Neutrinos from the Heavens & the Earth

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MAYORANA SCHOOL

Modica, Italy

J. A. Formaggio

MIT


What we will cover:

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Where do neutrinos come from?

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Neutrinos from the Heavens

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Neutrinos from the Heavens

Neutrinos from the Earth

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Where do neutrinos come from?

Neutrinos from the Heavens

Neutrinos from the Earth

Neutrinos from Man

What we will cover:

Where do neutrinos come from?

Neutrinos from the Heavens

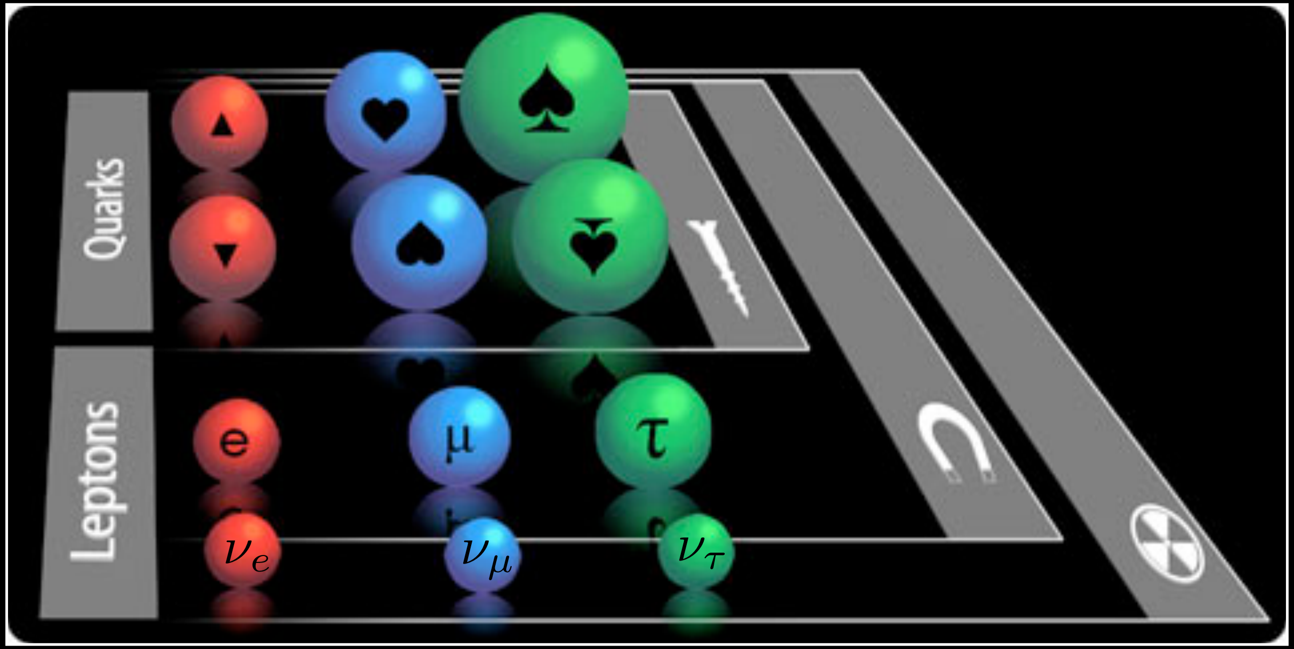
Neutrinos from the Earth

Neutrinos from Man

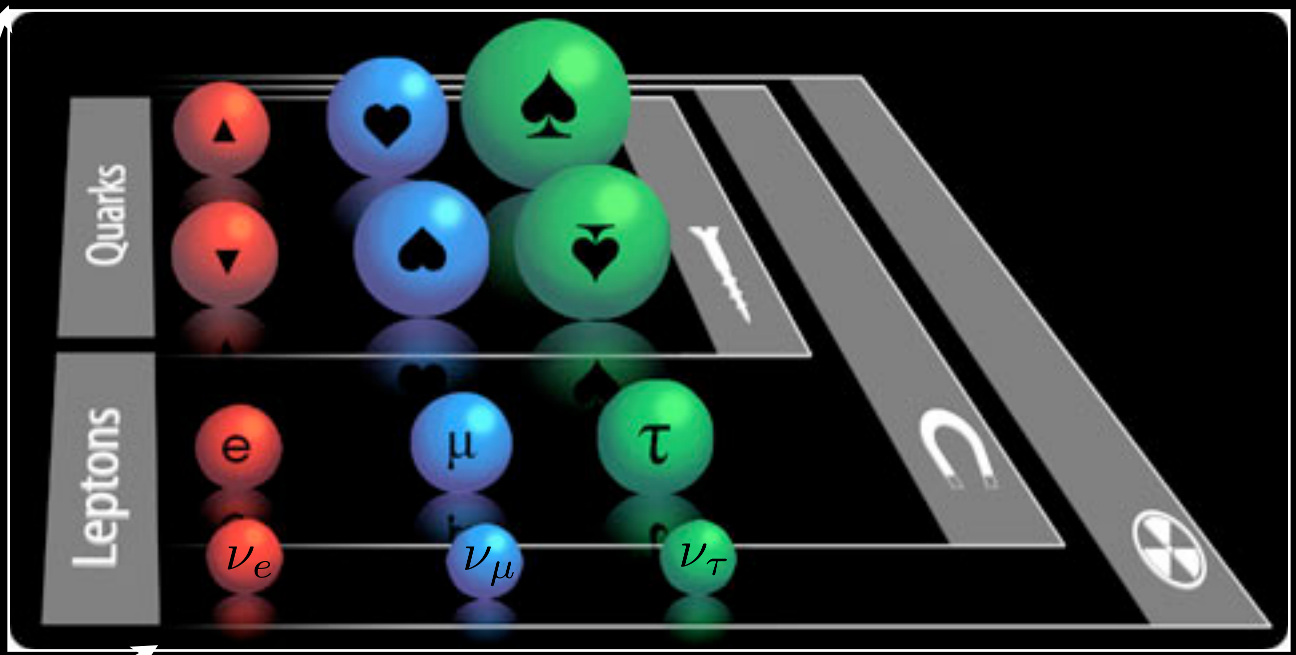
Where do neutrinos come from...?

Within the
Framework

Within the Framework

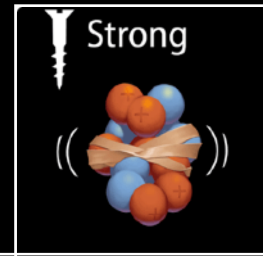


Within the Framework

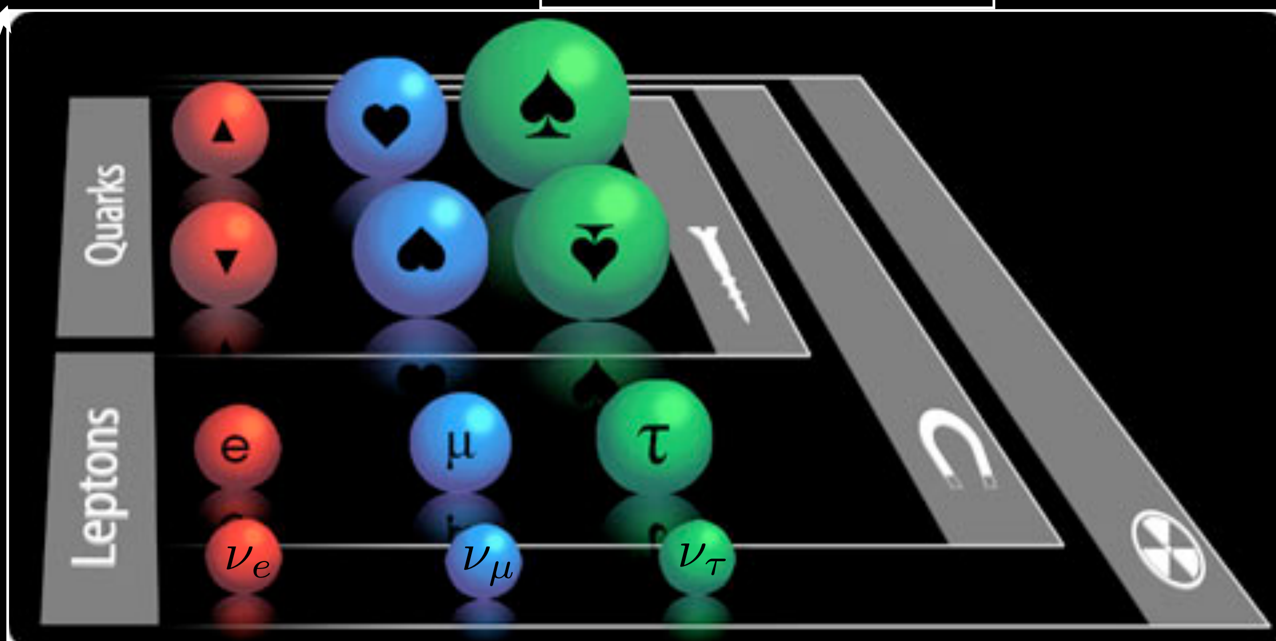


Spin 1/2

Within the Framework



Binds nucleii;
mediated by gluons;
only couples to quarks



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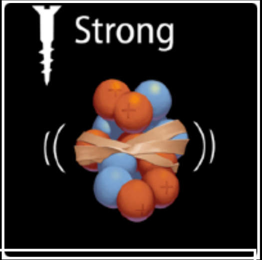

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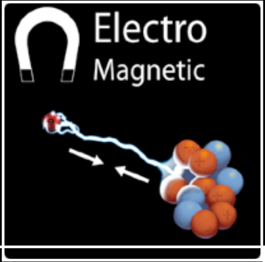
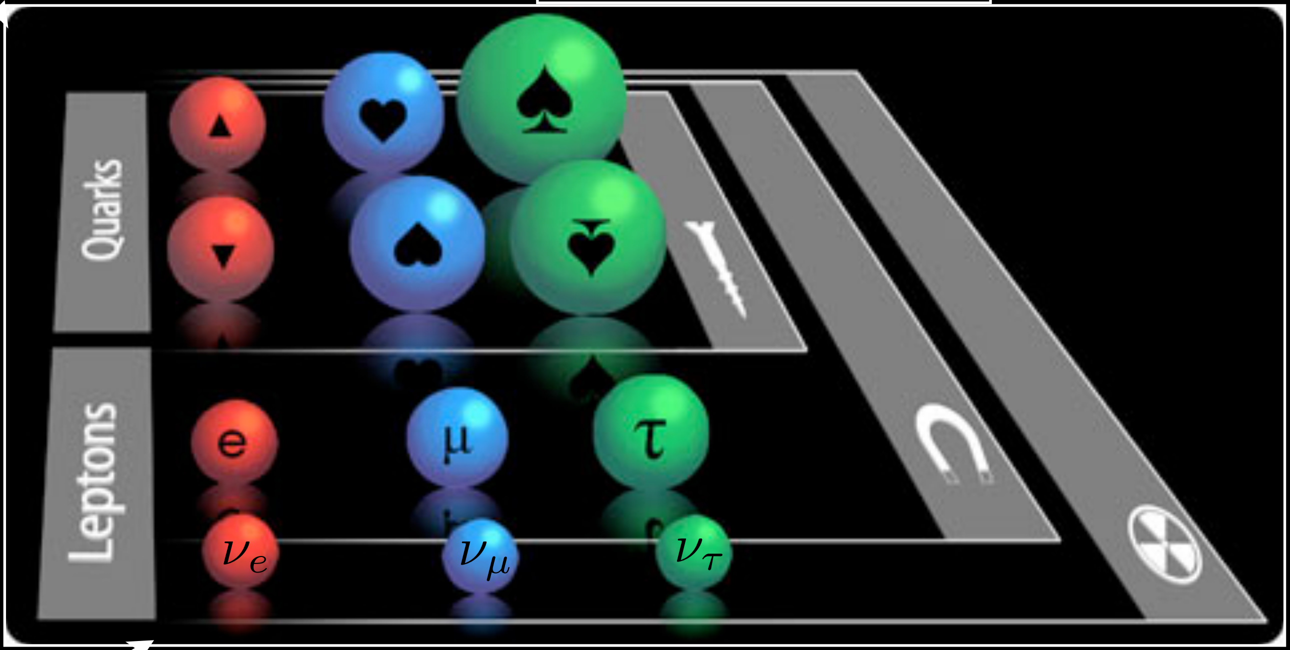
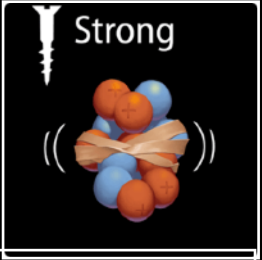


Couples to charge;
mediated by photons;
felt by quarks and leptons



Spin 1/2

Within the Framework



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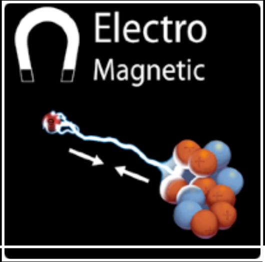

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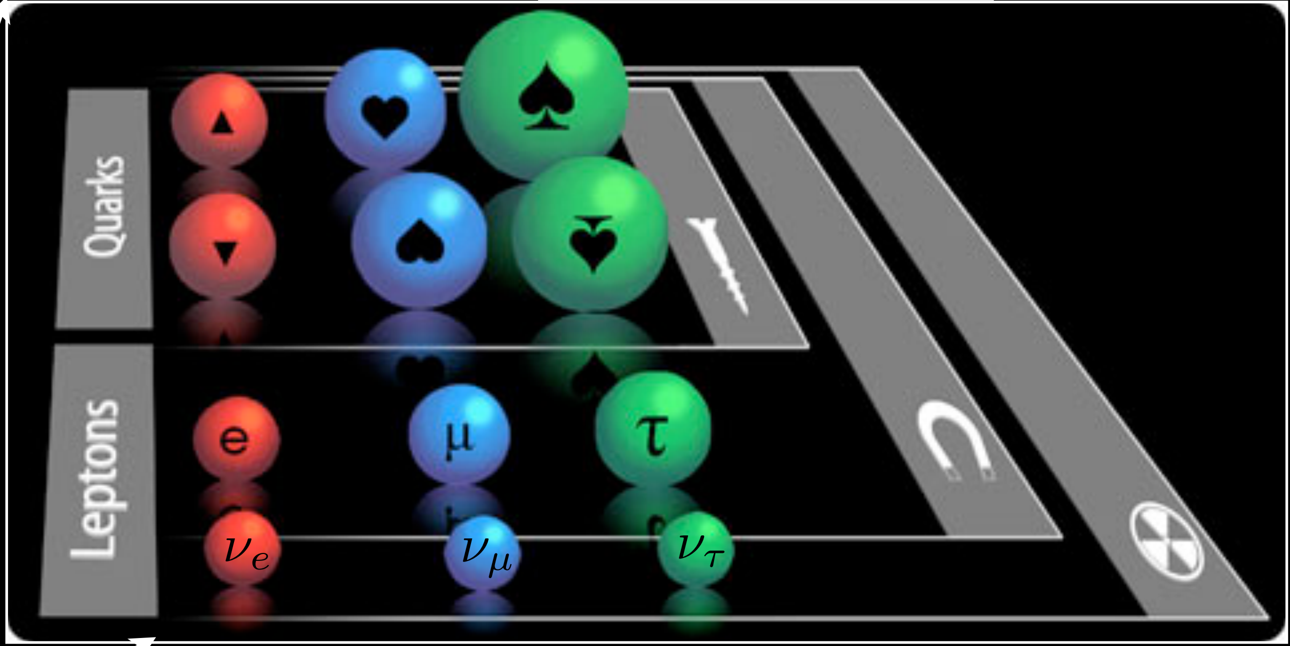
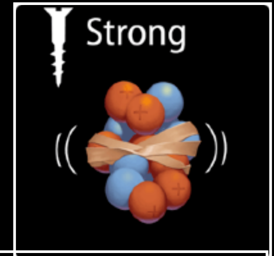


Spin 1/2

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

Within the Framework



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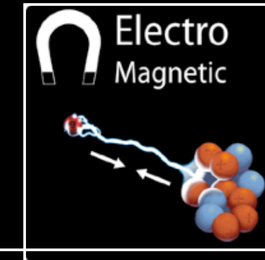

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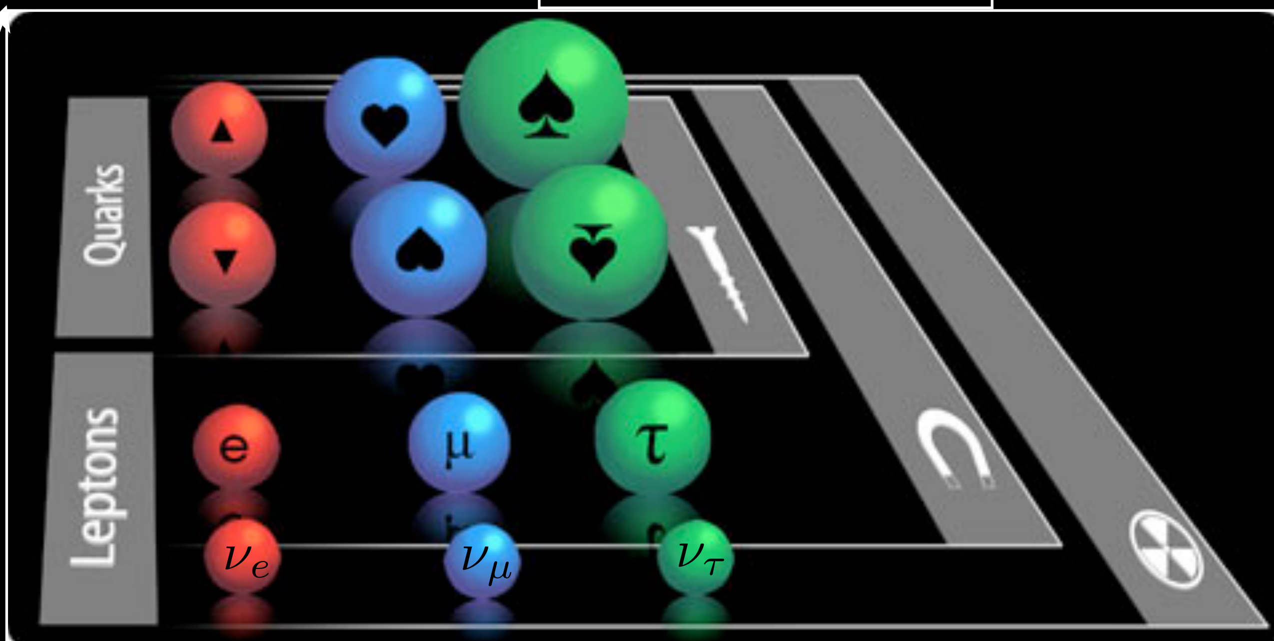
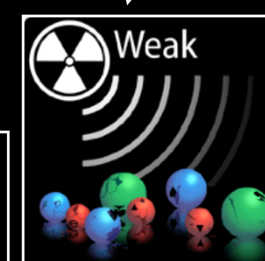


Spin 1

Spin 1/2



Common to all particles;
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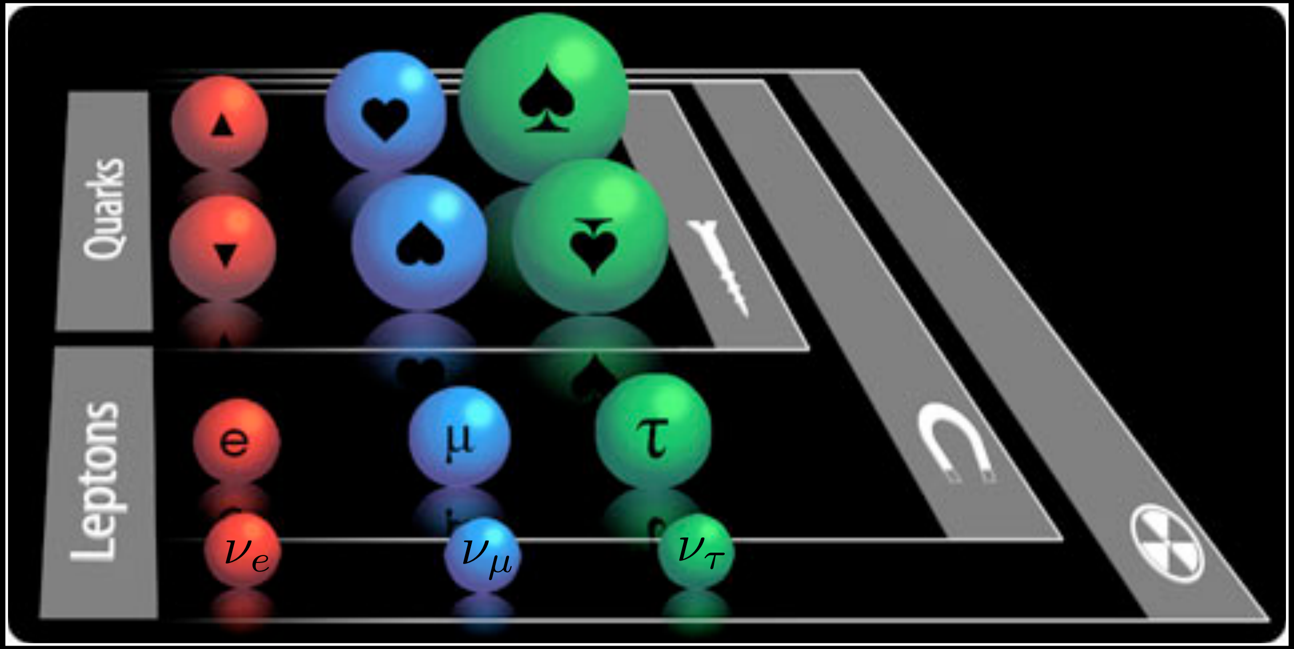
Limited Interactions

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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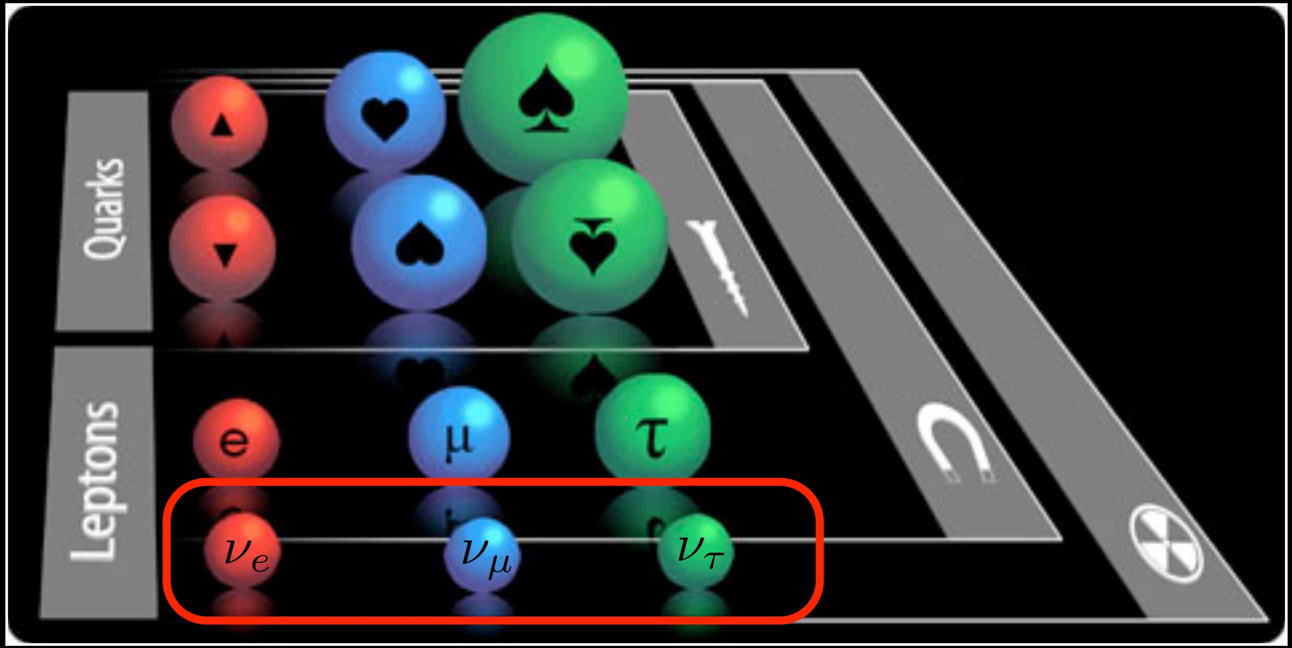

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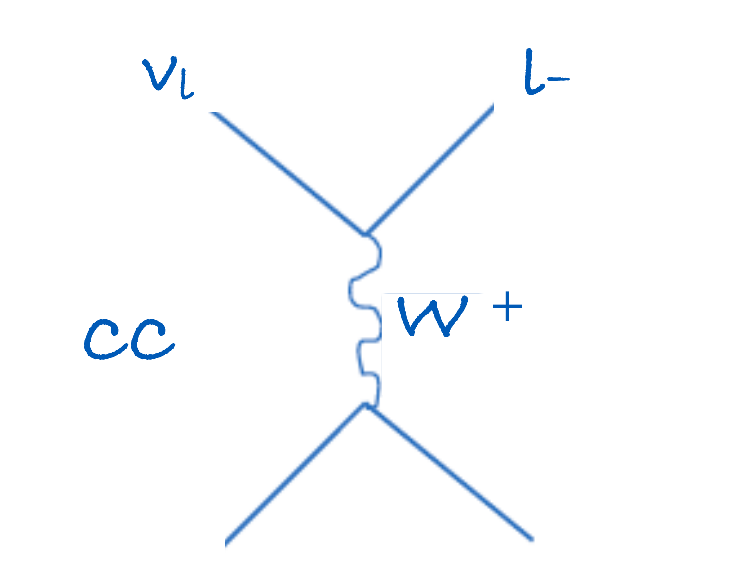
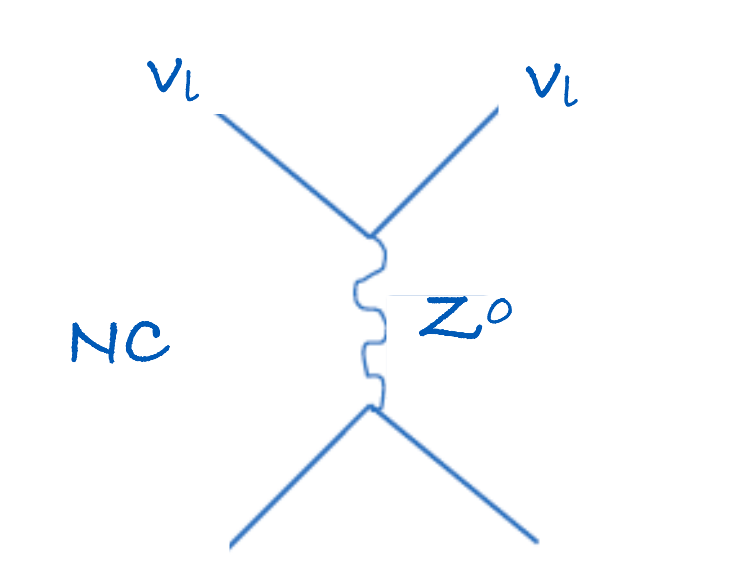
Two Basic Interactions



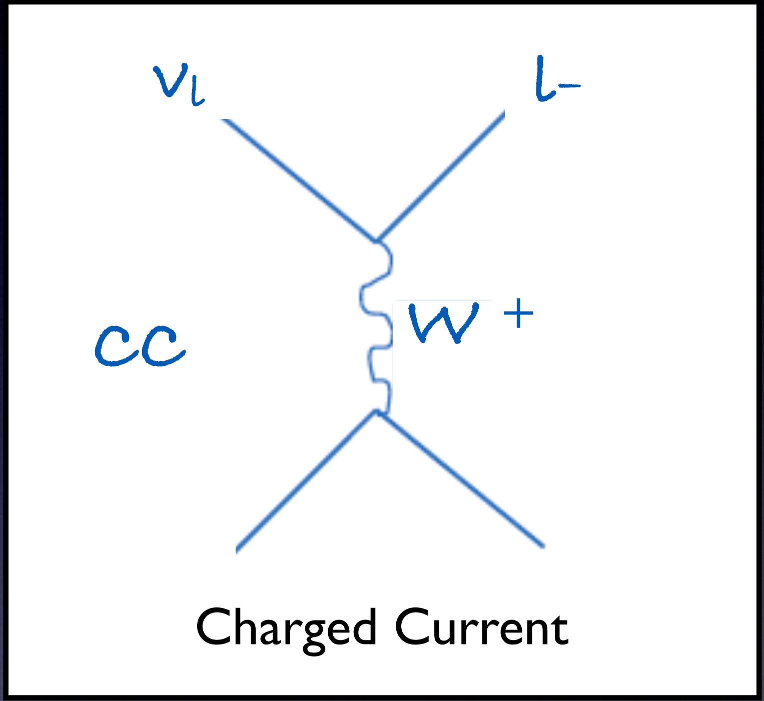
Charged Current

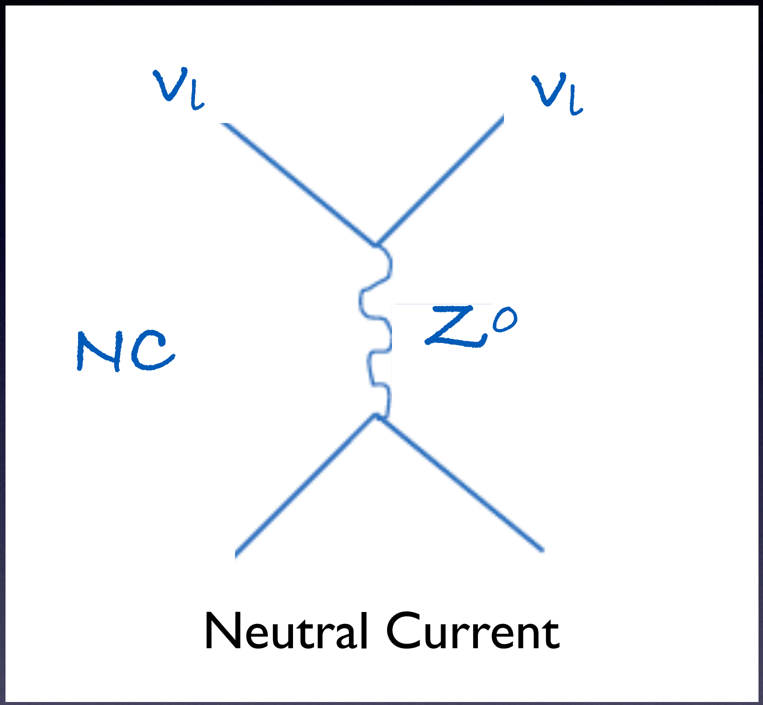


Neutral Current

Most interactions are limited to two basic type of interactions:

Two Basic Interactions





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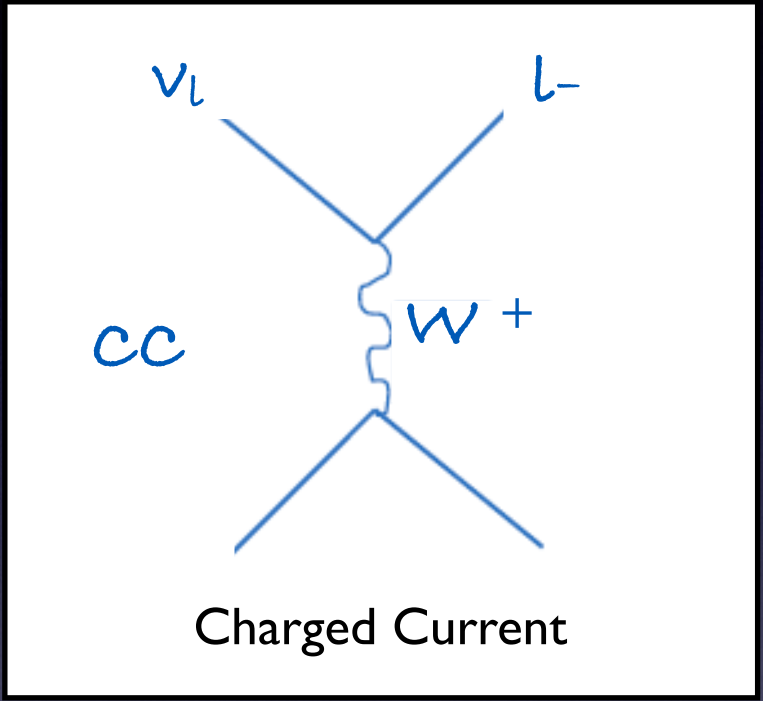
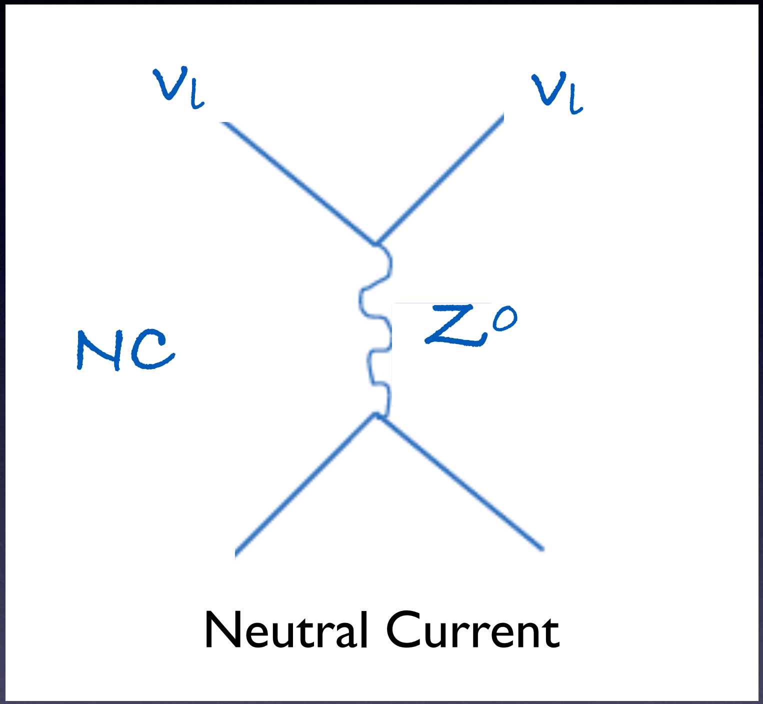
A charge W± is exchanged: Charged Current Exchange

Two Basic Interactions





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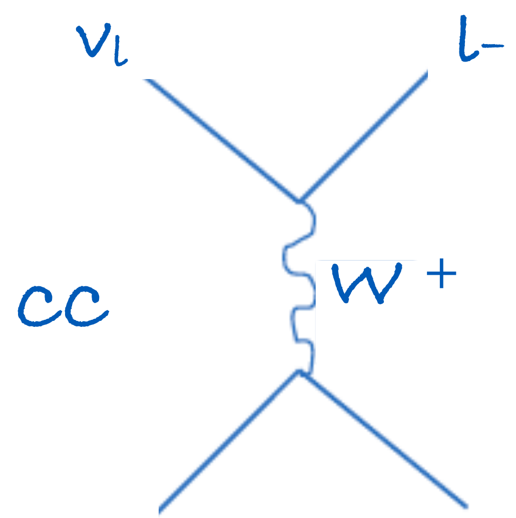
A charge $W^{\pm}$ is exchanged: Charged Current Exchange

A neutral Z^0 is exchanged: Neutral Current Exchange

Two Basic Interactions



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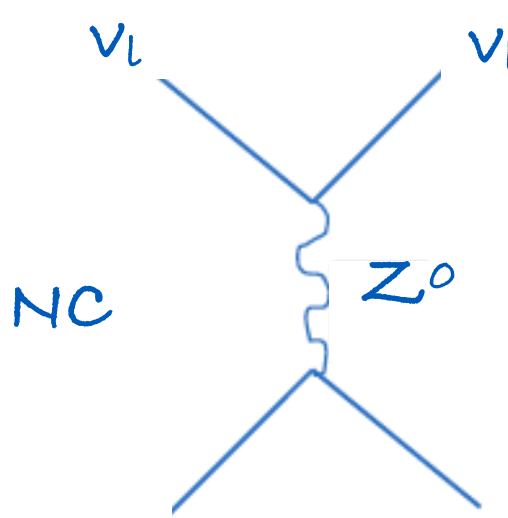


Neutral Current

Most interactions are limited to two basic type of interactions:

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

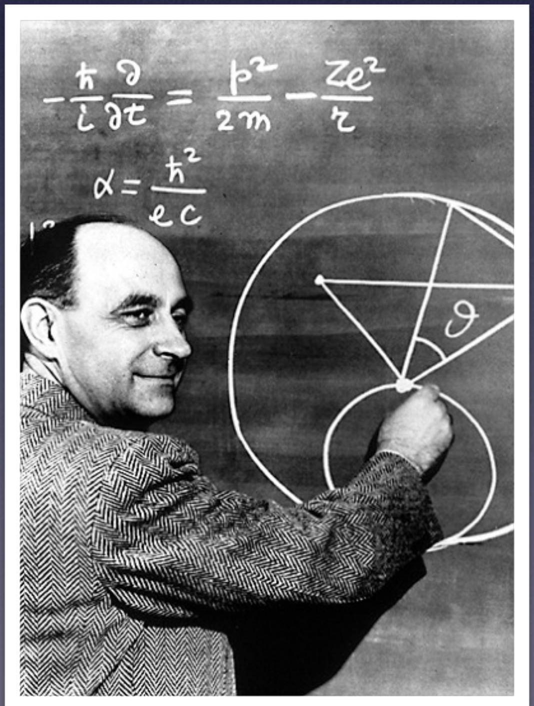
A neutral Z^0 is exchanged: Neutral Current Exchange

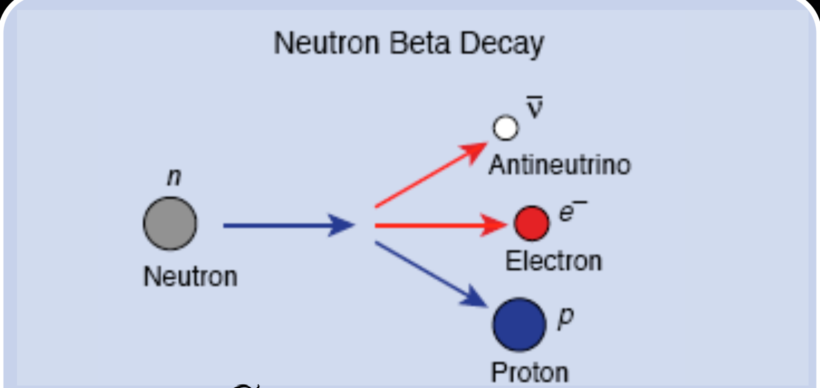
All neutrino reactions involve some version of these two exchanges.

