Neutrinos from the Heavens & the Earth

Neutrinos from the Heavens & the Earth

J.A. Formaggio

MIT

NEPPSR 2009

What we will cover:

What we will cover:

Where do neutrinos come from?

What we will cover:

Where do neutrinos come from?

Neutrinos from the Heavens


What we will cover:
Where do neutrinos come from?
Neutrinos from the Heavens
Neutrinos from the Earth

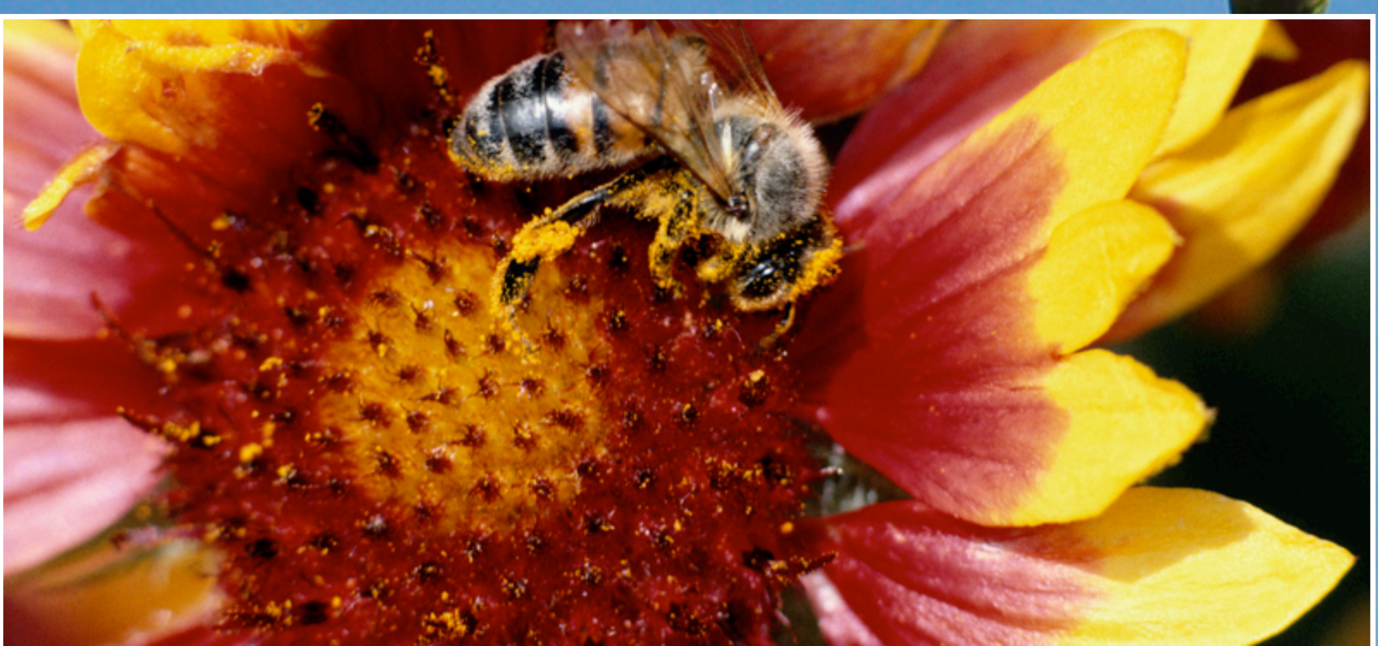
What we will cover:

Where do neutrinos come from?

Neutrinos from the Heavens

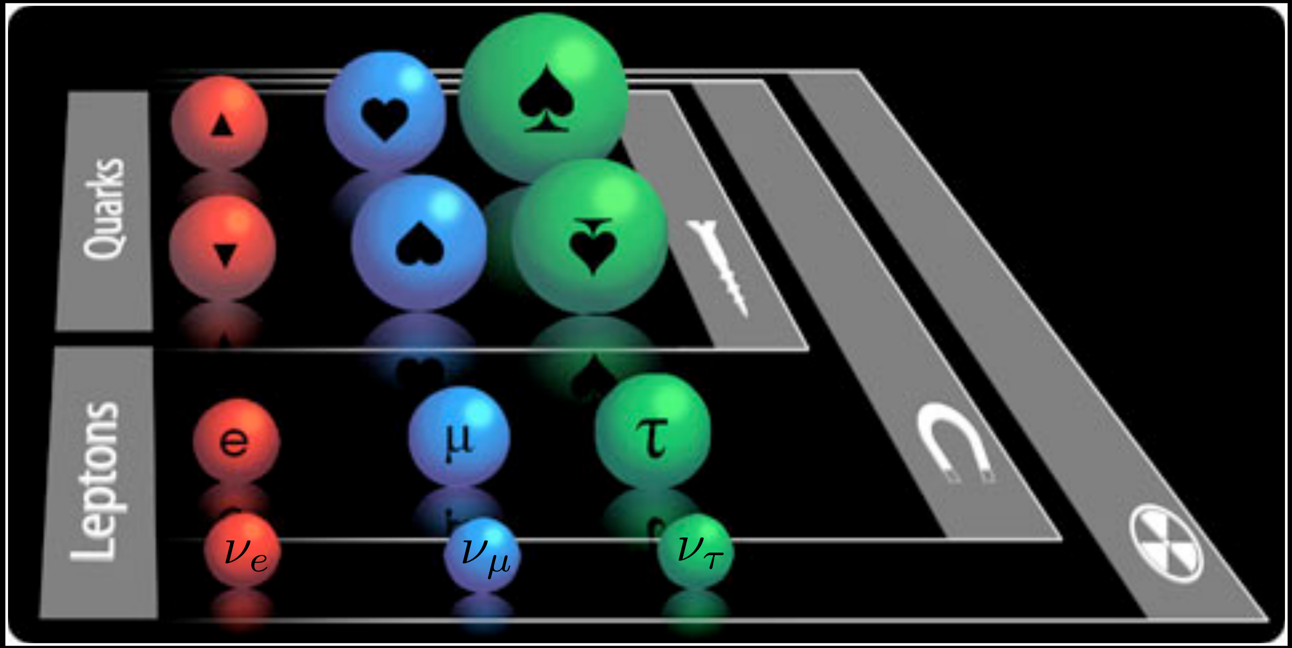
Neutrinos from the Earth

Where do neutrinos come from...?

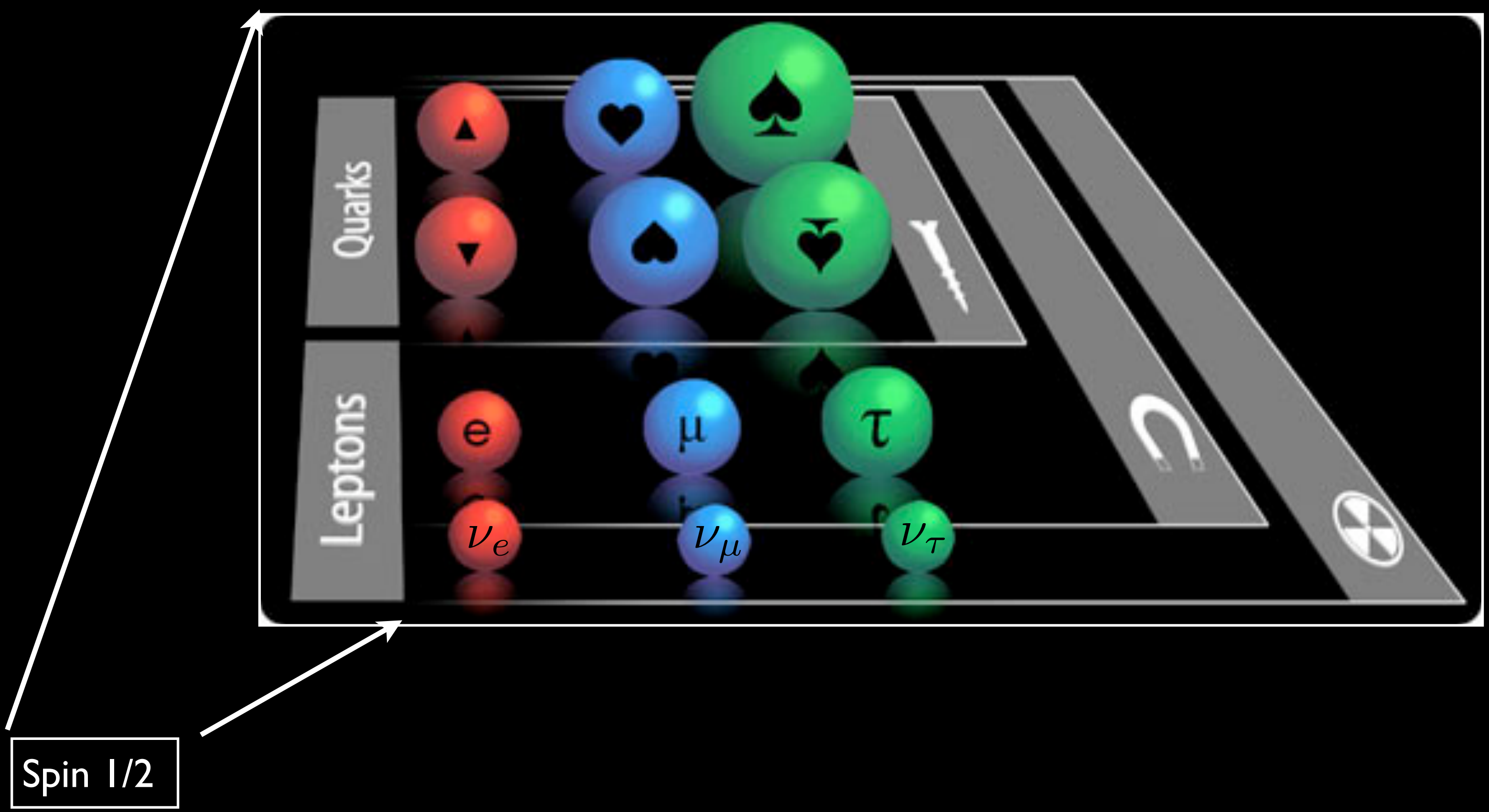


Within the Framework

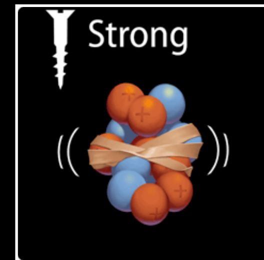
Within the Framework



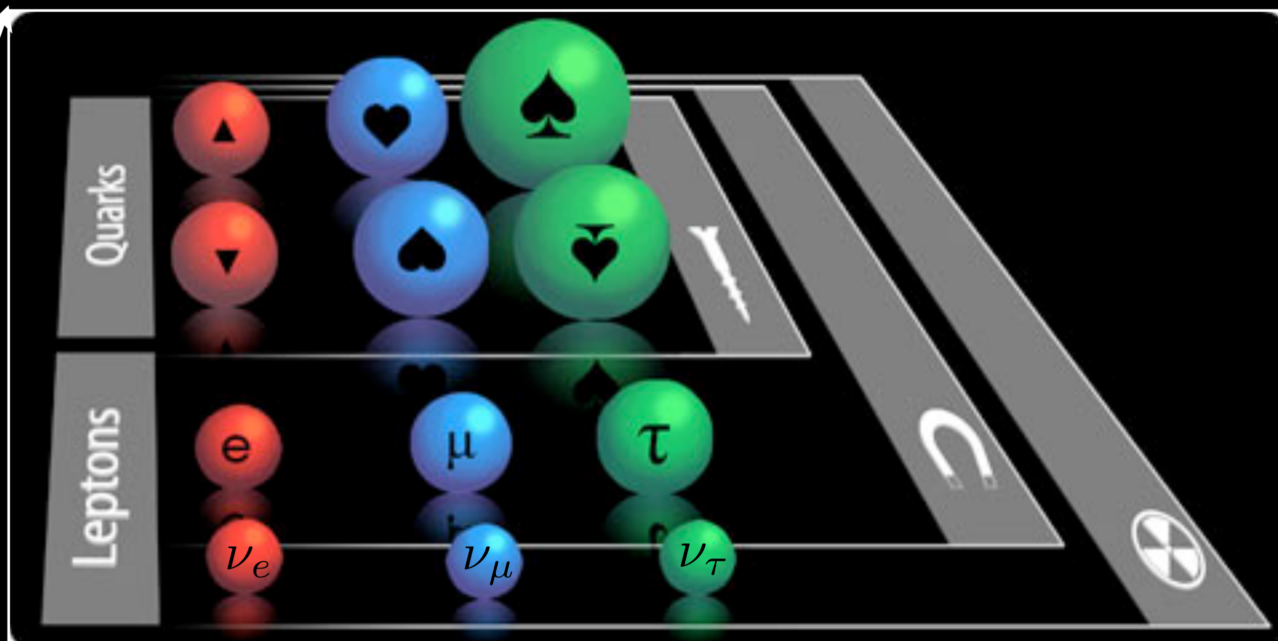
Within the Framework



Within the Framework

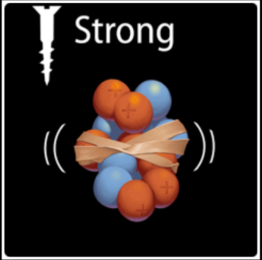


Binds nucleii;
mediated by gluons;
only couples to quarks

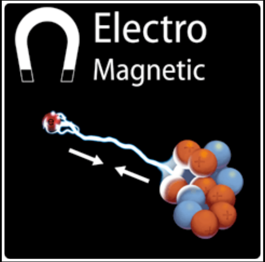


Spin 1/2

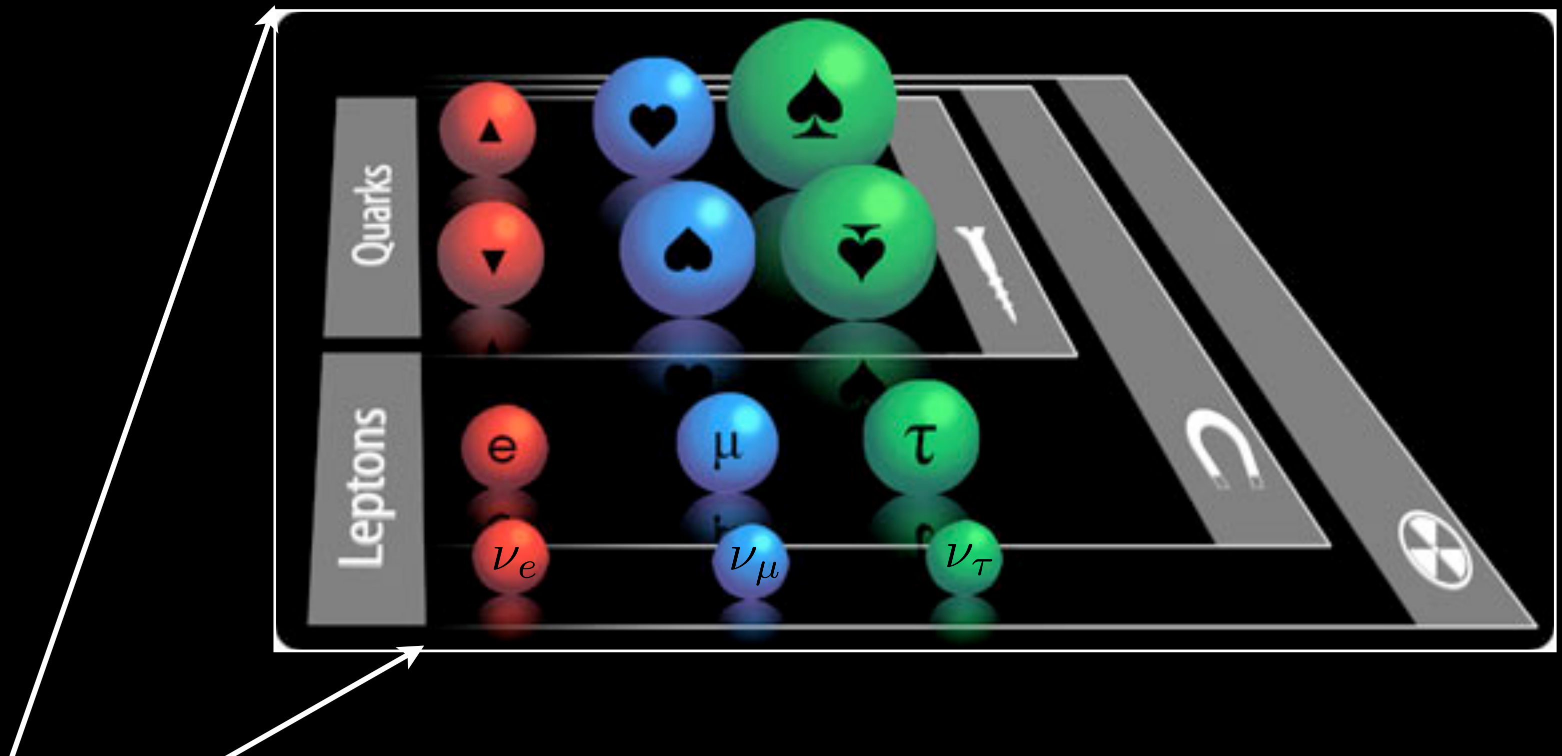
Within the Framework



Binds nucleii;
mediated by gluons;
only couples to quarks

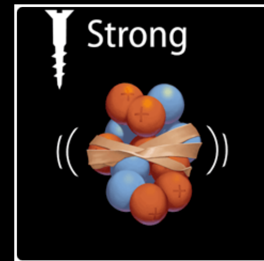


Couples to charge;
mediated by photons;
felt by quarks and leptons

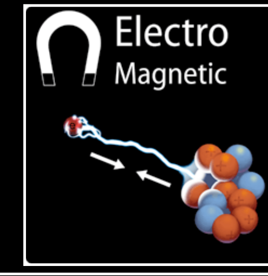


Spin 1/2

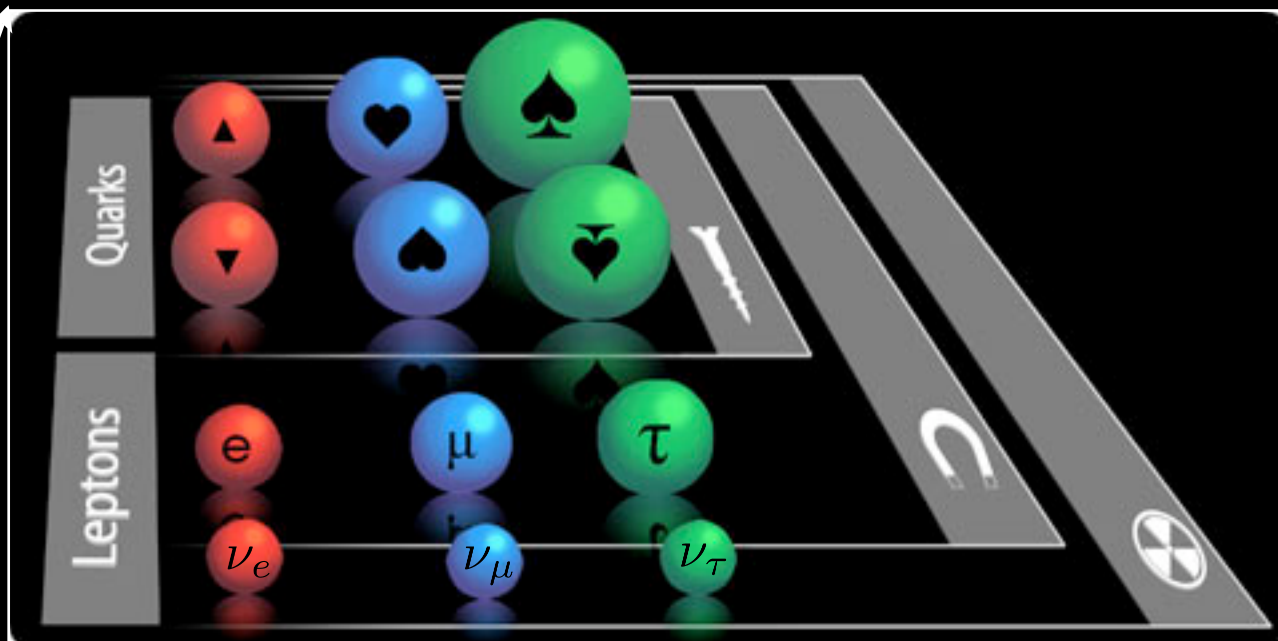
Within the Framework



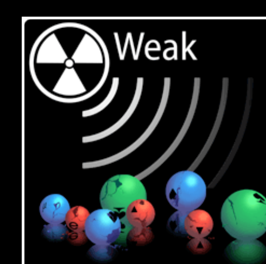
Binds nucleii;
mediated by gluons;
only couples to quarks



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

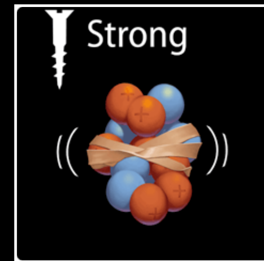


Spin 1/2

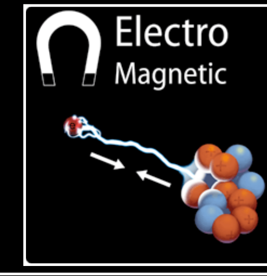


Common to all particles;
mediated by the $W^{\pm}/Z^0$ bosons.

