A personal short review on

Experimental Neutrino Physics

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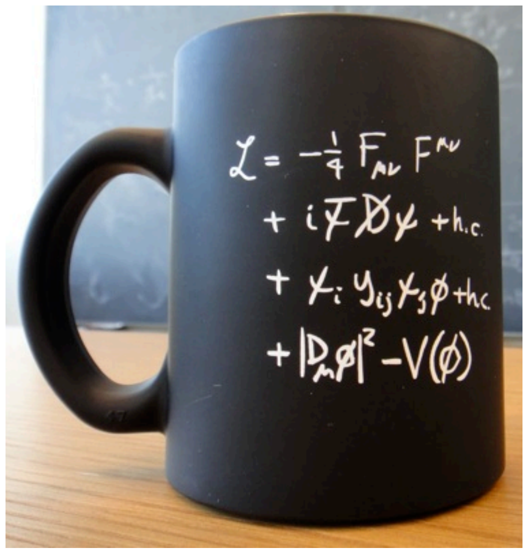
Università di Genova and INFN

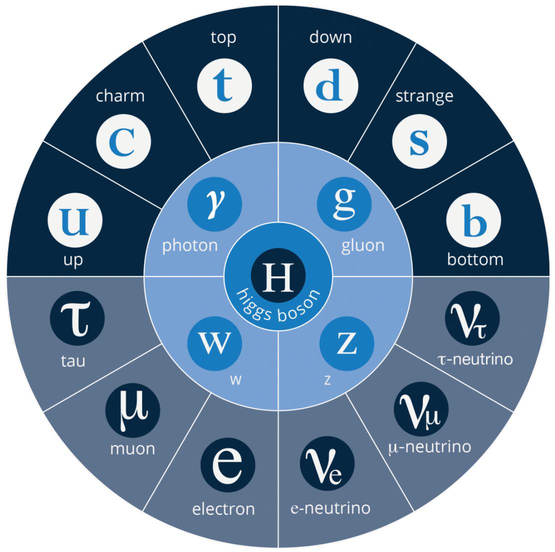
FPCapri2018
Capri, June 8-10, 2018

NEUTRINOS AS A BRIDGE

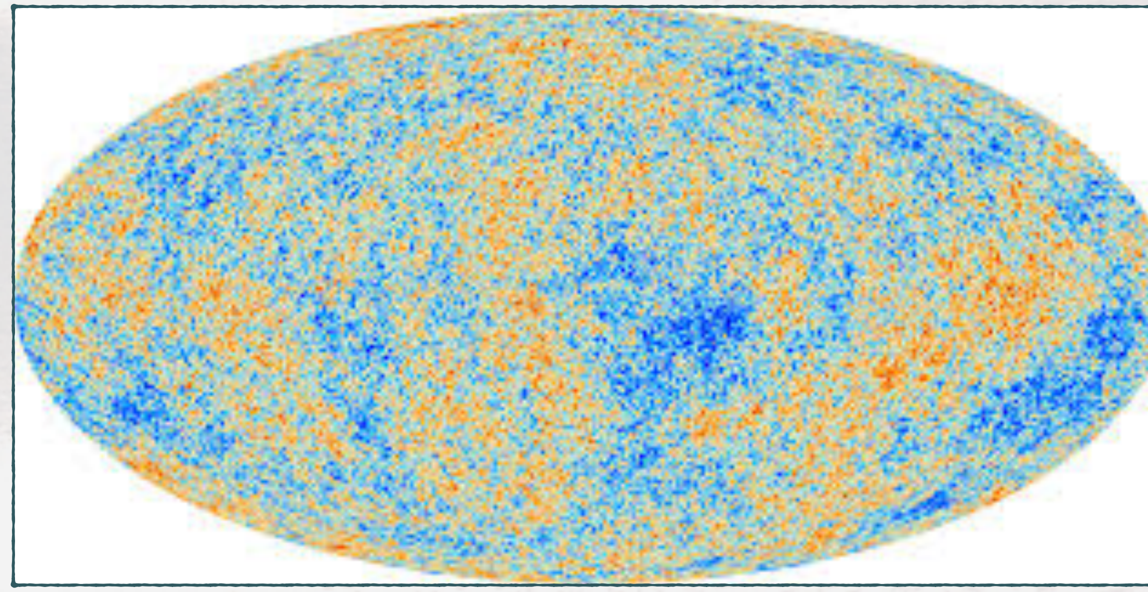
- Neutrino physics (as all astroparticle physics) is a bridge between ***two standard models***

Standard Model (of particles and fields)





Standard Model (ΛCDM Cosmology)



- Beautiful, but certainly **incomplete**
  - **Neutrinos:** m, $\nu=\bar{\nu}$?, δ_D ($\delta_{M1,2}$), hierarchy
  - No **dark matter candidates**
    - θ_{QCD} **?** Super-symmetry ? **Steriles ?** BSM
  - **No inflation** (connected with Higgs?)
  - **Gravity is classical only**
    - Quantum gravity ? Different paradigm ?
  - **CPV insufficient**
    - Can **neutrinos** help ?

- Beautiful, but somewhat **ad hoc**
  - ~ 95% of energy density is "dark"
    - **"Matter"**
      - Which role for neutrinos ?
    - **"Energy"**
      - A constant or a field ? Why so small ?
  - Inflation is postulated
  - Sakharov conditions imposed but not explained. **Which role for leptons ?**

- Neutrino physics (as all astroparticle physics) is a bridge between ***two standard models***

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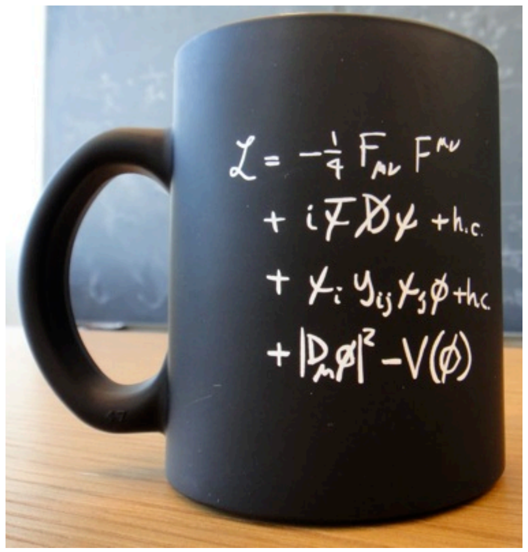

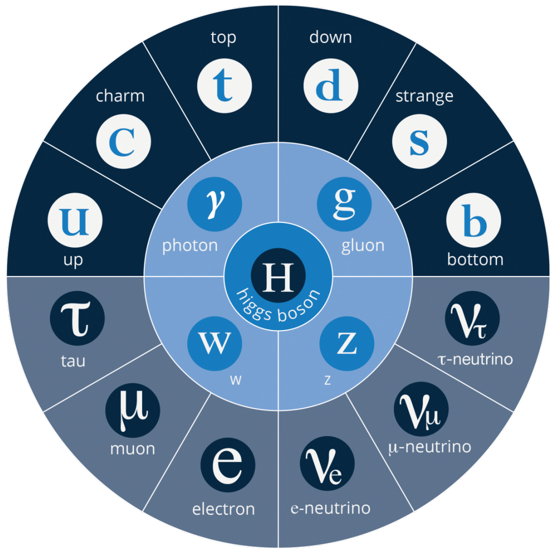

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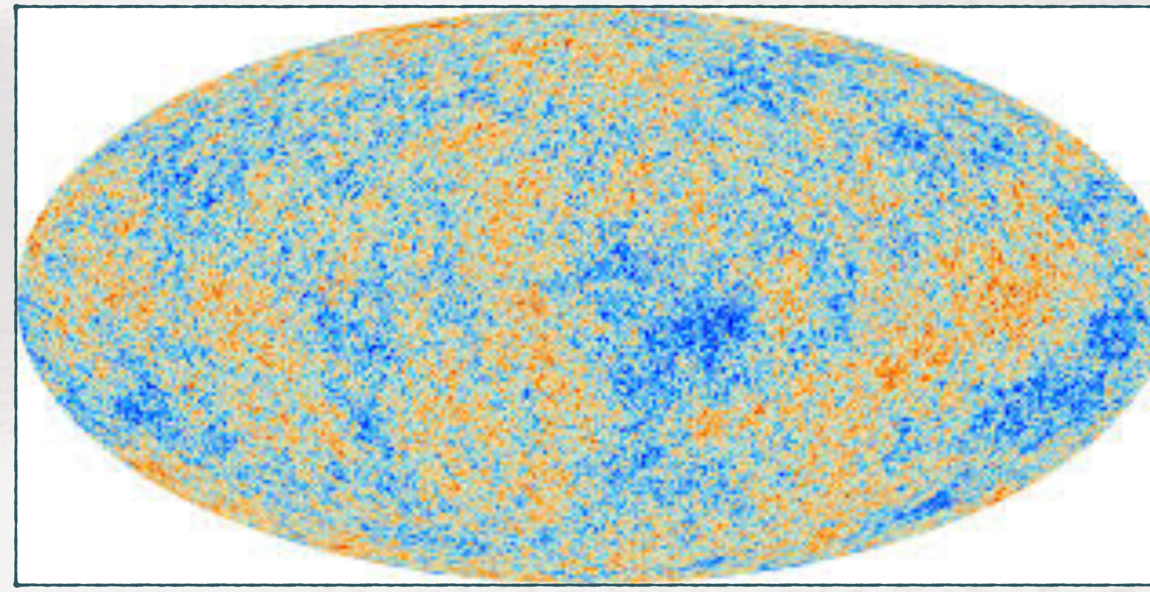

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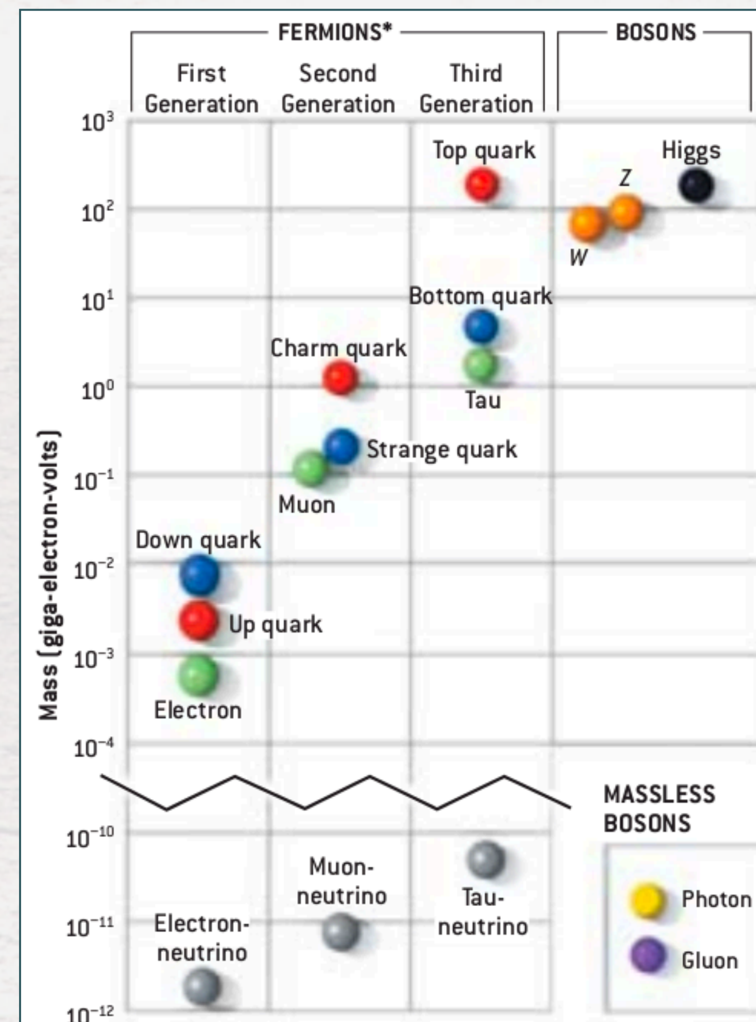
Standard Model

CP Violation
Majorana vs Dirac
Cross sections
Coherent scattering

Astrophysics & Cosmology

SN1987A

SuperNovae
G.W. and ν
CνB
High Energy ν
Leptogenesis

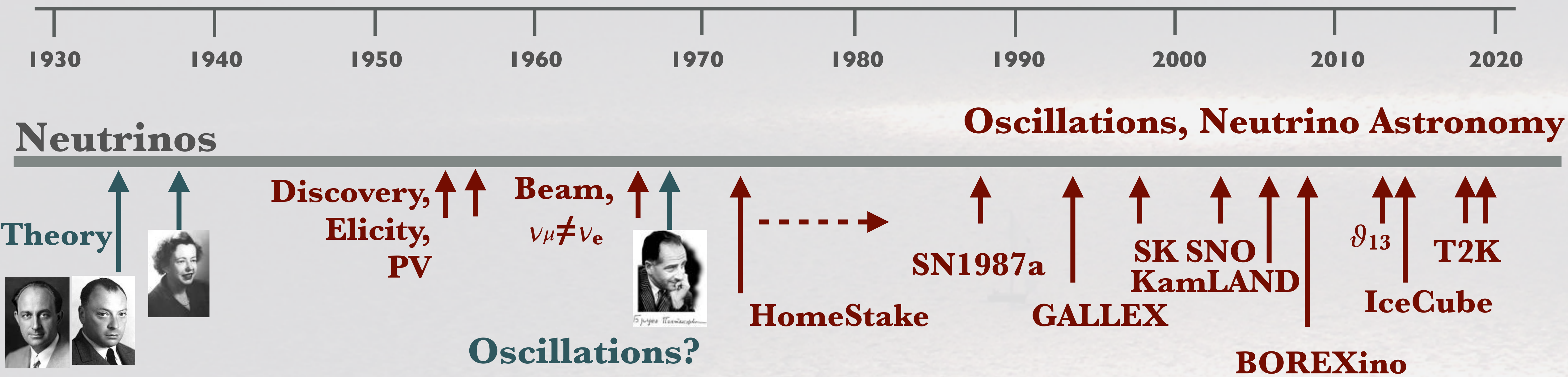


(image: G. Kane, Sci. Am.)

New Physics

0νββ
Mass scale
Sterile ν
Dark Matter

STATE OF THE ART



1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

Neutrinos — **Oscillations, Neutrino Astronomy**

Theory

Discovery, Elicity, PV

Beam, $\nu_\mu \neq \nu_e$

Oscillations?

HomeStake

SN1987a

GALLEX

SK SNO KamLAND

BOREXino

ϑ_{13}

IceCube

T2K

$|\Delta m^2| = 2.47 \pm 0.04\ 10^{-3}\ eV^2$

$\theta_{23} = 47.5 \pm 3.2°$

$\delta_D = ?\ (-\pi/2\ ?)$

$\theta_{13} = 8.56 \pm 0.15°$

$\delta m^2 = 7.40 \pm 0.21\ 10^{-5}\ eV^2$

$\theta_{12} = 33.6 \pm 0.77°$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_D} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_D} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

Atmospheric
Accelerators LBL
L ~ 700 km

Reactors L ~ 1 km
LBL L ~ 200 km

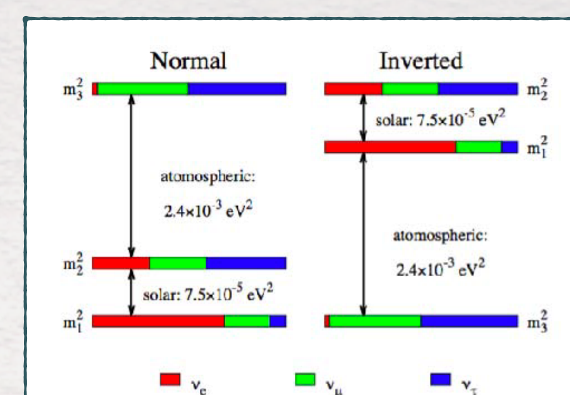
Solar
Reactors
L ~ 200 km

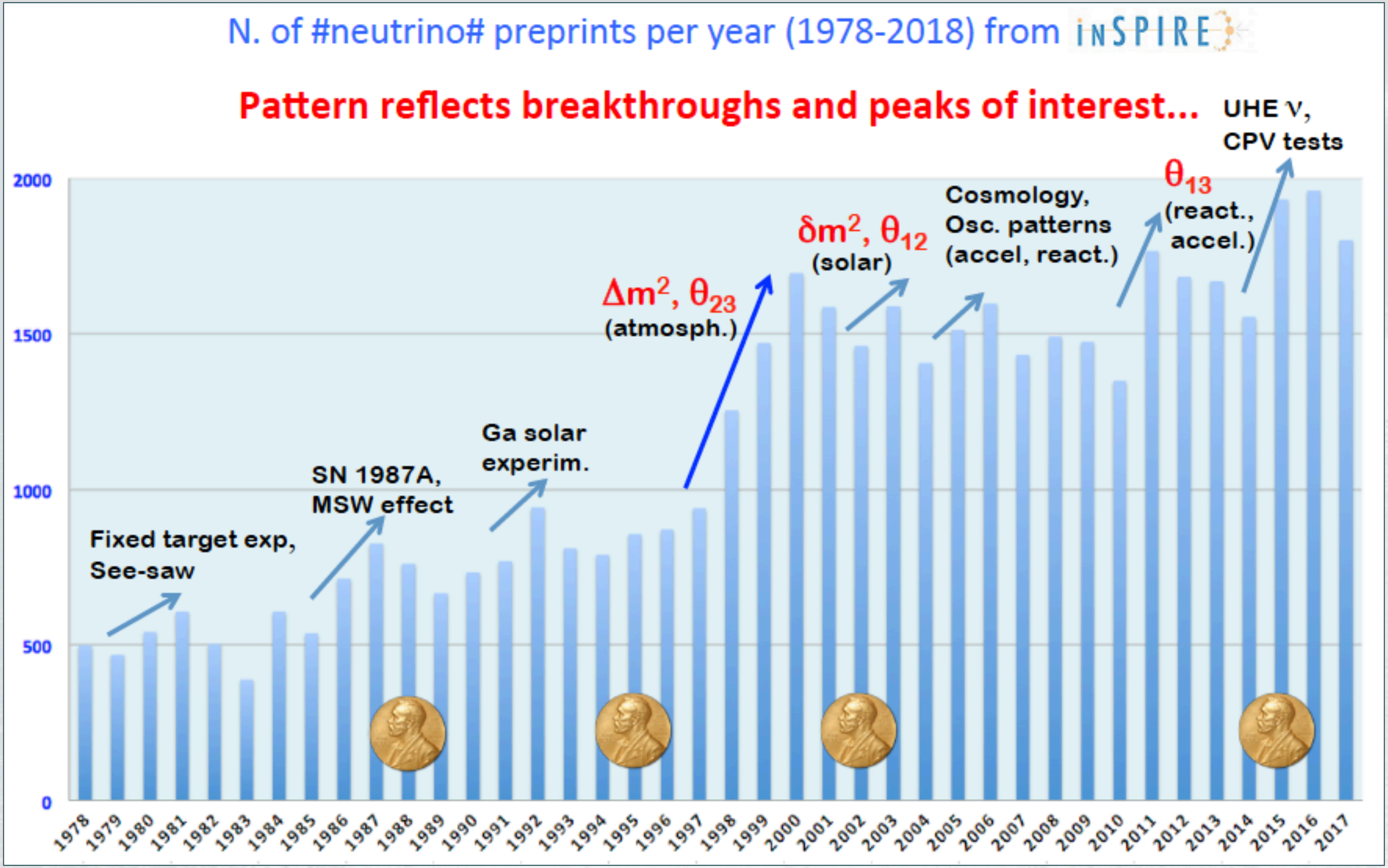
$0\nu\beta\beta$

Next generation (JUNO, T2HK, DUNE) has sufficient precision for global fits to almost all parameters

Combined T2K, Nova, etc analysis may yield an early "detection" of CP violation phase δ_D

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





From: E. Lisi Neutrino 2018

- Example: **NuFIT 3.2** (www.nu-fit.org) updated to **2018**

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

Phantom of the Opera: sterile neutrinos

Dirac vs Majorana ($\nu \neq \bar{\nu}$?) **$0\nu\beta\beta$**

U_{PMNS} unitary?

$\delta_{CP} \neq 0$?

$\Delta m^2 > 0$?

ϑ_{23} maximal? Octant ?

→ **OSCILLATIONS**

Absolute Mass scale — **Spectrometers, µBolometers, EUCLID**

CNO from the Sun — **BOREXino**

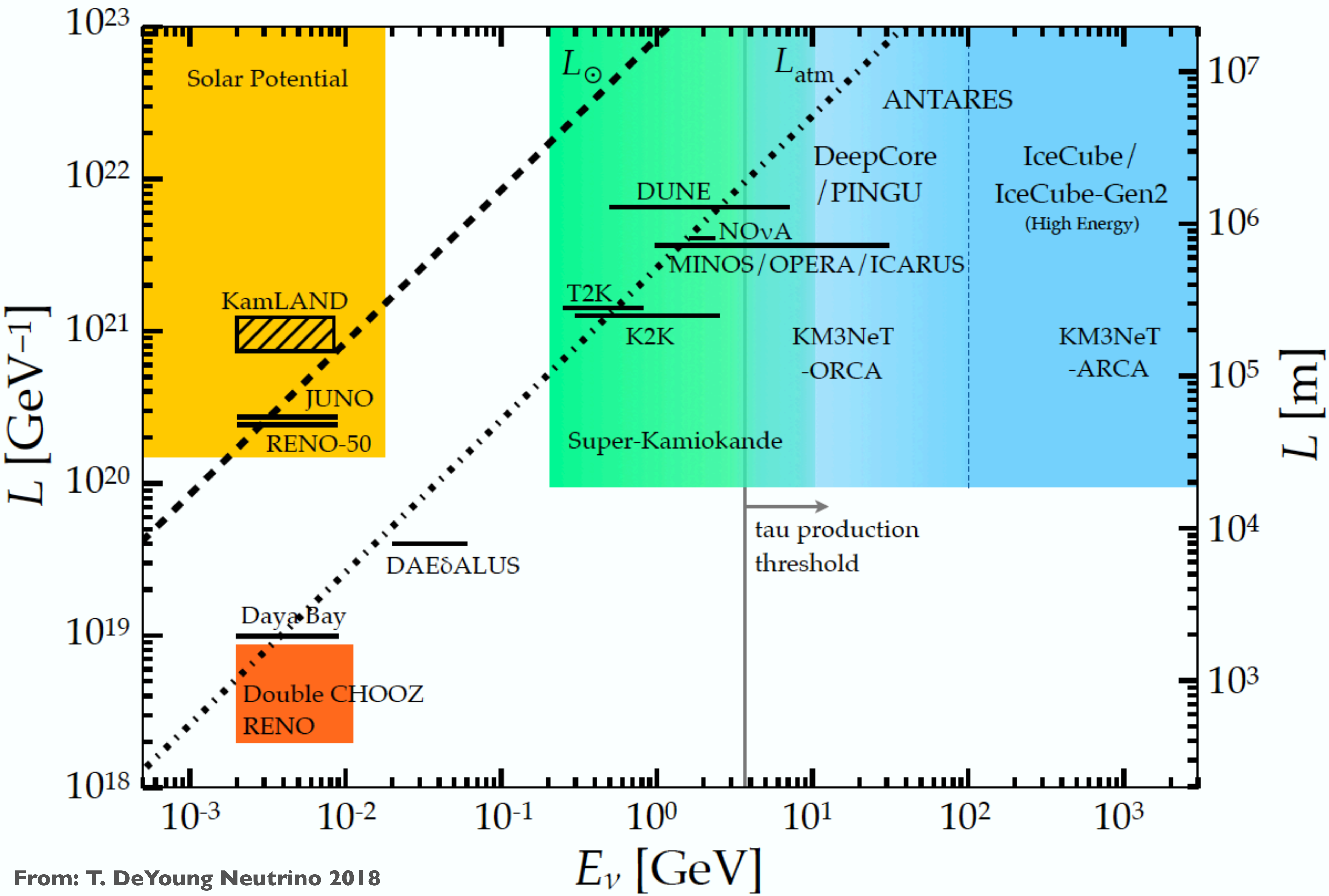
Astrophysics — **IceCUBE, KM3Net**

Multi-messenger (GW, photons) — **VIRGO-LIGO + Astronomy**

$C\nu B$ — **R&D for PTolemy, Euclid, CMB fits**

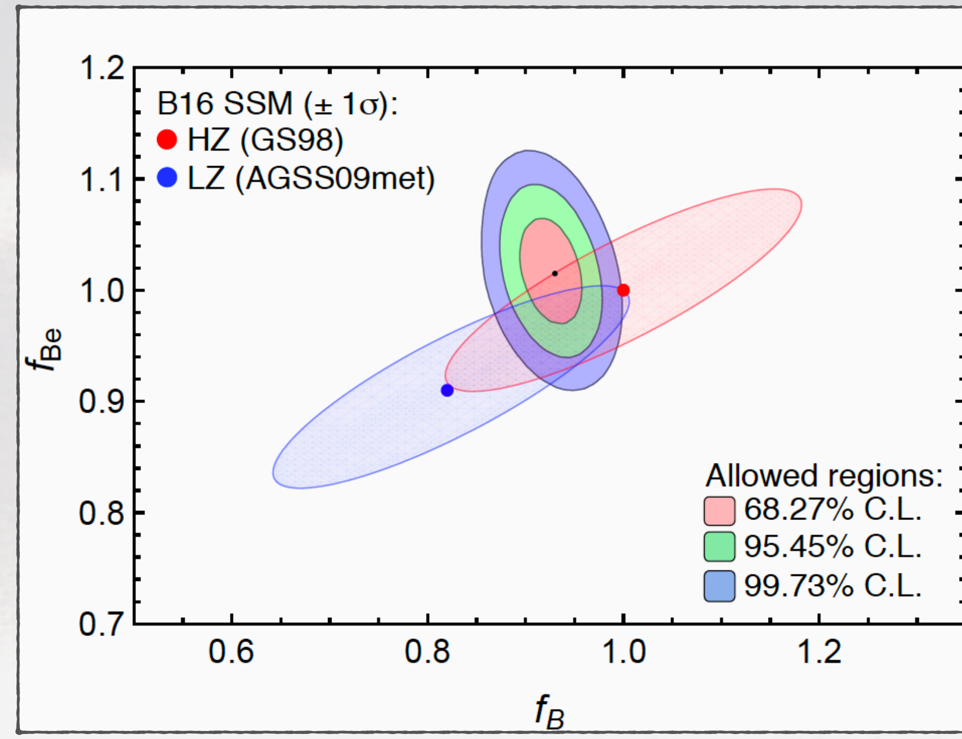
SN (pulse and relics) — **Borexino, LVD, JUNO, SK, HK, DUNE**