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:





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

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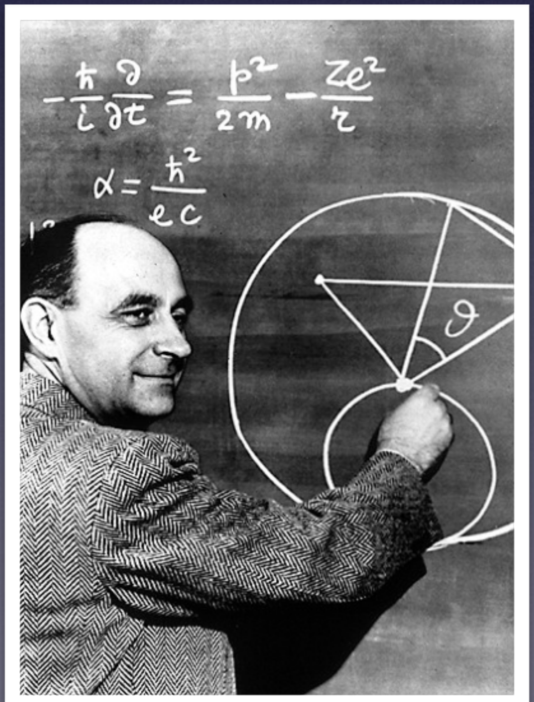
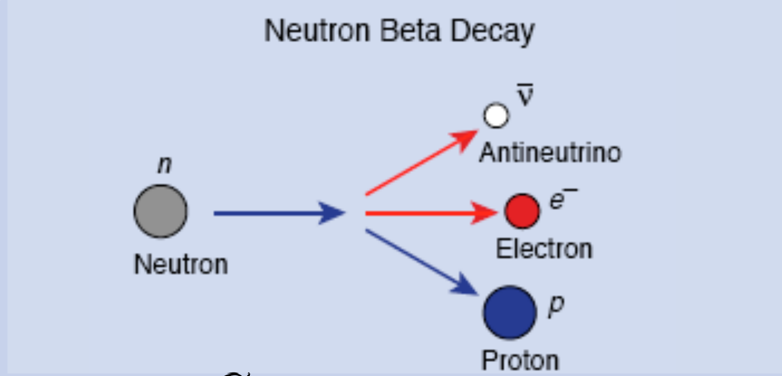




$$\mathcal{H} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu \nu][\bar{\Phi}_n \gamma^\mu \Phi_p]$$

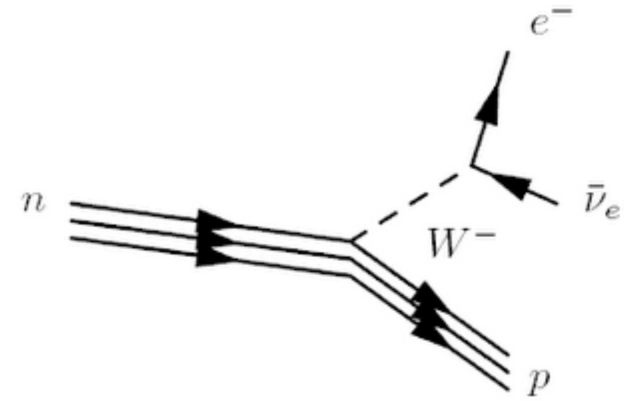
- Here, the theory describes a 4-point interaction (current-current model).

- 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

Within the Standard Model

- 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

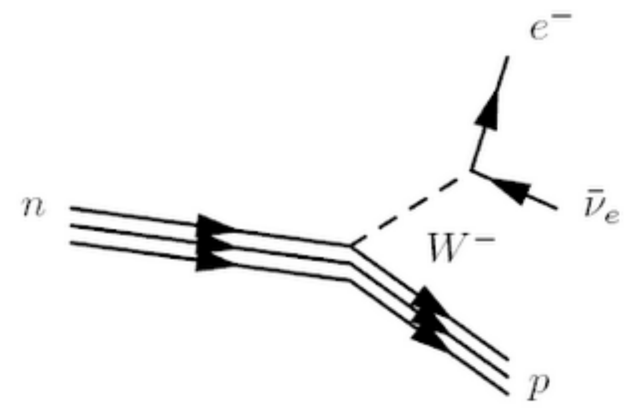
A Misnomer

- 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.



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

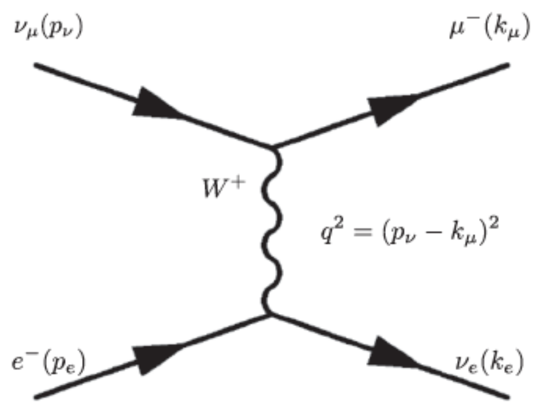
G_F is a small number...

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

Case Study: Neutrino-Lepton scattering

- We can study one of the simpler cross-sections, where the interaction is solely with another lepton (neutrino-lepton scattering).

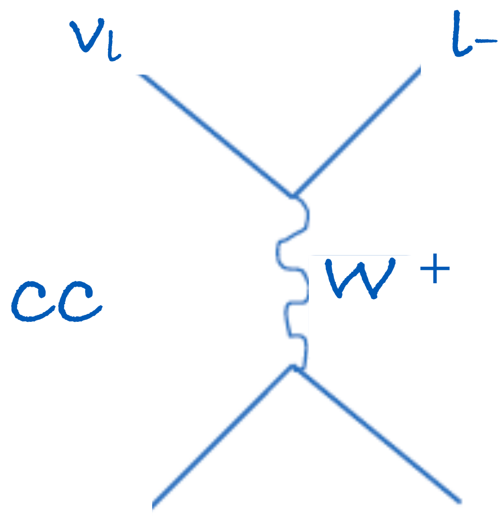
- The two-body interaction (and the smallness of the neutrino mass) simplify the cross-section to allow a direct connection with the matrix element ($|\mathcal{M}|^2$).



$$\frac{d\sigma}{dq^2} = \frac{1}{16\pi} \frac{|\mathcal{M}|^2}{(s-(m_e+m_\nu)^2)(s-(m_e-m_\nu)^2)}$$

$$\frac{d\sigma}{dq^2} = \frac{1}{16\pi} \frac{|\mathcal{M}|^2}{(s-m_e^2)^2}$$

Case Study: Neutrino-Lepton scattering (2)



Charged Current

$$\nu_\ell + e^- \to \ell^- + \nu_e \quad (\ell = \mu \text{ or } \tau).$$

$$\mathcal{M}_{\rm CC} = -\frac{G_F}{\sqrt{2}} \left[\left(\bar{\nu}_\mu \gamma^\mu (1-\gamma^5) \nu_\mu \right) \left(\bar{\nu}_e \gamma_\mu (1-\gamma^5) e \right) \right]$$

$$\frac{d\sigma(\nu_e e \to \nu_e \ell)}{dy} = \frac{2m_e G_F^2 E_\nu}{\pi} \left(1 - \frac{m_\ell^2 - m_e^2}{2m_e E_\nu} \right)$$

Consider the case of just the charged current process to apply (e.g. l = μ or t)

The SM has a simple prediction for the cross-section as a function of inelasticity (y).

At sufficiently high energies, where the threshold is irrelevant, we have the simple scaling...

$$\sigma \simeq \frac{2m_e G_F^2 E_\nu}{\pi} = \frac{G_F^2 s}{\pi}$$

Case Study: Neutrino-Lepton scattering (3)

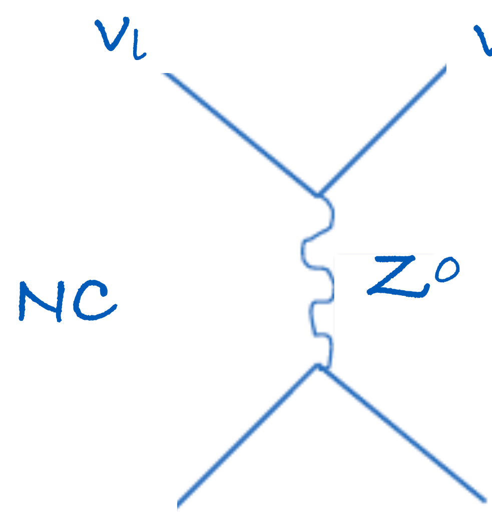
$$\bar{\nu}_e + e \to \bar{\nu}_\ell + \ell$$

$$\frac{d\sigma(\bar{\nu}_e e \to \bar{\nu}_\ell \ell)}{dy} = \frac{2m_e G_F^2 E_\nu}{\pi} \cdot \left((1-y)^2 - \frac{(m_\ell^2 - m_e^2)(1-y)}{2m_e E_\nu} \right)$$

Due to the available spins, the cross-section for the anti-neutrino version of this process looks different (helicity dependence)

Case Study: Neutral Current Processes

$$g_V^\nu = g_L^\nu + g_R^\nu = \sqrt{\rho}(+\tfrac{1}{2}),$$
$$g_A^\nu = g_L^\nu - g_R^\nu = \sqrt{\rho}(+\tfrac{1}{2}),$$
$$g_V^f = g_L^f + g_R^f = \sqrt{\rho}(I_3^f - 2Q^f \sin^2\theta_W).$$
$$g_A^f = g_L^f - g_R^f = \sqrt{\rho}(I_3^f).$$



Neutral Current

$$g_V \equiv 2g_L^\nu g_V^f$$
$$g_A \equiv 2g_L^\nu g_A^f$$

$$\mathcal{M}_{\rm NC} = -\sqrt{2}G_F \left[\bar{\nu}_\mu \gamma^\mu (g_V^\nu - g_A^\nu \gamma^5)\nu_\mu\right] \times \left[\bar{e}\gamma_\mu (g_V^f - g_A^f \gamma^5) e\right].$$

Now, let's examine a process by which the matrix incorporates the neutral current interaction.

The process now allows one to be sensitive to the Weinberg mixing angle directly

Case Study: Neutral Current Processes

Neutrino Scattering

$$\frac{d\sigma(\nu_\ell e \to \nu_\ell e)}{dy} = \frac{m_e G_F^2 E_\nu}{2\pi}\{(g_V + g_A)^2 + (g_V - g_A)^2\left((1-y)^2 - (g_V^2 - g_A^2)\frac{m_e y}{E_\nu}\right)\}$$

Anti-Neutrino Scattering

$$\frac{d\sigma(\bar{\nu}_\ell e \to \bar{\nu}_\ell e)}{dy} = \frac{m_e G_F^2 E_\nu}{2\pi}\{(g_V - g_A)^2 + (g_V + g_A)^2\left((1-y)^2 - (g_V^2 - g_A^2)\frac{m_e y}{E_\nu}\right)\}$$

Neutrino scattering thus becomes a powerful early test of the Standard Model couplings.

{N.B. if the incoming neutrino is an electron neutrino, there is an interference term between CC and NC (shift $g_{A/V}$ to $g_{A/V}$ +1)}

Standard Model Tests

At high energies, even the total cross-sections stand as precision tests of the Standard Model by probing the weak mixing angle.

Gargamelle experiment as a prime example of the observation of neutral currents.

The first candidate leptonic neutral-current event from the Gargamelle CERN experiment.

Reaction	Type	$\sigma(E_\nu \gg E_{\text{thresh}})/\sigma_0$
$\nu_e e^- \to \nu_e e^-$	CC and NC	$\frac{1}{4} + \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W$
$\bar{\nu}_e e^- \to \bar{\nu}_e e^-$	CC and NC	$\frac{1}{12} + \frac{1}{3}\sin^2\theta_W + \frac{4}{3}\sin^4\theta_W$
$\bar{\nu}_e e^- \to \bar{\nu}_\mu \mu^-$	CC	$\frac{1}{3}$
$\nu_\mu e^- \to \nu_e \mu^-$	CC	1
$\nu_\mu e^- \to \nu_\mu e^-$	NC	$\frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W$
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From Simple to not-so-Simple

$$\mathcal{H}_W^{\rm CC} = \frac{G_F V_{ud}}{\sqrt{2}} \int [J^{{\rm CC},\mu}(\vec{x}) H_\mu^{\rm CC}(\vec{x}) + {\rm H.c.}] d\vec{x},$$

$$\mathcal{H}_W^{\rm NC} = \frac{G_F}{\sqrt{2}} \int [J^{{\rm NC},\mu}(\vec{x}) H_\mu^{\rm NC}(\vec{x}) + {\rm H.c.}] d\vec{x},$$

$$H_\mu^{\rm CC}(\vec{x}) = V_\mu^{\pm}(\vec{x}) + A_\mu^{\pm}(\vec{x})$$

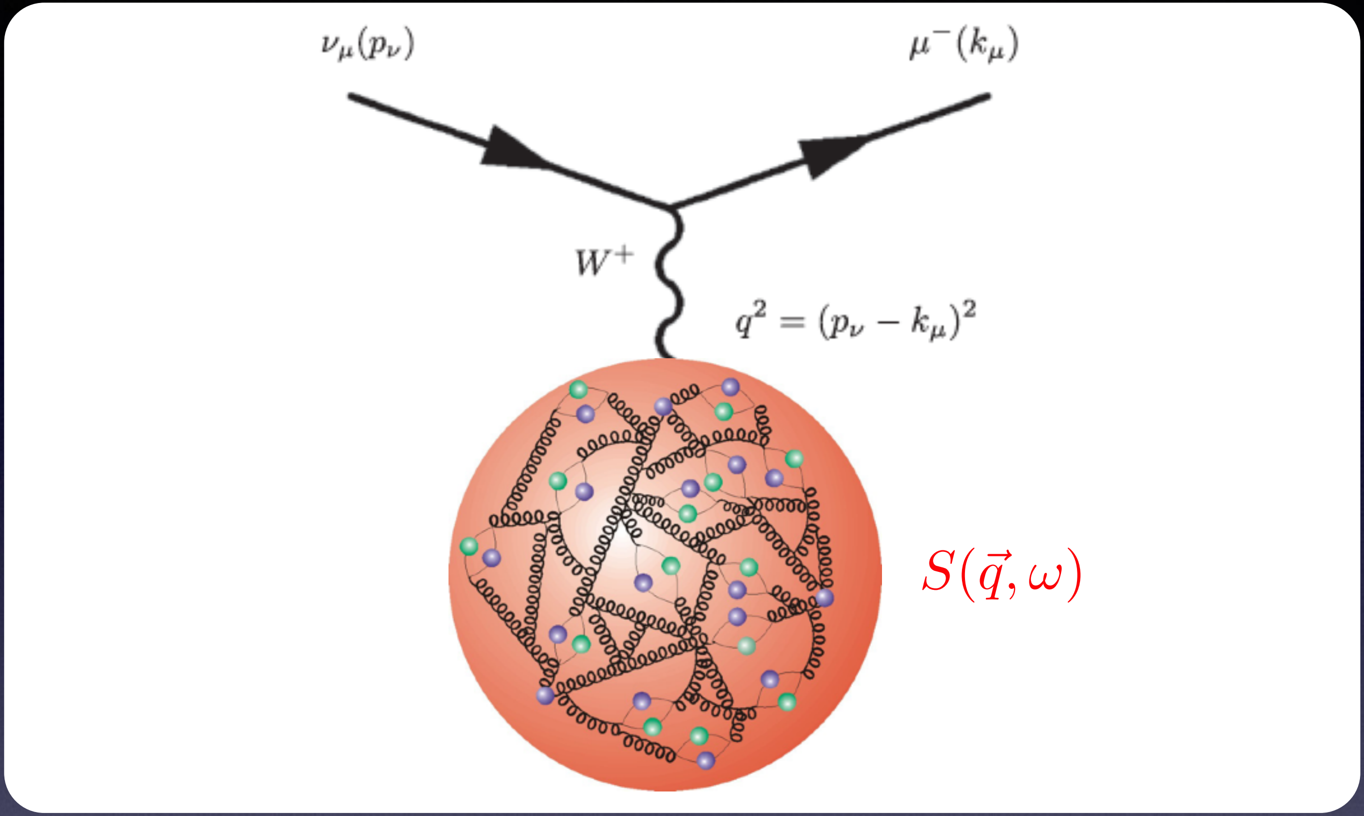
$$H_\mu^{\rm NC}(\vec{x}) = (1 - 2\sin^2\theta_W) V_\mu^0(\vec{x}) + A_\mu^0(\vec{x}) - 2\sin^2\theta_W V_\mu^s$$

Leptonic interactions illustrate the simplest case of neutrino cross-sections, since the target has no internal structure and there is no inner structure (aside from spin).

When it comes to nuclei / hadronic / atomic matter, the inner structure can play a major role in the cross-section behavior.

Convenient to introduce a spectral function, $S(q,\omega)$, to capture inner structure

From Simple to not-so-Simple



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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.

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E_ν~MeV

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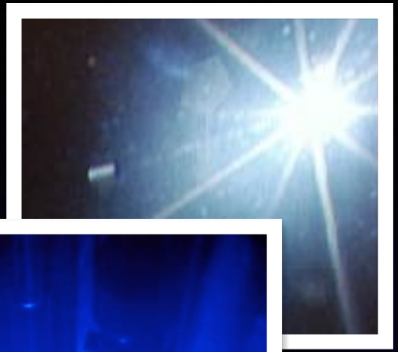

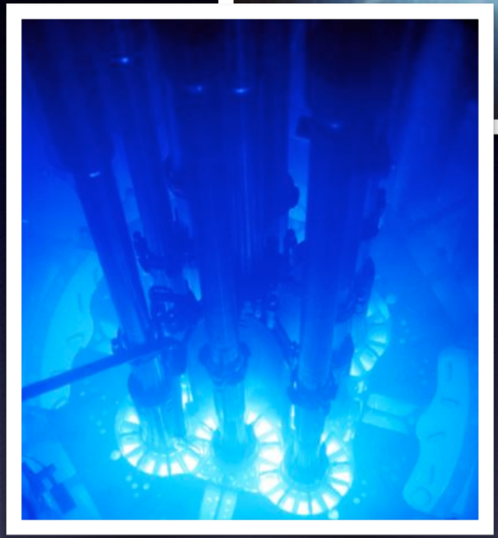

$E_\nu \sim$ MeV

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E_ν~GeV - TeV

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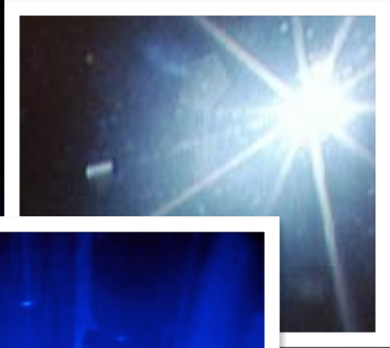
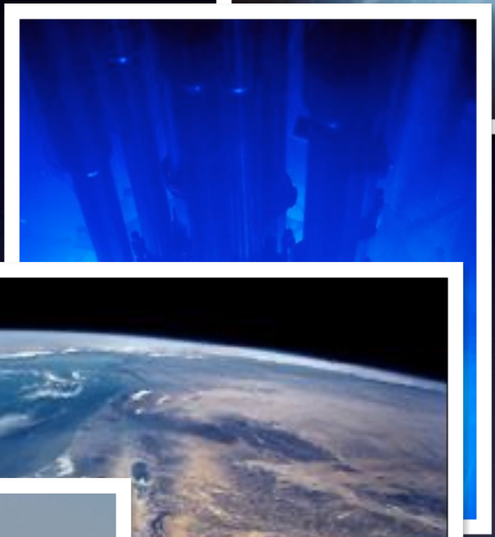
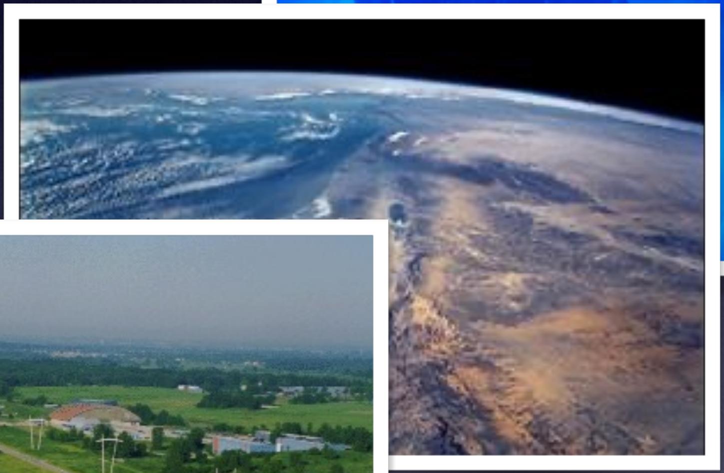






$E_\nu \gg$ TeV

What we will cover:

Where do neutrinos come from?

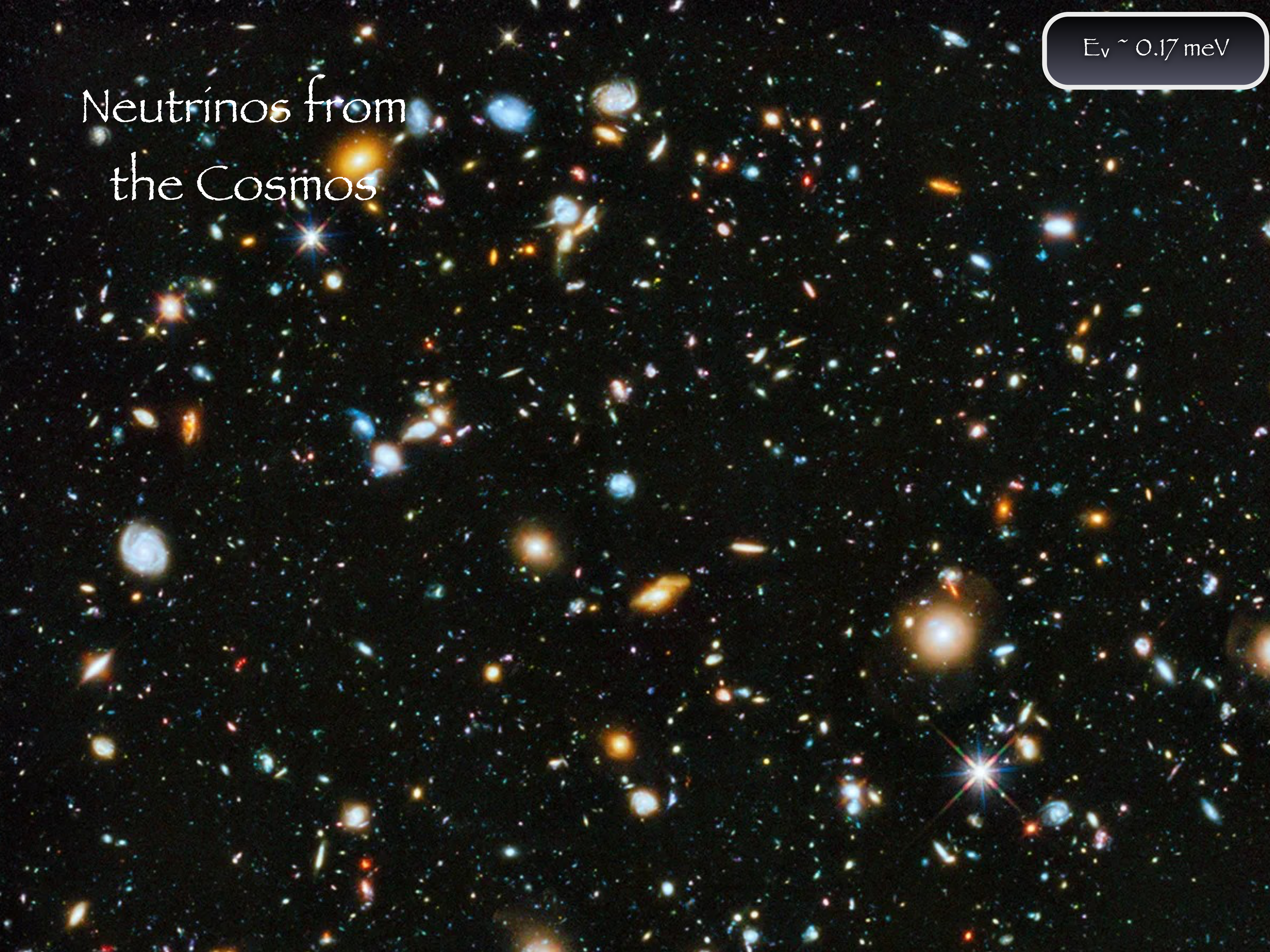
Neutrinos from the Heavens

Neutrinos from the Earth

Neutrinos from Man

Neutrinos from the Cosmos

$E_\nu \sim 0.17$ meV



Neutrinos from the Cosmos

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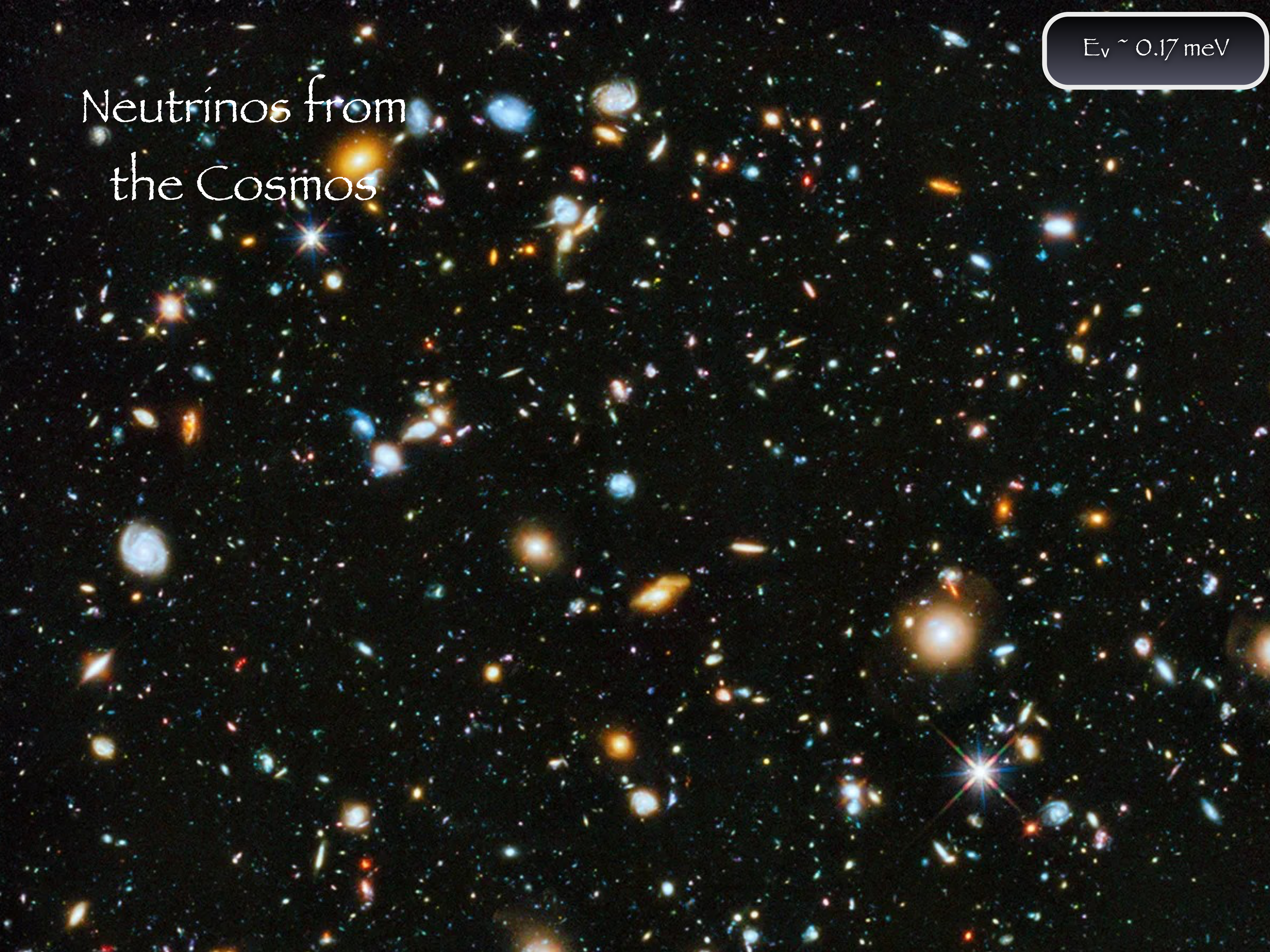

Neutrinos from the Cosmos

$E_\nu \sim 0.17$ meV

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

Annihilation Rate

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

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

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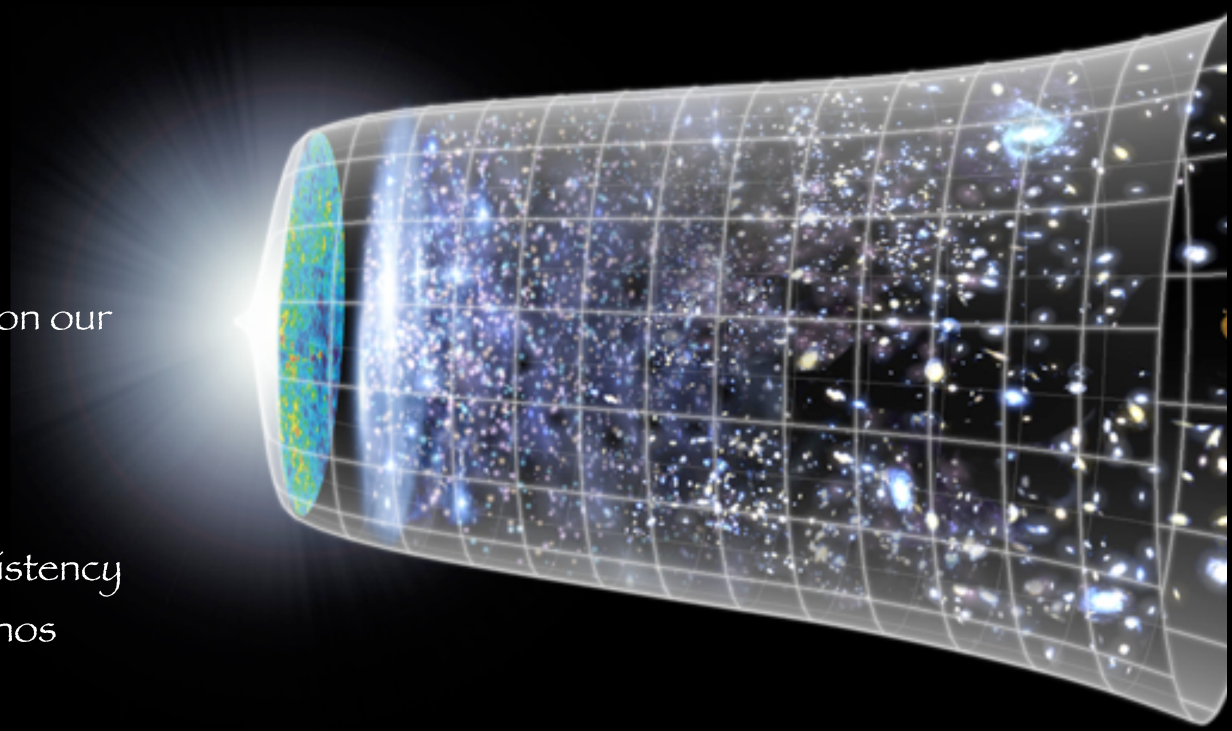
Expansion Rate

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.



