# Next (or maybe next$^2$) challenge: Detection of the Cosmic Neutrino Background

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Based on the paper with Rimas Lazauskas and Cristina Volpe, J. Phys. G. **38**, 025001 (2008).

Outline:

1) Number density of the Cosmic Neutrino Background
2) Clustering of CNB
3) Using coherence (or not)
4) Detection with radioactive targets

# Hot Big-Bang Cosmology
(concordance model of cosmology)

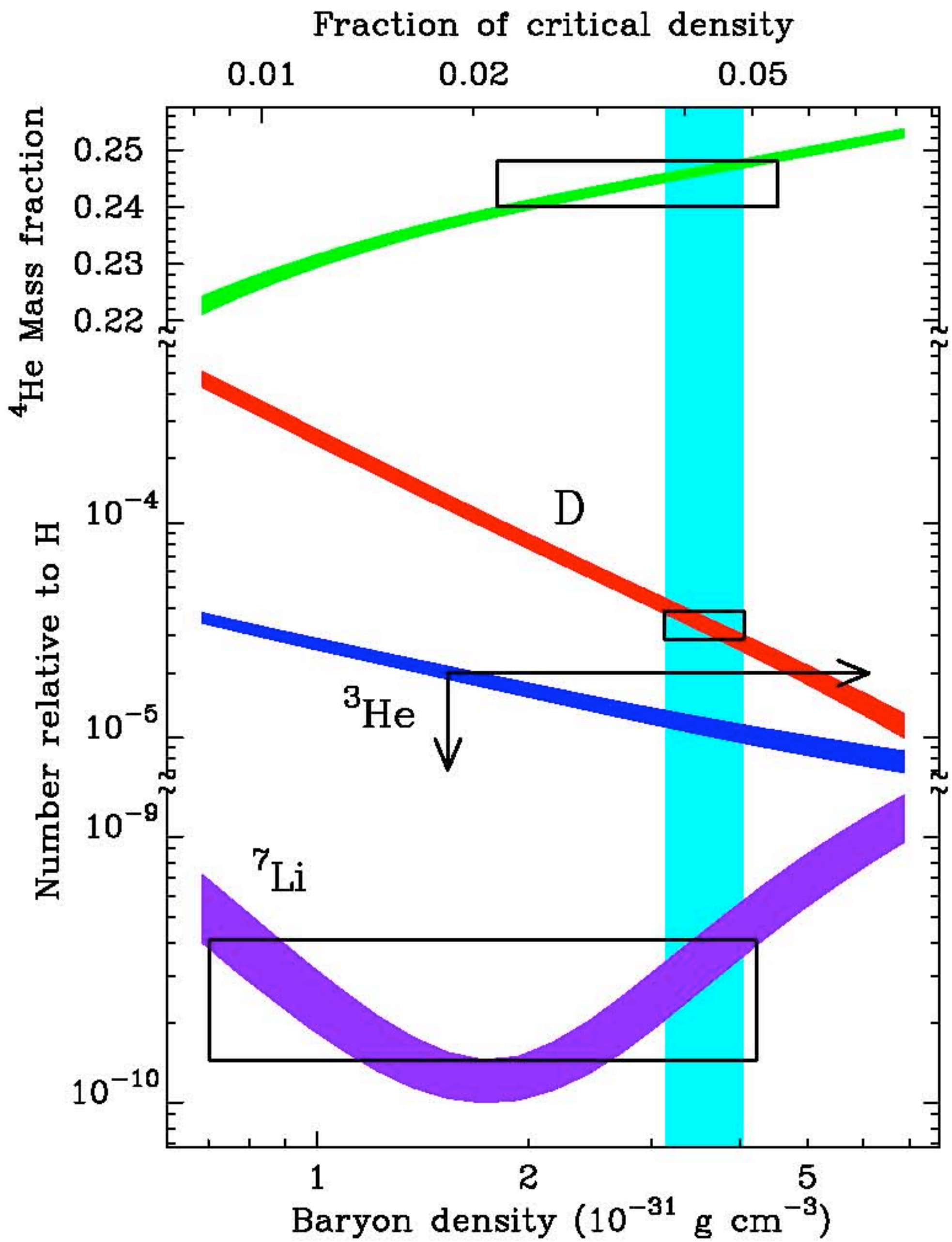
explains everything we know about the evolution of the Universe since early times with remarkable accuracy.

In particular, two 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 **Cosmic Microwave Background** (~400 ky) agree very well.

**Both sets of data also agree (albeit with large error bars) on the prediction that relativistic neutrinos of ~3 flavors were present at those epochs. Since these neutrinos have not interacted since that time with anything, they should be around us until now.**

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

# BBN – Predicted Primordial Abundances




**D, $^3$He, $^7$Li are BARYOMETERS**

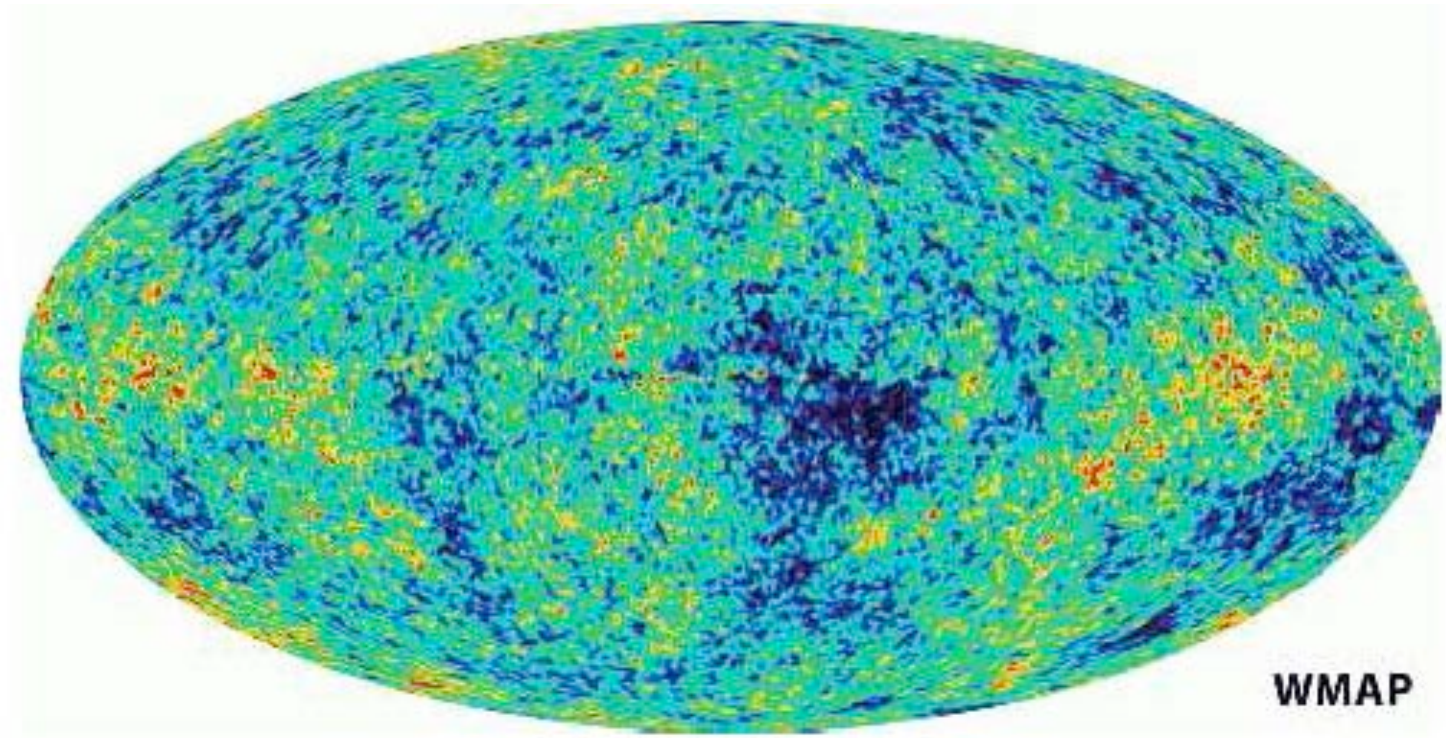
BBN probes the Universe at ~20 minutes

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

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

# CMB temperature fluctuations from WMAP

(snapshot at 380 k years)




Analysis gives $\rho_B^{CMB} = 4.0 \pm 0.6 \times 10^{-31}$ g cm$^{-3}$
(Freedman & Turner, 2003)

In the radiation dominated epoch energy density and time evolve as

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

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

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

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

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

($t_\nu$ - 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

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

At t ~ 10 s , $e^+$ and $e^-$ annihilate increasing $n_\gamma$.

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

Thus the photon density $n_\gamma$ 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

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

Reminder: Few textbook formulas re distribution functions 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 | $\rho$ | $\frac{\pi^2}{30} g T^4$ | $\frac{7}{8}\frac{\pi^2}{30} g T^4$ | $mn$ |
| pressure | $p$ | $\frac{\rho}{3}$ | | $nT \ll \rho$ |
| mean energy | $\langle E \rangle$ | $2{,}701 T$ | $3{,}151 T$ | $m + \frac{3}{2} T$ |

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

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

## 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 = $1.67\times10^{-4}$ 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 C$\nu$B.**

