Neutrinos from the Heavens & the Earth

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J.A. Formaggio

MIT

Fermilab Neutrino Summer School

What we will cover:

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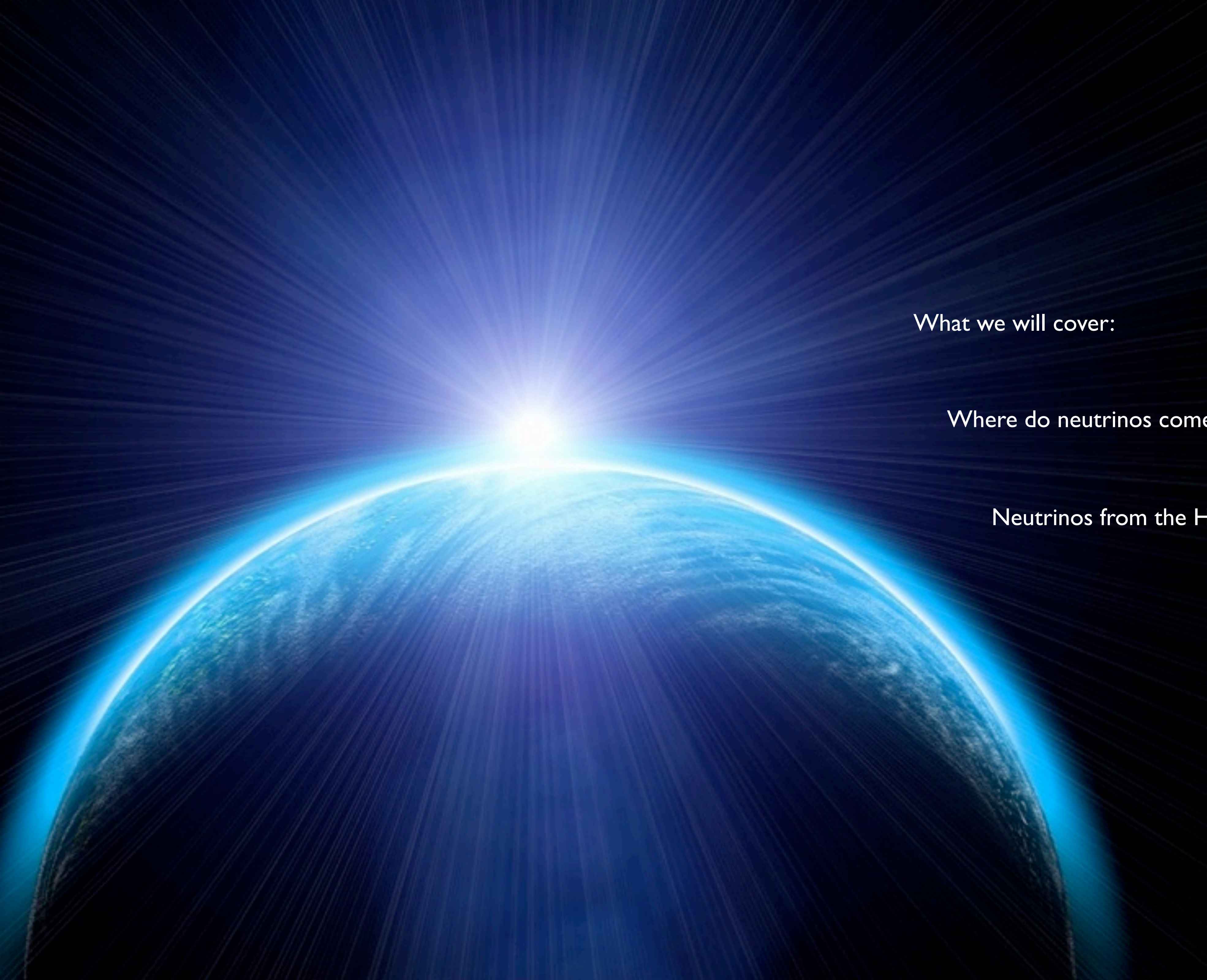
Where do neutrinos come from?



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?
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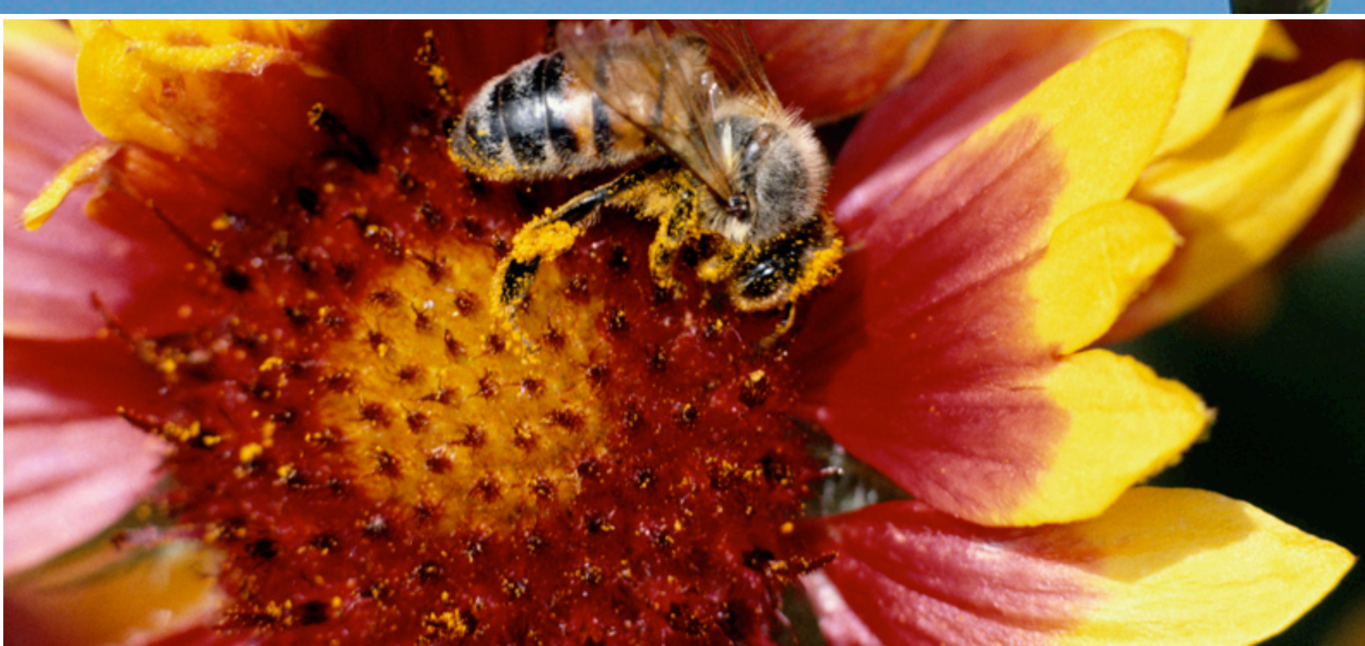
Where do neutrinos come from...?



Within the Framework

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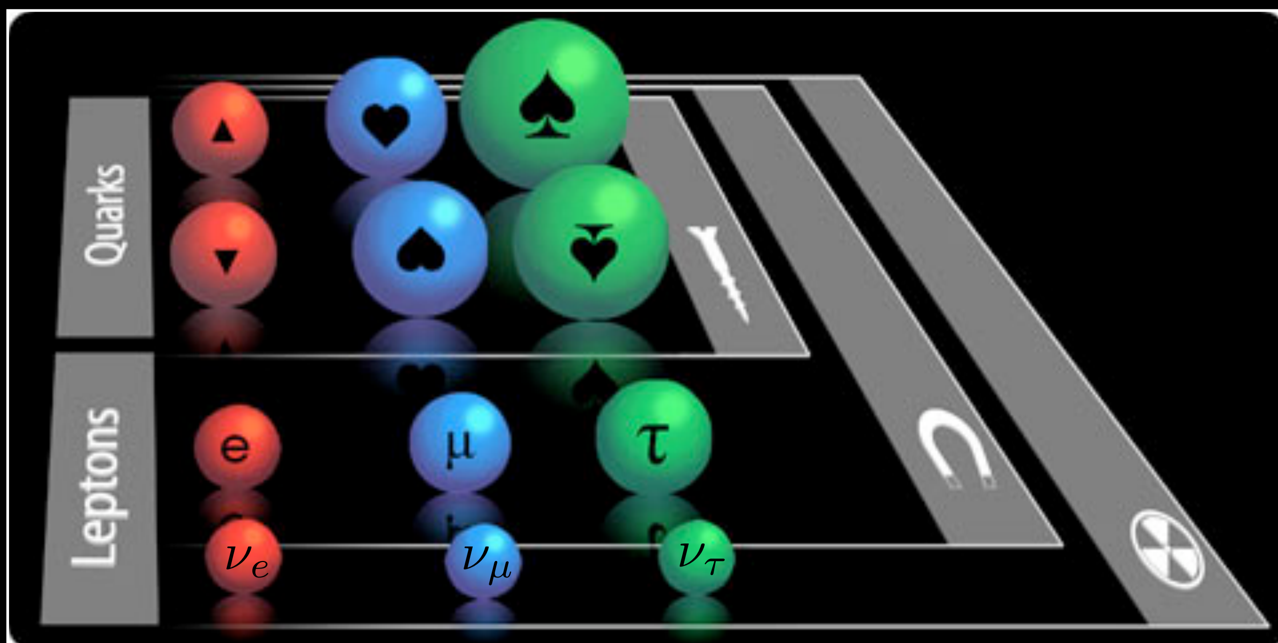

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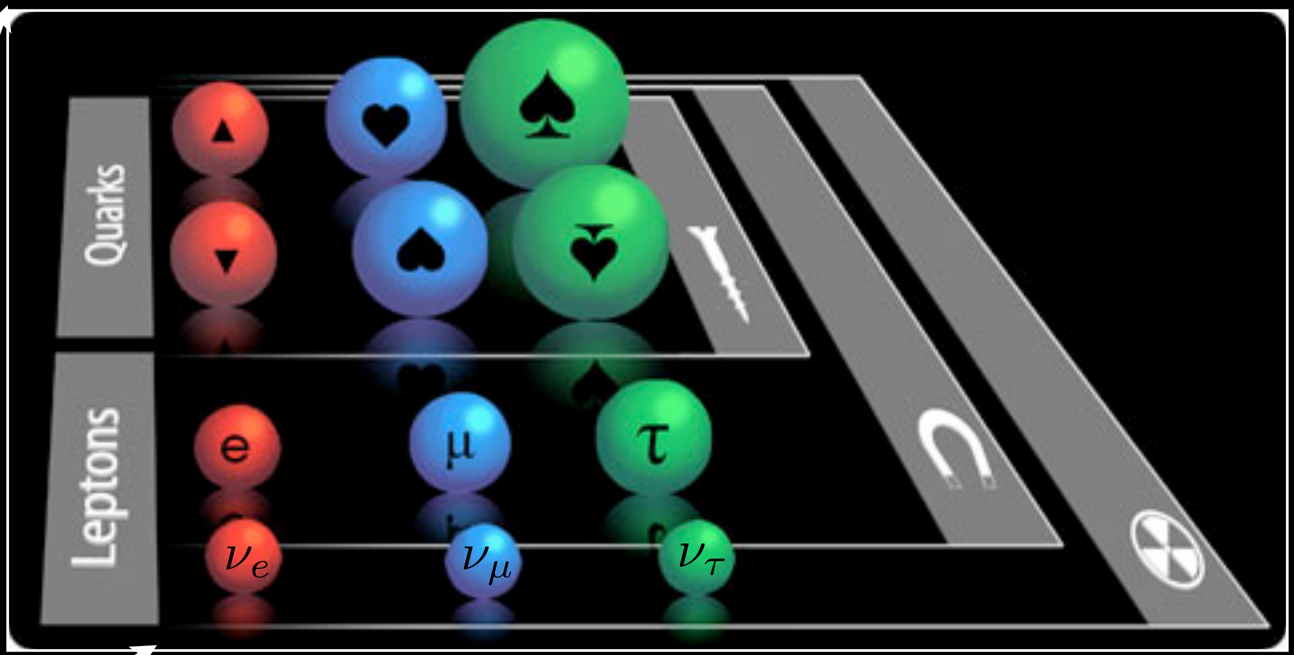
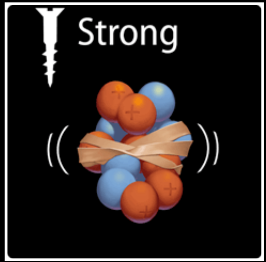
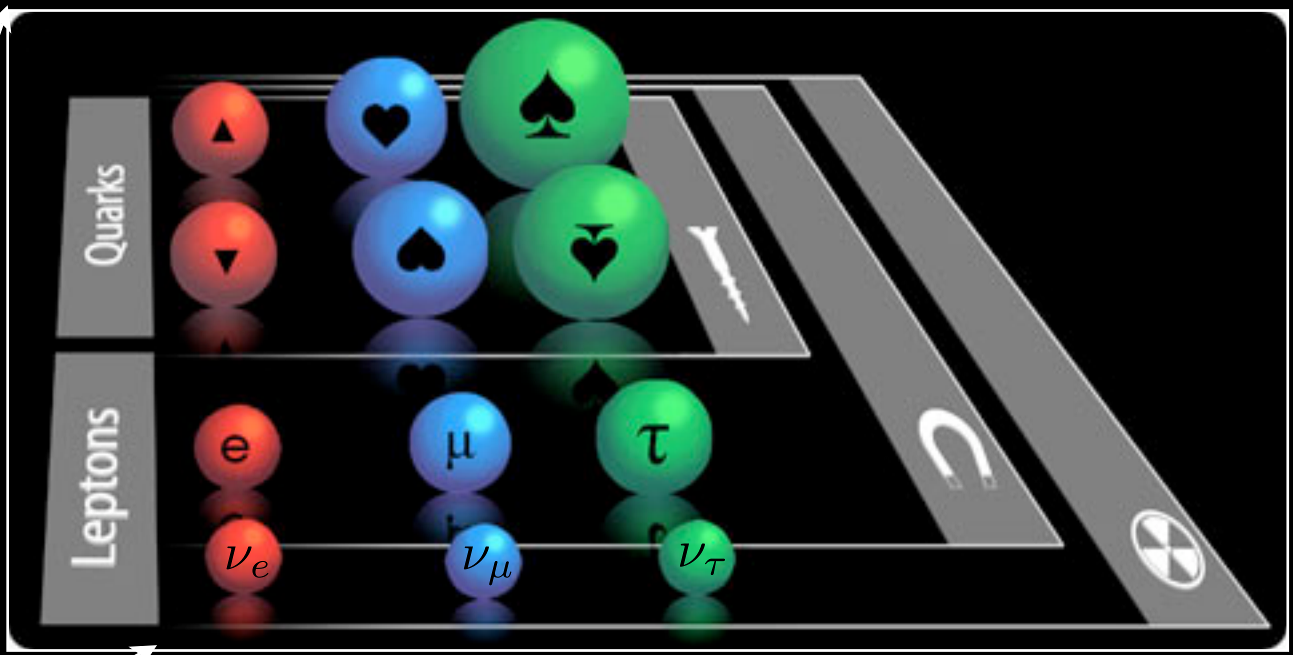


Spin 1/2

Within the Framework



Binds nucleii;
mediated by gluons;
only couples to quarks



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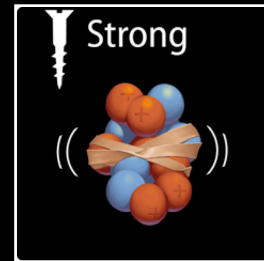

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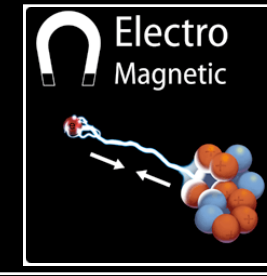
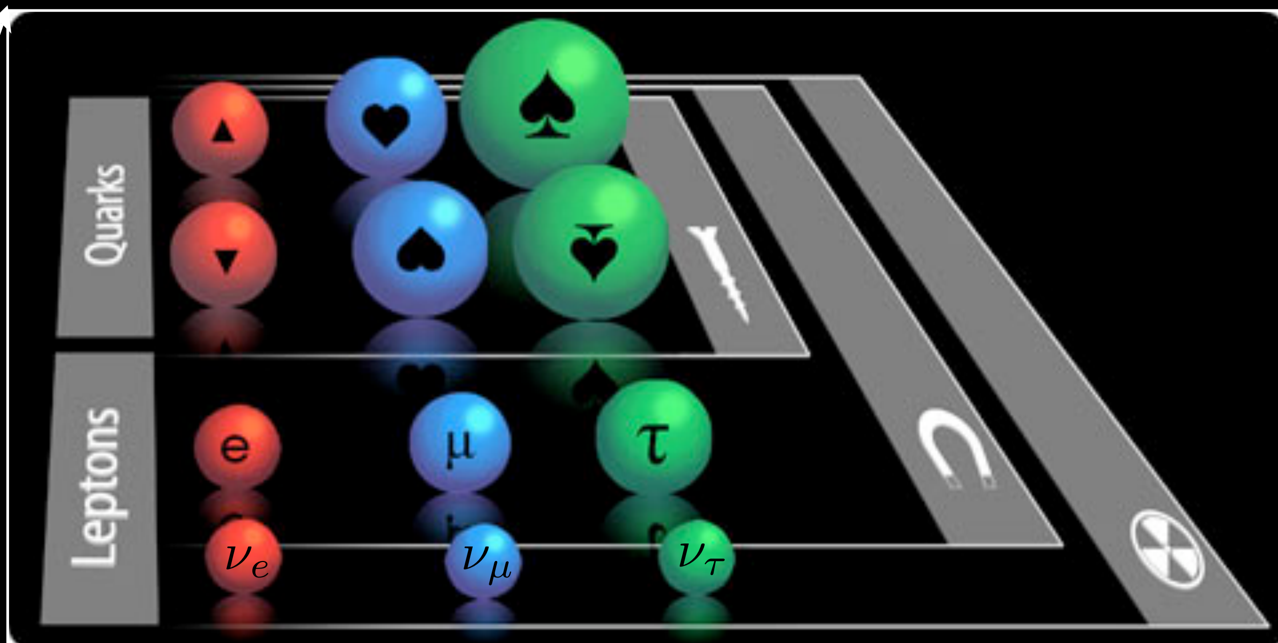


Couples to charge;
mediated by photons;
felt by quarks and leptons



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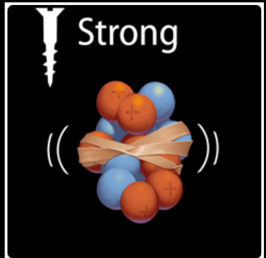

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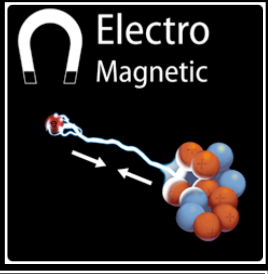

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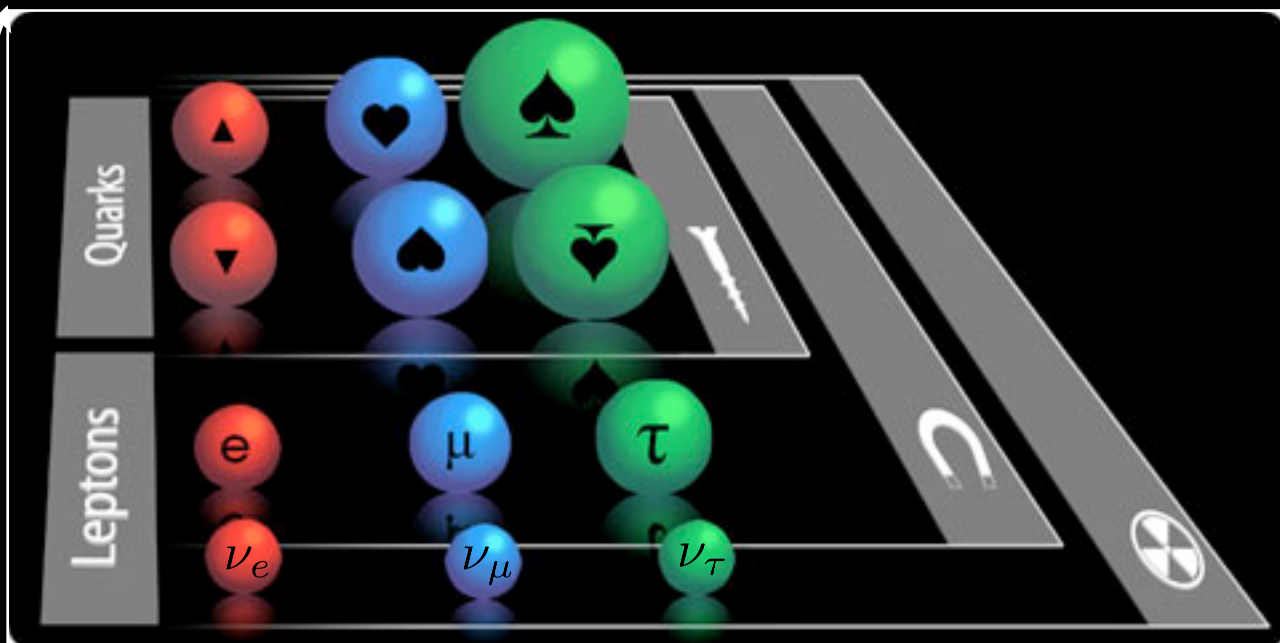
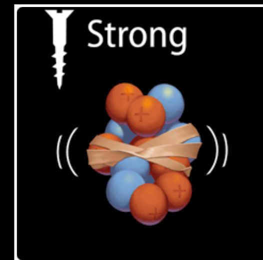


Spin 1/2

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

Within the Framework



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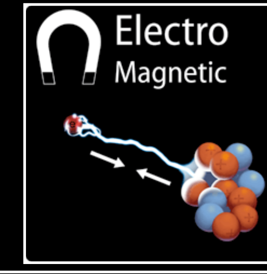

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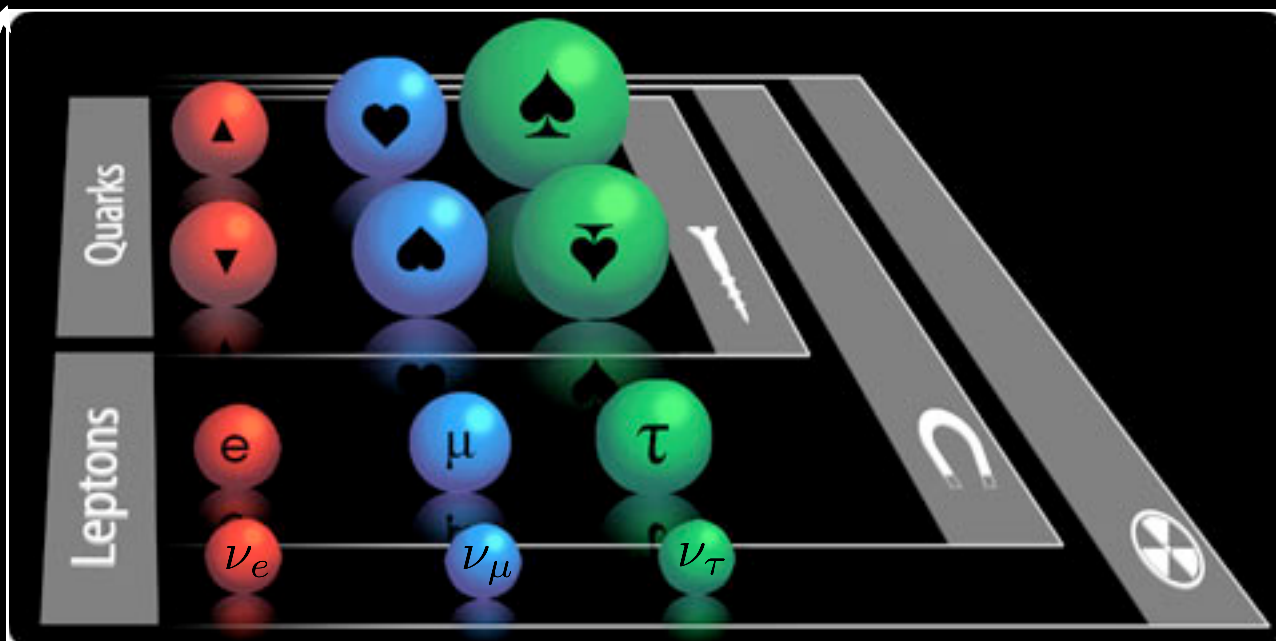
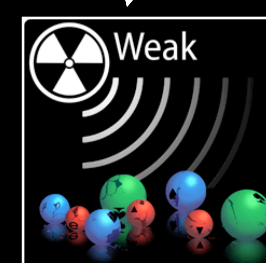


Spin 1

Spin 1/2



Common to all particles;
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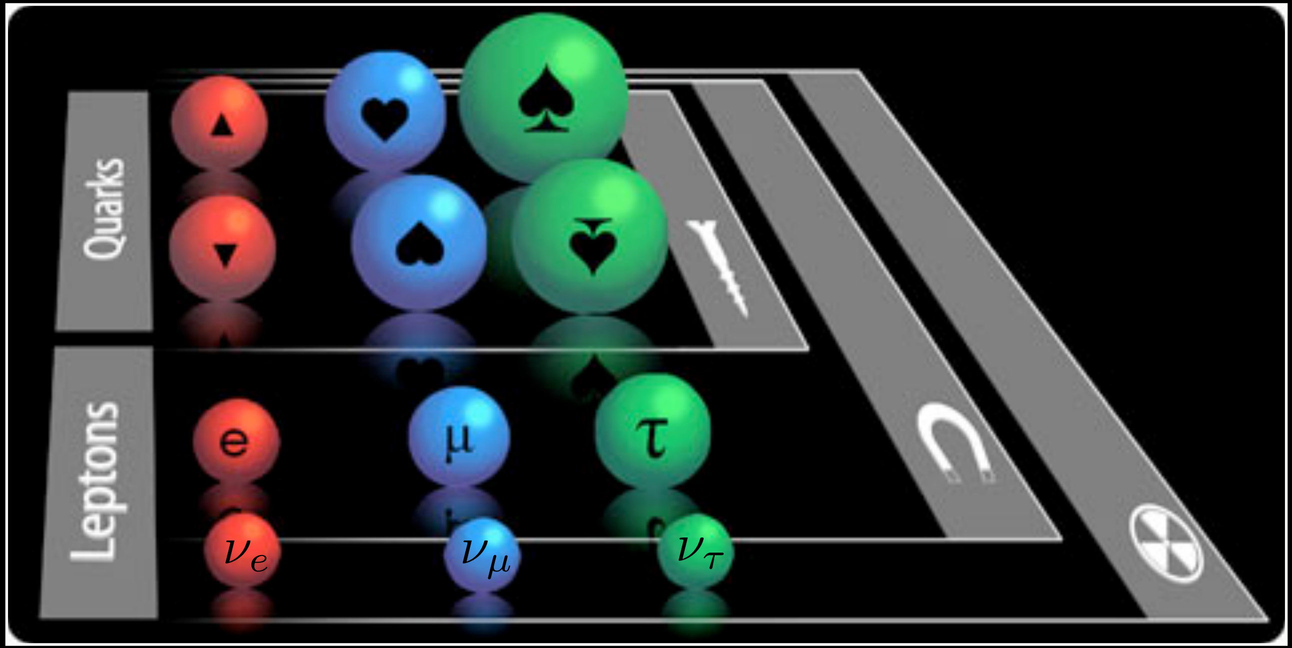
Limited Interactions

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

The number of interactions, therefore, is quite limited.



