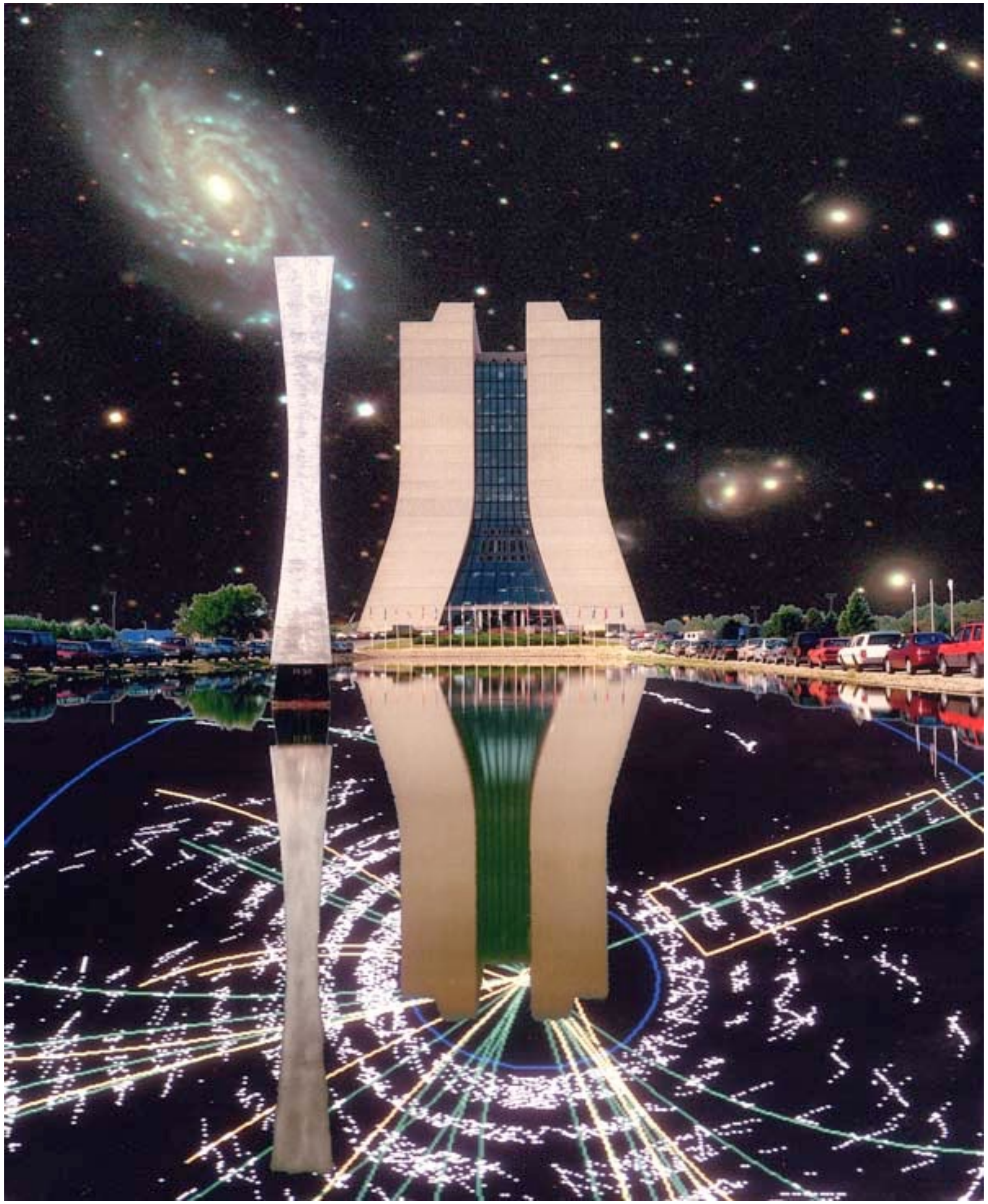
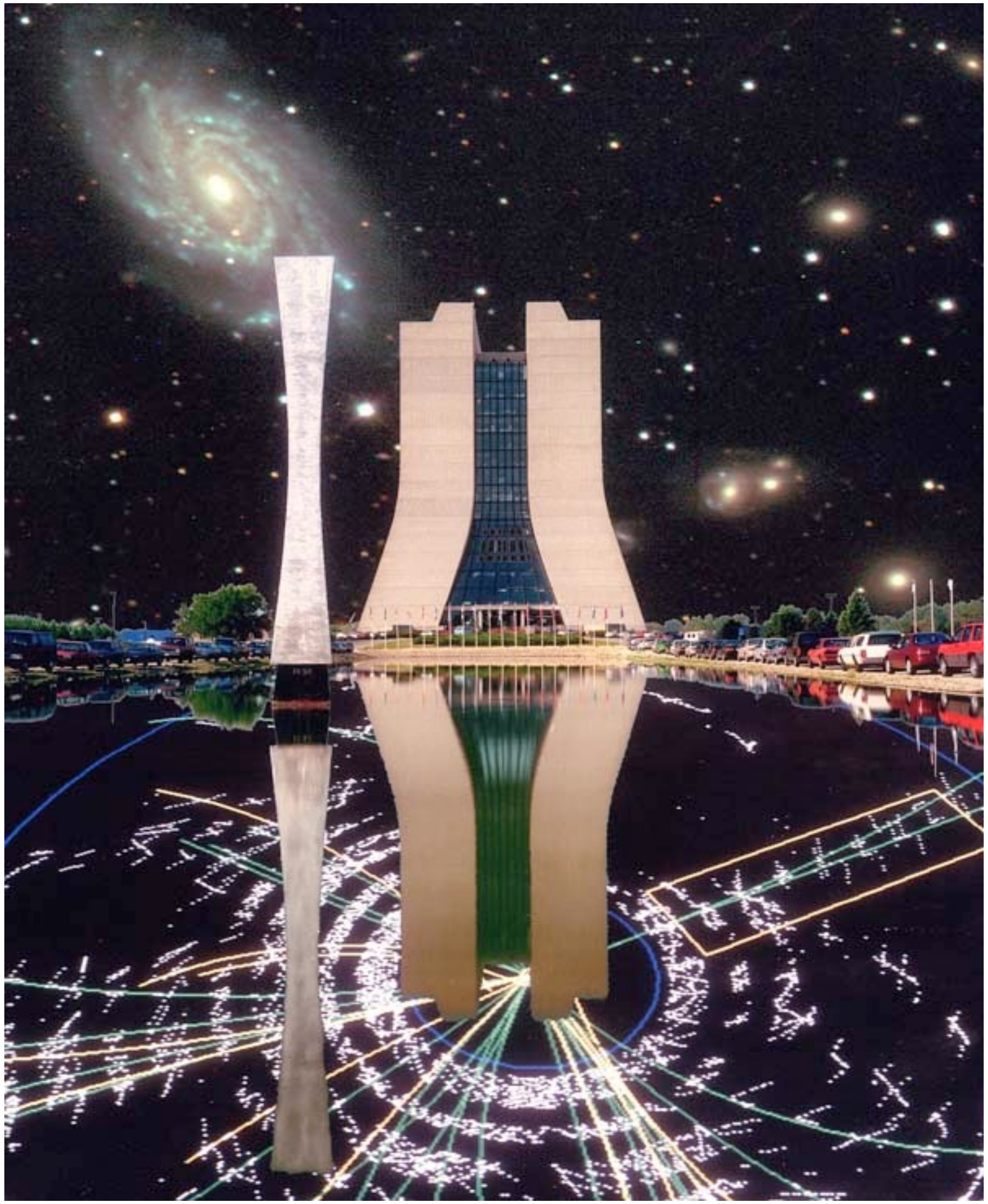


Neutrino Sources

Stephen Parke
Theoretical Physicist
Fermilab



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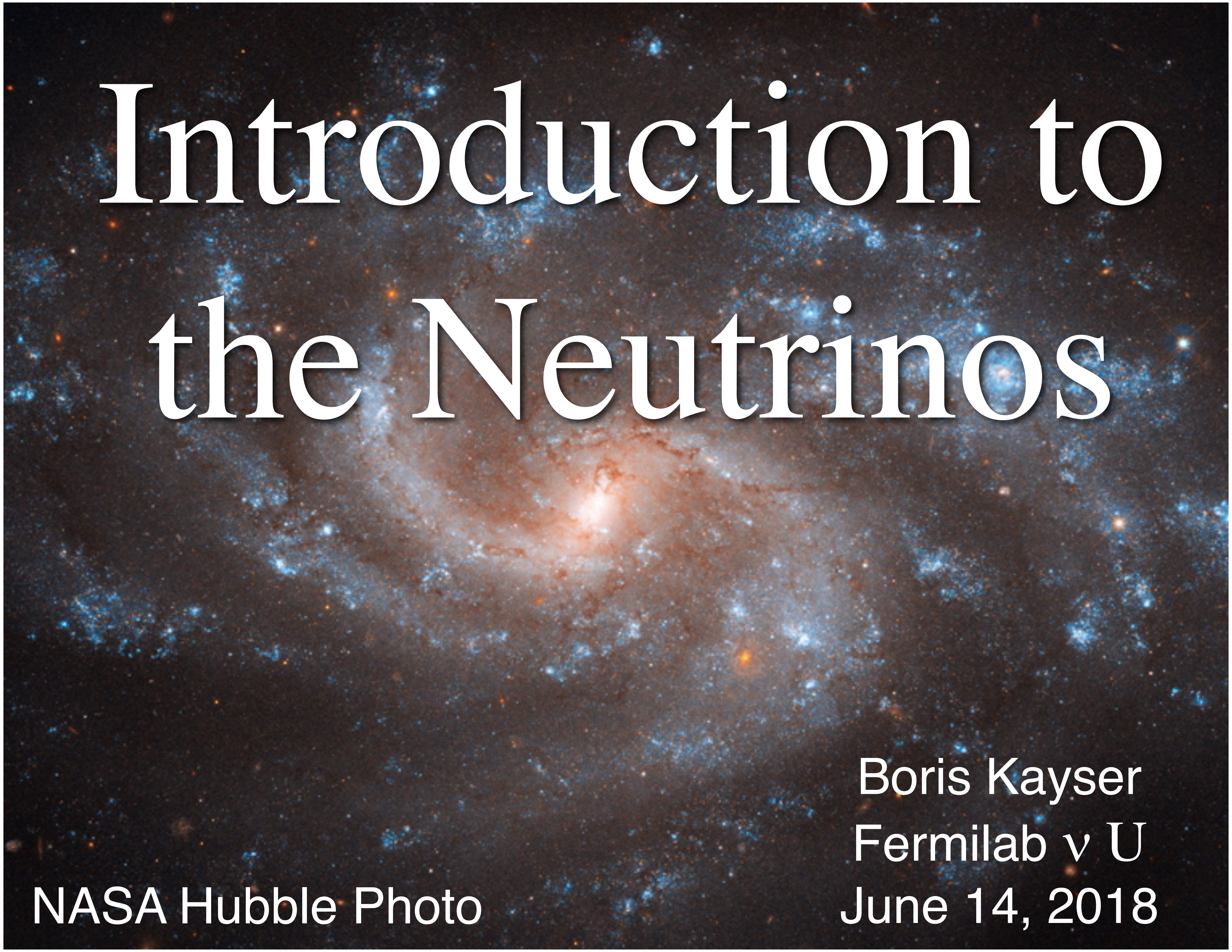

Introduction to
the Neutrinos
Boris Kayser
Fermilab ν U
June 14, 2018
NASA Hubble Photo

Brief Early History of the Neutrino

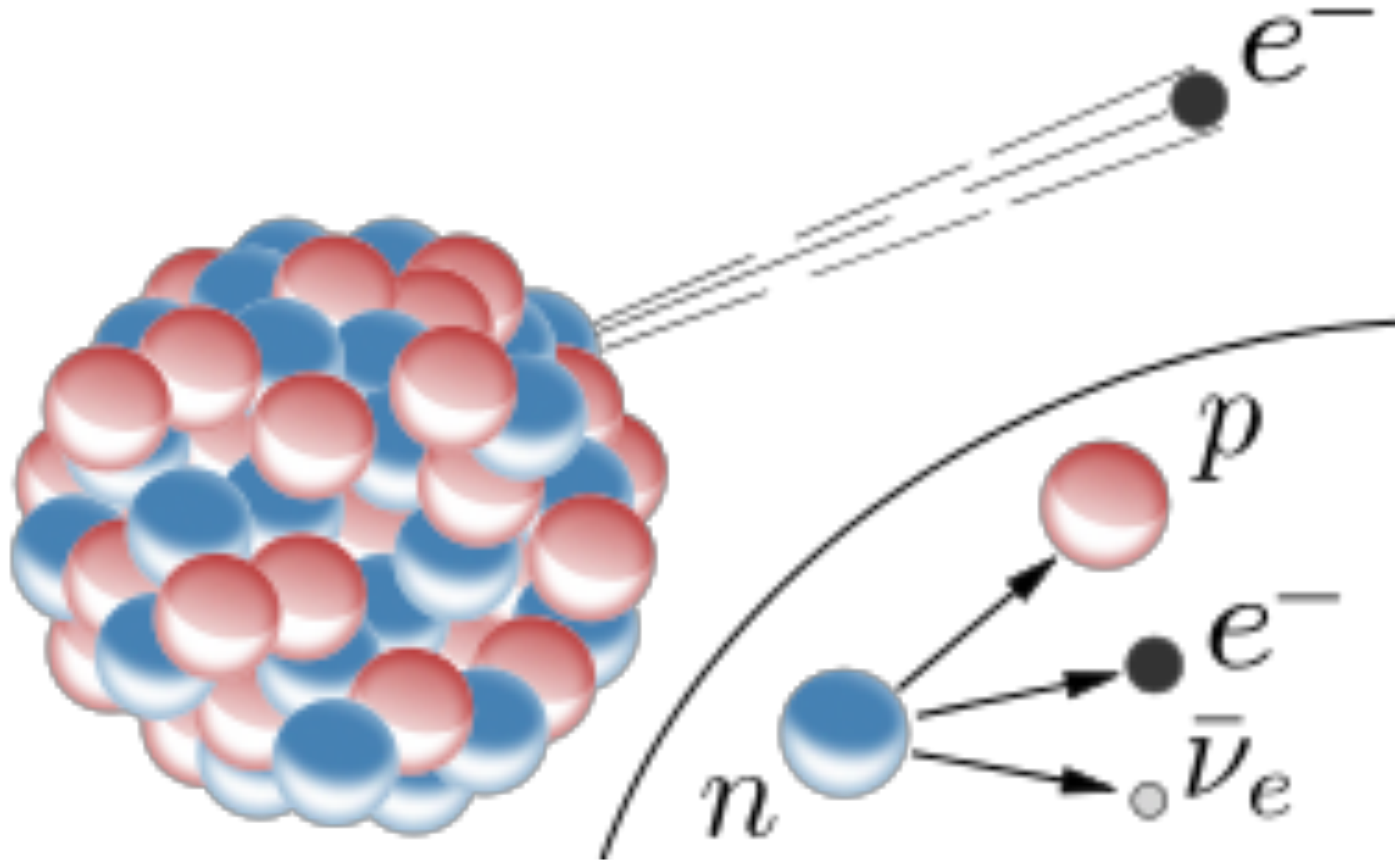
- 1930 – postulated by Wolfgang Pauli
  (to solve energy crisis in radioactive decay)

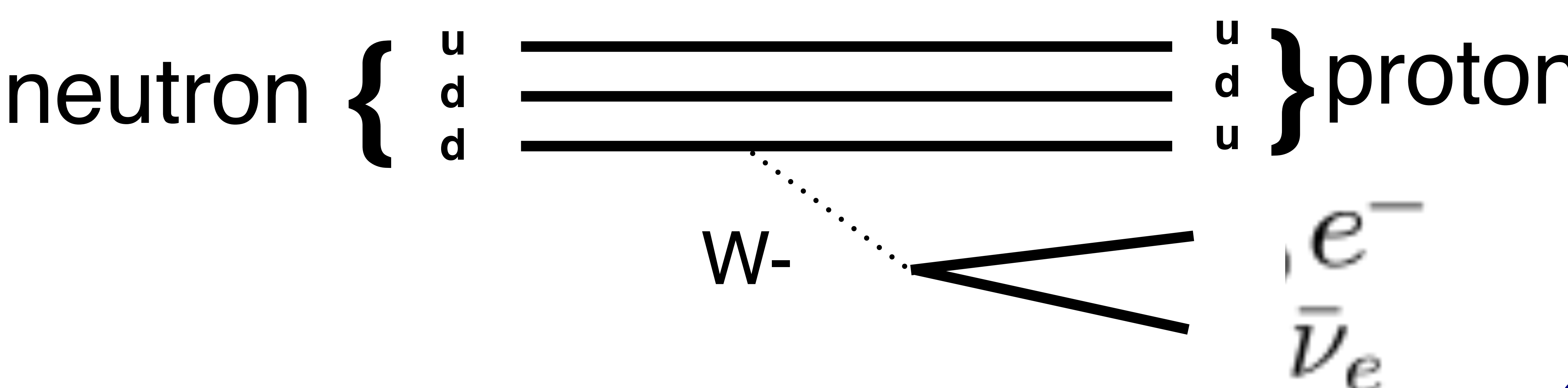
- 1933 – incorporated into theory of radioactive decay by Enrico Fermi who named the ``neutrino = little neutral one"

- 1957 – first observed by Cowan and Reines using nuclear reactor as the source.

