NEUTRINO SOURCES

Sam Zeller
Fermilab

SLAC Summer Institute

Lecture #1

July 15, 2013

- where do neutrinos come from?
  - neutrinos from the heavens
  - neutrinos on earth

(some we make ourselves and some we get for free)

Neutrinos are Everywhere

- together with photons, neutrinos are by far the most abundant particles in the universe … there are billions passing through you right now

ν's generated in Big Bang

ν's power the sun

ν's shower down on the earth

ν's drive supernovae explosions

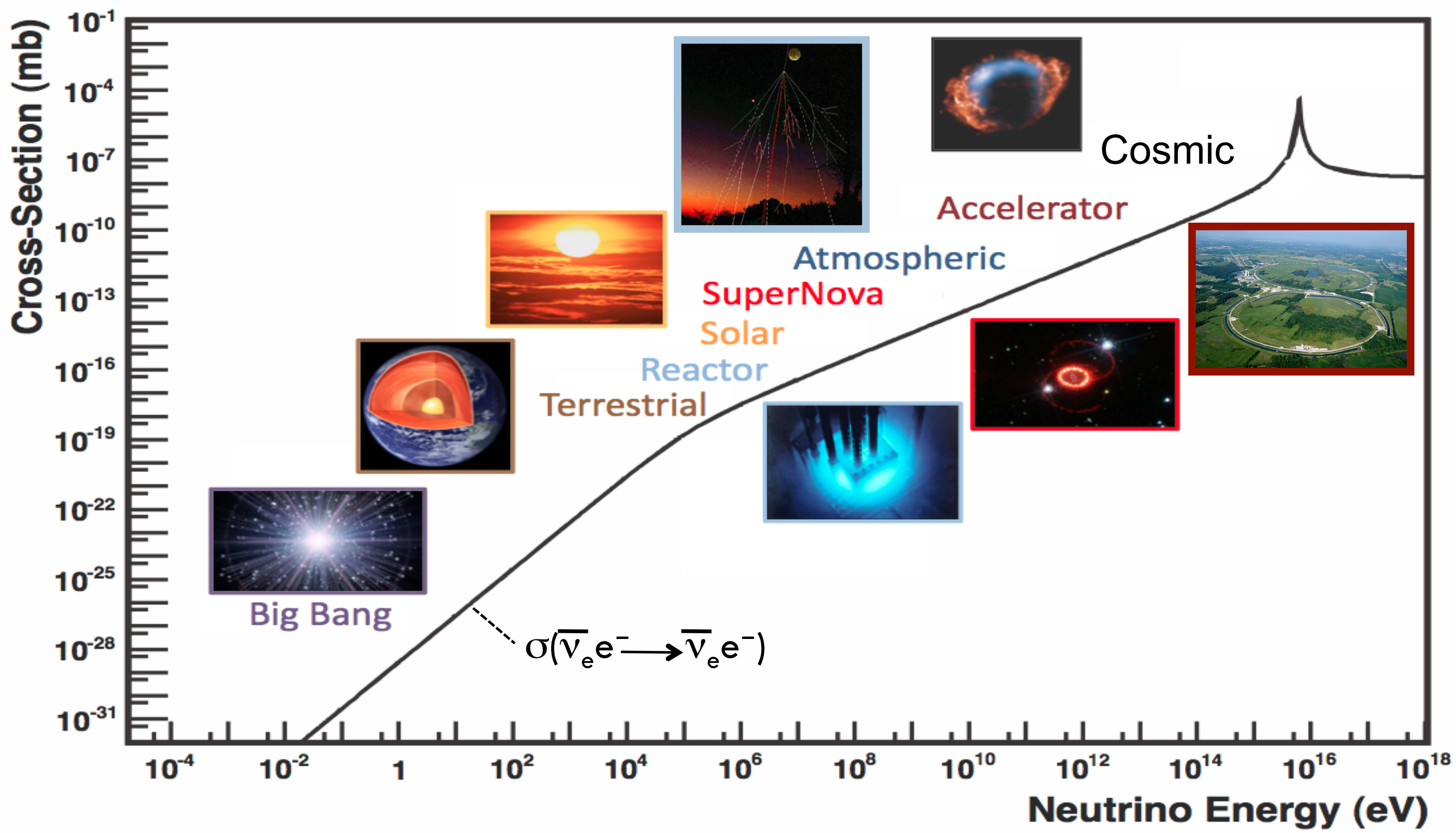
ν's are produced by nuclear reactors and particle accelerators

even bananas are ν emitters

- we are fortunate that there are many sources of neutrinos …

Energy Range

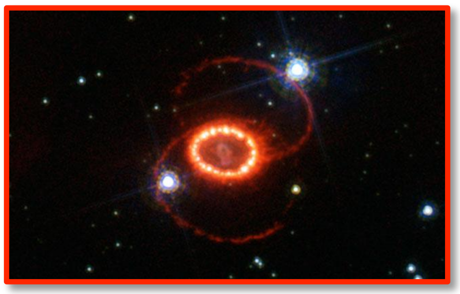
- neutrinos span an enormous energy range (eV to PeV)



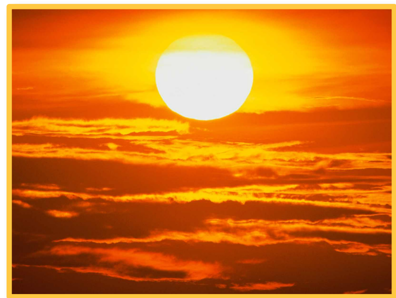
(Formaggio, Zeller, Rev. Mod. Phys. 84, 3, 2012)

- *we have detected ν's from almost all of these sources*
- *we have gotten a lot of info this way and made some important discoveries*

Neutrino Sources

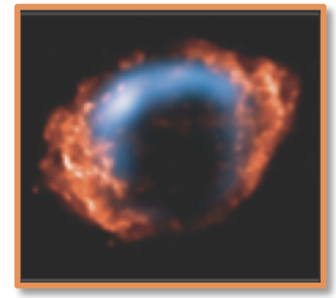


supernova neutrinos



solar neutrinos

atmospheric neutrinos



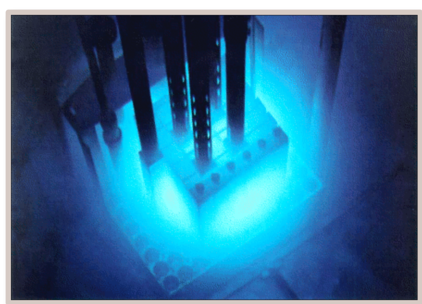
cosmic neutrinos

neutrinos from the heavens ("wild")

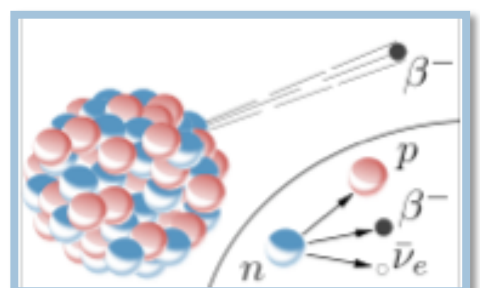
---

neutrinos from the earth ("tame")

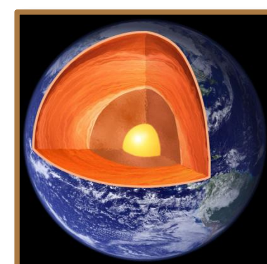
accelerator neutrinos



reactor neutrinos

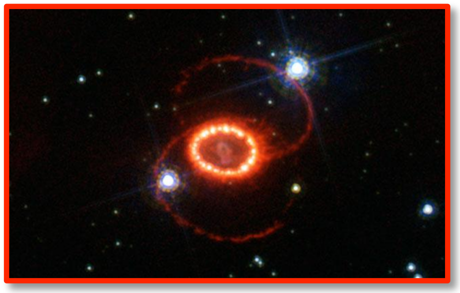


radioactive decays



geo neutrinos

Neutrino Sources



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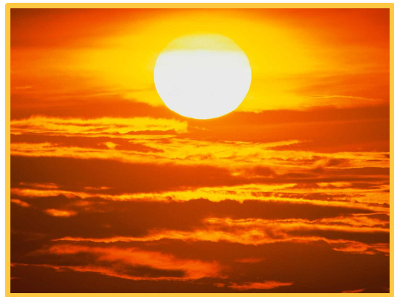

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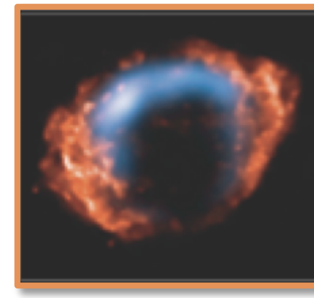

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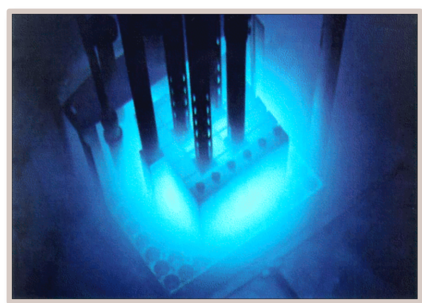

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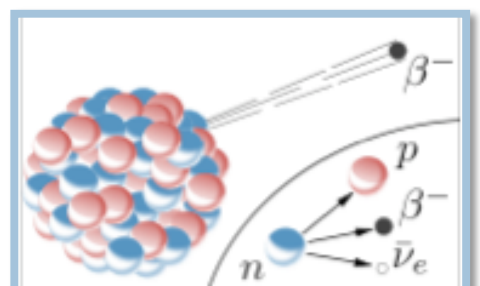

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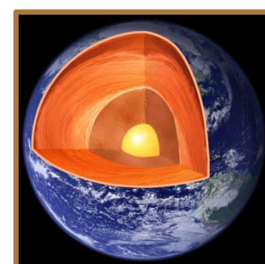
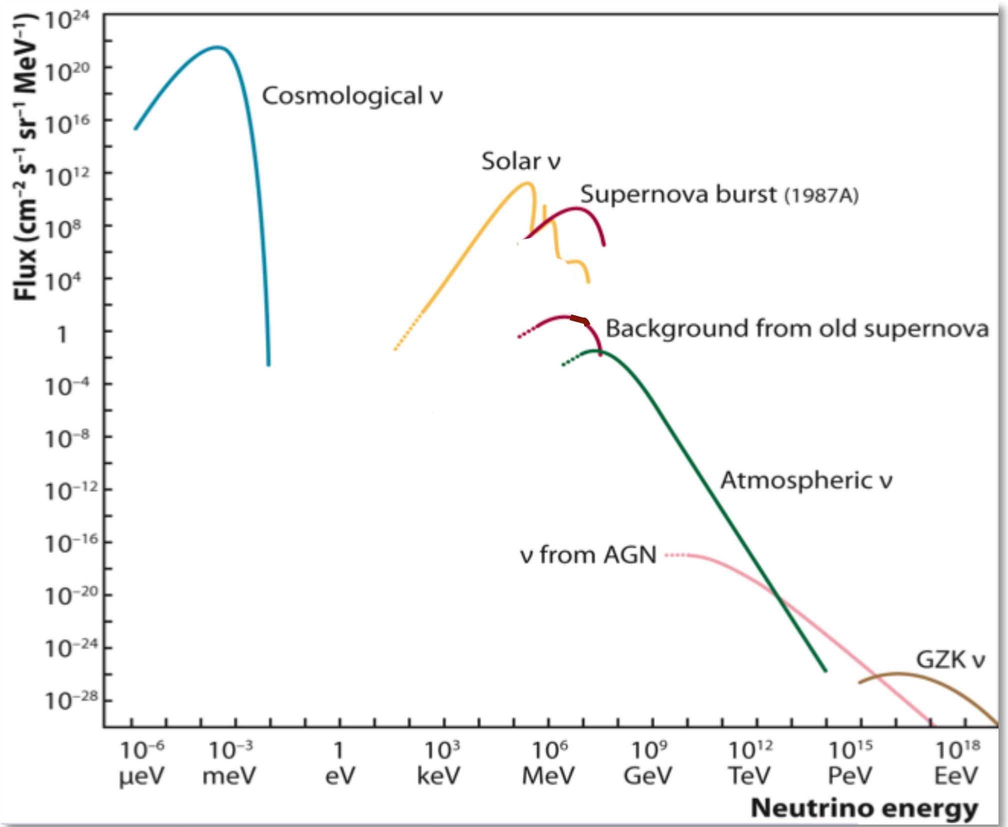


geo neutrinos

Neutrinos From the Heavens

- neutrinos are unique messengers …



neutrinos from stars

supernova, solar, atmospheric, and cosmic neutrinos

- they are not deflected by interstellar magnetic fields

  → *point back to their source*

- they rarely interact with matter

  → *arrive directly from regions where light cannot come*

- ν's carry information about the workings of the highest energy and most distant phenomenon in the univere

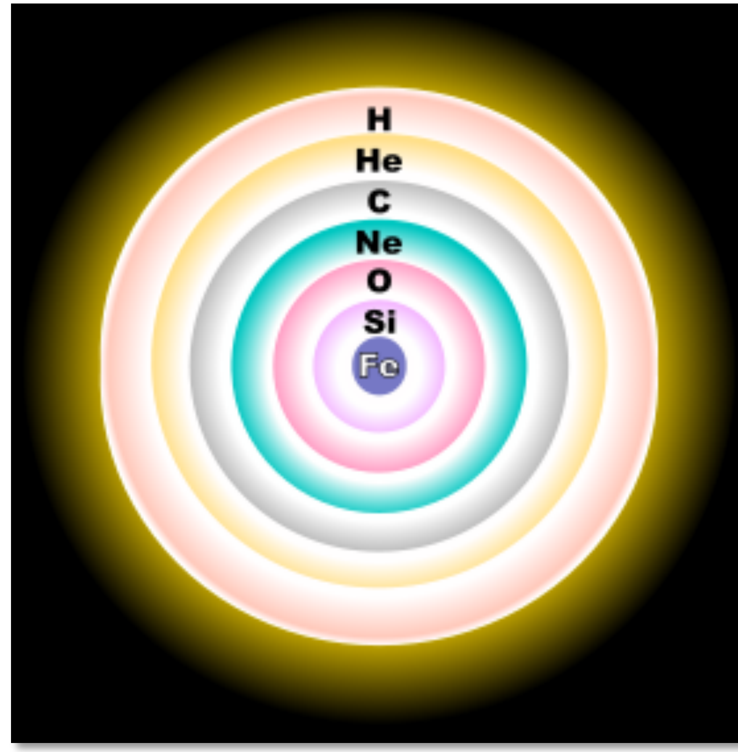
- "neutrino astronomy"

Supernova Burst Neutrinos

- the death of stars is a powerful source of ν's as nearly all (99%) of the gravitational energy from the collapse is radiated away by ν's

- core-collapse supernovae
  - *highest recorded energetic processes in the universe (~10^{53} ergs)*
  - *at these energies, all species of ν's can be produced*
  - *ν's are the only messengers that allow us to probe the inner workings*

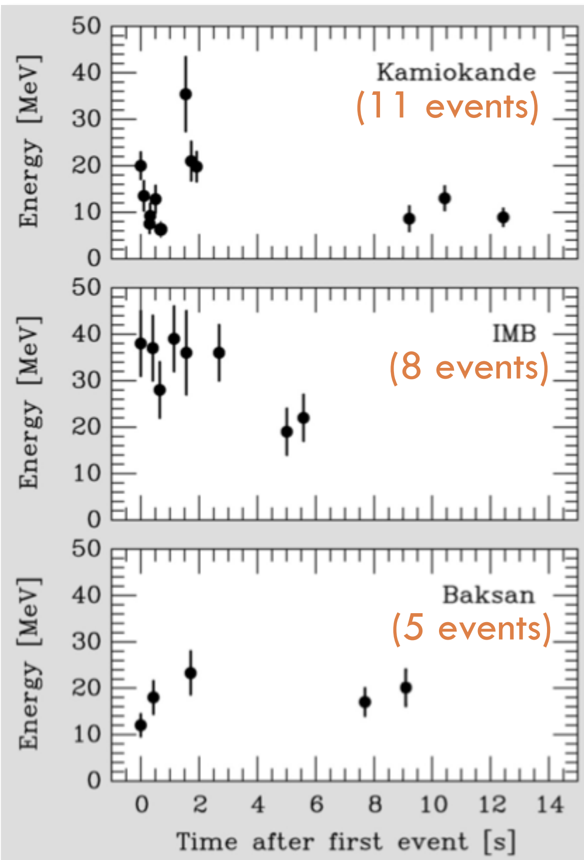
- ν's are emitted in a burst of a few 10's of secs in duration with energies of a few 10's of MeV



$$e^+ e^- \leftrightarrow \nu_i \bar{\nu}_i$$
$$\nu_e\, n \leftrightarrow p\, e^-$$
$$\bar{\nu}_e\, p \leftrightarrow n\, e^+$$

SN1987A

- we have detected ν's from one and only one such event: SN1987A which released more ν's than our sun will produce in its life



- the ν's arrived a few hours before the light
- all detected $\overline{\nu}_e$
  $\overline{\nu}_e\, p \rightarrow e^+\, n$
- future LAr TPCs will be sensitive to ν_e
  $\nu_e\, Ar \rightarrow e^-\, K^*$
- we are due for a SN!

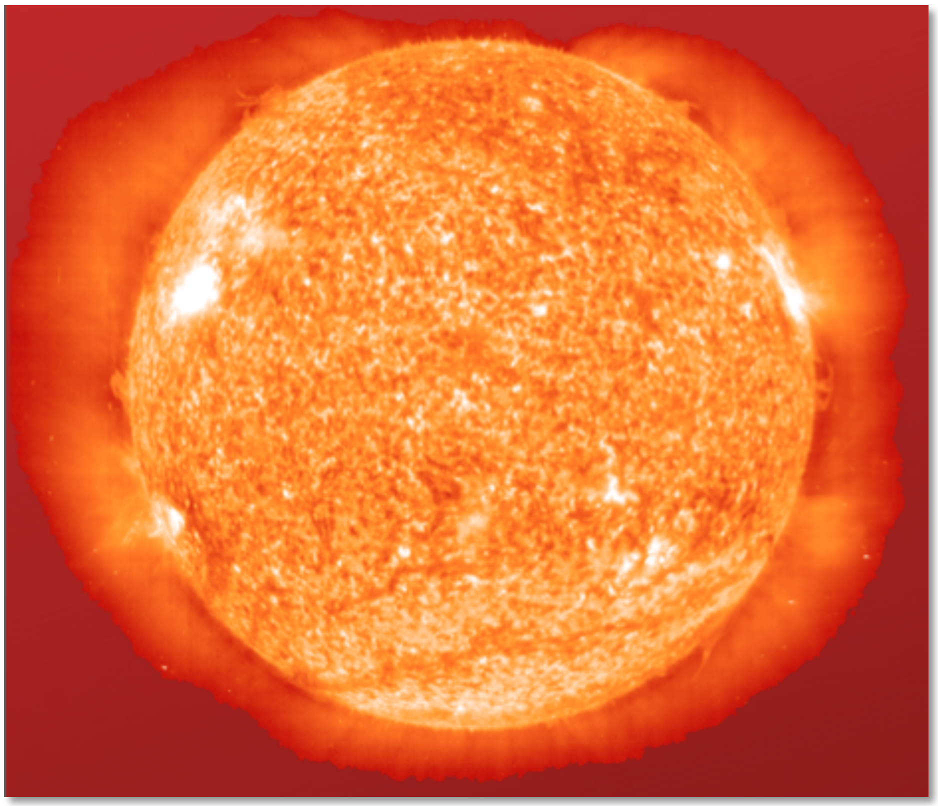
Before
($20M_\odot$)

During
(few days later)

After
(shock wave)

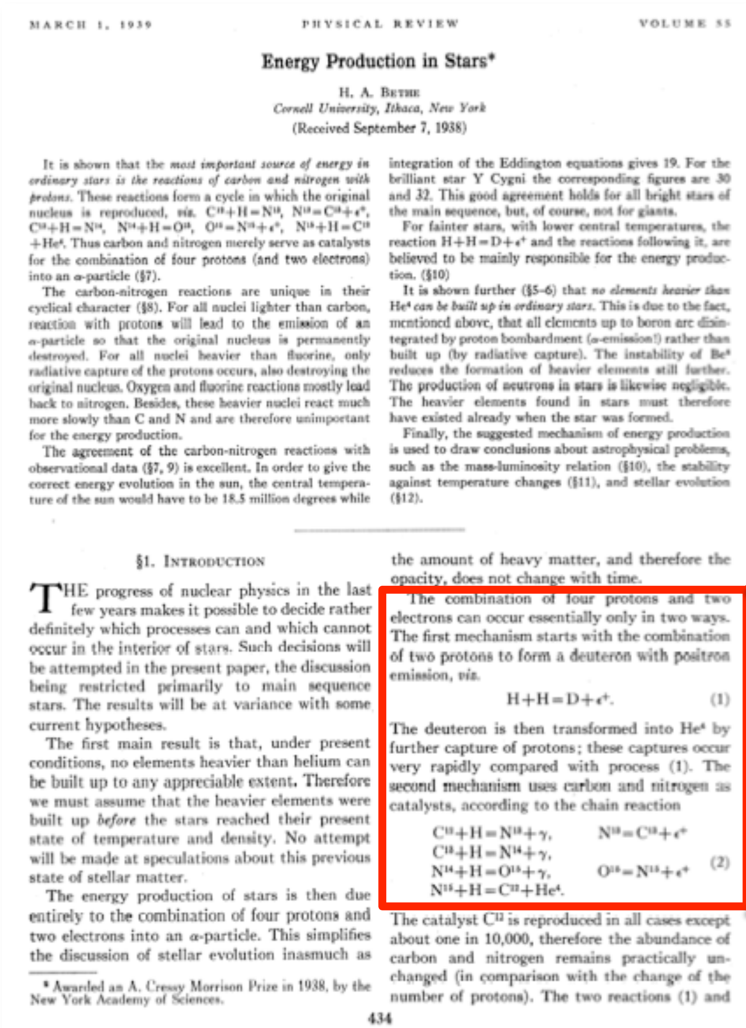
Neutrinos from Stars

- let's turn to a less violent example …



- our own sun is a copious source of neutrinos (ν_e's)

