Big Questions in Neutrino Physics

...

E. Caden (SNOLAB)
H. A. Tanaka (SLAC)

20 Nu-vember, 2020

Rough Outline:

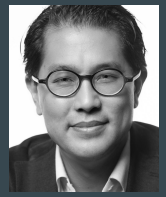
- Introductions:
  - E. Caden, H. A. Tanaka
  - The Neutrino
- “Big questions”, what we think is cool about neutrinos?
  - Properties
  - Role in universe
  - Detectors, experimental techniques
- Summary

Introductions:

Erica Caden (she/hers)

- PhD on Double Chooz
- underground neutrino experiments
  - SNO+
  - HALO
  - nEXO
- At SNOLAB since 2013
- erica.caden@snolab.ca

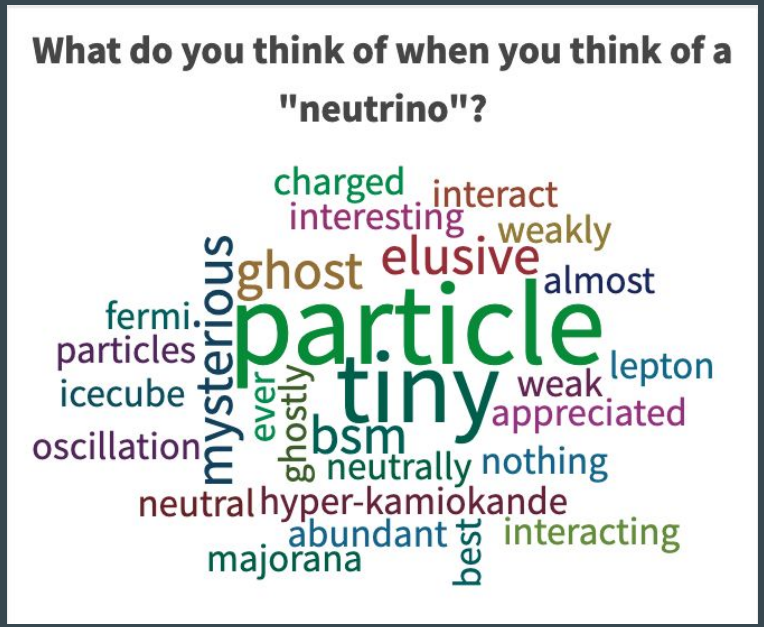
Hirohisa Tanaka (he/him/his)



- PhD on BaBar
- accelerator-based neutrino experiments
  - MiniBooNE
  - T2K, SK
  - ICARUS
  - DUNE
- At SLAC/Stanford since 2018
- hatanaka@stanford.edu

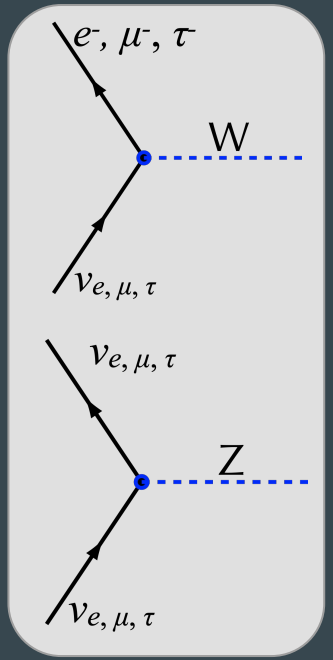
POLLEV:

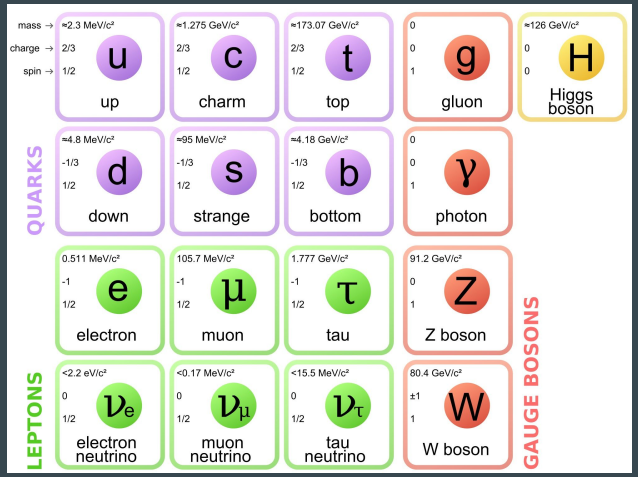
- Please connect to:
  - http://www.pollev.com/nuquestions524
- We'll try a few poll questions now . .



Introductions: the neutrino

- "Spin ½ fermion partnered with a charged lepton in a weak isospin doublet"





Courtesy: wikipedia

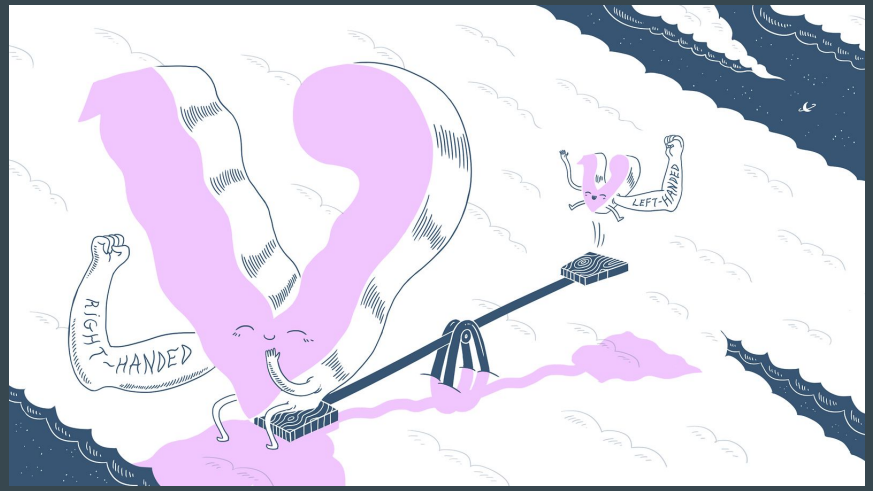
- Neutrinos have:
  - (Left-handed) weak interactions
  - Three (anti-)flavors (α)
  - A smidgen of (non-degenerate) mass (m_i)
  - Mixing between mass and flavor states
- Neutrinos do not have:
  - Electric charge
  - Color

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

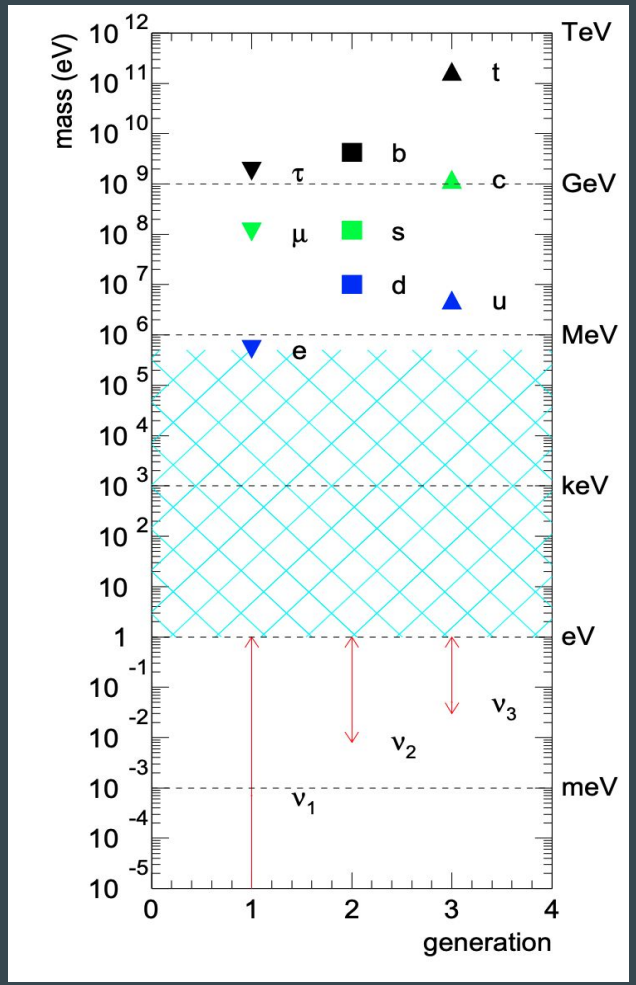
What is the Neutrino Mass?

Nature of Neutrino Mass

“Nonzero neutrino masses imply new degrees of freedom. We don’t know what they are nor what are their masses. They may be very light sterile fermions, very heavy sterile fermions, a Higgs boson triplet, a set of new charged fermions and scalars with TeV masses, new vector bosons, etc.” - André De Gouvêa



Seesaw Mechanism - Symmetry

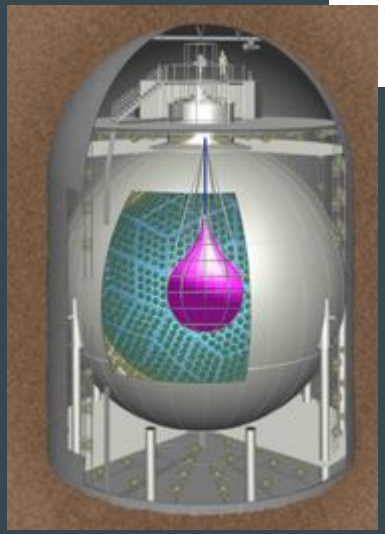


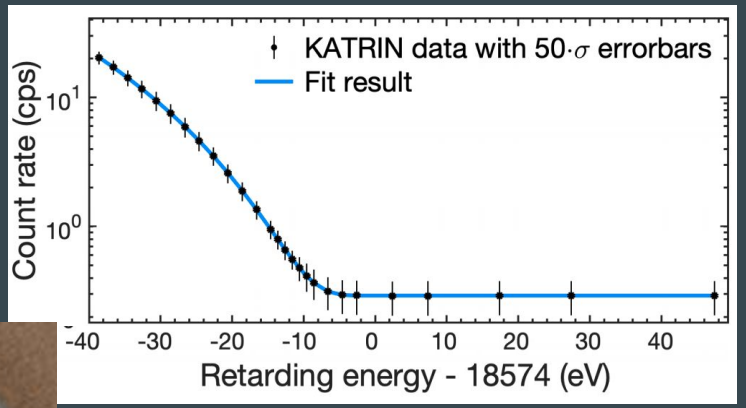
Neutrino Mass Models

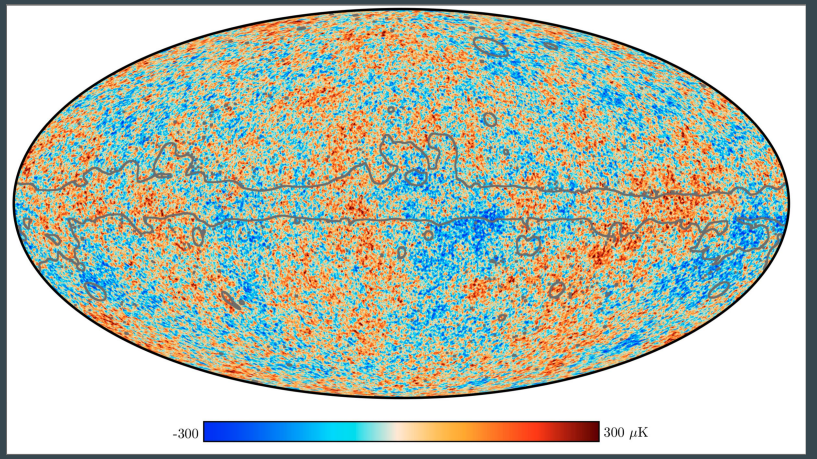
Probes of Neutrino Mass

$0\nu\beta\beta$ gives $m_{\beta\beta}$

[2019 Annual Review of DBD Experiments]