NEUTRINO OSCILLATIONS: GLOBAL VIEW

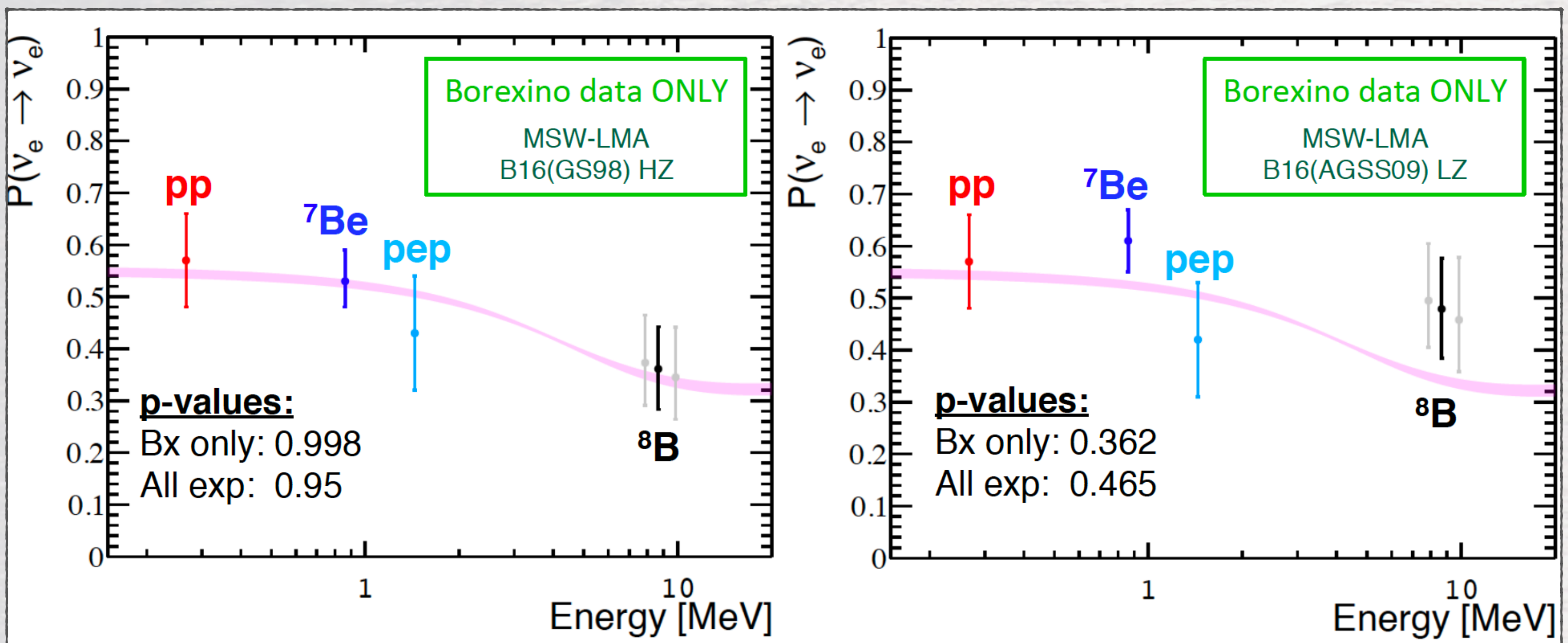


From: T. DeYoung Neutrino 2018

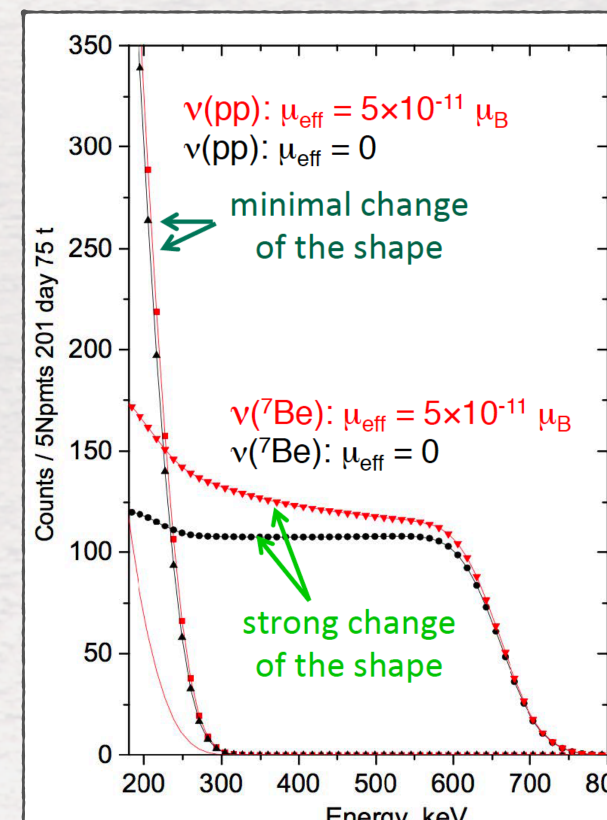
- **2017:** final **Borexino** results on **pp cycle**
  - Complete precision measurement of ***all components of the chain***
  - Precision Test of Standard Solar Model
  - Evidence of MSW on P_{ee}
  - **First hint on solar metallicity**
    - HZ favoured at 2σ



HZ **LOW Z**

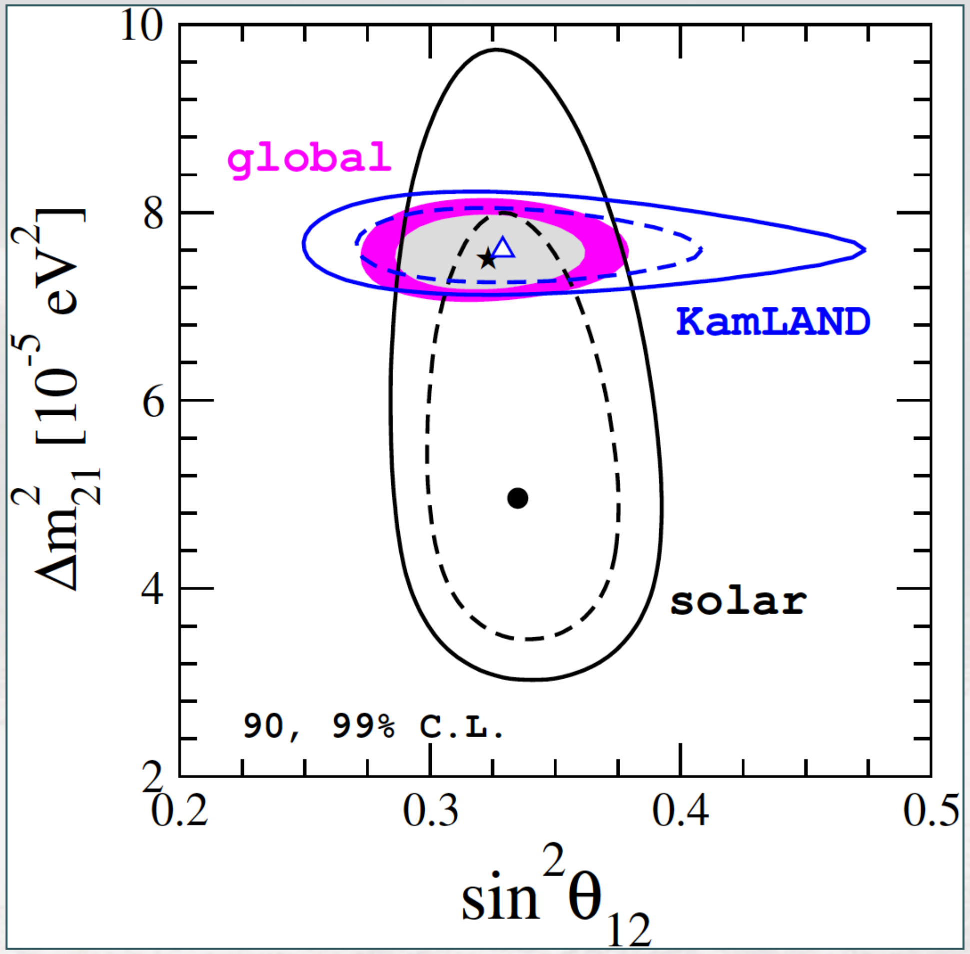


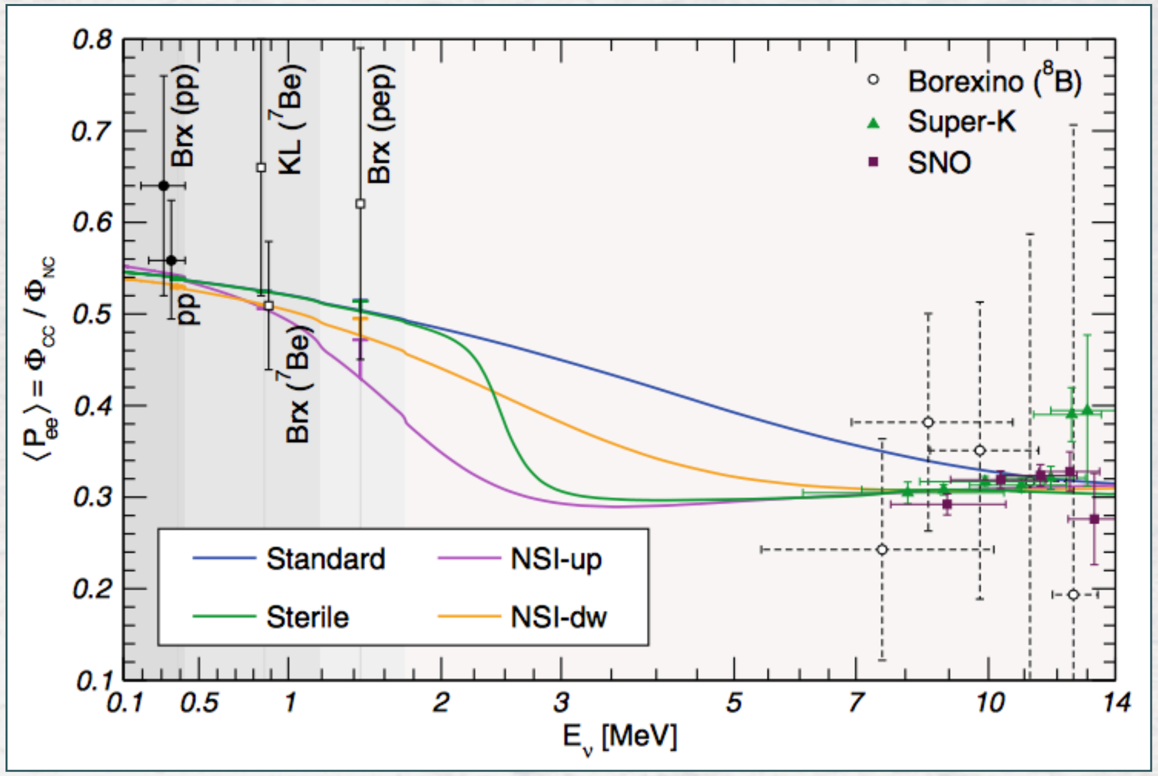
Magnetic Moment



TENSION SOLAR - KAMLAND

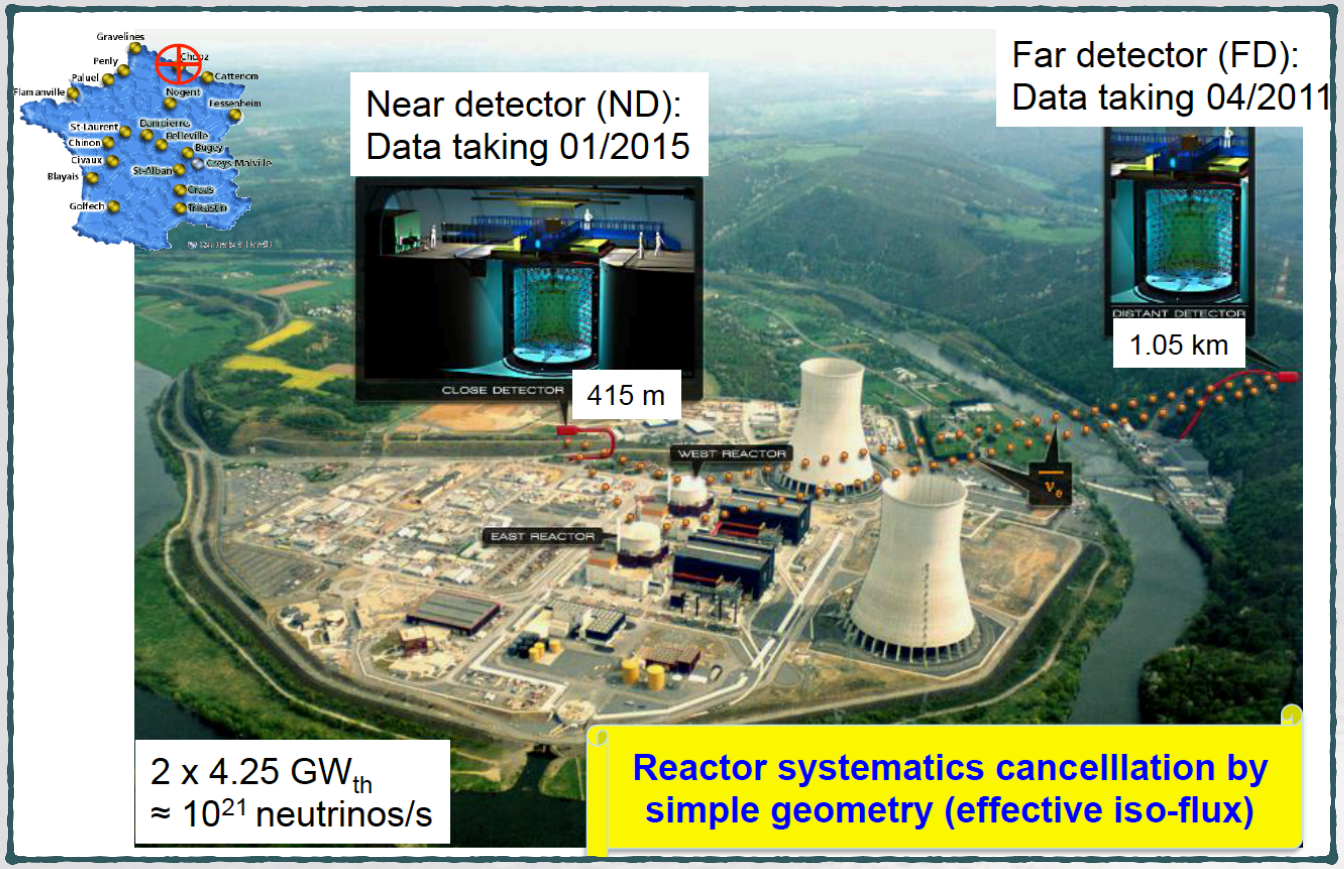
- Fit parameters measured by **KamLAND** at reactors and by global fit to **solar neutrino experiments** are in **small tension**
  - **2σ** tension on **δm^2**
  - KamLAND value would give a **steep upturn** and smaller **day-night effect in ^8B**
    - Better measurements are needed both at reactors (JUNO) and on solar neutrinos (HK ?)
- N.S.I. with $\varepsilon \sim 0.3$ can improve the fit



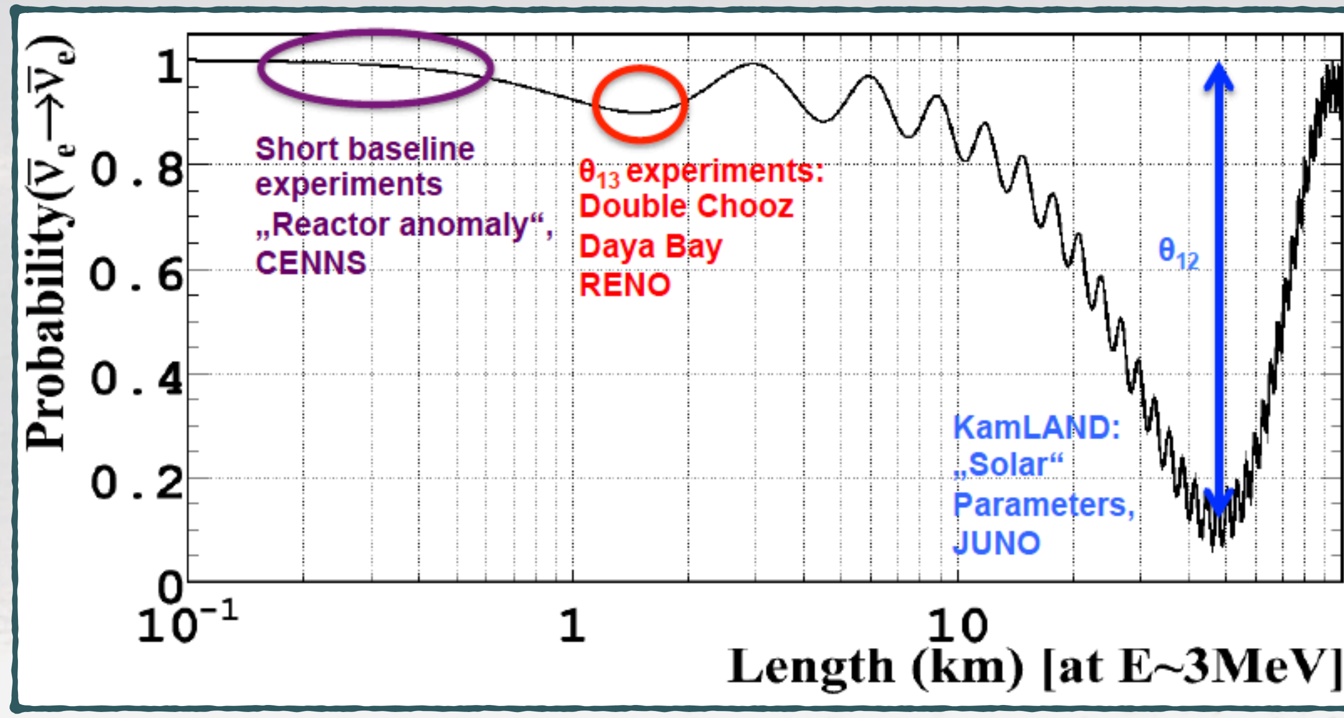


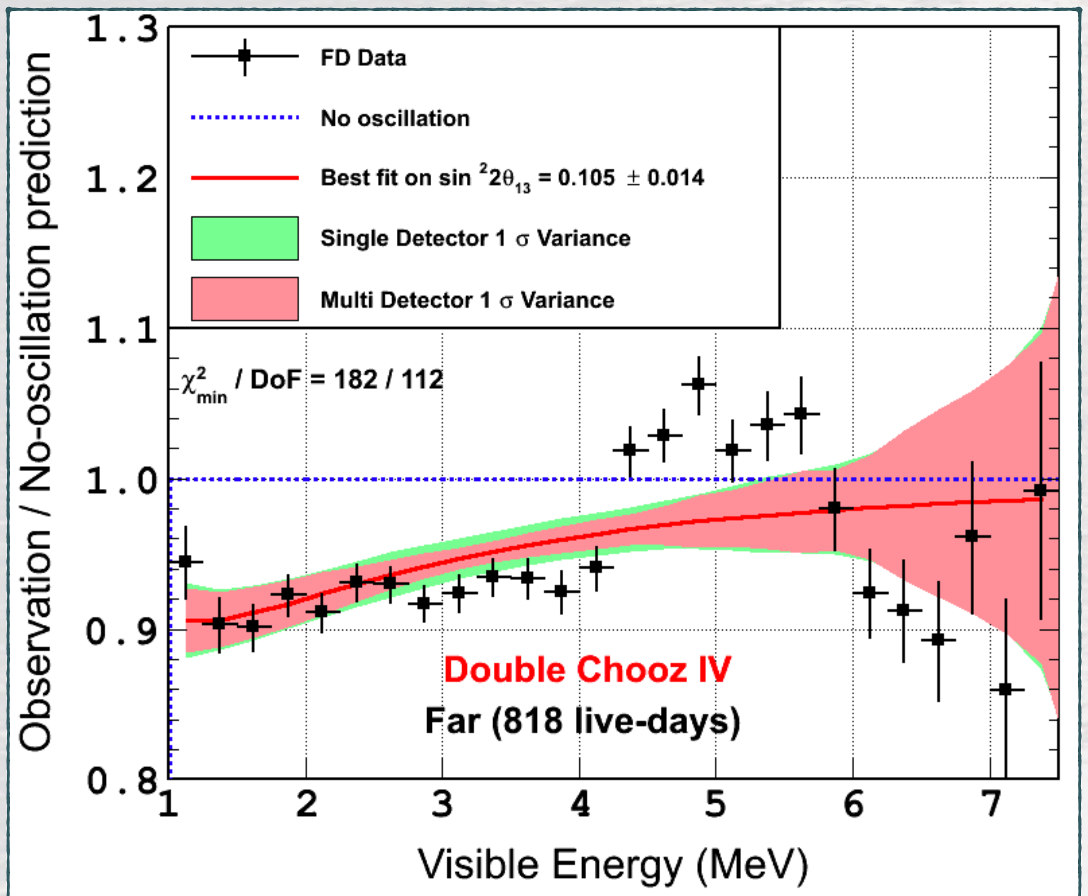
Maltoni & Smirnov - Eur. Phys. J. A (2016) 52: 87

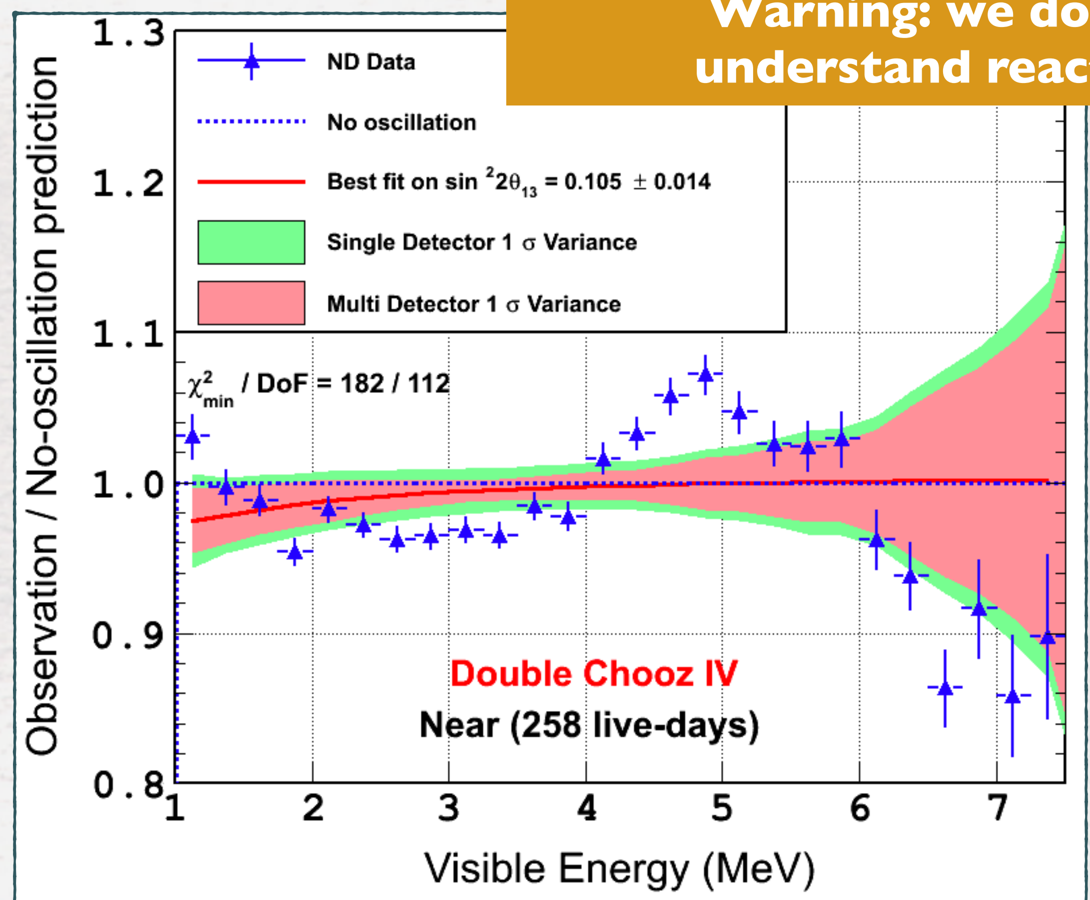
DOUBLE CHOOZ 2018



Reactor systematics cancelllation by simple geometry (effective iso-flux)







Warning: we do not understand reactors!