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

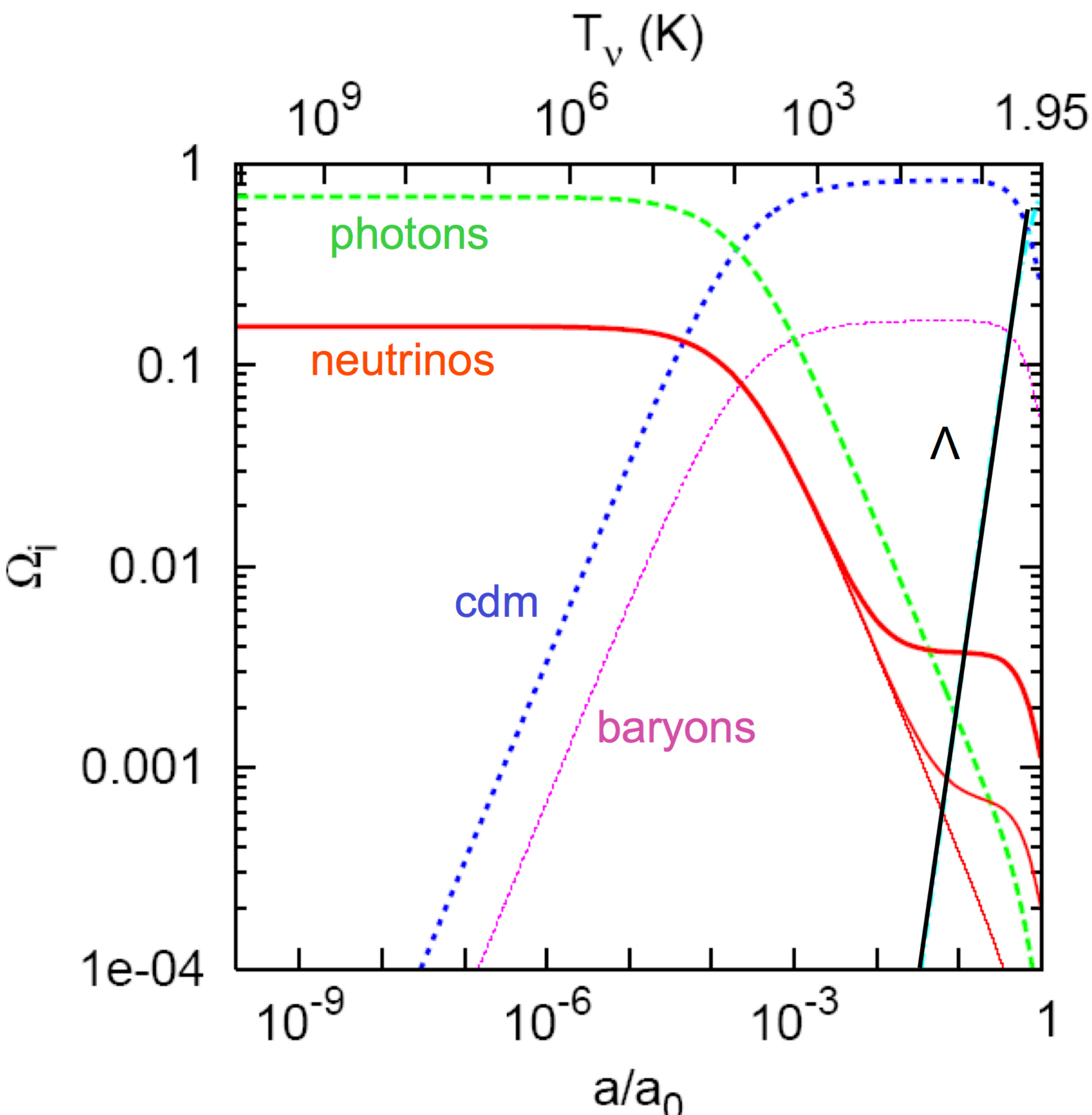
| Epoch | time | Temperature | z |
|---|---|---|---|
| CMB | $3.8 \times 10^5$y | 0.26 eV | 1100 |
| BBN | 100-1000s | 0.115-0.036MeV | $(4.9-1.8) \times 10^8$ |
| CNB | ~0.18s | ~2 MeV | $\sim 1.2 \times 10^{10}$ |

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.

From the results of oscillation experiments we know that at least two out of three mass eigenstates neutrinos have a finite mass.

For the normal hierarchy the minimum masses are
$m_1 = 0$, $m_2 = 0.009$ eV = 100 K, $m_3 = 0.060$ eV = 700 K .
And for the inverted hierarchy
$m_3 = 0$, $m_1 = 0.040$ eV = 460 K, $m_2 = 0.049$ eV = 570 K .

These masses are much larger than the corresponding relic Neutrino temperature of 1.94 K. Therefore, at the present time at least two out of the three neutrino mass states are **nonrelativistic**.




$\Omega_i = \rho_i/\rho_c$

$\rho_c = 3H^2/8\pi G_N$

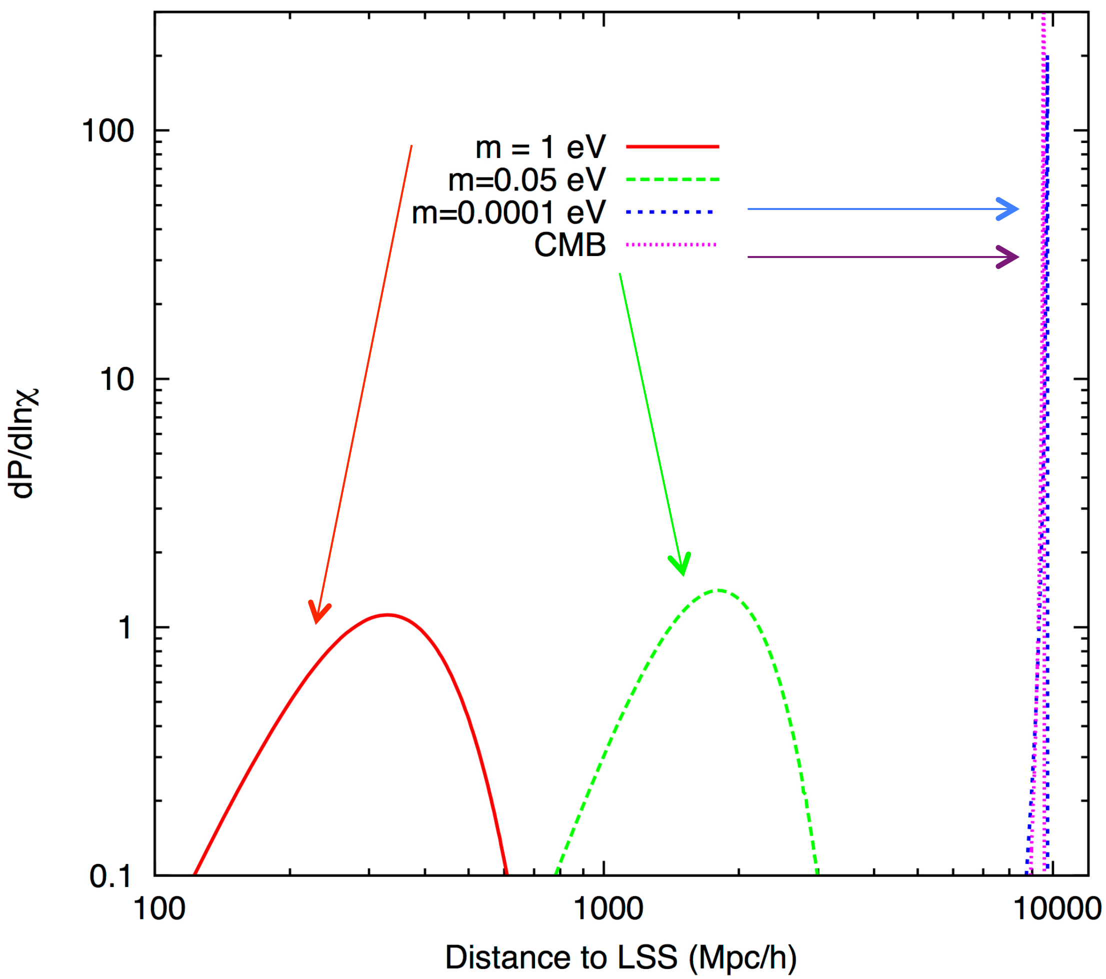
$\rho_c \sim 5$ keV/cm$^{-3}$

$\Omega_{tot} = 1$ 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 $\rho_\Lambda$ is time independent.

from Lesgourgues and Pastor, 1404.1740

An interesting and contraintuitive consequence of finite nuclear mass, and thus that neutrino are nonrelativistic now, is 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

## Clustering neutrino density enhancement

Massive particles become nonrelativistic when their mass exceeds the temperature of the Universe. From then 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

$$\rho_c = 1.05\times10^4\, h_{100}^2\ \mathrm{eV/cm^3} \sim 5\ \mathrm{keV/cm^3}\ (\text{since } h_{100} \sim 0.73)$$

| component | average $\rho$(keV/cm$^3$) | Structure | Enhancement |
|---|---|---|---|
| baryons | 0.2 | galaxy(disk) | $\sim 5\times10^6$ |
| dark matter | 1.0 | galaxy(halo) | $\sim 3\times10^5$ |
| **Neutrinos** | **112($\Sigma m_\nu$/keV)** | **clusters** | **~1 - 100** |

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 ~ 1.6x$10^2$/(m/eV) km/s. The escape velocity for Milky Way is ~ 500 km/s and for our supercluster it is ~ a few x $10^3$ km/s

In order to estimate the clustering enhancement 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 **$\Omega_\nu/\Omega_{CDM}$ ~ 112 ($m_\nu$/eV) / 1000 ~ 0.1 ($m_\nu$/eV)** for each flavor. 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.

