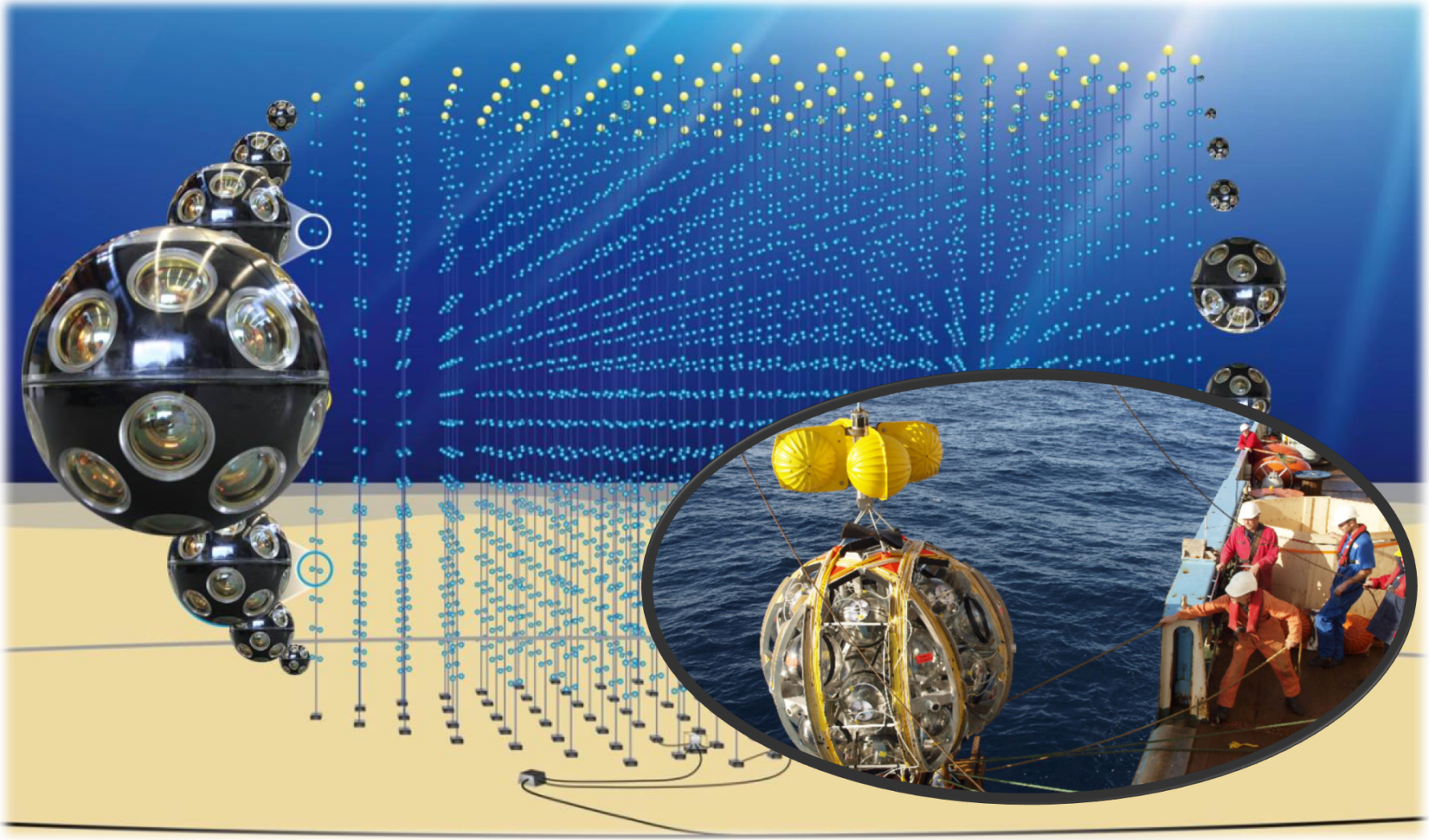
20±6 expected

54 observed

Origin: ?