From: C. Buck - Neutrino 2018

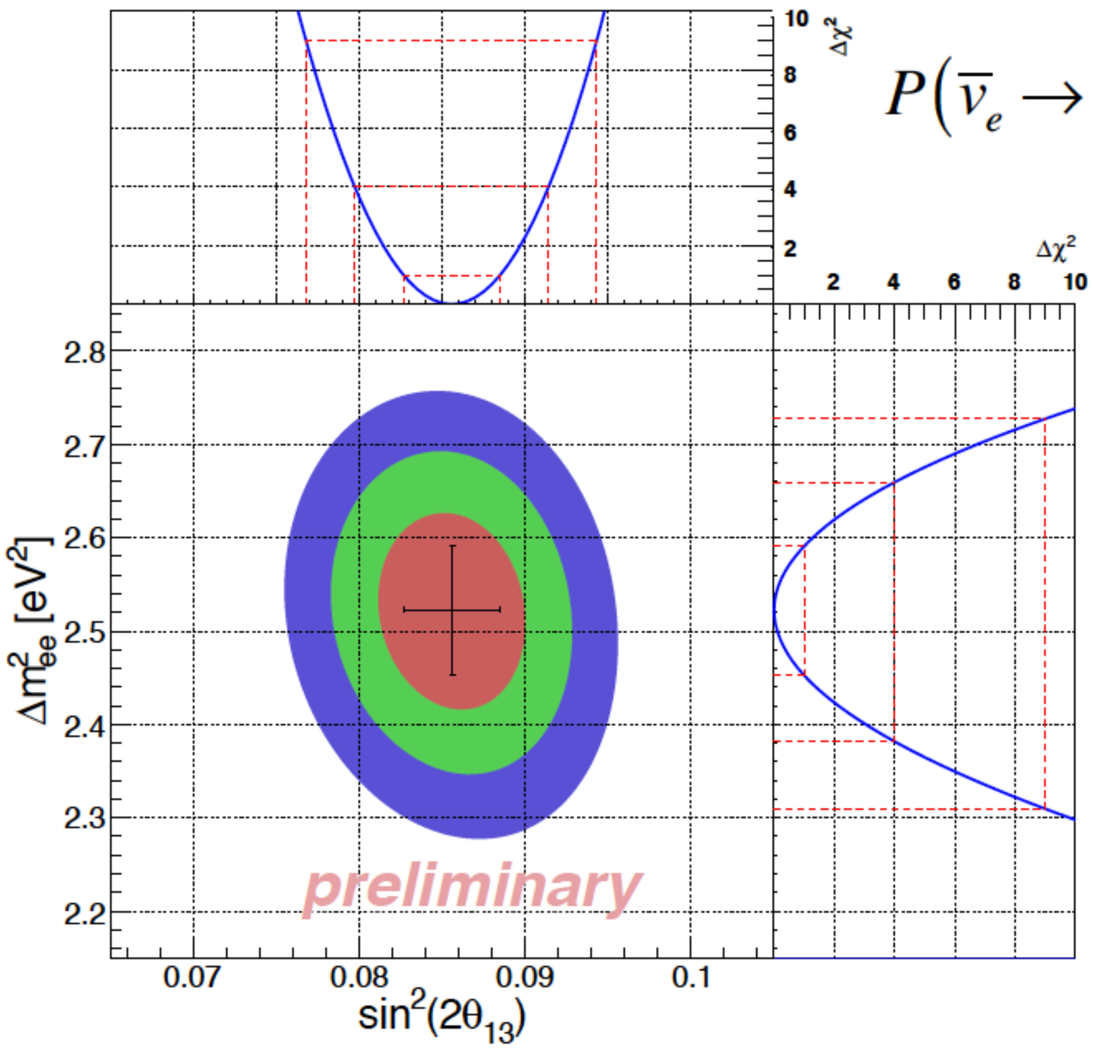
Neutrino 2018 Results with 1958 Days

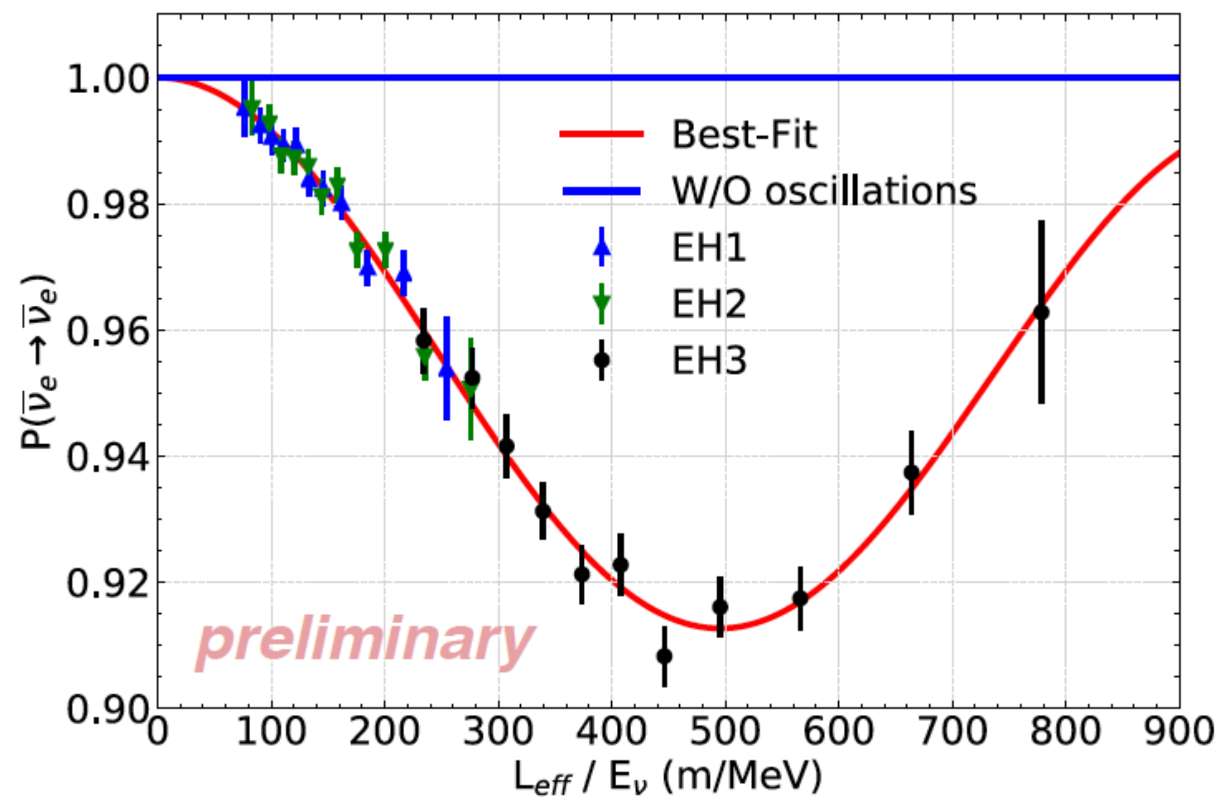
poster #6 (W)

- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively

effective mass splitting

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E} - \text{solar term}$$





results with 1958 days →

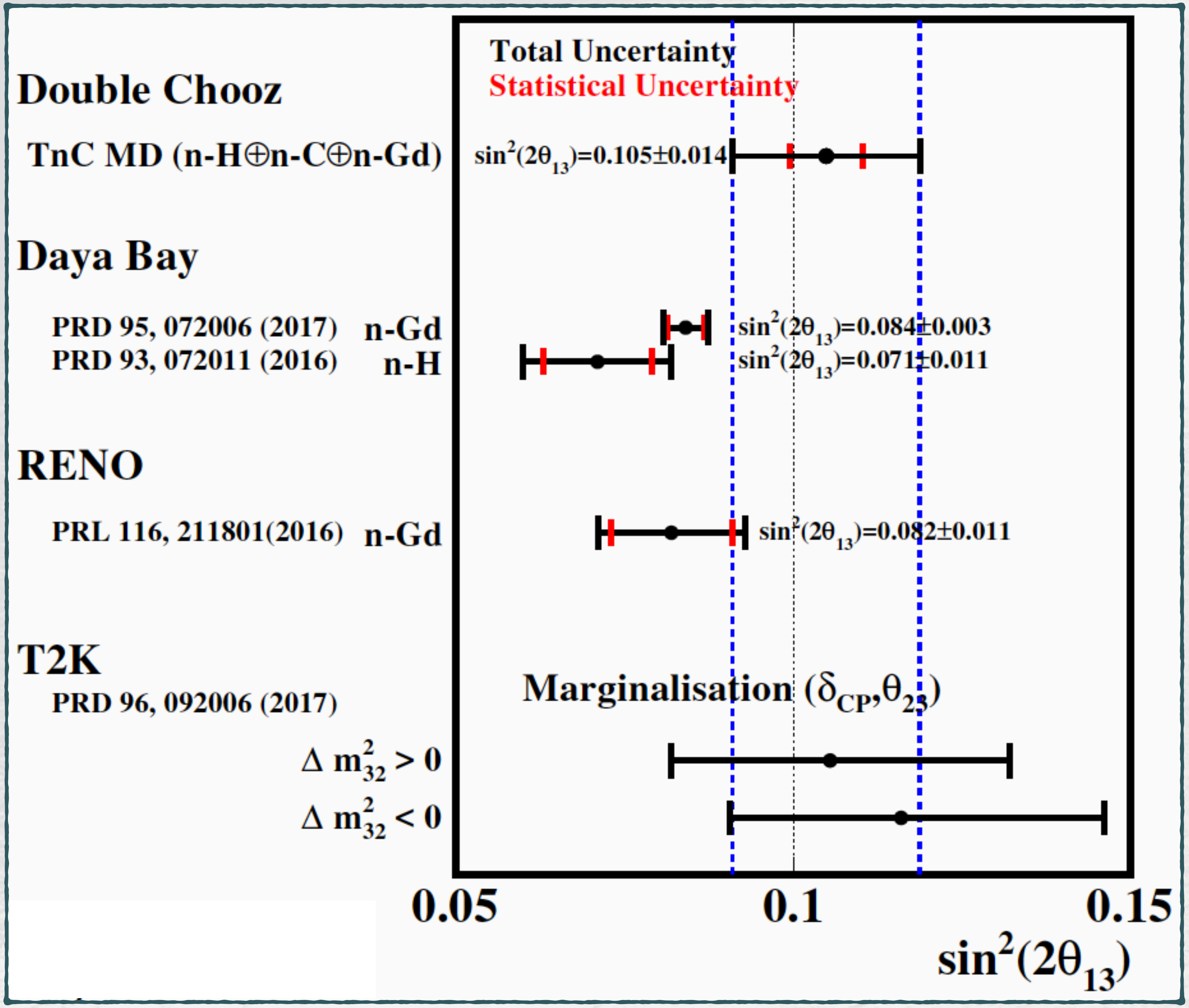
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

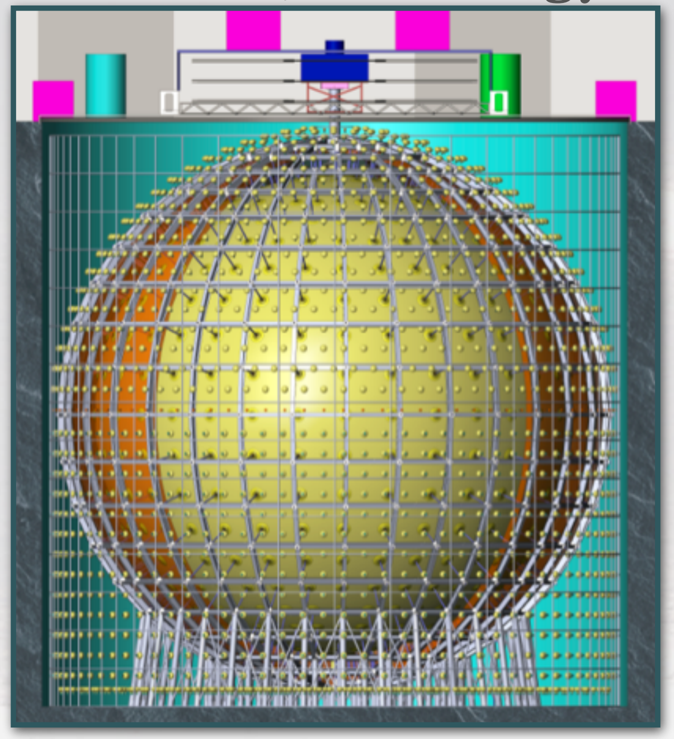
- Reactor experiments (disappearance) or T2K (appearance)

Neutrino 2018

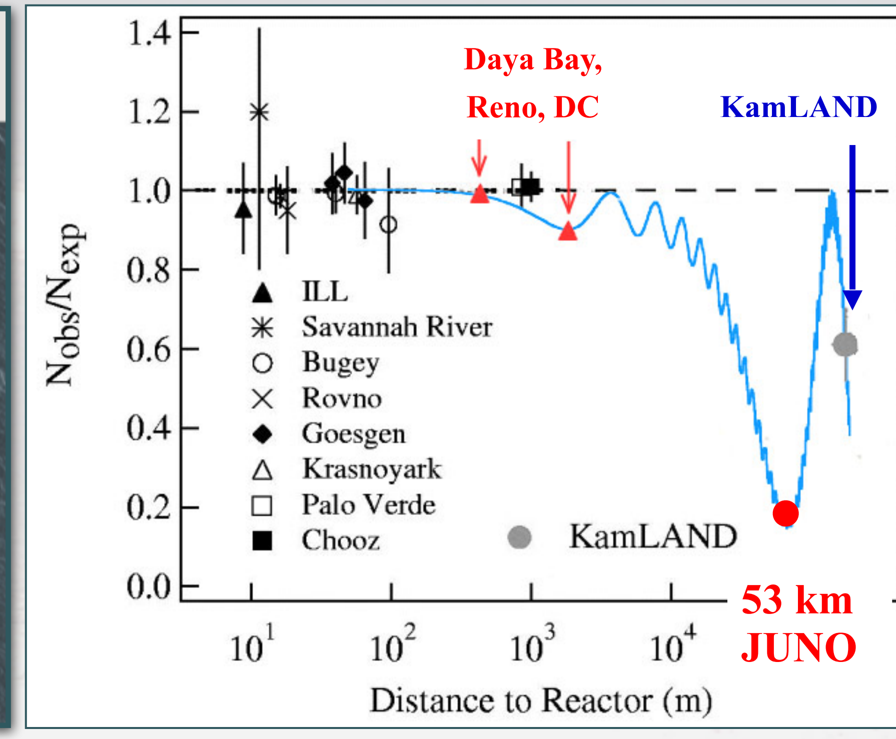


- **JUNO:** coming soon
  - Precision measurement of angles
  - **Unitarity, Hierarchy**
- Relevant INFN investment
  - **Purification** (Borexino legacy)
  - **Electronics PMTs and Tracker**

20 kt LS, 3% energy



"Medium" Baseline

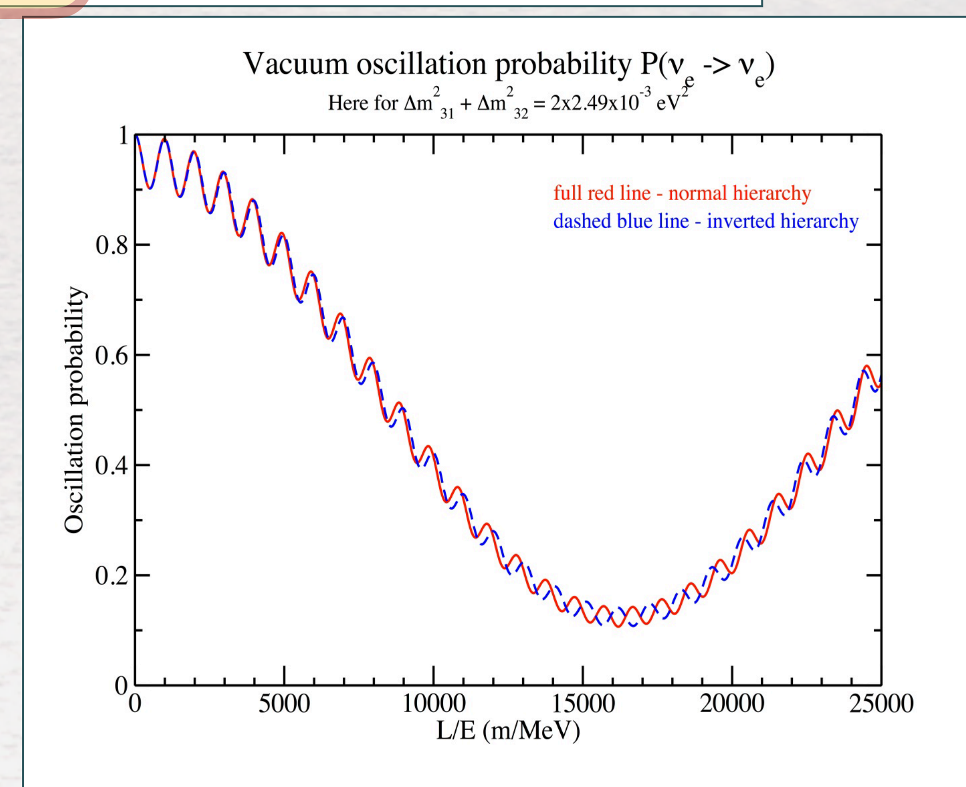


$$\mathbf{P}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\Delta m^2_{21}\frac{L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\,\sin^2\Delta m^2_{31}\frac{L}{4E} + \sin^2\theta_{12}\,\sin^2\Delta m^2_{32}\frac{L}{4E}\right)$$

$$\approx 1 - \cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\Delta m^2_{21}\frac{L}{4E} - \sin^2 2\theta_{13}\,\sin^2\Delta m^2_{ee}\frac{L}{4E} \quad ,\text{for} \quad \Delta m^2_{12} \ll \Delta m^2_{32}$$

- Very challenging detector resolution, accuracy and stability

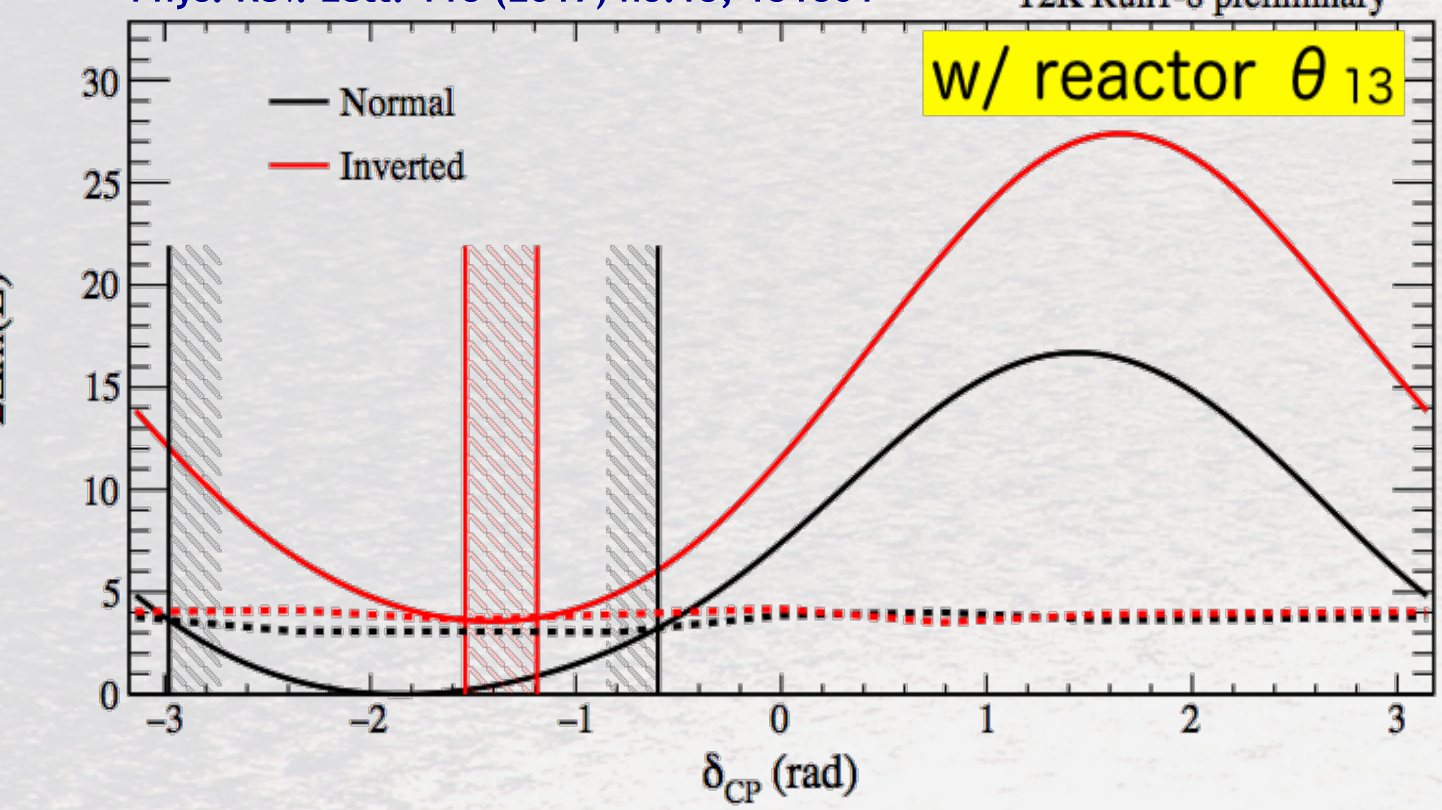
$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \text{NH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \text{IH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

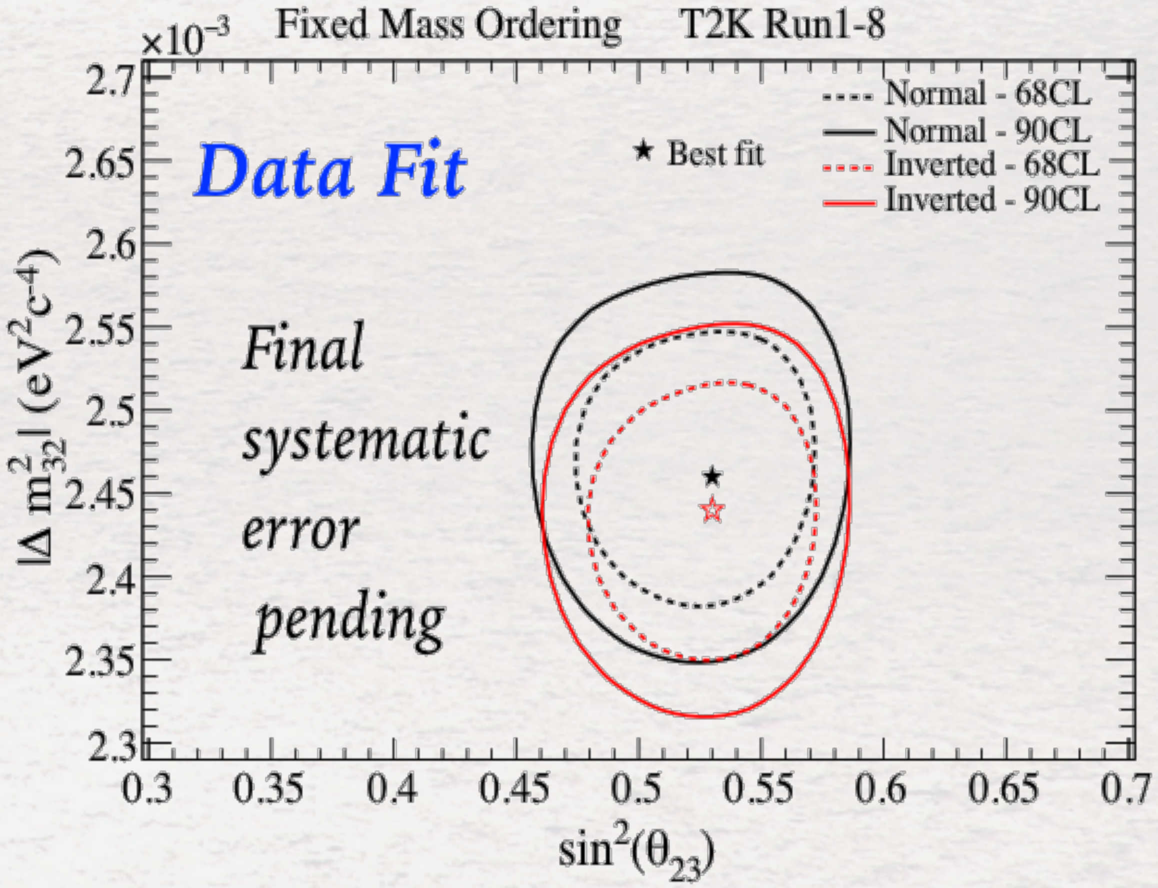


See Ciro Riccio's talk today

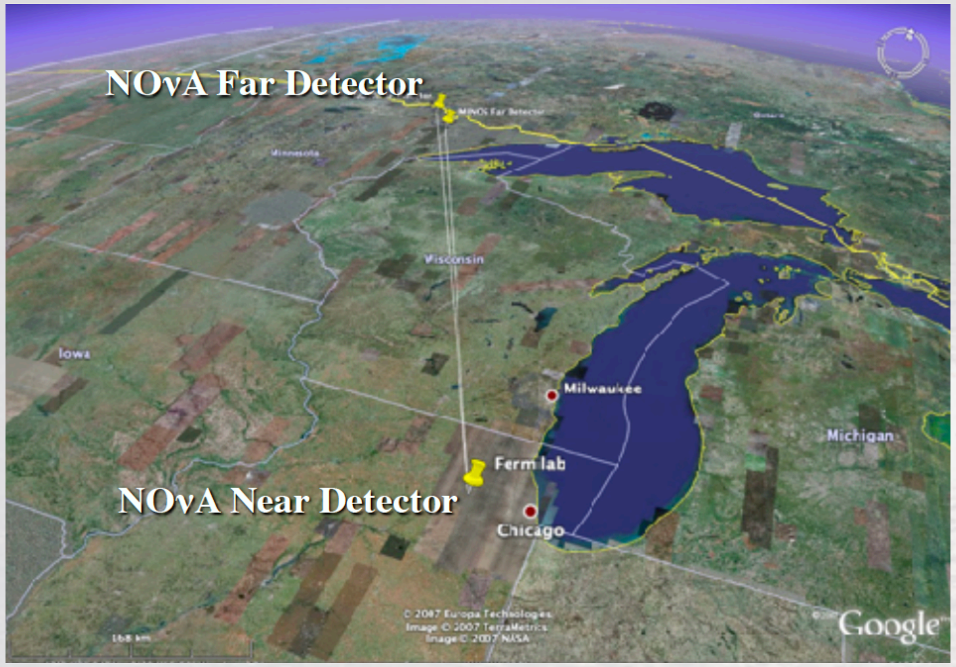
- **T2K:** working well, **470 kW**
  - $1.5\ 10^{21}$ p.o.t (ν) e $7.6\ 10^{20}$ ($\bar{\nu}$)
  - **2017:** new release δ_{CP} e θ_{12}
  - Upgrade T2K-II in progress (ND280)
    - **CPV 3σ ? Possible.**

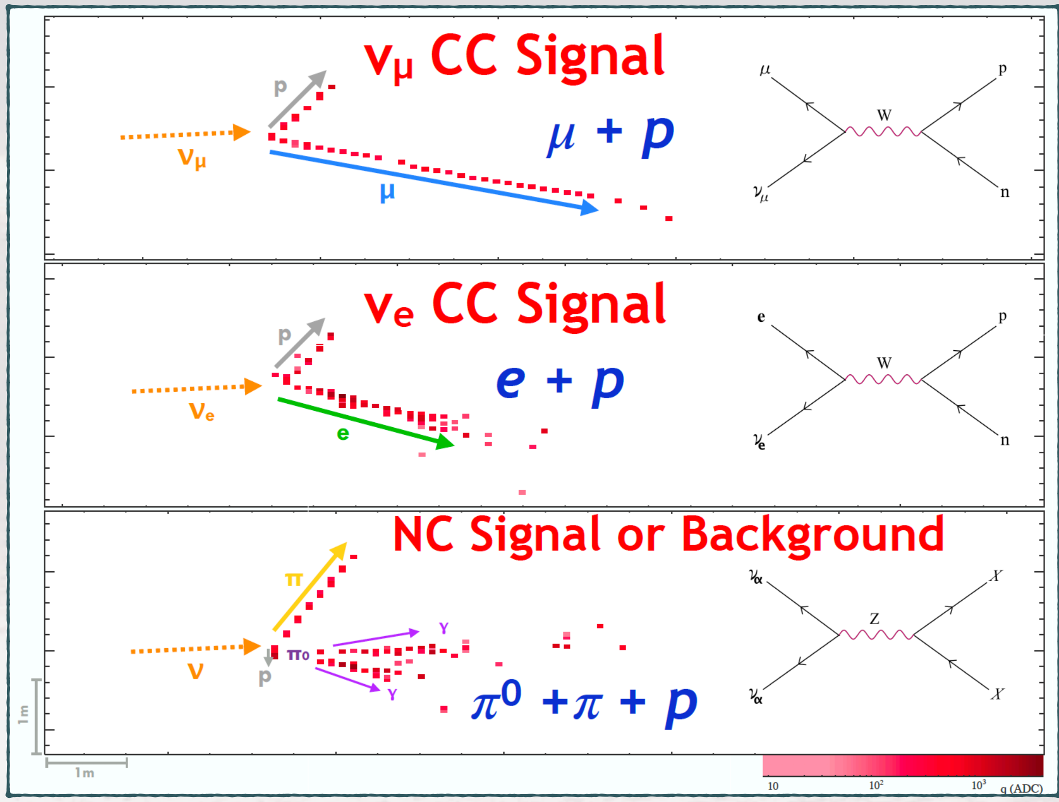
Phys. Rev. Lett. 118 (2017) no.15, 151801