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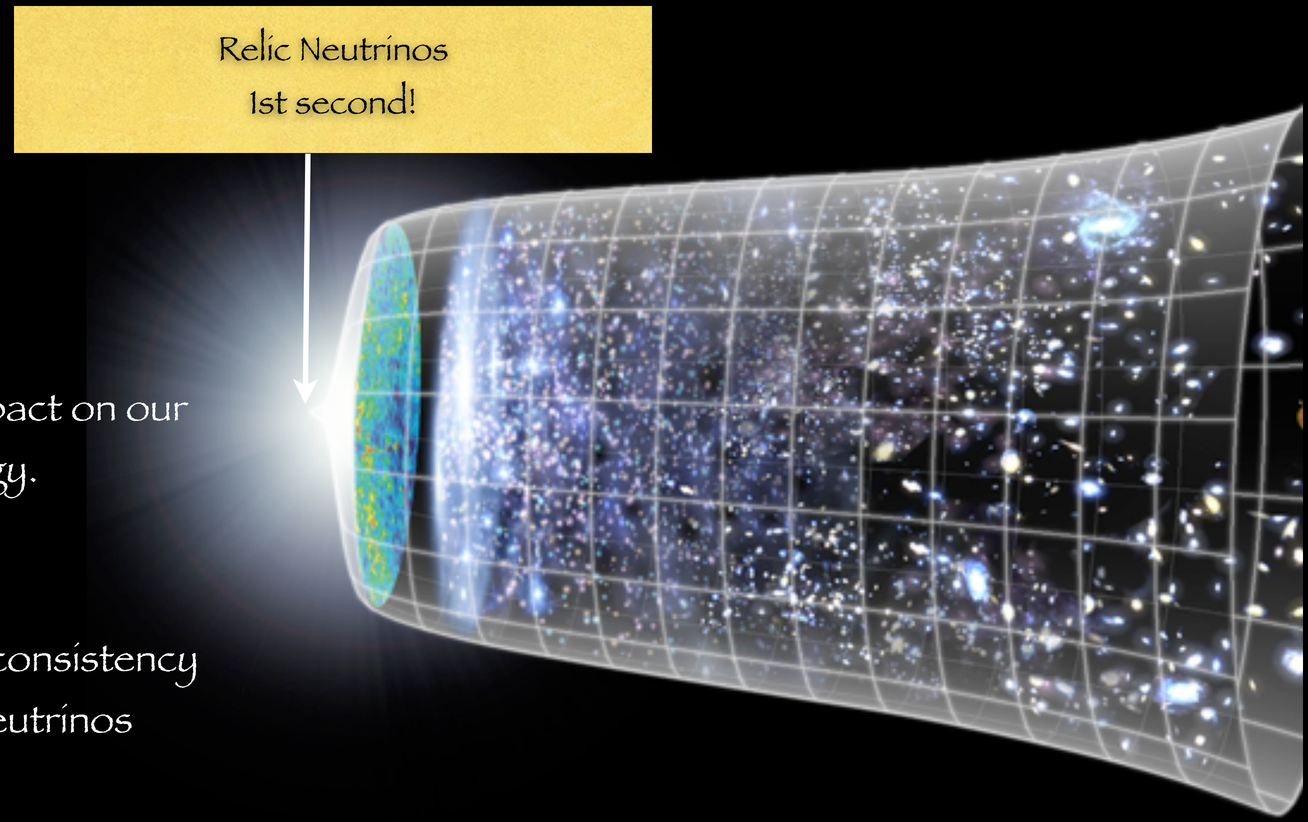

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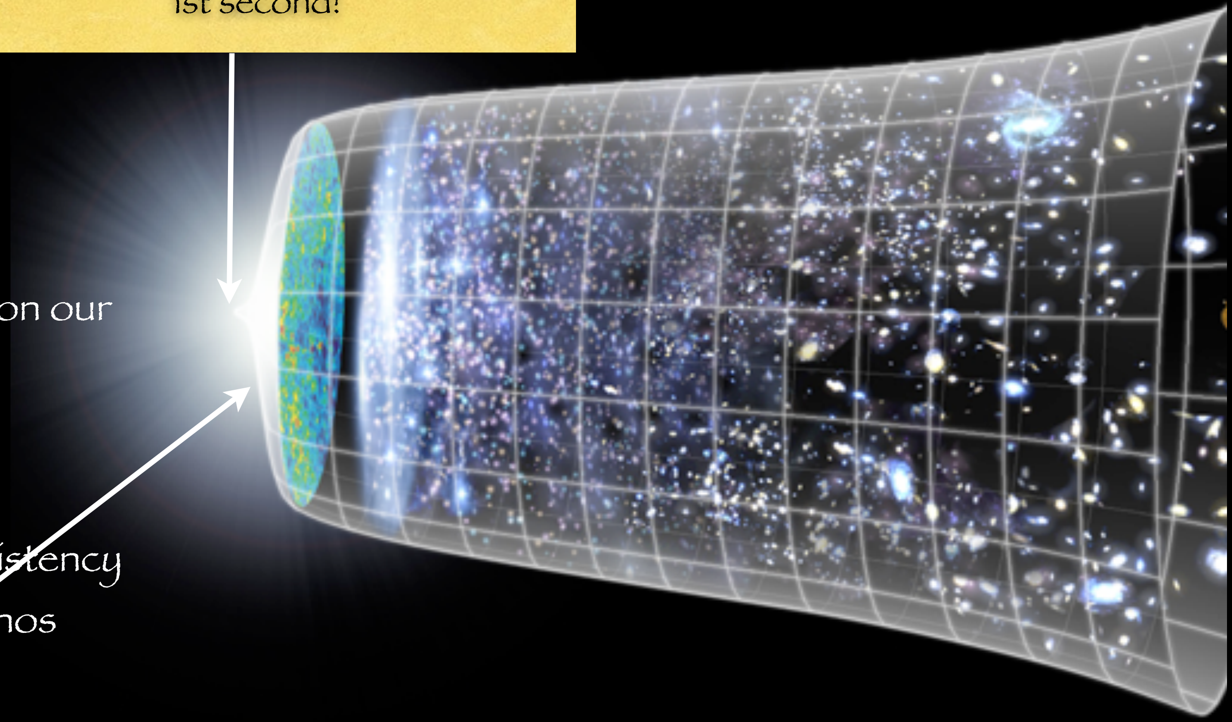
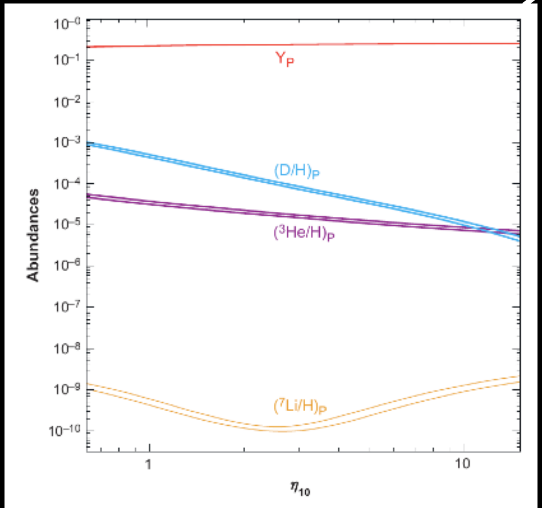
Relic Neutrinos
1st second!



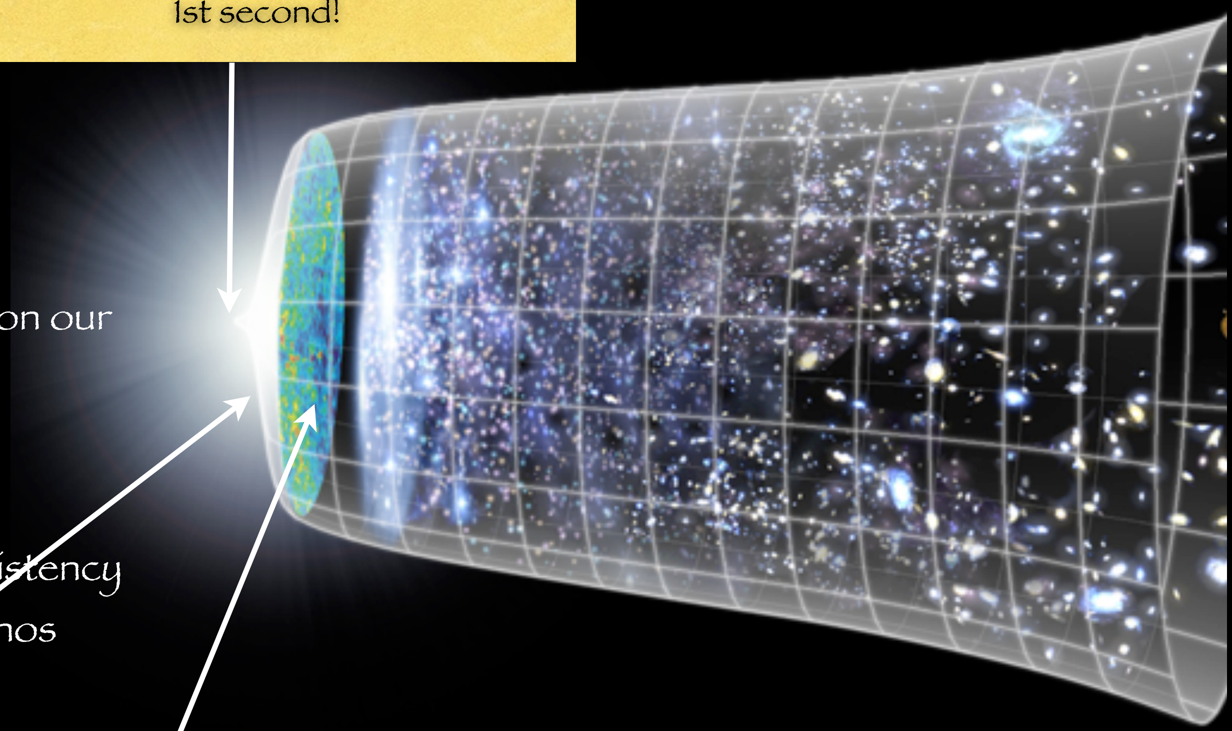


Primordial Nucleosynthesis

1st few minutes

Neutrinos Today

Relic Neutrinos
1st second!



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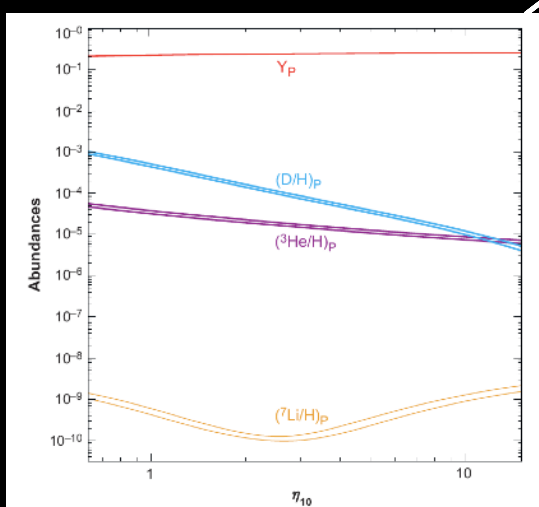

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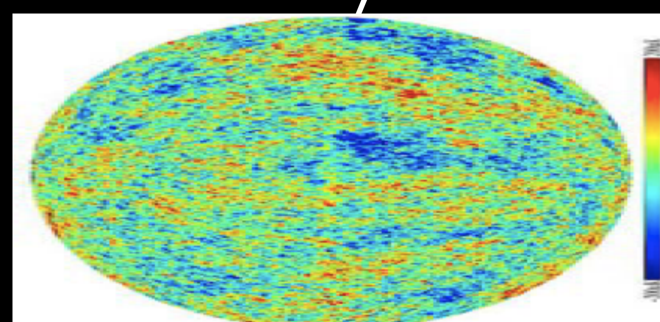
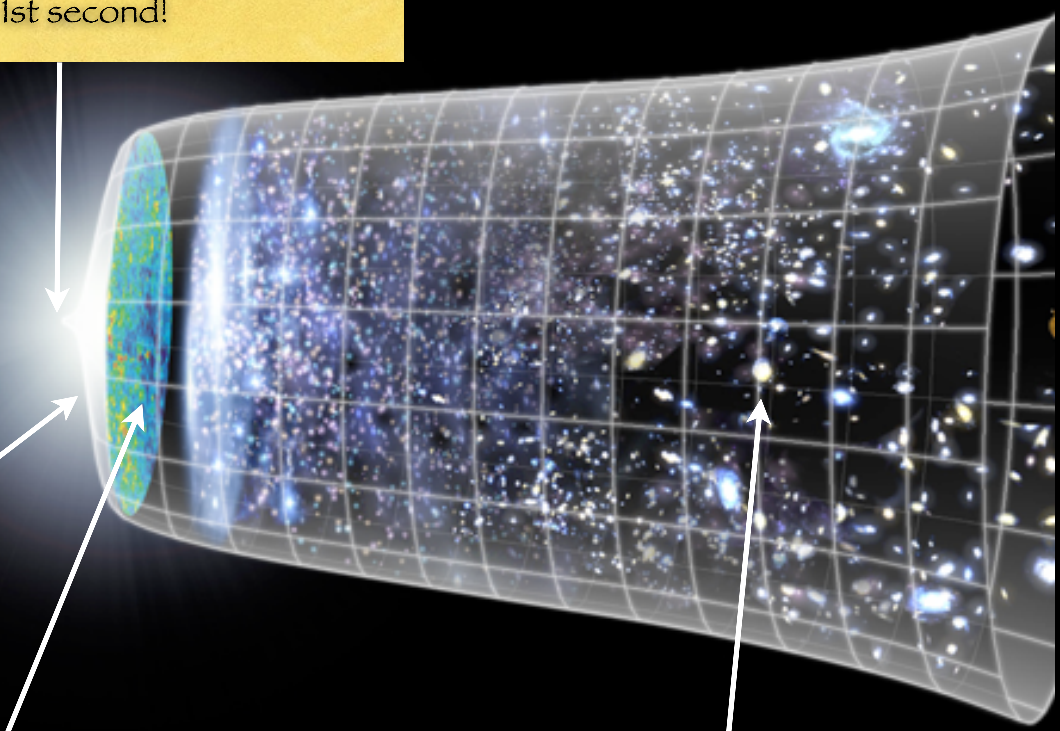


Cosmic Microwave Background
400 kyrs

Neutrinos Today

Relic Neutrinos
1st second!



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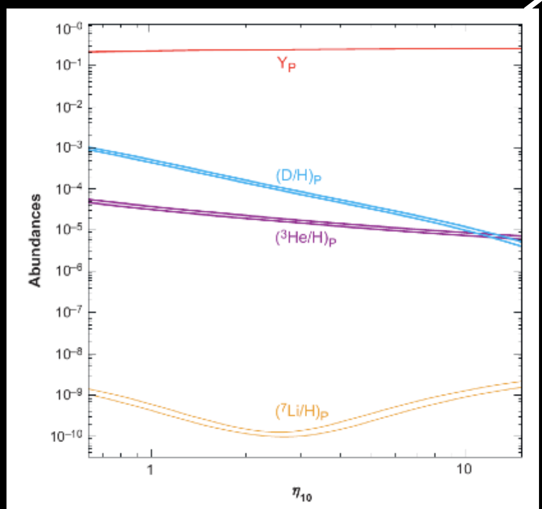

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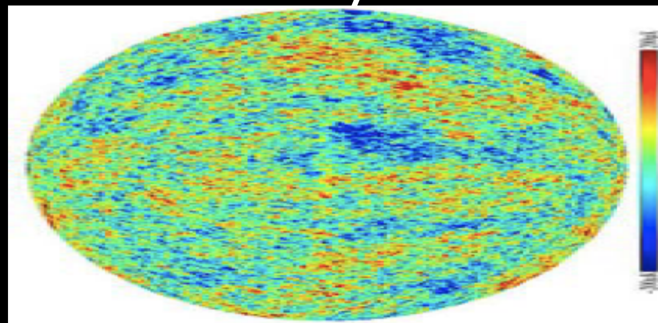

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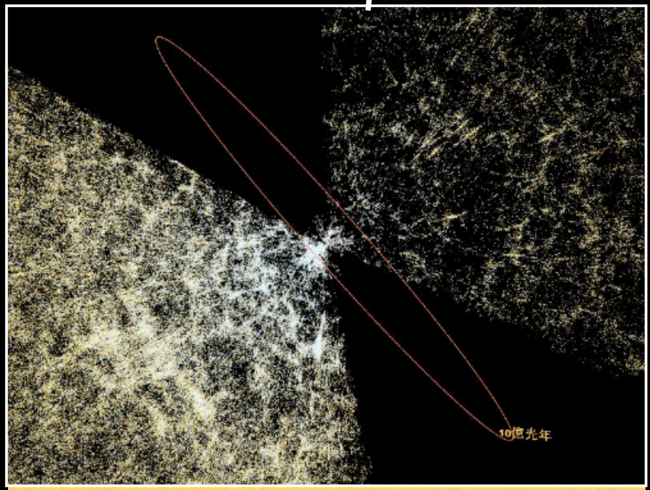
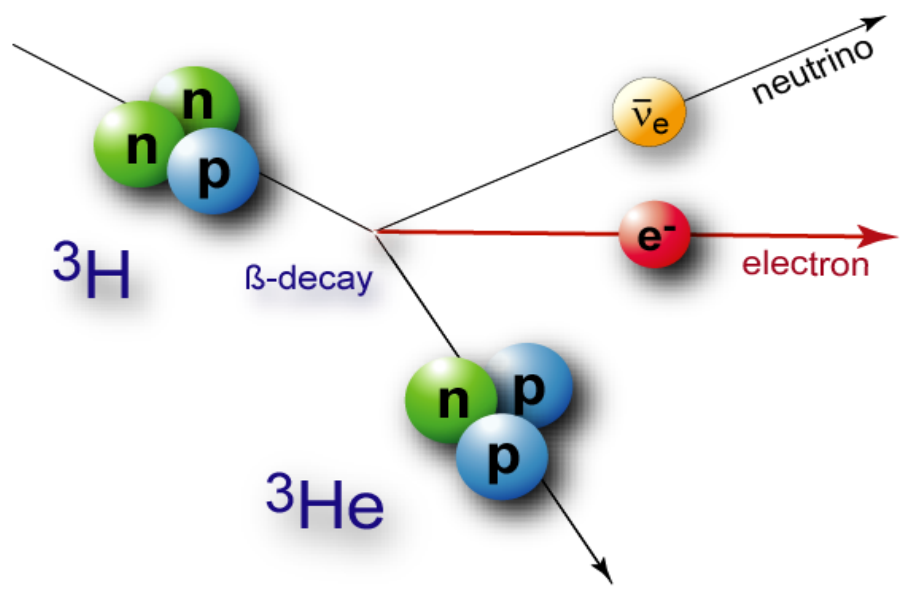


Large Scale Structures
Recent Epoch

Any Chance to Detect the CνB?

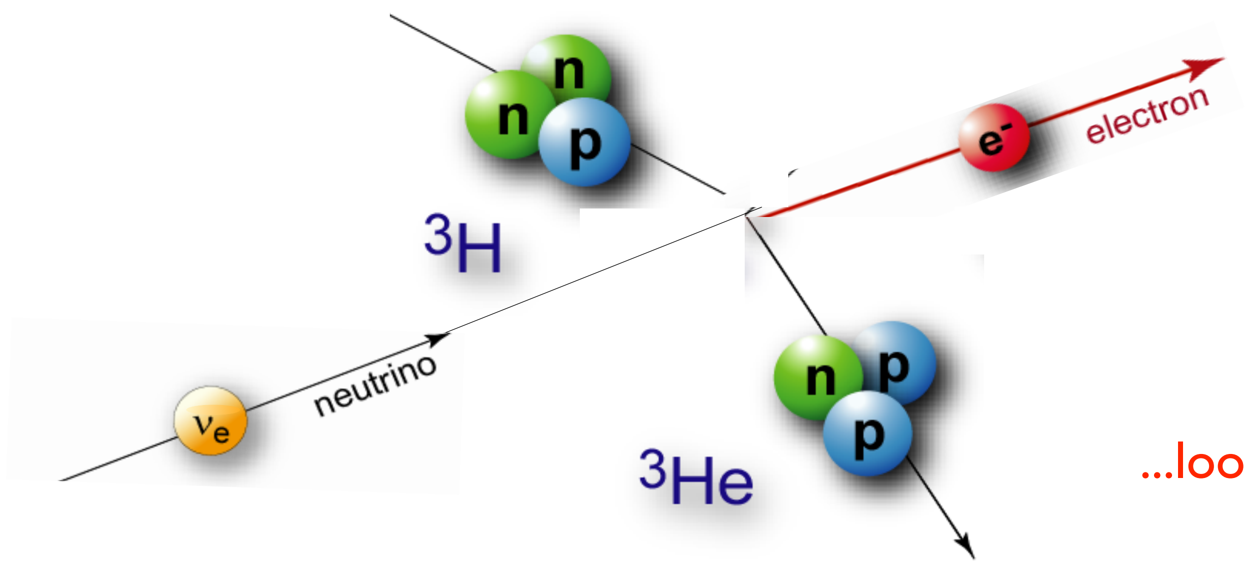
Instead of beta decay...

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



Any Chance to Detect the CνB?

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



...look for neutrino capture

The process is energetically allowed even at zero momentum.

This threshold-less reaction allows for relic neutrino detection

Any Chance to Detect the CνB?

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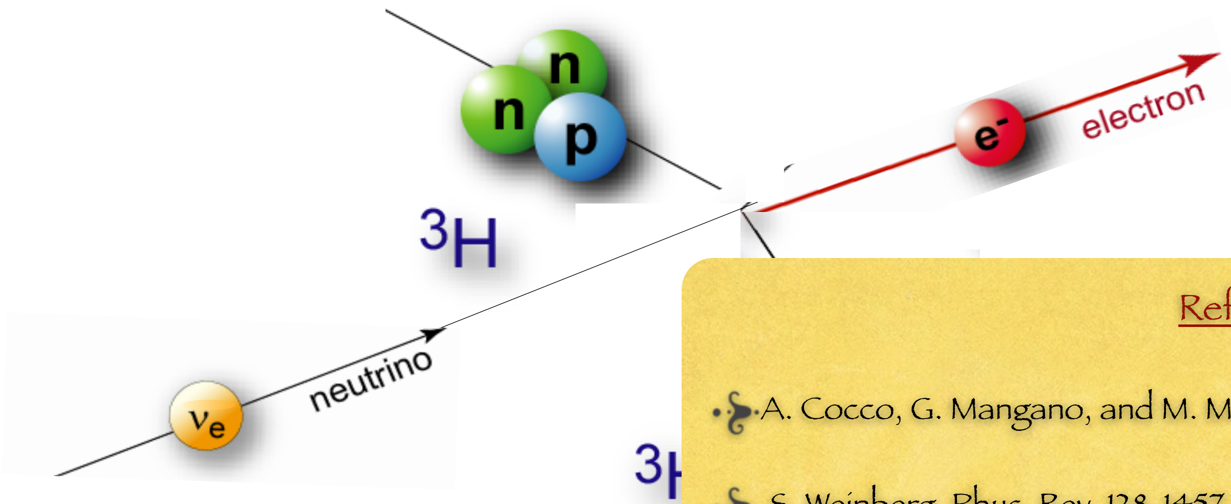

References

- A. Cocco, G. Mangano, and M. Messina, hep-ph/0703075 (2007).
- S. Weinberg, Phys. Rev. 128, 1457 (1962).
- T. W. Donnell and J. D. Walecka, Ann. Rev. Nucl. Sci. 25, 329 (1975).

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Neutrino Capture

Has three main advantages:

(i) The process is exothermic. There is enough energy for the decay to occur (because beta decay will happen anyway). Thus, it is threshold-less.

(ii) Electron energy is almost mono-energetic, after the endpoint energy.

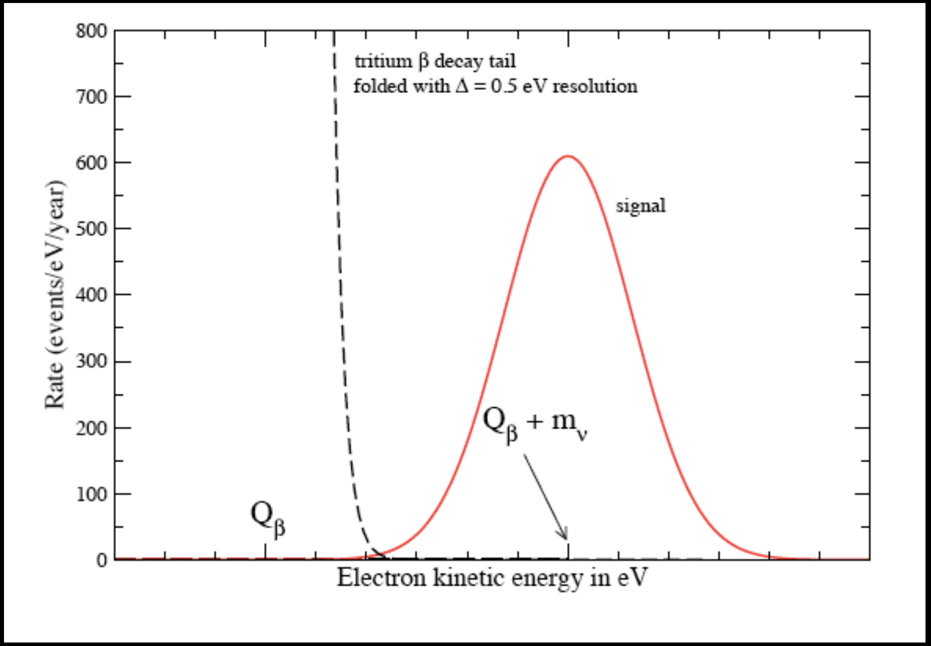
(iii) For tritium, 100 g corresponds to 10 events/year.

$$\lambda_\nu = \int \sigma_\nu \cdot v \cdot f(p_\nu)(\frac{dp}{2\pi})^3$$

Neutrino Capture Rate

$$\sigma_\nu \cdot \frac{v}{c} = (7.84 \pm 0.03) \times 10^{-45} cm^2$$

Tritium Cross-Section



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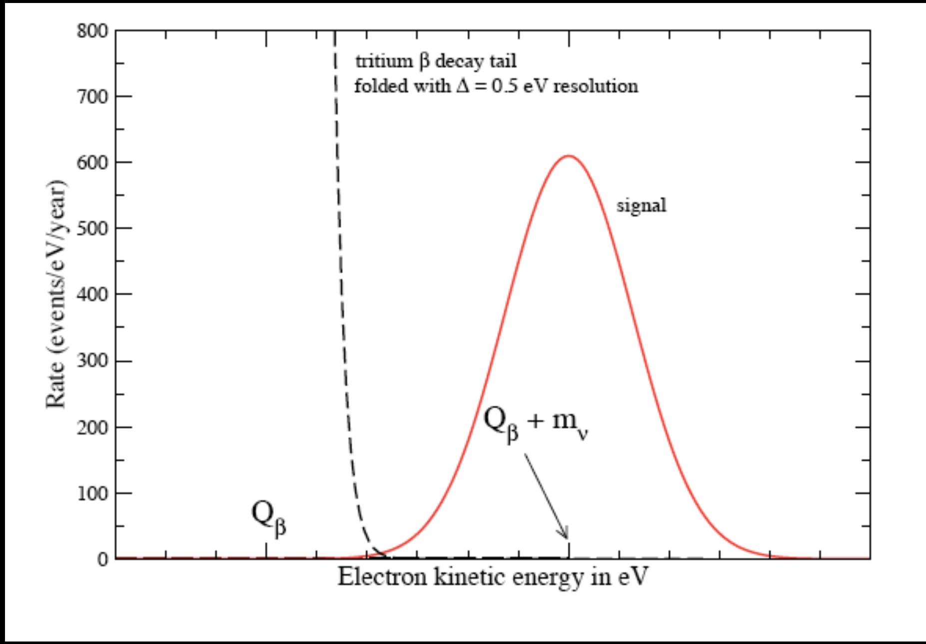


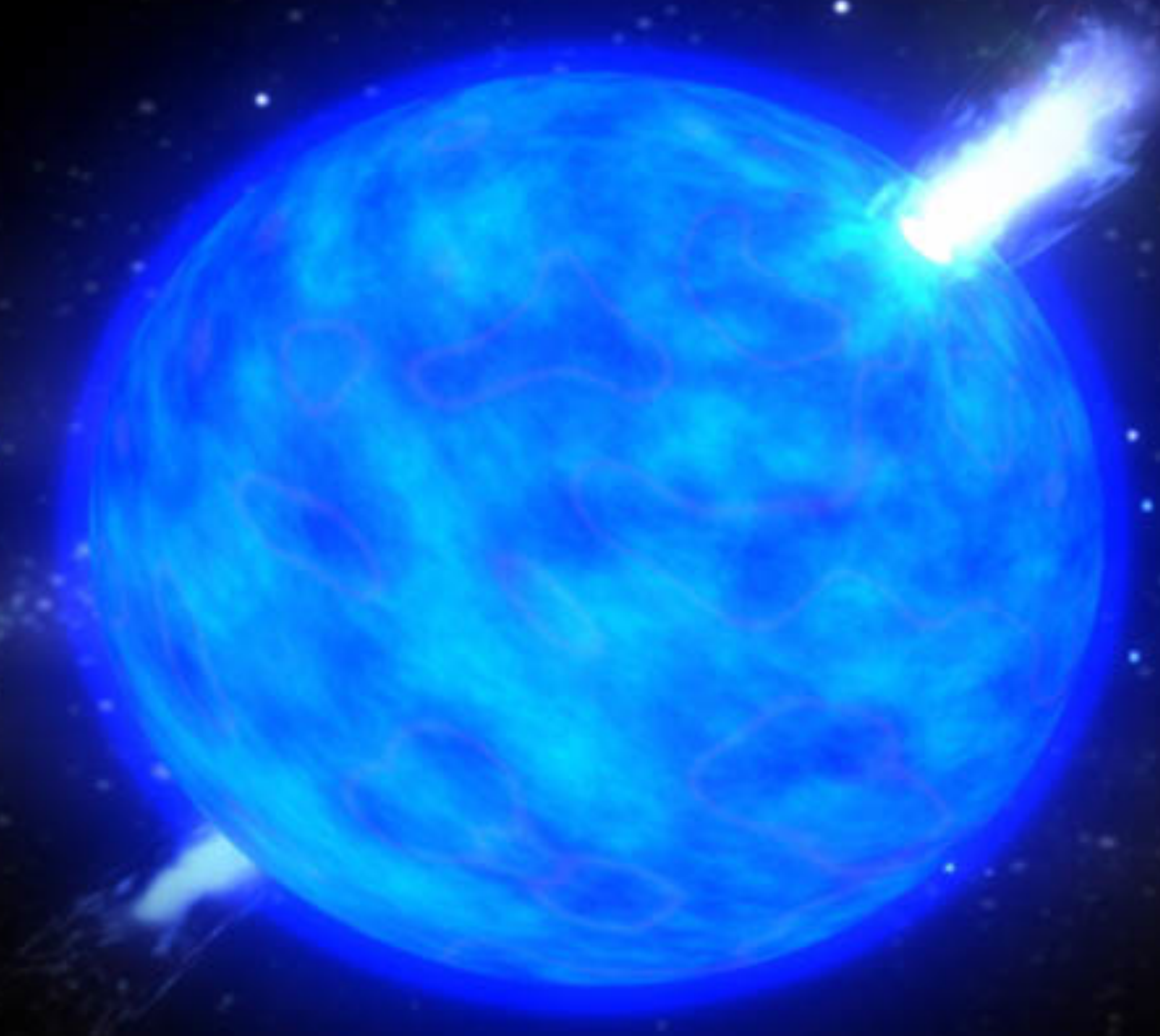
Any other way? Coherence may provide an option...

E_ν ~ 10-20 MeV

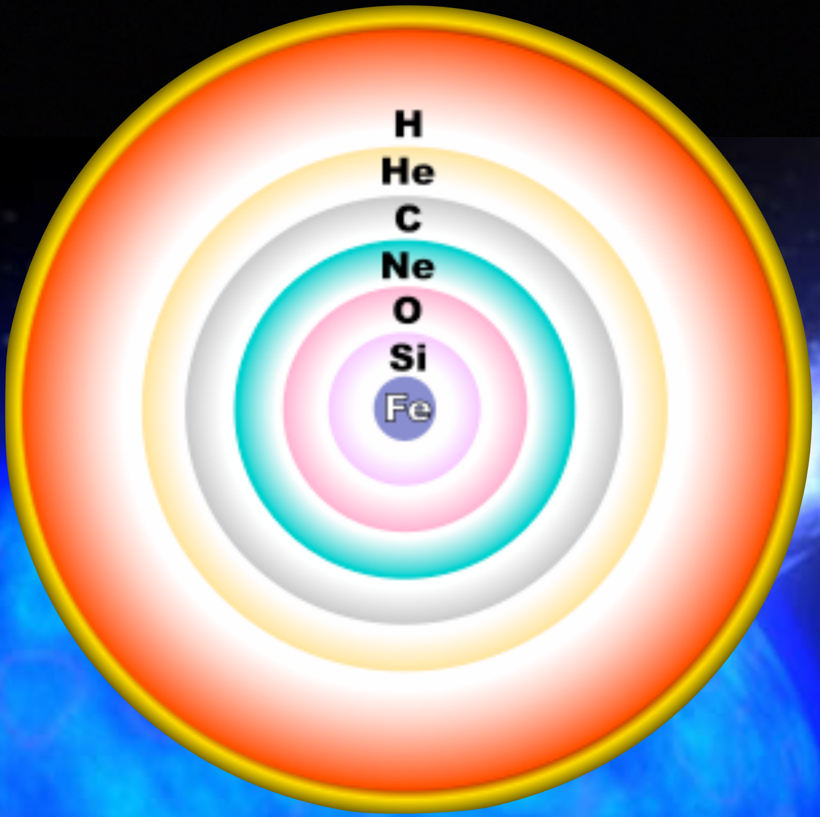
Neutrinos from the Stars

- 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

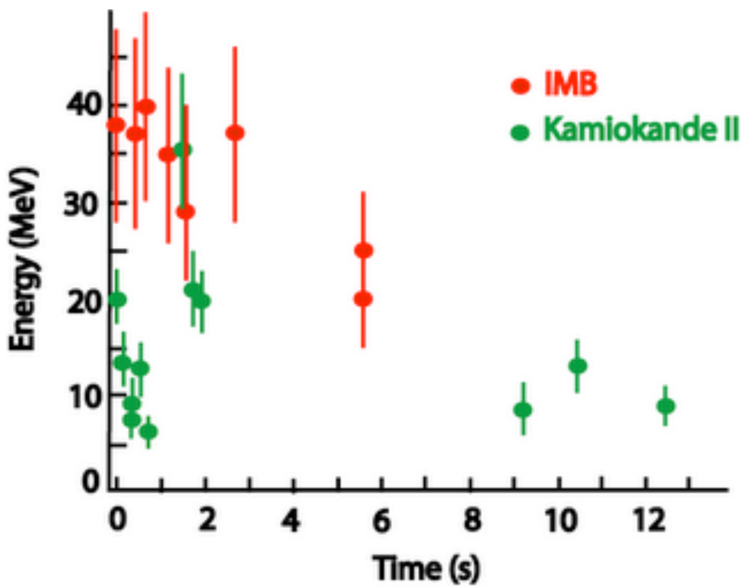


- Core-collapse supernovae are truly unique environments in our known universe:
  - Incredible matter densities: 10^{11}-10^{15} g/cm^3
  - Extreme high temperature: 1-50 MeV
  - Highest recorded energetic processes in the Universe: $10^{51\text{-}53}$ ergs
- At these energies, all species of neutrinos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

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

Supernovae Detection

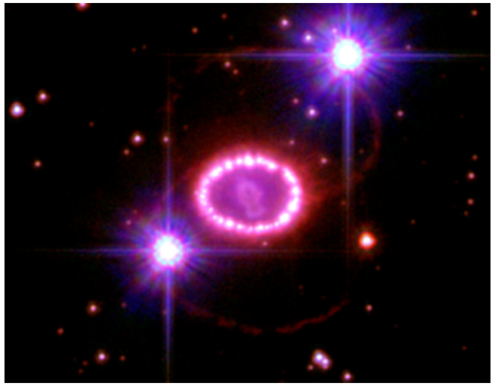
- Supernovae SN1987A detected using neutrino detectors, making use of the characteristic short burst of neutrinos.
- Still waiting for another such type of explosion close enough for detection

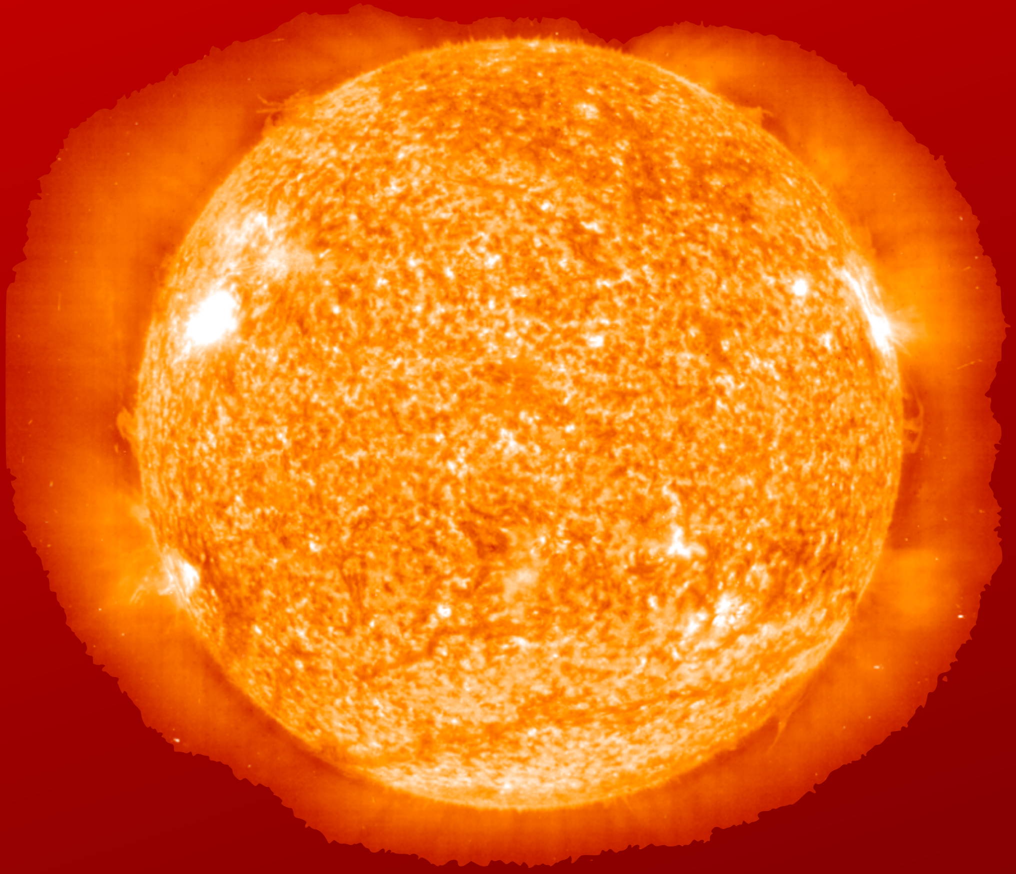


Before

During
(few days later)

After





E_ν ~ 0.01-10 MeV

Neutrinos from our star...