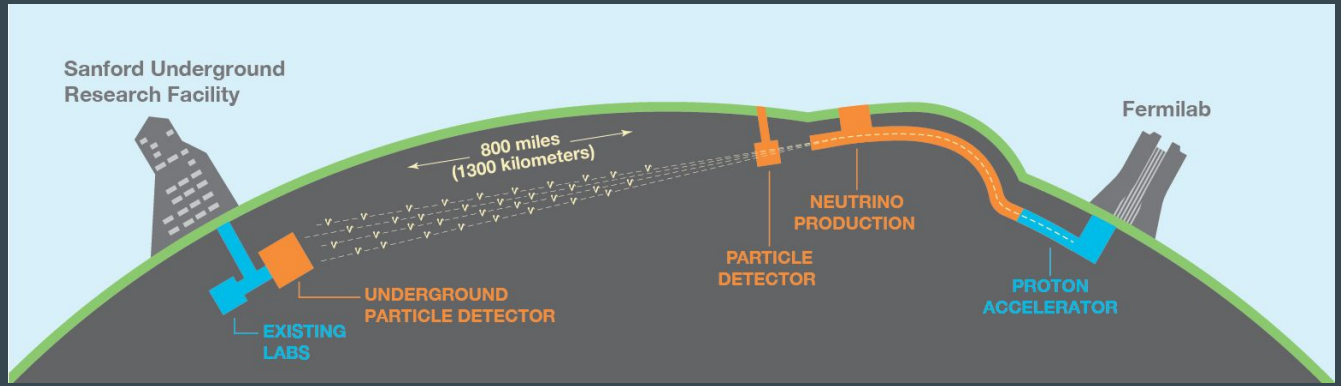






$m_\nu < 0.9$ eV (90% CL)
[Nu2020 Results]

$\Sigma m_\nu < 0.12$ eV
[Plank 2018 Results]



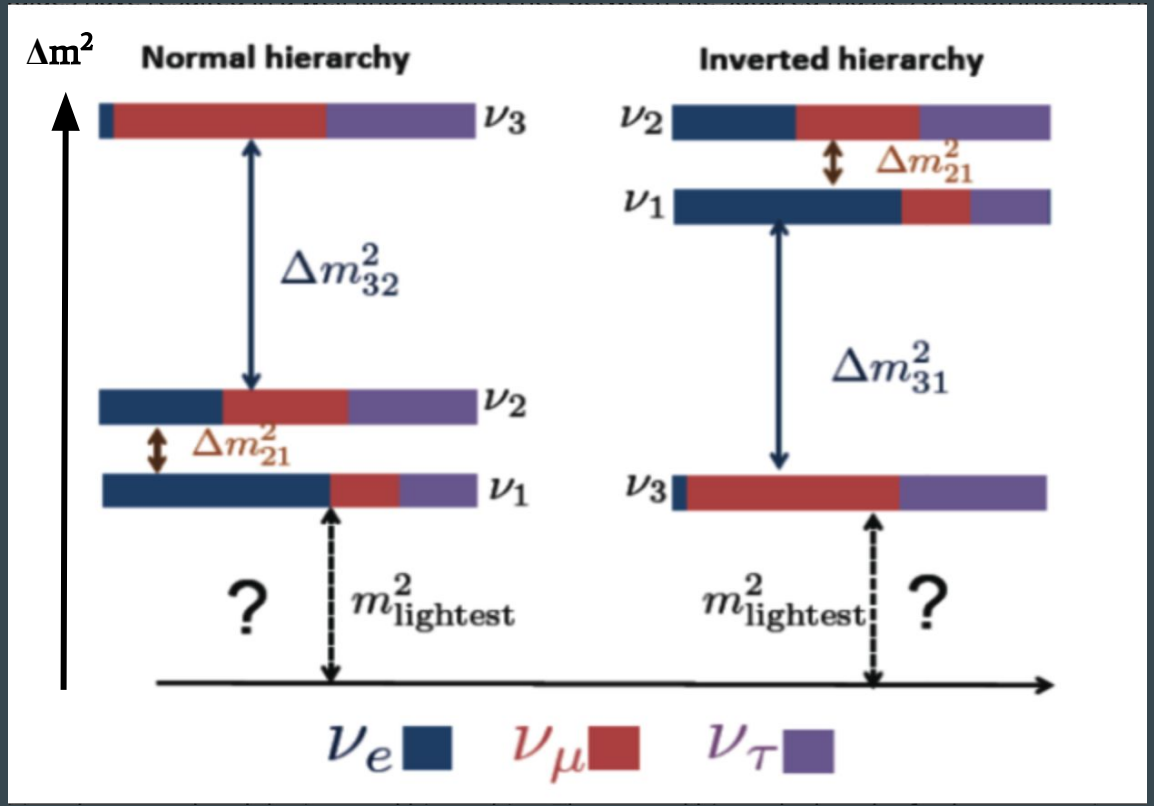
[DUNE]: Long baseline experiments give us hierarchy information

Neutrino Mass Hierarchy

- Known from oscillation experiments
- $\Delta m_{32}^2 = 2.45 \times 10^{-3}\ eV^2$
- $\Delta m_{21}^2 = 7.39 \times 10^{-5}\ eV^2$

- Don't know absolute scale
- Don't know hierarchy

PDG 2020



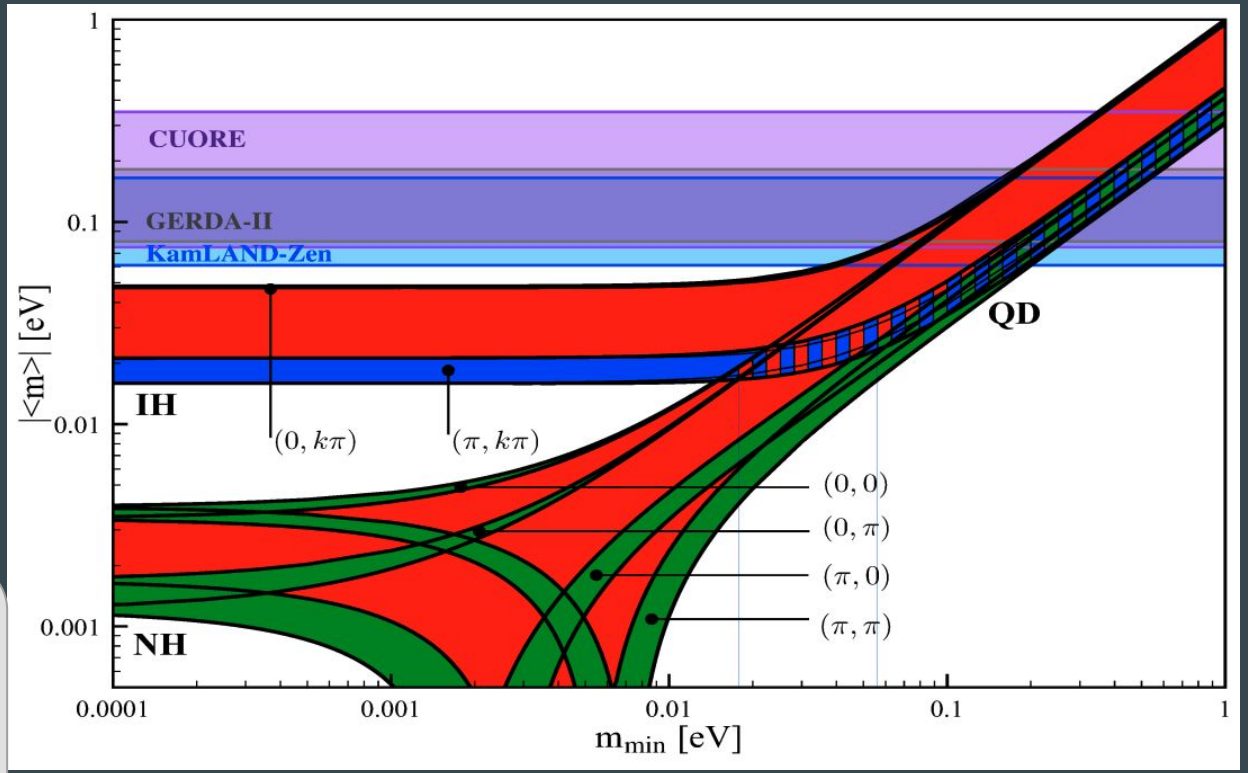
From E. Brown

Nature of Neutrino

- Is the neutrino a Dirac or Majorana particle?
- Can search for lepton number violation through Majorana process

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle = |\sum_i U^2_{ei} m_i|$$



S. T. Petcov, Nu2020

Is there an underlying pattern to Neutrino Mixing?

What is the mixing of neutrinos?

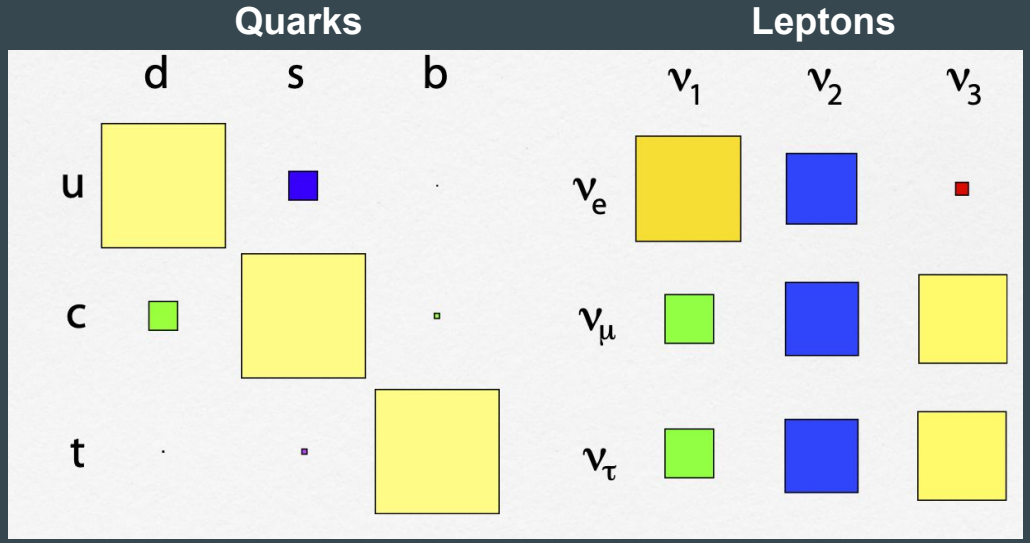


Figure from S. F. King @ DISCRETE 2014

Two Big questions:

- Why is the mixing of leptons so different from quarks?
- Is there a pattern behind the lepton mixing?

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

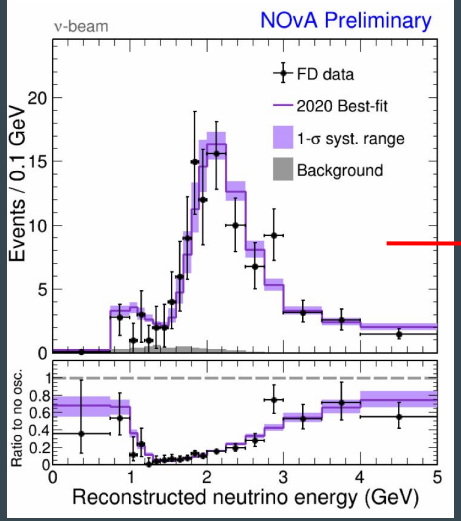
An explanation for either is **new physics** that has have been staring at us for some time.

