Relic Neutrinos

the holy grail of neutrino physics?

Fermilab Summer School 2009

J. A. Formaggio
MIT

What is this?

What is this?

Planck Satellite:

Launched May 15th, 2009

New Frontiers

- With the launch of the Planck satellite, the connection between neutrino physics and cosmology becomes even stronger.
- A strong verification of the existence of the relic neutrino background (via direct detection) may provide strong validation of our current cosmological model(s),
- Can direct detection of relic neutrinos be accomplished?

Knowledge of the Relic Neutrino Spectrum

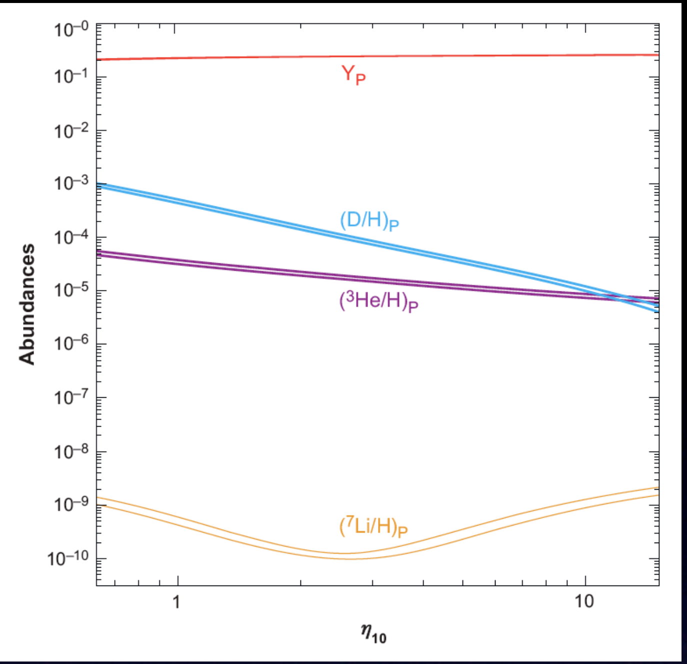
- By what means do we conclude that the relic neutrino background should exist?

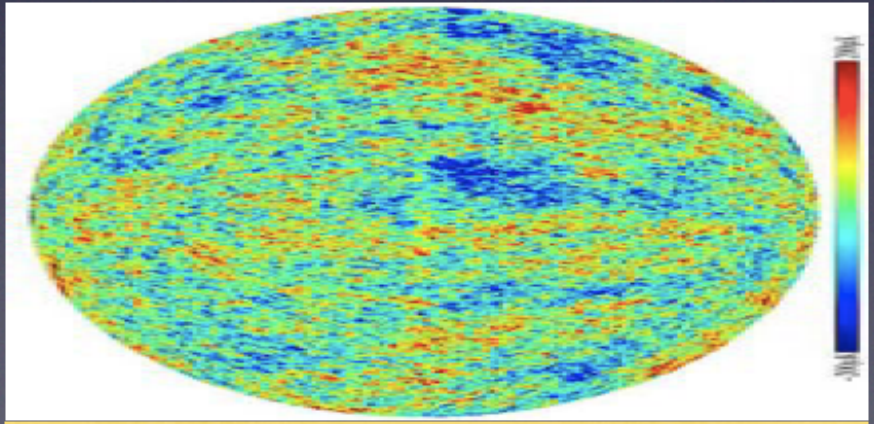
(1) Knowledge of the CMB spectrum.

(2) Primordial Nucleosynthesis

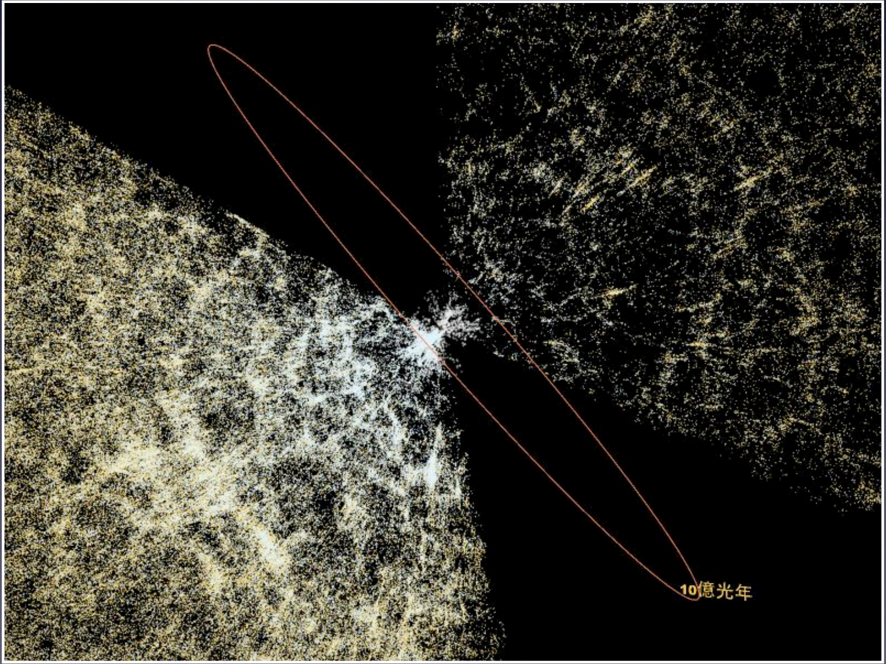
(3) Large Scale Structure

Primordial Nucleosynthesis





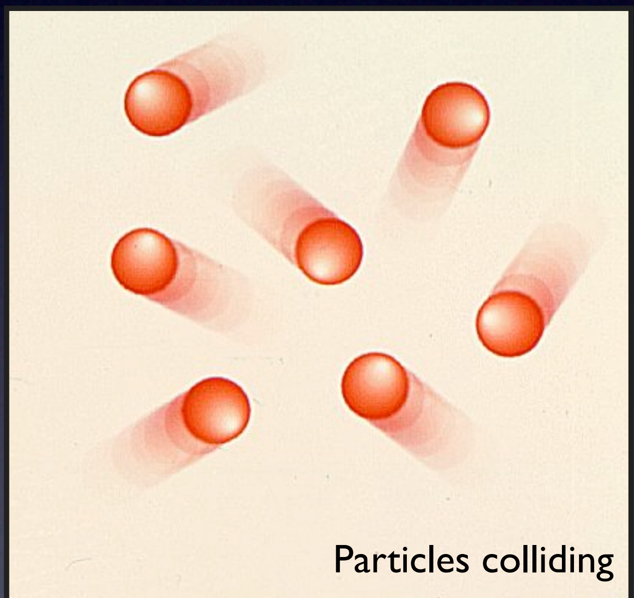
Cosmic Microwave Background



Large Scale Sctructure

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.


Particles colliding

Neutrino decoupling occurs when two rates are equal.


Universe cooling

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

Annihilation Rate

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

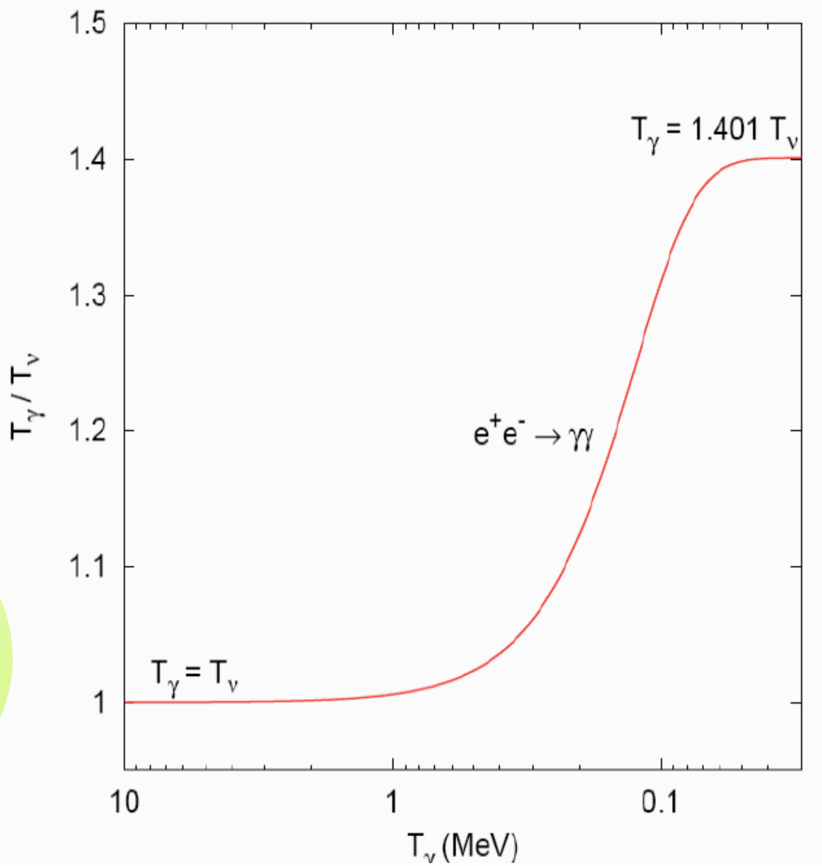
Expansion Rate

Knowledge of the Relic Neutrino Spectrum

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

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

turn off



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

turn off

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

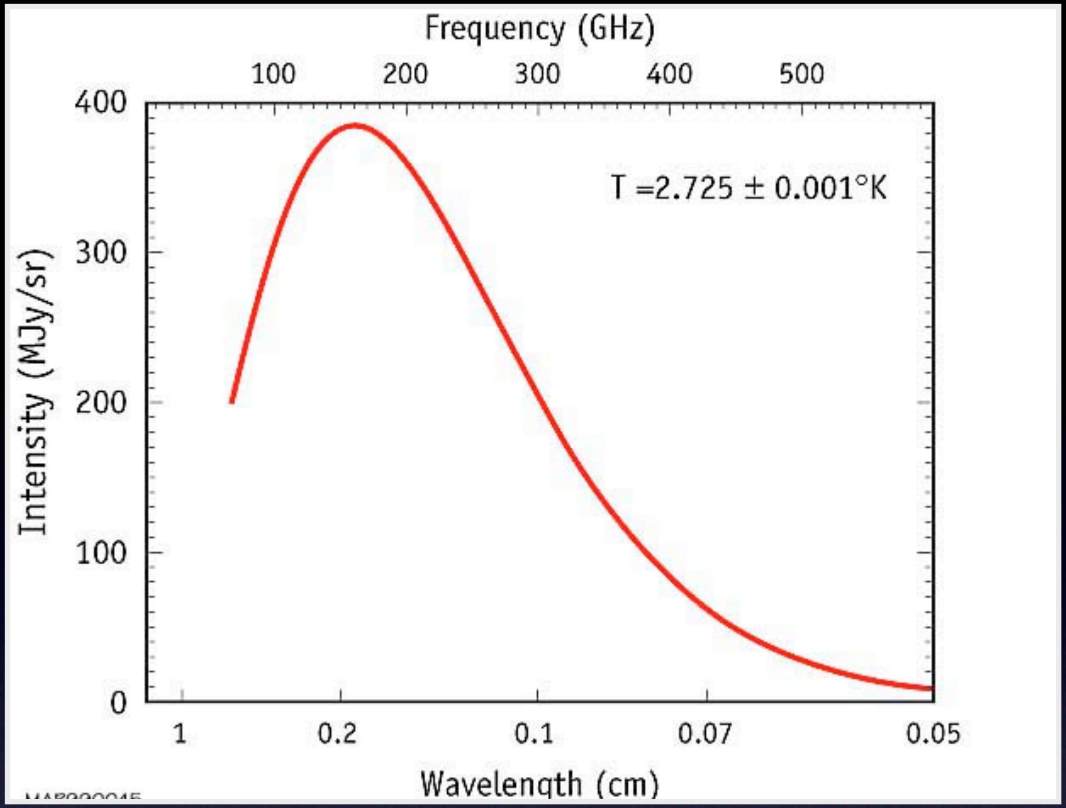
Knowledge of the Relic Photon Spectrum

- Photons from the cosmic microwave background still permeate today, cooled from the original decoupling temperature.
- Can be observed as a *perfect* blackbody spectrum with a peak at a frequency of ~175 GHz.
- Could be observed once radar technology was sufficiently developed.

Wilson and Penzias

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

Knowledge of the Relic Photon Spectrum

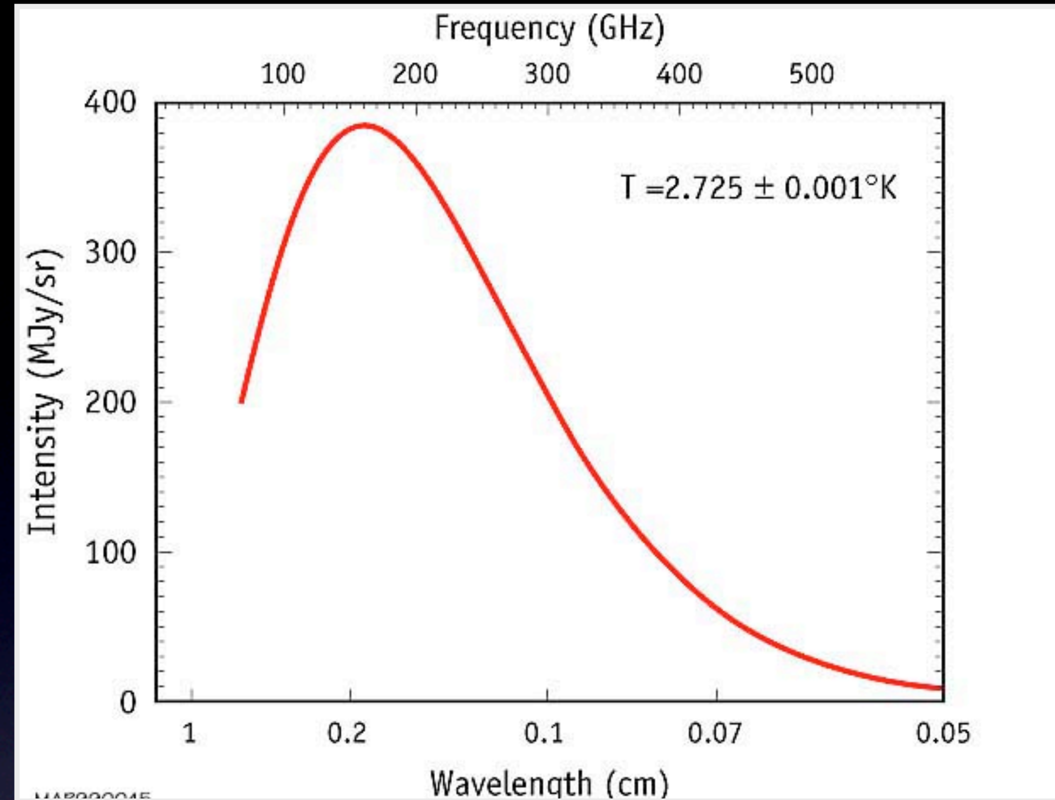


- The cosmic microwave background illustrates a perfect blackbody spectrum:

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

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

Knowledge of the Relic Photon Spectrum

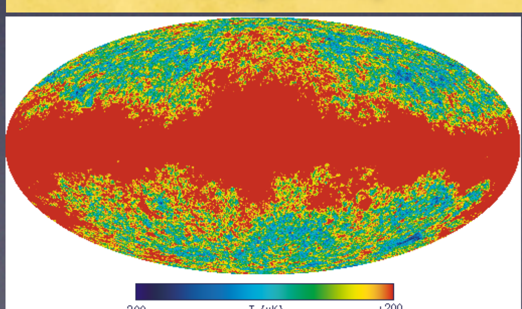


- The cosmic microwave background illustrates a perfect blackbody spectrum:

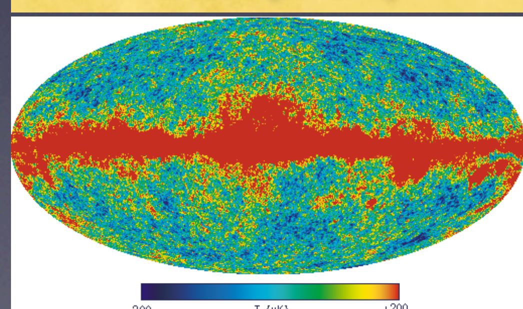
$$T_\gamma = 2.725 \pm 0.002K$$

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

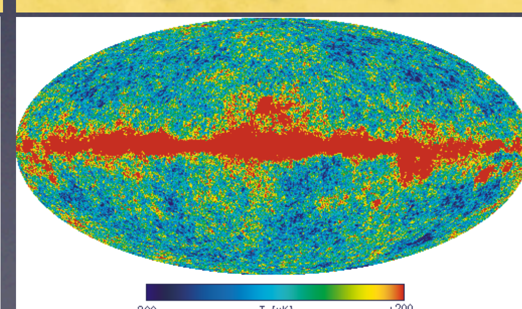
K-band (23 GHz)



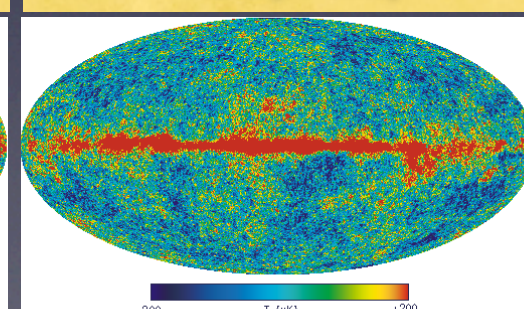
Ka-band (33 GHz)



Q-band (41 GHz)



V-band (61 GHz)