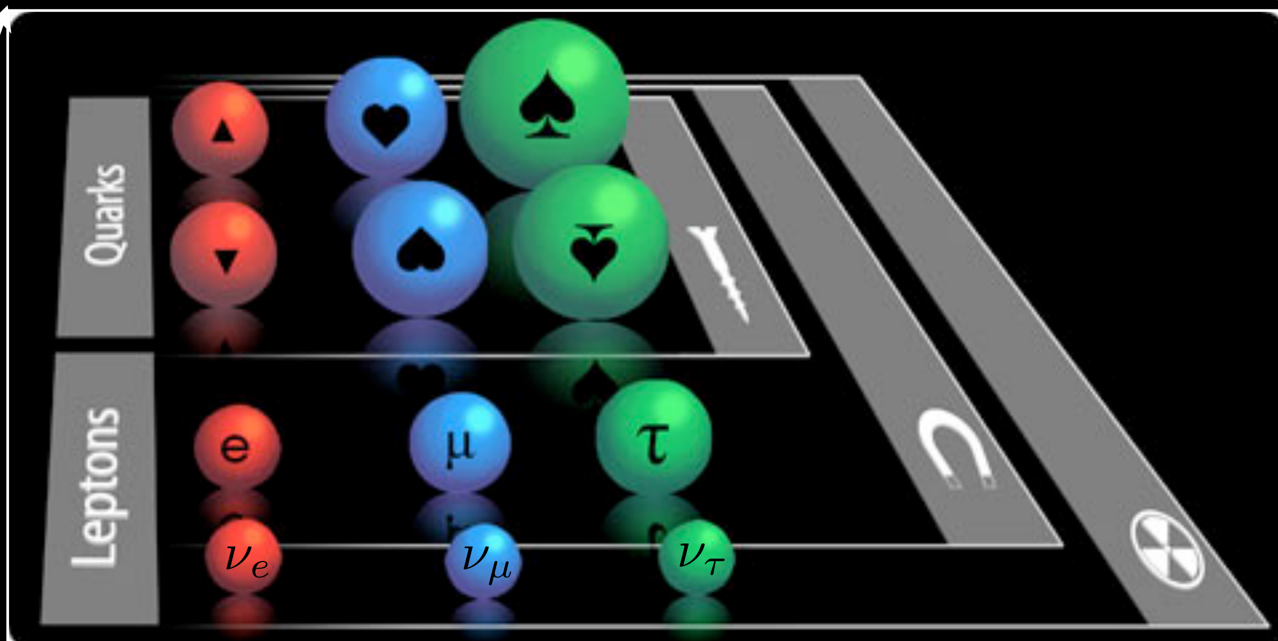
Within the Framework



Binds nucleii;
mediated by gluons;
only couples to quarks

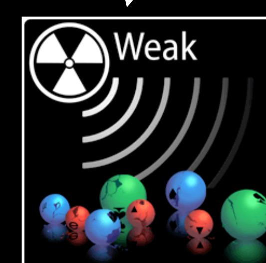


Couples to charge;
mediated by photons;
felt by quarks and leptons



Spin 1

Spin 1/2

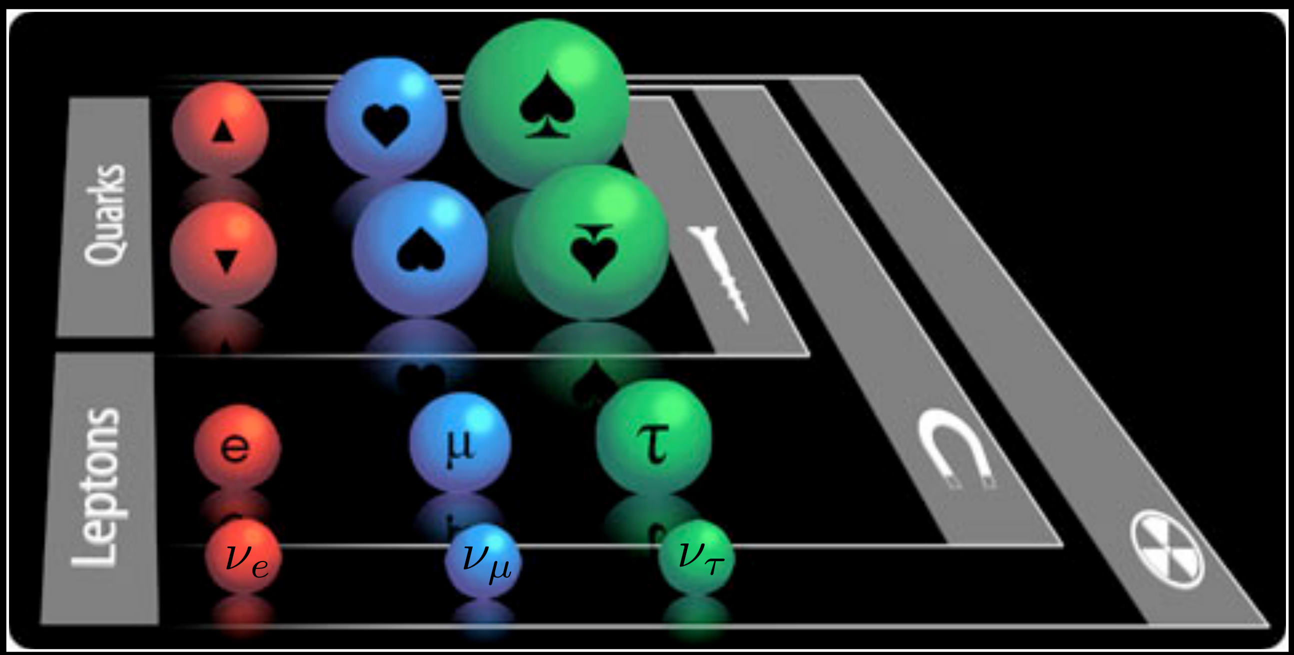


Common to all particles;
mediated by the $W^{\pm}/Z^0$ bosons.

Limited Interactions

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

The number of interactions, therefore, is quite limited.

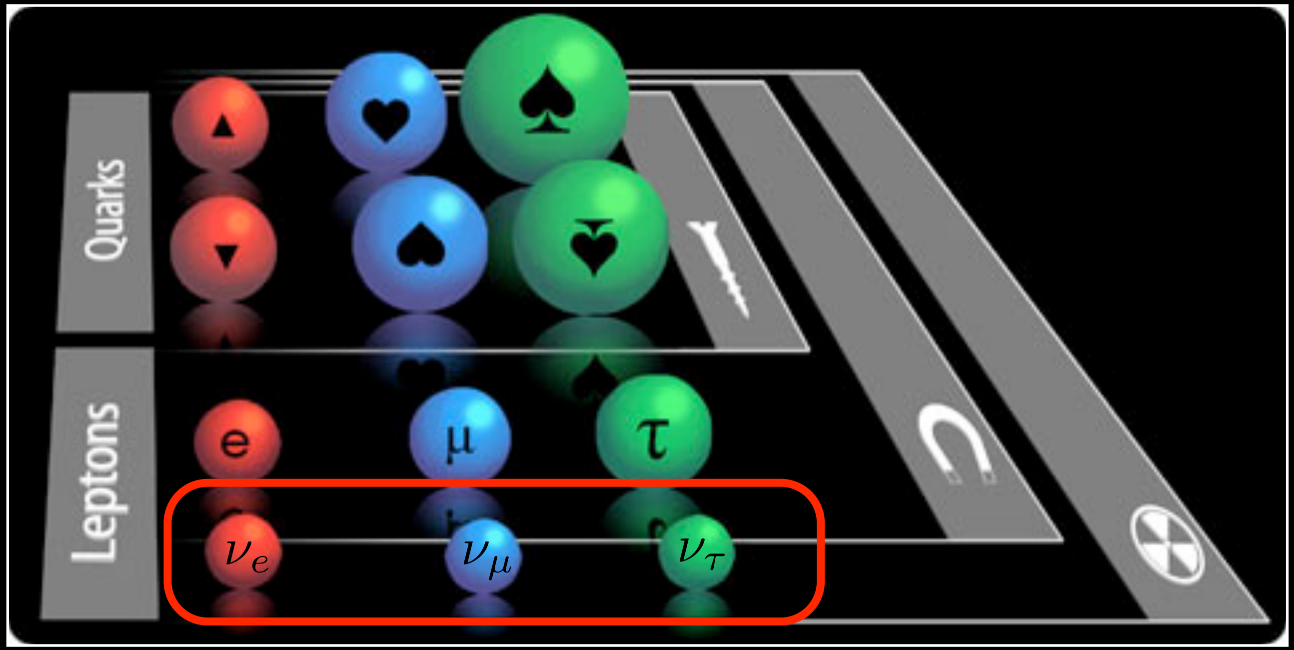


Common to all particles; mediated by the $W^{\pm}/Z^0$ bosons.

Limited Interactions

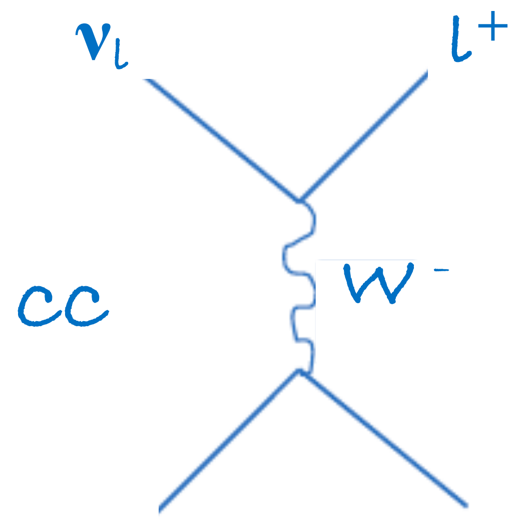
Unlike all the other particles, neutrinos can only interact via with the weak force.

The number of interactions, therefore, is quite limited.

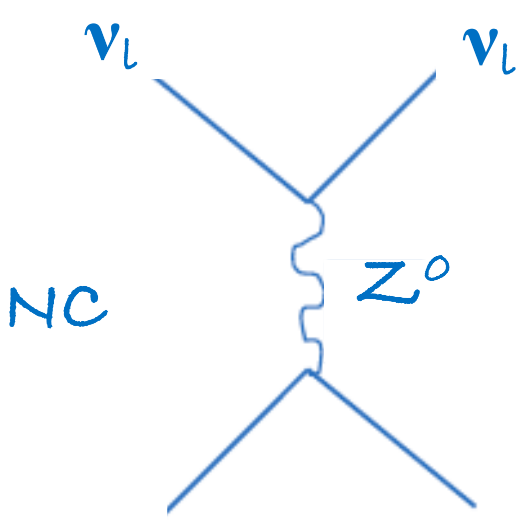


Common to all particles;
mediated by the $W^{\pm}/Z^0$ bosons.

Two Basic Interactions



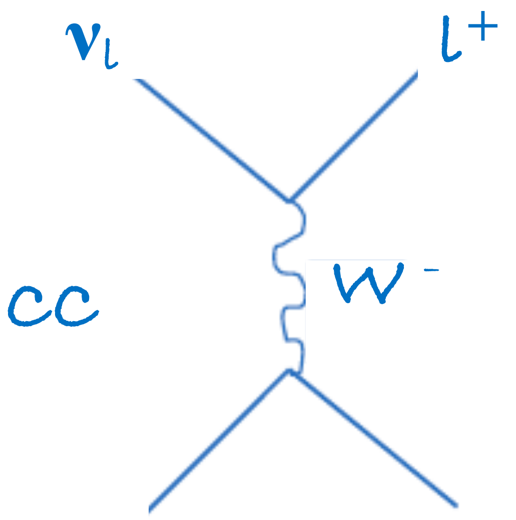
Charged Current



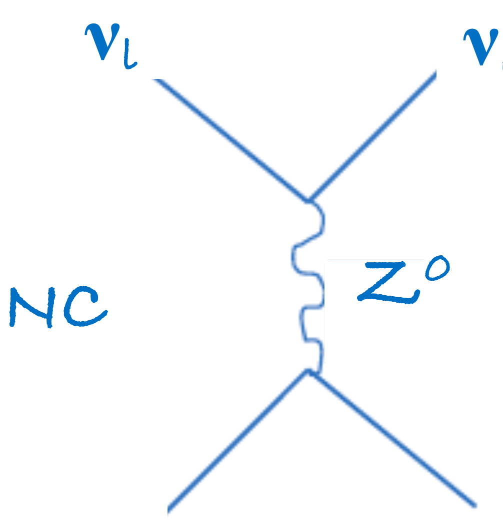
Neutral Current

Most interactions are limited to two basic type of interactions:

Two Basic Interactions



Charged Current

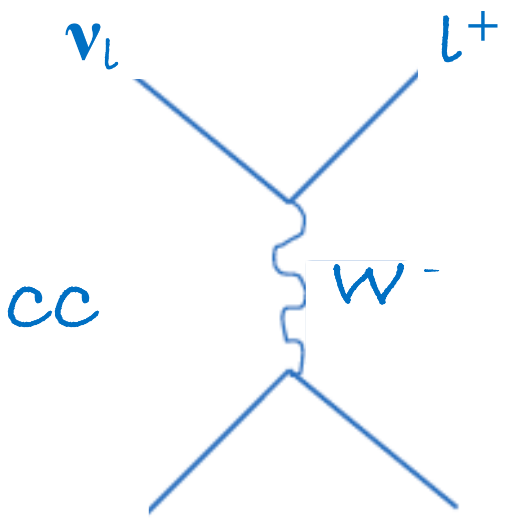


Neutral Current

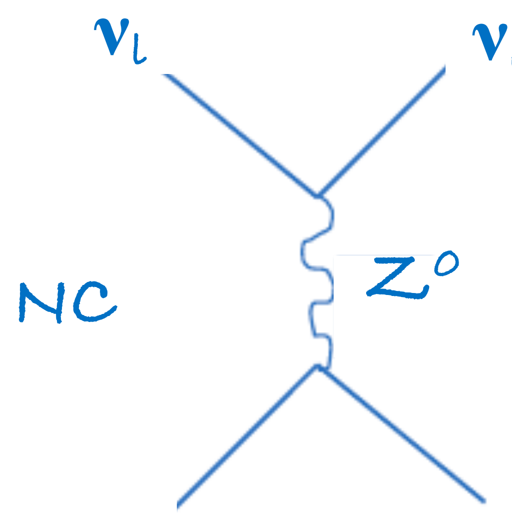
Most interactions are limited to two basic type of interactions:

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

Two Basic Interactions



Charged Current



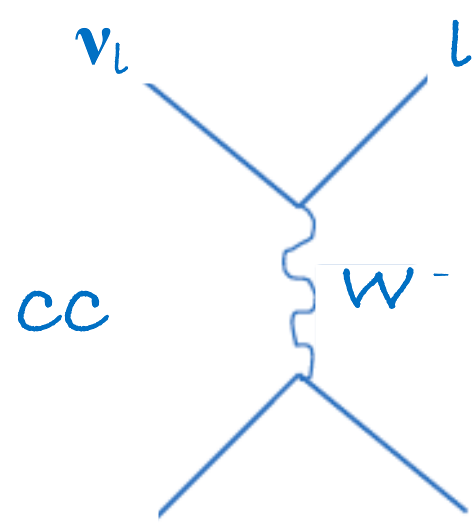
Neutral Current

Most interactions are limited to two basic type of interactions:

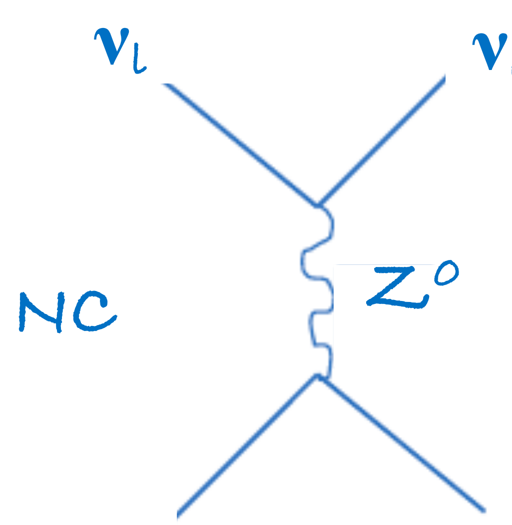
A charge $W^{\pm}$ is exchanged: Charged Current Exchange

A neutral Z^0 is exchanged: Neutral Current Exchange

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

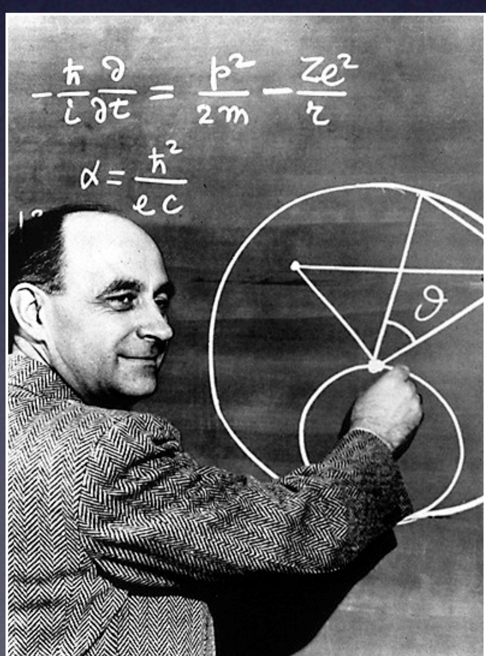
A neutral Z^0 is exchanged: Neutral Current Exchange

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:

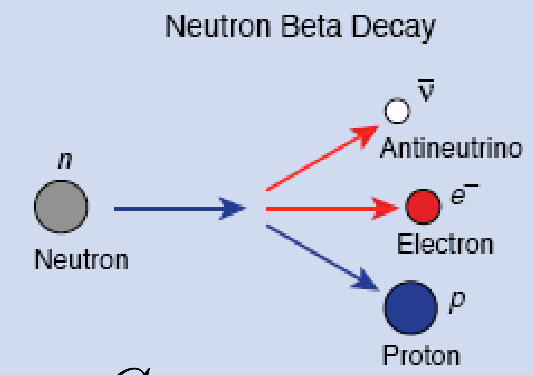


E. Fermi

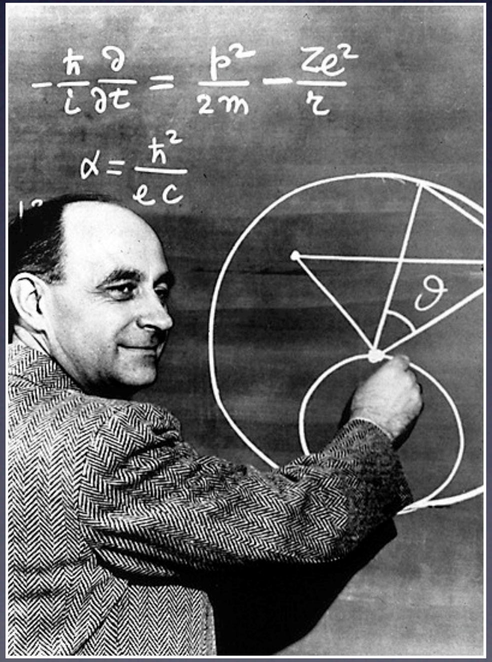
How Neutrinos Interact

- 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:



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



E. Fermi

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

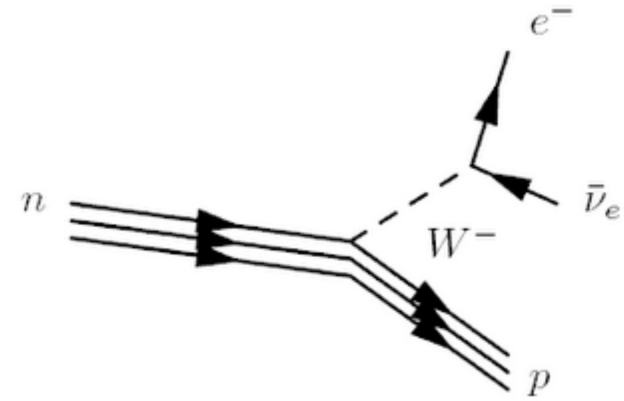
- The system does not have many of the features of the Standard Model, yet still remarkably descriptive.

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

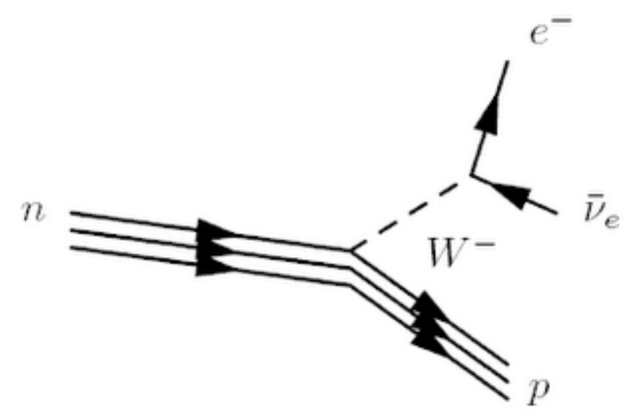
A Misnomer

- 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...

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

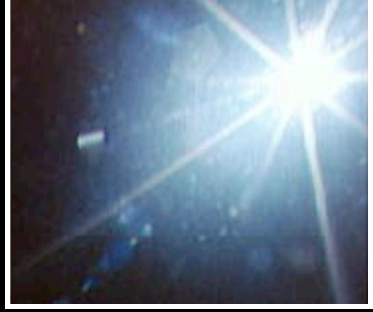
What Neutrinos do I Expect?

- 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.

What Neutrinos do I Expect?

E_ν~keV



- 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.

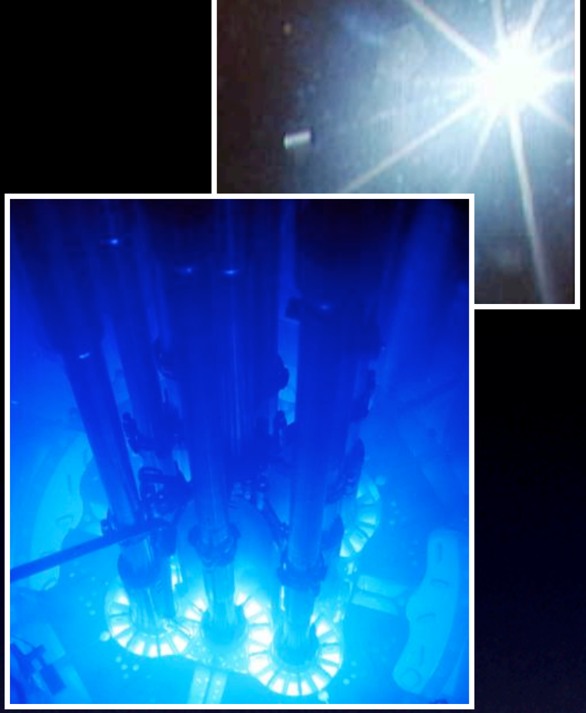
- If lepton flavor is conserved, then even the type of neutrino can be determined. However, neutrino oscillations clearly spoils this rule.

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.

$E_\nu \sim \mathrm{MeV}$



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_ν~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.

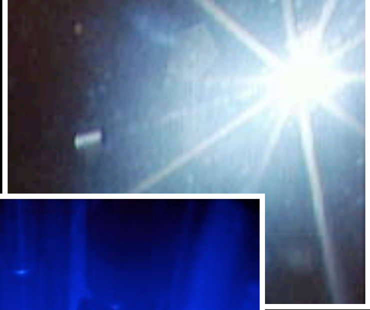
- If lepton flavor is conserved, then even the type of neutrino can be determined. However, neutrino oscillations clearly spoils this rule.

E_{ν}~GeV - TeV

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.





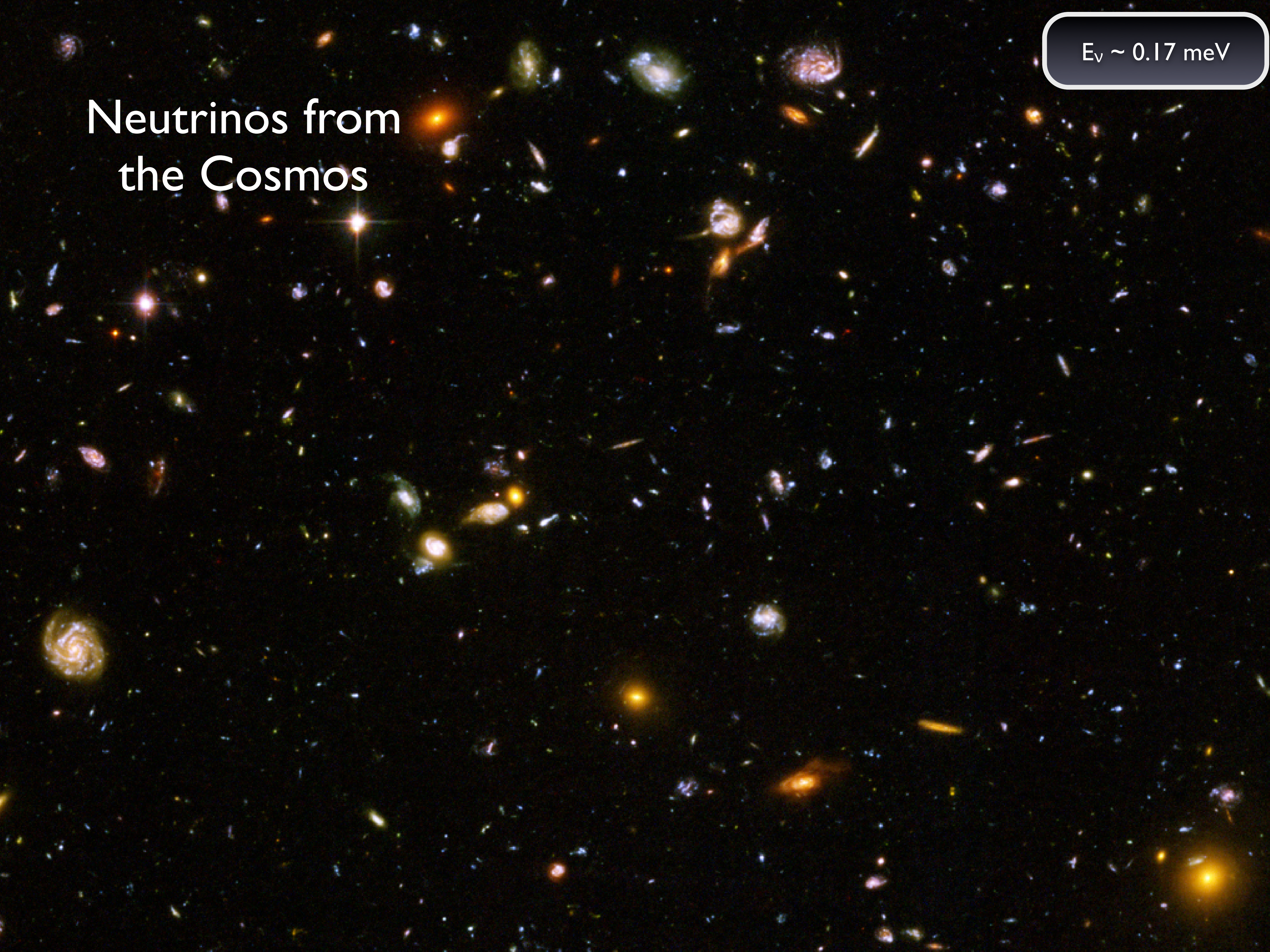
E_ν >> TeV

What we will cover:

Where do neutrinos come from?