1966

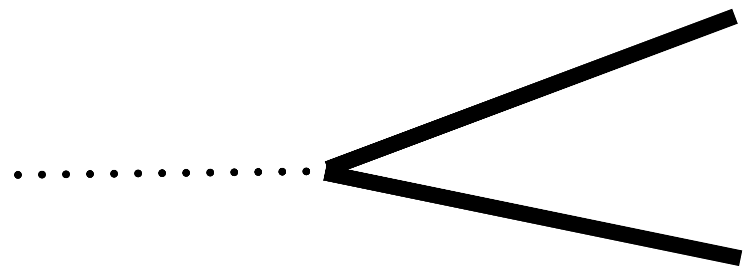
And yet the nothing-particle is not a nothing at all


e^-
p
e^-
$\bar{\nu}_e$
n


neutron
u
d
d
u
d
u
proton
W-
e^-
$\bar{\nu}_e$

Neutrino Interactions:

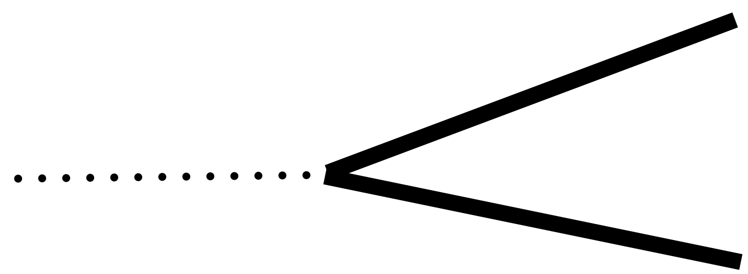
W-



e^- μ^- τ^-

$\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$

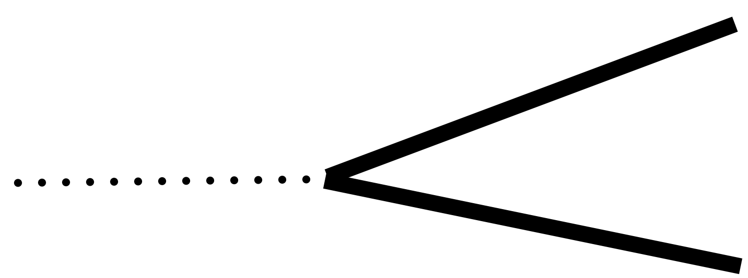
W+



e^+ μ^+ τ^+

ν_e ν_μ ν_τ

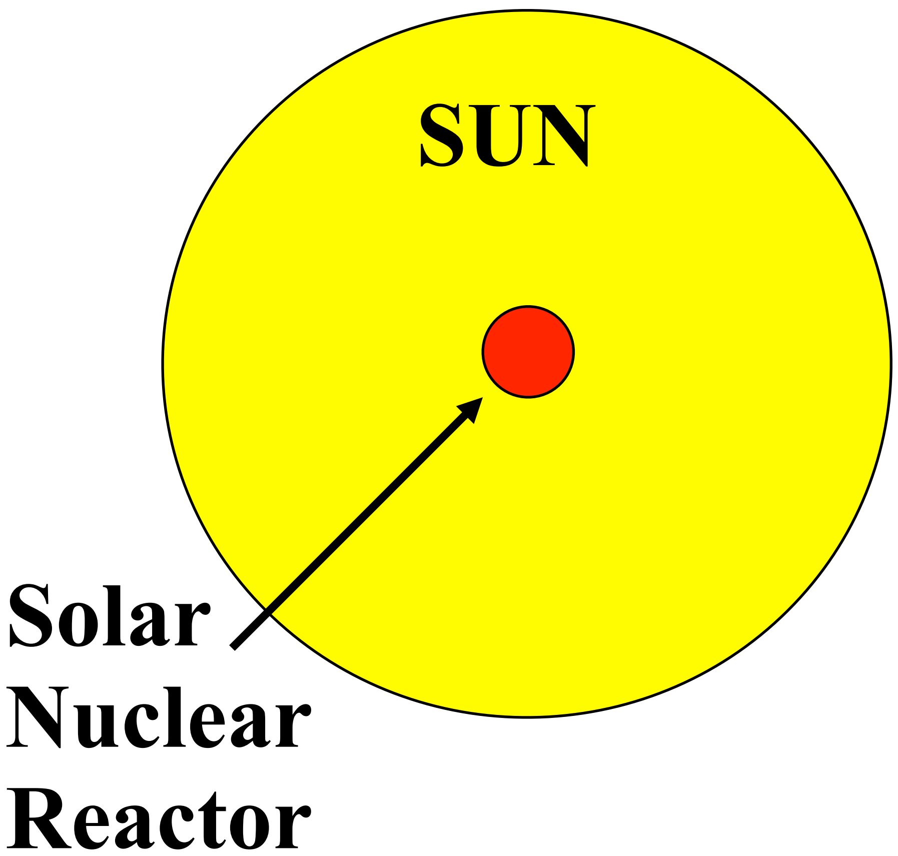
Z



ν_e ν_μ ν_τ

$\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$

SOLAR NEUTRINOS:



4 protons + 2 electrons

↓

Helium Nucleus (2p2n)

+

2 Neutrinos (2ν)

+

Energy (26.7 MeV)

at the earth

Using $E=mc^2$

60,000,000,000 neutrinos

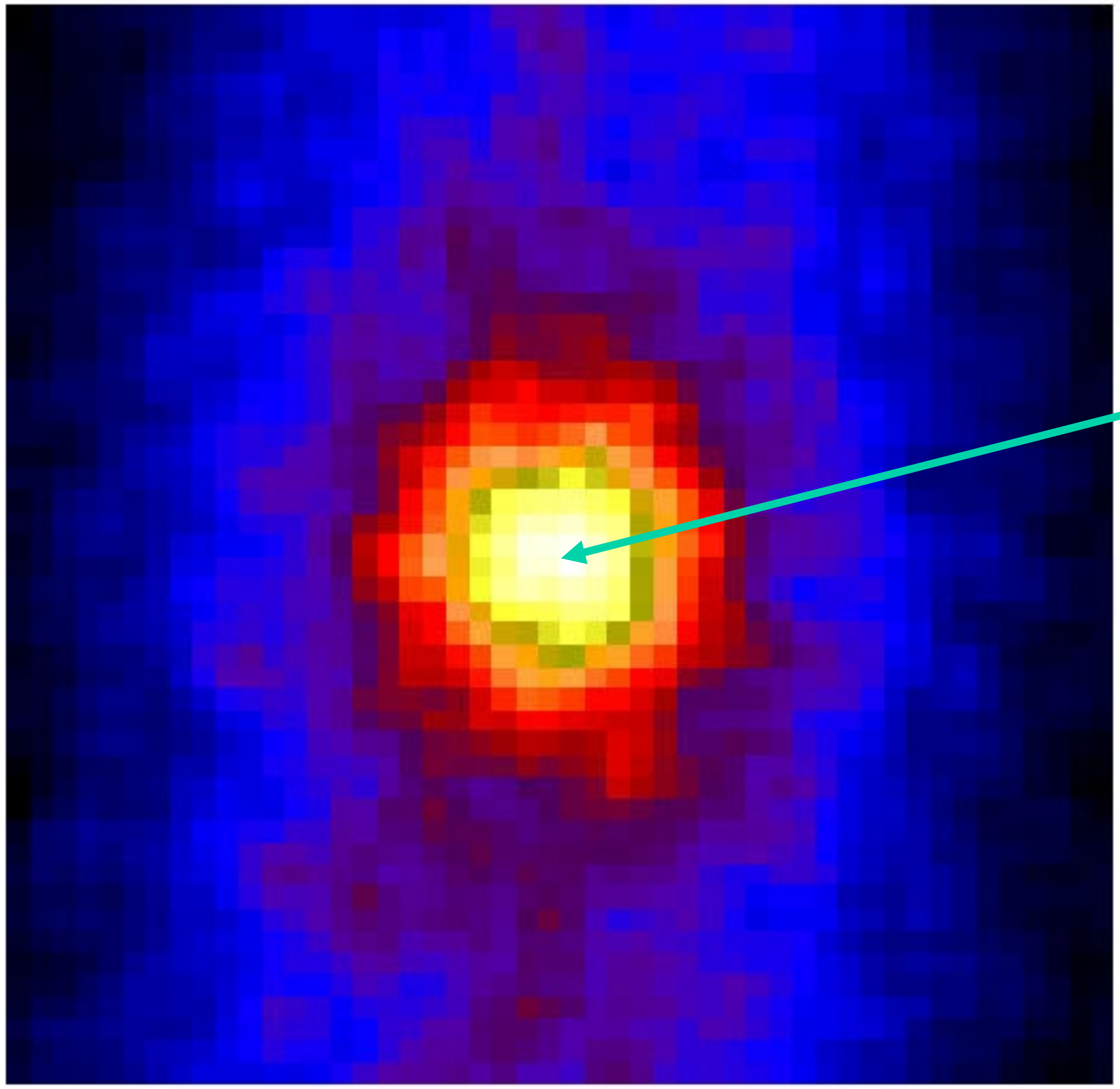
per square cm per sec

Day and Night!

$$\frac{D-N}{D+N} \leq 1\%$$

Neutrino Picture of the Sun

$10^{38}\ \nu/\mathrm{sec}$



Size of the Sun: about One pixel

4 yr exposure, big "camera"

The Energy produced takes 1,000,000 yrs to get to the surface.

The Neutrinos take 2 seconds to get to the surface.

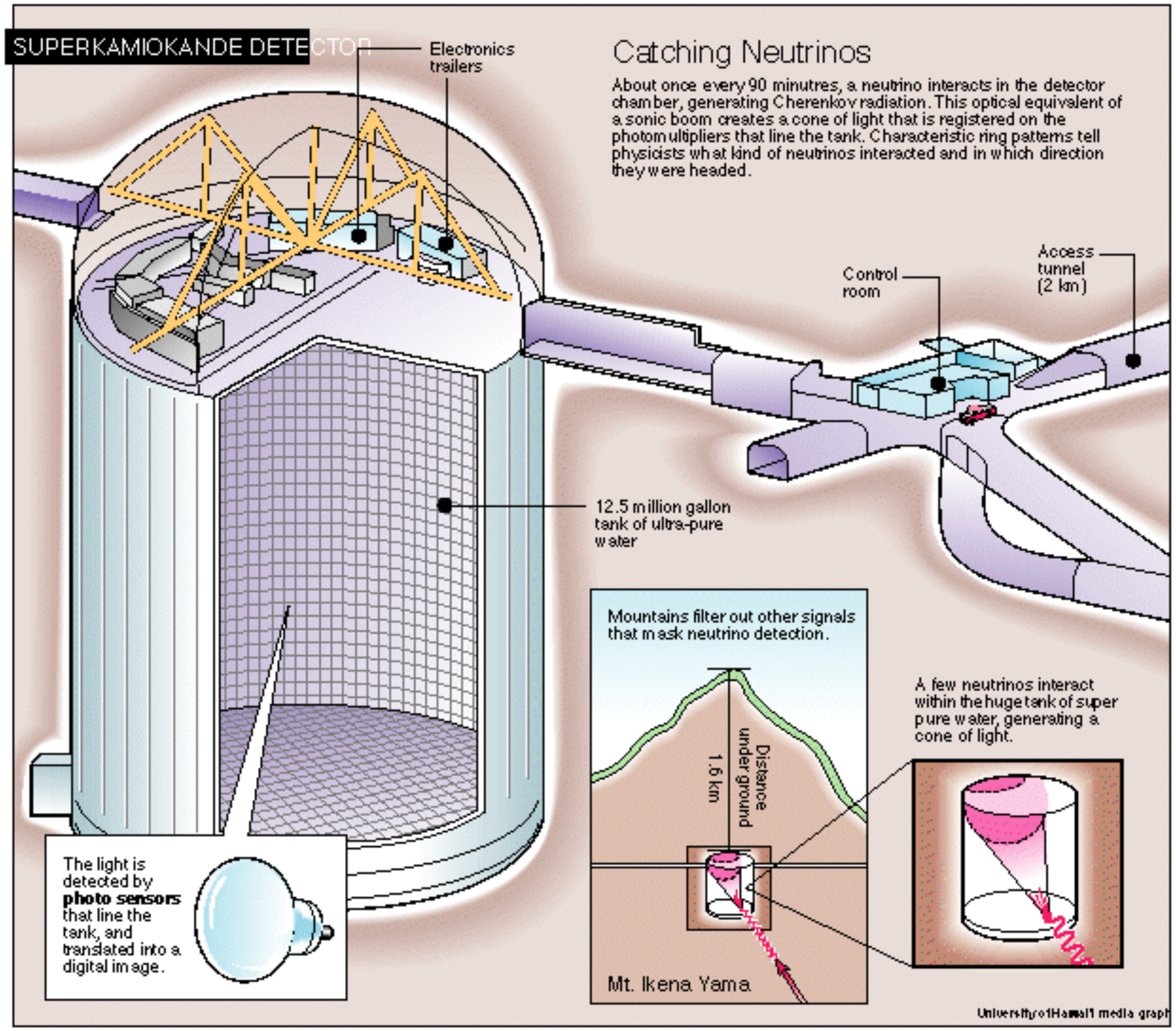
From the Sun to Earth takes 8 minutes.

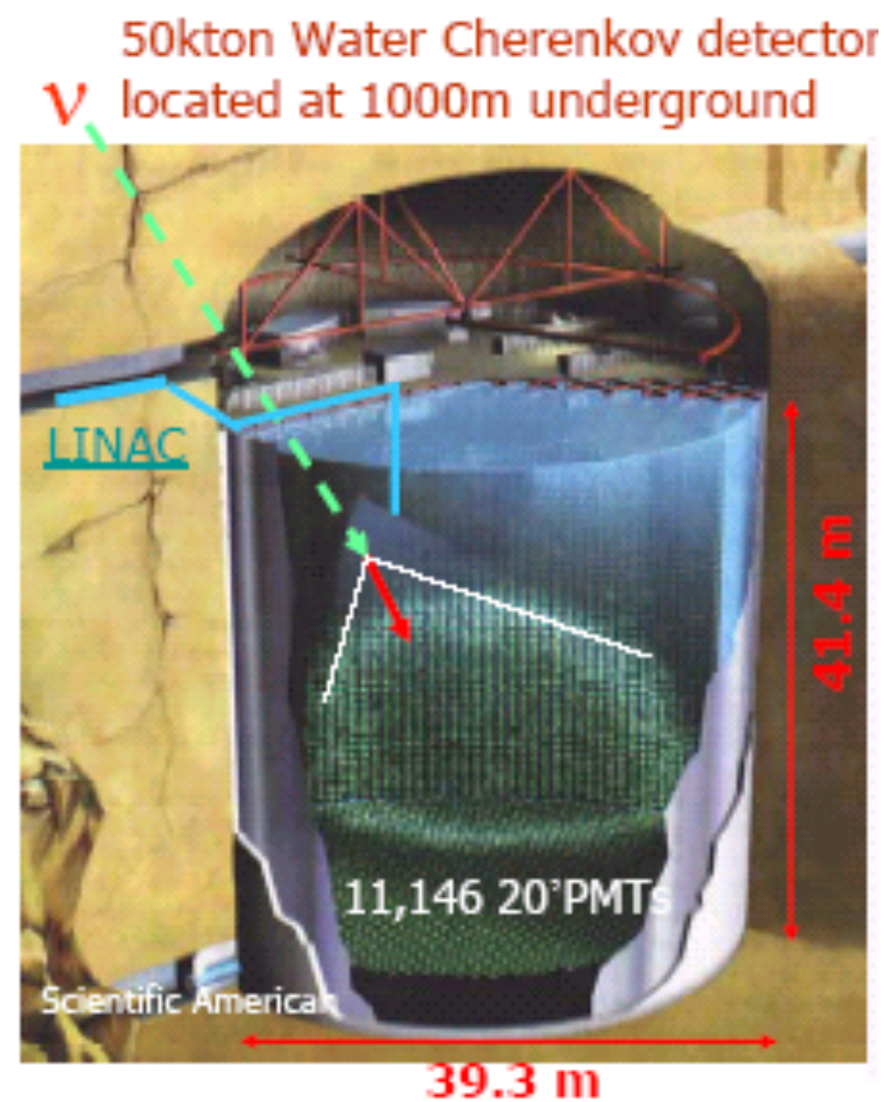
Star Trek: The Next Generation

The visor "sees" Neutrinos!!!