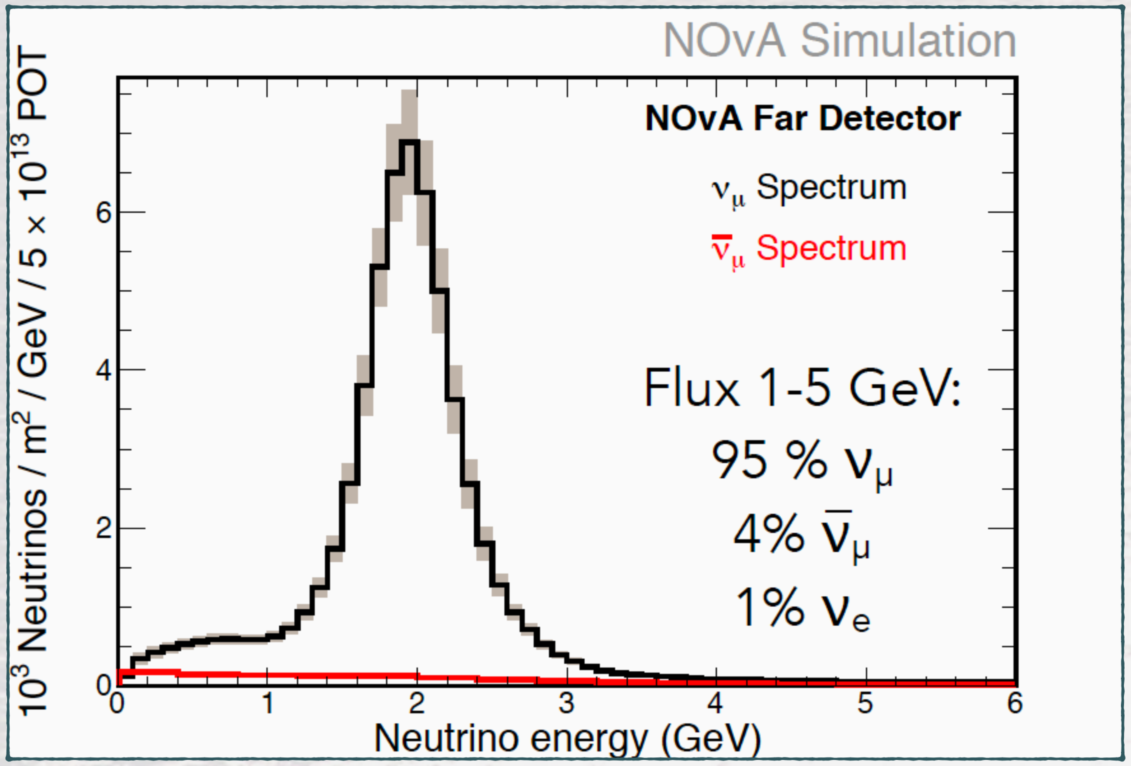


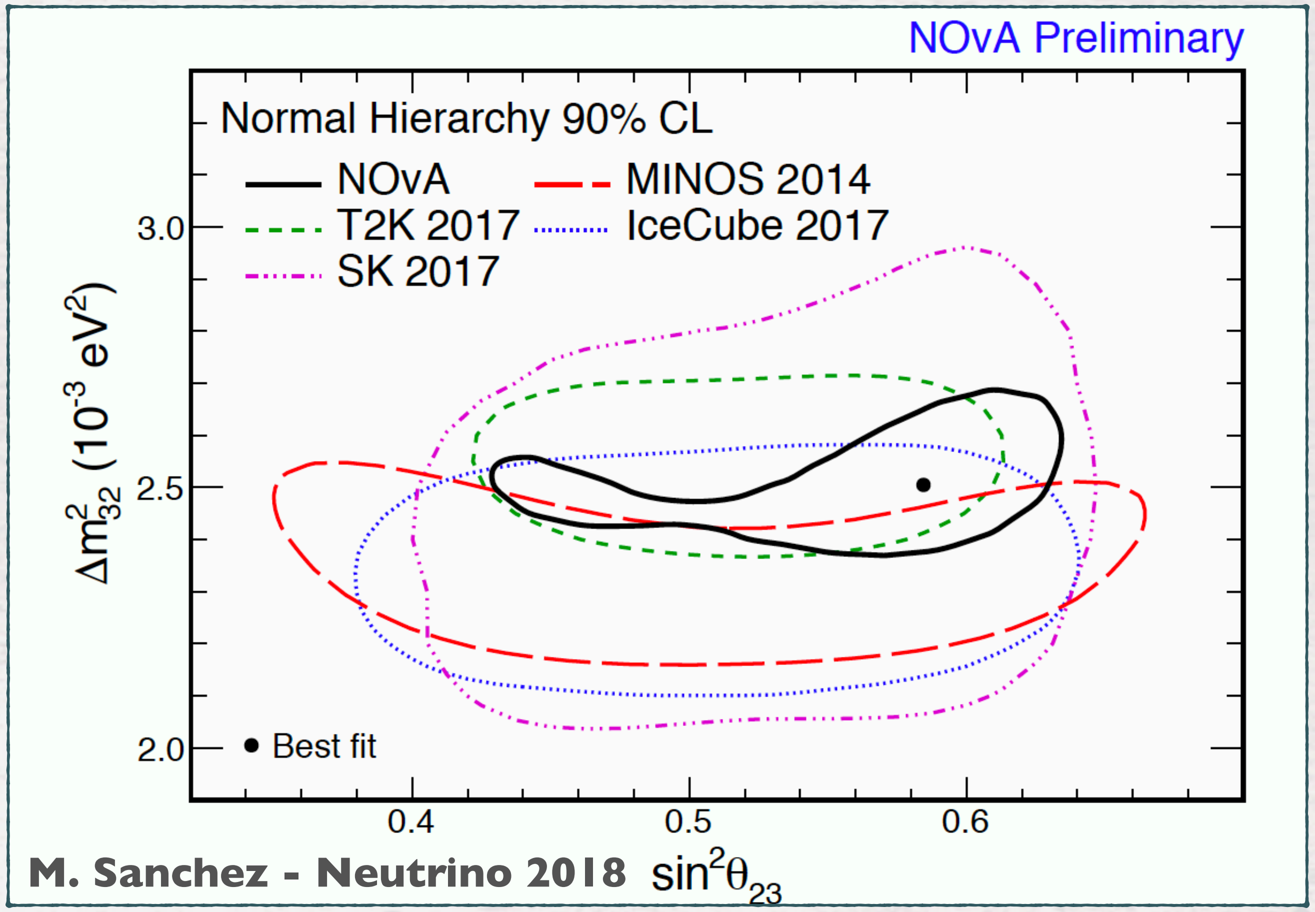


- NuMI: longest baseline, from FNAL to Minnesota
  - 700 kW, 810 km, off axis (narrow) neutrino beam
  - Disappearance, Appearance

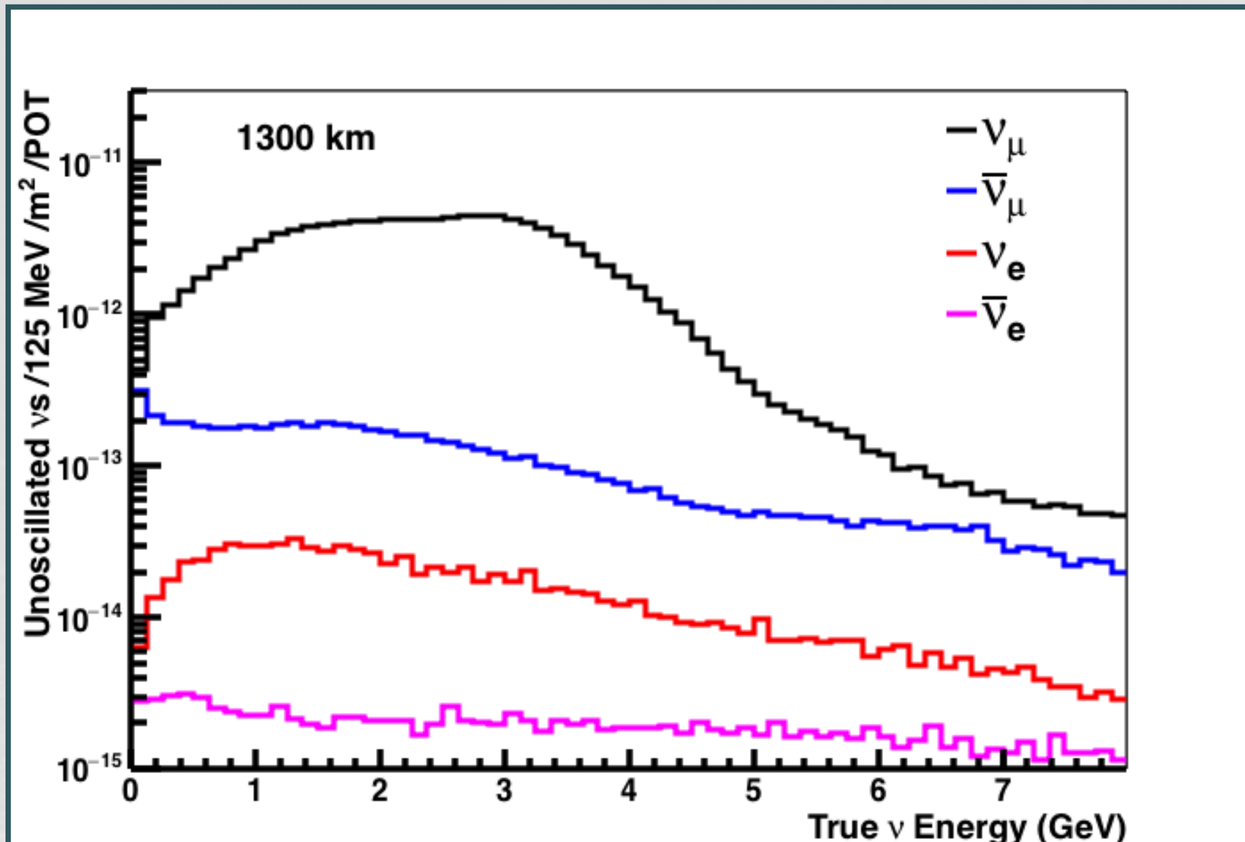


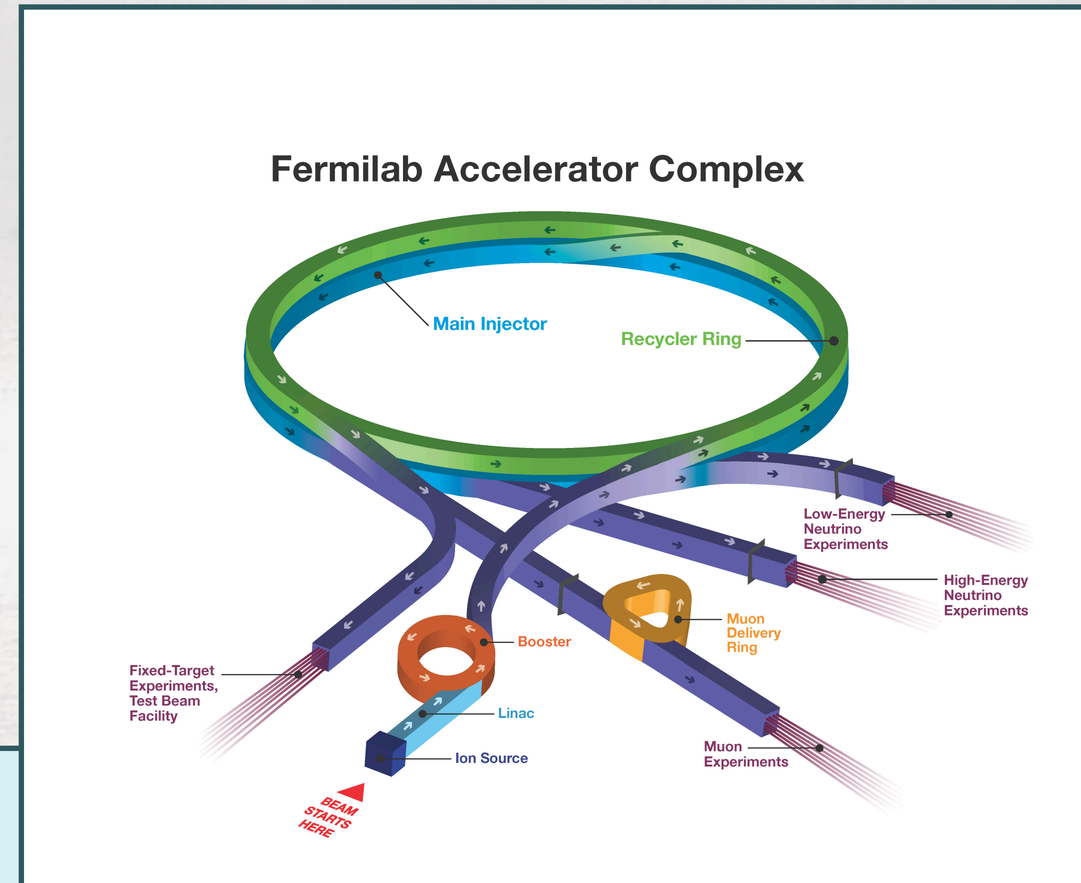


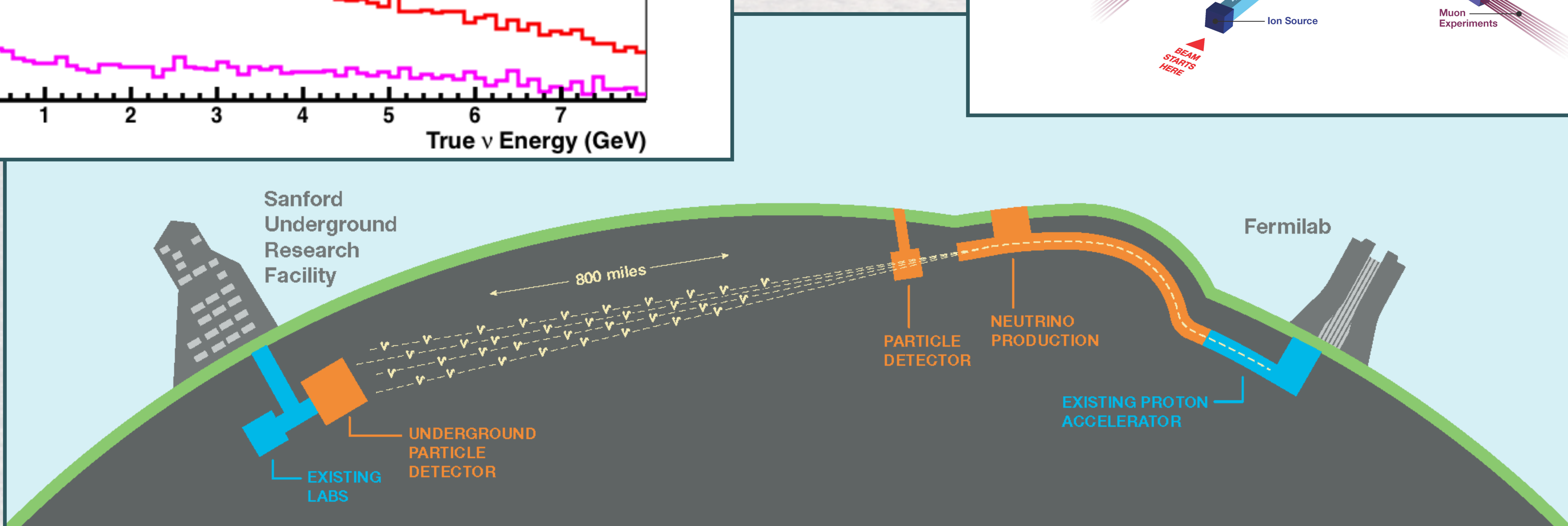




- Long base line experiment from Fermilab to SURF at Sanford (S.D.)
  - 60-120 GeV proton beam, 1.2 (2.4) MW, 1300 km
  - Neutrino and Anti-Neutrino mode

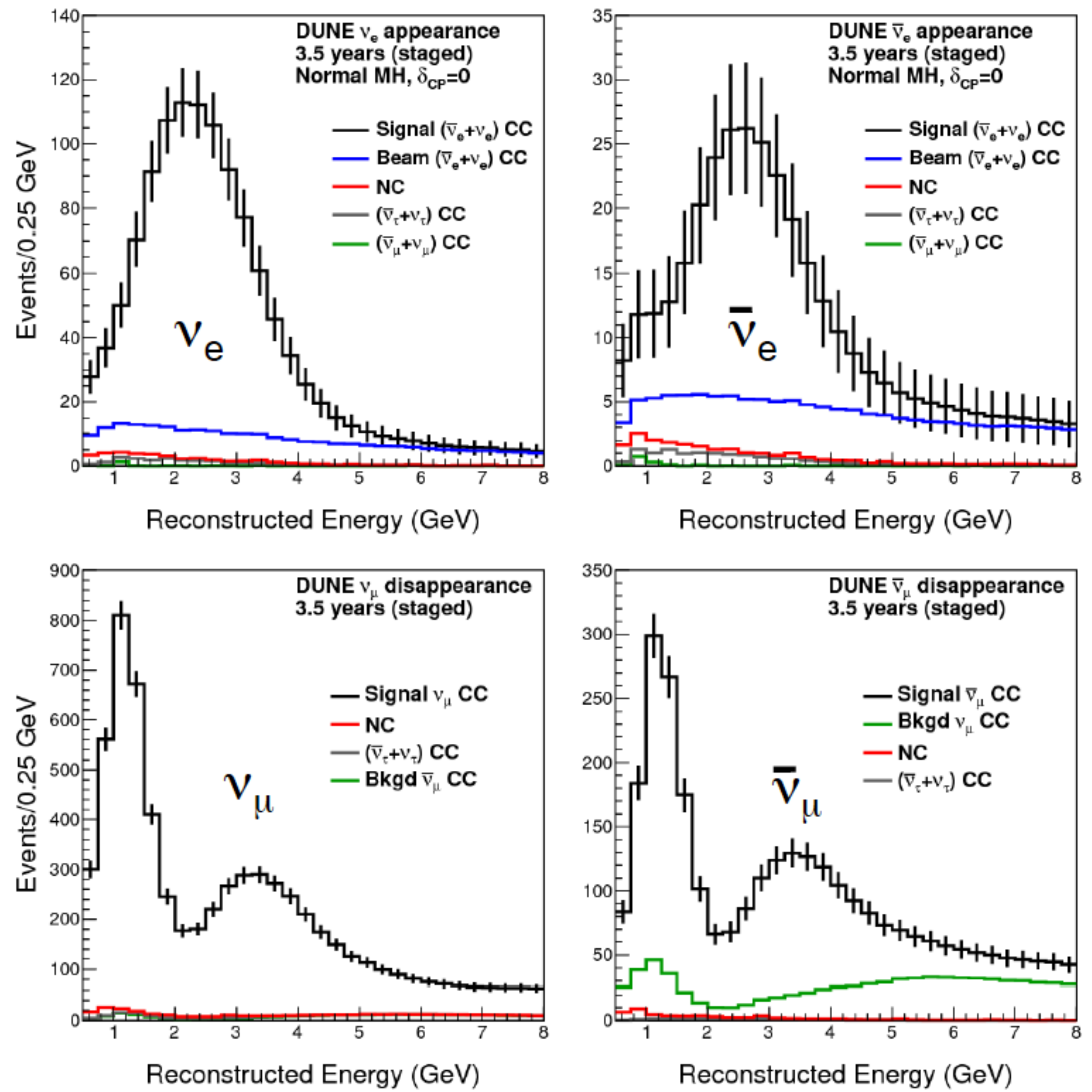




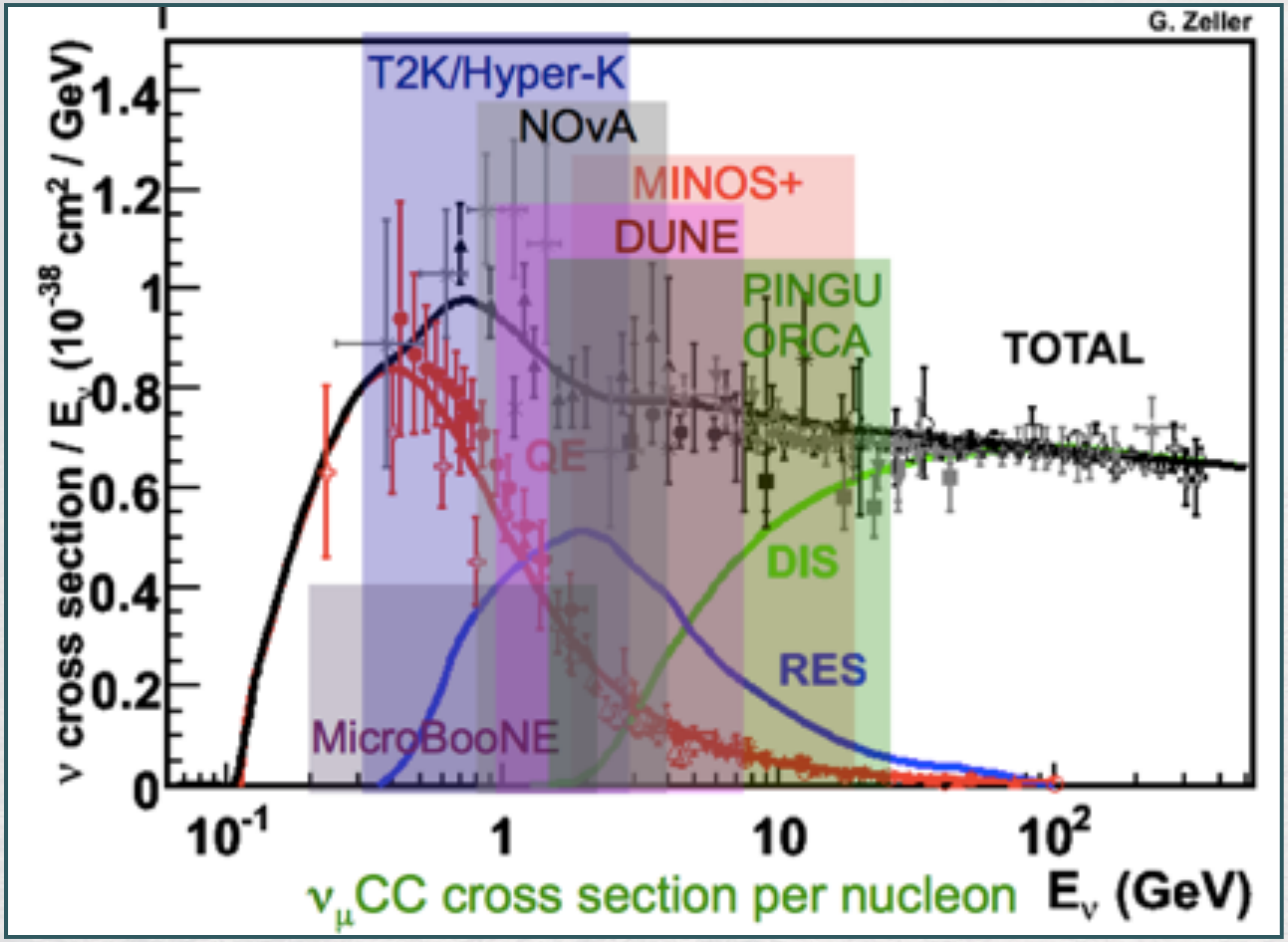


- GENIE event generation, Geant-4 beam, fast MC detector response
  - About **1000** $\boldsymbol{\nu_e}$ and $\boldsymbol{\nu_e}$ in 7 years
  - Full fit to four spectra to extract parameters
  - GLoBES configurations axXiv: 1606.09550
- In addition:
  - SN, proton decay, $\boldsymbol{\nu}$ cross sections, sterile $\boldsymbol{\nu}$, new physics

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148



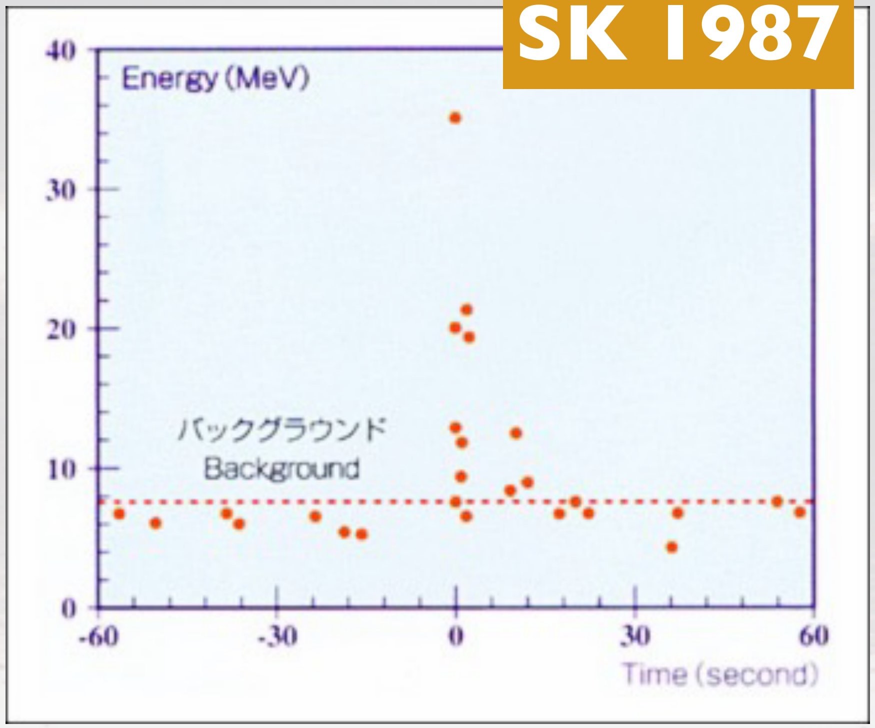
- The current understanding of neutrino cross sections with nuclei is not sufficient to extract all potential science from next generation neutrino experiments



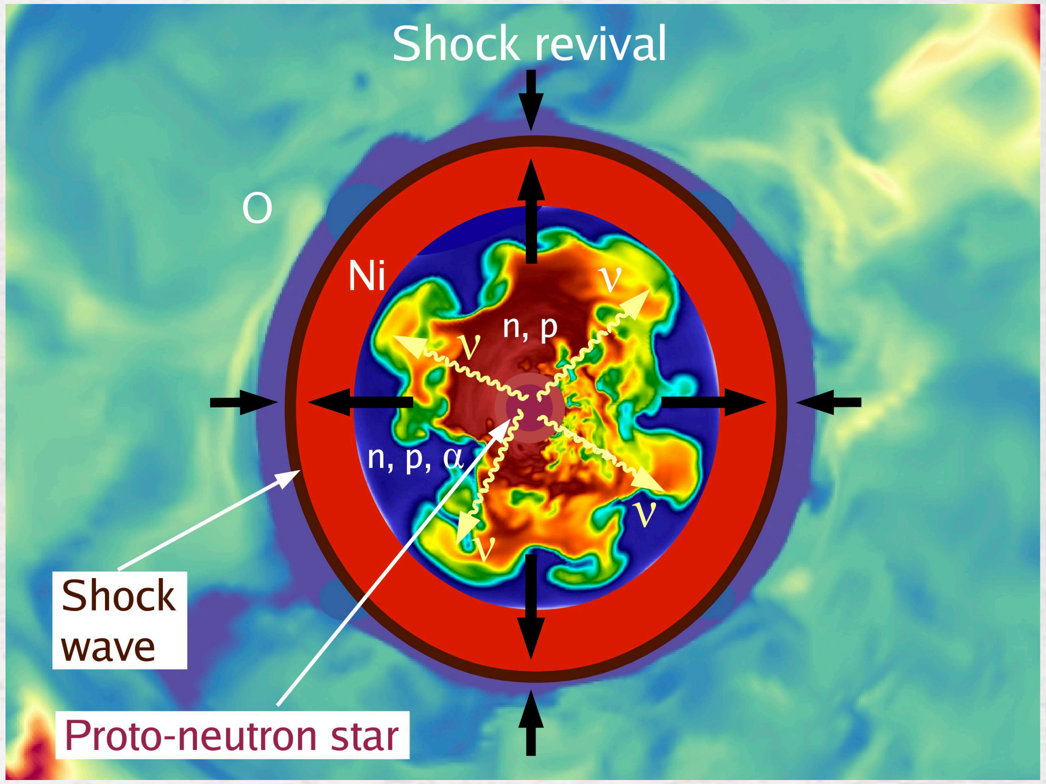
- Theoretical progress is crucial. Another example of the importance of strong interactions corrections to "weak physics" (ε'/ε, g_μ, $0\nu\beta\beta$ matrix elements, …..)