(the Sun)

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

Energy Production in Stars*

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

(Received September 7, 1938)

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

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.*

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

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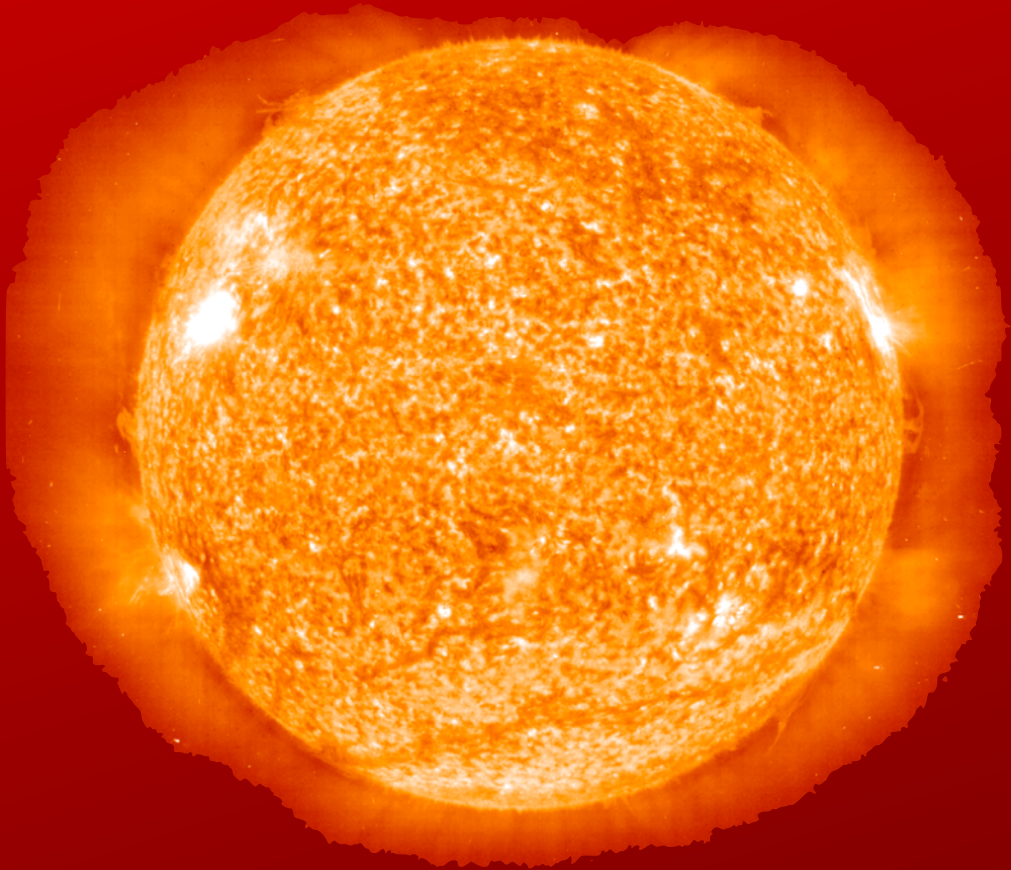
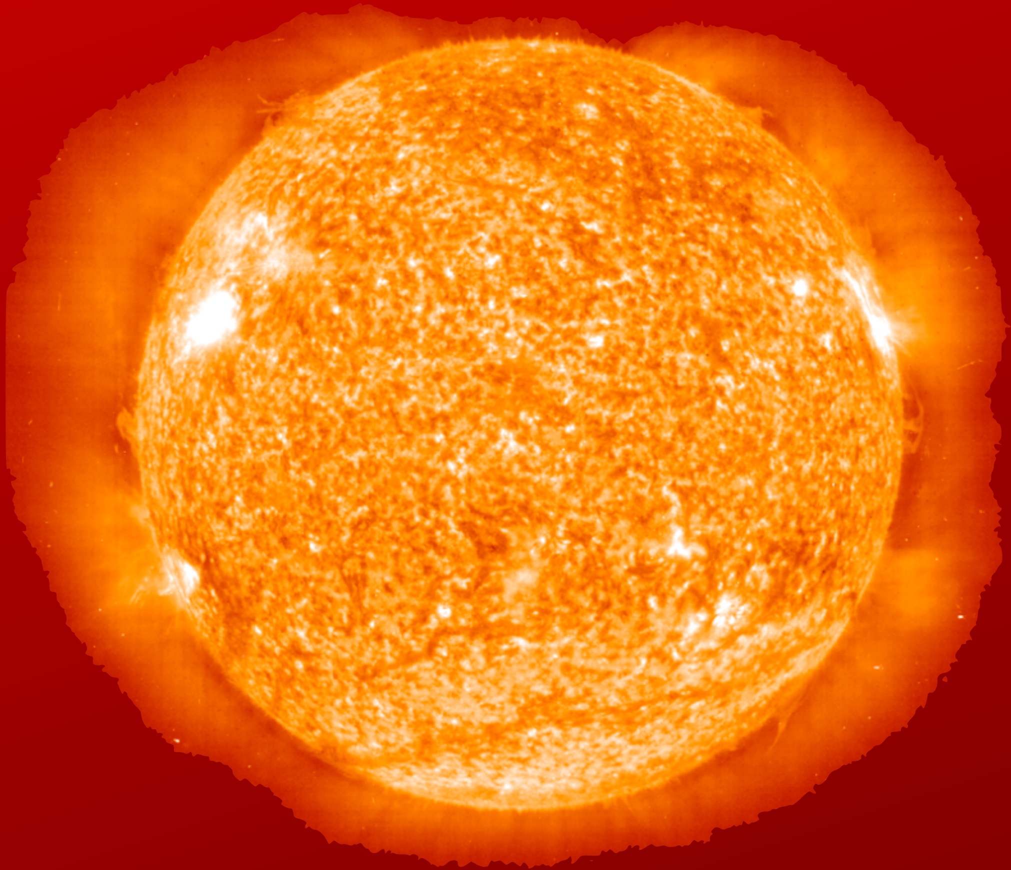


In the sixties, John Bahcall calculates the neutrino flux expected to be produced from the solar pp cycle.

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



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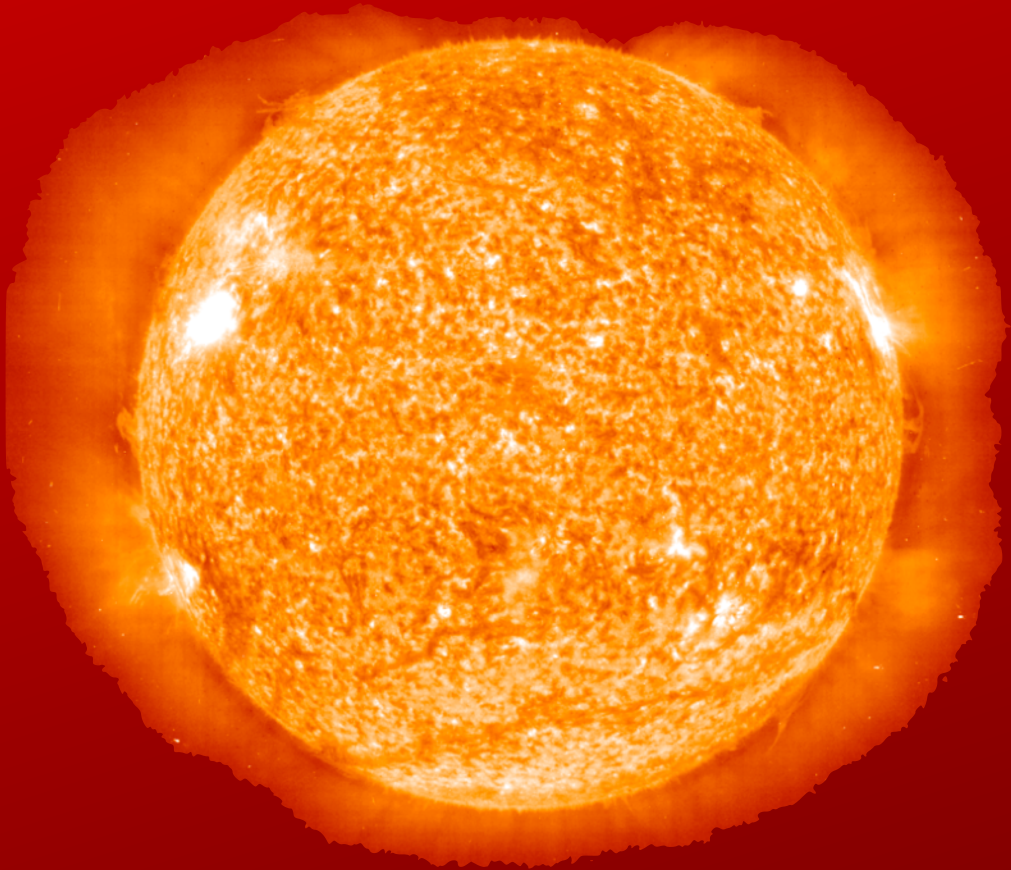

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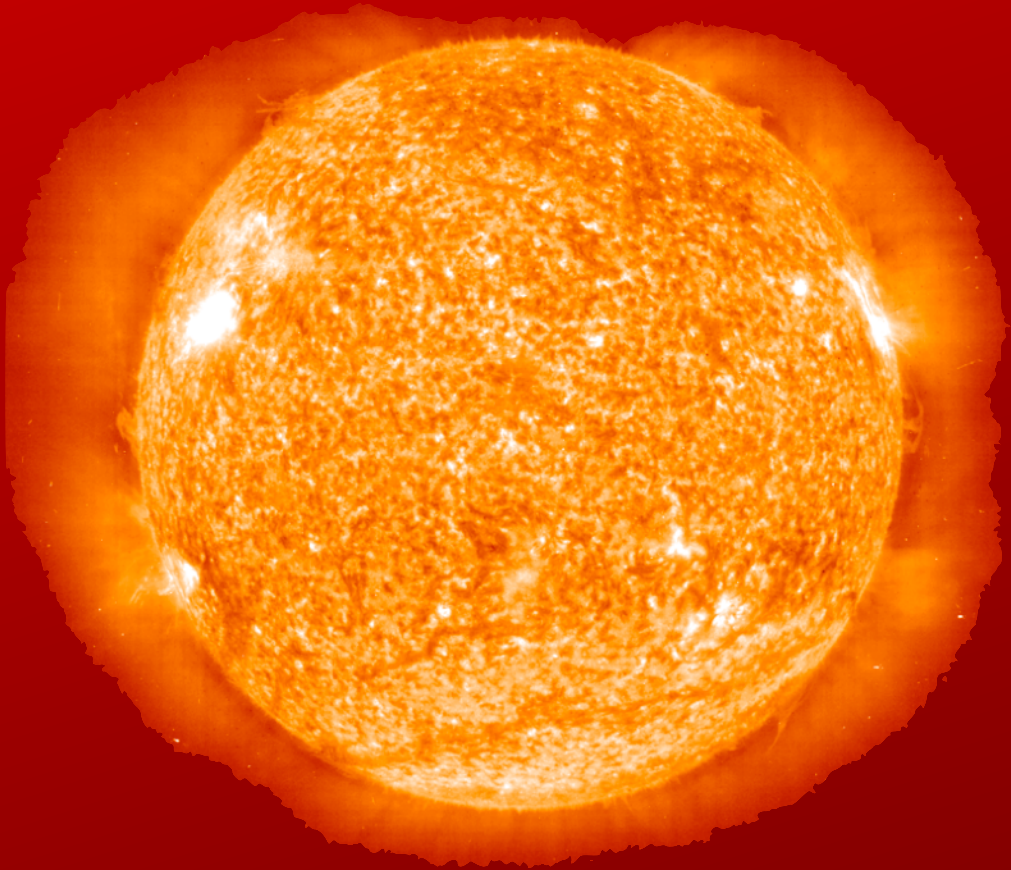

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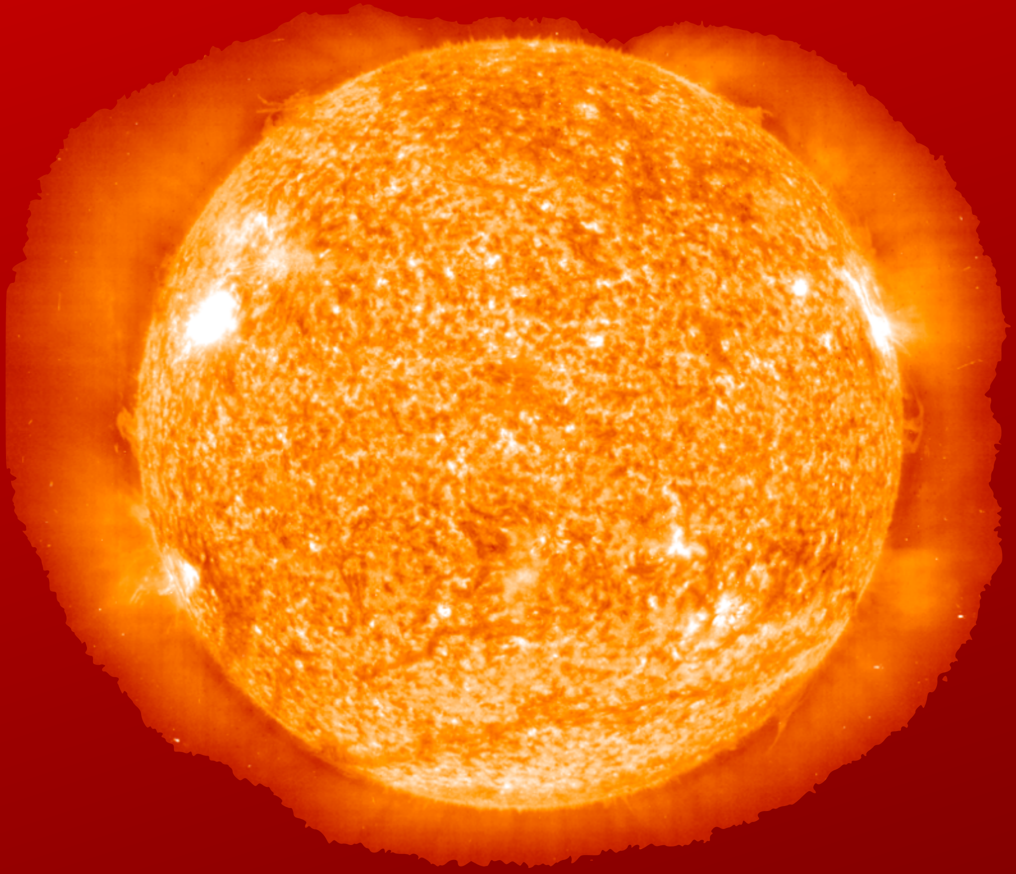

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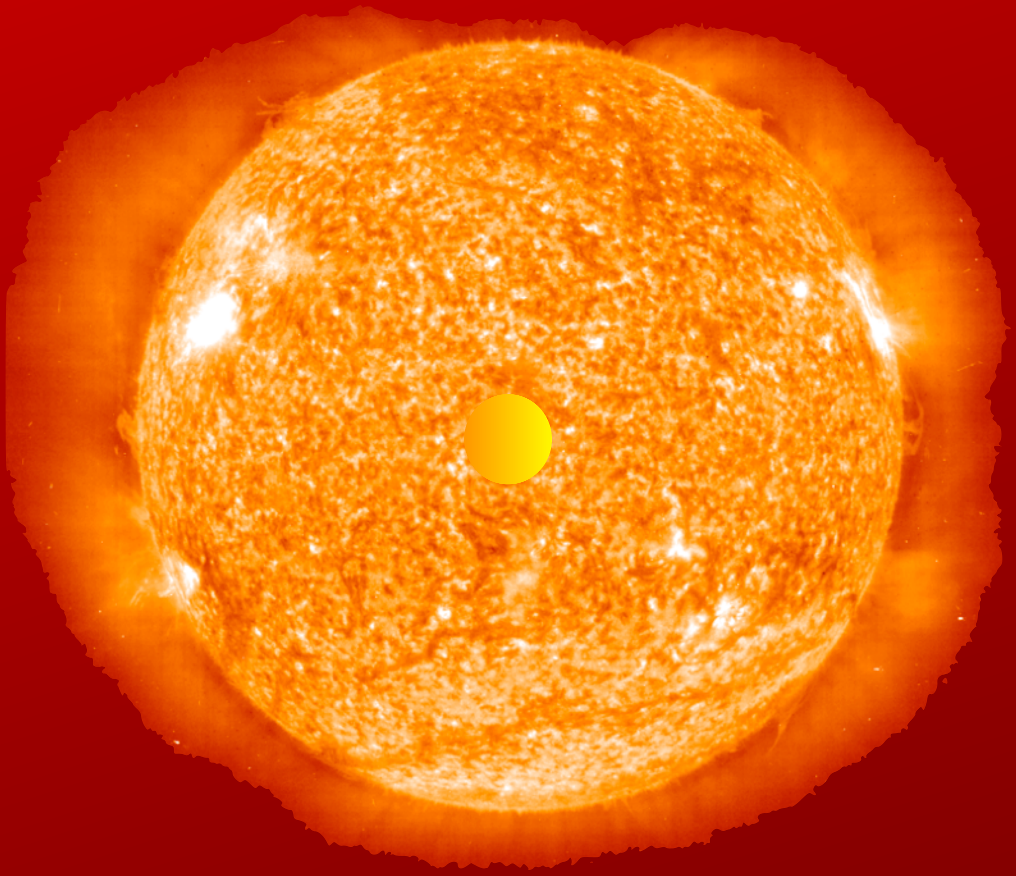
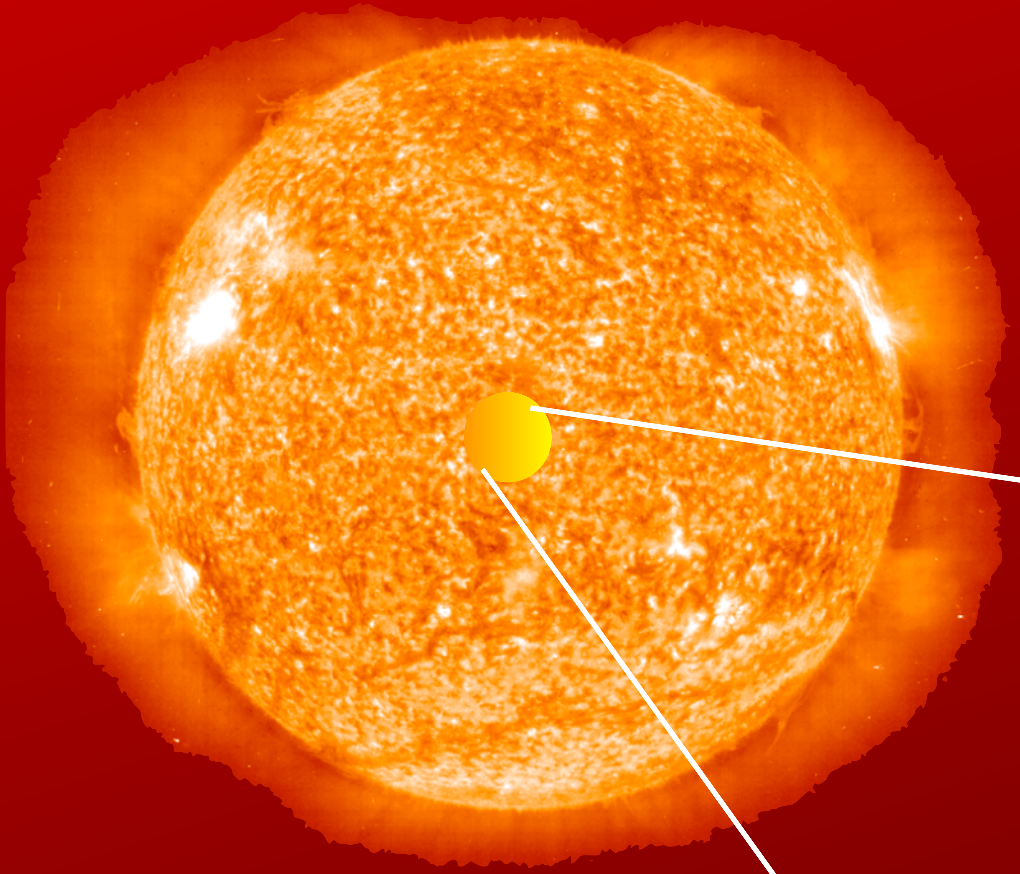


Basic Process:

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



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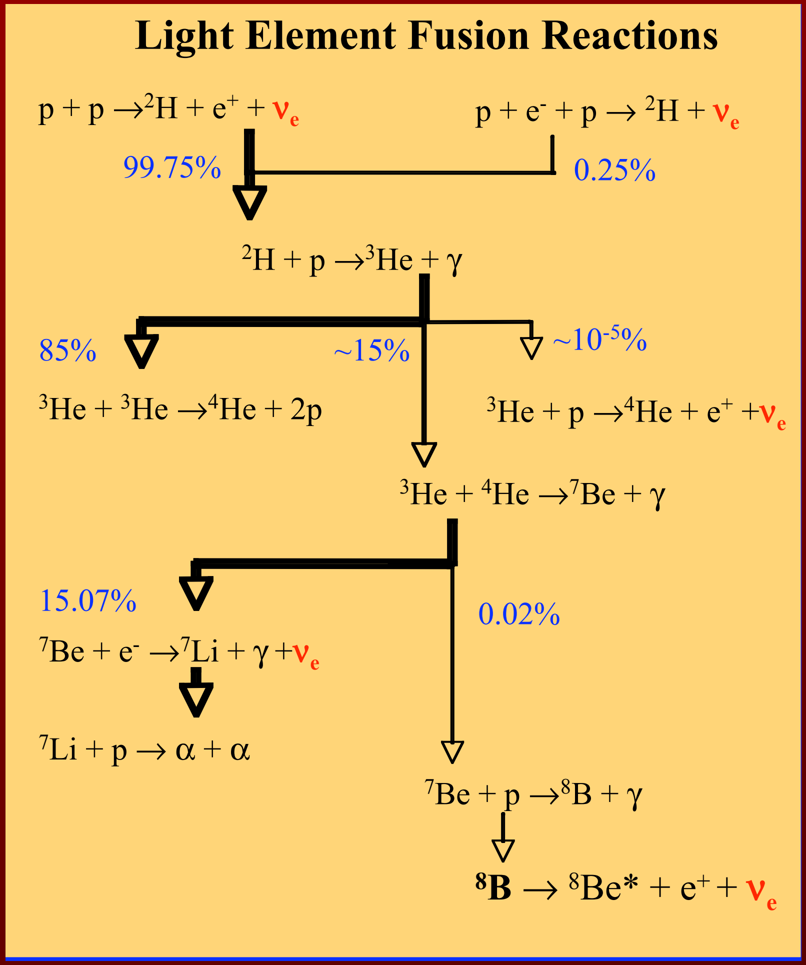
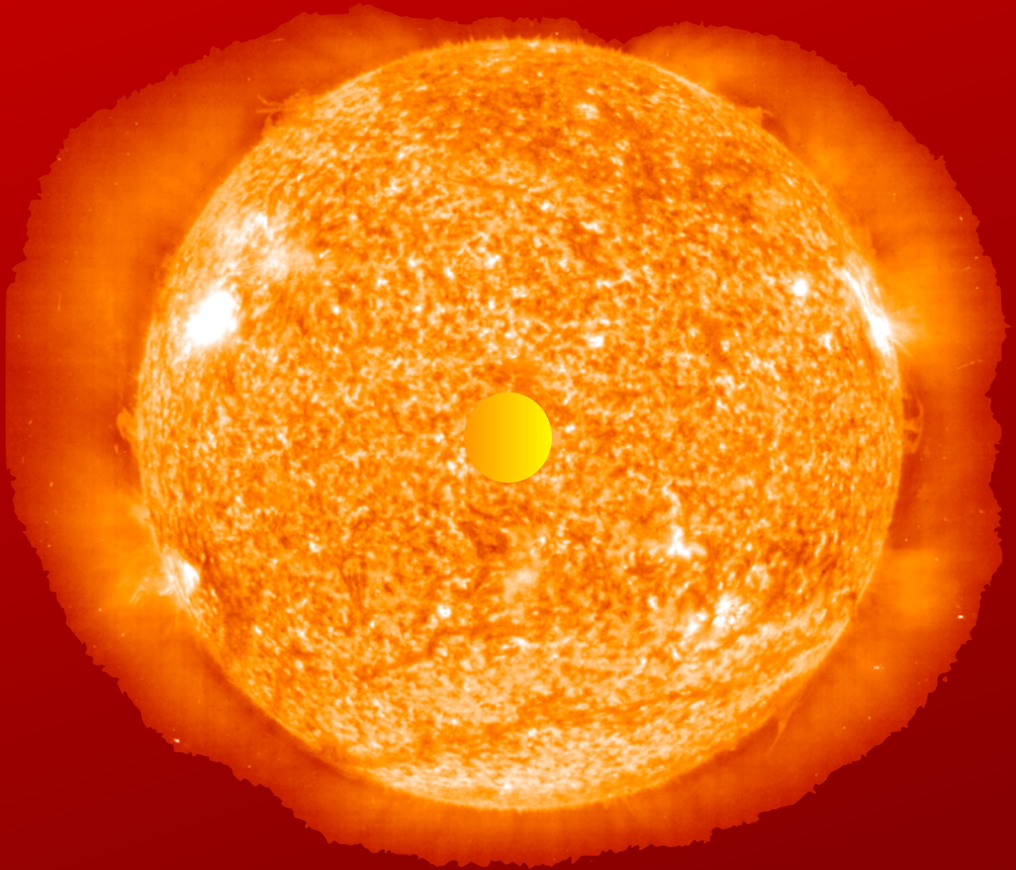


More detailed...

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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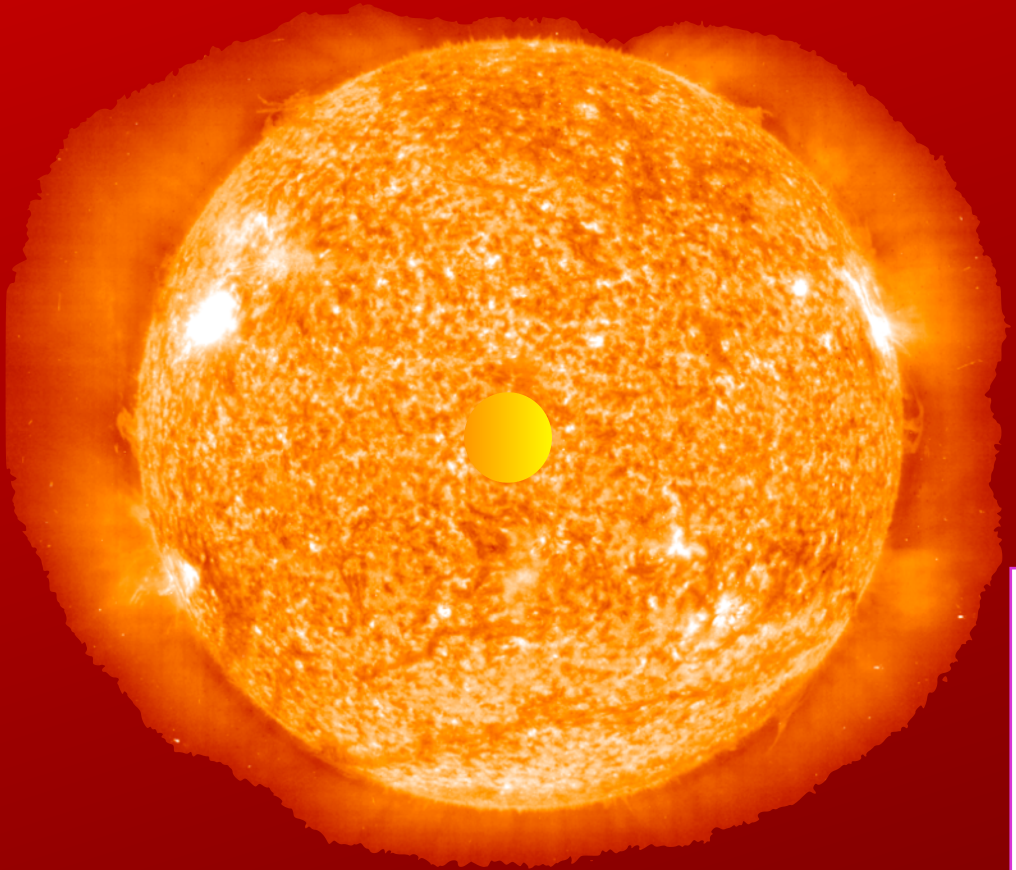

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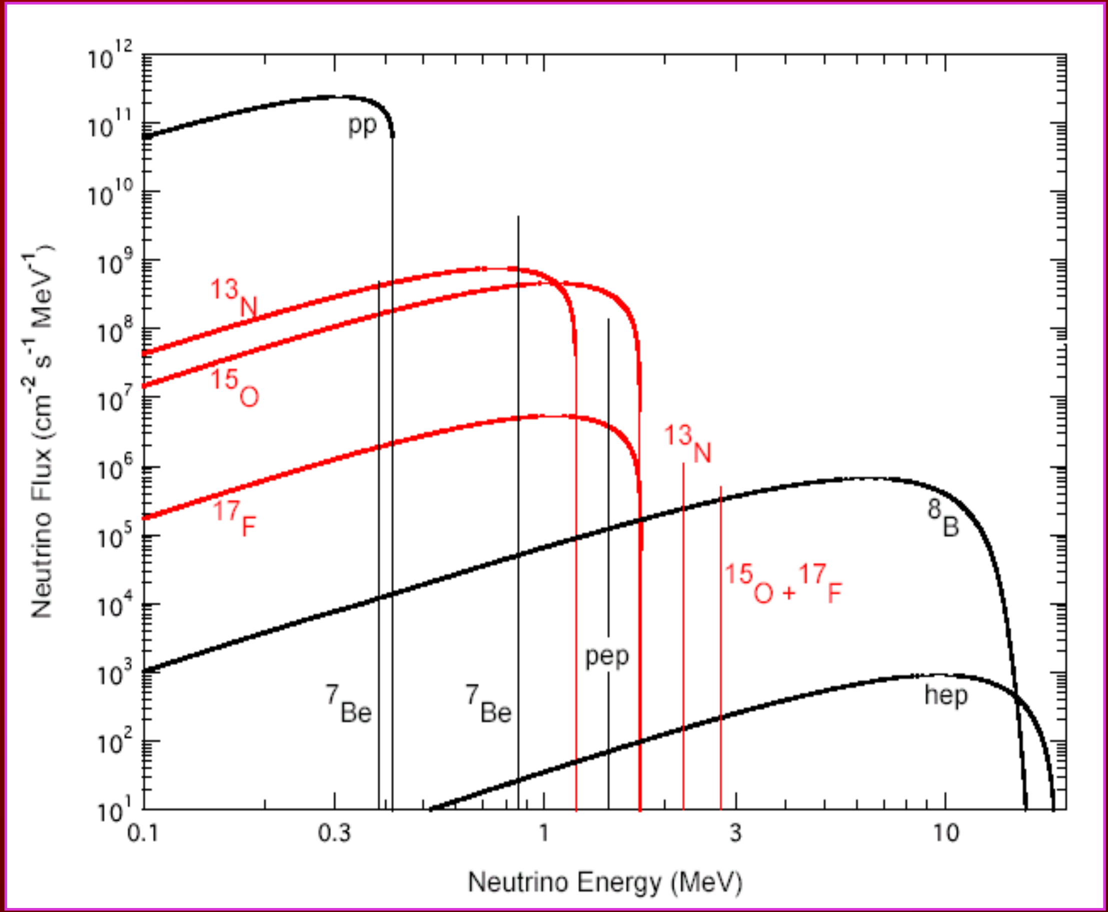

Detecting Solar Neutrinos
(Using deuterium)

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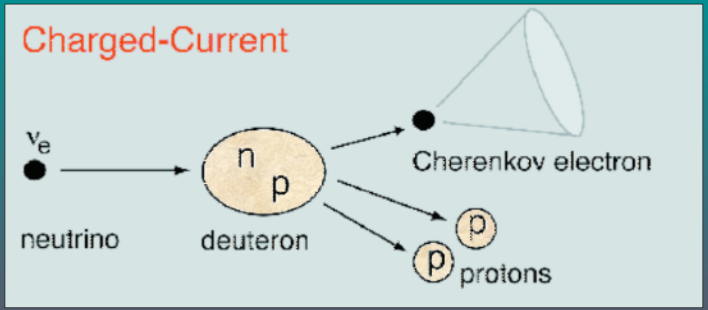
The Charged Current (CC) Interaction:

Signature: Cherenkov ring from ejected electron

Sensitive to ν_e flux only.



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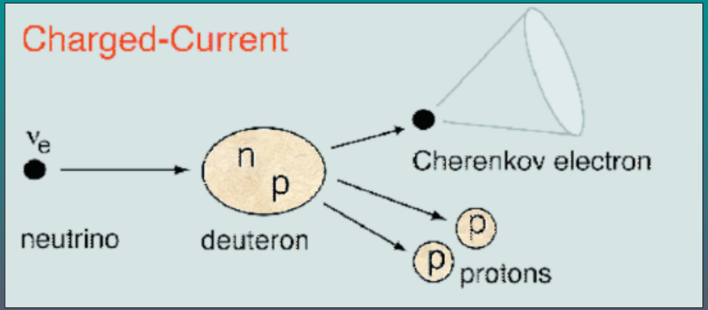
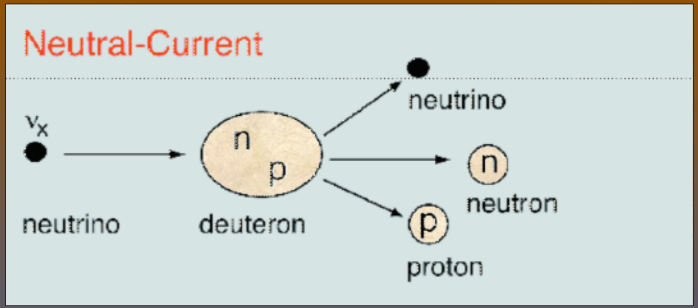


The Neutral Current (NC) Interaction:

Signature: Neutron emitted from deuterium break-up

Sensitive to ν_e, ν_μ, and ν_τ flux.