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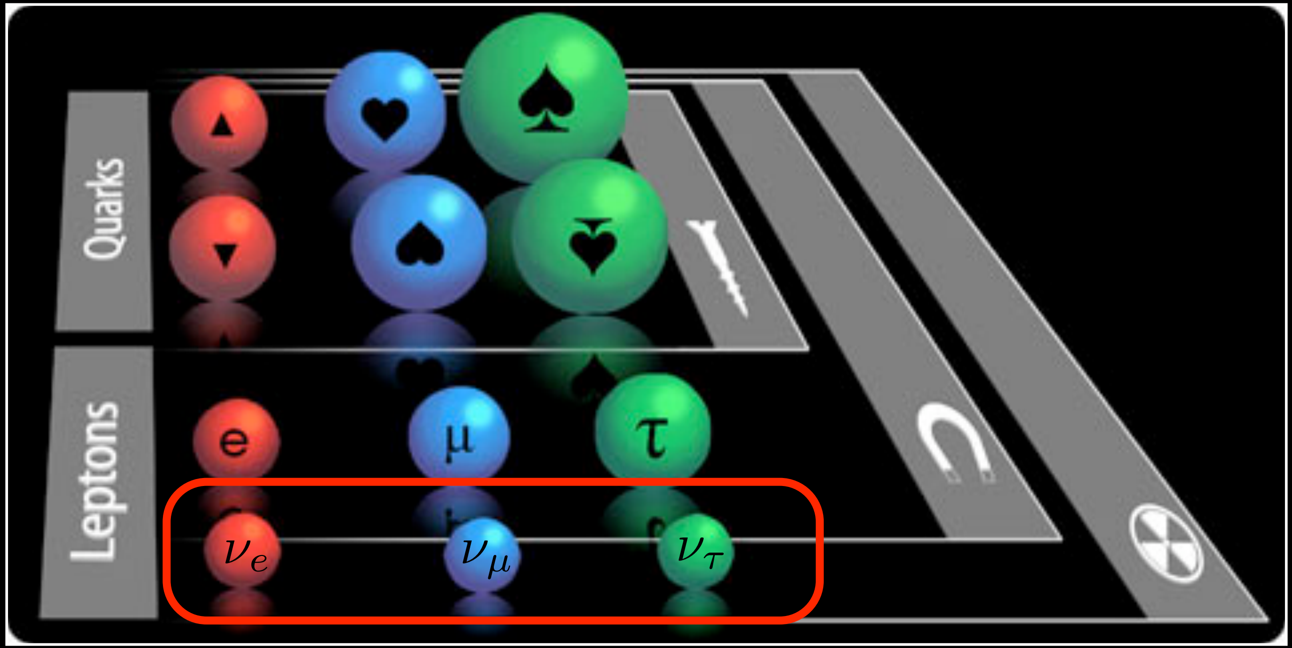

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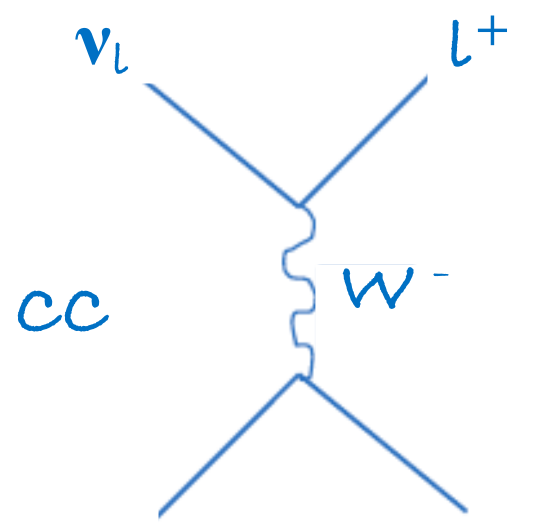
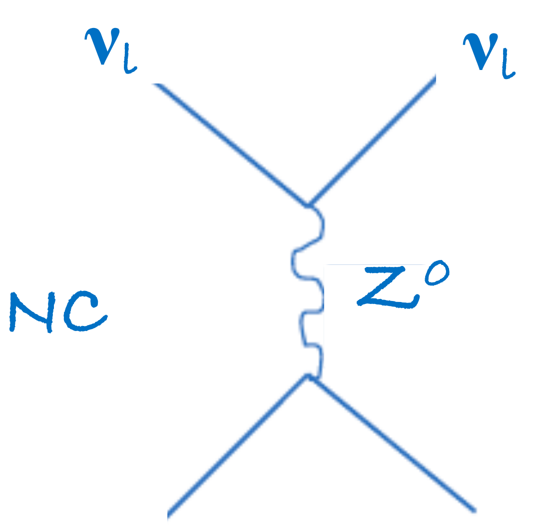
Two Basic Interactions



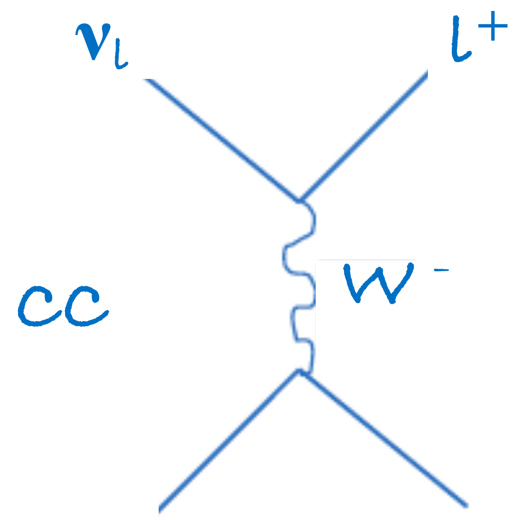
Charged Current



Neutral Current

Most interactions are limited to two basic type of interactions:

Two Basic Interactions



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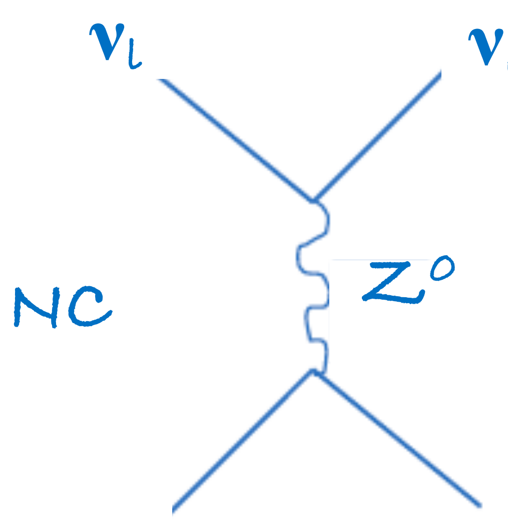

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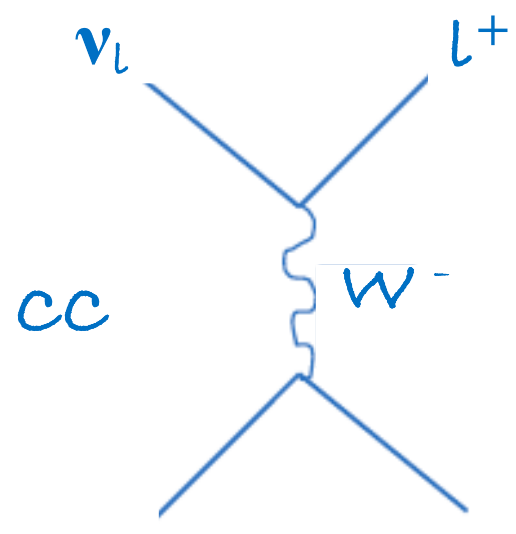
A charge $W^{\pm}$ is exchanged: Charged Current Exchange

Two Basic Interactions



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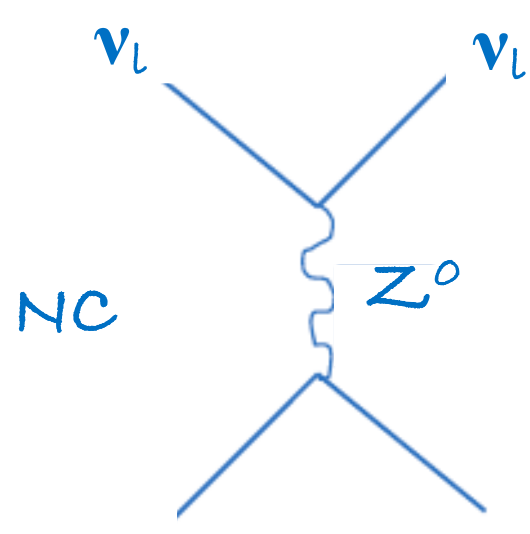

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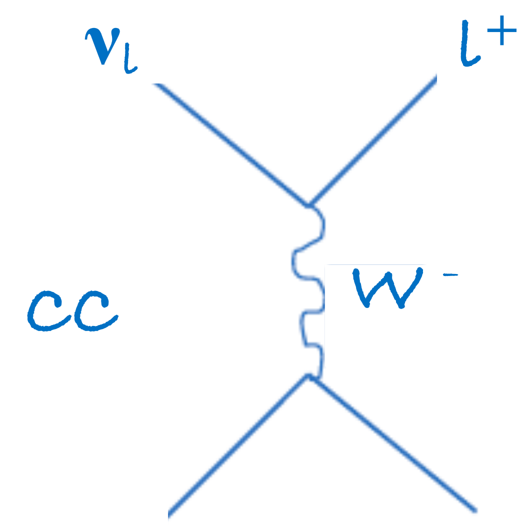

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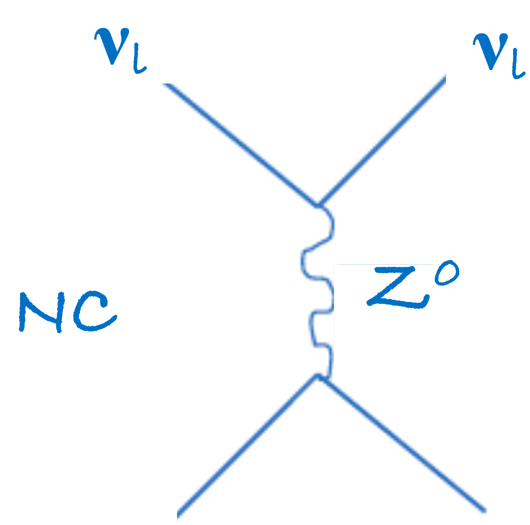


Neutral Current

Most interactions are limited to two basic type of interactions:

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

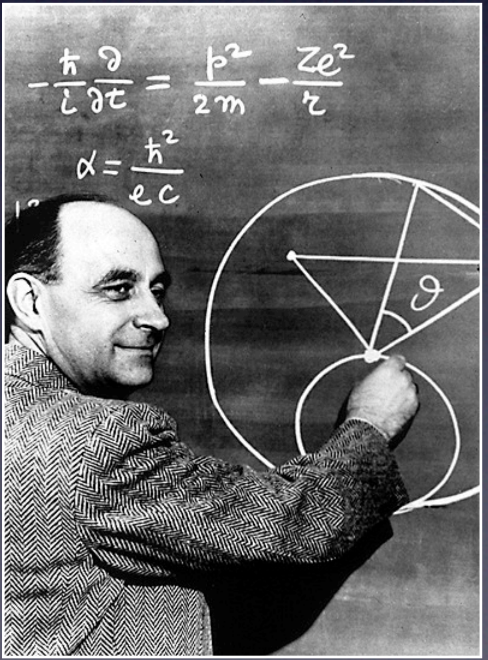
A neutral Z^0 is exchanged: Neutral Current Exchange

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

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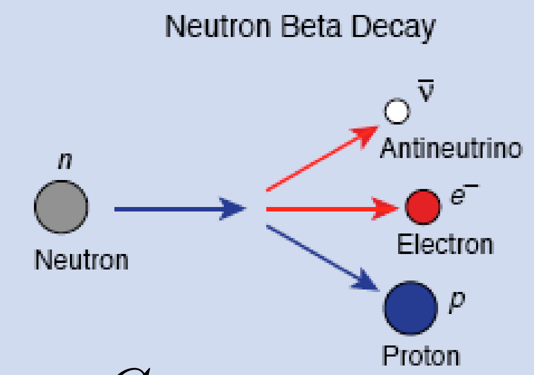
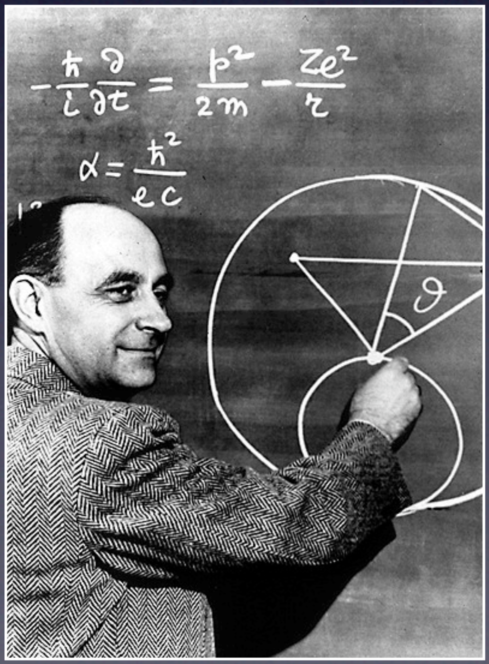


$$\mathcal{H} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu \nu][\bar{\Phi}_n \gamma^\mu \Phi_p]$$



E. Fermi

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

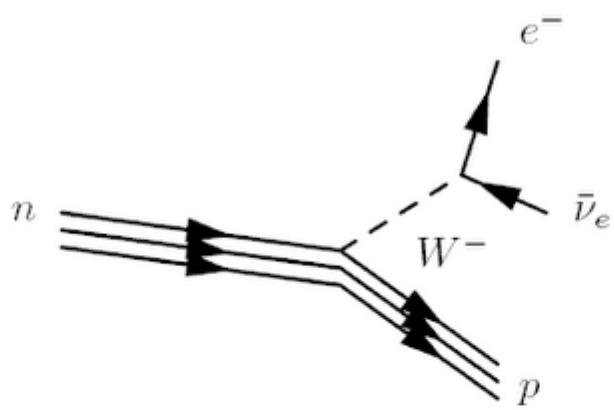
- The system does not have many of the features of the Standard Model, yet still remarkably descriptive.

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!



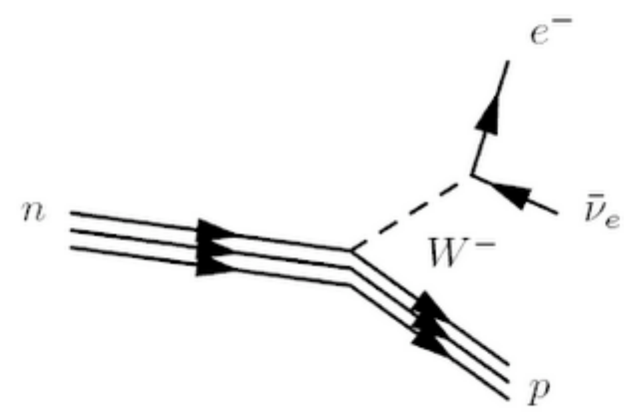
$$\mathcal{H} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e][\bar{\Phi}_n\gamma^\mu(V - A\gamma_5)\Phi_p]$$

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



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

- 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...

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

G_F is a small number...

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

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

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

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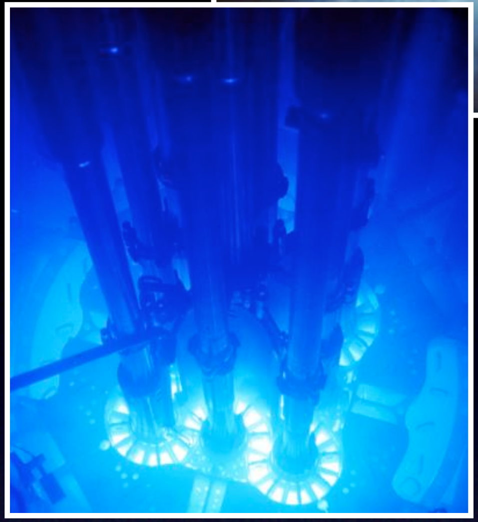
E_ν~MeV



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E_ν~GeV

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E_ν~GeV - TeV

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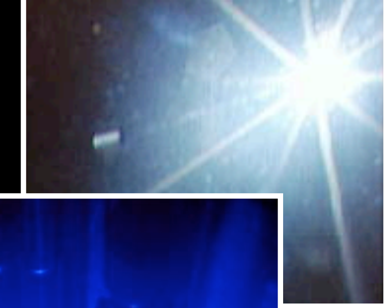
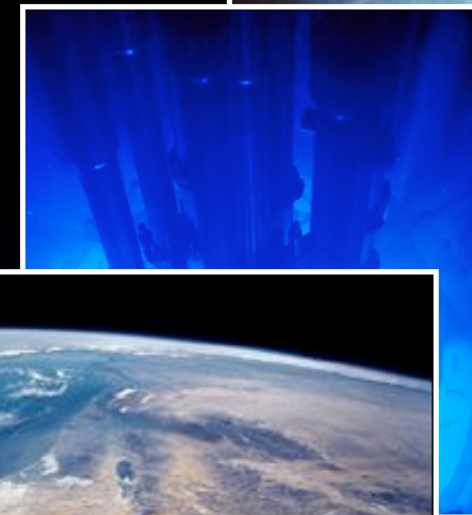
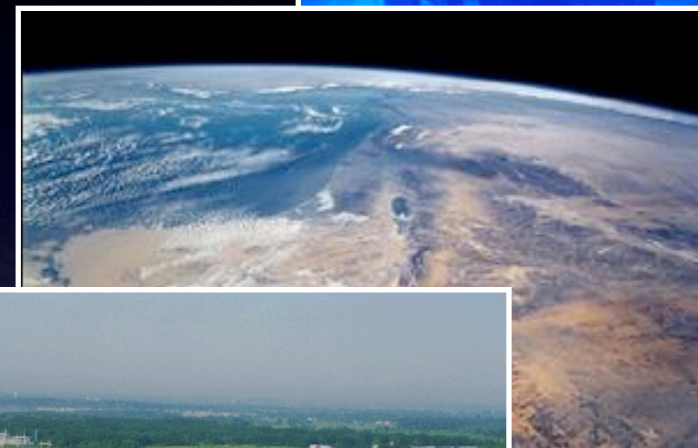
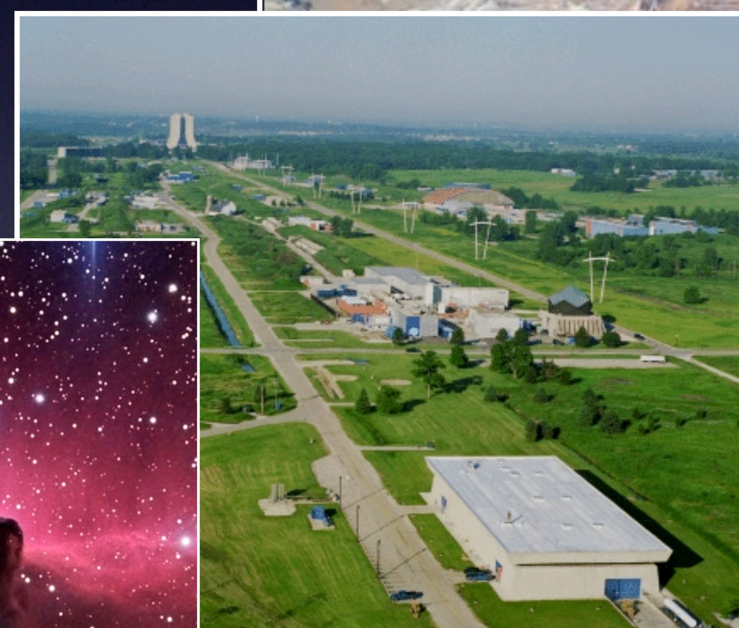
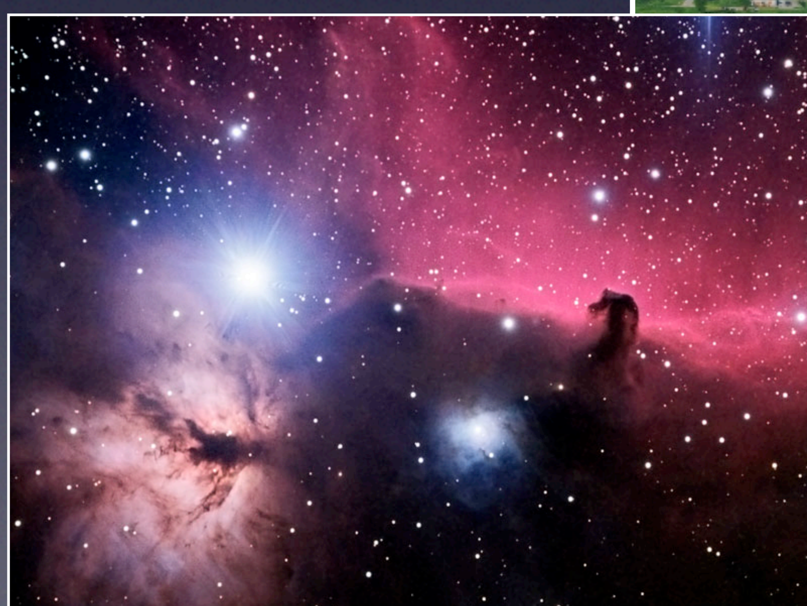






E_{ν} >> TeV

What we will cover:

Where do neutrinos come from?

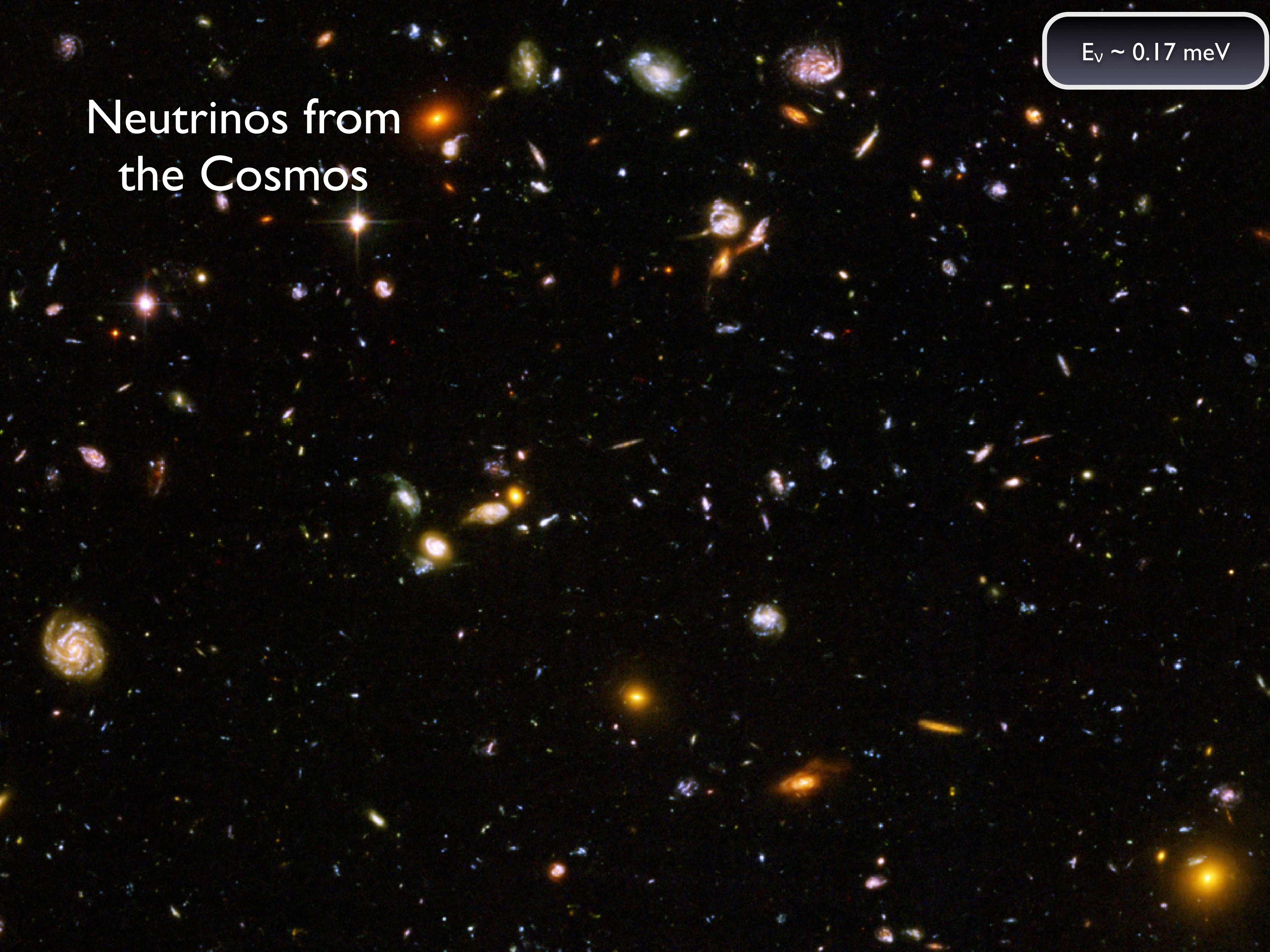
Neutrinos from the Heavens

Neutrinos from the Earth

Neutrinos from Man

Neutrinos from the Cosmos

$E_\nu \sim 0.17$ meV



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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.

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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.
- 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.

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Annihilation Rate

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

Expansion Rate

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Neutrino decoupling occurs when two rates are equal.

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

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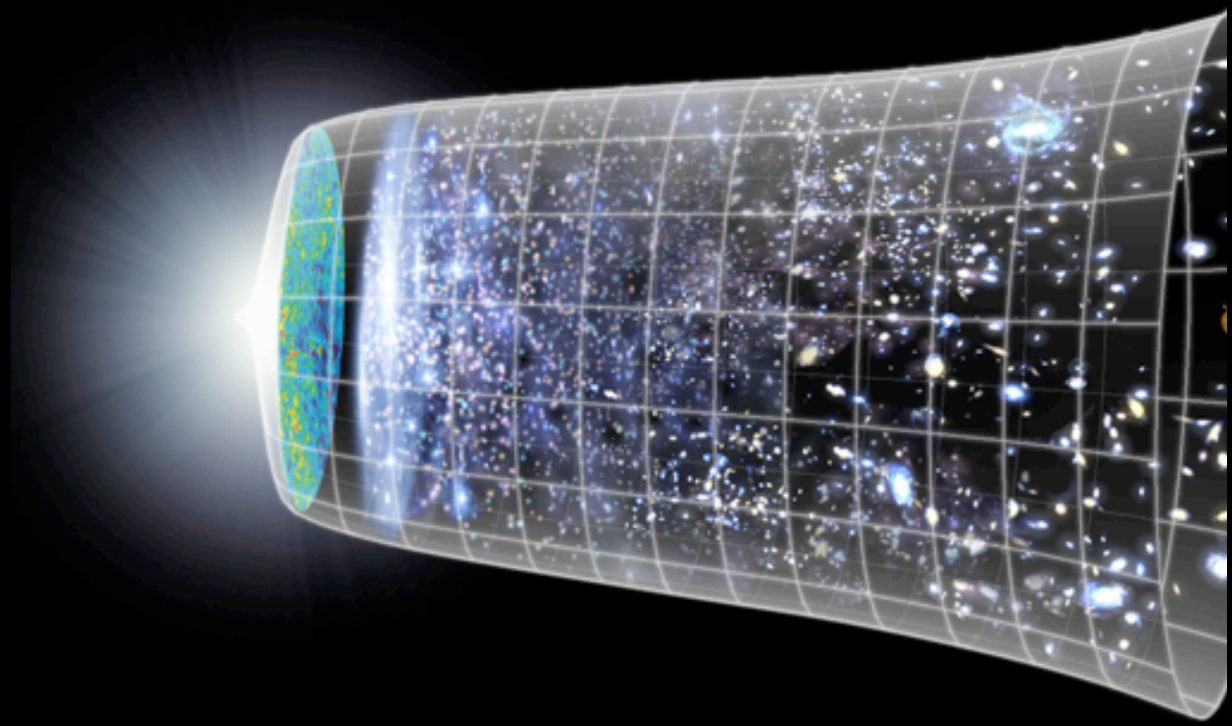
Expansion Rate

Neutrinos Today



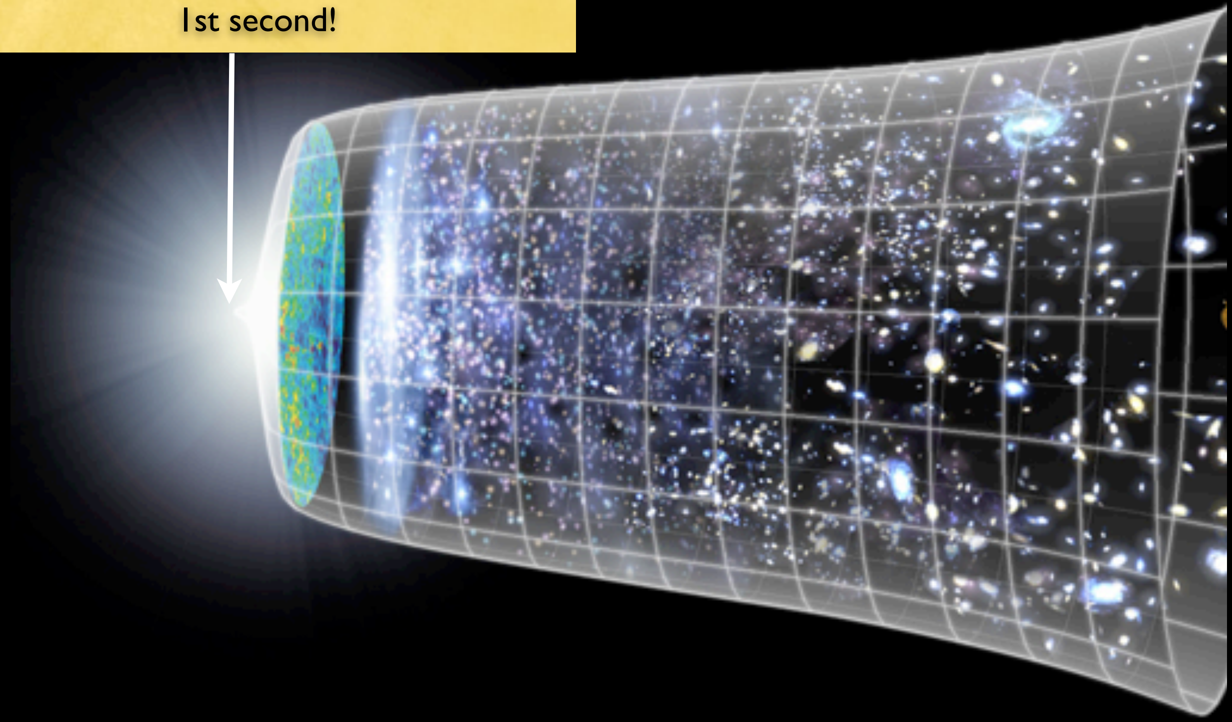
- The presence of neutrinos have a vast impact on our understanding of the universe's chronology.