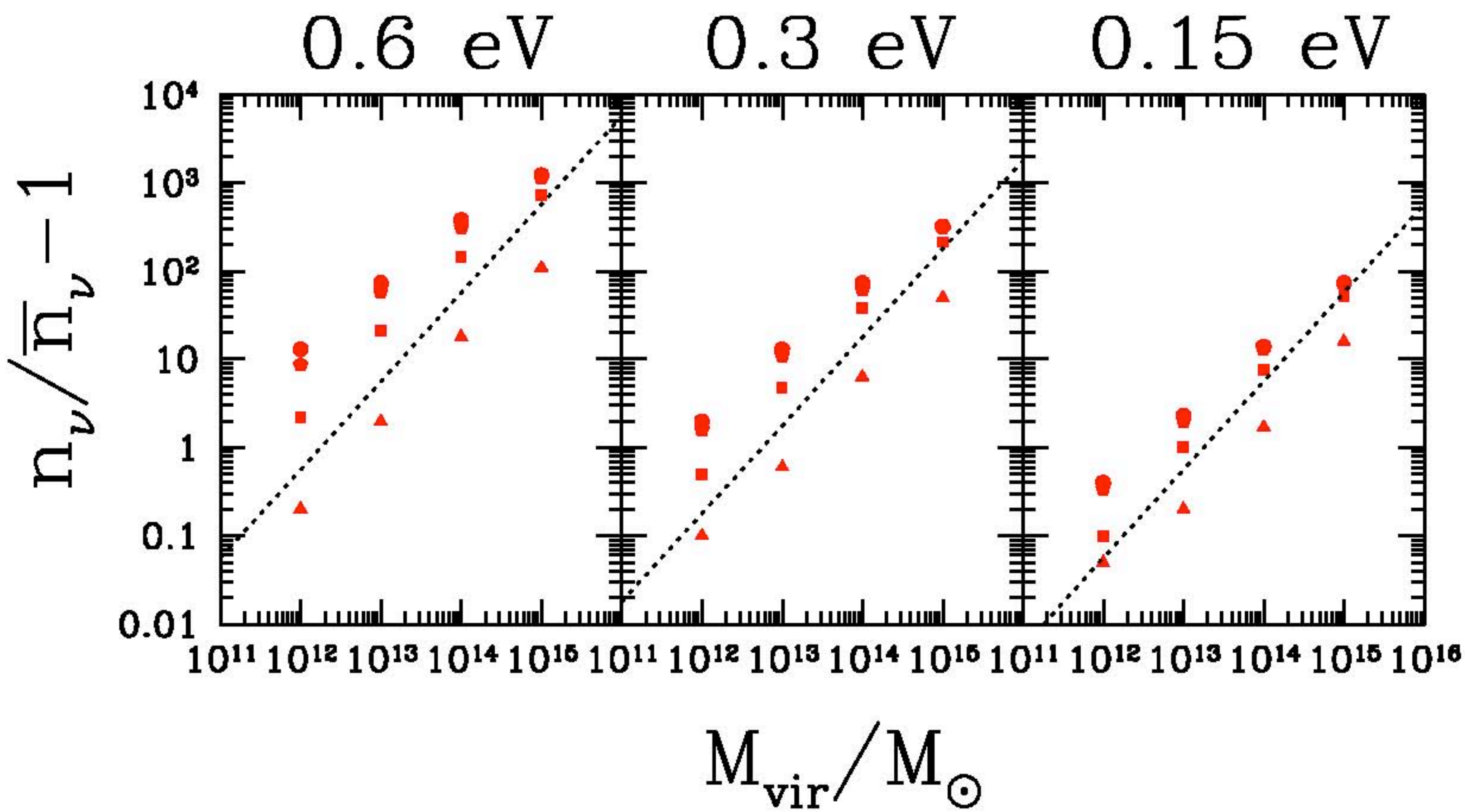
Assuming that the clustering occurs in structures with R ~ 100-200 $R_{galaxy}$ and using the ratio above we arrive at the crude estimate of the enhancement of the neutrino number density $n_\nu/\langle n_\nu\rangle$ ~ 100.

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

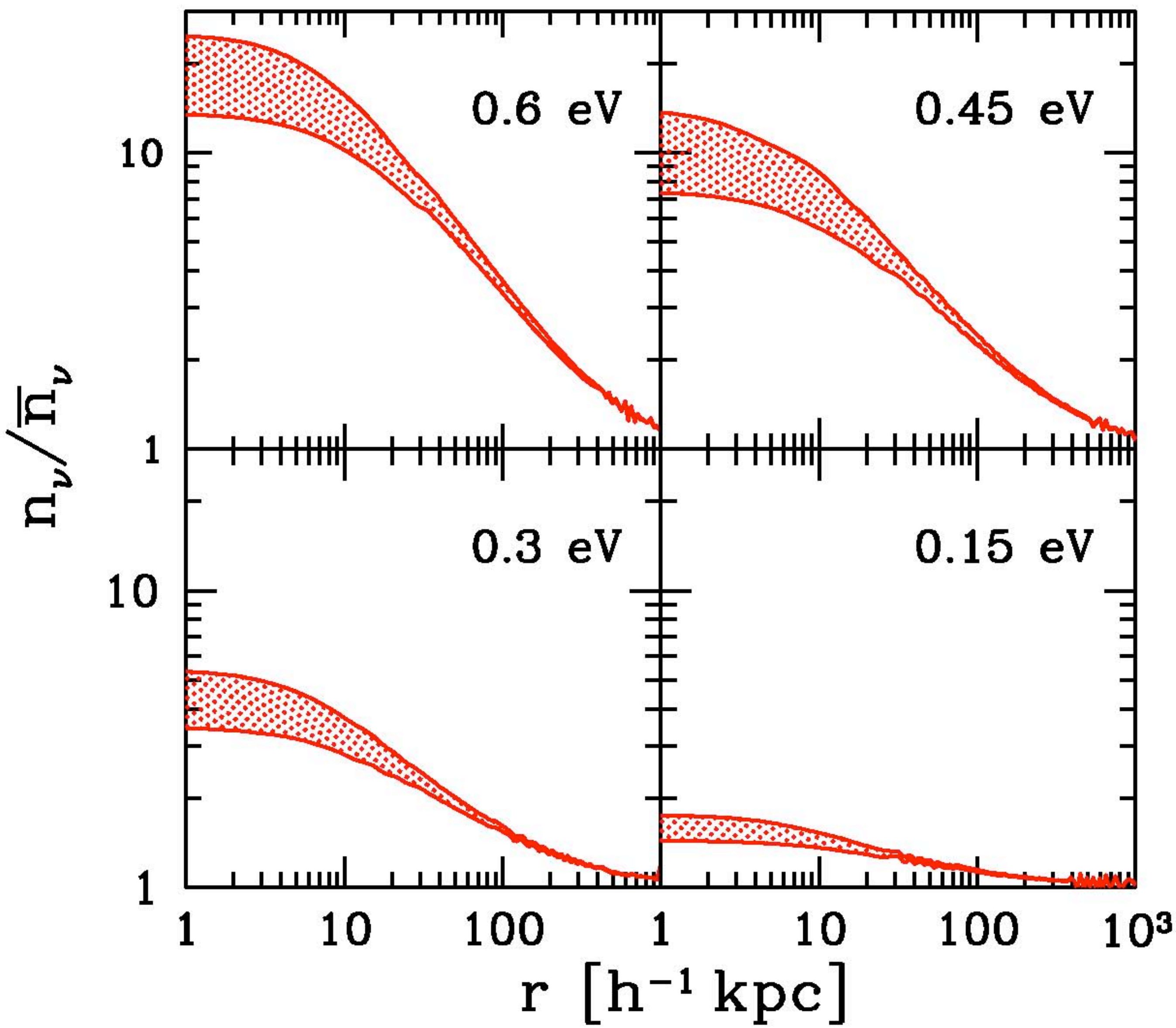
The red symbols indicate different distances from the cluster center,

▲ are for r = 1 Mpc/h.

For $M_{vir} = 10^{15}\, M_\odot$ , $m_\nu$ > 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.



Before discussing the CNB detection, lets consider first the fluxes and corresponding (kinetic) energies (for each neutrino flavor):

| | Average | With clustering ($v$=500kms$^{-1}$) |
|---|---|---|
| Flux (cm$^{-2}$ s$^{-1}$) | $0.9\times10^{9} \times (\mathrm{eV}/m_\nu)$ | $2.8\times10^{11}$ |
| Kin. energy(eV) | $1.4\times10^{-7} \times (\mathrm{eV}/m_\nu)$ | $1.4 \times10^{-6} (m_\nu/\mathrm{eV})$ |

These fluxes can be compared to the solar pp neutrino flux of ~$6\times10^{10}$/cm$^2$ s, distributed over 420 keV, or to the $\nu_e$ flux at a distance of 1 km from a power reactor, $4\times10^{9}$/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.**

# 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 = $\lambda_\nu$ contains ~ $10^{21}$ nucleons. If neutrinos interact coherently with all of them, it should help a lot.

# Use the coherent scattering on macroscopic objects:

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

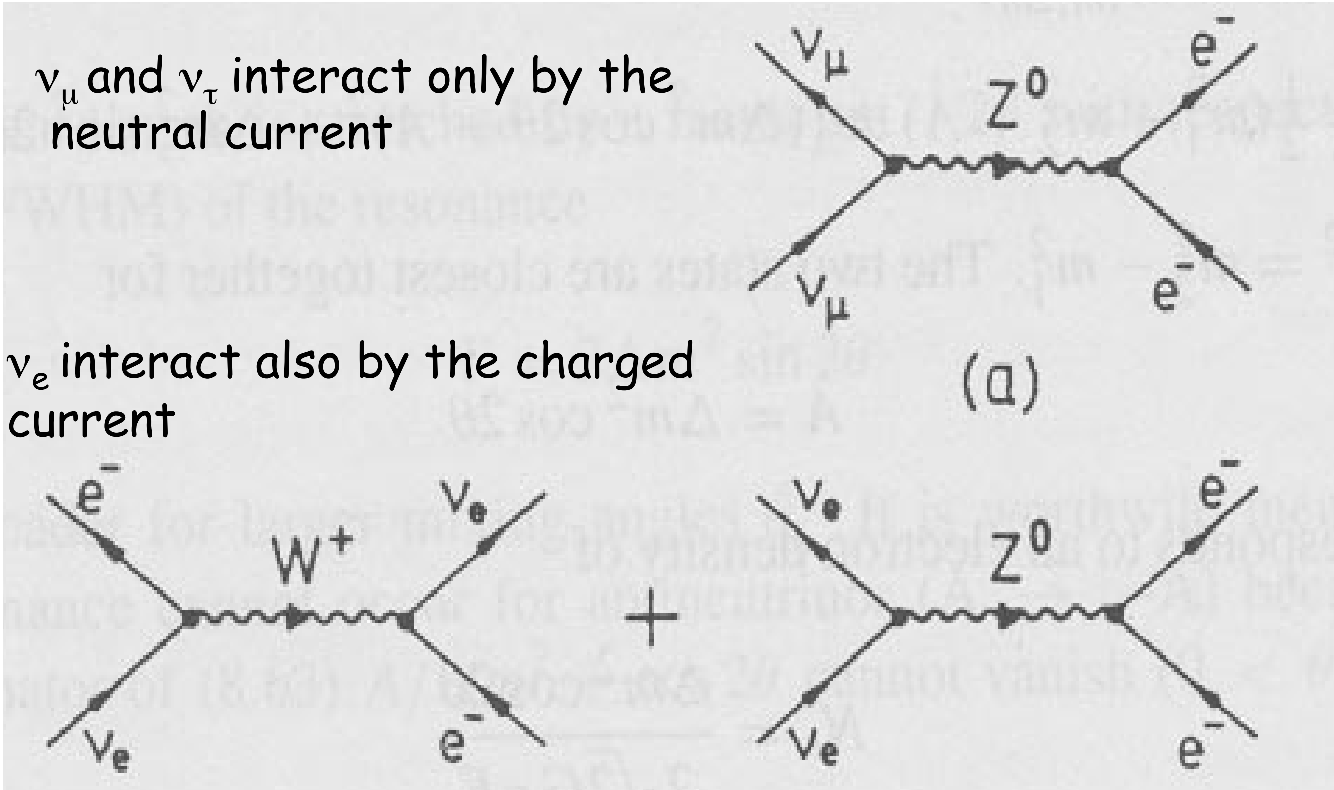
$$n = 1 + N \lambda_\nu^2 f(0)/2\pi,$$

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

Feynman graphs for the forward scattering amplitude f(0):

$\nu_\mu$ and $\nu_\tau$ interact only by the neutral current

$\nu_e$ interact also by the charged current




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

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

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

where $T_\nu$ is the kinetic energy of the nonrelativistic neutrinos.