Primordial Nucleosynthesis

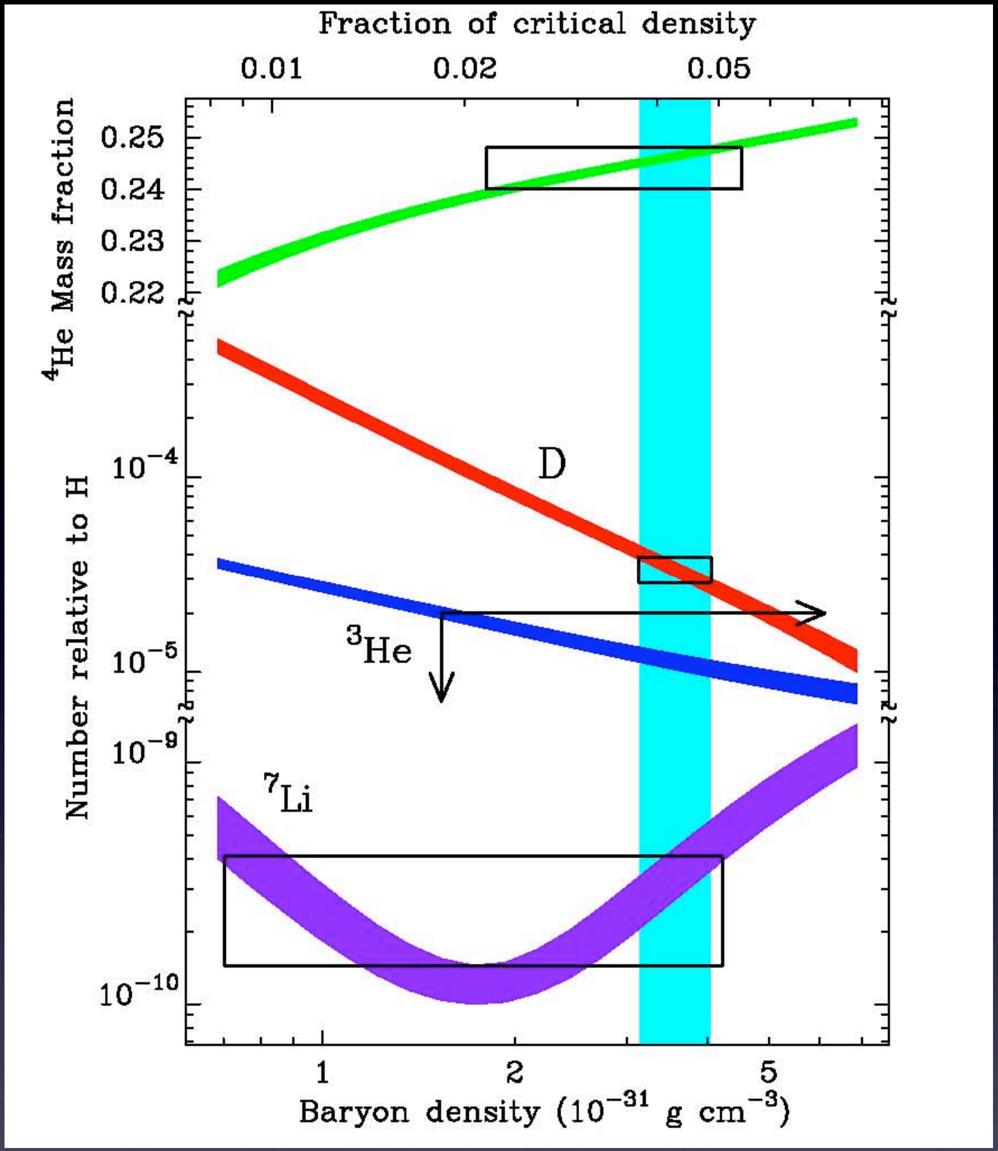
- Eventually neutrinos also decouple from neutrons and protons (below 1 MeV)

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

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

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

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



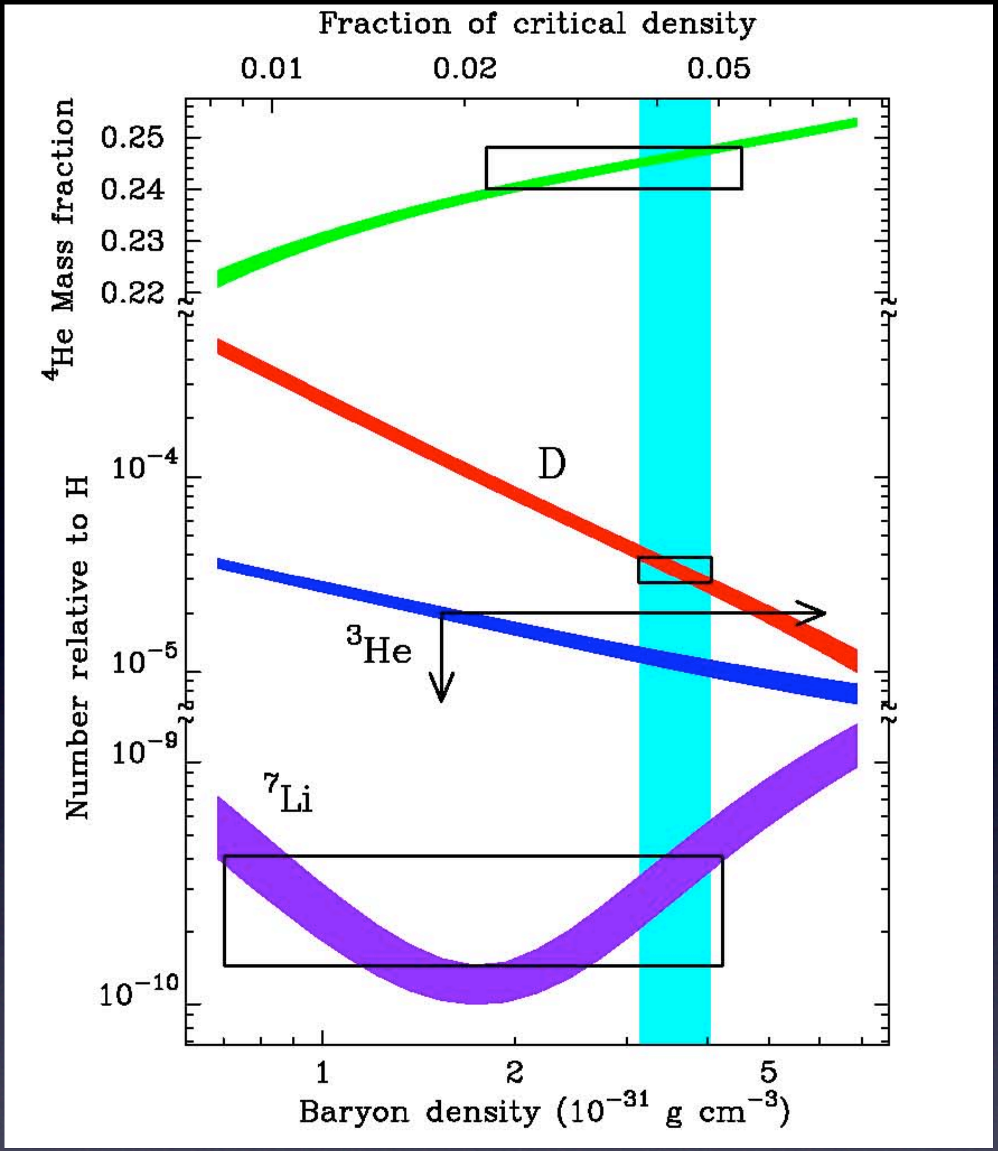
Primordial Nucleosynthesis

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

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

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

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

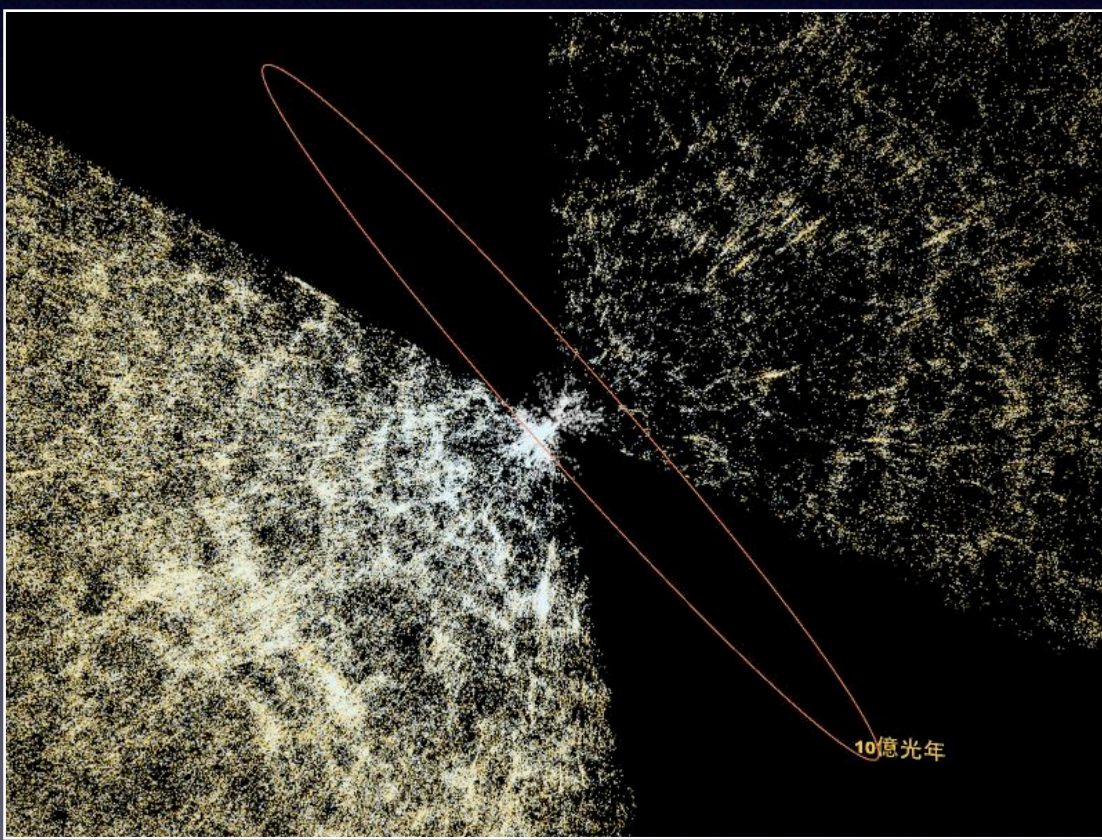


$$\eta_{10} \equiv 10^{10}(n_B/n_\gamma)$$

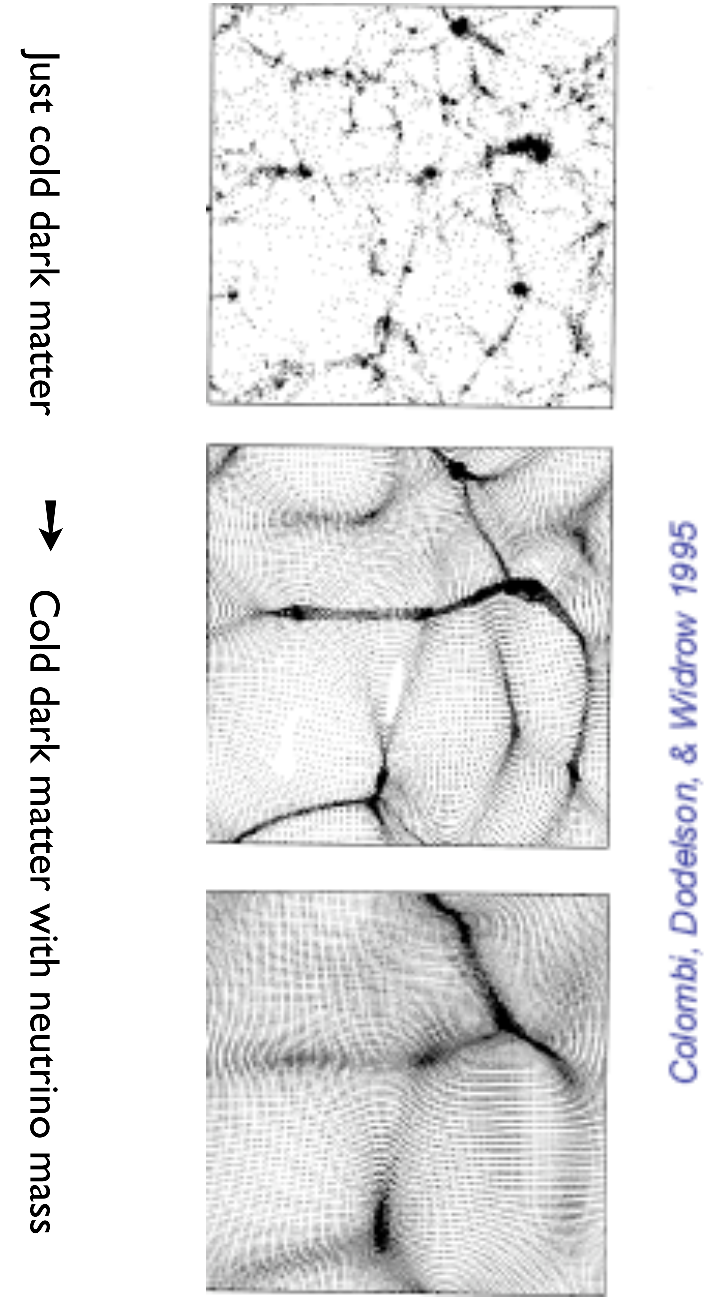
This quantity is unchanged at BBN, recombination, and now

Large Scale Structure

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



Large Scale Sctructure

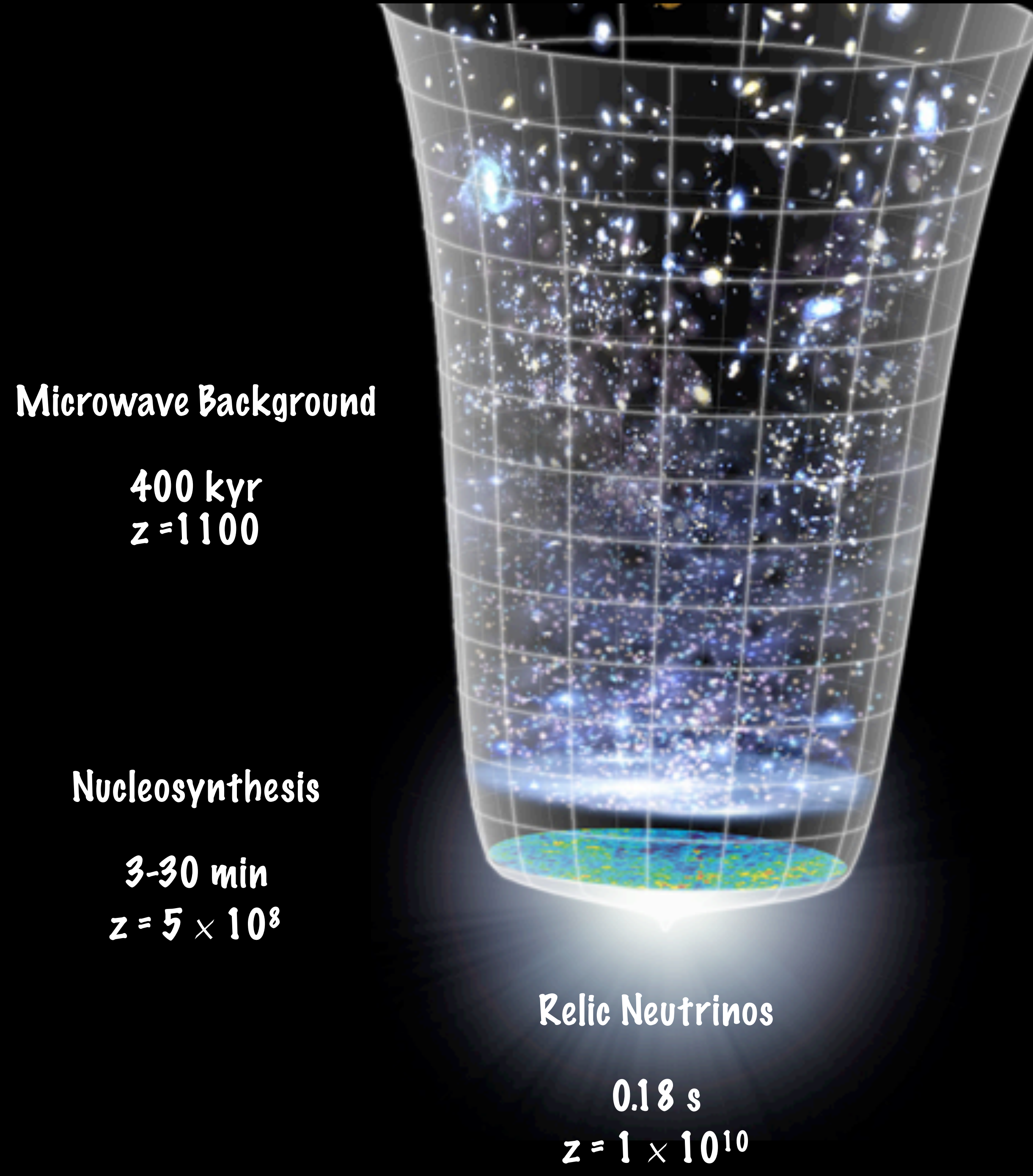


$$\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \frac{\sum_i m_{\nu,i} n_{\nu,i}}{\rho_{\text{critical}}}$$

The Triumph of Cosmology

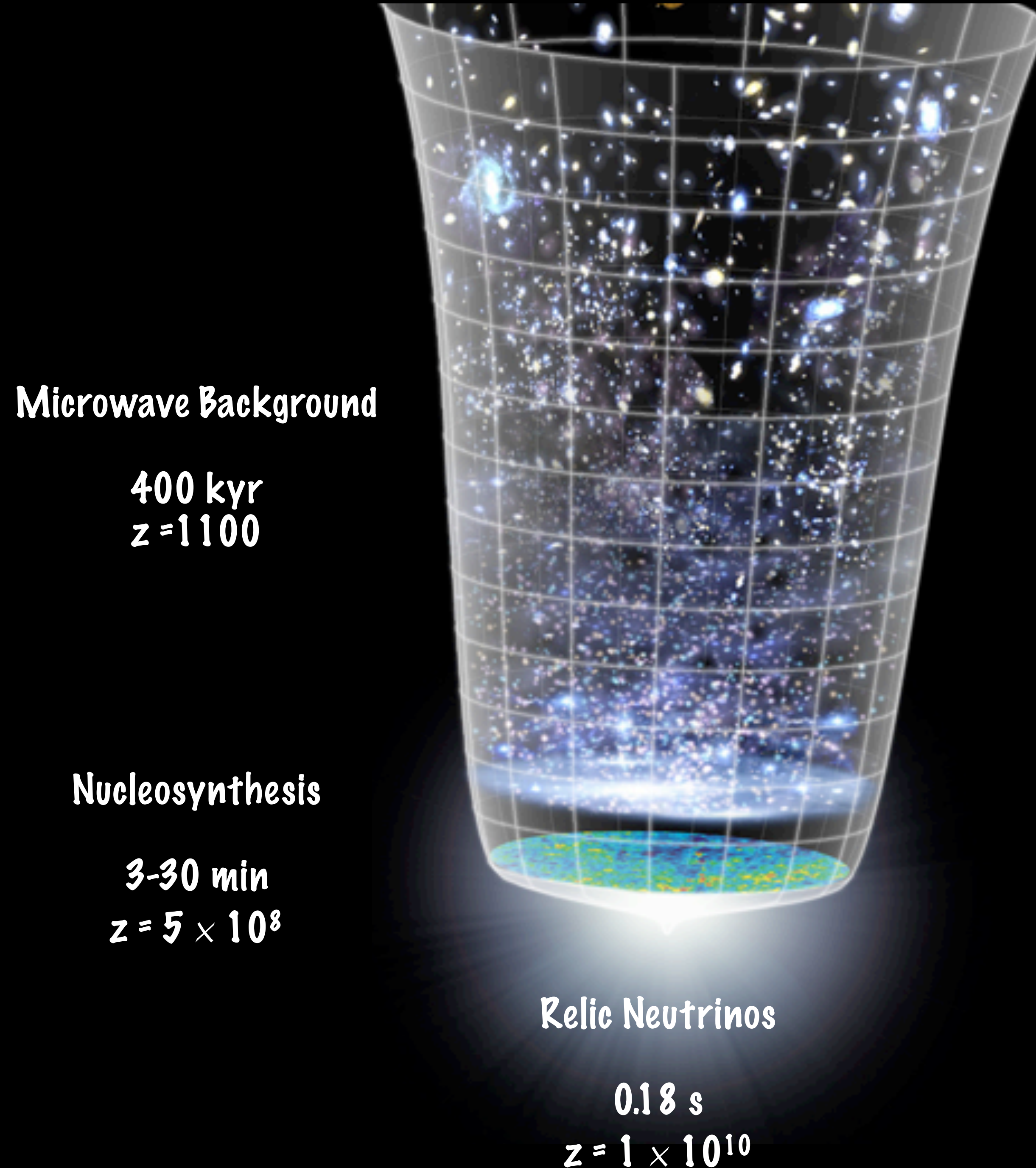
The Triumph of Cosmology

The Triumph of Cosmology



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

The Triumph of Cosmology



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

- Observation of the cosmological neutrinos would then provide a window into the 1st second of creation

Signal Properties

$$f_i(p,T) = \frac{1}{e^{\frac{E_i(p)-\mu_i}{T}} +}$$

- Cosmological neutrinos (or the CνB) are inherently connected to the photon microwave background. However, there are significant differences between the two.

