Neutrinos from the Heavens & the Earth

Neutrinos from the Heavens & the Earth

J.A. Formaggio

MIT

NNPSS 2011

What we will cover:

Where do neutrinos come from?

Neutrinos from the Heavens

Neutrinos from the Earth

Neutrinos from Man

What we will cover:

Where do neutrinos come from?

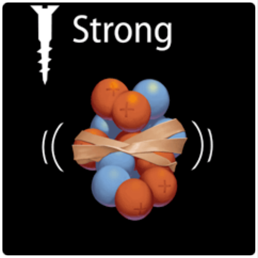
Neutrinos from the Heavens

Neutrinos from the Earth

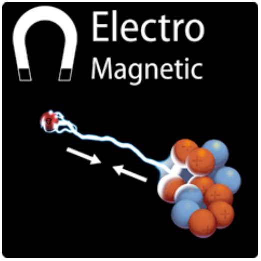
Neutrinos from Man

Where do neutrinos
come from...?

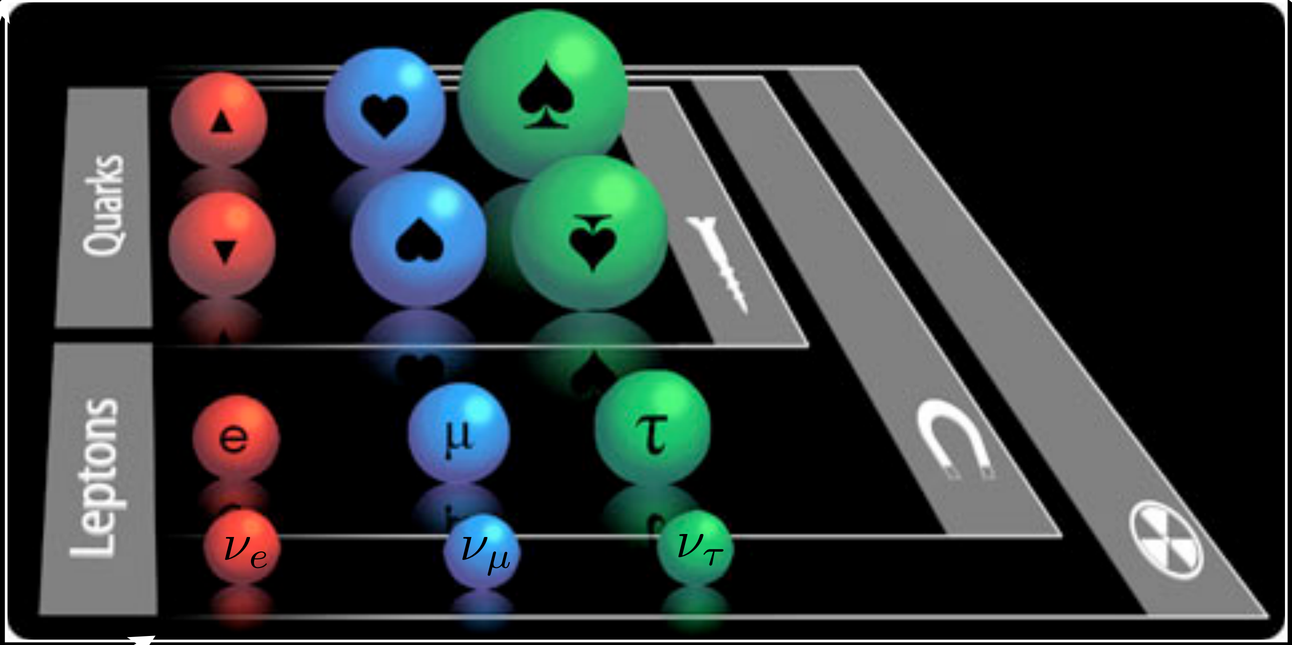
Within the Framework



Binds nucleii;
mediated by gluons;
only couples to quarks



Couples to charge;
mediated by photons;
felt by quarks and leptons



Spin 1

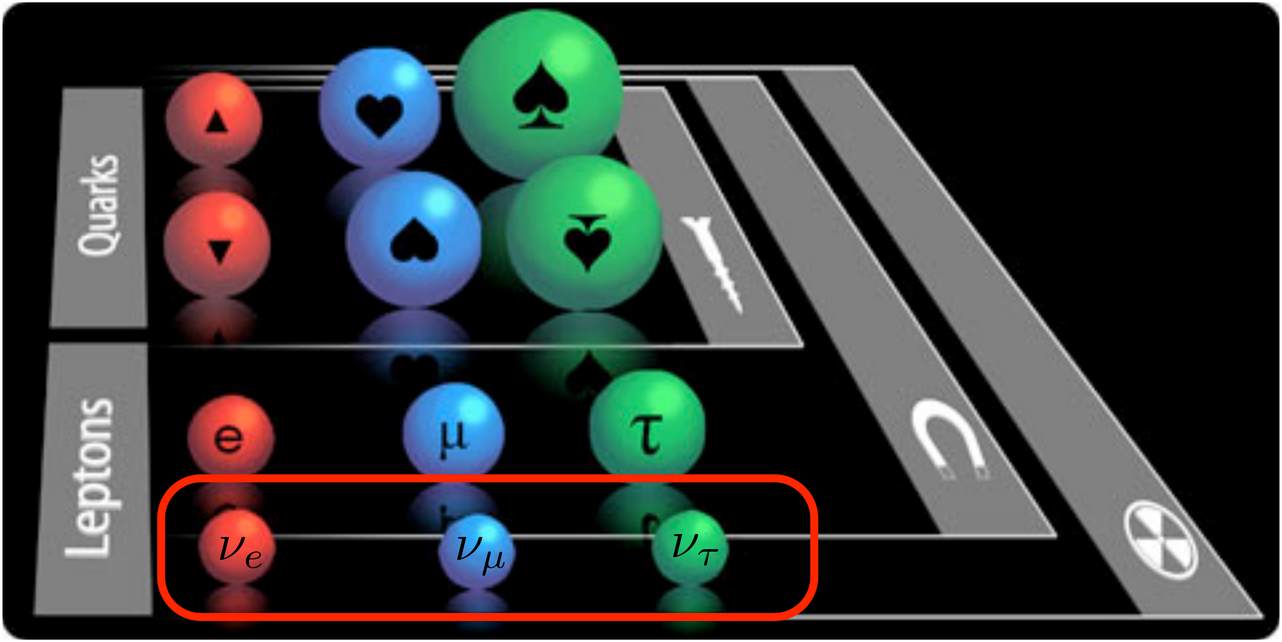
Spin 1/2

Common to all particles;
mediated by the $W^{\pm}/Z^0$ bosons.

Limited Interactions

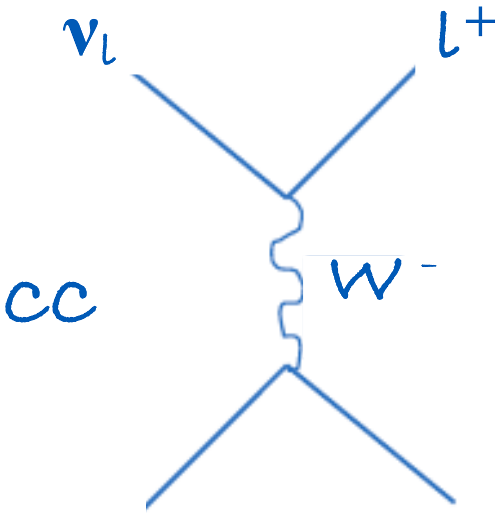
Unlike all the other particles, neutrinos can only interact via with the weak force.

The number of interactions, therefore, is quite limited.

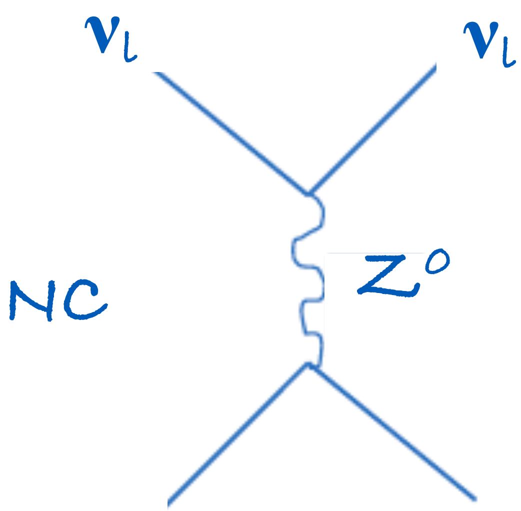


Common to all particles; mediated by the $W^{\pm}/Z^0$ bosons.

Two Basic Interactions



Charged Current



Neutral Current

Most interactions are limited to two basic type of interactions:

A charge $W^{\pm}$ is exchanged: Charged Current Exchange

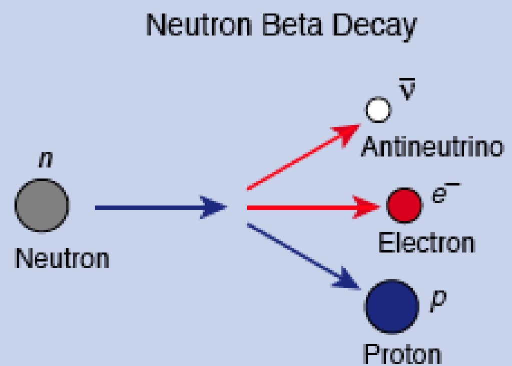
A neutral Z^0 is exchanged: Neutral Current Exchange

All neutrino reactions involve some version of these two exchanges.

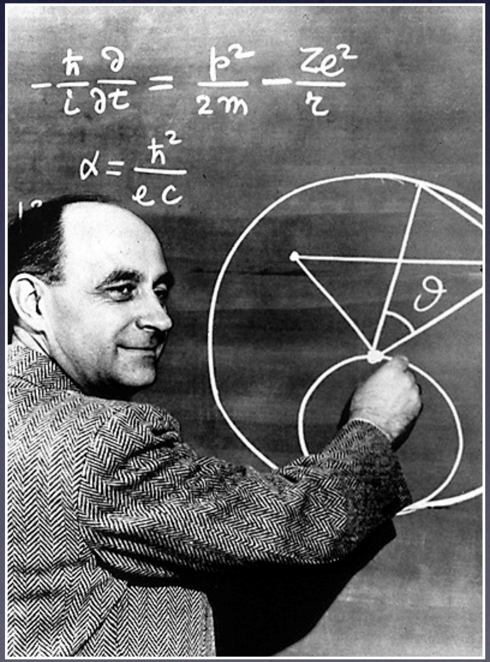
How Neutrinos Interact

- If we are to consider sources of neutrinos, it is important to review how neutrinos interact with the other particles in the Standard Model.

- Consider the first model of the weak interaction, as proposed by Fermi:


Neutron Beta Decay

$$\mathcal{H} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu\nu][\bar{\Phi}_n\gamma^\mu\Phi_p]$$



E. Fermi

- Here, the theory describes a 4-point interaction (current-current model).

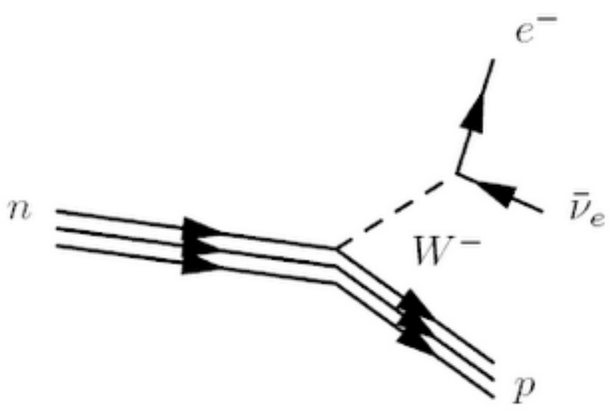
- The system does not have many of the features of the Standard Model, yet still remarkably descriptive.

The strength of the interaction is governed by the fermi constant, G_F

Present-Day Models

- In the Standard Model, the theory is not just a vector theory (like electromagnetism), but has both vector and axial vector components.

- The SM does not treat left-handed and right-handed particles the same!



$$\mathcal{H} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e][\bar{\Phi}_n\gamma^\mu(V - A\gamma_5)\Phi_p]$$

Note the presence of both vector (V) and axial vector (A) terms.

Sheldon Glashow, Abdus Salam, and Steven Weinberg sharing the Nobel Prize, 1979

The strength of the interaction is *still* governed by the fermi constant, *G_F*

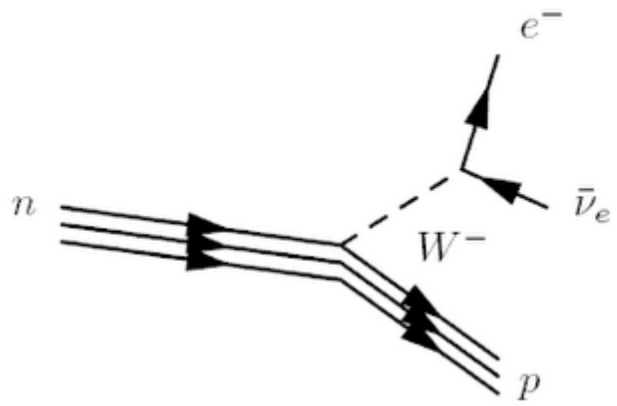
A Misnomer

- Consider now the propagator, which is a heavy gauge boson.

- For (massive) gauge bosons, the propagator is dominated by the mass of the exchange particle...

$$\frac{g_W^2}{q^2 - M_W^2}$$

- Even if g_W is the same order as the electromagnetic coupling, the mass of the W-boson makes it extremely small.

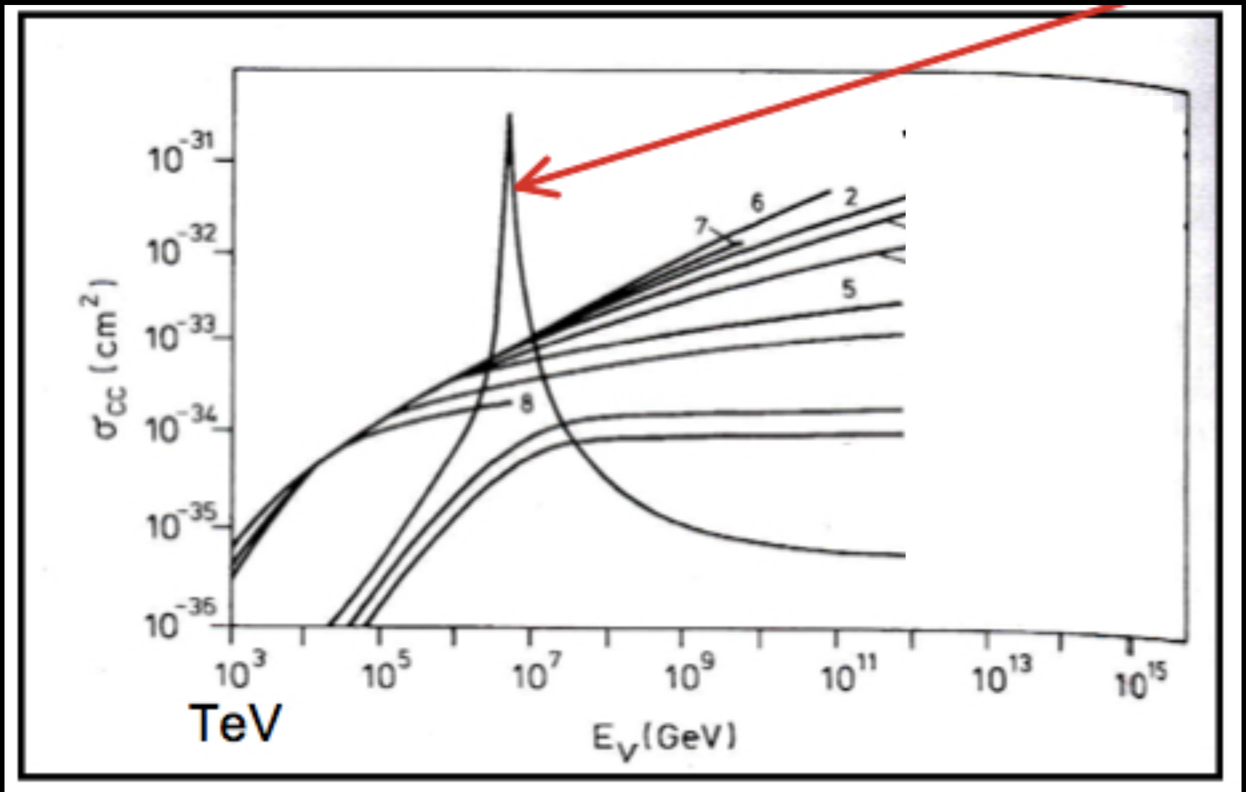


$$\mathcal{H} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e][\bar{\Phi}_n\gamma^\mu(V - A\gamma_5)\Phi_p]$$

G_F is a small number...

$$G_F = \frac{\sqrt{2}}{8}\frac{g_W^2}{M_W^2} = 1.166 \times 10^{-5}\mathrm{GeV}^{-2}$$

Question #1 for the Reader



The plot on the left is a list of cross-sections for neutrinos with ordinary matter.

(a) What reaction does the red arrow point to? Why is it so different?

(b) Why do all the cross-sections 7,6,2,5,8 have a “kink” at energies around 10^4 GeV?

What Neutrinos do I Expect?

- The neutrinos that I would expect from a known source depends almost entirely on the energy (and type of matter) that is available for the reaction.

- If lepton flavor is conserved, then even the type of neutrino can be determined. However, neutrino oscillations clearly spoils this rule.

$E_\nu >> \text{TeV}$


"...the ancient of days"
W. Blake

What we will cover:

- Where do neutrinos come from?
- Neutrinos from the Heavens
- Neutrinos from the Earth
- Neutrinos from Man

$E_\nu \sim 0.17$ meV

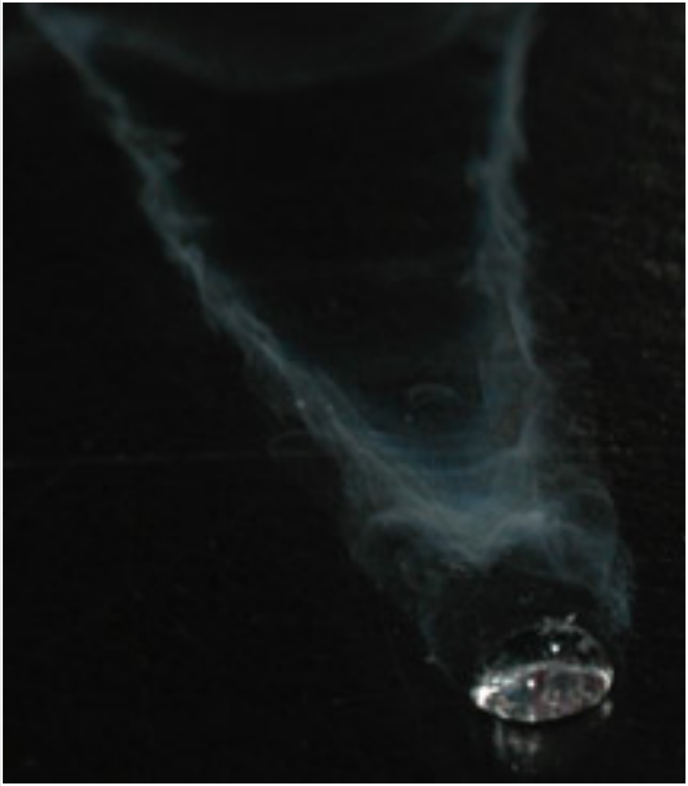
Neutrinos from the Cosmos

- Our understanding of the chronology of the cosmos is directly tied to knowing the existence of neutrinos and the role they play in the standard model.

- Cosmology allows us to interpolate events ranging from ~ 1 second after the universe was born to today.

Neutrino Decoupling

- Inference about the existence of the relic neutrino background comes from knowledge of the primordial *photon* background.
- As the universe expands (cools), neutrinos transition from a state where they are in thermal equilibrium with electrons, to one where they are decoupled from them.
- Standard model yields predictions for this decoupling temperature.



Neutrino decoupling occurs when two rates are equal.

$$T_D(\nu_e) \simeq 2.4 \text{ MeV}$$
$$T_D(\nu_{\mu,\tau}) \simeq 3.7 \text{ MeV}$$

$$\Gamma = < \sigma \; n \; v > \simeq \frac{16 G_F^2}{\pi^3} \left(g_L^2 + g_R^2\right) T^5$$

Annihilation Rate

$$H(t) = 1.66 g_*^{1/2} \frac{T^2}{m_{\text{Planck}}}$$

Expansion Rate

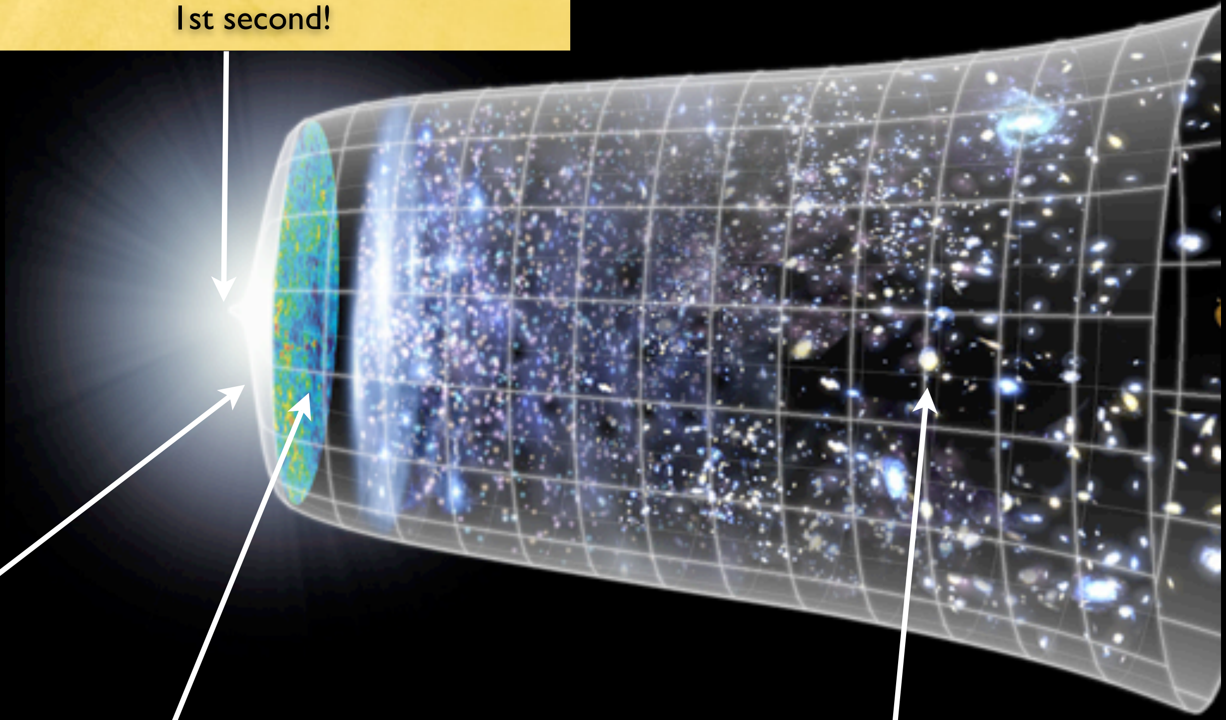
Neutrinos Today

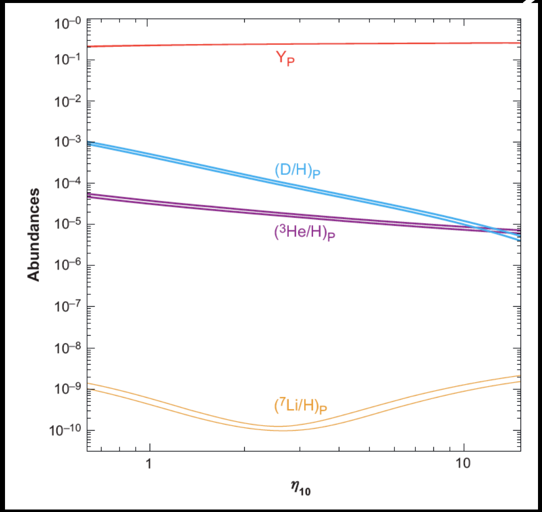
- The presence of neutrinos have a vast impact on our understanding of the universe's chronology.

