How difficult it would be to detect Cosmic Neutrino Background ?

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Hot Big-Bang Cosmology

(concordance model of cosmology)

explains everything we know about the evolution of the Universe since early times with remarkable accuracy.

In particular from the **Big-Bang Nucleosynthesis** (first few minutes) and from of the **Cosmic Microwave Background** (~400 ky) it follows that at these epochs **relativistic neutrinos of ~3 flavors were present**.

$N^{BBN}_{\nu} = 3.71^{+0.47}_{-0.45}$ (from D, ^4He) (Steigman 2012)
$N^{CMB}_{\nu} = 3.52^{+0.48}_{-0.45}$ (Planck collaboration 2013 uses also BAO and H_0, when BICEP2 is included $N_\nu \sim 4$)

Neutrinos **decouple** when the expansion rate exceeds the interaction rate: $\sigma \sim G_F^2\,(kT)^2$, $n_\nu \sim (kT)^3$, $t_\nu = (n_\nu \sigma v)^{-1} \sim G_F^{-2}\,(kT)^{-5}$, $t_{expansion} \sim G_N^{-1/2}\,(kT)^{-2}$, ➡ $kT \sim 1$ MeV, $t_{decoupling} \sim 1$ second.

Using elementary consideration one can show that $n_\nu/n_\gamma = 3/11$, thus ~112 neutrinos of each Majorana flavor /cm^3 and **$T_\nu/T_\gamma = (4/11)^{1/3} = 0.71$; $T_\nu = 1.94$ K $= 1.67\times10^{-4}$ eV**

These are then firm predictions of the Hot Big-Bang Cosmology:

Neutrino number density = 112 neutrinos/cm^3 for each flavor, i.e., **56 neutrinos and 56 antineutrinos of each flavor**

Neutrino temperature = 1.94 K = 1.67×10^{-4} eV

If one could confirm (or find deviations) from these predictions, one would test the theory at t ~ 1 sec, T ~ 1 MeV, and redshift z ~ 10^{10}, much earlier and hotter than the tests based on BBN and CMB.

There is, therefore, strong motivation to try to detect these CνB.

Clustering neutrino density enhancement

Massive particles become nonrelativistic when their mass exceeds the temperature of the Universe. From than on they can become bound, i.e., concentrate in structures of various sizes. Their densities in these structures can far exceed the average density derived from cosmological measurements and arguments.

The overall energy density (critical density for $\Omega = 1$) of the Universe is

$$\rho_c = 1.05\text{x}10 \;\; h_{100} \;\; \text{eV/cm} \;\; \sim 5 \text{ keV/cm} \quad (\text{since } h_{100} \sim 0.73)$$

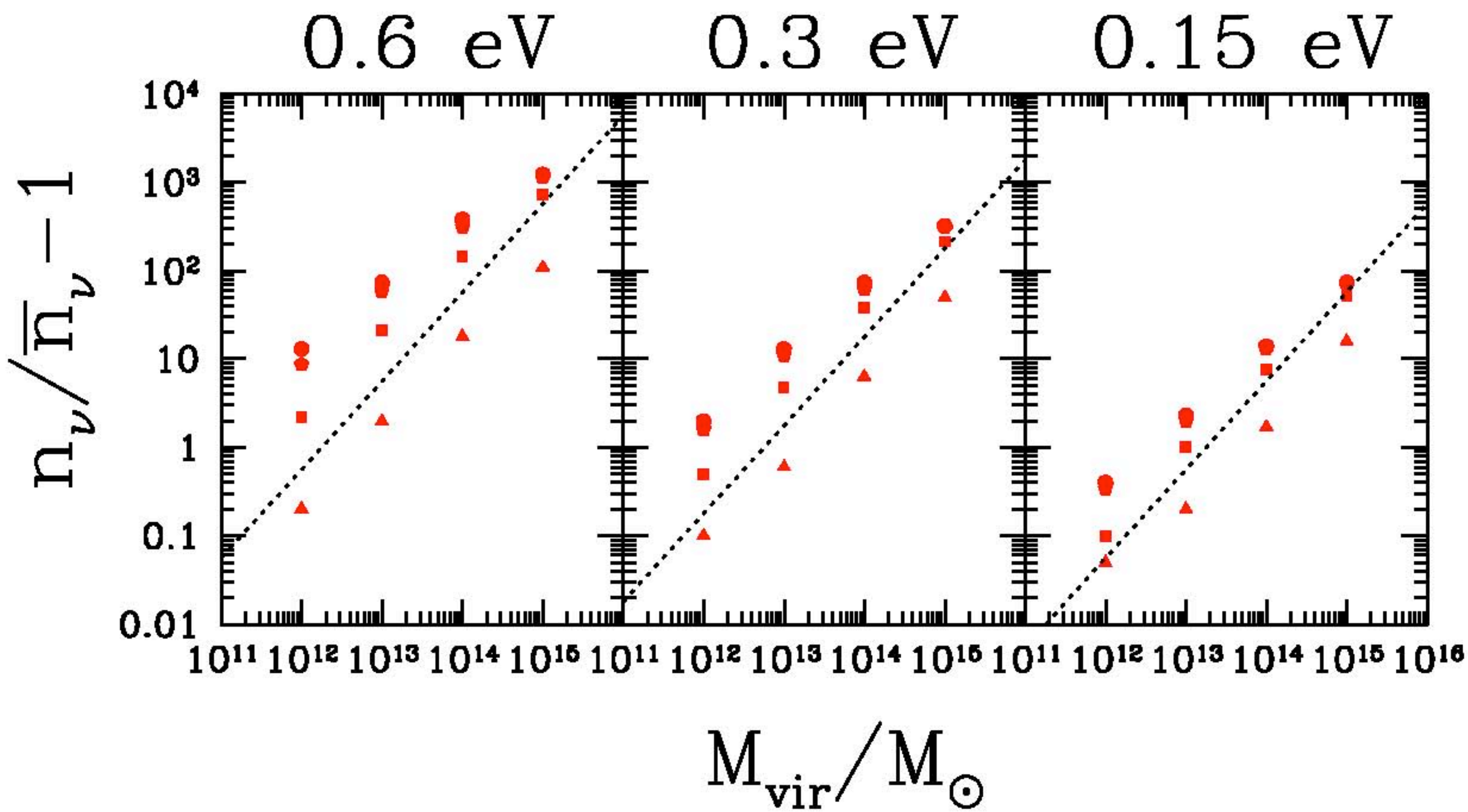
component	average ρ(keV/cm^3)	Structure	Enhancement
baryons	0.2	galaxy(disk)	~$5\text{x}10^6$
dark matter	1.0	galaxy(halo)	~$3\text{x}10^5$
Neutrinos	**112(Σm_ν/keV)**	**clusters**	**~1 - 100**

Dependence of the overdensity on the mass of the cluster and on the neutrino mass (from Ringwald & Wong, 04, similar to Singh & Ma 04)

The red symbols indicate different distances from the cluster center,

▲ are for r = 1 Mpc/h.

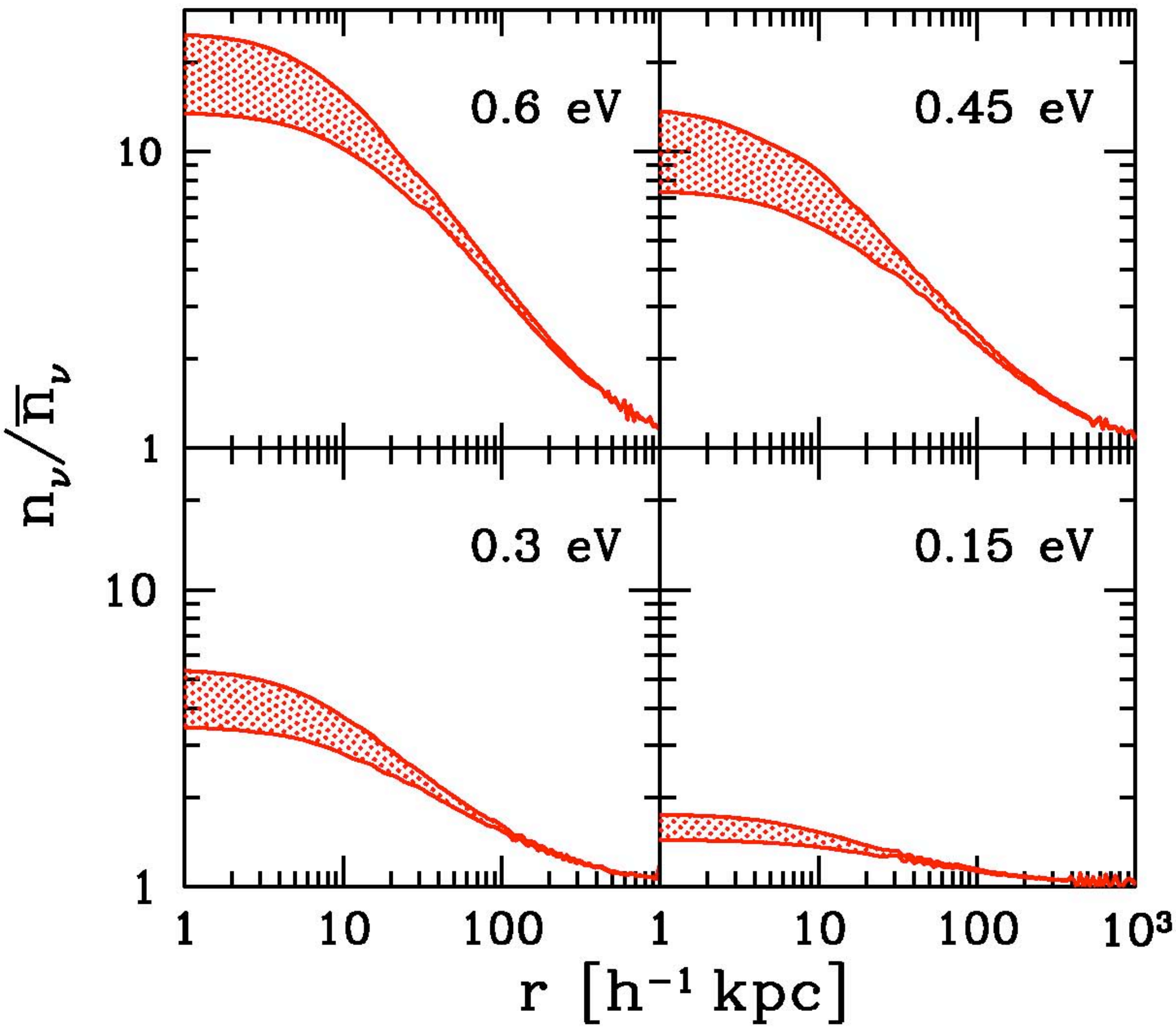
For $M_{vir} = 10^{15}\, M_{\odot}$, m_{ν} > 0.3 eV our estimate $n_{\nu}/\langle n_{\nu}\rangle$ = 100 looks OK



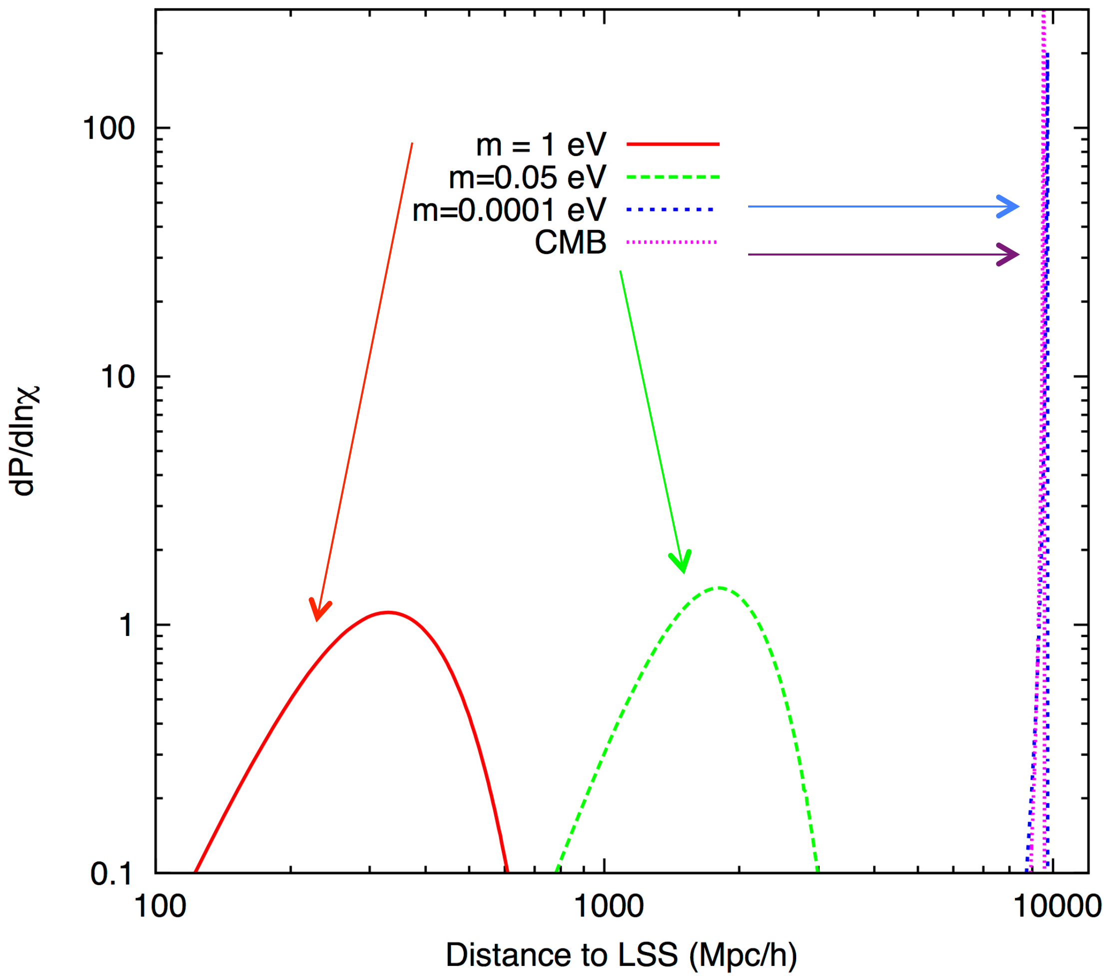
Clustering evaluation for the Milky Way (Ringwald & Wong 04)

At 8 kpc the overdensity is less than what we estimated.

