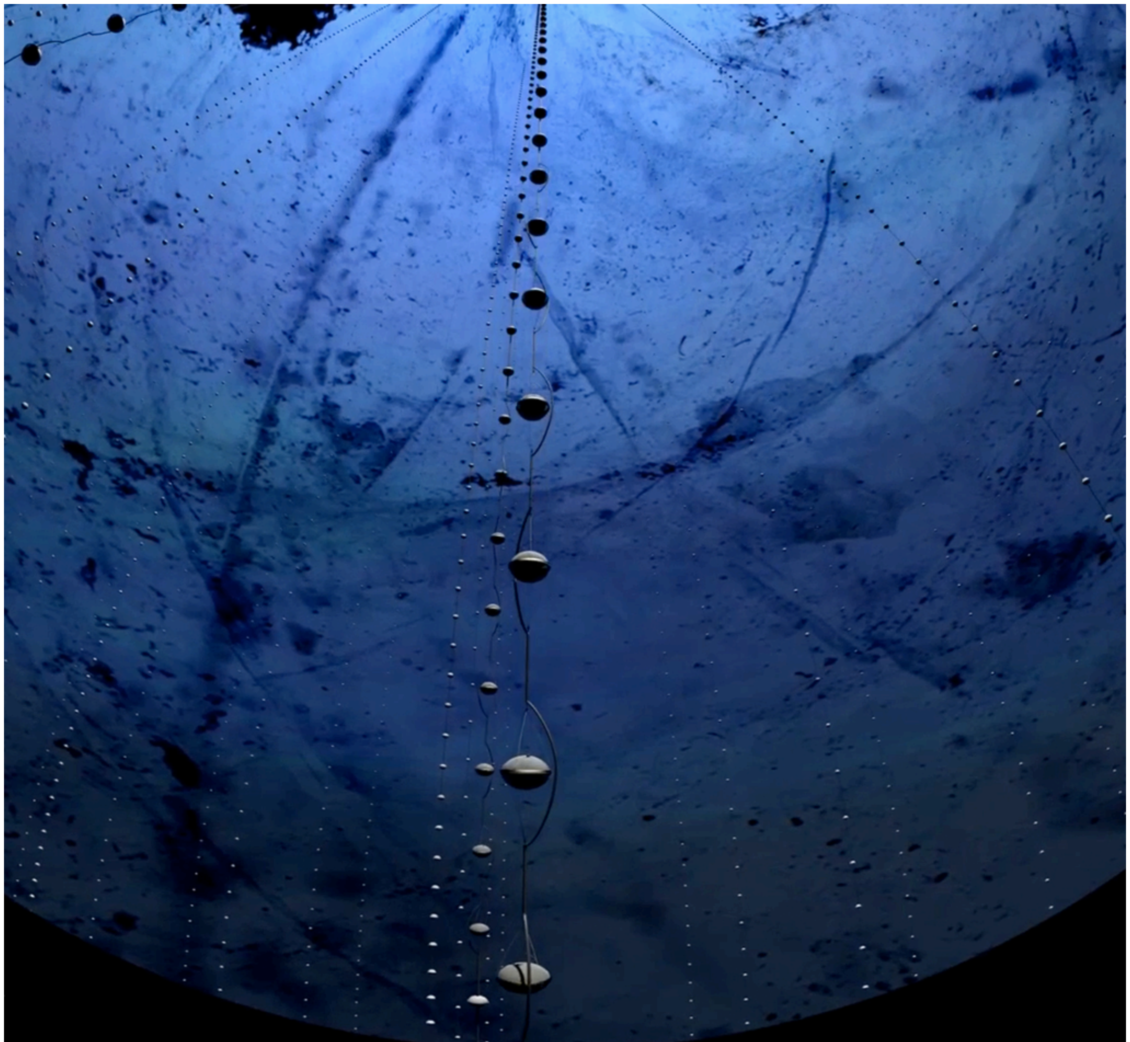
Neutrino Physics, Day 2

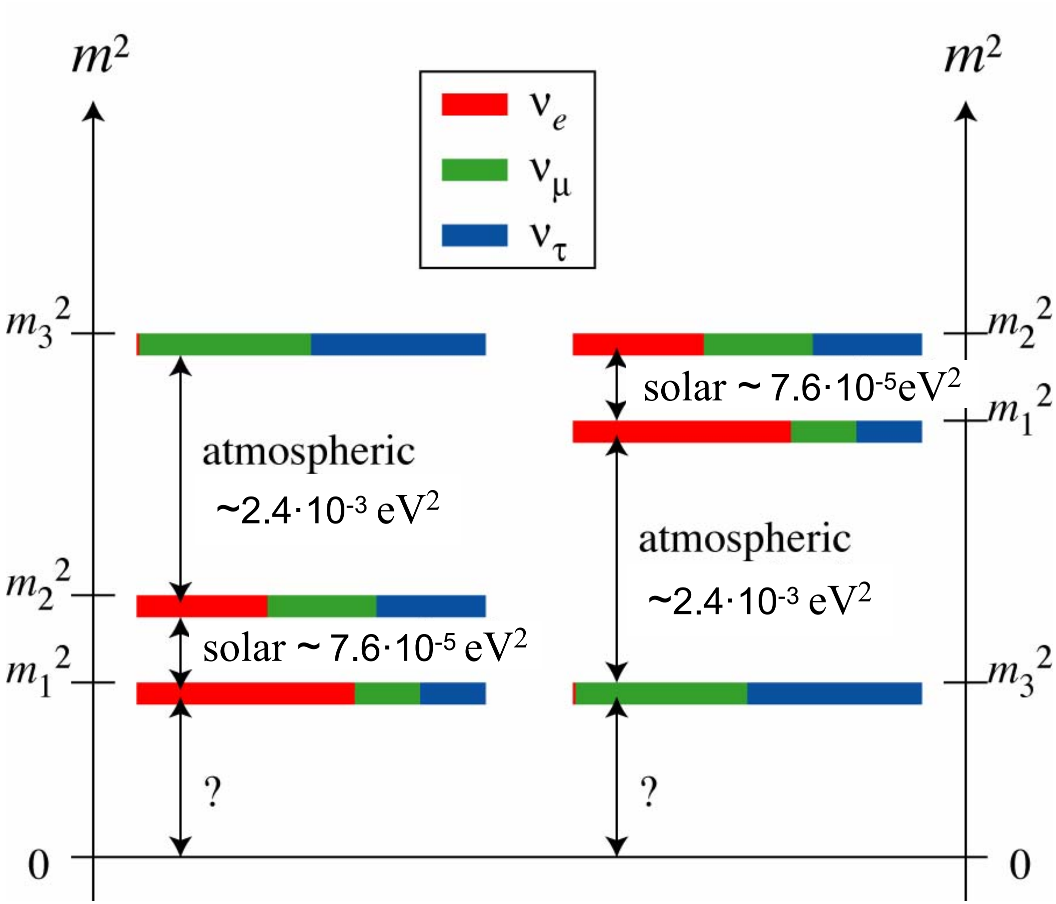


Michelle Dolinski

Drexel University

TRISEP, 15 June 2021

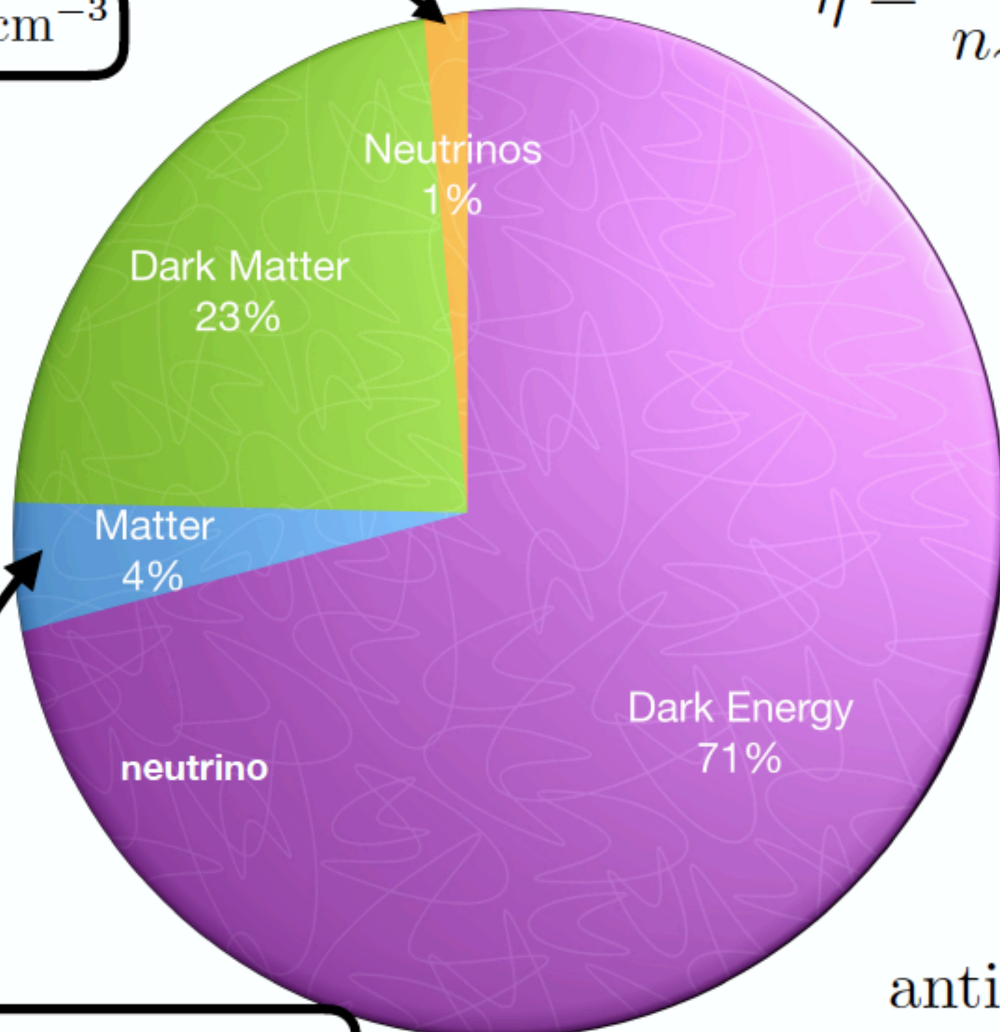
Summary of Day 1



Energy Budget of the Universe

$$\eta = \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

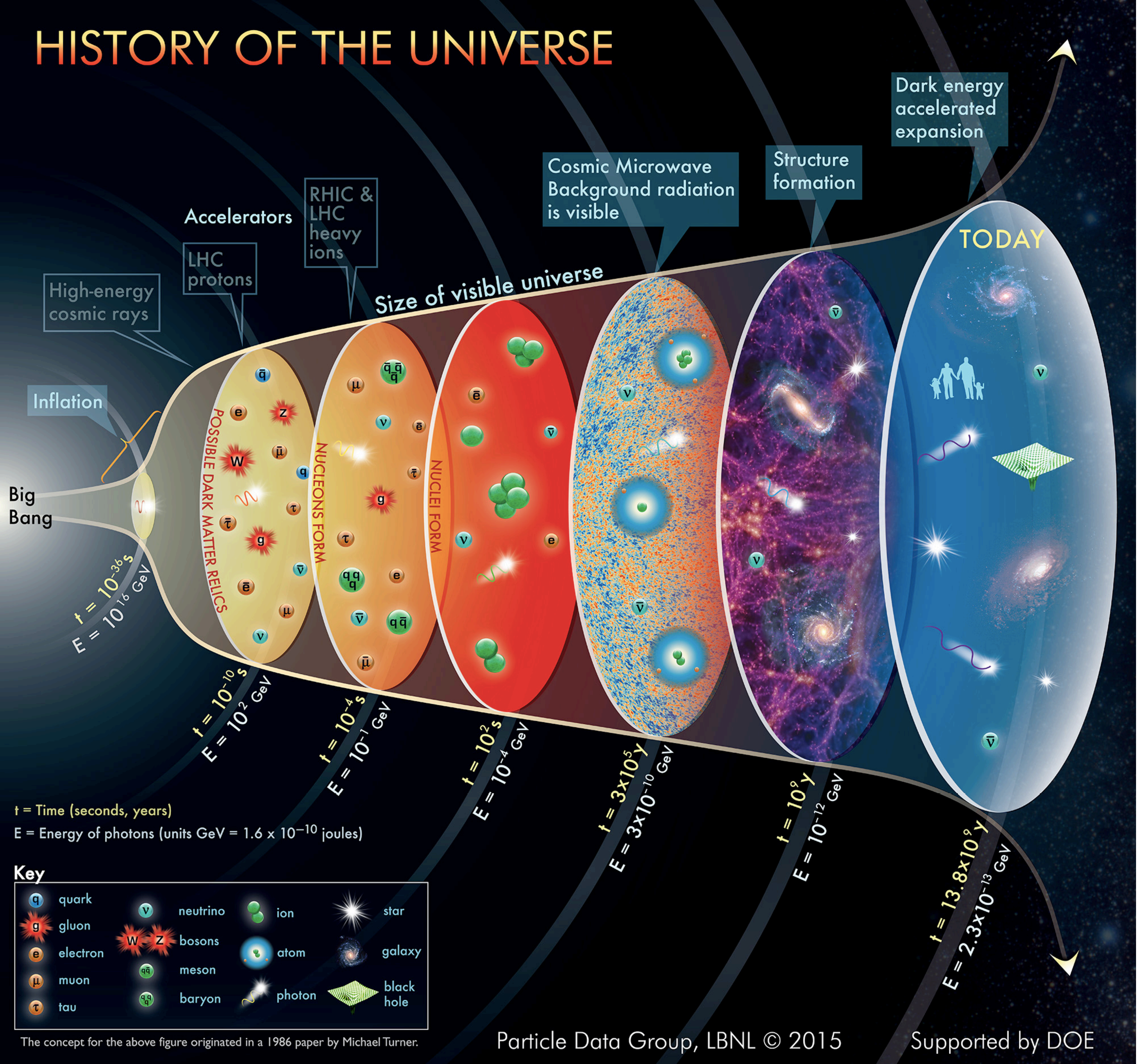
neutrinos $\sim 300\,\mathrm{cm}^{-3}$



protons, neutrons, electrons $\sim 10^{-6}\mathrm{cm}^{-3}$

anti-matter 0%

Slide from J. Turner



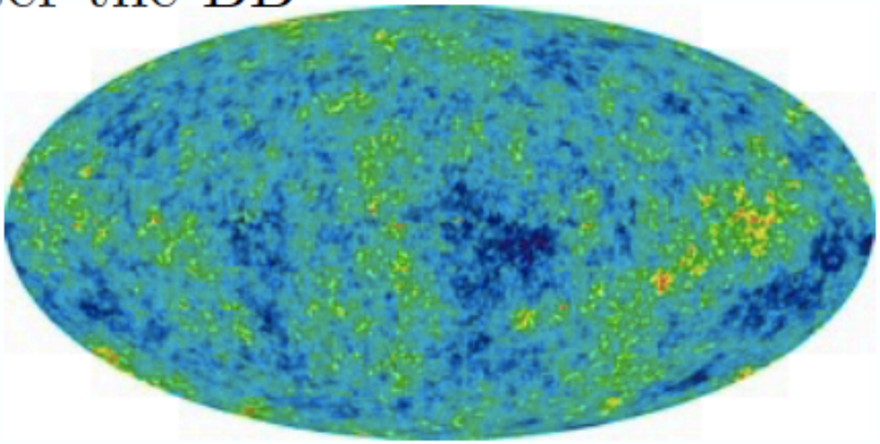
ν decoupling: 1s

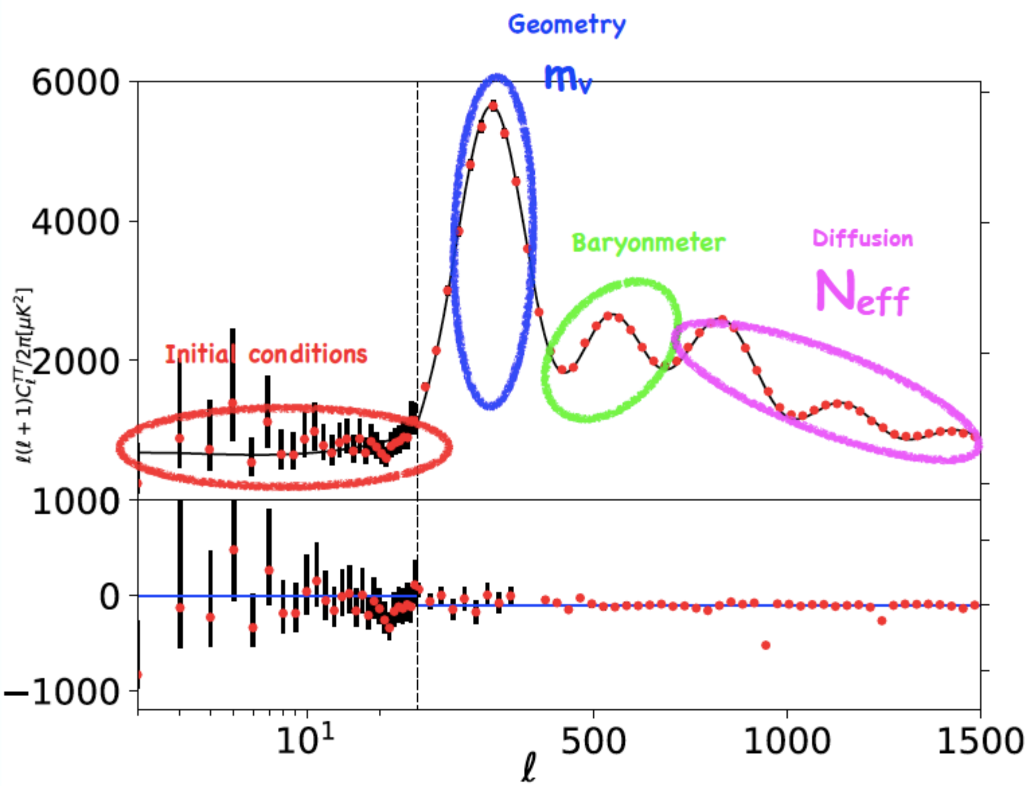
BBN: 3 min

CMB: 380k y

Cosmic Microwave Background

370,000 years after the BB $\qquad T \sim 3000\,\mathrm{K}$



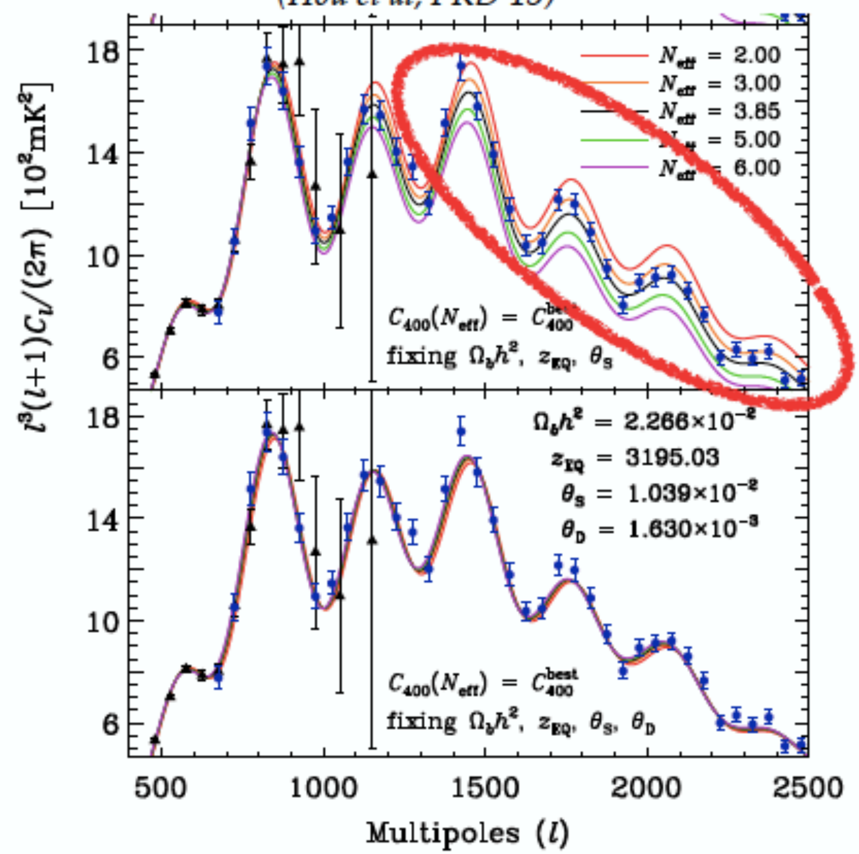


Slide: O. Mena

N_{eff} from CMB

$$r_d^2 \propto \int_0^{a_\star} \frac{da}{a^3 \sigma_T n_e H}$$

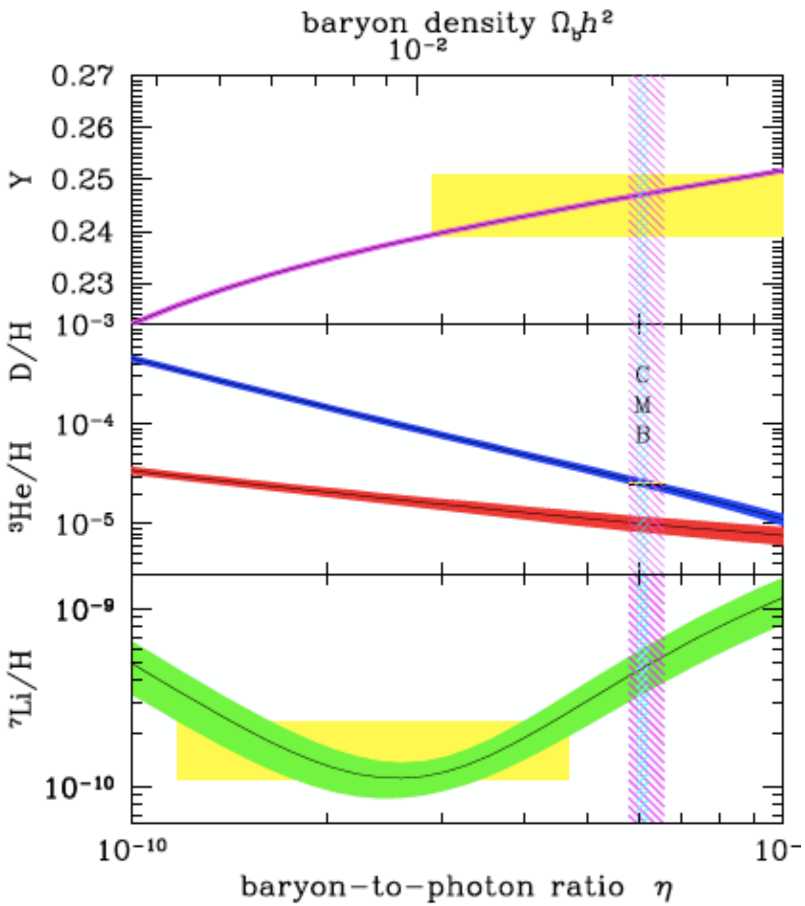
(Hou et al, PRD'13)