Neutrinos from Stars



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

The progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \tag{1}$$

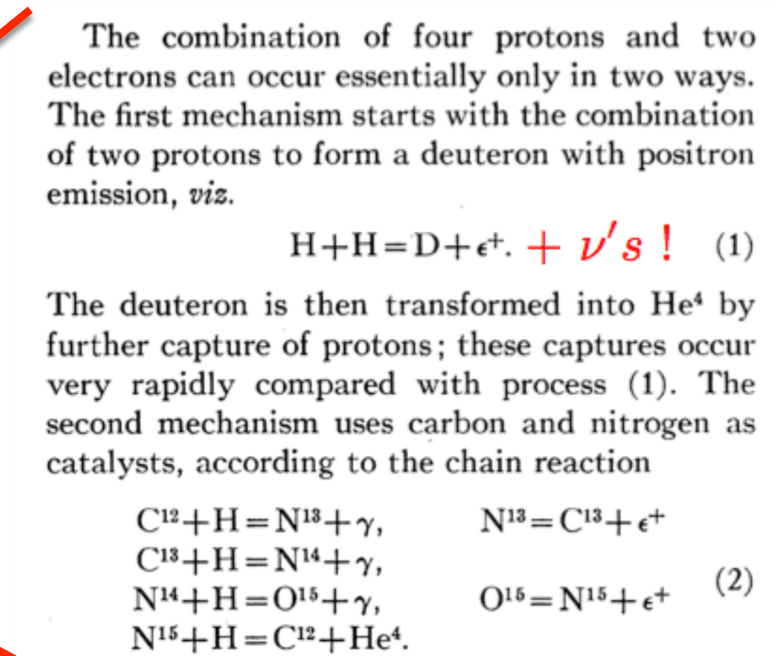
The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, &&N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, &&O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. && \end{aligned} \tag{2}$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

- in Hans Bethe's original paper, neutrinos aren't even in the picture! (Phys. Rev. 33, 434, 1939)



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$$H+H=D+\epsilon^+. + \nu's\ ! \tag{1}$$

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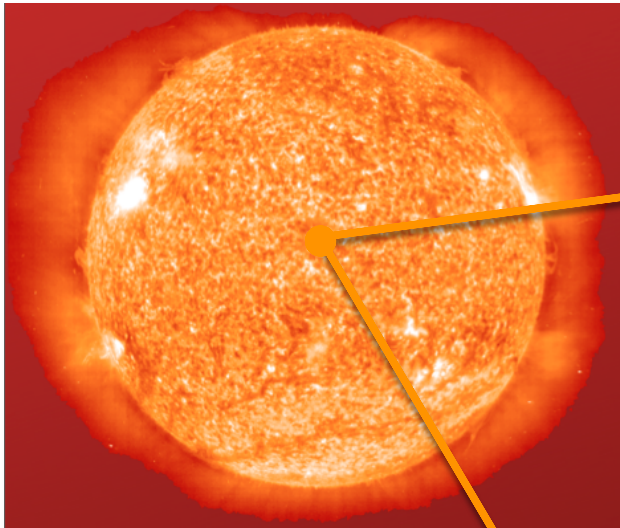
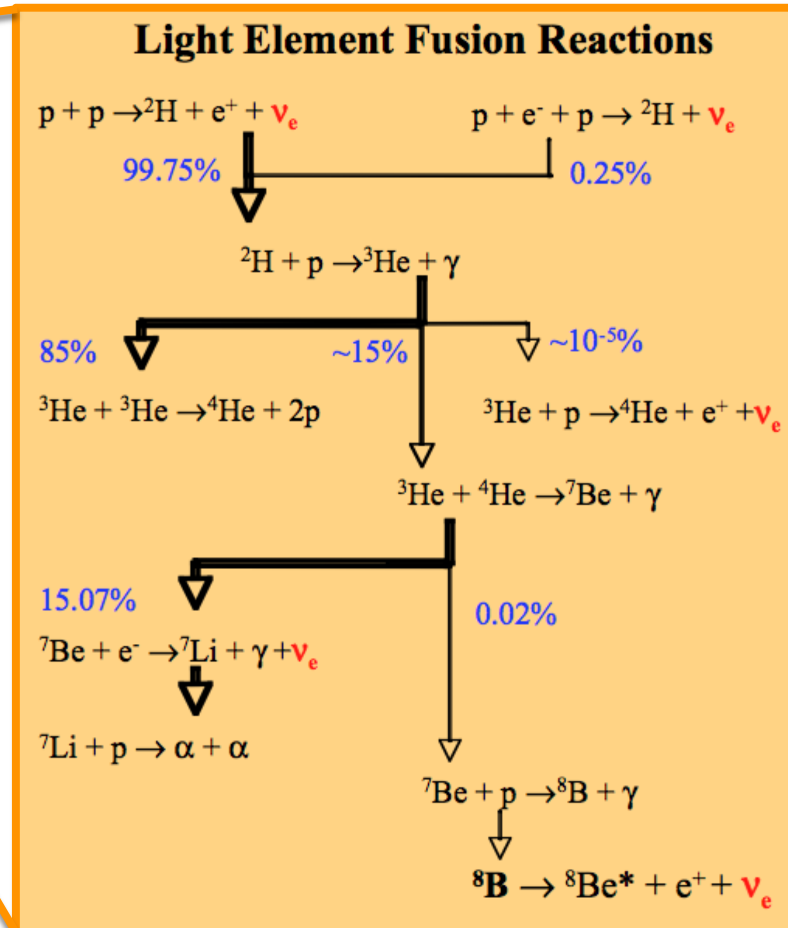
Basic Process



- nuclear processes that power the sun produce a huge number of ν's (10^{38} ν/sec)

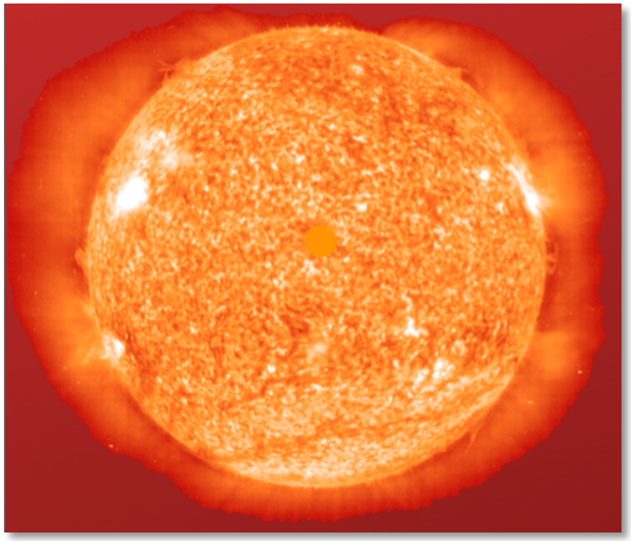


- this is known as the pp fusion chain

(also a sub-dominant CNO cycle)

- only ν_e's are produced
- $E_\nu \lesssim 20$ MeV

Basic Process



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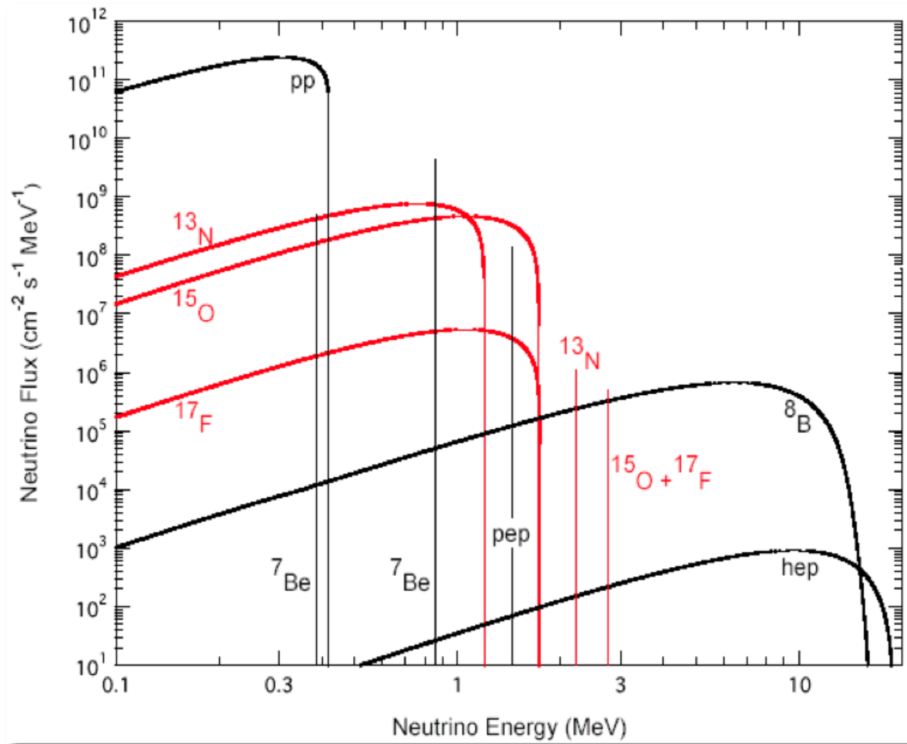

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- only ν_e's are produced
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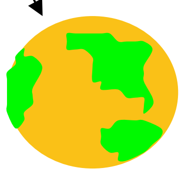
- in the 1960's, John Bahcall worked out what type of ν emission you might expect

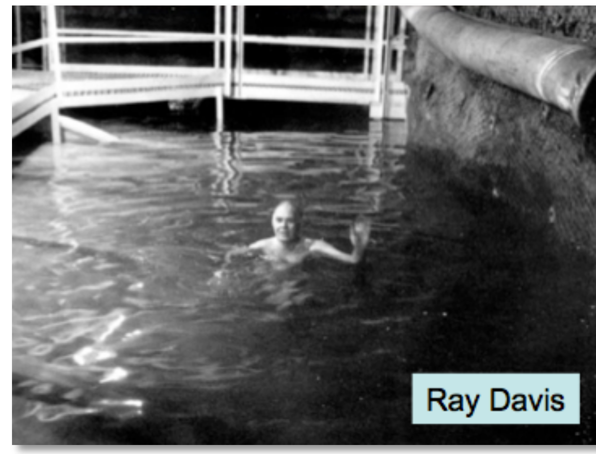
Solar Neutrinos

- In the 1960's, Ray Davis builds the first large scale detector to look for ν's from the sun ...

ν_e

takes about 8 mins for those ν's to reach earth





- ν's recognized as a tool to do astrophysics and as a means to learn about the sun

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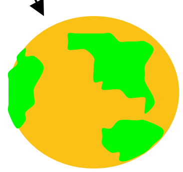


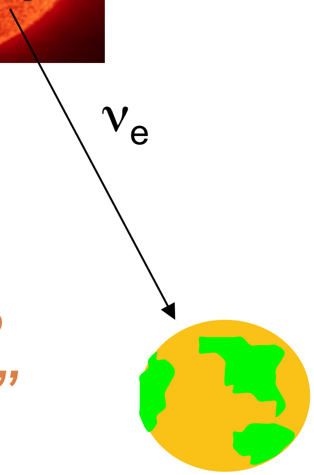
Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and this verifies directly the hypothesis of nuclear energy generation in stars

– John Bahcall, PR (1964)

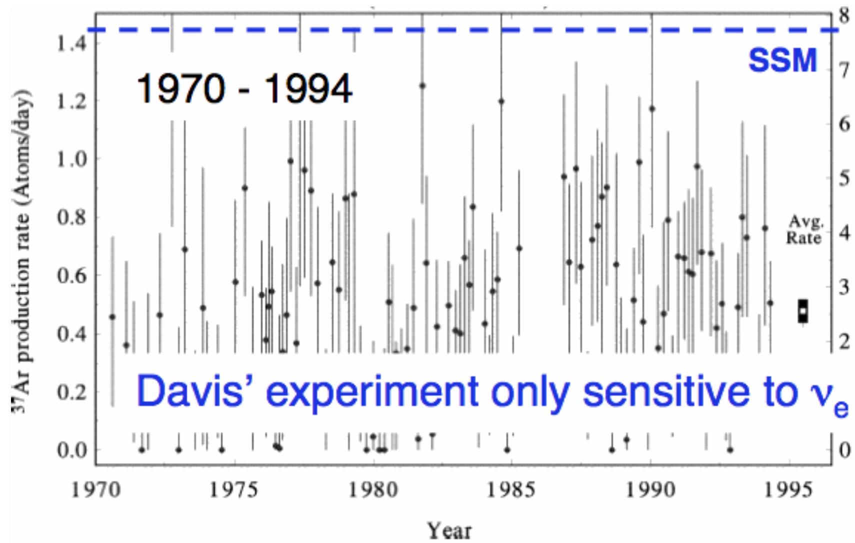
- when we started this game, we were trying to figure out how the sun works

Solar Neutrinos

- instead what we learned is that neutrinos oscillate …



"solar neutrino problem"

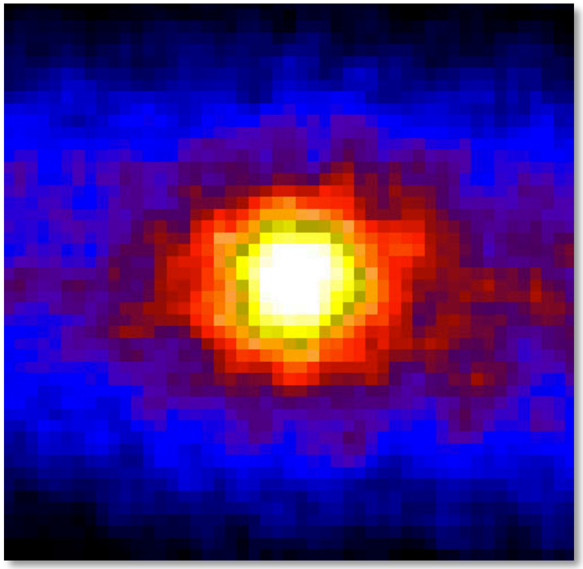


(by the time they get to earth, experiments were seeing only ~1/3 of the ν_e's expected)

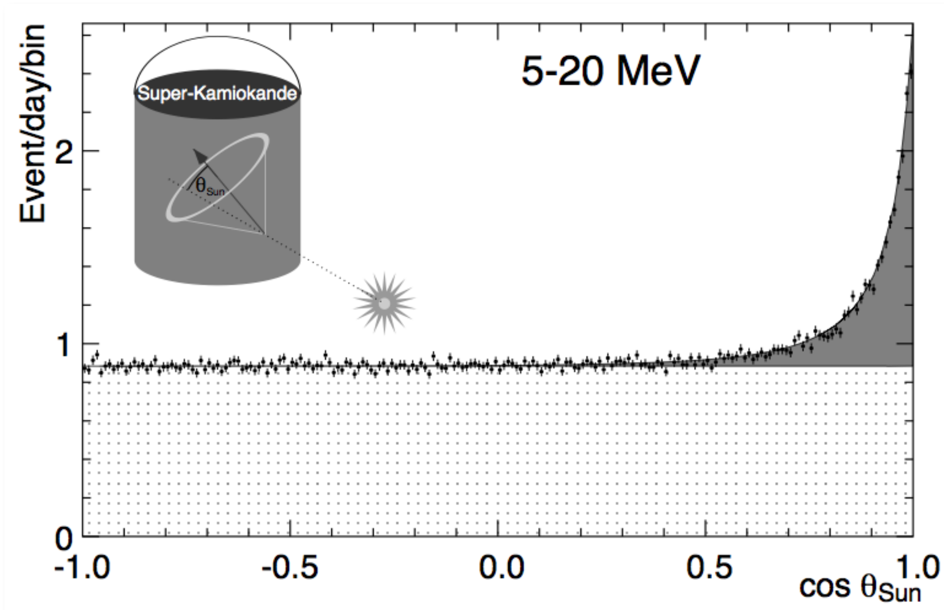
- after 40 yrs of hard work, we learned that the sun works as expected, but ν's have mass and can oscillate from one type to another

(so it wasn't the sun we screwed up but the neutrinos!)

Solar Neutrinos



- neutrino image of the sun (the sun seen in "neutrino light")
  - *500 day exposure of 50kton Super-Kamiokande detector*

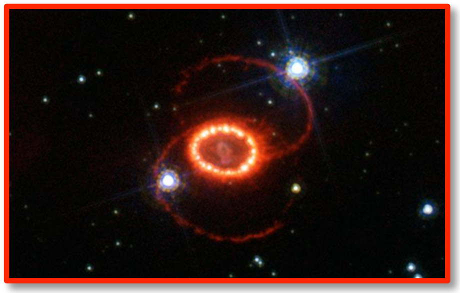


- proof that these were coming from the sun

$$\nu_e\, e^- \rightarrow \nu_e\, e^-$$

- this ability to point back was first conclusive evidence that the sun is powered by nuclear reactions in its core

Neutrino Sources



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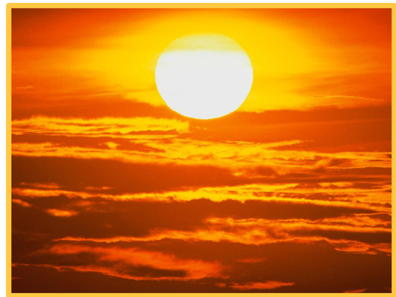

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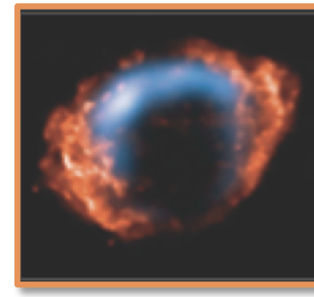

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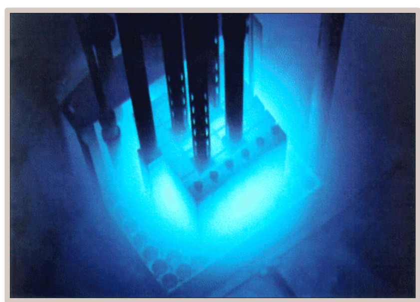

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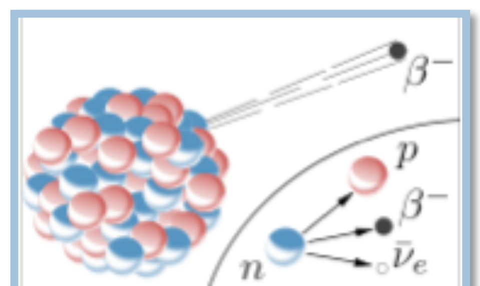

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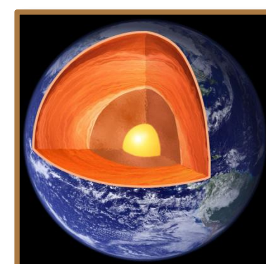


geo neutrinos

Neutrinos From the Sky

- such strange behavior and neutrino deficits were seen in another source: **atmospheric neutrinos**

- ν's can be produced in collisions of cosmic ray protons with atmospheric nuclei

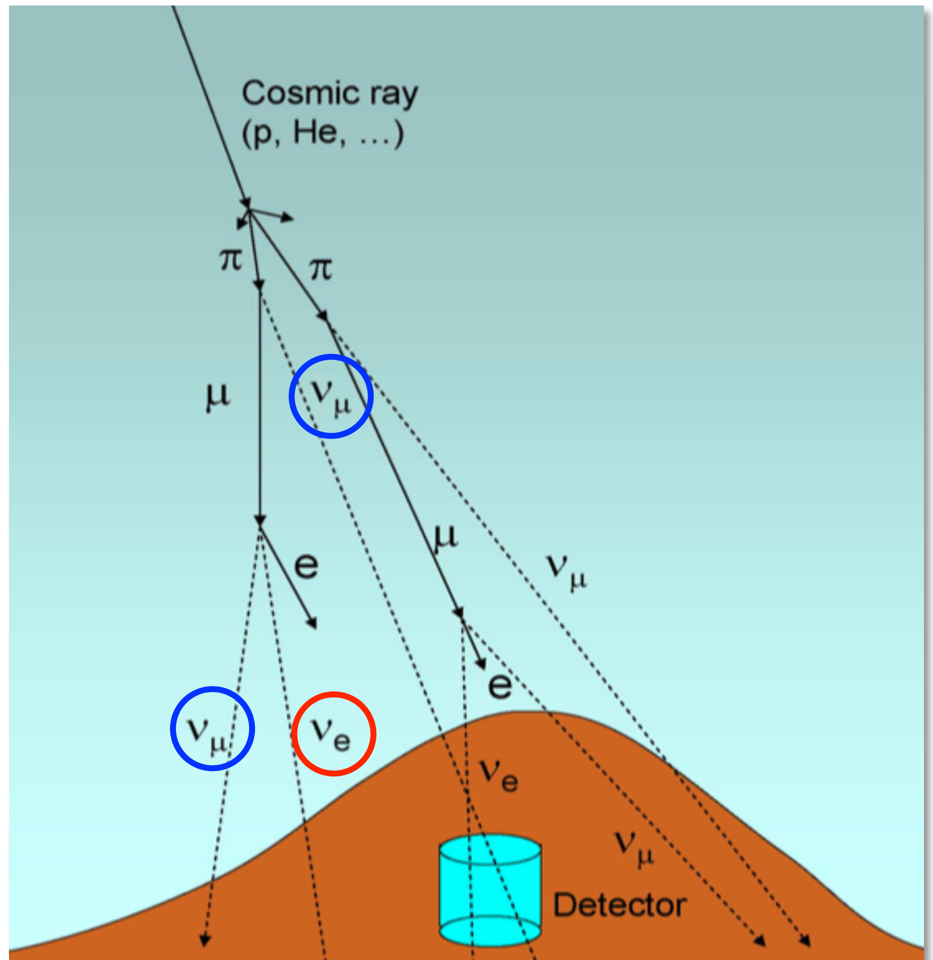
$\nu_\mu : \nu_e = 2:1$

(fixed by the π/μ cacade)

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

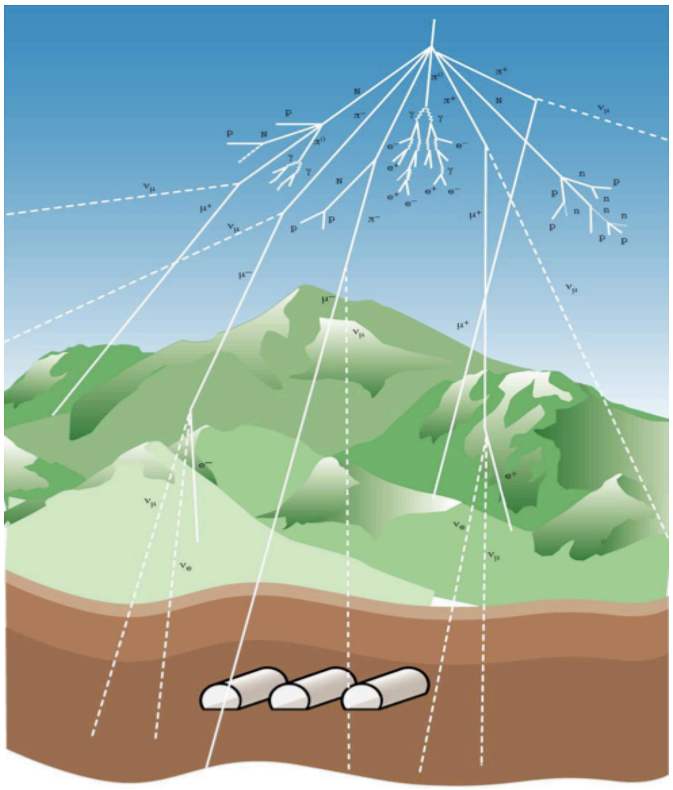
$\quad \hookrightarrow e^+ \overline{\nu}_\mu \nu_e$