In fact, for m ~ 0.1 eV the overdensity is essentially absent.



An interesting and contraintuitive consequence of finite nuclear mass, and thus the fact that neutrino are nonrelativistic now, is the fact that the last scattering surface for them is much closer that for the CMB photons even though they decoupled earlier.



The probability that a neutrino of mass *m* last scatters at a given comoving distance from us. The large spread is the consequence of the momentum distribution of the neutrinos.

From Dodelson & Vesterinen, PRL**103**,2009

How do we detect Cosmic Neutrino Background (CNB)?

de Broglie wavelength $\lambda_\nu = h/p_\nu \sim 2.4$ mm (for $p_\nu \sim 3T_\nu$)

A sphere with d = λ_ν contains ~ 10^{21} nucleons. If neutrinos interact coherently with all of them, it should help a lot.

The first idea, from ~1980 when people believed that $m_\nu \sim 30$ eV, was to use the coherent scattering on macroscopic objects.

To describe the reflection or refraction on a thin foil, it was proposed to use the concept of index of refraction

$$n = 1 + N \lambda_\nu^2 f(0)/2\pi,$$

where N is the number of density of target atoms and f(0) is the forward scattering amplitude.

Deviation of index of refraction from unity is obtained the same way as in the treatment of the MSW effect for matter neutrino oscillations

$$n-1 = \pm [G_F N (3Z - A)]/(2^{3/2} T_\nu) \quad \text{for } \nu_e\ (\nu_e)$$

$$n-1 = \pm [G_F N (Z - A))]/(2^{3/2} T_\nu) \quad \text{for } \nu_\mu, \nu_\tau\ (\nu_\mu, \nu_\tau)$$

T_ν is the kinetic energy of the nonrelativistic neutrinos.

For ν_μ on gold **$1-n \approx 10^{-7}$ (eV/m_ν)** for v_ν = 500 km/s
and the critical scattering angle θ_c = **$[2(1-n)]^{1/2} \approx 1.5$ arcmin**

Consider neutrinos with flux density **j (neutrinos/sr cm^2 sec)**.
Collision rate for area of 1 cm^2 with angles less than θ_c is
$2\pi j\, \theta_c$ and the momentum transfer is **$p_\nu\, \theta_c$**

The **pressure** of the `neutrino wind' is then
$dp/dt = 4\pi\, \rho_\nu N\, G_F (A-Z) / 2^{1/2}$
linear in G_F and independent of v_ν (Opher,74,82; Lewis,80)

Unfortunately, this derivation is wrong !!!

(Cabibbo & Maiani, 82; Langacker,Leveille & Sheiman, 83)

$$F = -\Delta p_\nu/\Delta t \simeq G_F \int d^3x\, \rho_A(x)\, \nabla\, n_\nu(x)$$

With ρ_A atomic number density of the target, and $\nabla n_\nu(x)$ gradient of the local neutrino density. This gradient vanishes since $n_\nu(x)$ is uniform at the scale of the detector, except for the weak scattering waves that are of order G_F. **Thus the force is G_F^2.**

Another proposal to use coherence, this time $\sim G_F^2$

(Shvartsman, Braginski, Gershtein, Zeldovich, and Khlopov, 82)

Scatter relic neutrinos on spheres with $r = \lambda$; use the virial motion of Earth with respect to the relic neutrinos, $v \sim 300$km/s and measure the force on such spheres.

Cross section $\sigma = G_F^2\, m_\nu^2\, k_L^2/\pi$, $k_L = 3Z-A$ (for ν_e), $A-Z$ (for ν_μ,ν_τ)

Force $F = 2n_\nu v\, m_\nu v\, \sigma\, N_A^2$

(n_ν = density of relic neutrinos, N_A = number of target atoms in each sphere)

Acceleration of each sphere $a = F/m_{sphere}$ is independent of m_ν since $N_A \sim \lambda^3 \sim m_\nu^{-3}$.

$$a_t \approx 2\times 10^{-28}\left(\frac{n_\nu}{\bar{n}_\nu}\right)\left(\frac{10^{-3}c}{v_{relative}}\right)\left(\frac{\rho_t}{\mathrm{g/cm^3}}\right)\left(\frac{r_t}{\bar{\lambda}}\right)^3 \mathrm{cm/s^2}$$

Take **iron** spheres, assume clustering $n_\nu/\langle n_\nu\rangle = 100$,

$a \sim 3 \times 10^{-25}$ cm s^{-2}, $F \sim 3 \times 10^{-29}$ dyne

This is ~12 orders of magnitude from the sensitivity of the current Dicke - Eotvos type experiments.

For Majorana ν there is a further $(v_{rel}/c)^2$ suppression.

Using resonance absorption of UHE neutrinos on CνB

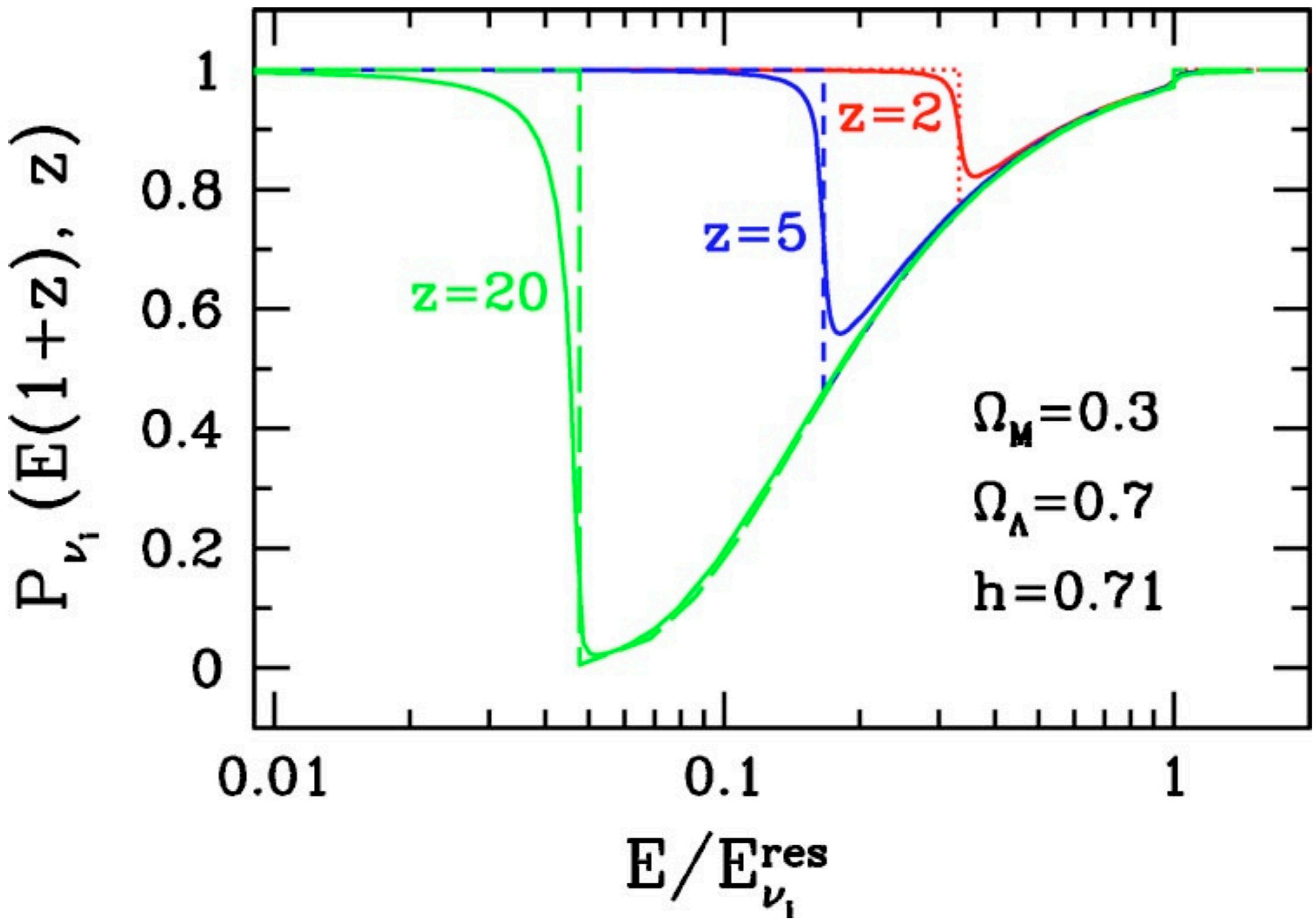
The Universe is transparent to neutrinos with the exception of the resonance annihilation into Z-bosons (Weiler 82).

The resonance energy is $E_\nu^{res} = m_Z^2/2m_\nu = 4.2\text{x}10^{22}$ eV (0.1 eV/m_ν), and the cross section is $\langle\sigma_{\nu\nu}^{ann}\rangle = 2\pi\sqrt{2}G_F = 40.4$ nb.

When the UHE neutrinos are injected at redshift *z* with energy E_i, They are detected at Earth with $E = E_i/(1+z)$. Thus, the ``dip" in the observed spectrum will be broadened and *z* dependent.

Clearly, the observable effect will depend on the *z* and energy Distribution, so far unknown, of the UHE neutrino sources.

Note that the highest energy neutrinos observed so far have energies ~PeV = 10^{15} eV.



Survival probability of a cosmic neutrino injected at redshift *z* with energy E_i, so that at Earth it has energy $E = E_i/(1+z)$, in units of the resonance energy $E_\nu^{res} = m_Z^2/2m_\nu$. Full treatment (full lines) and the narrow width approximation are compared (from Eberle et al, 04)

Since none of these proposals work, by a huge margin, lets consider the usual way of detecting neutrinos, by <u>charged current weak interactions</u>.

The problems to solve:

1) **Can one find an appropriate target?**
2) **How many target atoms can one use in practice?**
3) **What is the cross section, and is the event rate sufficient?**
4) **Can one separate the signal from background?**

Each of these items is challenging, but it turns out that the needed technological improvements are ***only(??!!)*** one or few orders of magnitude each, so it is worthwhile to consider them in more detail.

Since the momentum of the CNB $p_\nu \to 0$, we must consider only exothermic reaction, i.e., reactions on unstable targets.
Take the $\nu_e + n \rightarrow p + e^-$ (hypothetical, there are no free neutrons) reaction with $E_e = M_n - M_p + E_\nu$ which remains positive and $E_e \geq m_e$ even when $E_\nu \to 0$?

$$\frac{d\sigma}{d\cos\theta} = \frac{\bar{G}^2}{v_\nu} E_e p_e [(f^2 + 3g^2) + (f^2 - g^2) v_e v_\nu \cos\theta]$$

The cross section now contains **$1/v_\nu$**, which
means that the rate, **σv_ν** , remain finite even when **$v_\nu \to 0$**.
(see Weinberg 62, Cocco,Mangano,Messina 07)

Naturally, the $1/v_\nu$ factor should be there even for the endothermic reactions, but becomes irrelevant since in that case **$v_\nu \to c$** (=1 here). This is a general result for reactions with nonrelativistic projectiles (known long time ago for the case of slow neutrons).