- Precision cosmology can now look at the consistency of the theory across different epochs. Neutrinos play a role across each of these phases.

Relic Neutrinos

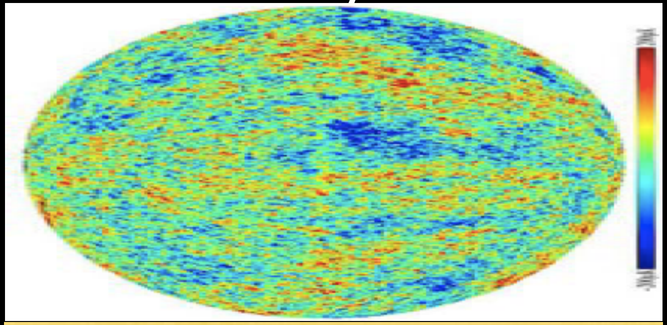
1st second!





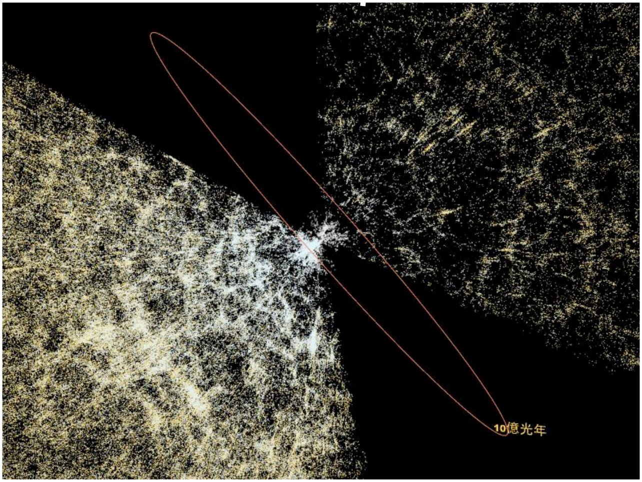
Primordial Nucleosynthesis

1st few minutes



Cosmic Microwave Background

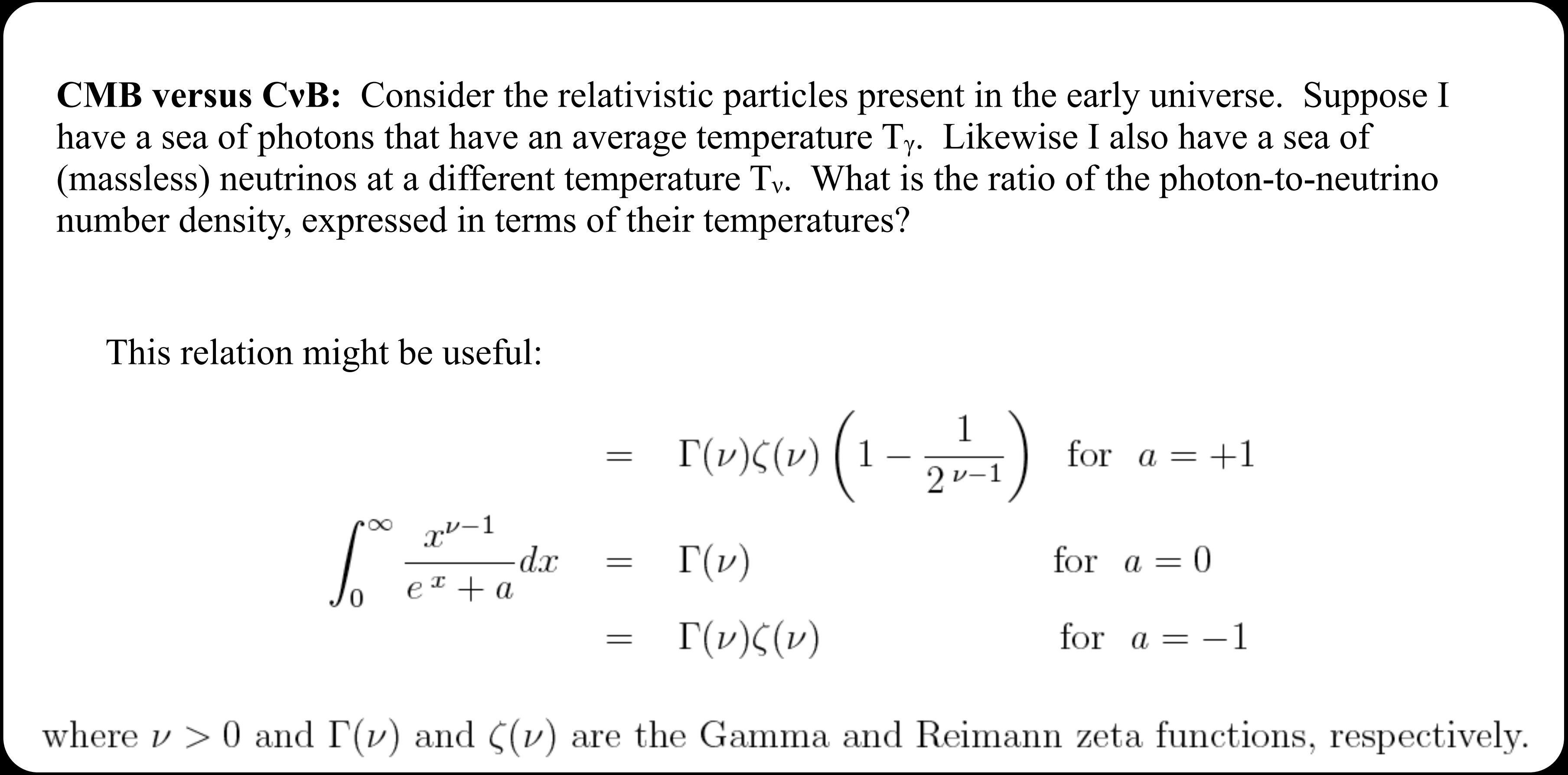
400 kyrs



Large Scale Structures

Near Today

Question # 2 for the Reader



CMB versus CνB: Consider the relativistic particles present in the early universe. Suppose I have a sea of photons that have an average temperature T_γ. Likewise I also have a sea of (massless) neutrinos at a different temperature T_ν. What is the ratio of the photon-to-neutrino number density, expressed in terms of their temperatures?

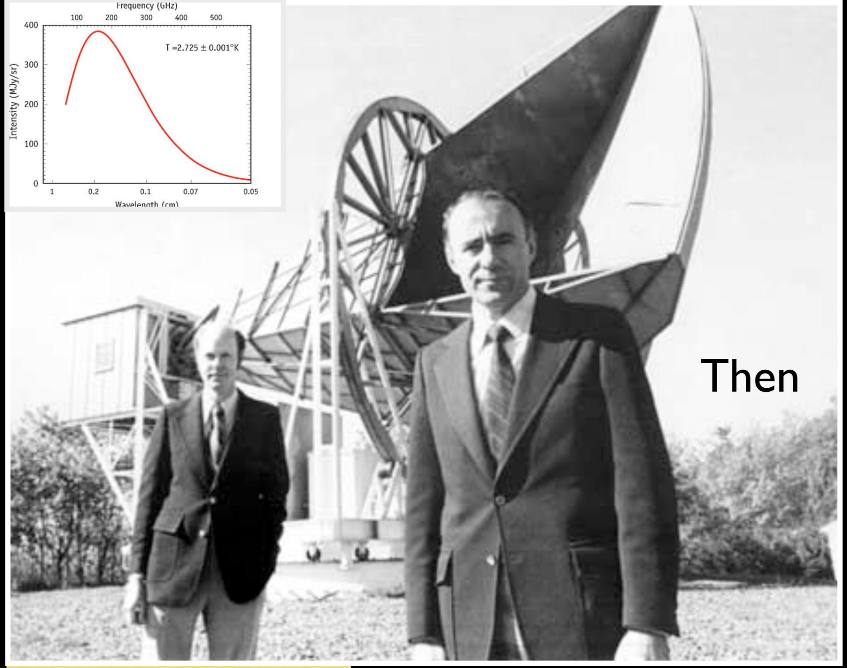
This relation might be useful:

$$\int_0^\infty \frac{x^{\nu-1}}{e^{\,x}+a}dx \quad \begin{aligned} &= \Gamma(\nu)\zeta(\nu)\left(1-\frac{1}{2^{\,\nu-1}}\right) && \text{for } a=+1 \\ &= \Gamma(\nu) && \text{for } a=0 \\ &= \Gamma(\nu)\zeta(\nu) && \text{for } a=-1 \end{aligned}$$

where $\nu > 0$ and $\Gamma(\nu)$ and $\zeta(\nu)$ are the Gamma and Reimann zeta functions, respectively.

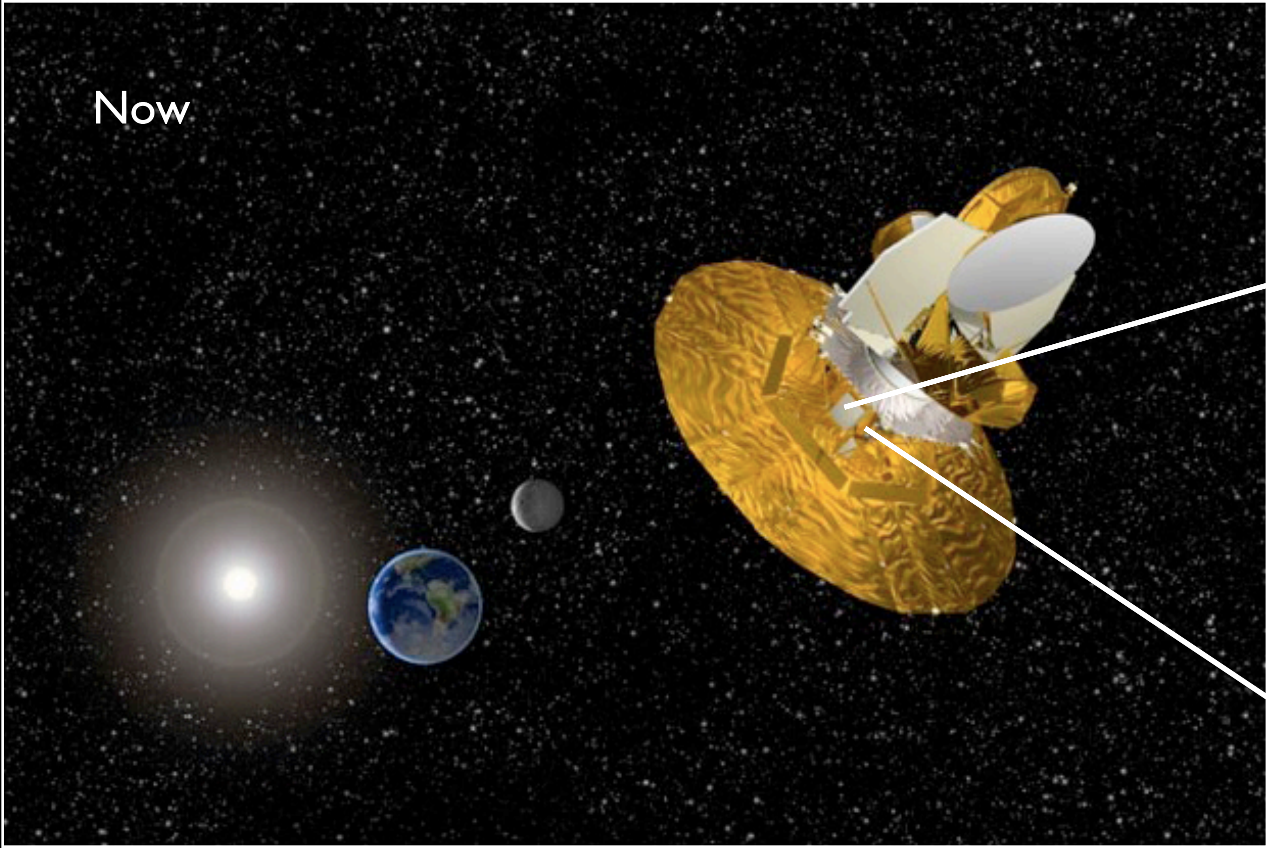
Precision Cosmology

- Mapping the cosmic microwave background has reach unprecedented precision and, along with that, great predictive power.



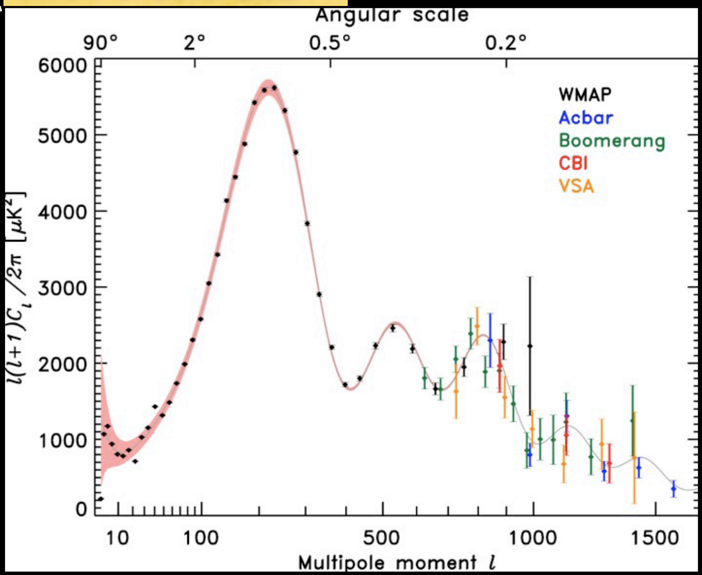
Then

Wilson and Penzias



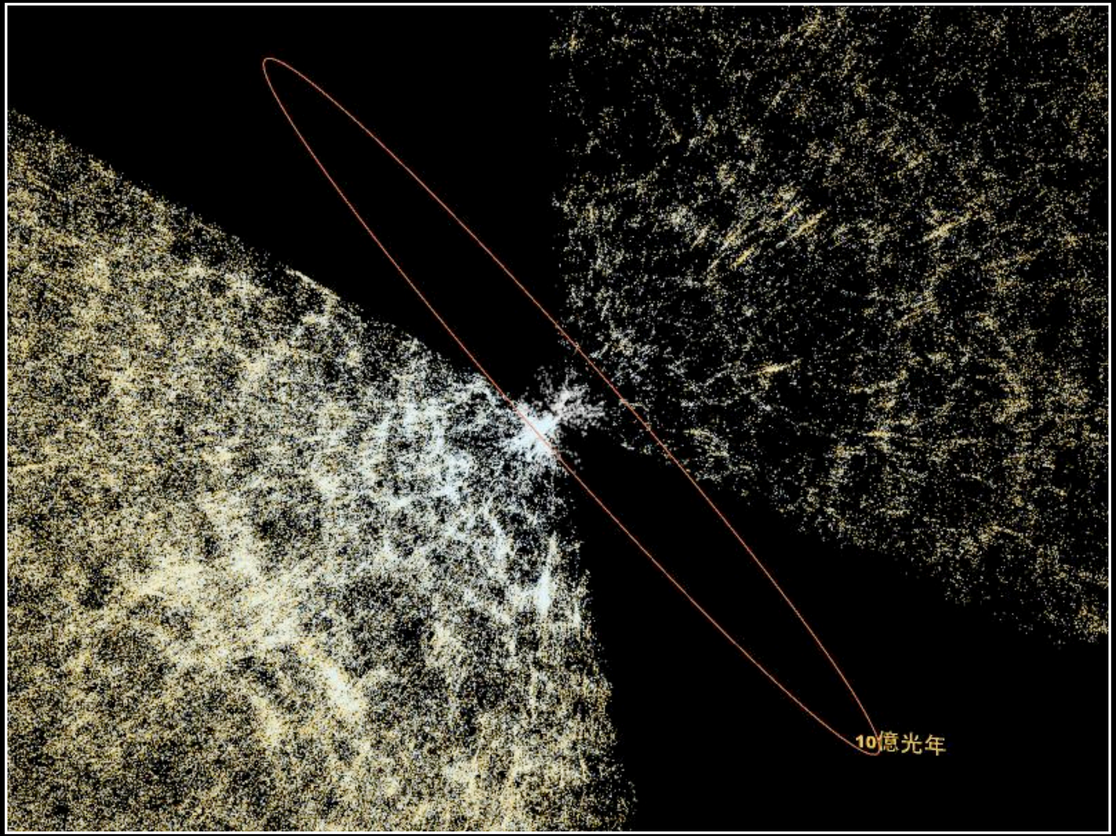
Now

WMAP & Other Data

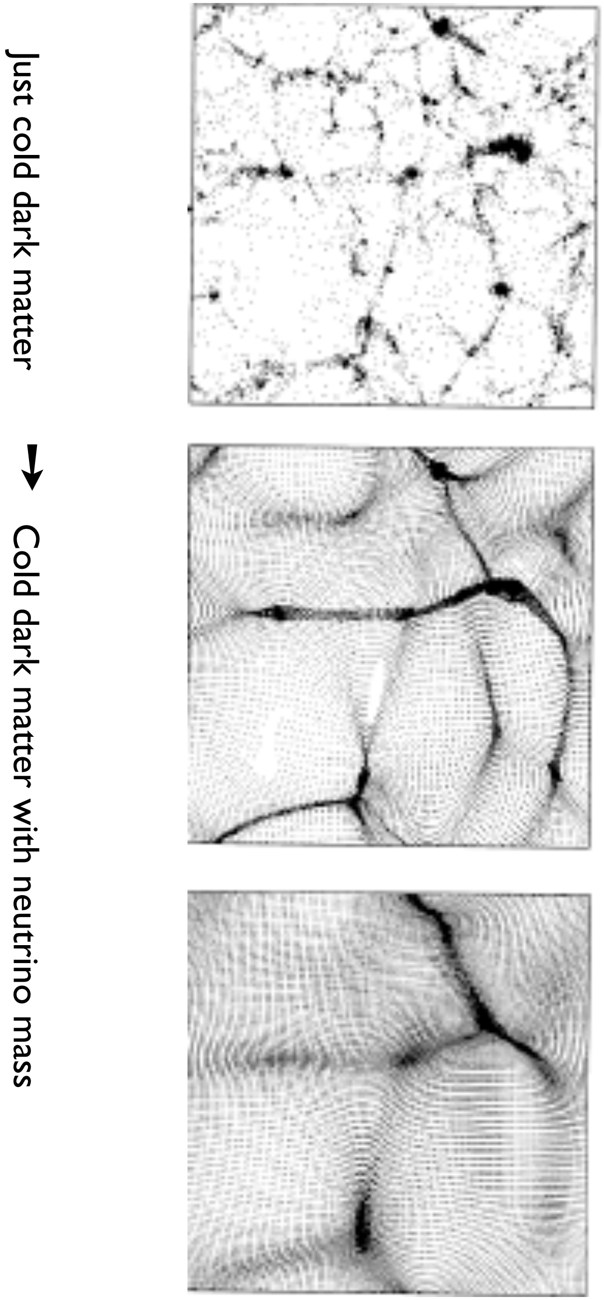


Neutrino Masses from Cosmology

- Cosmology looks at the *sum* of neutrino masses (their gravitational effect)



Large Scale Sctructure



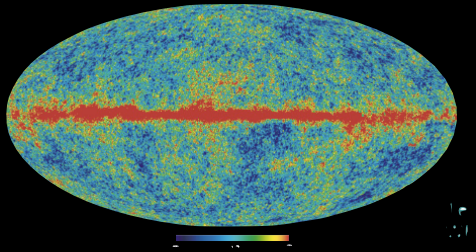
Colombi, Dodelson, & Widrow 1995

$$\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \frac{\sum_i^{n_\nu} m_{\nu,i}}{\rho_{\text{critical}}}$$