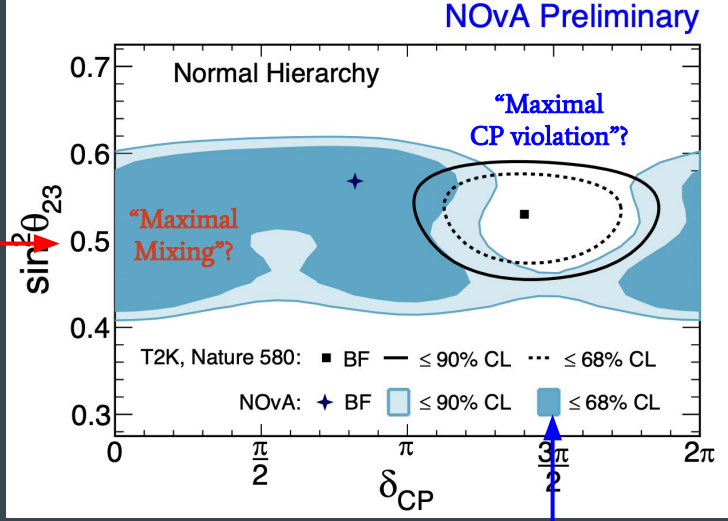
See talks at NP01 workshop 1
(M.C. Gonzalez-Gracia, P. Shanahan, F. Sanchez, R. Wendell)

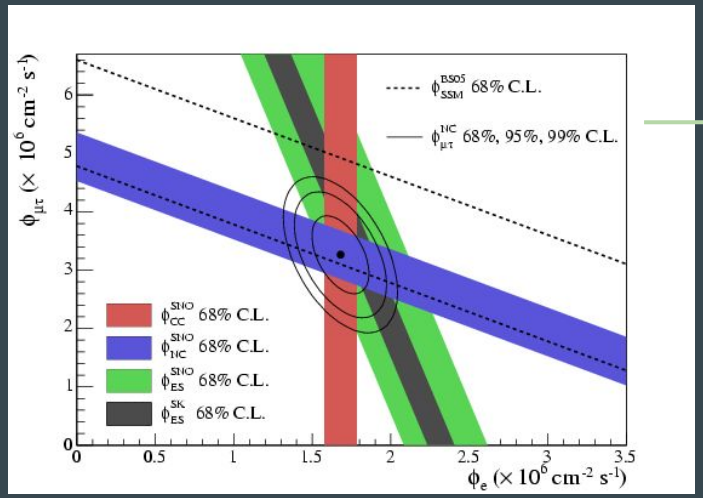
Hints?

Big Question: Do neutrino mixing parameters take on "interesting" or "special" values that result from an underlying symmetry?

See talks at NP01 workshop 1
(M.C. Gonzalez-Gracia, P. Shanahan, F. Sanchez)







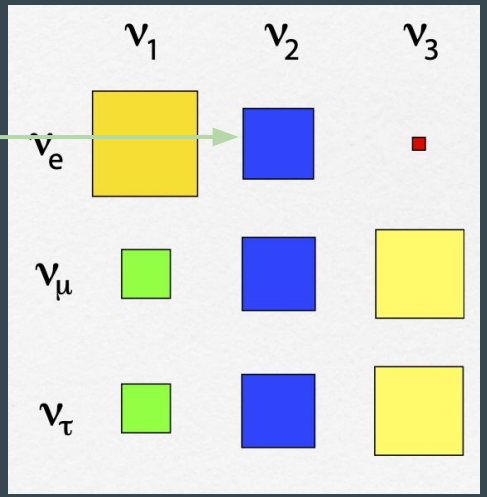
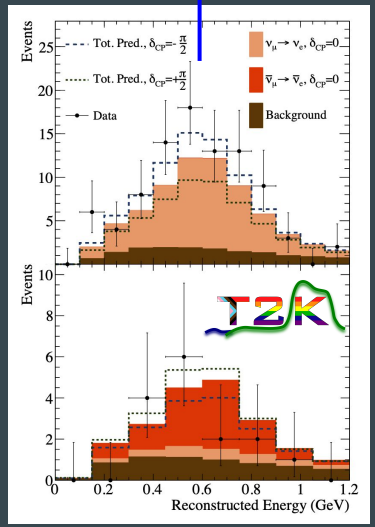


Figure from S. F. King @ DISCRETE 2014



Potential Directions?

Are there flavor symmetries?

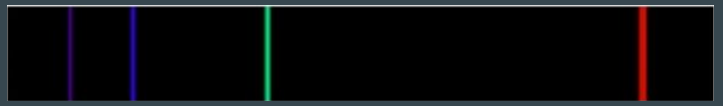
- A number of discrete symmetries can give rise patterns that approximate the observed mixing . . . .

See talk by S. Petcov at NP01 Workshop 4

$$U_{\text{PMNS}} \cong \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & \epsilon \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}}(?) \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}}(?) \end{pmatrix}$$

- And predict their values . . . .
- Motivates precision measurements

See talks at NP01 workshop 2, 4, 5
Z. Yu, R. Wendell, T. Stuttard, E. Worcester, T. Nakadaira, S. Seo



Pseudo-historic analogy

- 1880s: Balmer and Rydberg uncovered a pattern in the hydrogen emission spectra
- Understanding the origins of this pattern took ~50 years and one of the largest paradigm shifts in scientific history

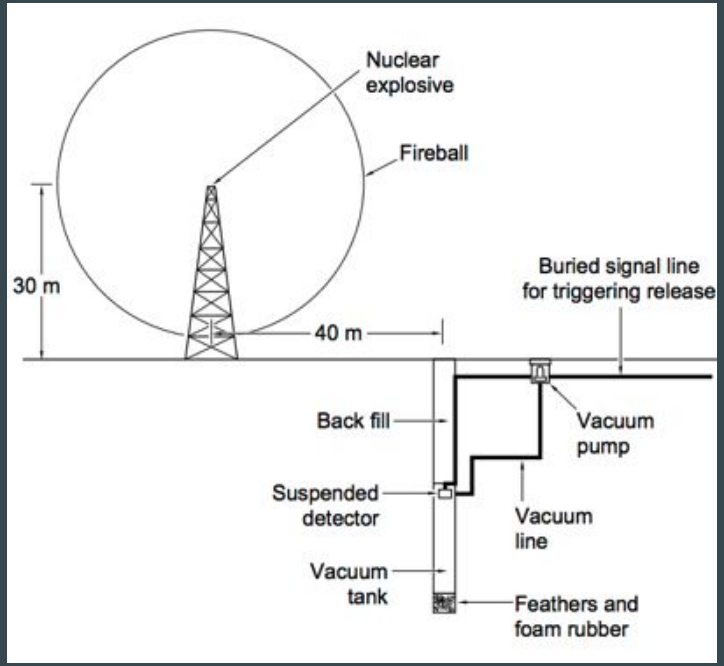
For neutrinos . . . we're not there yet and don't know where this will go . . .

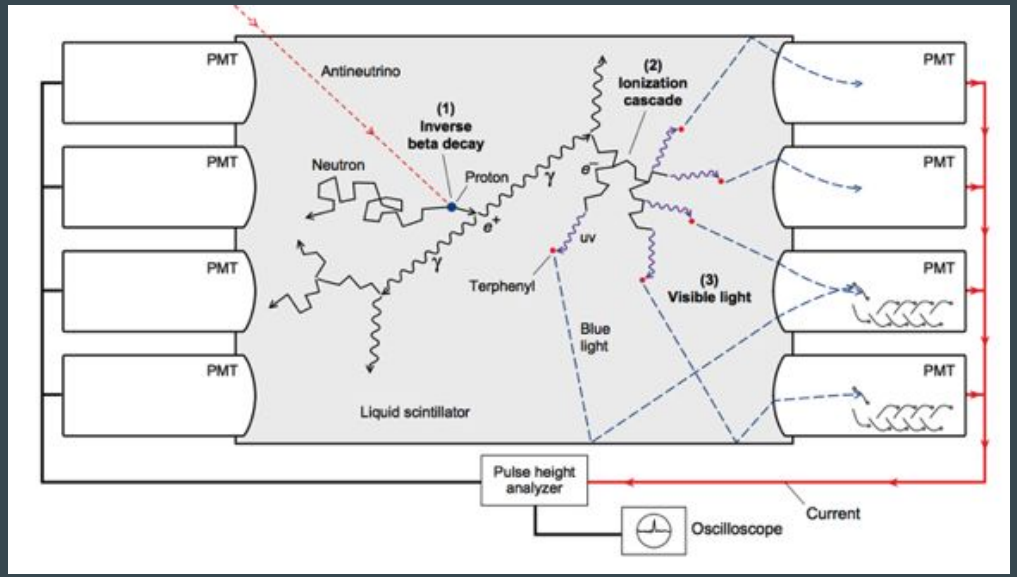
How can Detector Technologies help us answer these Big Questions?

Brief History of Neutrino Detection

Fred Reines

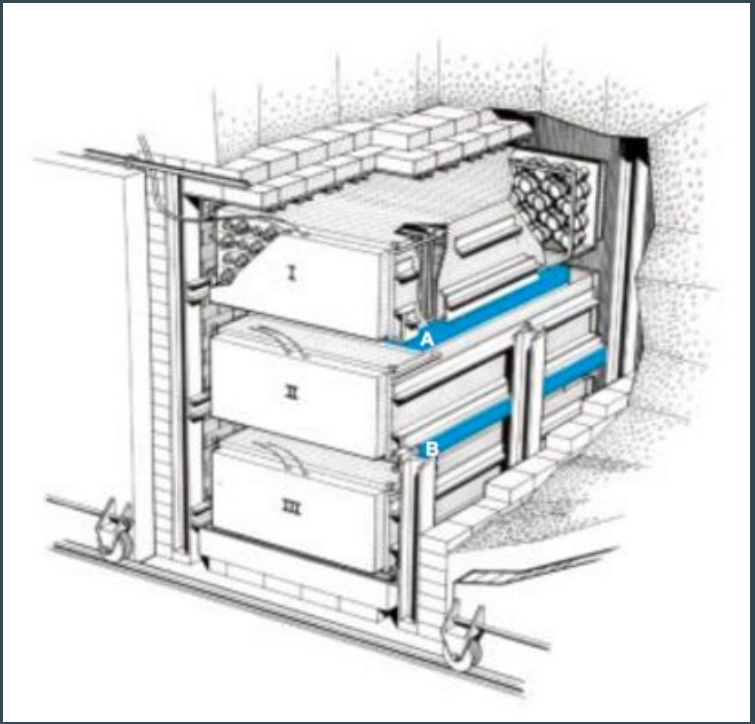
Clyde Cowan





Los Alamos Science Number 25 1997

Savannah River

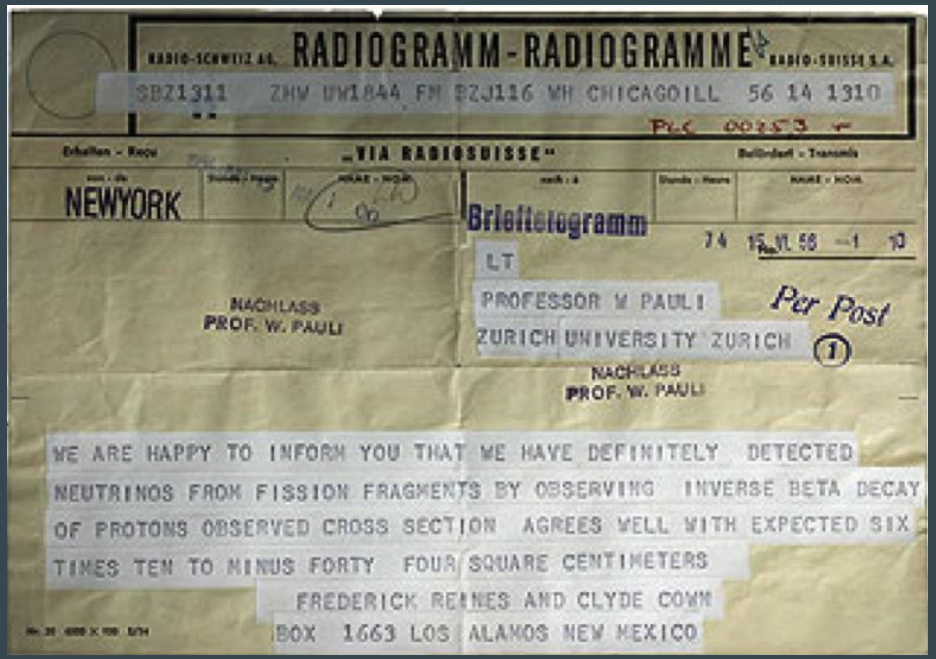


- Two large, flat plastic tanks filled with H_2O as target for inverse beta decay
- Cd_2Cl_4 dissolved in the water for neutron capture

- Are coincidences from e+ and n?
  a. Dissolve ^{64}Co in the water to understand e+
  b. Doubled Cd_2Cl_4 to watch time decrease
- Does signal strength vary with number of protons?
  a. Filled half of tanks with heavy water, decreased IBD cross section on deuterium
- Is signal really cosmic rays & reactor backgrounds?
  a. varied the thickness and type of shielding

Los Alamos Science Number 25 1997

Success!