KM3NeT/Arca – 1 km^3

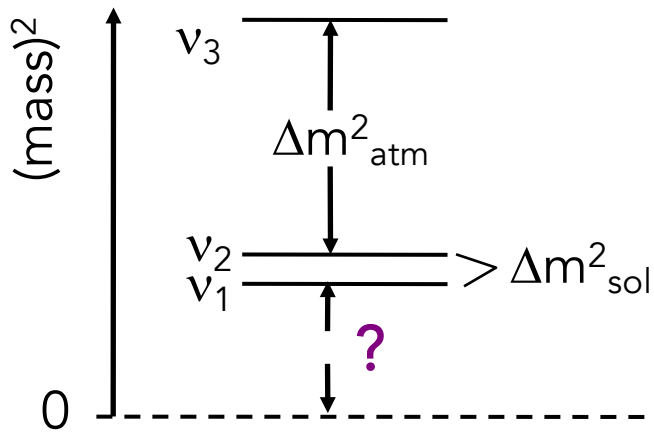
Observation of GeV – PeV neutrino sources of cosmic origin



All my apologies if your favorite topic could not be covered

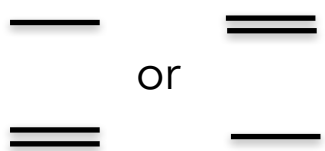
Facts & open questions

- Masses of the mass eigenstates ν_i?



} <10% precision achieved

} Impressive cosmological bounds
KATRIN coming soon

- Spectral pattern  or ?

} Will be known by 2025

- Lepton Number conservation (Dirac or Majorana) ?

} No signal yet - See Next Talk

- Precise measurements of PMNS matrix?

} Impressive results on θ_{13} – 4% precision

- Is CP violated in the neutrino sector?

} Trends from global fits. See Next Talk

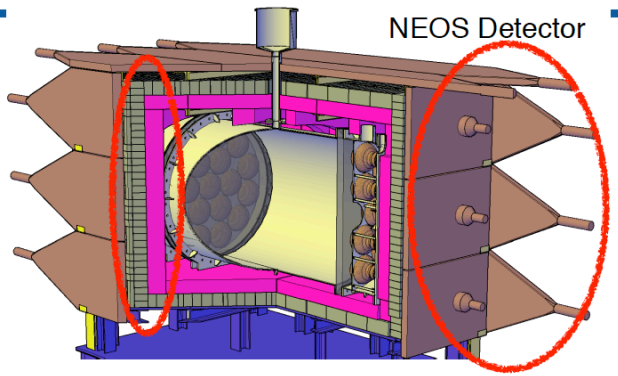
- Are there additional (sterile) neutrino states