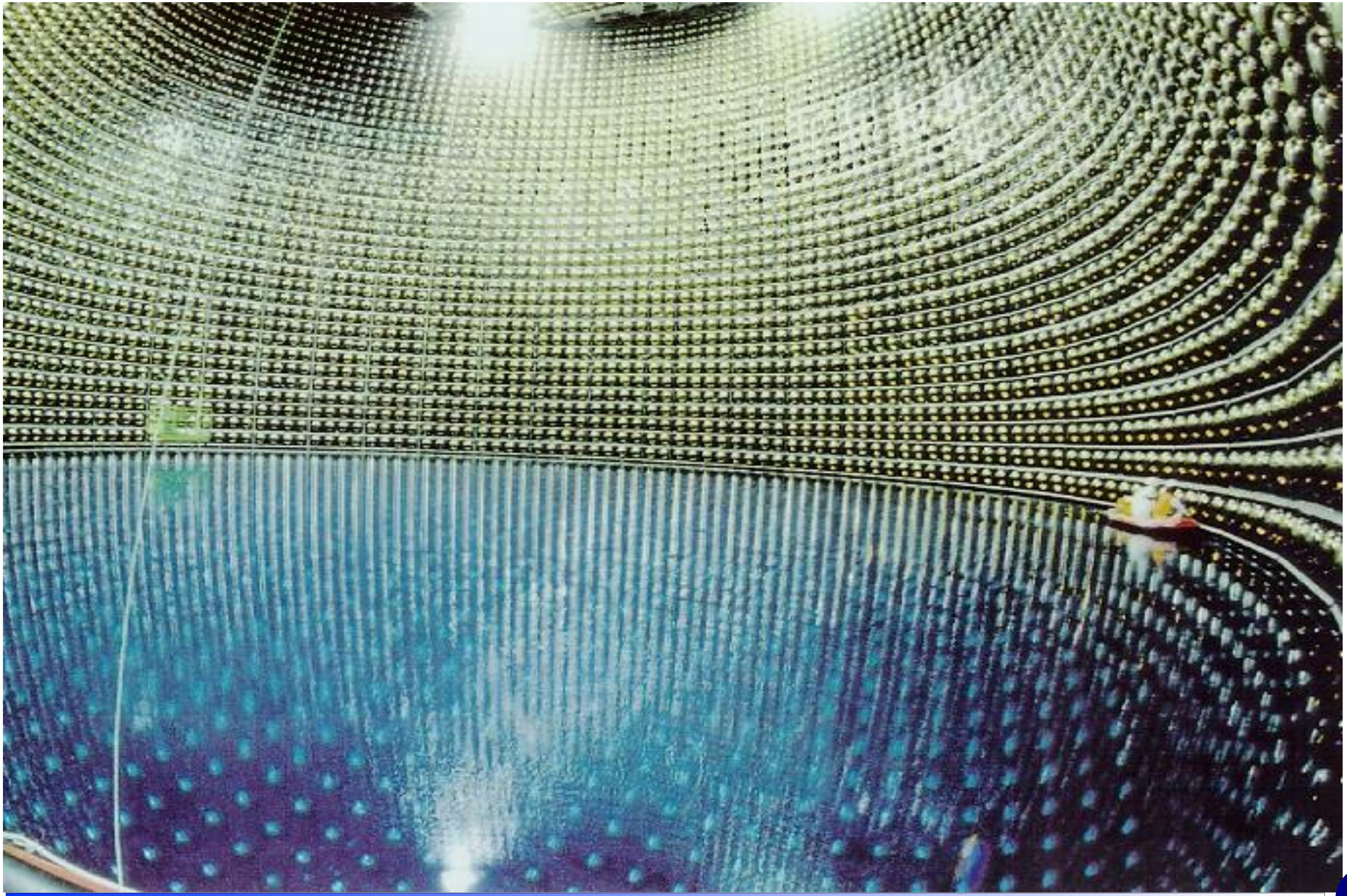
Geordi La Forge: in "The Enemy"

SuperKamiokande





SuperKamiokande



Solar Spectrum:

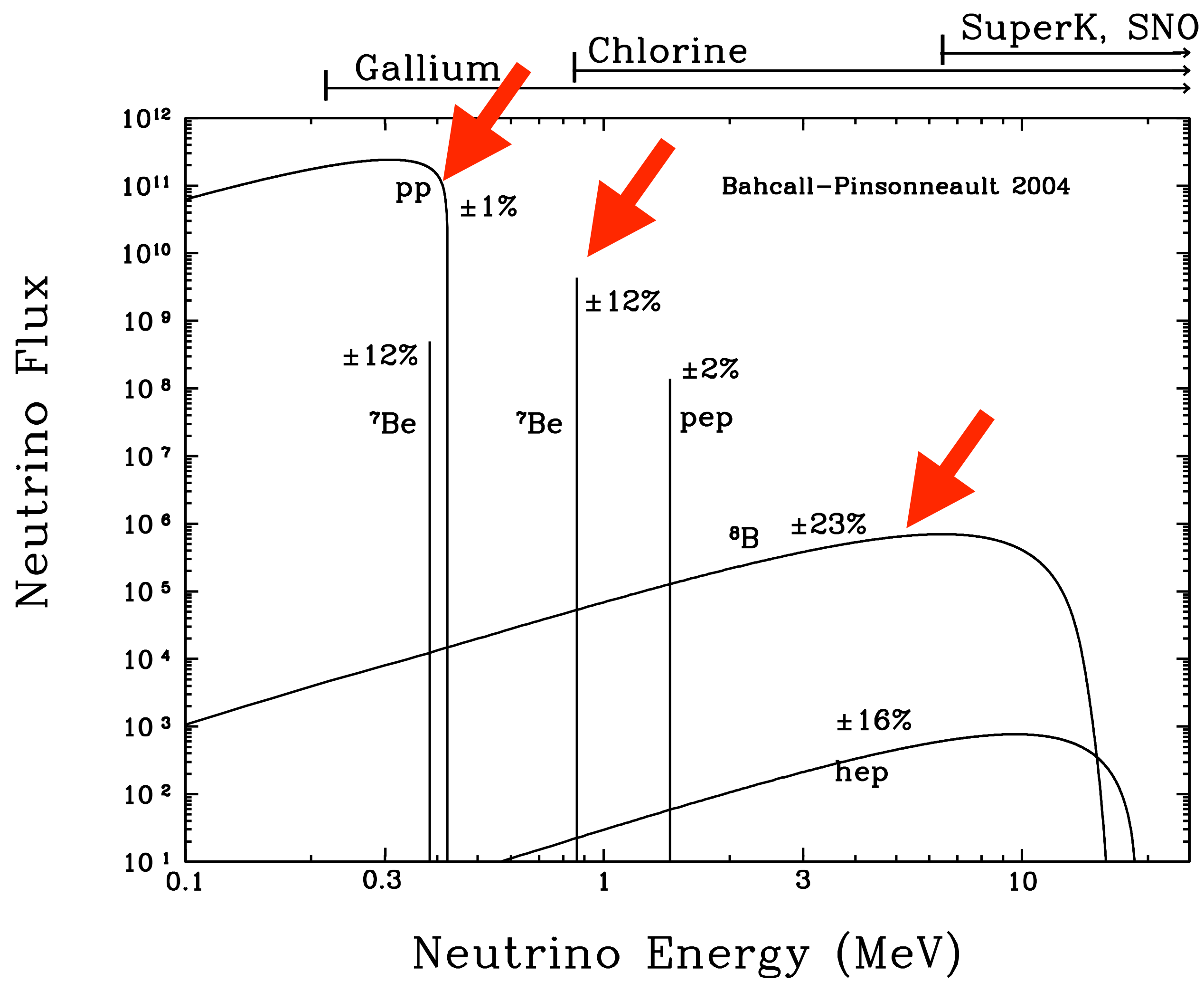


Figure 1. The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [22]. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2}\,s^{-1}\,MeV^{-1}$ at the Earth's surface. For line sources, the units are number of neutrinos $cm^{-2}\,s^{-1}$. Total theoretical uncertainties taken from column 2 of table 1 are shown for each source. To avoid complication in the figure, we have omitted the difficult-to-detect CNO neutrino fluxes (see table 1).

$$p + p \to {}^2H + e^+ + \nu_e$$

$$\phi_{pp} = 5.94(1 \pm 0.01) \times 10^{10} cm^{-2} sec^{-1}$$

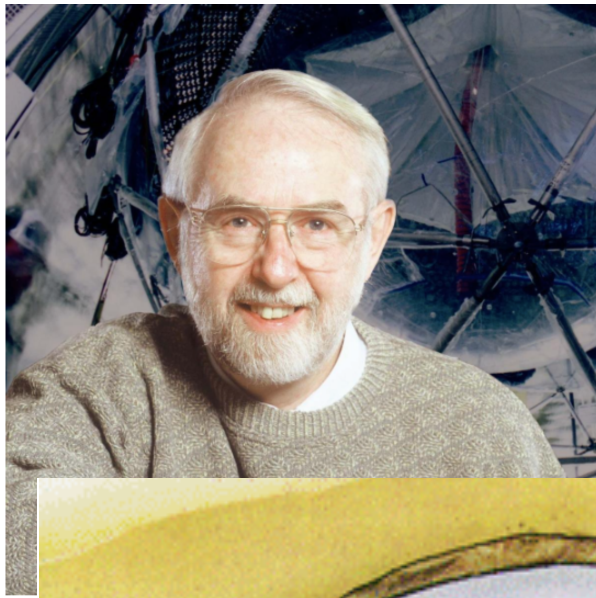
$$^7Be + e^- \to {}^7Li + \nu_e$$

$$\phi_{^7Be} = 4.86(1 \pm 0.12) \times 10^9 cm^{-2} sec^{-1}$$

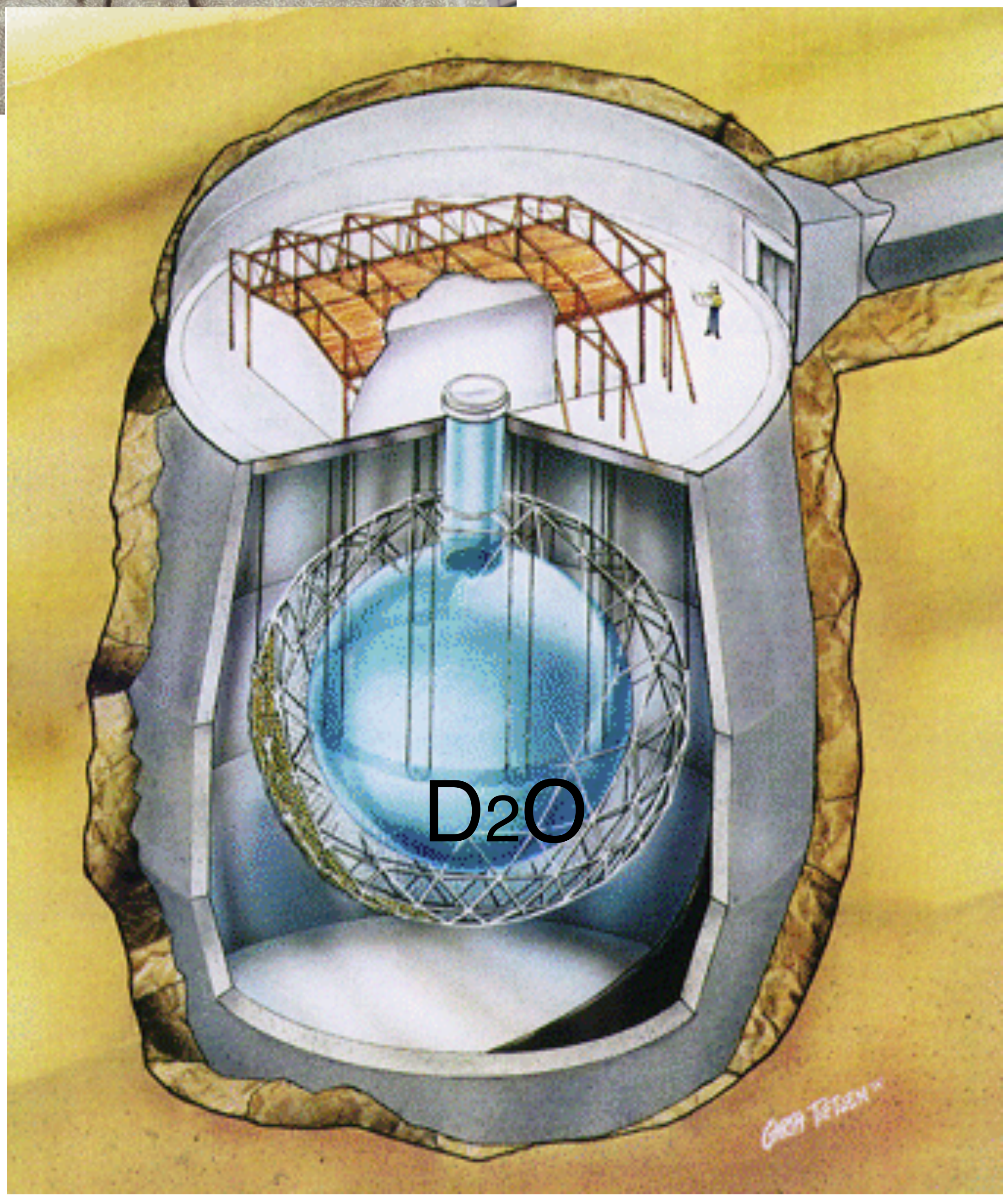
$$^7Be + p \to {}^8B \to {}^8Be^* + e^- + \nu_e$$

$$\phi_{^8B} = 5.82(1 \pm 0.23) \times 10^6 cm^{-2} sec^{-1}$$

Art McDonald and SNO



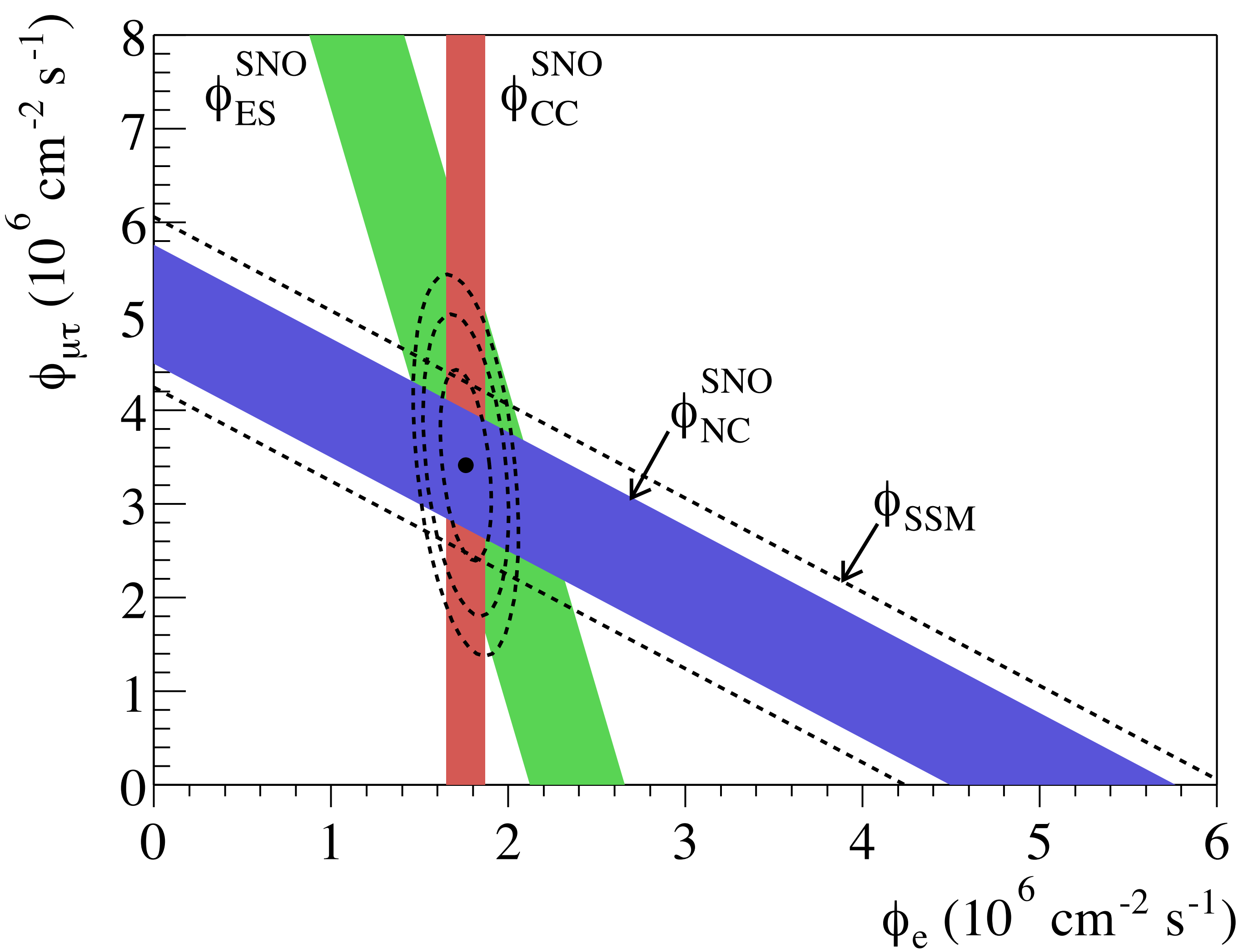
2001



CC: $\nu_e + D \rightarrow p + p + e^-$

NC: $\nu_x + D \rightarrow p + n + \nu_x$

ES: $\nu_e + e^- \rightarrow \nu_e + e^-$
and $\nu_{\mu/\tau} + e^- \rightarrow \nu_{\mu/\tau} + e^-$



Beacom and SP: hep-ph/0106128

Atmospheric Neutrinos:

"All the News That's Fit to Print"

The New York Times

VOL. CXLVII . . . . No. 51,179 Copyright © 1998 The New York Times FRIDAY, JUNE 5, 1998

20+ years ago

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, 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 much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, 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.