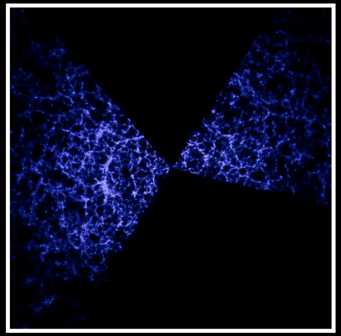
The Strategy

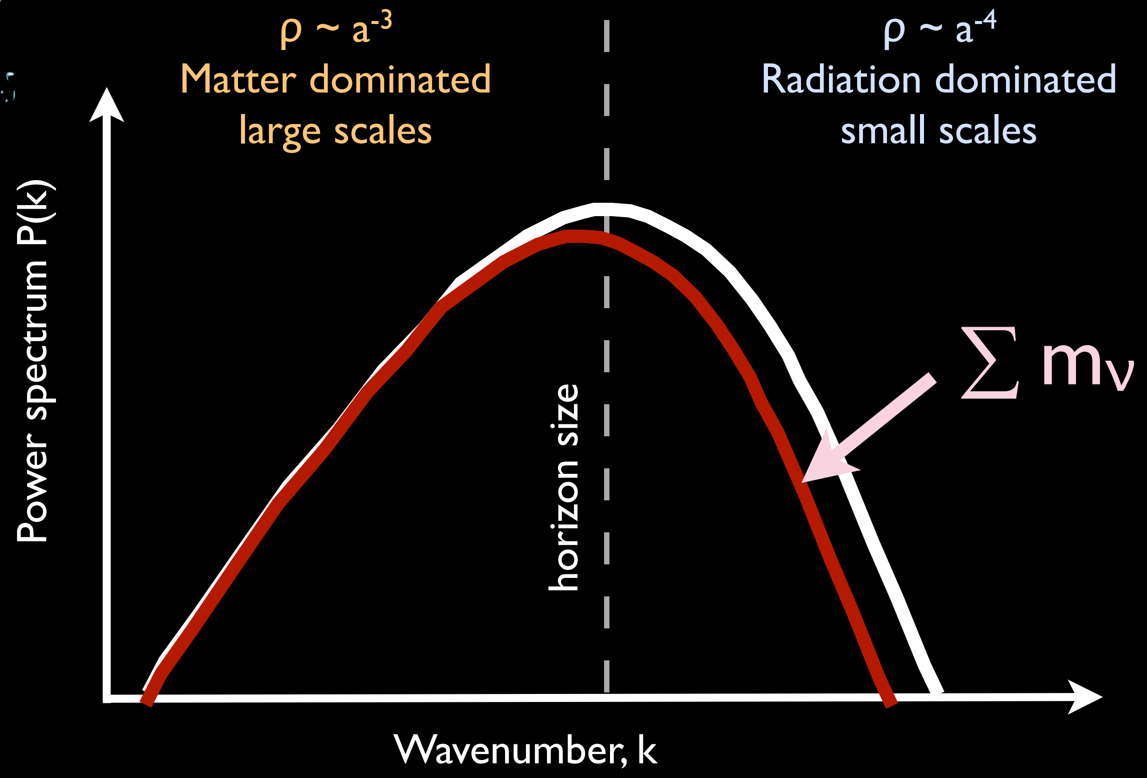
(a naive view)

WMAP Temperature Map

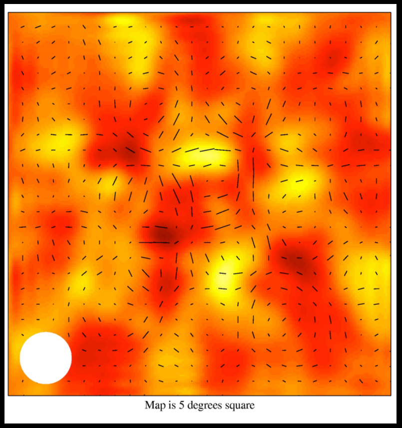


Galaxy Surveys

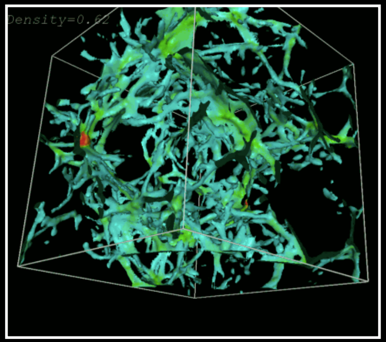




Weak lensing



CMB Polarization



Lyman α

$$\delta(x) = (\rho(x) - \bar{\rho})/\bar{\rho}$$

Neutrinos come to affect the power spectrum,

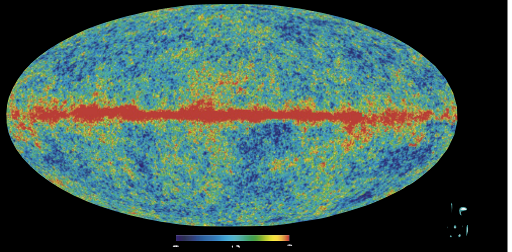
particularly at small distance scales

$$P(k) = \langle |\delta(k)|^2 \rangle$$

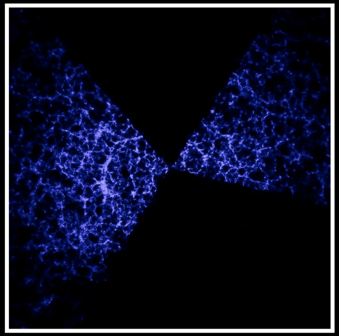
The Strategy

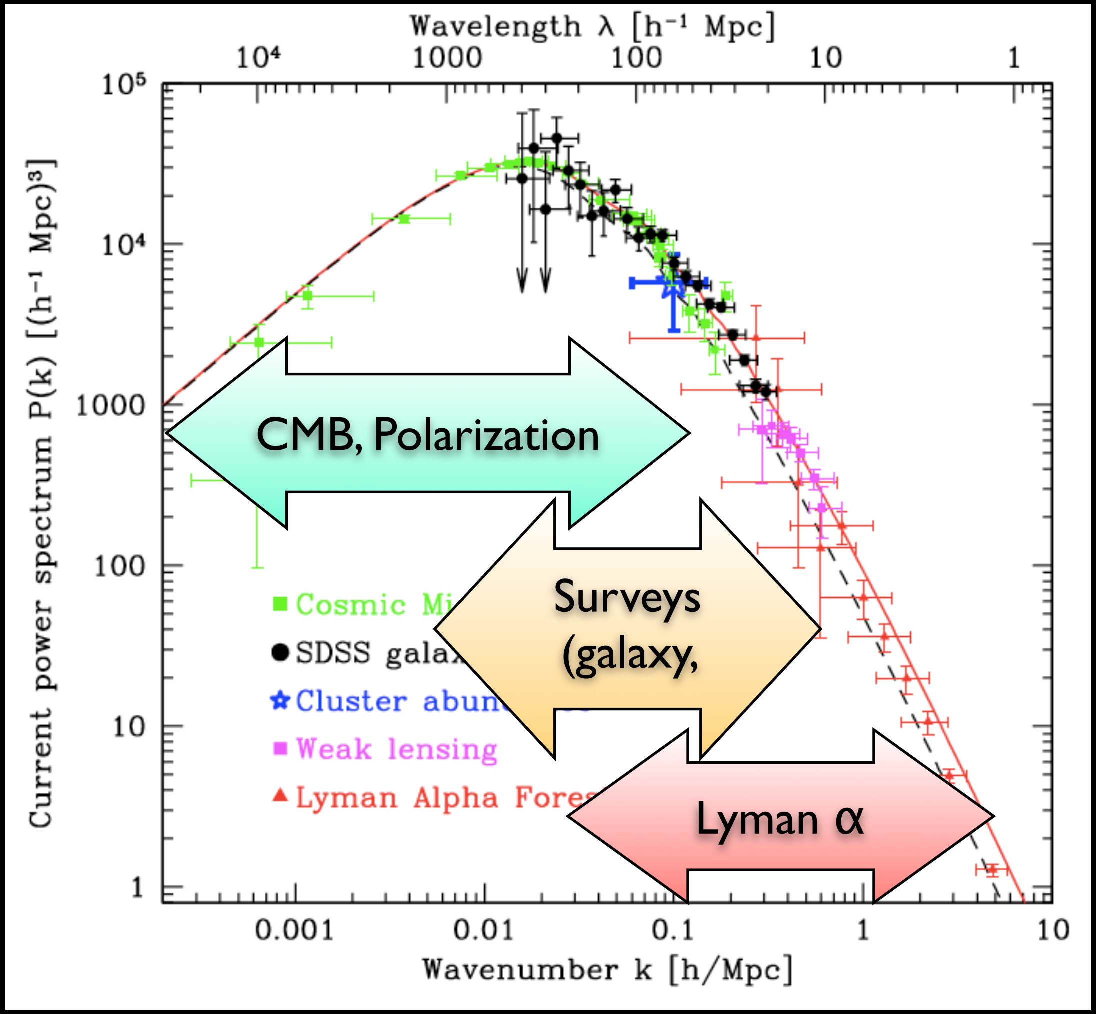
(a naive view)

WMAP Temperature Map



Galaxy Surveys



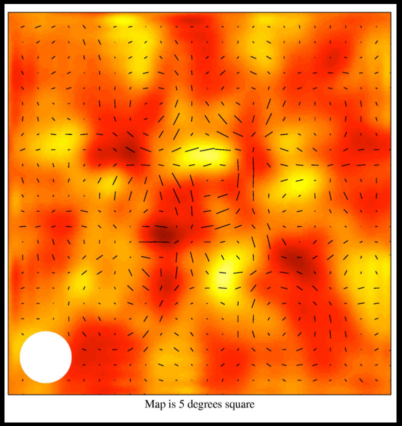


CMB, Polarization

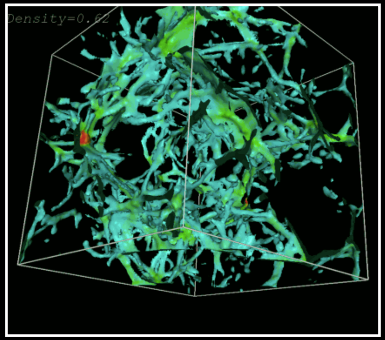
Surveys (galaxy,

Lyman α

Weak lensing



CMB Polarization



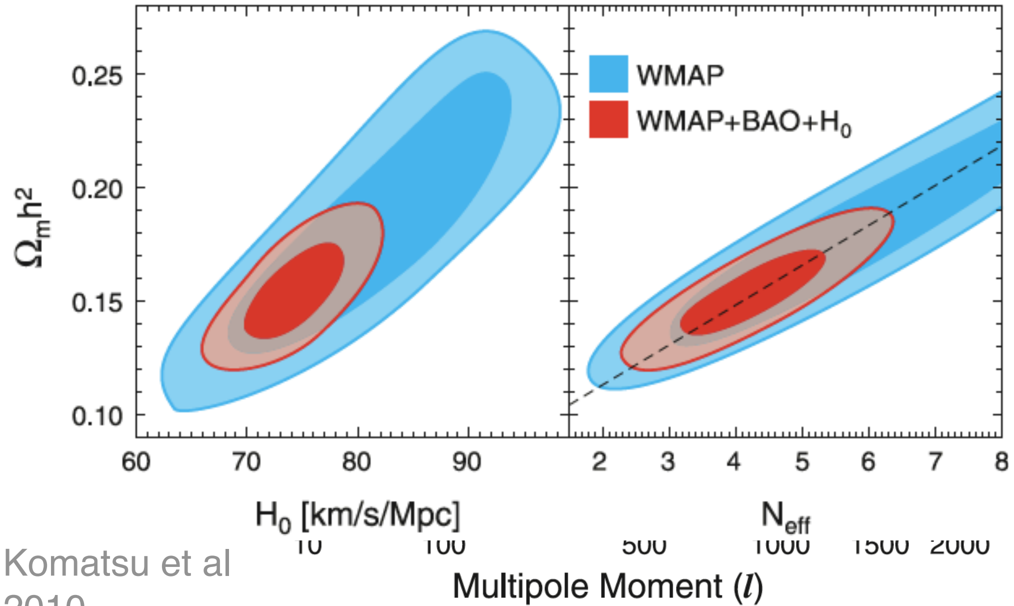
Lyman α

Max Tegmark, 2005

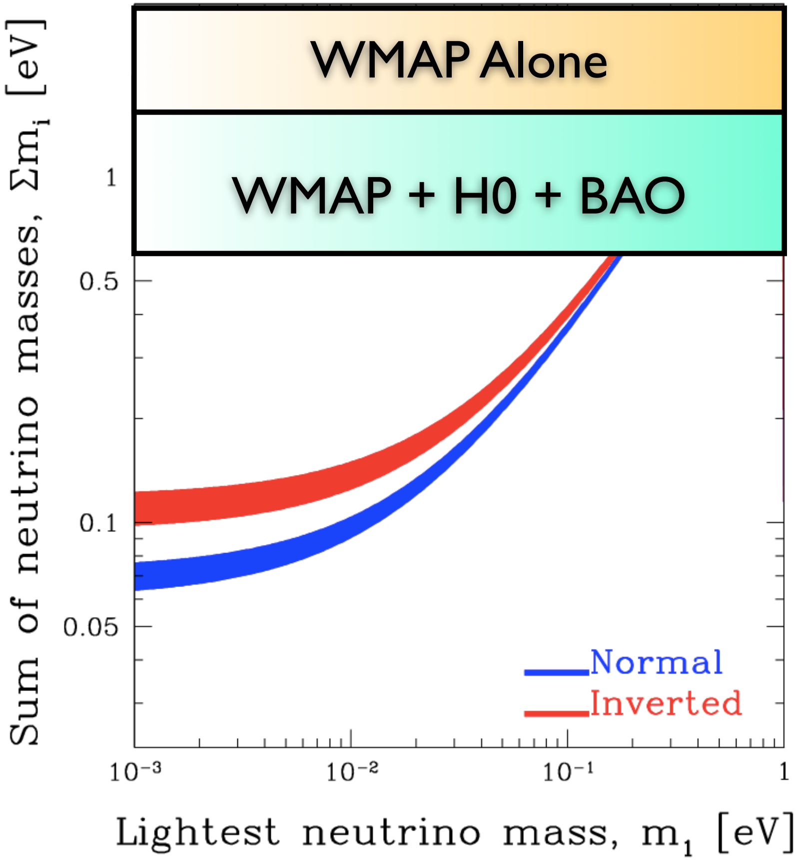
Current Limits

- Limits for neutrino masses depend in part on:
  - Which data is used, and...
  - ...what assumptions are made.

Set	$w = -1$	$w \neq -1$
WMAP 7 only	$\Sigma m_\nu < 1.3$ eV	$\Sigma m_\nu < 1.4$ eV
WMAP7 + BAO + H0	$\Sigma m_\nu < 0.58$ eV	$\Sigma m_\nu < 1.3$ eV
WMAP7 + BAO + SN	$\Sigma m_\nu < 0.7$ eV	$\Sigma m_\nu < 0.9$ eV



Komatsu et al 2010



Gonzales-Garcia

arXiv: 1006.3795v2

(and many others)

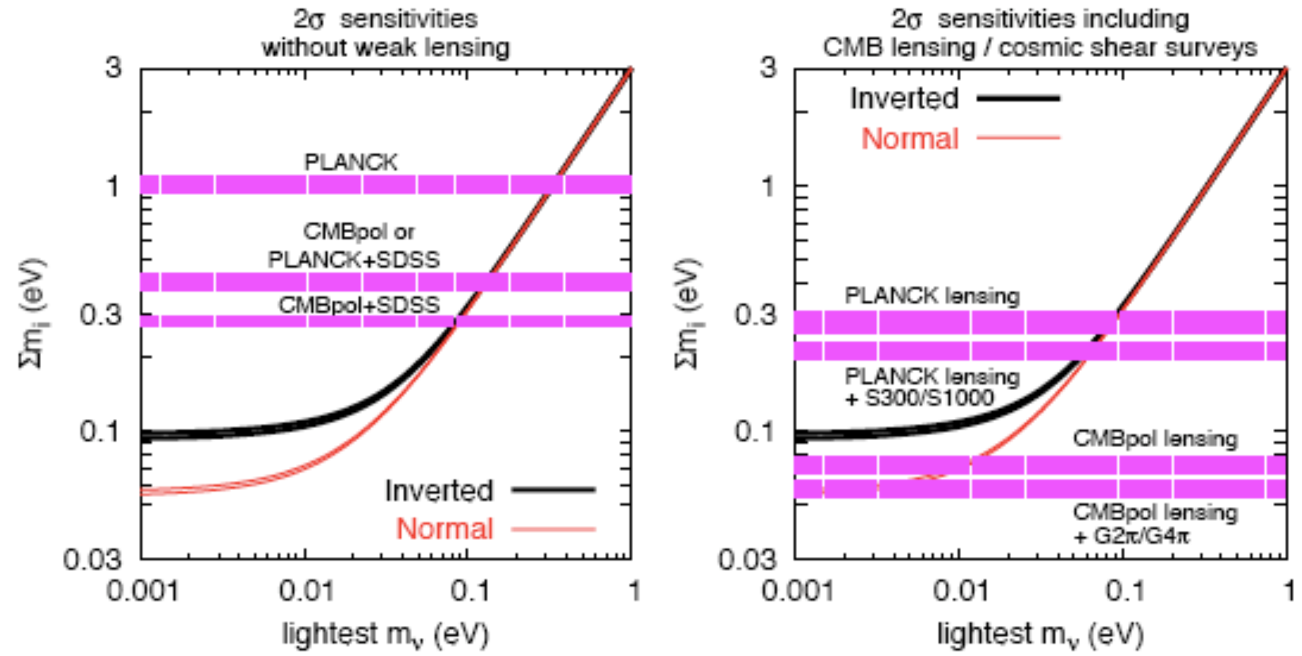
New Frontiers

©2009 ESA-CNES-ARIANESPACE / Optique Vidéo du CSG - P BAUDON

Planck Satellite:

Launched May 14th, 2009

Upcoming Data



- Planck alone can push neutrino limits down 1 eV.
- Host of new experiments coming to the forefront.

Probe	Current	Mission	Reach
CMB	1.3 eV	CMBPol	0.6 eV
CMB Lensing	None	CMBPol	0.05 eV
Galaxy Distribution	0.6 eV	LSST	0.1 eV
21 cm	None	SKA	0.05 eV

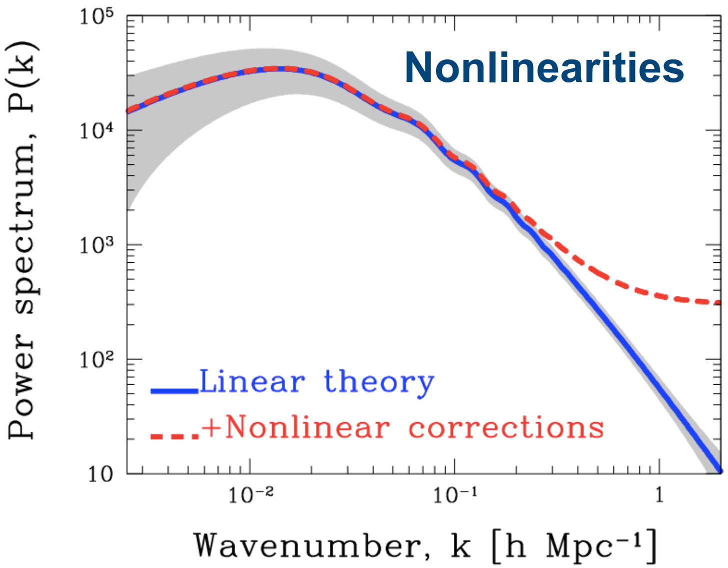
Moving Forward...

Moving to the normal hierarchy scale now requires 1% precision on the power spectrum.

$$\frac{\Delta P}{P} \simeq -12\frac{\Omega_\nu}{\Omega_m} \simeq 1\%$$

Systematic Effects

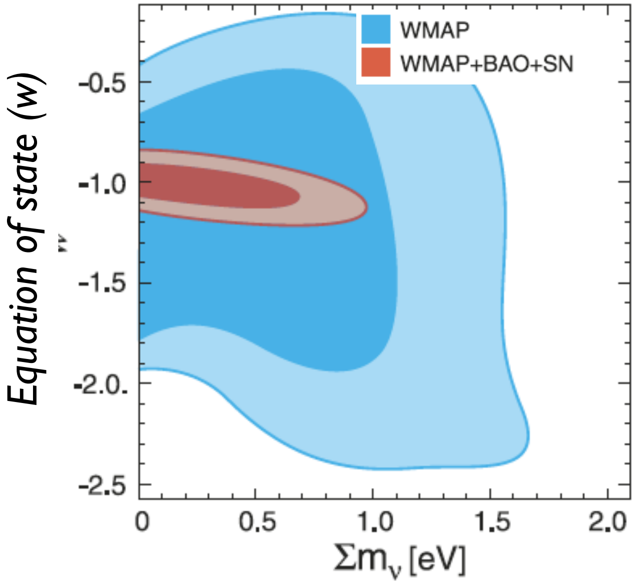
- As precision demands moves to 1%, non-linear effects, degeneracies, baryons, etc. all begin to play a role.
- Numerical simulations and semi-analytical techniques used to address.