- GeV as opposed to MeV (solar ν)
  ν energies extend up to ~100 TeV



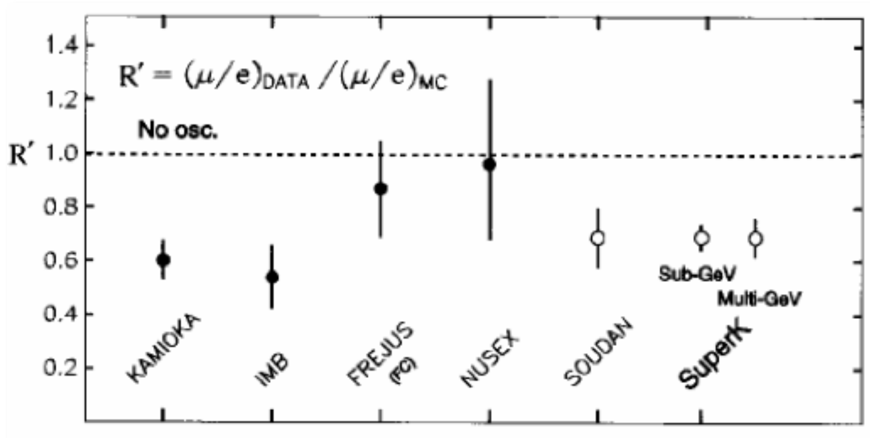
Atmospheric Neutrinos

- the real explosion in atm ν's happened in 1980-1990's when large underground detectors became available to study proton decay



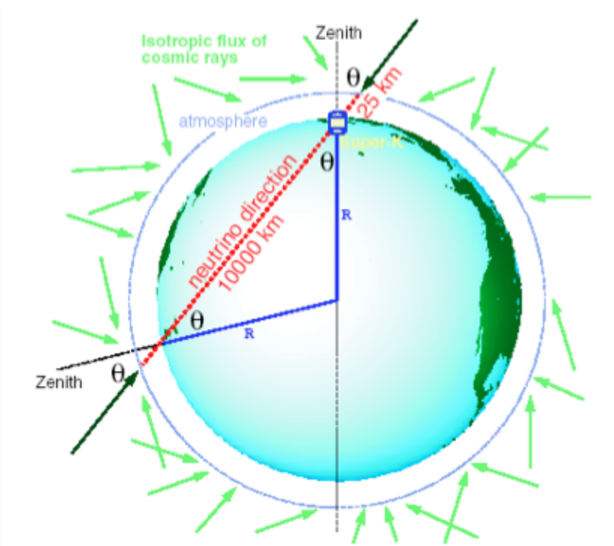
atmospheric ν's offered the possibility to study ν's in an E range that was not accessible in particle accelerators at the time

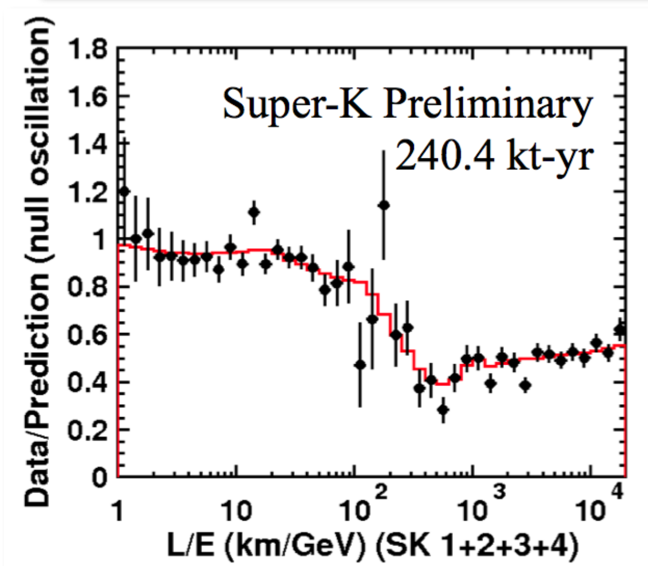
- no protons decays were detected, but a new mystery emerged …



- half of the predicted atmospheric ν_μ's are missing! so here too, the experiments fall short

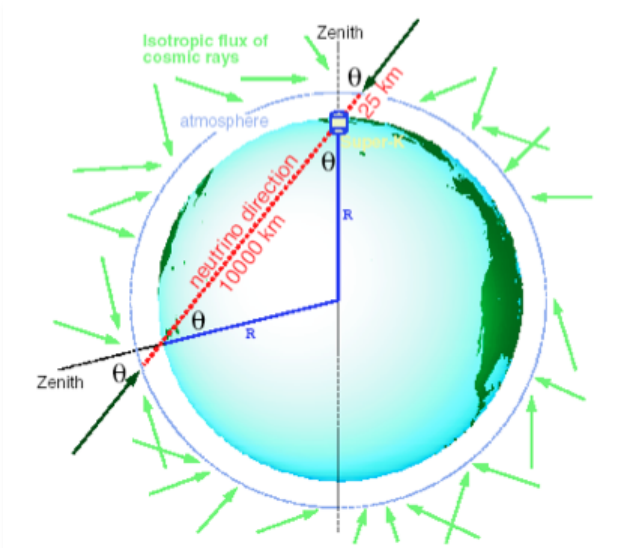
Atmospheric Neutrinos

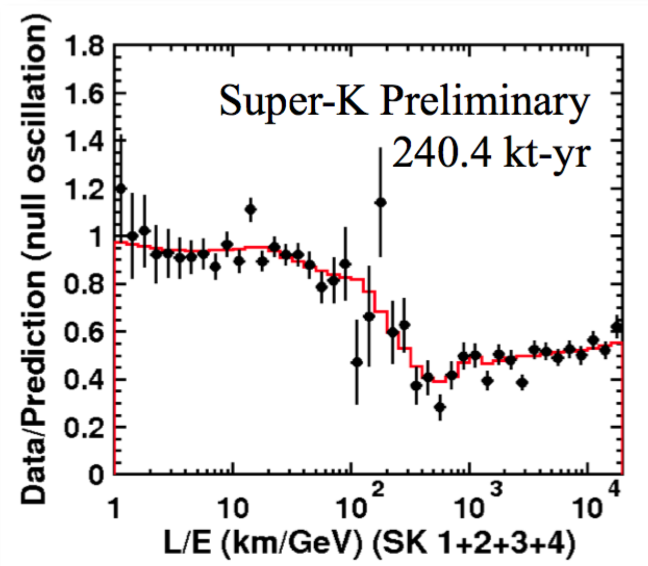




- can also detect atmospheric ν's coming in from different directions
- see a large deficit in the # of ν's traveling the largest distance
  (if go far enough away, the ν_μ's will have disappeared)
- this too pointed to something totally new going on with neutrinos:
  - *neutrinos oscillate!*
  - *neutrinos have mass!*
- provided ompletely independent evidence from solar ν's and at a very different L,E

Atmospheric Neutrinos





"All the News That's Fit to Print"

The New York

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

1 Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

2 . . . and collide with other particles . . .

3 . . . producing a cone-shaped flash of light.

4 The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

LIGHT

LIGHT AMPLIFIER

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

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

'ENEMY OF CONSTITUTION'

Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

DENVER, June 4 — Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. Matsch of Federal District Court, said, "This was not a murder case."

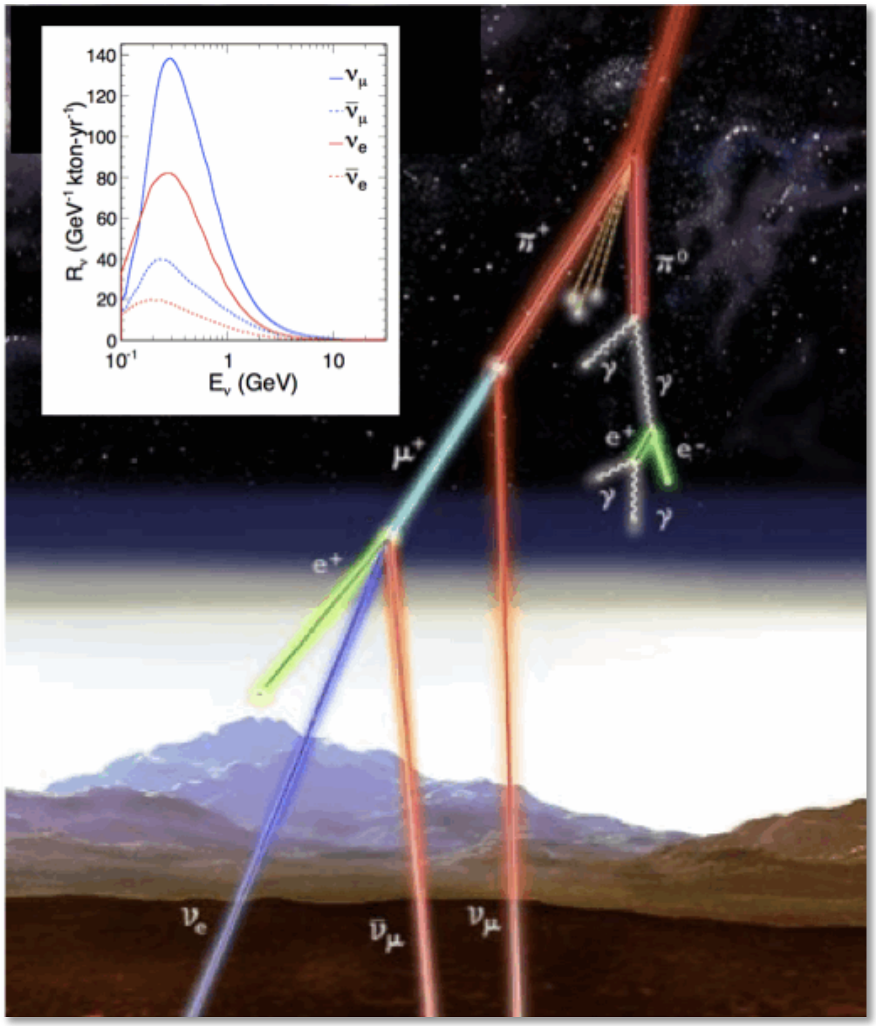
He added: "It is a crime and the victims have spoken eloquently here. But it is not a crime as to them so much as it is a crime against the Constitution of the United States. That's the victim."

Last December, Mr. Nichols was convicted of conspiring with Timothy J. McVeigh to use a weapon of mass destruction in the April 19, 1995, bombing of the Alfred P. Murrah Federal Building, but was acquitted of Federal murder charges in the deaths of eight Federal agents who died. Mr. Nichols was found guilty of involuntary manslaughter in those deaths and today was given the maximum sentence of six years in prison for each, to run concurrently with his life sentence. He was also acquitted of actually committing the bombing.

While the conspiracy charge carried a possible death sentence, the jurors need to vote unanimously for such punishment, and they could not do so. The sentencing then fell to Judge Matsch.

this made headline news in 1998

Atmospheric Neutrinos Today

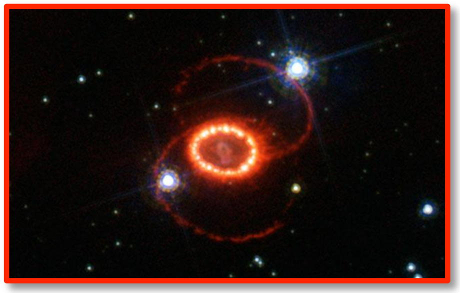


- unique source of neutrinos to study oscillations
- 1^{st} unambiguous evidence for ν oscillations in Super-K (1998)
- oscillations play out over several decades of E and path length

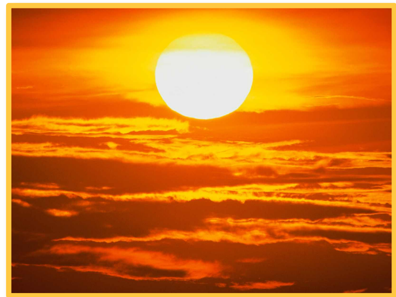
  E ~ 0.1 GeV – TeV
  L ~ 10–13,000 km

- for $\theta_{13} \neq 0$, matter effects play a large role and offer a possible means of determining the ν mass hierarchy

Neutrino Sources

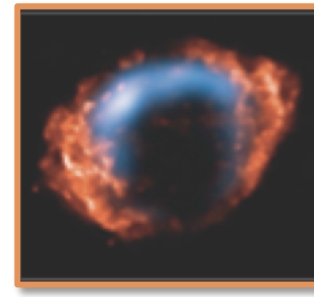


supernova neutrinos



solar neutrinos

atmospheric neutrinos



cosmic neutrinos

neutrinos from the heavens ("wild")

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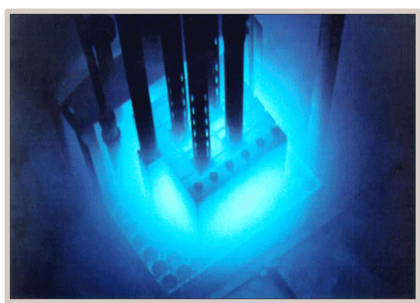
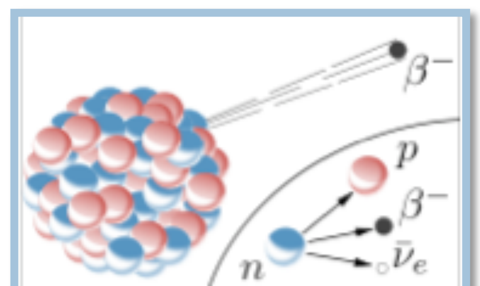
neutrinos from the earth ("tame")

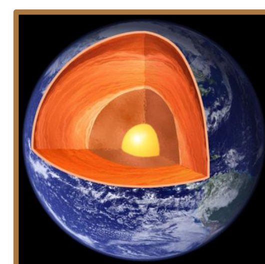
accelerator neutrinos



reactor neutrinos

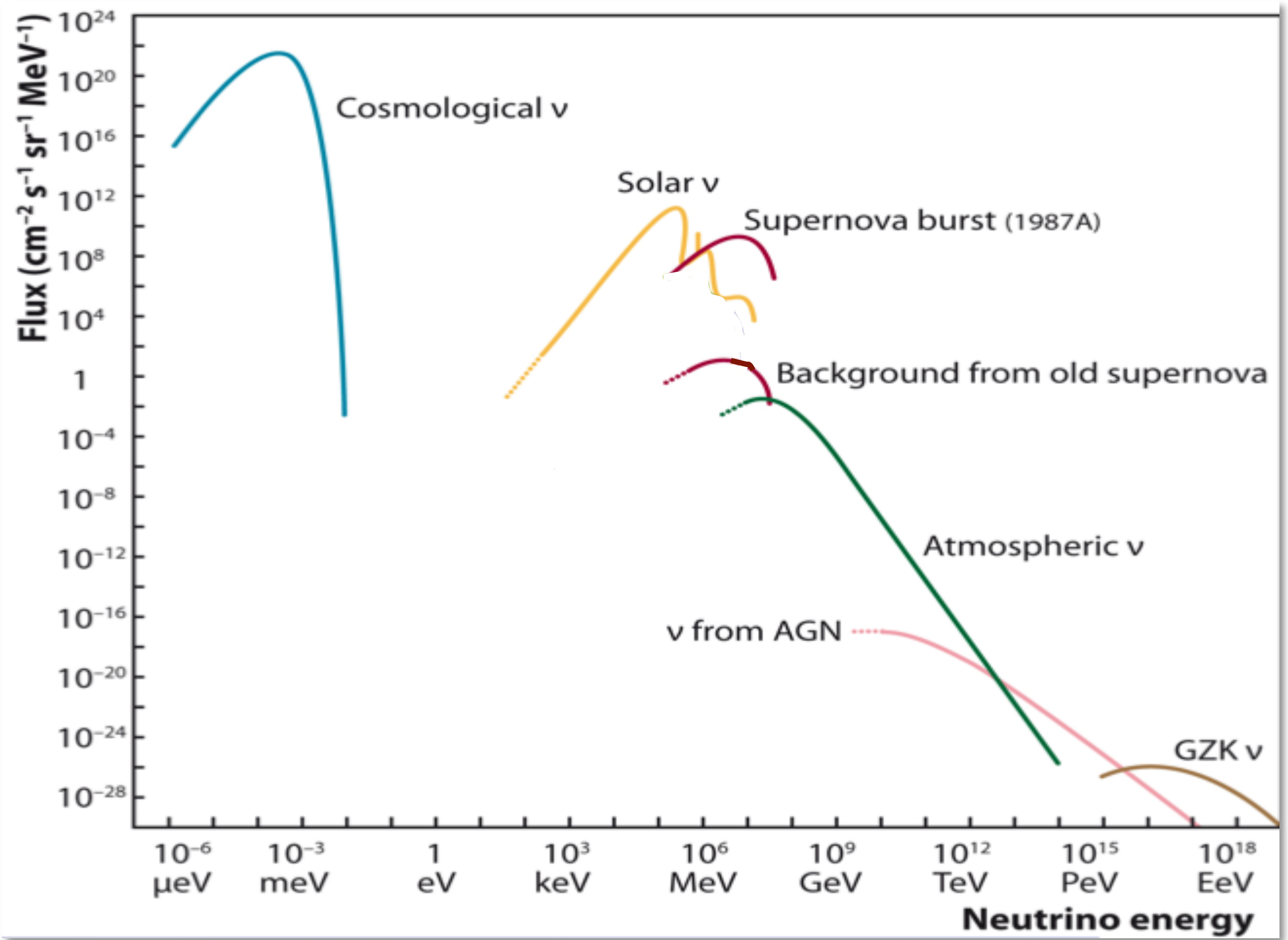


radioactive decays



geo neutrinos

Neutrinos From the Heavens



Astrophysical Sources

- high energy ν's ($E_\nu \gtrsim$ TeV) are emitted as a by-product of collisions of cosmic rays with matter

$$p + (p,\gamma) \rightarrow \pi \rightarrow \nu$$

natures accelerators

  - proton interactions with CMB (GZK neutrinos)

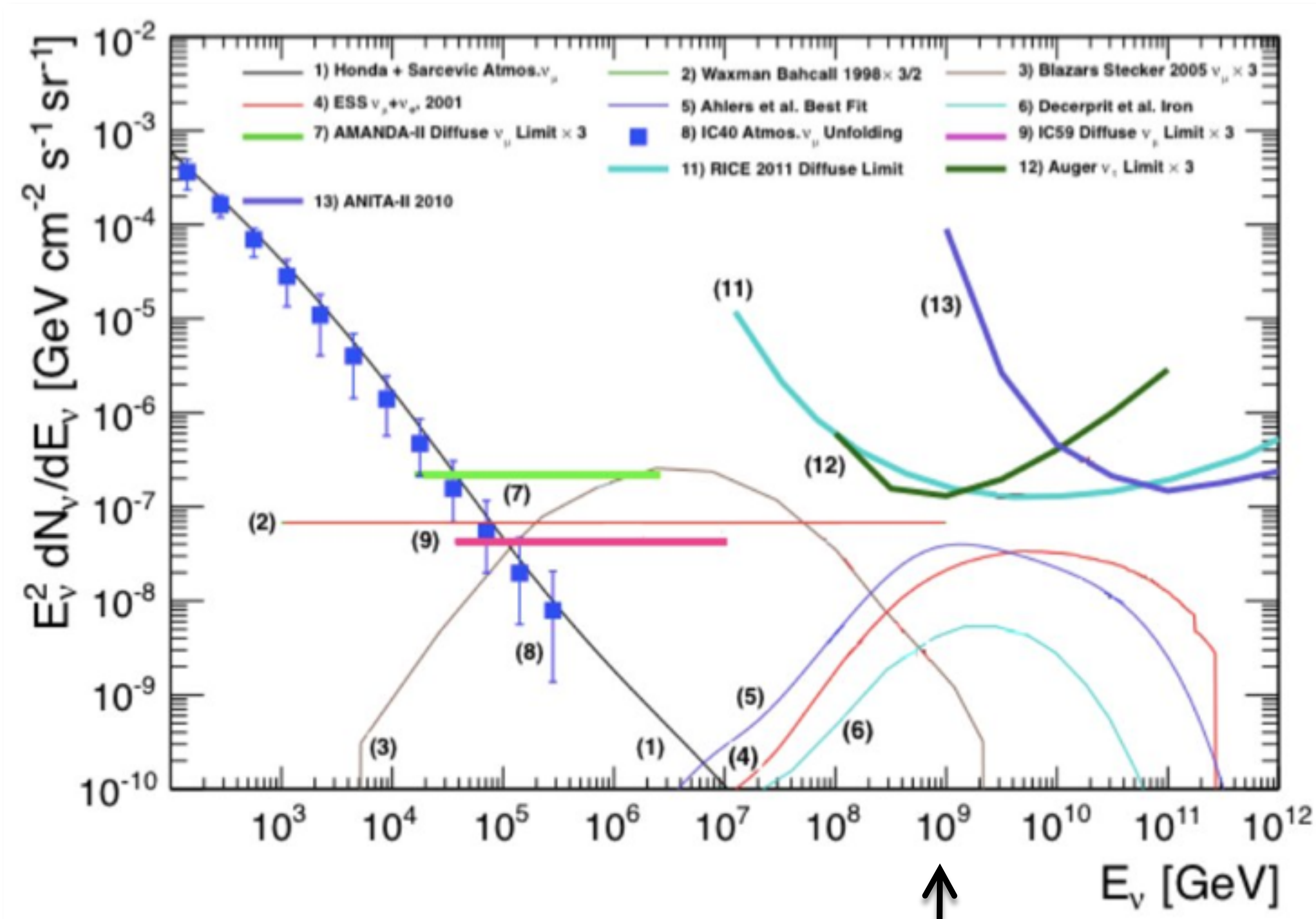
- and in more extreme environments
  - active galactic nuclei (AGNs)
  - gamma ray bursts (GRBs)
  - WIMPs

- ν's can give us valuable clues

Ultra High Energy Neutrinos

(Chang Ha's talk on Thurs)

- see conventional neutrinos from known sources (earth's atmosphere) up to ~400 TeV
- beyond that, there are limits from large detector arrays & ν telescopes looking for ν's <u>not</u> coming from the atmosphere



goal: GZK neutrinos (EeV)