Neutrinos from the Heavens

Neutrinos from the Earth


Neutrinos from the Cosmos
E_ν ~ 0.17 meV

E_{ν} ~ 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.

$E_\nu \sim 0.17$ 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.

$E_\nu \sim 0.17$ 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.

$E_\nu \sim 0.17$ 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.

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.

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

Annihilation Rate

Neutrino decoupling occurs when two rates are equal.

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.

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

Annihilation Rate

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

Expansion Rate

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.

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

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

Annihilation Rate

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

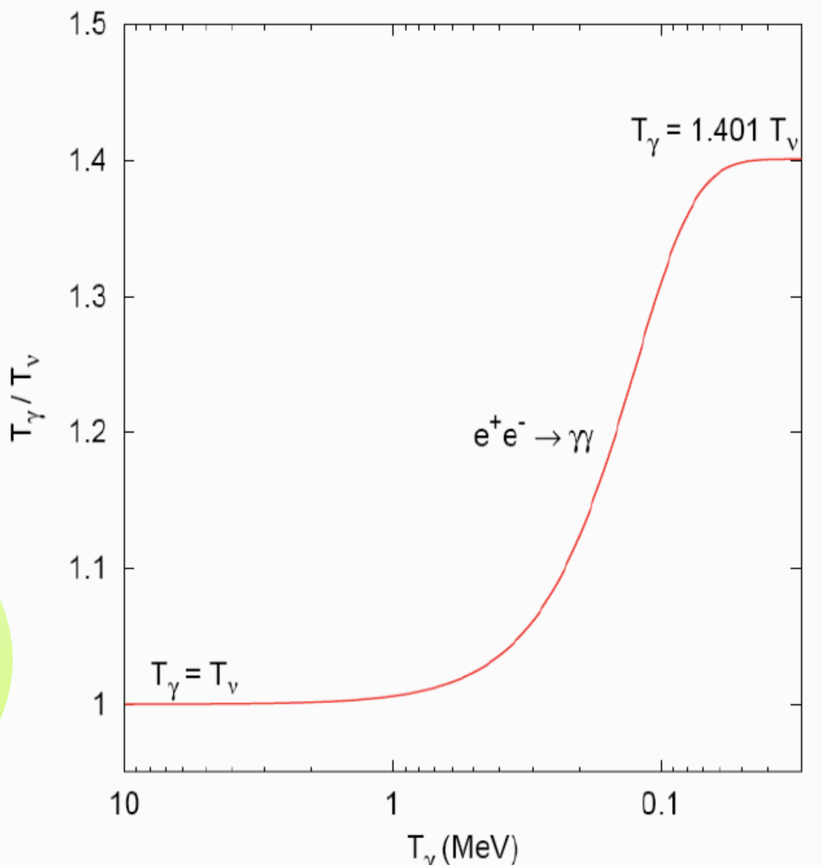
Expansion Rate

Knowledge of the Relic Neutrino Spectrum

- After neutrinos decouple, photons can still continue heating.
- Photon/neutrino temperature directly related to each other.

$$\nu_i \nu_j \rightarrow \nu_i \nu_j$$
$$\nu_i \bar{\nu}_j \rightarrow \nu_i \bar{\nu}_j$$
$$\nu_i e^- \rightarrow \nu_i e^-$$
$$\nu_i \bar{\nu}_j \rightarrow e^+ e^-$$

turn off



$$e^+ e^- \rightarrow \gamma\gamma$$

turn off

$$T_\nu = (\frac{4}{11})^{\frac{1}{3}} T_\gamma$$

Knowledge of the Relic Photon Spectrum

- Photons from the cosmic microwave background still permeate today, cooled from the original decoupling temperature.

- Can be observed as a *perfect* blackbody spectrum with a peak at a frequency of ~175 GHz.

- Could be observed once radar technology was sufficiently developed.

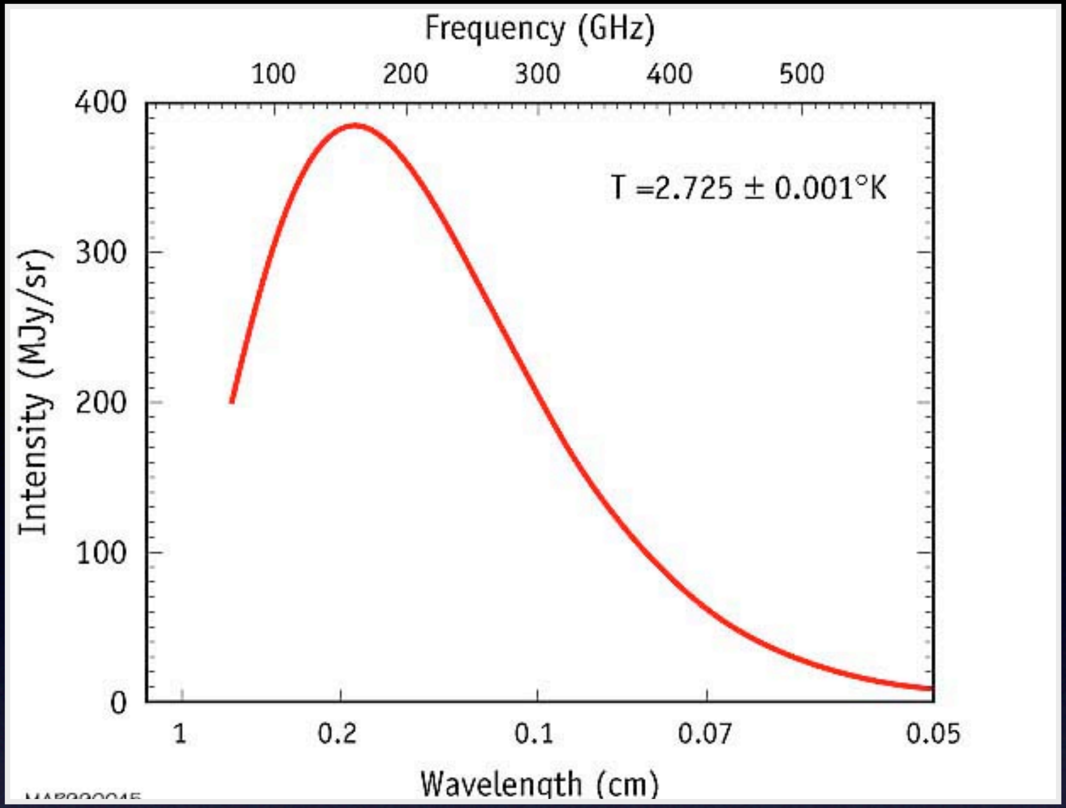
Wilson and Penzias

Wilson and Penzias looked at all possible noise sources, including
“white dielectric deposits of organic origin”

Knowledge of the Relic Photon Spectrum

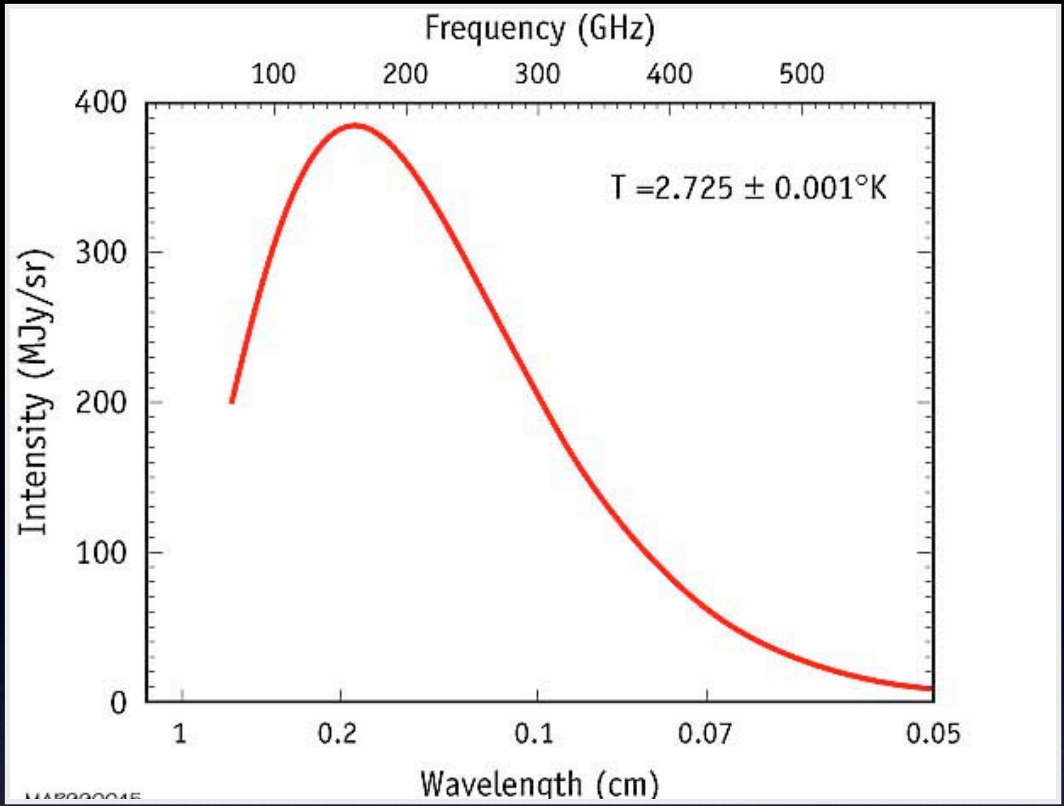
- The cosmic microwave background illustrates a perfect blackbody spectrum:

$$T_\gamma = 2.725 \pm 0.002K$$



- Observation of the cosmic microwave background is now a cornerstone of cosmology. Likewise, is a standard prediction of cosmology and the Standard Model.

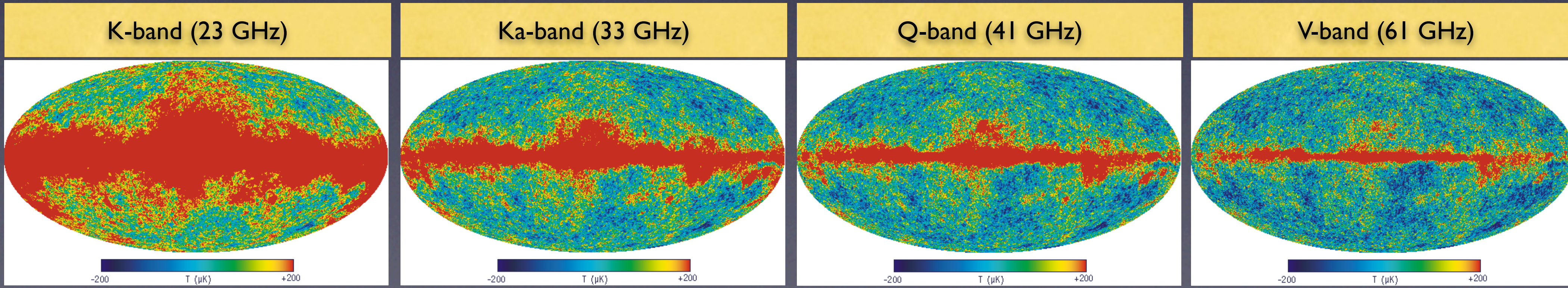
Knowledge of the Relic Photon Spectrum



- The cosmic microwave background illustrates a perfect blackbody spectrum:

$$T_\gamma = 2.725 \pm 0.002 K$$

- Observation of the cosmic microwave background is now a cornerstone of cosmology. Likewise, is a standard prediction of cosmology and the Standard Model.



Primordial Nucleosynthesis

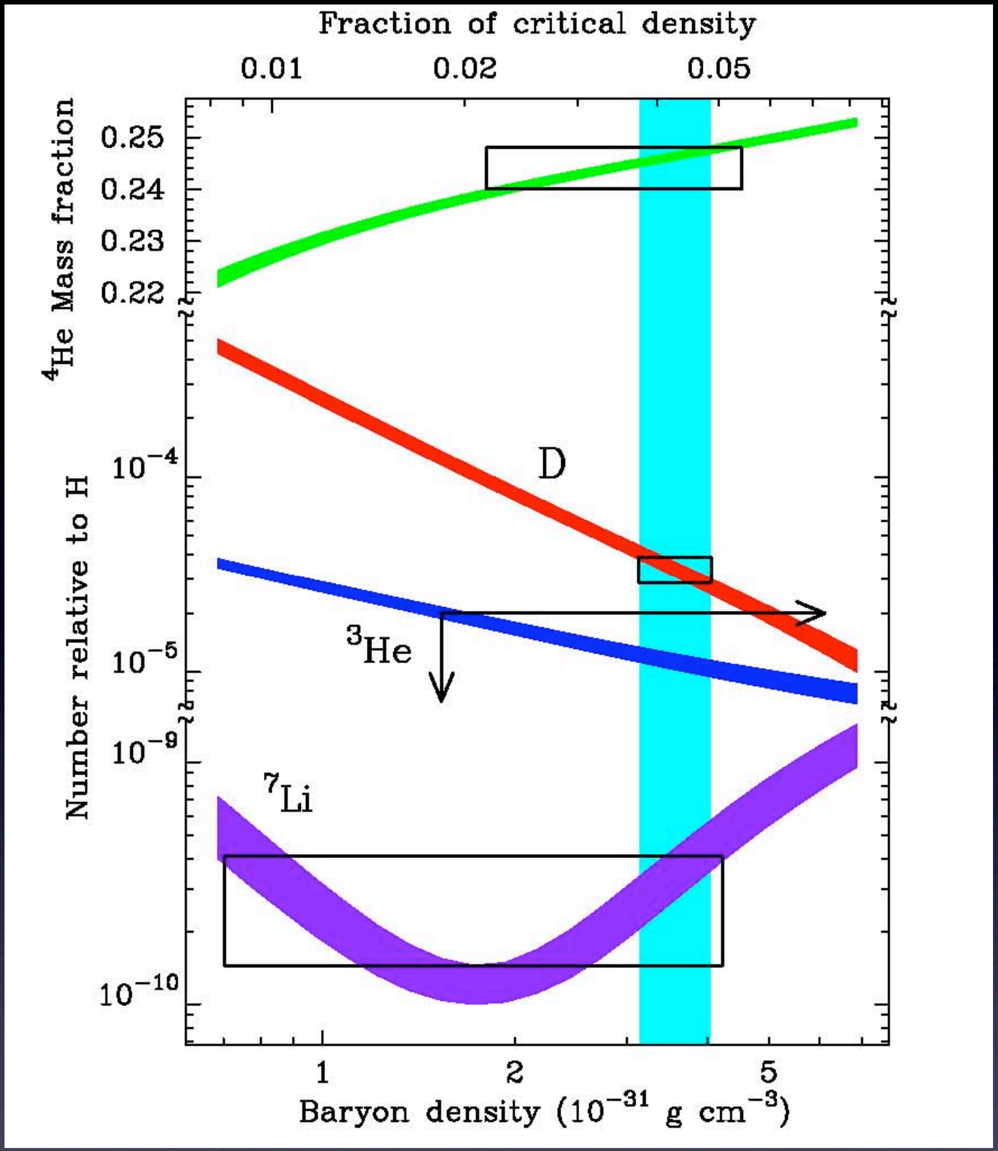
- Eventually neutrinos also decouple from neutrons and protons (below 1 MeV)

- This governs the production rate of light elements. These include elements such as ^2H, ^3He, ^4He, and ^7Li.

$$\rho_r = \rho_\gamma + \rho_\nu = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \rho_\gamma$$

- These abundances depend on the baryon density ratio, η_{10}, and the expansion rate of the universe.

$$\eta_{10} \equiv 10^{10}(n_B/n_\gamma)$$



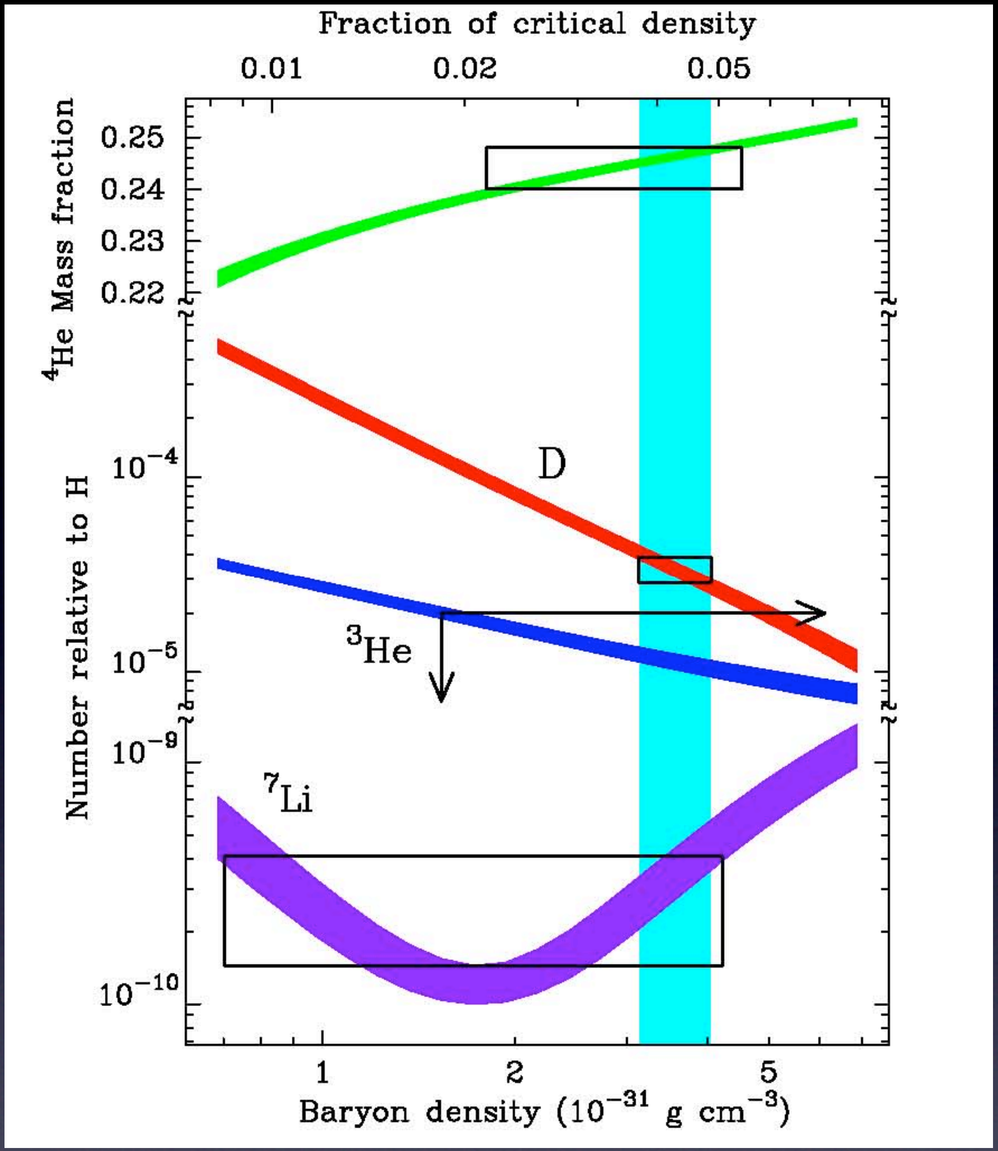
Primordial Nucleosynthesis

- Eventually neutrinos also decouple from neutrons and protons (below 1 MeV)

- This governs the production rate of light elements. These include elements such as ^2H, ^3He, ^4He, and ^7Li.

$$\rho_r = \rho_\gamma + \rho_\nu = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \rho_\gamma$$

- These abundances depend on the baryon density ratio, η_{10}, and the expansion rate of the universe.