RADIOGRAMM-RADIOGRAMME

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„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

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LT

PROFESSOR W PAULI

Per Post

ZURICH UNIVERSITY ZURICH (1)

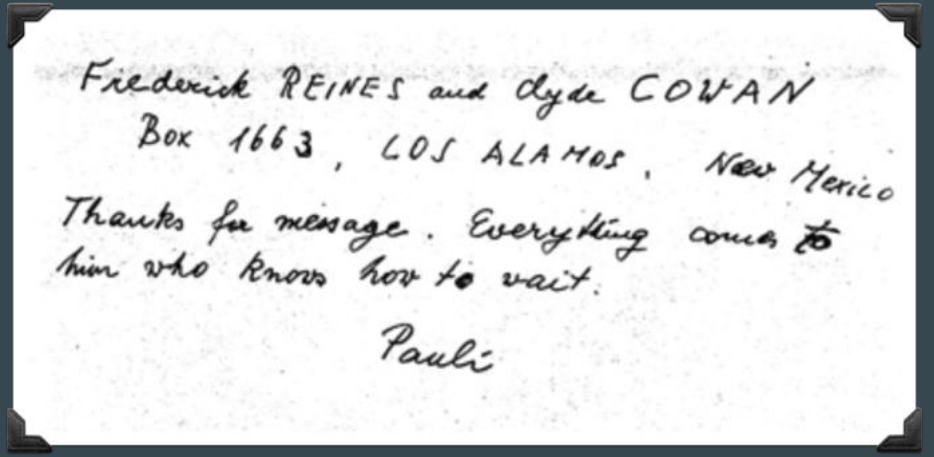
NACHLASS PROF. W. PAULI

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO



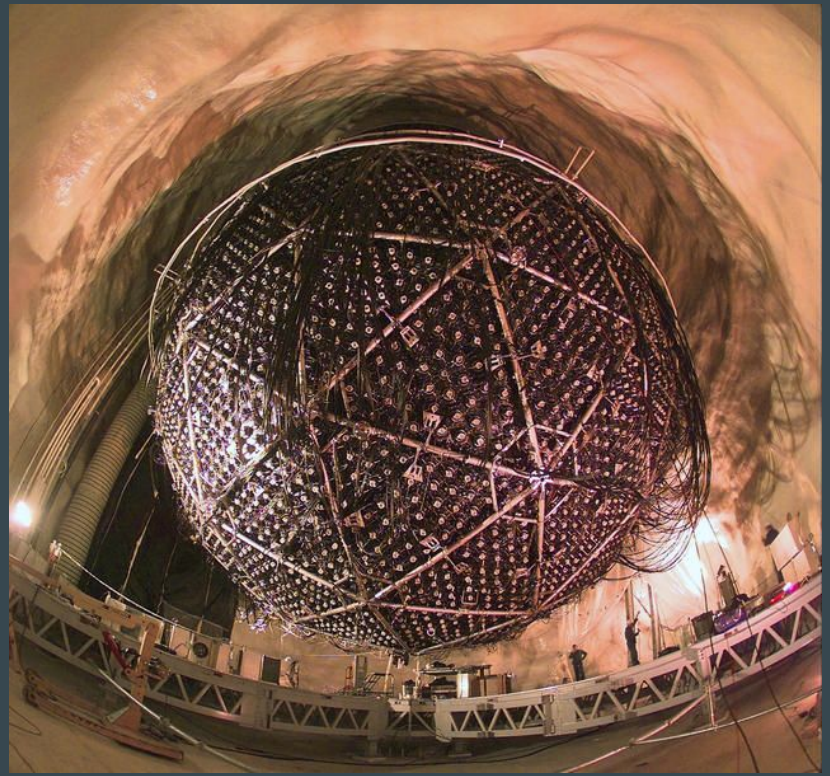
Frederick REINES and Clyde COWAN

Box 1663, LOS ALAMOS, New Mexico

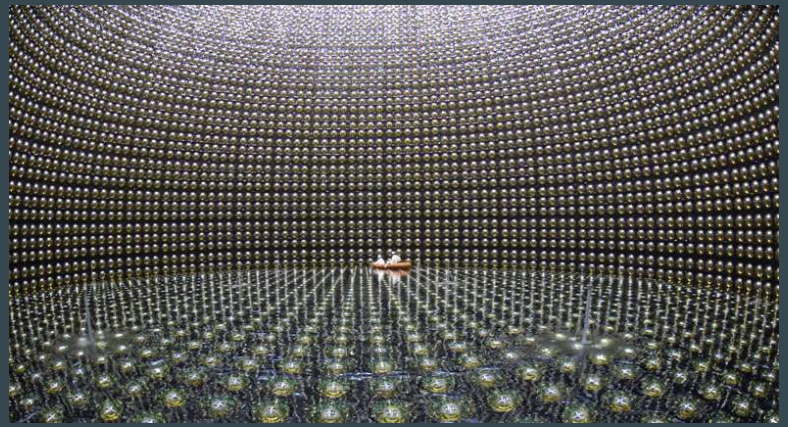
Thanks for message. Everything comes to him who knows how to wait.

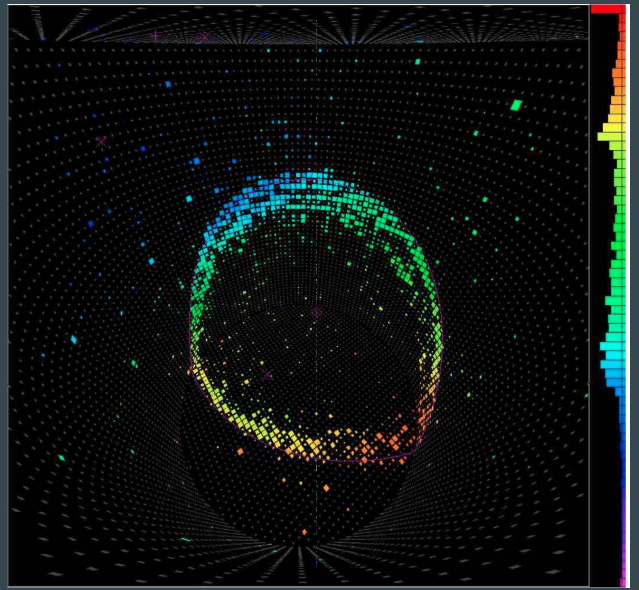
Pauli

Water Cherenkov



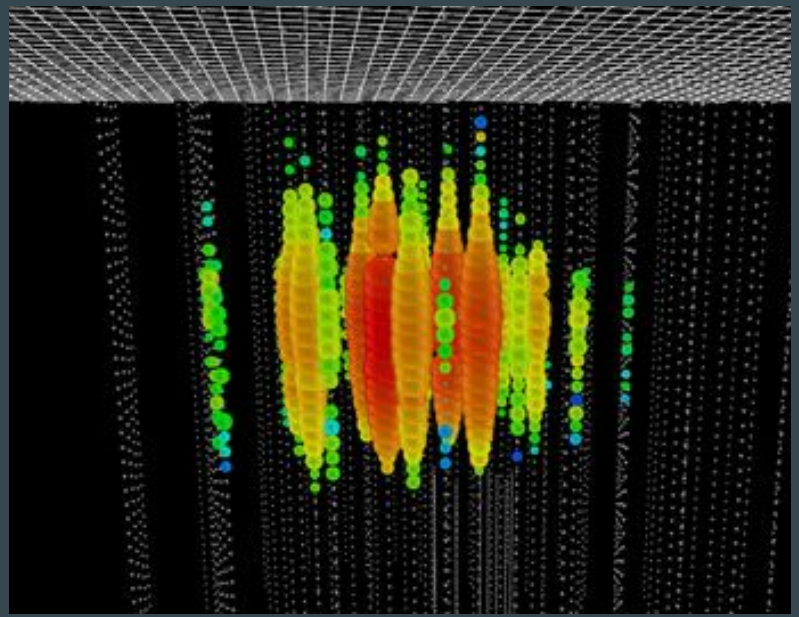
SNO/SNO+ Detector

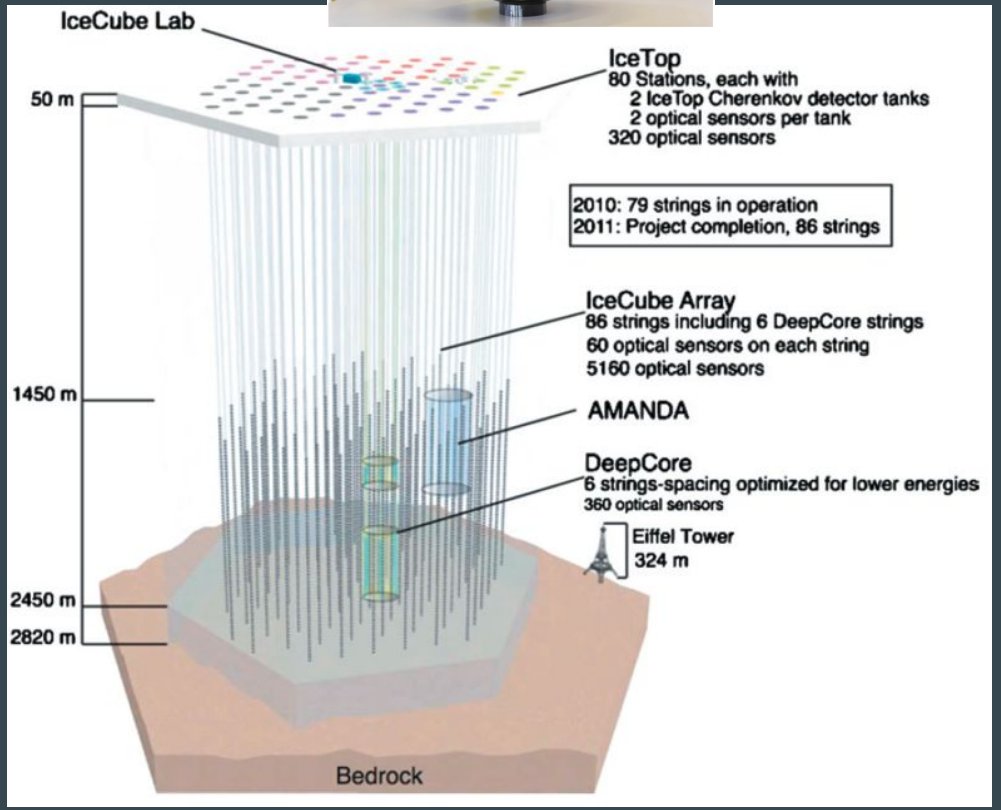




SuperK Detector
SuperK Event

Water Cherenkov - Volumetric





[Ice Cube]
[KM3Net]