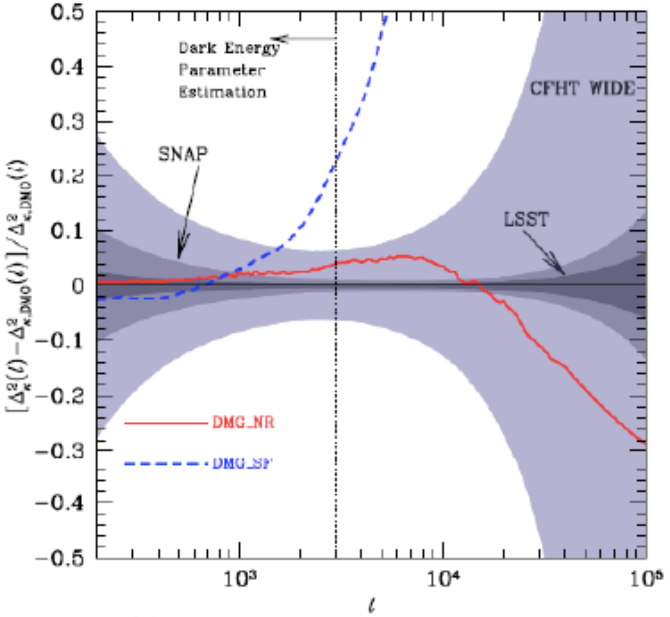
Y. Y. Y. Wong, 2010

Degeneracies

S. Hannestad
Phys. Rev. Lett 95 221301



Baryon Effects



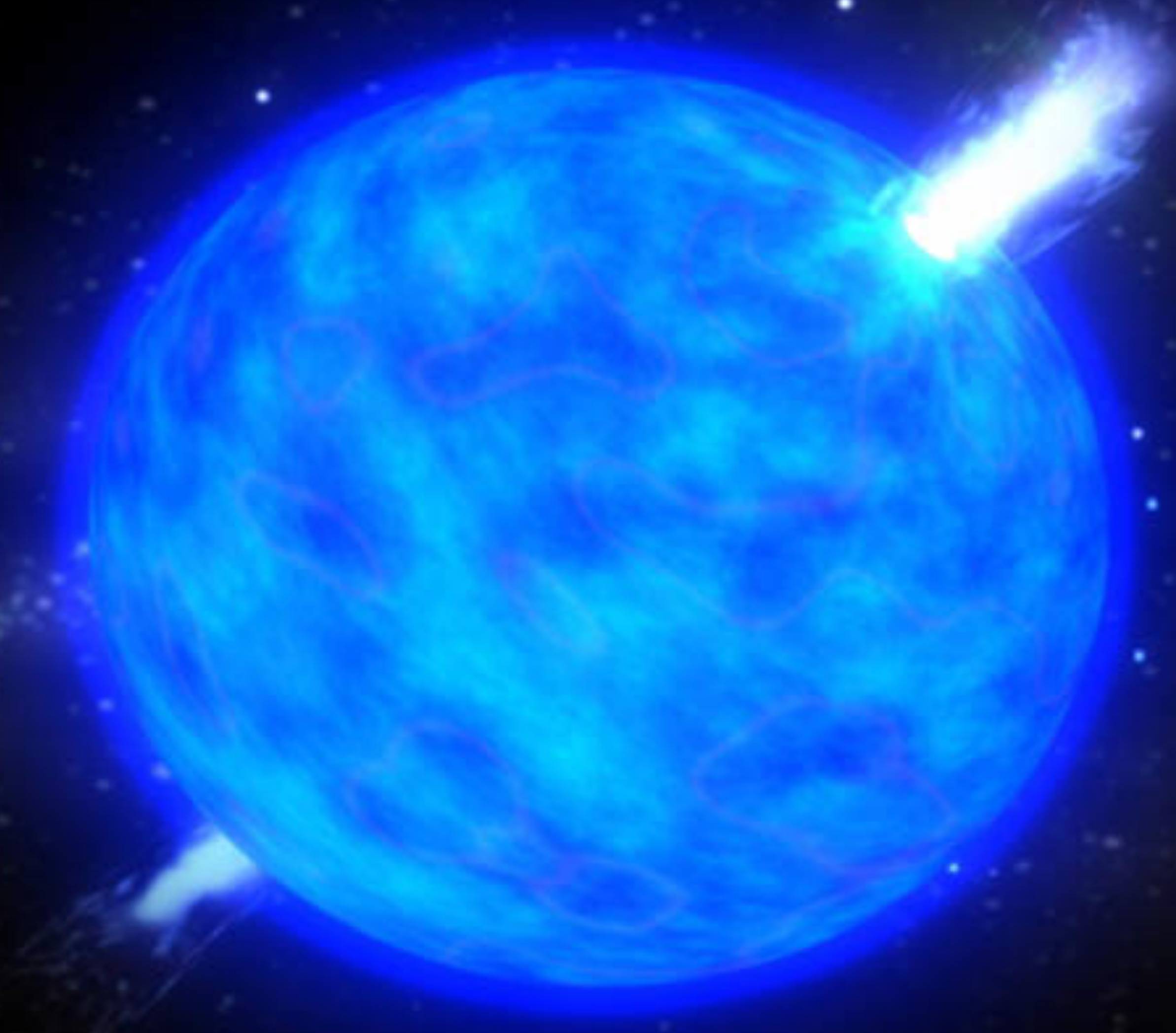
Rudd, Zentner & Kravtsov, 2007

$E_\nu \sim 10\text{-}20$ MeV

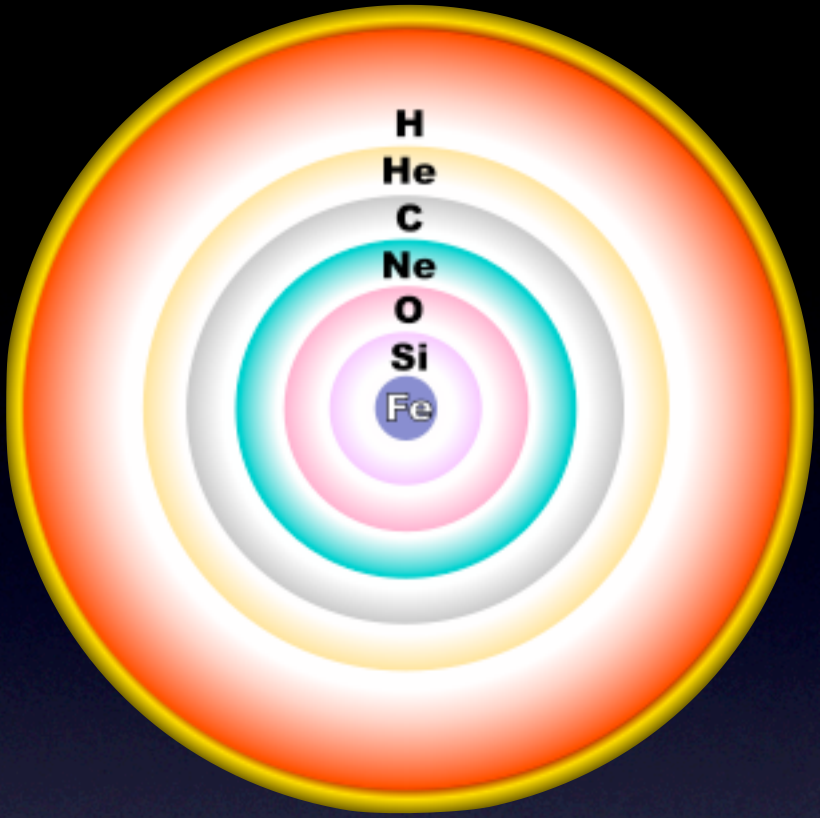
Neutrinos from the Stars

- Stellar deaths are also powerful sources of neutrinos, as nearly all of the gravitational energy from the collapse is radiated away by neutrinos.

- Can be observed via sudden bursts of neutrino flux, with times characteristic of the stellar collapse.



Neutrinos from the Stars



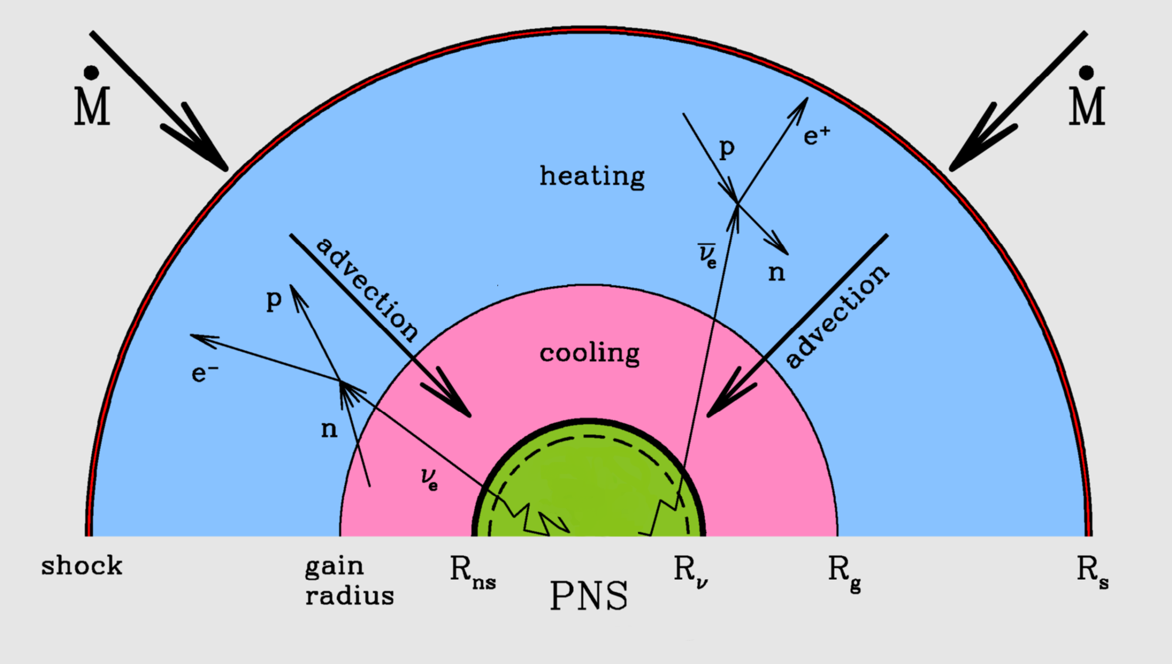
- Core-collapse supernovae are truly unique environments in our known universe:
  - Incredible matter densities: 10^{11}-10^{15} g/cm^3
  - Extreme high temperature: 1-50 MeV
  - Highest recorded energetic processes in the Universe: $10^{51\text{-}53}$ ergs
- At these energies, all species of neutrinos can be produced:

$$e^+\ e^- \leftrightarrow \nu_i\bar{\nu}_i$$

$$\nu_e\ n \leftrightarrow p\ e^-$$

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

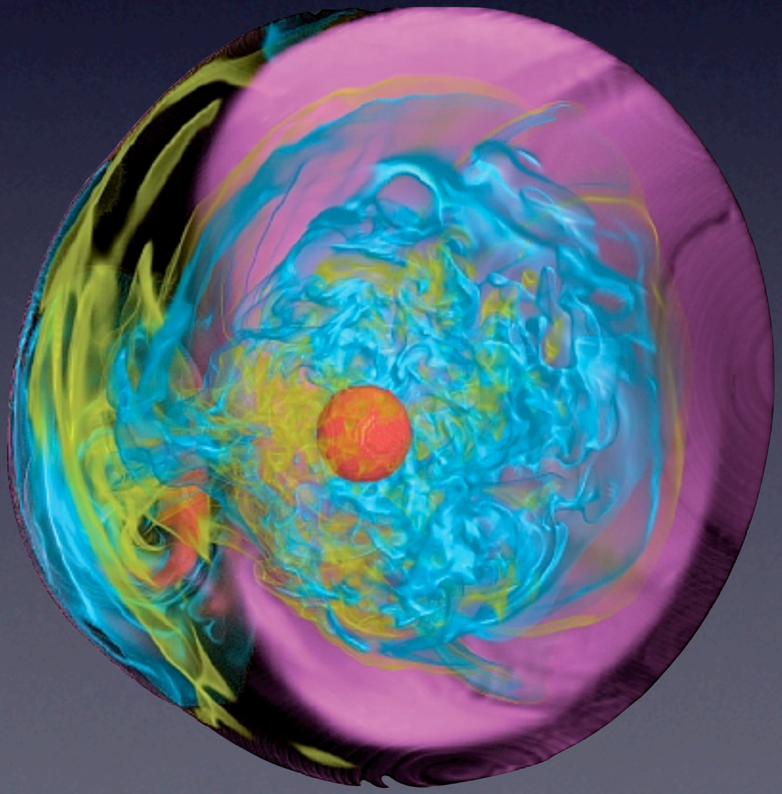
Neutrinos from the Stars



- Eventually nuclear burning is insufficient to maintain the star from collapsing, causing the stellar core to fall inward until core densities reach nuclear levels, causing the core to bounce.

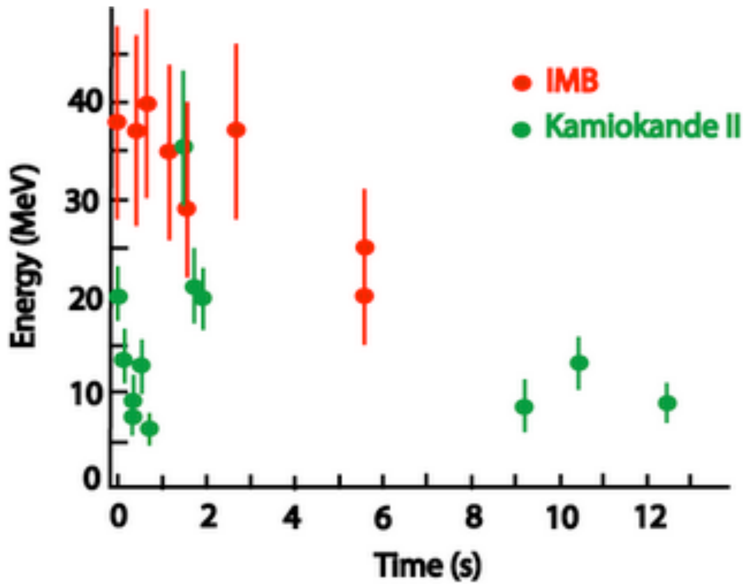
- Most neutrinos remain trapped between core and outer stellar region, heating the star until the energy is released.

- Neutrino flux dense enough for terrestrial detection.



Supernovae Detection

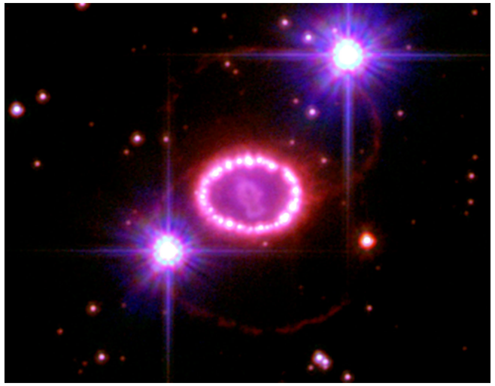
- Supernovae SN1987A detected using neutrino detectors, making use of the characteristic short burst of neutrinos.
- Still waiting for another such type of explosion close enough for detection.

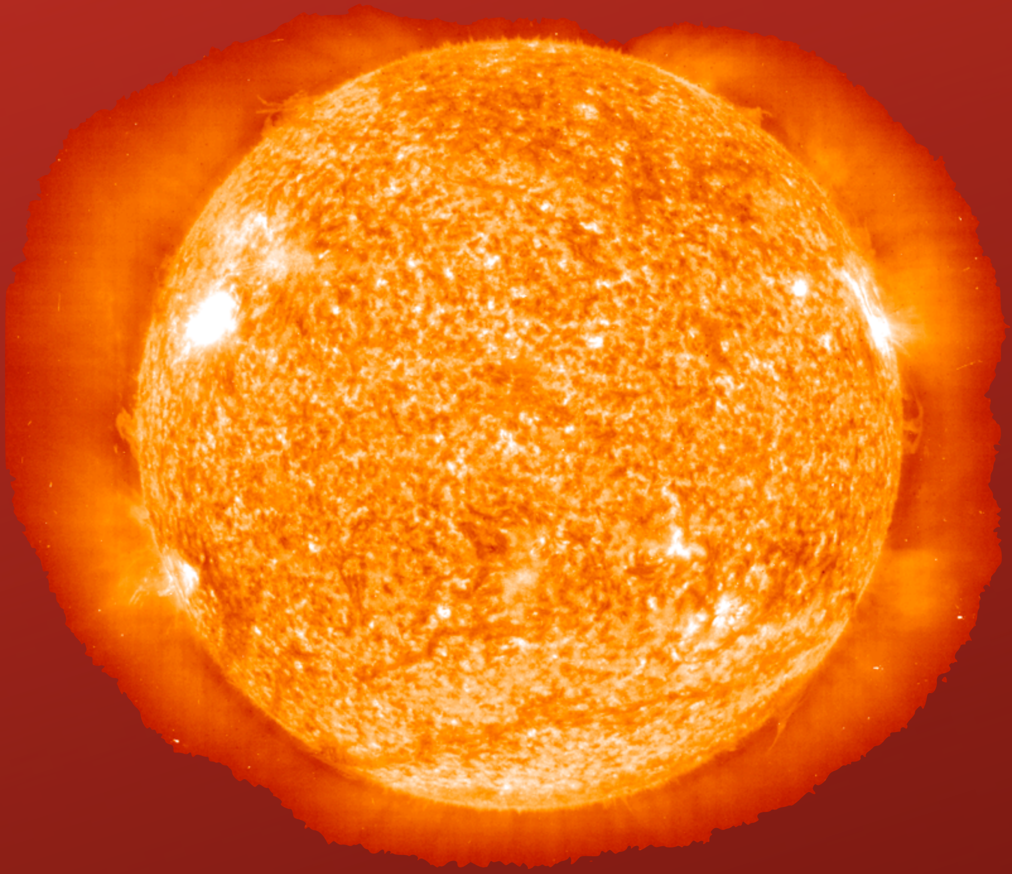


Before

During
(few days later)

After



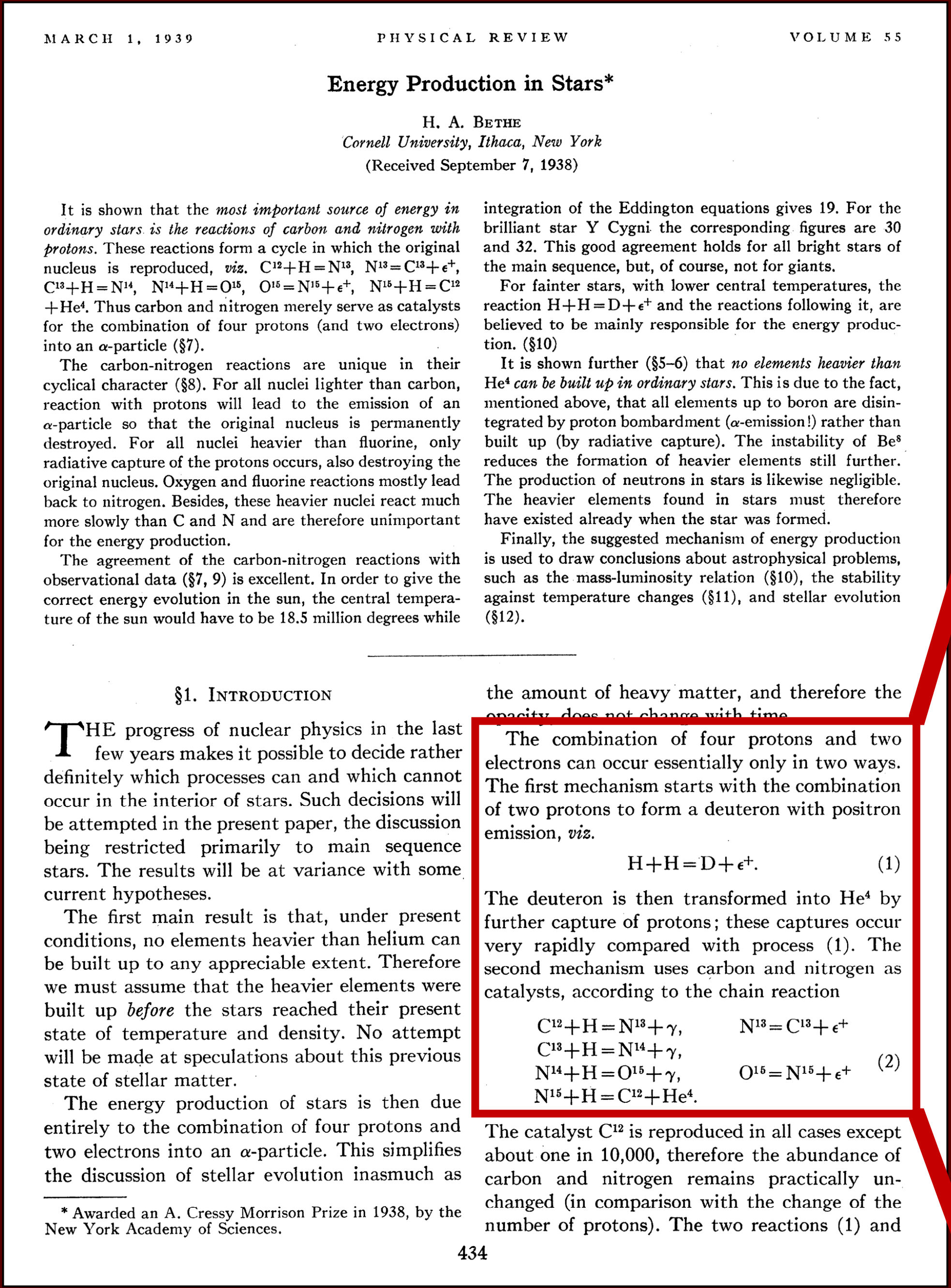


$E_\nu \sim 0.01\text{-}10$ MeV

Neutrinos from our star...
(the Sun)

In Bethe's original paper, neutrinos are not even in the picture.

(H.A. Bethe, Phys. Rev. 33, 1939)



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.*

$$H+H=D+\epsilon^+. \qquad (1)$$

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

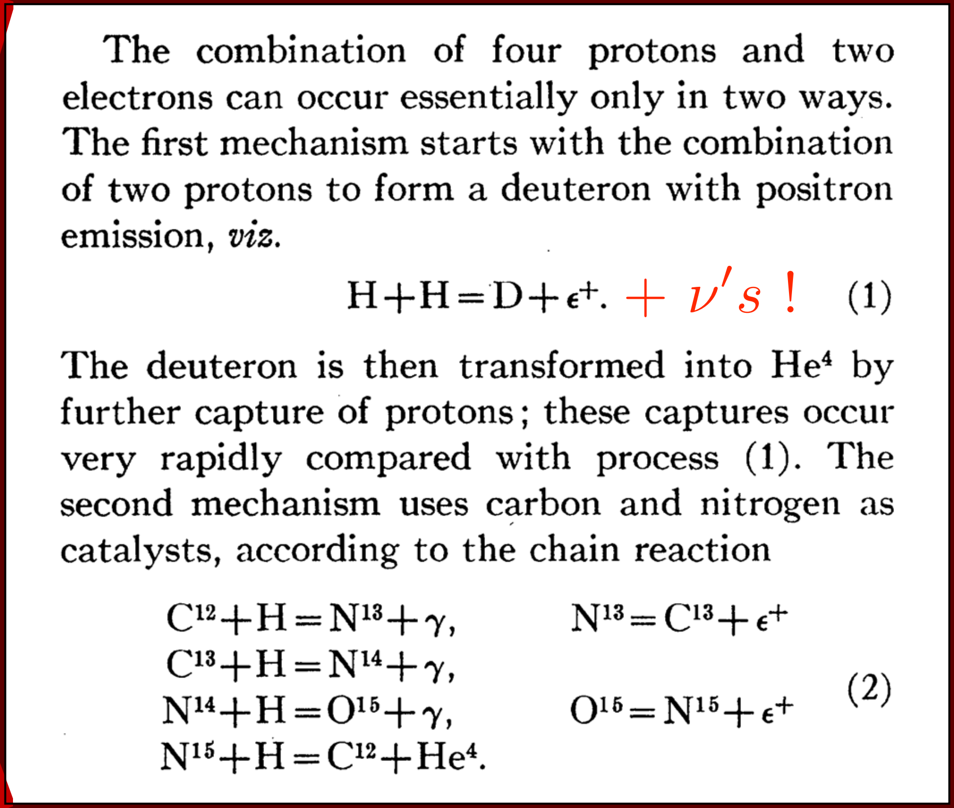
$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \qquad (2)$$

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.

