"Other Physics with Large Detectors"

or

Neutrinos Gone WILD!
(and other exotica)

“Proton decay has never been witnessed”
Stina Fisch, pen & ink, 2011

Jen Raaf

Summer Undergraduate
Lecture Series

Fermilab

July 9, 2015

Topics

(don't worry, this is not an outline)

- ✧ Wild neutrinos

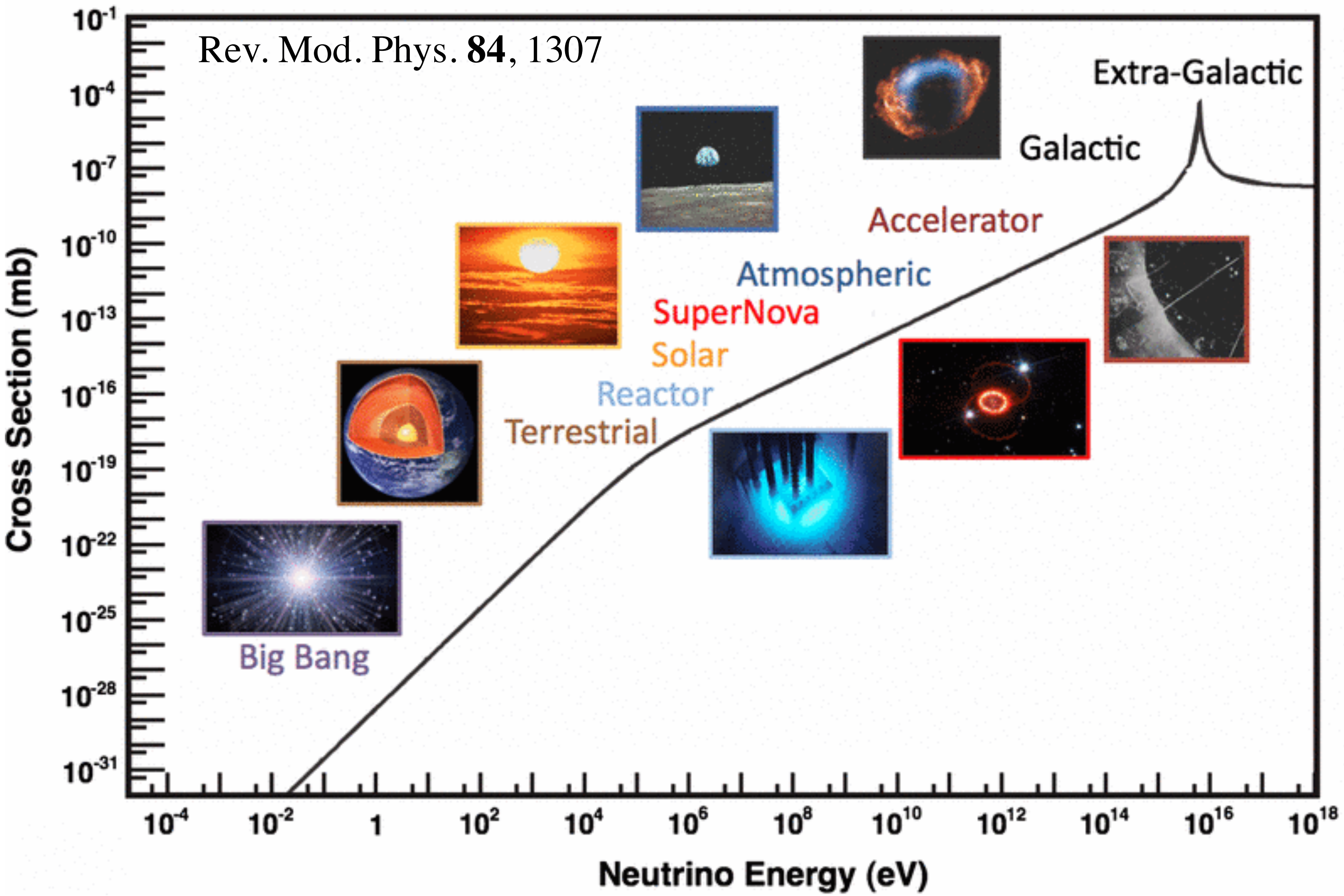
solar	cosmological
supernova	terrestrial
atmospheric	astrophysical

- ✧ Exotica

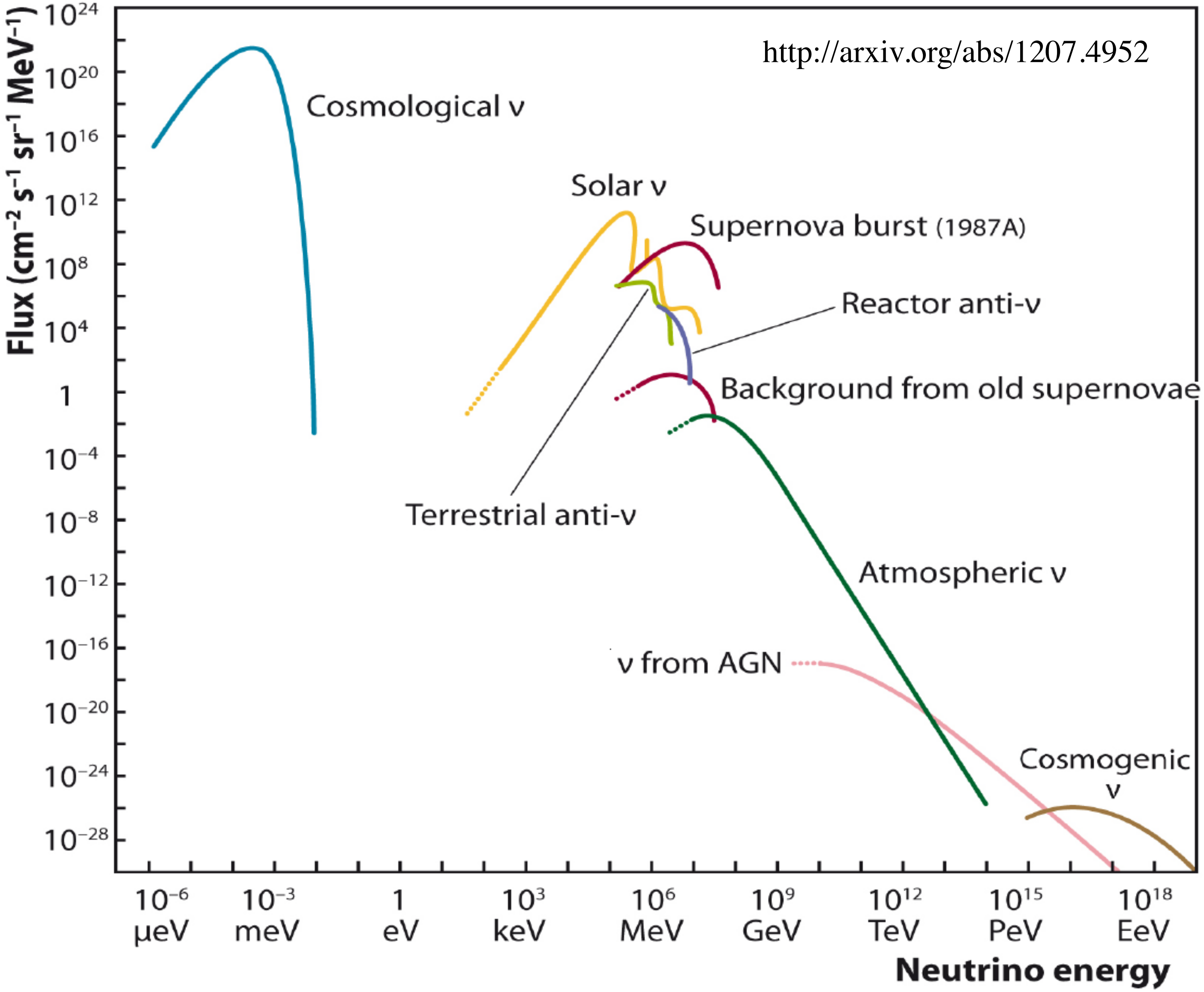
proton decay	neutron-antineutron oscillation
dark matter	magnetic monopoles
Q-balls	etc.

Disclaimer: Mostly I will use Super-Kamiokande here in examples, but these types of analyses can be done in other large (underground) detectors as well.

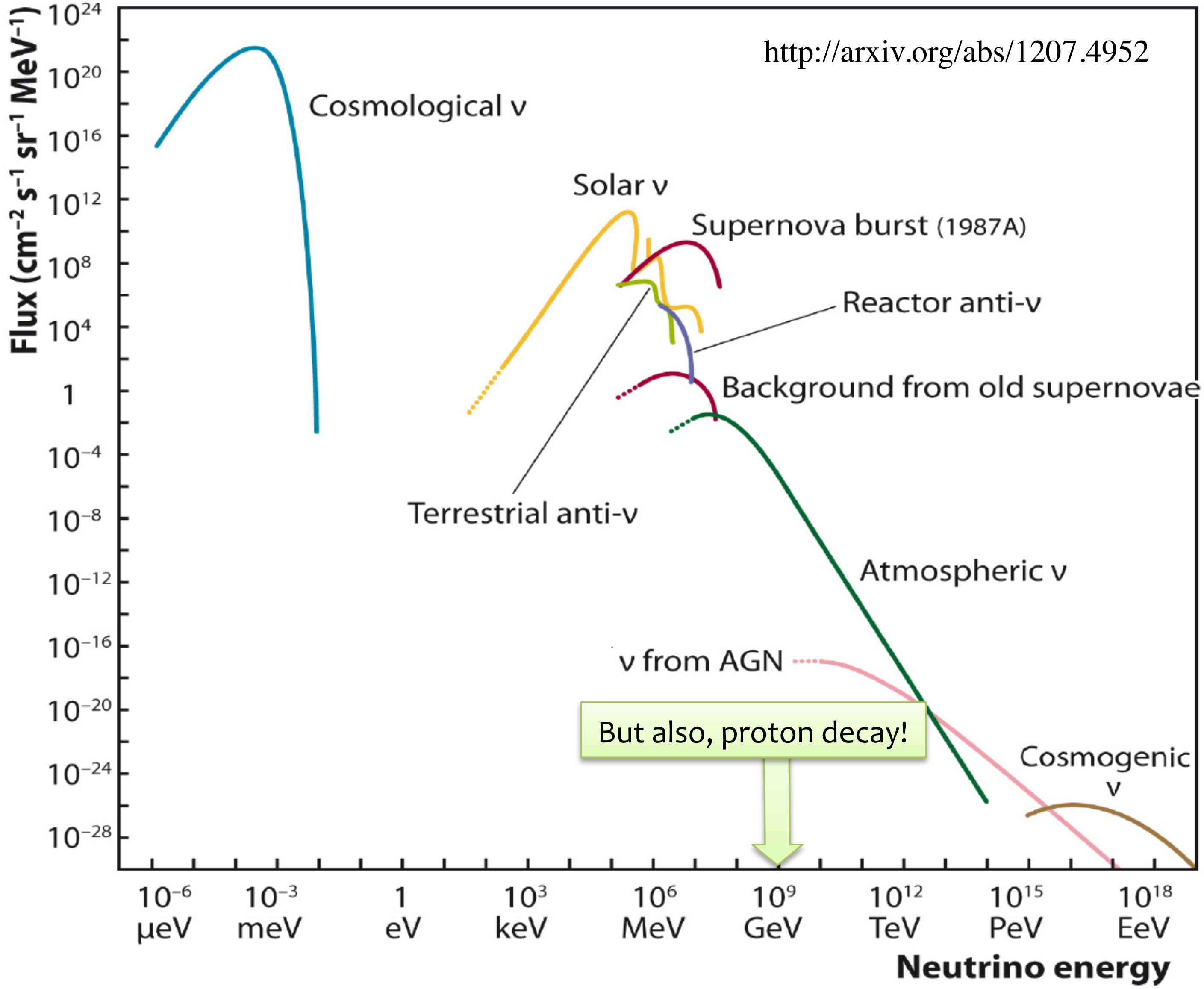
Remember this from previous talks?



Another way to look at things

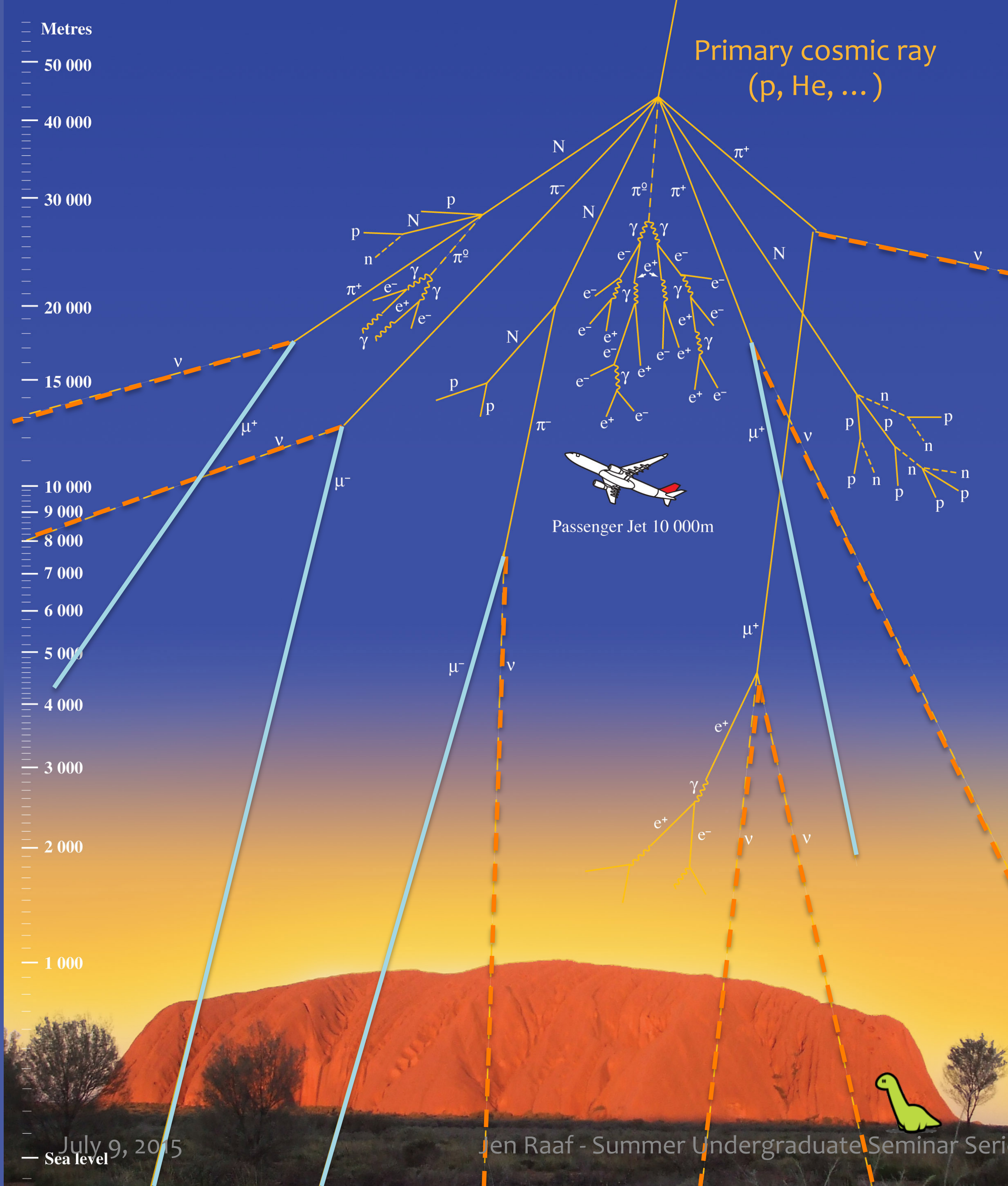


Another way to look at things



First things first: go find a cave

(maybe a slightly bigger one)

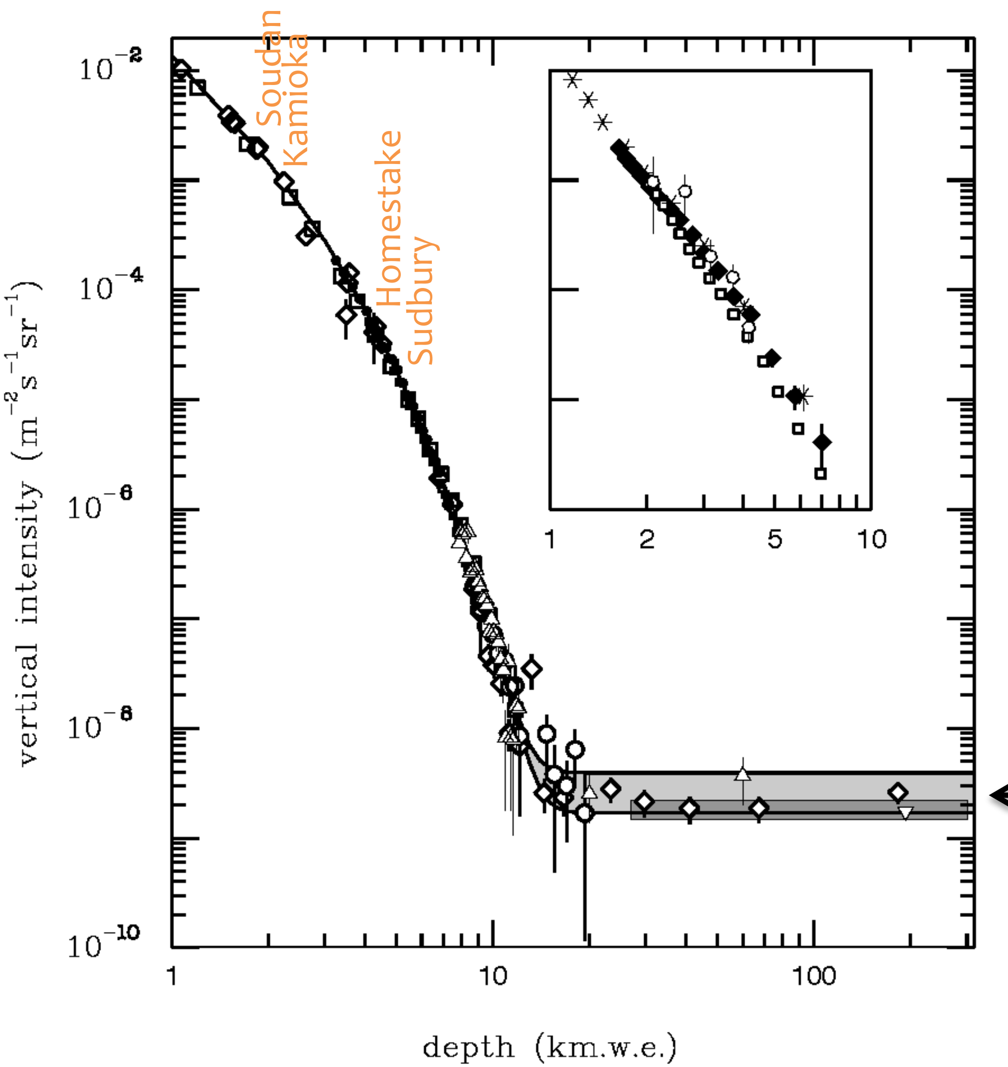


Because cosmic rays

Neutrinos are what we want to study.