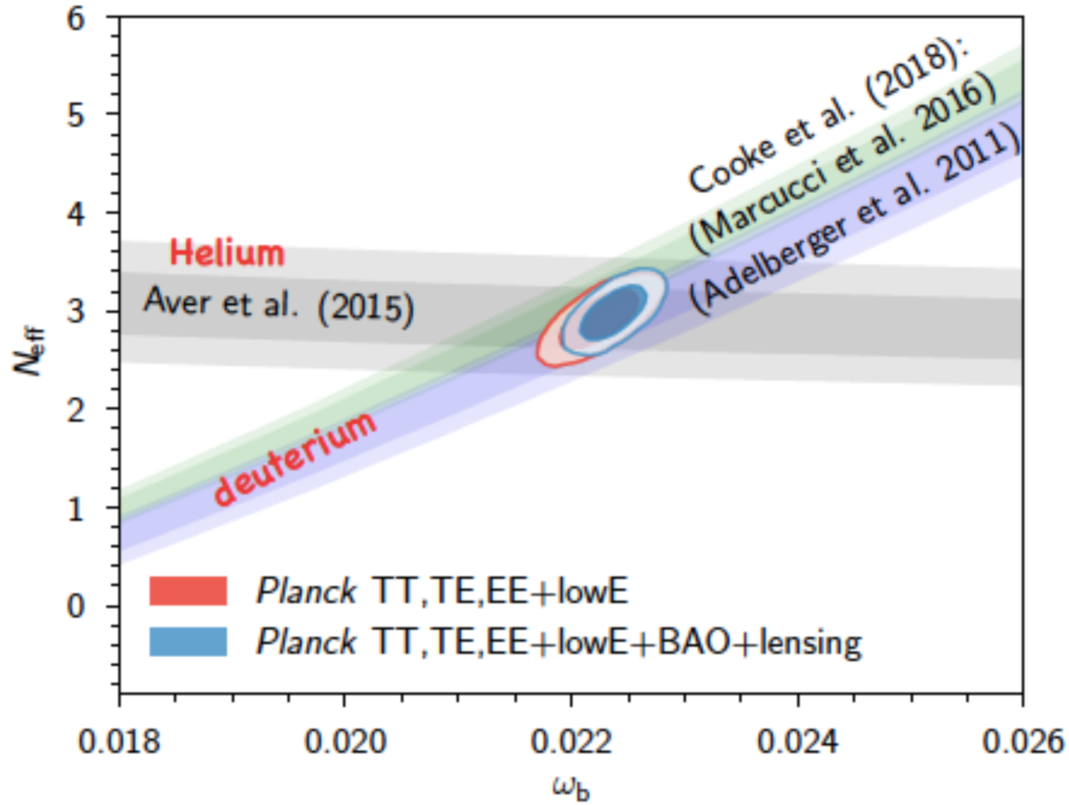


Slide: O. Mena

$N_{\rm eff}$ results for CMB and BBN

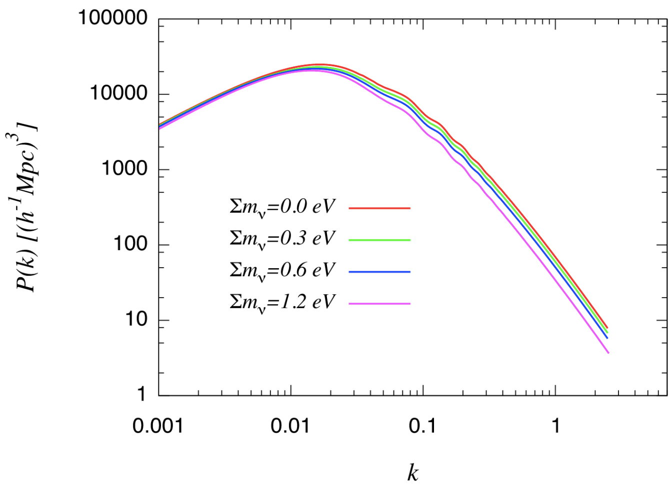
$$N_{eff} = 2.99^{+0.34}_{-0.33} \quad (95\%, \ \text{TT,TE,EE+lowE+lensing+BAO}).$$



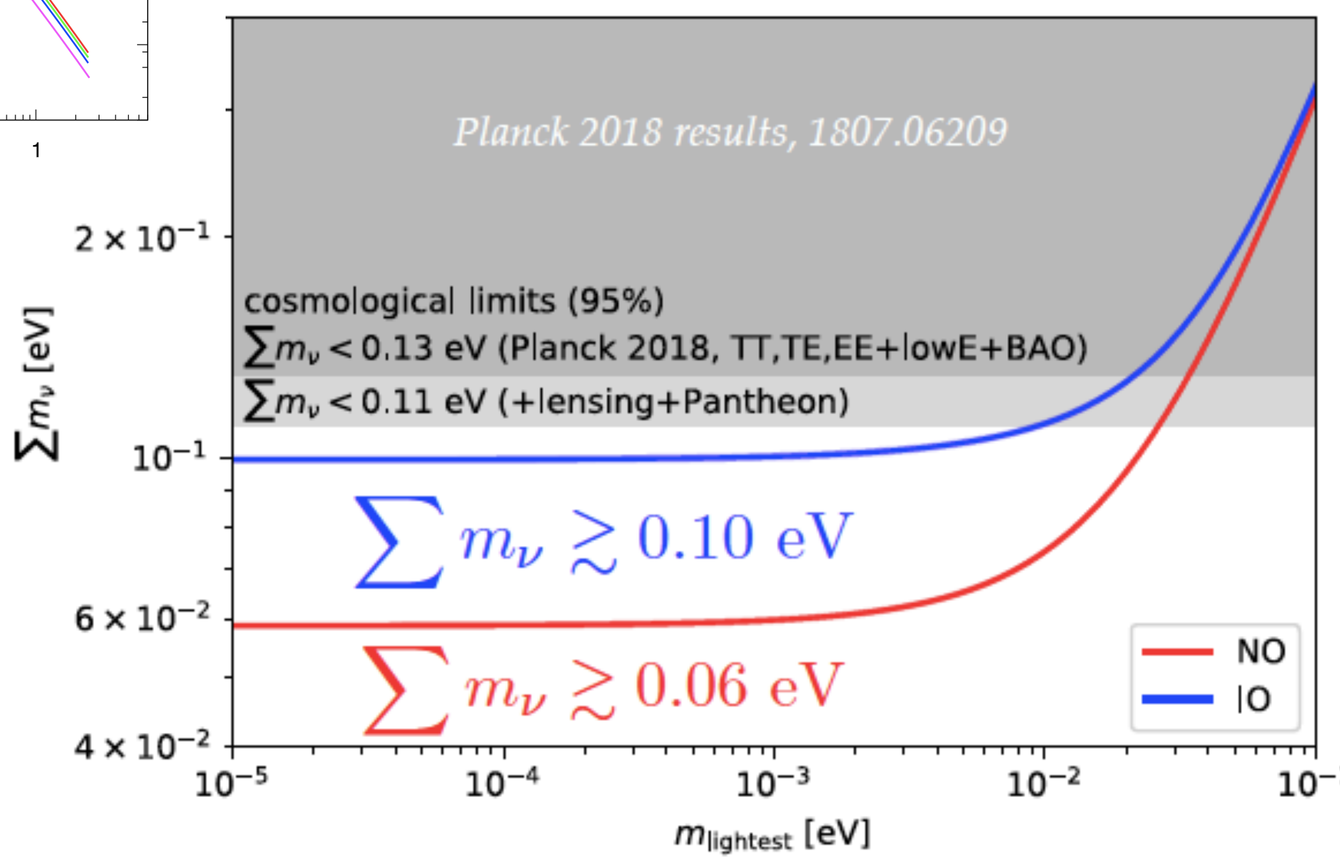


Slide: O. Mena

Σm_ν from large scale structure



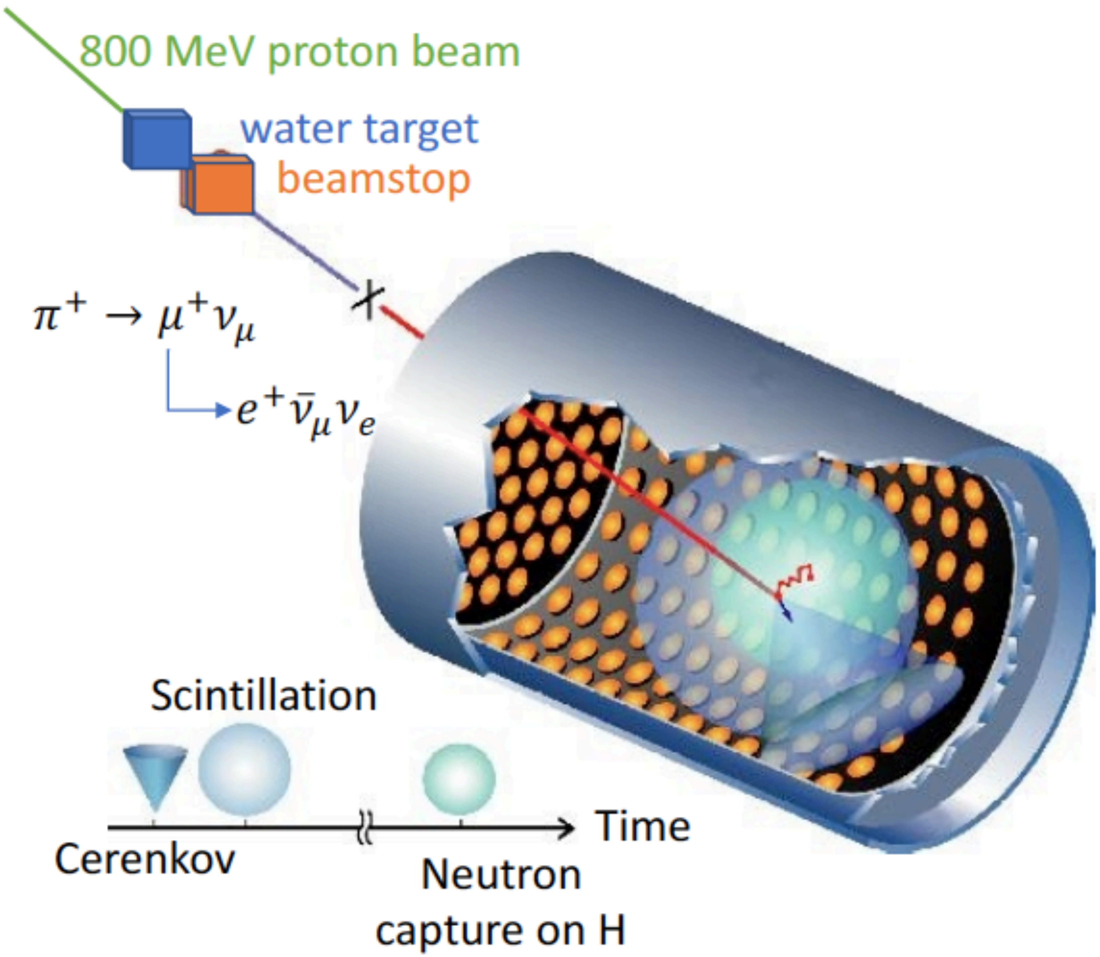
$$\left.\begin{array}{l} N_{eff} = 2.96^{+0.34}_{-0.33}, \\ \sum m_\nu < 0.12\ \text{eV}, \end{array}\right\} \quad \begin{array}{l} 95\%,\ \textit{Planck} \\ \text{TT,TE,EE+lowE+lensing+BAO.} \end{array}$$



From: O. Mena

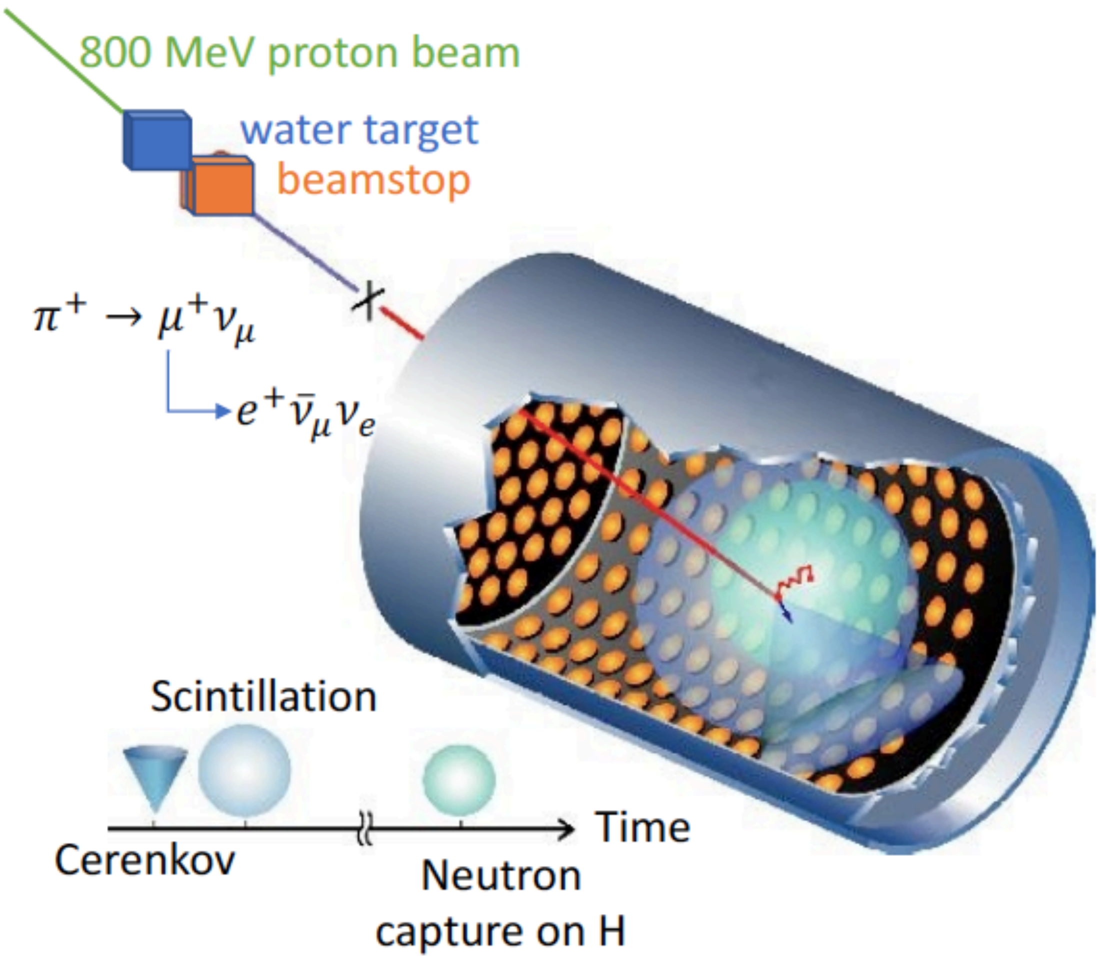
What's wrong with the 3 ν picture?

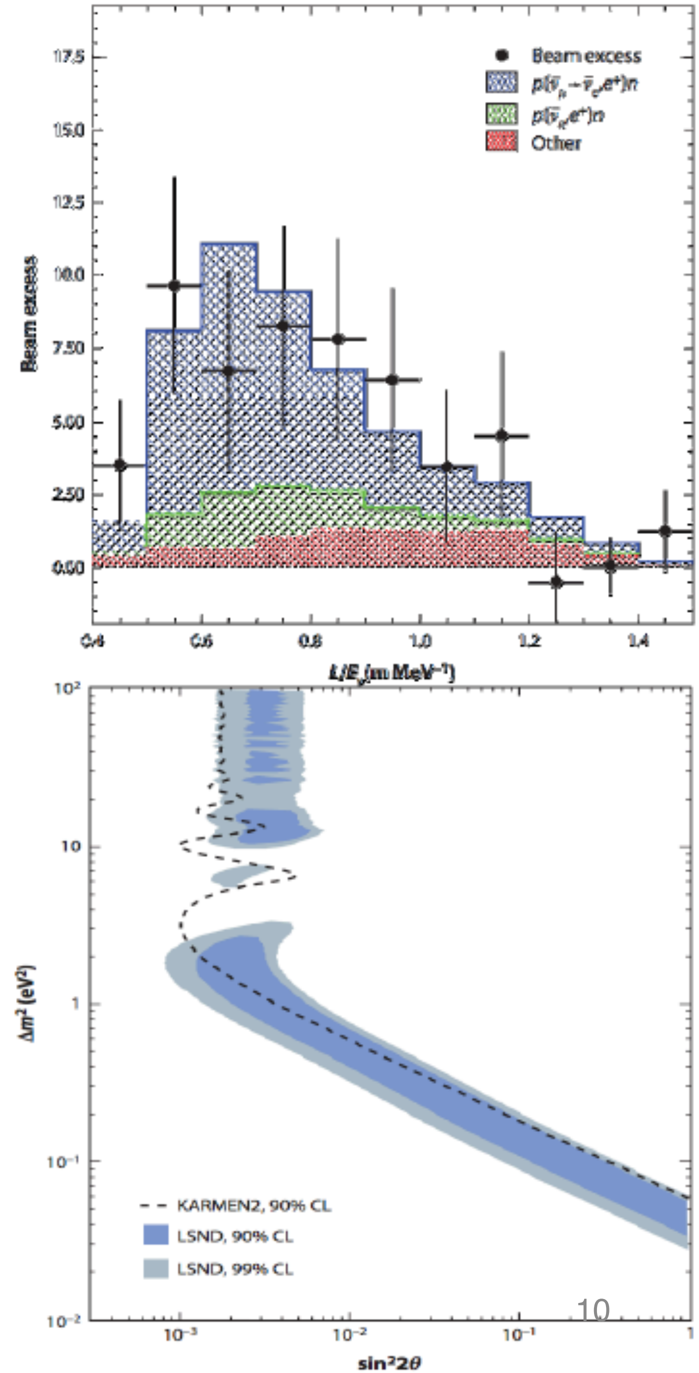
ν_e appearance!
(mediated by ν_s?)