434

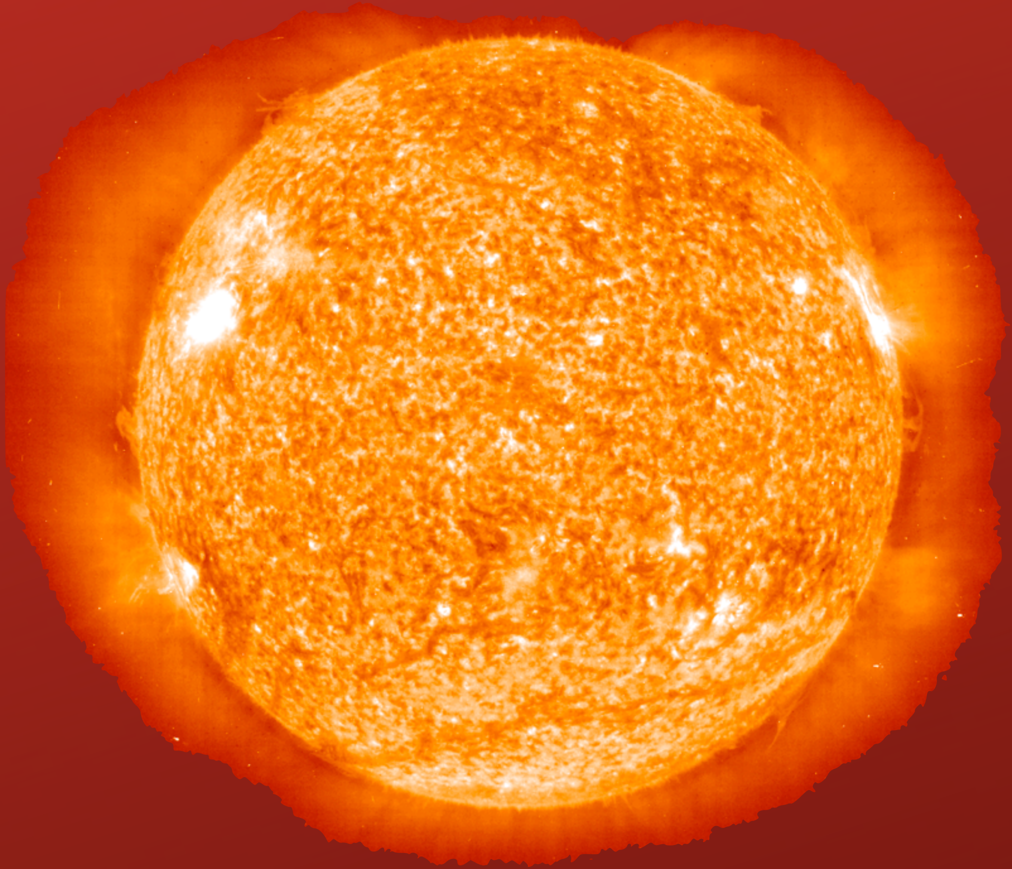


The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \; + \nu's \; ! \qquad (1)$$

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

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \qquad (2)$$



In the sixties, John Bahcall calculates the neutrino flux expected to be produced from the solar pp cycle.

Basic assumptions of what is known as the Standard Solar Model...

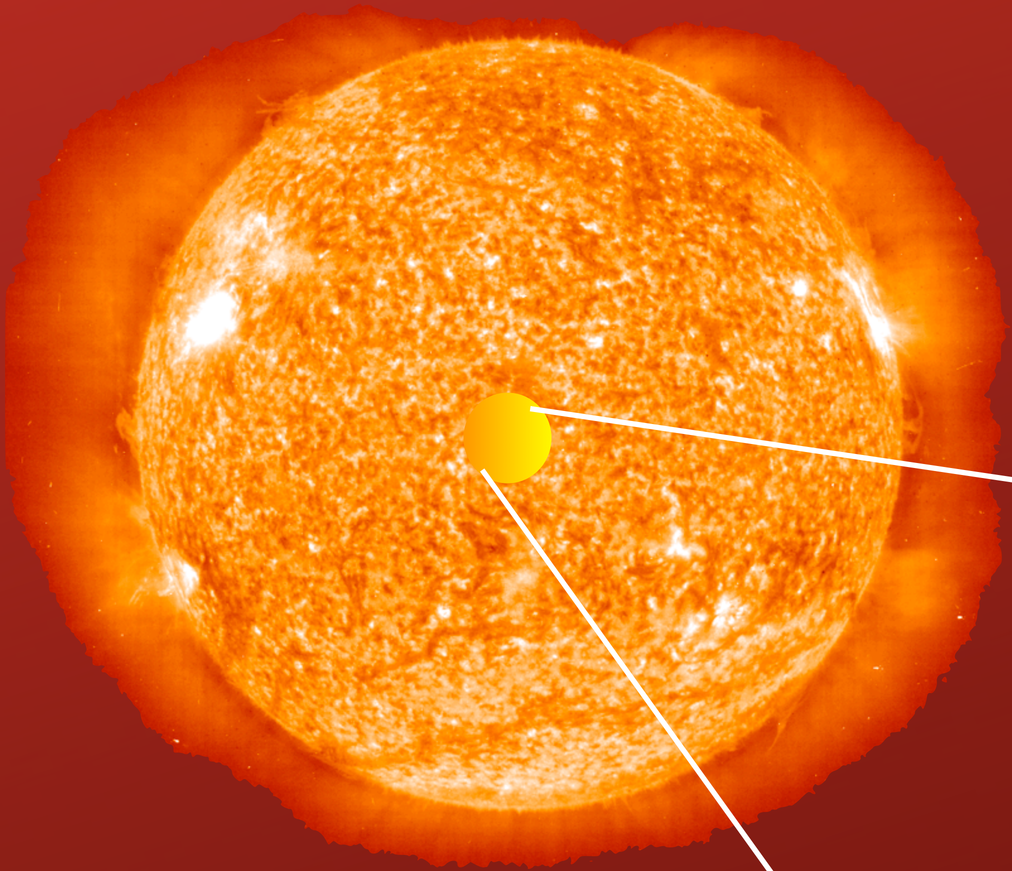
(1) Sun is in hydrostatic equilibrium.

(2) Main energy transport is by photons.

(3) Primary energy generation is nuclear fusion.

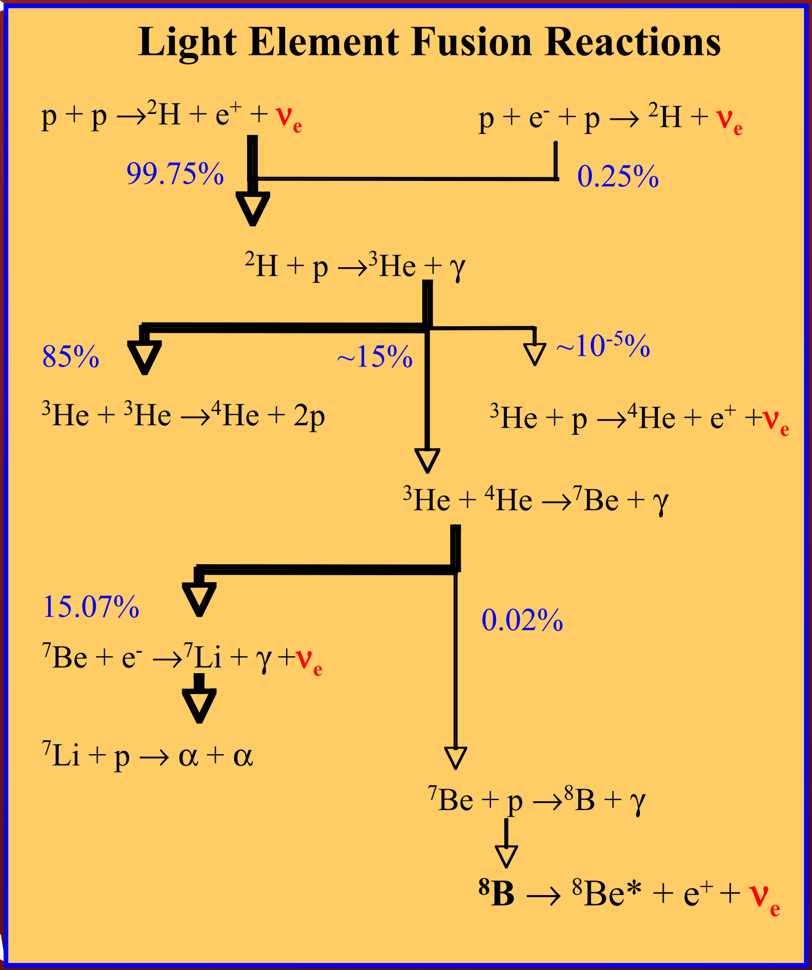
(4) Elemental abundance determined solely from fusion reactions.

John Bahcall
1934 - 2005



Basic Process:

$$4p + 2e^{-} \rightarrow He + 2\nu_e + 26.7\ \text{MeV}$$



Light Element Fusion Reactions

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

$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

99.75%

0.25%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

85%

~15%

$\sim 10^{-5}\%$

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

15.07%

0.02%

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

${}^{7}Li + p \rightarrow \alpha + \alpha$

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

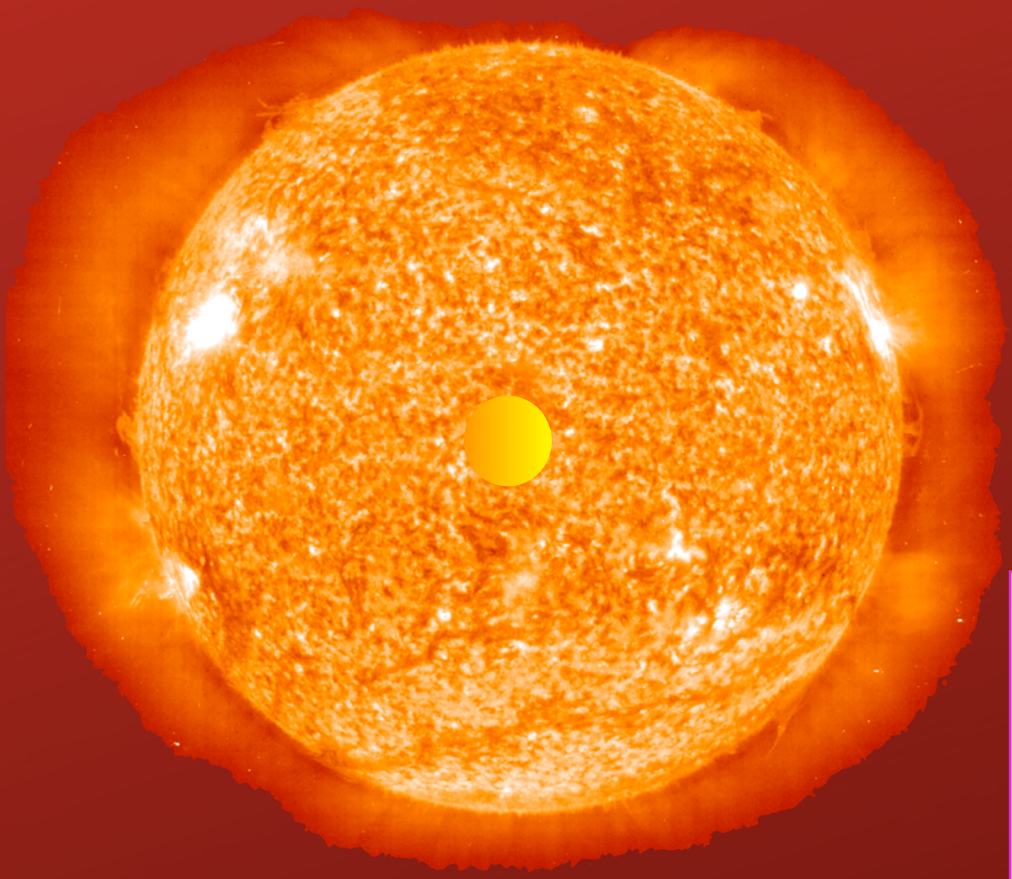
$\mathbf{{}^{8}B} \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

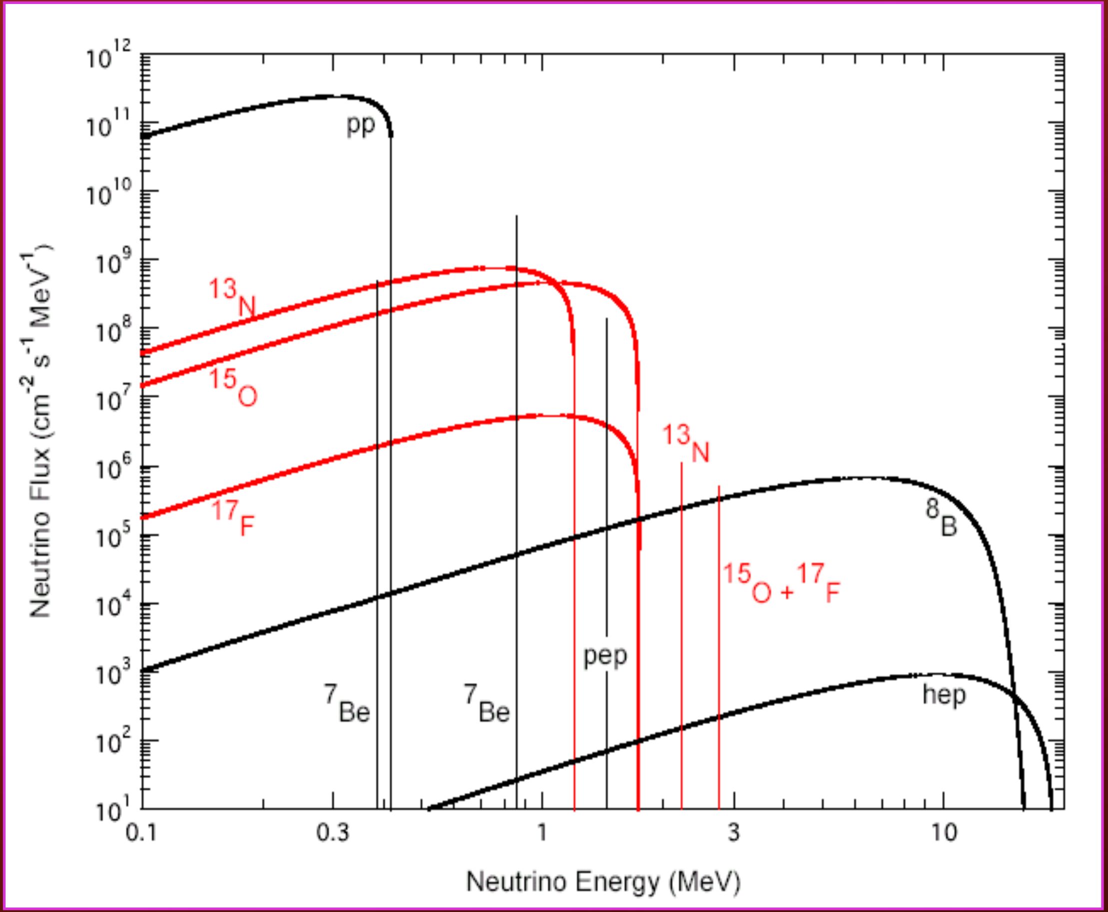
More detailed...

This is known as the pp fusion chain.

Sub-dominant CNO cycle also exists.

The Solar Neutrino Spectrum

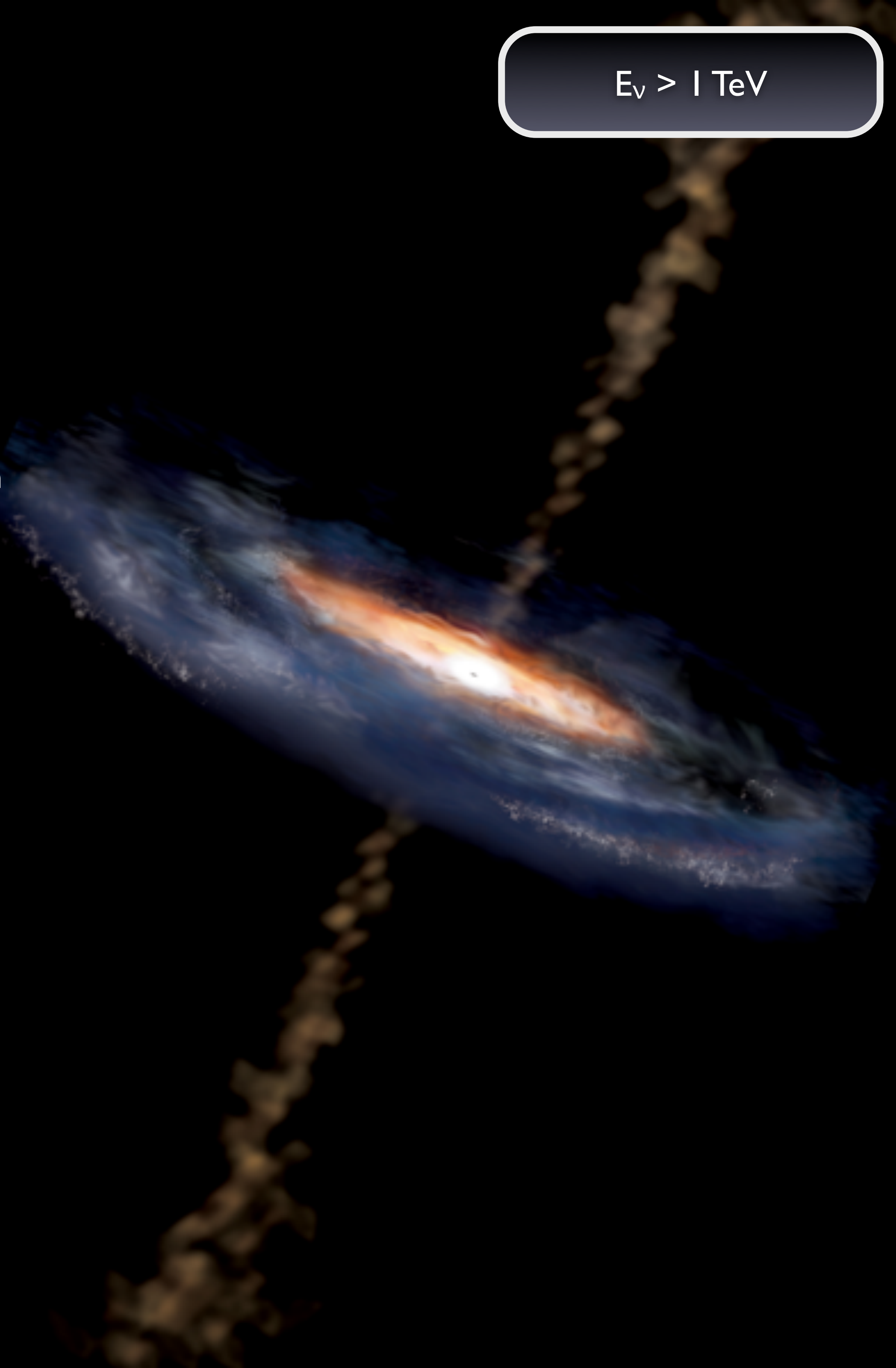




- Only electron neutrinos are produced initially in the sun (thermal energy below and threshold).
- Spectrum dominated mainly from pp fusion chain, but present only at low energies.

Ultra-High Energy Neutrinos

$E_\nu > 1$ TeV



- Galactic and extra-galactic celestial objects are known sources of extremely high energy cosmic rays (protons, etc.) and neutrinos.

- Three possible creation mechanisms:

  (1) Acceleration processes

  (2) GZK neutrinos

  (3) Annihilation and decay of heavy particles.

Acceleration Processes

- Evidence of ultra-high energy neutrinos would prove the validity of proton acceleration models.

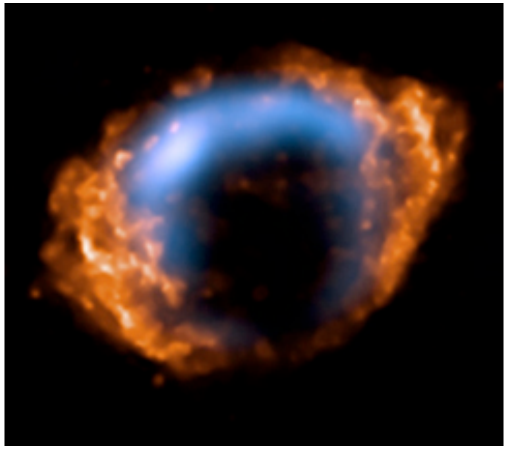
- Neutrinos would be produced from the decay of unstable mesons (π^0, $\pi^\pm$, $K^\pm$, etc.).

$$pp \to NN + \text{pions}; \qquad p\gamma \to p\pi^0,\ n\pi^+$$

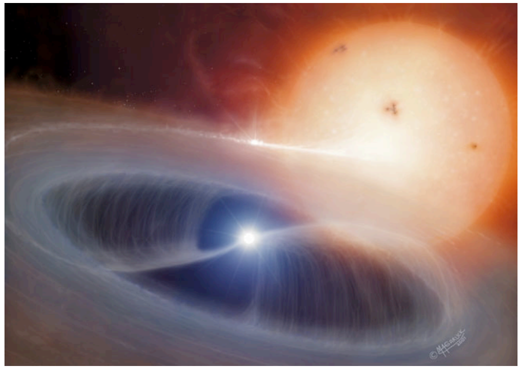
$$\begin{array}{l} \pi^+ \to \nu_\mu + \mu^+ \\ \qquad\qquad\quad\ \downarrow \\ \qquad\qquad\quad\ \bar{\nu}_\mu + e^+ + \nu_e \end{array}$$

- For extremely high energy cosmic rays or extra-galastic sources, extreme acceleration environments such as AGNs and GRBs need to be considered.