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

Neutrinos Today

Relic Neutrinos

1st second!



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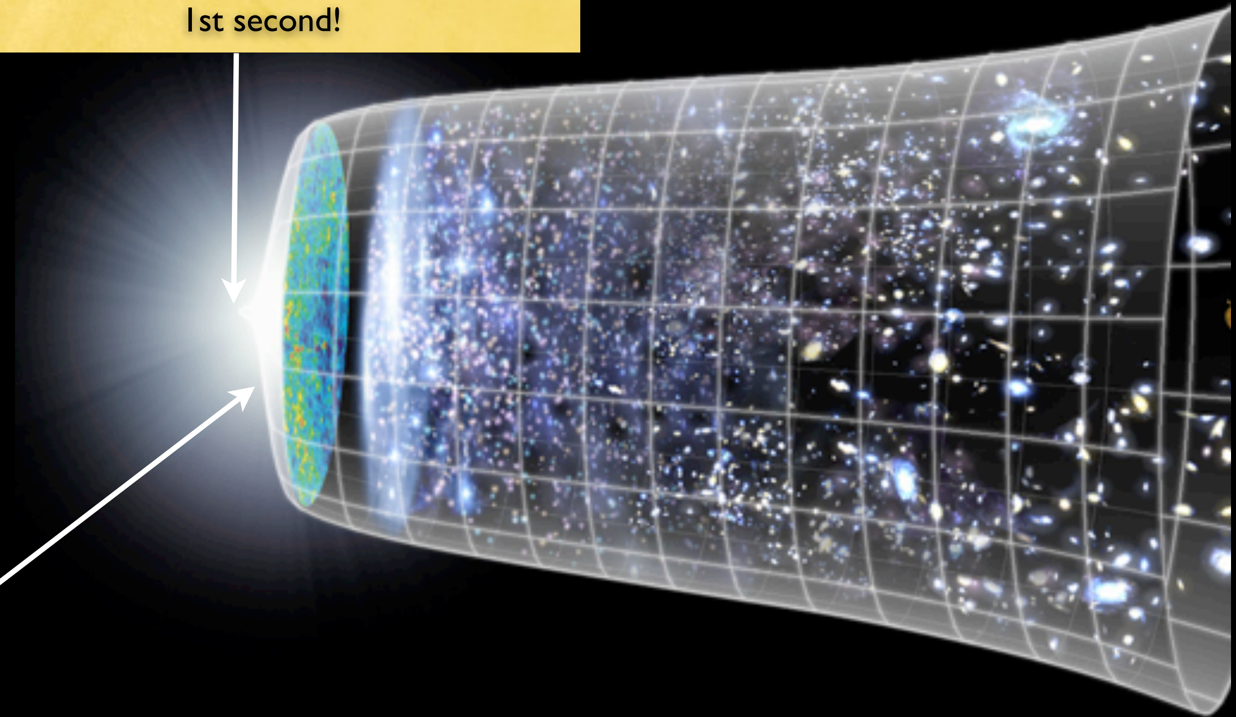

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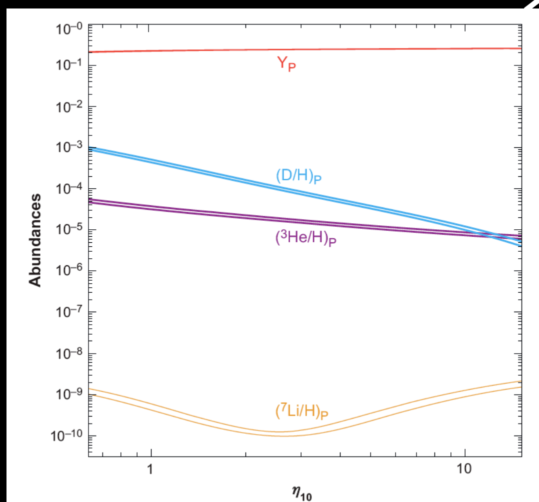

Primordial Nucleosynthesis

1st few minutes

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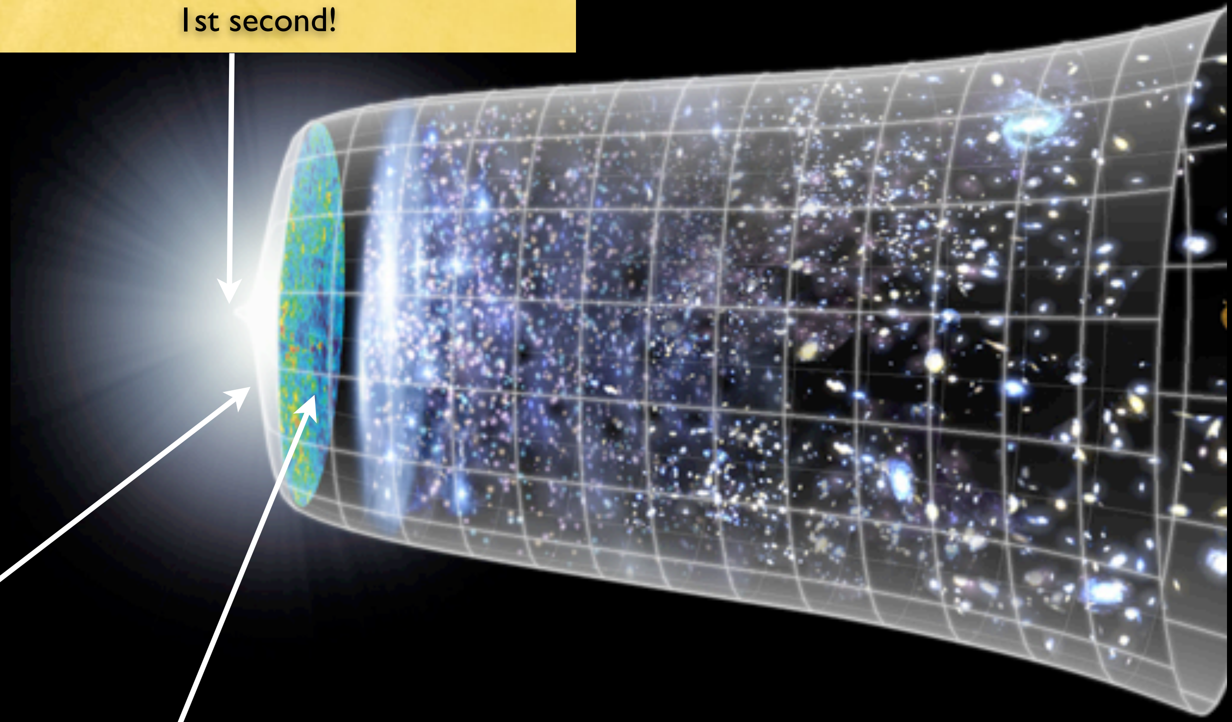

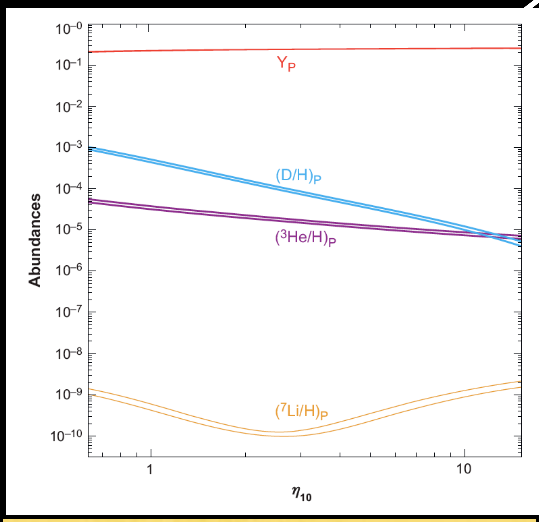

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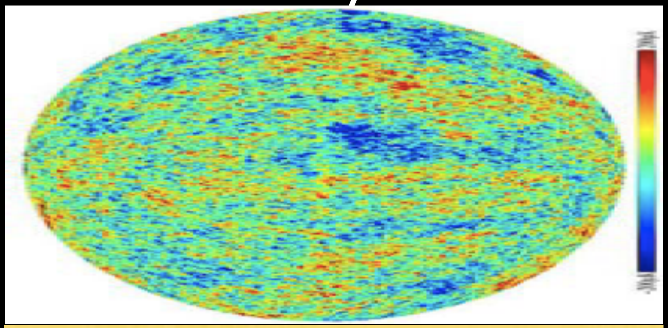

Cosmic Microwave Background

400 kyrs

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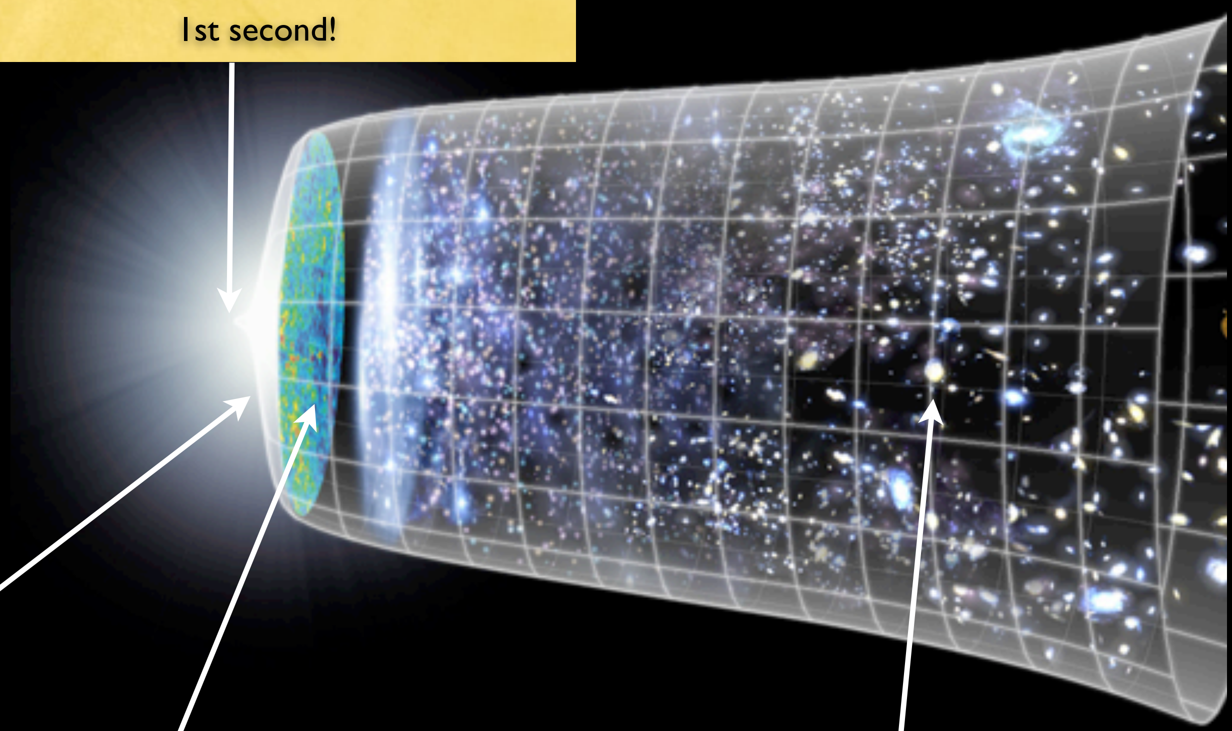

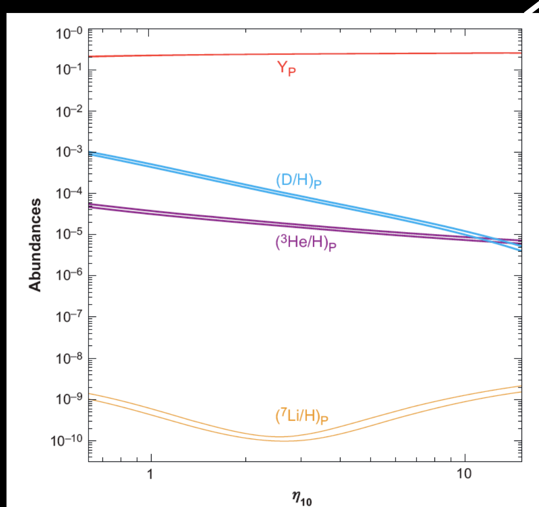

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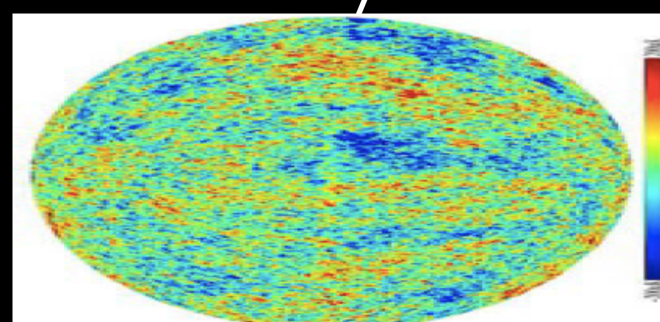
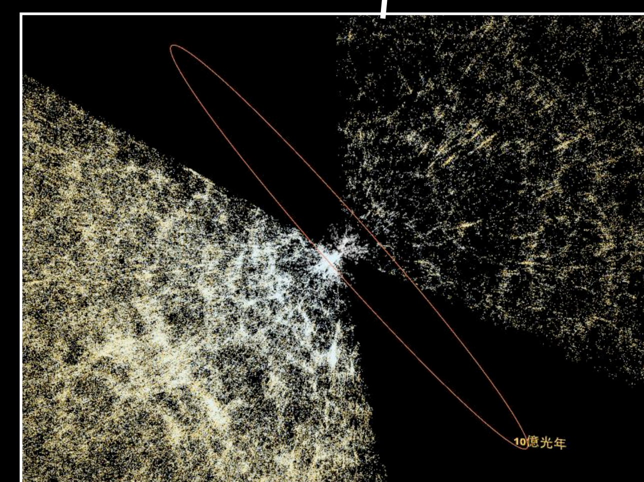


Cosmic Microwave Background

400 kyrs



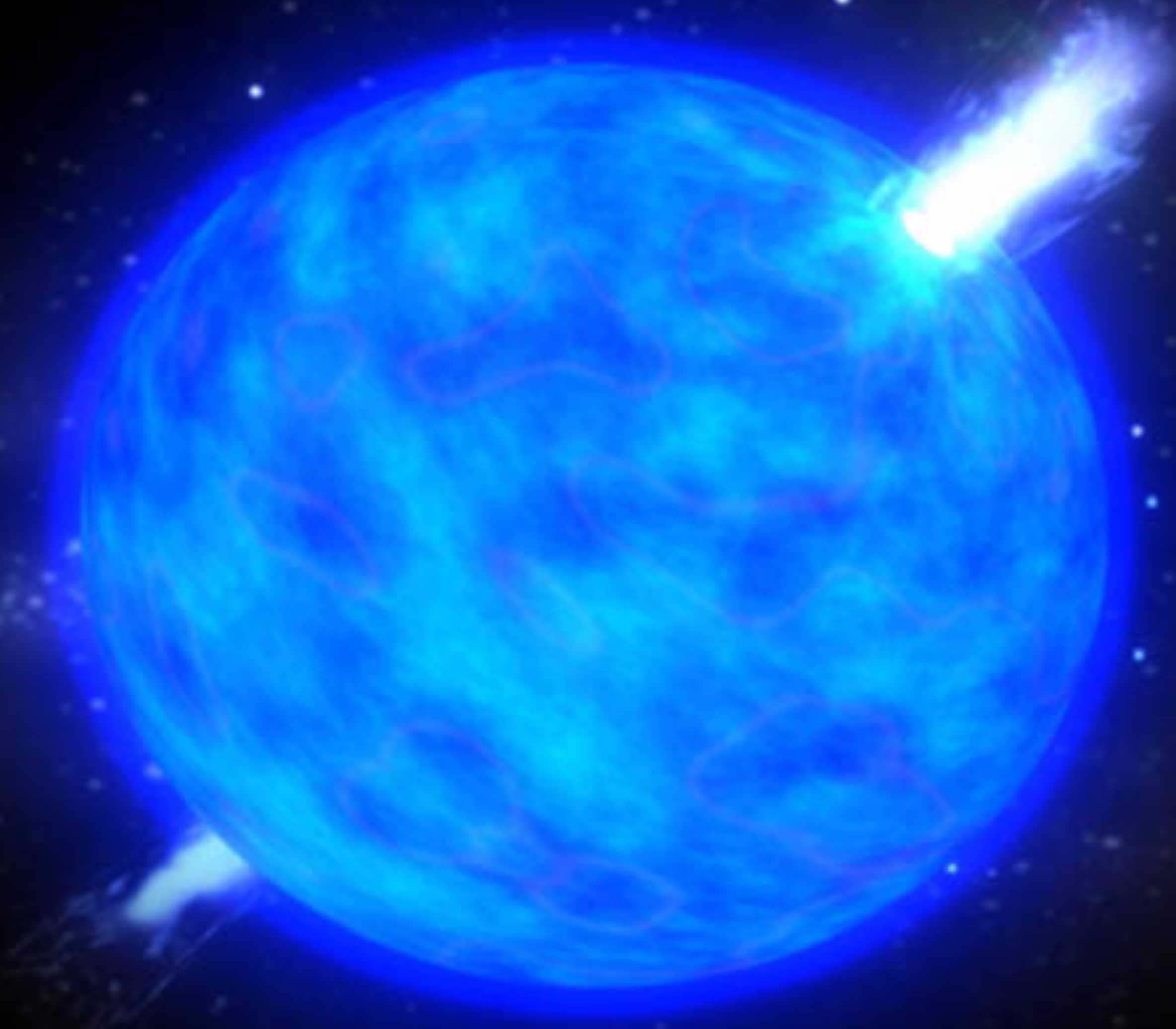
Large Scale Structures

Near Today

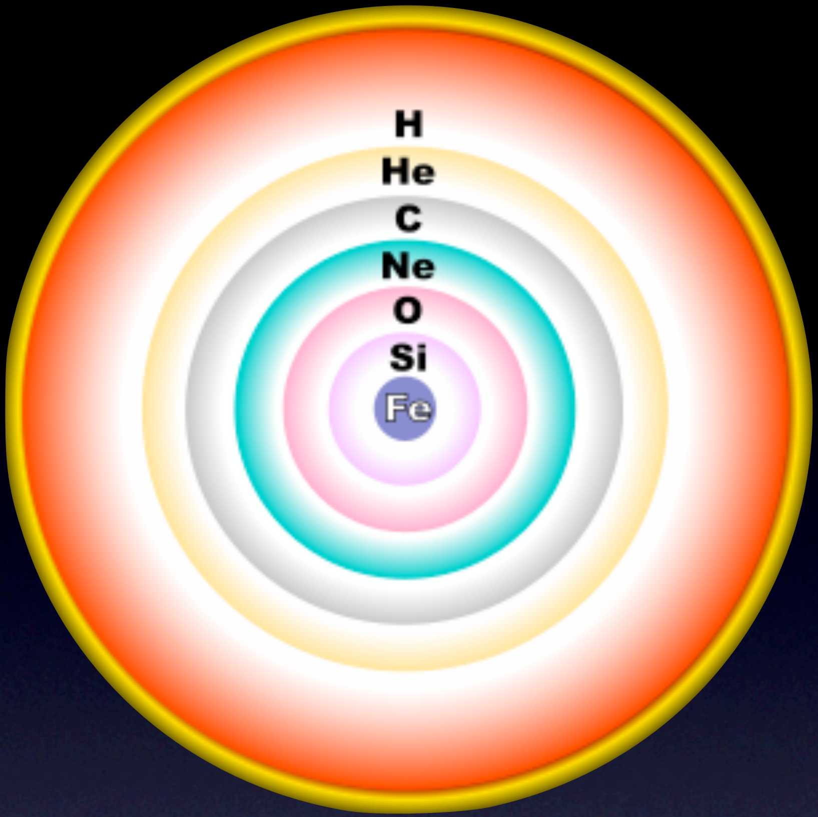
$E_\nu \sim$ 10-20 MeV

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.



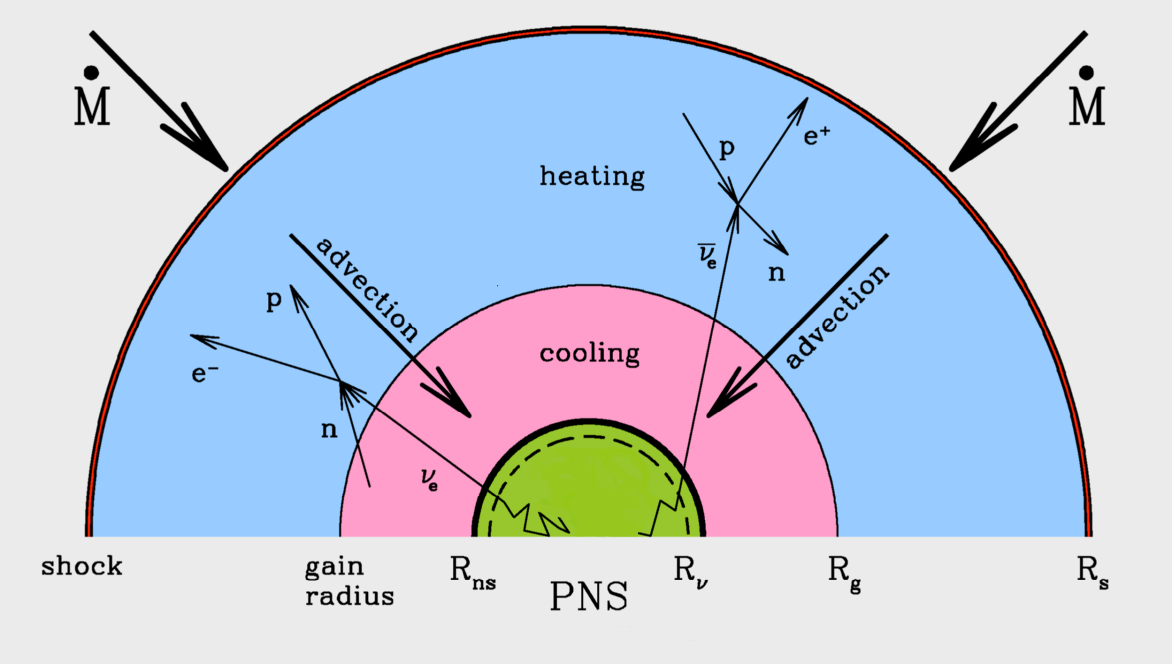
Neutrinos from the Stars



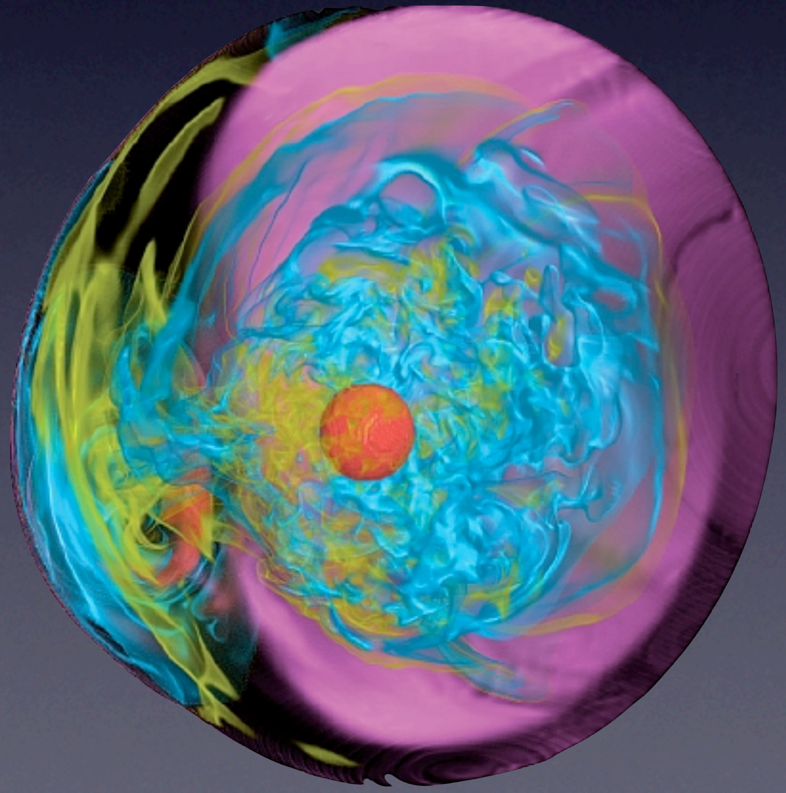
- Core-collapse supernovae are truly unique environments in our known universe:
  - Incredible matter densities: 10^{11}-10^{15} g/cm^3
  - Extreme high temperature: 1-50 MeV
  - Highest recorded energetic processes in the Universe: 10^{51-53} ergs
- At these energies, all species of neutrinos can be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



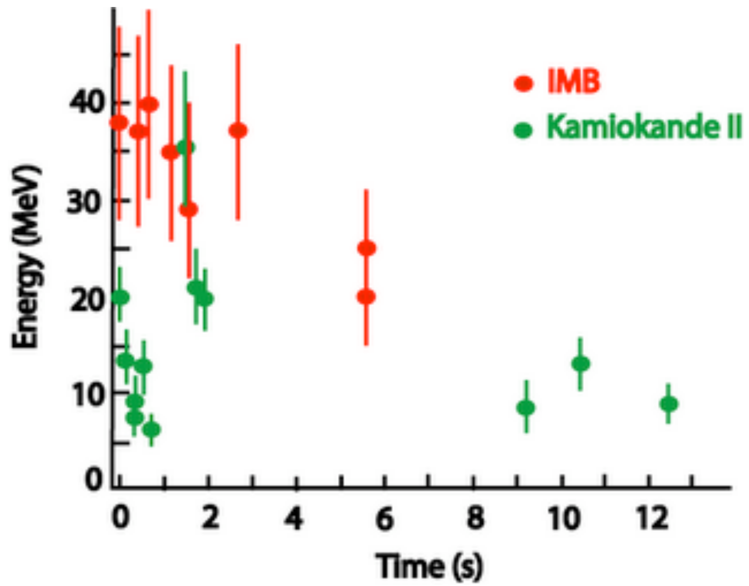
- Eventually nuclear burning is insufficient to maintain the star from collapsing, causing the stellar core to fall inward until core densities reach nuclear levels, causing the core to bounce.
- Most neutrinos remain trapped between core and outer stellar region, heating the star until the energy is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

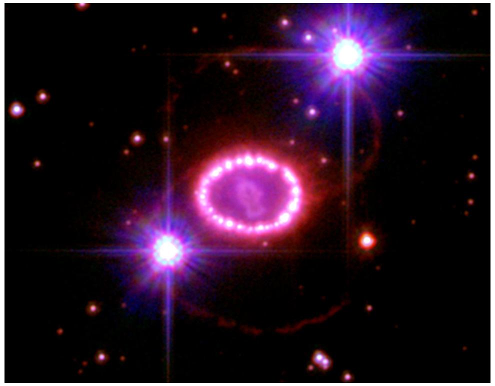
- Still waiting for another such type of explosion close enough for detection.