Analogous reactions on unstable nuclear targets A_Z are

$\nu_e + A_Z \rightarrow e^- + A_{Z+1}$ or $\bar{\nu}_e + A_Z \rightarrow e^+ + A_{Z-1}$

where the allowed $\beta^\pm$ decay of $A_{Z\pm1}$ is characterized by the known nuclear matrix element $|M_{nucl}|^2 \approx 6300/ft_{1/2}$.

The cross section in cm^2 for these exothermic reactions is

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

with

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C {m_e}^2}{\pi} |M_{nucl}|^2 = \frac{2.64 \times 10^{-41}}{ft_{1/2}}$$

When $v_\nu \rightarrow 0$ the **e**$^\pm$ energies are monoenergetic $E_e = Q + m_e + m_\nu$

They are separated from the $e^\pm$ β-decay spectrum by $2m_\nu$.

We can consider now the answer to our first question:

Can one find an appropriate target?

Clearly the unstable A_Z target should have halflife $t_{1/2}$ longer than the duration of the measurement, i.e.,
$t_{1/2} \geq$ years.
It could be manmade, or it could exist in nature. However, natural radioactivity has **$t_{1/2} \geq 10^9$ years**.

The target A_Z should also have minimal possible **$ft_{1/2}$** so that the cross section is as large as possible. This means that the superallowed decays, with **$ft_{1/2} \sim 1000$** are preferred.

Now, lets consider the second question:

How many target atoms can one use in practice?

When reviewing possible targets, the tritium (^3H) clearly comes to mind. Its halflife **$t_{1/2}$ = 12.3 years** is just right, and **$ft_{1/2}$ = 1143** is almost as small as the $ft_{1/2}$ for the free neutron decay.

The technology of production is well developed, and using as much as **1 Mcu (2.1x10^{25} tritium atoms)** is very challenging but appears to be technologically possible.

This corresponds to just ~100 g of pure tritium.
(Note, however, that the Karlsruhe facility, handling all tritium for the KATRIN experiment, as well as for ITER, is licensed for maximum only 20 g of tritium.)

What is the cross section, and the event rate?

To estimate the relic neutrino velocity, lets neglect the virial motion and use $v_\nu/c \sim 3T_\nu/m_\nu$, with $T_\nu = 1.9$ K.
With this assumption $\sigma = 1.5\text{x}10^{-41} (m_\nu/\text{eV})\ \text{cm}^2$

The CNB capture rate is then independent of m_ν, and v_ν

$R = \sigma \times v_\nu \times n_\nu \approx 1.8 \times 10^{-32} \times n_\nu/\langle n_\nu\rangle\ s^{-1}$

The number of events is
$N_{\nu\ capt} \approx 83\ \text{yr}^{-1}\ \text{Mcu}^{-1}$ for $n_\nu/\langle n_\nu\rangle = 10$
So, the number of events would be reasonably large.

Note that this rate is for Majorana ν, for Dirac ν it is reduced by 0.5 (Long et al. arXiv: 1405.7654.)
Also, there will be a ~1% annual modulation depending on the velocity distribution (Safdi et al., PRD90,043001)

Can we understand that it is possible to have a reasonably large neutrino capture rate with only ~100g of tritium compared with ~500 ton (fiducial) of scintillator in KamLAND?

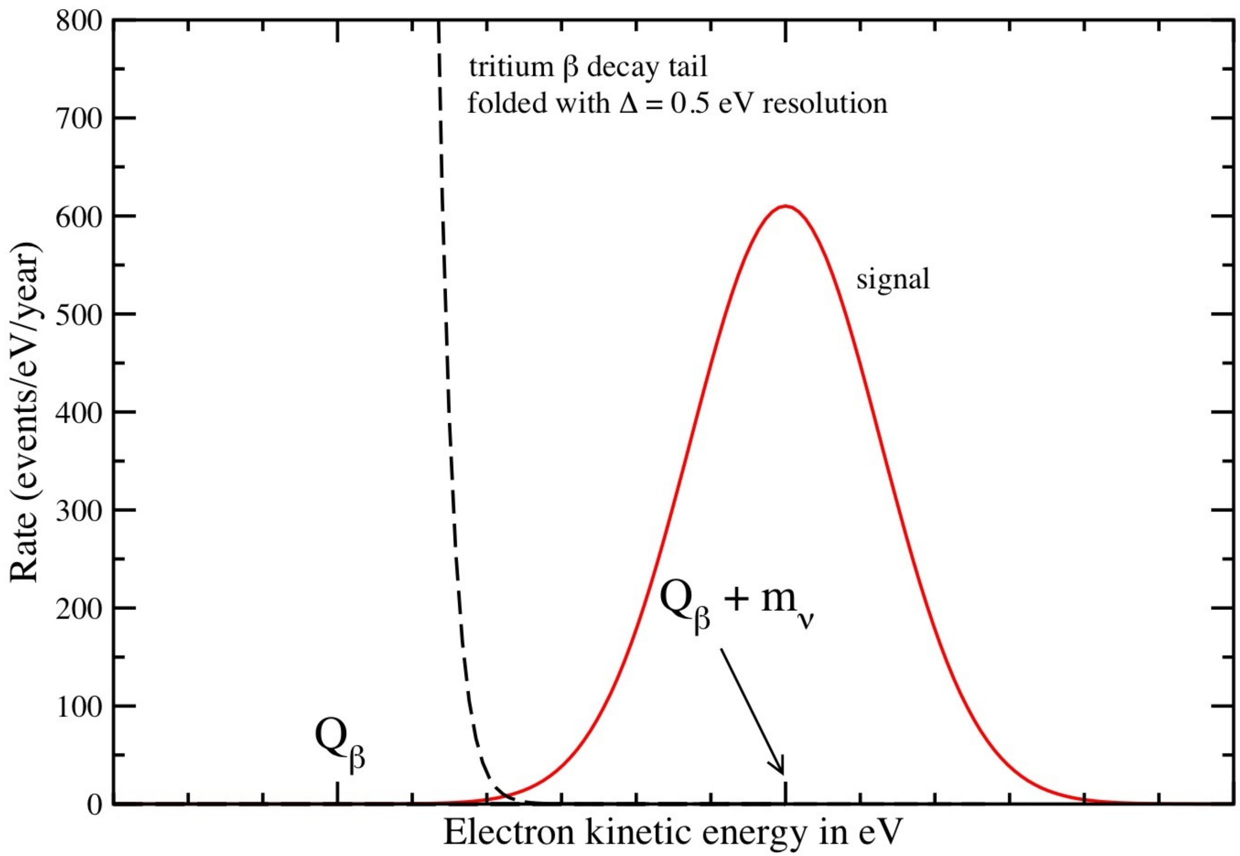
Here are the ratios tritium/KamLAND:

Cross section	~100
Number of targets	~5×10^{-7}
Flux	~10^4
Total	~0.5

Finally, the last and most difficult question:

Can one separate the signal from background?

There are 3.7×10^{16} tritium β decays/s , and hence emitted electrons distributed over the energy interval 0 — Q_β - m_ν and smeared by the detector energy resolution. The fraction of electrons in the energy interval of width Δ just below the endpoint is ~ $(\Delta/Q_\beta)^3$



This is for Δ =0.5 eV m_ν=1 eV and $n_\nu/\langle n_\nu\rangle$ = 50.

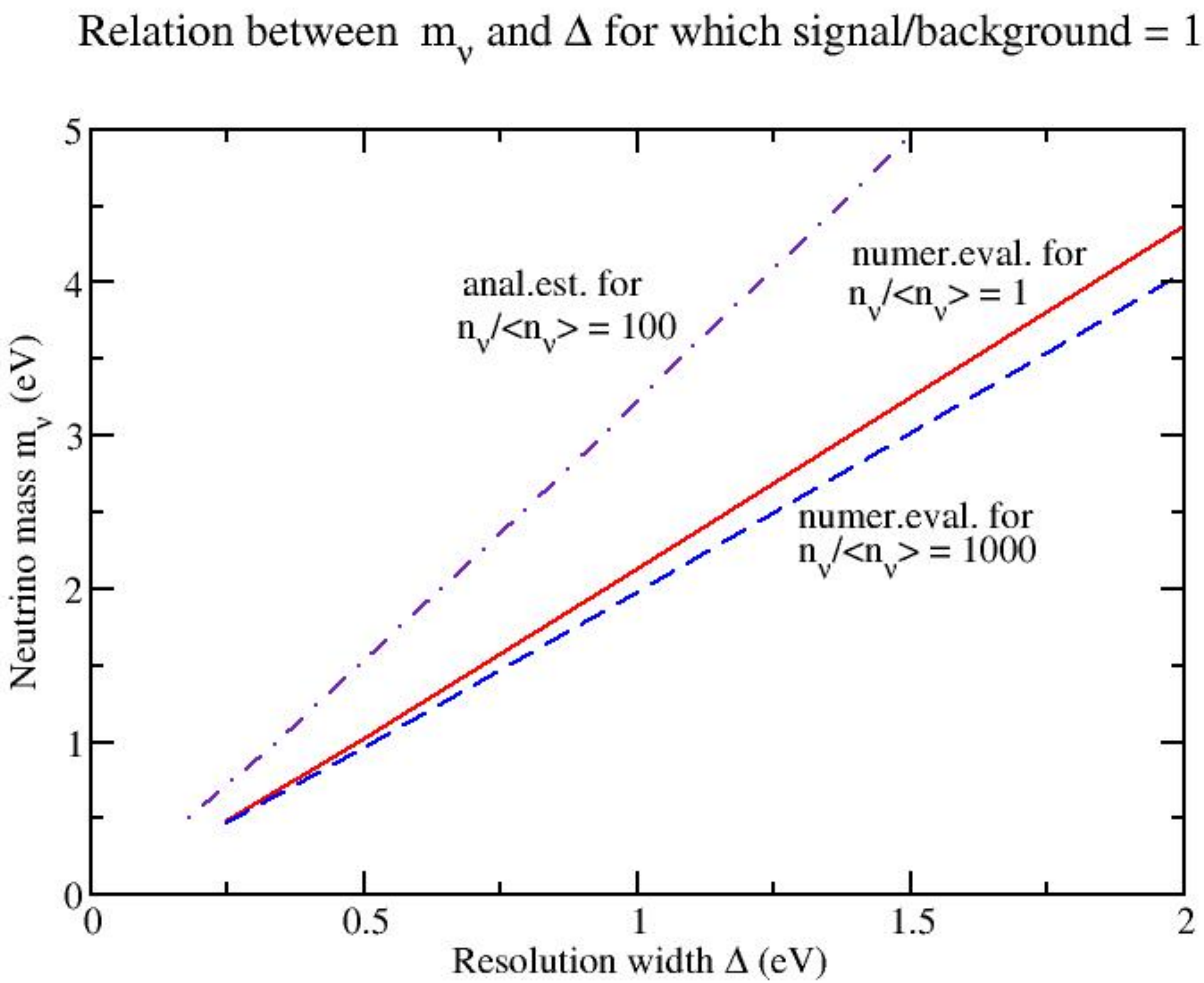
There are, thus, two challenging problems:

1) Can one filter out up to the ~10^{16} electrons/s that have energies below the endpoint?
In KATRIN design the ratio between electrons in the window of planned 0.2 eV sensitivity and the total decay rate is ~10^{15}. So, the filter used in KATRIN will be essentially capable to reach the required rejection ratio.
2) Can one reach the required energy resolution? And how the signal to background ratio depends on the resolution Δ and on the neutrino mass m_ν?
It turns out one can make an analytic estimate of the ratio

$$\lambda_\nu/\lambda_\beta = 6\pi^2 n_\nu/\Delta^3 \times (2\pi)^{1/2} e^{2z}, \quad z = (m_\nu/\Delta)^2$$

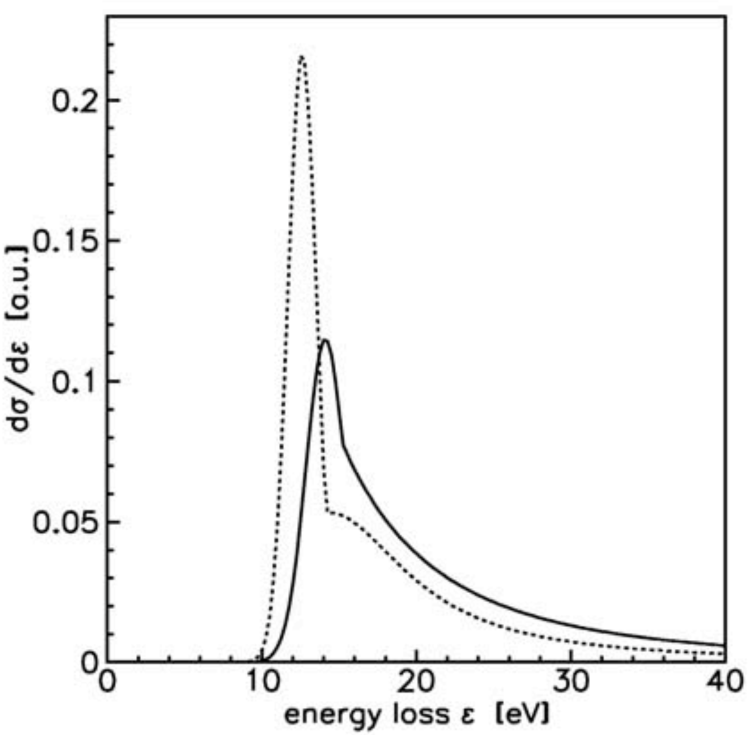
valid reasonably well as long as $m_\nu > \Delta$ (Cocco *et al.*)

The analytic formula suggest that **$m_\nu/\Delta \sim 3$** is needed, numerical evaluation gives **$m_\nu/\Delta \sim 2$** , a somewhat more favorable ratio.