Muons can be useful, but also annoying if too abundant. Solution: go underground!

Muon rate underground

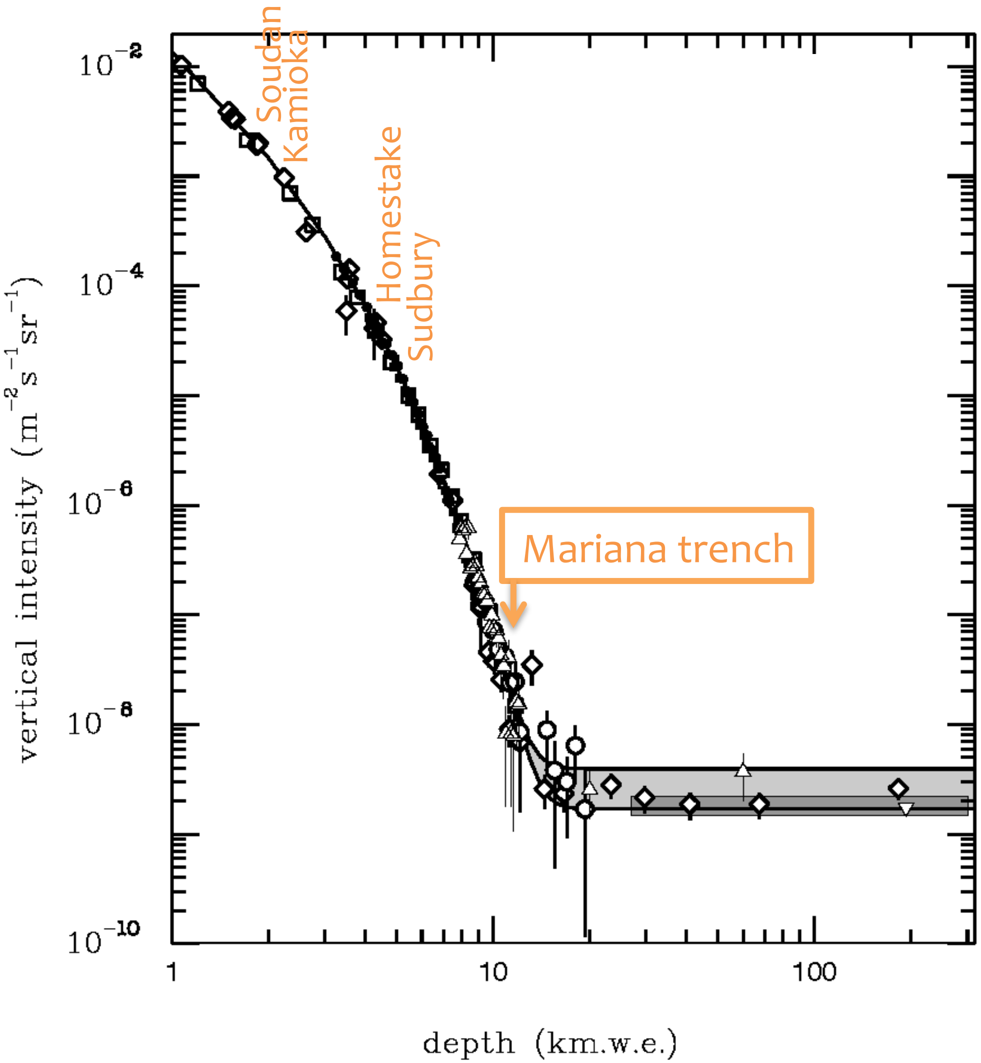


(kilo)meters water equivalent:
Divide by average rock density ($\sim$2.7 g/cm^3) to get ~actual depth

Number of muons decreases as you go deeper underground

Neutrino-induced muons (from atmospheric neutrinos)

Muon rate underground

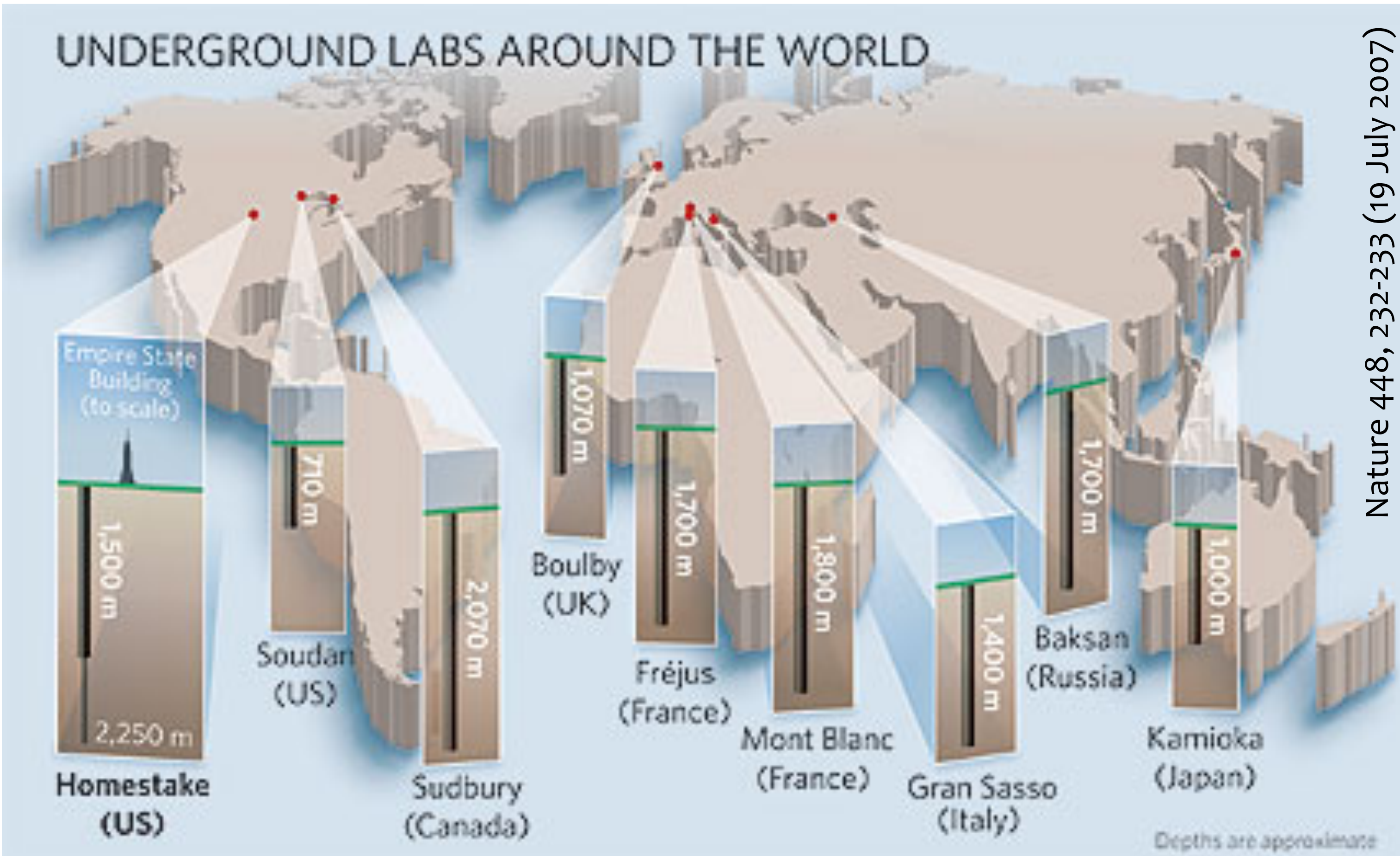


A lab under ~3.7 km of rock would be shielded from cosmic rays equivalent to being 10 km below the surface of a body of water, like the snailfish…

(almost… the snailfish is a pansy; it only lives at a depth of 8.2 km, whereas this amphipod lives at 10 km without being crushed!)

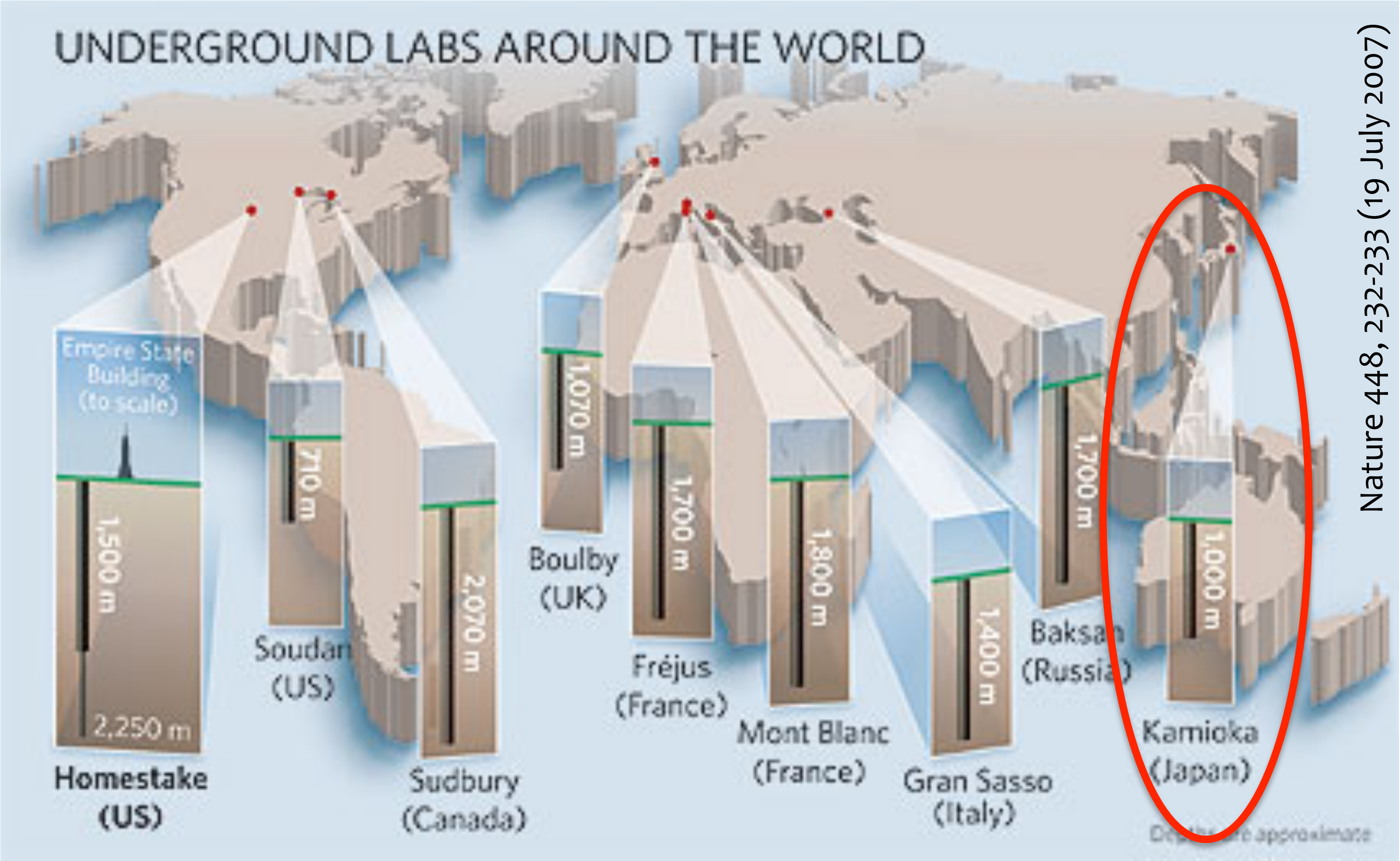
http://www.bbc.com/news/science-environment-17060360

Where can we go?



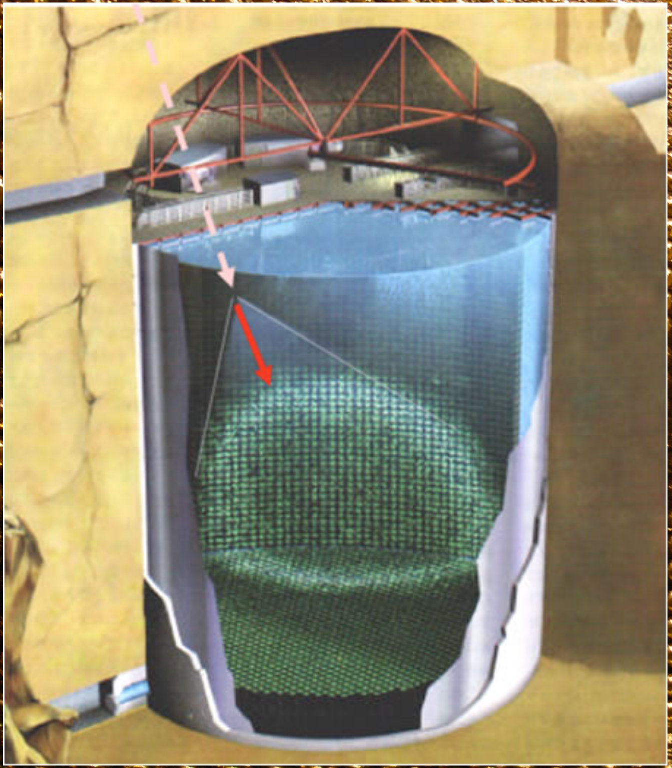
Nature 448, 232-233 (19 July 2007)

Where can we go?



Nature 448, 232-233 (19 July 2007)

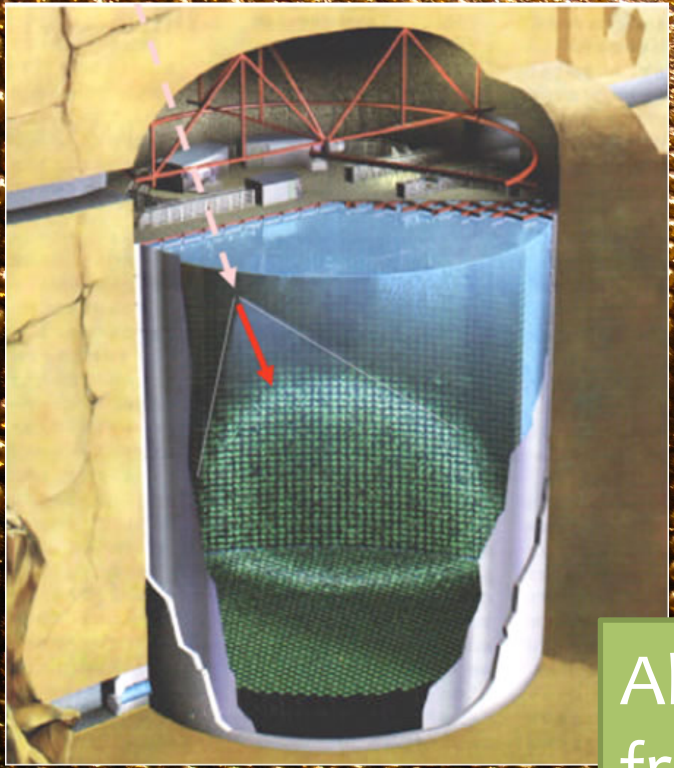
Super-Kamiokande



- Kamioka zinc mine
- 2700 m.w.e. (1000 m rock overburden)
- 50,000 tons of pure water
- ~11,000 50-cm PMTs