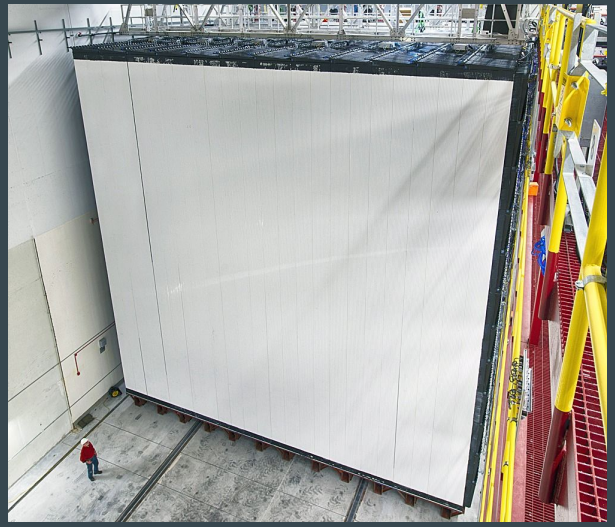
The New York Times

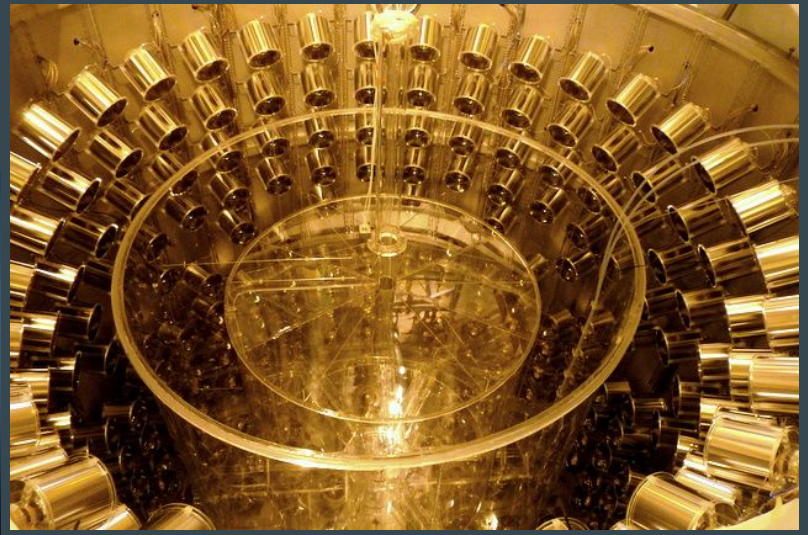
Masatoshi Koshiba, 94, Dies; Nobel Winner Tracked Ghostly Neutrinos

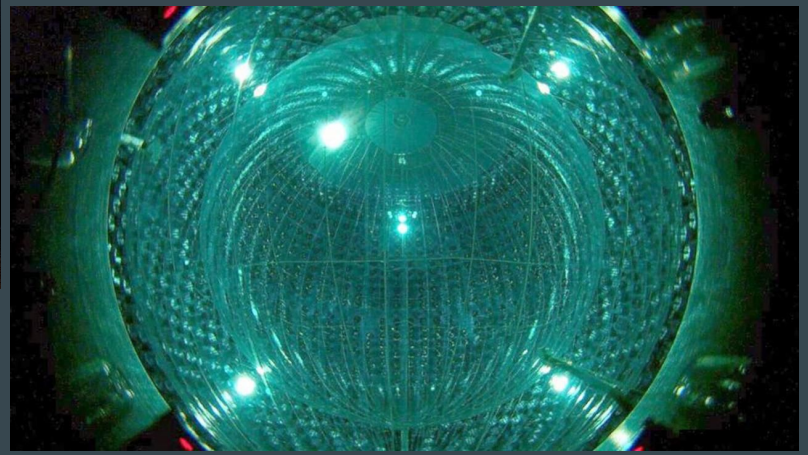
19 September 1926 -
12 November 2020

Development of 20-inch PMTs
Blowing the 20-inch PMTs

Scintillator





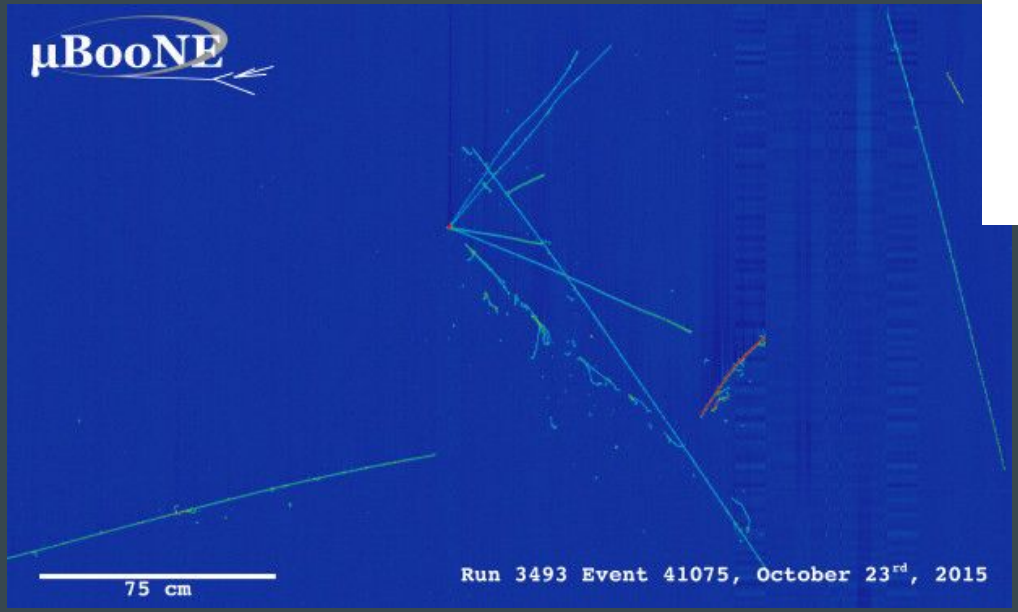


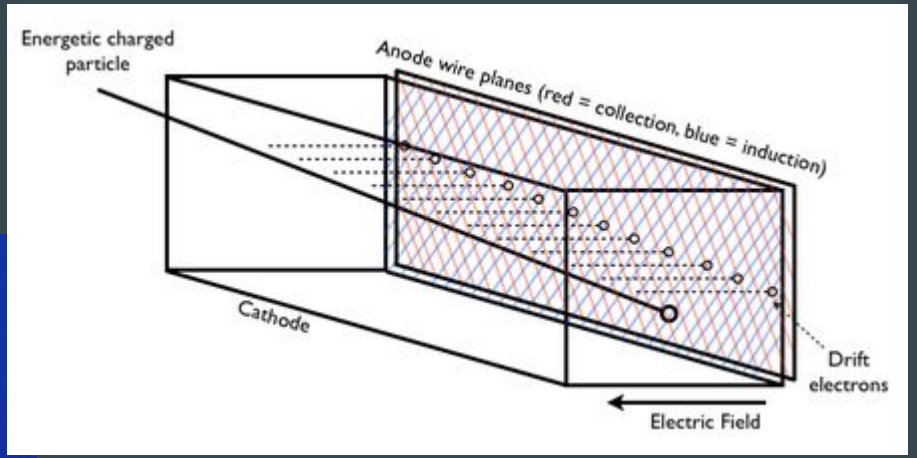
NOvA

COHERENT

Double Chooz
Borexino

Time Projection Chambers



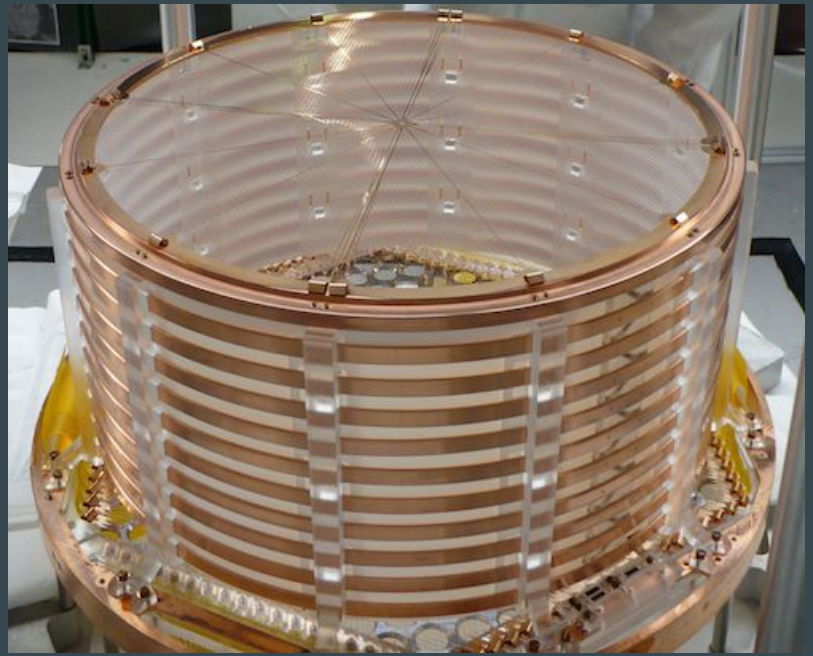


"It appears possible to realize a Liquid Argon Time Projection Chamber which gives and ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques" - Carlo Rubbia

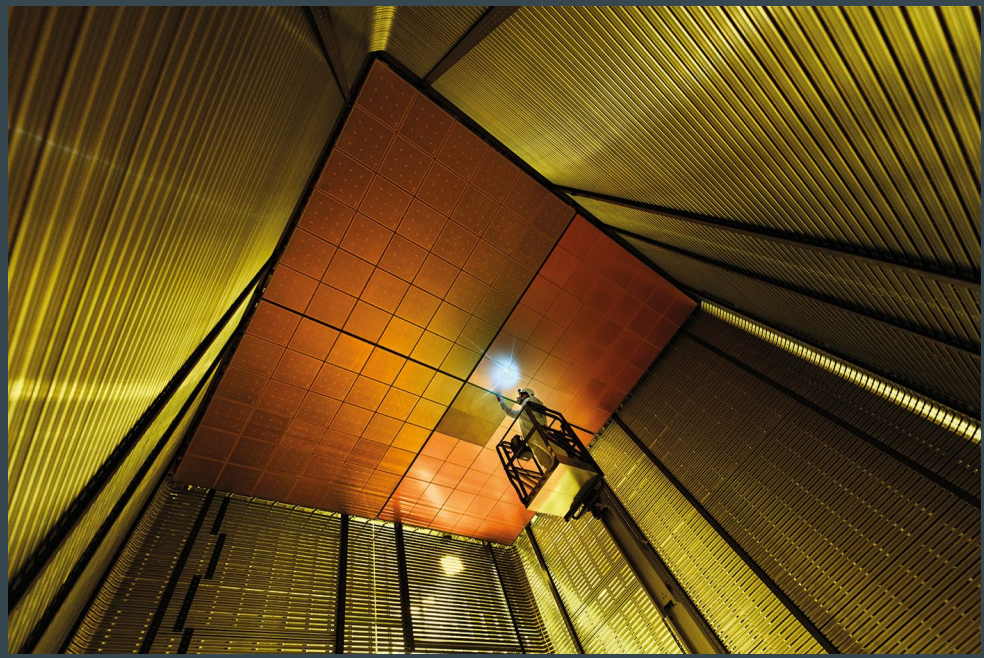
The Liquid Argon Time Projection Chamber: A New Concept for Neutrino Detectors, 1977