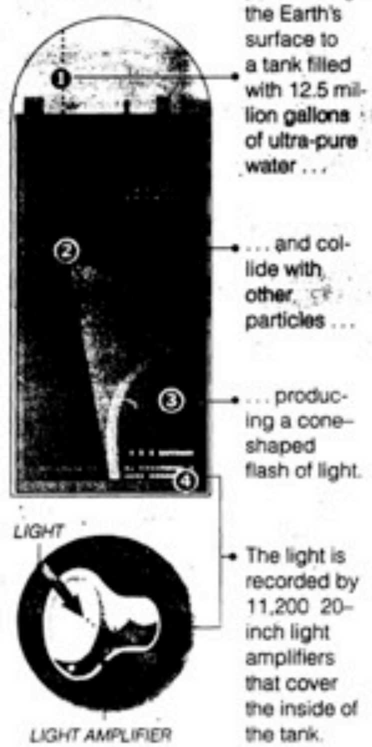
Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

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

The New York Times

ν98, @Takayama
June 1998

Atmospheric neutrino results from Super-Kamiokande & Kamiokande

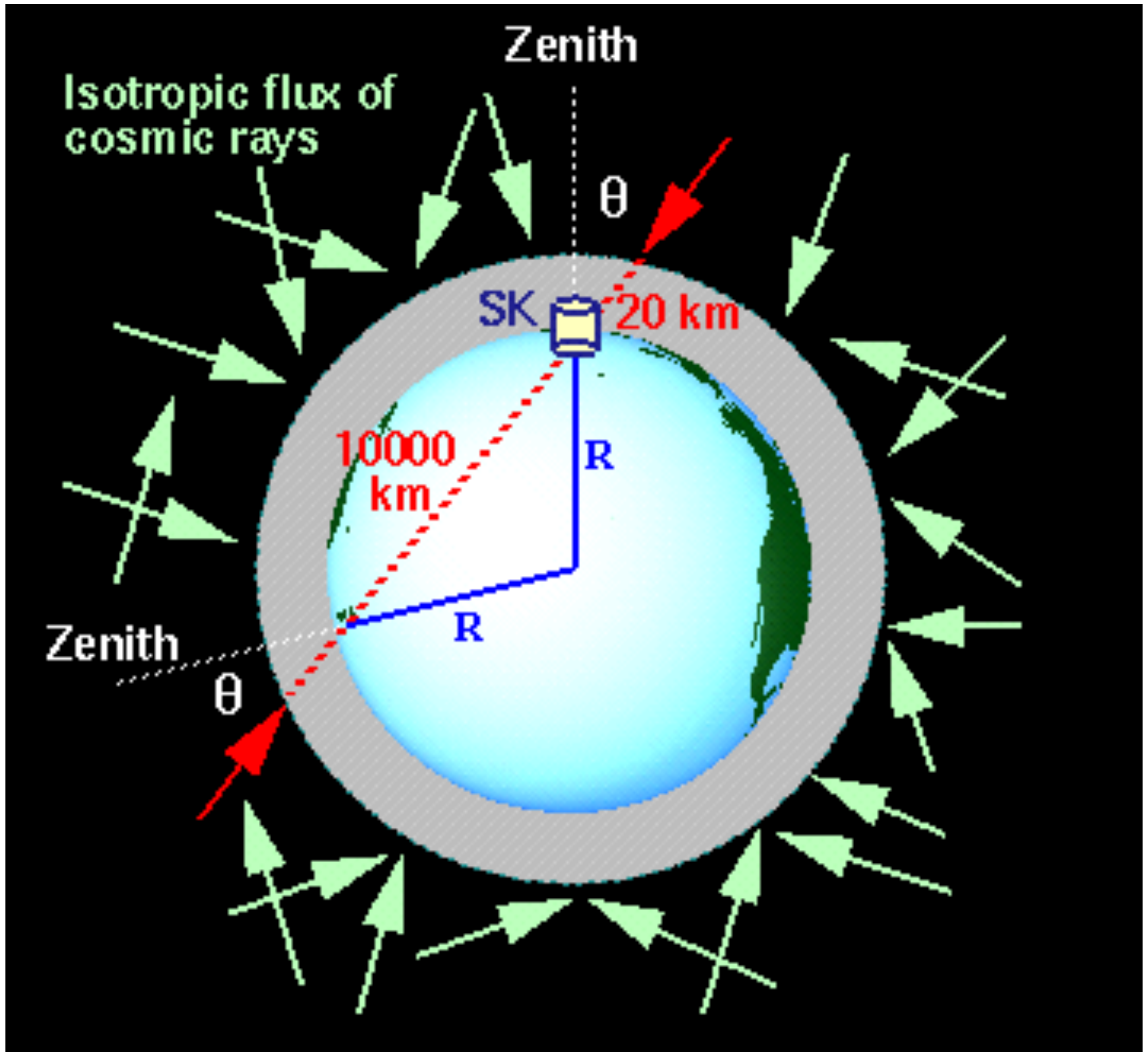
— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo

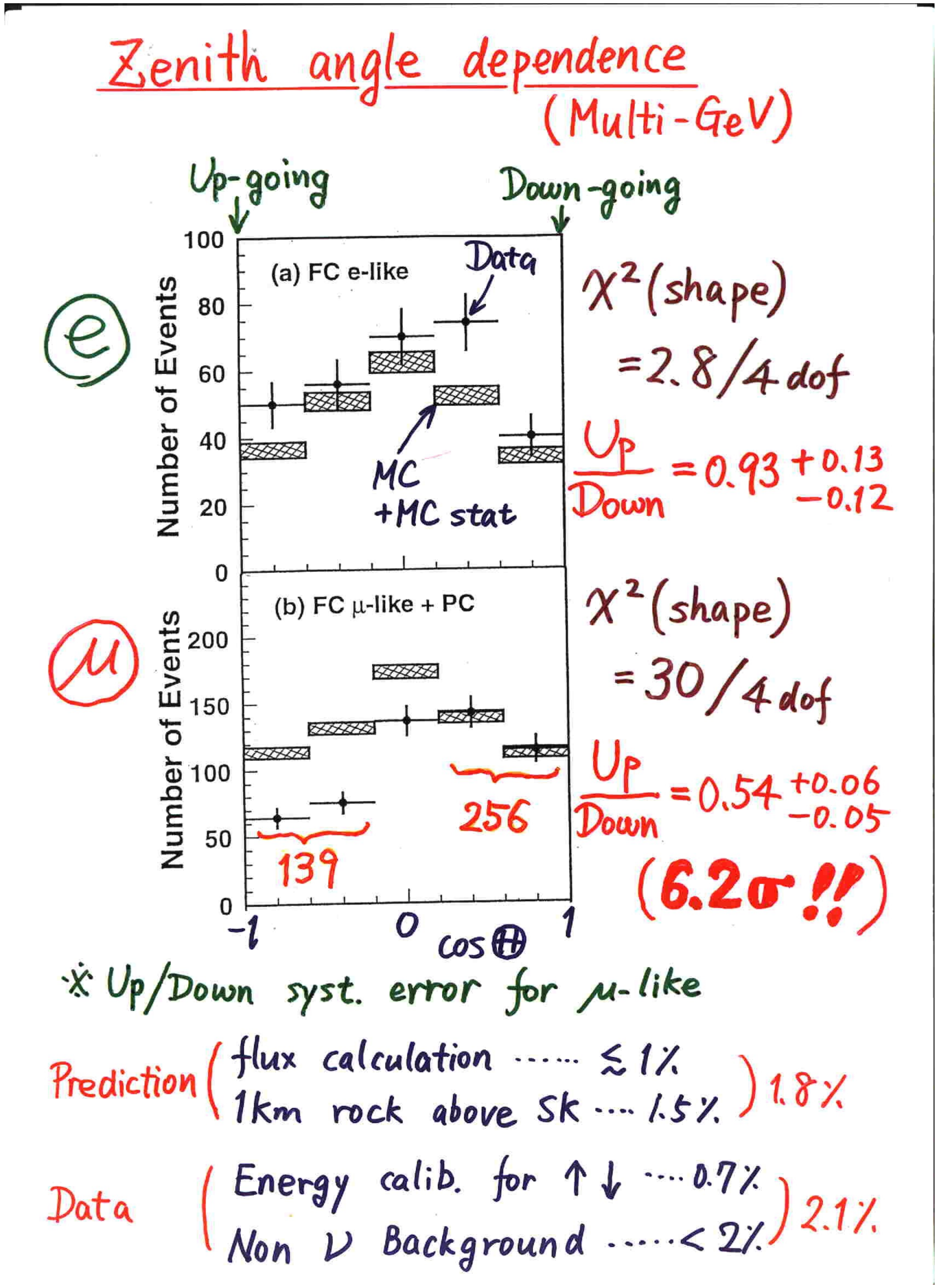
for the {Kamiokande, Super-Kamiokande} Collaborations

http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/

Slide 13:

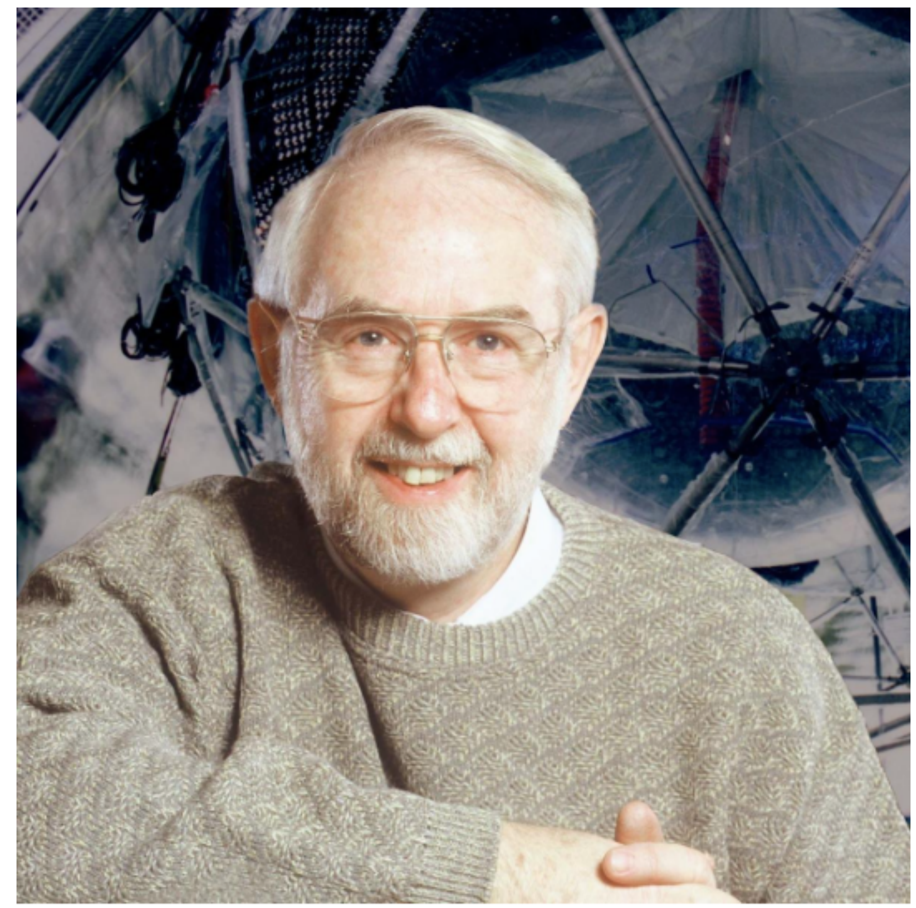


Zenith
Isotropic flux of cosmic rays
θ
SK
20 km
10000 km
R
R
Zenith
θ



Zenith angle dependence
(Multi-GeV)
Up-going
Down-going
(a) FC e-like
Data
MC +MC stat
Number of Events
e
χ^2(shape) = 2.8/4 dof
Up/Down = 0.93 +0.13 −0.12
(b) FC μ-like + PC
μ
χ^2(shape) = 30/4 dof
Up/Down = 0.54 +0.06 −0.05
(6.2σ !!)
139
256
−1 0 cos Θ 1
※ Up/Down syst. error for μ-like
Prediction (flux calculation ······ ≲ 1% ; 1km rock above SK ···· 1.5%) 1.8%
Data (Energy calib. for ↑↓ ···· 0.7% ; Non ν Background ·····< 2%) 2.1%

2015 Nobel Prize



Takaaki Kajita

Art MacDonald

Lunch !!!

Potassium: 0.01% K^40

358 mg / 100gm

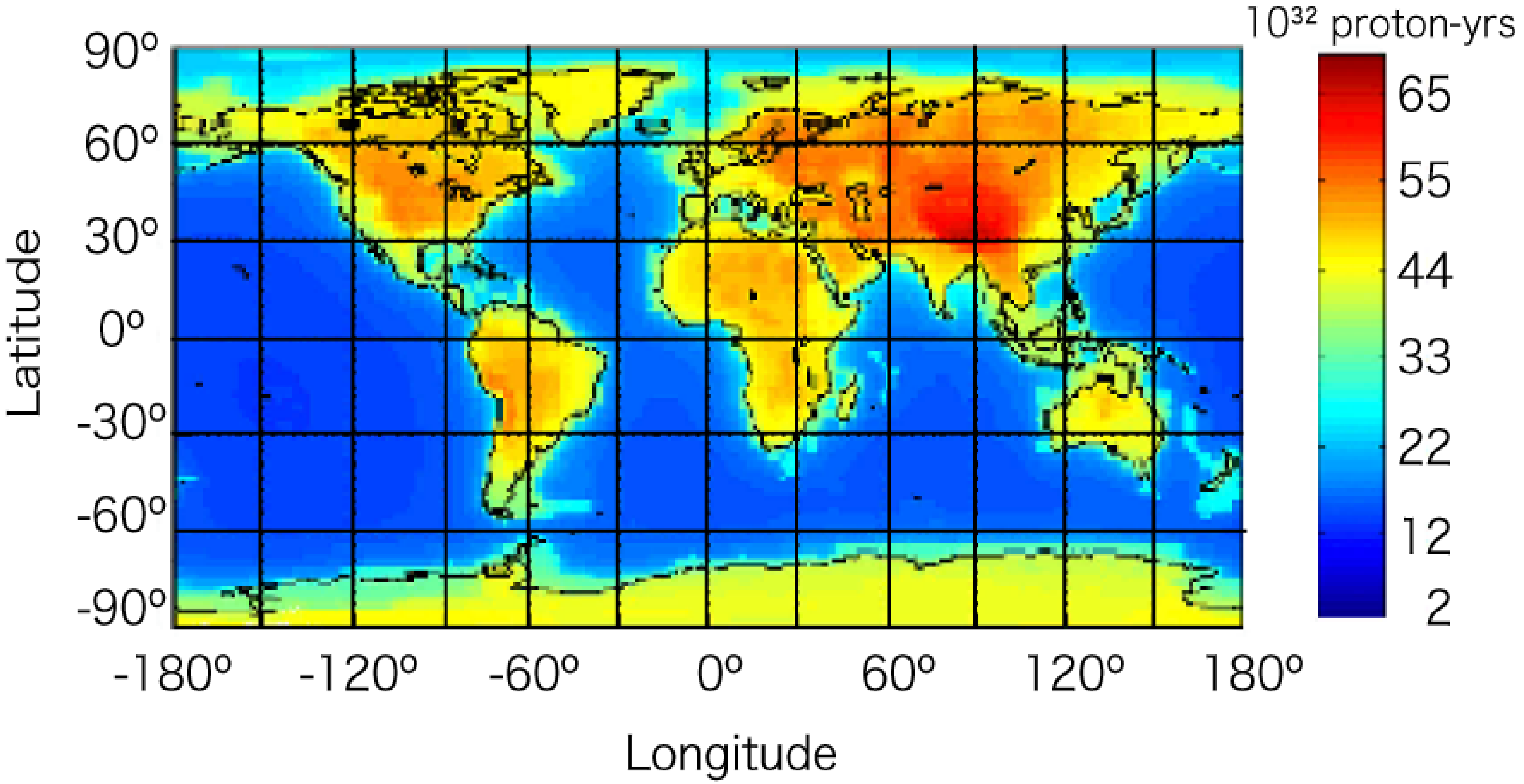
1 million neutrinos/day

312 mg / 100gm

485 mg / 100gm

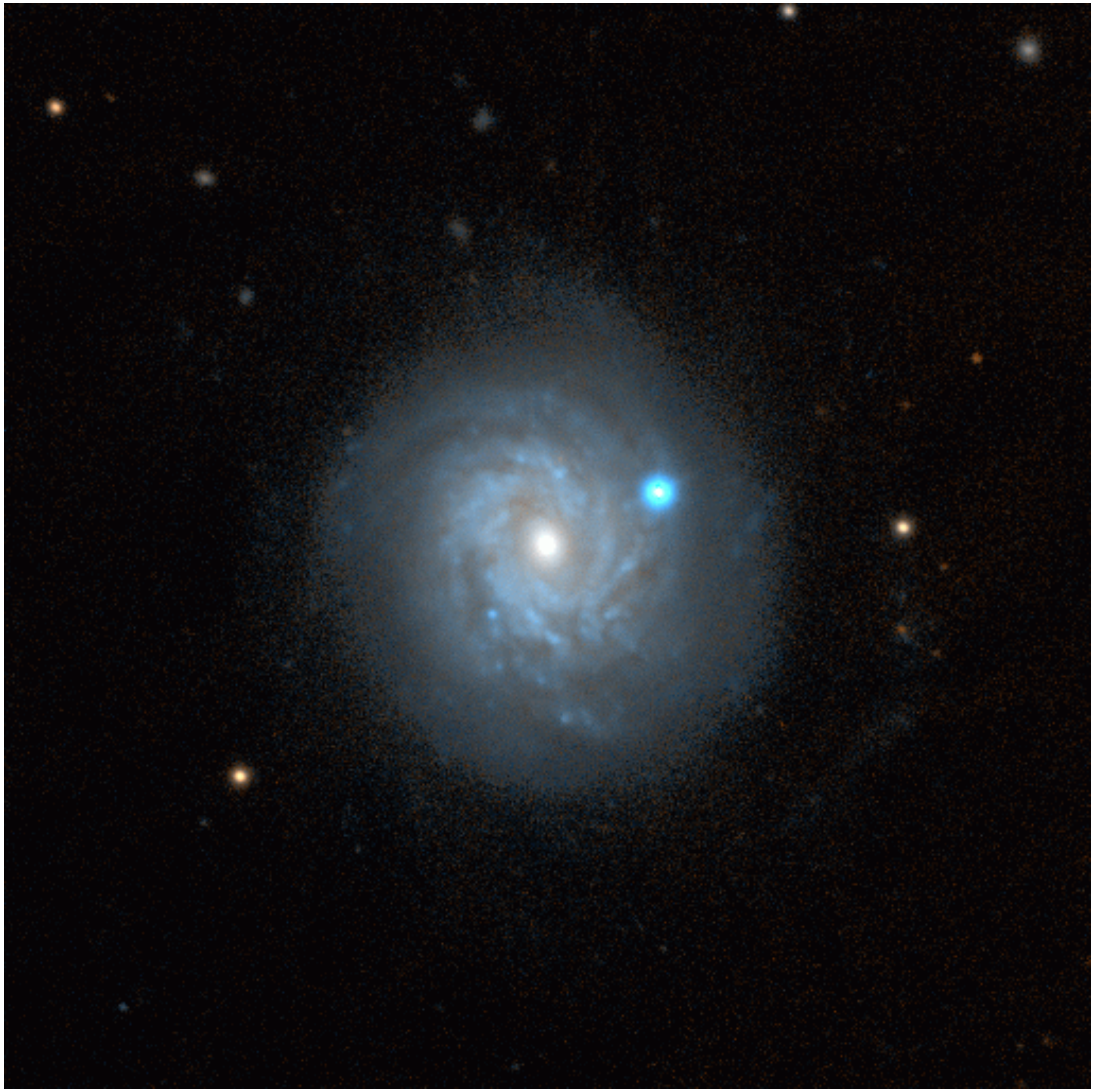
beta decay 89% (Ca) and electron capture 11% (Ar)