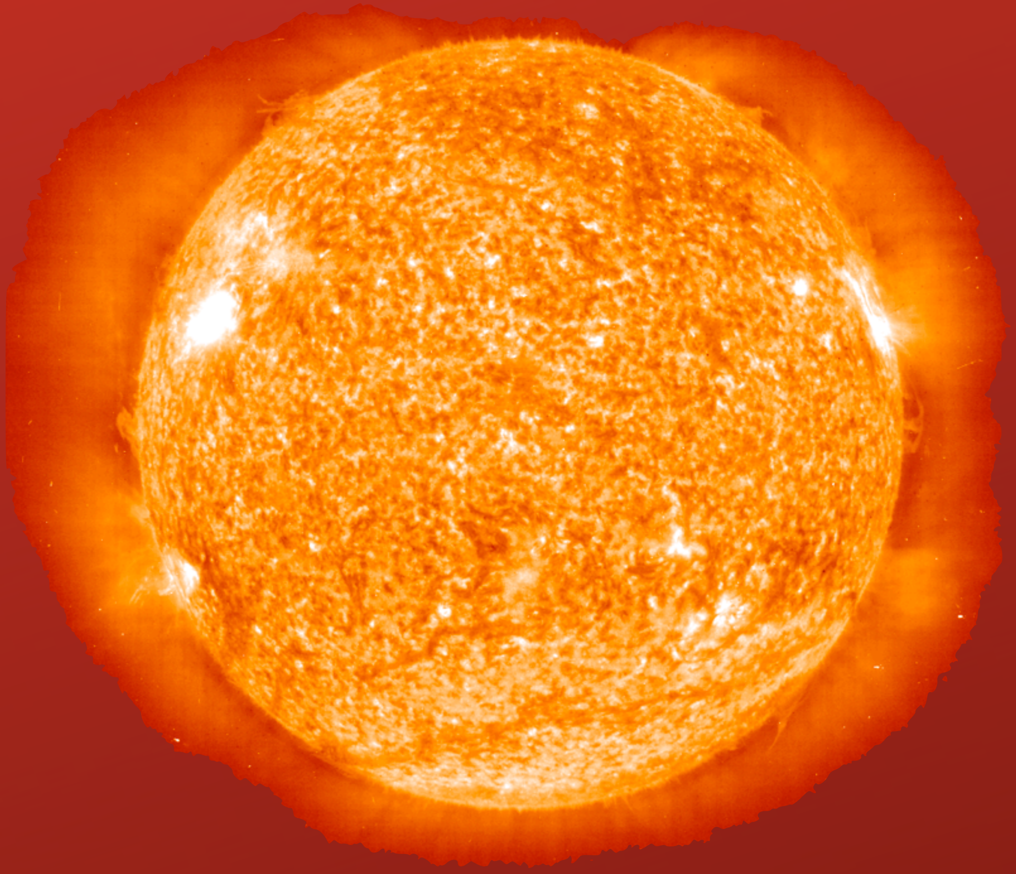
Before

During
(few days later)

After



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



Neutrinos from our star...
(the Sun)

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).

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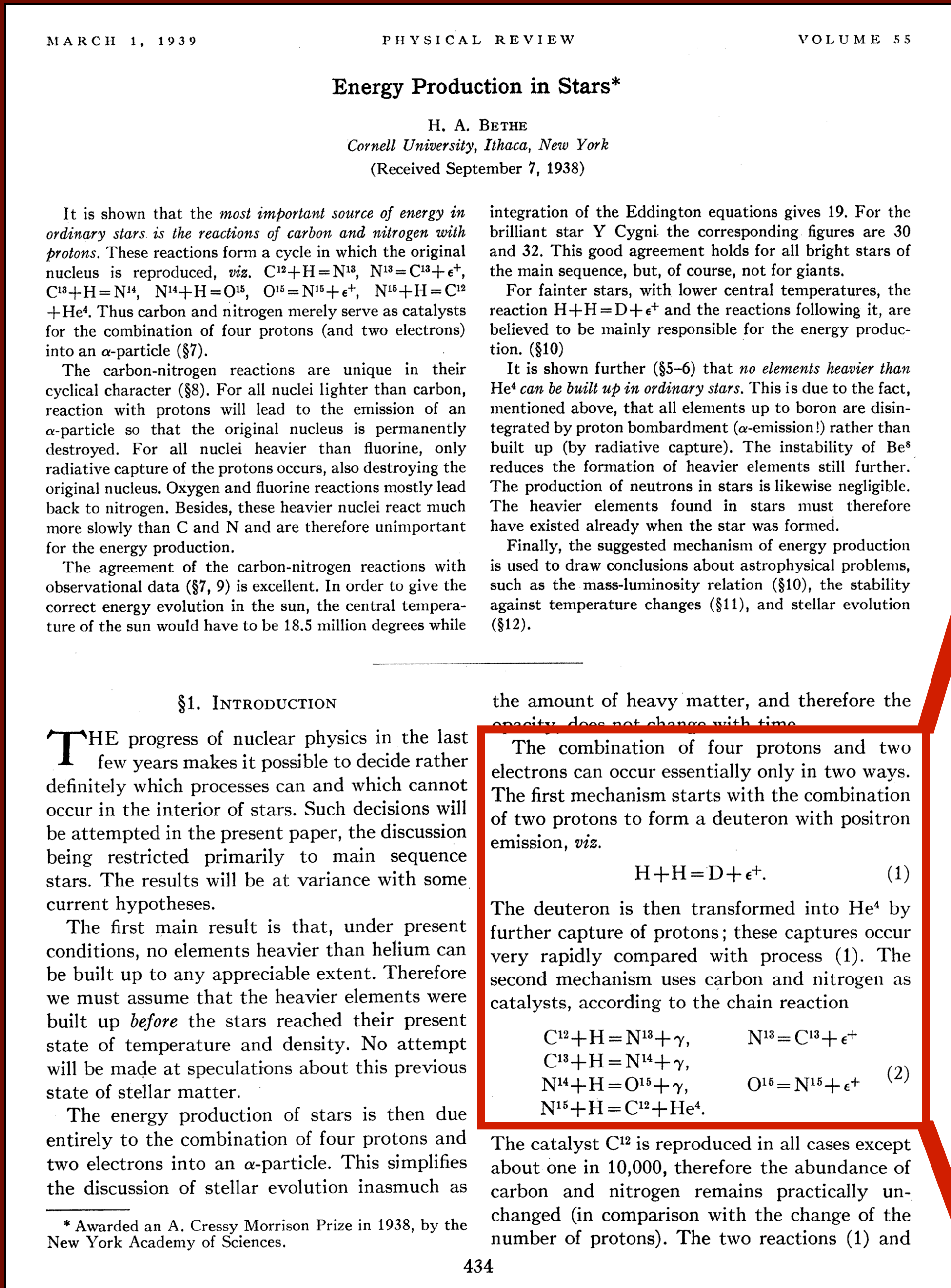

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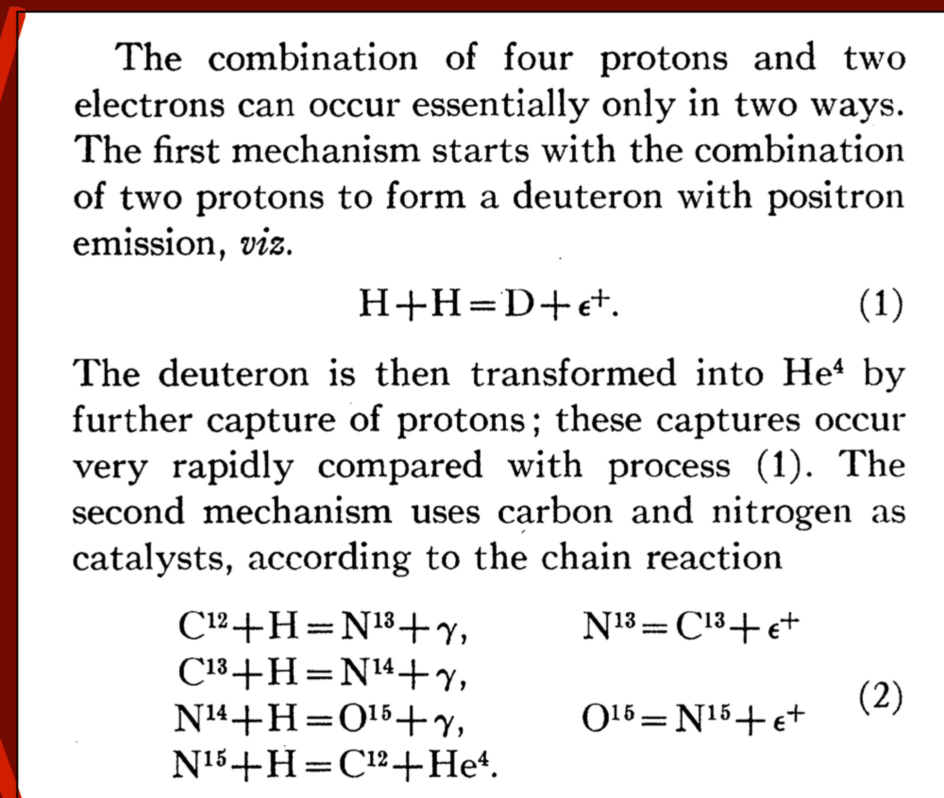

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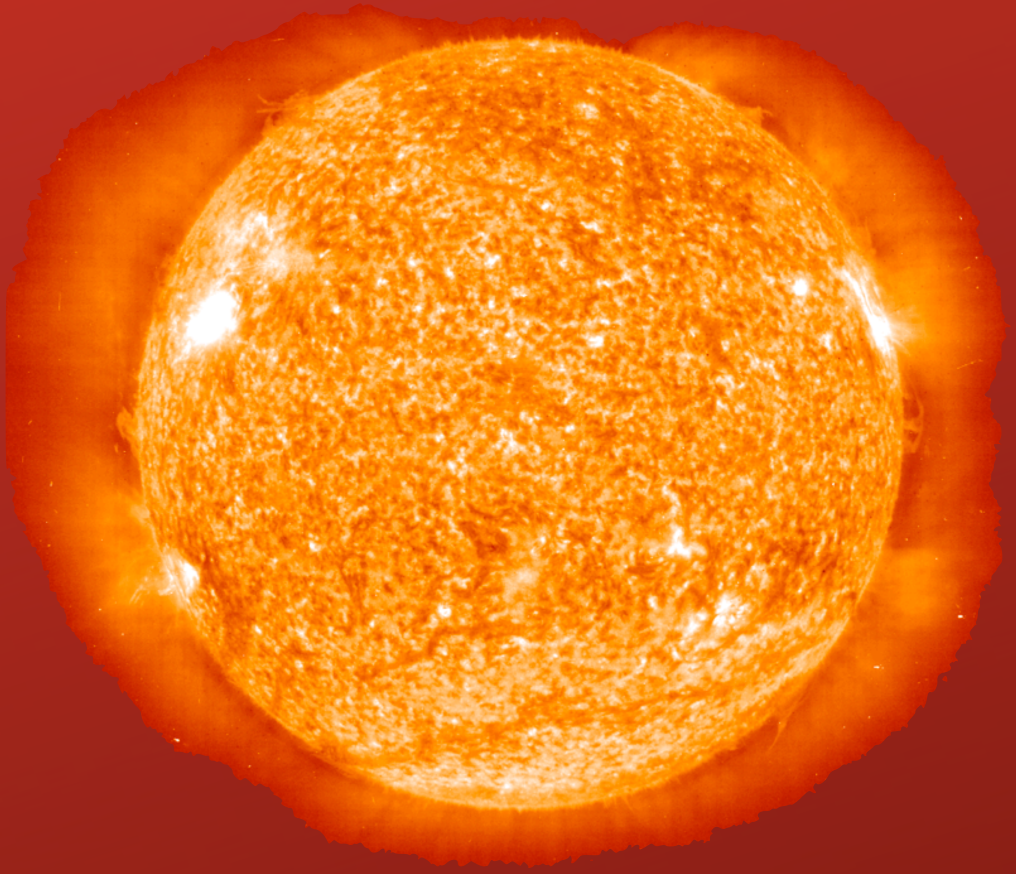
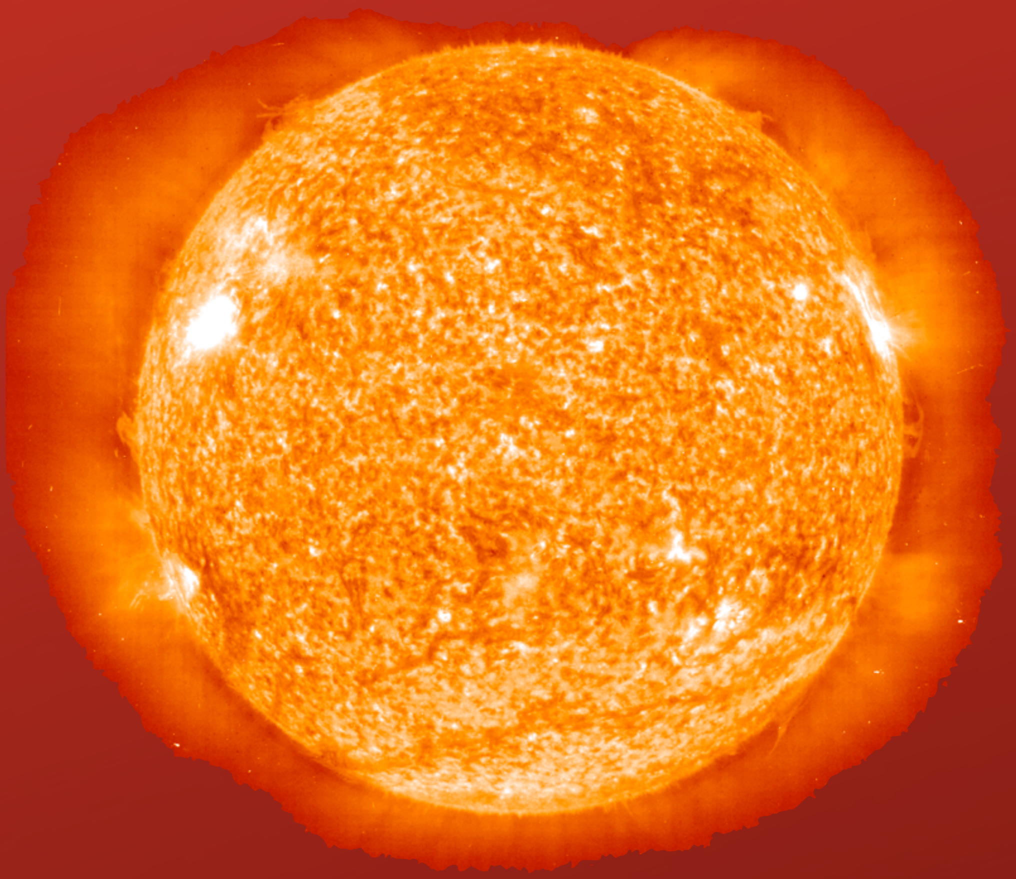


In the sixties, John Bahcall calculates the neutrino flux expected to be produced from the solar pp cycle.

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

John Bahcall
1934 - 2005



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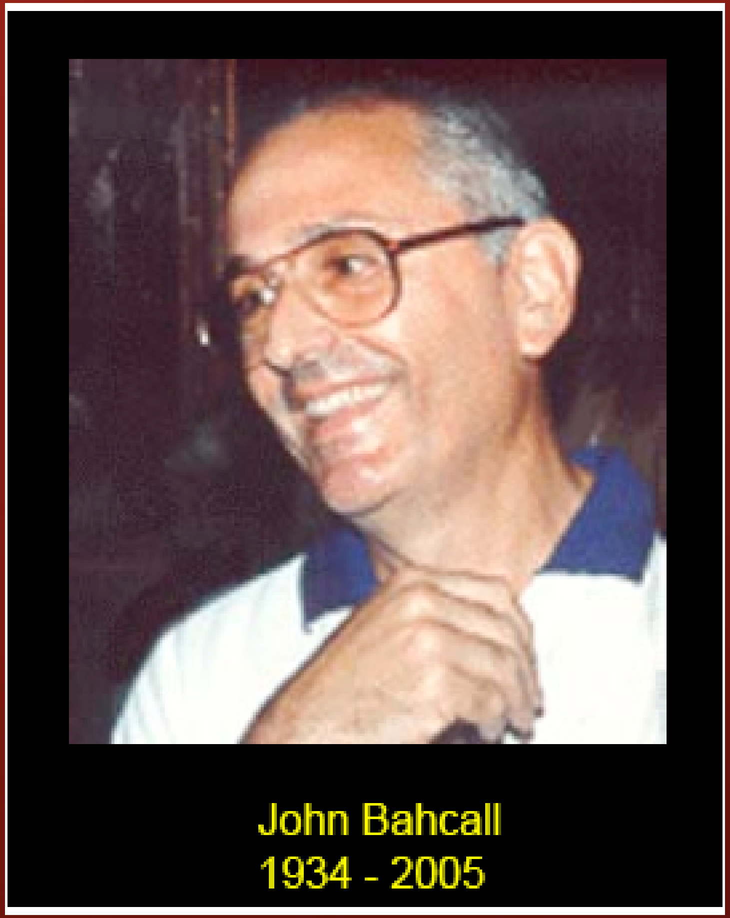

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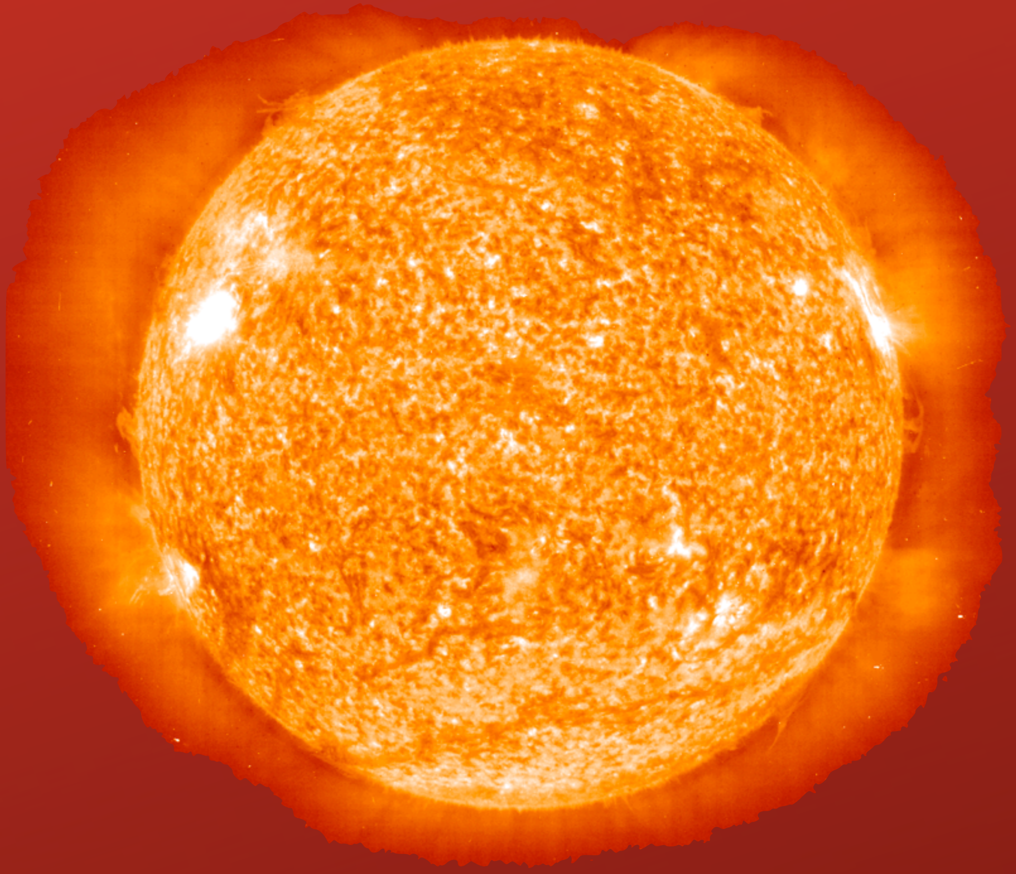

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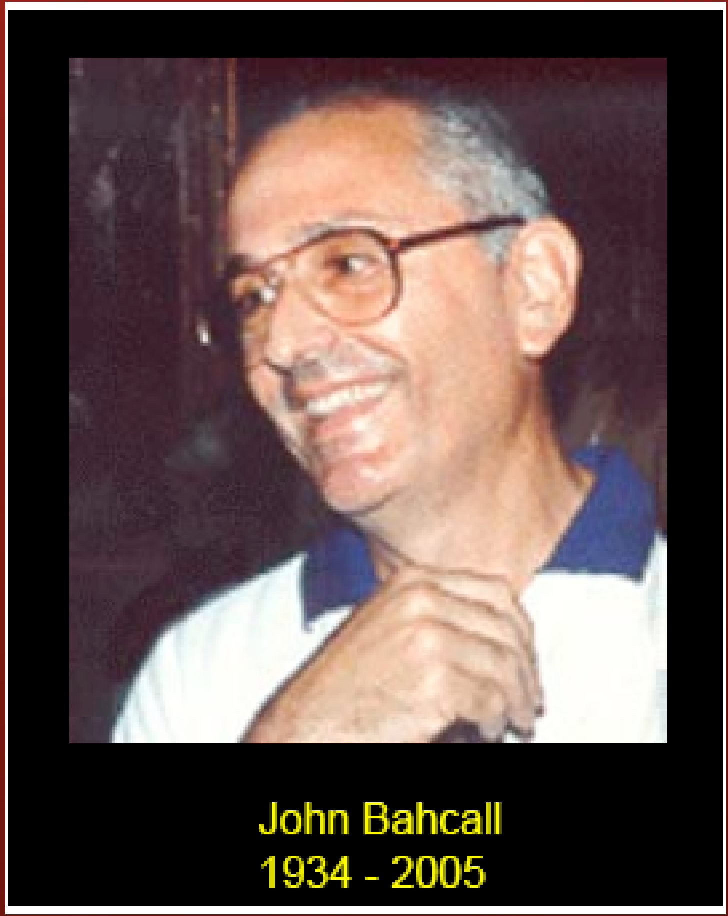

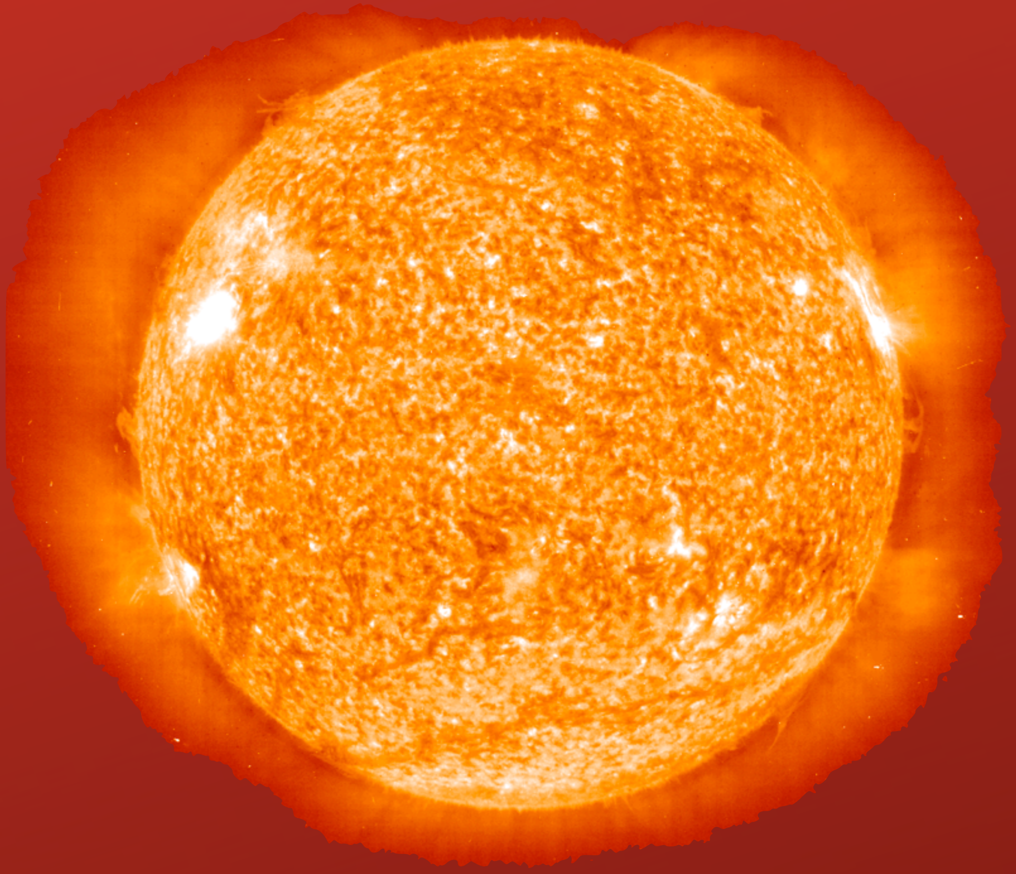

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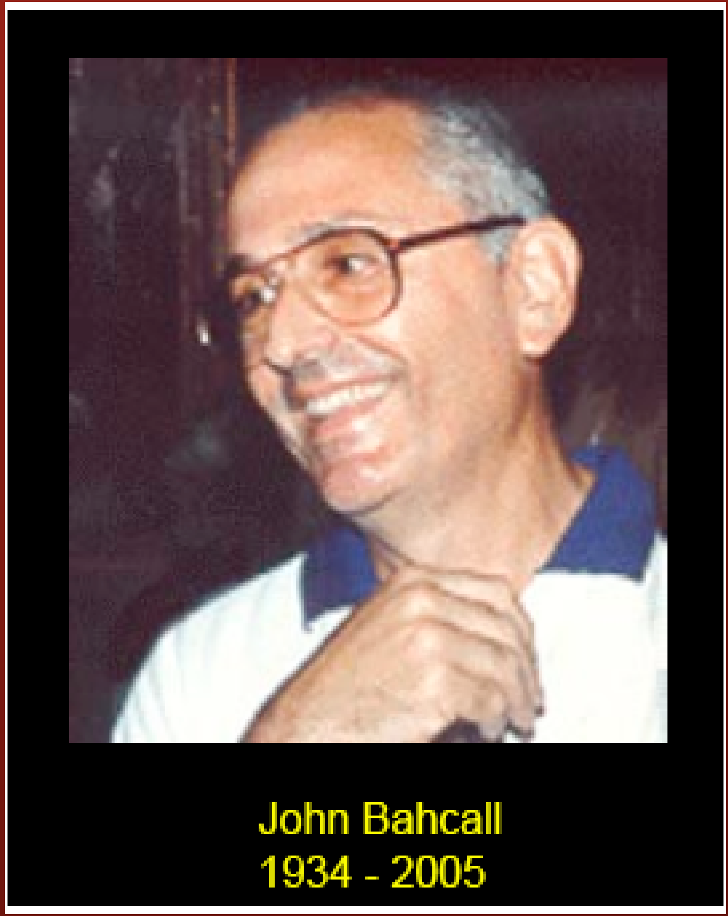