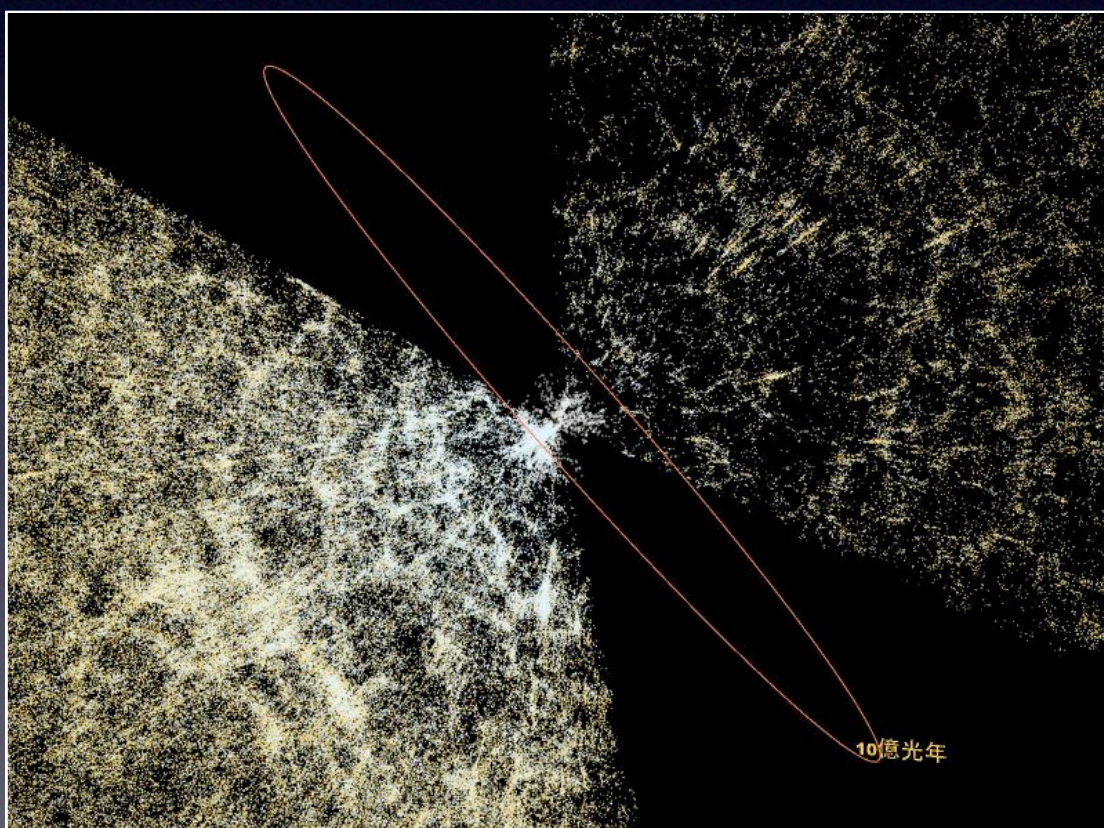


$$\eta_{10} \equiv 10^{10}(n_B/n_\gamma)$$

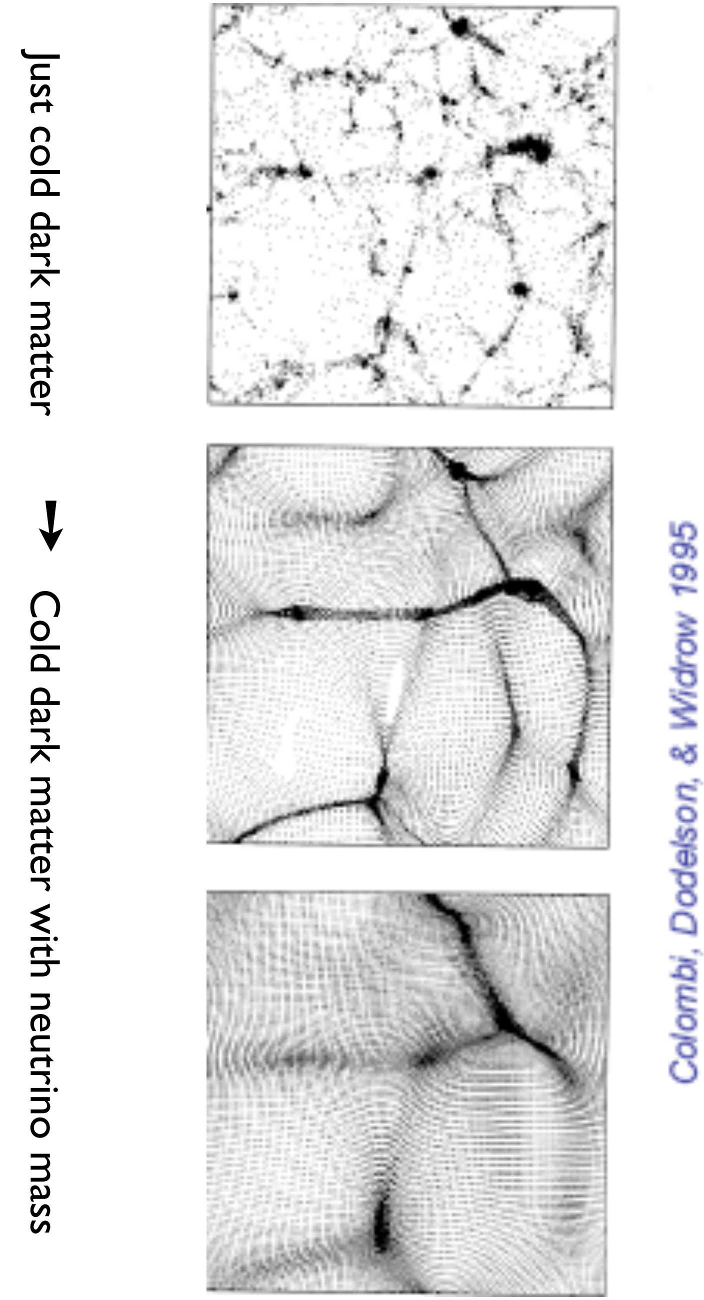
This quantity is unchanged at BBN, recombination, and now

Large Scale Structure

- Neutrinos can also affect the clustering of galaxies (affected both by the number of neutrino species and the mass of the neutrinos)



Large Scale Sctructure



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

The Triumph of Cosmology

The Triumph of Cosmology

Microwave Background

400 kyr
z =1100

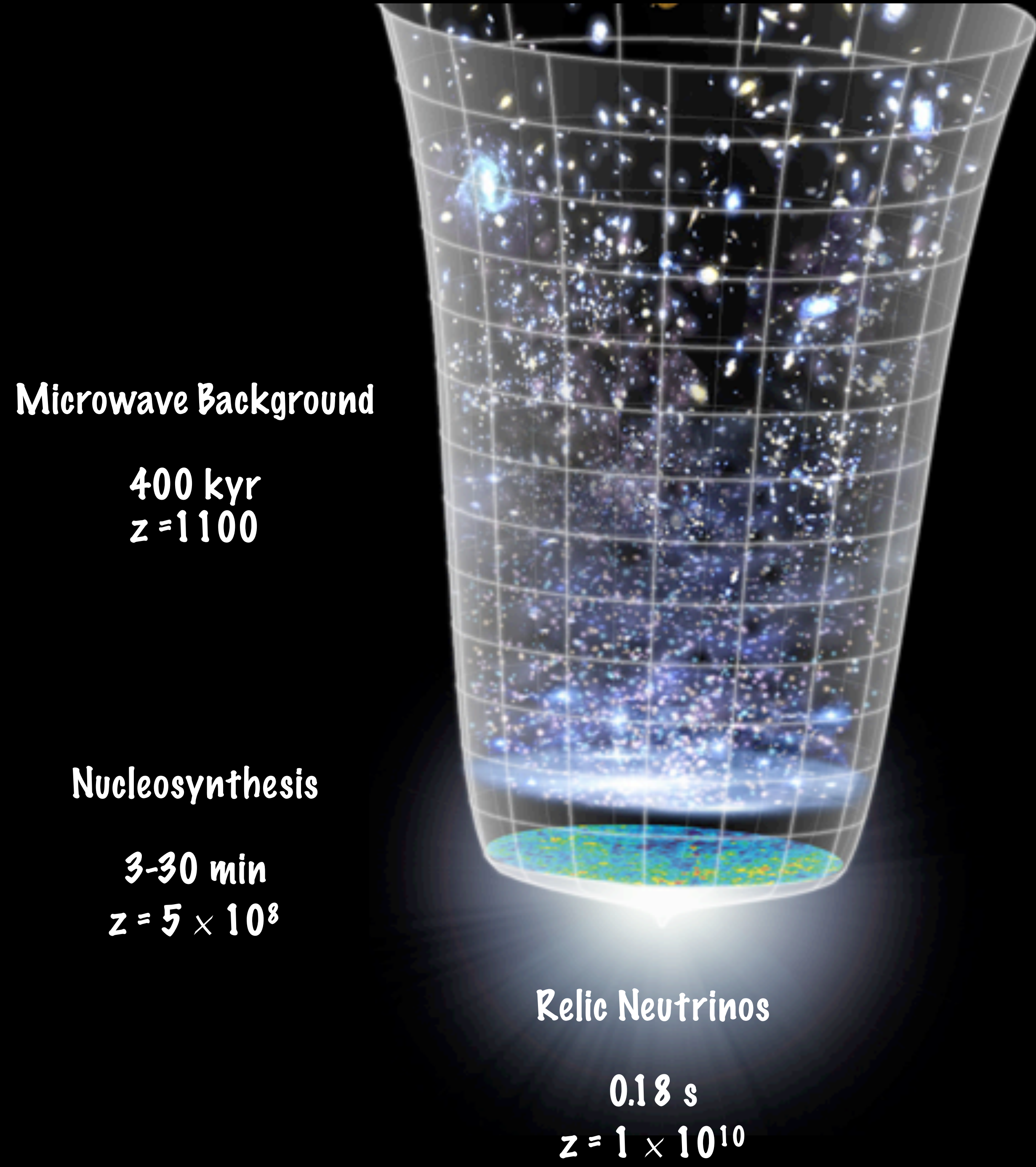
Nucleosynthesis

3-30 min
$z = 5 \times 10^8$

Relic Neutrinos

0.18 s
$z = 1 \times 10^{10}$

The Triumph of Cosmology



- The combination of the standard model of particle physics and general relativity allows us to relate events taking place at different epochs together.

The Triumph of Cosmology

Microwave Background

400 kyr
$z = 1100$

Nucleosynthesis

3-30 min
$z = 5 \times 10^8$

Relic Neutrinos

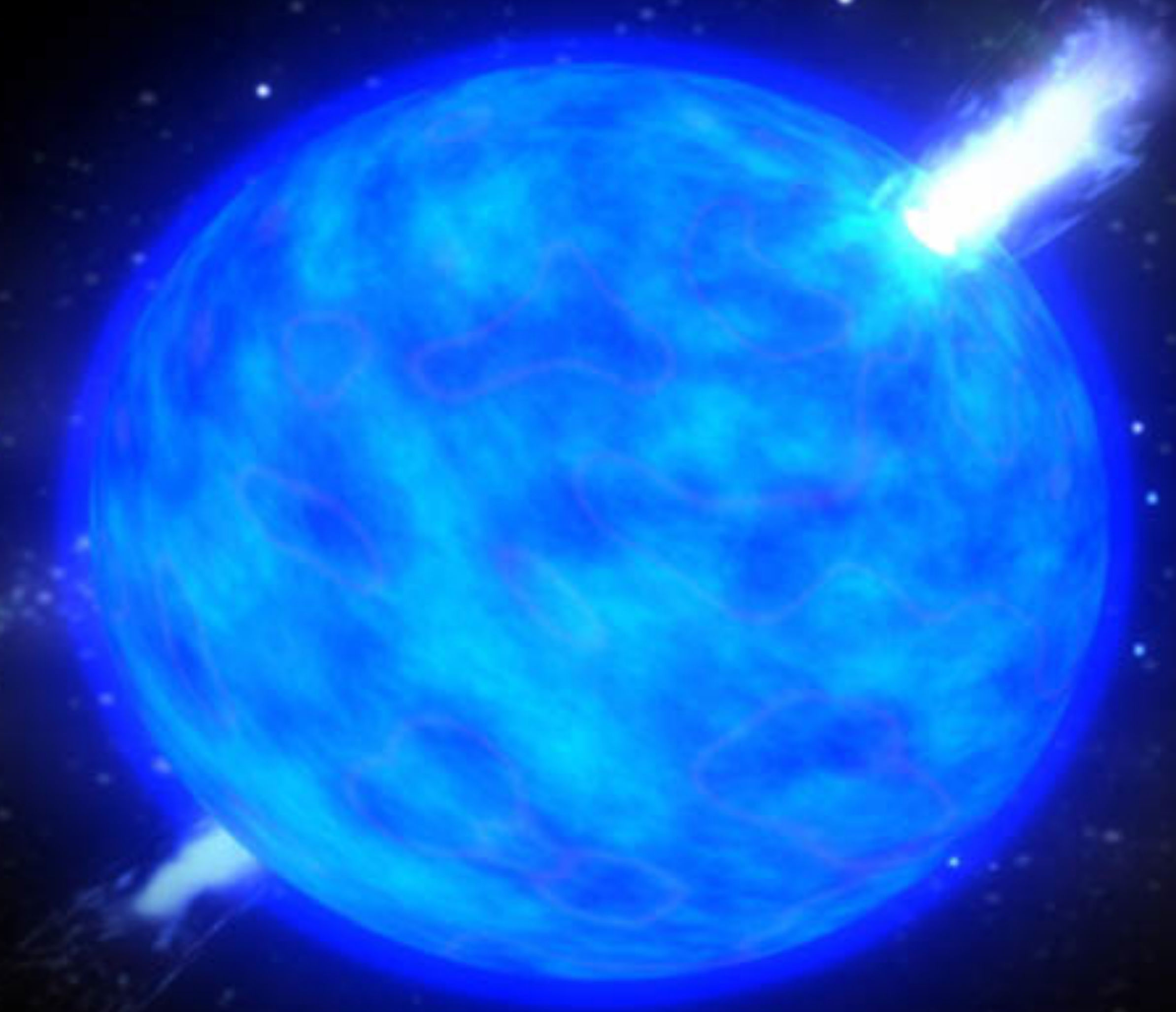
0.18 s
$z = 1 \times 10^{10}$

- The combination of the standard model of particle physics and general relativity allows us to relate events taking place at different epochs together.
- Observation of the cosmological neutrinos would then provide a window into the 1^{st} second of creation

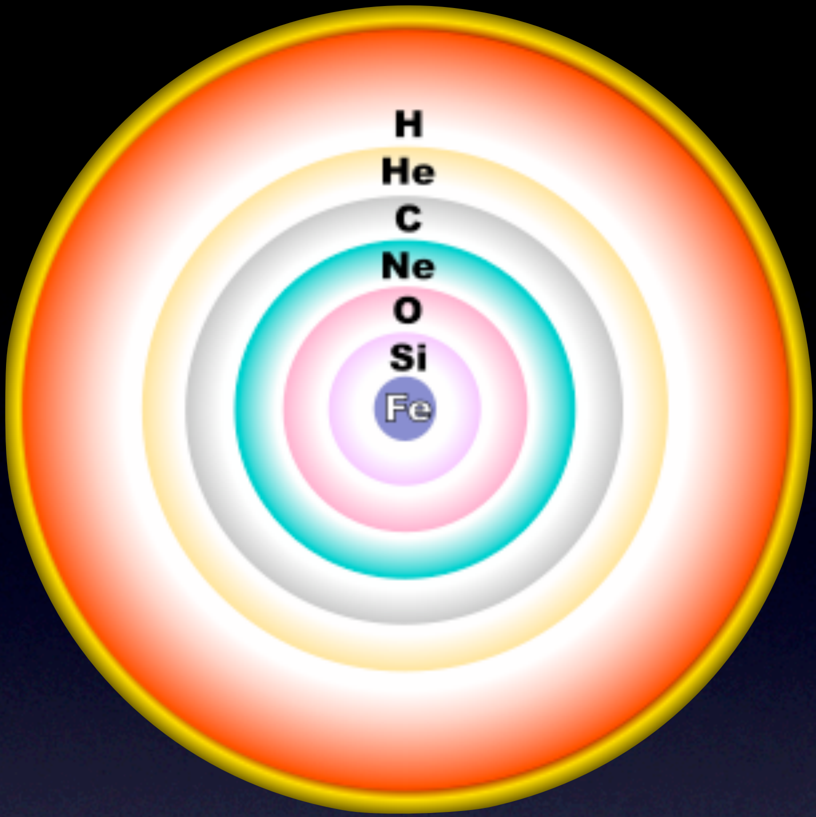
$E_\nu \sim 10\text{-}20$ MeV

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.



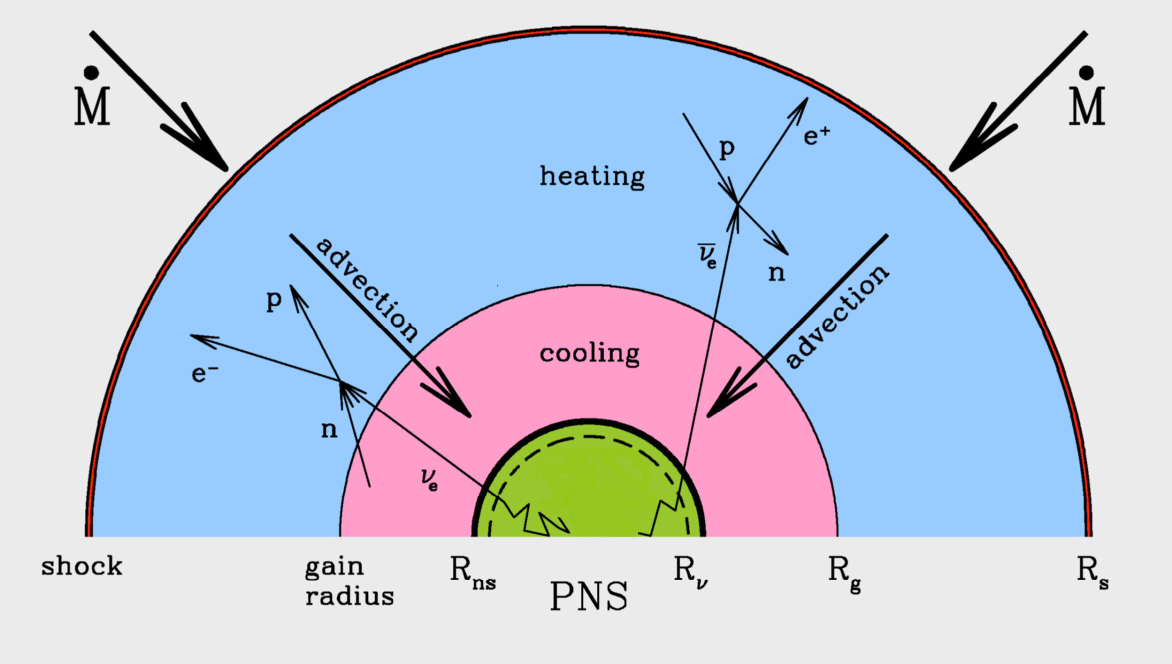
Neutrinos from the Stars



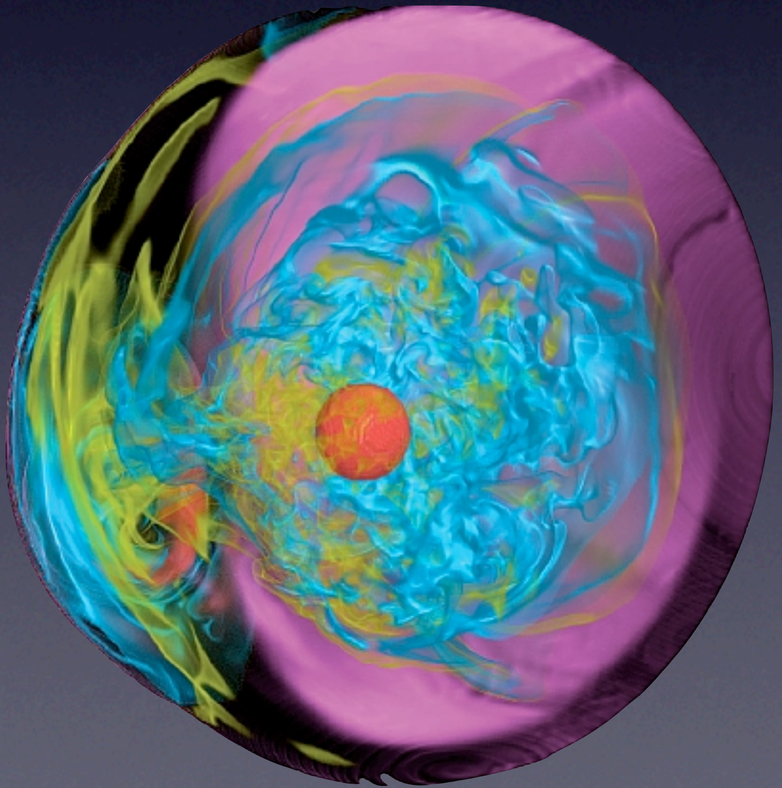
- Core-collapse supernovae are truly unique environments in our known universe:
  - Incredible matter densities: 10^{11}-10^{15} g/cm^3
  - Extreme high temperature: 1-50 MeV
  - Highest recorded energetic processes in the Universe: 10^{51-53} ergs
- At these energies, all species of neutrinos can be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



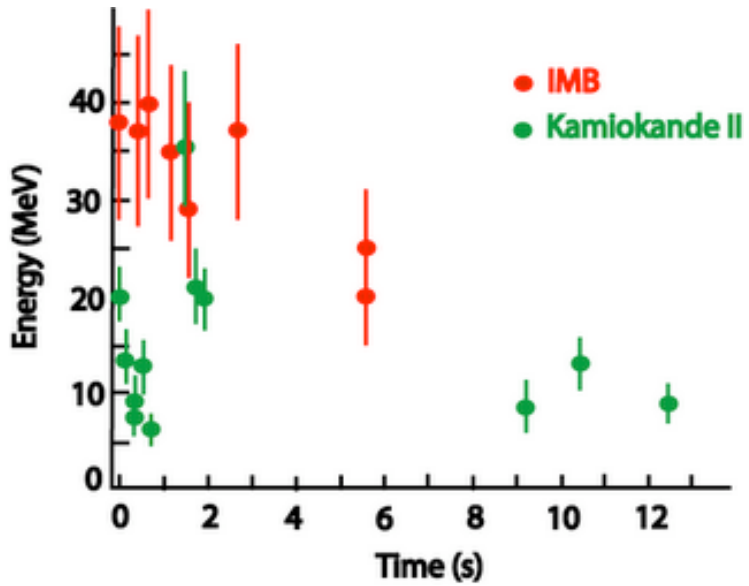
- Eventually nuclear burning is insufficient to maintain the star from collapsing, causing the stellar core to fall inward until core densities reach nuclear levels, causing the core to bounce.
- Most neutrinos remain trapped between core and outer stellar region, heating the star until the energy is 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.

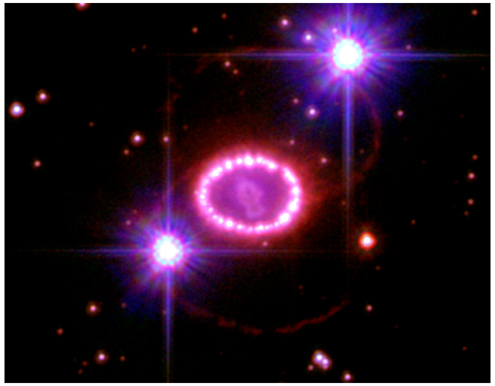
- Still waiting for another such type of explosion close enough for detection.



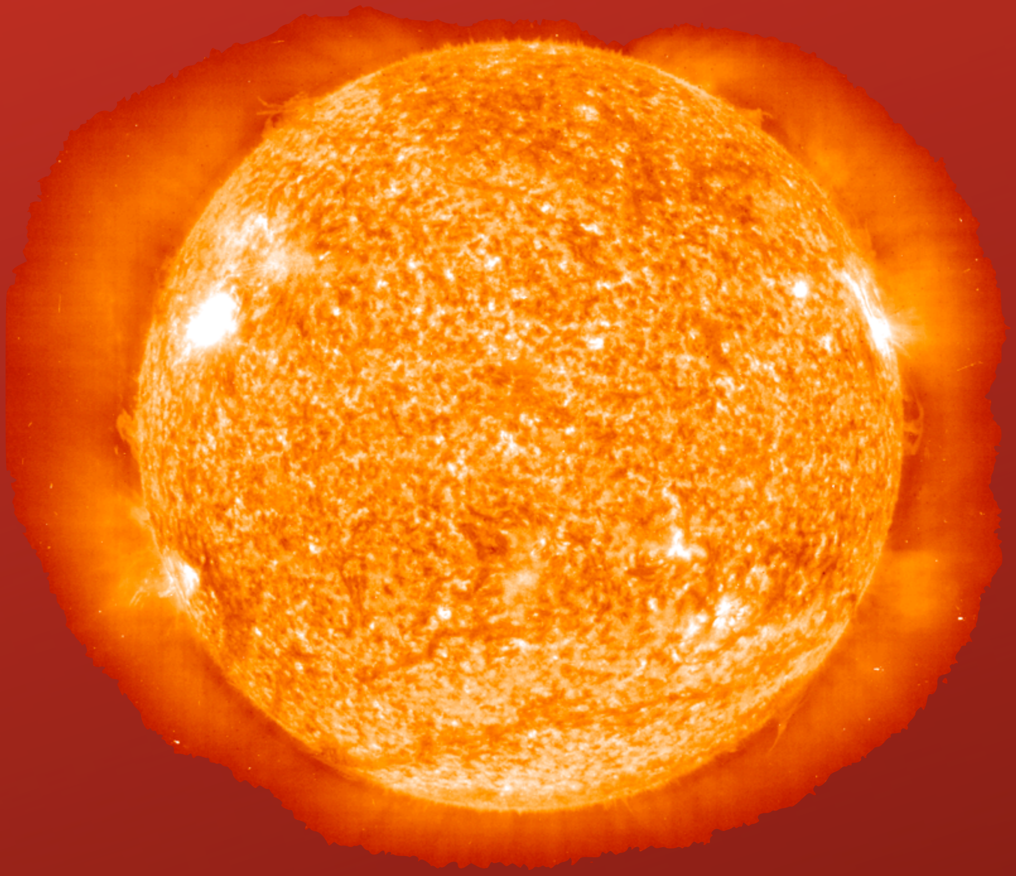
Before

During
(few days later)

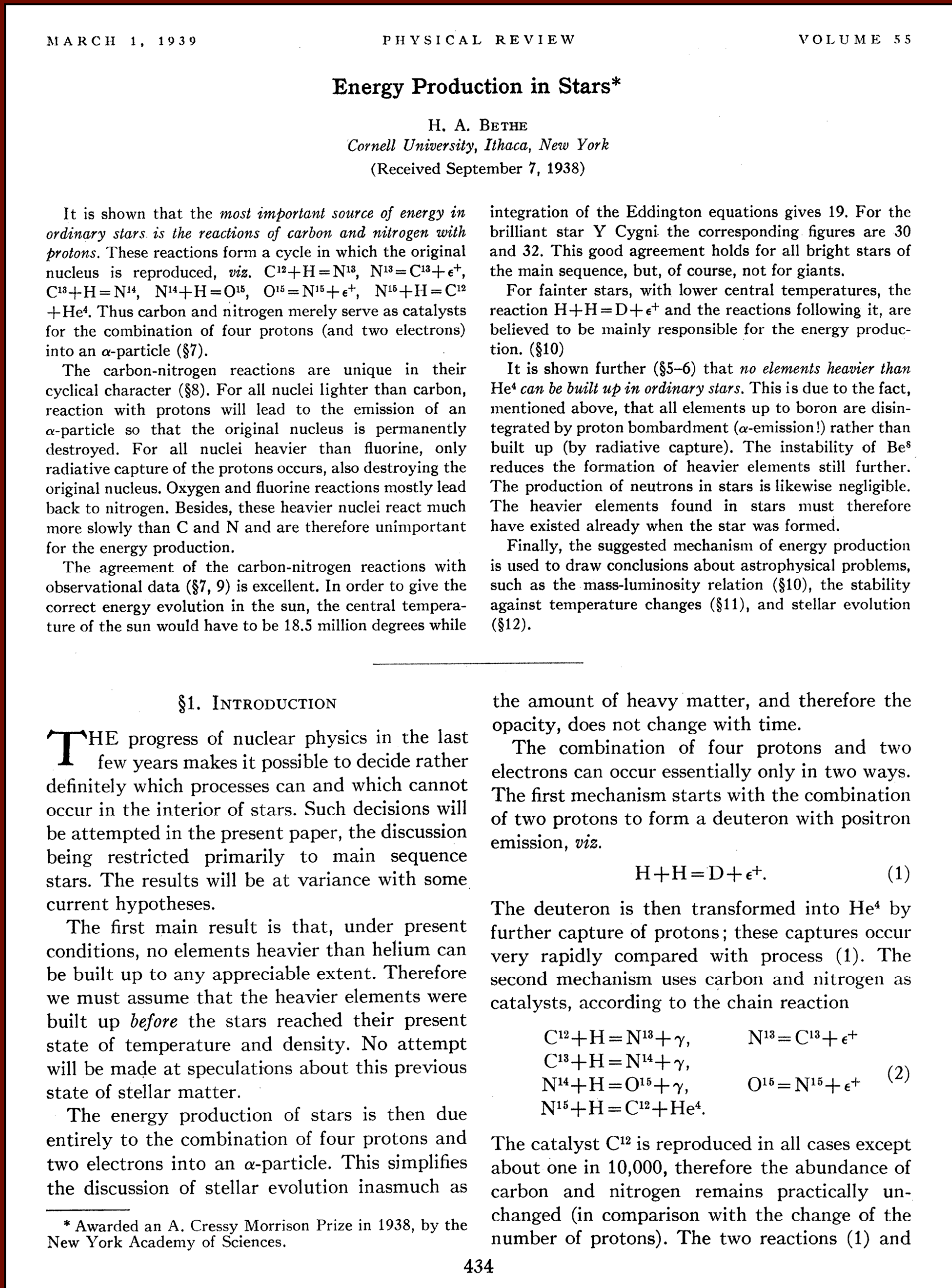
After



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



Neutrinos from our star...
(the Sun)



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.*

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

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

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

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

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

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.*

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

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

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

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.