Time Projection Chamber MicroBooNE

Liquid Noble TPCs

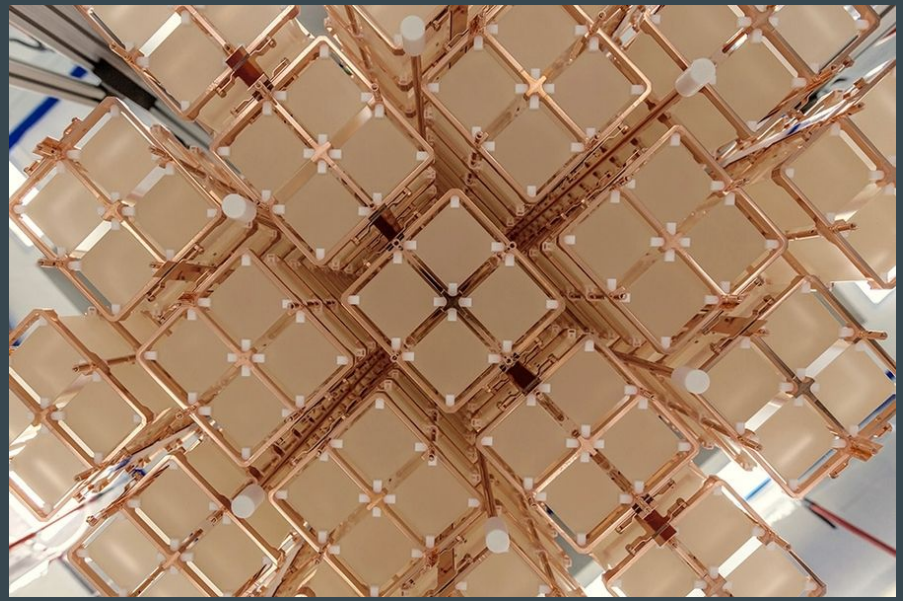


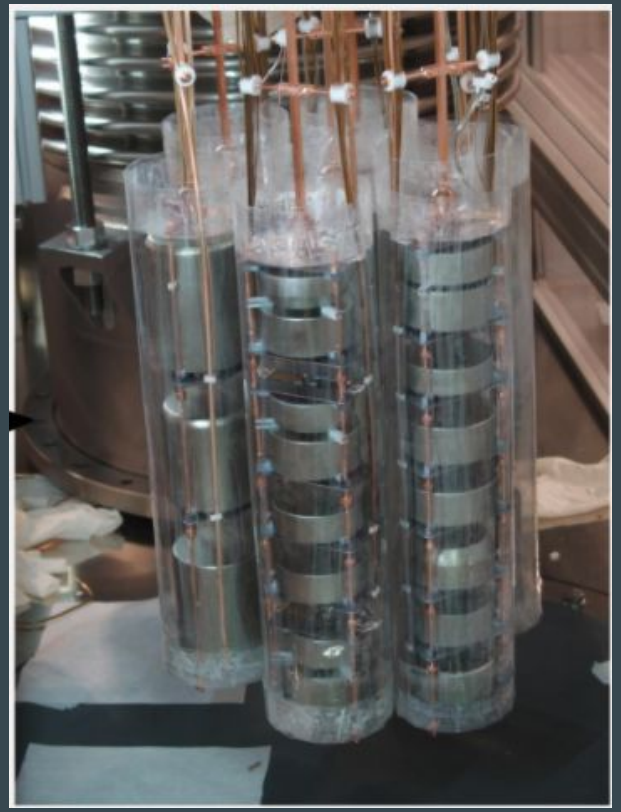
EXO-200



ProtoDUNE

Crystals





CUORE

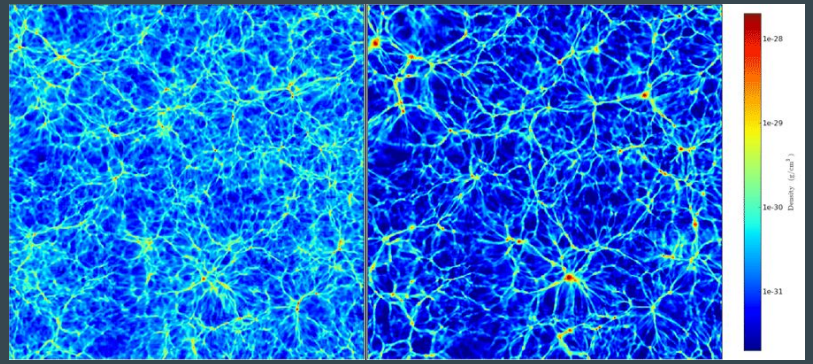
GERDA

What is the role of neutrinos in shaping the universe?

Structure in the Universe

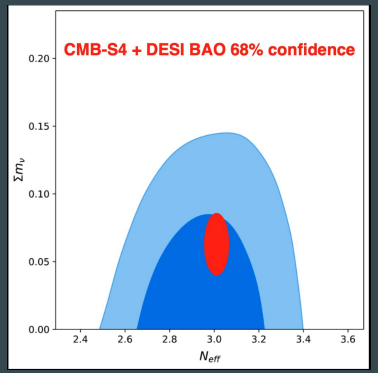
- As the 2nd most abundant particle in the universe, neutrinos profoundly impact the evolution of the universe.
- Even their minuscule masses leave a definite imprint on the universe at its largest scales.

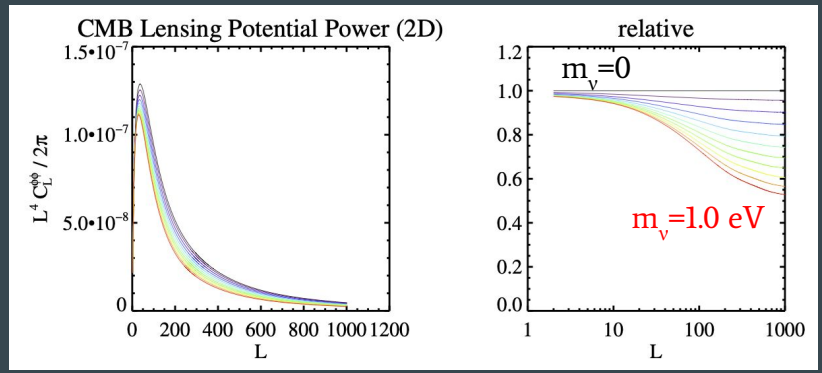
m_ν = 1.9 eV m_ν = 0 eV



S. Agarwal, H. Feldman

- Some of this has been seen . . . some of it may be around the corner.
- **Will we ever see the Cosmic Neutrino Background?**





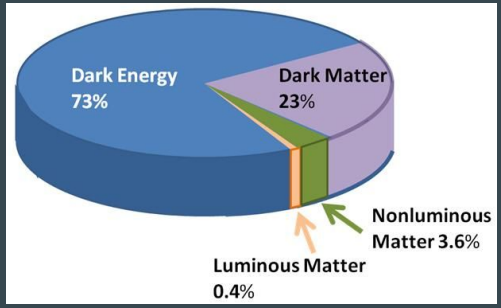
See M. G. Betti et al. Snowmass LOI

L. Knox, Neutrino 2020

K. Abazajian et al., CMB S4 Science Book

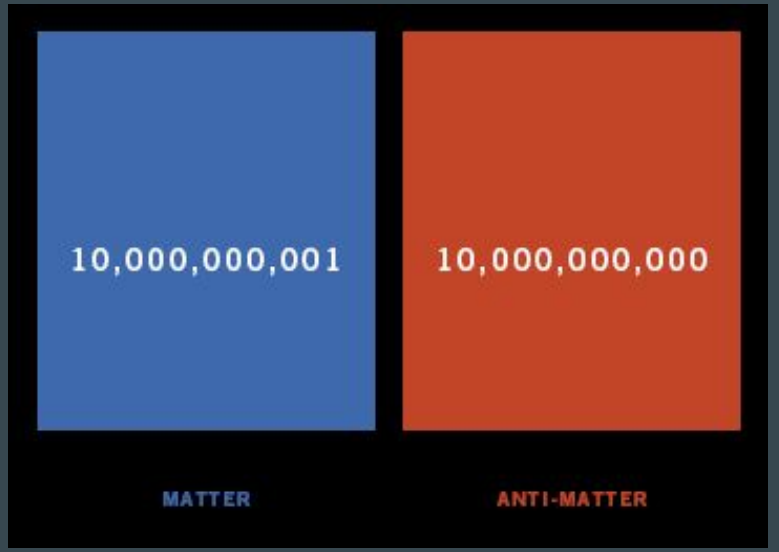
Baryon Asymmetry of the Universe

Courtesy, wikipedia.org



"Why is there matter everywhere we look?"

- Why is only matter left over from the Big Bang?
  - Why does the universe exist?
- New sources of CP violation beyond quark mixing are needed to explain this



H. Murayama, "What's ν"

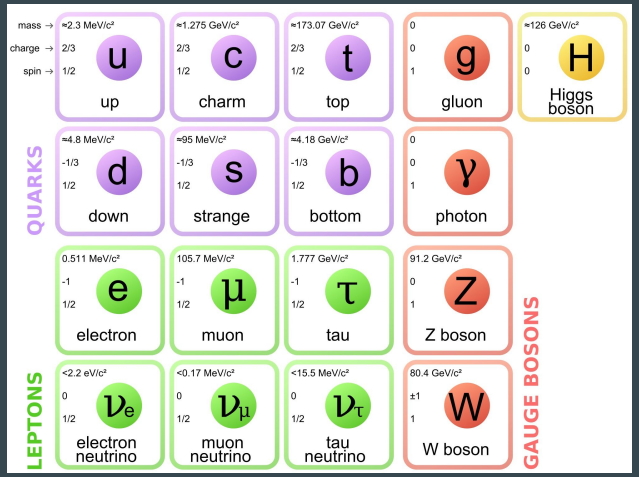
Big question: What (if anything) does neutrino CP violation have to do with this?

What additional properties could neutrinos be hiding?

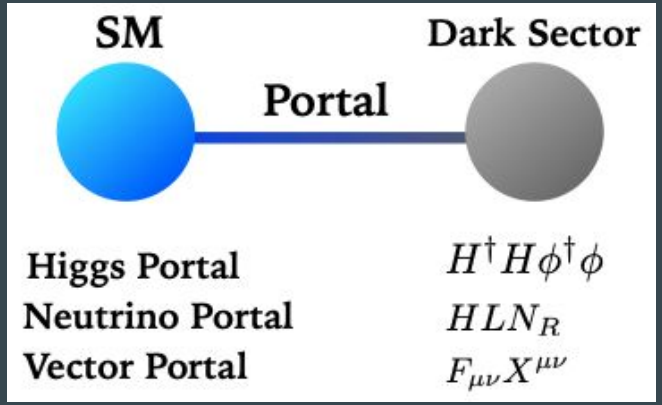
Some Possibilities;

- Fermions come in 3 generations
  - Why?
  - Could there be additional types of neutrinos?
  - For various reasons, they would be an even more exotic form that do not participate in the weak interaction
    - "Sterile neutrinos"
- Do neutrinos have interactions or mixing with new physics?
  - And does it have to do with anything else (e.g. dark sector)

This area is so broad that we'll leave it at this for now . . but definitely a huge question!



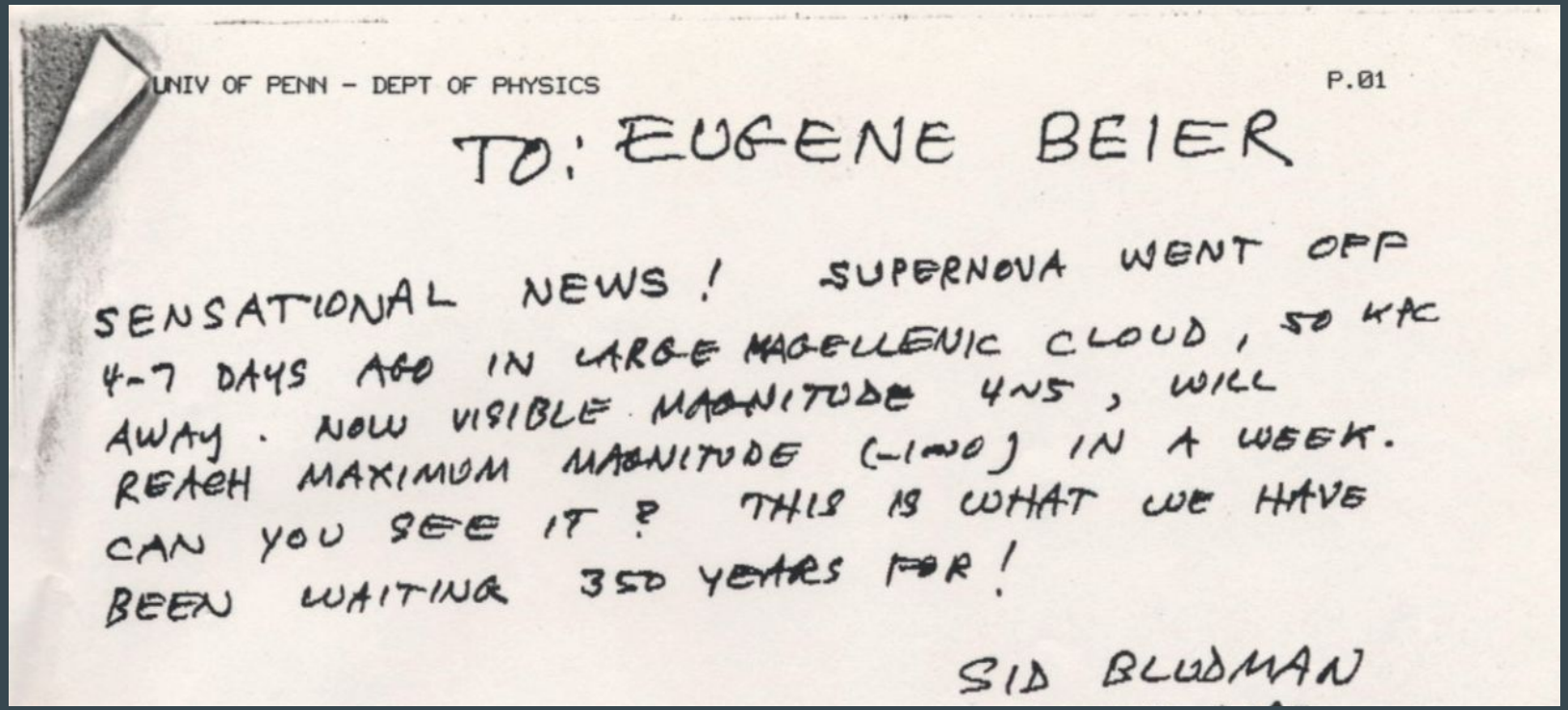
Courtesy: wikipedia



M. Aoki (Neutrinos: the quest for a new physics scale)

Are neutrinos good for anything?