For $\nu_\mu$ on gold **$1-n \approx 10^{-7}$ $(eV/m_\nu)$** for $v_\nu$ = 500 km/s
and the critical scattering angle $\theta_c$ **$= [2(1-n)]^{1/2} \approx 1.5$ arcmin**

Consider neutrinos with flux density **j (neutrinos/sr cm$^2$ sec)**.
Collision rate for area of 1 cm$^2$ with angles less than $\theta_c$ 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 $v_\nu$** (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 $\rho_A$ 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 **$\sigma = G_F^2\ m_\nu^2\ k_L^2/\pi$** , $k_L = 3Z\text{-}A$ (for $\nu_e$), $A\text{-}Z$ (for $\nu_\mu,\nu_\tau$)

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

($n_\nu$ = density of relic neutrinos, $N_A$ = number of target atoms in each sphere)

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

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

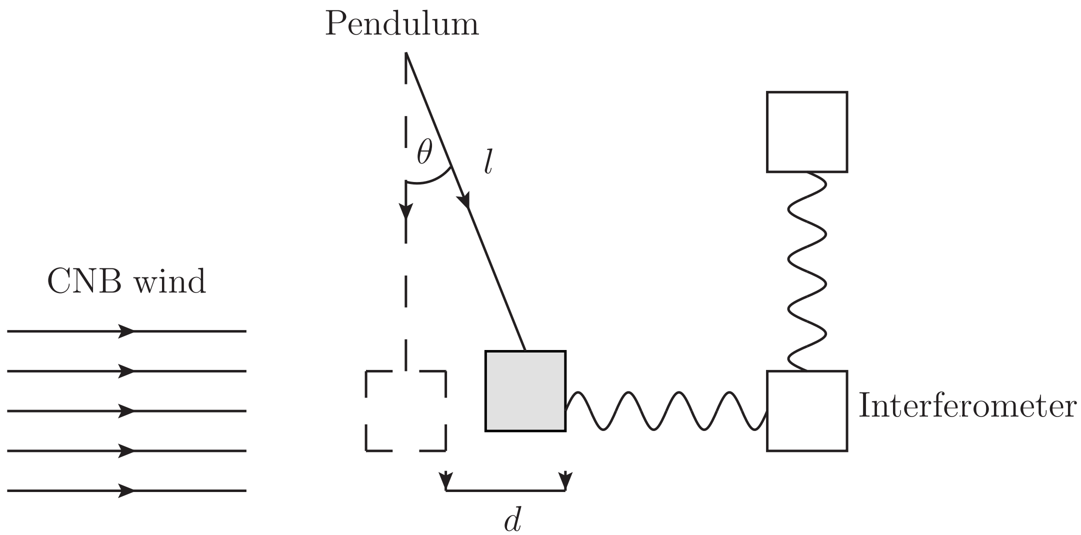
Take **iron** spheres, assume clustering **$n_\nu/\langle n_\nu\rangle = 100$,**

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

**<u>This is ~12 orders of magnitude from the sensitivity of the current Dicke - Eotvos type experiments.</u>**

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

What about laser interferometers, remembering LIGO ?




LIGO current displacement sensitivity is $\Delta d \sim 1\times10^{-17}\ (\Delta f/10\ \mathrm{Hz})^{1/2}$ cm.
This translates into the acceleration sensitivity

$a_{min} = g\ \Delta d/l \sim 1\times10^{-16}\ \mathrm{cm/s^2}$ for length $l$ = 100 cm.

We are thus still missing about 10 orders of magnitude

Domcke and Spinrath, 1703.08629

## Use resonance absorption of UHE neutrinos on C$\nu$B:

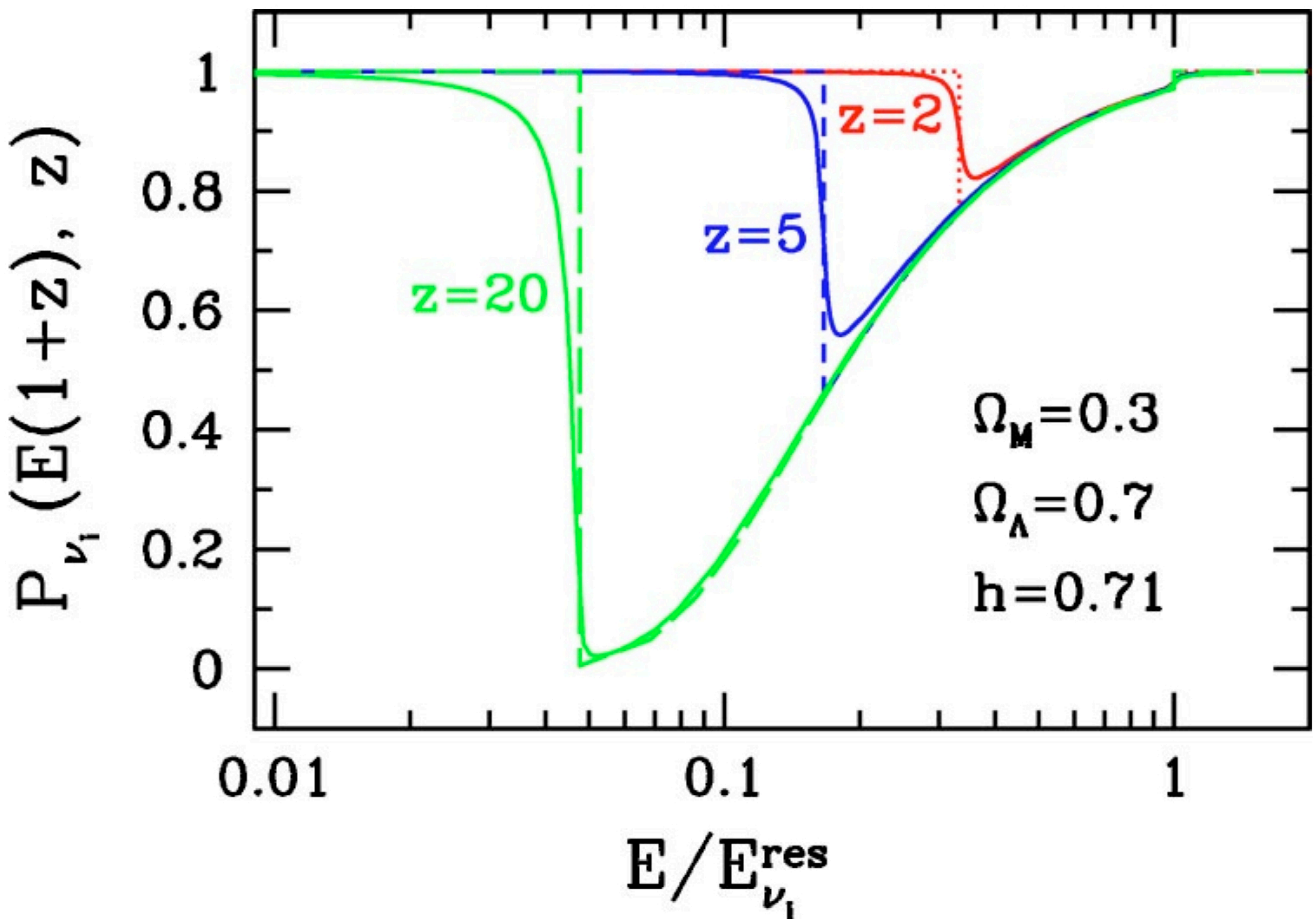
The Universe is transparent to neutrinos with the exception of the resonance annihilation into Z-bosons (Weiler 82).

The resonance energy is $E_\nu^{res} = m_Z^2/2m_\nu = 4.2\times10^{22}$ eV (0.1 eV/$m_\nu$), 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 on the 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 charged current weak interactions.**

**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(??!!)*** few orders of magnitude each, so it is worthwhile to consider them in more detail.

Since the momentum of the CNB $p_\nu \rightarrow 0$, 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 $E_\nu \rightarrow 0$

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

The cross section now contains **$1/v_\nu$**, which means that the rate, $\sigma v_\nu$ , remain finite even when **$v_\nu \rightarrow 0$**.
(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 **$v_\nu \rightarrow c$** (=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 $e^{\pm}$ $\beta$-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 (2.1x$10^{25}$ 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.)

## Are there other possibilities?

There are, in nature, unstable targets in the form of the $\beta\beta$ decay candidate nuclei. These can be obtained in ton like quantities. Capturing relic neutrinos on them leads to the reaction

$$\nu_e + (Z,A) \rightarrow (Z+2,A) + 2e + \bar{\nu}_e$$

The corresponding electron spectrum is continuous, with a shape rather similar to the competing $2\nu\beta\beta$ decay shape.

The ratio of rates of these two competing processes is, up to a numerical factor that does not affect the qualitative conclusions,

$$\lambda_{capt}/\lambda_{\beta\beta} = (\hbar c)^3/Q^3 \, n_\nu ,$$

where Q is the endpoint value and $n_\nu$ the relic neutrino number density. This ratio is so small that this possibility is firmly excluded.