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.*

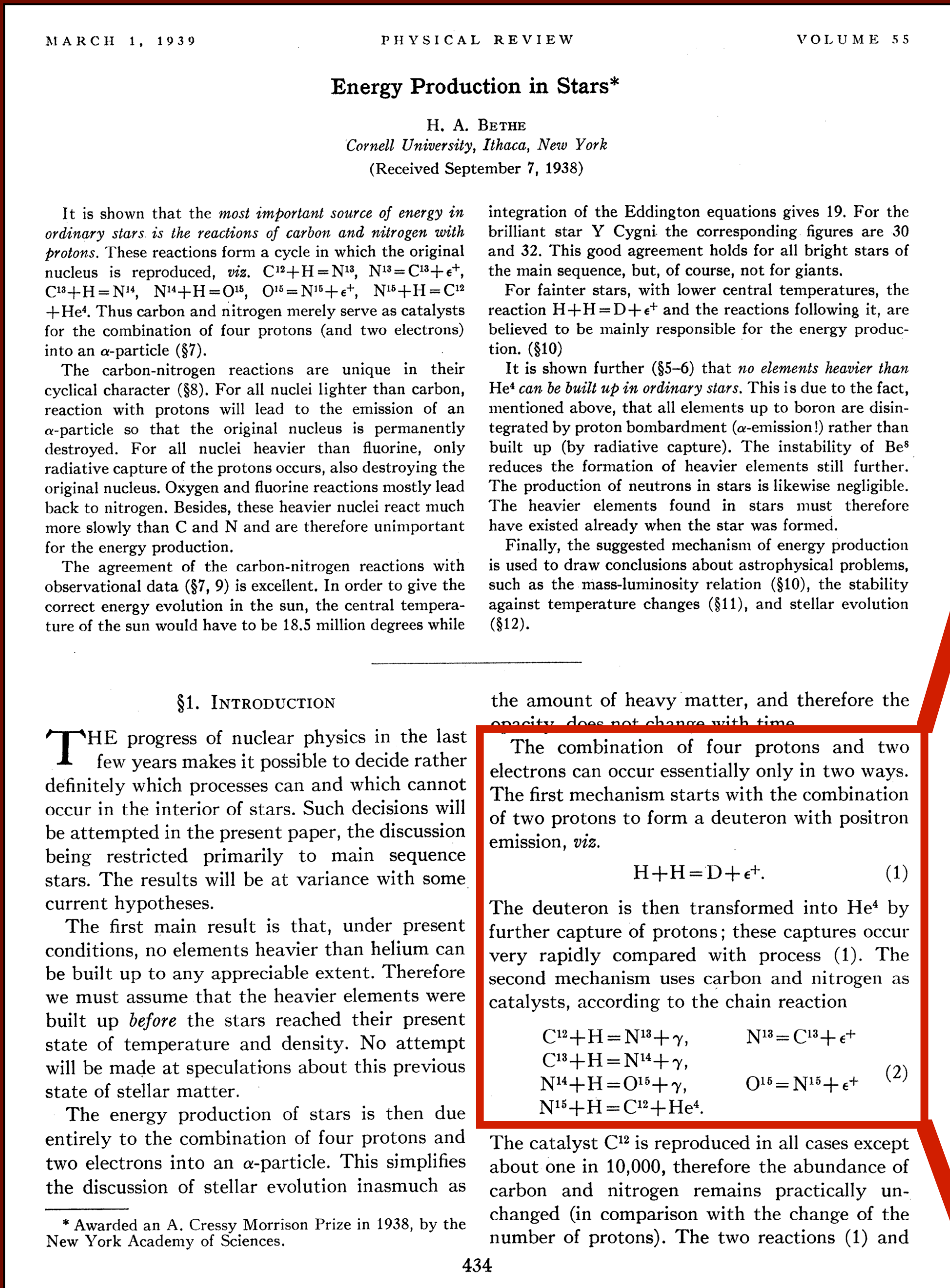
$$H+H=D+\epsilon^+. \quad (1)$$

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

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

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.*

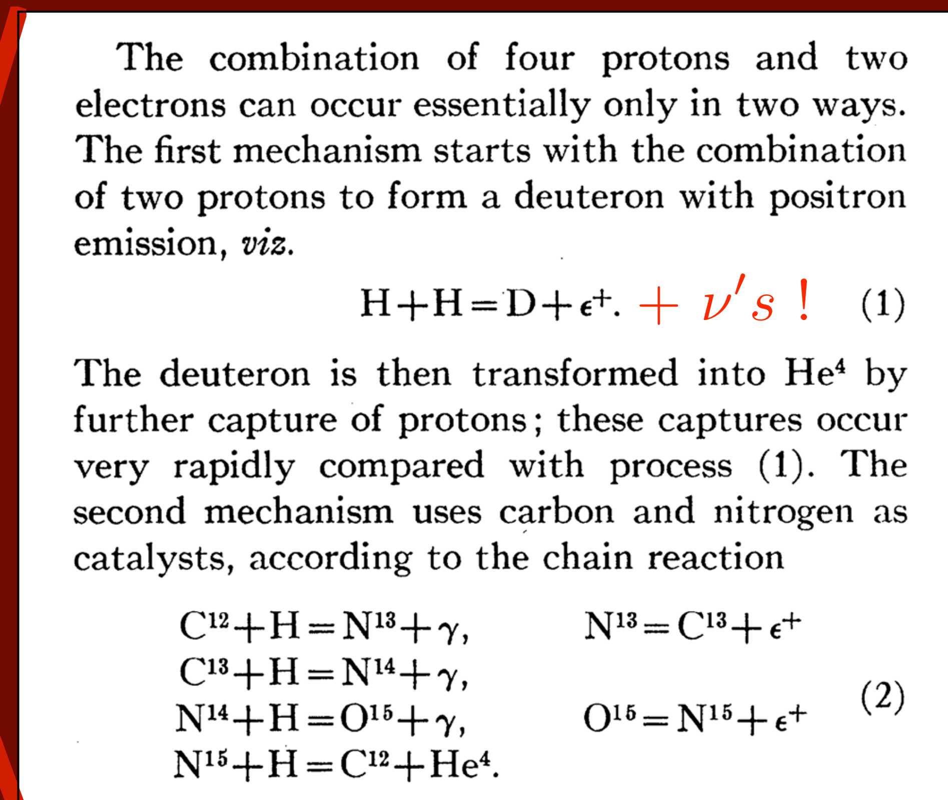
$$H+H=D+\epsilon^+. \quad (1)$$

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

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

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.

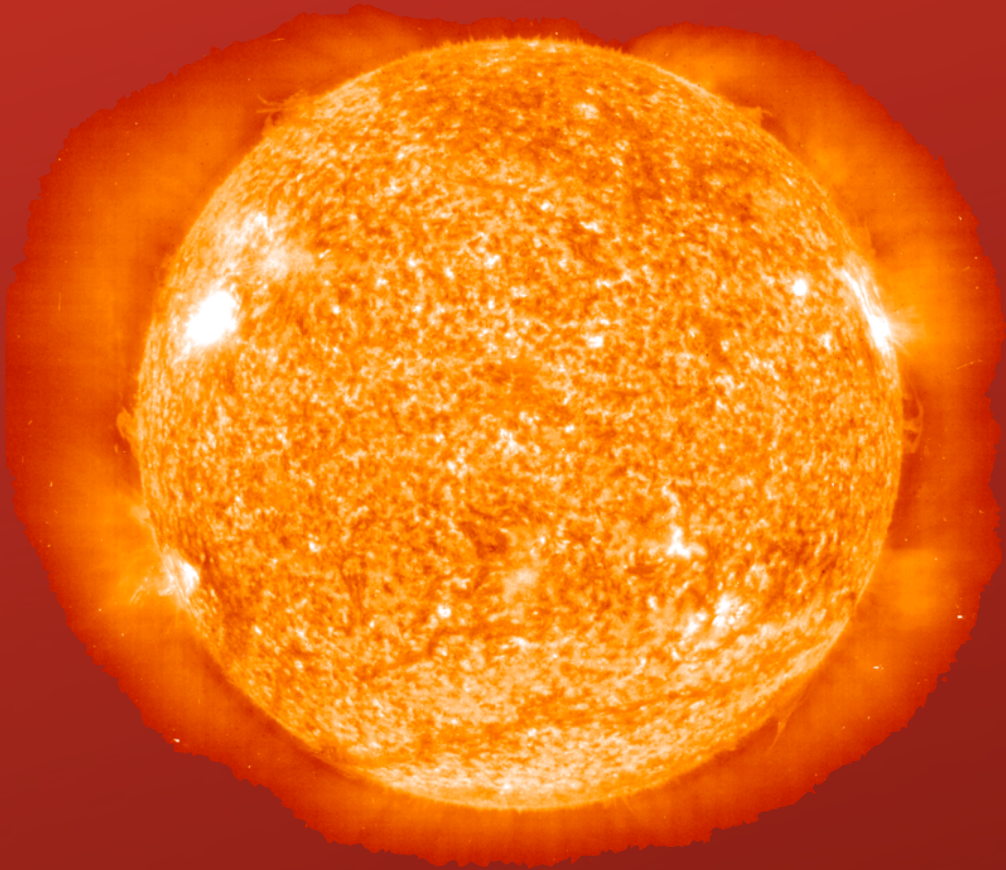


The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

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

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

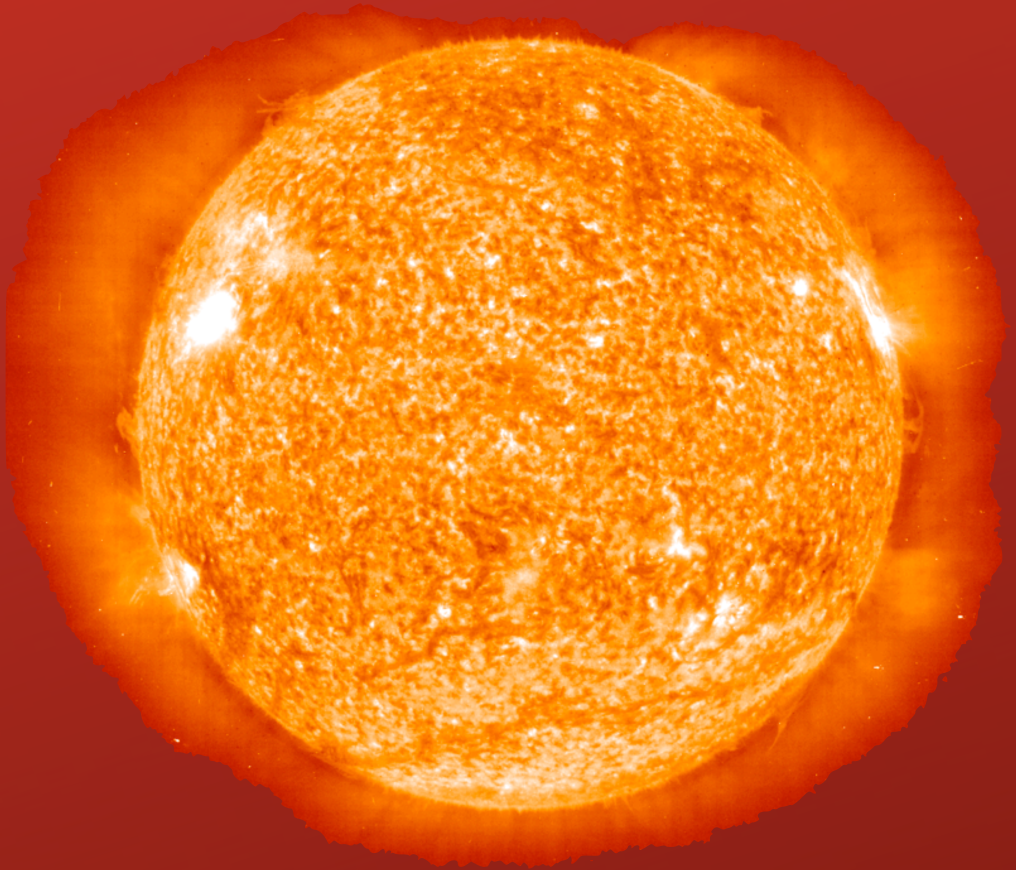
$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, && N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, && O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. && \end{aligned} \quad (2)$$



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...

John Bahcall
1934 - 2005

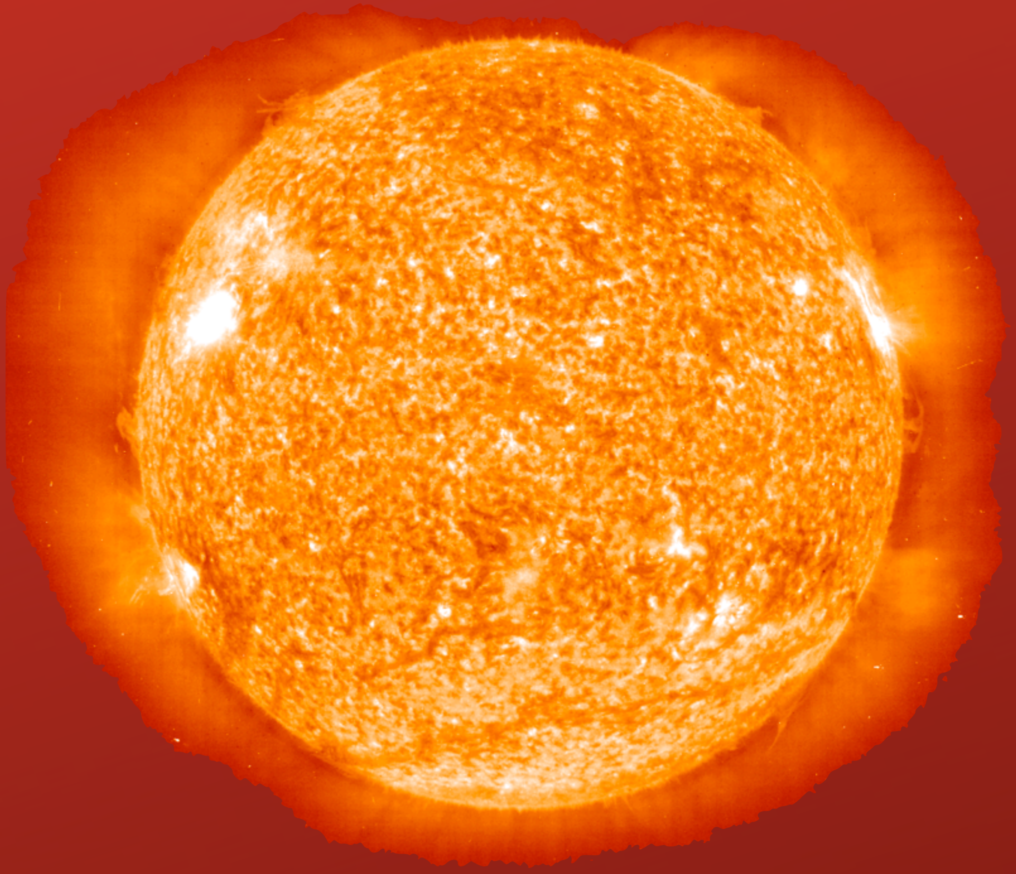


In the sixties, John Bahcall calculates the neutrino flux expected to be produced from the solar pp cycle.

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

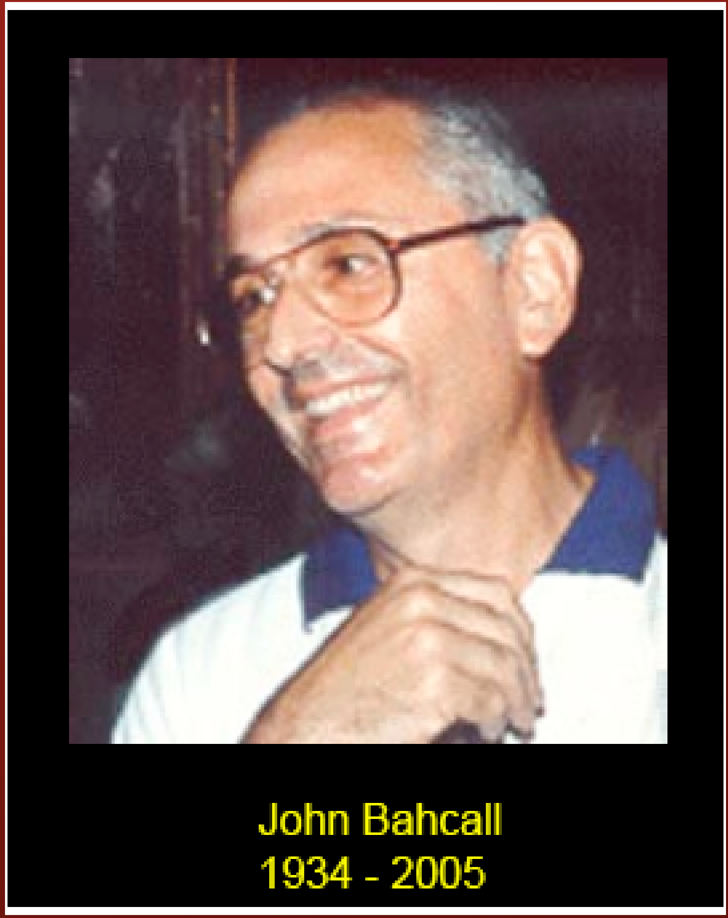
John Bahcall
1934 - 2005

(1) Sun is in hydrostatic equilibrium.



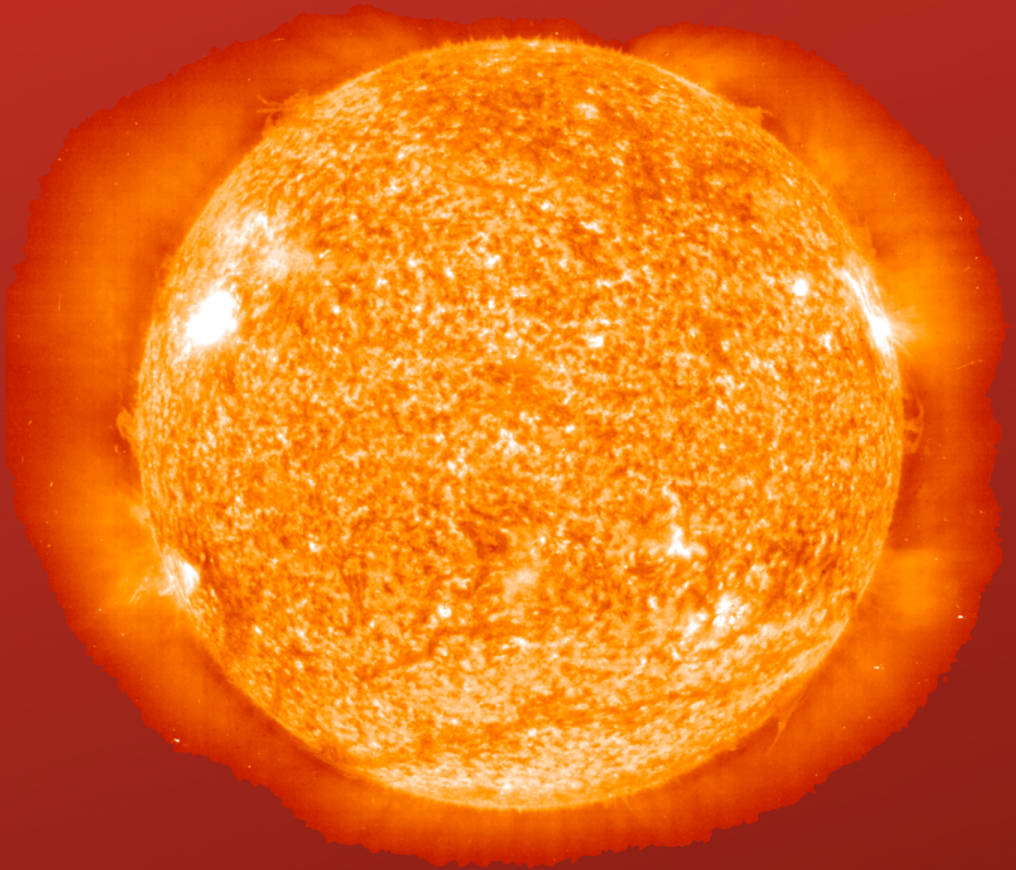
In the sixties, John Bahcall calculates the neutrino flux expected to be produced from the solar pp cycle.

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



(1) Sun is in hydrostatic equilibrium.

(2) Main energy transport is by photons.