En-Chuan Huang, Neutrino 2018

LSND Anomaly



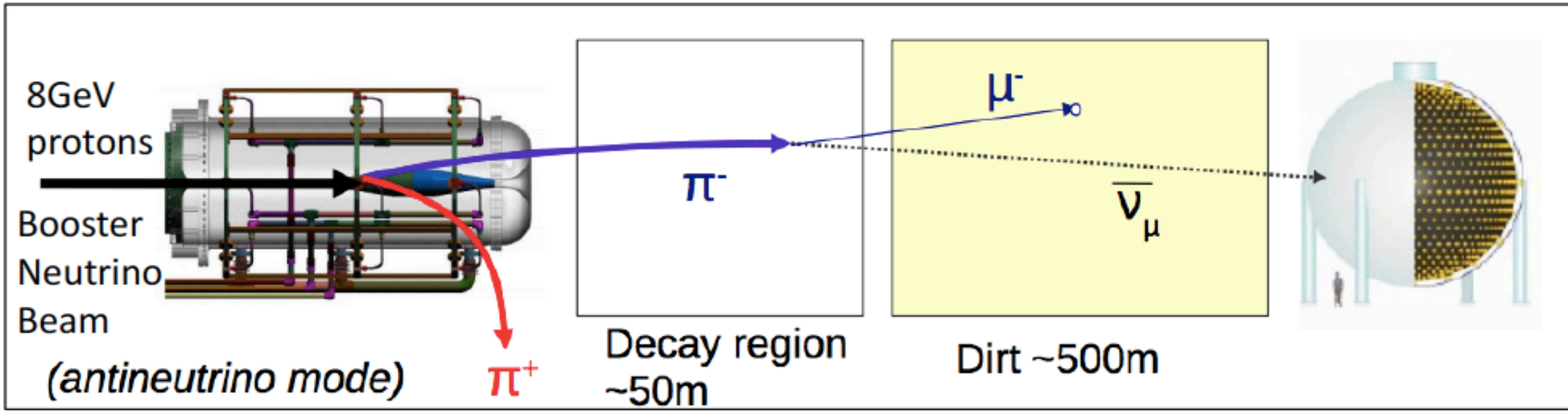


LSND observed a 3.8σ excess

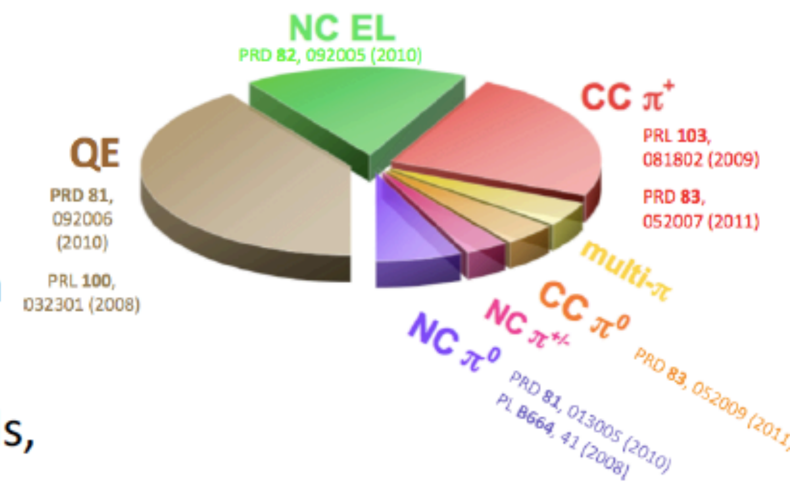
Annu. Rev. Nucl. Part. Sci., *63*(1), 45–67.

En-Chuan Huang, Neutrino 2018

MiniBooNE



- Similar L/E
  - MiniBooNE ~500m/500MeV
  - LSND ~30m/30MeV
- 800-ton mineral oil Cherenkov detector
- Different systematics
  - Different flux, event signatures, and backgrounds from LSND
- Horn polarity determines ν or $\bar{\nu}$ mode
- Flux monitor for short baseline neutrino program (SBN)
- Well-understood detector with 26 publications(4900+ citations) in different channels, as well as recent
  - ν_μ from K^+ decay at rest from NuMI beam
  - Dark matter search



Physicists Say They Have Evidence For A New Fundamental Particle

June 5, 2018 · 5:13 AM ET
Heard on Morning Edition

https://www.npr.org/2018/06/05/616803143/physicists-say-they-have-evidence-for-a-new-fundamental-particle

JOE PALCA

Physicists' understanding of the nature of the universe has taken a blow. An experiment with neutrinos has produced a result that breaks the rules scientists think govern the subatomic world.

The new MiniBooNE result

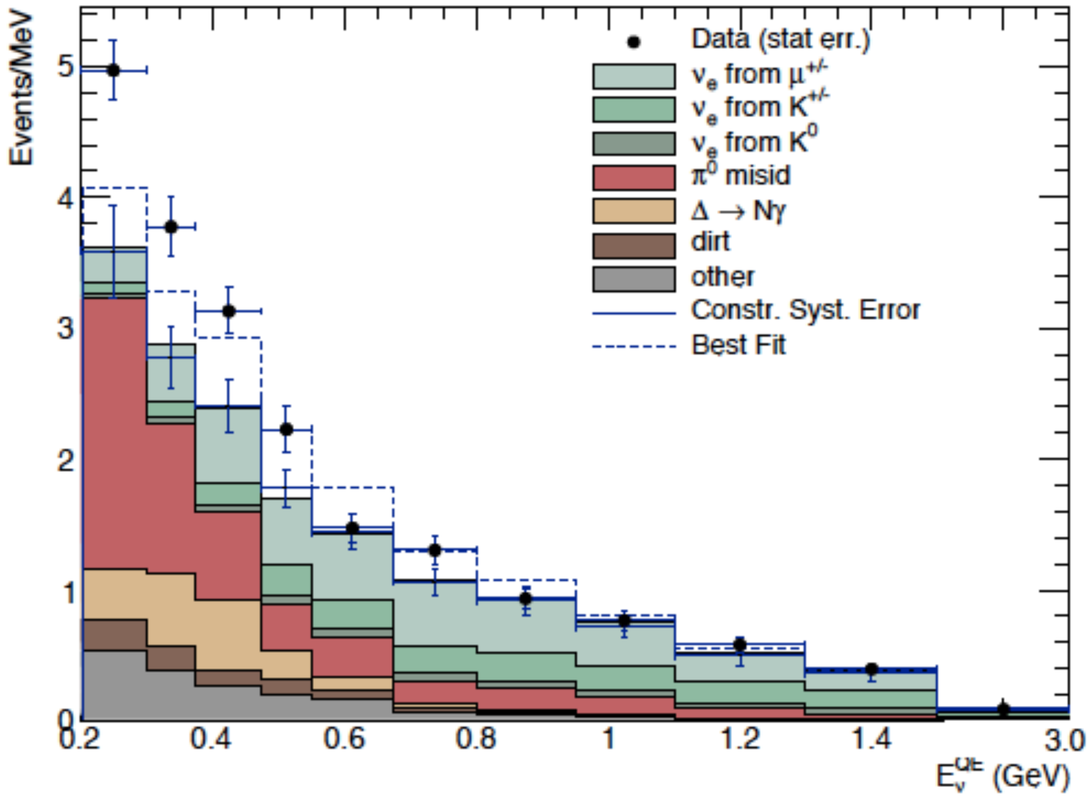


FIG. 1: The MiniBooNE neutrino mode E_ν^{QE} distributions, corresponding to the total 12.84×10^{20} POT data, for ν_e CCQE data (points with statistical errors) and background (histogram with systematic errors). The dashed curve shows the best fit to the neutrino-mode data assuming standard two-neutrino oscillations.

arXiv:1805.12028

Comparison with LSND

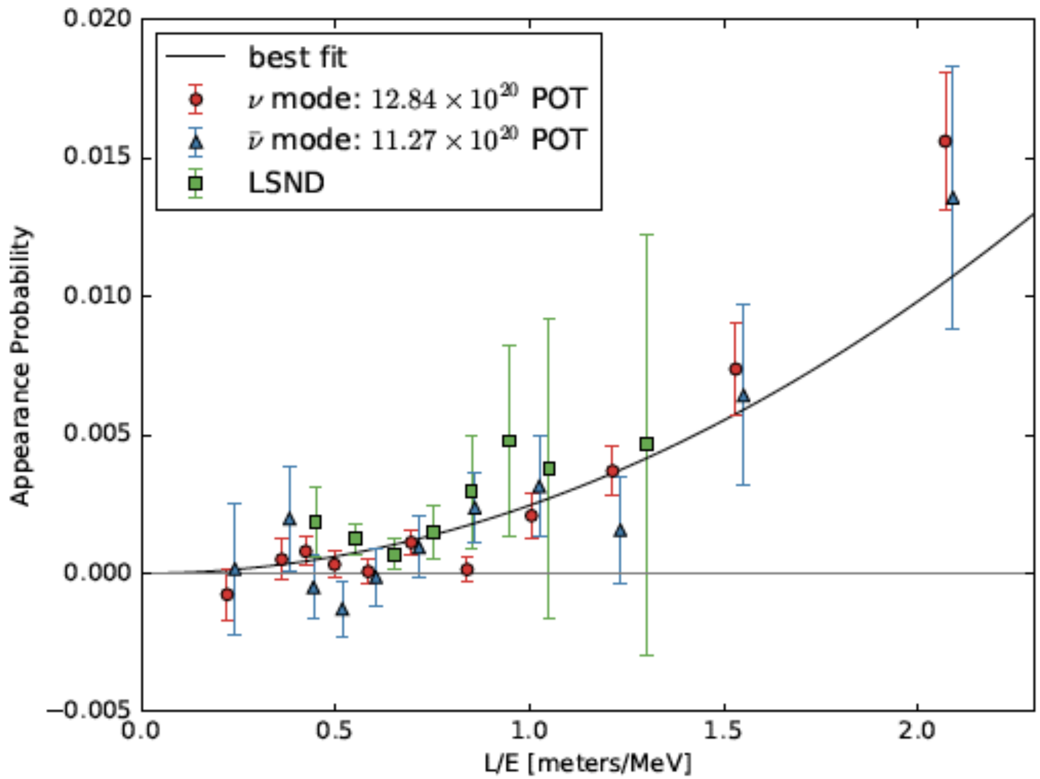
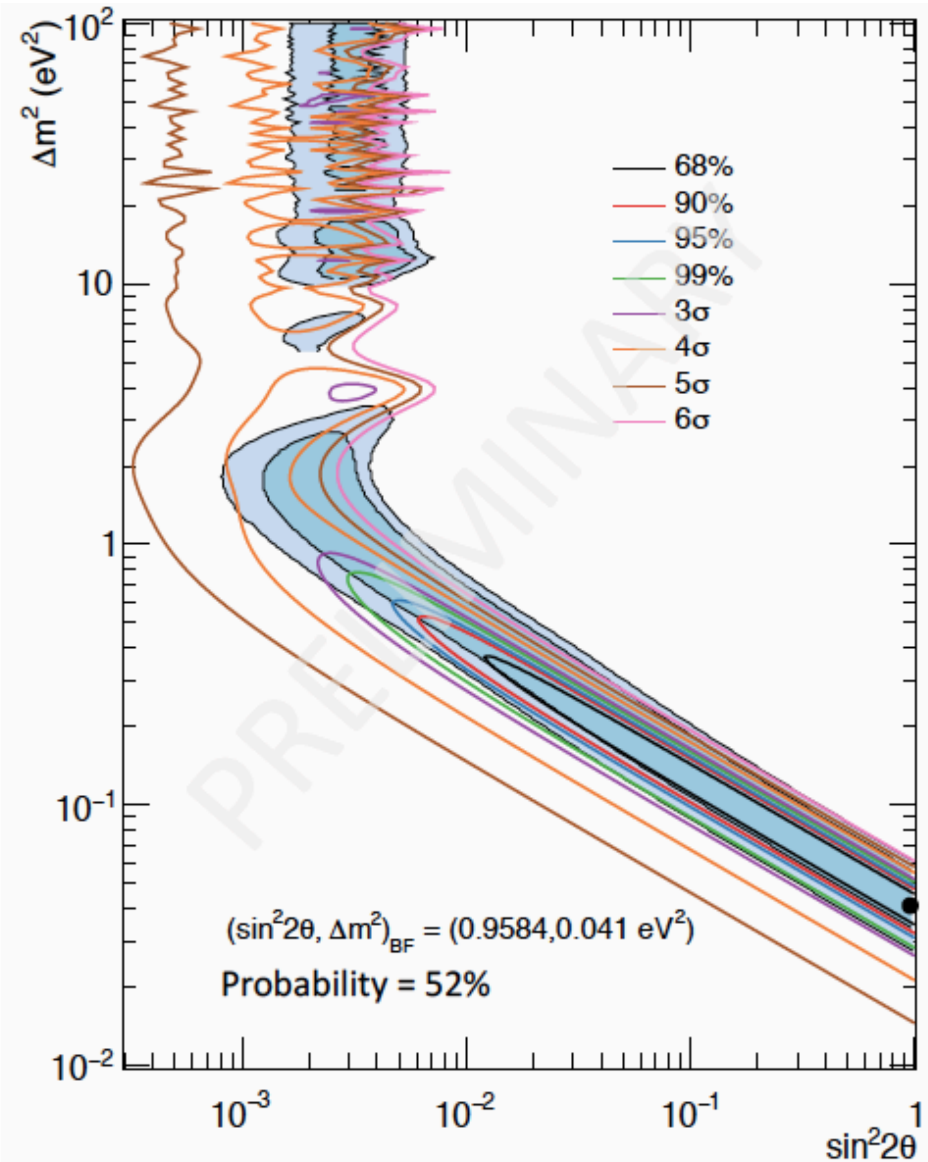


FIG. 3: A comparison between the L/E_ν^{QE} distributions for the MiniBooNE data excesses in neutrino mode (12.84×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) to the L/E distribution from LSND [1]. The error bars show statistical uncertainties only. The solid curve shows the best fit to the LSND and MiniBooNE data assuming standard two-neutrino oscillations. The excess of MiniBooNE electron-neutrino candidate events is consistent with the LSND excess.

arXiv:1805.12028

Combination with LSND



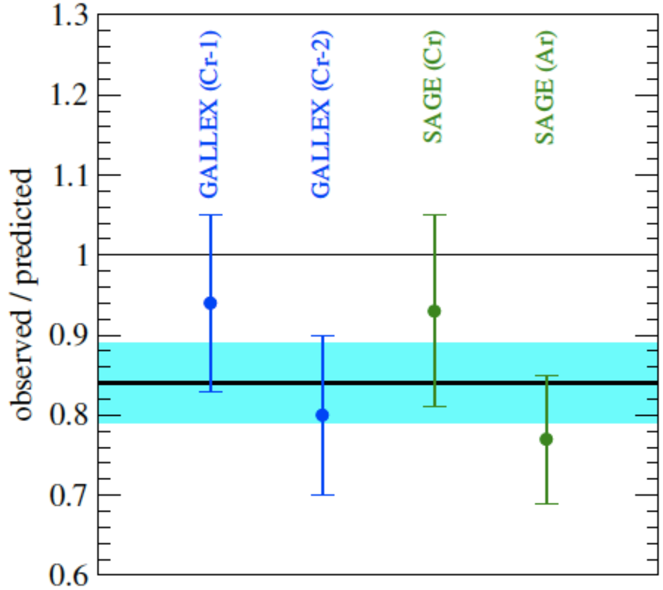
Combine MiniBooNE with LSND to achieve claimed 6σ fit:

- Assumes no correlation between the two experiments.
- Consistent best fit results.

More to come from the SBN progam at Fermilab!

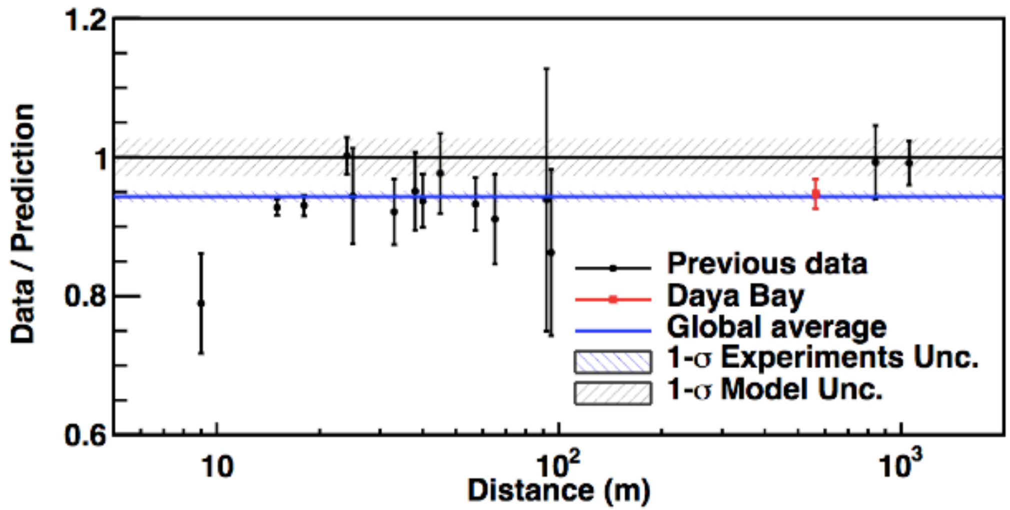
En-Chuan Huang, Neutrino 2018

Ga and reactor anomalies

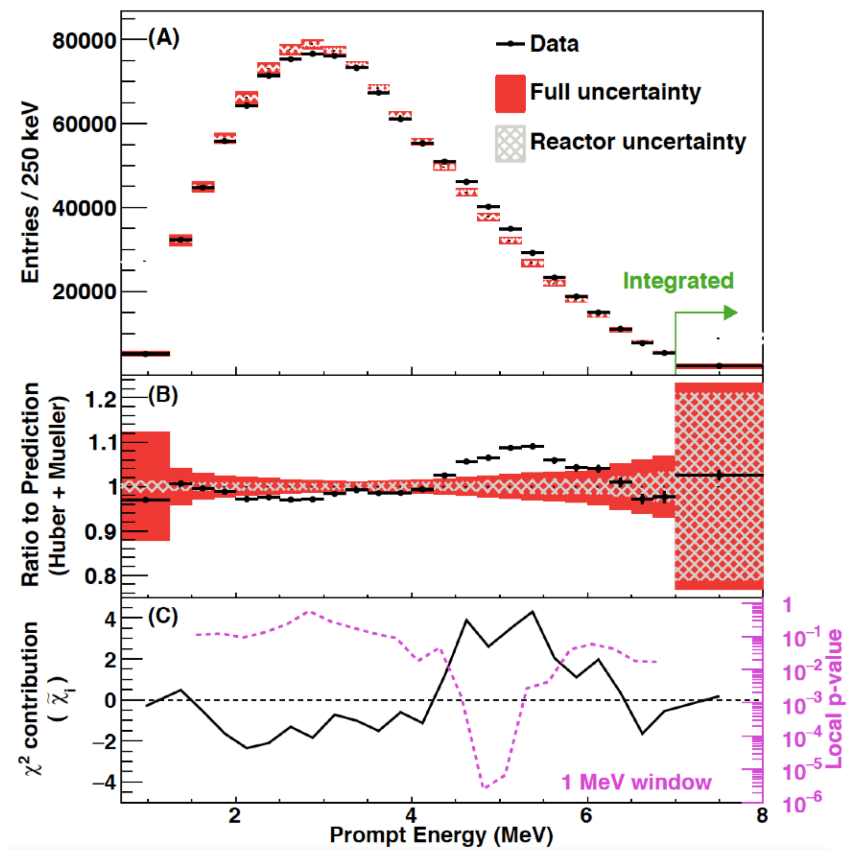


Ga anomaly

ν_e disappearance!
(ν_s appearance?)