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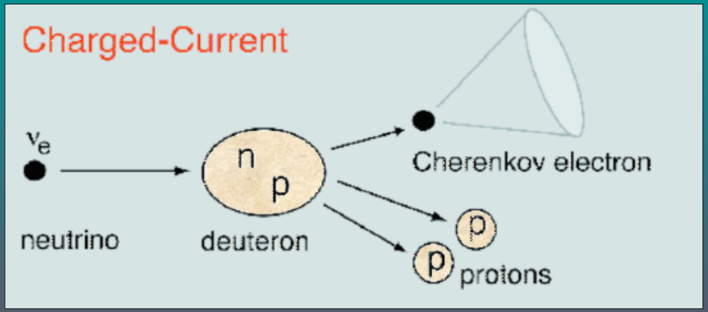

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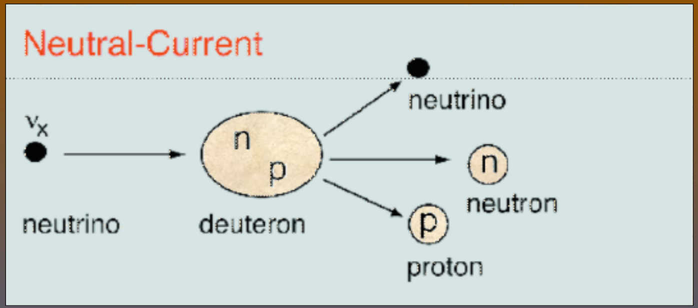
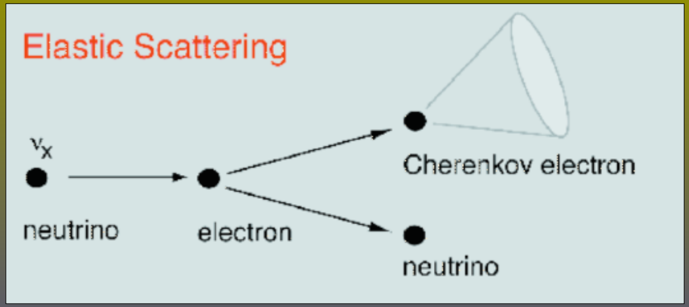


The Elastic Scattering (ES) Interaction:

Signature: Electron with high directional correlation to the sun

Sensitive mainly to ν_e . Some sensitivity to ν_μ, and ν_τ.



The Essence of the Measurement…

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If one looks only
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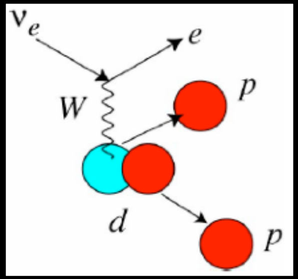

Charged Current

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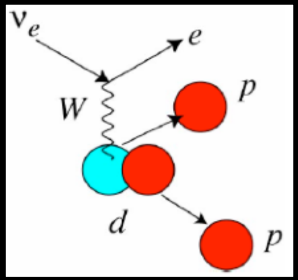

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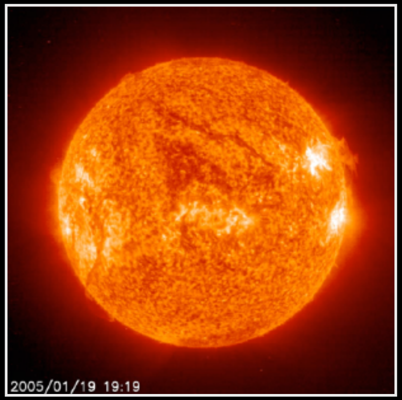

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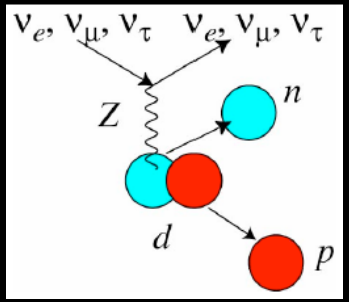

Neutral Current

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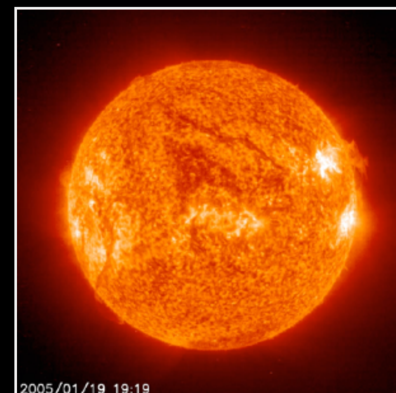
$\div$



= Oscillations

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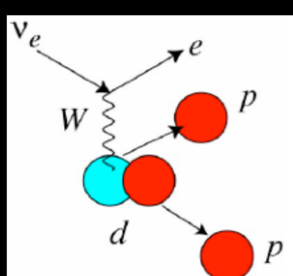

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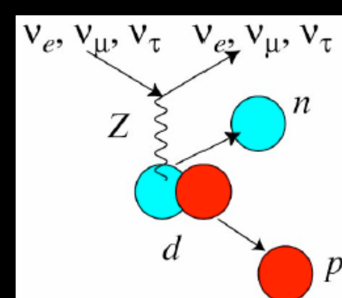

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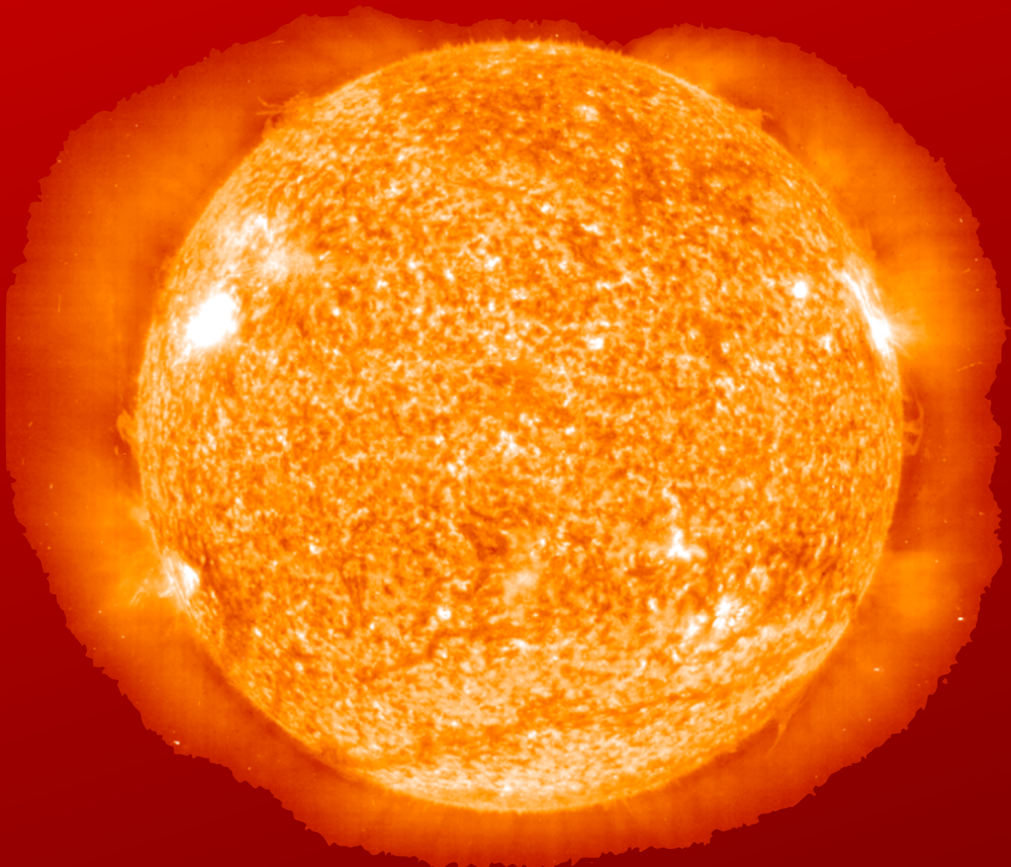
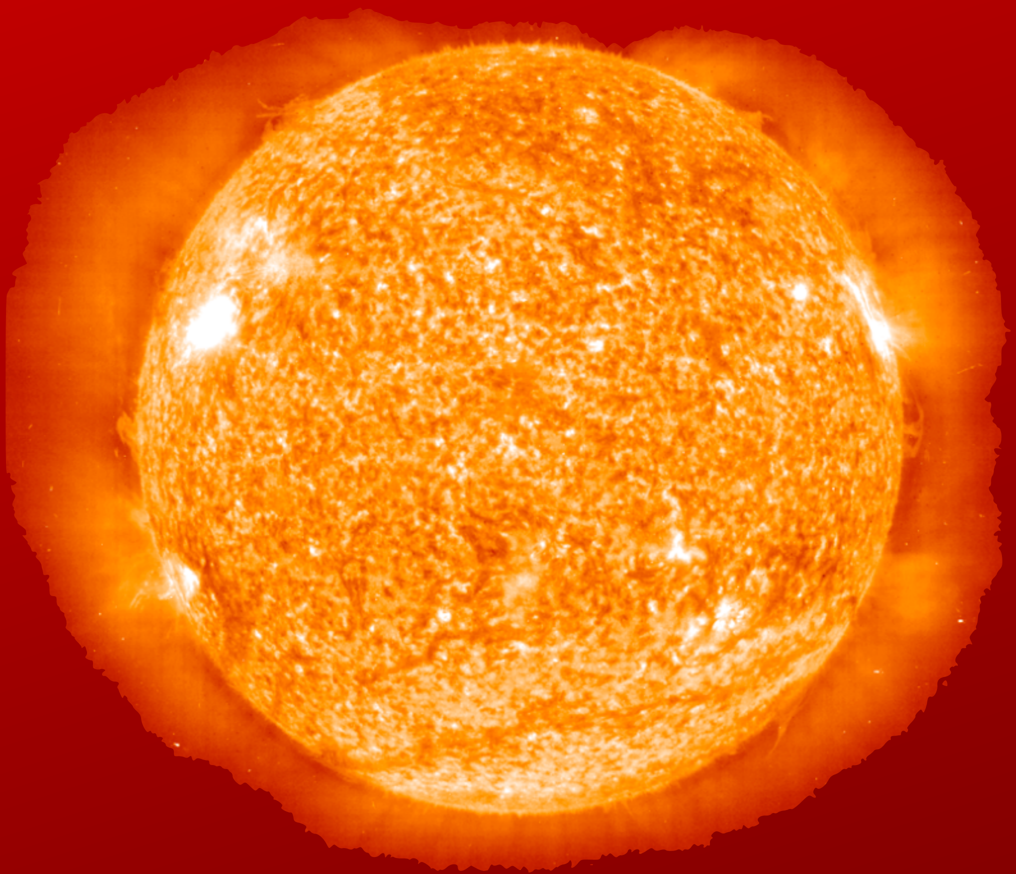


Deuterium Cross-sections

- Direct measurements of deuterium cross-sections at low energy (MeV scale) come mainly from reactor measurements or stopped pion beams.
- A simple nucleus (pn) allows for good agreement with calculations. However, axial form factor (usually called $L_{1,A}$ in the literature) represents largest uncertainty.
- Recently, lattice QCD has been adding independent calculation of axial form factors, reducing uncertainty.

Experiment	Measurement	$\sigma_{\rm fission}(10^{-44}\ {\rm cm}^2/{\rm fission})$	$\sigma_{\rm exp}/\sigma_{\rm theory}$
Savannah River (Pasierb *et al.*, 1979)	$\bar{\nu}_e$CC	1.5 ± 0.4	0.7 ± 0.2
ROVNO (Vershinsky *et al.*, 1991)	$\bar{\nu}_e$CC	1.17 ± 0.16	1.08 ± 0.19
Krasnoyarsk (Kozlov *et al.*, 2000)	$\bar{\nu}_e$CC	1.05 ± 0.12	0.98 ± 0.18
Bugey (Riley *et al.*, 1999)	$\bar{\nu}_e$CC	0.95 ± 0.20	0.97 ± 0.20
Savannah River (Pasierb *et al.*, 1979)	$\bar{\nu}_e$NC	3.8 ± 0.9	0.8 ± 0.2
ROVNO (Vershinsky *et al.*, 1991)	$\bar{\nu}_e$NC	2.71 ± 0.47	0.92 ± 0.18
Krasnoyarsk (Kozlov *et al.*, 2000)	$\bar{\nu}_e$NC	3.09 ± 0.30	0.95 ± 0.33
Bugey (Riley *et al.*, 1999)	$\bar{\nu}_e$NC	3.15 ± 0.40	1.01 ± 0.13



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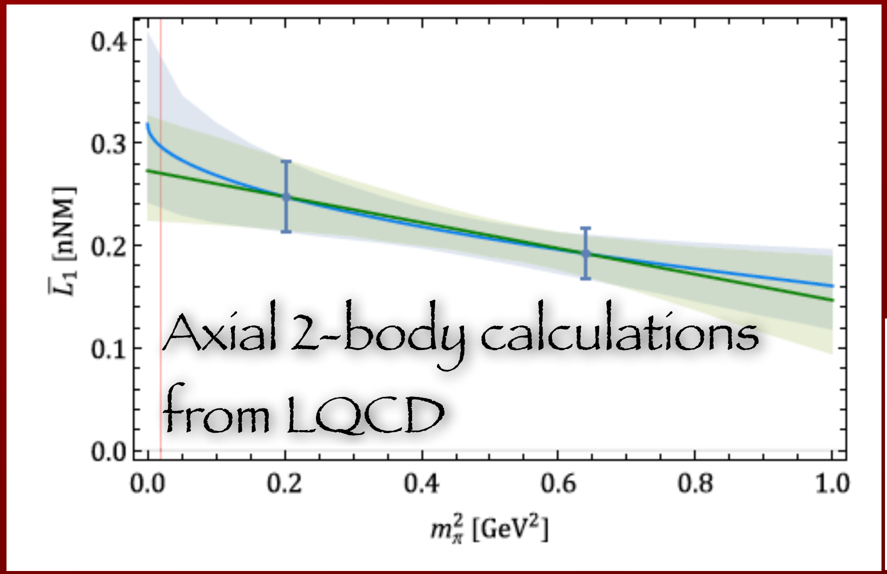

Method	Extracted $L_{1,A}$(fm^3)
Reactor	3.6 ± 5.5
Solar	4.0 ± 6.3
Helioseismology	4.8 ± 6.7
$^3H \rightarrow {}^{3+}He\ e^- \bar{\nu}_e$	6.5 ± 2.4

Ultra-High Energy Neutrinos

$E_\nu > 1$ TeV

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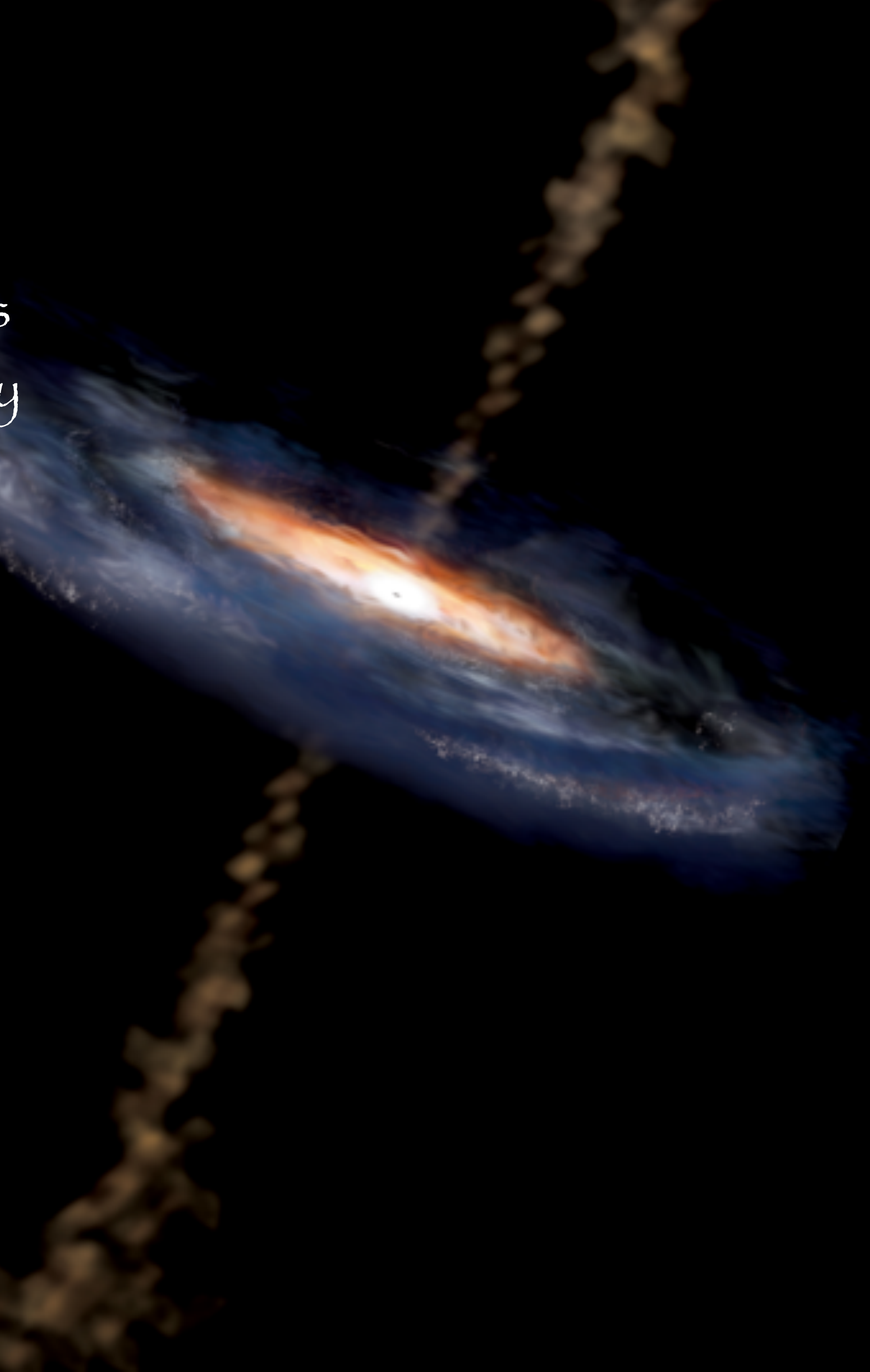

- Galactic and extra-galactic celestial objects are known sources of extremely high energy cosmic rays (protons, etc.) and neutrinos.

- Three possible creation mechanisms:

  (1) Acceleration processes

  (2) GZK neutrinos

  (3) Annihilation and decay of heavy

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.).

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

$$\pi^+ \rightarrow \nu_\mu + \underset{\displaystyle \downarrow \atop \displaystyle \bar{\nu}_\mu + e^+ + \nu_e}{\mu^+}$$

- 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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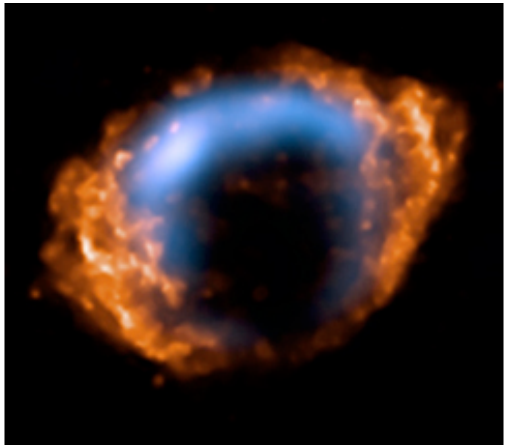
Supernova remnants



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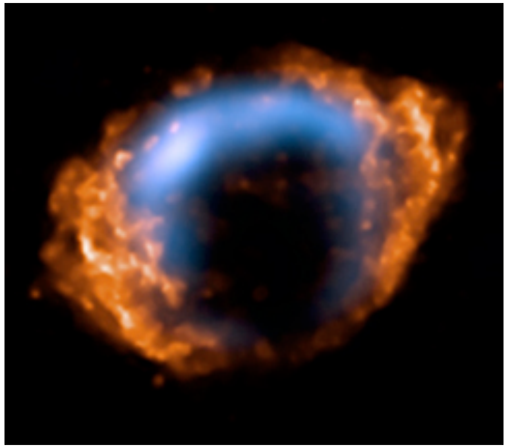
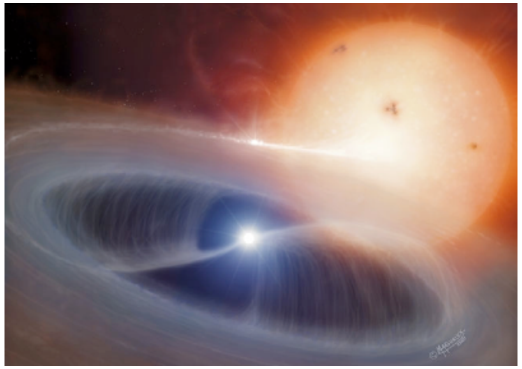


Binary systems



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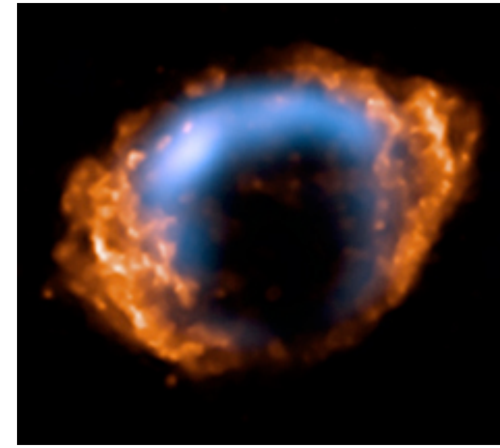

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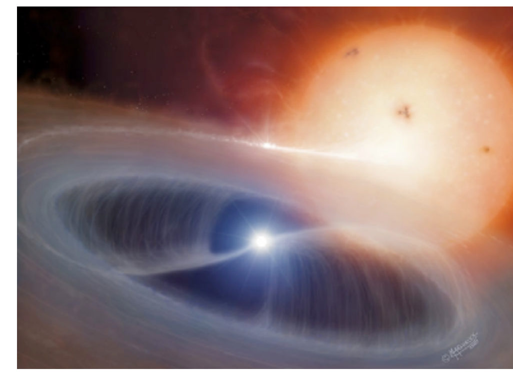
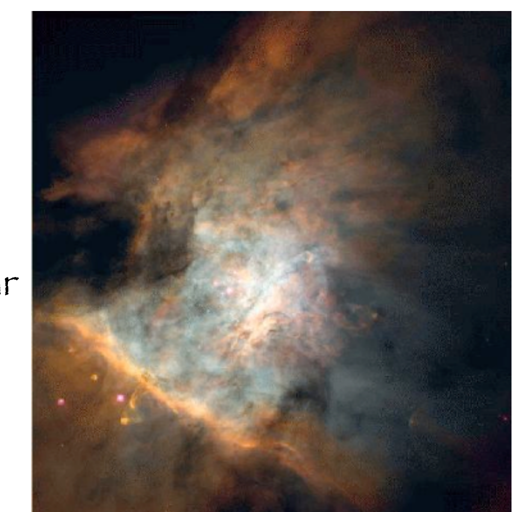
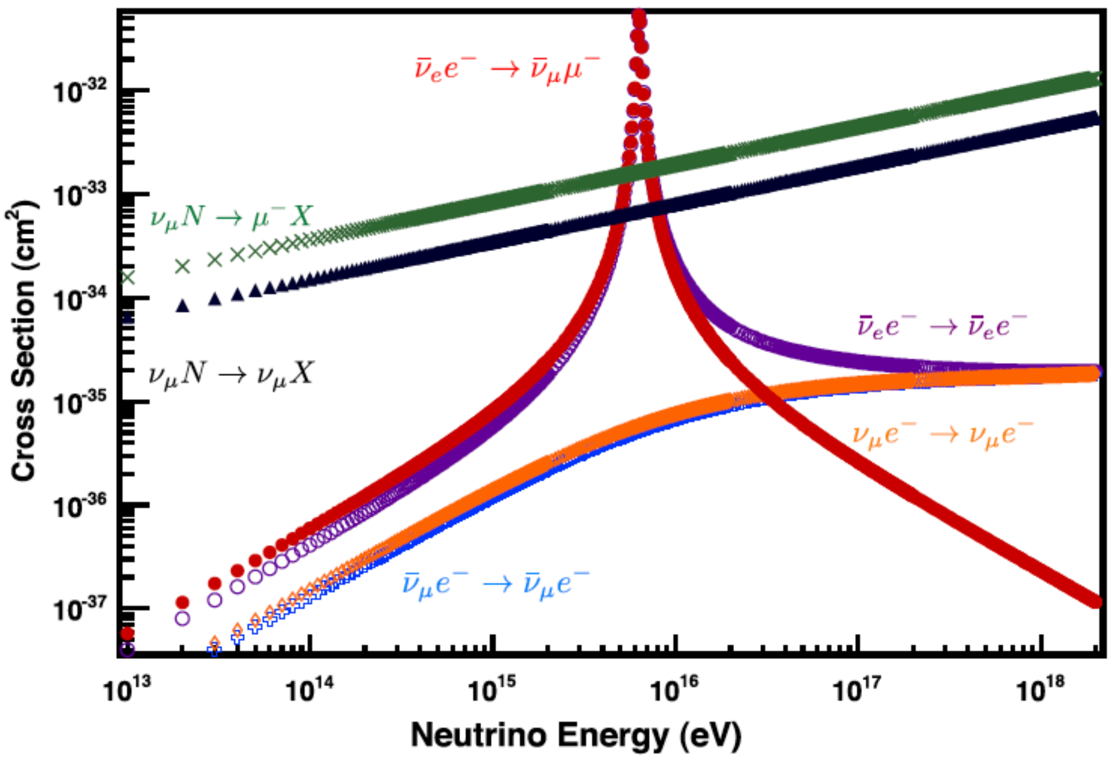


Interaction with interstellar medium



High Energy Neutrinos

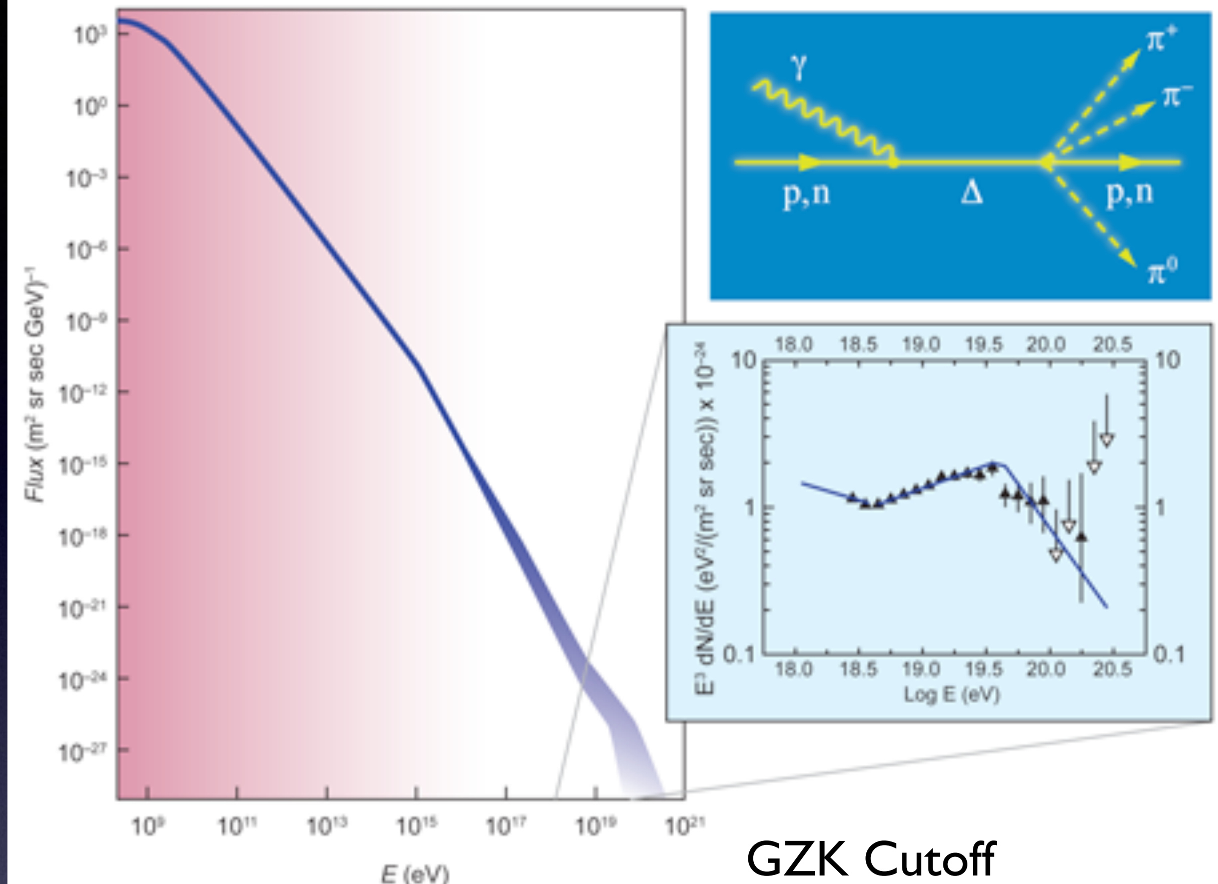


- A nice oddity of neutrino cross-sections at this scale (since the energies are sooooo high)
- One can observe a resonance between the W and Z bosons!
- First suggested by Glashow in 1960 as a means to directly detect the W boson

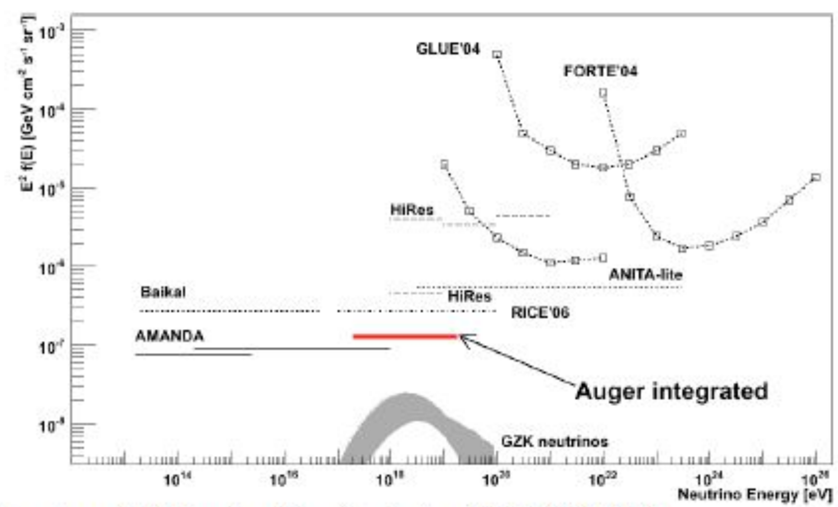
$$\frac{d\sigma(\bar{\nu}_e e^- \to \bar{\nu}_e e^-)}{dy} = \frac{2G_F^2 m_e E_\nu}{\pi}\left[\frac{g_R^2}{(1+2m_e E_\nu y/M_Z^2)^2} + \left|\frac{g_L}{1+2m_e E_\nu y/M_Z^2} + \frac{1}{1-2m_e E_\nu/M_W^2 + i\Gamma_W/M_W}\right|^2\right]$$

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

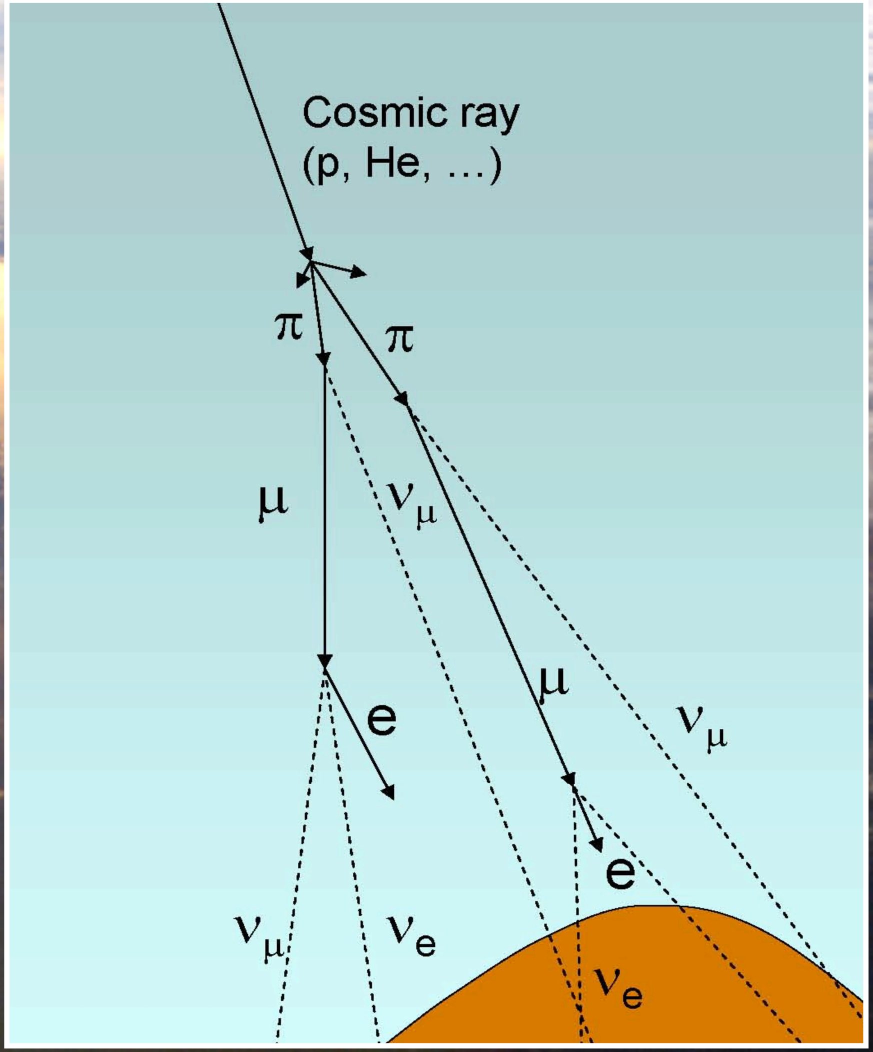
Neutrinos from the Earth

Neutrinos from Man

Atmospheric Neutrinos

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

Atmospheric Neutrinos



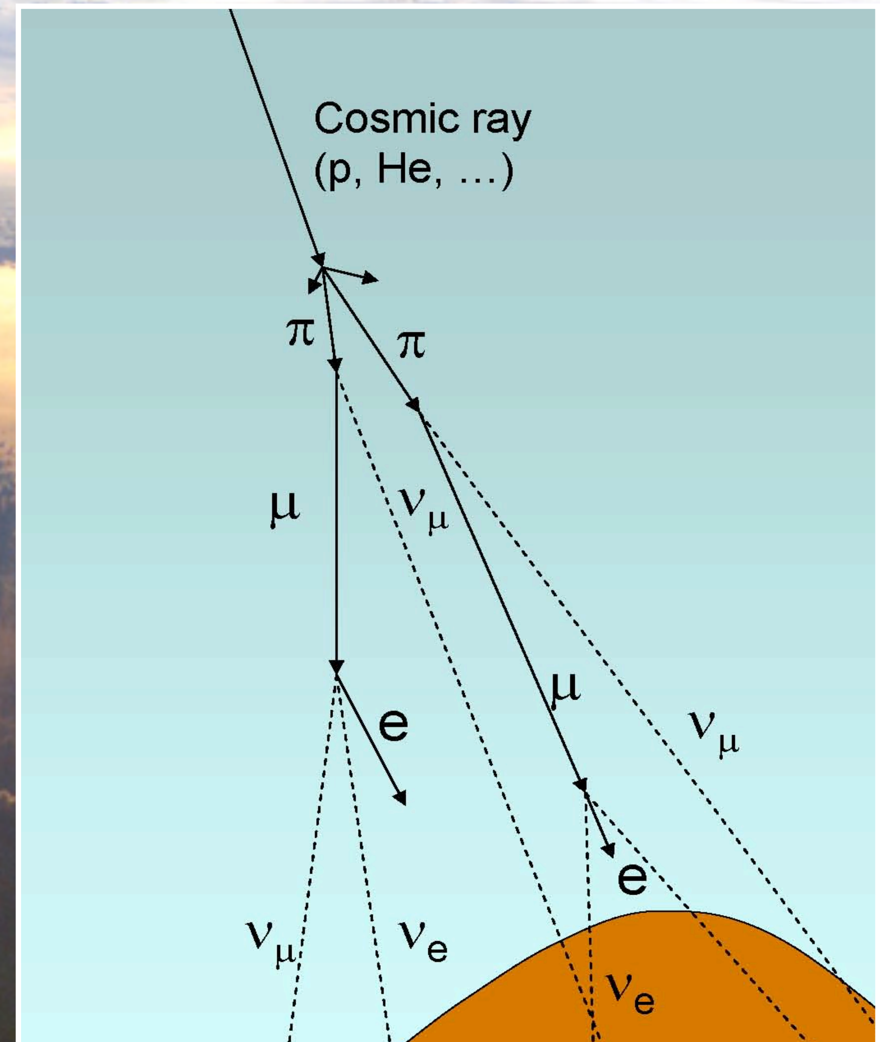
Atmospheric Neutrinos

- 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, several key steps must be taken into account:

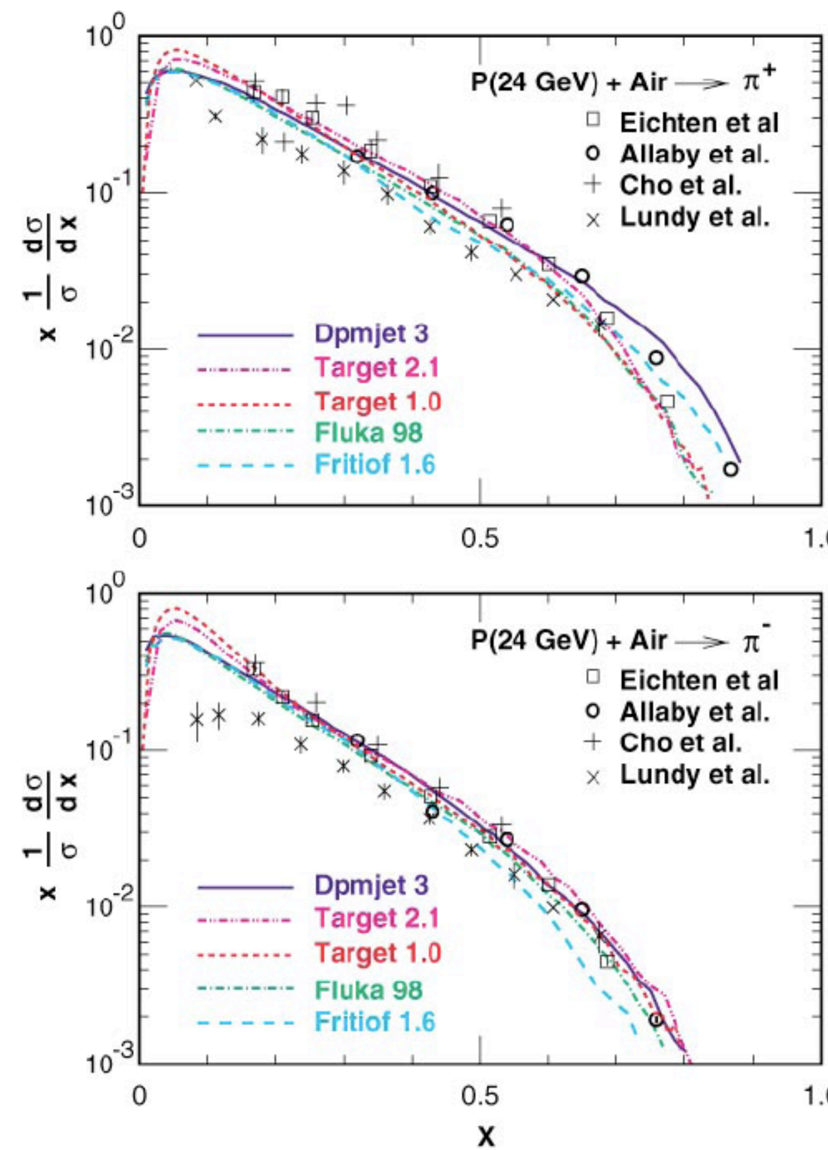
    1. Primary cosmic ray flux. This is measured using large array telescopes and balloon measurements.