} Will be fixed within 3-5 years

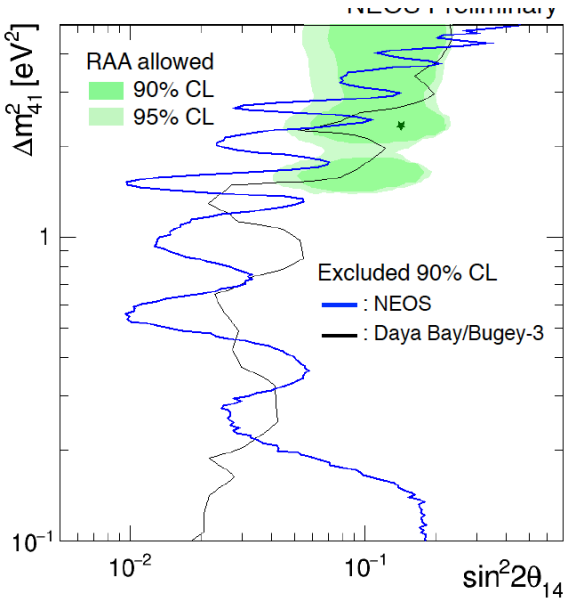
Thanks for your attention

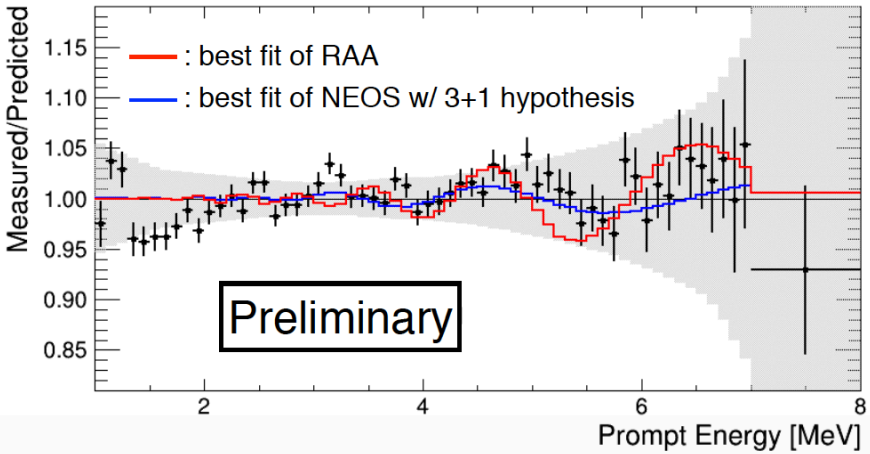
NEOS @Hanbit (Korea)

NEOS



Detector installed





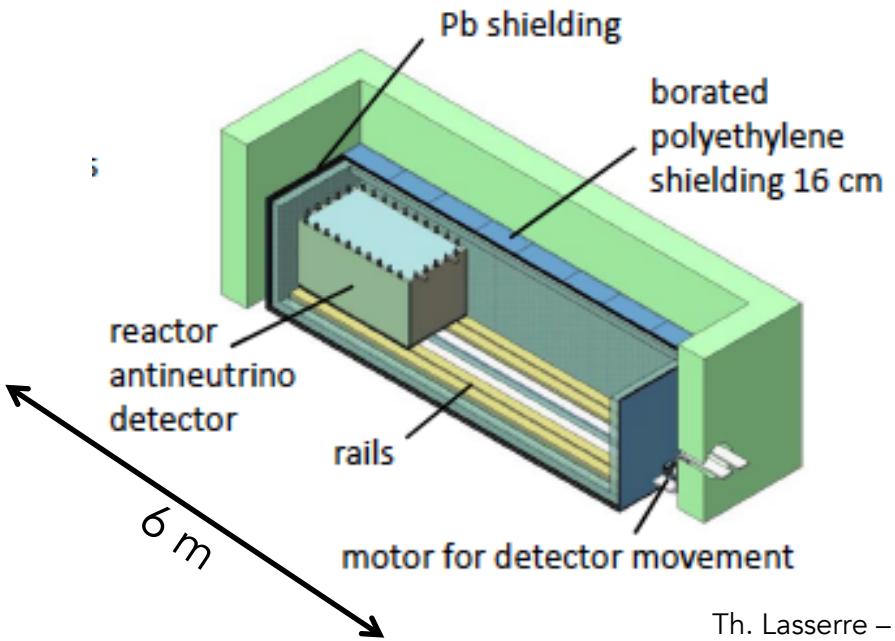
- Single-volume GdLS detector with pulse shape discrimination and 5% Energy Resolution
- Located in tendon gallery at Hanbit power reactor at ~25m from reactor core, S:B ~23, 2000 IBDs/day(!)
- Initial data run finished in 2016, spectral oscillation search starting to probe best-fit region