Reactor flux anomaly

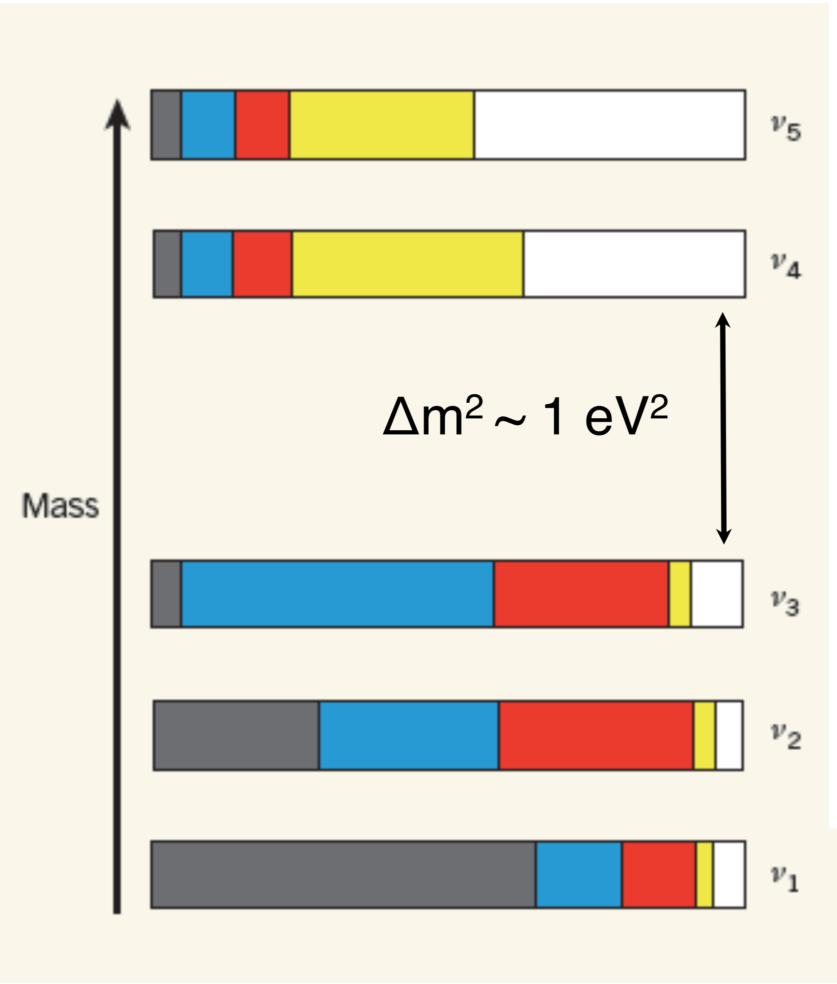


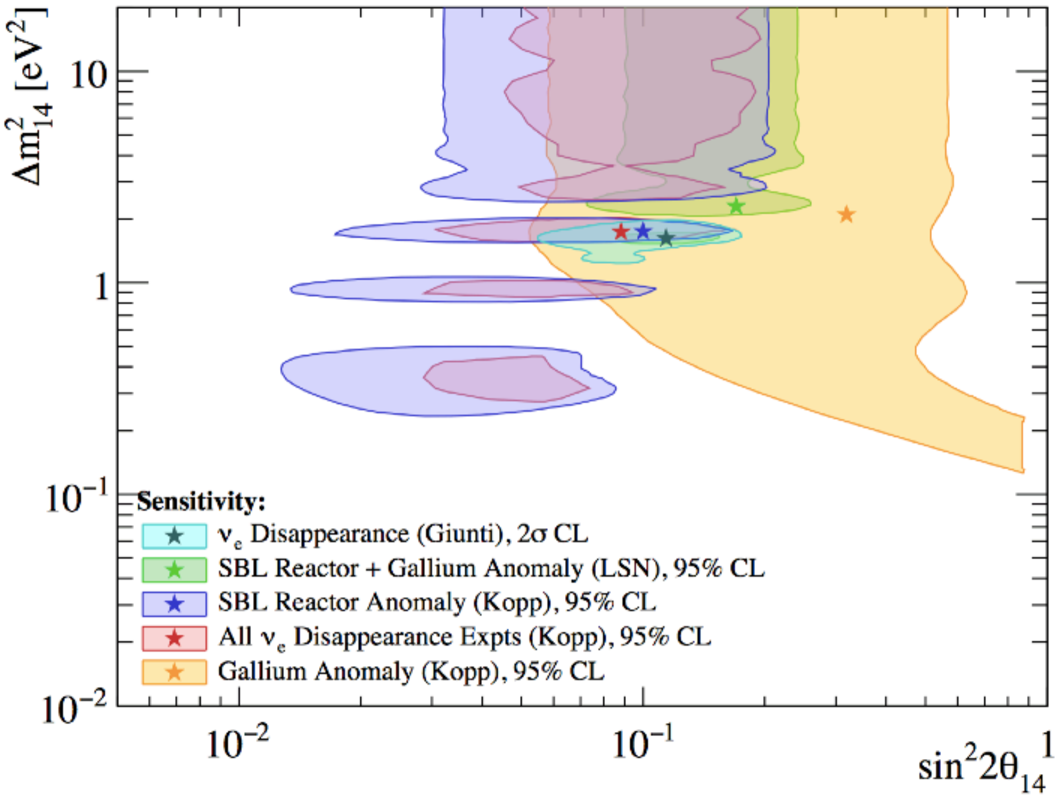
Reactor spectrum anomaly

Daya Bay, *CPC* **41**, 1 (2017)

Sterile neutrinos

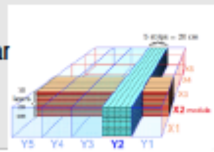
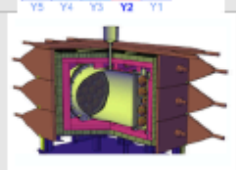
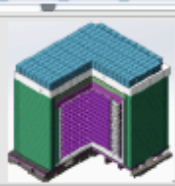
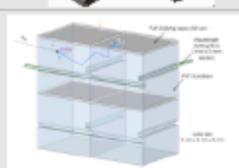
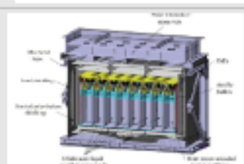
What does the hypothesis of 4th (or 5th, 6th, 7th…) “sterile” neutrino imply? Doesn’t couple to the SM W or Z boson…





PROSPECT, *J Phys G* **43** (2016)

How do we test the reactor anomaly?

Experiment		Reactor/Fuel	Baseline (m)	Mobility	Detection Material	Segmentation	Readout	Energy Resolution	PID
DANSS Kalinin nuclear reactor (Russia)		3000 MWth LEU	10.7-12.7	Yes	PS+Gd Sheets	2D, 5mm	WLS fibers + SiPM and PMT	25%/√E	Topology
NEOS Hanbit nuclear power complex (Korea)		2800 MWth LEU	~24	No	GdLS	-	PMT Double-ended	5% @ 1MeV	Recoil PSD
Neutrino-4 SM-3 reactor (Russia)		100 MWth HEU	6-12	Yes	GdLS	2D, 10 cm	PMT Single-ended	Not available	Topology
PROSPECT High Flux Isotope Reactor (USA)		**85 MWth HEU**	**7-12**	**Yes**	**^{6}LiLS**	**2D, 14.6 cm**	**PMT Double-ended**	**4.5%/√E**	**Topology + recoil and capture PSD**
Solið BR2 research reactor (Belgium)		40-80 MWth HEU	6-9	No	PVT cubes+ ^{6}Li:ZnS(Ag) sheets	3D, 5 cm	WLS fibers + SiPM	20%/√E	Topology + capture PSD
STEREO ILL research reactor (France)		58 MWth HEU	9-11	No	GdLS	2D, 25 cm	PMT Single-ended	12% @ 2 MeV	Recoil PSD

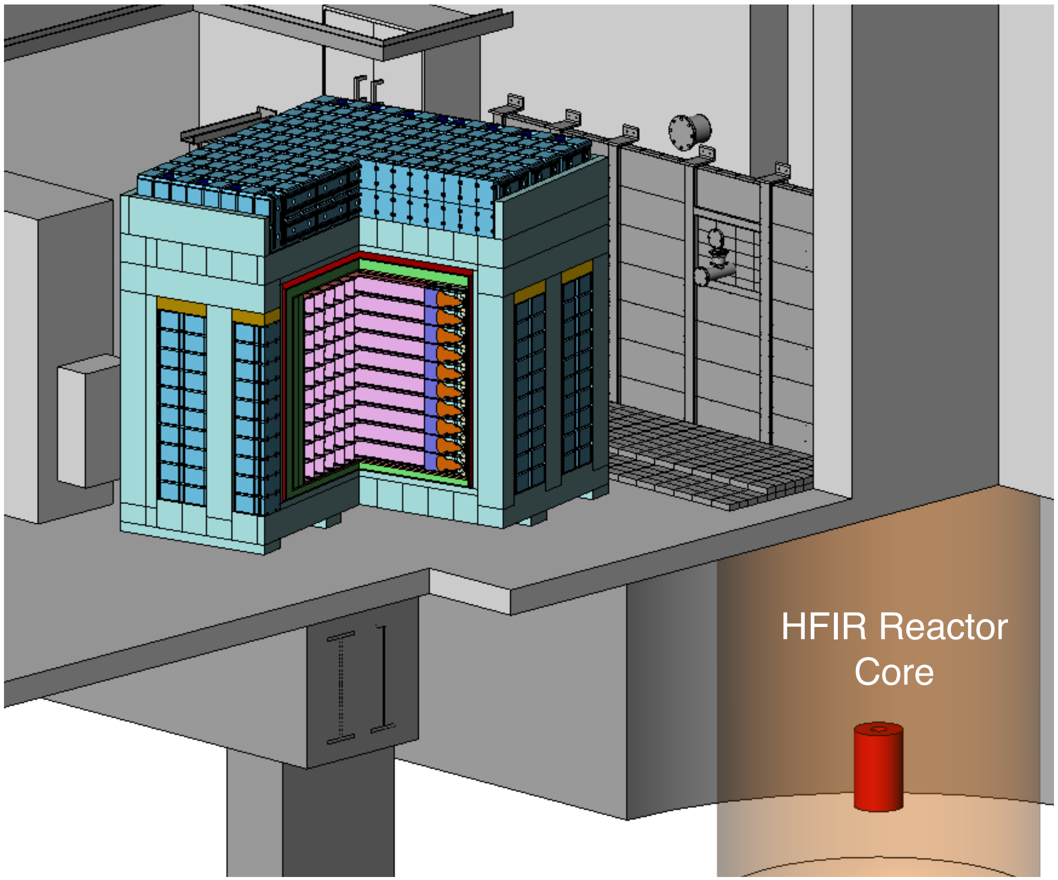
Some values from Mauro Mezzetto,

*Neutrino-4 claim: Physics of Atomic Nuclei volume 83, 930–936 (2020)

PRecision Oscillation and SPECTrum experiment

Physics objectives:

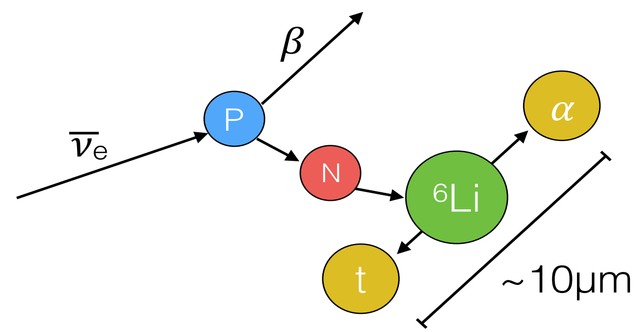
- Precision measurement of ^{235}U energy spectrum
- Search for eV-scale sterile neutrinos via oscillations at short baselines



PROSPECT, *NIM* A 922 (2018) 287

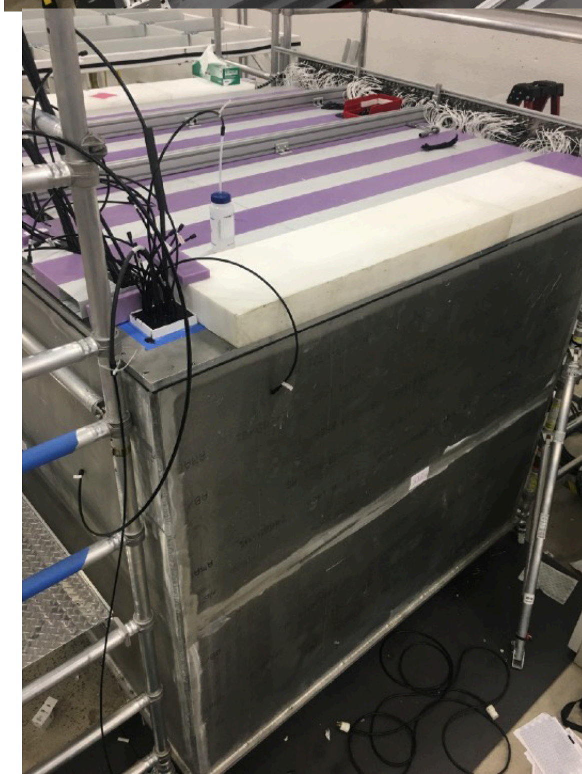
Design:

- 4-ton ^{6}Li-loaded liquid scintillator optically segmented detector.

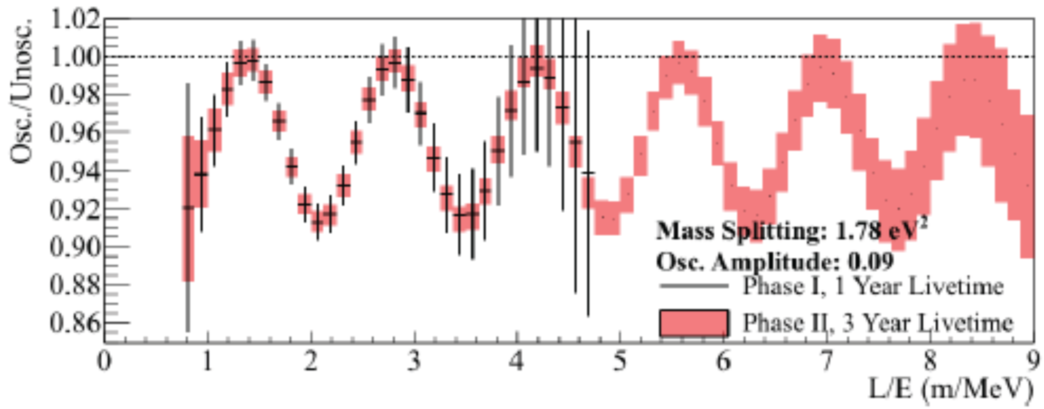


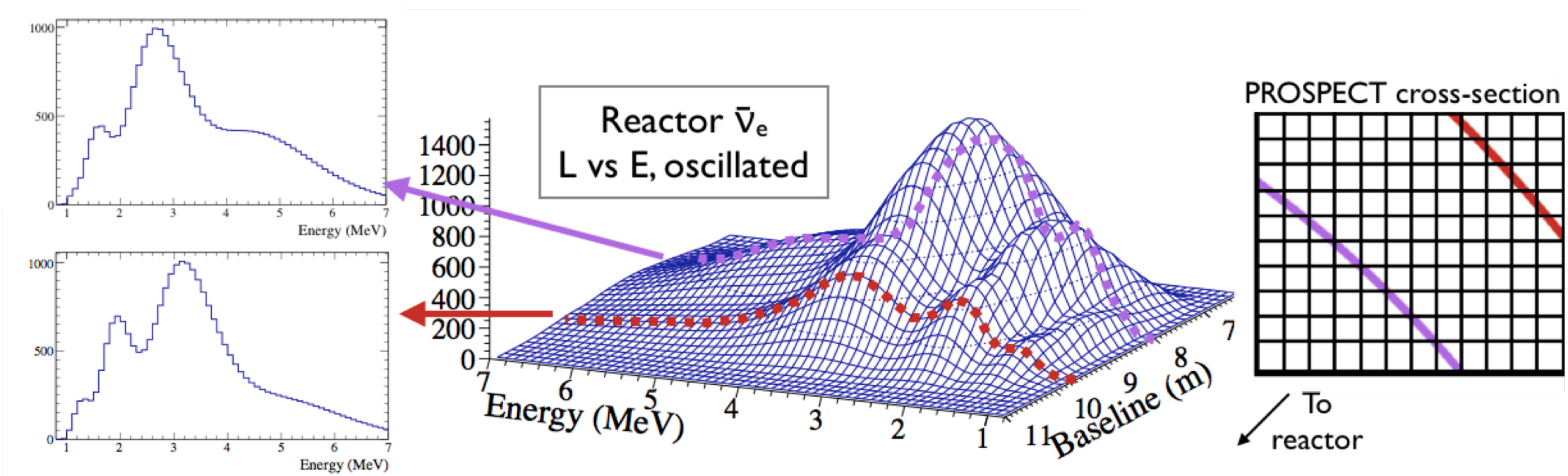
- Measures inverse beta decay event rate and energy spectrum at baselines of 7 – 12 m from HFIR reactor.



Sterile neutrino search





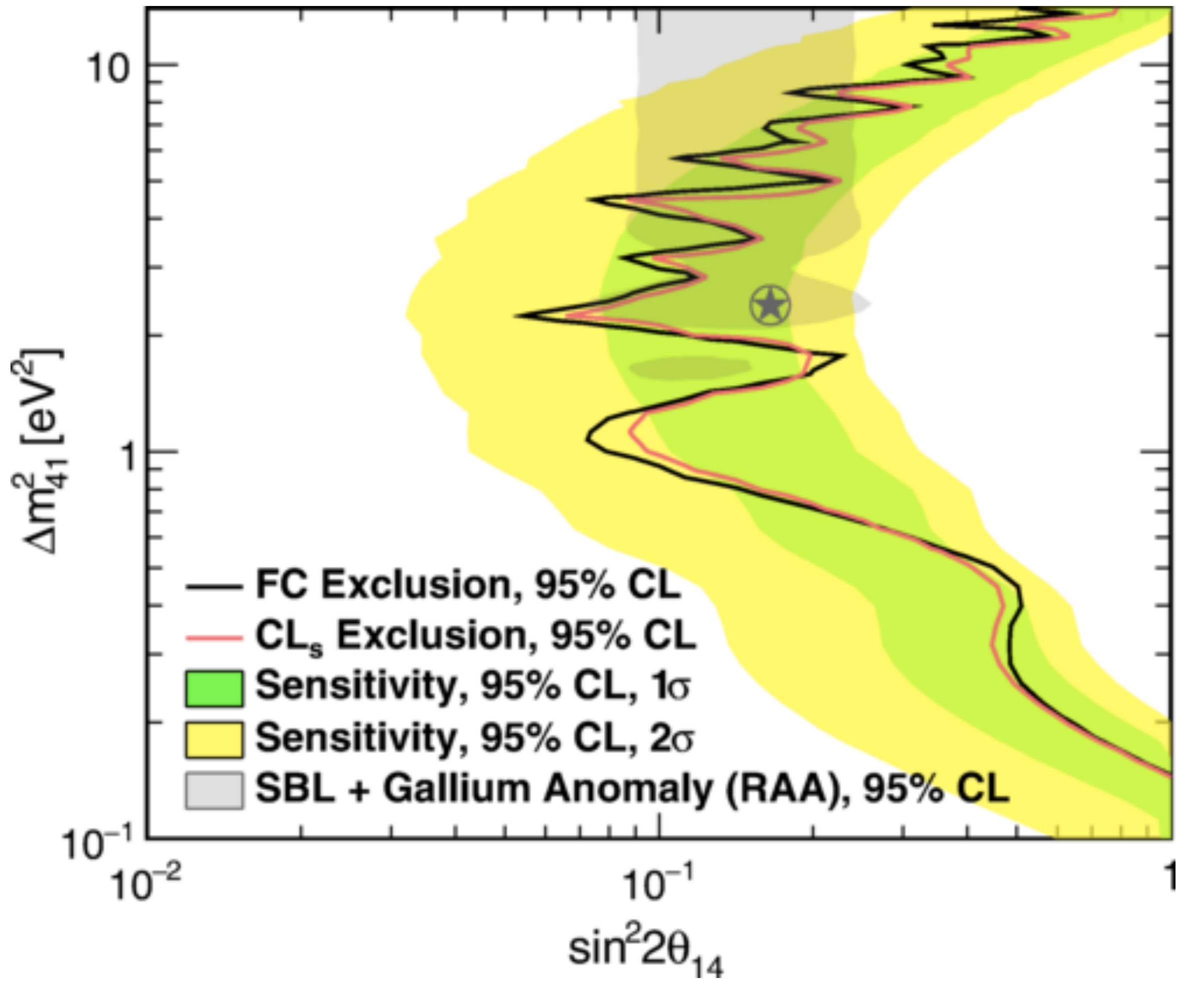
Relative measurement between 154 detector segments – no spectrum dependence.