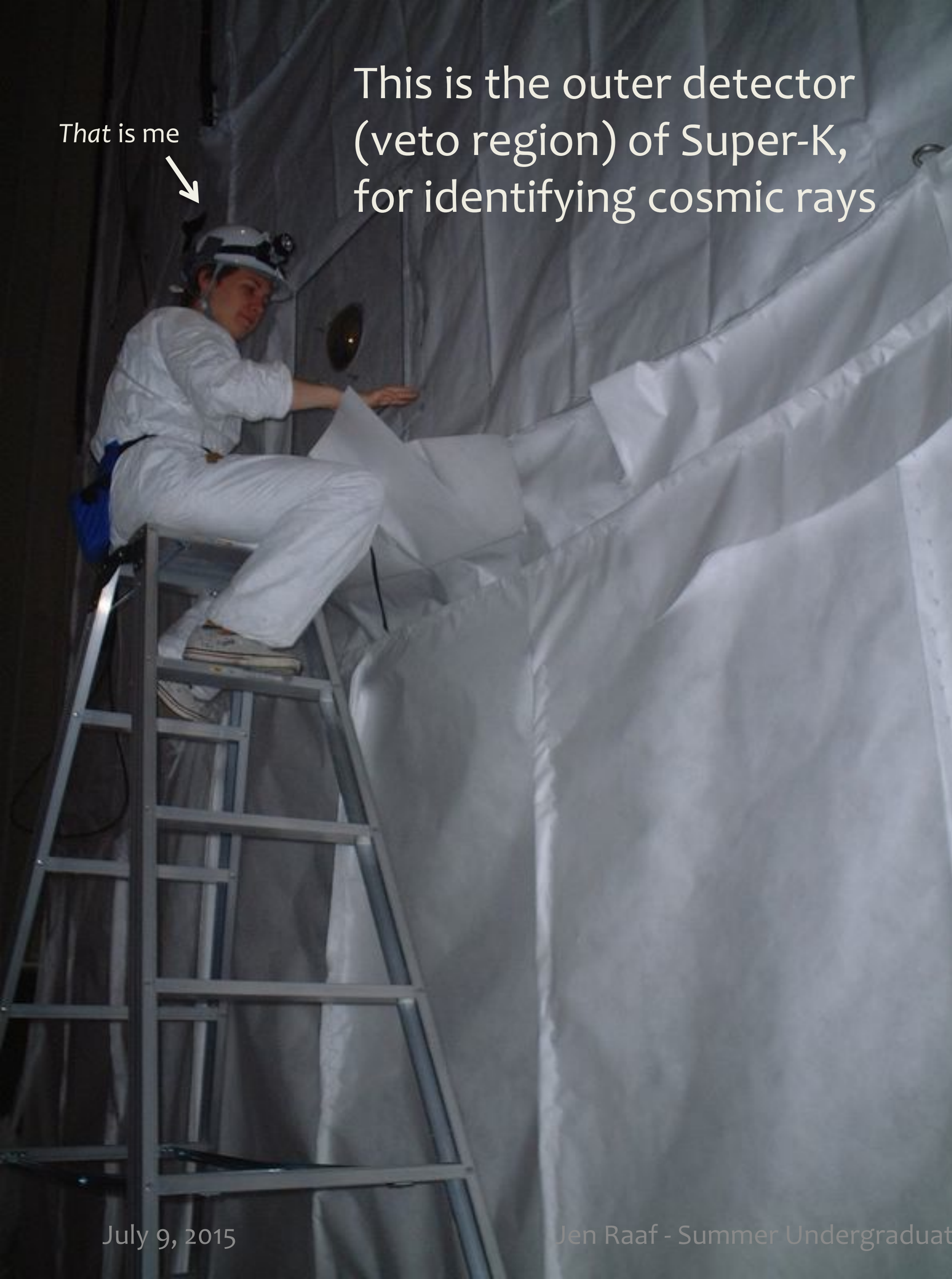
That is not me

Super-Kamiokande

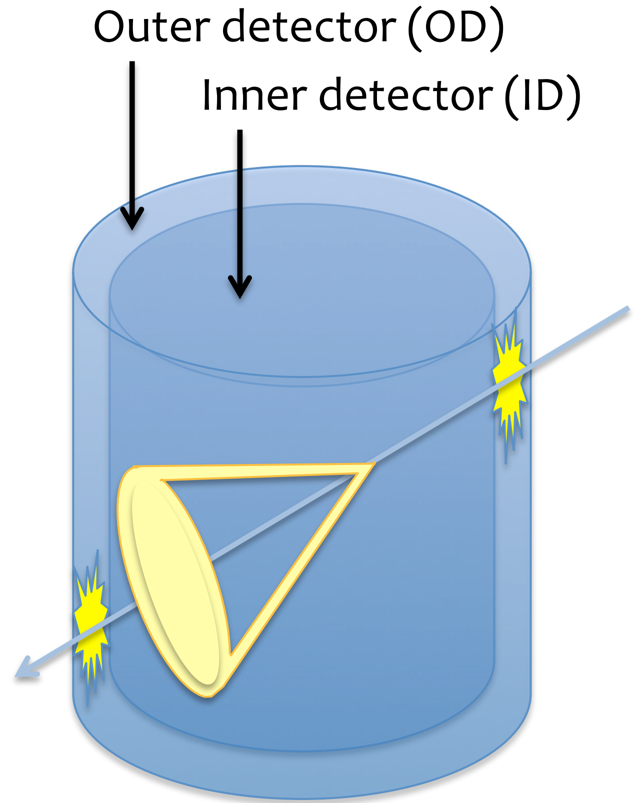


Kamioka zinc mine
2700 m.w.e. (1000 m rock overburden)
50,000 tons of pure water
~11,000 50-cm PMTs

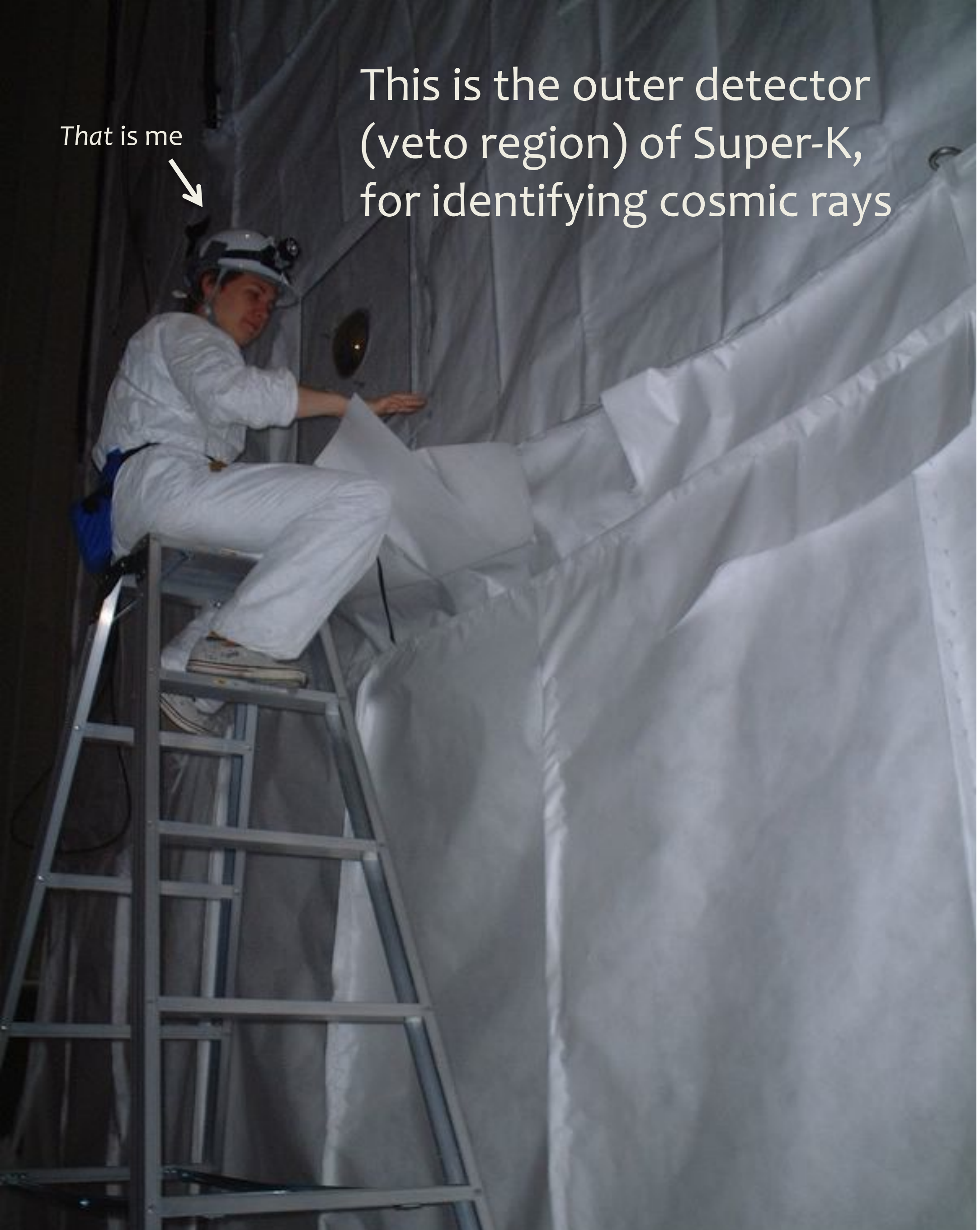
About the same height as from ground to ~8th floor of Wilson Hall



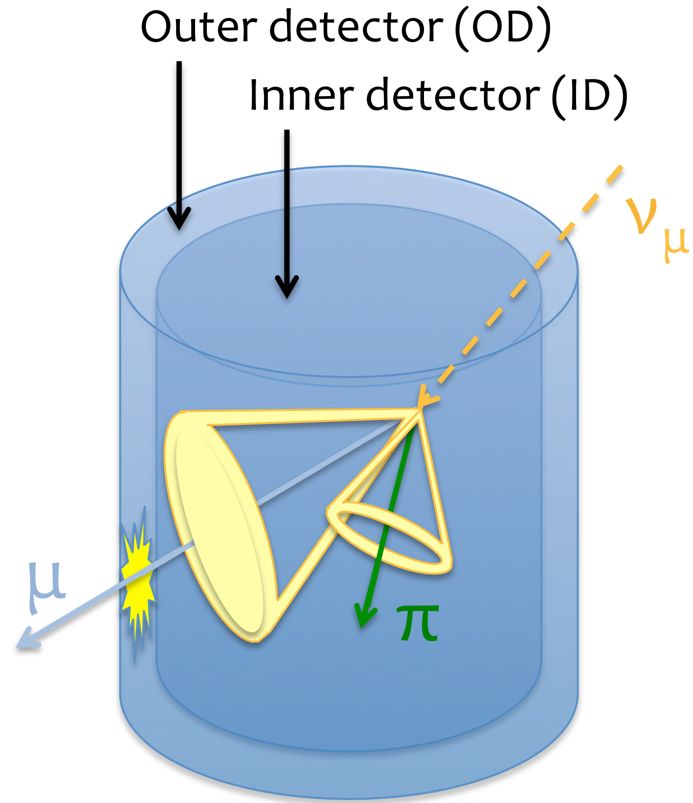
This is the outer detector (veto region) of Super-K, for identifying cosmic rays



Cosmic ray muons deposit energy in the outer detector when entering (and often also exiting). Pretty easy to remove them.

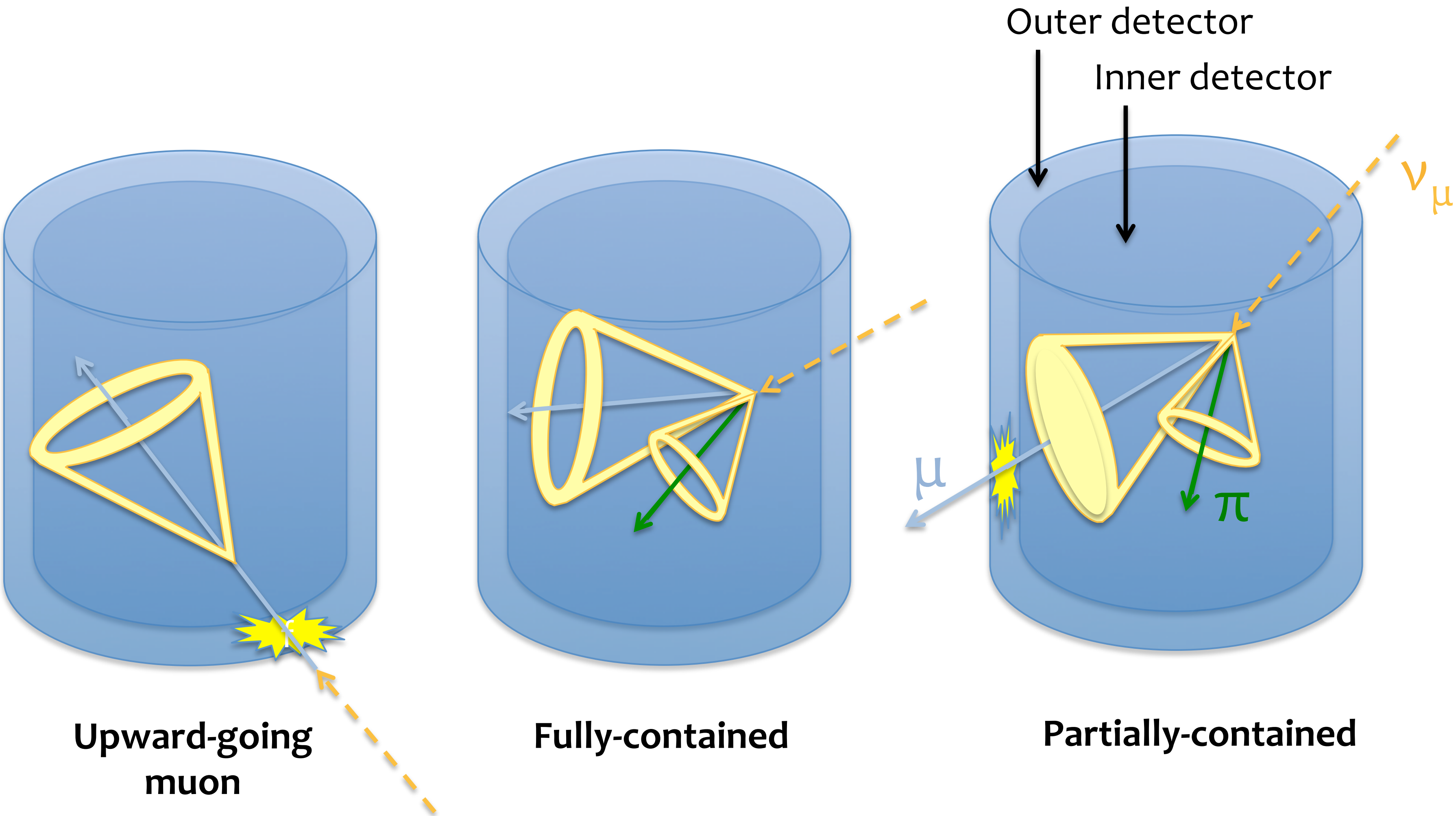


This is the outer detector (veto region) of Super-K, for identifying cosmic rays



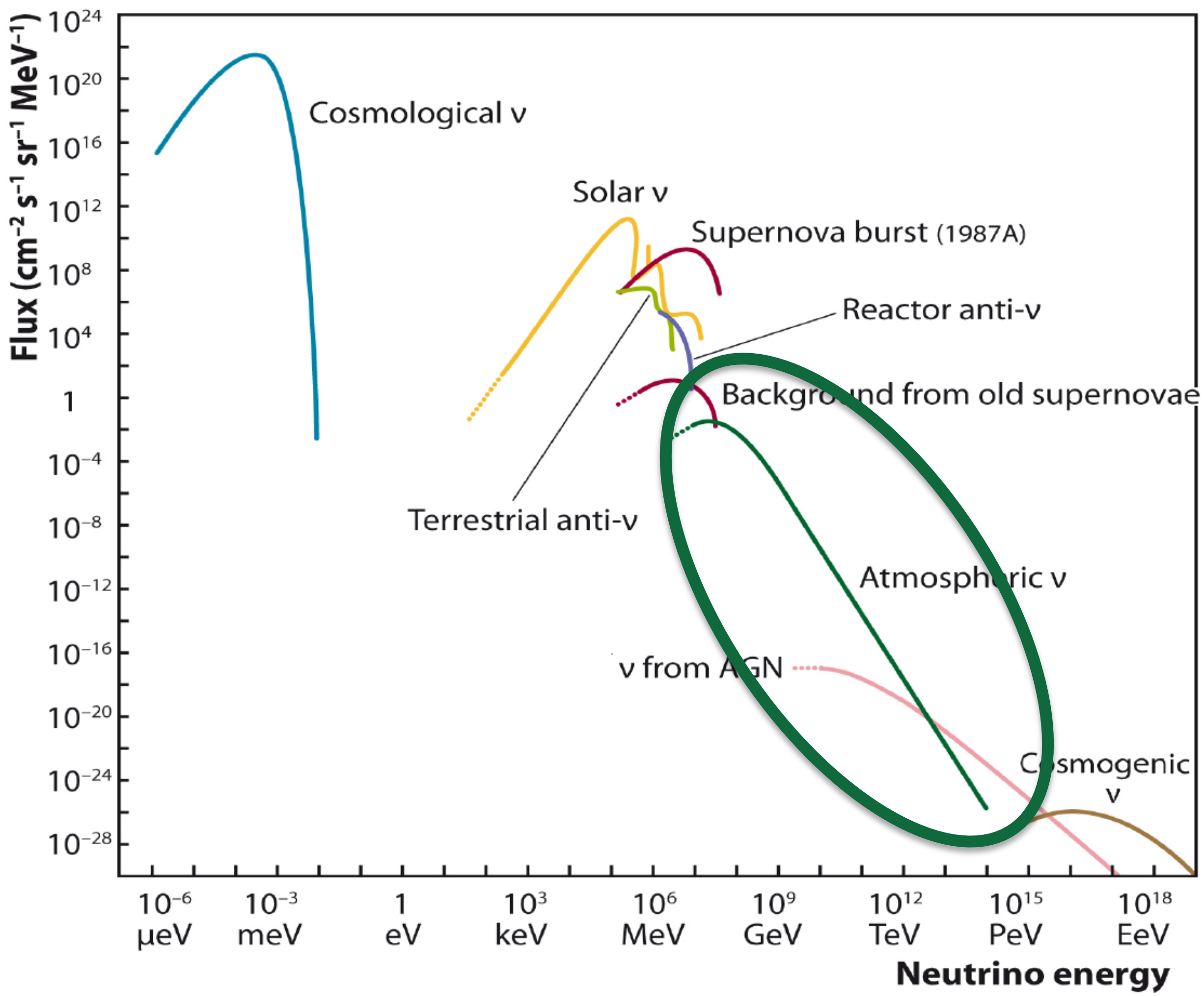
Neutrinos have no outer detector activity at the entering point, but products of their interactions may make light in the OD if they exit.