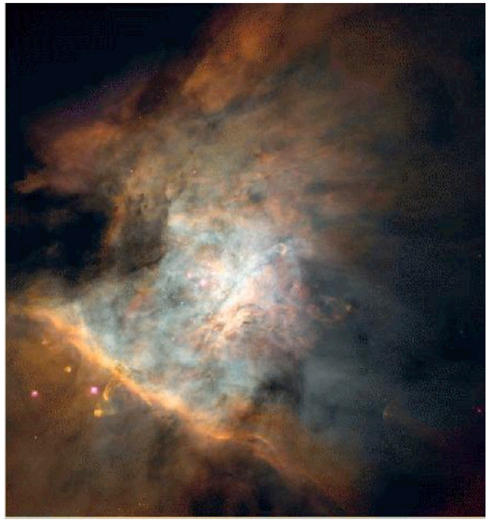
Supernova remnants



Binary systems

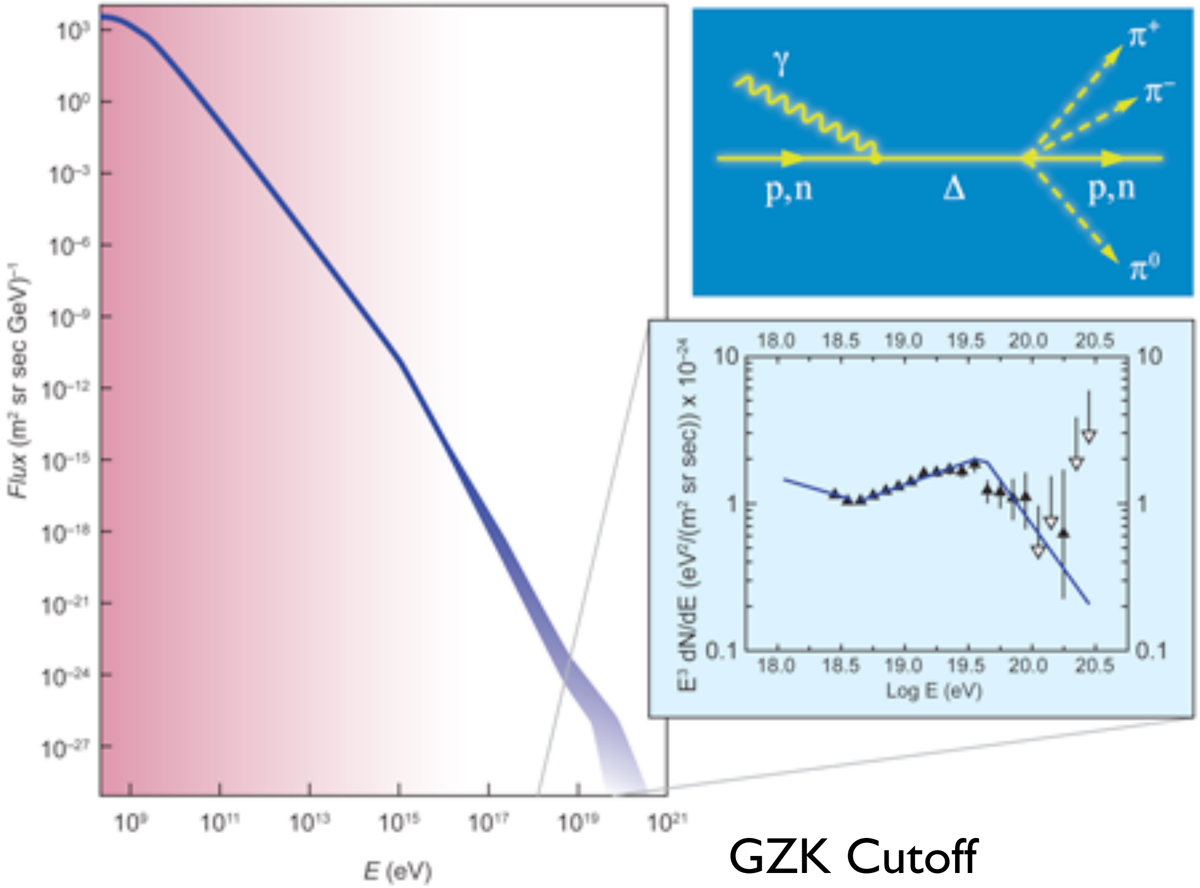


Interaction with interstellar medium

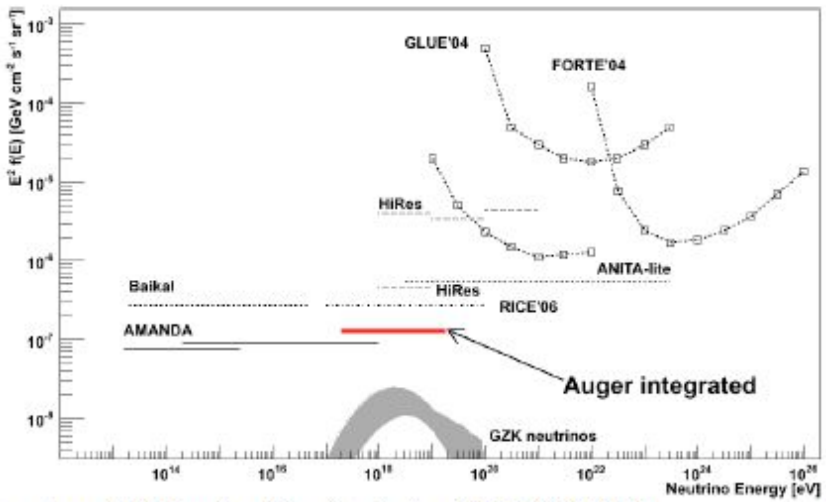


GZK Neutrinos

- At high enough energies, protons interact with the cosmic microwave background, providing a mechanism to create high energy neutrinos.
- Due to the known existence of high energy cosmic rays and the CMB, GZK neutrinos are a guaranteed signal.
- In addition, one can also look for massive particles that decay into high energy neutrinos as a signature for physics beyond the standard model.



GZK Cutoff



Pierre Auger Collaboration, Phys. Rev. Letters 100 (2008) 211101

"...down they fell, driven headlong from the pitch of heaven, down into this deep...", Paradise Lost

What we will cover:

Where do neutrinos come from?

Neutrinos from the Heavens

Neutrinos from the Earth

Neutrinos from Man

Atmospheric Neutrinos

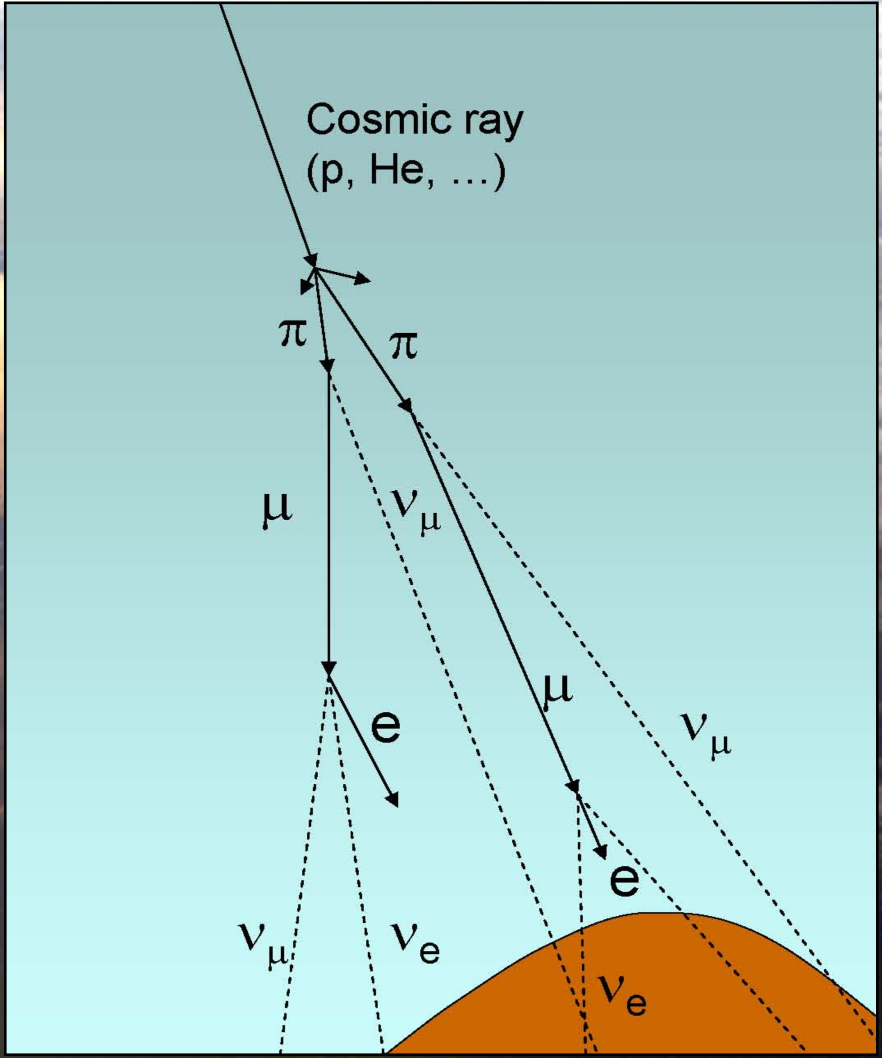
$E_\nu \sim 1\text{-}100$ GeV

Atmospheric Neutrinos

- Created by high energy cosmic rays impeding on the Earth's upper atmosphere.
- Dominant production mechasism comes from pion decay.

$$p +^{16} N \rightarrow \pi^{+}, K^{+}, D^{+}, \text{etc.}$$

$$\begin{tikzcd}[column sep=small] \pi^{+} \rightarrow \nu_{\mu} + \mu^{+} \arrow[d] \\ \bar{\nu}_{\mu} + e^{+} + \nu_{e} \end{tikzcd}$$



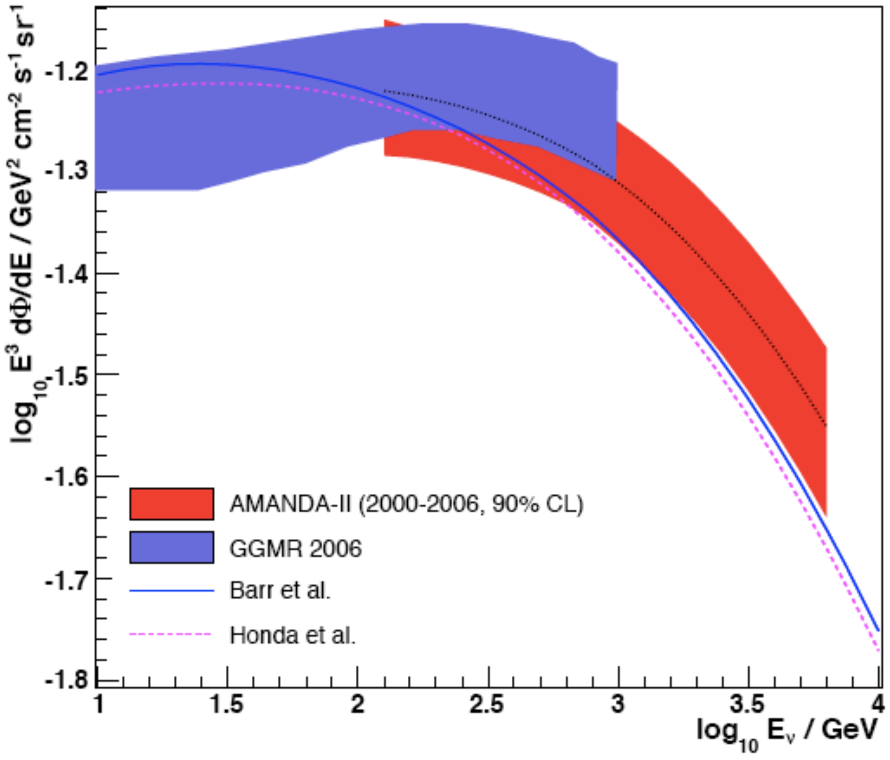
Atmospheric Neutrinos

- To calculate the predicted neutrino flux, a number of key steps must be taken into account:

  1. Primary cosmic ray flux. This is measured using large array telescopes and ballon measurements.
  2. Hadronization. Constrained by beam measurements.
  3. Optical depth, decay length and transport.

- Often one needs to take into account other subtle effects such as the Earth's magnetic field. Important at low energies.

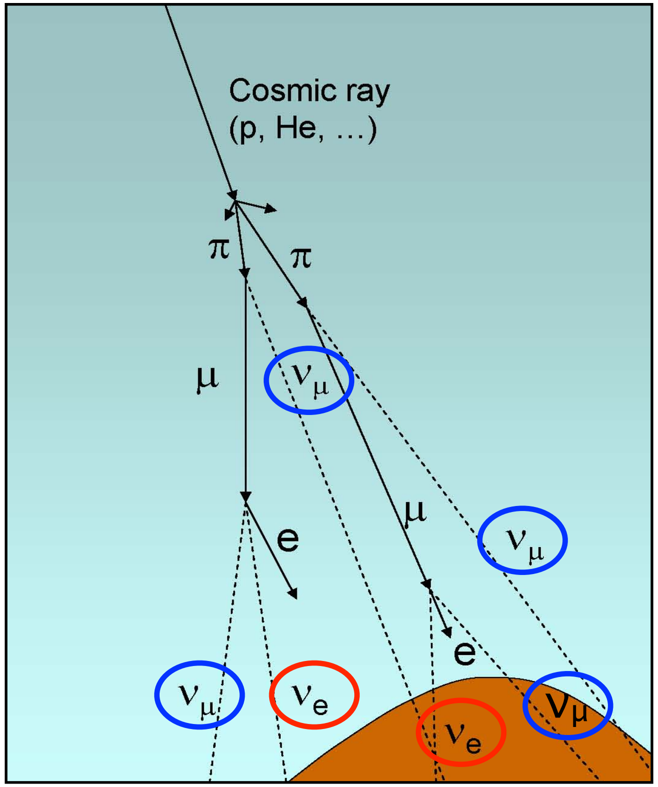
Predicted and Measured Atmospheric ν_μ Flux



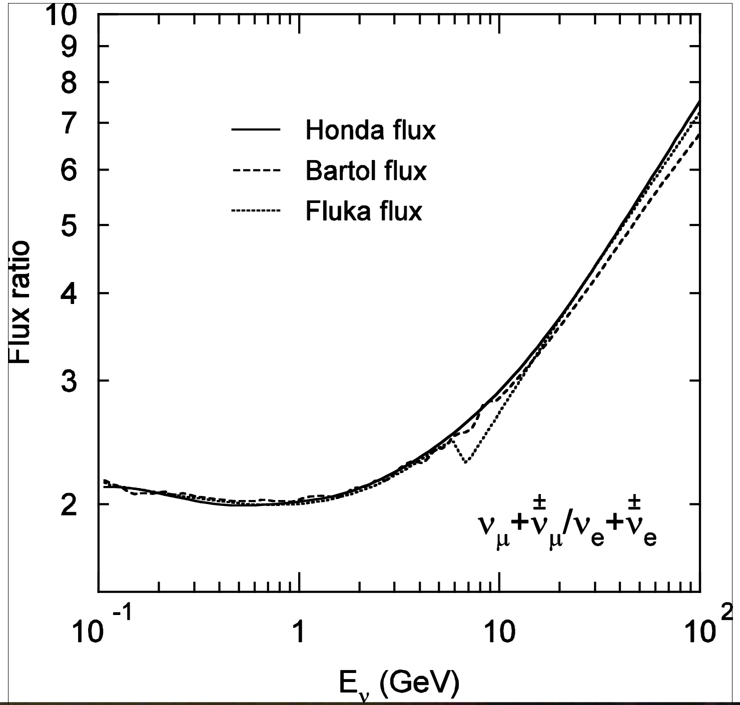
Uncertainties on the absolute flux near ±20%

Atmospheric Neutrinos

- The absolute flux uncertainty is fairly high, so people use other useful properties of the atmospheric neutrino flux:
  1. $\nu_\mu:\nu_e$ ratio: This ratio is fixed from the pion/muon cascade.
  2. Zenith variation: Allows one to probe neutrinos at very different production distances (essential for oscillation signatures).
  3. Compare cosmic muon flux



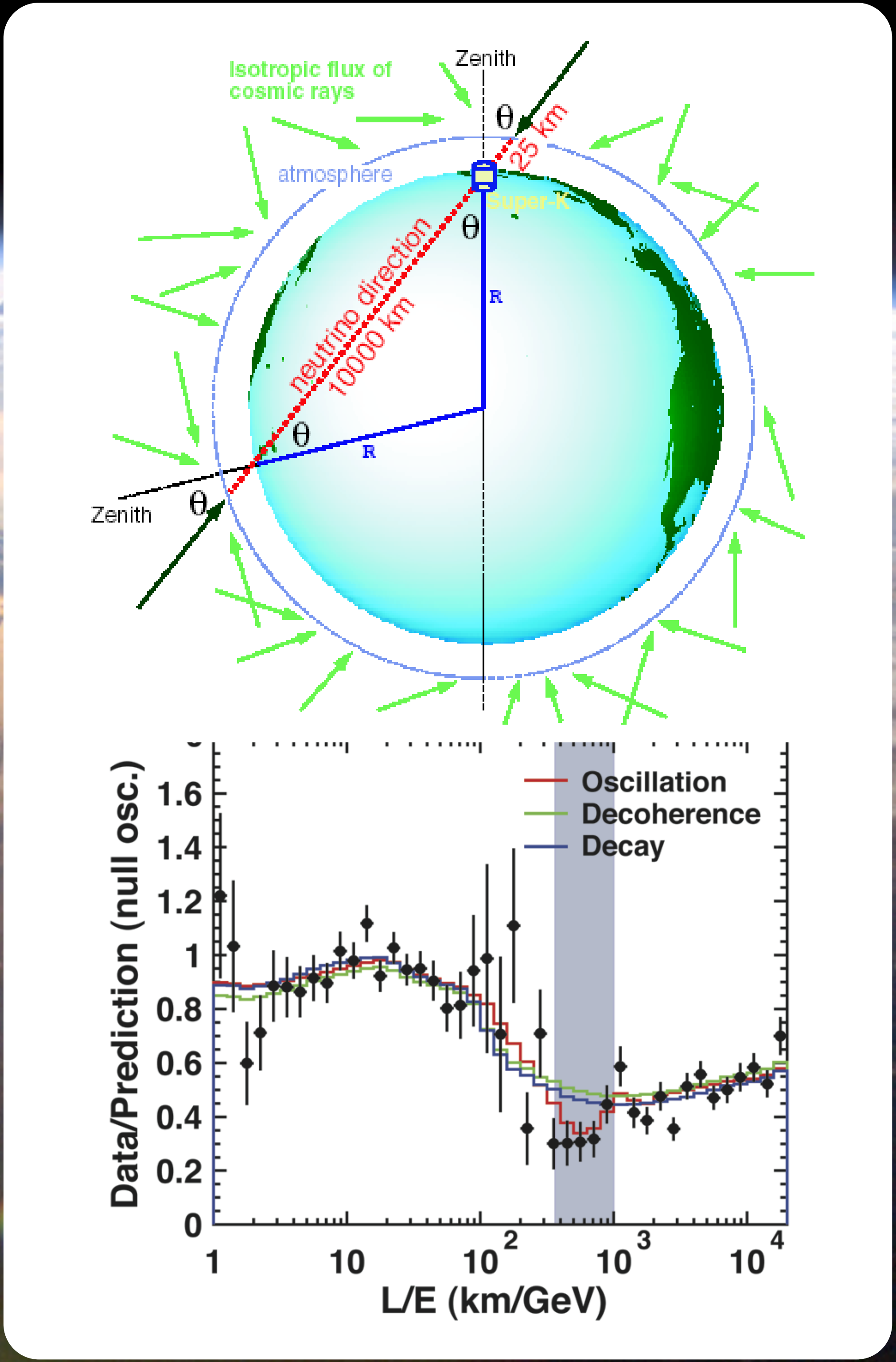
$\nu_\mu:\nu_e$ ratio near 2:1



Atmospheric Neutrinos

- The absolute flux uncertainty is fairly high, so people use other useful properties of the atmospheric neutrino flux:

  1. ν_μ:ν_e ratio: This ratio is fixed from the pion/muon cascade.
  2. Zenith variation: Allows one to probe neutrinos at very different production distances (essential for oscillation signatures).
  3. Compare cosmic muon flux



$E_\nu \sim 0.1\text{-}5$ MeV

Neutrinos from Radioactivity

Neutrinos from Radioactivity

- Nuclear transitions, such as beta decay, allow for the changing of the atomic number (Z) with no change in the atomic mass (A).

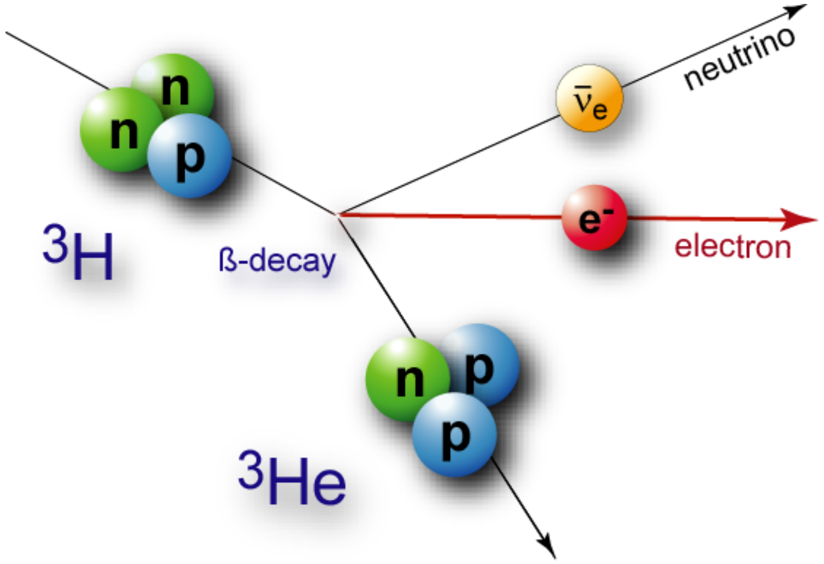
- One can consider three such reactions:

$$(Z, A) \rightarrow (Z+1, A) + e^- + \bar{\nu}_e \quad (\ \beta^- \ \text{Decay})$$

$$(Z, A) \rightarrow (Z-1, A) + e^+ + \nu_e \quad (\ \beta^+ \ \text{Decay})$$

$$(Z, A) + e^- \rightarrow (Z-1, A) + \nu_e \quad (\ \text{Electron Capture})$$

- In each of these cases, a neutrino (or anti-neutrino) is produced. Prominent in many neutrino production interactions (such as in the sun).