Here are potential killer problems:

1) Past and planned experiments use molecular T_2. The rotational-vibrational states in the final ^3HeT molecule are spread over ~0.36 eV. That essentially limits the achievable resolution. However, using atomic T would be very difficult but obviously necessary.
2) Electrons scatter on T_2 with $\sigma=3x10^{-18}cm^2$. This limits the source column density and makes sources of 1kCu or more impossible. Totally new arrangement would be needed for stronger sources.



Schematic idea of the `Project 8' of Monreal and Formaggio

Phys. Rev. D80, 051301(2009).

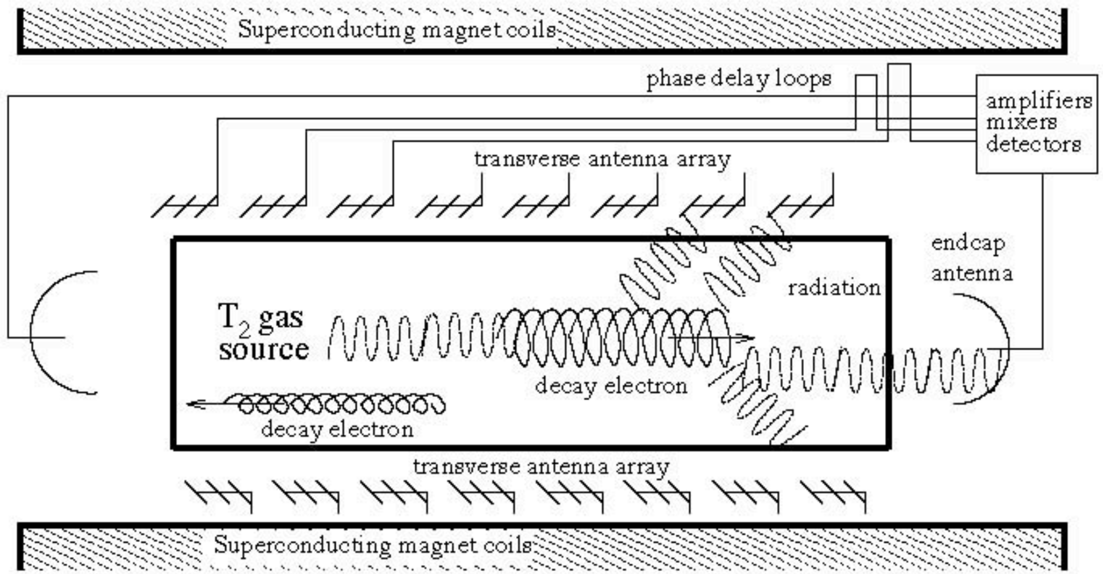


FIG. 1: Schematic of the proposed experiment. A chamber encloses a diffuse gaseous tritium source under a uniform magnetic field. Electrons produced from beta decay undergo cyclotron motion and emit cyclotron radiation, which is detected by an antenna array. See text for more details.

Cyclotron frequency depends on the electron kinetic energy: $\omega = qB/(m_e + E)$

Each electron emits microwaves at frequency ω and total power

$P(\beta,\theta) =$
$1/4\pi\varepsilon_0 \times 2q^2\omega^2/3c \times \beta^2 \sin^2\theta/(1-\beta^2)$

where β is the electron velocity and θ is the pitch angle

With 100Ci source of atomic tritium the projected sensitivity to neutrino mass of 0.007 eV is estimated.

That the basic idea works as expected was recently demonstrated using a small cell with the gaseous monoenergetic conversion electron source Kr^{83m} (Asner et al., arXiv: 1408:5362)

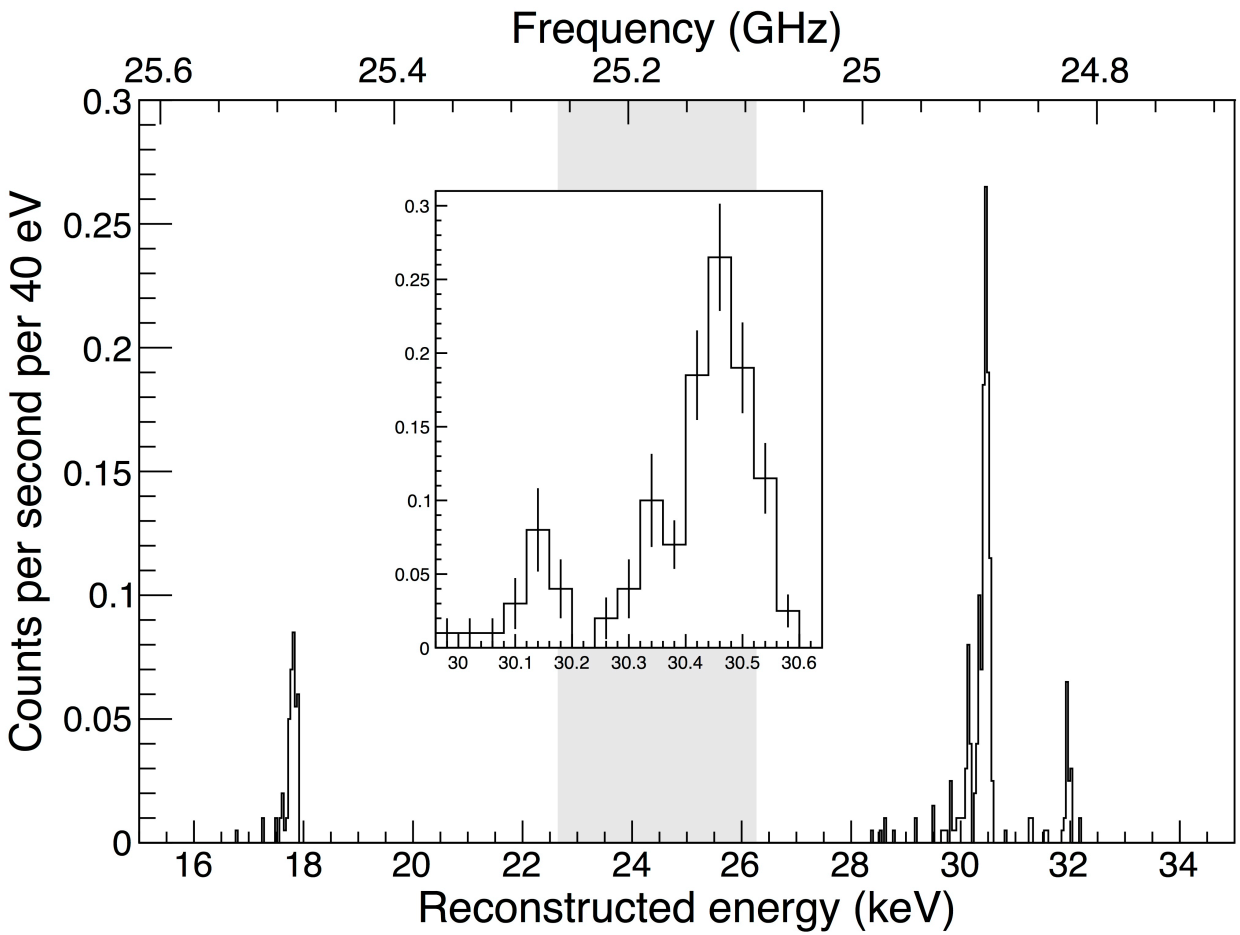
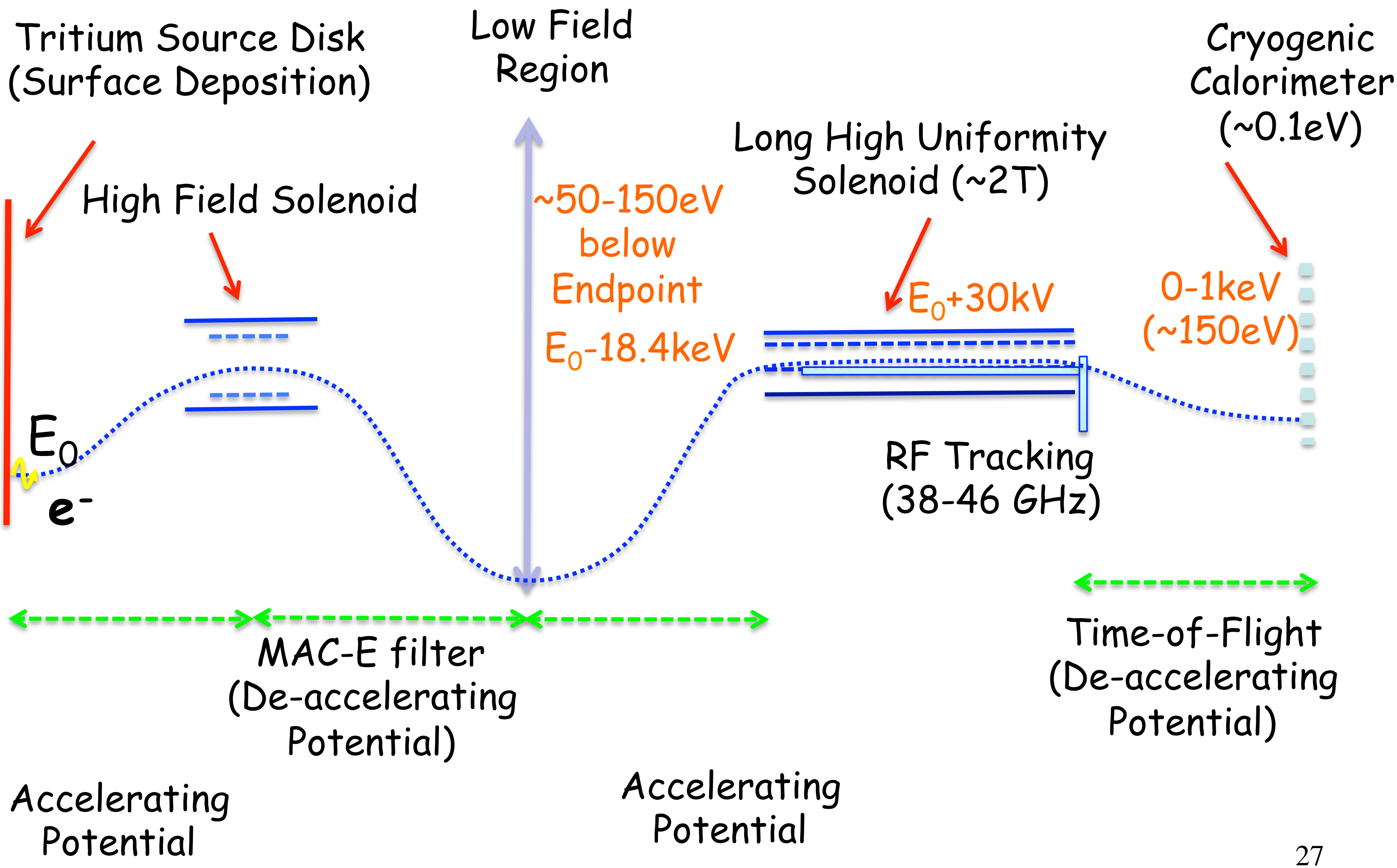


FIG. 3. The kinetic energy distribution of conversion electrons from ^{83m}Kr as determined by CRES. The spectrum shows both the 17 keV, 32 keV and 30 keV-complex conversion electron lines. The shaded region indicates the bandwidth where no data were collected. Insert: An expanded view of the 30 keV energy region, where the 30.4 keV conversion electrons can be seen.