Neutrino Event Classification in Super-K

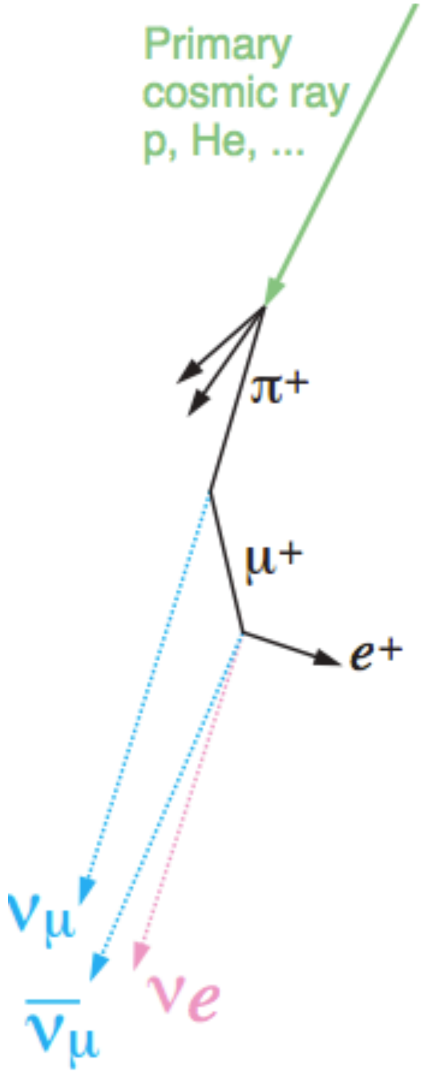


All of these (and more) are used in Super-K analyses

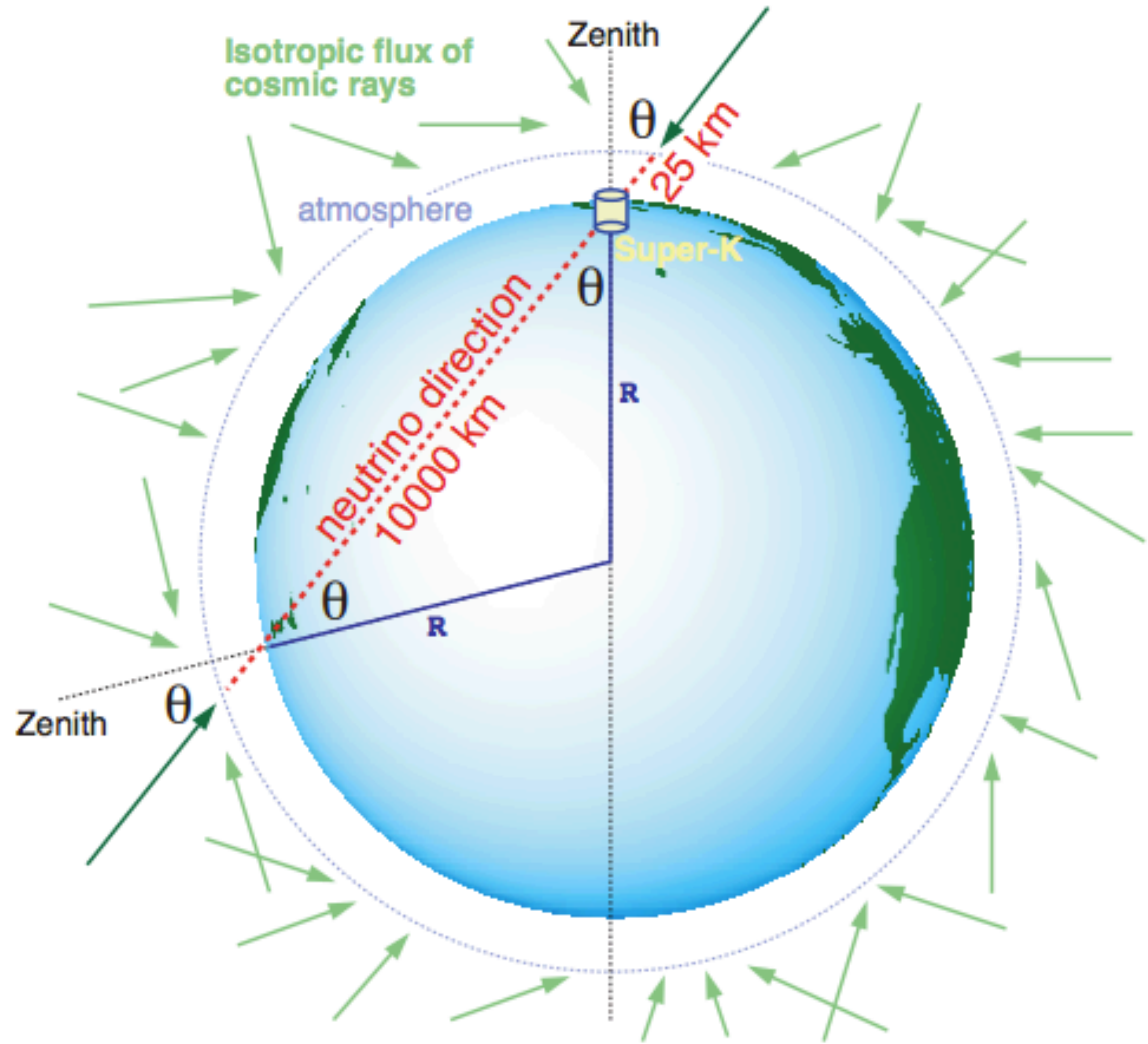
“Wild” neutrino source: Atmosphere



Atmospheric Neutrinos



2:1 Ratio

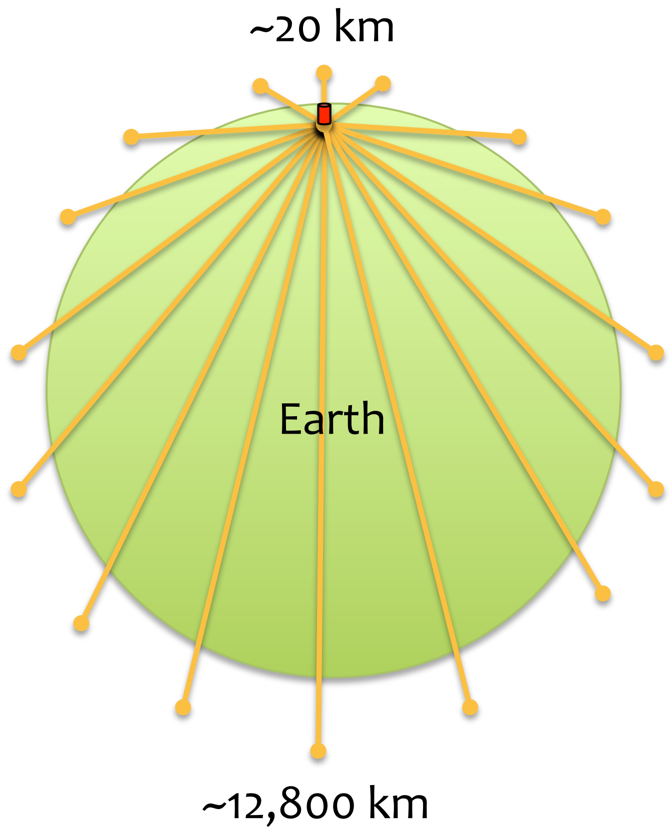


Up/Down Symmetric Flux

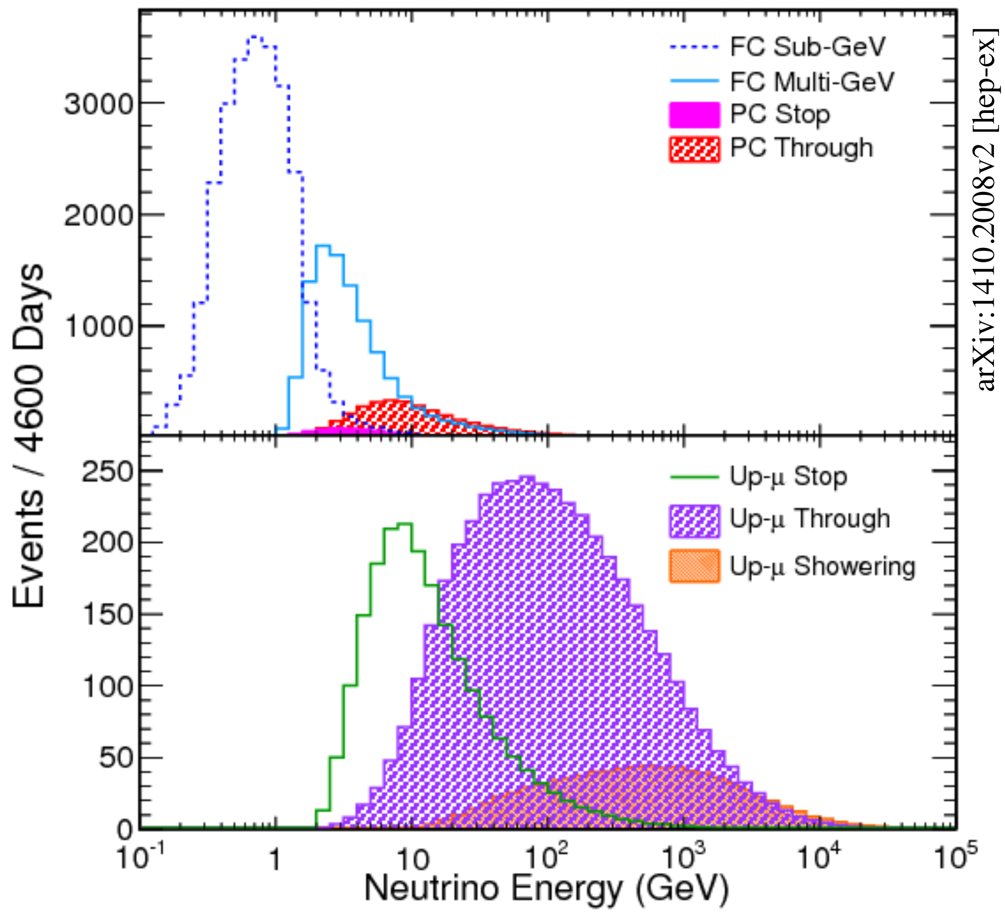
Image blatantly stolen from Ed Kearns

Huge range in pathlength and energy

4 orders of magnitude in path length



5 orders of magnitude in energy

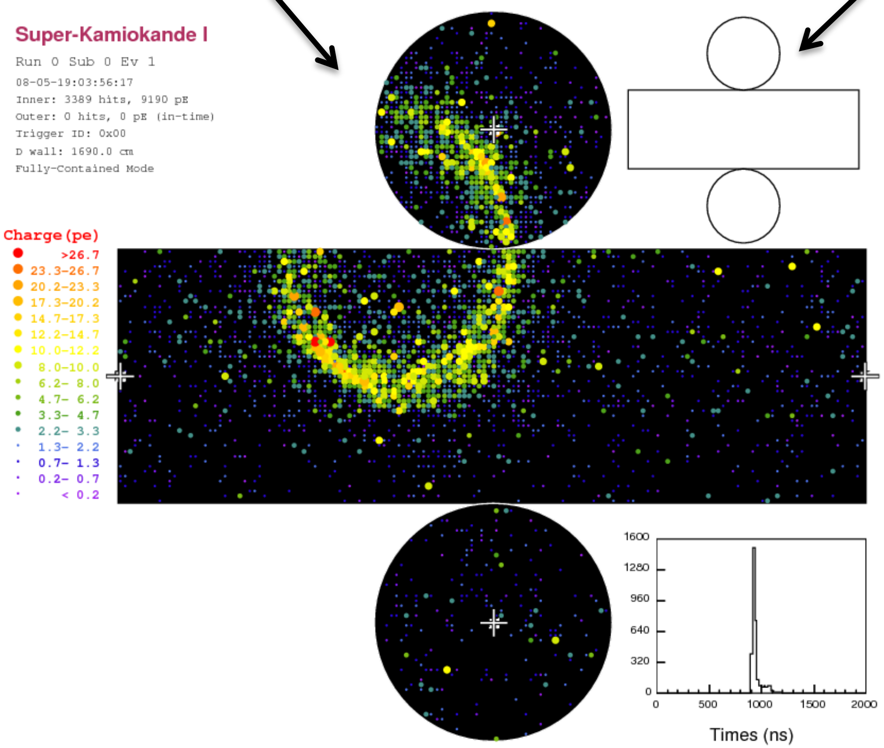


What they look like in Super-K

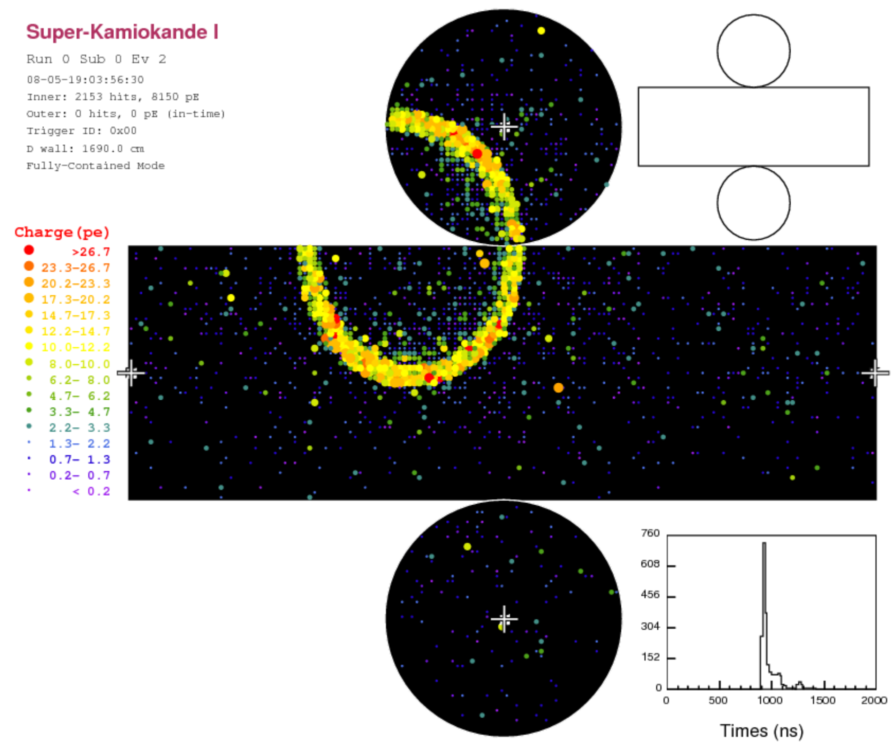
"Unrolled" view: like cutting open a soup can and laying it out flat 

Inner detector

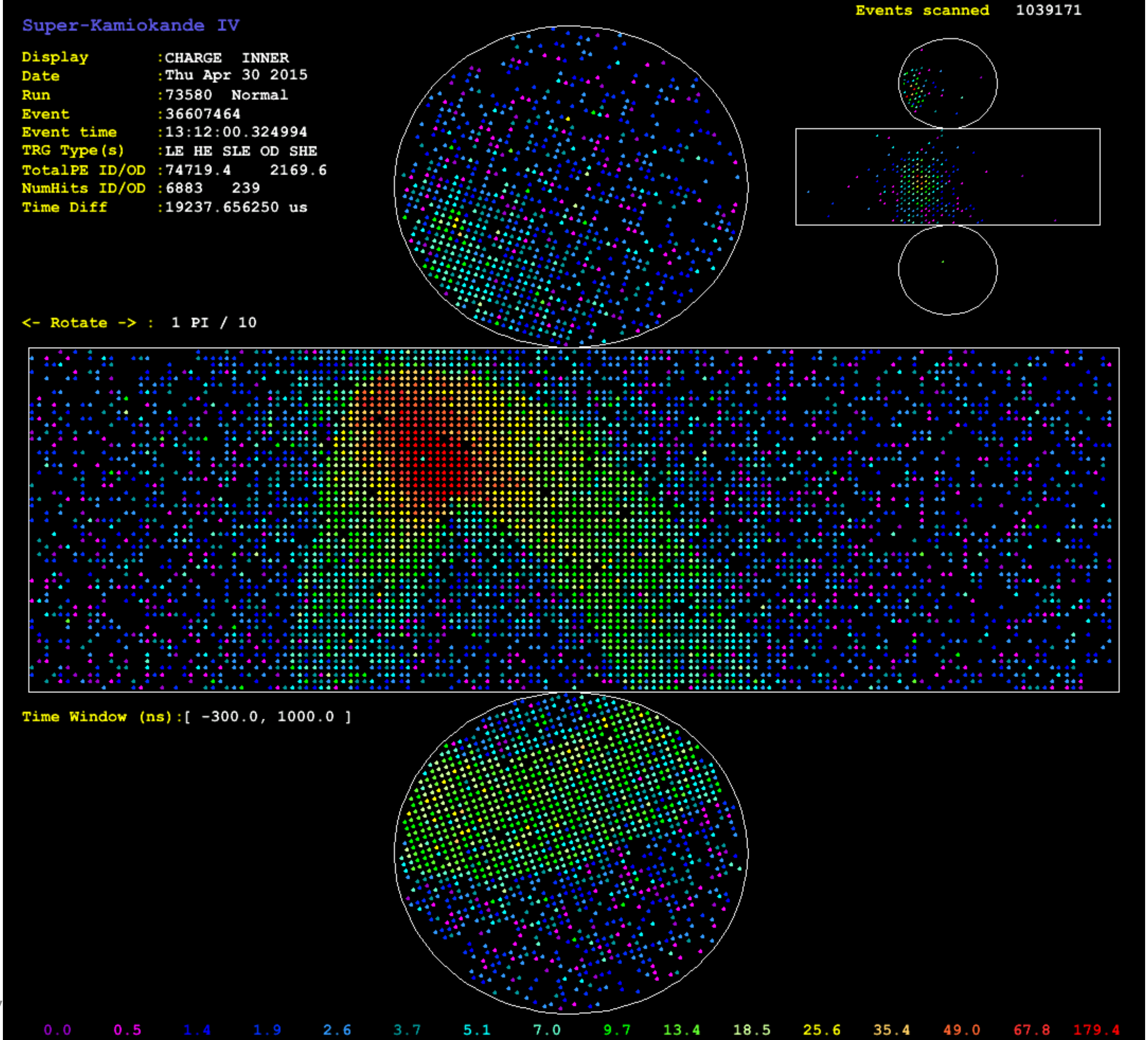
Outer detector



1 GeV electron
"showering ring"



1 GeV muon
"non-showering ring"


Events scanned 1039171
Super-Kamiokande IV
Display :CHARGE INNER
Date :Thu Apr 30 2015
Run :73580 Normal
Event :36607464
Event time :13:12:00.324994
TRG Type(s) :LE HE SLE OD SHE
TotalPE ID/OD :74719.4 2169.6
NumHits ID/OD :6883 239
Time Diff :19237.656250 us
<- Rotate -> : 1 PI / 10
Time Window (ns):[-300.0, 1000.0]
0.0 0.5 1.4 1.9 2.6 3.7 5.1 7.0 9.7 13.4 18.5 25.6 35.4 49.0 67.8 179.4

Oscillations!

The New York Times

Copyright © 1998 The New York Times — NEW YORK, FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, Friday, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter, the Standard Model.