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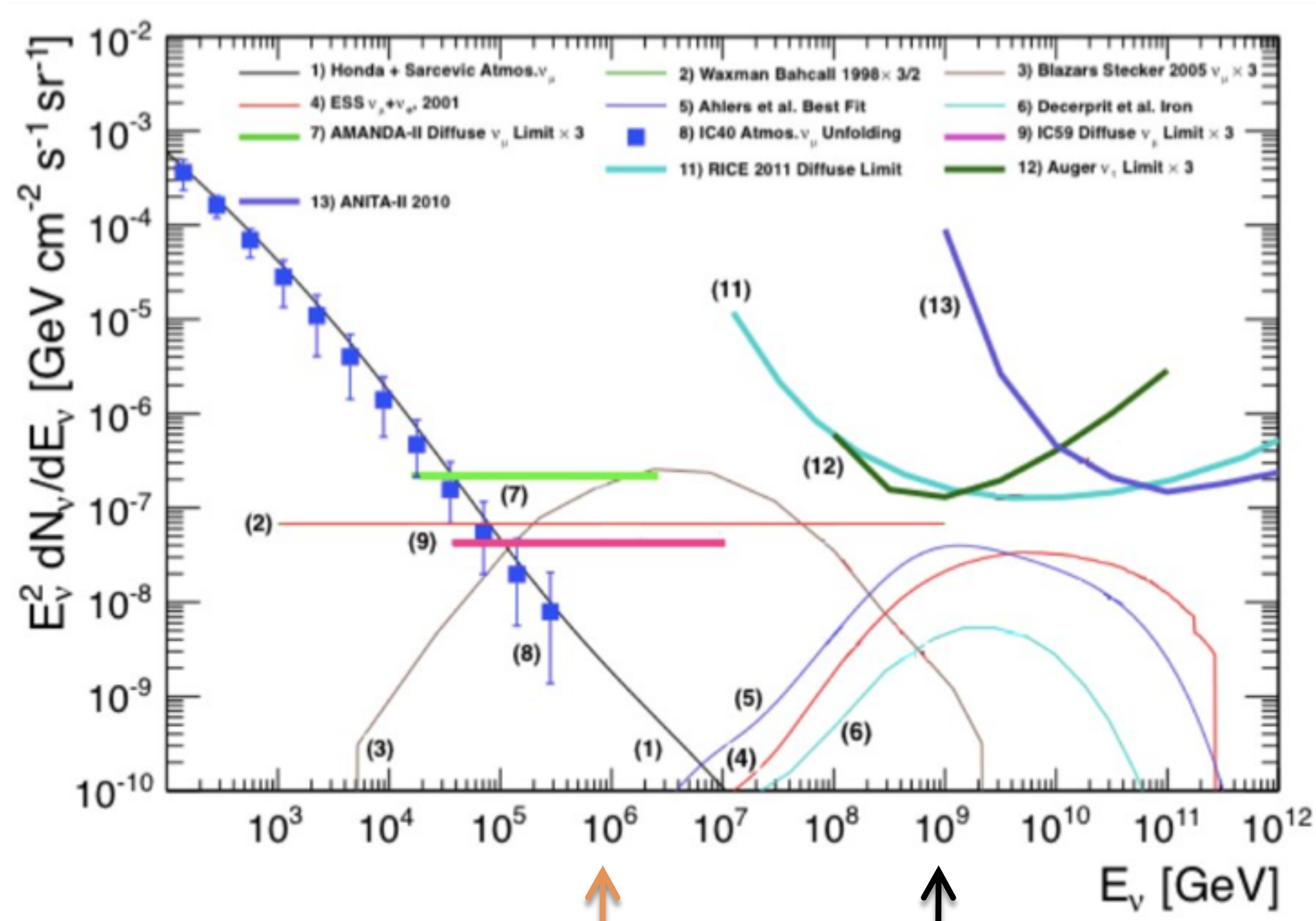


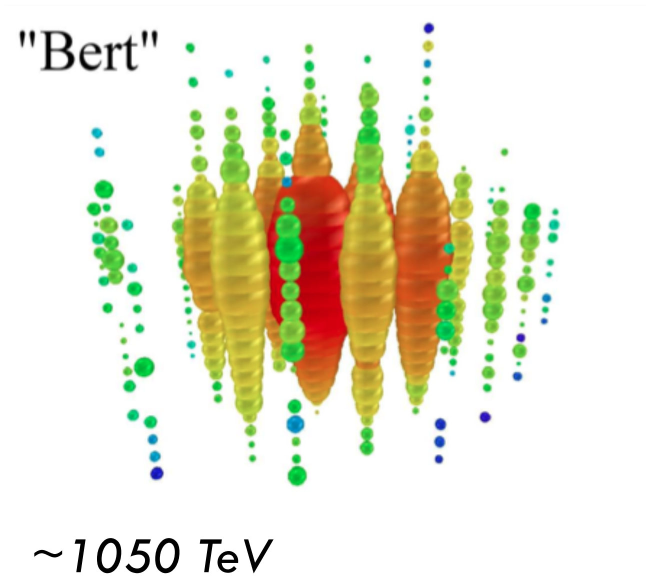
IceCube PeV neutrinos

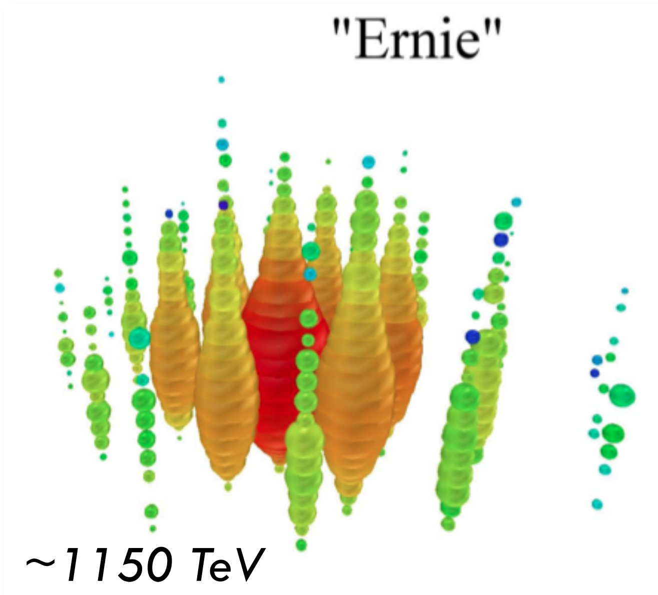
goal: GZK neutrinos (EeV)

PeV Neutrinos!

(Chang Ha's talk on Thurs)

- IceCube recently reported the detection of two PeV neutrinos





highest energy neutrinos ever detected

arXiv:1304.5356

PeV Neutrinos!

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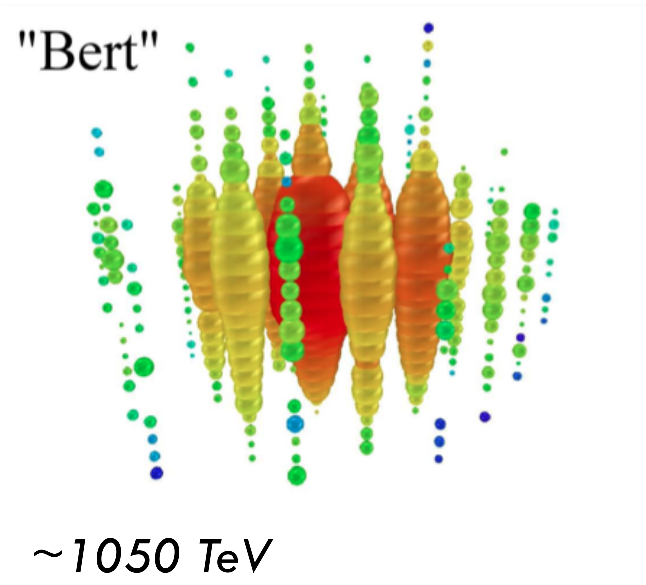
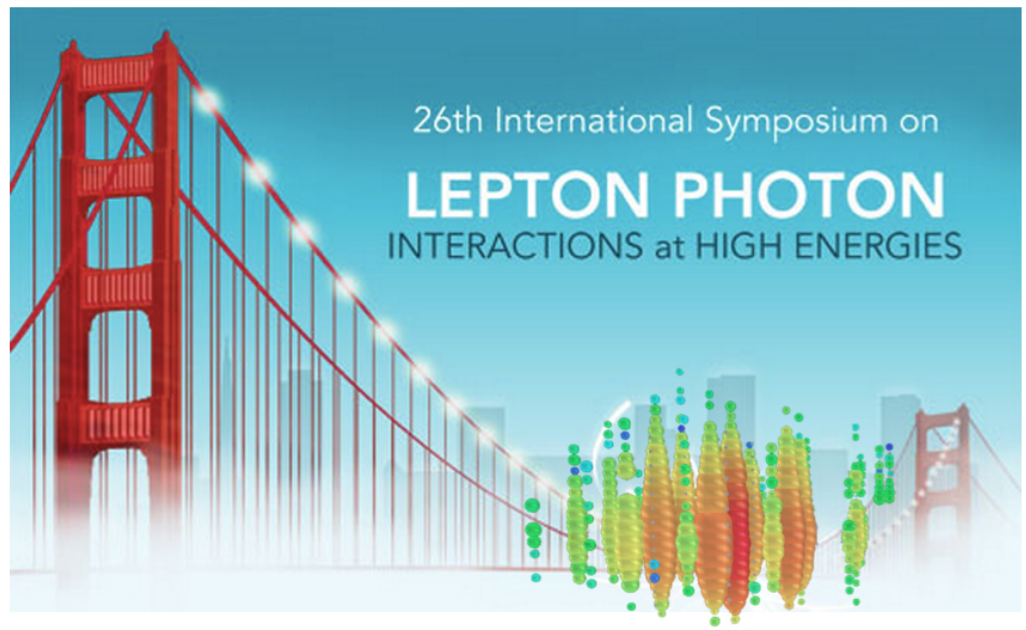


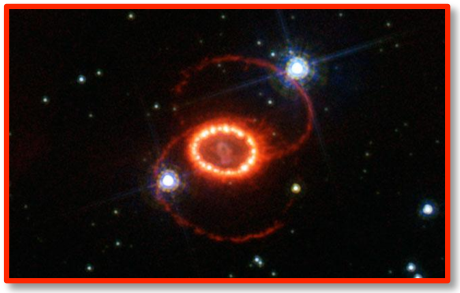


(Darren Grant, Lepton/Photon July 2013)

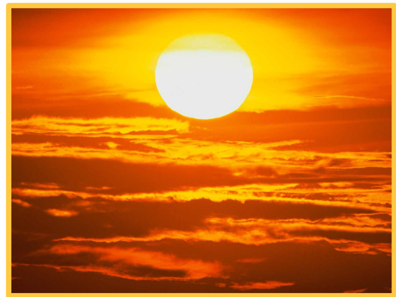
- naturally, a lot of interest in these neutrinos and their source
- first hint of high energy astrophysical neutrinos?

- *ref: C. Spiering, "Towards High Energy ν Astronomy a Historical Review", EPJ. H37, 515 (2012)*

Neutrino Sources

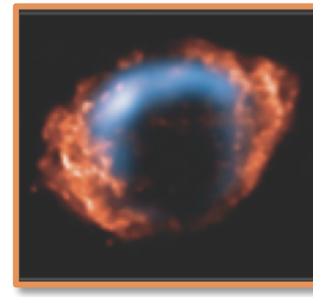


supernova neutrinos



solar neutrinos

atmospheric neutrinos

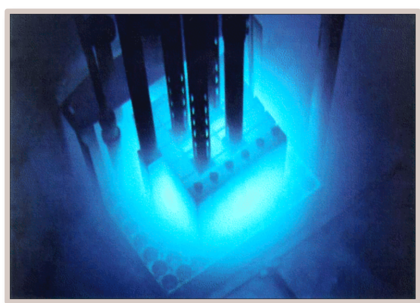


cosmic neutrinos

neutrinos from the heavens ("wild")

neutrinos from the earth ("tame")

accelerator neutrinos



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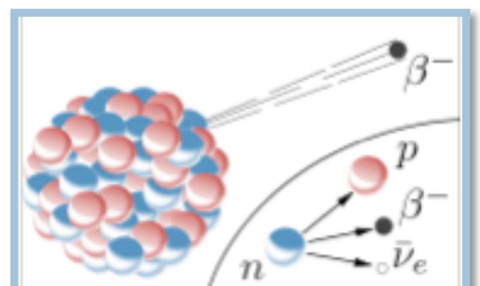

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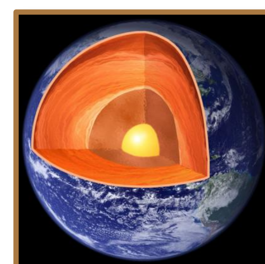
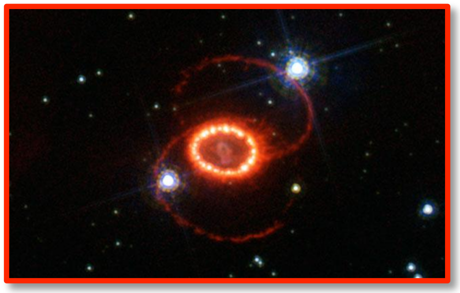


geo neutrinos

Neutrino Sources



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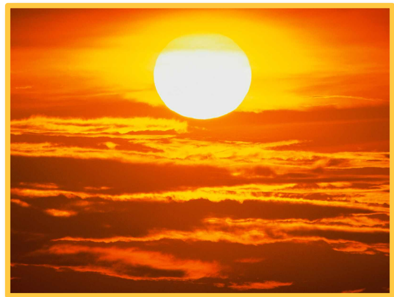

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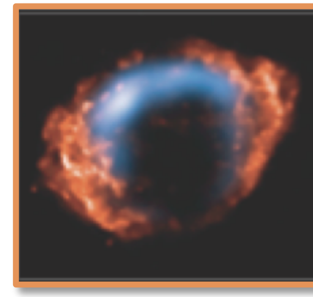


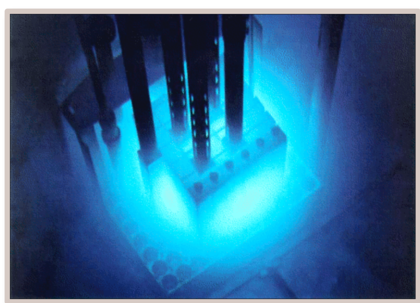
cosmic neutrinos

neutrino oscillations

neutrinos from the heavens ("wild")

neutrinos from the earth ("tame")

accelerator neutrinos



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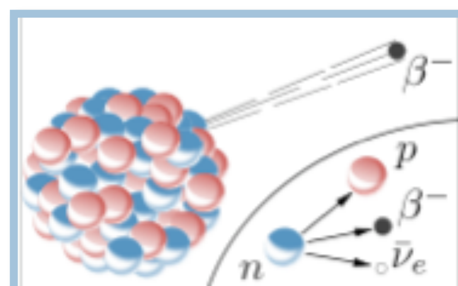

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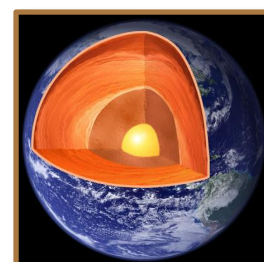


geo neutrinos

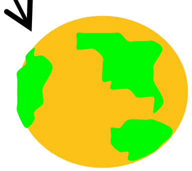
Neutrino Oscillations

- solar and atmospheric neutrinos were responsible for the very important discovery that ν's can change from one type to another

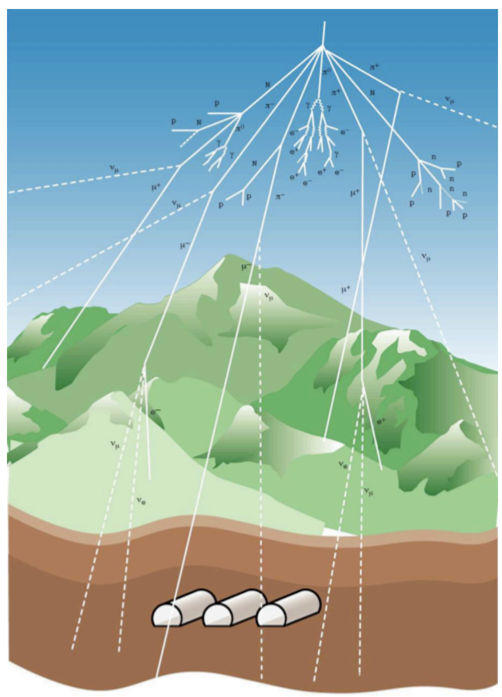
Solar Neutrinos

ν_e

1st experimental hints of ν oscillations



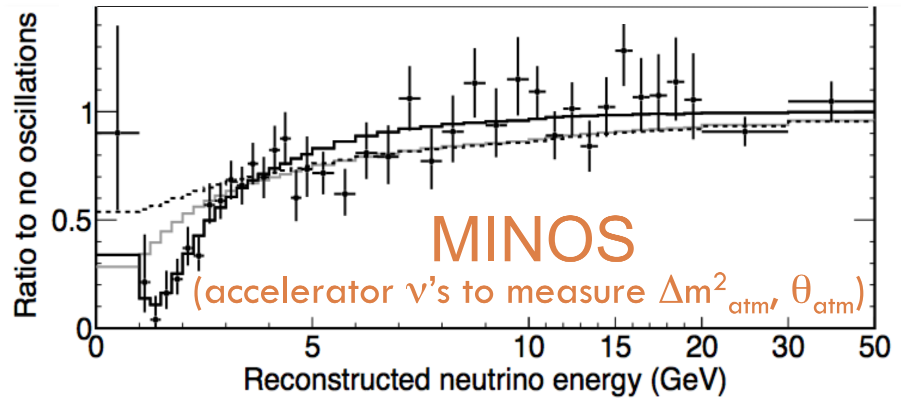
Atmospheric Neutrinos

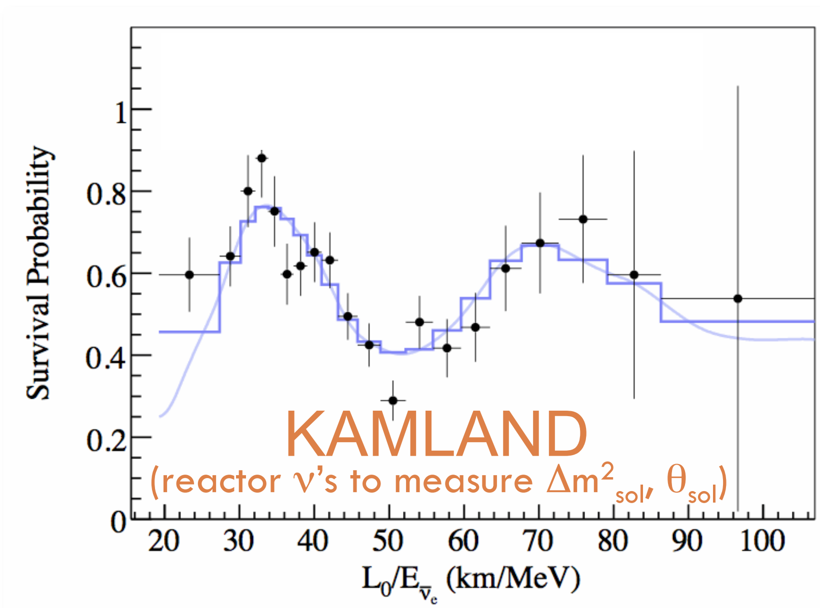


- evidence came when we were trying to study something else
  - *sun*
  - *proton decay*

- discovery of ν oscillations has really changed the field of neutrino physics

Accelerator & Reactor Neutrinos





- while the 1st indications of ν oscillations were observed in astrophysical sources, we have also carefully tested this in controlled experiments

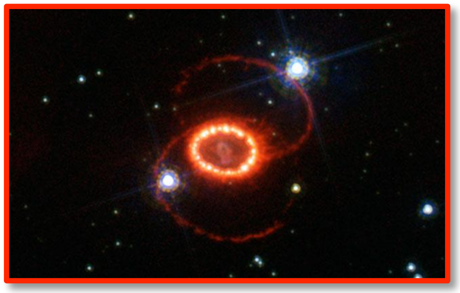
  - *particle accelerators*
  - *nuclear reactors*

- fixed L, well-known E_ν

- have played a crucial role in the confirmation of the neutrino oscillation phenomenon

combined, these are very powerful tests

Neutrino Sources



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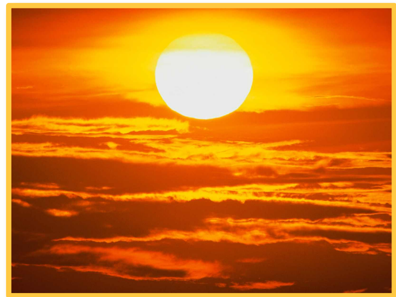

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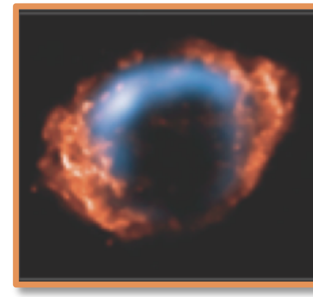

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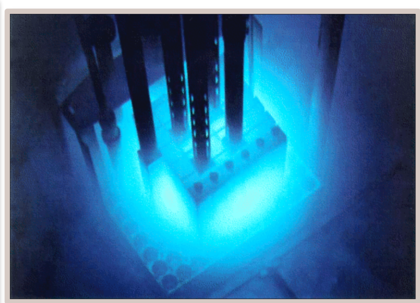

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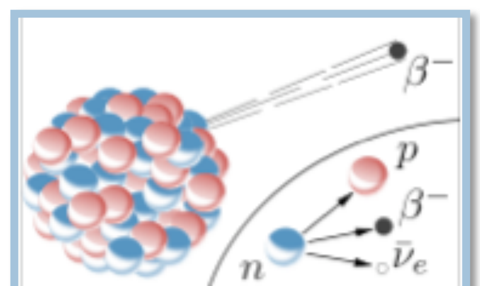

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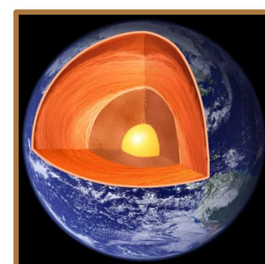
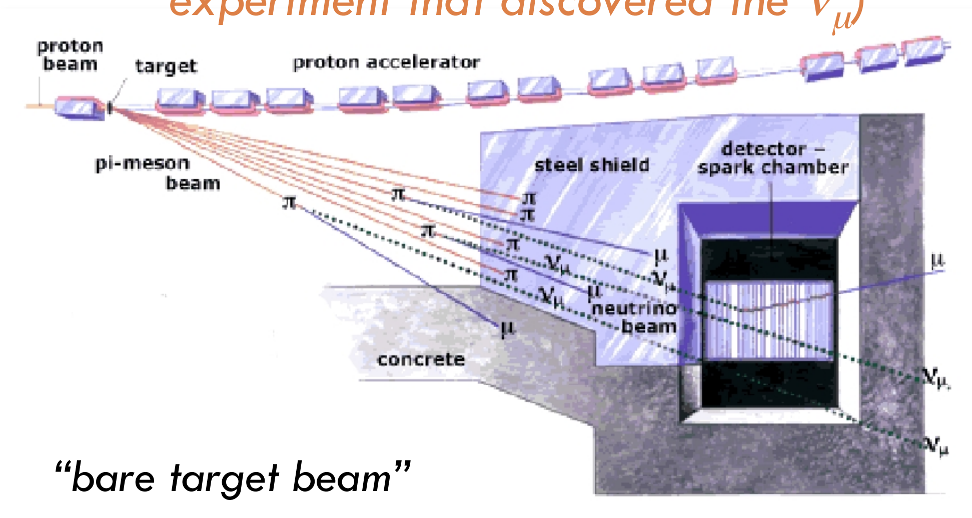


geo neutrinos

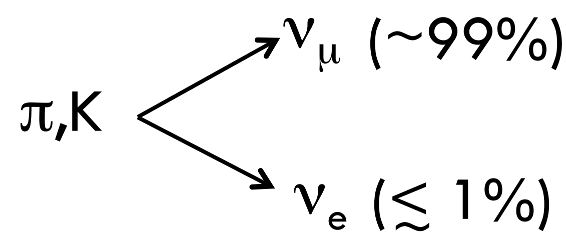
Accelerator Neutrinos

- we continue to produce neutrinos in essentially the same way we did in the first accelerator-based neutrino experiment