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

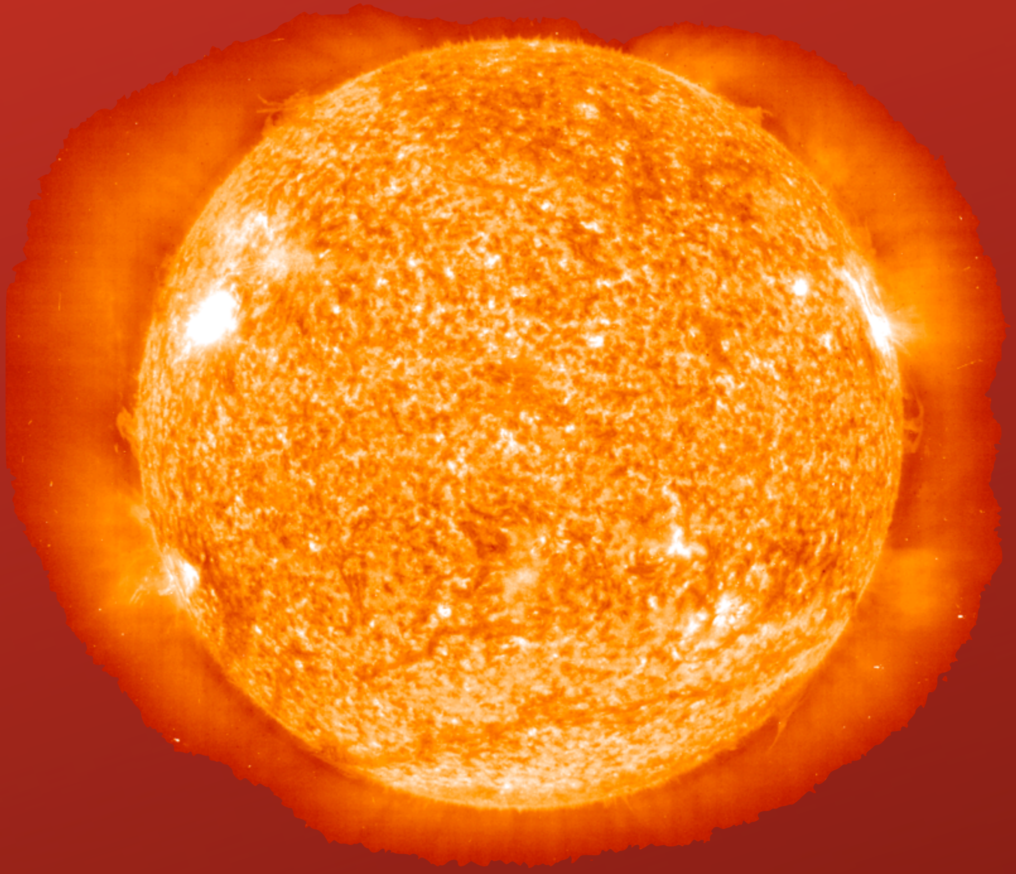
Basic assumptions of what is known as the Standard Solar Model...

(1) Sun is in hydrostatic equilibrium.

(2) Main energy transport is by photons.

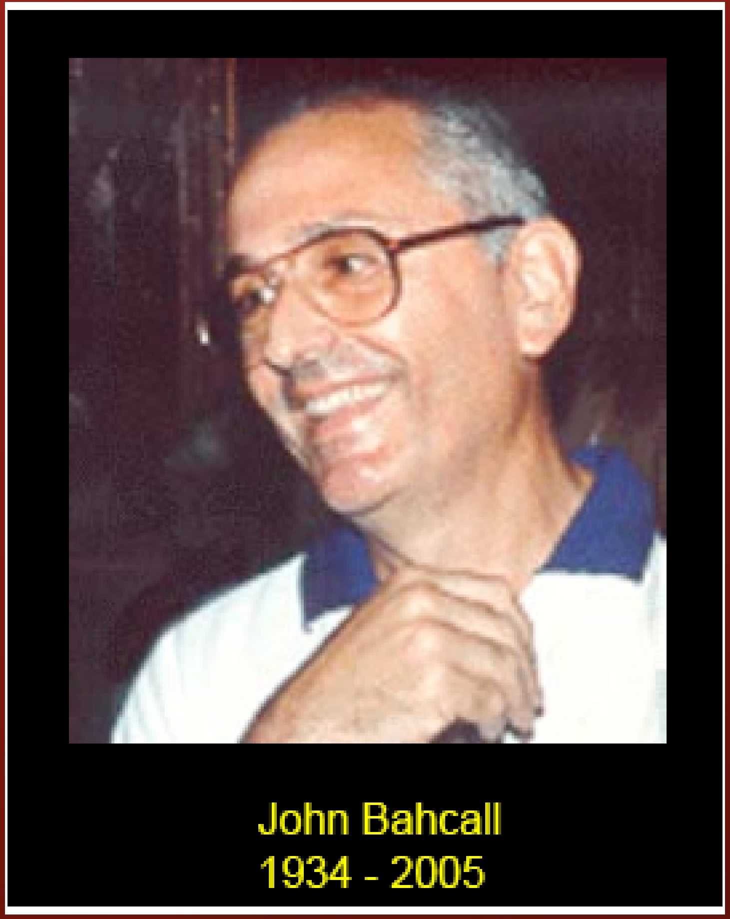
(3) Primary energy generation is nuclear fusion.

John Bahcall
1934 - 2005



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...

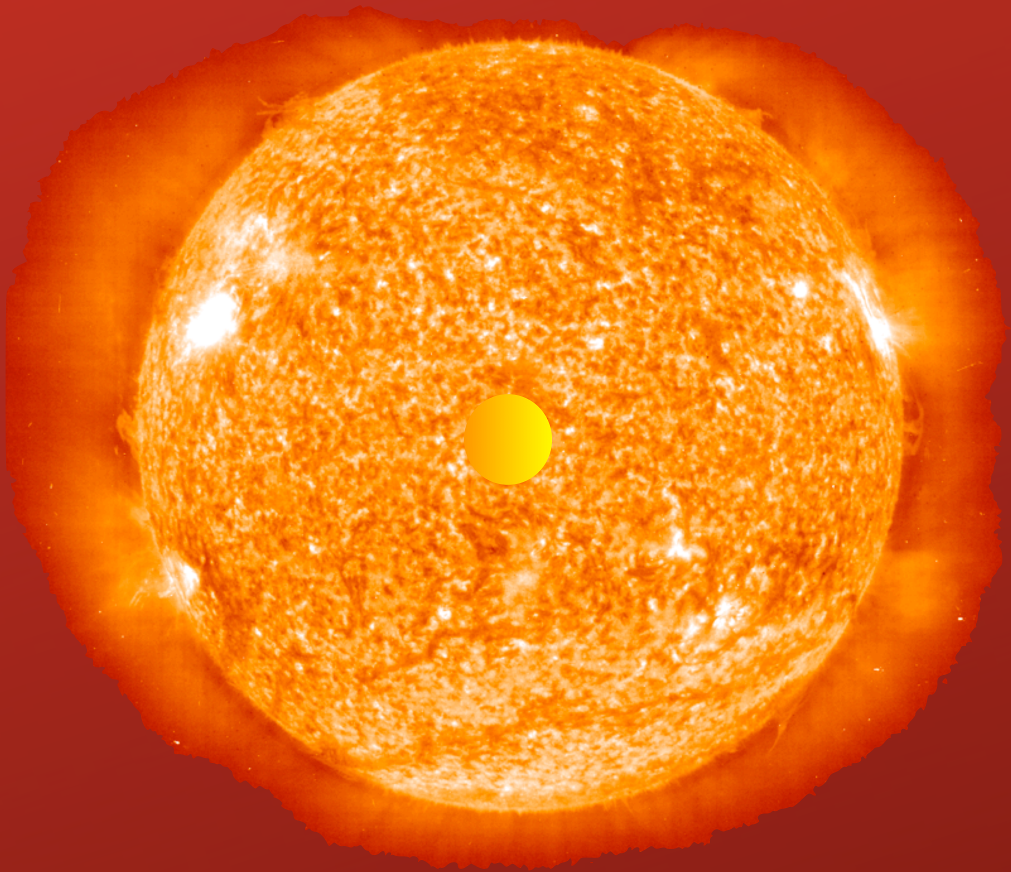


(1) Sun is in hydrostatic equilibrium.

(2) Main energy transport is by photons.

(3) Primary energy generation is nuclear fusion.

(4) Elemental abundance determined solely from fusion reactions.

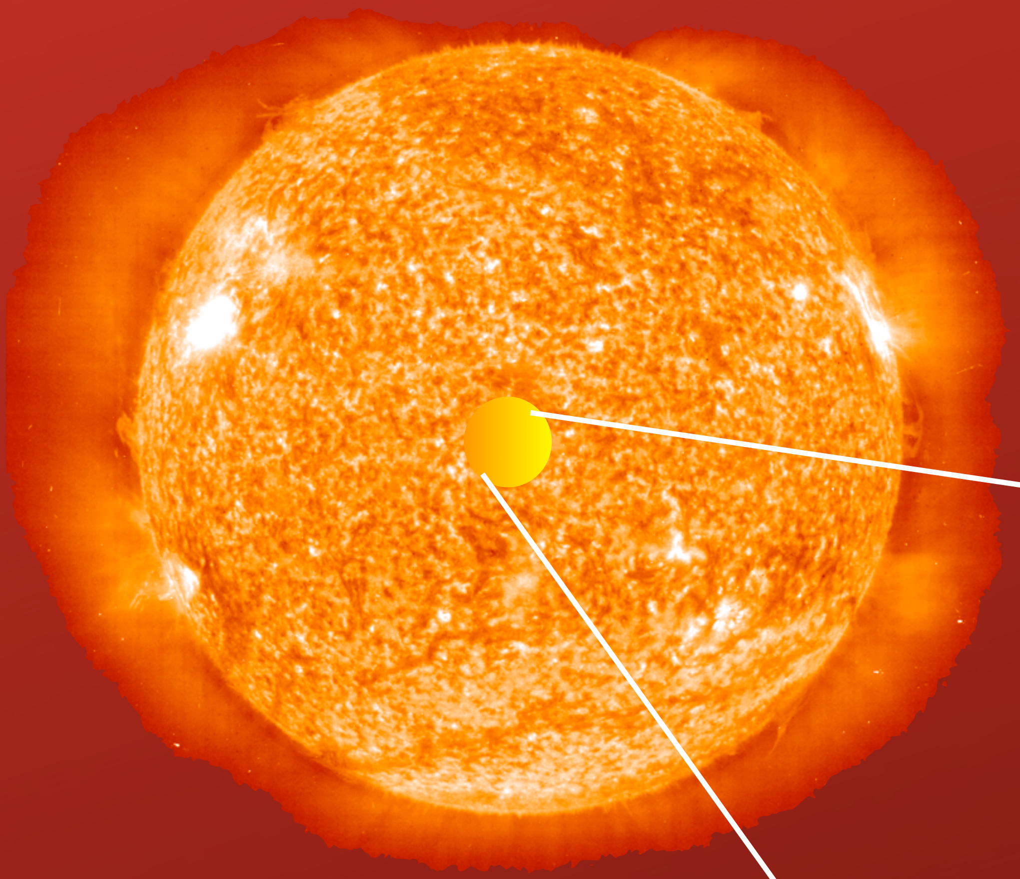


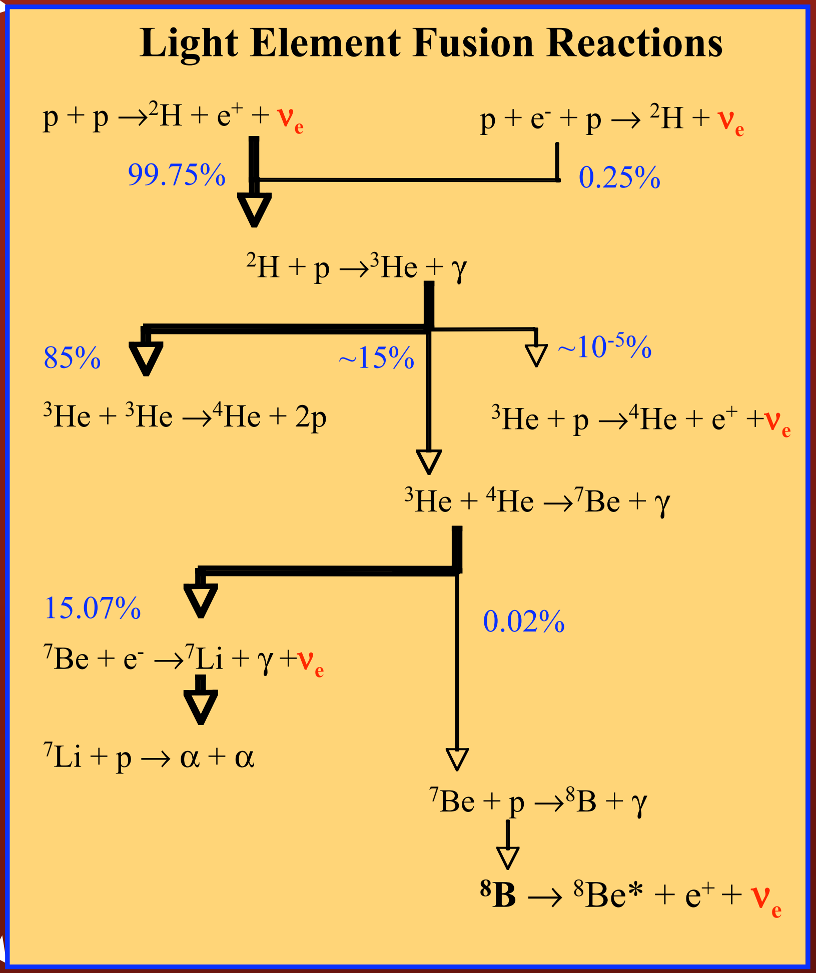
Basic Process:

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

Basic Process:

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



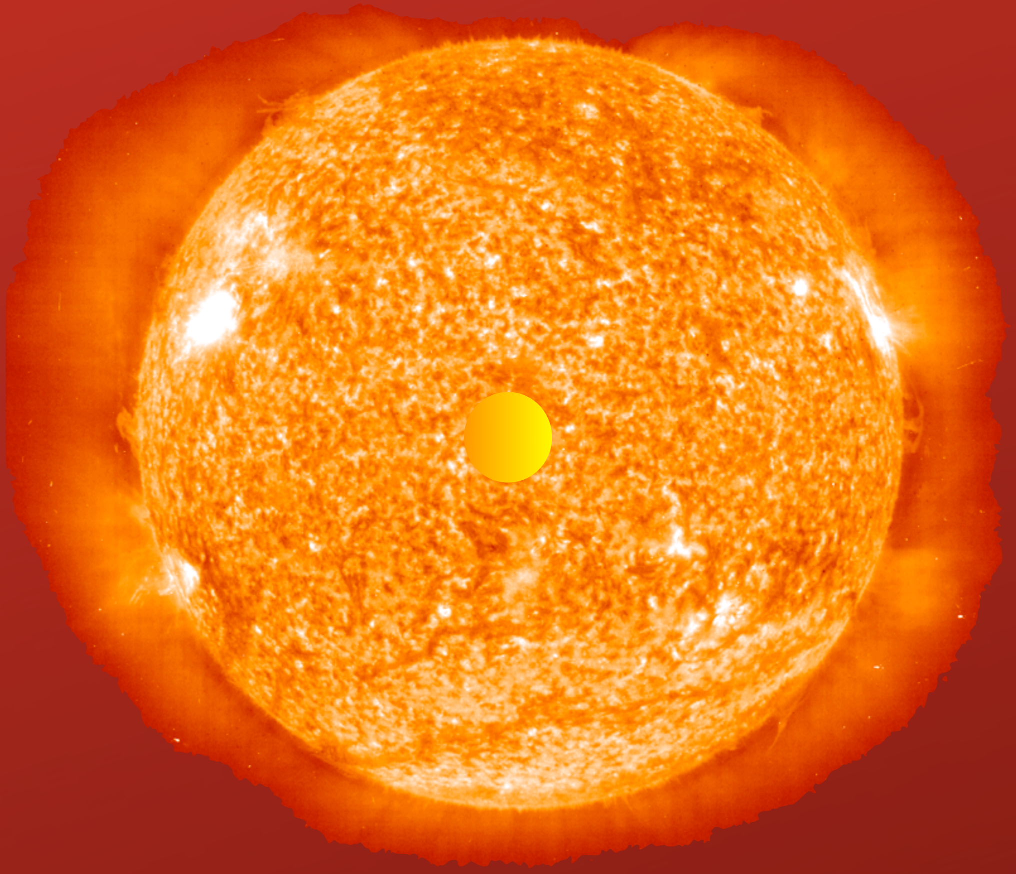


More detailed...

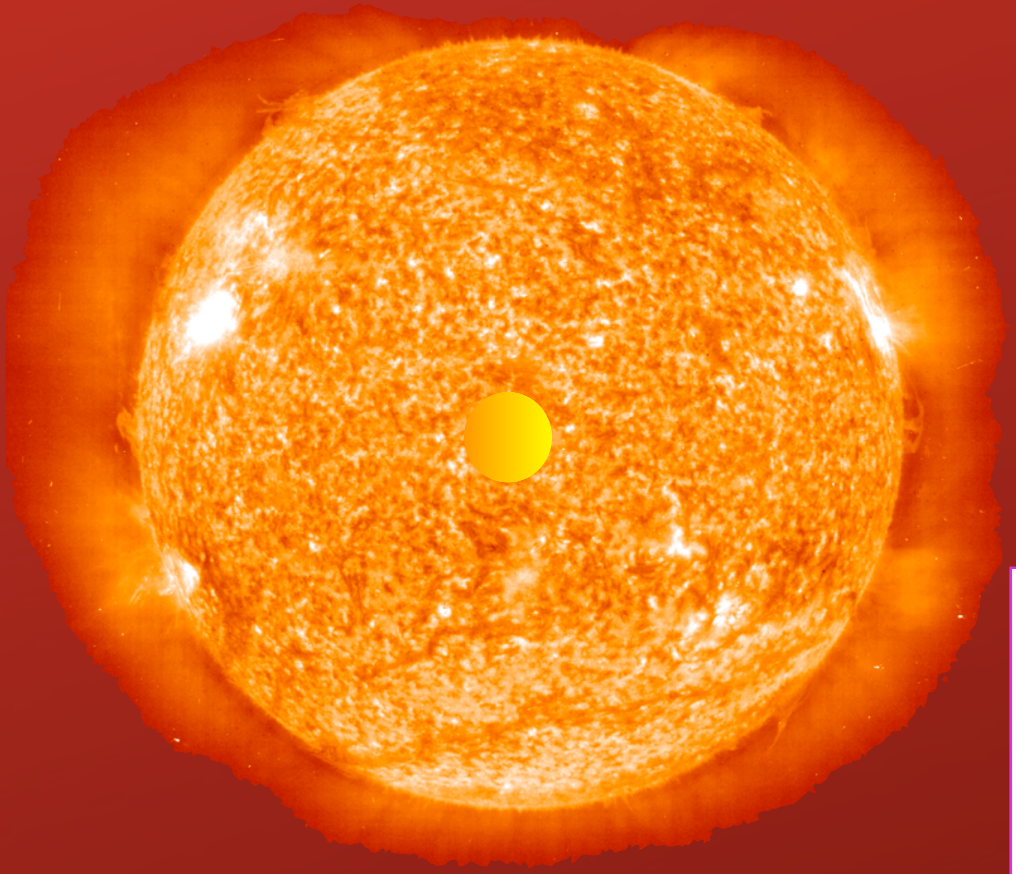
This is known as the pp fusion chain.

Sub-dominant CNO cycle also exists.

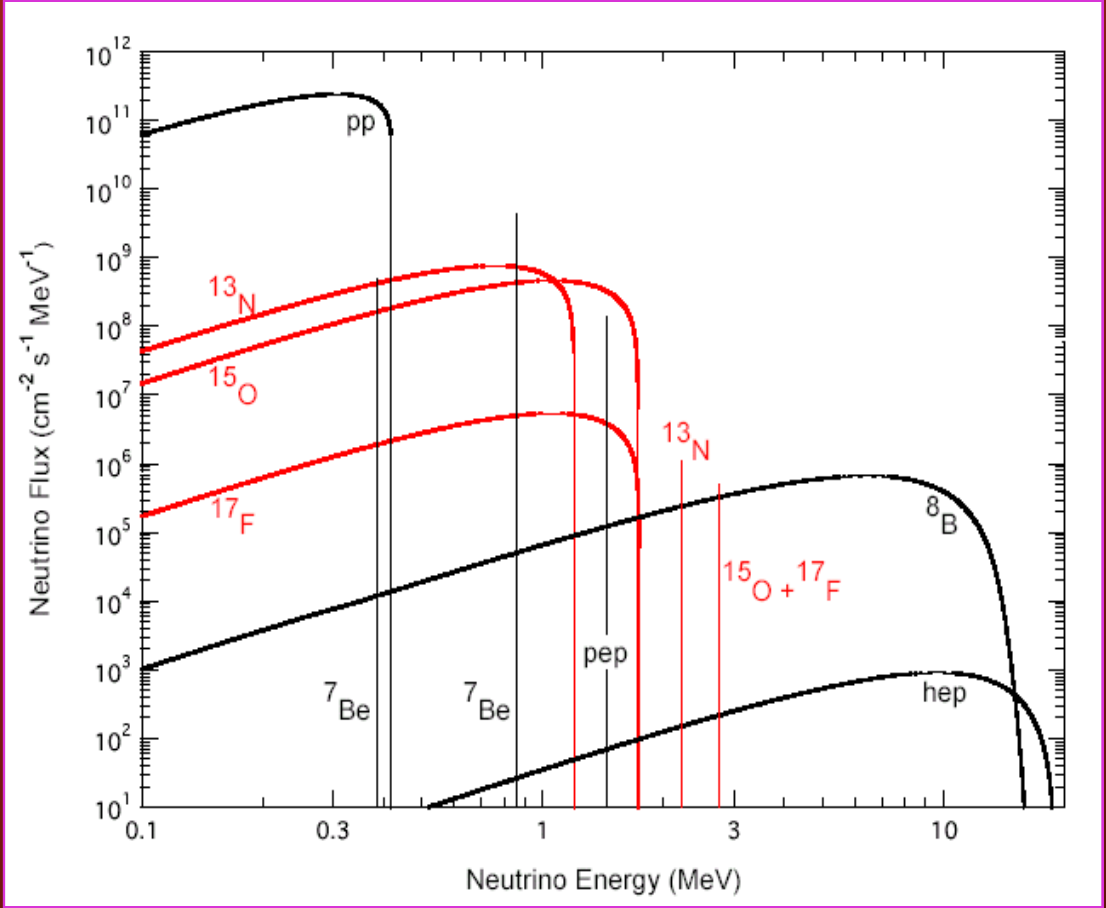
The Solar Neutrino Spectrum



- 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.