Sample β-decay

$$^3\text{H} \rightarrow {}^3\text{He} + e^- + \nu_e$$

Neutrinos from Radioactivity

- To determine the rate of a particular reaction, one needs to take into account of a number of factors:
  - The **phase space** of the decay (i.e. how many different states can occupy a particular momentum).
  - Corrections due to the Coulomb field, or **Fermi function**.
  - The **matrix element** related to the initial and final states of the decay.

Transition	ΔI	Parity change?
Superallowed	0, ± 1	No
Allowed	0, ± 1	No
1st Forbidden	0, ± 1	Yes
Unique 1st Forbidden	± 2	Yes
2nd Forbidden	± 2	No
3rd Forbidden	± 3	Yes

Spin of states govern type of exchange
E.g.: $0^+ \rightarrow 0^+$ is superallowed

Fermi Function

$$\frac{dN}{dE} = C \times |M|^2 F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

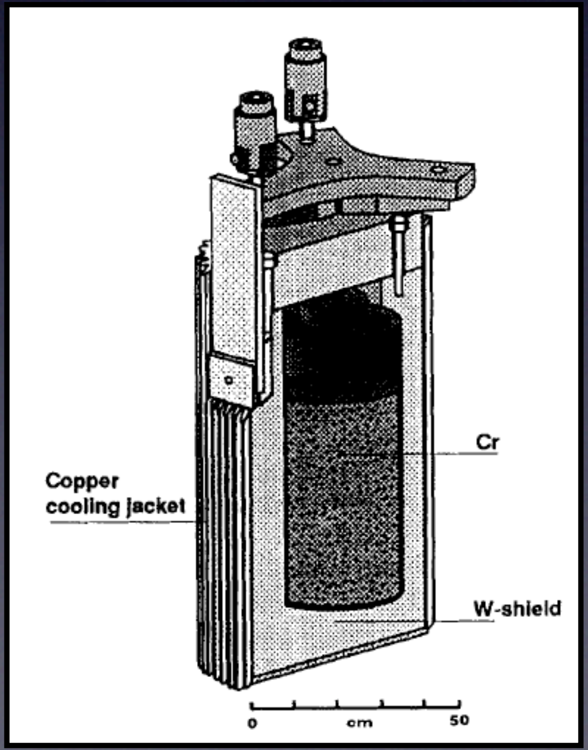
Matrix Element

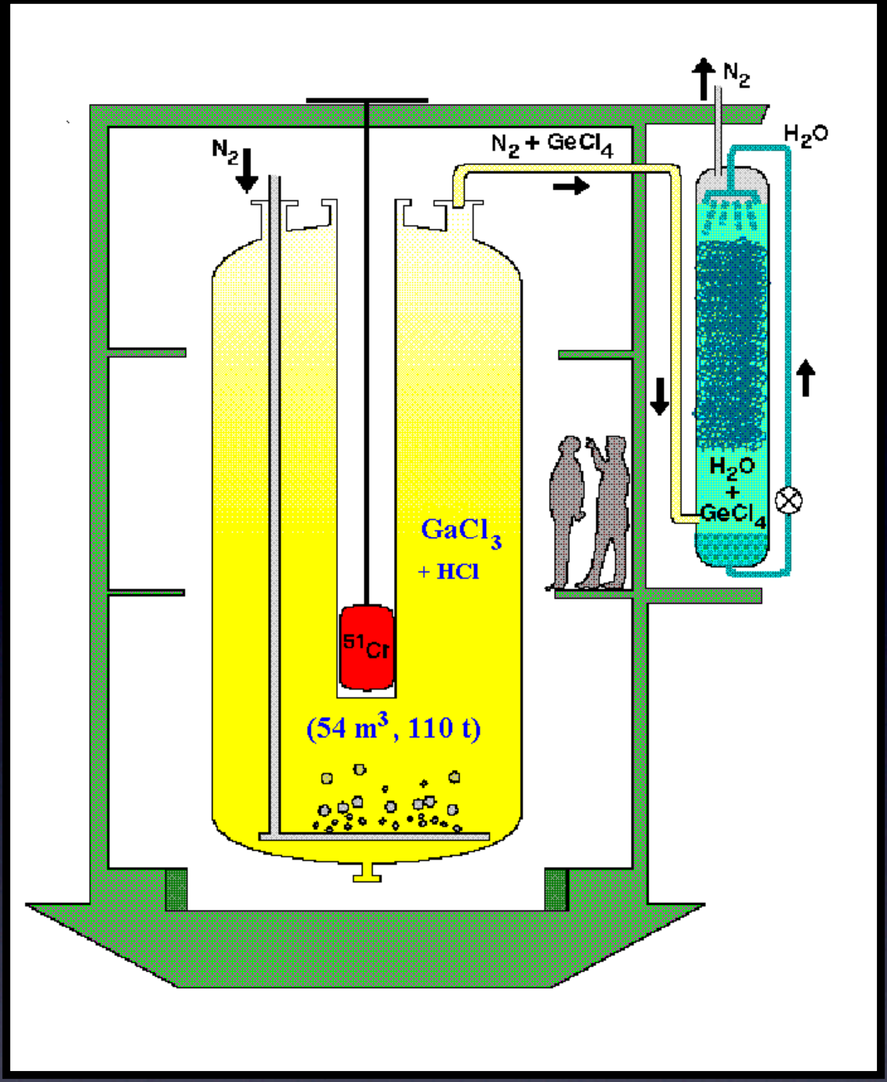
Phase space

Possible Source?

- Though neutrinos from radioactive decay play an important role in many astrophysical sources, we rarely use them as a source, per se.

- Except we did to calibrate some of our solar neutrino detectors!



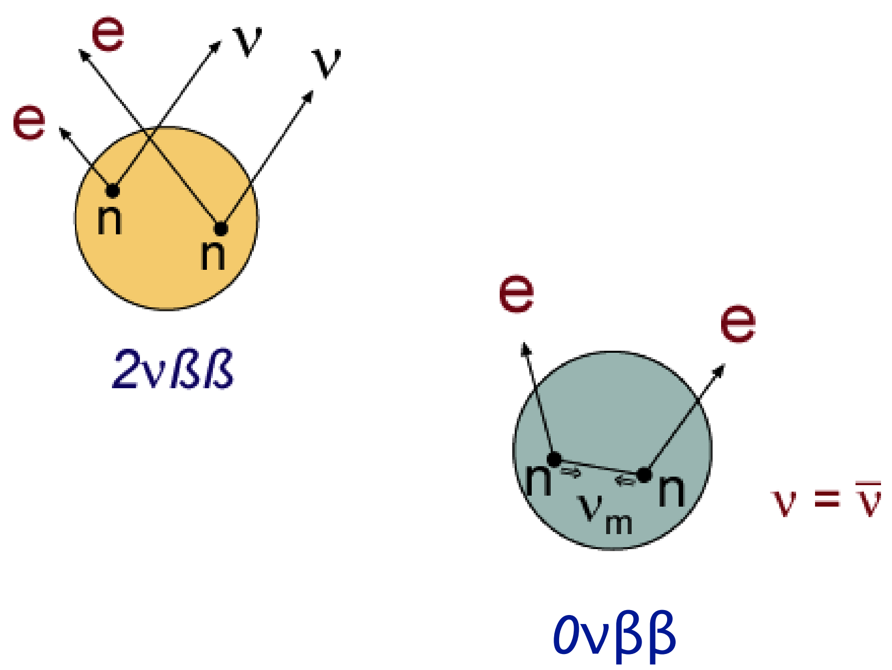


Total activity of the source: 60 PBq!

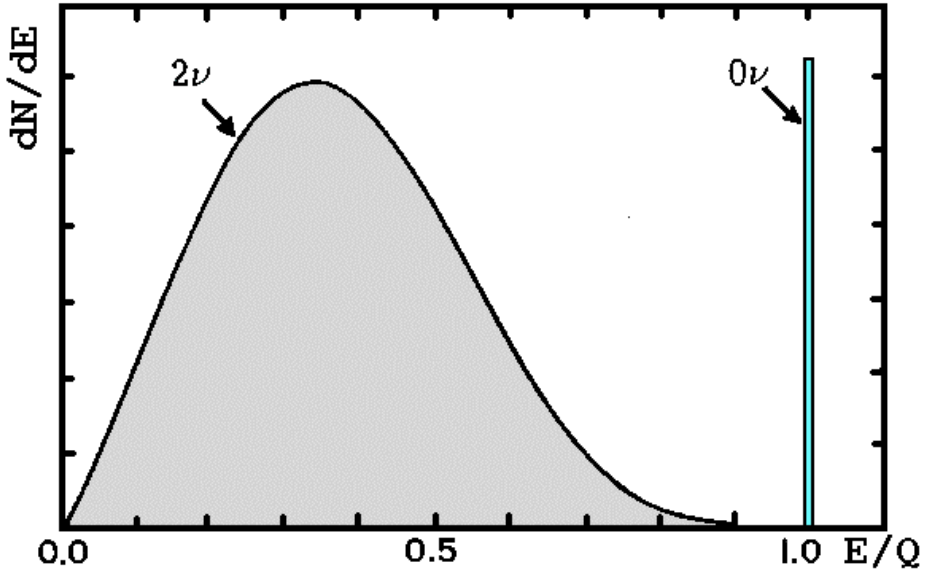
Emitted ~300 W of heat

You can do it twice...

- It is possible to have a nucleus undergo beta decay twice (as long as it is allowed from energy and spin considerations).
- Highly suppressed due to G_F^4 suppression.
- If the neutrino is its own anti-particle, then the neutrino can mediate the reaction. No neutrinos are emitted.
- This is not a neutrino source per se, except its has incredible consequences.



The signature

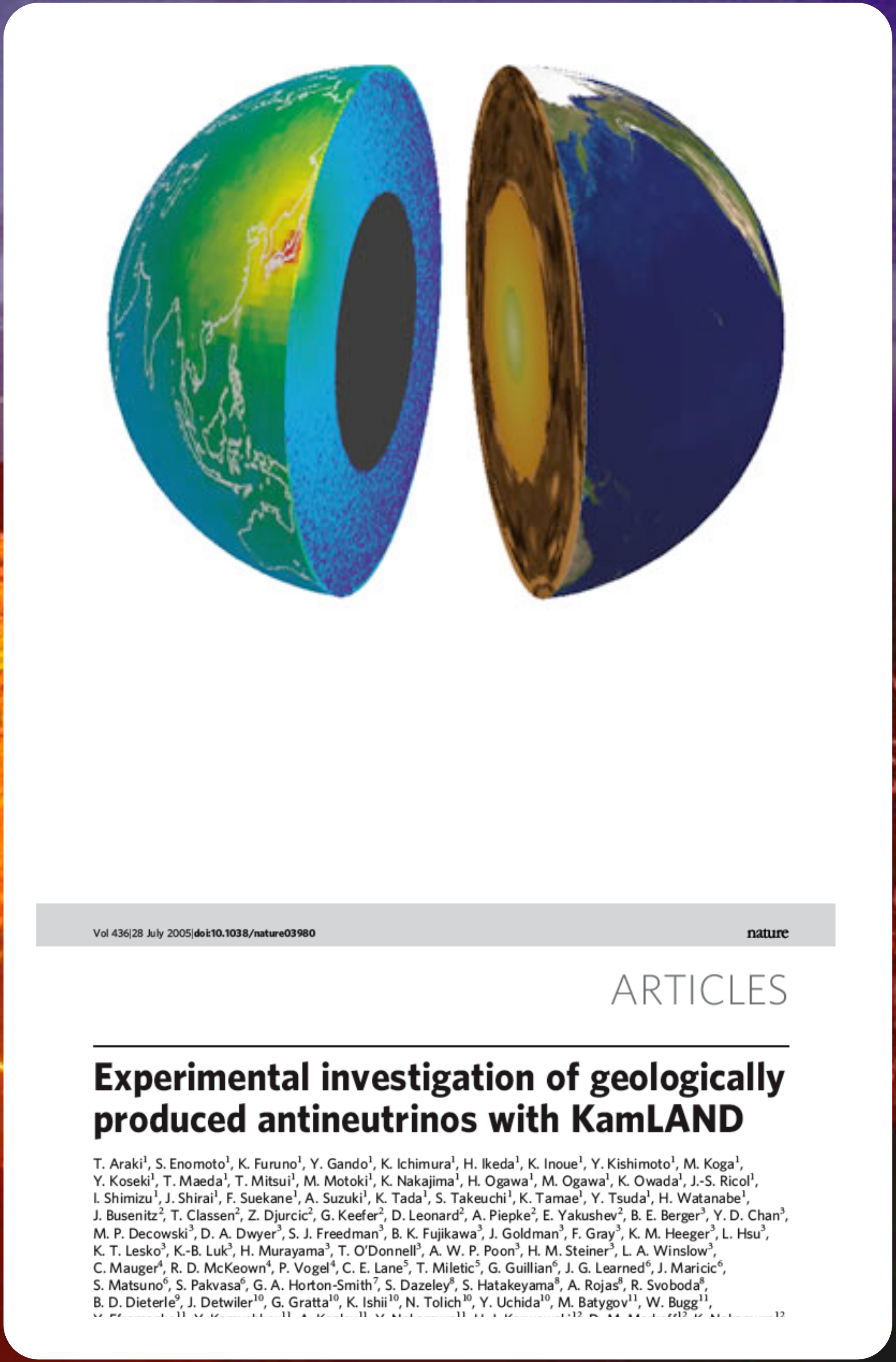


Geoneutrinos

$E_\nu \sim 1$ MeV

Geoneutrinos

- Radiogenic heat from U and Th decays in the earth's crust and mantle provide a sufficient flux of neutrinos at low energies.
- Radiogenic heat is expected to be a significant portion of the Earth's heating source (~40-60% of 40 TW).
- First geoneutrinos detected only recently (from Kamland).



Vol 436|28 July 2005|**doi:10.1038/nature03980** **nature**

ARTICLES

Experimental investigation of geologically produced antineutrinos with KamLAND

T. Araki[1], S. Enomoto[1], K. Furuno[1], Y. Gando[1], K. Ichimura[1], H. Ikeda[1], K. Inoue[1], Y. Kishimoto[1], M. Koga[1], Y. Koseki[1], T. Maeda[1], T. Mitsui[1], M. Motoki[1], K. Nakajima[1], H. Ogawa[1], M. Ogawa[1], K. Owada[1], J.-S. Ricol[1], I. Shimizu[1], J. Shirai[1], F. Suekane[1], A. Suzuki[1], K. Tada[1], S. Takeuchi[1], K. Tamae[1], Y. Tsuda[1], H. Watanabe[1], J. Busenitz[2], T. Classen[2], Z. Djurcic[2], G. Keefer[2], D. Leonard[2], A. Piepke[2], E. Yakushev[2], B. E. Berger[3], Y. D. Chan[3], M. P. Decowski[3], D. A. Dwyer[3], S. J. Freedman[3], B. K. Fujikawa[3], J. Goldman[3], F. Gray[3], K. M. Heeger[3], L. Hsu[3], K. T. Lesko[3], K.-B. Luk[3], H. Murayama[3], T. O'Donnell[3], A. W. P. Poon[3], H. M. Steiner[3], L. A. Winslow[3], C. Mauger[4], R. D. McKeown[4], P. Vogel[4], C. E. Lane[5], T. Miletic[5], G. Guillian[6], J. G. Learned[6], J. Maricic[6], S. Matsuno[6], S. Pakvasa[6], G. A. Horton-Smith[7], S. Dazeley[8], S. Hatakeyama[8], A. Rojas[8], R. Svoboda[8], B. D. Dieterle[9], J. Detwiler[10], G. Gratta[10], K. Ishii[10], N. Tolich[10], Y. Uchida[10], M. Batygov[11], W. Bugg[11],

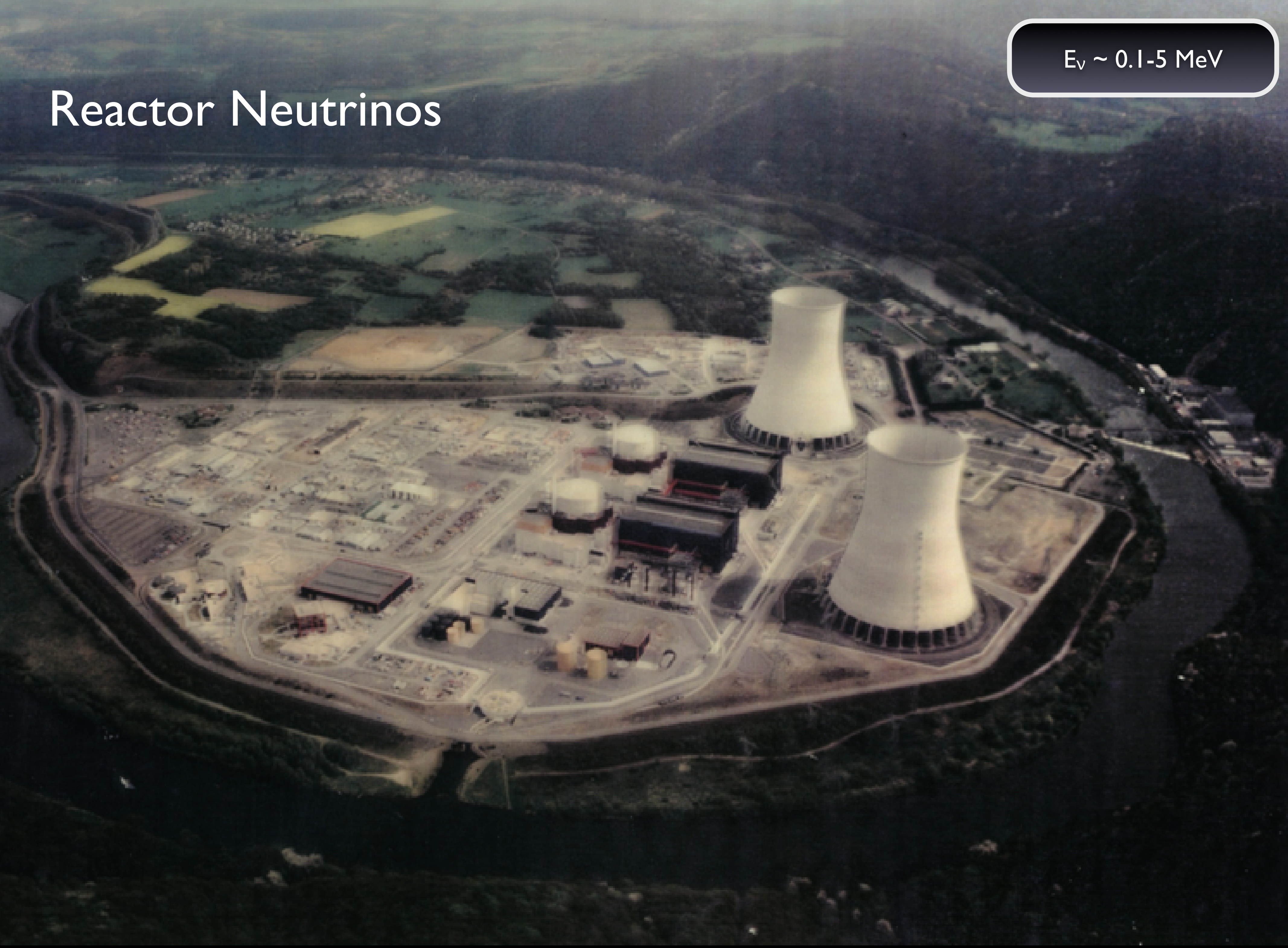
> "…and Prometheus was punished for giving fire back to mankind…"

What we will cover:

- Where do neutrinos come from?
- Neutrinos from the Heavens
- Neutrinos from the Earth
- Neutrinos from Man

Reactor Neutrinos

$E_\nu \sim 0.1\text{-}5$ MeV



Neutrinos from Fission

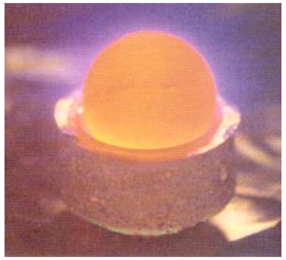
- Reactor neutrinos stem mostly as a by-product from fission, as numerous unstable nuclei are produced and beta decay to more stable isotopes.
- Four main neutrino fuel sources:

^{238}U, ^{235}U, ^{239}Pu and ^{241}Pu

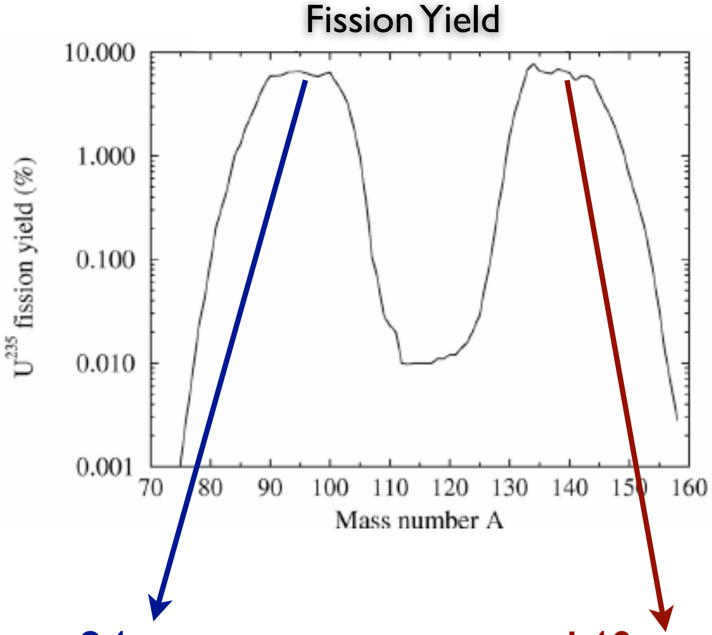
$$ {}^{235}_{92}U + n \to X_1 + X_2 + 2n \to \ldots {}^{94}_{40}Zr + {}^{140}_{58}Ce $$