    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



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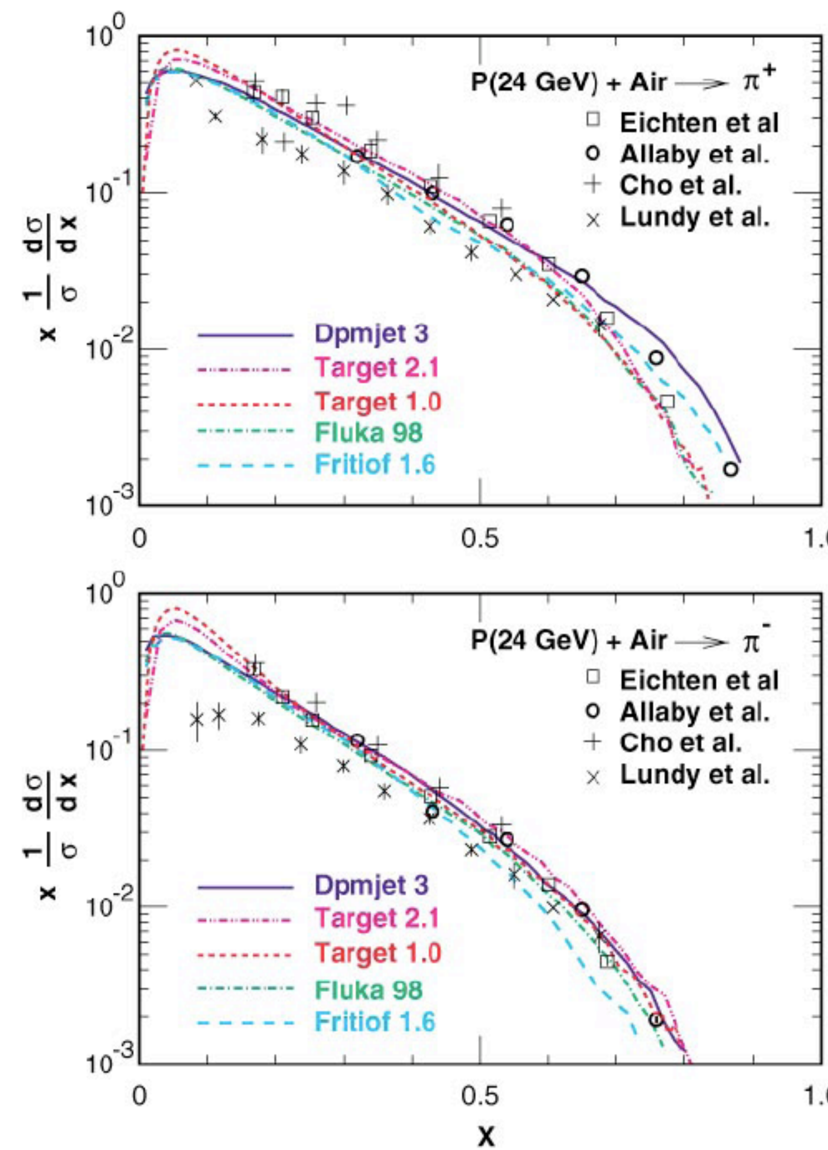

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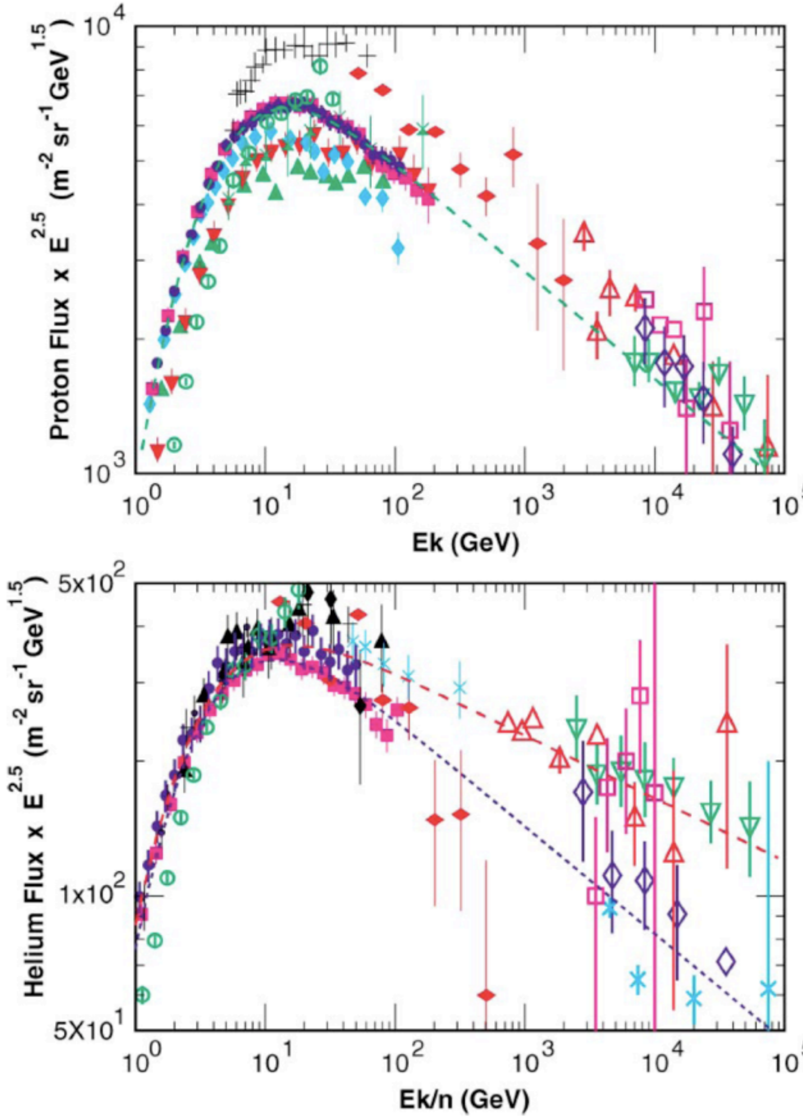
Primary CR flux



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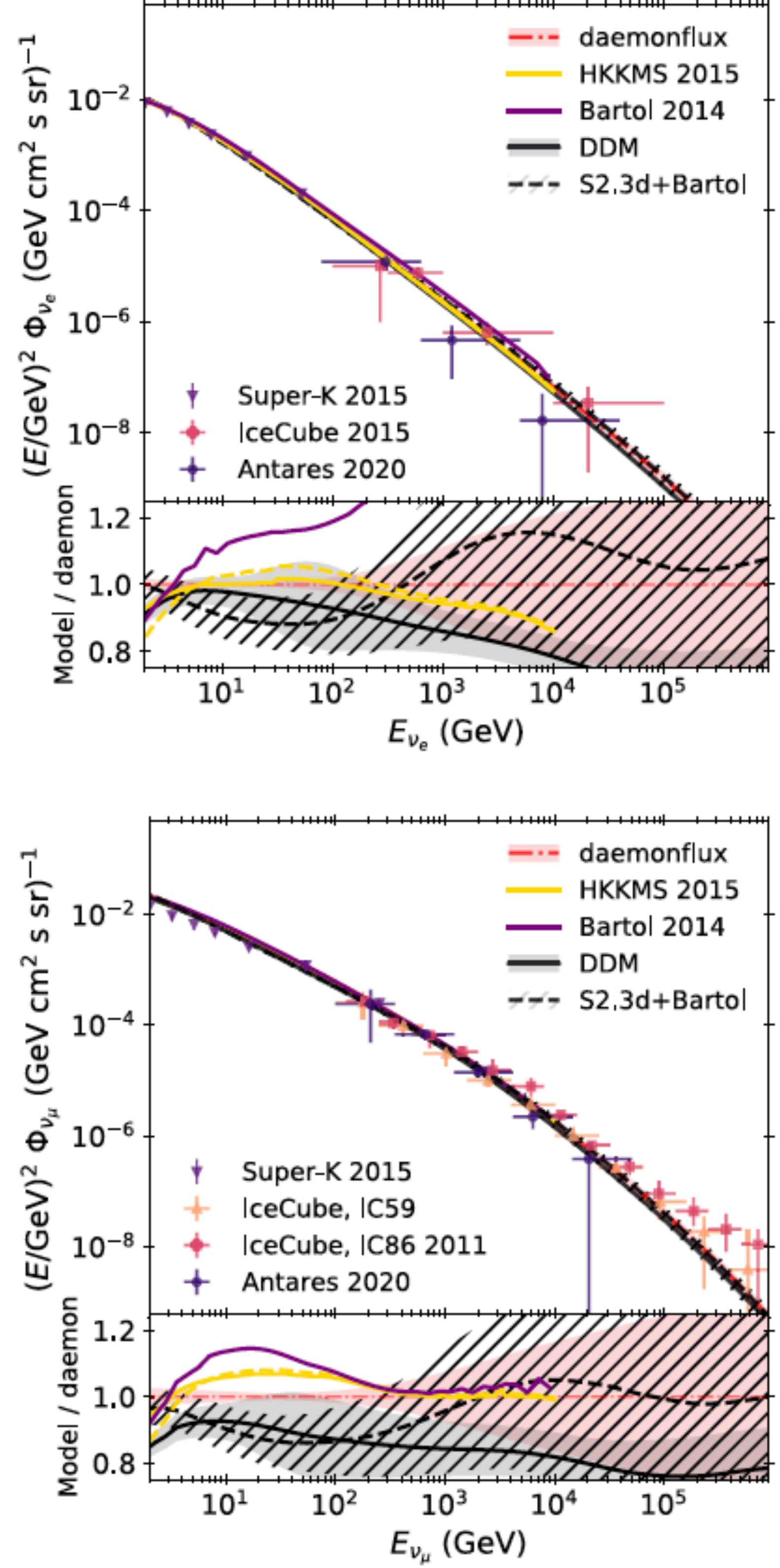
    2. Hadronization. Constrained by beam measurements.

    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/ν_e Fluxes



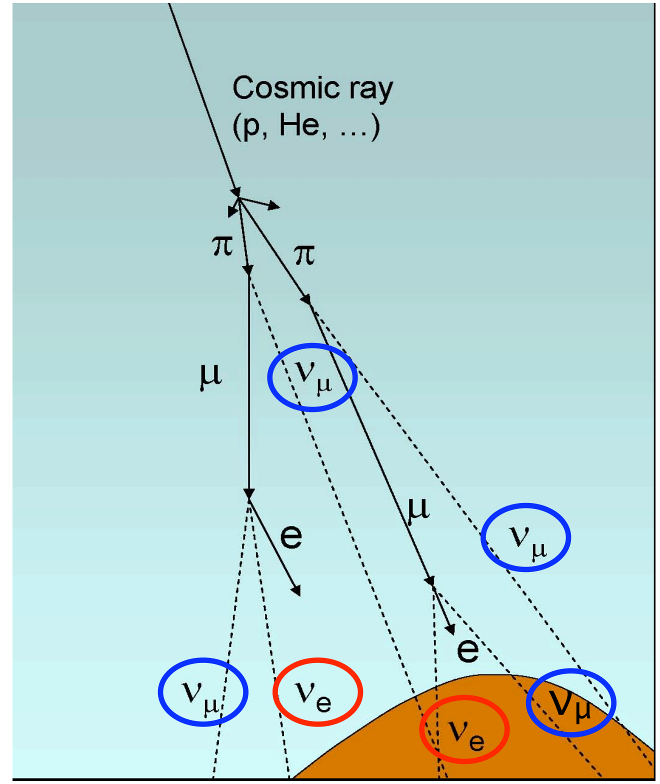
Atmospheric Neutrinos

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

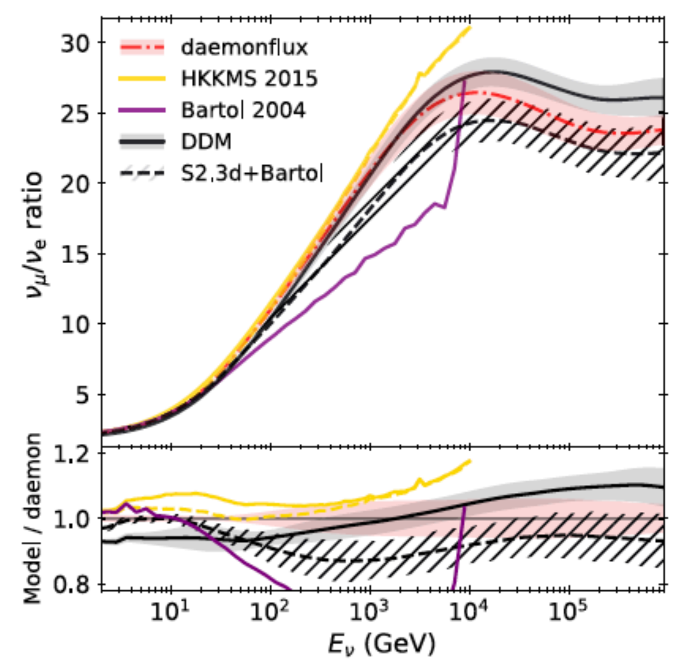
    1. ν_μ:ν_e ratio: This ratio is fixed from the pion/muon cascade.

    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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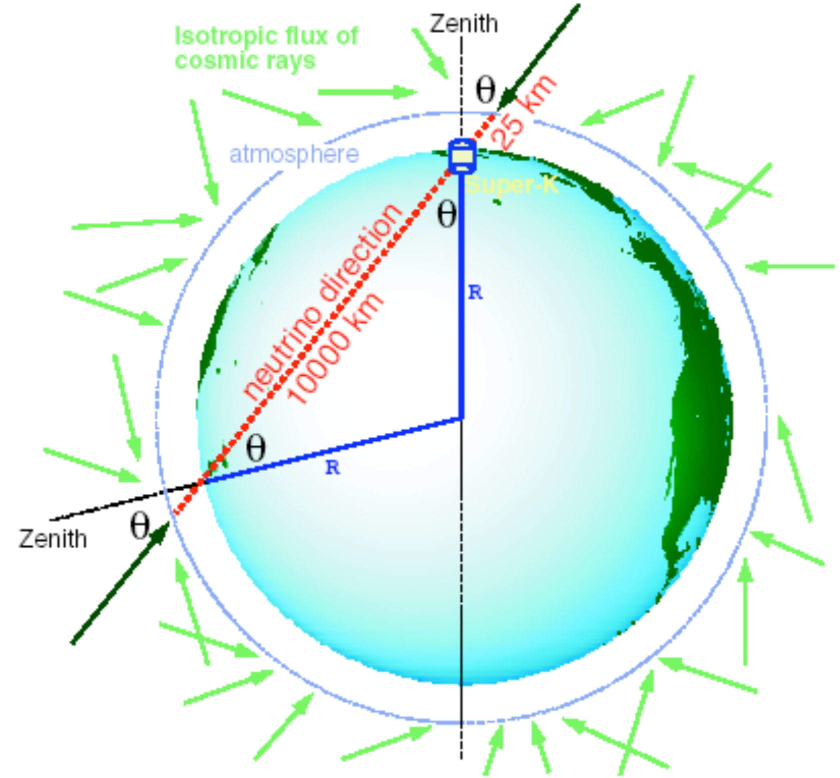
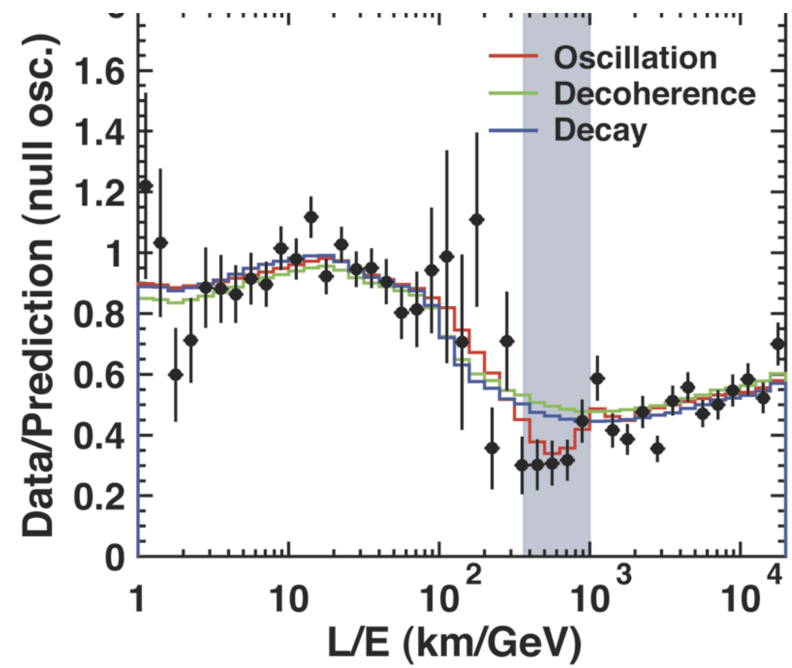


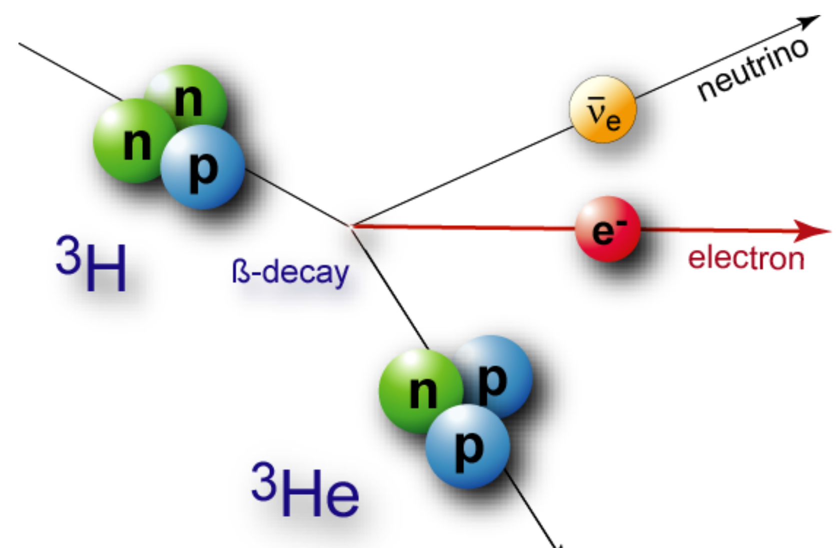



$E_\nu \sim 0.1$-5 MeV
Neutrinos from Radioactivity

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:



Sample β-decay

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

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

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

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

Neutrinos from Radioactivity

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

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

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).

$$\frac{dN}{dE} = C \times \underbrace{|M|^2}_{\text{Matrix Element}} \overbrace{F(Z,E)}^{\text{Fermi Function}} \underbrace{p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}}_{\text{Phase space}}$$

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- To determine the rate of a particular reaction, one needs to take into account of a number of factors:
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  - The matrix element related to the initial and final states of the decay

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

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

Fermi Function

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

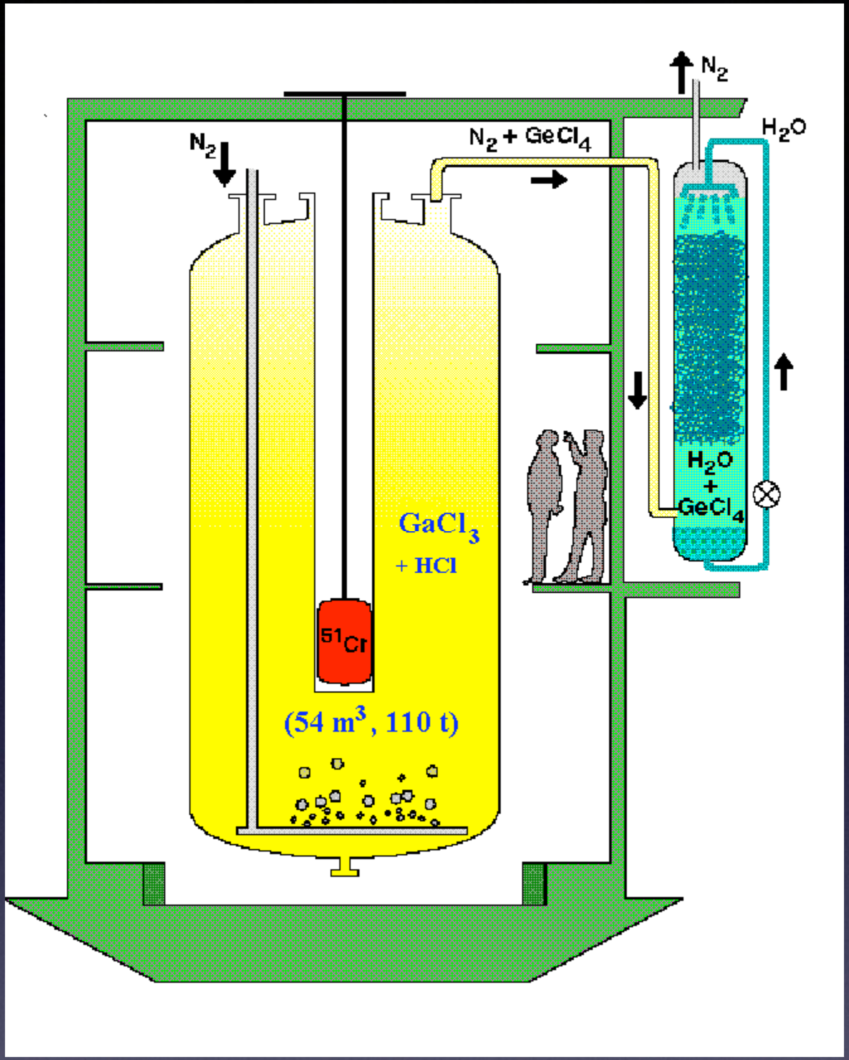
Matrix Element

Phase space

Possible Source?

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

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



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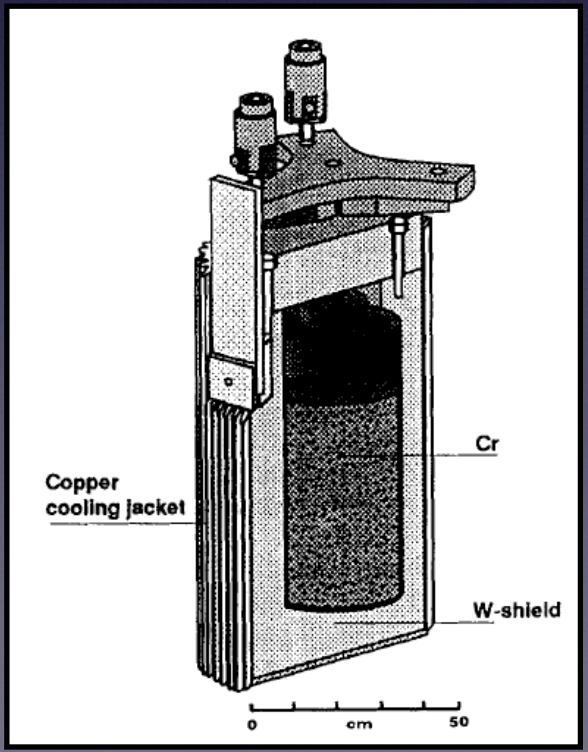
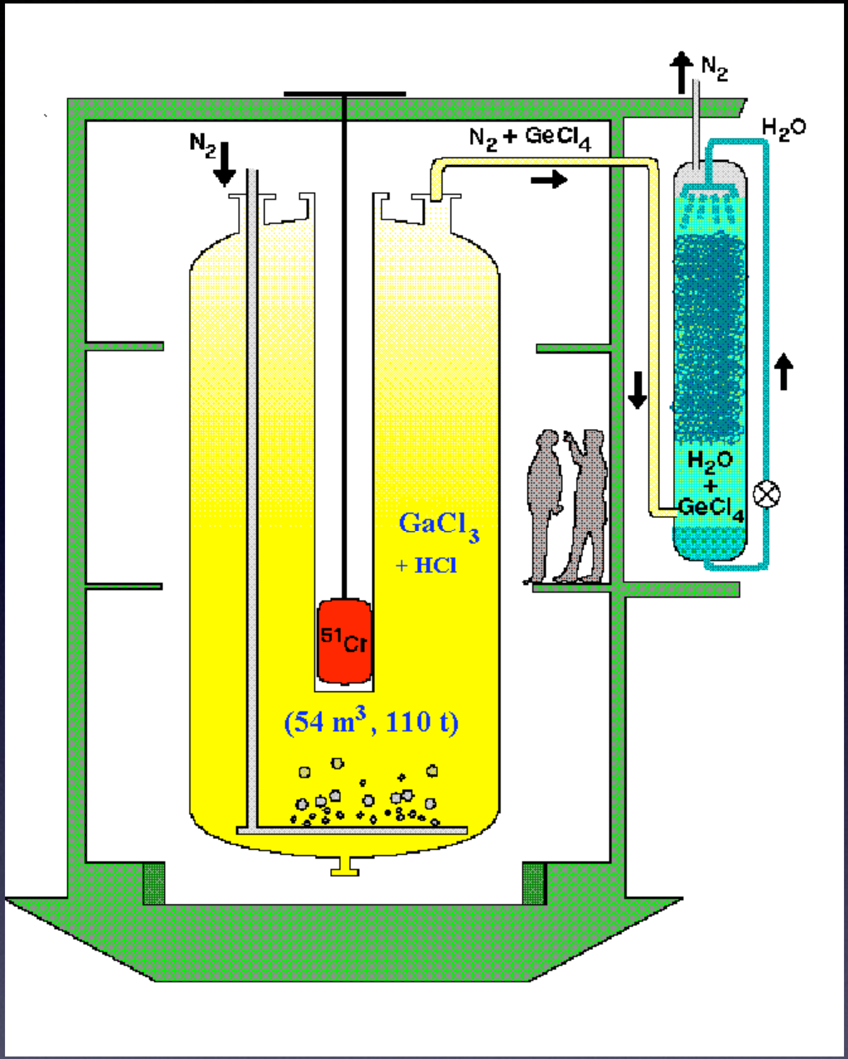




Total activity of the source: 60 PBq!

Emitted ~300 W of heat

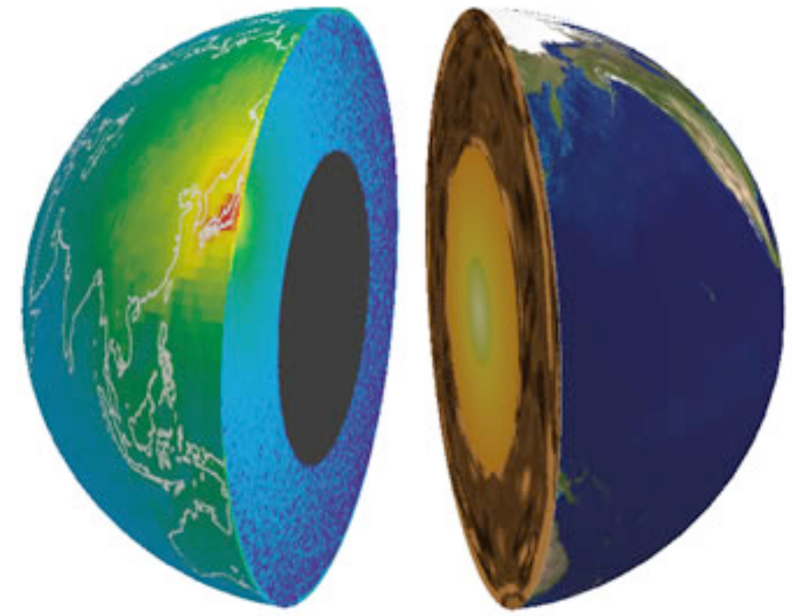

Geoneutrinos
Eν ~ 1 MeV

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_ν ~ 1-5 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.

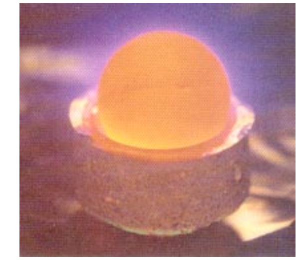
- Four main neutrino fuel sources:

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

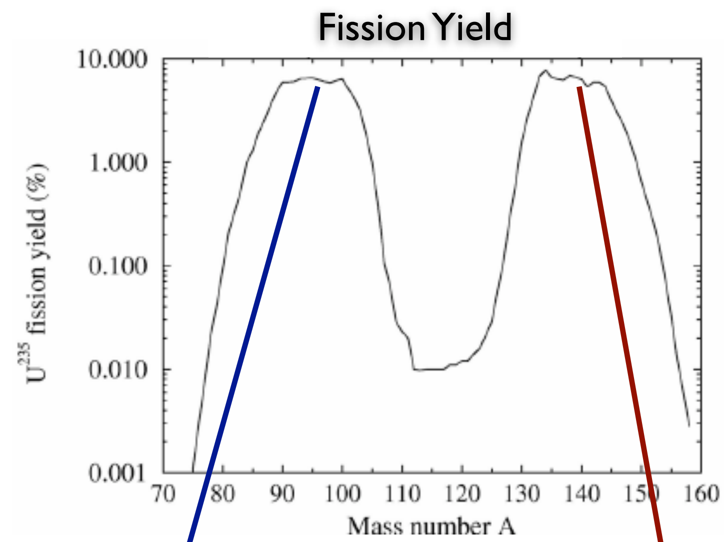
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n \rightarrow \\ \ldots ^{94}_{40}Zr + ^{140}_{58}Ce$$

Sample Fission: ^{235}U

^{235}U



^{239}Pu



^{94}Zr

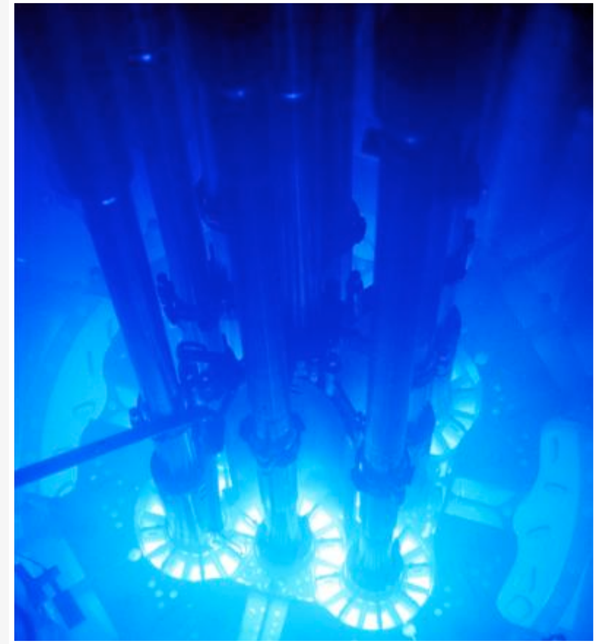
^{140}Ce

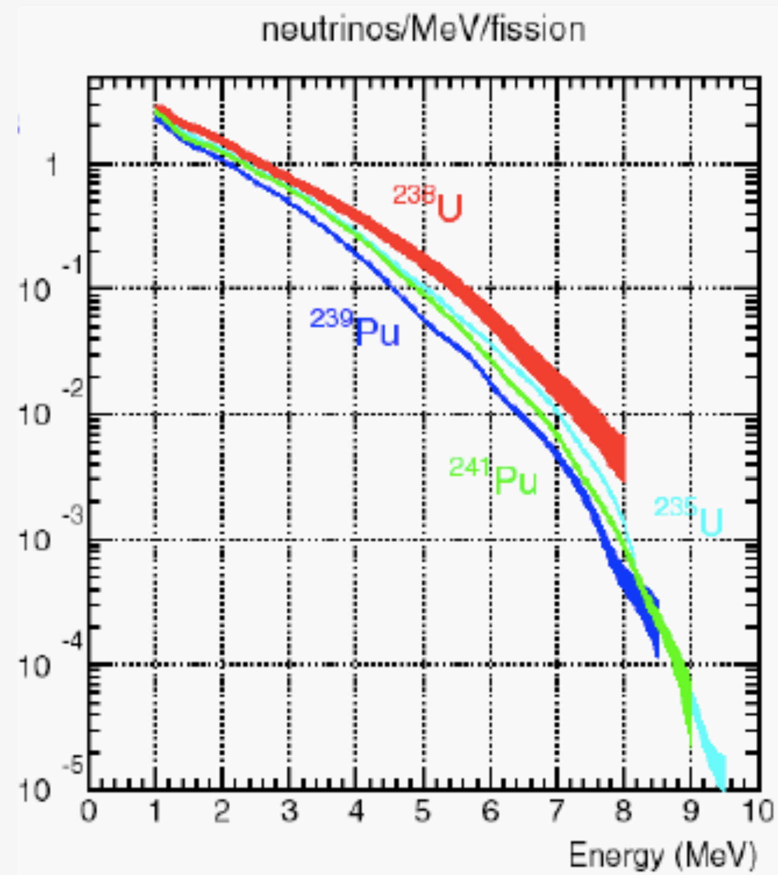
Neutrinos from Fission

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

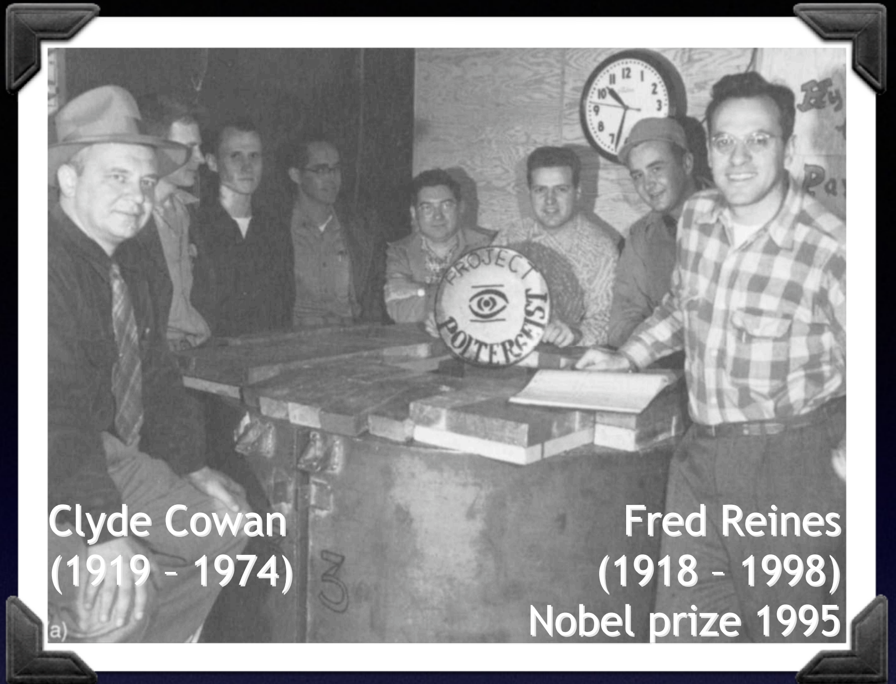
- About 6 anti-neutrinos are produced per fission. Since each fission cycle produces 200 MeV, one can convert power to neutrino flux.