Predicted geo-neutrino signal

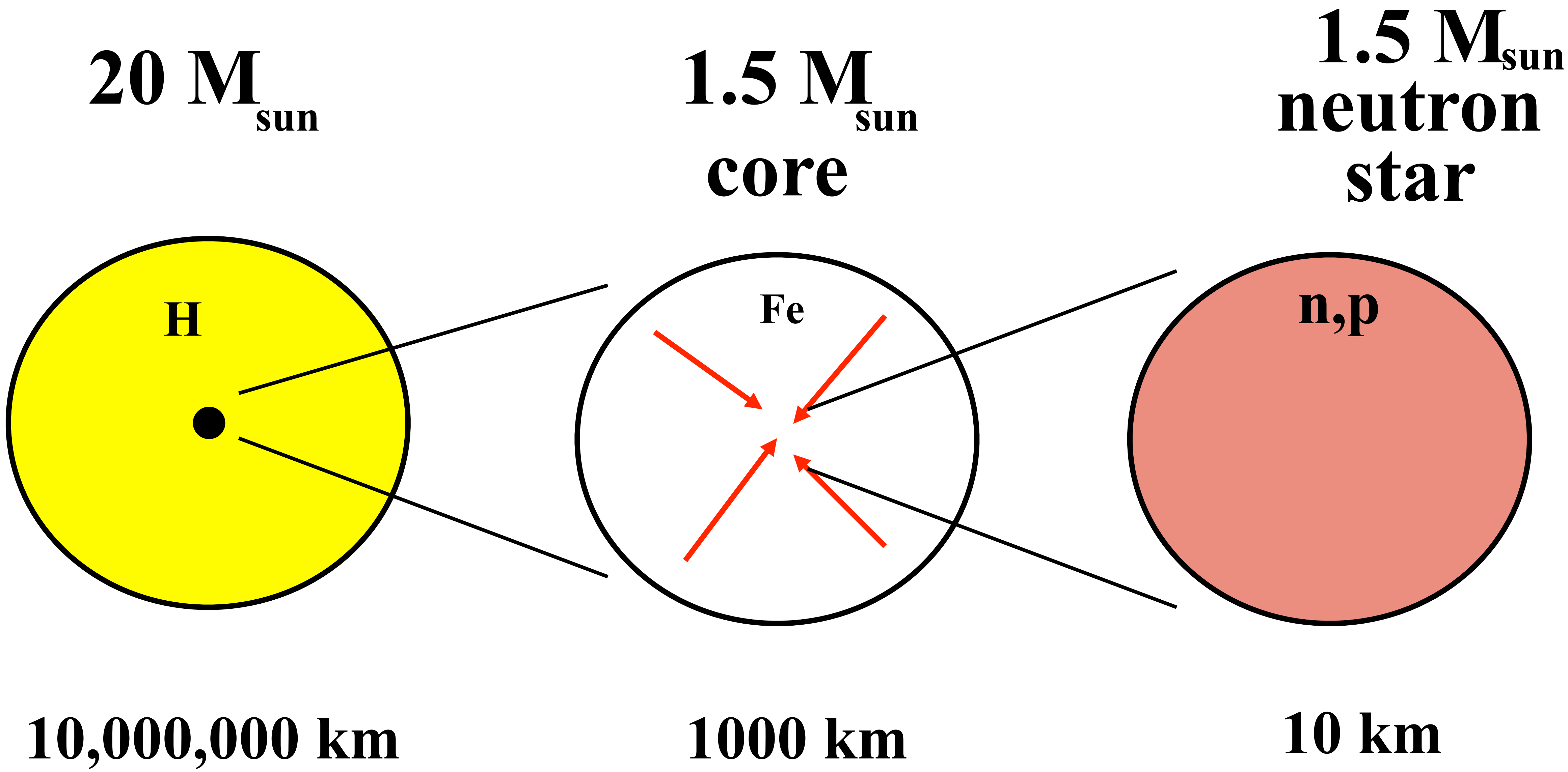


SuperNova

Supernova



Mechanics of a Supernova



Energy Released 10^{40} kilowatt-hours!!!

equivalent to 0.1 M_{sun}

Supernova Energy Budget = $100

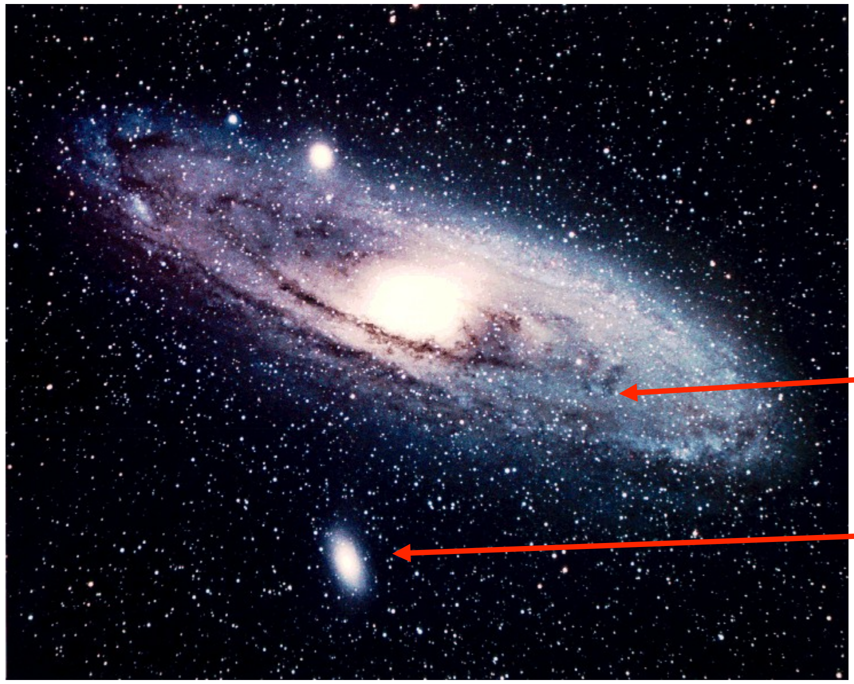
- **Light show** 1c = 0.01%
- **Blowing Star Apart** $1 = 1%
- **Neutrinos** $99 = 99%

Light show lasts months

Neutrino tsunami lasts 10-20 seconds !!!

$$\mathbf{10^{58}} \quad \boldsymbol{\nu + \bar{\nu}}$$

Supernova 1987a - Feb 24

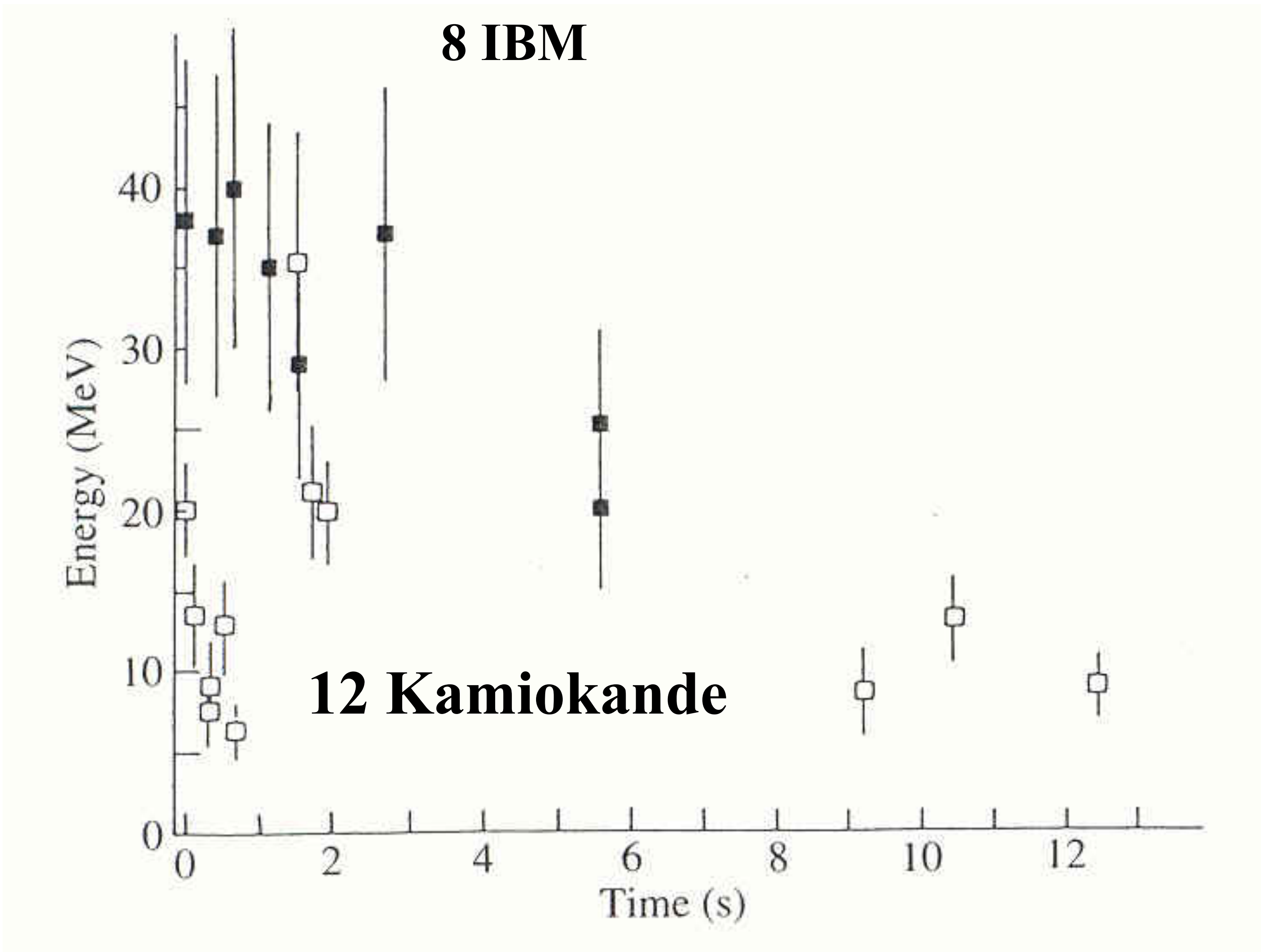


We are here

Large Magelanic Cloud
170,000 light years away !

First time in over 300 yrs SN visible to naked eye

Neutrinos from SN 1987a



100,000 times brighter than our Sun in Neutrinos arrived 3 hours before the light?

~ 500

Supernova Neutrino Tsunamis

are on their way

from supernova in our galaxy!!!

Bigger Detectors,   More Detectors

Rate ???

2 +/- 1 per century !

Nobel Prize 2002

"….for the detection of cosmic neutrinos"

Davis, USA

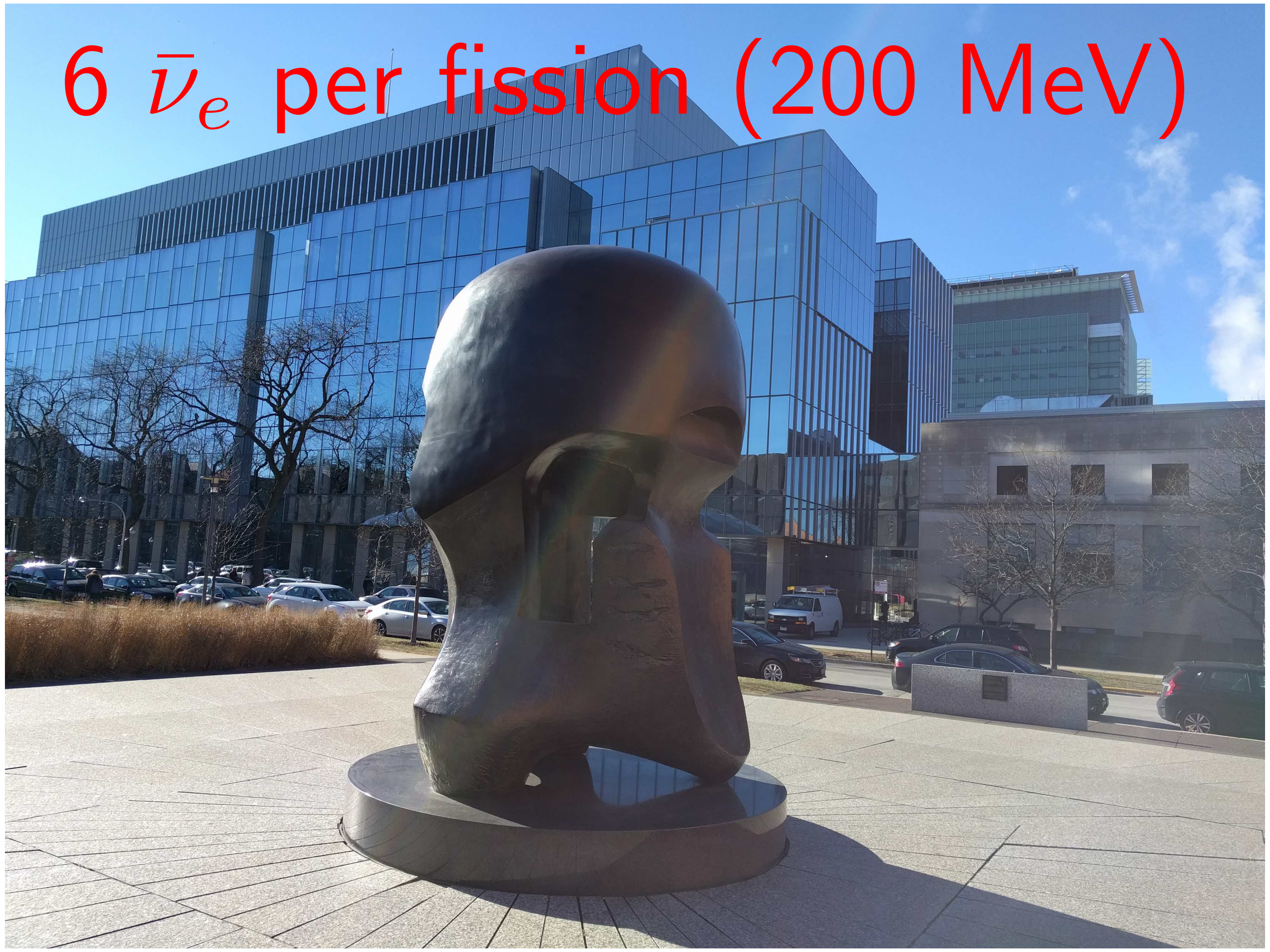
solar

Koshiba, Japan

supernova

Reactor Neutrinos

1 watt reactor !