- Some characteristics:

  - The CνB **temperature** is related to the photon temperature (including reheating).

  - The CνB is inherently a gas of spin 1/2 particles: obey **Fermi-Dirac statistics** rather than Bose-Einstein).

  - The CνB **density** is predicted directly from the photon density.

	Bose-Einstein (γ's)	Fermi-Dirac (ν's)
Temperature (Now)	2.725 K	1.945 K
Number density	$\frac{\zeta\{3\}}{\pi^2} g T_\gamma^3$	$\frac{3}{4}\frac{\zeta\{3\}}{\pi^2} g T_\nu^3$
Energy Density	$\frac{\pi^2}{30} g T_\gamma^4$	$\frac{7}{8}\frac{\pi^2}{30} g T_\nu^4$

Signal Properties

$$f_i(p,T) = \frac{1}{e^{\frac{E_i(p)-\mu_i}{T}} + }$$

- Cosmological neutrinos (or the CνB) are inherently connected to the photon microwave background. However, there are significant differences between the two.

- Some characteristics:

  - The CνB **temperature** is related to the photon temperature (including reheating).

  - The CνB is inherently a gas of spin 1/2 particles: obey **Fermi-Dirac statistics** rather than Bose-Einstein).

  - The CνB **density** is predicted directly from the photon density.

	Bose-Einstein (γ's)	Fermi-Dirac (ν's)
Temperature (Now)	2.725 K	1.945 K
Number density	$\frac{\zeta\{3\}}{\pi^2} g T_\gamma^3$	$\frac{3}{4}\frac{\zeta\{3\}}{\pi^2} g T_\nu^3$
Energy Density	$\frac{\pi^2}{30} g T_\gamma^4$	$\frac{7}{8}\frac{\pi^2}{30} g T_\nu^4$

From CMB, the neutrino density is ~110 ν's/cm^3 per flavor.

(neutrino and anti-neutrino)

What about Asymmetries?

- Apriori, we would expect the neutrino and anti-neutrino populations to be the same.
- If they are not, it is an equivalent statement that one can assign a "chemical" potential to their distribution
- Some limits already exist based in cosmological constraints.

$$L_{\nu} = \frac{n_{\nu} - n_{\bar{\nu}}}{n_{\gamma}} = \frac{1}{12\zeta(3)}\left(\frac{T_{\nu}}{T_{\gamma}}\right)^{3}\left[\pi^{2}\xi_{\nu} + \xi_{\nu}^{3}\right]$$

Asymmetries for neutrinos & anti-neutrinos

$$-0.01 \le \xi_{e} \le 0.22 \qquad \left|\xi_{\mu,\tau}\right| \le 2.4$$

Local Enhancement

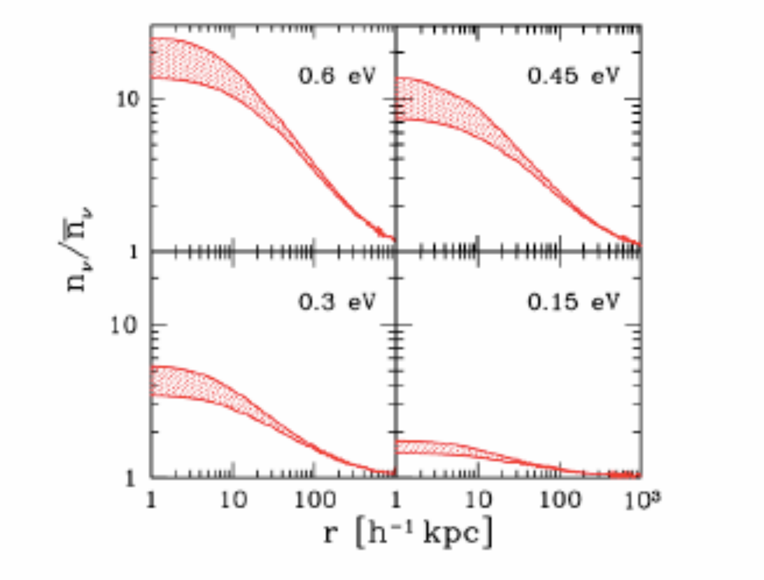
- Because neutrinos have a small (but non-zero) mass, they feel the force of gravity and are thereby affected by it.

- Given the present-day cosmological neutrinos are non-relativistic, one could expect a *local* enhancement of the density of neutrinos in our galaxy.

- Any enhancement should increase the chance at detecting them (a higher local flux).

Local Enhancement

- Because neutrinos have a small (but non-zero) mass, they feel the force of gravity and are thereby affected by it.
- Given the present-day cosmological neutrinos are non-relativistic, one could expect a *local* enhancement of the density of neutrinos in our galaxy.
- Any enhancement should increase the chance at detecting them (a higher local flux).

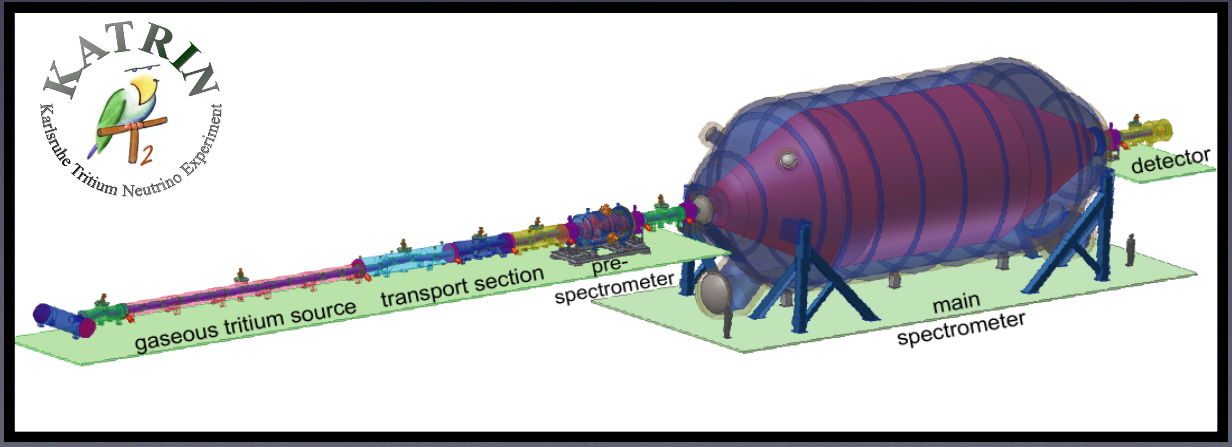


Neutrino Mass & Cosmology

- Beta decay experiments, such as KATRIN, are designed to probe a fundamental *Standard Model* physics parameter:
neutrino mass (m_ν).

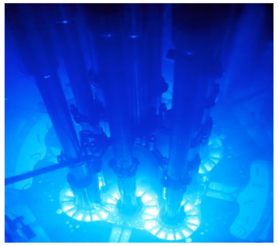
- Such experiments, conversely, can also be cast as measuring a fundamental *cosmological* parameter:
neutrino mass density (Ω_ν) or, indirectly, the number of neutrino species.

- However, can there be sensitivity to the cosmic relic neutrino density (n_ν), or the relic neutrino temperature (T_ν)?



We have a good track record...

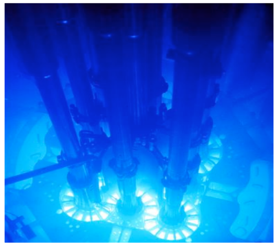
We have a good track record...



Neutrinos from reactors.

Detected (1950s)

We have a good track record...



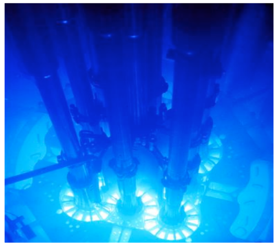
Neutrinos from reactors.

Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

We have a good track record...



Neutrinos from reactors.

Detected (1950s)

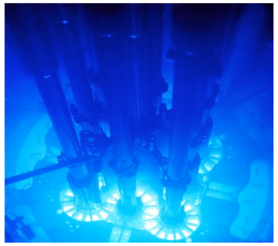
Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

Detected (1960s)

We have a good track record...



Neutrinos from reactors.

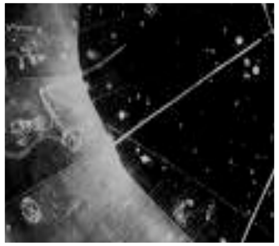
Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

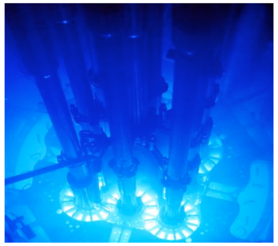
Detected (1960s)



Neutrinos from accelerators.

Created & detected (1960s)

We have a good track record...



Neutrinos from reactors.

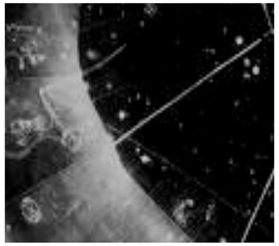
Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

Detected (1960s)



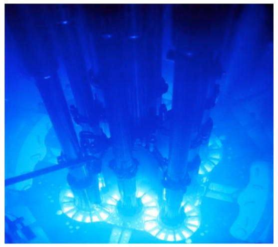
Neutrinos from accelerators.

Created & detected (1960s)

Neutrinos from supernovae.

Detected (1980s)

We have a good track record...



Neutrinos from reactors.

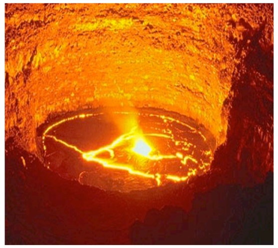
Detected (1950s)

Neutrinos from supernovae.

Detected (1980s)

Neutrinos from the sun.

Detected (1960s)

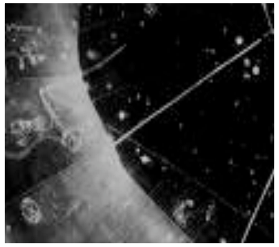


Neutrinos from the Earth.

Detected (2000s)

Neutrinos from the atmosphere.

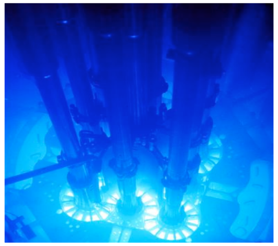
Detected (1960s)



Neutrinos from accelerators.

Created & detected (1960s)

We have a good track record...



Neutrinos from reactors.

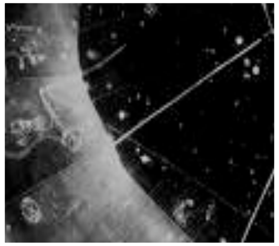
Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

Detected (1960s)

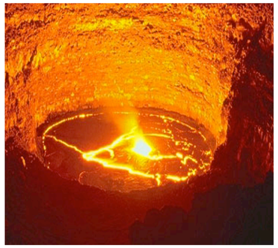


Neutrinos from accelerators.

Created & detected (1960s)

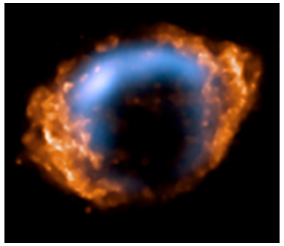
Neutrinos from supernovae.

Detected (1980s)



Neutrinos from the Earth.

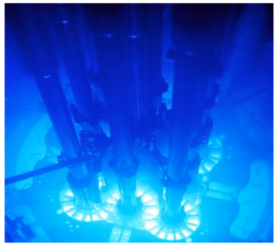
Detected (2000s)



Neutrinos from galactic sources.

Not yet (but close!)

We have a good track record...



Neutrinos from reactors.

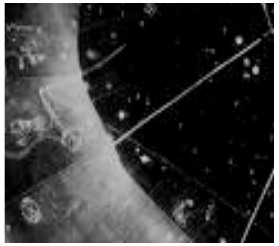
Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

Detected (1960s)

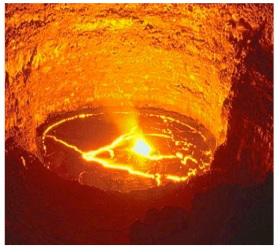


Neutrinos from accelerators.

Created & detected (1960s)

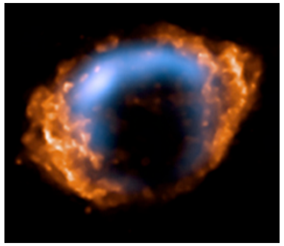
Neutrinos from supernovae.

Detected (1980s)



Neutrinos from the Earth.

Detected (2000s)



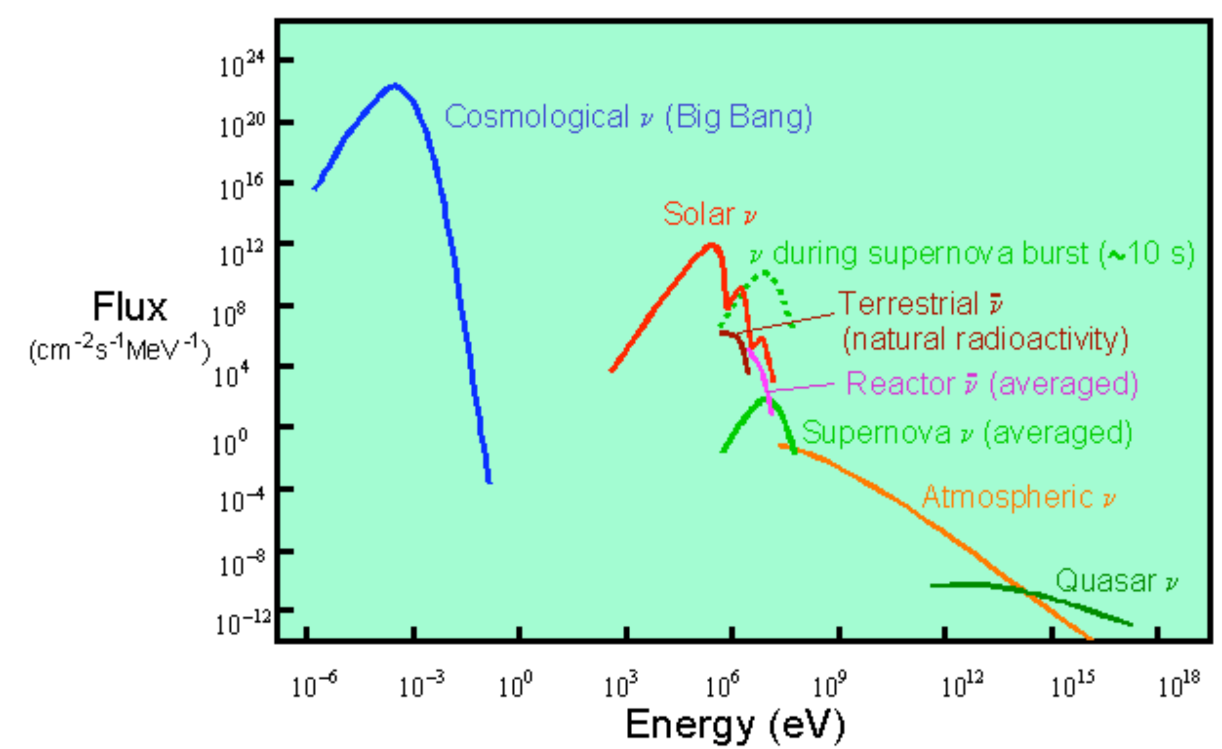
Neutrinos from galactic sources.

Not yet (but close!)

Neutrinos from the Big Bang.

Not even close...

Why is it so hard???



Flux on earth of neutrinos from various sources, in function of energy

- Cosmological neutrinos comprise the most intense natural source of neutrinos available to us from nature.
- The cosmological photon background has been measured incredibly well. The noise from the early big bang still rings today.

So??

What's the problem?!

Why is it so hard???

"Choice. The problem is choice."

- Actually, the problem is THRESHOLD.
- Consider, for example, ordinary inverse beta decay.

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

$$E_\nu + m_p \geq m_e + m_n$$

- Since energy is conserved, you need the neutrino to have enough energy to initiate the process.
- But here the kinetic energy from relics is very small.

$$< K >= 6.5 T_\nu^2 / m_\nu \text{ or } 3.15 T_\nu$$

- For most nuclei, you just do not have enough energy. You need a threshold-less process.

Some quotes....

Some quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

Some quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

Some Ideas on the Table...

- Various methods proposed:

  (1) Mechanical force due to coherent scattering.

  (2) Neutrino scattering on accelerator beams.