Sterile neutrino search

PROSPECT operated at HFIR from March to October 2018.

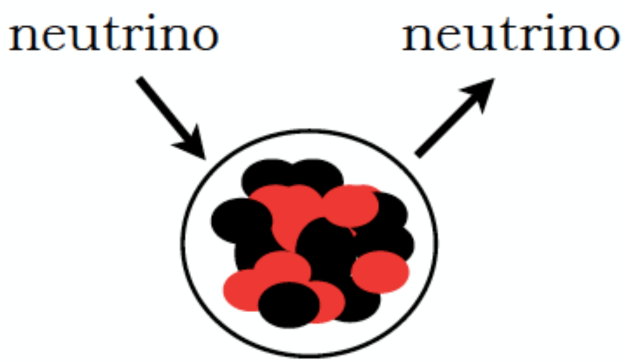
- 96 calendar days of data
- observed more than 50,000 ν_e interactions
- Excludes RAA best-fit point (and Neutrino-4) at >95% C.L.

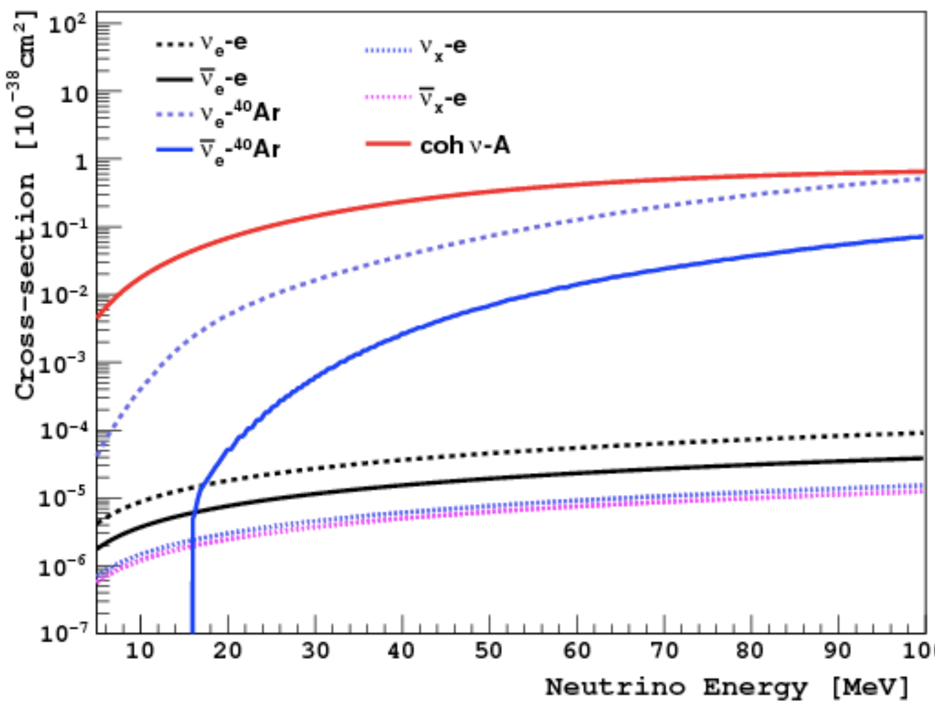
Similar exclusions by other short baseline reactor experiments!



Phys. Rev. D 103, 032001

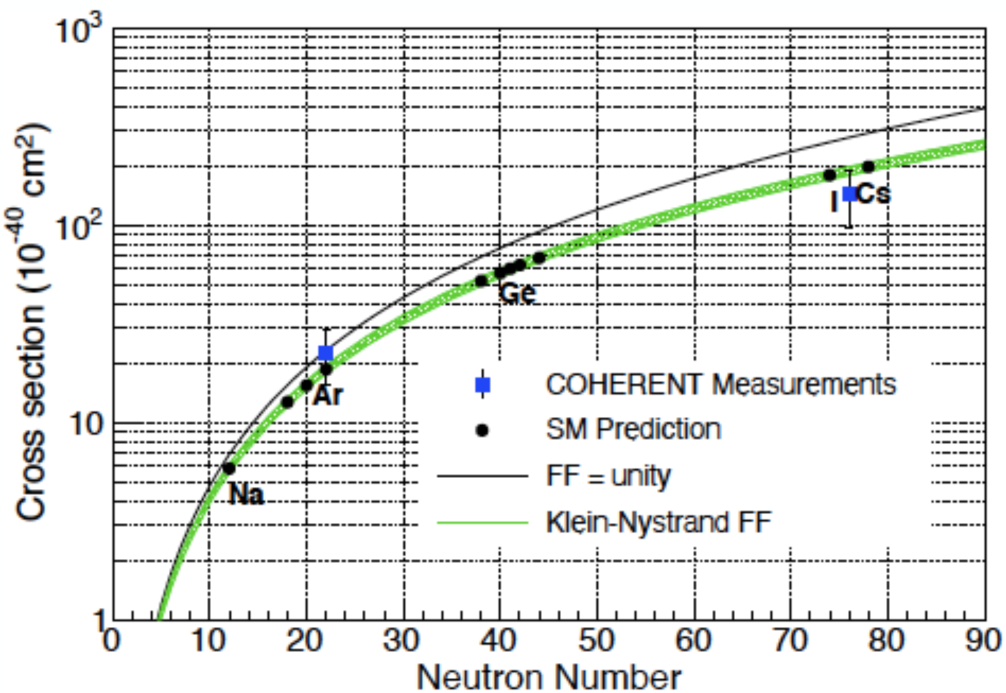
CEνNS





- Neutral current interaction
- Total scattering amplitude sum of that on constituent nucleons
- Small momentum transfer relative to target size -> coherent enhancement
- Low energy recoil distribution -> difficult to detect

COHERENT and other searches



COHERENT collaboration first detection at the SNS, pulsed source. *Science 15 Sep 2017: Vol. 357, Issue 6356, pp. 1123-1126*

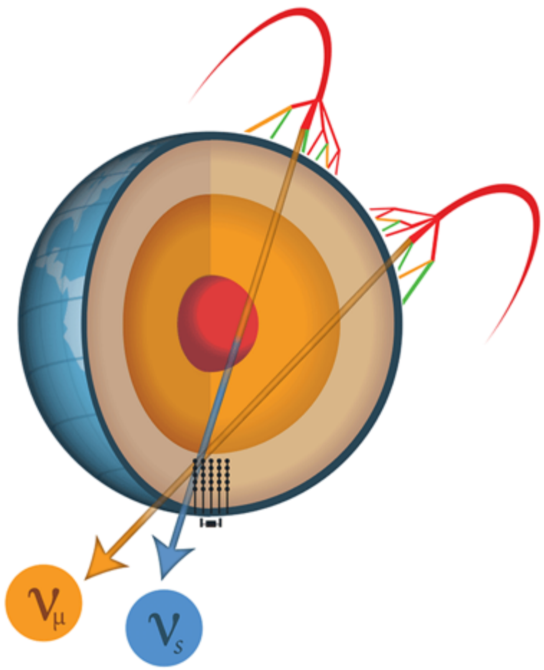
Lots of future experiments planned, including search for coherent scattering of solar neutrinos and reactor neutrinos!

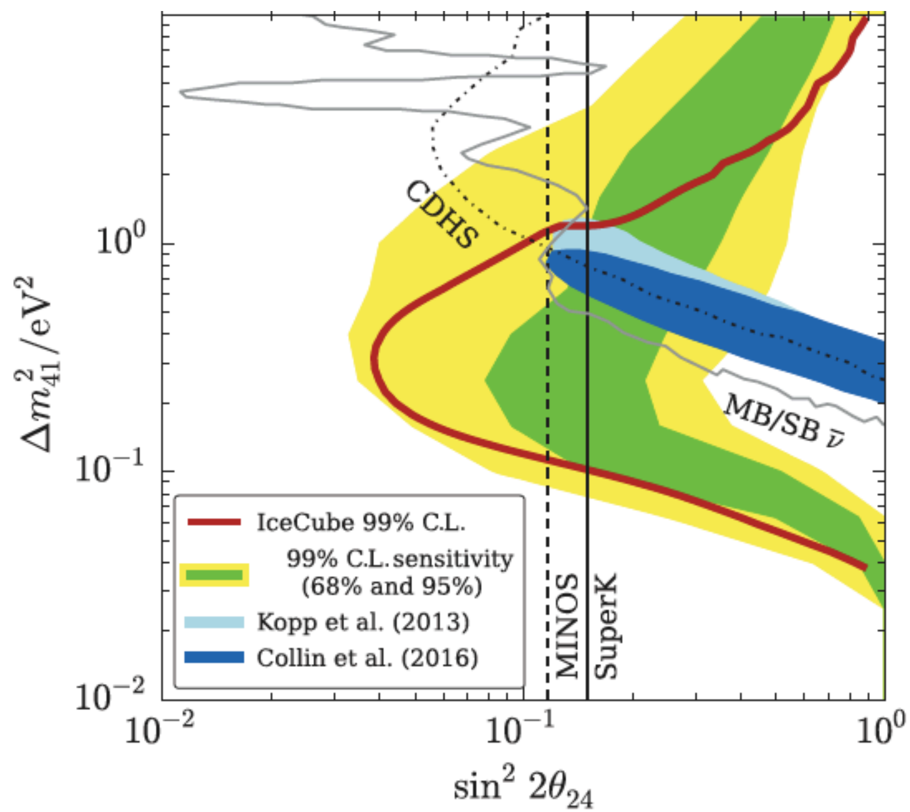
ν_μ disappearance

(3+1): $P_{\nu_\mu\to\nu_e} \propto |U_{e4}U_{\mu4}|^2$ with $\begin{cases} |U_{e4}|^2 \propto P_{\nu_e\to\nu_e}\,, \\ |U_{\mu4}|^2 \propto P_{\nu_\mu\to\nu_\mu}\,; \end{cases}$

We don't see it!

hence, $P_{\nu_\mu\to\nu_e} > 0$ requires $\begin{cases} P_{\nu_e\to\nu_e} > 0\,, \\ P_{\nu_\mu\to\nu_\mu} > 0\,; \end{cases}$





IceCube Collaboration, *PRL* **117**, 071801 (2016)

Physics Today 69, 10, 15 (2016); https://doi.org/10.1063/PT.3.3316

Sterile neutrinos give IceCube and other experiments the cold shoulder

Recent null results heighten the tension between the bulk of neutrino experiments and the few that hint at the putative particle's existence.

Under kilometers of ice at the South Pole, the IceCube Neutrino Observatory's 5160 optical detectors keep watch for neutrinos that have traveled through Earth from the opposite side of the globe. (See the article by Francis Halzen and Spencer R. Klein, PHYSICS TODAY, May 2008, page 29.) The observatory was built primarily to serve as a telescope to study neutrinos from astrophysical sources. However, it also detects neutrinos born in the aftermath of cosmic-ray protons crashing into nuclei in the upper atmosphere. About once every six minutes, one of those atmospheric neutrinos finds its way to IceCube's monitoring zone, collides with a nucleus in the ice or bedrock, and produces a charged particle that can be detected from the Cherenkov light it gives off. Figure 1 shows the IceCube Laboratory, which houses the computers that

reactor-neutrino experiment in France,

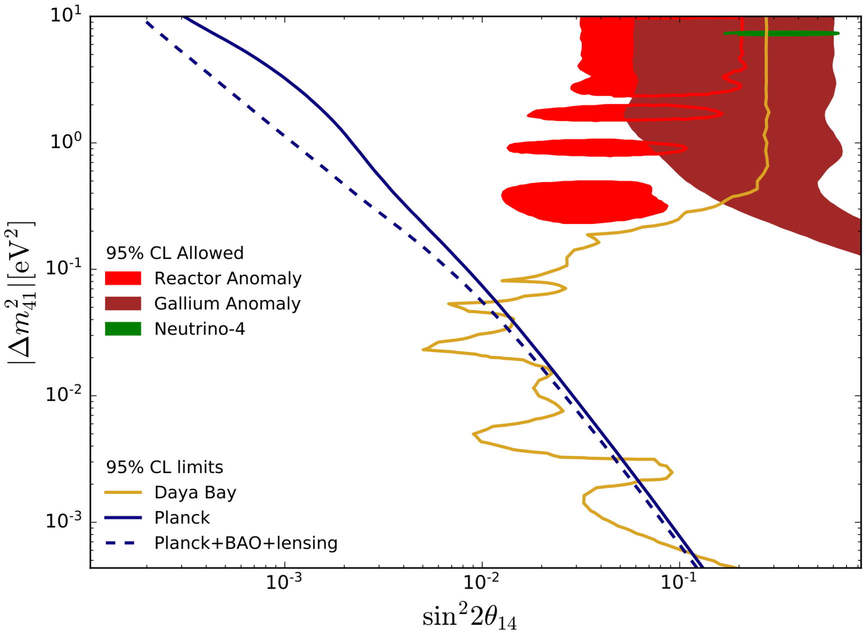
FIGURE 1. THE ICECUBE LABORATORY

Adding in cosmology…

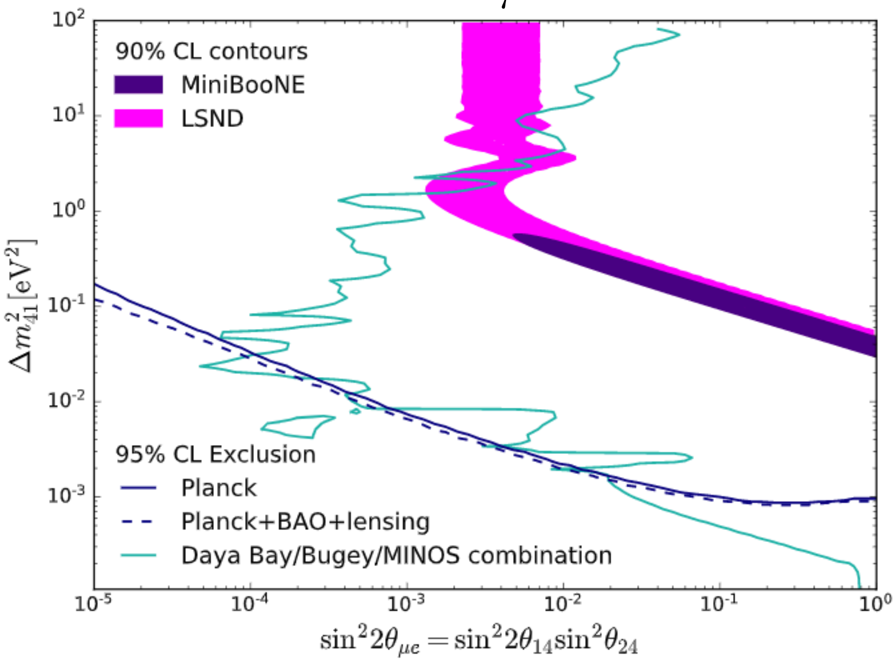
"Cosmological and particle physics searches for sterile neutrinos can be compared in the same parameter space."

(but of course this is model dependent…)