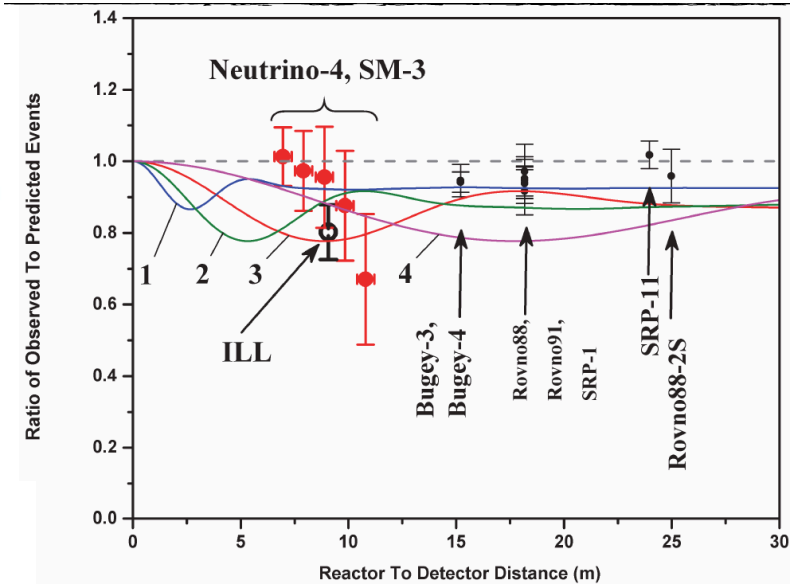
Neutrino-4 @ SM3 (*Gd-LS*)

- 350l LS target, 5 sections movable detector [6-12] m
- 100 MW compact core

- Detector at Surface

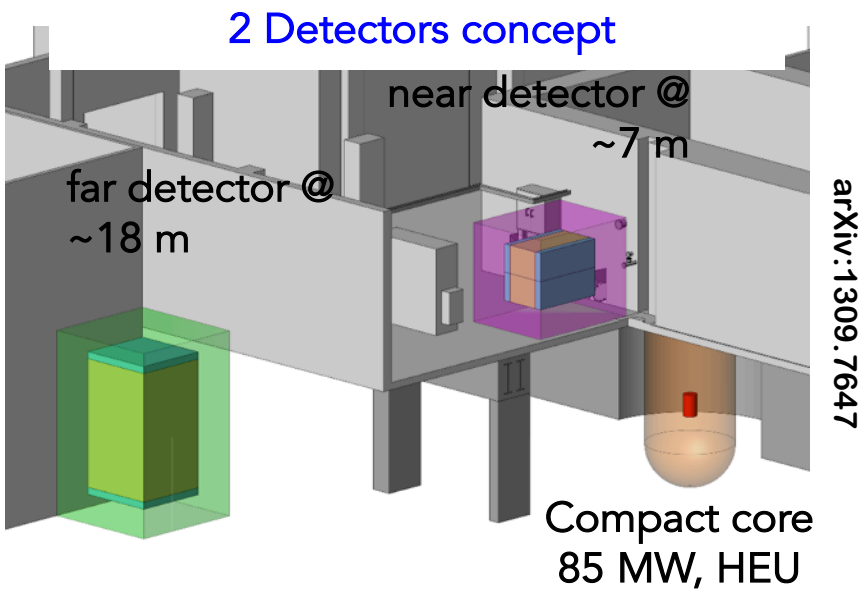
- Status:
  - Proto: On/Off ν-data
  - Started in 2015
  - Larger det. planned