Prospects for Relic Neutrino Detection at PTOLEMY: Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

Plans to use monoatomic tritium source deposited on a graphene substrate and a combination of MAC-E filters, cryogenic calorimetry, RF tracking and time-of-flight systems.
(see Betts et al. arXiv: 1307.4738)

PTOLEMY Experimental Layout



Summary

1) We have discussed the challenges and promises of detecting the primordial neutrinos (in particular the ν_e component) using the neutrino capture on radioactive nuclei, with emphasis on tritium as target.
2) Among the various technological challenges of such program, the requirement that the detector resolution is better that the neutrino mass by a factor 2 - 3, appears to be the most difficult one to achieve. It essentially restricts the applicability of the discussed approach.
3) In the next few years a variety of approaches (KATRIN, cosmology & astrophysics, $0\nu\beta\beta$ decay) promise to reach sensitivity to $m_\nu \sim 0.2$ eV or even better. If one or all of these approaches find positive evidence, e.g.. if we can conclude that $m_\nu \geq 0.2$ eV, it would be certainly worthwhile, and perhaps even imperative, to pursue the indicated program vigorously.

Spares

Outline:

1) Number density of the Cosmic Neutrino Background
2) Clustering of CNB
3) Using coherence (or not)
4) Using resonance absorption of the UHE neutrinos
5) Detection with radioactive targets $\Rightarrow$ main topic
6) Present efforts

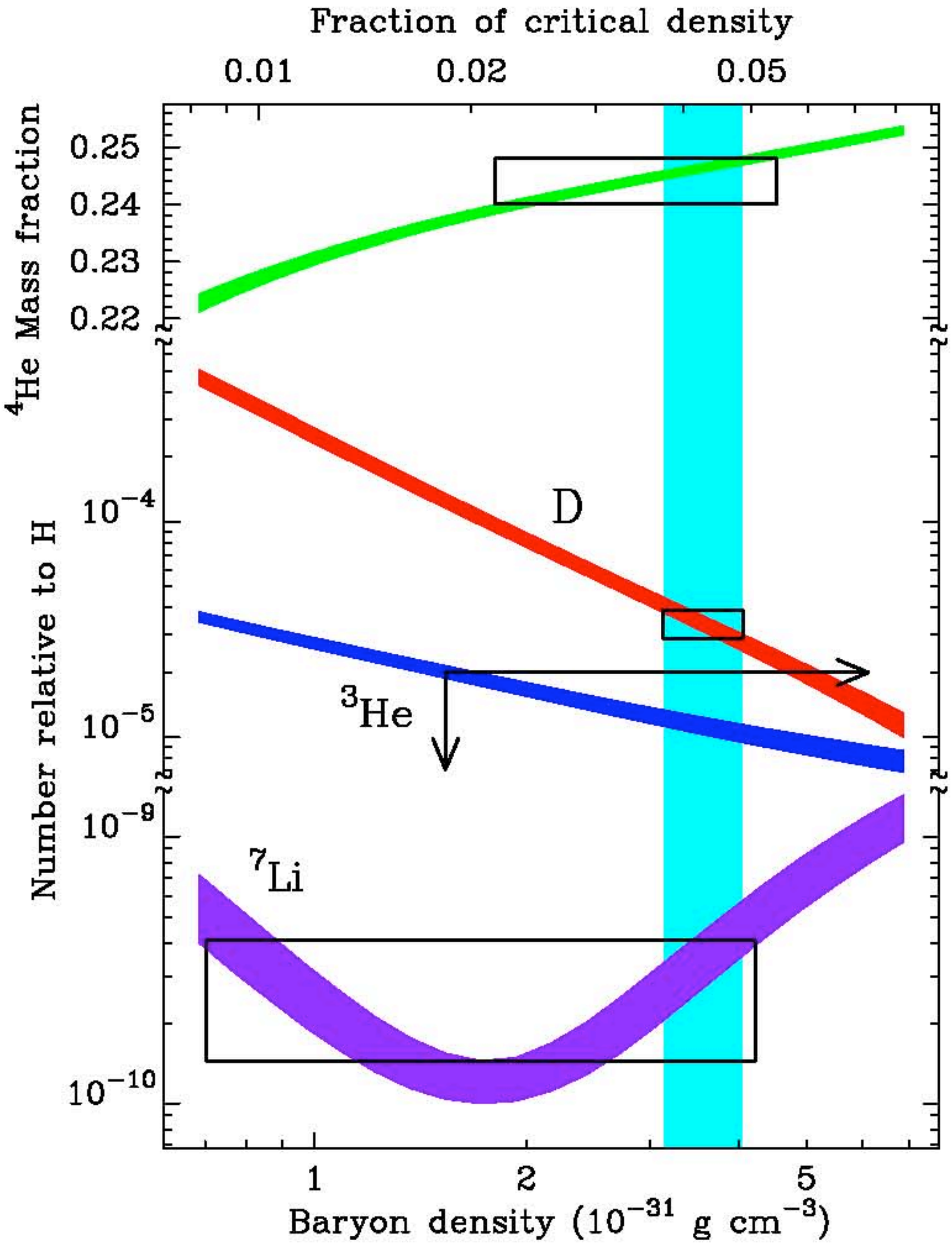
Hot Big-Bang Cosmology
(concordance model of cosmology)

explains everything we know about the evolution of the Universe since early times with remarkable accuracy.

In particular, two totally independent ways of determining the baryon average density (or the ratio of baryons to photons), one from the **Big-Bang Nucleosynthesis** (first few minutes), and the other one from analysis of the temperature fluctuations of the **Cosmic Microwave Background** (~400 ky) agree very well.

Both sets of data also agree (with rather large error bars) on the prediction that relativistic neutrinos of ~3 flavors were present at those epochs. These neutrinos have not interacted since that time with anything, thus they should be around us until now. In fact, these neutrinos are expected to be the second (after CMB photons) most abundant particles in the Universe.

BBN – Predicted Primordial Abundances



D, ^{3}He, ^{7}Li are BARYOMETERS

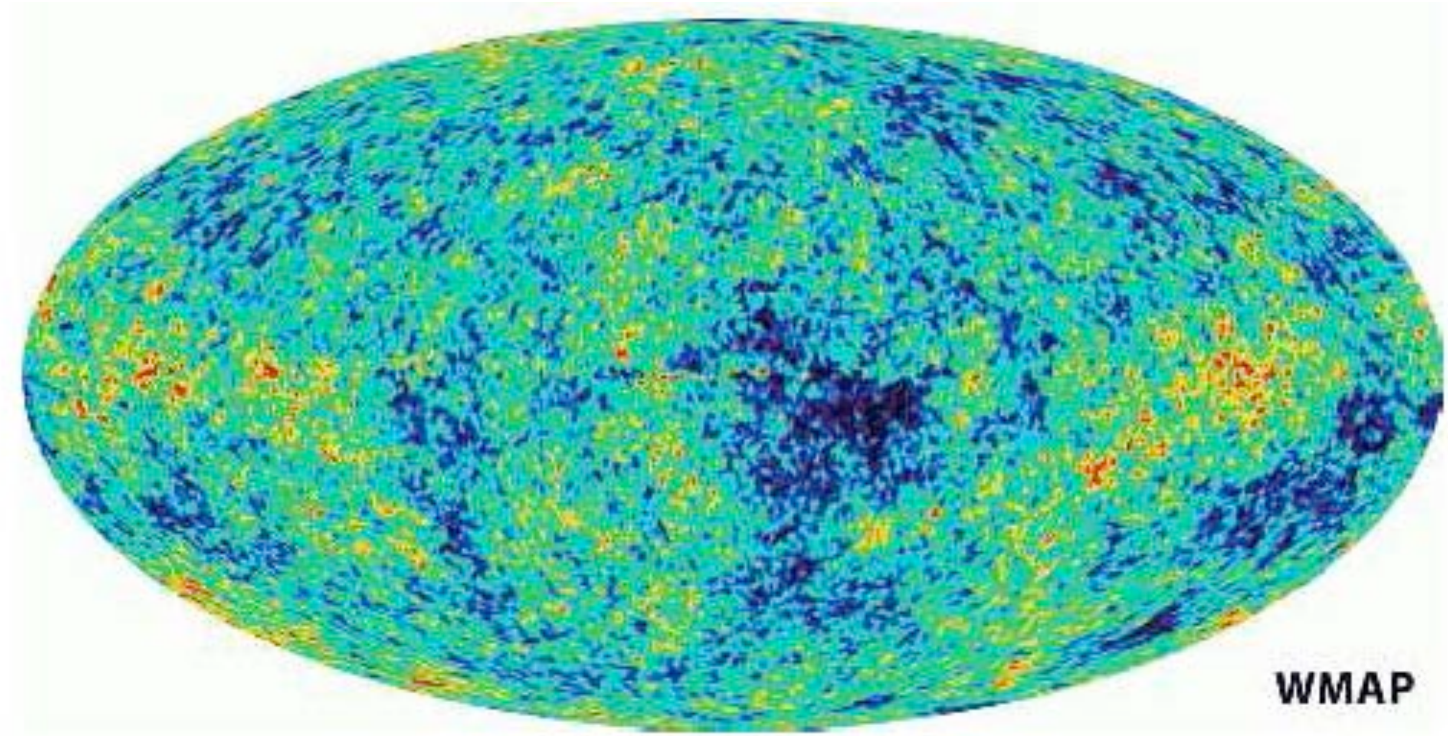
BBN probes the Universe at ~1-20 minutes

$\rho_B^{BBN} = 3.8 \pm 0.2 \times 10^{-31}$ g cm^{-3}
(Freedman & Turner, 2003)

$N_\nu = 3.71^{+0.47}_{-0.45}$ (from D,^{4}He)
(Steigman 2012)

Note that 3.8×10^{-31}g/cm^3 is the same as $n_B = 2.2\times10^{-7}$ nucleons/cm^3, which in turn is the same as $n_B/n\gamma = 6\times10^{-10}$, the usual value.

CMB temperature fluctuations from WMAP
(snapshot at 380 k years)



Analysis gives ρ_B^{CMB} = 4.0±0.6 x 10^{-31} g cm^{-3}
(Freedman & Turner, 2003)

N_ν = $3.52^{+0.48}_{-0.45}$ (Planck collaboration 2013 uses also BAO and H_0, when BICEP2 is included $N_\nu \sim 4$)

In the radiation dominated epoch energy density and temperature evolve as

$\rho = 3c^2/(32\pi G_N)\, t^{-2}$; $kT = [45\, h^3 c^5/(32\pi^3 G_N\, g_s^*)]^{1/4}\, t^{-1/2}$,
$kT/\mathrm{MeV} \sim (t/s)^{-1/2}$

Where $g_s^* = 1 + 7/4 + 3\mathrm{x}7/8$ (photons,electrons,3 neutrino flavors)

Neutrinos **decouple** when the expansion rate exceeds the interaction rate:

$\sigma \sim G_F^2\,(kT)^2$, $n_\nu \sim (kT)^3$, $t_\nu = (n_\nu \sigma v)^{-1} \sim G_F^{-2}\,(kT)^{-5}$

$t_{expansion} \sim G_N^{-1/2}\,(kT)^{-2}$

(t_ν - interval between weak interactions, t_{exp} - characteristic expansion time)

From $t_\nu = t_{exp}$ ➡ $kT \sim 1$ MeV, $t_{decoupling} \sim 1$ second

(detailed calculations give $kT(\nu_e) \sim 2$ MeV, $kT(\nu_\mu, \nu_\tau) \sim 3$ MeV), While in equilibrium the number density of each Majorana neutrino flavor is proportional to the photon number density

$n_\nu / n_\gamma = 3/4$ (for relativistic Fermi and Bose gases)

At t ~ 10 s , e^+ and e^- annihilate increasing n_γ.