The Solar Neutrino Spectrum



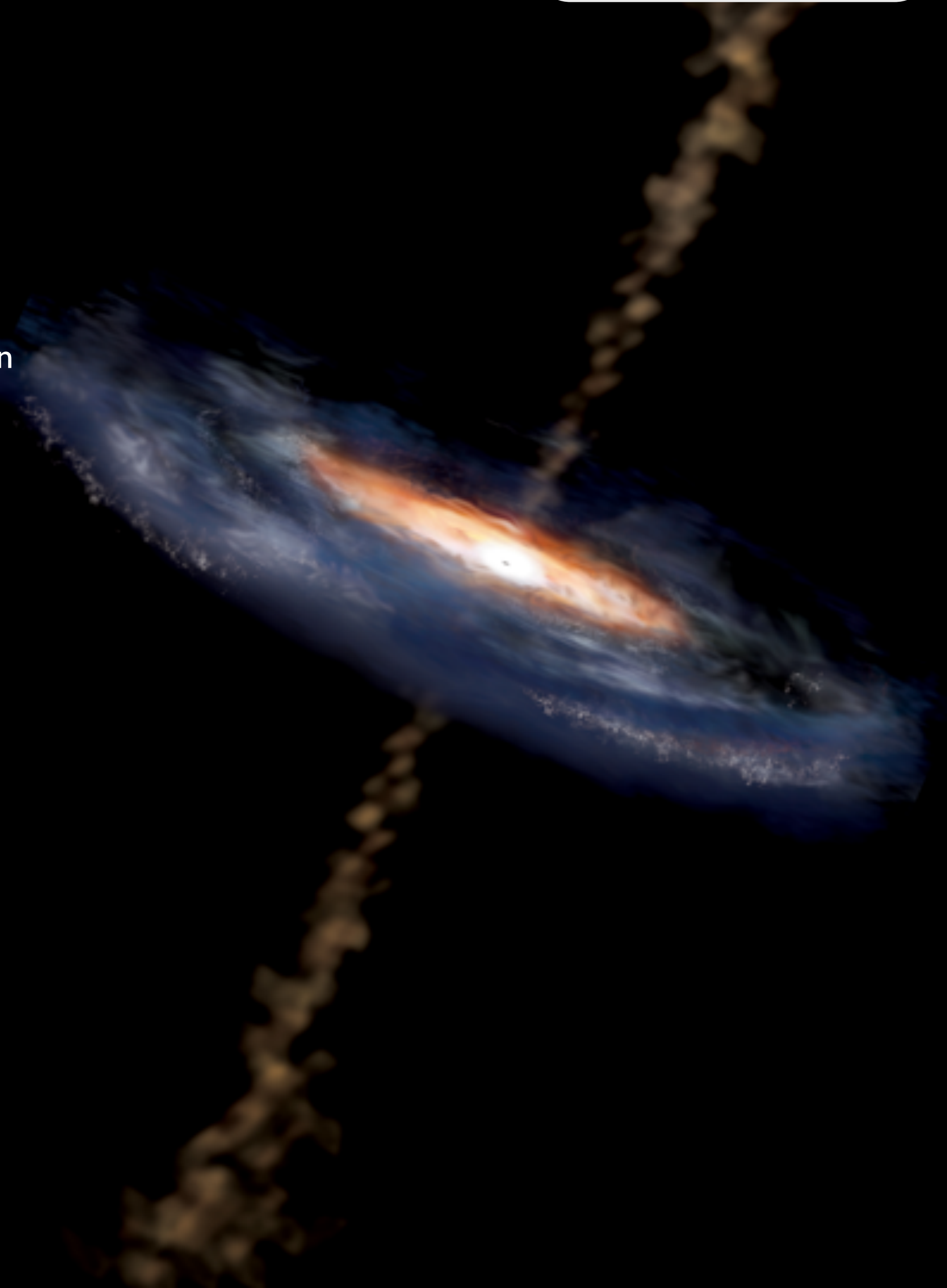
- Only electron neutrinos are produced initially in the sun (thermal energy below and threshold).
- Spectrum dominated mainly from pp fusion chain, but present only at low energies.

Ultra-High Energy Neutrinos

$E_\nu > 1$ TeV

$E_\nu > 1$ TeV

Ultra-High Energy Neutrinos



- 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.).

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

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

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

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

Acceleration Processes

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

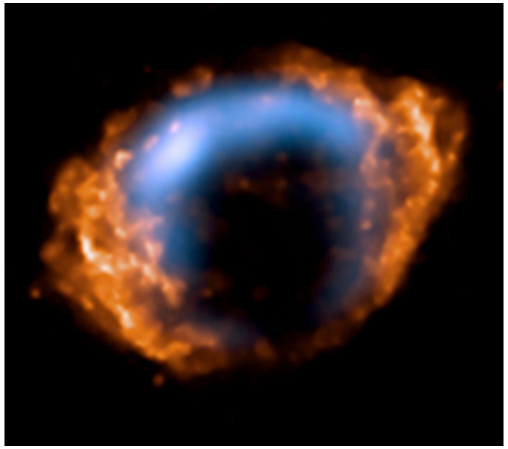
- Neutrinos would be produced from the decay of unstable mesons (π^0, $\pi^{\pm}$, $K^{\pm}$, etc.).

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

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

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

Supernova remnants



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.).

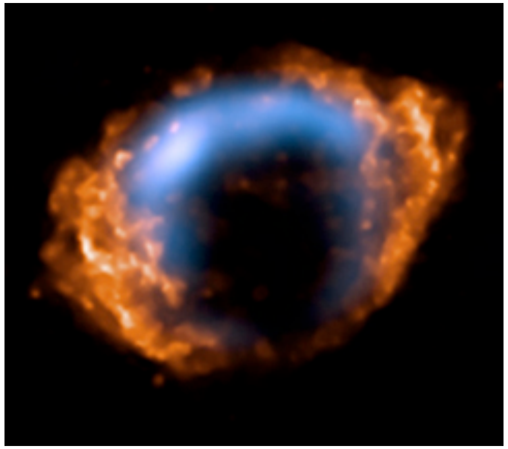
$$pp \rightarrow NN + \text{pions}; \qquad p\gamma \rightarrow p\pi^0,\ n\pi^+$$

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

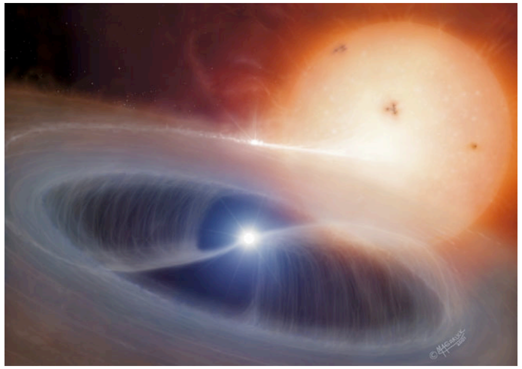
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

- 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



Acceleration Processes

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

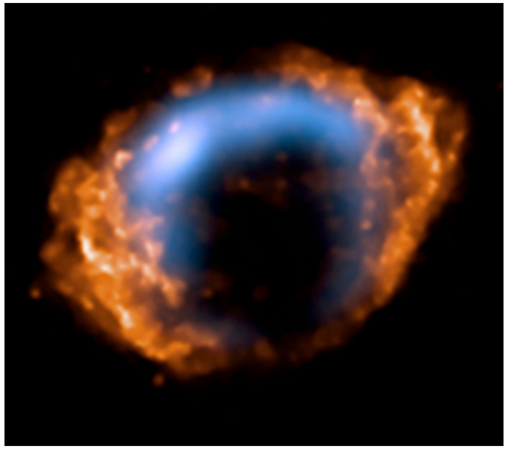
- Neutrinos would be produced from the decay of unstable mesons (π^0, $\pi^\pm$, $K^\pm$, etc.).

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

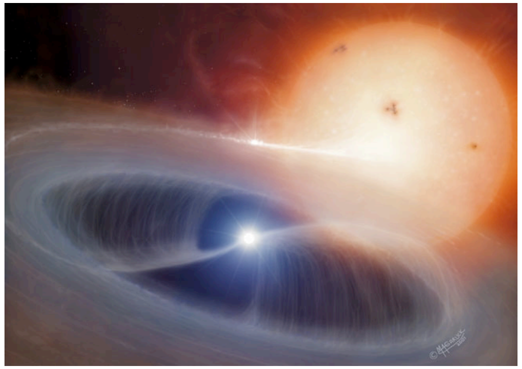
$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

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

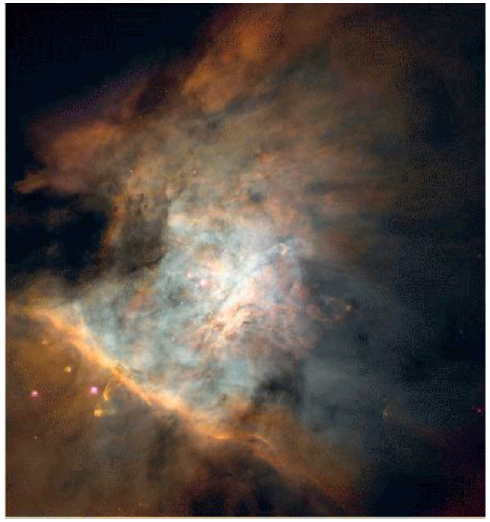
Supernova remnants



Binary systems

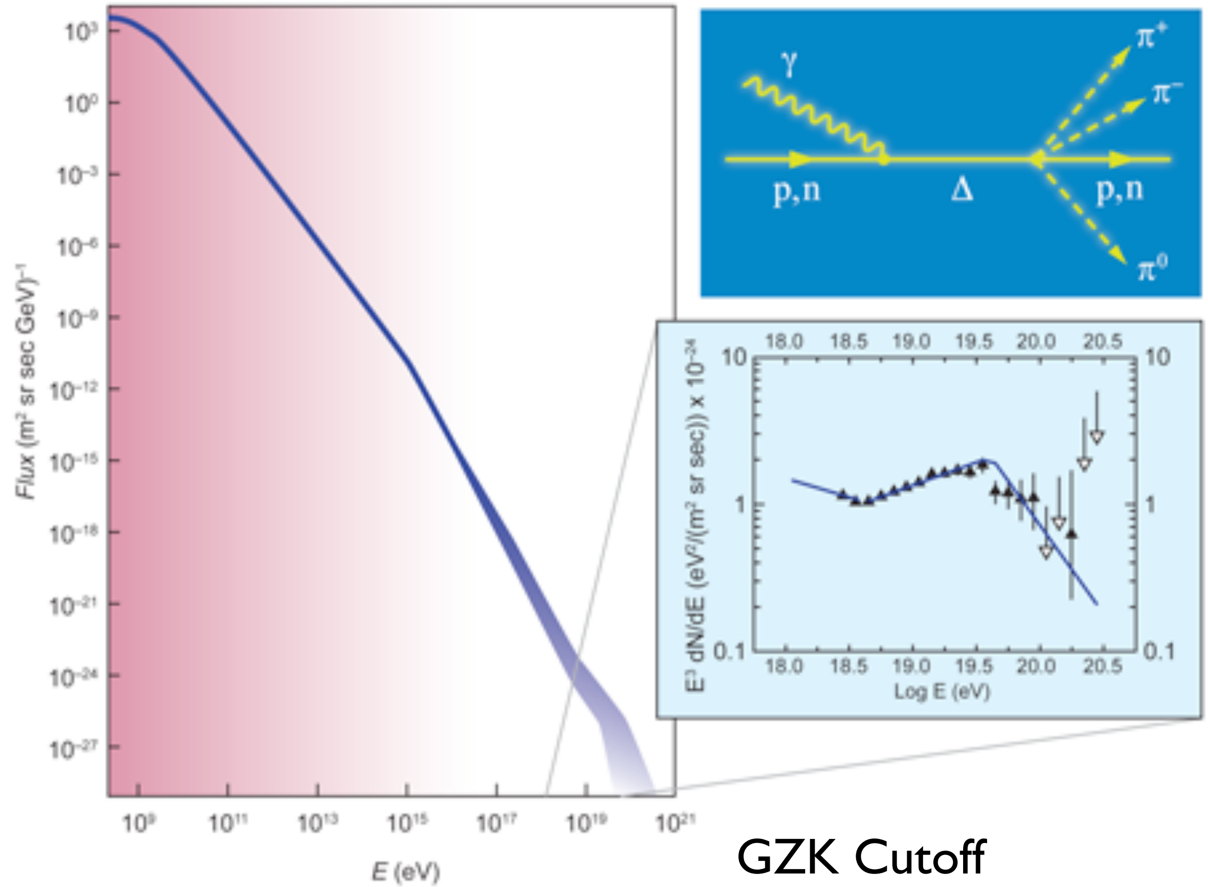


Interaction with interstellar medium

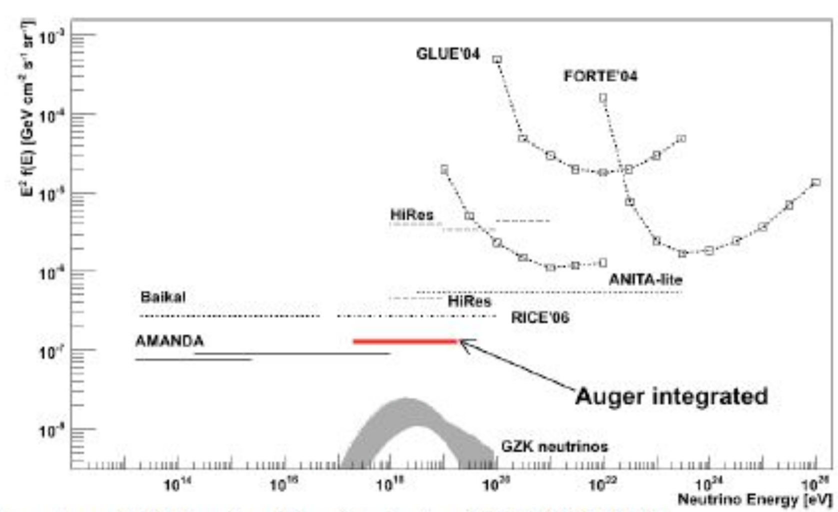


GZK Neutrinos

- 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

What we will cover:

Where do neutrinos come from?

Neutrinos from the Heavens

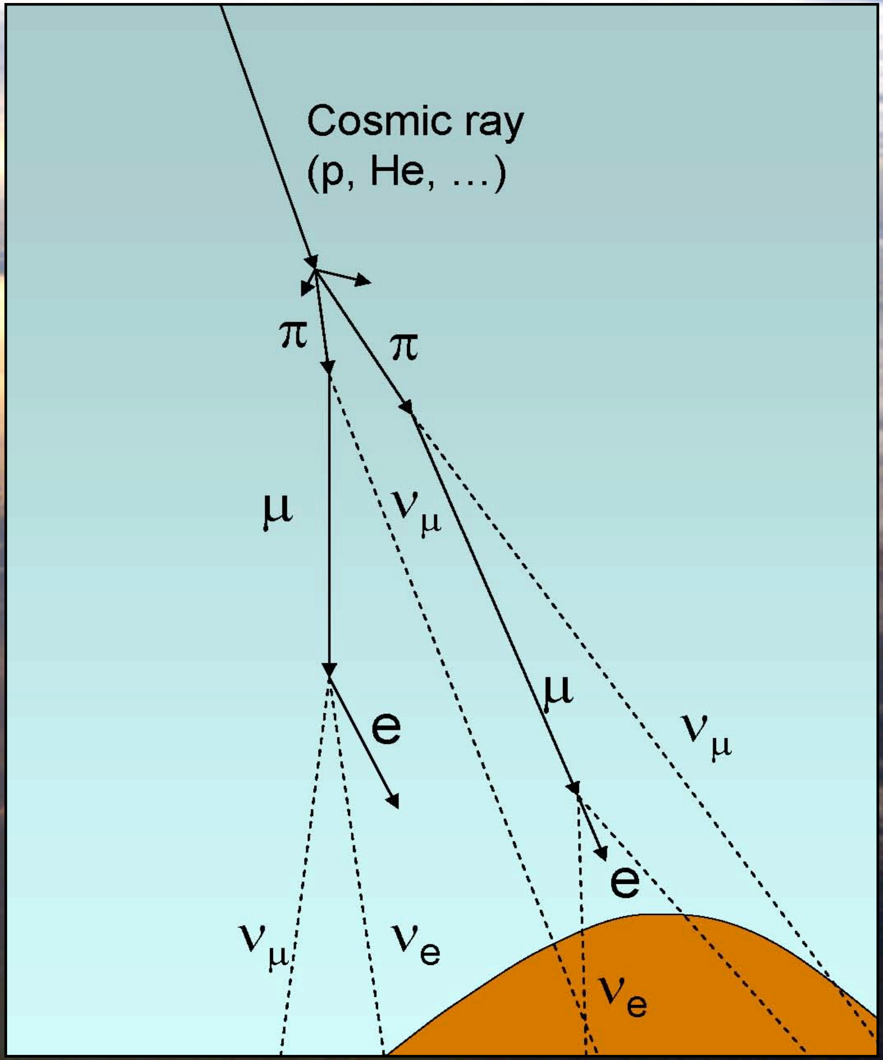
Neutrinos from the Earth

Neutrinos from Man

Atmospheric Neutrinos

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

Atmospheric Neutrinos



Atmospheric Neutrinos

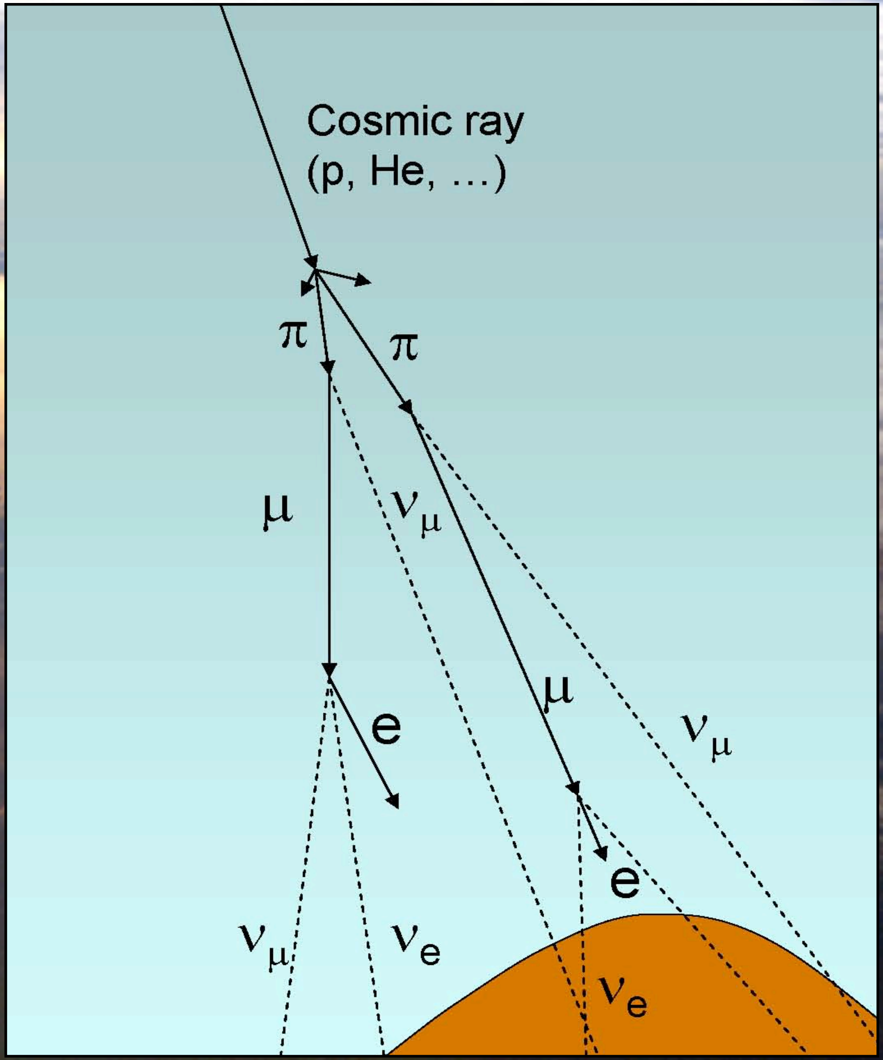
- Created by high energy cosmic rays impeding on the Earth's upper atmosphere.
- Dominant production mechasism comes from pion decay.

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

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

$$\downarrow$$

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



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.

Atmospheric Neutrinos

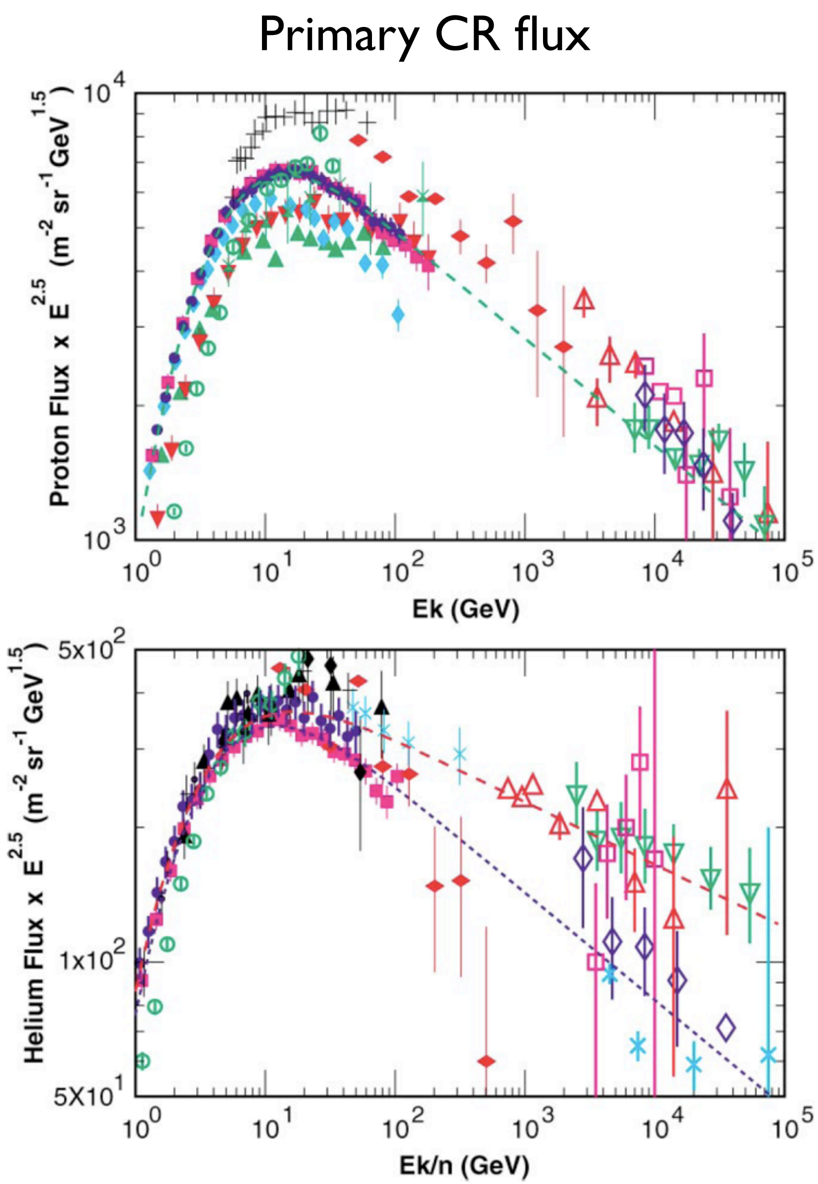
- To calculate the predicted neutrino flux, a number of key steps must be taken into account:

    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.