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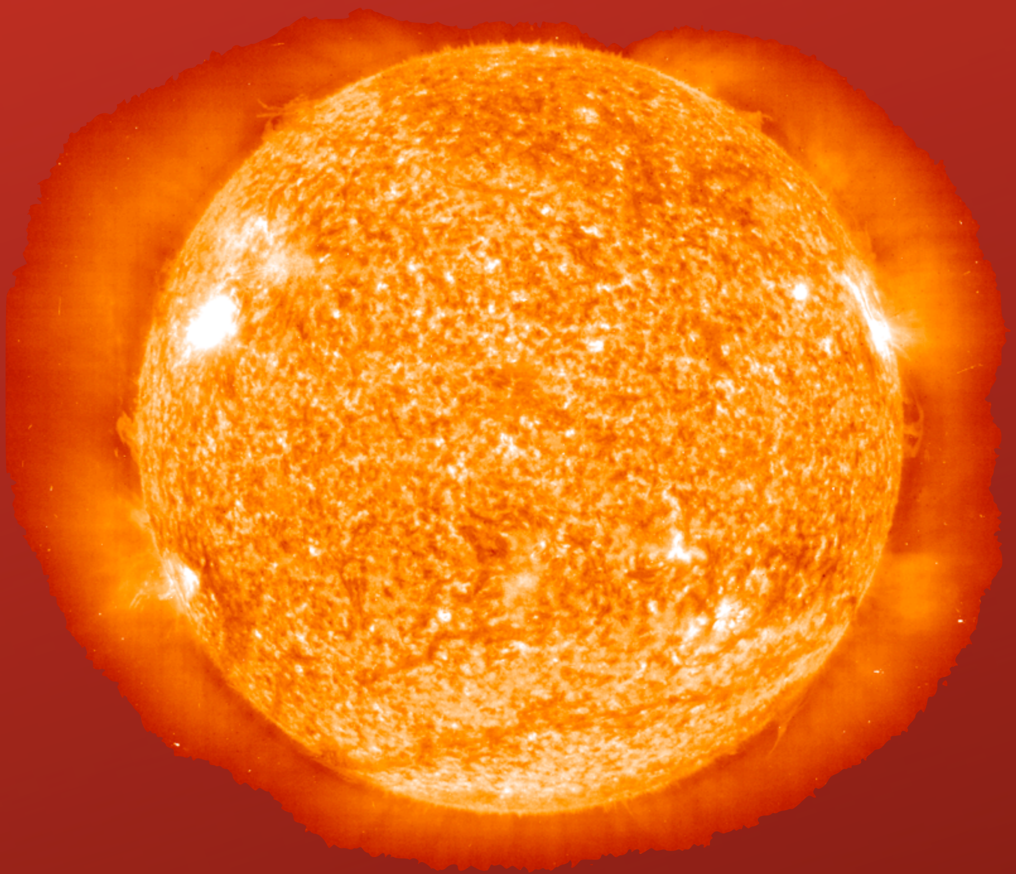

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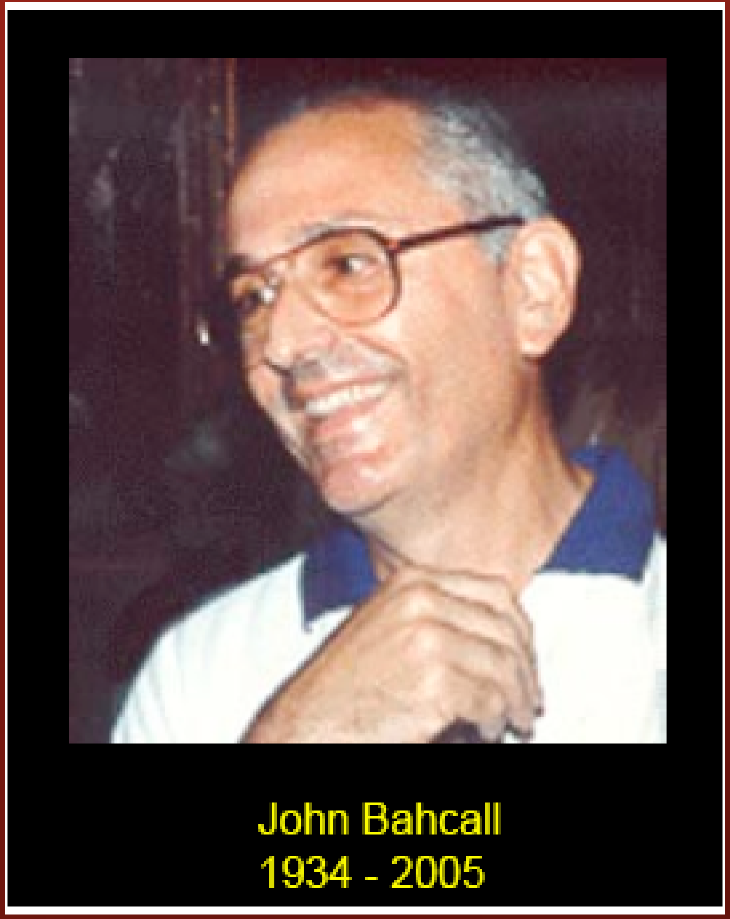

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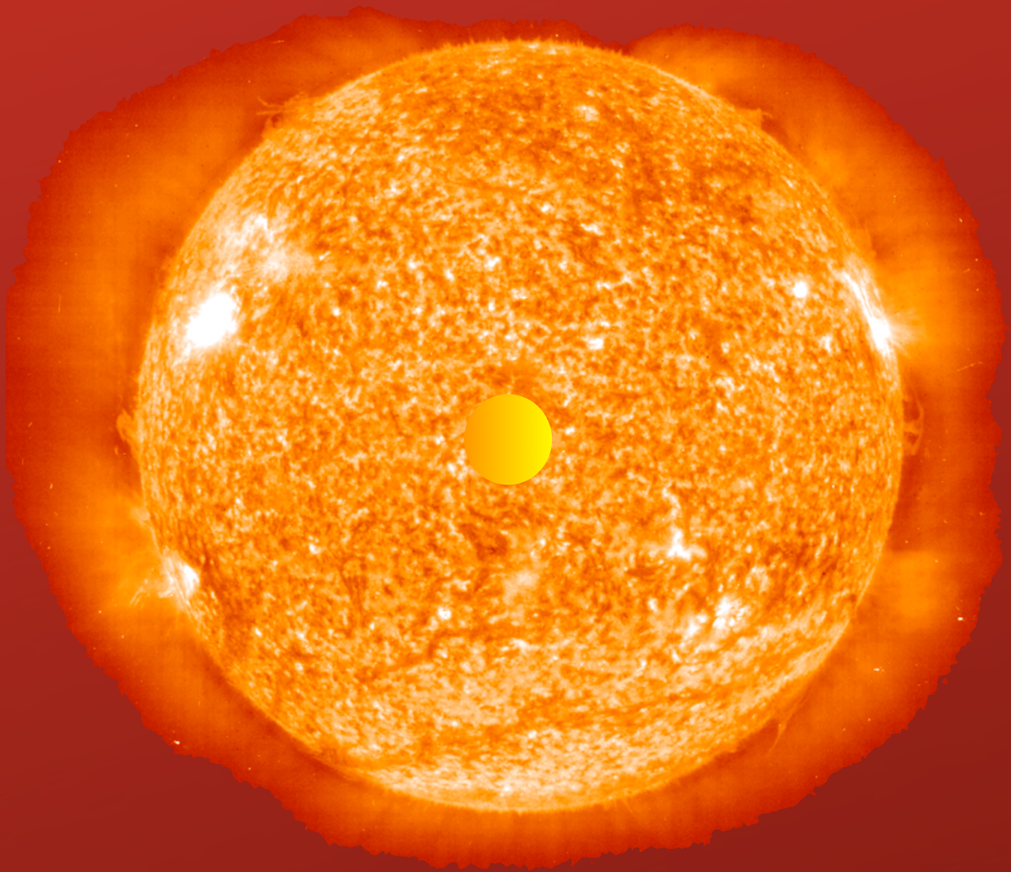

Basic Process:

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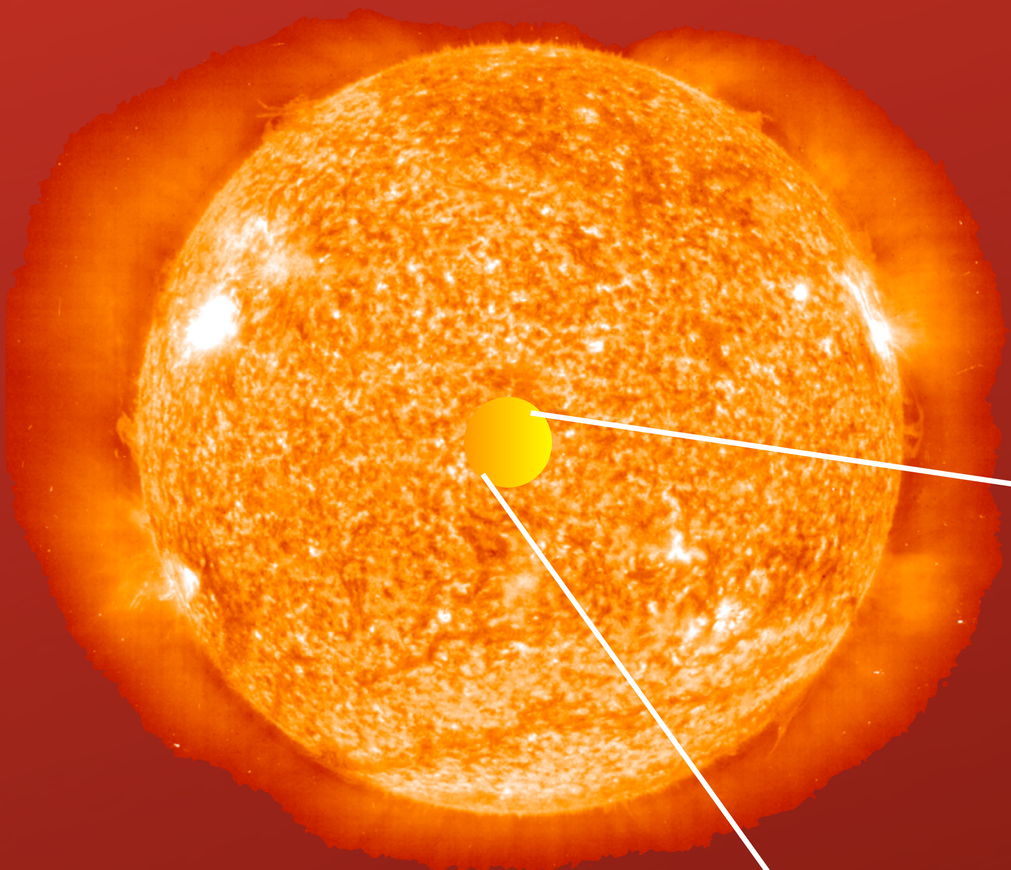
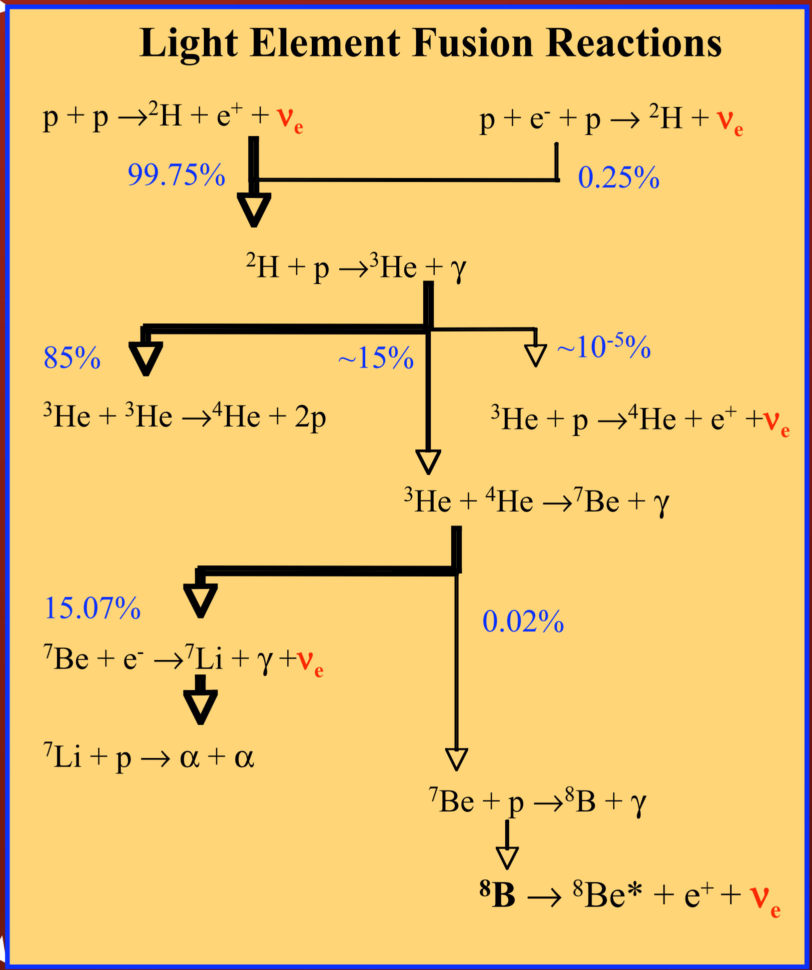


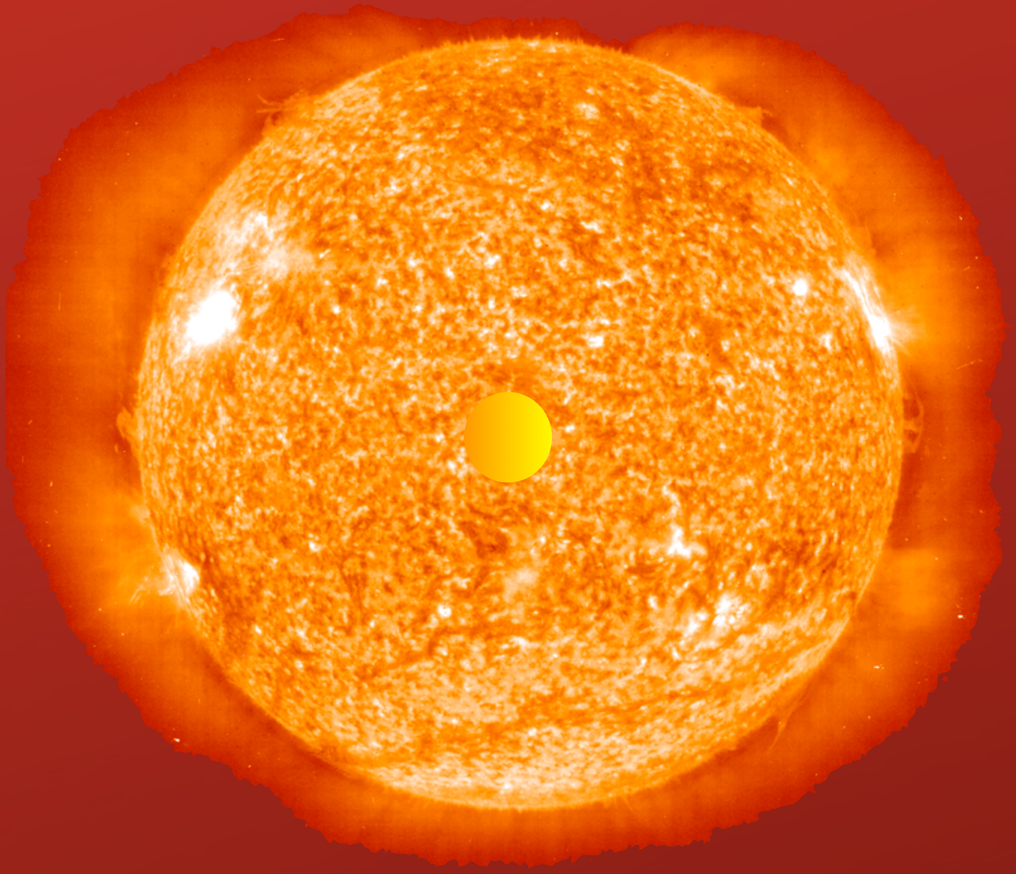


More detailed...

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.

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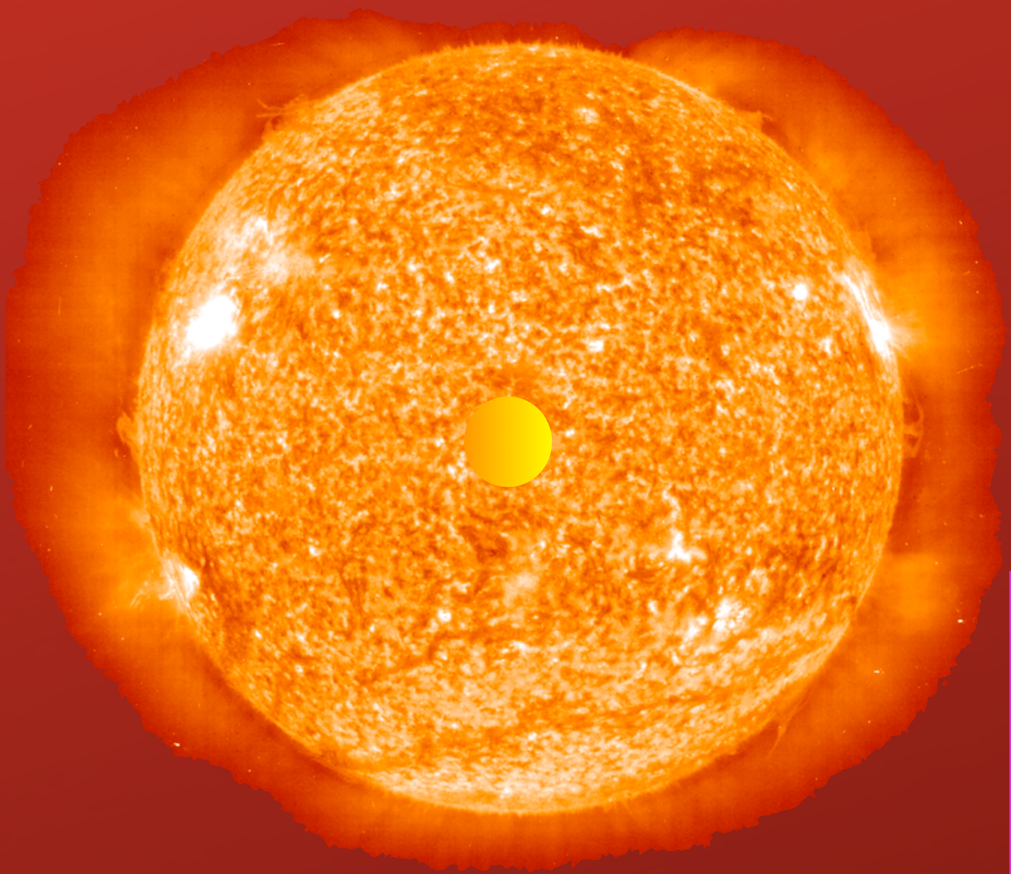

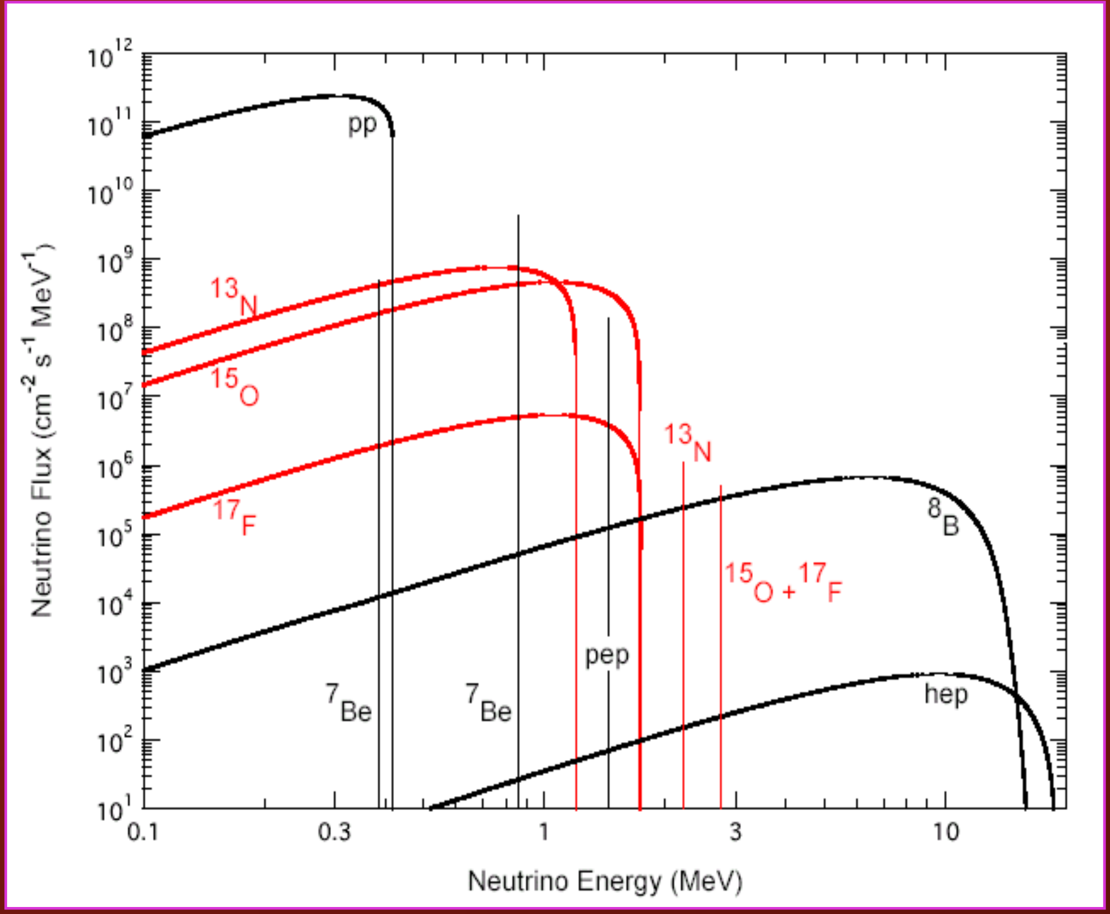

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Ultra-High Energy Neutrinos

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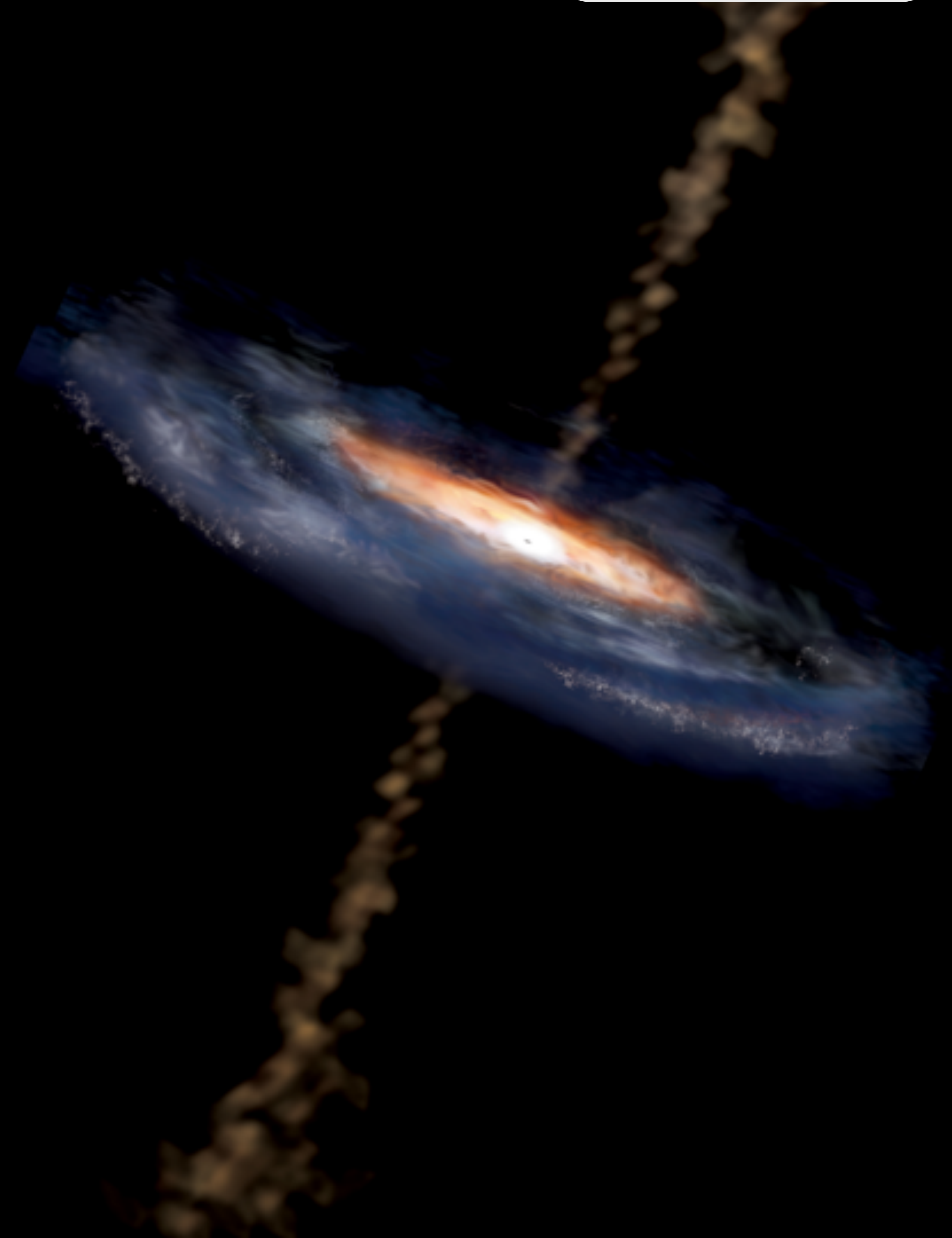

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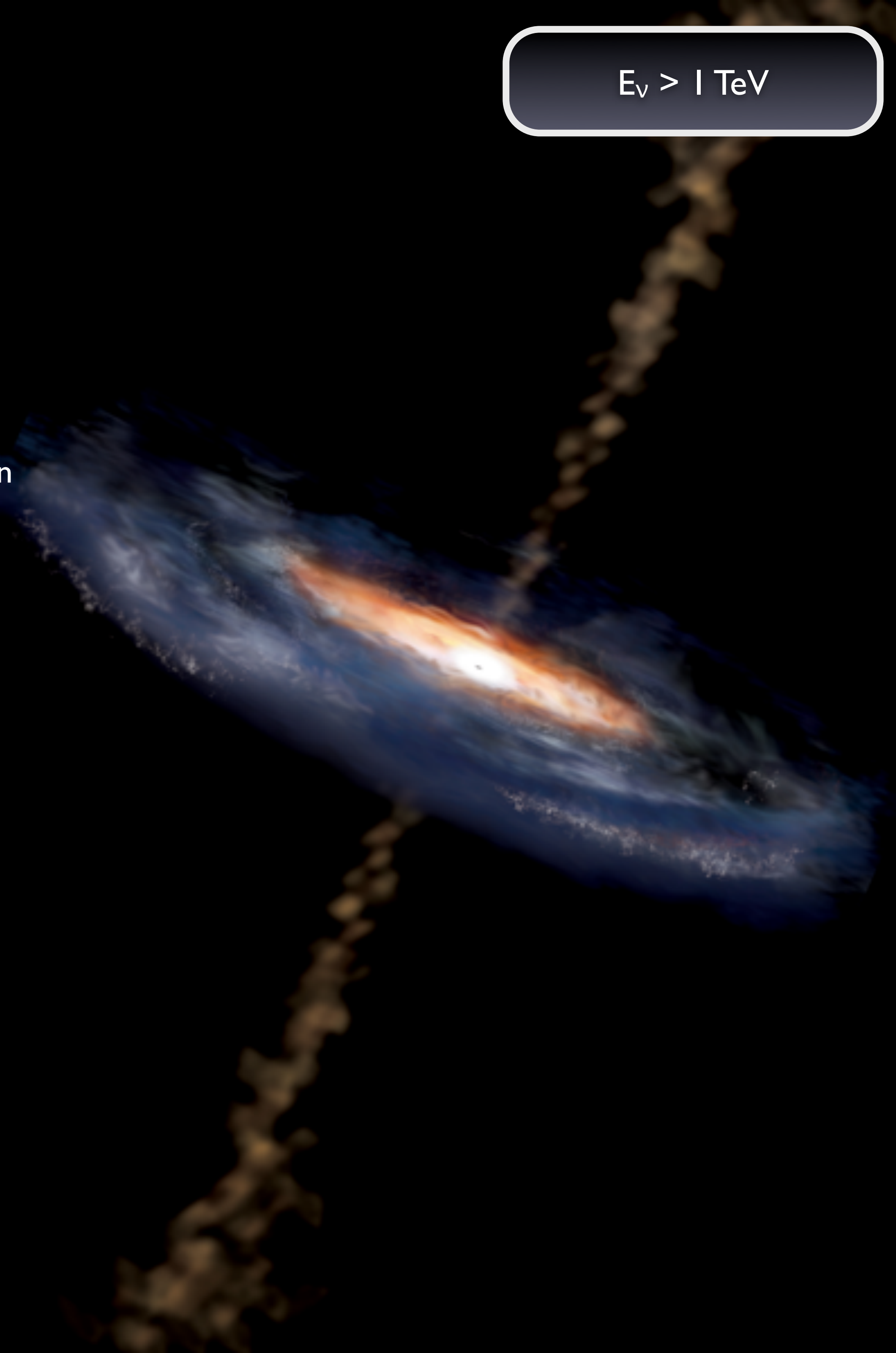

- Galactic and extra-galactic celestial objects are known sources of extremely high energy cosmic rays (protons, etc.) and neutrinos.