That process conserves entropy, $s \sim \rho/T$

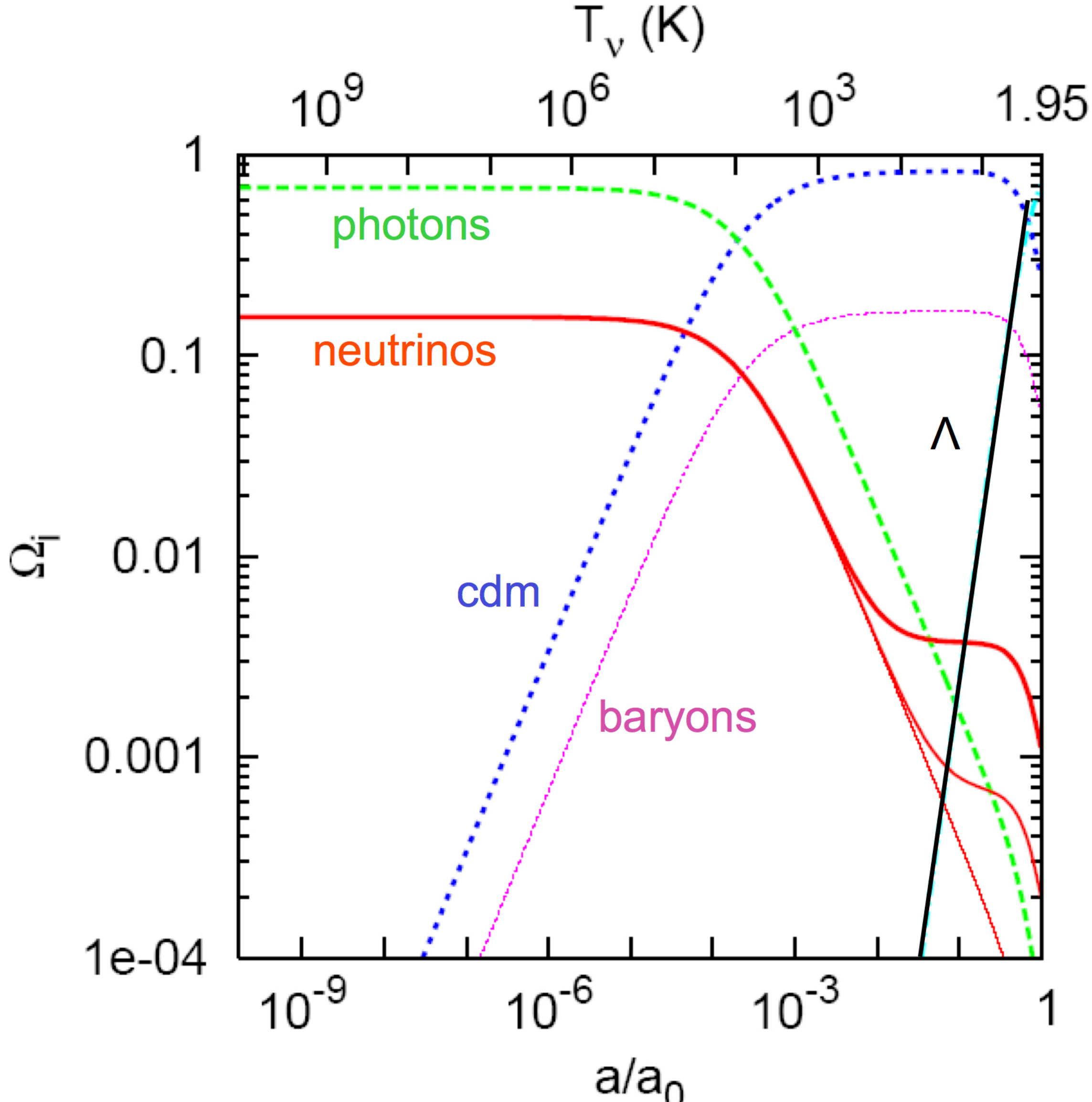
Thus the photon density n_γ increases by the factor (1 + 2x7/8) = 11/4

$n_\nu = (4/11)(3/4)\, n_\gamma \sim 112$ neutrinos of each Majorana flavor /cm^3

and **$T_\nu/T_\gamma = (4/11)^{1/3} = 0.71$; $T_\nu = 1.94$ K $= 1.67\times10^{-4}$ eV**

Neutrinos keep their momentum distribution as that of a relativistic Fermi gas, even when nonrelativistic. However, virial motion in the galactic halo will modify the momentum distribution

$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu} + 1}$$



$\Omega_i = \rho_i/\rho_c$

$\rho_c = 3H^2/8\pi G_N$
$\rho_c \sim 5$ keV/cm^{-3}

$\Omega_{tot} = 1$ is assumed

Background energy densities as a function of temperature (or scale *a*). Evaluated from T = 1 MeV until now with $h_{100} = 0.7$. The neutrino curves are for $m_1 = 0$, $m_2 = 0.009$ eV and $m_3 = 0.05$ eV. Massless particles scale like a^{-4}, nonrelativistic particle scale like a^{-3}, and ρ_Λ is time independent.

from Lesgourgues and Pastor, 1404.1740

In order to motivate the need for CNB detection even more, lets compare the time, temperature, and redshift of different epochs:

Epoch	time	Temperature	z
CMB	3.8×10^5y	0.26 eV	1100
BBN	100-1000s	0.115-0.036MeV	$(4.9-1.8) \times 10^8$
CNB	~0.18s	~2 MeV	$\sim 1.2 \times 10^{10}$

In other words, by observing CNB we would extend our observational capabilities by almost two orders of magnitude in in temperature and redshift and by almost four orders of magnitude by time since Big Bang.

These are then <u>firm</u> predictions of the Hot Big-Bang Cosmology:

Neutrino number density = 112 neutrinos/cm^3 for each flavor, i.e., **56 neutrinos and 56 antineutrinos of each flavor**

Neutrino temperature = 1.94 K = 1.67×10^{-4} eV

If one could confirm (or find deviations) from these predictions, one would test the theory at t ~ 1 sec, T ~ 1 MeV, much earlier and hotter than the tests based on BBN and CMB.

I assumed that neutrinos will concentrate in **clusters of ~5-10 Mpc** size with the total mass of ~10^{15} $M_\odot$ and that their enhancement in them will be similar to the average enhancement of baryons and cold dark matter.

Note that **$\Omega_\nu/\Omega_{baryon}$ ~ 112 (m_ν/eV) / 200 eV ~ 0.5 (m_ν/eV)** for each flavor. I assumed that this ratio remains fixed in the structures where both neutrinos and baryons cluster.

Note also, that the energy density, and naturally also the number density of neutrinos scales as R^{-3}, where R is the characteristic size of of the clustering region.

Cosmic background neutrinos can become bound only in structures where their velocity is less than the escape velocity of the structure. For nonrelativistic neutrinos the thermal velocity is v_{th} = <p>/m ~ $3.15 T_\nu/m$.

Consider first the fluxes and corresponding (kinetic) energies (for each neutrino flavor):

	Average	With clustering (v=500kms^{-1})
Flux (cm^{-2} s^{-1})	$0.8 \times 10^{9} \times (eV/m_\nu)$	2.8×10^{11}
Kin. energy(eV)	$1.2 \times 10^{-7} \times (eV/m_\nu)$	$1.4 \times 10^{-6} (m_\nu/eV)$

These fluxes can be compared to the solar pp neutrino flux of ~6×10^{10}/cm^2 s, distributed over 420 keV, or to the ν_e flux at a distance of 1 km from a power reactor, 4×10^{9}/cm^2 s spread over several MeV.

So, at the very small, sub eV, energies the CNB flux dominates over any other neutrino fluxes by a very large factor.

Since the momentum of the CNB $p_\nu \to 0$, we must consider only exothermic reaction, i.e., reactions on unstable targets.
What is the behavior of the cross section when $p_\nu \to 0$?

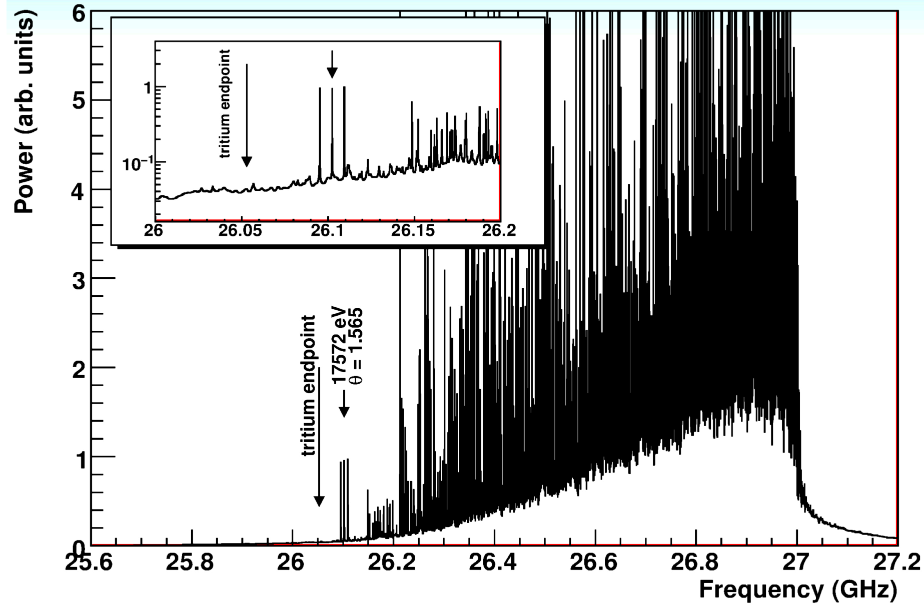
The well known endothermic reaction $\bar{\nu}_e + p \to e^+ + n$ has threshold (recoil neglected) $E_{thr} = M_n - M_p + m_e = 1.8$ MeV and cross section

$$\frac{d\sigma}{d\cos\theta} = \bar{G}^2 E_e p_e [(f^2 + 3g^2) + (f^2 - g^2) v_e v_\nu \cos\theta]$$

with $\bar{G} = G_F \cos\theta_C / \sqrt{2\pi}$.

The positron energy is $E_e = E_\nu - E_{thr.}$ Clearly, this will not go if $E_\nu \to 0$.

University of Washington
PNNL
MIT & Haystack Observatory
UC Santa Barbara
NRAO
Caltech



Monreal & Formaggio, Phys. Rev D 80, 051301(R) (

Monte Carlo showing combined spectra of 10^5 events from tritium distribution + 1 endpoint event

Goal:
Develop cyclotron radiation technology for the next generation tritium beta decay experiment

Prototype Goals

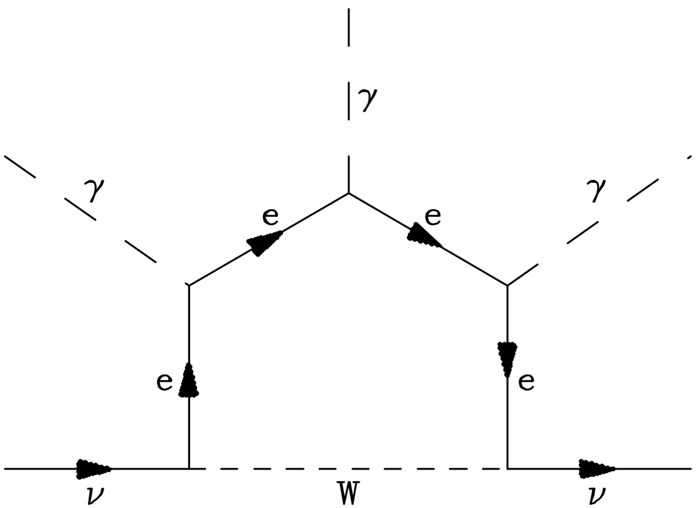
Use cyclotron radiation to measure electron energy of ^{83m}Kr decay

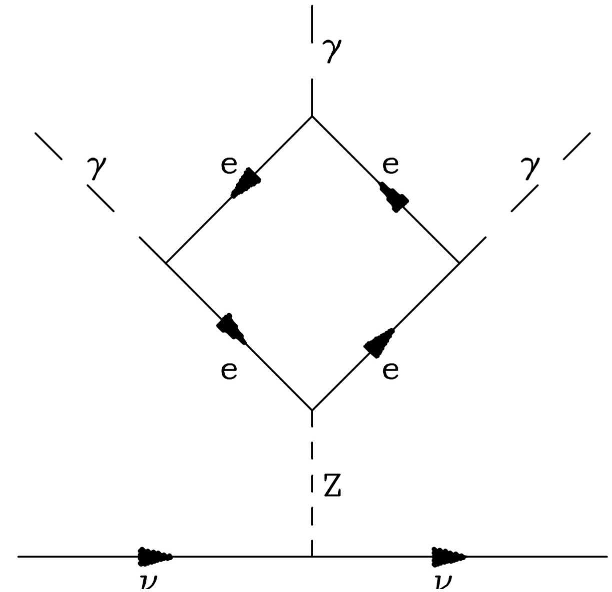
- Refine analysis of cyclotron RF signal
- Identify potential backgrounds to a Tritium measurement

PTOLEMY Conceptual Design

- High precision on endpoint
  - Cryogenic calorimetry energy resolution
  - **Goal: 0.1eV resolution**
- Signal/Background suppression
  - RF tracking and time-of-flight system
  - **Goal: sub-microHertz background rates above endpoint**
- High mass, high resolution tritium target
  - Surface deposition (tenuously held) on conductor in vacuum
  - **Goal: for CNB: maintains 0.1eV signal features with high efficiency**
  - **For sterile nu search: maintains 10eV signal features w/ high eff.**
- Scalable mass/area of tritium source and detector
  - **Goal: relic neutrino detection at 100g**
  - **Sterile neutrino (w/ % electron flavor) at ~1g**

Neutrino-antineutrino annihilation within the Standard Model
Dicus and Repko, Phys.Rev.Lett. 79 (1997) 569-571