- One of the most **challenging theoretical problems,** all **at the extreme**
  - Strong coupling effects of EW interactions
  - Highly non-linear and poorly understood **flavour evolution** problem
  - A unique lab for
    - **Particle physics, Nuclear Physics, General Relativity**
    - Strong feedback from neutrino-matter dynamics in truly unique conditions

SK 1987



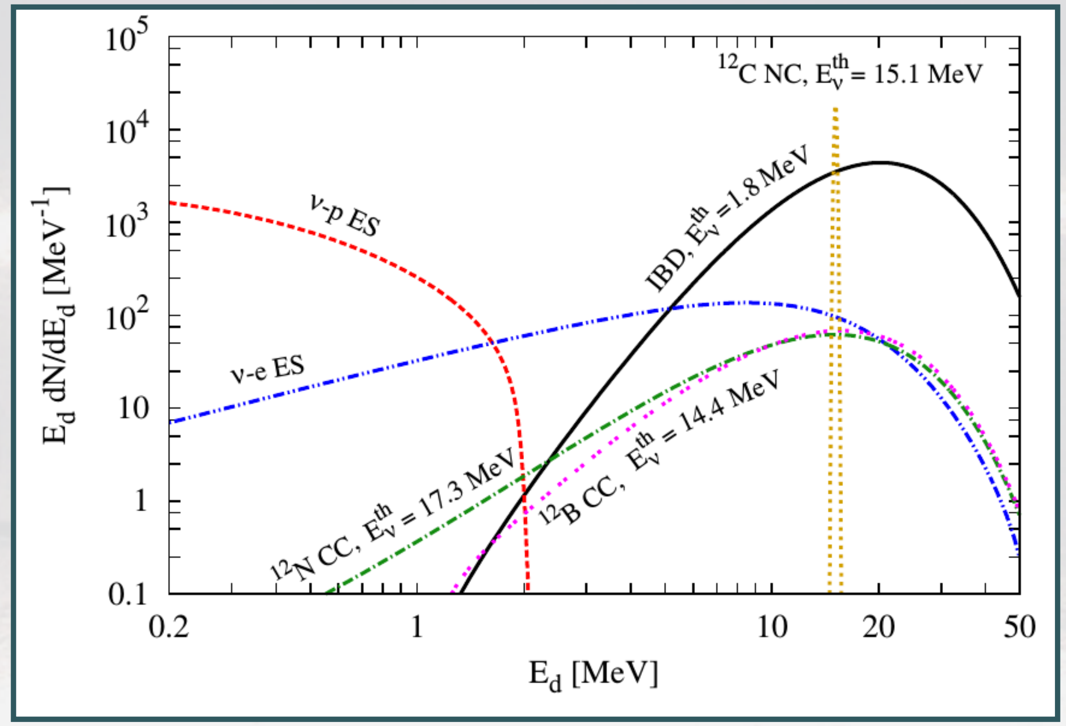
+ ν ?



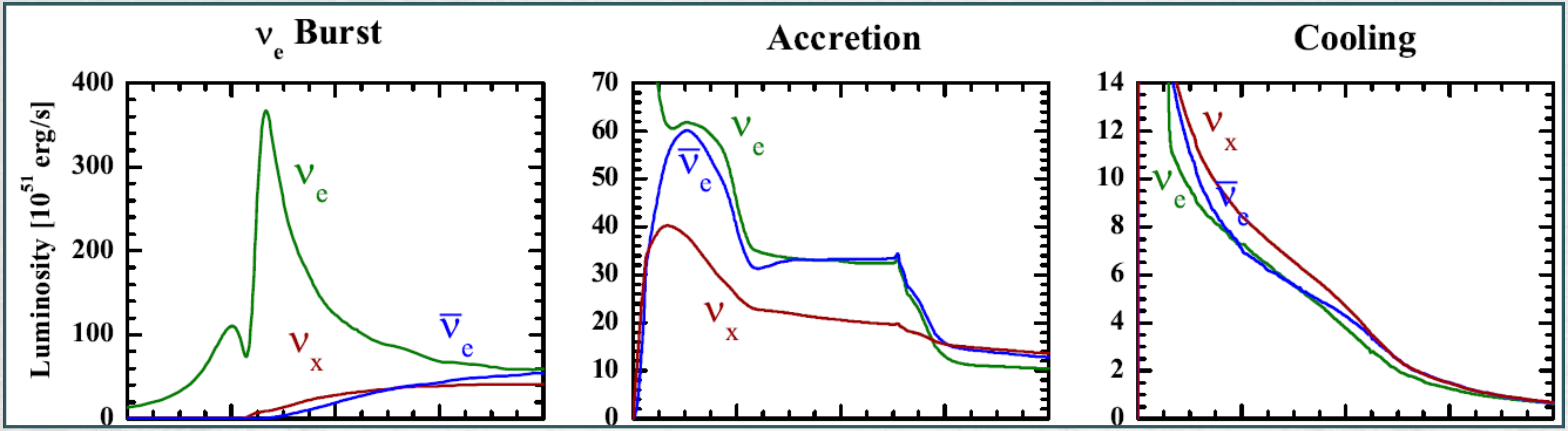
Janka 2018

- Potential breakthrough because of the very large number of events and resolution

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

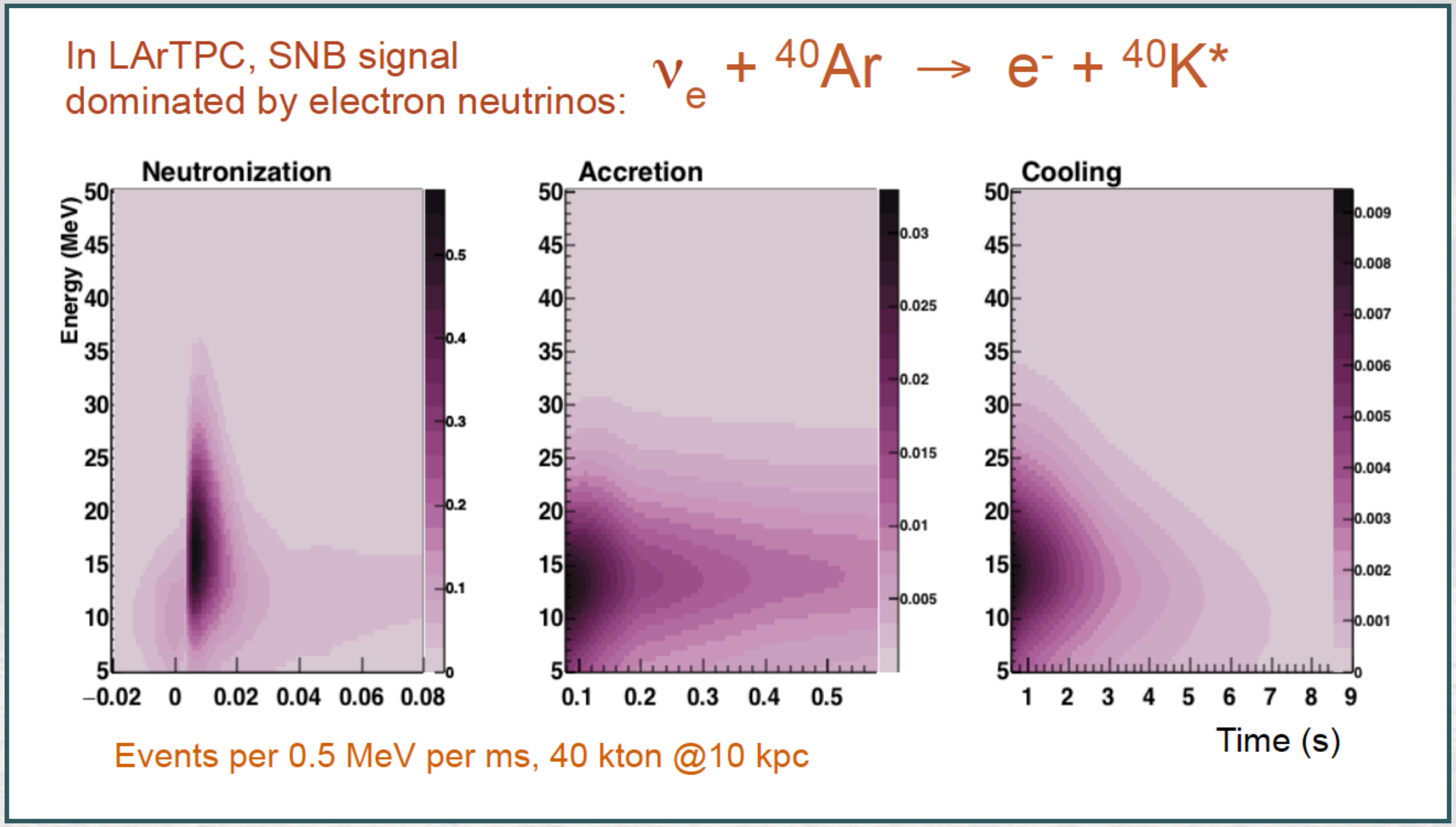


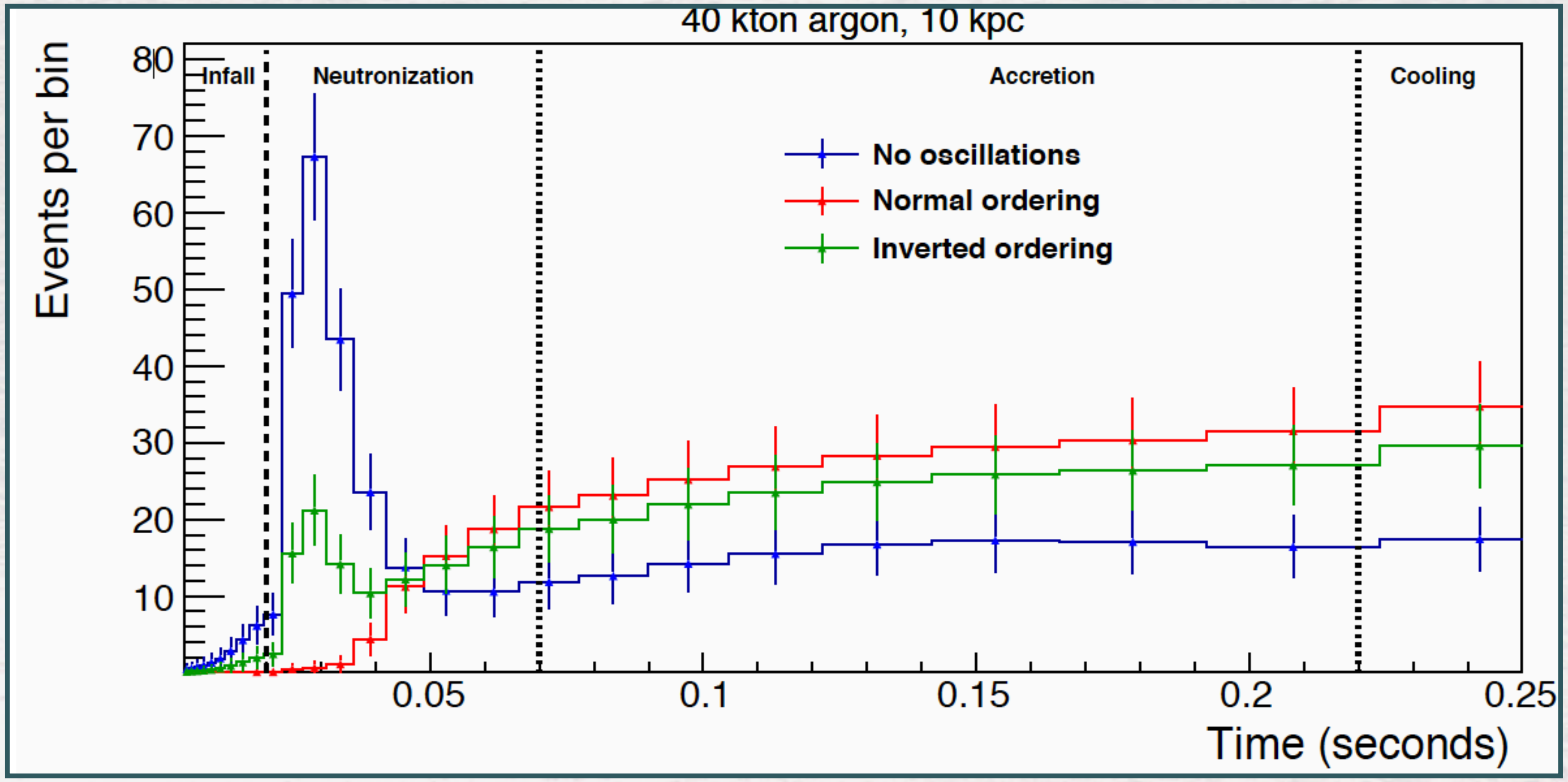
JUNO collab., arXiv:1507.05613



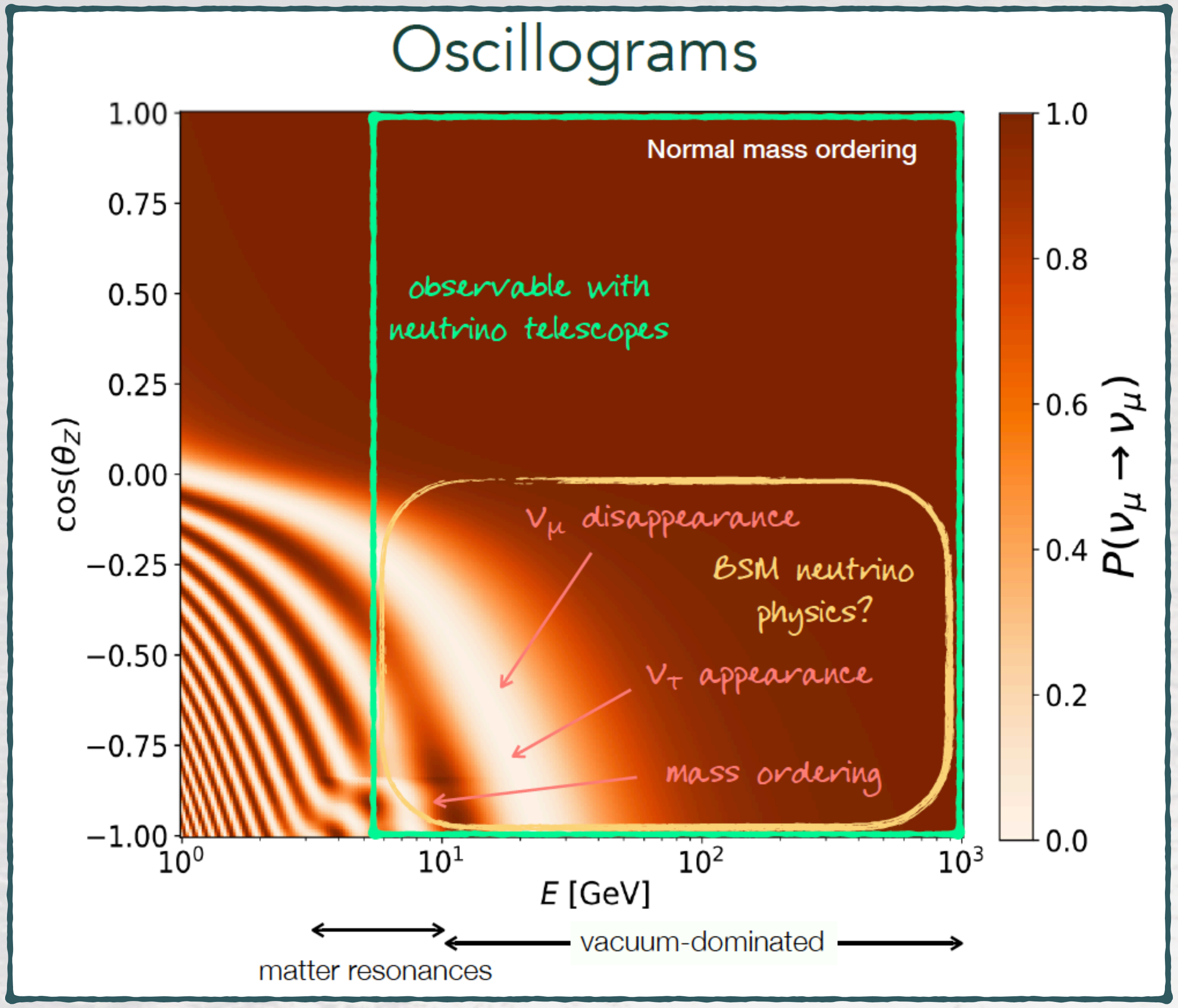
A. Mirizzi et. al., arXiv:1508.00785

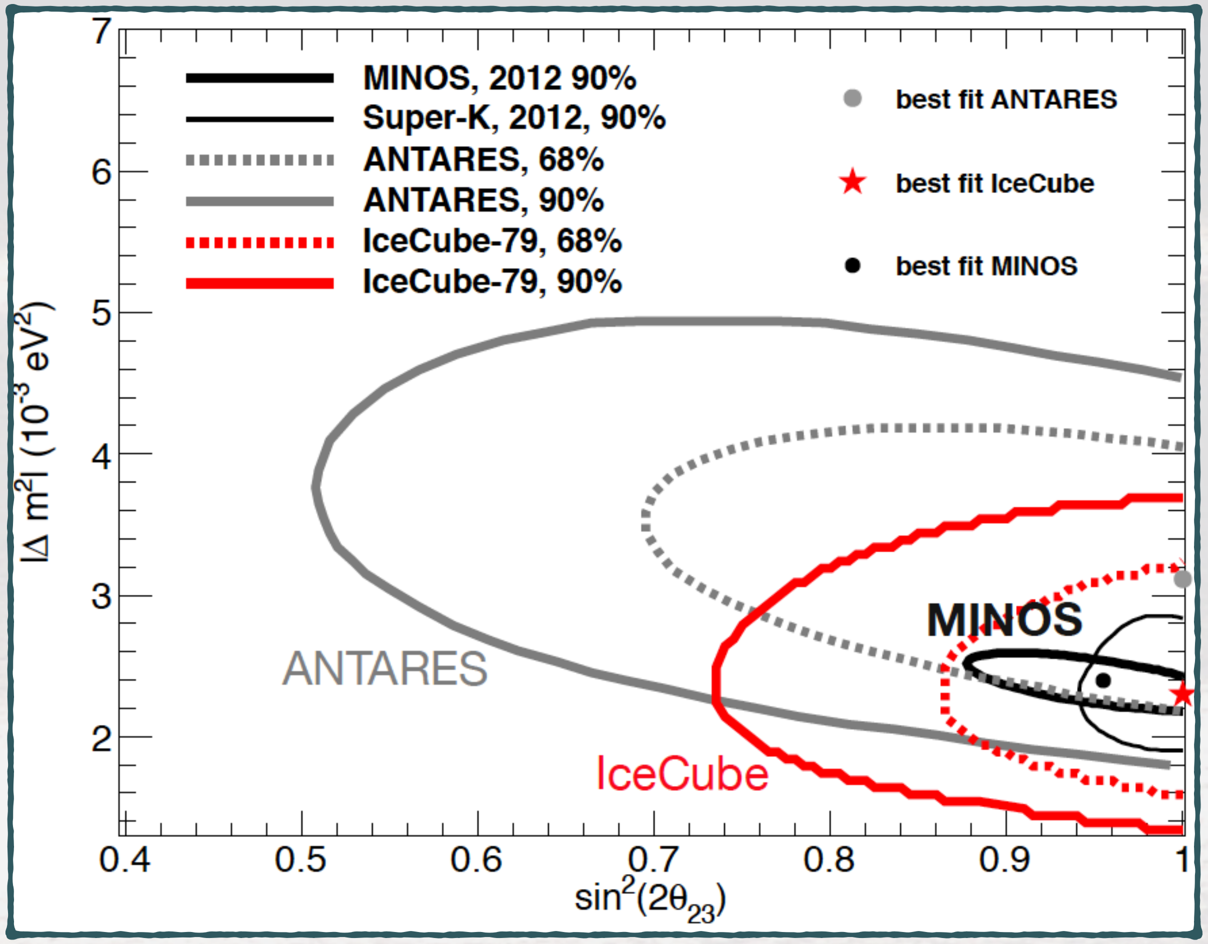
- No single event analysis, total charge (or light) signal as a function of time
- Sensitivity to mass hierarchy and SN model with early time detection

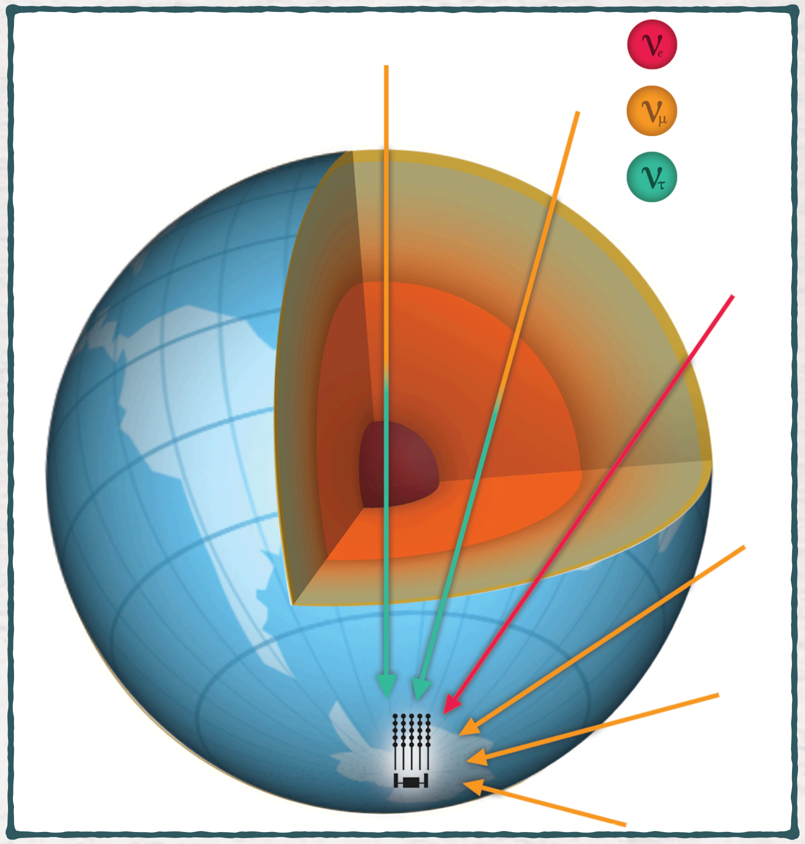




- Smaller precision, but completely different energy range (up to 100 TeV)
    - IceCube and Antares data so far
    - Sensitivity to new physics and mass hierarchy