  (3) Cosmic ray scattering

  (4) Neutrino capture on beta nuclei

Coherent Scattering

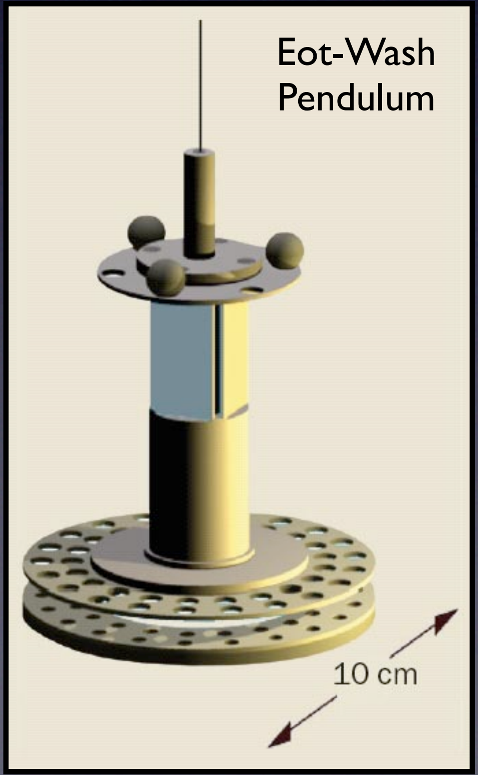
- Consider the scattering of a macroscopic object against the neutrino *wind*.
- This wind is actually the motion of the earth with respect to the neutrinos (similar to moving through a dark matter halo).
- Consider the coherent scattering of neutrinos against an object (spheres) and look at the force imposed by the neutrino wind.

$$\sigma = G_F^2 m_\nu^2 \frac{k_L^2}{\pi} \quad \text{(scattering)}$$

$$\frac{d\vec{p}}{dt} = F_\nu \sigma \Delta p \quad \text{(mom. trans.)}$$

Coherent Elastic Scattering

- Effect takes advantage of a macroscopic de Broglie wavelength (for these momenta).
- Equivalent to measuring a small acceleration on a macroscopic object.
- Currently can measure accelerations down to 10^{-13} cm/s^2. Can push this down to 10^{-23} cm/s^2 in the future.



$$a_t \simeq (10^{-46} - 10^{-54}) \frac{A}{100} \text{ cm s}^{-2}$$

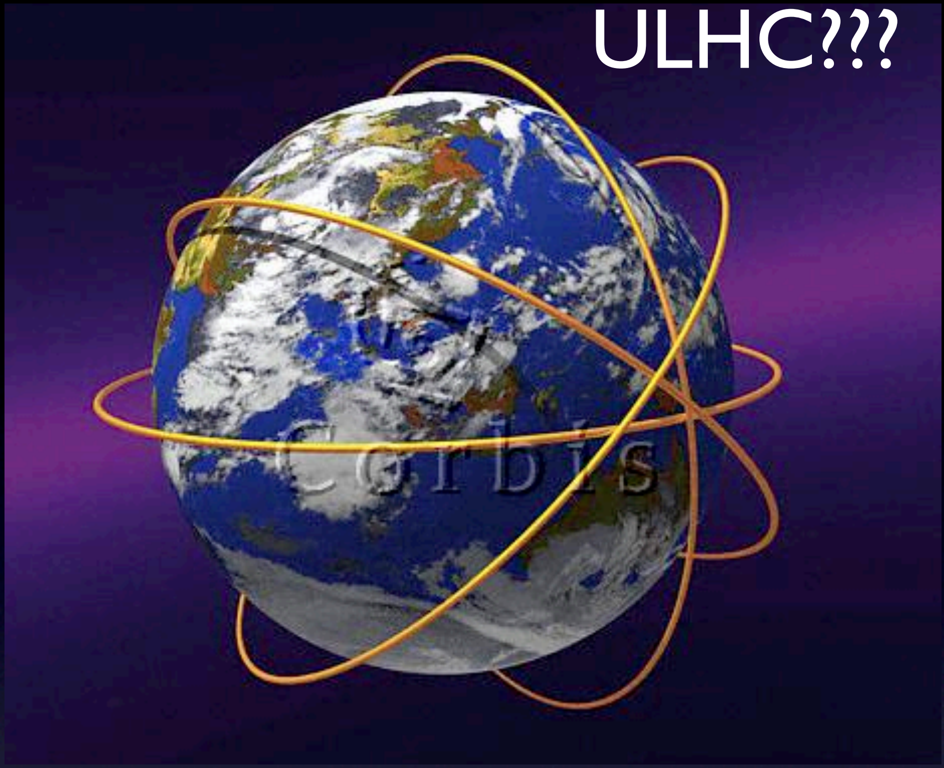
High Energy Scattering : Beams

- Take advantage of cross-section growth with energy, using very high energy isotopes as probes.
- Two possible sources: high energy accelerators & cosmic rays.
- Most parameters necessary for relic neutrino detection beyond scope of conventional machines.

accel.	N	E_N [TeV]	L [km]	I [A]	$\frac{R_\nu A}{\left[\frac{n_\nu}{\bar{n}_\nu}\frac{m_\nu}{\mathrm{eV}}\right]}$ [yr^{-1}]
LHC	p	7	26.7	0.6	2×10^{-8}
	Pb	574	26.7	0.006	1×10^{-5}
VLHC	p	87.5	233	0.06	2×10^{-7}
	Pb	7280	233	0.0006	1×10^{-4}
ULHC	p	10^7	40 000	0.1	10

$$R_\nu = 2 \times 10^{-9} \cdot \frac{m_\nu}{\mathrm{eV}} \frac{A^2}{Z} \frac{E_n}{10\mathrm{TeV}} \frac{L}{\mathrm{km}} \frac{I}{\mathrm{A}} [\mathrm{yr}^{-1}]$$

High Energy Scattering : Beams



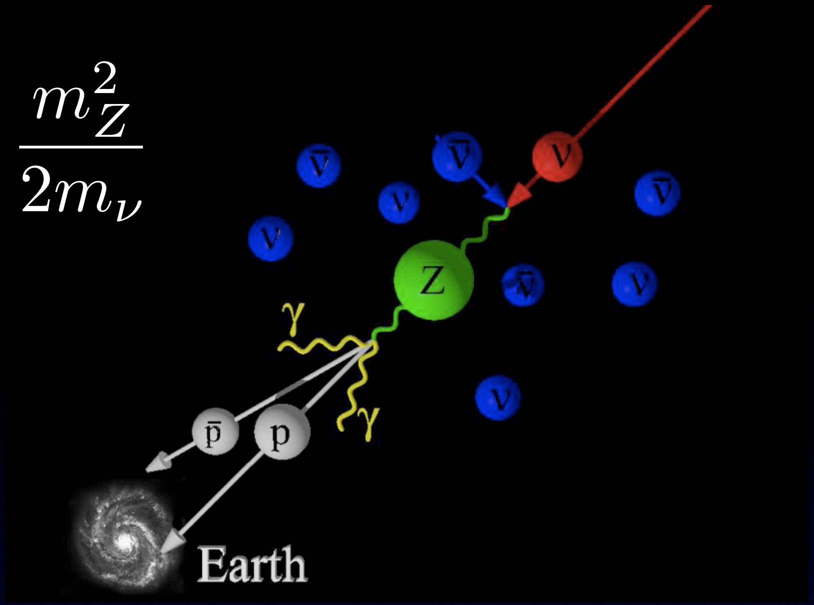
- Take advantage of cross-section growth with energy, using very high energy isotopes as probes.
- Two possible sources: high energy accelerators & cosmic rays.
- Most parameters necessary for relic neutrino detection beyond scope of conventional machines.

accel.	N	E_N [TeV]	L [km]	I [A]	$\frac{R_\nu A}{\left[\frac{n_\nu}{\bar{n}_\nu}\frac{m_\nu}{\mathrm{eV}}\right]}$ [yr^{-1}]
LHC	p	7	26.7	0.6	2×10^{-8}
	Pb	574	26.7	0.006	1×10^{-5}
VLHC	p	87.5	233	0.06	2×10^{-7}
	Pb	7280	233	0.0006	1×10^{-4}
ULHC	p	10^7	40 000	0.1	10

$$R_\nu = 2 \times 10^{-9} \cdot \frac{m_\nu}{\mathrm{eV}} \frac{A^2}{Z} \frac{E_n}{10\mathrm{TeV}} \frac{L}{\mathrm{km}} \frac{I}{\mathrm{A}} [\mathrm{yr}^{-1}]$$

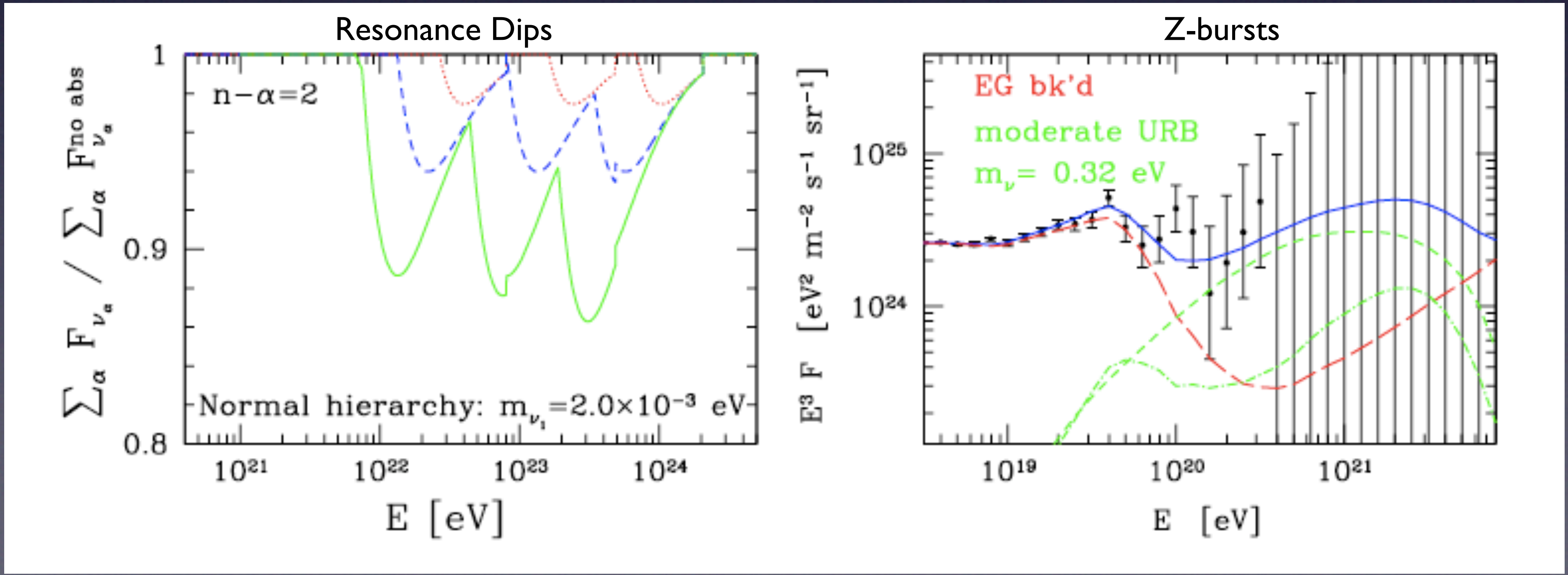
High Energy Scattering : Cosmic Rays

$$E_\nu^{\mathrm{res}} = \frac{m_Z^2}{2m_\nu}$$



- Conversely, one can use cosmic rays as the high energy source.

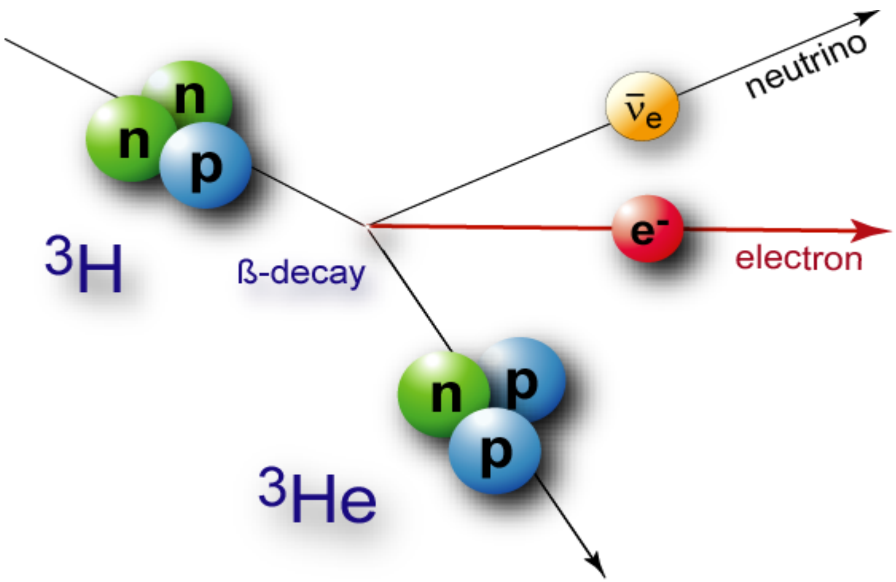
- One can look at absorption of extremely high energy neutrinos near the Z-resonance, or for emission features above the natural GZK cutoff.



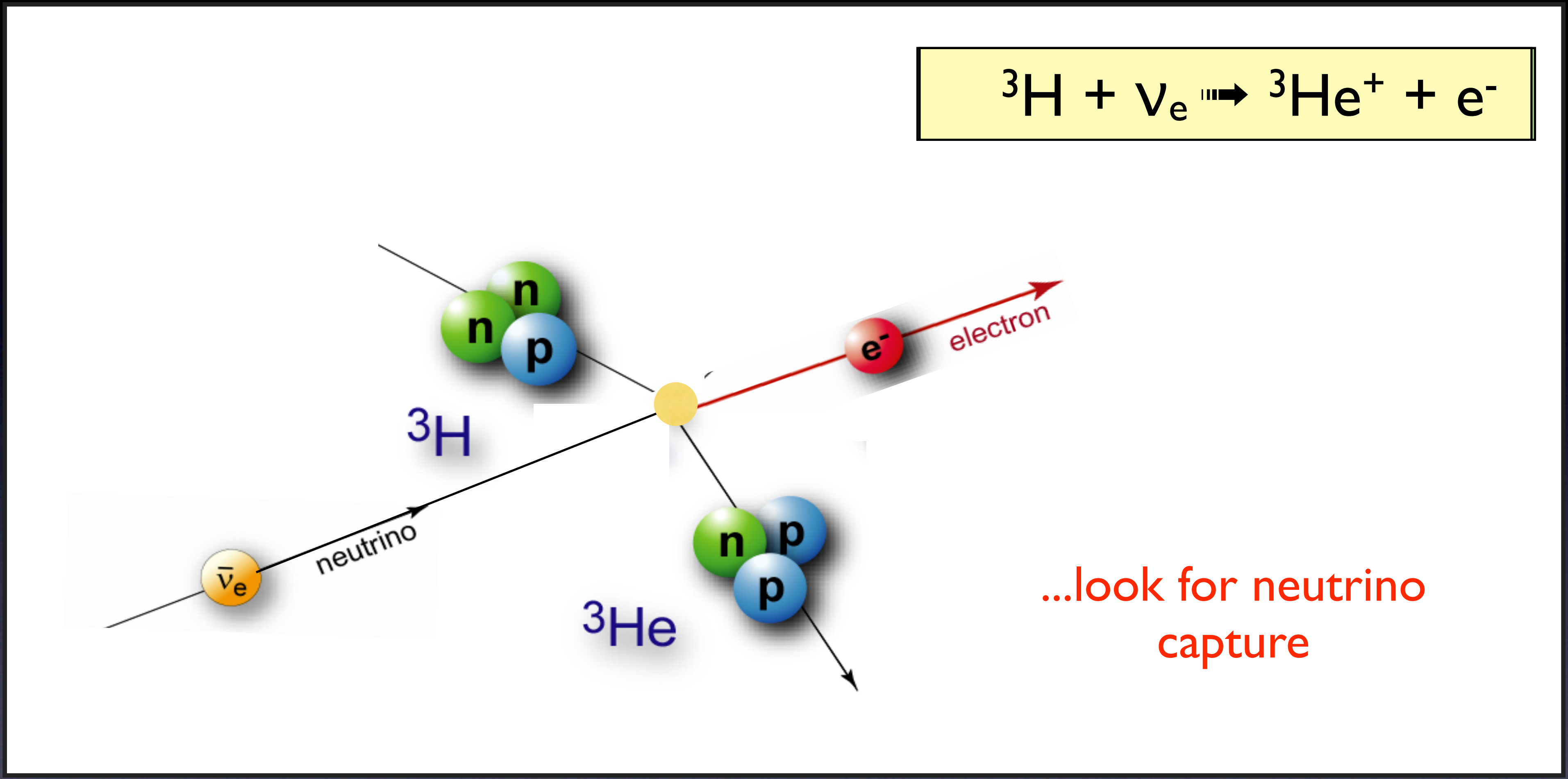
Neutrino Capture

Instead of beta decay...

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



Neutrino Capture

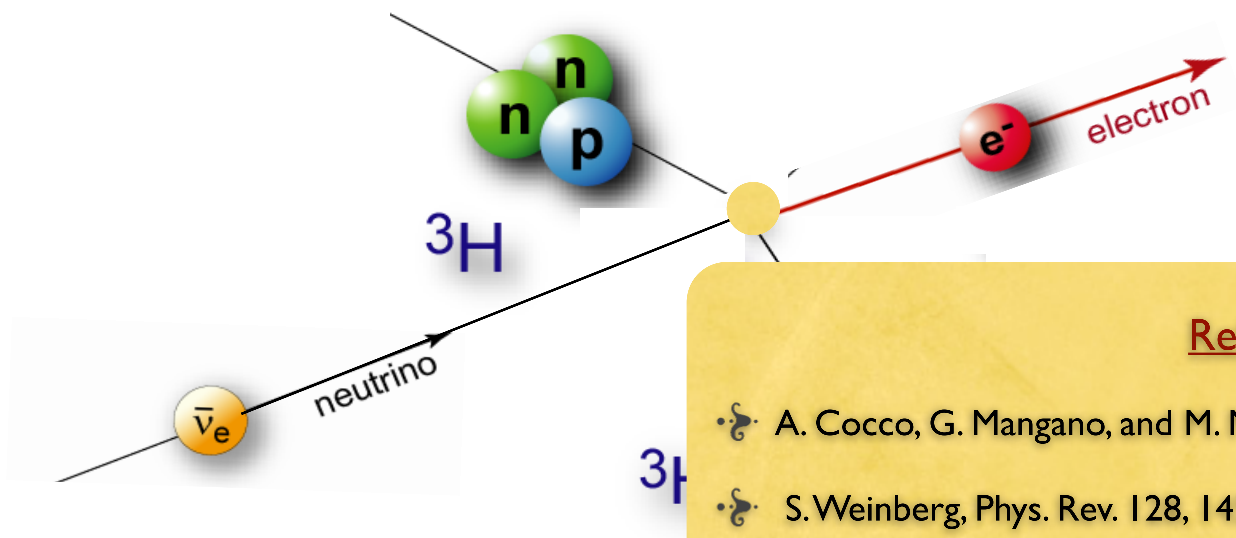


The process is energetically allowed even at zero momentum.