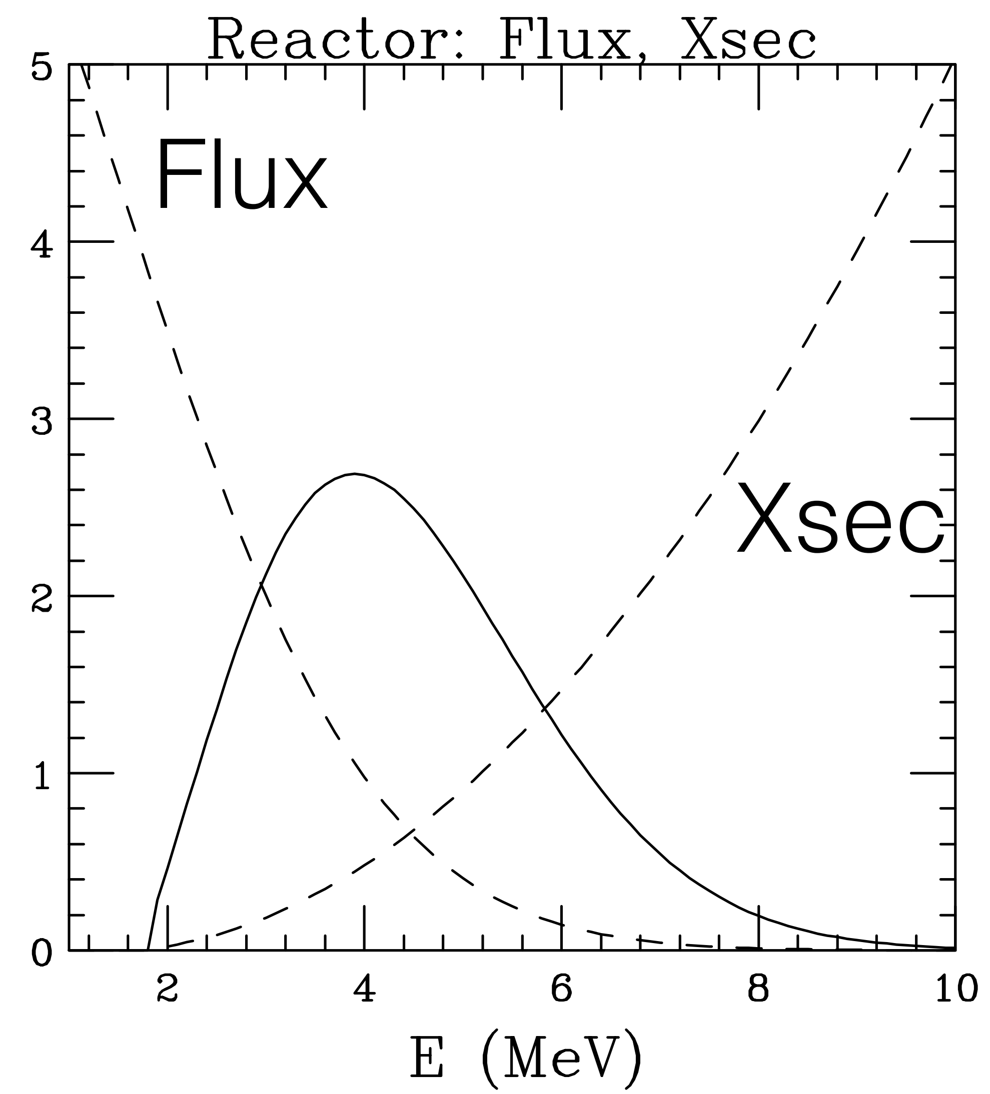
produced $10^{11}\,\bar{\nu}_e$ per second

Discovery of the Neutrino:

- **1957 – first observed by Cowan and Reines using nuclear reactor as the source.**

Flux & Cross Section:

Total is
2 x 10^20 /sec/GW-Th



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

Reactor θ_{13} Experiments

Daya Bay

RENO

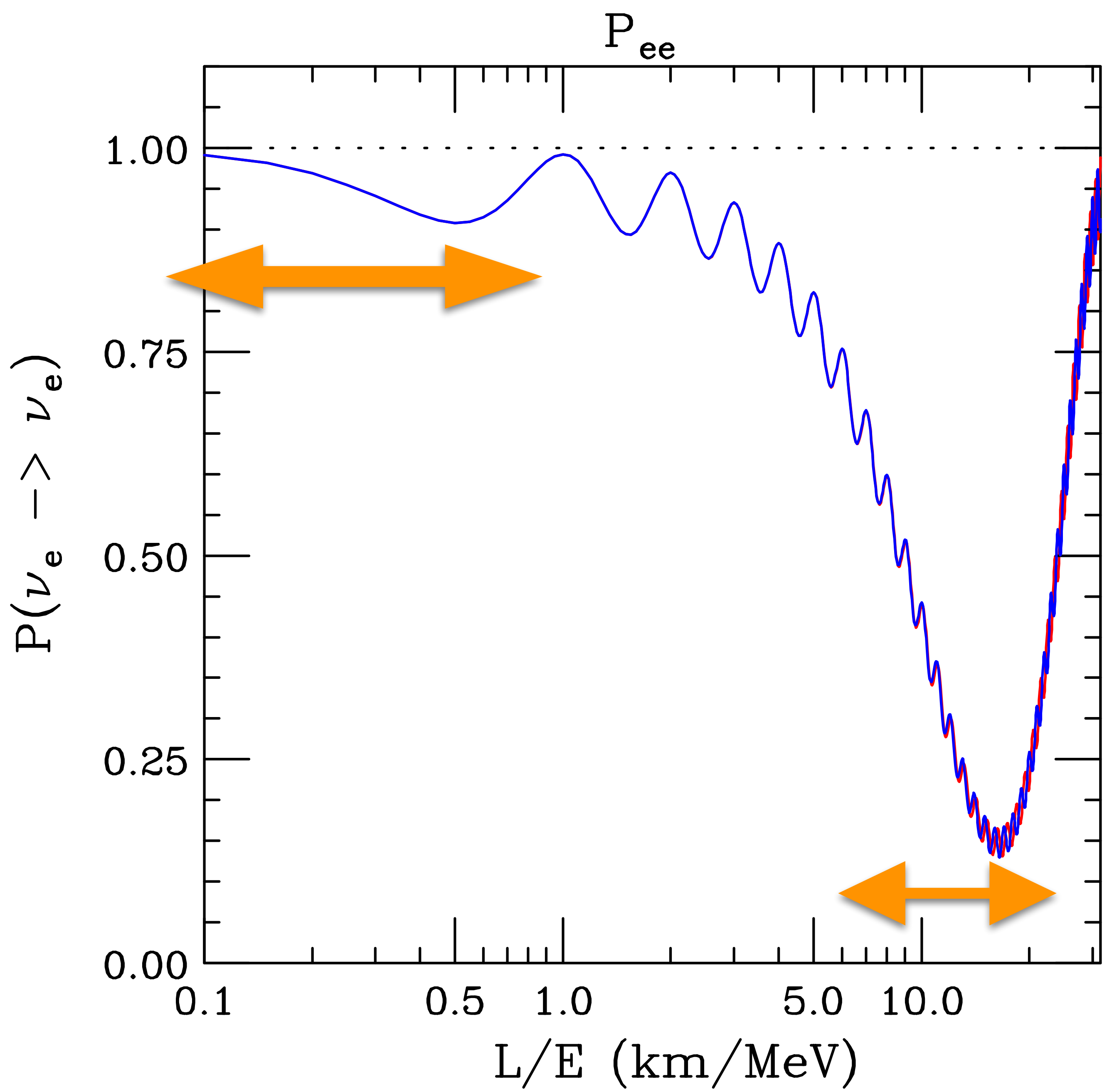
Double Chooz

produce $\mathbf{2 \times 10^{20}}\, \bar{\nu}_e$ per GW_{th} per second

100's of MW into neutrinos !!!!