# 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 $\sigma = 1.5\times10^{-41}\,(m_\nu/\mathrm{eV})\ \mathrm{cm}^2$

The CNB capture rate is then independent of $m_\nu$, and $v_\nu$

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

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

Note that this rate is for Majorana $\nu$, for Dirac $\nu$ 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?

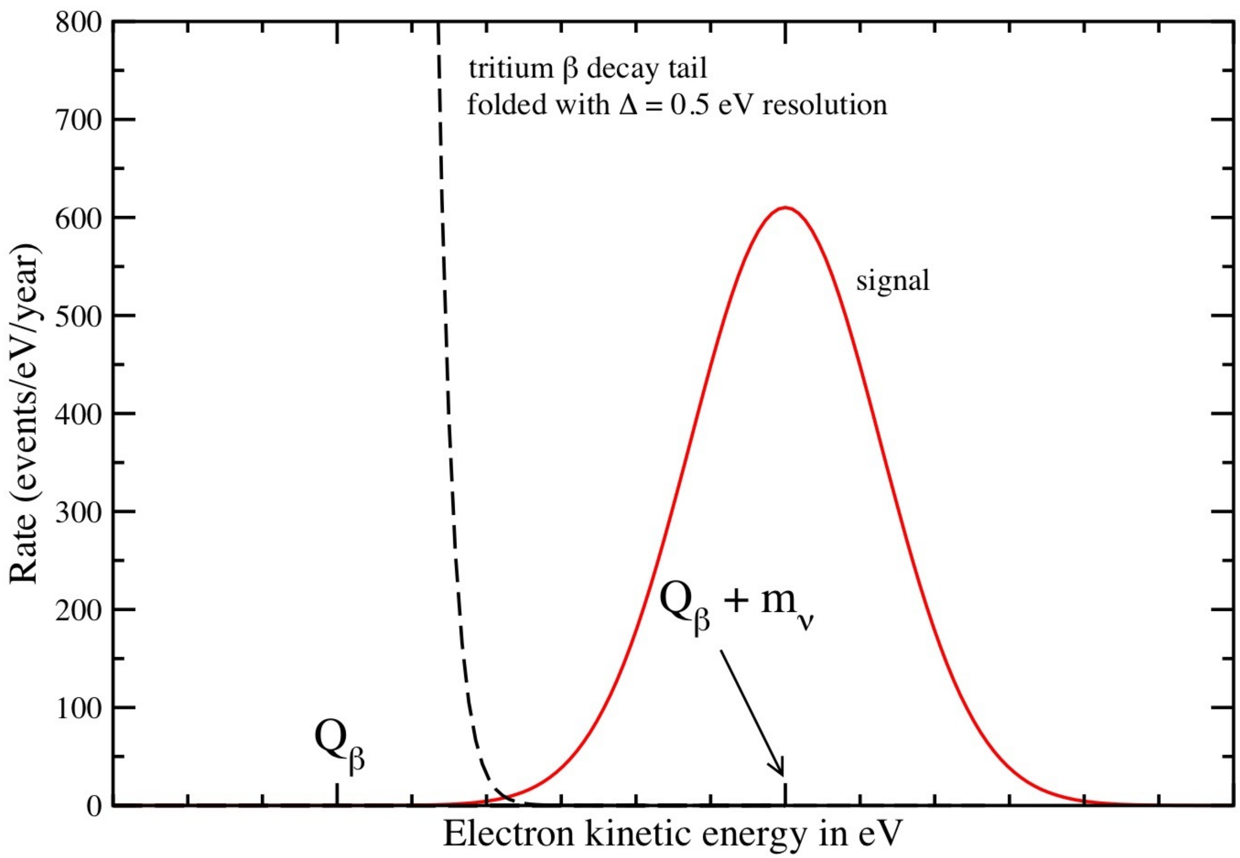
Here are the ratios tritium/KamLAND:

| | |
|---|---|
| Cross section | ~100 |
| Number of targets | ~$5 \times 10^{-7}$ |
| Flux | ~$10^4$ |
| Total | ~0.5 |

Finally, the last and most difficult question:

## Can one separate the signal from background?

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




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

There are, thus, two challenging problems:

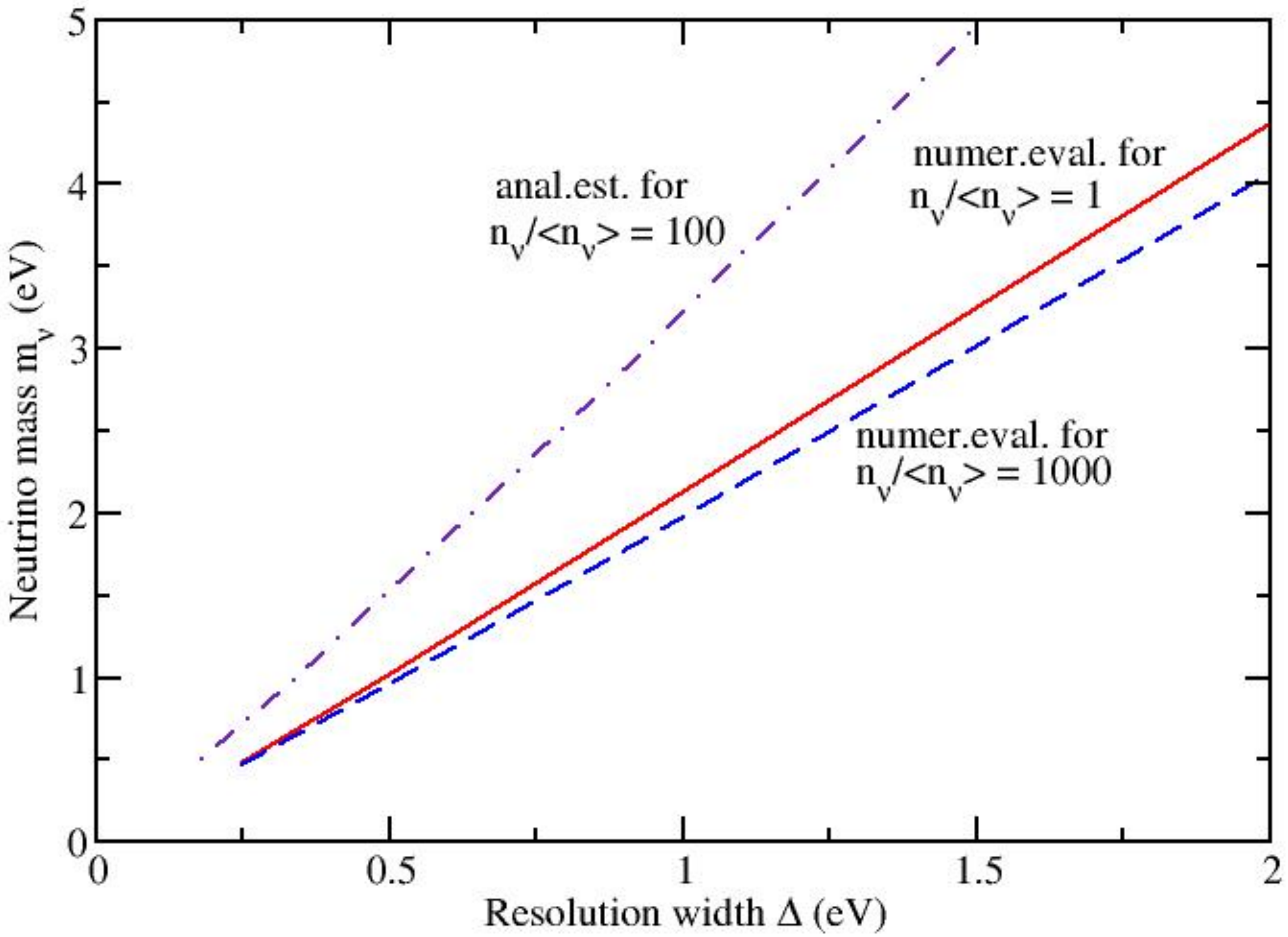
1) Can one filter out up to the ~$10^{16}$ electrons/s that have energies below the endpoint?
   In KATRIN design the ratio between electrons in the window of planned 0.2 eV sensitivity and the total decay rate is ~$10^{15}$. So, the filter used in KATRIN will be essentially capable to reach the required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

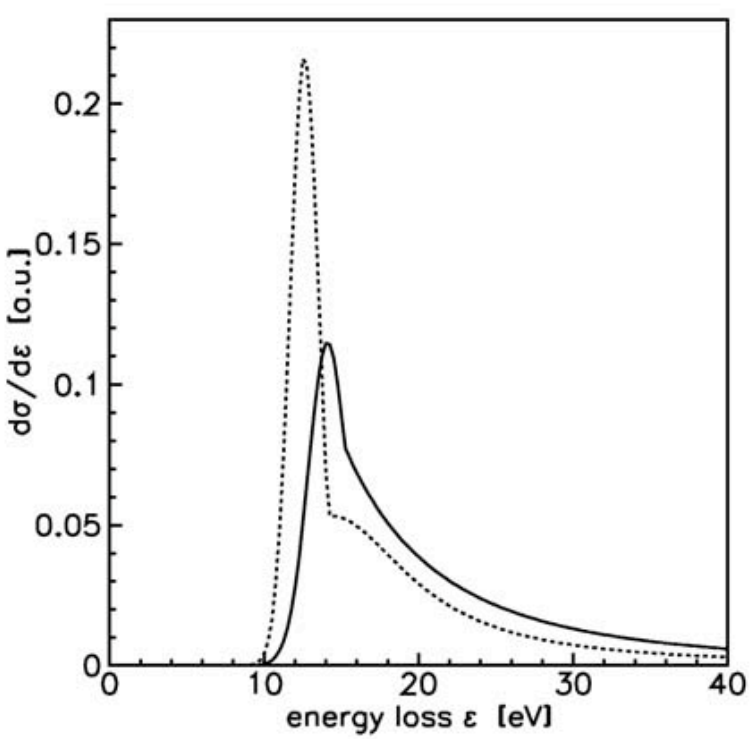
The analytic formula suggest that $m_\nu/\Delta \sim 3$ is needed, numerical evaluation gives $m_\nu/\Delta \sim 2$ , a somewhat more favorable ratio.

Relation between $m_\nu$ and $\Delta$ for which signal/background = 1



# Here are potential killer problems:

1) Past and planned experiments use molecular $T_2$. The rotational-vibrational states in the final $^3$HeT 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 $\sigma$=3x$10^{-18}$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).