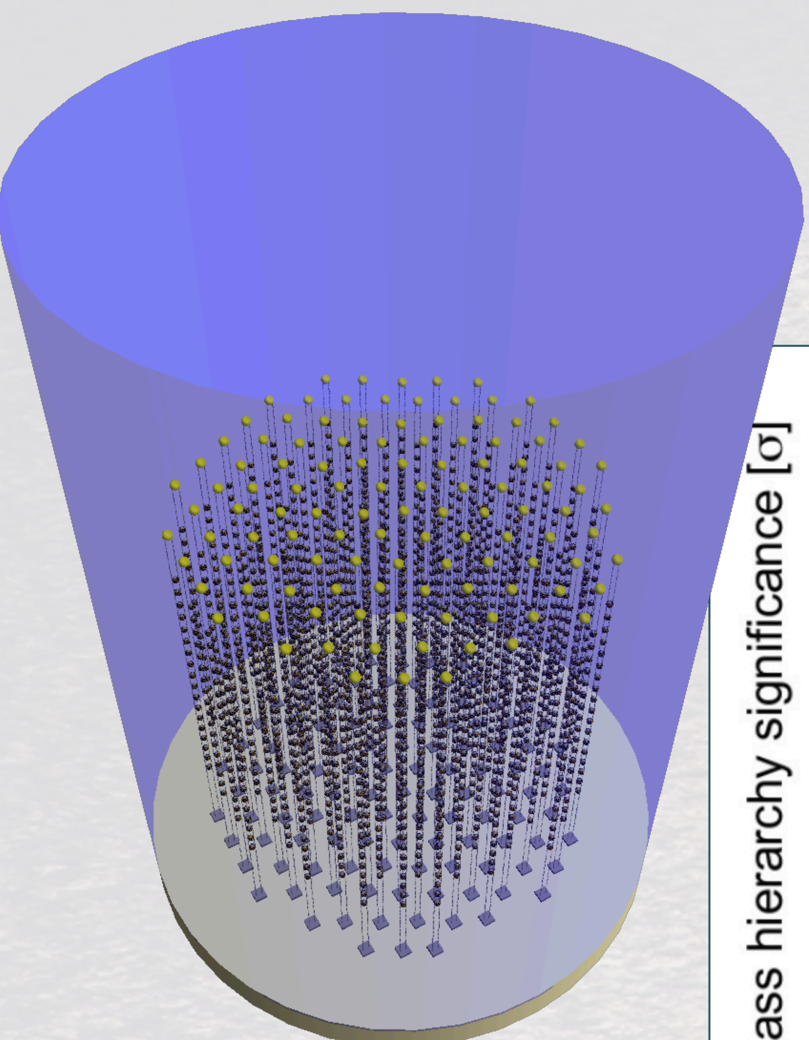


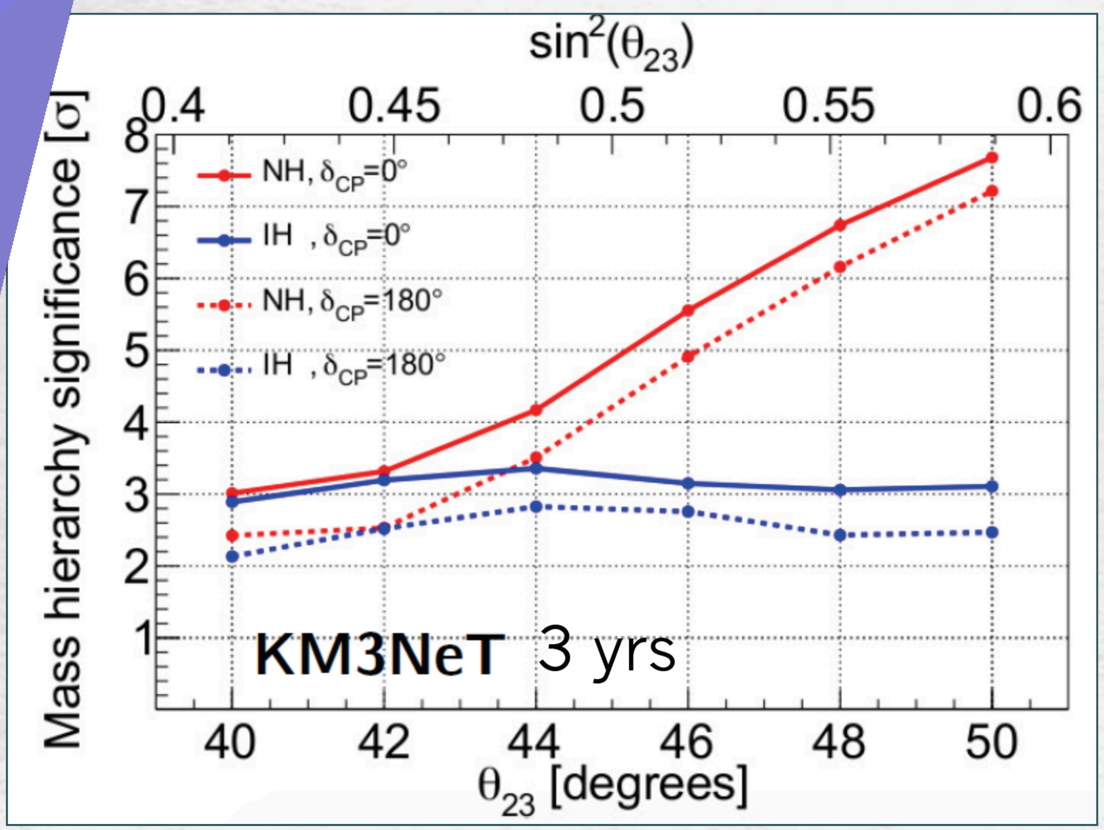


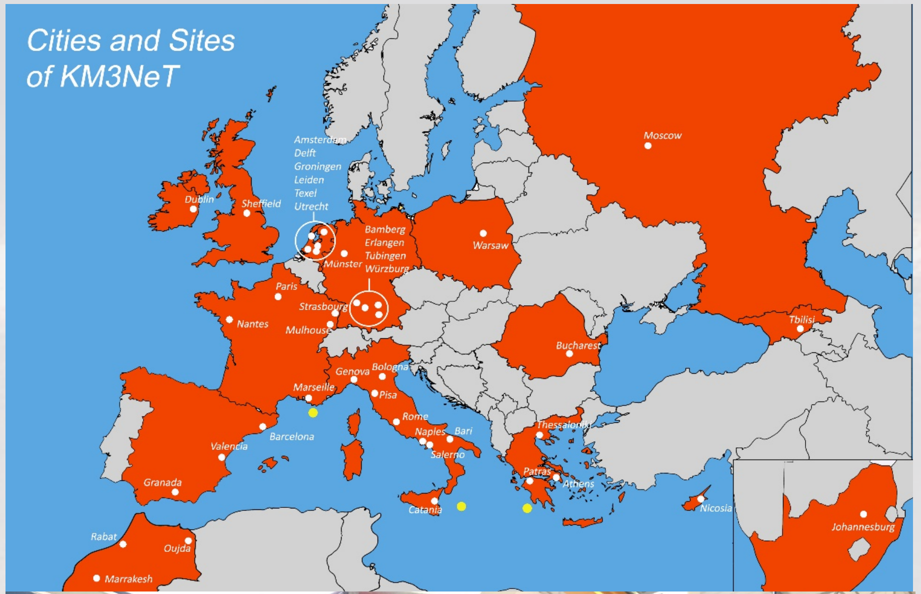


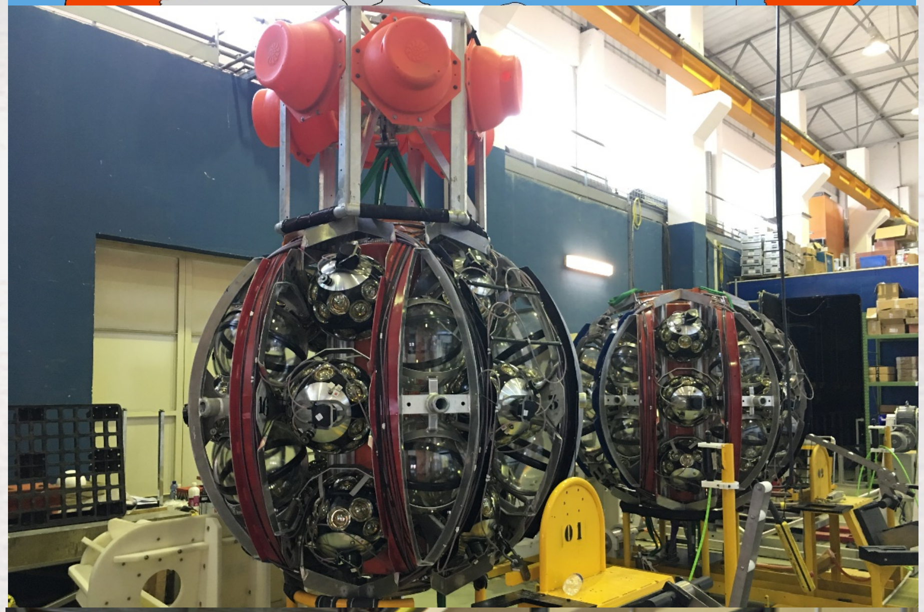
From: T. DeYoung Neutrino 2018

- **KM3Net**: key European project for **multi-messenger ν**
  - ARCA: Neutrino Astrophysics
    - Sources, Acceleration mechanisms
  - ORCA (Mass hierarchy)

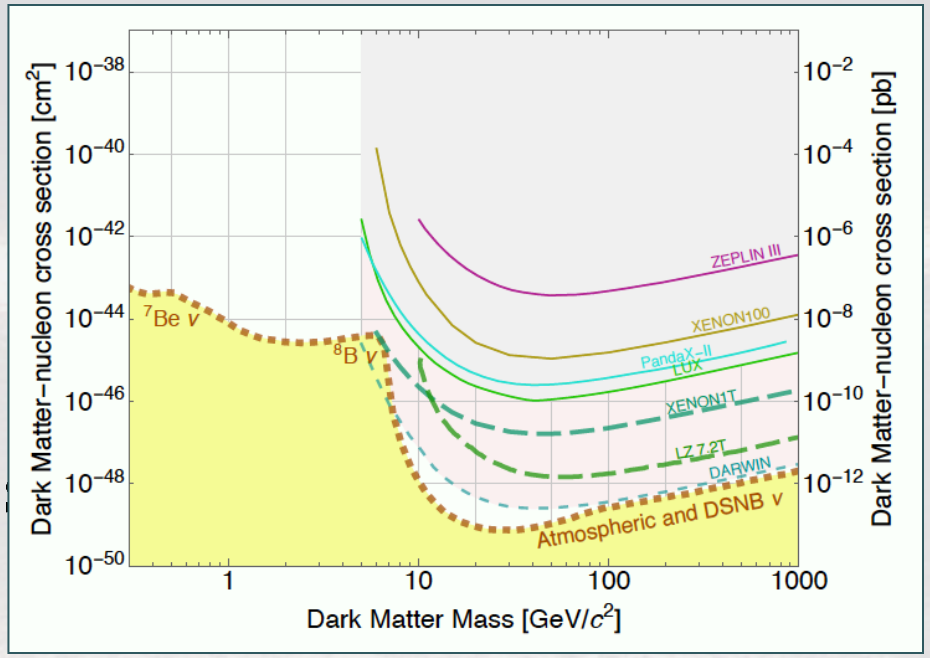


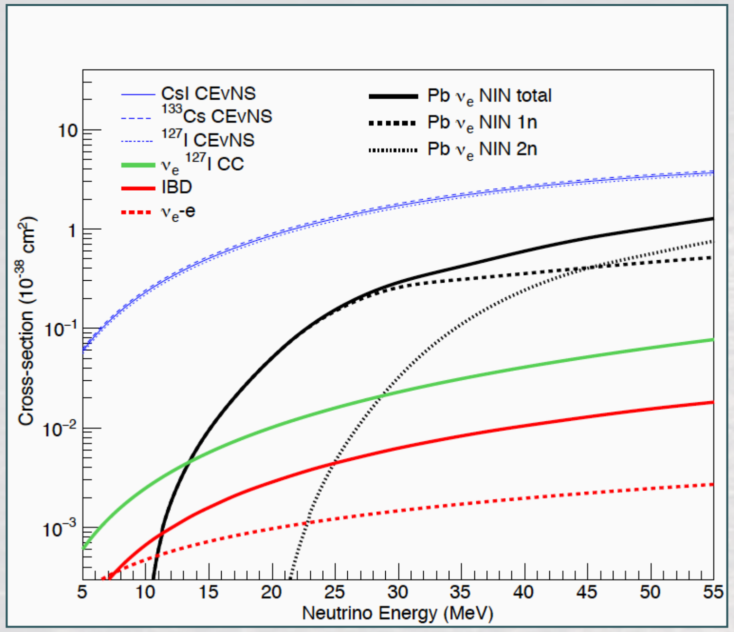






- Coherent neutrino scattering finally observed
  - Predicted in 1974, very difficult measurement
    - Cross section is large, energy recoil very small
  - Fundamental physics, SuperNovae, Dark Matter

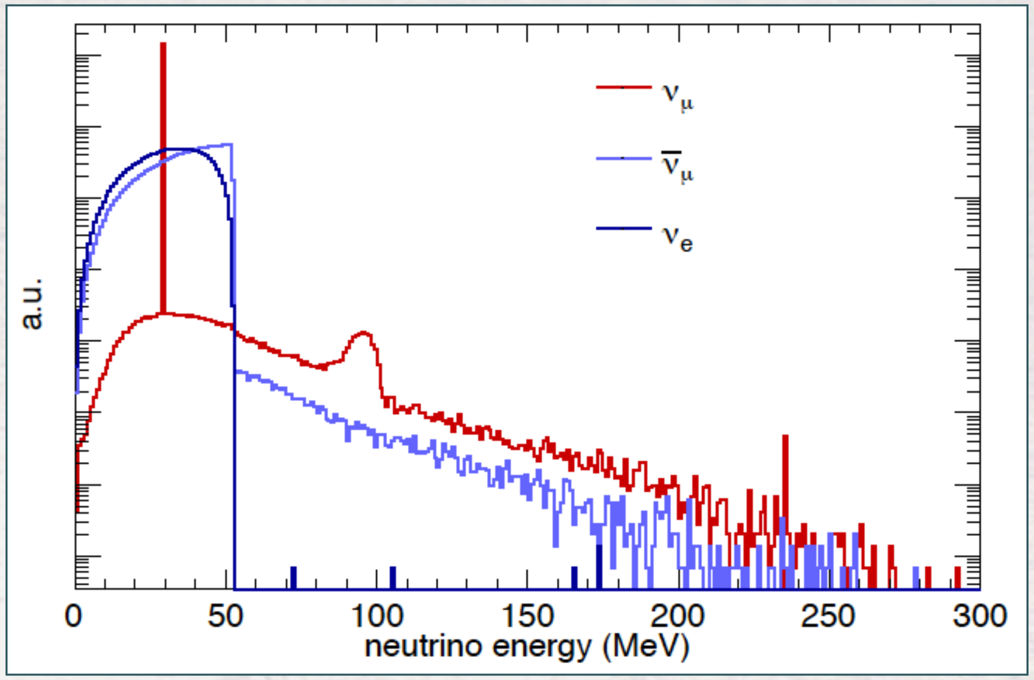




$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} \left[Z \left(1 - 4\sin^2\theta_W \right) - N \right]^2 F^2(Q^2) \qquad E_\nu \leq 50MeV$$

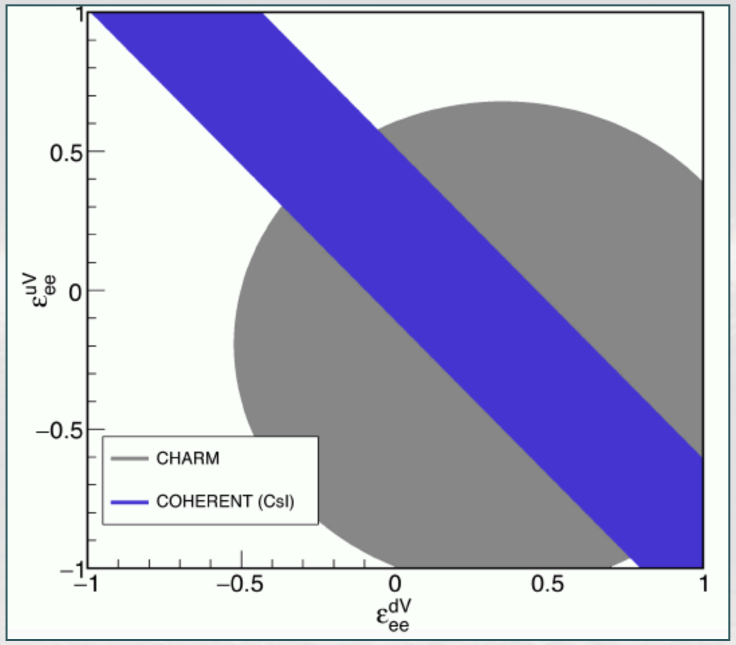
$$E_{nr} = \frac{2E^2}{M} = 15 - 160keV \quad @E_\nu = 30MeV$$

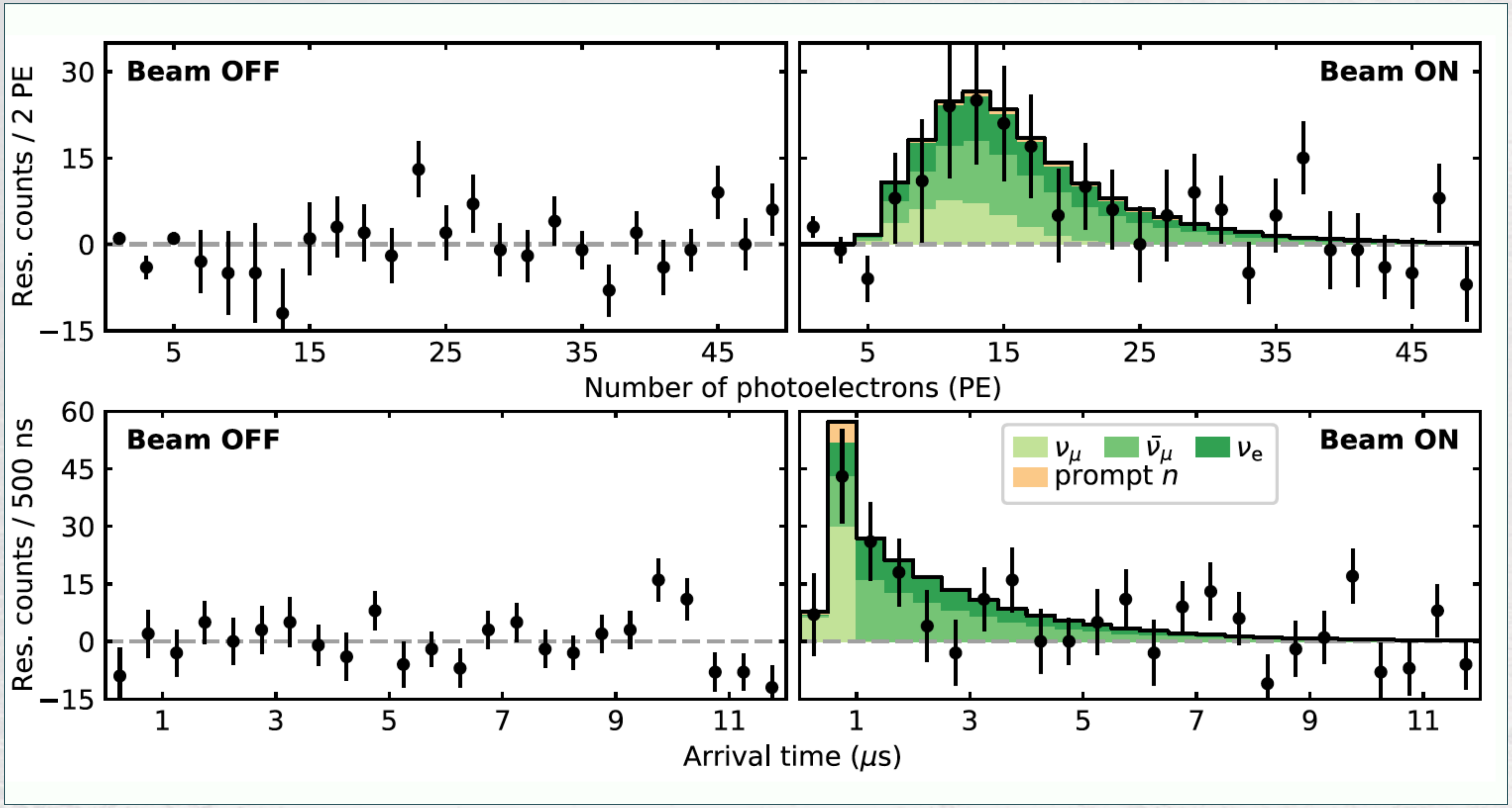
- Experiment at the SNS, Spallation Neutron source at Oak Ridge, Tennessee
  - Most intense pulsed neutron source
  - Very low threshold CsI detectors



COHERENT RESULT

- $1.4\ 10^{23}$ **p.o.t (6 GWhr)**
  - **Observed: 136 ± 31 ev, expected 134 ± 22**
  - No signal excluded at **6.7** σ
    - Already ***constraining NSI***

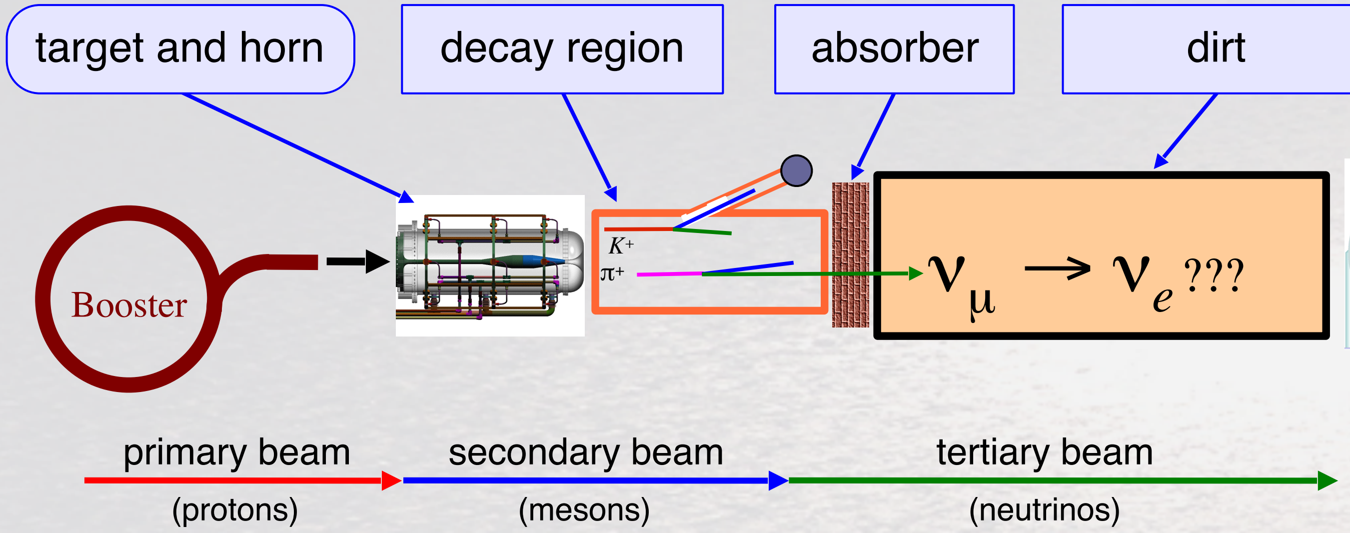


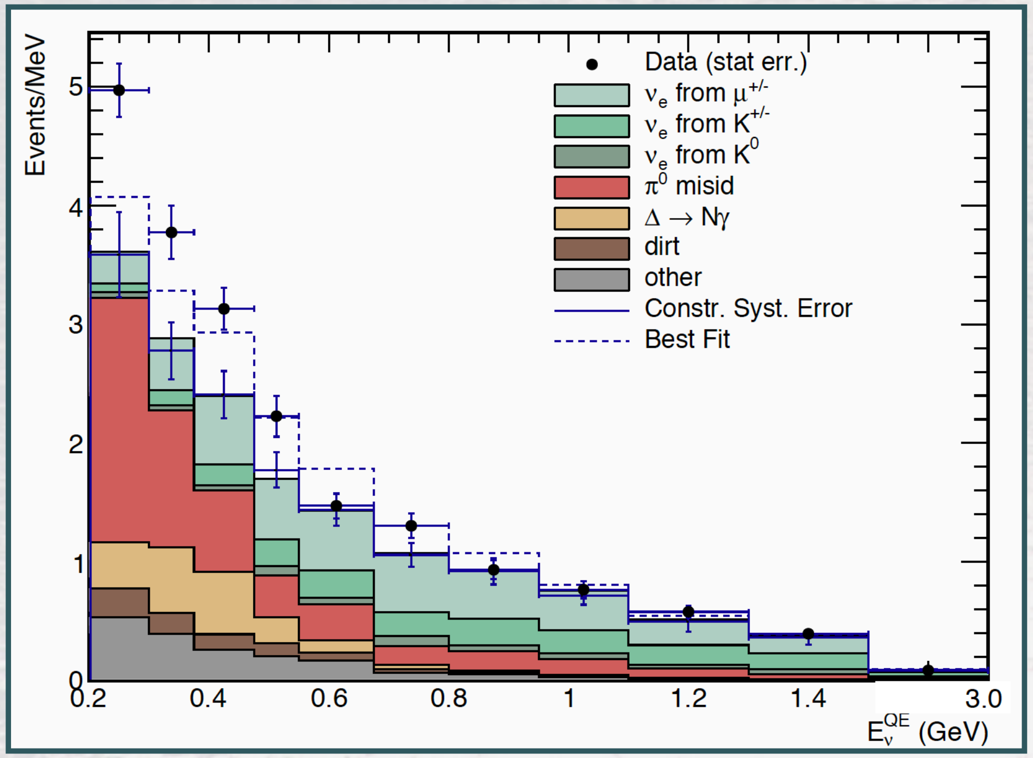


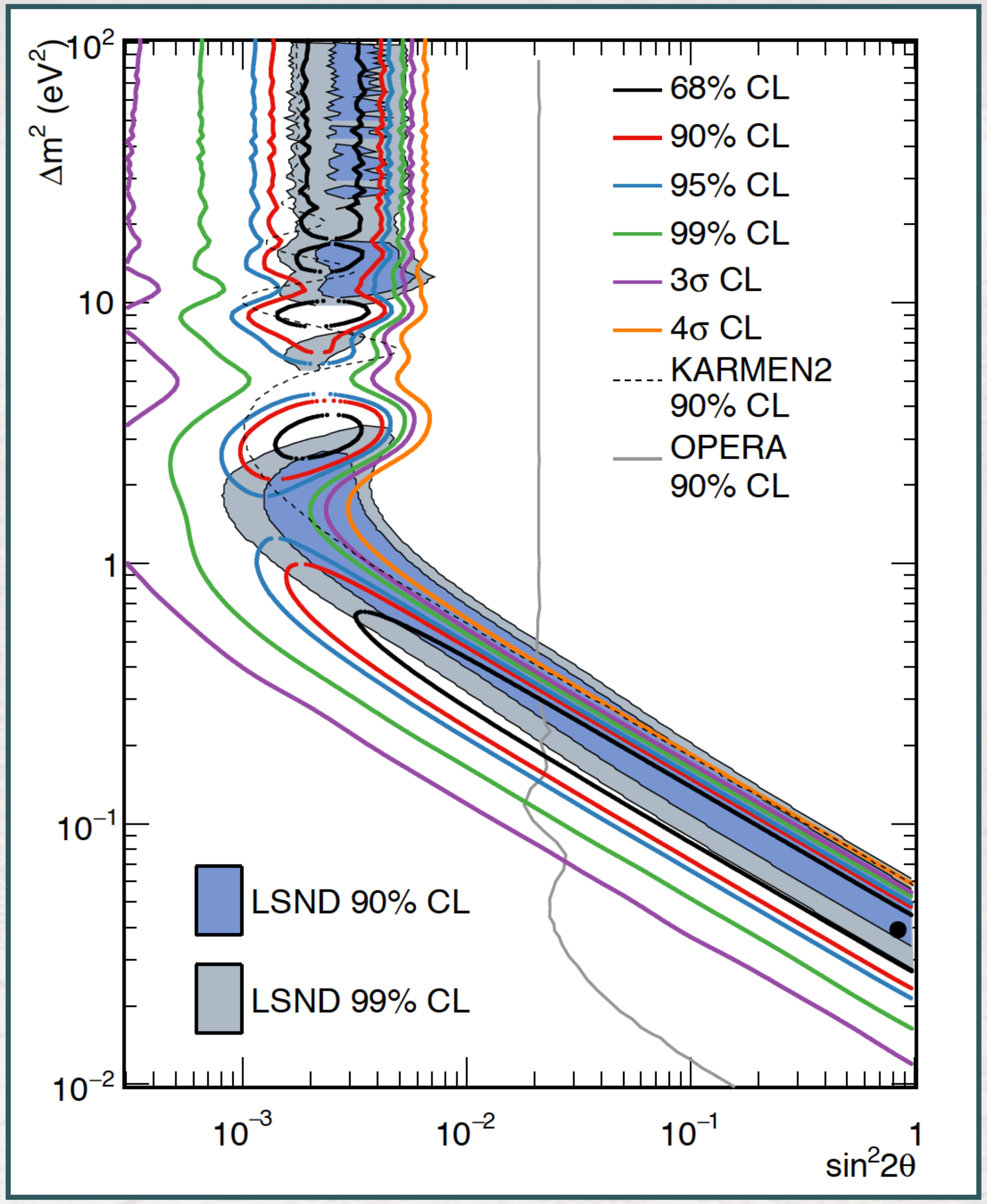
arXiv:1805.12028v1 May 30th, 2018

- Breaking news (well, maybe….)
  - MiniBoone excess of low energy electron appearance confirmed!
    - Very very confusing…..