This threshold-less reaction allows for relic neutrino detection

Neutrino Capture

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



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).

The process is energetically allowed even at zero momentum.

This threshold-less reaction allows for relic neutrino detection

Beta Decay: Review

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

Beta Decay: Review

- 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).

Beta Decay: Review

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

  - The **phase space** of the decay (i.e. how many different states can occupy a particular momentum).

  - Corrections due to the Coulomb field, or **Fermi function**.

Beta Decay: Review

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

    - The **phase space** of the decay (i.e. how many different states can occupy a particular momentum).

    - Corrections due to the Coulomb field, or **Fermi function**.

    - The **matrix element** related to the initial and final states of the decay.

Beta Decay: Review

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

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

Beta Decay: Review

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

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

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

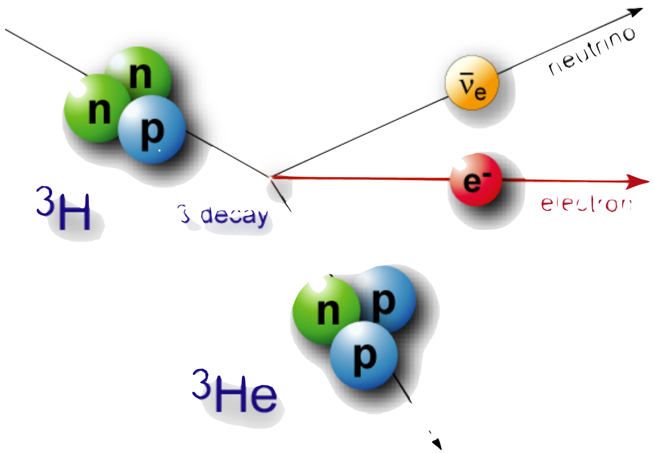
Fermi Function

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

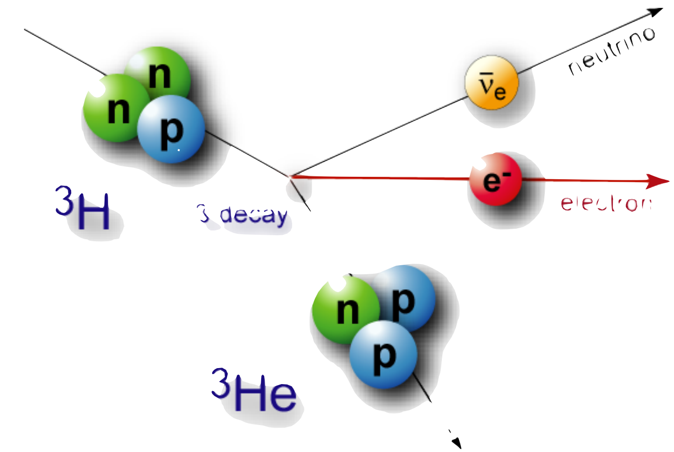
Matrix Element

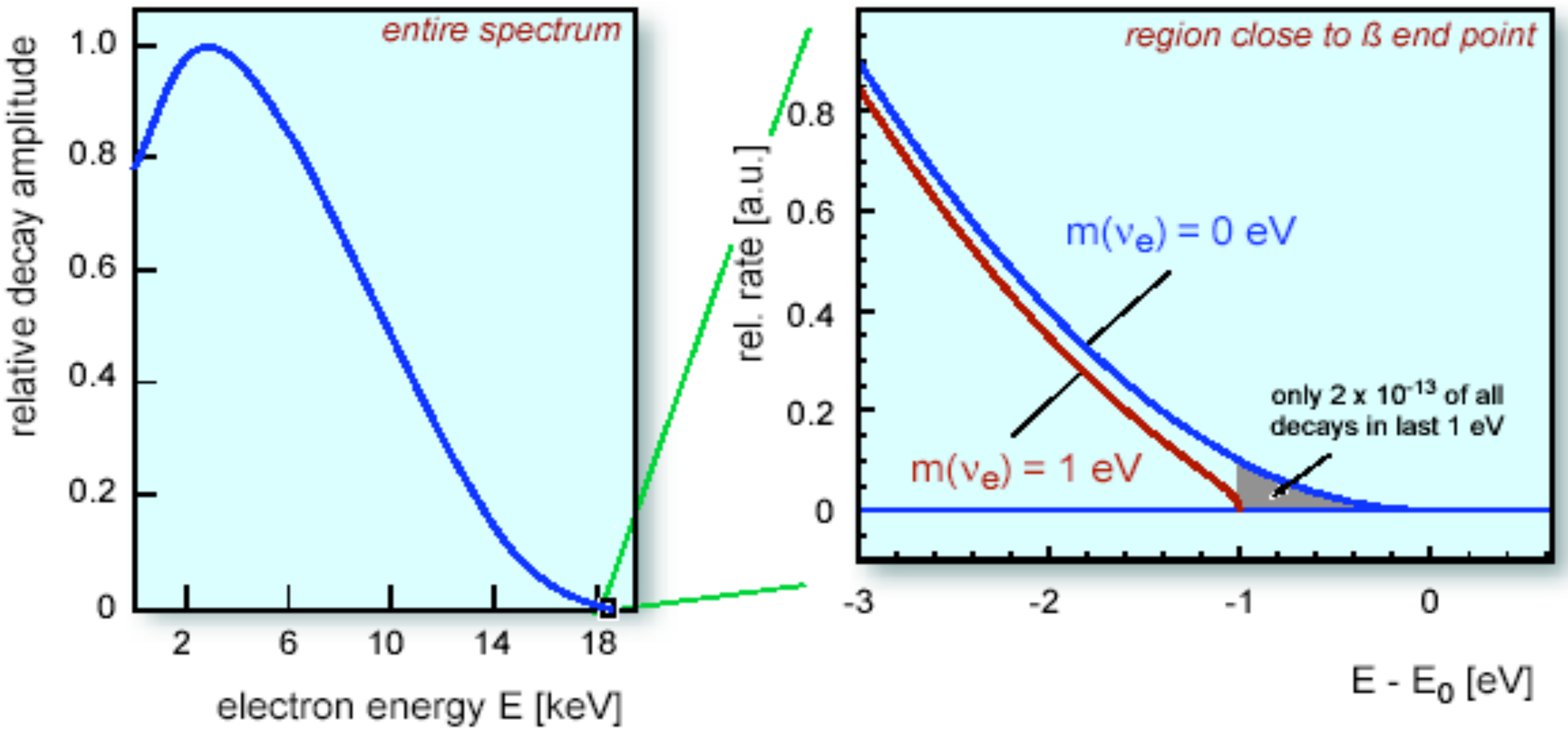
Phase space

Measuring the Endpoint *Spectrum*



Measuring the Endpoint *Spectrum*





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

Detecting the Impossible

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

Neutrino Capture Rate

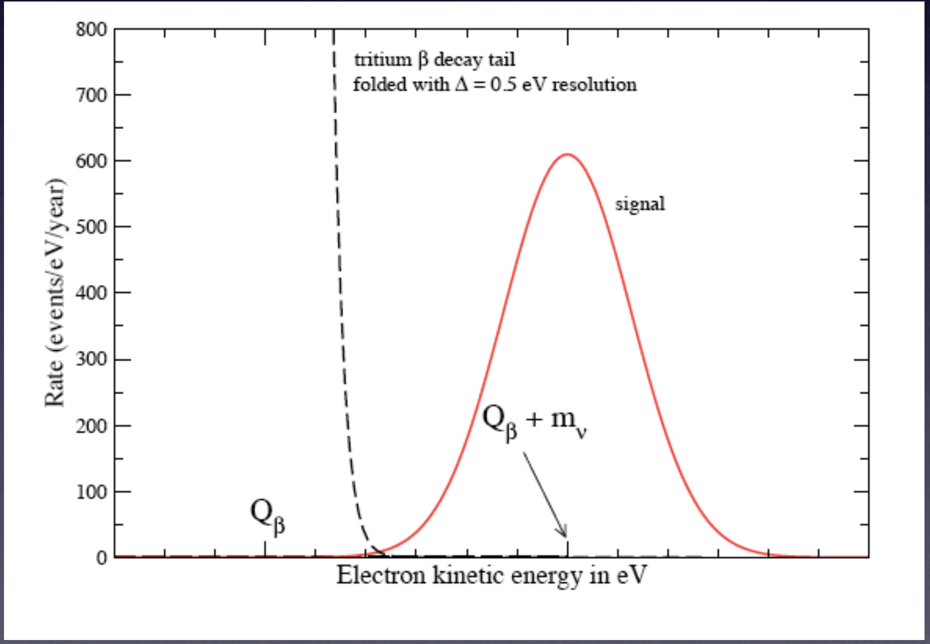
$$\sigma_\nu \cdot \frac{v}{c} = (7.84 \pm 0.03) \times 10^{-45} cm^2$$

Tritium Cross-Section

- The process is exothermic. There is enough energy for the decay to occur (because beta decay will happen anyway).

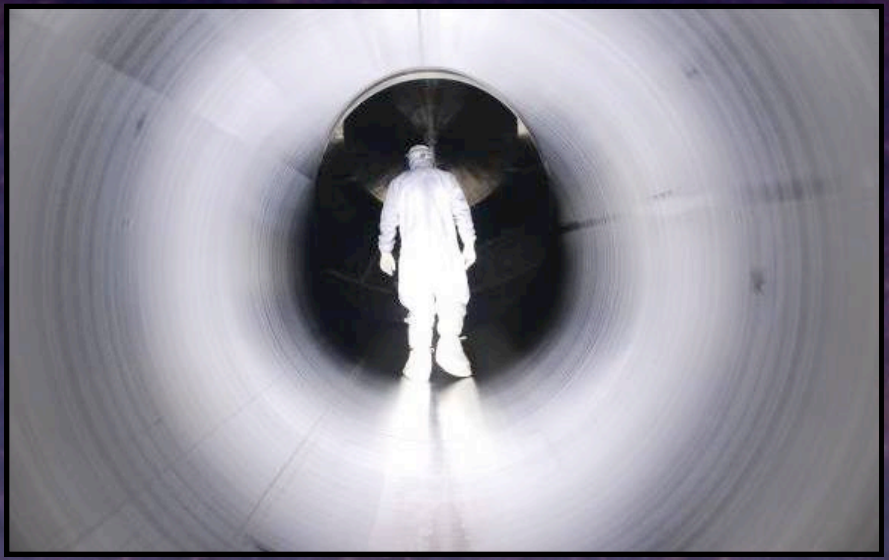
- Cross-section falls like the inverse velocity, while flux depends on velocity, so event rate is constant.

$$\sigma = \sigma_0 \times \langle \frac{c}{v_\nu} E_e p_e F(Z, E_e) \rangle \frac{2I' + 1}{2I + 1}$$



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

Obstacles for a Relic Neutrino Measurement



Obstacles for a Relic Neutrino Measurement

31.25 Mpc/h

Experimental needs

Obstacles for a Relic Neutrino Measurement

Target:

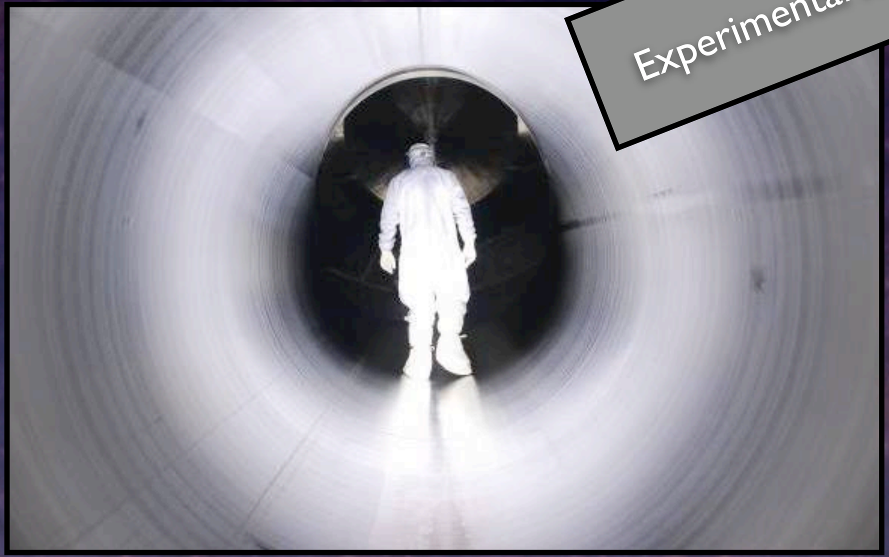
What targets are best suited for this technique?

31.25 Mpc/h

Experimental needs

Obstacles for a Relic Neutrino Measurement

31.25 Mpc/h



Experimental needs

Target:

What targets are best suited for this technique?

Energy Resolution:

How to best separate the radioactivity from signal?

Obstacles for a Relic Neutrino Measurement

31.25 Mpc/h

Experimental needs

Target:

What targets are best suited for this technique?

Energy Resolution:

How to best separate the radioactivity from signal?

Backgrounds:

What about other background activities?

The Targets

- The half-life of the beta-decay isotope essentially determines the rate at which the neutrino capture reaction occurs.
- Rate (for nominal neutrino density) can therefore be computed.
- Tritium emerges as the one isotope adaptable for relic neutrino detection.

Isotope	Endpoint (keV)	Half-Life (s)	Cross-Section (10^{-41} cm^2)	Rate (yr^{-1} kg^{-1})
^{3}H	18.591	3.89×10^8	7.84×10^{-4}	75
^{106}Ru	39.4	3.23×10^7	5.88×10^{-4}	1.6
^{187}Re	2.64	1.37×10^{18}	4.32×10^{-11}	4.7×10^{-11}
^{11}C†	960.	1.27×10^3	4.66×10^{-3}	120.8
^{13}N†	1199.	5.99×10^2	9.75×10^{-3}	116.2
^{15}O†	1732.	1.22×10^2	9.75×10^{-3}	185.3

The Targets

- The half-life of the beta-decay isotope essentially determines the rate at which the neutrino capture reaction occurs.
- Rate (for nominal neutrino density) can therefore be computed.
- Tritium emerges as the one isotope adaptable for relic neutrino detection.

Isotope	Endpoint (keV)	Half-Life (s)	Cross-Section (10^{-41} cm^2)	Rate (yr^{-1} kg^{-1})
^{3}H	18.591	3.89×10^{8}	7.84×10^{-4}	75
^{106}Ru	39.4	3.23×10^{7}	5.88×10^{-4}	1.6
^{187}Re	2.64	1.37×10^{18}	4.32×10^{-11}	4.7×10^{-11}
^{11}C†	960.	1.27×10^{3}	4.66×10^{-3}	120.8
^{13}N†	1199.	5.99×10^{2}	9.75×10^{-3}	116.2
^{15}O†	1732.	1.22×10^{2}	9.75×10^{-3}	185.3

The Targets

- The half-life of the beta-decay isotope essentially determines the rate at which the neutrino capture reaction occurs.
- Rate (for nominal neutrino density) can therefore be computed.
- Tritium emerges as the one isotope adaptable for relic neutrino detection.

Isotope	Endpoint (keV)	Half-Life (s)	Cross-Section (10^{-41} cm^2)	Rate (yr^{-1} kg^{-1})
^{3}H	18.591	3.89×10^8	7.84×10^{-4}	75
^{106}Ru	39.4	3.23×10^7	5.88×10^{-4}	1.6
^{187}Re	2.64	1.37×10^{18}	4.32×10^{-11}	4.7×10^{-11}
^{11}C†	960.	1.27×10^3	4.66×10^{-3}	120.8
^{13}N†	1199.	5.99×10^2	9.75×10^{-3}	116.2
^{15}O†	1732.	1.22×10^2	9.75×10^{-3}	185.3

The Targets

- The half-life of the beta-decay isotope essentially determines the rate at which the neutrino capture reaction occurs.
- Rate (for nominal neutrino density) can therefore be computed.
- Tritium emerges as the one isotope adaptable for relic neutrino detection.

Isotope	Endpoint (keV)	Half-Life (s)	Cross-Section (10^{-41} cm^2)	Rate (yr^{-1} kg^{-1})
^{3}H	18.591	3.89×10^{8}	7.84×10^{-4}	75
^{106}Ru	39.4	3.23×10^{7}	5.88×10^{-4}	1.6
^{187}Re	2.64	1.37×10^{18}	4.32×10^{-11}	4.7×10^{-11}
$^{11}C^{\dagger}$	960.	1.27×10^{3}	4.66×10^{-3}	120.8
$^{13}N^{\dagger}$	1199.	5.99×10^{2}	9.75×10^{-3}	116.2
$^{15}O^{\dagger}$	1732.	1.22×10^{2}	9.75×10^{-3}	185.3

The Targets

- The half-life of the beta-decay isotope essentially determines the rate at which the neutrino capture reaction occurs.
- Rate (for nominal neutrino density) can therefore be computed.
- Tritium emerges as the one isotope adaptable for relic neutrino detection.