Atmospheric Neutrinos

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

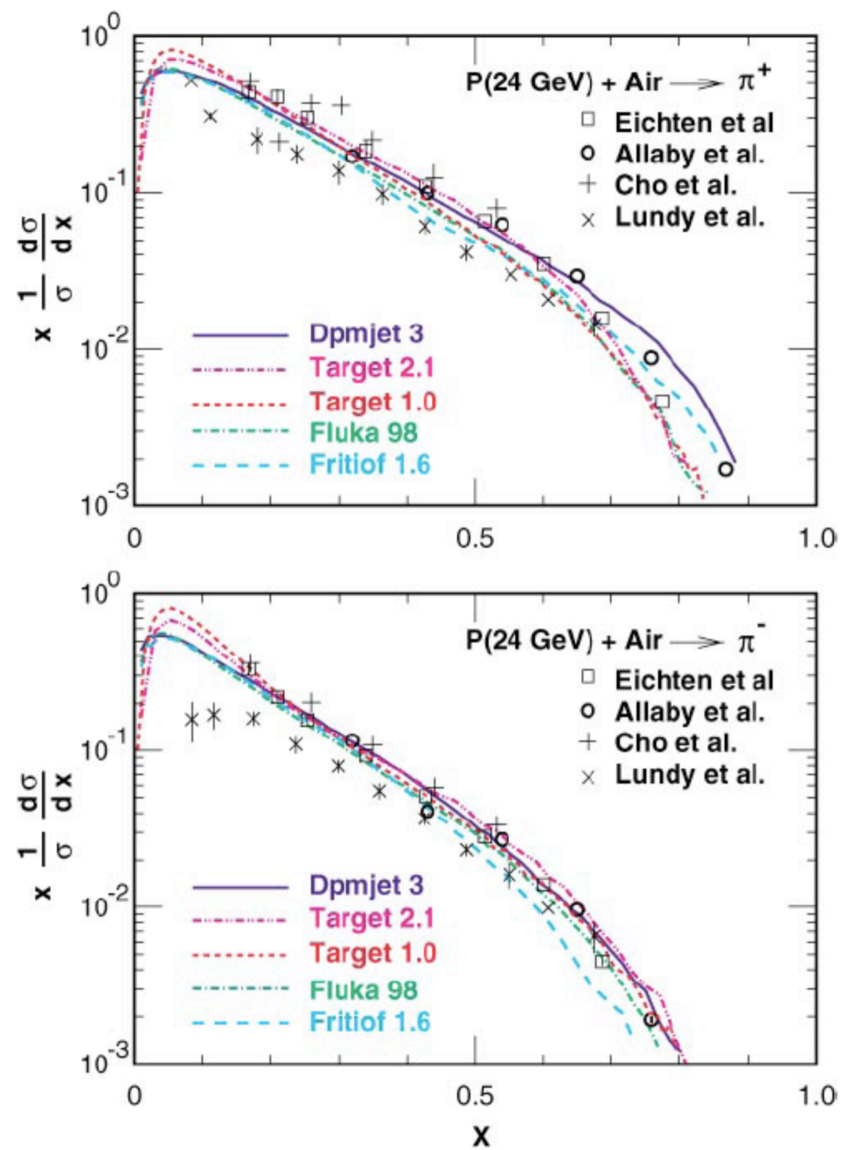
    1. Primary cosmic ray flux. This is measured using large array telescopes and ballon measurements.

    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.

Hadronization



Atmospheric Neutrinos

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

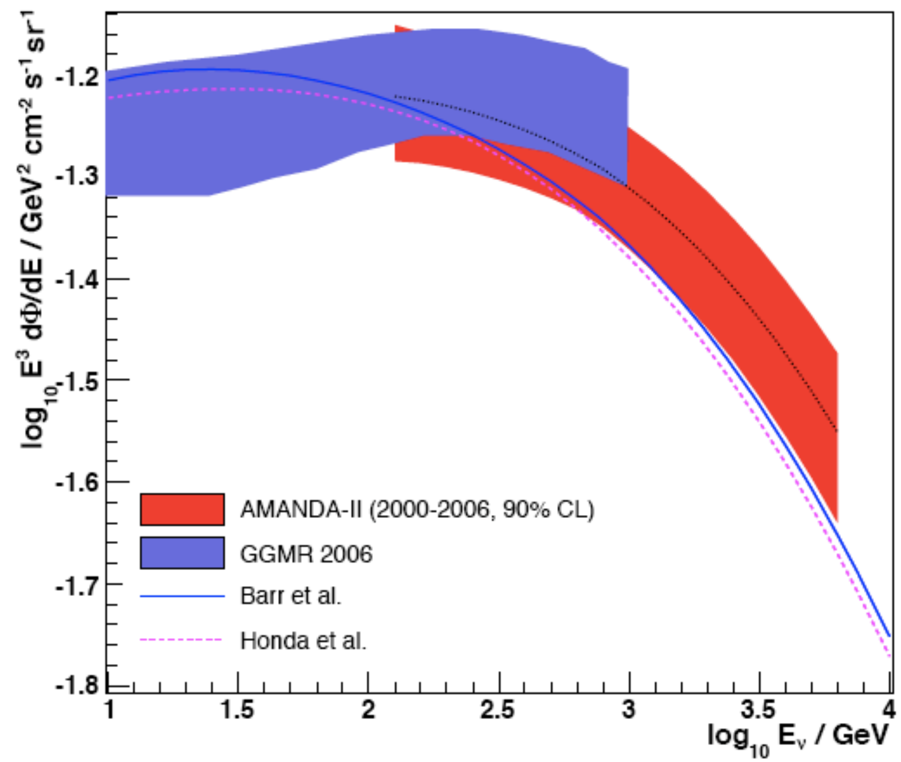
    1. Primary cosmic ray flux. This is measured using large array telescopes and ballon measurements.

    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 $\pm$20%

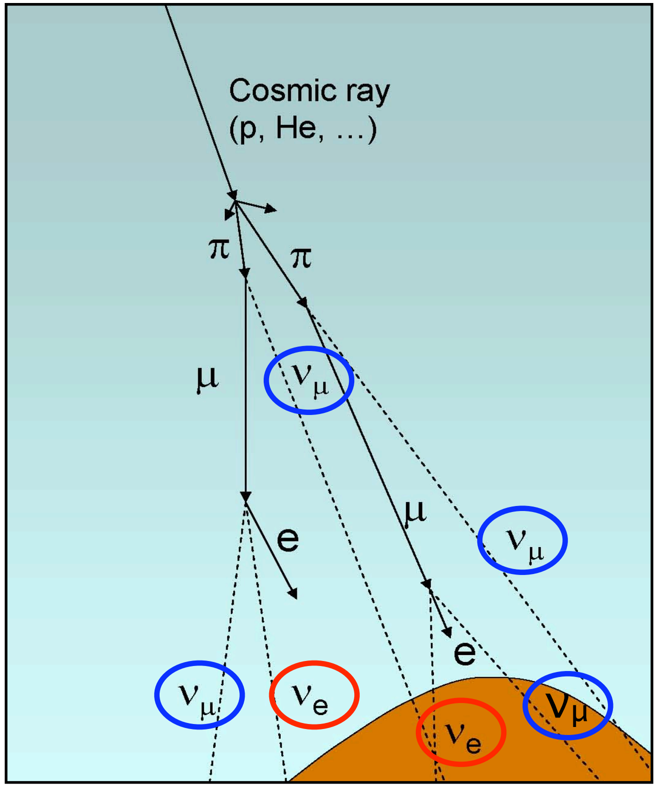
Atmospheric Neutrinos

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

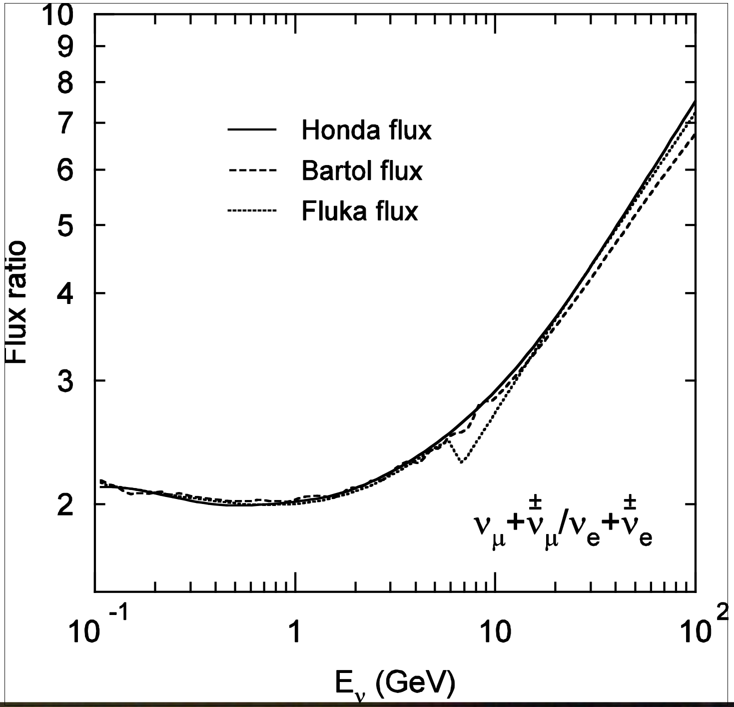
    1. ν_μ:ν_e ratio: This ratio is fixed from the pion/muon cascade.

    2. Zenith variation: Allows one to probe neutrinos at very different production distances (essential for oscillation signatures).

    3. Compare cosmic muon flux



ν_μ:ν_e ratio near 2:1



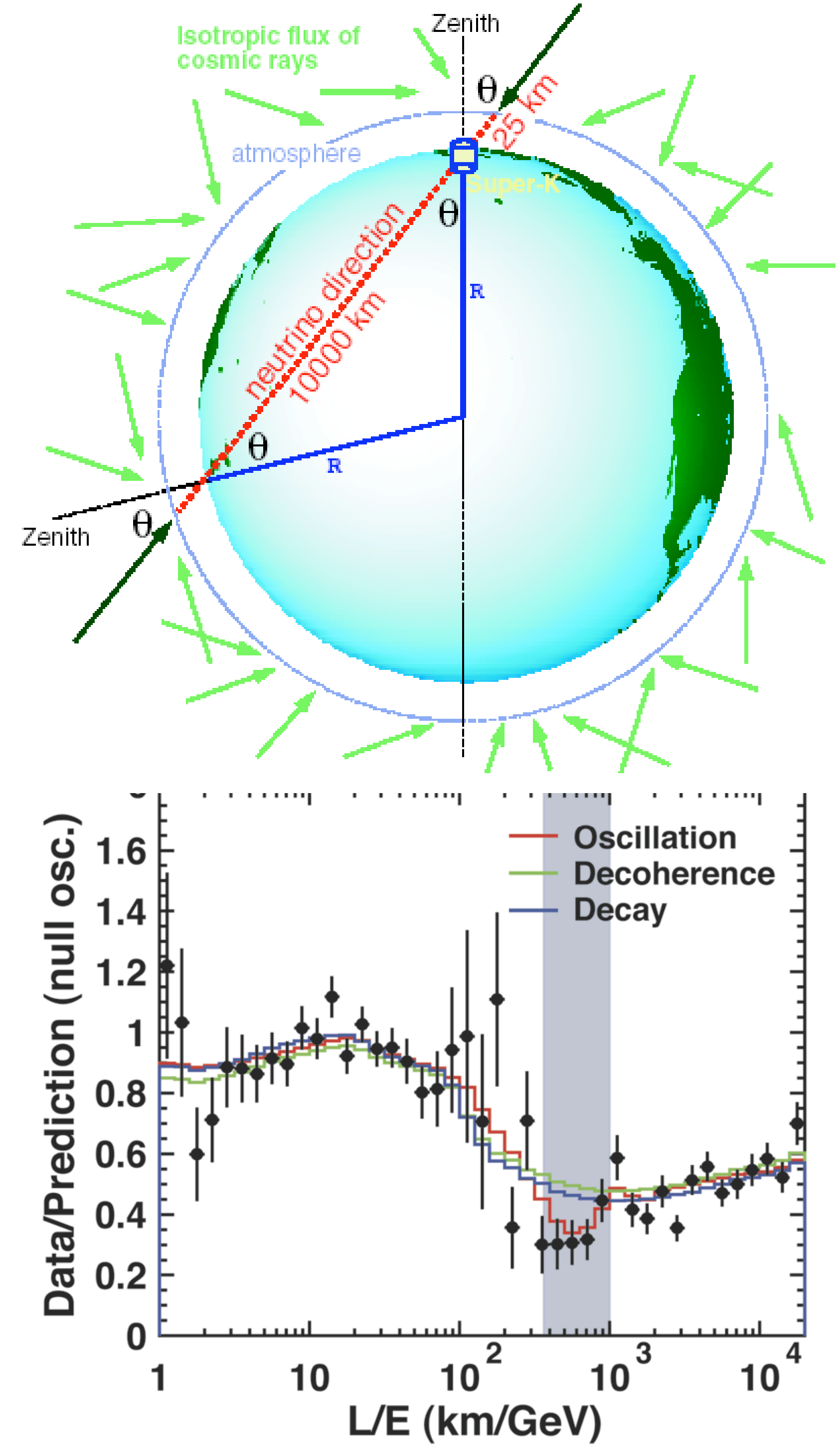
Atmospheric Neutrinos

- 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).

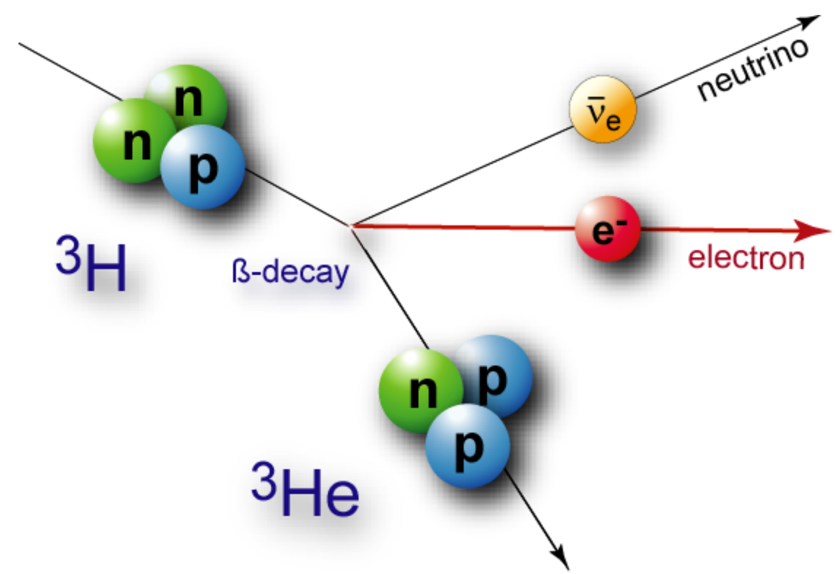
- One can consider three such reactions:

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

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

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

- 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

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

Neutrinos from Radioactivity

- To determine the rate of a particular reaction, one needs to take into account of a number of factors:

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).

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**.

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.

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.

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

Fermi Function

Matrix Element

Phase space

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, $\pm$ 1	No
Allowed	0, $\pm$ 1	No
1st Forbidden	0, $\pm$ 1	Yes
Unique 1st Forbidden	$\pm$ 2	Yes
2nd Forbidden	$\pm$ 2	No
3rd Forbidden	$\pm$ 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?

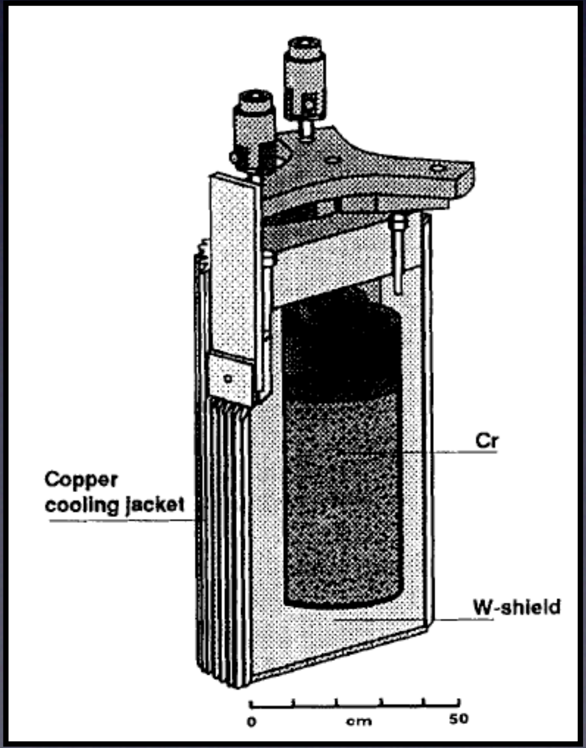
- Though neutrinos from radioactive decay play an important role in many astrophysical sources, we rarely use them as a source, per se.

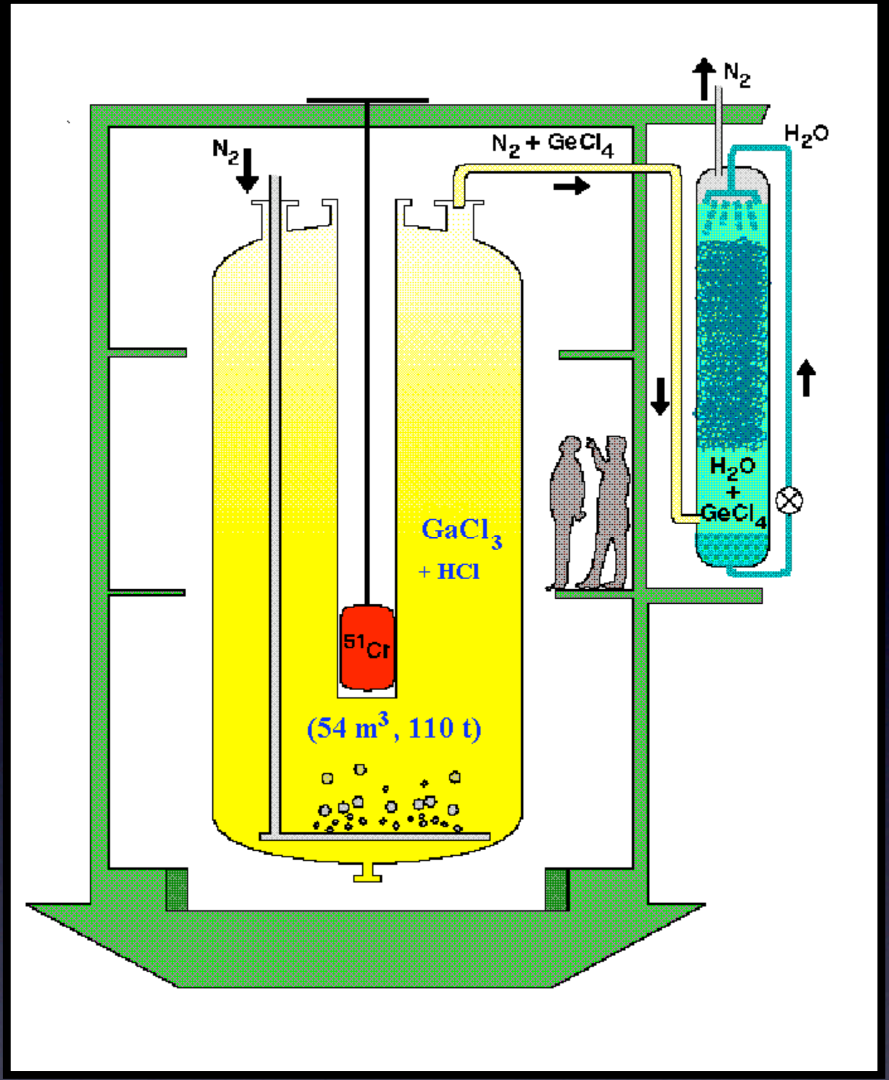
- Except we did to calibrate some of our solar neutrino detectors!

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!



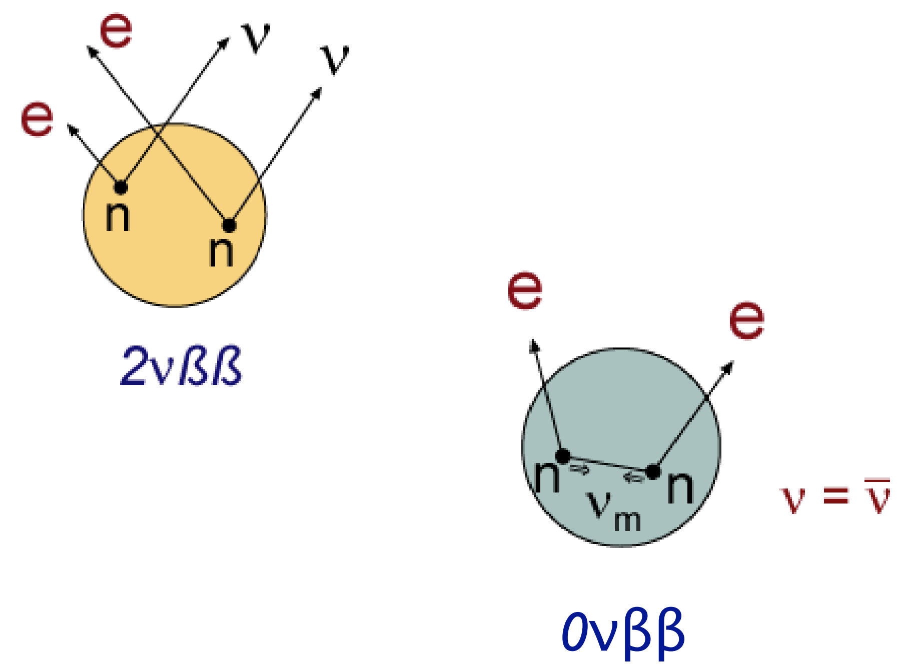


Total activity of the source: 60 PBq!

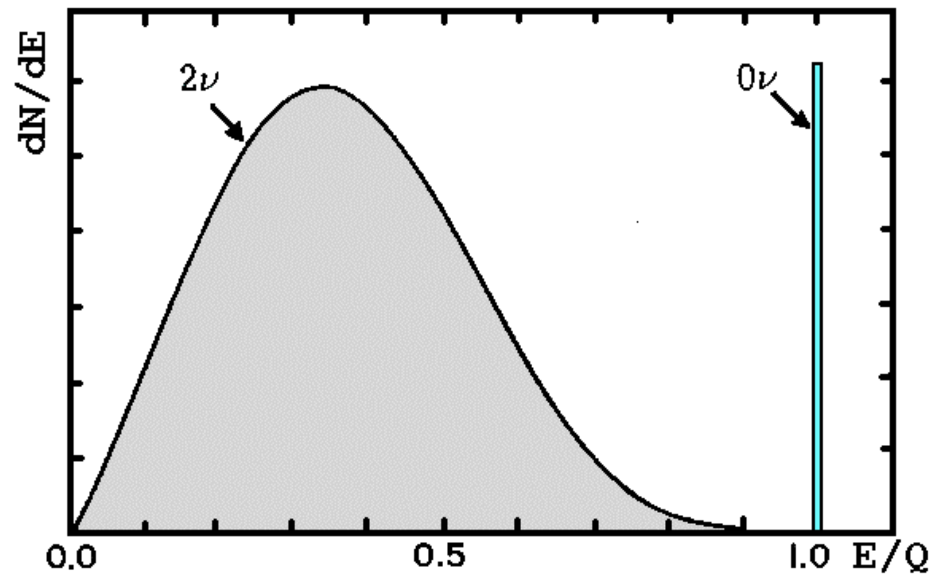
Emitted ~300 W of heat

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.



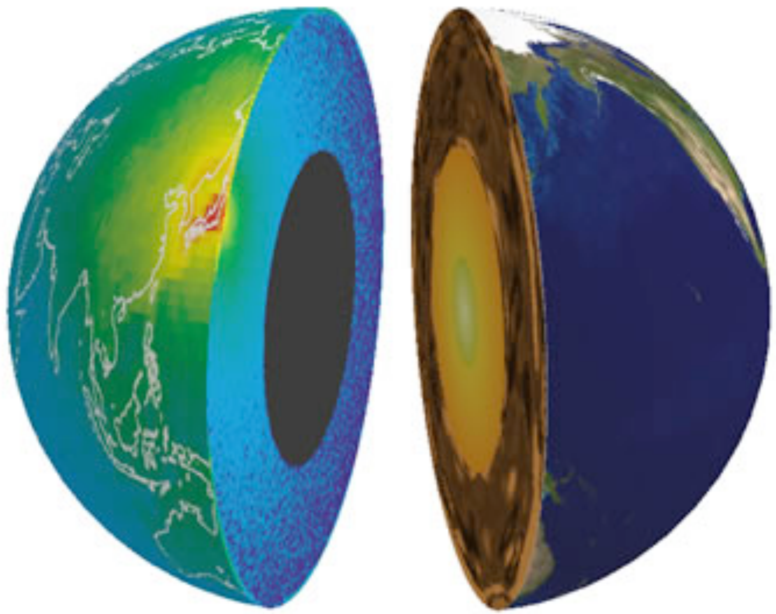
The signature




Geoneutrinos
E_{ν} ~ 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],

- 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...

- 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.

"...and Prometheus was punished for giving fire back to mankind..."

Later today:

Neutrinos from Man...


Fin