- 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.).

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

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

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

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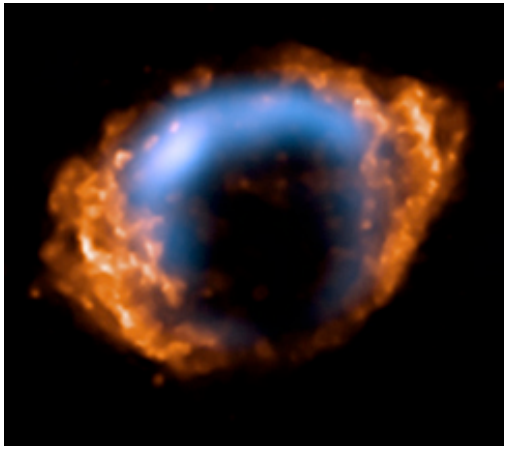
Supernova remnants



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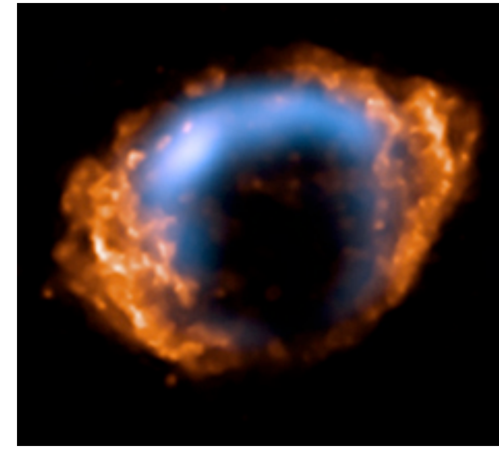
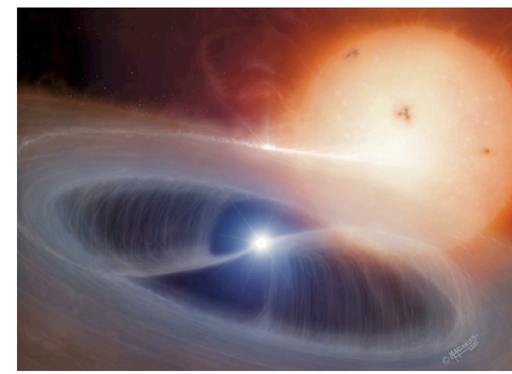


Binary systems



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.).

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

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

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

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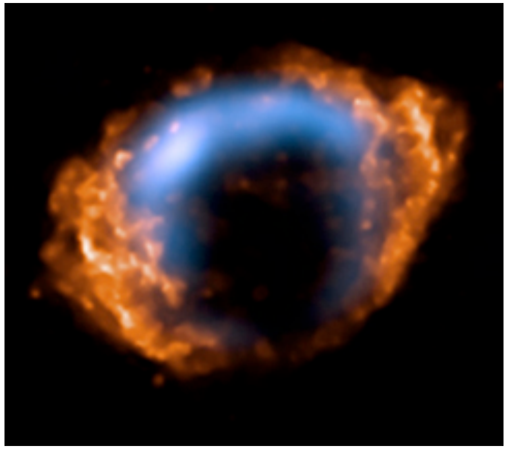

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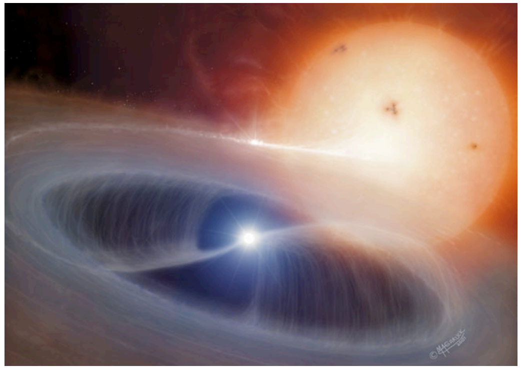
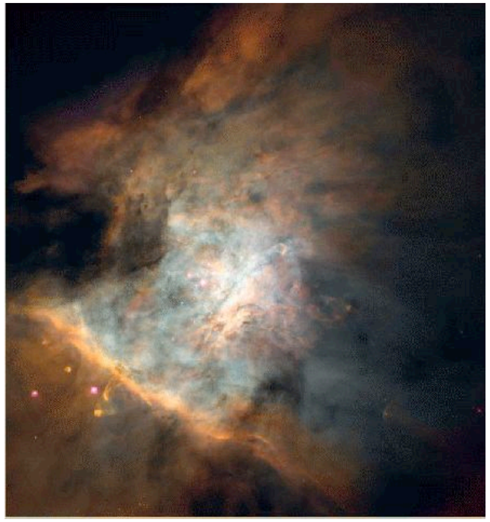
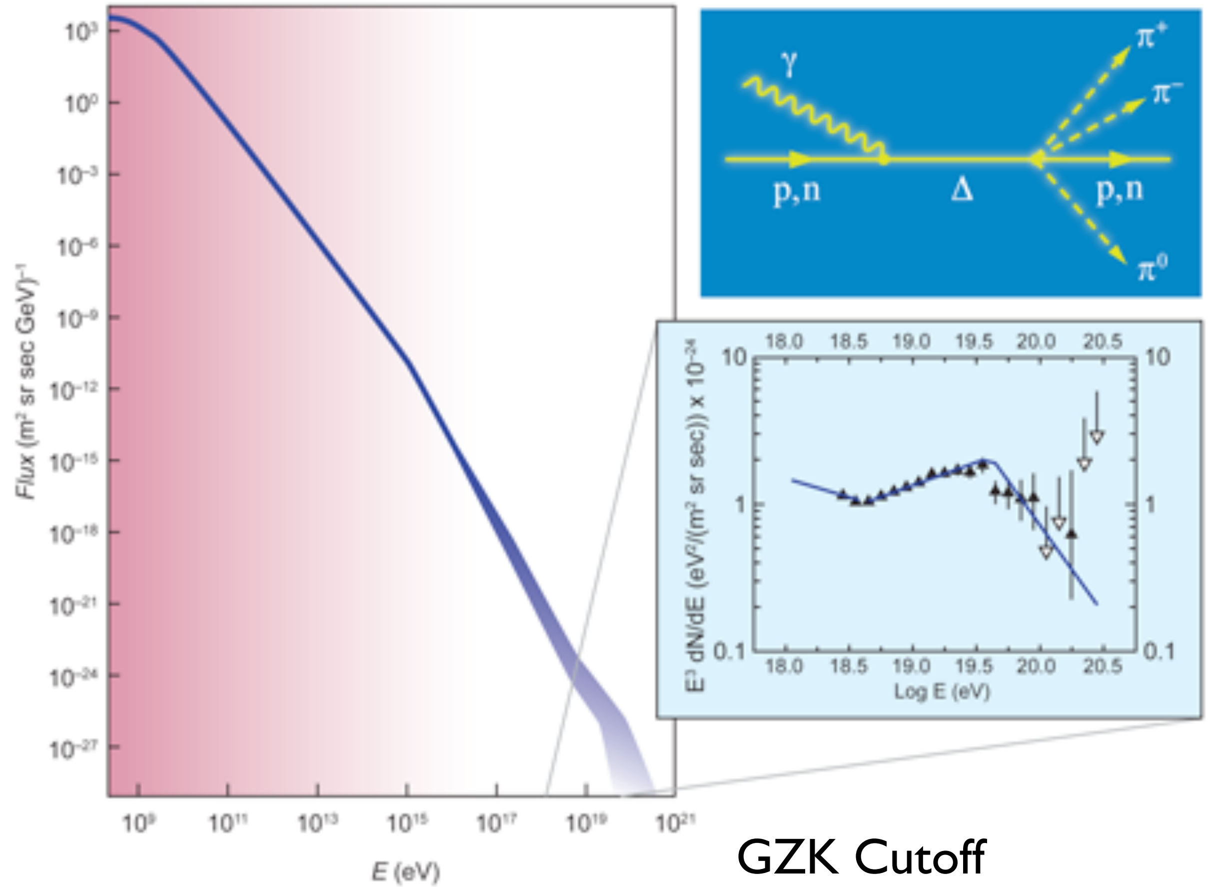


Interaction with interstellar medium

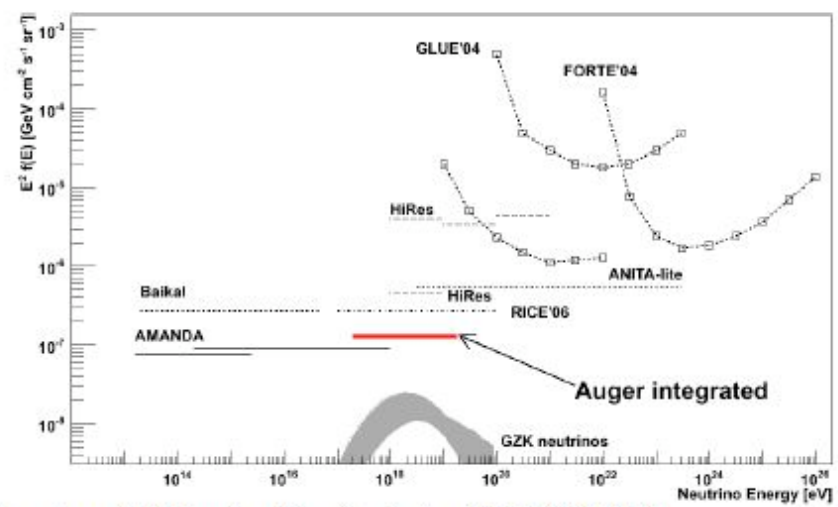


GZK Neutrinos

- 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

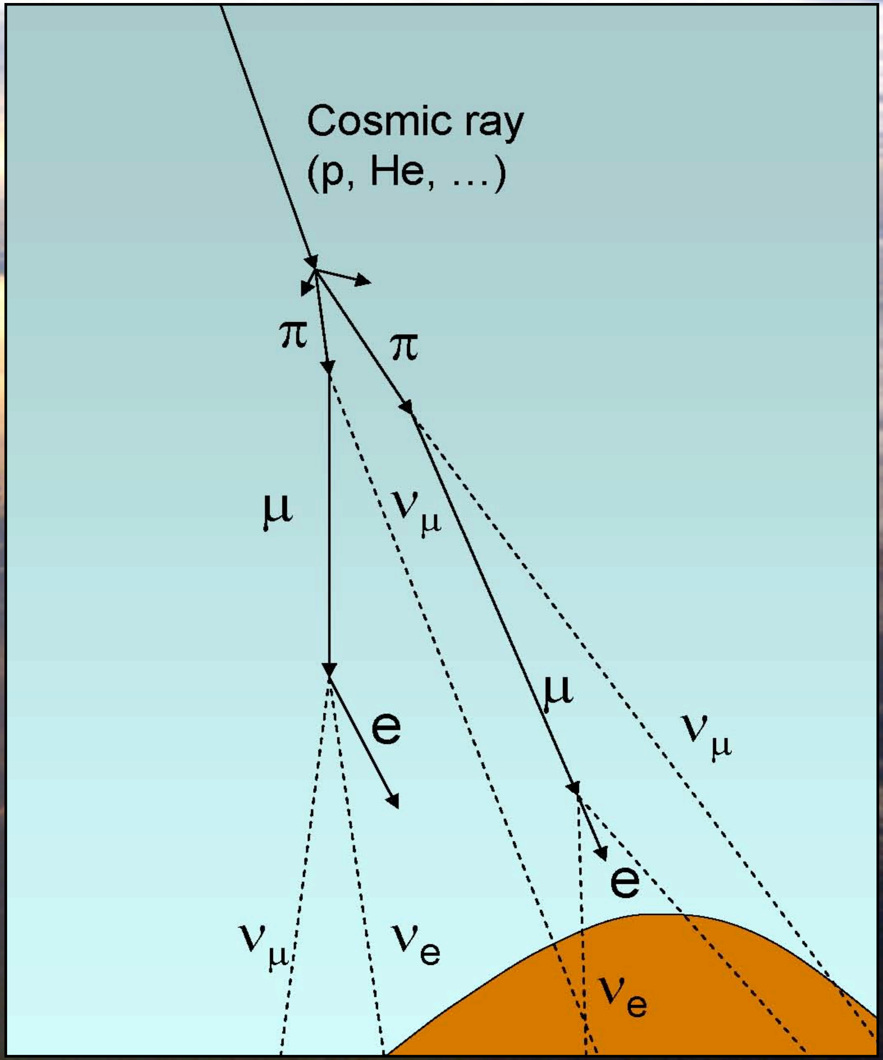
Neutrinos from the Earth

Neutrinos from Man

Atmospheric Neutrinos

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

Atmospheric Neutrinos



Atmospheric Neutrinos

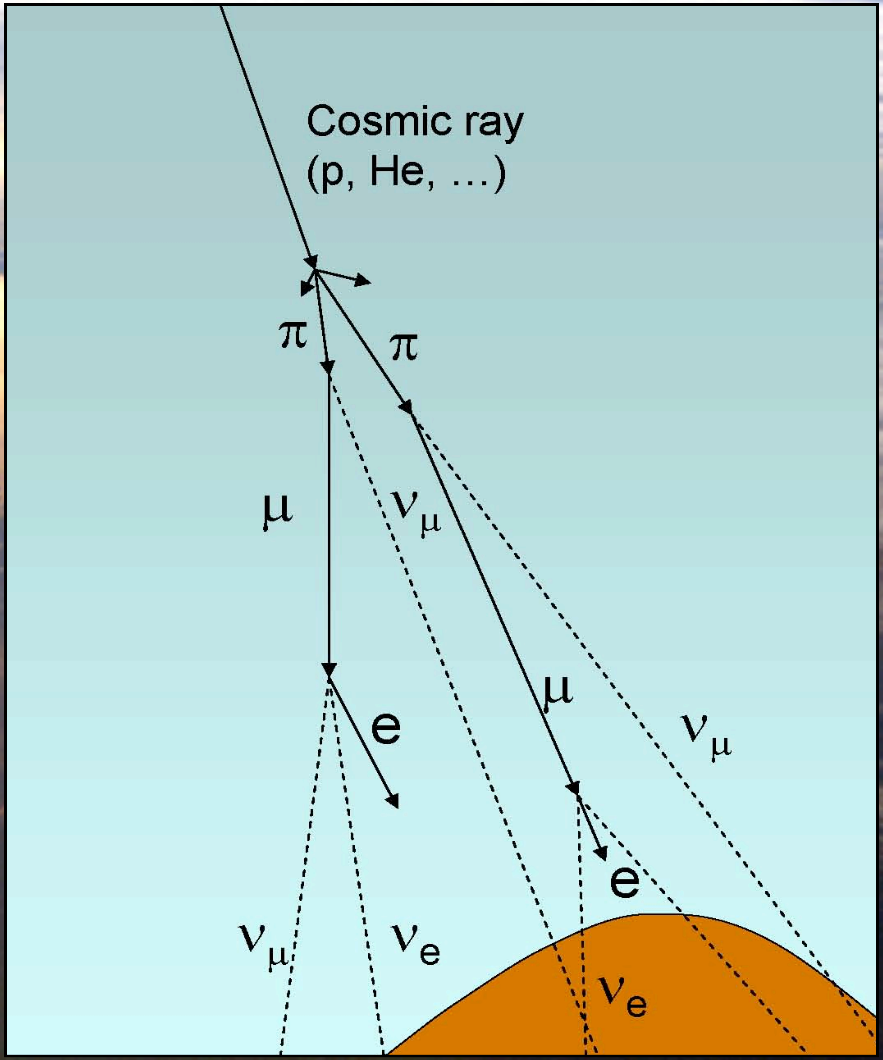
- Created by high energy cosmic rays impeding on the Earth's upper atmosphere.
- Dominant production mechasism comes from pion decay.

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

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

$$\downarrow$$

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



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.

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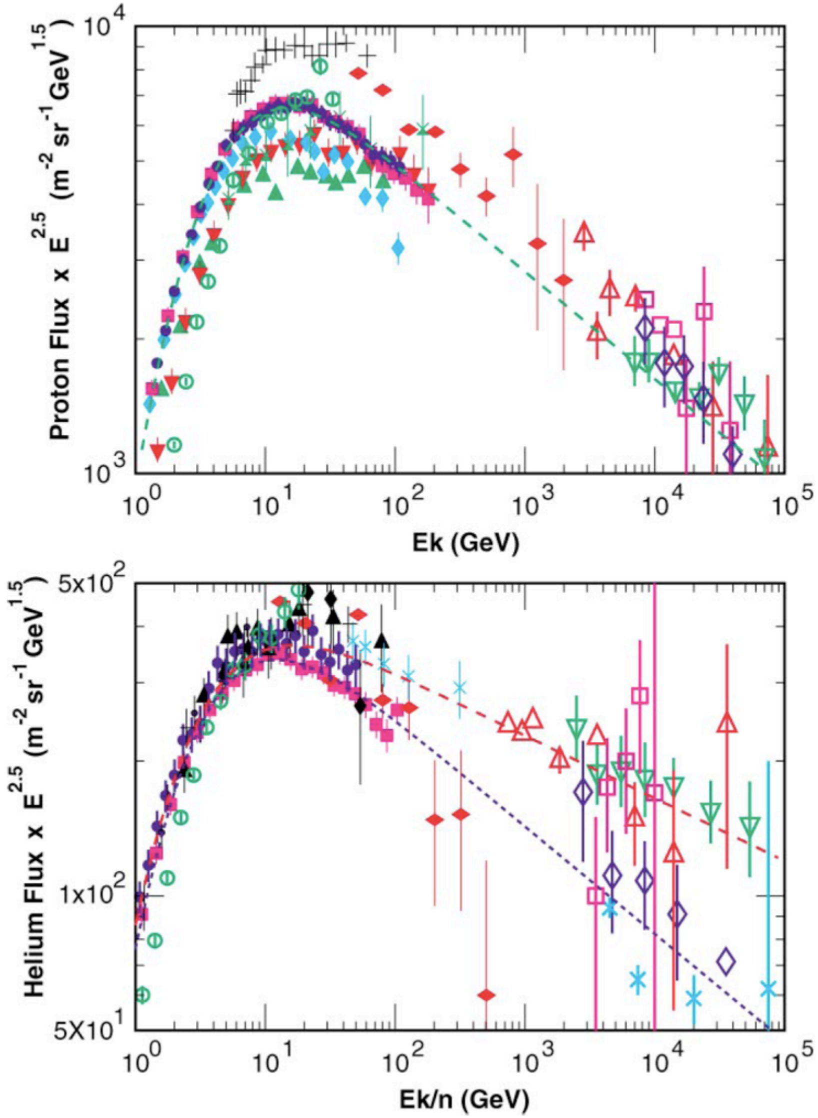
Primary CR flux



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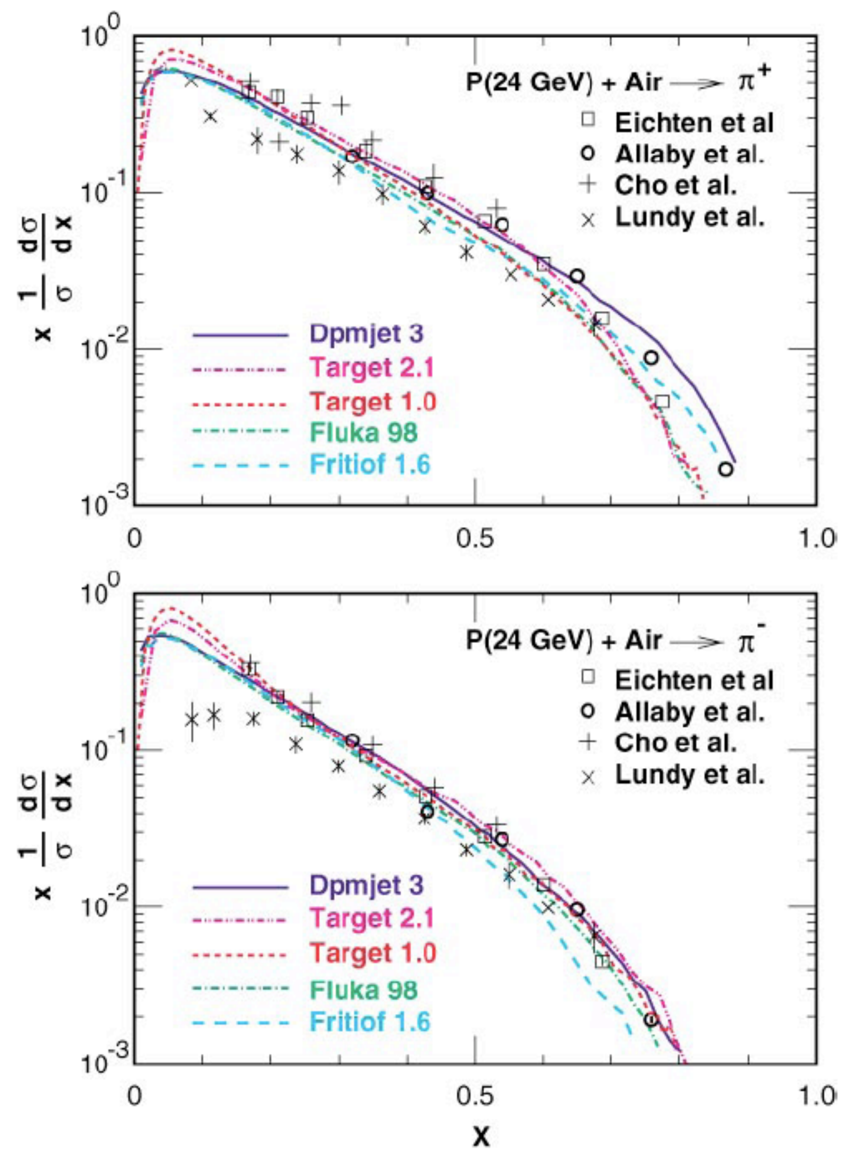
Hadronization



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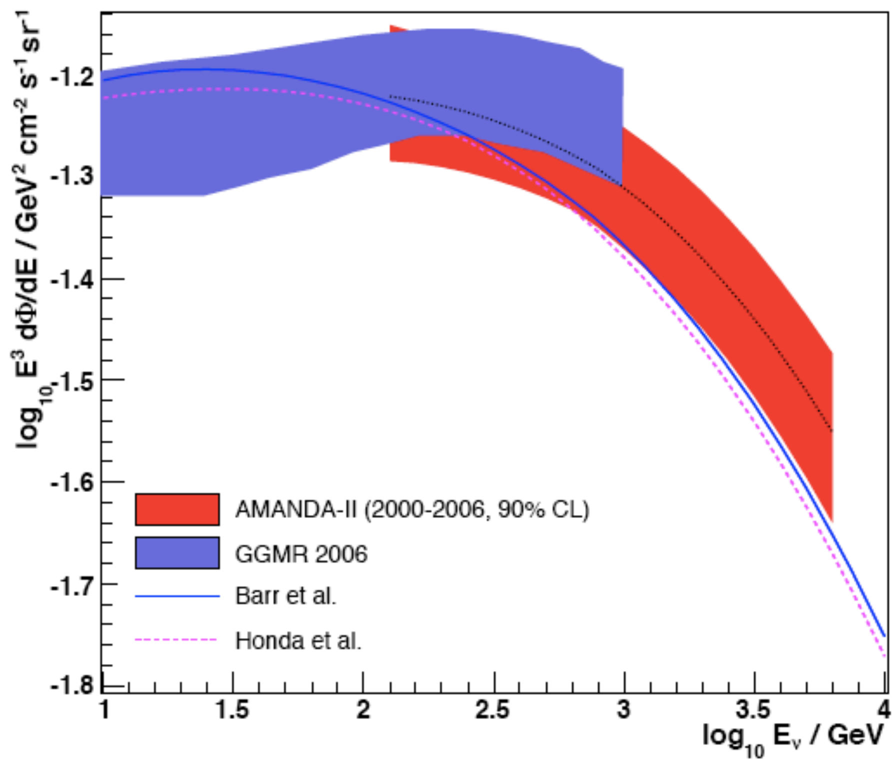
Predicted and Measured Atmospheric ν_μ Flux