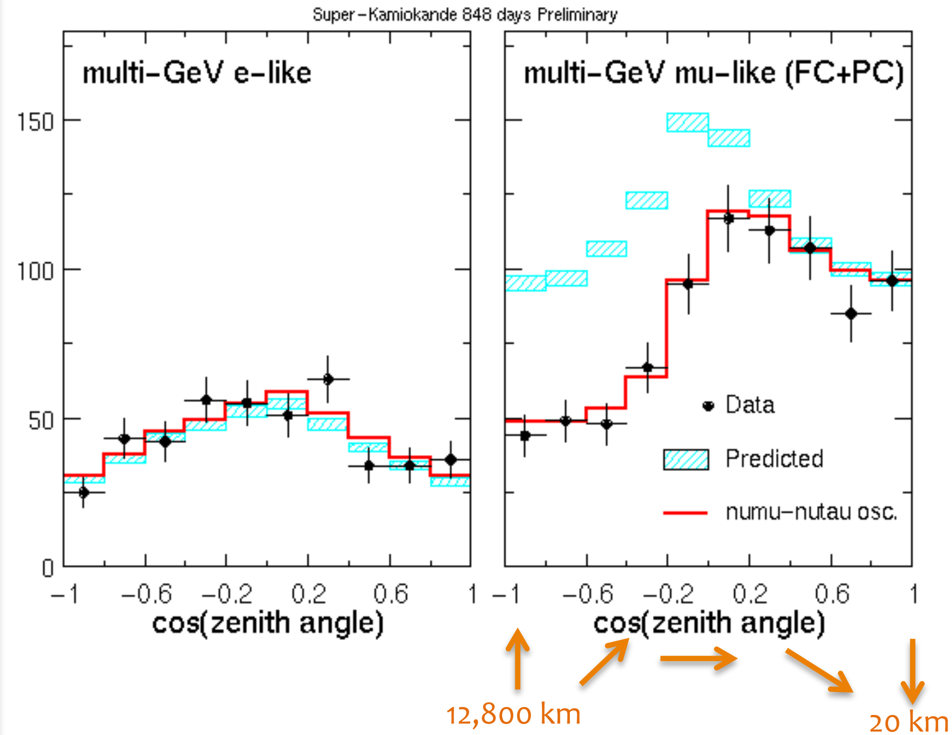
Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Detecting Neutrinos

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

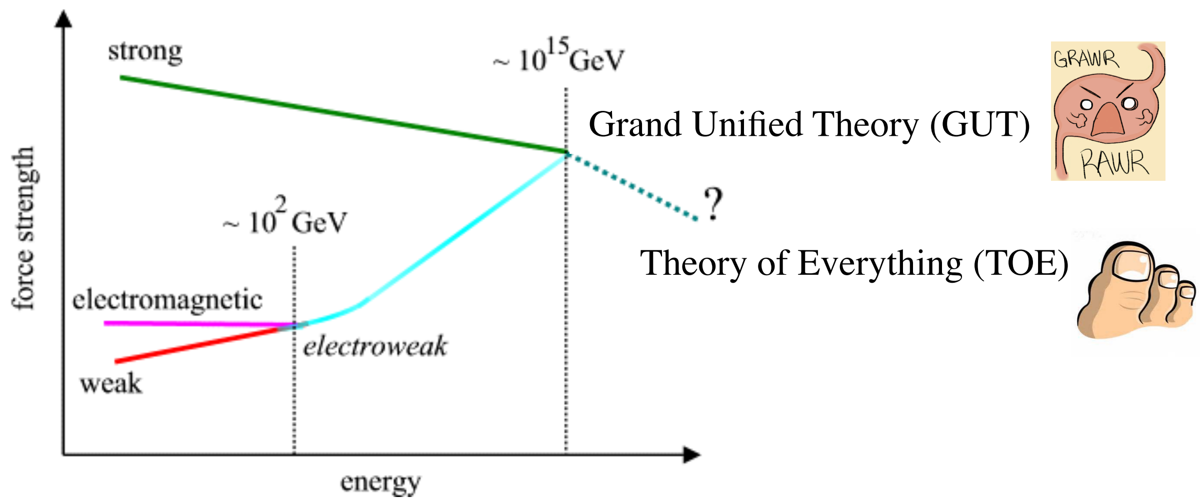


First evidence of atmospheric oscillations: only ~50% of the expected upward-going events were seen!

We study many other oscillation effects with these data as well.

So you've got a bunch of protons…

- What else can you do? Test grand unification!
  - Electroweak force successfully combines EM & weak forces
  - Next: combine electroweak and strong forces (so-called "grand unification")
  - Then what? Add in gravity: "Theory of Everything"



- Energy scale for grand unification is ~10^{11} times higher than achievable in accelerators, but we can indirectly test GUTs by looking for processes they often predict:
  - nucleon decay (protons and bound neutrons)
  - magnetic monopoles
  - neutron-antineutron oscillations, …

The first proton decay analysis

THE SEARCH FOR PROTON DECAY - A LOOK BACK*

BNL--41757

DE89 001606

Maurice Goldhaber
Brookhaven National Laboratory**
Upton, NY 11973

Dedicated to Reines on his 70th birthday

My young friend Fred Reines and I have been interested in the question of proton stability for more than a third of a century, when we made the first explicit attempt to test it. At that time there was a widespread belief that the proton is absolutely stable, as expressed first by Weyl in 1929, ten years later by Stueckelberg, and ten years later again by Wigner. But what was the reason for this belief? One might say, these physicists felt it in their bones that the proton is stable, but the bones, one can estimate, are only sensitive to proton life times $\lesssim 10^{16}$ years; for shorter lifetimes one might have to file an environmental impact statement before filling a lecture hall. It is interesting to see how Wigner argued (Proc. Am. Philos. Soc. 93, 521 (1949), p. 525, footnote):

Maurice Goldhaber observed that because we (humans) don't die from radiation sickness, from nucleon decays irradiating our bones, the proton must have a lifetime of longer than 10^{16} years. Later he made another estimate based on isotope abundances, that $\tau_{proton} > 10^{23}$ years. Eventually extended limit up to $> 10^{30}$ years by dedicated experiments.

But how can we see a proton decay if it lives for $>10^{30}$ years?

Watch one proton for

10,000,000,000,000,000,000,000,000,000,000

years (10^{31})

or

Watch 10^{31} protons for 1 year

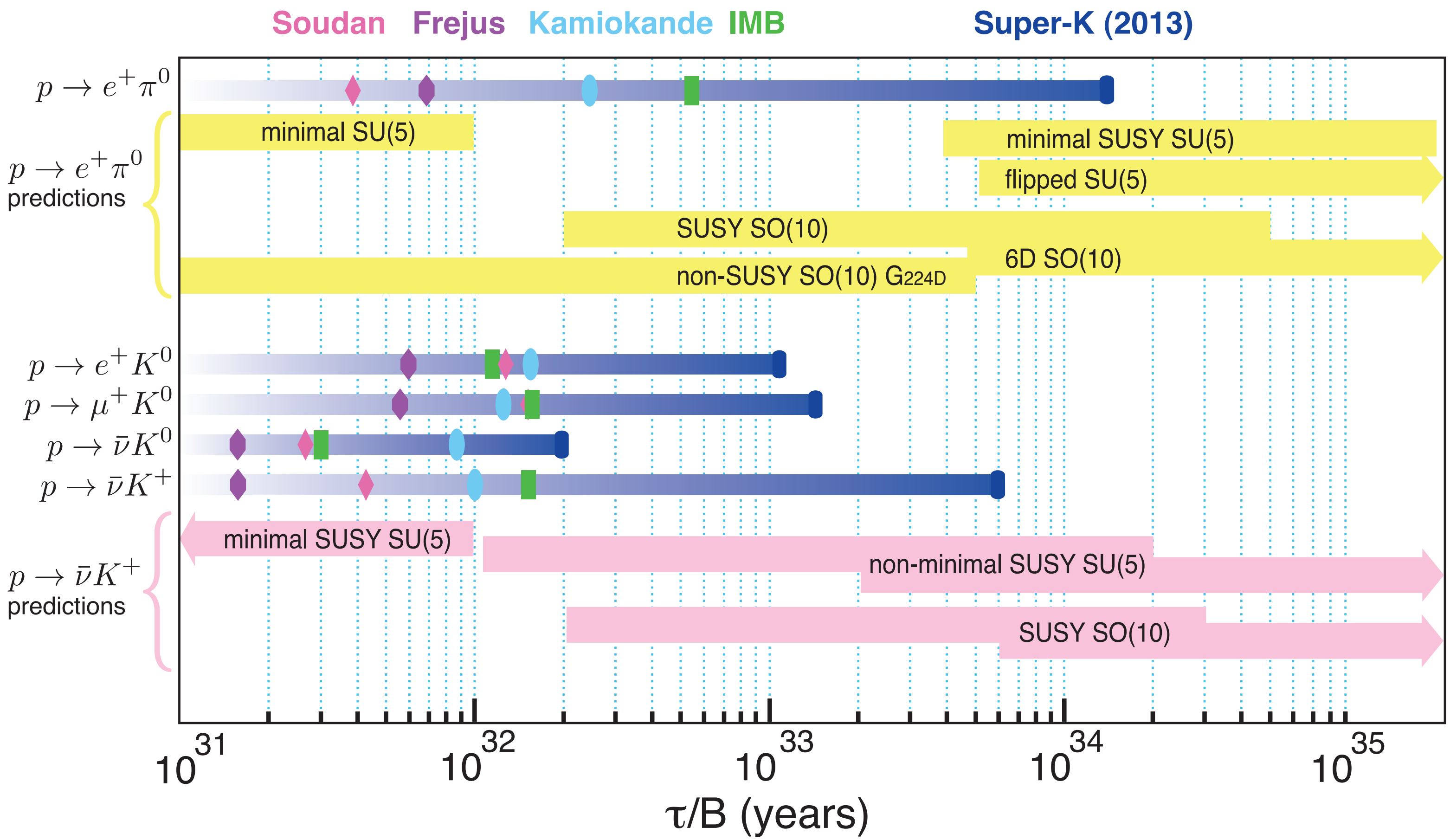
(about 100 tons of H_2O)

(= ~25,000 cats*,**)

*Assuming average cat is 5kg, and body mass is 80% water

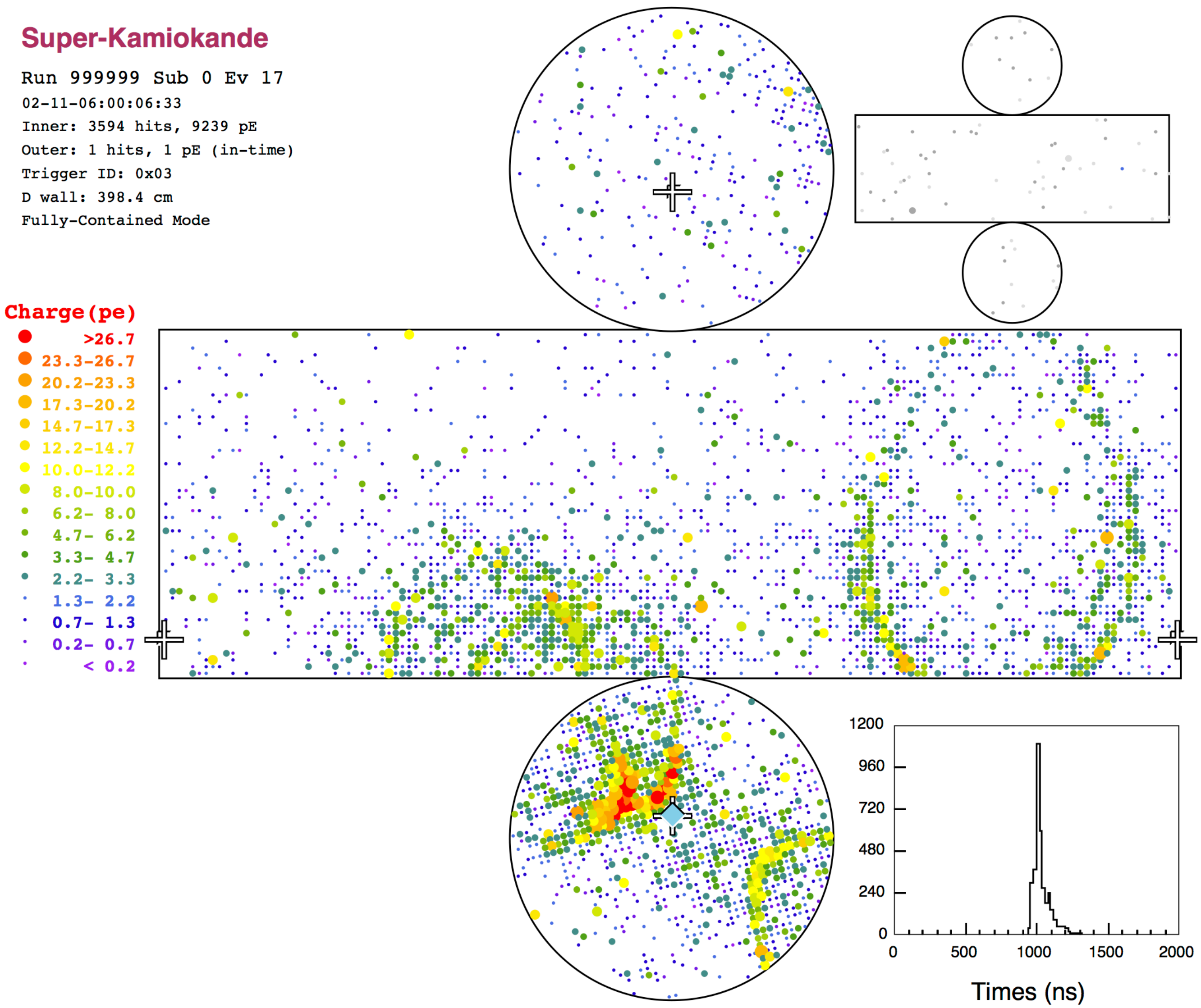
**It's very difficult to collect and analyze proton decay data from cats

Lifetime predictions vary…



These are only a few of the GUT model classes (and only a few of the decay modes)
⟹allowed lifetimes span a large range, so it's very hard to rule them out entirely!

QUIZ! What decay mode is this?



How many rings?

Showering or not?

Options:

$$p \rightarrow \mu^+ \pi^0$$

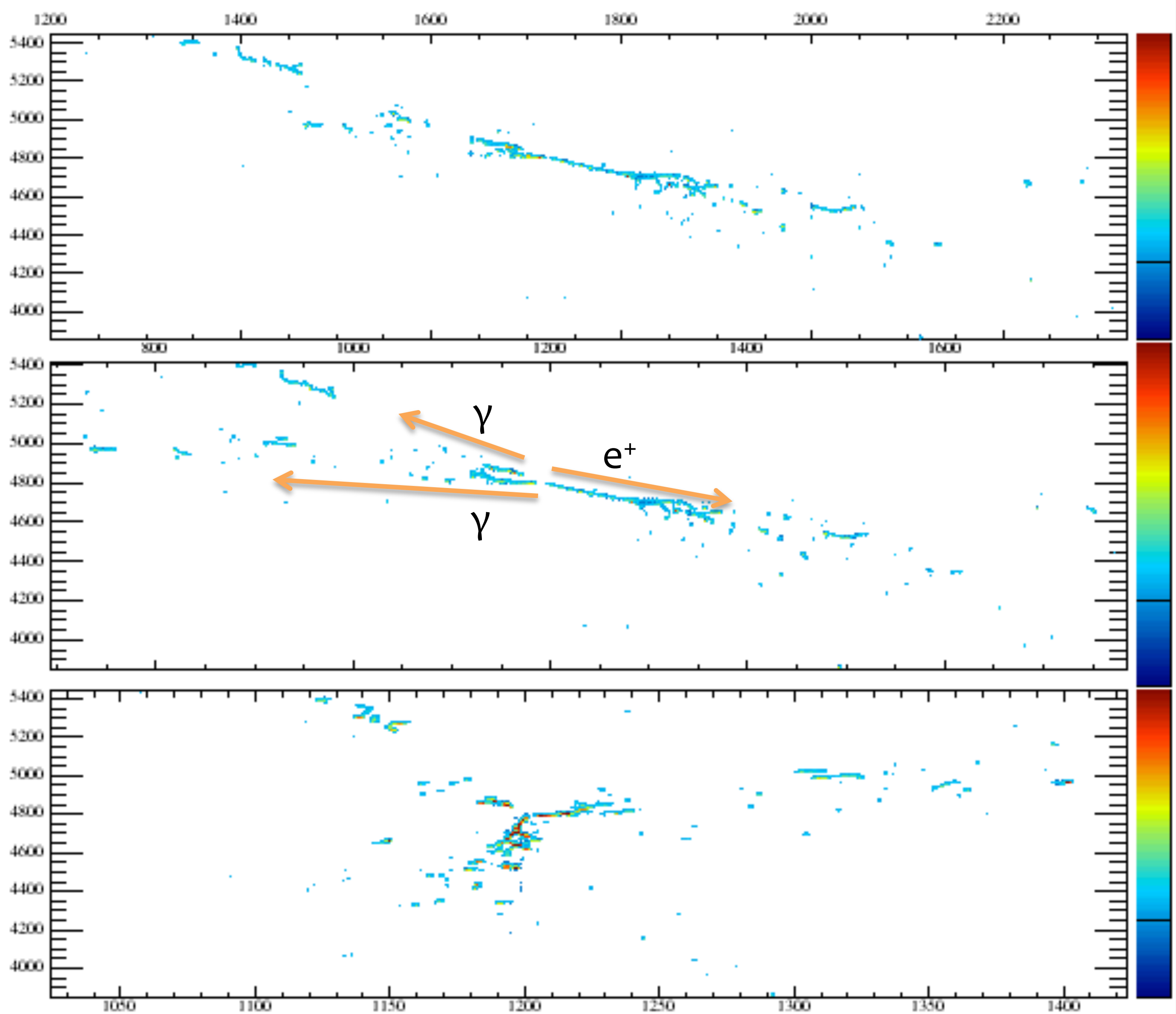
$$p \rightarrow \bar{\nu} K^+$$

$$p \rightarrow e^+ \pi^0$$

$$n \rightarrow e^+ \pi^-$$

$$p \rightarrow e^+ K^0$$

What that looks like in a LArTPC



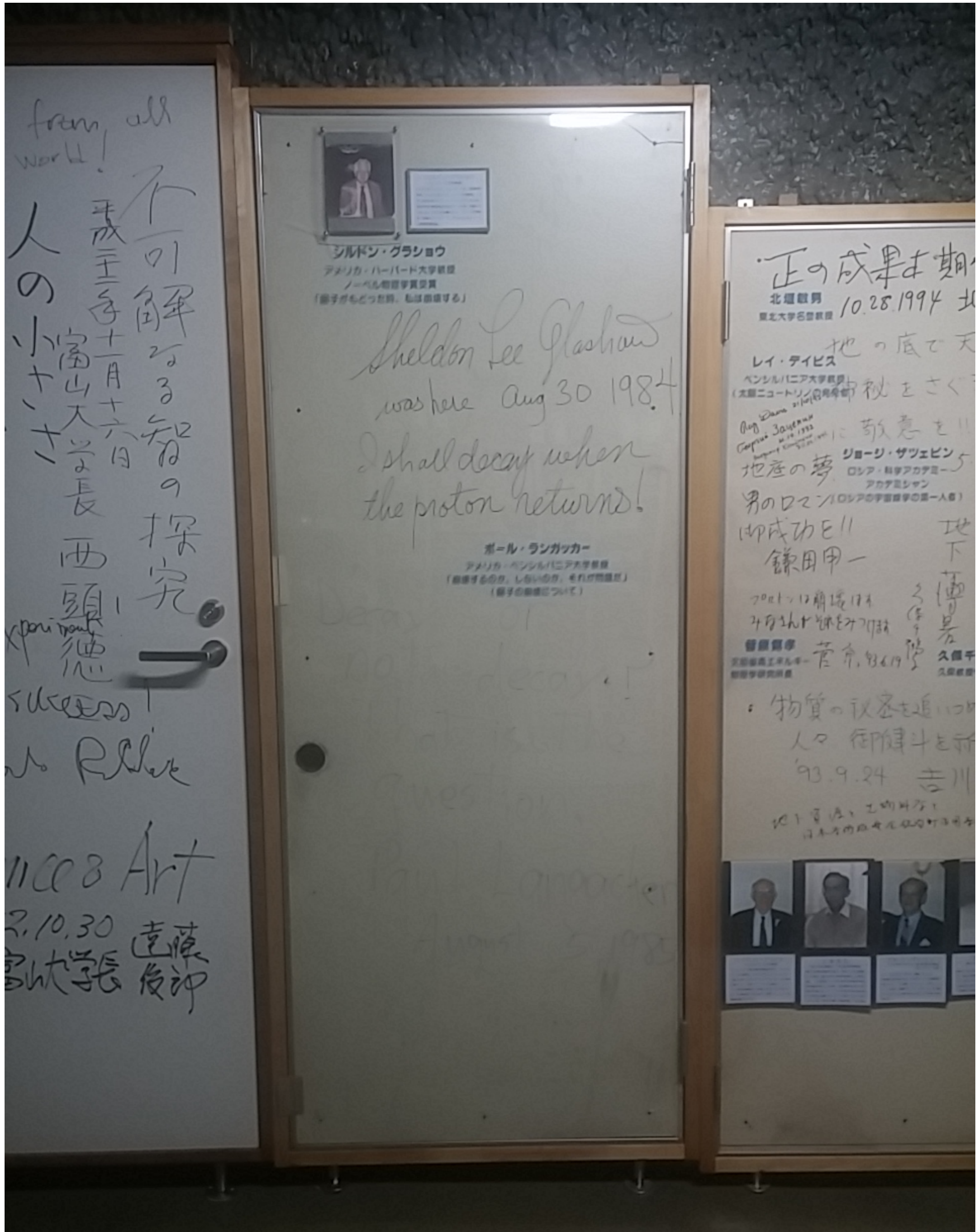
Backgrounds

It's not always as simple as I made it sound in the last few slides.
Backgrounds can trick you – atmospheric neutrinos and cosmics create the backgrounds!