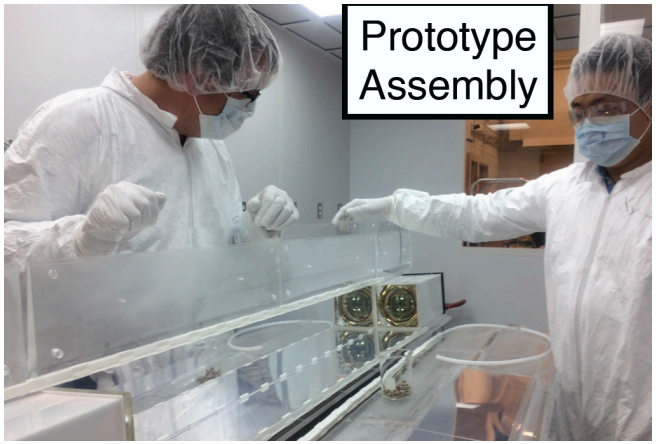




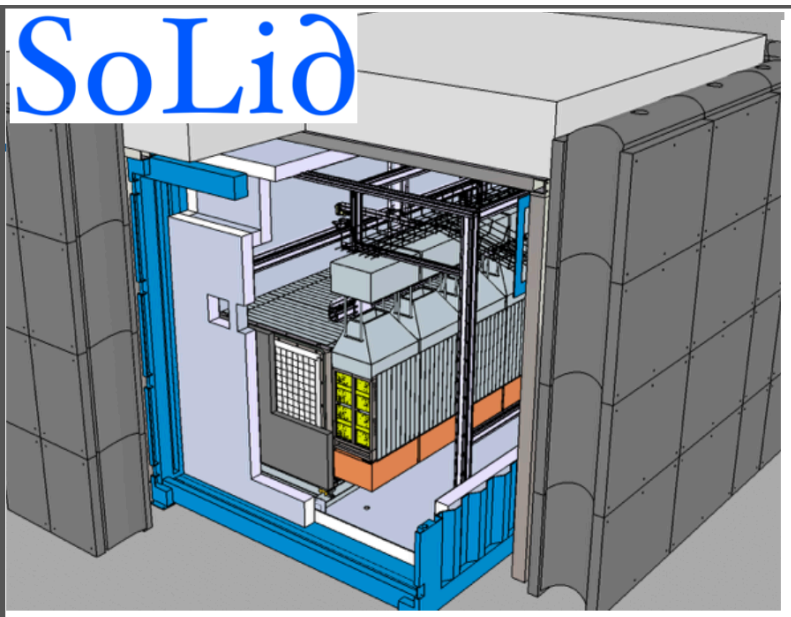
Prospect @HFIR (USA)

- Reactor sites
  - HFIR – 85 MW
- 7-18 m baselines
- Surface location
- Detector
  - 4t movable Segmented
  - ^{6}Li-doped (+PSD)
- Status:
  - Installation in 2017

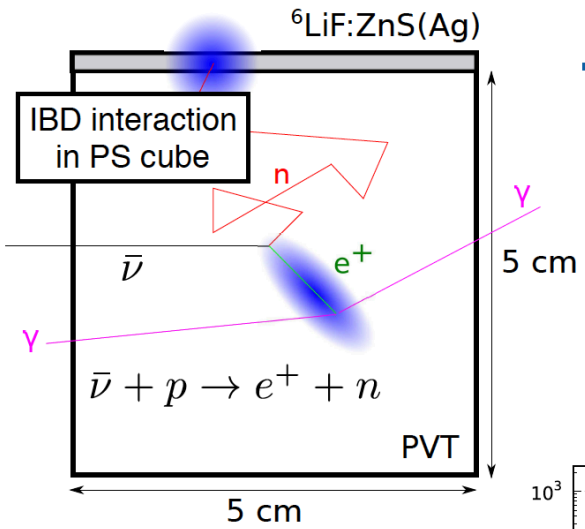


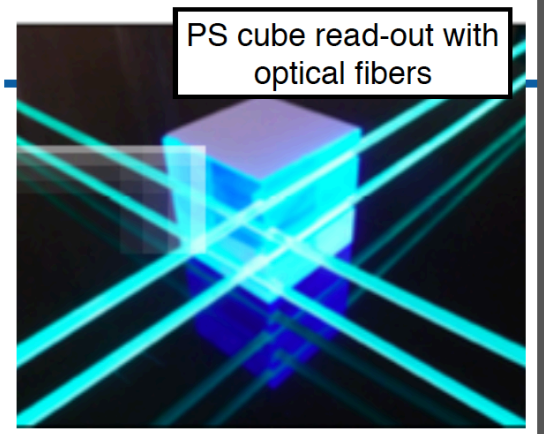


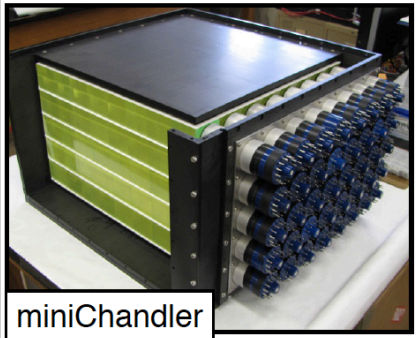
Solid @BR-2 (Belgium)