Isotope	Endpoint (keV)	Half-Life (s)	Cross-Section (10^{-41} cm^2)	Rate (yr^{-1} kg^{-1})
^{3}H	18.591	3.89×10^{8}	7.84×10^{-4}	75
^{106}Ru	39.4	3.23×10^{7}	5.88×10^{-4}	1.6
^{187}Re	2.64	1.37×10^{18}	4.32×10^{-11}	4.7×10^{-11}
$^{11}C^{\dagger}$	960.	1.27×10^{3}	4.66×10^{-3}	120.8
$^{13}N^{\dagger}$	1199.	5.99×10^{2}	9.75×10^{-3}	116.2
$^{15}O^{\dagger}$	1732.	1.22×10^{2}	9.75×10^{-3}	185.3

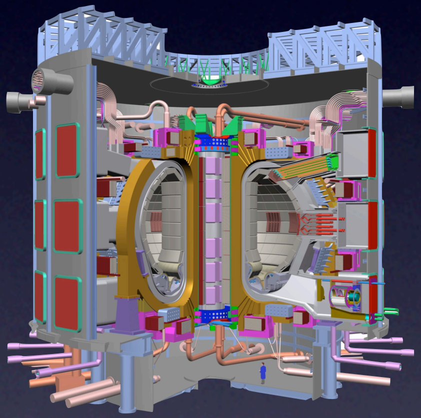
Bottom Line: 100 g of ^{3}H provides ~10 events/year

Intense Tritium Sources

KATRIN:

~100 µg (target)

ITER:



~3 kg (initial)

Exit Signs:

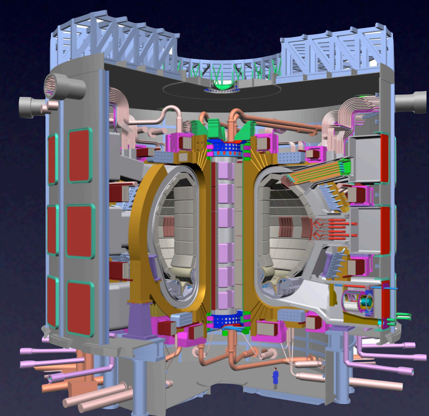
~1 mg

Intense Tritium Sources

KATRIN:

~100 μg (target)

ITER:



~3 kg (initial)

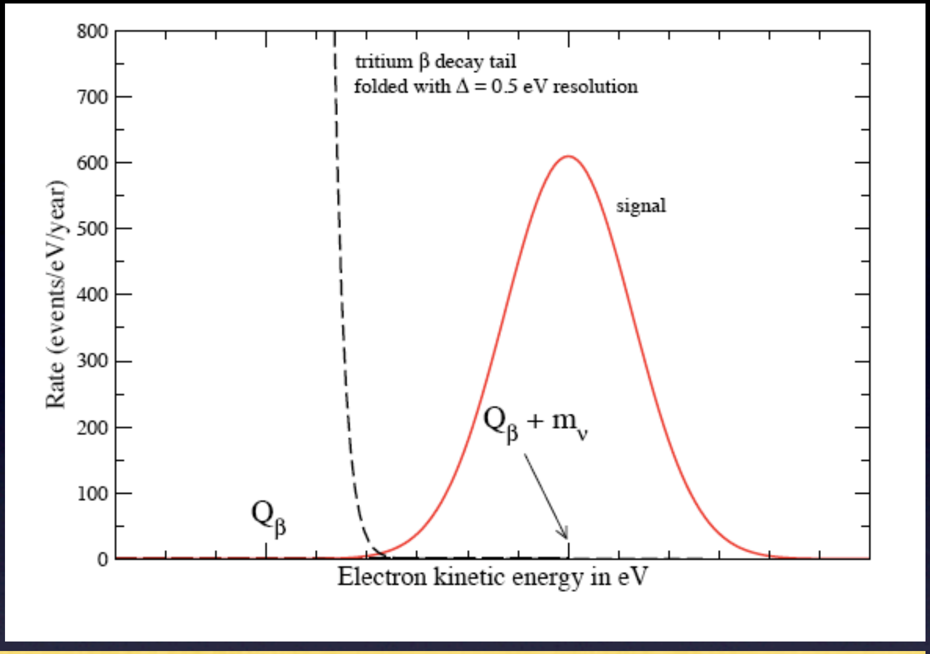
Exit Signs:

~1 mg

Intense tritium sources (order ~100 g) are obtainable

The Need for Resolution...

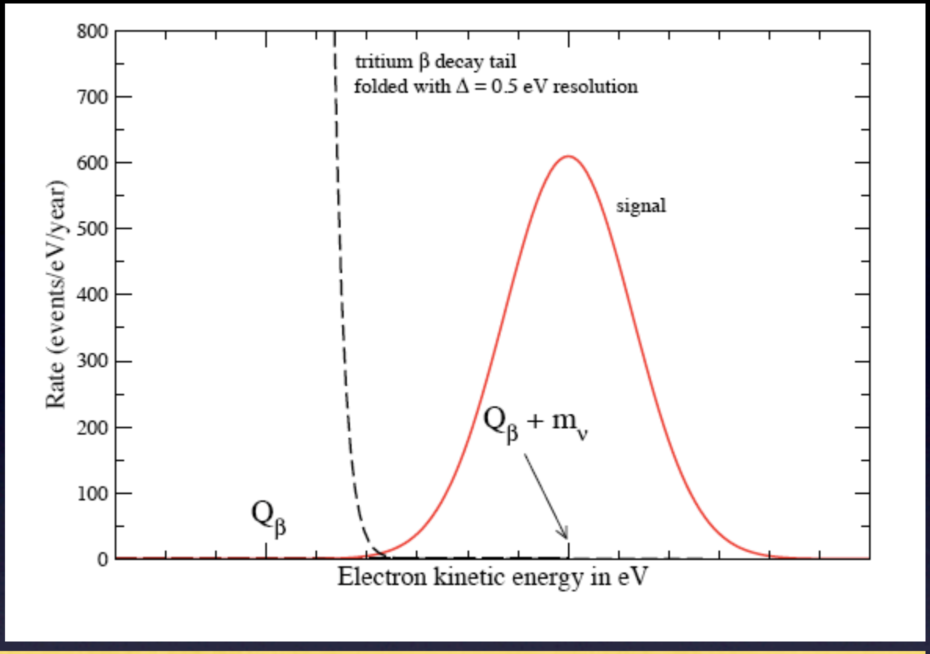
- Resolution is a key ingredient in the tagging of this process.
- As in neutrinoless double beta decay, one must separate the (more abundant) beta decay rate from the (rare) neutrino capture signal.
- The only separation stems from the energy difference (i.e. $2m_\nu$).
- Even if achieved, the background in the signal region must be < 1 event/year.



R. Lazauskas, P. Vogel, C. Volpe arXiv:0710.5312

The Need for Resolution...

- Resolution is a key ingredient in the tagging of this process.
- As in neutrinoless double beta decay, one must separate the (more abundant) beta decay rate from the (rare) neutrino capture signal.
- The only separation stems from the energy difference (i.e. $2m_\nu$).
- Even if achieved, the background in the signal region must be < 1 event/year.



R. Lazauskas, P. Vogel, C. Volpe arXiv:0710.5312

In general, we want $\Delta \leq m_\nu$

Some More Quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

Some More Quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

"... In all fairness, this method [neutrino capture] appears to have survived the longest." *P. Fisher*

Some More Quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

"... In all fairness, this method [neutrino capture] appears to have survived the longest." *P. Fisher*

"Anyone who can measure relic neutrinos via neutrino capture will have made an amazing neutrino mass measurement..." *G. Drexlin*

Some More Quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

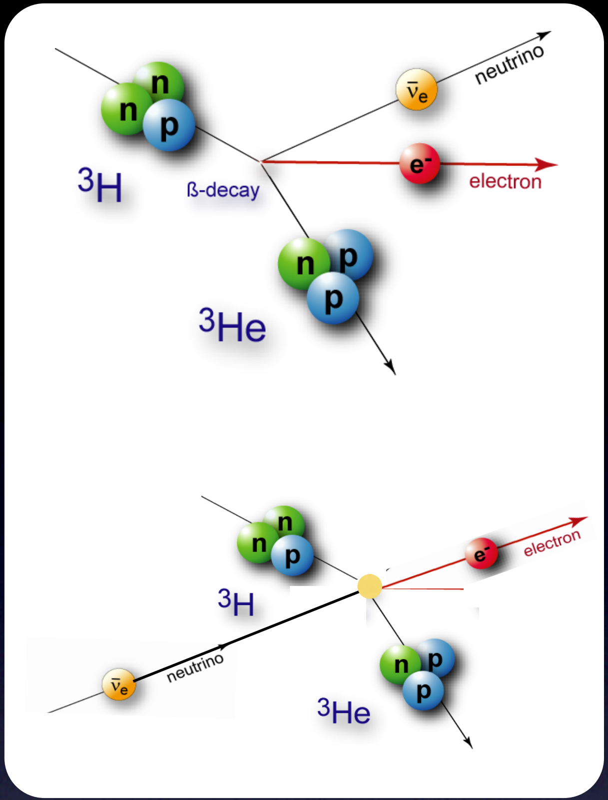
"... In all fairness, this method [neutrino capture] appears to have survived the longest." *P. Fisher*

"Anyone who can measure relic neutrinos via neutrino capture will have made an amazing neutrino mass measurement..." *G. Drexlin*

"If it were easy, we'd be done by now..." *my translation*

The Connection between Neutrino Mass and Relic Detection

- It is clear that the methods one would employ for a next-generation kinematic neutrino mass measurement would apply equally to neutrino capture.
- Let's highlight the methods on the table and examine their scalability.



- The KATRIN tritium beta decay experiment
- The MARE bolometric neutrino experiment

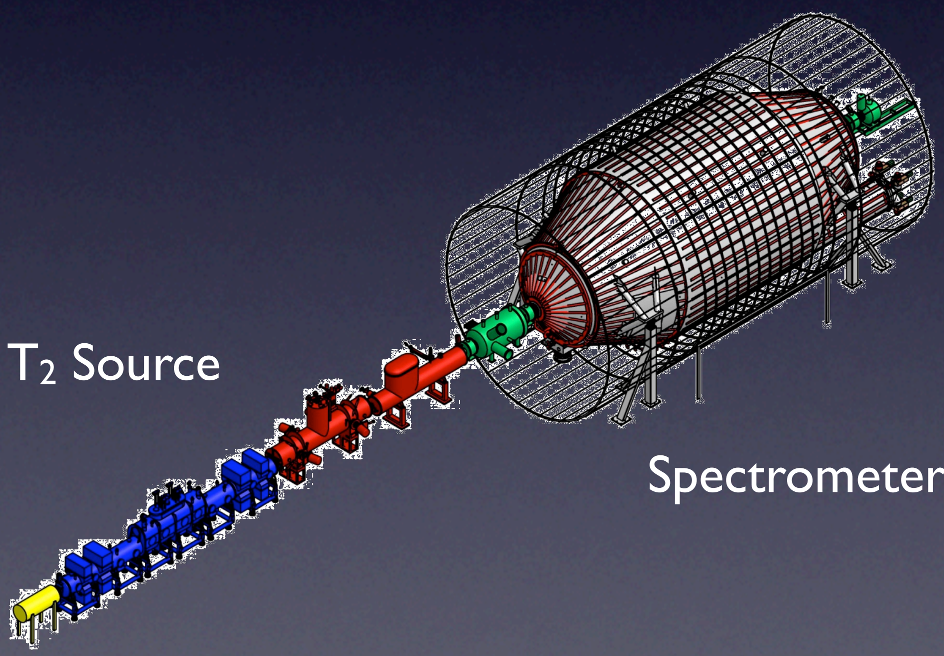
Ongoing experiments

- Atomic tritium trap with full kinematic reconstruction
  - (M. Jerkins, J. Klein, J. Majors, F. Robichaeux, M. Raizen, arXiv:0901:3111)
- Decay of radioactive ions in a storage ring
  - M. Lindroos, B. McElrath, C. Orme, T. Shwetz arXiv:0904:1091)
- Detection of RF cyclotron radiation from β orbiting in magnetic field
  - B. Monreal, J.F. arXiv:0904:2860)

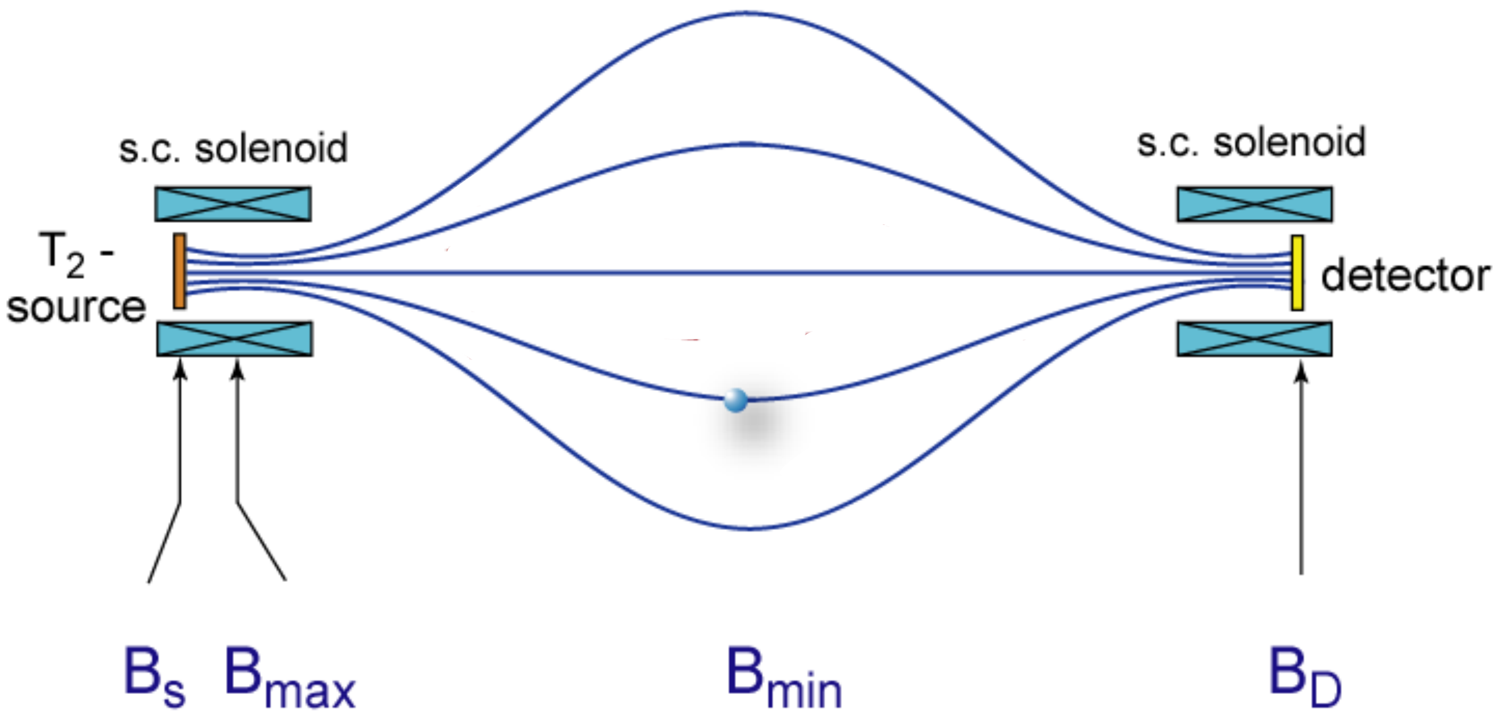
Future Ideas

The KATRIN Experiment

- The KATRIN experiment uses *magnetic adiabatic collimation* with *electrostatic filtering* to achieve its energy resolution.
- Target activity is approximately 4.7 Ci. Energy resolution from spectrometer is 0.93 eV.



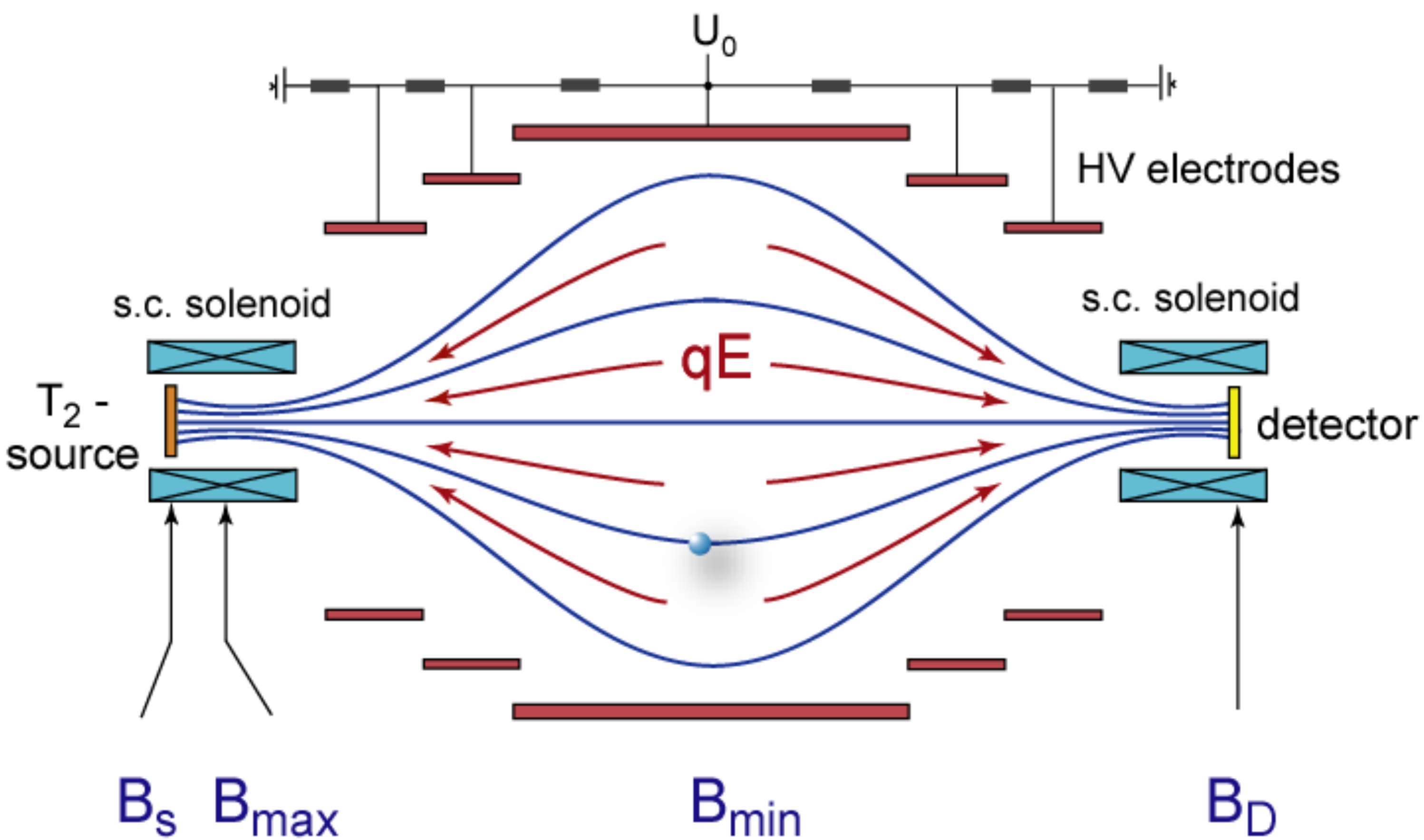
The MAC-E Filter Technique



Magnetic Adiabatic Collimation:

- Use adiabatic guiding to move β^- particles along B-field lines.
- Field constrained by 2 s.c magnets.