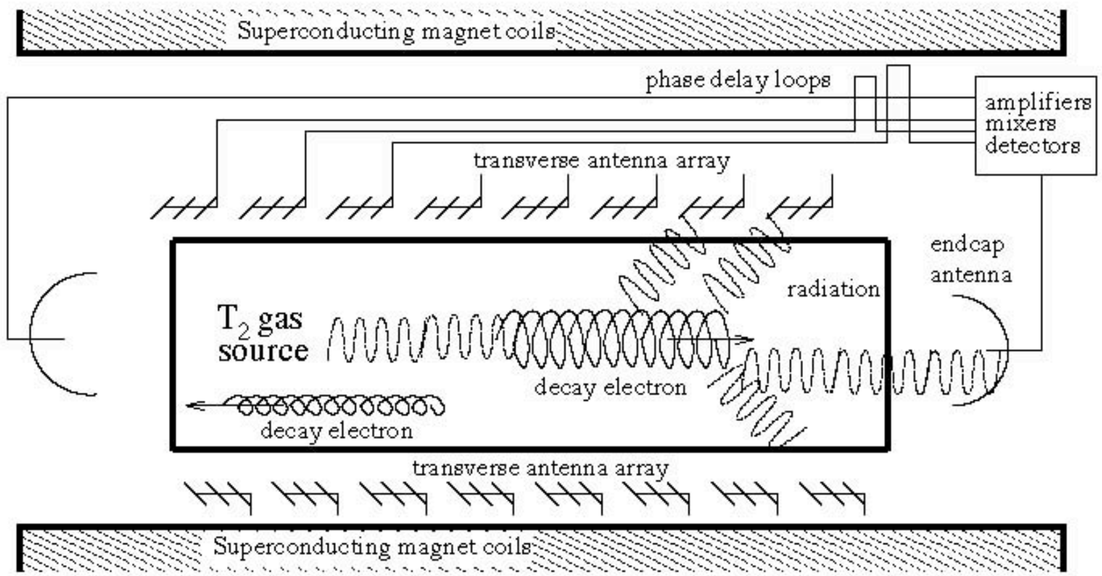



FIG. 1: Schematic of the proposed experiment. A chamber encloses a diffuse gaseous tritium source under a uniform magnetic field. Electrons produced from beta decay undergo cyclotron motion and emit cyclotron radiation, which is detected by an antenna array. See text for more details.

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

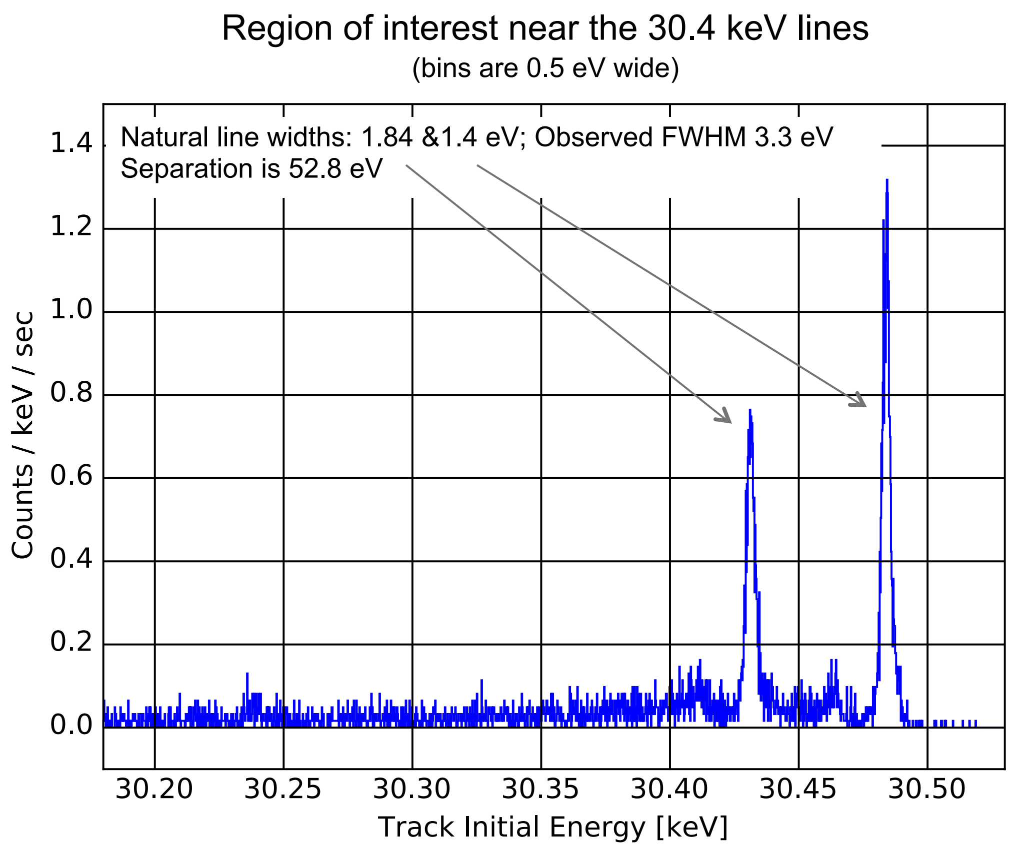
Each electron emits microwaves at frequency $\omega$ and total power

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

where $\beta$ is the electron velocity and $\theta$ 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 demonstrated using a small cell with the gaseous monoenergetic conversion electron source $Kr^{83m}$ ( Asner et al., arXiv: 1408:5362)

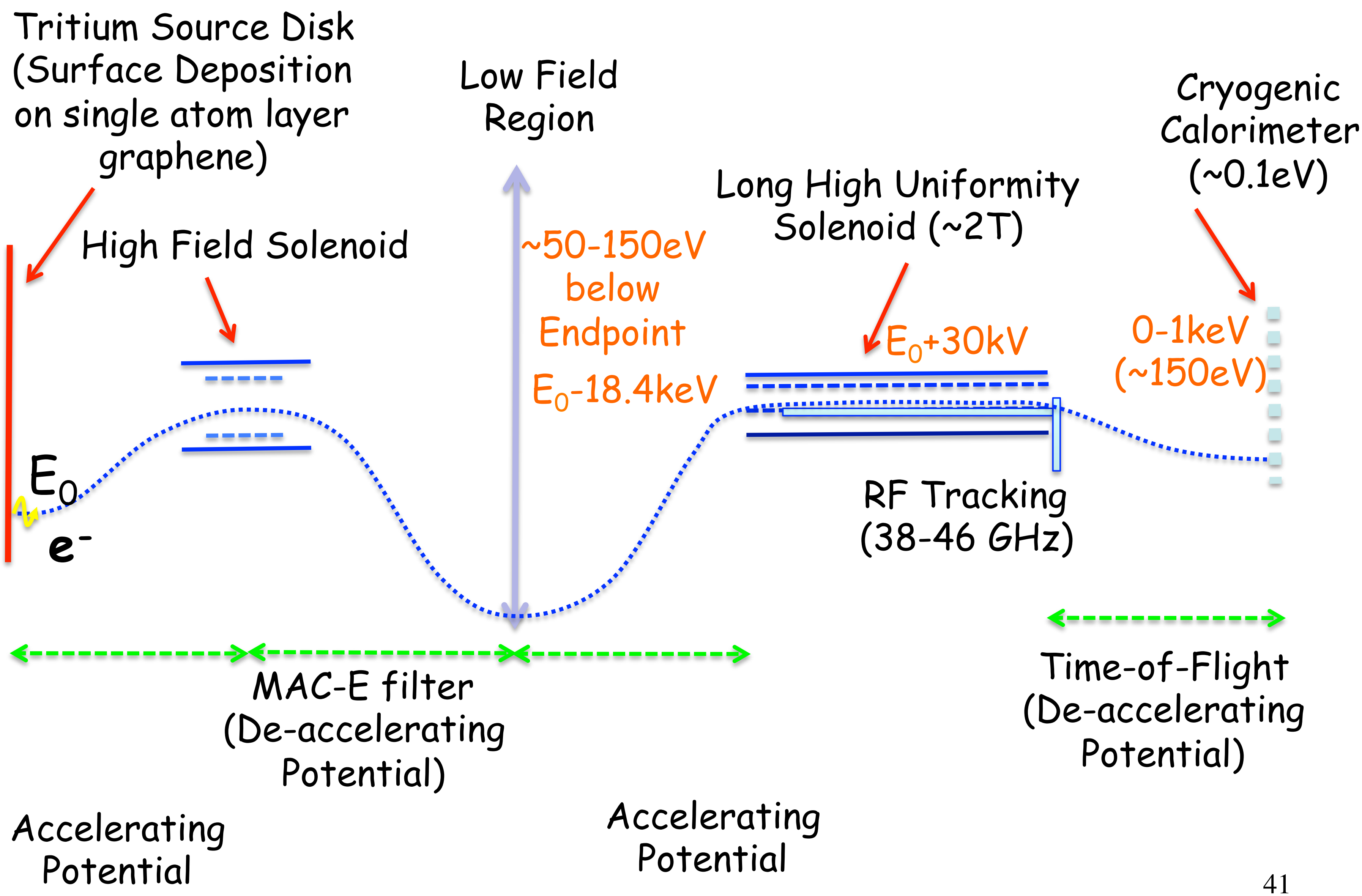



Energy resolution achieved in the Phase 1 of the project (Esfahani et al., 1703.02037)

# 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 $\nu_e$ 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

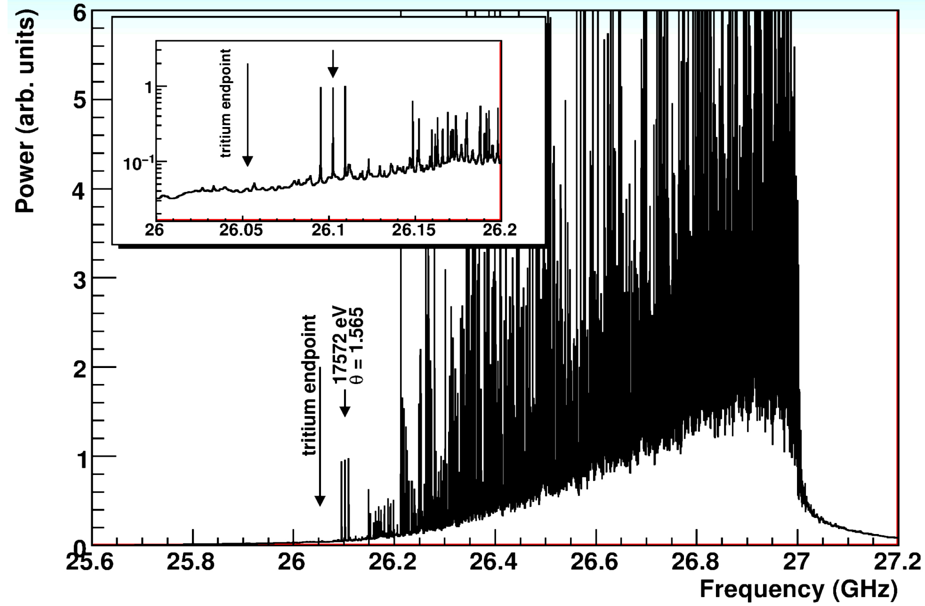
Since the momentum of the CNB $p_\nu \to 0$, we must consider only exothermic reaction, i.e., reactions on unstable targets.
What is the behavior of the cross section when $p_\nu \to 0$ ?