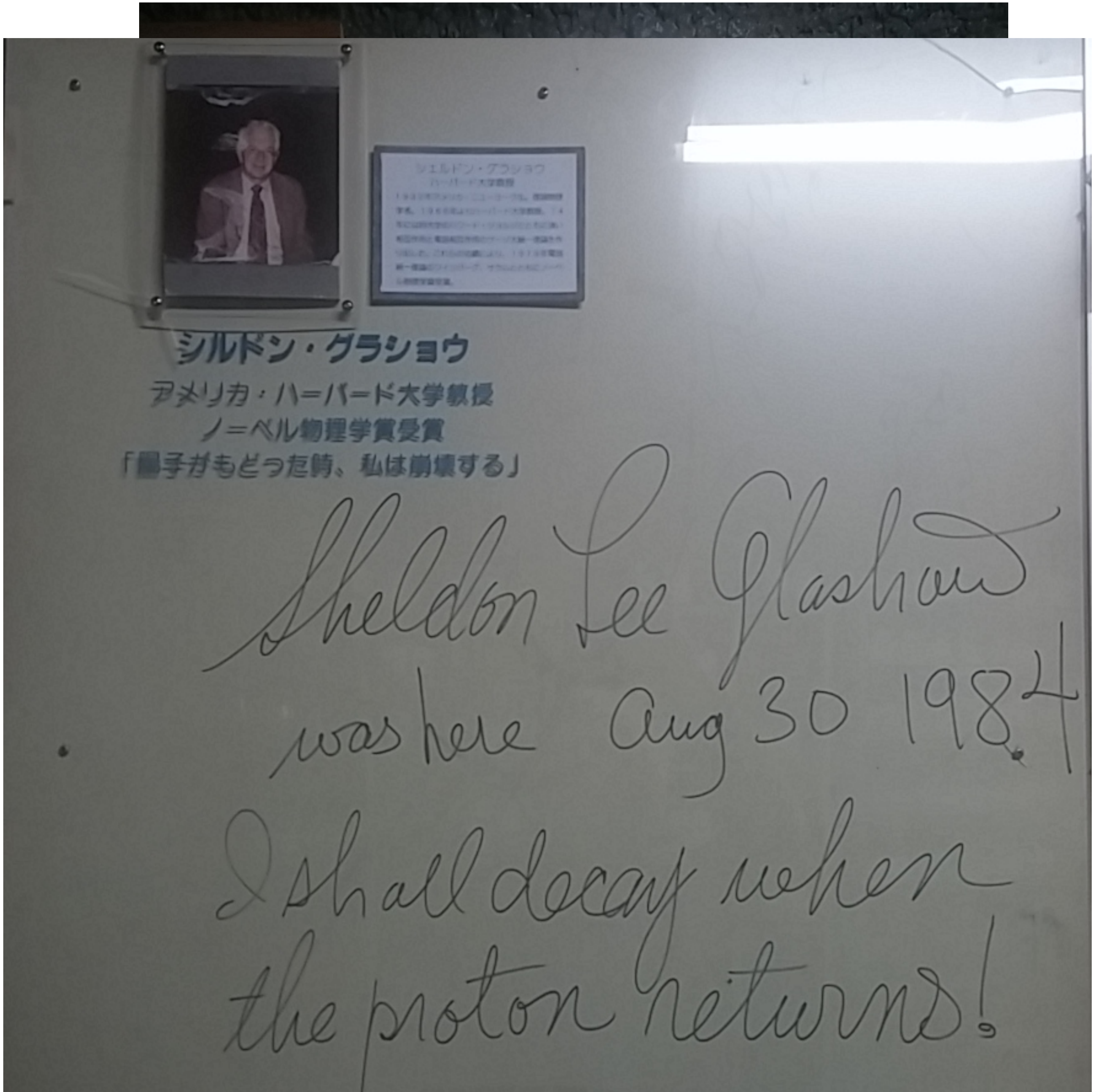
> Note that our aim was modest. We only wanted to test to what "extent the stability of nucleons could be experimentally demonstrated". When later theoretical predictions of proton decay came along and candidates for proton decay were quickly found our modesty paid off: We always remembered that the most important thing about a candidate was his background.

Goldhaber, funny yet again…

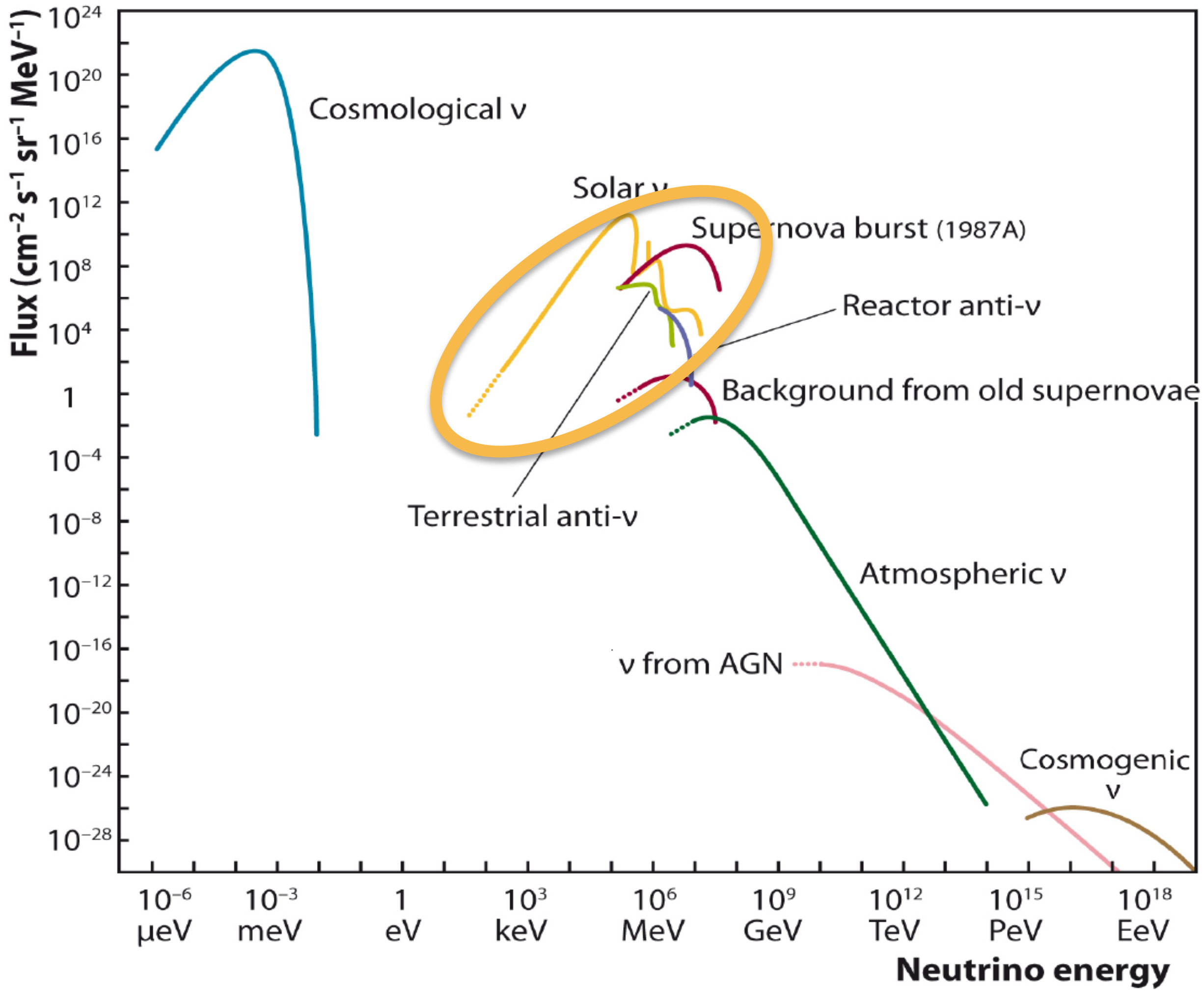
So the name of the game is to have a lot of ~~cats~~ protons to watch, and eliminate the backgrounds.



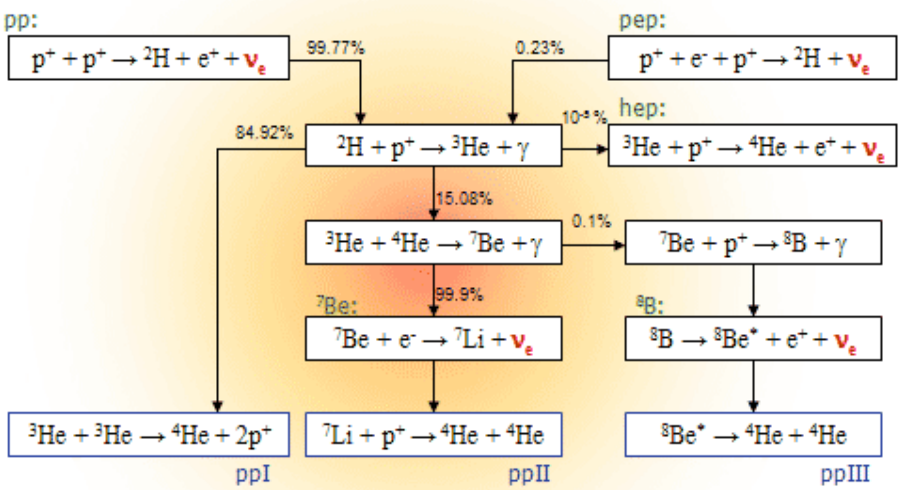
シルドン・グラショウ
Sheldon Lee Glashow was here Aug 30 1984
I shall decay when the proton returns!
ポール・ランガッカー


シルドン・グラショウ
アメリカ・ハ=バード大学教授
ノ=ベル物理学賞受賞
「陽子がもどった時、私は崩壊する」
Sheldon Lee Glashow
was here Aug 30 1984
I shall decay when
the proton returns!

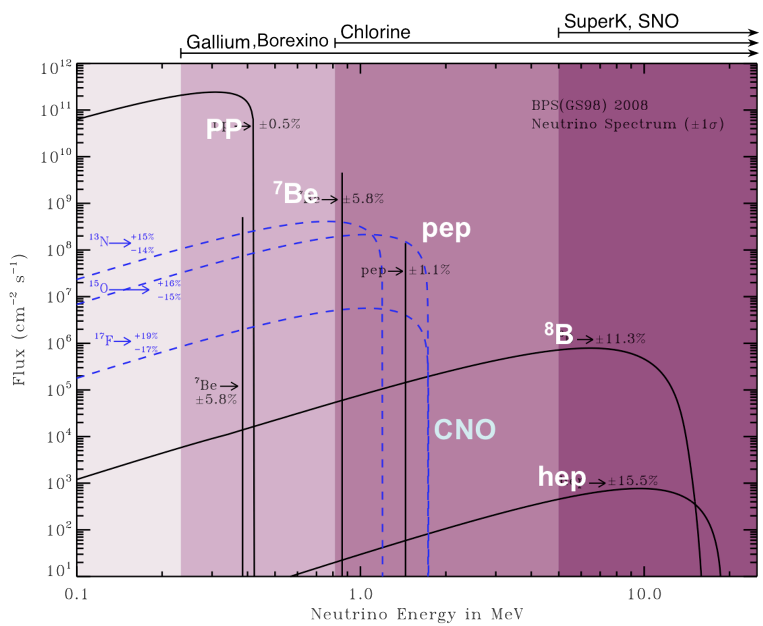
“Wild” neutrino source: Sun



How does the Sun make neutrinos?

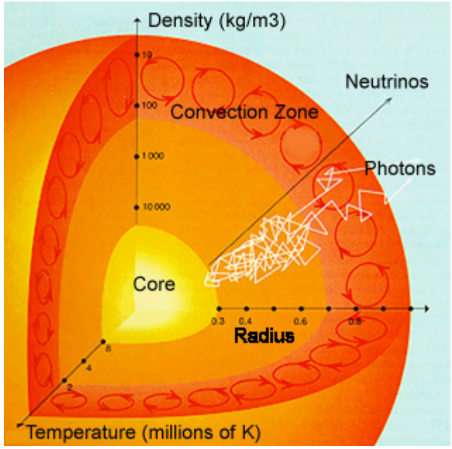


- Several different nuclear fusion and decay processes
- 420 billion per second per square inch at Earth!



- Higher energy neutrinos (~5-20 MeV seen in Super-K) come from ^{8}B decay
- Other types of experiments are sensitive to lower energy solar ν's

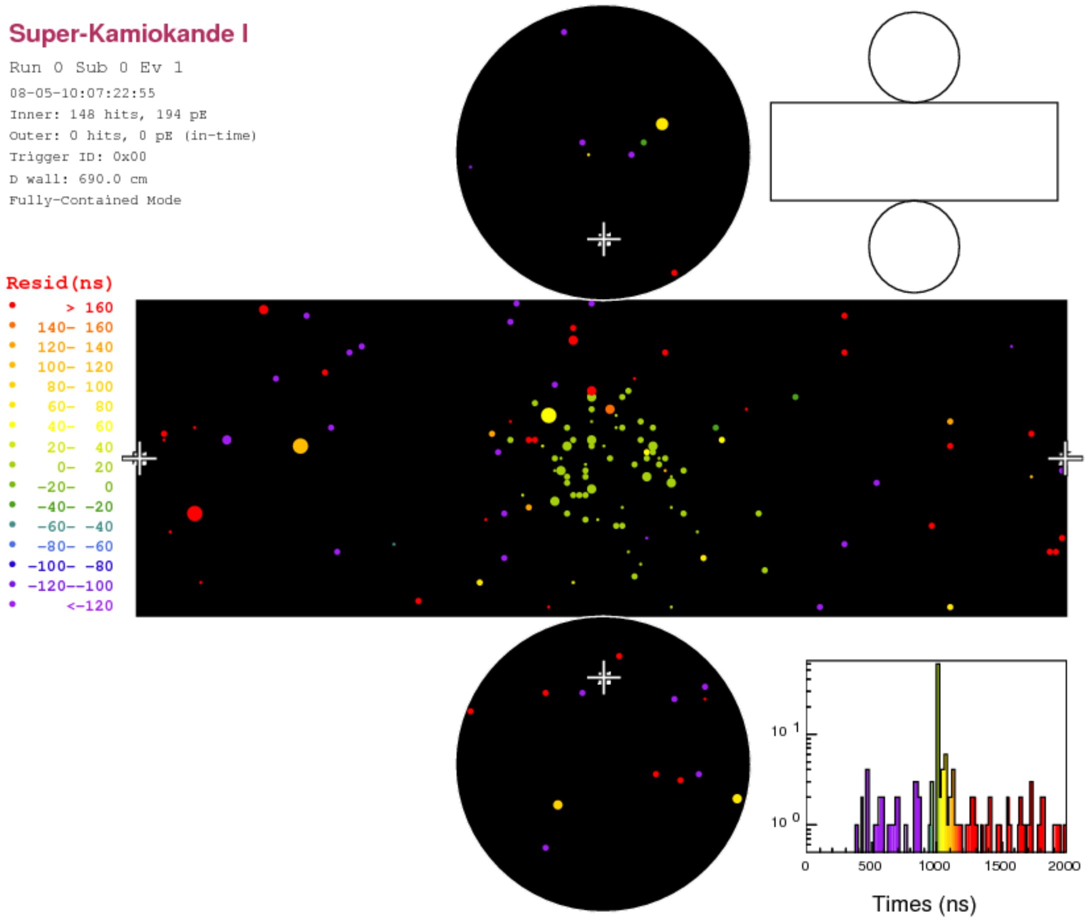
What can we learn from solar ν's?