The MAC-E Filter Technique



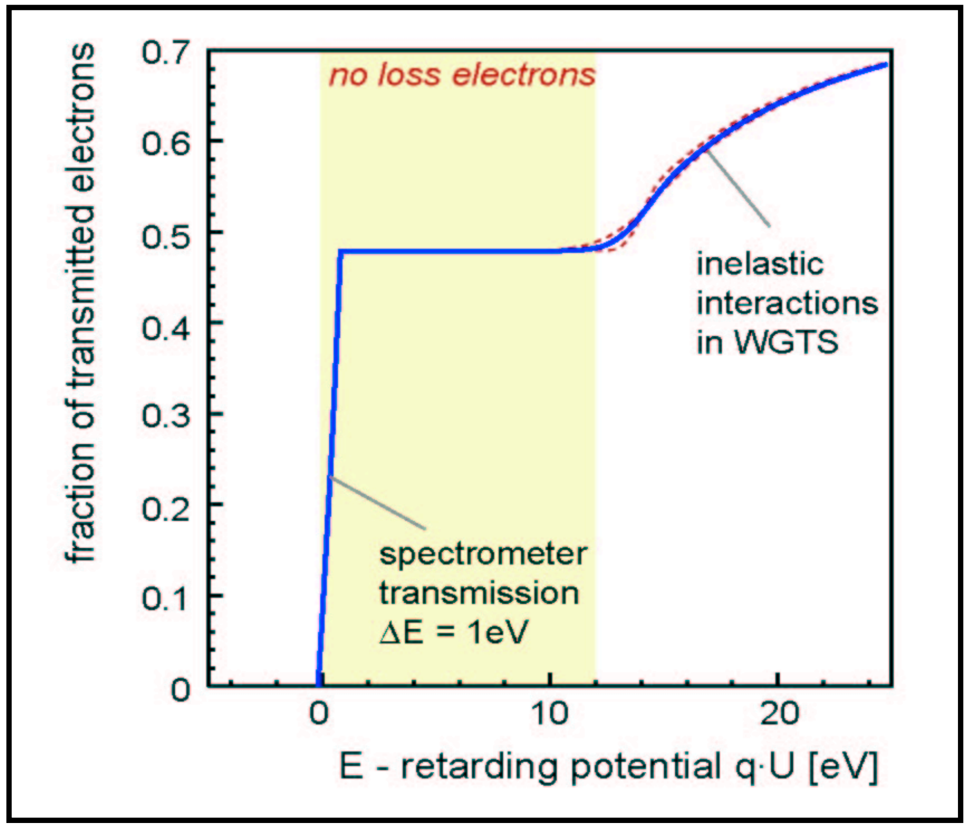
Magnetic Adiabatic Collimation:

- Use adiabatic guiding to move β⁻ particles along B-field lines.
- Field constrained by 2 s.c magnets.

Electrostatic Filter:

- Use retarding potential to remove β⁻ particle below threshold.
- High pass filter (variable potential)

The MAC-E Filter Technique



Magnetic Adiabatic Collimation:

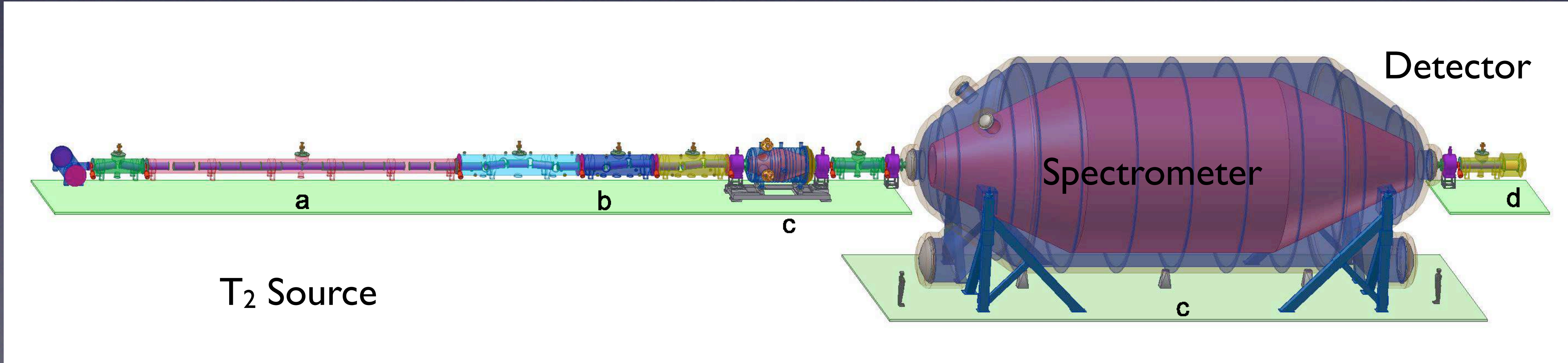
- Use adiabatic guiding to move β^-particles along B-field lines.
- Field constrained by 2 s.c magnets.

Electrostatic Filter:

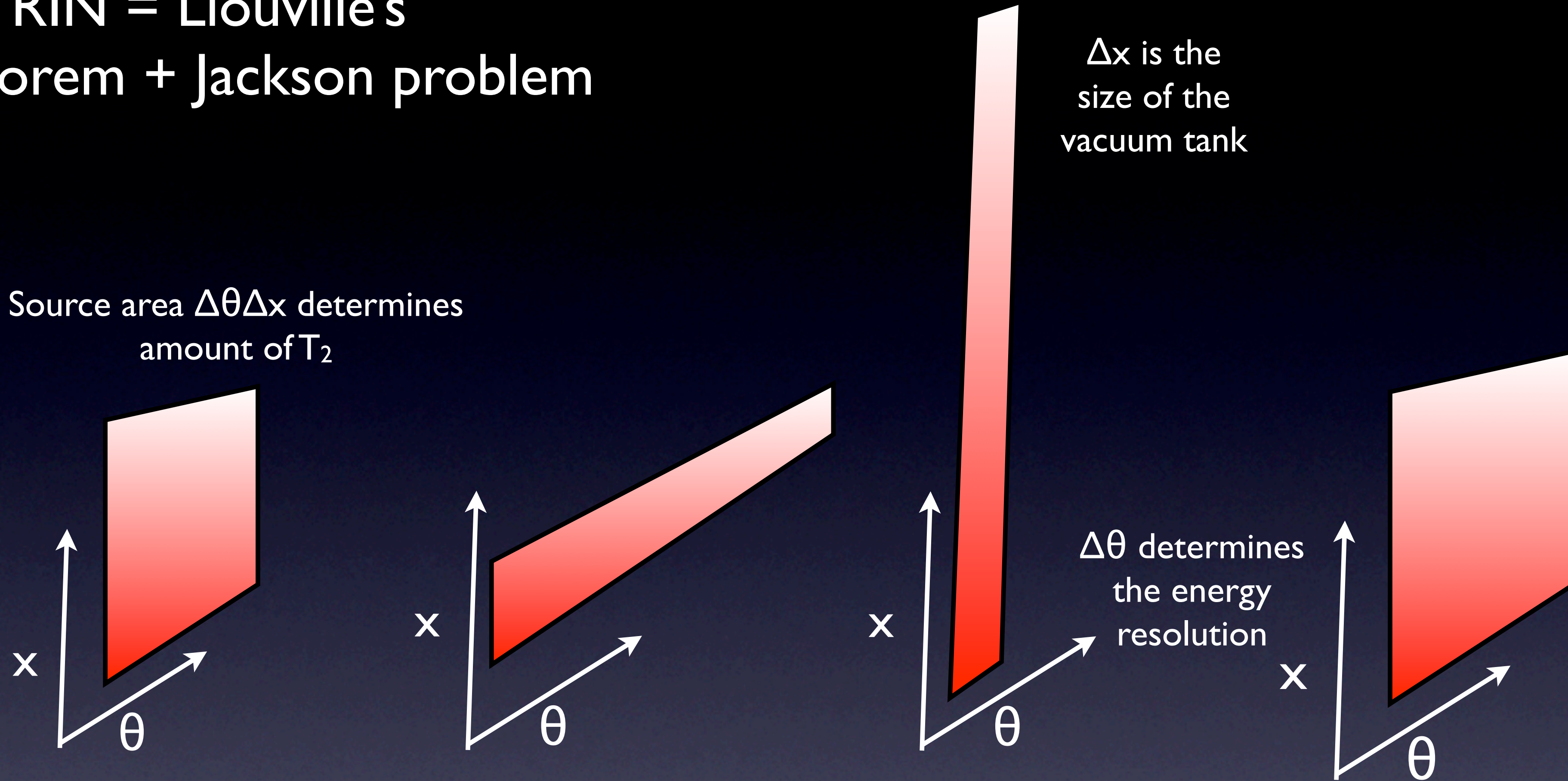
- Use retarding potential to remove β^- particle below threshold.
- High pass filter (variable potential)

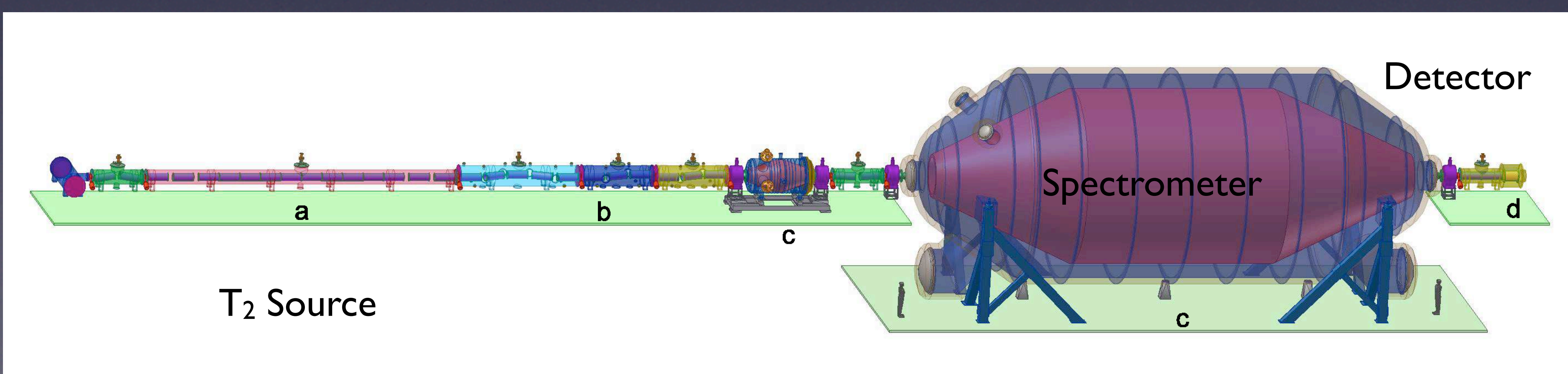
KATRIN = Liouville's Theorem + Jackson problem

- Electrons from tritium decay need to overcome a known potential Φ in order to be counted to the detector. Measures an integrated spectrum.
- Problem: decays are isotropic, but filter acts on cos(θ).
- Solution: adiabatically rearrange their phase space.



KATRIN = Liouville's Theorem + Jackson problem





Limitations of the KATRIN Experiment

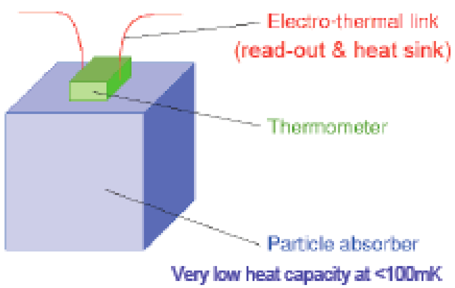
- Both the resolution of KATRIN and its activity scale as the area (not the volume).
- KATRIN will certainly be able to probe very low in neutrino mass, but its ability to see relic neutrinos is hampered by the source strength required.
- Some new approach is required.

Direct Neutrino Probes: MARE

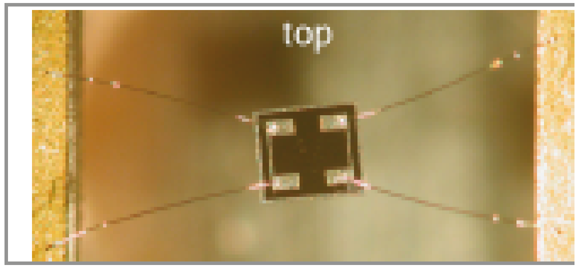
- Use bolometers to measure the full energy deposit from beta decay,
- Use ^{187}Re as beta decay isotope ($\tau_{1/2} = 4.3 \times 10^{10}$ y, Q = 2.46 keV)
- All the energy in the final states are measured (good!)
- Scales with volume, not area (good!)
- Cross-section *really* small for relic detection (not so good...)

Bolometry

MIBETA
&
MARE



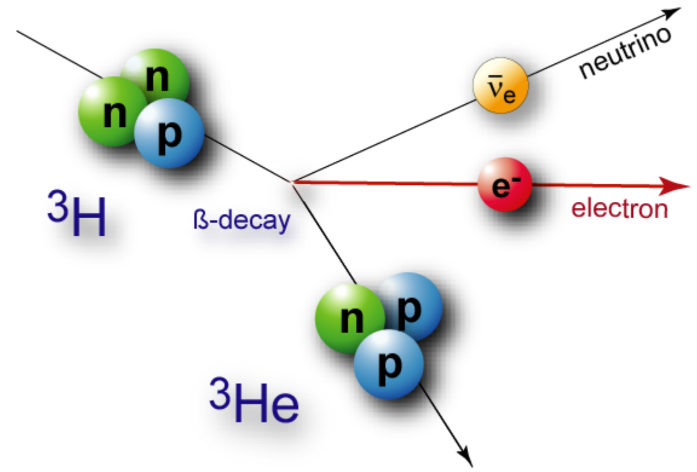
$$^{187}\text{Re} \rightarrow {}^{187}\text{Os} + e^- + \bar{\nu}_e$$



1 mm→| |←

Atomic Trapping of Tritium

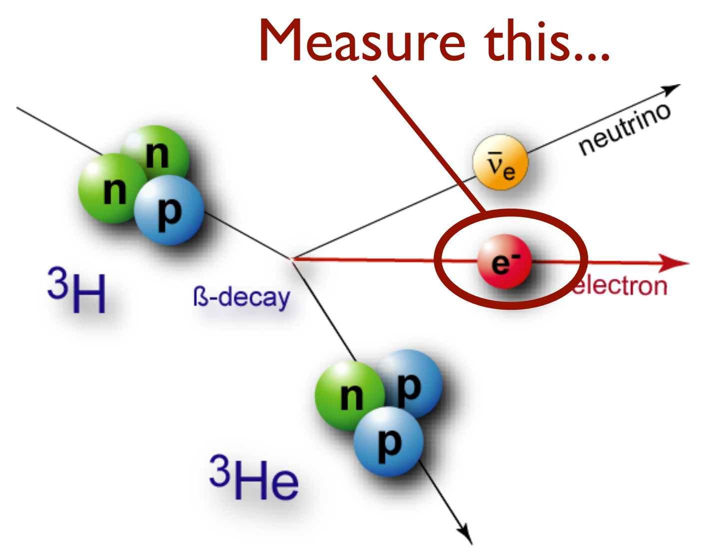
- Trap atomic tritium by magnetically cooling an atomic beam of tritium. Technique demonstrated on oxygen and hydrogen. Being extended to tritium next.
- Measure both the ion ($^3He+$) and the electron to reconstruct the neutrino mass kinematically.
- This technique avoids the need for measuring the endpoint (rather it reconstructs the mass itself), thus requires less target (good!).
- As a result, they will not have the target mass required for relic detection (not so good...).



M. Jerkins, J. Klein, J. Majors, F. Robichaux, M. Raizen, arXiv:0901:3111

Atomic Trapping of Tritium

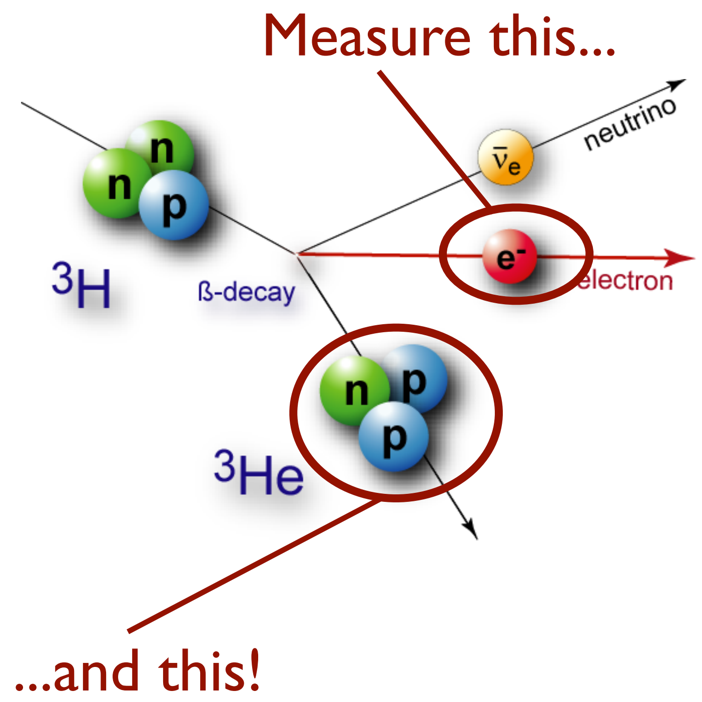
- Trap atomic tritium by magnetically cooling an atomic beam of tritium. Technique demonstrated on oxygen and hydrogen. Being extended to tritium next.
- Measure both the ion (^{3}He+) and the electron to reconstruct the neutrino mass kinematically.
- This technique avoids the need for measuring the endpoint (rather it reconstructs the mass itself), thus requires less target (good!).
- As a result, they will not have the target mass required for relic detection (not so good...).



M. Jerkins, J. Klein, J. Majors, F. Robichaeux, M. Raizen, arXiv:0901:3111

Atomic Trapping of Tritium

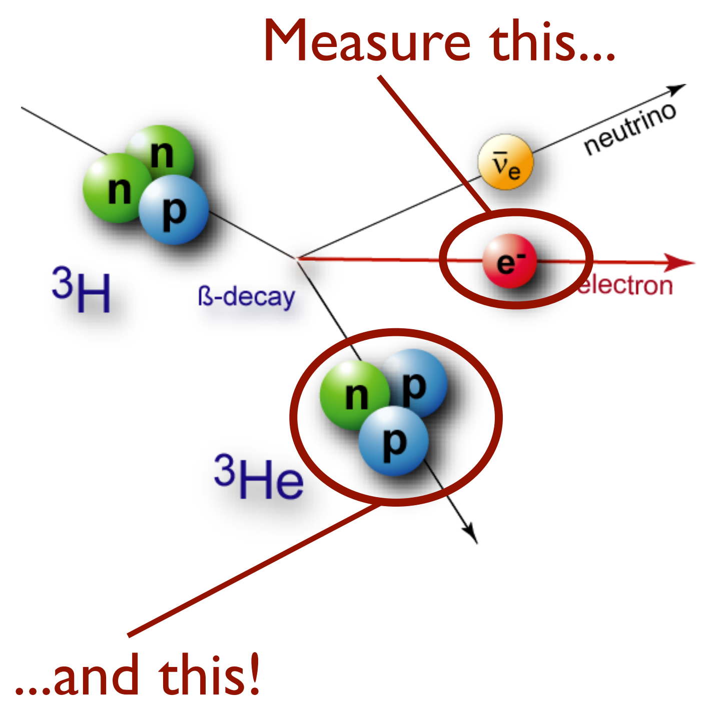
- Trap atomic tritium by magnetically cooling an atomic beam of tritium. Technique demonstrated on oxygen and hydrogen. Being extended to tritium next.
- Measure both the ion ($^{3}He+$) and the electron to reconstruct the neutrino mass kinematically.
- This technique avoids the need for measuring the endpoint (rather it reconstructs the mass itself), thus requires less target (good!).
- As a result, they will not have the target mass required for relic detection (not so good...).