$\overline{\nu_e}$ disappearance, 1+1 model



3+1 model for $\nu_\mu \rightarrow \nu_e$ analysis

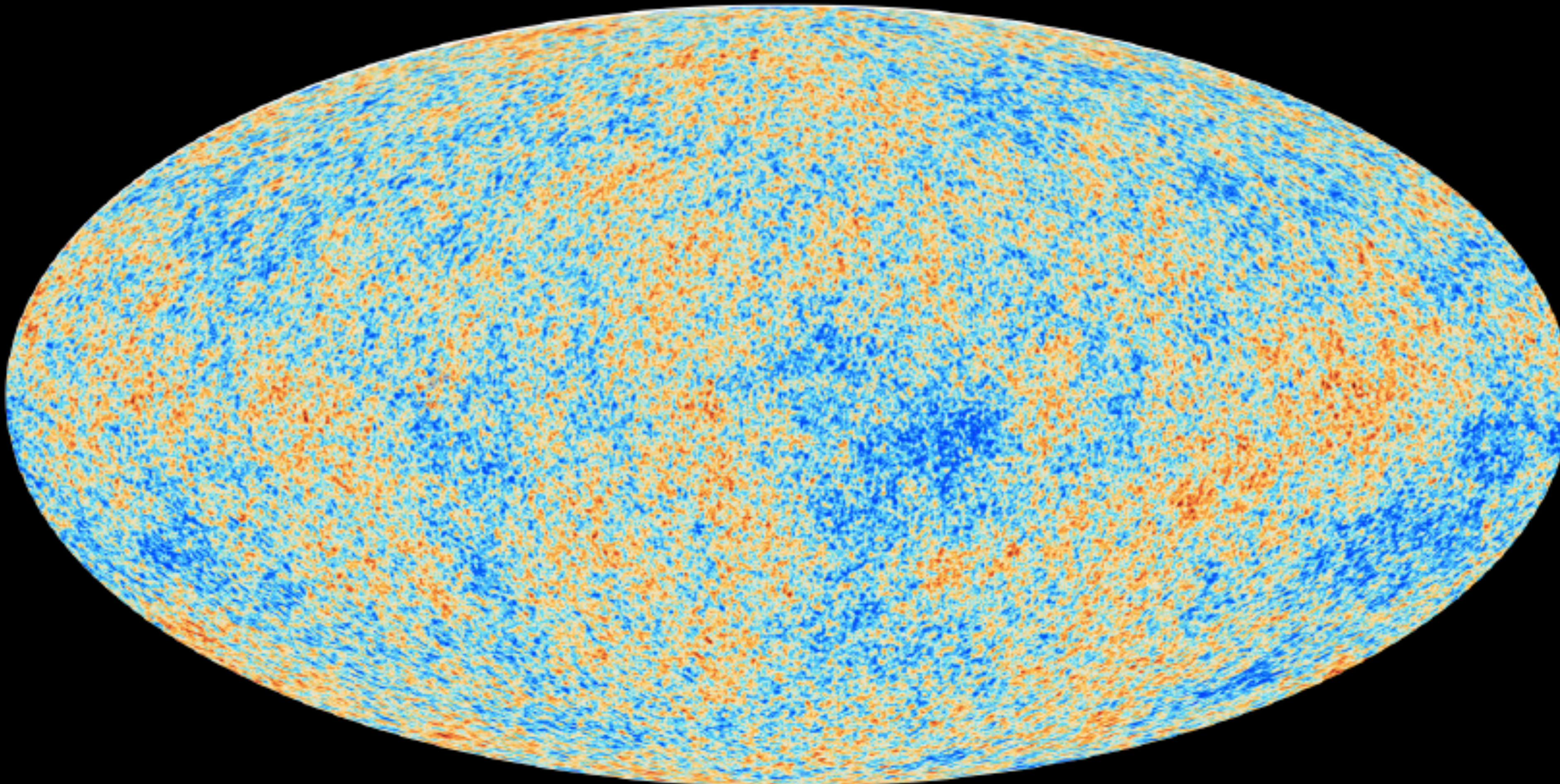


https://inspirehep.net/literature/1781295

Multi-messenger astronomy with neutrinos

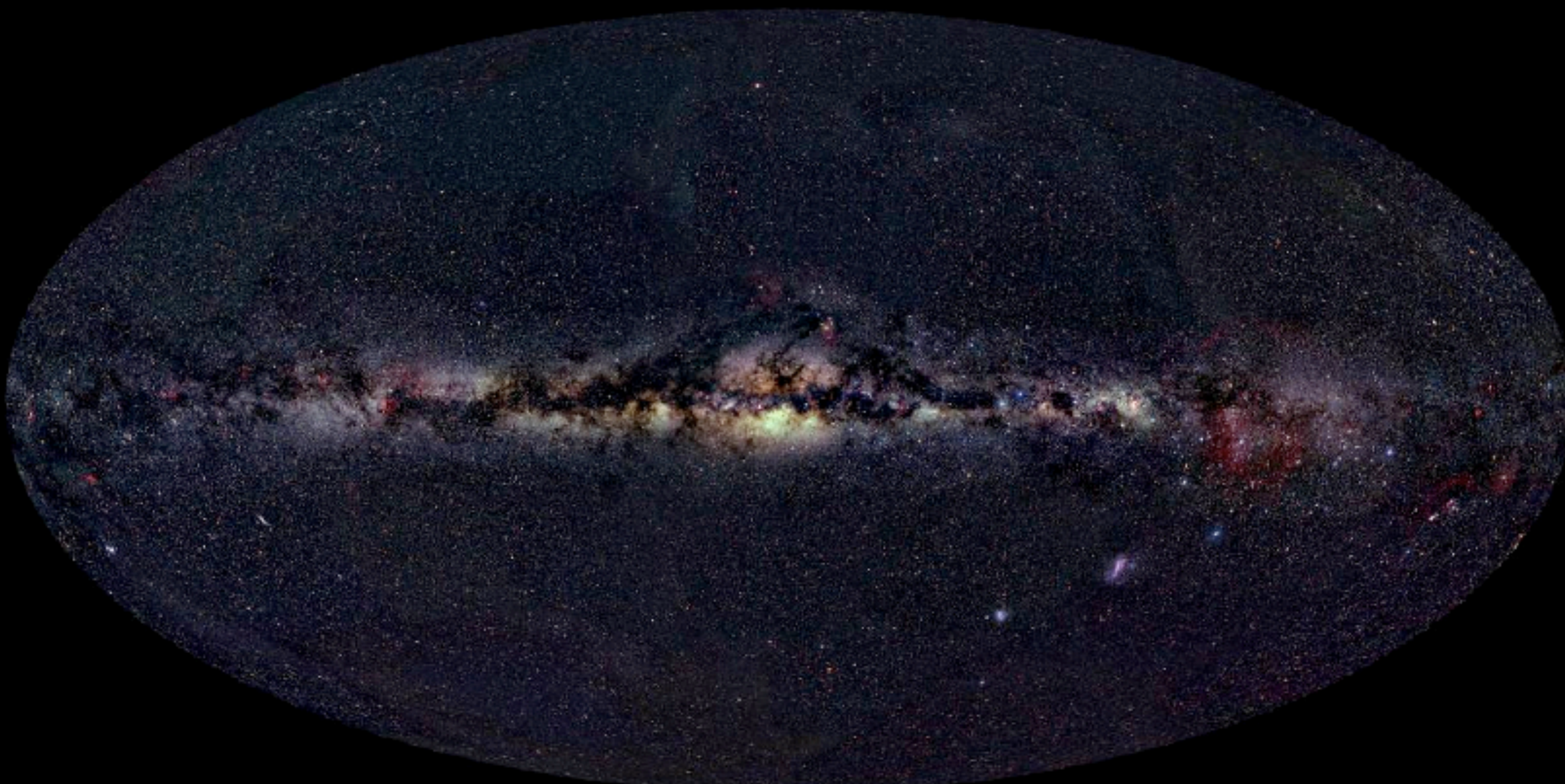
Slides stolen from Francis Halzen

Cosmic Horizons – Microwave Radiation
380.000 years after the Big Bang



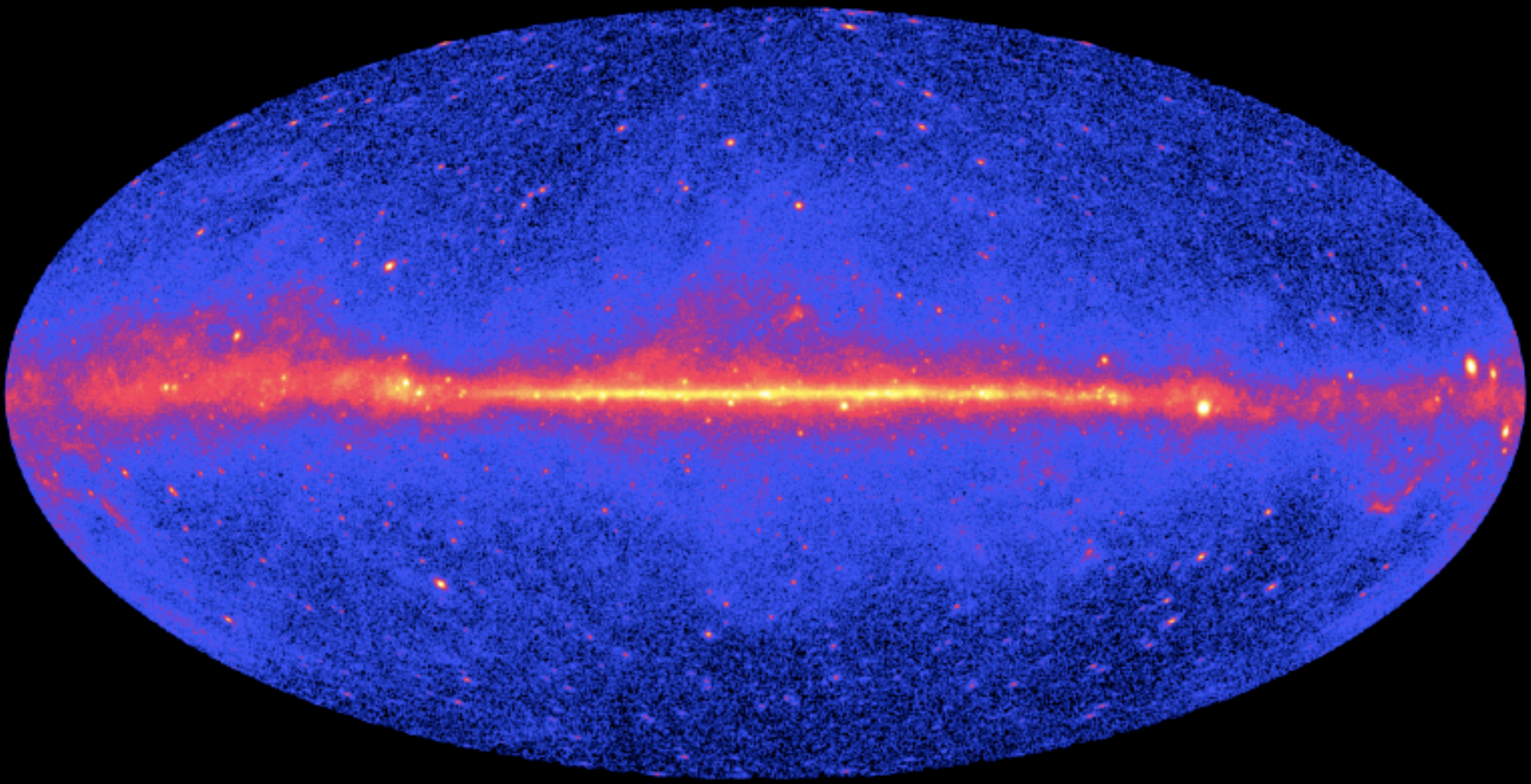
wavelength = 1 mm ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



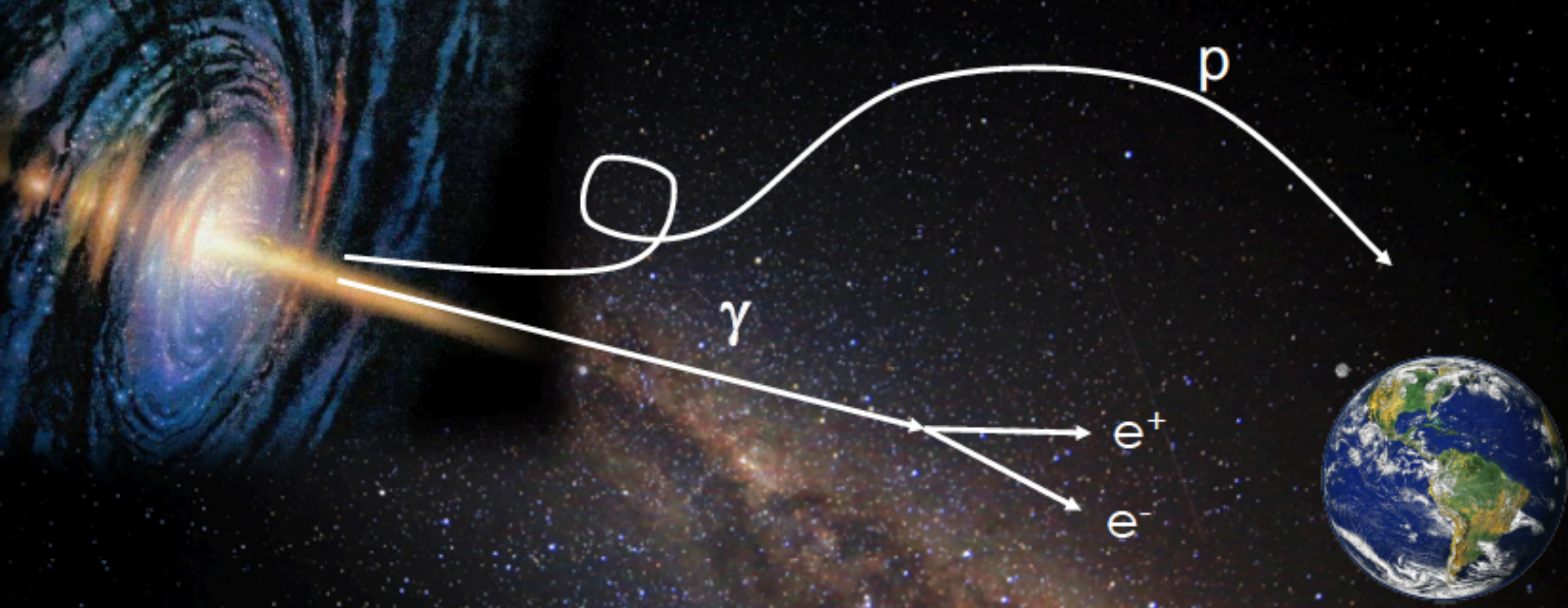
wavelength = 10^{-6} m $\Leftrightarrow$ energy = 1 eV

Cosmic Horizons – Gamma Radiation



wavelength = 10^{-15} m $\Leftrightarrow$ energy = 10^{9} eV

The opaque Universe

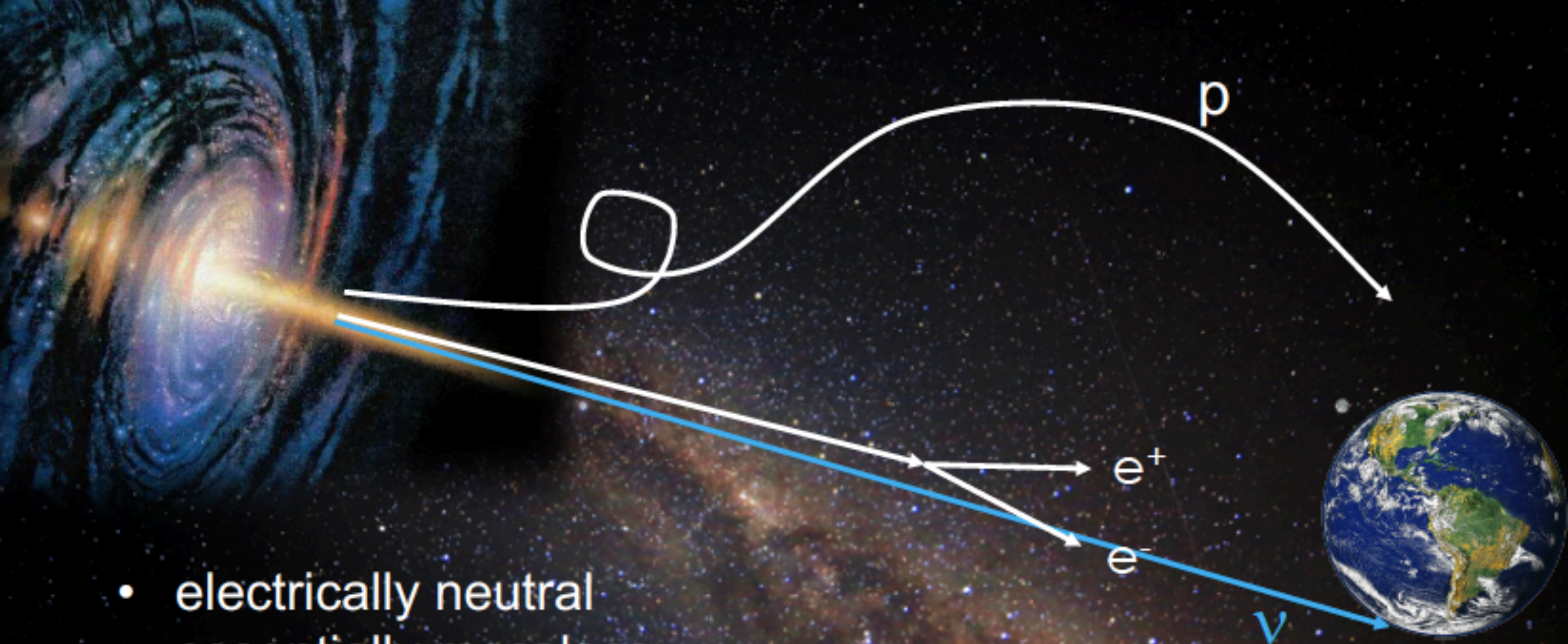


$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes

enter: neutrinos

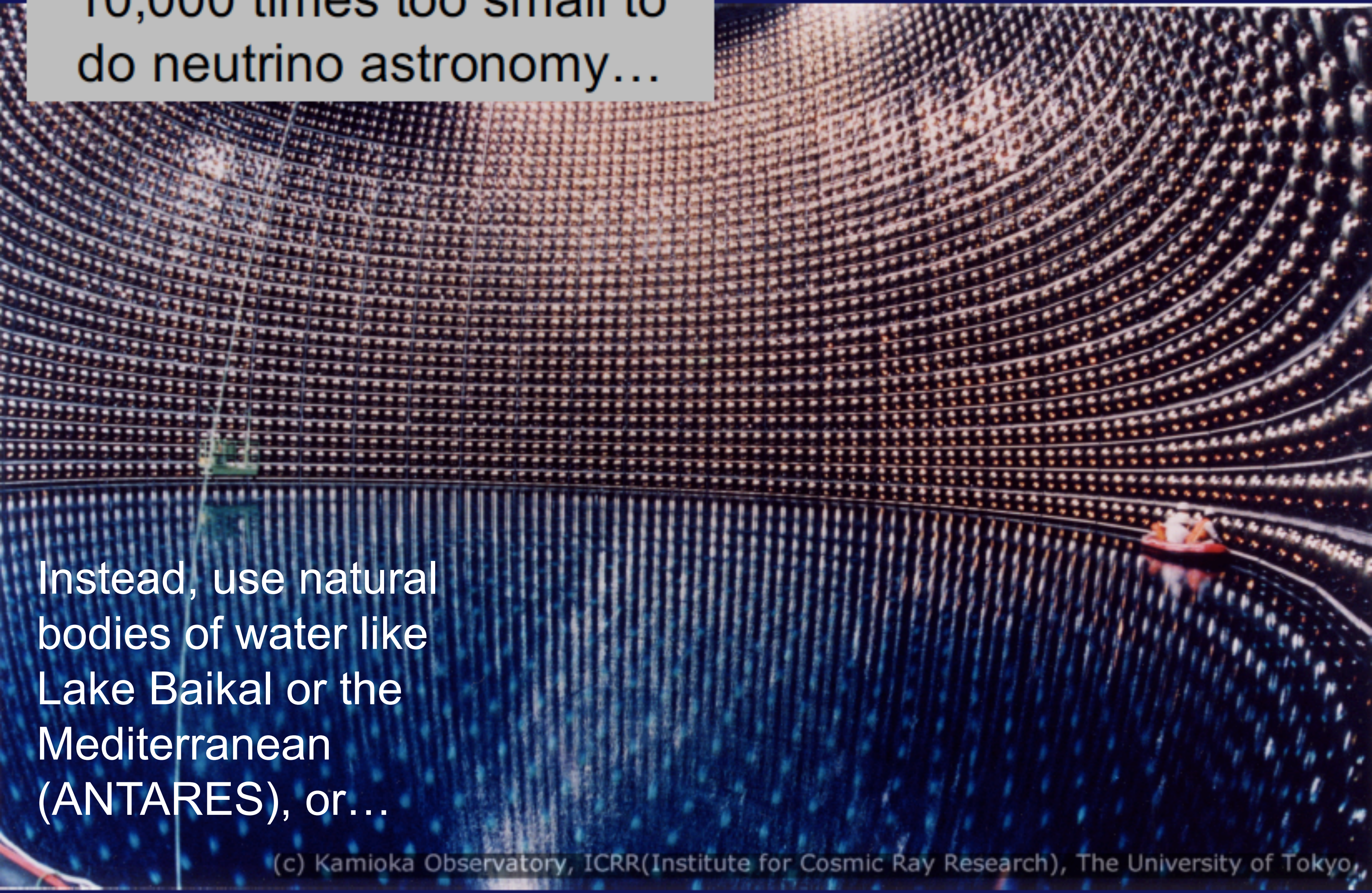
Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect: how large a detector?

10,000 times too small to do neutrino astronomy…



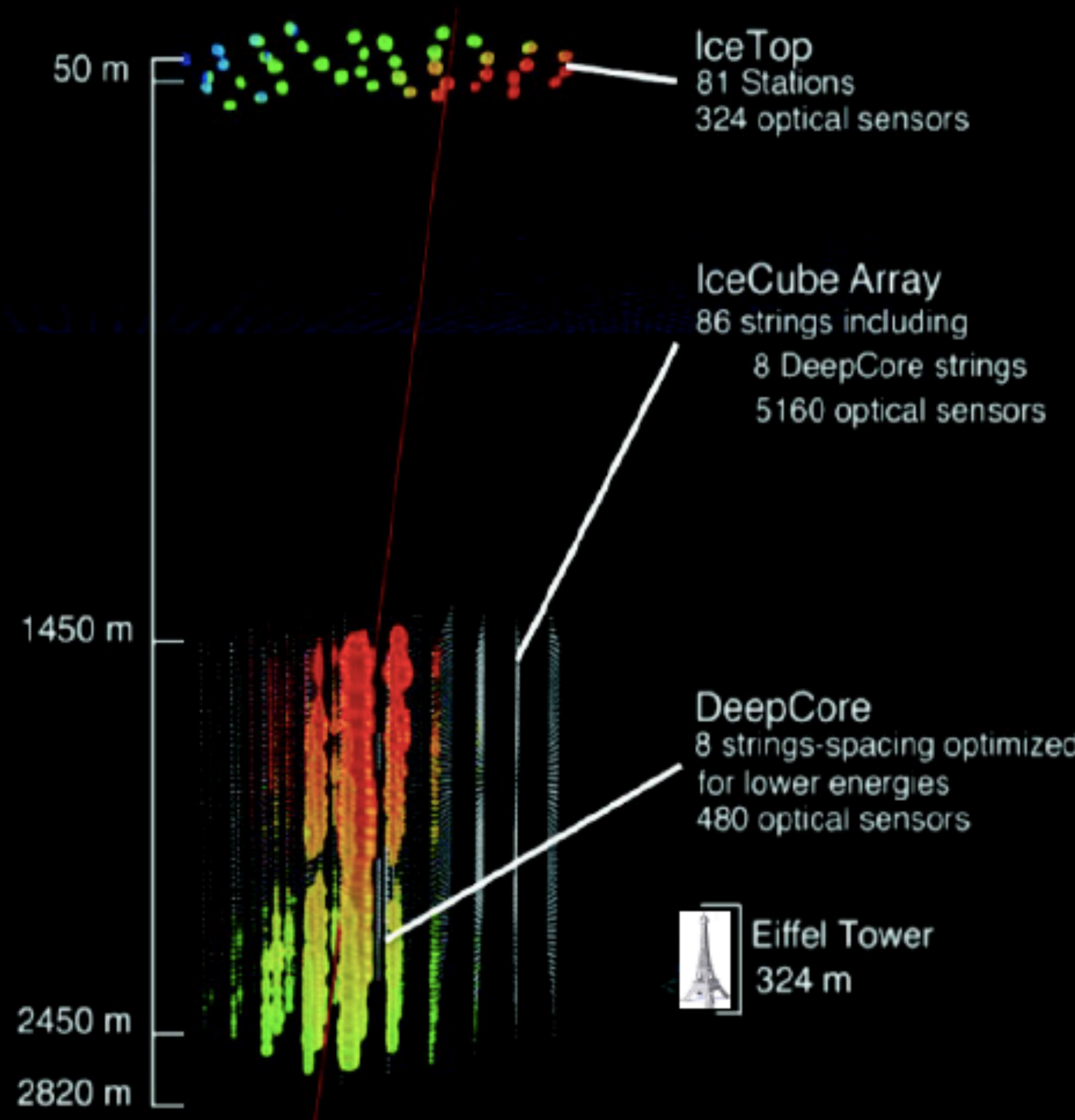
Instead, use natural bodies of water like Lake Baikal or the Mediterranean (ANTARES), or…