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





Reactor Experiments: Pioneering Efforts



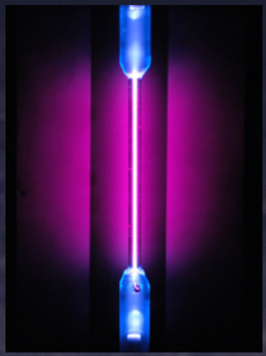
First experimental detection of neutrinos came indeed from the high flux of neutrinos created in reactors.

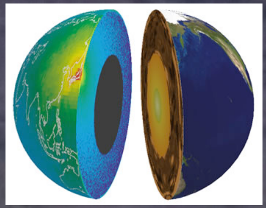
$$\bar{\nu} + p \rightarrow n + e^{+} \longrightarrow \text{signal here}$$

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

Anchoring Low Energy Cross-sections

For neutrino energies at MeV energy scales (such as nuclear reactors, supernovae, and terrestrial sources) we can anchor the cross-sections to careful studies of nuclear decay.





$$\frac{d\sigma(\bar{\nu}_e p \to e^+ n)}{d\cos\theta} = \frac{G_F^2 |V_{ud}|^2 E_e p_e}{2\pi} \{g_V(0)(1+\beta_e \cos\theta) + 3g_A(0)(1-\frac{\beta_e}{3}\cos\theta)\}$$

Inverse Beta Decay

Neutron Lifetime

$$\tau_n = \{\frac{m_e^5}{2\pi^3} f_R G_F^2 |V_{ud}|^2 (1 + 3(\frac{g_A}{g_V})^2)\}^{-1}$$

Neutron lifetime

For example, the neutron lifetime can be directly related to the cross-section for inverse beta decay...

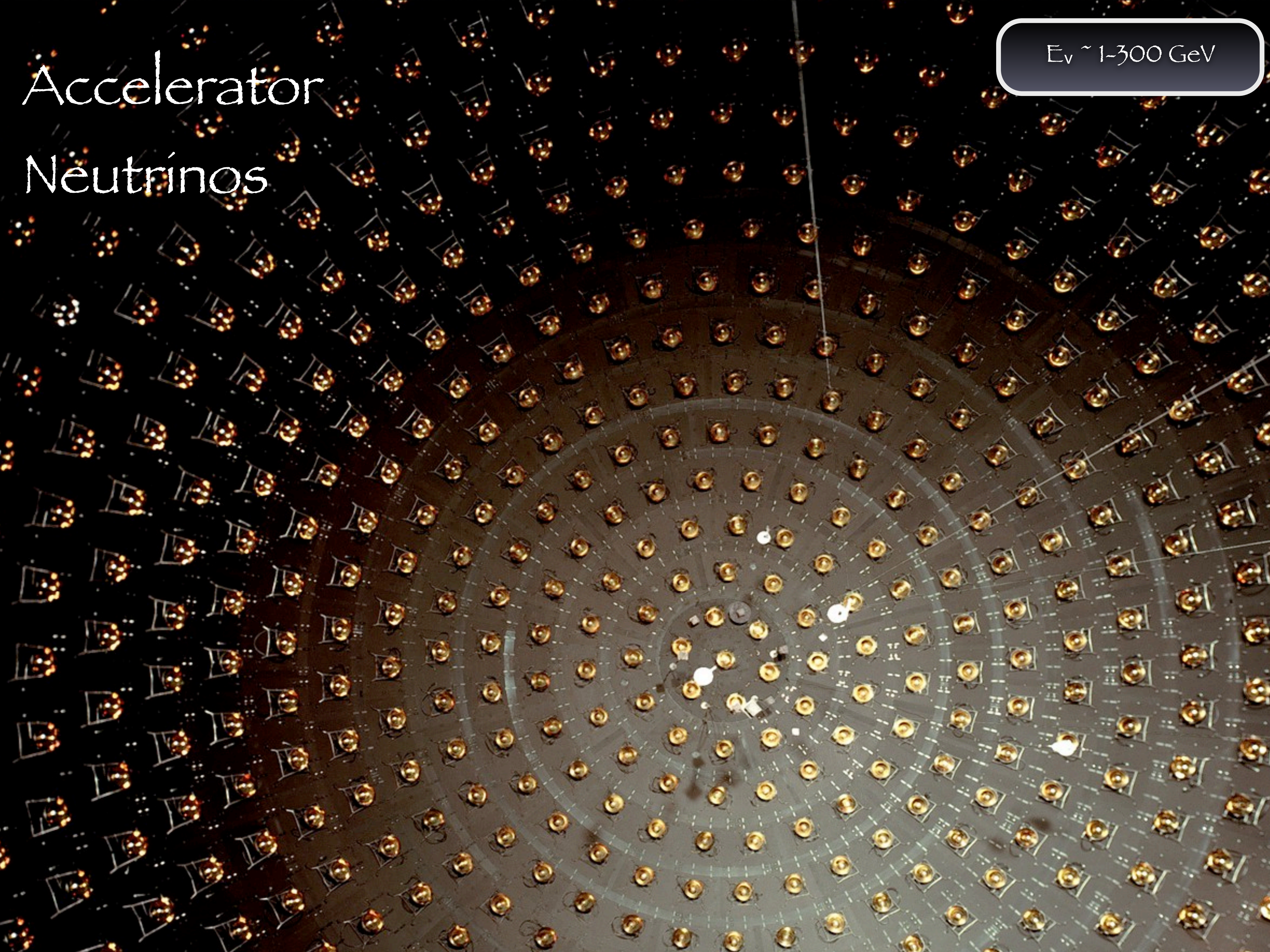
Superallowed decays can also help constrain factors such as $|V_{ud}|$

$$\frac{d\sigma(\bar{\nu}_e p \to e^+ n)}{d\cos\theta} = \frac{G_F^2 |V_{ud}|^2 E_e p_e}{2\pi} \{g_V(0)(1 + \beta_e \cos\theta) + 3g_A(0)(1 - \frac{\beta_e}{3}\cos\theta)\}$$

Inverse Beta Decay

Accelerator Neutrinos

$E_\nu \sim$ 1-300 GeV



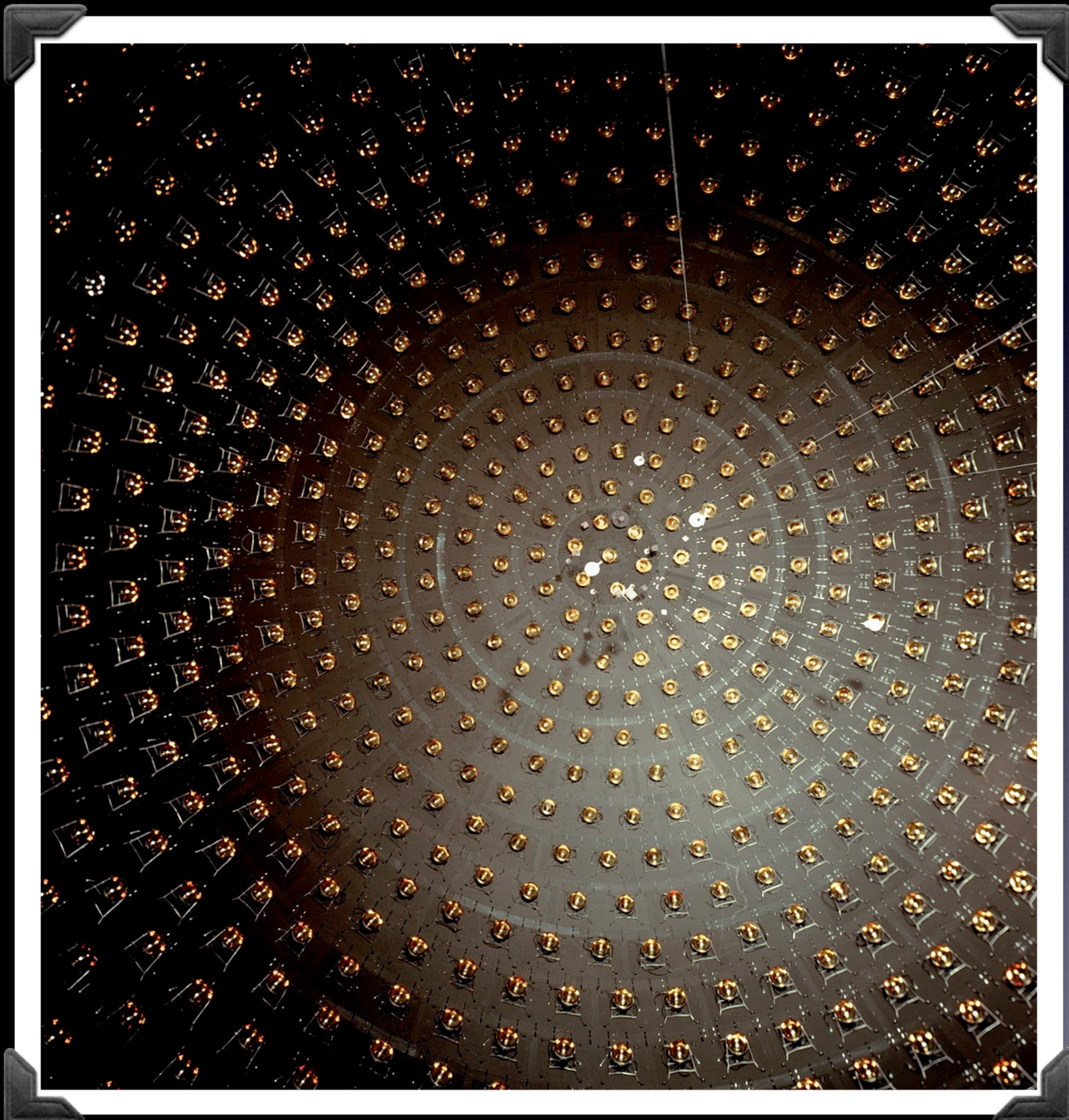
Accelerator Neutrinos

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

  (a) Proton driver ("conventional" beams)

  (b) Beta beams

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

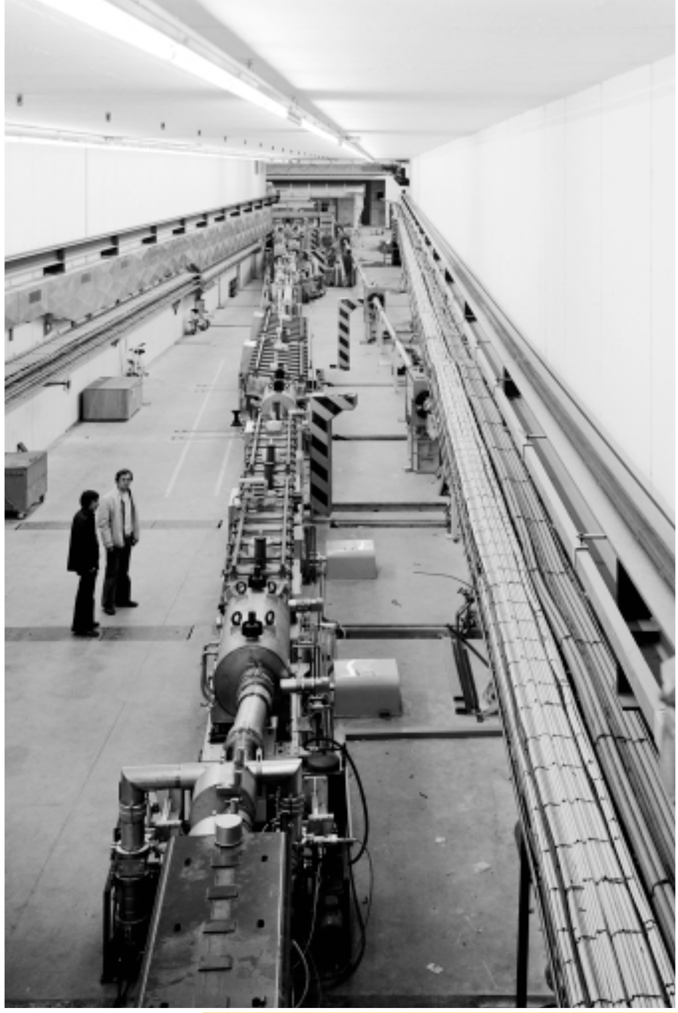


Conventional Beams

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:

- Neutrino flavor purity,
- Selected energy range & distance,
- Intensity



CERN's WA21 beamline

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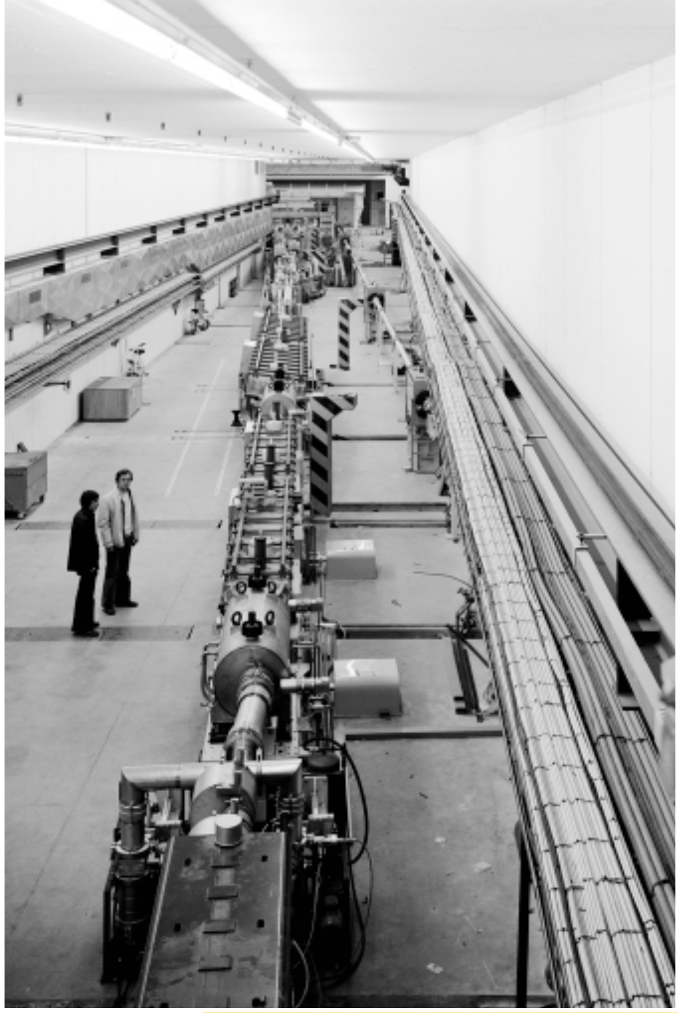

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Neutrino flavor purity, → Allows selection of final state

Selected energy range & distance,

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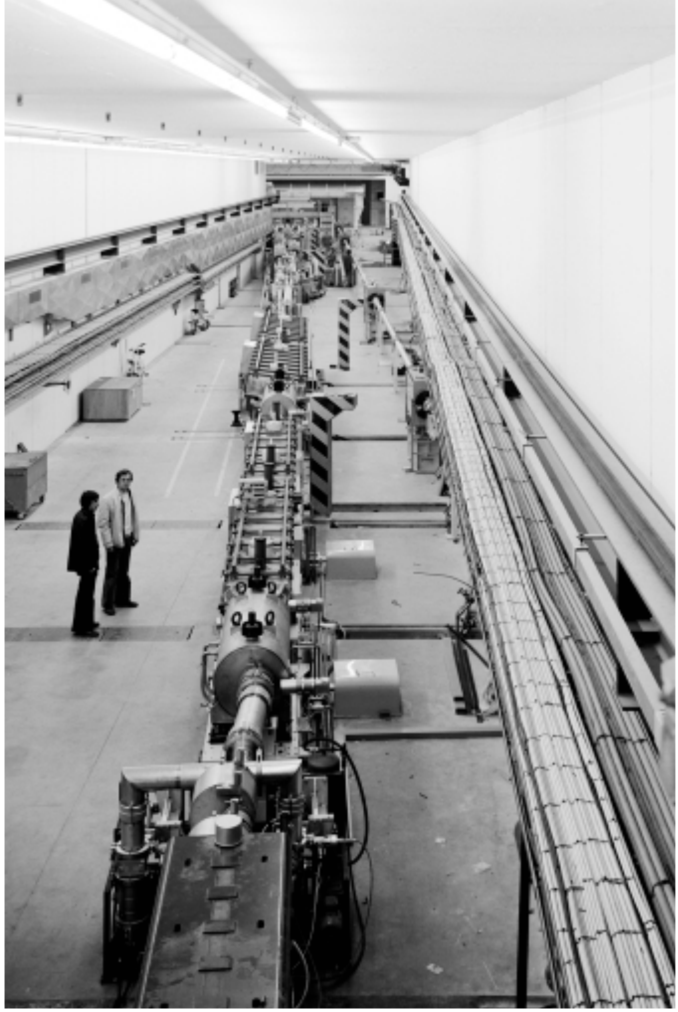

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Neutrino flavor purity, → Allows selection of final state

Selected energy range & distance, → Optimization of oscillation wavelength

Intensity

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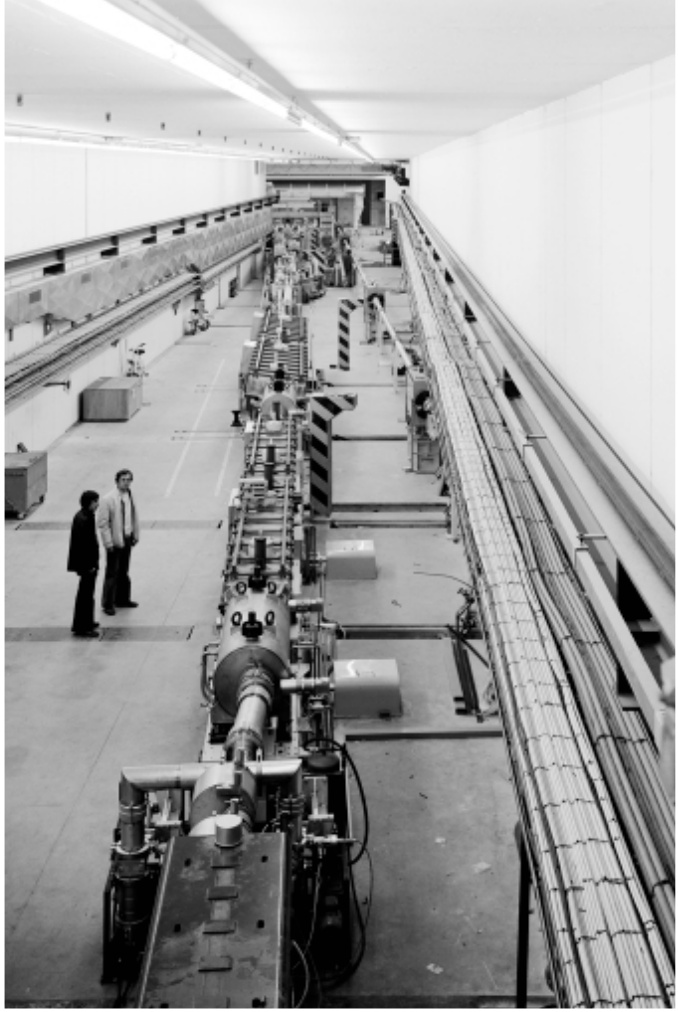


CERN's WA21 beamline

- Neutrino flavor purity, → Allows selection of final state
- Selected energy range & distance, → Optimization of oscillation wavelength
- Intensity → You always want more...

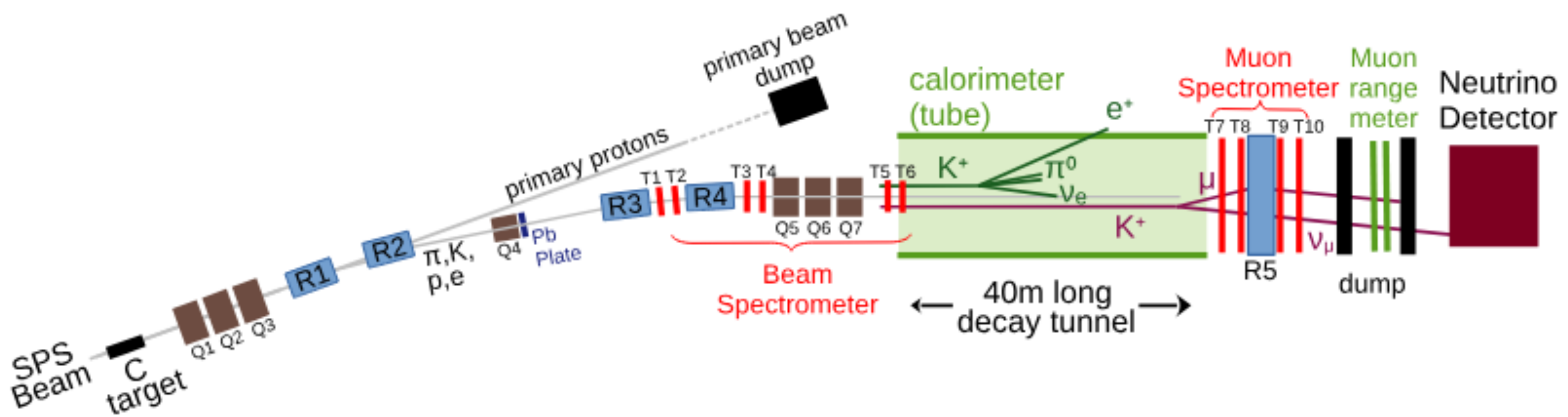
Stages

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

Decay/Absorber Region

Region for pion/kaon decay to occur.

Absorber removes unwanted charged particles & neutrons on route to detector



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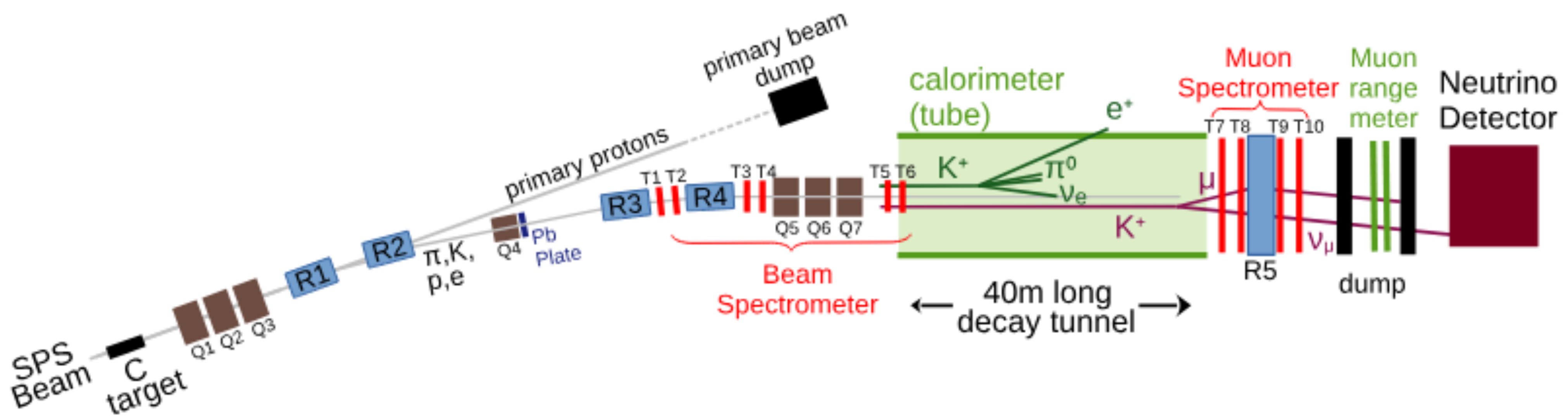
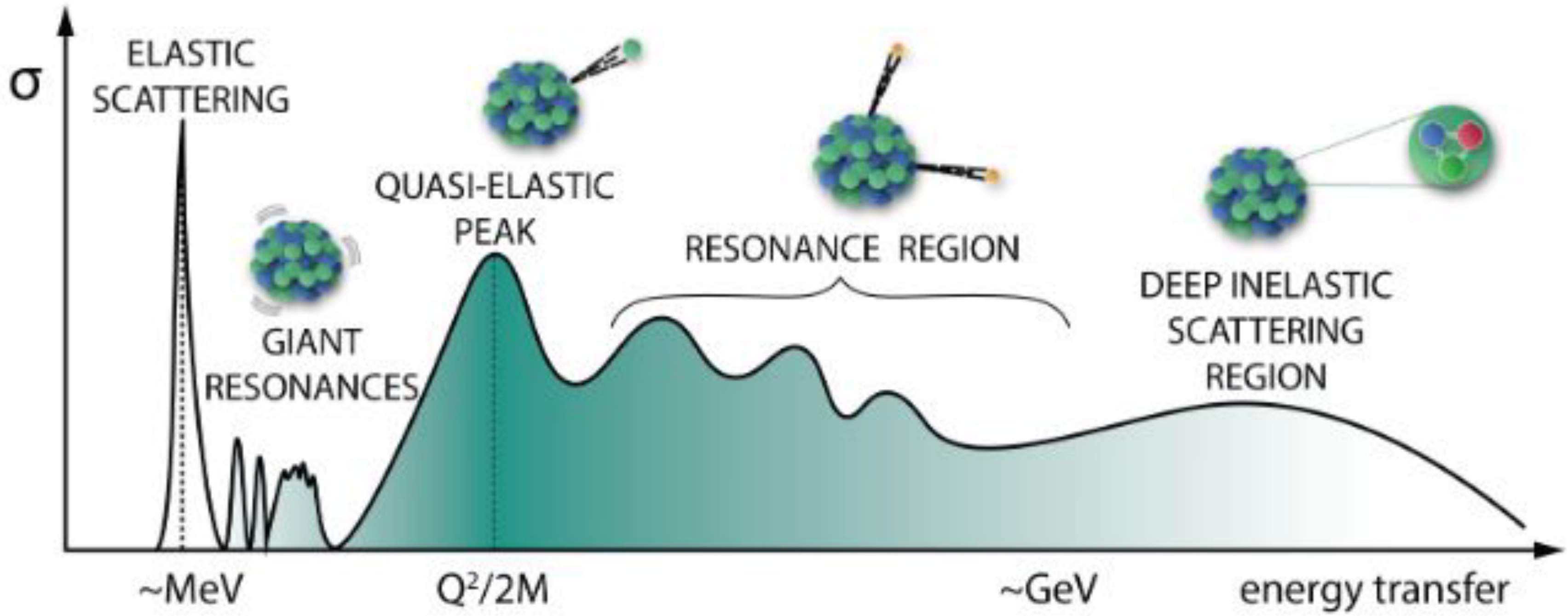


A Complex Region...



At the GeV scale, there is considerable structure to nuclei that makes cross-section modeling challenging.

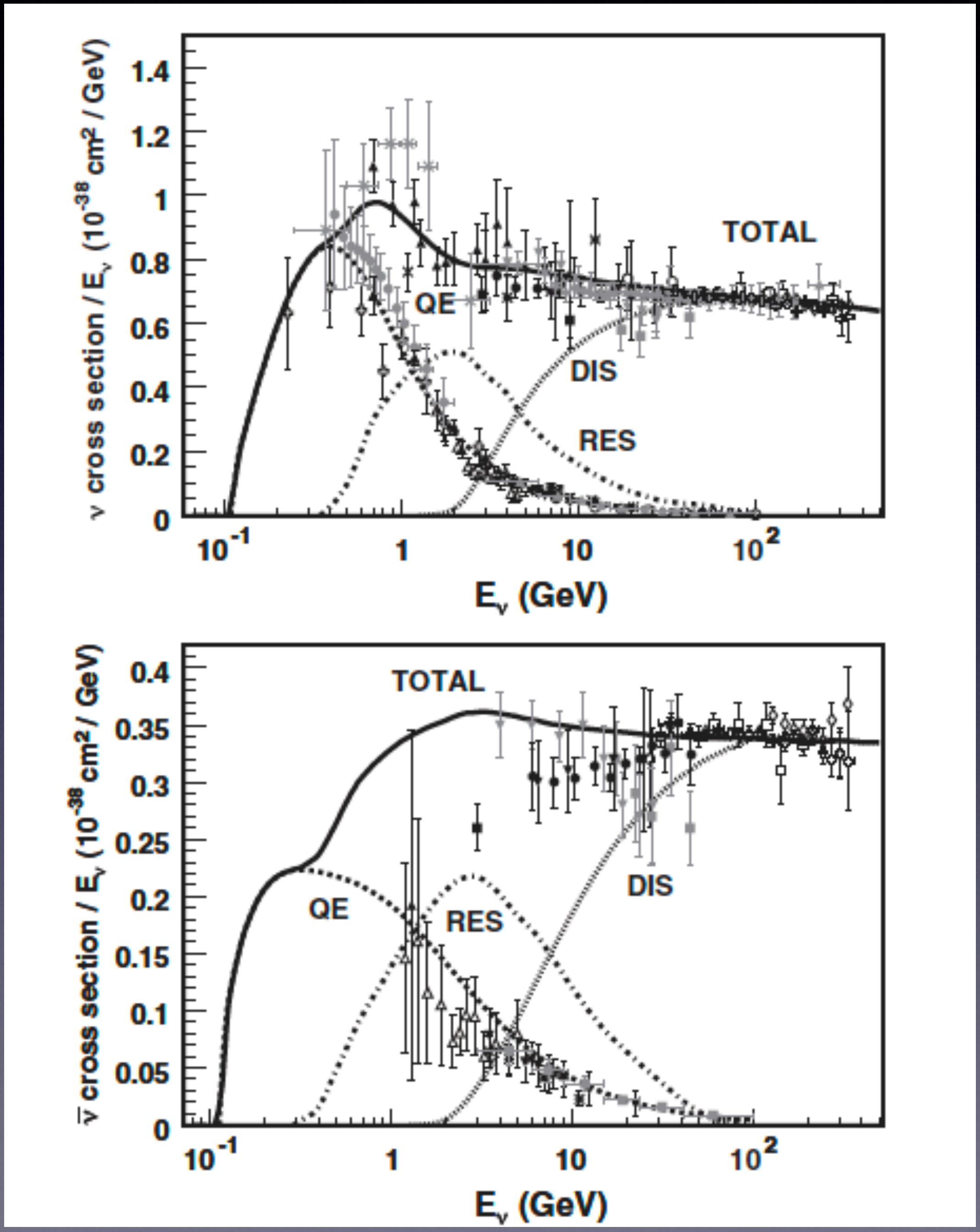
Nuclear initial state

Final-state interactions

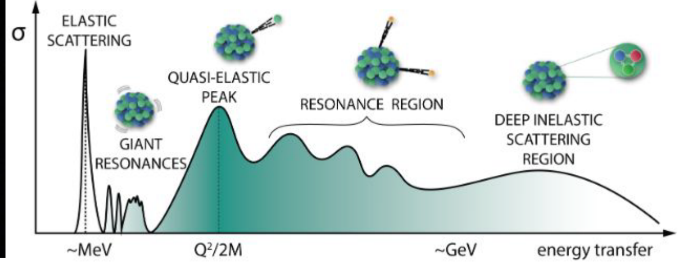
Multi-nucleon effects

Pion/hadron resonances

Lots of Experiments Work Here...



Quasi-Elastic Scattering



$$\frac{d\sigma}{dq^2}\left(E_\nu, q^2\right) = \frac{G_F^2 \left|V_{ud}\right|^2}{2\pi}\frac{M_N^2}{E_\nu^2}\left[\left(\tau + r_\ell^2\right) A\left(\nu, q^2\right) - \frac{\nu}{M_N^2} B\left(\nu, q^2\right) + \frac{\nu^2}{M_N^4}\frac{C\left(\nu, q^2\right)}{1+\tau}\right]$$

$$A = \tau\left(G_M^v\right)^2 - \left(G_E^v\right)^2 + (1+\tau)F_A^2 - r_\ell^2\left[\left(G_M^v\right)^2 + F_A^2 + 4F_P\left(F_A - \tau F_P\right)\right]$$

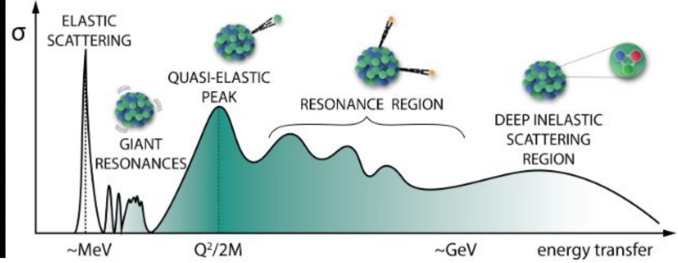
$$B = 4\eta\tau G_M^v F_A$$

$$C = \tau\left(G_M^v\right)^2 + \left(G_E^v\right)^2 + (1+\tau)F_A^2.$$

Let's consider the "simplest" process at this scale, i.e. quasi-particle scattering. Even in this process, the cross-section depends on several form factors, i.e. electric (G_E), magnetic (G_M), axial (F_A) and psuedoscalar (F_P).

Although some can be accessed through electron-nucleon scattering, others are unique to the weak force.