$$n + {}^6\mathrm{Li} \rightarrow {}^3\mathrm{H} + \alpha + 4.78\ \mathrm{MeV}$$

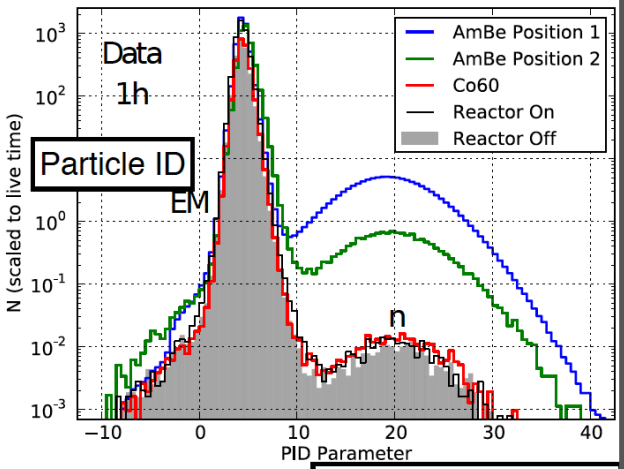






miniChandler Prototype

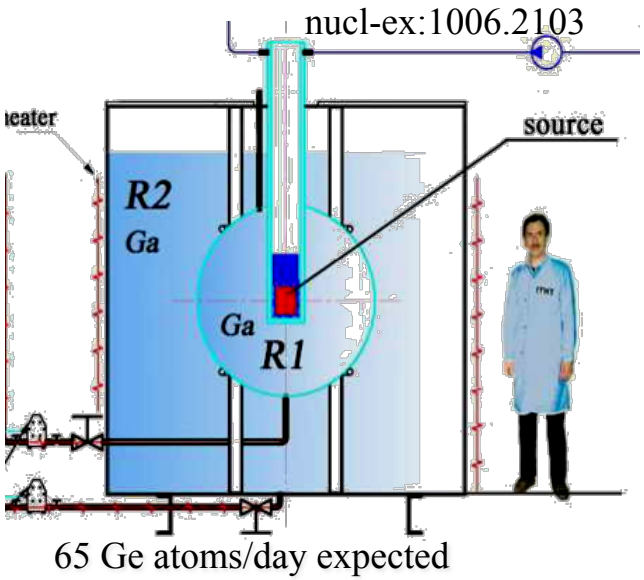
- 13000 5cm PS cubes read out by fiber
- Neutron tag from Li-loaded inorganic scintillator sheets surrounding cubes
- Deploy 1600kg detector at BR-2 reactor early 2017
- Detector R&D study (Chandler) underway, would expand high Δm^2 sensitivity