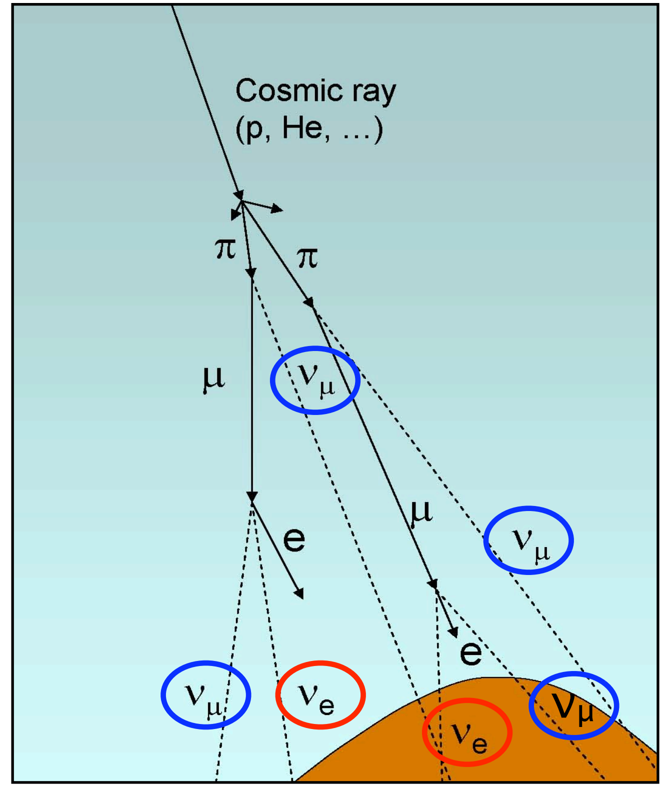


Uncertainties on the absolute flux near ±20%

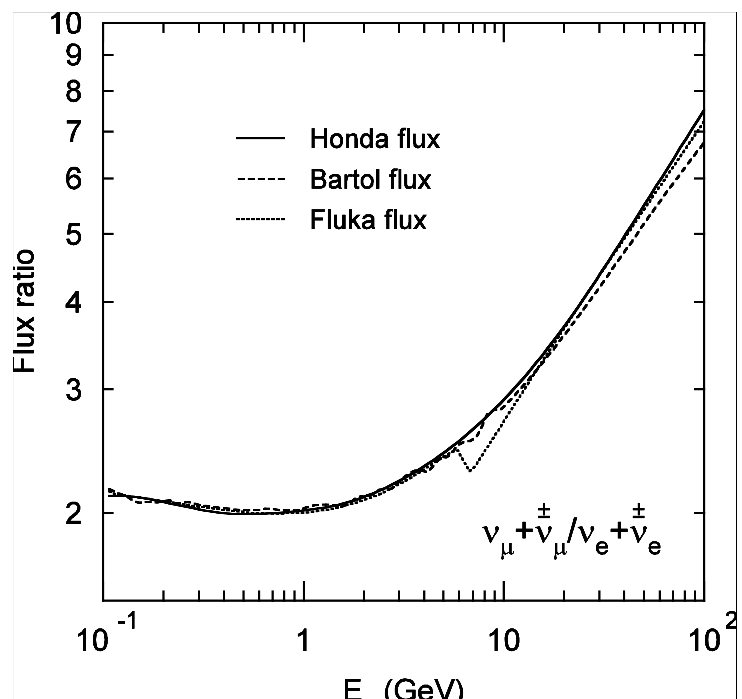
Atmospheric Neutrinos

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

  1. 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



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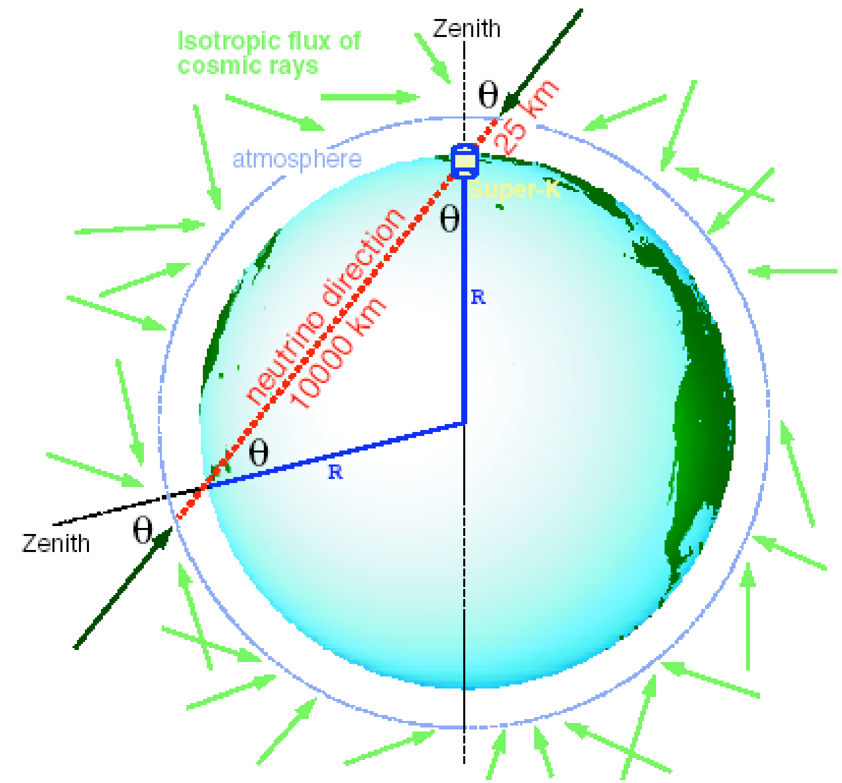
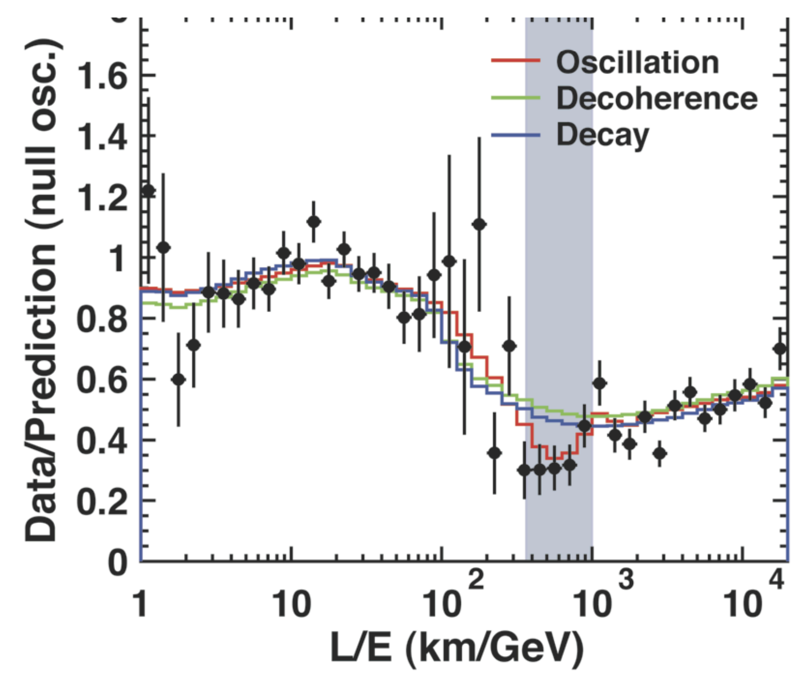





$E_\nu \sim 0.1\text{-}5$ MeV
Neutrinos from Radioactivity

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).

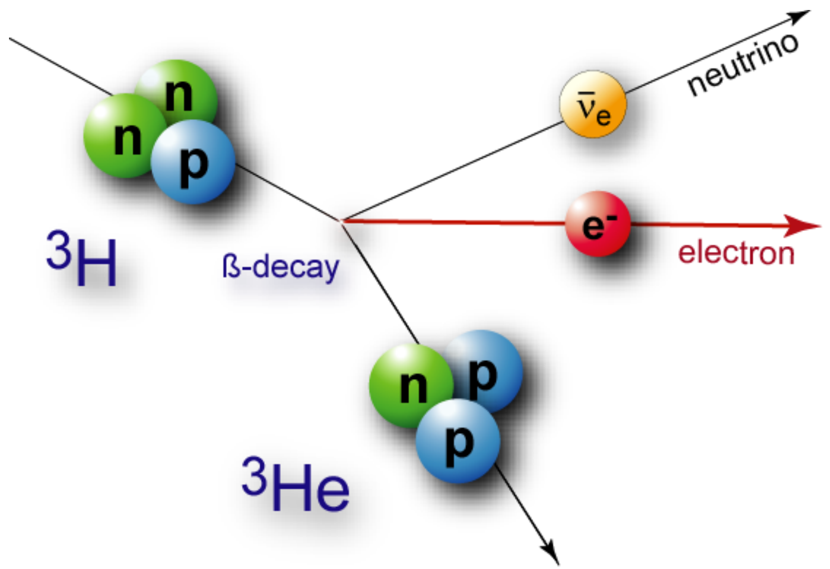
- One can consider three such reactions:

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

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

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

- 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

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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

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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

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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!

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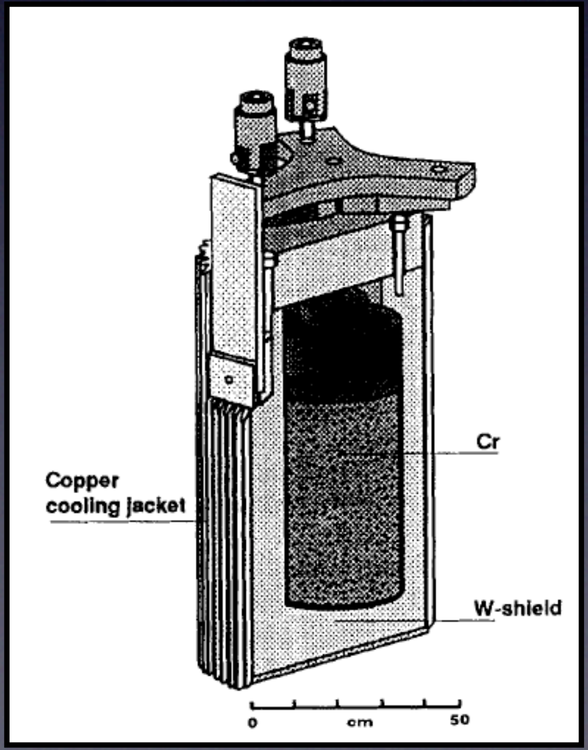
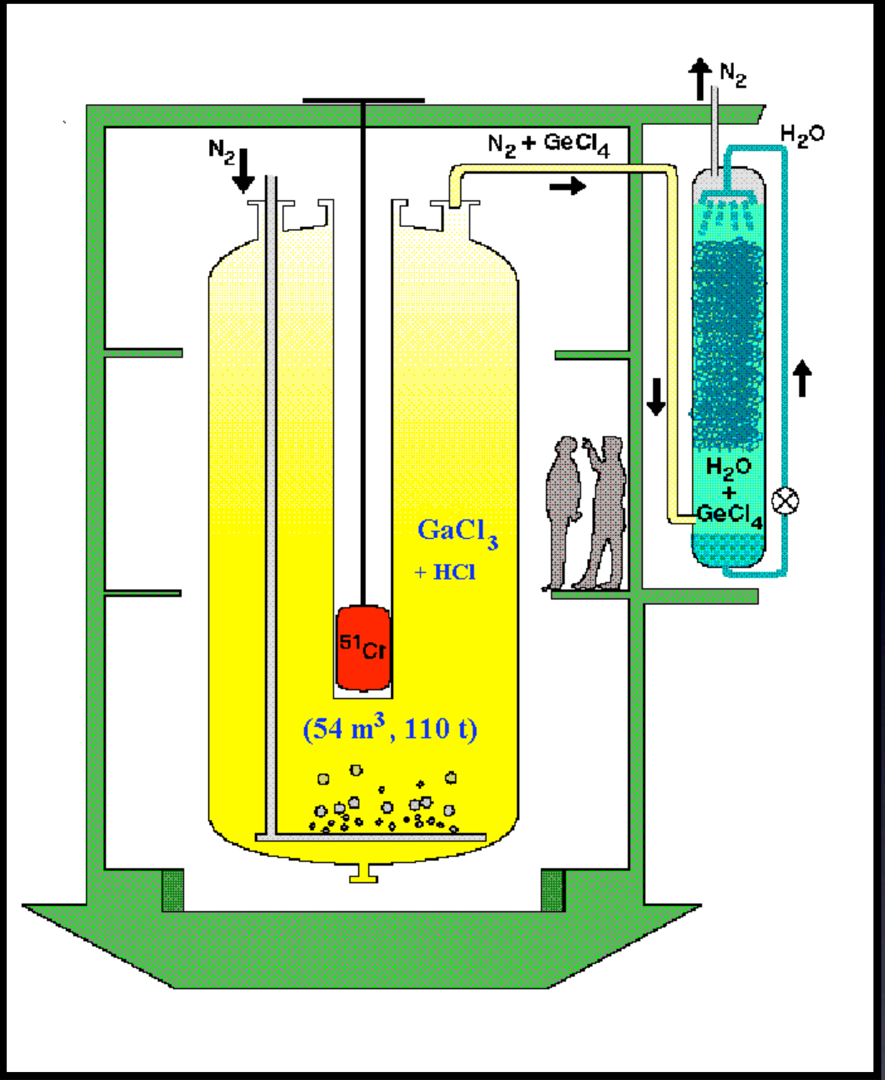


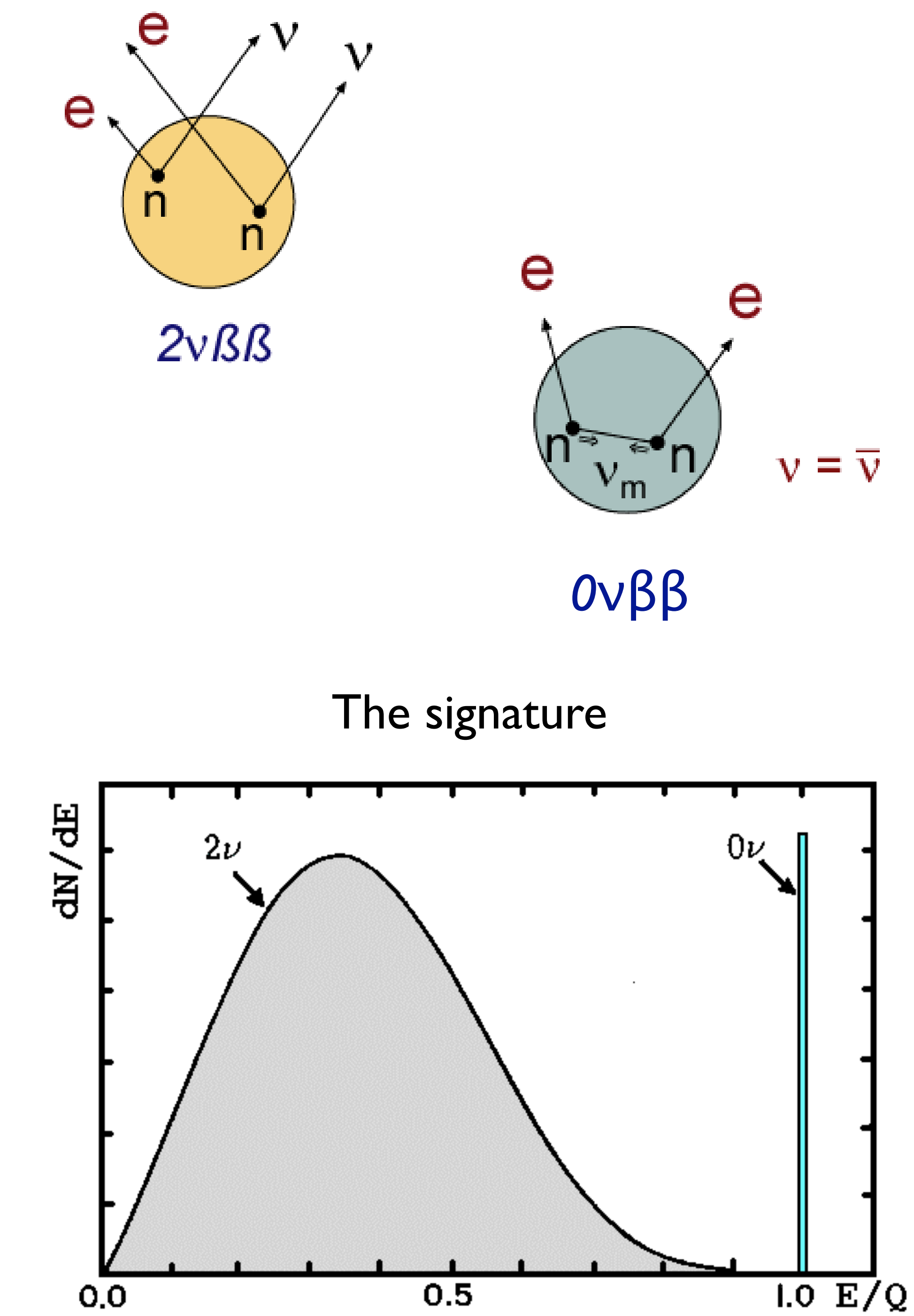


Total activity of the source: 60 PBq!

Emitted ~300 W of heat

You can do it twice...

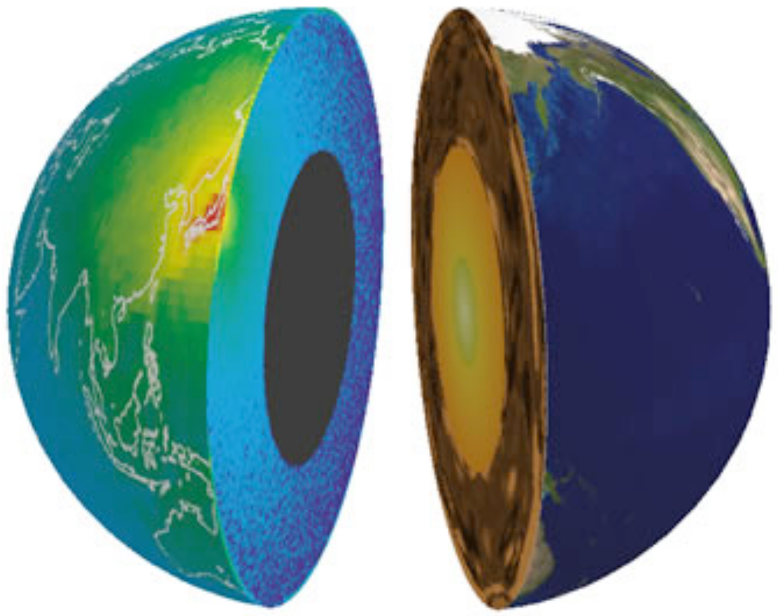
- It is possible to have a nucleus undergo beta decay twice (as long as it is allowed from energy and spin considerations).
- Highly suppressed due to G_F^4 suppression.
- If the neutrino is its own anti-particle, then the neutrino can mediate the reaction. No neutrinos are emitted.
- This is not a neutrino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




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],

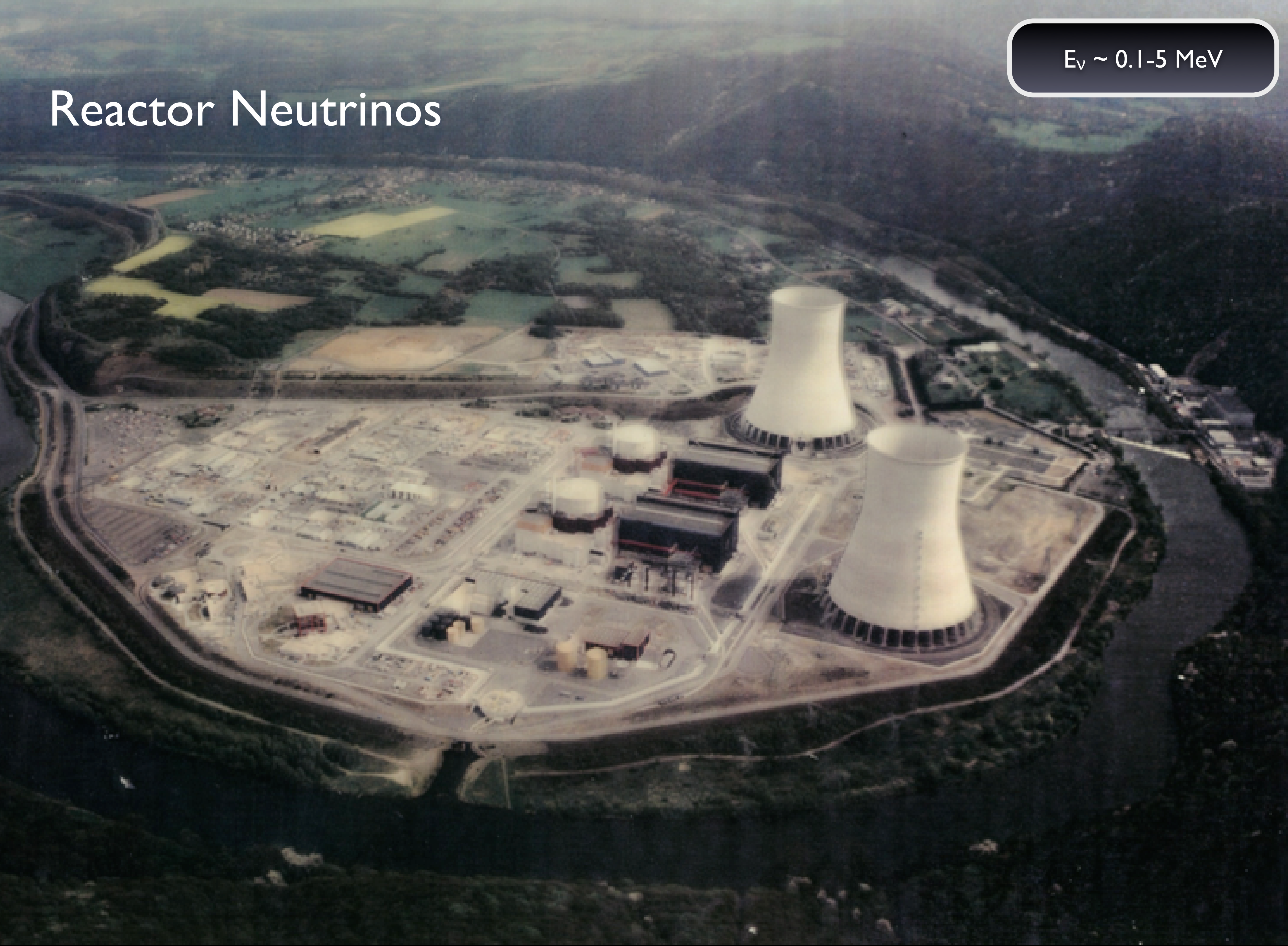
"...and Prometheus was punished for giving fire back to mankind..."

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.

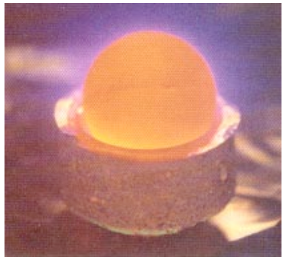
- Four main neutrino fuel sources:

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

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

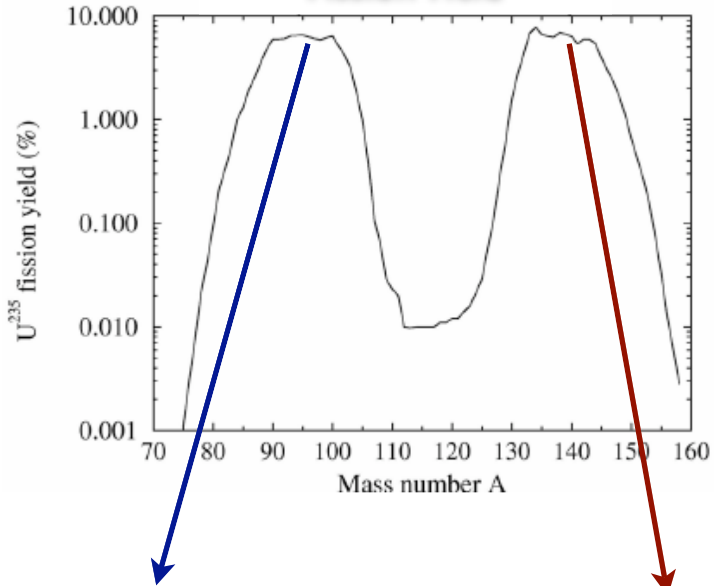
Sample Fission: ^{235}U

^{235}U



^{239}Pu

Fission Yield



^{94}Zr

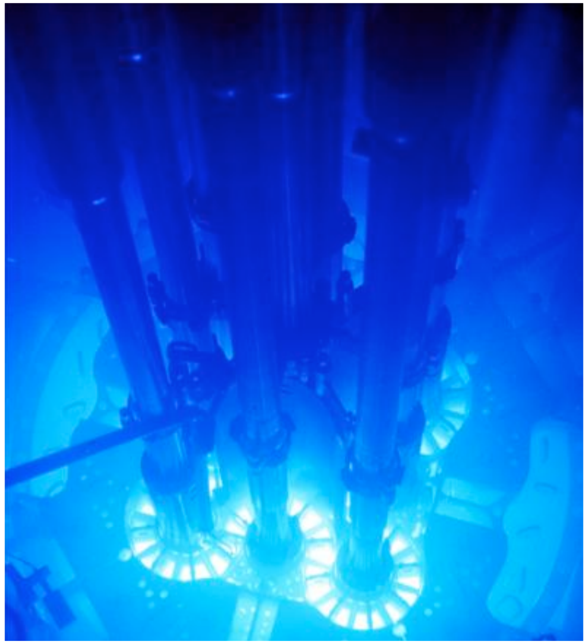
^{140}Ce

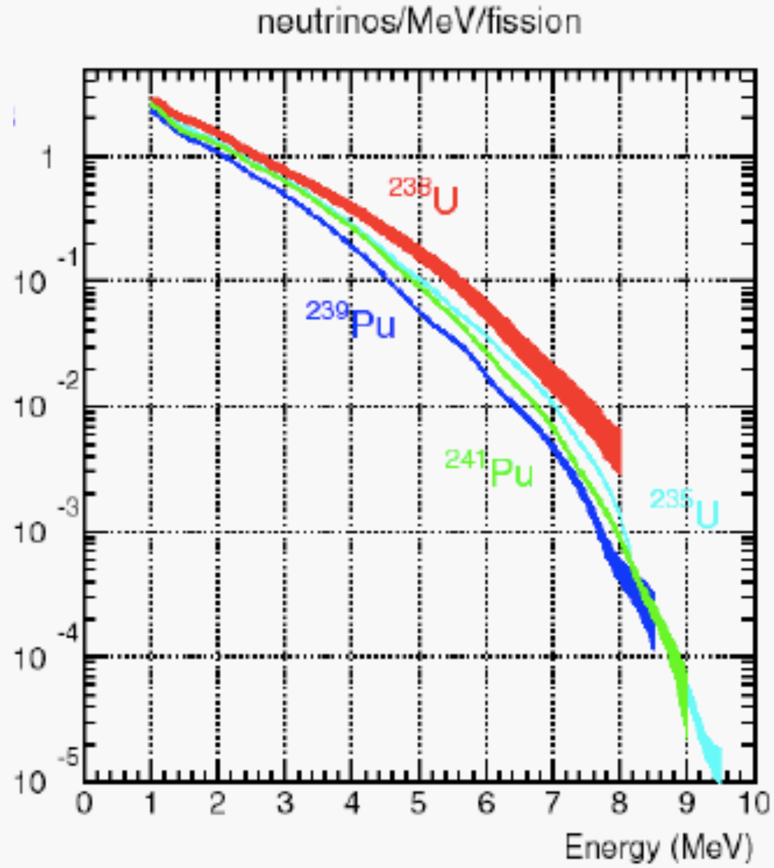
Neutrinos from Fission

- Eventually reaction produces stable isotopes, such as Zr and Ce. In the process, 6 protons must have beta-decayed to 6 neutrons.

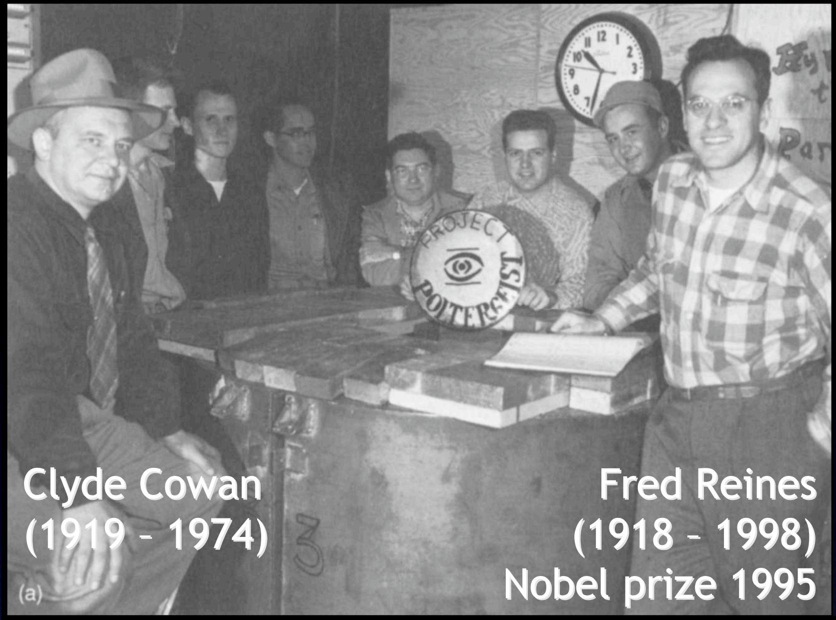
- About 6 anti-neutrinos are produced per fission. Since each fission cycle produces 200 MeV, one can convert power to neutrino flux.