Quasi-Elastic Scattering



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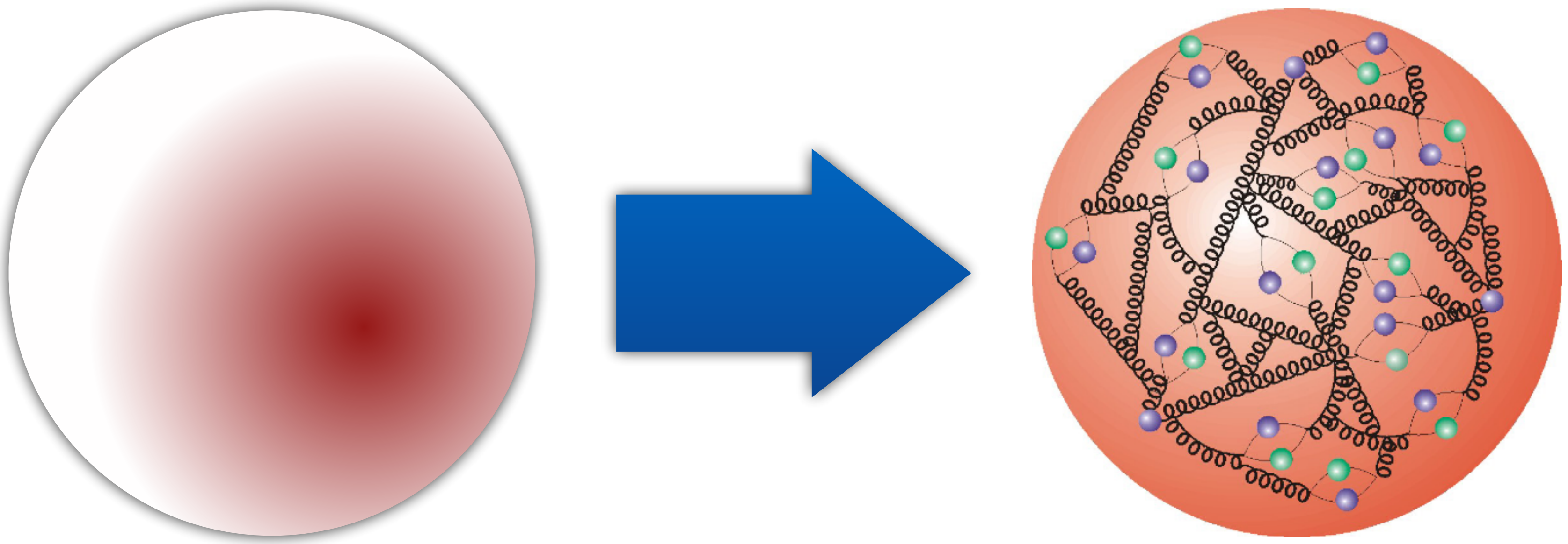
Theoretical Tools

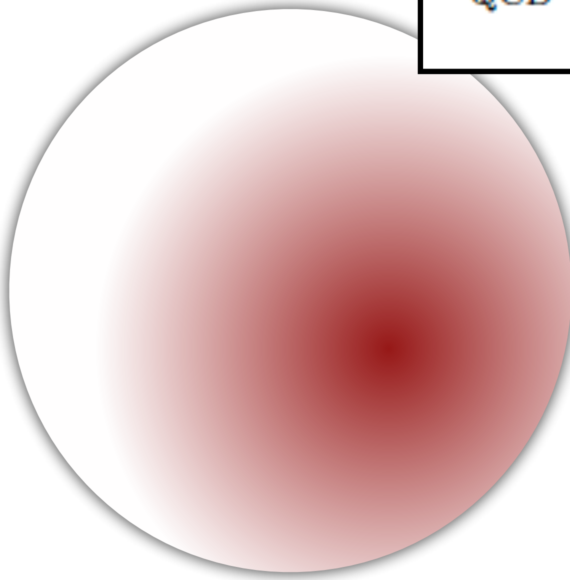


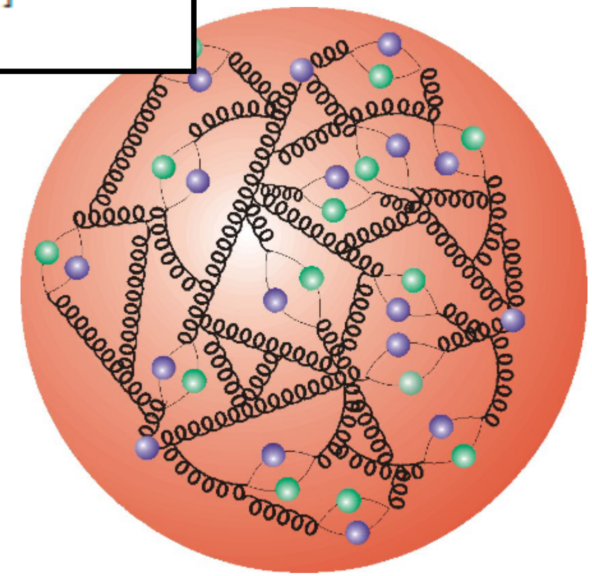
Theoretical and phenomenological models allow one to capture the inner structure of the target nucleus for details predictions.

Effective field theories, superscaling and sum rules provide strong models for predicting cross-section evolution versus probe momentum.

Lattice QCD

$$Z_{\rm QCD} = \int DU \, {\rm Det}[\not{D}(U) + m_q] \, e^{-S_{\rm G}(U)}$$

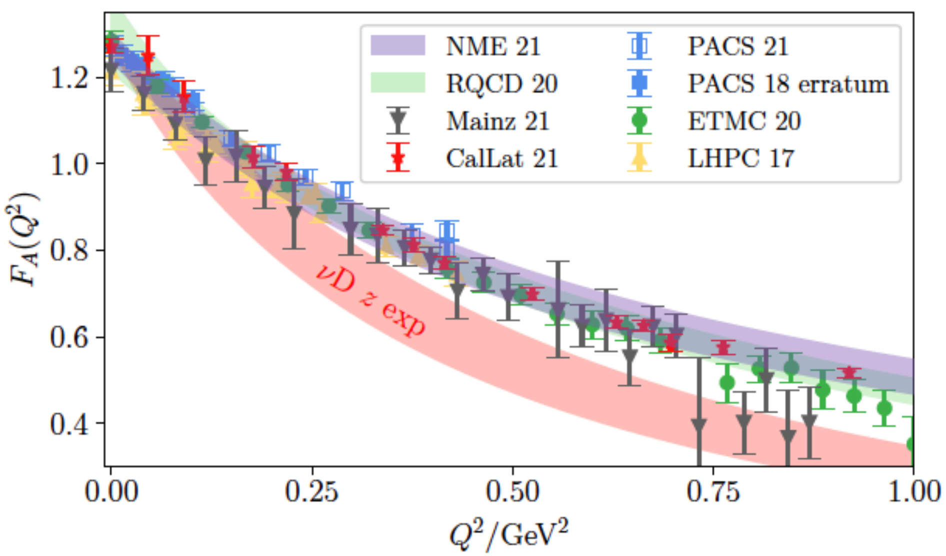


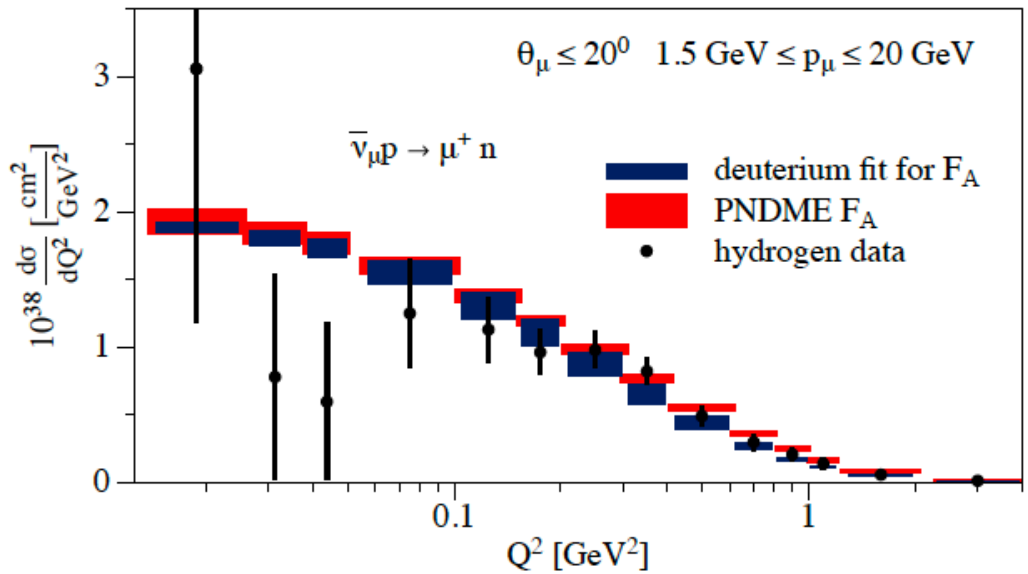


Lattice QCD is a recent, power tool in determining the correlation functions for neutrino-nucleon scattering.

Unlike other approaches, QCD is completely self-determined and ideal for 2-point correlation functions (provided one has sufficient computing power)

Lattice QCD





Lattice QCD calculations have advanced sufficiently that they can now provide ad initio calculations of nuclear structure form factors, such as axial and pseudovector form factors.

Direct comparisons to available data (deuterium, hydrogen, MINERVA, etc) are now possible, at the 10% level. Good agreement with g_A measurements.

Beta Beams

Different from conventional beams, as they use accelerated beta-decaying ions as the source of neutrinos.

Extremely pure beam of electron (or anti-electron neutrinos).

Spectrum extremely well known, since it comes from a boosted beta decay rather than a complex nucleon production scheme.

Production of ion source still considerable challenge, but research is ongoing.

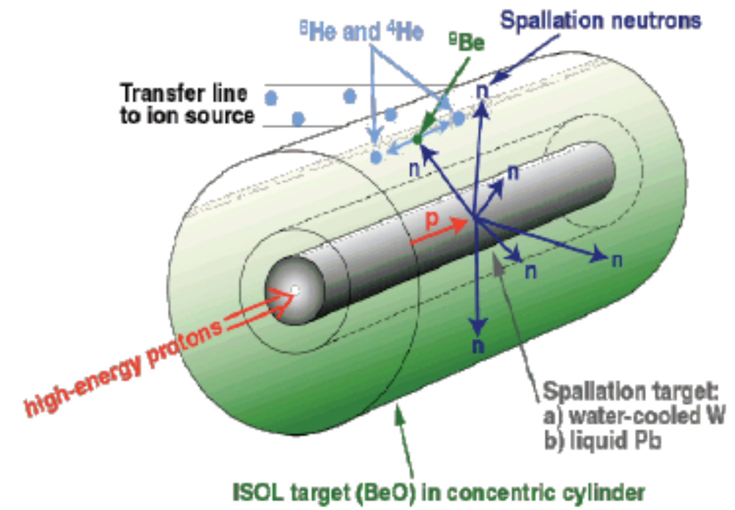
Neutrinos from Beta Decay

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

Electron Anti-neutrino Source

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

Electron Neutrino Source



Neutrino Factories

Driving mechanism comes from muon decay rather than pion decay.

Ideal "beam" for many oscillation studies.

Main Advantages

Extremely pure beam due to use of delayed decays.

Well known beam profile

Typically intense source envisioned.

Main Disadvantages

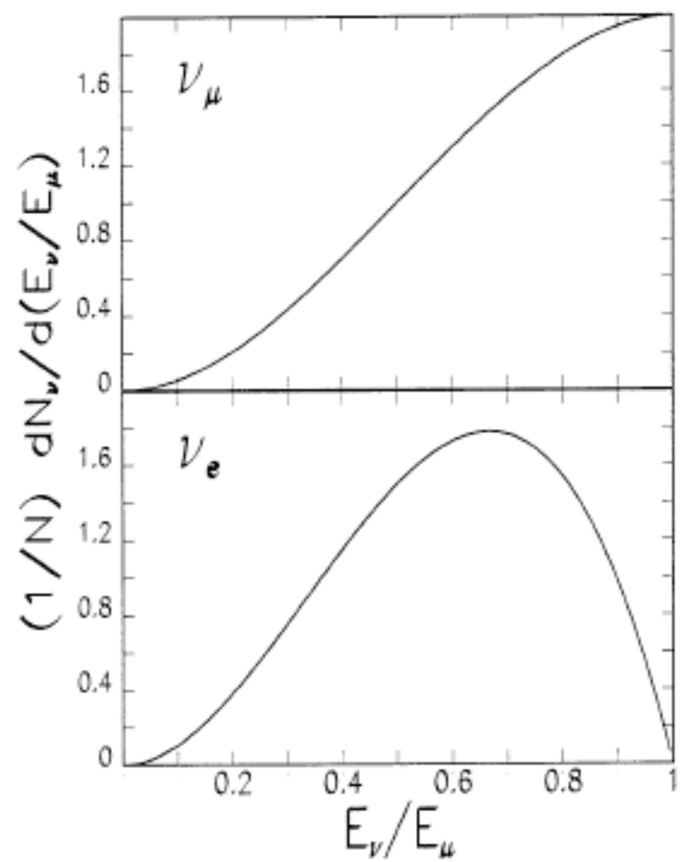
Both neutrino & anti-neutrino are present in the beam at once

Extremely short storage times

Challenging technology

Neutrinos from Muon Decay

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




$E_\nu \sim 50$ MeV
Spallation
Neutron Sources

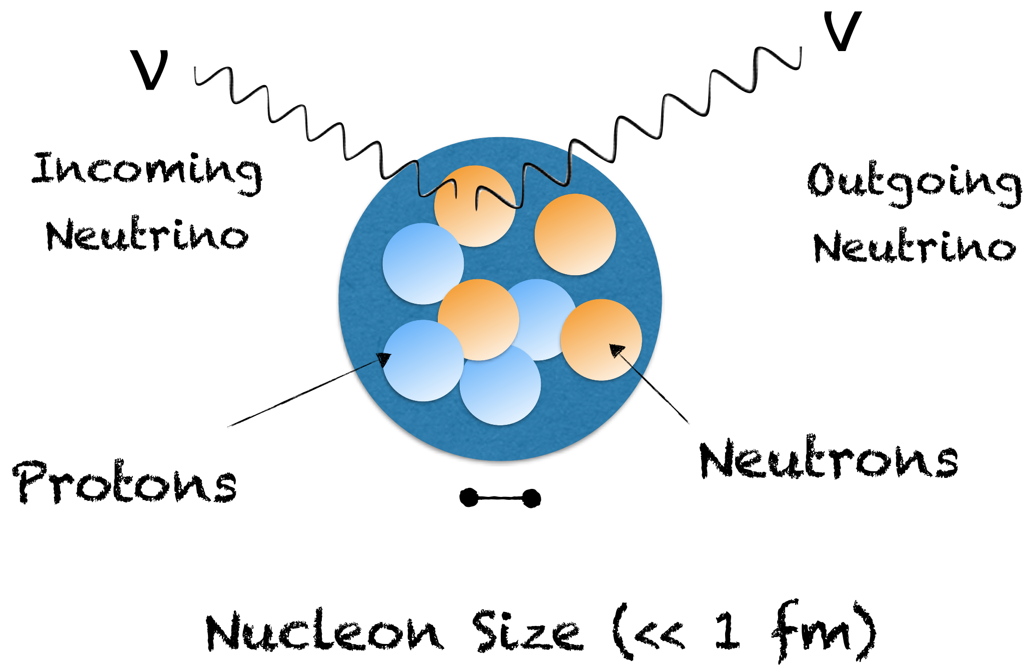
Any reaction that can produce an intense pion source is effectively an excellent neutrino source.

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.

- Pulsed beam ensures clean tagging of neutrino events.
- Intensity neutrino source (10^{15} ν/s)\
- Can be used for oscillation studies & coherent neutrino scattering.

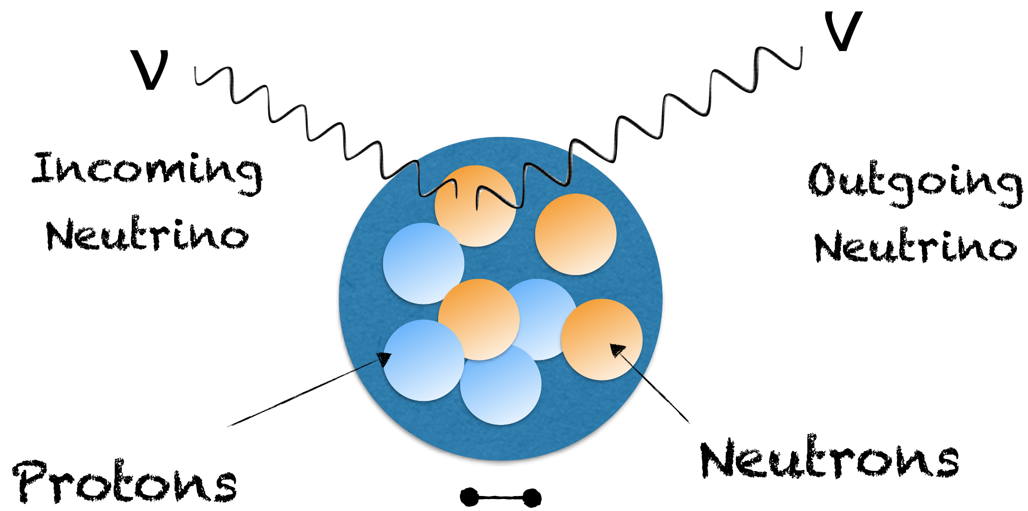
What's So Special About Coherence?



One can think of the energy (really, momentum) the neutrino imparts on its target as a way to probe the nucleus.

The higher the imparted momentum, the finer the probe.

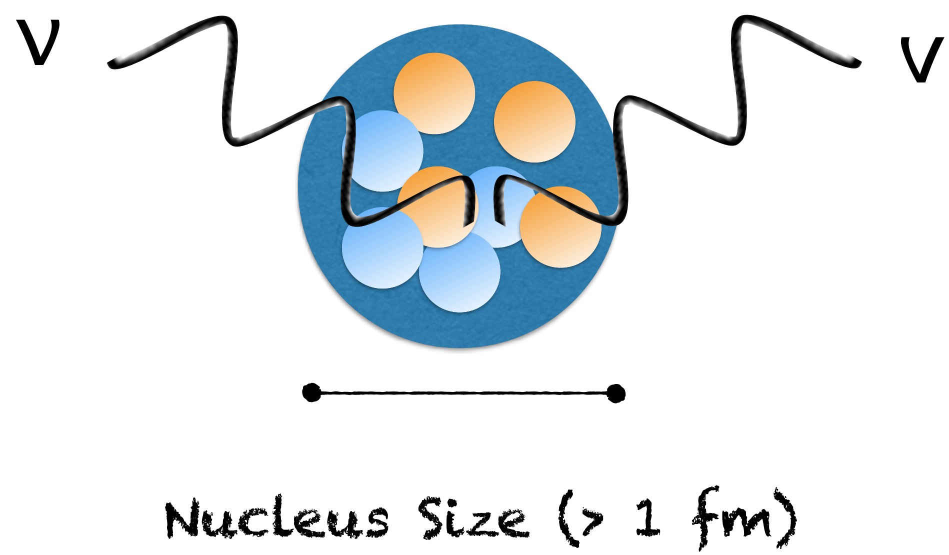
Non-Coherenct Interactions



Nucleon Size (<< 1 fm)

In this case, the probe momentum is such that it singles out a single neutron or proton.

All Together Now…



However, if the exchange momentum is small enough, the probe just sees the entire nucleus, and no single proton or neutron is singled out.

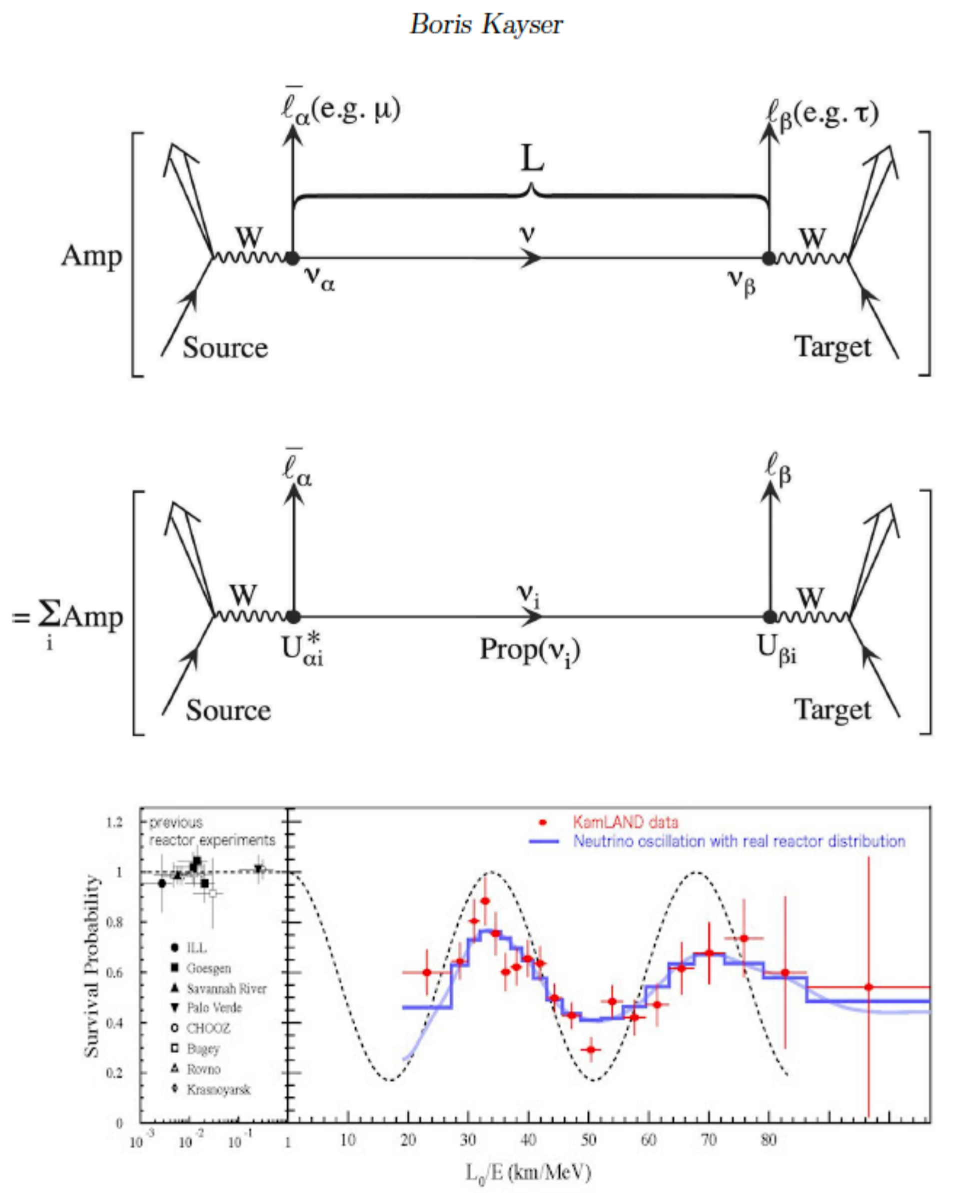
Result: Interaction probability scales as the number of nucleons squared.

Oscillations as Coherence

Numerous analogies exist between neutrino oscillations and optical phenomena.

For example, the interference between neutrino mass states with different de Brogile wavelengths (oscillations) have a direct optical analog in the propagation and recombination of differently polarized photons through birefringent media.

One can even set up an optics experiment to mimic oscillation behavior…



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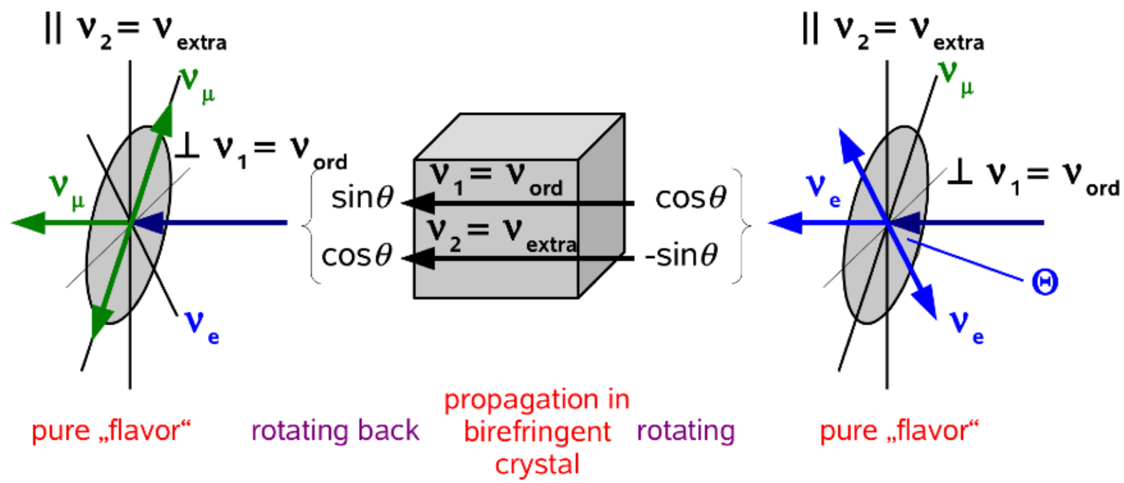

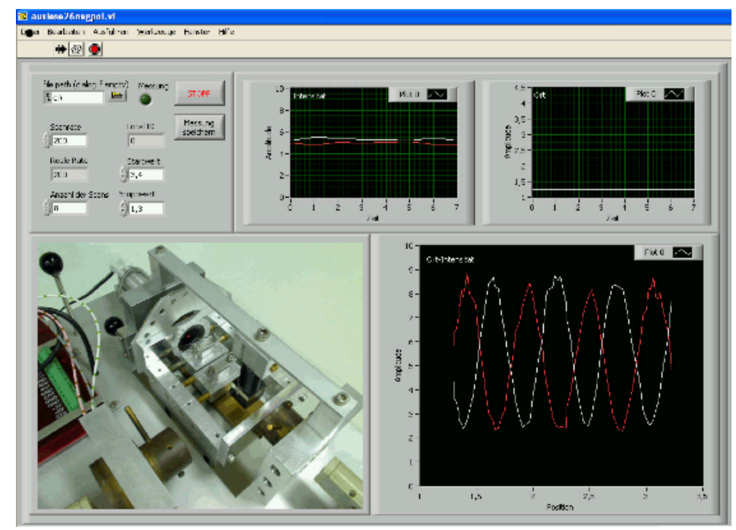

C Weinheimer.
Progress in Particle and Nuclear Physics, 64(2):205–209, 2010.

Coherent Enhancement

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The

Coherence effect

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(Q^2)^2$$

$$Q_W = N - (1 - 4\sin^2\theta_W) Z$$

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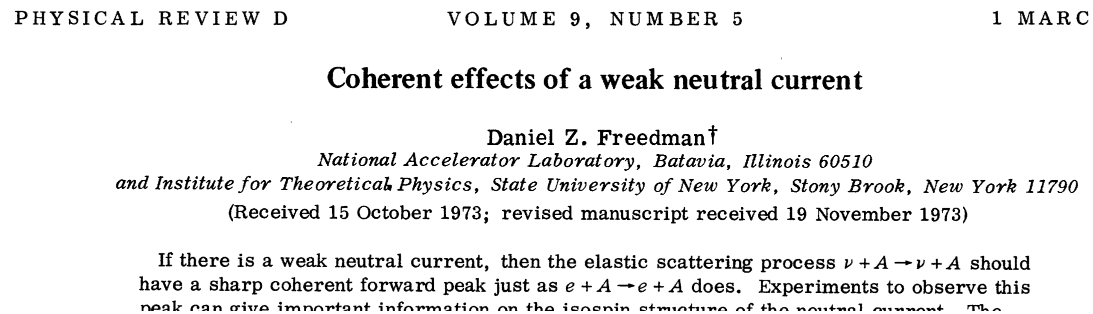
Coherent Elastic Neutrino Nuclear Scattering (CEvNS) has been proposed and schemed as a means of detecting neutrinos.

It took 40+ years, but the effect has finally been observed experimentally using a spallation source.

Coherent Enhancement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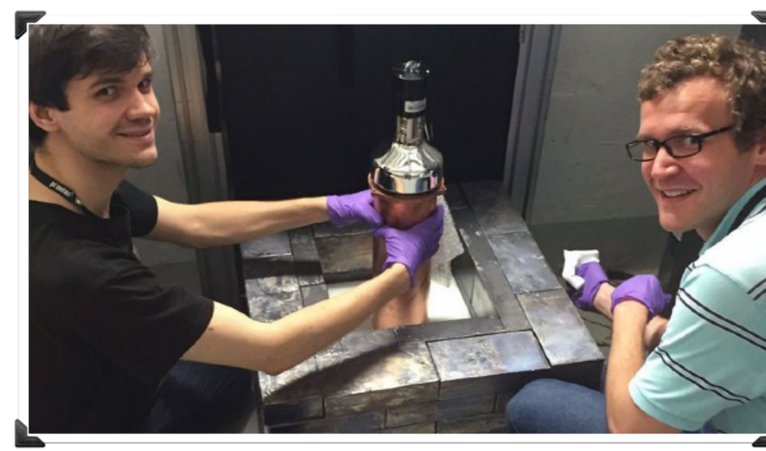


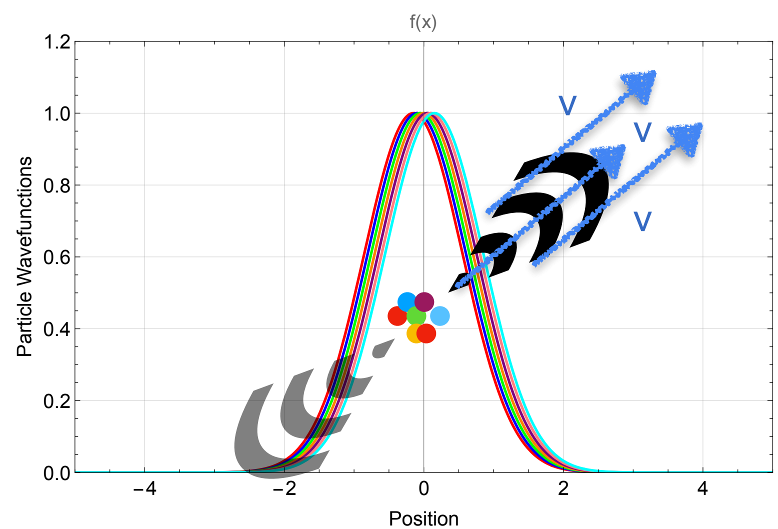
Opening the Door for Coherence?

Superradiant Interactions
of the Cosmic Neutrino Background, Axions, Dark Matter, and Reactor Neutrinos

Asimina Arvanitaki,[1,*] Savas Dimopoulos,[2,1,†] and Marios Galanis[1,‡]
[1]Perimeter Institute for Theoretical Physics, Waterloo, ON N2L 2Y5, Canada
[2]Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA
(Dated: November 6, 2024)

Superradiant Neutrino Lasers from Radioactive Condensates

B.J.P. Jones[1,*] and J. A. Formaggio[2,†]
[1]Department of Physics, University of Texas at Arlington, Arlington, Texas 76019, USA
[2]Laboratory for Nuclear Science and Dept. of Physics,
Massachusetts Institute of Technology, Cambridge, MA 02139, USA



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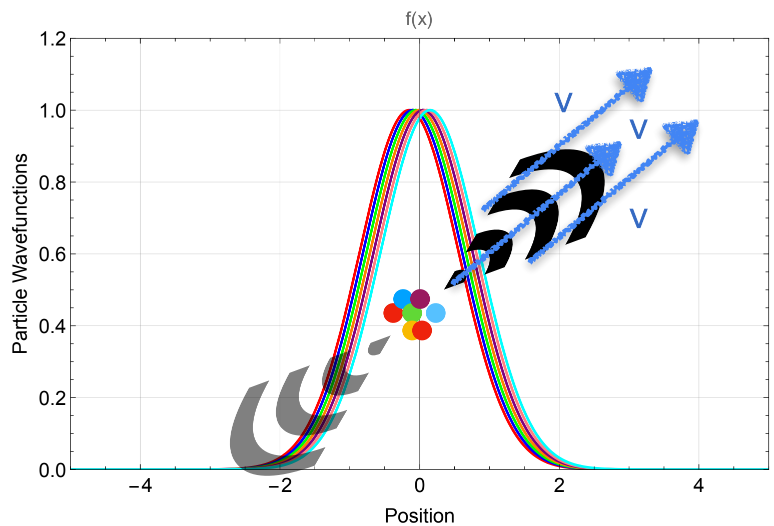
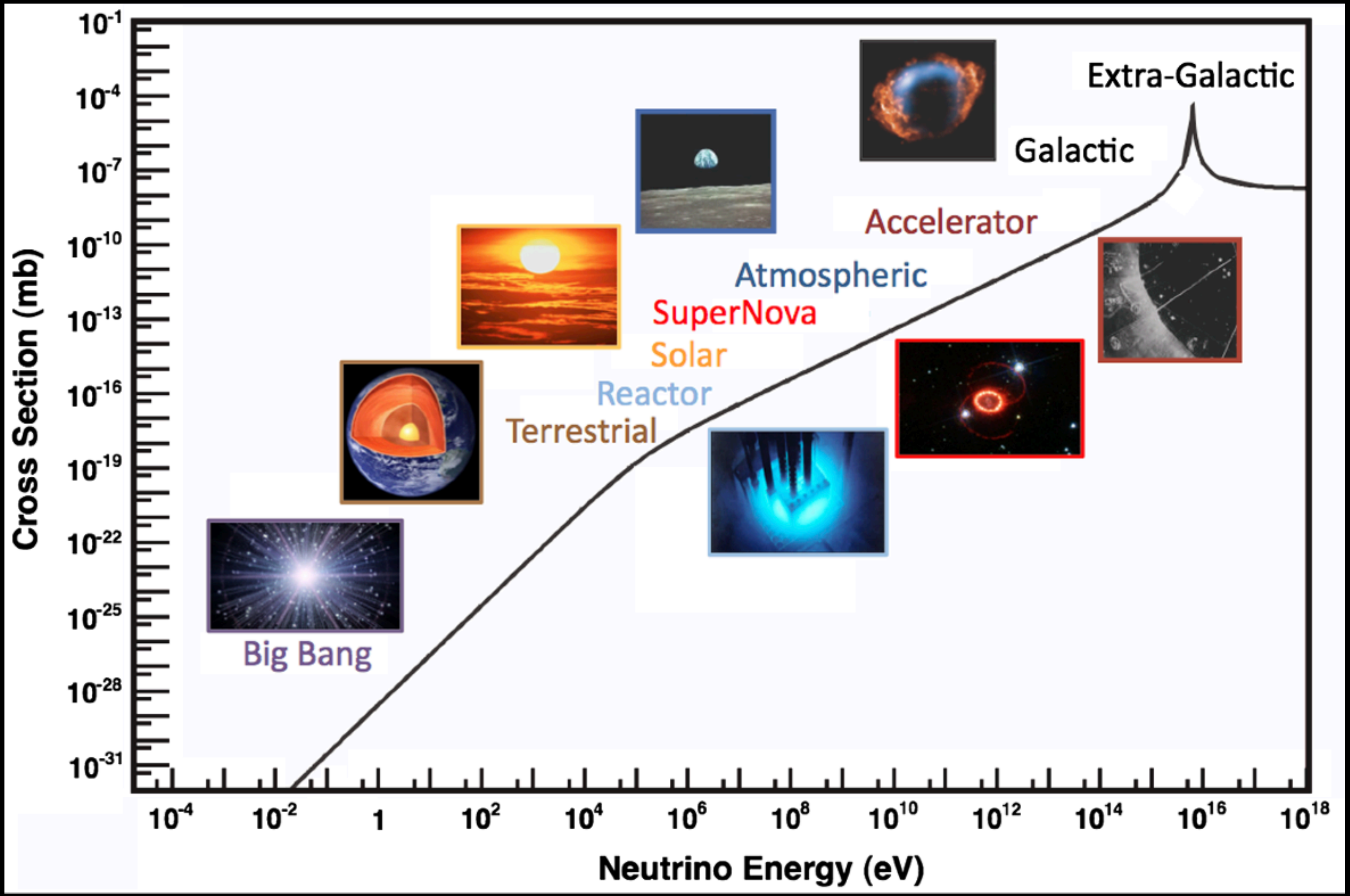


CEνNS is (in my opinion) just the beginning of using coherence in neutrino physics.

Are there other potential avenues for coherence to be used in neutrino physics?

One option: Superradiance

Might be *the* way to measure the CνB…



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.

Texts I find useful...

- “Fundamentals of Neutrino Physics and Astrophysics” by Carlo Guinti
- “From eV to EeV: Neutrino cross sections across energy scales,” by JAF and G. P. Zeller (RMP 84, 1307)
- “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
- “Massive Neutrinos in Physics and Astrophysics,” Mohapatra and Pal.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