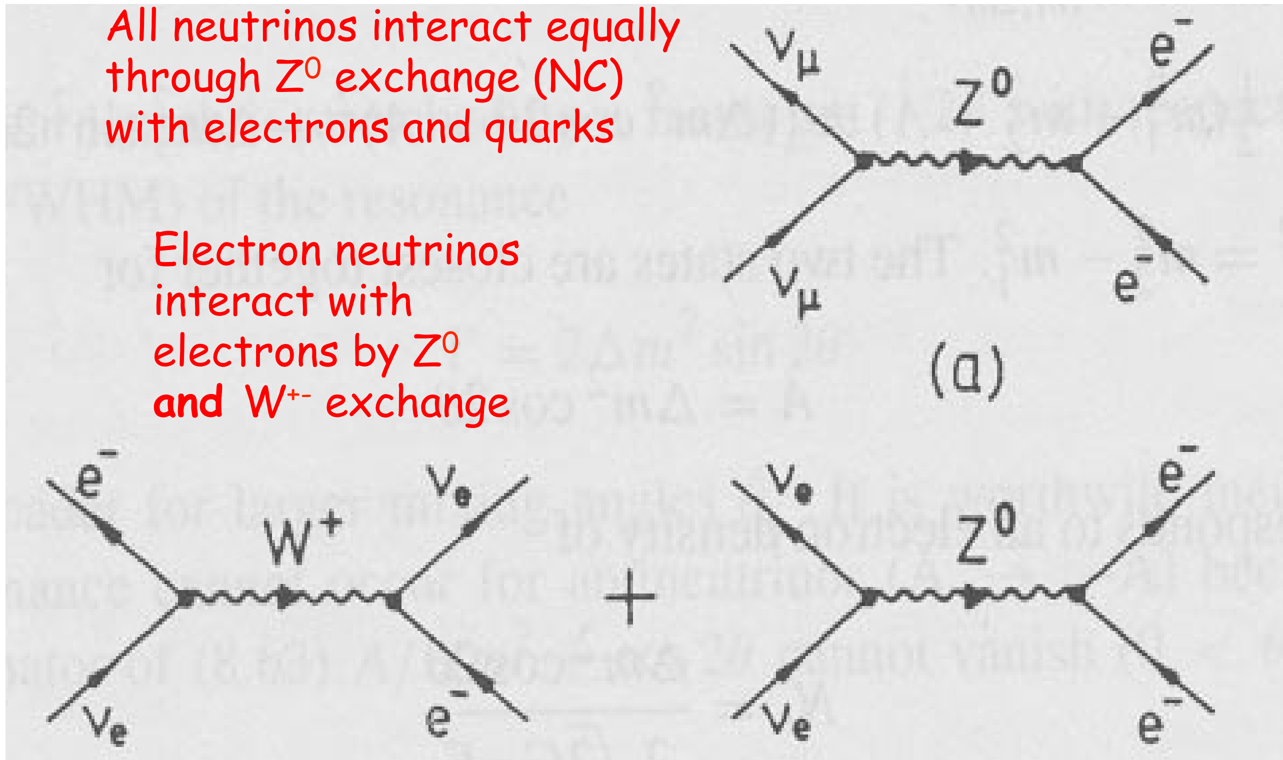




$$\sigma(\nu\bar{\nu} \to \gamma\gamma\gamma) = \frac{136}{91,125}\frac{G_F^2\, a^2\, \alpha^3}{\pi^4}\left(\frac{\omega}{m_e}\right)^8 \omega^2$$

$a = 1 - \frac{1}{2}(1\text{-}4\sin^2\theta_w)$, ω is the C.M. energy

In order to evaluate n-1, the deviation of index of refraction from unity, proceed exactly the same way as in the treatment of the MSW effect for matter neutrino oscillations, namely evaluate these graphs:

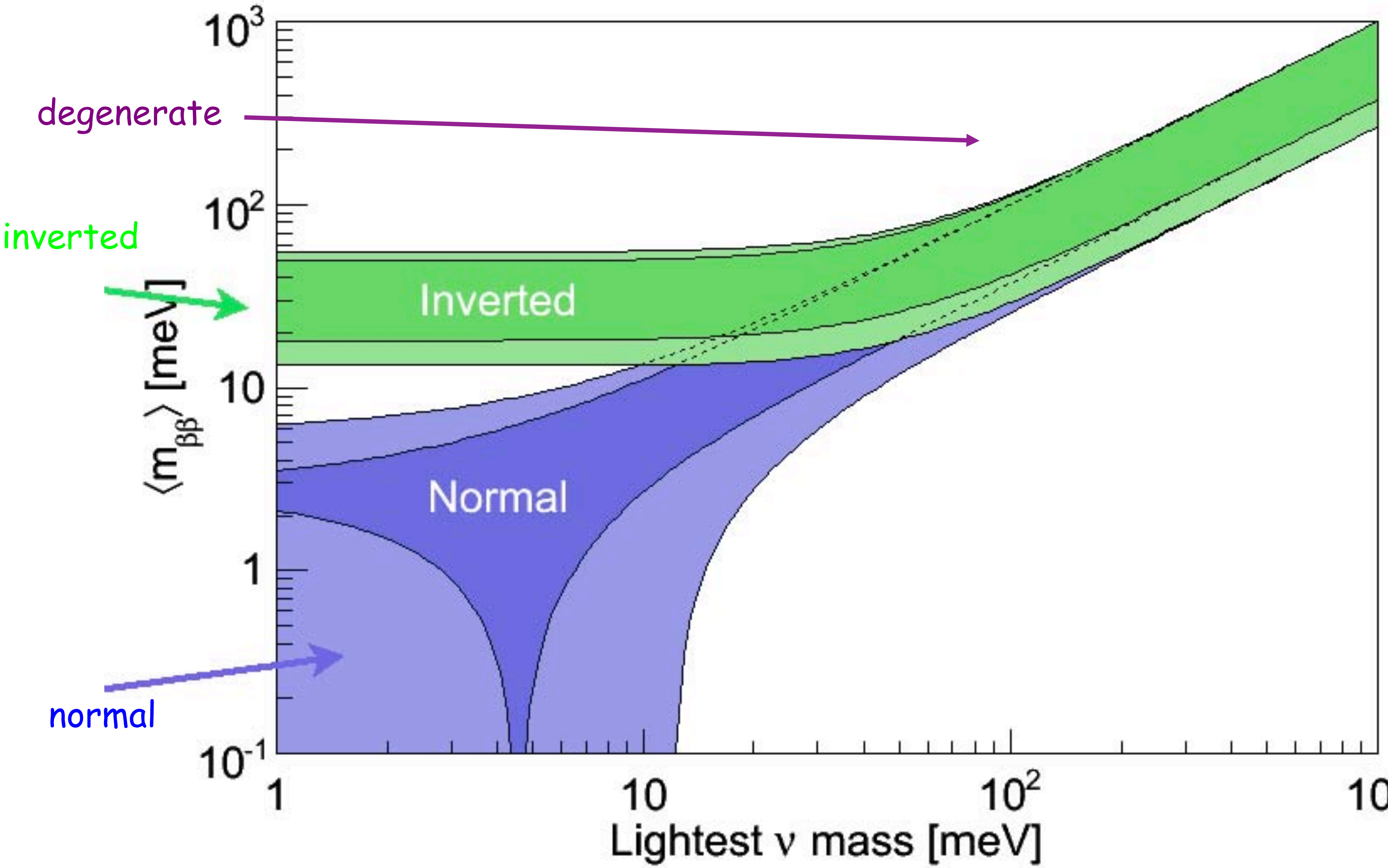


Thus $n-1 = \pm [G_F N (3Z - A)]/(2^{3/2} T_\nu)$ for ν_e ($\bar{\nu}_e$)

$n-1 = \pm [G_F N (Z - A))]/(2^{3/2} T_\nu)$ for ν_μ, ν_τ ($\bar{\nu}_\mu, \bar{\nu}_\tau$)

where T_ν is the kinetic energy of nonrelativistic neutrinos

Representation of the three different possible neutrino mass patterns.
The method of detecting CNB discussed here appears to be very challenging,
but with effort applicable for the case of degenerate mass pattern



In the radiation dominated epoch energy density and time evolve as

$\rho = 3c^2/(32\pi G_N)\, t^{-2}$; $kT = [45\hbar^3 c^5/(32\pi^3 G_N g_s^*)]^{1/4}\, t^{-1/2}$,
$kT/\text{MeV} \sim (t/s)^{-1/2}$

Where $g_s^* = 1 + 7/4 + 3x7/8$ (photons,electrons,3 neutrino flavors)

Neutrinos **decouple** when the expansion rate exceeds the interaction rate:

$\sigma \sim G_F^2\,(kT)^2$, $n_\nu \sim (kT)^3$, $t_\nu = (n_\nu \sigma v)^{-1} \sim G_F^{-2}\,(kT)^{-5}$

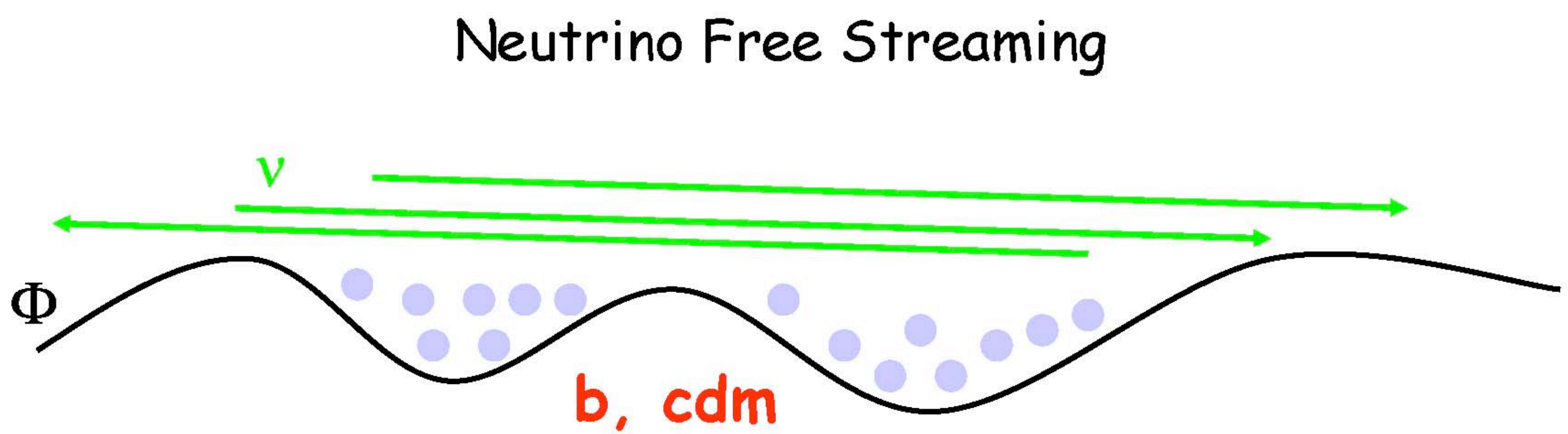
$t_{expansion} \sim G_N^{-1/2}\,(kT)^{-2}$

(t_ν - interval between weak interactions, t_{exp} - characteristic expansion time)

From $t_\nu = t_{exp}$ ➡ $kT \sim 1$ MeV, $t_{decoupling} \sim 1$ second

(detailed calculations give $kT(\nu_e) \sim 2$ MeV, $kT(\nu_\mu, \nu_\tau) \sim 3$ MeV),