SN 1987A news



UNIV OF PENN - DEPT OF PHYSICS P.01

TO: EUGENE BEIER

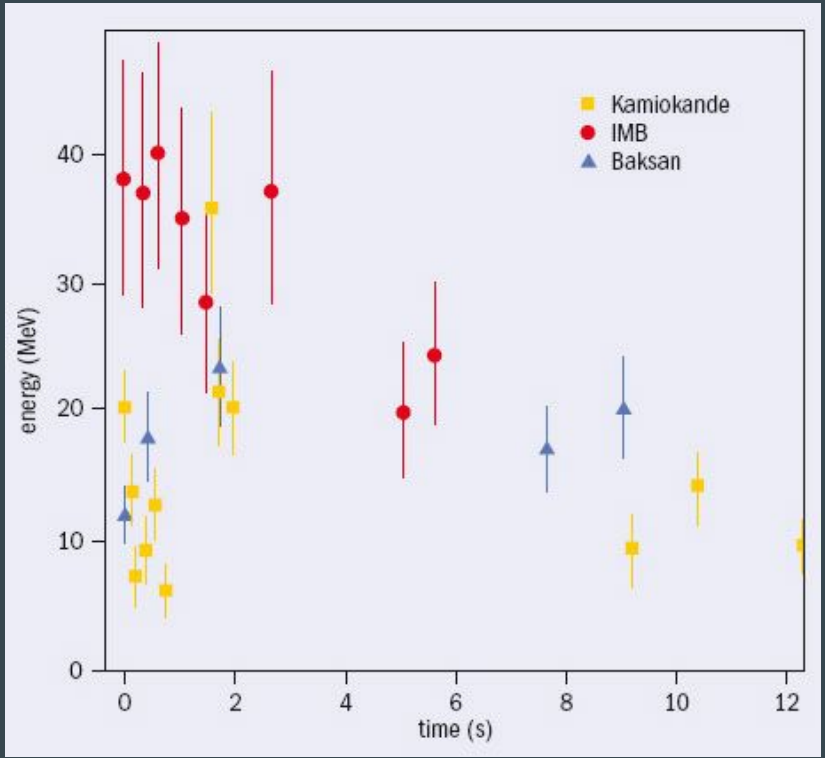
SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4N5, WILL REACH MAXIMUM MAGNITUDE (-1N0) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

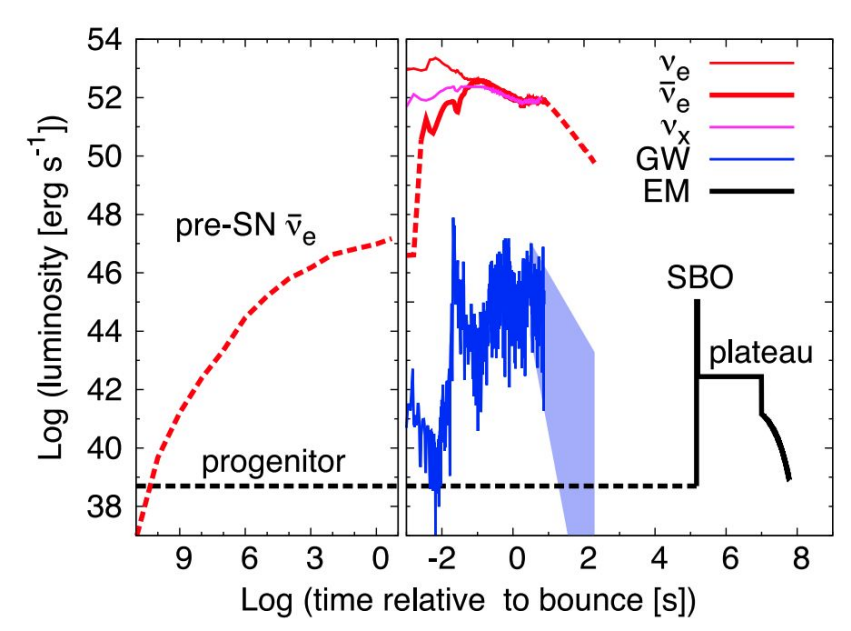
SID BLUDMAN

Cern Courier

Sent on February 25, 1987

Supernovae

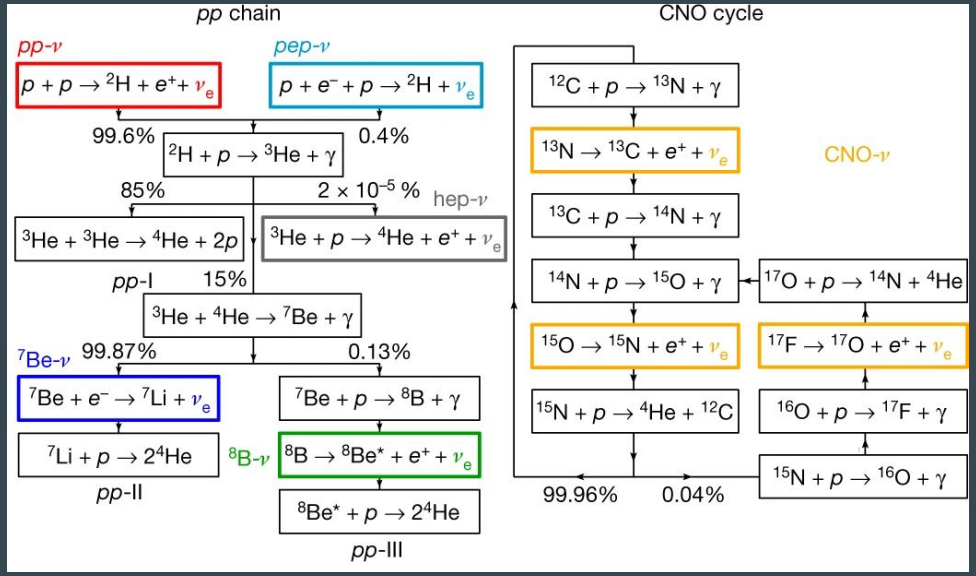


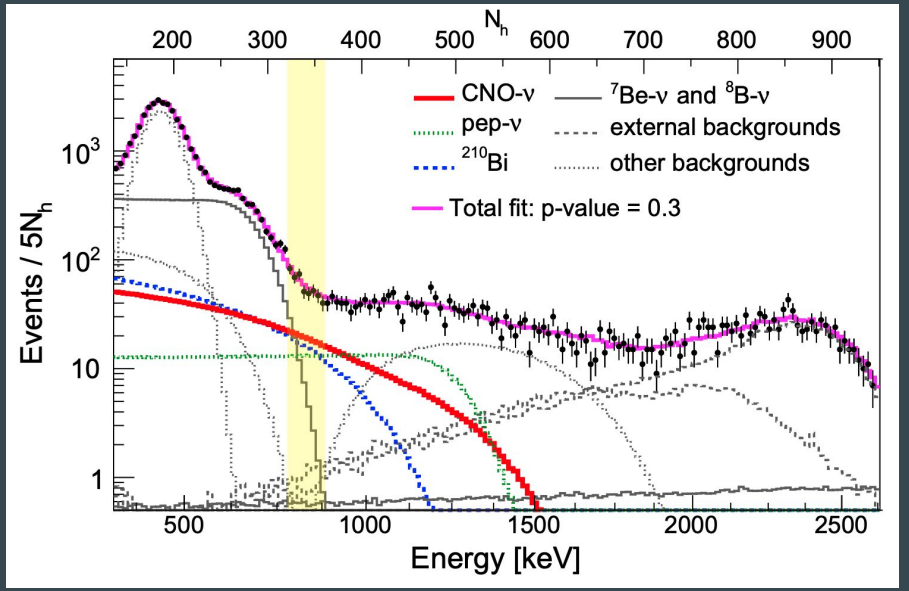


Cern Courier

Multimessenger signals of ... supernova simulations

Can Neutrinos be useful?