(Lederman, Schwartz, Steinberger, BNL 1962 experiment that discovered the ν_μ)



"bare target beam"

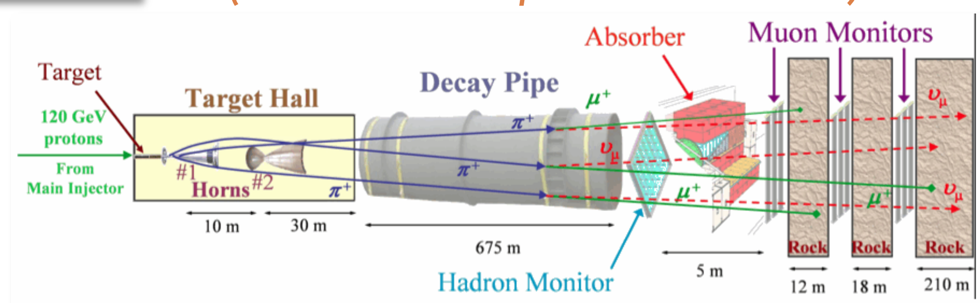


$$\pi,K \rightarrow \nu_\mu \ (\sim 99\%), \quad \nu_e \ (\lesssim 1\%)$$

- primarily one ν flavor: ν_μ
- nuisance background of ν_e

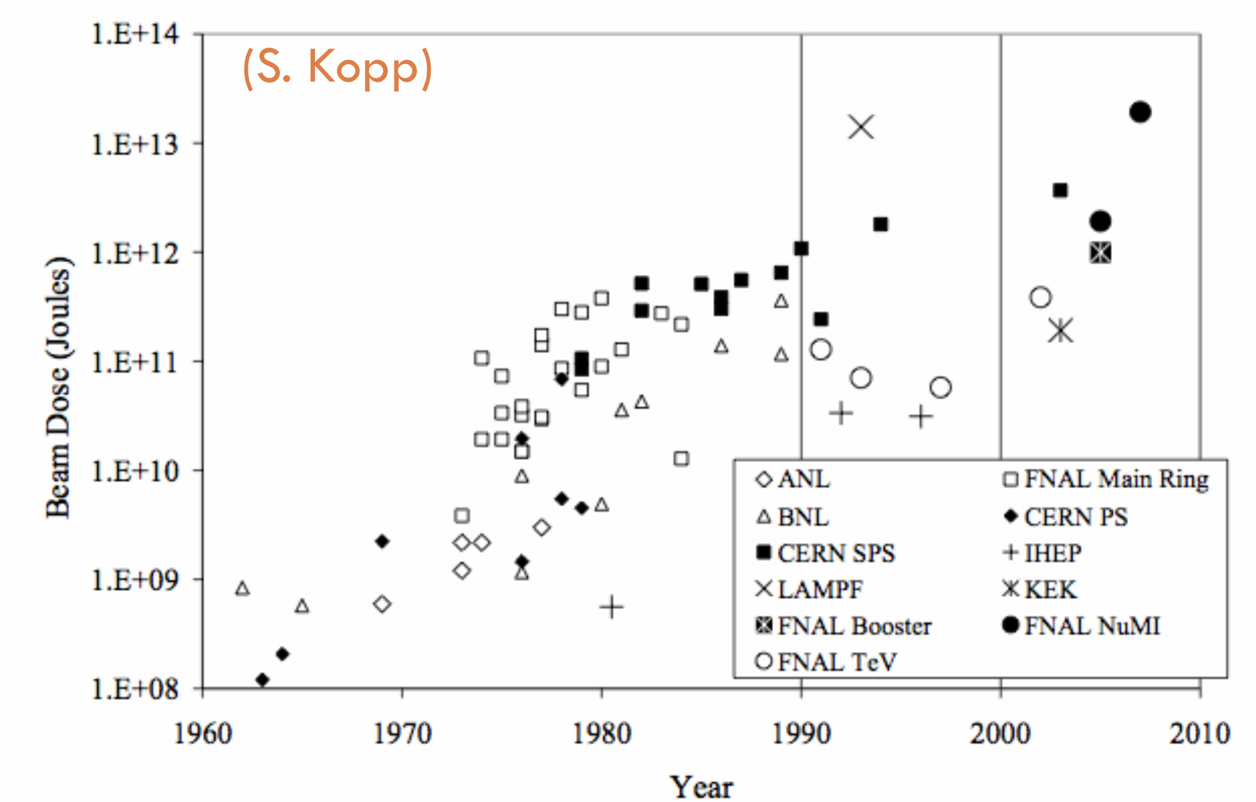
(modern example: NuMI beam)

- now, horn-focused high powered ν beams (0.8 kW → 100's kW)



Accelerator Neutrinos

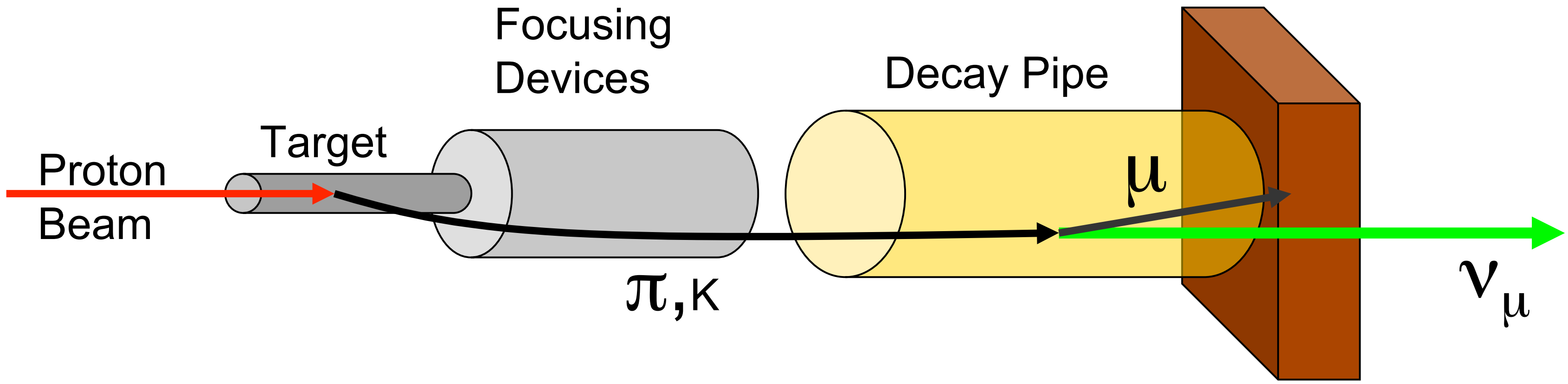
- shows beam power delivered since the first accelerator ν experiment



not only are these ν beams becoming more powerful ("superbeams") but they are also becoming more precisely known thanks to improved hadro-production measurements

- after 50 years of innovation, ν beams have improved dramatically; has risen from a few ν's detected per week to a few ν's per second

Conventional Neutrino Beam



- **proton target**

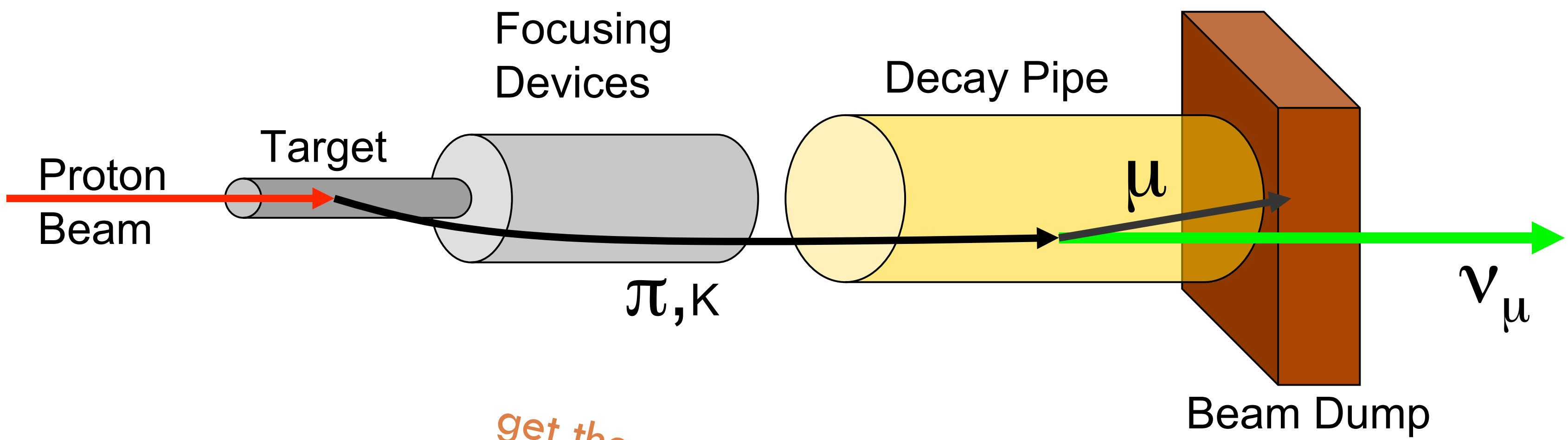
(graphite target with Al casing)

- low Z material

- typically 1-2 interaction lengths
  cylinder or ruler with longest dimension in beam direction

- target has to withstand proton beam (shock and heating)
  air or water cooled, often segmented

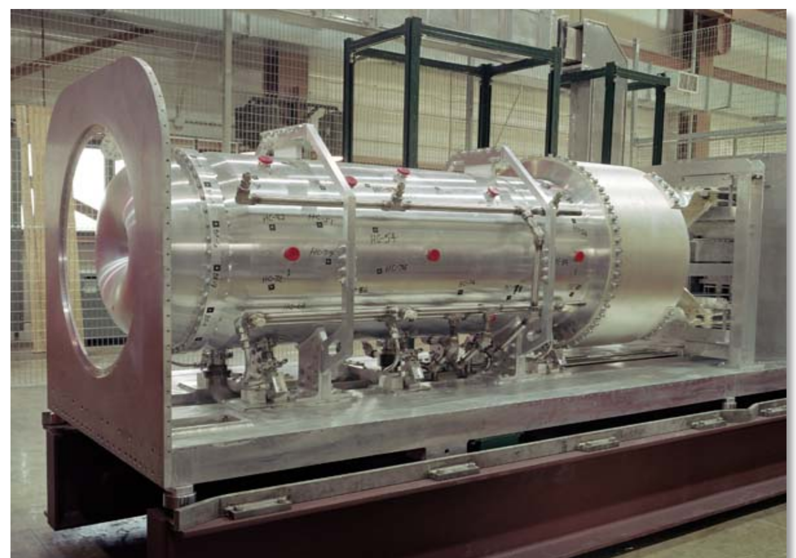
Conventional Neutrino Beam



get the most out of your beam!

- **magnetic focusing horn**
  - collects secondary π, K's and directs them toward downstream experiment thereby increasing the ν flux
  - selects π, K charge
  - multi-horn systems

$$\pi^+ \to \mu^+ \nu_\mu$$
or
$$\pi^- \to \mu^- \bar{\nu}_\mu$$



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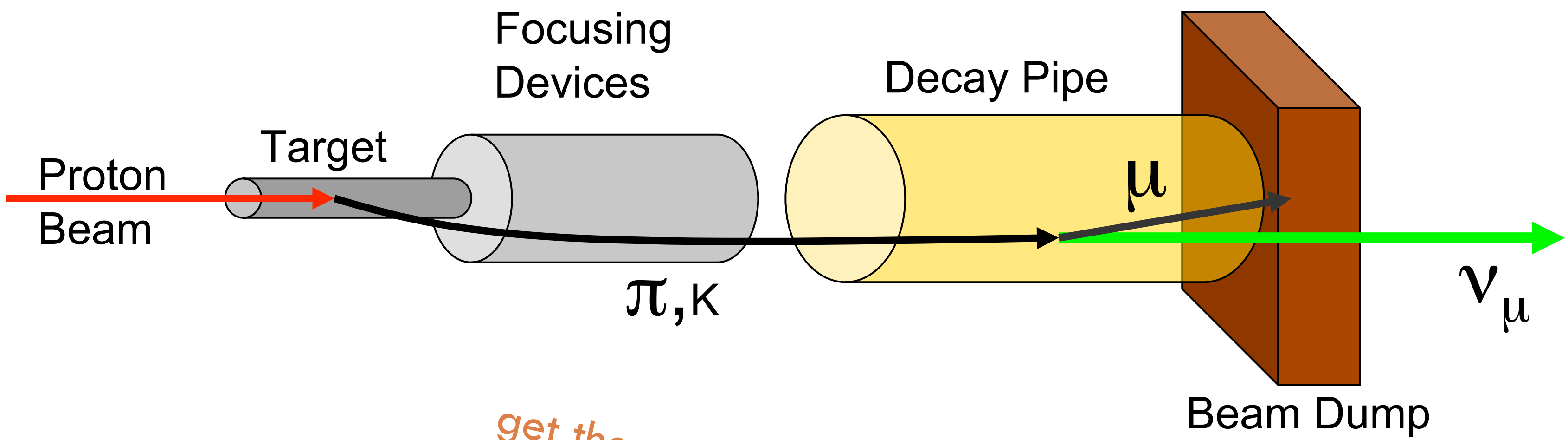

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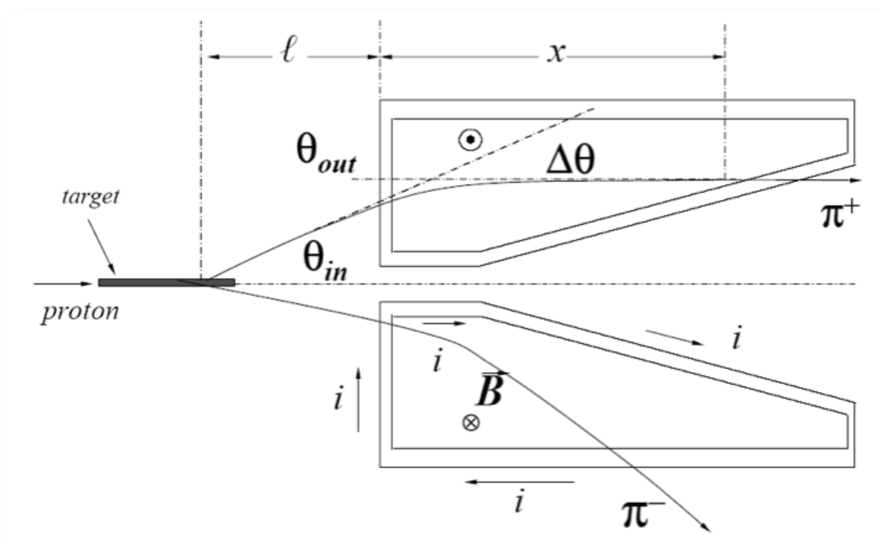

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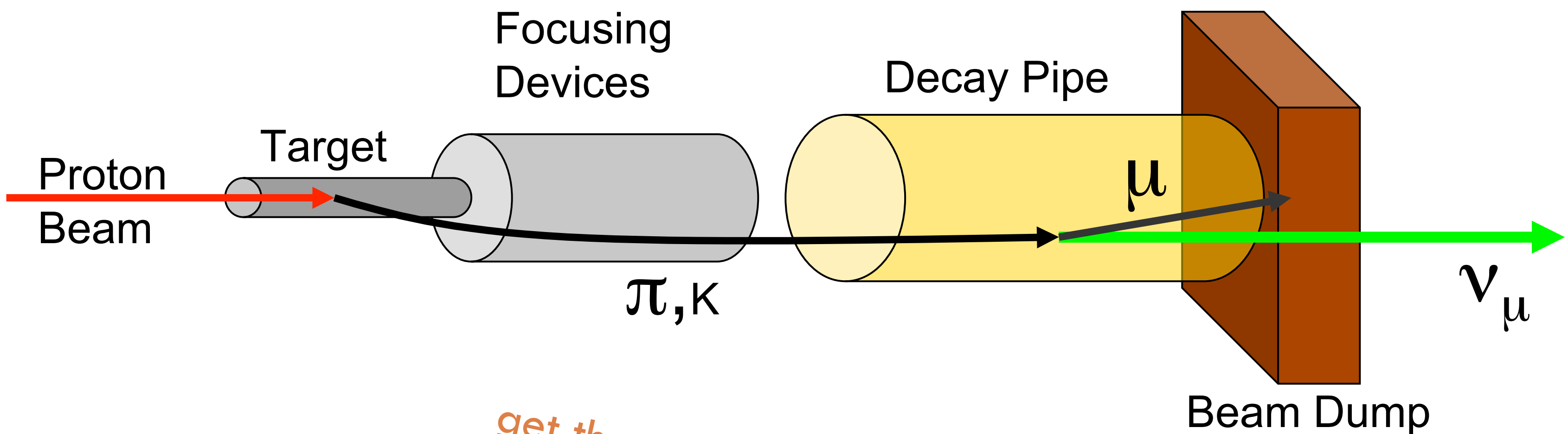

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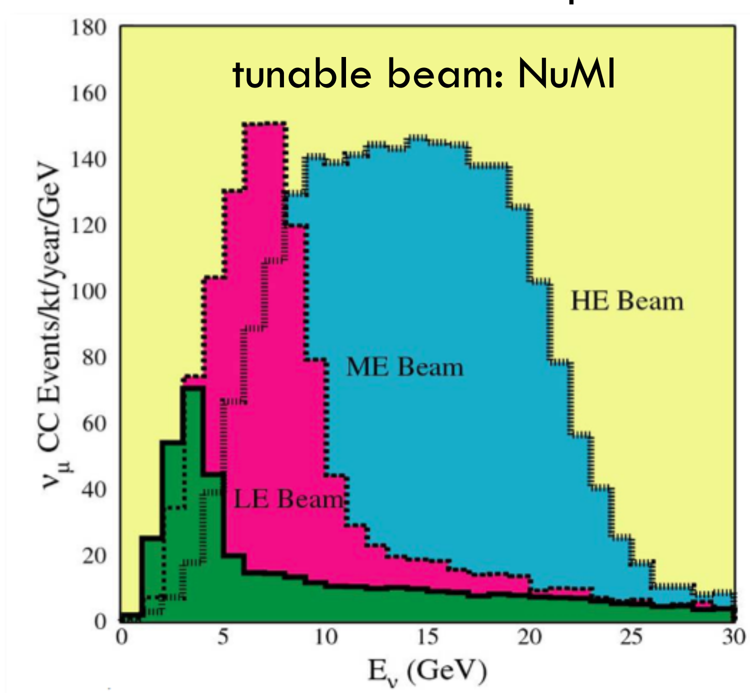
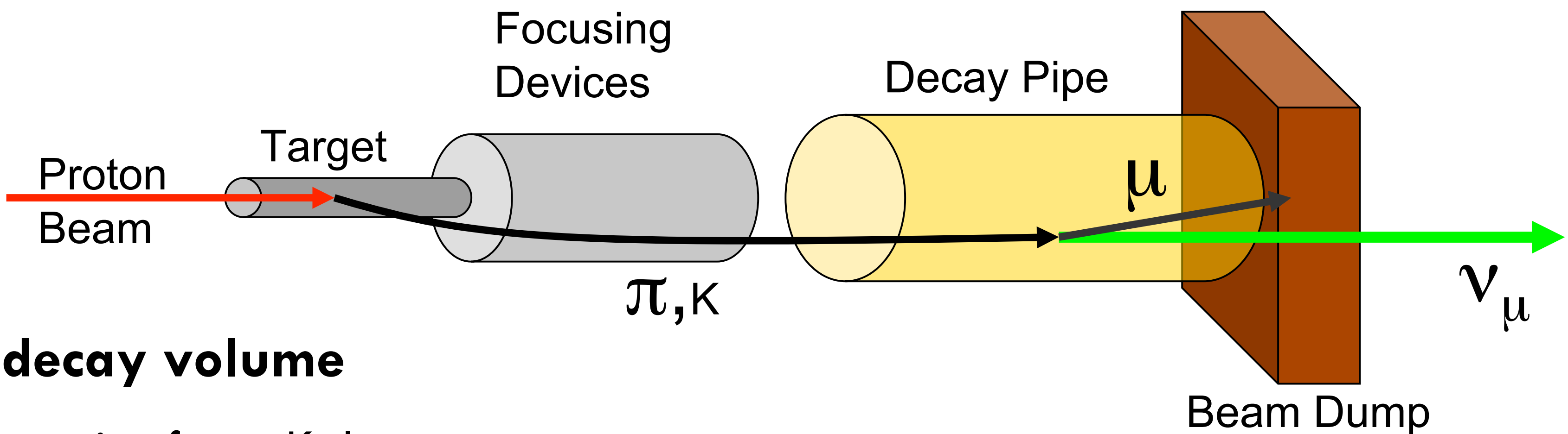


Conventional Neutrino Beam



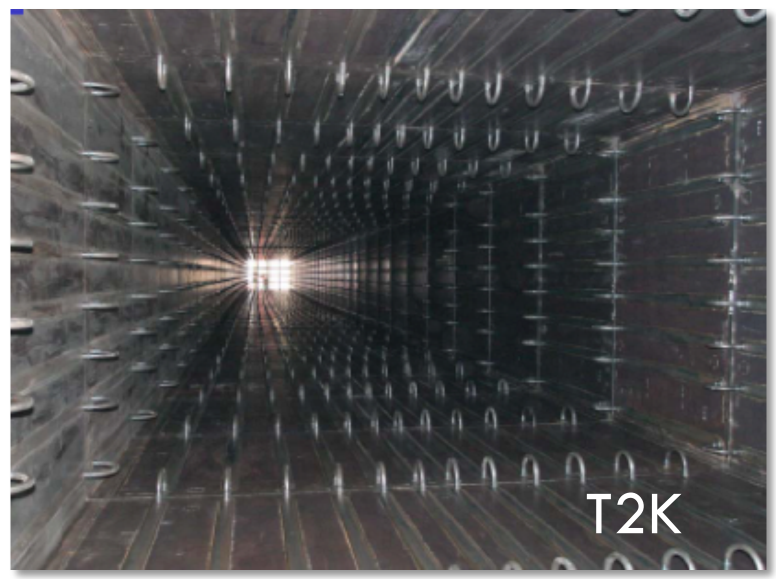
- **decay volume**
  - region for π, K decay to occur