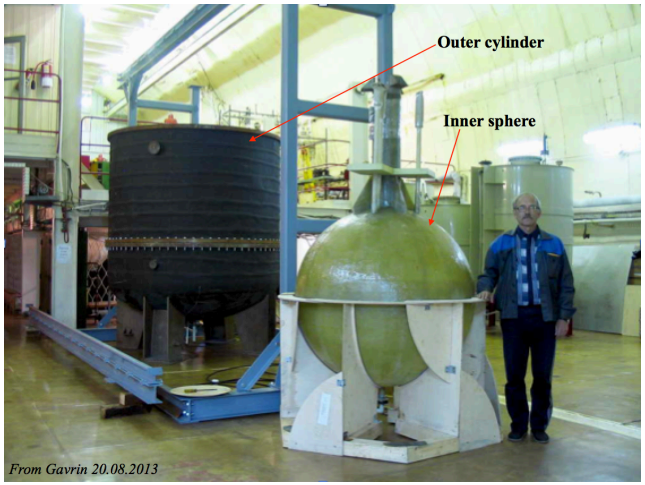


N. Ryder - AAP 2016

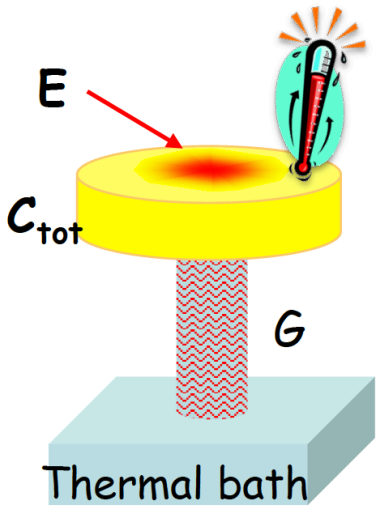
^{51}Cr: 2-Zone Ga detector (Best)

- ^{51}Cr Source:
  - Enrichment of 3.5 kg ^{50}Cr (97%)
  - Irradiation to reach 110 PBq at research reactor SM-3
- 2-layer detector in Baksan
  - Metallic Ga Target
  - Zone 1: 8 t - Zone 2: 42 t
  - SAGE procedures well understood
  - Insensitive to γ-ray background
- Observable
  - Ratio of ν_e capture rates to predicted rate in inner (R1) and outer zone (R2)
- Status: funding?

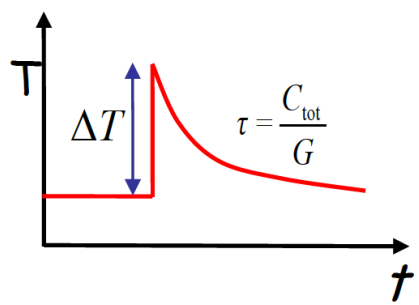


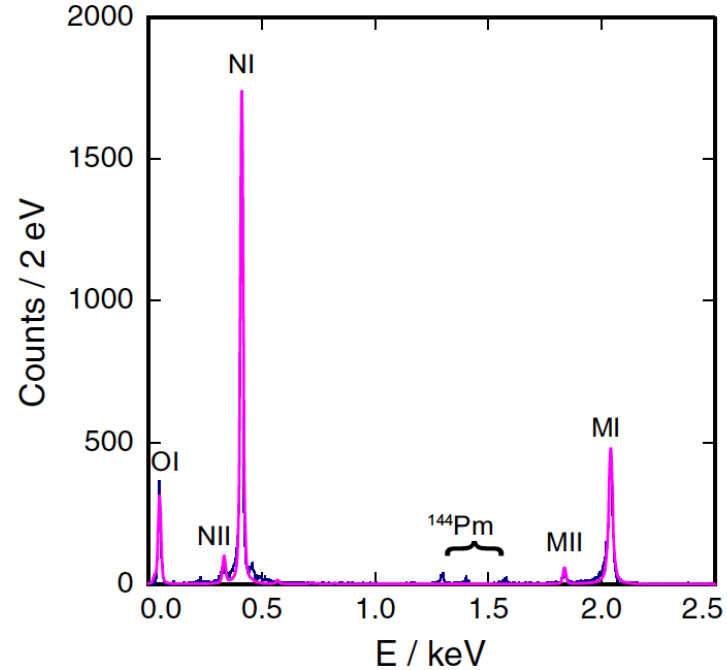


ECHo/Holmes/Numecs – ^{163}Ho EC



$$\Delta T \cong \frac{E}{C_{tot}}$$





- Phase 1: 10^{10} decays – 10 eV-scale sensitivity – soon…
- Phase 2: 10^{16} decays – 10^{6} pixels – 100 meV-scale sensitivity