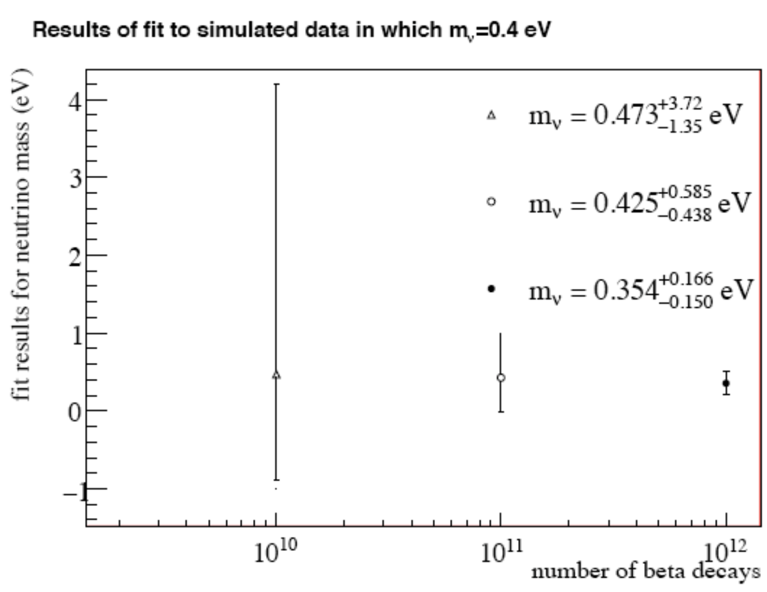


M. Jerkins, J. Klein, J. Majors, F. Robichaeux, M. Raizen, arXiv:0901:3111

Atomic Trapping of Tritium

- Trap atomic tritium by magnetically cooling an atomic beam of tritium. Technique demonstrated on oxygen and hydrogen. Being extended to tritium next.
- Measure both the ion ($^3He+$) and the electron to reconstruct the neutrino mass kinematically.
- This technique avoids the need for measuring the endpoint (rather it reconstructs the mass itself), thus requires less target (good!).
- As a result, they will not have the target mass required for relic detection (not so good...).

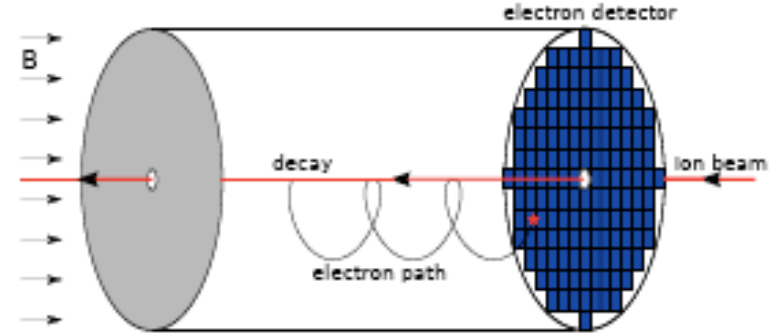


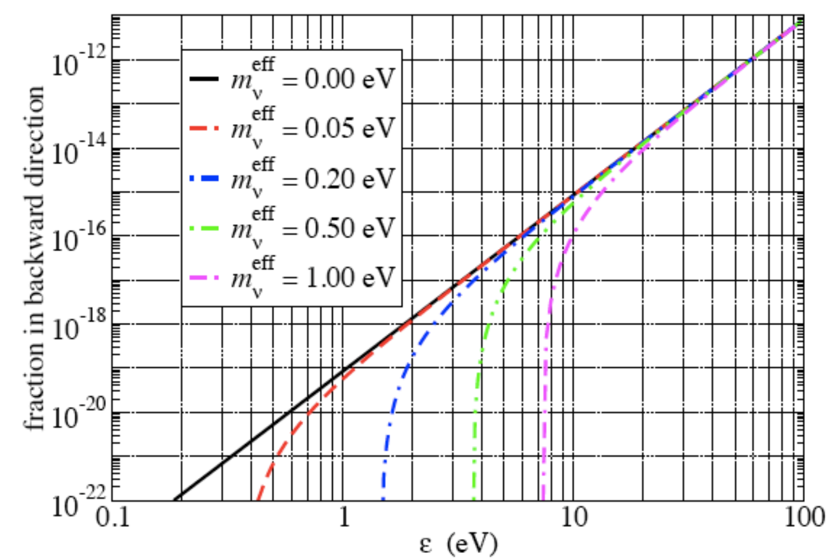


M. Jerkins, J. Klein, J. Majors, F. Robichaeux, M. Raizen, arXiv:0901:3111

Radioactive Ions in a Storage Ring

- Use kinematics of tritium decay an exploit that decays near/at the endpoint carry all momenta (as two-body decay).
- Count electrons emerging anti-parallel to emerging ion beam.
- Requires:
  - (a) Intense ion source (10^{18}-10^{20} decays for KATRIN-like sensitivity)
  - (b) Extremely narrow momentum beam ($\delta p/p \sim 10^{-5}$)
  - (c) Issues with recoil ions and space charge effects from such an intense beam.

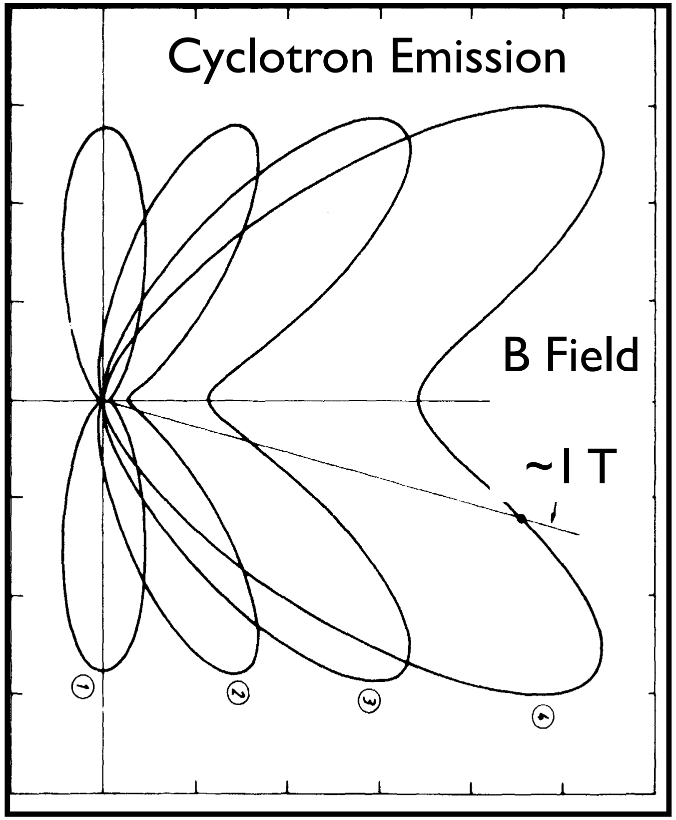




M. Lindroos, B. McElrath, C. Orme, T. Shwetz
arXiv:0904:1091

RF Cyclotron Measurements

- Make use of cyclotron emission to measure electron energy in terms of frequency.
- Accuracy of measurement is determined by Nyquist's limit, or how long you can observe the electron radiating.
- Column density determines maximum time to observe
- Scaling the volume both improves the accuracy and increases the activity strength (good!).
- Inherently, this is a frequency measurement, something we know how to do really well (good).

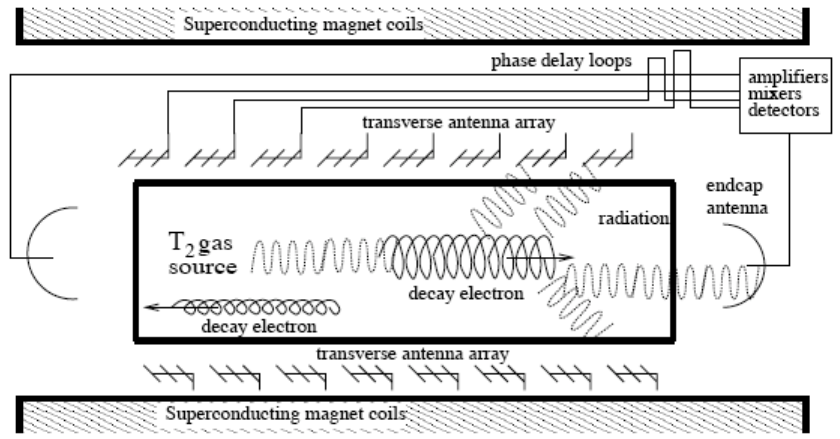


$$\omega_\gamma = \frac{\omega_c}{\gamma} = \frac{eB}{\gamma m_e c^2}$$

B. Monreal, JAF arXiv:0904:2860

RF Cyclotron Measurements

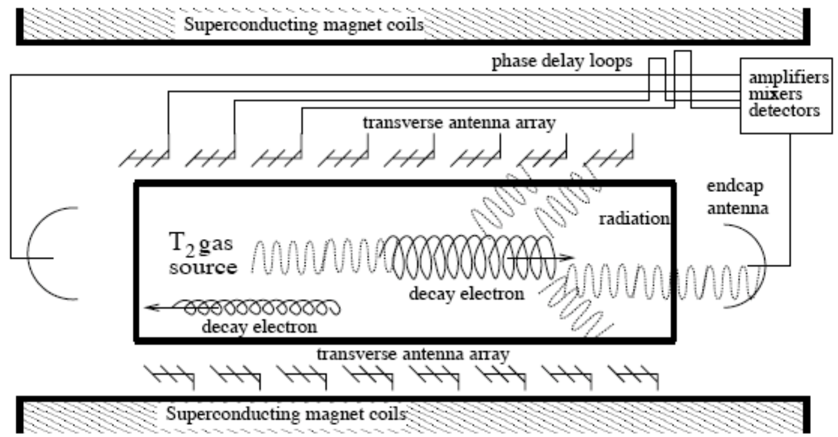
- Make use of cyclotron emission to measure electron energy in terms of frequency.
- Accuracy of measurement is determined by Nyquist's limit, or how long you can observe the electron radiating.
- Column density determines maximum time to observe
- Scaling the volume both improves the accuracy and increases the activity strength (good!).
- Inherently, this is a frequency measurement, something we know how to do really well (good!).

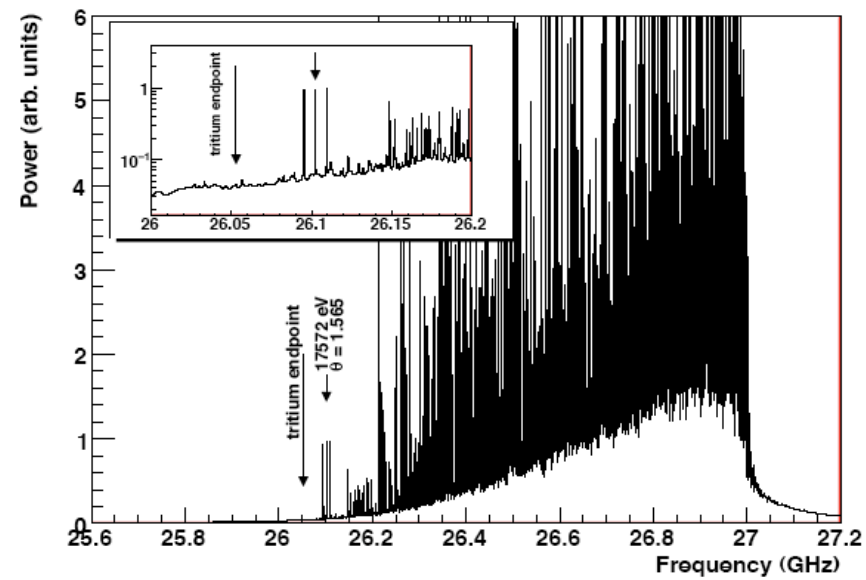


B. Monreal, JAF arXiv:0904:2860

RF Cyclotron Measurements

- Make use of cyclotron emission to measure electron energy in terms of frequency.
- Accuracy of measurement is determined by Nyquist's limit, or how long you can observe the electron radiating.
- Column density determines maximum time to observe
- Scaling the volume both improves the accuracy and increases the activity strength (good!).
- Inherently, this is a frequency measurement, something we know how to do really well (good!).





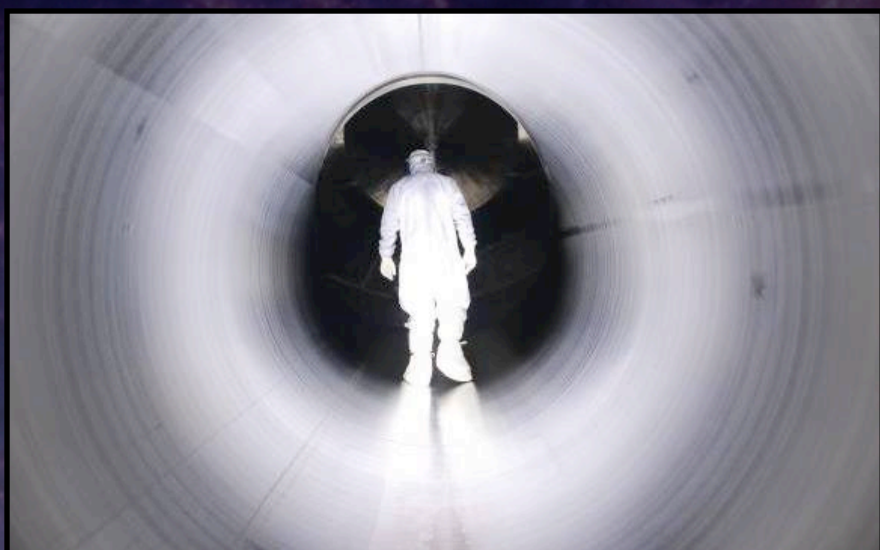
B. Monreal, JAF arXiv:0904:2860

Obstacles for a Relic Neutrino Measurement

Obstacles for a Relic Neutrino Measurement

Target:

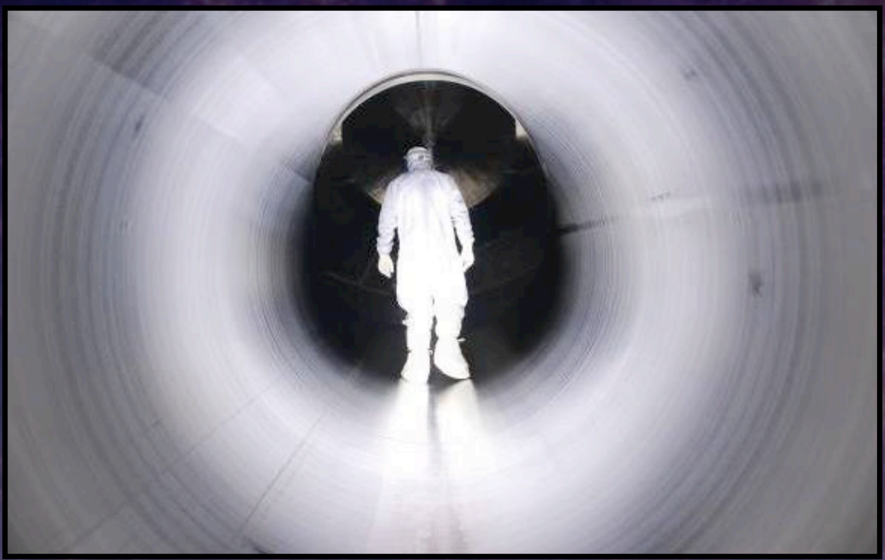
Tritium appears still as most favorable isotope.
High activity targets (~1 MCi) of tritium necessary.
Eventually need to switch to atomic tritium to push resolution.



Obstacles for a Relic Neutrino Measurement

Target:

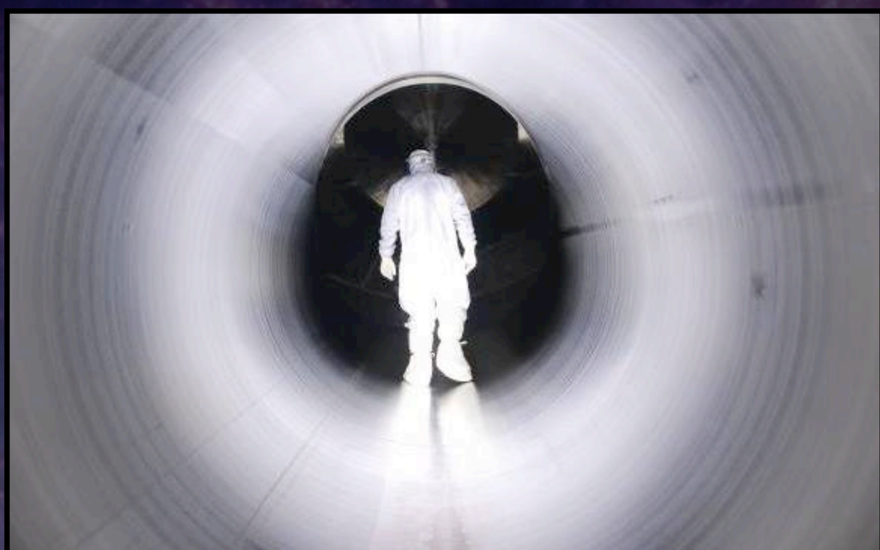
Tritium appears still as most favorable isotope. High activity targets (~1 MCi) of tritium necessary. Eventually need to switch to atomic tritium to push resolution.



Energy Resolution:

Need to achieve high resolution ($\Delta < m_\nu$) for any chance of signal background separation. One order of magnitude desirable.

Obstacles for a Relic Neutrino Measurement



Target:

Tritium appears still as most favorable isotope. High activity targets (~1 MCi) of tritium necessary. Eventually need to switch to atomic tritium to push resolution.

Energy Resolution:

Need to achieve high resolution ($\Delta < m_\nu$) for any chance of signal background separation. One order of magnitude desirable.

Backgrounds:

Need to achieve less that few events/year in region of interest. Cosmic rays and other activity will eventually play a role.

Summary

Summary

The issue of relic neutrino detection still remains a great challenge to our community.

Summary

The issue of relic neutrino detection still remains a great challenge to our community.

From a purely "what is within our technological reach", neutrino capture appears the most viable approach, albeit still very challenging.