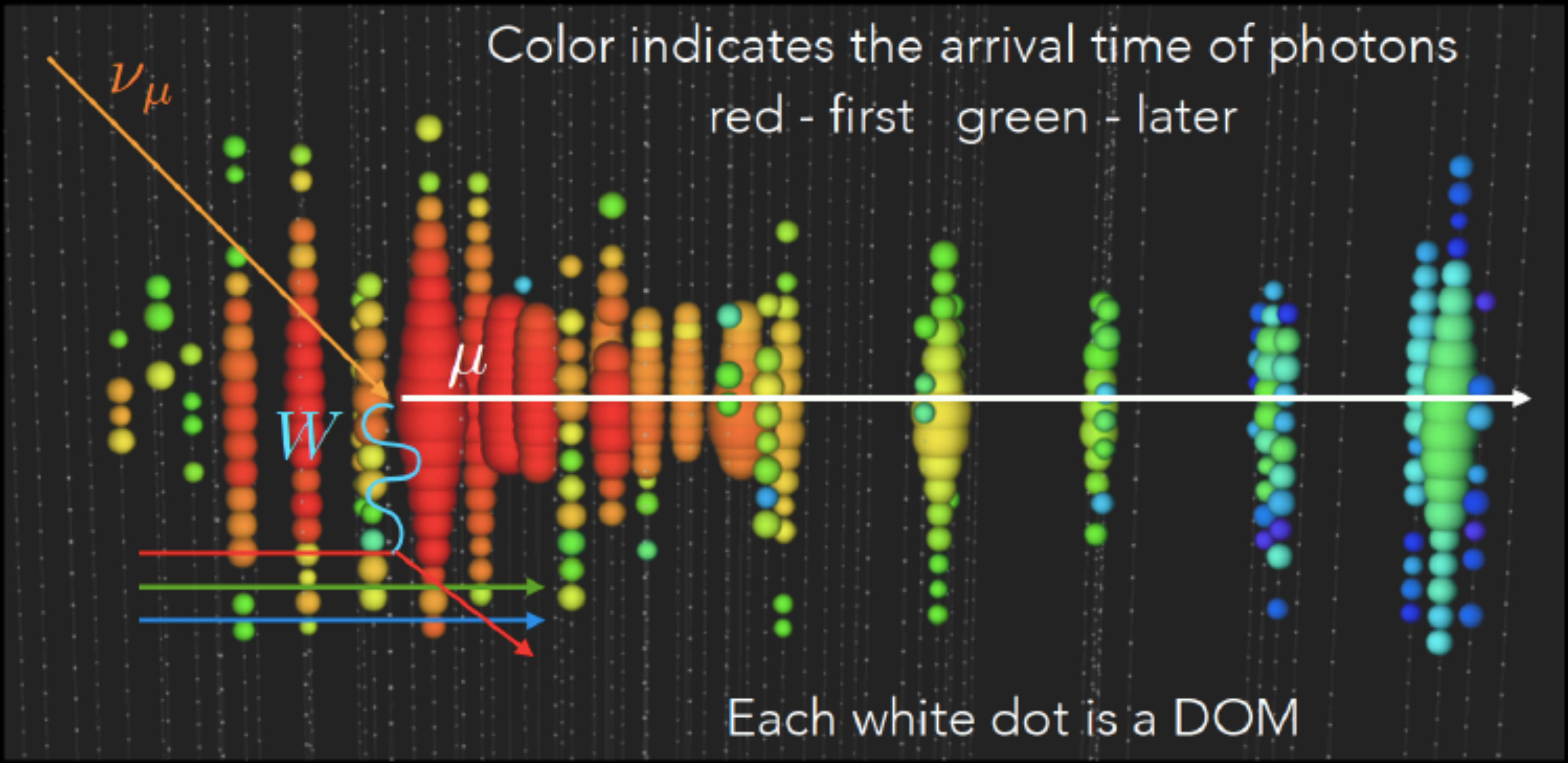

ultra-transparent ice below 1.5 km

the IceCube Neutrino Observatory

5160 DOMs
instrumenting 1 km^3
(1 GT) of clear ice

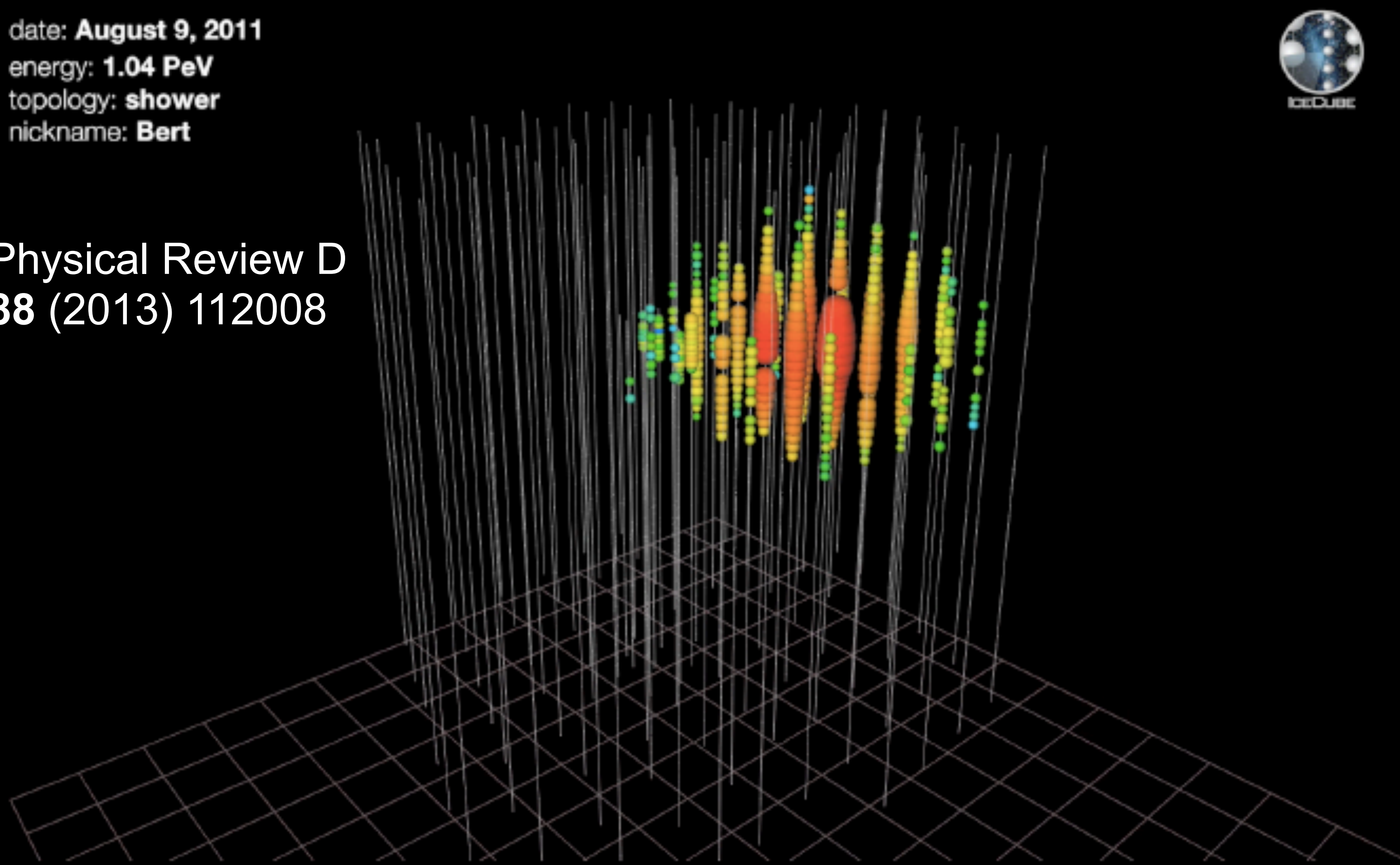
2 ns time resolution





Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

GZK neutrino search: two neutrinos with > 1,000 TeV



Physical Review D
88 (2013) 112008

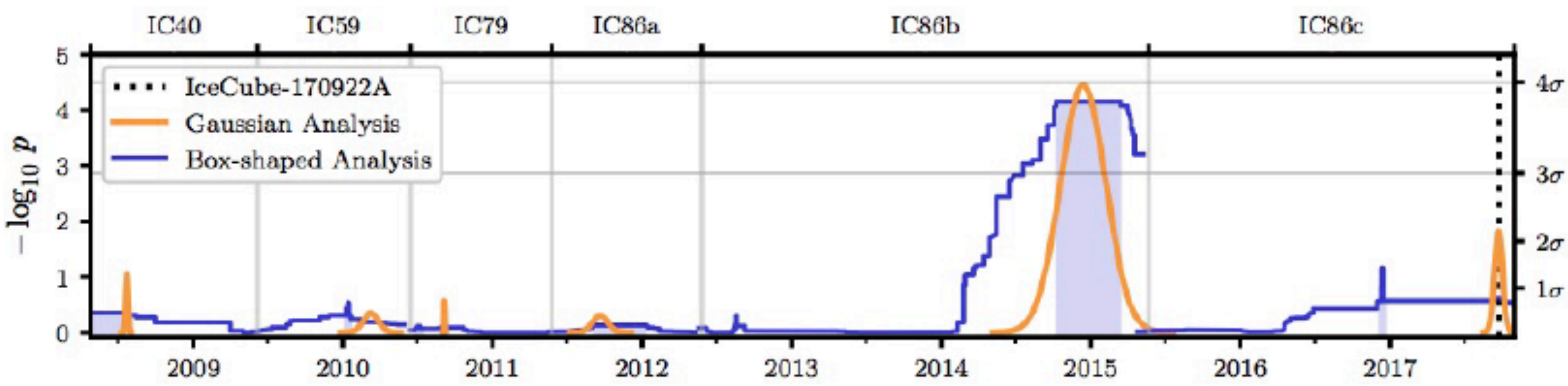
Since 2011, building up statistics! But where do they come from?

multiwavelength campaign launched by IC 170922

IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

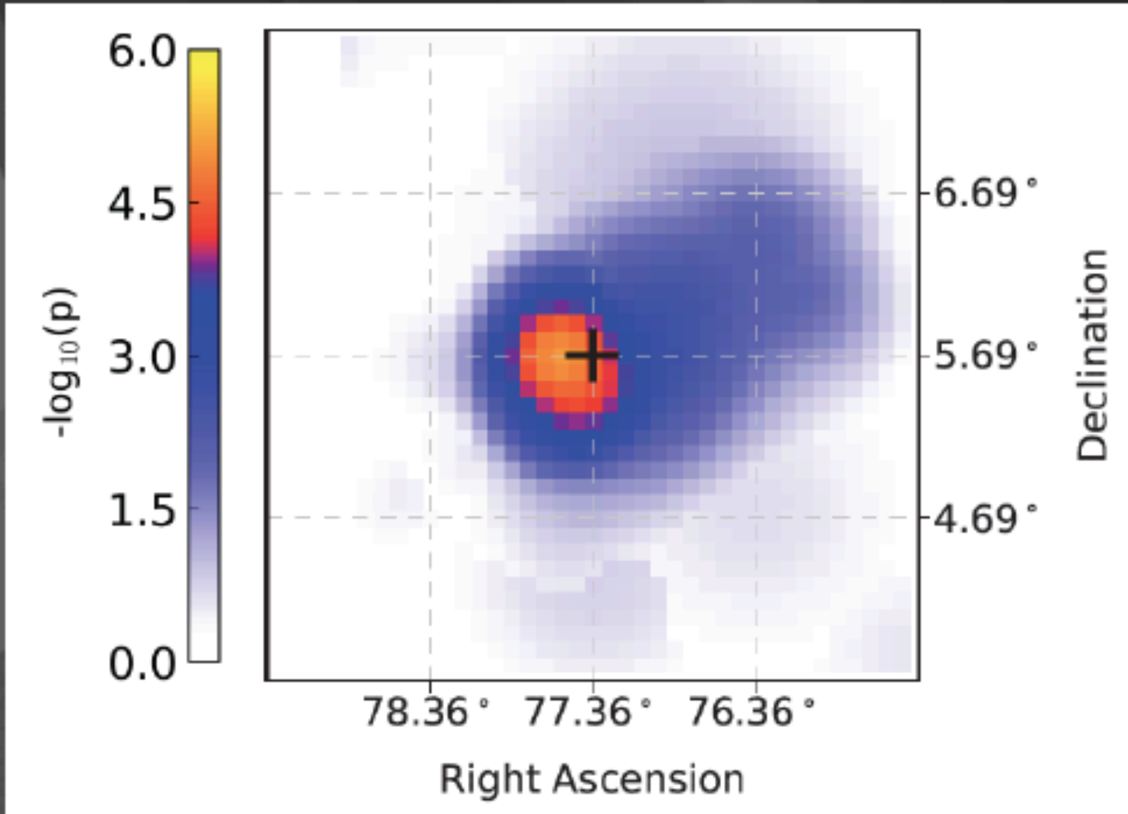
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43° Dec 5.72°
- Fermi-LAT: flaring blazar within 0.1° (7x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

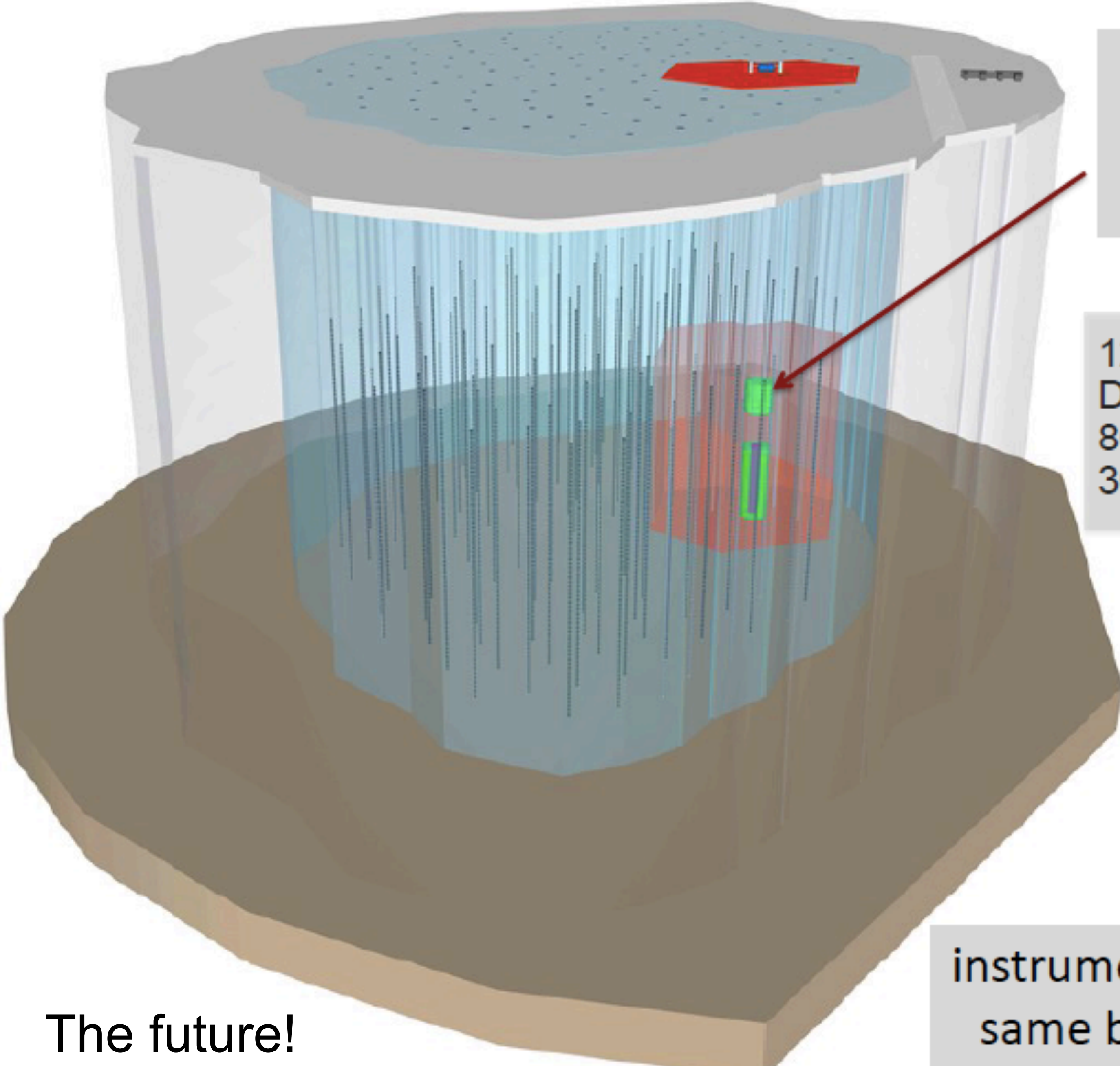
Science 13 Jul 2018: Vol. 361, Issue 6398, eaat1378
Science 13 Jul 2018: Vol. 361, Issue 6398, pp. 147-151



search in archival IceCube data:

- 150 day flare in December 2014 of 19 events (bkg <6)
- 2.10^{-5} bkg.probability
- spectrum $E^{-2.1}$





PINGU infill
40 strings
GeV threshold

120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

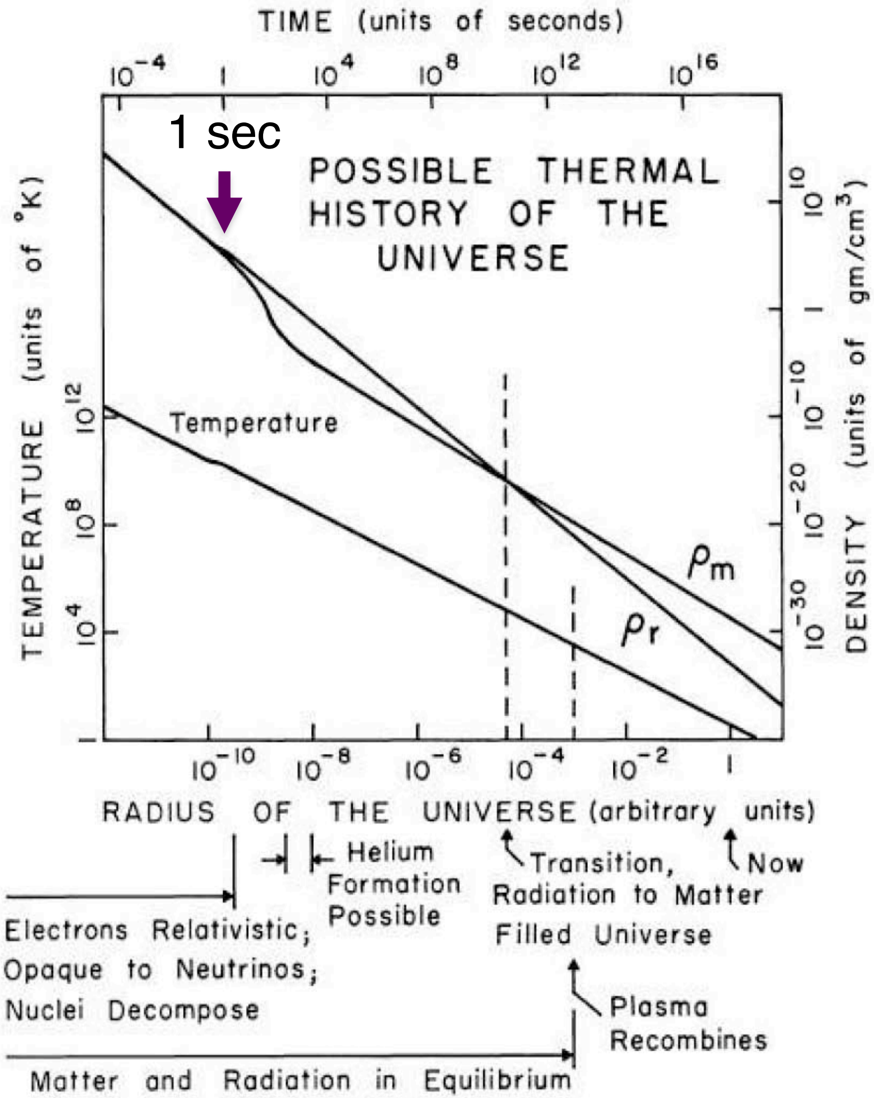
instrumented volume: x 10
same budget as IceCube

The future!