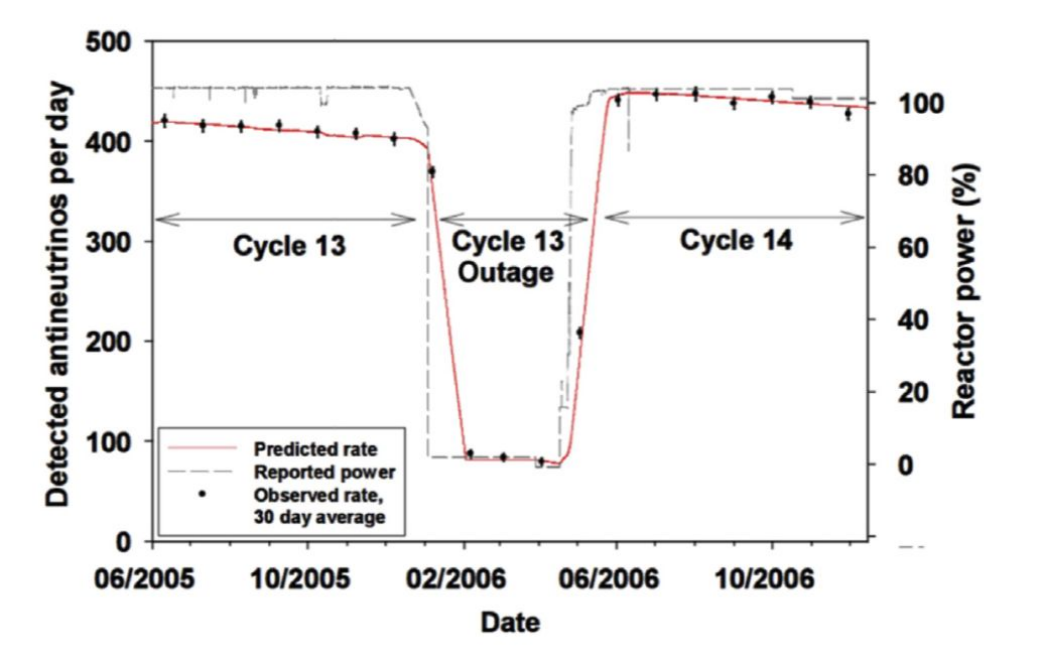


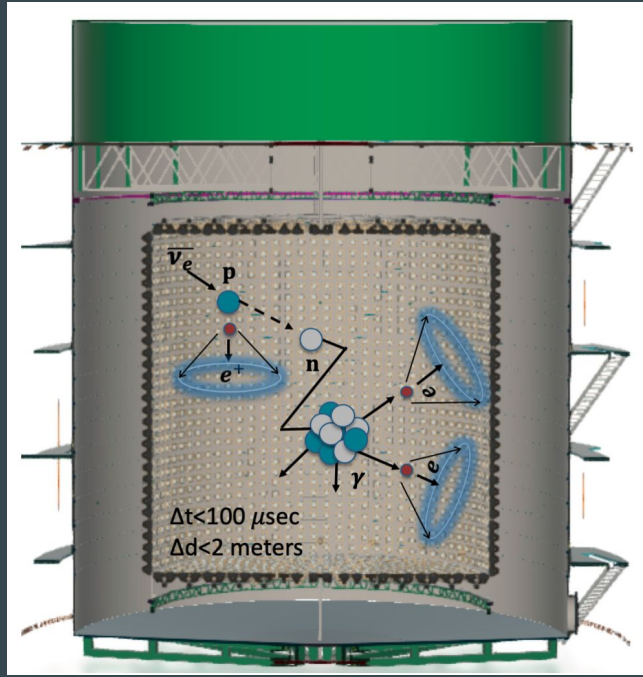


Borexino, Nature, 2018

Borexino, Nu2020

Nuclear Reactor Monitoring



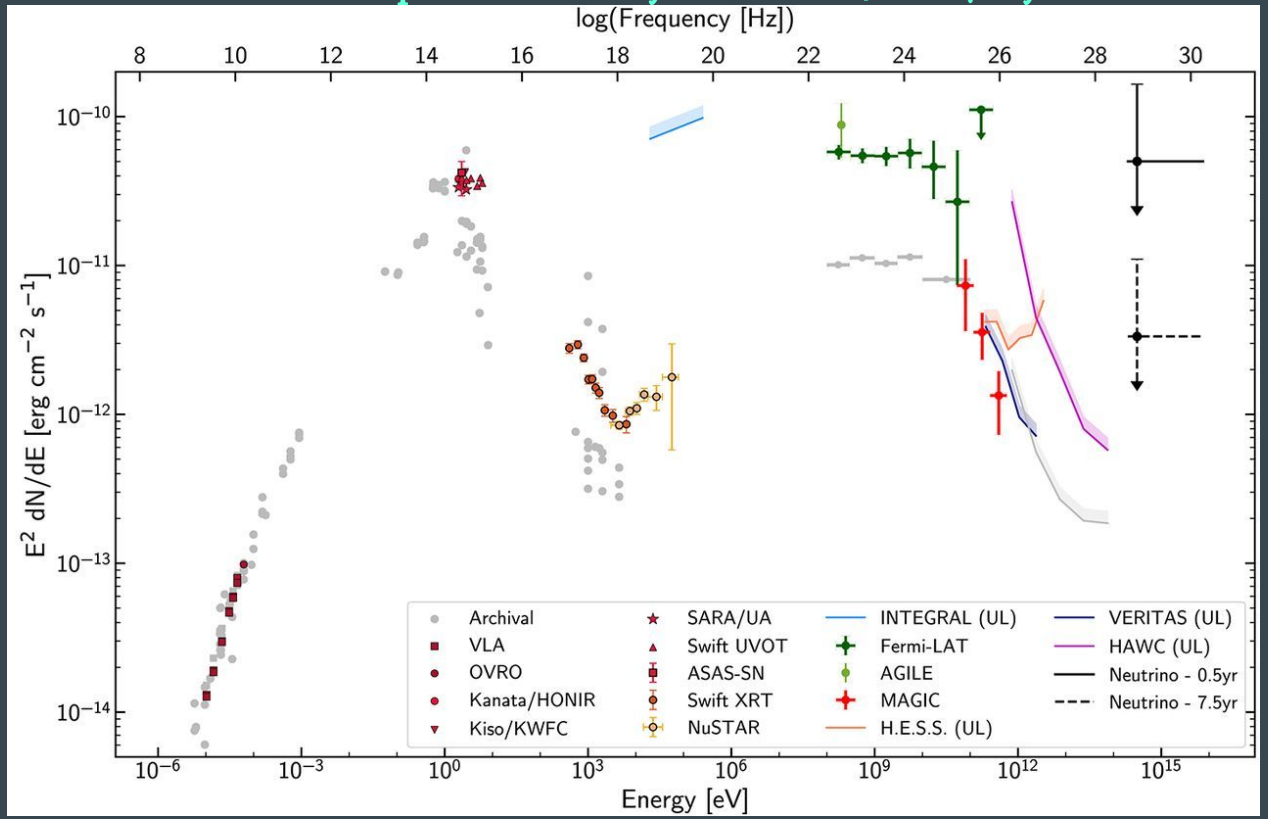


IAEA Report, 2008

T. Akindele, AAP 2019

Multi-Messenger Astronomy

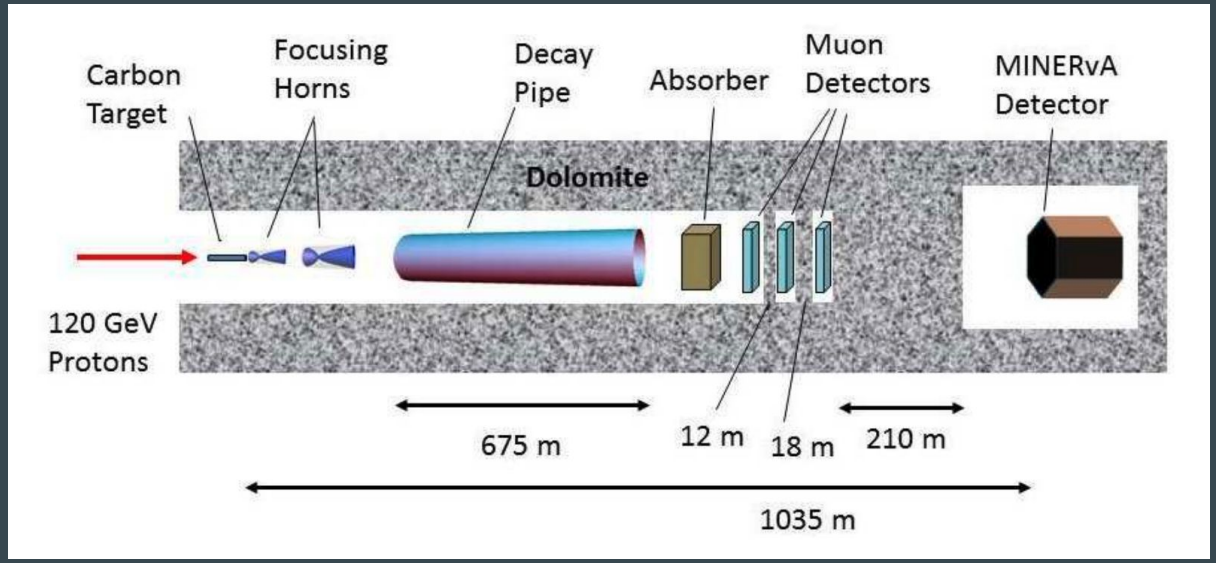
Radio Optical X-ray HE/VHE γ-ray Neutrinos

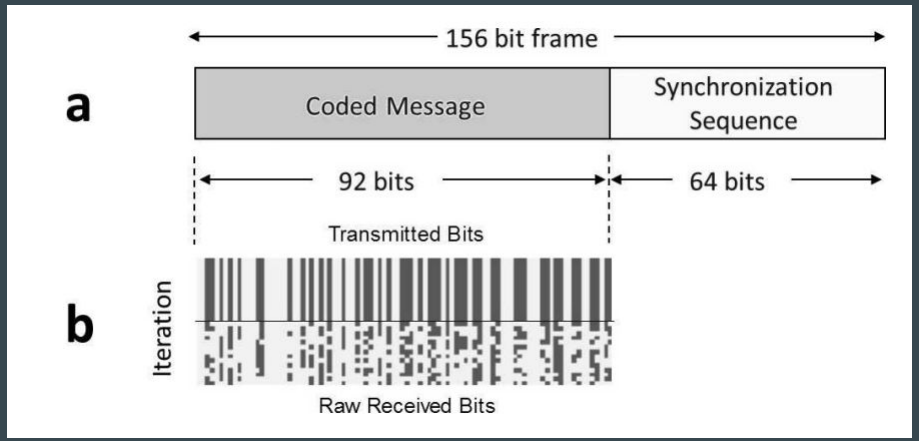


Multimessenger observations ... coincident with ... IceCube-170922A

Neutrino Messages?

An overall data rate of about 0.1 Hz was realized, with an error rate of less than 1% for transmission of neutrinos through a few hundred meters of rock. This result illustrates the feasibility, but also shows the **significant improvements in neutrino beams and detectors required for practical applications.**





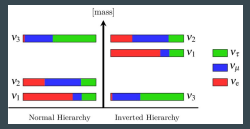
[Demonstration of Communication using Neutrinos]

“I don’t say that the **neutrino** is going to be a practical thing, but it has been a time-honored pattern that science leads, and then technology comes along, and then, put together, these things make an enormous difference in how we live.”

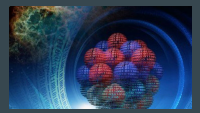
-Fred Reines, *LA Times, March 12, 1985*

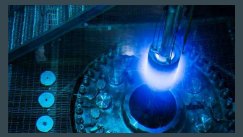
Neutrino mass

Neutrino mixing

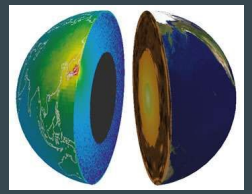


Neutrino probes of nucleon/nucleus

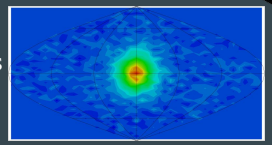


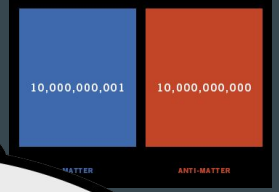


geoneutrinos

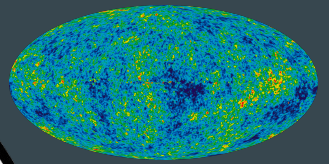


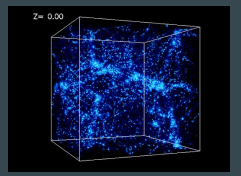
Stellar neutrinos





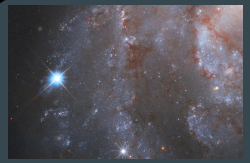
Early Universe





Large Scale Structure

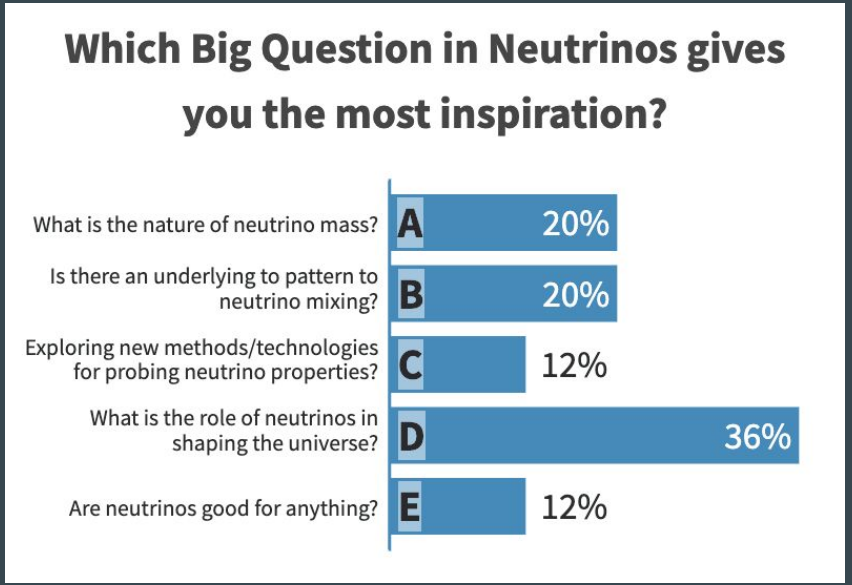
Astrophysical sources



scale

Summary

- Our biased view of the “Big Questions” in neutrinos
- One last poll question
  - http://www.pollev.com/nuquestions524



Thanks for your attention!

Let’s continue the conversation:

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Hirohisa Tanaka (hatanaka@stanford.edu)