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

$$\boxed{\frac{d\sigma}{d\cos\theta} = \bar{G}^2 E_e p_e[(f^2 + 3g^2) + (f^2 - g^2)v_e v_\nu \cos\theta] \quad \text{with } \bar{G} = G_F \cos\theta_C/\sqrt{2\pi}.}$$

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

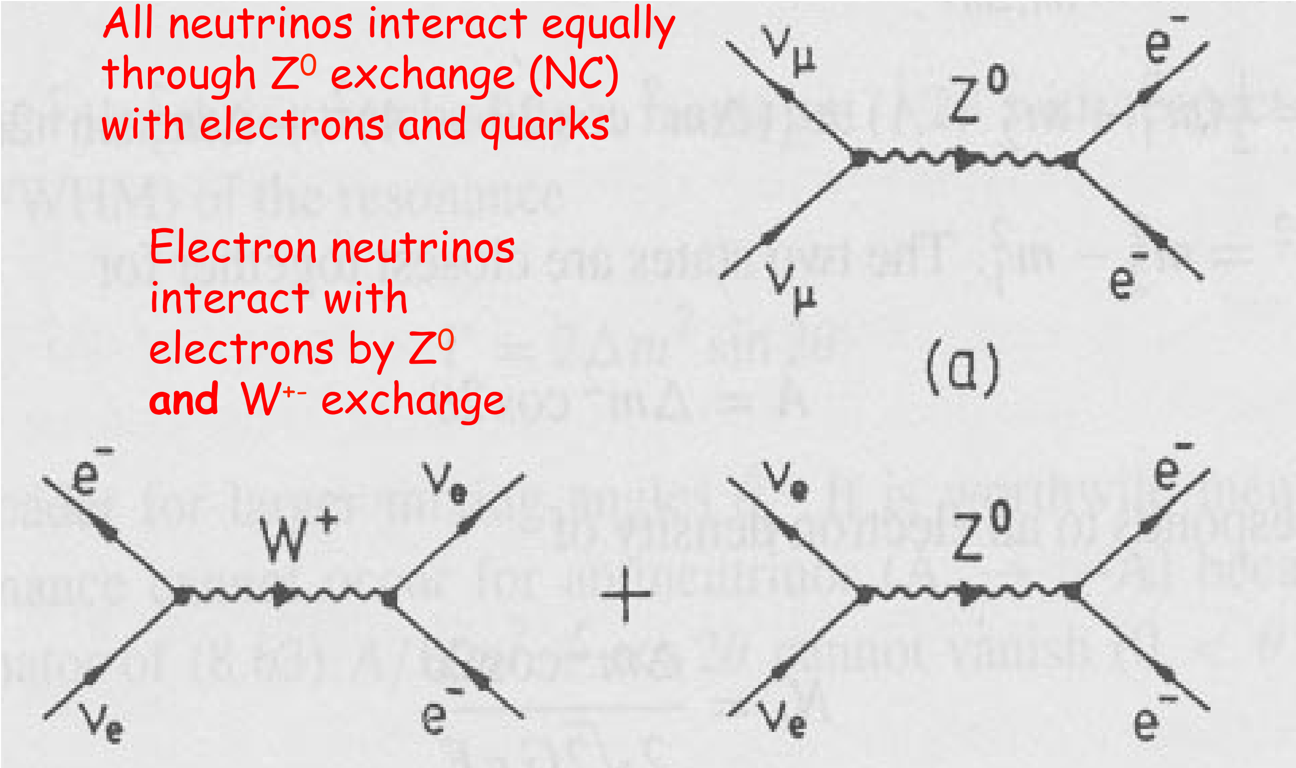
Use cyclotron radiation to measure electron energy of $^{83m}$Kr decay

- 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**

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:

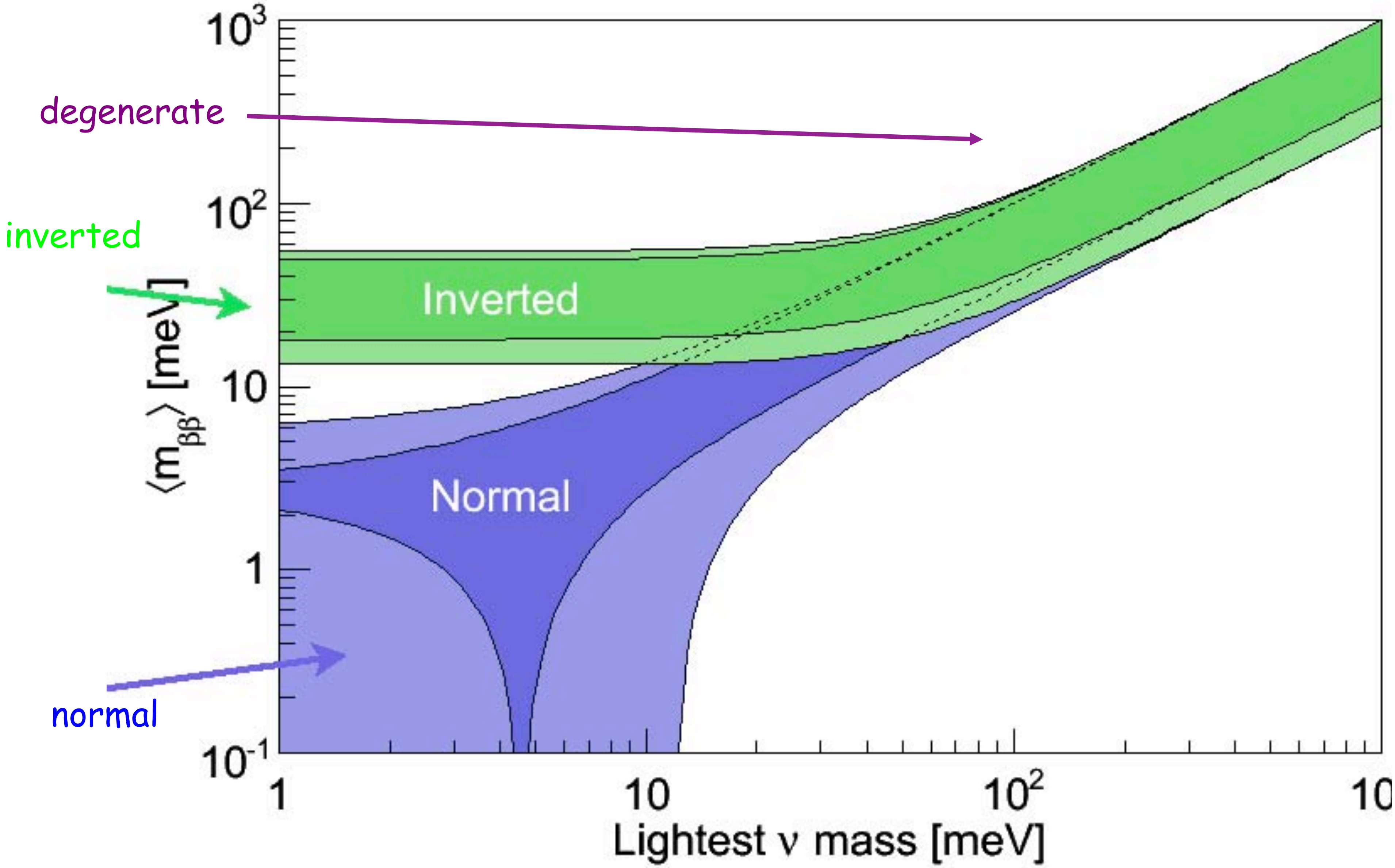



Thus $\mathbf{n-1 = \pm [G_F\, N\, (3Z - A)]/(2^{3/2}\, T_\nu)}$ **for** $\nu_e$ $(\bar{\nu}_e)$