Sample Fission: ^{235}U

^{238}U



^{239}Pu



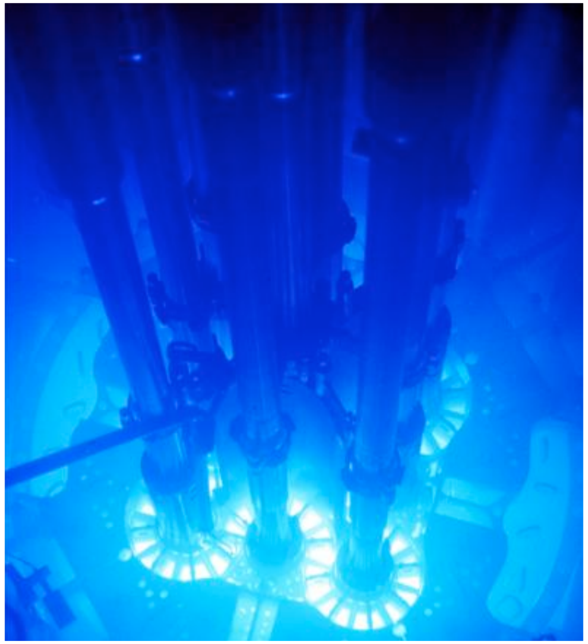
^{94}Zr

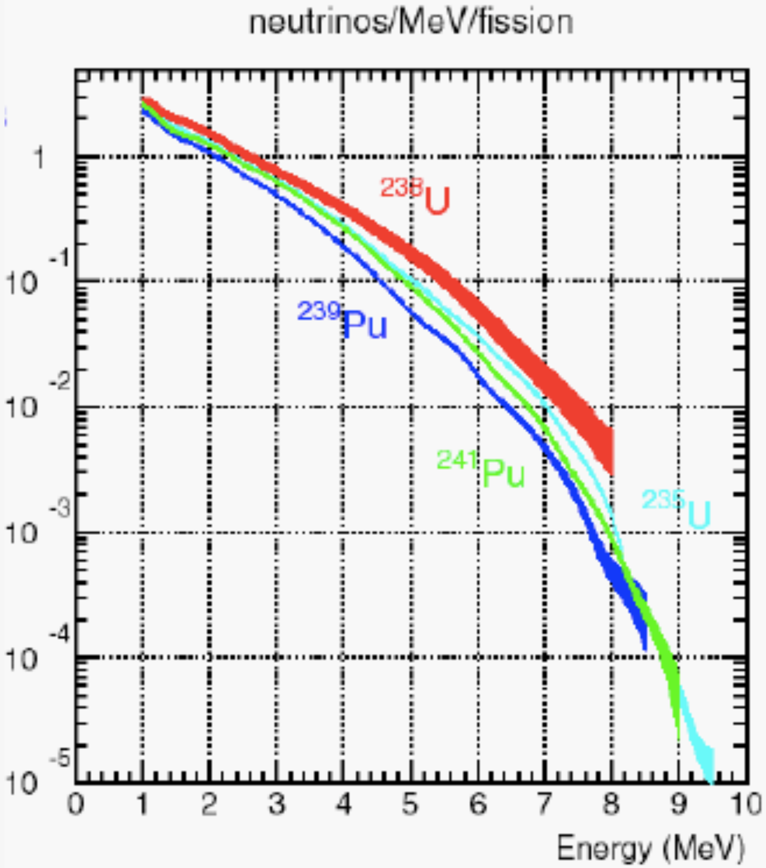
^{140}Ce

Neutrinos from Fission

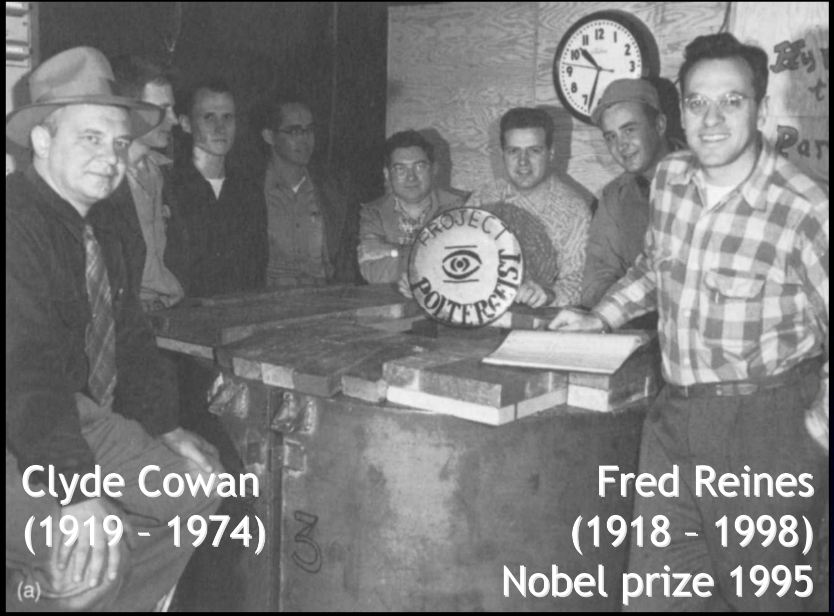
- Eventually reaction produces stable isotopes, such as Zr and Ce. In the process, 6 protons must have beta-decayed to 6 neutrons.
- About 6 anti-neutrinos are produced per fission. Since each fission cycle produces 200 MeV, one can convert power to neutrino flux.

1 GW (thermal) ≈ $1.8 \times 10^{20}\ \bar{\nu}_e$ / second





Reactor Experiments: Pioneer Efforts


Clyde Cowan (1919 – 1974)

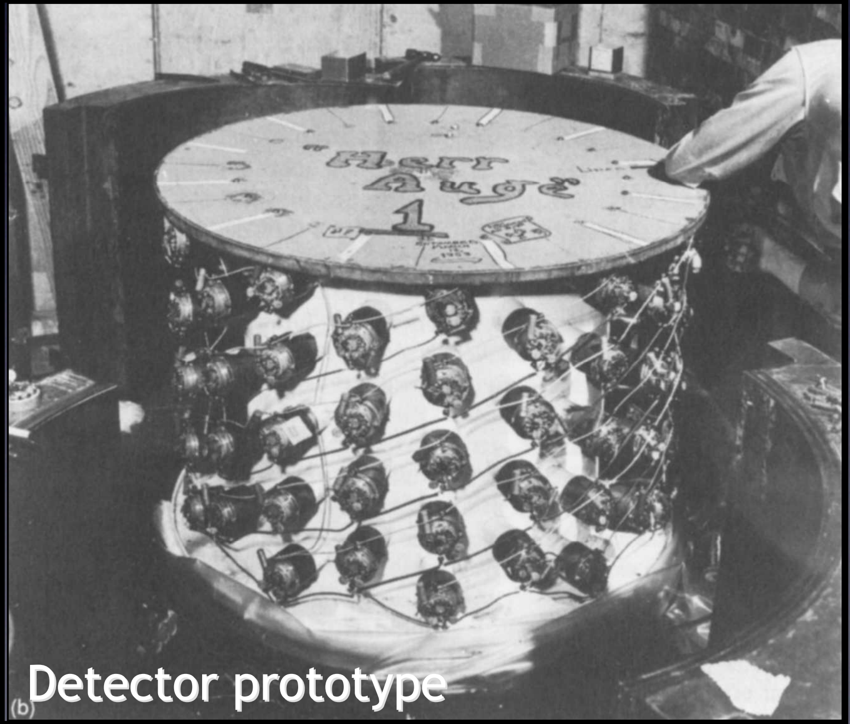
Fred Reines (1918 – 1998) Nobel prize 1995

(a)

First experimental detection of neutrinos came indeed from the high flux of neutrinos created in reactors.

$$\bar{\nu} + p \rightarrow n + e^{+} \longrightarrow \text{signal here}$$

$$\searrow n + {}^{113}\mathrm{Cd} \rightarrow \gamma' s \searrow \text{and here!}$$



Detector prototype

(b)

Upcoming Reactor Experiments

- Advanced development of new reactor experiments (Double Chooz, Daya Bay, RENO, and Angra).
- All experiments will push down on the last unmeasured oscillation mixing angle in next few years.


Double Chooz


Daya Bay

Accelerator Neutrinos

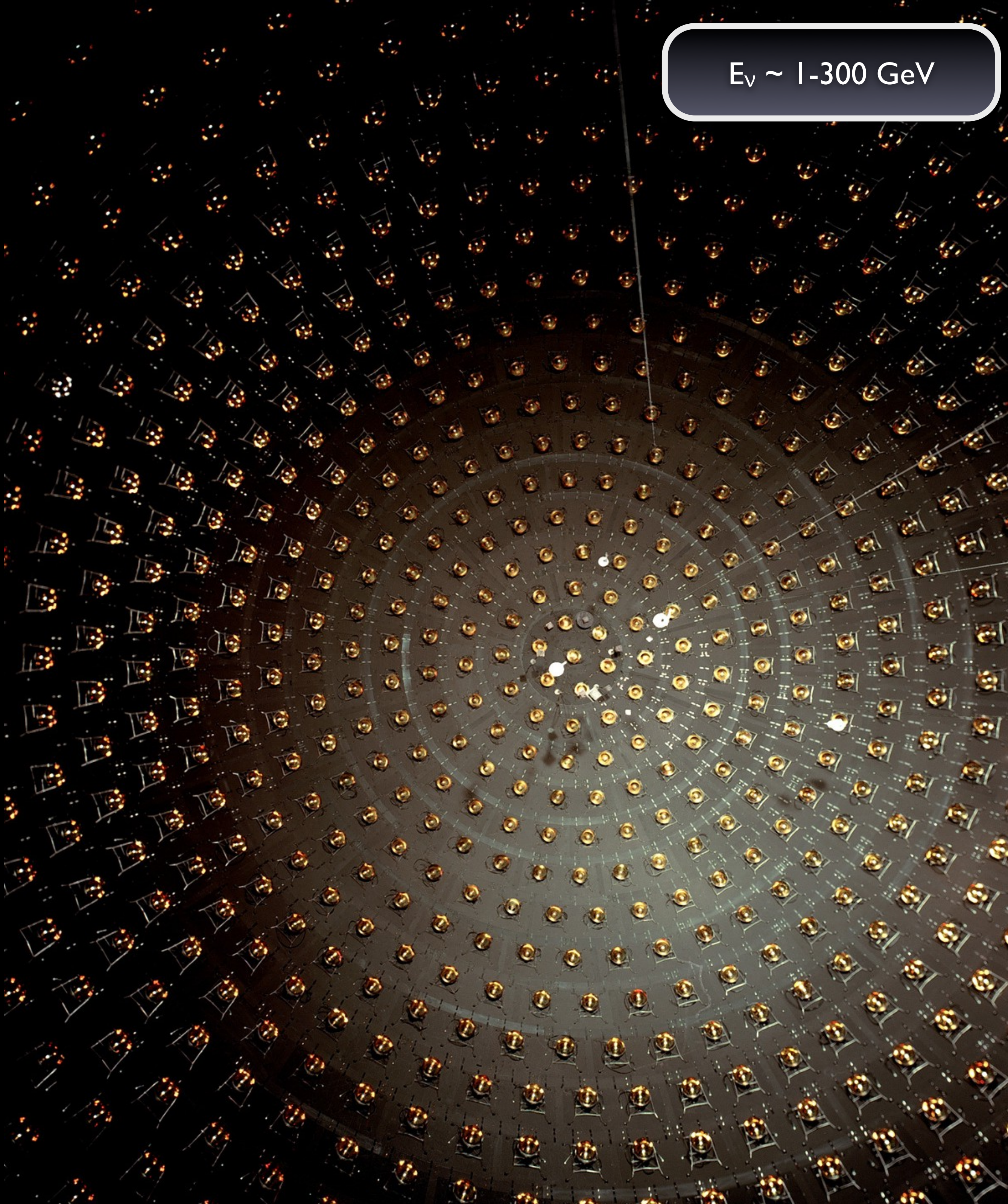
E_ν ~ 1-300 GeV

- We can consider three very broad types of accelerator neutrino sources:

  (a) Proton driver (or "conventional") beams

  (b) Beta beams

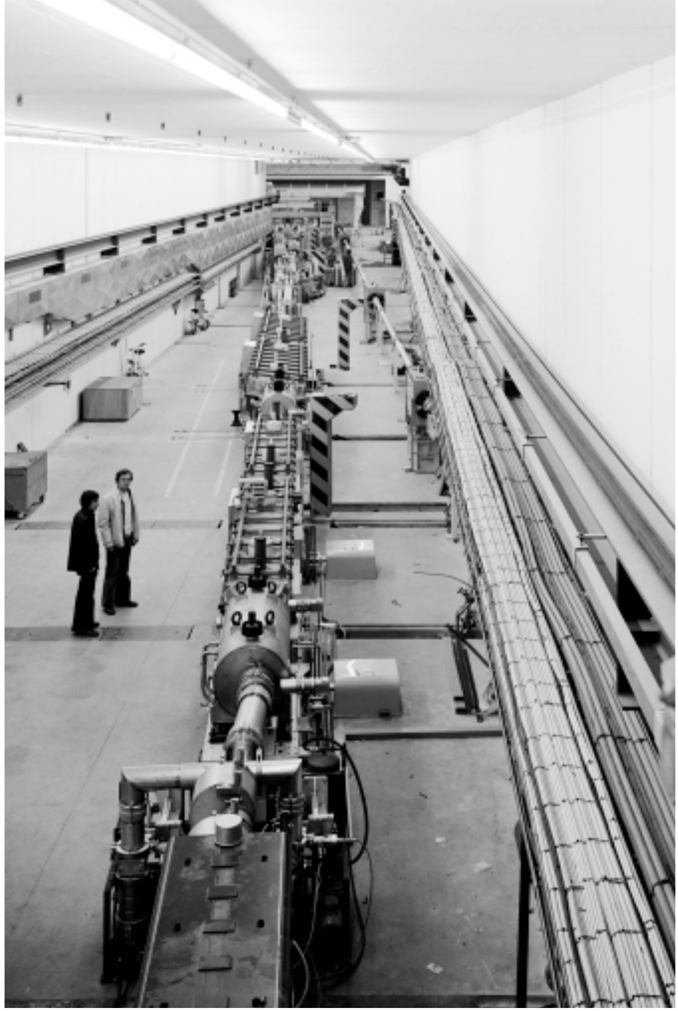
  (c) Muon storage beam ("neutrino factories")



Conventional Beams

- Beam creation very similar to atmospheric neutrinos (protons drive the production mechanism; neutrinos produced from pion decay).

- Beam creation allows for greater selectivity of the beam properties. Typical the beam user will create beam with a given:



CERN's WA21 beamline

(a) Neutrino flavor purity, → Allows selection of final state

(b) Selected energy range & distance, → Optimization of oscillation wavelength

(c) Intensity → You always want more...

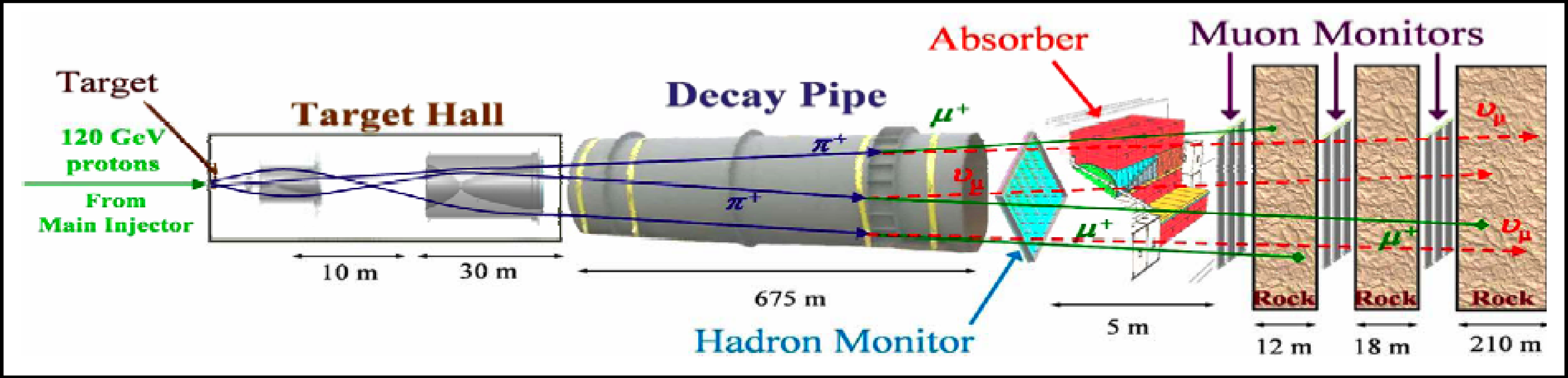
Stages

- Basic ingredients of target, focusing region, decay region, absorber, and detector found in almost all accelerators.
- How system is optimized depends on type of beam desired.

Decay/Absorber Region

Region for pion/kaon decay to occur.

Absorber removes unwanted charged particles & neutrons on route to detector



Beta Beams

- Different from conventional beams, as they use accelerated beta-decaying ions as the source of neutrinos.
- Extremely pure beam of electron (or anti-electron neutrinos).
- Spectrum extremely well known, since it comes from a boosted beta decay rather than a complex nucleon production scheme.
- Production of ion source still considerable challenge, but research is ongoing.

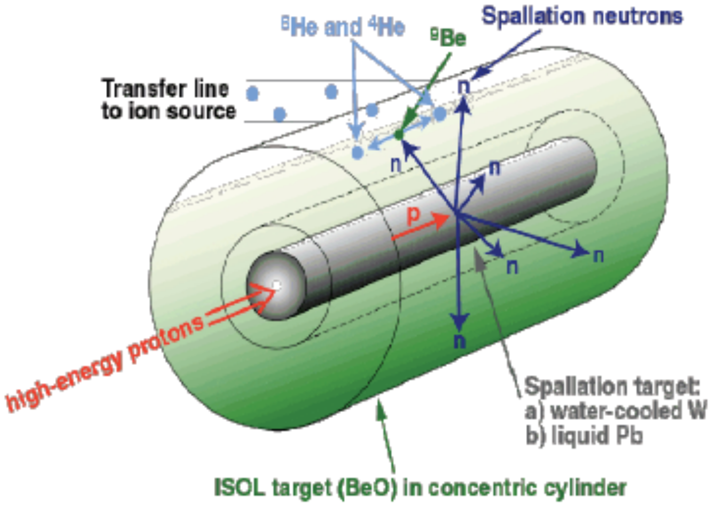
Neutrinos from Beta Decay

$$^{6}\mathrm{He} \longrightarrow \; ^{6}\mathrm{Li}\; e^{-} \;\; \bar{\nu}_e$$

Electron Anti-neutrino Source

$$^{18}\mathrm{Ne} \longrightarrow \; ^{18}\mathrm{F}\; e^{+} \;\; \nu_e$$

Electron Neutrino Source



Neutrino Factories

- Driving mechanism comes from muon decay rather than pion decay.
- Ideal "beam" for many oscillation studies.

Main Advantages

Extremely pure beam due to use of delayed decays.

Well known beam profile

Typically intense source envisioned.

Main Disadvantages

Both neutrino & anti-neutrino present in the beam at once

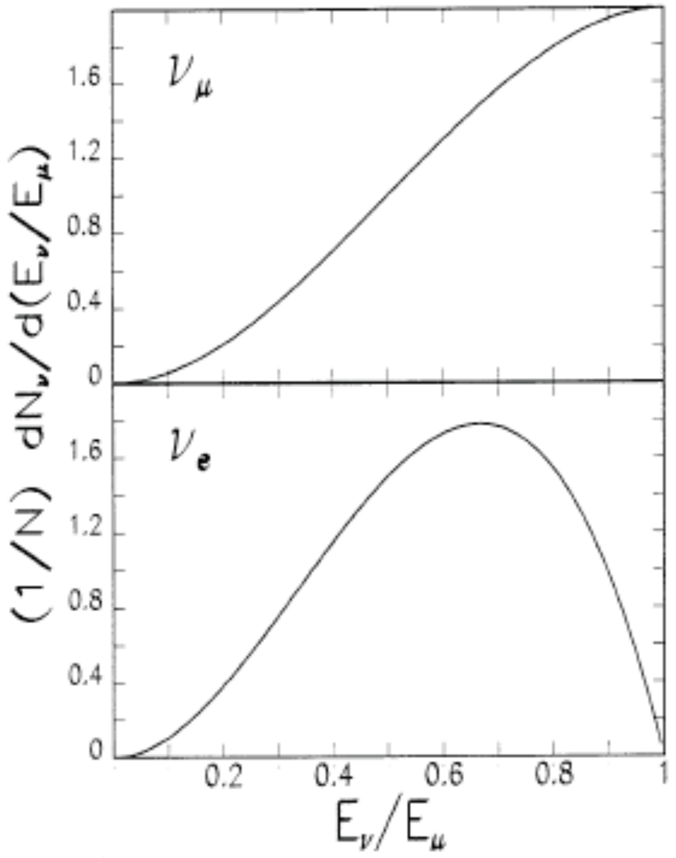
Extremely short storage times

Challenging technology

Neutrinos from Muon Decay

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

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



$E_\nu \sim 50$ MeV

Spallation Neutron Sources

SNS as a Neutrino Source

- Any reaction that can produce an intense pion source is effectively an excellent neutrino source.

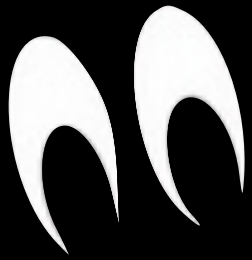
- In this case, there is no boost from a relativistic proton (pions created at rest).

- The Spallation Neutron Source (high intensity neutron source) can also double as an excellent neutrino source.

  1. Pulsed beam ensures clean tagging of neutrino events.

  2. Intensity neutrino source (10^{15} ν/s)\

  3. Can be used for oscillation studies & coherent neutrino scattering.



- As you can see, neutrinos are EVERYWHERE in the universe; playing a crucial role in many natural interactions.

- Given so many abundant sources of neutrinos, they provide an excellent means to probe the universe around us.

- How? Stay tuned...

Texts I find useful...

- “Neutrino Physics”, by Kai Zuber
- “Particle Physics and Cosmology”, by P.D.B. Collins, A.D. Martin, and E.J. Squires.
- “The Physics of Massive Neutrinos,” (two books by the same title, B. Kayser and P. Vogel, F. Boehm
- “Los Alamos Science: Celebrating the Neutrino”, a good 1st year into into neutrinos, albeit a bit outdated now.
- “Massive Neutrinos in Physics and Astrophysics,” Mohapatra and Pal.

Fin