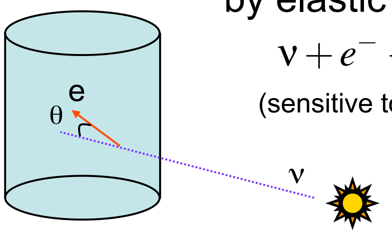
- It takes tens of thousands of years for the energy made at the sun's center to migrate to its surface. But neutrinos from the sun's center can reach Earth in about 8 minutes!
  - Neutrinos reveal what the sun's surface will be like many thousands of years in the future: forecasting the sun's energy production
    (you can tell your mom not to worry… the sun won't die any time soon)

- The first experiments detecting solar neutrinos only saw 1/3 the number expected, known as the "solar neutrino problem"
  - Solved! The ν_e's produced by the sun were oscillating to ν_μ and ν_τ

Solar Neutrino in Super-K



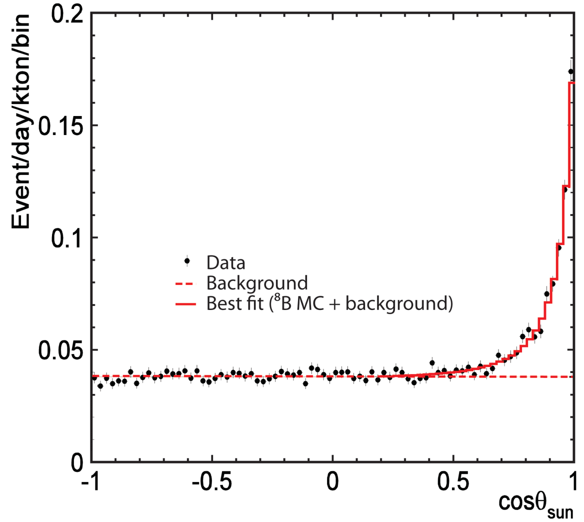
10 MeV solar ν event



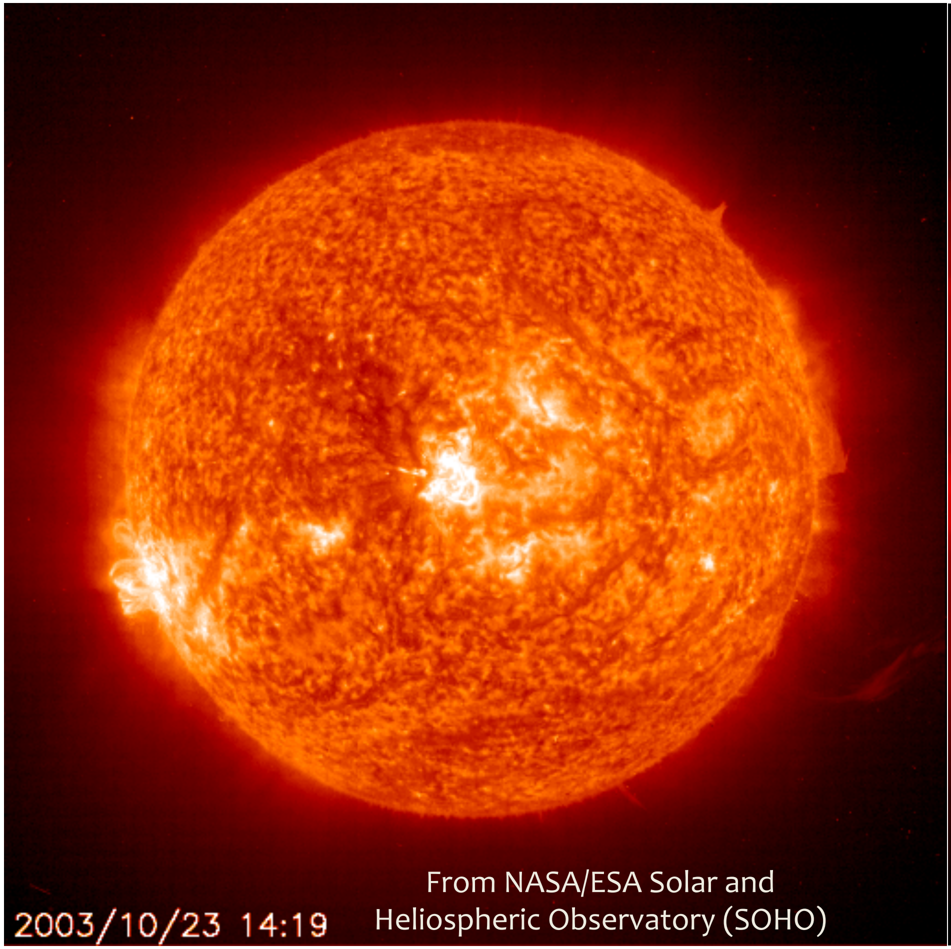
^{8}B neutrino measurement by elastic scattering:

$$\nu + e^- \rightarrow \nu + e^-$$

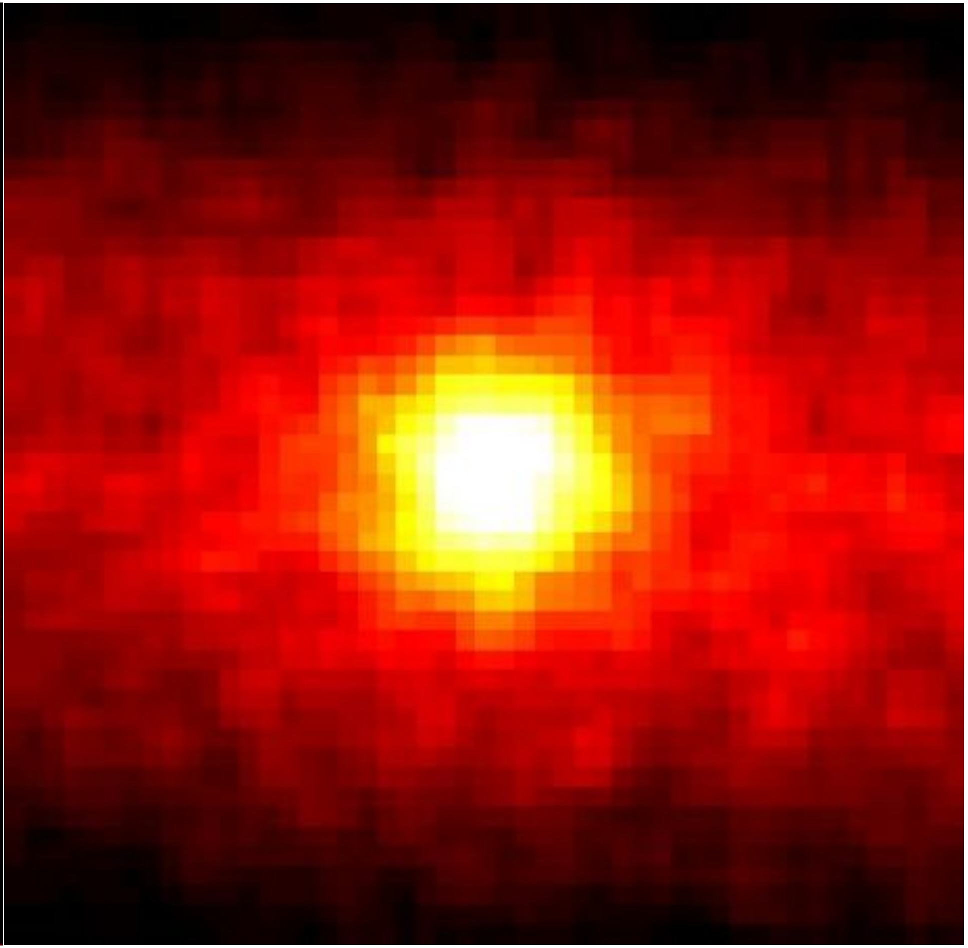
(sensitive to all ν flavors)



Solar Neutrinos

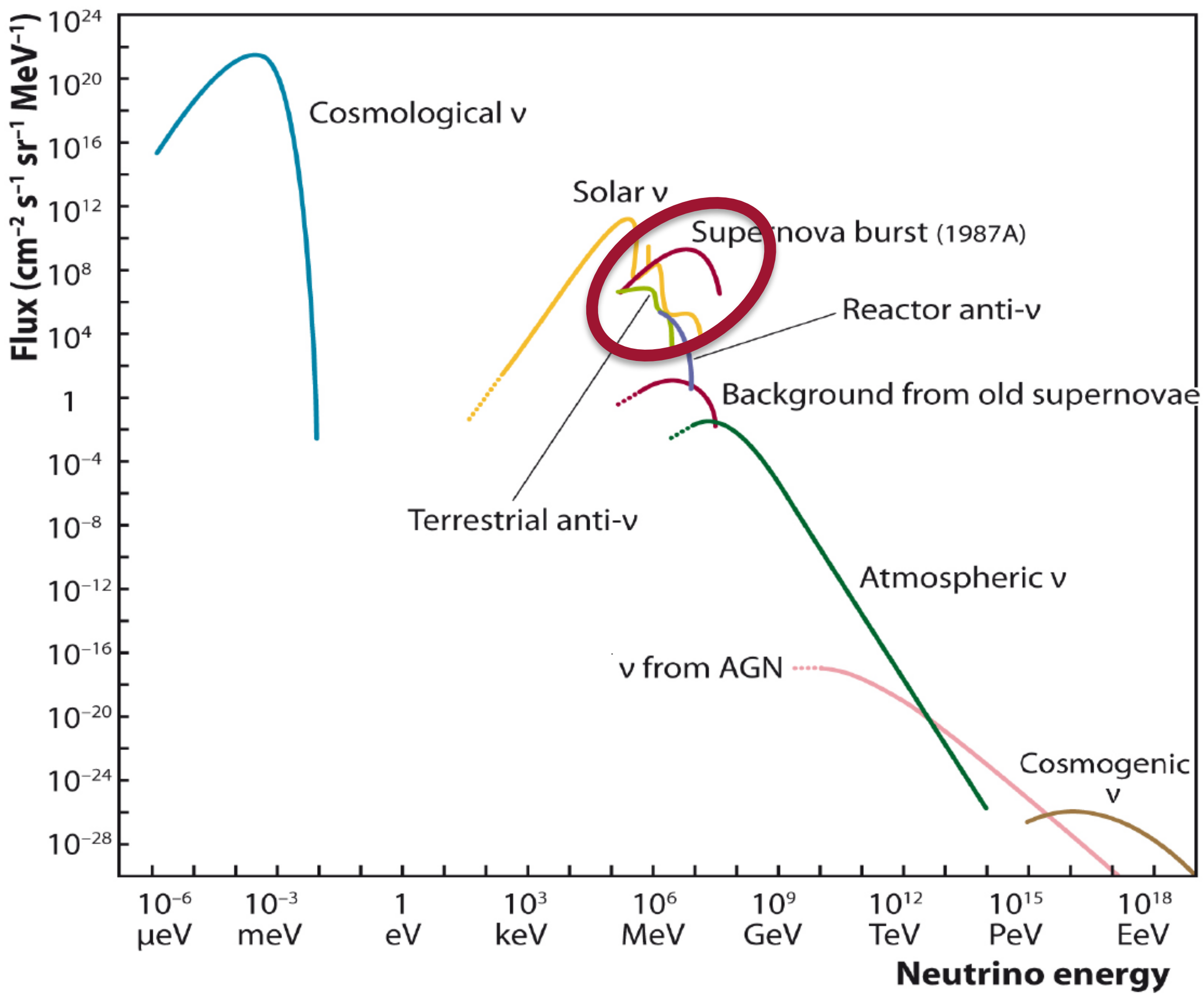


The Sun (imaged in UV light)

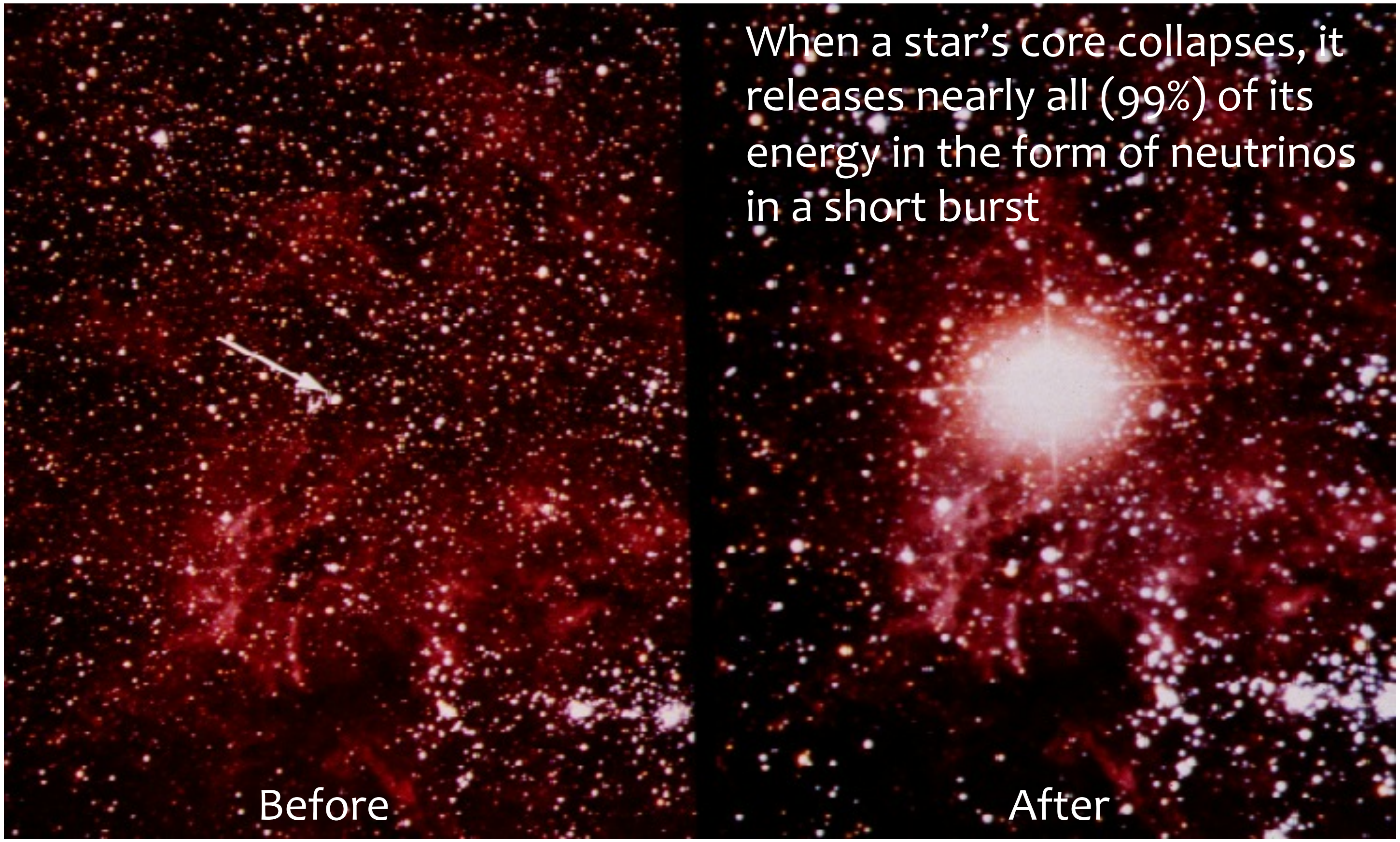


The Sun (imaged by neutrino-electron scattering using neutrinos from the sun)

“Wild” neutrino source: Supernovæ



Supernova burst neutrinos



These are the most energetic processes ever recorded in our universe!

Lethal Neutrinos

https://what-if.xkcd.com/73/

How close would you have to be to a supernova to get a lethal dose of neutrino radiation?

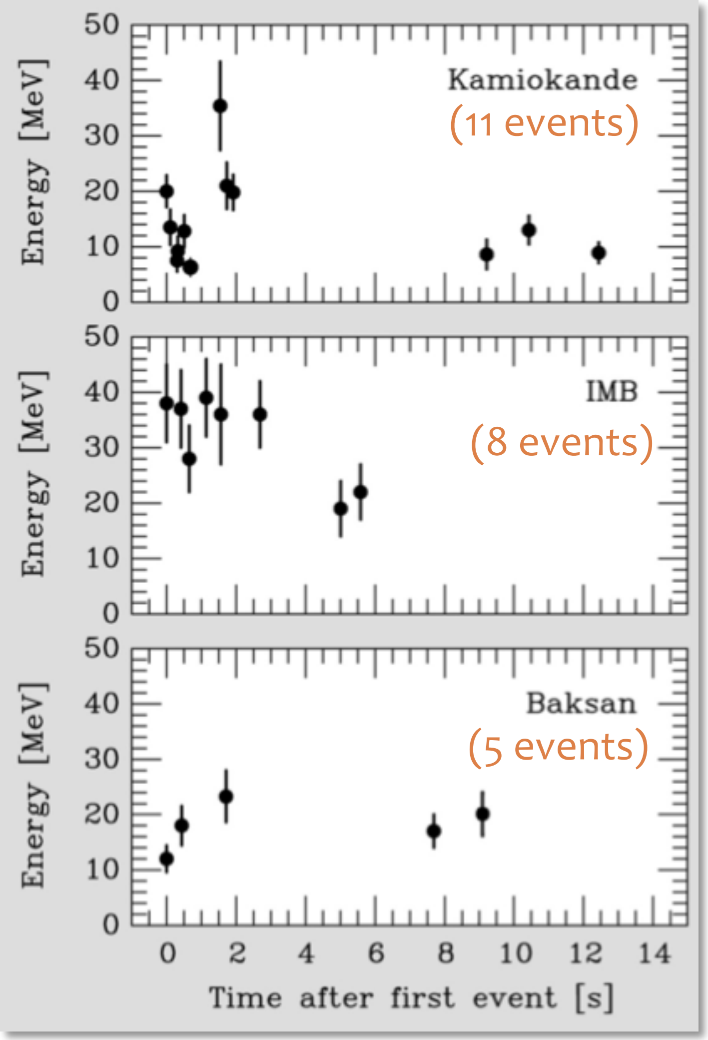
Which of the following would be brighter, in terms of the amount of energy delivered to your retina:

1. A supernova, seen from as far away as the Sun is from the Earth, or
2. The detonation of a hydrogen bomb *pressed against your eyeball?*