500 MeV, 500 m

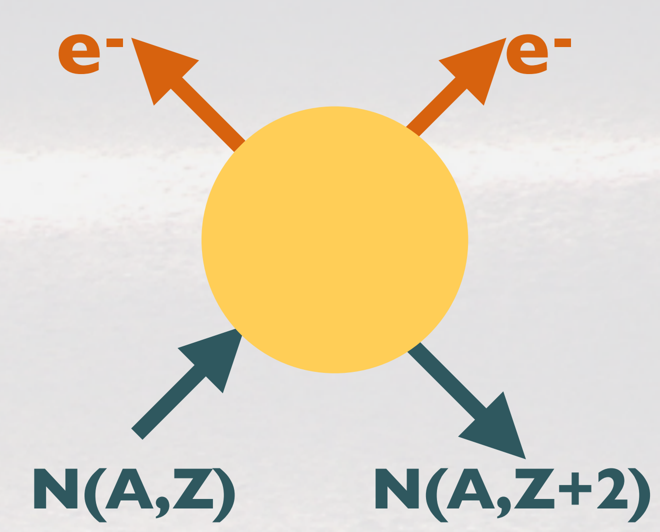


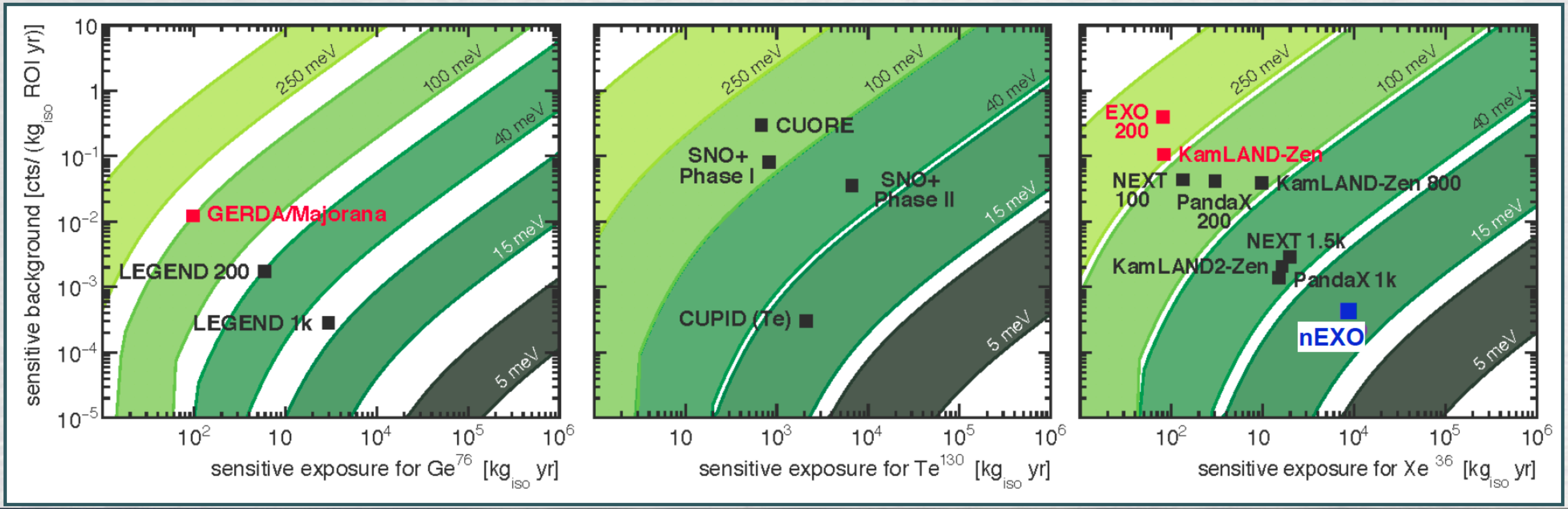




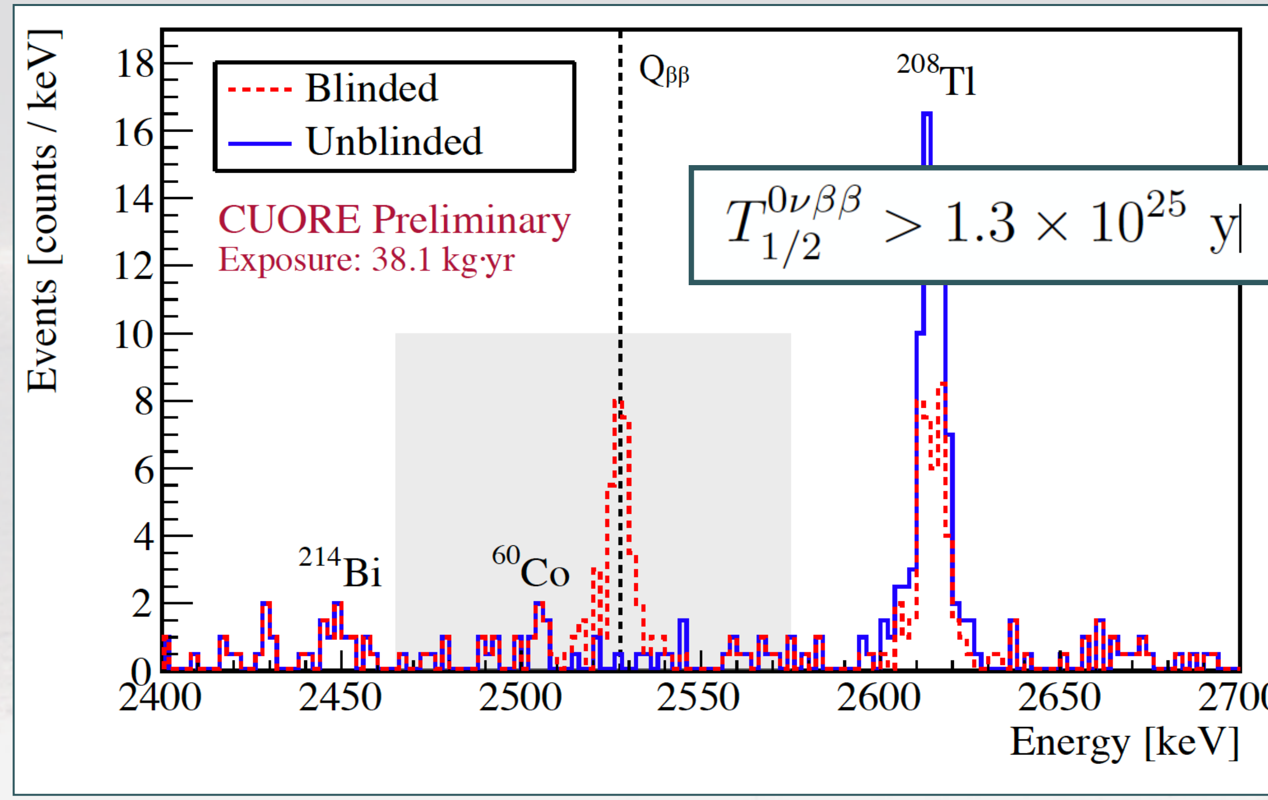
- Neutrino-less double beta decay is a ***portal to new physics***
  - Its observation requires **probes scales beyond SM**
    - **Lepton number** violation
    - Majorana vs Dirac mass terms
    - New **mass generation** mechanisms
    - **Bariogenesis and/or Leptogenesis** mechanisms
  - NOT necessarily linked to Majorana ν, although it implies non-zero Majorana mass
- Roughly, sensitivity from **10^{26} y to 10^{28} y,** corresponds to collider energy increase by a factor 20 (e.g. from Tevatron to LHC)
  - Well…., with many less channels for exploration …..

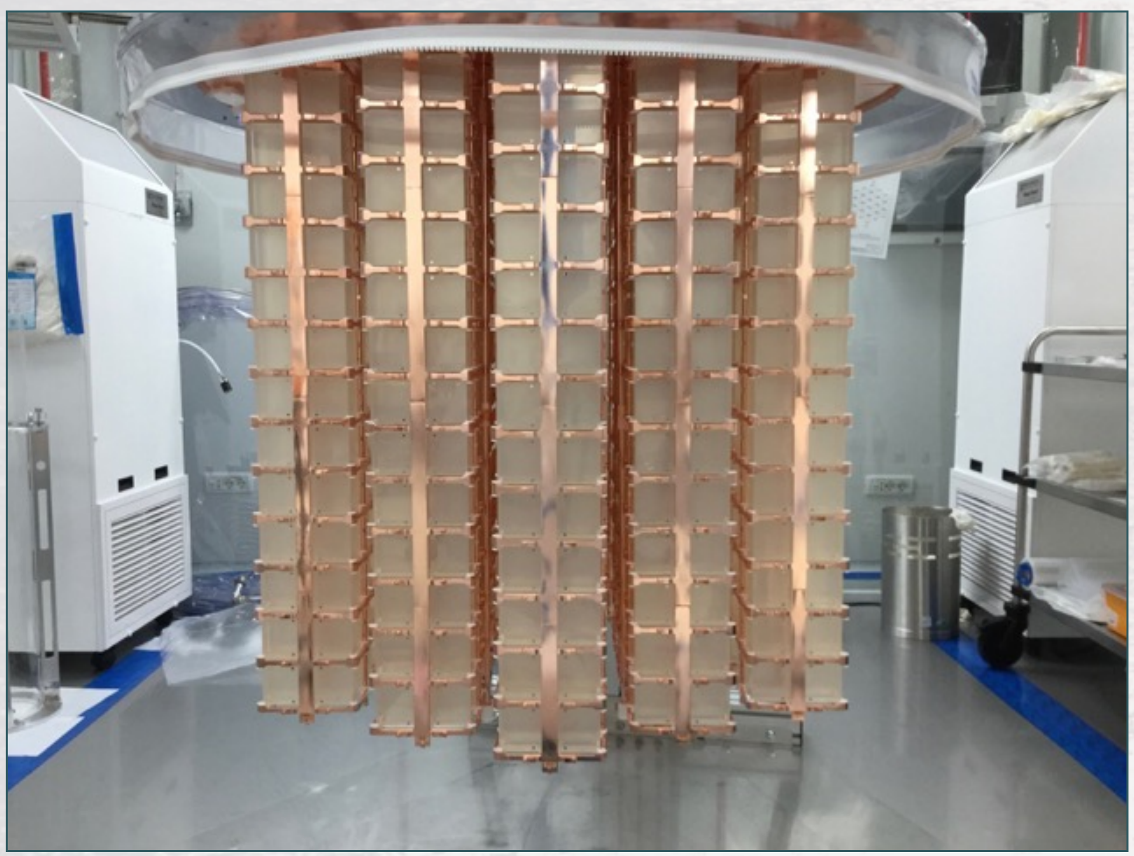
J. Schechter and J.W.F. Valle, PRD25 (1982) 2951





- **CUORE:** Cryogenic bolometers ^{130}Te
    - The coldest m3 of the Universe!
    - First release: Oct. 23rd, 2017
    - Neutrino 2018: 2 neutrino signal



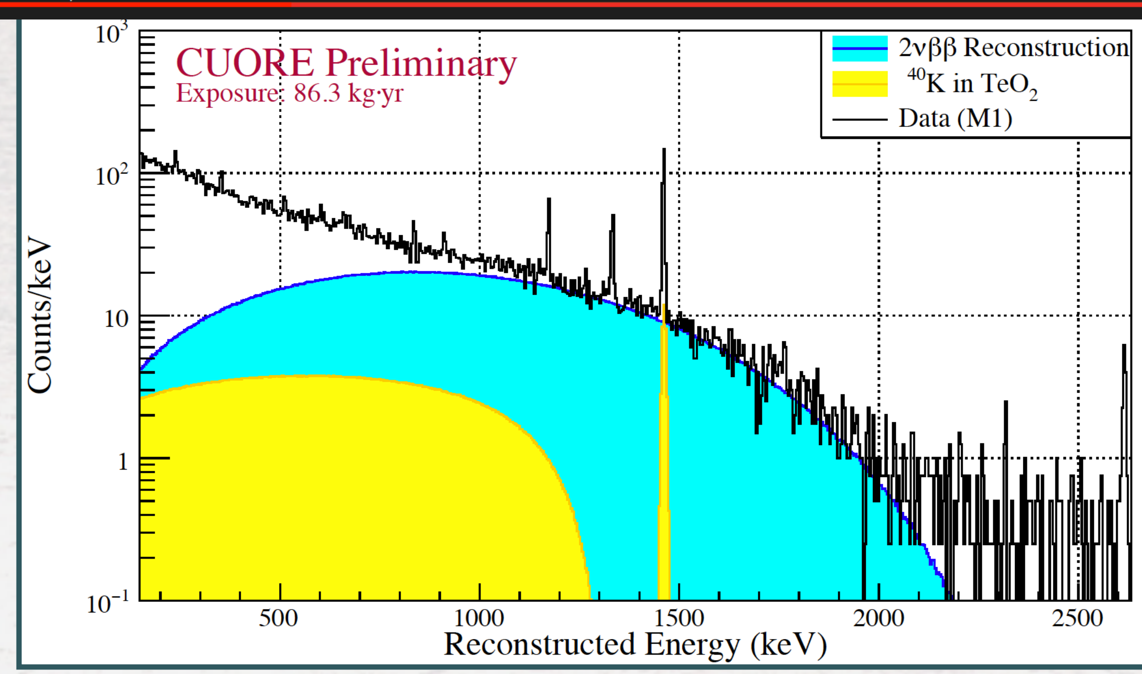


Measurement of the 2νββ Decay Half-life

$$\Gamma_{1/2}^{2\nu} = [8.7 \pm 0.1\,(\text{stat.}) \pm 0.2\,(\text{syst.})] \times 10^{-22}\ \text{yr}^{-1}$$

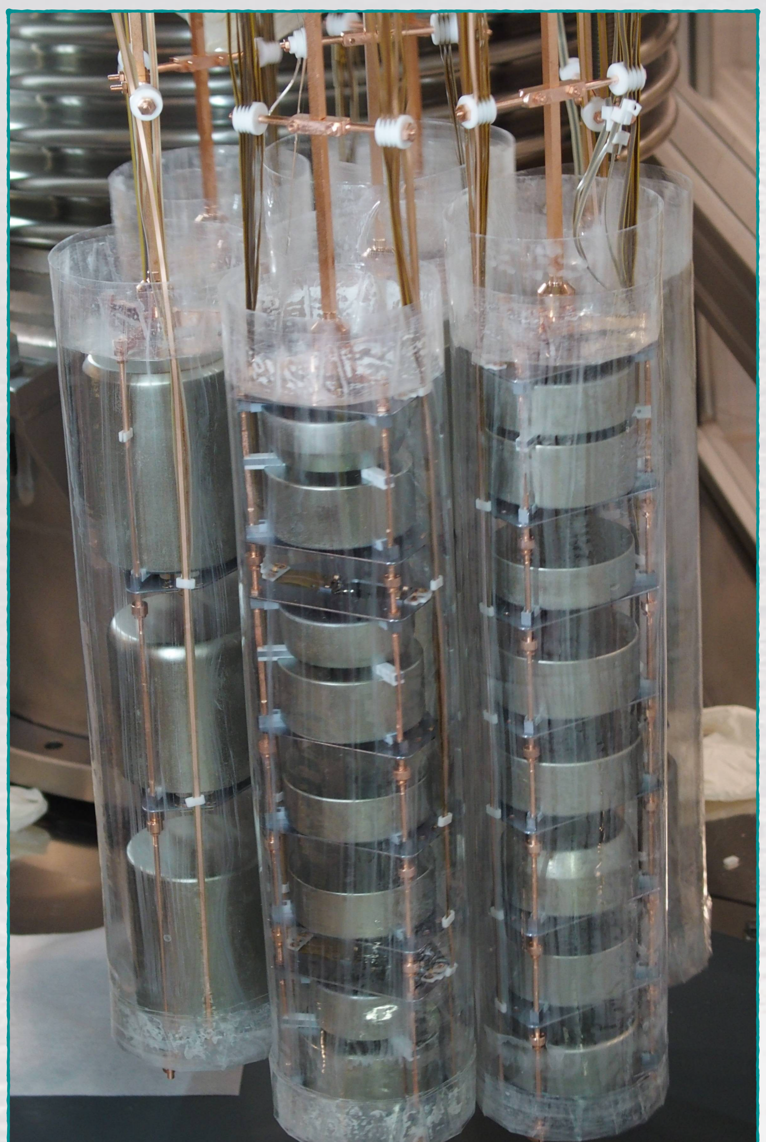
$$T_{1/2}^{2\nu} = [7.9 \pm 0.1\,(\text{stat.}) \pm 0.2\,(\text{syst.})] \times 10^{20}\ \text{yr}$$

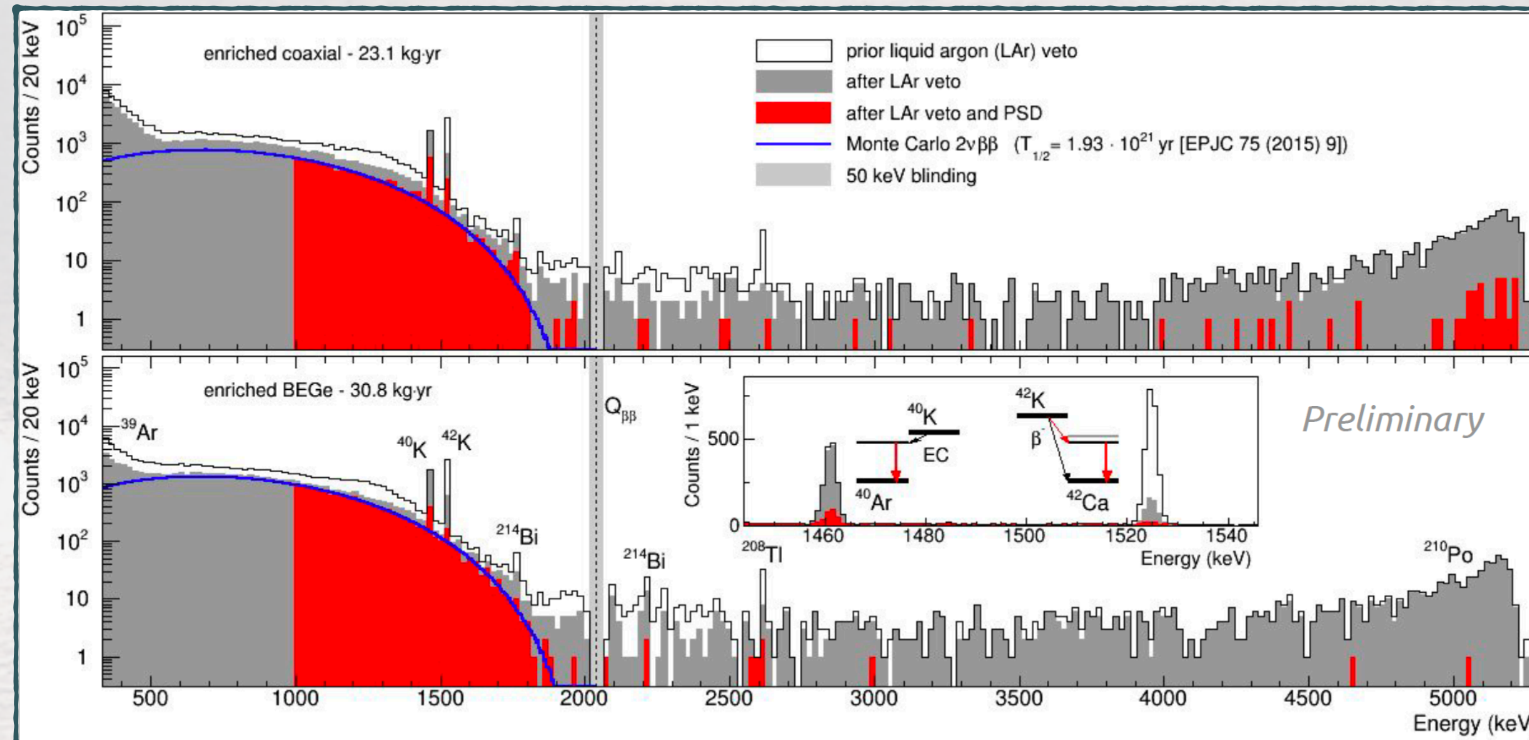
(Preliminary)

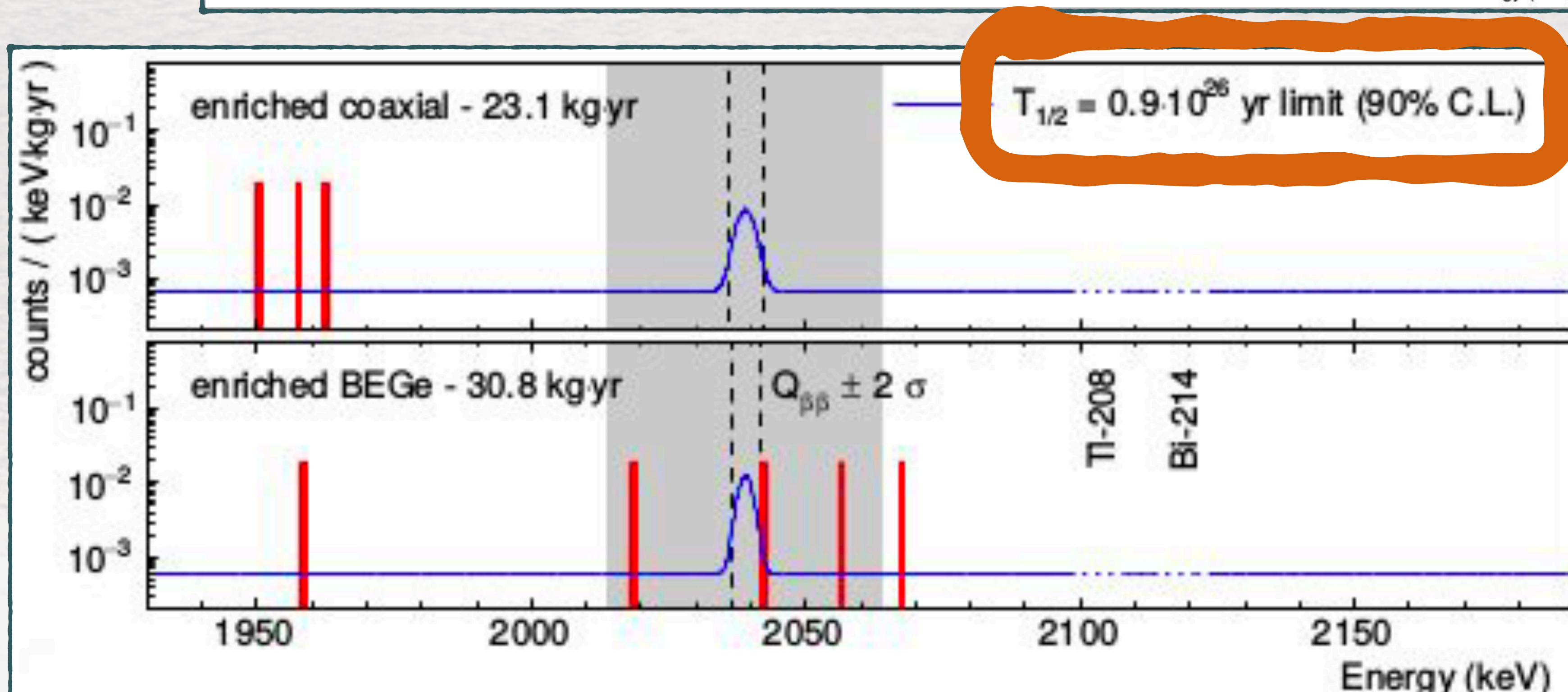


- ^{76}Ge enriched, ~ 30 kg
  - First 0νββ experiment with zero background
    - 6 10^{-4} c keV^{-1} kg^{-1}
  - Upgrade at 200 kg approved
    - LEGEND 200