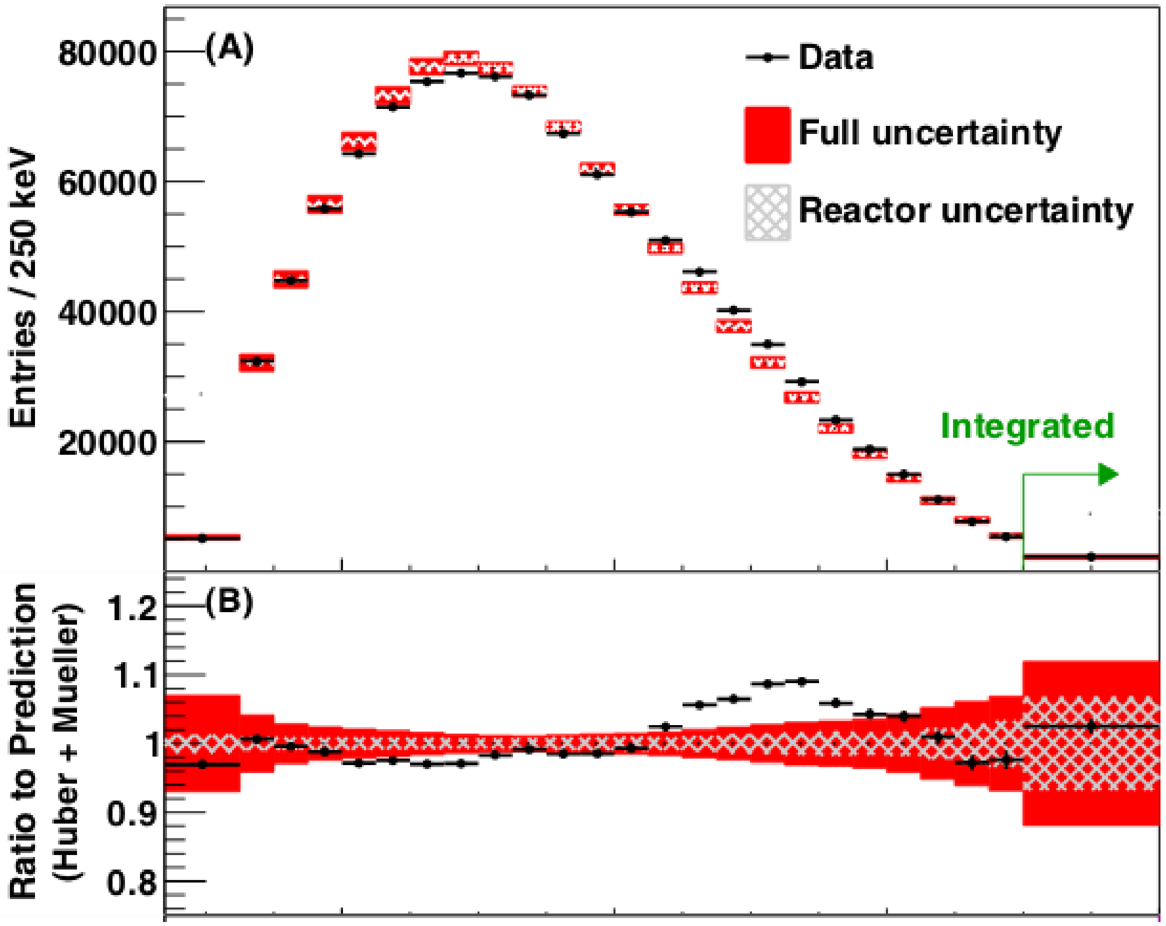
nu_e Disappearance

Daya Bay
RENO
D-Chooz

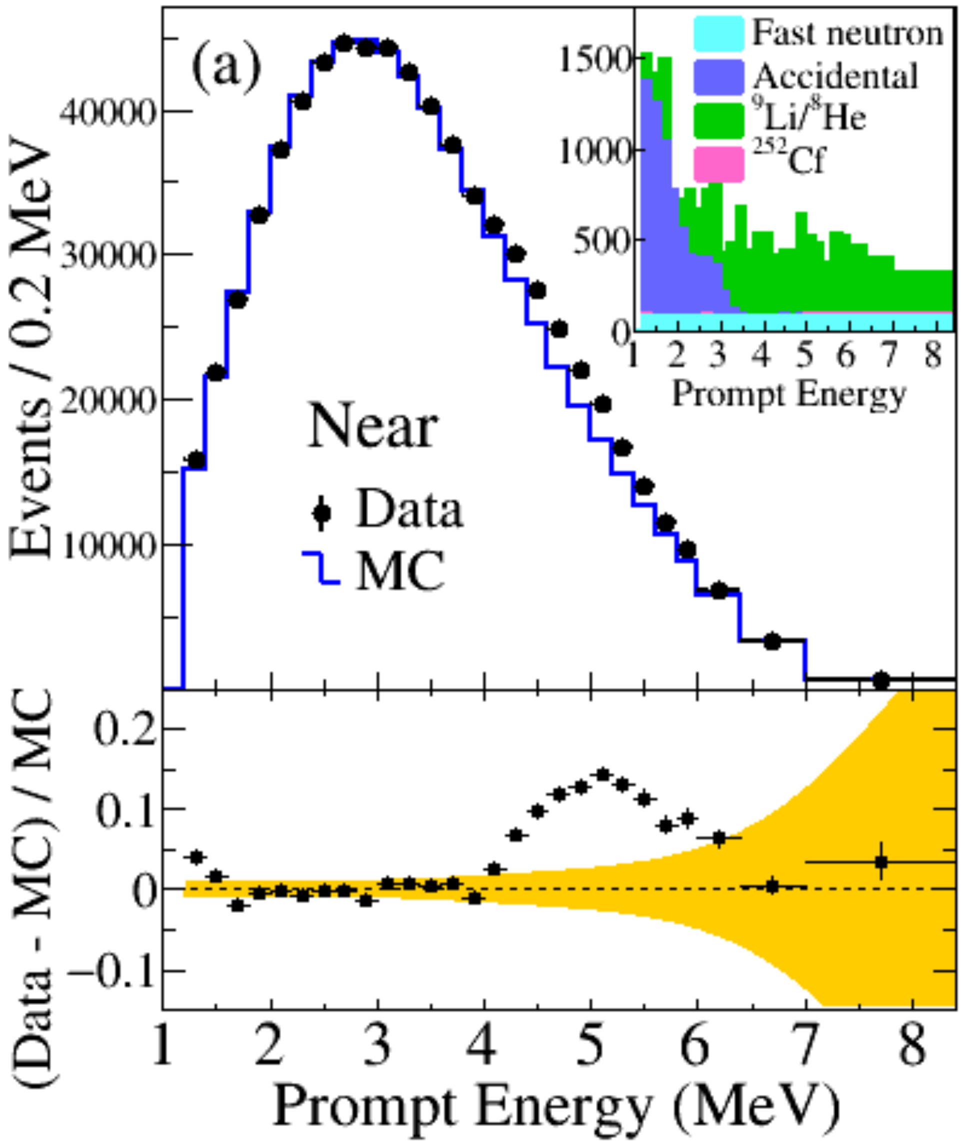


JUNO
RENO 50

Daya Bay



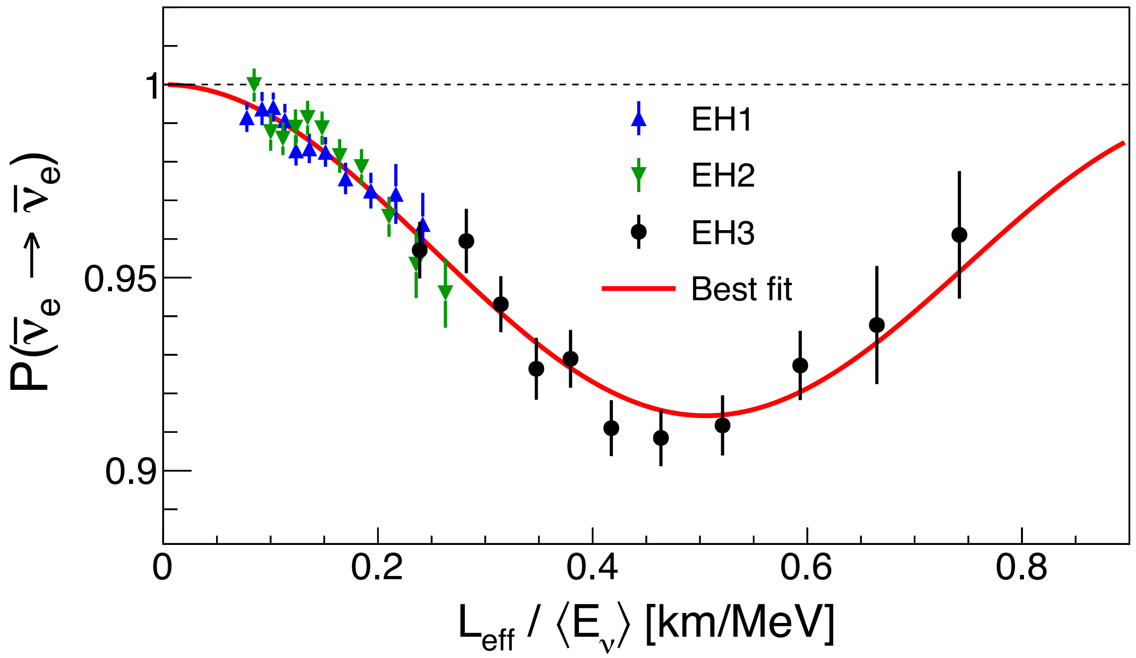
RENO



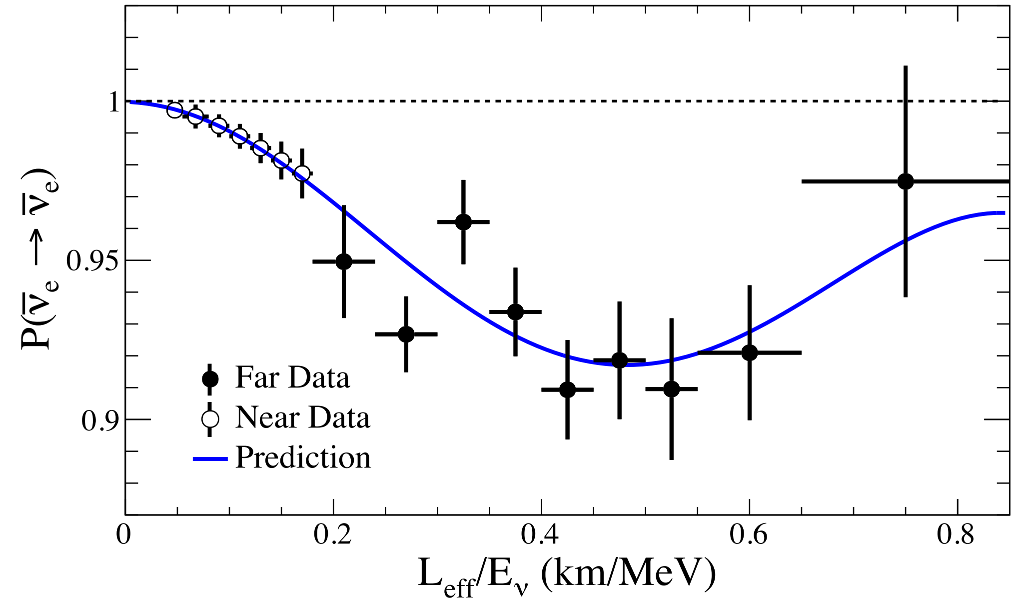
- **4.4σ local significance at 4~6MeV**

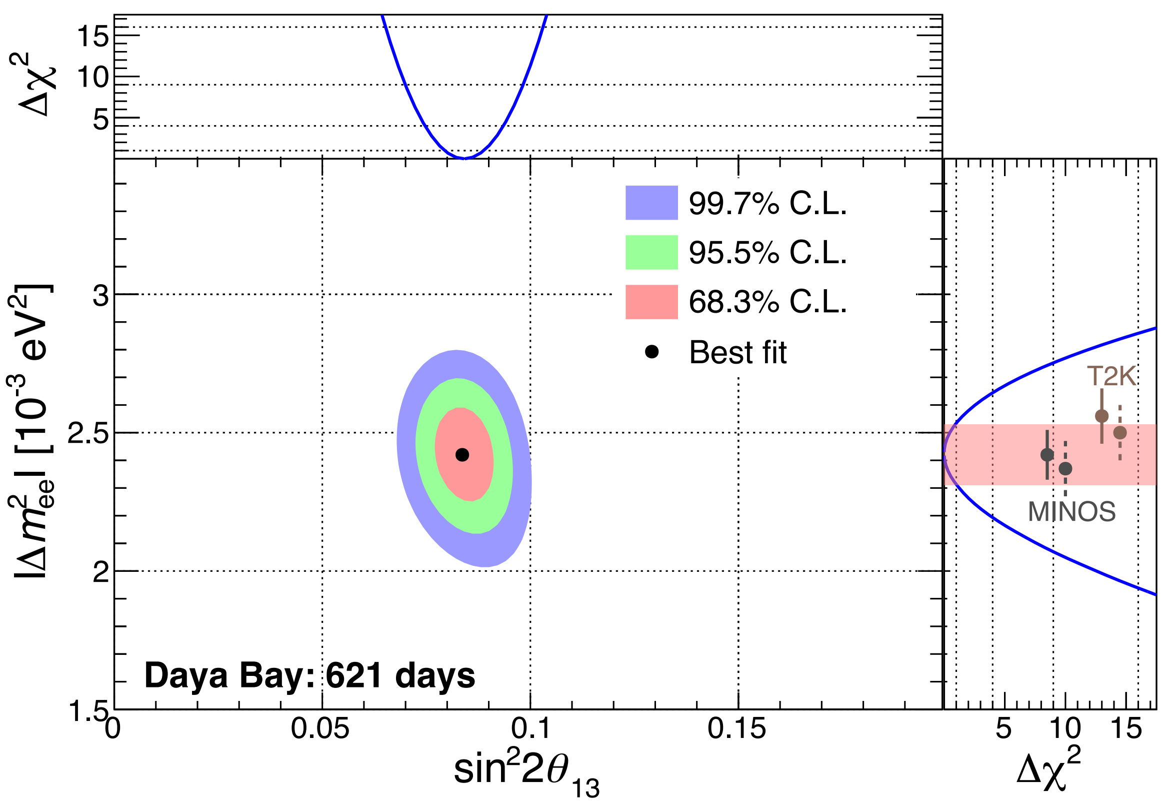
Fraction of 5 MeV excess: **2.46 ± 0.27 (%)**

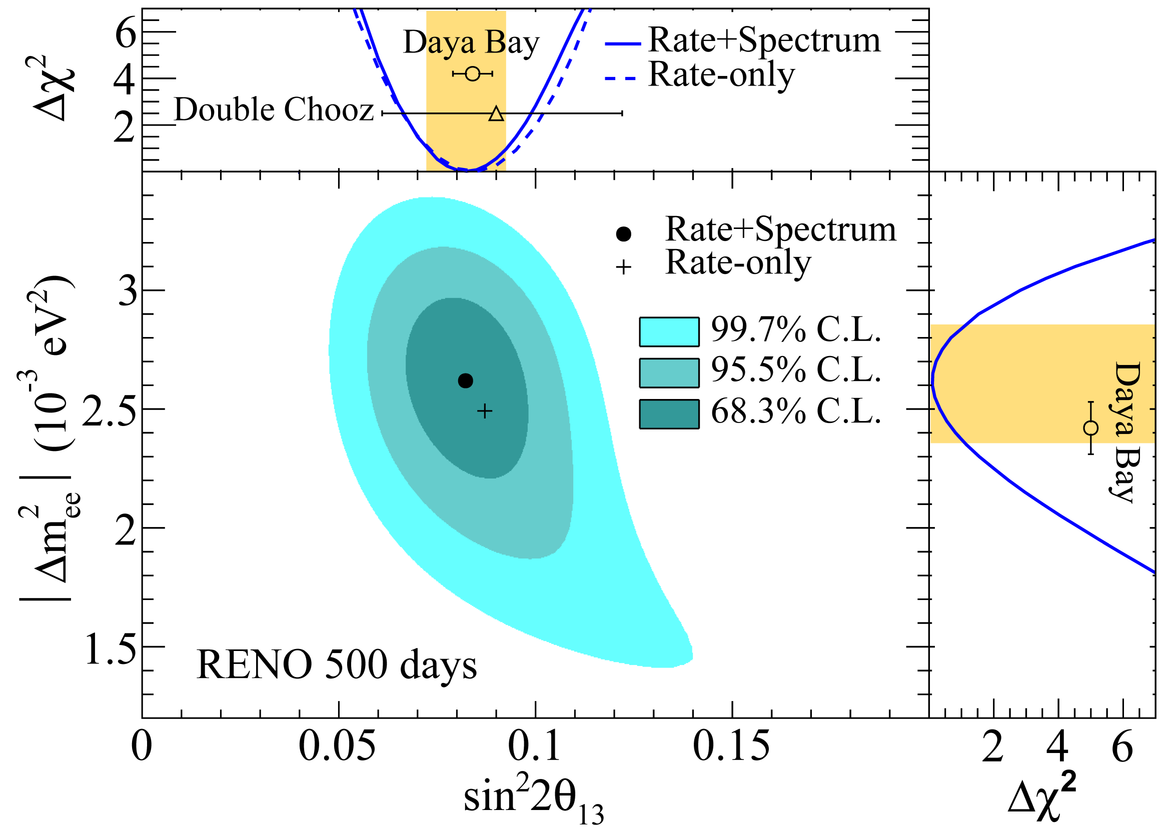
Significance of the 5 MeV excess: ~**9σ** from Daya Bay: arXiv:1505.03456



from RENO arXiv:1511.05849





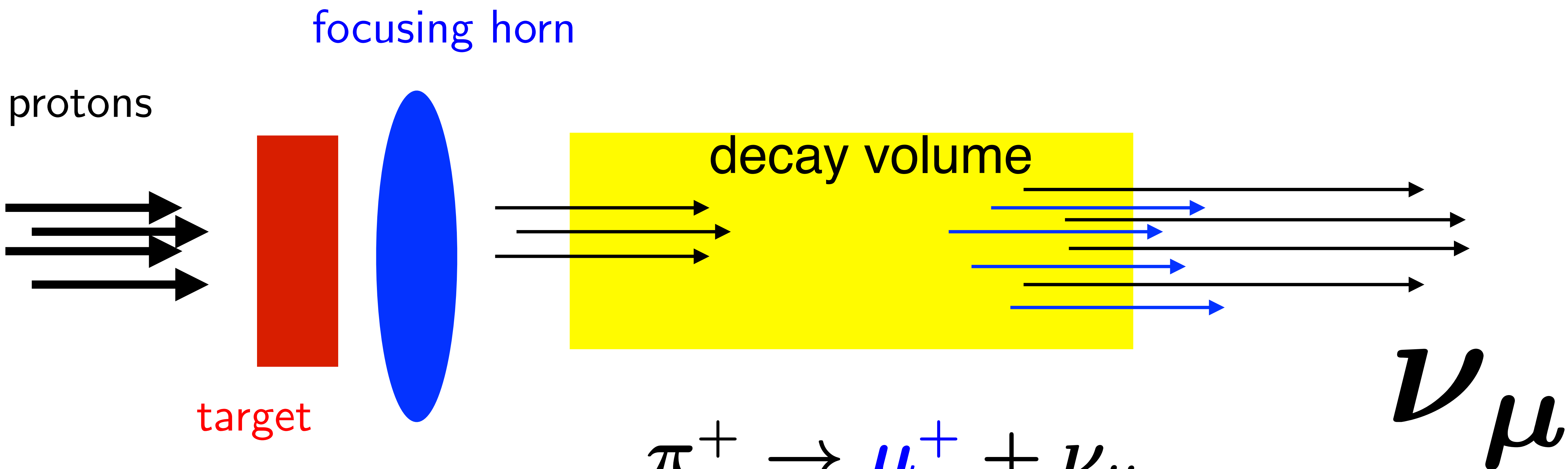


$$\Delta m^2_{ee} \equiv c^2_{12}\, \Delta m^2_{31} + s^2_{12}\, \Delta m^2_{32}$$

Double Chooz ?

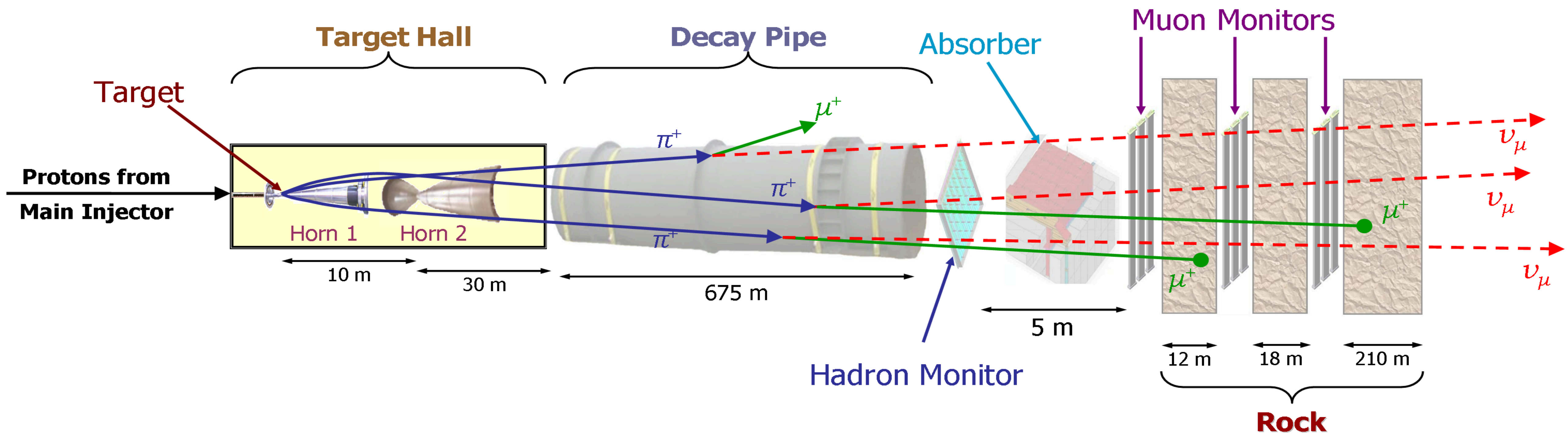
Accelerator Neutrinos

Neutrino Beam:



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Also muon storage ring !



Target Hall
Decay Pipe
Absorber
Muon Monitors
Target
Protons from
Main Injector
Horn 1
Horn 2
π^+
μ^+
ν_μ
10 m
30 m
675 m
5 m
Hadron Monitor
12 m
18 m
210 m
Rock

Fermilab Neutrino BeamLines

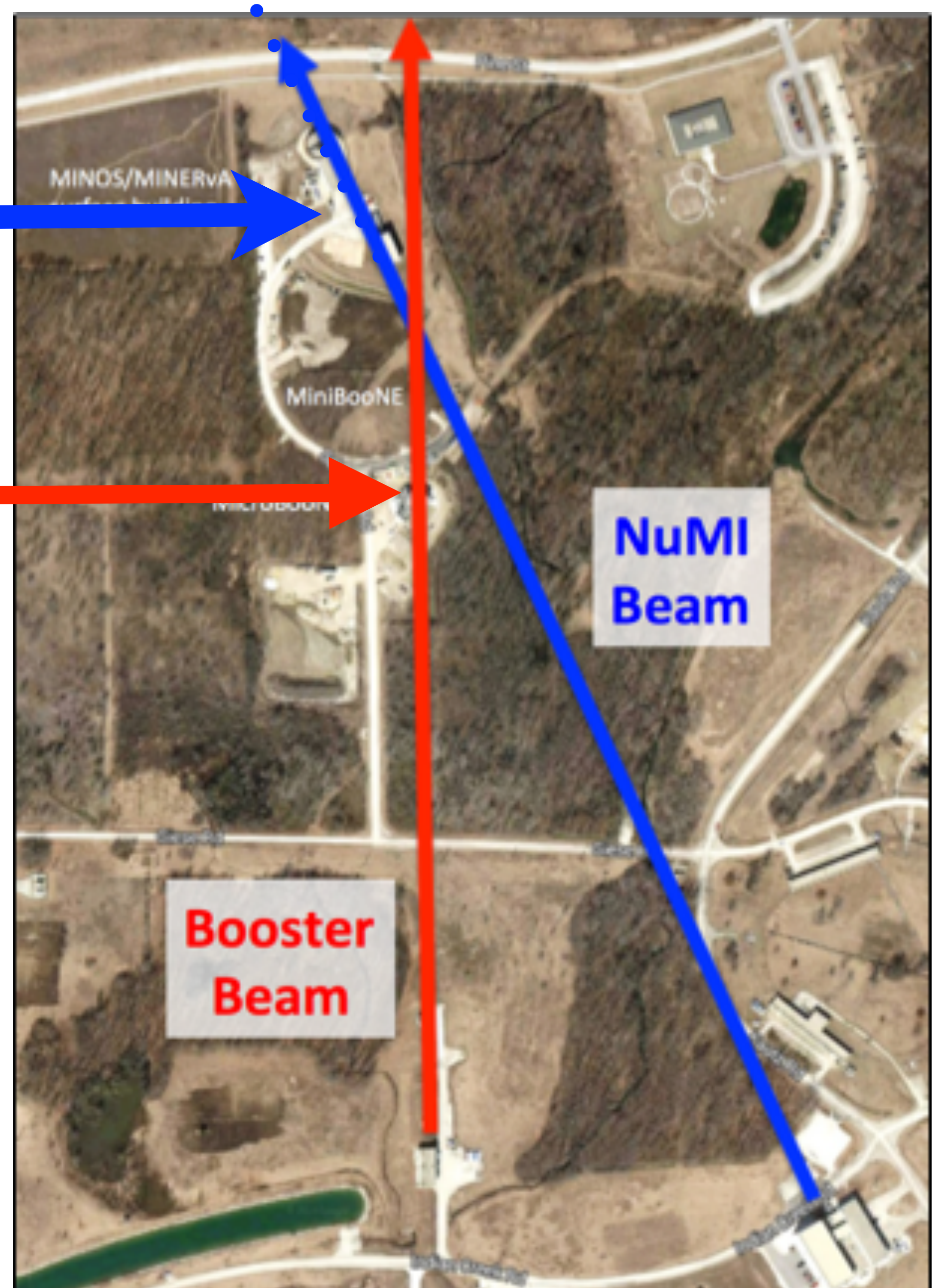
NOvA
810km

MINOS+
735km

MINOS ND -100m
Minerva
NOvA ND

-10m

MicroBooNE



Booster Neutrino Beamline (BNB) 10 kW

MINOS and Minerva have been running for years

Near Term:

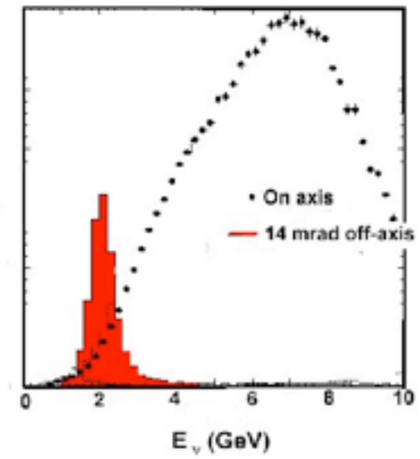
NOvA construction completed 8/2014: now data taking, first physics by end of 2014