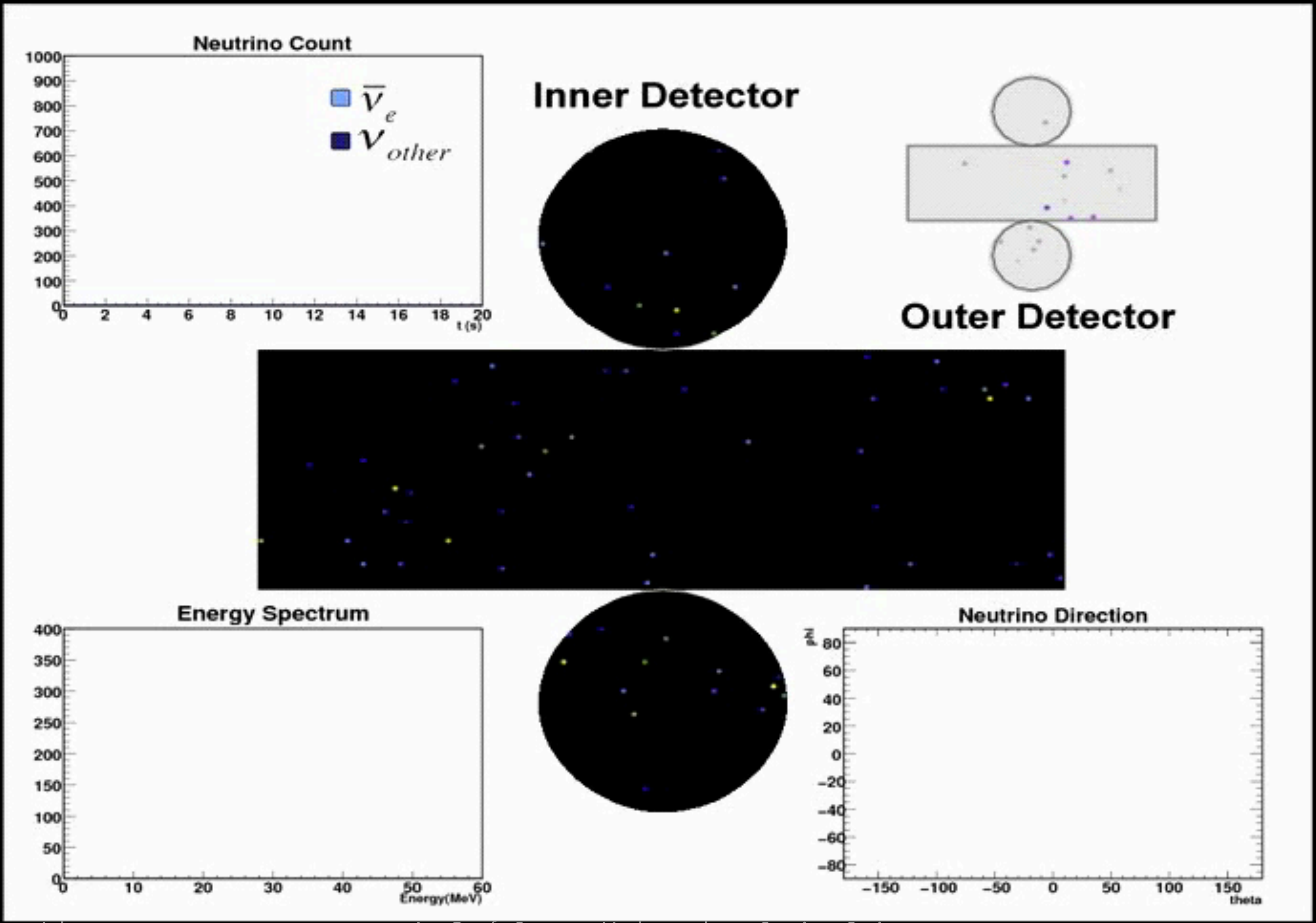
Applying the physicist rule of thumb suggests that the supernova is brighter. And indeed, it is ... by *nine orders of magnitude.*

SN 1987A (in Large Magellanic Cloud, 55 kpc)

- We have detected neutrinos from *only one* supernova so far
  - luckily there were a few neutrino detectors in operation at the time
- The normal rate of neutrino events in this energy range was ~1 per week (in IMB), so seeing 8 in 10 seconds was certainly something unique, especially when simultaneously seen in other detectors too
- These events have allowed us to probe the inner workings of a supernova explosion, but there is still much more to learn

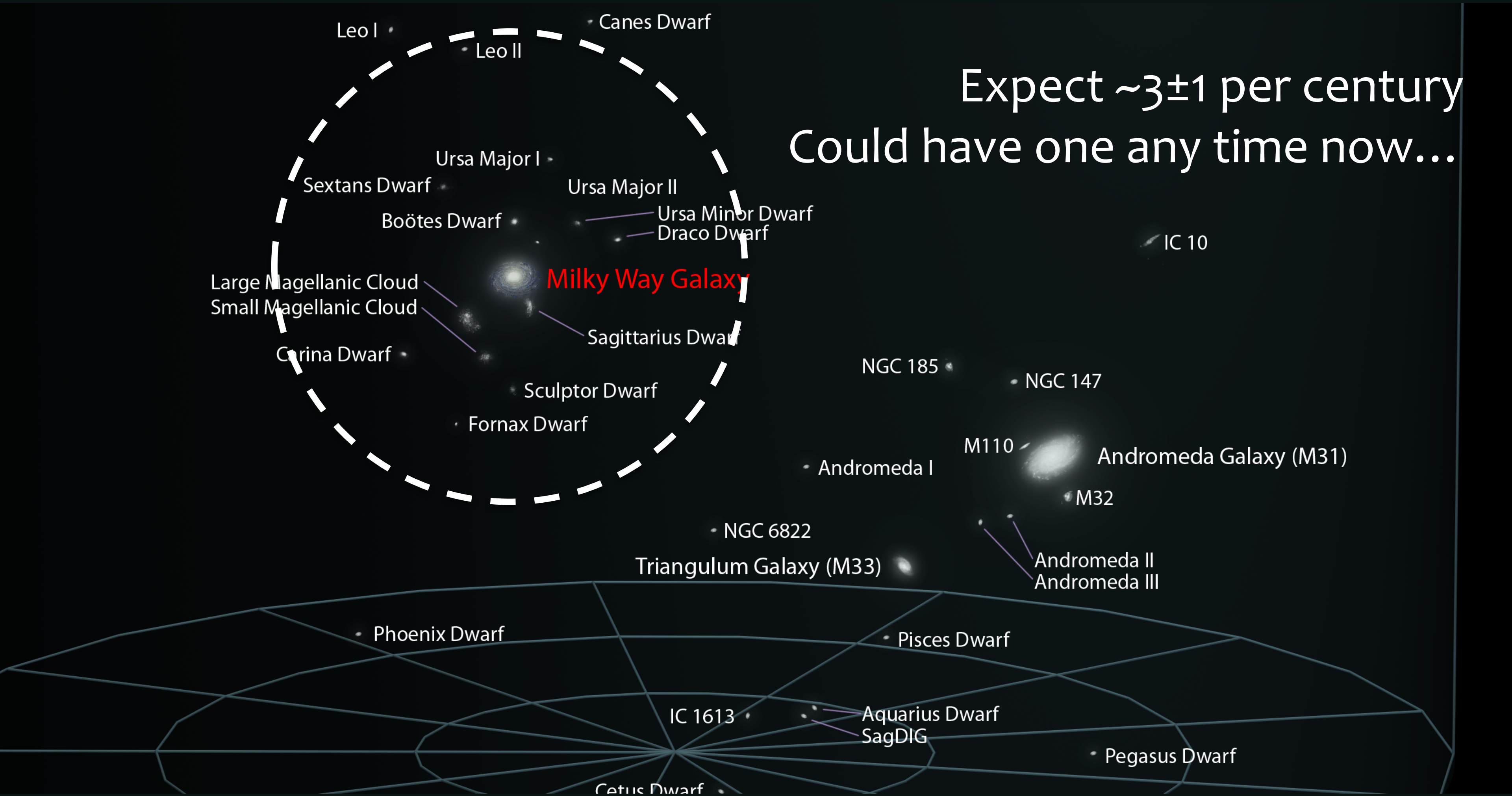


http://snews.bnl.gov/SNmovieEXTRA/ http://snews.bnl.gov/snmovie.html



Existing neutrino detectors are only sensitive to a few hundred kpc (mostly just the Milky Way)

Expect ~3±1 per century
Could have one any time now…



SuperNova Early Warning System

- ✧ Neutrinos reach us before light from the burst
  - Use neutrinos as an early warning system! Many neutrino experiments already participate.
- ✧ Astronomers (and anyone with interest, including you!) can sign up to receive alerts.

My favorite alternate acronym that didn't win the naming contest:

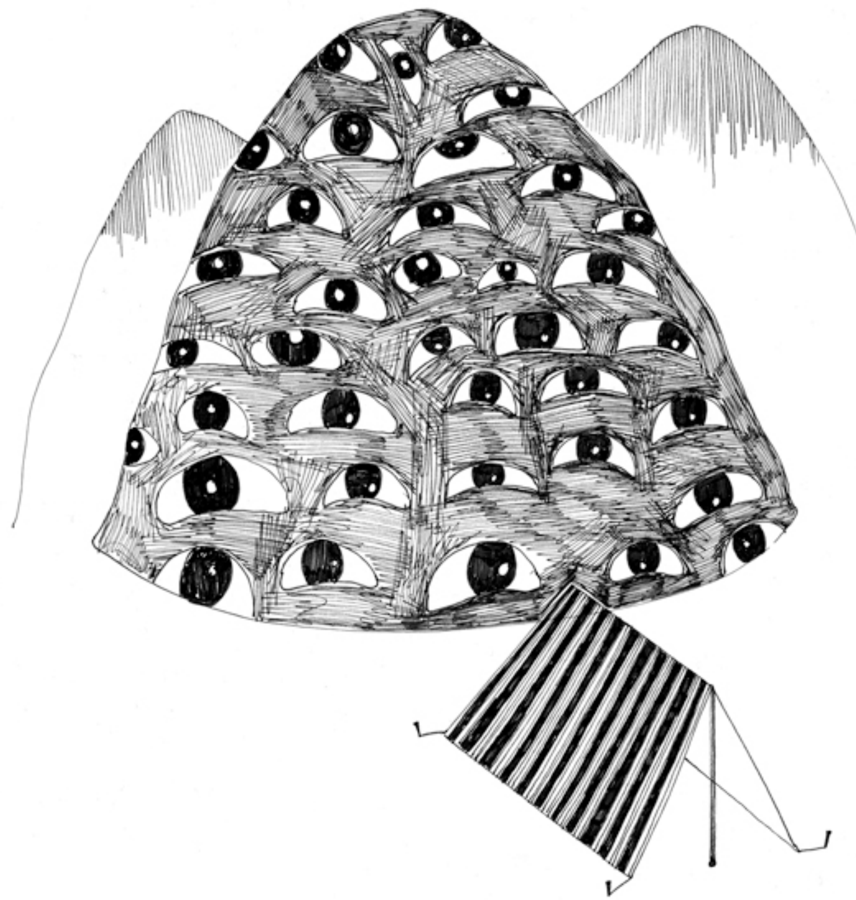
Point
Over
There
At
That
Old
Exploding
Star

(http://snews.bnl.gov/amuse.html)

Summary

- ✧ Large-scale neutrino detectors can do more than just neutrino physics!
- ✧ But while we're waiting for the next SN burst, or for a proton to decay, there is plenty of oscillation physics to keep us entertained, so…

Thank you!



"Proton decay has never been witnessed"
Stina Fisch, pen & ink, 2011

Simplest GUT as an example: SU(5)

representations of
quarks and leptons

$$\bar{5} = \begin{pmatrix} \bar{d}_g \\ \bar{d}_r \\ \bar{d}_b \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 = \begin{pmatrix} 0 & \bar{u}_b & -\bar{u}_r & -u_g & -d_g \\ & 0 & \bar{u}_g & -u_r & d_r \\ & & 0 & -u_b & -d_b \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L$$

generators allow quarks to transform to leptons (and vice versa)

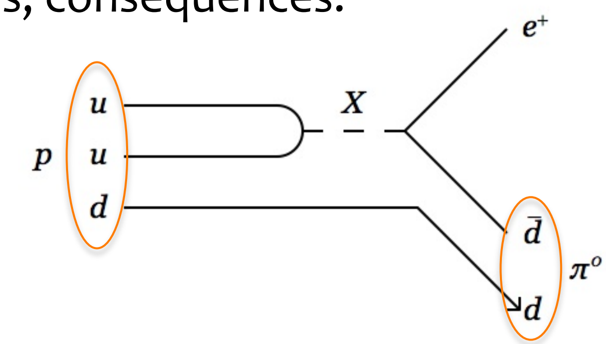
$$24 = \begin{pmatrix} G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & \bar{X}_1 & \bar{Y}_1 \\ G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & \bar{X}_2 & \bar{Y}_2 \\ G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & \bar{X}_3 & \bar{Y}_3 \\ X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{pmatrix}$$

gluons

New X,Y bosons

W, Z, γ

- ✧ Standard Model SU(3)xSU(2)xU(1) embedded in larger symmetry group (SU5)
- ✧ New interactions mediated by new X and Y bosons, consequences:
  - proton decay
  - baryon number (B) not conserved, but B-L is
- ✧ However, not perfect predictions:
  - massless neutrinos (oops!)
  - not-so-close value for $\sin^2\theta_W$
  - unification isn't exact either…

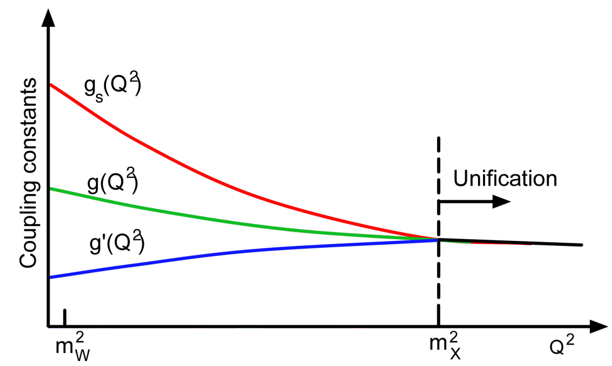


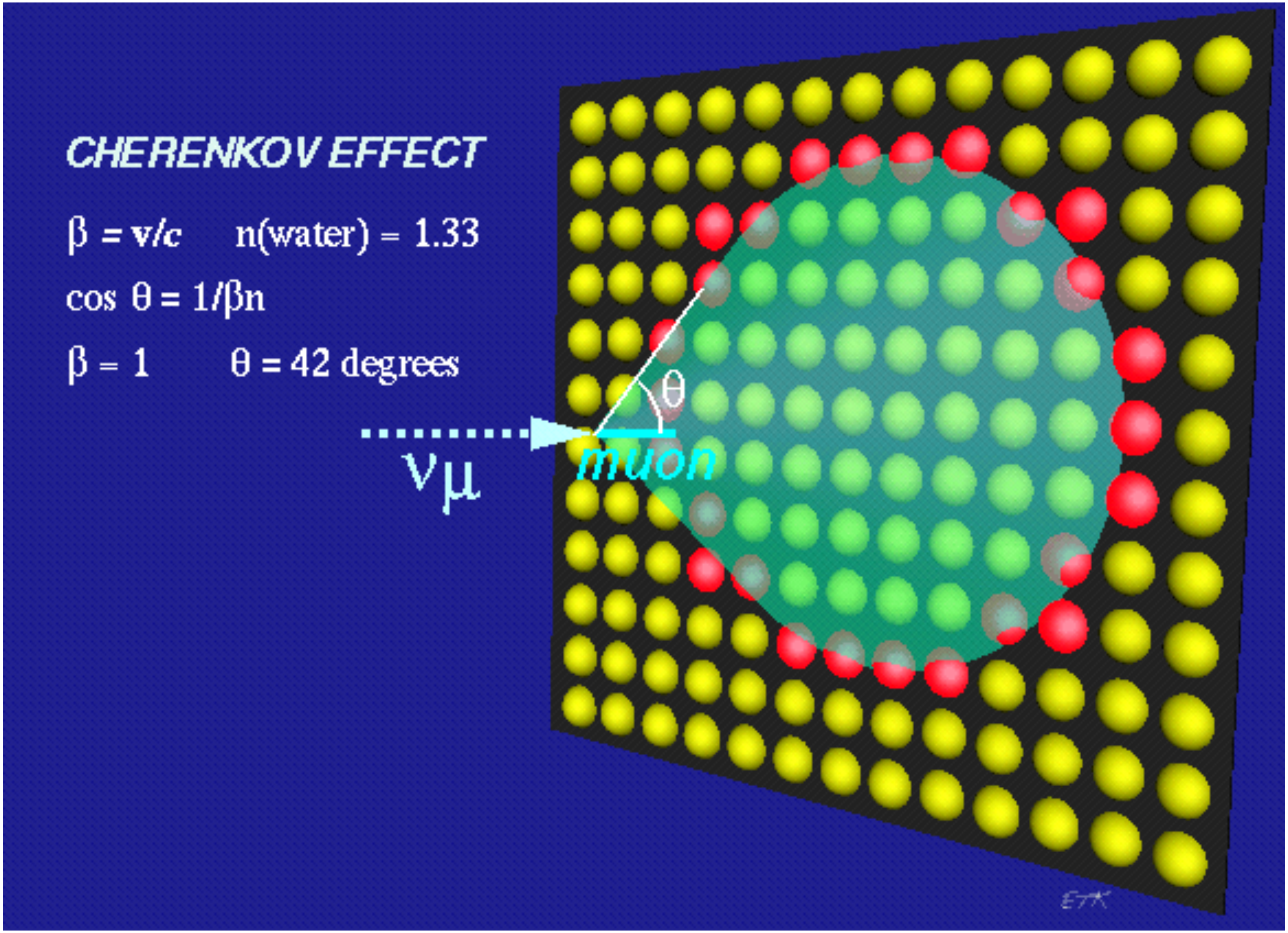
- ✧ But there are many other GUTs as well, some with better predictions

Grand Unified Theories

- Standard Model of particle physics
  - Represented by the product of symmetry groups SU(3) x SU(2) x U(1)
    - Local gauge symmetries are responsible for forces that mediate EM, weak, and strong interactions
  - Finite, but unobservably long, proton lifetime due to baryon number (B) conservation
    - Introduced empirically! No good motivation…
    - Other conserved quantities (e.g., electrical charge) result from gauge symmetries
- Grand Unified Theories
  - Motivated partly by desire to constrain quantities that are seemingly arbitrary in SM
  - Attempt to unify the 3 fundamental interactions
  - Coupling constants that describe strong, weak, and EM forces are unified at large energies

    ⟹ fundamental forces are low-energy manifestations of a single unified force





http://hep.bu.edu/~superk