$\pi^\pm \rightarrow \mu^\pm \nu_\mu$
$K^\pm \rightarrow \mu^\pm \nu_\mu$ } mostly
$K_L \rightarrow \pi\mu\nu_\mu$

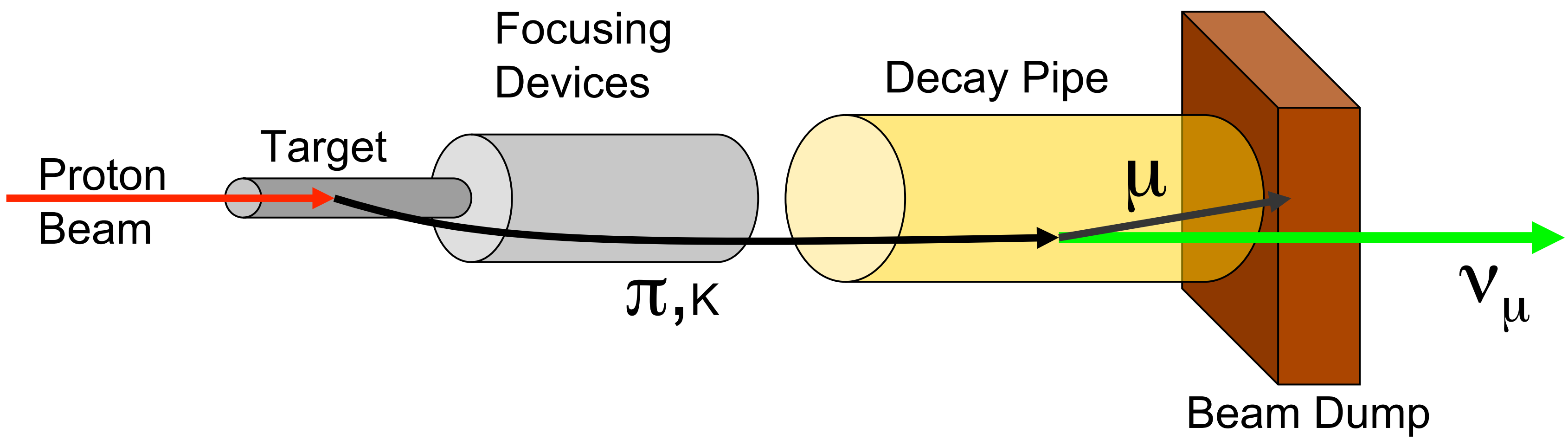
$\mu \rightarrow e\nu_\mu\nu_e$, $K_L \rightarrow \pi e \nu_e$

(at high energy, $D_s \rightarrow \tau\ \nu_\tau$)

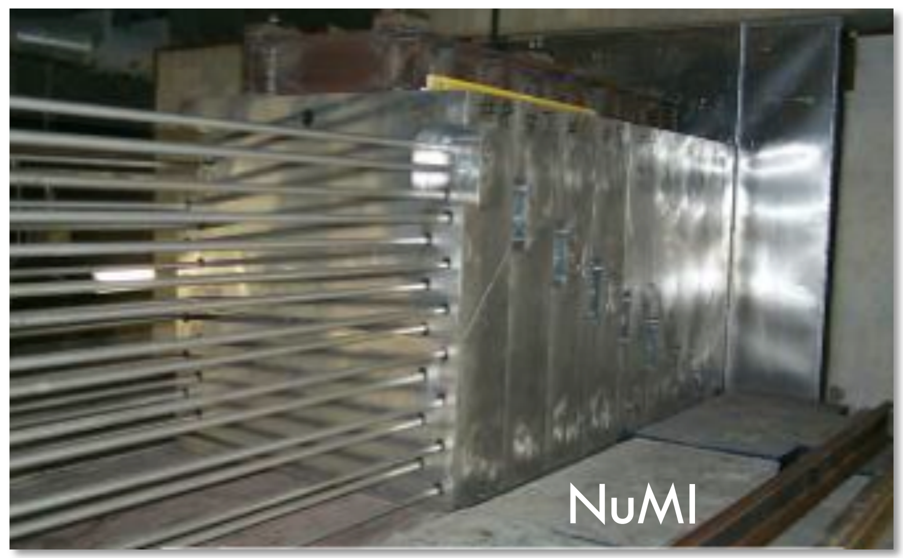
  - often evacuated or filled with He to reduce absorption/rescattering



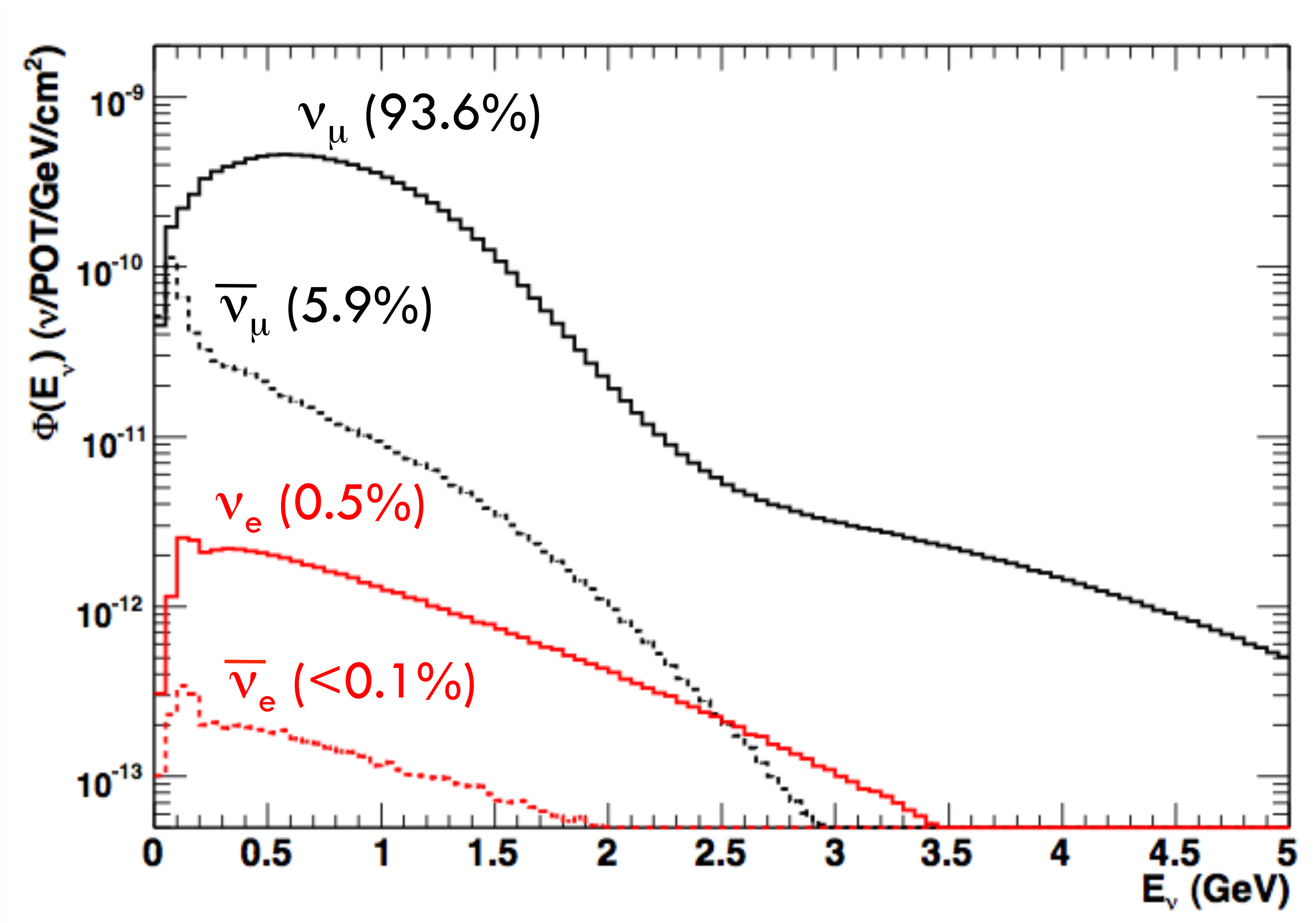
Conventional Neutrino Beam



- **beam dump**
  - absorber to get rid of undecayed particles
  - also, often a downstream dirt berm to act as a muon filter



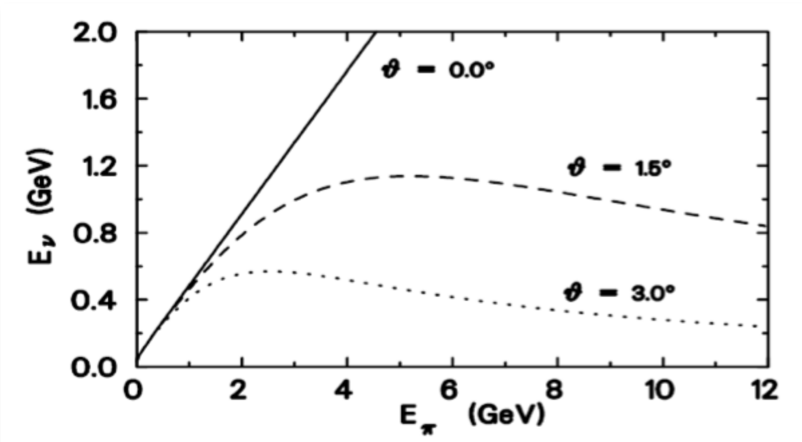
Composition of a Horn-Focused Beam



(example: Fermilab Booster neutrino beam in neutrino mode, 8 GeV protons)

Off-Axis Technique

$$E_\nu = \frac{(1-(m_\mu/m_{(\pi,K)})^2)E_{(\pi,K)}}{(1+\gamma^2\theta^2)}$$

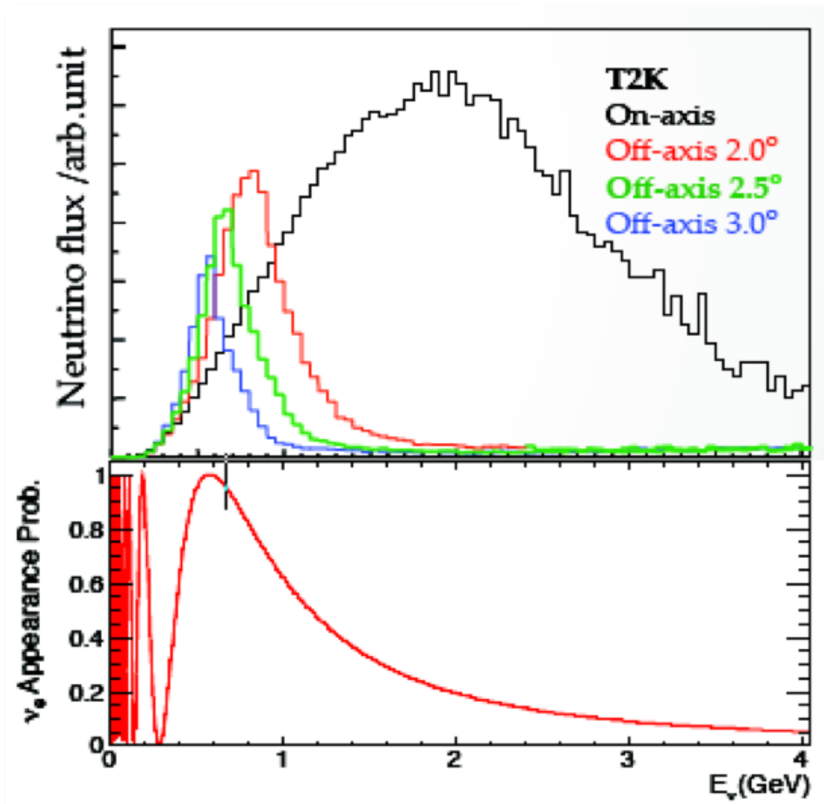


- results in a flux of ν's created in a desired energy range
- on-axis = wide band beam

  (ex. MINOS, LBNE)
- off-axis = narrow band beam

  (ex. T2K, NOvA)

- OA concept: at certain angles, pions of different nergies generate ν's in a relatively narrow band of energies



(Silvestro Di Luise's T2K talk on Thurs)

Physics with Accelerator Neutrinos

- discoveries of ν_μ and ν_τ
- neutrino cross sections
- discovery of neutral currents
- electroweak physics ($\sin^2\theta_W$)
- probes of nucleon structure (form factors, structure functions)
- measurements of ν oscillations
- probes BSM physics

	PS (CERN)				SPS (CERN)				PS (KEK)	Main Ring (JPARC)
Date	1963	1969	1972	1983	1977	1977	1995	2006	1999	2009
Proton Kinetic Energy (GeV)	20.6	20.6	26	19	350	350	450	400	12	30 (50)
Protons per Pulse (10^{12})	0.7	0.6	5	5	10	10	18	50	6	135 (330)
Cycle Time (s)	3	2.3	-	-	-	-	14.4	6	2.2	2.56 (3.5)
Beam Power (kW)	0.8	0.9	-	-	-	-	55	510	5	250 (750)
Secondary Focussing	1-horn WBB	3-horn WBB	2-horn WBB	bare target	dichromatic NBB	2-horn WBB	2-horn WBB	2-horn WBB	2-horn WBB	3-horn off-axis
Decay Pipe Length (m)	60	60	60	45	290	290	290	994	200	96
$\langle E_\nu \rangle$ (GeV)	1.5	1.5	1.5	1	$50,150^\dagger$	20	24.3	17	1.3	0.6
Experiments	HLBC, Spark Ch.	HLBC, Spark Ch.	GGM, Aachen-Padova	CDHS, CHARM	CDHS, CHARM, BEBC	GGM,CDHS, CHARM, BEBC	NOMAD, CHORUS	OPERA, INCARUS	K2K	T2K

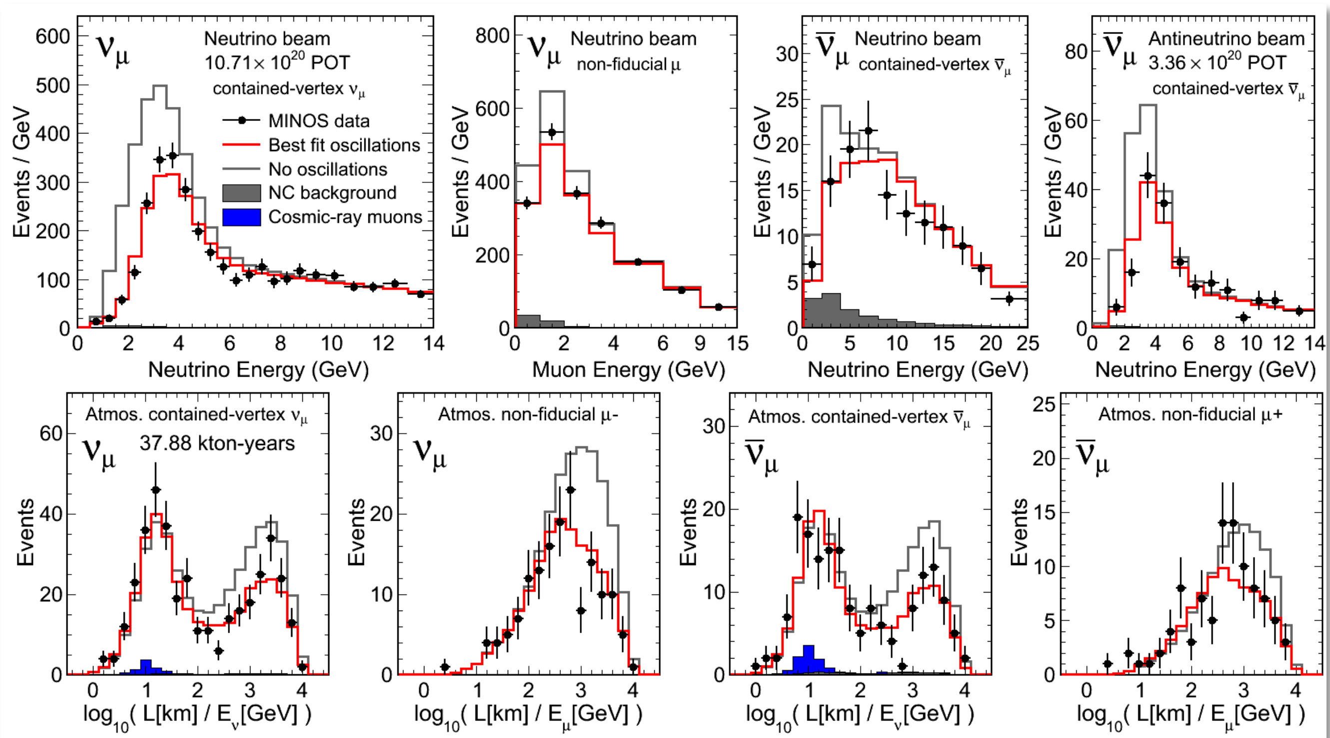
	Main Ring (Fermilab)							Booster (Fermilab)	Main Injector (Fermilab)	
Date	1975	1975	1974	1979	1976	1991	1998	2002	2005	2013
Proton Kinetic Energy (GeV)	300,400	300,400	300	400	350	800	800	8	120	120
Protons per Pulse (10^{12})	10	10	10	10	13	10	12	4.5	37	(49)
Cycle Time (s)	-	-	-	-	-	60	60	0.5	2	(1.333)
Beam Power (kW)	-	-	-	-	-	20	25	12	350	(700)
Secondary Focussing	bare target	quad trip., SSBT	dichromatic NBB	2-horn WBB	1-horn WBB	quad trip.	SSQT WBB	1-horn WBB	2-horn WBB	2-horn off-axis
Decay Pipe Length (m)	350	350	400	400	400	400	400	50	675	675
$\langle E_\nu \rangle$ (GeV)	40	$50,180^\dagger$	$50,180^\dagger$	25	100	90,260	70,180	1	$3\text{-}20^\ddagger$	2
Experiments	HPWF	CITF, HPWF	CITF, HPWF, 15' BC	15' BC	HPWF 15' BC	15' BC, CCFRR	NuTeV	MiniBooNE, SciBooNE	MINOS, MINERνA	NOνA, MINERνA, MINOS+

- *reference: S. Kopp, "Accelerator Based ν Beams", Phys. Rept. 439, 101 (2007)*

One Example

- **MINOS** - all data sets (accelerator, atmospheric, both ν_μ and $\overline{\nu}_\mu$) combined for final disappearance measurements

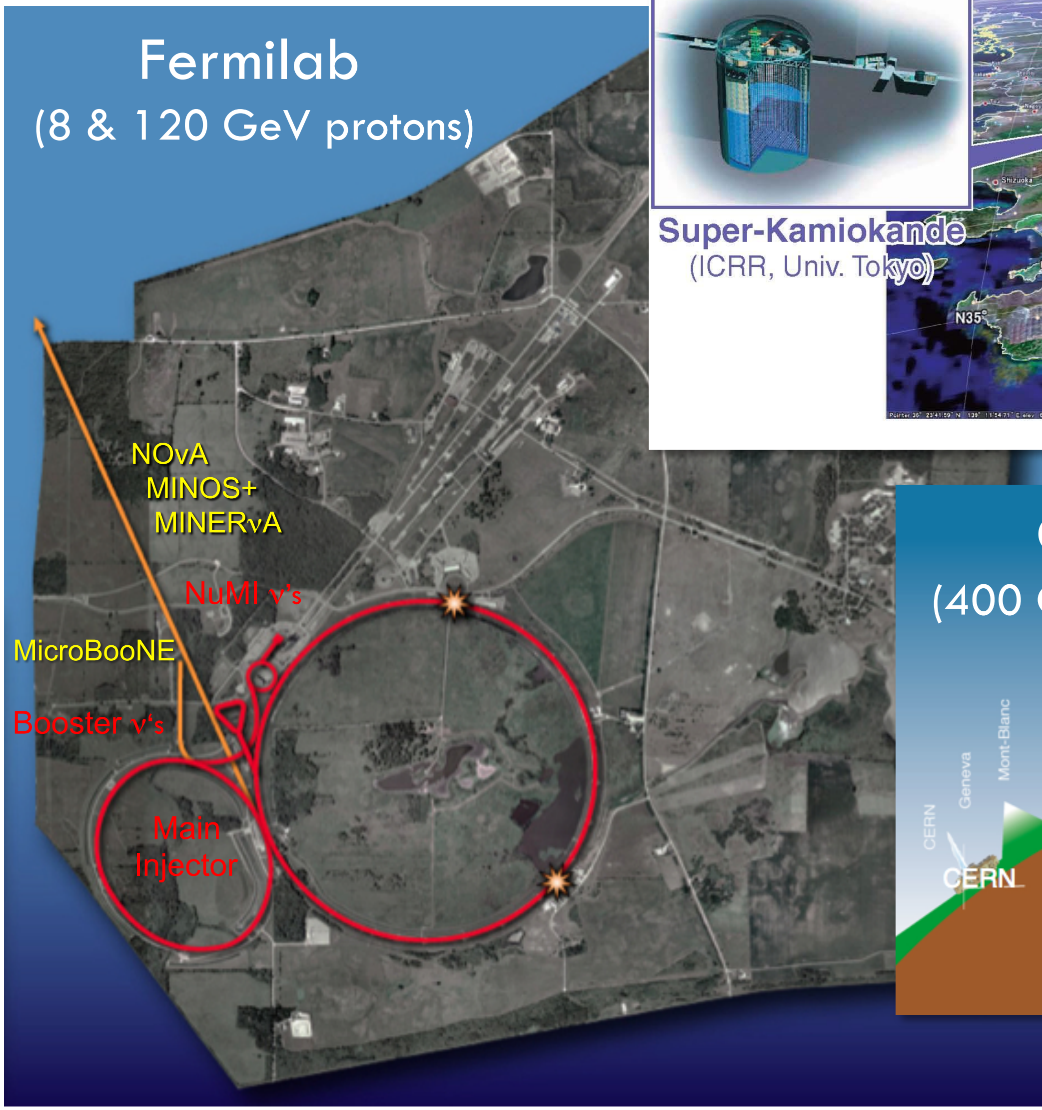
shows how this data all works together & the power of these combinations