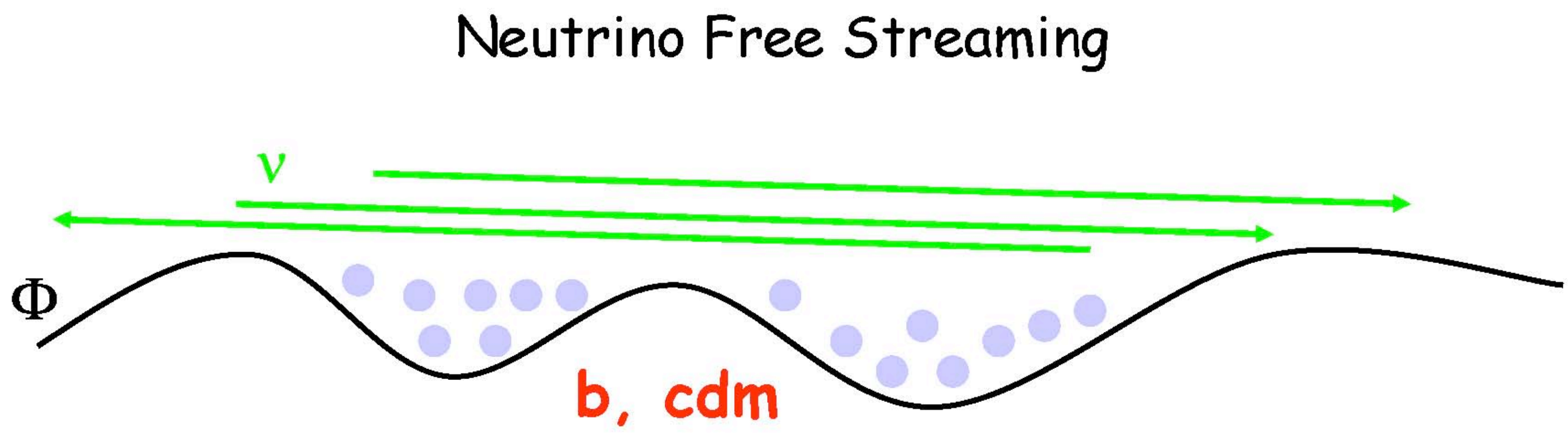
$\mathbf{n-1 = \pm [G_F\, N\, (Z - A))]/(2^{3/2}\, T_\nu)}$ **for** $\nu_\mu, \nu_\tau$ $(\bar{\nu}_\mu, \bar{\nu}_\tau)$

where $T_\nu$ 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



# Neutrinos are natural Hot Dark Matter (HDM)candidates

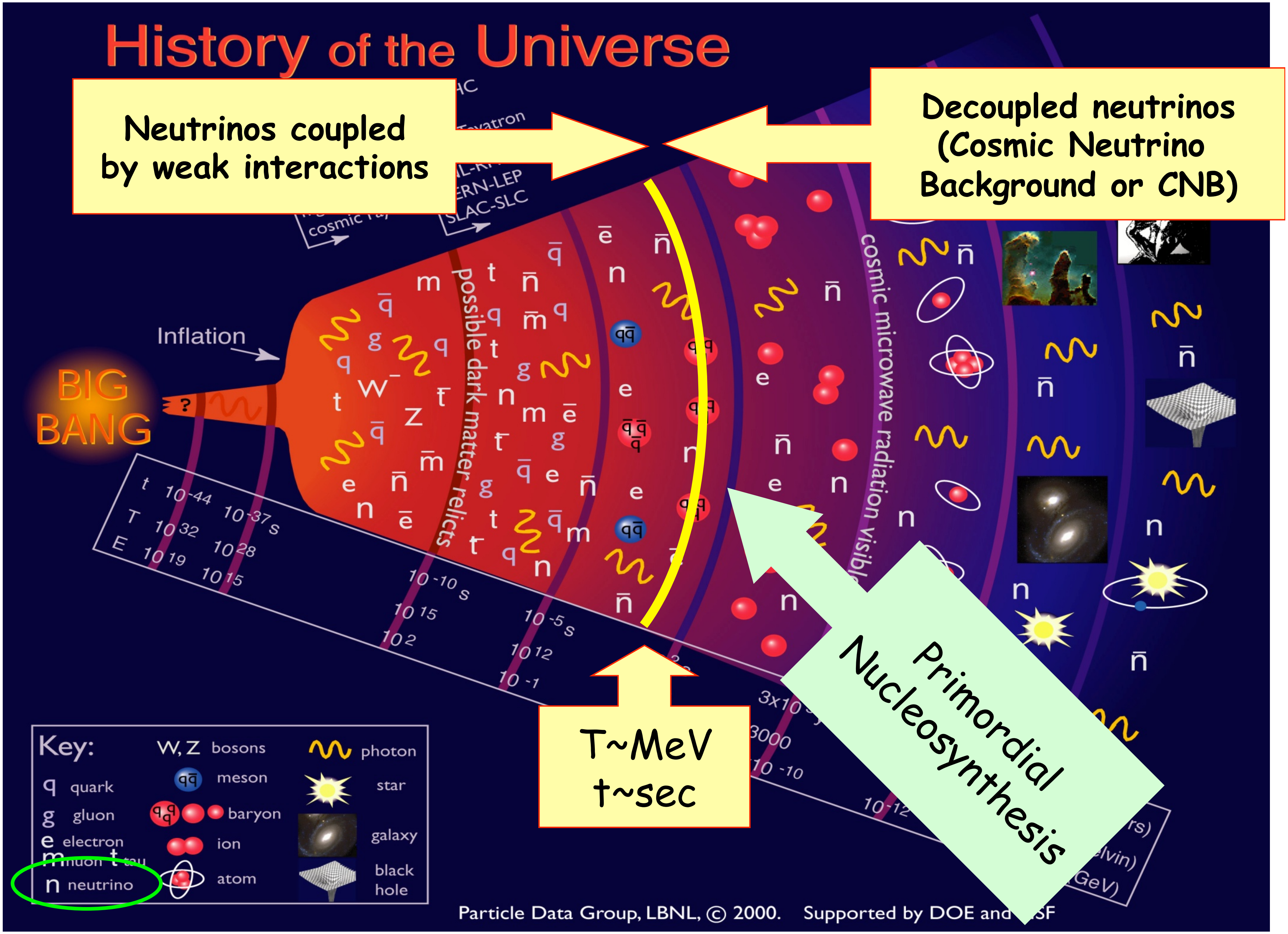



An alternative estimate of the enhancement $n_\nu/\langle n_\nu\rangle$ is obtained by considering the HDM clustering with a velocity dispersion *v* (Peebles):

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

Obtained for $\langle n_\nu\rangle = 110\ \text{cm}^{-3}$ 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
Neutrinos coupled by weak interactions
Decoupled neutrinos (Cosmic Neutrino Background or CNB)
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
T~MeV
t~sec
Primordial Nucleosynthesis
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
galaxy
e electron
ion
muon tau
n neutrino
atom
black hole
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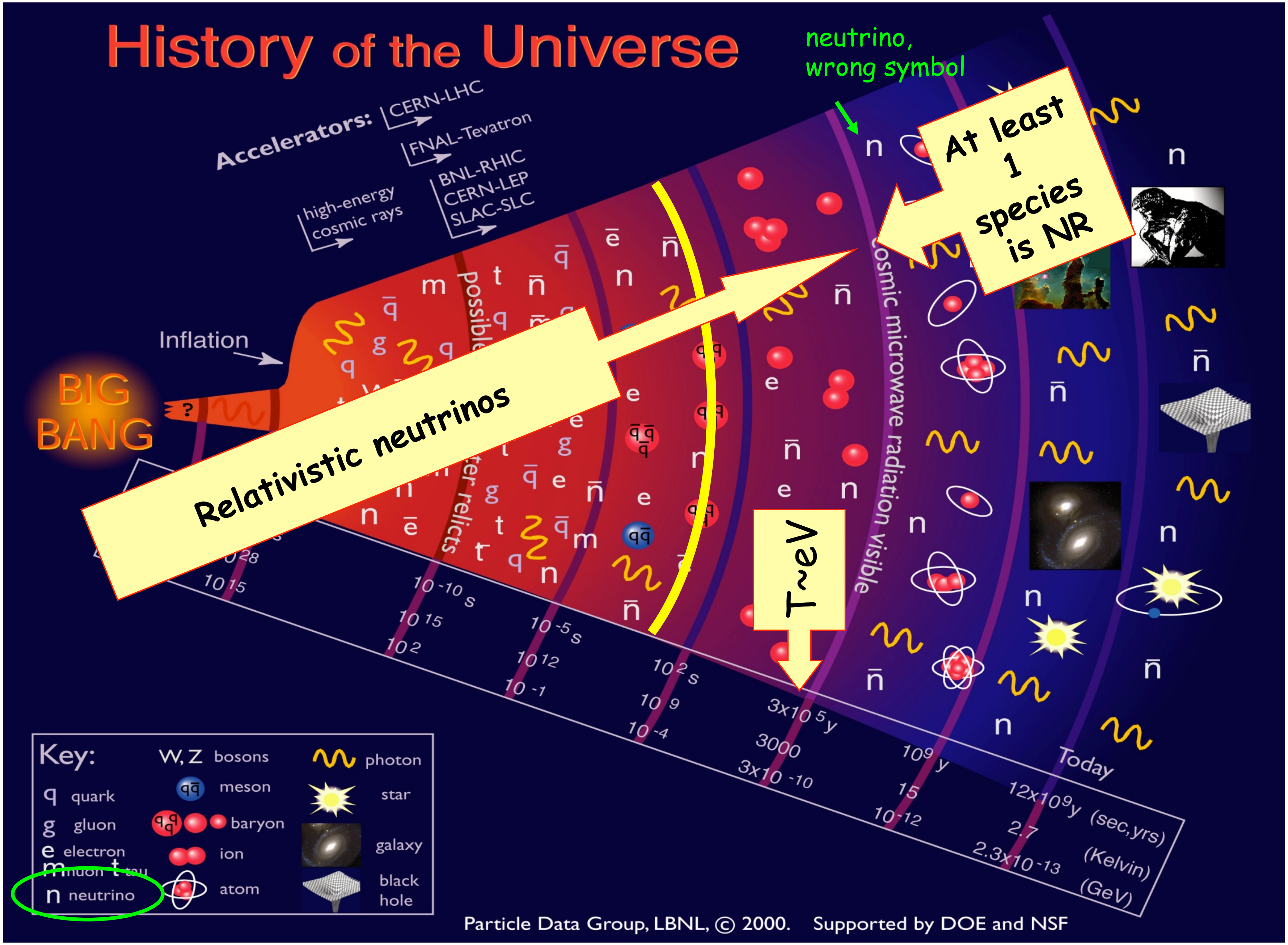

History of the Universe
neutrino, wrong symbol
At least 1 species is NR
Relativistic neutrinos
T~eV
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible matter relics
cosmic microwave radiation visible
$10^{-10}$ s
$10^{15}$
$10^{2}$
$10^{-5}$ s
$10^{12}$
$10^{-1}$
$10^{2}$ s
$10^{9}$
$10^{-4}$
$3\times10^{5}$ y
3000
$3\times10^{-10}$
$10^{9}$ y
15
$10^{-12}$
Today
$12\times10^{9}$ y
2.7
$2.3\times10^{-13}$
(sec,yrs)
(Kelvin)
(GeV)
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
ion
galaxy
m muon
t tau
n neutrino
atom
black hole
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