MicroBooNE completed by early 2015

NuMI (ME tune)
300 -> 500 -> 700 kW

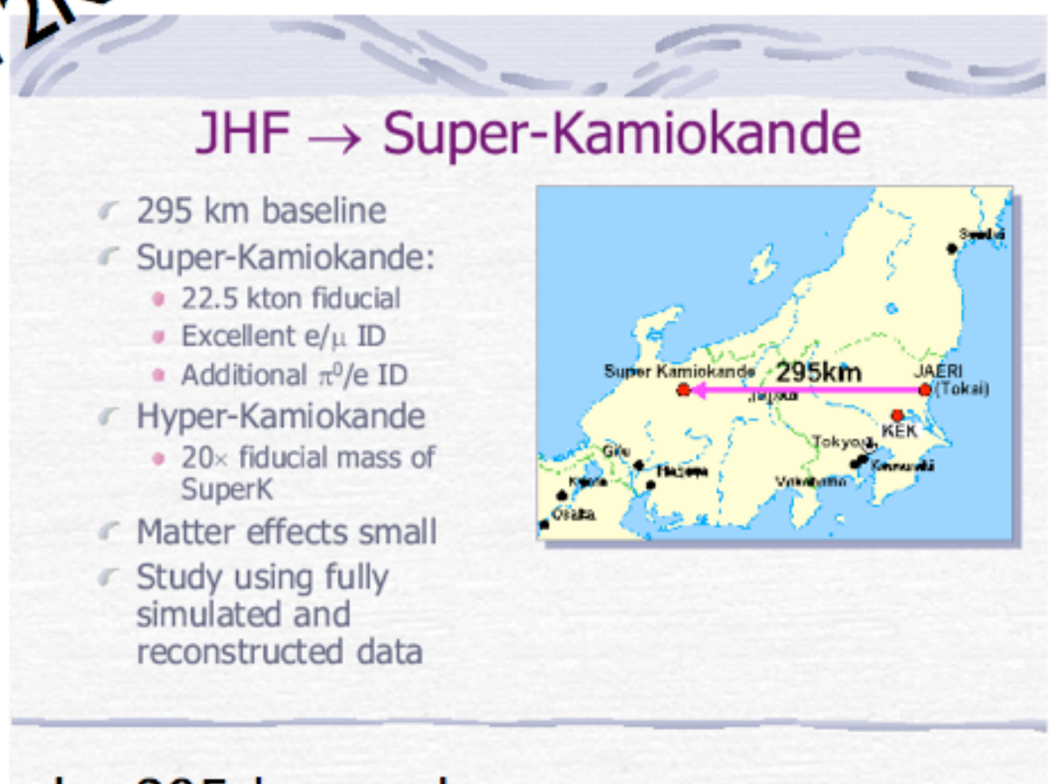
Off-Axis Beams

BNL 1994

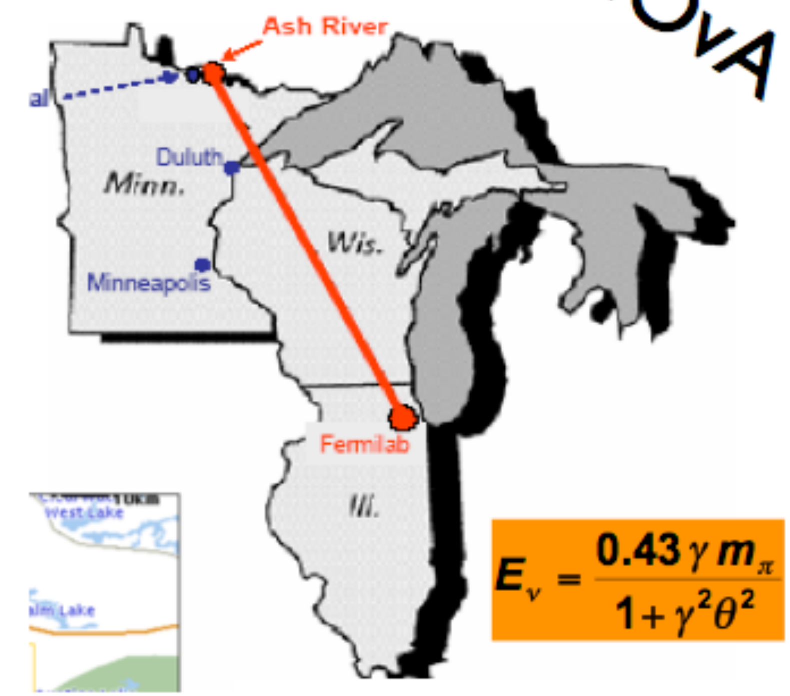


π^0 suppression

T2K



NOvA



L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{\frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2}\right\}$$

0.75 upgrade to 4 MW

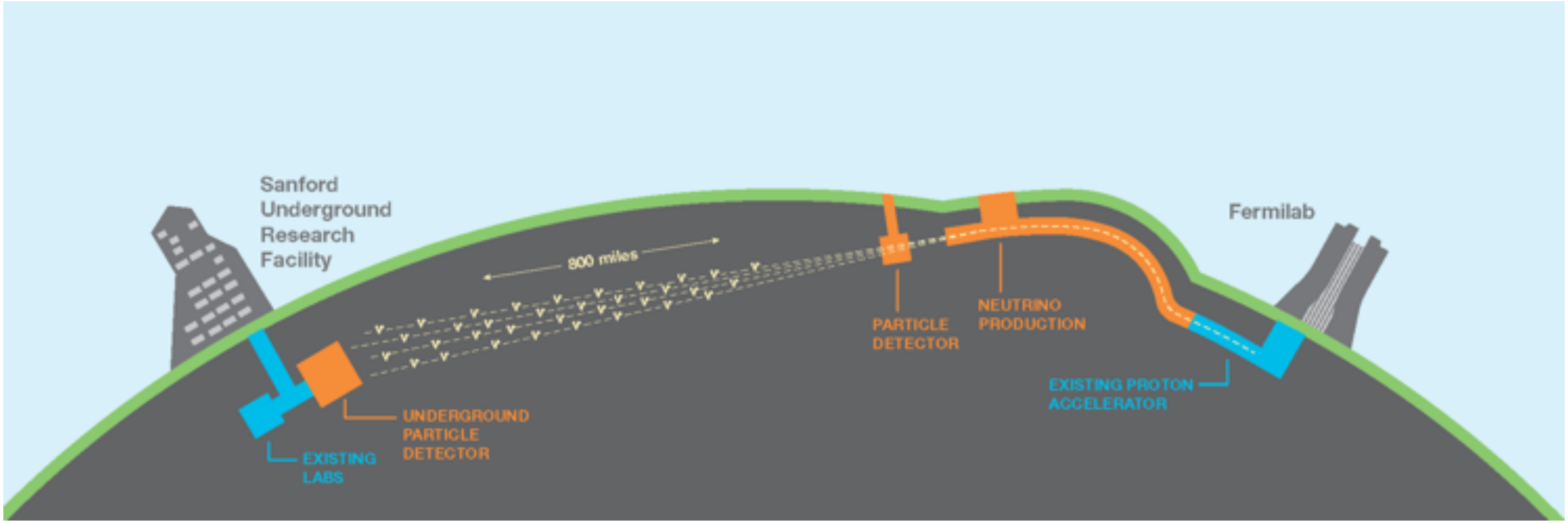
L=700 - 1000 km and

Energy near 2 GeV

$$E_{vom} = 1.8\ GeV \left\{\frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2}\right\} \times \left\{\frac{L}{820\ km}\right\}$$

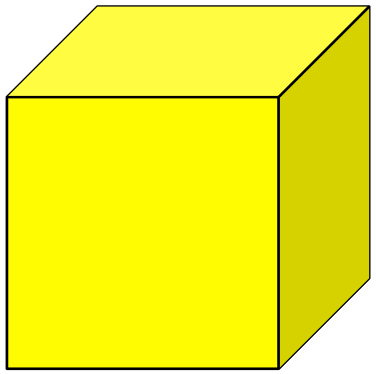
0.4 upgrade to 2 MW

DUNE and LBNF:



Neutrinos from the BIG BANG

1 cm^3

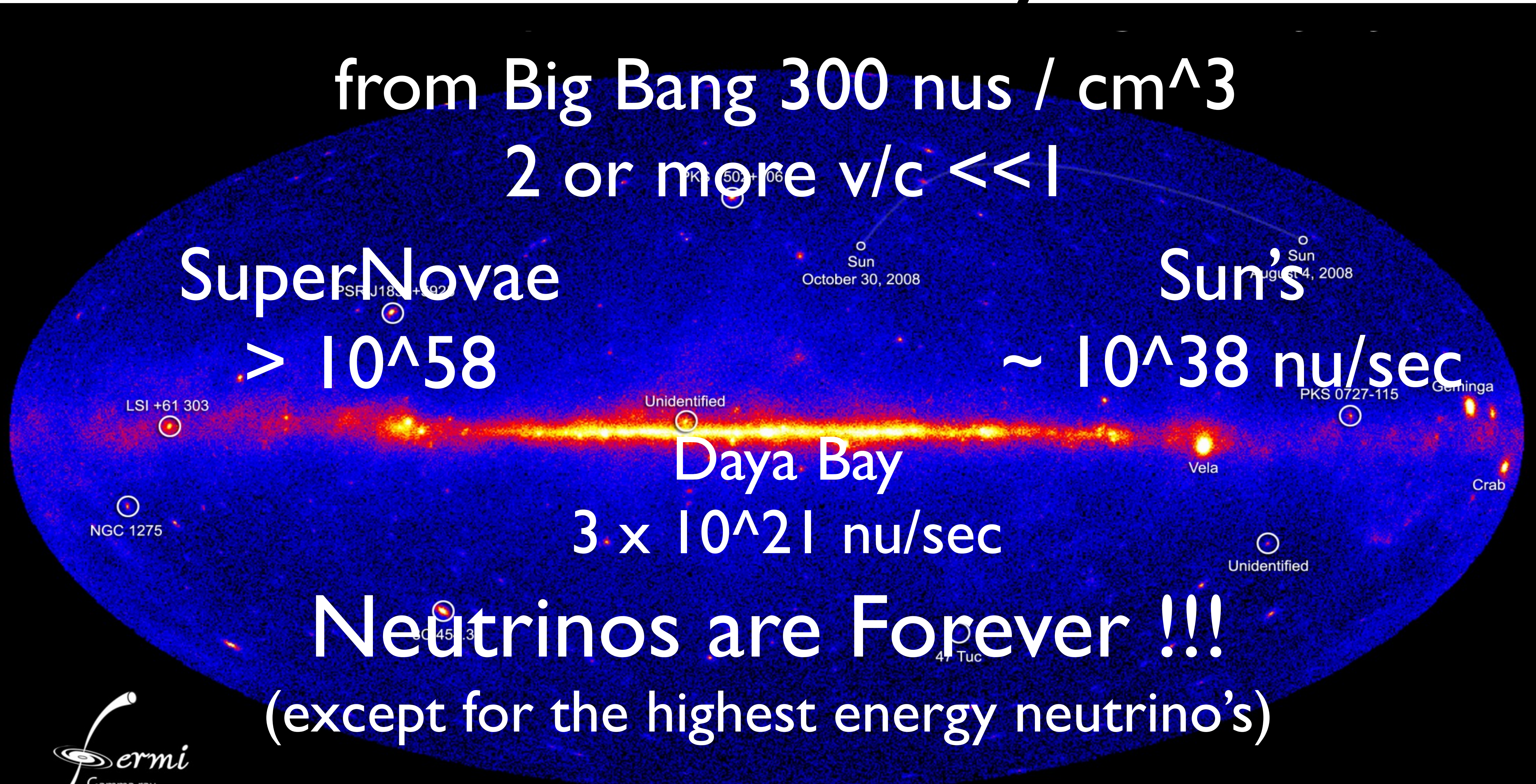


300 ν from Big Bang
(more than 100x solar)

30,000,000 inside YOU!!!

Neutrinos are Everywhere
Abundant but Elusive

Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

Neutrinos are Forever !!!

(except for the highest energy neutrino's)

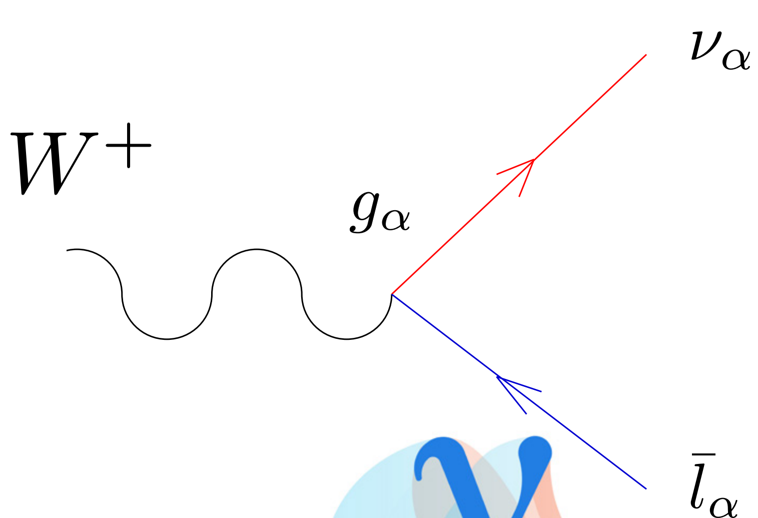
therefore in the Universe: $$\frac{\partial N_\nu}{\partial t} > 0$$

Why I find Neutrinos Interesting !

Neutrino Standard Model:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathbf{U}_{e1} & \mathbf{U}_{\mathbf{e2}} & \mathbf{U}_{e3} \\ U_{\mu 1} & U_{\mu 2} & \mathbf{U}_{\mu\mathbf{3}} \\ U_{\tau 1} & U_{\tau 2} & \mathbf{U}_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

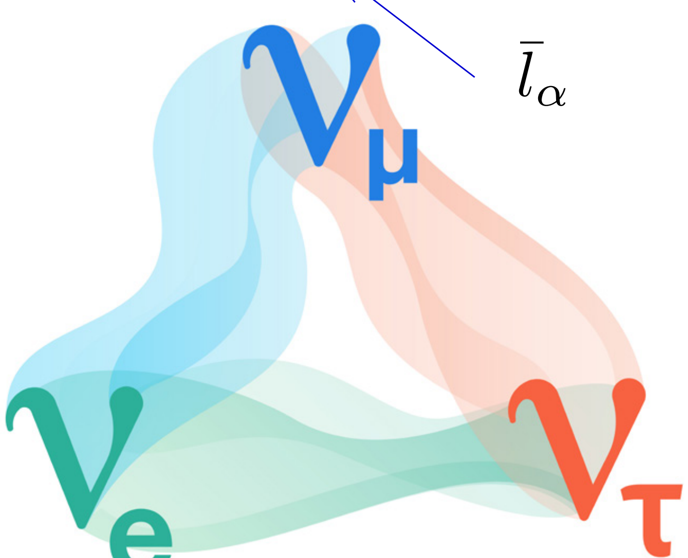
$$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$$



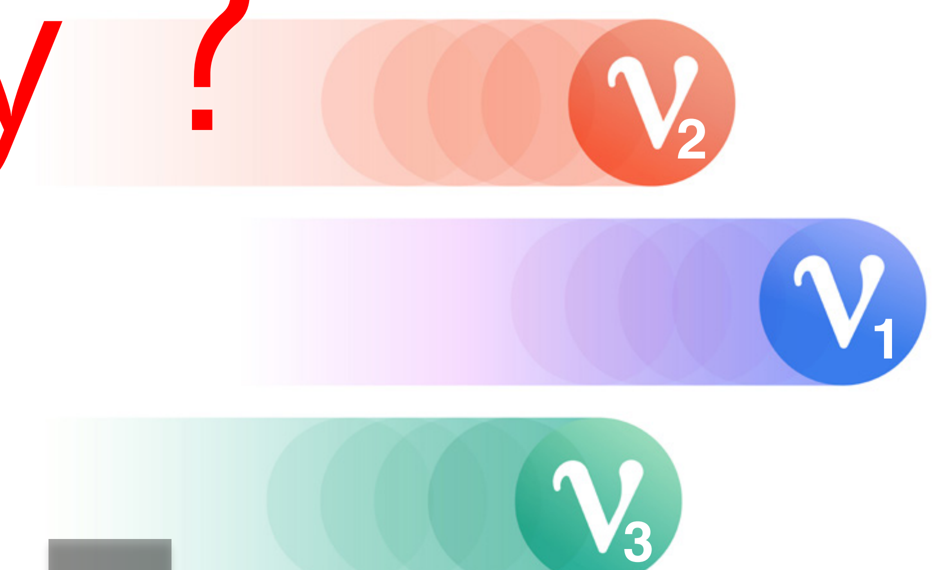
Mixing Matrix

ν_i ——— ν_j

$$\delta_{ij}\ e^{-im_i^2 L/2E}$$



Unitary ?



accuracy: ■ (blue) >> ■ (red) > ■ (green) > ■ (gray)

Neutrinos are Everywhere, Abundant but Elusive

yet Fascinating
and
maybe Responsible for our Existence in Universe.

Asimov: The Neutrino
http://www.pbs.org/wgbh/nova/neutrino/