Cosmic neutrino background

Next few slides stolen from a talk by Chris Tully at LNGS in 2017
for more on PTOLEMY, see arXiv:1902.05508

Cosmic neutrino background



Dicke, Peebles, Roll, Wilkinson (1965)

$$n_\nu = \left(\frac{3}{4}\right)\left(\frac{4}{11}\right) n_\gamma = 112/\mathrm{cm}^3$$

per neutrino species (neutrino+antineutrino)

$$T_\nu(t) = \left(\frac{4}{11}\right)^{1/3} T_{CMB}$$

T_ν~1.95K

start of nucleosynthesis
n/p~0.15*0.74~0.11

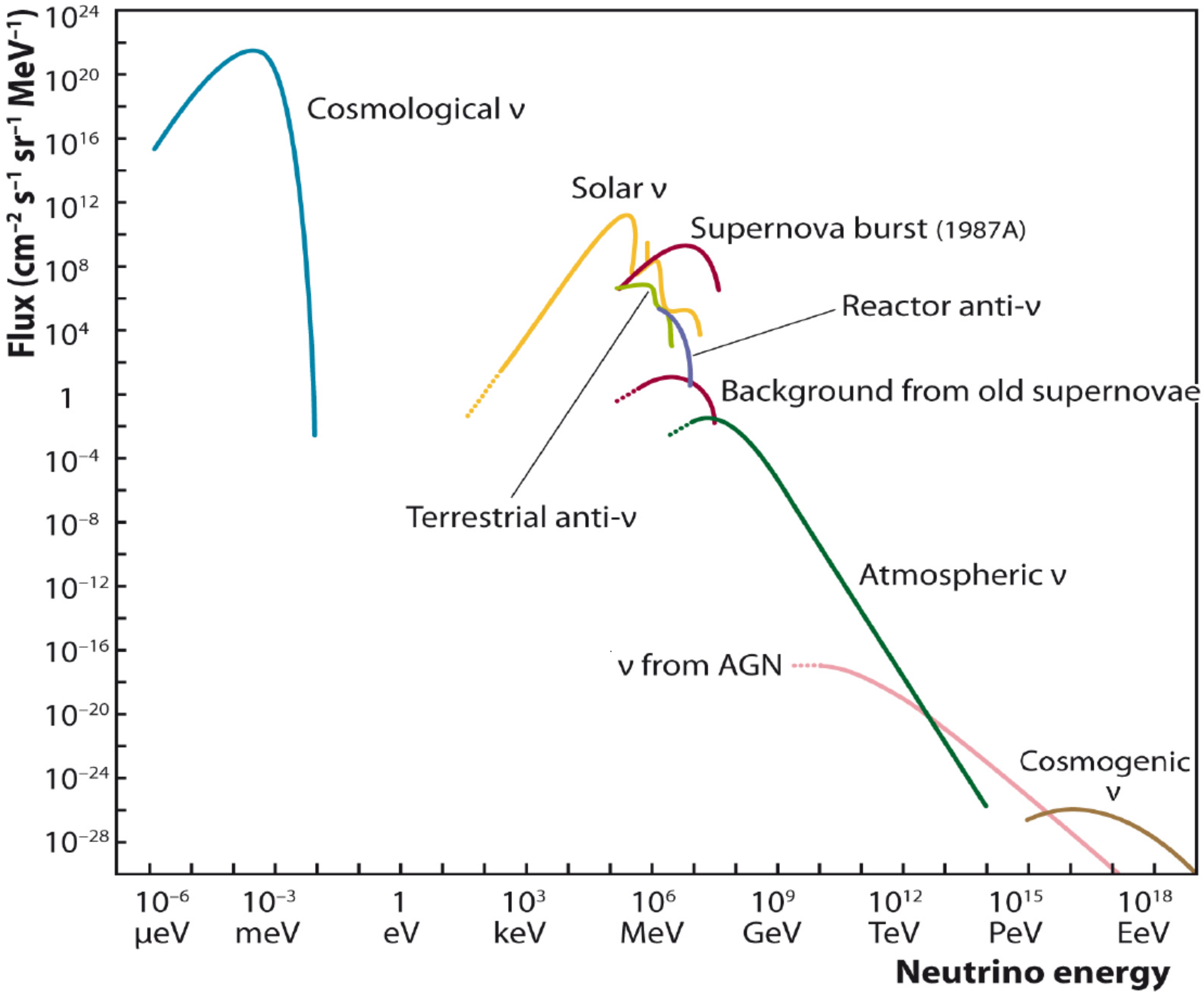
$$\frac{\lambda(p \to n)}{\lambda(n \to p)} = e^{-Q/kT}$$

Relic velocity depends on mass

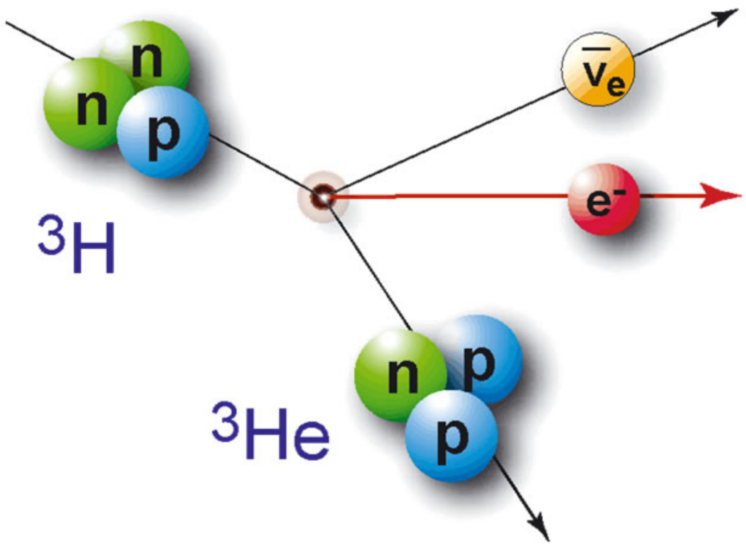
$$\langle \mathrm{v}_{rms} \rangle \propto T/m_\nu \text{ instead of } \propto \sqrt{T/m_\nu}$$

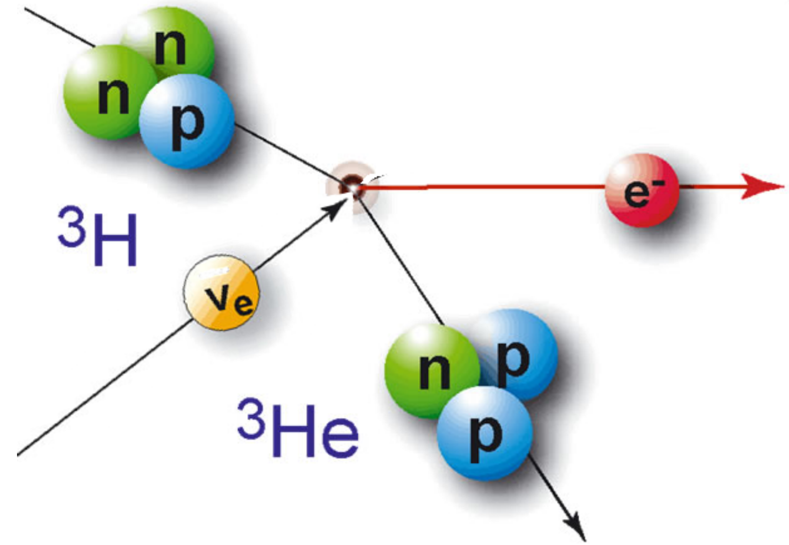
$$\langle \mathrm{v}_{rms} \rangle = 160 \text{ km/s} \left(1 \text{ eV}/m_\nu\right)$$

Cosmic neutrino background



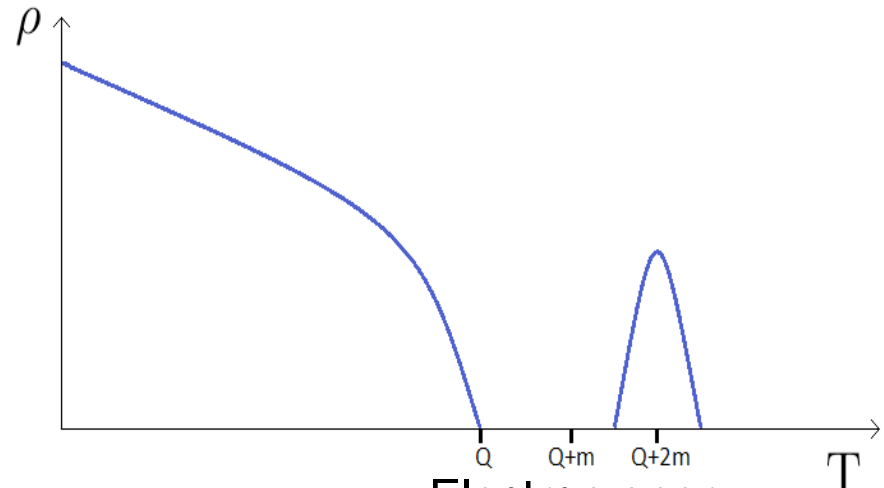
Neutrino capture





Capture cross section * (v/c) ~ 10^{-44} cm^2 (flat up to 10 keV)

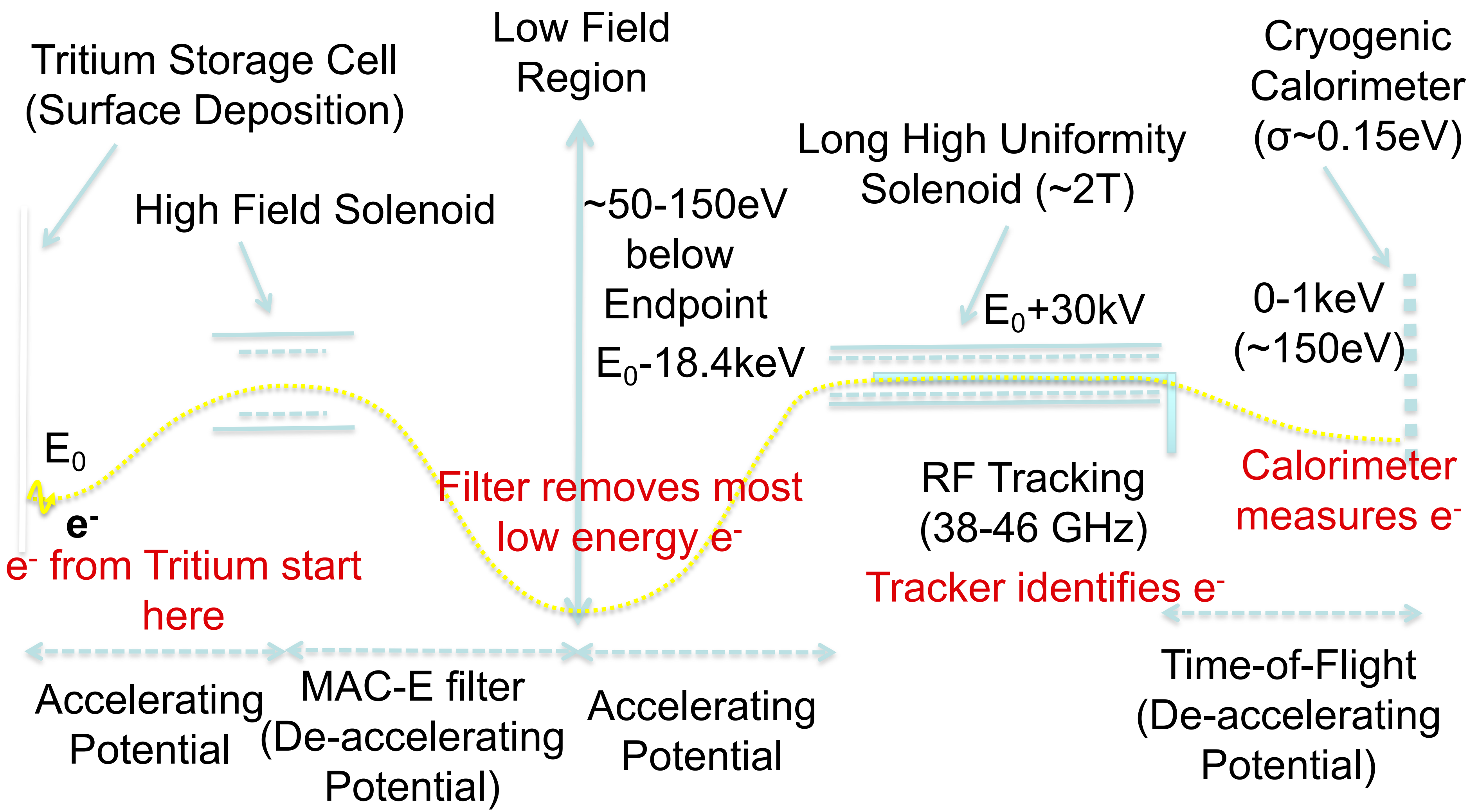
Original idea: Steven Weinberg in 1962,
Phys. Rev. 128:3, 1457
JCAP 0706 (2007)015, hep-ph/0703075,
Cocco, Mangano, Messina



Electron energy

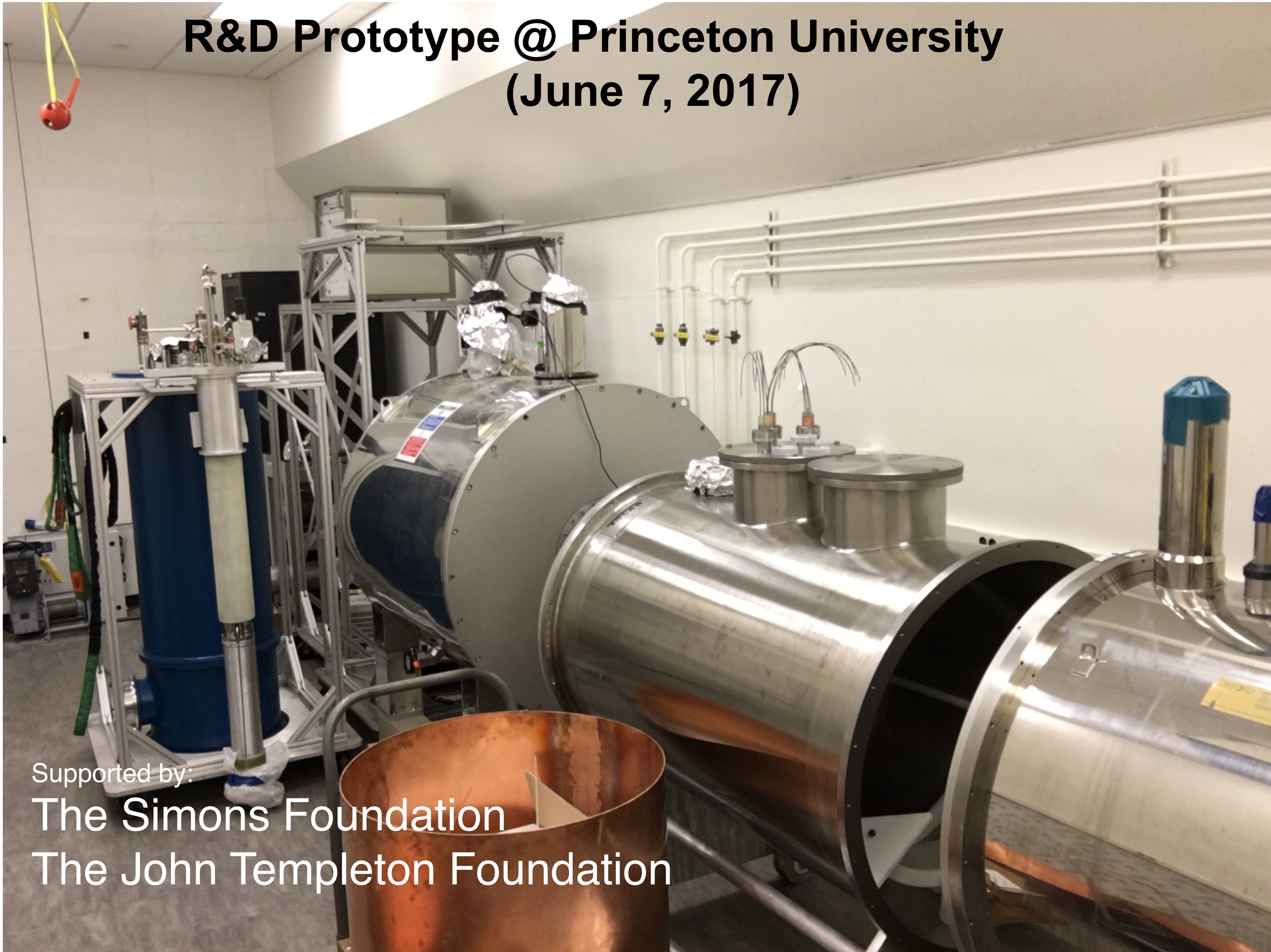
A little bit of everything: PTOLEMY

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield




PTOLEMY
R&D Prototype @ PPPL
(August 2, 2016)
Supported by:
The Simons Foundation
The John Templeton Foundation

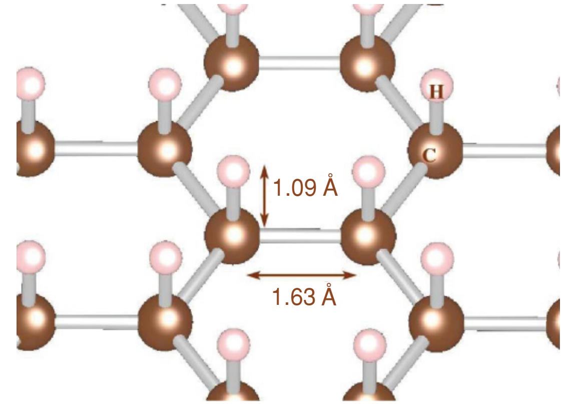
R&D Prototype @ Princeton University (June 7, 2017)



Supported by:
The Simons Foundation
The John Templeton Foundation

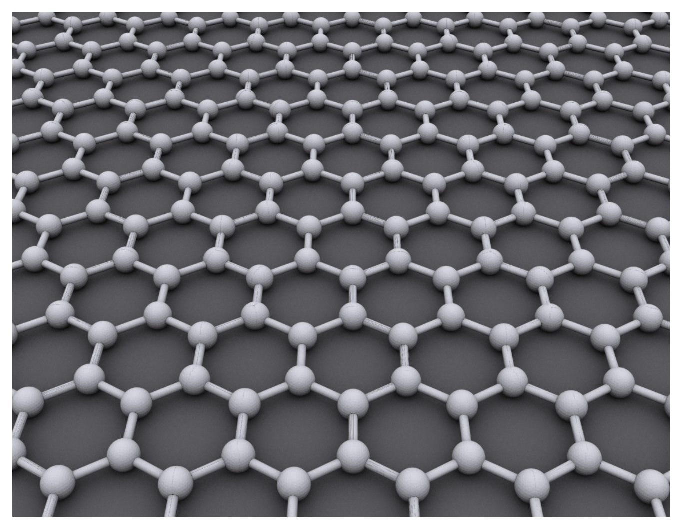
Major challenges

- Reduce molecular smearing
  - New source (Tritiated-Graphene or Cryogenic Au(111))
- Measure the energy spectrum directly with a resolution comparable to the neutrino mass
  - High-resolution electron microcalorimeters
- Compress a 70m spectrometer length – KATRIN's length – down to ~cm scale and replicate it at lower precision – final measurement from microcalorimeter
  - New filter concept (Newtonian vs. Galilean)
  - RF trigger system (Project 8 development)
  - G-FET as a potential trigger system



< 3eV binding energy

Graphene



Summary

- Neutrinos and cosmology are intertwined in more ways than one, and cosmology can constrain neutrino properties.
- Coherent neutrino scattering experiments are a relatively new detection tool, and allow us to search for non-standard interactions.
- 3ν picture may not be complete – the search for sterile neutrinos continues…
- Finally, astrophysical neutrinos are being used as cosmic messengers, giving us a new window on the universe.
- We may even be able to detect the cosmic neutrino background someday!