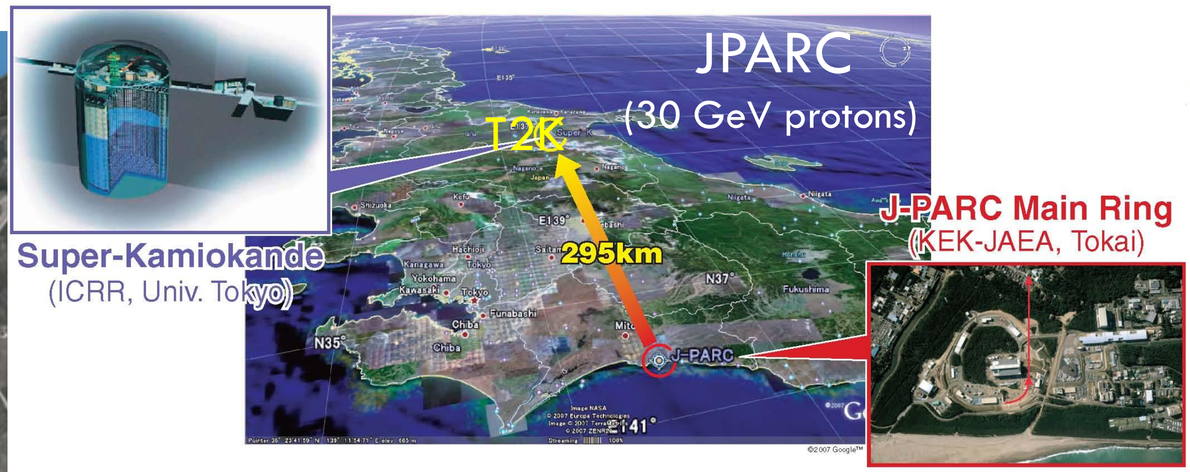


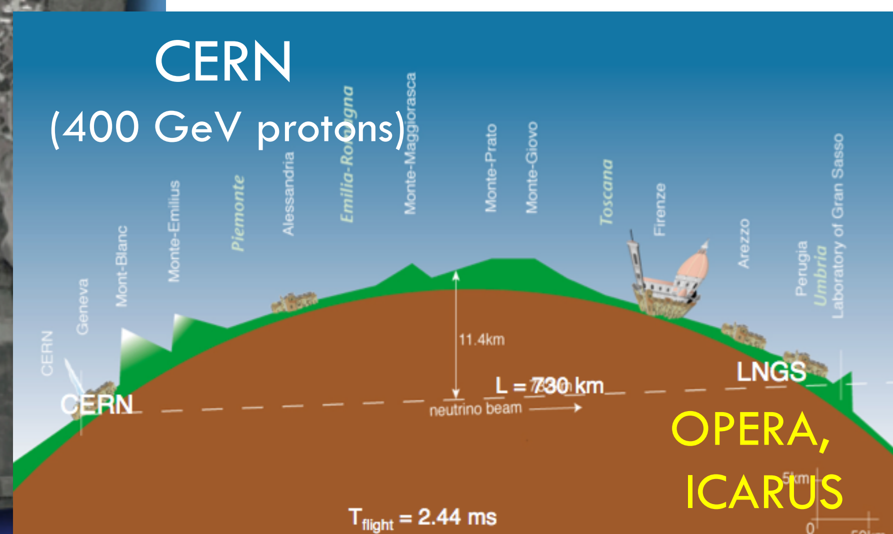
(Adamson et al., arXiv:1304.6335)

- accelerator ν's (K2K, MINOS, T2K, NOvA) provide precision measurements of ν_μ disappearance (1st seen with atm ν's) & are now studying $\nu_\mu \rightarrow \nu_e$

Current Neutrino Beams



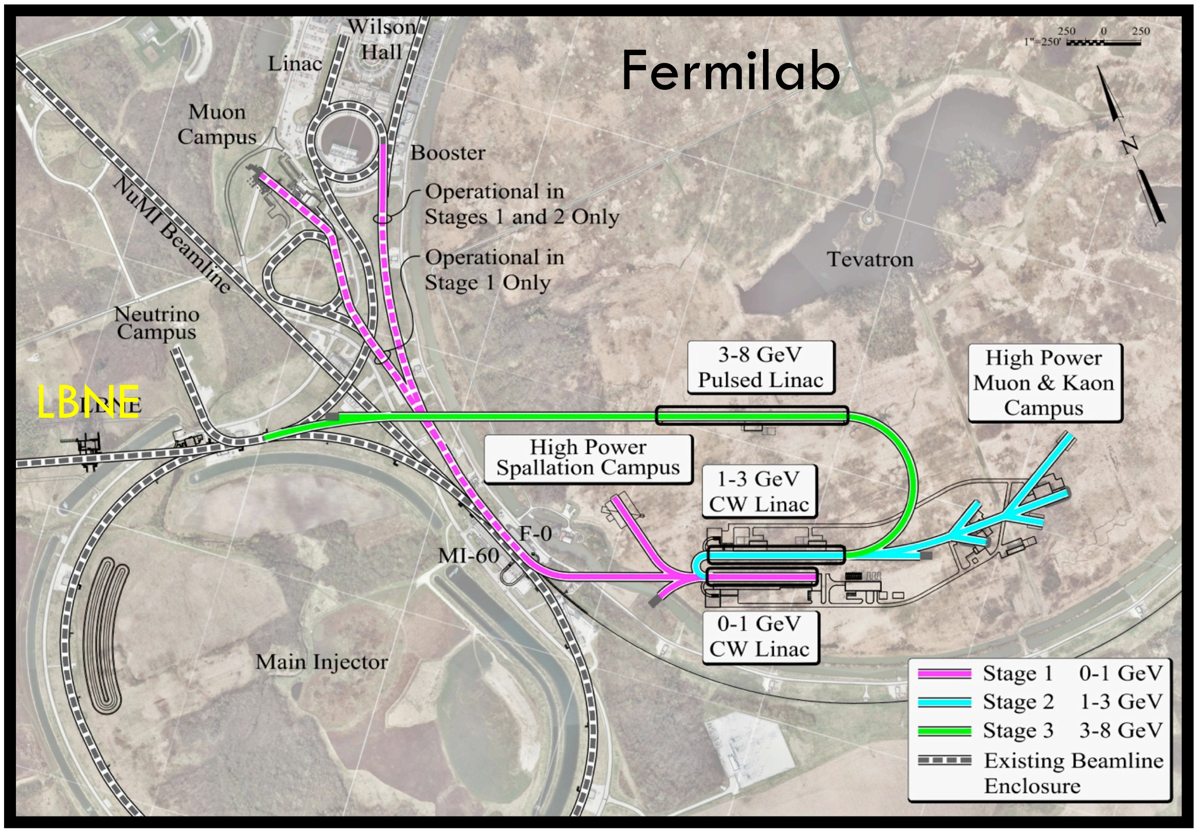




- ν oscillations, σ_ν, BSM

Future Accelerator ν's: Project-X

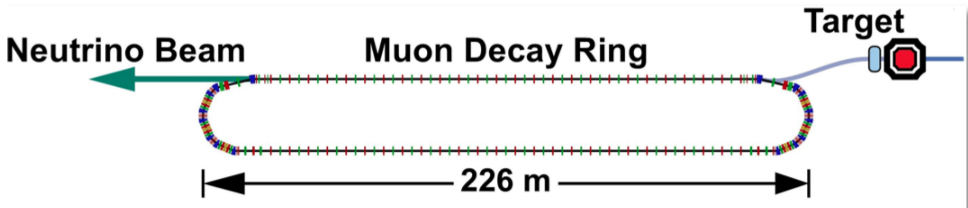
- upgraded proton beam power to MW needed for future precision intensity frontier physics … long-baseline ν physics!



http://theory.fnal.gov/people/ask/PX-book/

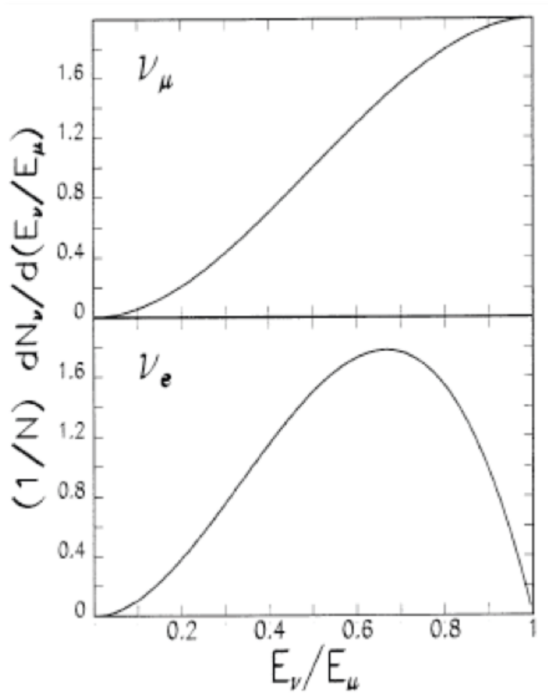
- Project-X
  (Bob Tschihart's talk on Fri)
- 700 kW (NOvA)
  → 2.3 MW
- discovery of $\not{C}$P
  in the ν sector
- precision BSM
  ν investigations

Muons As A Source



(νSTORM,
Neutrino Factory)

- people have also been thinking about using muon storage rings to produce ν's



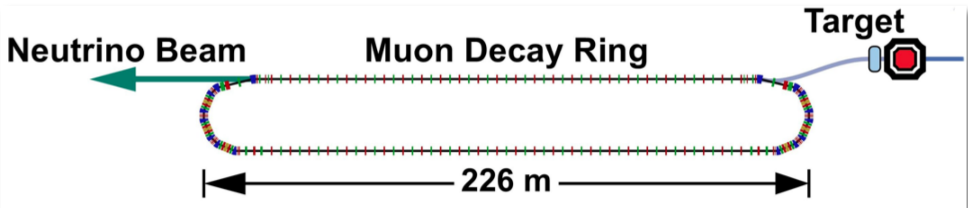
- 50/50 mix of both ν flavors

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- very well-known flux (flavor content and E_ν spectra)

Muons As A Source



(νSTORM, Neutrino Factory)

- for these types of experiments, you can see why you need **magnetized detectors**

(similarly for μ^+)

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \longrightarrow \mu^-$$

$$\bar{\nu}_\mu \to \mu^+$$

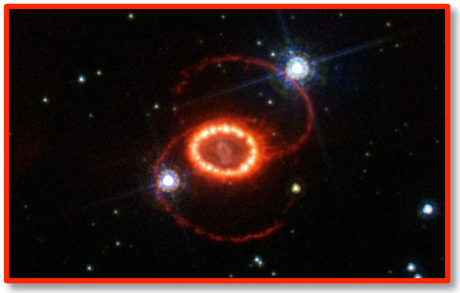
Golden Mode

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e \longrightarrow e^+$$

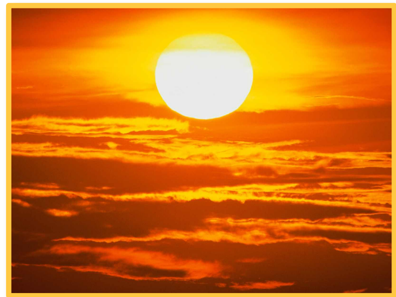
$$\nu_e \to e^-$$

Platinum Mode

Neutrino Sources

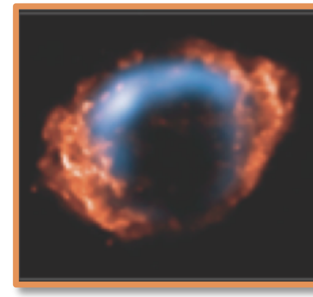


supernova neutrinos



solar neutrinos

atmospheric neutrinos



cosmic neutrinos

neutrinos from the heavens ("wild")

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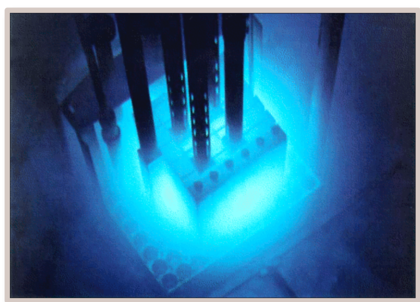
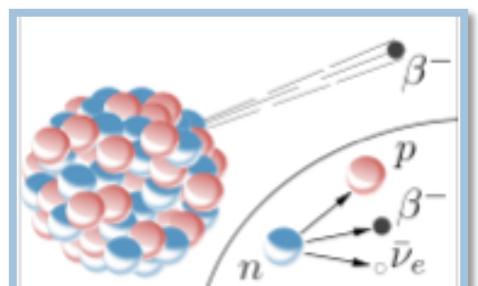
neutrinos from the earth ("tame")

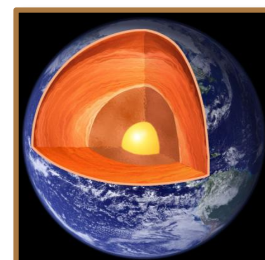
accelerator neutrinos



reactor neutrinos



radioactive decays



geo neutrinos

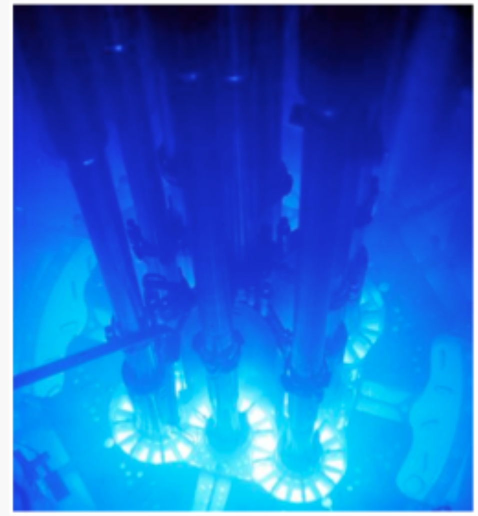
Reactor Neutrinos

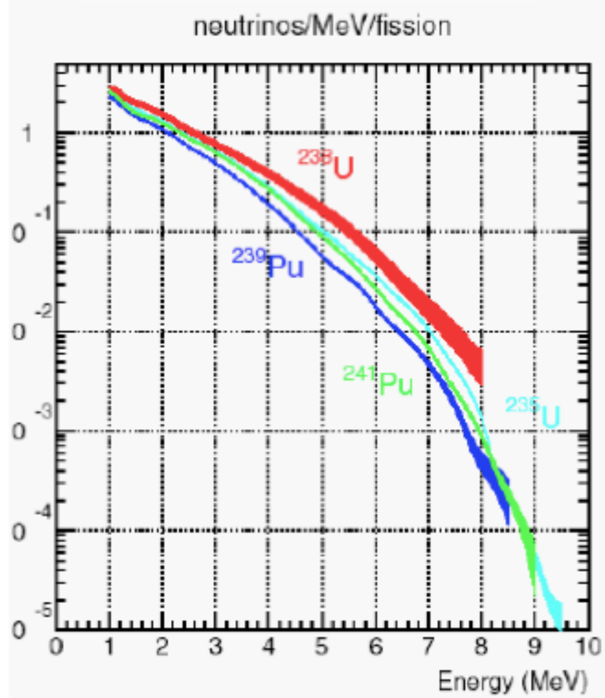
- reactor neutrinos are a by-product of fission as numerous unstable nuclei are produced & beta decay to more stable isotopes

^{235}U

^{239}Pu

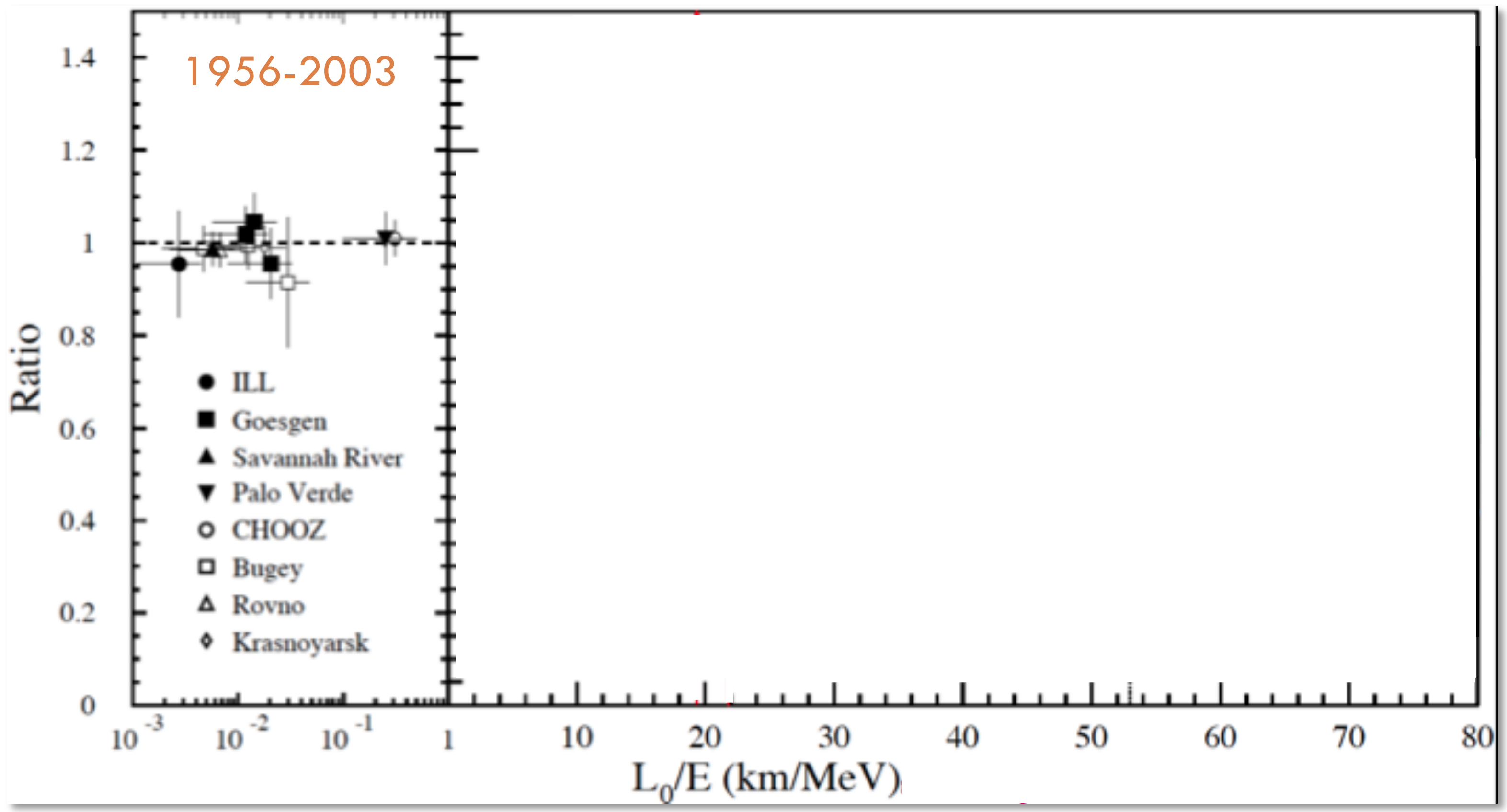
- reactors are a very intense source of $\overline{\nu}_e$'s, $E_\nu \lesssim 10$ MeV
  - * 1 GW (thermal) ~ $1.8\times10^{20}\ \overline{\nu}_e$/sec
  - * pure $\overline{\nu}_e$ source
- this is how we discovered neutrinos & more recently, ν oscillation measurements





Reactor Neutrinos

- we have been studying neutrinos from nuclear reactors since the 1950s



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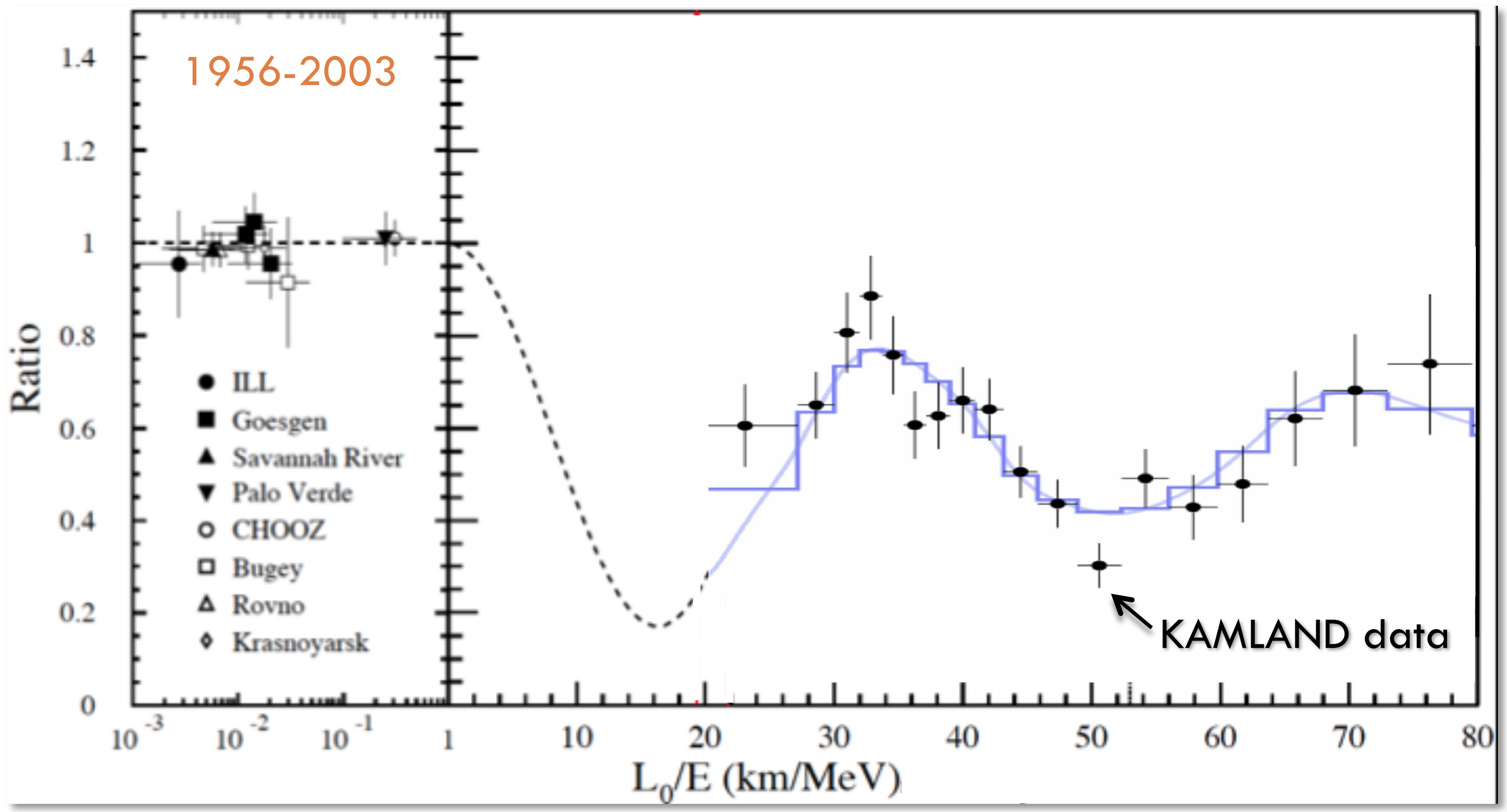
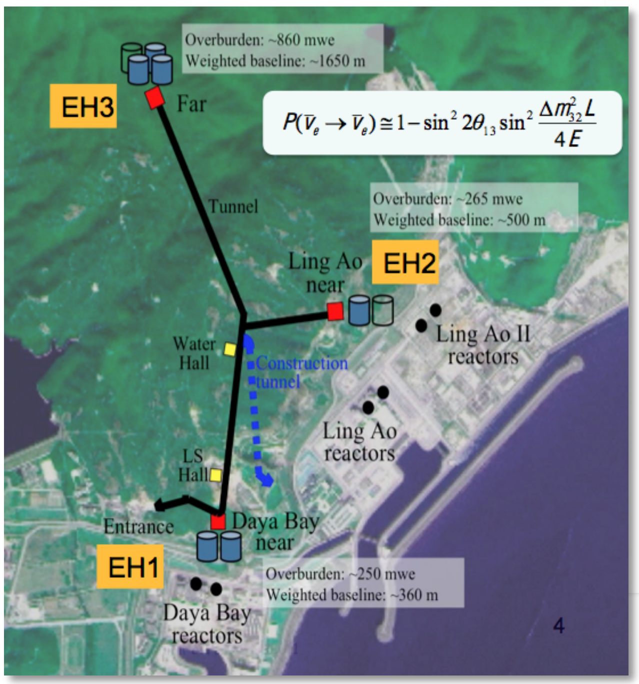