Neutrino 2018





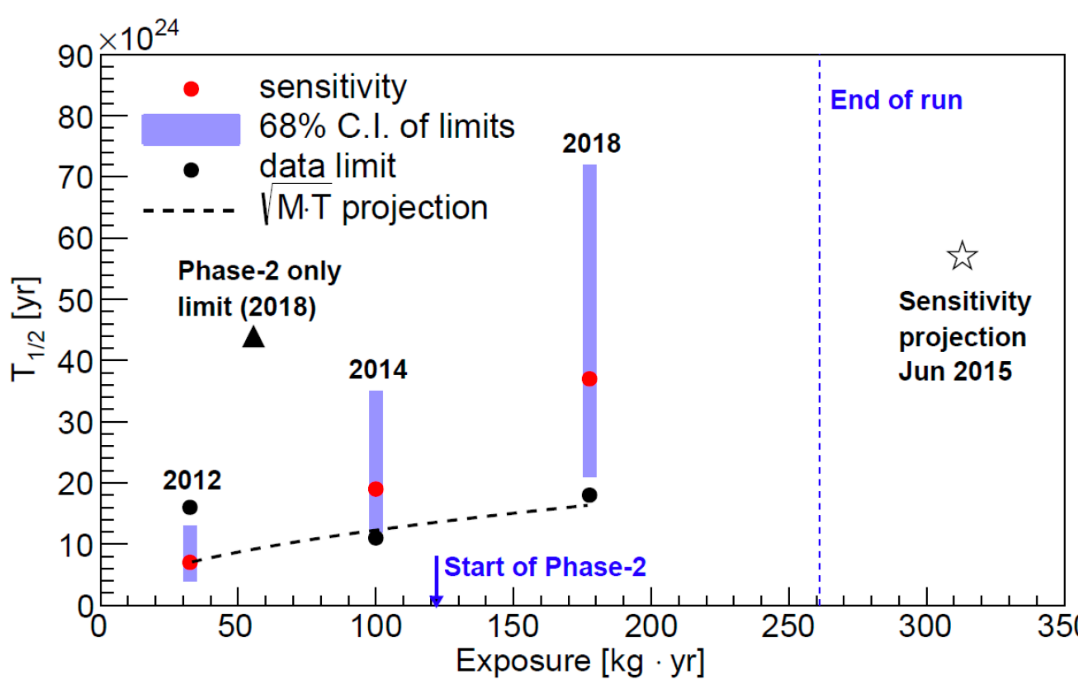


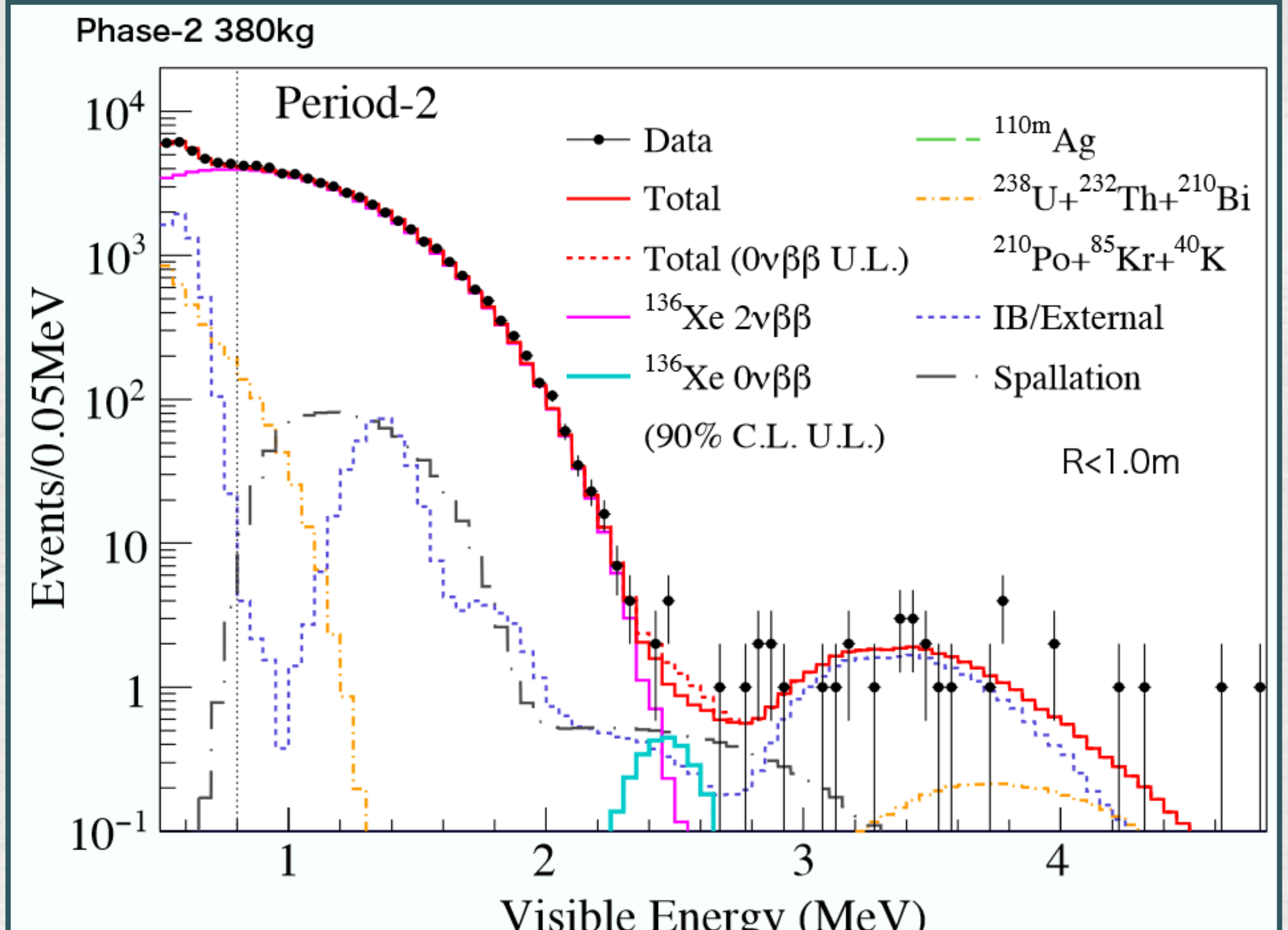
- EXO (liquid) and KamLAND-ZEN (dissolved in liquid scintillator) search for $0\nu\beta\beta$ of ^{136}Xe
  - Larger backgrounds, lower E resolution, but much larger masses (ton scale)

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\ \mathrm{yr}$$

A brief history of EXO-200 results

	Sensitivity (yr)	90% CL Limit (yr)	<$m_{\beta\beta}$> (meV)
PRL 109, 032505 (2012)	0.7×10^{25}	1.6×10^{25}	
Nature 510, 229 (2014)	1.9×10^{25}	1.1×10^{25}	
PRL 120 072701 (2018)	3.8×10^{25}	1.8×10^{25}	147-398



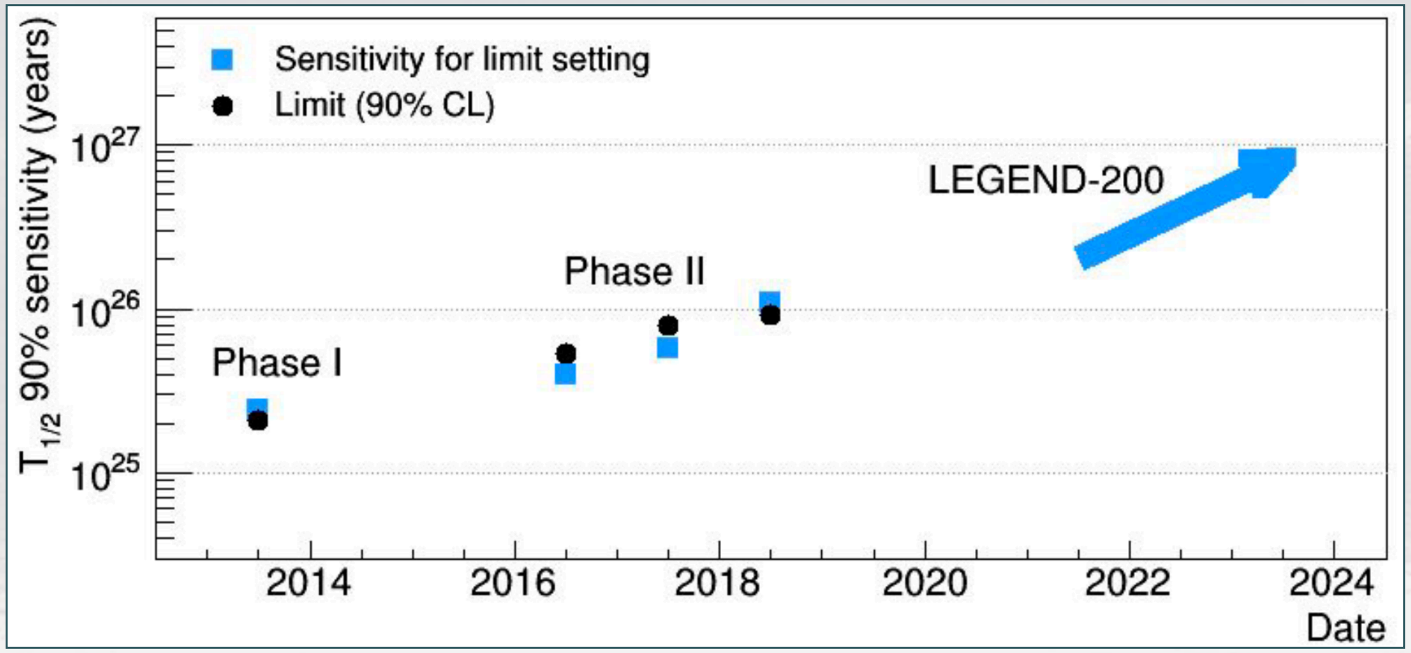


Gratta - Neutrino 2018

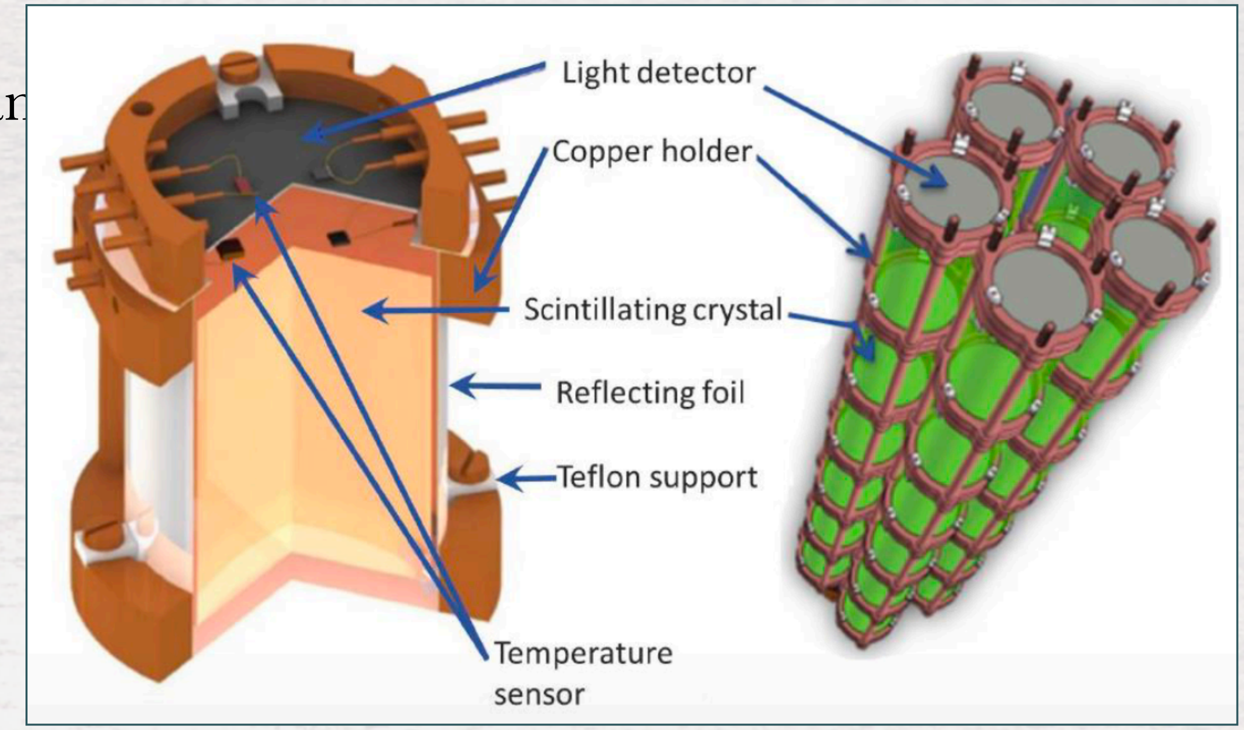
London - Dec. 2017

$$\langle m_{\beta\beta}\rangle < (61 - 165)\ \mathrm{meV}$$

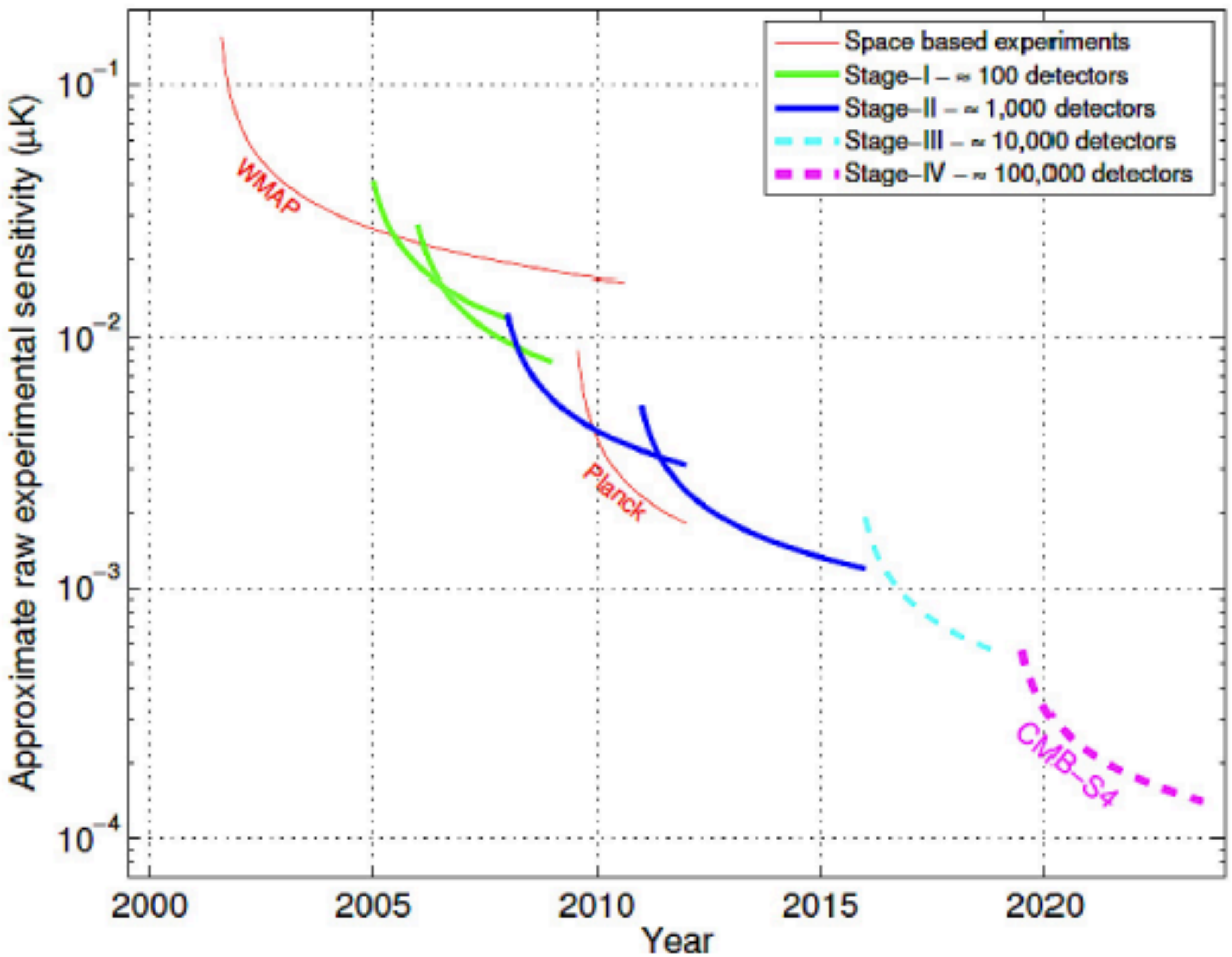
- ^{76}**Ge:** GERDA II-2 and LEGEND 200 kg
  - LNGS 200 kg
  - Background free experiment possible
  - Agreement with US Majorana group

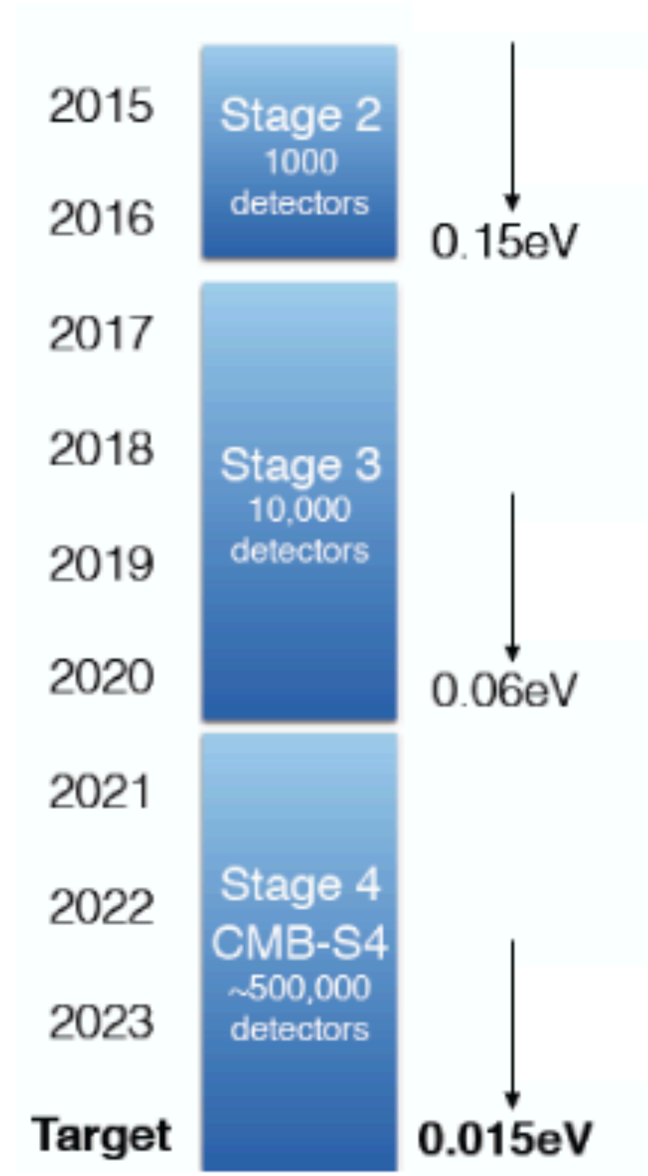


- **Bolometers**
  - **CUPID** program to identify the best technology an
    - **Scintillating Bolometers ?**
    - **Cherenkov from Te ?**
    - ^{130}**Te,** ^{100}**Mo,** ^{82}**Se ?**
  - Zn^{82}Se run in progress and first results
  - ^{100}Mo at Modane



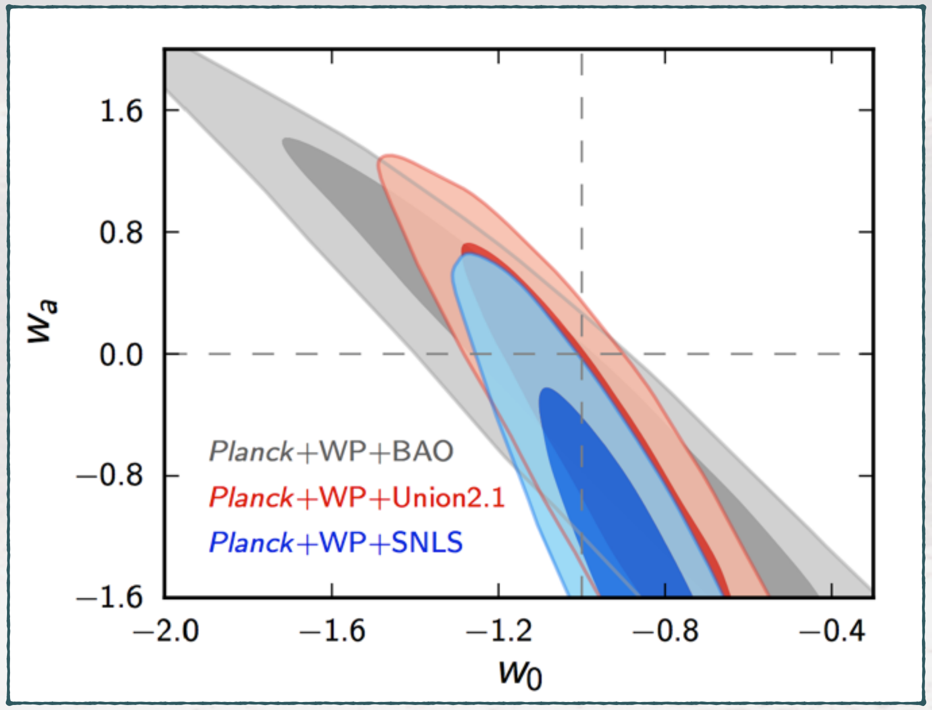
Moore's law of CMB sensitivity in μK ...and expected error on Σm_ν

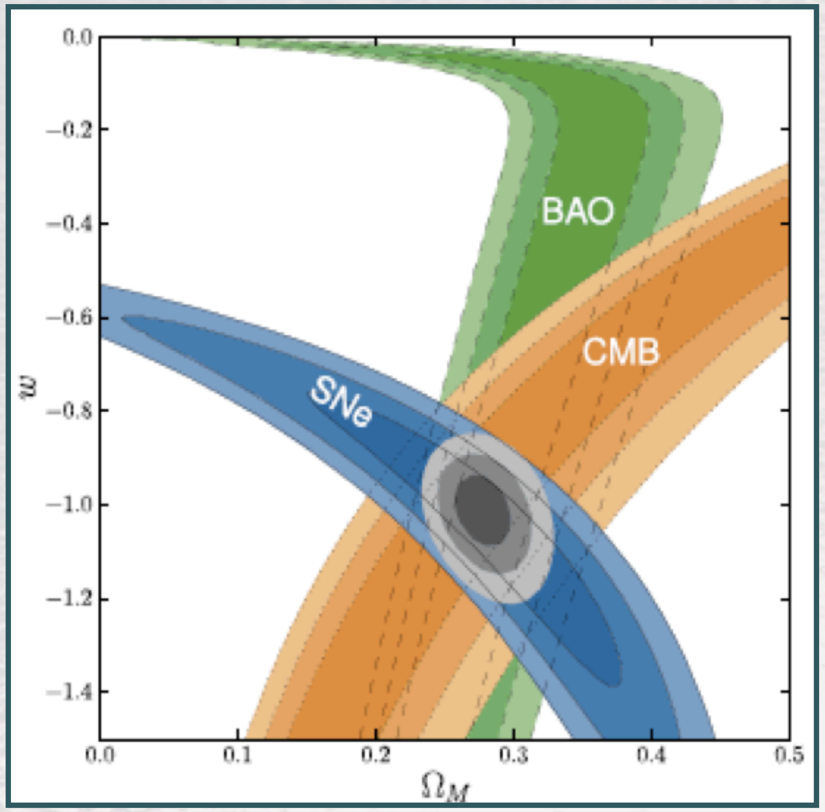




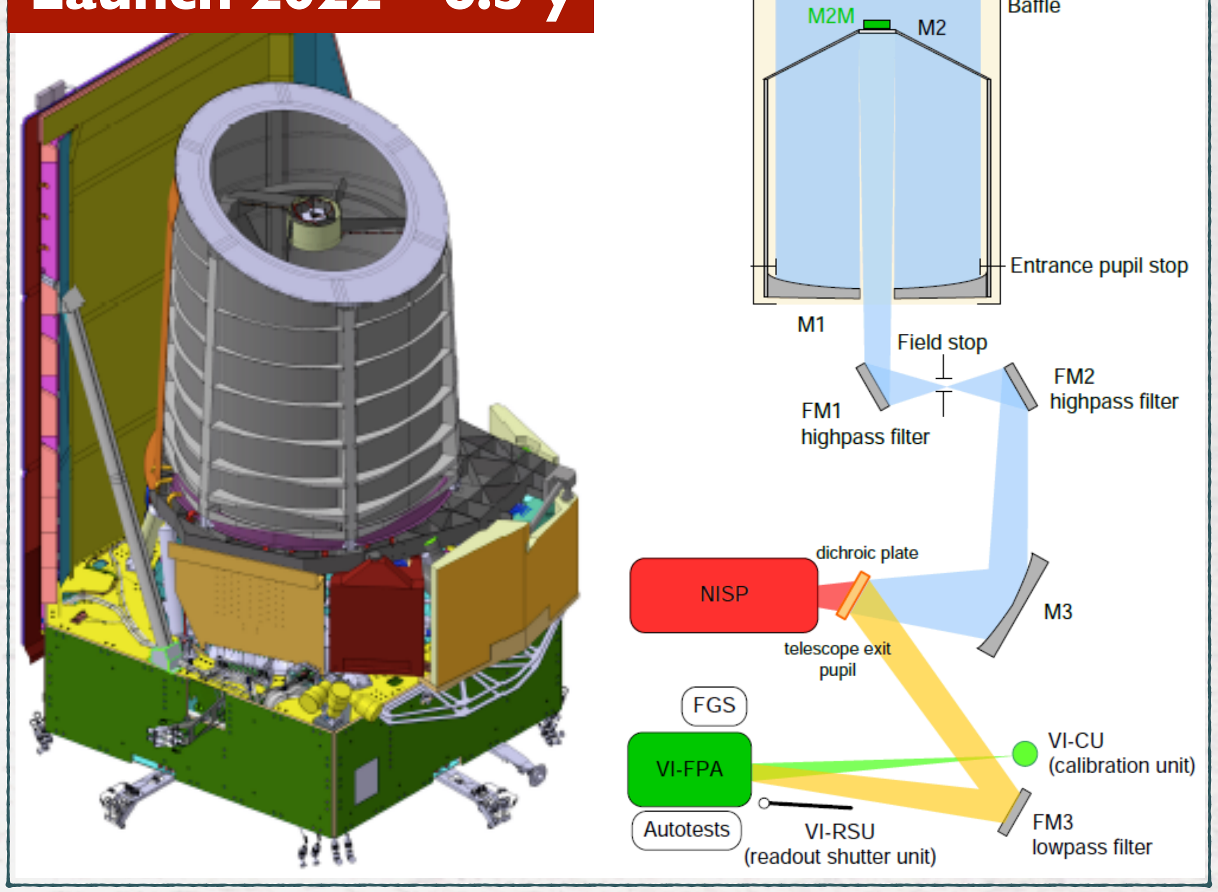
$w = w_0 + w_a(1-a)$

- *Λ*≠0 ? **RG wrong on large scale ? Field ?**
  - **Mission:** Measure the evolution of gravitational potential and matter over 10 Gy (z<2) using:
    - Cluster formation (BAO)
    - Weak Lensing
  - **Neutrino mass ! Sensitivity down to 0.3 eV in the sum of all neutrinos**
- **Two instruments:**
  - Near **Infrared** Spectro-Photometer (NISP)
  - **Visible CCD (VIS)**





Launch 2022 - 6.5 y



- Not covered for lack of time
  - Direct neutrino mass with **Katrin, Project 8,** microBolometers
  - Many **sterile neutrino searches** at reactors
  - Many **DBD experiments around the world**
  - Many future projects (e.g. ESS)
- **Neutrino physics is a very active field of research**
- Next decade might bring:
  - Hierarchy and CPV in lepton sector
  - Neutrino mass scale (likely from Cosmology first)
- **Hard to tell**
  - DBD ?
  - Sterile ?

Neutrinos are always Surprising !