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





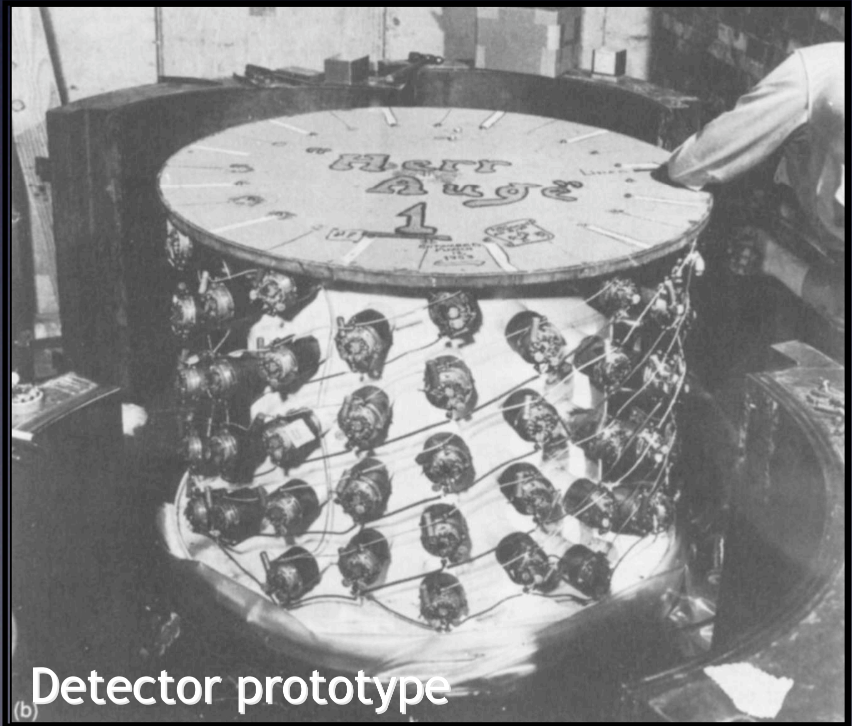
Reactor Experiments: Pioneer Efforts



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

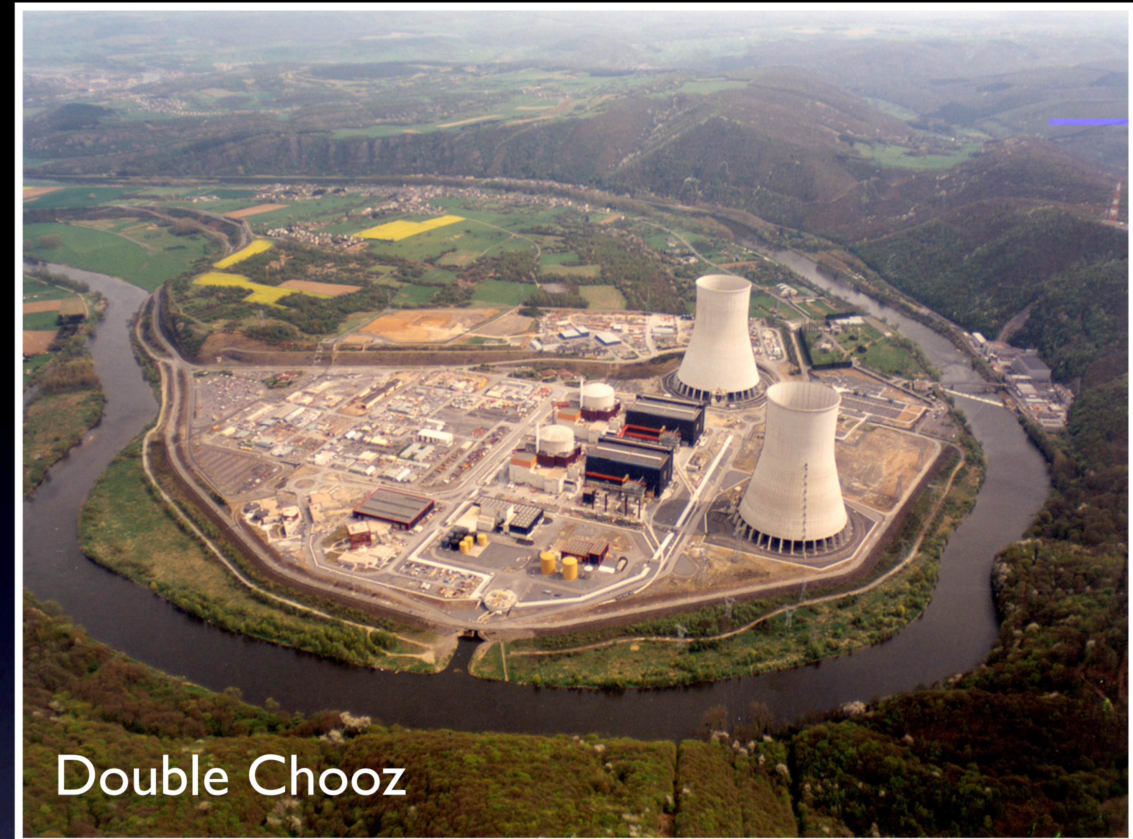
$$\bar{\nu} + p \rightarrow n + e^+ \quad \text{signal here}$$

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



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.



Accelerator Neutrinos

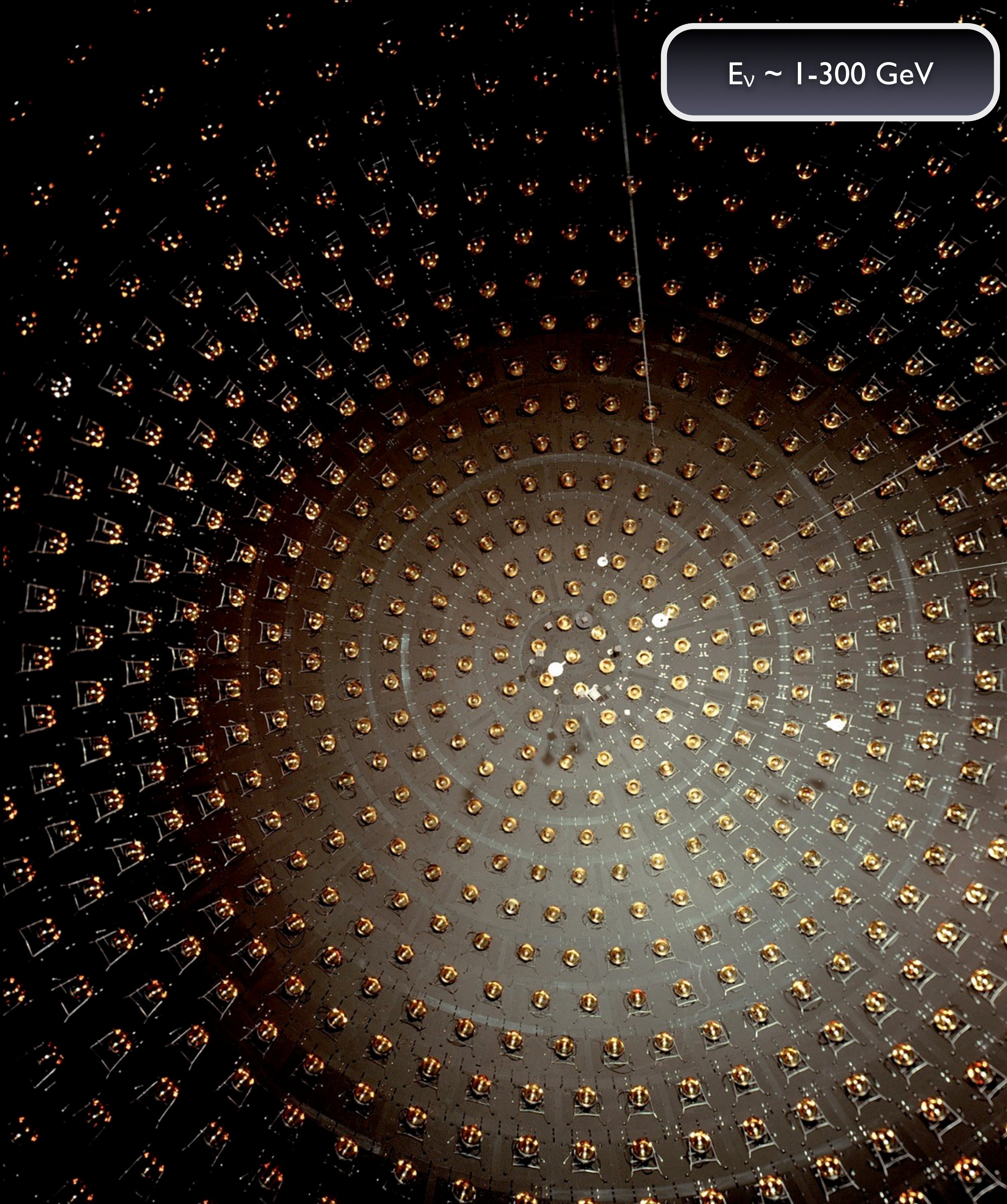
E_ν ~ 1-300 GeV

- 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

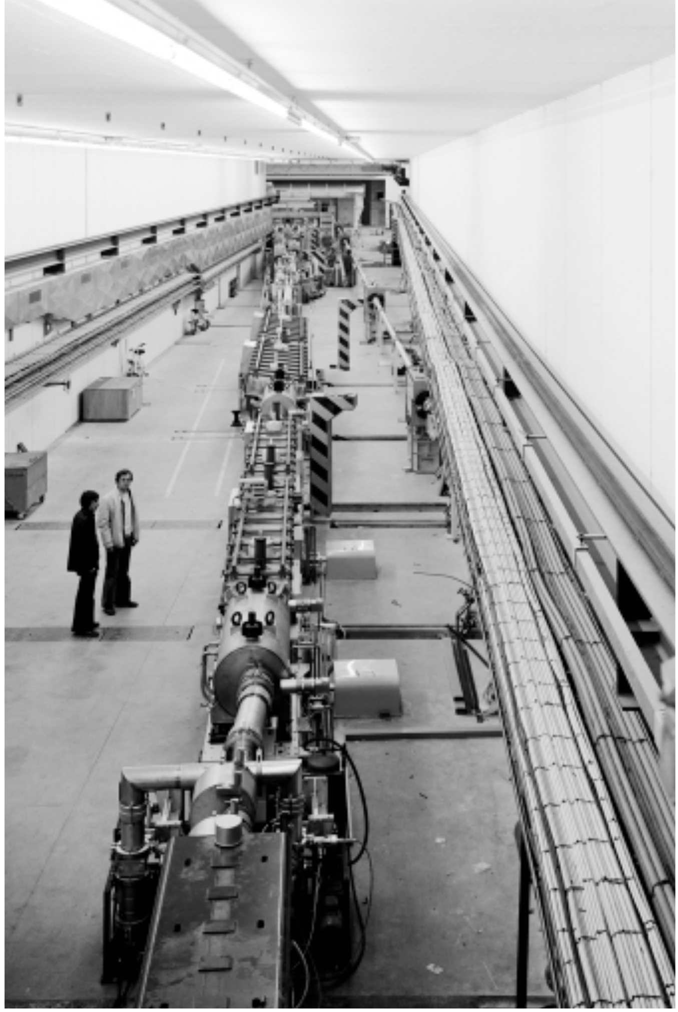
- Beam creation very similar to atmospheric neutrinos (protons drive the production mechanism; neutrinos produced from pion decay).

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

  (a) Neutrino flavor purity,

  (b) Selected energy range & distance,

  (c) Intensity



CERN's WA21 beamline

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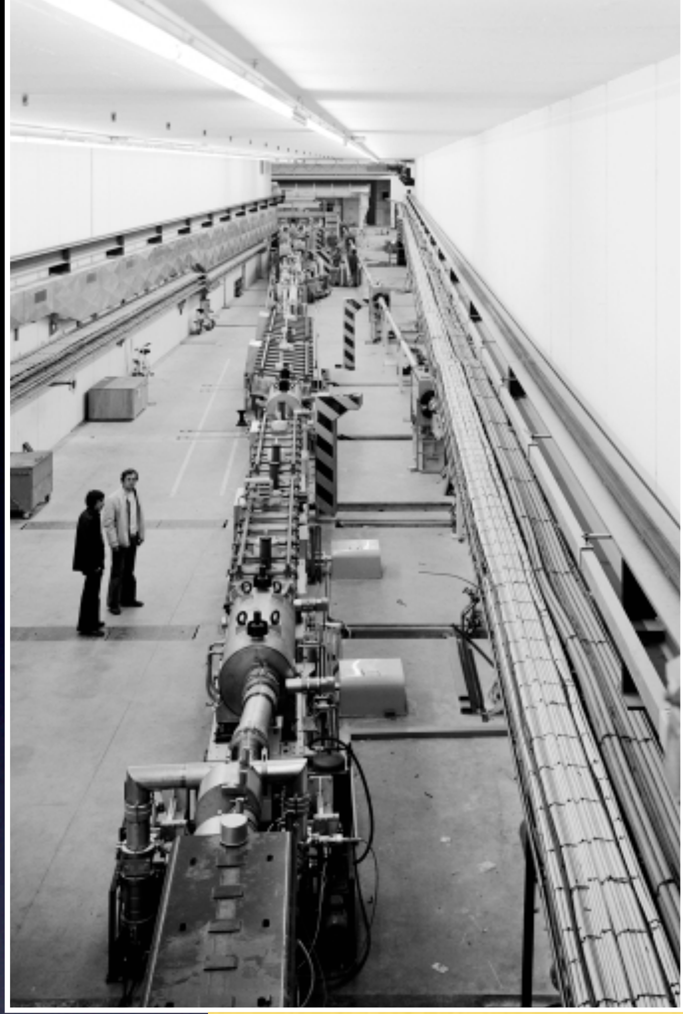

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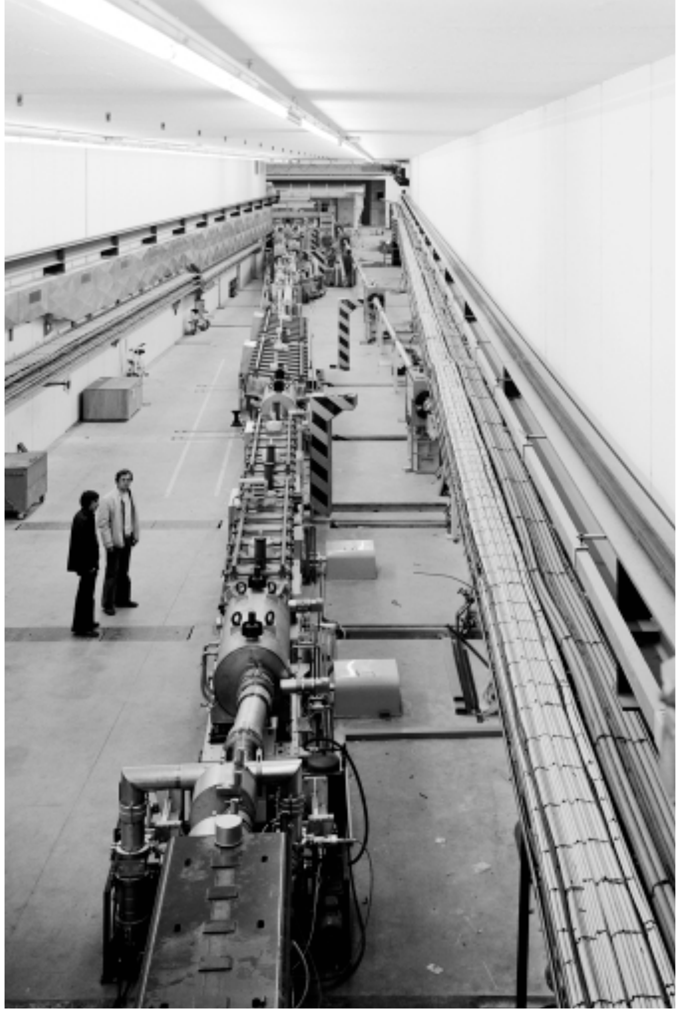

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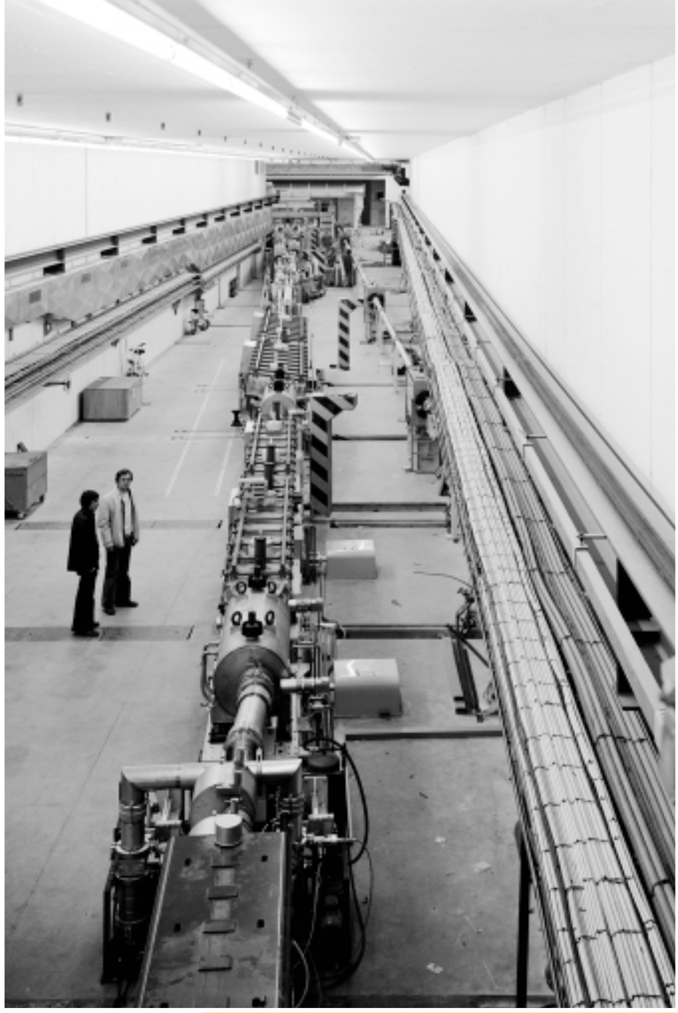


CERN's WA21 beamline

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

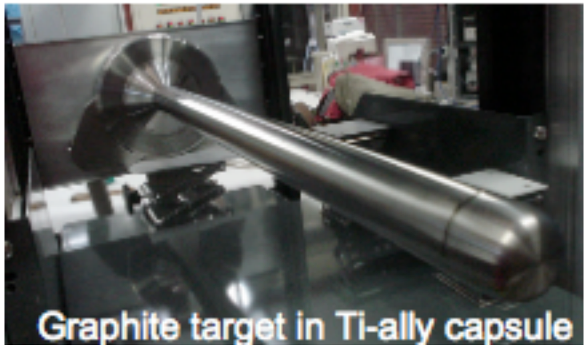
(b) Selected energy range & distance, → Optimization of oscillation wavelength

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

Stages

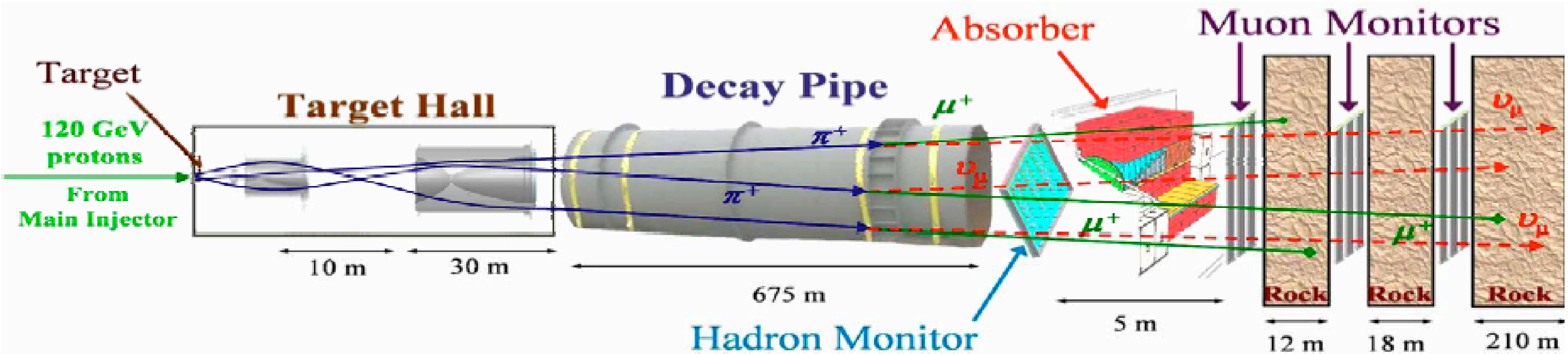
- Basic ingredients of target, focusing region, decay region, absorber, and detector found in almost all accelerators.
- How system is optimized depends on type of beam desired.

Target Region



Region of primary interaction.

Concerns include heating and attenuation of particles



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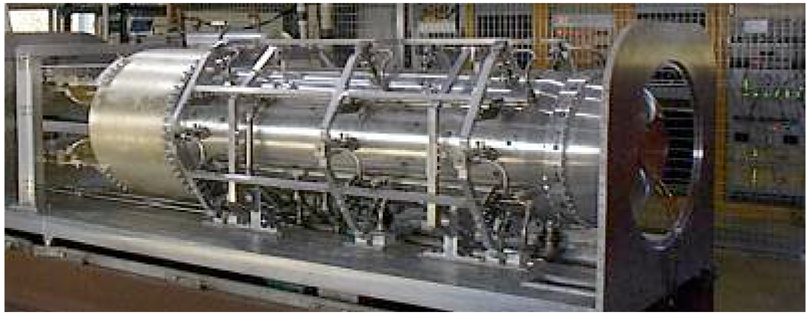
Focusing Region



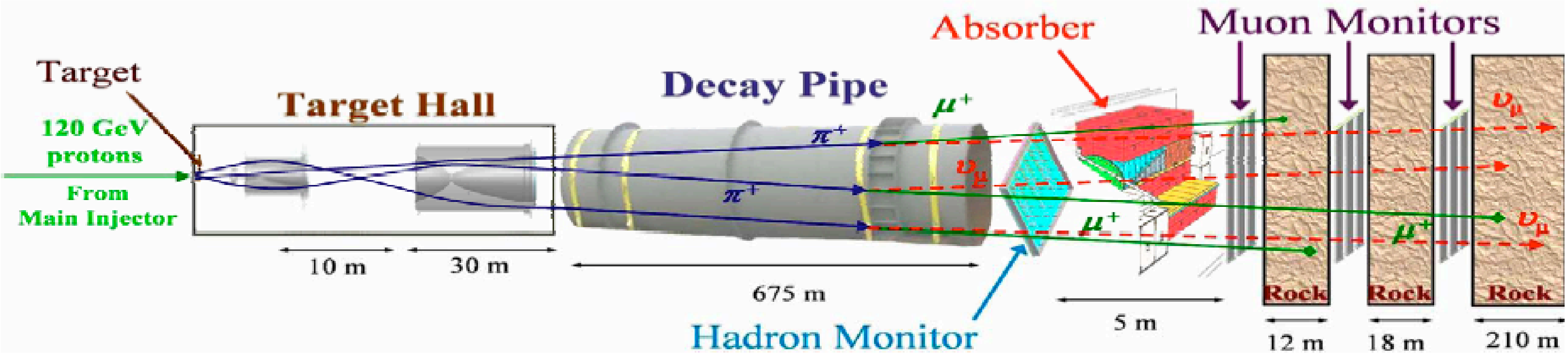
$$\pi^+ \longrightarrow \mu^+ \nu_\mu$$

or

$$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu$$

Selects pion/kaon charge (neutrino or anti-neutrino running)

Can also be used to ensure beam purity.



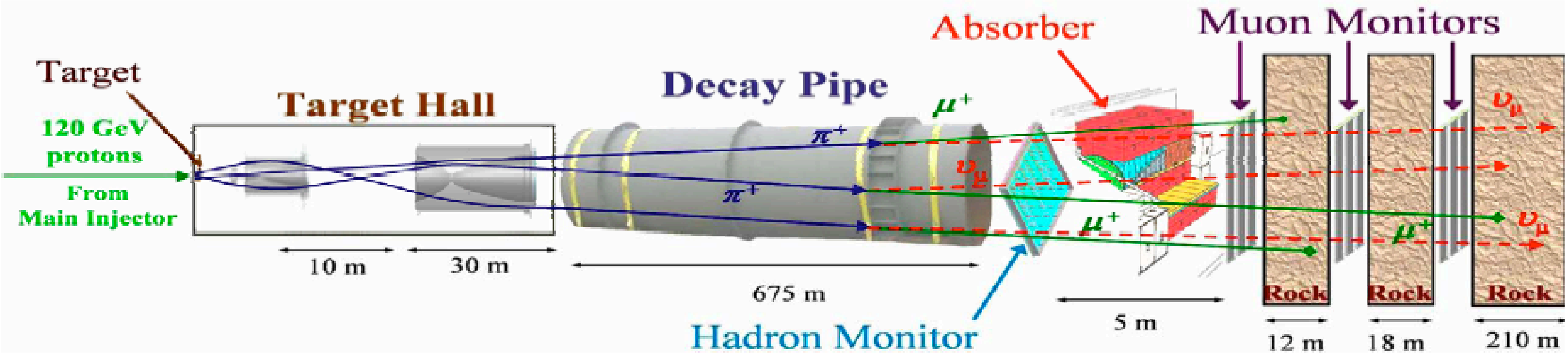
Stages

- 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.

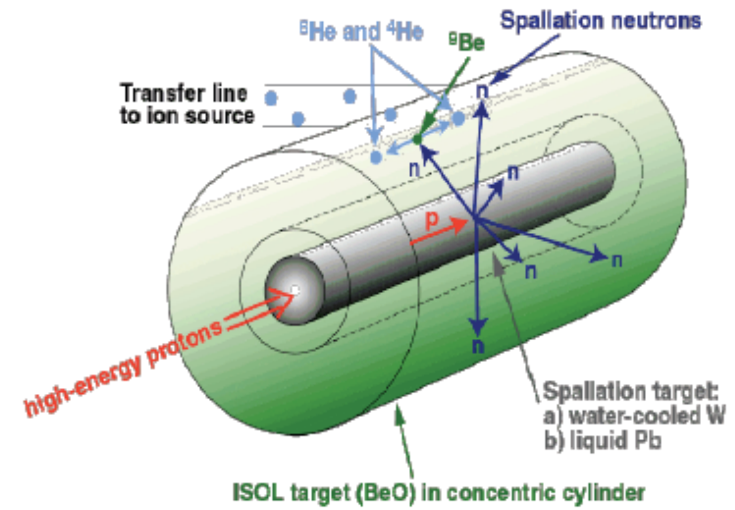
Neutrinos from Beta Decay

$$^{6}\text{He} \rightarrow \; ^{6}\text{Li} \; e^{-} \; \bar{\nu}_e$$

Electron Anti-neutrino Source

$$^{18}\text{Ne} \rightarrow \; ^{18}\text{F} \; e^{+} \; \nu_e$$

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

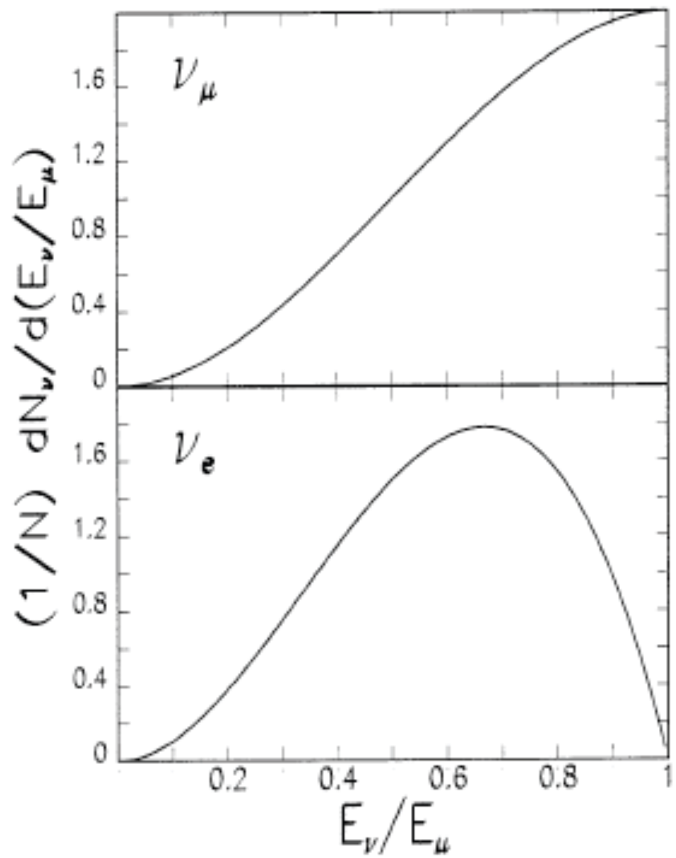
Extremely short storage times

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...

- 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.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