Neutrinos are natural Hot Dark Matter (HDM)candidates

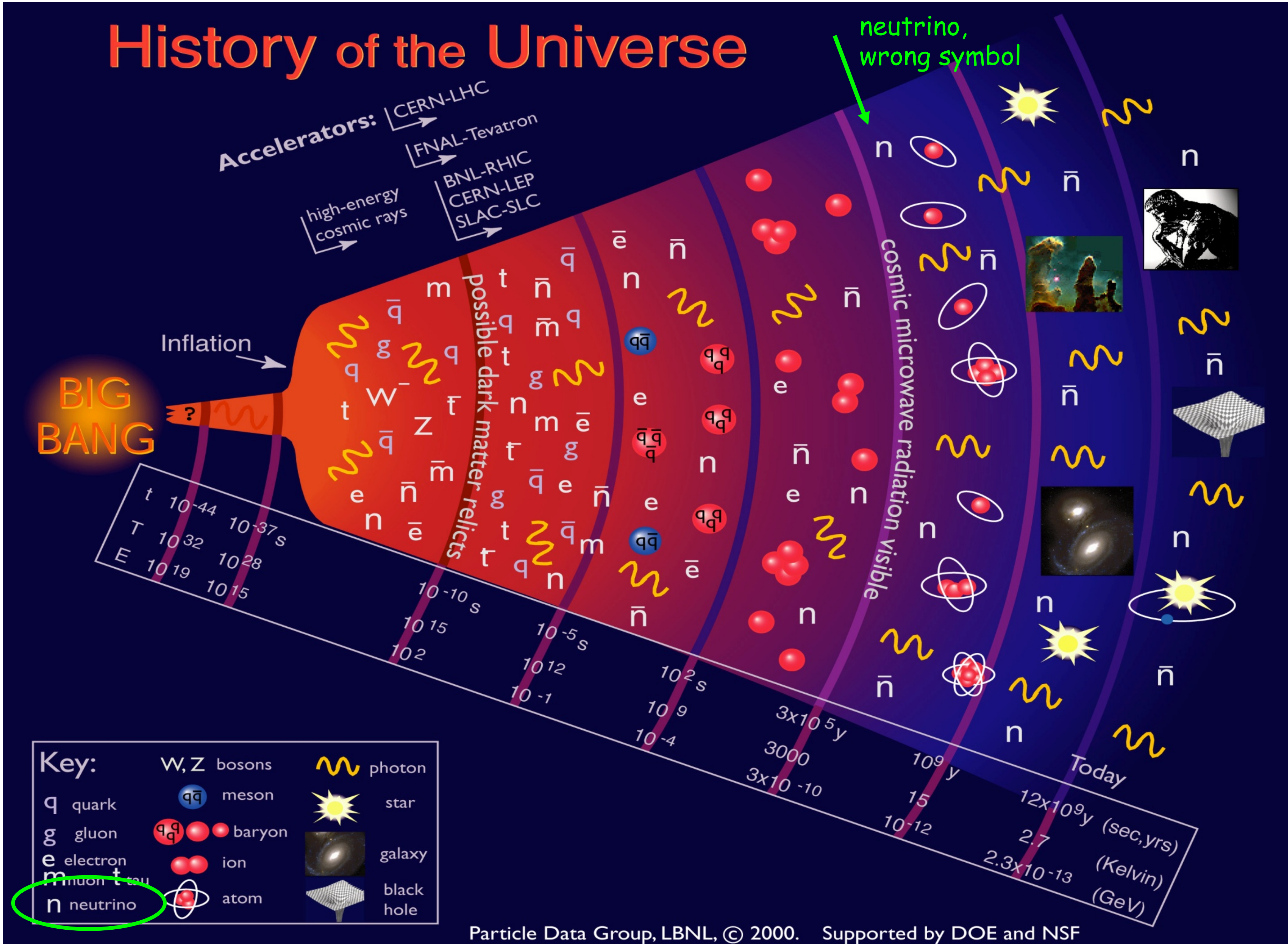


An alternative estimate of the enhancement $n_\nu/\langle n_\nu\rangle$ is obtained by considering the HDM clustering with a velocity dispersion *v* (Peebles):

$$n_\nu/\langle n_\nu\rangle \approx v^3\, m_\nu^3/(2\pi)^{3/2} = 330\ (v/500\ \mathrm{km/s})^3\ (m_\nu/\mathrm{eV})^3$$

Obtained for $\langle n_\nu\rangle = 110\ \mathrm{cm}^{-3}$ neutrino average number density.

Thus this estimate agrees with our previous $n_\nu/\langle n_\nu\rangle \approx 100$
(as far as the order of magnitude is concerned)



History of the Universe
neutrino,
wrong symbol
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy
cosmic rays
Inflation
BIG
BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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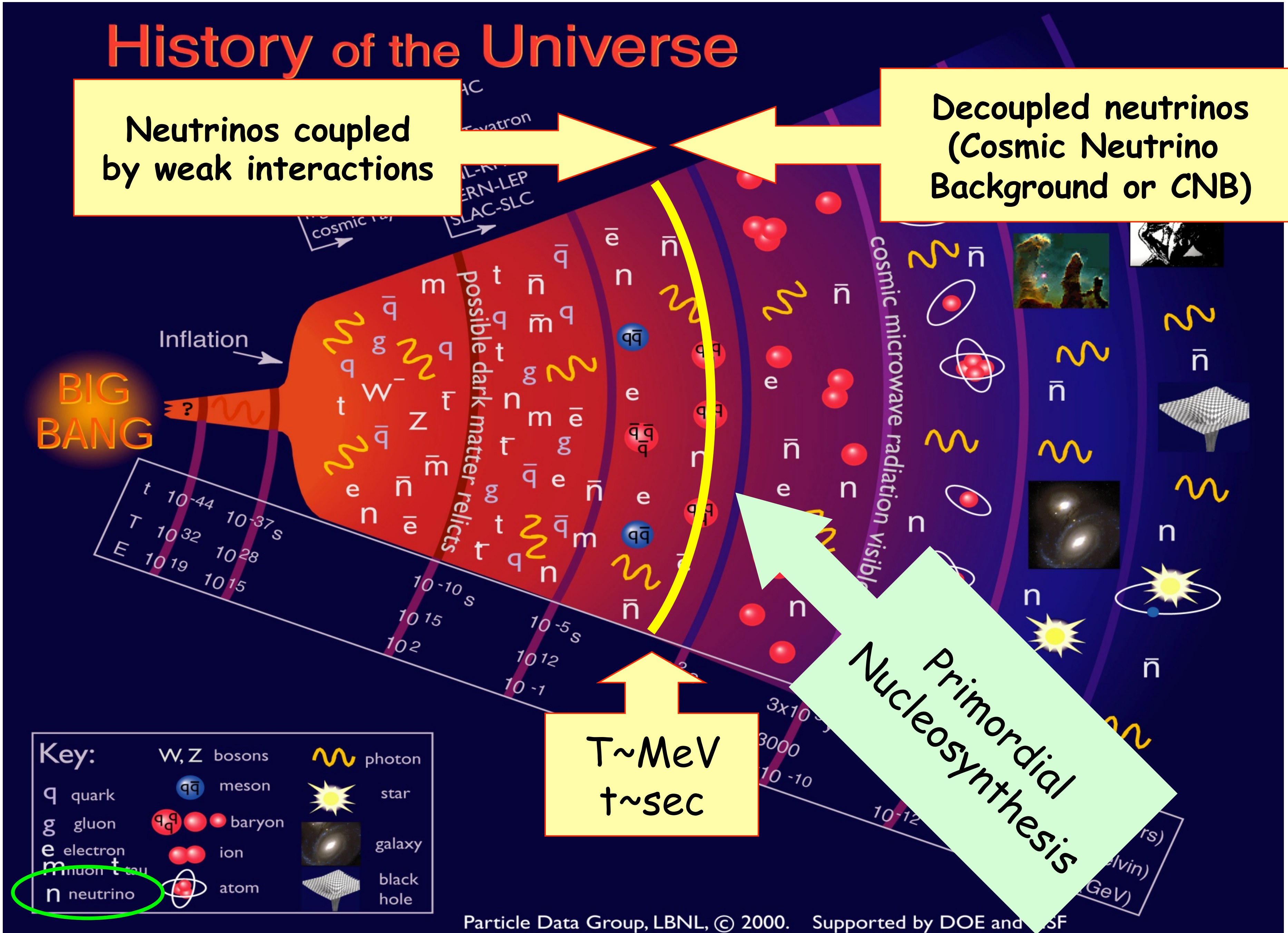
Distribution function of particle momenta in thermal equilibrium

$$f_i^{eq}(p,T) = \left[\exp\left(\frac{E_i - \mu_i}{T}\right) \mp 1\right]^{-1}$$

		relativistic Bose-Einstein	relativistic Fermi-Dirac	nonrelativistic
number density	n	$\frac{\zeta(3)}{\pi^2} g T^3$	$\frac{3}{4}\frac{\zeta(3)}{\pi^2} g T^3$	$g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$
energy density	ρ	$\frac{\pi^2}{30} g T^4$	$\frac{7}{8}\frac{\pi^2}{30} g T^4$	mn
pressure	p	$\frac{\rho}{3}$		$nT \ll \rho$
mean energy	$\langle E \rangle$	$2{,}701 T$	$3{,}151 T$	$m + \frac{3}{2} T$

$$n = g_i \int \frac{d^2\vec{p}}{(2\pi)^3} f_i(p,T) \qquad \rho = g_i \int \frac{d^2\vec{p}}{(2\pi)^3} E_i \; f_i(p,T)$$

$$p = g_i \int \frac{d^2\vec{p}}{(2\pi)^3} \frac{p^2}{3E_i} f_i(p,T) \qquad \langle E \rangle = \rho / n$$


History of the Universe
Neutrinos coupled by weak interactions
Decoupled neutrinos (Cosmic Neutrino Background or CNB)
T~MeV
t~sec
Primordial Nucleosynthesis
BIG BANG
Inflation
possible dark matter relicts
cosmic microwave radiation visible
SLAC-SLC
Key:
q quark
g gluon
e electron
n neutrino
W, Z bosons
meson
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black hole
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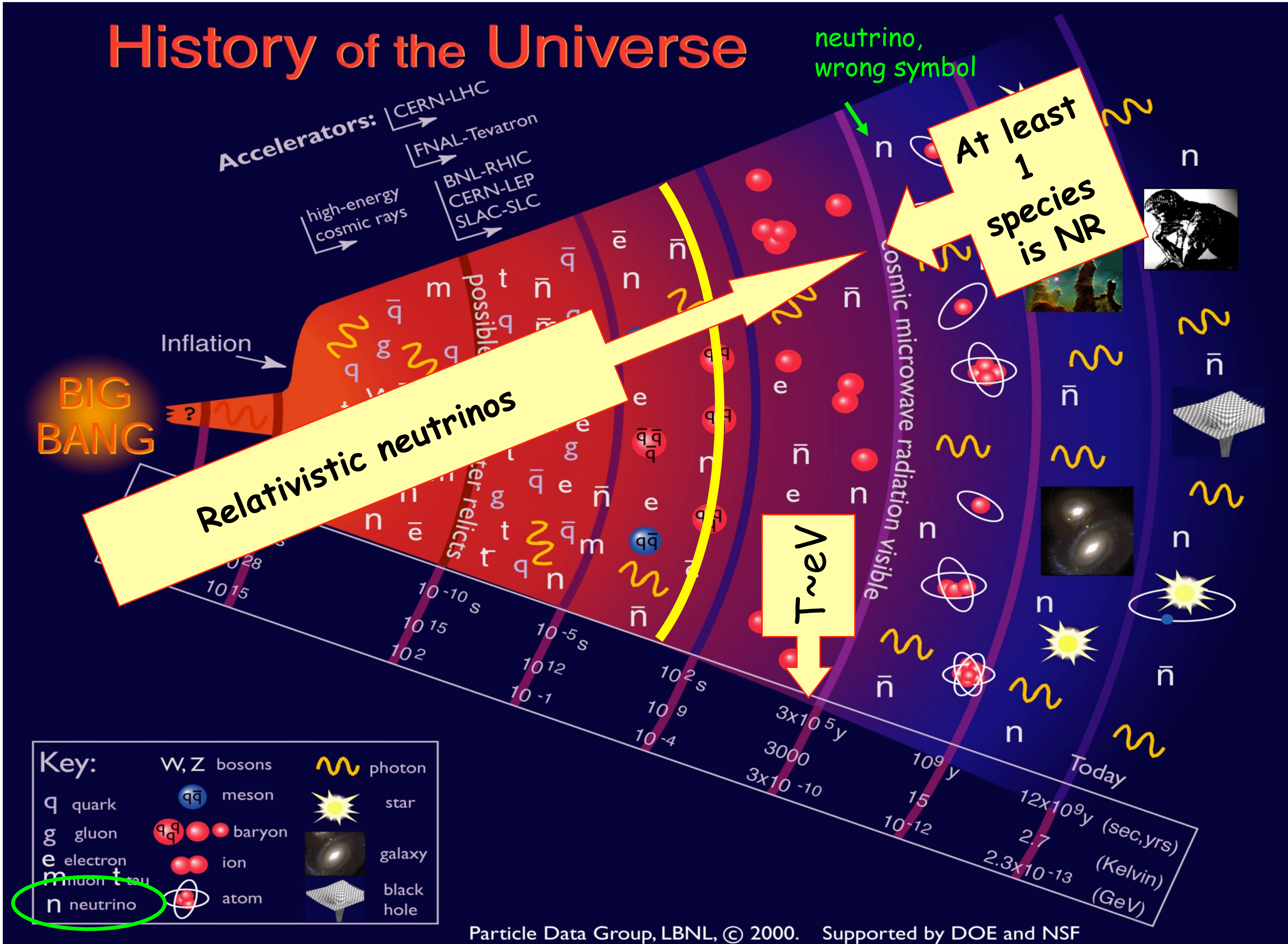
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10 9
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3000
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15
10 -12
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