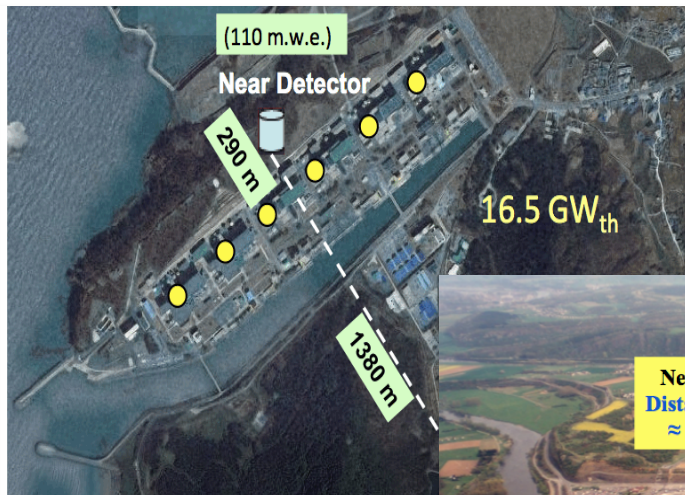
- reactor neutrinos provide important confirmation and precision measurement of ν oscillations first seen with solar neutrinos

Current Reactor Experiments

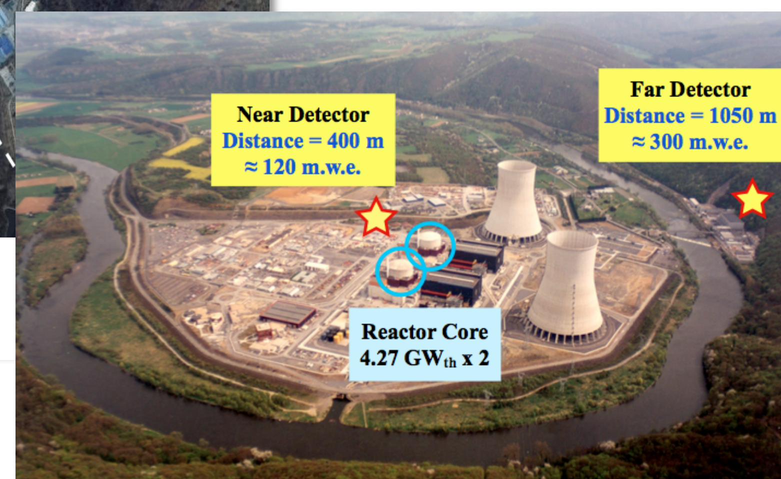
- **Daya-Bay** (China)
  - *6 reactors, 8 detectors*
  - *Sept 2011 - present*



- **RENO** (Korea)
  - *6 reactors, 2 detectors*
  - *August 2011 - present*



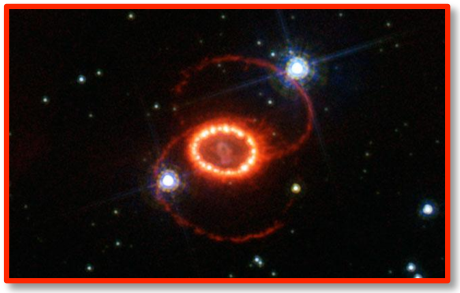
- **Double Chooz** (France)
  - *2 reactors, 1 detector (ND in 2014)*
  - *Apr 2011 - present*



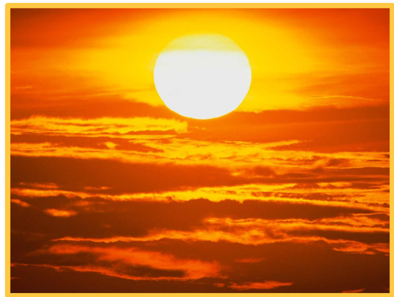
(Kazu Terao's θ_{13} talk on Thurs)

- more recently, θ_{13} measurements with reactor ν's have brought us good news (θ_{13}~9^0) and paved the way for our future ν program ($\not{C}$P, MH)

Neutrino Sources

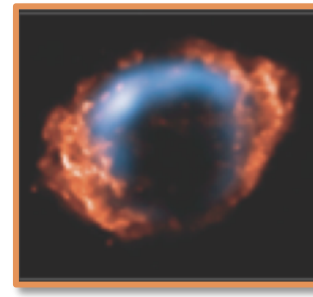


supernova neutrinos



solar neutrinos

atmospheric neutrinos



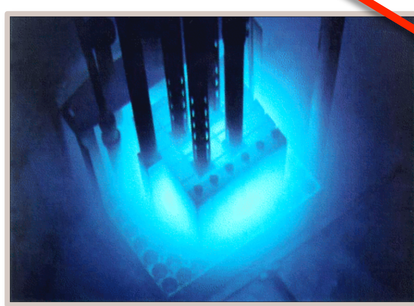
cosmic neutrinos

signal for some experiments, bkg for others

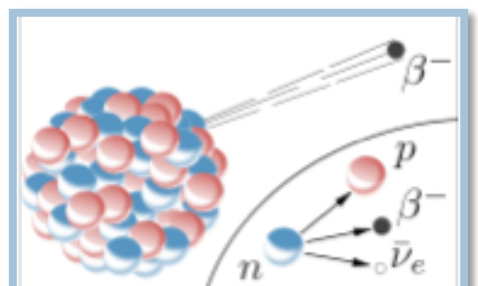
neutrinos from the heavens ("wild")

neutrinos from the earth ("tame")

accelerator neutrinos



reactor neutrinos

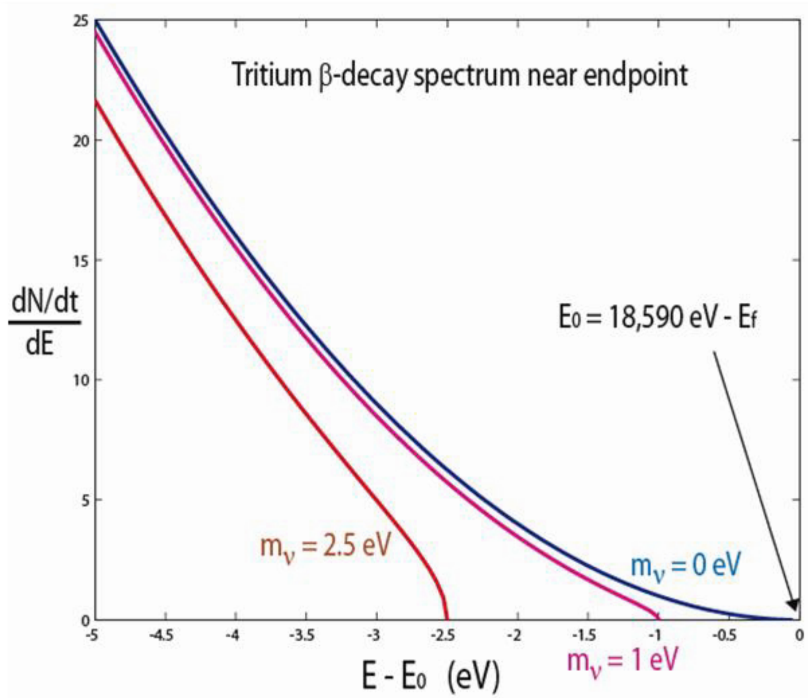


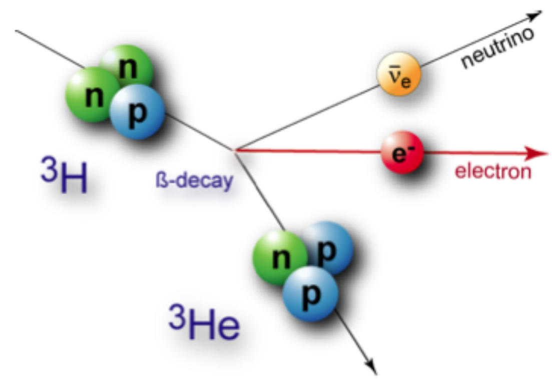
radioactive decays

geo neutrinos

Neutrinos From Radioactivity

- beta decay
- want to use these sources as a means to measure the absolute neutrino mass
- need a lot of statistics and really good energy resolution



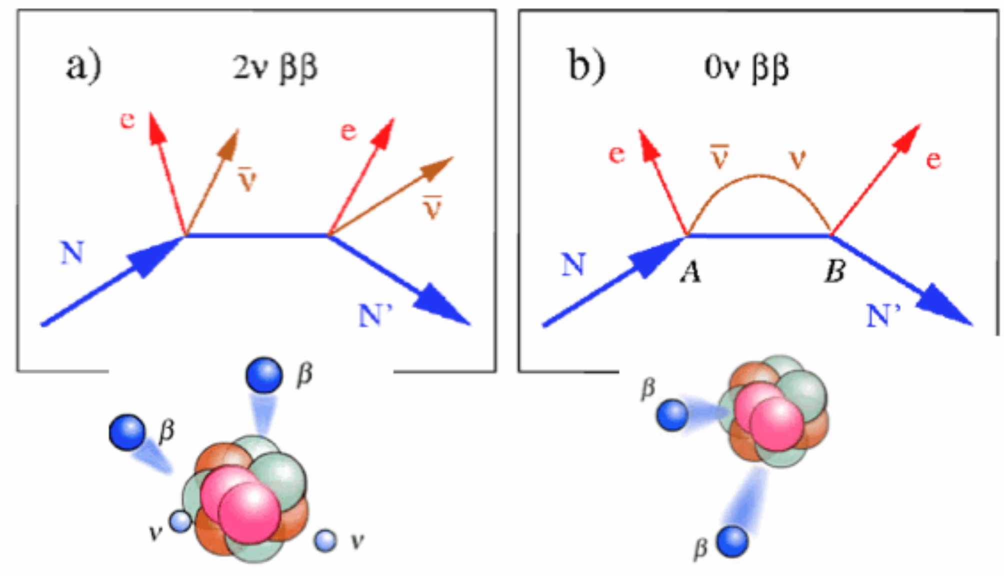


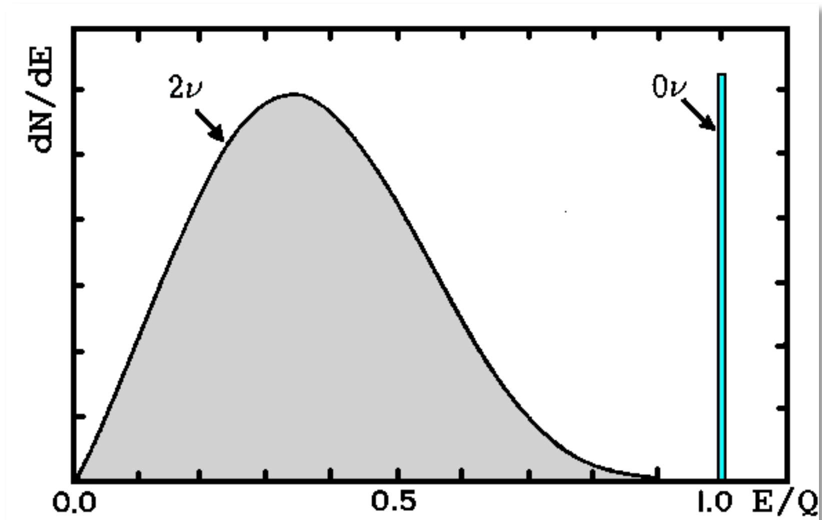
$^3H \rightarrow {}^3He + e^- + \overline{\nu}_e$

these are not table top experiments

You Can Do it Twice

- since the neutrino has no electric charge it can be it's own antiparticle ($\nu = \overline{\nu}$)
- are neutrinos Dirac or Majorana?



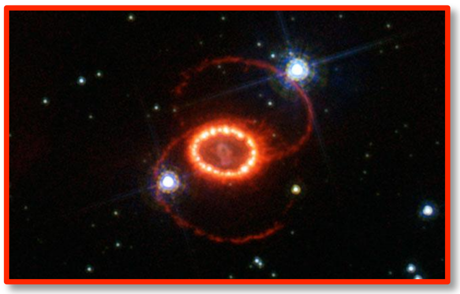


if ν's are Majorana, they may fit into leptogenesis and could yield insight into the origin of ν masses

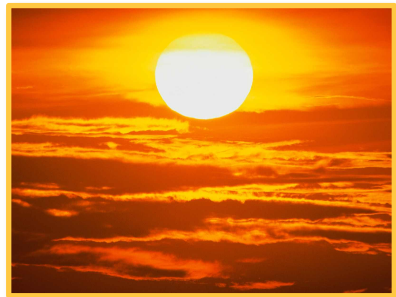
- if ν's are Majorana particles ($\nu = \overline{\nu}$) then it allows this special process ($0\nu\beta\beta$)

(Michelle Dolinski's talk tomorrow)

Neutrino Sources

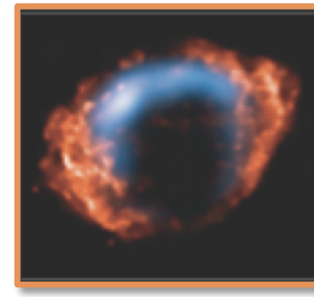


supernova neutrinos



solar neutrinos

atmospheric neutrinos



cosmic neutrinos

neutrinos from the heavens ("wild")

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neutrinos from the earth ("tame")

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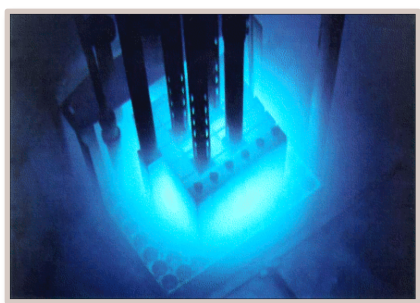
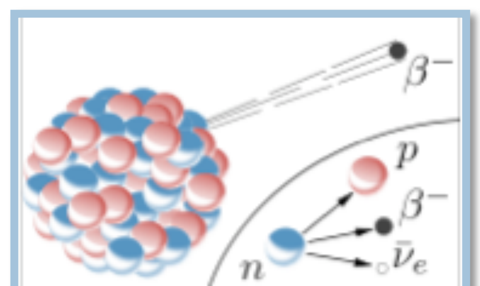
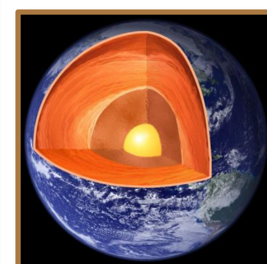


reactor neutrinos



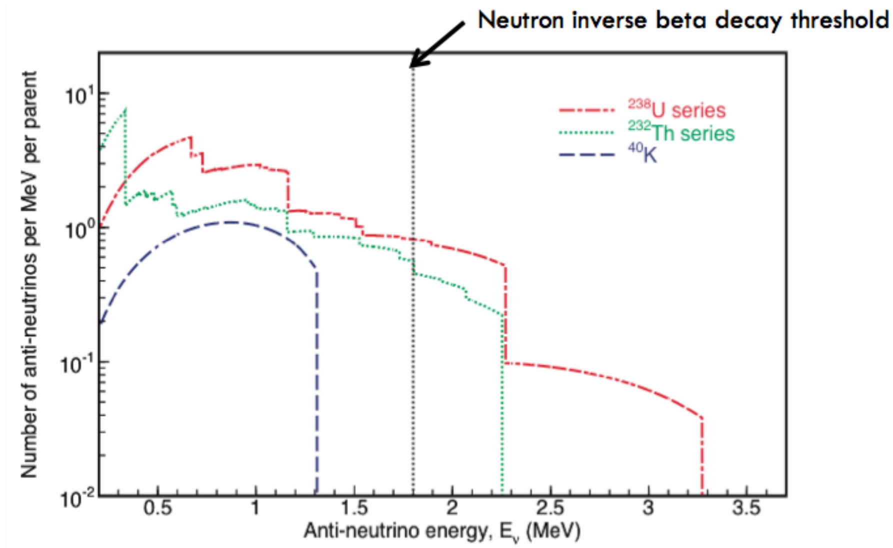
radioactive decays

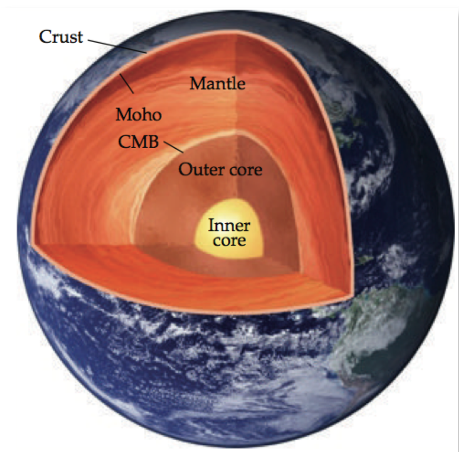


geo neutrinos

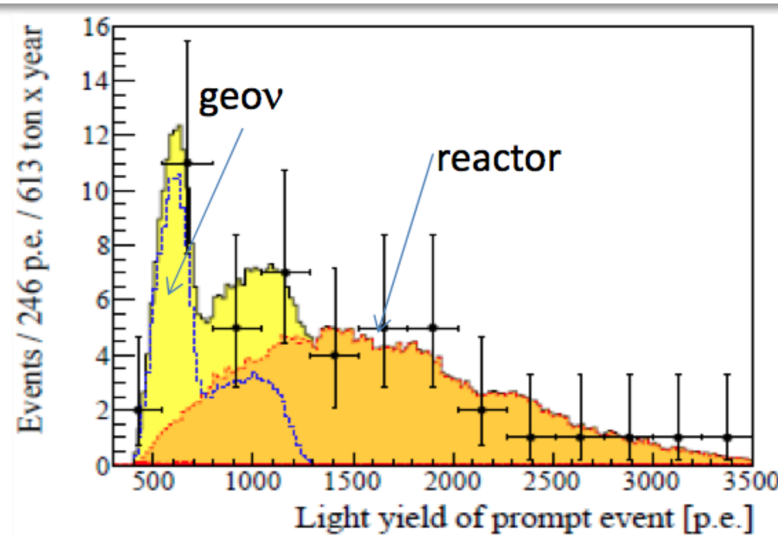
GeoNeutrinos

- radioactive decays of U and Th in the earth's crust and mantle provide a source of very low energy antineutrinos
- have been recently detected by
  - KAMLAND (arXiv:1303.4667)
  - Borexino (PLB 722, 4 (2013))





- means to measure the heat output of our planet



ν's can provide info on earth's internal radioactivity not obtainable by any other means

Conclusions

- all of these neutrino sources work together to tell us more about the world we live in

"wild" neutrinos			"tame" neutrinos
	- solar	- accelerator	
	- supernova	- reactor	
	- atmospheric	- radioactive decays	
	- cosmic	- geo-neutrinos	

- hopefully you got a sense of all these sources *(how they are produced & what we've learned from them so far)*

- mechanisms for production are not all that different *(weak force)* but their energies span an enormous range *(MeV to PeV)*

- given their abundance, unique nature, & this large dynamic range, we've learned a lot from ν's

… they hold the key to answering many profound questions

Next …

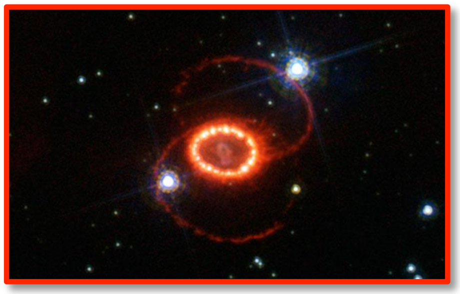
- we just covered neutrinos sources

  - how do we produce neutrinos?

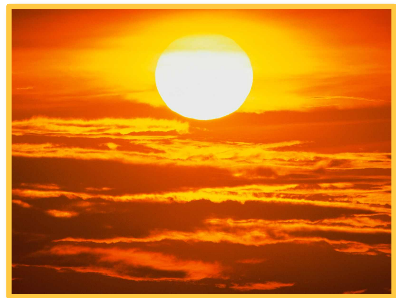
- next …

  - how do we detect neutrinos?

Neutrino Sources

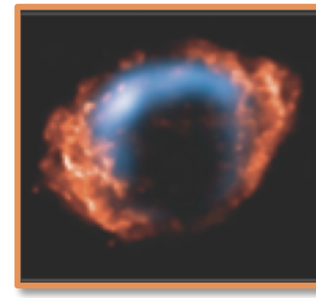


supernova neutrinos



solar neutrinos

atmospheric neutrinos



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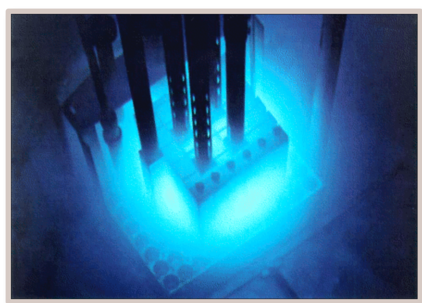
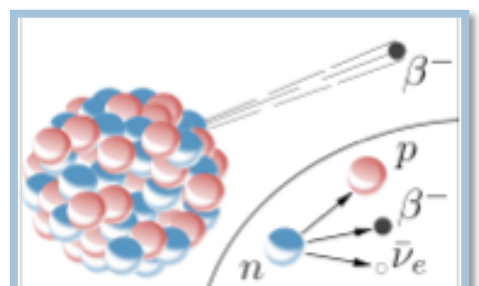


reactor neutrinos



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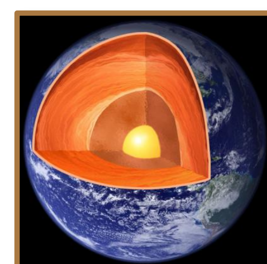

geo neutrinos